Explosive phenomena: SNe and GRBs

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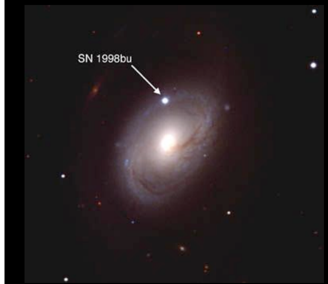

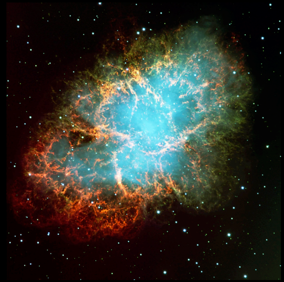

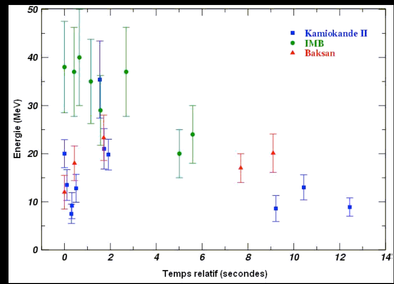

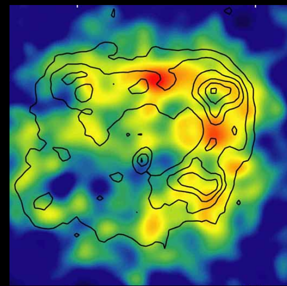

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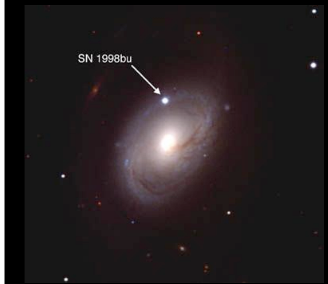

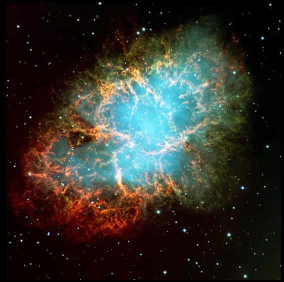

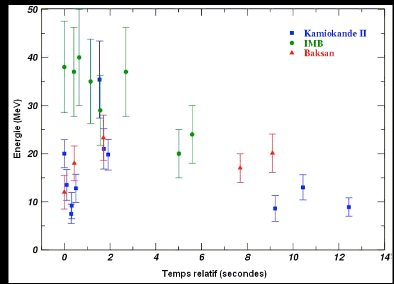

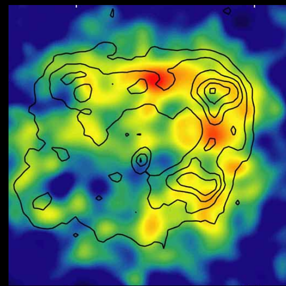

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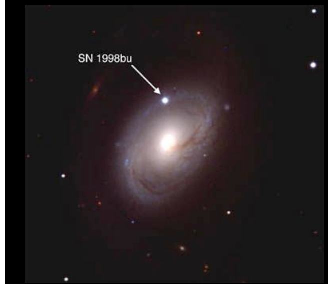

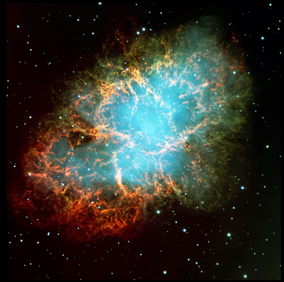

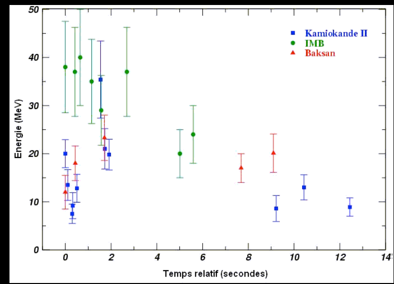

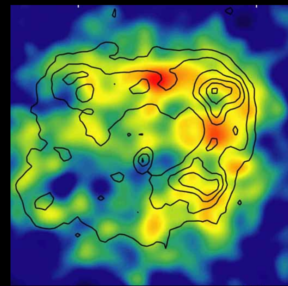

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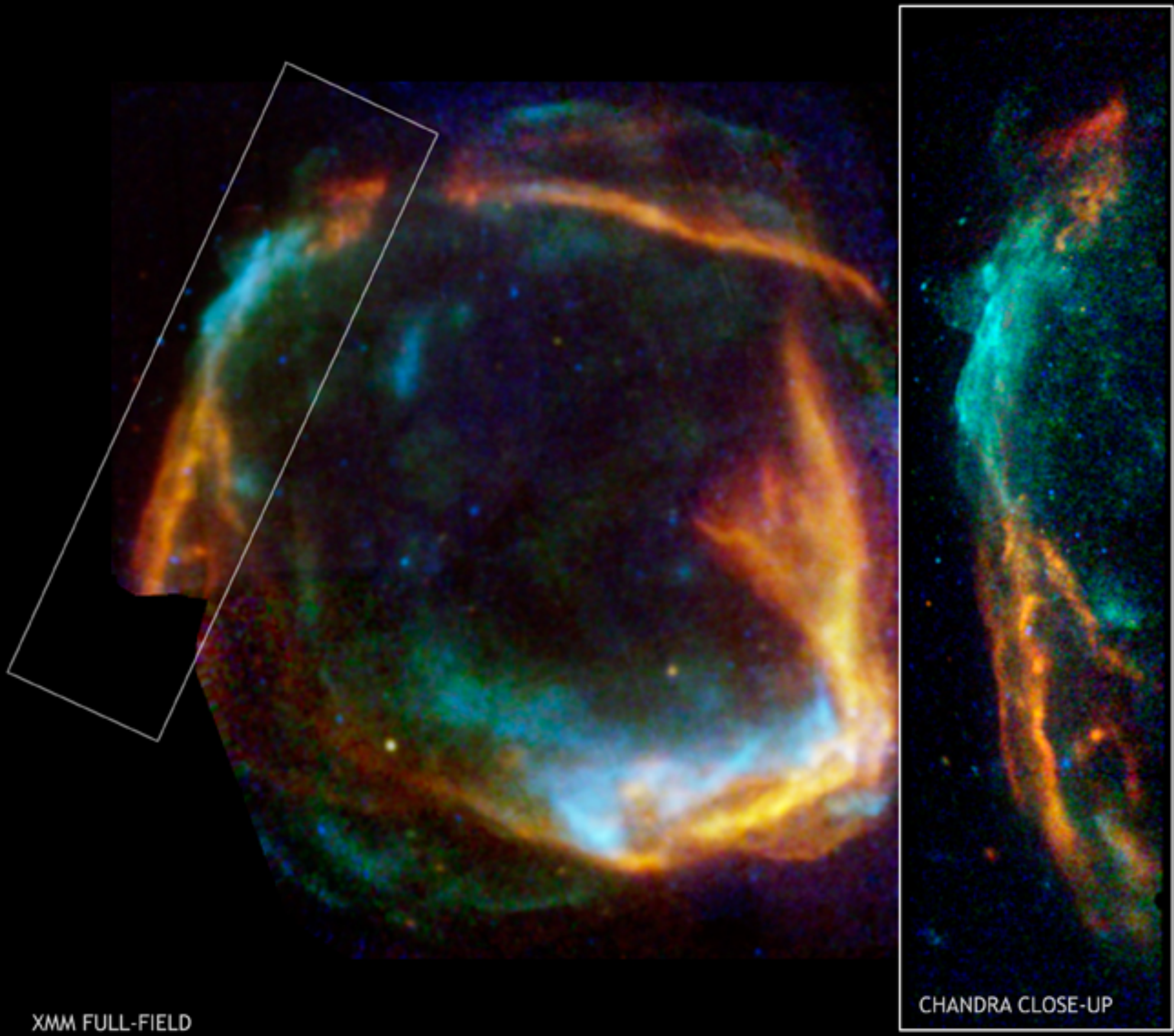
SN 2007f (type Ia) in NGC 5584 - VLT

Historical remarks

- possible ancient supernovae (China -1400 ; China 185 ; China 386-387)

FIGURE 42 – **Les plus anciens témoignages écrits d'une supernova ?** *Gauche et milieu :* deux fragments d'os sacrés (ou fragments de carapace de tortue) datant du XIV^{e} siècle av. JC, sous la dynastie Shang. Ils rapportent l'observation d'événements qui pourraient être des supernovae. Seul le second fragment donne une direction, on ne peut donc pas dire s'il s'agit de deux descriptions du même phénomène. *Droite :* inscription chinoise trouvée sur le fragment du milieu *« Le septième jour du mois, un jour « Ji-Si », une nouvelle étoile remarquable apparaît en compagnie d'*[Antarès (α Sco)] » (figure tirée de Z. Wang, 1996).

SN 185 ? : RCW 86



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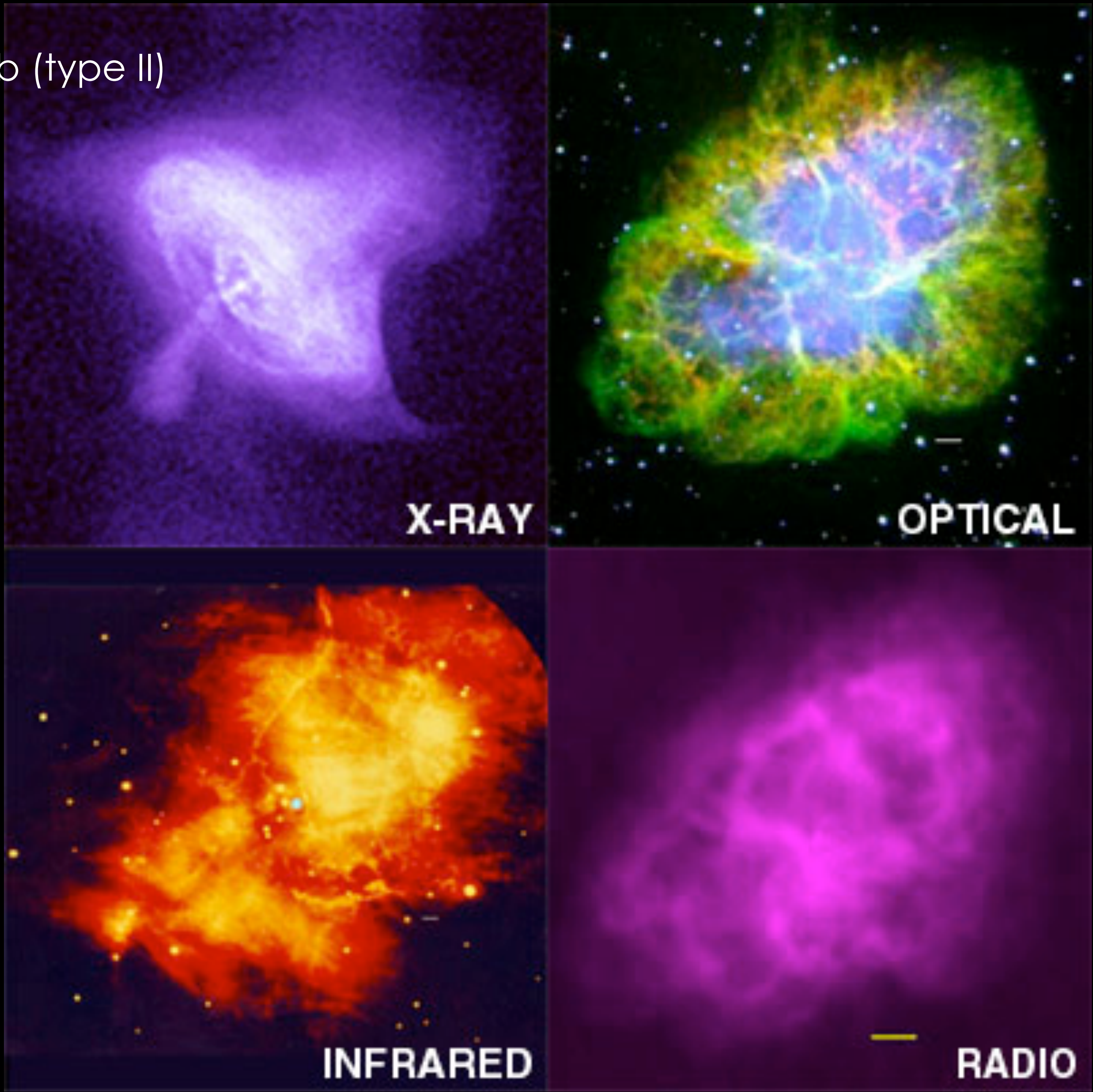
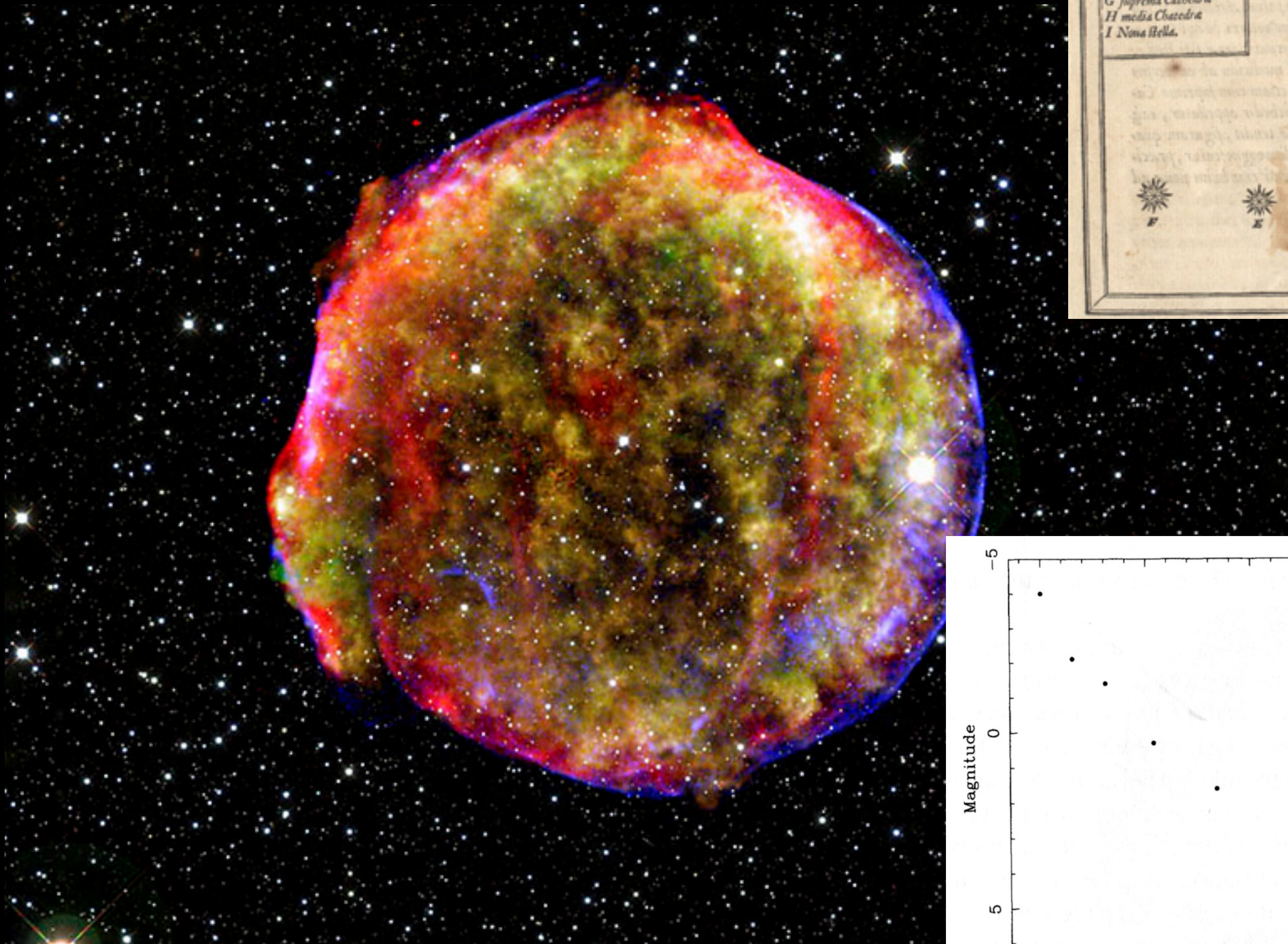
- SN 1181 (China & Japan)

- SN 1572 : Tycho-Brahé (visible for 15 months in Cassiopea) - "*nova stella*"
- SN 1604 : Kepler (visible for 1 year in Ophuchius)

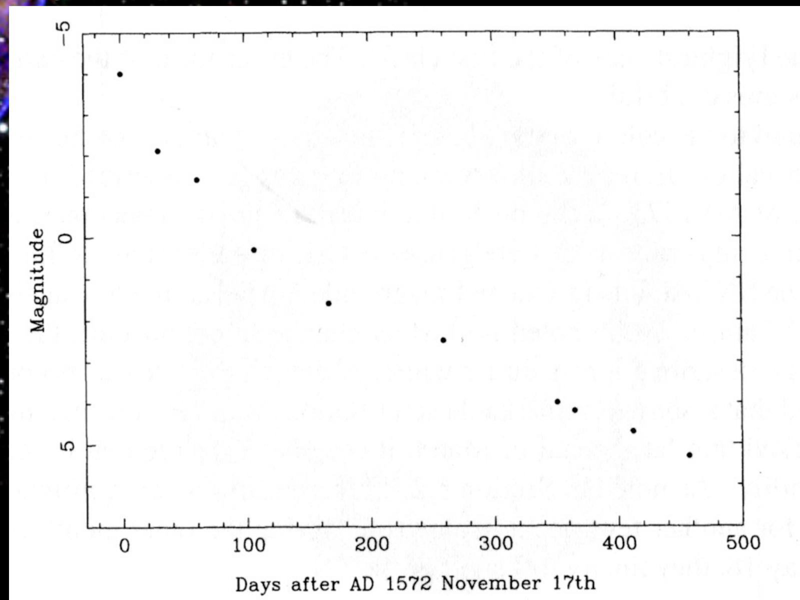
SN 1054 : Crab (type II)



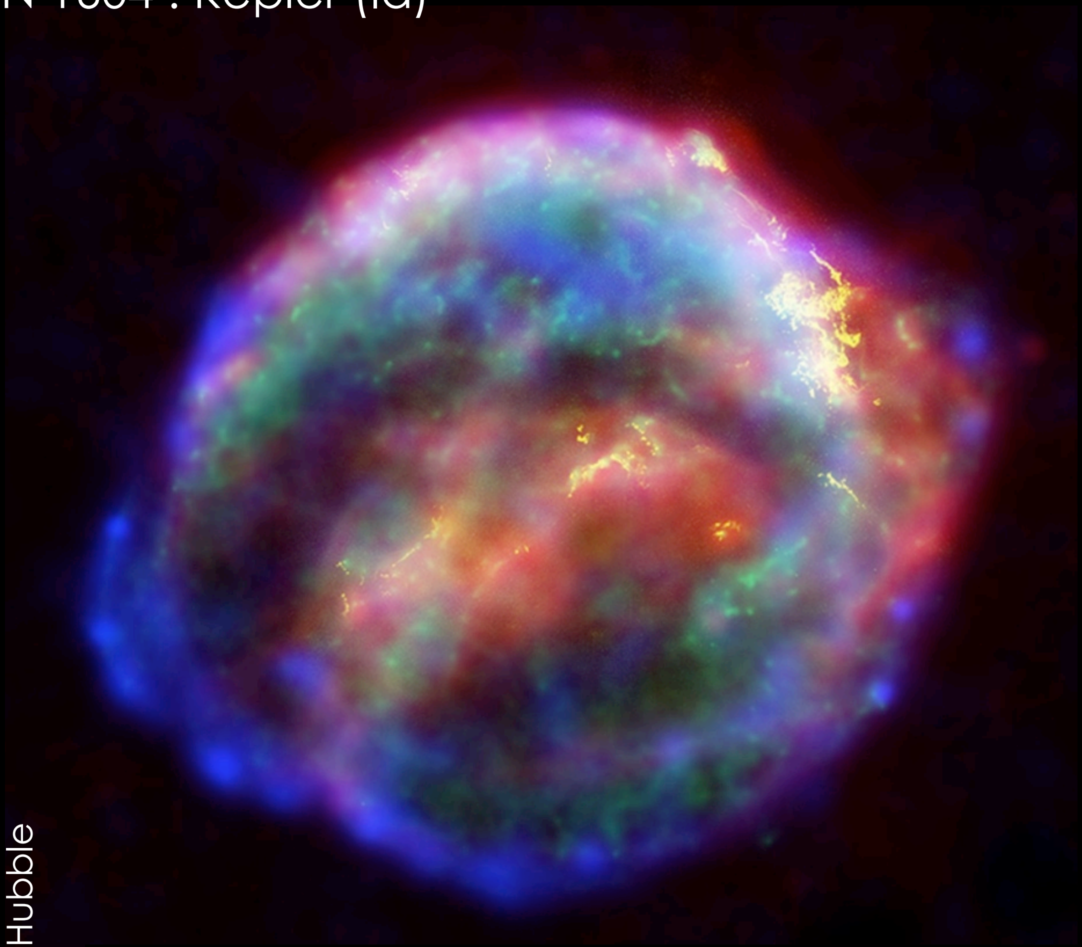
SN 1572 : Tycho (type Ia)

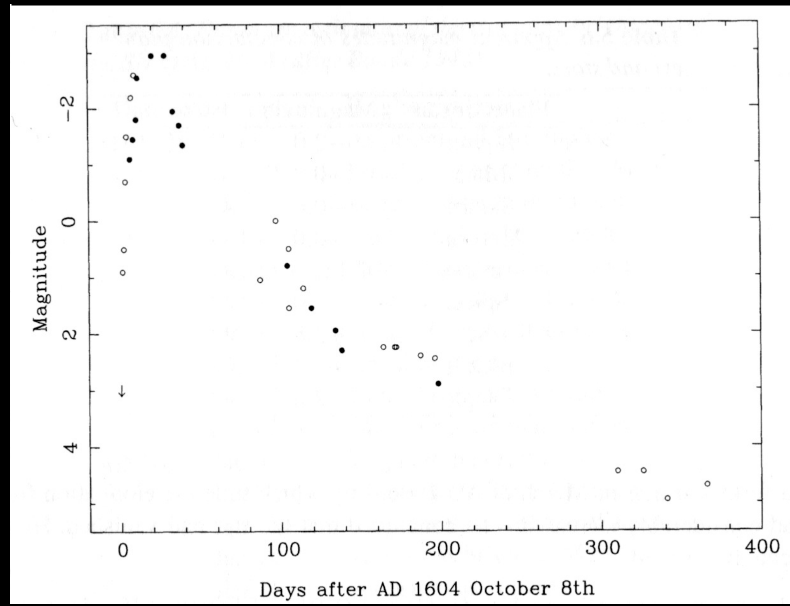


Chandra - Spitzer - Calar Alto

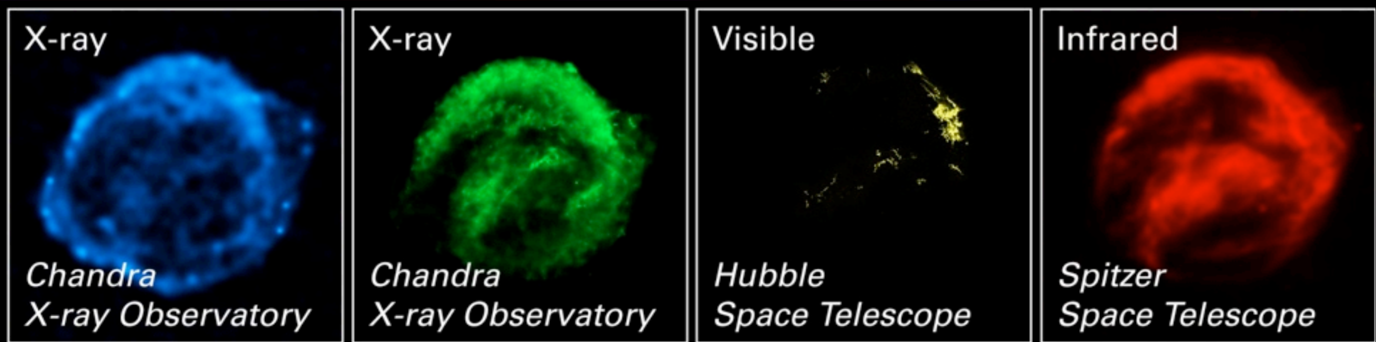


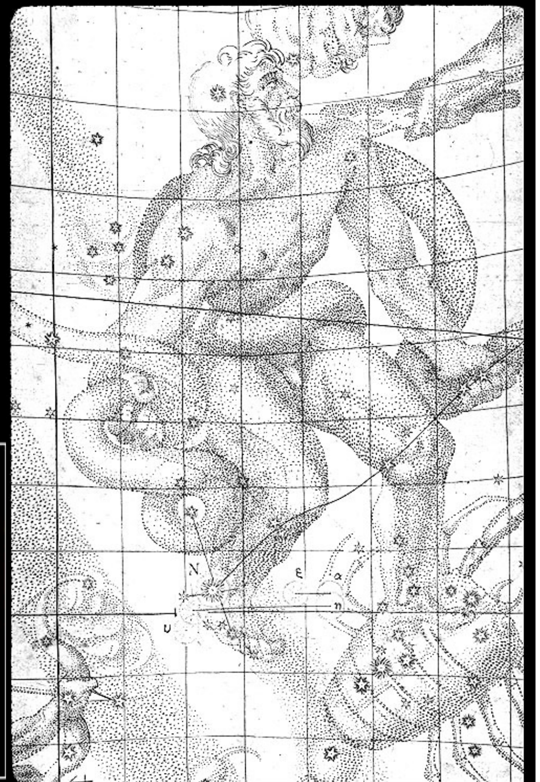
SN 1604 : Kepler (Ia)





Chandra - Spitzer - Hubble





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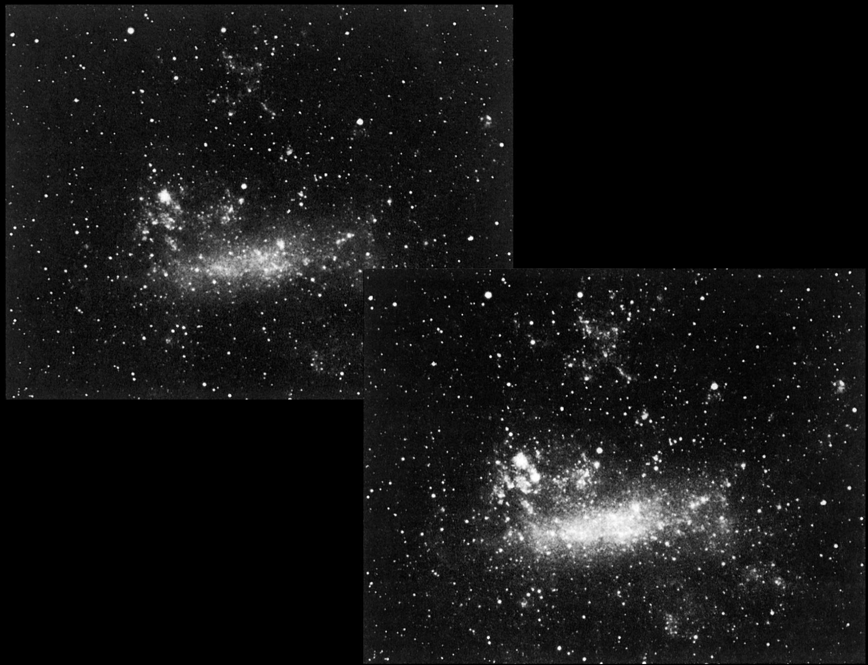
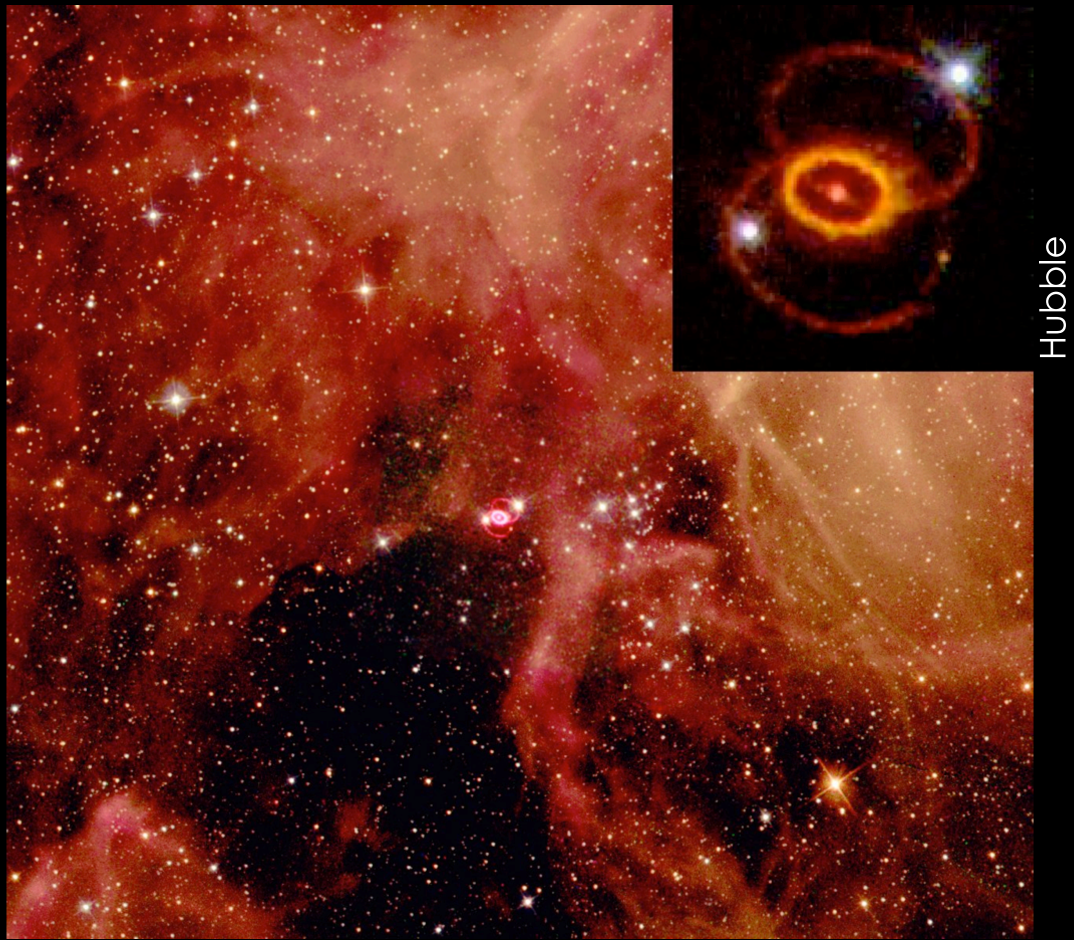
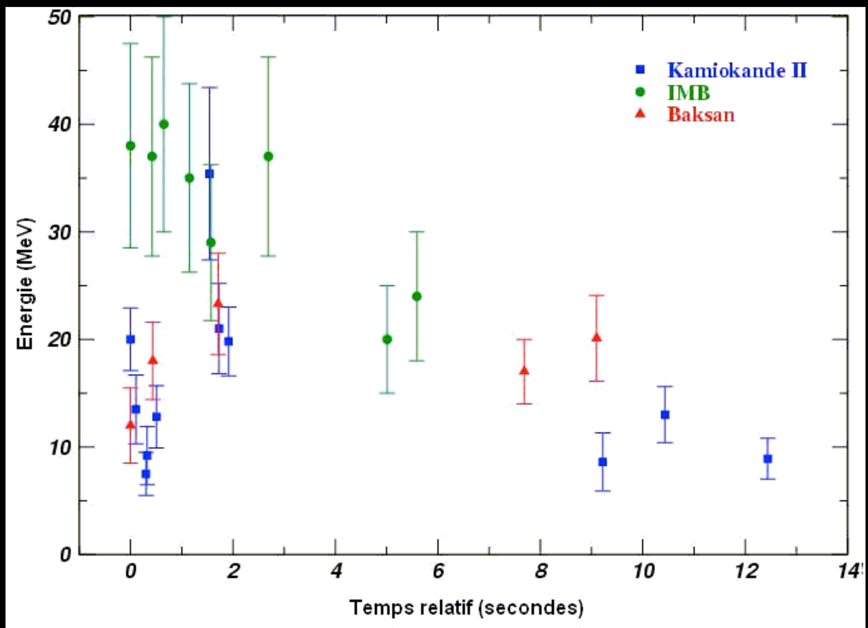
- Baade & Zwicky 1934 : *"supernovae"*

- SN 1987A in the Large Magellanic Cloud

SN 1987A : type II

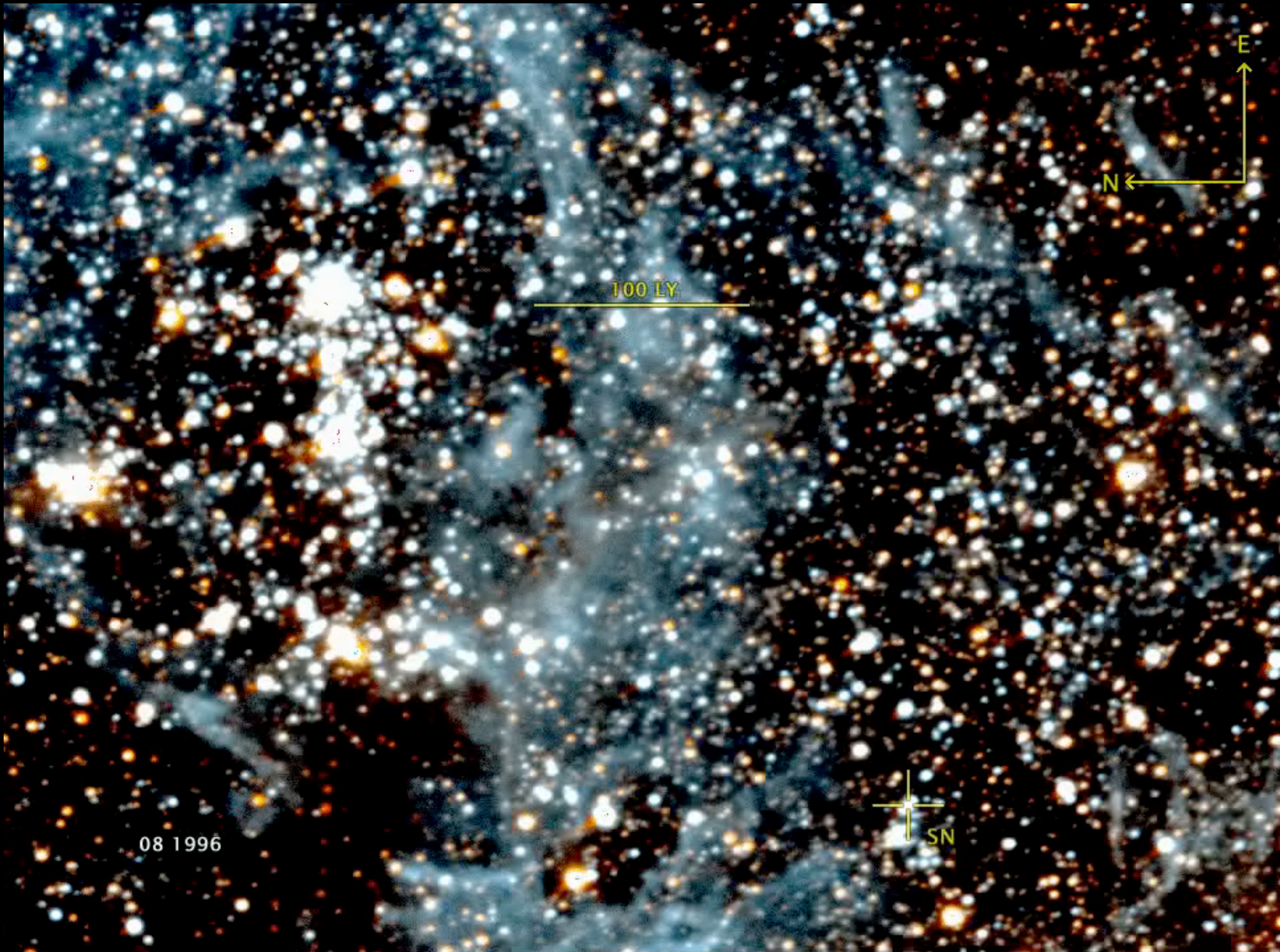






Anti-neutrinos :
11 (Kamiokande II) + 8 (IMB) + 5 (Baksan)
duration : 13 s, neutrino-light delay : about 3 hours

Light echo from SN1987A in LMC (video taken from EROS collaboration)



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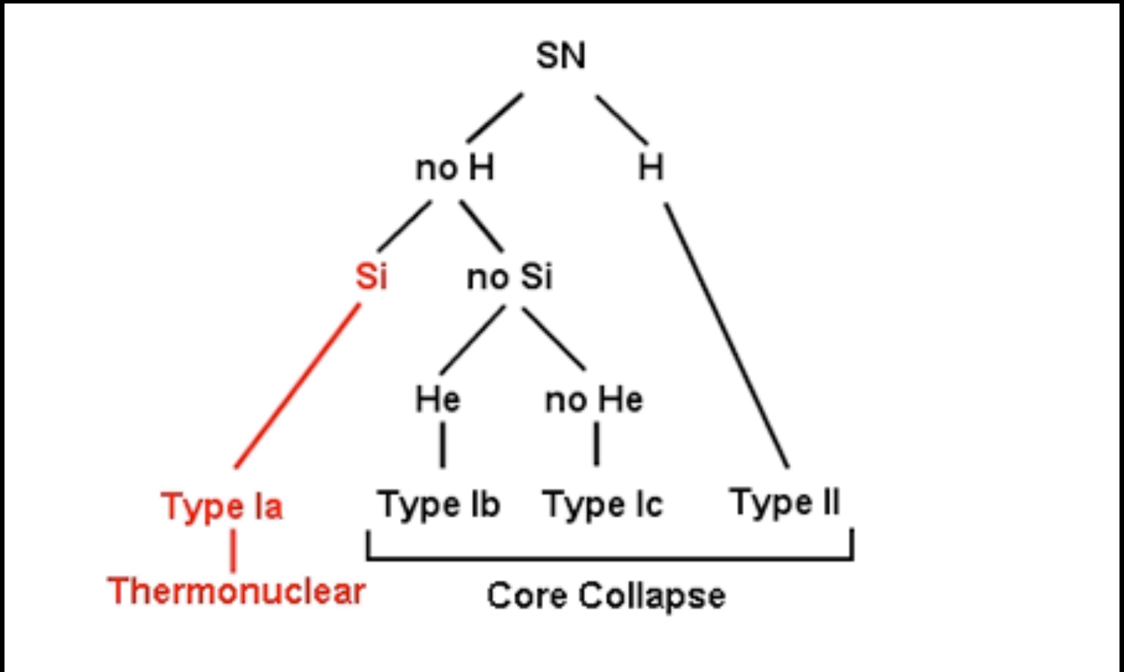
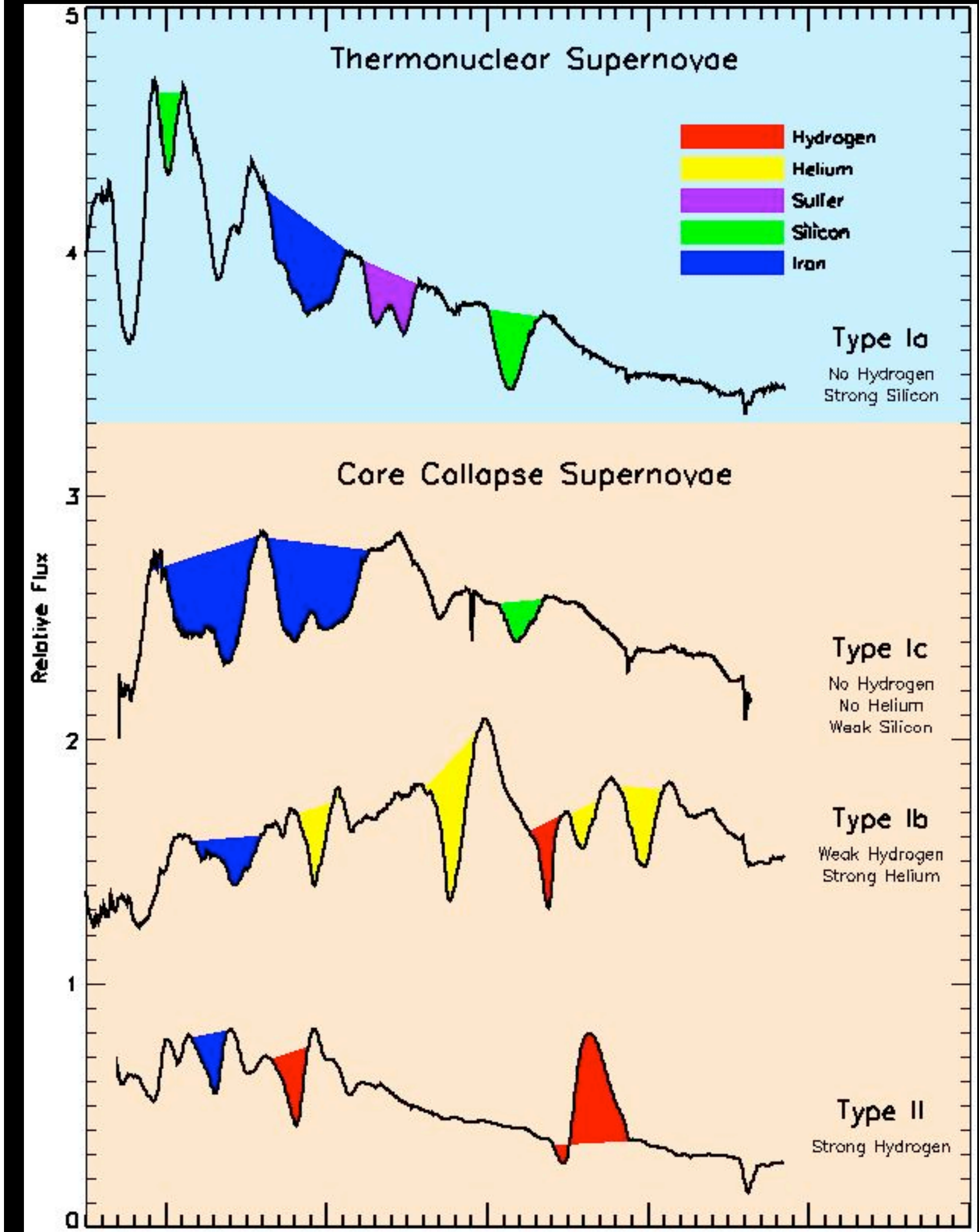
- Baade & Zwicky 1934 : *"supernovae"*

- SN 1987A in the Large Magellanic Cloud

Spectral classification :

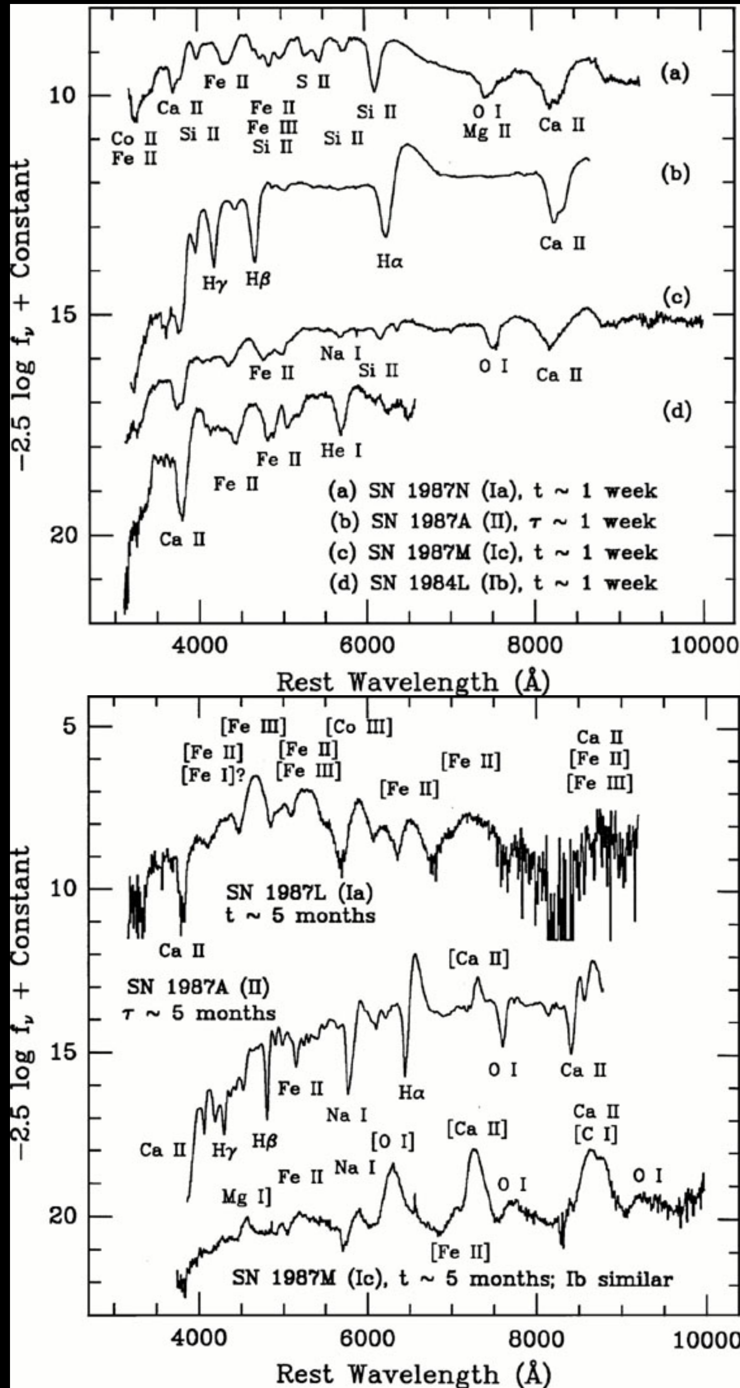
- Hydrogen lines : SNII
- no hydrogen lines : SNI
  * Silicium lines : SNIa
  * no Silicium lines :
    SNIb (Helium lines)
    SNIc (no Helium lines)





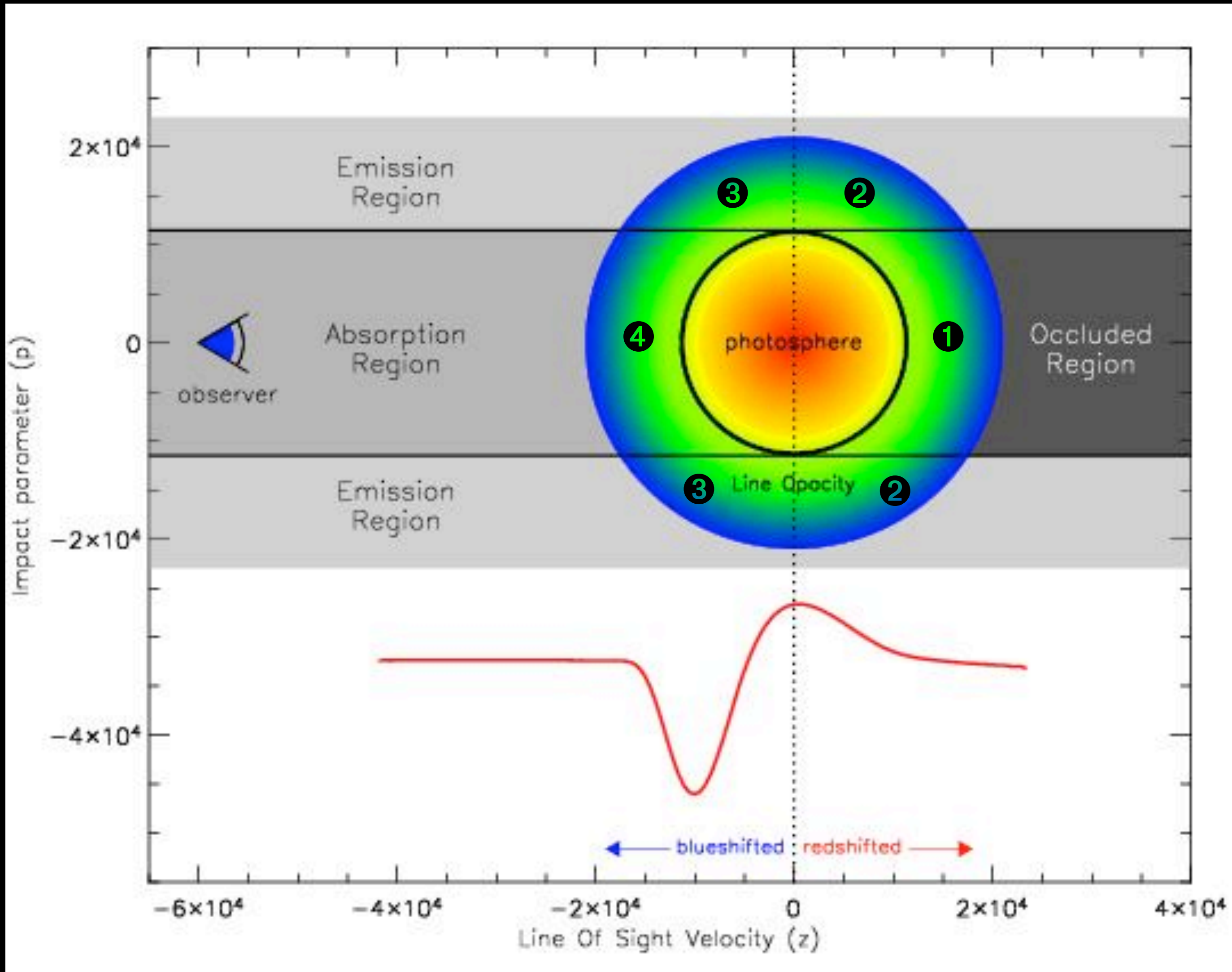
Photospheric spectrum

Nebular spectrum

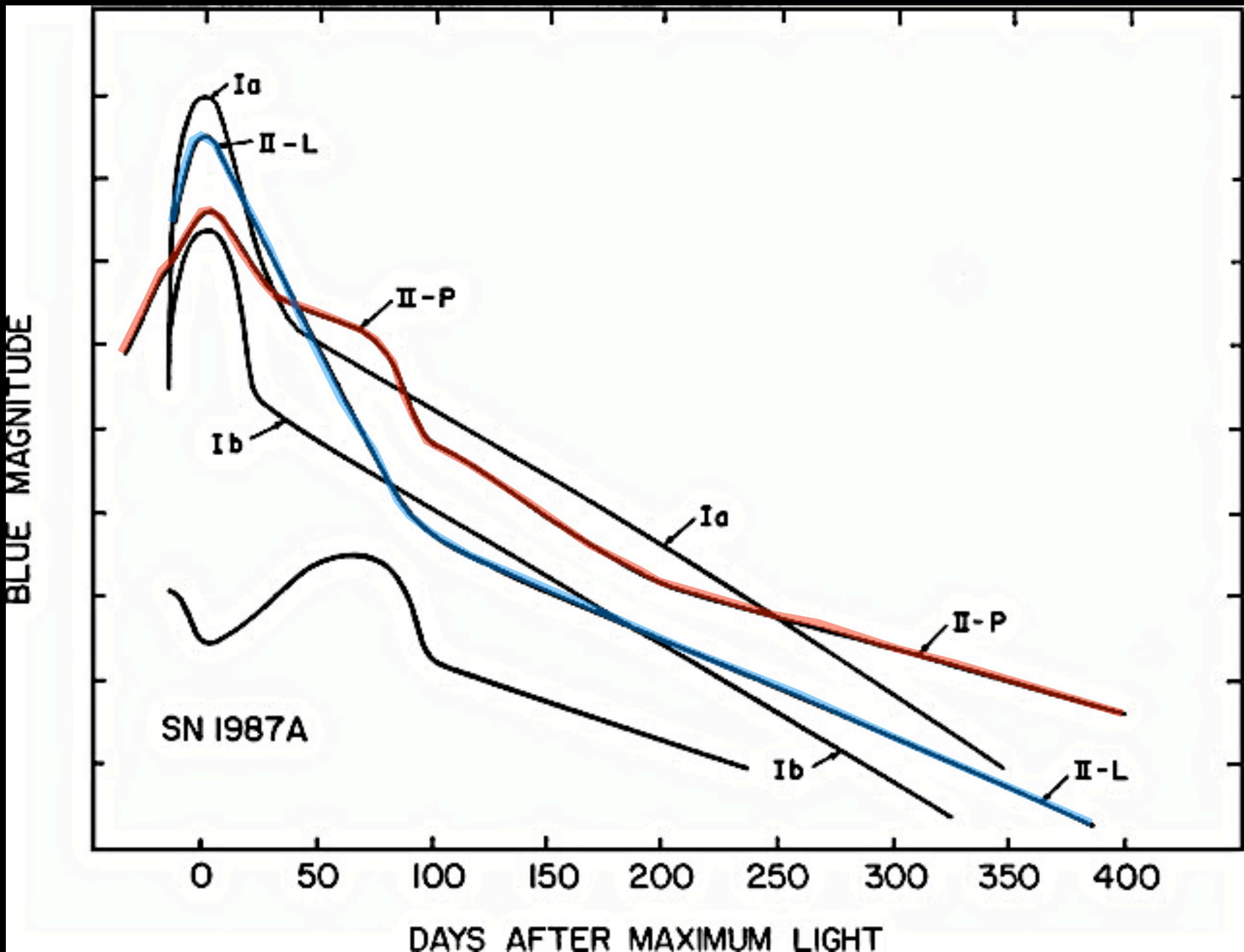


“P-Cygni” line profile

❶ not observed
❷ emission (red)
❸ emission (blue)
❹ emission (blue)+absorption(blue)



Type II SNe: additional classification based on the light curve (type II-P vs type II-L)



Supernova rates

Host galaxy	Supernova rate (SNU) (from Allen's astrophysical quantities, A.N. Cox Editors) Ia	Ib / Ic	II
Elliptical E	0.11		
Lenticular SO	0.15		
Spirals SOa, Sa, Sab, Sb	0.20 ± 0.07	0.11 ± 0.06	0.40 ± 0.19
Spirals Sbc, Scd, Sc, Sdm, Im	0.24 ± 0.09	0.16 ± 0.08	0.88 ± 0.37

1 SNU = 1 supernova per century per 10^{10} $L_\odot$

Estimate for the Mily Way : Sb galaxy with L ~ 2×10^{10} $L_\odot$

0.3 SNe Ia per century

0.2 SNe Ib/c per century
1.7 SNe II per century

Total ~ 2.2 SNe per century ; **IF** constant for 10 Gyr : 220 000 000 supernovae ...

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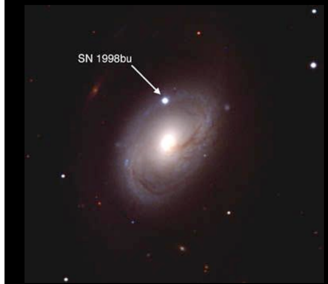

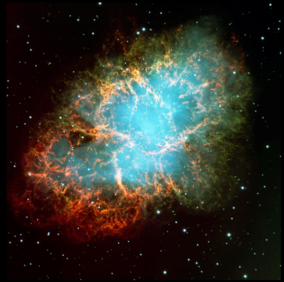

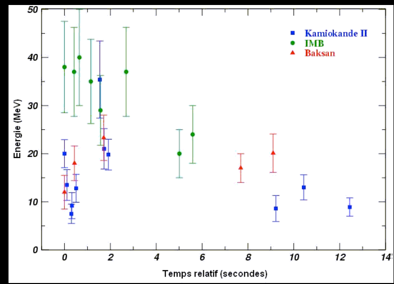

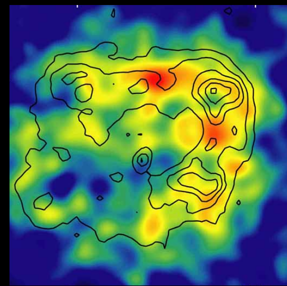

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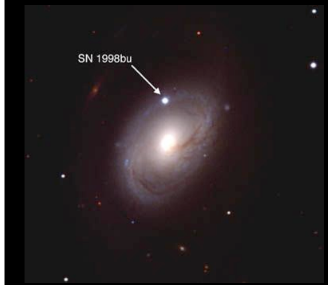

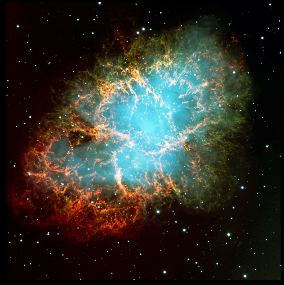

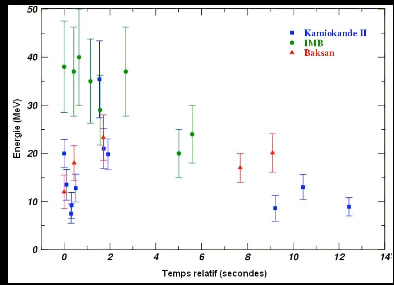

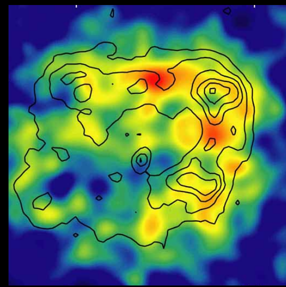

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Two different mechanisms

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Type Ia supernovae = thermonuclear destruction of a white dwarf

- explanation for the host statistics : long delay between star formation and explosion (progenitor is not a massive star)
- explanation for the spectrum : no H in white dwarfs, observed products of CO nuclear burning

Type Ib/Ic and II supernovae = gravitational collapse of a massive star

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not discussed in this lecture

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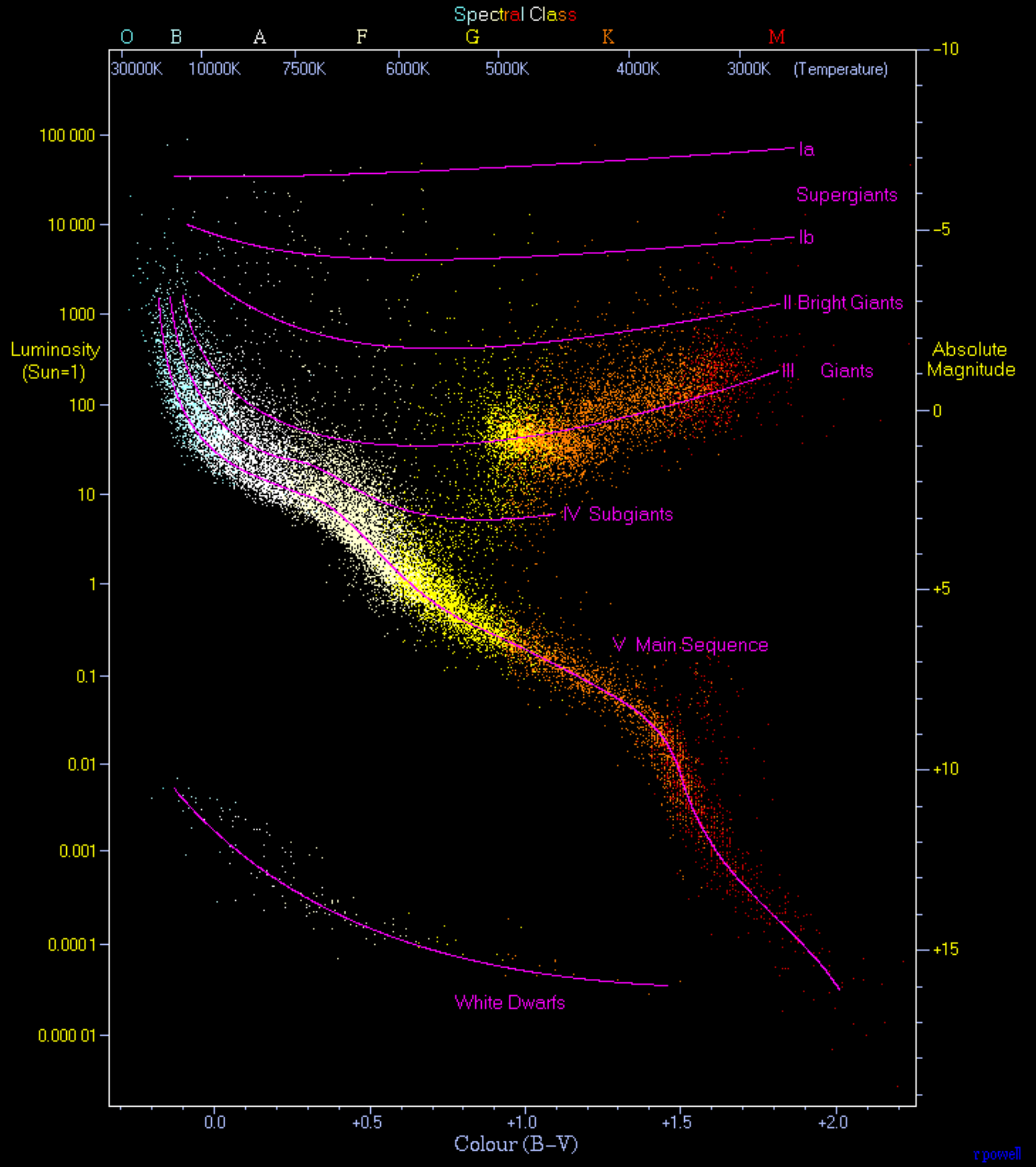
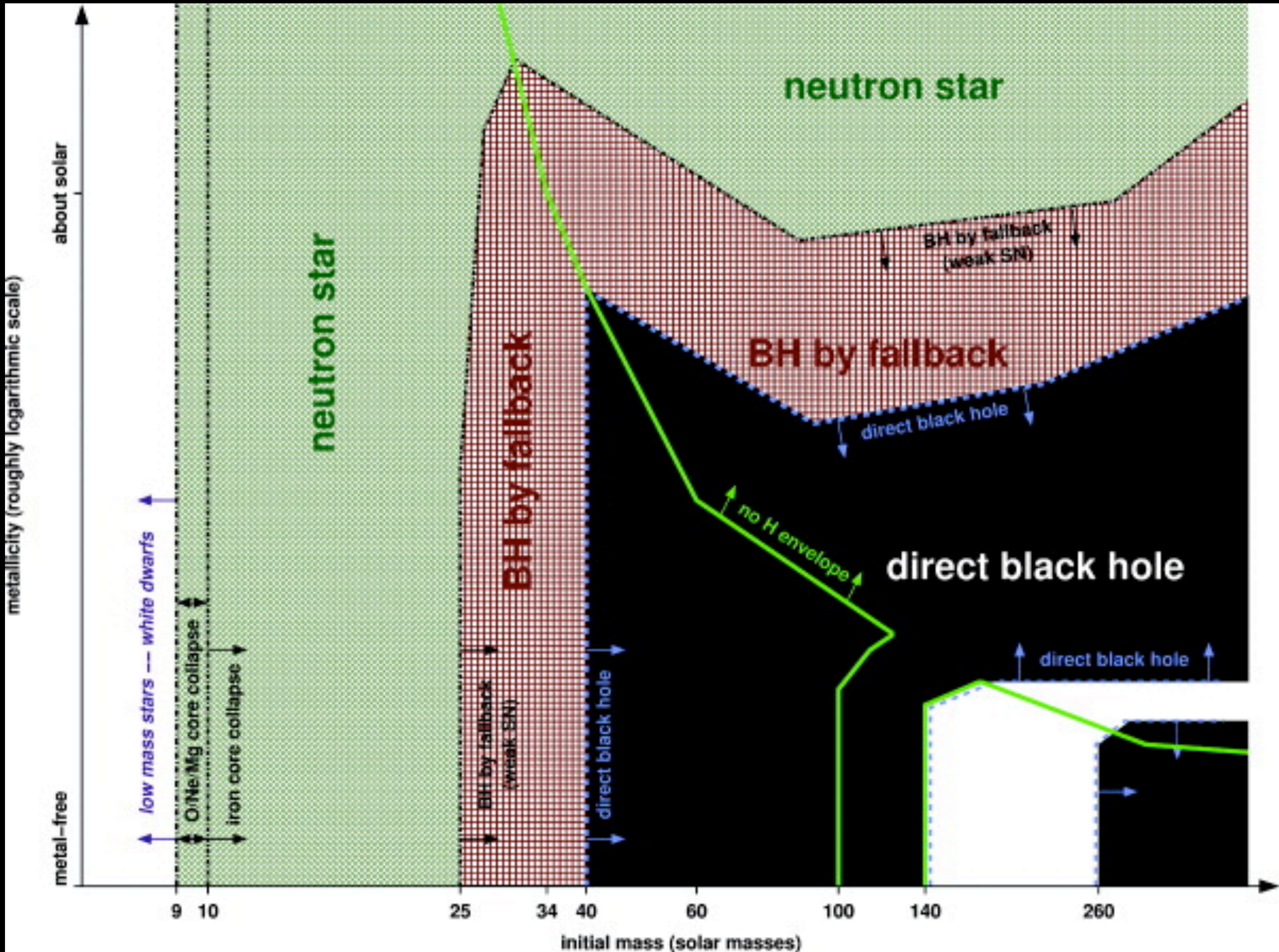
Hertzsprung-Russell (1914)



Hipparcos + Gliese

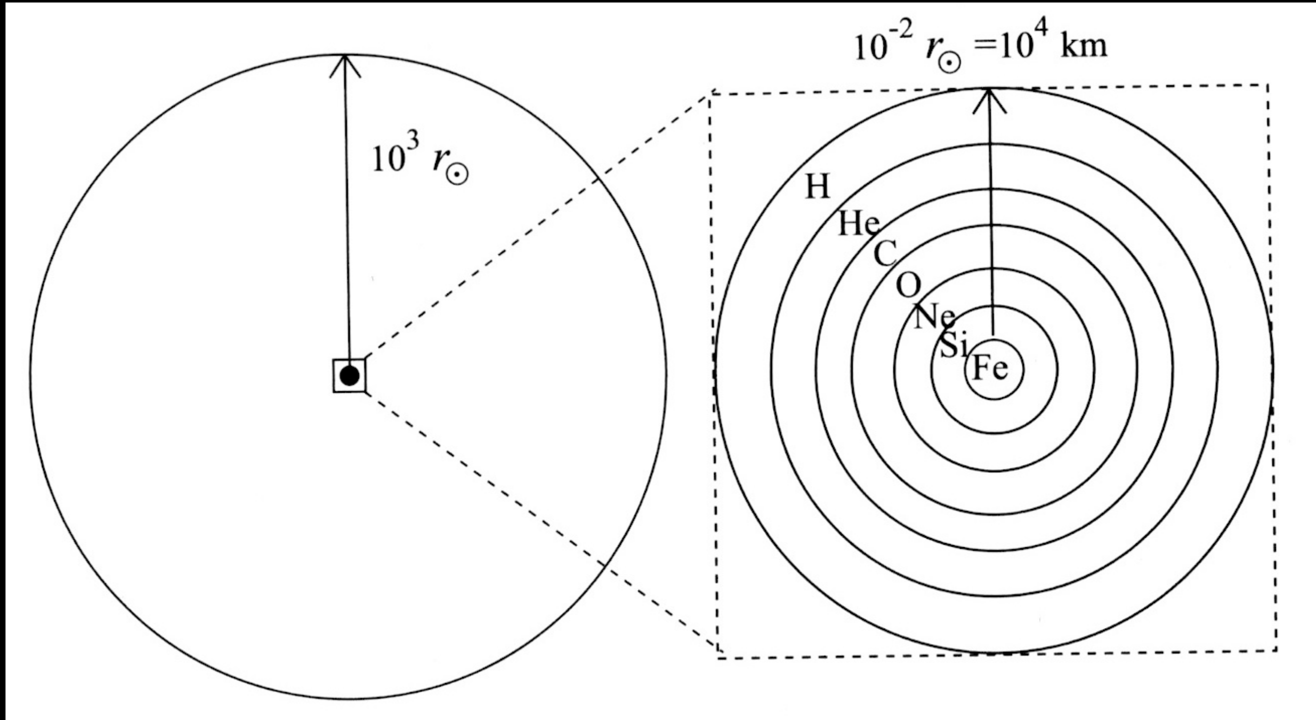


Heger et al. 2003

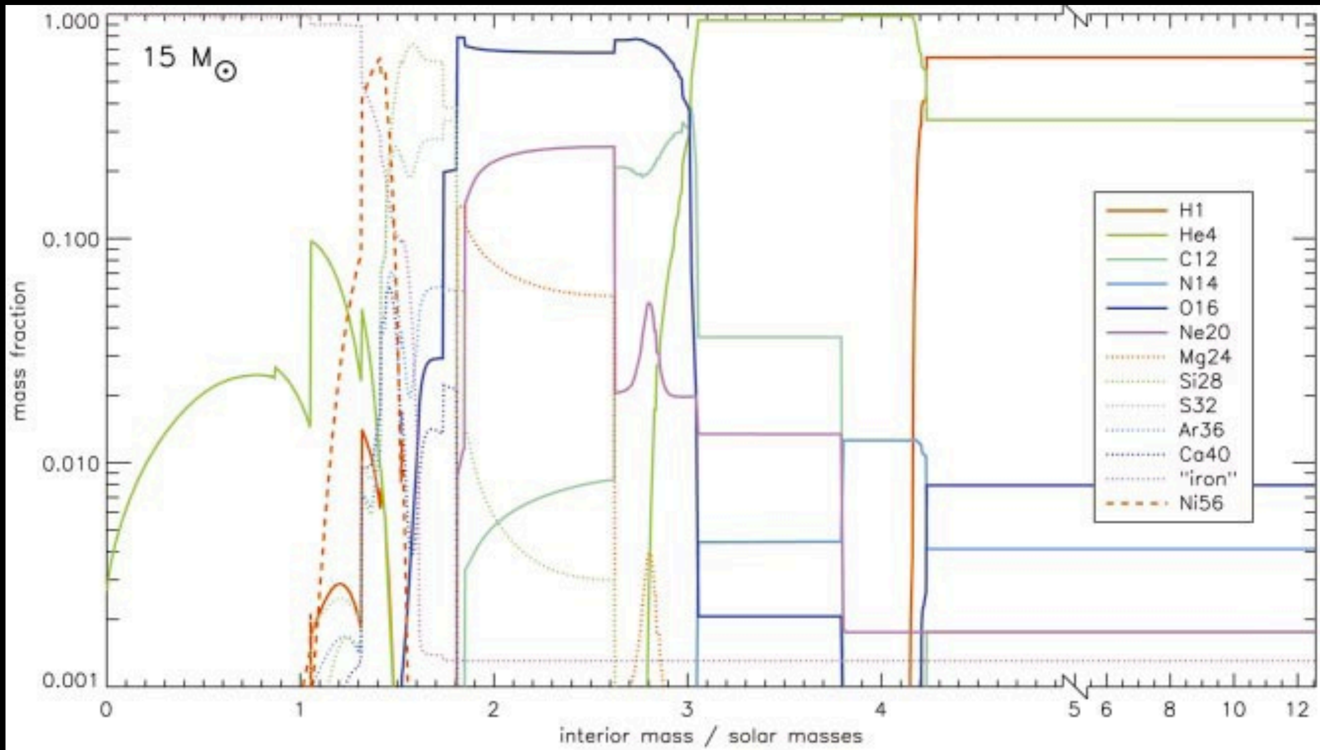
All these stars are in still on the main sequence

Initial mass		Final state
$\sim 0.1\text{-}9\ M_\odot$ Nuclear burning stops before the production of an iron core.	$\sim 0.1\text{-}0.8\ M_\odot$	WD He
	$\sim 0.8\text{-}8\ M_\odot$	WD C,O
	$\sim 8\text{-}9\ M_\odot$	WD O,Ne,Mg
$\gtrsim 9\ M_\odot$ Production of an iron core	$\sim 8\text{-}25\ M_\odot$	NS + SN
	$\sim 8\text{-}40\ M_\odot$?	NS$\rightarrow$BH + SN ?
	$\gtrsim 40\ M_\odot$?	BH ?

Pre-supernova star



Maoz 2007



Woosley, Heger & Weaver 2002

Pre-supernova star

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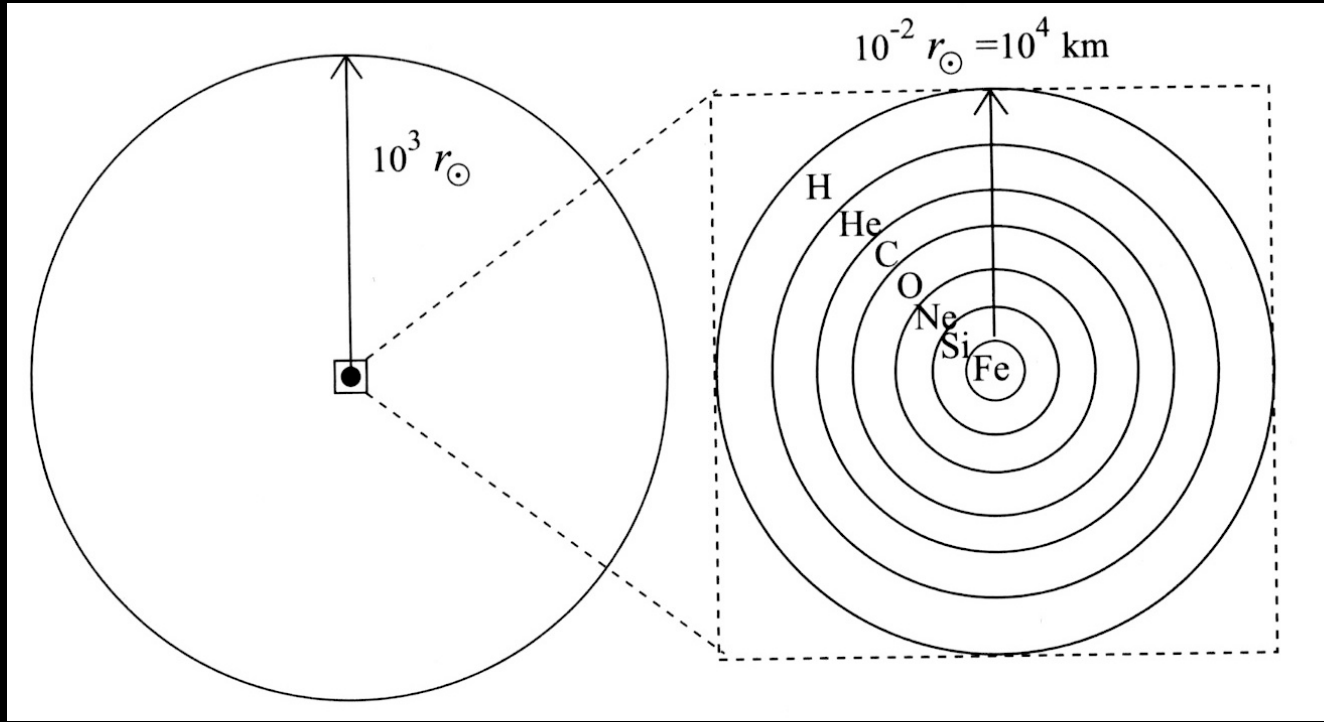


Pre-supernova M ~ 15 $M_\odot$

Element	Fe	C,O,Ne,Si	He	H
Masse	~ 1.4 $M_\odot$	~ $M_\odot$	~ 2 $M_\odot$	~ 10 $M_\odot$
Radius	~ 1 000 km	~ 40 000 km	~ 300 000 km ~0.4 $R_\odot$	~ 1 000 $R_\odot$ (RSG) ~ 60 $R_\odot$ (BSG)

More massive progenitors : Wol-Rayet stars (WR)
external enveloppe (H + possibly He, C, O ...) is expelled (dense stellar wind)

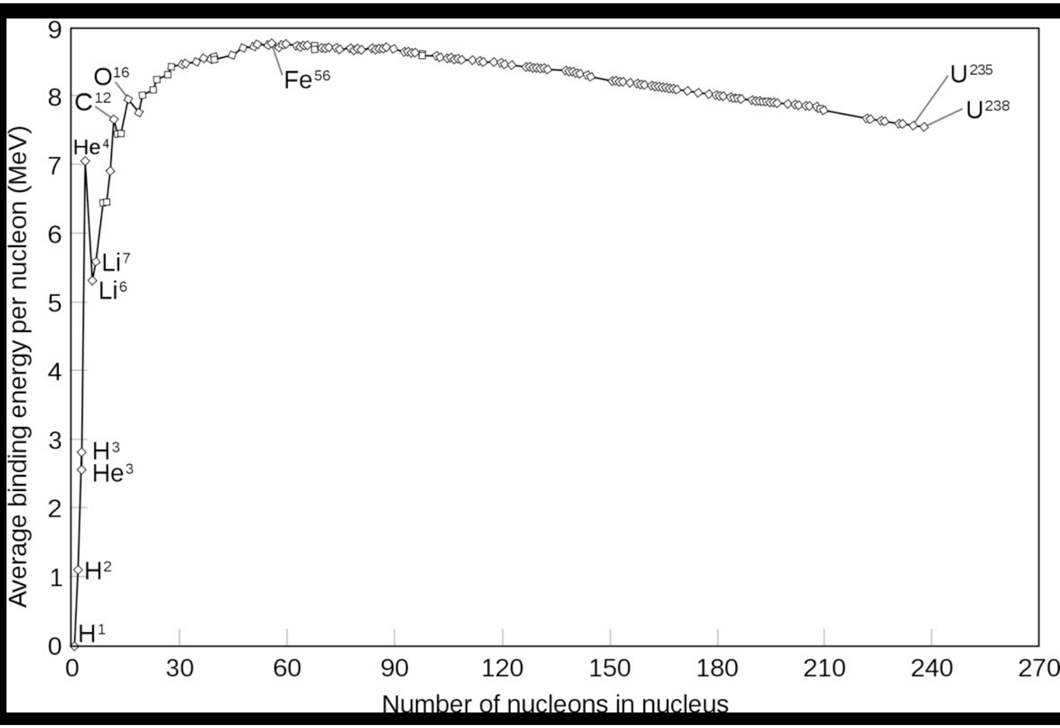
Iron core : no new possible nuclear reactions to release energy !

	H	He	C	O	Ne	Si	**Fe**	**U**
A	1	4	12	16	20	28	**56**	**238**
Z	1	2	6	8	10	14	**26**	**92**
Mass m (u.m.a)	1	4.0026	12	15.9949	19.9924	27.9769	**55.9349**	**238.0508**
Binding energy B / A (MeV / nucleon)	0	7.08	7.68	7.98	8.03	8.45	**8.79**	**7.57**

binding energy of a nucleus (Z,A) :

$$B = (Z\, m_p + (A-Z)\, m_n - m)\, c^2$$

m_p = 1.0073 u.m.a
m_n = 1.0087 u.m.a



From the gravitational collapse to the bounce and the explosion : summary

1. Triggering the collapse

- pressure in the iron core is dominated by degenerate electrons
- gravitational instability when M = Chandrasekhar mass $M_{Ch} = 1.457\ (Y_e / 0.5)^2\ M_\odot$

  (Y_e = number of free electrons per nucleon ; here $Y_e < 0.5$)

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A few details...

- Core of a pre-supernova with $M = 15\ M_\odot$:

$T \sim 3 \times 10^9$ K (temperature for Si burning at the surface of the core

$\rho \sim 3 \times 10^{12}$ kg/m^3

- Such conditions strongly favor iron-like elements : e.g. $^{56}\mathrm{Ni}/^{28}\mathrm{Si} \sim 10^7$!
- Free electrons per nucleon : $Y_e \sim 0.43$-0.45
- Fermi impulsion and temperature of electrons :

$$x_{\mathrm{F,e}} = \frac{p_{\mathrm{F,e}}}{m_{\mathrm{e}} c} \simeq 11 \left(\frac{Y_{\mathrm{e}}}{0.45}\right)^{1/3} \left(\frac{\rho}{3 \times 10^{12}\ \mathrm{kg/m^3}}\right)^{1/3}$$

$$T_{\mathrm{F,e}} = 7 \times 10^9\ \mathrm{K} \left(\frac{x_{\mathrm{F,e}}}{11}\right)$$

-Electrons are degenerate ($T_{F,e} > T$) and relativistic ($p_{F,e} > m_e c$) : E.O.S $P = \kappa(Y_{\mathrm{e}})\rho^{4/3}$

-Chandrasekhar mass : $M_{\mathrm{Ch}} \simeq 1.2\, M_\odot \left(\frac{Y_{\mathrm{e}}}{0.45}\right)^2$

From the gravitational collapse to the bounce and the explosion : summary

1. Triggering the collapse
2. Neutron enrichment

- Normal matter : balance between β and inverse β decay

$$n \to p + e^- + \bar{\nu}_e$$
$$p + e^- \to n + \nu_e$$

-Collapsing core : neutron production is favored by the degeneracy of electrons
(β decay necessitates to produce a very energetic electron above the Fermi energy)
-This leads to neutron enrichment by electron capture

$$^{56}Fe + e^- \to ^{56}Mn + \nu_e$$
$$^{56}Mn + e^- \to ^{56}Cr + \nu_e$$
$$\ldots$$

-Exotic chemical composition with neutron rich nuclei
-Emission of electronic neutrinos ν_e that escape the star

-A few details... evolution of the chemical composition

Masse volumique ρ (kg.m^{-3})	Energie de Fermi des électrons libres E_F (MeV)	Caractéristiques moyennes des noyaux A	Z	Nombre d'électrons libres par nucléon Y_e
10^{13}	8.2	69	29 (Cu)	0.42
$10^{13.5}$	11.9	71	30 (Zn)	0.418
10^{14}	17.5	76	31 (Ga)	0.41
$10^{14.5}$	25	86	34 (Se)	0.389
10^{15}	36	105	37 (Rb)	0.358

Evolution of the chemical composition in the core during the collapse

Masse volumique ρ (kg.m^{-3})	Energie de Fermi des électrons libres E_F (MeV)	Caractéristiques moyennes des noyaux A	Z	Nombre d'électrons libres par nucléon Y_e
10^{13}	8.2	69	29 (Cu)	0.42
$10^{13.5}$	11.9	71	30 (Zn)	0.418
10^{14}	17.5	76	31 (Ga)	0.41
$10^{14.5}$	25	86	34 (Se)	0.389
10^{15}	36	105	37 (Rb)	0.358

From the gravitational collapse to the bounce and the explosion : summary

1. Triggering the collapse
2. Neutron enrichment
3. **Gravitational collapse**

- Pressure in the core is dominated by the pressure of ultra-relativistic degenerate electrons (adiabatic index $\gamma = 4/3$)
- Due to the neutron enrichment, the number of free electrons per nucleon Y_e decreases
- Then the Chandrasekhar mass decreases : $M_{Ch} = 1.457\ (Y_e / 0.5)^2\ M_\odot$ which favors the collapse

  - In such conditions, the collapse is homologous (self-similar profiles for velocity, density, ...)

  - **The collapse lasts for a dynamical time, i.e. free fall timescale ~ 100 ms !**

- A few details...
  - Dynamical time (free fall) : $$t_{\rm dyn} \simeq \frac{1}{\sqrt{G\rho}} \simeq 0.07\,{\rm s} \left(\frac{\rho}{3\times 10^{12}\,{\rm kg/m^3}}\right)^{-1/2}$$
  - Sound speed : $$c_{\rm S} \simeq 0.05c \left(\frac{\rho}{3\times 10^{12}\,{\rm kg/m^3}}\right)^{1/6}$$
  - Sonic time : $$t_{\rm son} \simeq t_{\rm dyn}$$
  - The inner part of the collapsing core can always communicate internally with sound waves : homologous collapse (Goldreich & Weber 1980) : collapse duration t_0 ~ 0.2 s
$$v(r,t) \simeq -\frac{2}{3}\frac{r}{t_0 - t}$$
  - The external part cannot adjust fast enough : free fall

Self-similar collapse of the core (analytical solution by Yahil 1983)

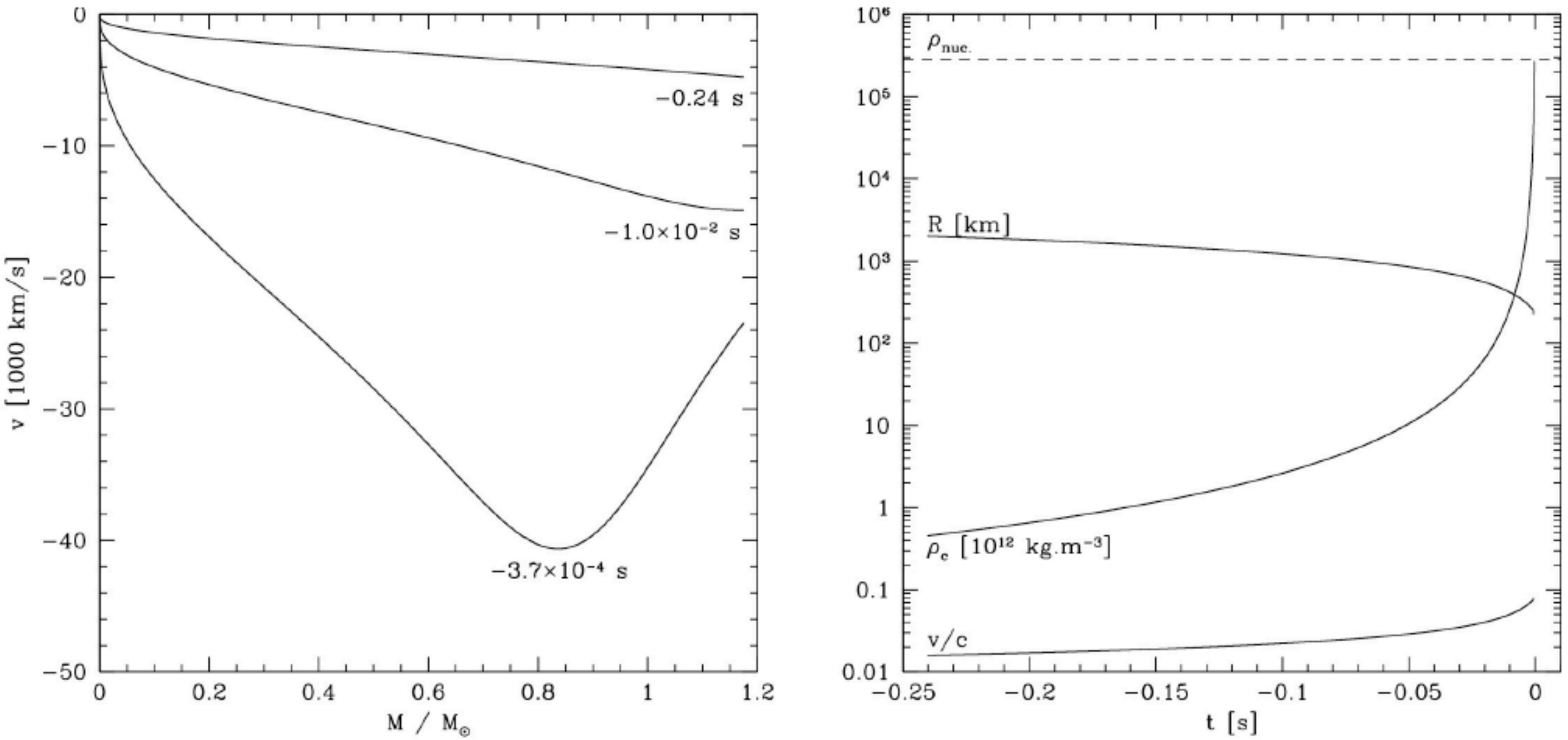
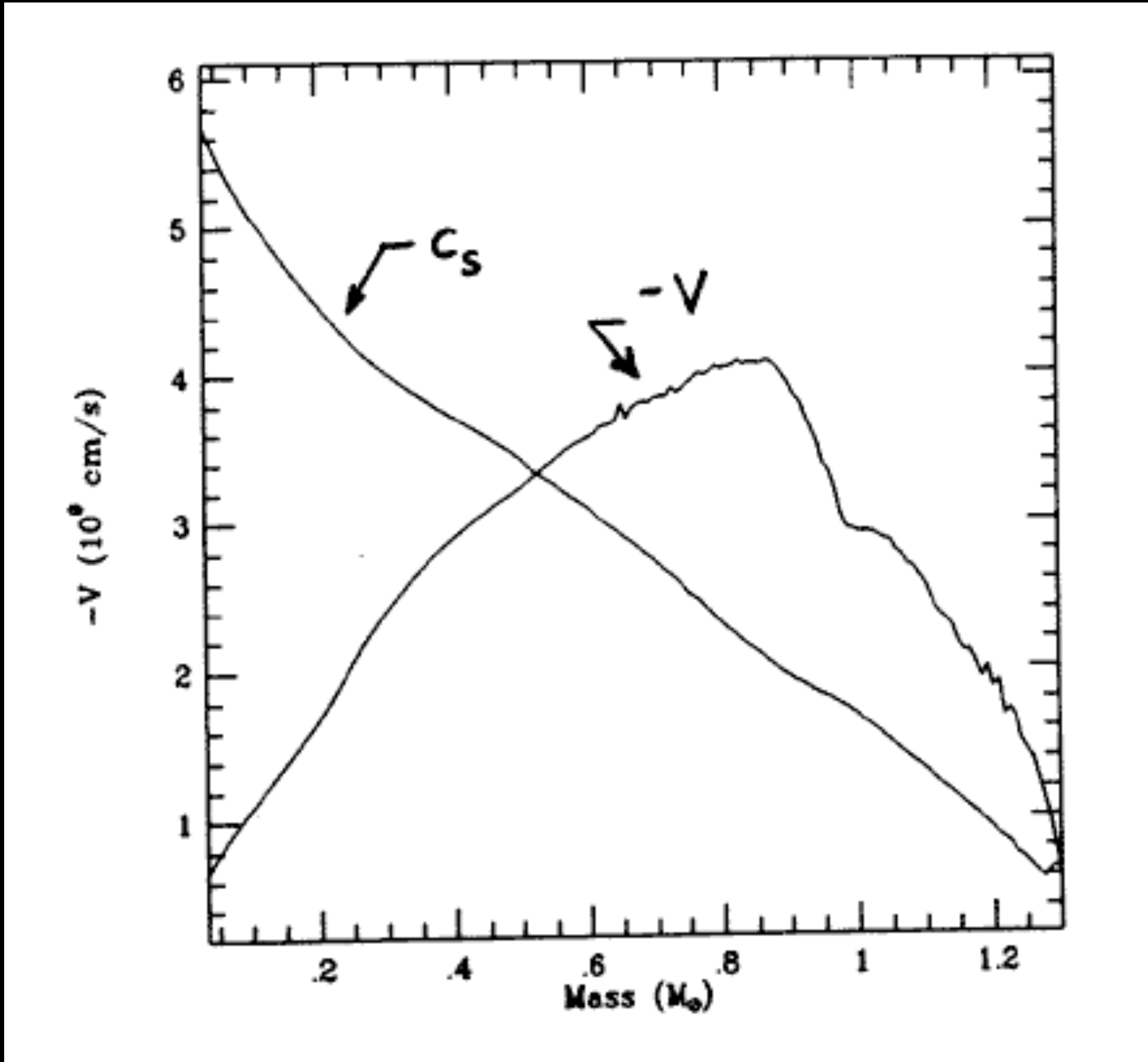


FIGURE 53 – **Effondrement auto-similaire du cœur.** La solution détaillée au § G.5.4 est représentée pour $\gamma = 1.3$. *Gauche :* profil de vitesse dans le cœur à différents instants. On note le comportement homologue dans la région interne et l'apparition d'une zone externe en chute libre ; *Droite :* évolution du rayon R du cœur, de la vitesse v à sa surface et de la masse volumique centrale ρ_c (Crédits : F. Daigne, IAP ; UPMC).

Mass of the core : M = 1.3 $M_\odot$
Initial radius : R = 2 000 km
Effective adiabatic index : γ = 1.3
Duration of the collapse : 0.24 s

Collapse of the iron core (18 $M_\odot$ star)



Cooperstein & Baron 1990

From the gravitational collapse to the bounce and the explosion : summary

1. Triggering the collapse
2. Neutron enrichment
3. Gravitational collapse
4. **Evolution of the equation of state - gravitational collapse stops - formation of a neutron star**

- Due to the collapse, the density in the core increases rapidly

  - At very large densities, individual nuclei do not exist anymore : neutron-rich mixture of n,p,e
  - The neutron enrichment goes on (neutronization) by direct inverse β decay

$$p + e^- \rightarrow n + \nu_e$$

  - When the density becomes of the order of the nuclear density (2.6×10^{17} kg/m3 ~ 0.16 n / fm^3), the E.O.S. evolves due to the repulsive nature of the nuclear force (strong interaction) at short distances : a new dominant pressure appears

  - the collapse stops (if the mass of the core is not too large, otherwise a BH will form...)
  - the core becomes a neutron star

- A few details...
  - Binding energy of the new born neutron star :

$$B_{NS} \simeq -6 \times 10^{44}\,\mathrm{J}\left(\frac{f}{0.1}\right)\left(\frac{Y_\mathrm{e}}{0.36}\right)^2\left(\frac{\rho}{\rho_\mathrm{nuc}}\right)$$

  - Details are highly uncertain ...
  - Initially the NS oscillate, but very rapidly it stabilizes
  - The NS will cool, which can contribute to the next steps of the scenario

From the gravitational collapse to the bounce and the explosion : summary

1. Triggering the collapse
2. Neutron enrichment
3. Gravitational collapse
4. Evolution of the equation of state - gravitational collapse stops - formation of a neutron star
5. **Neutrino trapping**

- At the end of the collapse, the density in the central region is so high that neutrinos are trapped !
(very unique conditions, usually not found in the Universe except just after the Big Bang ($t < 10^{-12}$ s))

- Neutrino adopt a thermal distribution in equilibrium with the other species
  - The core cools by emitting neutrino thermal radiation (photons cannot escape) $\gamma\gamma \to e^+e^- \to \nu\bar{\nu}$
    = a neutrino « black body»
  - The neutrinosphere as a radius of a few 10 km. The rest of the star is transparent.
  - **Neutrinos and anti-neutrinos of the 3 flavors are emitted !**
    (cf. detection of electronic anti-neutrino SN1987A)
  - Electron captures stop : $Y_e = 0.36$; Final Chandrasekhar mass : $M_{Ch} = 0.75\,(Y_e / 0.36)^2\, M_\odot$

- A few details...
  - For $\rho_c < 10^{15}$ kg/m^3 : the core is transparent for the neutrinos produced by electron captures
  - Dominant interaction : elastic scattering on nuclei
  - Cross section : $\sigma_{\nu,el} \simeq 9 \times 10^{-47}\,\mathrm{m}^2\, A^2\, (1 - Y_\mathrm{e})^2 \left(\frac{\epsilon_\nu}{15\,\mathrm{MeV}}\right)^2$
  - Mean free path :

$$\ell_\nu \simeq \frac{1}{(\rho/Am_u)\,\sigma_{\nu,\mathrm{el}}} \simeq 4.3 \times 10^3 \left(\frac{A}{69}\right)^{-1} \left(\frac{1-Y_\mathrm{e}}{1-0.42}\right)^{-2} \left(\frac{\epsilon_\nu}{15\,\mathrm{MeV}}\right)^{-2} \left(\frac{\rho_\mathrm{c}}{10^{13}\,\mathrm{kg/m^3}}\right)^{-1}$$

  - Collapse of an initial core R = 2 000 km and $\rho = 3\times10^{12}$ kg/m^3 : $\rho_c = 10^{15}$ kg/m^3 when R = 300 km
  - At this stage : $\ell_{\nu,el}$ = 23 km << R
    The diffusion time is $t_{\nu,el} \sim R^2 / (c\,\ell_{\nu,el}) \sim 15$ ms comparable to the dynamical time
  - When R ~ 10 km : $t_{\nu,el} \gg t_{dyn}$: neutrinos are trapped !

From the gravitational collapse to the bounce and the explosion : summary

1. Triggering the collapse
2. Neutron enrichment
3. Gravitational collapse
4. Evolution of the equation of state - gravitational collapse stops - formation of a neutron star
5. Neutrino trapping
6. **Bounce - Formation and propagation of a shock wave**

   - As the dynamical timescale for the gravitationnal collapse of the core is very short (< 1 s)
     The enveloppe cannot react immediately

   - When the neutron star forms, the still infalling external region of the core bounces on it

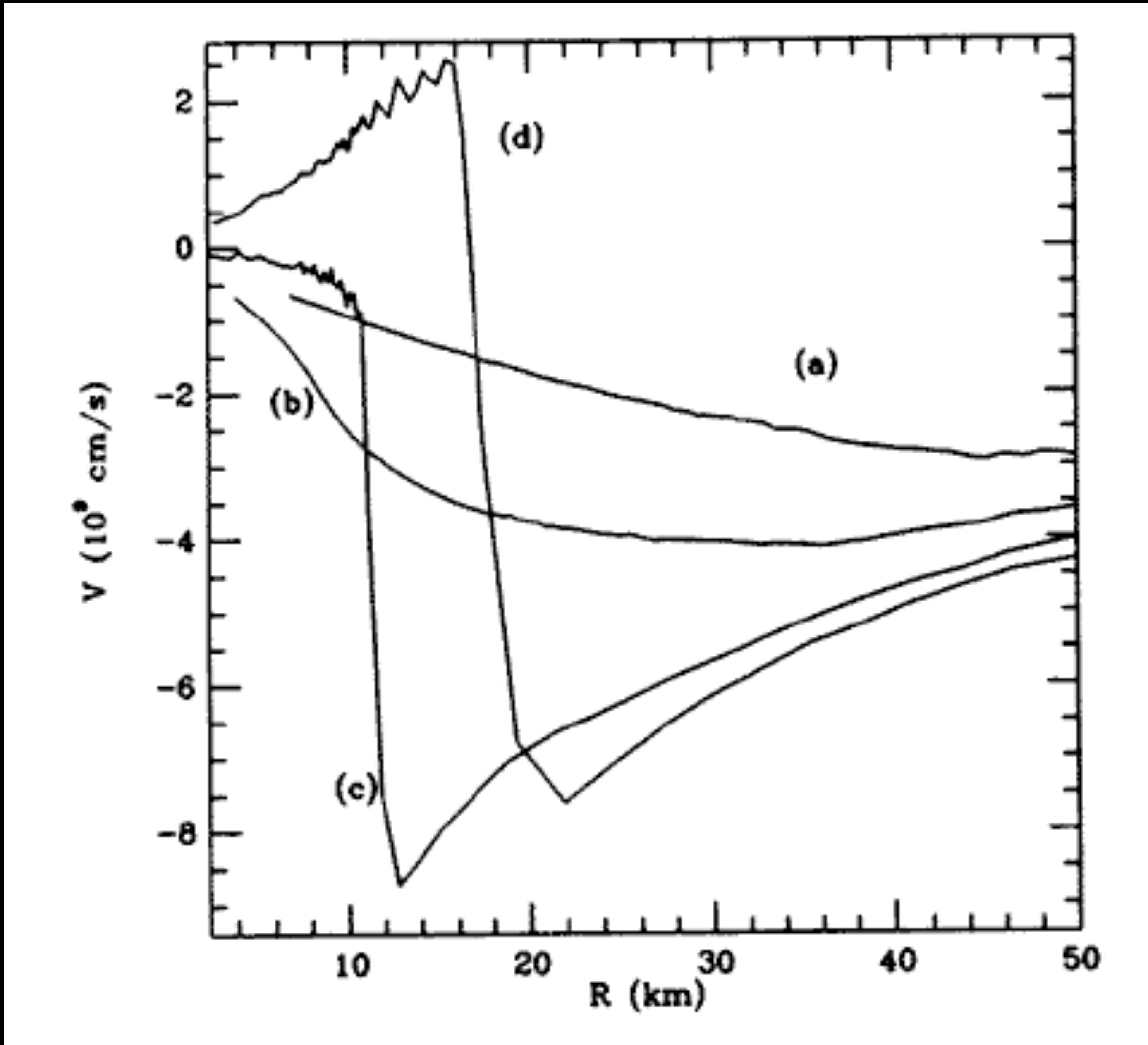
   - This triggers the formation of a shock wave propagating outwards
     $R > R_{shock}$: the medium is still infalling ($v<0$)
     $R < R_{shock}$: the medium is moving outwards ($v>0$) and has been heated

     Huge discontinuity for the velocity : 100 000 km/s !

   - The kinetic energy carried by the shock is $E_{SN} \sim -B_{NS} \sim 6 \times 10^{44}$ J

   - The shock wave deposits kinetic and thermal energy in the shocked medium
     (equipartition as it is a strong shock)

Implosion et bounce



Cooperstein & Baron 1990

From the gravitational collapse to the bounce and the explosion : summary

1. Triggering the collapse
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6. Bounce - Formation and propagation of a shock wave
7. **Photo-disintegration of iron - Shock stops**

- The close vicinity of the new-born neutron star (where the shock initially propagates) is made of iron and other heavy elements
- Most of the energy of the shock is lost by photo-disintegration of iron

$$\gamma + {}^{56}Fe \rightarrow 13\,{}^{4}He + 4n$$
$$\gamma + {}^{4}He \rightarrow 2p + 2n$$

- Energetic cost :
  124 MeV per Fe nucleus (2.2 MeV/nucleon) and 28.3 MeV per He nucleus,
  i.e. 8.8 MeV / nucleon (binding energy of iron)

- This is equivalent to 1.7×10^{45} J/$M_\odot$: a few 0.1 $M_\odot$ of iron is enough to stop the shock
  ~ 0.4 $M_\odot$ is enough to stop the shock if photo-disintegration is complete
  ~ 0.7 $M_\odot$ if photo-disintegration stops at He
- The shock becomes an accretion shock at a radius of ~ 150-300 km
- Without a new process to deposit more energy in the shocked region so that the shock can start again, in ~ 1s, the new-born neutron star will accrete enough mass (mass flux >> 1 $M_\odot$/s) to reach the maximum mass and collapse into a black hole : the supernova has failed !

- A few details...
  - energy per nucleon deposited by the initial shock (discontinuity of velocity 100 000 km/s) kinetic energy = thermal energy ~ 1/2 $(100\,000\ \mathrm{km/s})^2$ ~ 26 MeV / nucleon
  - temperature is large enough to produce a large number of photons above 10 MeV which allows iron photo-disintegration
  - what is the available mass of iron ? 1.2 (initial) - 0.8 (inner core: NS formation) ~ 0.4 $M_\odot$

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7. Photo-desintegration of iron - Shock stops
8. **Shock starts again and crosses the whole star : explosion !**

- In reality, massive stars do explode as supernovae. However, the mechanism at work to help the shock to start again remains unclear...

- Candidates which are currently investigated :
  - Realistic microphysics (equation of state, electron captures, ...)
  - Neutrino heating (Bethe & Wilson, 1985)
  - Hydrodynamic instabilities / convection
  - Magneto-rotational driving
  - ?

- A few details...
  - The neutrino luminosity of the core is :

$$L_\nu \simeq 4\pi R^2 \left(\frac{7}{2}\sigma\right) T^4 \simeq 7\times 10^{46}\,\mathrm{W} \left(\frac{R}{50\,\mathrm{km}}\right)^2 \left(\frac{T}{5\,\mathrm{MeV}}\right)^4$$

  - If ~ 1 % of this pwer is deposited in the shocked matter, the shock can start to propagate again

  - Hydrodynamics : a lot of discussion around SASI - Bonus : explosion is asymetric (pulsar kick)

Role of E.O.S

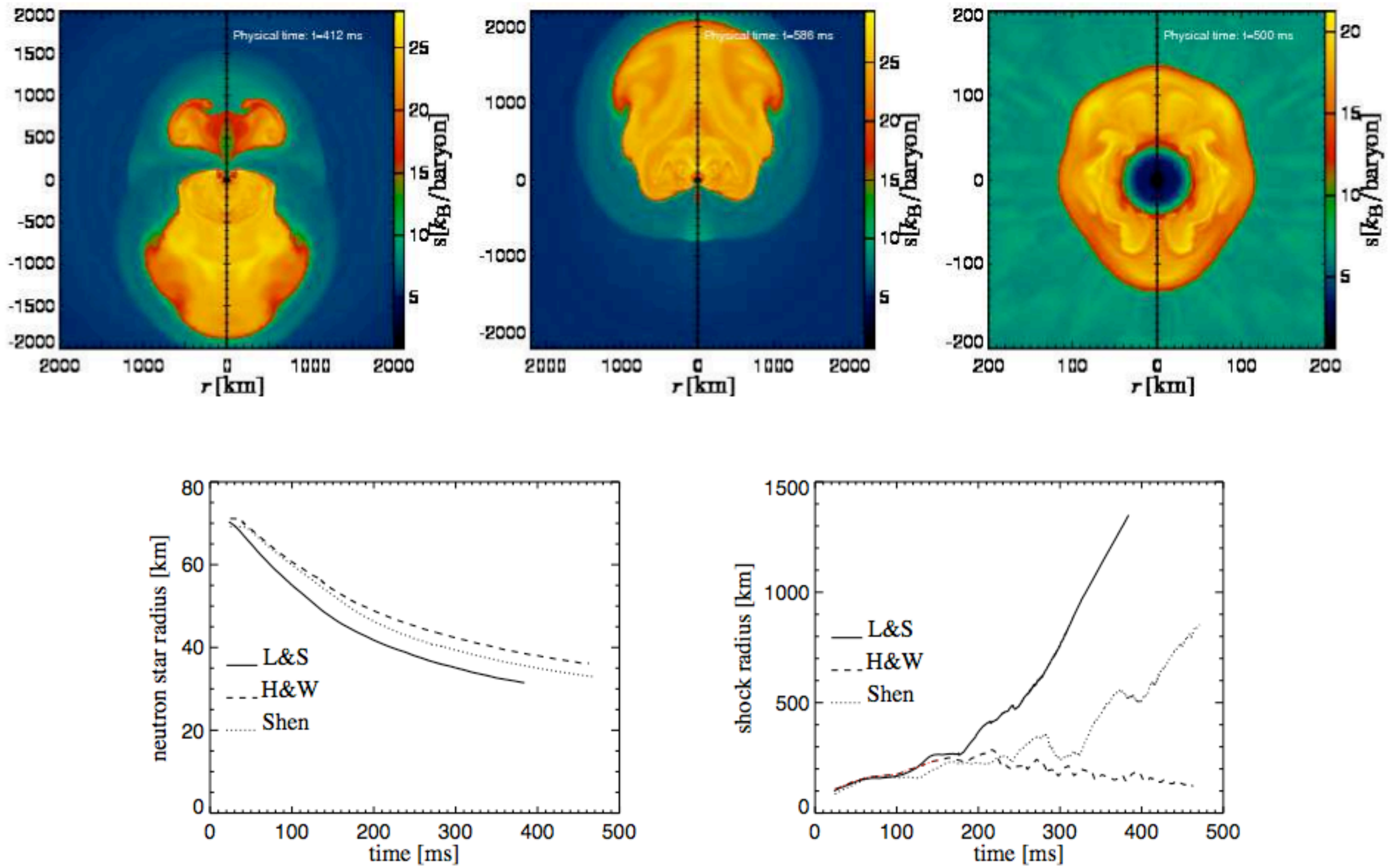


FIG. 4: Two-dimensional SN simulations [121] of an 11.2 $M_\odot$ star [22] for three different nuclear EoSs. The *upper panels* show cross-sectional entropy distributions at 412 ms after bounce for the LS180-EoS (*left*), at 586 ms p.b. for the STOS-EoS (*middle*), and at 500 ms p.b. for the Hillebrandt & Wolff EoS [122]. The last is the stiffest EoS of the set. It leads to the slowest contraction of the PNS (*bottom left*) and because of weaker neutrino heating and less vigorous hydrodynamic mass motions does not yield an explosion within the simulated time as visible in the evolution of the average shock radius (*bottom right*).

(Janka 2012, arXiv:1206.2503)

Role of neutrino heating

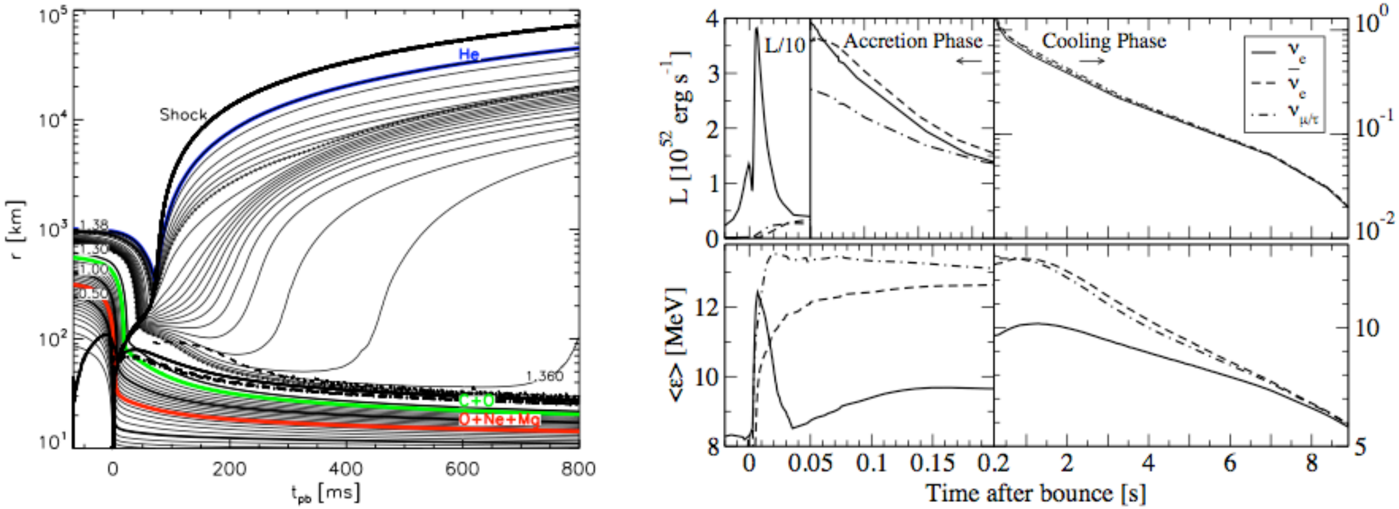


FIG. 5: *Left panel:* Neutrino-powered ECSN of an 8.8 $M_\odot$ star with ONeMg core [21, 28] visualized by mass-shell trajectories of a 1D simulation (from [105]). The SN shock (bold, outgoing line) expands for $\sim$50 ms as accretion shock (the downstream velocities are negative) before it accelerates by reaching the steep density gradient at the edge of the core. Neutrino heating subsequently drives a baryonic "wind" off the PNS surface. Colored lines mark the inner boundaries of the Mg-rich layer in the O-Ne-Mg core (red; at $\sim$0.72 $M_\odot$), C-O shell (green; at $\sim$1.23 $M_\odot$), and He-shell (blue; at $\sim$1.38 $M_\odot$). The outermost dashed line indicates the gain radius, and the inner (bold) solid, dashed, and dash-dotted lines are the neutrinospheres of ν_e, $\bar{\nu}_e$, and ν_x, respectively. *Right panel:* Neutrino luminosities and mean energies from an ECSN for the infall, ν_e breakout-burst, accretion phase, and PNS cooling evolution (from [107]). The average energies are defined as the ratio of energy to number fluxes. (The left panel is reproduced with permission; copyright: ESO.)

(Janka 2012, arXiv:1206.2503)

Role of neutrino heating

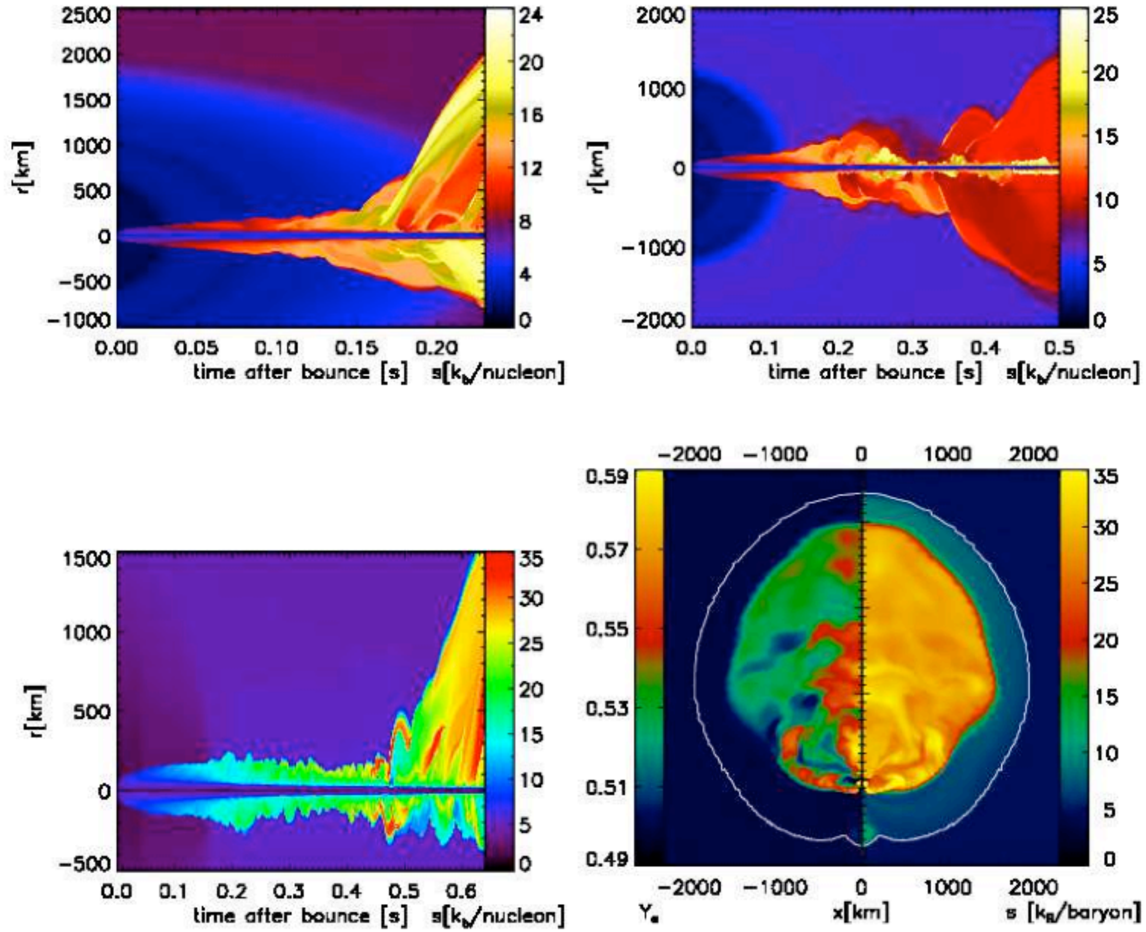
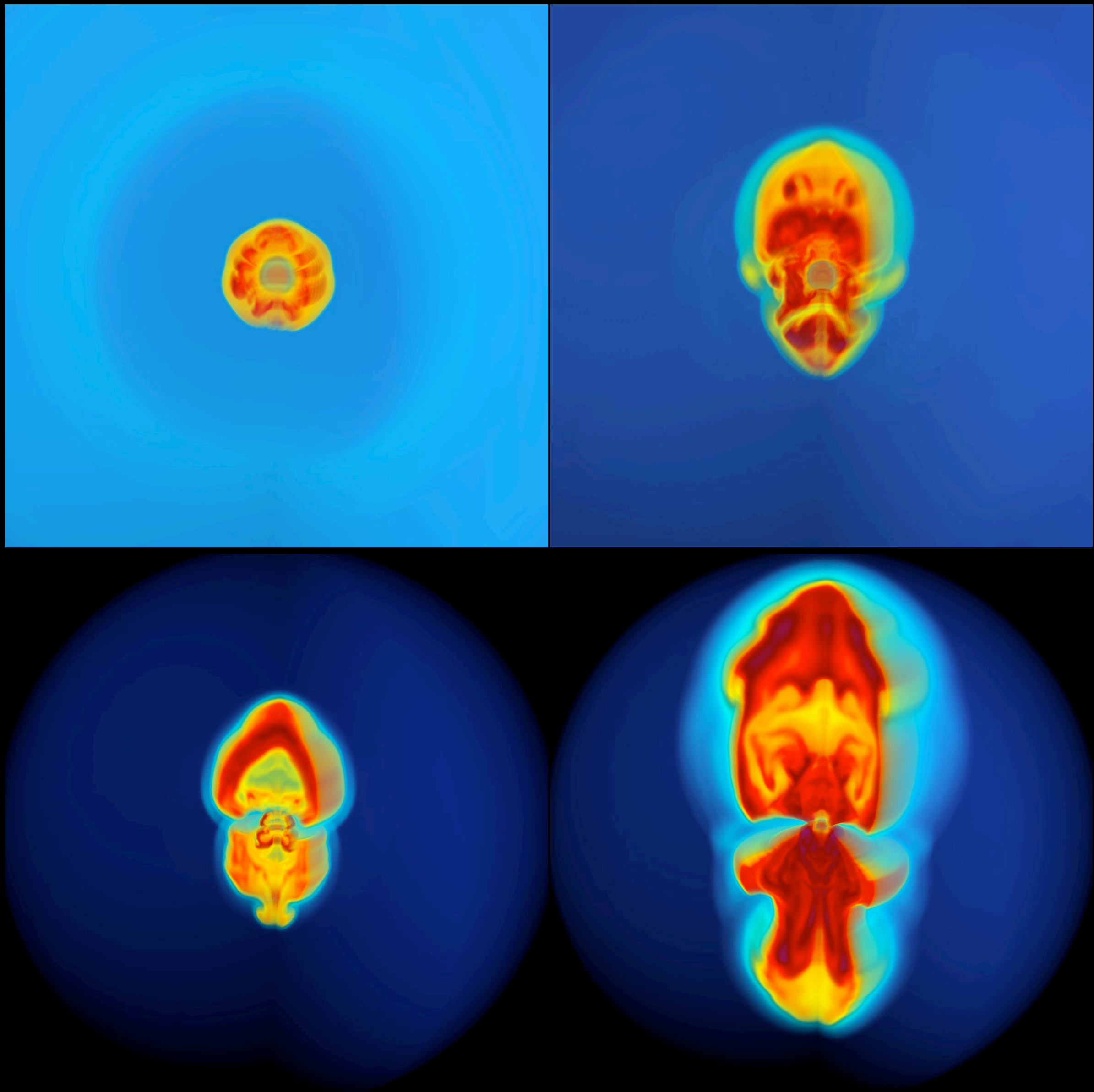


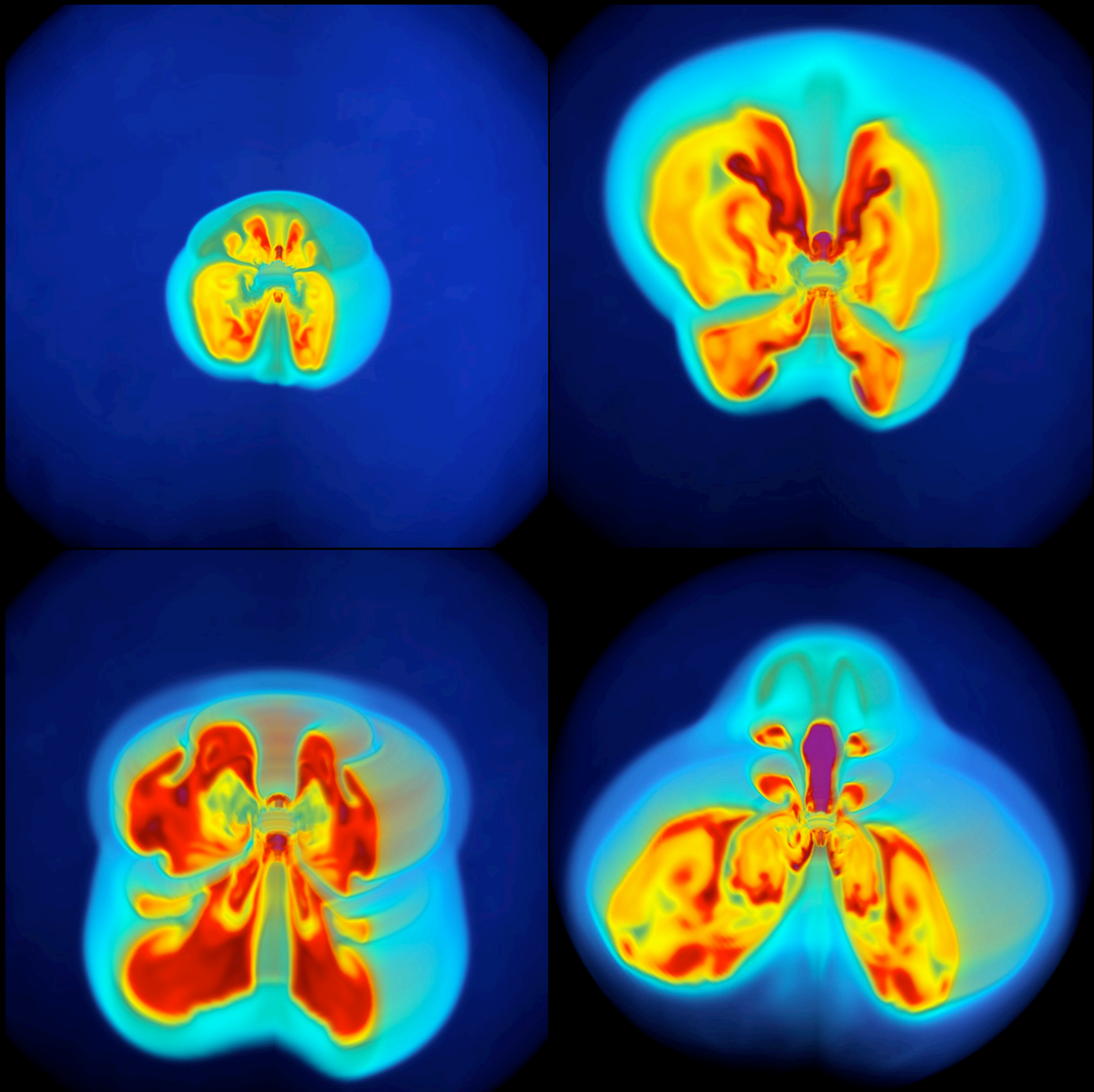
FIG. 6: Neutrino-driven explosions of Fe-core progenitors [81, 147]. The *upper left, upper right, and lower left panels* display the time evolution of color-coded entropy profiles in the north and south pole directions for 2D simulations of an 8.1 $M_\odot$ ultra metal-poor (10^{-4} solar metallicity) star (A. Heger, private communication), and 11.2 $M_\odot$ [22] and 15 $M_\odot$ [23] solar-metallicity stars, respectively. The shock position is clearly visible as a sharp boundary between high-entropy (yellow, red) and low-entropy (blue, black) regions. Shock oscillations are associated with violent convective activity in the neutrino-heating region and strong, bipolar SASI sloshing motions of the whole postshock layer. The explosions develop highly aspherically in all cases. The *lower right panel* shows, for example, an extreme dipole asymmetry of the cross-sectional distribution of electron fraction (Y_e; *left*) and entropy at 775 ms p.b. for the 15 $M_\odot$ model, which explodes in a unipolar way. The NS is located at the position of the lowermost long tickmark on the vertical axis, far away from the geometrical center of the roundish shock contour (white line).

(Janka 2012, arXiv:1206.2503)

Realistic model ? "Garching" version (11 $M_{\odot}$ star : 0.1 - 0.18 - 0.26 and 0.32 s)



Realistic model ? "Garching" version (15 $M_{\odot}$ star : 0.53 - 0.61 - 0.65 and 0.7 s)



From the gravitational collapse to the bounce and the explosion : summary

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- Candidates which are currently investigated :
  - Realistic microphysics (equation of state, electron captures, ...)
  - Neutrino heating
  - Hydrodynamic instabilities / convection
  - Magneto-rotational driving
  - ?

- The first emission of light occurs when the shock reaches the surface of the star : shock break-out
- At this stage, the whole enveloppe has been put in motion and is ejected

- The supernova lightcurve is due to the light radiated by the cooling ejecta

- During the propagation of the shock wave in the inner part of the star : explosive nucleosynthesis
- Radioactive elements are produced (^{56}Ni)
- The radioactive decay of ^{56}Ni and ^{56}Co is the dominant source that powers the SN light curve

- Initially, the ejecta expands freely. Then, it starts to be decelerated by the external medium : formation of a supernova remnant.

Energetics of the explosion

1. Radiated energy

- Lightcurve + bolometric correction + time-integration : estimate of E_{ph}

- Typically : $E_{ph} \sim 10^{42}$ J
  (this is equivalent to $L_{\odot}$ during 80 Myr)

- At the maximum of the lightcurve $L \sim 10^{9}\ L_{\odot}$: the supernova is as bright as its host galaxy

Energetics of the explosion

1. Radiated energy : $E_{ph} \sim 10^{42}$ J
2. **Kinetic energy**
   - Spectroscopy : velocity v_{exp} of the ejecta (Doppler effect)
   - Initially : free expansion - this allows to estimate the radius $$R \simeq v_{\rm exp} t$$
   - The surface density of the ejecta can be estimated at the transition $t=t_{neb}$ from the photospheric to the nebular phase :

$$\Delta R \simeq \ell \qquad \ell = \frac{1}{n\sigma} = \frac{1}{\rho\kappa} \qquad \rho \Delta R \simeq \frac{1}{\kappa}$$

   - This allows to measure the mass of the ejecta and to deduce the kinetic energy :

$$M_{\rm ej} \simeq 4\pi R^2 \Delta R \rho \Big|_{t_{\rm neb}} \simeq \frac{4\pi v_{\rm exp}^2 t_{\rm neb}^2}{\kappa} \simeq 5\, M_\odot \left(\frac{v_{\rm exp}}{5000\,{\rm km/s}}\right)^2 \left(\frac{t_{\rm neb}}{1\,{\rm yr}}\right)^2$$

$$E_{\rm kin} \simeq \frac{1}{2} M_{\rm ej} v_{\rm exp}^2 \simeq 10^{44}\ {\rm J} \left(\frac{v_{\rm exp}}{5000\,{\rm km/s}}\right)^4 \left(\frac{t_{\rm neb}}{1\,{\rm yr}}\right)$$

Energetics of the explosion

1. Radiated energy : $E_{ph} \sim 10^{42}$ J
2. Kinetic energy : $E_{kin} \sim 10^{44}$ J
3. **Gravitational energy released by the collapse**

- A neutron star is a compact object : its gravitational energy is a significant fraction of its mass energy

- Energy released by the collapse of the iron core into a neutron star :

$$\Delta E \simeq \alpha G M_{\rm Fe}^2 \left(\frac{1}{R_{\rm NS}} - \frac{1}{R_{\rm Fe}} \right) \simeq \frac{\alpha G M_{\rm Fe}^2}{R_{\rm NS}}$$

$$\Delta E \simeq 3\alpha \times 10^{46}\ \mathrm{J} \left(\frac{M_{\rm Fe}}{1.1\, M_\odot} \right)^2 \left(\frac{R_{\rm NS}}{10\,\mathrm{km}} \right)^{-1}$$

Energetics of the explosion

1. Radiated energy : $E_{ph} \sim 10^{42}$ J
2. Kinetic energy : $E_{kin} \sim 10^{44}$ J
3. Gravitational energy released by the collapse : $\Delta E \sim 3 \times 10^{46}$ J
4. **Energy emitted as neutrinos**
   - Most of the gravitational energy released by the collapse is radiated as neutrinos !

   - **The case of SN 1987A (D = 50 kpc) :**
     - A flash (duration 13 s) of electronic anti-neutrinos has been detected ~ 3 h before the SN
     - Kamiokande-II : a tank of water (2×10^6 kg)

$$N_{\mathrm{H_2O}} = \frac{2 \times 10^6\,\mathrm{kg}}{18\,\mathrm{u.m.a}} \simeq 6.5 \times 10^{31}$$

$$\bar{\nu}_{\mathrm{e}} + p \rightarrow n + e^+$$

One of the two H of a molecule H_2O

$v > c_{water} = c / n_{water} \sim 0.75$ c : detection of Cerenkov light

- Cross section : $\sigma_{\bar{\nu}\mathrm{p}} = 1.5 \times 10^{-45}\,\mathrm{m}^2 = 1.5 \times 10^{-17}\,\mathrm{barn}$

- Detection of $N_{det} = 12$ anti-neutrinos with a mean energy of 15 MeV

- Number of electronic anti-neutrinos emitted by SN 1987A : $N_{\bar{\nu}_{\mathrm{e}}} \simeq 2 \times 10^{57}$

$$N_{\mathrm{det}} \simeq \frac{N_{\bar{\nu}_{\mathrm{e}}}}{4\pi D^2} \times (2N_{\mathrm{H_2O}}) \times \sigma_{\bar{\nu}\mathrm{p}}$$

- Total energy emitted as neutrinos : $E_\nu \simeq 6N_{\bar{\nu}_{\mathrm{E}}} \times \langle \epsilon_\nu \rangle \simeq 3 \times 10^{46}\,\mathrm{J}$

Energetics of the explosion

1. Radiated energy : $E_{ph} \sim 10^{42}$ J
2. Kinetic energy : $E_{kin} \sim 10^{44}$ J
3. Gravitational energy released by the collapse : $\Delta E \sim 3 \times 10^{46}$ J
4. Energy emitted as neutrinos : $E_\nu \sim 3 \times 10^{46}$ J

The proposed scenario for core-collapse supernovae is very well supported by observations :

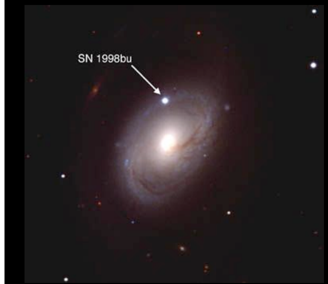
- SN1054 (in Taurus) reported by Chinese and Japanese astronomers in 1054
- Centuries later : the Crab nebula is discovered
- 1968 : discovery of the Crab pulsar
- The age of the Crab pulsar is ~ 950 yr
- The link massive stars - supernovae - neutron stars is demonstrated !

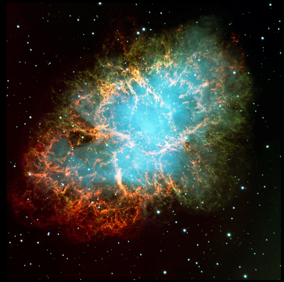
- SN1987A : the detection of electronic anti-neutrinos proves that a very dense region is formed (dense enough to be opaque for neutrinos) : gravitational collapse
- The duration and mean energy of neutrinos coincide well with the theoretical estimate of the size and temperature of this central region
- The estimate of the energy emitted as neutrinos is comparable to the energy release by the gravitational collapse of an iron core into a neutron star

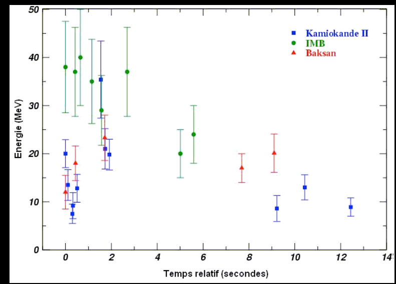
But the details of the mechanism are still unclear ...

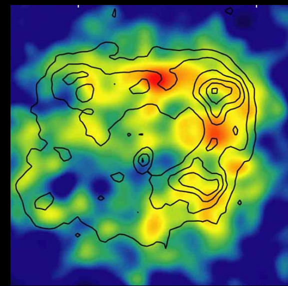
Explosive phenomena: SNe and GRBs

Frédéric Daigne
Institut d'Astrophysique de Paris, Université Pierre et Marie Curie
Institut Universitaire de France









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A. Core collapse supernovae

1. Observations - Classification
2. Theory: overview
3. Gravitational collapse
4. **Emission**
5. Remnant
6. Conclusion

Neutrino emission

Let us dream...

A core-collapse supernova at 5 kpc ?

100 times more neutrinos than
for SN 1987A :
neutrino lightcurve & spectrum !

(Janka 2012, arXiv:1206.2503)

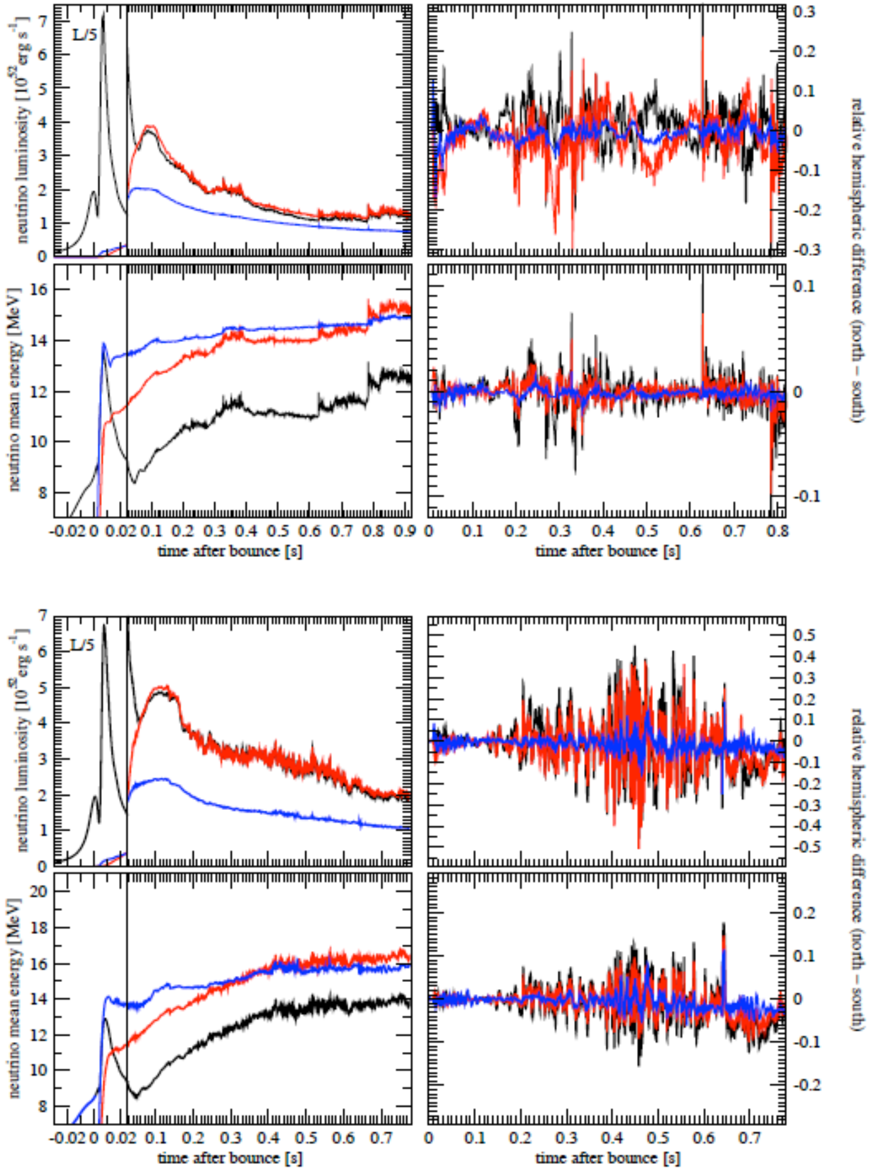


FIG. 7: Neutrino signals from general relativistic 2D simulations of core collapse and explosion of $11.2\,M_\odot$ (*upper plot*) and $15\,M_\odot$ (*lower plot*) stars shown in Fig. 6 [147]. The *left panels* of each plot show luminosities (i.e., total neutrino-energy loss rates of the PNS; *upper panels*) and mean energies (defined by the ratio of total neutrino energy-loss rate to number-loss rate, $\dot{E}_\nu/\dot{N}_\nu$; *lower panels*) with black lines for ν_e, red for $\bar{\nu}_e$, and blue for one kind of heavy-lepton neutrino ν_x. The right panels display the corresponding relative hemispheric differences after core bounce (the infall remains spherical). All quantities are measured in the lab frame at large distance. Note that the fluctuations, sudden jumps, and north-south differences at $t > 300$ ms in the upper plot are caused by violent, time-dependent, anisotropic downflows and corresponding changes of the accretion rate of the PNS.

Photon emission

Delay (photon-neutrino) = crossing time of the enveloppe by the shock

$$t_* \simeq \frac{R_*}{v_{\rm shock}} \simeq \left\{ \begin{array}{lr} 1.6\,{\rm day}\left(\frac{R_*}{1000\,R_\odot}\right)\left(\frac{v_{\rm shock}}{5000\,{\rm km/s}}\right)^{-1} & (RSG) \\ 2\,{\rm h}\left(\frac{R_*}{50\,R_\odot}\right)\left(\frac{v_{\rm shock}}{5000\,{\rm km/s}}\right)^{-1} & (BSG) \end{array} \right.$$

When the shock reaches the enveloppe : first flash of light = shock breakout (observation is very rare)

The observed lightcurve is emitted by the ejecta

Initial condition U = E_{kin} ~ 3×10^{44} J

Initial density is low but temperature is high : pressure is dominated by P_{rad} = fireball !

Evolution : three reservoirs

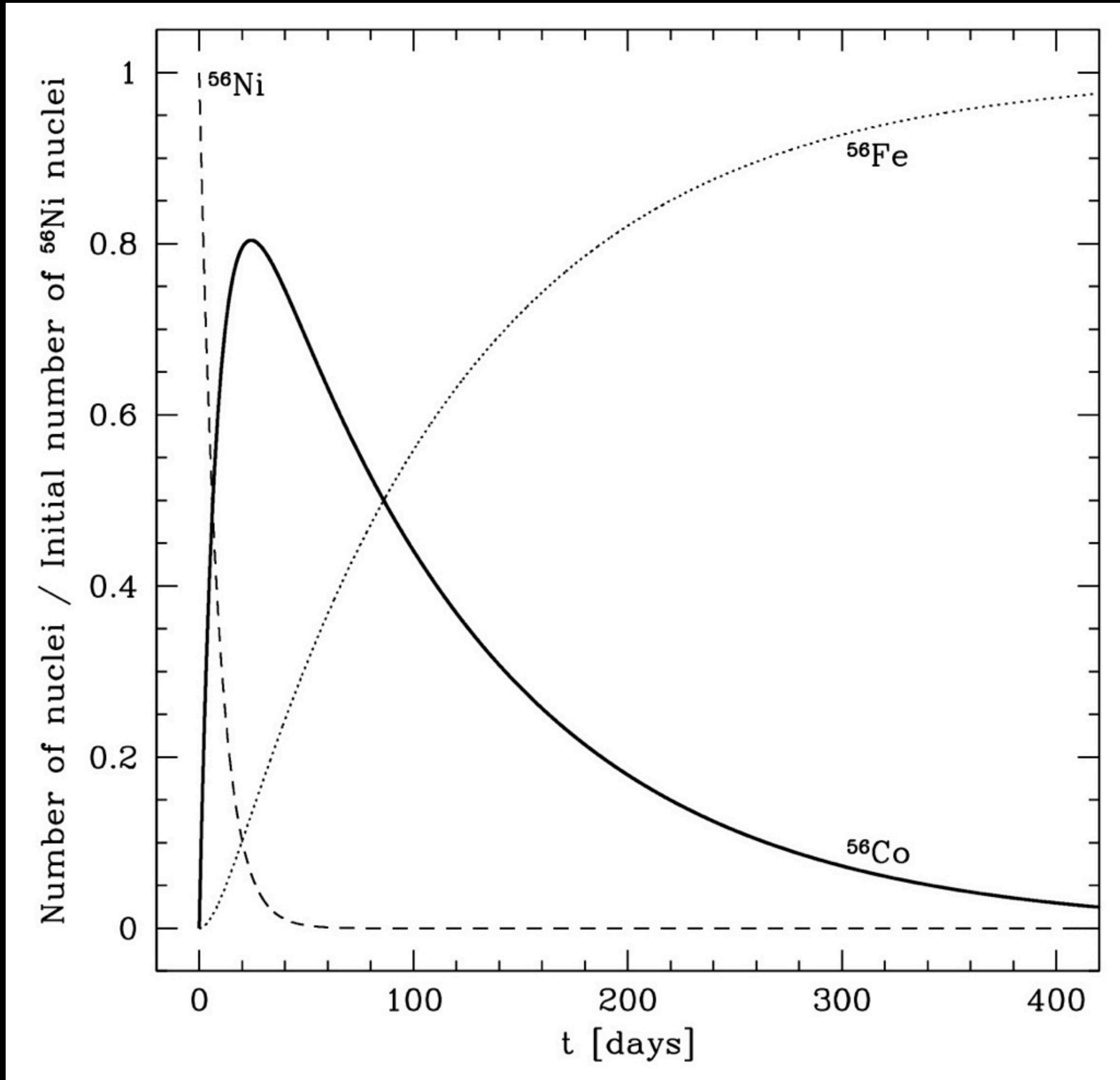
- kinetic energy ~ cst as long as the swept-up mass of external medium is low
- internal energy : high initially, then decreases (adiabatic cooling + radiation)
- radioactivity : additional source of energy which is dominant

^{56}Ni → ^{56}Co → ^{56}Fe (stable)

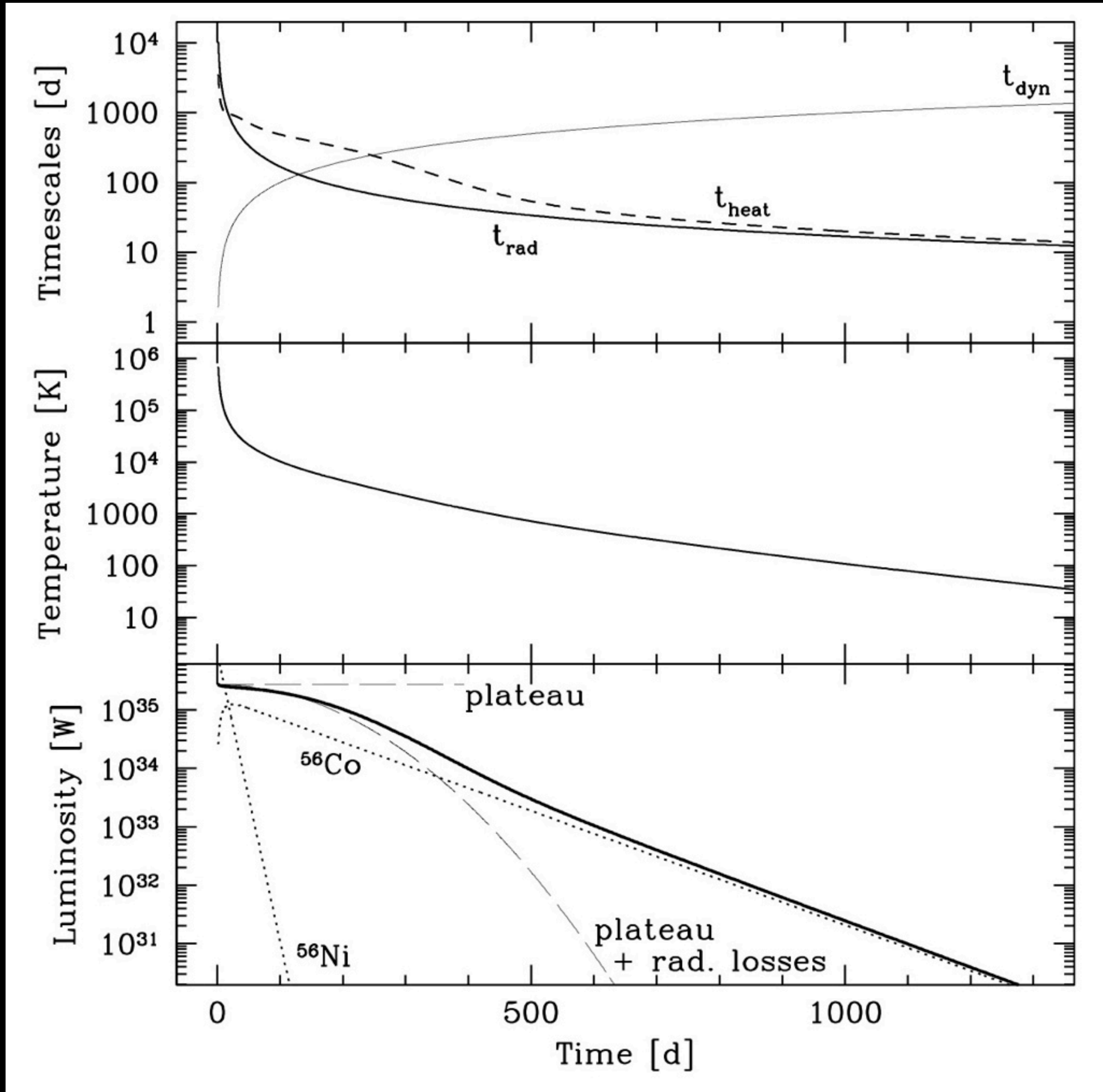
	Demie-vie $\tau_{1/2}$	Vie moyenne $\bar{\tau} = \tau_{1/2}/\ln 2$	énergie libérée par désintégration q_*
$^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co}$	6.1 d	8.8 d	2.1 MeV
$^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$	77 d	111d	4.4 MeV

Main parameter : initial mass of nickel

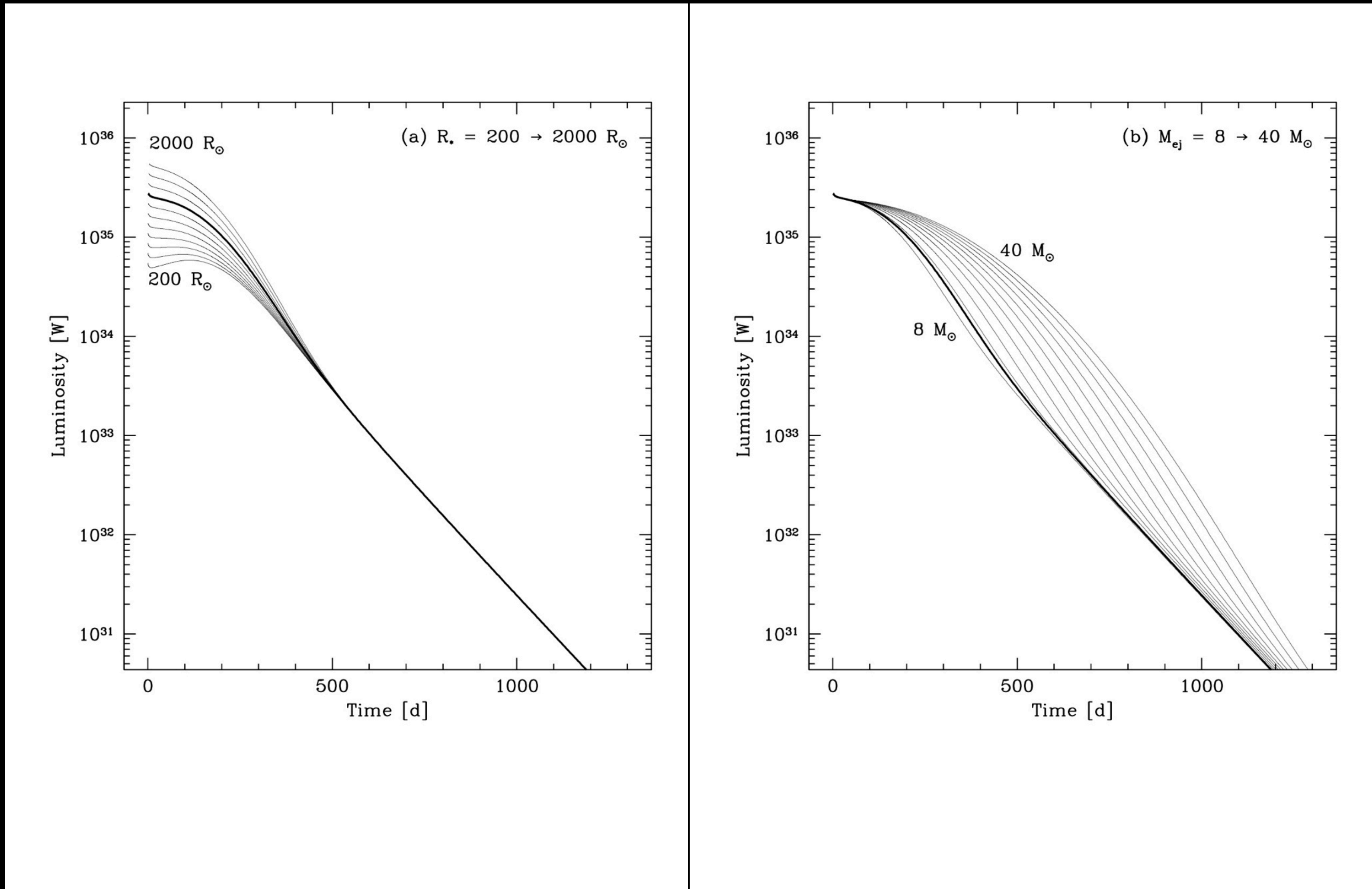
Radioactive decay of nickel ^{56}Ni and cobalt ^{56}Co



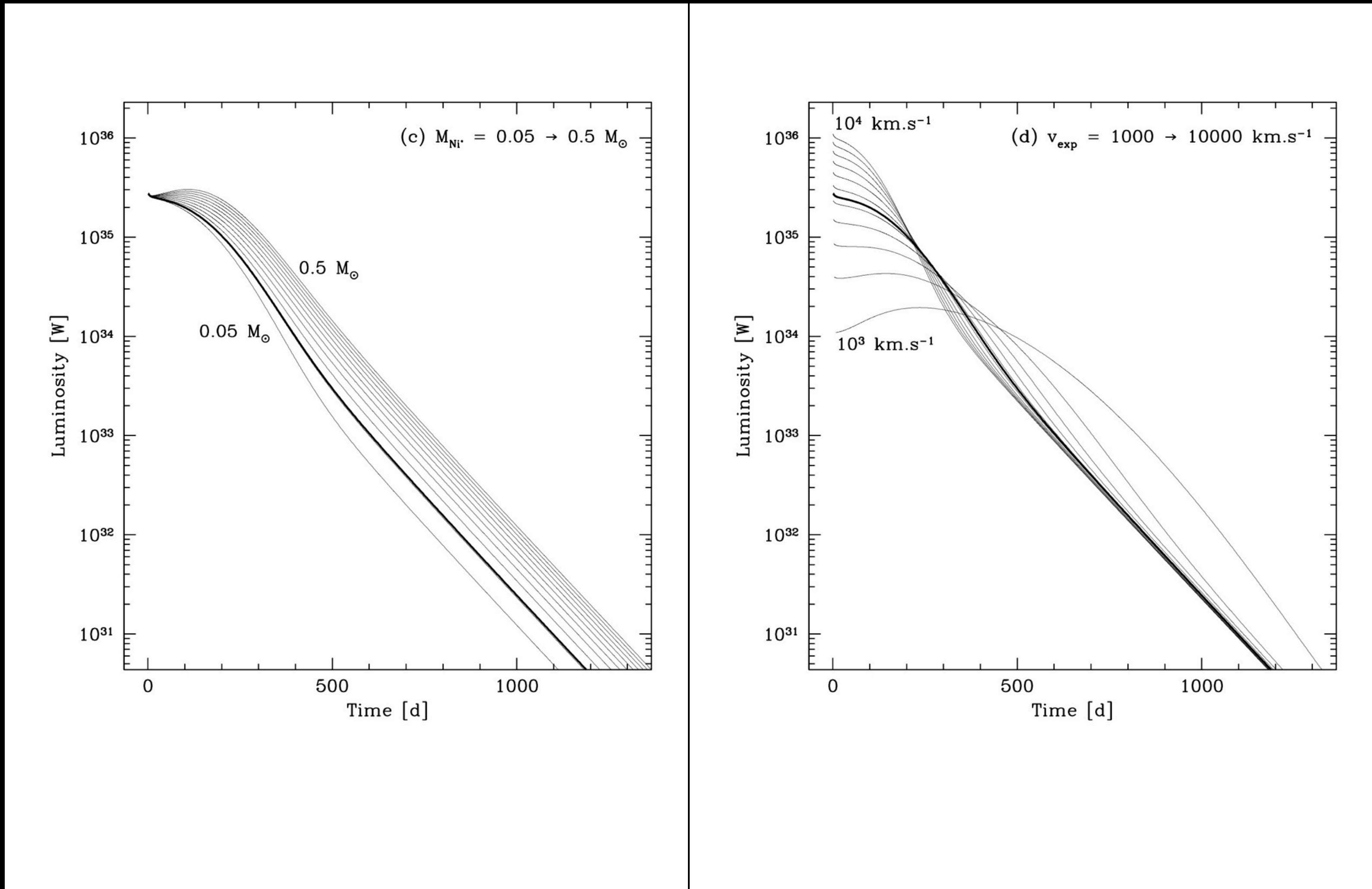
A simple model of the supernova lightcurve



A simple model of the supernova lightcurve



A simple model of the supernova lightcurve



Gravitational waves ?

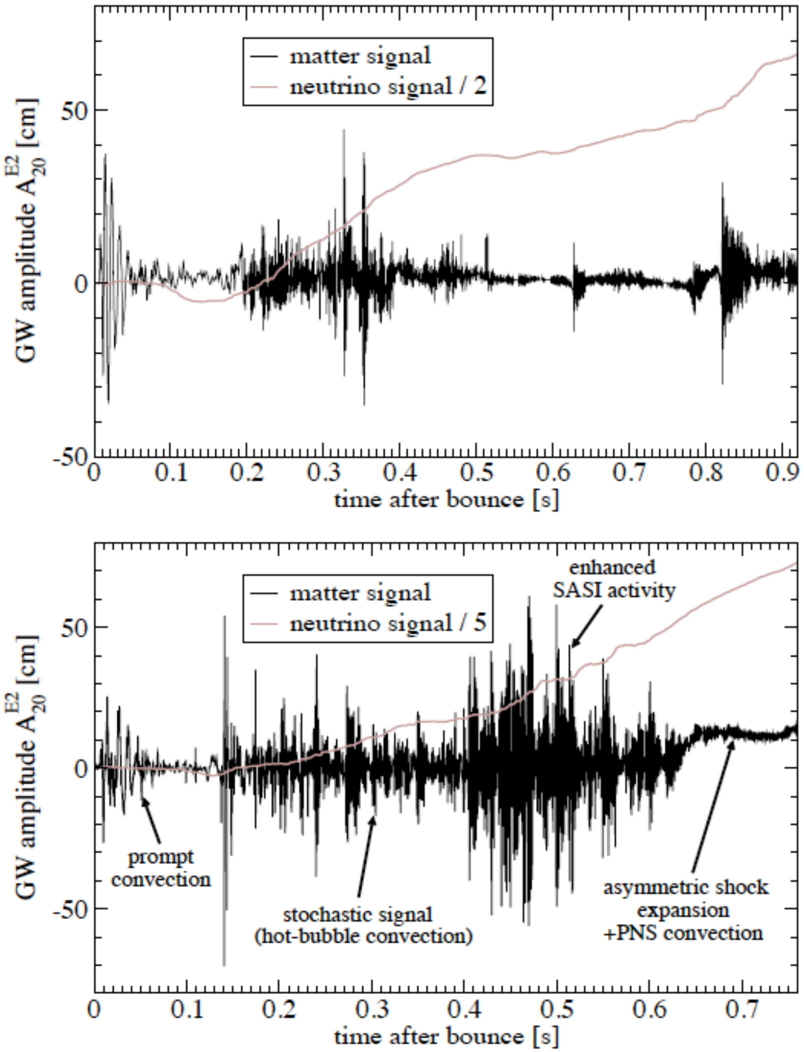


FIG. 8: Amplitudes of gravitational waves (GWs) from the general relativistic 2D simulations of core collapse and explosion of $11.2\,M_\odot$ (*upper plot*) and $15\,M_\odot$ (*lower plot*) stars shown in Fig. 6 [147]. The light brown lines (scaled down by factors of two and five in the upper and lower panel, respectively) display the growing amplitude connected with the asymmetric neutrino emission. The matter signal (solid black line) exhibits activity phases associated with strong, prompt postbounce convection (for $t_{\rm pb} \lesssim 50$ ms), increasingly violent convective and SASI mass motions in the postshock layer before the explosion sets in (between ~100 ms and 350 ms (500 ms) in the $11.2\,M_\odot$ ($15\,M_\odot$) case), and the continued impact of asymmetric accretion downdrafts on the PNS after the launch of the explosion. The non-zero value of the matter signal at late times is a consequence of the aspherical expansion of the shocked ejecta.

(Janka 2012, arXiv:1206.2503)

Explosive phenomena: SNe and GRBs

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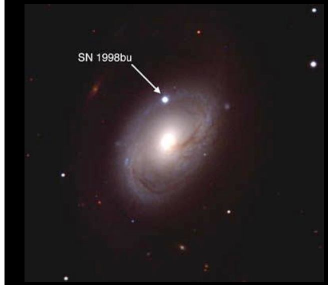

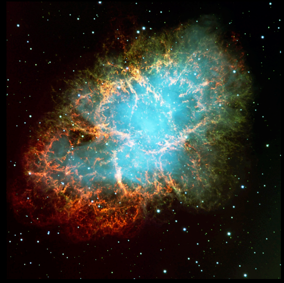

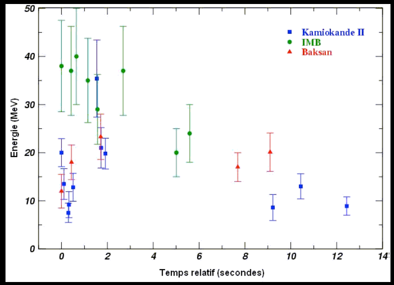

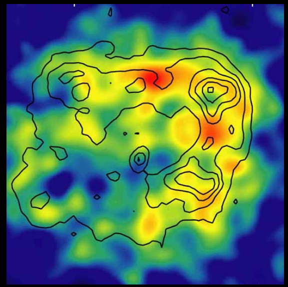

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A. Core collapse supernovae

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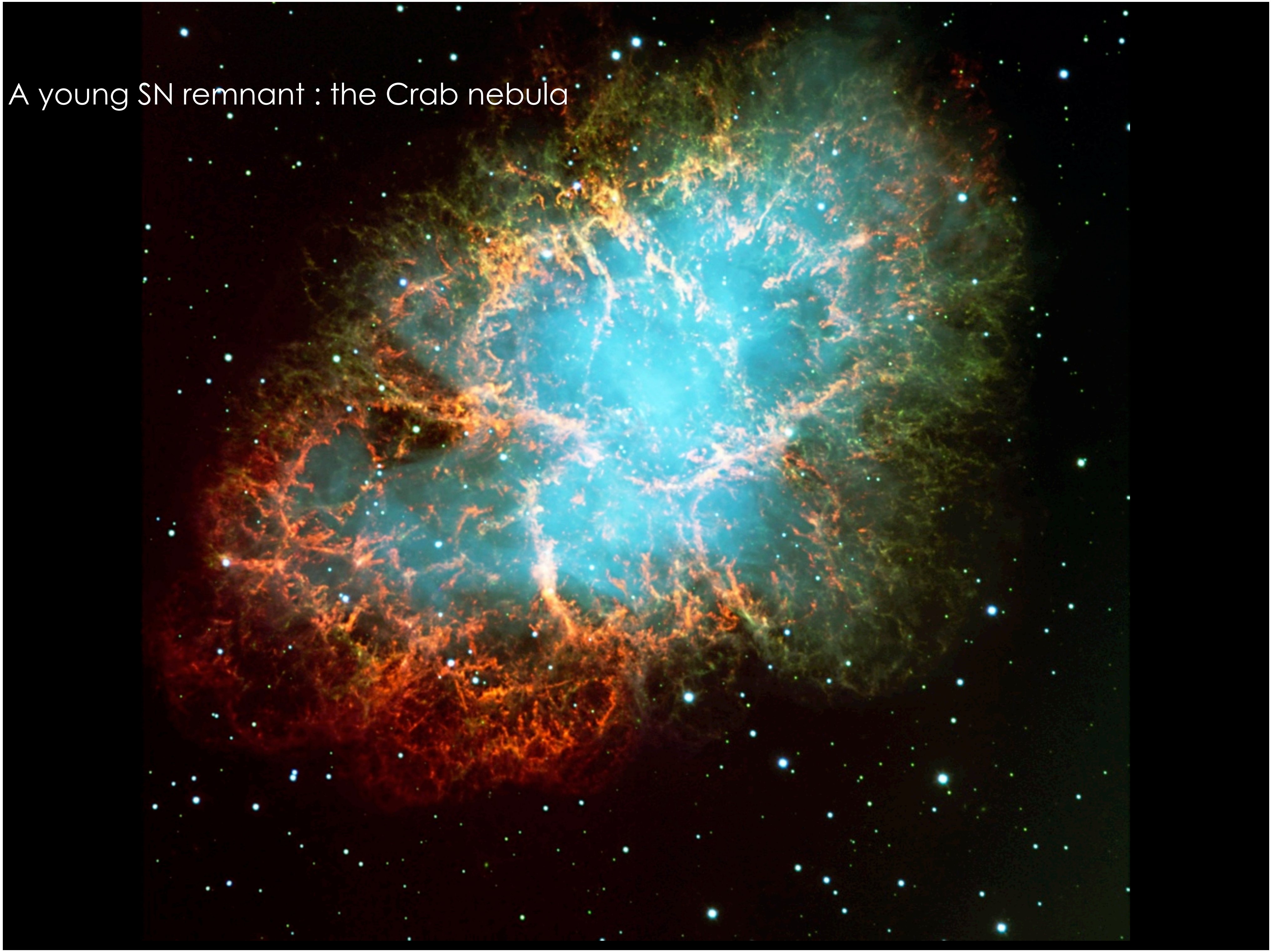
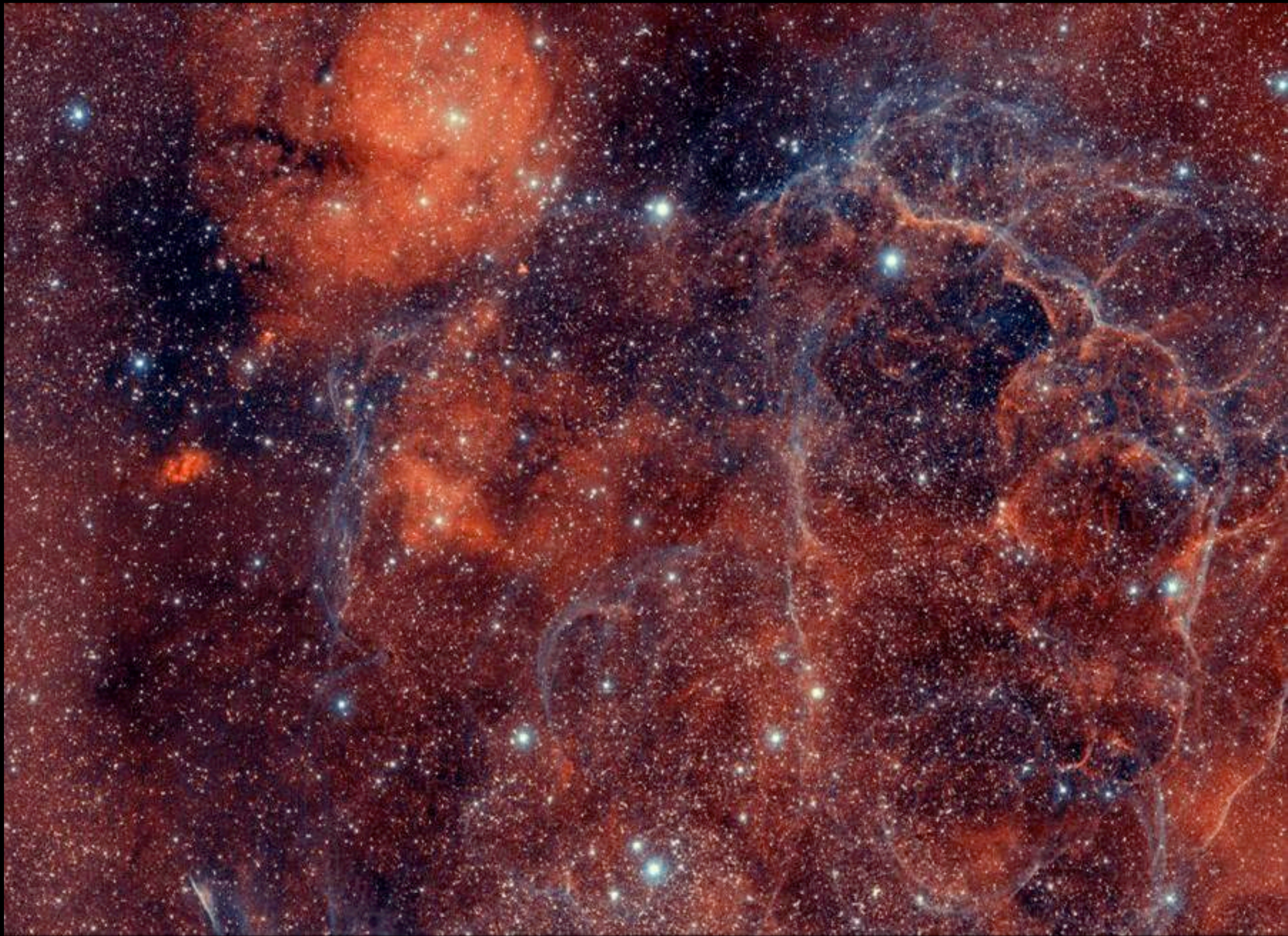
5. **Remnant**
6. Conclusion

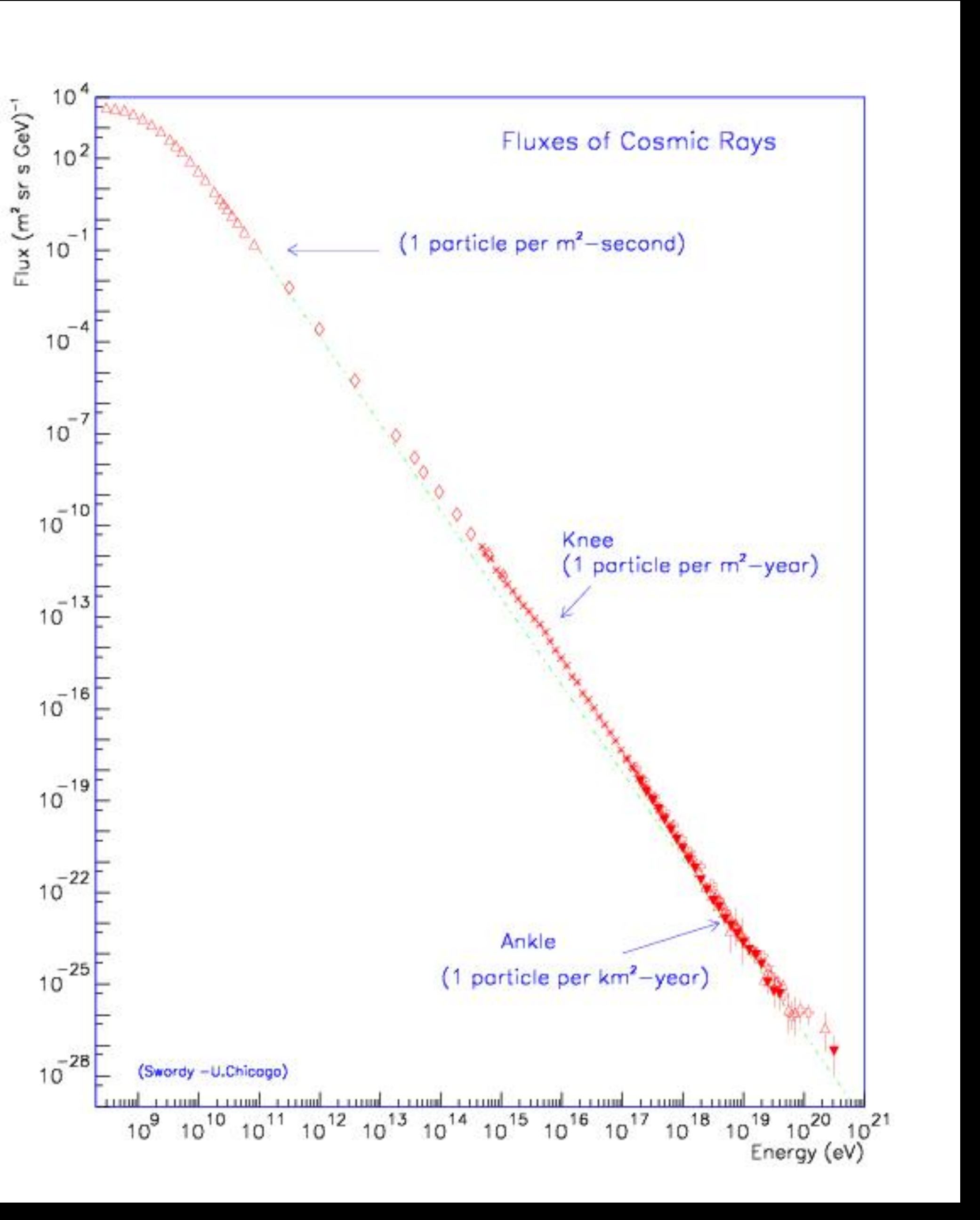
A young SN remnant : the Crab nebula



A old SN remnant : Vela

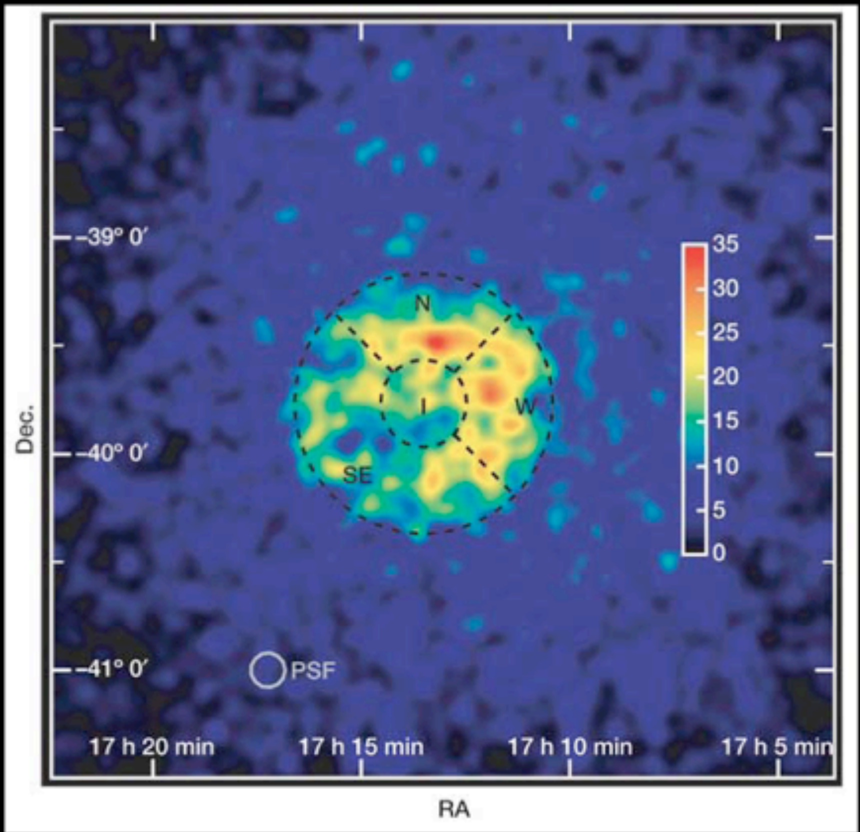


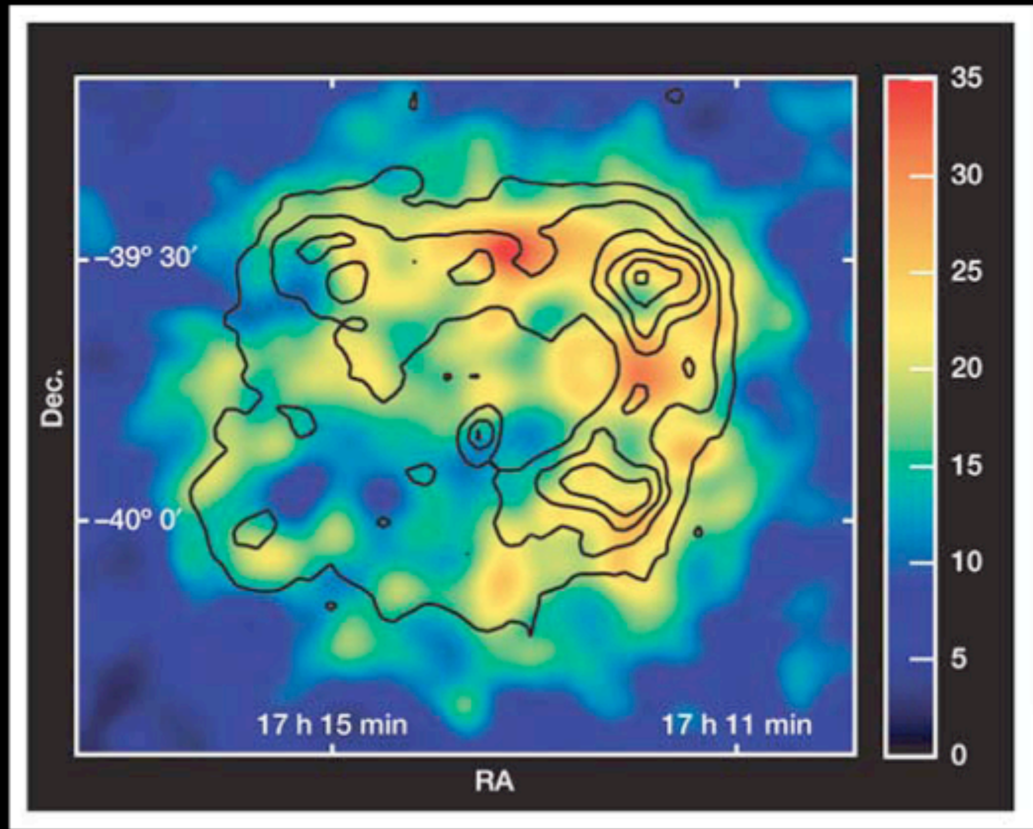
Supernovae and cosmic rays



Supernovae and cosmic rays

Un reste de supernova jeune (RX J1713.7-3946) :
émission au TeV détectée par HESS
(des particules de très haute énergie sont accélérées dans les SNRs).





Explosive phenomena: SNe and GRBs

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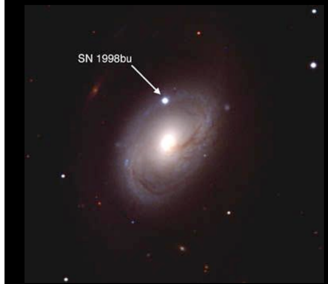

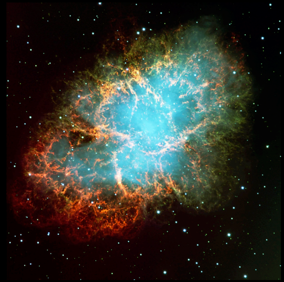

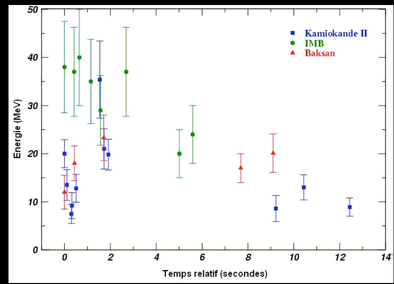

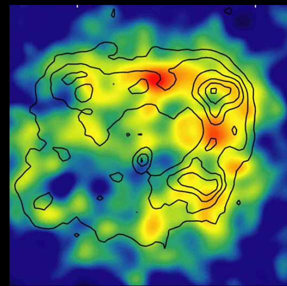

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Many open questions

Link between a given type of core collapse supernova and a given progenitor

Conditions to produce a NS or a BH (fractions of progenitors ?)

Initial properties of the new born compact object ?
(does it explain the velocity distribution of pulsars ?)

What would we learn with a neutrino detection of a nearby SN ?
(physical conditions in ultra-dense matter)

What would we learn with a GW detection of a nearby SN ?
(dynamics)

Contribution of explosive nucleosynthesis to the chemical evolution of the Universe

Contribution of the energy released by supernovae to the evolution of galaxies
(ISM heating, star formation trigger, galactic winds, ...)

Explosive phenomena: SNe and GRBs

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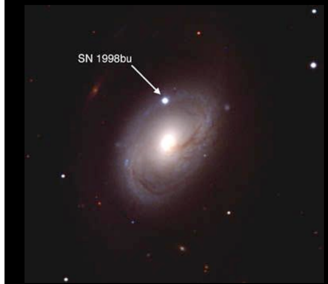

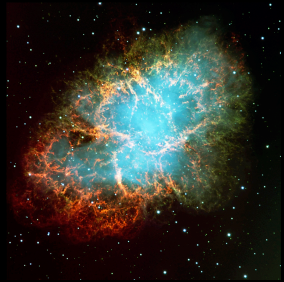

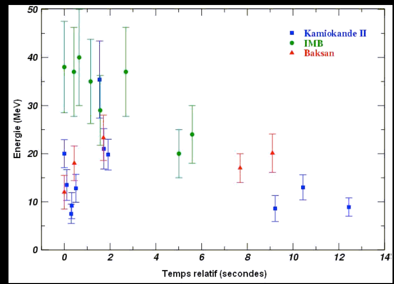

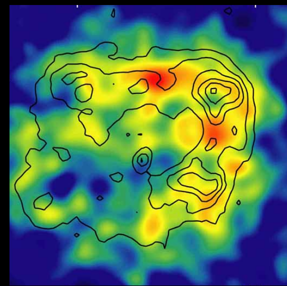

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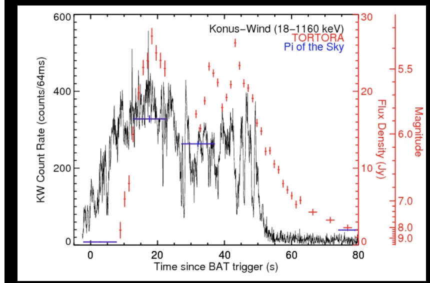

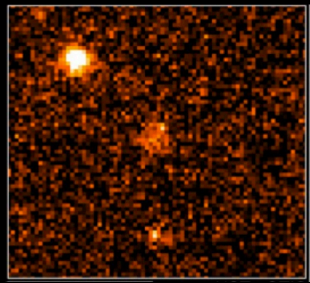

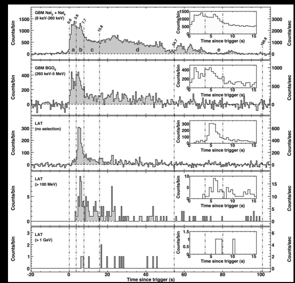

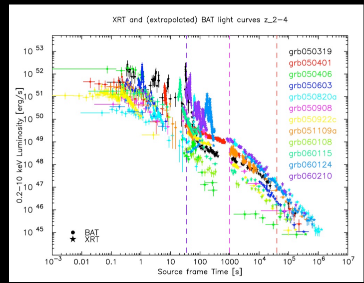

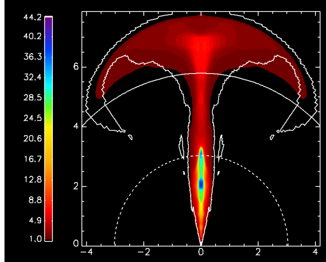

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Neutrinos and supernovae

Neutrinos and anti-neutrinos of the 3 flavours are directly emitted by the central region of a collapsing star (even without mixing during the propagation).

Processes :

TABLE I: Neutrino reactions with stellar-medium particles and between neutrinos in the Garching models. N means either n or p, $\nu \in \{\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau\}$, and $\nu_x \in \{\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau\}$. In addition to "inelastic" nucleon recoil, thermal motions, phase-space blocking, high-density N-N-correlations [51] and weak magnetism corrections [52], also quenching of the axial-vector coupling [53] and the reduction of the effective nucleon mass at high densities [54] are taken into account in the rates marked with a dagger (†). A prime indicates that the neutrino can exchange energy with the scattering target (non-conservative or "inelastic" scattering)

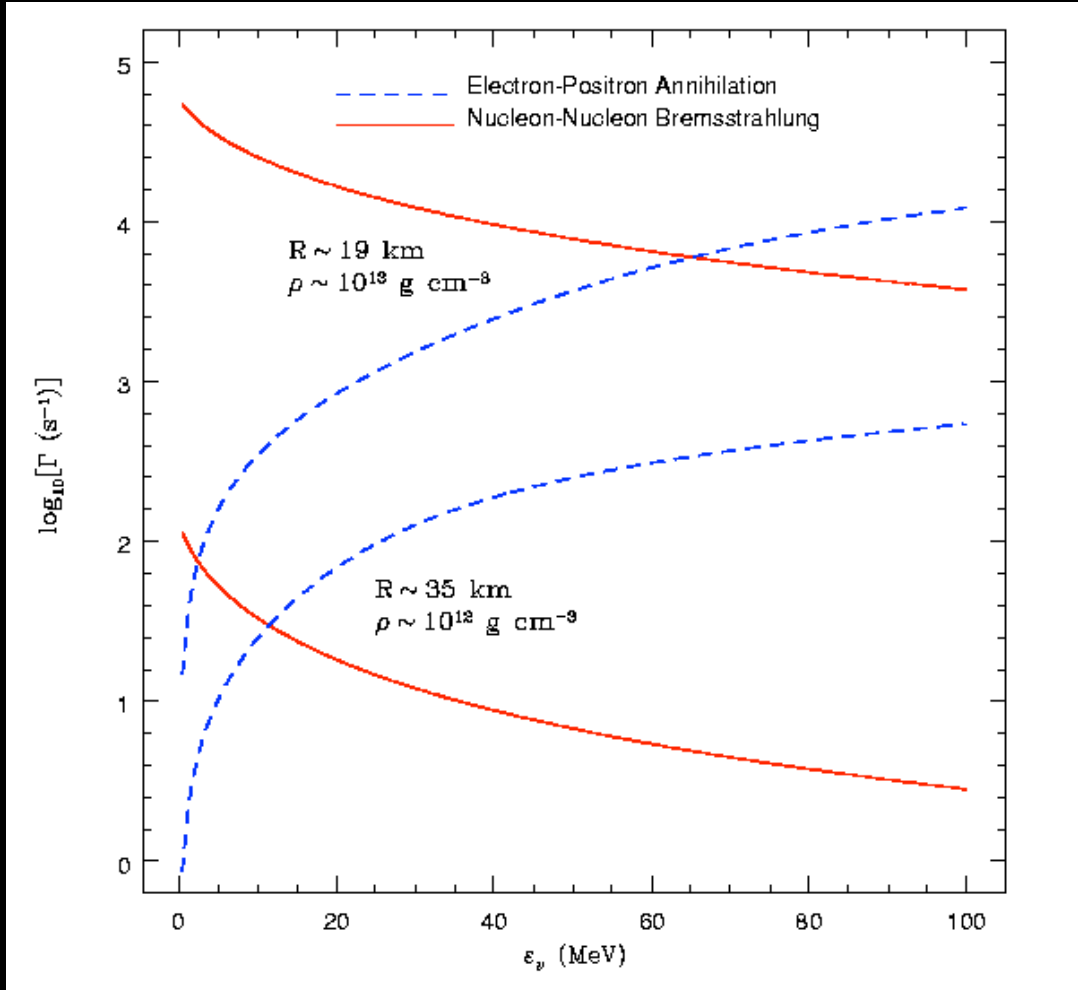
Process	References
Beta-Processes	
$\nu_e + n \rightleftharpoons e^- + p$	[51]†
$\bar{\nu}_e + p \rightleftharpoons e^+ + n$	[51]†
$\nu_e + (A,Z) \rightleftharpoons e^- + (A,Z+1)$	[55]
Scattering Reactions	
$\nu + (A,Z) \rightleftharpoons \nu' + (A,Z)$	[56] (ion-ion correlations)
	[57] (inelastic contribution)
$\nu + N \rightleftharpoons \nu' + N$	[51]†
$\nu + e^\pm \rightleftharpoons \nu' + e^\pm$	[58]
("Thermal") Pair Production	
$\nu + \bar{\nu} \rightleftharpoons e^- + e^+$	[59, 60]
Nucleon-Nucleon Bremsstrahlung	
$\nu + \bar{\nu} + N + N \rightleftharpoons N + N$	[61]
Reactions between Neutrinos	
$\nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau} \rightleftharpoons \nu_e + \bar{\nu}_e$	[62]
$\nu_x + \{\nu_e, \bar{\nu}_e\} \rightleftharpoons \nu'_x + \{\nu'_e, \bar{\nu}'_e\}$	[62]

(Janka 2012, arXiv:1206.2503)

Neutrinos and supernovae

Neutrinos and anti-neutrinos of the 3 flavours are directly emitted by the central region of a collapsing star (even without mixing during the propagation).

ν_μ, ν_τ are produced by several processes : nucleon-nucleon bremsstrahlung, electron-positron annihilation



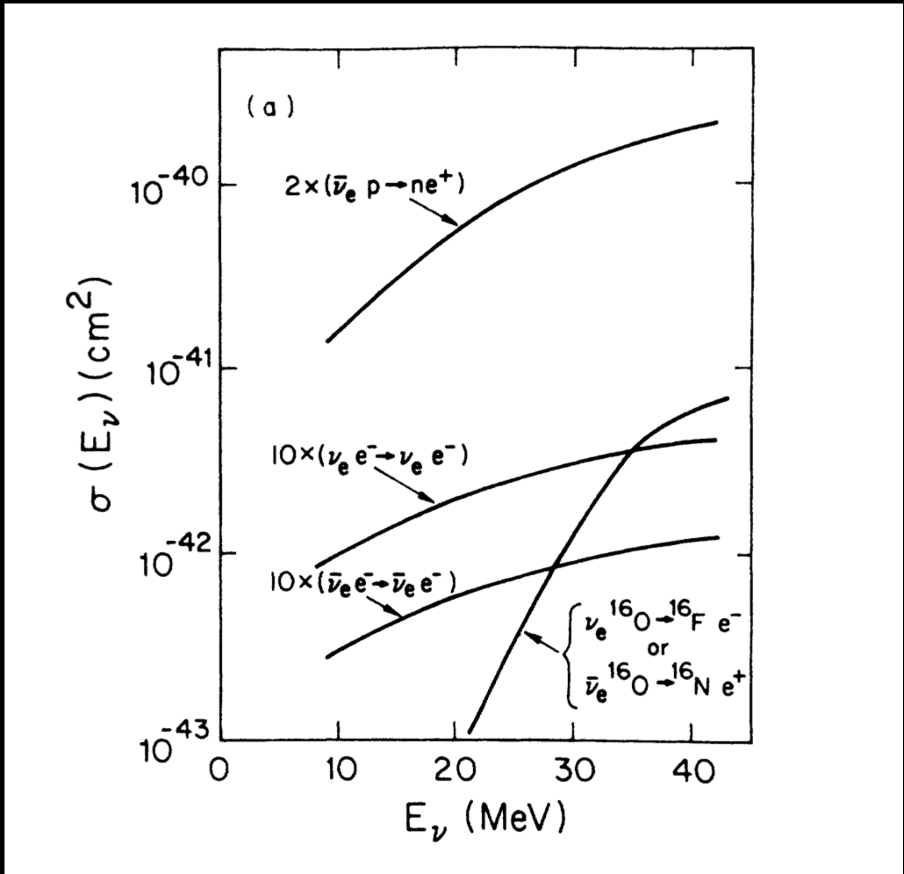
Neutrino number production rate

Neutrino energy (MeV)

Thompson, Burrows & Horvath, Phys. Rev. C, 62, 035802 (2000)

Neutrinos and supernovae

In the case of SN 1987A, Kamiokande detected only electron anti-neutrinos because of a better sensitivity (compare to electron neutrinos) in the considered energy range (15-20 MeV). In fact, Hirata et al., Phys. Rev. D, 38, 448 (1998) (paper presenting the discovery) discusses the possibility that one of the 12 events is a electron neutrino...



$=E(e^+) + 1.3$ MeV, and is so calculated for all but the first event in the burst. Event 1 is consistent with production through $\sigma(\nu_e e^- \rightarrow \nu_e e^-)$. [The latter reconstruction program yielded for event 1, $\theta(e,\mathrm{LMC}) = (10\pm18)$ deg in agreement with the original value of (18 ± 18) deg.] As seen from Fig. 14, of order one event from that reaction might be expected in Kamiokande-II.

Given the electron energies in Table II, the electron detection efficiency versus energy relationship in Fig. 3, and assuming all but event 1 are due to $\bar{\nu}_e p_{\mathrm{free}} \rightarrow e^+ n$, the resultant integrated flux of $\bar{\nu}_e$ in the burst at 7:35:35 is 1.1×10^{10} cm^{-2} for $\bar{\nu}_e$ with energies above 8.8 MeV. This in turn leads to a $\bar{\nu}_e$ output of SN1987A of 9×10^{52} ergs for an (observed) average energy of 15 MeV.

The internal time structure and the energies of the events in the burst, as given in Fig. 9 and Table II, have been addressed in studies[13] that attempt to extract the initial-state properties and time evolution of SN1987A. A detailed, precise comparison of the burst data from Kamiokande-II and from the IMB detector[9] is not possible because the absolute time of the beginning of the neutrino burst in Kamiokande-II is given with an error of ±1

Hirata et al. (1988)

Explosive phenomena: SNe and GRBs

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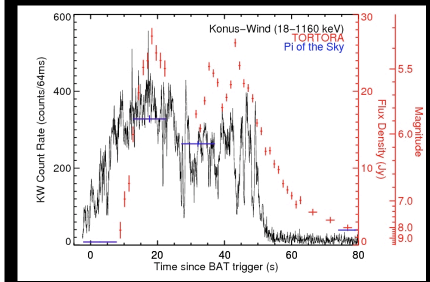

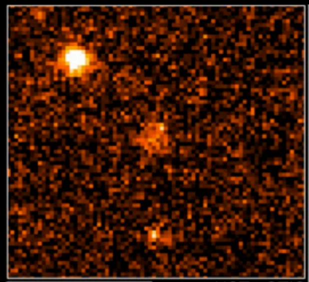
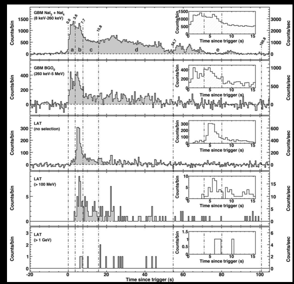
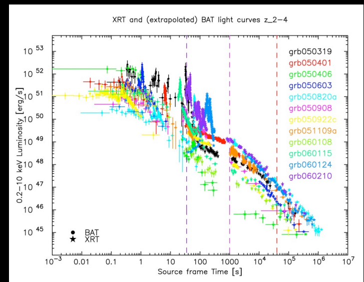

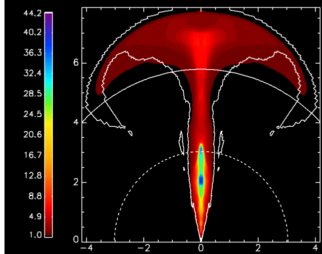

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B. Gamma-ray bursts

1. Observations - Classification
2. Theory: summary of the observational constraints
3. Central engine
4. Prompt emission
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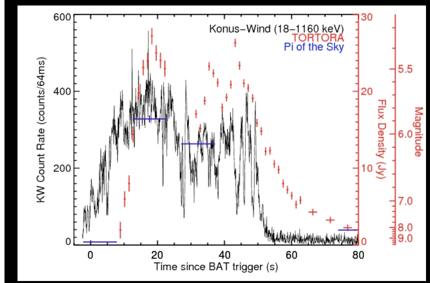

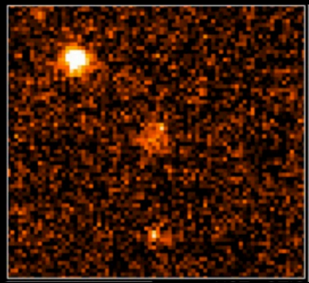

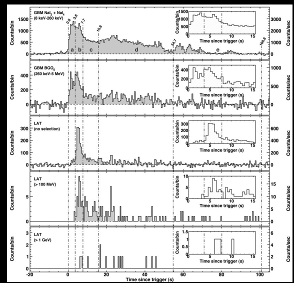

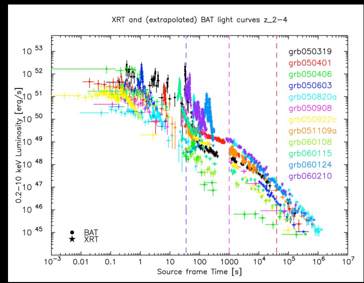

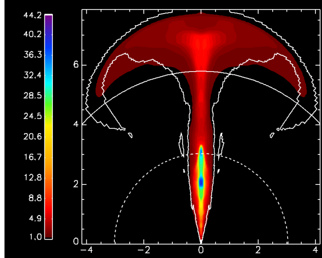

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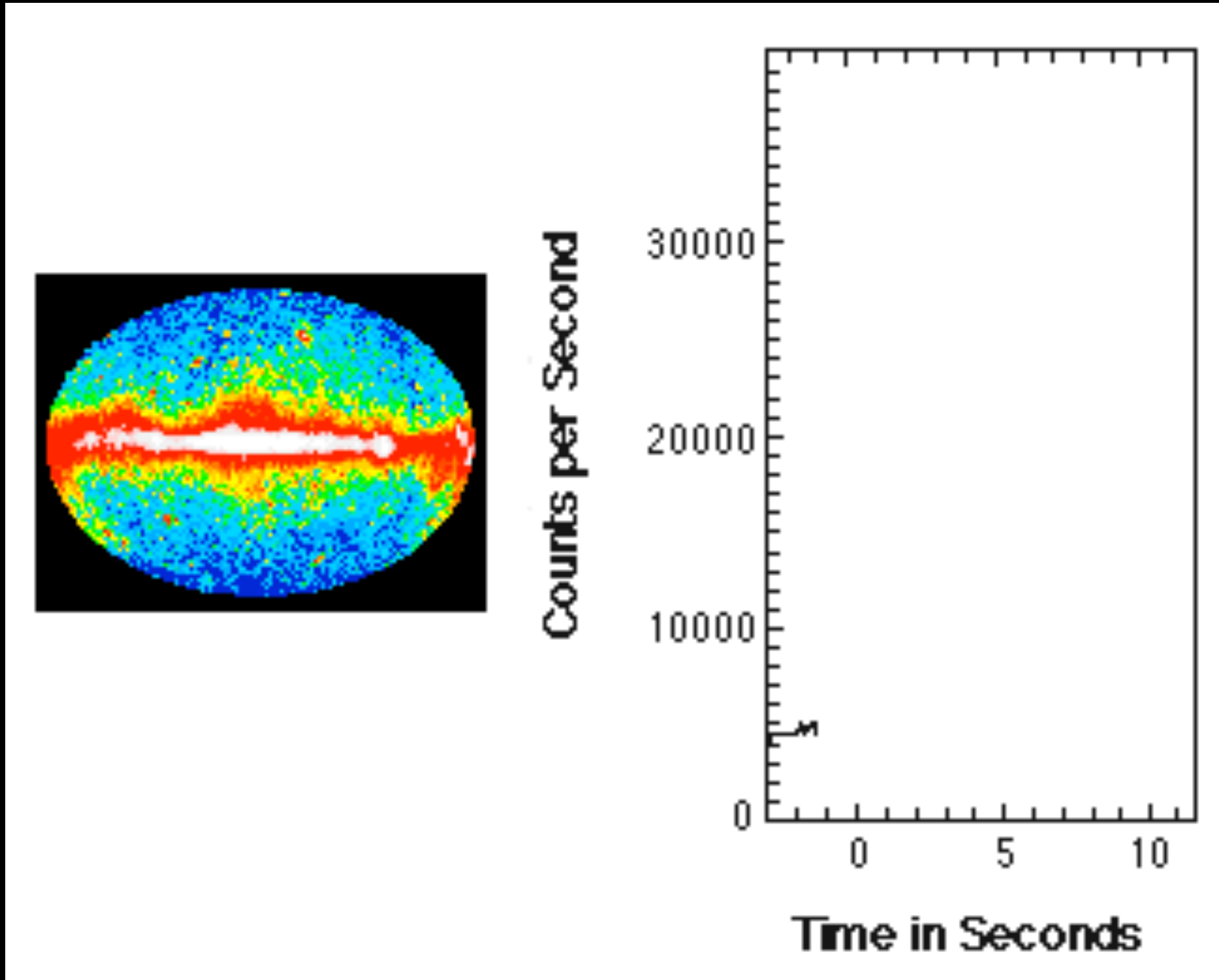
Gamma-ray bursts



Gamma-ray bursts

Historical remarks :

- VELA satellites

Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and under Water
Signed by the Original Parties, the Union of Soviet Socialist Republics, the United Kingdom of Great Britain and Northern Ireland and the United States of America at Moscow : 5 August 1963

The Governments of the United States of America, the United Kingdom of Great Britain and Northern Ireland, and the Union of Soviet Socialist Republics, hereinafter referred to as the « Original Parties, »

Proclaiming as their principal aim the speediest possible achievement of an agreement on general and complete disarmament under strict international control in accordance with the objectives of the United Nations which would put an end to the armaments race and eliminate the incentive to the production and testing of all kinds of weapons, including nuclear weapons,

Seeking to achieve the discontinuance of all test explosions of nuclear weapons for all time, determined to continue negotiations to this end, and desiring to put an end to the contamination of man's environment by radioactive substances,

Have agreed as follows :

Article I

1. Each of the Parties to this Treaty undertakes to prohibit, to prevent, and not to carry out any nuclear weapon test explosion, or any other nuclear explosion, at any place under its jurisdiction or control :

   (a) in the atmosphere; beyond its limits, including outer space; or under water, including territorial waters or high seas; or

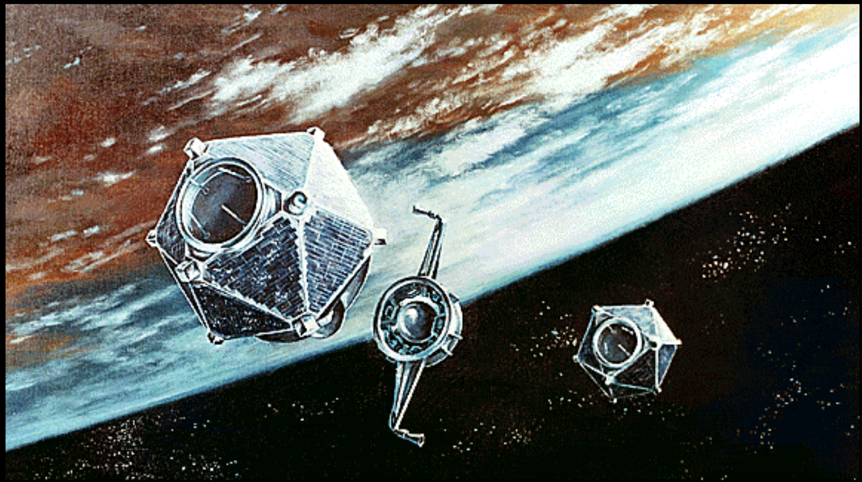
   (b) in any other environment if such explosion causes radioactive debris to be present outside the territorial limits of the State under whose jurisdiction or control such explosion is conducted. It is understood in this connection that the provisions of this subparagraph are without prejudice to the conclusion of a Treaty resulting in the permanent banning of all nuclear test explosions, including all such explosions underground, the conclusion of which, as the Parties have stated in the Preamble to this Treaty, they seek to achieve.

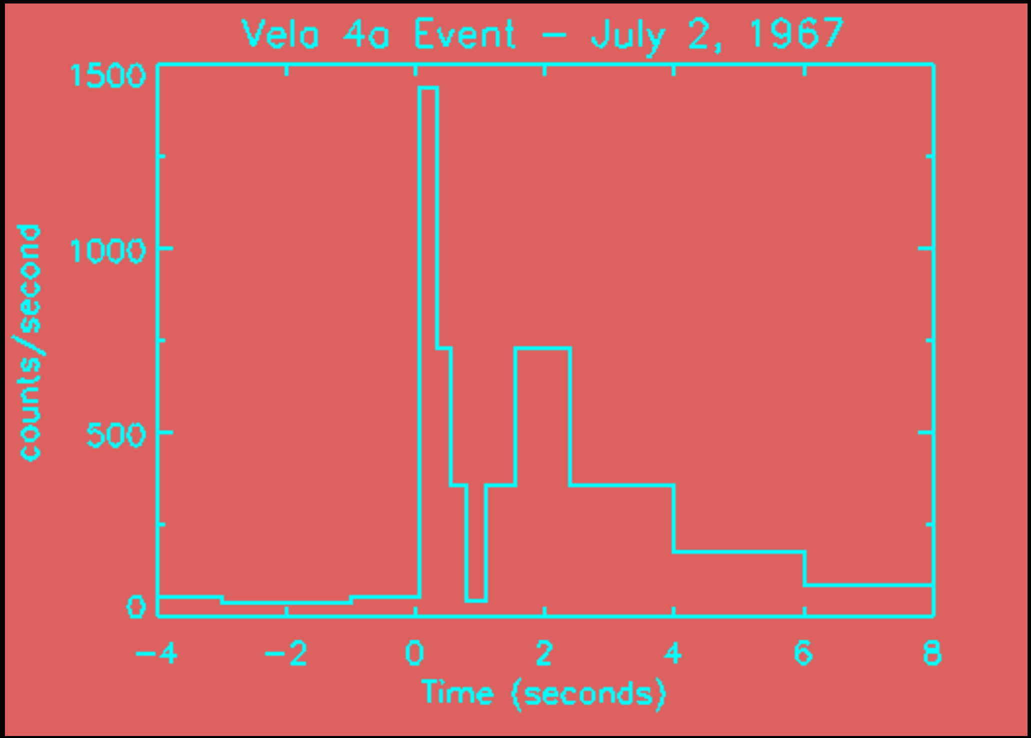
2. Each of the Parties to this Treaty undertakes furthermore to refrain from causing, encouraging, or in any way participating in, the carrying out of any nuclear weapon test explosion, or any other nuclear explosion, anywhere which would take place in any of the environments described, or have the effect referred to, in paragraph 1 of this Article.

Gamma-ray bursts

Historical remarks :

- VELA satellites : 3 times 2 satellites : 1963, 64 et 65





Gamma-ray bursts

Historical remarks :

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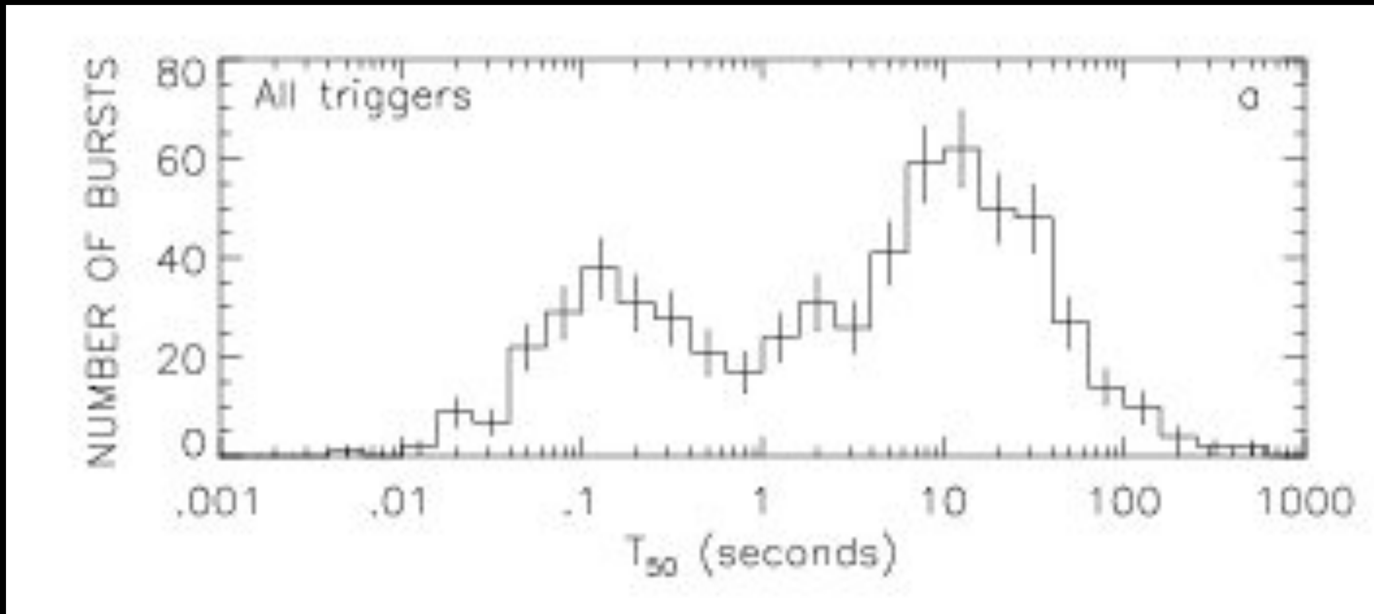
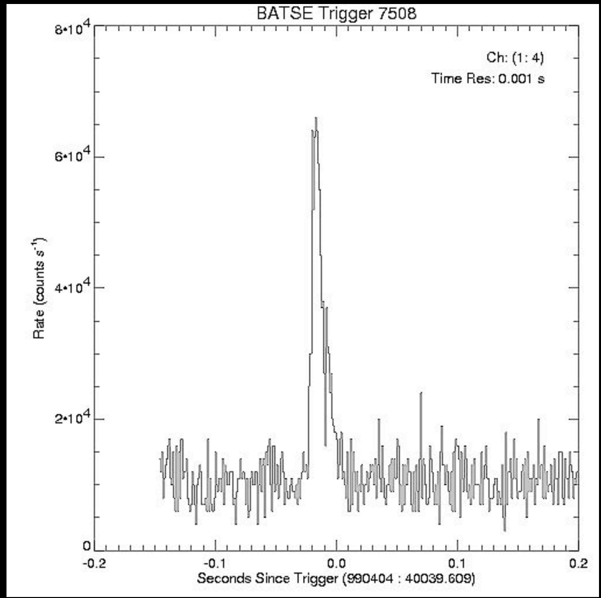
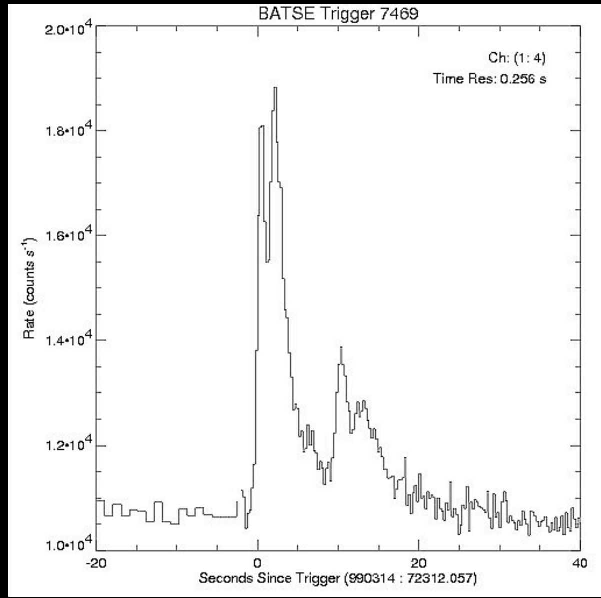
- 1970-1980 : studies of GRBs by scientific satellites

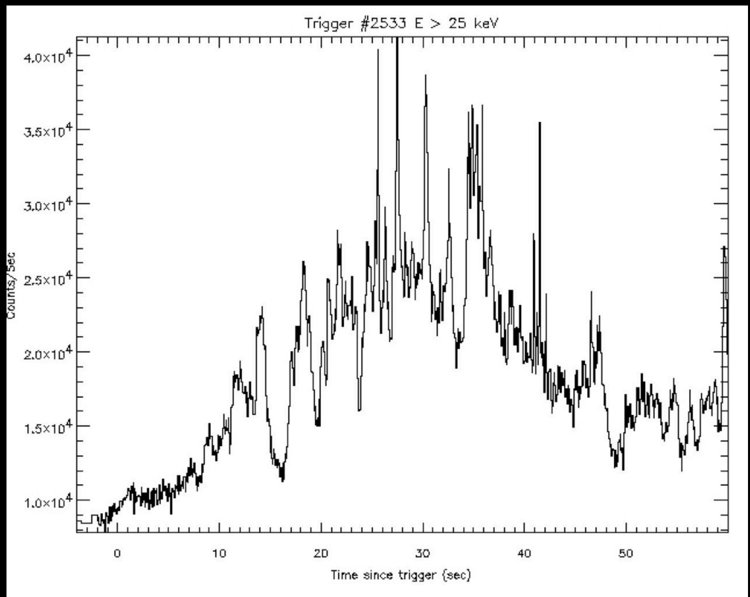
Gamma-ray bursts : duration

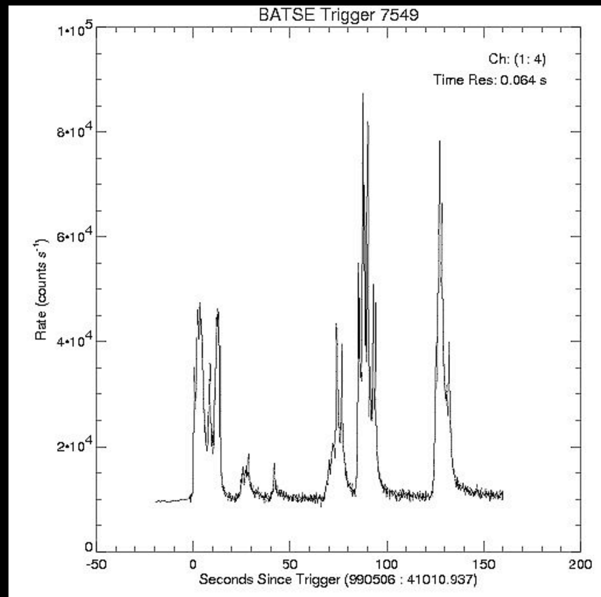


Gamma-ray bursts : lightcurves

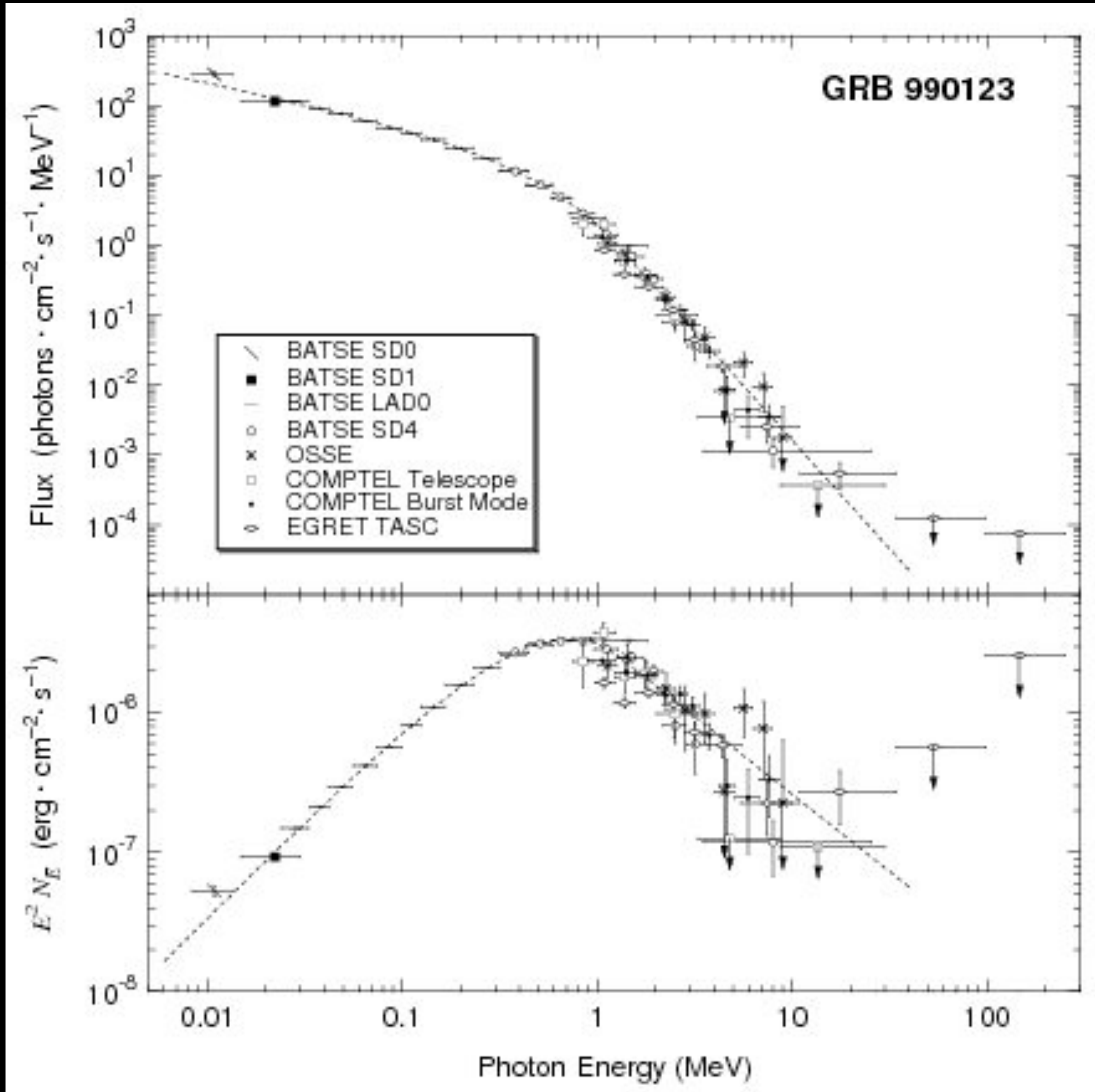








Gamma-ray bursts : spectrum



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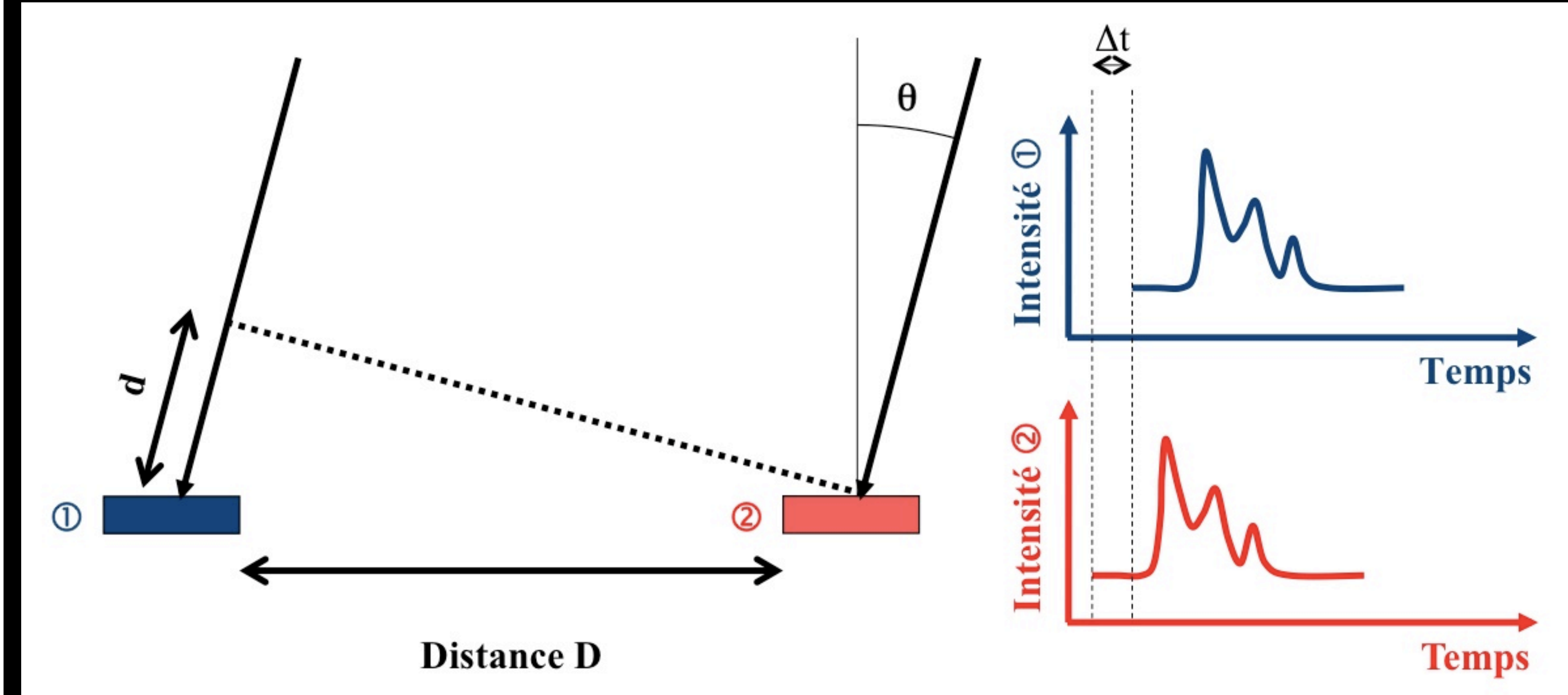
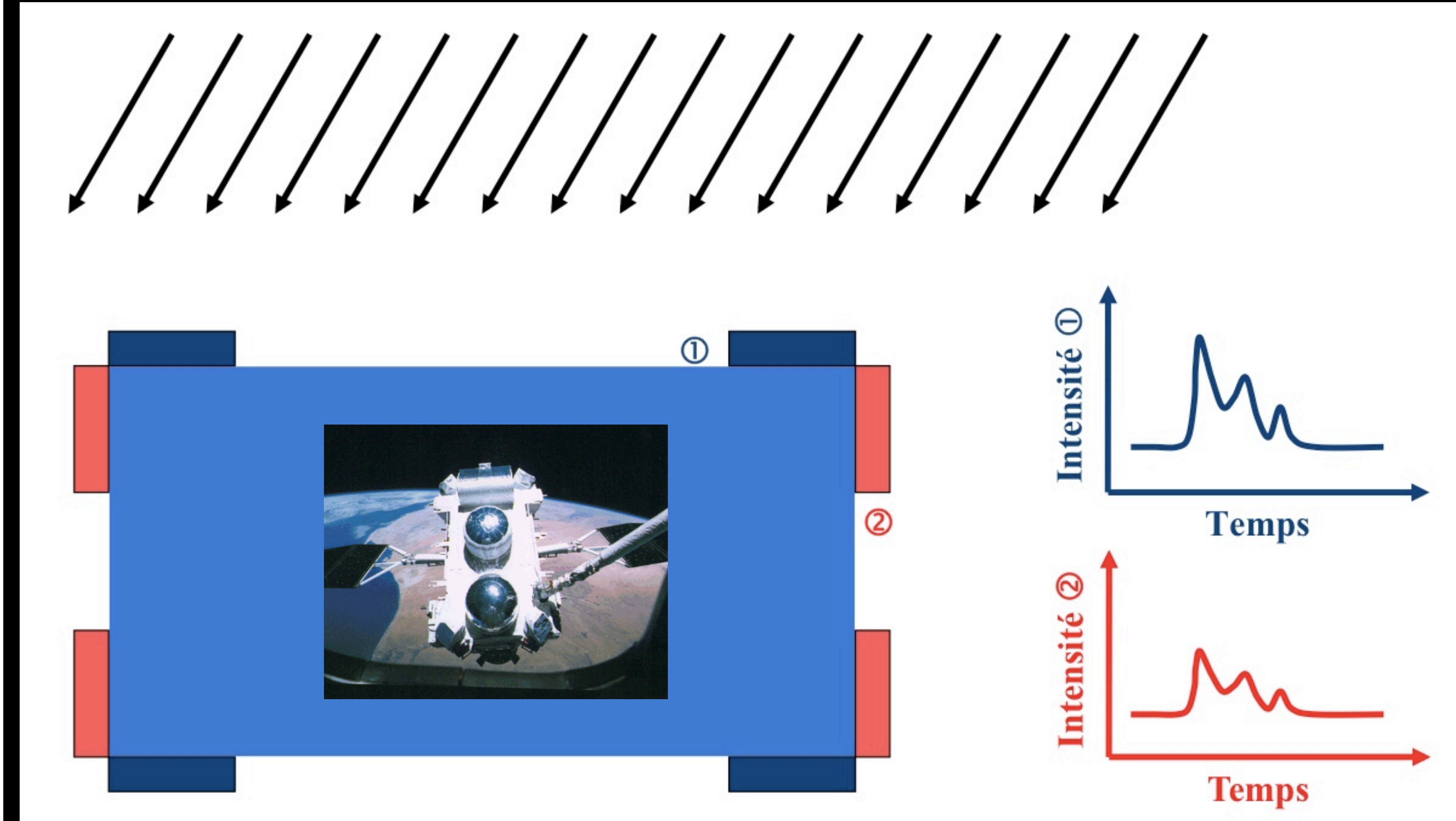
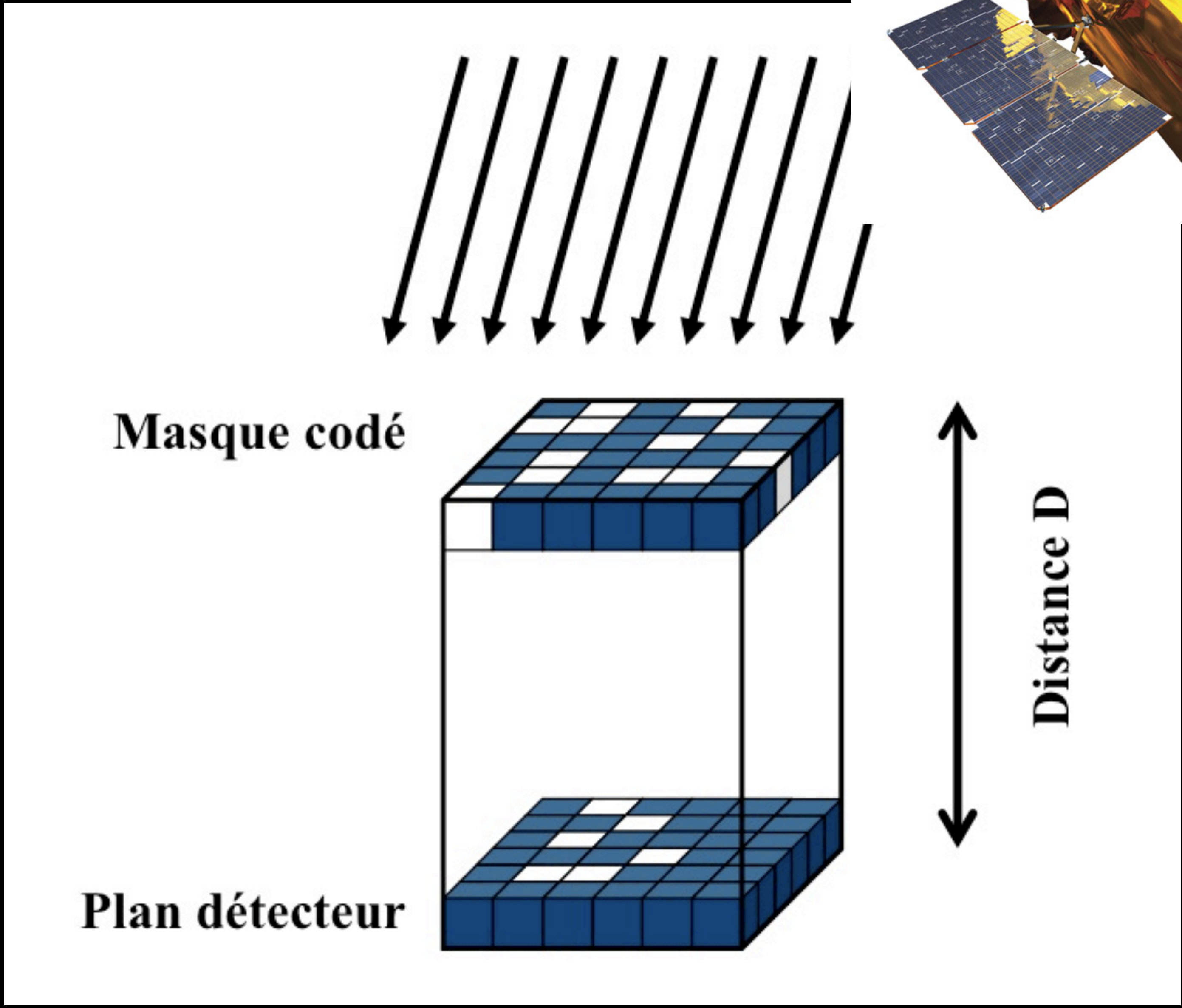
Gamma-ray bursts : localization

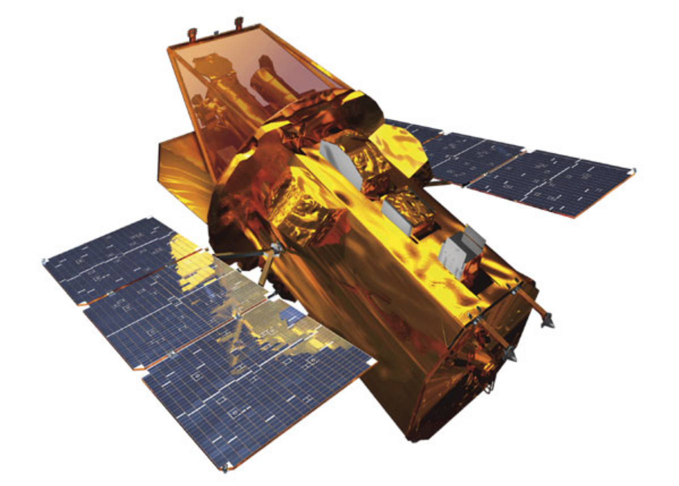


Gamma-ray bursts : localization



Gamma-ray bursts : localization





The coded mask of Swift

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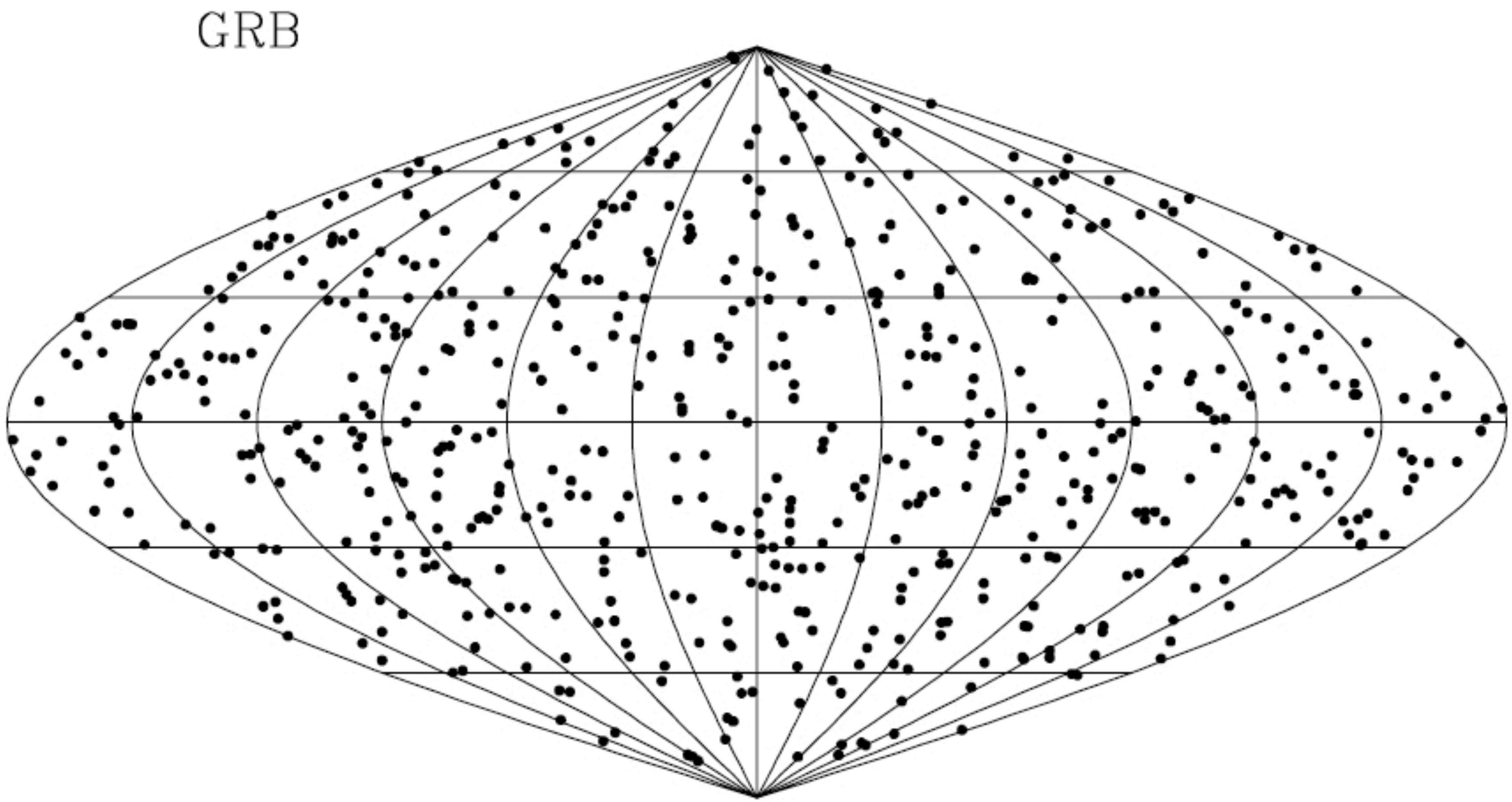
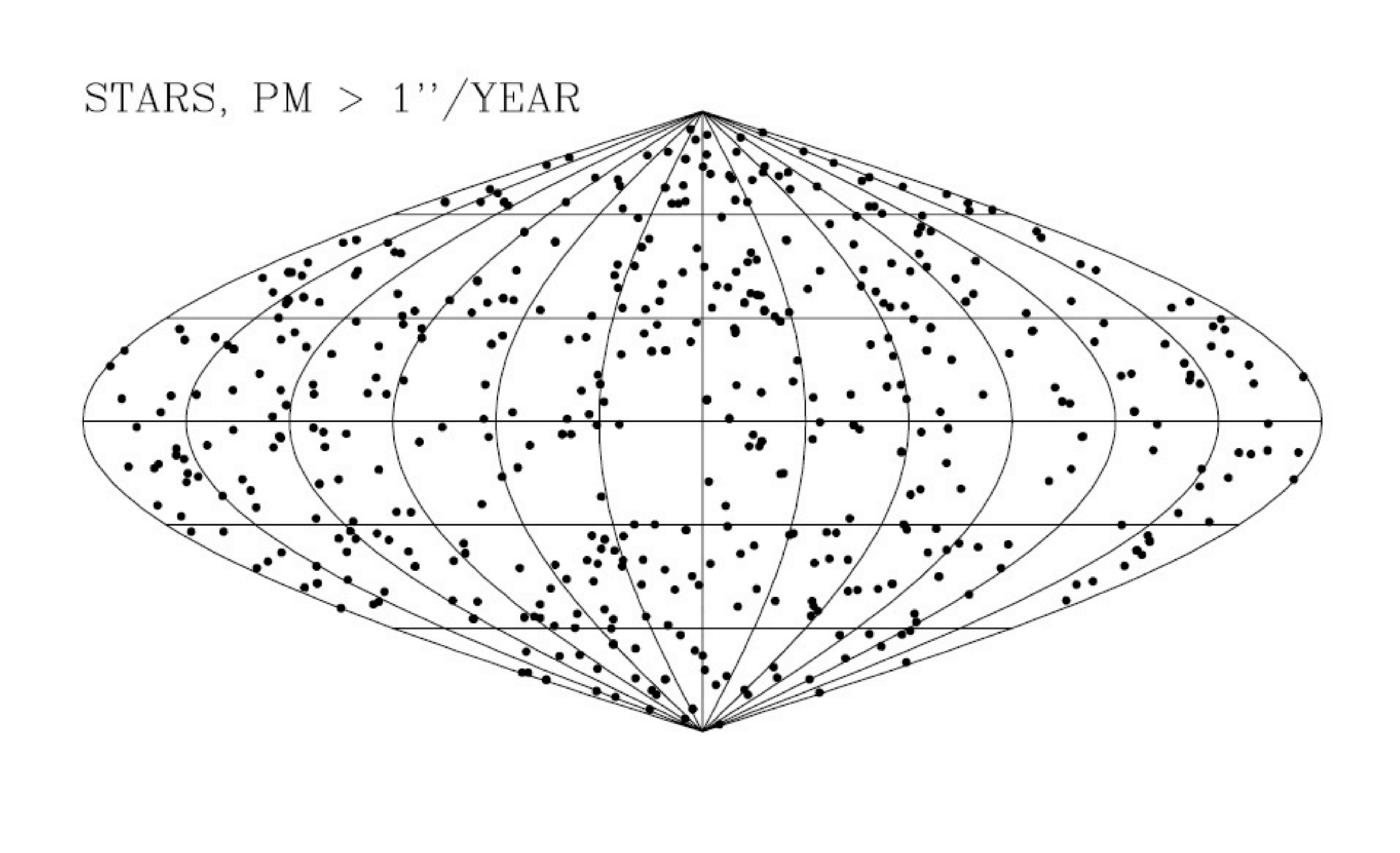
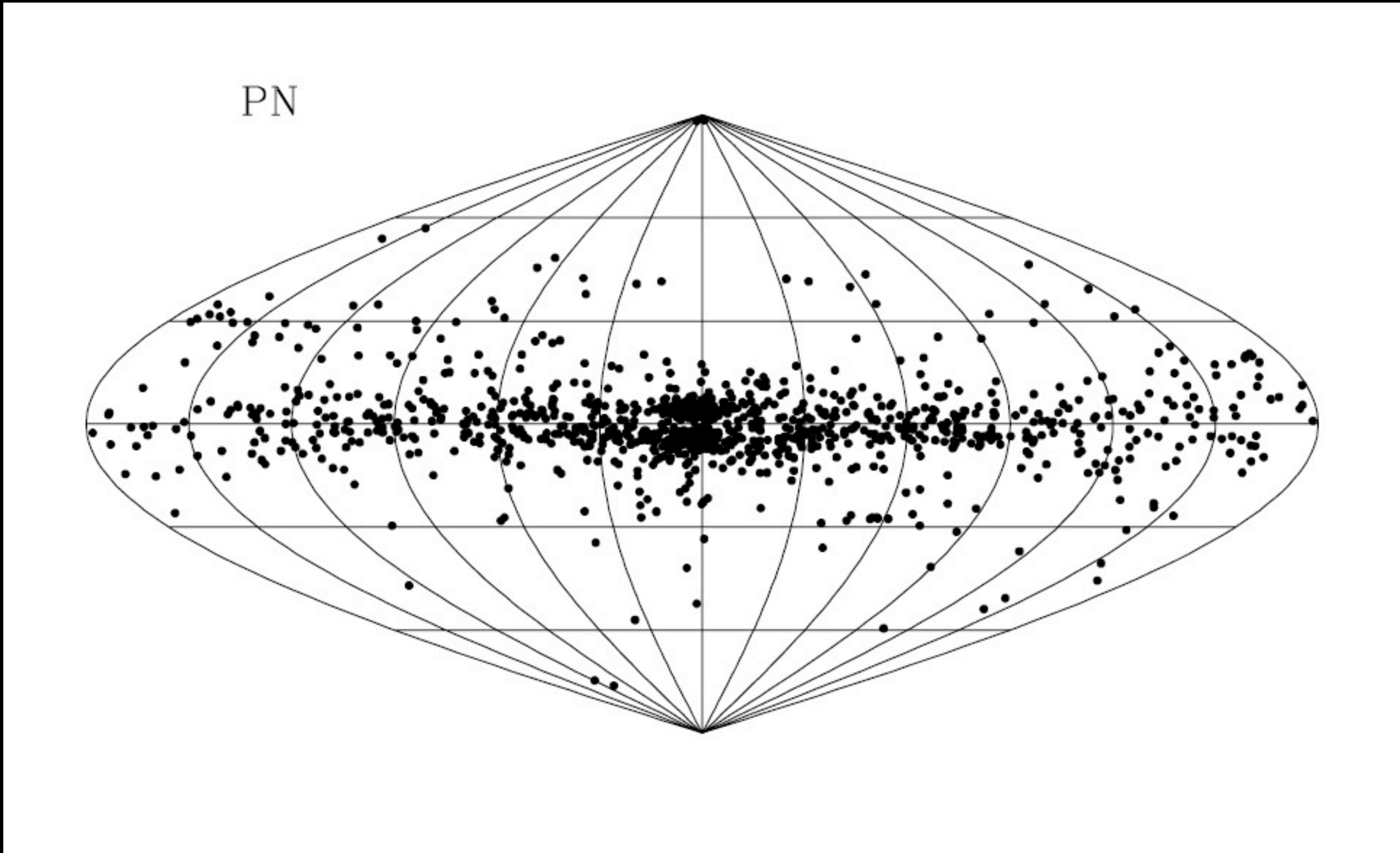
Gamma-ray bursts : sky map (BATSE, 1994)



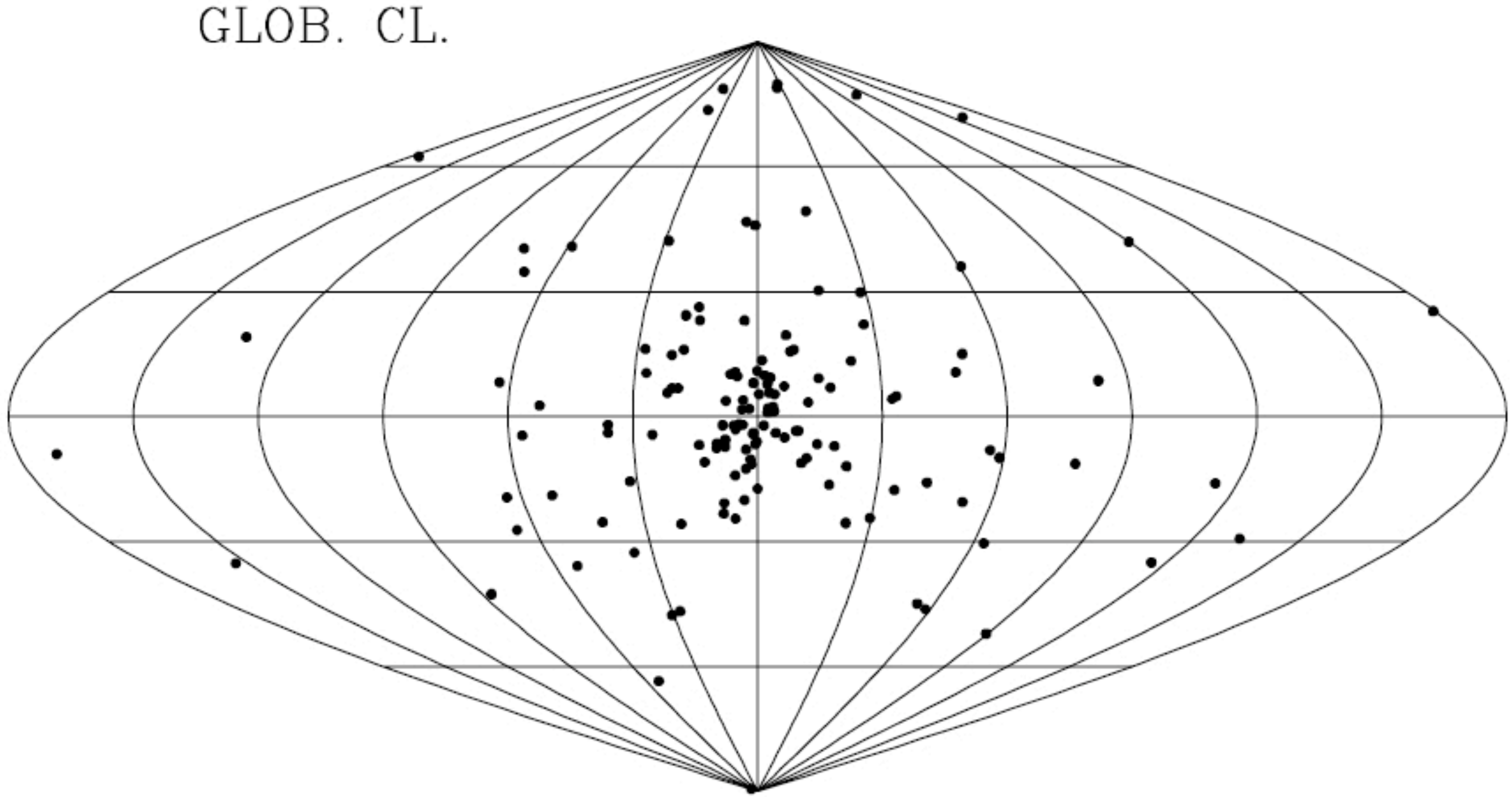
Nearby stars : isotropy + proper motion



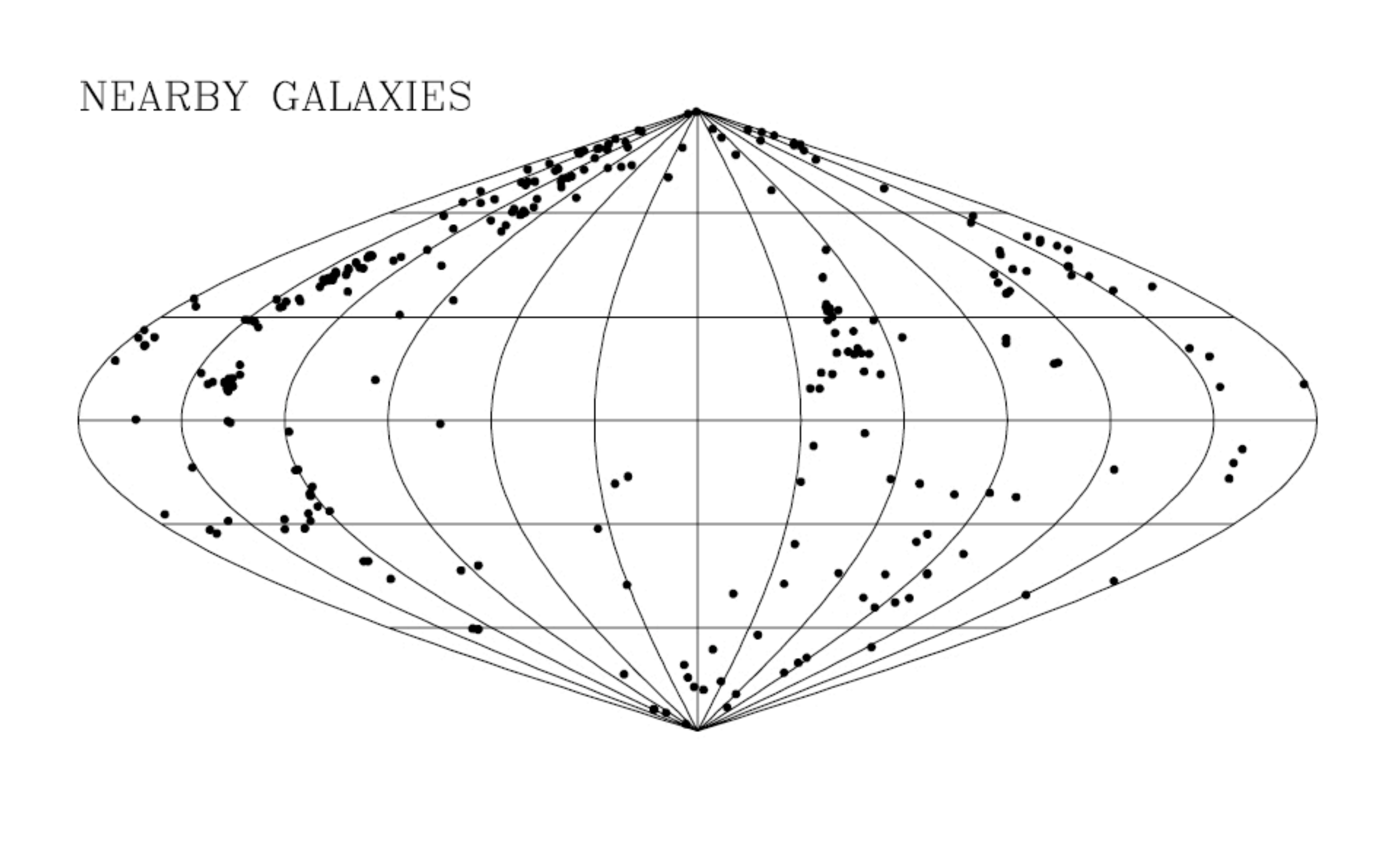
Planetary nebulae : Galactic disk



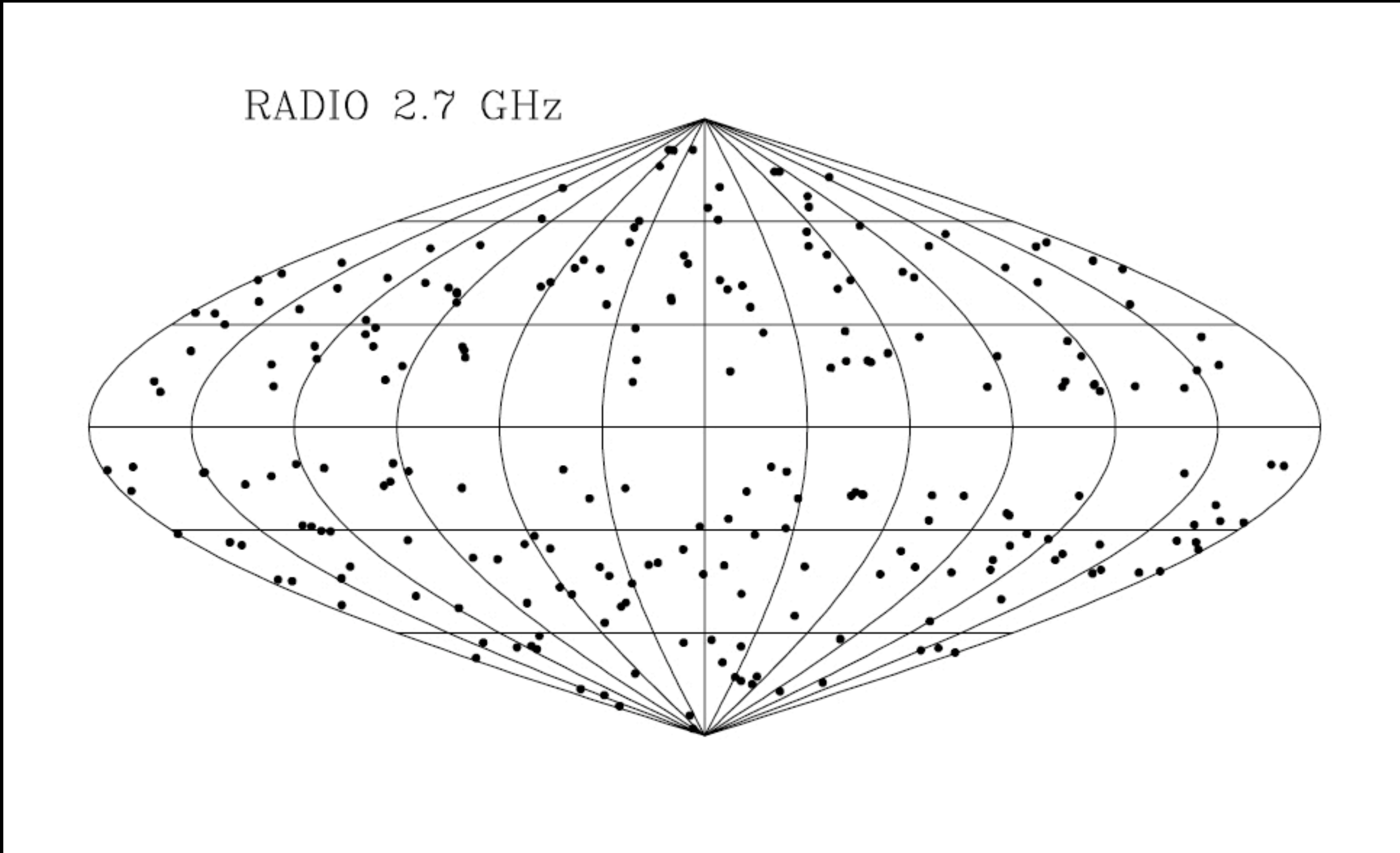
Globular clusters : spherical Galactic halo - Sun is not at the center



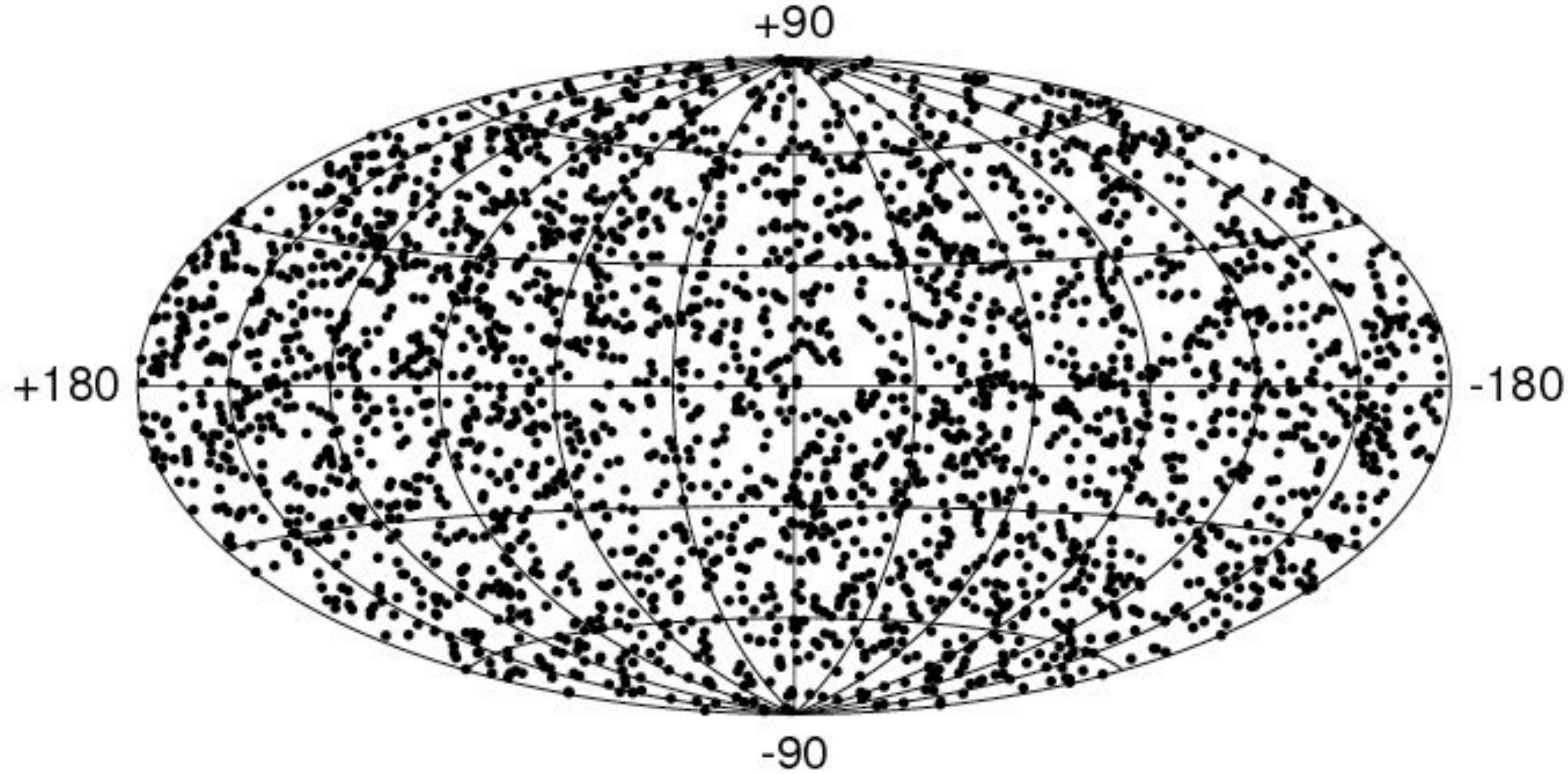
Nearby galaxies : Large Structures



Radio-galaxies : isotropy



Gamma-ray bursts : sky map (complete BATSE catalog)



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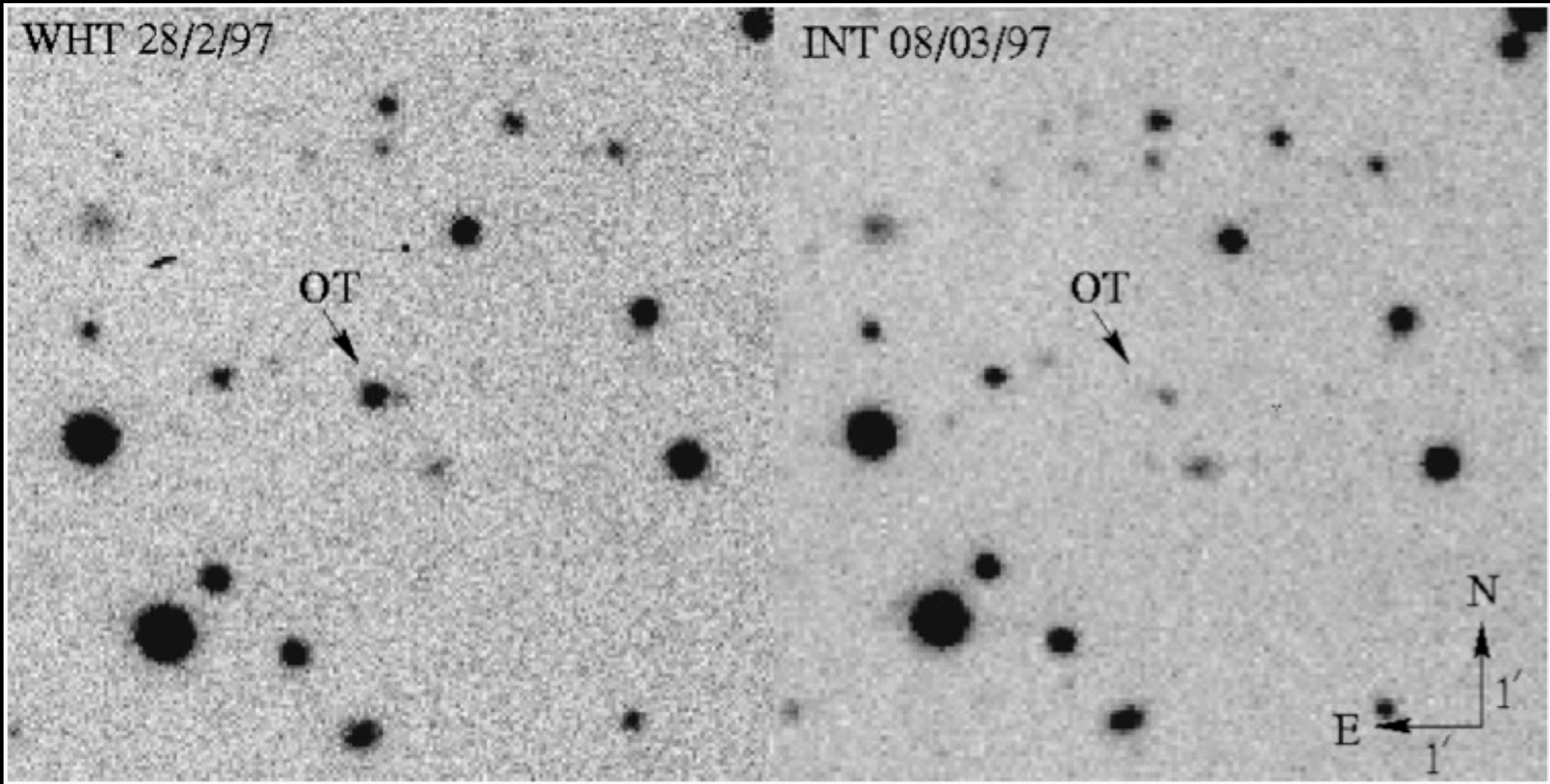
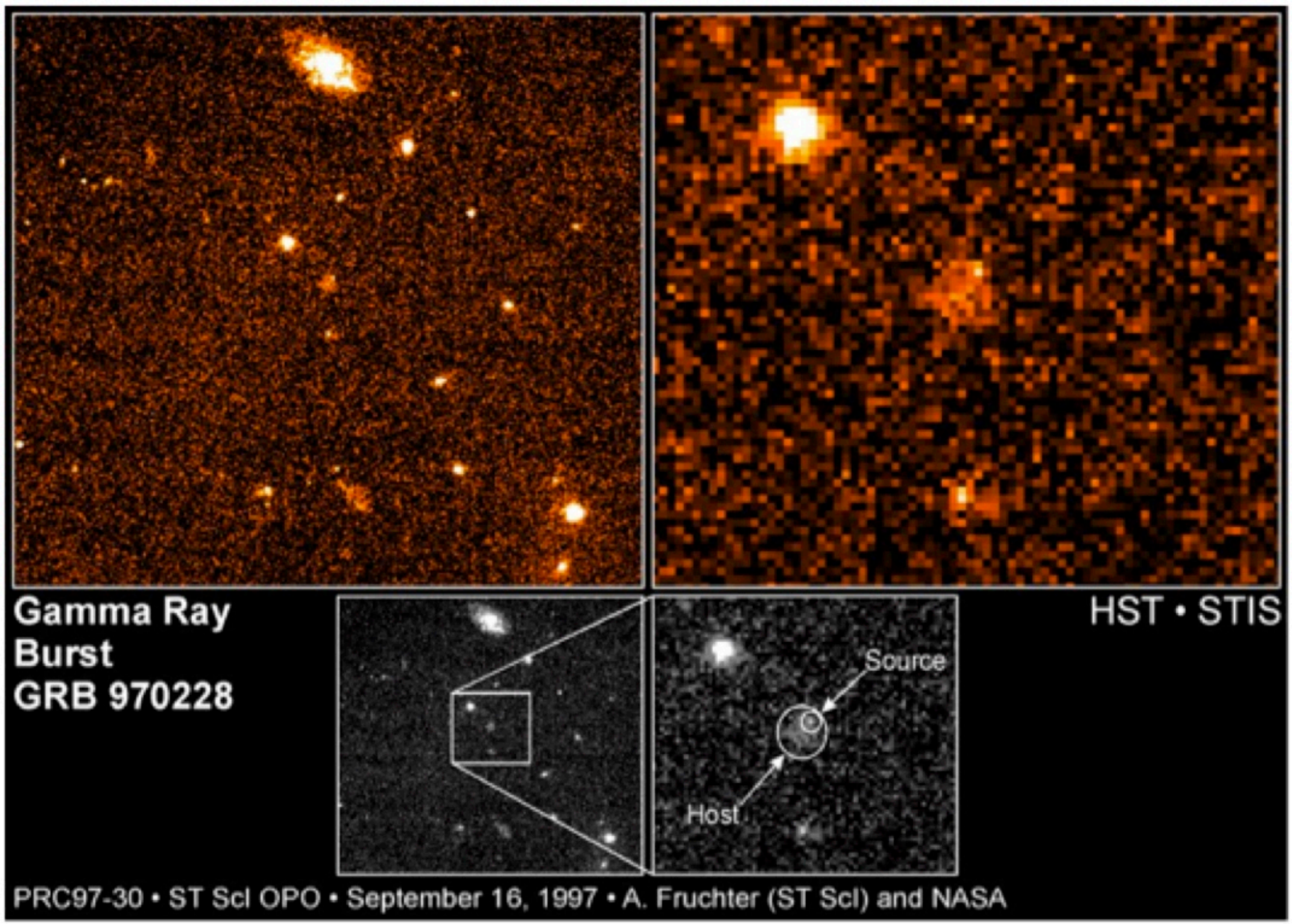
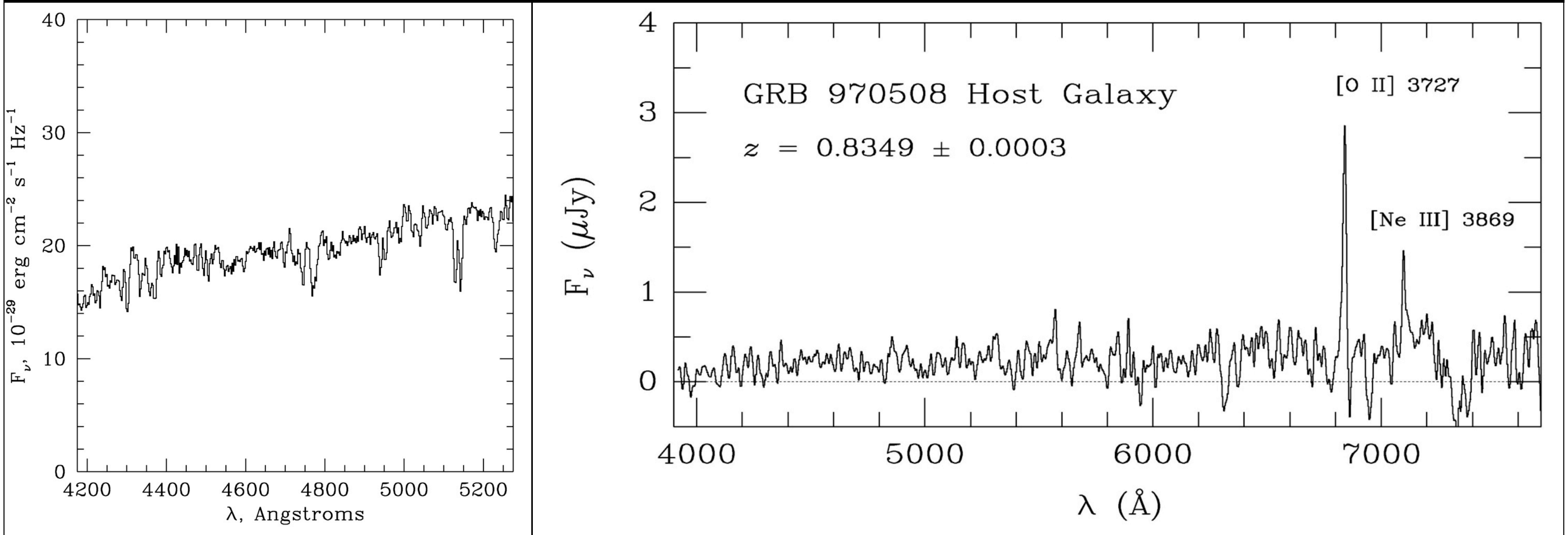
The first GRB afterglow (GRB 970228)



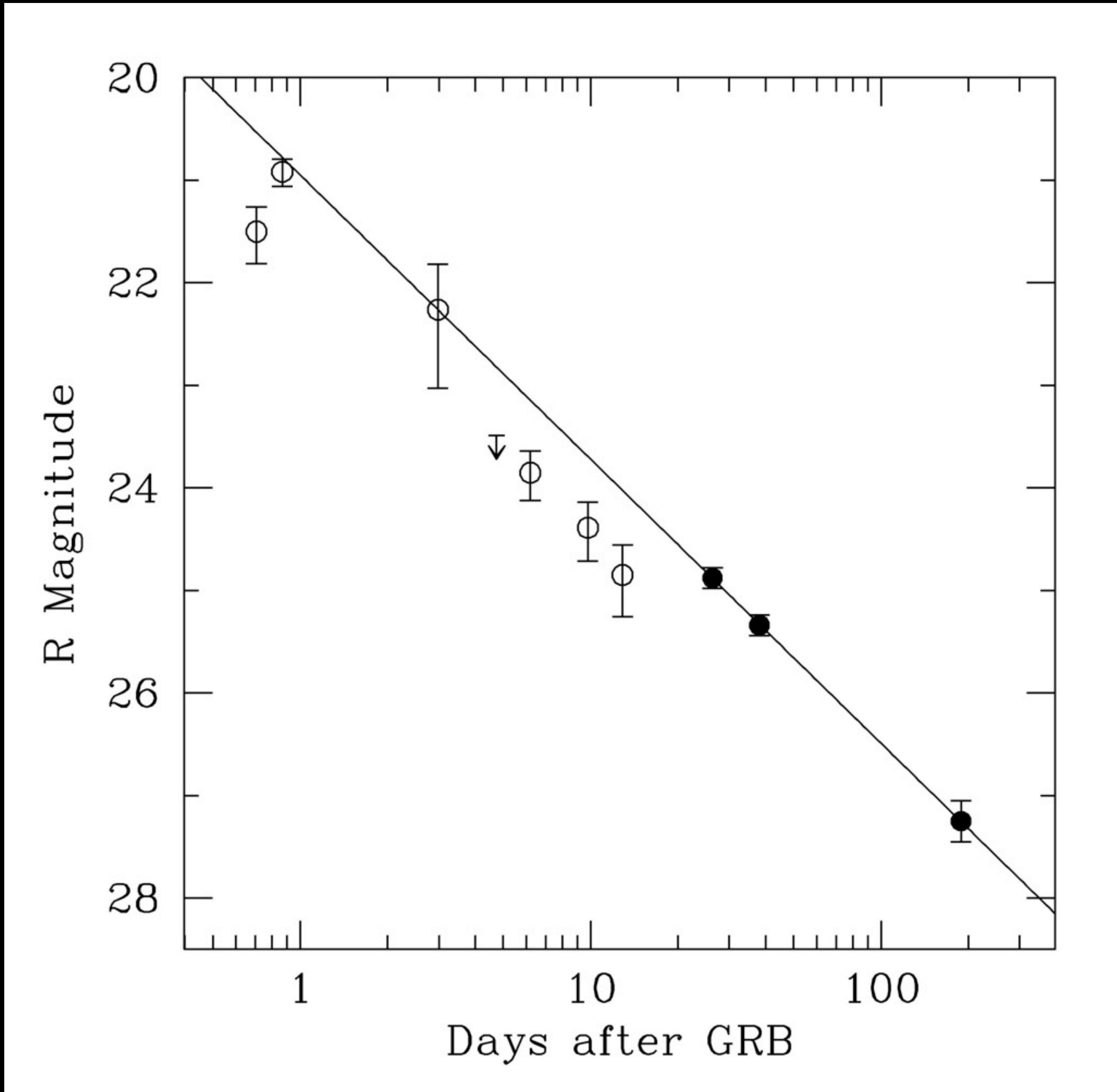
The first GRB afterglow (GRB 970228) : host galaxy



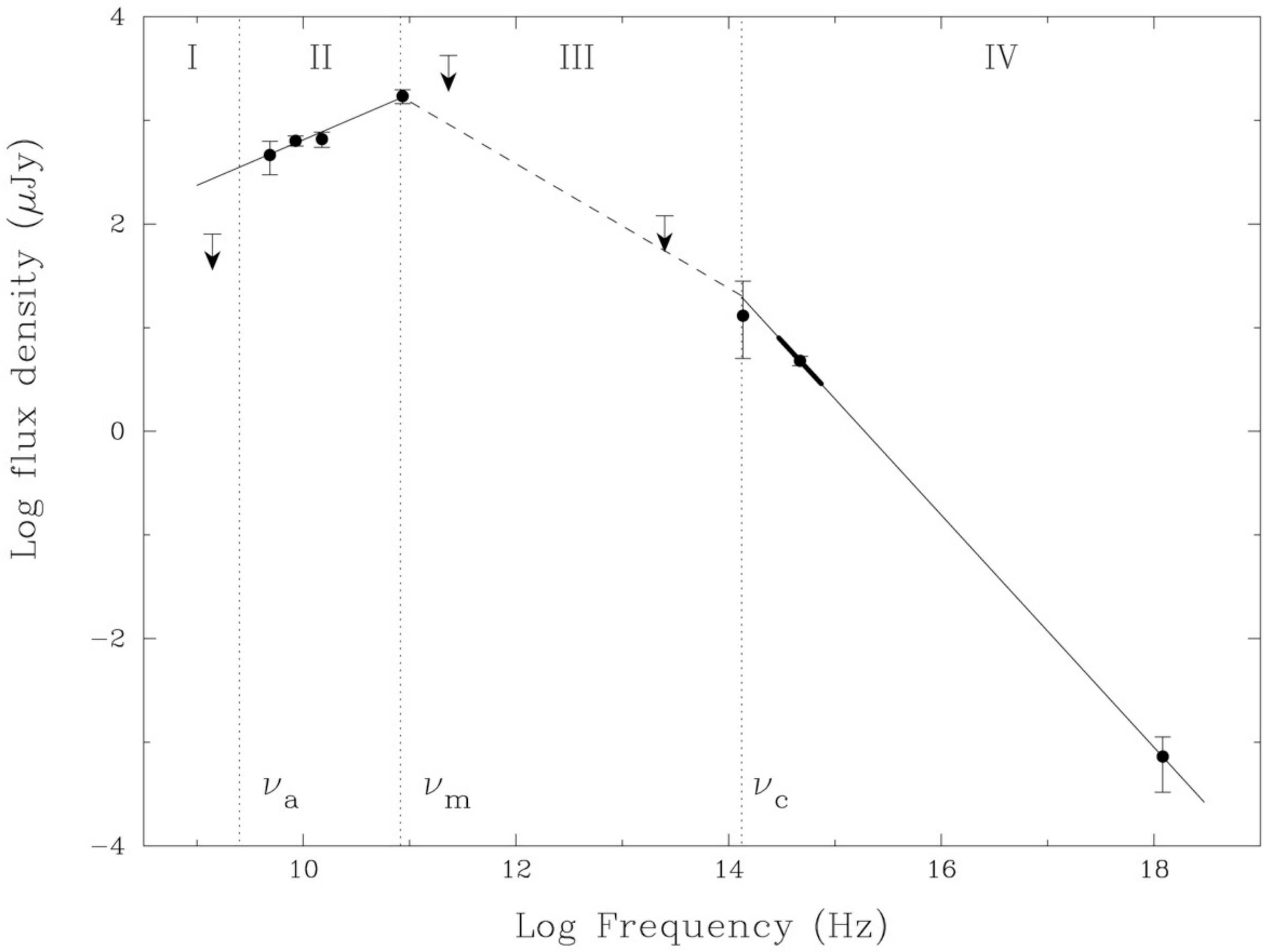
The first spectrum of a GRB visible afterglow : GRB 070508 and its host galaxy (z = 0.835)



Lightcurve of the first GRB afterglow (GRB 970228)



Afterglow spectrum of GRB 970508 (radio → X)



Models : before and after 1997...

Table 1

#	Author	Year Pub	Reference	Main Body	2nd Body	Place	Description
1.	Colgate	1968	CJPhys, 46, S476	ST		COS	SN shocks stellar surface in distant galaxy
2.	Colgate	1974	ApJ, 187, 333	ST		COS	Type II SN shock brem, inv Comp scat at stellar surface
3.	Stecker et al.	1973	Nature, 245, PS70	ST		DISK	Stellar superflare from nearby star
4.	Stecker et al.	1973	Nature, 245, PS70	WD		DISK	Superflare from nearby WD
5.	Harwit et al.	1973	ApJ, 186, L37	NS	COM	DISK	Relic comet perturbed to collide with old galactic NS
6.	Lamb et al.	1973	Nature, 246, PS52	WD	ST	DISK	Accretion onto WD from flare in companion
7.	Lamb et al.	1973	Nature, 246, PS52	NS	ST	DISK	Accretion onto NS from flare in companion
8.	Lamb et al.	1973	Nature, 246, PS52	BH	ST	DISK	Accretion onto BH from flare in companion
9.	Zwicky	1974	Ap & SS, 28, 111	NS		HALO	NS chunk contained by external pressure escapes, explodes
10.	Grindlay et al.	1974	ApJ, 187, L93	DG		SOL	Relativistic iron dust grain up-scatters solar radiation
11.	Brecher et al.	1974	ApJ, 187, L97	ST		DISK	Directed stellar flare on nearby star
12.	Schlovskii	1974	SovAstron, 18, 390	WD	COM	DISK	Comet from system's cloud strikes WD
13.	Schlovskii	1974	SovAstron, 18, 390	NS	COM	DISK	Comet from system's cloud strikes NS
14.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	ST		COS	Absorption of neutrino emission from SN in stellar envelope
15.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	ST	SN	COS	Thermal emission when small star heated by SN shock wave
16.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	NS		COS	Ejected matter from NS explodes
17.	Pacini et al.	1974	Nature, 251, 399	NS		DISK	NS crustal starquake glitch; should time coincide with GRB
18.	Narlikar et al.	1974	Nature, 251, 590	WH		COS	White hole emits spectrum that softens with time
19.	Tsygan	1975	A&A, 44, 21	NS		HALO	NS corequake excites vibrations, changing E & B fields
20.	Chanmugam	1974	ApJ, 193, L75	WD		DISK	Convection inside WD with high B field produces flare
21.	Prilutski et al.	1975	Ap & SS, 34, 395	AGN	ST	COS	Collapse of supermassive body in nucleus of active galaxy
22.	Narlikar et al.	1975	Ap & SS, 35, 321	WH		COS	WH excites synchrotron emission, inverse Compton scattering
23.	Piran et al.	1975	Nature, 256, 112	BH		DISK	Inv Comp scat deep in ergosphere of fast rotating, accreting BH
24.	Fabian et al.	1976	Ap & SS, 42, 77	NS		DISK	NS crustquake shocks NS surface
25.	Chanmugam	1976	Ap & SS, 42, 83	WD		DISK	Magnetic WD suffers MHD instabilities, flares
26.	Mullan	1976	ApJ, 208, 199	WD		DISK	Thermal radiation from flare near magnetic WD
27.	Woosley et al.	1976	Nature, 263, 101	NS		DISK	Carbon detonation from accreted matter onto NS
28.	Lamb et al.	1977	ApJ, 217, 197	NS		DISK	Mag grating of accret disk around NS causes sudden accretion
29.	Piran et al.	1977	ApJ, 214, 268	BH		DISK	Instability in accretion onto rapidly rotating BH
30.	Dasgupta	1979	Ap & SS, 63, 517	DG		SOL	Charged intergal rel dust grain enters sol sys, breaks up
31.	Tsygan	1980	A&A, 87, 224	WD		DISK	WD surface nuclear burst causes chromospheric flares
32.	Tsygan	1980	A&A, 87, 224	NS		DISK	NS surface nuclear burst causes chromospheric flares
33.	Ramaty et al.	1981	Ap & SS, 75, 193	NS		DISK	NS vibrations heat atm to pair produce, annihilate, synch cool
34.	Newman et al.	1980	ApJ, 242, 319	NS	AST	DISK	Asteroid from interstellar medium hits NS
35.	Ramaty et al.	1980	Nature, 287, 122	NS		HALO	NS core quake caused by phase transition, vibrations
36.	Howard et al.	1981	ApJ, 249, 302	NS	AST	DISK	Asteroid hits NS, B-field confines mass, creates high temp
37.	Mitrofanov et al.	1981	Ap & SS, 77, 469	NS		DISK	Helium flash cooled by MHD waves in NS outer layers
38.	Colgate et al.	1981	ApJ, 248, 771	NS	AST	DISK	Asteroid hits NS, tidally disrupts, heated, expelled along B lines
39.	van Buren	1981	ApJ, 249, 297	NS	AST	DISK	Asteroid enters NS B field, dragged to surface collision
40.	Kuznetsov	1982	CosRes, 20, 72	MG		SOL	Magnetic reconnection at heliopause
41.	Katz	1982	ApJ, 260, 371	NS		DISK	NS flares from pair plasma confined in NS magnetosphere
42.	Woosley et al.	1982	ApJ, 258, 716	NS		DISK	Magnetic reconnection after NS surface He flash
43.	Fryxell et al.	1982	ApJ, 258, 733	NS		DISK	He fusion runaway on NS B-pole helium lake
44.	Hameury et al.	1982	A&A, 111, 242	NS		DISK	e- capture triggers H flash triggers He flash on NS surface
45.	Mitrofanov et al	1982	MNRAS, 200, 1033	NS		DISK	B induced cyclo res in rad absorp giving rel e-s, inv C scat
46.	Fenimore et al.	1982	Nature, 297, 665	NS		DISK	BB X-rays inv Comp scat by hotter overlying plasma
47.	Lipunov et al.	1982	Ap & SS, 85, 459	NS	ISM	DISK	ISM matter accum at NS magnetopause then suddenly accretes
48.	Baan	1982	ApJ, 261, L71	WD		HALO	Nonexplosive collapse of WD into rotating, cooling NS
49.	Ventura et al.	1983	Nature, 301, 491	NS	ST	DISK	NS accretion from low mass binary companion
50.	Bisnovatyi- et al.	1983	Ap & SS, 89, 447	NS		DISK	Neutron rich elements to NS surface with quake, undergo fission
51.	Bisnovatyi- et al.	1984	SovAstron, 28, 62	NS		DISK	Thermonuclear explosion beneath NS surface
52.	Ellison et al.	1983	A&A, 128, 102	NS		HALO	NS corequake + uneven heating yield SGR pulsations
53.	Hameury et al.	1983	A&A, 128, 369	NS		DISK	B field contains matter on NS cap allowing fusion
54.	Bonazzola et al.	1984	A&A, 136, 89	NS		DISK	NS surface nuc explosion causes small scale B reconnection
55.	Michel	1985	ApJ, 290, 721	NS		DISK	Remnant disk ionization instability causes sudden accretion
56.	Liang	1984	ApJ, 283, L21	NS		DISK	Resonant EM absorp during magnetic flare gives hot sync e-s
57.	Liang et al.	1984	Nature, 310, 121	NS		DISK	NS magnetic fields get twisted, recombine, create flare
58.	Mitrofanov	1984	Ap & SS, 105, 245	NS		DISK	NS magnetosphere excited by starquake
59.	Epstein	1985	ApJ, 291, 822	NS		DISK	Accretion instability between NS and disk
60.	Schlovskii et al.	1985	MNRAS, 212, 545	NS		HALO	Old NS in Galactic halo undergoes starquake
61.	Tsygan	1984	Ap & SS, 106, 199	NS		DISK	Weak B field NS spherically accretes, Comptonizes X-rays
62.	Usov	1984	Ap & SS, 107, 191	NS		DISK	NS flares result of magnetic convective-oscillation instability
63.	Hameury et al.	1985	ApJ, 293, 56	NS		DISK	High Landau e-s beamed along B lines in cold atm of NS
64.	Rappaport et al.	1985	Nature, 314, 242	NS		DISK	NS + low mass stellar companion gives GRB + optical flash
65.	Tremaine et al.	1986	ApJ, 301, 155	NS	COM	DISK	NS tides disrupt comet, debris hits NS next pass
66.	Muslimov et al.	1986	Ap & SS, 120, 27	NS		HALO	Radially oscillating NS
67.	Sturrock	1986	Nature, 321, 47	NS		DISK	Flare in the magnetosphere of NS accelerates e-s along B-field
68.	Paczynski	1986	ApJ, 308, L43	NS		COS	Cosmo GRBs: rel e- e+ opt thk plasma outflow indicated
69.	Bisnovatyi- et al	1986	SovAstron, 30, 582	NS		DISK	Chain fission of superheavy nuclei below NS surface during SN
70.	Alcock et al.	1986	PRL, 57, 2088	SS	SS	DISK	SN ejects strange mat lump craters rotating SS companion
71.	Vahia et al.	1988	A&A, 207, 55	ST		DISK	Magnetically active stellar system gives stellar flare
72.	Babul et al.	1987	ApJ, 316, L49	CS		COS	GRB result of energy released from cusp of cosmic string
73.	Livio et al.	1987	Nature, 327, 398	NS	COM	DISK	Oort cloud around NS can explain soft gamma-repeaters
74.	McBreen et al.	1988	Nature, 332, 234	GAL	AGN	COS	G-wave bkgrd makes BL Lac wiggle across galaxy lens caustic
75.	Curtis	1988	ApJ, 327, L81	WD		COS	WD collapses, burns to form new class of stable particles
76.	Melia	1988	ApJ, 335, 965	NS		DISK	Be/X-ray binary sys evolves to NS accretion GRB with recurrence
77.	Ruderman et al.	1988	ApJ, 335, 306	NS		DISK	e+ e- cascades by aligned pulsar outer-mag-sphere reignition
78.	Paczynski	1988	ApJ, 335, 525	CS		COS	Energy released from cusp of cosmic string (revised)
79.	Murikami et al.	1988	Nature, 335, 234	NS		DISK	Absorption features suggest separate colder region near NS
80.	Melia	1988	Nature, 336, 658	NS		DISK	NS + accretion disk reflection explains GRB spectra
81.	Blaes et al.	1989	ApJ, 343, 839	NS		DISK	NS seismic waves couple to magnetospheric Alfen waves
82.	Trofimenko et al.	1989	Ap & SS, 152, 105	WH		COS	Kerr-Newman white holes
83.	Sturrock et al.	1989	ApJ, 346, 950	NS		DISK	NS E-field accelerates electrons which then pair cascade
84.	Fenimore et al.	1988	ApJ, 335, L71	NS		DISK	Narrow absorption features indicate small cold area on NS
85.	Rodrigues	1989	AJ, 98, 2280	WD	WD	DISK	Binary member loses part of crust, through L1, hits primary
86.	Pineault et al.	1989	ApJ, 347, 1141	NS	COM	DISK	Fast NS wanders though Oort clouds, fast WD bursts only optical
87.	Melia et al.	1989	ApJ, 346, 378	NS		DISK	Episodic electrostatic accel and Comp scat from rot high-B NS
88.	Trofimenko	1989	Ap & SS, 159, 301	WH		COS	Different types of white, "grey" holes can emit GRBs
89.	Eichler et al.	1989	Nature, 340, 126	NS	NS	COS	NS - NS binary members collide, coalesce
90.	Wang et al.	1989	PRL, 63, 1550	NS		DISK	Cyclo res & Raman scat fits 20, 40 keV dips, magnetized NS
91.	Alexander et al.	1989	ApJ, 344, L1	NS		DISK	QED mag resonant opacity in NS atmosphere
92.	Melia	1990	ApJ, 351, 601	NS		DISK	NS magnetospheric plasma oscillations
93.	Ho et al.	1990	ApJ, 348, L25	NS		DISK	Beaming of radiation necessary from magnetized neutron stars
94.	Mitrofanov et al.	1990	Ap & SS, 165, 137	NS	COM	DISK	Interstellar comets pass through dead pulsar's magnetosphere
95.	Dermer	1990	ApJ, 360, 197	NS		DISK	Compton scattering in strong NS magnetic field
96.	Blaes et al.	1990	ApJ, 363, 612	NS	ISM	DISK	Old NS accretes from ISM, surface goes nuclear
97.	Paczynski	1990	ApJ, 363, 218	NS	NS	COS	NS-NS collision causes neutrino collisions, drives super-Ed wind
98.	Zdziarski et al.	1991	ApJ, 366, 343	RE	MBR	COS	Scattering of microwave background photons by rel e-s
99.	Pineault	1990	Nature, 345, 233	NS	COM	DISK	Young NS drifts through its own Oort cloud
100.	Trofimenko et al.	1991	Ap & SS, 178, 217	WH		HALO	White hole supernova gave simultaneous burst of g-waves from 1987A
101.	Melia et al.	1991	ApJ, 373, 198	NS		DISK	NS B-field undergoes resistive tearing, accelerates plasma
102.	Holcomb et al.	1991	ApJ, 378, 682	NS		DISK	Alfen waves in non-uniform NS atmosphere accelerate particles
103.	Haensel et al.	1991	ApJ, 375, 209	SS	SS	COS	Strange stars emit binding energy in grav rad and collide
104.	Blaes et al.	1991	ApJ, 381, 210	NS	ISM	DISK	Slow interstellar accretion onto NS, e- capture starquakes result
105.	Frank et al.	1992	ApJ, 385, L45	NS		DISK	Low mass X-ray binary evolve into GRB sites
106.	Woosley et al.	1992	ApJ, 391, 228	NS		HALO	Accreting WD collapsed to NS
107.	Dar et al.	1992	ApJ, 388, 164	WD		COS	WD accretes to form naked NS, GRB, cosmic rays
108.	Hanami	1992	ApJ, 389, L71	NS	PLAN	COS	NS - planet magnetospheric interaction unstable
109.	Meszaros et al.	1992	ApJ, 397, 570	NS	NS	COS	NS - NS collision produces anisotropic fireball
110.	Carter	1992	ApJ, 391, L67	BH	ST	COS	Normal stars tidally disrupted by galactic nucleus BH
111.	Usov	1992	Nature, 357, 472	NS		COS	WD collapses to form NS, B-field brakes NS rotation instantly
112.	Narayan et al.	1992	ApJ, 395, L83	NS	NS	COS	NS - NS merger gives optically thick fireball
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114.	Brainerd	1992	ApJ, 394, L33	AGN	JET	COS	Synchrotron emission from AGN jets
115.	Meszaros et al.	1992	MNRAS, 257, 29P	BH	NS	COS	BH-NS have neutrinos collide to gammas in clean fireball
116.	Meszaros et al.	1992	MNRAS, 257, 29P	NS	NS	COS	NS-NS have neutrinos collide to gammas in clean fireball
117.	Cline et al.	1992	ApJ, 401, L57	BH		DISK	Primordial BHs evaporating could account for short hard GRBs
118.	Rees et al.	1992	MNRAS, 258, 41P	NS	ISM	COS	Relativistic fireball reconverted to radiation when hits ISM

Table from: Nemiroff, R. J. 1993, Comments on Astrophysics, 17, No. 4, in press

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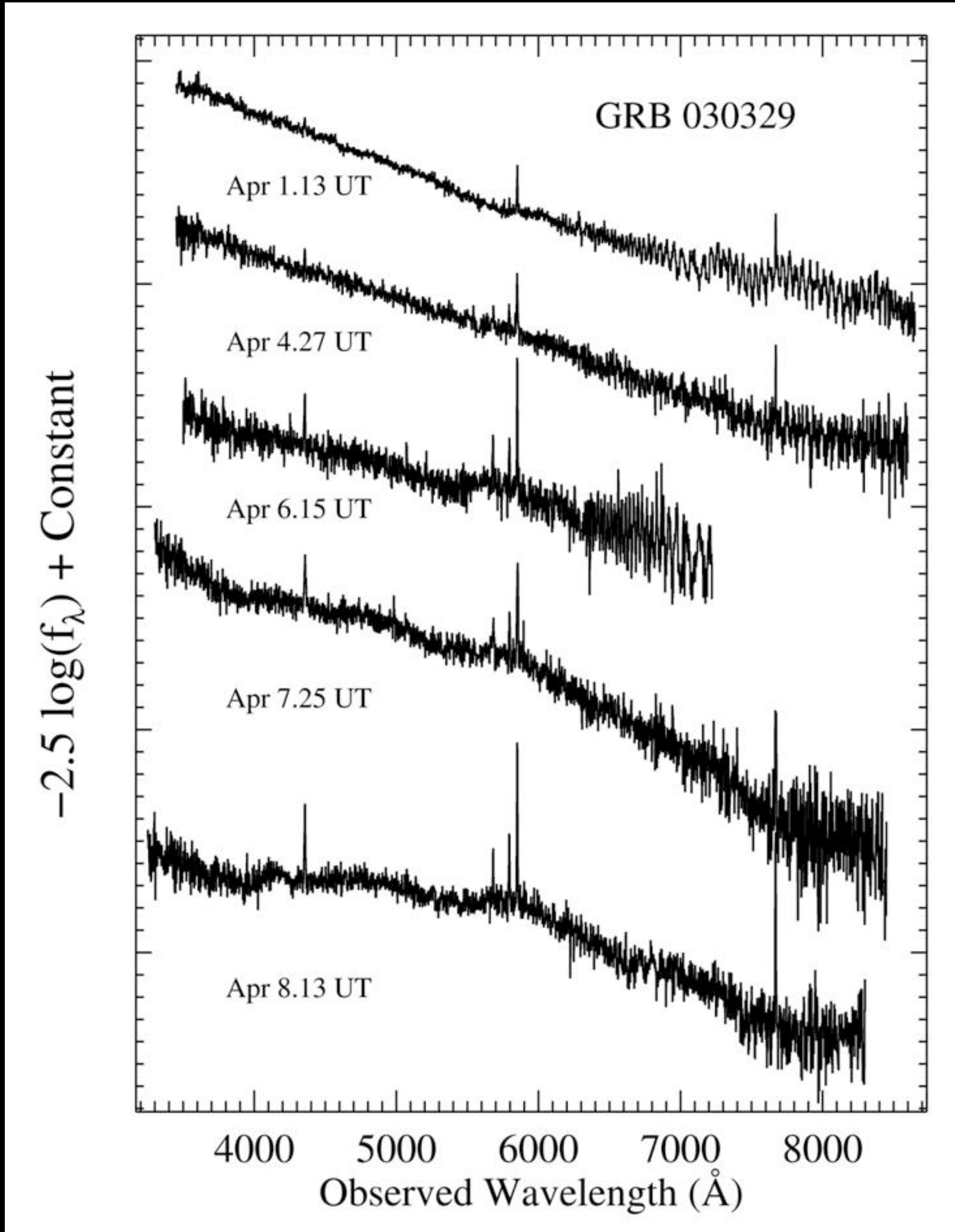
- Beppo-SAX, HETE-2, ... : afterglow studies - network for the ground-based follow-up
  Association of long GRBs with massive stars

Association of GRB 030329 (HETE2) with a type Ic supernova



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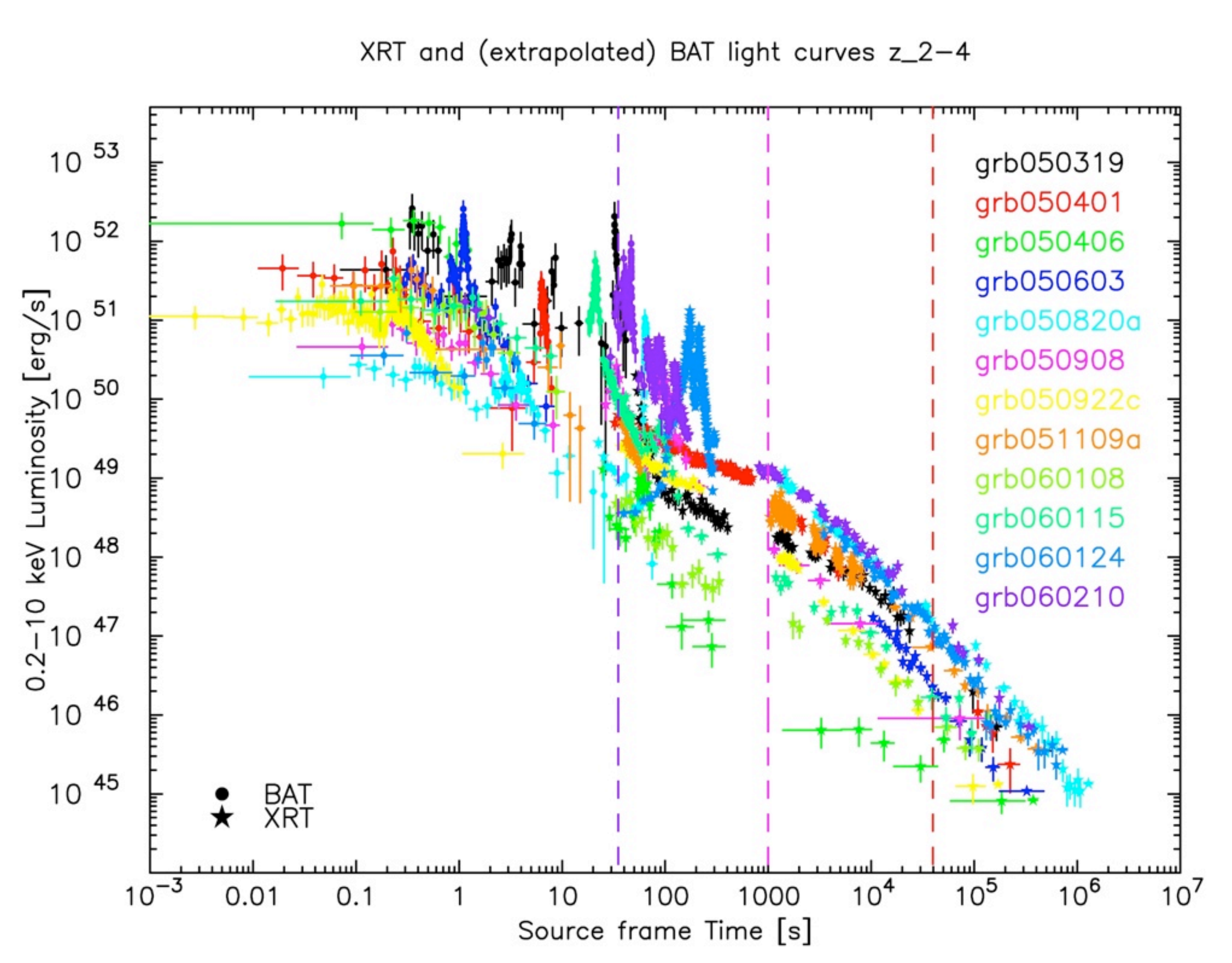
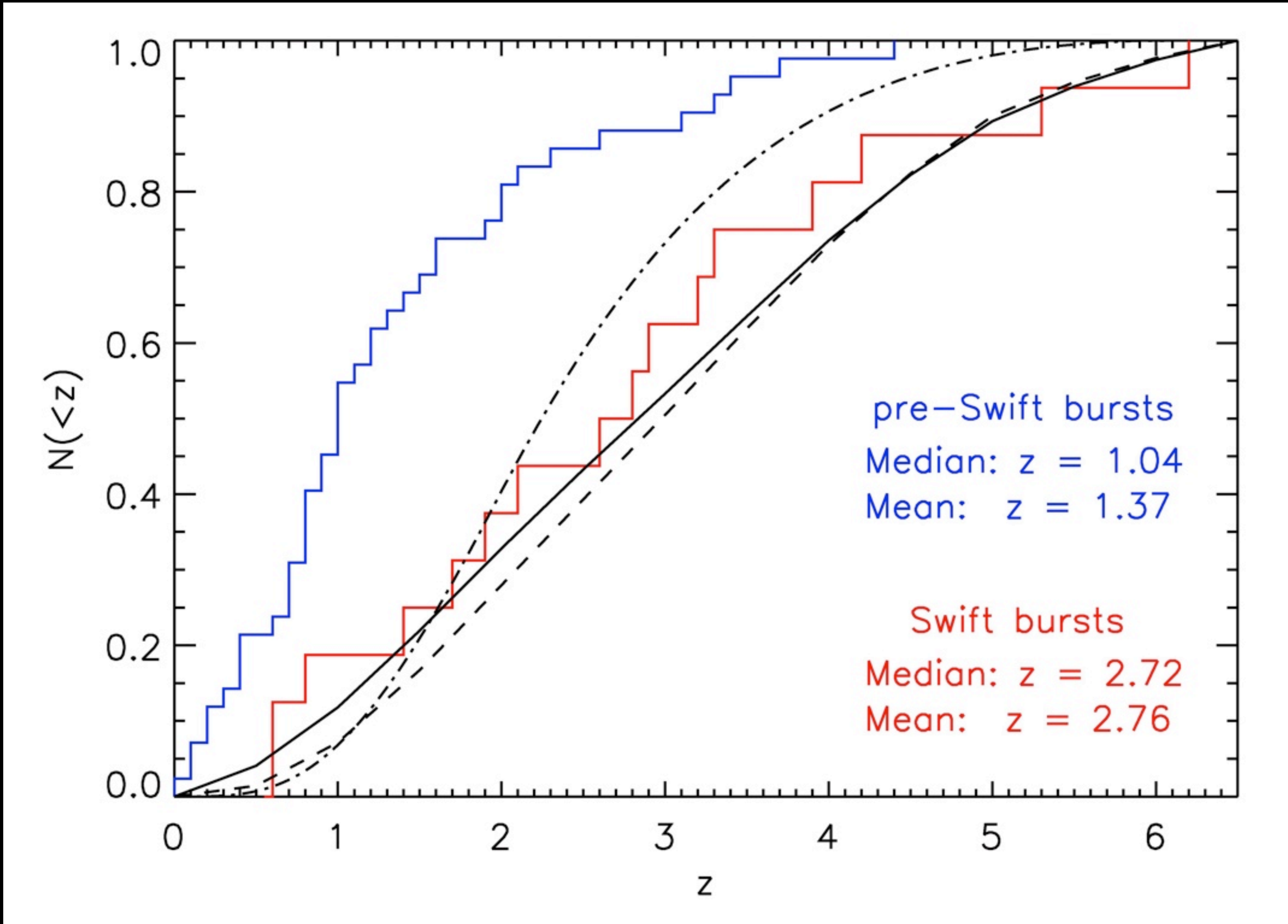
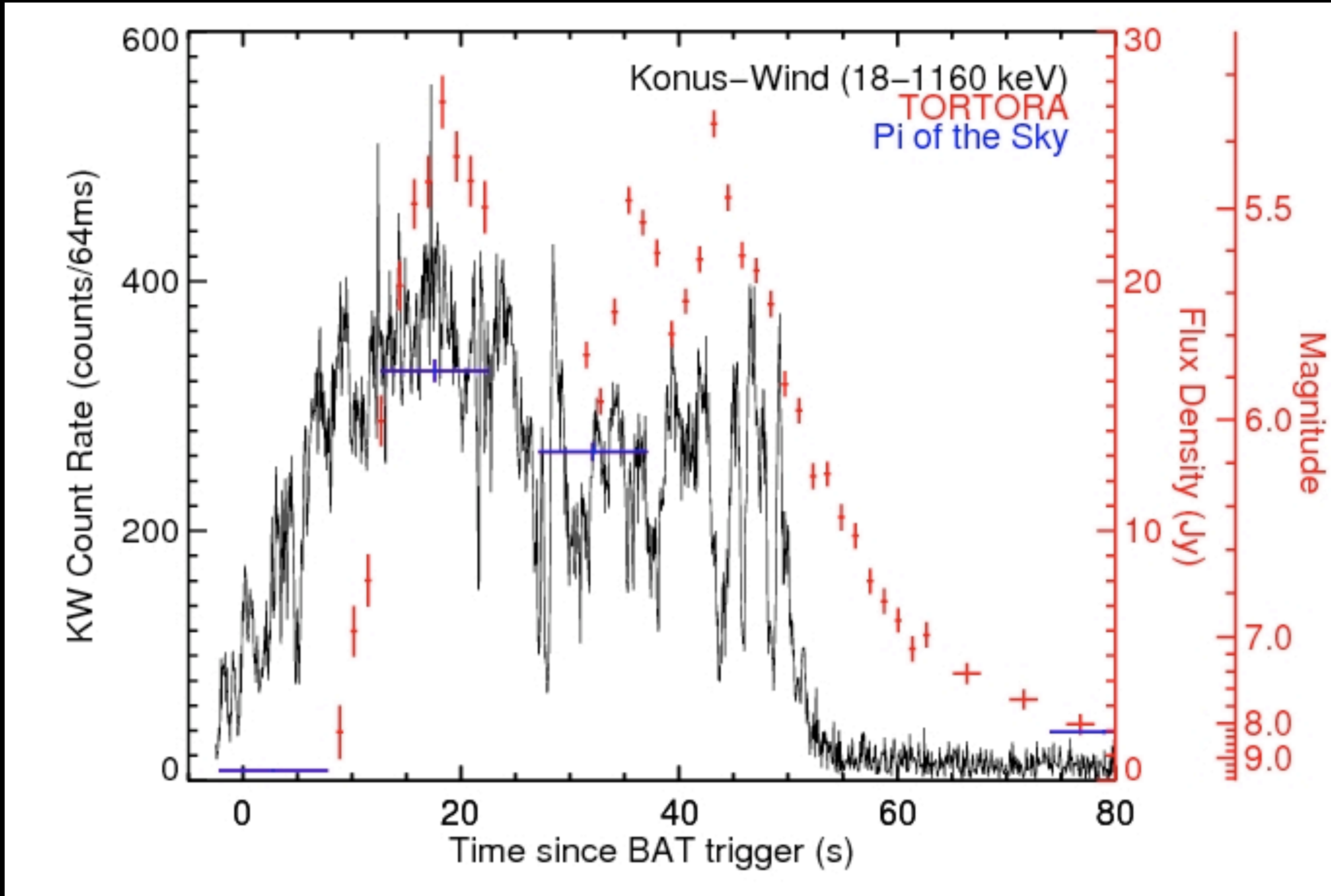
Complexity of the early X-ray afterglow (Swift)



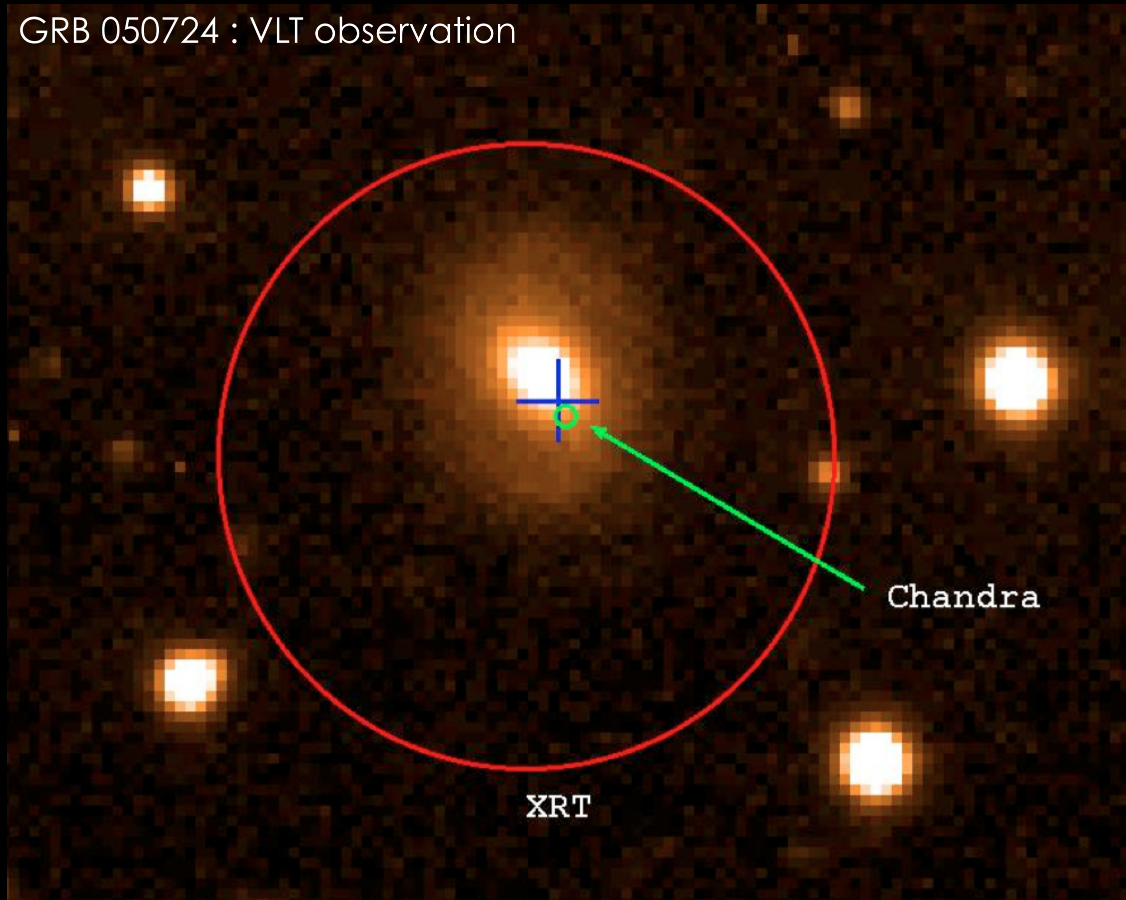
Gamma-ray bursts : redshift distribution (Swift)



Prompt optical emission in GRBs : the naked-eye burst ! (Swift)



Host galaxies of short GRBs (HETE2, Swift)



Barthelmy et al. 2005

Only a few host galaxies of short GRBs are identified:

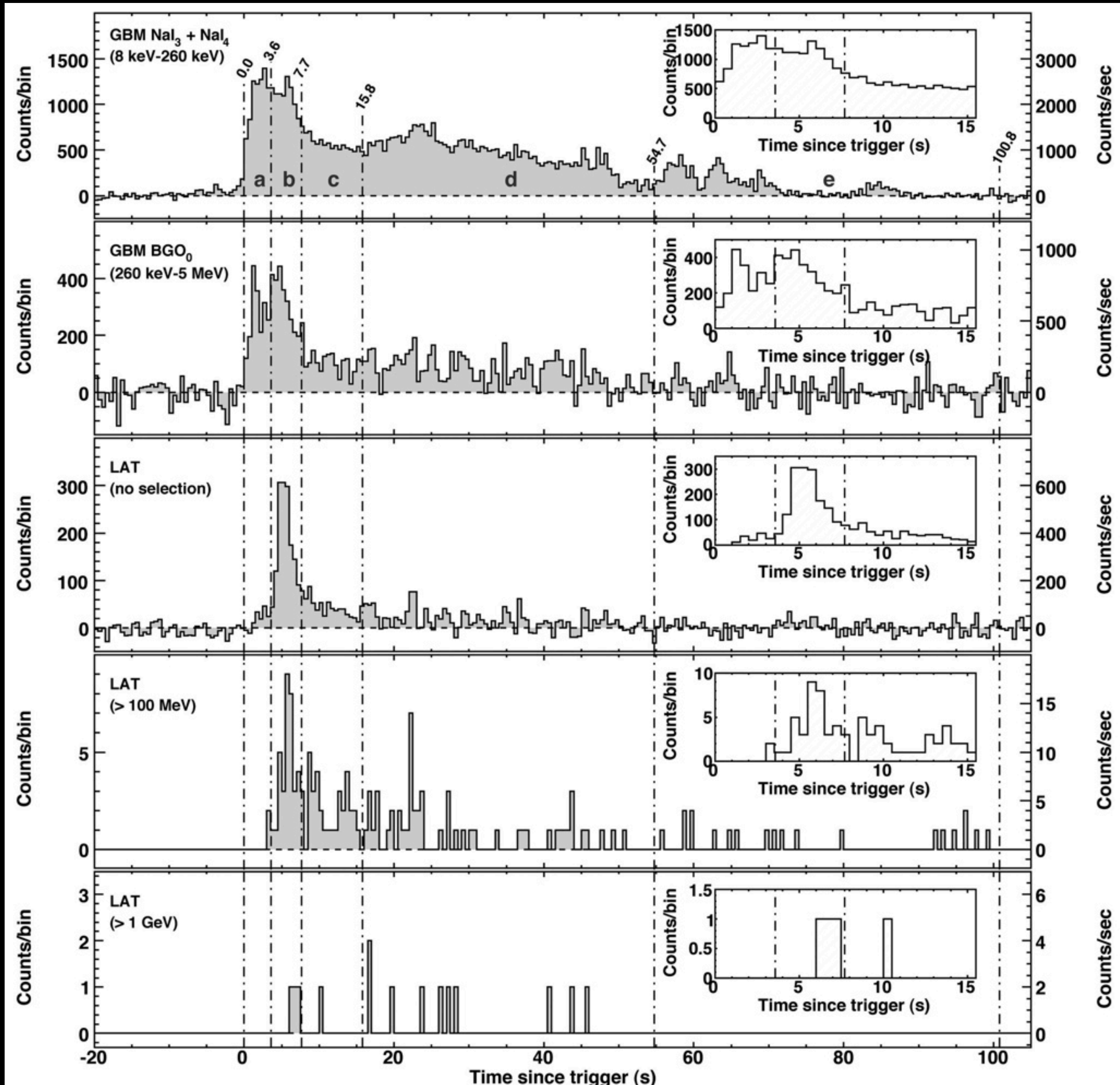
- some are elliptical galaxies (e.g. GRB 050509B; GRB 050724; …)
  sometimes the afterglow has a large offset
- some are star-forming galaxies (e.g. GRB 050709; GRB 051221A; …)

Gamma-ray bursts

Historical remarks :

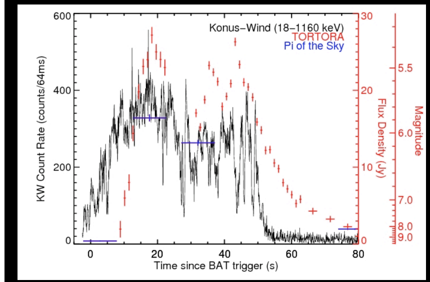
- VELA satellites : 3 times 2 satellites : 1963, 64 et 65
- 1973 : the first paper (Klebesadel et al.)
- 1970-1980 : studies of GRBs by scientific satellites
- 1973-1997 : the question of the distance scale, Galactic models
- 1994 : the Great Debate : Galactic vs Extragalactic models
- the discovery of afterglows in 1997 (Beppo-SAX, van Paradijs et al.) : GRBs are cosmological !
- Beppo-SAX, HETE-2, ... : afterglow studies - network for the ground-based follow-up
  Association of long GRBs with massive stars
- Swift: early afterlow
- Fermi : GeV emission in GRBs

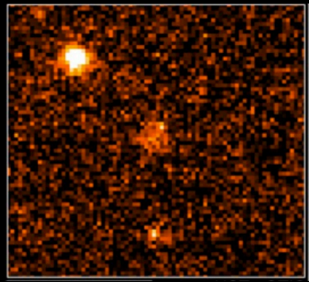
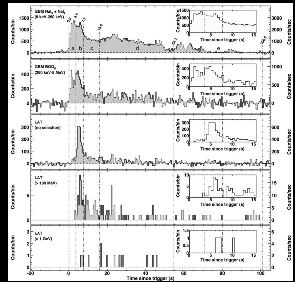
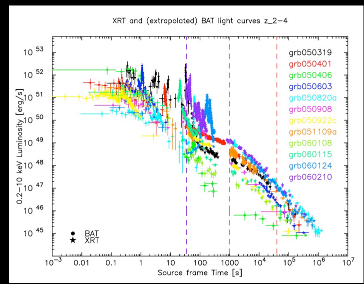
High-energy emission in GRBs (Fermi)

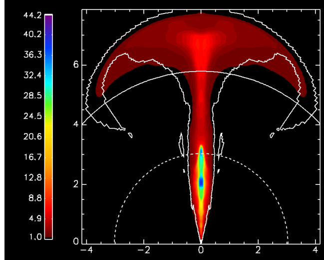


Explosive phenomena: SNe and GRBs

Frédéric Daigne
Institut d'Astrophysique de Paris, Université Pierre et Marie Curie
Institut Universitaire de France





International **S**chool on **A**stro**P**article **P**hysics **2012** - Multi-messenger approach in High Energy Astrophysics

B. Gamma-ray bursts

1. Observations - Classification
2. **Theory: summary of the observational constraints**
3. Central engine
4. Prompt emission
5. Afterglow
6. Conclusion

Summary of the main constraints:

1. Cosmological distance : $z = 0.0085$ to 9.4 [$z = 9.4$, Universe is 524 Myr old]

Prompt emission

2. Huge release of gamma-rays : $E_{\gamma,iso} \sim 10^{41} \rightarrow 10^{48}$ J
   For comparison :
   - Supernova : $E_{\nu} \sim 3\times10^{46}$ J ; $E_{kin} \sim 10^{44}$ J ; $E_{\gamma} \sim 10^{42}$ J
   - rest-mass energy of the sun : $M_{\odot}\, c^2 = 1.8 \times 10^{47}$ J

3. Short timescale variability : $t_{var} \sim 1$ - 10 ms

4. Non-thermal spectrum
   - MeV photons are detected in most GRBs
   - GeV photons have been detected in a few GRBs by Fermi

Afterglow + host galaxy

5. Long GRBs are most probably associated with the gravitational collapse of some massive stars

6. Short GRBS seem to occur in any types of galaxies : no correlation with star formation

Theory (1) Necessity of a compact source

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Compact source ($R < c\, t_{var} \sim 300\text{-}3000$ km)
+
Huge energy release
⇒
Catastrophic event leading to the formation of a stellar mass compact object

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-Long GRBs : association with massive stars $\Rightarrow$ **gravitational collapse**
 Collapsar scenario (Woosley, 1993)

-Short GRBs : best candidate = NS+NS (or NS+BH) mergers (no direct evidence)

Theory (2) Necessity of a relativistic ejection

1. Cosmological distance : $z = 0.0085$ to 9.4 [$z = 9.4$, Universe is 524 Myr old]

Prompt emission

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Compactness problem :

small size + large number of photons
= huge opacity for $\gamma\gamma$ annihilation

One should not observe photons
above $m_e c^2$!

Solution = relativistic motion (Rees, 1966)

Afterglow + host galaxy

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$\gamma\gamma \to e^+e^-$ annihilation

Seuil pour l'annihilation $\gamma\gamma$: un photon d'énergie E_1 peut s'annihiler avec un photon d'énergie E_2 si

$$\left(\frac{E_1}{m_{\rm e}c^2}\right)\left(\frac{E_2}{m_{\rm e}c^2}\right) \geq \frac{2}{1-\cos\theta}\,, \tag{282}$$

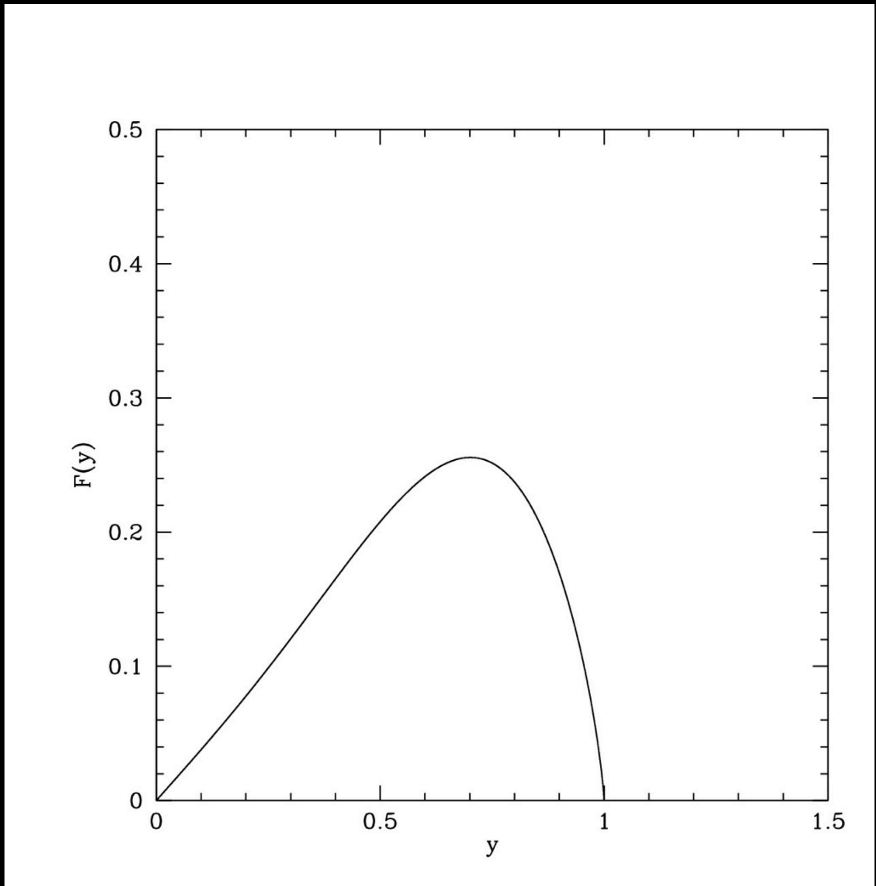
où θ est l'angle entre les directions incidentes des deux photons.

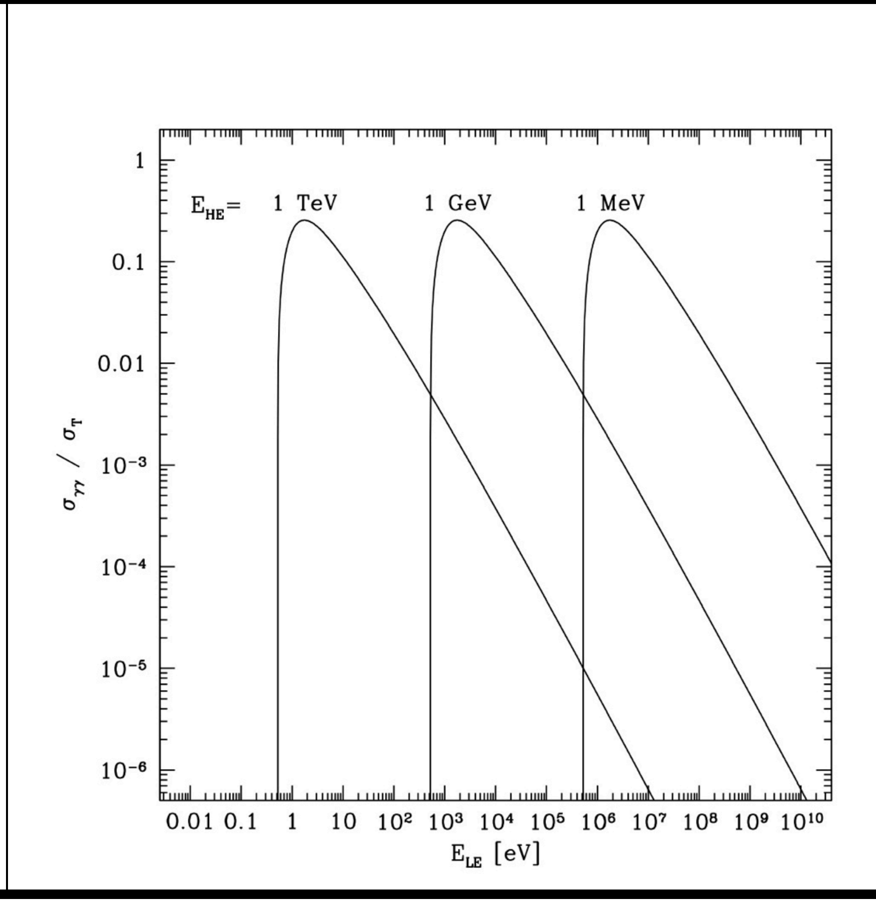
Section efficace pour l'annihilation $\gamma\gamma$:

$$\sigma_{\gamma\gamma}\left(E_1, E_2, \theta\right) = \sigma_{\rm T} \times f(y) \tag{283}$$

avec

$$f(y) = \frac{3}{16}(1-y^2)\left[(3-y^4)\ln\frac{1+y}{1-y} - 2y(2-y^2)\right] \quad \text{et} \quad y^2 = 1 - 2\frac{\left(m_{\rm e}c^2\right)^2}{E_1E_2\left(1-\cos\theta\right)}\,. \tag{284}$$





$\gamma\gamma \rightarrow e^+e^-$ annihilation

- Preferred energy of the low-energy photon (E_{LE}) that can annihilate with a high-energy photon E_{HE}

$$E_{\rm LE} = \frac{4}{1-\cos\theta_{12}} \frac{\left(m_e c^2\right)^2}{E_{\rm HE}} \simeq 1\,{\rm keV} \left(\frac{E_{\rm HE}\left(1-\cos\theta_{12}\right)}{1\,{\rm GeV}}\right)^{-1}$$

Energy	Interaction angle θ_{12} (rad)				
E_{HE}	π	$\pi/2$	0.1	0.01	0.001
1 TeV	0.5 eV	1 eV	200 eV	20 keV	2 MeV
1 GeV	0.5 keV	1 keV	200 keV	20 MeV	2 GeV
1 MeV	0.5 MeV	1 MeV	200 MeV	20 GeV	2 TeV

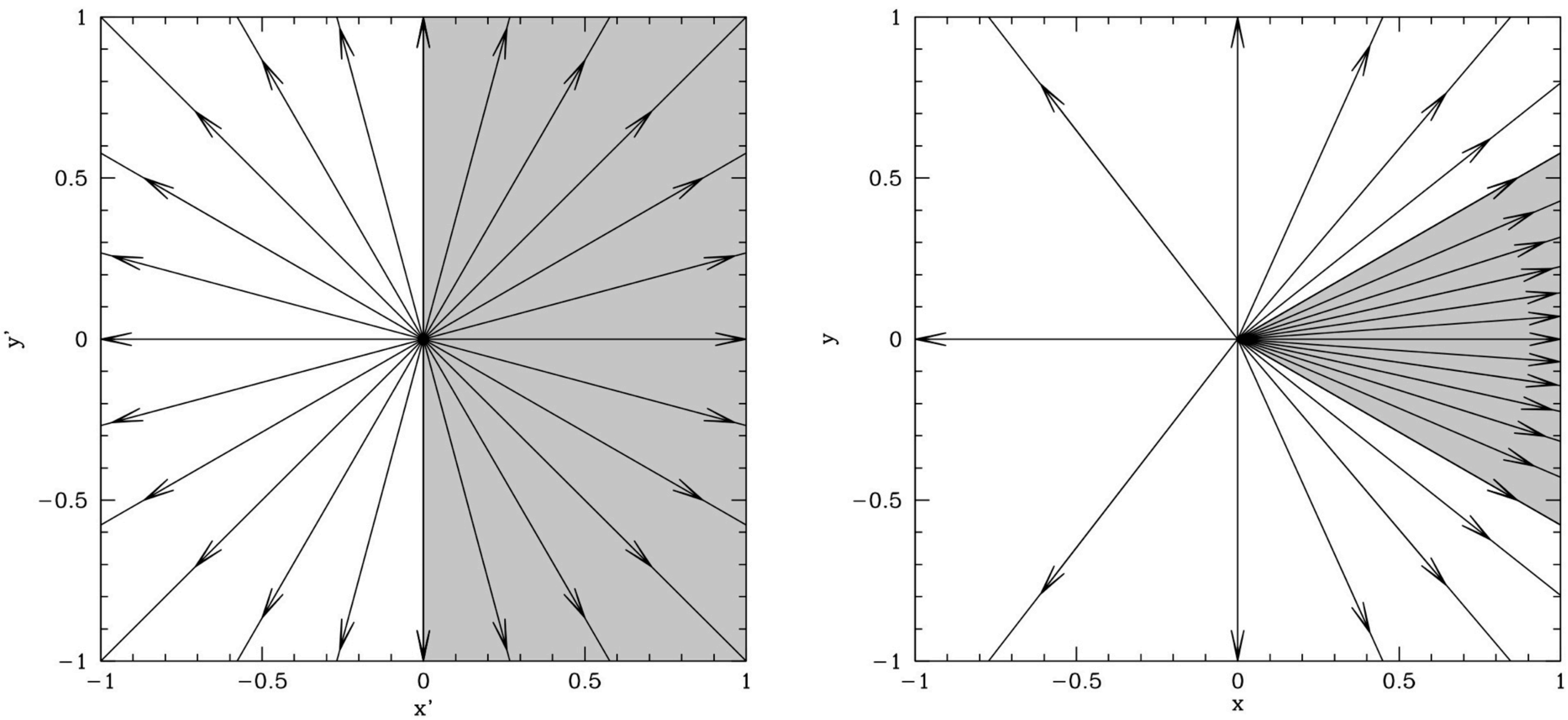
- MeV photons should self-annihilate !

- Solution (Rees, 1966) = relativistic motion

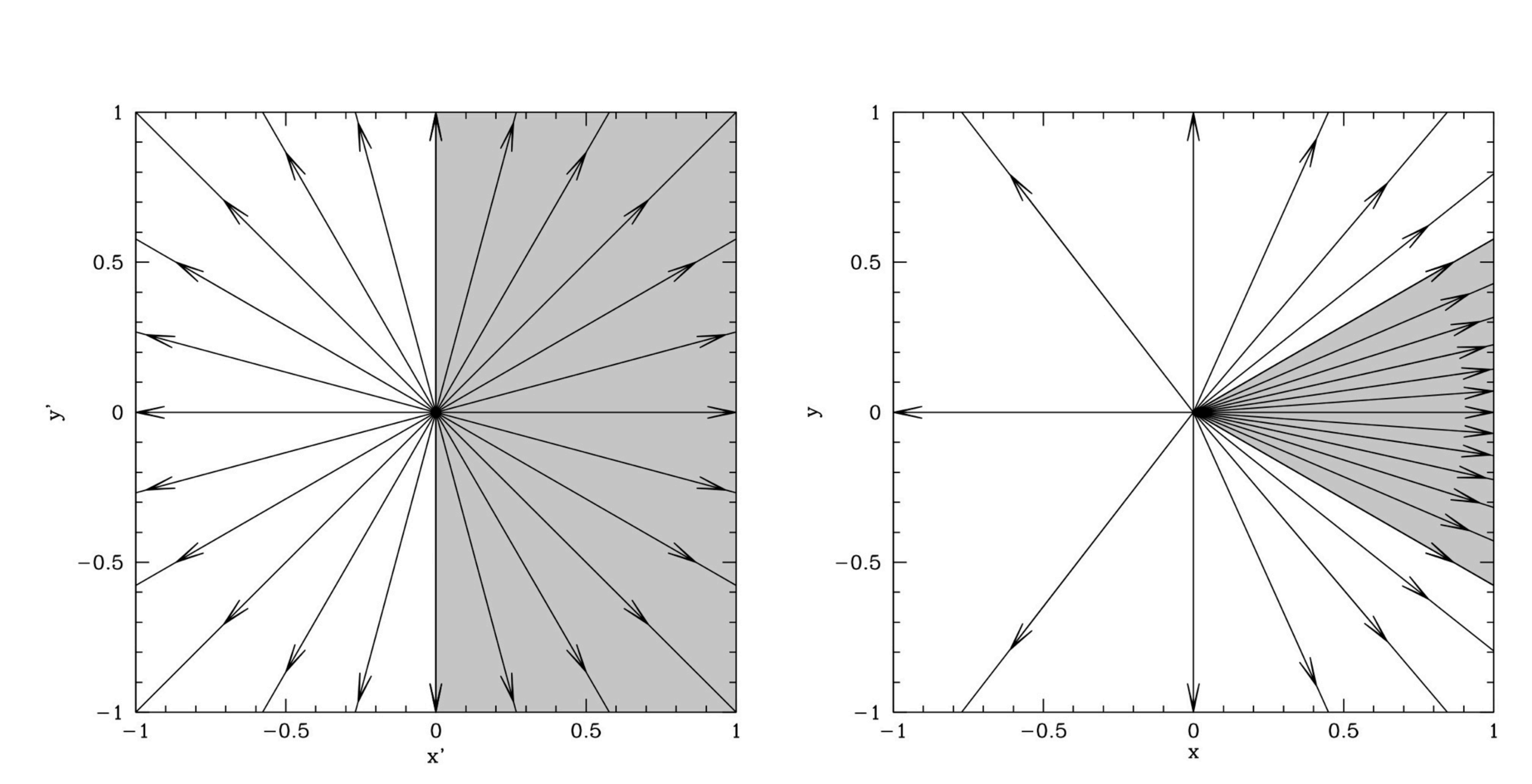
  Assume the source has a velocity v → c with $\Gamma = (1 - v^2/c^2)^{-1}$ >>1

- Due to the relativistic beaming, the source size must be revised
- Due to the relativistic beaming, the typical interaction angle is much smaller than π

Relativistic beaming



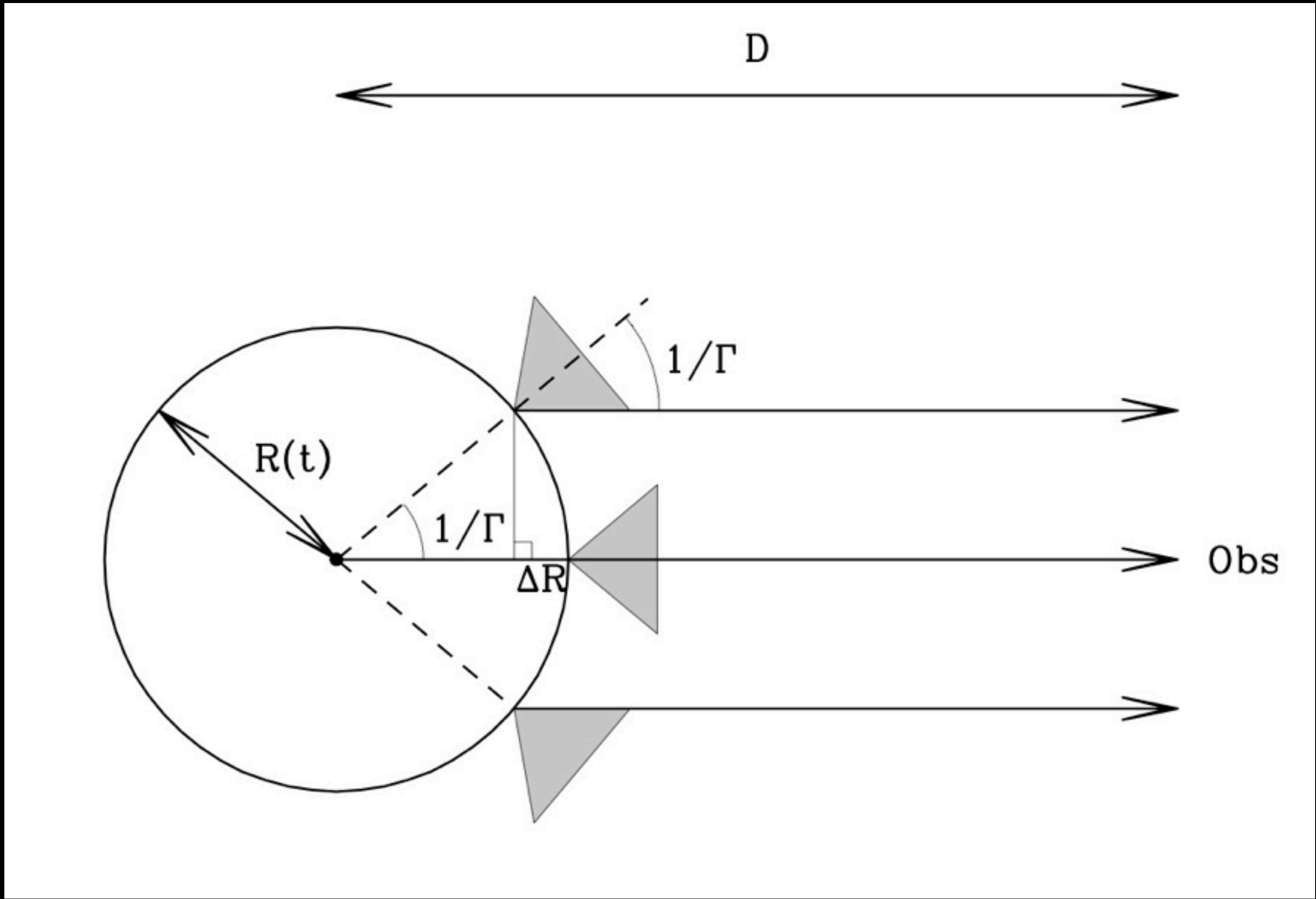
Relativistic beaming



Typical interaction angle = $1/\Gamma$: threshold for photon photon annihilation is multiplied by Γ^2

$$E_{\rm LE} \simeq 8\Gamma^2 \frac{\left(m_{\rm e}c^2\right)^2}{E_{\rm HE}} \simeq 21\,{\rm MeV}\,\left(\frac{\Gamma}{100}\right)^2 \left(\frac{E_{\rm HE}}{1\,{\rm GeV}}\right)^{-1}$$

Geometry of a relativistically moving source



Source size is multiplied by Γ^2

$$R \leq 2\Gamma^2 c t_{\rm var} \simeq 6 \times 10^7\,{\rm km} \left(\frac{\Gamma}{100}\right)^2 \left(\frac{t_{\rm var}}{10\,{\rm ms}}\right)$$

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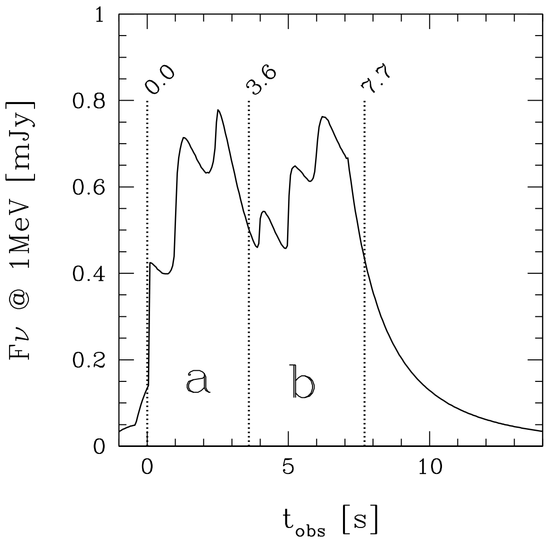
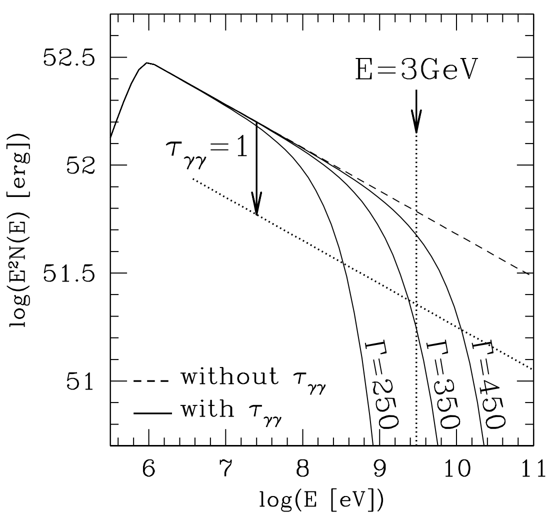
If photons are detected up to energy E_{max} : constraint = opacity(E_{max}) < 1 : this gives a minimum Lorentz factor

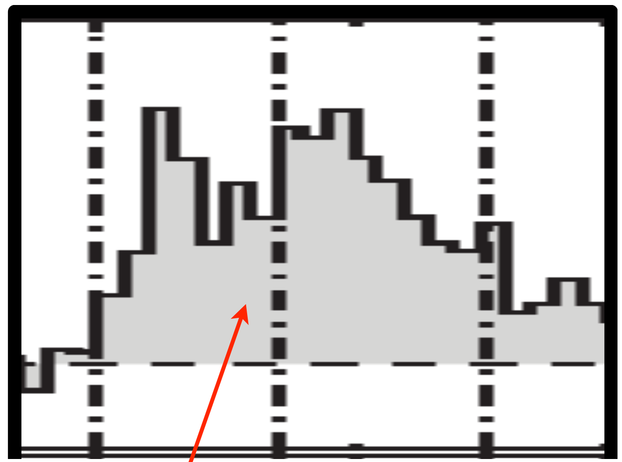
- pre-Fermi era : $E_{max} \sim$ MeV : $\Gamma \sim 100$-300 (Lithwick & Sari 2001)
- Fermi era : $E_{max} \sim$ GeV : $\Gamma \sim 1000$!!! (Abdo et al. 2009)

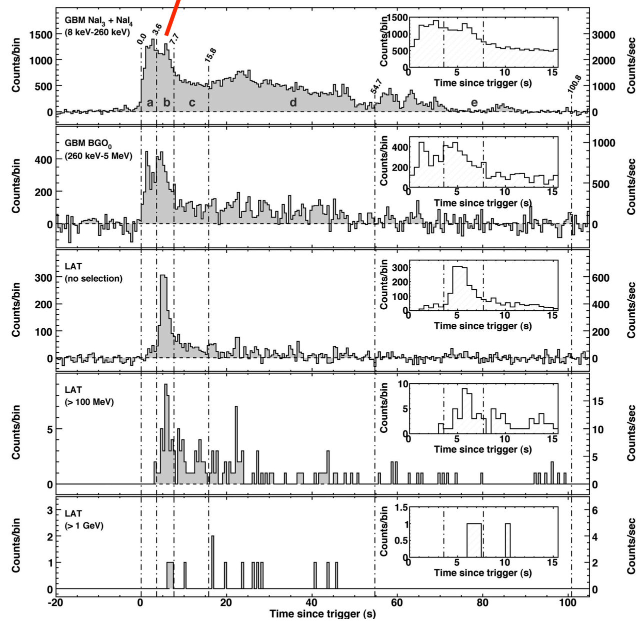
These estimates are based on single zone models.
More detailed models with a time/space/direction dependent radiation field leads to $\Gamma \sim 300$ for the brightest Fermi bursts (Hascoet, Daigne et al. 2012)

Theory (2) Necessity of a relativistic ejection









GRB 080916C (Abdo et al. 2009)

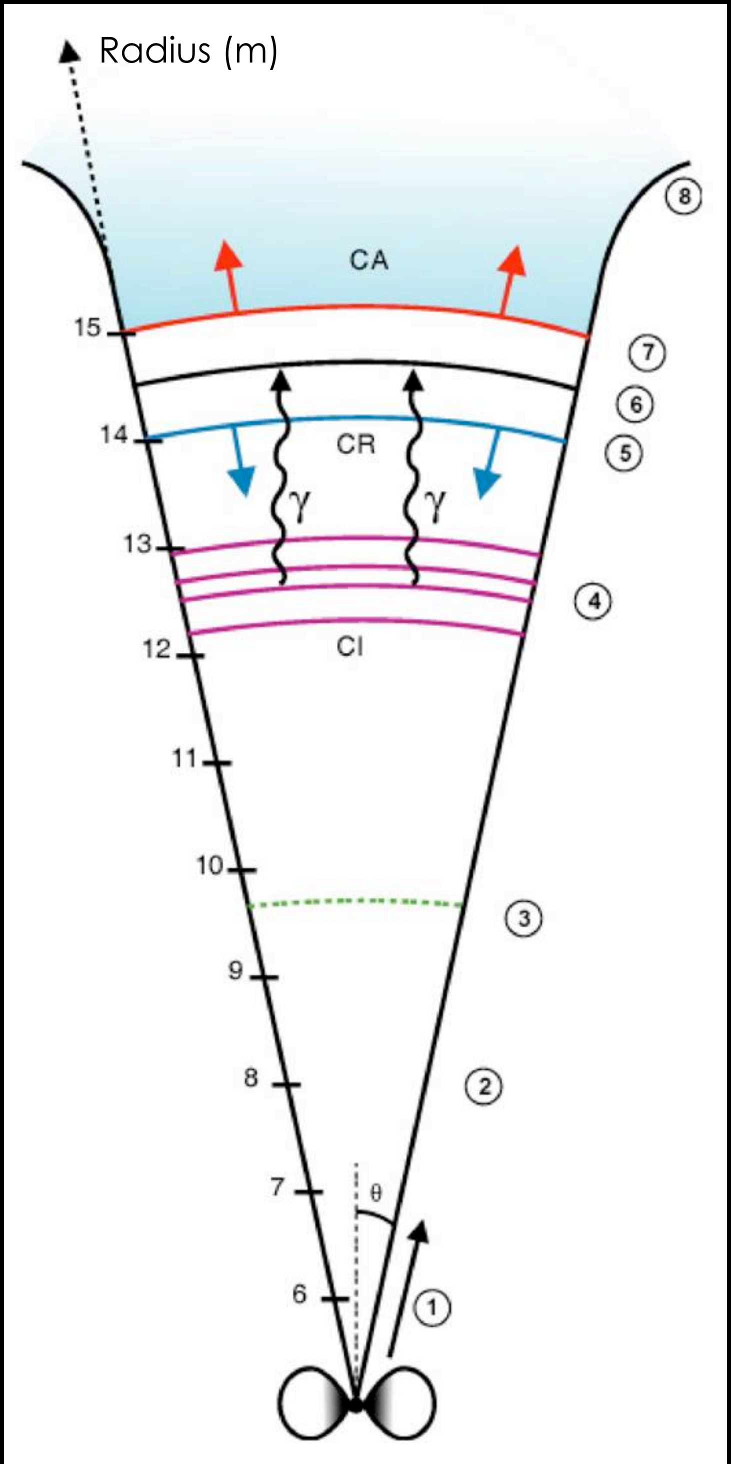
Model of bins a+b in GRB 080916C :

Γ_{min} ~ 360 (Hascoët et al. 2012)

instead of ~ 900 (Abdo et al. 2009)

GRB Theory

1. Initial event = formation of a compact object
   Central engine =
   - accreting stellar mass black hole
   - magnetar ?



GRB Theory

1. Initial event = formation of a compact object
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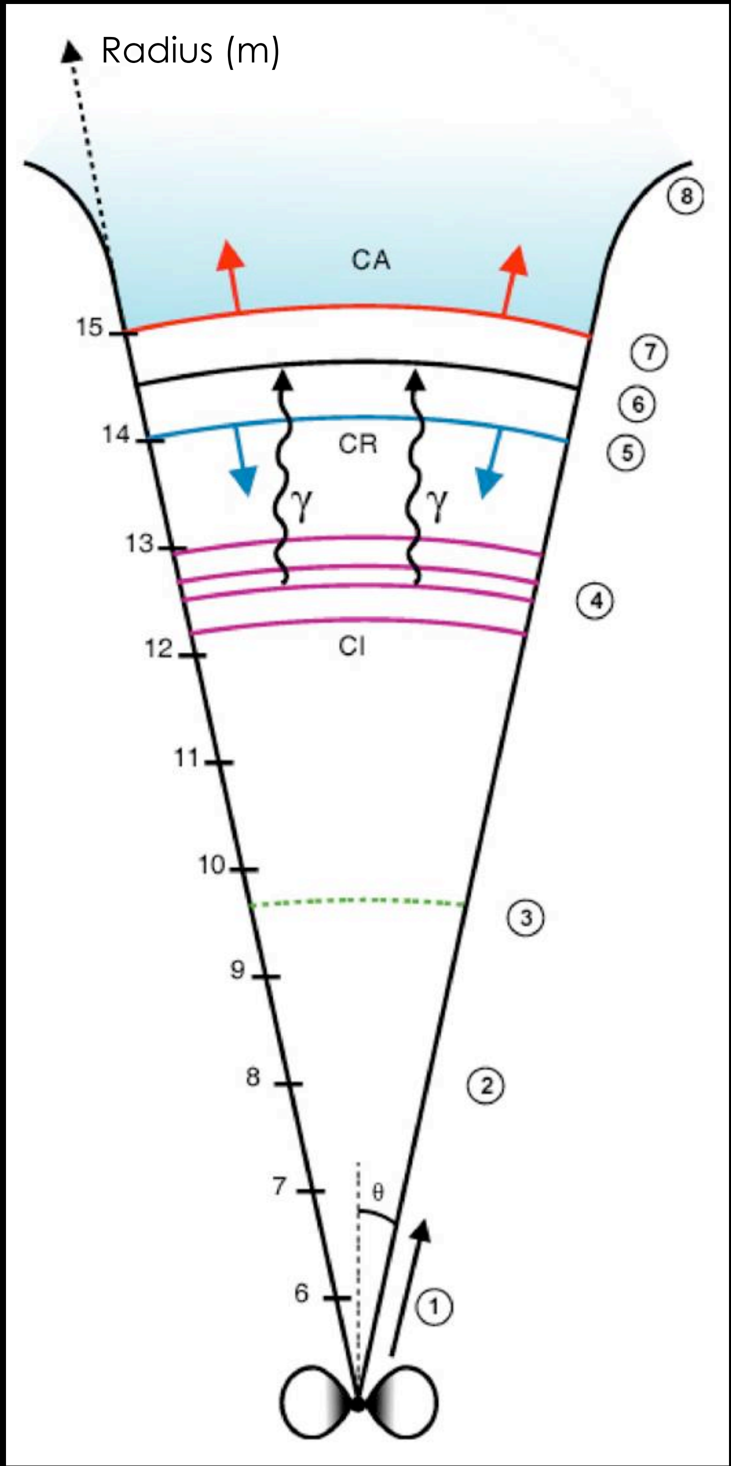
2. Relativistic ejection

Steps 1 & 2 = no electromagnetic signal
(medium is opaque for its own radiation)

Gravitational waves ?
Neutrinos ?



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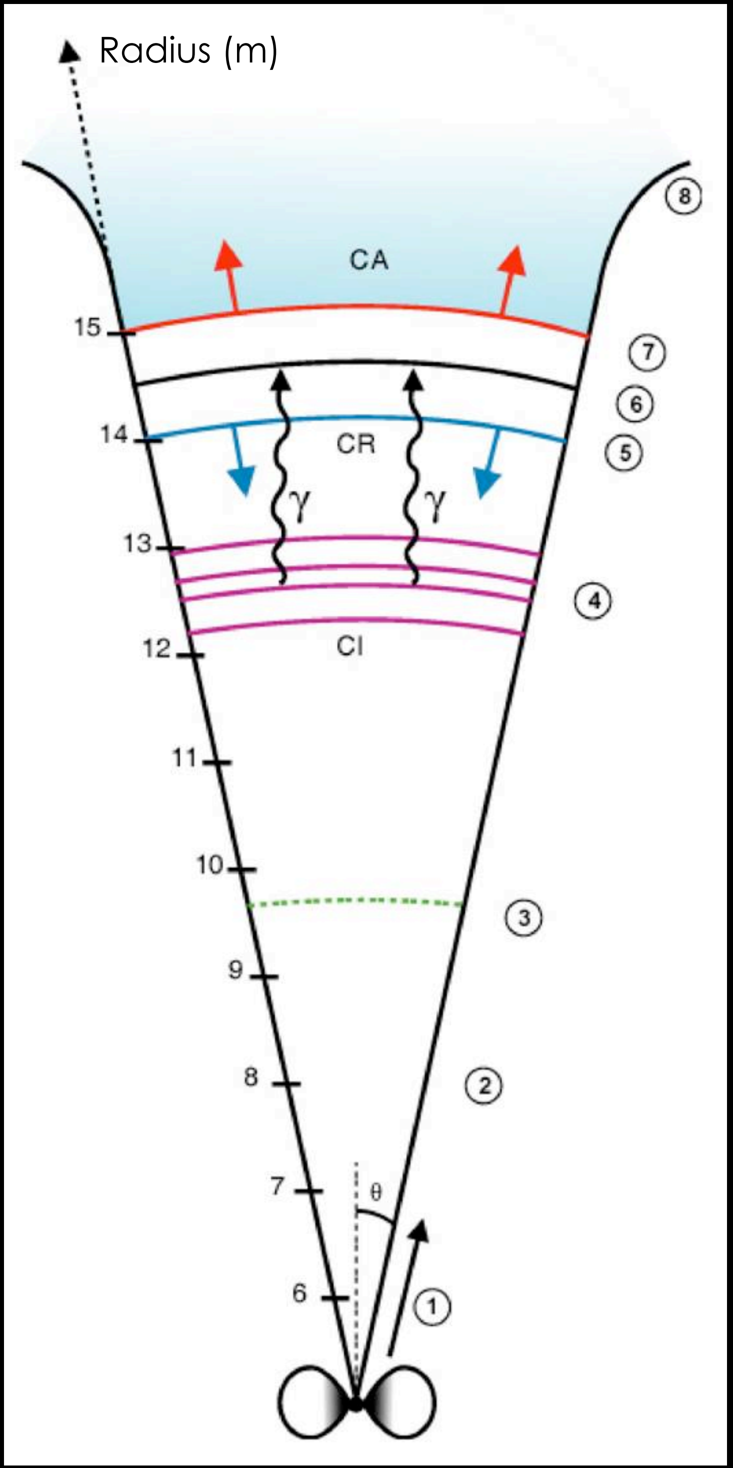

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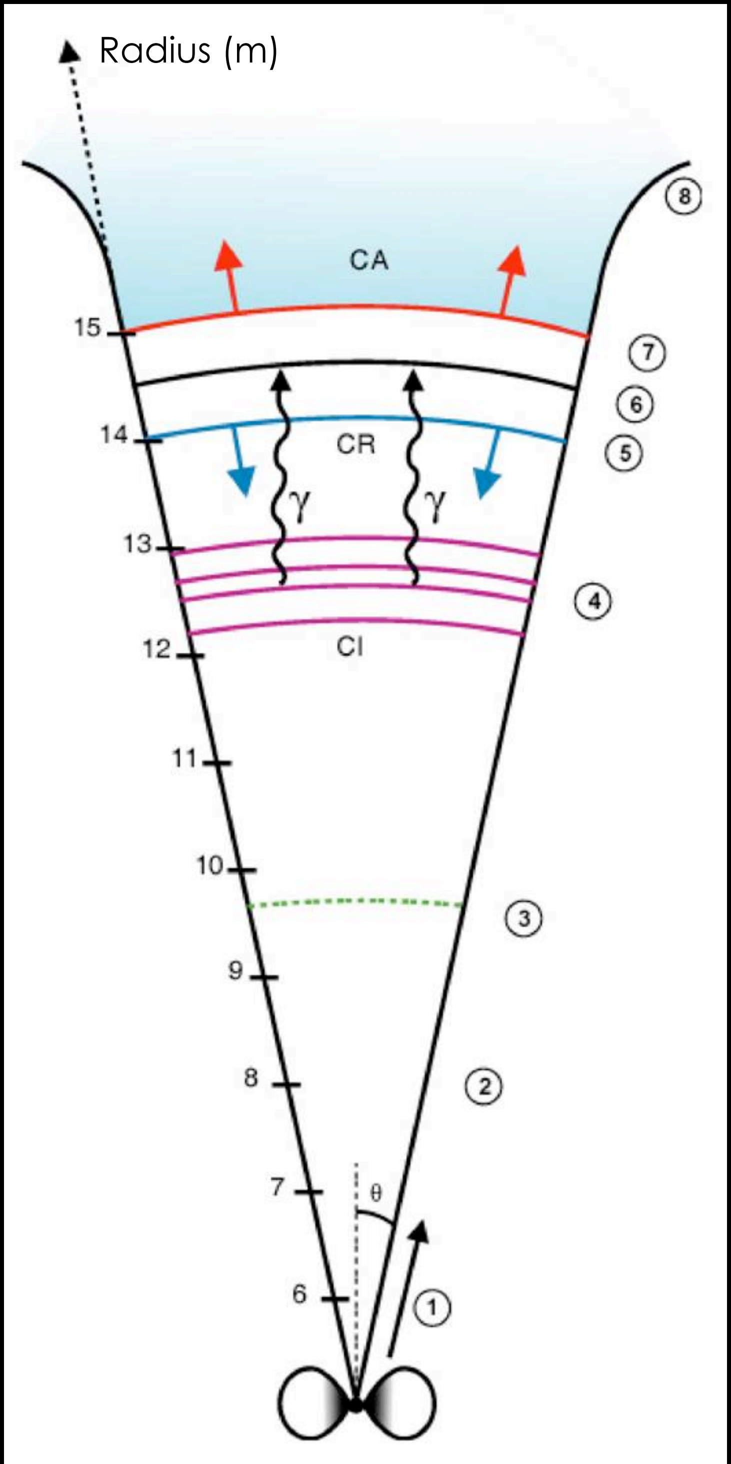
4. Internal dissipation in the relativistic outflow : prompt emission

   - If the outflow has a low magnetization at large distance :
     extraction of kinetic energy by internal shocks
     radiation is produced by shock-accelerated electrons

   - If the outflow is highly magnetized : reconnection



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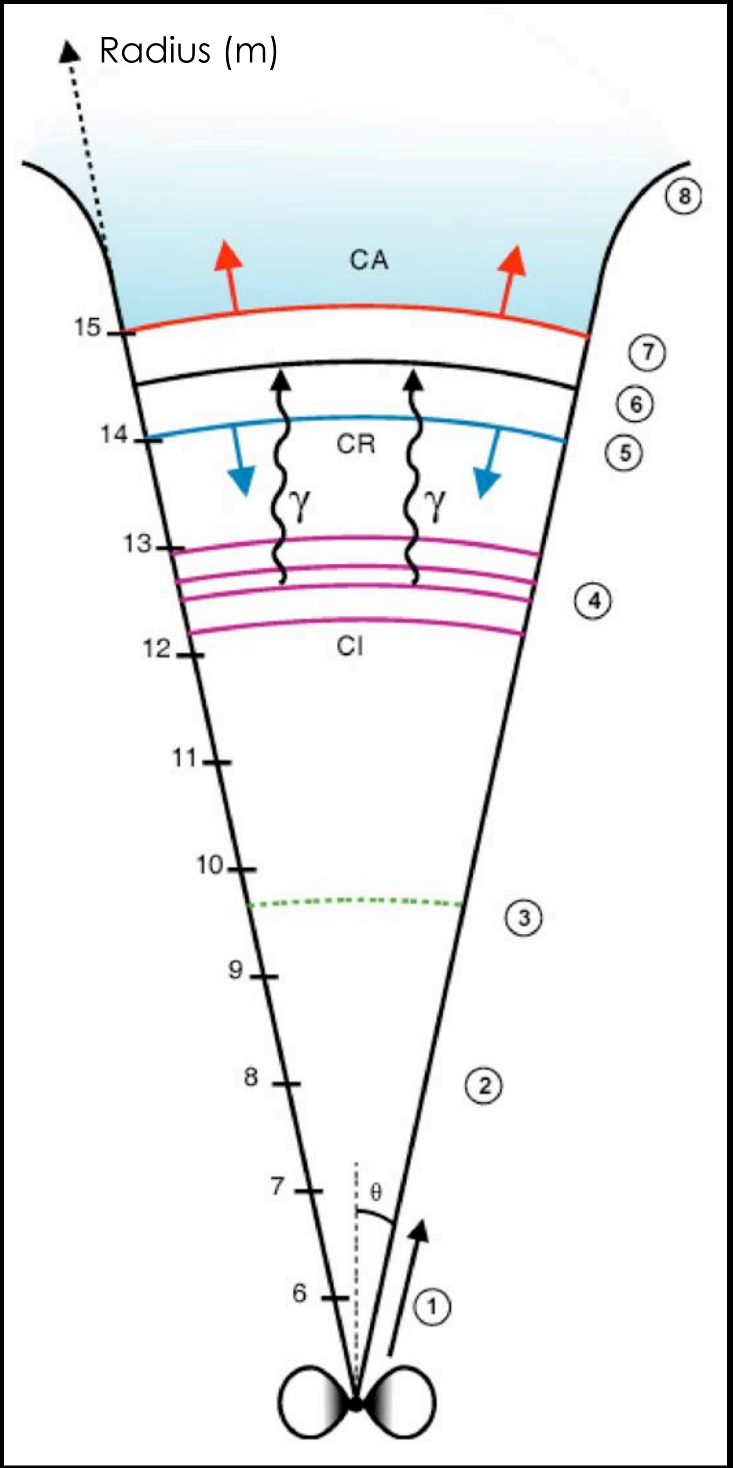
5. Reverse shock : contribution to the emission is unclear
   (prompt optical / early afterglow emission ? X-rays ? ...)

6. Contact discontinuity

7. Forward shock : strong ultra-relativistic shock : afterglow



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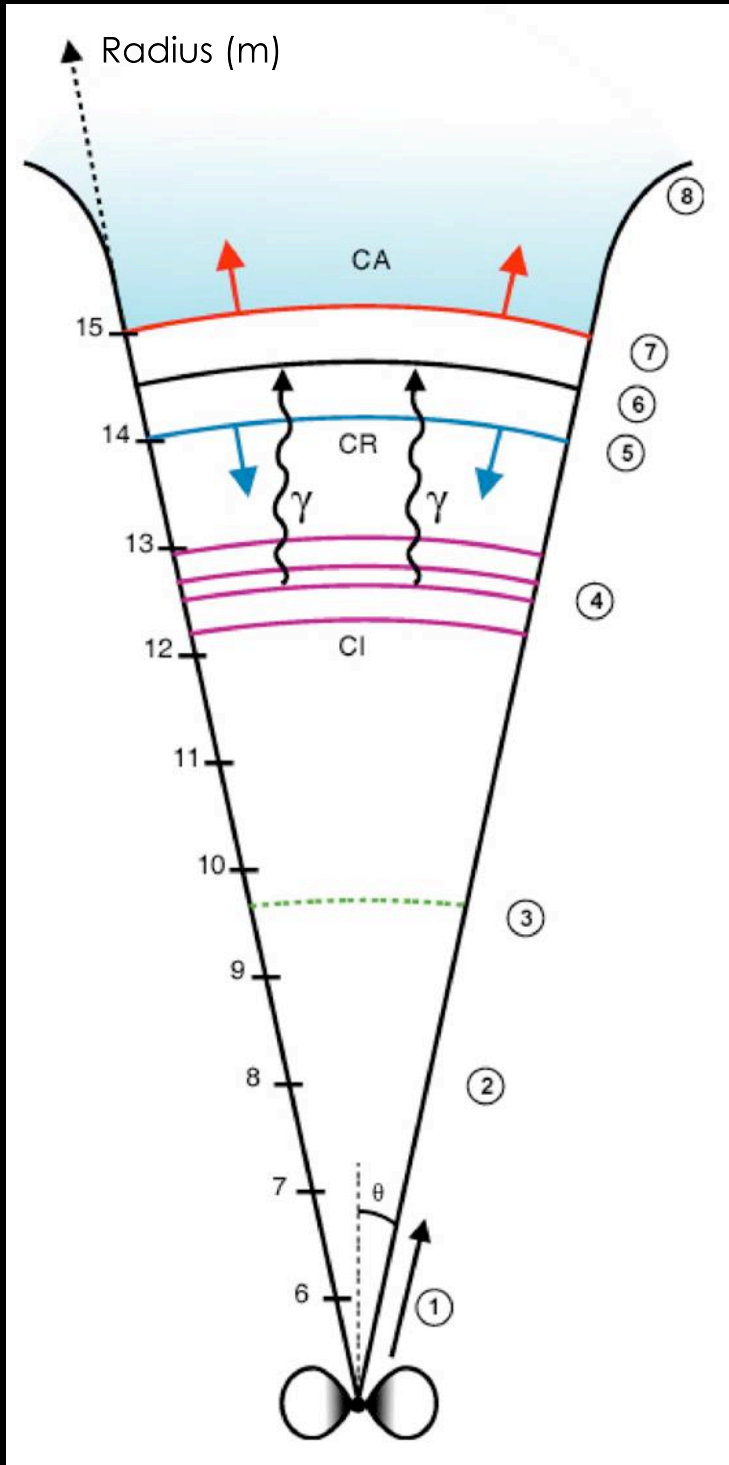
8. Late evolution : Newtonian motion + lateral expansion
   A GRB remnant should look like a SN remnant after a few 10^4 yr



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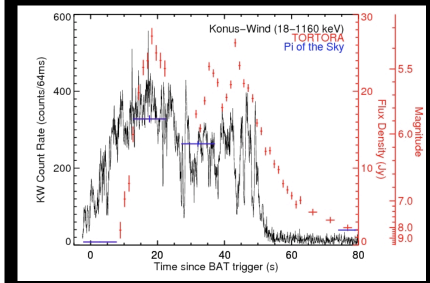

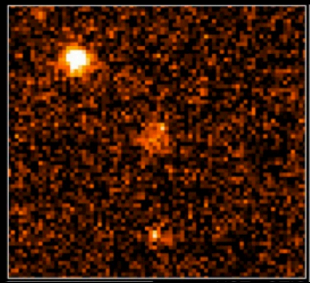

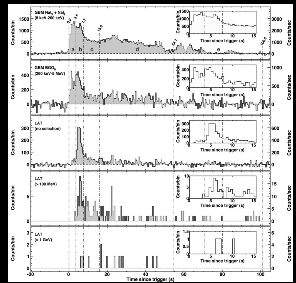

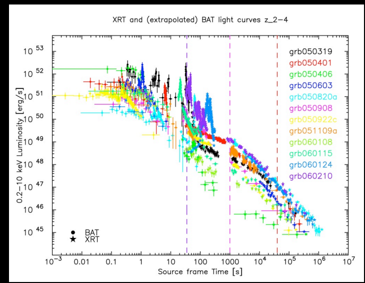

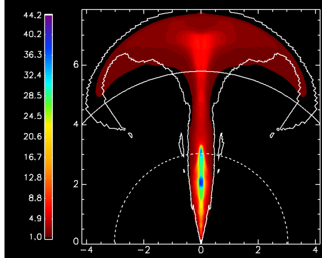

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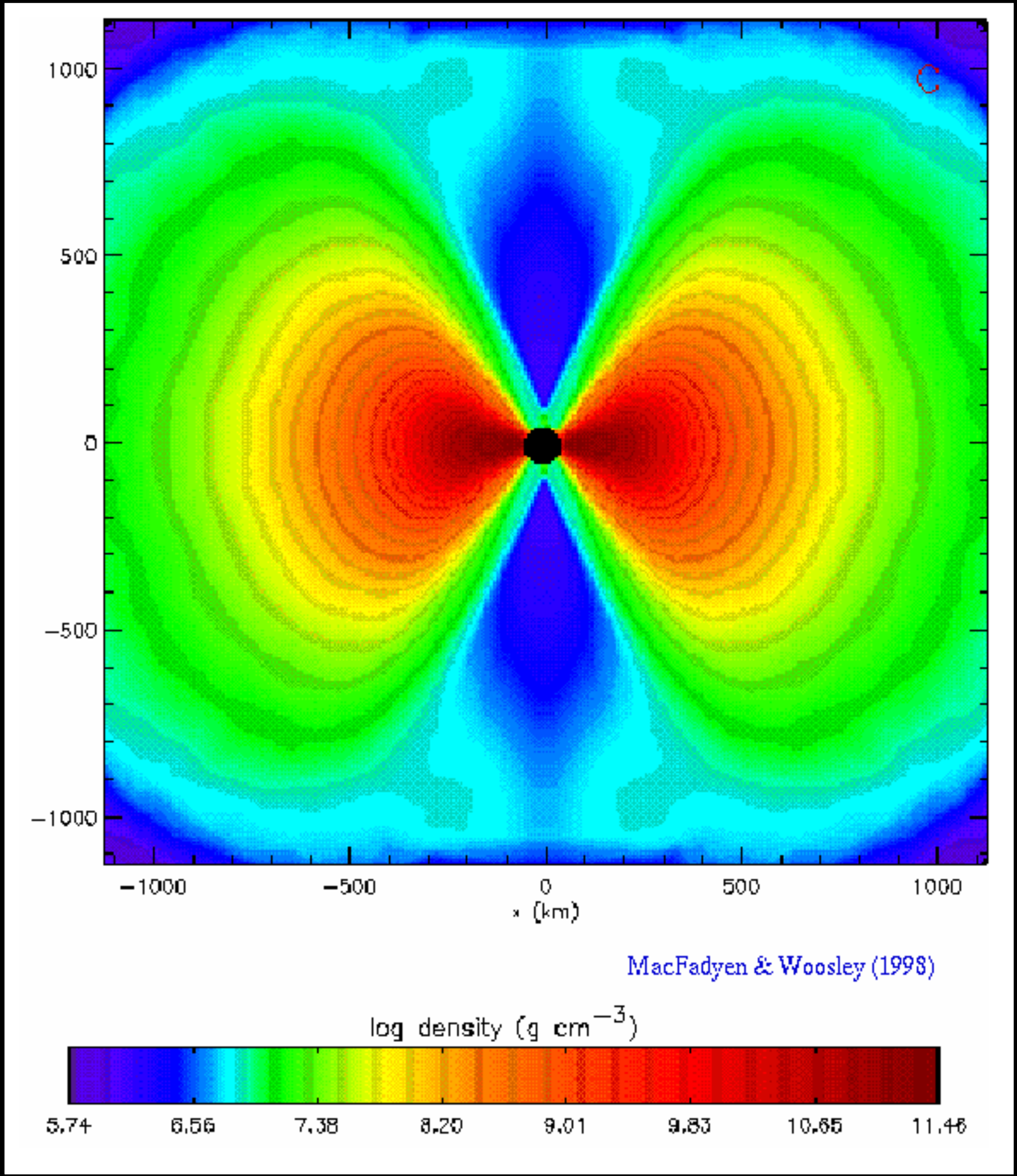
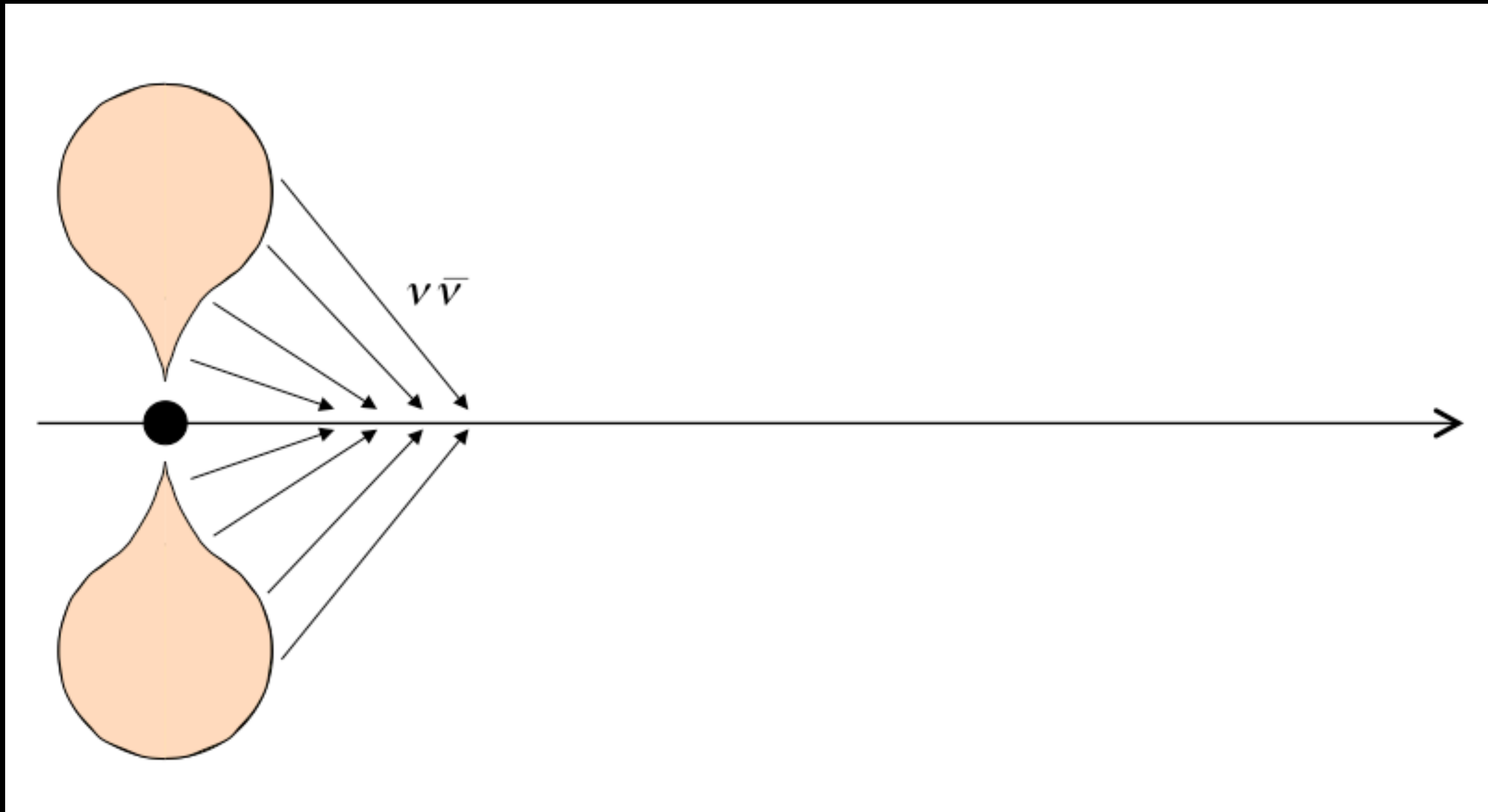
Collapsar

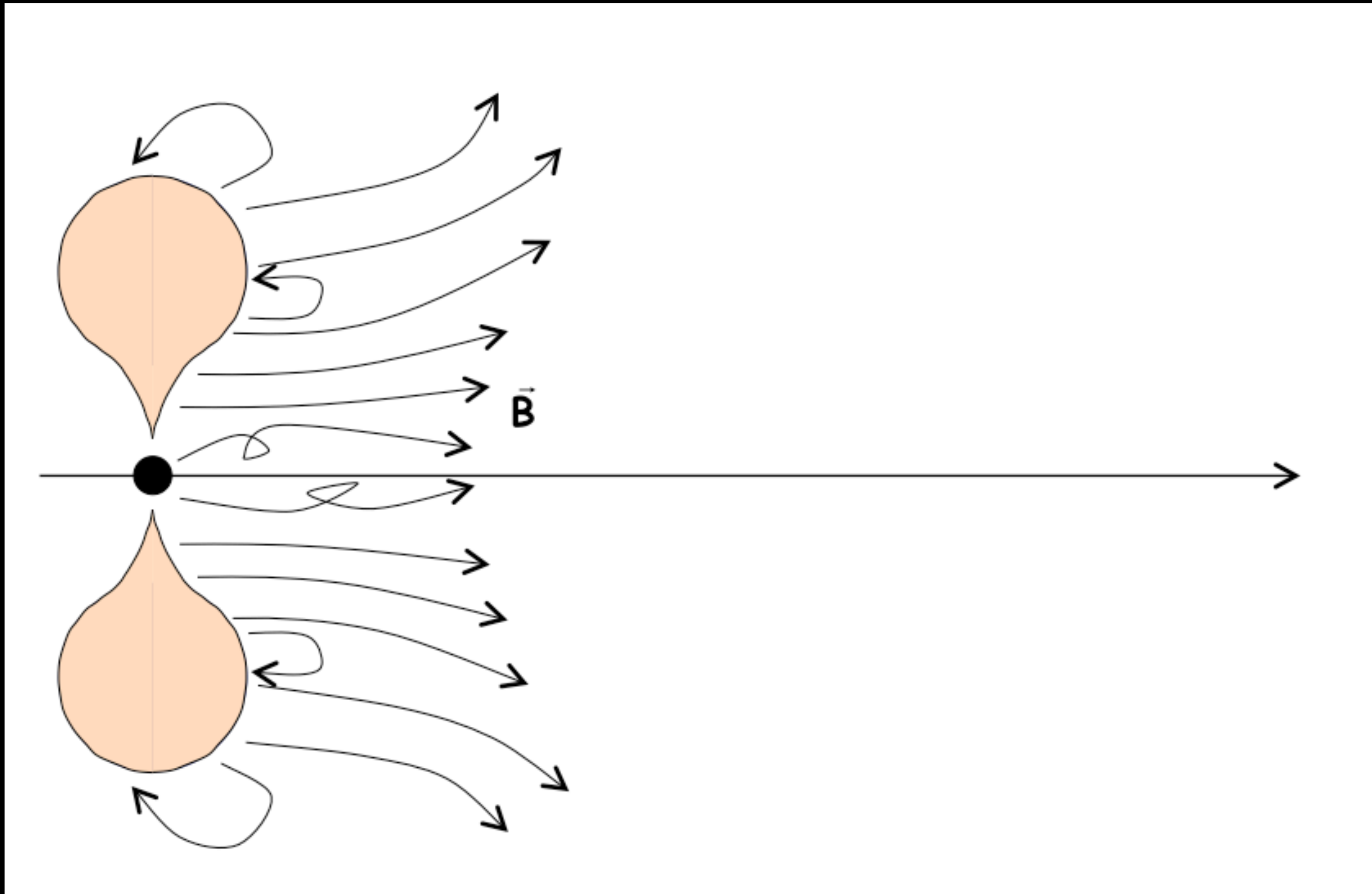


C
1000
500
0
−500
−1000
−1000
−500
0
500
1000
x (km)
MacFadyen & Woosley (1998)
log density (g cm^{-3})
5.74
6.56
7.38
8.20
9.01
9.83
10.65
11.46

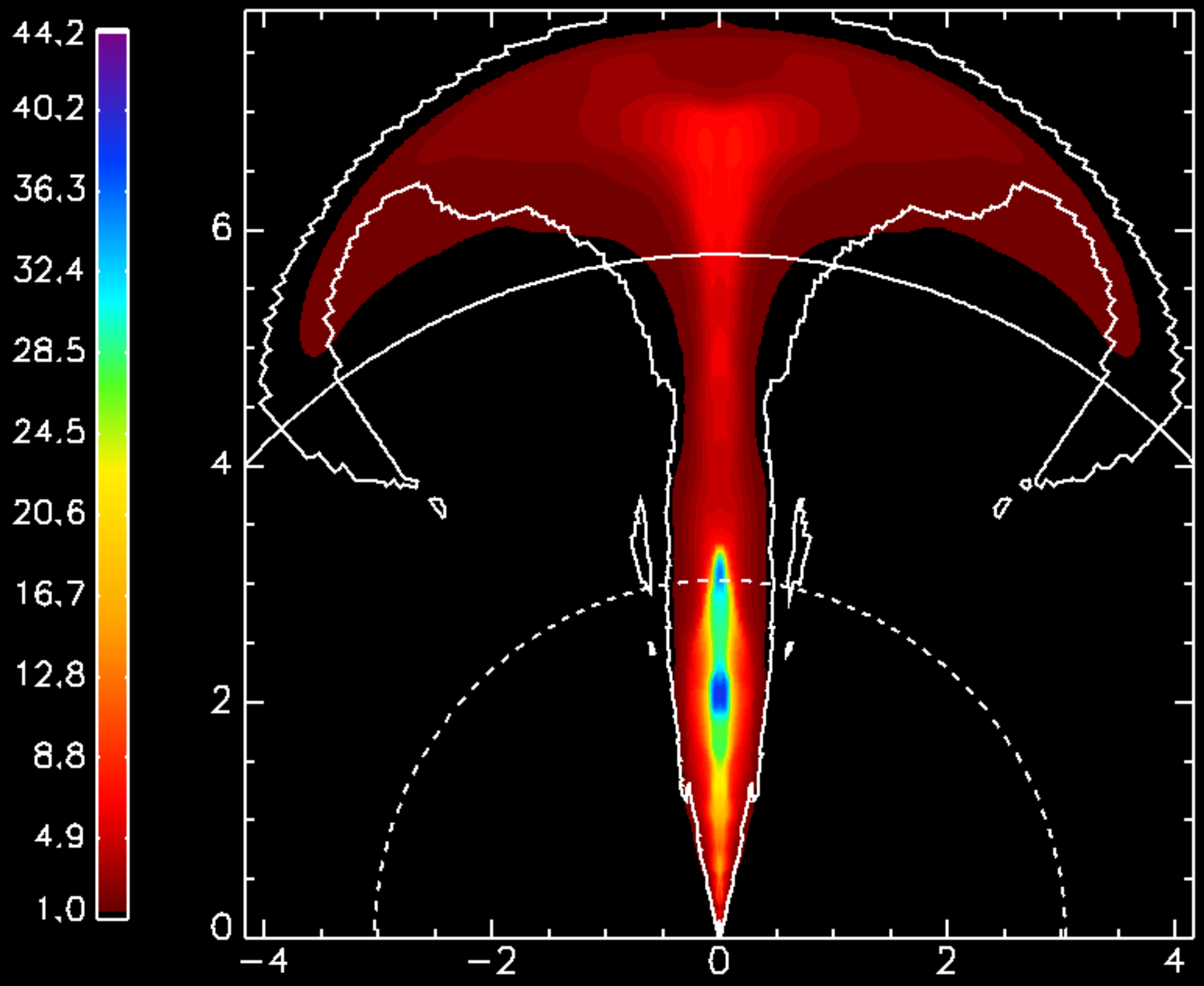
Relativistic ejection : neutrino-antineutrino annihilation ?



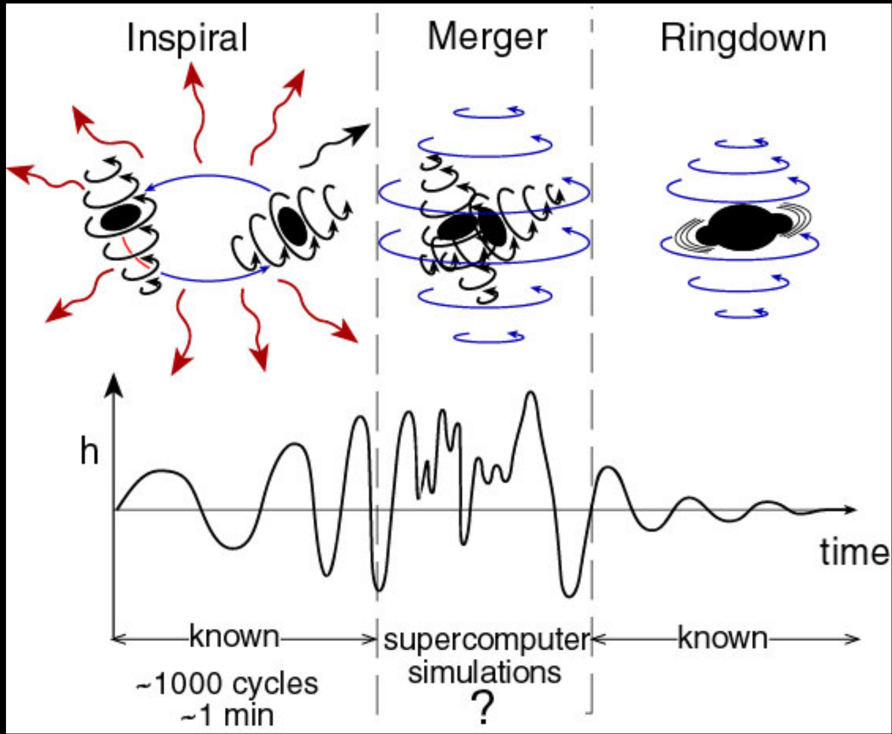
Relativistic ejection : magnetic outflow ? (Blandford-Payne / Blandford-Znajek ?)

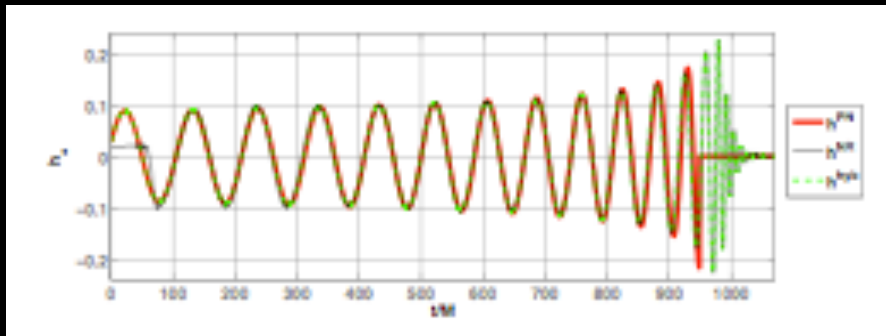


Breaking out from a collapsing star



Gravitational waves ? Best candidate = short GRBs if associated to NS-NS mergers



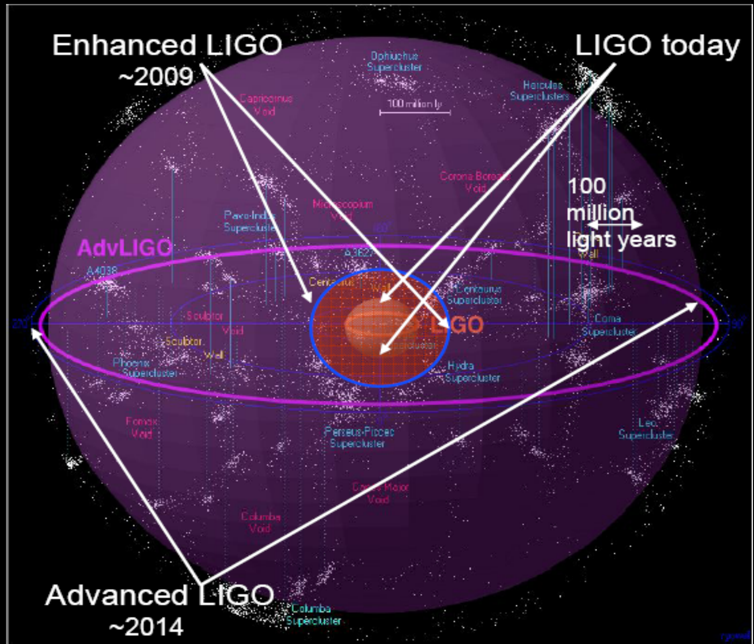


Ajith et al, CQG 24, S689 (2007)

Proof of the formation of black hole, mesure of its mass and spin...

Gravitational waves ? Best candidate = short GRBs if associated to NS-NS mergers

Horizon	NS-NS	NS-BH
LIGO I / Virgo	15 Mpc	30 Mpc
Advanced LIGO / Advanced Virgo	200 Mpc	420 Mpc



Rate	NS-NS	NS-BH
LIGO I / Virgo	0.02 yr^{-1} (0.0002 to 0.2)	0.004 yr^{-1} (0.000 07 to 0.1)
Advanced LIGO / Advanced Virgo	40 yr^{-1} (0.4 to 400)	10 yr^{-1} (0.2 to 300)

The population of NS-NS or NS-BH binaries is not well known...

population synthesis (highly uncertain)

Only a few systems are observed :
e.g. PSR B 1913+16 (merger in ~ 100 Myr)

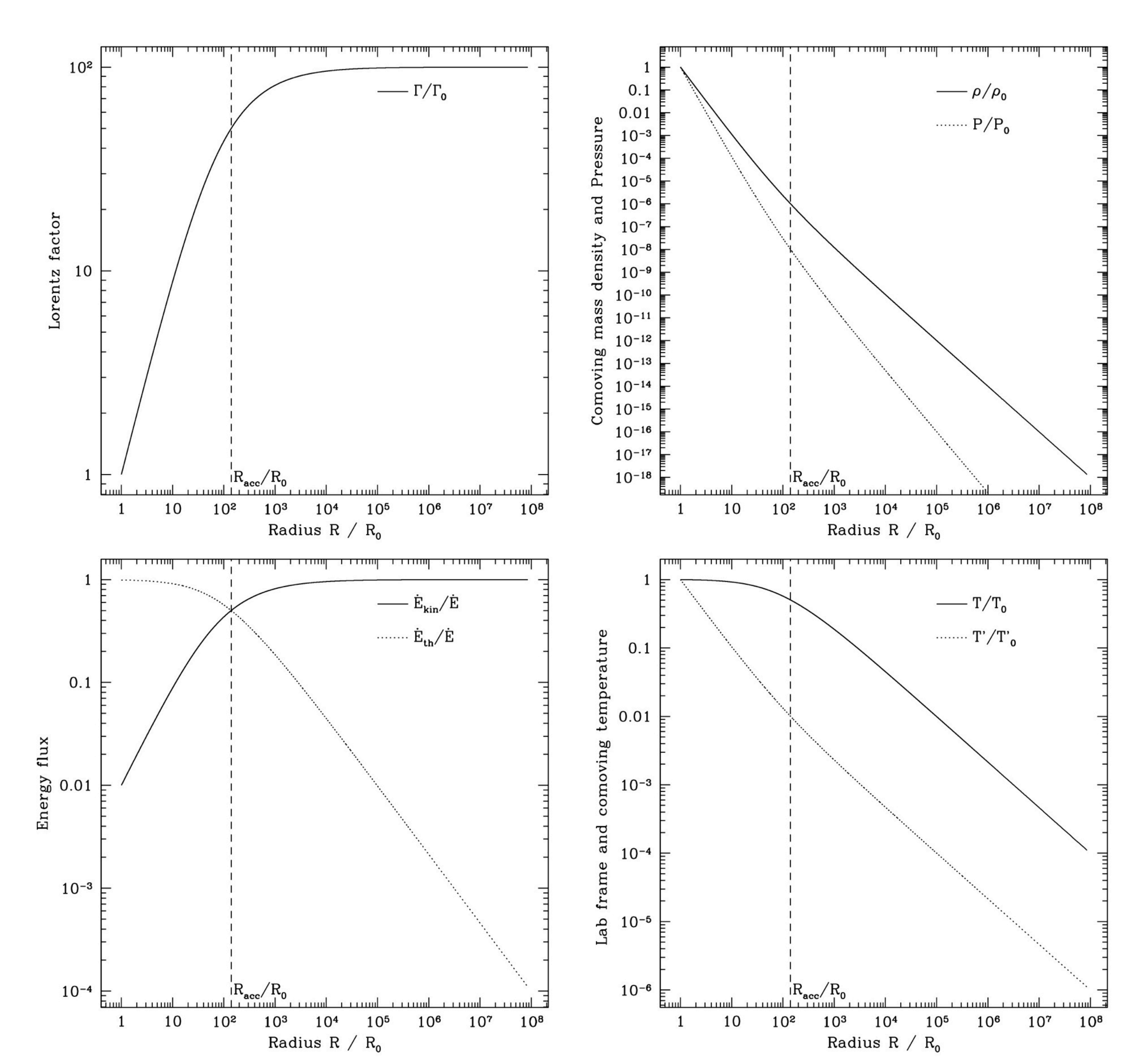
Fireball

The most simple model for the acceleration of the outflow
=
thermal acceleration

Two phases :
- radiation dominated era
- matter dominated era

(cf. Big Bang)

Final Lorentz factor
$\Gamma = E / M c^2$



Explosive phenomena: SNe and GRBs

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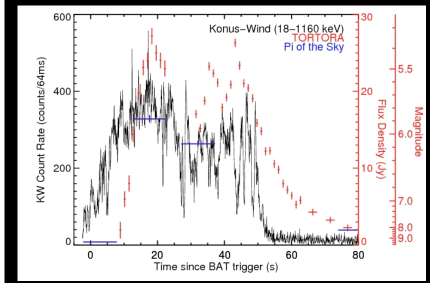

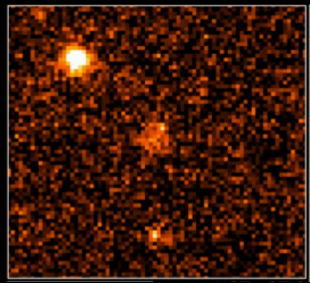
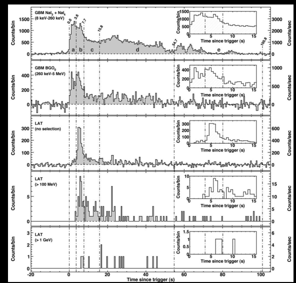
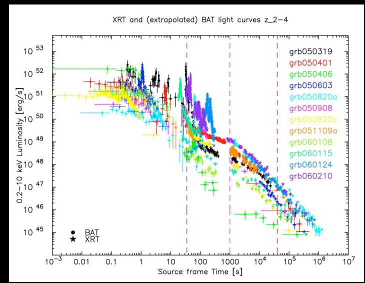

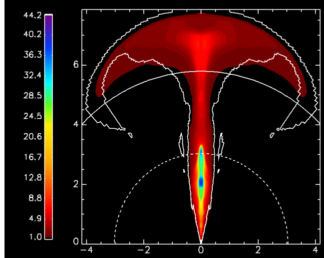

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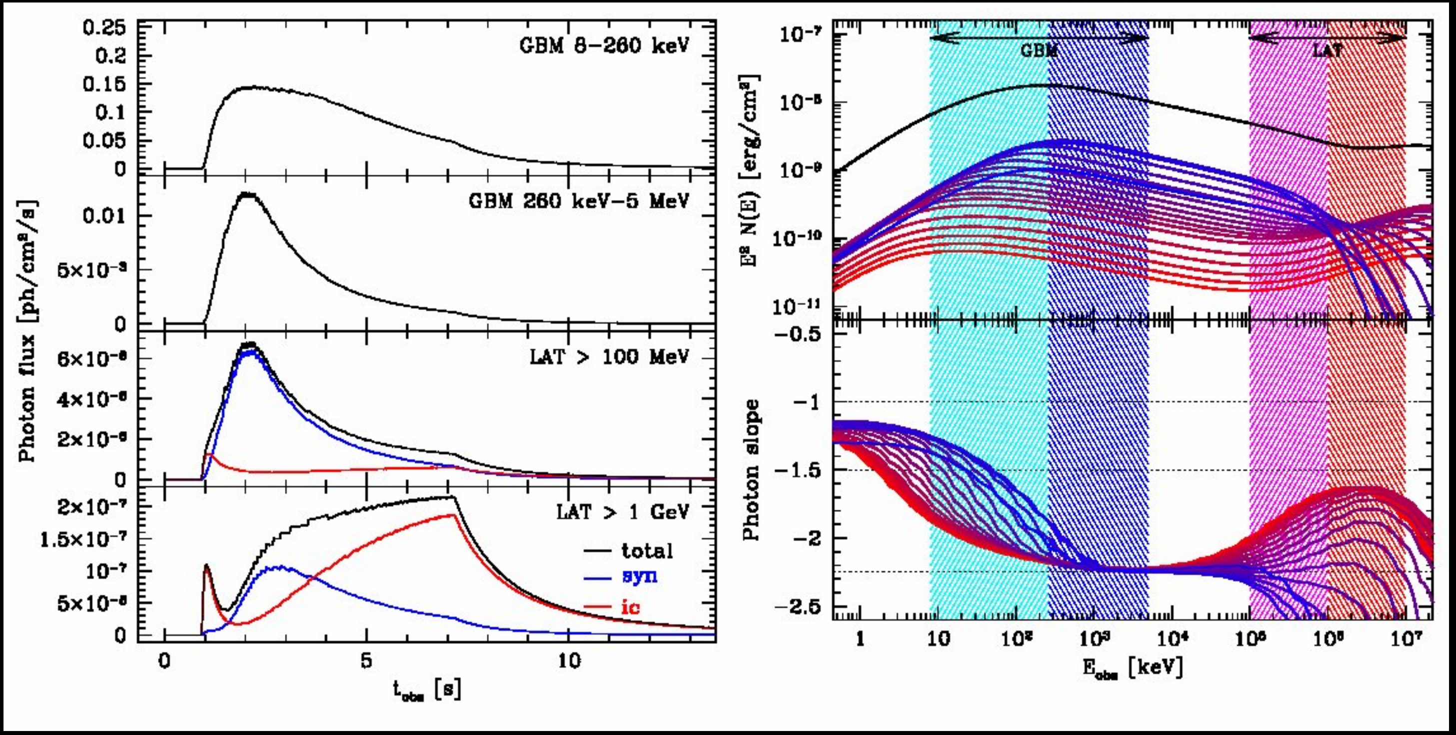
Internal shocks

1. The variability of the lightcurve is a miror of the activity of the central engine with the same time scales

2. The dynamics is well understood

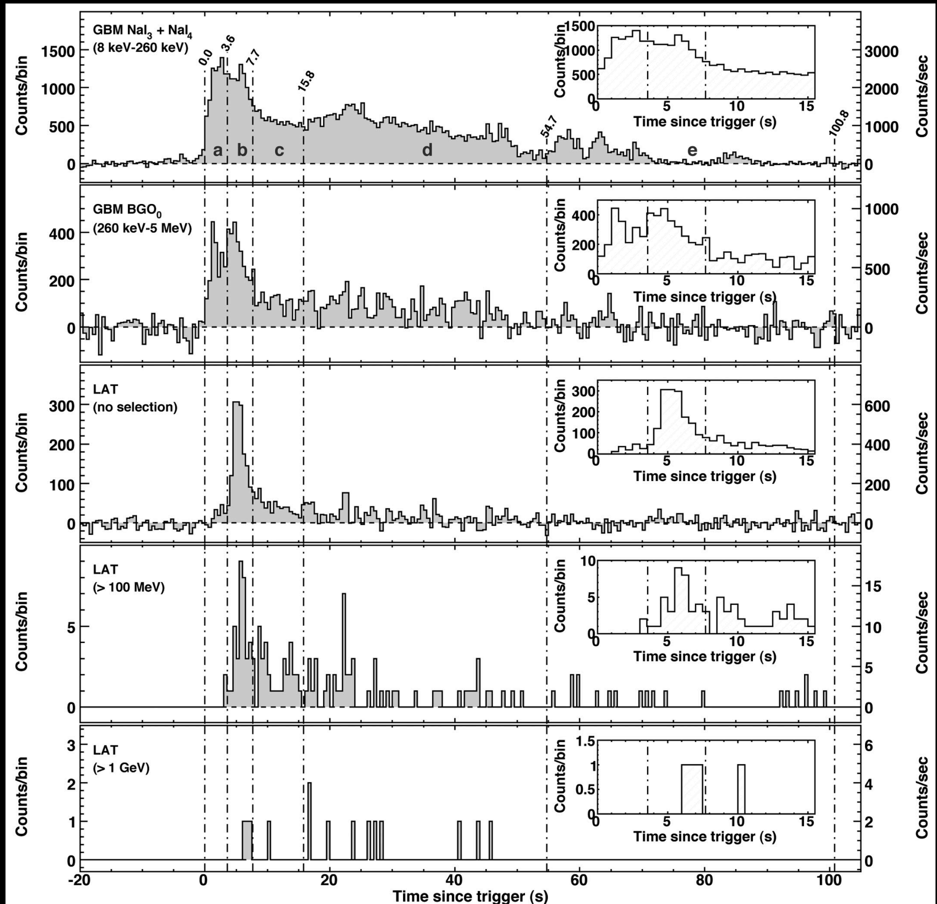
3. The microphysics in the shocked region is highly uncertain (mildly relativistic shocks)
   - amplification of the magnetic field ?
   - particle acceleration ?
   - dominant radiative processes ?

Fermi observations favor dominant synchrotron (MeV component) + weak IC in KN regime (GeV component)

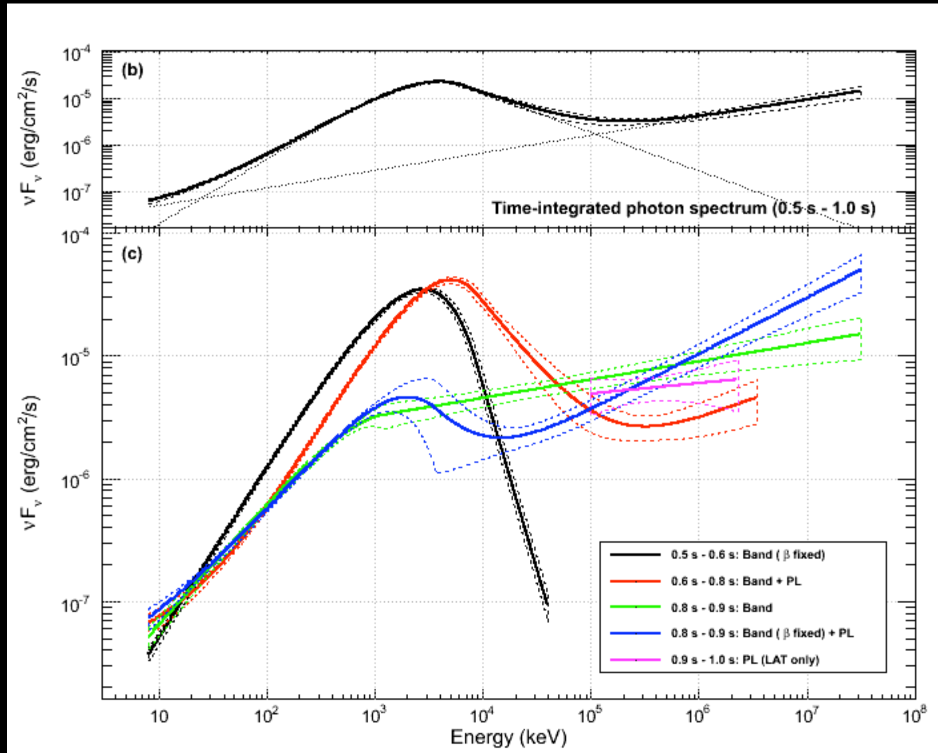


(Bošnjak, Daigne & Dubus 2009)

Internal shocks



GRB 080916C (Abdo et al. 09)



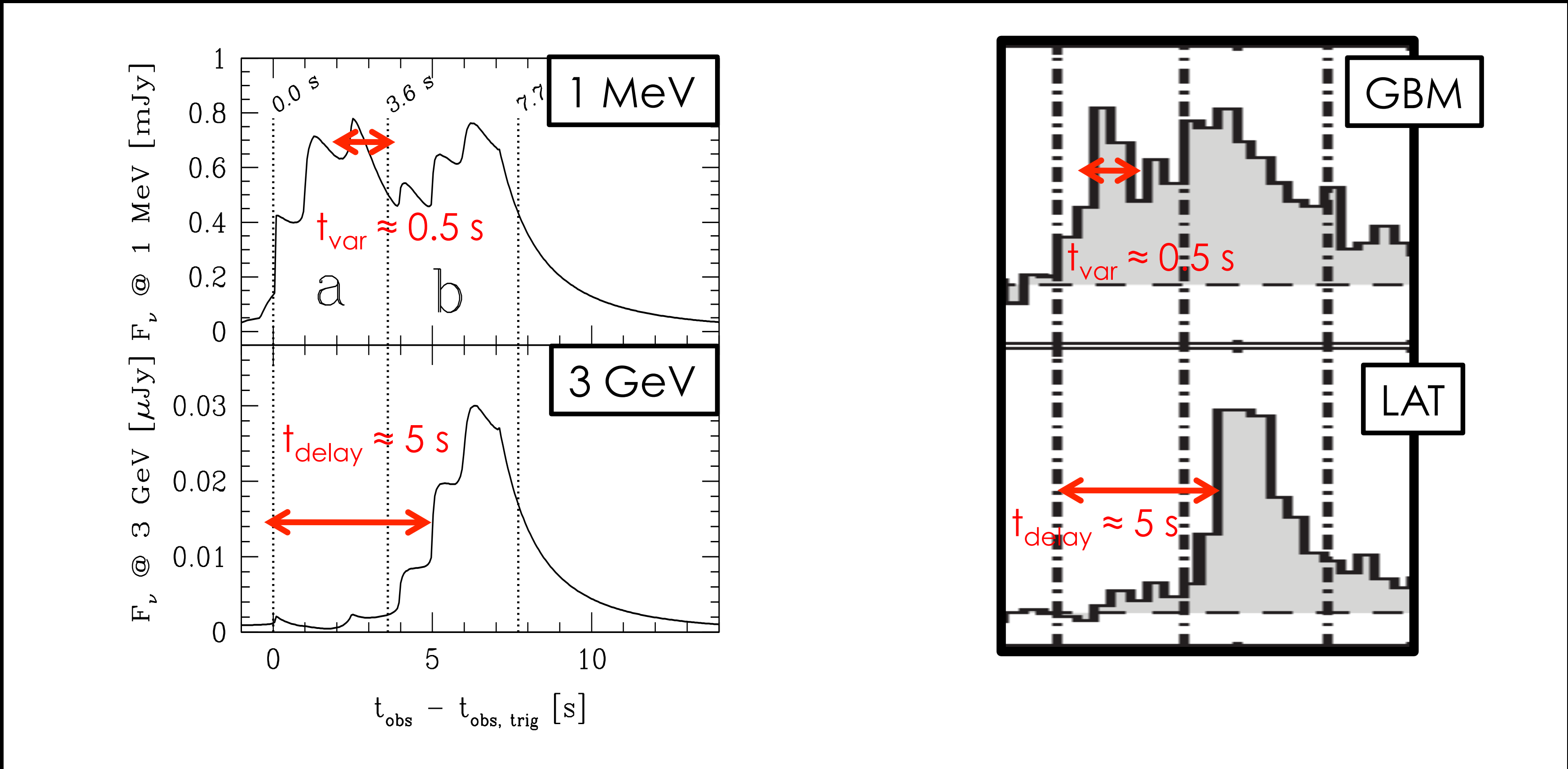
GRB 090510 (Abdo et al. 09)

(Abdo et al. 2009)

Delayed GeV onset + additional component :

- spectral evolution (IC vs syn)
- external IC compton (seed photons : photosphere ?) : needs fine tuning
- emergence of a hadronic component : inefficient (energy crisis)
- for the delay : gamma gamma opacity effect ?

Internal shocks : gamma gamma opacity effects



Model of bins a + b of GRB 080916C (Hascoet, Daigne et al. 2012)

First collisions are at smaller radii : opacity is larger

A delayed GeV onset can be reproduced, with a duration larger than the variability timescale in the GBM

Prompt emission

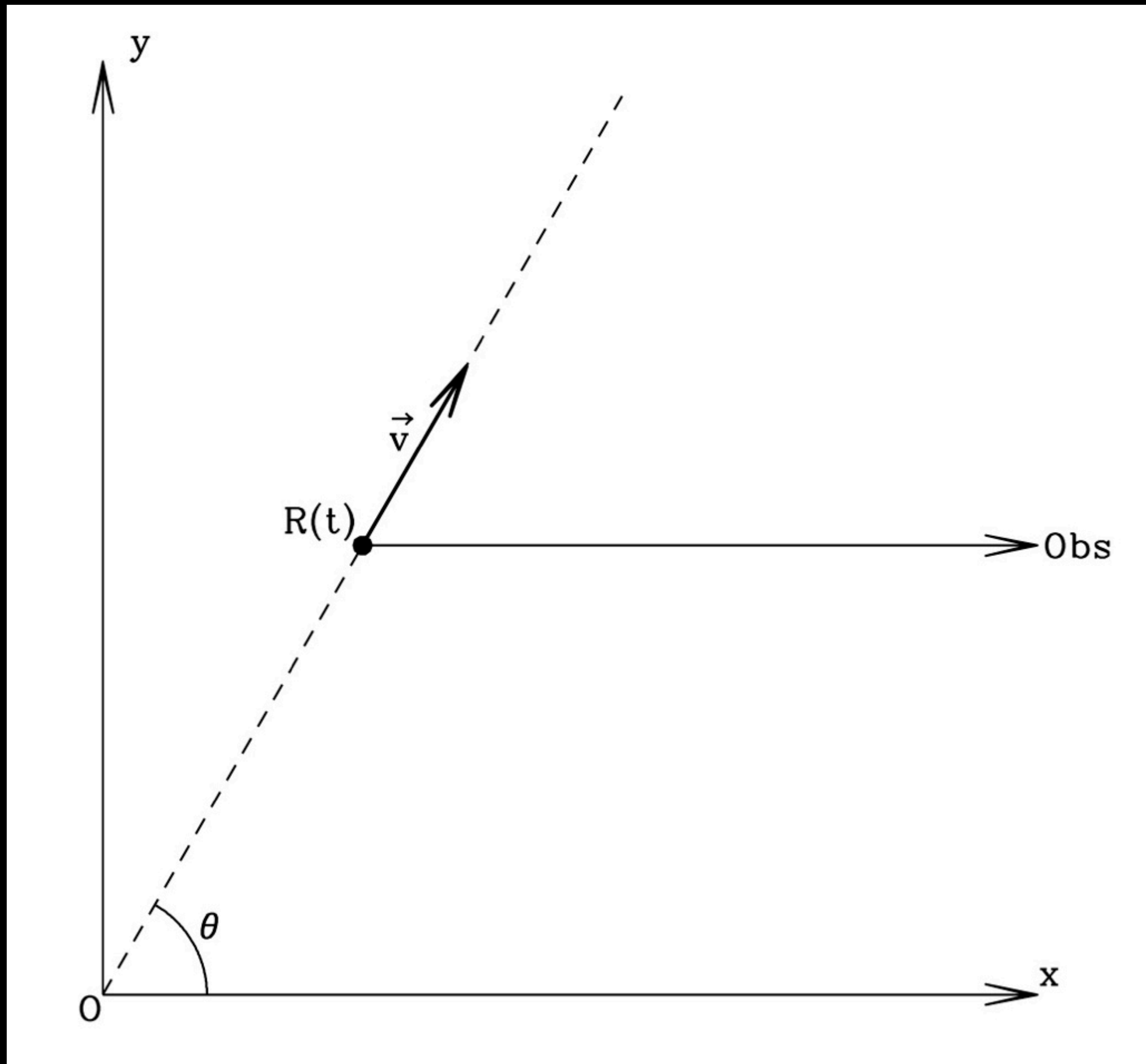
1. Internal shocks :
    - Pro : good agreement with temporal and spectral properties (including GeV emission)
    - Cons : low efficieny / microphysics highly uncertain

2. Photosphere :
    - Pro : simple physics / high efficiency
    - Cons : needs additional sub-photospheric dissipation to avoid a thermal spectrum / cannot produce GeV

3. Magnetic reconnection

?????

Superluminal (apparent) motion



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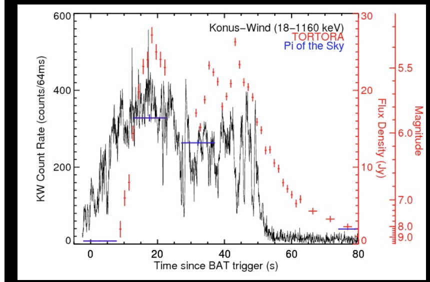

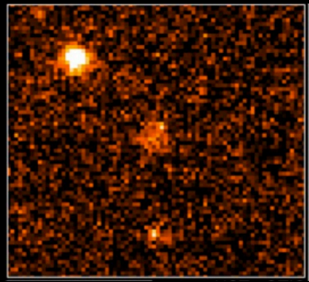

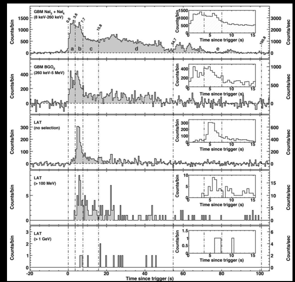

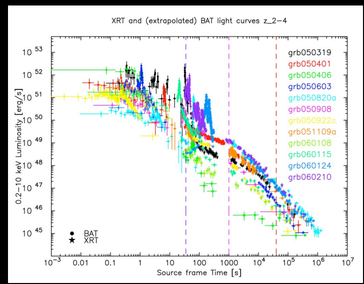

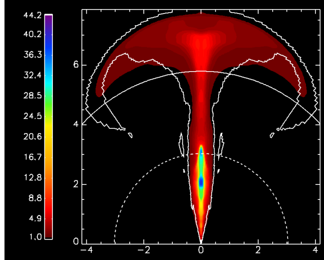

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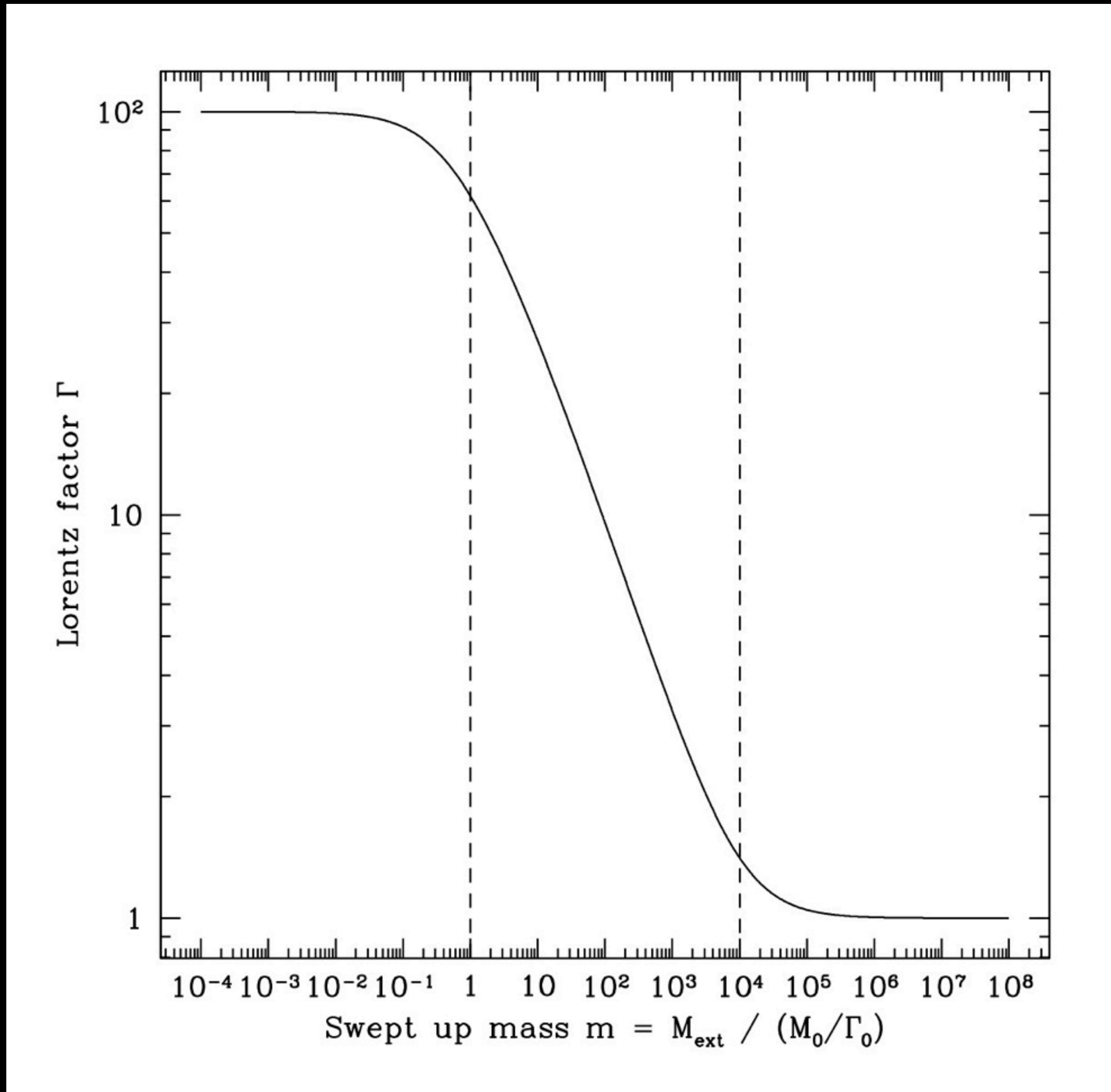
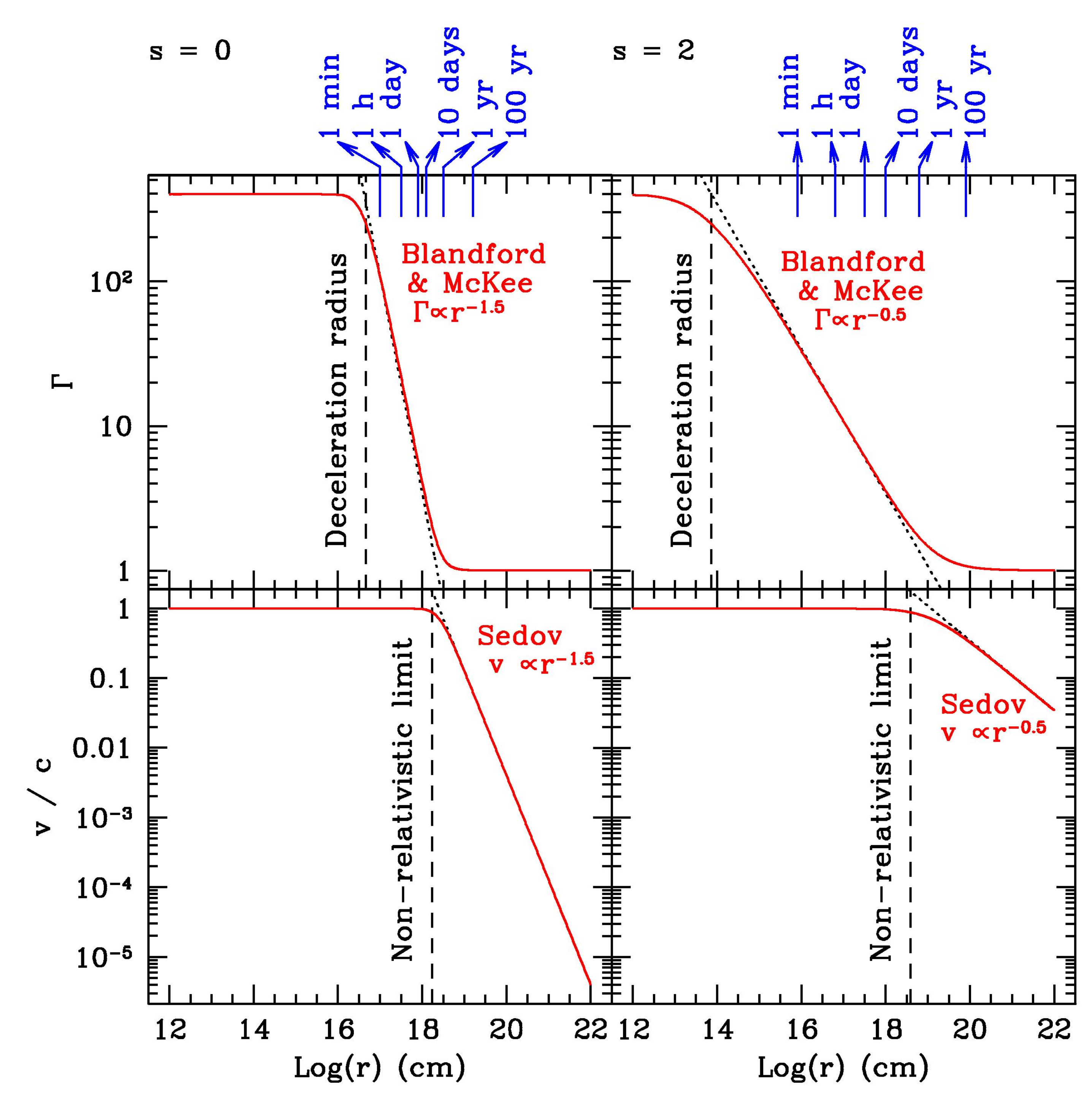
Afterglow : deceleration by the external medium

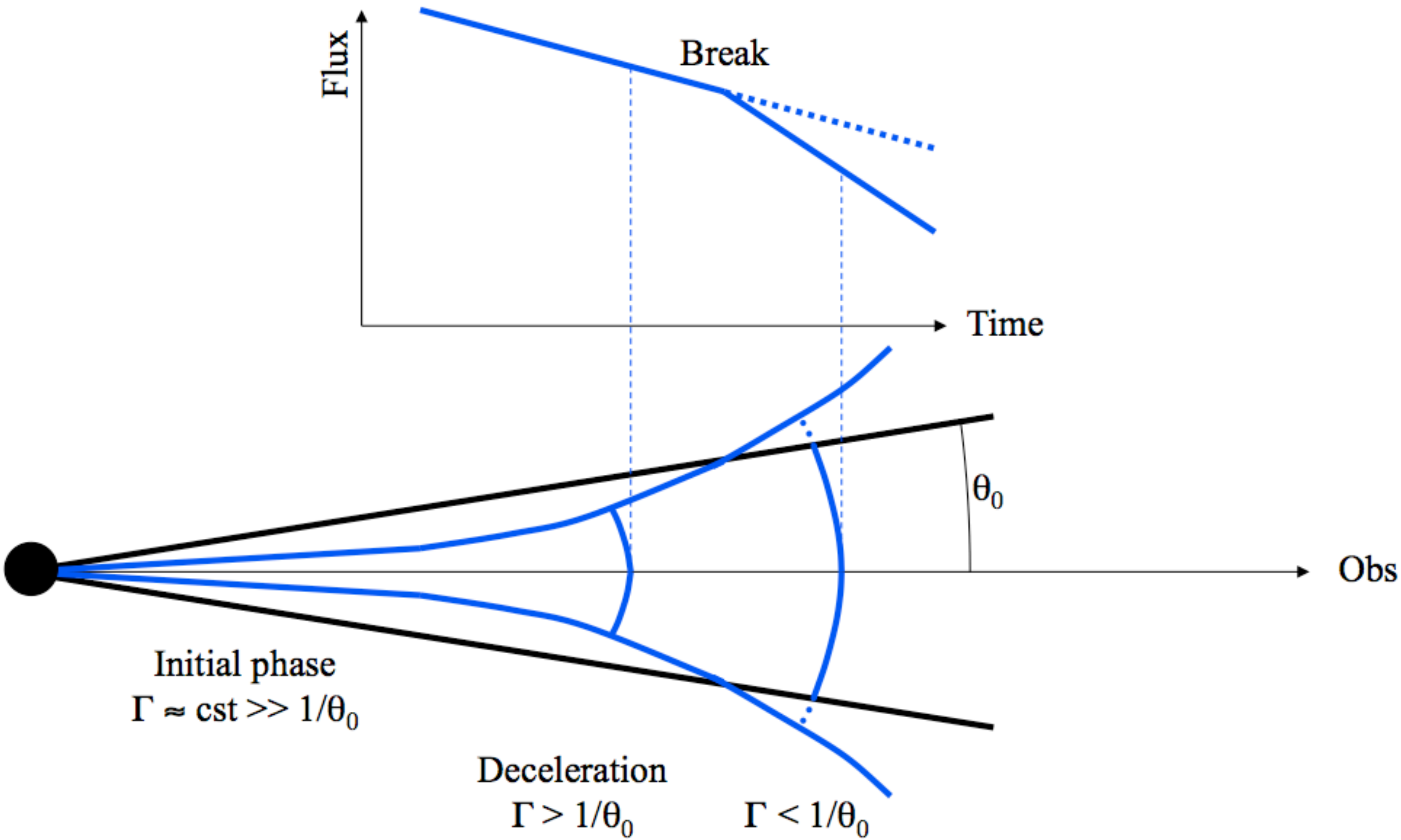


Afterglow

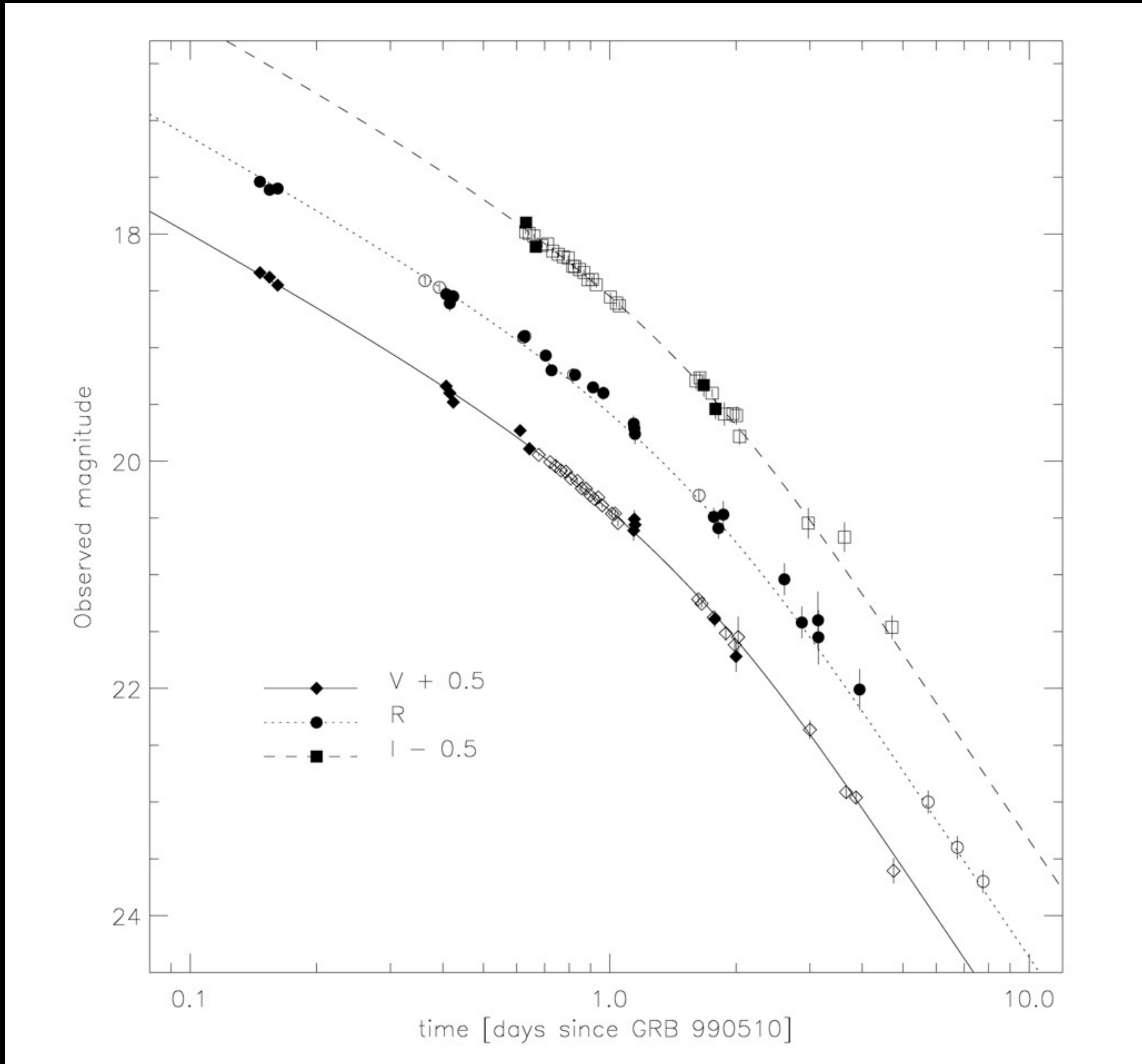


s = 0
s = 2
1 min
1 h
1 day
10 days
1 yr
100 yr
Deceleration radius
Blandford & McKee
Γ∝r^−1.5
Γ∝r^−0.5
Γ
Non-relativistic limit
Sedov
v ∝r^−1.5
v ∝r^−0.5
v / c
Log(r) (cm)

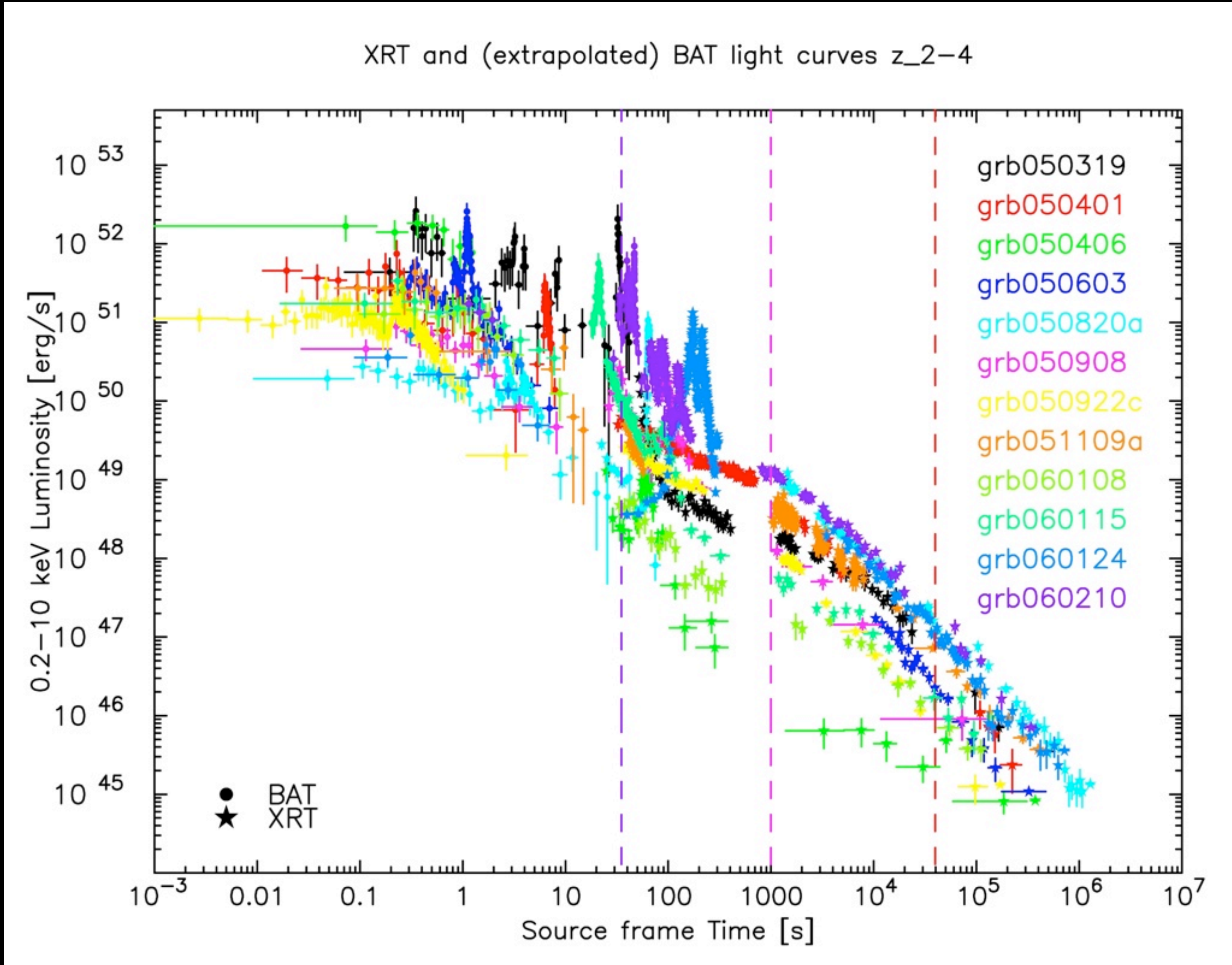
Achromatic jet break ?



Achromatic jet break ?



Complexity of the early X-ray afterglow (Swift) : un-predicted !



Afterglow

1. Seems to be the best understood part of the scenario (very natural : deceleration of the outflow, like in SNRs)

2. But Swift observations have revealed a complexity which was not predicted...

- Modifications of the ‘standard’ external shock model ?

  late energy injection (plateau), late activity of the source (flares)

  strong constraints on the central engine (energetics, lifetime) & the prompt emission mechanism (efficiency)

- Change of paradigm ?

  e.g. the afterglow (at least at early times) is dominated by a long-lived reverse shock
  it implies a tail of low Γ material + a radiatively inefficient forward shock (magnetized external medium ?)

One possible issue : the origin of the long lasting emission above 100 MeV detected in a few GRBs by Fermi-LAT

GRBs as cosmic accelerators

1. Outflow is made of leptons + hadrons
   (not a electron-positron jet)

2. Mildly or relativistic shocks are present
   (do they accelerate particles ?)
   or magnetic reconnection regions

3. Electrons are accelerated to high Lorentz factors
   (GeV emission detected by Fermi)

4. No evidence yet for proton acceleration
   (radiation too inefficient to contribute in LAT range)

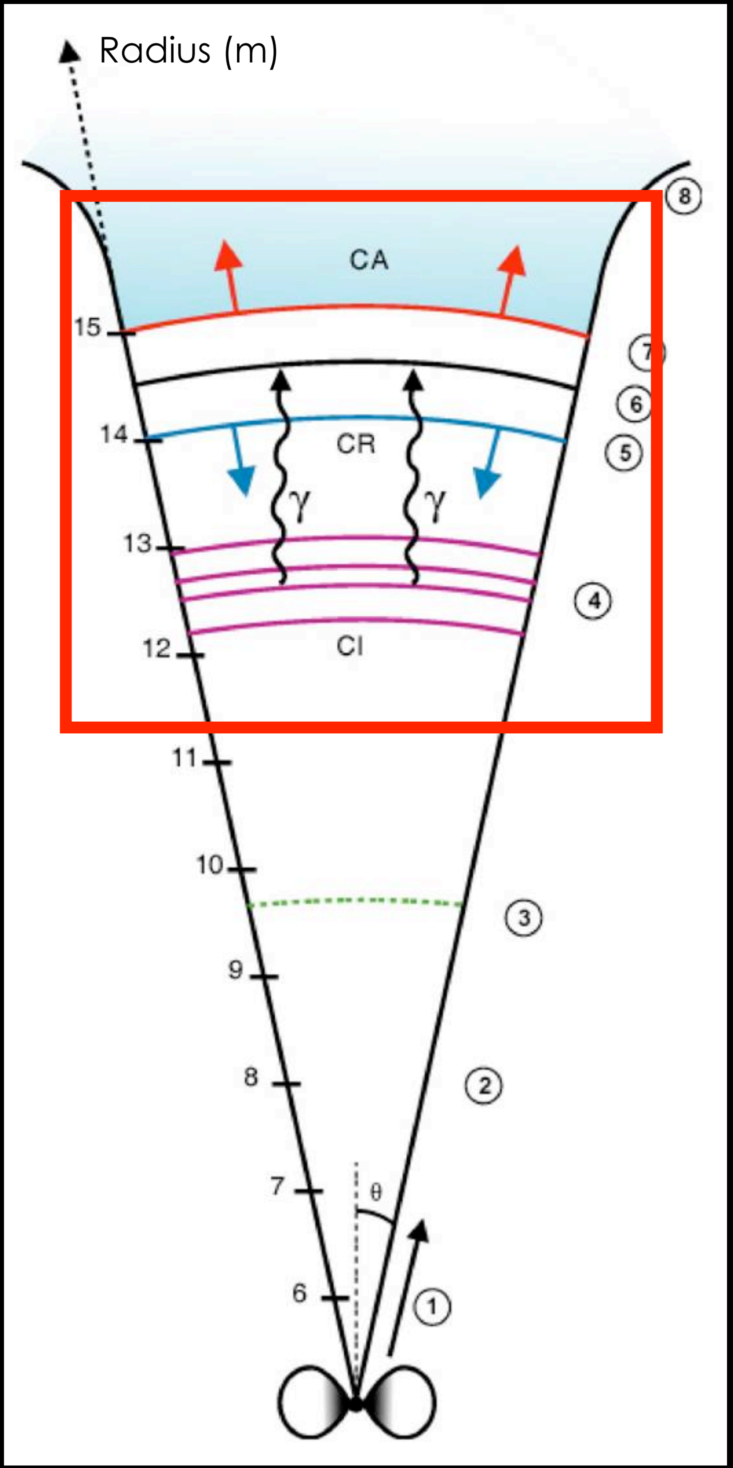
   TeV ?

5. If the same energy is deposited in accelerated protons and
   electrons : HE neutrino emission is expected

   (ICECUBE : sensitivity has reached the most optimistic models...)

   Note : this is the case even if protons are not accelerated above 10^{18} eV

6. Acceleration in relativistic shocks is highly uncertain but GRBs
   may have the capacity to acceleration hadrons above 10^{20} eV



Acceleration in relativistic shocks ?

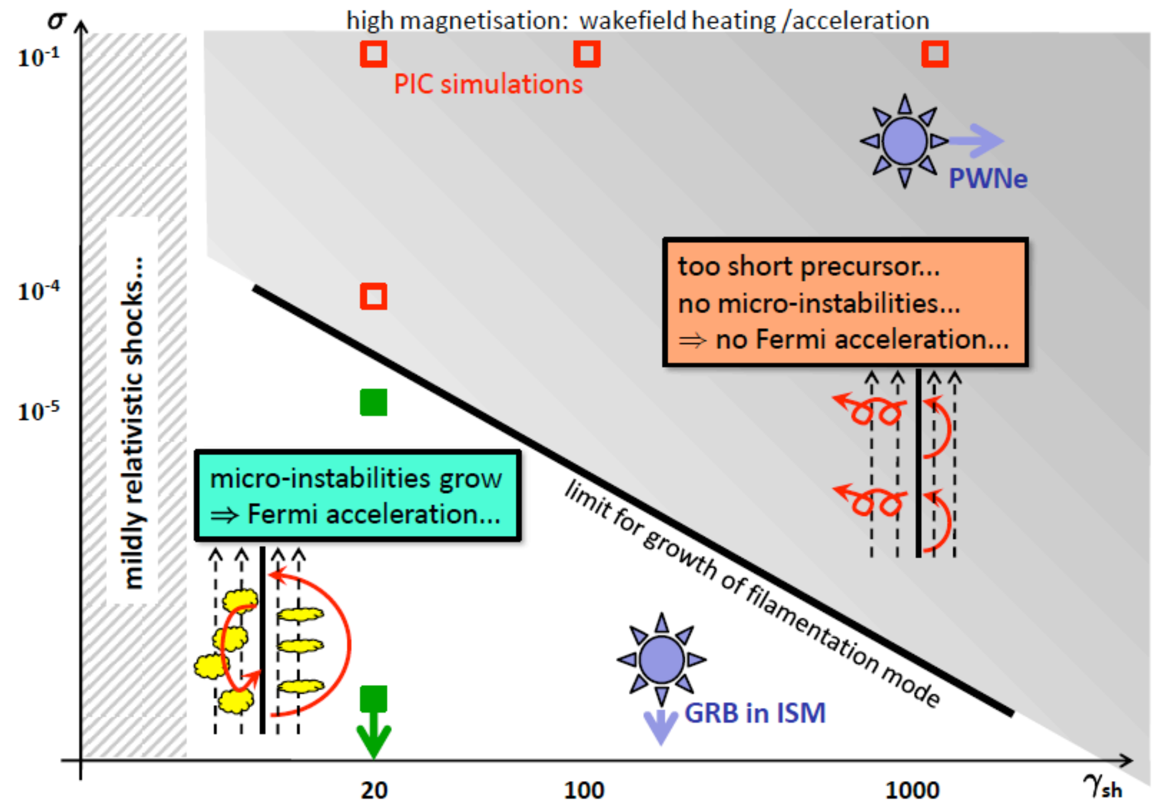


Figure 1: Parameter space for relativistic shocks with shock Lorentz factor $\gamma_{\rm sh}$ in abscissae and magnetization of the incoming plasma σ in ordinates. In the gray region, the precursor is too short to allow the growth of micro-instabilities by suprathermal particles, hence Fermi acceleration cannot take place (under the assumptions discussed in the text). The squares indicate the results of recent PIC simulations (Sironi & Spitkovsky 2011a), which validate where applicable, this model: empty squares indicate no evidence for particle acceleration while filled squares mean that powerlaw Fermi type acceleration has been observed. The region at low $\gamma_{\rm sh}$ corresponding to mildly relativistic shocks is yet unexplored. See Lemoine & Pelletier (2010) for a more detailed version of this figure.

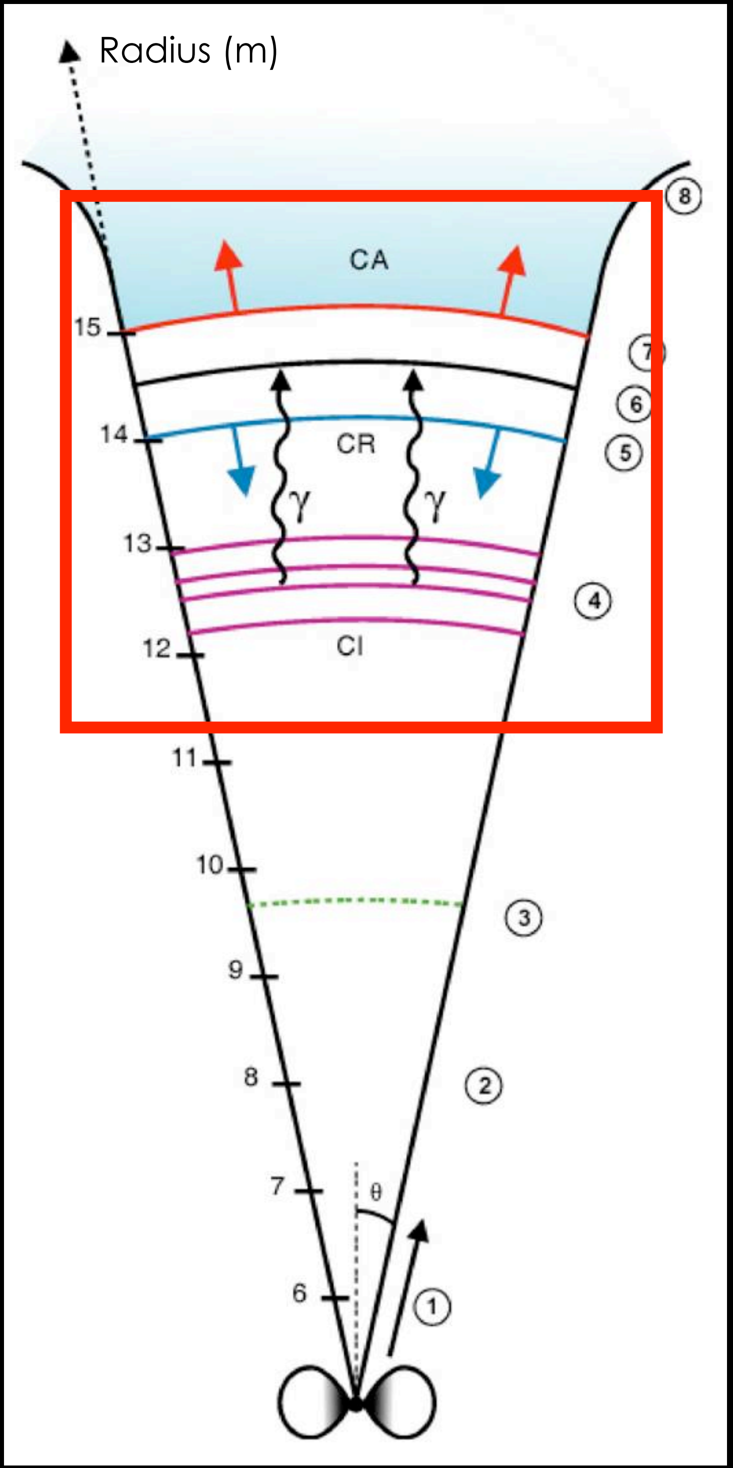
Lemoine & Pelletier 2011

GRBs as a source of HE neutrinos

1. Waxman & Bahcall estimate of the neutrino flux :

   based on the assumption that GRBs are the source of UHECRs (this gives the normalization)

2. Other estimates are even more model dependent



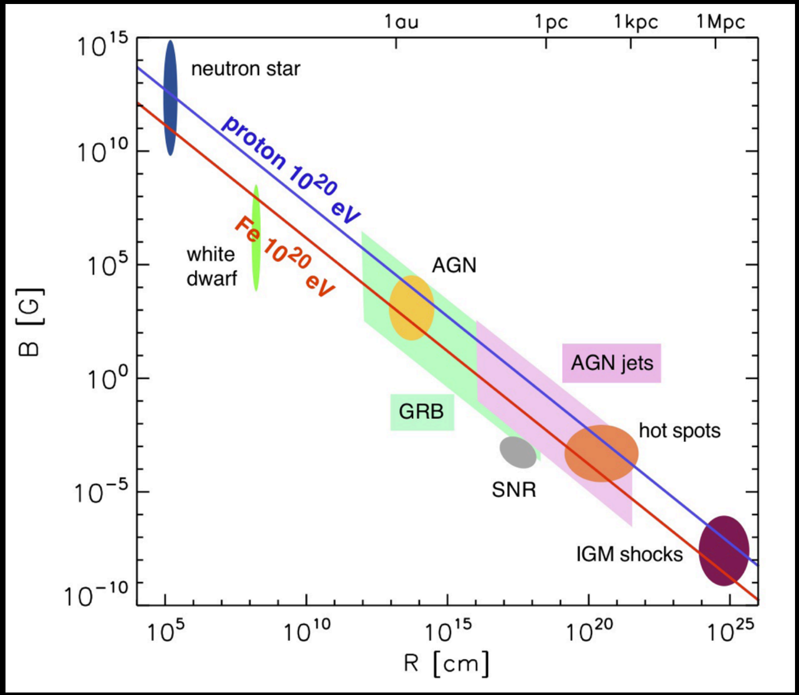
GRBs as the source of UHECRs ?

1. Energy : may be

- Simple criterion (Hillas) : $R_L < R$

- More refined criterion : $t_{acc} < \min(t_{loss}, t_{esc})$

  This implies an object by object study...



Kotera & Olinto 2011

- Acceleration in a relativistic outflow (from Lemoine & Waxman 09)

  - Acceleration time scale : $t_{acc} \sim A\, t_L$ with $A > 1$ [non relativistic Fermi 1 : $A \sim g / \beta_{sh}^2$ with $g \gtrsim 1$]
    (comoving frame) [Larmor time $t_L = E / Z e B c^2$]

  - Time available for acceleration : $t_{dyn} \sim R / \beta \Gamma c$
    (comoving frame)

  - Maximal energy : $t_{acc} < t_{dyn}$ leads to $E_{max} = A^{-1} Z e B R c / \beta$

  - 'Magnetic' luminosity of the source : $L_B = (4 \pi R^2)\ (\vartheta_j^2 / 2) \times (B^2 / 2 \mu_0) \times (\beta \Gamma^2 c)$

  - Minimum luminosity :

    $$L_{bol} > (2 \pi \vartheta_j^2) \times (A^2 \beta^3 \Gamma^2 Emax^2) / (2 \mu_0 Z^2 e^2 c) \sim 0.65\ 10^{38}\ \mathrm{W}\ (A^2 \beta^3 \Gamma^2 / Z^2)\ (Emax / 10^{20}\ \mathrm{eV})^2$$

    For reasonnable values of the parameters, one finds typically $L_{bol} > 10^{38}$ W / Z^2 :
    only most powerful AGNs (not Cen A : a factor 100 less bright) ; GRBs ; magnetars

GRBs as the source of UHECRs ?

1. Energy : may be

2. Composition : not so easy if heavy nuclei

3. Propagation ?

GZK cutoff expected (GRBs are at large distance)

The detected flux should be due to a few tens of events per ~ 10^4 yr within ~ 100 Mpc
(one source contribute for a long duration : dispersion in arrival times is large !)

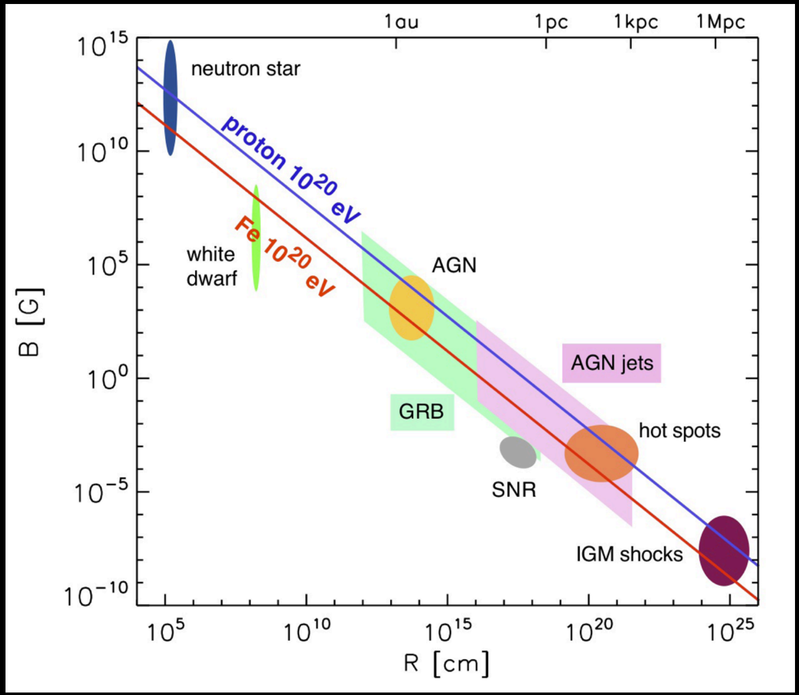
No counterpart should be seen
(rather the last scattering on a magnetized region)

Excess in Cen A : a lot of matter in this direction (including Cen supercluster)
The last few GRBs from this region could produce an excess

4. Rate ?

Local GRB rate is uncertain : difficult to constrain the fraction of energy that should be injected in UHECRs
(beaming ? role of low-L GRBs ?)

10^{46} J per GRB for 1 GRB per yr and per Gpc^3 ? difficult...



Kotera & Olinto 2011

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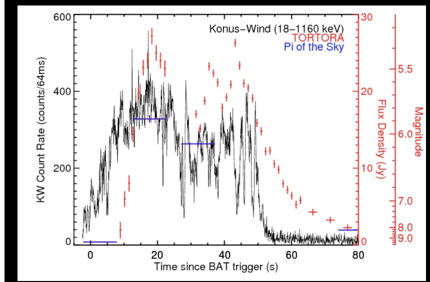

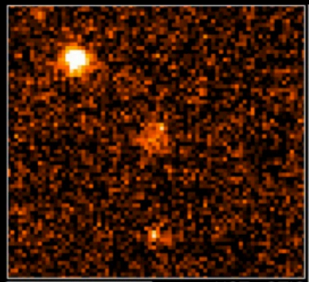
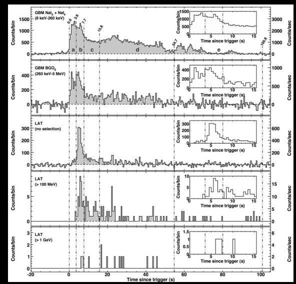
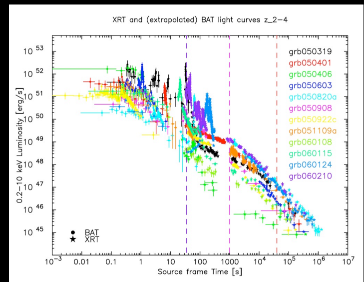

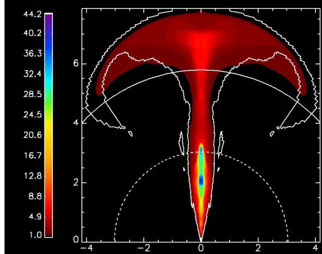

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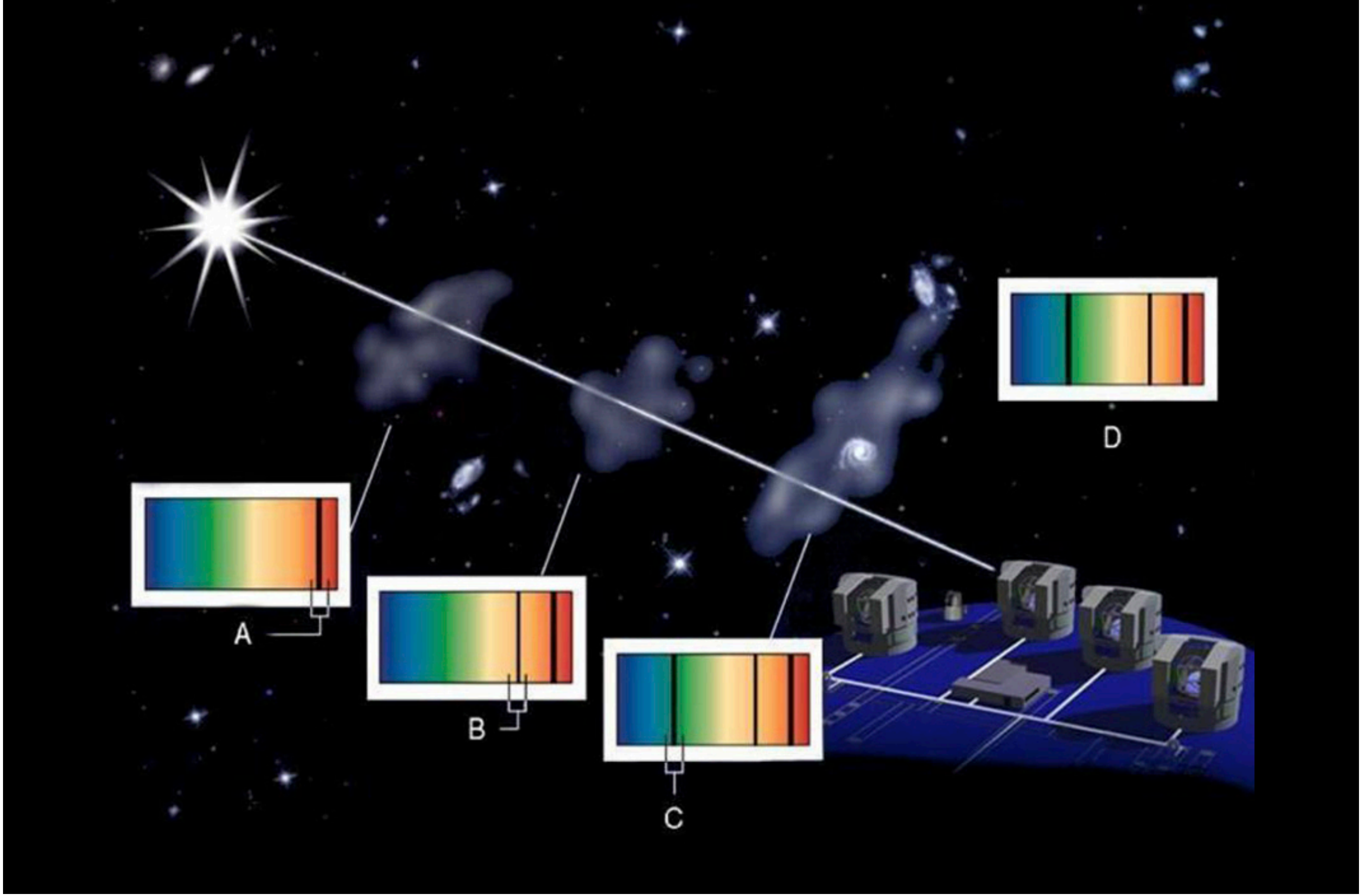
Gamma-ray bursts as a tool to probe the distant Universe



Many open questions

What are exactly the progenitors of GRBs ?
Long GRBs : conditions for a massive star to produce a GRB ?
(mass, metallicity, rotation, binarity, ...)
Short GRBs : how to prove the merger scenario ?

What is the nature of the centrale engine ? (accreting BH vs magnetar)

How is the outflow accelerated to relativistic speed ?

What is the dominant internal dissipation mechanism responsible for the prompt ?
(photosphere vs internal shocks vs magnetic reconnection)

What are the radiating particles ? the dominant processes ? (including at HE)

How is the outflow decelerated by the external medium ?

Can we expect TeV emission ?

What would we learn from GW detection ? (physics of the central engine)
What would we learn from HE neutrino detection ? (particle acceleration)

What is the maximum energy for the acceleration of hadrons ?
Can GRBs be the source of UHECRs ?
...

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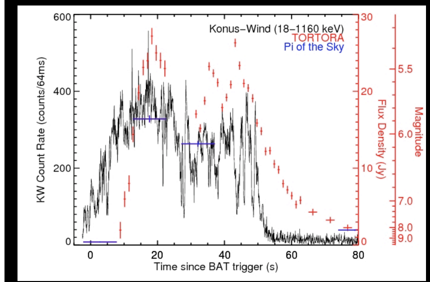
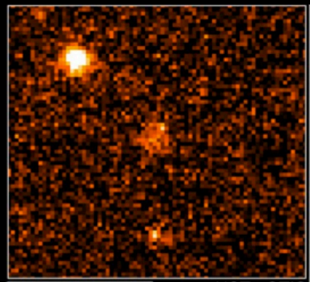
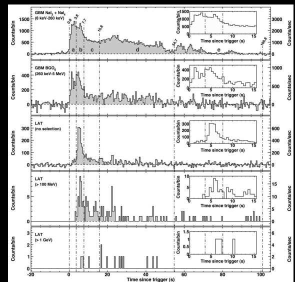
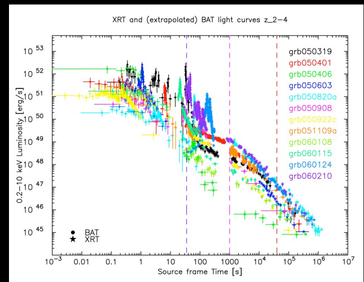
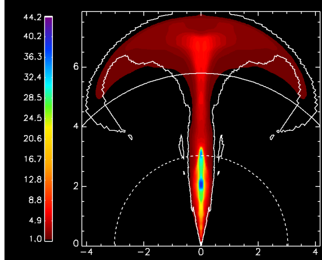

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