PULSARS AND PULSAR WIND NEBULAE

Lecture 1

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OUTLINE

LECTURE 1

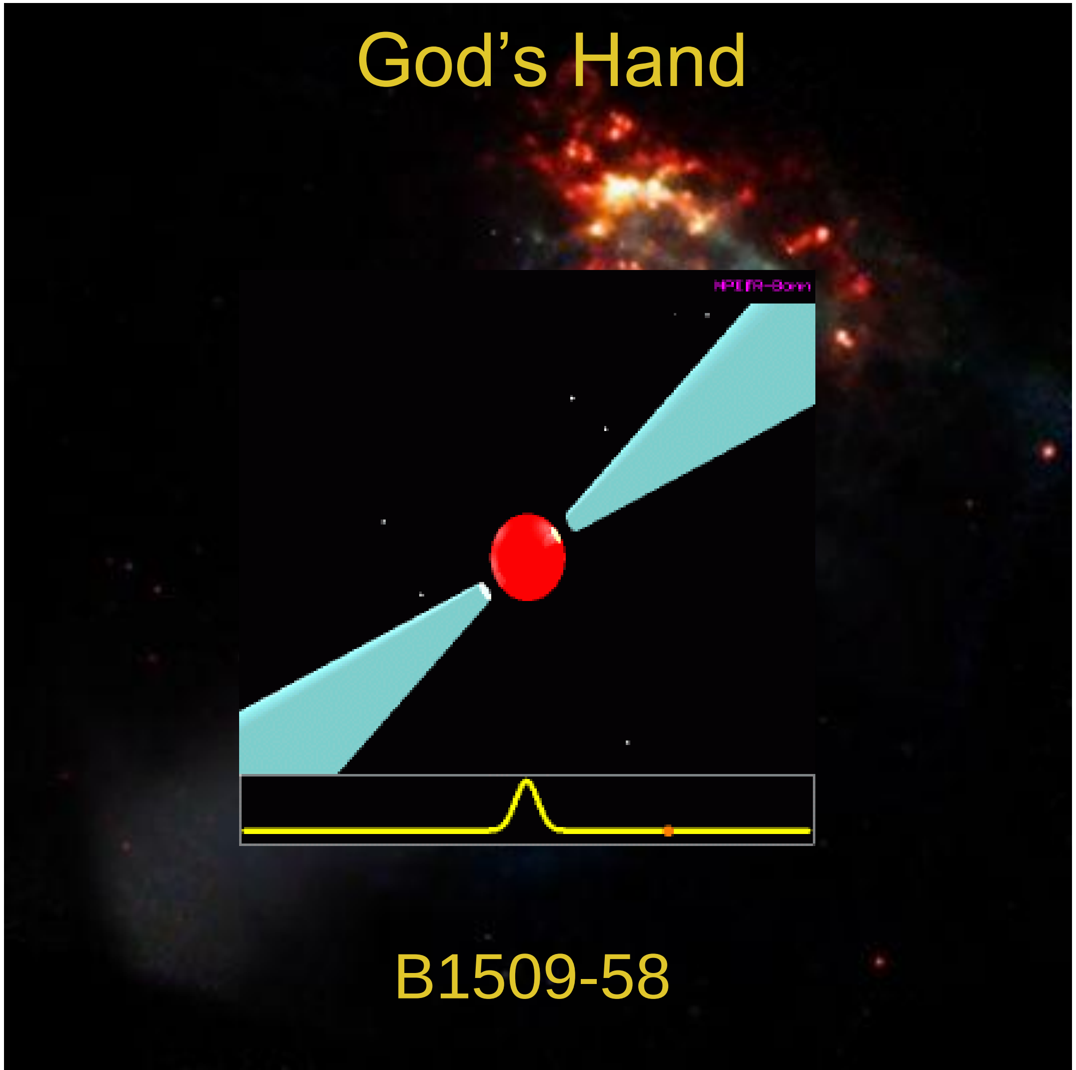
- INTEREST FOR ASTROPARTICLE PHYSICS
- PULSAR THEORY:
  - CHARGE EXTRACTION, PAIR PRODUCTION, FORMATION OF A WIND
  - GLOBAL ENERGY LOSSES, GAMMA-RAY EMISSION
  - LATEST ADVANCES AND CHALLENGES
- PULSAR WIND NEBULAE
  - BASIC INFERECES FROM SYNCHROTRON THEORY
  - EVOLUTIONARY ONE-ZONE MODELS
  - CHALLENGES

LECTURE 2

- MHD MODELING OF NEBULAE AND THEIR RADIATION
  - 1-D MHD MODELING
  - 2-D MHD MODELING
  - VARIABILITY
- PARTICLE ACCELERATION AT THE MOST RELATIVISTIC SHOCKS IN NATURE
- OLD NEBULAE, FAST PULSARS AND THE ELECTRON-POSITRON EXCESS IN COSMIC RAYS

INTRODUCTION

PULSAR WIND NEBULAE & PULSARS



WHY ARE PULSARS INTERESTING?

- ✓ MATTER IN EXTREME CONDITIONS
- ✓ BEST KNOWN COSMIC CLOCKS
- ✓ PRIMARY SOURCES OF ANTIMATTER IN THE GALAXY
- ✓ EXCELLENT LABS TO TEST GENERAL RELATIVITY
- ✓ AMONG THE FEW OBJECTS IN THE GALAXY WITH POTENTIAL DROPS IN EXCESS OF 1 PeV

WHY ARE PWNe INTERESTING?

- ✓ **They enclose most of the pulsar spin-down energy**: pulsed emission really is the tip of the iceberg
- ✓ **Best-suited laboratories for the physics of relativistic astrophysical plasmas:** close to c and close to us
- ✓ **Particle acceleration at the highest speed shocks in Nature** ($10^4 < \Gamma < 10^7$): a formidable challenge
- ✓ **As many positrons as electrons:** something to do with Pamela excess?
- ✓ **Only sources showing direct evidence for PeV particles**

THE PERFECT TIME TO STUDY THESE OBJECTS

HESS AND Fermi ERA

ENERGY RANGE: 100 GeV<E_γ<100 TeV

ANGULAR RESOLUTION: ~1’

Nobel Prize 1936

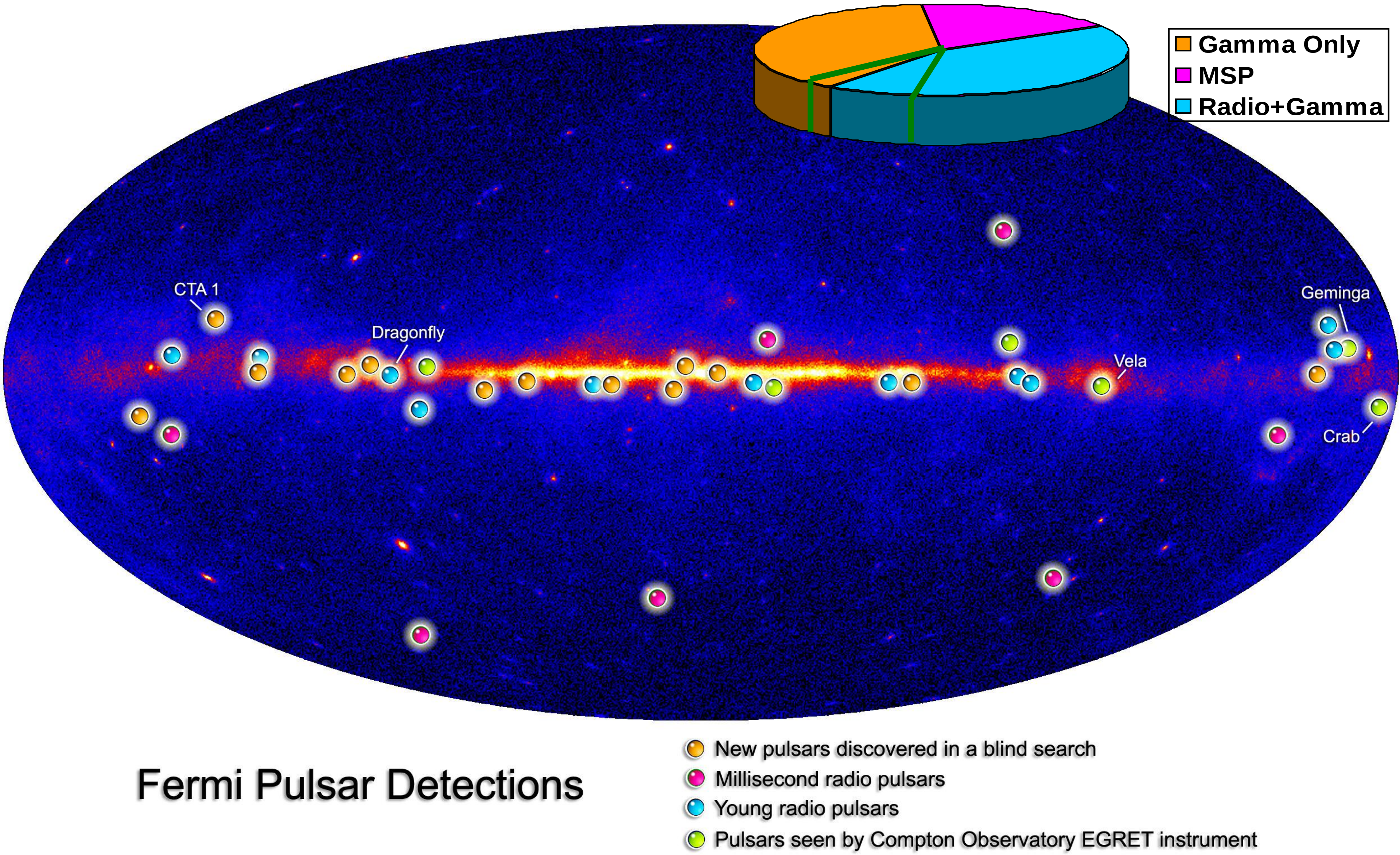
ENERGY RANGE:
100 MeV < E_γ<300 GeV

ANGULAR RESOLUTION:
~30’

THE GOLDEN AGE OF PSRs

γ-Ray Pulsars Known Before Fermi

with New *Fermi* LAT Pulsars



UPDATED….

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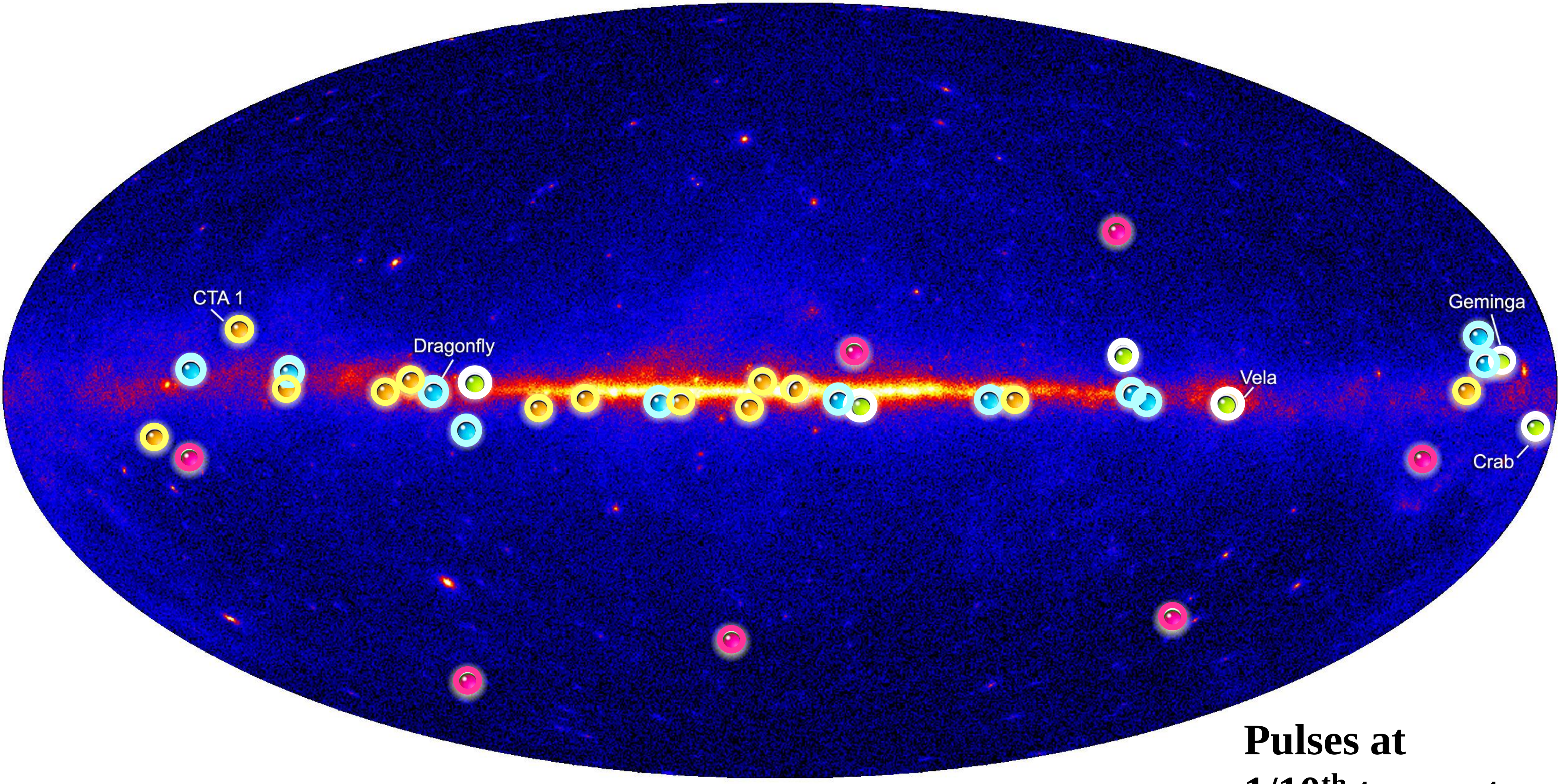
THE PULSING GeV SKY



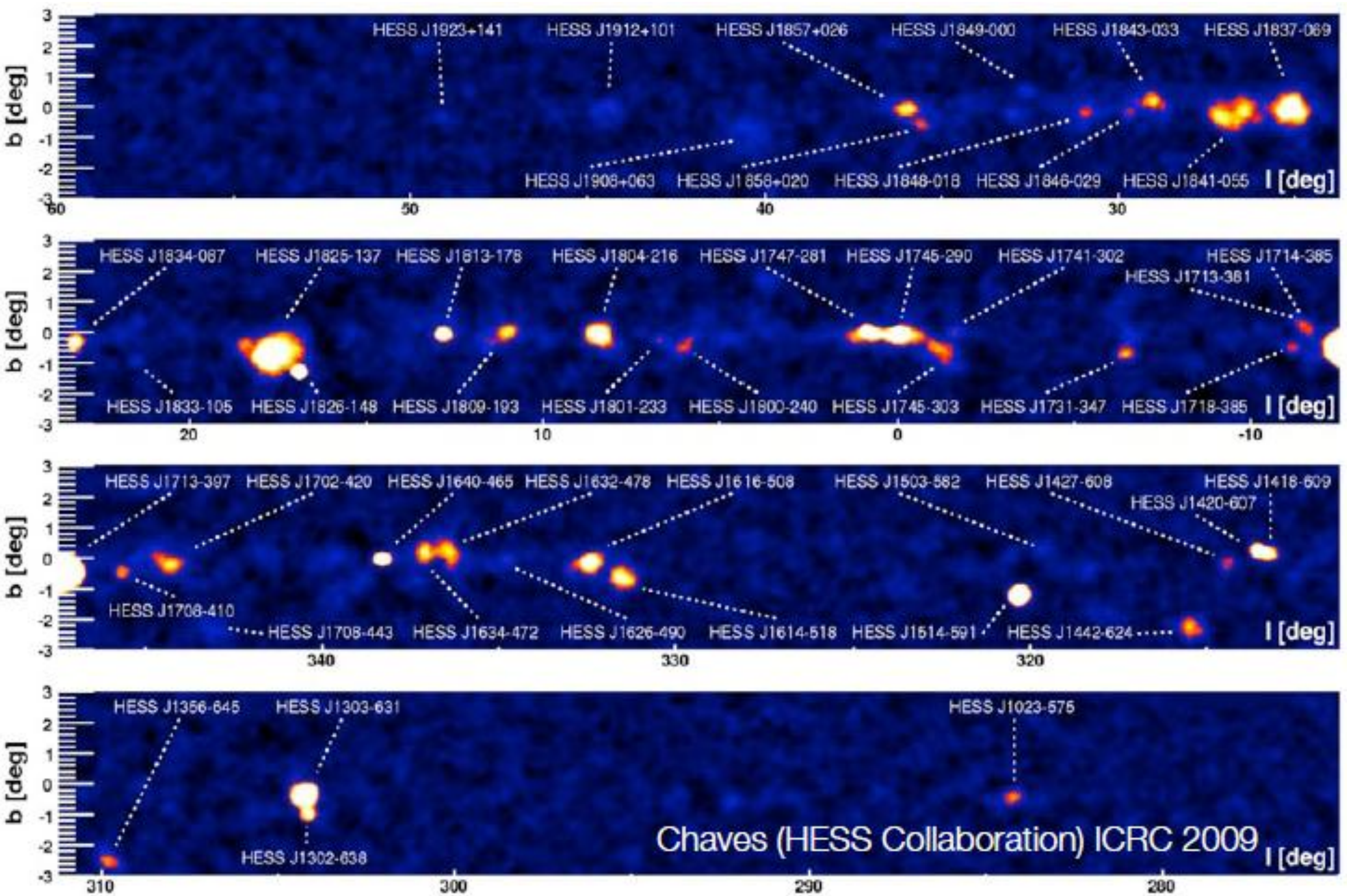
Pulses at $1/10^{th}$ true rate

Fermi Pulsar Detections

- New pulsars discovered in a blind search
- Millisecond radio pulsars
- Young radio pulsars
- Pulsars seen by Compton Observatory EGRET instrument

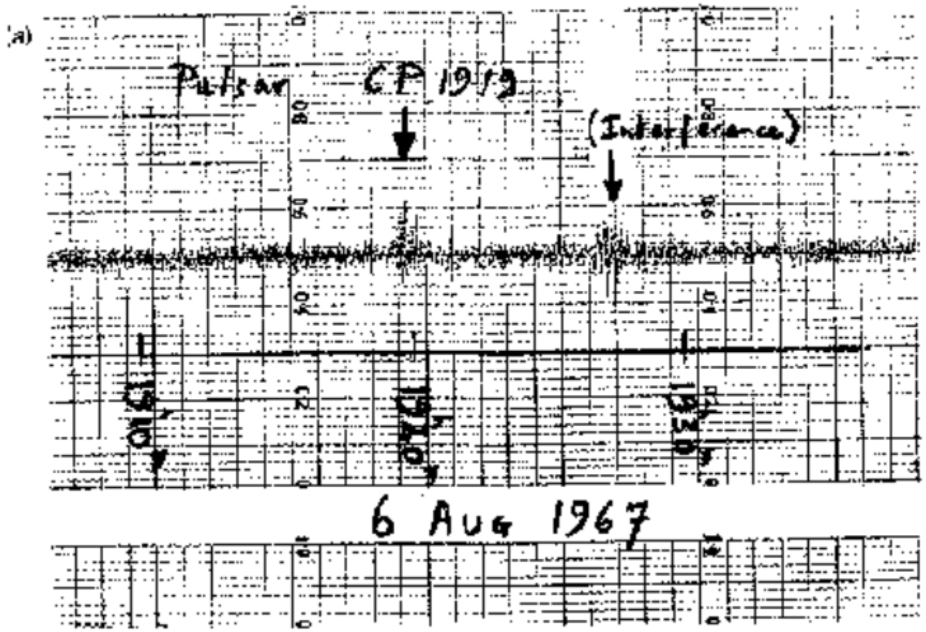
THE NEBULOUS TeV SKY

More than 1/2 of HESS sources associated with PWNe



PULSARS

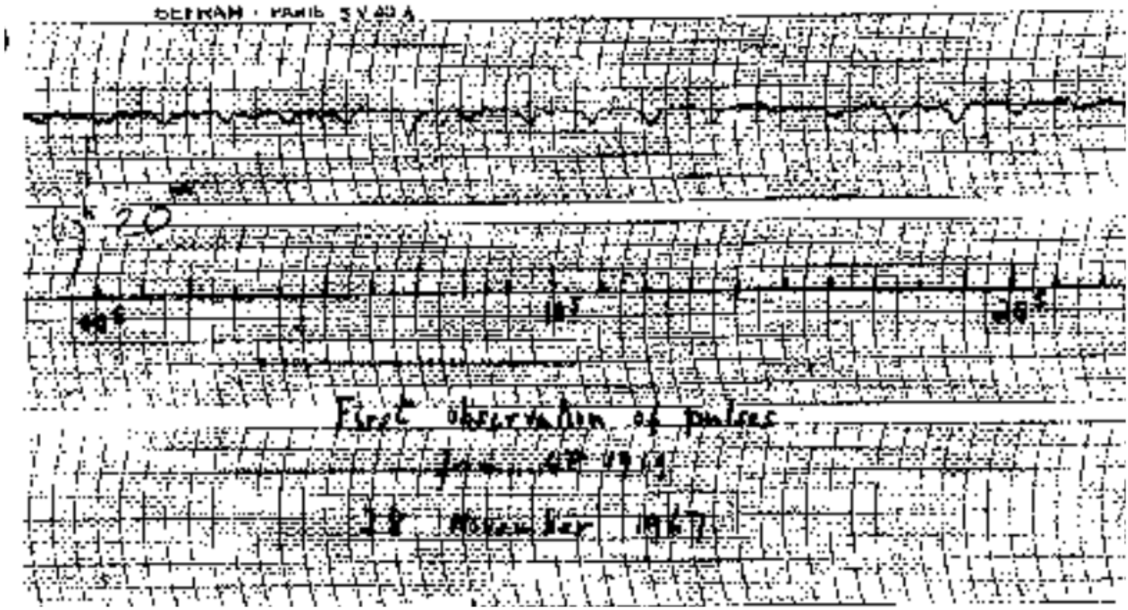
DISCOVERY



IMPULSE WITH P≈1.33S
LASTING ≈1/100 S…

D<cT POINTS TO
PLANET

WHITE DWARF?
TOO FAST!!!



NEUTRON STARS

PREDICTED IN THE '30s
(Baade & Zwicky)
AS FINAL PRODUCTS OF STELLAR COLLAPSE

$$R \approx 10\,km$$

$$\Omega R^2 = const \Rightarrow \Omega \approx 10^3\,Hz$$

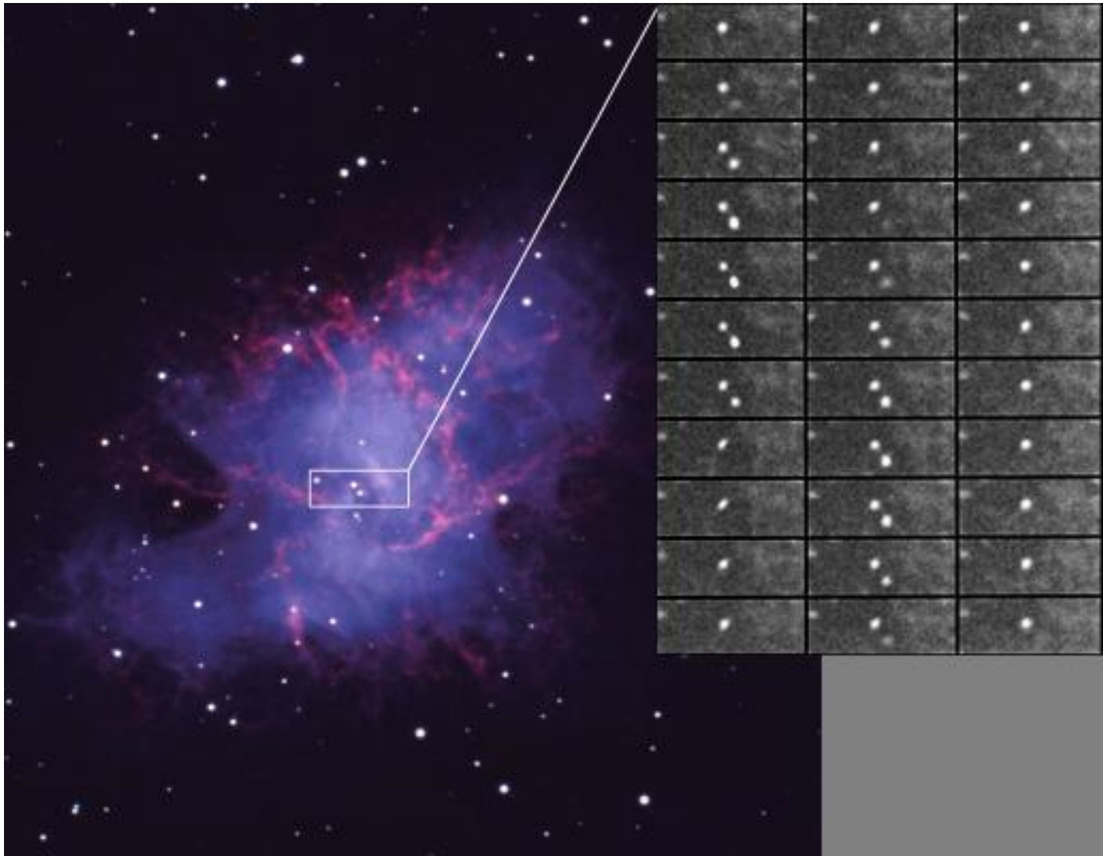
$$BR^2 = const \Rightarrow B \approx 10^{12}\,G$$

ASSOCIATION PROVEN!!!

CRAB PULSAR

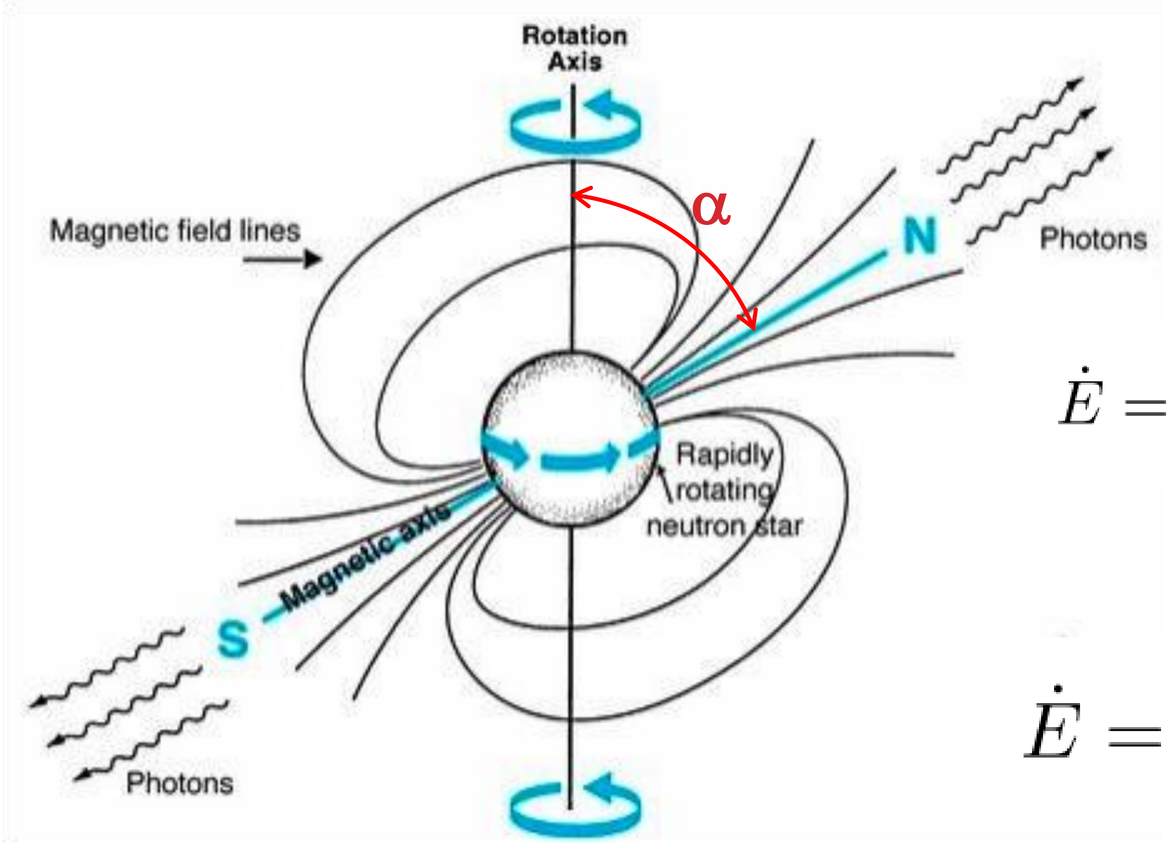
PREDICTED 1967 (Pacini)

DETECTED 1968
(Staelin & Reifenstein)



OBLIQUE ROTATING MAGNETIC DIPOLE

$$\vec{\mu} = \frac{B_* R_*^3}{2} \left[\sin\alpha \left(\cos\left(\Omega t\right)\hat{x} + \sin\left(\Omega t\right)\hat{y}\right) + \cos\alpha\,\hat{z}\right]$$



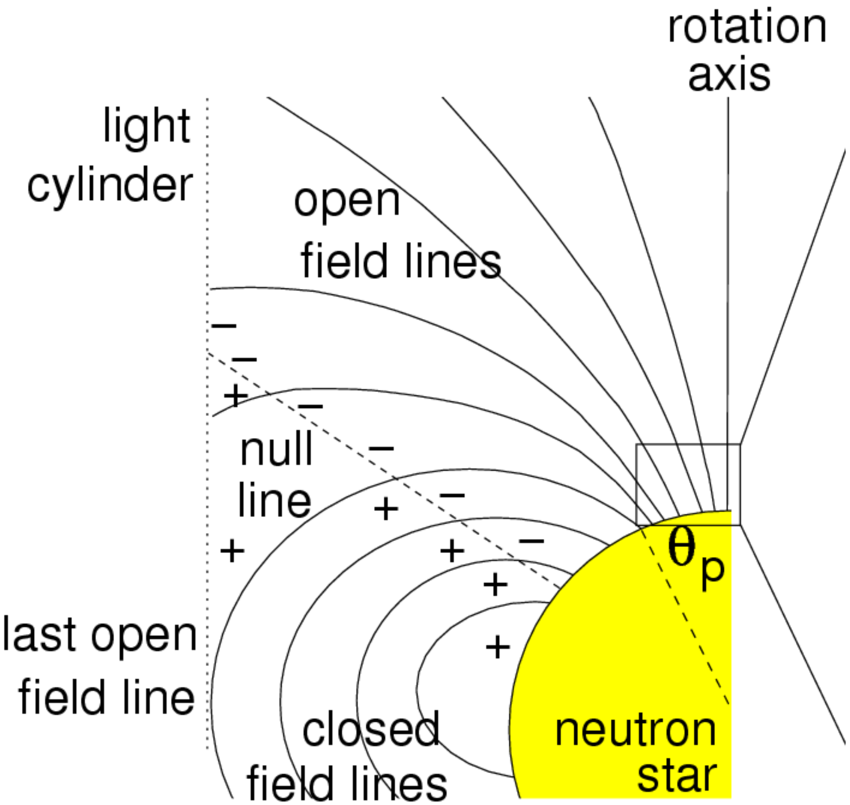
$$\frac{dE}{dt} = -\frac{2}{3c^3}\left|\frac{d^2\vec{\mu}}{dt^2}\right|^2$$

$$\dot{E} = -\frac{c}{6} B_*^2 R_*^2 \left(\frac{R_*\Omega}{c}\right)^4 \sin^2\alpha$$

$$\dot{E} = 10^{40}\ \frac{B_{12}^2}{P_{-3}{}^4}\ erg\ s^{-1}$$

THIS IS ALL IN VACUUM

NO VACUUM PHYSICS…



STAR IS AN EXCELLENT CONDUCTOR

$$\vec{E} + \frac{\vec{v}}{c} \times \vec{B} = 0$$

$$\vec{E}_{in} = -\left(\frac{\vec{\Omega} \times \vec{r}}{c}\right) \times \vec{B}$$

IF VACUUM OUTSIDE: $\nabla^2 \Phi = 0$

WHERE $\vec{E} = -\vec{\nabla}\Phi$

BOUNDARY CONDITION AT STAR SURFACE

$$E_\theta^{in}(R_*) = E_\theta^{out}(R_*)$$

$\Phi \rightarrow \vec{E}$ $\qquad \left(E_r^{out} - E_r^{in}\right)_{R_*} = 4\pi\sigma \neq 0$ FINITE SURFACE CHARGE DENSITY

$(\vec{E} \cdot \vec{B})_{R_*} \neq 0$ $\qquad eE_{\|} = e\frac{B_* \Omega R_*}{c} \cos^2 \theta$

AND A LARGE FIELD TO EXTRACT IT

$$\frac{eE_{\|}}{GM_* m / R_*^2} = 8 \times 10^{12} \frac{B_{12}}{P_{100}}$$

THE GOLDREICH AND JULIAN MAGNETOSPHERE…

CHARGES EXTRACTED UNTIL E-FIELD CONTINUOUS AT STAR SURFACE
(Goldreich & Julian, 1969)

THE PULSAR DEVELOPS A COROTATING MAGNETOSPHERE

$$\vec{E} = -\frac{\Omega r \sin\theta}{c}\mathbf{e}_\phi \times \vec{B}$$

THROUGHOUT COROTATION REGION

QuickTime™ and a
decompressor
are needed to see this picture.

COROTATION ONLY POSSIBLE UNTIL v<c

LIGHT CYLINDER

$$R_L = \frac{c}{\Omega} = 5 \times 10^8 P_{100} cm$$

CHARGE DISTRIBUTION

$$\vec{B} = \frac{B_* R_*^3}{r^3}\left[\cos\theta \mathbf{e}_r + \frac{\sin\theta}{2}\mathbf{e}_\theta\right]$$

$$\vec{E} = -\frac{\Omega r \sin\theta}{c}\mathbf{e}_\phi \times \vec{B}$$

CHARGE DENSITY?

$$\rho_{\mathrm{GJ}} = \frac{\vec{\nabla}\cdot\vec{E}}{4\pi} = -\frac{\vec{\Omega}\cdot\vec{B}}{2\pi c}\frac{1}{\left[1 - \frac{\Omega^2 r^2}{c^2}\sin^2\theta\right]}$$

ρ_{GJ} CHANGES SIGN WHERE

$$\vec{\Omega}\cdot\vec{B} = 0 \Rightarrow \cos\theta_q = \frac{1}{3}$$

LAST CLOSED FIELD LINE TANGENT TO R_{LC} AT THE EQUATOR

$$\frac{dr}{r\ d\theta} = \frac{B_\theta}{B_r}$$

$$r(\theta) = R_* \frac{\sin^2\theta}{\sin^2\theta_*}$$

$$\theta_{pc} = \sqrt{\frac{R_*}{R_{LC}}}$$

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decompressor
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THE WIND ZONE

$$J_{GJ} = c\rho_{GJ} = \frac{\vec{\Omega}\cdot\vec{B}}{2\pi}$$

ACTS AS SOURCE OF TOROIDAL FIELD: B_T COMPARABLE TO B_P AT THE LIGHT CYLINDER

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AT LARGER DISTANCES FIELD LINES ARE OPEN: B_P MONOPOLE LIKE

$$B_p = B_r = B_{LC}\left(\frac{R_{LC}}{r}\right)^2$$

$$B_\phi = \pm B_{LC}\left(\frac{R_{LC}}{r}\right)\sin\theta$$

TOROIDAL FIELD BECOMES DOMINANT

$$\dot{E} = \frac{c}{4\pi}4\pi R_{LC}^2\left(\vec{E}\times\vec{B}\right)_{R_{LC}} = cR_{LC}^2 B_{LC}^2$$

$$\dot{E} = cB_*^2 R_*^2\left(\frac{R_*^4\Omega^4}{c^4}\right)$$

~SAME AS FOR OBLIQUE DIPOLE IN VACUUM

PULSAR SPIN DOWN

$$\dot{E} = -\frac{c}{6} B_*^2 R_*^2 \left(\frac{R_* \Omega}{c} \right)^4 \sin^2 \alpha \qquad \dot{E} = c B_*^2 R_*^2 \left(\frac{R_*^4 \Omega^4}{c^4} \right)$$

$$\dot{E} = I \Omega \dot{\Omega} = -a \Omega^4$$

MORE GENERALLY: $\dot{\Omega} = -a\Omega^n \qquad \dot{E} = I\Omega\dot{\Omega} = aI\Omega^{n+1}$

AFTER INTEGRATION $\Omega(t) = \dfrac{\Omega_0}{[1 + t/\tau_0]^{1/(n-1)}} \qquad \tau_0 = \dfrac{\Omega_0^{1-n}}{a(n-1)}$

$$\Rightarrow \dot{E} = \frac{aI\Omega_0^{n+1}}{[1 + t/\tau_0]^{\frac{n+1}{n-1}}}$$

n=BRAKING INDEX.
n=3 FOR A DIPOLE FIELD
AND <3 FOR OTHER CASES

DERIVING n IMPLIES MEASURING d^2P/dt^2
MEASURED FOR 4 PSRs ONLY: ALWAYS LESS THAN 3!!!!

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decompressor
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P-Pdot DIAGRAM

PULSAR CHARACTERISTIC AGE

$$\tau = \frac{P}{2\dot{P}}$$

MORE CORRECTLY

$$\tau = \frac{P_0}{(n-1)\dot{P}_0}$$

ALSO

$$I\Omega\dot{\Omega} = \frac{B_*^2 R_*^6}{c^3}\Omega^4$$

PROVIDES A MEASURE OF B_*

POTENTIAL DIFFERENCE

$$\theta_{pc} = \sqrt{\frac{R_*}{R_{LC}}} \qquad \vec{B} = \frac{B_* R_*^3}{r^3}\left[\cos\theta \mathbf{e}_r + \frac{\sin\theta}{2}\mathbf{e}_\theta\right] \qquad \vec{E} = -\frac{\Omega r \sin\theta}{c}\mathbf{e}_\phi \times \vec{B}$$

$$\Phi = \int_{cap} \vec{E}\cdot d\vec{l} = \int_0^{\theta_0} E_\theta r d\theta = \frac{1}{2}\left(\frac{\Omega R_*}{c}\right)^2 R_* B_*$$

$$\boxed{E_{max} = e\Phi = 2\times 10^{15}\frac{B_{12}}{P_{100}^2} eV}$$

UNSCREENED POTENTIAL ⇒ ACCELERATION TO E»"KNEE"

IN CRAB $E_{max} \approx 60$ PeV

FOR PSRs Φ IS MEASURED DIRECTLY:

$$\Phi = \frac{1}{2}\left(\frac{\Omega R_*}{c}\right)^2 R_* B_*$$

$$\dot{E} = c B_*^2 R_*^2 \left(\frac{R_*^4 \Omega^4}{c^4}\right)$$

$$\Rightarrow \Phi = \sqrt{\dot{E}/c}$$

$$\dot{E} = I\Omega\dot{\Omega} = 4\pi I \frac{\dot{P}}{P^3}$$

P-Pdot DIAGRAM

$$\dot{E} = I\Omega\dot{\Omega} = 4\pi I \frac{\dot{P}}{P^3}$$

$$\Phi = \sqrt{\dot{E}/c}$$

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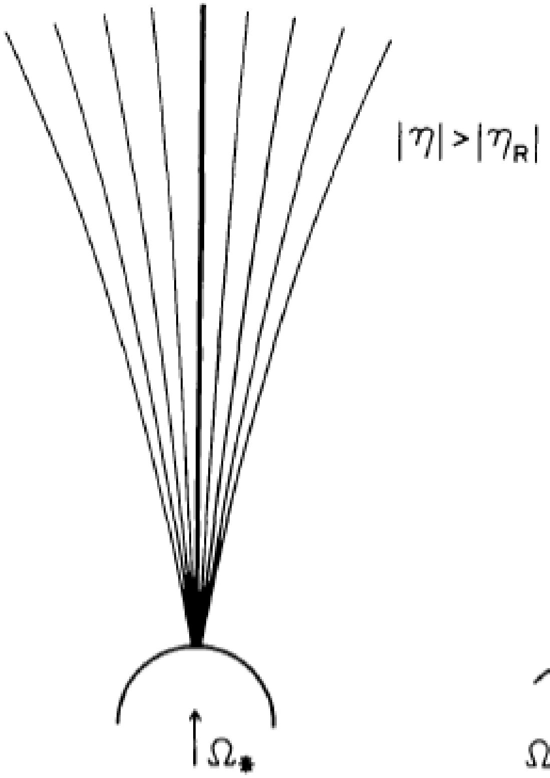
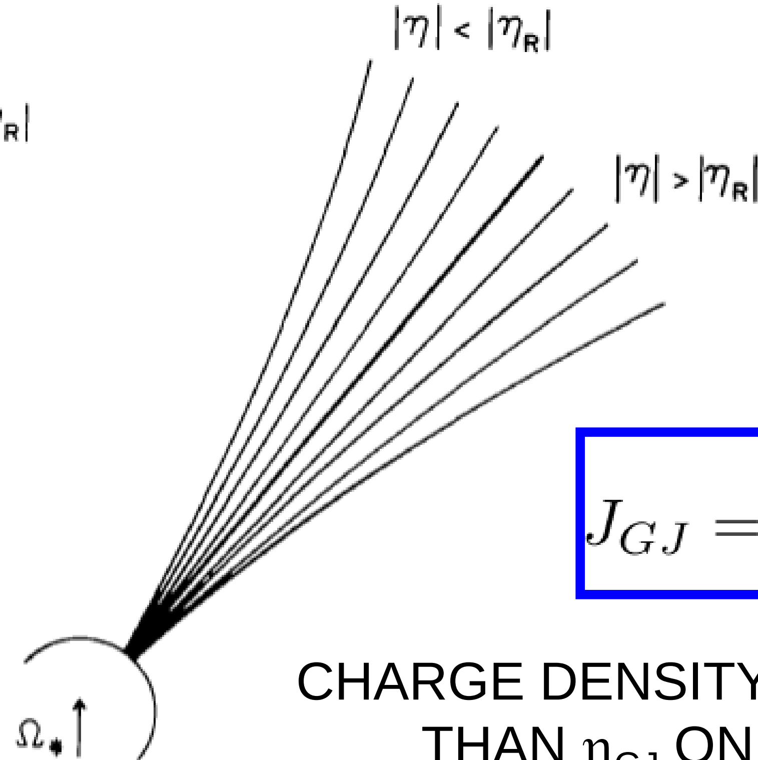
decompressor
are needed to see this picture.

$$\Phi = \sqrt{\frac{4\pi^2 I}{c} \frac{\dot{P}}{P^3}}$$

$$e\Phi = 300\ TeV\ \sqrt{\frac{I_{45}\dot{P}_{-15}}{P_{100}^3}}$$

CHARGE-SEPARATED FLOW?





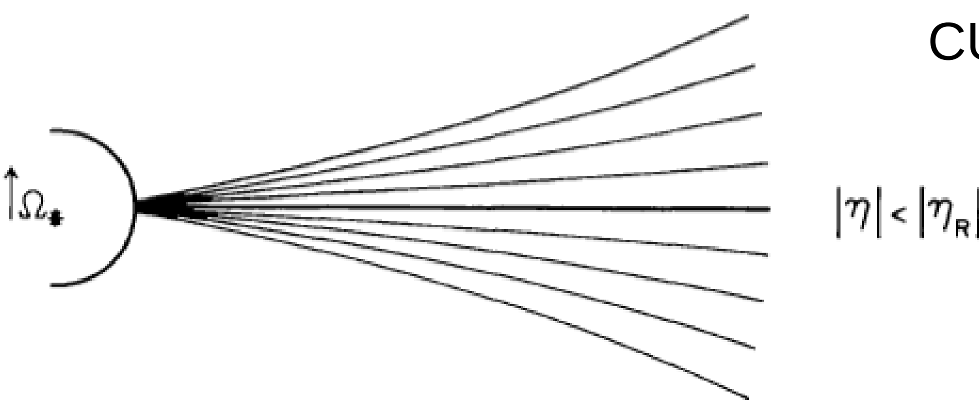
NOT FOR LONG!

$$J_* = \eta^*_{GJ}\, c$$

$$\boxed{J = J_* \frac{B}{B_*} \propto B}$$

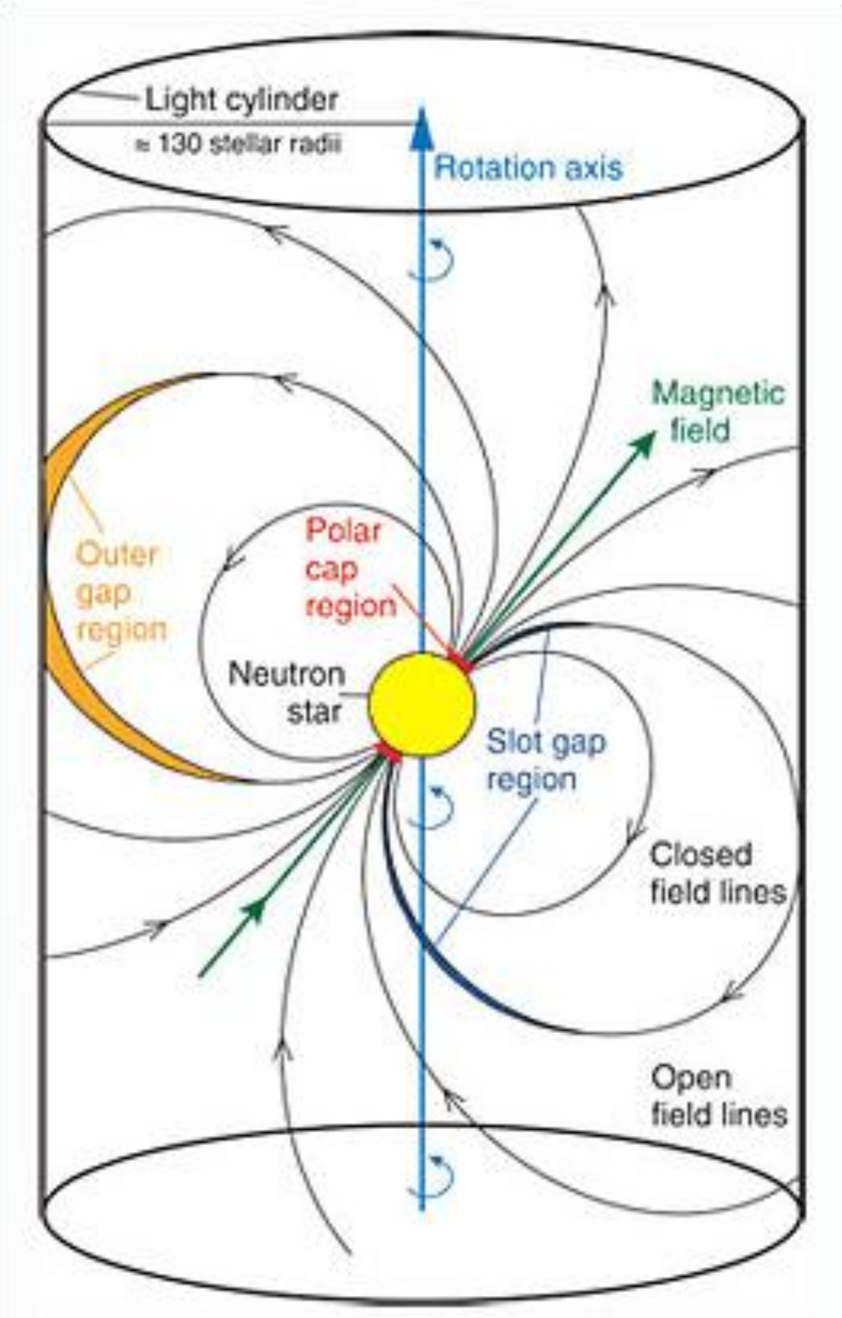
$$\boxed{J_{GJ} = c\eta_{GJ} = \frac{\vec{\Omega}\cdot\vec{B}}{2\pi} \propto B_z}$$

CHARGE DENSITY IS (SMALLER) LARGER THAN η_{GJ} ON (UN)FAVOURABLY CURVED FIELD LINES



EITHER VACUUM
OR SPACE-CHARGE
LIMITED GAPS CREATE

PAIR PRODUCTION SITES



POLAR CAPS

CLOSE TO STAR
UNSCREENED
$E_{//}$ DUE TO FIELD LINE CURVATURE
VACUUM OR SCL

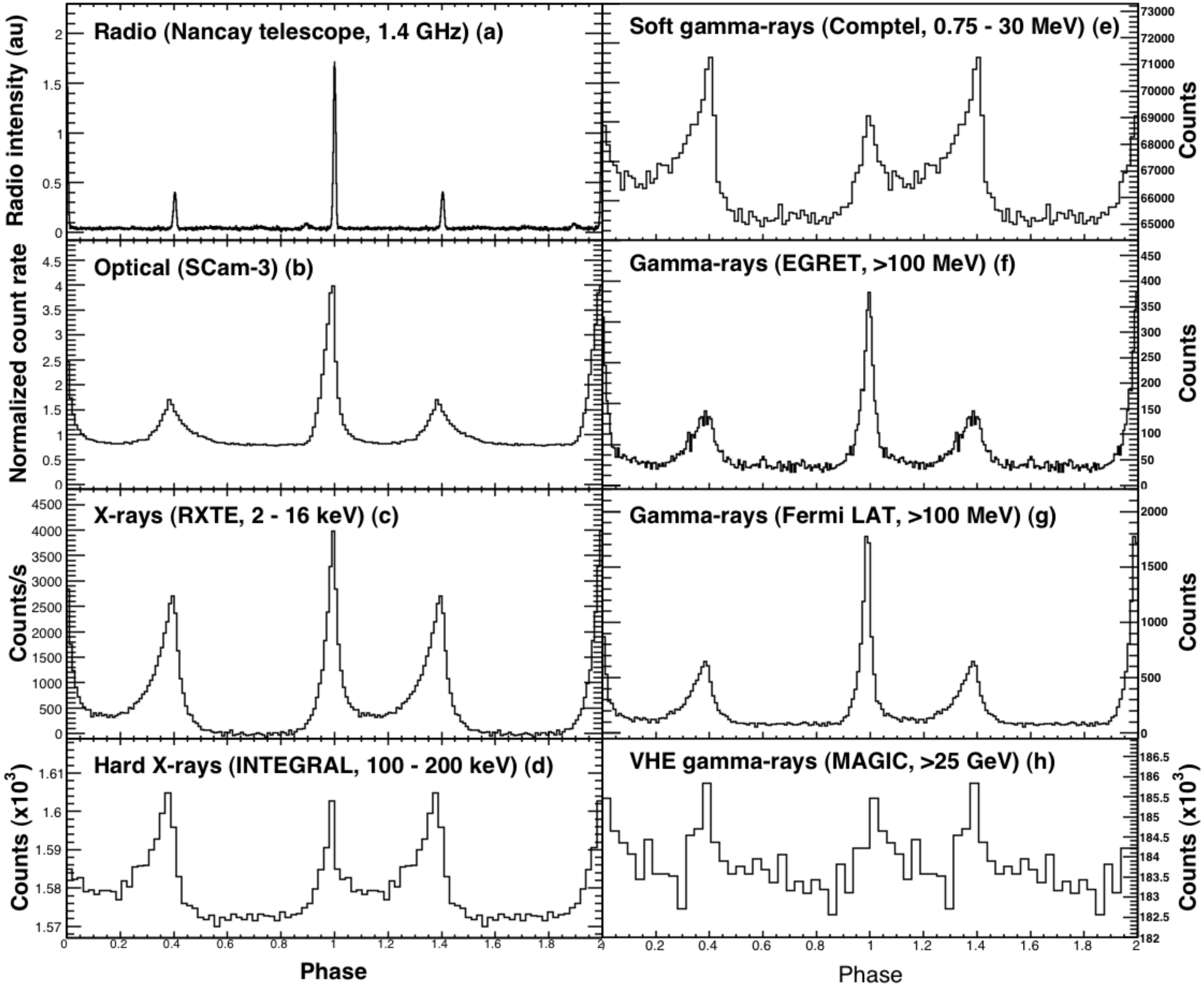
SLOT GAPS

SAME BUT ON POLAR CAP BOUNDARY $\Rightarrow$ MORE EXTENDED

OUTER GAPS

ALONG LAST CLOSED FIELD LINE AT R_{LC}

PULSAR EMISSION AT DIFFERENT ENERGIES



FERMI GAMMAS RESEMBLE OPTICAL

VHE GAMMA RESEMBLE HARD X-RAYS

ORIGIN OF RADIATION
AT DIFFERENT ENERGIES

EGRET
PULSARS

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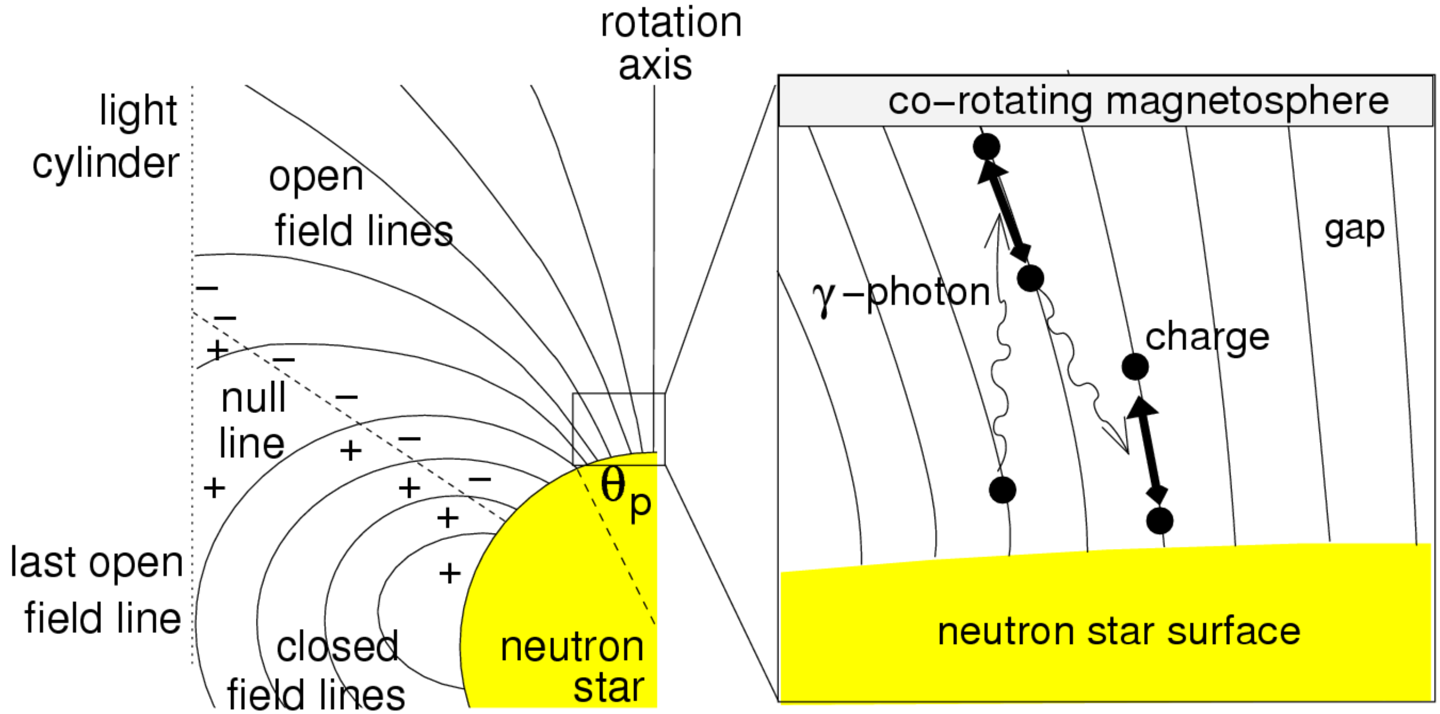
RADIO: COHERENT FROM POLAR CAP

FROM OPTICAL TO GAMMA-RAYS: CURVATURE FROM FURTHER OUT

POLAR CAPS



VACUUM GAPS (Ruderman & Sutherland 75, ….) $|\eta-\eta_{GJ}|\approx\eta_{GJ}$
SPACE-CHARGE LIMITED (Arons & Scharlemann 79,…) $|\eta-\eta_{GJ}|<<\eta_{GJ}$

e^- ⇨ Curvature or ICS on star X-rays ⇨ γ ($E\gamma$>50 MeV) ⇨ $\gamma+B\rightarrow e^++e^-$

$\gamma_{primary}\sim10^7$ $\gamma_{secondary}\sim10^{2-3}$

HARD γ-RAY SPECTRA: $E^{-1.5/-2}$ WITH SUPERXP. CUTOFF AT FEW GeV

PAIR MULTIPLICITY: $\kappa\approx10^3$-10^4

FERMI RESULTS

THE CRAB PULSAR SPECTRUM

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POLAR CAPS EXCLUDED!
EXTENDED EMISSION FROM UP TO
A FEW R_* REQUIRED

SLOT GAPS

VELA LIGHT-CURVE

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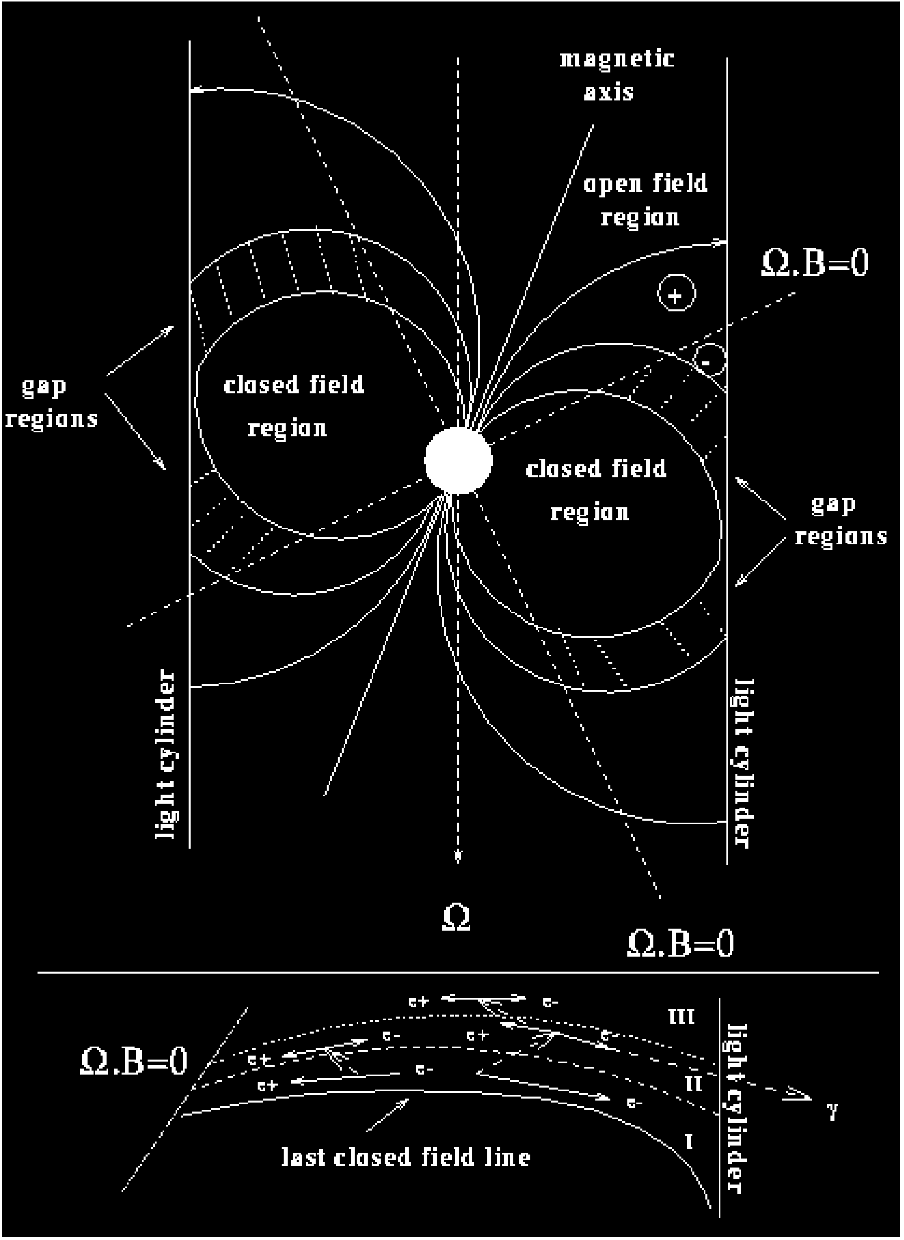
ALTITUDE OF PFF VARIES WITH
MAGNETIC COLATITUDE (Arons 83):

$E_{//}$ DECREASES TOWARDS RIM$\Rightarrow$
$\Rightarrow$PFF AT LARGER DISTANCE

SPECIAL RELATIVISTIC EFFECTS
LEAD TO **CAUSTICS** (Dyks & Rudack 03)

CUTOFF IS EXPONENTIAL



OUTER GAPS

TPC

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VELA

Romani & Watters 10

OUTER GAP

$|\eta-\eta_{GJ}|\approx\eta_{GJ}$

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(Cheng, Ho, Ruderman 86; Hirotani, Romani…)

- EXPONENTIAL CUTOFF
- MULTIPLICITY?

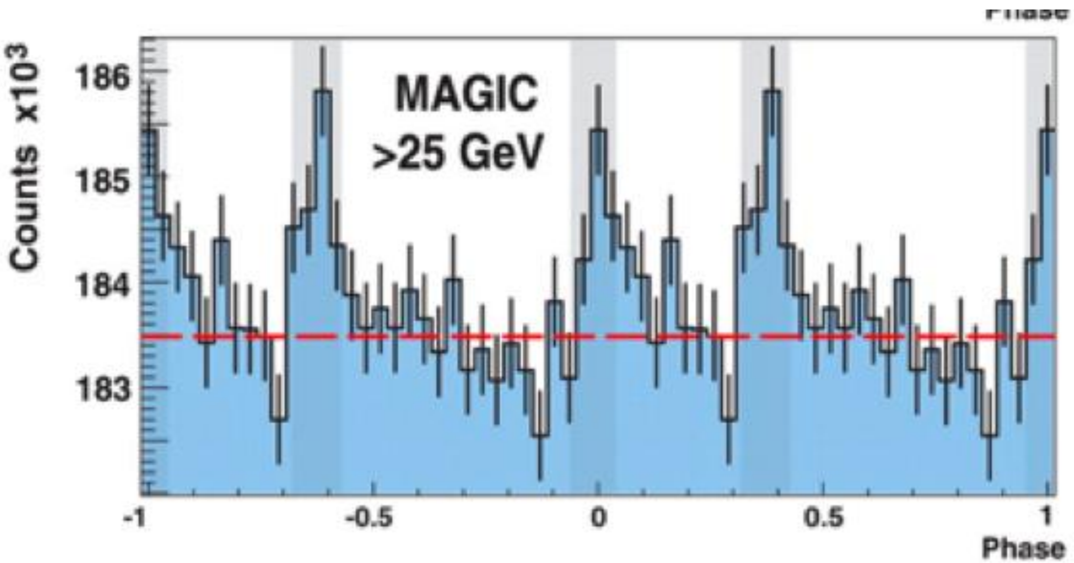
LATEST DEVELOPMENTS ON PULSAR γ-RAY EMISSION

MAGIC & VERITAS RESULTS ON CRAB

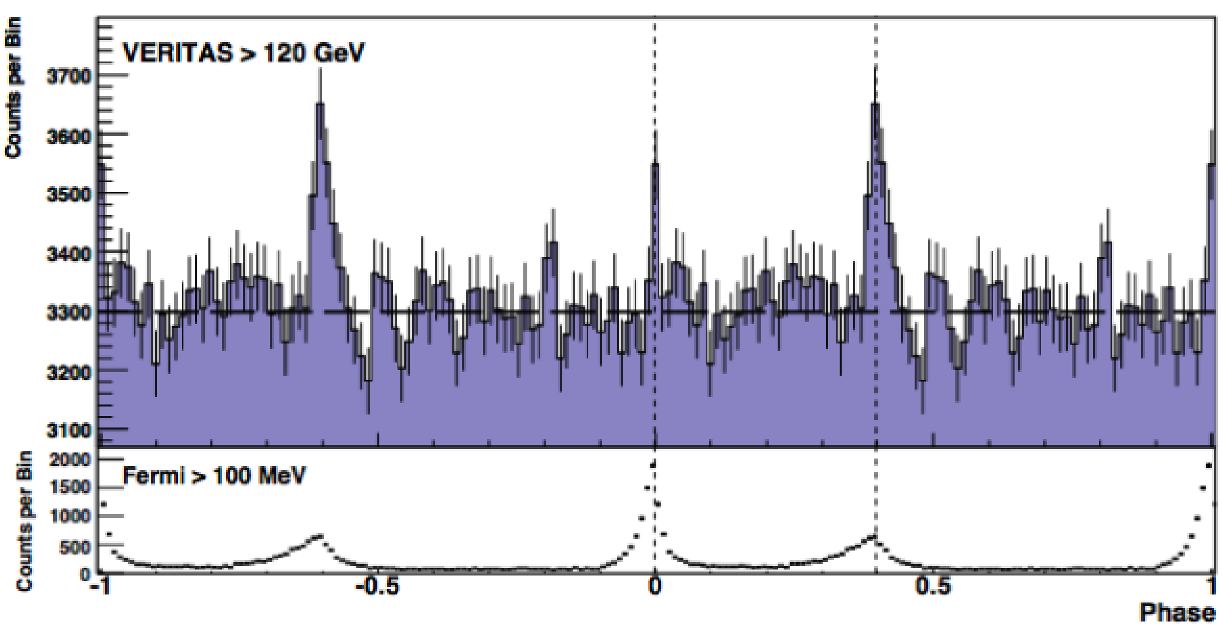
FORCE-FREE LIGHT CURVES

PARADIGM SHIFT?

MAGIC & VERITAS



(Aliu et al 08, 11; Aleksic et al 11, 12)



- •EMISSION MUST COME FROM R>30-40R$_*$
- •AND PROBABLY CANNOT BE CURVATURE AT ALL

MAGIC & VERITAS

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- SINGLE PARTICLE CURVATURE SPECTRUM HAS A BREAK
- MAXIMUM PARTICLE ENERGY IS LIMITED BY LOSSES

CURVATURE RADIATION SPECTRUM MUST BREAK

$$\epsilon_{br} = 5\ GeV\ \eta_{-2}^{3/4} \sqrt{\xi}$$

(Aliu et al 08, 11; Aleksic et al 11, 12)

ICS PROPOSED AS AN ALTERNATIVE

(Lyutikov, Otte, McCann 11, Aharonian et al 12)

NEW PROPOSALS

REPROCESSING X-RAYS THROUGH ICS

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decompressor
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(Lyutikov, Otte, McCann 11;
Aharonian, Bogovalov, Khangulyan 12)

THE FORCE FREE MAGNETOSPHERE

FIELD LINES IN THE $\mu\ \Omega$ PLANE FOR 60^0 INCLINATION

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INTENSITY OF B_φ

INTENSITY OF J

Spitkovsky 08

FROM VACUUM TO FORCE-FREE

MAGNETOSPHERE IS POPULATED WITH PAIRS!!!!

MULTIPLICITY $\kappa > 10^4$ REQUIRED FROM PWN OBSERVATIONS

GAPS BECOME LARGER (Bai & Spitkovsky 10)

TPC OG

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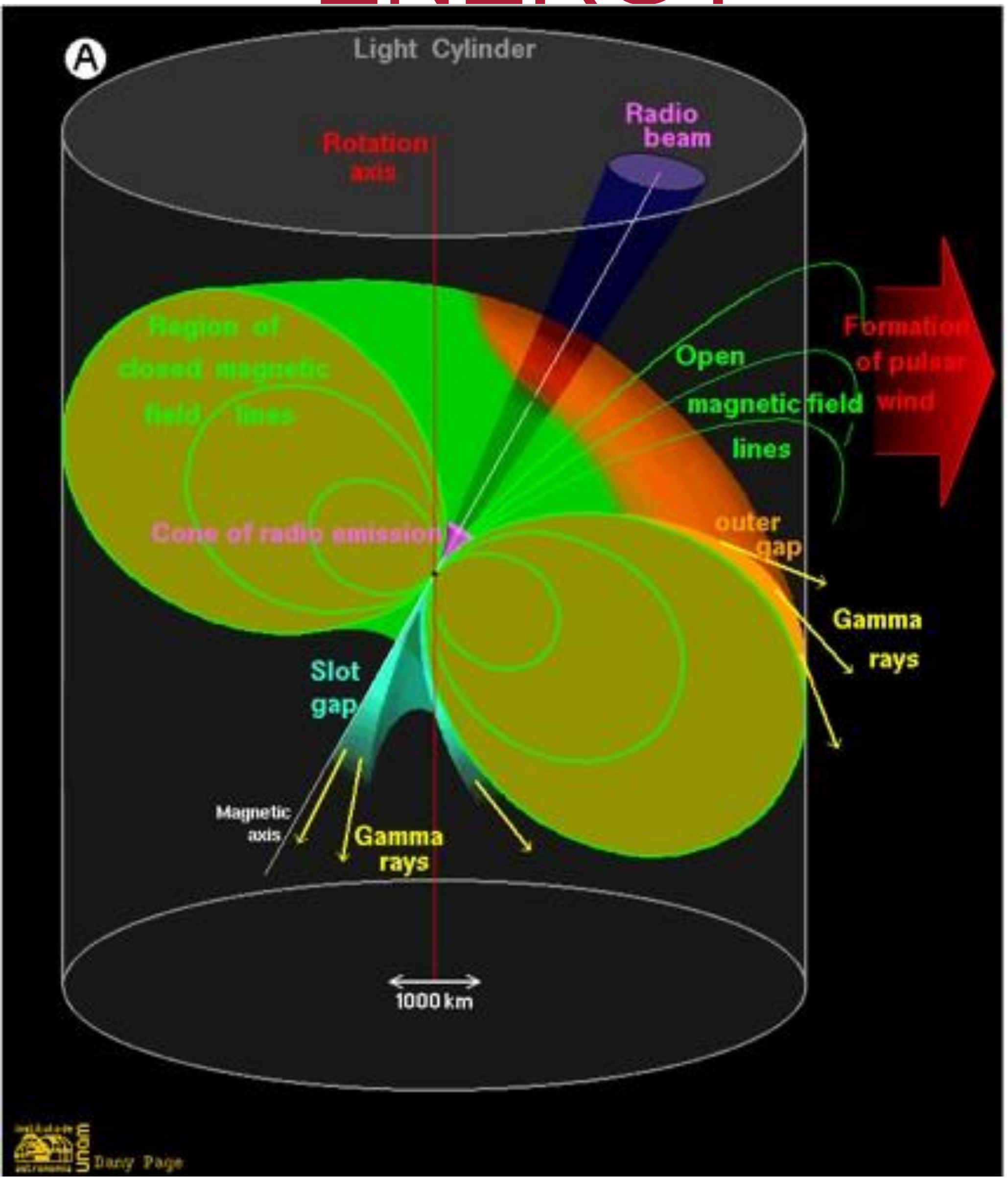
WHY
SHOULD FORCE-FREE
BE BETTER?

BECAUSE WE
MEASURE
VERY LARGE MULTIPLICITIES

FOLLOW THE ENERGY



γ-RAYS
(AND PULSED
EMISSION IN GENERAL)
IS NOT WHERE
THE ENERGY GOES!!!!!

$$L_{radio} \leq 10^{-10}\, \dot{E}_R$$

$$L_{\gamma} \leq 10^{-2}\, \dot{E}_R$$

ON THE OTHER HAND…

$$L_{PWN} \geq 0.1\, \dot{E}_R$$

THE PWN IS WHERE
THE ENERGY GOES!!!!

CONSTRAINTS ON PAIR PRODUCTION

THE PULSAR WIND ENERGY

$$\dot{E}_R = \frac{B_0^2 R_0^6 \Omega^4}{c^3} = \int d\vec{S} \left[\frac{c}{4\pi} \vec{E} \times \vec{B} + \Gamma_{wind} \left(n_\pm m_e + n_i m_i \right) c^3 \right]$$

$$\dot{E}_R = \kappa \dot{N}_{GJ} \, m_\pm \, c^2 \, \Gamma_{wind} \left(1 + \frac{m_i}{\kappa m_\pm} \right) \left(1 + \sigma \right) \qquad \kappa = \frac{\dot{N}}{\dot{N}_{GJ}}$$

$$\dot{N}_{GJ} \approx \pi R_0^2 \, \vartheta_p^2 c \left| \frac{\eta_{GJ0}}{e} \right| \approx 3 \times 10^{32} \frac{\mu_{30}}{P_{100}^2} \, s^{-1} \qquad \sigma = \frac{B^2}{4\pi m_{eff} n_{eff} c^2 \Gamma_{wind}^2}$$

AT R_{LC} σ IS VERY LARGE!!!!

IN THE NEBULAE WE "OBSERVE"

κ is very large (e.g. $10^4 < \kappa < 10^6$ in Crab)

Γ_{wind} is very large (e.g. $10^4 < \kappa < 10^6$ in Crab))

OPEN QUESTIONS

$$\dot{E}_R = \kappa \, \dot{N}_{GJ} \, m_{\pm} \, c^2 \, \Gamma_{wind} \left(1 + \frac{m_i}{\kappa m_{\pm}}\right)(1+\sigma)$$

- WHAT IS κ?
- WHAT IS σ?
- IS IT IONS WHO CARRY THE RETURN CURRENT?
- WHAT IS Γ_{wind}?

NOTE: for $\Gamma_{wind}=10^6$
These would be PeV
Protons or 30PeV Fe
And dominate the energy

DETAILED MODELING OF PWNE REQUIRED FOR QUANTITATIVE ANSWERS

κ is very large

No charge sep.
But
MHD

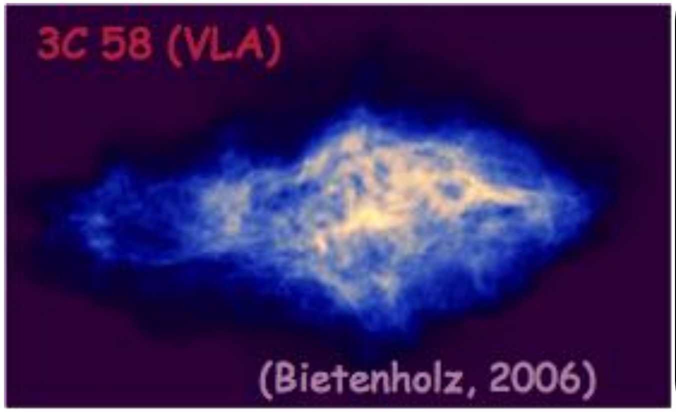
LEARNING FROM PWNe

FIRST LESSON:
A DENSE OUTFLOW

SIMPLEST DESCRIPTION:

- **FORCE FREE CLOSE TO THE STAR**
- **MHD FURTHER OUT**

PULSAR WIND NEBULAE



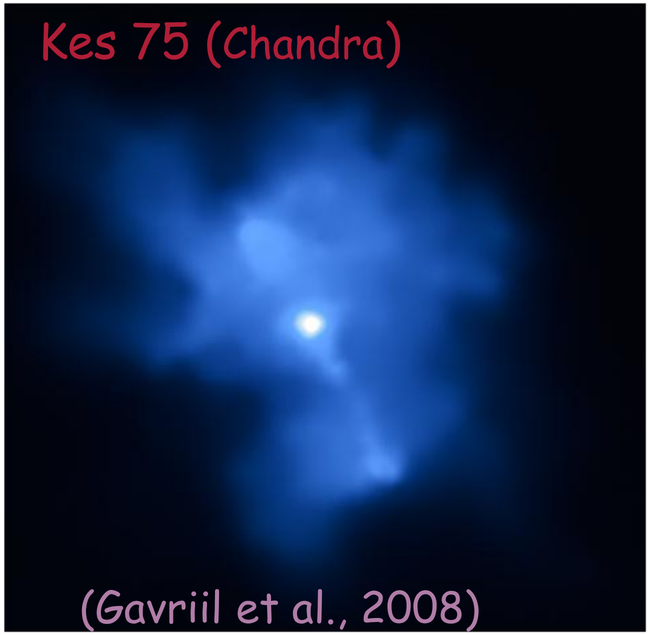
Plerions:

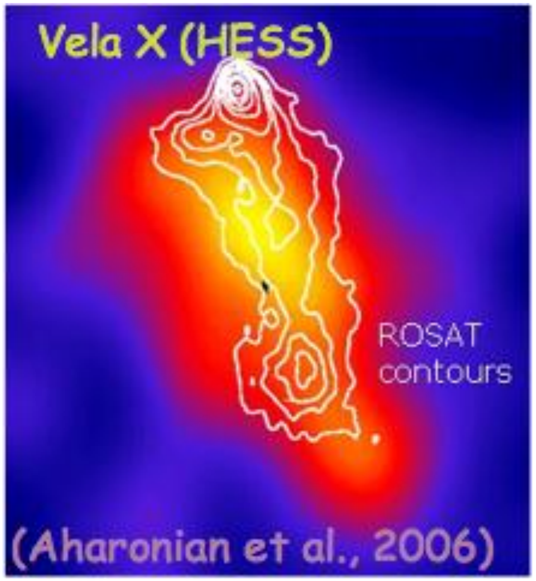
✓Supernova Remnants with a center filled morphology

✓Flat radio spectrum (α_R<0.5)

✓Very broad non-thermal emission spectrum (from radio to X-ray and even γ-rays)

(~15 objects at TeV energies)





“THE” PULSAR WIND NEBULA

Chaco Canyon Anasazi Painting

ONE OF BEST STUDIED OBJECTS IN THE UNIVERSE

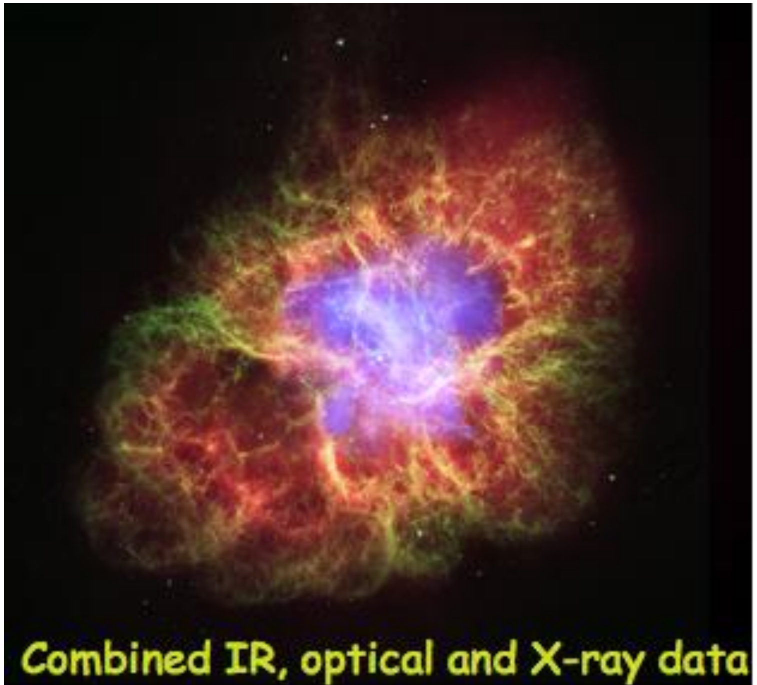
D=6000 lyr

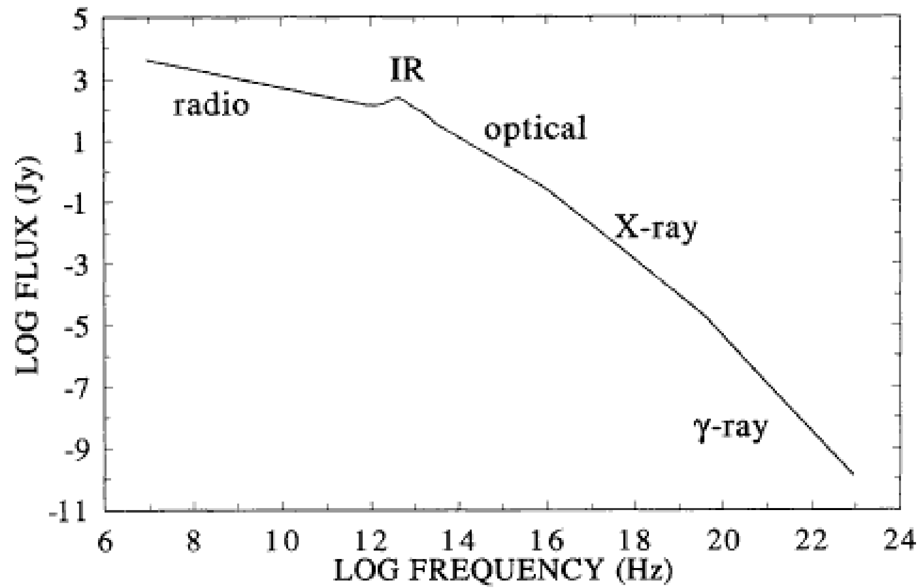
BIRTH=1054 A.C.

Chinese astronomers and native americans: “a guest star in Taurus, 4 times brighter than Venus at maximum”

visible during the day for 23 days and at night for 2 years

"THE" PULSAR WIND NEBULA





PRIMARY EMISSION MECHANISM: SYNCHROTRON RADIATION BY RELATIVISTIC PARTICLES IN AN *INTENSE* (>FEW X 100 B_{ISM}) *ORDERED* (HIGH DEGREE OF RADIO POLARIZATION) MAGNETIC FIELD

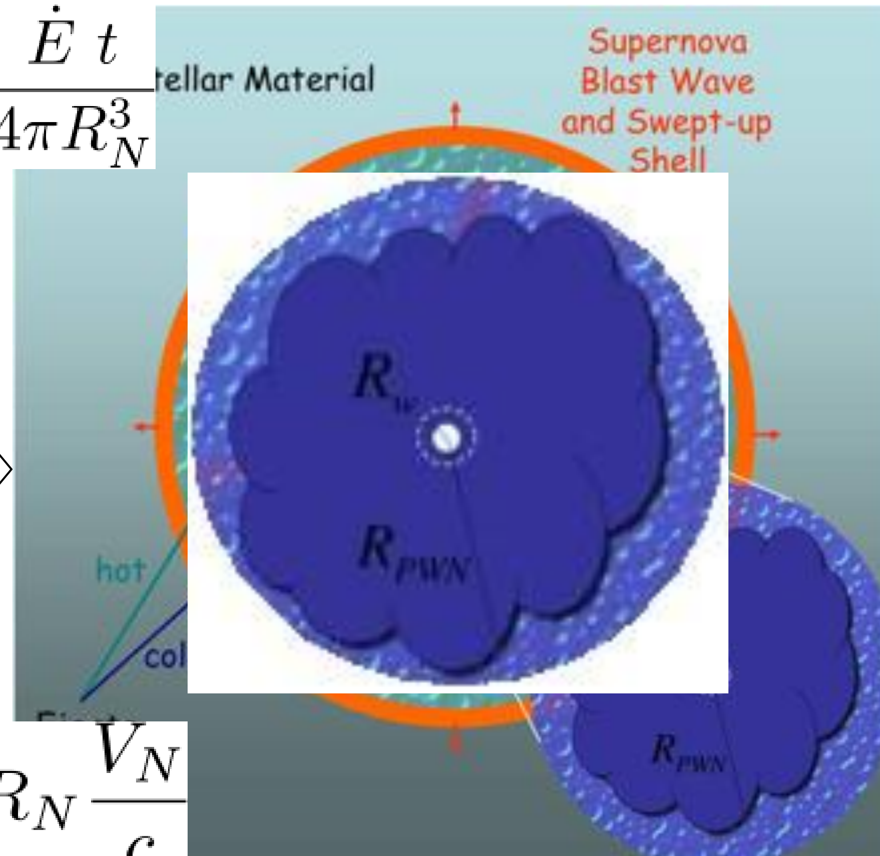
SOURCE OF BOTH MAGNETIC FIELD AND PARTICLES:
NEUTRON STAR SUGGESTED BEFORE PULSAR DISCOVERY (Pacini 67)

BASIC PICTURE OF A PWN

ELECTROMAGNETIC BRAKING OF FAST-SPINNING MAGNETIZED NS → MAGNETIZED RELATIVISTIC WIND

IF WIND IS EFFICIENTLY CONFINED BY SURROUNDING SNR → STAR ROTATIONAL ENERGY *VISIBLE* AS NON-THERMAL EMISSION OF THE MAGNETIZED RELATIVISTIC PLASMA

$$\frac{\dot{E}}{4\pi c R_{TS}^2} = \frac{\dot{E}\ t}{4\pi R_N^3}$$

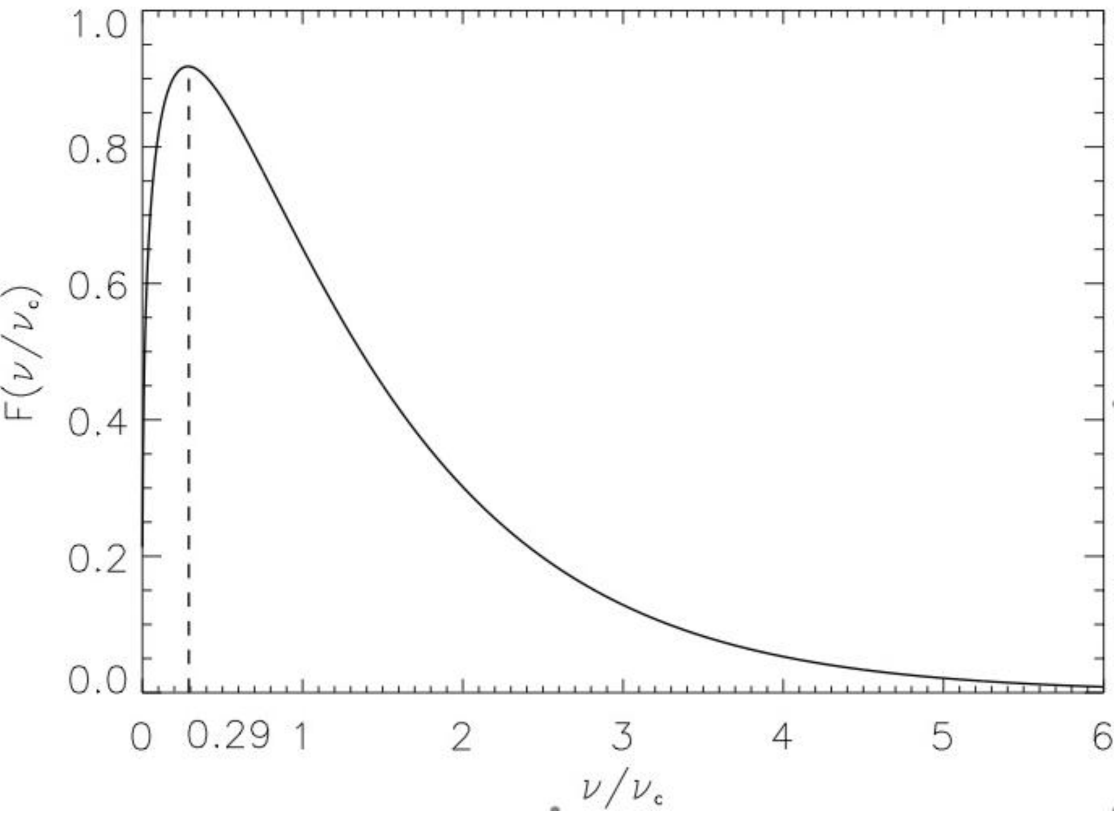


$$R_{TS} = R_N \frac{V_N}{c}$$

MODELING OF PWNe

- BASIC ARGUMENTS
- 1-ZONE MODELING
- 1-D MAGNETOHYDRODYNAMICAL MODELING
- 2-D AXISYMMETRIC MHD MODELING

SYNCHROTRON RADIATION SPECTRUM



$$\nu_s = 0.29 \frac{3}{2} \sqrt{\frac{2}{3}} \gamma^2 \nu_L$$

$$P_{tot} = \frac{4}{3} c \sigma_T \gamma^2 \beta^2 \frac{B^2}{8\pi}$$

$$\boxed{P_\nu(\nu) = P_{tot}(\gamma)\delta(\nu - \nu_s(\gamma))}$$

$$P_\nu(\gamma) = a_1 \gamma^2 B^2 \delta(\nu - \nu_s(\gamma))$$

$$\nu_s(\gamma) = a_2 \gamma^2 B$$

SYNCHROTRON RADIATION SPECTRUM

SINGLE PARTICLE SPECTRUM

$$P_\nu(\gamma) = a_1 \gamma^2 B^2 \delta(\nu - \nu_s(\gamma))$$

$$\nu_s(\gamma) = a_2 \gamma^2 B$$

POWER-LAW PARTICLE DISTRIBUTION

$$N(\gamma) = k\gamma^{-p}$$

$$S_\nu(\nu) = \int_{\gamma_{\min}}^{\gamma_{\max}} N(\gamma) P_\nu(\gamma)\, d\gamma = a_1 B^2 \int_{\gamma_{\min}}^{\gamma_{\max}} \gamma^2\, k\, \gamma^{-p}\, \delta(\nu - \nu_s(\gamma))\, d\gamma$$

$$\delta(\nu - \nu_s(\gamma)) = \frac{\delta(\gamma - \gamma_0)}{\nu_s'(\gamma_0)} = \frac{\delta(\gamma - \gamma_0)}{2 a_2 \gamma_0 B} = \frac{\delta(\gamma - \gamma_0)}{2 a_2^{1/2} B^{1/2} \nu^{1/2}}$$

$$S_\nu^{sync}(\nu) = \frac{a_1}{2} a_2^{(\alpha-1)}\, k\, B^{\alpha+1}\, \nu^{-\alpha} \qquad \alpha = \frac{p-1}{2}$$

IN ORDER TO ESTIMATE K AND γ WE NEED TO KNOW B

ESTIMATES OF B
IN NON-THERMAL SOURCES

EQUIPARTITION OR MINIMUM ENERGY

EQUIPARTITION

$$N(\gamma) = k\,\gamma^{-p} \qquad \gamma_{\min} < \gamma < \gamma_{\max}$$

$$W_{tot} = V\left(\frac{B^2}{8\pi} + \int_{\gamma_{\min}}^{\gamma_{\max}} N(\gamma)\, m c^2 \gamma\, d\gamma\right) = V\left(\frac{B^2}{8\pi} + \int_{\gamma_{\min}}^{\gamma_{\max}} k\, m c^2 \gamma^{1-p}\, d\gamma\right)$$

$$W_{tot} = V\left(\frac{B^2}{8\pi} + \frac{kmc^2}{2-p}\left(\gamma_{\max}^{(2-p)} - \gamma_{\min}^{(2-p)}\right)\right)$$

$$\boxed{w_{part} = kmc^2\left(\frac{\left(\gamma_{\max}^{(2-p)} - \gamma_{\min}^{(2-p)}\right)}{2-p}\right)}$$

$$S_\nu(\nu) = \frac{c_1}{2} c_2^{(\alpha-1)} k\, B^{\alpha+1} \nu^{-\alpha} \quad \Rightarrow \quad \boxed{k = \frac{2S_\nu}{c_1 c_2^{(\alpha-1)}} B^{-(\alpha+1)} \nu^{\alpha}}$$

$$\boxed{\gamma_0 = \left(\frac{\nu}{c_2 B}\right)^{1/2}}$$

$$\boxed{w_{part} = \frac{2S_\nu mc^2}{c_1 c_2^{(\alpha-1)}} B^{-(\alpha+1)} \nu^{\alpha} \left(\frac{\left(\nu_{\max}^{(2-p)/2} - \nu_{\min}^{(2-p)/2}\right)}{2-p}\right) c_2^{(p-2)/2}\, B^{(p-2)/2}}$$

EQUIPARTITION FIELD

$$w_{part} = \frac{2S_\nu mc^2}{c_1 c_2^{(\alpha-1)}} B^{-(\alpha+1)} \nu^\alpha \left(\frac{\left(\nu_{\max}^{(2-p)/2} - \nu_{\min}^{(2-p)/2}\right)}{2-p} \right) c_2^{(p-2)/2} B^{(p-2)/2}$$

$$p = 2\alpha + 1$$

$$\boxed{\xi_\nu = \frac{4S_\nu mc^2}{c_1 c_2^{3/2}} \nu^\alpha \left(\frac{\left(\nu_{\min}^{-(2\alpha-1)/2} - \nu_{\max}^{-(2\alpha-1)/2}\right)}{2\alpha-1} \right)}$$

$$\boxed{W_{part} = \xi_\nu B^{(p-2)/2} B^{-(\alpha+1)} = \xi_\nu B^{-3/2}} \Rightarrow \boxed{W_{tot} = V\left(\frac{B^2}{8\pi} + \xi_\nu B^{-3/2}\right)}$$

$$\frac{\partial W_{tot}}{\partial B} = V\left(\frac{B}{4\pi} - \frac{3}{2}\xi_\nu B^{-5/2}\right) = 0 \quad \Rightarrow \quad \boxed{B_{\min} = (6\pi\xi_\nu)^{2/7}}$$

$$W_B = W_{part} \quad \Rightarrow \quad \boxed{B_{eq} = (8\pi\xi_\nu)^{2/7}}$$

CAVEATS!!!!

CAVEATS ON EQUIPARTITION

SAME VOLUME AND HOMOGENEITY

$$W_{tot} = V\left(\frac{B^2}{8\pi} + \xi_\nu B^{-3/2}\right)$$

MIN AND MAX FREQ. NOT KNOWN IN GENERAL

$$\xi_\nu = \frac{4S_\nu mc^2}{c_1 c_2^{3/2}}\nu^\alpha\left(\frac{\left(\nu_{\min}^{-(2\alpha-1)/2} - \nu_{\max}^{-(2\alpha-1)/2}\right)}{2\alpha-1}\right)$$

RADIO EMITTING PARTICLES MIGHT NOT CARRY MOST OF THE ENERGY

WHY EQUIPARTITION OR MINIMUM ENERGY?

EQUIPARTITION FIELD IN CRAB

$$B_{eq} \approx 300\ \mu G$$

$$\Downarrow$$

RADIO EMITTING PARTICLES HAVE $\gamma \approx 10^4$

THEIR EMISSION CORRESPONDS TO $\dot{N} \approx 10^{40}\ s^{-1}$

$$\Downarrow$$

$$\boxed{\Gamma_w \approx 10^4 \qquad k \approx 10^6}$$

NOTE: EVEN IF IONS ARE THERE,
THEY CANNOT BE ENERGETICALLY DOMINANT

BUT…

IN ~SAME B, X-RAYS COME FROM PARTICLES CORRESPONDING TO

$$\boxed{\Gamma_w \approx 10^6 \qquad k \approx 10^4}$$

- **SYNCHROTRON SOURCES EVOLVE WITH TIME**
- **X-RAY EMITTING PARTICLES HAVE SHORT SYNCHROTRON LIFETIMES**
- **MIGHT RADIO EMITTING PARTICLES BE FOSSILE?????**

1-ZONE EVOLUTIONARY MODELS

EVERYTHING IS SPATIALLY HOMOGENEOUS BUT TIME-DEPENDENT (Pacini & Salvati 73):
CHANGING PULSAR INPUT, SYNCHROTRON AND ADIABATIC LOSSES OF PARTICLES AND FIELD ARE INCLUDED

INJECTION SPECTRUM PER UNIT TIME AND ENERGY INTERVAL:

$$\boxed{J(E,t) = k(t)\ E^{-\gamma}}$$

K(t)← $$\int_{E_{min}}^{E_{max}} J(E,t)\ E\ dE = \eta_p L(t)$$

CONSERVATION OF PARTICLE NUMBER

$$dN(E,t)\ dE = J(E_i,t_i)dt_i dE_i$$

$$\boxed{N(E,t) = \int_E^{E_{\max}} J[E_i;t_i(E_i,E,t)]\frac{\partial t_i}{\partial E}dE_i}$$

RELATION NEEDED BETWEEN E, E_i, t_i

SINGLE PARTICLE EVOLUTION

$$\frac{dE}{dt} = -c_1 B^2(t) E^2 - \frac{E}{3}\frac{1}{V(t)}\frac{dV}{dt}$$

SYNCHROTRON
AND
ADIABATIC LOSSES

$$\frac{V^{-1/3}}{E^2}\frac{dE}{dt} + \frac{V^{-4/3}}{3E}\frac{dV}{dt} = -c_1 B^2(t) V^{-1/3}(t) \quad \Longrightarrow \quad \frac{d}{dt}\left(\frac{1}{EV^{1/3}}\right) = c_1 B^2(t) V^{-1/3}(t)$$

$$\boxed{\frac{1}{EV^{1/3}(t)} - \frac{1}{E_i V^{1/3}(t_i)} = \int_{t_i}^{t} c_1 B^2(t') V^{-1/3}(t') dt'}$$

CONTAINS SEEKED RELATION BETWEEN E, E_i, t_i

$$\boxed{\frac{\partial t_i}{\partial E} = \frac{E_i}{E^2}\left(\frac{d \log V_i^{1/3}}{dt_i}\right)^{-1}\left(1 + \frac{E_i}{E_b(t_i)}\right)^{-1}}$$

$$\boxed{E_b(t) = \left(c_1 B^2(t) \frac{d \log V^{1/3}}{dt}\right)^{-1}}$$

BREAK ENERGY: SYNCHROTRON AND ADIABATIC LOSSES EQUAL

MAGNETIC FIELD EVOLUTION

$$\frac{dW_B}{dt} = \eta_B L(t) - \frac{W_B}{3V(t)}\frac{dV}{dt}$$

$$V(t) = \frac{4\pi}{3}R(t)^3$$

$$W_B(t) = \frac{B^2(t)}{8\pi}\frac{4\pi}{3}R(t)^3$$

$$\frac{d}{dt}\left(B^2R^3\right) + B^2R^2\frac{dR}{dt} = 6\eta_B L(t)$$

$$\frac{dB^2}{dt}R^3 + 4B^2R^2\frac{dR}{dt} = 6\eta_B L(t)$$

CONSERVATION OF MAGNETIC FLUX!

$$\frac{d}{dt}\left(B^2R^4\right) = 6\eta_B L(t)R(t) \quad \Rightarrow \quad B^2R^4 - B_0^2R_0^4 = 6\eta_B\int_{t_0}^{t} L(t)R(t)dt$$

$$\dot{E} = \frac{aI\Omega_0^{n+1}}{\left[1+t/\tau_0\right]^{\frac{n+1}{n-1}}}$$

$$L(t) = \dot{E} = \frac{L_0}{(1+t/\tau)^{\alpha}}$$

$$\alpha = \frac{n+1}{n-1}$$

MAGNETIC FIELD EVOLUTION

$$B^2R^4 - B_0^2R_0^4 = 6\eta_B \int_{t_0}^{t} L(t)R(t)dt \qquad L(t) = \dot{E} = \frac{L_0}{(1+t/\tau)^{\alpha}}$$

- EXPANSION WITH CONSTANT VELOCITY
- CONSTANT ENERGY SUPPLY: $t \ll \tau$

$$\begin{cases} R(t) = \mathrm{v}t \\ L(t) = L_0 \end{cases} \Rightarrow \qquad B^2 = \frac{6\eta_B L_0 \mathrm{v} t^2}{\mathrm{v}^4 t^4} \qquad \boxed{B(t) = \left(\frac{6\eta_B L_0}{\mathrm{v}^3}\right)^{1/2} \frac{1}{t}}$$

QuickTime™ and a
decompressor
are needed to see this picture.

- EXPANSION WITH CONSTANT VELOCITY
- DECAYING ENERGY SUPPLY: $t \gg \tau$

BR^2=cost

$$\boxed{B(t) = \left(\frac{6\eta_B L_0 \tau^2}{(\alpha - 1)(\alpha - 2)\mathrm{v}^3}\right)^{1/2} \frac{1}{t^2}}$$

BACK TO THE PARTICLES

$$R(t) = \mathrm{v}t$$

$$B(t) = \frac{B_0}{t^a}$$

$$\frac{1}{EV^{1/3}(t)} - \frac{1}{E_i V^{1/3}(t_i)} = \int_{t_i}^{t} c_1 B^2(t')V^{-1/3}(t')dt'$$

$$\frac{1}{Et} - \frac{1}{E_i t_i} = \frac{c_1}{2a}\left(B^2(t_i) - B^2(t)\right)$$

CONSTANT ENERGY INPUT: a=1

$$\frac{\partial t_i}{\partial E} = \frac{E_i t_i}{E^2}\left(1 + \frac{E_i}{E_b(t_i)}\right)^{-1} = \frac{E_i}{E^2 t_i}\left(1 + \frac{E_i t}{E_b(t) t_i}\right)^{-1}$$

$$t_i = \frac{Et}{2E_i}\left\{1 + \left[1 + 4\frac{E_i^2}{EE_b(t)}\left(1 + \frac{E}{2E_b(t)}\right)\right]^{1/2}\right\}\left(1 + \frac{E}{2E_b(t)}\right)^{-1}$$

$$E_b(t) = \frac{1}{c_1 B^2(t) t} \propto t$$

- **BREAK WAS ONCE AT VERY LOW ENERGY**
- **INITIAL RADIO PARTICLES CANNOT HAVE SURVIVED**

LOW ENERGY LIMIT

$$t_i = \frac{Et}{2E_i}\left\{1+\left[1+4\frac{E_i^2}{EE_b(t)}\left(1+\frac{E}{2E_b(t)}\right)\right]^{1/2}\right\}\left(1+\frac{E}{2E_b(t)}\right)^{-1}$$

$$\frac{\partial t_i}{\partial E} = \frac{E_i t_i}{E^2}\left(1+\frac{E_i}{E_b(t_i)}\right)^{-1} = \frac{E_i}{E^2 t_i}\left(1+\frac{E_i t}{E_b(t)t_i}\right)^{-1}$$

$$E_b(t) = \frac{1}{c_1 B^2(t)t} \propto t$$

E<<E_b OR $E_B \rightarrow \infty$: ADIABATIC LOSSES ONLY

$$t_i = \frac{Et}{E_i} \qquad \frac{\partial t_i}{\partial E} = \frac{E_i t_i}{E^2} = \frac{t}{E}$$

$$N(E,t) = \int_E^{E_{\max}} J\left[E_i; t_i(E_i, E, t)\right]\frac{\partial t_i}{\partial E}dE_i \qquad J(E,t) = k(t)\,E^{-\gamma}$$

$$\boxed{N(E,t) = k\frac{t}{E}\int_E^{E_{\max}} E_i^{-\gamma}dE_i \approx ktE^{-\gamma}}$$

HIGH ENERGY LIMIT

$E>E_B$: SYNCHROTRON LOSSES DOMINATE

$$t_i = \frac{Et}{2E_i}\left\{1+\left[1+4\frac{E_i^2}{EE_b(t)}\left(1+\frac{E}{2E_b(t)}\right)\right]^{1/2}\right\}\left(1+\frac{E}{2E_b(t)}\right)^{-1}$$

$$t_i = \frac{Et}{2E_i}\left(\frac{2E_i^2}{EE_b(t)}\frac{E}{2E_b(t)}\right)^{1/2}\left(\frac{E}{2E_b(t)}\right)^{-1} \approx \frac{Et}{E_i}\frac{E_i}{E_b}\frac{E_b}{E} \Rightarrow \boxed{t_i = t}$$

$$\frac{\partial t_i}{\partial E} = \frac{E_i t_i}{E^2}\left(1+\frac{E_i}{E_b(t_i)}\right)^{-1}$$

$$\frac{\partial t_i}{\partial E} = \frac{E_i t_i}{E^2}\left(\frac{E_i}{E_b(t_i)}\right)^{-1} \Rightarrow \boxed{\frac{\partial t_i}{\partial E} = \frac{t_i E_b}{E^2}}$$

$$N(E,t) = K\int_E^{E_{\max}} E_i^{-\gamma}\frac{\partial t_i}{\partial E}dE_i$$

$$N(E,t) = \frac{ktE_b}{E^2}\int_E^{E_{\max}} E_i^{-\gamma}dE_i \approx kt\frac{E_b}{E^2}E^{-\gamma+1}$$

$$\boxed{N(E,t) \approx ktE_b E^{-\gamma-1}}$$

SPECTRUM STEEPENS BY -1
RADIATION SPECTRUM BY -1/2

SYNCHROTRON BREAK

$$S_\nu^{sync}(\nu) = \frac{a_1}{2} a_2^{(\alpha-1)} k\, B^{\alpha+1}\, \nu^{-\alpha} \qquad \alpha = \frac{p-1}{2}$$

PARTICLE SPECTRUM

$$N(E,t) \approx ktE^{-\gamma} \qquad E < E_b$$

$$N(E,t) \approx ktE_b E^{-\gamma-1} \qquad E > E_b$$

RADIATION SPECTRUM

$$S_\nu(\nu,t) \propto \nu^{-(\gamma-1)/2} \qquad \nu < \nu_b$$

$$S_\nu(\nu,t) \propto \nu^{-\gamma/2} \qquad \nu > \nu_b$$

$$\nu_b \approx c_2 B E_b^2 = c_2 B \left(\frac{1}{c_1 B^2 t}\right)^2$$

$$\Rightarrow \quad \nu_b = \frac{c_2}{c_1^2} \frac{1}{B^3 t^2}$$

$$\begin{cases} c_1 = \dfrac{a_1}{(mc^2)^2} = \dfrac{\sigma_T c}{9\pi (mc^2)^2} \\ c_2 = \dfrac{a_2}{(mc^2)^2} = 0.29\sqrt{\dfrac{2}{3}}\,\dfrac{3}{2}\,\dfrac{ec}{2\pi (mc^2)^3} \end{cases}$$

MAGNETIC FIELD IN A SOURCE OF KNOWN AGE

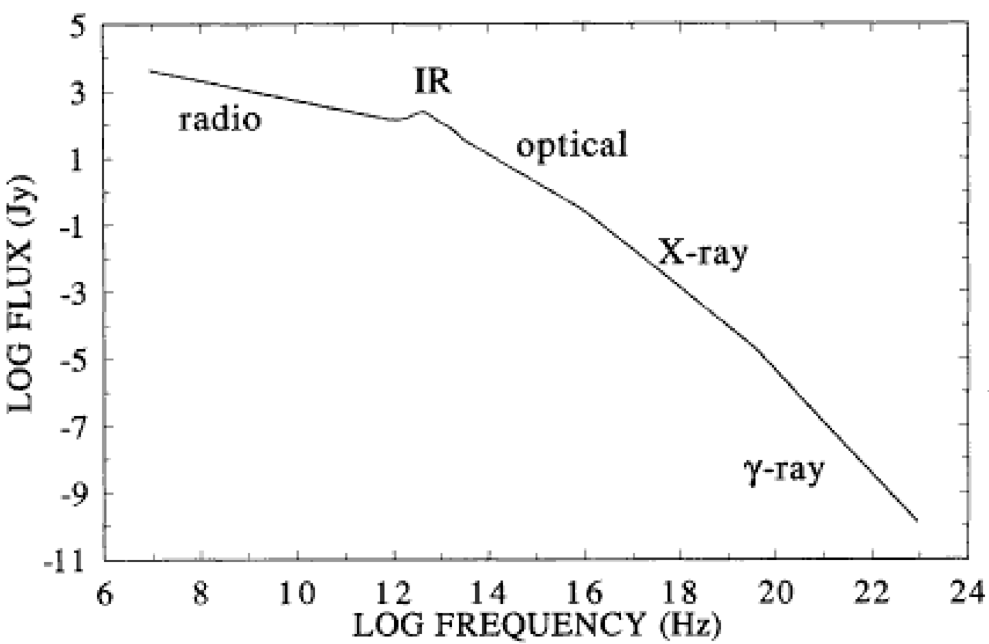
$$B = \left(\frac{c_2}{c_1^2} \frac{1}{t^2 \nu_b}\right)^{1/3} = 8 \times 10^{-5}\ G\ t^{-2/3}[kyr]\ \nu_b^{-1/3}[GHz]$$

THE CRAB NEBULA

$$\nu_b = 5\times 10^{13} Hz \quad \Rightarrow \quad B = 300\mu G \quad \rightarrow \quad N_1(E) = k\begin{cases} E^{-p_1} & E < E_b \\ E_b E^{-(p_1+1)} & E_b < E < E_0 \\ E_0^{(p_2-p_1)} E_b E^{-(p_2+1)} & E_0 < E < E_{\max} \end{cases}$$

$$\begin{cases} p_1 = 1.6 \\ p_2 = 2.2 \end{cases}$$

$$\nu_b = 2\times 10^{15} Hz \quad \Rightarrow \quad B = 100\mu G \quad \rightarrow \quad N_2(E) = k\begin{cases} E^{-p_1} & E < E_0 \\ E_0^{(p_2-p_1)} E^{-p_2} & E_0 < E < E_b \\ E_0^{(p_2-p_1)} E_b E^{-(p_2+1)} & E_b < E < E_{\max} \end{cases}$$



TWO BREAKS BETWEEN RADIO AND GAMMA-RAYS: WHICH ONE IS SYNCHROTRON AND WHICH IS AGE?

$$\boxed{B = \frac{80\mu G}{\left(t^2[kyr]\nu_b[GHz]\right)^{1/3}}}$$

ADD ICS

$$P_\nu^{sync}(\gamma) = P_{tot}^{sync}(\gamma)\delta(\nu - \nu_s(\gamma)) = a_1\gamma^2 B^2 \delta(\nu - \nu_s(\gamma))$$

$$\nu_s(\gamma) = a_2\gamma^2 B$$

$$\alpha = \frac{p-1}{2}$$

$$S_\nu^{sync}(\nu) = \frac{a_1}{2} a_2^{(\alpha-1)} k\, B^{\alpha+1}\, \nu^{-\alpha}$$

$$P_\nu^{ICS}(\gamma) = P_{tot}^{ICS}(\gamma)\delta(\nu - \nu_c(\gamma)) = 8\pi a_1\gamma^2 U_{rad}\delta(\nu - \nu_c(\gamma))$$

$$\nu_c(\gamma) = 3\gamma^2 \nu_T$$

$$S_\nu^{ICS}(\nu) = 4\pi a_1 (3\nu_T)^{(\alpha-1)} U_{rad} k\, \nu^{-\alpha}$$

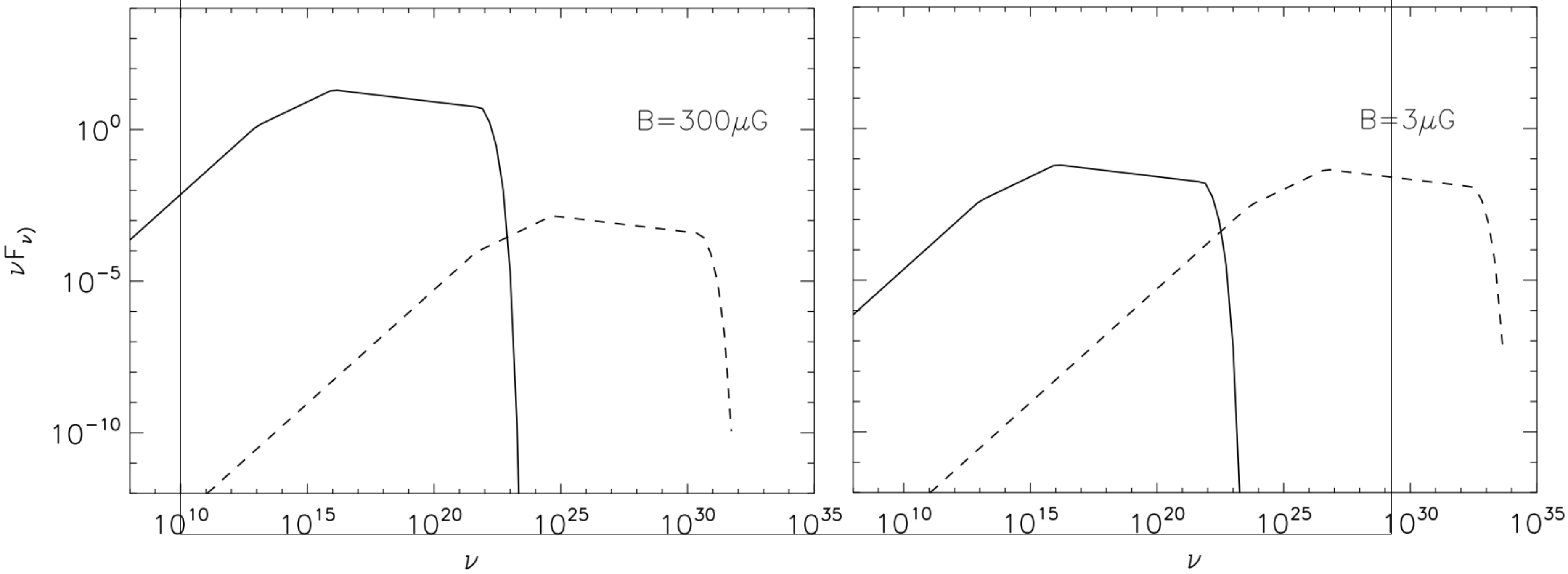
$$\begin{cases} a_1 = \dfrac{\sigma_T c}{9\pi} \\ a_2 = 0.29\sqrt{\dfrac{2}{3}}\dfrac{3}{2}\dfrac{e}{2\pi mc} \end{cases}$$

EXAMPLE CASE

$$N(E) = k\begin{cases} E^{-p_1} & E < E_0 \\ E_0^{(p_2-p_1)}E^{-p_2} & E_0 < E < E_b \\ E_0^{(p_2-p_1)}E_b E^{-(p_2+1)} & E_b < E < E_{\max} \end{cases}$$

CHECK OUT RELATIVE NORMALIZATION

$$\begin{cases} p_1 = 1.6 \\ p_2 = 2.1 \end{cases}$$



$$\begin{cases} \nu_0 = 10^{13}Hz & \Rightarrow & \gamma_0(300) = 2\times10^5 & and & \gamma_0(3) = 2\times10^6 \\ \nu_b = 10^{16}Hz & \Rightarrow & \gamma_1(300) = 6\times10^6 & and & \gamma_0(3) = 6\times10^7 \\ \nu_b = 10^{23}Hz & \Rightarrow & \gamma_1(300) = 2\times10^{10} & and & \gamma_0(3) = 2\times10^{11} \end{cases}$$

THE CRAB NEBULA AGAIN

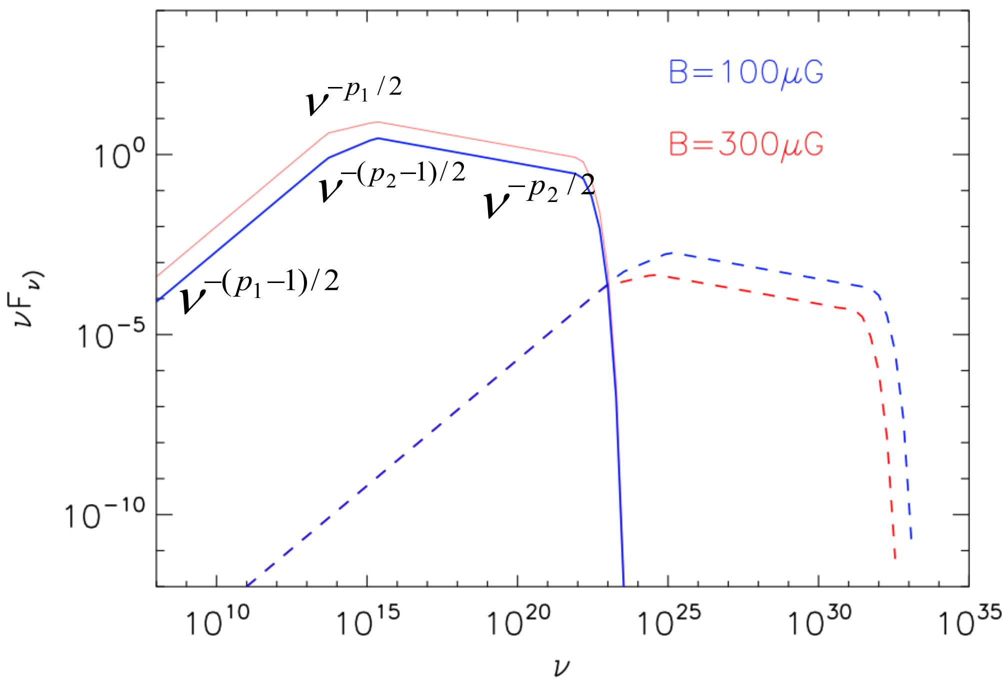
$$\nu_b = 5\times 10^{13} \Rightarrow B = 300\mu G \rightarrow N_1(E) = k\begin{cases} E^{-p_1} & E < E_b \\ E_b E^{-(p_1+1)} & E_b < E < E_0 \\ E_0^{(p_2-p_1)} E_b E^{-(p_2+1)} & E_0 < E < E_{\max} \end{cases}$$

$$\boxed{B = \frac{80\mu G}{\left(t^2[kyr]\nu_b[GHz]\right)^{1/3}}}$$

$$\begin{cases} p_1 = 1.6 \\ p_2 = 2.2 \end{cases}$$

$$\nu_b = 2\times 10^{15} \Rightarrow B = 100\mu G \rightarrow N_2(E) = k\begin{cases} E^{-p_1} & E < E_0 \\ E_0^{(p_2-p_1)} E^{-p_2} & E_0 < E < E_b \\ E_0^{(p_2-p_1)} E_b E^{-(p_2+1)} & E_b < E < E_{\max} \end{cases}$$

$$\boxed{\alpha = \frac{p-1}{2}}$$



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1-ZONE MODELS FOR THE PWN EVOLUTION

$$\dot{N}(E,t) = C_o(t)(E/\epsilon_c)^{-\gamma_1} \; for \; \epsilon_c < E < \epsilon_v$$

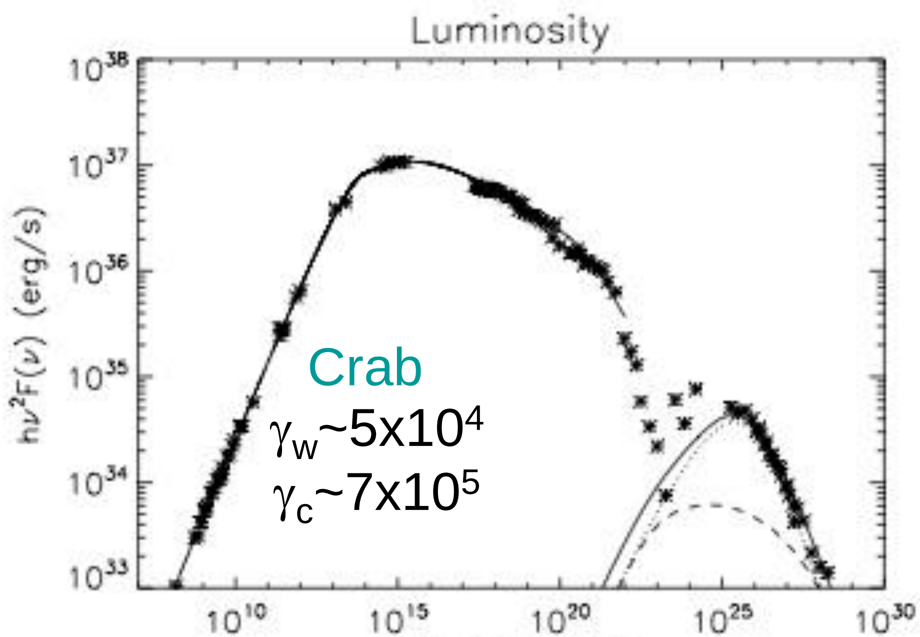
$$\dot{N}(E,t) = C_o(t)(E/\epsilon_c)^{-\gamma_2} \; for \; \epsilon_m < E < \epsilon_c$$

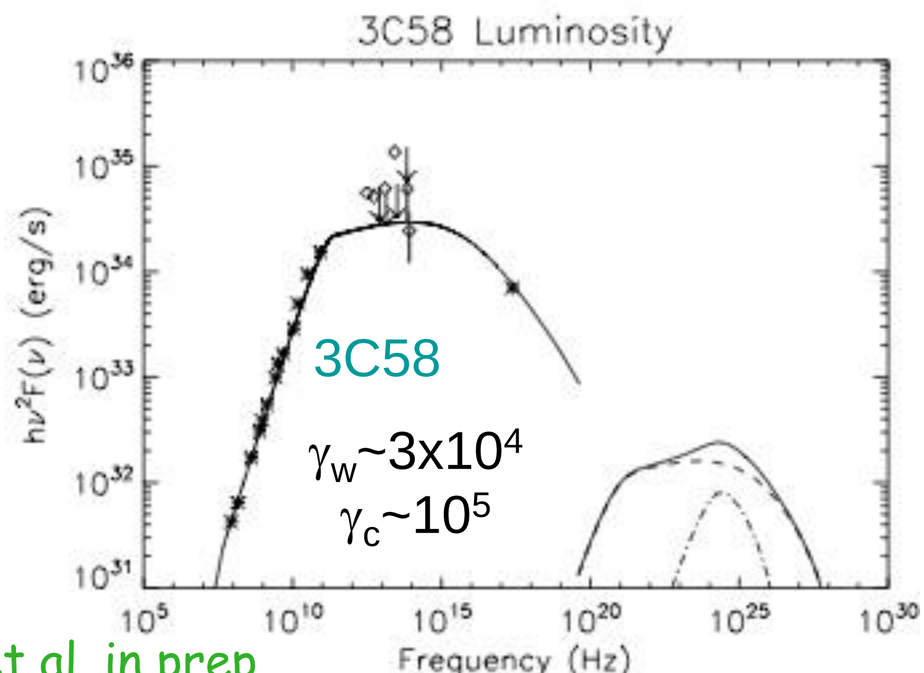
$$\eta_e L(t) = \int_{\epsilon_m}^{\epsilon_v} \dot{N}(E,t) E dE$$

$$\dot{N}(t) = \int_{\epsilon_m}^{\epsilon_v} \dot{N}(E,t) dE$$

$$N(E,t) = \int_E^{\infty} \dot{N}(E_o t_o) \frac{\partial t_o}{\partial E}(E, E_o, t) dE_o$$

$\varepsilon_v \propto L(t)^{1/2}$ $\varepsilon_c/\varepsilon_v$=cost $\gamma_w = L(t)/(dN/dt)$





Bucciantini et al. in prep

INFERRED MULTIPLICITIES

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decompressor
are needed to see this picture.

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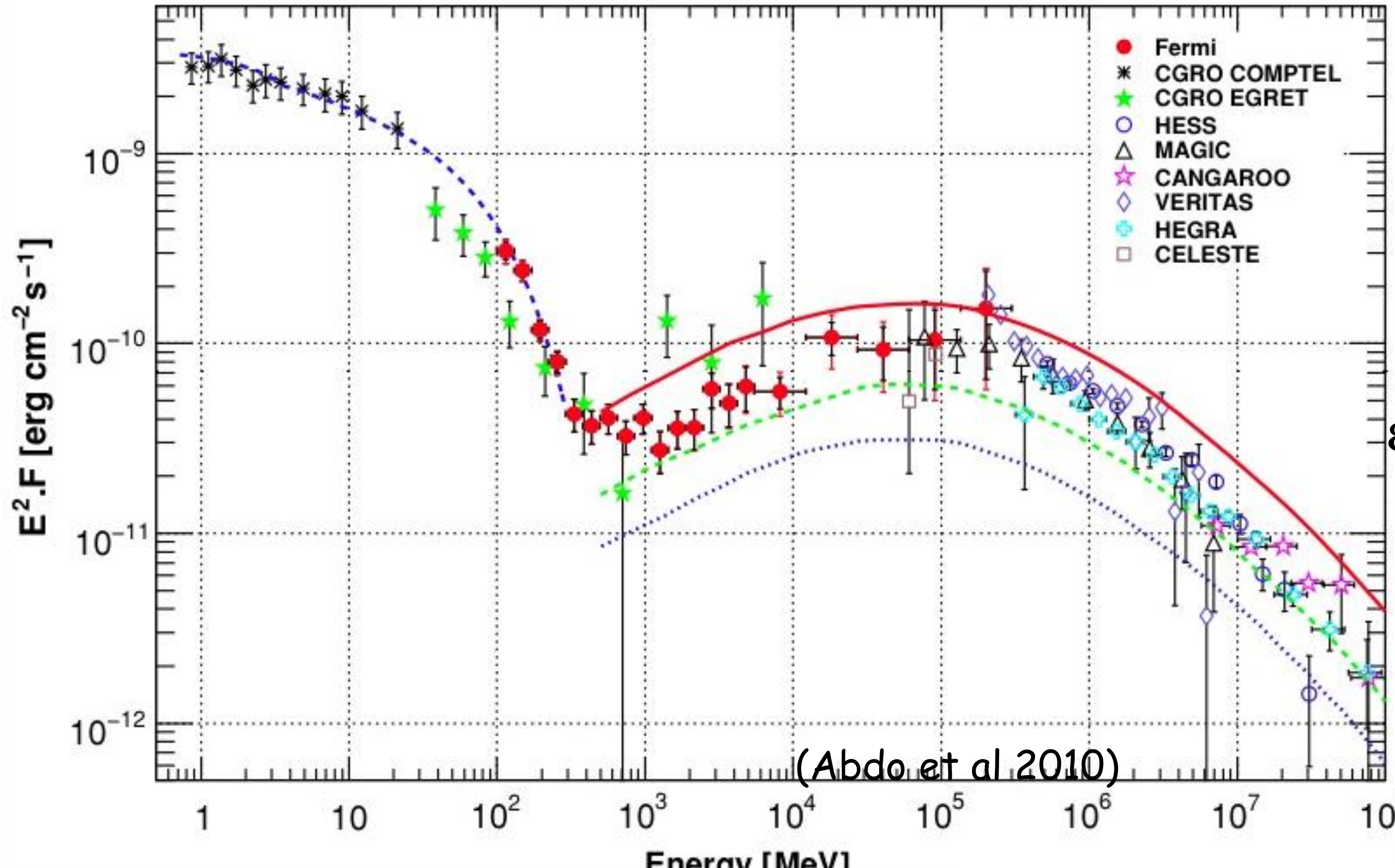
decompressor
are needed to see this picture.

PeV PARTICLES WE SAID….



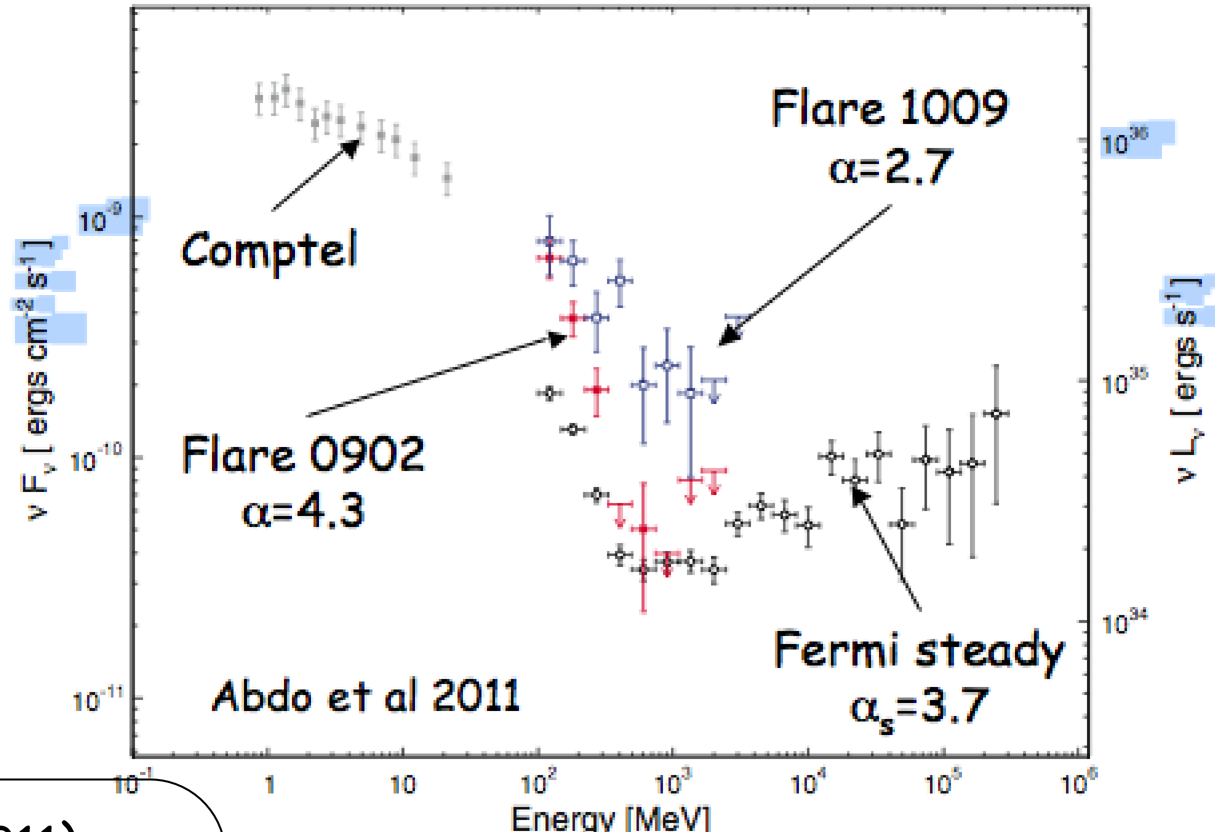
EGRET:
ε_{max}~30 MeV

Fermi:
ε_{max}~100 MeV

$$\epsilon = \frac{3h}{2}\frac{eB}{2\pi m_e c}\gamma^2 \Rightarrow E_e = 1.5PeV\left(\frac{B}{100\mu G}\right)^{-1/2}$$

GETTING CLOSE TO MAXIMUM AVAILABLE POTENTIAL DROP

γ-RAY FLARES



AGILE (Tavani et al. 2011)
and *Fermi* (Abdo et al. 2011)

Feb. 2009: δF/F~5.5; ΔT~16d

Sept. 2010: δF/F~4; ΔT~4d

THE BIG ONE!

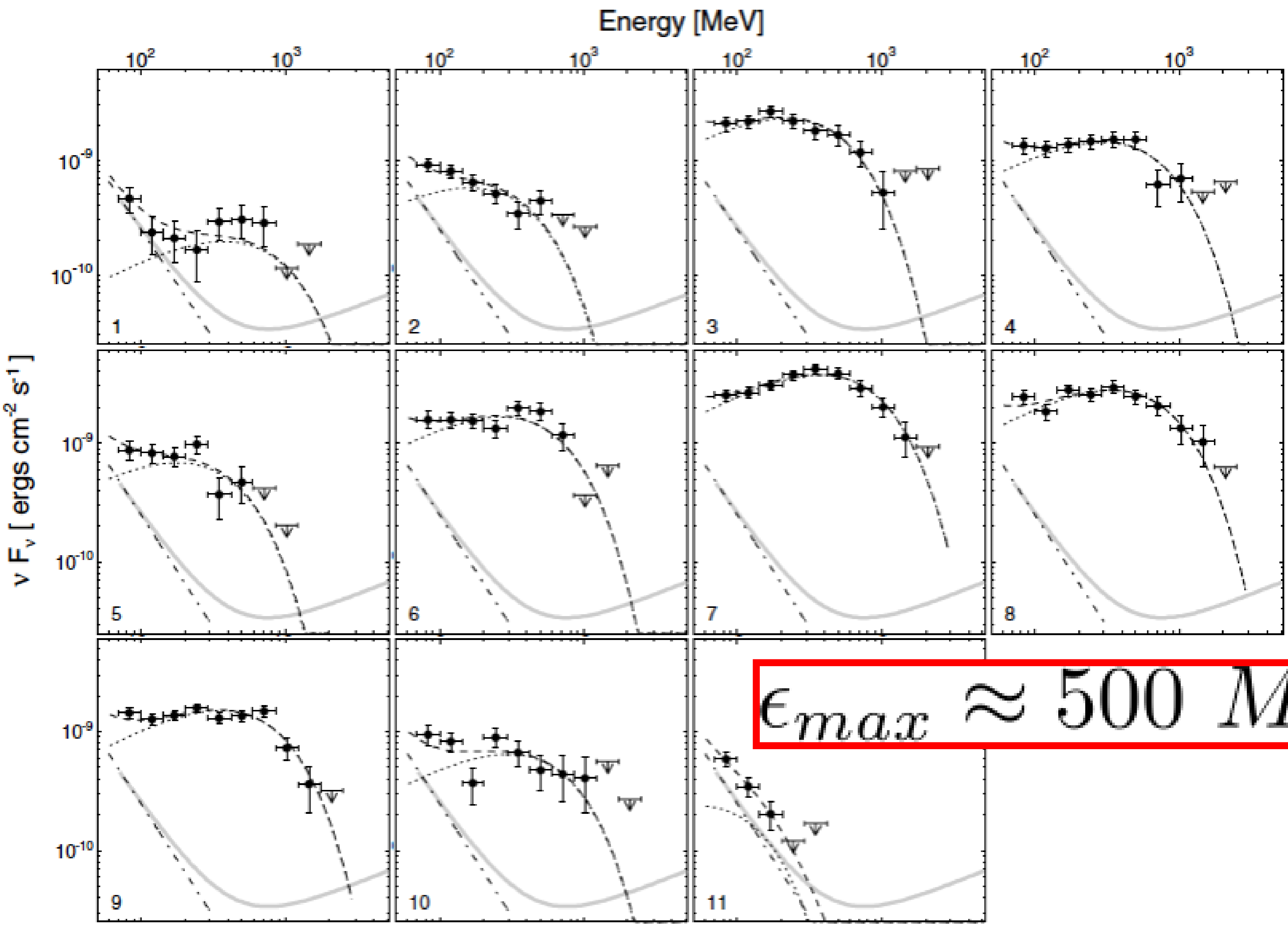
Buehler et al 12

QuickTime™ and a
decompressor
are needed to see this picture.

APRIL 2011:

- **A FACTOR OF 30 INCREASE IN LUMINOSITY**
- **DURATION~10 DAYS**
- **VARIABILITY TIME-SCALE~HOURS**

FLARE SPECTRUM



$$\epsilon_{max} \approx 500\ MeV$$

LOSS-LIMITED ACCELERATION

$$t_{loss} = \frac{E}{(dE/dt)_{sync}} = \frac{6\pi}{\sigma_T}\frac{mc}{B^2\gamma}$$

$$t_{acc} = \frac{E}{(dE/dt)_{acc}} \geq \frac{m\gamma c^2}{e|\vec{E}|c} = \frac{m\gamma c}{feB} \qquad f \leq 1$$

$$t_{acc} = \eta\frac{D_B}{u^2} = \eta\frac{cr_L}{c^2} = \eta\frac{m\gamma c}{eB} \qquad \eta \geq 1$$

$$t_{acc} \leq t_{loss} \quad \Rightarrow \quad \gamma_{\max} = \sqrt{f\frac{6\pi e}{B\sigma_T}} \approx 1.5\times10^{10}\frac{\sqrt{f}}{\sqrt{B[100\,\mu G]}}$$

$$\varepsilon_{\max} = \frac{3h}{2}\frac{eB}{2\pi mc}\gamma_{\max}^2 = f\,\frac{9h}{2}\frac{e^2}{mc\sigma_T} \approx 230\, f\ MeV$$

NOTE: ALREADY FERMI STEADY IS CHALLENGING!!!!

EXOTIC ACCELERATION PHYSICS?

WHAT CAN HELP….

- **E-FIELDS LARGER THAN B-FIELD (LIKE IN RECONNECTION LAYERS)**
- **RELATIVISTIC BOOSTING: HELPS WITH CUT-OFF FREQUENCY AND TIME-SCALES**

MORE TOMORROW….

- **MHD MODELING**
- **PARTICLE ACCELERATION MECHANISMS**
- **SOURCES OF VARIABILITY IN PWNE AND THEIR TIME-SCALES**