Detecting Gamma Rays

Part 1: MeV and GeV gamma rays and the high-energy universe

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International School of Astro-Particle Physics, Paris 2012

OUTLINE

Lecture 1: Context and HE gamma rays

- Gamma Rays
- Context: gamma ray astrophysics
- MeV gamma ray detection
- GeV gamma ray detection
- Gamma-ray interactions in the atmosphere

Lecture 2: VHE gamma rays

- The atmospheric Cherenkov technique (history and method)
- Other detection methods
- Current and future instruments
- Signal extraction and background modelling

OUTLINE

Gamma Rays

Context: gamma ray astrophysics

MeV gamma ray detection

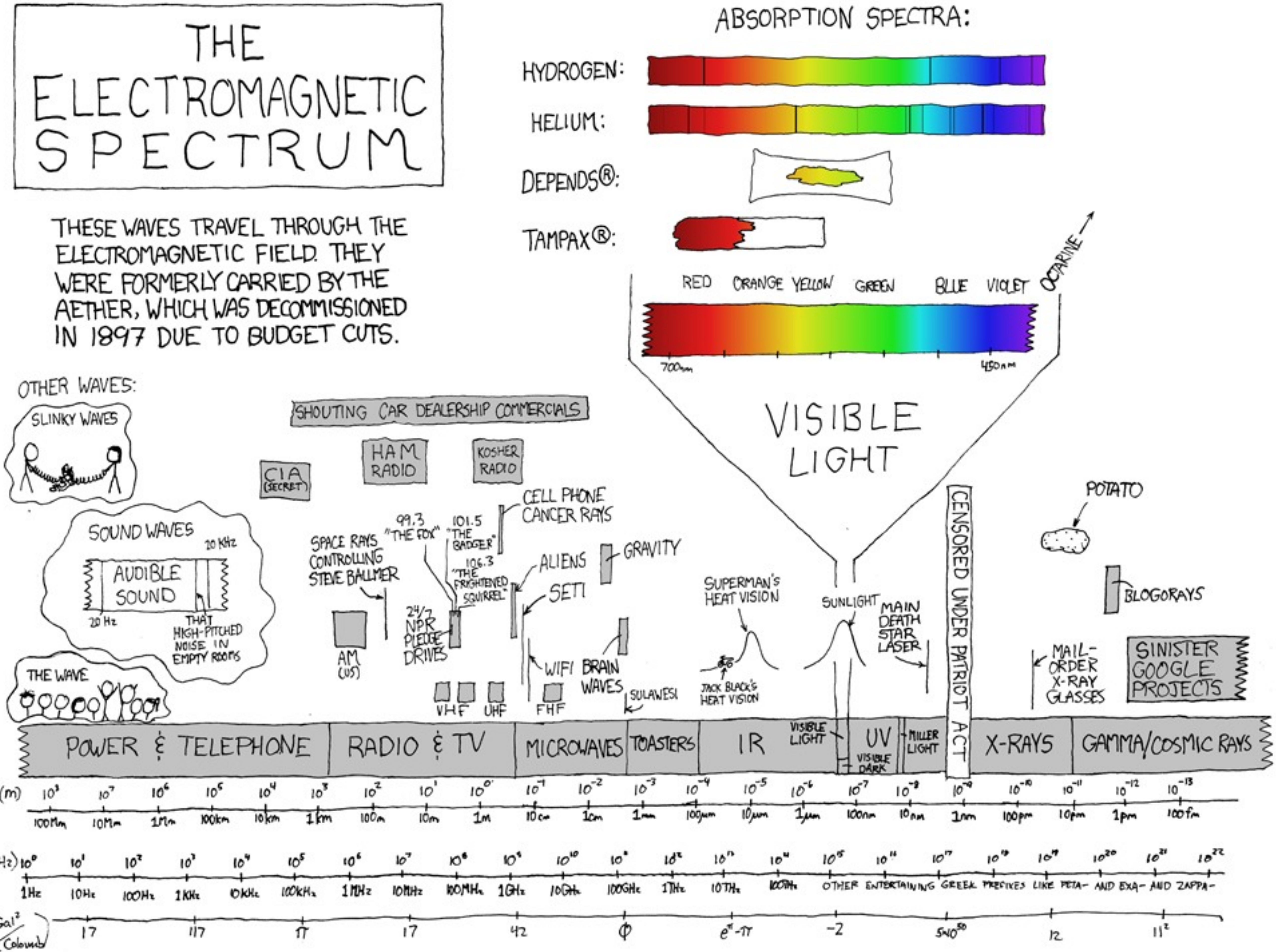
GeV gamma ray detection

Gamma-ray interactions in the atmosphere

Gamma Rays

Characteristics of high-energy radiation

http://xkcd.com/273/



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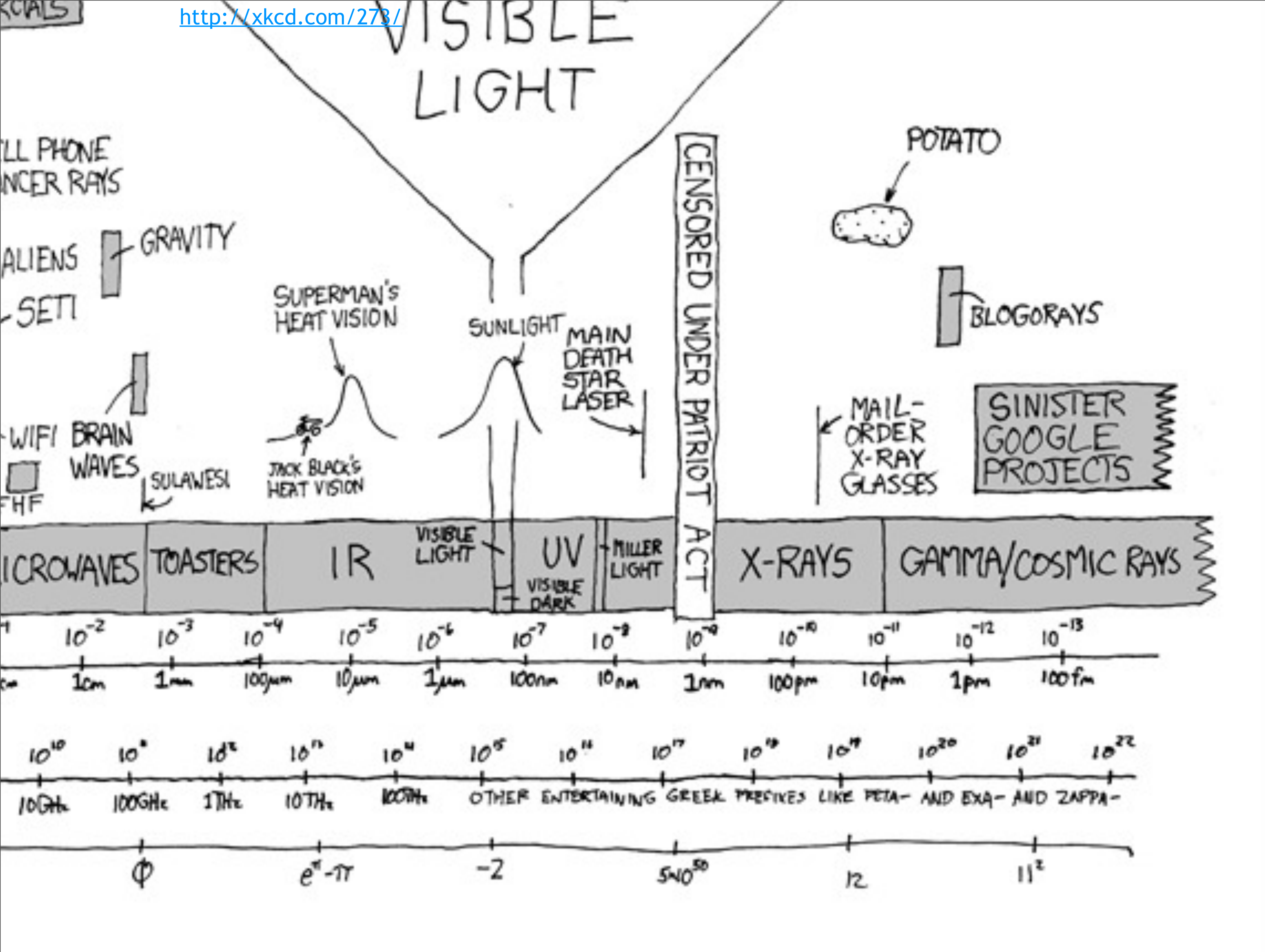

Gamma Rays

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Definitions:

- Medium-Energy Gamma Rays **(MeV)**
- High-Energy (HE) Gamma Rays **(100 MeV-50 GeV)**
- Very-high-energy Gamma-Rays **(50 GeV - 100 TeV)**

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Astrophysical gamma rays:

- indicate the presence of a parent population of high-energy massive particles
- little effect from absorption in the galaxy
- carry information directly from the sites of acceleration

Gamma Ray Astrophysics

Allows the study of:

- Non-thermal processes
- the highest energy window in the EM spectrum
- the "most violent places in the universe"
  - extreme densities, masses
  - intense radiation fields
  - ultra-relativistic outflows/jets
  - energetic shock waves and turbulence

Gamma Ray Astrophysics

a multi-disciplinary field!

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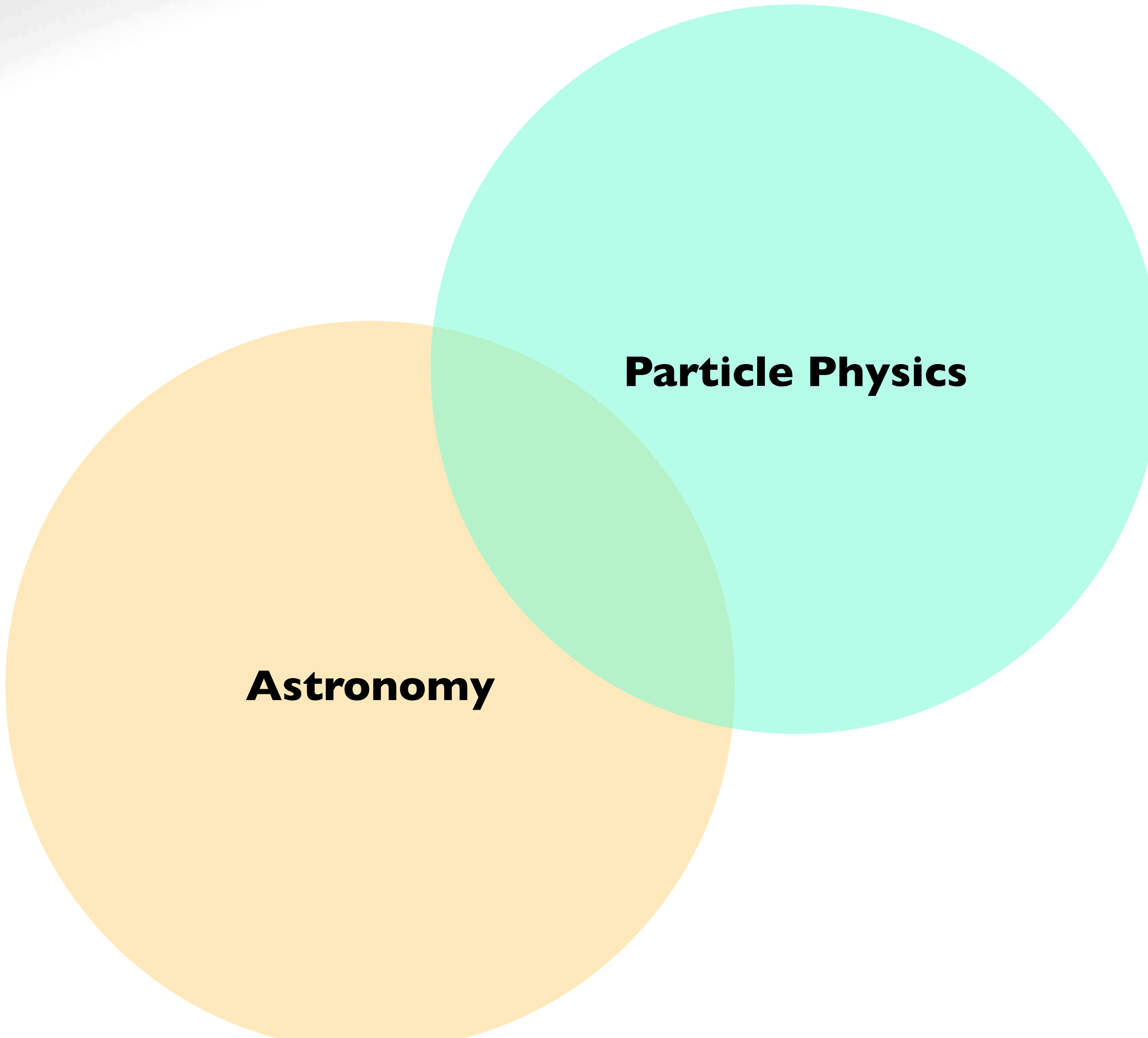

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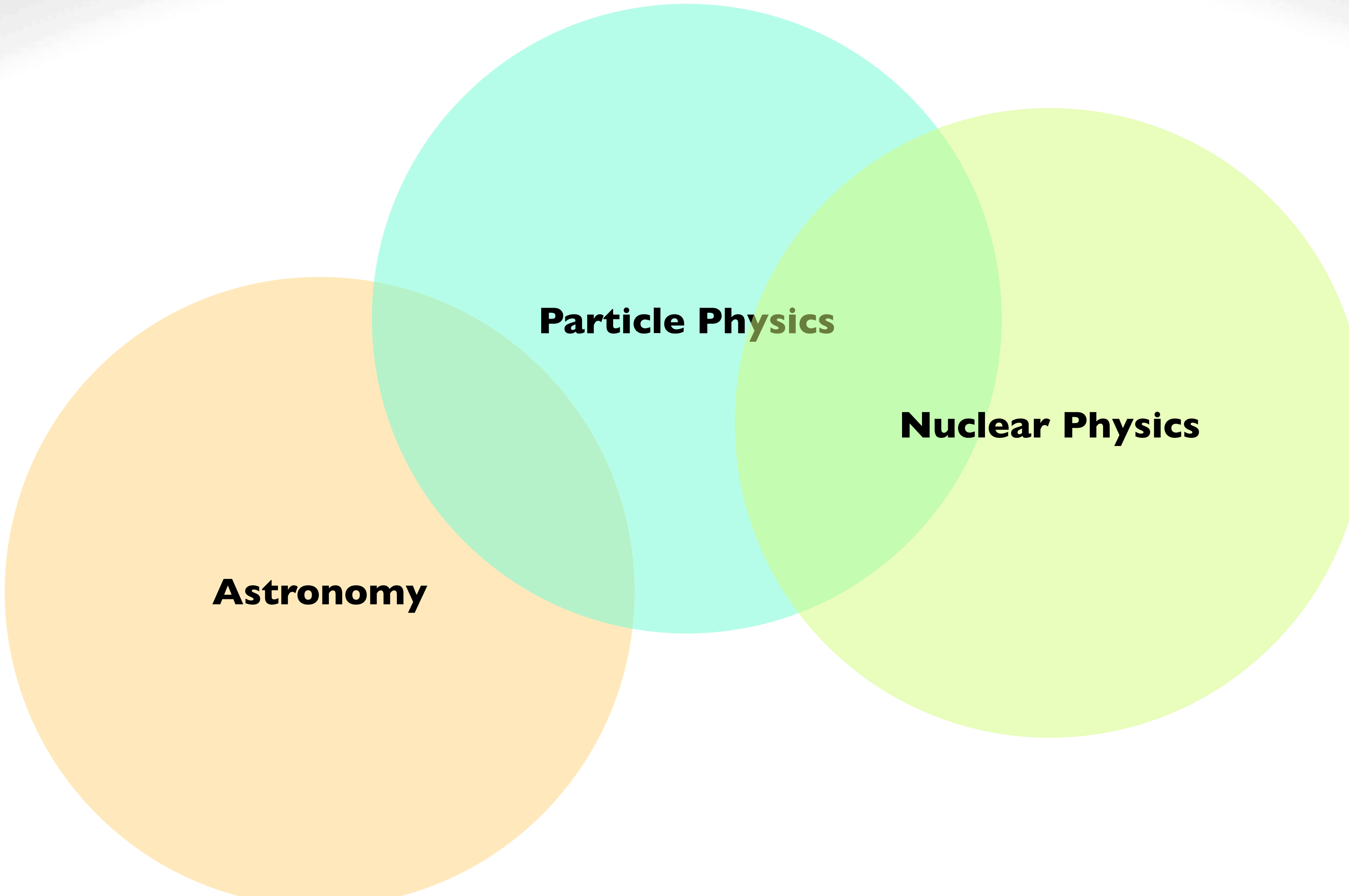

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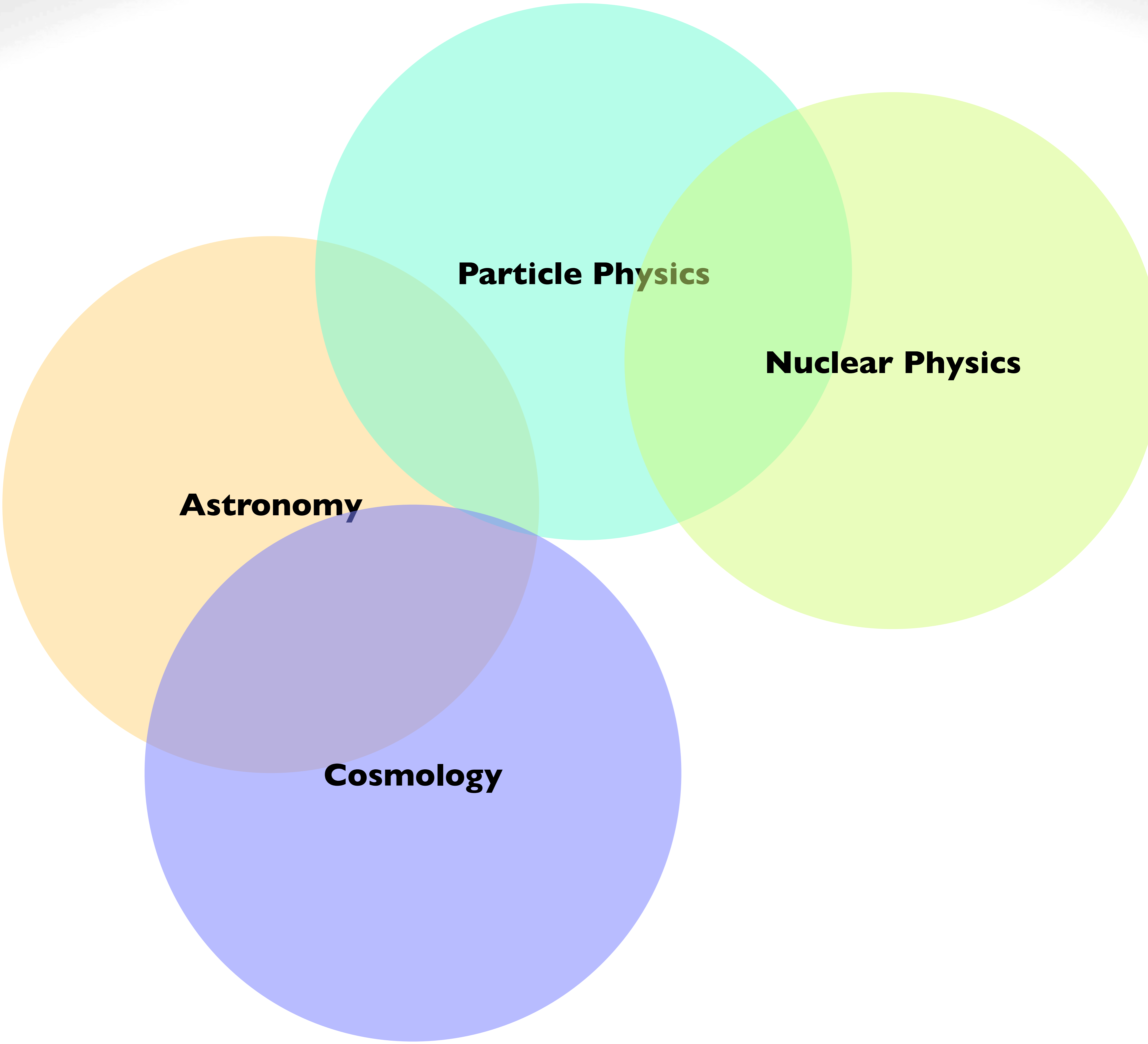

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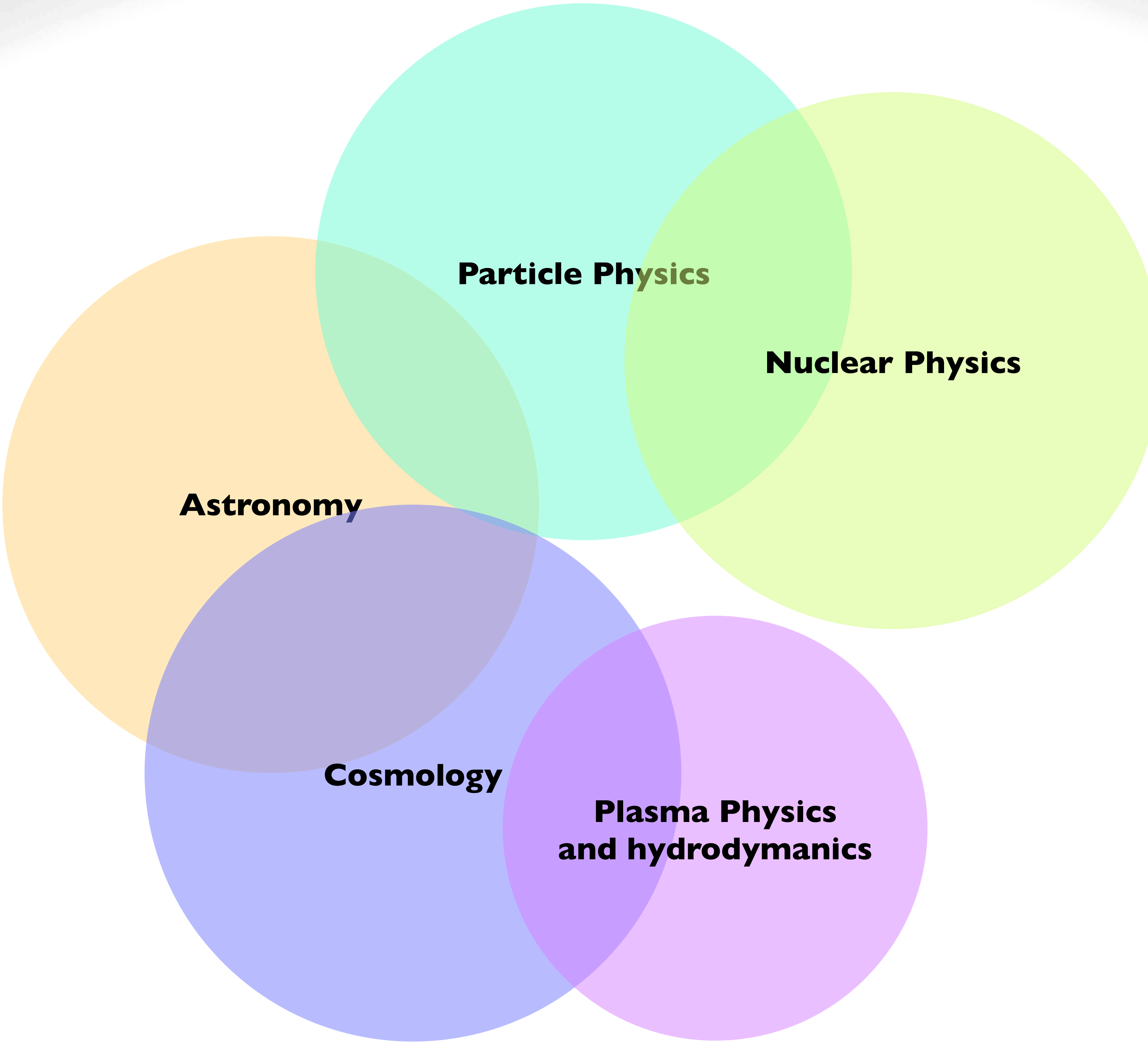

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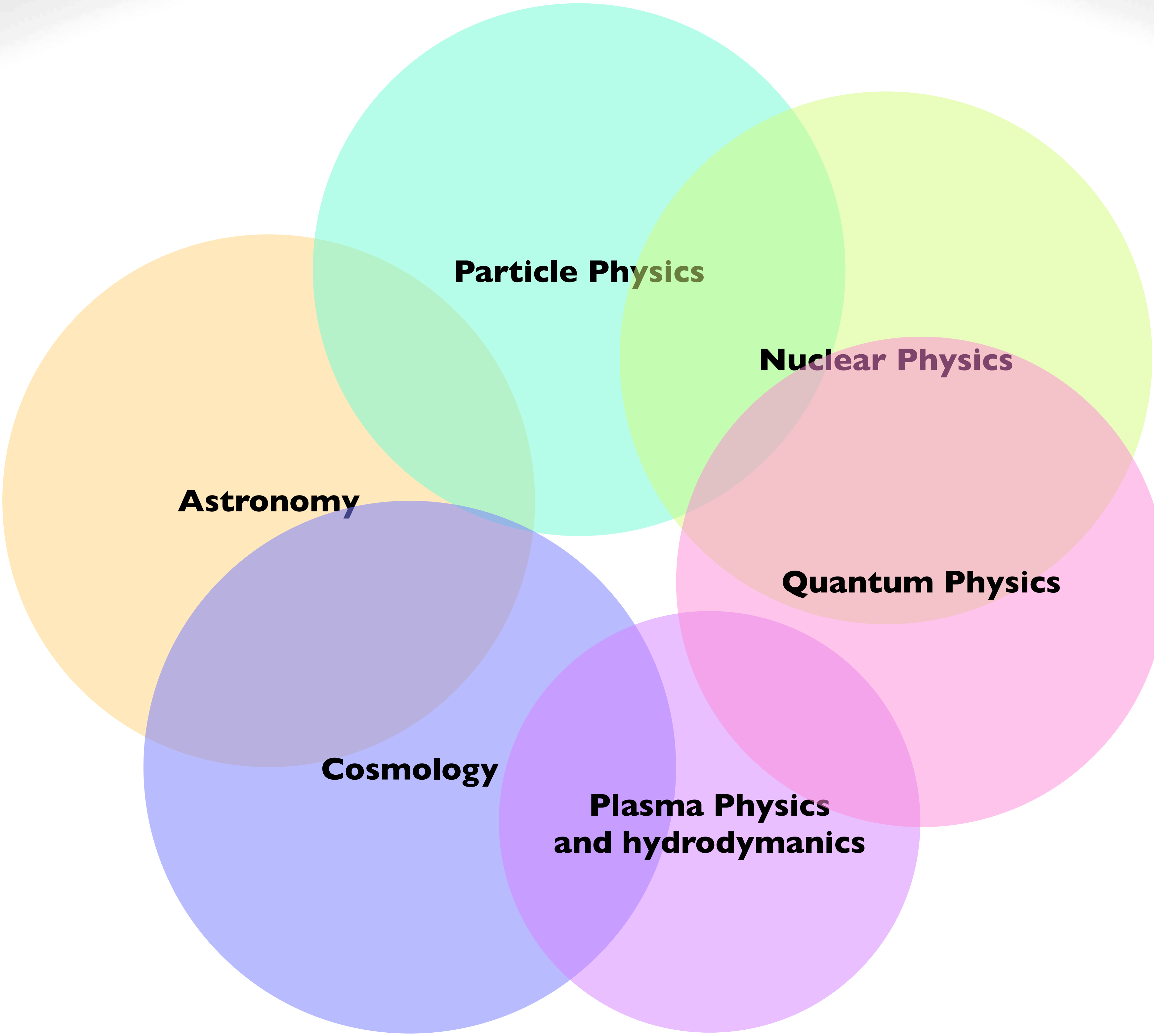

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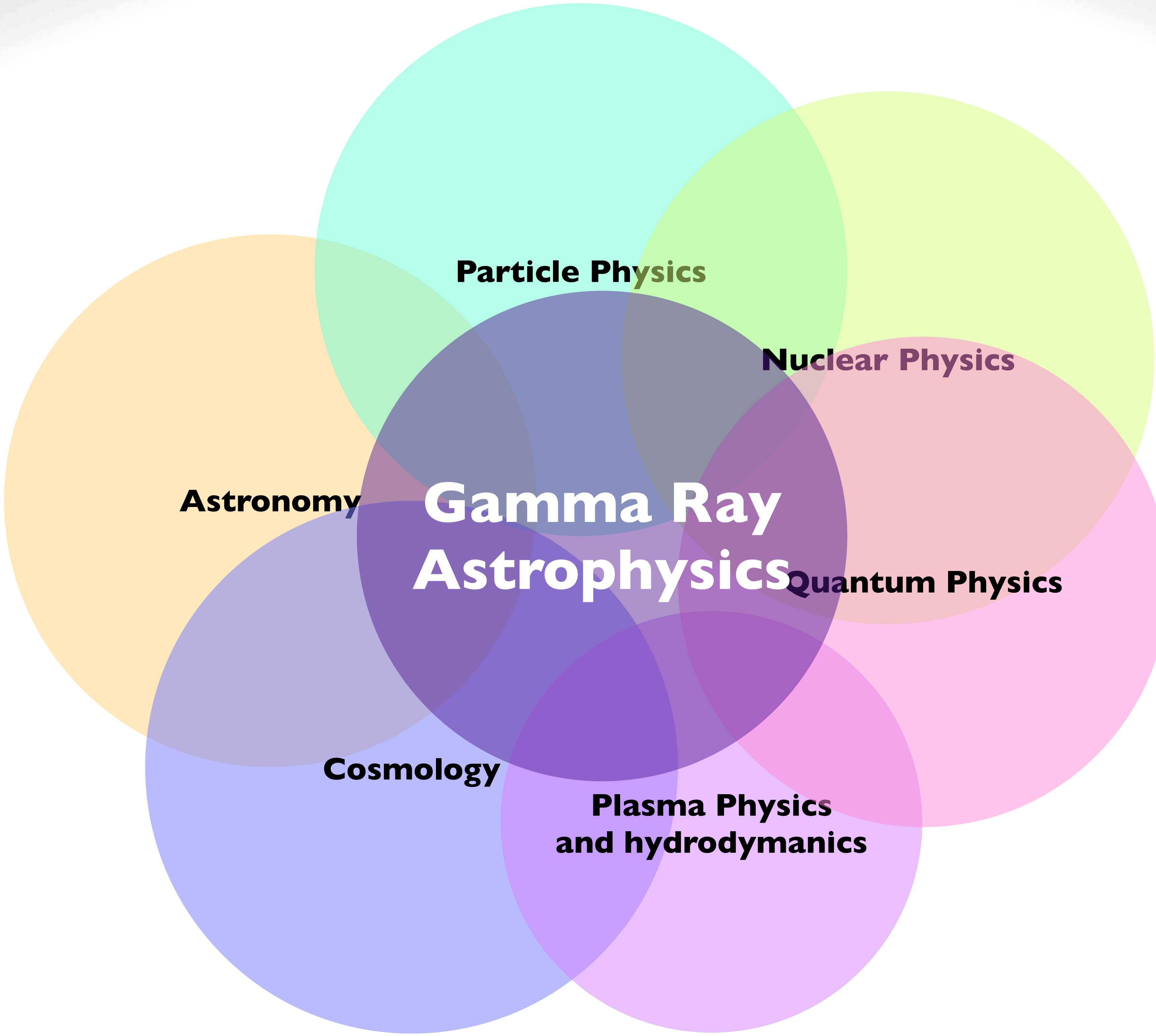

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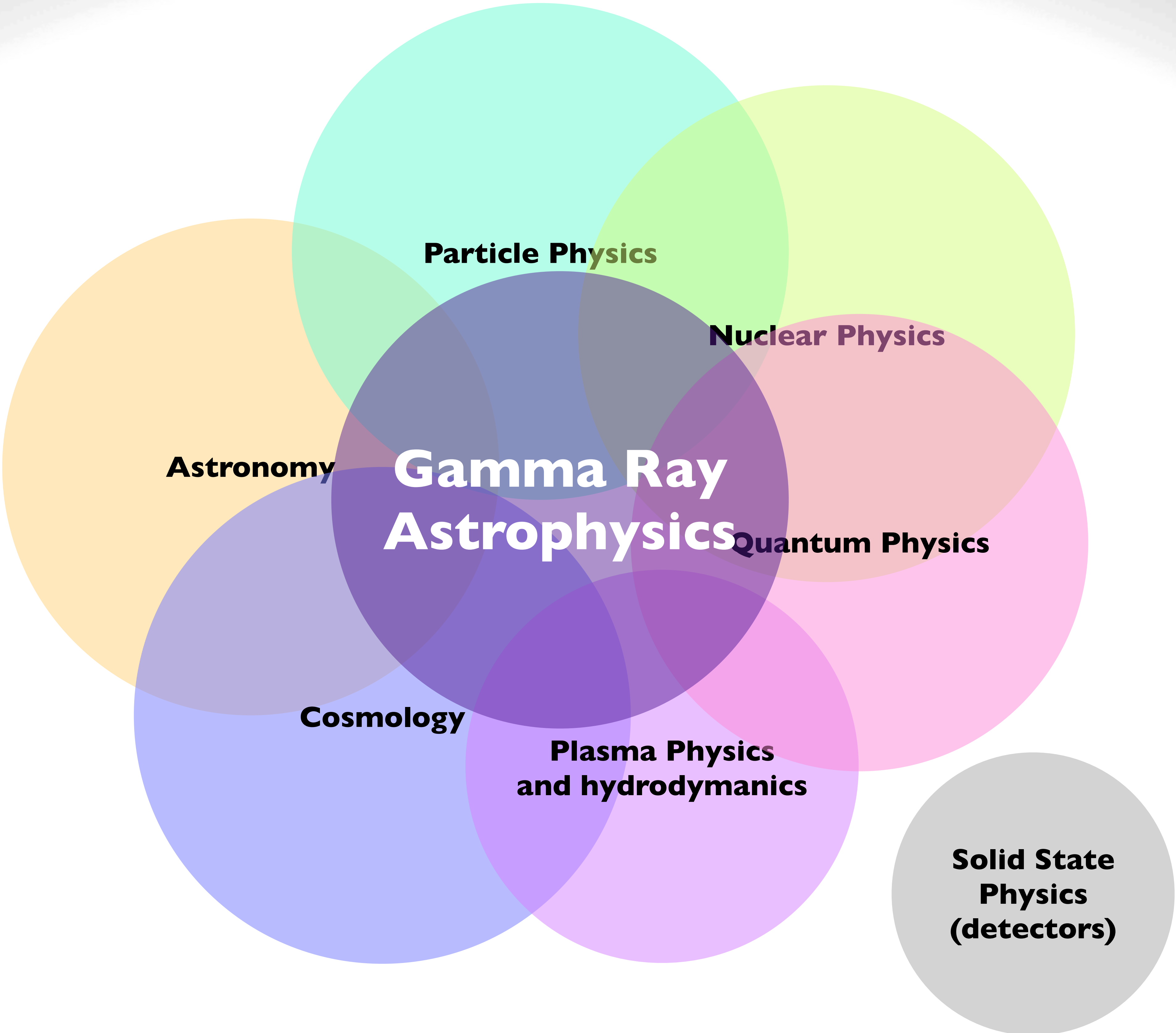

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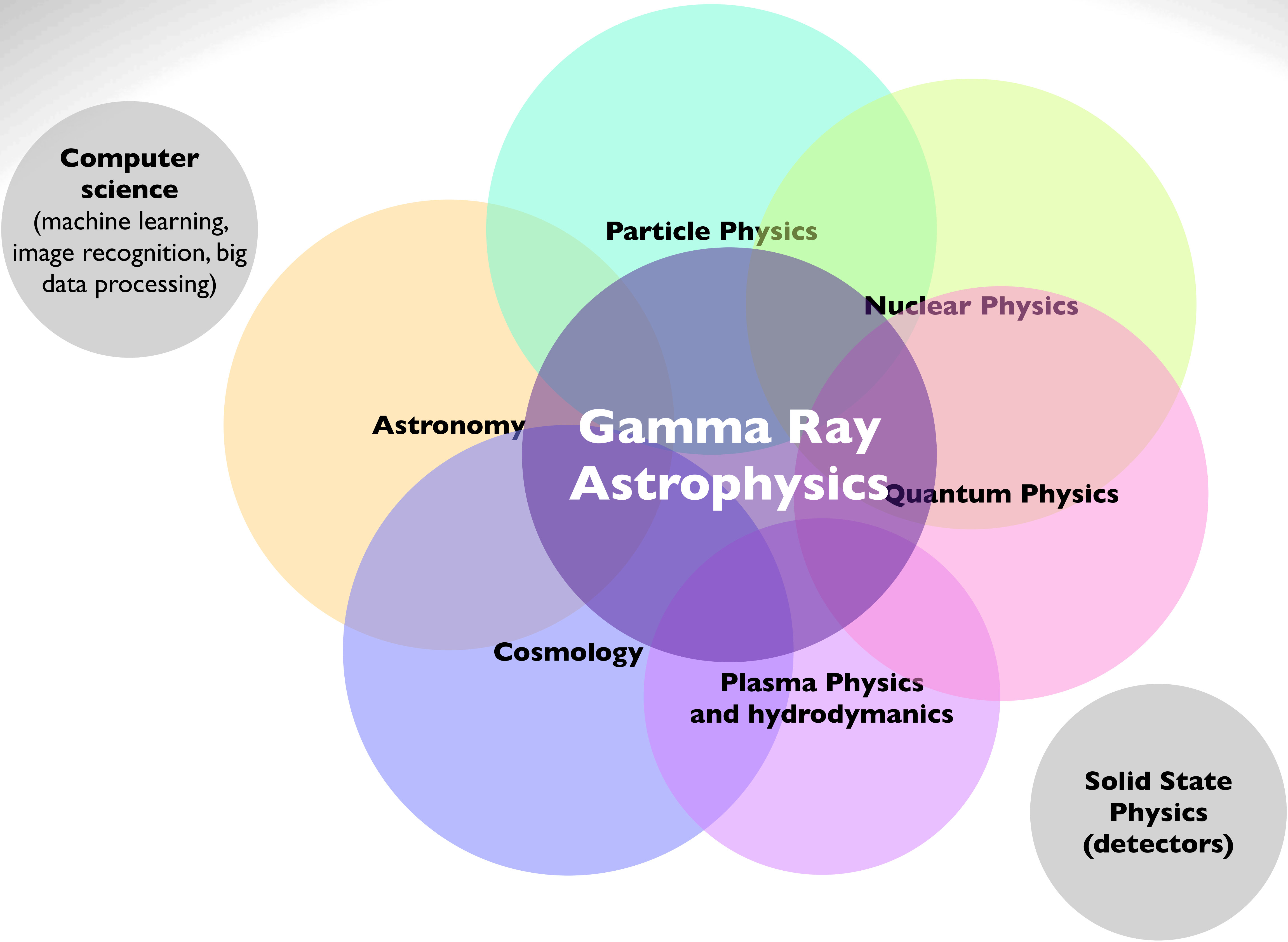
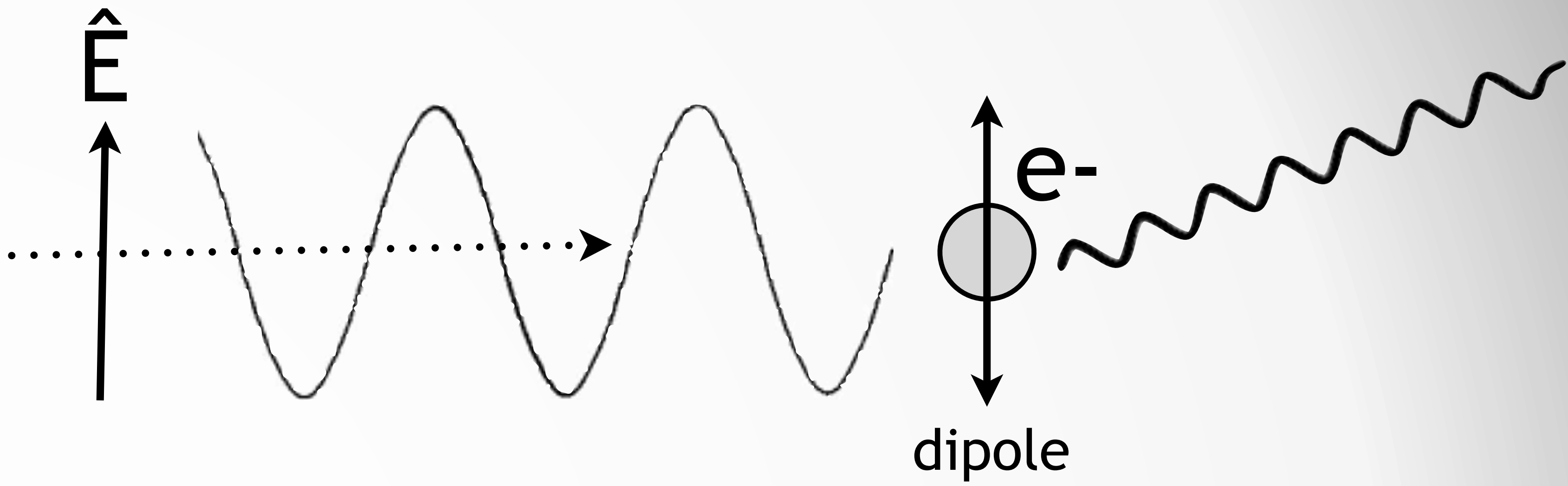


First, a quick reminder of the last lecture…

particle interactions



Recall: Thomson Scattering

- $\mathbf{F} = m\mathbf{a} = q\mathbf{E}\sin(\omega_0 t)$
- $h\nu \ll mc^2$
- Completely elastic
  - no change in energy (frequency) of scattered photon

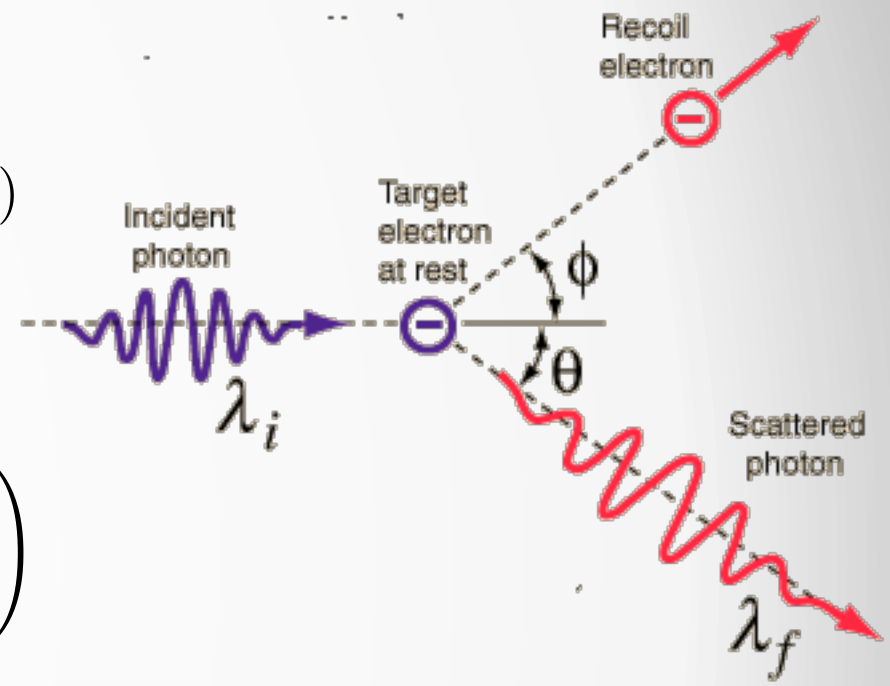
$$\sigma_t = \frac{8}{3}\pi r_e$$

$$r_e \equiv \frac{e^2}{m_e c^2}$$ (CGS units)

Including relativity, we get Compton scattering:

$$\mathbf{P}^i_\gamma = \frac{E^i_\gamma}{c}(1, \hat{n}_i)$$

$$\mathbf{P}^f_\gamma = \frac{E^f_\gamma}{c}(1, \hat{n}_f)$$

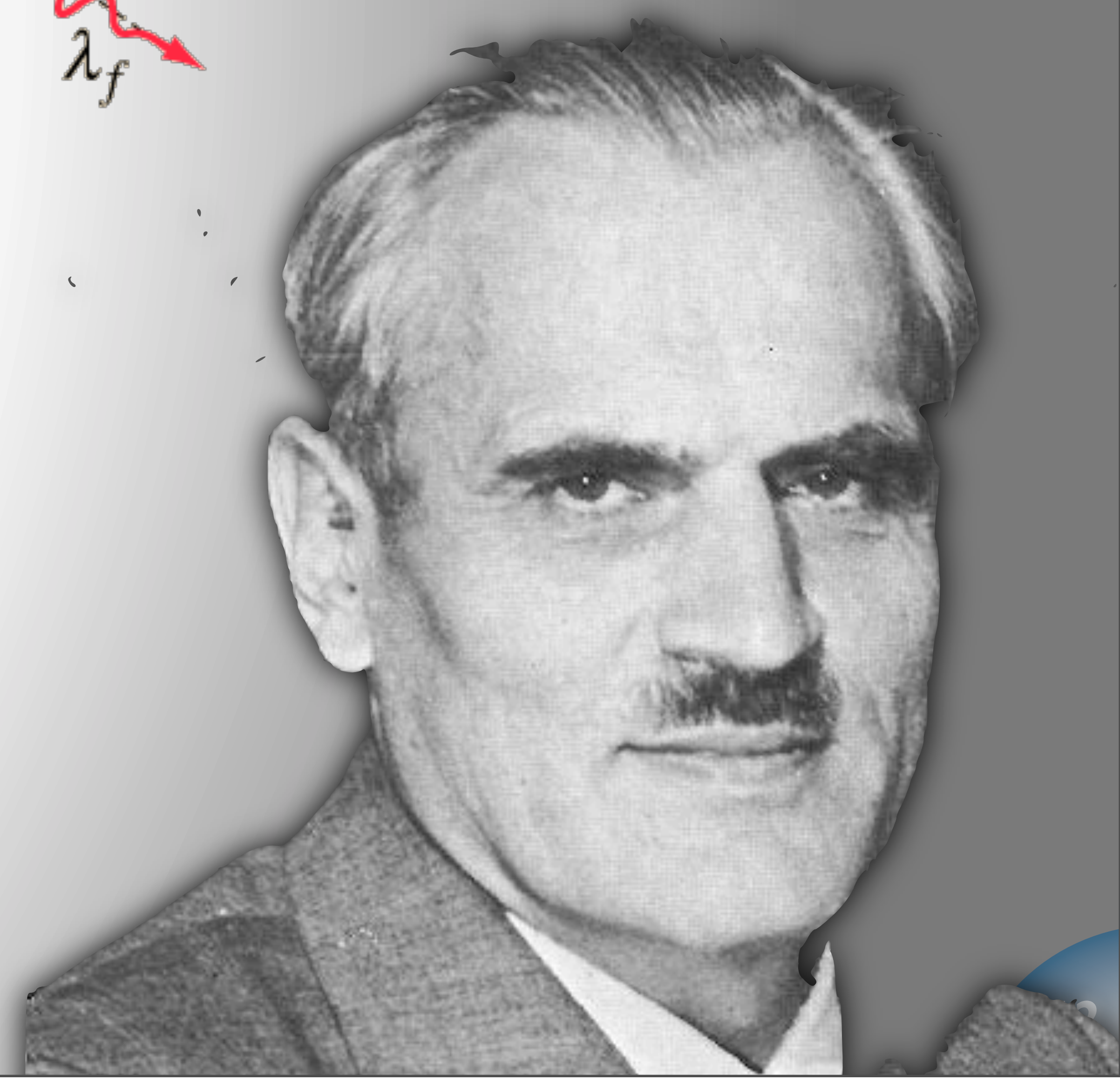


$$\mathbf{P}^i_{e^-} = (m_e c, \vec{0})$$

$$\mathbf{P}^f_{e^-} = \left(\frac{E^f_{e^-}}{c}, \vec{p}\right)$$

$$\mathbf{P}^i_\gamma + \mathbf{P}^i_{e^-} = \mathbf{P}^f_\gamma + \mathbf{P}^f_{e^-}$$

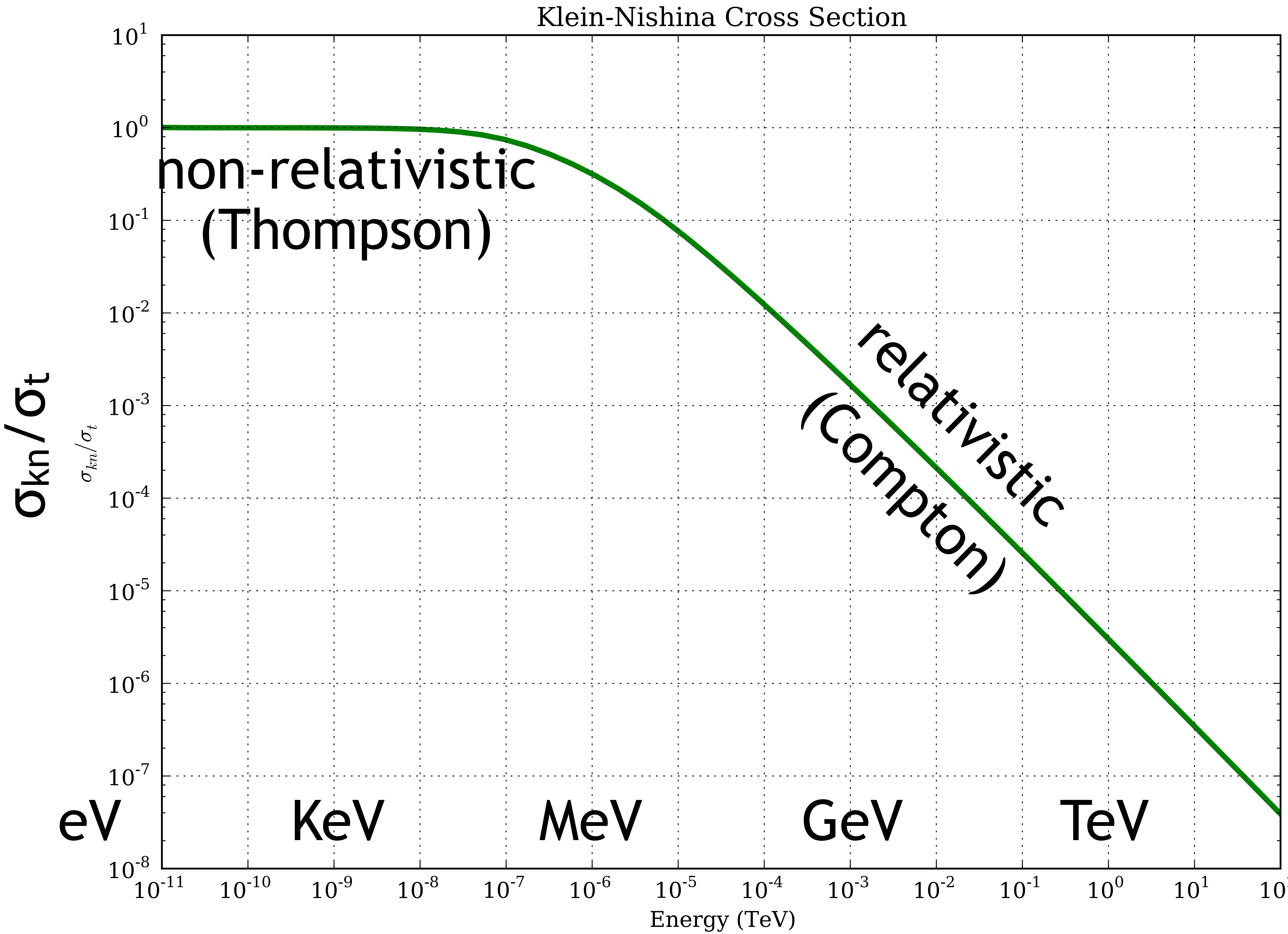
Compton Scattering



- Initial and final energy of the electron is not the same (electron gains energy in recoil)

$$\lambda_f - \lambda_i = \frac{h}{m_e c}(1 - \cos\theta)$$

- Cross-section is energy-dependent (Klein Nishina)


Klein-Nishina Cross Section
non-relativistic
(Thompson)
relativistic
(Compton)
σkn/σt
σ_{kn}/σ_t
eV
KeV
MeV
GeV
TeV
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
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Energy (TeV)

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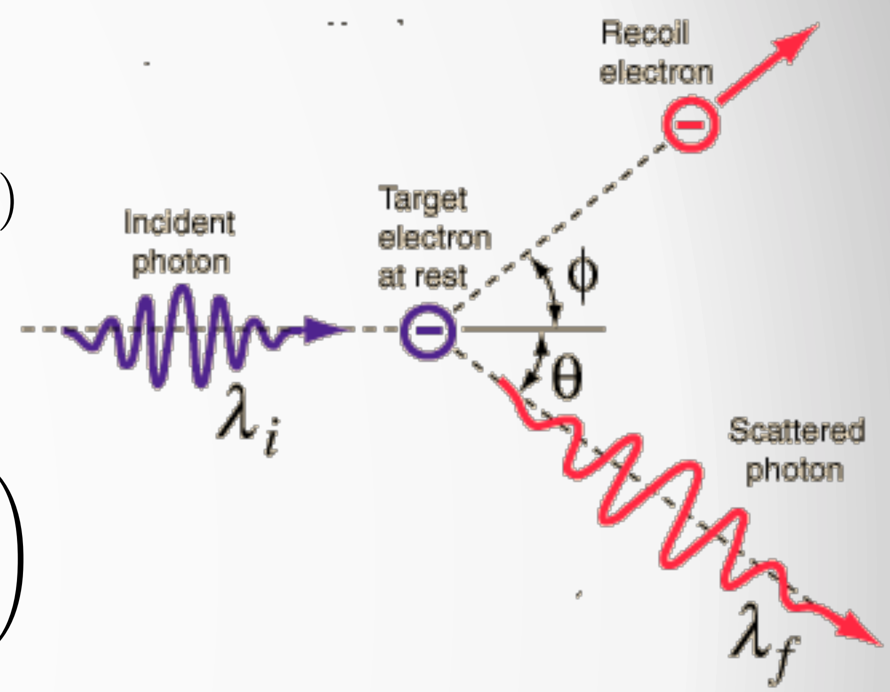

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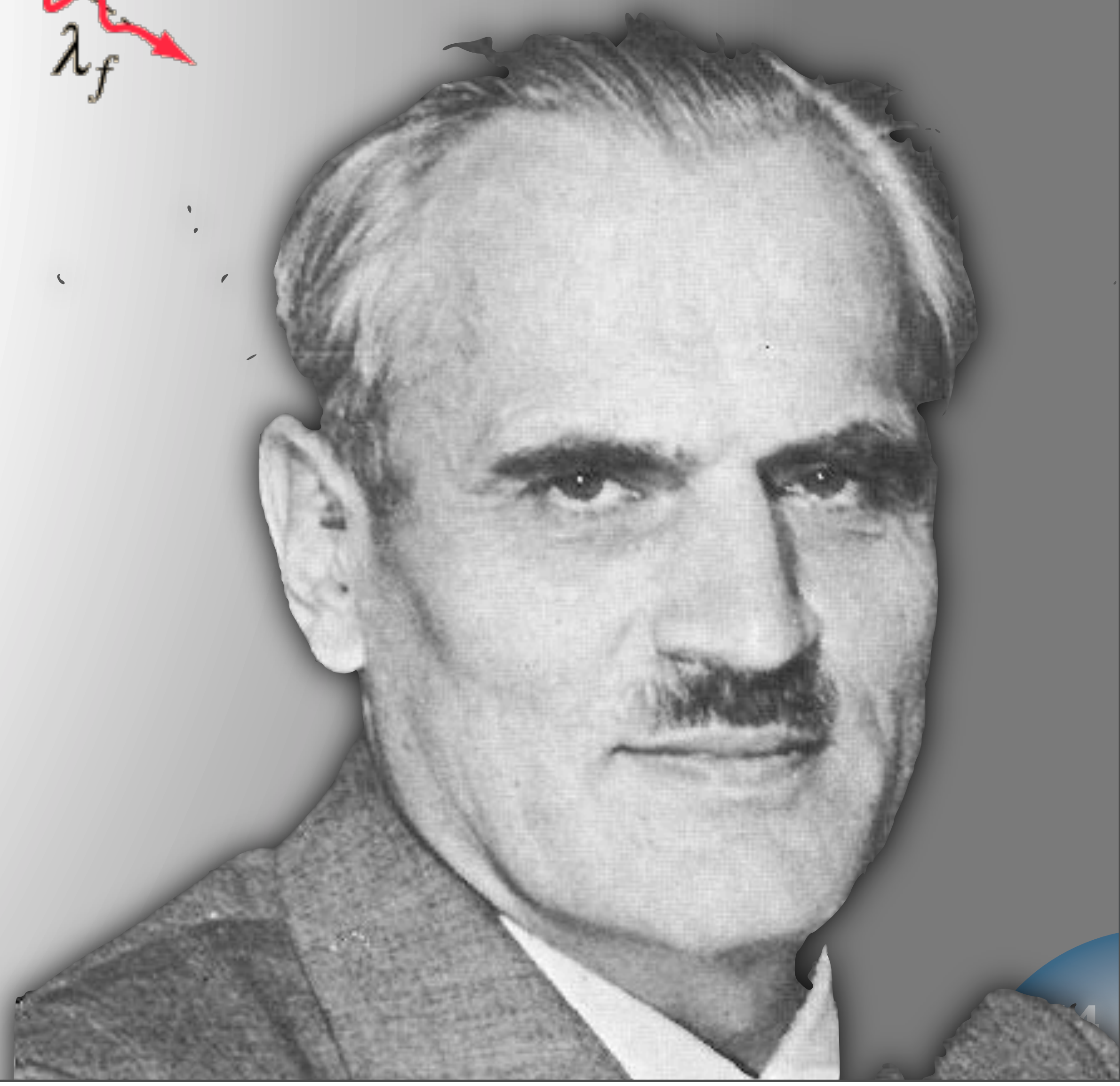
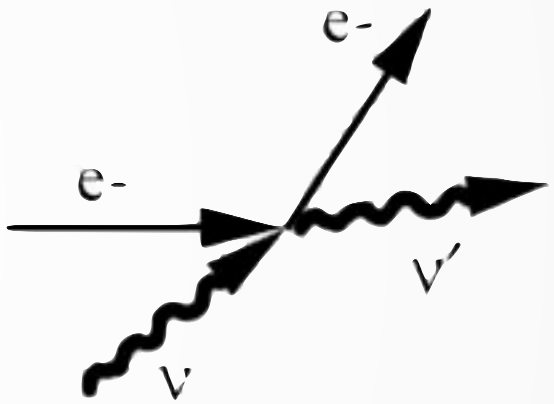


Case where scattering particle is not at rest

- Electron starts out with large amount of energy (ultra-relativistic)
- the photon may now <u>gain</u> energy from the electron (upscattering)



Important in high-energy astrophysics:

- populations of high-energy particles can upscatter radio, CMBR, optical, etc photons to GeV - TeV energies!
- therefore **when you have high-energy electrons, you can see them with gamma-ray telescopes**!

Inverse-Compton

Pair Produciton

$$\gamma \rightarrow e^{+} + e^{-}$$

Creation of a particle-antiparticle pair when a gamma-ray interacts with another particle

- typically a nucleus in the detector medium or in Earth's atmosphere

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Nope.

- good! gamma rays travel relatively unimpeded from source to a detector.

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But... We never really have free space

- extra-galactic background light! (more on this later...)
- light-by-light scattering has a very small cross section, but it is non-zero and distances in space are large!
- implies an energy-dependent distance limit to how far gamma-rays can travel

Pair Produciton

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

Cosmic Rays

A large level of ionizing radiation can be detected on Earth

Originally assumed to be from underground radiation sources.

Victor Hess in 1912:

- Balloon flight with an electroscope for measuring radiation level
- Expected radiation to *decrease* as one moves further from the ground
- The opposite is true:
  - implies cosmic origin of these particles

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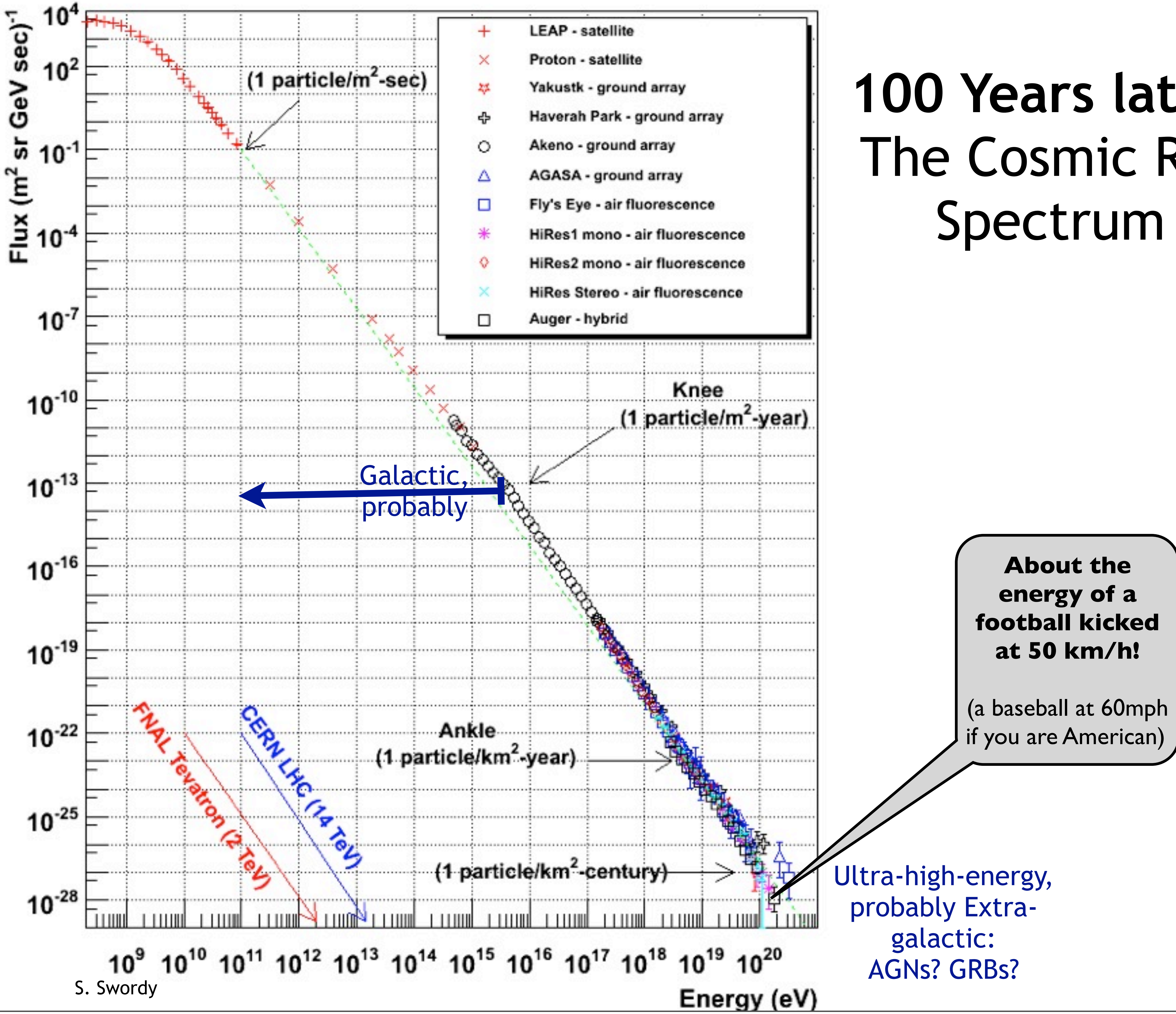
100 Years later: The Cosmic Ray Spectrum



S. Swordy

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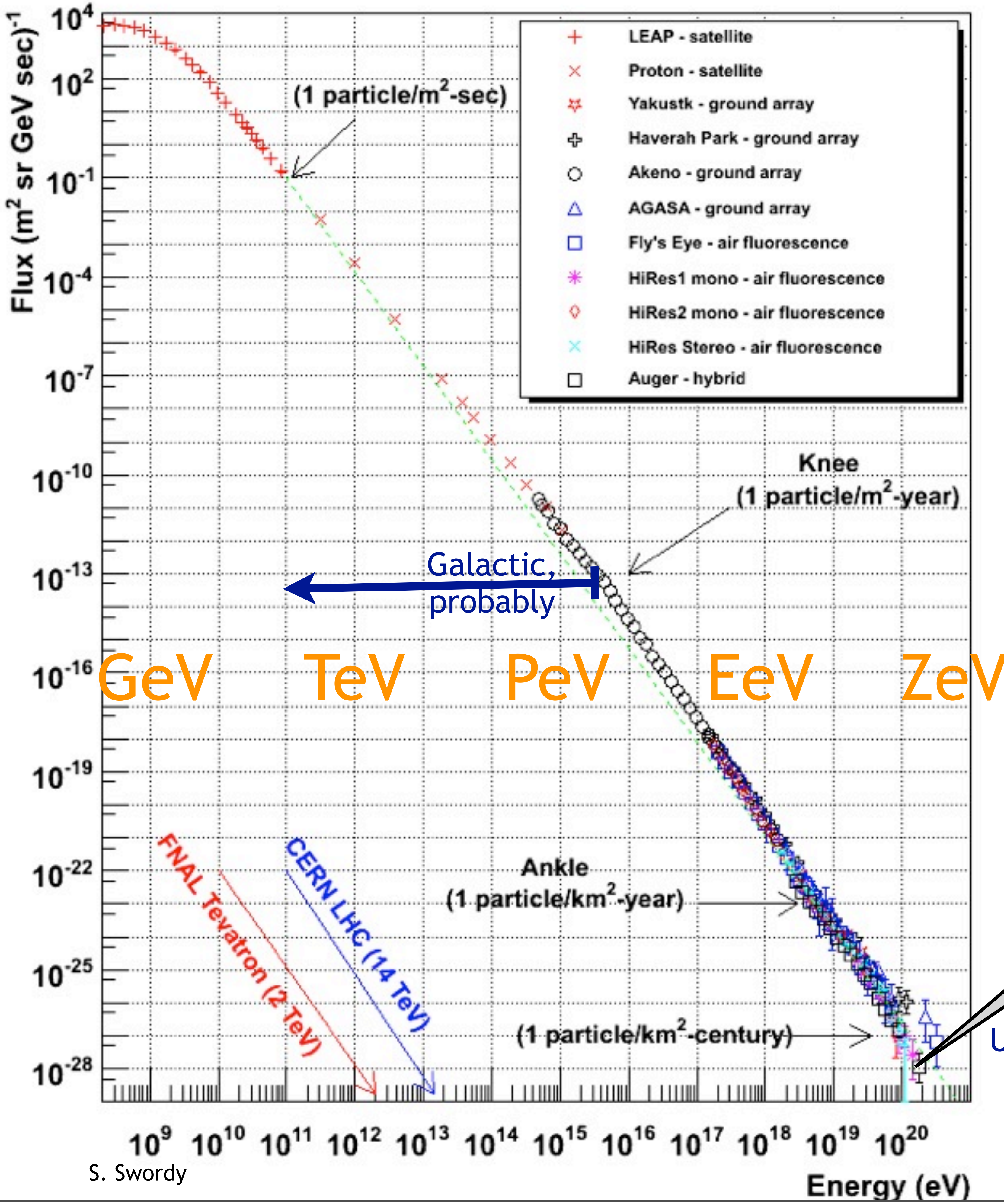


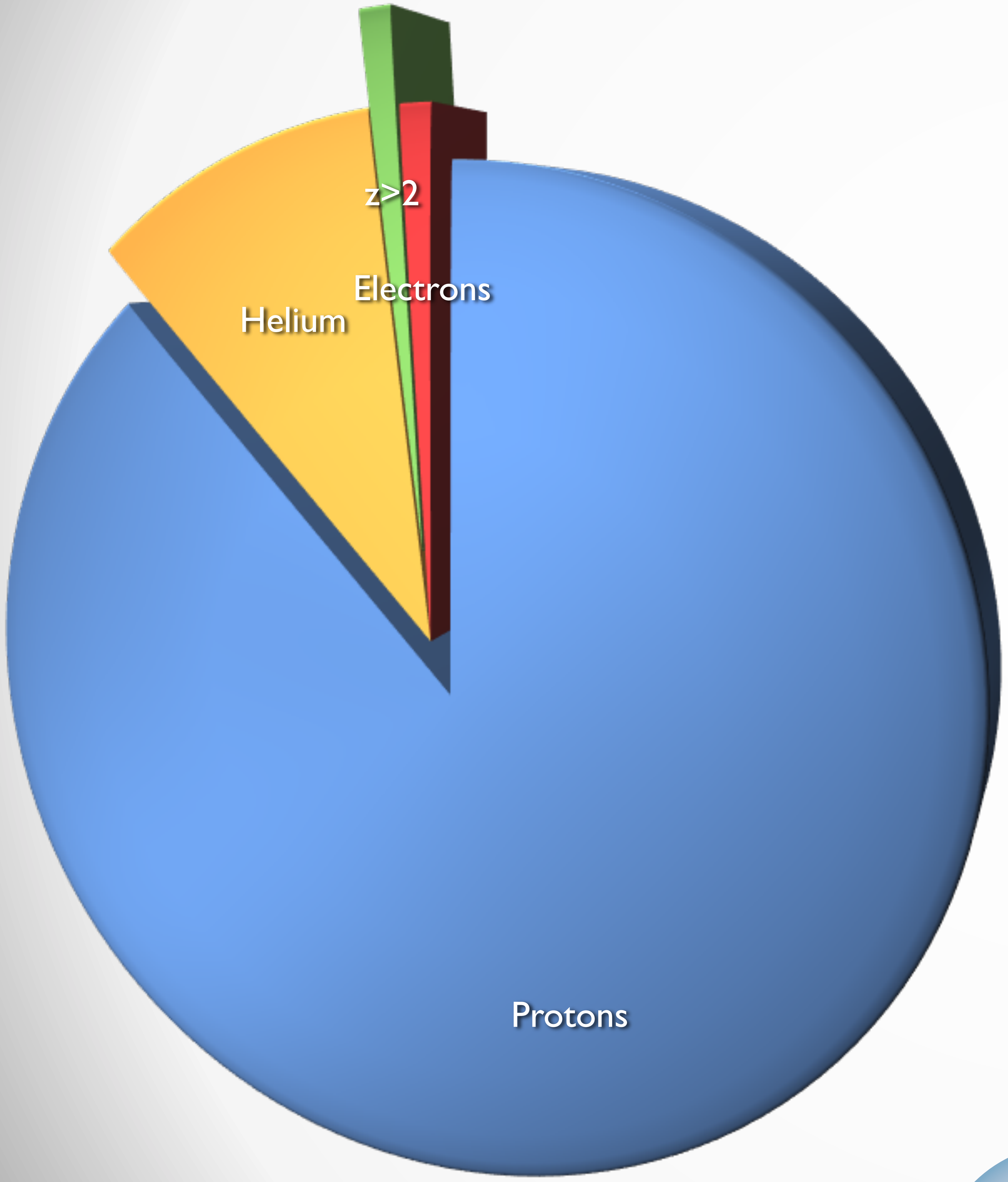
S. Swordy

About the energy of a football kicked at 50 km/h!

(a baseball at 60mph if you are American)

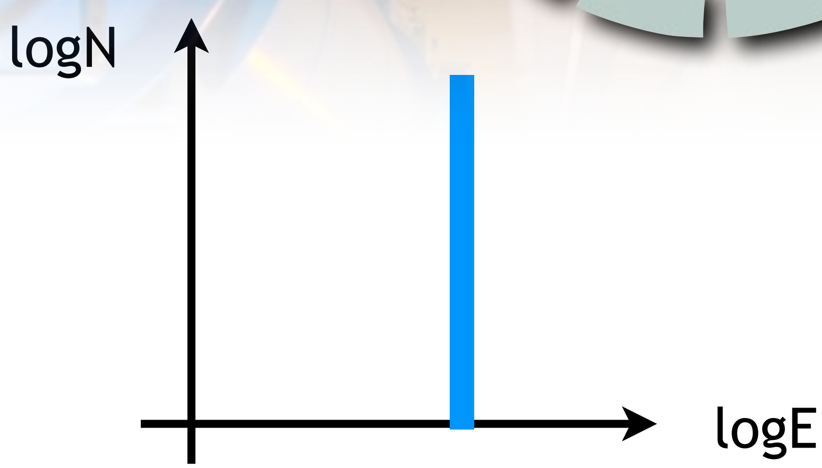
Ultra-high-energy, probably Extra-galactic: AGNs? GRBs?

Cosmic Rays detected at Earth



Particle Accelerators

Man-made accelerators



Particles are accelerated in radio-frequency cavities

Mono-energetic "beam" of particles
E ≈ 10 TeV

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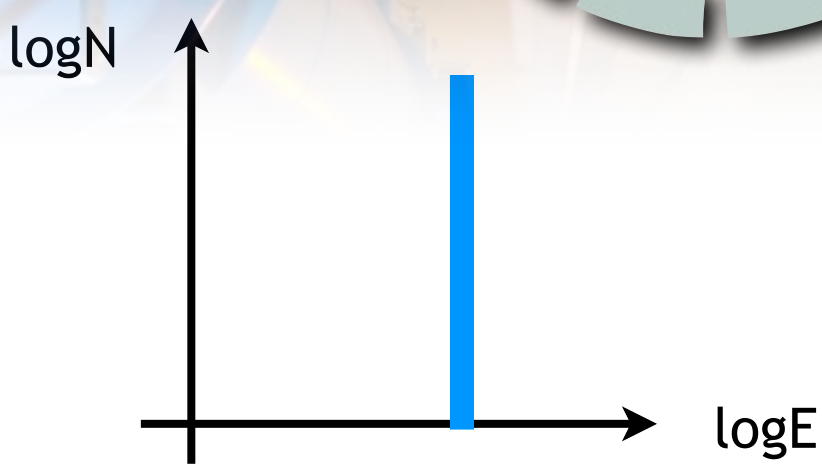

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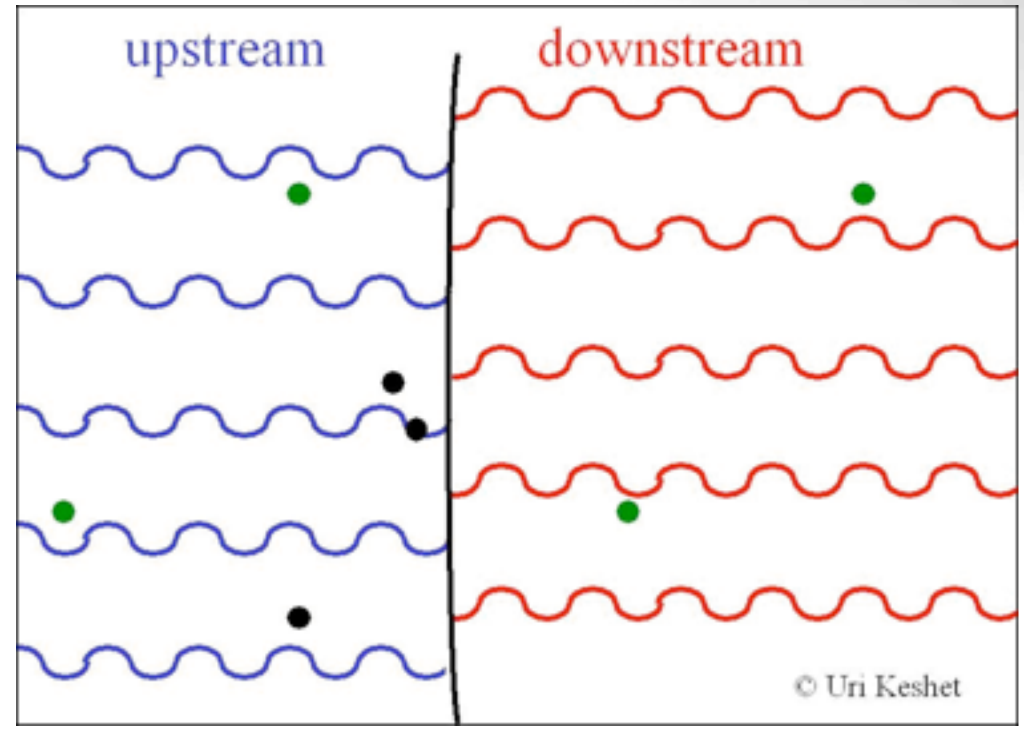
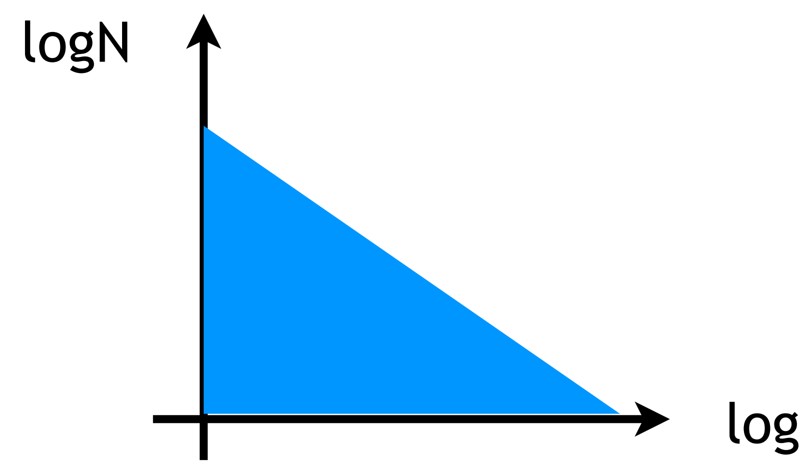




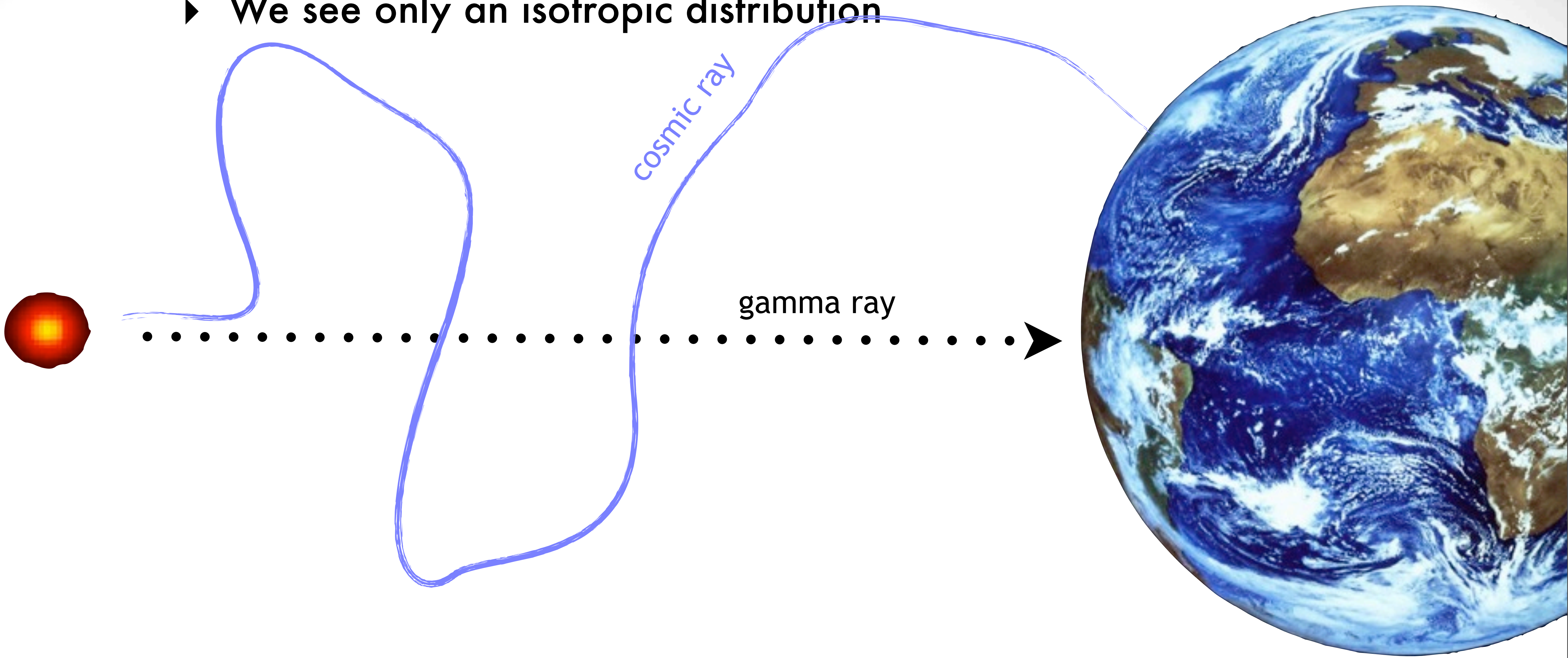
Particles are accelerated in shocks

power-law distribution of particle energies
E as high as PeV!

Cosmic Ray Origin

The cosmic rays we detect at earth (except the very highest-energies) do not point back to their source

- We see only an isotropic distribution



Gamma rays allow us to "see" the sites of acceleration of cosmic rays!

Gamma Ray Production

Leptonic gamma-ray production:

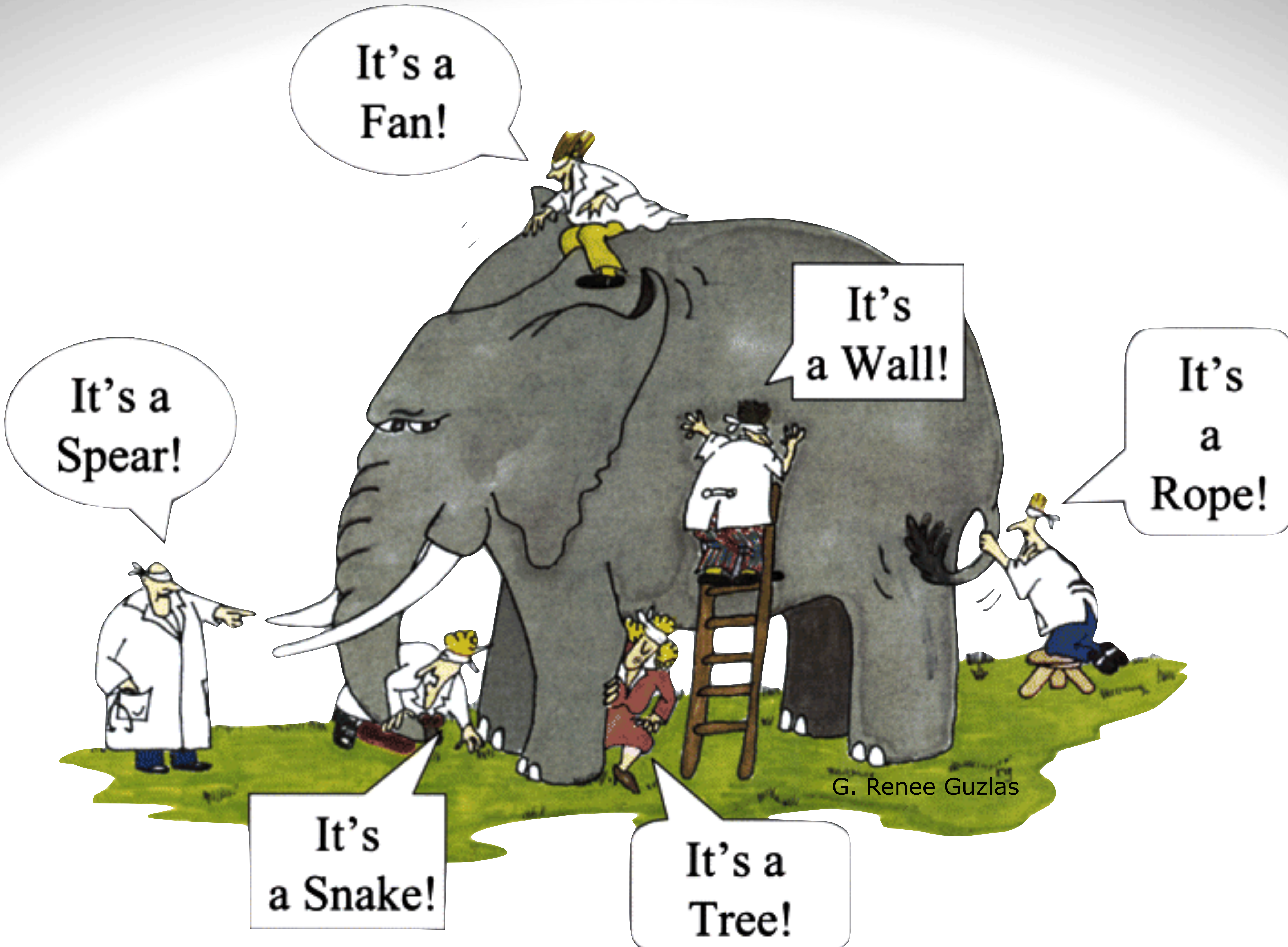
- Start with a population of energetic electrons/positrons
- gamma rays produced via **Inverse-Compton upscattering** of surrounding photon fields
  - the CMBR is a nice target! (and it's always there)
  - could also be synchrotron photons produced by the electron population itself

Hadronic gamma-ray production:

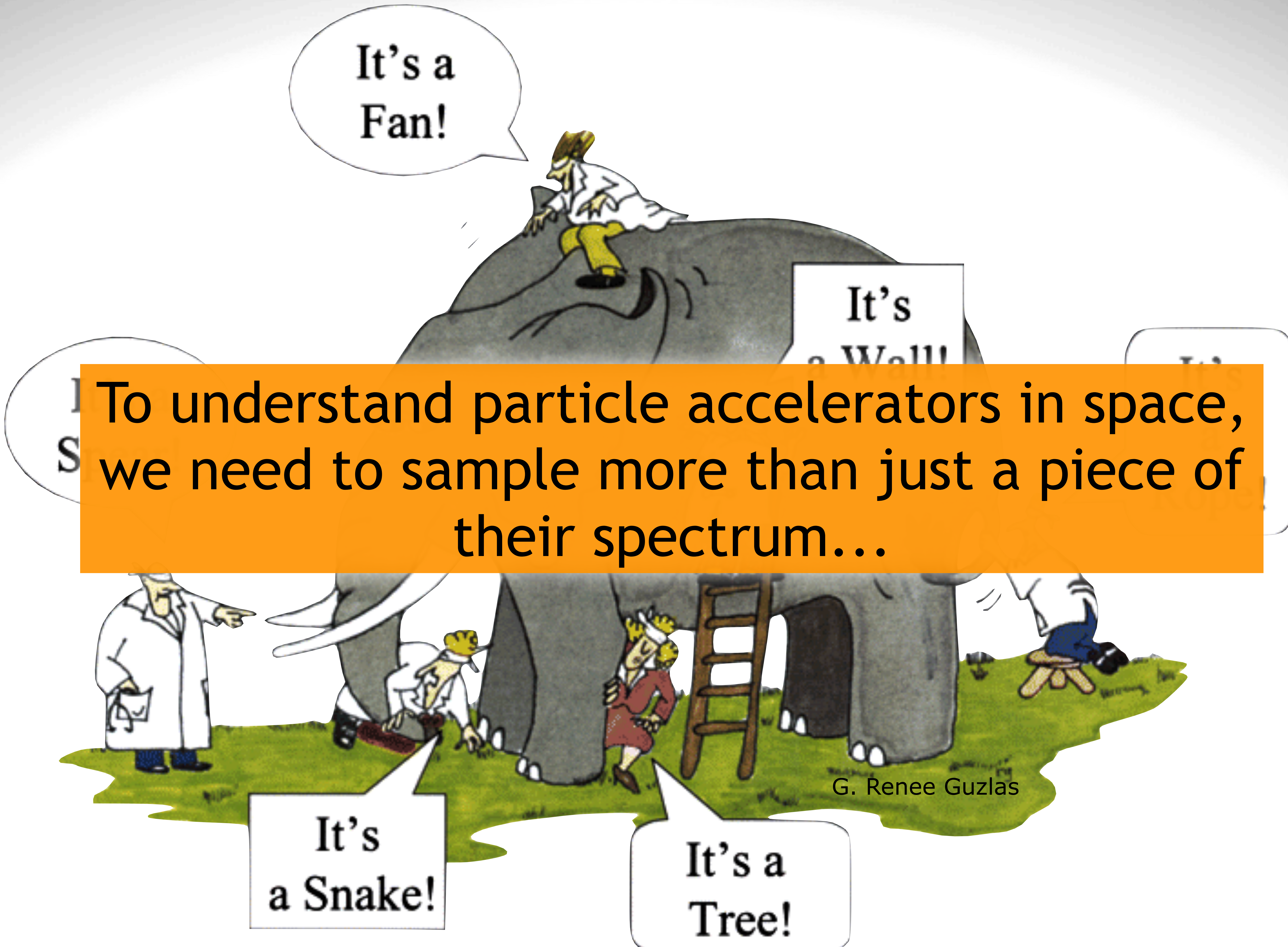
- Start with a population of energetic protons (CRs)
- p + nucleus = π^0 + X, p + nucleus = $\pi^{\pm}$ + X
- gamma rays are produced when **π^0s decay** ($\pi^0 \rightarrow \gamma+\gamma$)

Multi-wavelength view

Multi-wavelength view



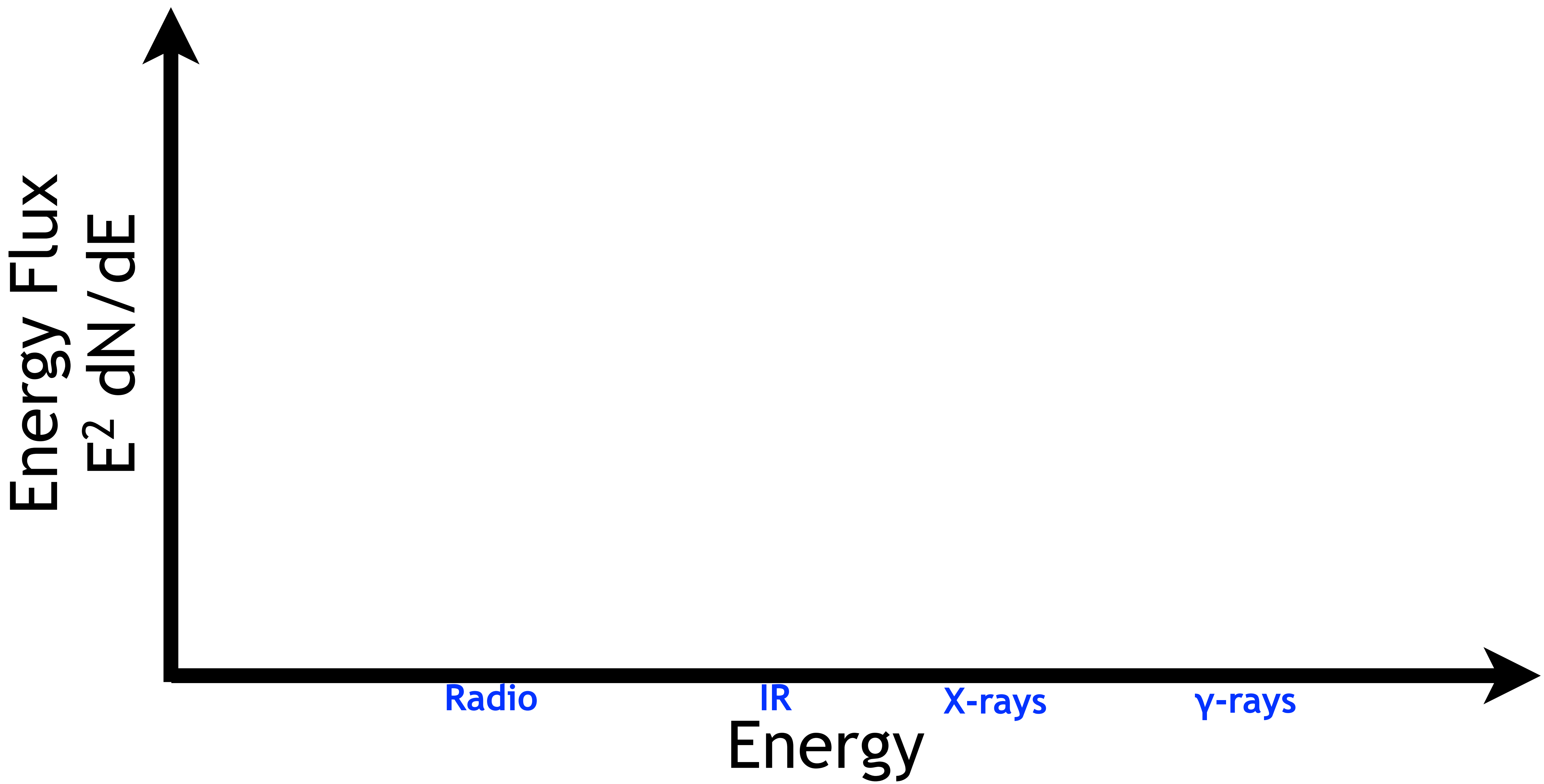
Multi-wavelength view



To understand particle accelerators in space, we need to sample more than just a piece of their spectrum...

Non-thermal Spectral Energy Distribution

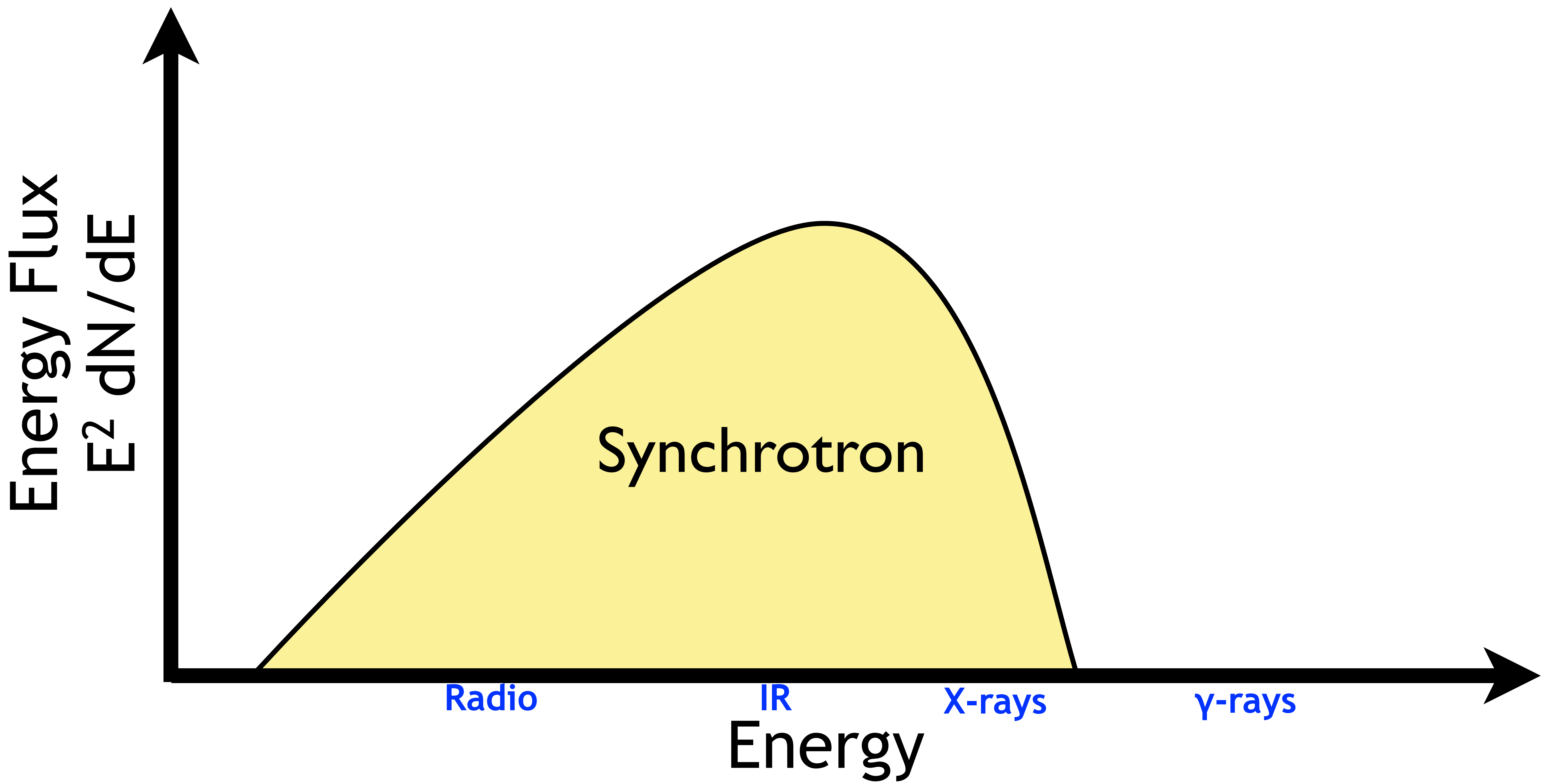
Electron Population   Proton Population



Non-thermal Spectral Energy Distribution

Electron Population
+ B field

Proton Population

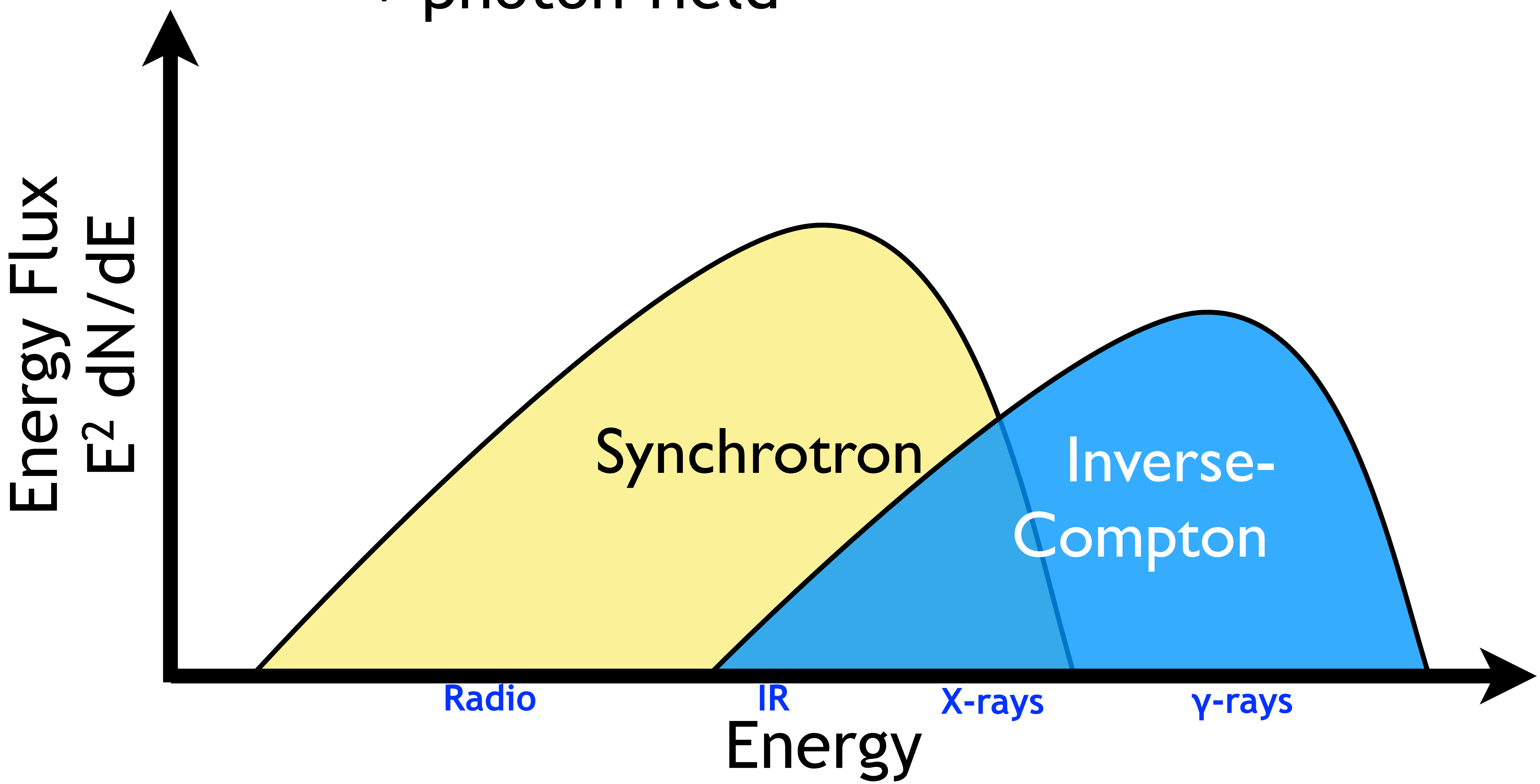


Non-thermal Spectral Energy Distribution

Electron Population **Proton Population**

+ B field

+ photon field



Non-thermal Spectral Energy Distribution

Electron Population
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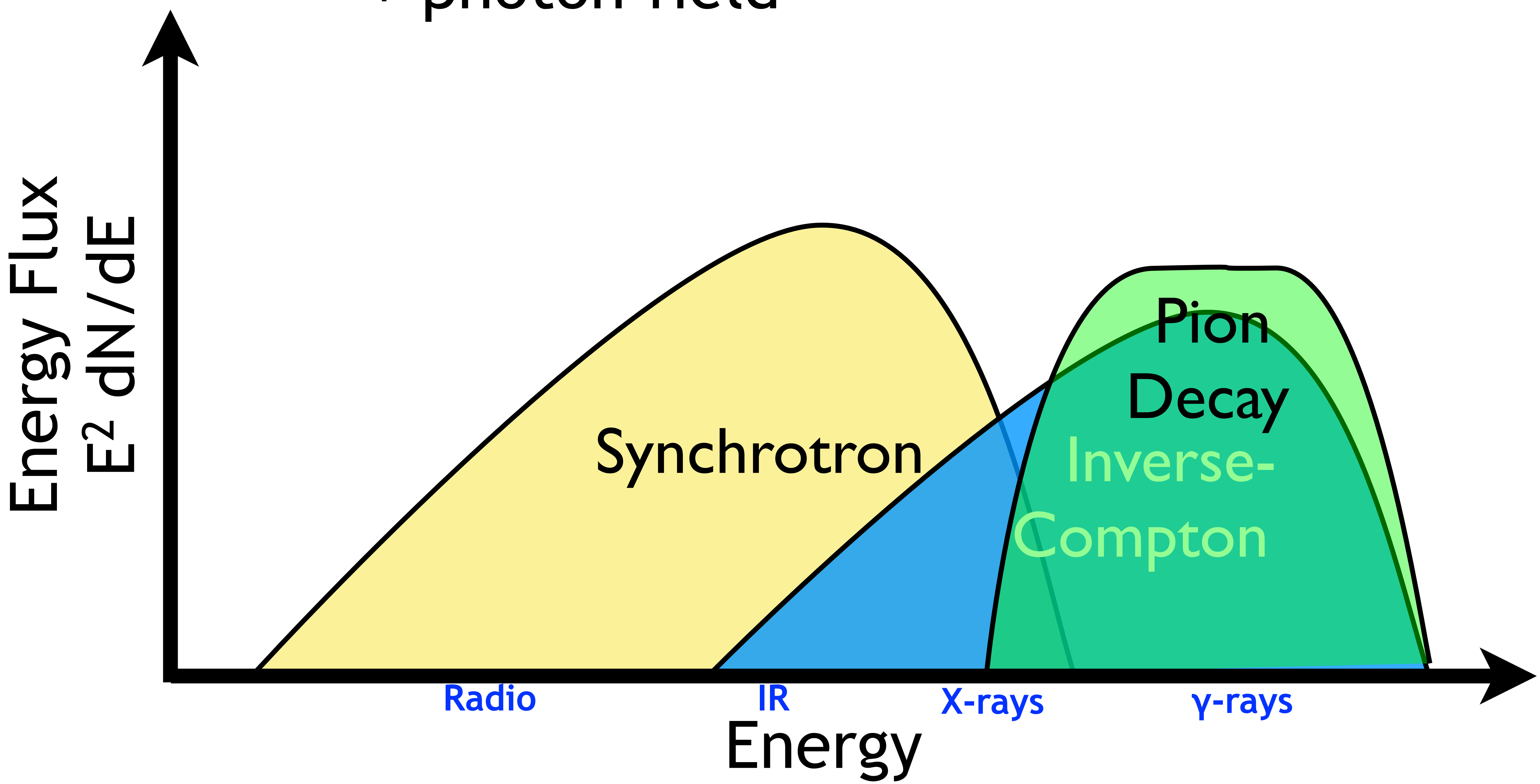
Proton Population
+ target material



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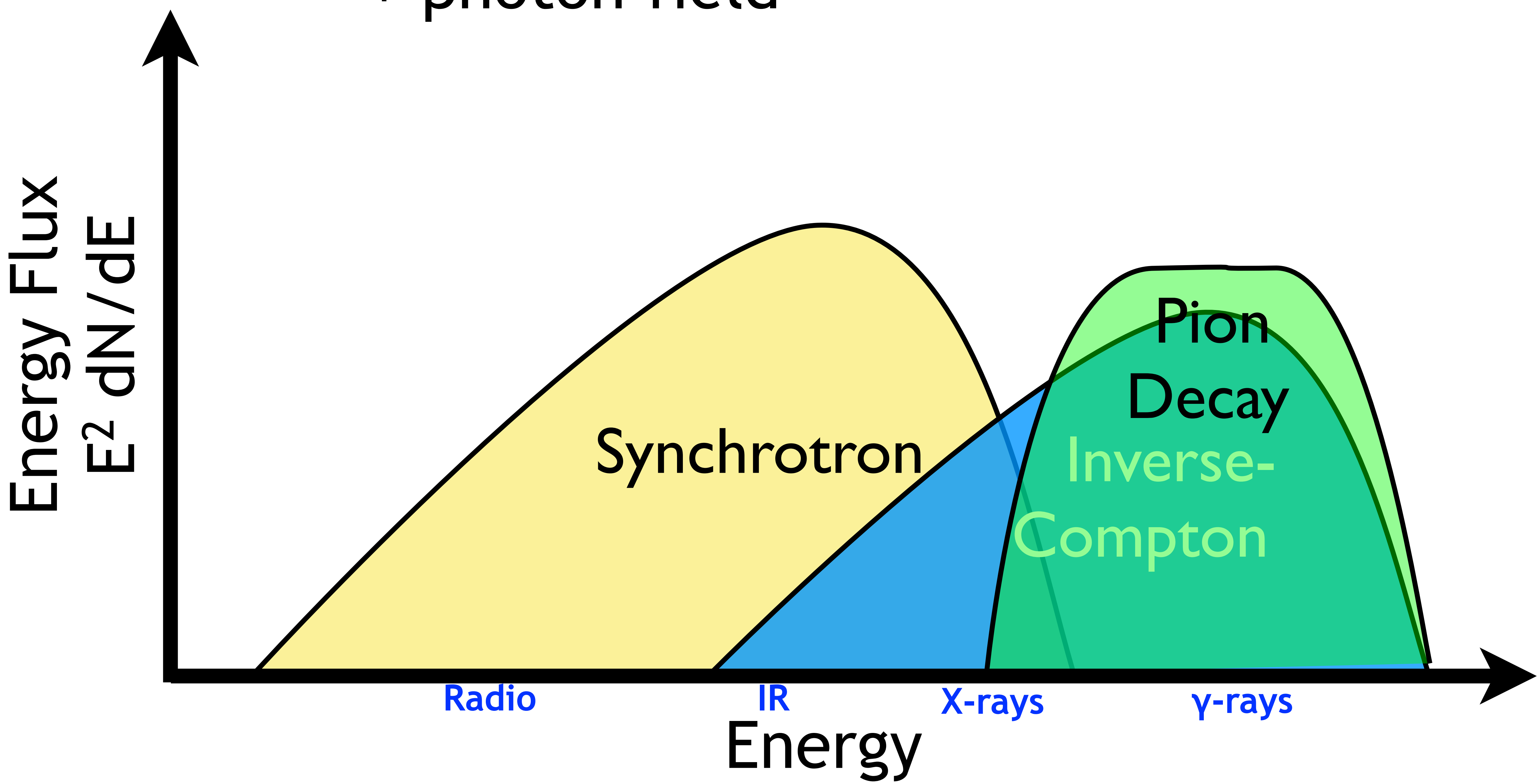

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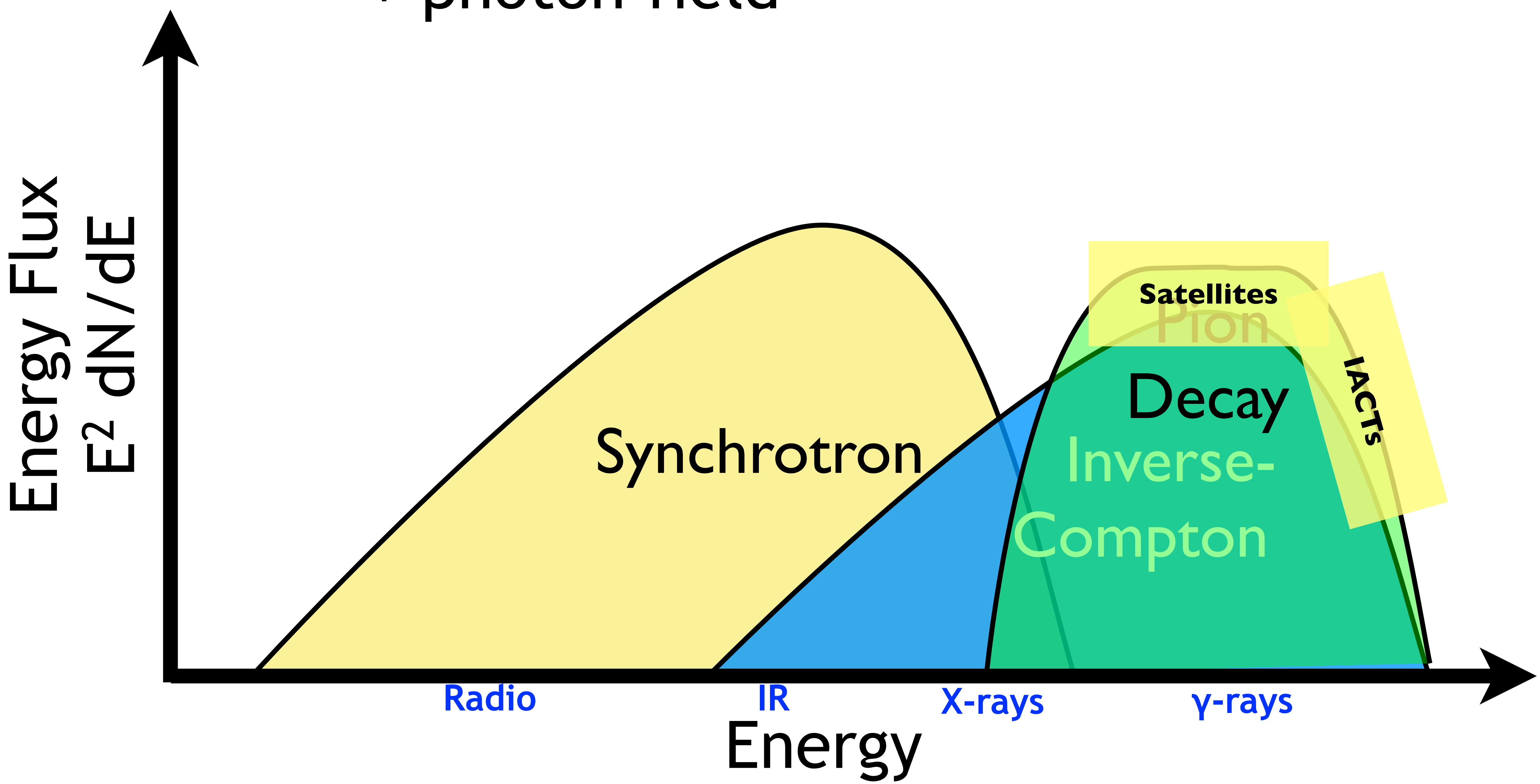
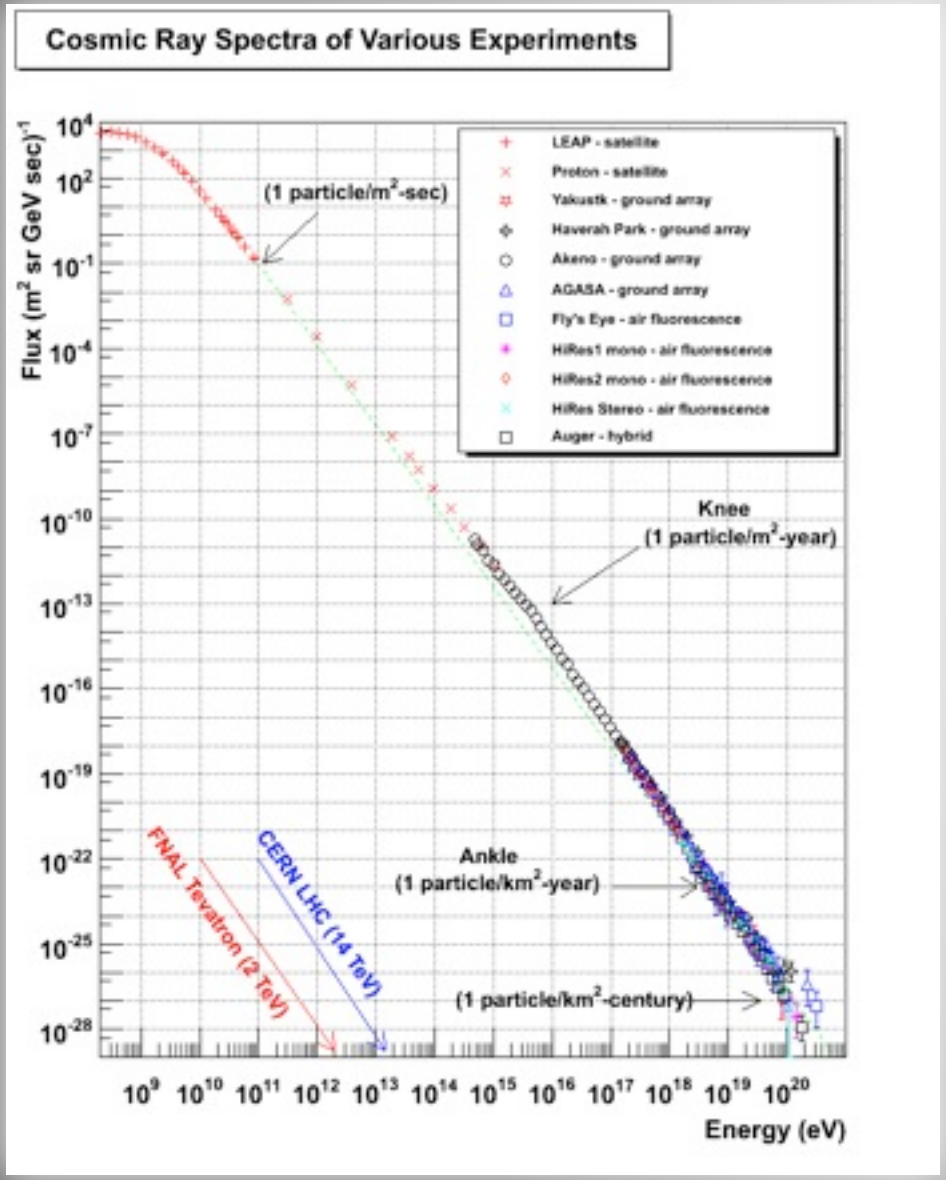
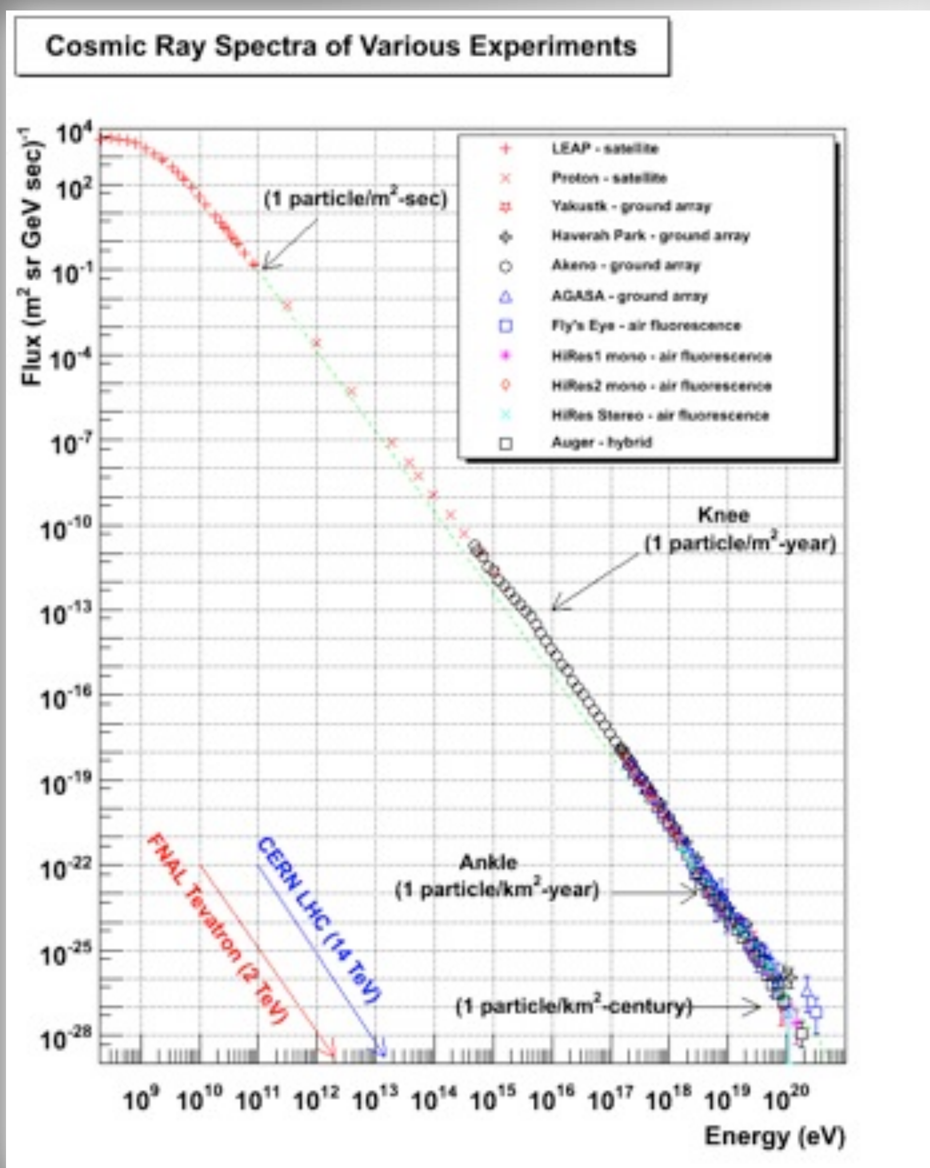


Cosmic Rays



- E<knee: probably galactic, **maybe SNRs**. What can accelerate particles up to PeV energies?
- Higher energies: unknown: combination of Galactic + Extragalactic sources probably
- at energies of 1PeV, gamma-rays should be produced up to ≈100 TeV! Should be able to see the sources as hard-spectrum gamma emitters!

Cosmic Rays



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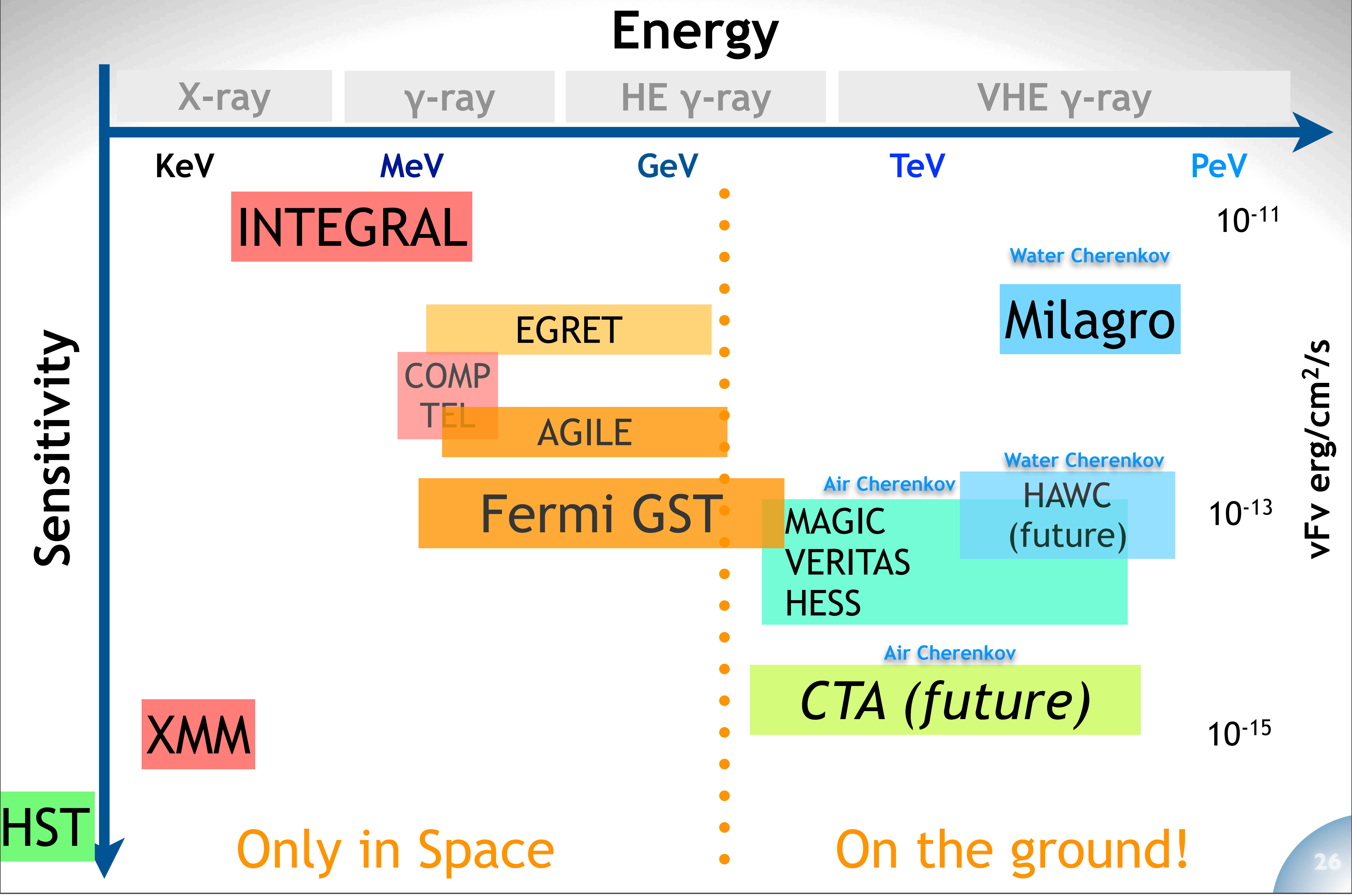
(See lecture by Stefano Gabici)

Some High Energy Instruments



OUTLINE

Gamma Rays

Context: gamma ray astrophysics

MeV gamma ray detection

GeV gamma ray detection

Gamma-ray interactions in the atmosphere

Context

What can we learn from gamma-ray observations?

What's the Point?

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?

- **Can we understand the physics behind the most violent environments in the universe?**
  - Where are particles **accelerated** in space?
  - What is the origin of the high-energy **cosmic rays**?
  - How do astrophysical **shocks** work?
  - How does accretion around a black hole produce **jets** and outflows?

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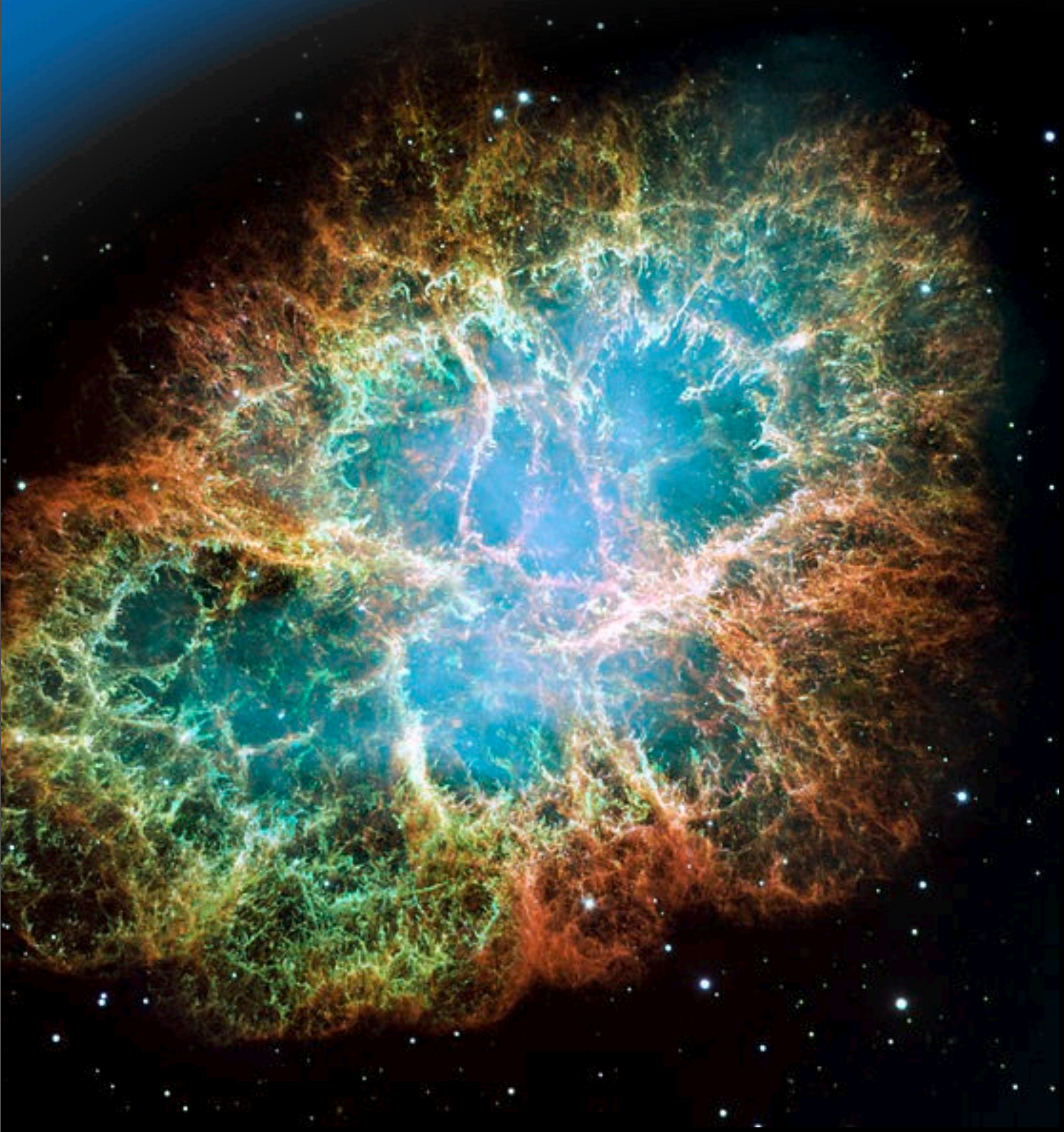
- **What is the distribution of background light in the universe?**

The Crab Nebula (M1)



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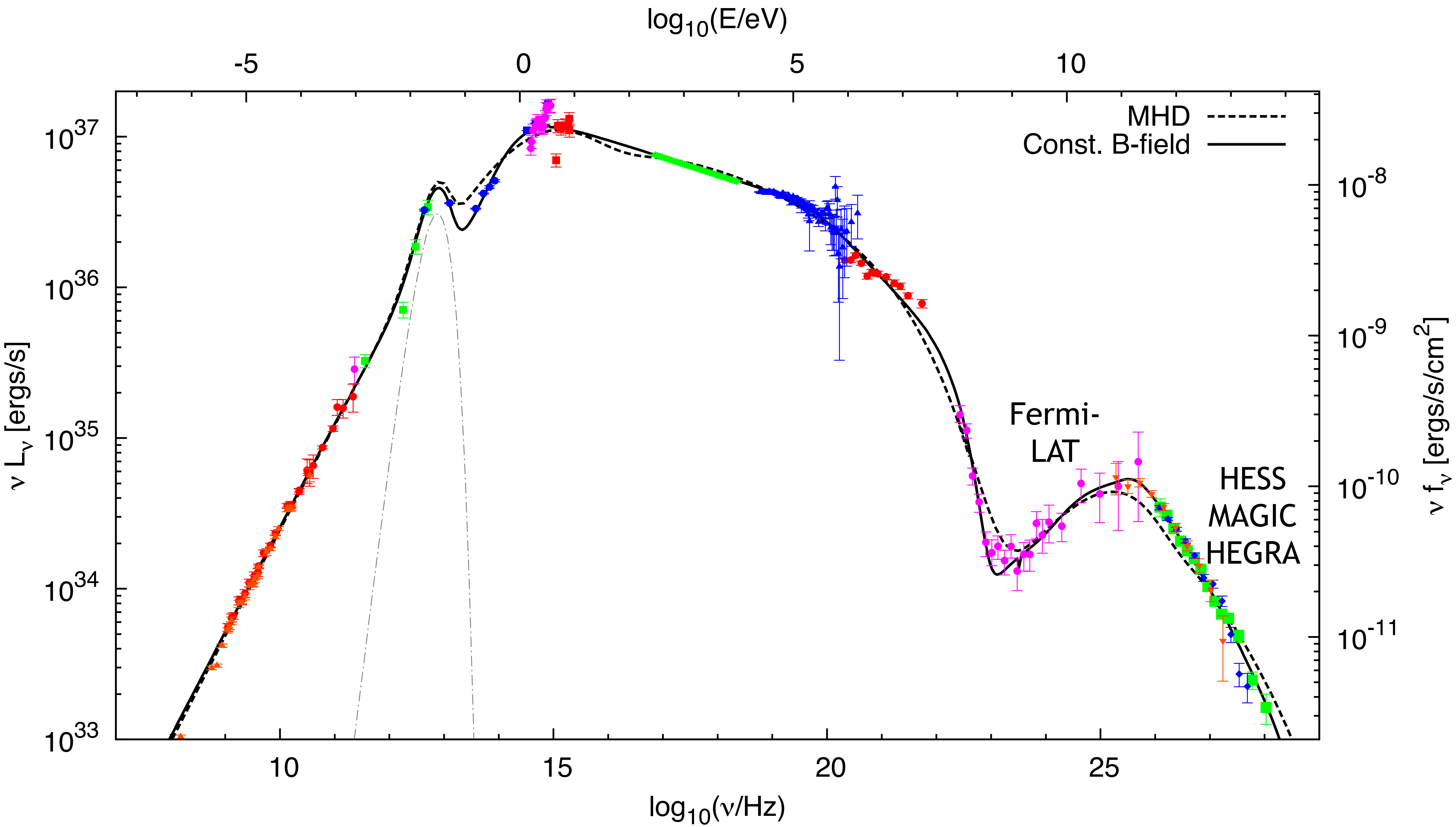
- **Brightest steady* source of gamma-rays in the sky, $L = 10^{38}$ erg/s,**
  - much in X-ray and gamma-ray wavebands
  - Excellent source for high-energy detectors, well studied
  - used as a “standard candle”
    - often see results in “Crab units”
    - not always easy to compare, since the spectrum is different in different wavebands


1054年的超新星爆发纪录
客星没，客去之兆也'，
初，至和元年五月，晨
出东方，守天关，昼见
如太白，芒角四出，色
赤白，凡见二十三日。"
从至和元年（1054
年）到嘉佑元年（公元
1056年），当时的天文
学家对这颗"天关客星"
连续观测了近两年的时间，这一奇特的天
象震动了全国。675年之后，1731年
中国最早的彗星纪
殷末（公元前１１世纪
王伐纣时所见的彗星，
于《淮南子・兵略训》
王伐纣，……彗星出，
殷人其柄。时有彗星，
东方，可以扫西人也。
条记录可见这颗彗星的
之长。

Spectral Energy Distribution of the Crab Nebula



plot from Meyer et al 2010

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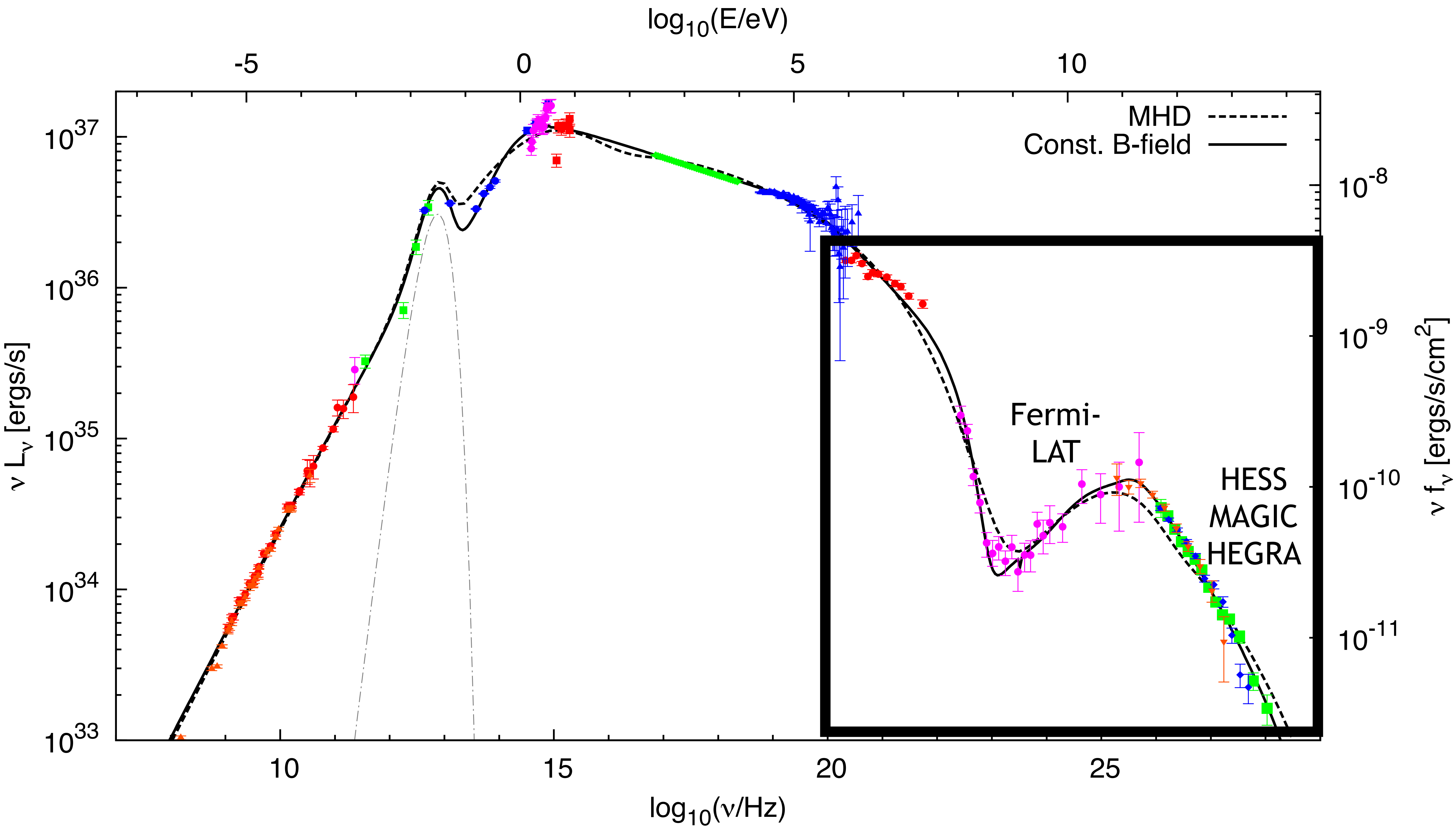

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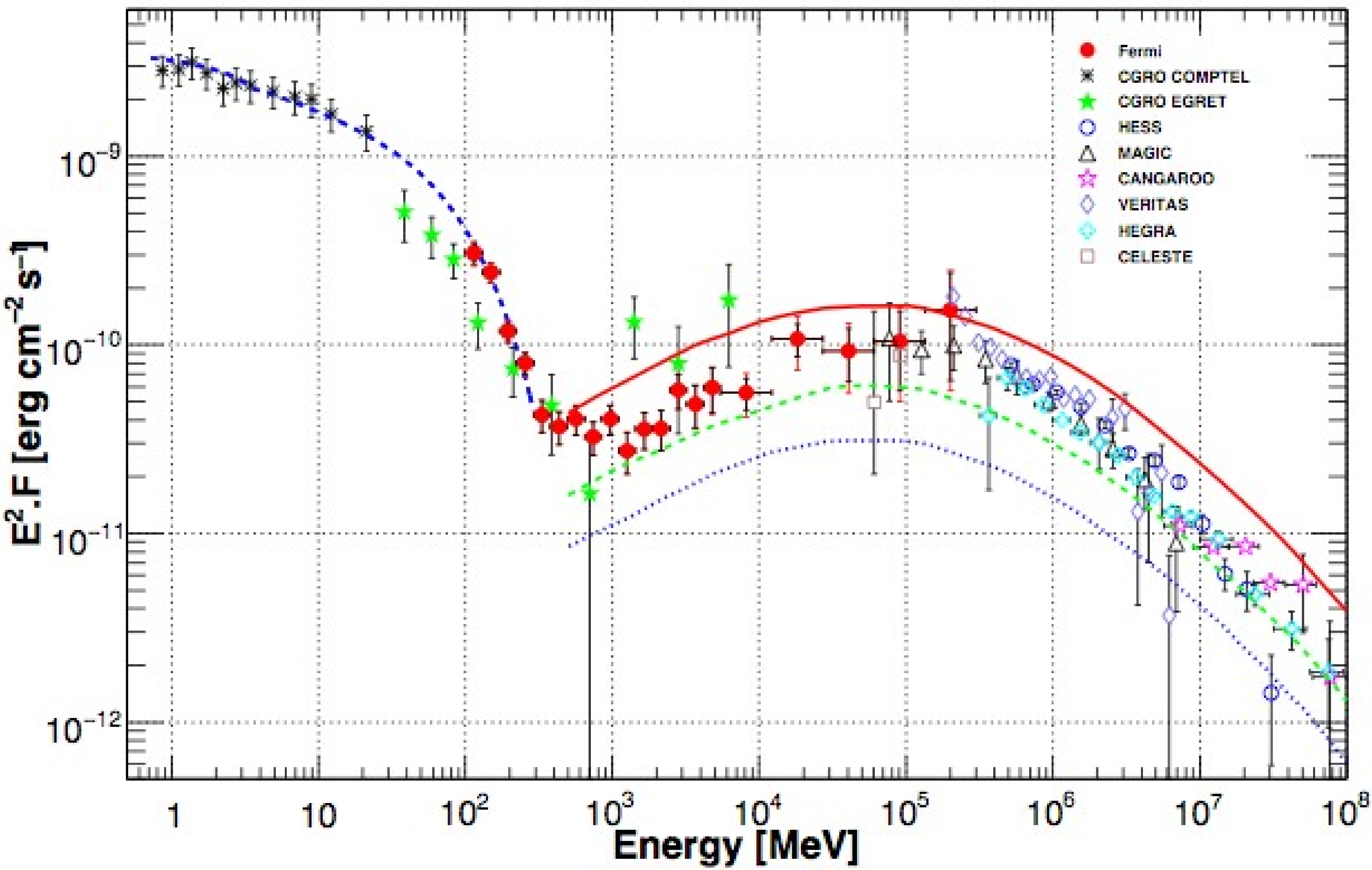
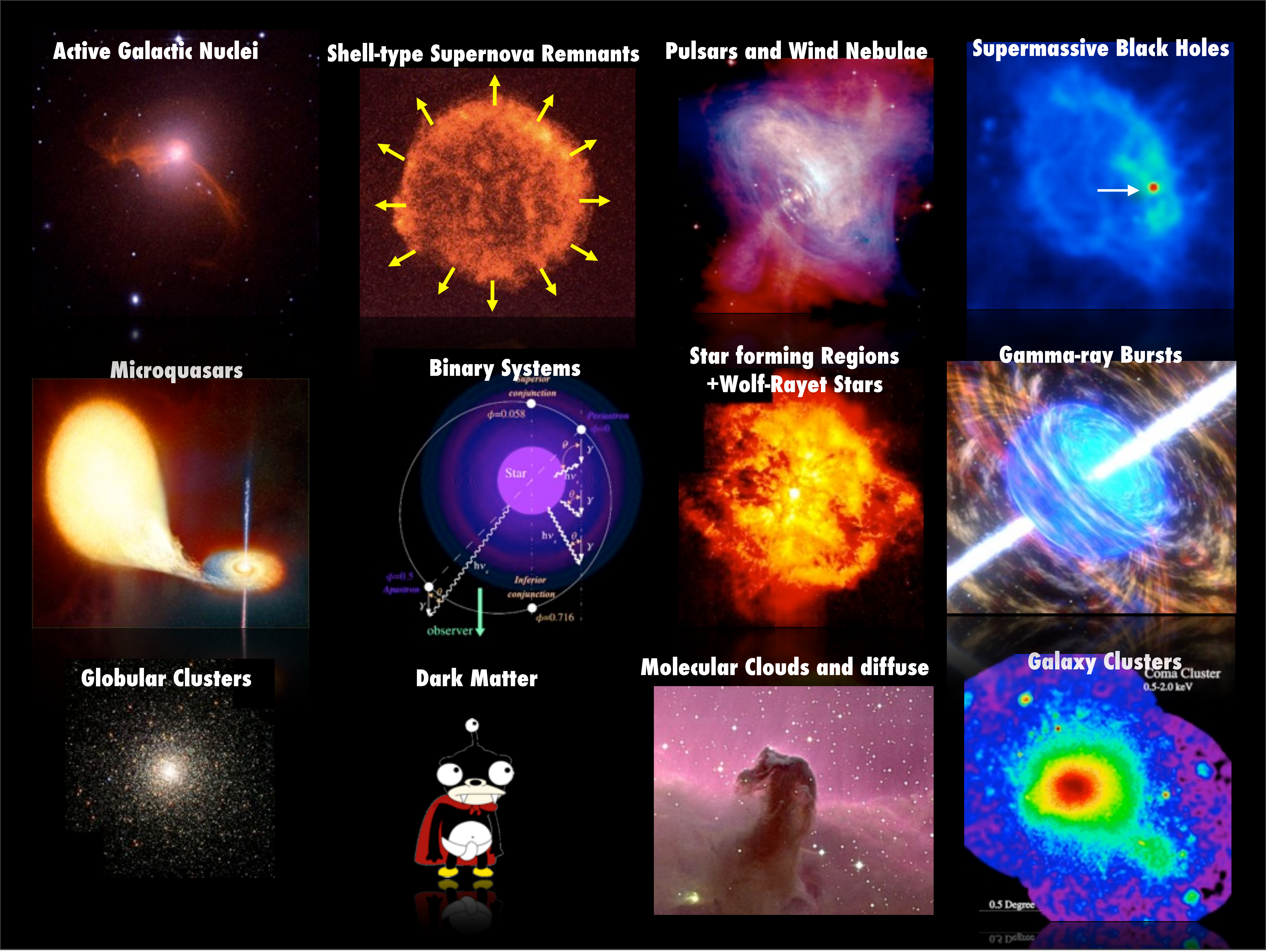


Fermi
CGRO COMPTEL
CGRO EGRET
HESS
MAGIC
CANGAROO
VERITAS
HEGRA
CELESTE
$E^2.F$ [erg cm^{-2} s^{-1}]
Energy [MeV]

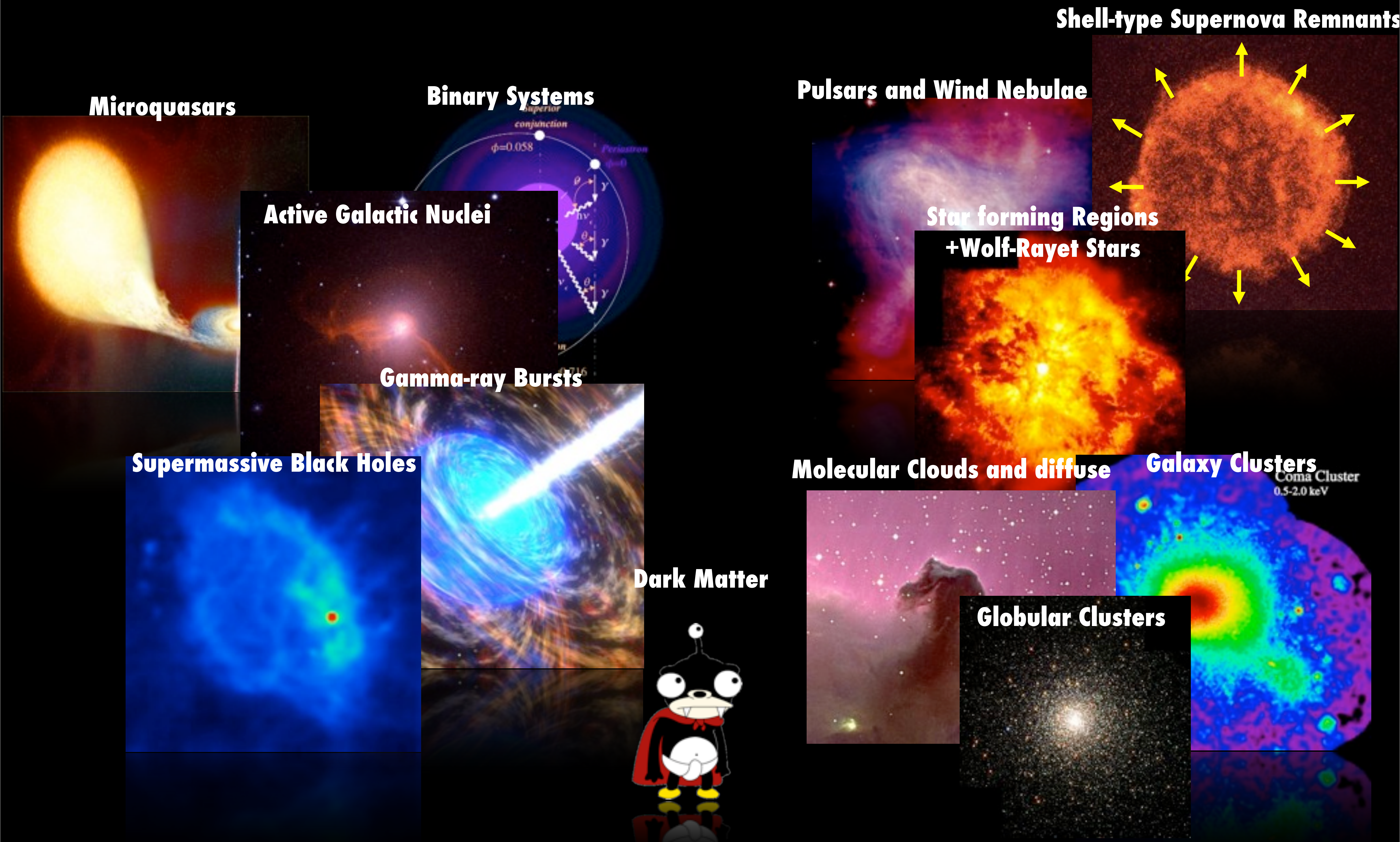
The Crab Nebula

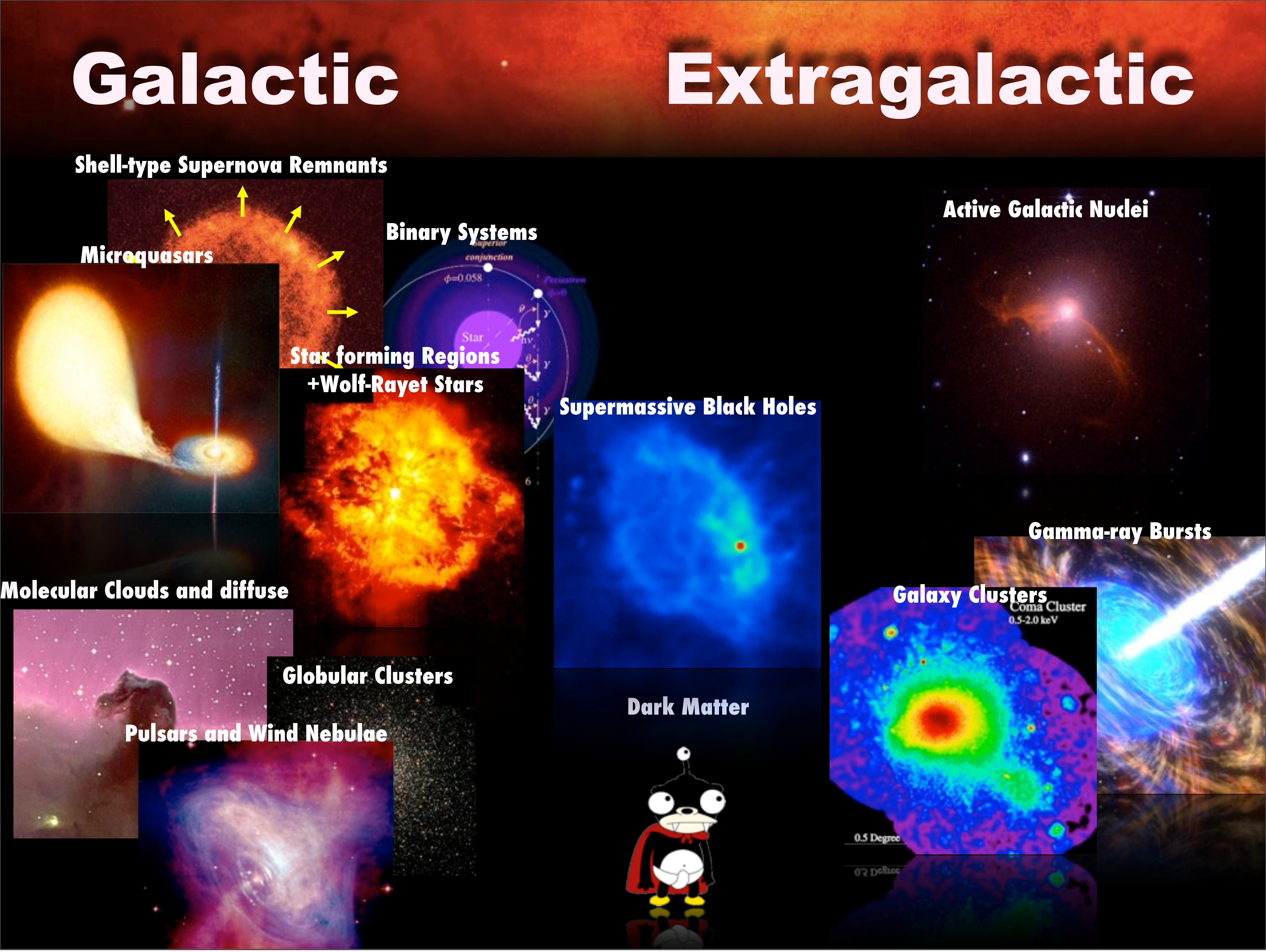
- **Continuous injection**
  - central nebula bright above 10 keV, implies electrons > 10^{14} eV
  - lifetime < 1 year, so requires injection: continuous acceleration, not from the supernova, but the wind nebula!
- **not a very efficient gamma-ray emitter (IC bump quite low)**
  - due to high B-field, short electron cooling time
  - Still very bright only because of it's extreme spindown luminosity.
  - Other, older PWNe, should have lower B-fields and be **more efficient gamma-ray emitters**


Active Galactic Nuclei
Shell-type Supernova Remnants
Pulsars and Wind Nebulae
Supermassive Black Holes
Microquasars
Binary Systems
conjunction
φ=0.058
Star
hν
Inferior
conjunction
φ=0.716
observer
Star forming Regions
+Wolf-Rayet Stars
Gamma-ray Bursts
Globular Clusters
Dark Matter
Molecular Clouds and diffuse
Galaxy Clusters
Coma Cluster
0.5-2.0 keV
0.5 Degree

Accretion

Accleration

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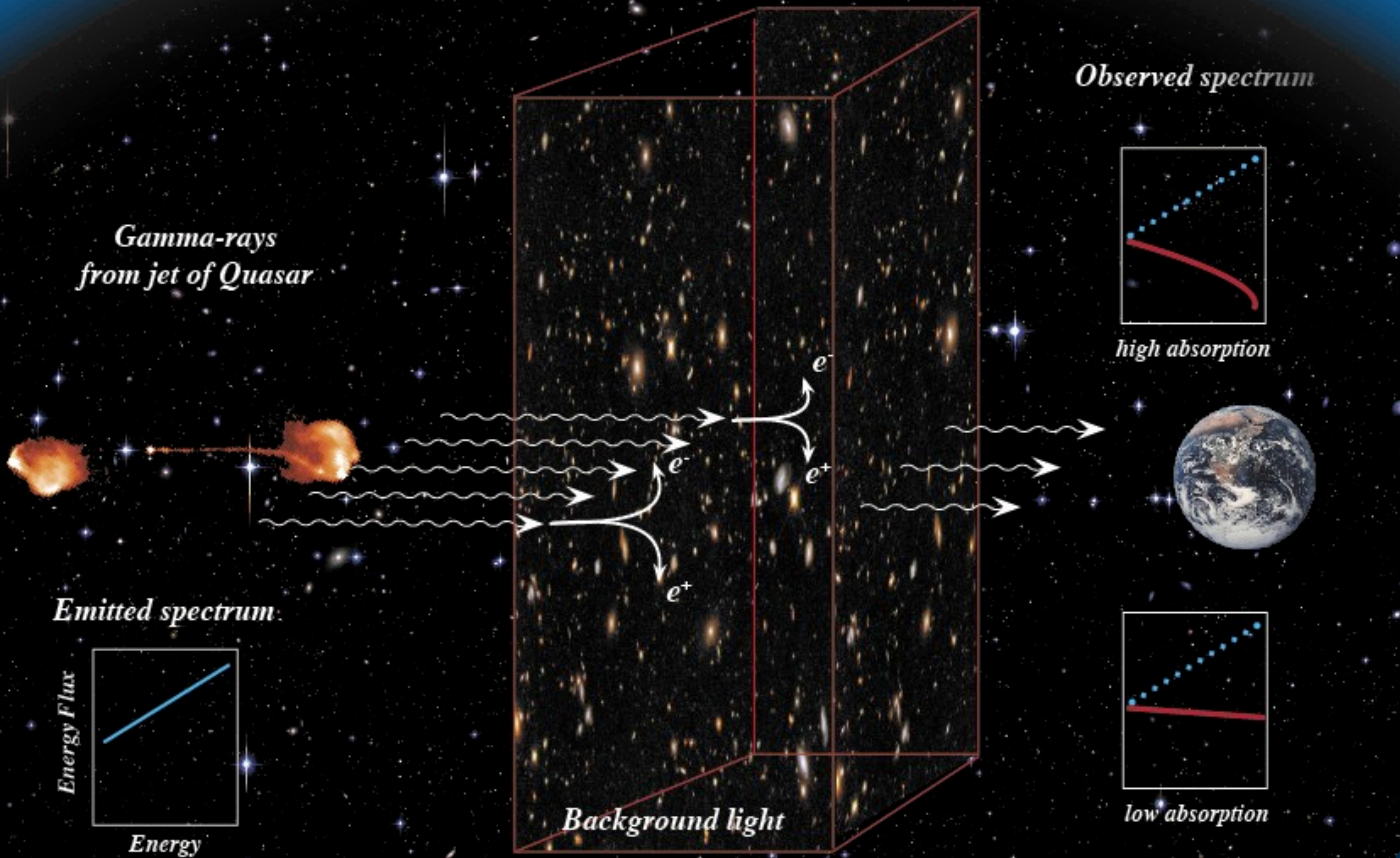
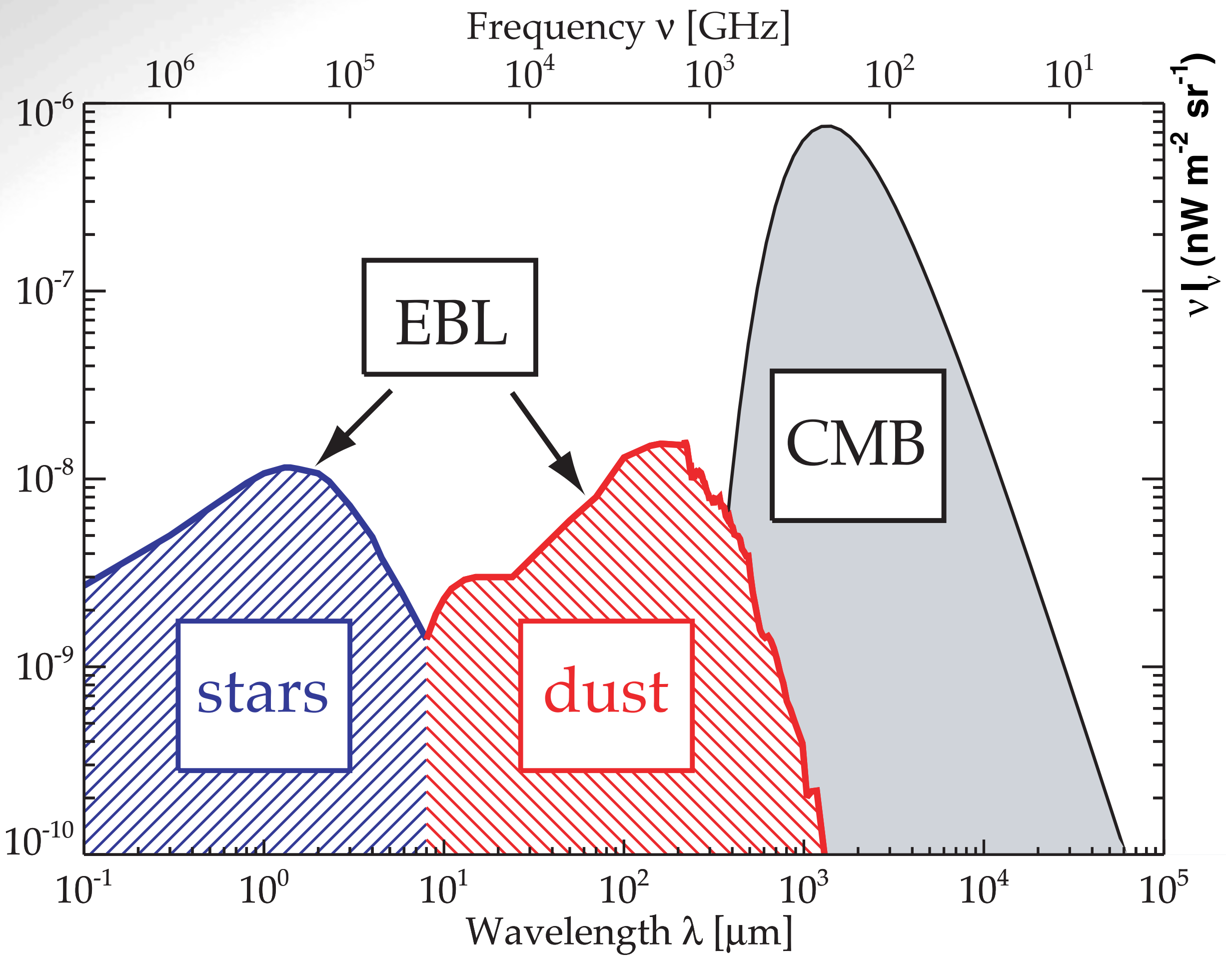
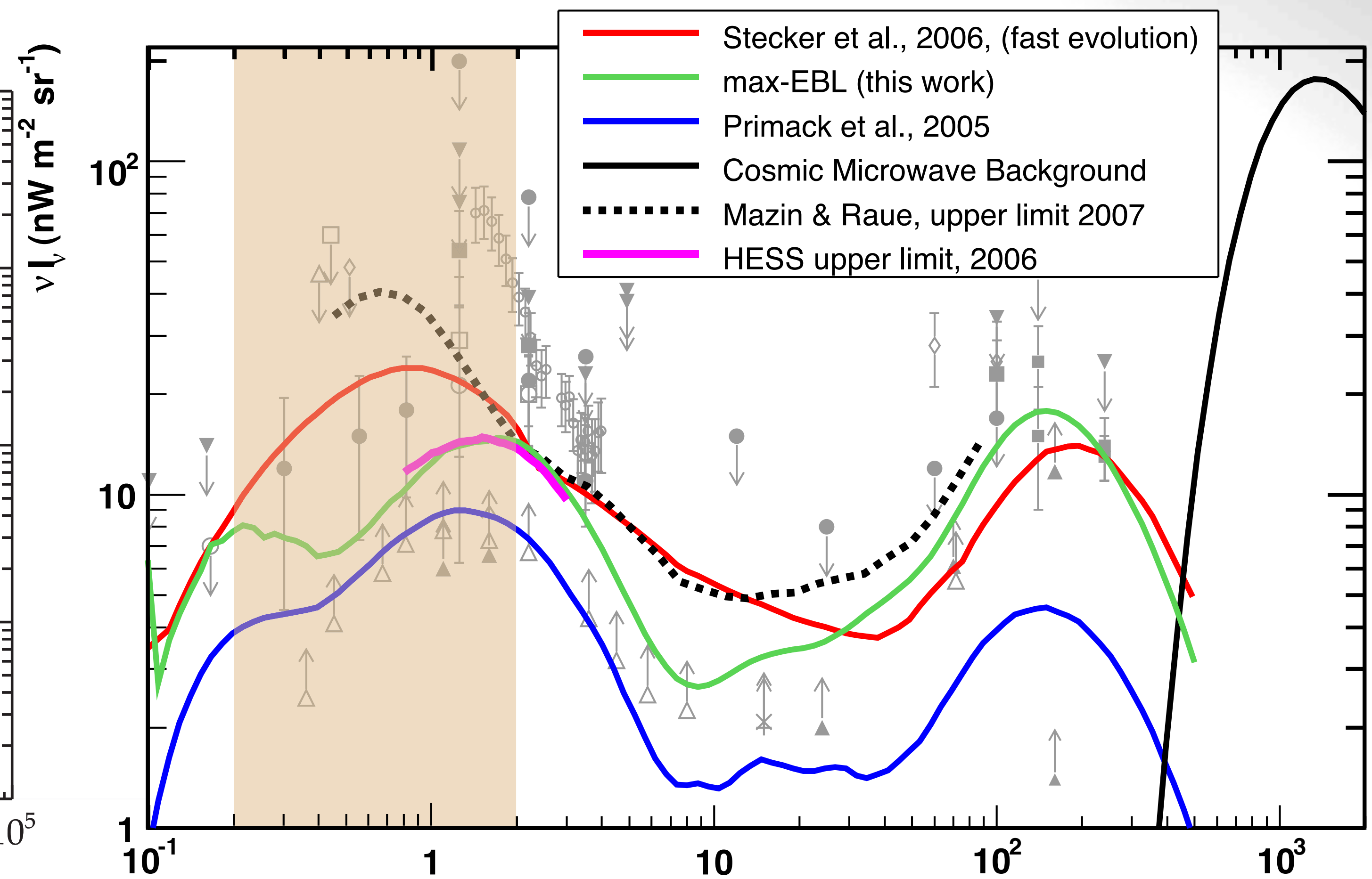
Gamma-ray Horizon



Background light



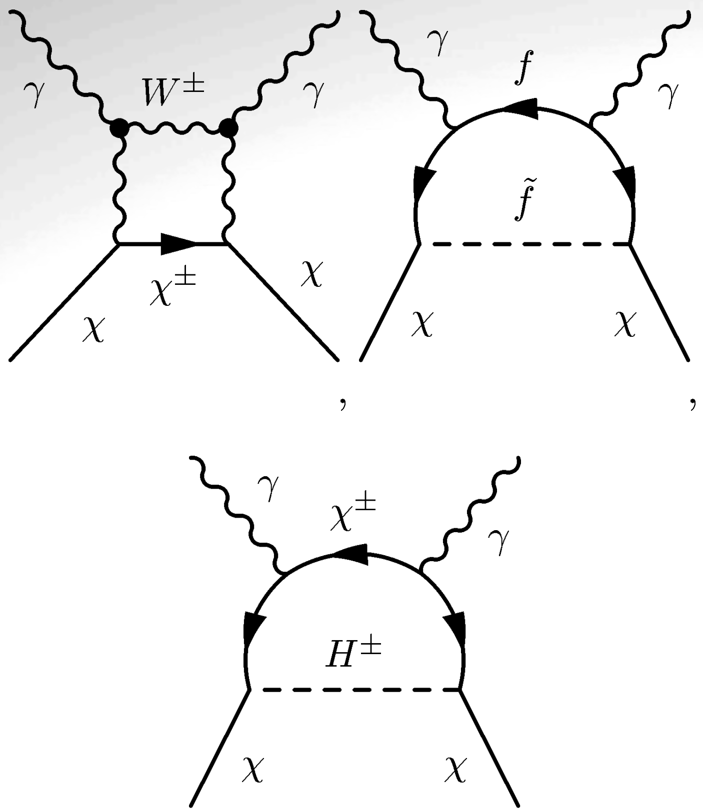


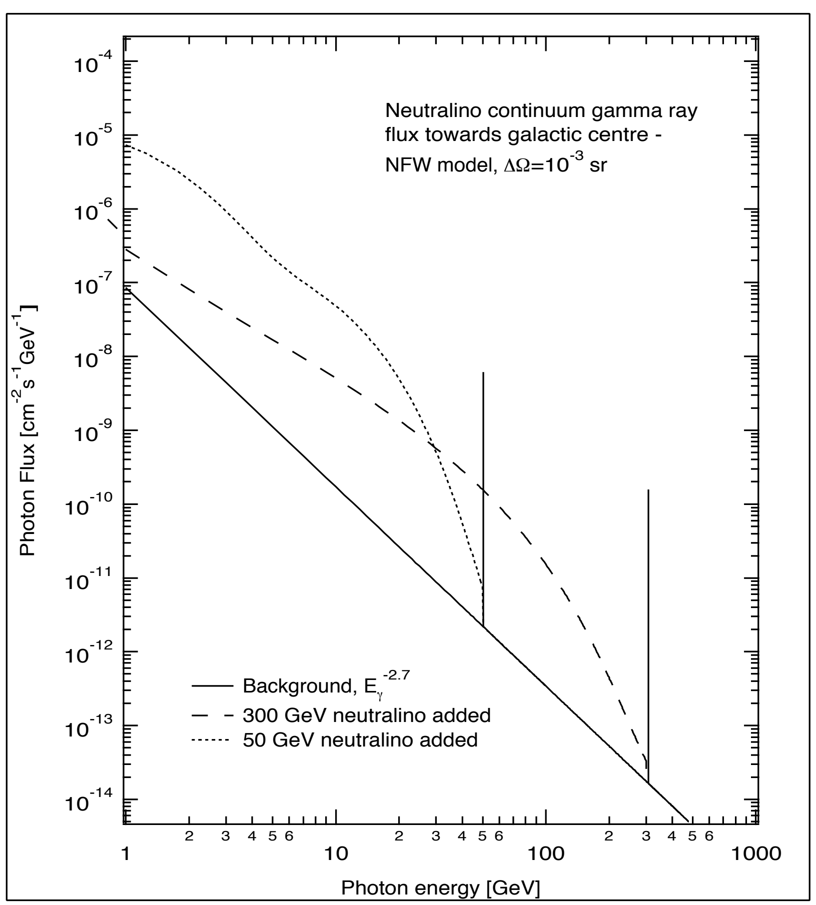
Magic Collaboration, Science 2008

Scattering target for the highest-energy gamma rays

- limits detection at >TeV energies to about Z<0.3 with current instruments

Dark matter cosmology

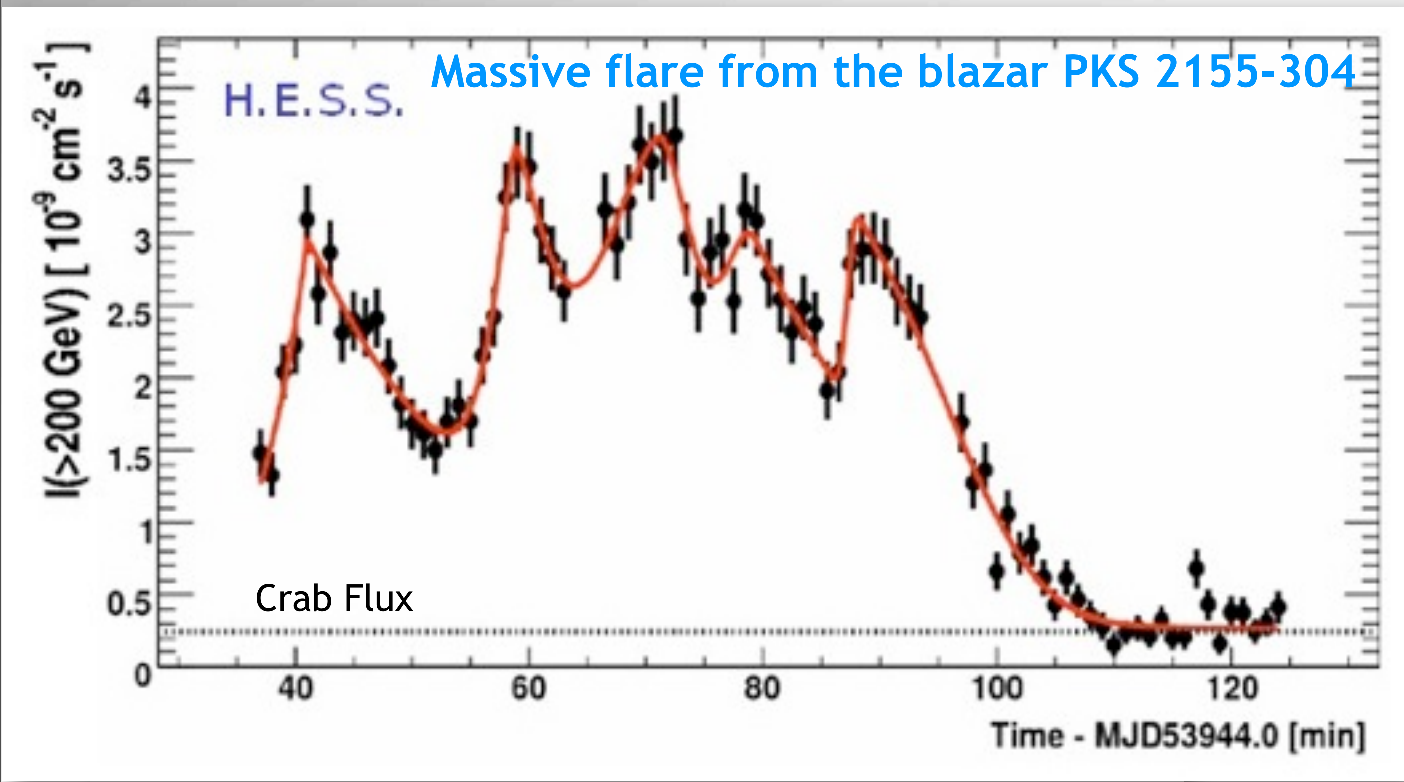


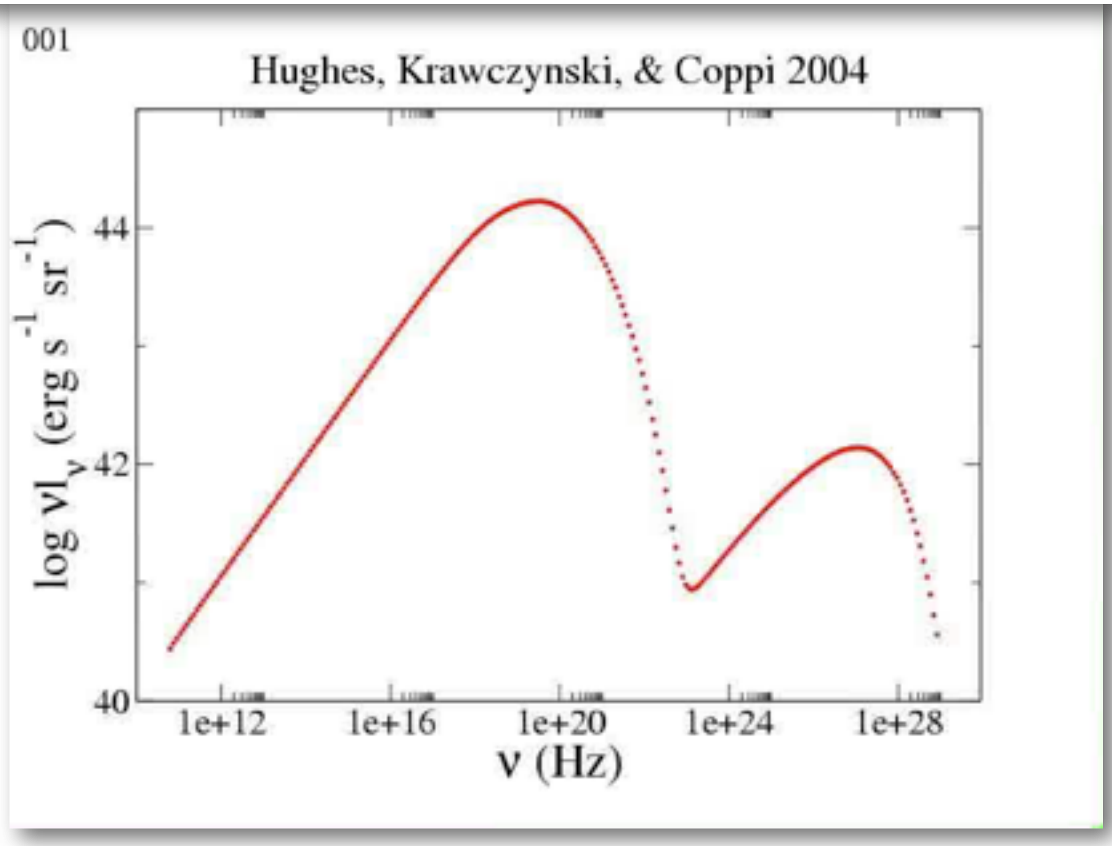


WIMPs (weakly interacting massive particles)

- common candidates for dark matter
- relic abundance left over from Big Bang
- some theoretical WIMPs (neutralinos, axions, etc) should annihilate to gamma rays
- signal proportional to density. Therefore look at:
  - center of our galaxy
  - dwarf spheroidals

Variability





Synchrotron-Self-Compton (SSC) model of a Blazar (a type of active galaxy), with injected flares

Jet and accretion powered sources may be variable (in flux and spectrum) due to changes in accretion rate

- Active Galactic Nucleii are a classic example
- Binary systems and micro-quasars

Time structure can tell us:

- the size and site of gamma-ray production region
-

OUTLINE

Gamma Rays

Context: gamma ray astrophysics

MeV gamma ray detection

GeV gamma ray detection

Gamma-ray interactions in the atmosphere

ME and HE Detection

Detecting High-Energy radiation with satellite telescopes

- Detecting MeV gamma rays
- Detecting GeV gamma rays
- Source Modeling

Space-based Detectors

Blocked by Earth's atmosphere

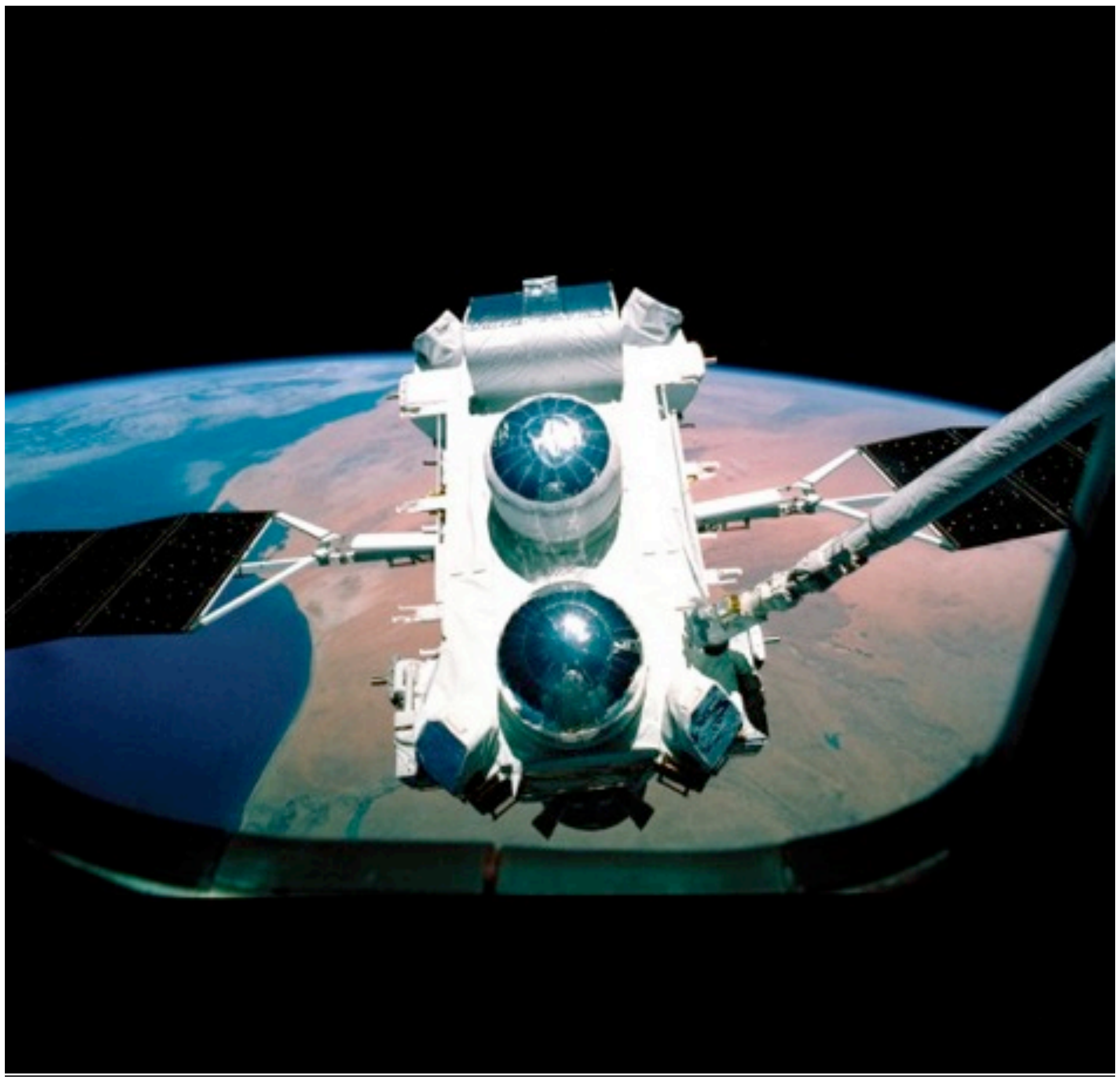
Can't use lenses or mirrors!

- X-rays are the limit for focusing optics (for the most part)

Need to look to particle physics...

- Interaction of high-energy particles with matter
  - Compton telescopes
  - pair conversion telescopes

Compton Gamma-ray Observatory
1991 - 2000



Second of NASA's "Great Observatories" (after Hubble, before Chandra)

- detect photons from 20 keV to 30 GeV

Two gamma-ray detectors:

- COMPTEL (Compton Telescope)
- EGRET (Energetic Gamma Ray Experiment Telescope)

Compton Gamma-ray Observatory
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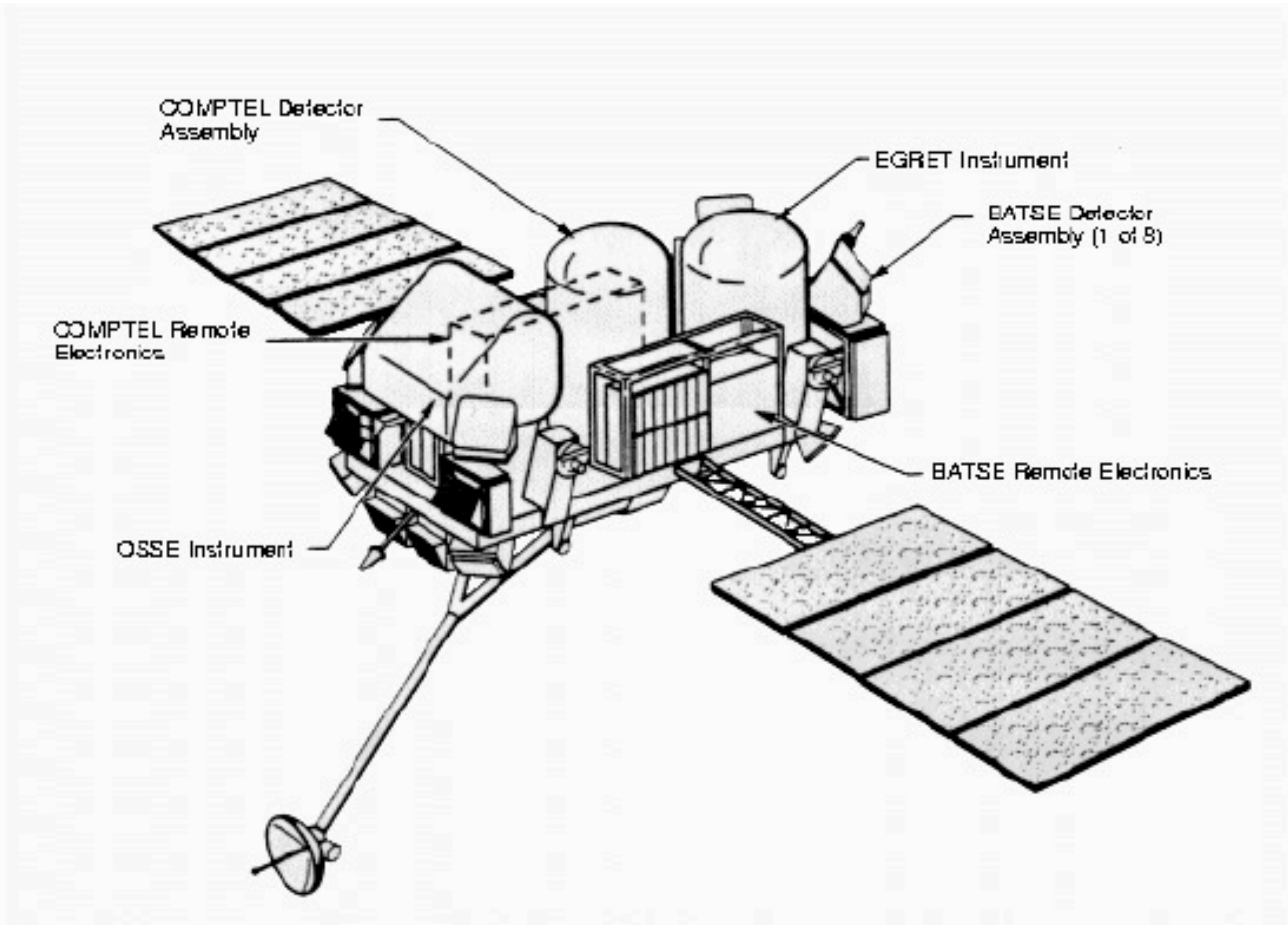

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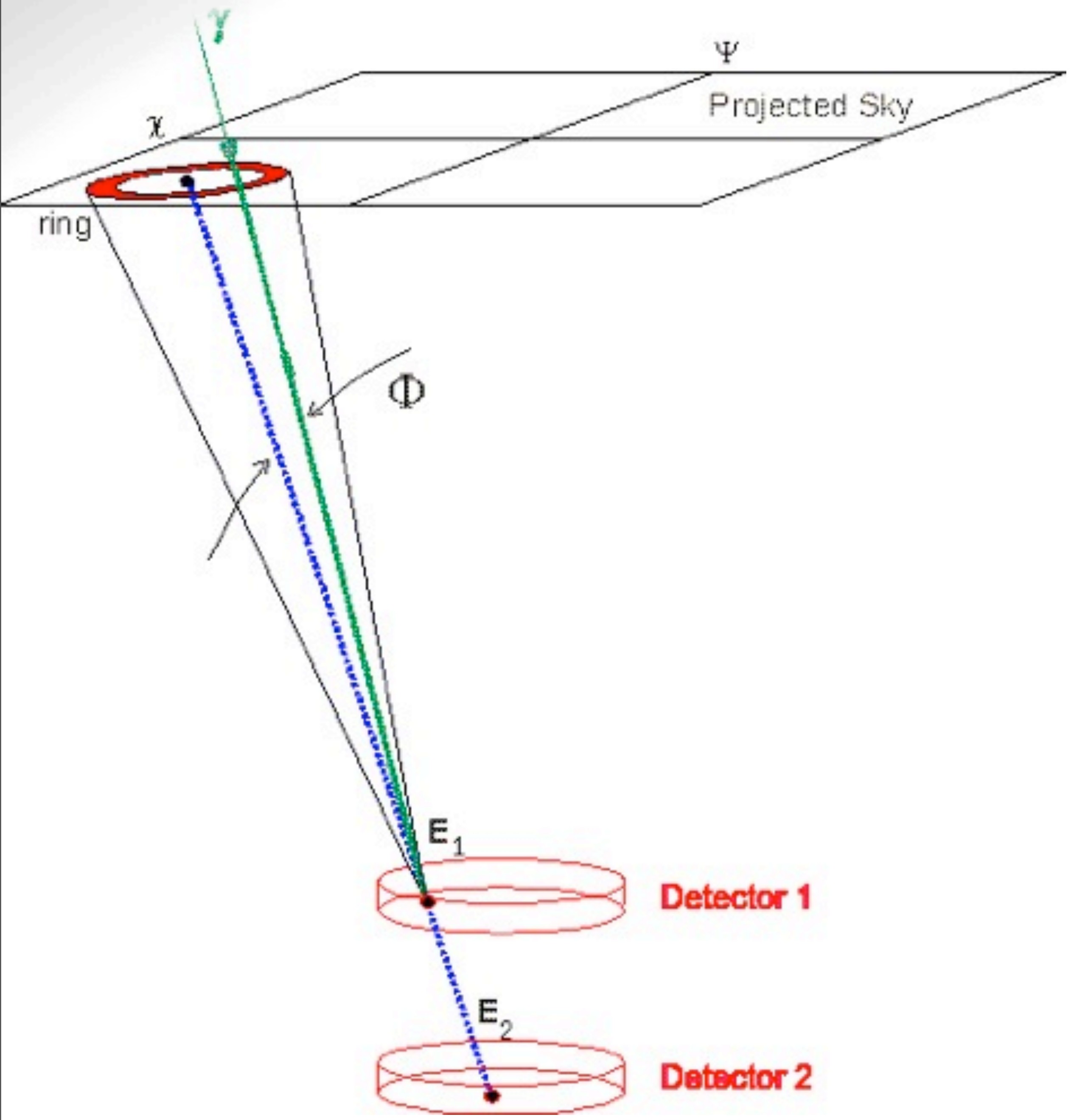
Instruments

	previous		current-gen
	COMPTEL	EGRET	Fermi-LAT
Energy Range	0.8 - 30 MeV	20 MeV - 30 GeV	20 MeV - 300 GeV
Energy Resolution	≈7%	20%	10%
peak A_{eff} (m^2)	0.005	0.15	1.0
FOV	1 sr	0.6 sr	>2 sr
PSF	1°	5° (100 MeV)	3° (100 MeV) 0.2° (10 GeV)

Detecting MeV Gamma Rays

Compton Telescopes



Gamma ray Compton scatters off electron in detector 1

- energy E1 of scattered electron is measured, along with its position P1 in the detector

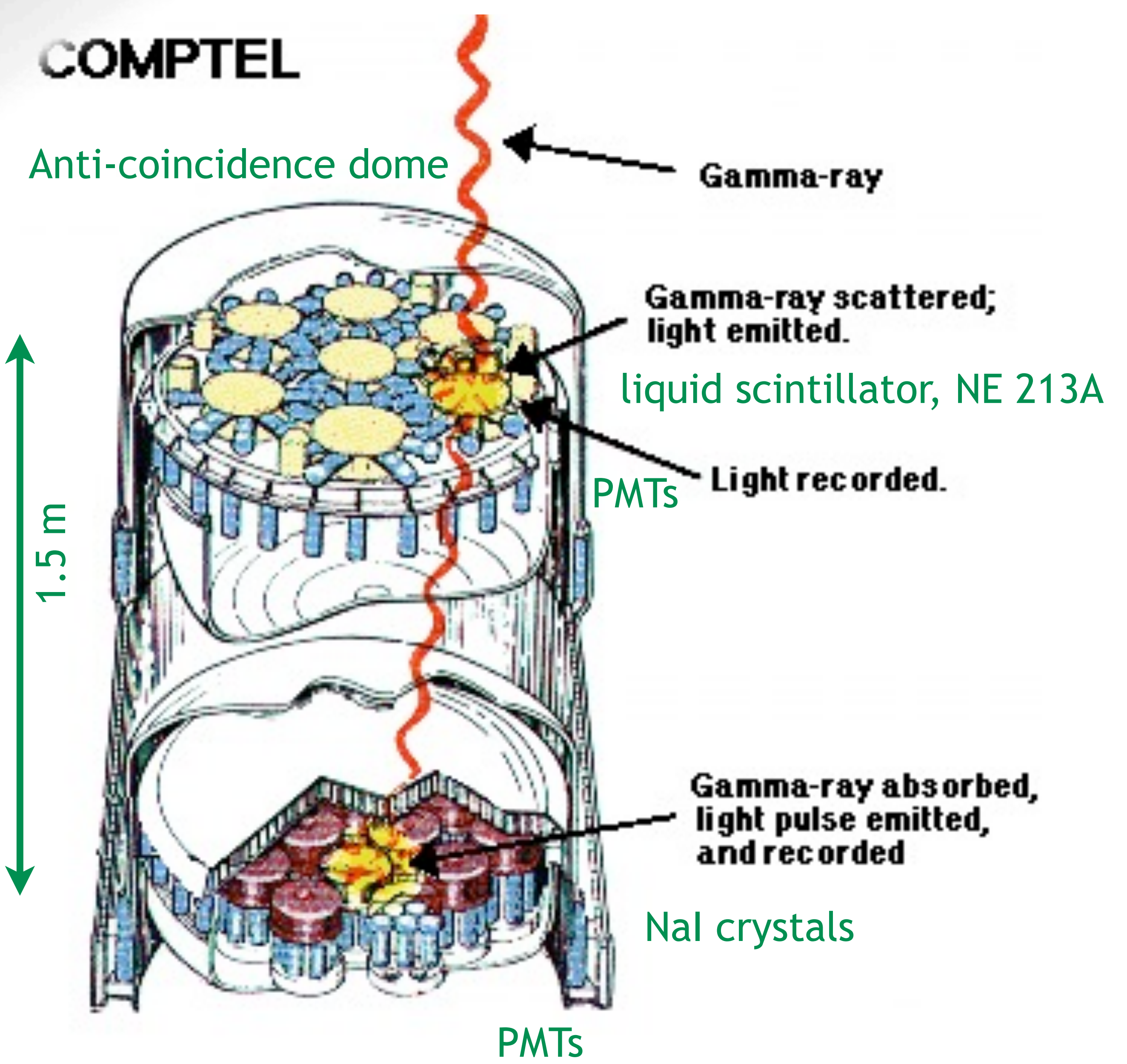
Scattered photon is seen in detector 2

- its energy E2 and position P2 are measured

Reconstruction:

- From this one can calculate the scattering angle, which give the position on the sky within a cone about the position vector
- Summing event circles from many events: signal will grow at correct position, other parts of the ring contribute to background
- Energy = E1 + E2

COMPTEL

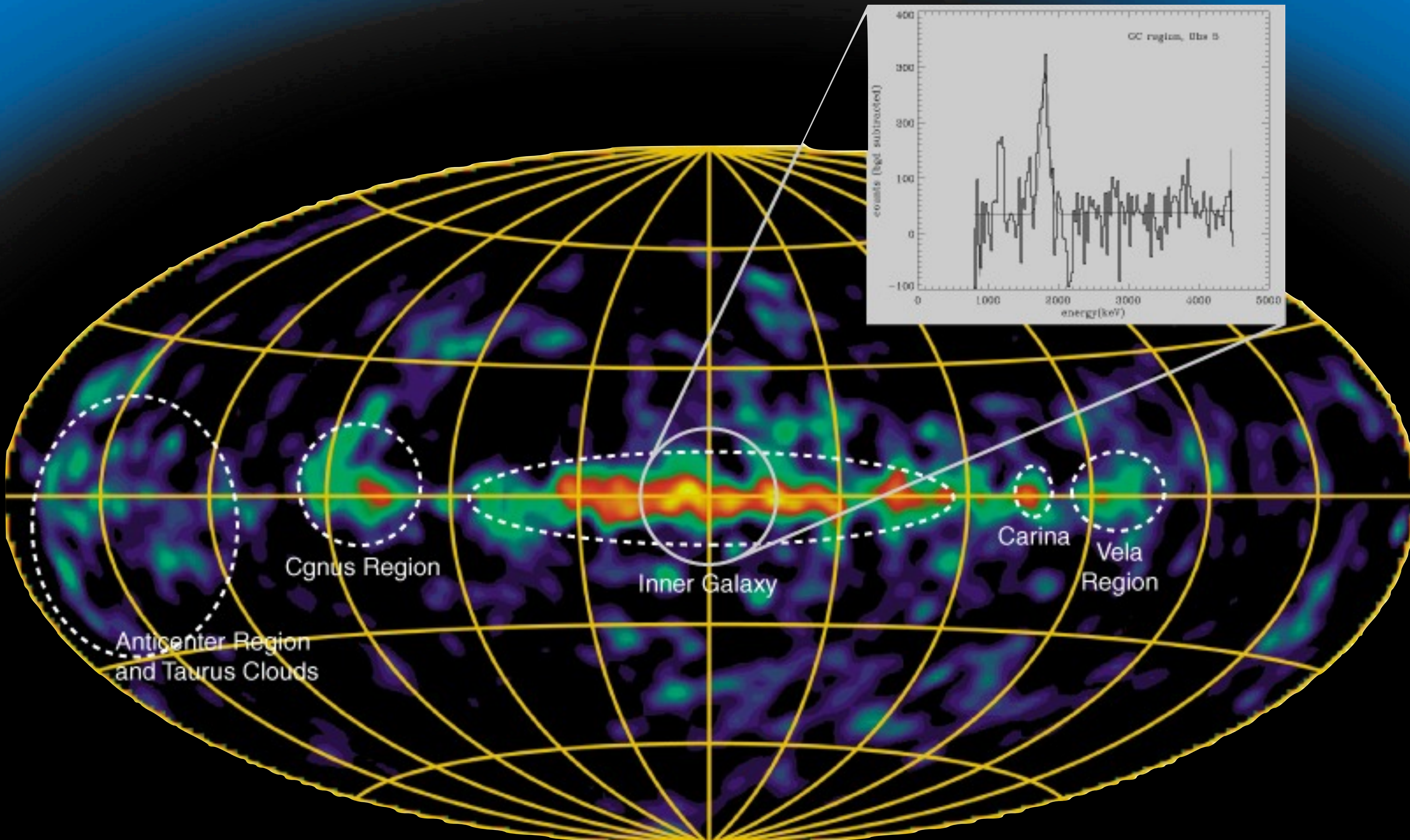


Background rejection via coincidence in time between 2 detectors

Study the sources of MeV gamma rays

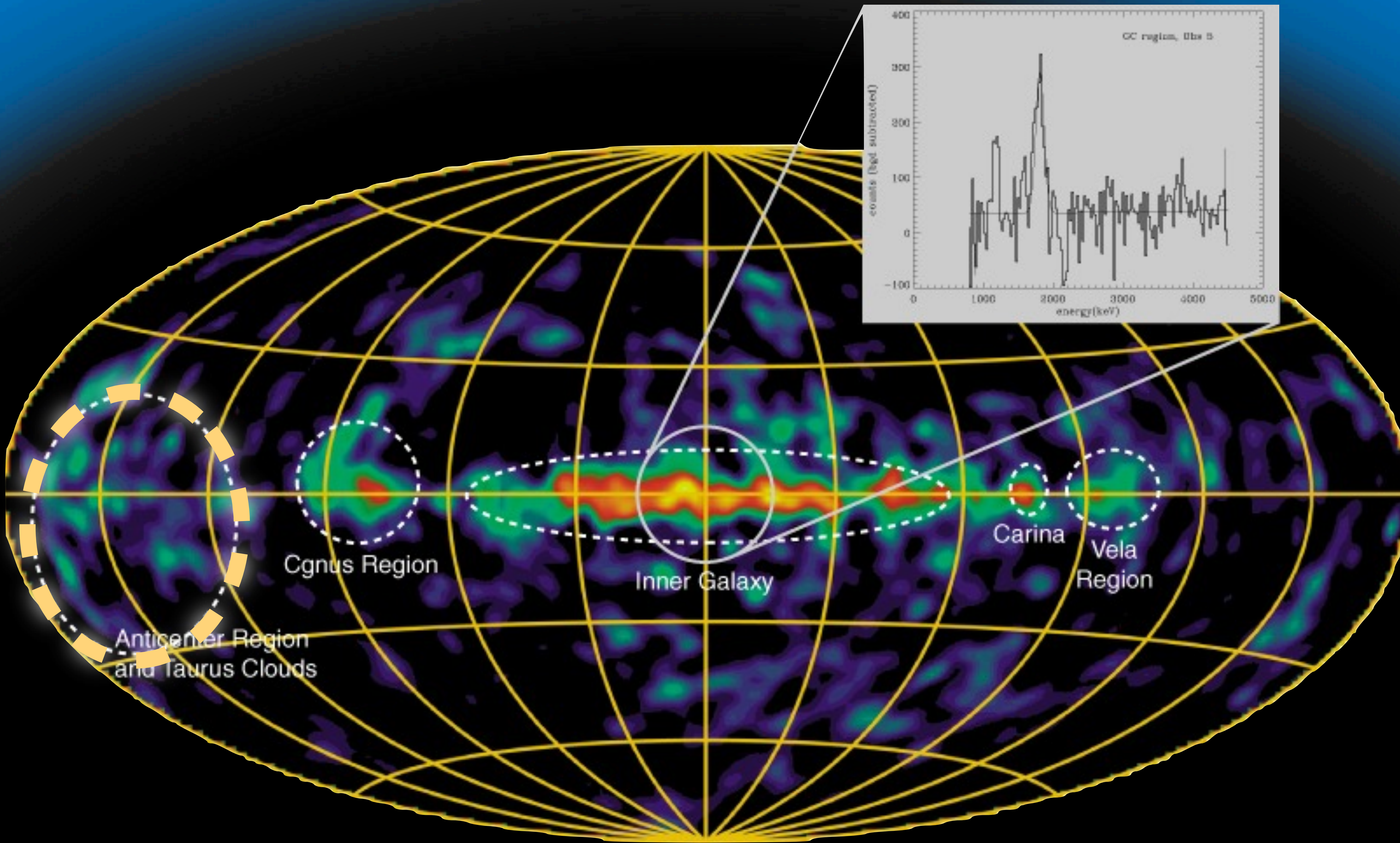
- Diffuse emission
- compact sources
- pulsed emission, etc
- in particular, in this energy range: *gamma-ray line spectroscopy*

Line emission with Comptel



Comptel map of the galaxy at 1.8 MeV
(radioactive decay of Al^{26}, indicating nucleosynthesis in SNRs)

Line emission with Comptel



Comptel map of the galaxy at 1.8 MeV
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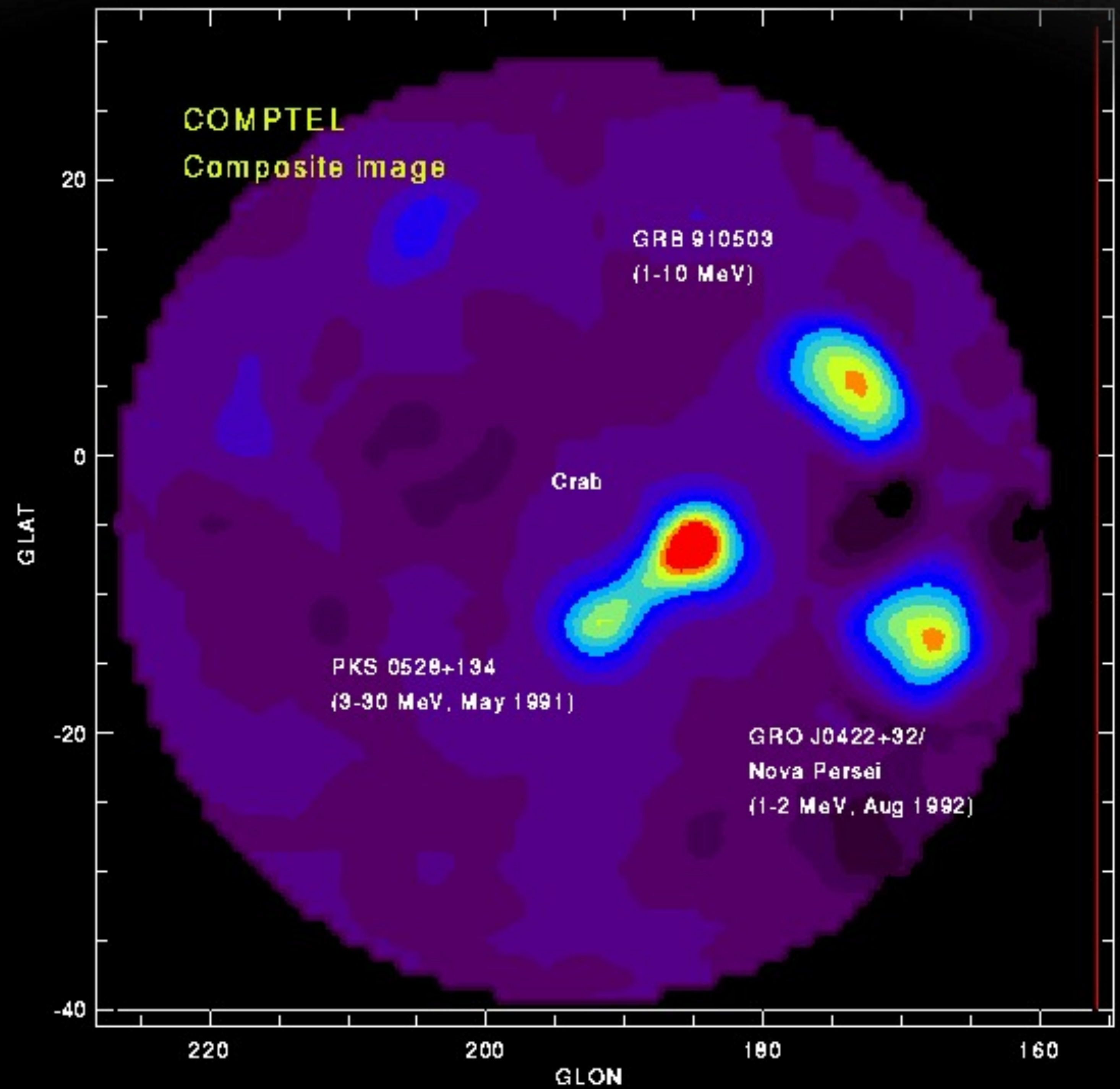
Crab with COMPTEL

Galactic Anti-center region

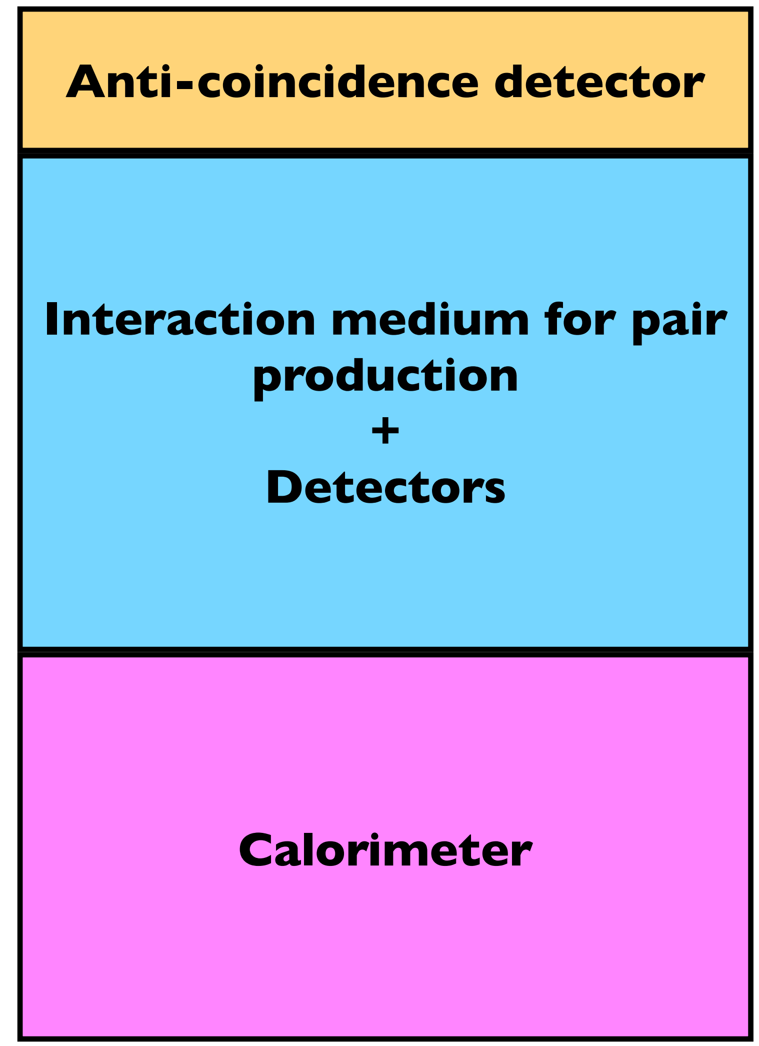


Gamma-ray Satellites: GeV energies

Pair-conversion Telescopes

The basic components:

- **Anti-coincidence detector** discriminates between charged particles and photons. Charged particles are vetoed.
- **Interaction medium** provides a environment for pair-production to occur.
- **Tracking Detectors** track the progress of the sub-particles in the medium, providing the *direction* of the primary
- **Calorimeter** measures the *energy* of the pair, which stop within it.



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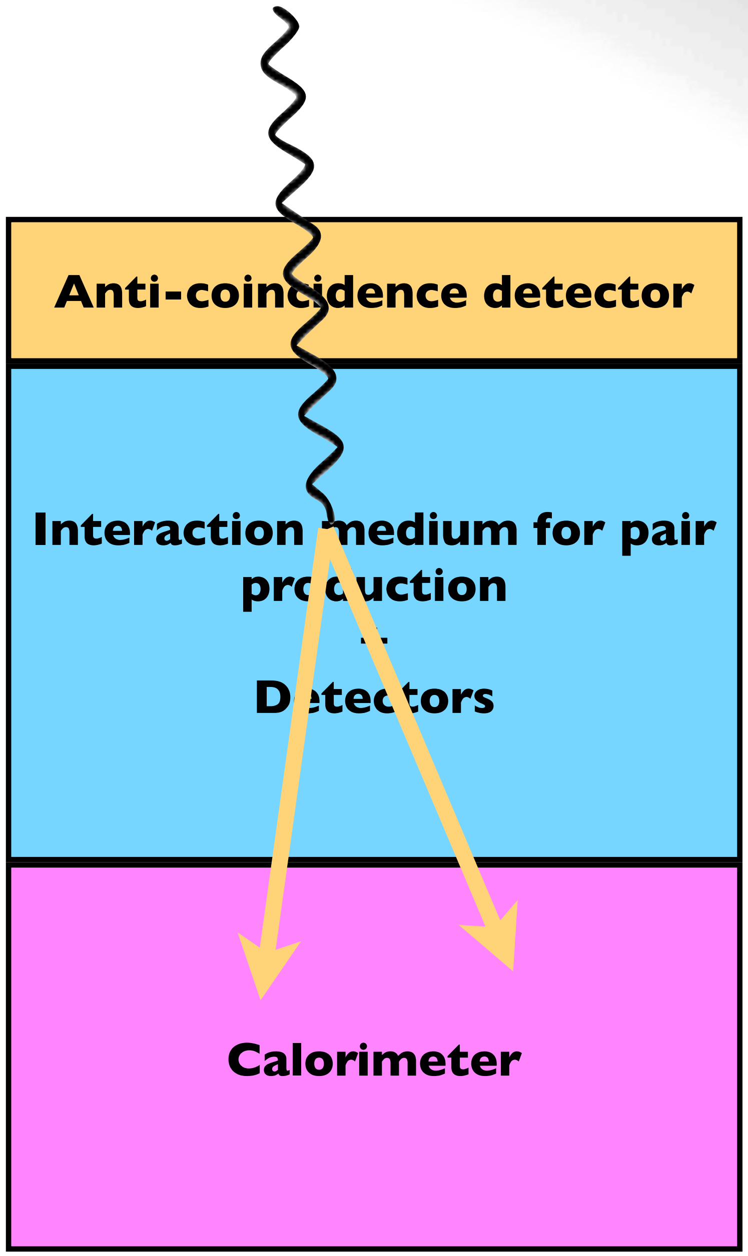
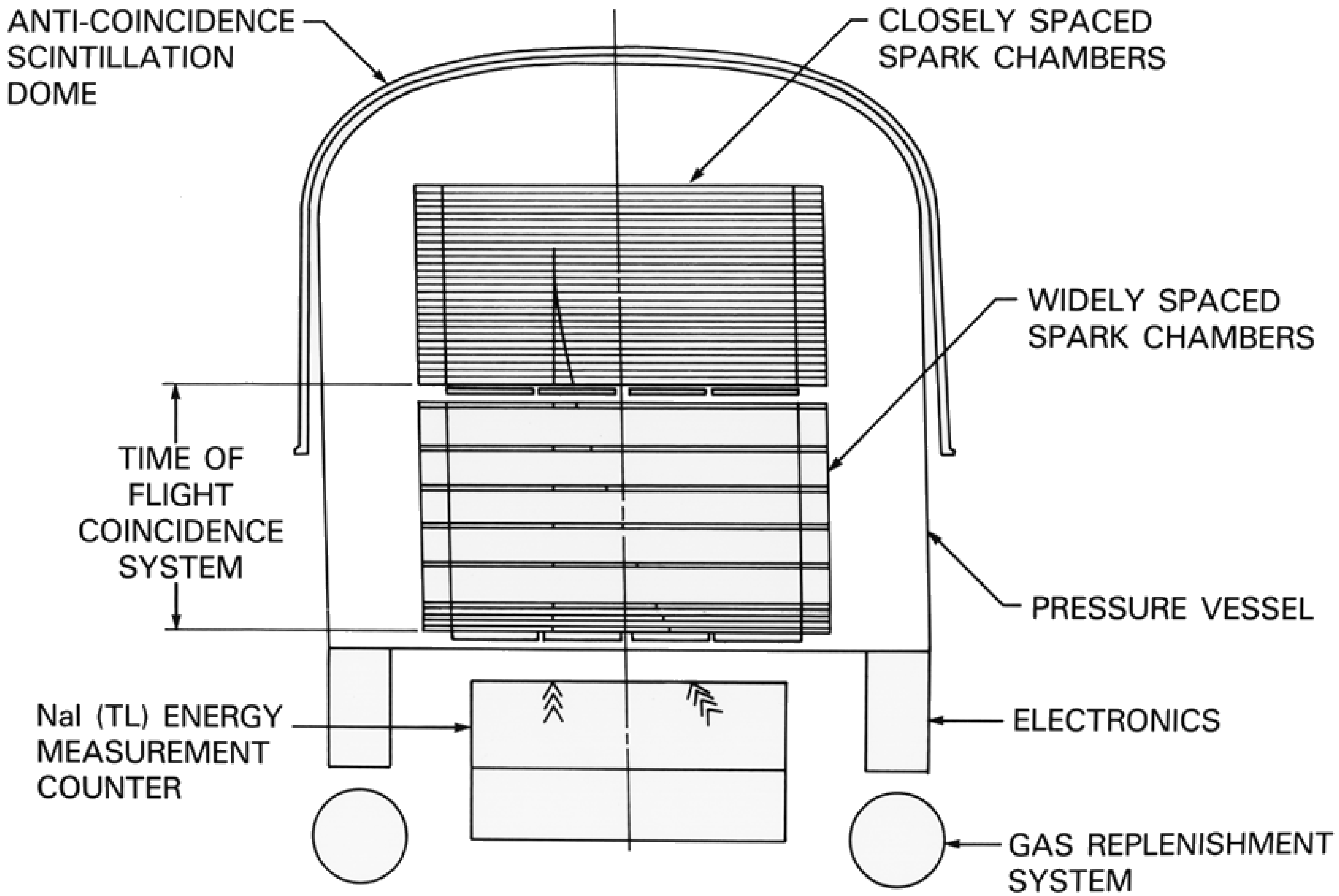
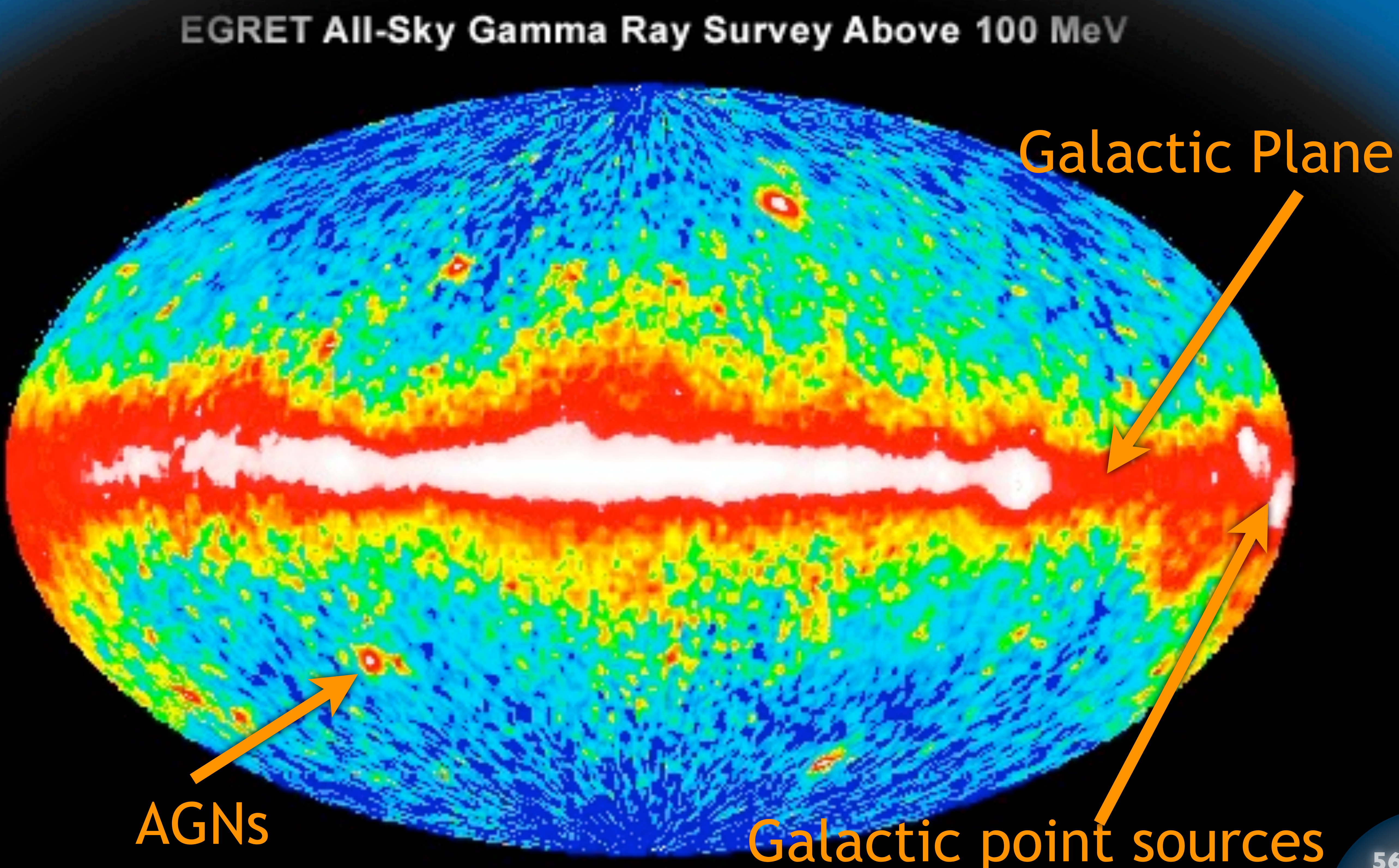


CGRO: EGRET

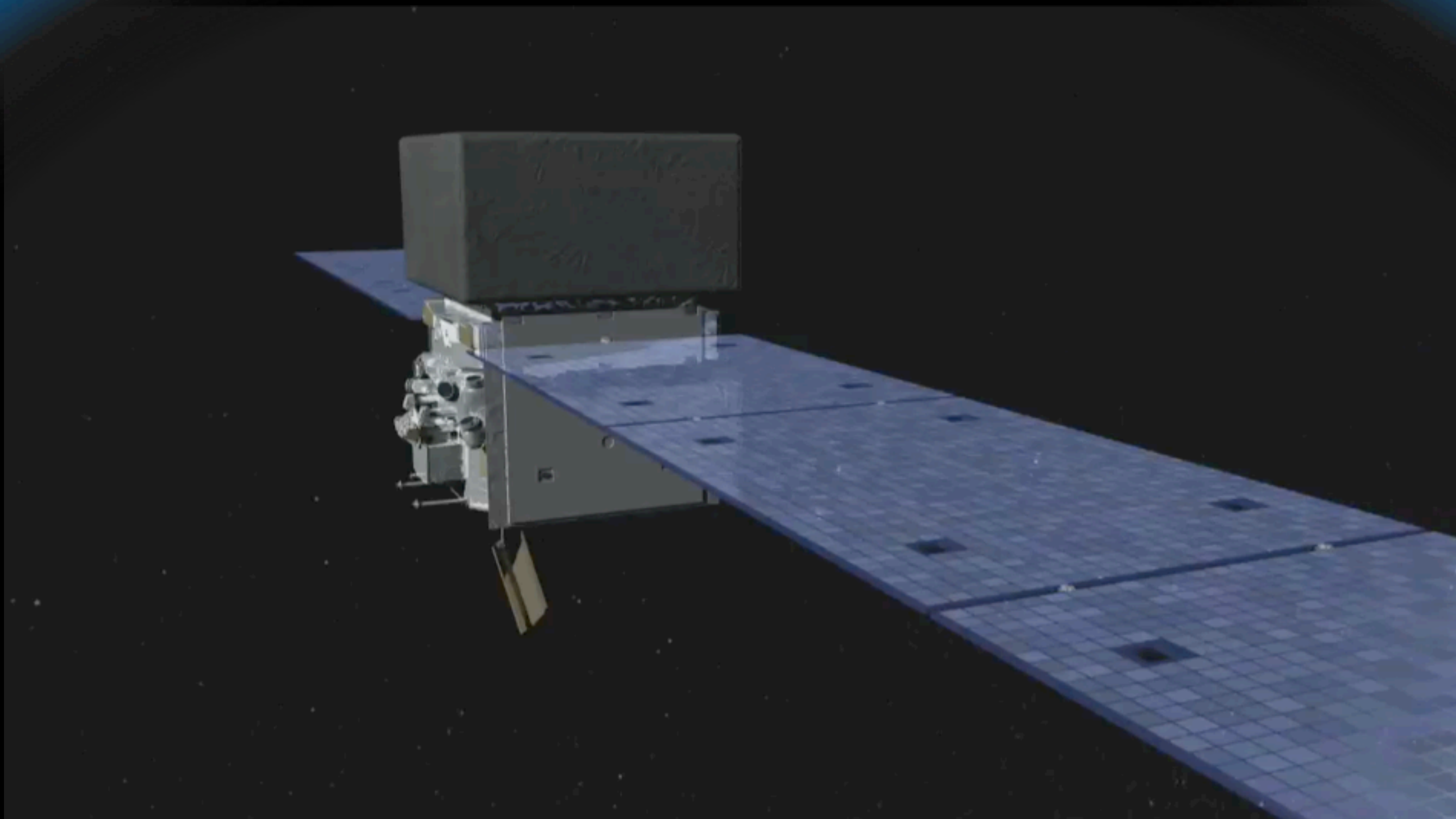


ANTI-COINCIDENCE
SCINTILLATION
DOME
CLOSELY SPACED
SPARK CHAMBERS
WIDELY SPACED
SPARK CHAMBERS
TIME OF
FLIGHT
COINCIDENCE
SYSTEM
PRESSURE VESSEL
NaI (TL) ENERGY
MEASUREMENT
COUNTER
ELECTRONICS
GAS REPLENISHMENT
SYSTEM

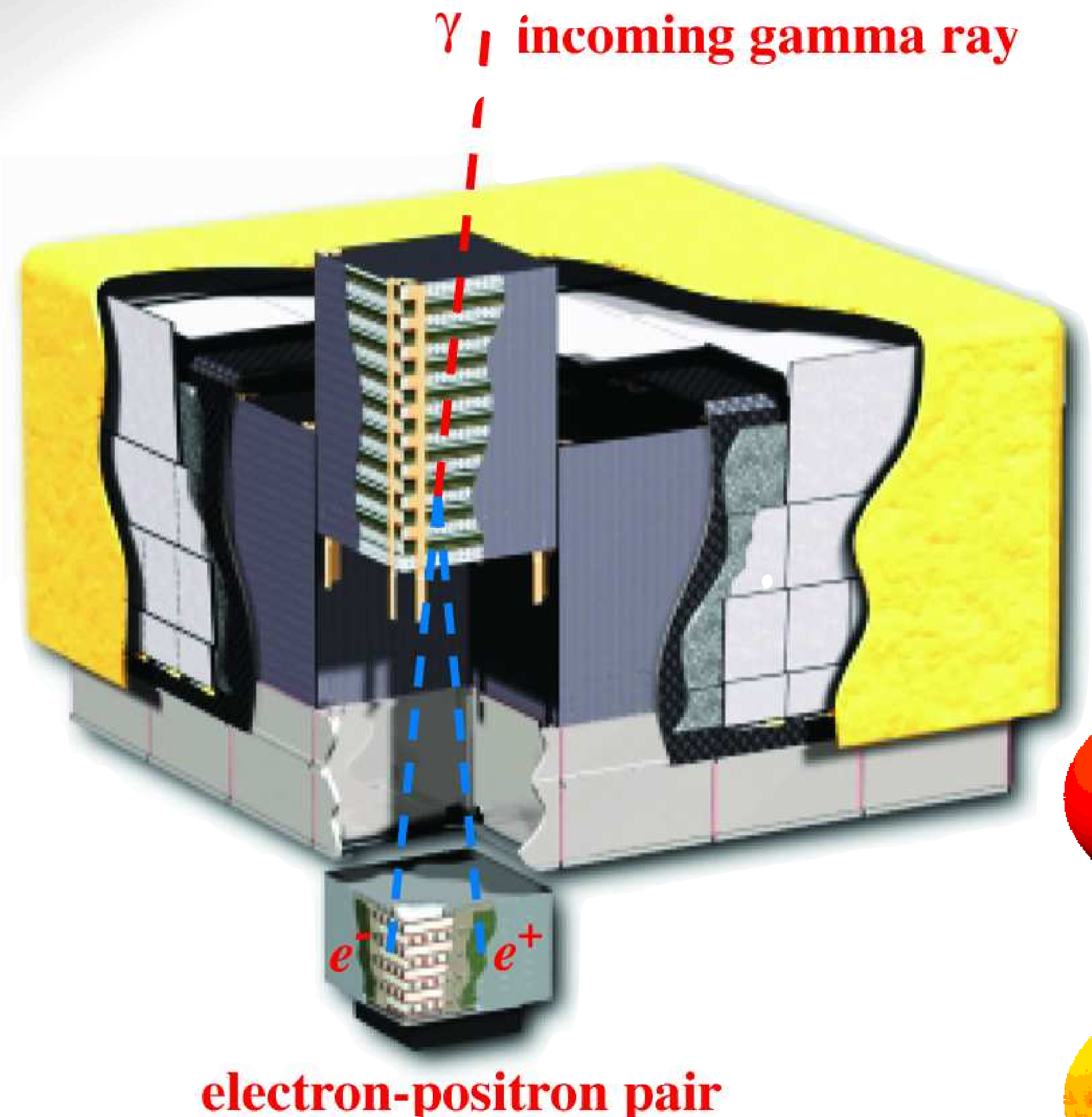
The Sky with EGRET



Modern Generation: Fermi GST



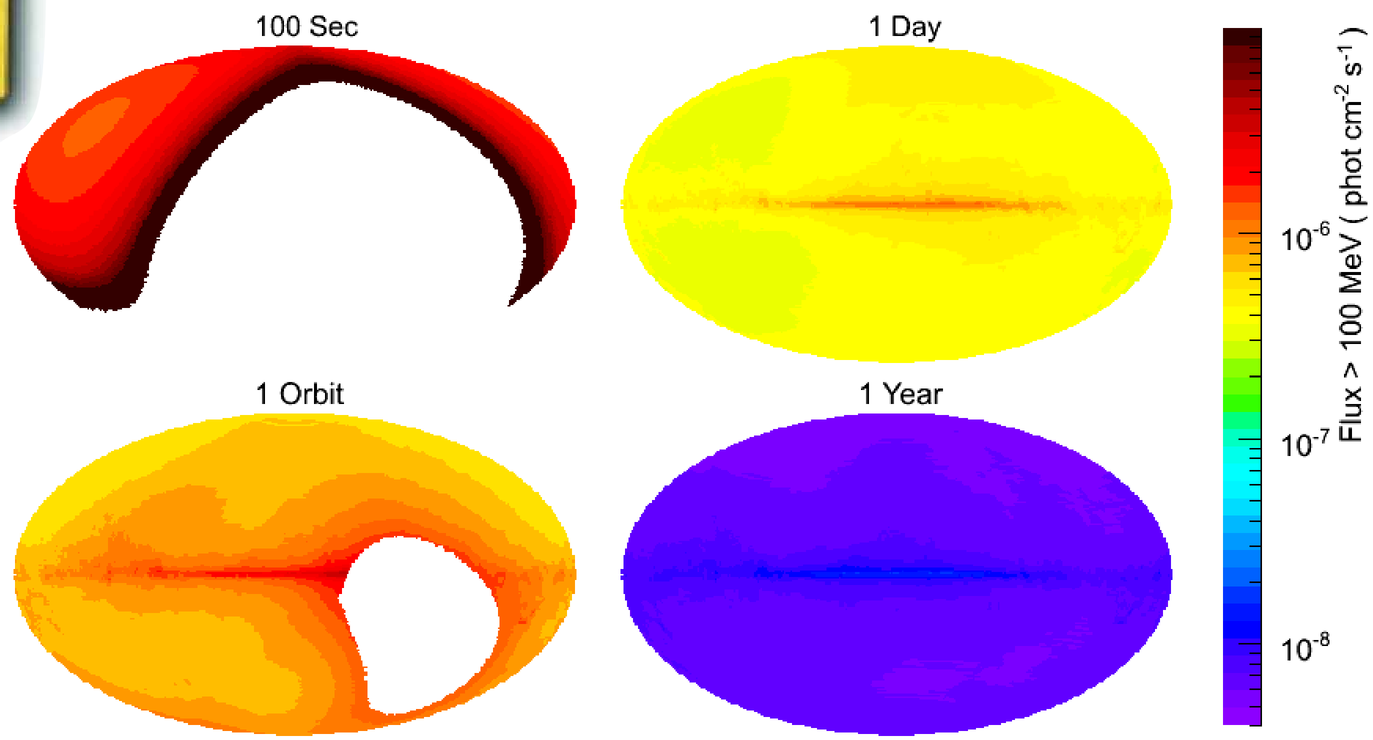
Fermi LAT



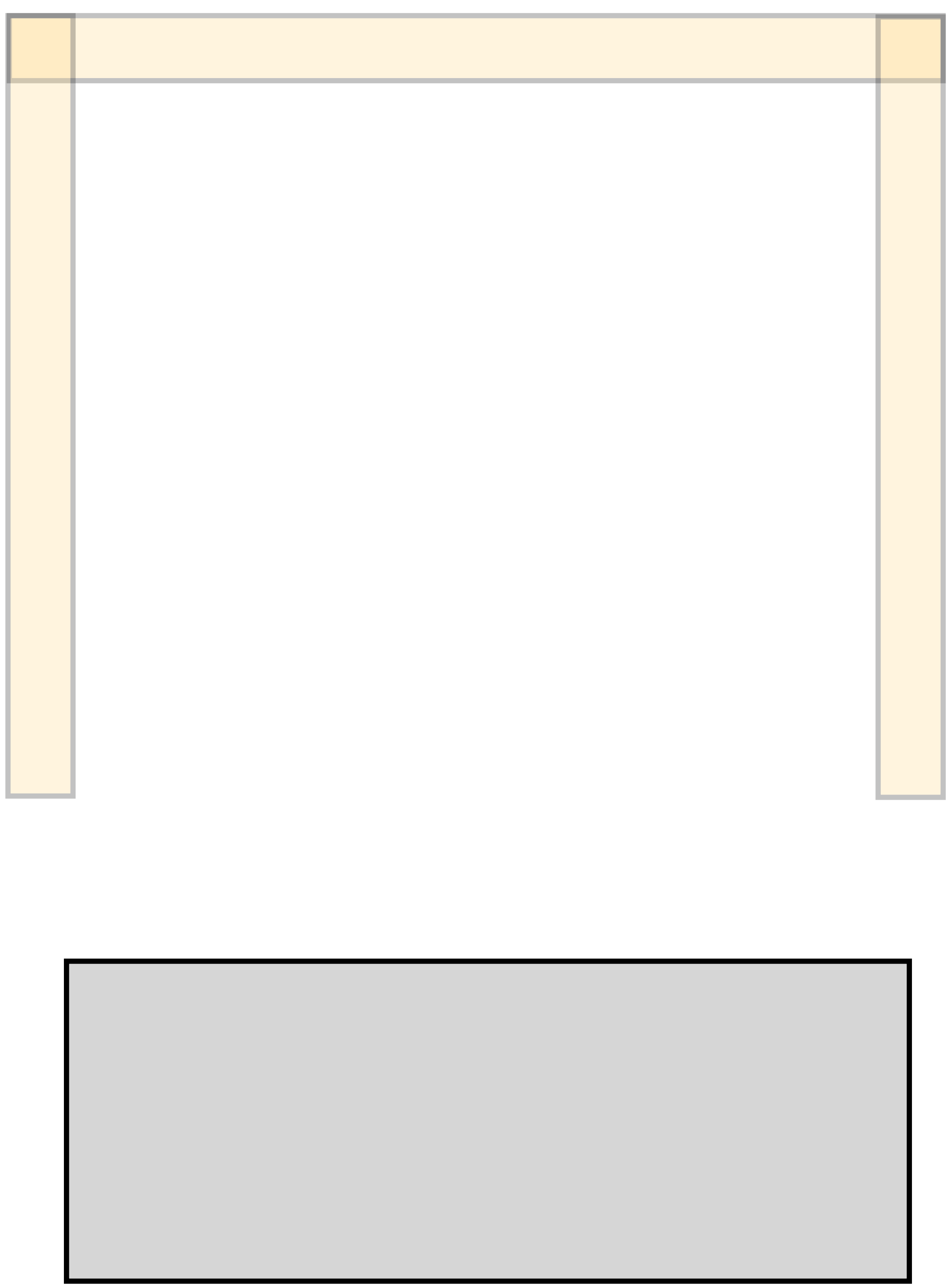
≈16x sensitivity of EGRET

Better PSF, Energy resolution

Wide FOV (nearly flat exposure



Pair-conversion Details...



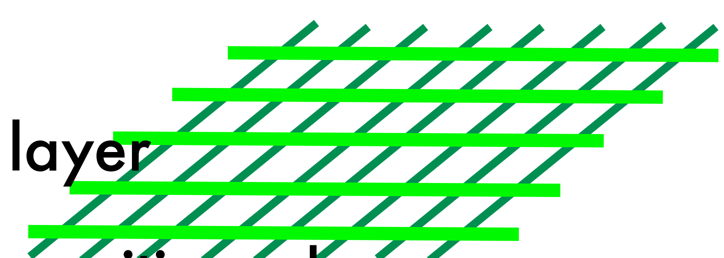
Anti-coincidence plastic scintillators

- generate light when a charged particle passes through them, but not a photon
- readout by PMTs
- provide anti-coincidence time veto for cosmic rays (reject 99.97%)

Layers of heavy material (tungston)

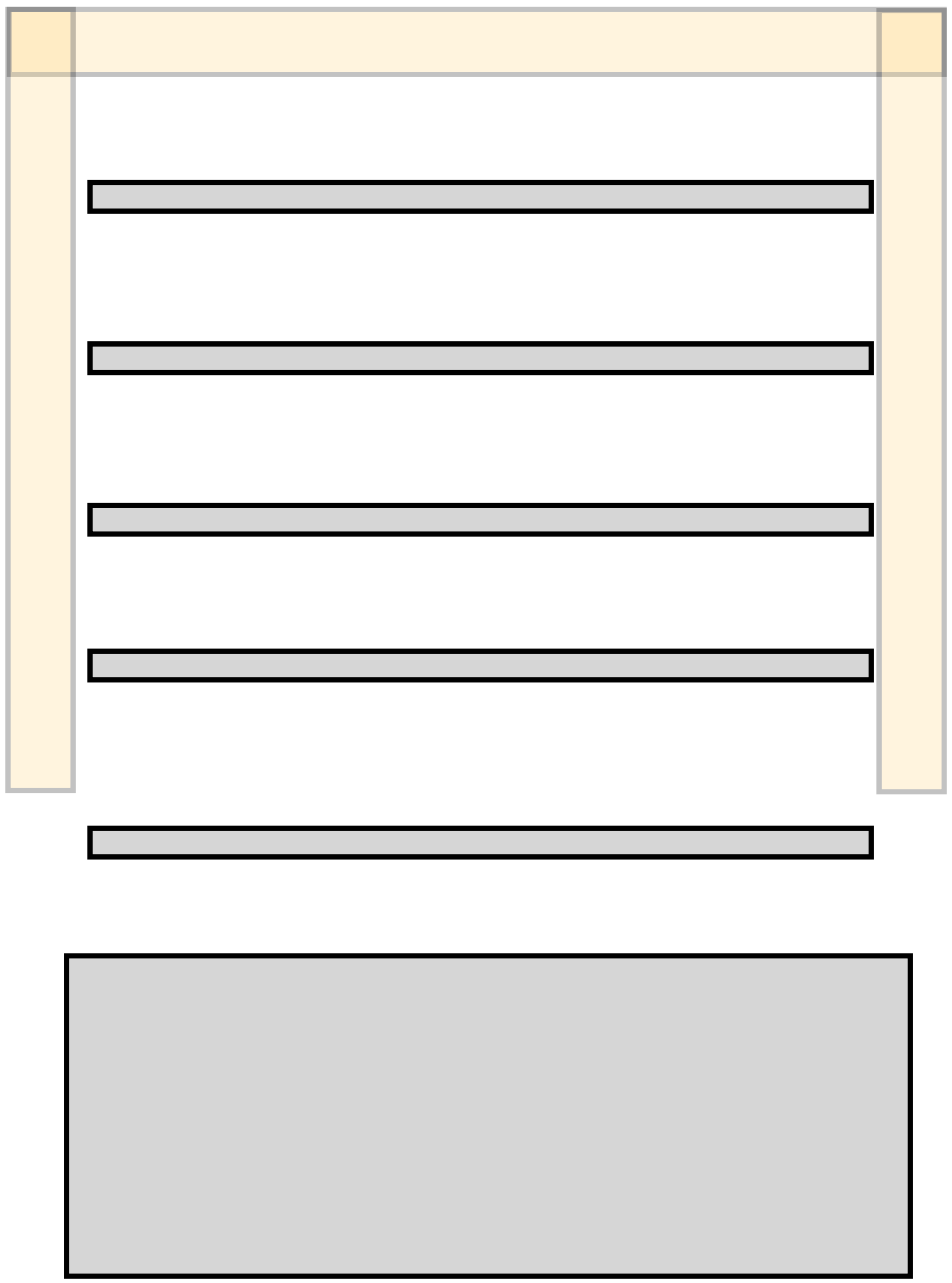
- provide target nucleii for pair production

Silicon tracker strips



- between each tungston layer
- provide time and x or y position when particle ionizes atoms in the silicon
- alternating x and y strips give 2D position

Pair-conversion Details...



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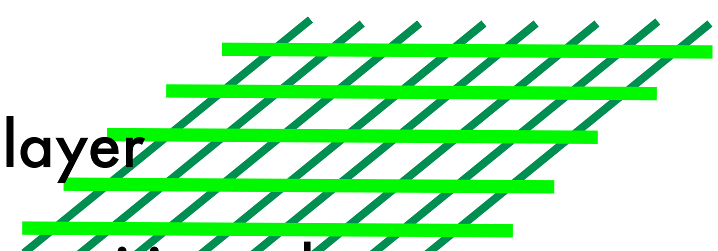

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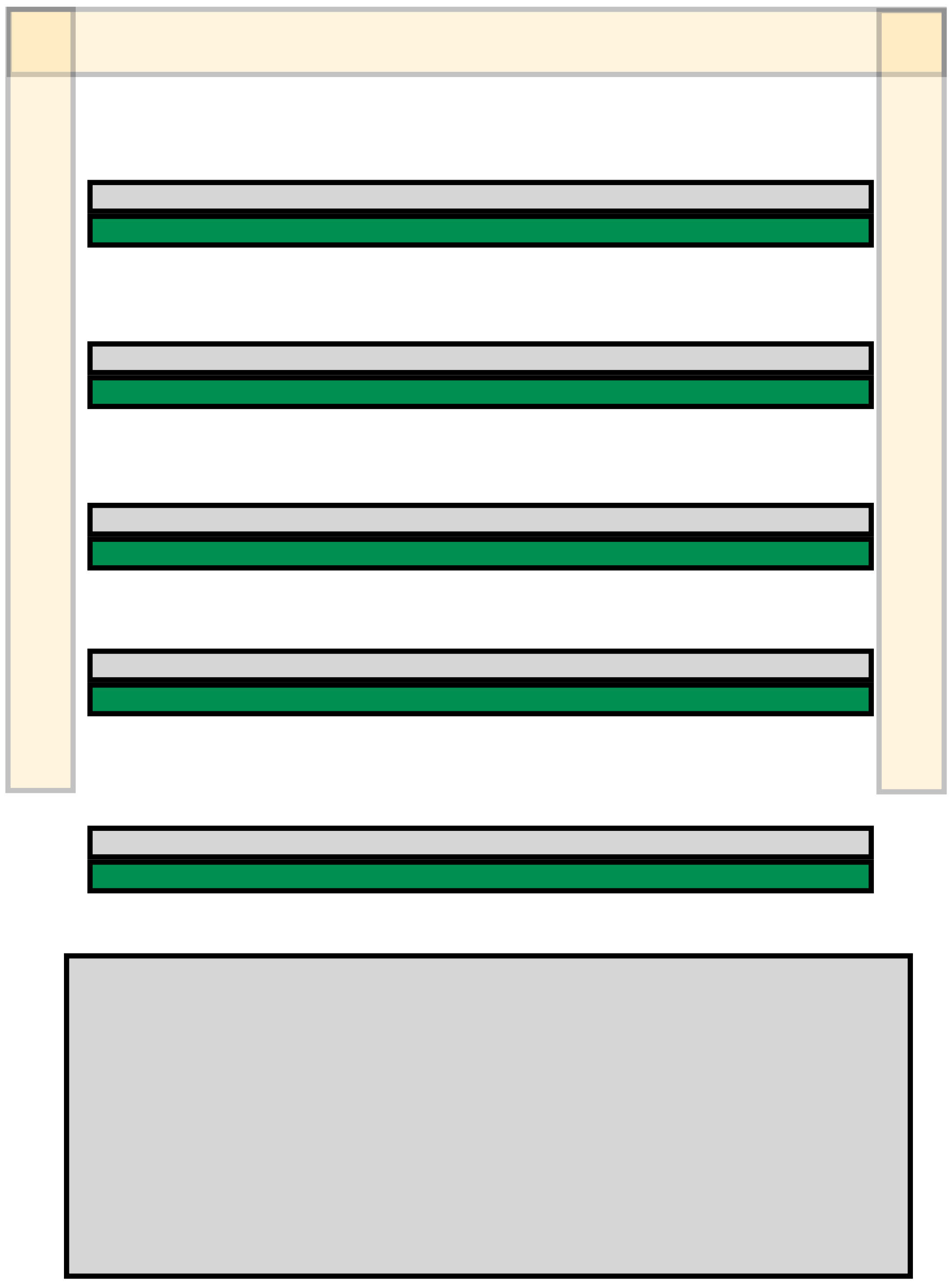

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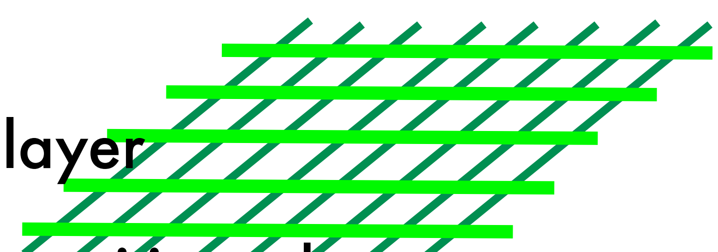

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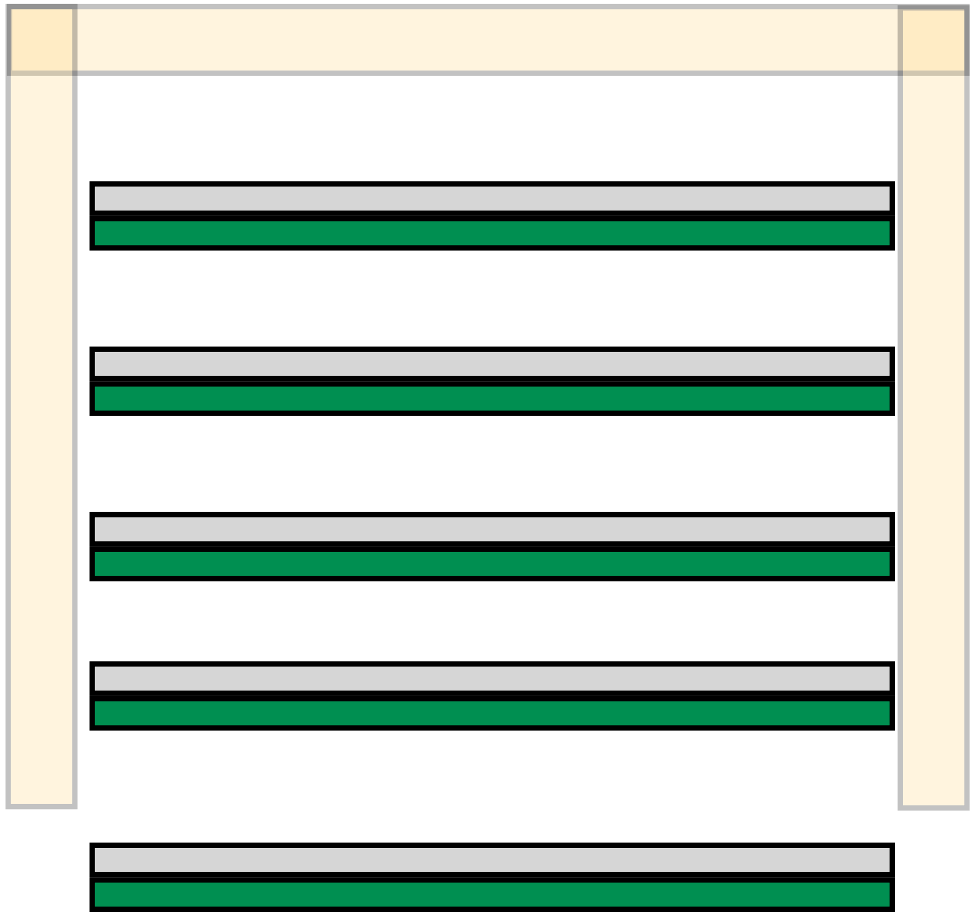
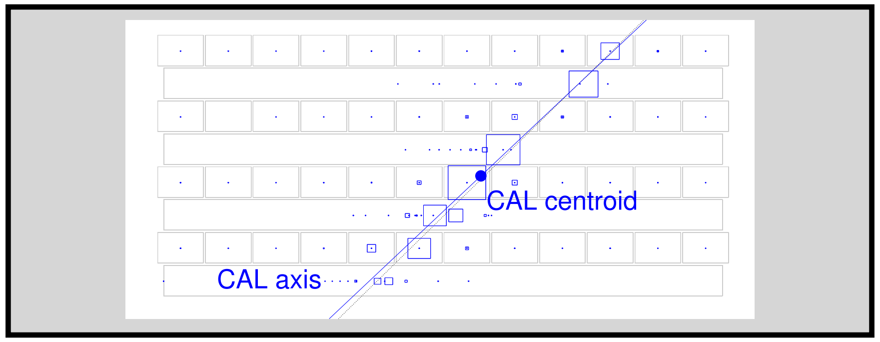




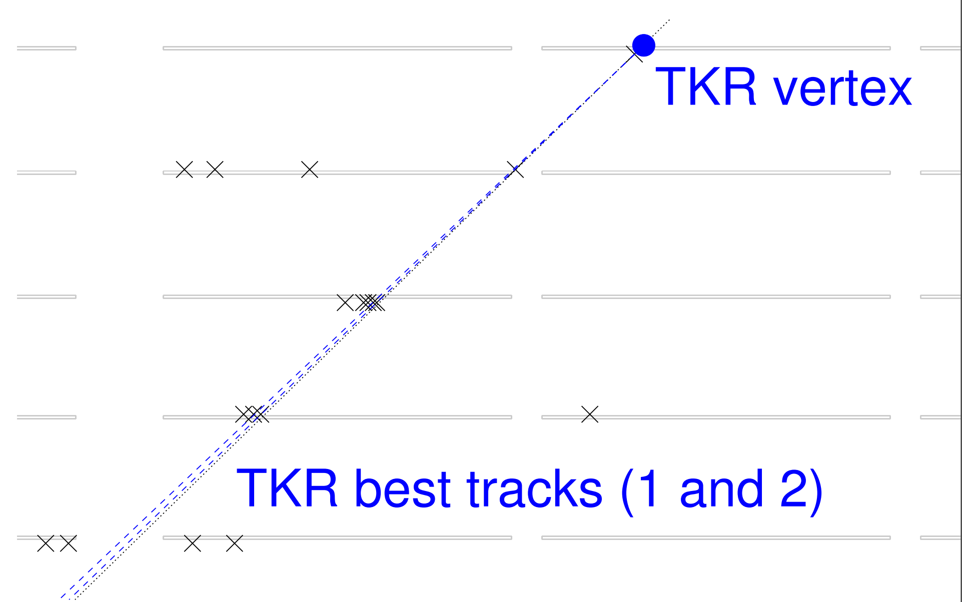
Calorimeter

- 12 “logs” of CsI crystal scintillators in 8 layers per tower, alternating in X and Y directions (a hodoscope)
- logs are covered with a material that produces decreasing light along the length, to provide measure of position.
- photodiodes read out each “log”, providing full 3-D image of energy deposited
- above 3 GeV, showers no longer contained, 100 GeV half leak out

Event Reconstruction

Tracker:

- have:
  - binary hit pattern of each tracker element
  - initial estimate of direction from calorimeter (sometimes)
- use iterative pattern recognition algorithms to identify the particle track
  - weighted towards solutions that point toward the calorimeter's centroid
  - above 1 GeV, can reject solutions that do not (below may have transverse motion)



Event Reconstruction

get reconstruction parameters from each detector (anti-concidence + tracker + calorimeter)

- direction + energy + other reconstruction parameters
- want: **probability that it is a gamma ray**

Use classification tree analysis, trained to select gamma ray events:

- choose best reconstruction method
- provide probability of being a gamma ray
- reject probably background events

Events are finally classified based on:

- goodness of energy recon,
- goodness of direction recon

End-user can choose class (e.g. how much background rejection, best PSF, etc)

Machine learning algorithm(s) for classifying data with a set of parameters

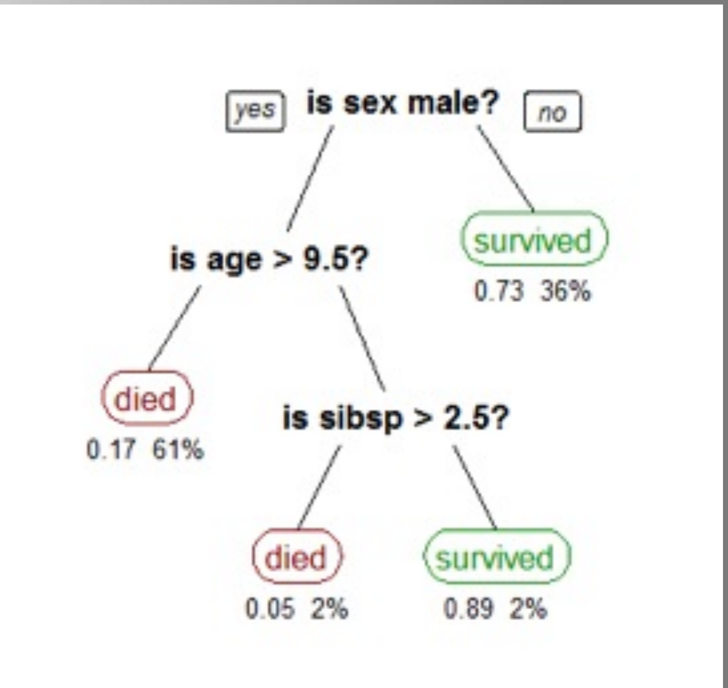
- event X is parameterized as (x0,x1,x2...)
- Classes are chosen
- **Training** is done using a set of data with known classes (simulations)
- Produces a tree of thresholds, with leaves that give a measure of the classification variable
- cuts usually made on the distribution of the classification parameter to distinguish signal from background

Types of decision tree algorithms:

- Classification Tree
- Boosted Decision Tree, Regression Tree
- Random Forest

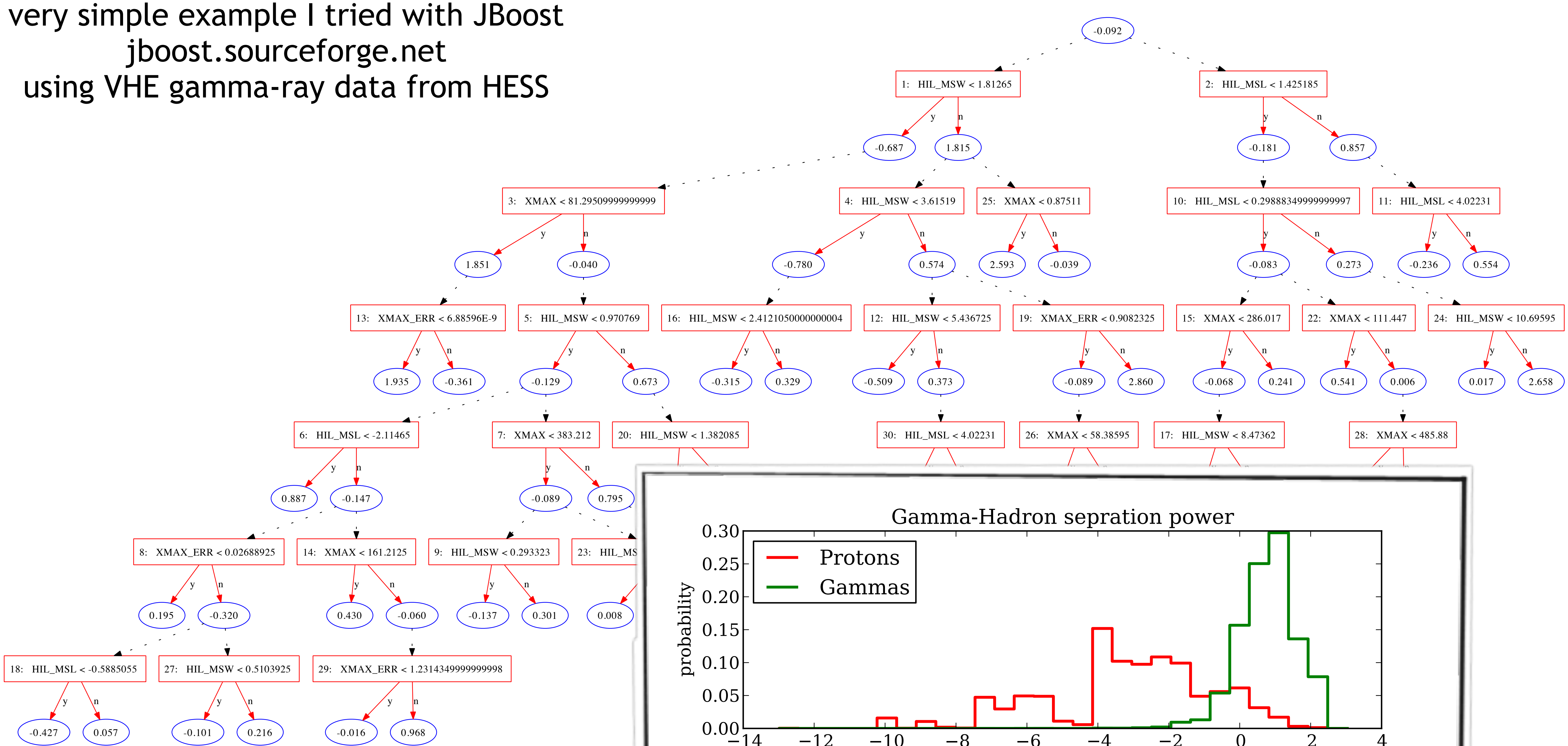
See e.g. TMVA, JBoost, Weka, etc if you want to try it out yourself...

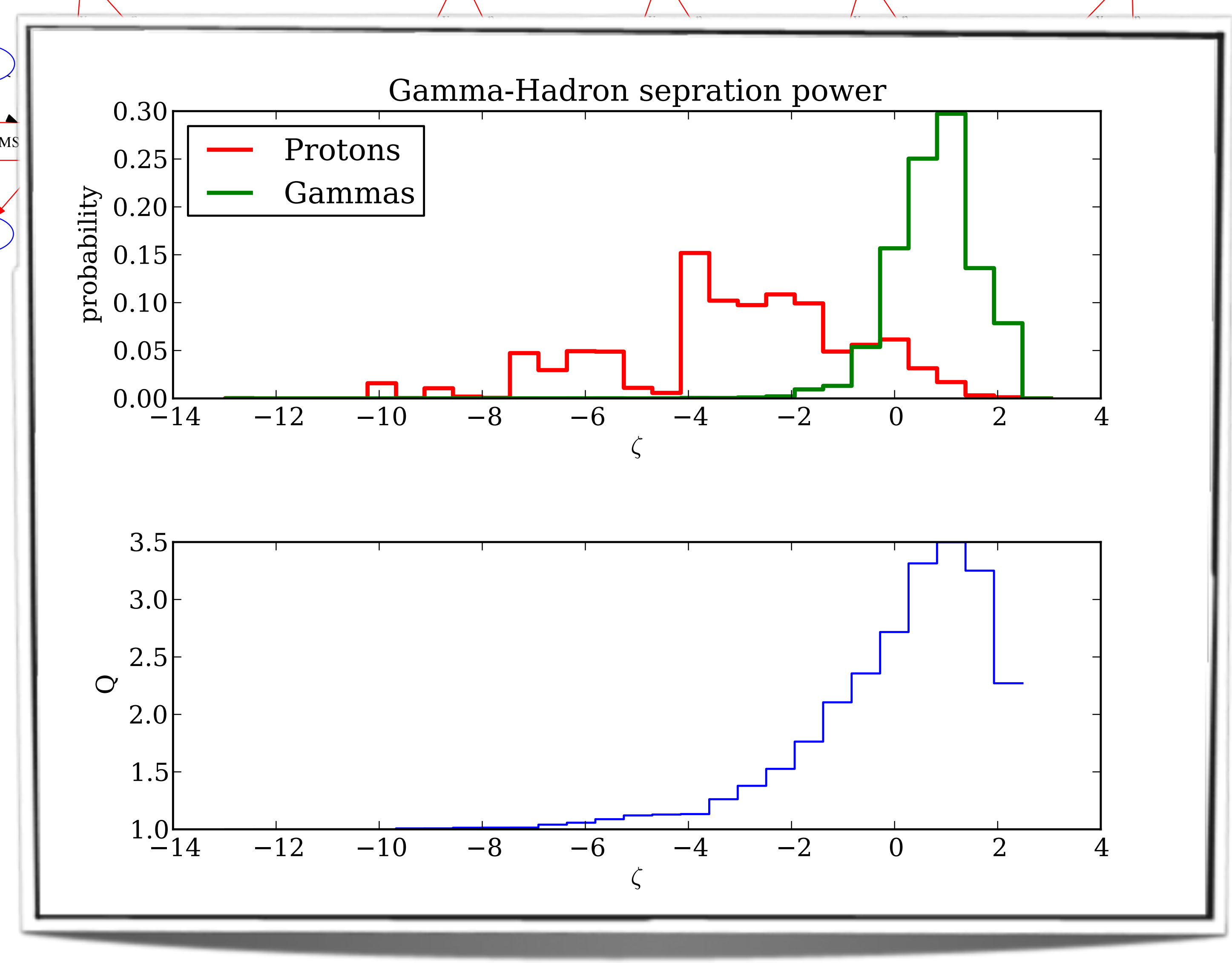
Aside: Decision Trees



wikipedia's somewhat morbid example

very simple example I tried with JBoost
jboost.sourceforge.net
using VHE gamma-ray data from HESS

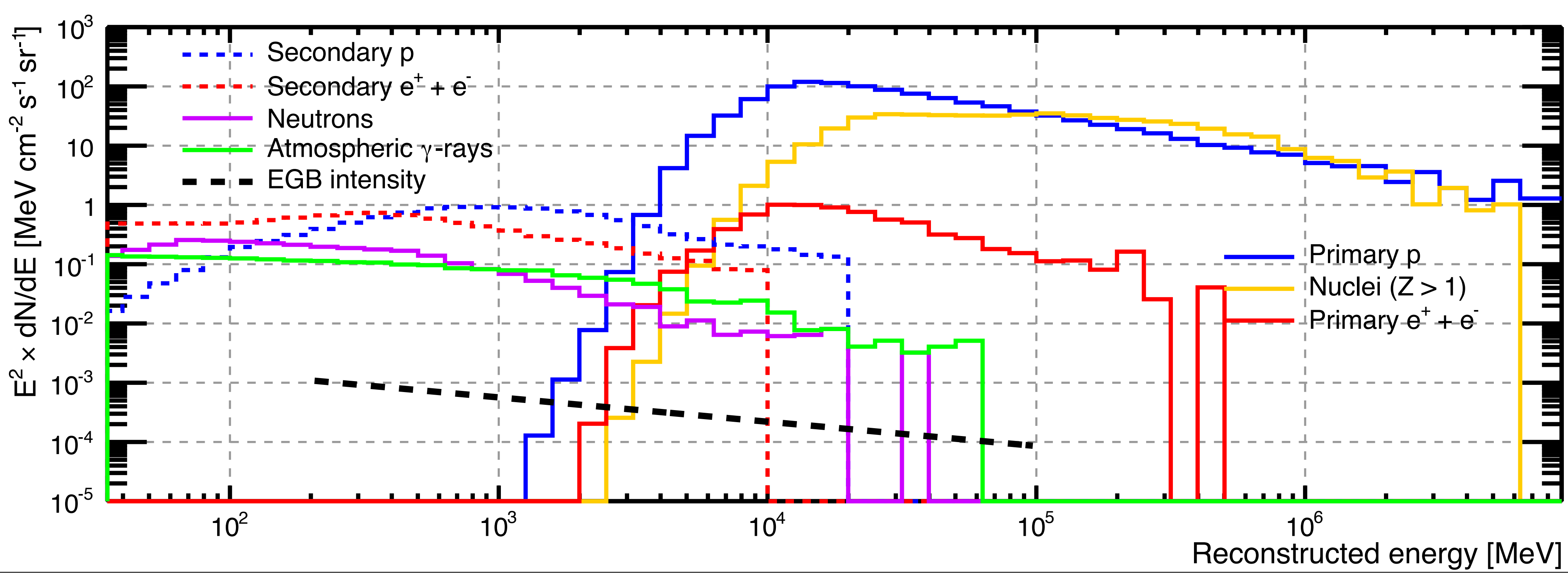




Background Modeling

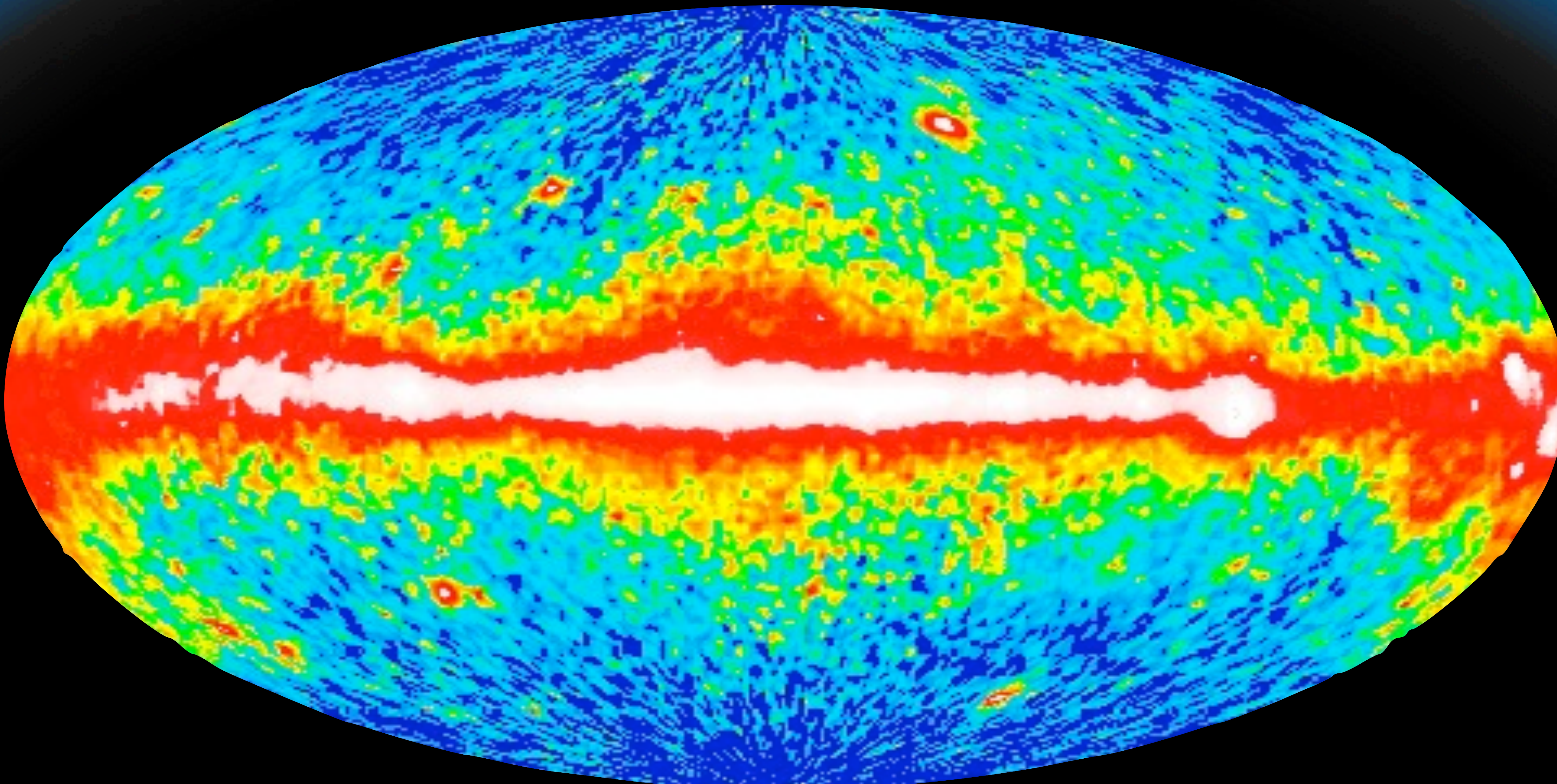
Residual Particle Background: (essentially isotropic)

- CRs can scatter off material around the anti-coincidence detector, producing secondary gamma-rays that will be detected
- CRs can interact in the atmosphere, producing e+/e- that in some cases come back out of the atmosphere. Most are rejected by the ADC, but some may annihilate closeby
- Neutral secondary particles (gammas and neutrons) created in Earth's atmosphere by CR interactions can make it to the detector (predominantly when looking close to Earth's limb)



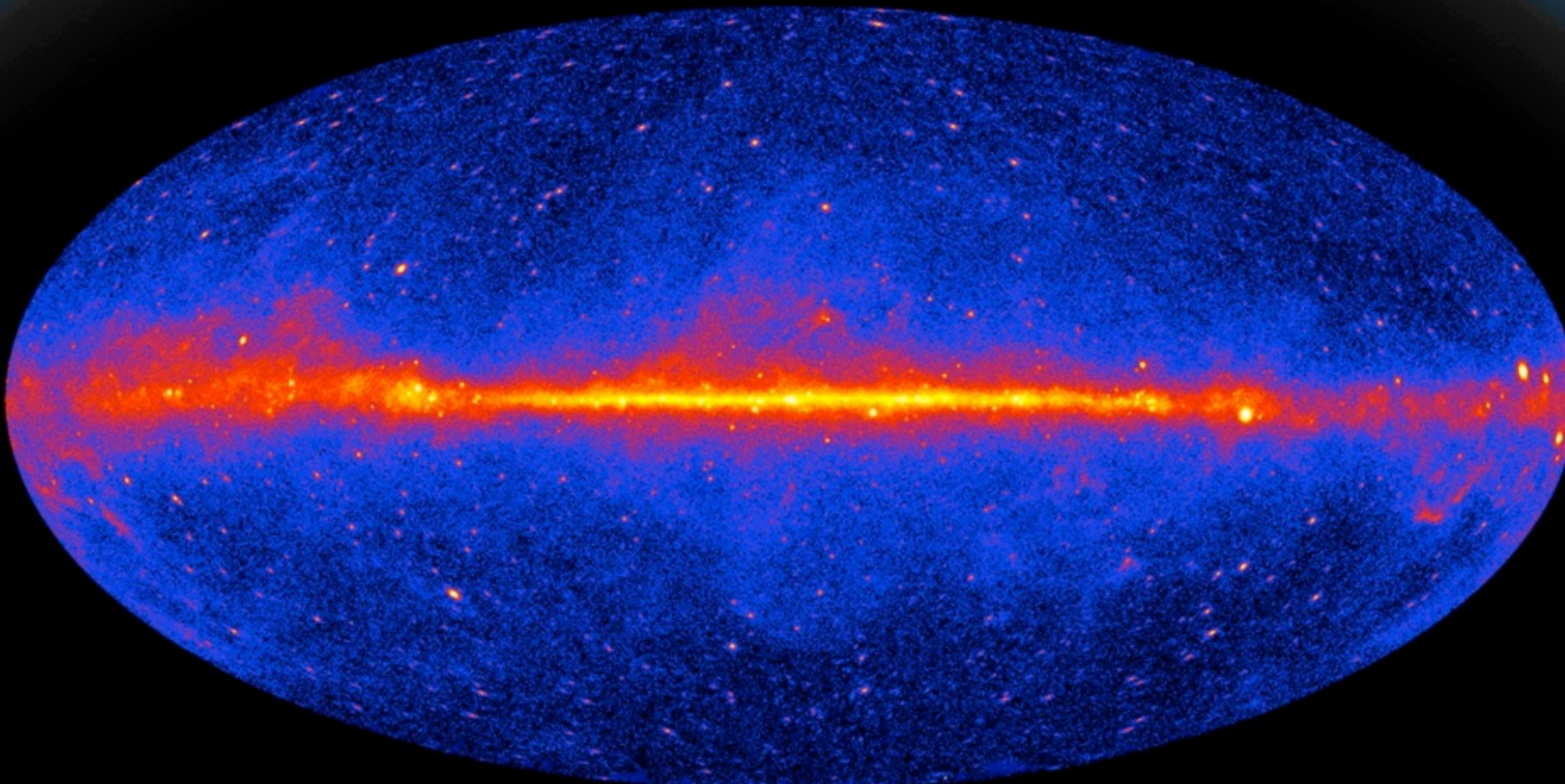
Source Modeling

Fermi All-Sky, 3 Years



EGRET -> FERMI -> FERMI (E>10GeV)

Fermi All-Sky, 3 Years



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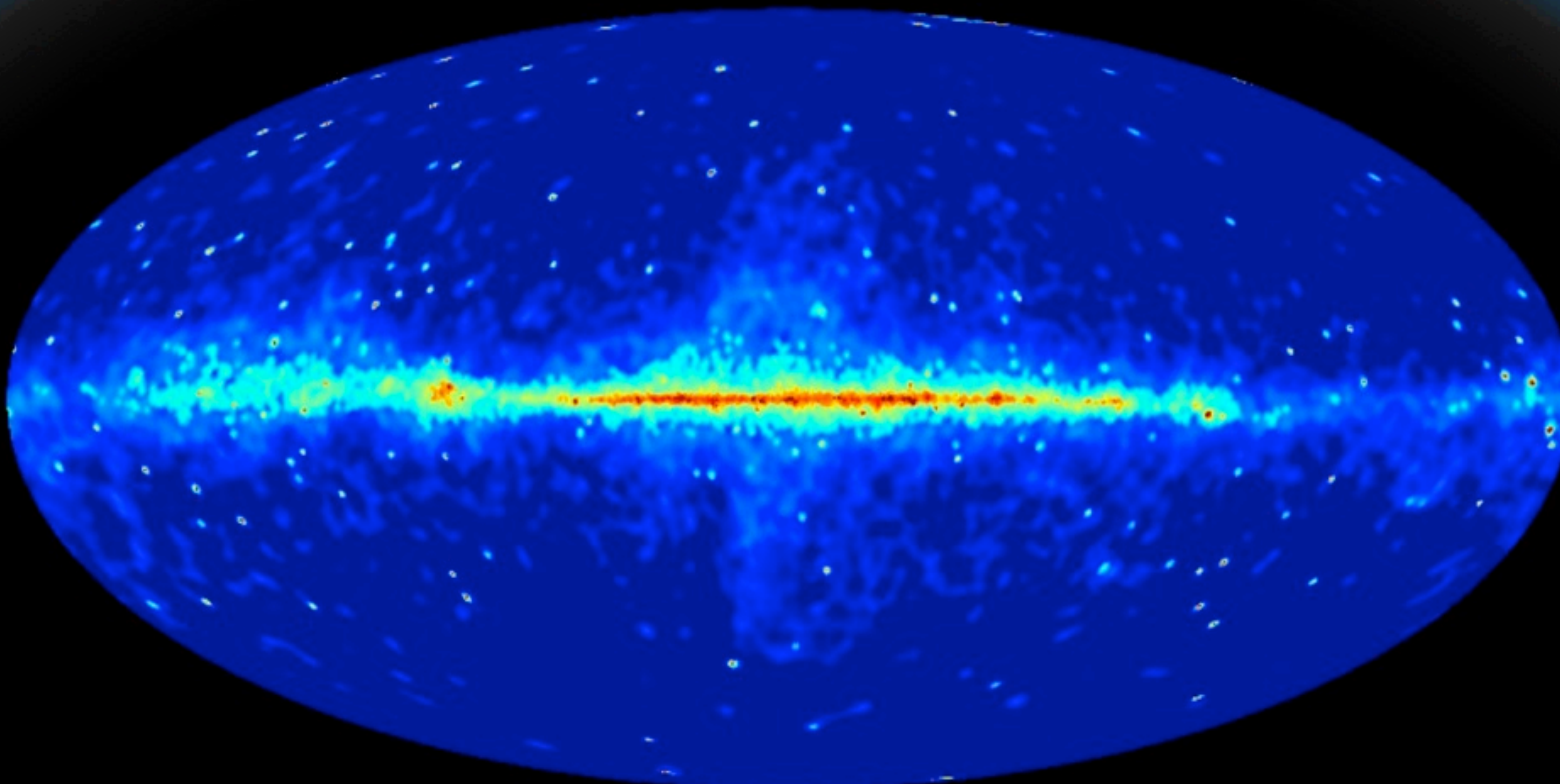

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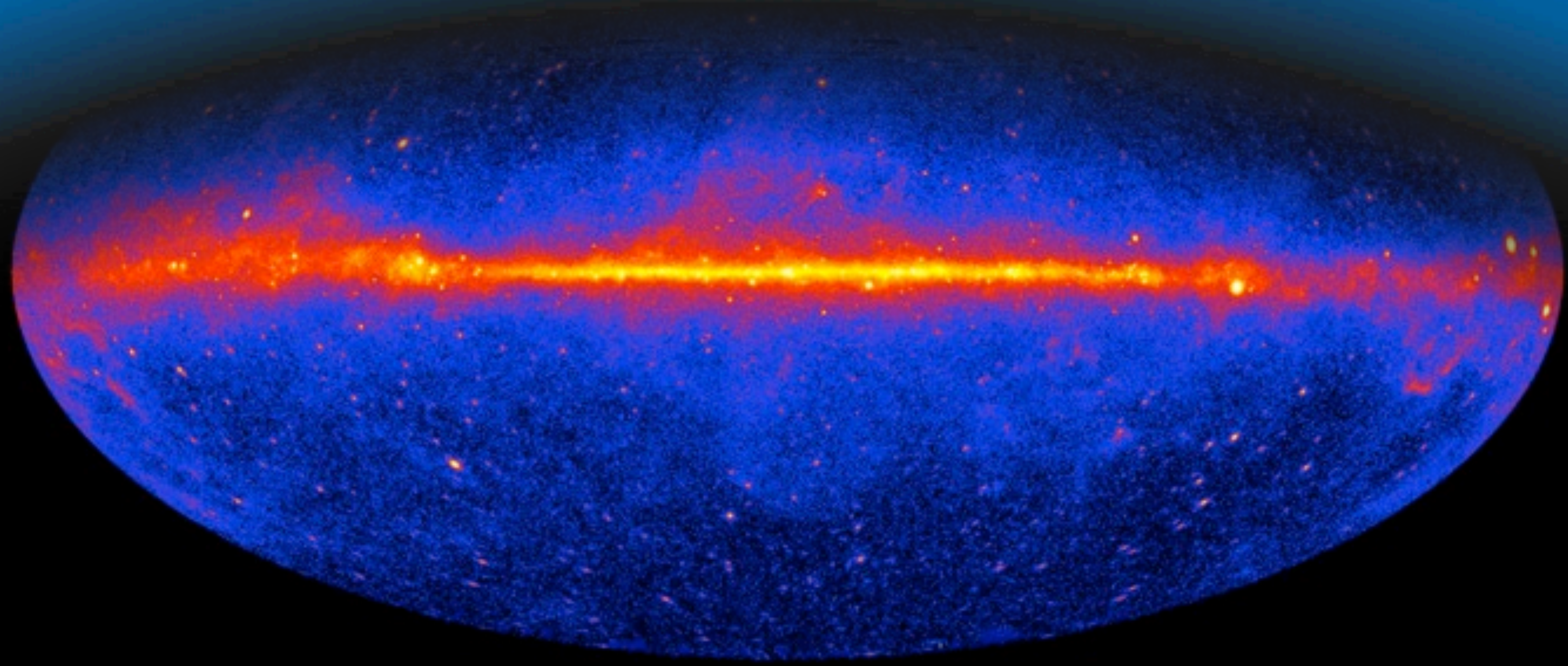

- **Note that there is significant diffuse emission obscuring the galactic plane**
  - interaction of galactic cosmic rays with target material:
    - molecular clouds
    - H2 regions

Background Modeling

Diffuse Gamma Rays:

- a non-isotropic background
- generated by interactions of **galactic cosmic rays** with **target material**: interstellar medium, giant molecular clouds
- a significant component of the galactic gamma-ray emission!
  - must be modeled and subtracted to see individual sources in the galaxy

Diffuse Background Model

Diffuse Background Model

Step one: model the distribution of cosmic rays in the galaxy

- model propagation of charged particles and associated diffuse emission components in the galaxy (e.g. GALPROP software Strong et al, http://galprop.stanford.edu/)
  - nuclear physics + ionization and interaction losses
  - diffuse gammas from interaction with matter: Bremsstrahlung, Inverse-Compton, and pion decay

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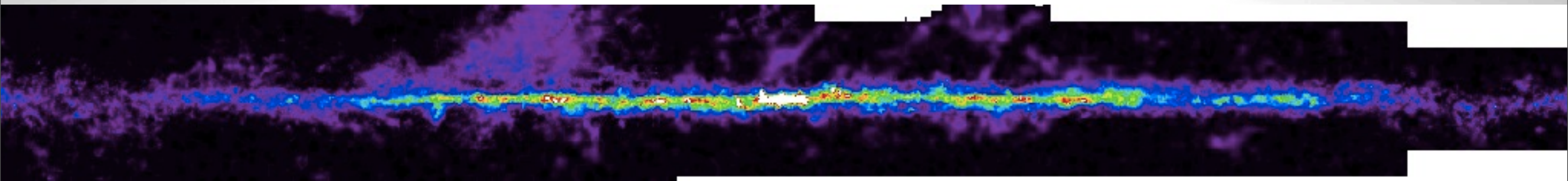
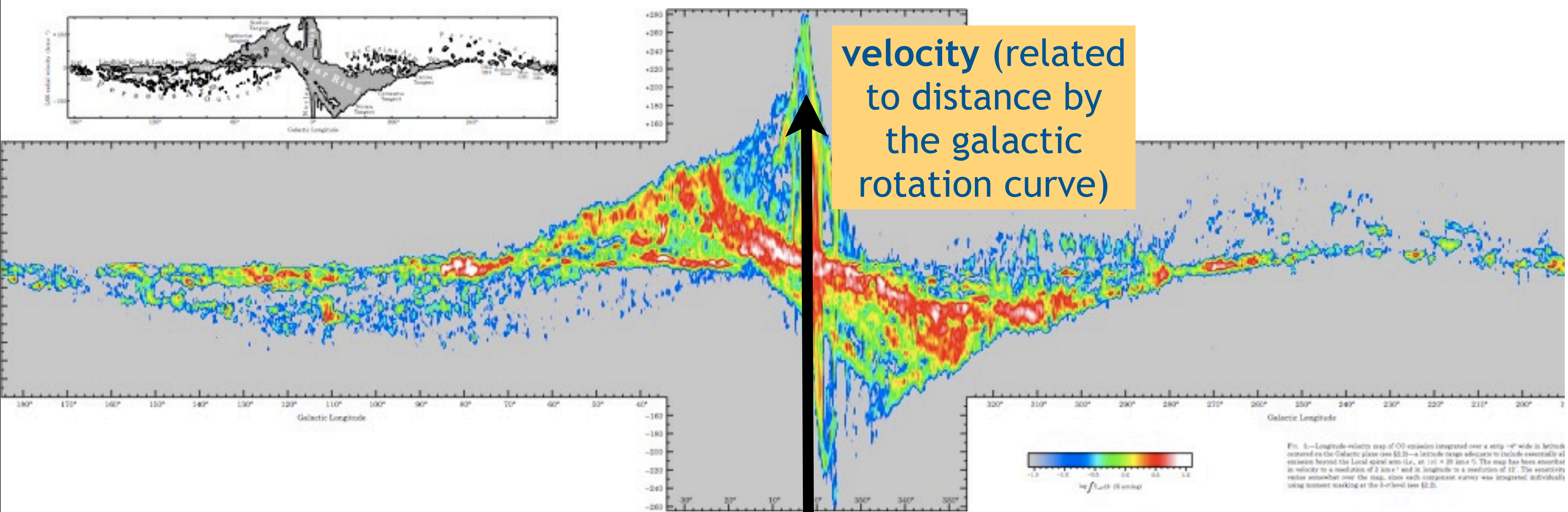
Step two: model the distributions of interstellar matter (target material)

- HI surveys (neutral hydrogen)
  - in cases where HI column density is under or over estimated, use IR observations of dust to correct it
- CO surveys as a tracer of H2 (molecular hydrogen)
  - e.g. ^{12}CO, J=1—›0 transition line can be used to estimate the amount of HII.
  - $X = N_{H2} / W_{CO} \approx 1.8 \times 10^{20}\ cm^{-2}\ K^{-1}\ km^{-1}\ s^{-1}$
    [Dame et al 2001]
- Calculate gamma-ray emissivity
  - fit to number of counts (simple)
  - calculate CR density with numerical model (Galprop) and multiply by cross-section (fancier)

CO Surveys

Dame et al. 2001, ^{12}CO survey

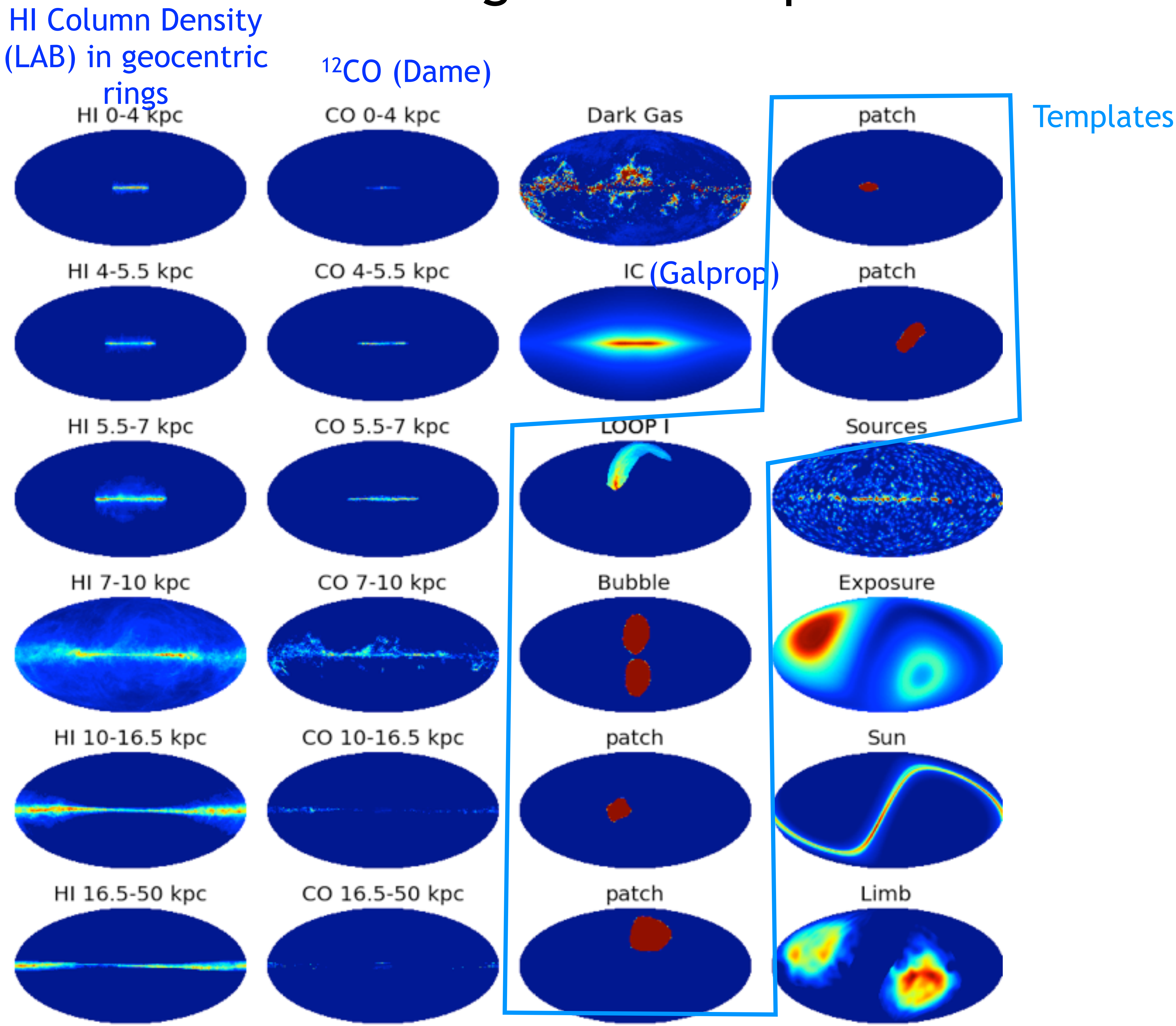




velocity (related to distance by the galactic rotation curve)

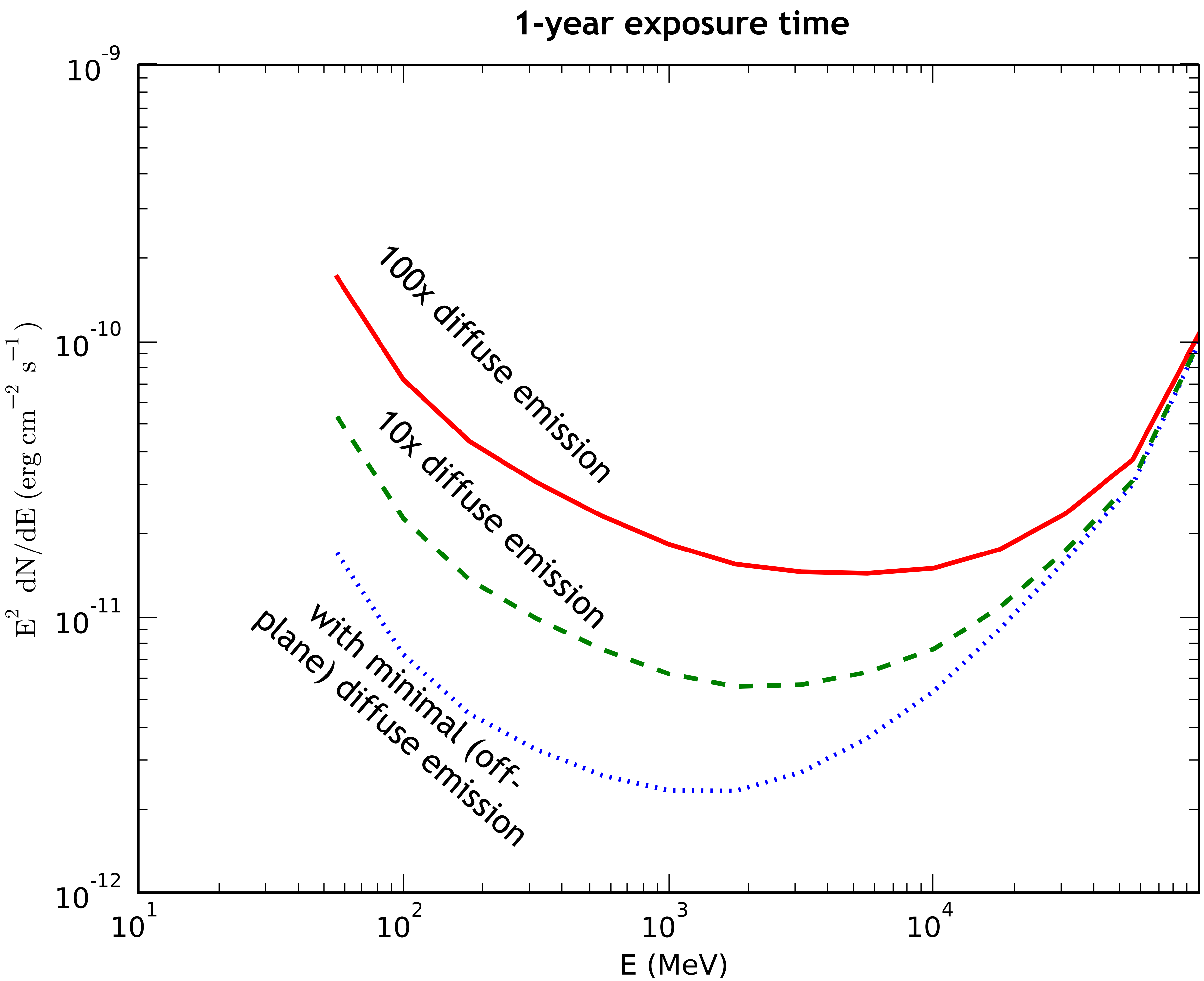
Galactic Longitude

Fermi Background Components



J-M. Casandiian

Fermi Sensitivity



Signal Extraction

Basic principle: model (in space and energy) everything you know about in the field-of-interest.

- The residual particle background
- the diffuse background
- For all known compact sources:
  - basic source morphology
  - energy spectrum (may vary with position)
  - unknown parameters left free, can vary in fitting procedure

Fit your model and subtract, looking for residuals

- If a residual is seen, try to model it!
- May use multi-wavelength data to constrain parameters, morphology
- Compute a "test statistic" for each model component (significance of model fit)

Iterate until no significant residuals.

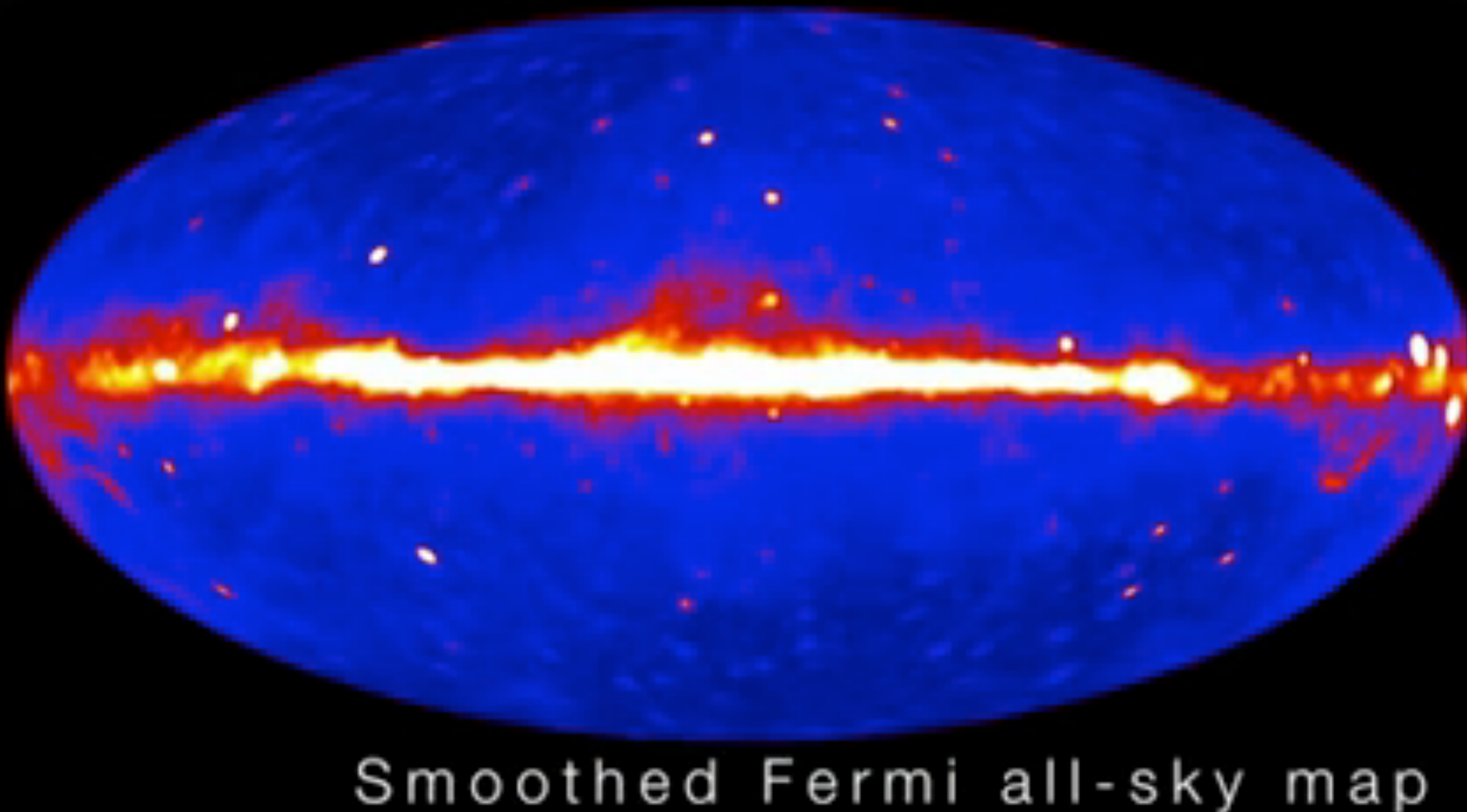
How to make a TS

Test every point i
for point-like sour

Bubbles

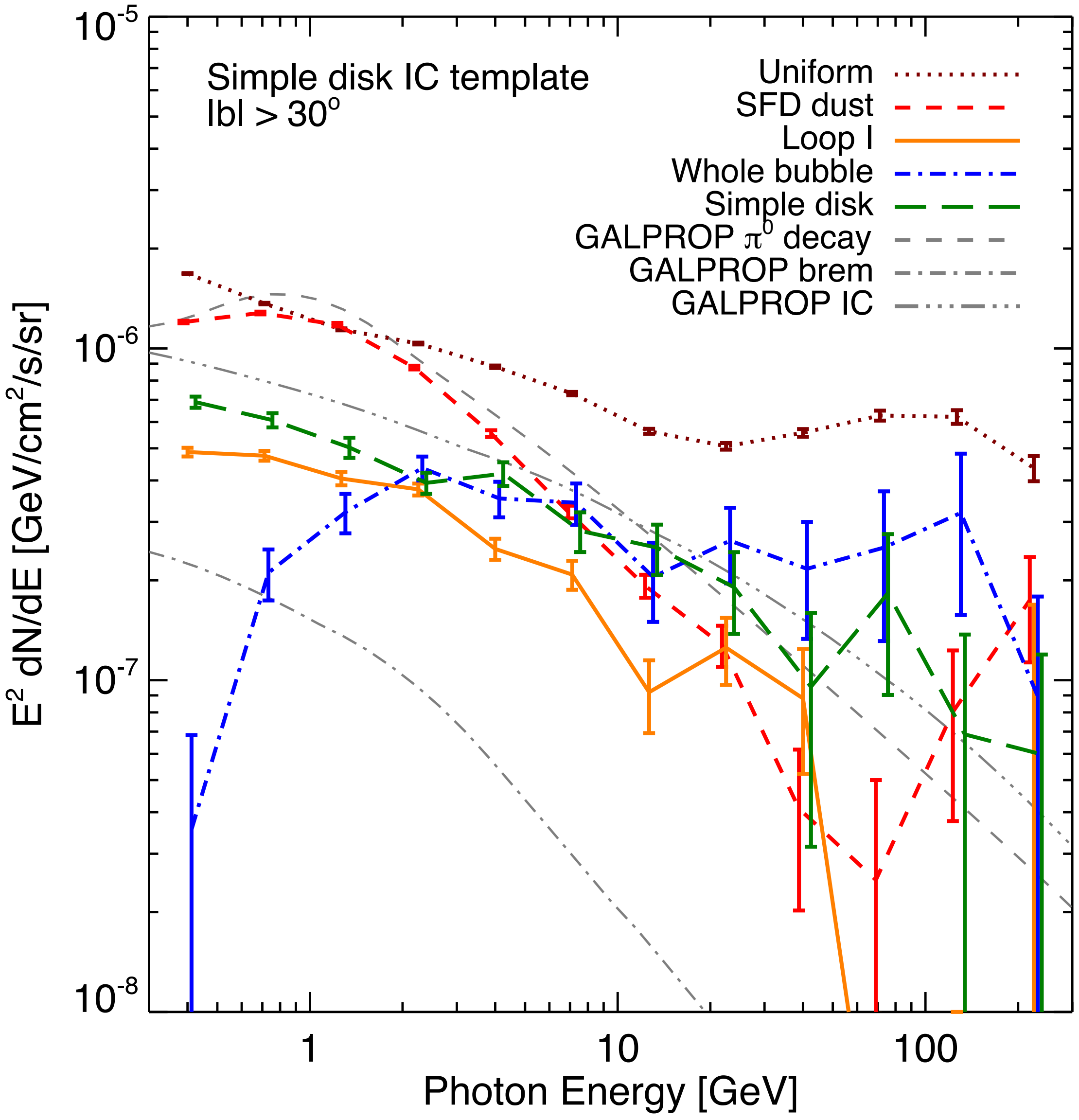
video from NASA, www.nasa.gov/goddard

Bubbles



video from NASA, www.nasa.gov/goddard

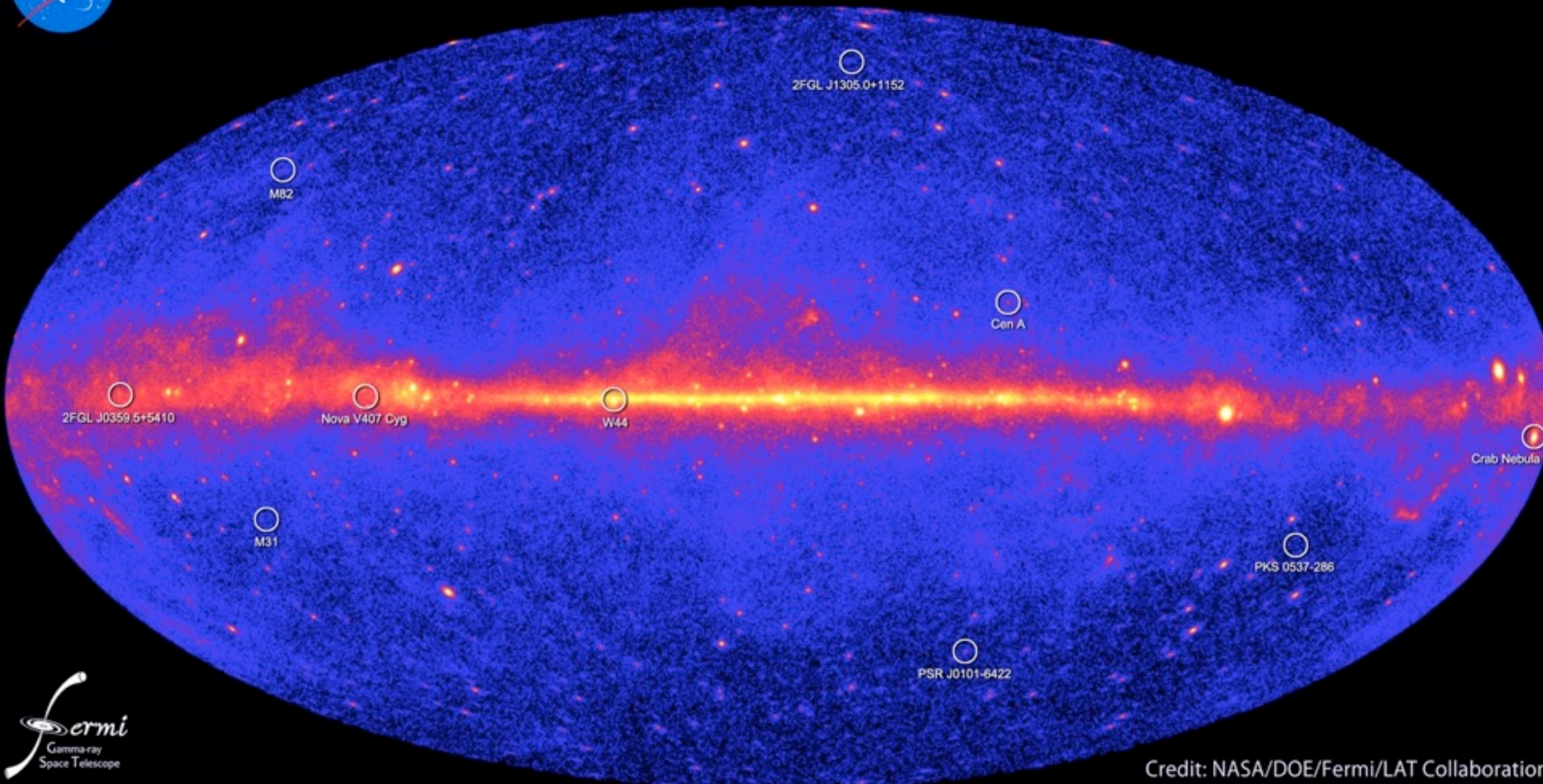
Source reconstruction



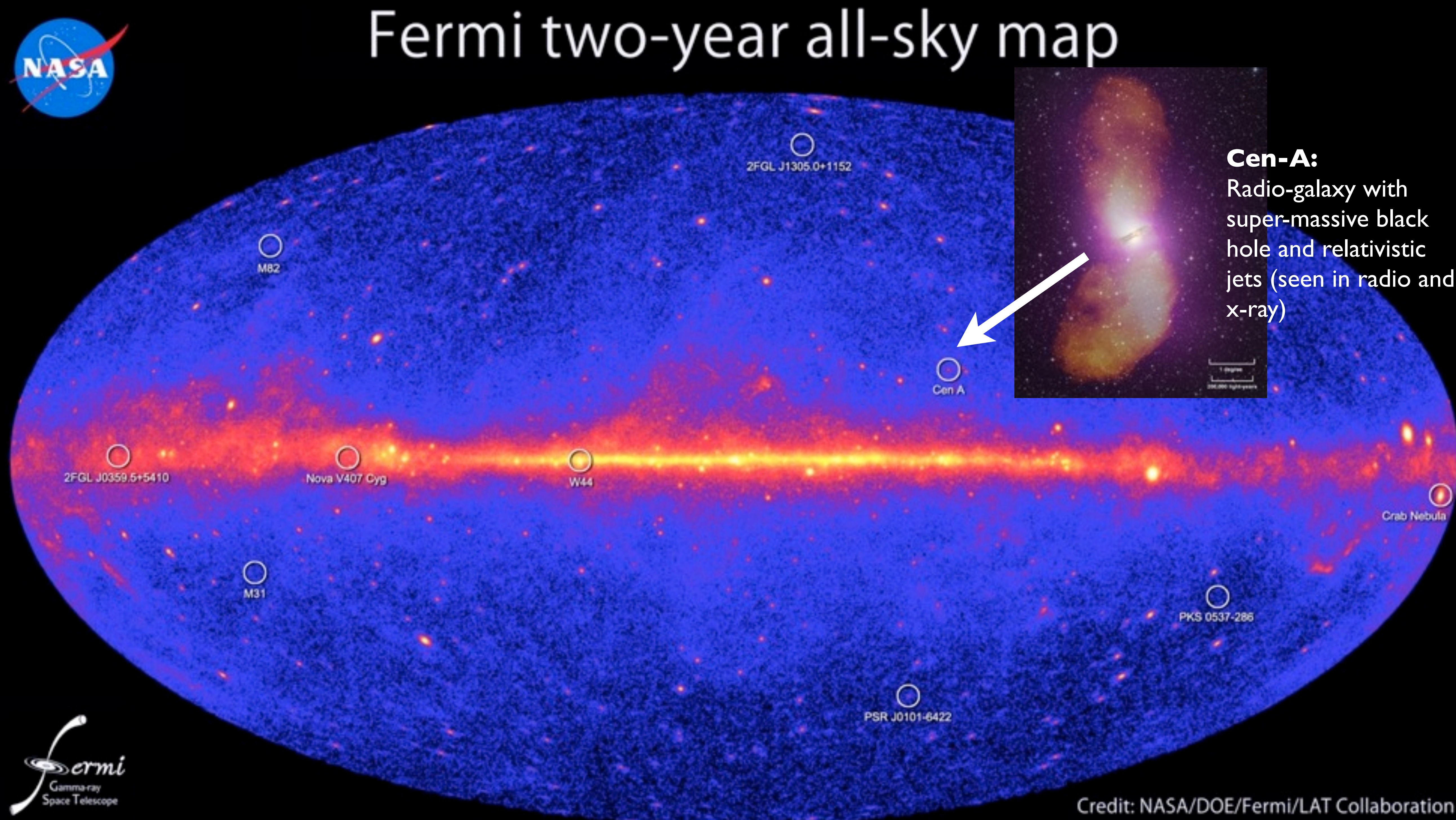
Even with a pre-computed model for the diffuse emission, detecting new sources is complicated!

- energy-dependent PSF
- source confusion

Fermi two-year all-sky map

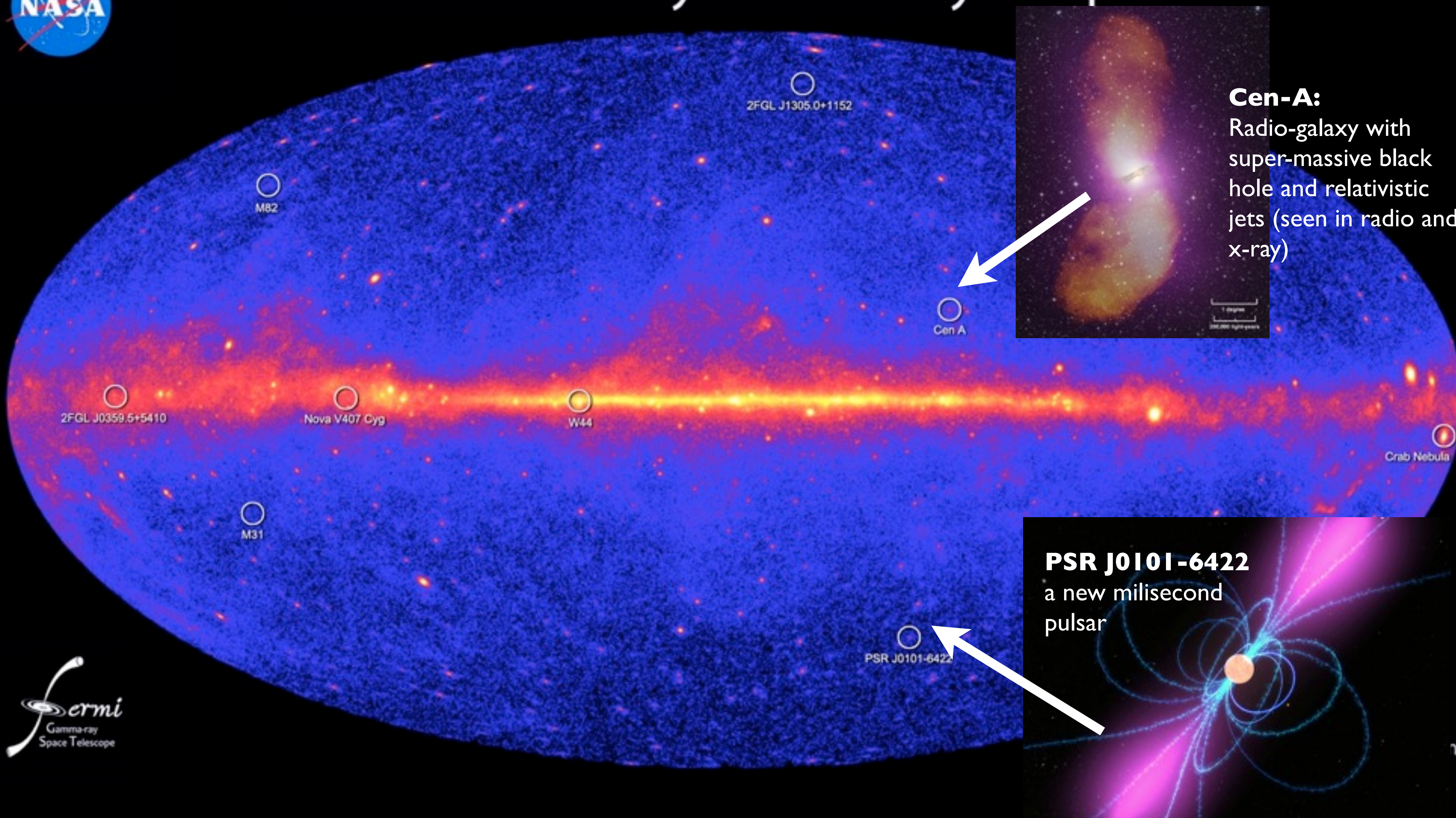


Credit: NASA/DOE/Fermi/LAT Collaboration



Cen-A:
Radio-galaxy with super-massive black hole and relativistic jets (seen in radio and x-ray)

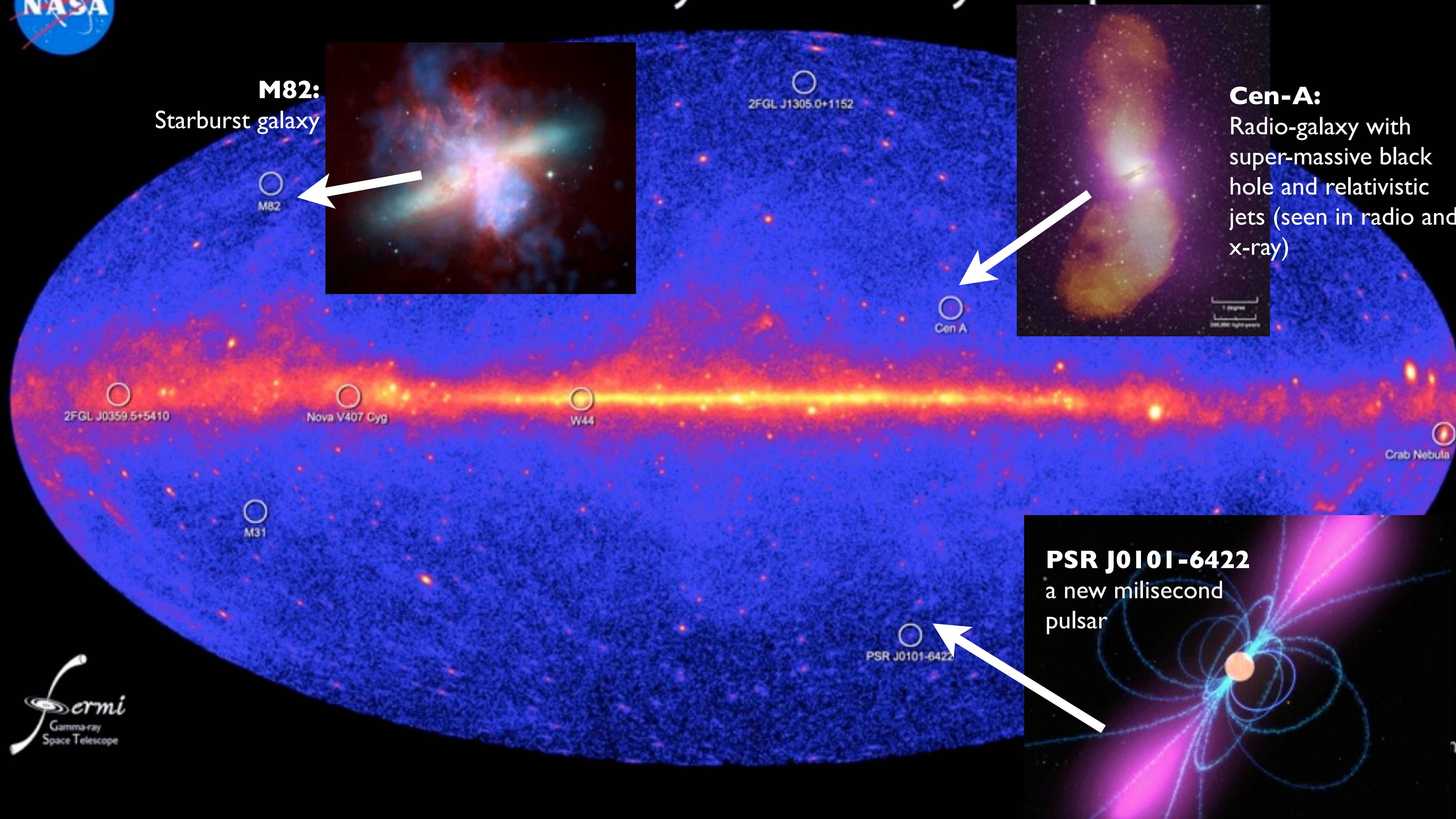
Fermi two-year all-sky map

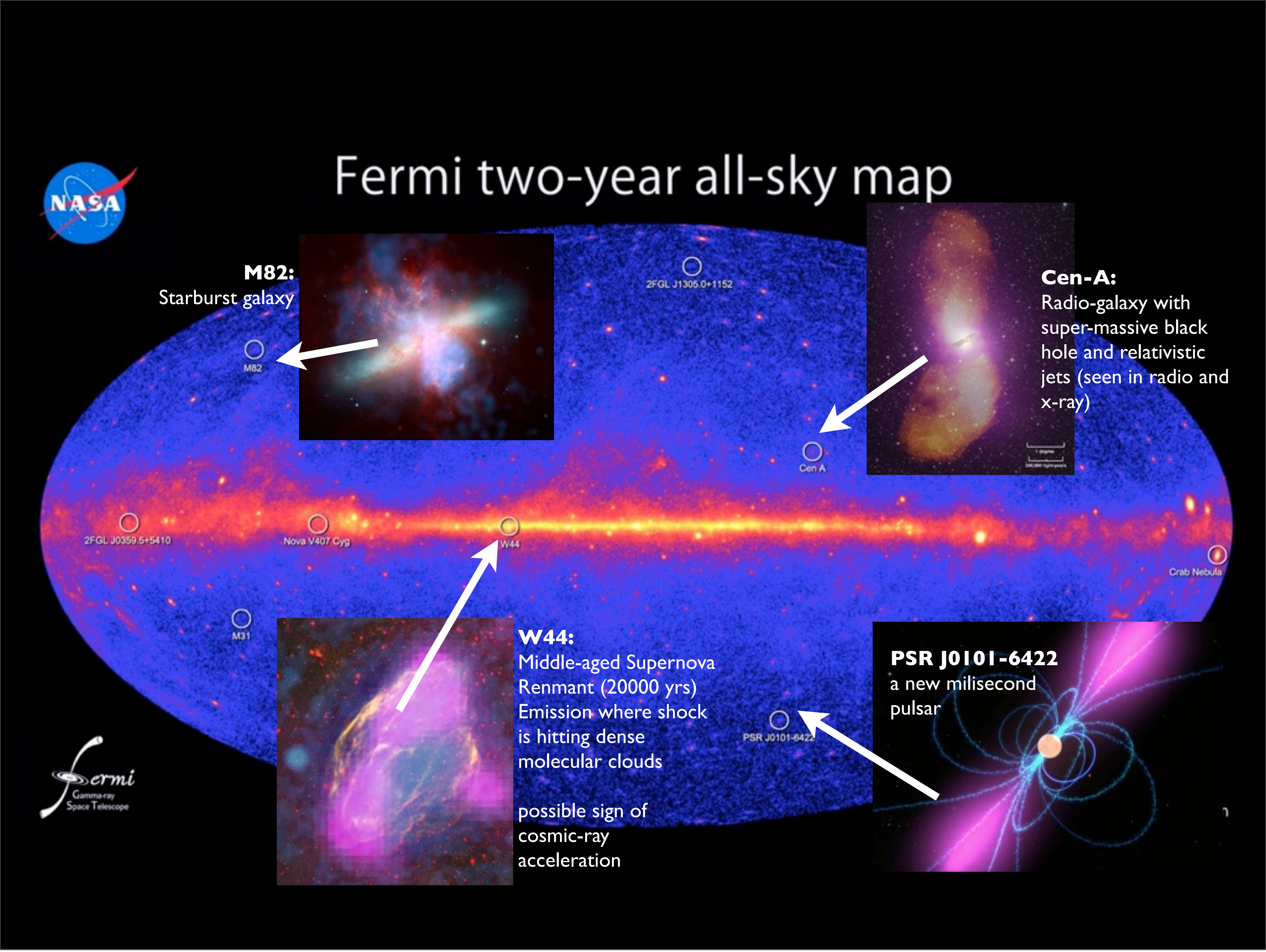


Cen-A:
Radio-galaxy with super-massive black hole and relativistic jets (seen in radio and x-ray)

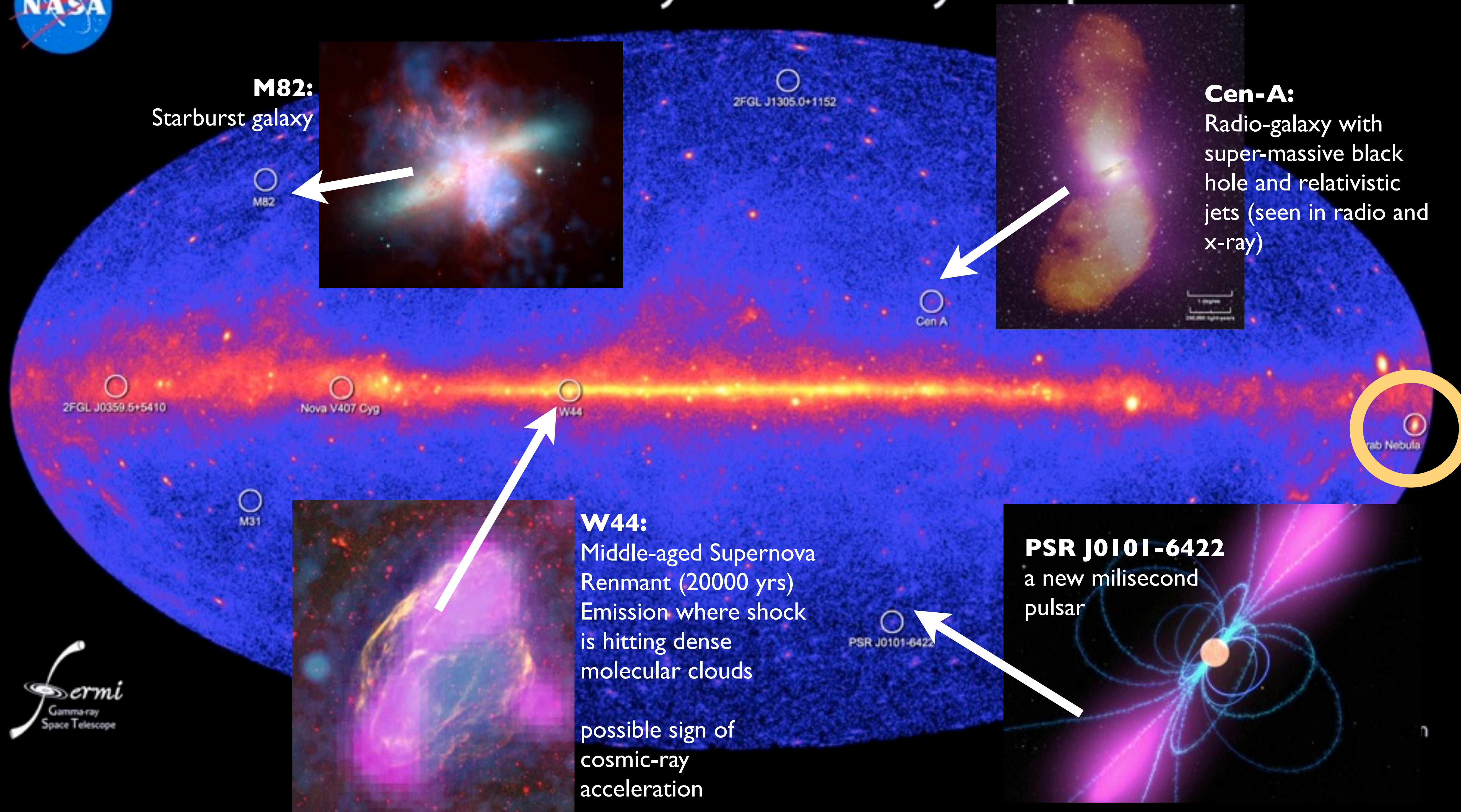
PSR J0101-6422
a new milisecond pulsar

Fermi two-year all-sky map




Fermi two-year all-sky map
NASA
M82:
Starburst galaxy
M82
2FGL J1305.0+1152
Cen-A:
Radio-galaxy with
super-massive black
hole and relativistic
jets (seen in radio and
x-ray)
Cen A
2FGL J0359.5+5410
Nova V407 Cyg
W44
Crab Nebula
M31
W44:
Middle-aged Supernova
Renmant (20000 yrs)
Emission where shock
is hitting dense
molecular clouds
possible sign of
cosmic-ray
acceleration
PSR J0101-6422
PSR J0101-6422
a new milisecond
pulsar
Fermi
Gamma-ray
Space Telescope

Fermi two-year all-sky map



Fermi Crab Nebula

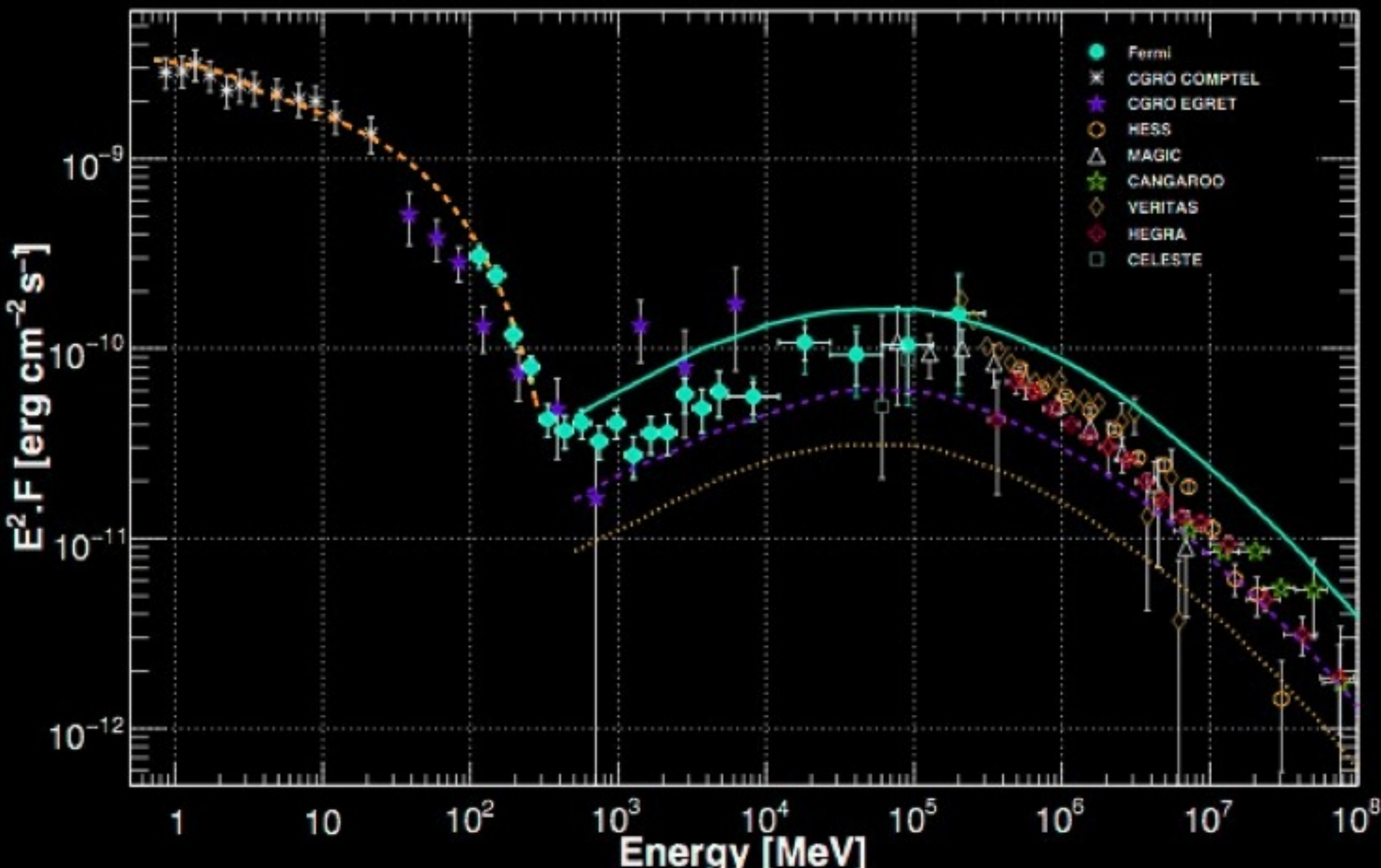
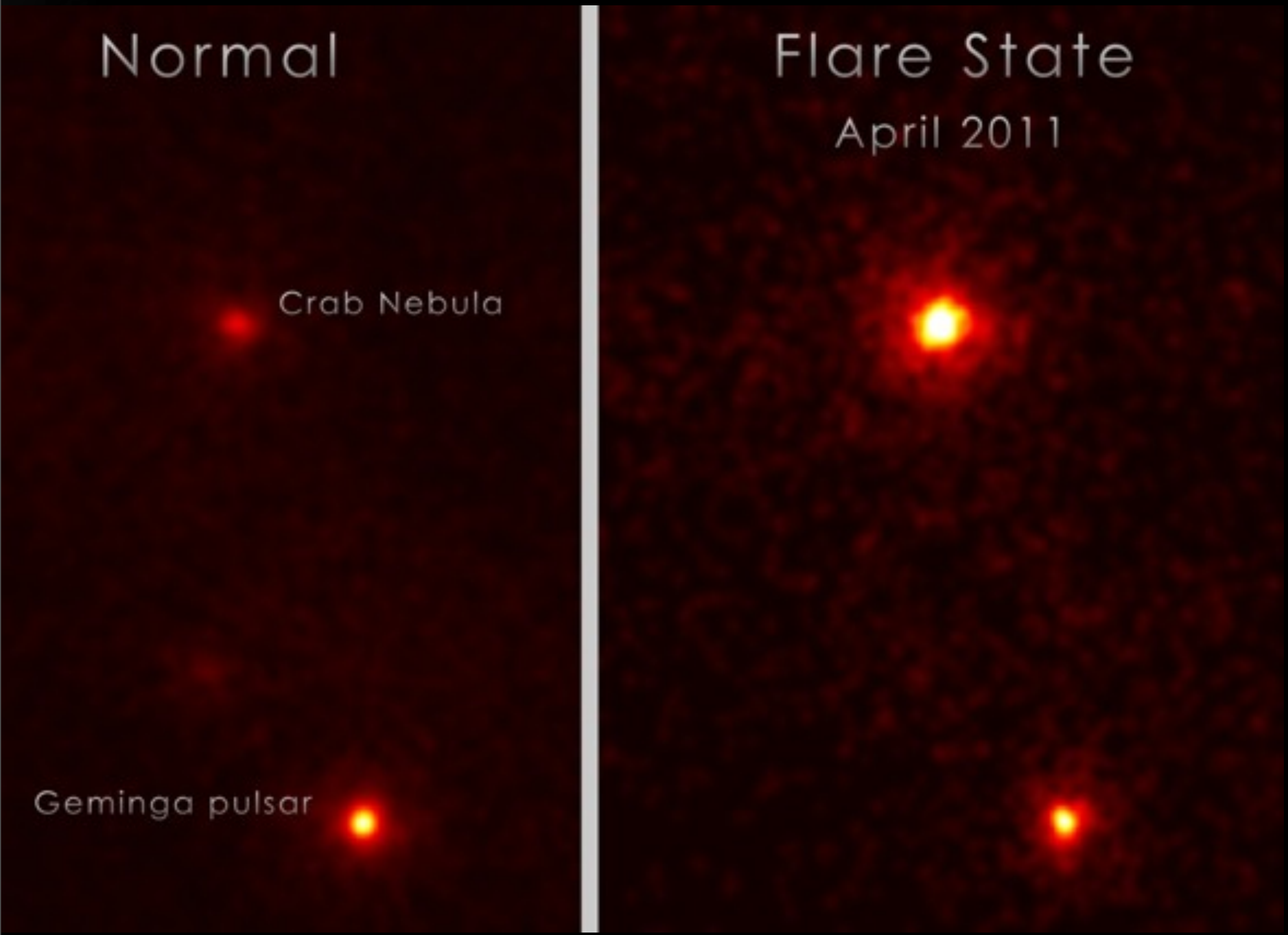


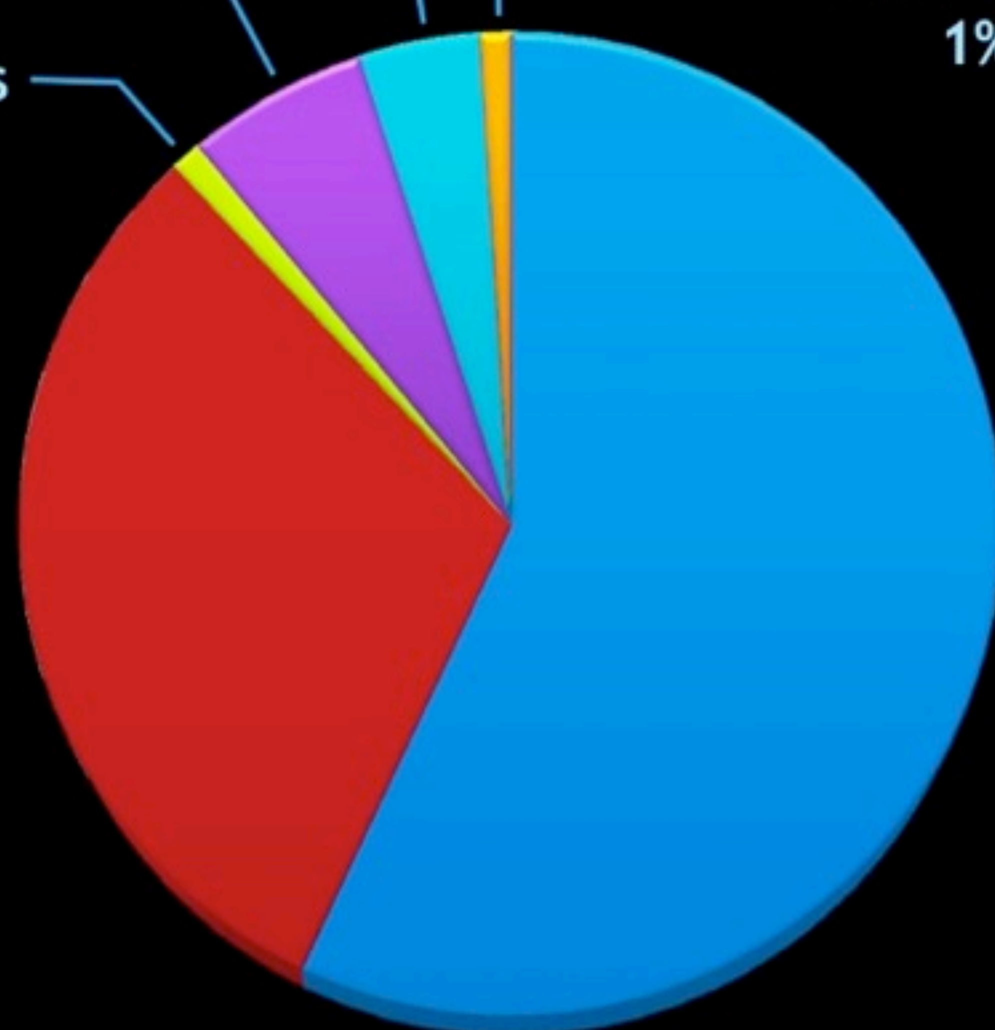
FIG. 9.— The spectral energy distribution of the Crab Nebula from soft to very high energy γ-rays. The fit of the synchrotron component, using COMPTEL nd LAT data (blue dashed line), is overlaid. The predicted inverse Compton spectra from Atoyan and Aharonian (1996) are overlaid for three different values of ne mean magnetic field: 100 μG (solid red line), 200 μG (dashed green line) and the canonical equipartition field of the Crab Nebula 300 μG (dotted blue line). eferences: CGRO COMPTEL and EGRET: Kuiper et al. (2001); MAGIC: Albert et al. (2008); HESS: Aharonian et al. (2006); CANGAROO: Tanimori et al. 1997); VERITAS: Celik (2007); HEGRA: Aharonian et al. (2004); CELESTE: Smith et al. (2006)

Crab Nebula Variability



- **Flares seen from Crab region**
  - up to 30x quiescent flux!
  - Not expected from theory...
  - Not related to the pulsed emission: can be cut out in time (look off-pulse)
  - No correlation in X-rays (Chandra)
- **Emission region must be close to pulsar**
  - possible sudden restructuring of strong B-fields near the pulsar

What has Fermi found: The LAT two-year catalog



Credit: NASA/Goddard Space Flight Center

OUTLINE

Gamma Rays

Context: gamma ray astrophysics

MeV gamma ray detection

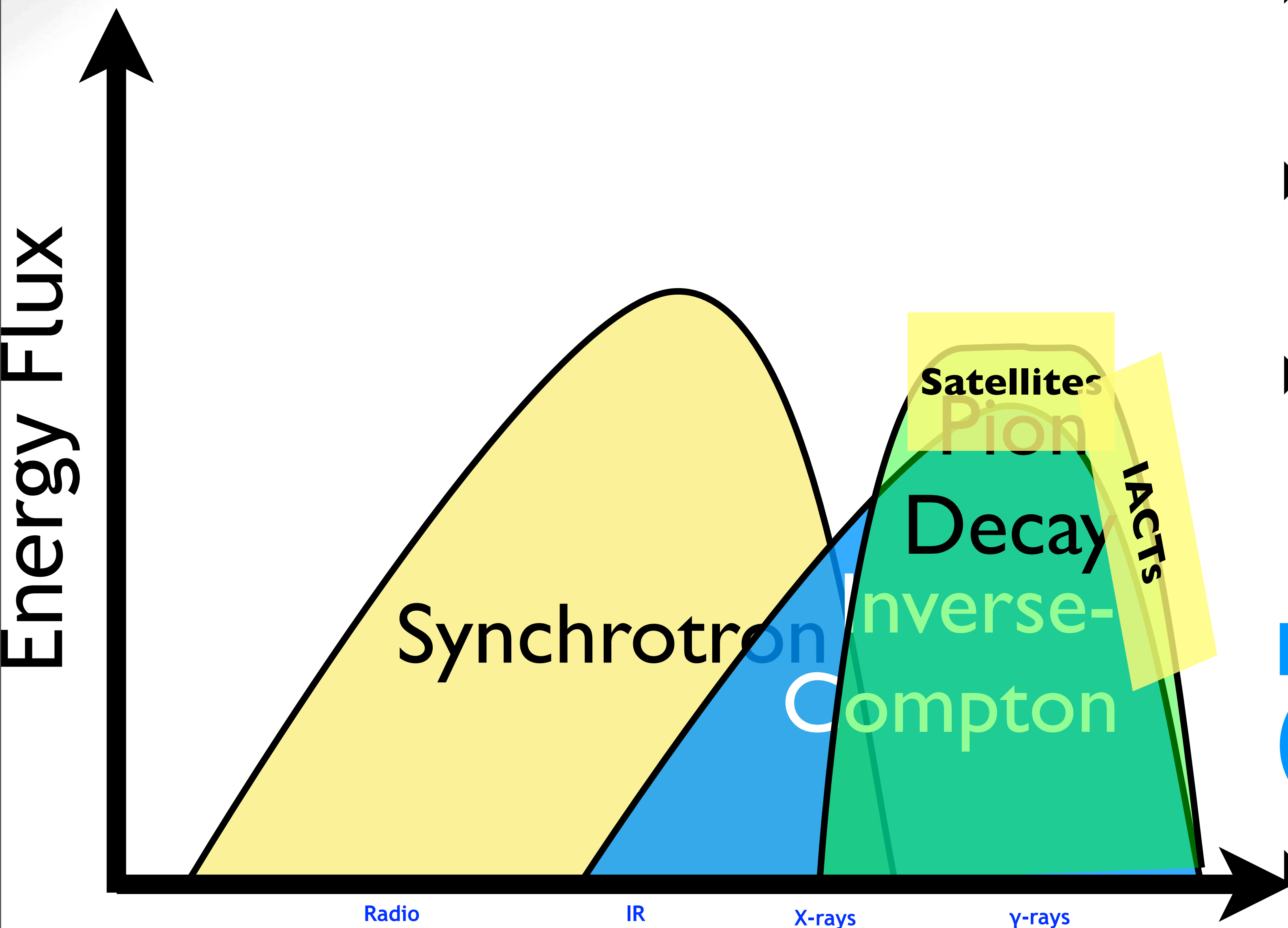
GeV gamma ray detection

Gamma-ray interactions in the atmosphere

Gamma Rays in the Atmosphere

Prelude to the detection of TeV gamma rays

Overview



What we've discussed so far:

- reminder of simple particle physics
- astrophysical sources of gamma radiation
- detection of ME and HE gamma-rays with CGRO and Fermi-GST

Next: even higher-energies (VHE gammas)

- Need to fully cover the inverse-Compton/pion-decay part of the non-thermal spectrum

Recall:

At high-energies, steep power-law photon spectra

- e.g. flux ≈ $E^{-2.5}$
- due to steep underlying particle spectra
- with the effective area of Fermi ($1 m^2$), **count rate** of Crab Nebula above 1 TeV would be **≈10^{-7} Hz!**
  - a gamma ray detected every few months!

Need <u>much larger</u> effective areas!

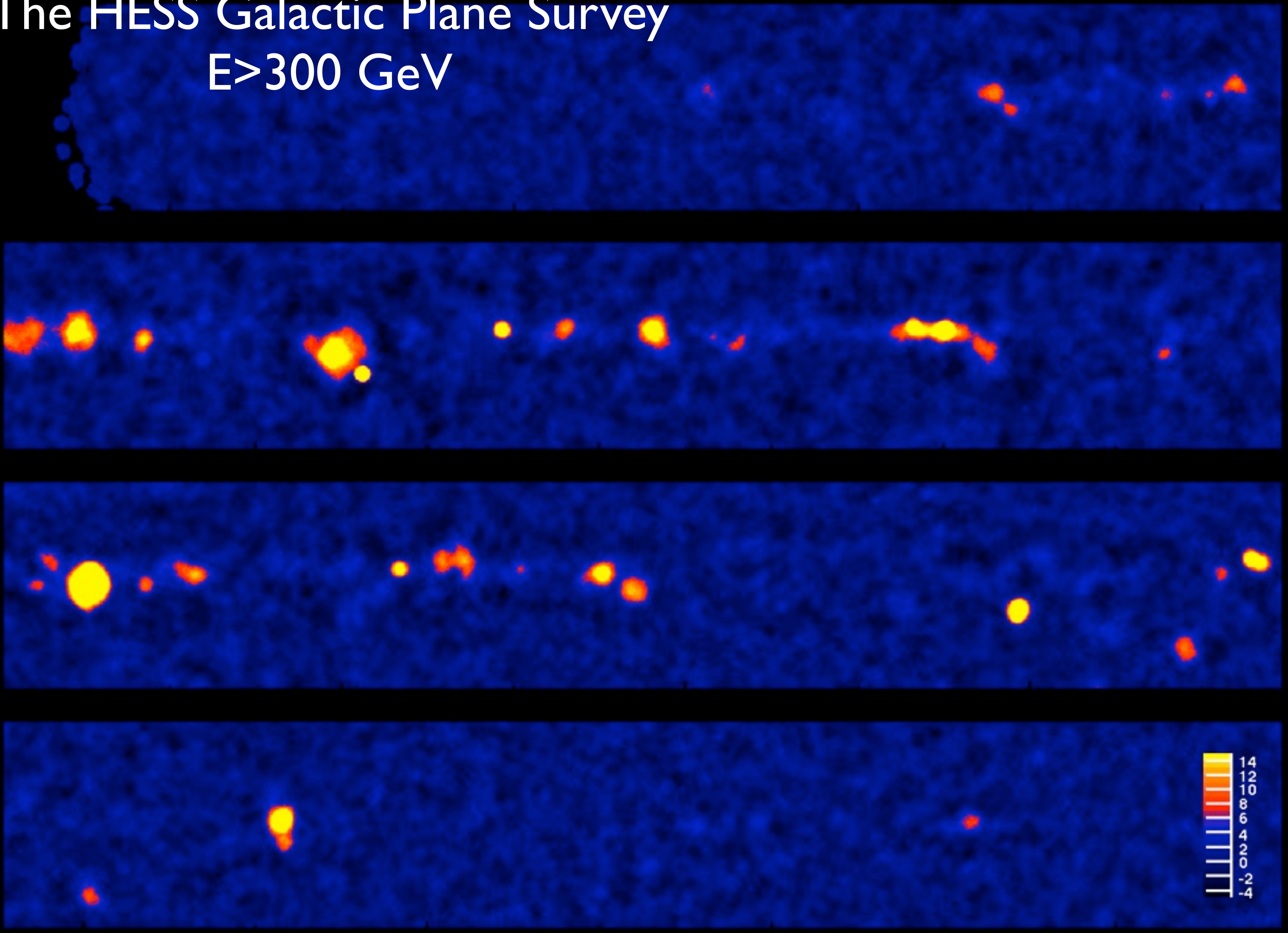
Can't do it from space!

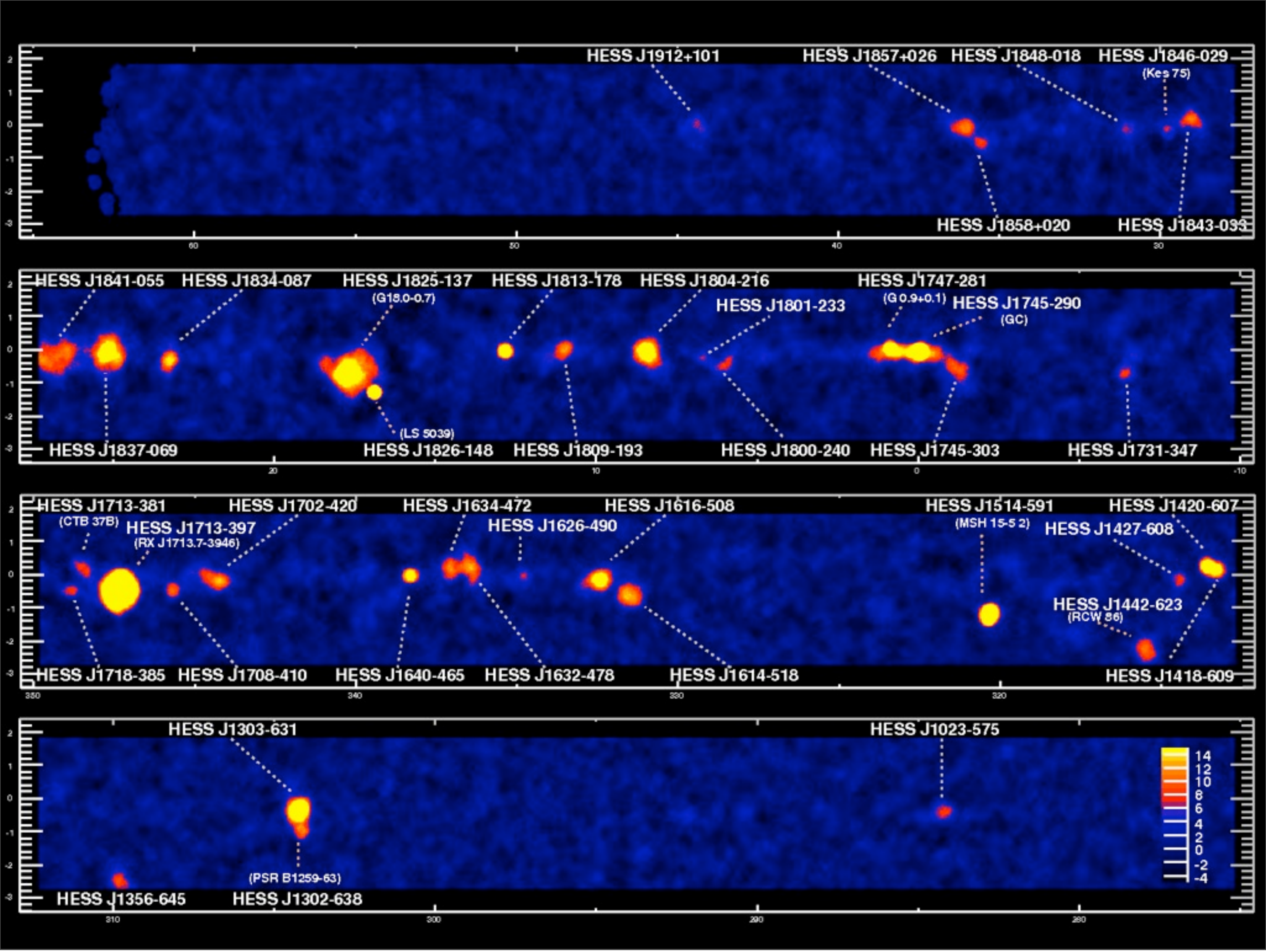
VHE Gammas

As we move to higher energies:

- the interaction of galactic cosmic rays with molecular clouds (e.g. the diffuse gamma-ray background) goes away due to the steep spectrum
  - (at least within the detection limits of current instruments)
- Galactic plane is therefore mostly free of diffuse astrophysical background!
- but, have large particle background due to detection technique

The HESS Galactic Plane Survey
E>300 GeV




HESS J1912+101
HESS J1857+026
HESS J1848-018
HESS J1846-029
(Kes 75)
HESS J1858+020
HESS J1843-033
HESS J1841-055
HESS J1834-087
HESS J1825-137
(G18.0-0.7)
HESS J1813-178
HESS J1804-216
HESS J1801-233
HESS J1747-281
(G 0.9+0.1)
HESS J1745-290
(GC)
(LS 5039)
HESS J1837-069
HESS J1826-148
HESS J1809-193
HESS J1800-240
HESS J1745-303
HESS J1731-347
HESS J1713-381
(CTB 37B)
HESS J1713-397
(RX J1713.7-3946)
HESS J1702-420
HESS J1634-472
HESS J1626-490
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HESS J1514-591
(MSH 15-5 2)
HESS J1427-608
HESS J1420-607
HESS J1442-623
(RCW 86)
HESS J1718-385
HESS J1708-410
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HESS J1632-478
HESS J1614-518
HESS J1418-609
HESS J1303-631
HESS J1023-575
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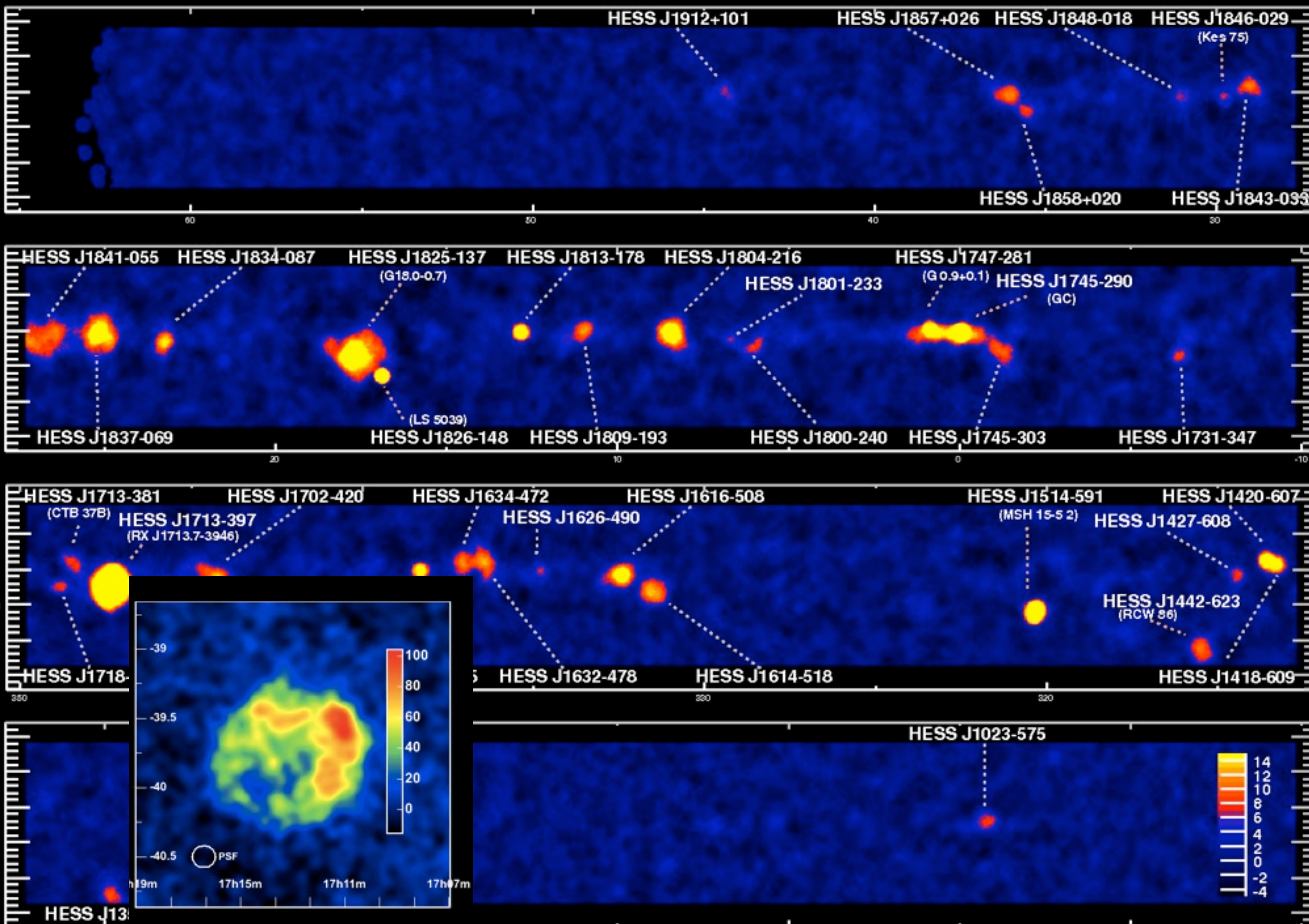
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PSF
17h15m
17h11m
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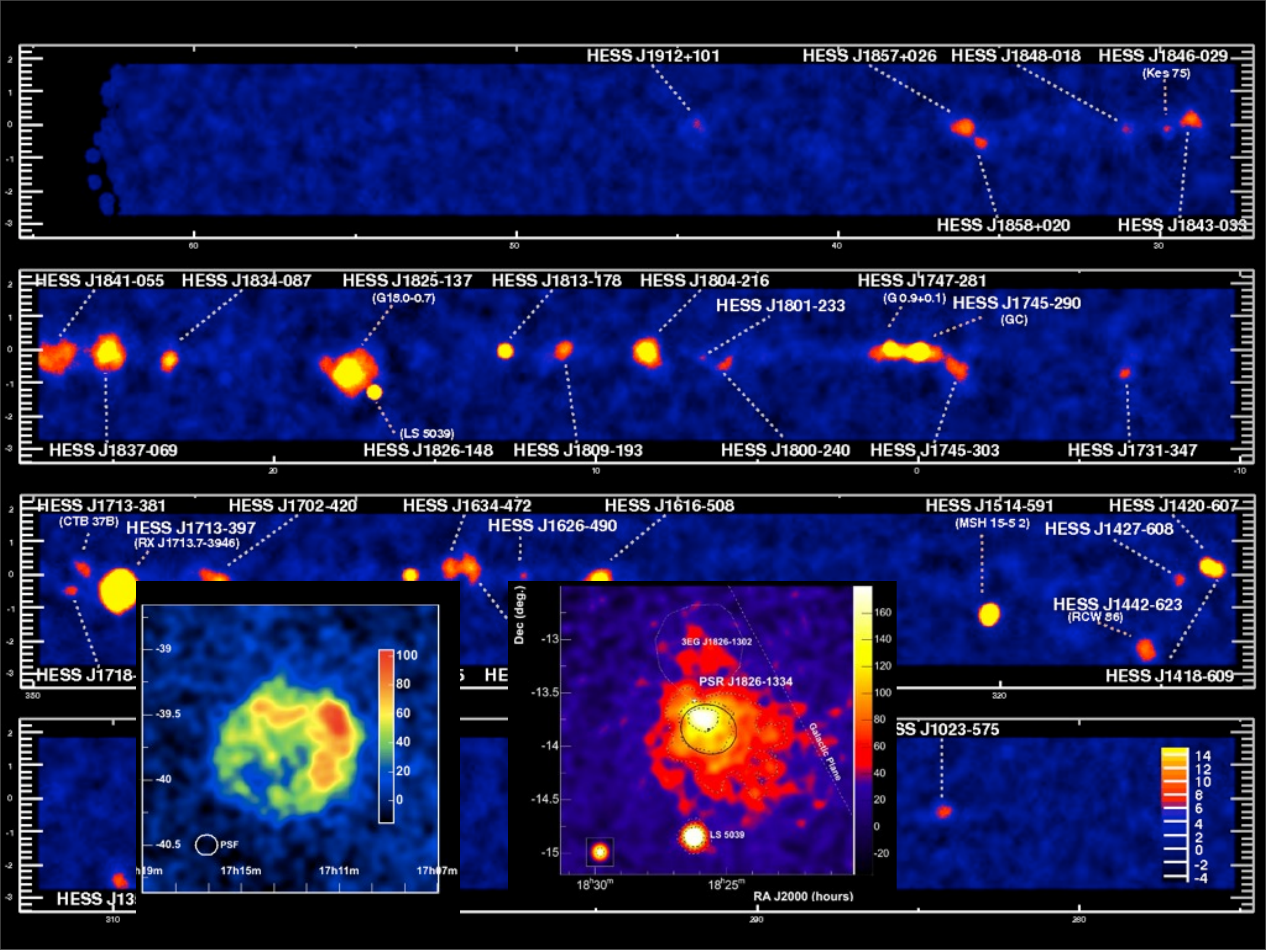
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(RCW 86)
HESS J1418-609
HESS J1718-
HE
HESS J13
SS J1023-575
PSF
17h15m
17h11m
17h07m
3EG J1826-1302
PSR J1826-1334
Galactic Plane
LS 5039
Dec (deg.)
RA J2000 (hours)

Ground-based Gamma-ray detection part 1:
Extensive Air Showers

Questions…

Questions...

Earth is being constantly bombarded with high-energy radiation: particles and gamma-rays

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Though we might get a sunburn outside from UV light, we don't need to put on radiation or gamma-ray-proof outerwear!

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So, why would we try to put gamma-ray detectors on the ground?

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Clearly, our atmosphere absorbs this radiation...

So, why would we try to put gamma-ray detectors on the ground?

What happens when a high-energy particle hits the atmosphere?

Pair Production

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

Bremsstrahlung

Important processes for ground-based detectors

Extensive Air showers

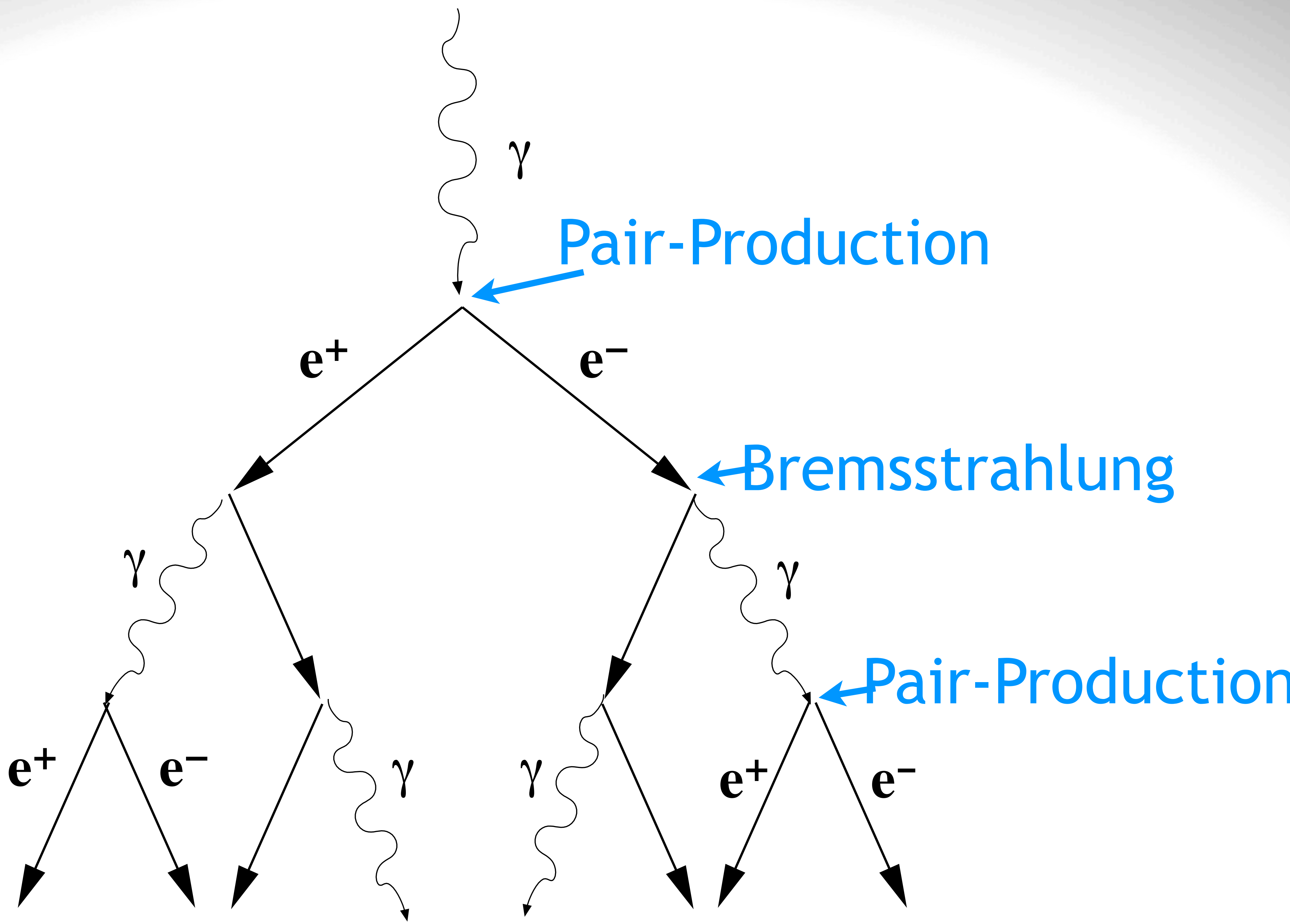
Cascades of sub-particles created when an incident high-energy particle enters Earth's atmosphere and interacts with an air nucleus

These cascades may be initiated by:

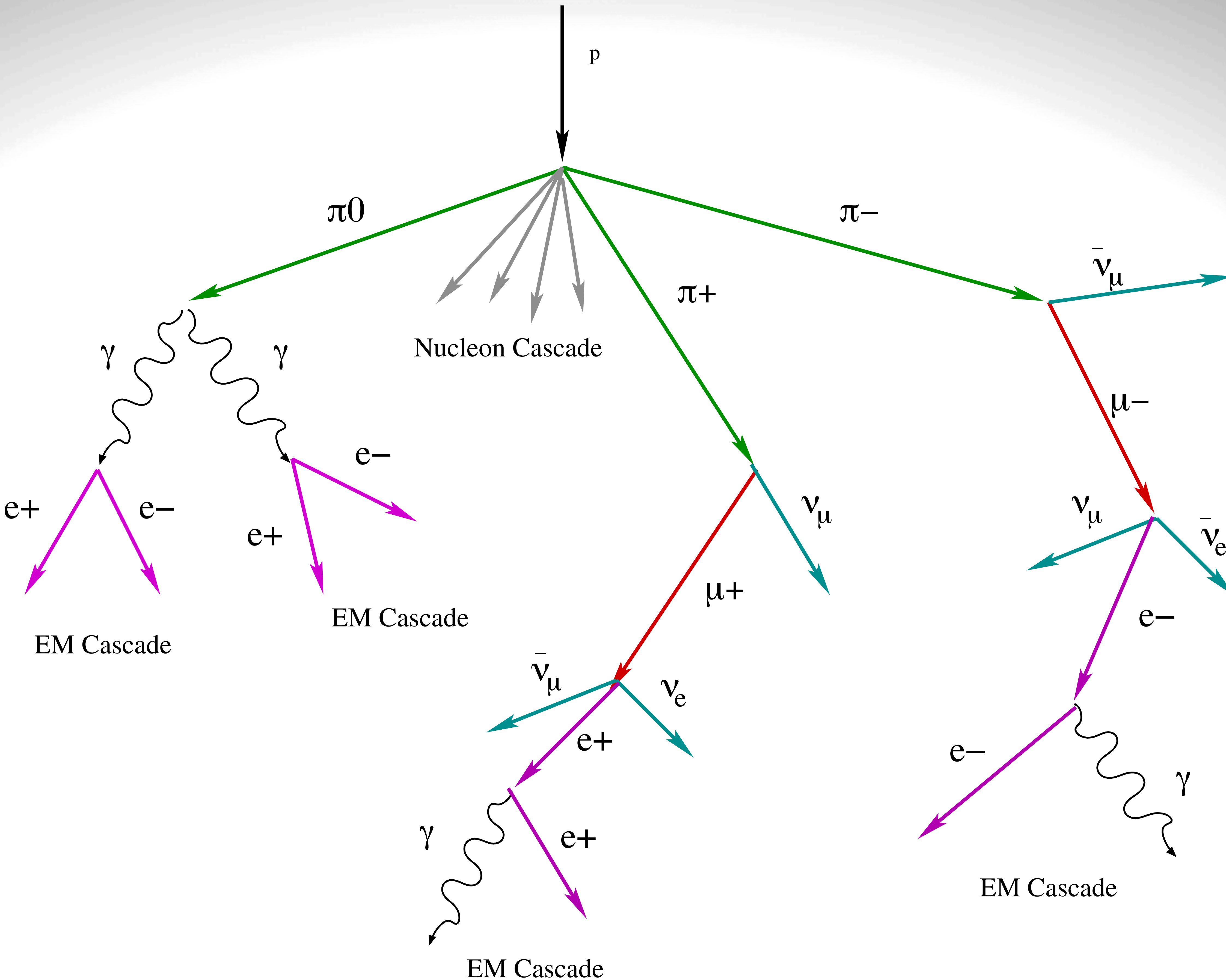
- Photons (as long as they have enough energy to penetrate, e.g. gamma rays)
- Charged particles (i.e. cosmic rays)

See lecture by Ralf Engles for the details of EAS's, but here is a short intro...

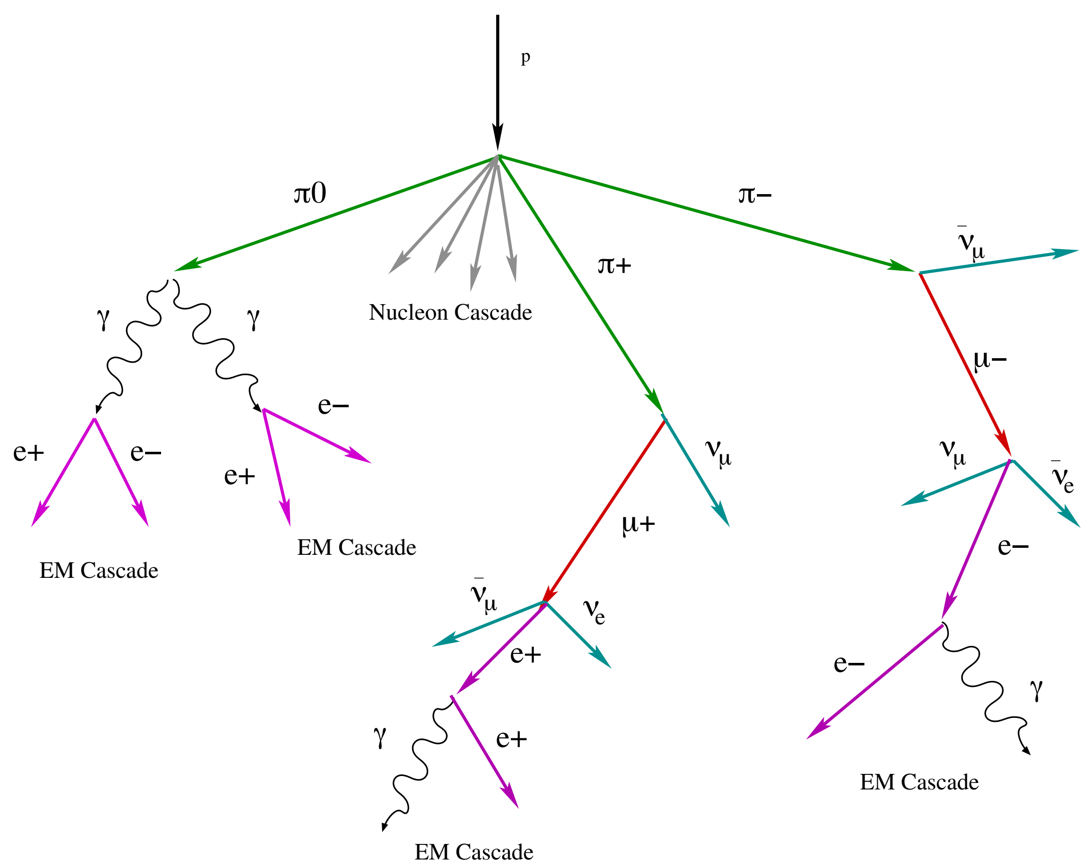
Electromagnetic Showers



Hadronic showers

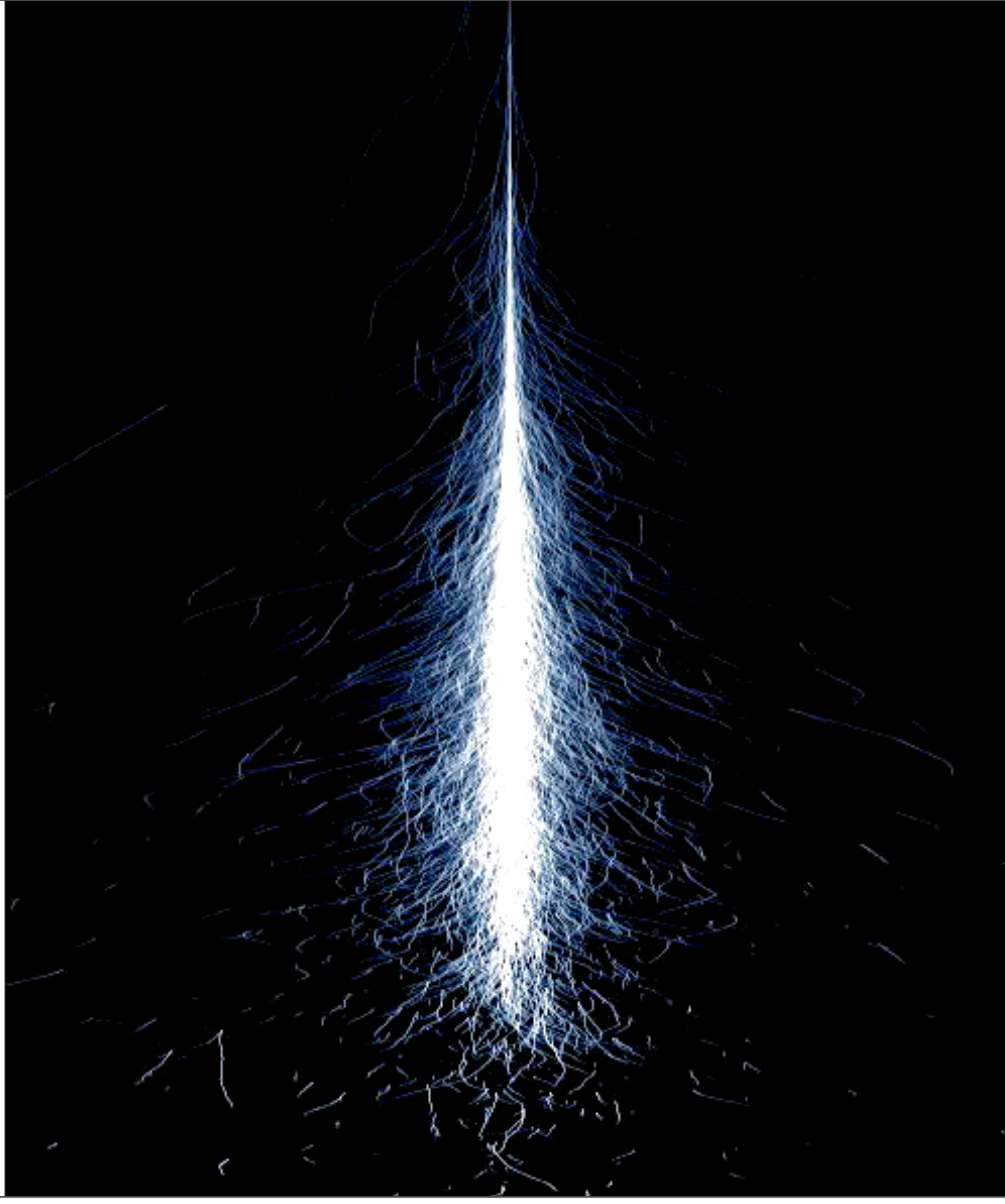


Hadronic showers



Key points:

- Cosmic ray shows produce EM sub-showers
- Higher transverse momentum due to pions
- Muons are produced



Animation by
K. Bernlöhr,
2000

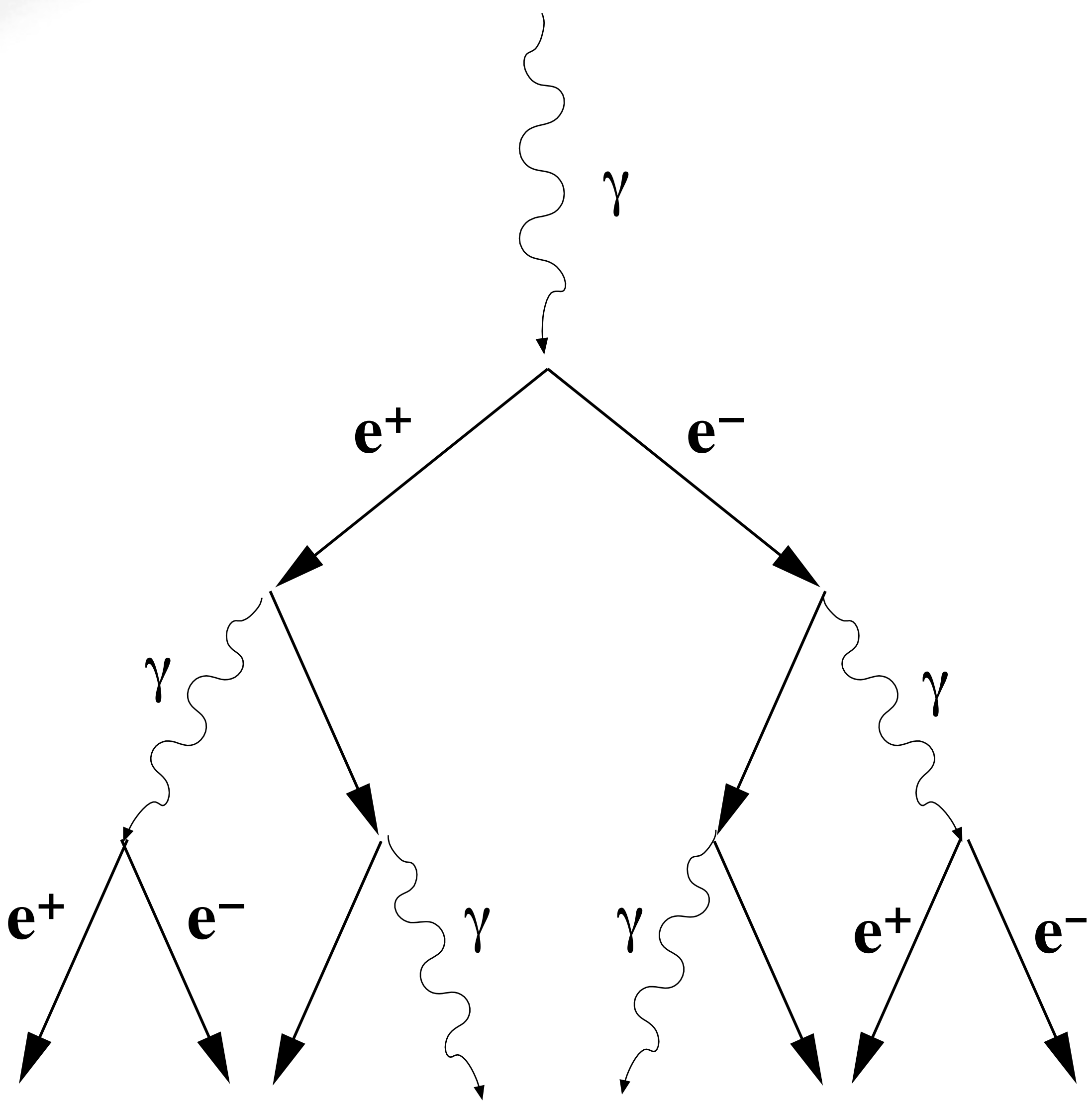
The Heitler model for EM showers

(Heitler 1954)

Semi-empirical model for EM cascades

- Do we need one? Not really, since we now have powerful computers, but it's useful to visualize the basic properties
- In 1954, detailed particle simulation was impossible
  - number of particles to track can exceed 10^9

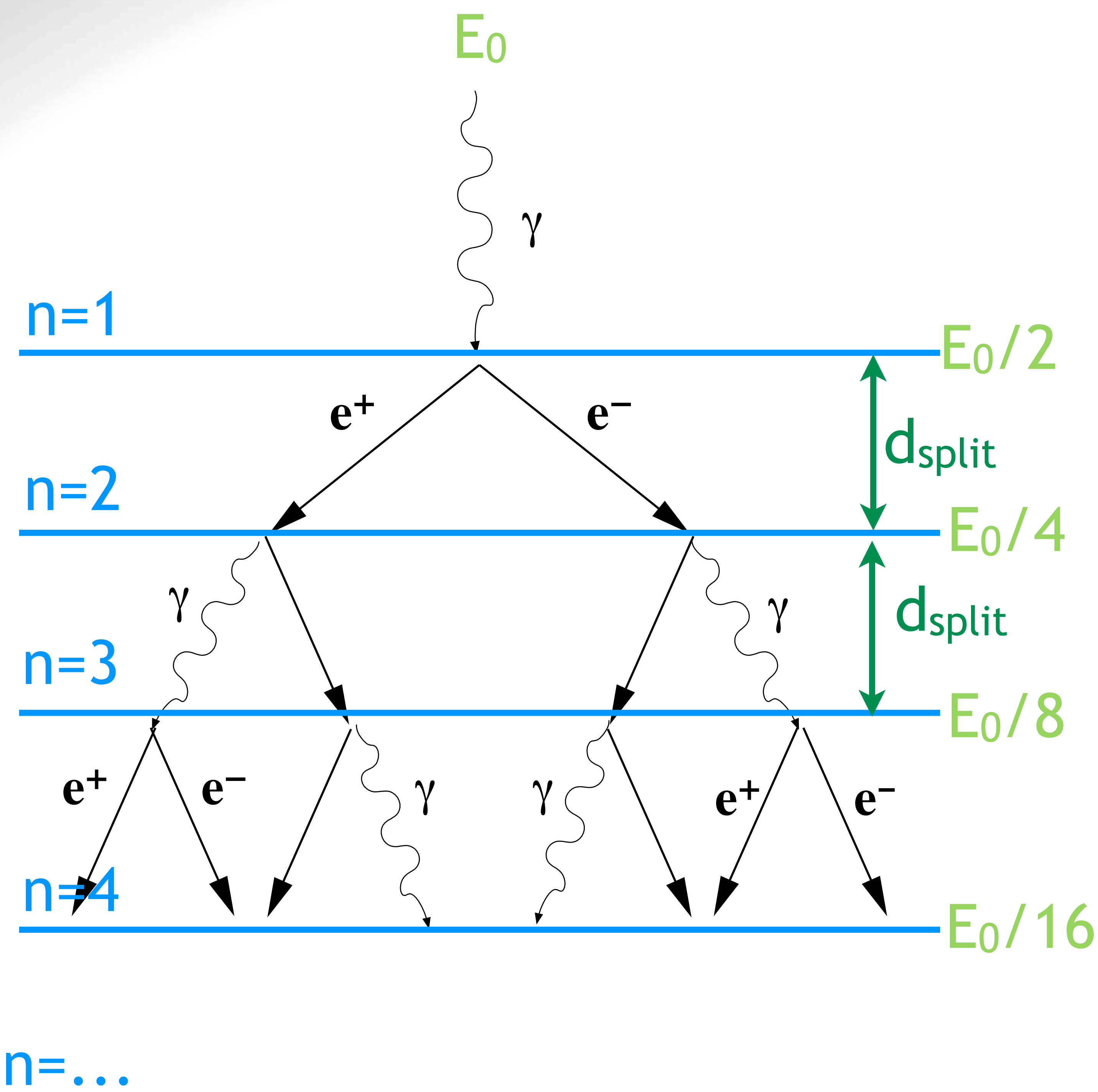
The Heitler model



Simple assumptions:

- two processes: *pair production* + single-particle *bremsstrahlung*
- distance between both interactions is a fixed length d_{split} (here "length"=g/cm^2)
- When the energy of a particle drops below a critical energy E_{crit}, the cascade stops abruptly

Heitler Model



$$d_{\text{split}} = \ln 2 \lambda_r$$

= Distance over which electron loses half its energy via radiation

After n steps,

shower depth

$$x = n d_{\text{split}} = n \lambda_r \ln 2$$

total number of particles (e+,e-, γ)

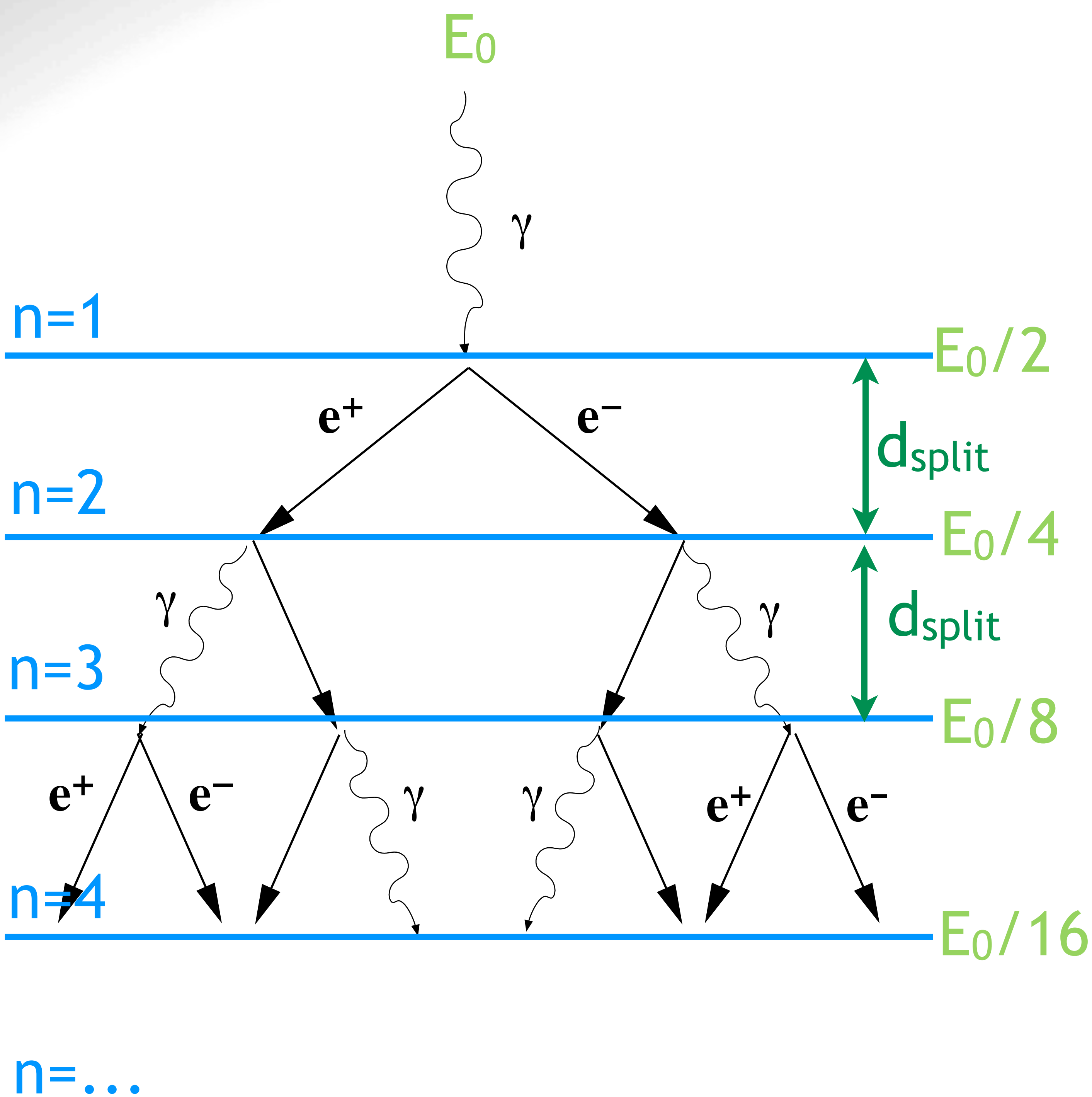
$$N = 2^n = e^{\frac{x}{\lambda_r}}$$

What is the maximum shower "size" (total number of particles)?

Occurs when all particles have $E=E_{crit}$

$$N_{\text{max}} = E_0 / E_{\text{crit}}$$

Heitler Model



$$d_{\text{split}} = \ln 2 \lambda_r$$

$$x = n d_{\text{split}} = n \lambda_r \ln 2$$

$$N = 2^n = e^{\frac{x}{\lambda_r}}$$

$$N_{\max} = E_0 / E_{\text{crit}}$$

How deep is N_{max}? When $n = n_{crit}$, all particles have E_{crit}:

$$N_{\max} = 2^{n_{\text{crit}}}$$

$$\frac{E_0}{E_{\text{crit}}} = 2^{n_{\text{crit}}}$$

$$\ln \frac{E_0}{E_{\text{crit}}} = n_{\text{crit}} \ln 2$$

$$x_{\max} = n_{\text{crit}} \lambda_r \ln 2$$

$$= \lambda_r \ln \frac{E_0}{E_{\text{crit}}}$$

Heitler Model

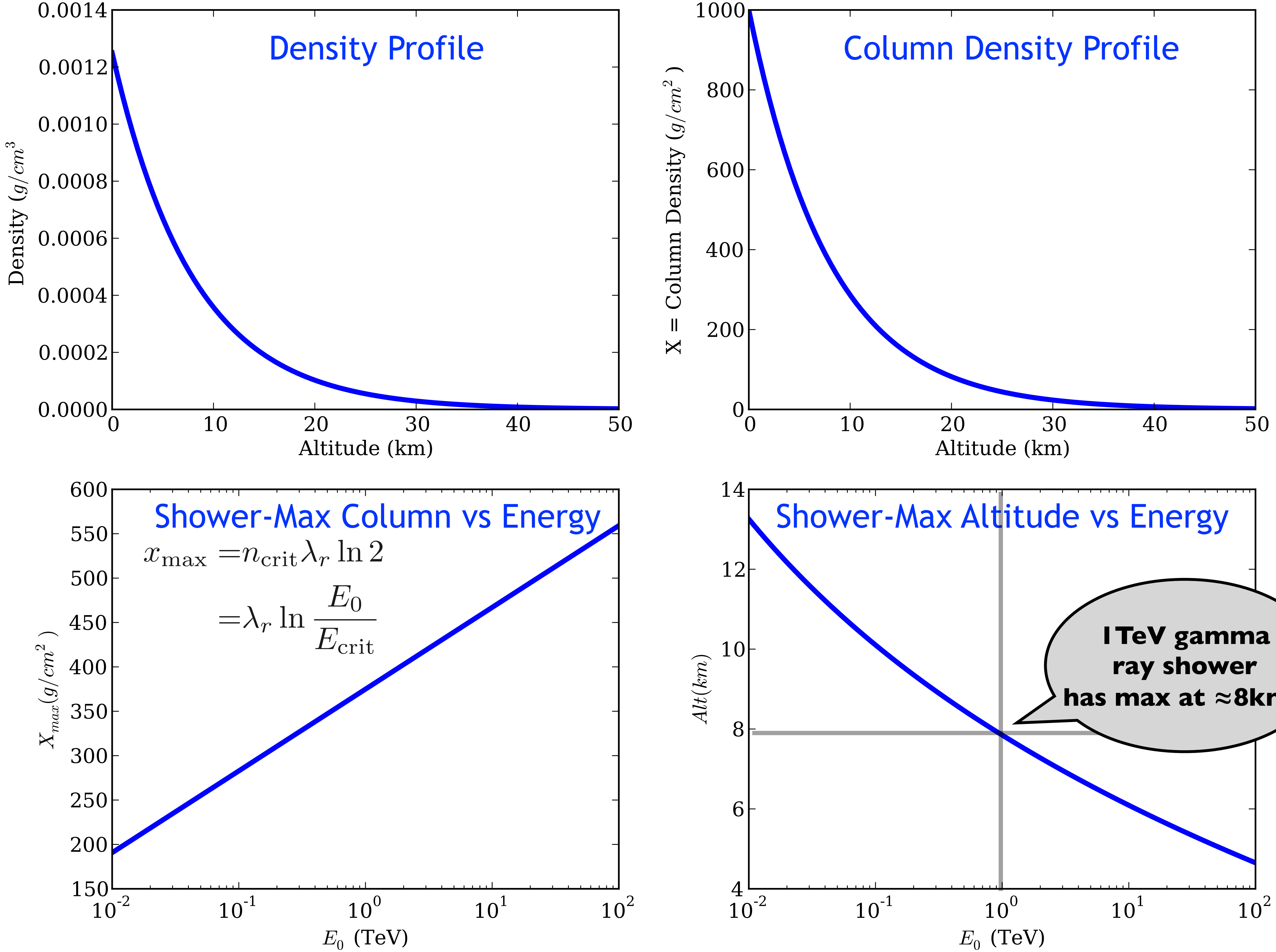
In Atmosphere:

- $\lambda_r \approx 40\ \mathrm{g/cm^2}$
- $E_{crit} \approx 85$ MeV
- total depth of atmosphere $\approx 1000\ \mathrm{g/cm^2}$
- density profile:

$$\rho = \rho_0 e^{-h/h_0} \qquad x \equiv \int_\infty^h \rho(h')dh'$$

$$h_0 \simeq 8\,\mathrm{km}$$

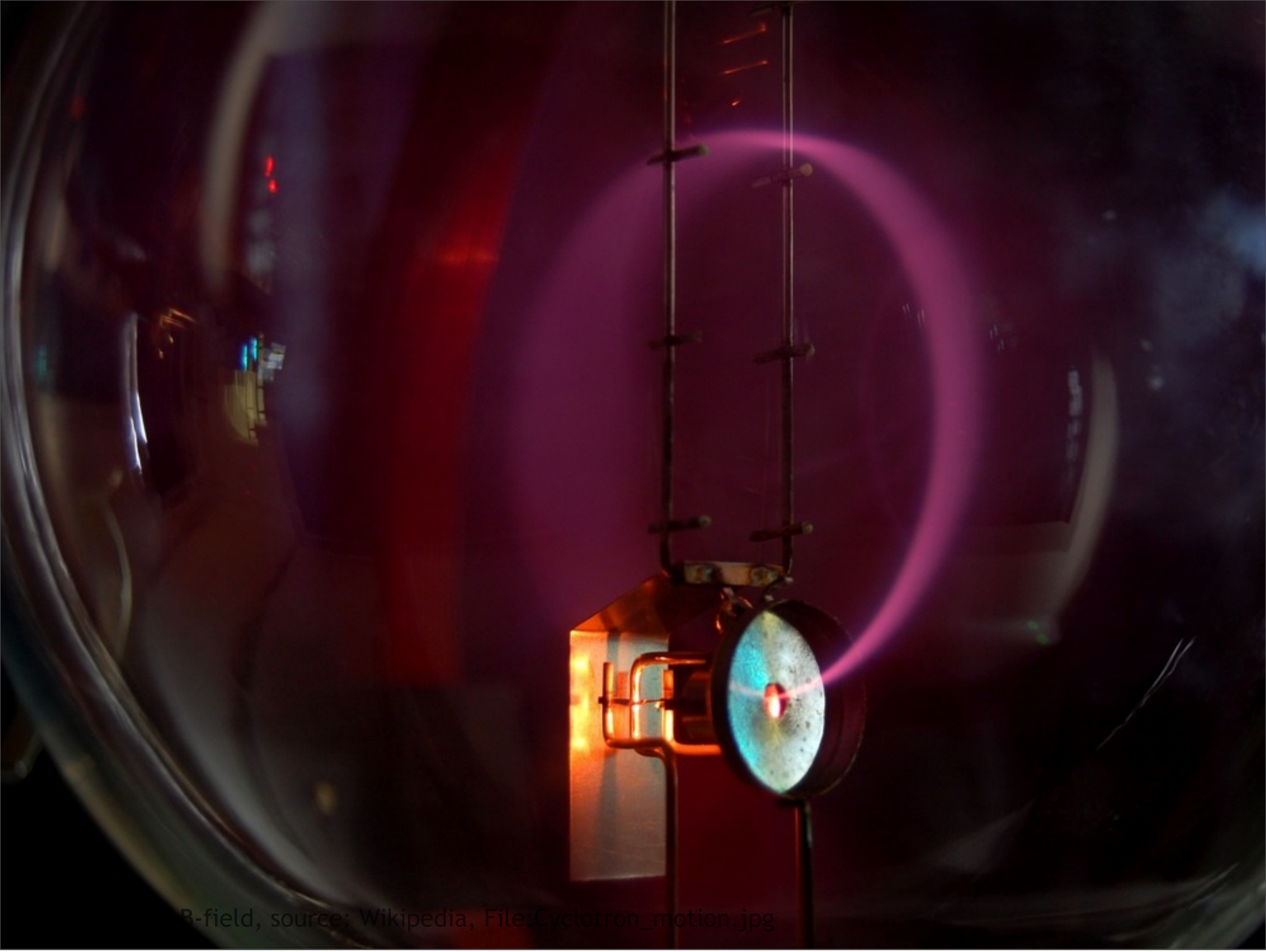
  - therefore $\rho_0 \approx 0.00125$
  - height of first interaction: ≈ 20 km


Density Profile
Density (g/cm^3)
Altitude (km)
Column Density Profile
X = Column Density (g/cm^2)
Altitude (km)
Shower-Max Column vs Energy
$x_{\max} = n_{\rm crit} \lambda_r \ln 2$
$= \lambda_r \ln \frac{E_0}{E_{\rm crit}}$
$X_{max} (g/cm^2)$
E_0 (TeV)
Shower-Max Altitude vs Energy
$Alt (km)$
E_0 (TeV)
1TeV gamma ray shower has max at ≈8km

Heitler Model

How good is it?

- doesn't account for particle loss
- assumes abrupt stop of shower after E_{crit}
- assumes single-photon emitted during bremsstrahlung
  - reality is several, so overestimates lepton fraction
  - approximately: $N_\gamma \approx 10\ N_e$ (can be used as a simple correction factor)
- still, actually not far from detailed simulations and reality!

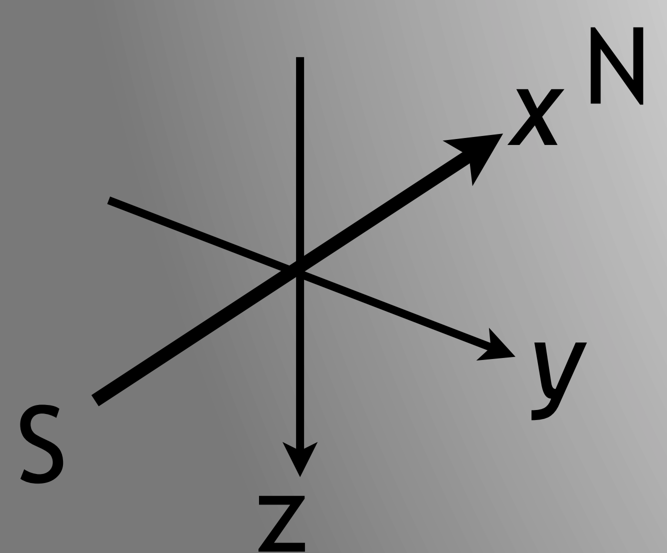

B-field, source: Wikipedia, File:Cyclotron_motion.jpg

Magnetic Field effects

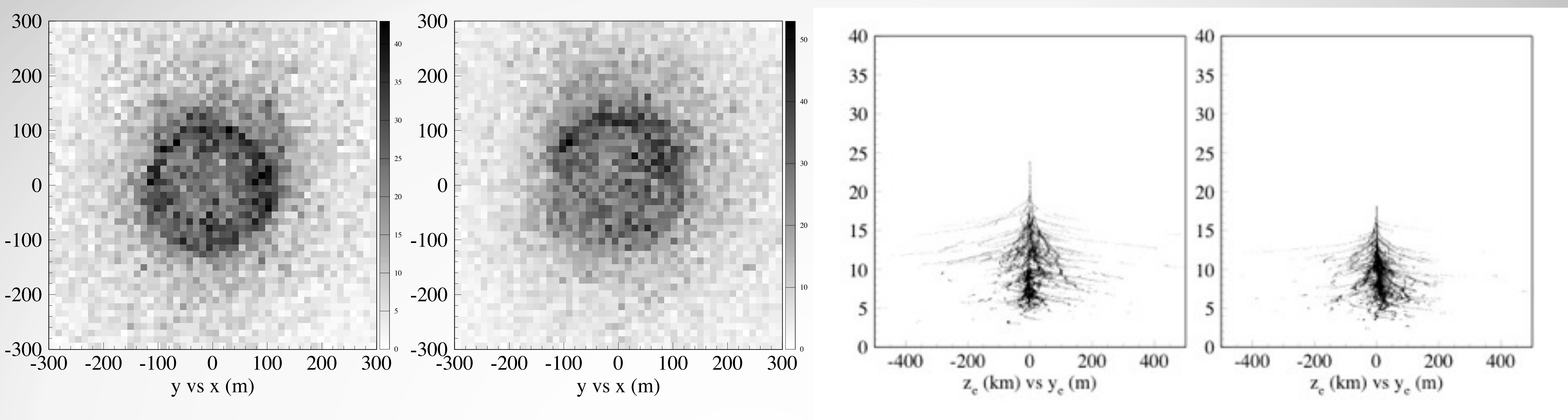
Showers are deflected by the Lorentz force:

- **B** = [H,0,Z]
- **F** = q**v**×**B**
- proportional to the field perpendicular to the observation direction

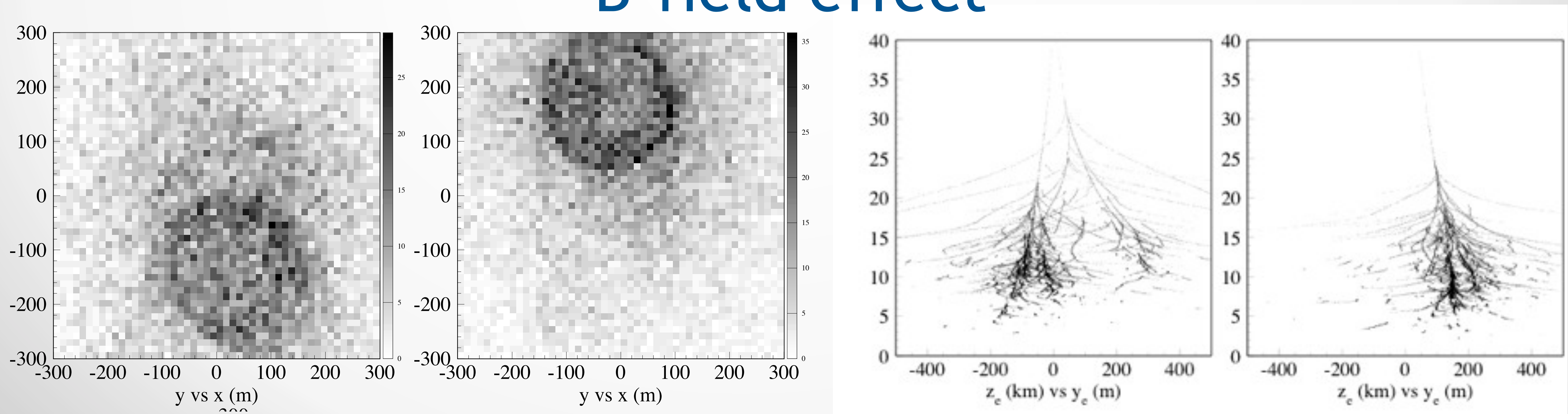
$$B_\perp \simeq \sqrt{H^2\left(\cos^2\theta + \sin^2\theta\sin^2\phi\right) - HZ\sin^2\theta\cos\phi + Z^2\sin^2\phi}$$



no strong B-field effect

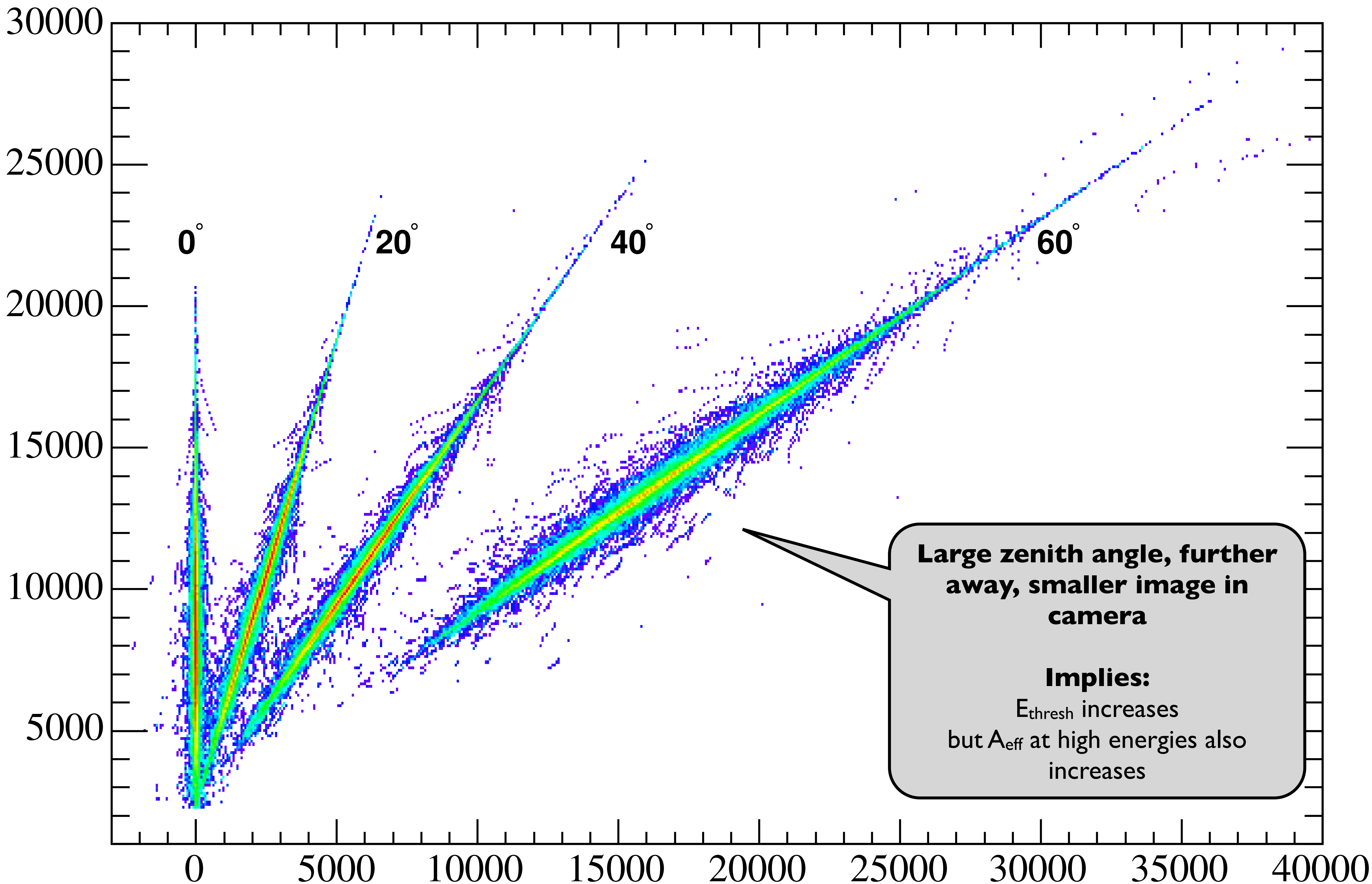


B-field effect



Hofmann, 1998

Zenith Dependence of 1 TeV Gamma Ray



Key points

Gamma-rays (and cosmic rays) are absorbed by the atmosphere

- but the information is not lost
- extensive air showers give us a wealth of knowledge about the incident particle, if we know some basic particle physics

The atmosphere acts as both a calorimeter and a tracking medium

- the principle is not so different from space-based detectors, or even from those at particle accelerators
- We can leverage this to build a detector with much larger effective area than would be practical in an enclosed system.

Next time:

Using air showers to detect primary gamma rays and reject cosmic rays

- using Earth's atmosphere as part of a gamma ray telescope! (the imaging atmospheric Cherenkov technique)
- methods for reconstructing the properties of a shower and gamma-ray from shower information
- Alternative detector methods
- details of analysis of VHE gamma ray sources:
  - background modeling
  - signal extraction