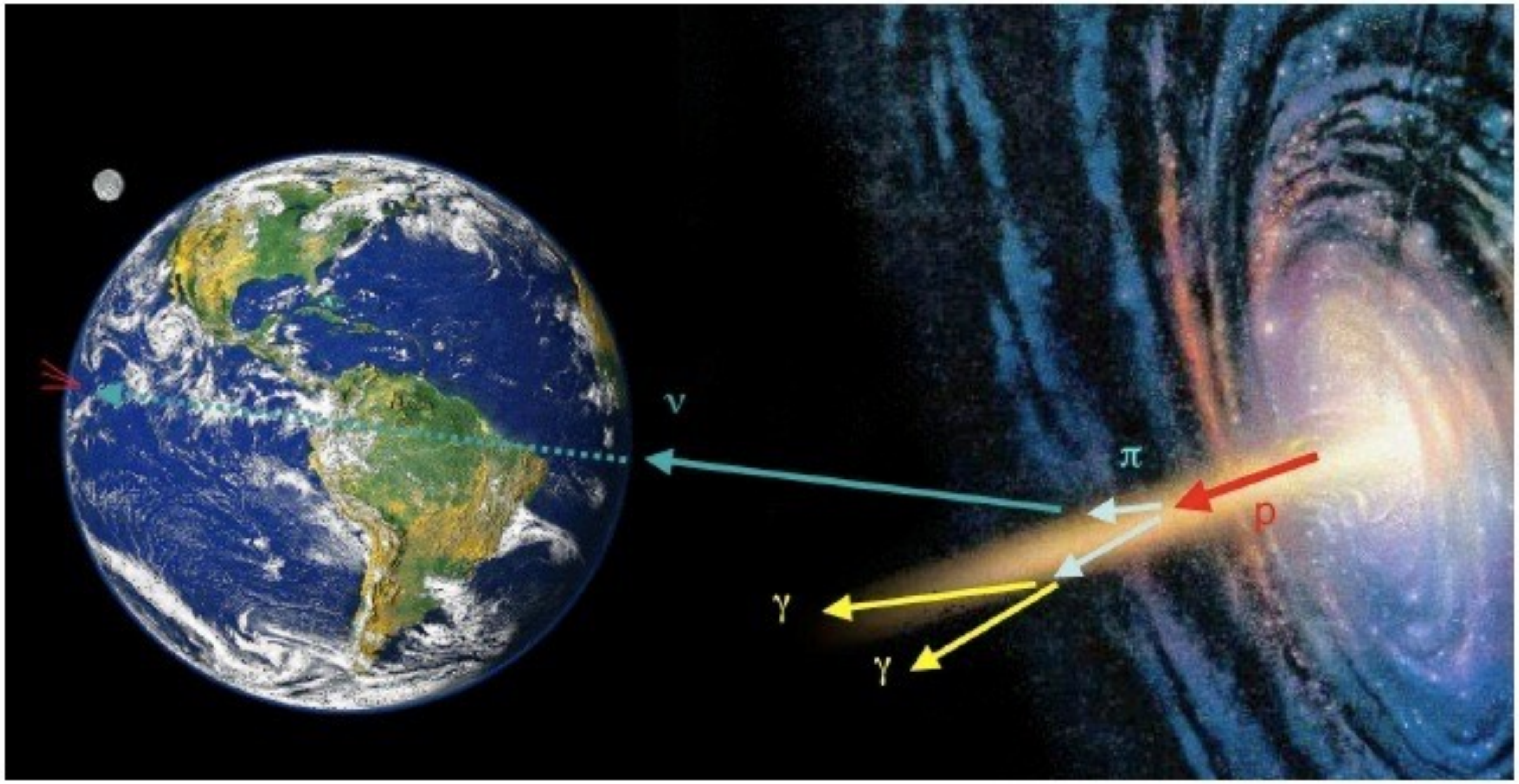
Teilchenphysik mit kosmischen und mit erdgebundenen Beschleunigern



09. Cosmic Rays II

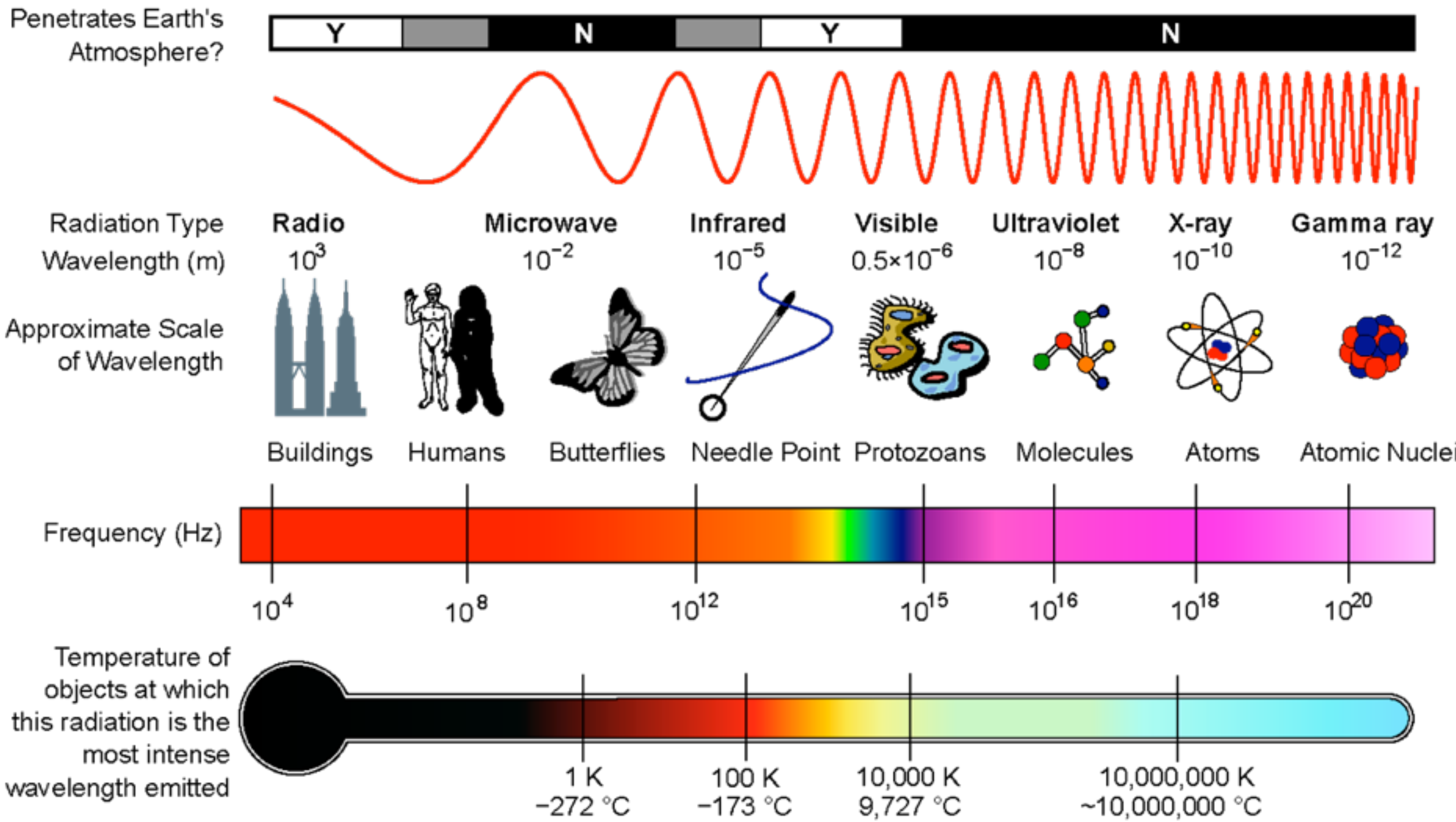
10.07.2017

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Prof. Dr. Siegfried Bethke
Dr. Frank Simon

Neutral Cosmic Rays

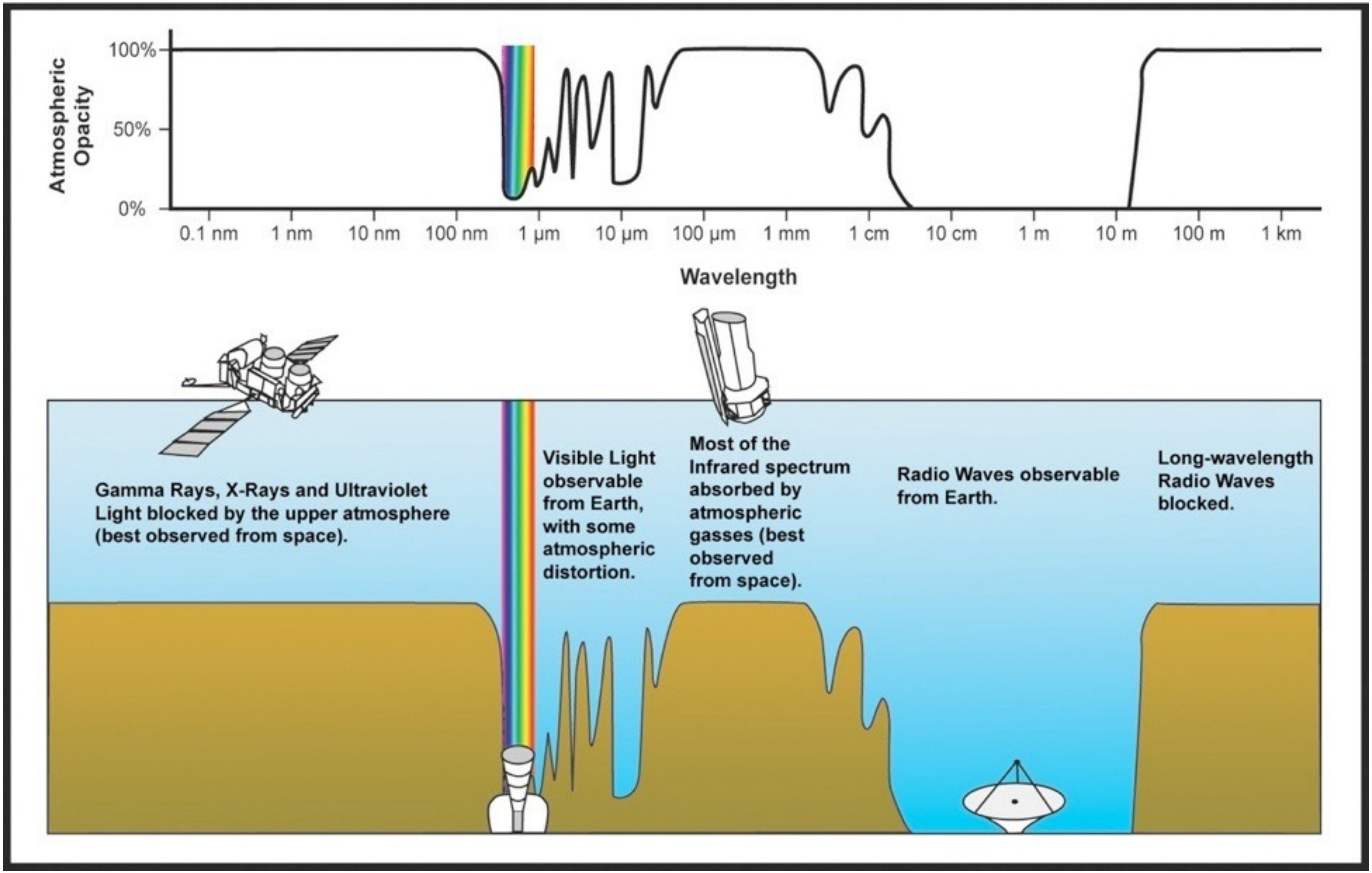
Electromagnetic Radiation



Energy: ~10^{-9} eV ~10^{-4} eV ~1 eV ~10^{4} eV ~10^{6} eV

$$E = h\nu = \nu \times 4.14 \times 10^{-15}\,\mathrm{eVs}$$

Electromagnetic Radiation & The Atmosphere



Emission of Electromagnetic Radiation

- Thermal Radiation:
  - for example the sun: Emits at 5700 K (surface temperature of the sun)
  - Two-particle interactions lead to thermal equilibrium

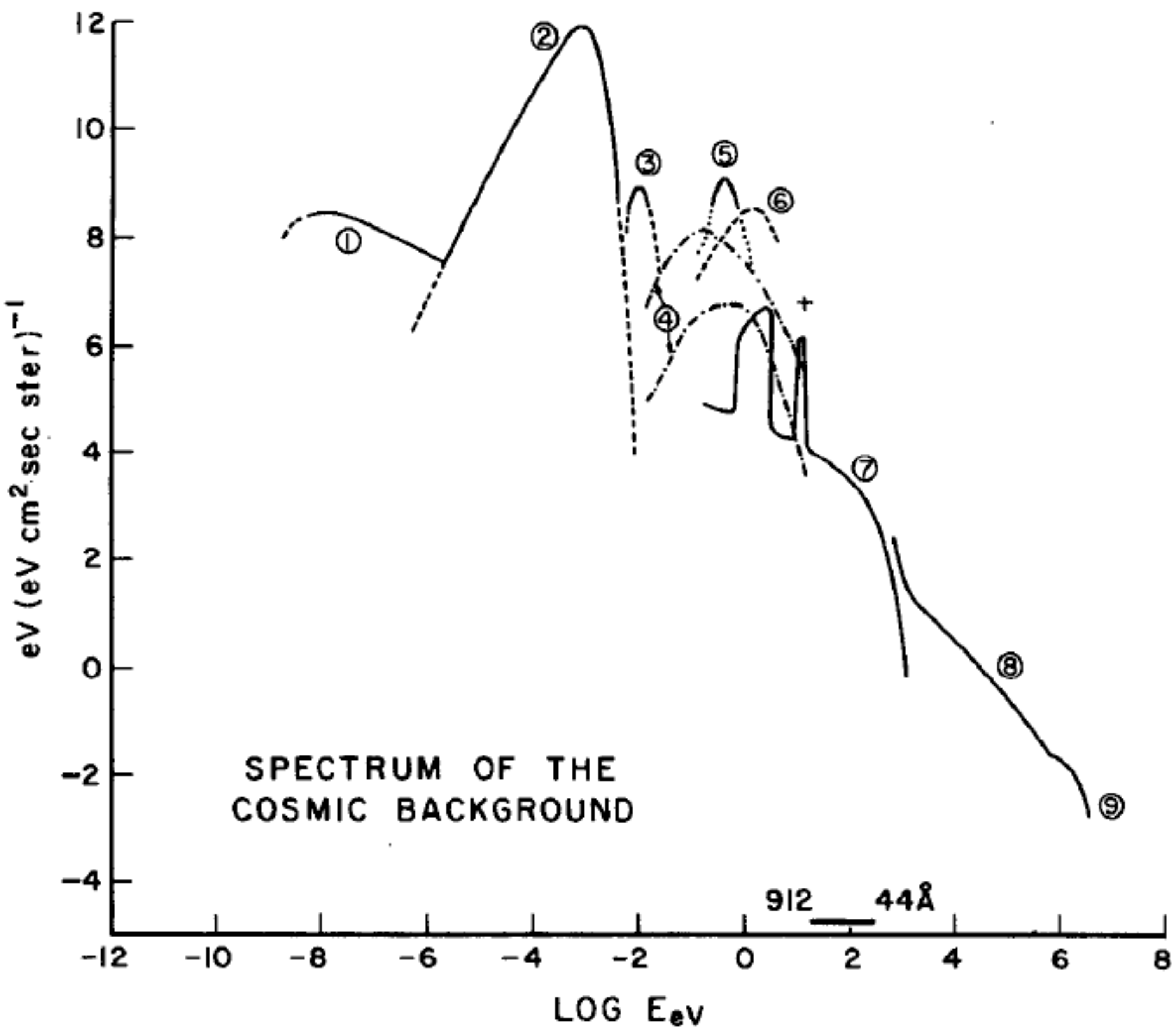
$$\propto e^{-\frac{E}{kT}}$$

- Non-thermal radiation:
  - low density of plasma particles
  - a few particles can reach very high energies in interactions

$$\propto E^{-\gamma}$$

- Thermal and non-thermal components of a gas can exist in parallel and can interact with each other

Cosmic Background

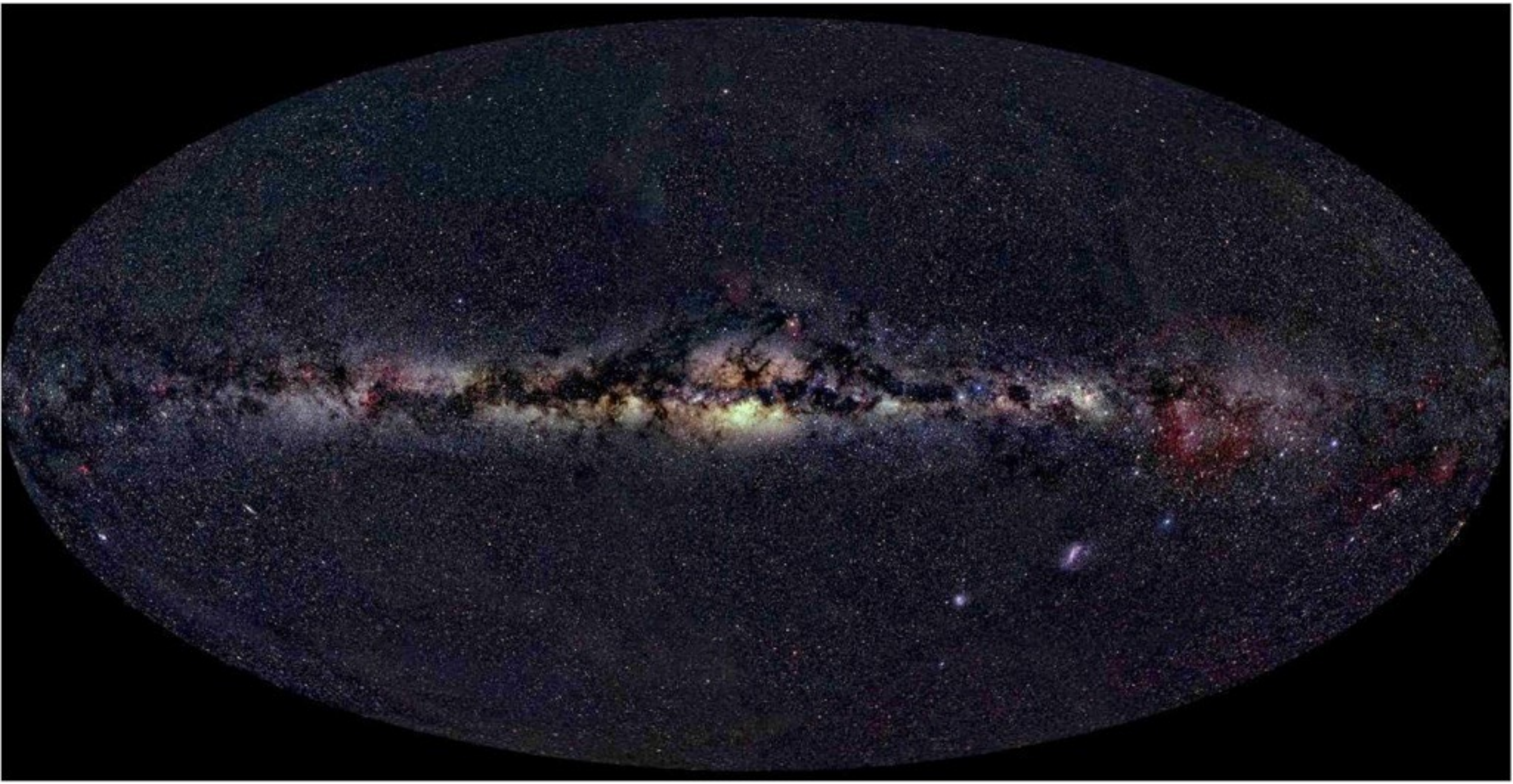


Annu. Rev. Astron. Astrophys. 9, 89 (1991)

1. Radio background, synchrotron radiation of e^- in galactic B field
2. Microwave background, 2.7 K
3. Emissions of cold interstellar dust
4. Emissions of distant galaxies
5. Hot interstellar dust
6. Optical background: scattering of sunlight on interstellar dust
7. Ionised intergalactic medium
8. X-ray background
9. Diffuse gamma background

Observation at different Wavelengths

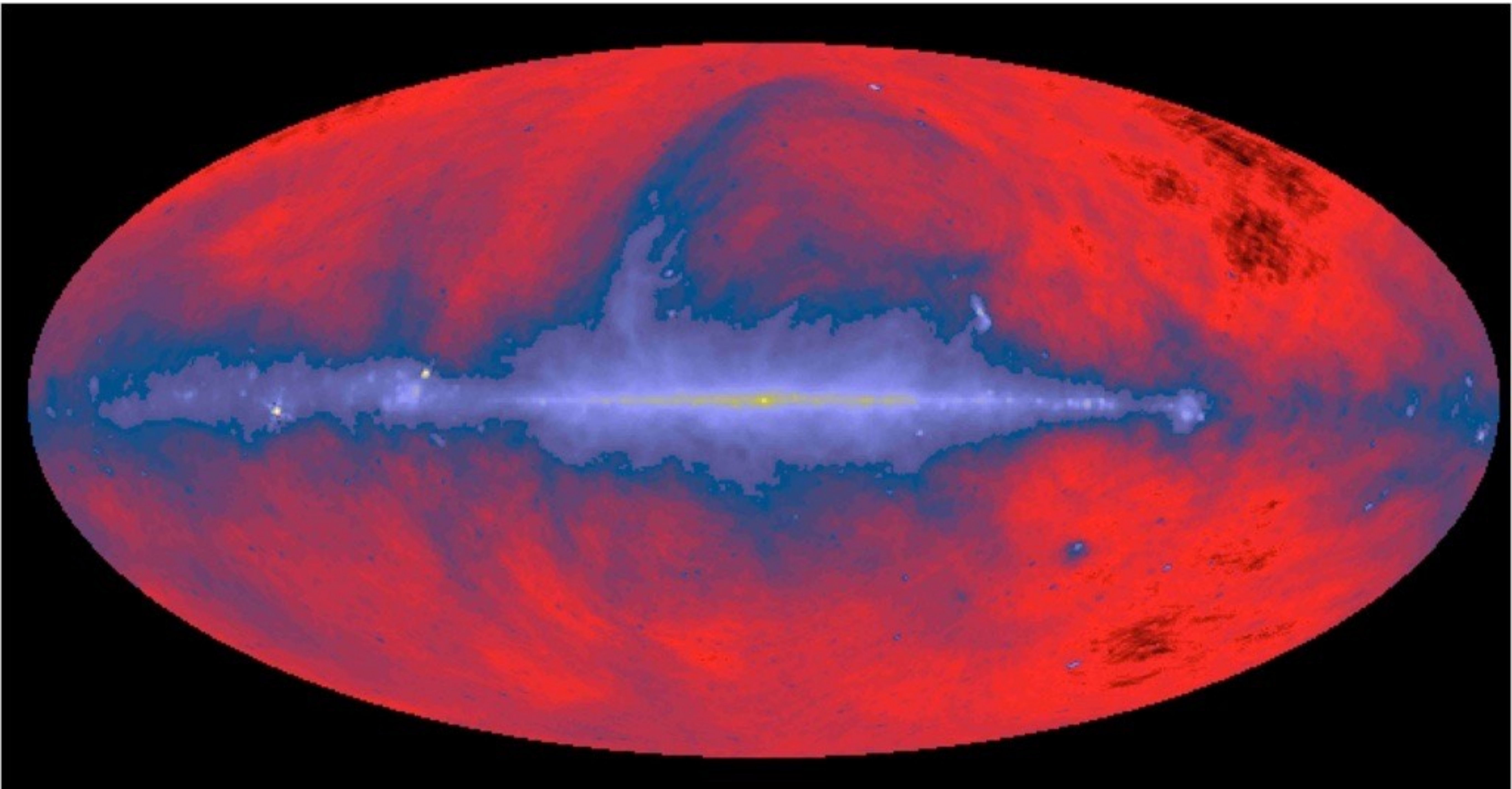
Radio (10^{-6} eV) IR (10^{-2} eV) visible (1 eV) X-Ray (10^{3} eV) Gamma (10^{9} eV)



- Central regions of the Milky Way hidden by dust

Observation at different Wavelengths

Radio (10^{-6} eV) IR (10^{-2} eV) sichtbar (1 eV) X-Ray (10^{3} eV) Gamma (10^{9} eV)



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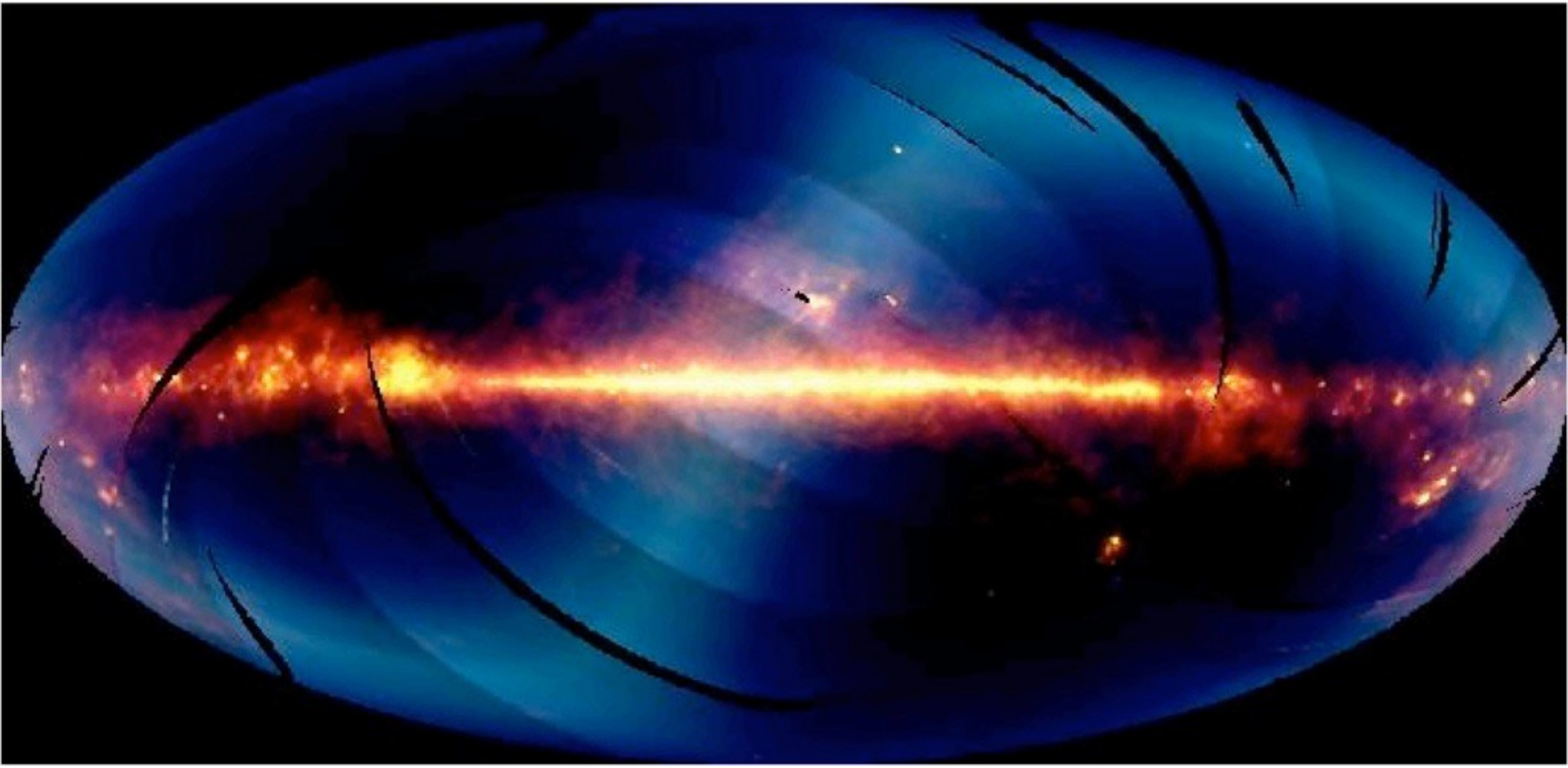
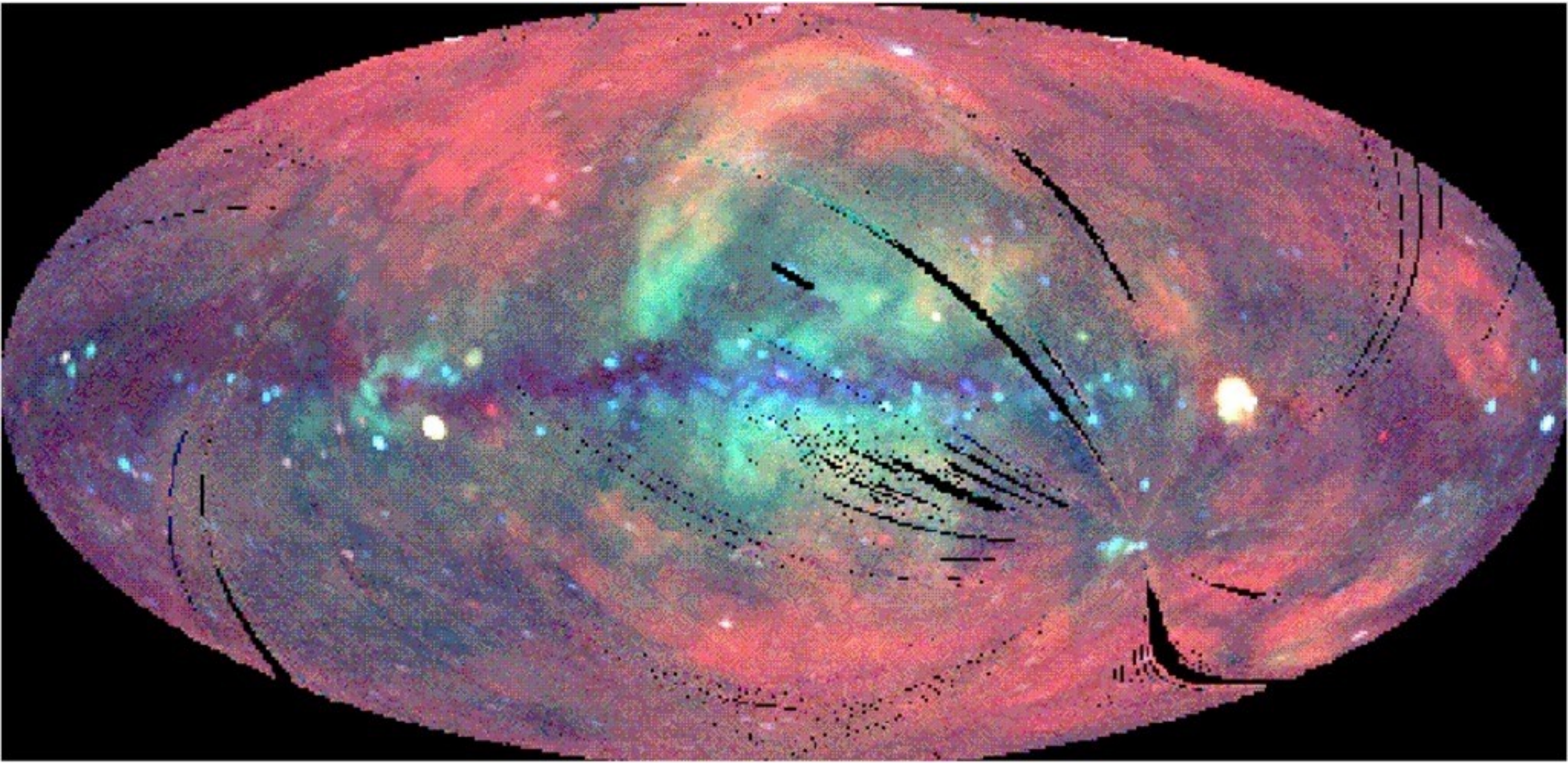


- Dust in the Milky Way transparent to IR: Observation of the galactic center

Observation at different Wavelengths

Radio (10^{-6} eV) IR (10^{-2} eV) sichtbar (1 eV) X-Ray (10^{3} eV) Gamma (10^{9} eV)



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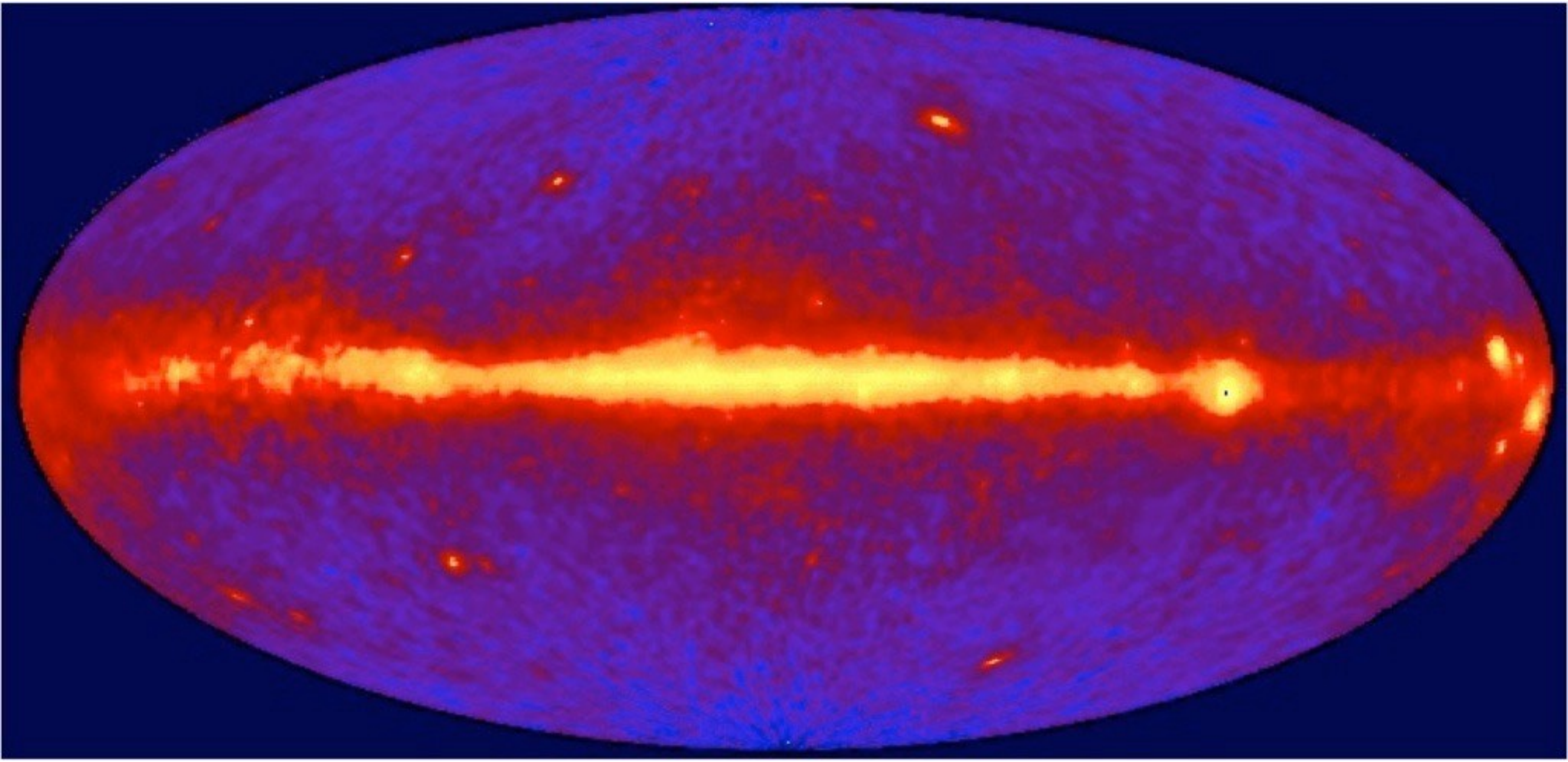
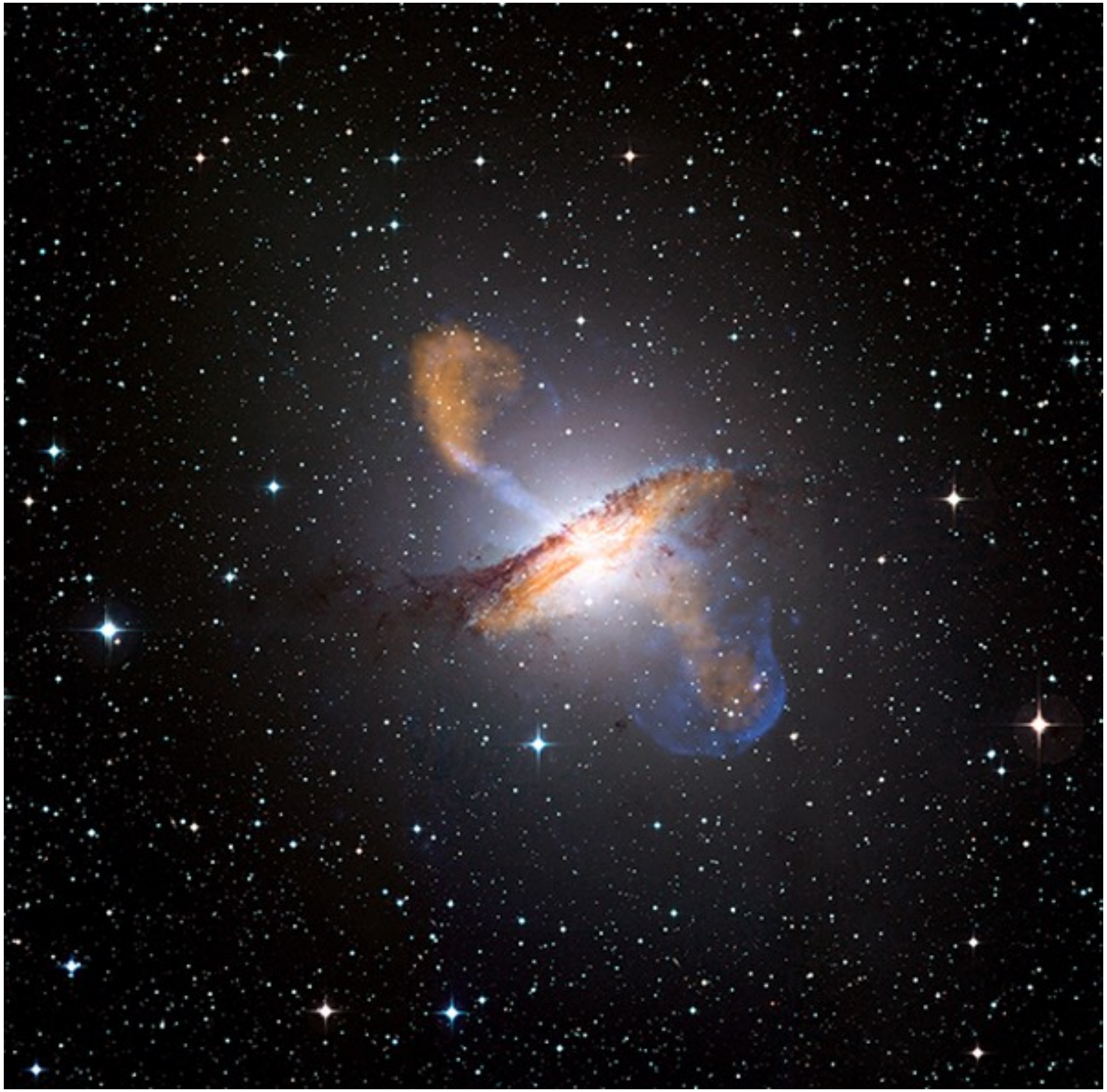


- Combination of all wavelengths provides a detailed picture

An Example: Cen A



Credit: X-ray: NASA/CXC/CfA/R.Kraft et al.; Submillimeter: MPIfR/ESO/APEX/A.Weiss et al.; Optical: ESO/WFI

- Combined image of Centaurus A, an active galaxy at a distance of 10 Mlyr
  - visible light: white
  - sub-mm: orange
  - x-ray: blue

Photons: “Acceleration”

- Photons themselves are not accelerated since they are uncharged
  - The energy originates from charged particles
  - Acceleration of charged particles in shock fronts
  - Conversion to photons through various processes

  - The photons only receive a fraction of the energy of the primary particle
  - Photons are substantially suppressed compared to hadrons at the same energy

- In the TeV region:

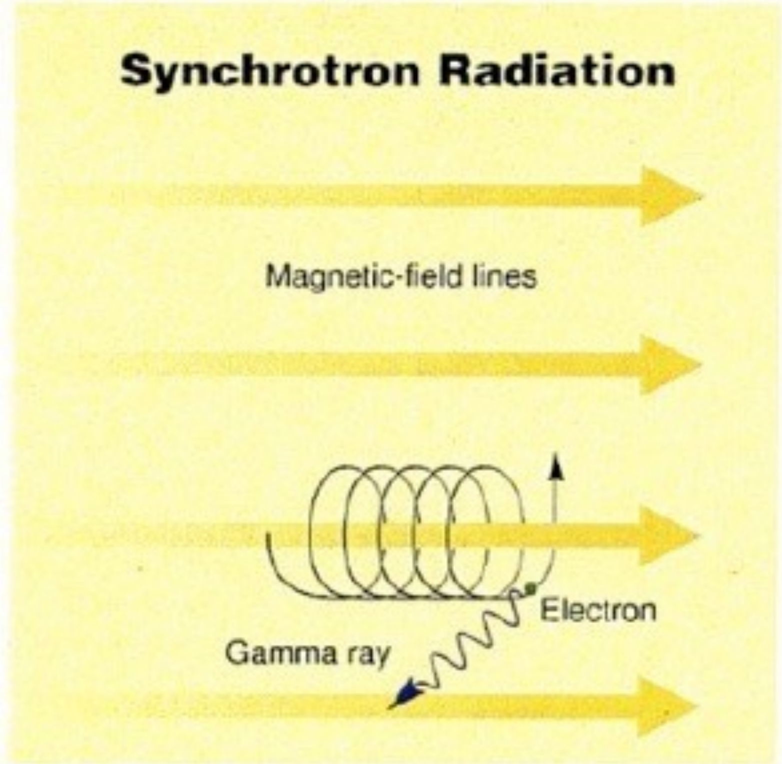
  $\text{Flux}(\gamma) \sim 10^{-4} \times \text{Flux(hadrons)}$

  - A challenge for experiments: Excellent photon/hadron separation required

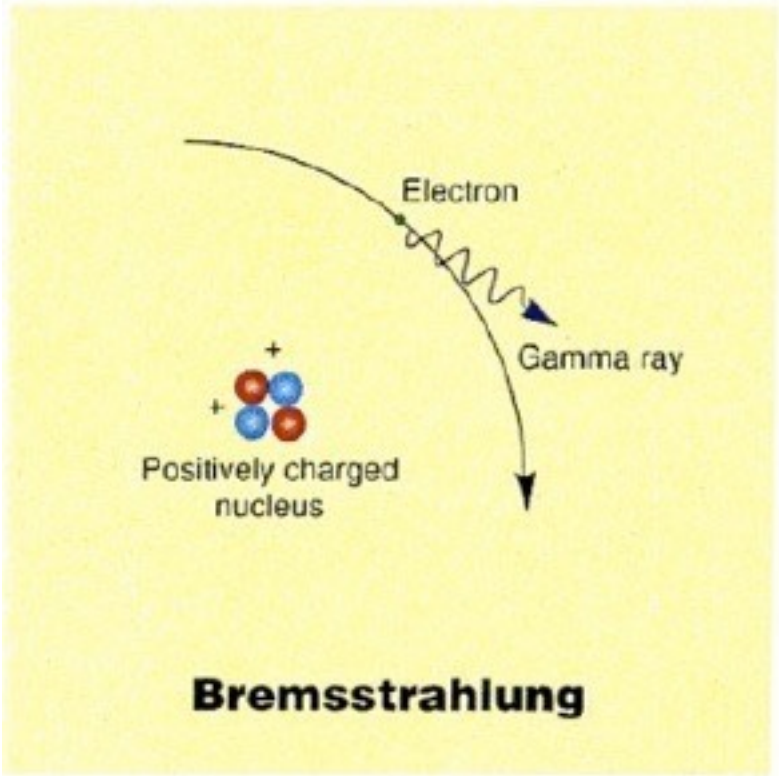
Photon Production

- Accelerated charges emit radiation

- On circular orbits in magnetic fields:
  Synchrotron radiation



- Acceleration (deceleration!) in strong electric fields of nuclei:
  Bremsstrahlung



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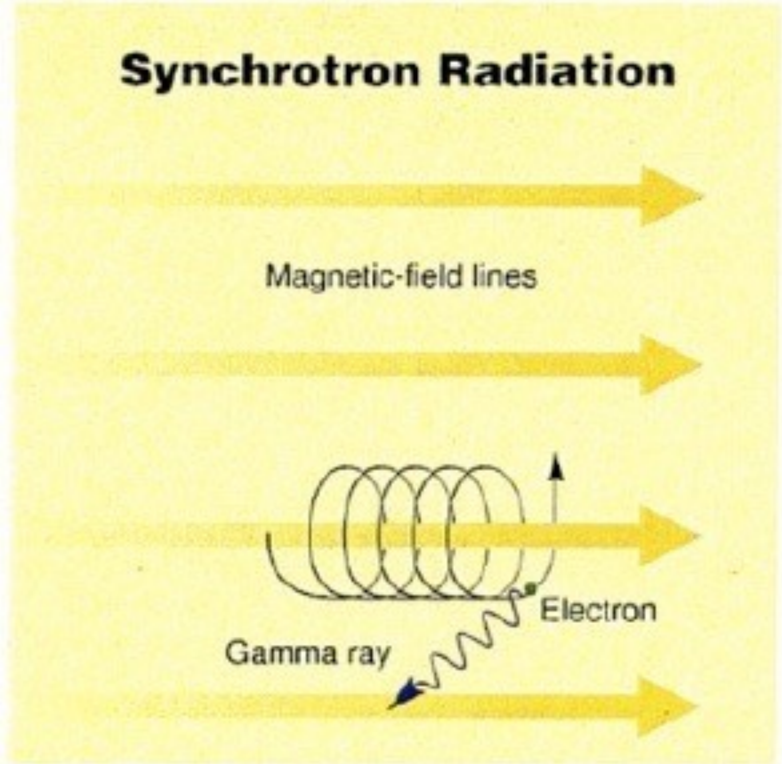

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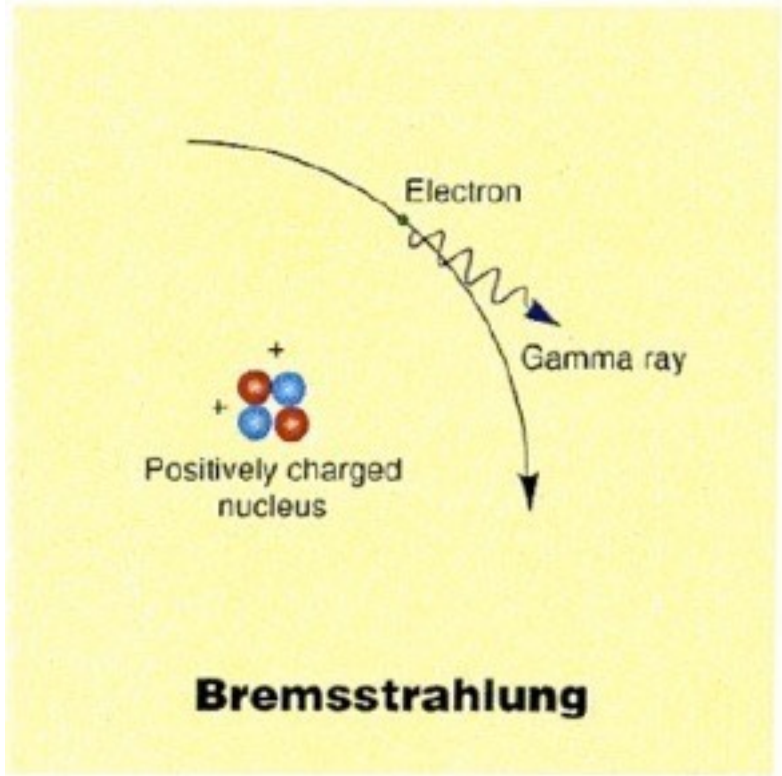


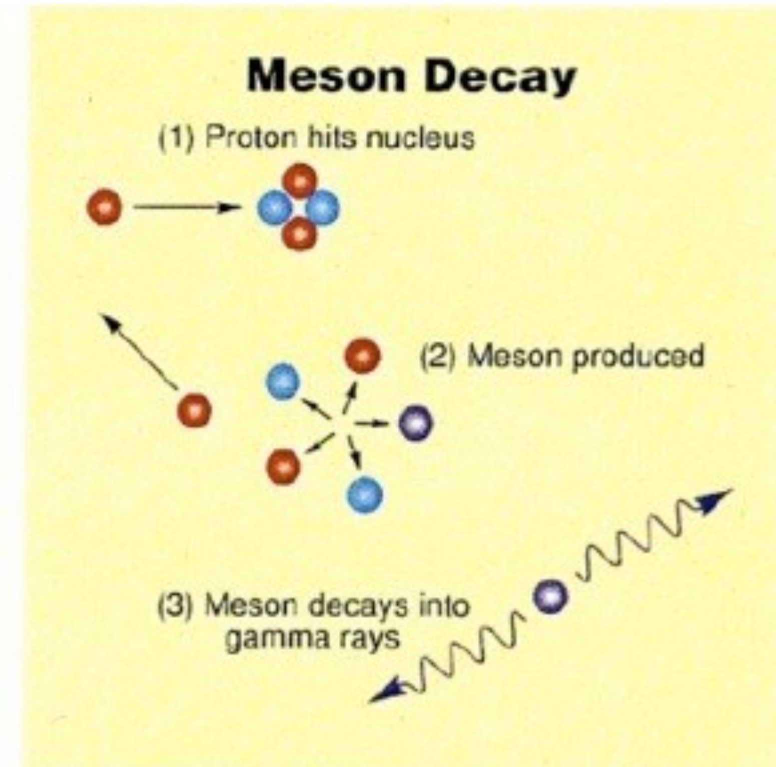
In addition: Thermal radiation!

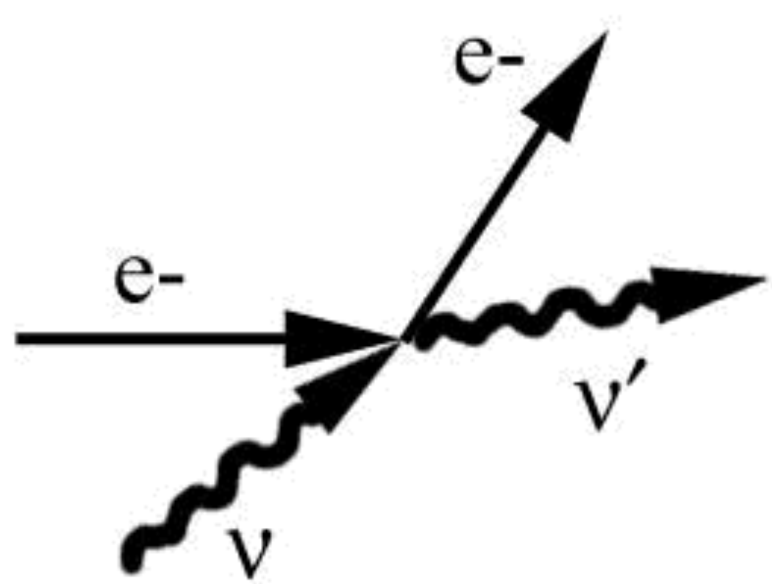
Photon Production II

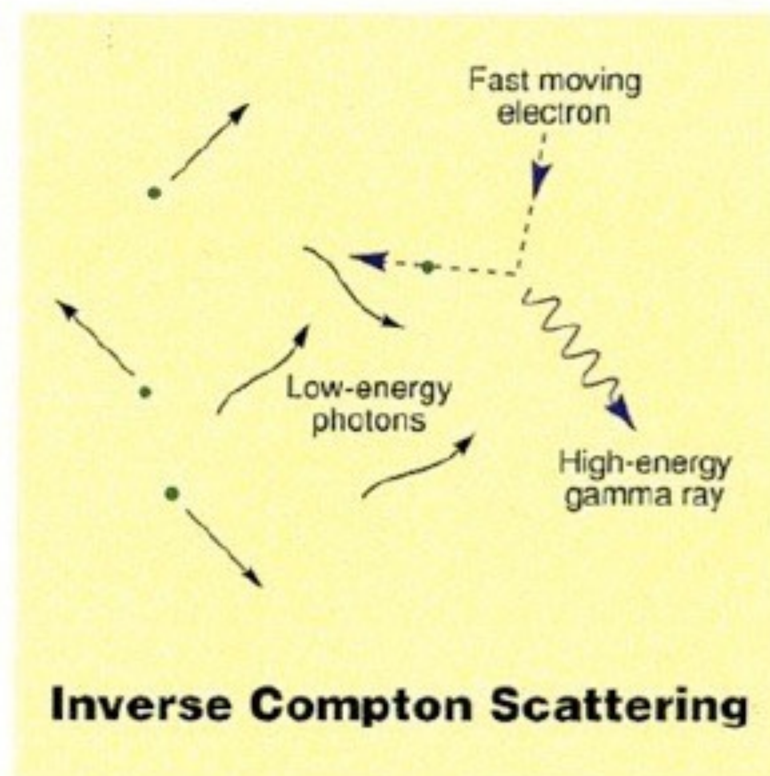
- Hadronic production of photons via meson production in hadronic interactions and consecutive decay

$$p \;+\; Kern \;\rightarrow\; X \;+\; \pi^0$$
$$\pi^0 \;\rightarrow\; \gamma\,\gamma$$

- Energy increase of a photon via scattering off highly energetic electrons: (inverse Compton scattering)

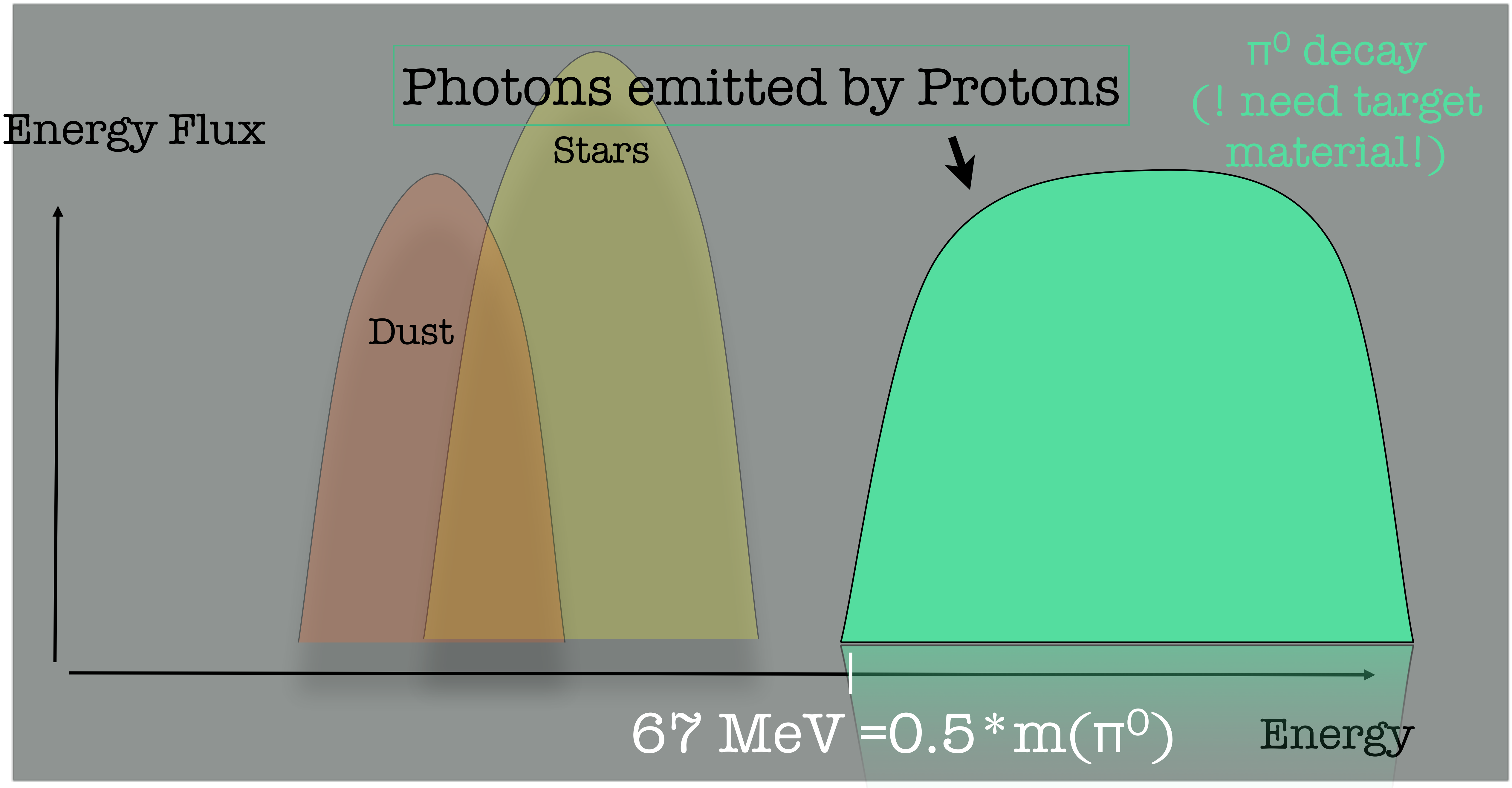






Expected Gamma Ray Spectrum of Sources

- Depends on the mechanism of γ creation



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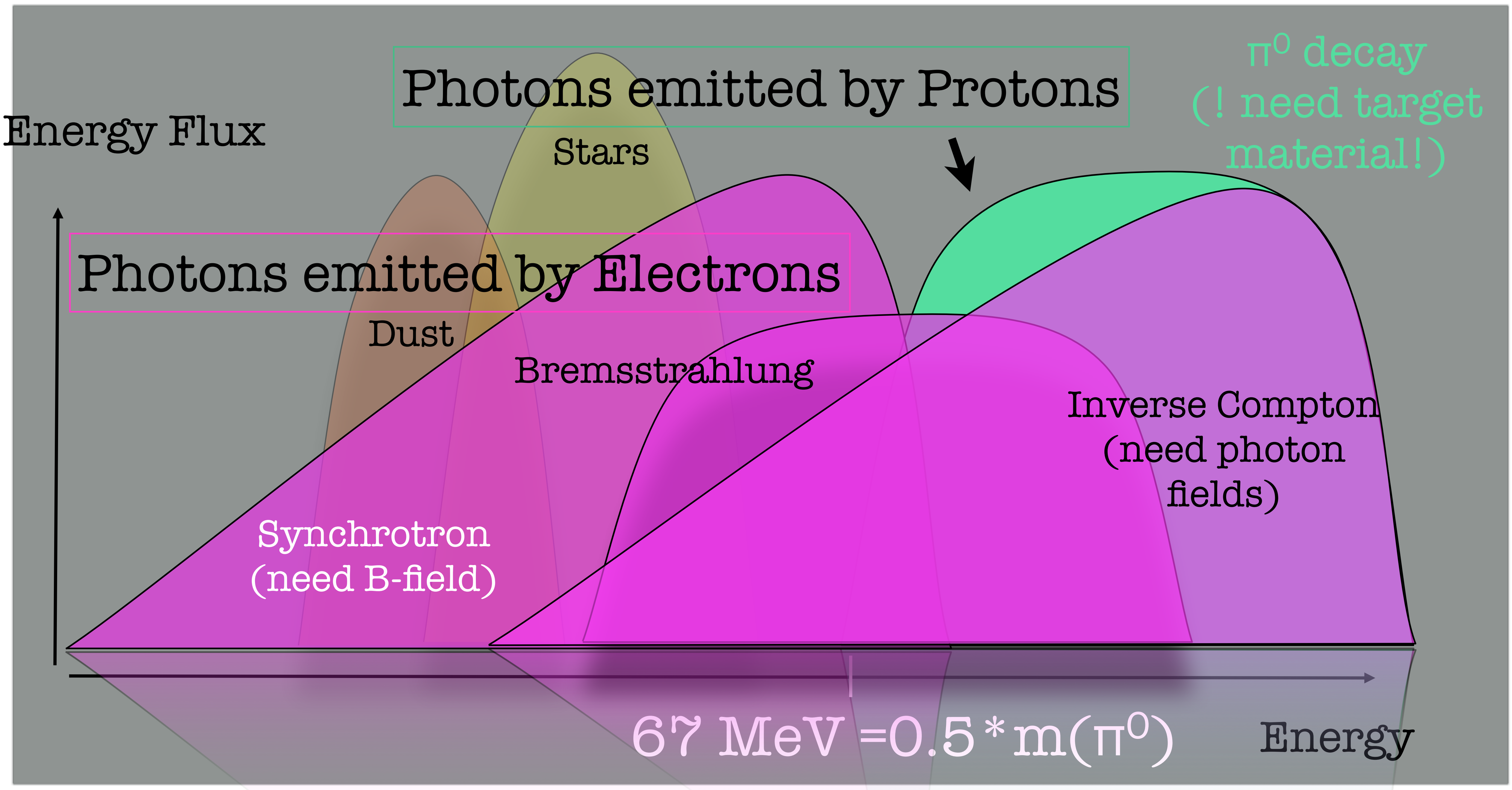

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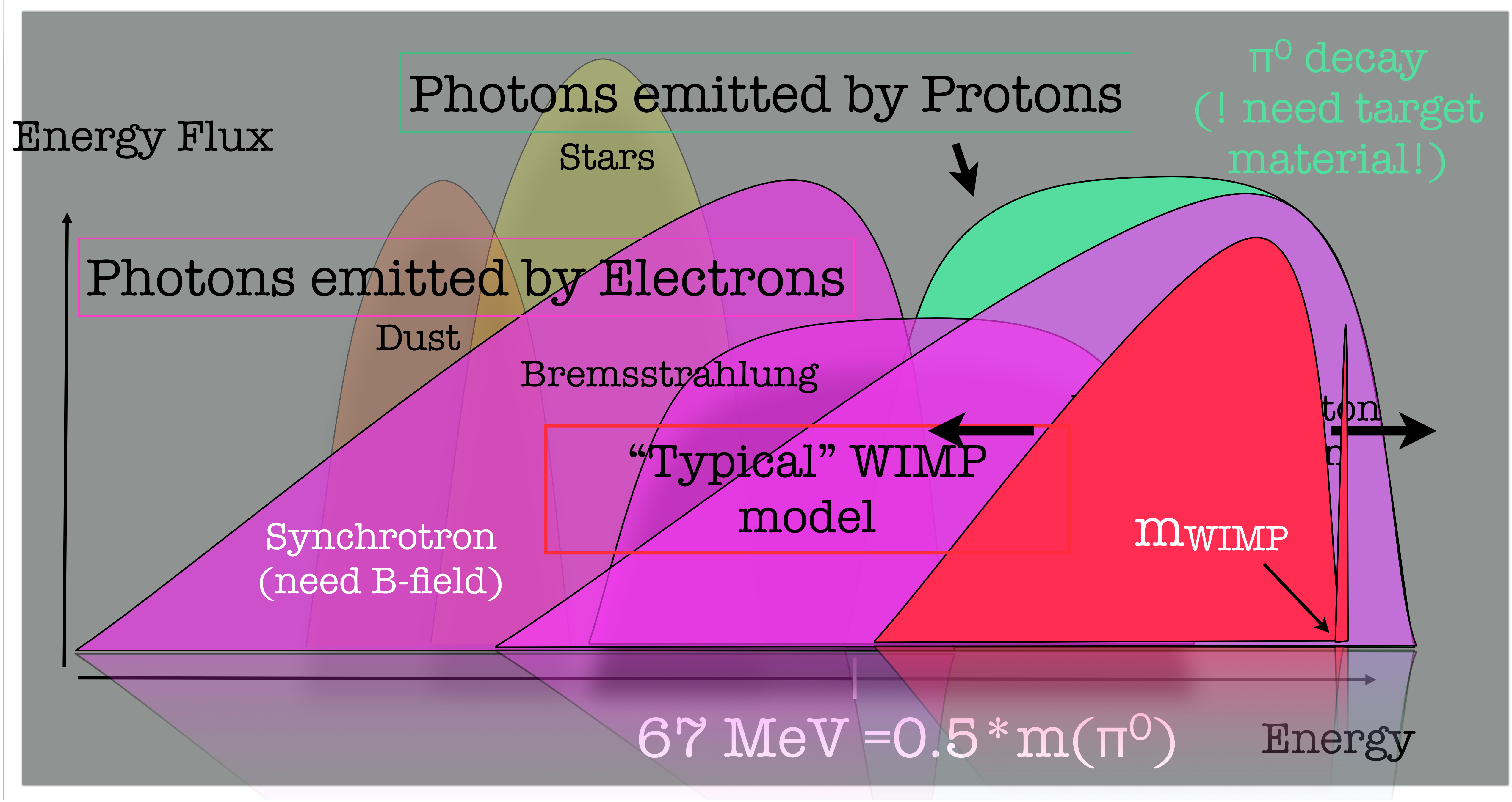
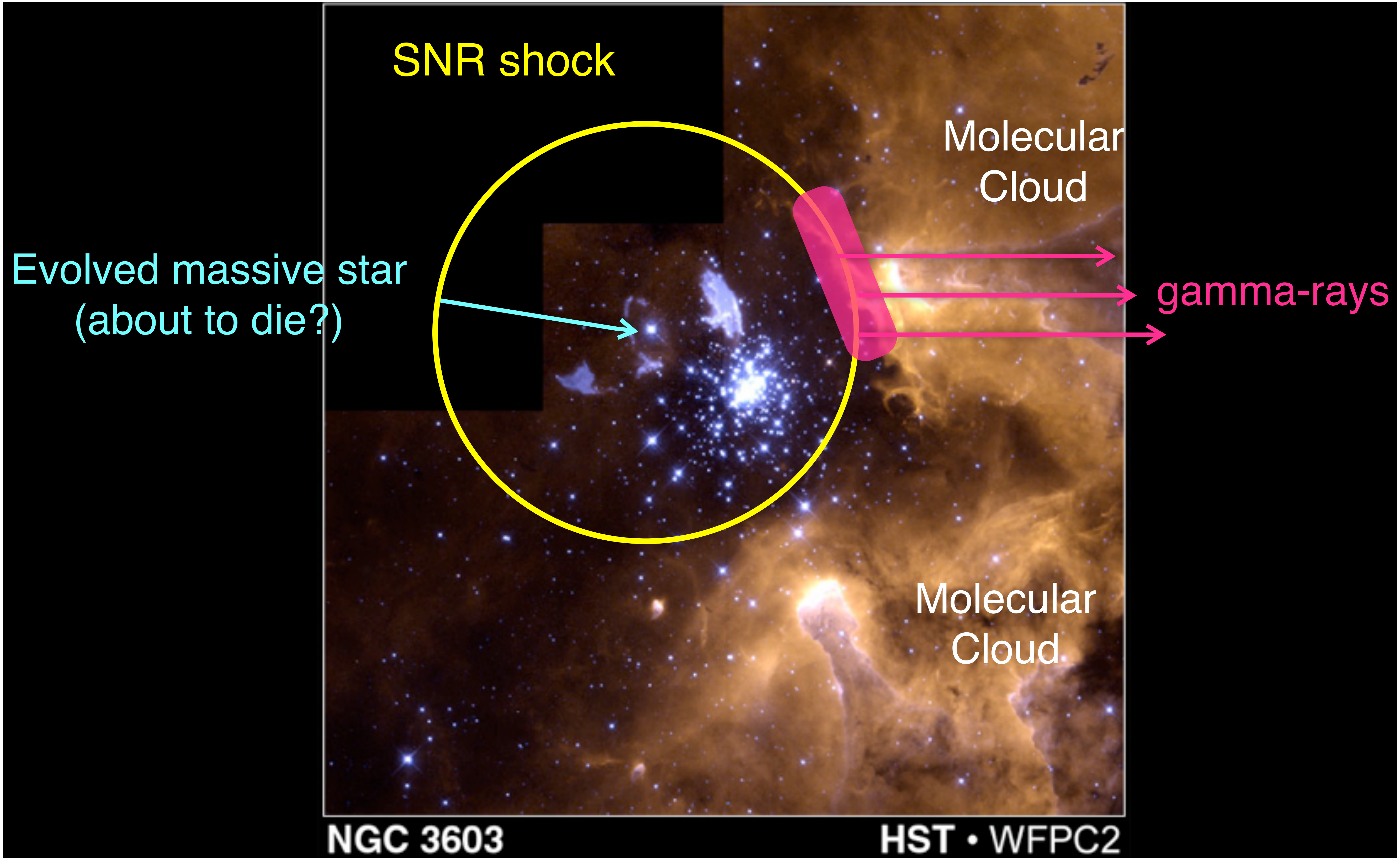
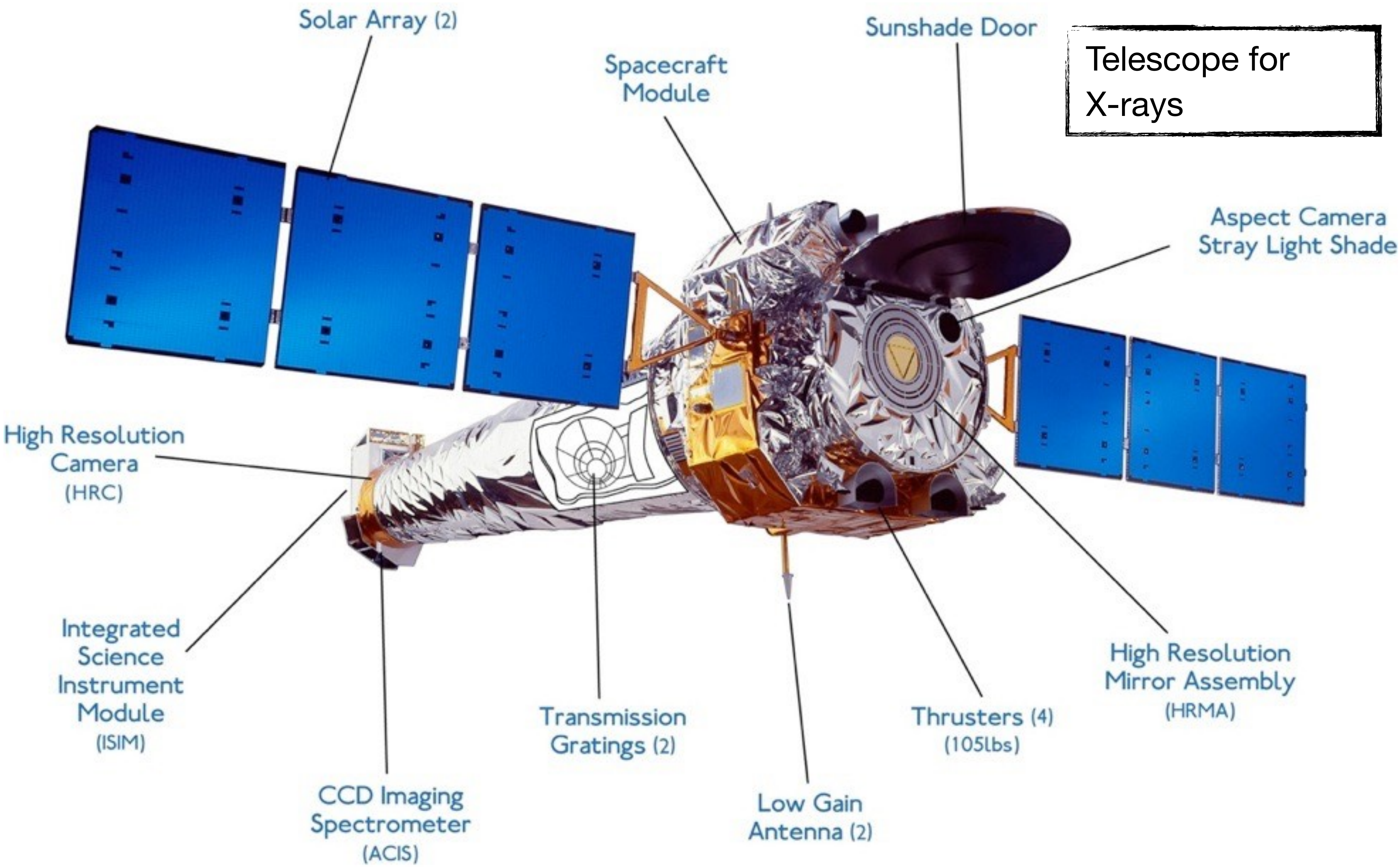


Gamma Creation: The General Idea

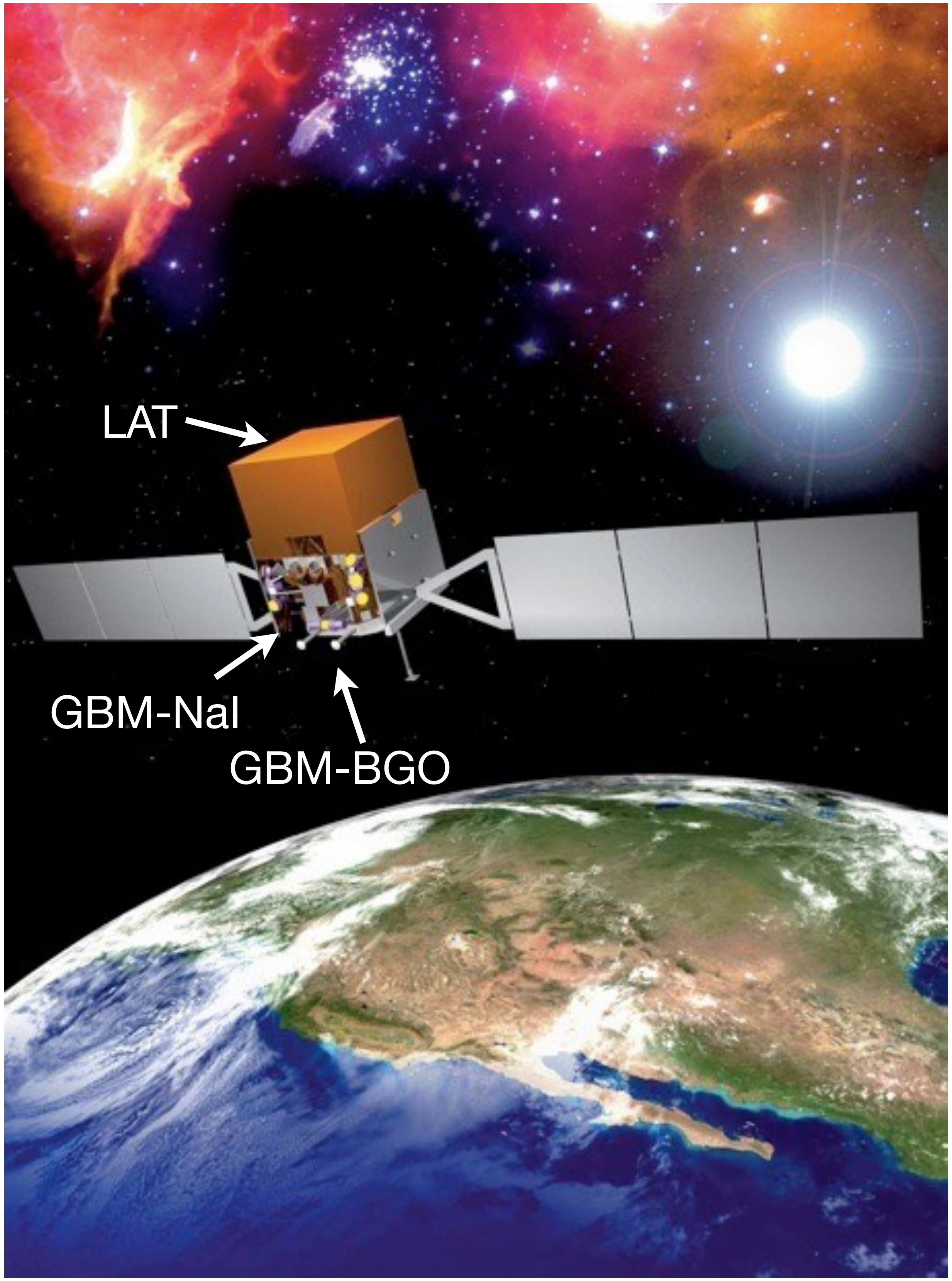


Direct Measurement: Satellites: Chandra



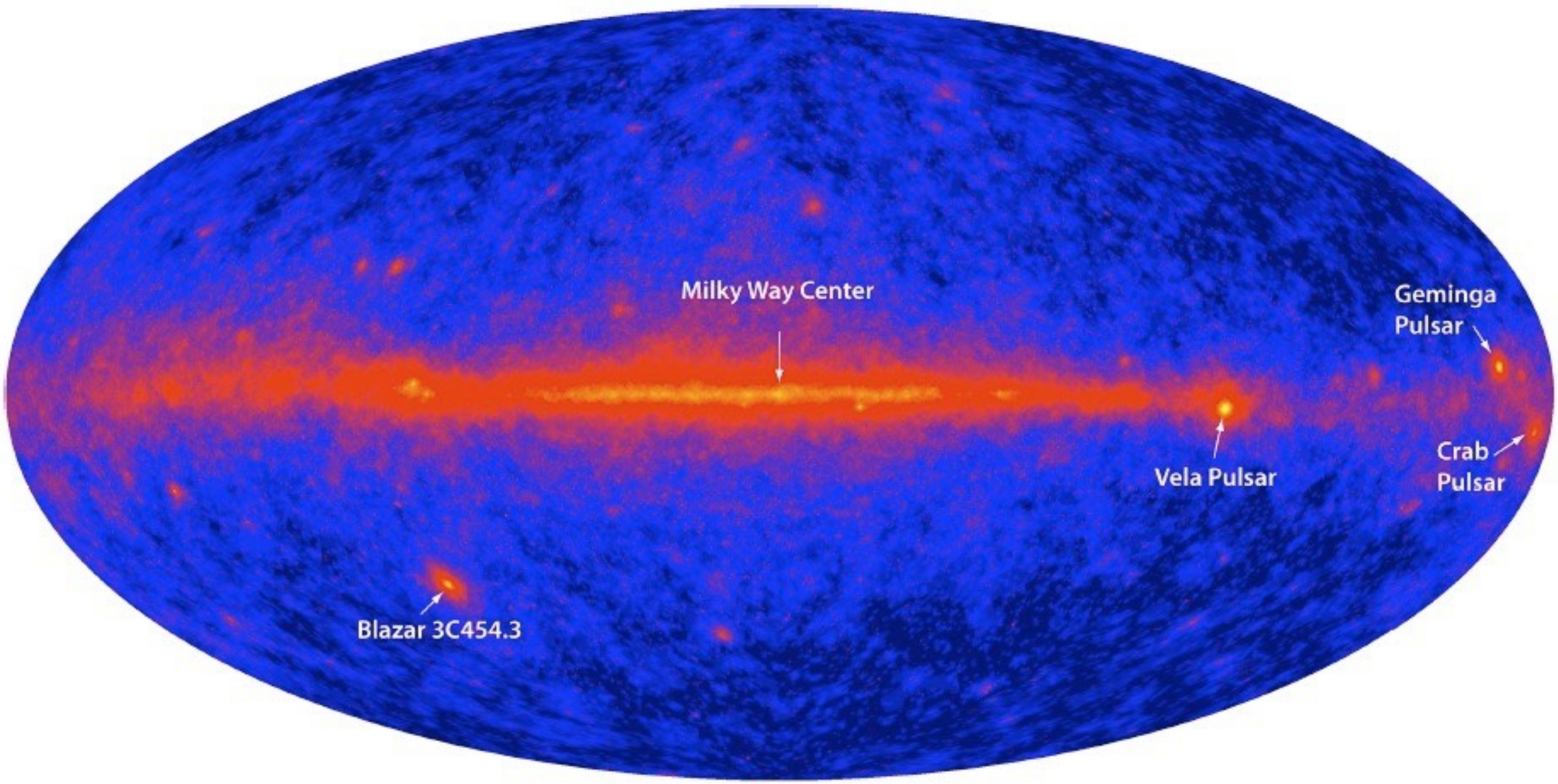
Telescope for X-rays

Direct Measurement: Satellites: Fermi

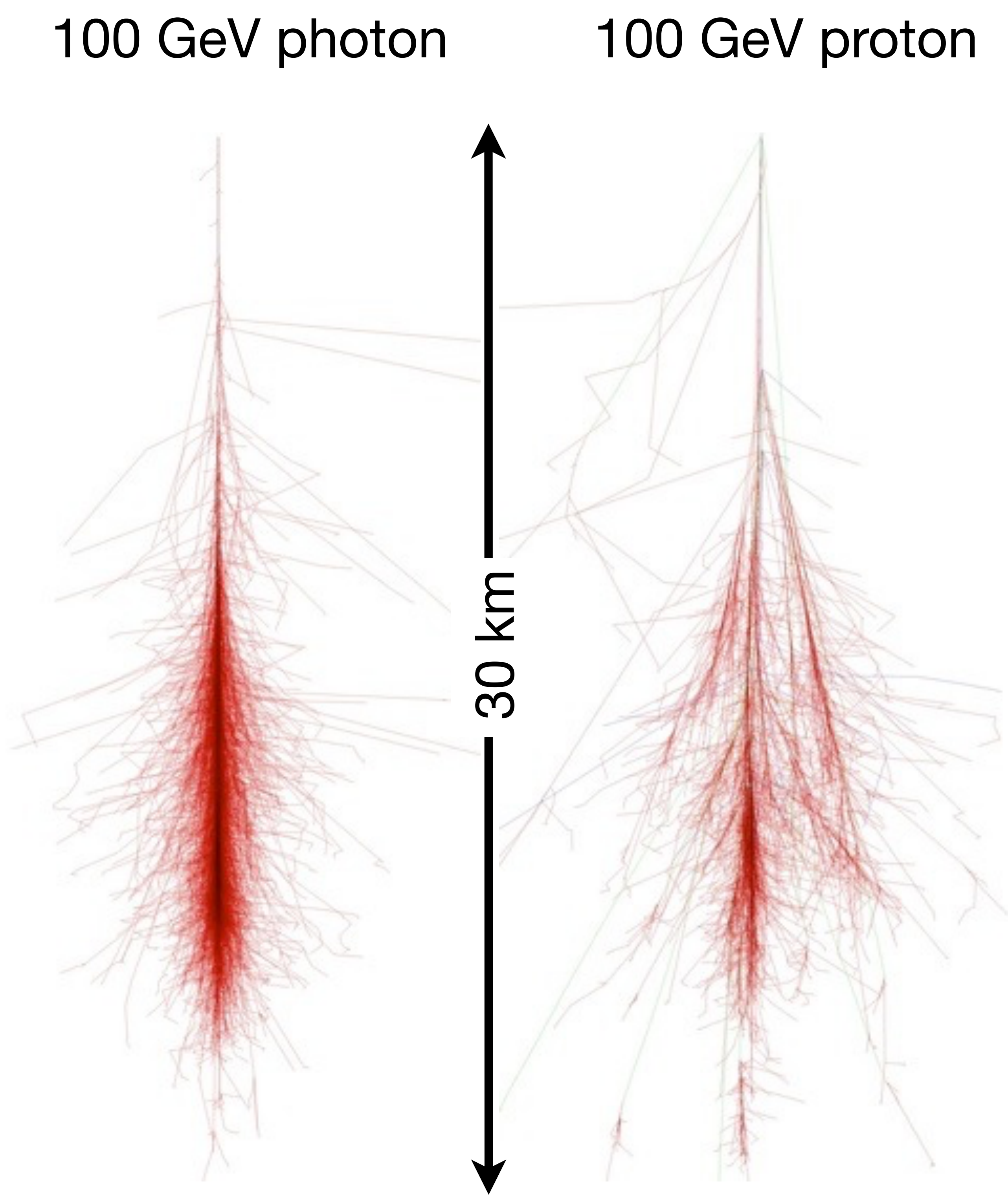


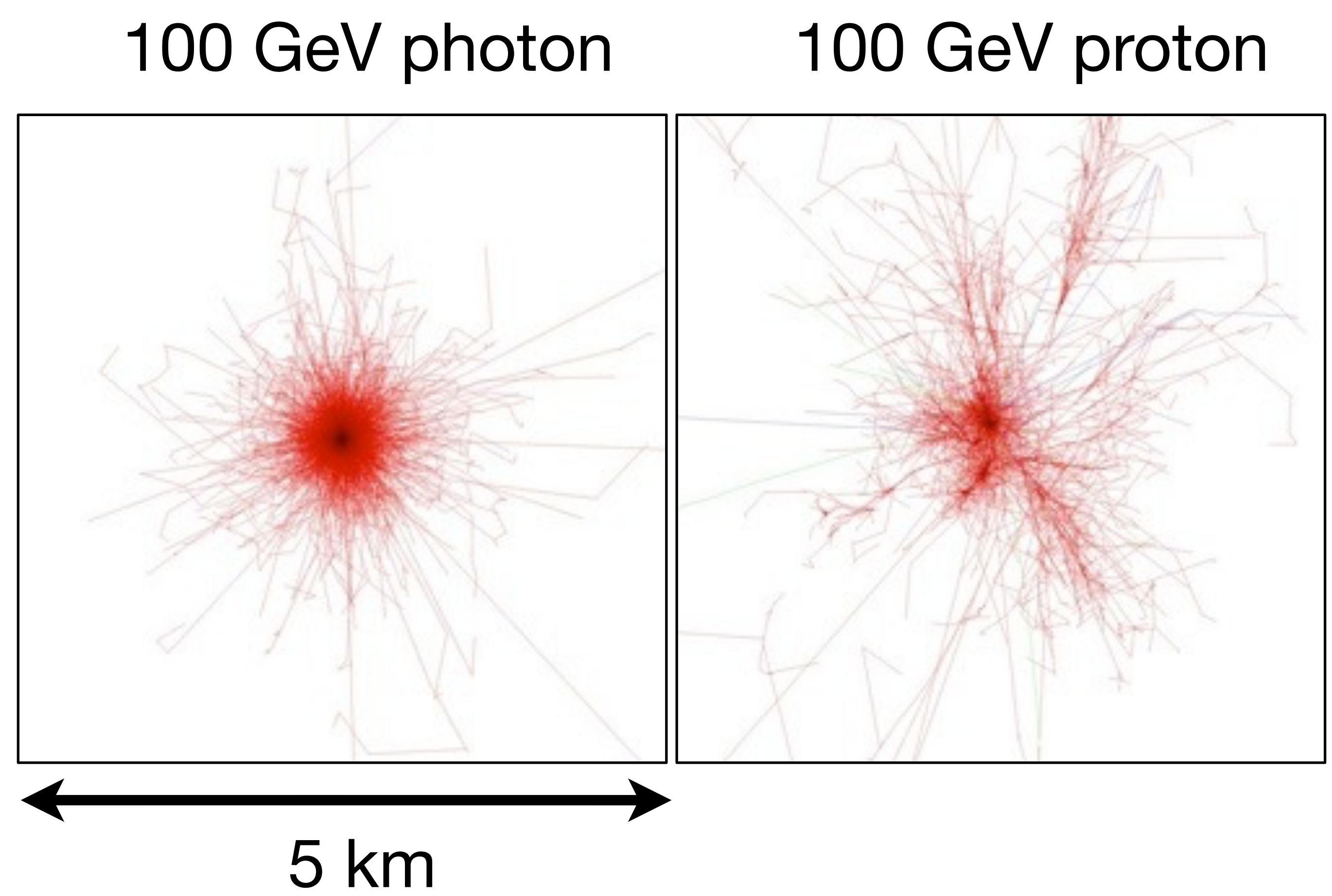
- Satellites can cover the full sky
- Good resolution at relatively low energies
- The newest instrument: Fermi (formerly GLAST (Gamma-ray Large Area Telescope))
  - started on 11.06.2008

The Fermi Sky



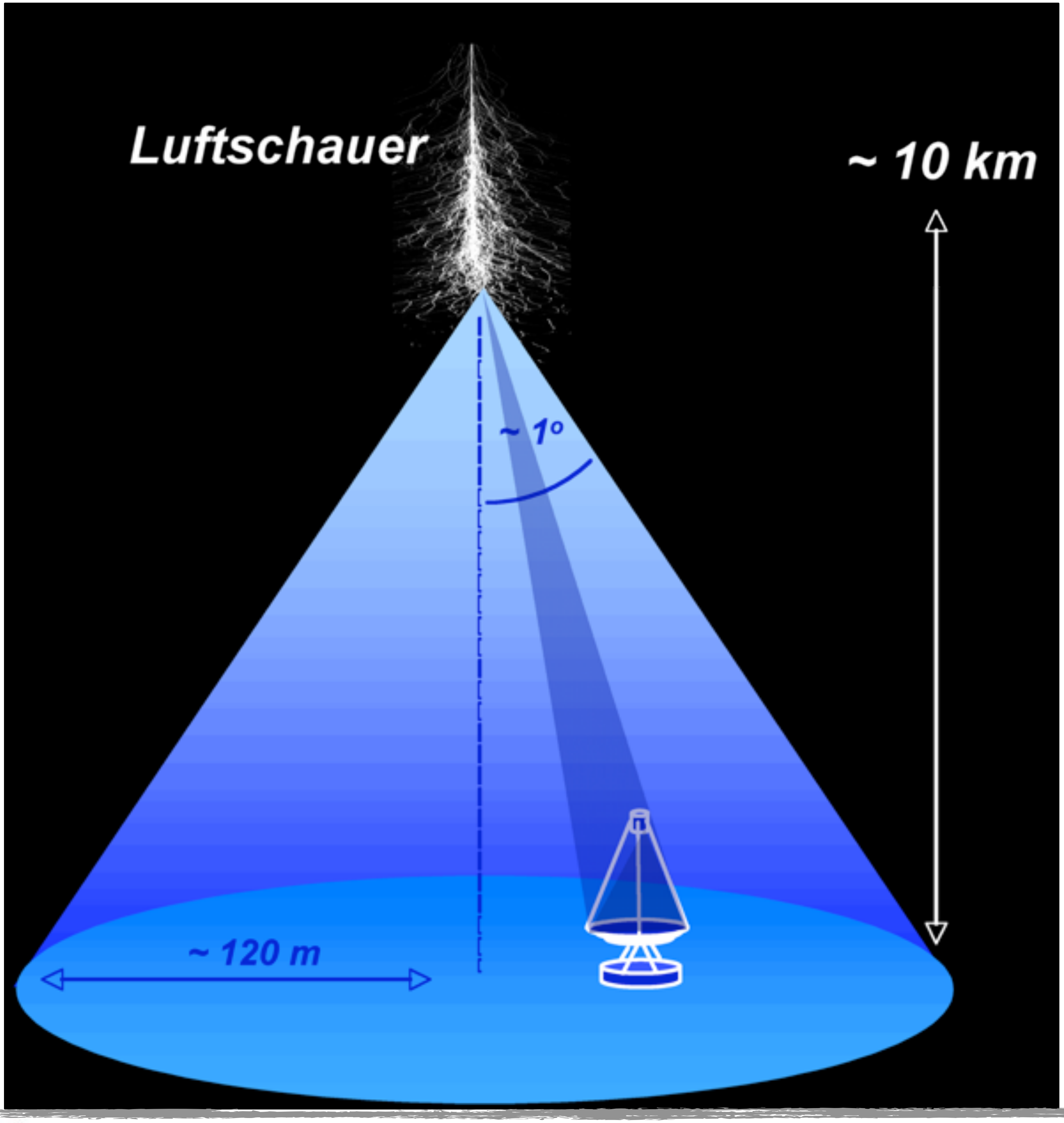
Photon and Hadron - induced Air Showers





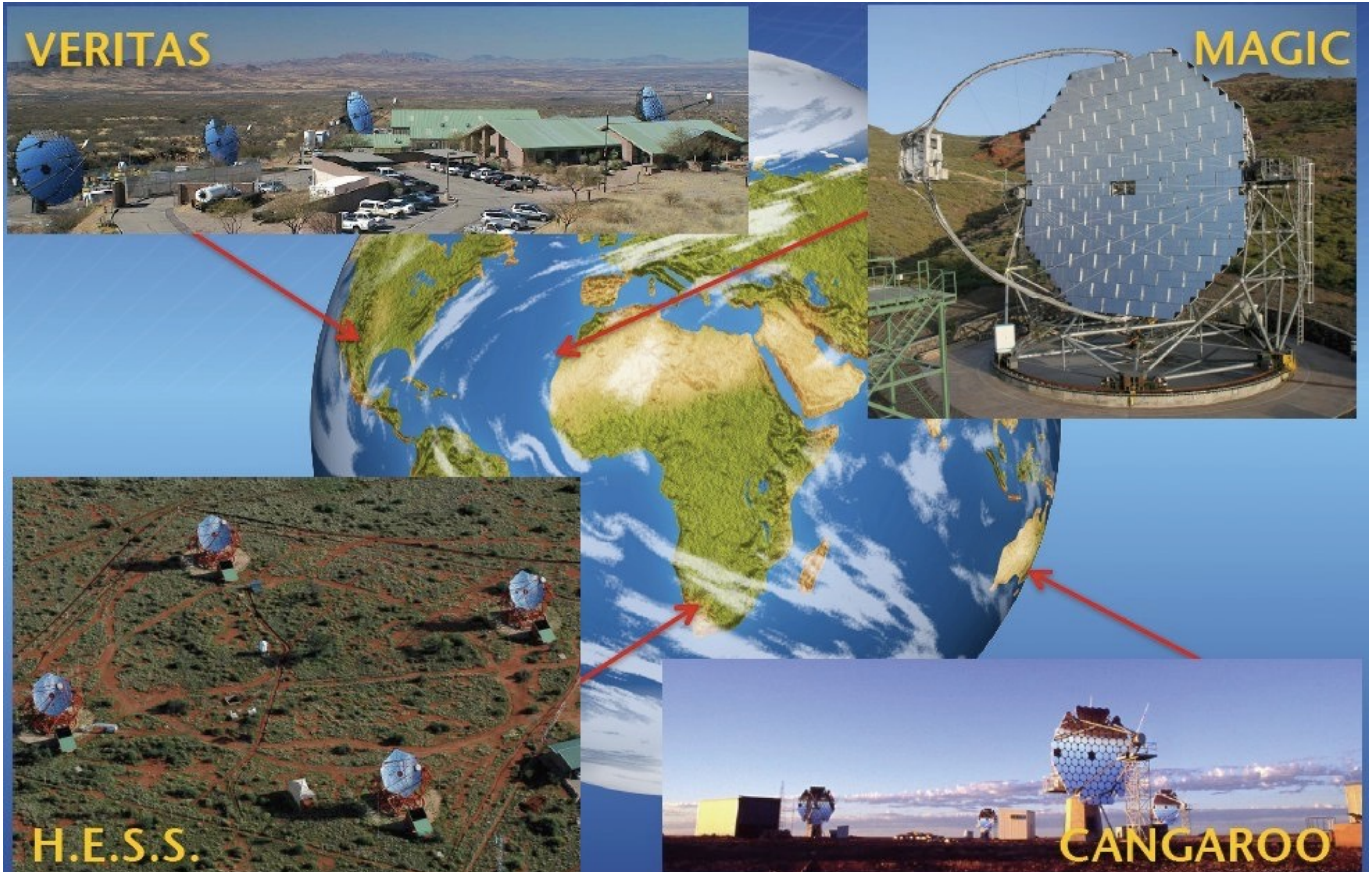
- Separation based on shower shape:
    - hadron showers are substantially more spread out and more “uneven”

Airshower Cherenkov Telescopes

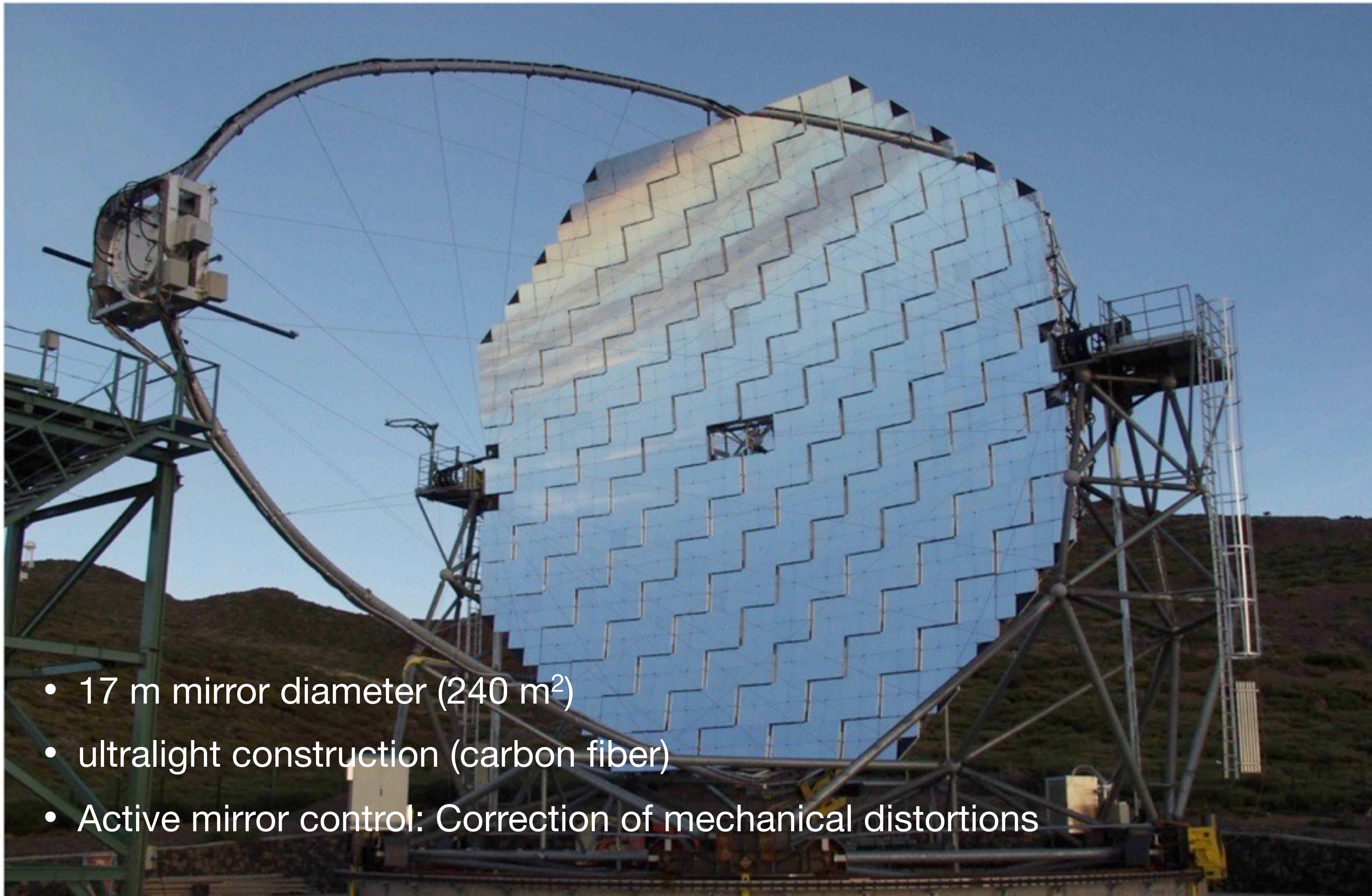


- Cherenkov light is created by electrons in showers in an altitude of ~ 10 km
  - The photons are spread over an area with a radius of~120 m on ground level
  - Detection with a telescope is possible within this area.

Large IACTs

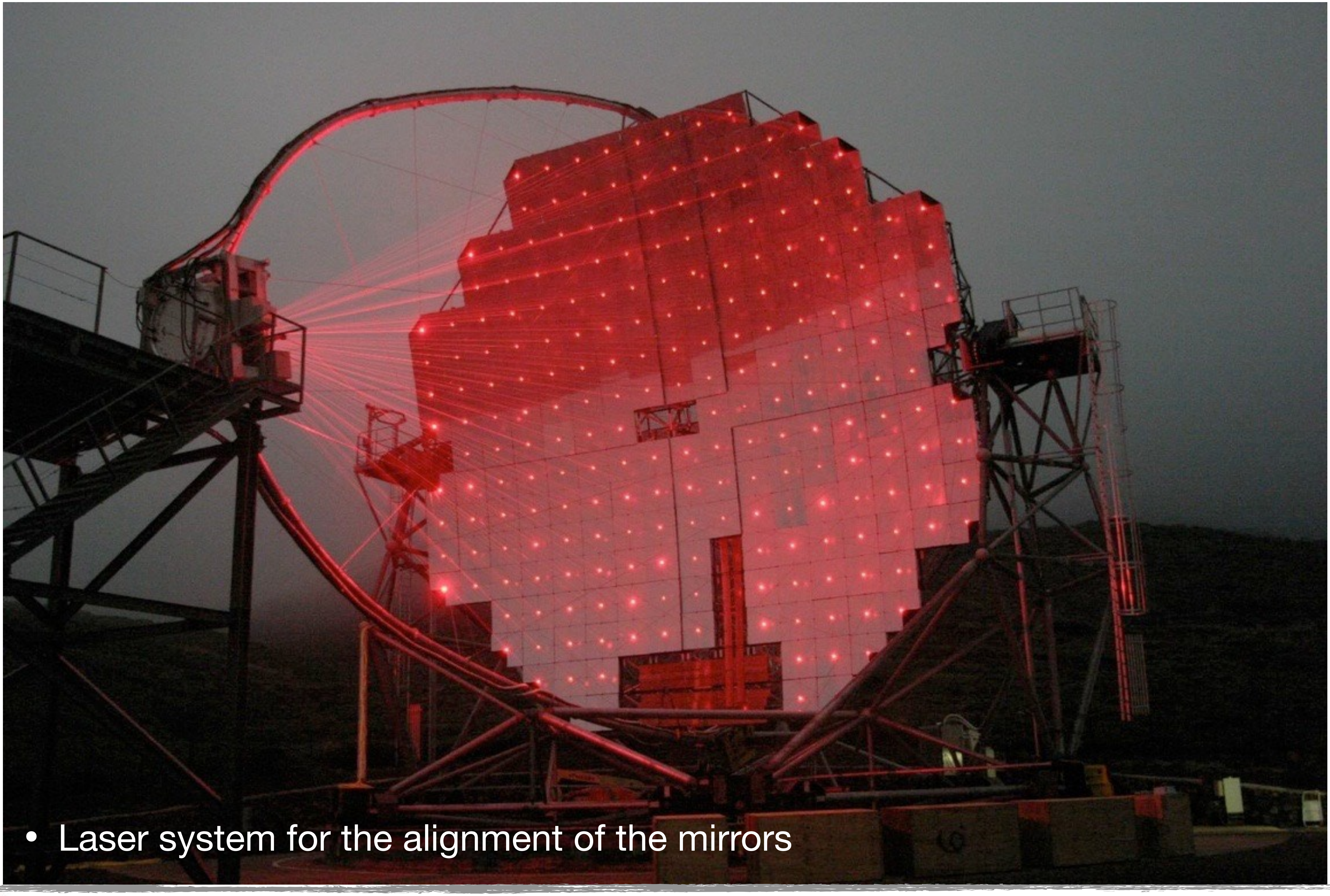


MAGIC: A large Cherenkov Telescope



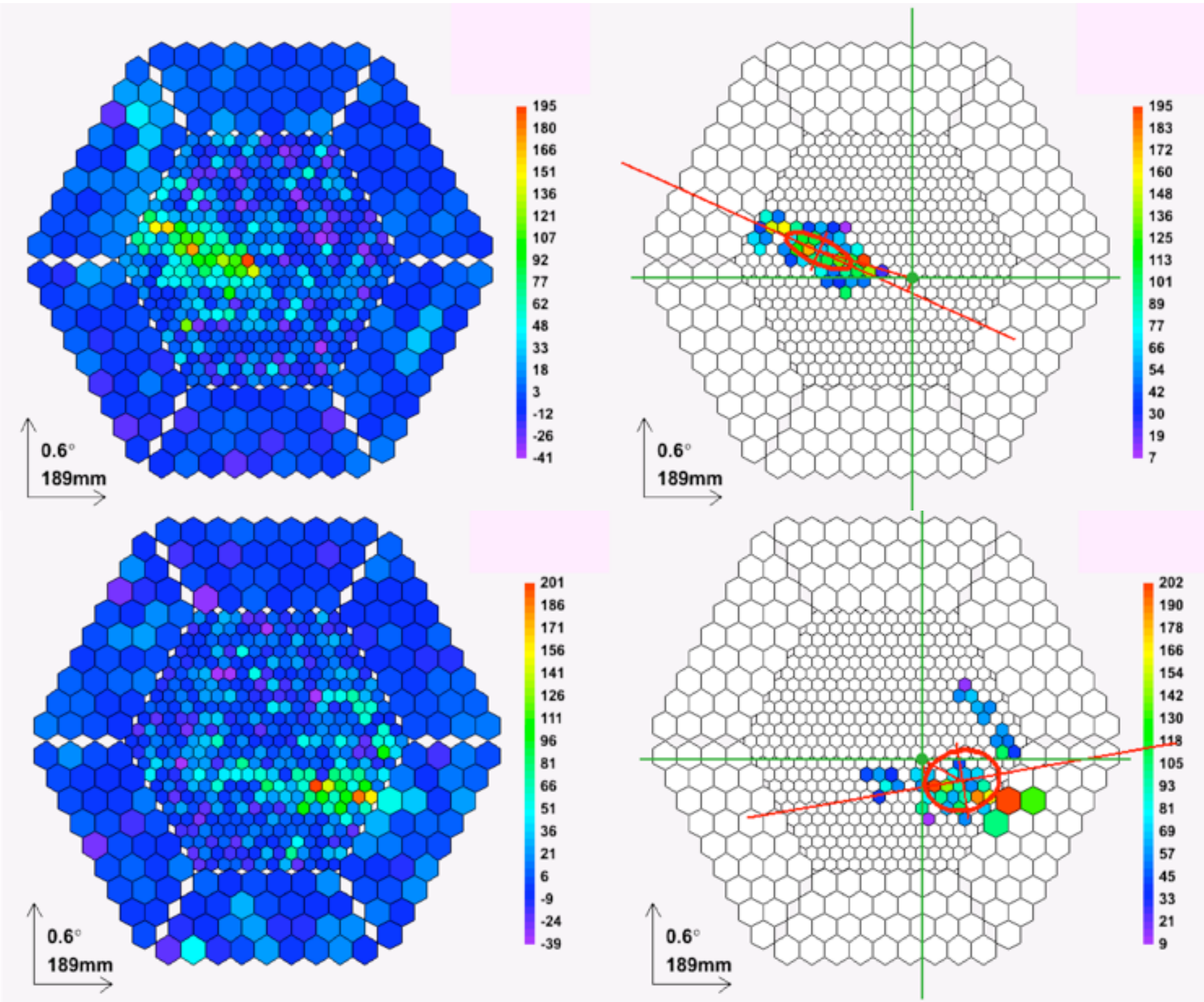
- 17 m mirror diameter (240 m^2)
- ultralight construction (carbon fiber)
- Active mirror control: Correction of mechanical distortions

MAGIC



• Laser system for the alignment of the mirrors

MAGIC: Separation of Photons and Hadrons

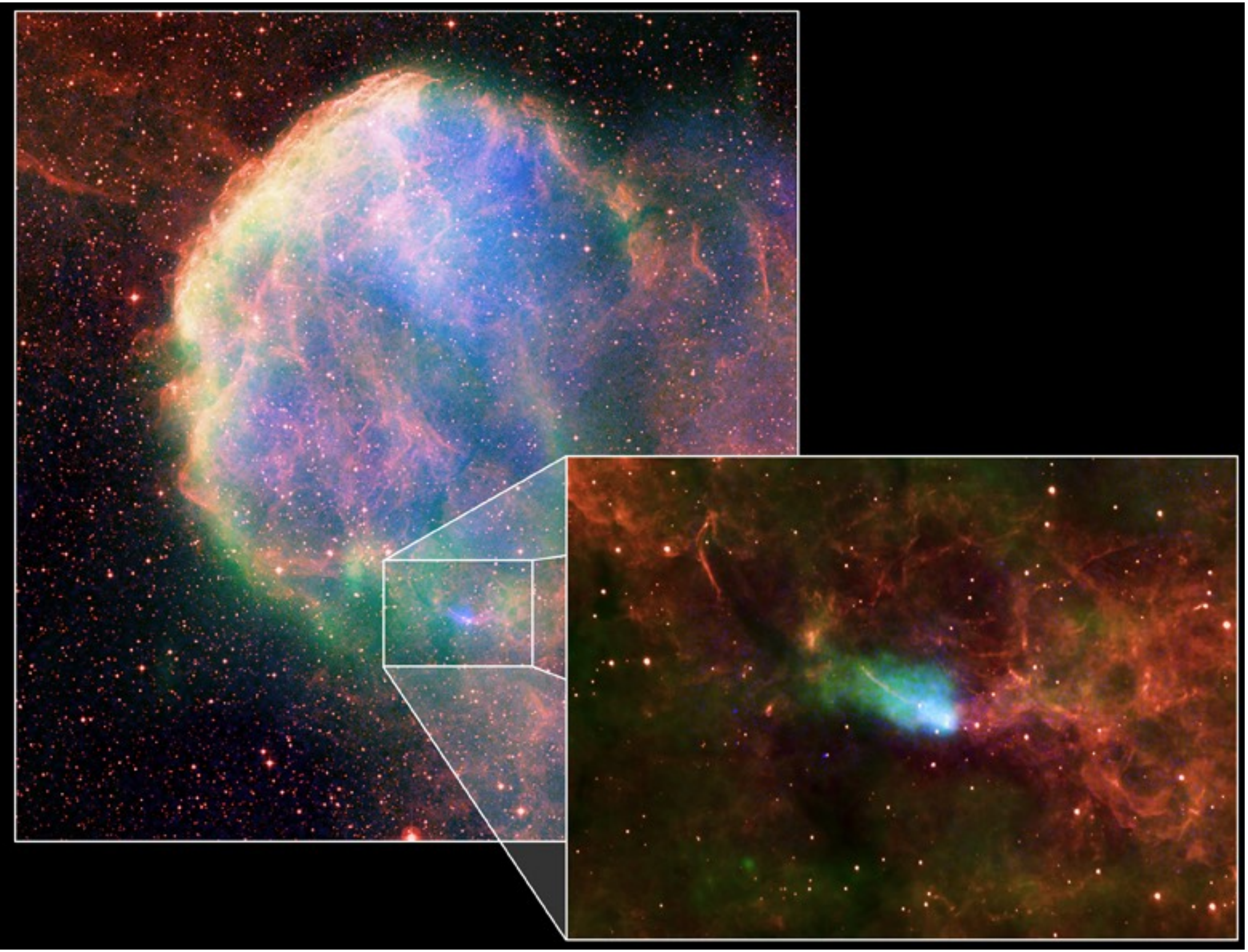


Photon (signal)

- Suppression of hadron background better than 10^{-4}

Hadron (background)

SNR IC 443



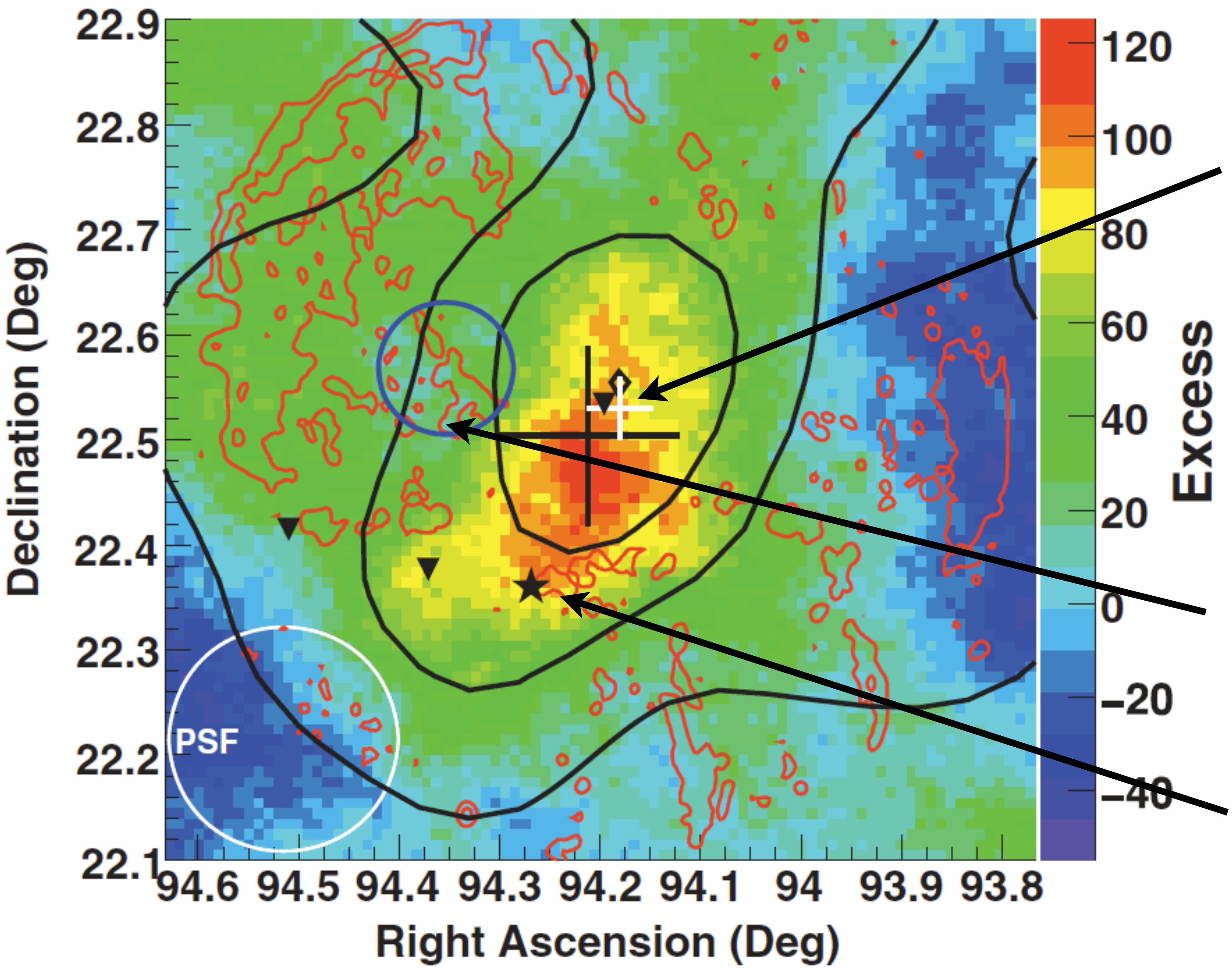
blue: x-ray
green: radio
red: optical

Neutron star

Supernova remnant, 3000 to 30 000 years old, distance 1.5 kpc

Credit: Chandra X-ray: NASA/CXC/B.Gaensler et al; ROSAT X-ray: NASA/ROSAT/Asaoka & Aschenbach; Radio Wide: NRC/DRAO/D.Leahy; Radio Detail: NRAO/VLA; Optical: DSS

SNR IC 443 seen in Gamma Rays



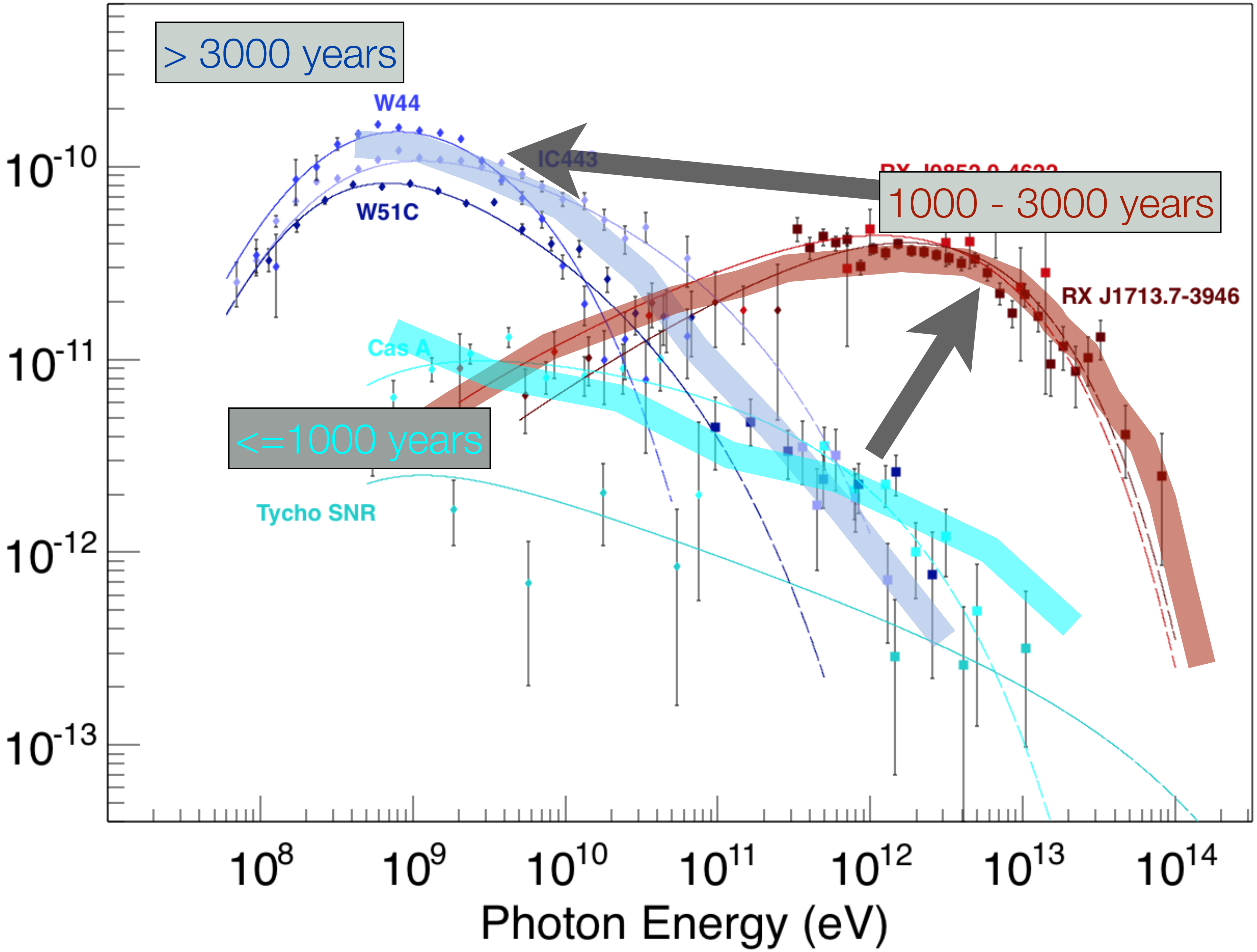
Source of TeV Gammas: MAGIC and VERITAS
Highly energetic electrons or hadrons, captured in an interstellar cloud?

>100 MeV Gammas, Fermi LAT

Position of the neutron star

Supernova Acceleration: Age & Energy

- Age dependence of cosmic accelerators



~ 1000 years needed to reach peak energy (see lecture 3)

Weakening of shock wave and magnetic fields with increasing age

Active Galactic Nuclei: AGNs

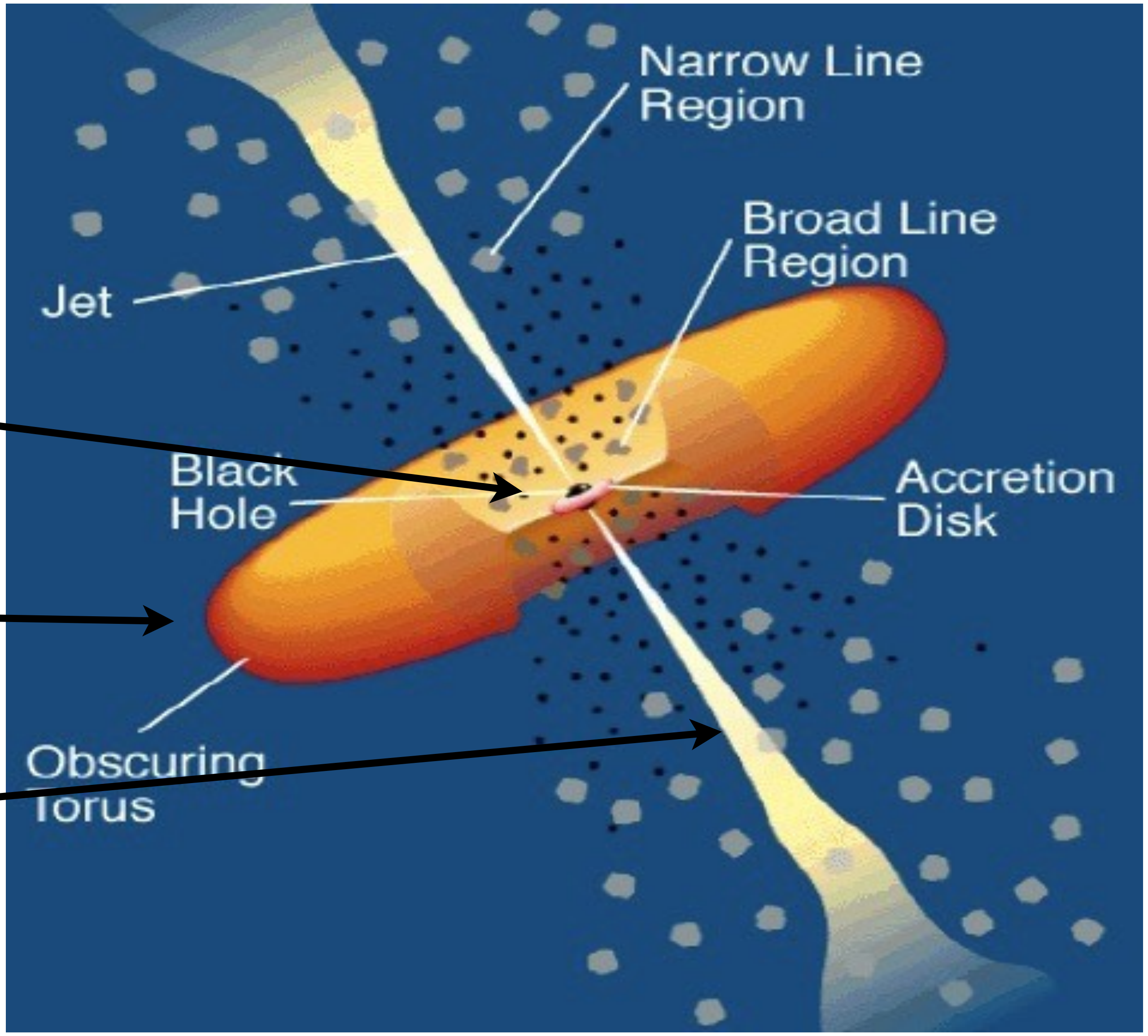
- Supermassive black holes (10^7 - 10^{10} solar masses) in the center of galaxies
- Accretion of matter
  - depending on configuration a jet can be formed
  - approx 5% of all galaxies are active

Electromagnetic radiation from AGNs:

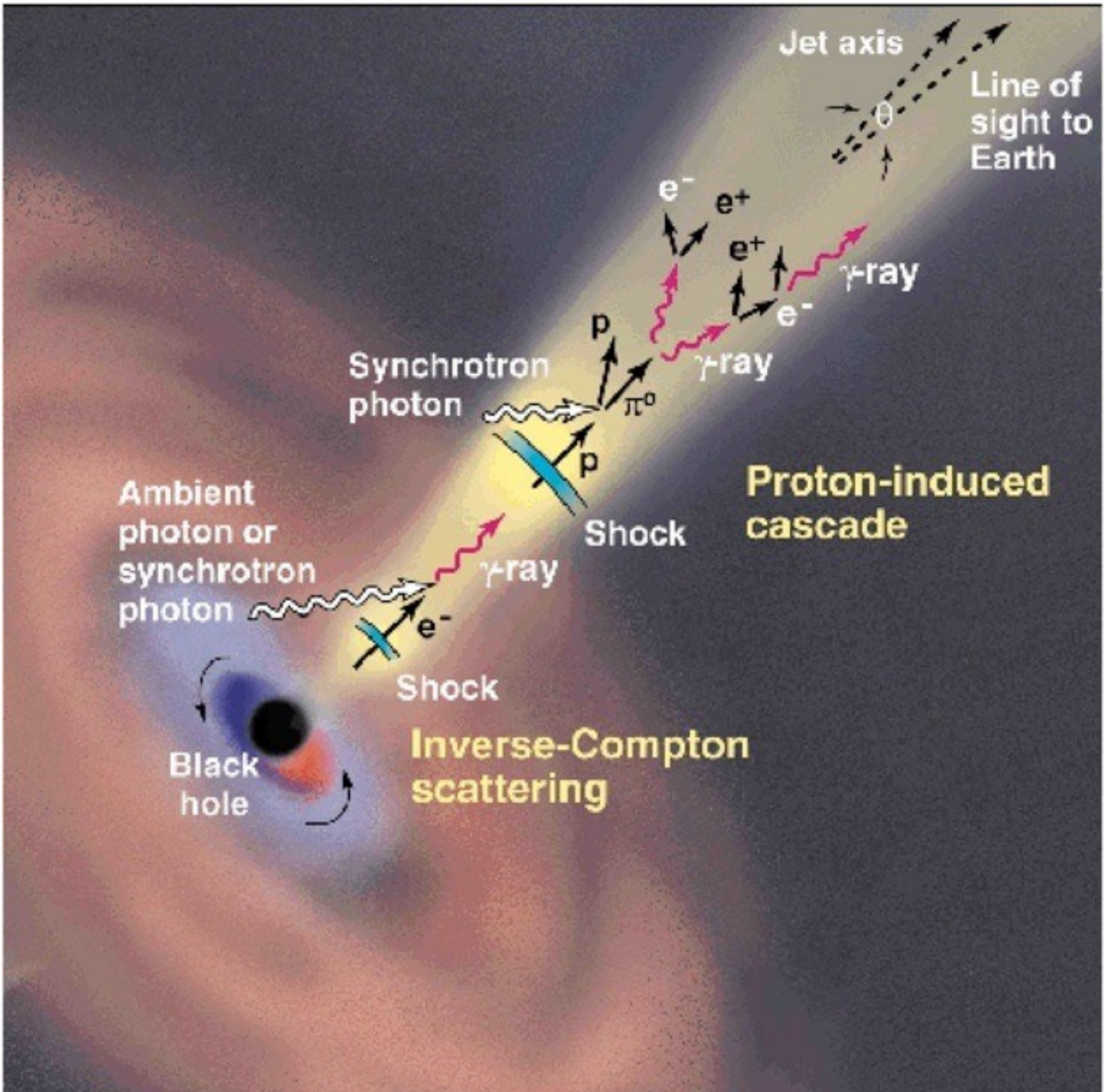
Infrared to X-Ray

Infrared

Radio, Gamma (non-thermal)

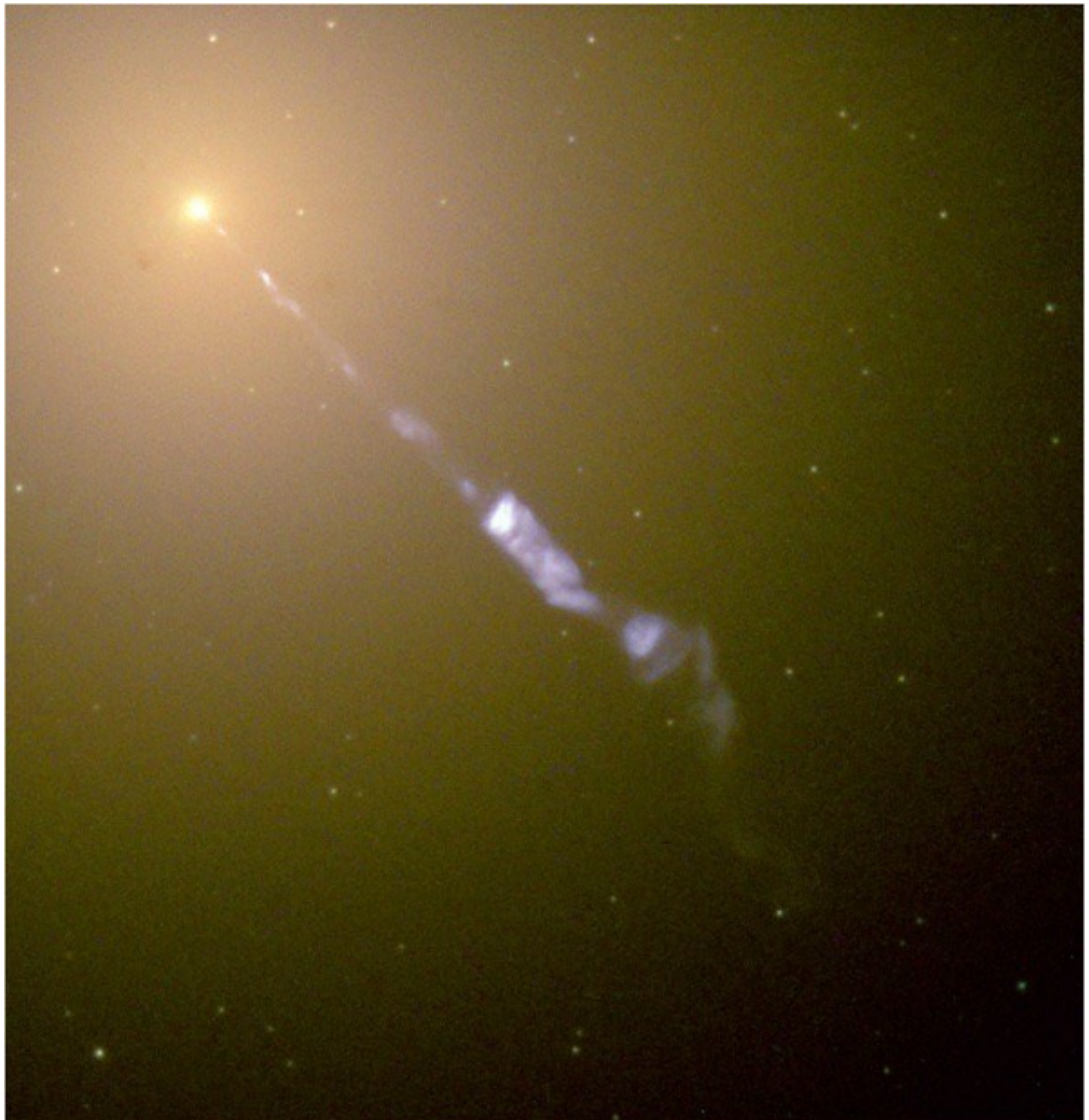


Formation of Gammas in Jets

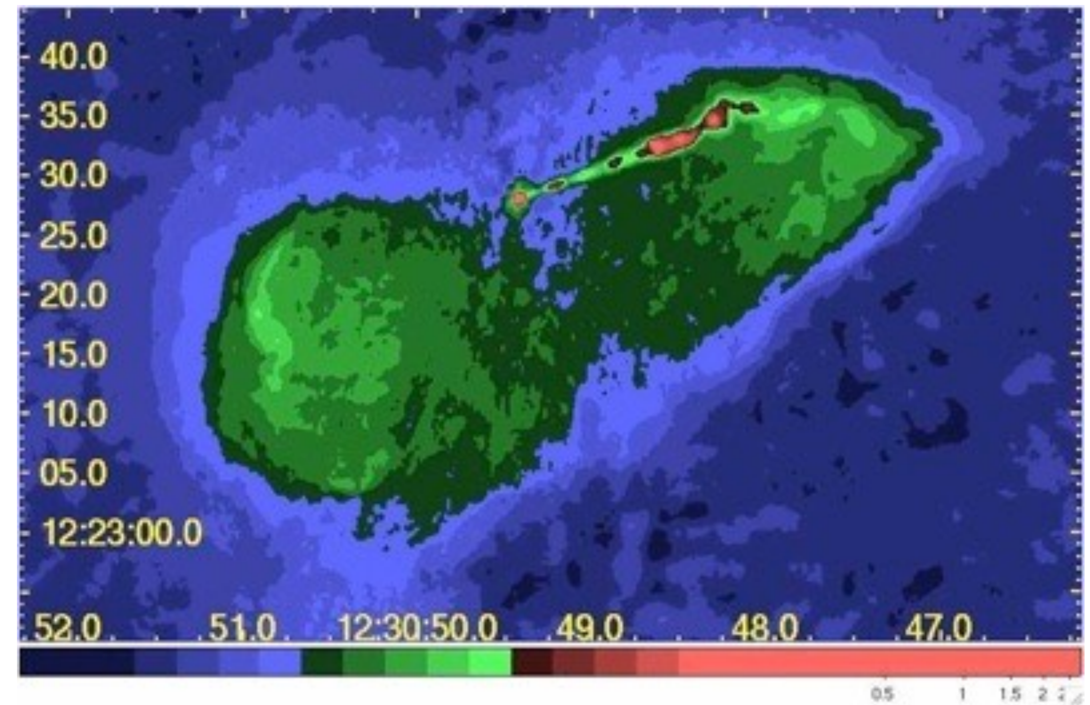


- Electrons and protons are accelerated in shock fronts
- Synchrotron radiation in magnetic fields
- Inverse Compton processes
- Proton induced cascades resulting in photons from neutral pion decay

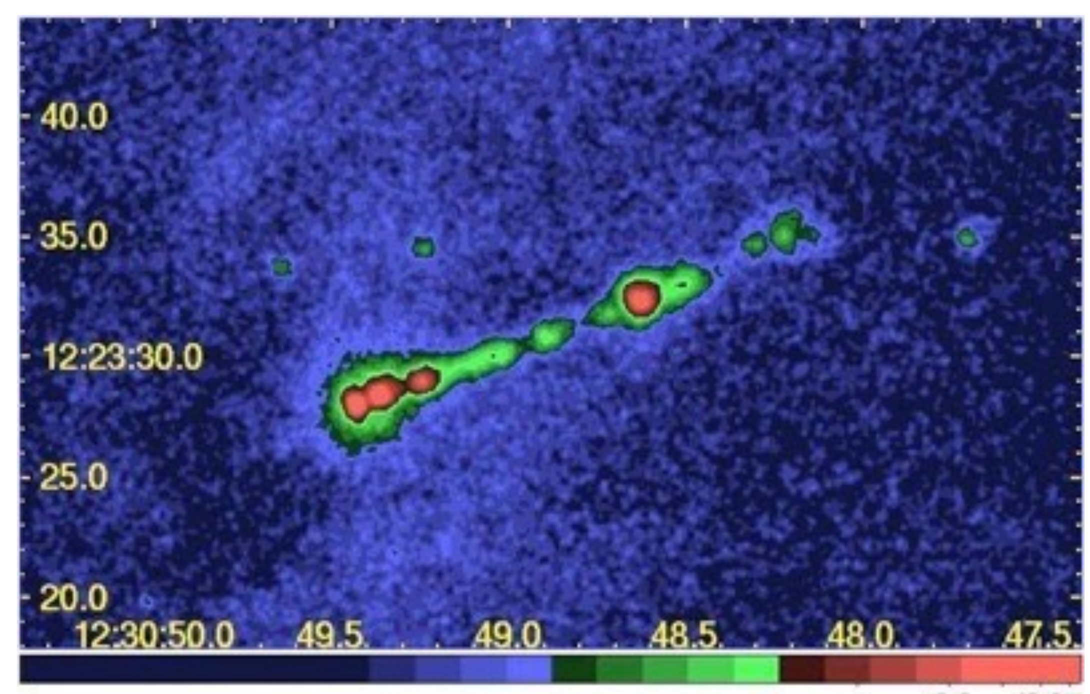
AGN M87



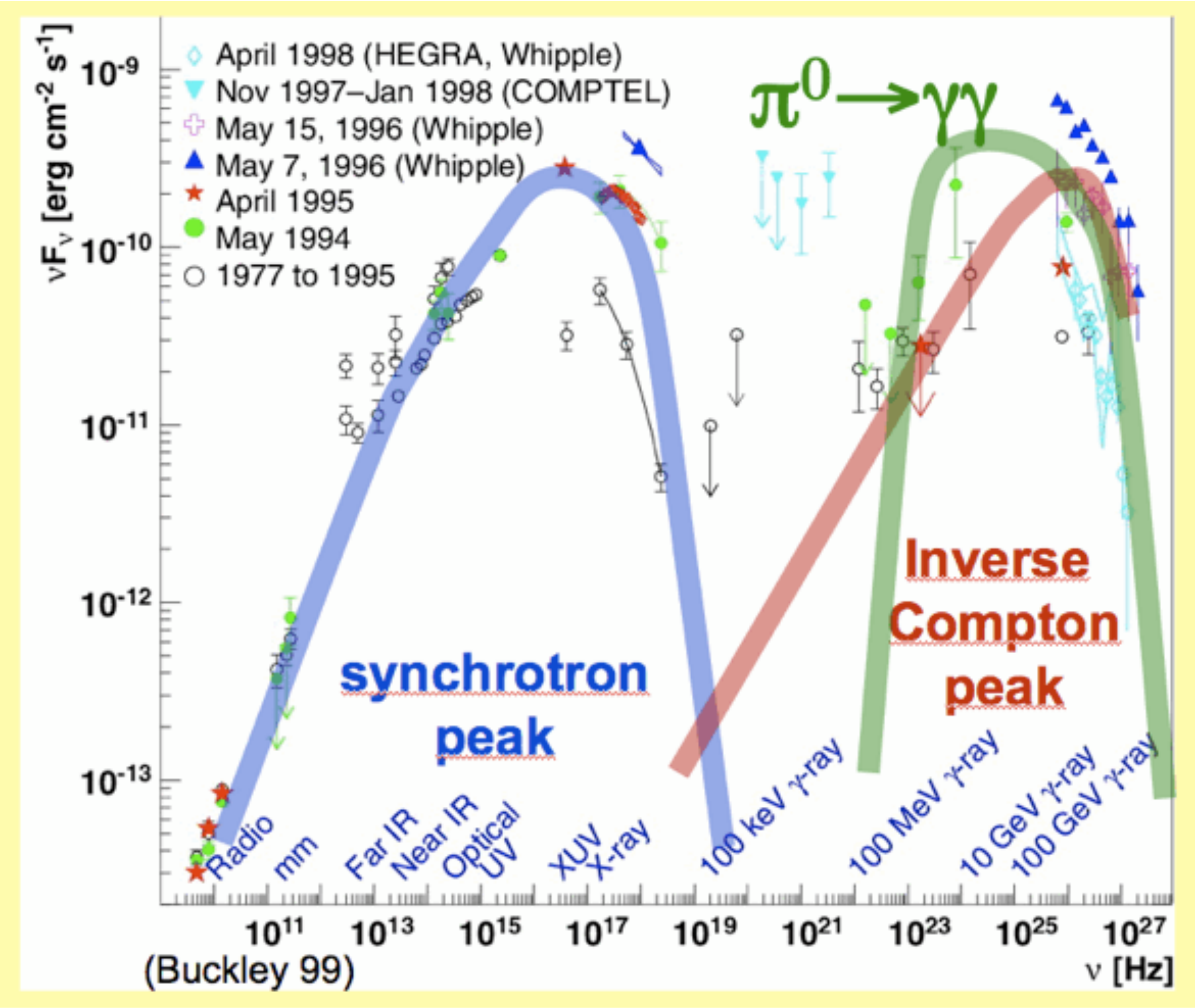
X-Ray:



Gamma:



AGNs: Photon Spectrum



- Typical “double hump” structure observed

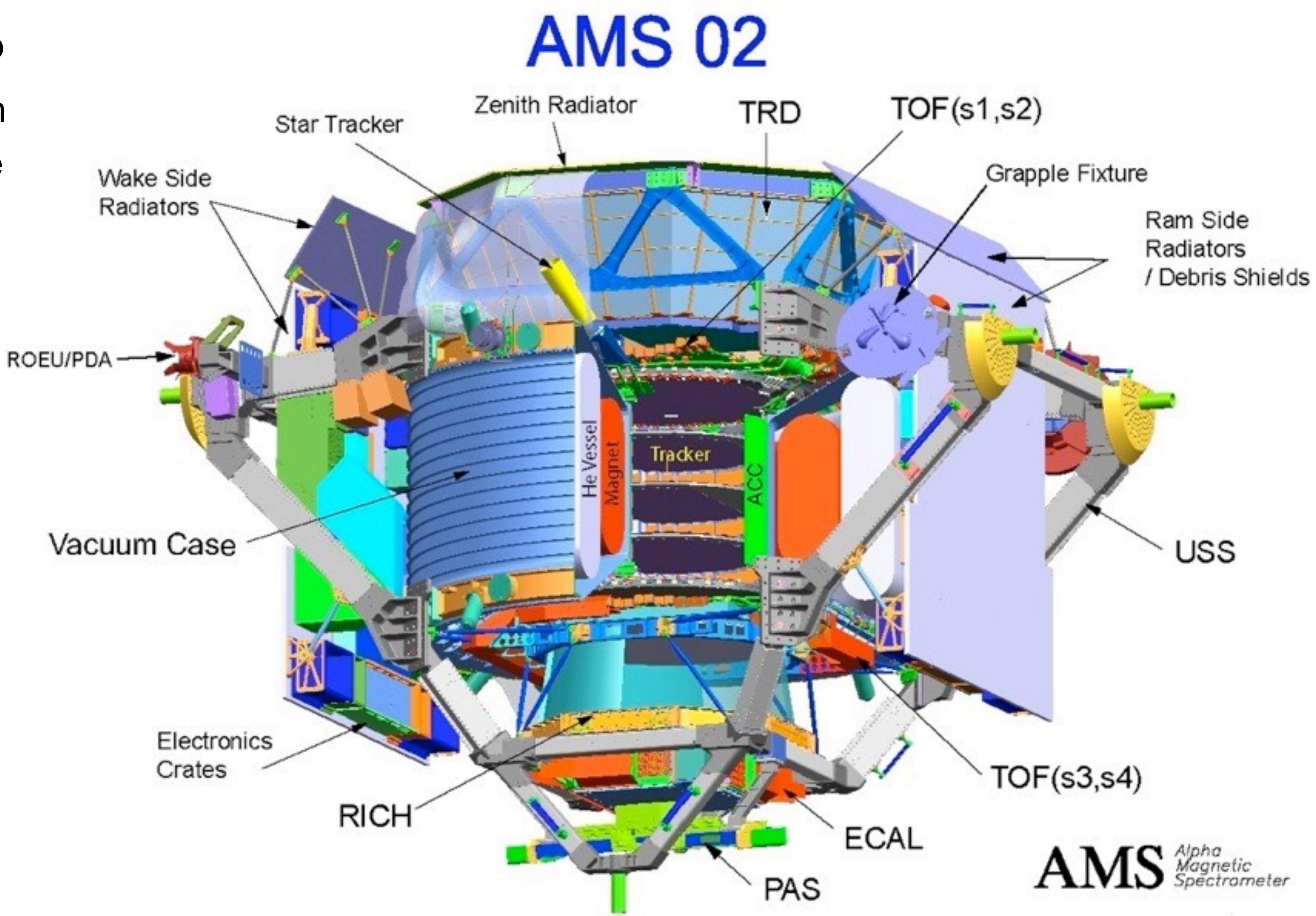
Low Energy Cosmic Rays

AMS

- A complete particle physics detector in space
  - The goal: Search for antimatter in cosmic rays, detailed study of the composition, search for new phenomena

AMS

- A co
  - Th
    se

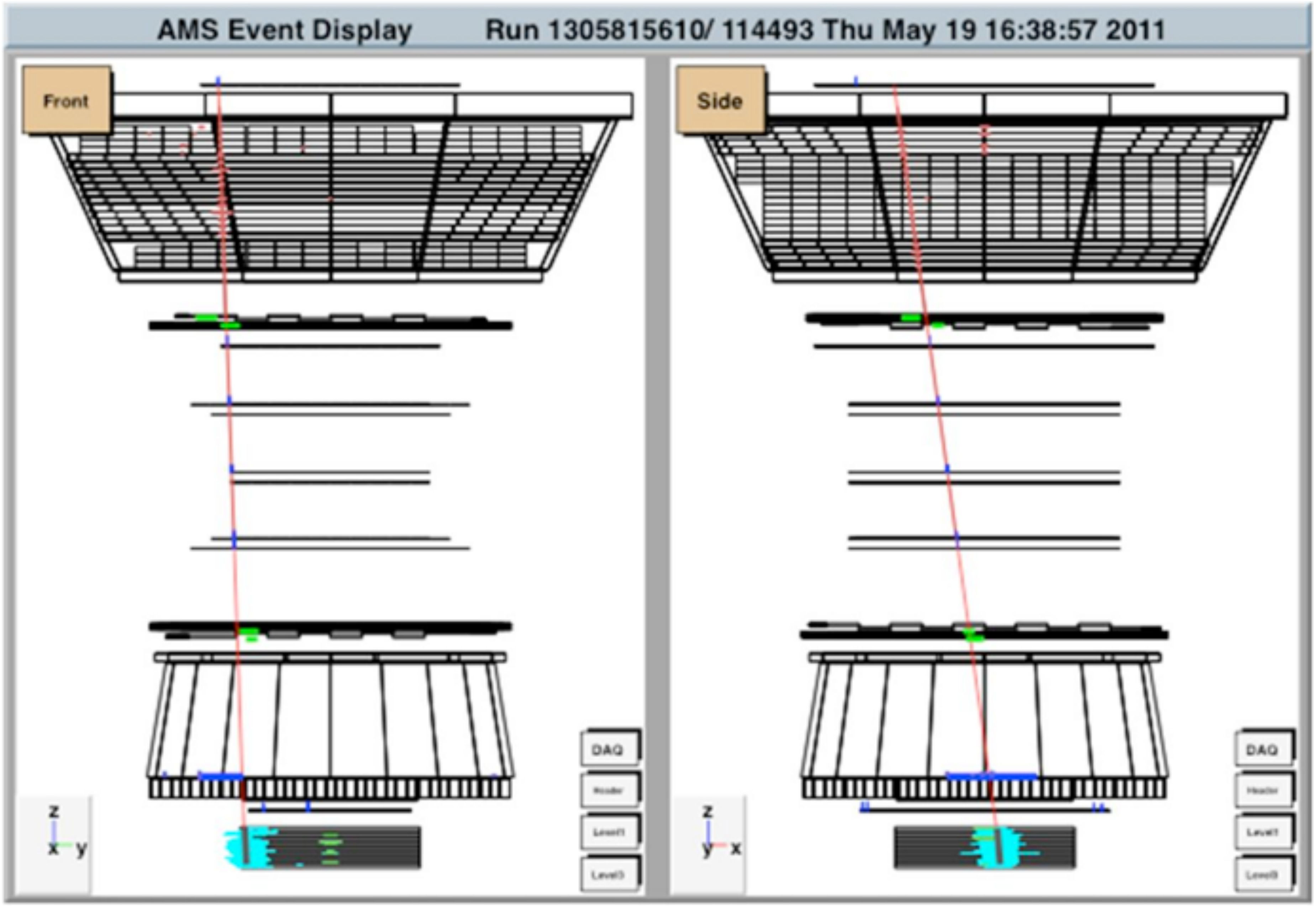


AMS 02
Zenith Radiator
TRD
TOF(s1,s2)
Star Tracker
Grapple Fixture
Wake Side Radiators
Ram Side Radiators / Debris Shields
ROEU/PDA
He Vessel
Magnet
Tracker
ACC
Vacuum Case
USS
Electronics Crates
TOF(s3,s4)
RICH
ECAL
PAS
AMS Alpha Magnetic Spectrometer

AMS - Since 4 years on the ISS

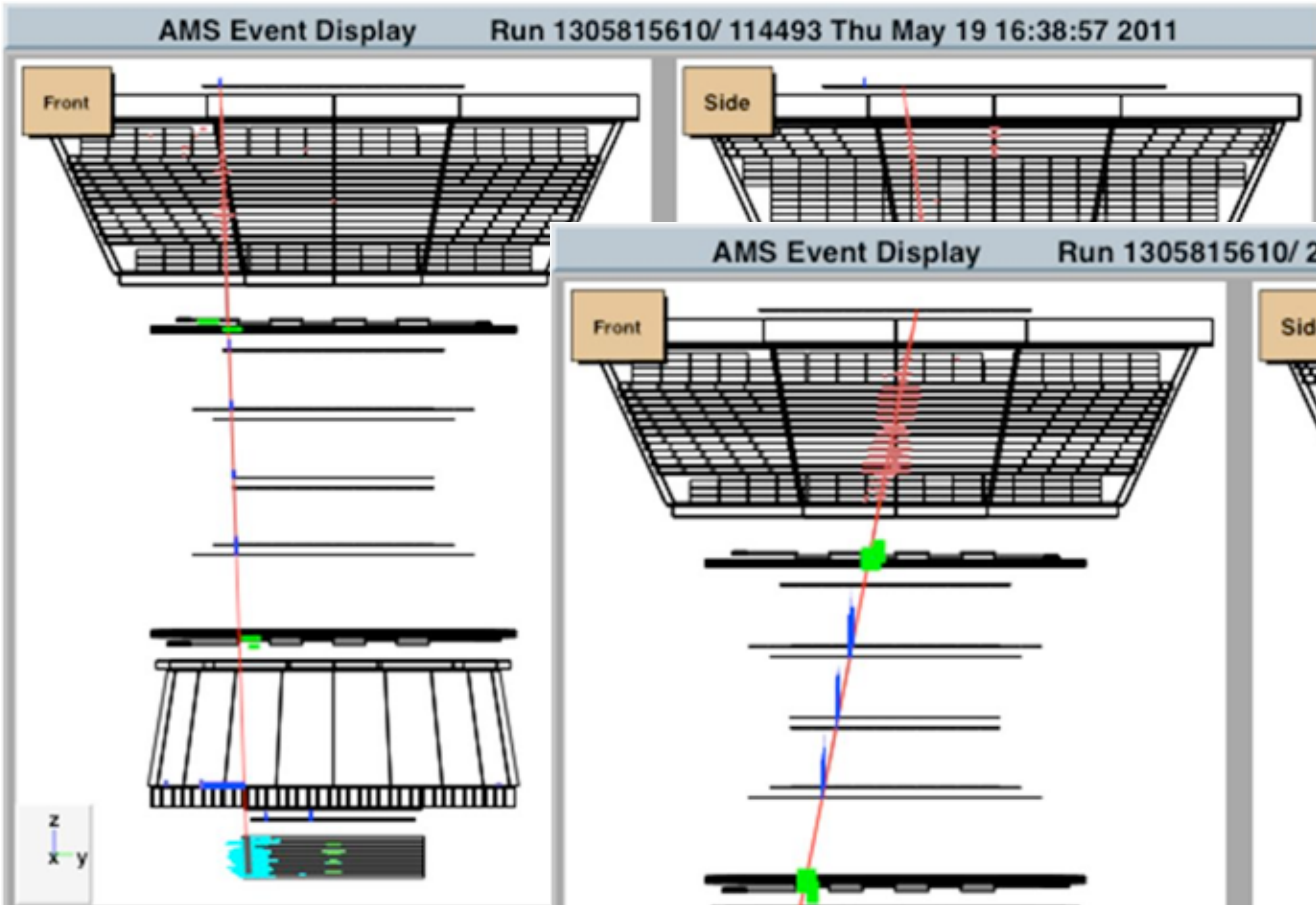
- Successful start on May 16 2011 - Data taking since then

AMS - Illustration of Events

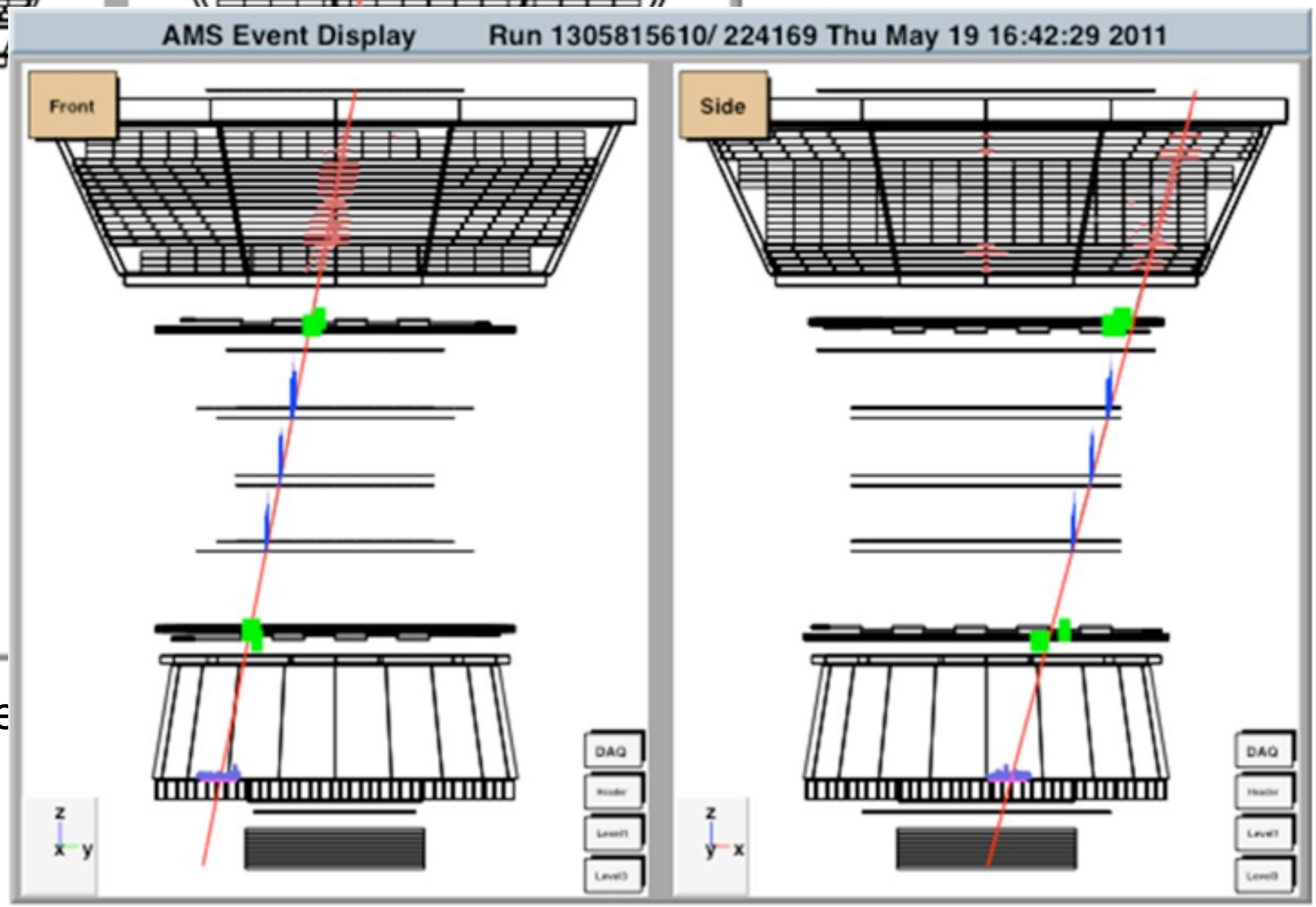


20 GeV electron

AMS - Illustration of Events



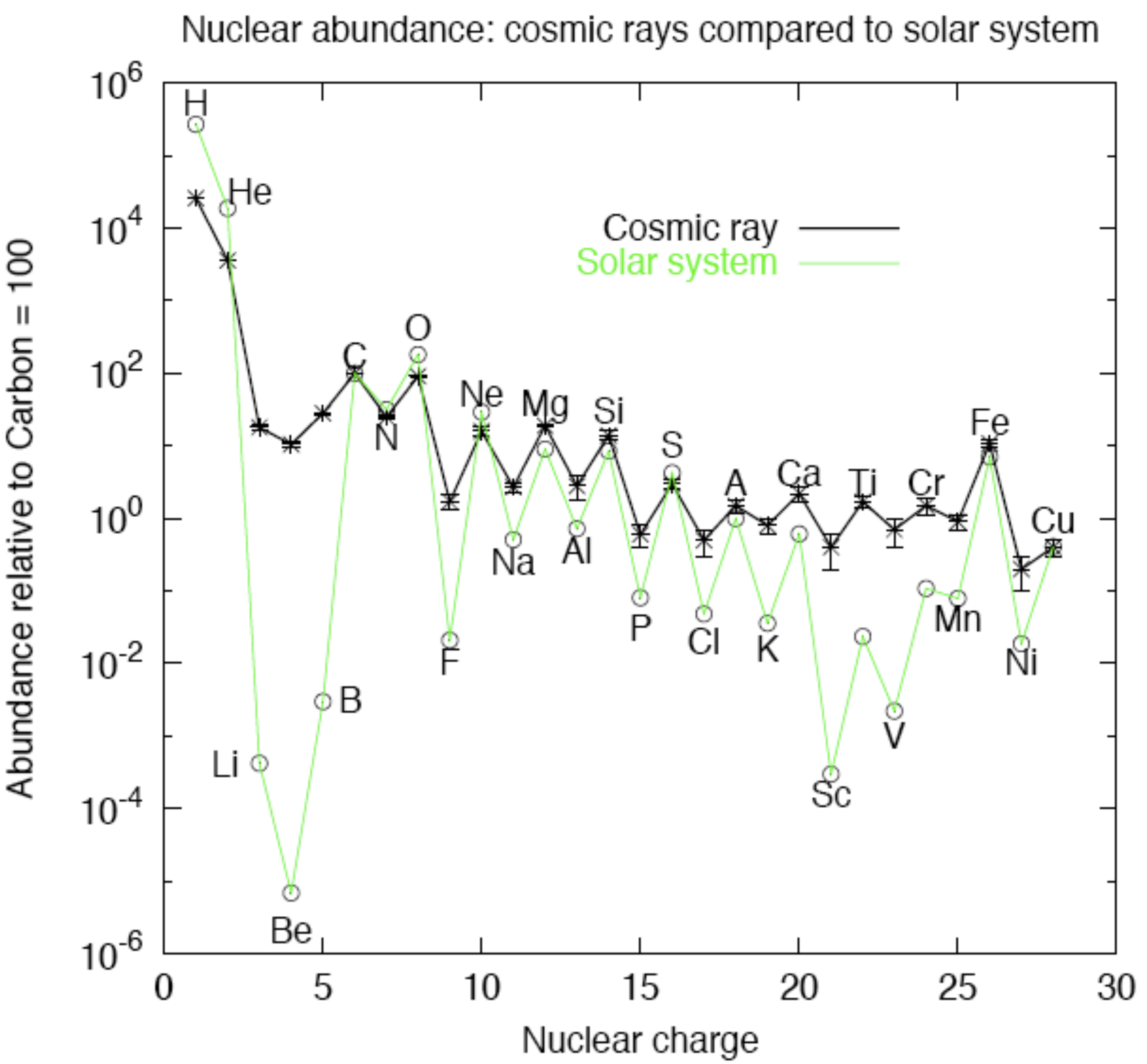
20 GeV e



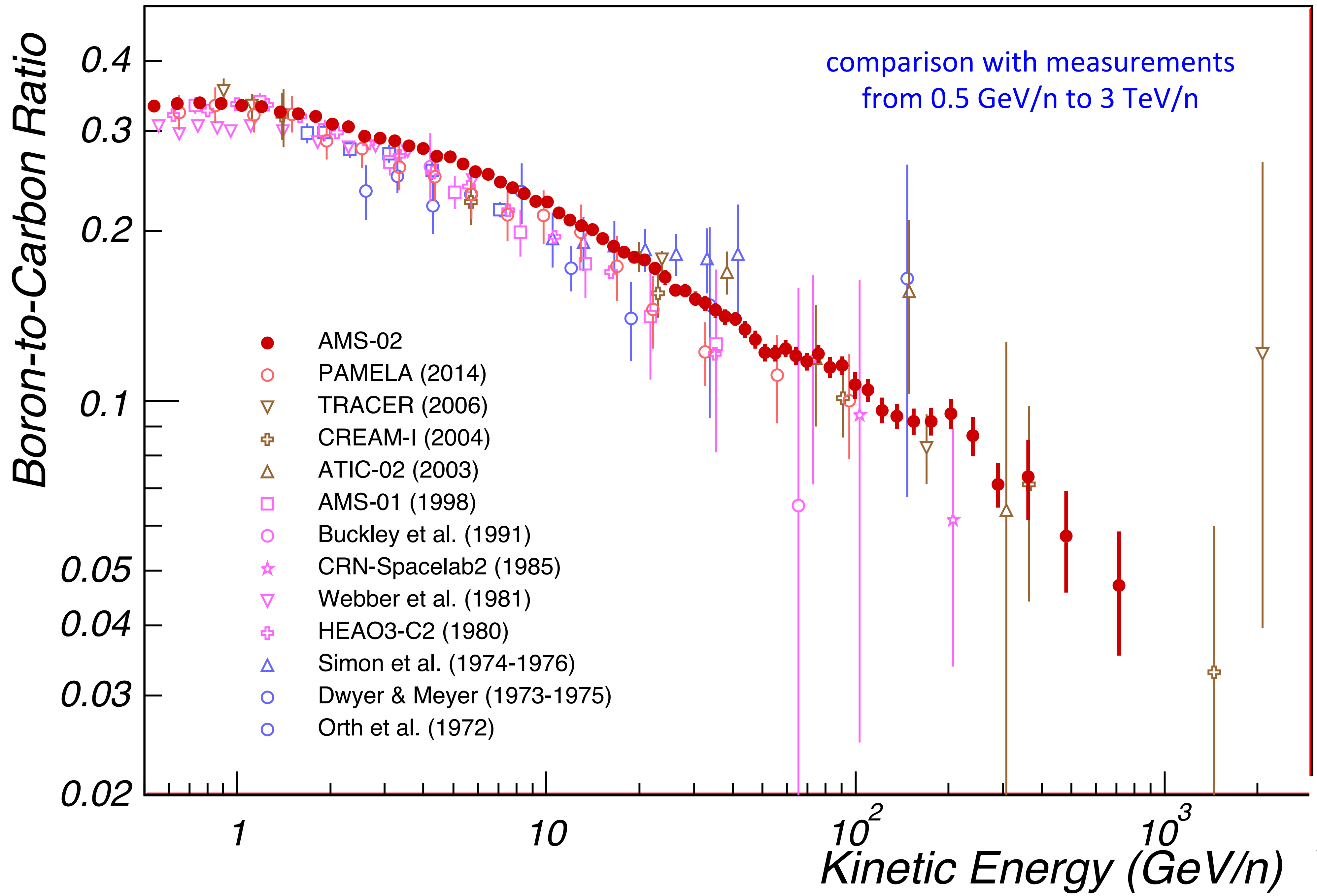
42 GeV carbon ion

Composition of Cosmic Rays

- Comparison to the isotope abundance in the solar system (known from absorption lines in the sun, meteorites)
- Agreement for medium-mass nuclei: Maxima for even Z, A: stable nuclei preferred in fusion reactions in stars
- Deviation for light nuclei: Acceleration less efficient for H, He
- Li, Be, B are “burned” in stars instantly
    - Elements heavier than Li do not occur primordially
    - these are created in cosmic rays via spallation



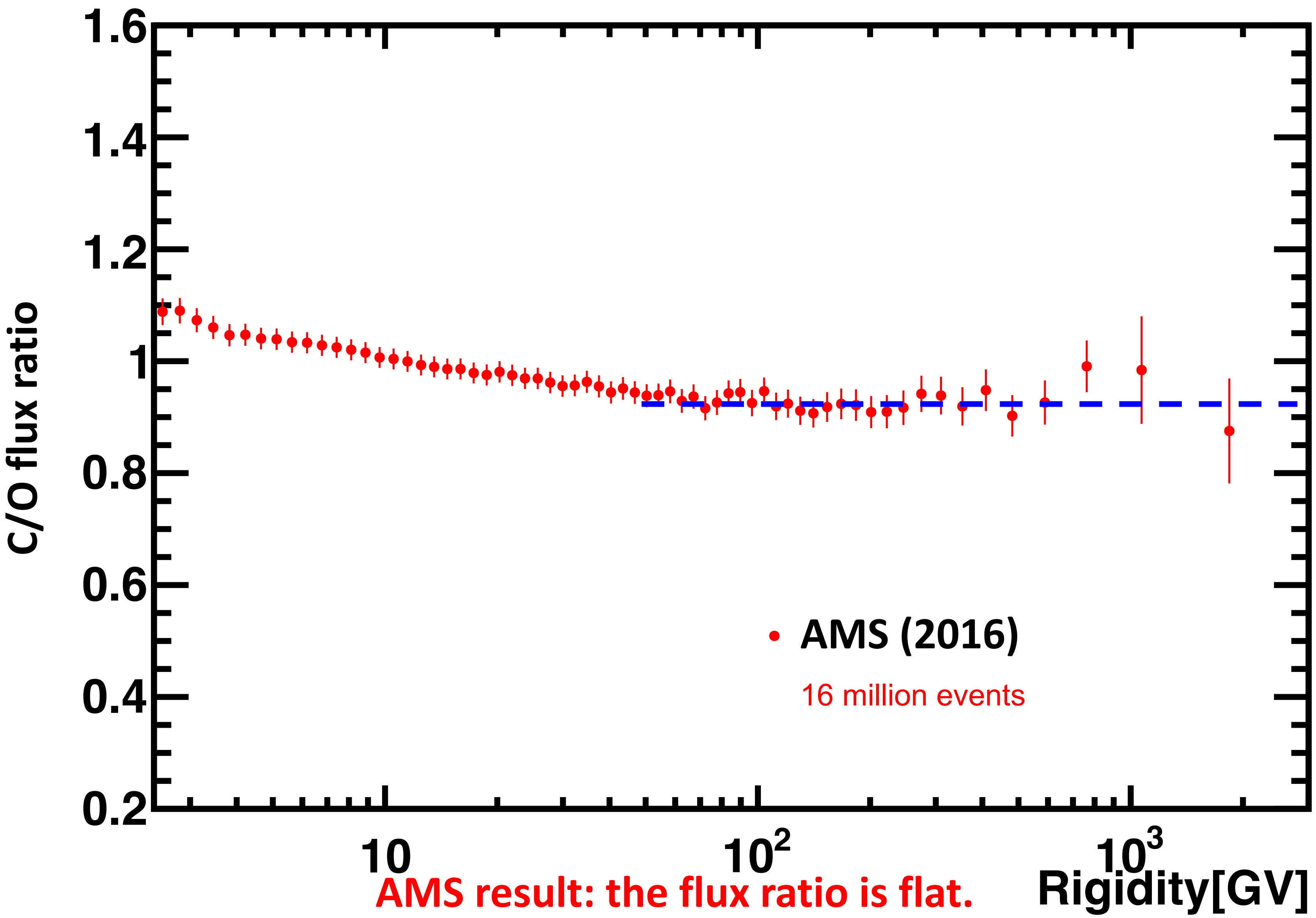
Energy Dependence of Composition



Boron does not occur in primary cosmic rays: production via spallation, Carbon is a primary component

➯ Boron observed predominantly at low energy!

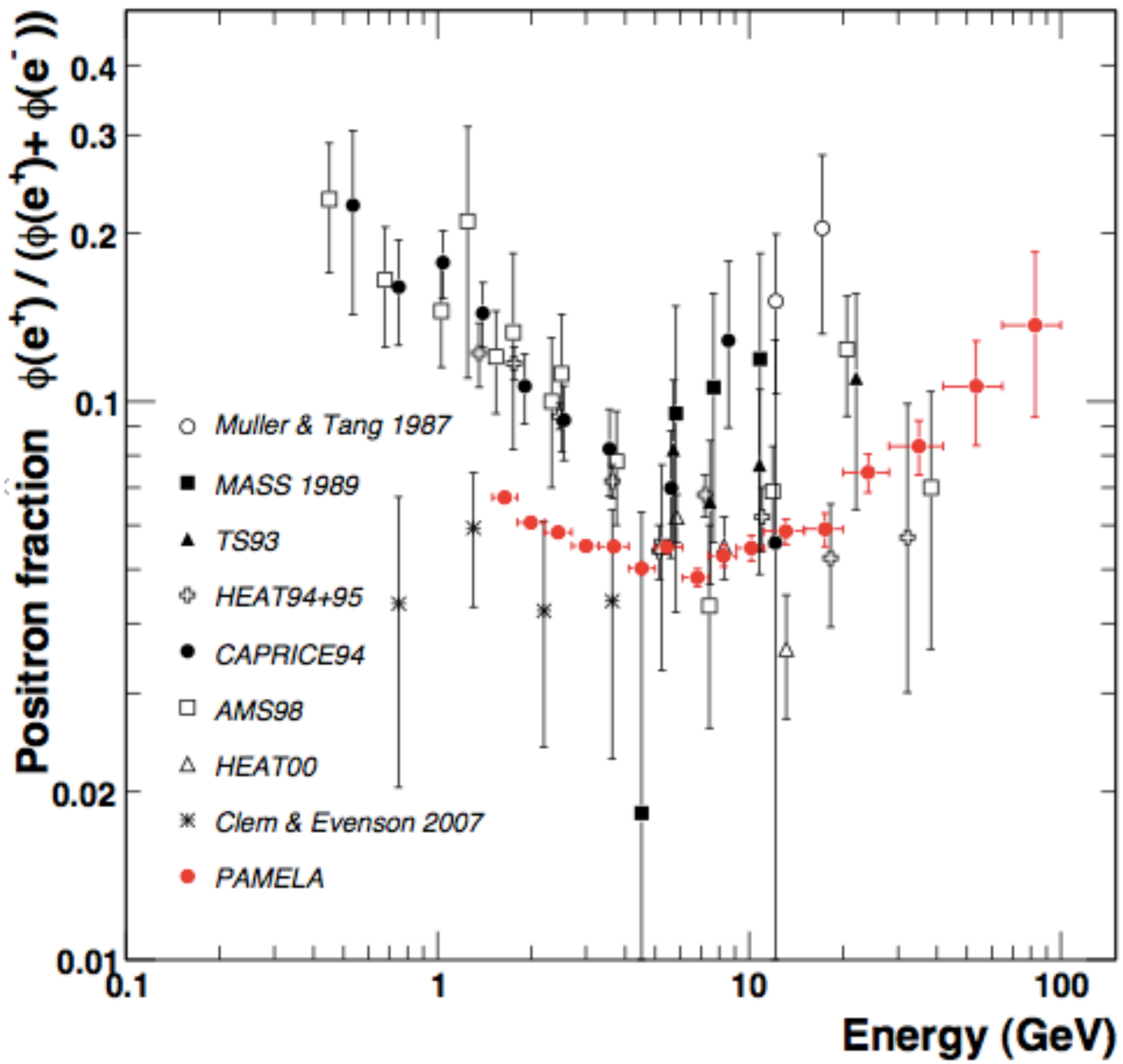
Energy Dependence of Composition

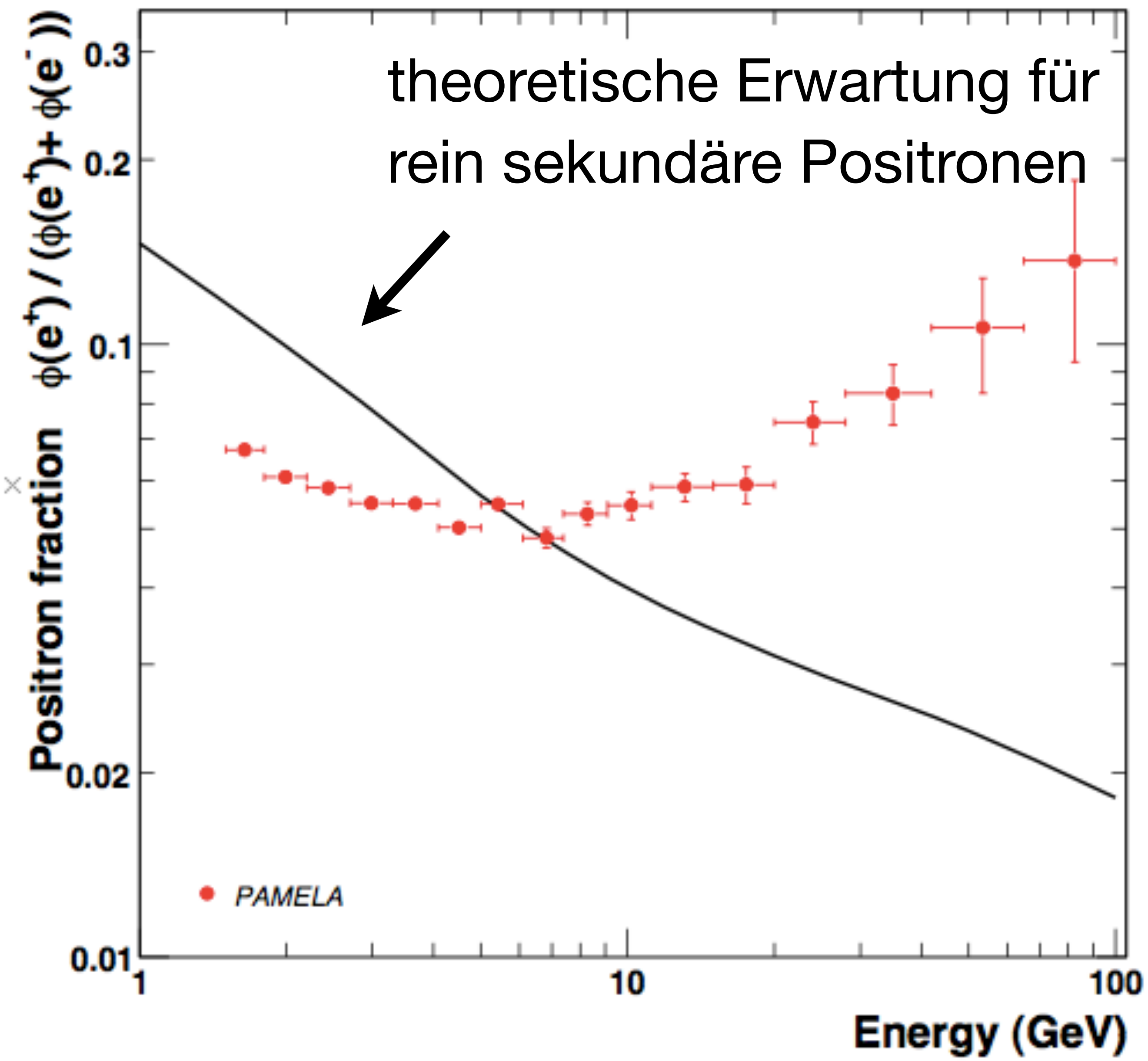


Both Oxygen and Carbon are primary particles in cosmic rays, both have Z/A = 0.5: identical energy spectrum!

Positrons in Cosmic Rays

- Interesting (and unexpected!) results by PAMELA (Nature, April 2009):





arXiv:0810.4995

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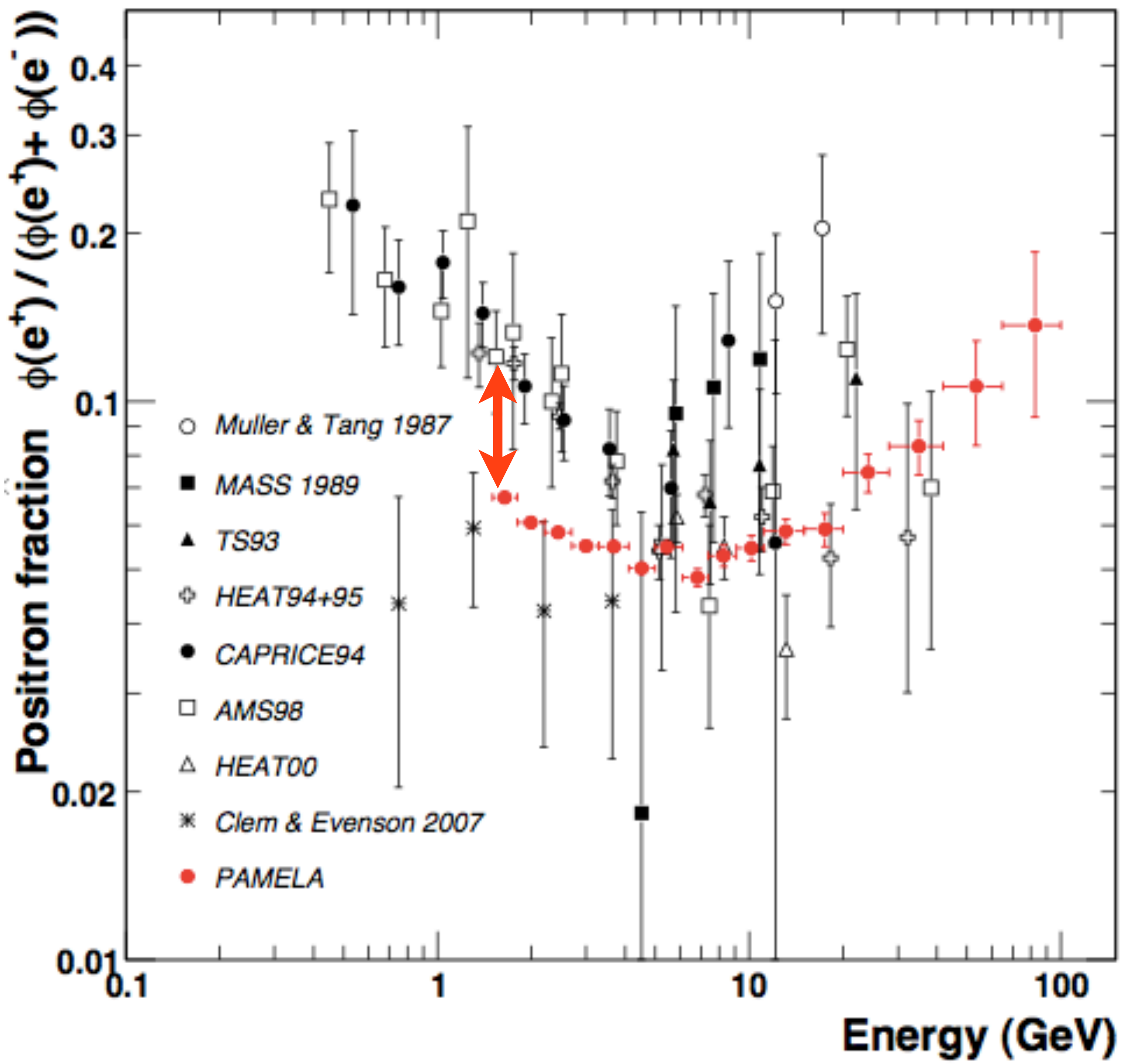
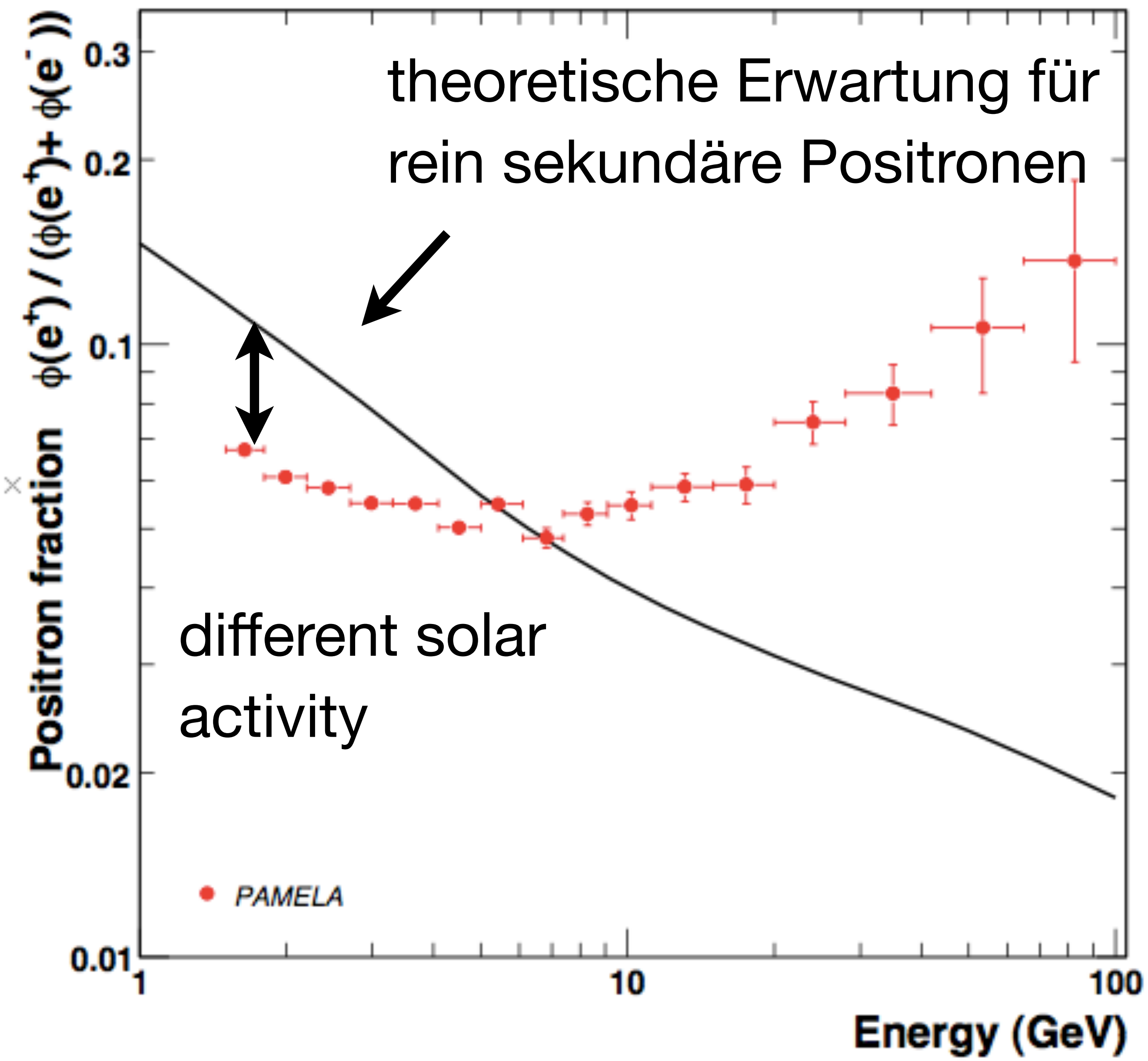
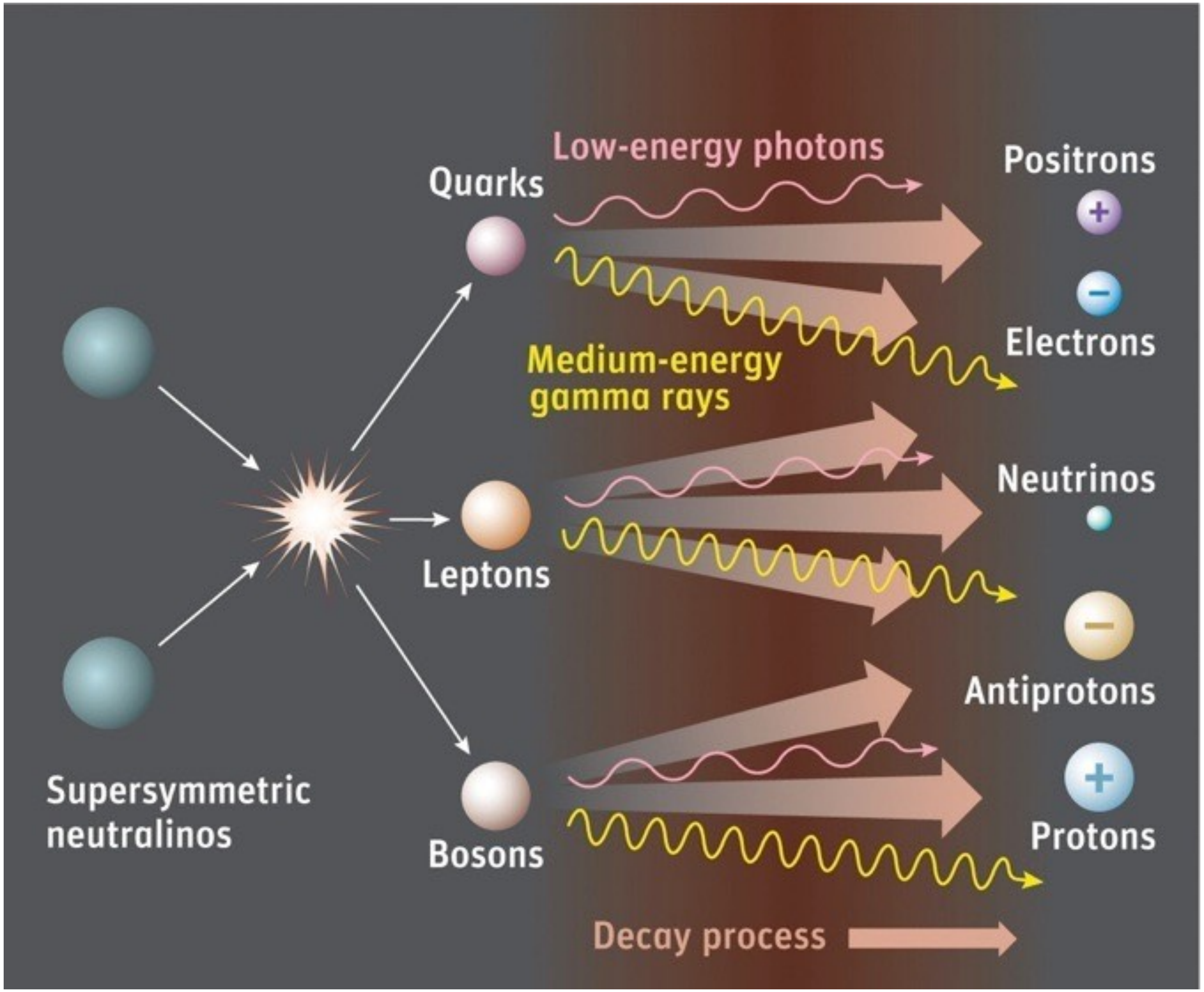




arXiv:0810.4995

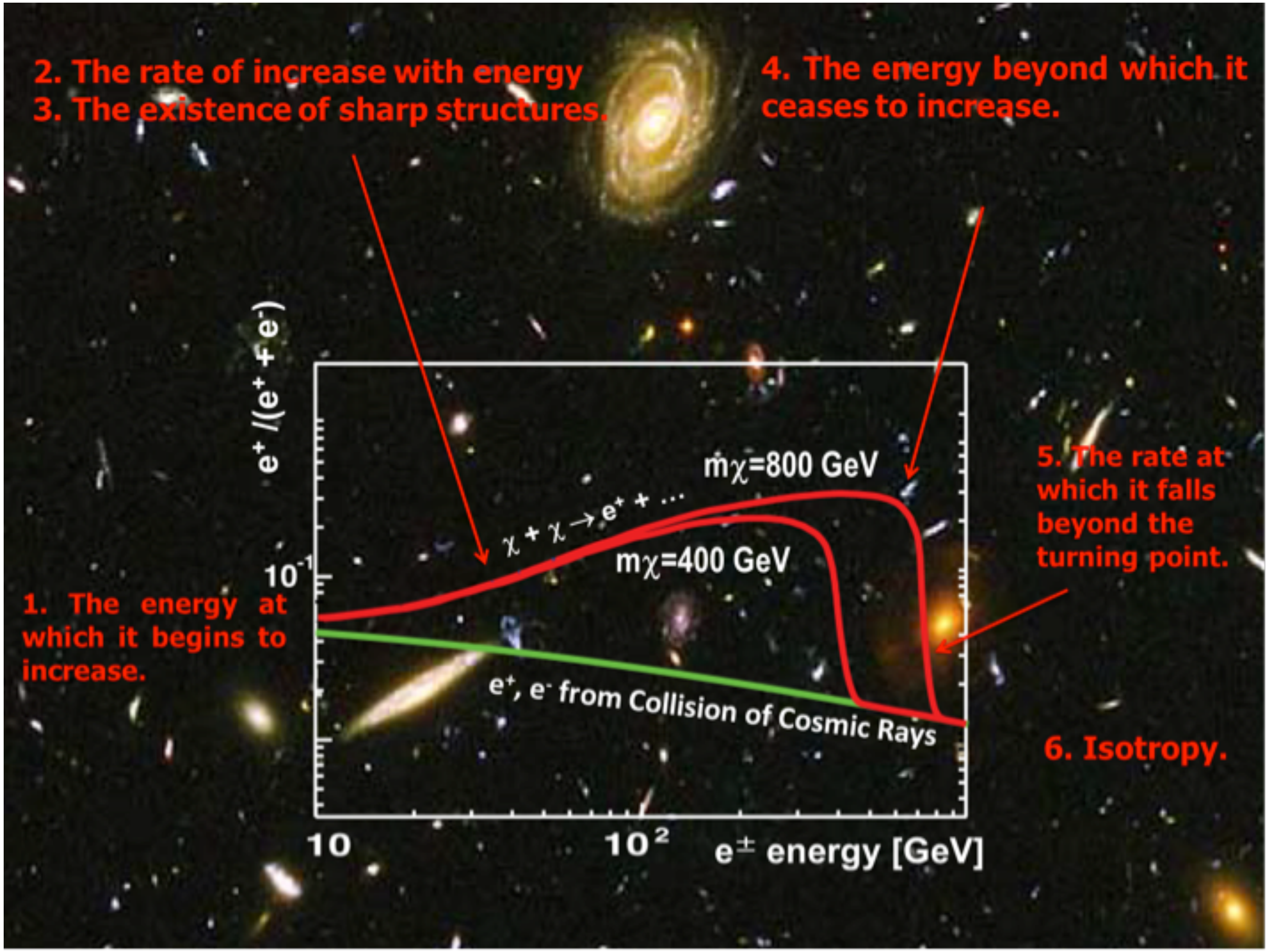
Possible Explanation: Dark Matter



- Triggered a lot of activity: Several hundred papers with Dark Matter interpretations of PAMELA data within a few months

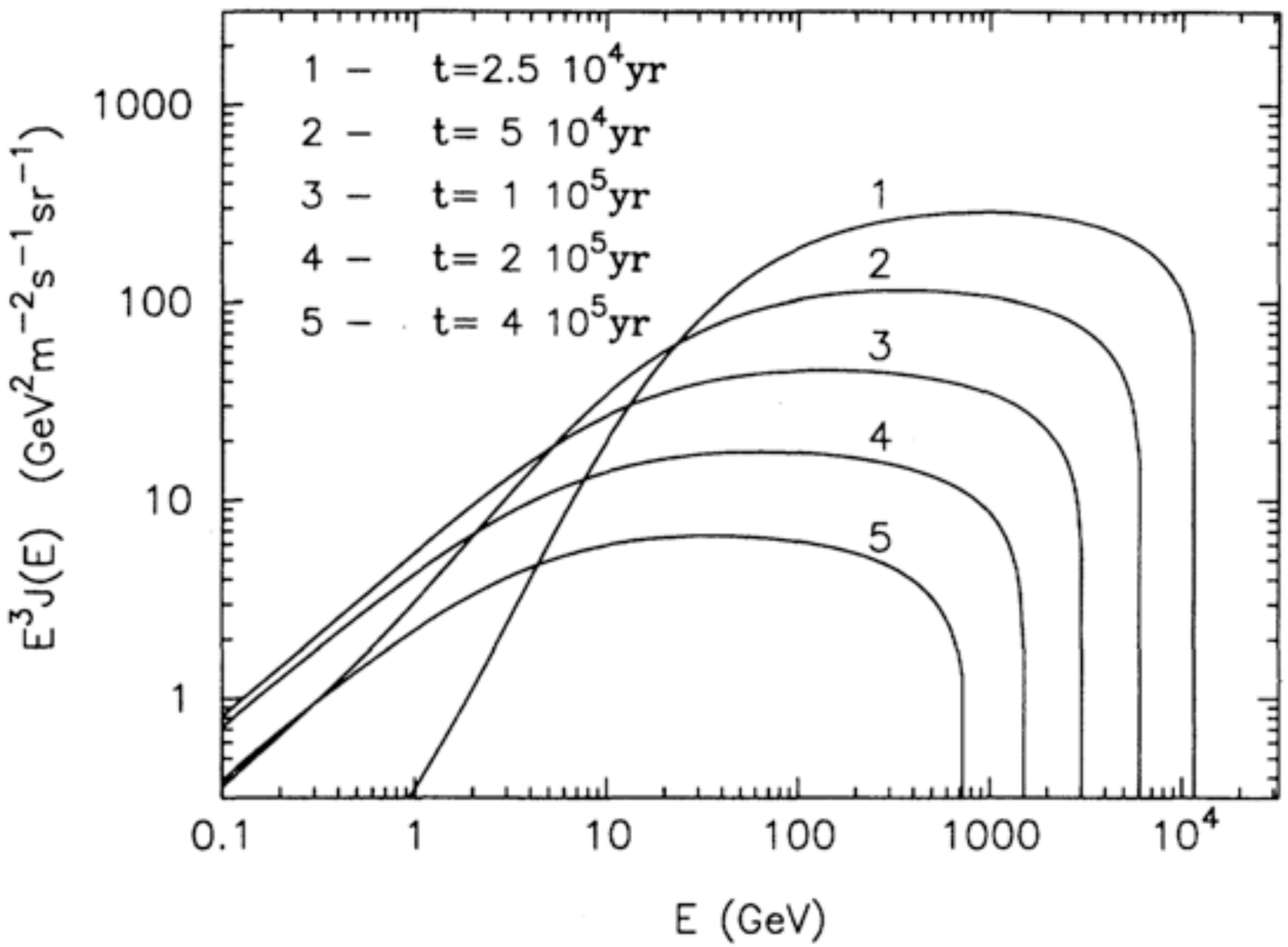
Would lead to a “Peak” in positrons, at higher energies the curve should go back to the expected behavior

Dark Matter: Consequence on Positron Fraction



Less Spectacular Explanation

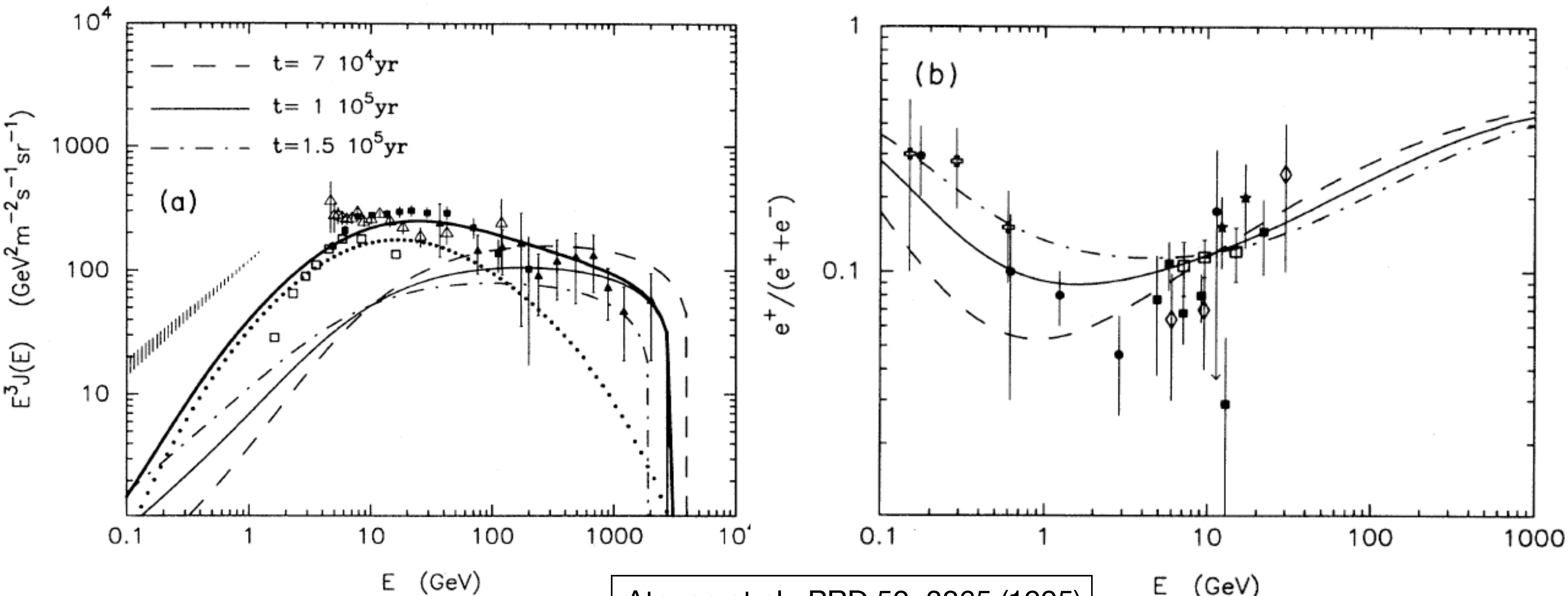
- There has to be another primary source of positrons!
  - Production von positrons for example in near-by pulsars: Highly energetic gamma rays produce e^+e^- pairs



Electrons (and positrons) quickly loose energy in the ISM via Compton scattering and synchrotron radiation ➯ Sources for highly-energetic positrons have to be close!

Atoyan et al., PRD 52, 3265 (1995)

Electrons and Positrons from Pulsars



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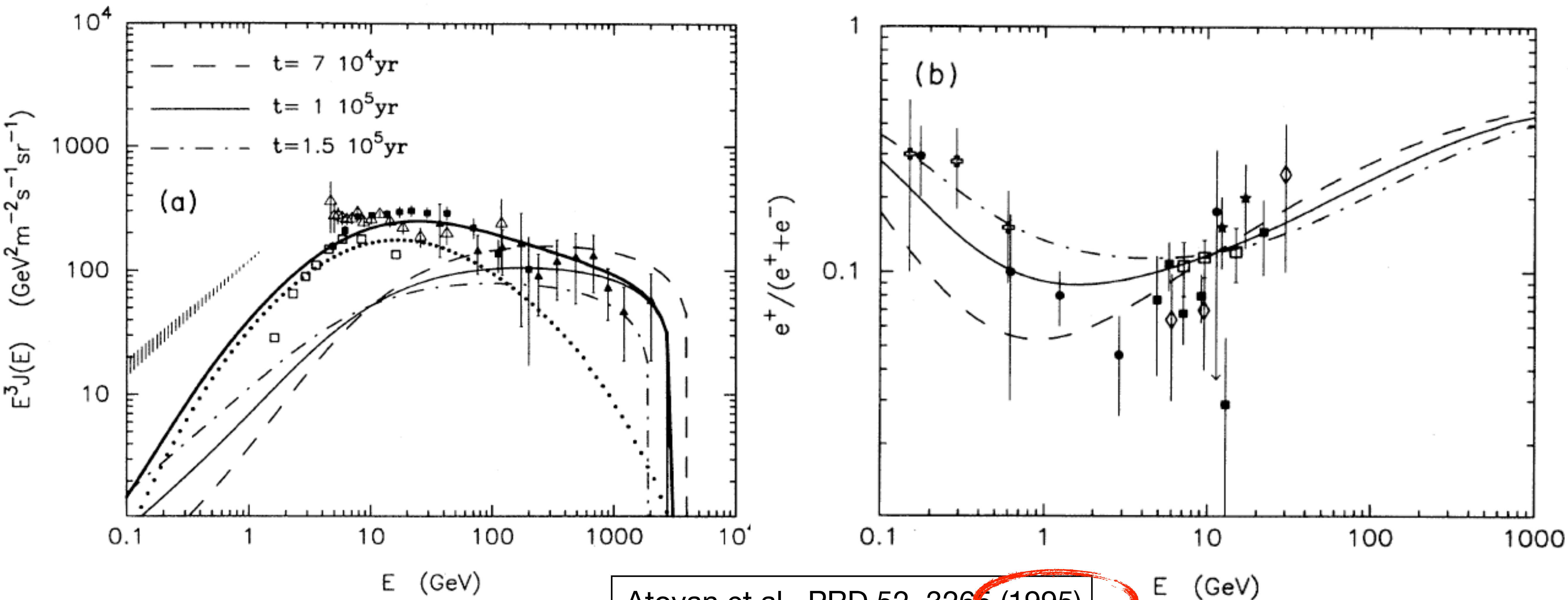
Electrons and Positrons from Pulsars



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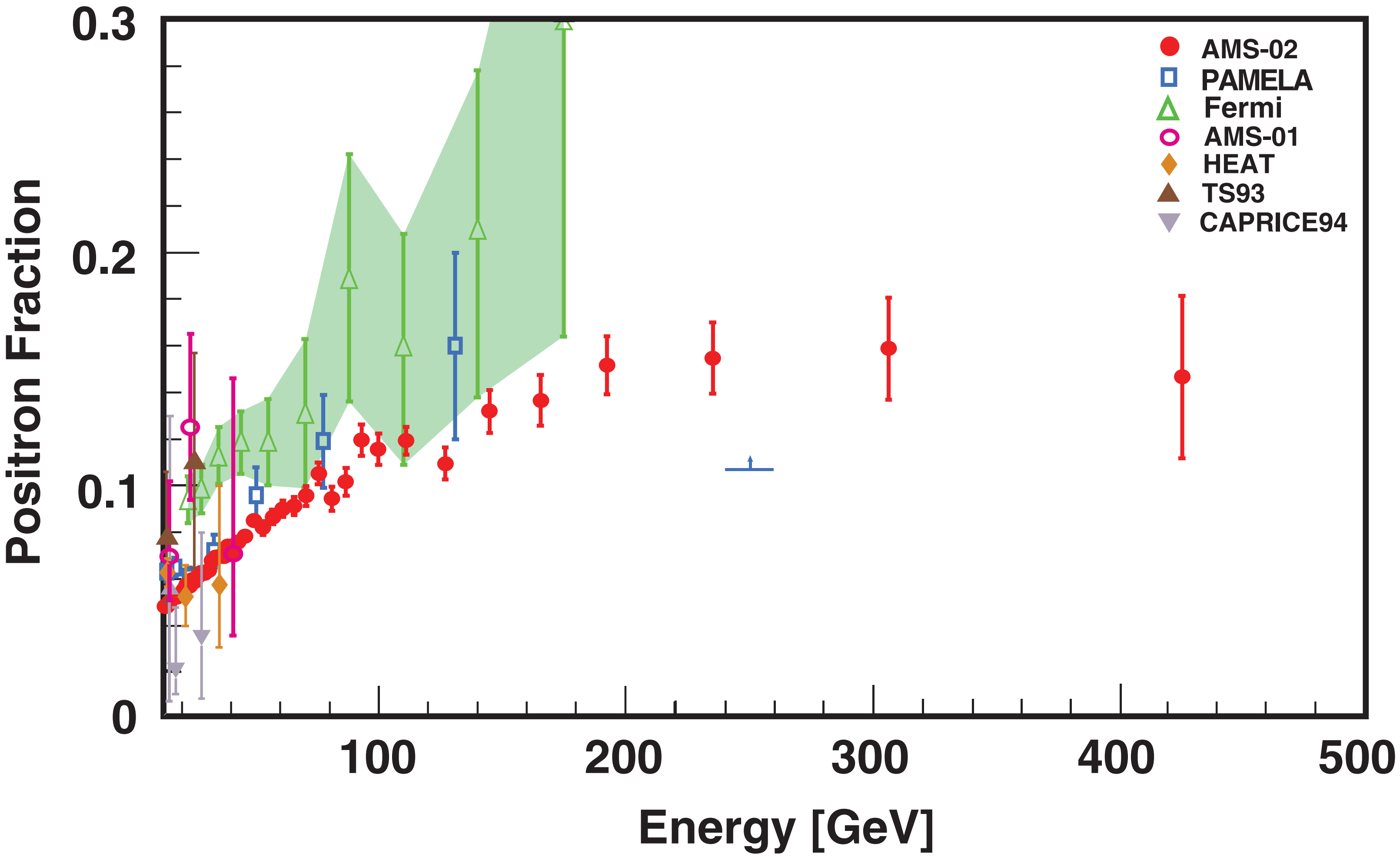
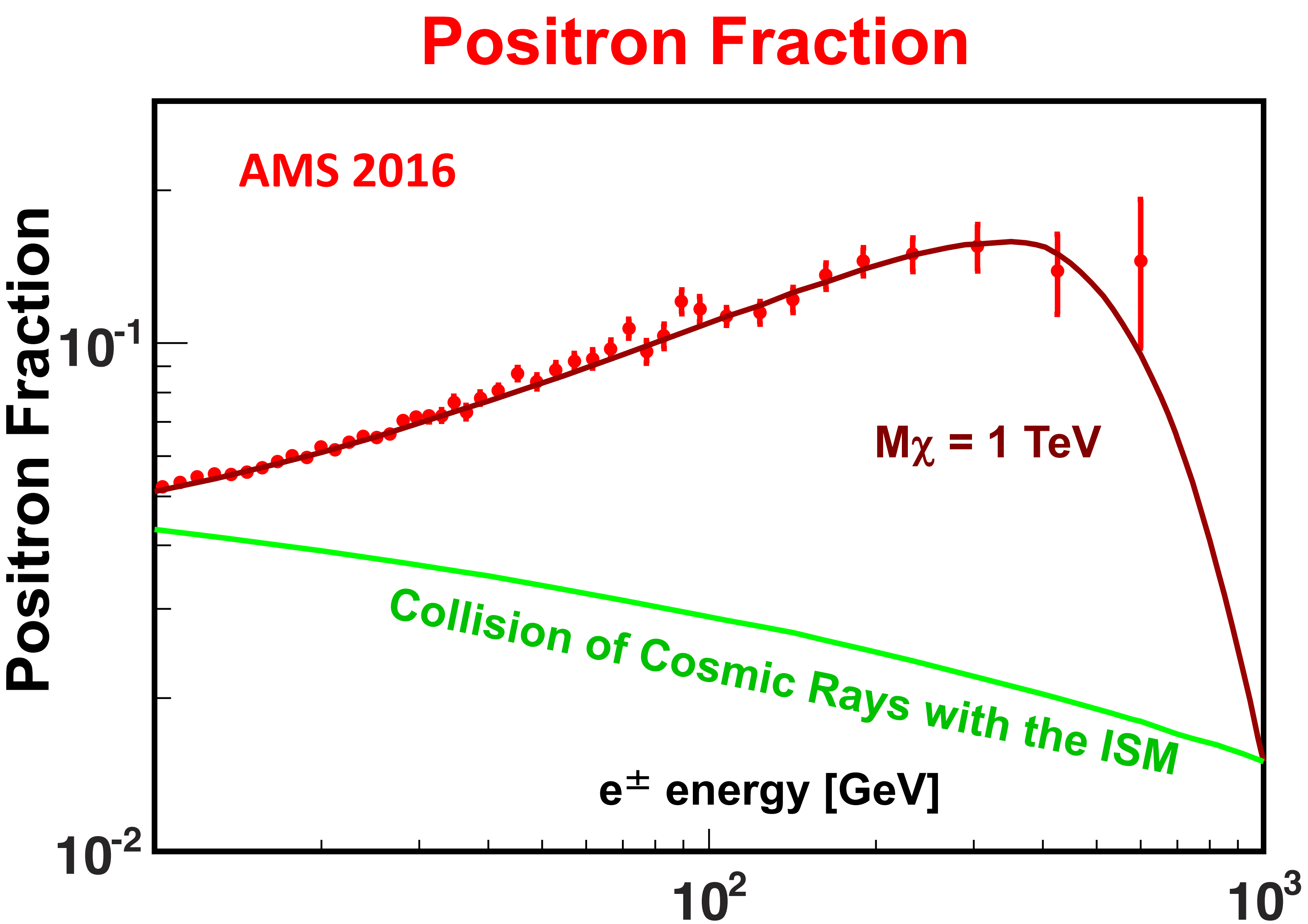
Confirmation by AMS and Fermi

Phys. Rev. Lett. 113, 121101 (2014)



- AMS proves: the effect is real - also supported by Fermi results
    - Detailed analyses show (up to now) no anisotropy in the distribution of the positron excess - no preferred direction

Positron Excess: What is it?



- Newest results indicate maximum is reached by experiments

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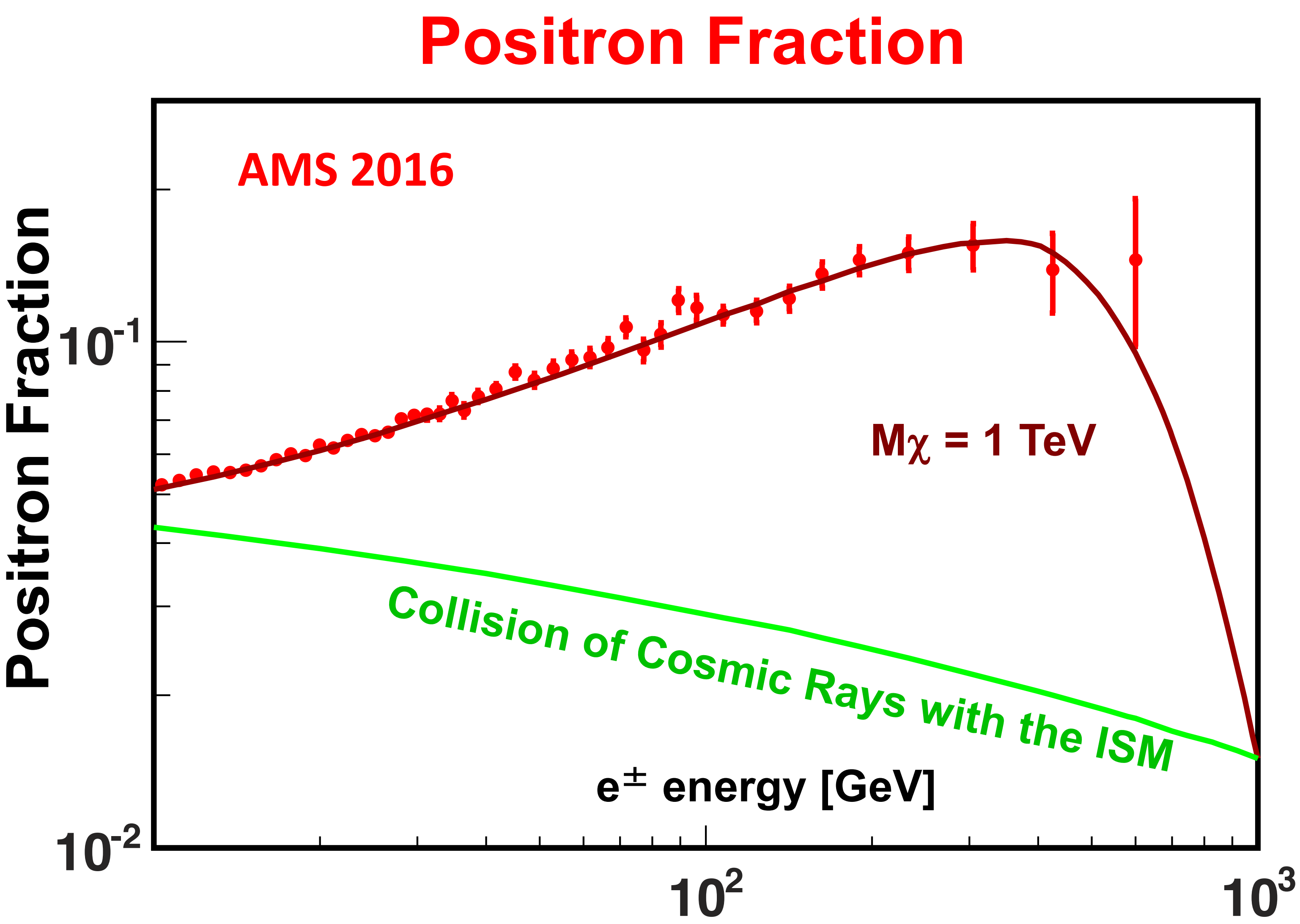

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➯ Consistent with “particle physics origin” (Dark Matter), but other explanations can not be excluded: Pulsars, possible mistakes in propagation models, …

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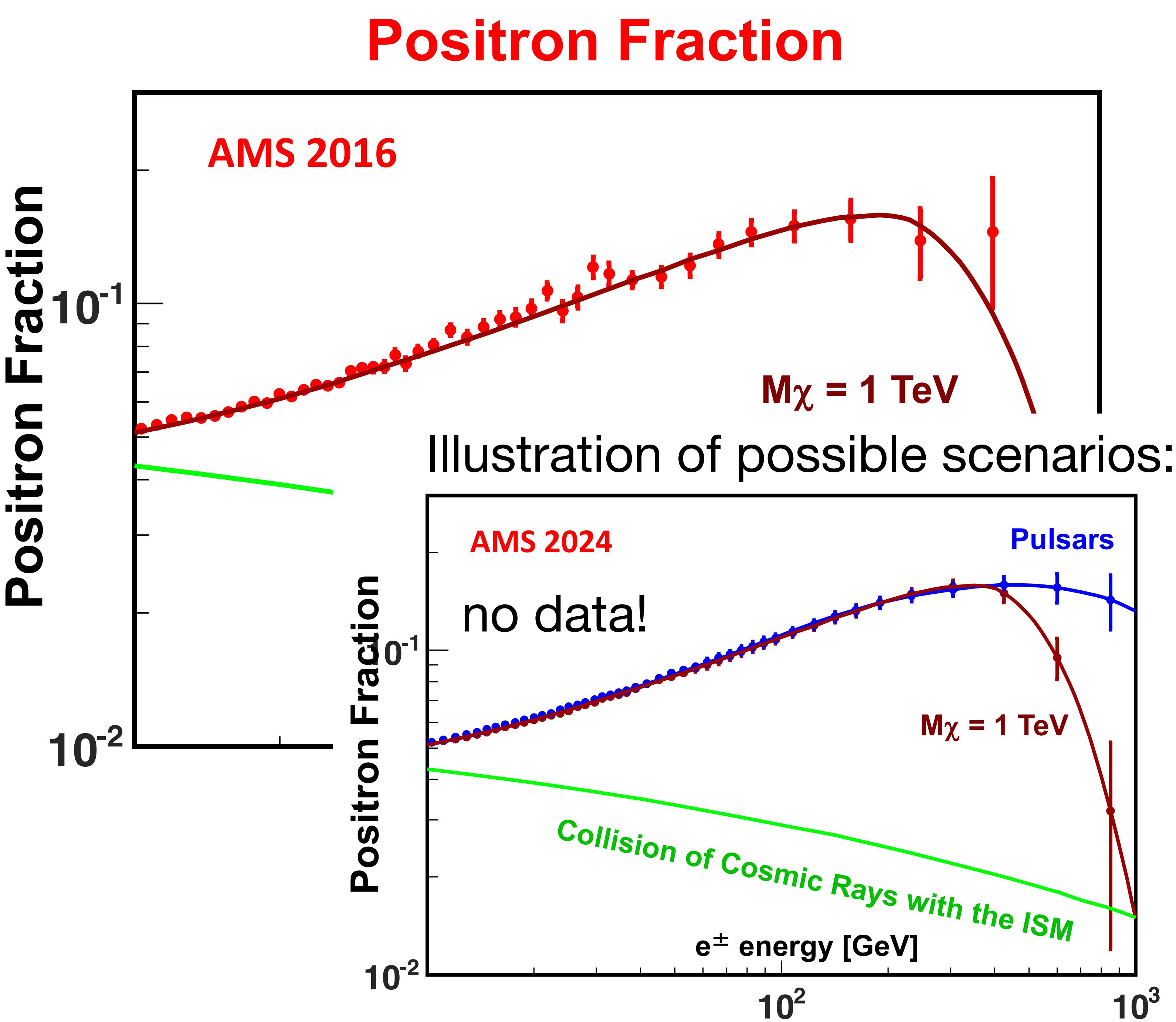

- Newest results indicate maximum is reached by experiments
- Continuation to higher energy crucial for interpretation: Dark matter predicts steep drop, pulsars would lead to a slower drop, and a dipole asymmetry

➩ Consistent with “particle physics origin” (Dark Matter), but other explanations can not be excluded: Pulsars, possible mistakes in propagation models, …

Summary

- Electromagnetic radiation is important: The combination of different spectral ranges allows detailed investigations of sources
- Highly energetic photons are observed with Cherenkov telescopes
  - Production via synchrotron radiation, inverse Compton processes and hadron decays
  - Provides insight into acceleration mechanisms
- Gamma sources in the Milky Way and beyond:
  - Pulsars
  - Active galactic nuclei,…
- Composition of cosmic rays at low energy well understood - primary and secondary components
- Exciting observation: Positron excess A hint of New Physics, or pulsars or shortcomings of our understanding of particle propagation in the galaxy?

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Next Lecture: 17.07., “Precision Experiments”, S. Bethke

Lecture Overview

24.04.	Introduction & Accelerators
01.05.	**Holiday - No Lecture**
08.05	Cosmic Accelerators
15.05.	Detectors
22.05.	The Standard Model
29.05.	QCD and Jets
05.06.	**Holiday - No Lecture**
12.06.	Neutrinos I
19.06.	Neutrinos II
26.06	**No Lecture**
03.07.	Cosmic Rays I
10.07.	Cosmic Rays II
17.07.	Precision Experiments
24.07.	Dark Matter, Dark Energy & Gravitational Waves