What Satellites See:
Gamma-ray Eyes Above the Skies

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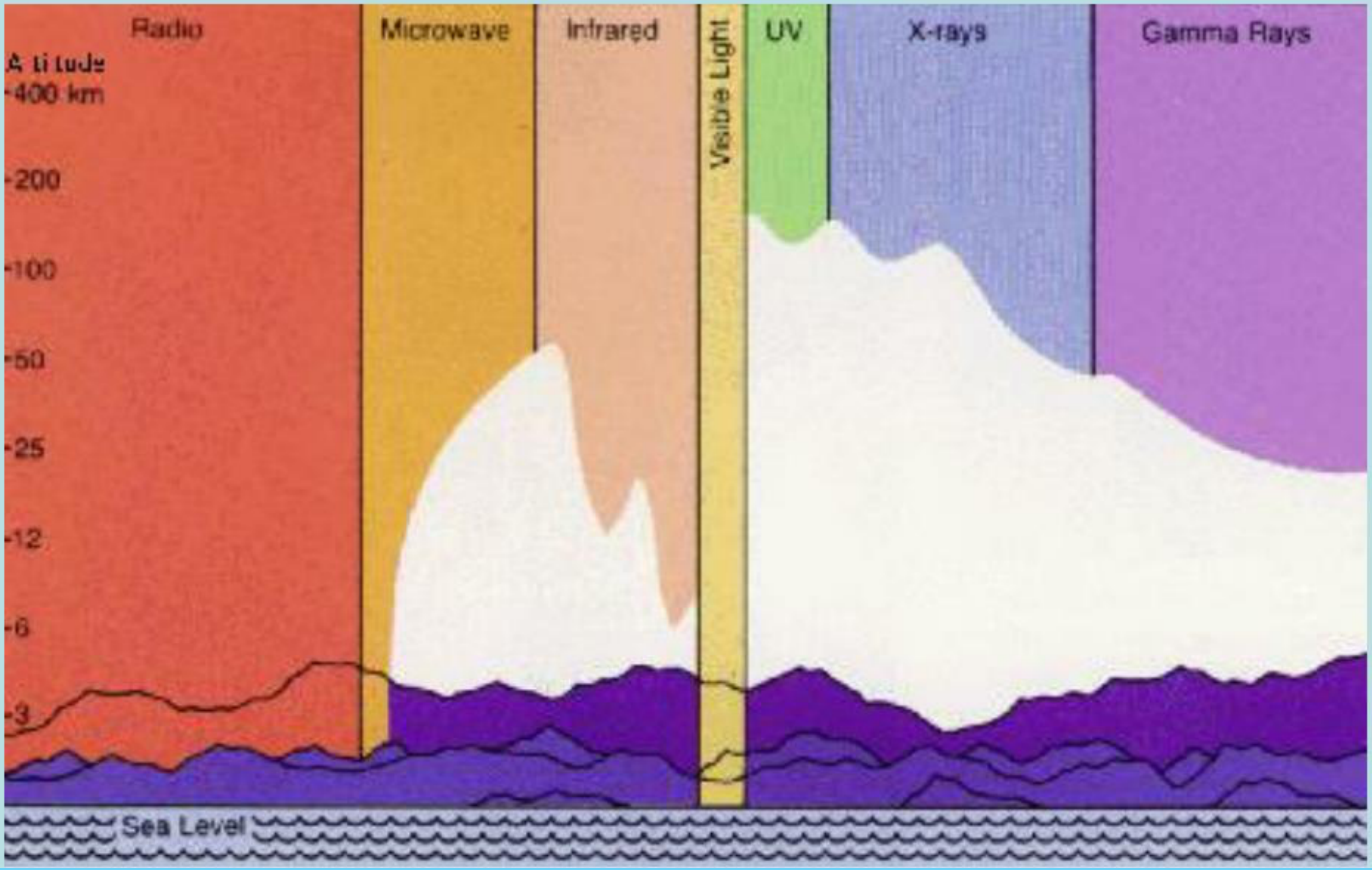
What other eyes do we have?

- UHECR
- GAMMA RAYS finish origin of cosmic rays
- X-rays
- ACE, stereo
- Parker probe

- Other
- Gravitational waves
- CALET

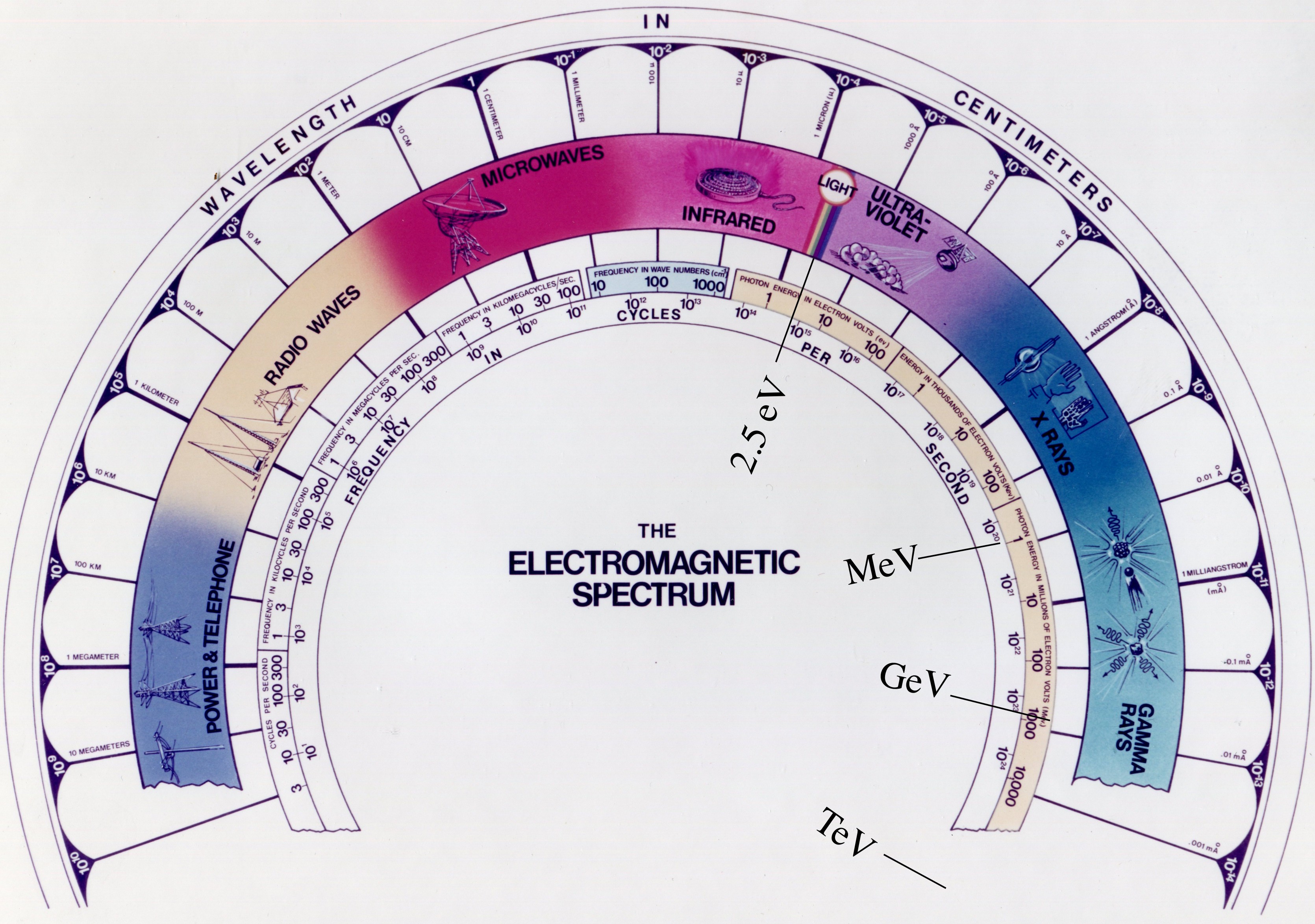
For some types of light, space is the only solution, as the atmosphere is opaque



Vocabulary review charged particles

- Electron the very light particle that orbits the nucleus with charge -1
- Proton the nucleus of a hydrogen atom, charge +1
- Nuclei the nucleus of many atoms in the periodic table
- Helium an atom with charge 2 and mass 3 or 4
- Alpha particle the nucleus of a helium atom
- Anti-proton just like a proton but with charge -1
- Pions, π-mesons. π^+, π^- π^o. particles that carry the nuclear force
  the π^o have extremely short lives
- Muons, μ-mesons. μ^+, μ^- particles that do not interact with the nuclear force; they are like heavy electrons
  they penetrate through the atmosphere

All these guys are photons



Vocabulary review - photons

- **Photon an electromagnetic wave that carries energy and momentum but has no charge**

Boundaries are fuzzy

- Gamma-ray a very high energy photon > 1 MeV
- X-ray somewhat less energetic photon >250 eV = .25 keV
- Ultraviolet still less energetic photon >3 eV
- Visible
- Infrared 0.7 μ–meters (700 nmeters) – 1 mm
- Millimeter waves 1 – 10 mm (30-300 GHz)
- Microwave 300 μ–meters – 1 meter (1-30 GHz)
- Radio

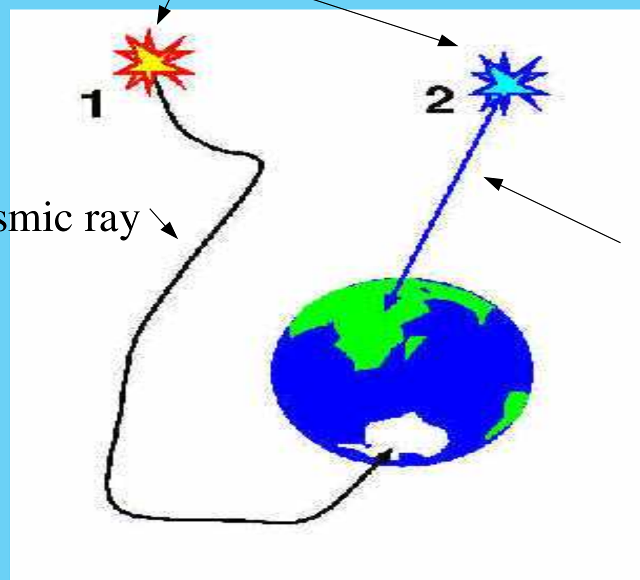
Why did NASA care about the High Energy Universe?
Scientific curiosity?

**Not really. Studies were politically motivated by space race, peaceful competition vs. nuclear war. Needed to understand the radiation environment in space
(astronaut safety).**

Cosmic rays don’t point back to their source

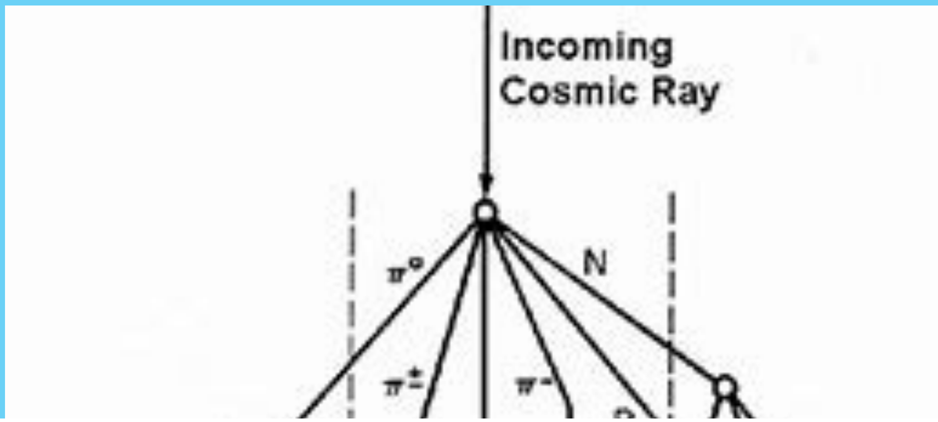
Distant sources of cosmic rays

Charged cosmic ray



Gamma Ray
not deflected by magnetic
fields – points to source

Particle zoo



collision

p+p -> $\pi^+ + \pi^- + \pi^o$

unstable particles decay

$\pi^+ \rightarrow \mu^+$ and $\pi^- \rightarrow \mu^-$

$\pi^o \rightarrow 2\gamma$

The spectrum of the gamma-rays has a peak at the mass of the π^o, 900 MeV

The muons proceed to penetrate the atmosphere and into the ground.

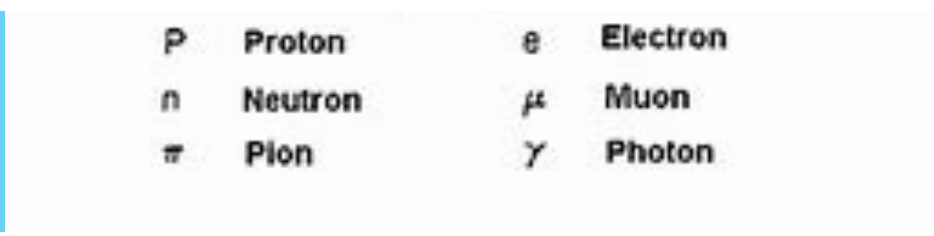
But now there is plenty of time for all the unstable secondary to decay.

$\pi^+ \rightarrow \mu^+ \rightarrow \nu + e^+$

$\pi^- \rightarrow \mu^- \rightarrow \nu + e^-$

$\pi^o \rightarrow 2\gamma$

We should be able to see electrons, positrons, and most interesting, gamma-ray photons coming from the gas and dust in the galaxy.

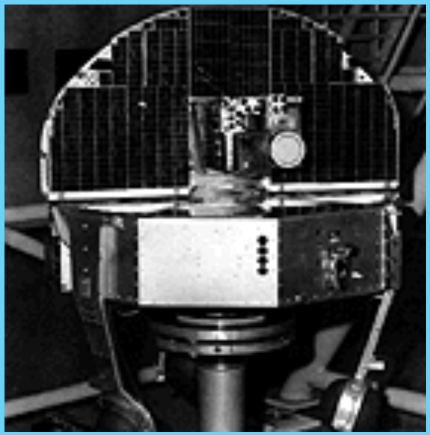


Maybe gamma rays can find the sources of cosmic rays?

Should see gamma-ray photons from cosmic rays colliding with interstellar gas and dust.

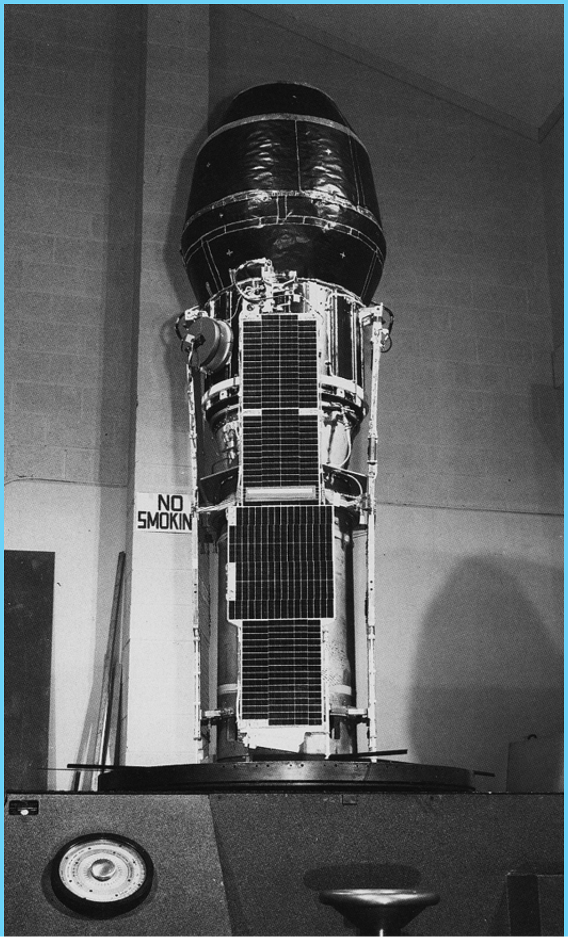
Maybe we can see sites of origin of cosmic rays around supernova remnants.

OSO-3, SAS-2 & COS-B

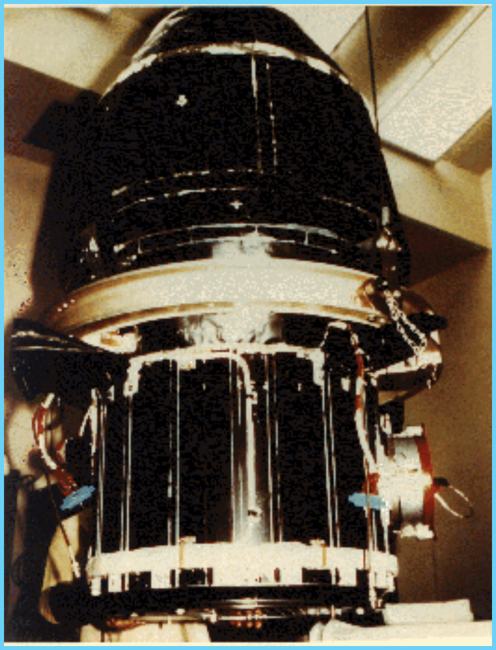


OSO 3: Mar. 8, 1967
Kraushar et al., 1972,
Astrophysical Journal, 177, 341

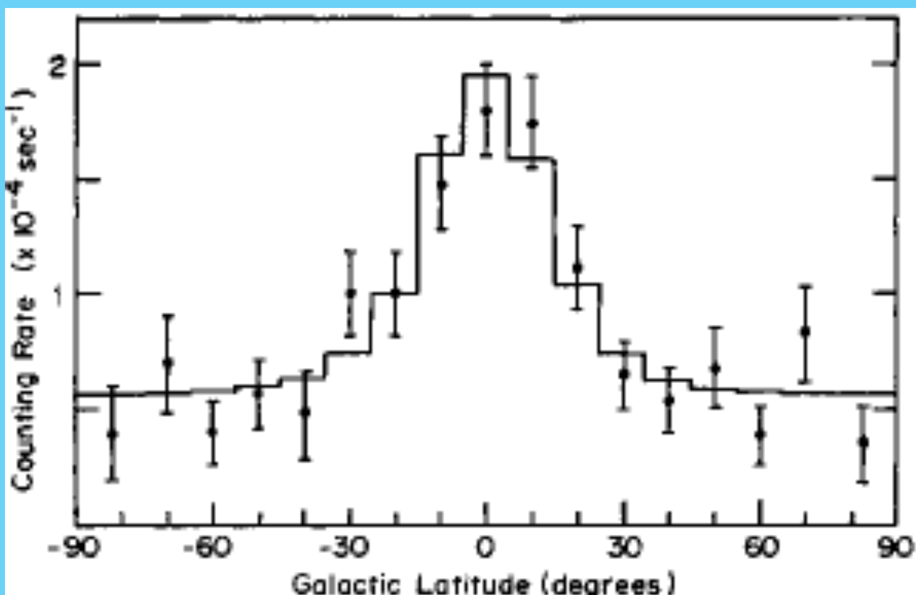
SAS-2: Nov. 15, 1972: Crab, Vela, Geminga
Fichtel et al., 1975, ApJ, 198, 163

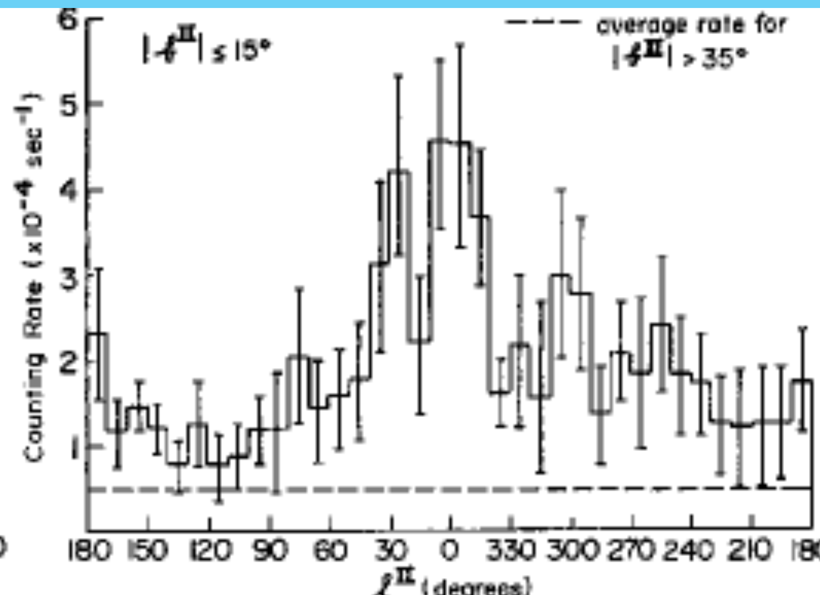


COS-B Aug. 9, 1975
25 sources, 3C279



OSO 3 shows gamma rays from Milky Way



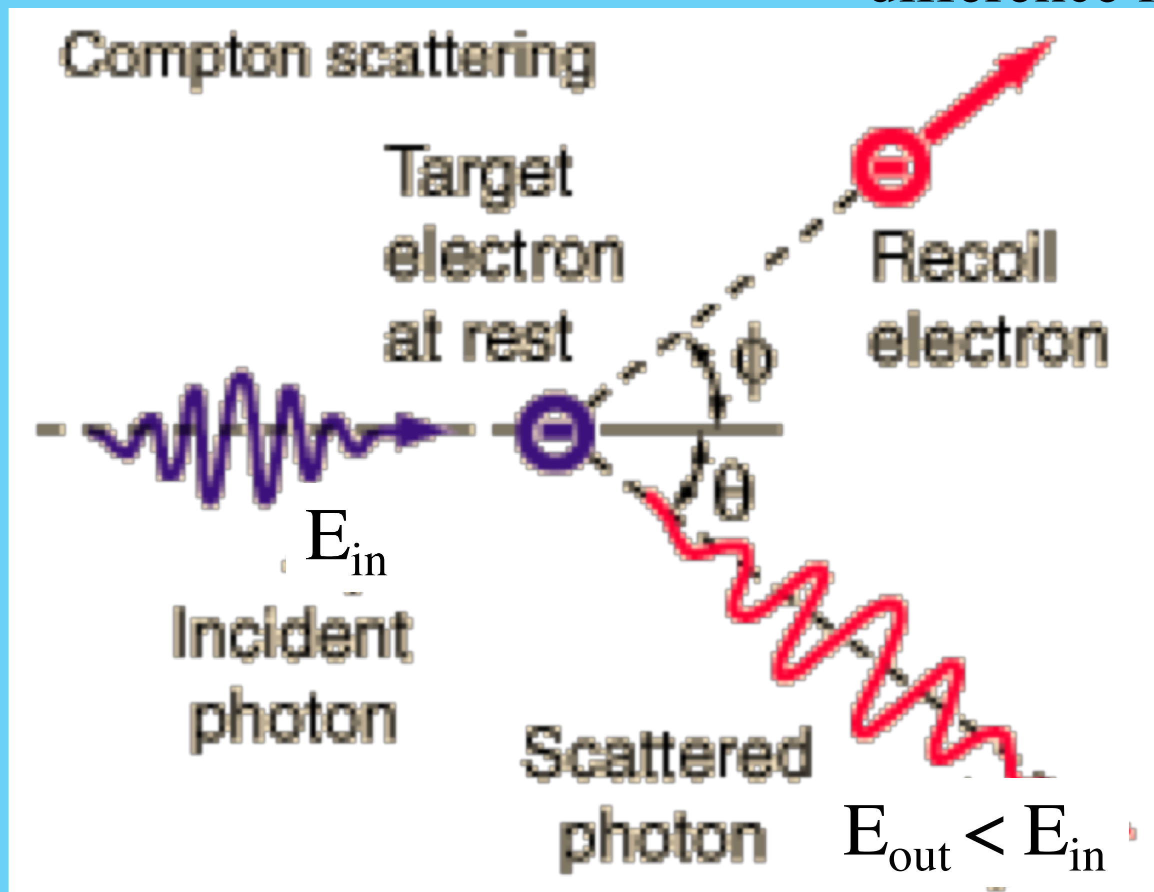


Galactic latitude

Galactic longitude

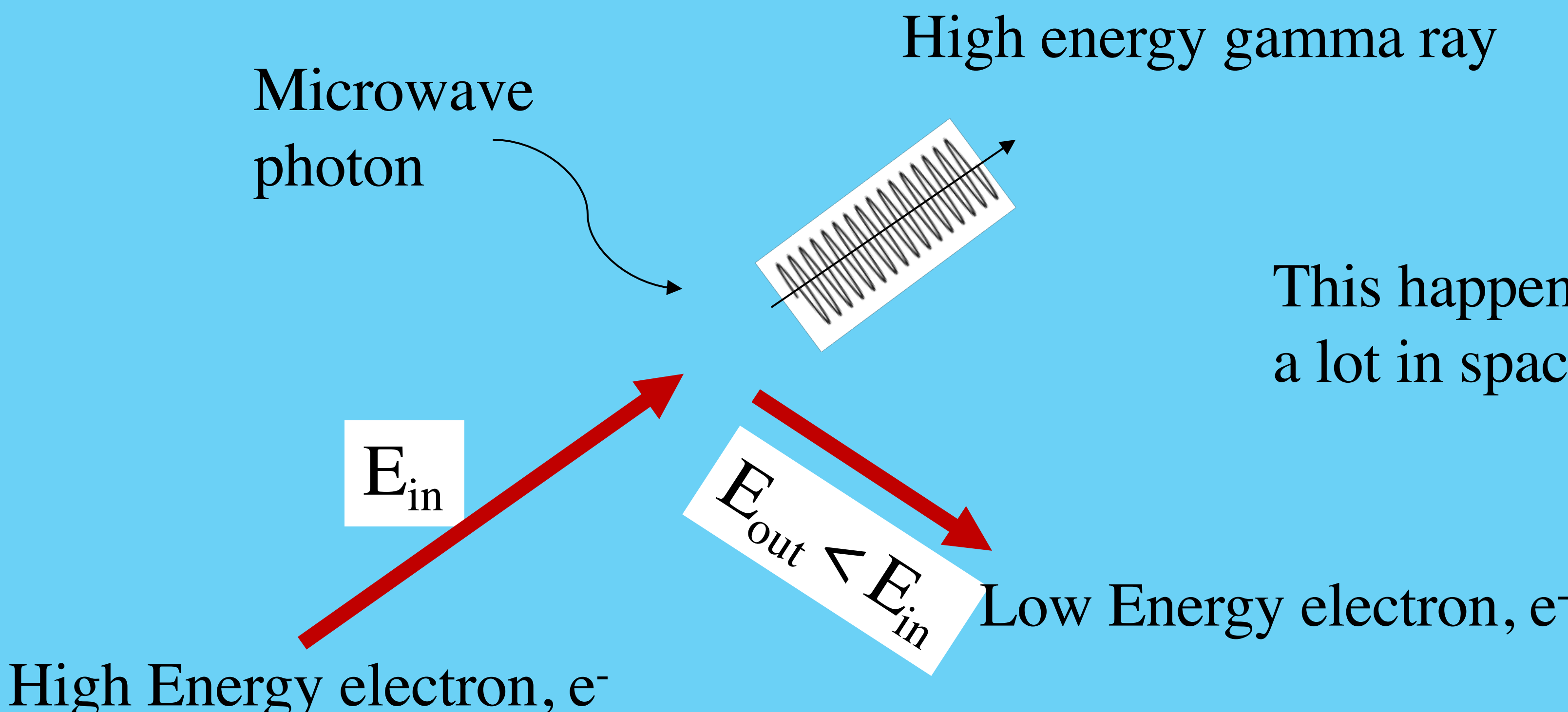
Compton scattering

e^- takes away the difference in energy.

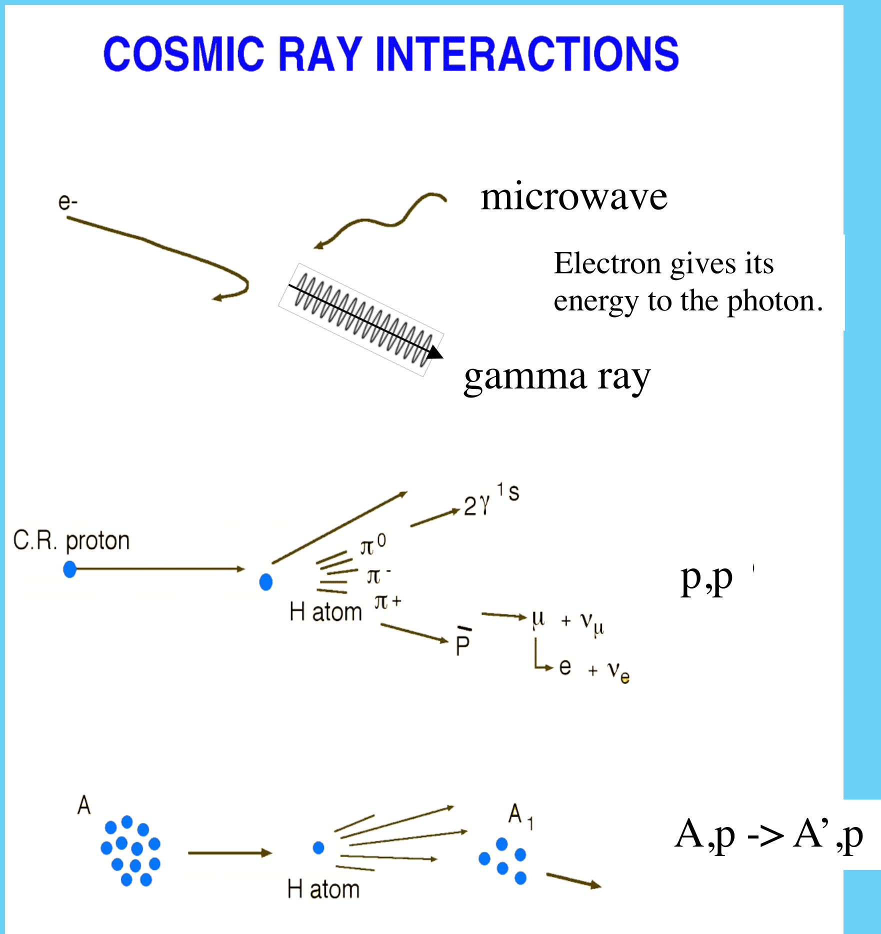


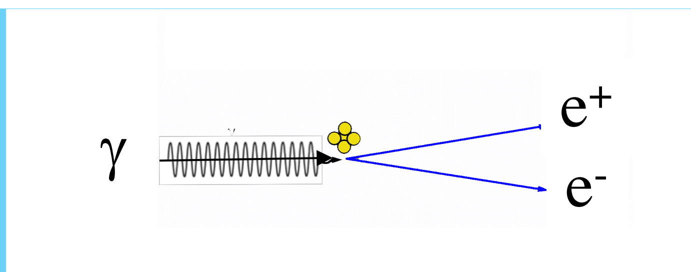
Inverse Compton scattering

High energy incident e- gives its Energy to a low energy photon.

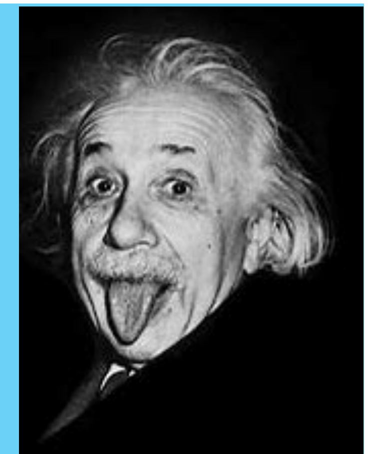


This happens a lot in space.



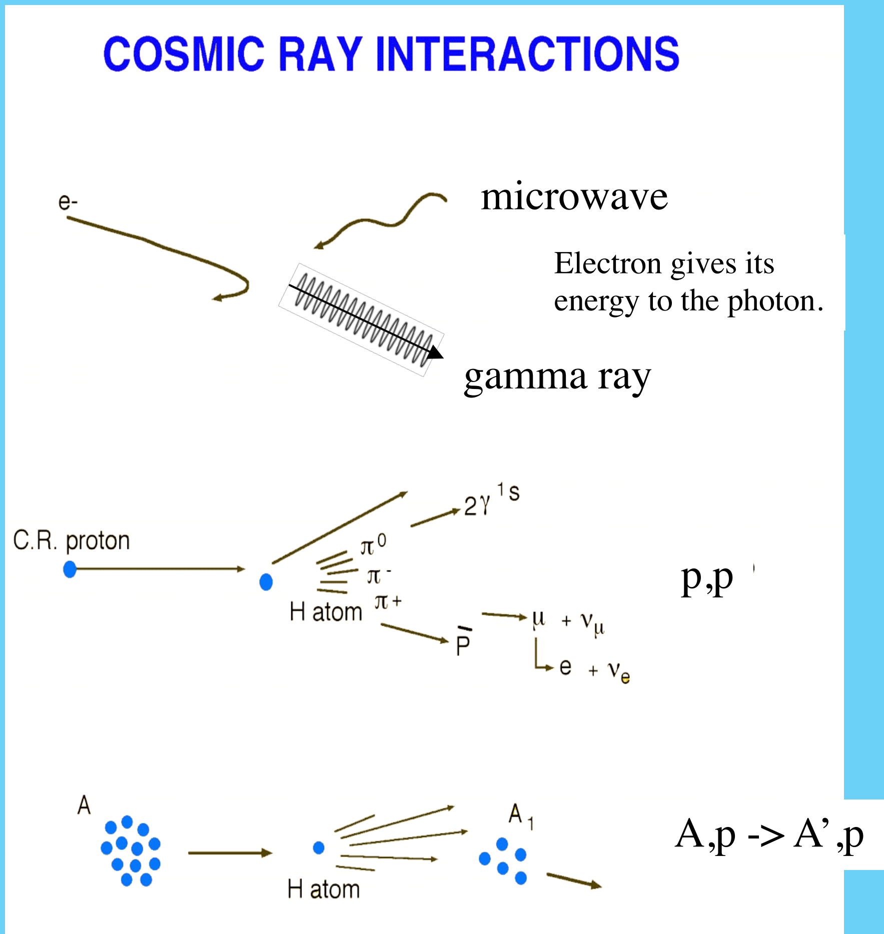


$E = mc^2$

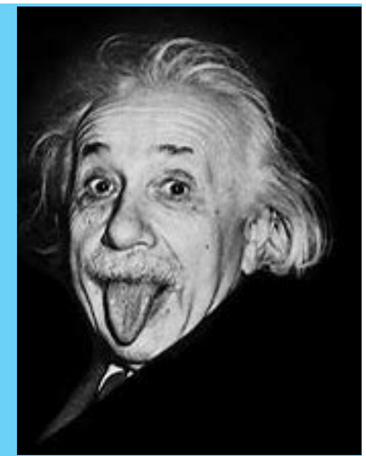


Where there are energetic electrons in space there will be high-energy gamma-ray photons.

Where there are high-energy gamma-ray photons in space there will be high-energy electrons.



$$E = mc^2$$



Where there are energetic nuclei colliding in space there will be high-energy gamma-ray photons

and there will be neutrinos from the decay of muons into electrons and neutrinos.

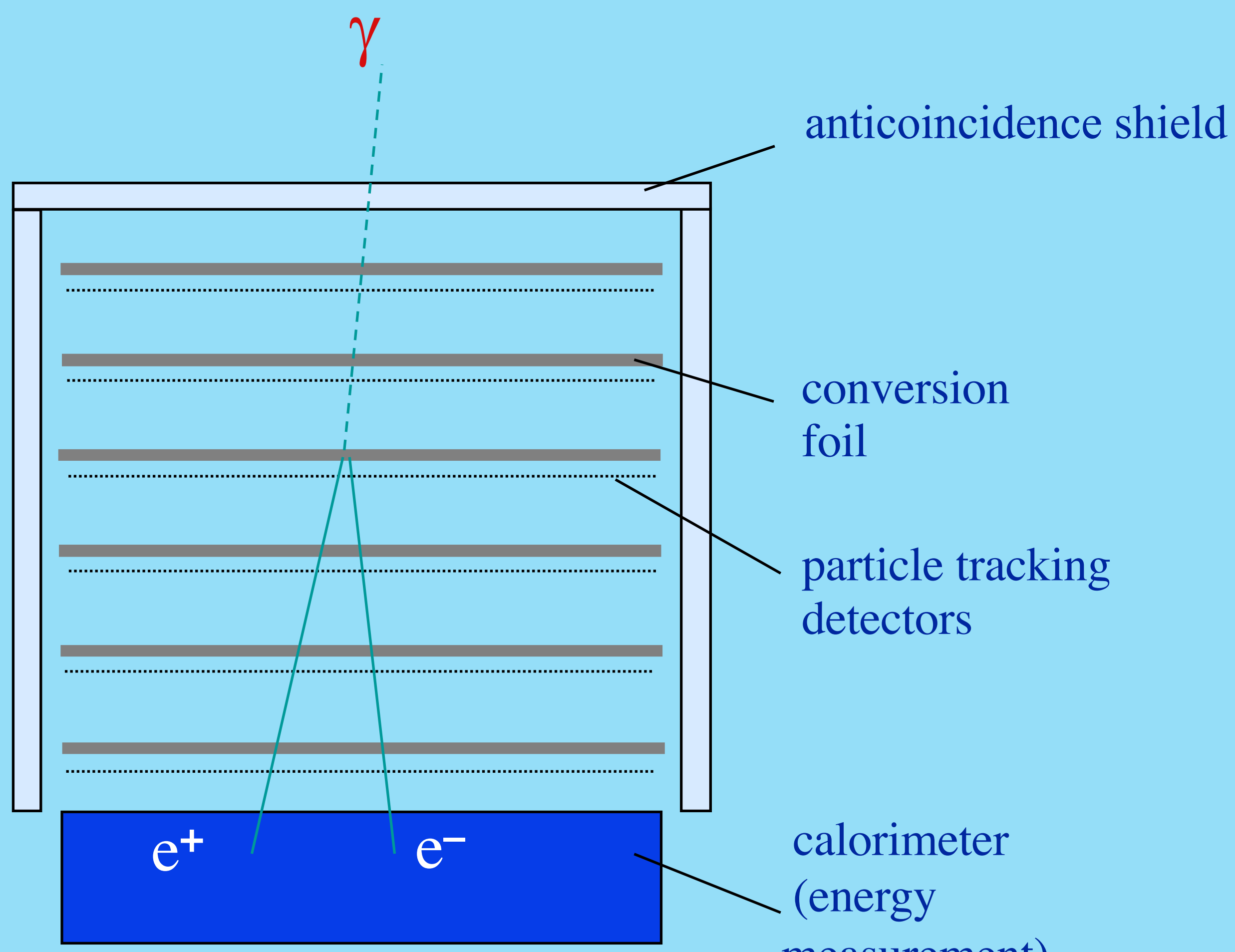
Source physics

- Any source that produces high energy electrons or protons can start an electromagnetic cascade
  - Protons interact with protons and give π^o; π^o -> 2γ
  - Electrons interact with photons and give γ

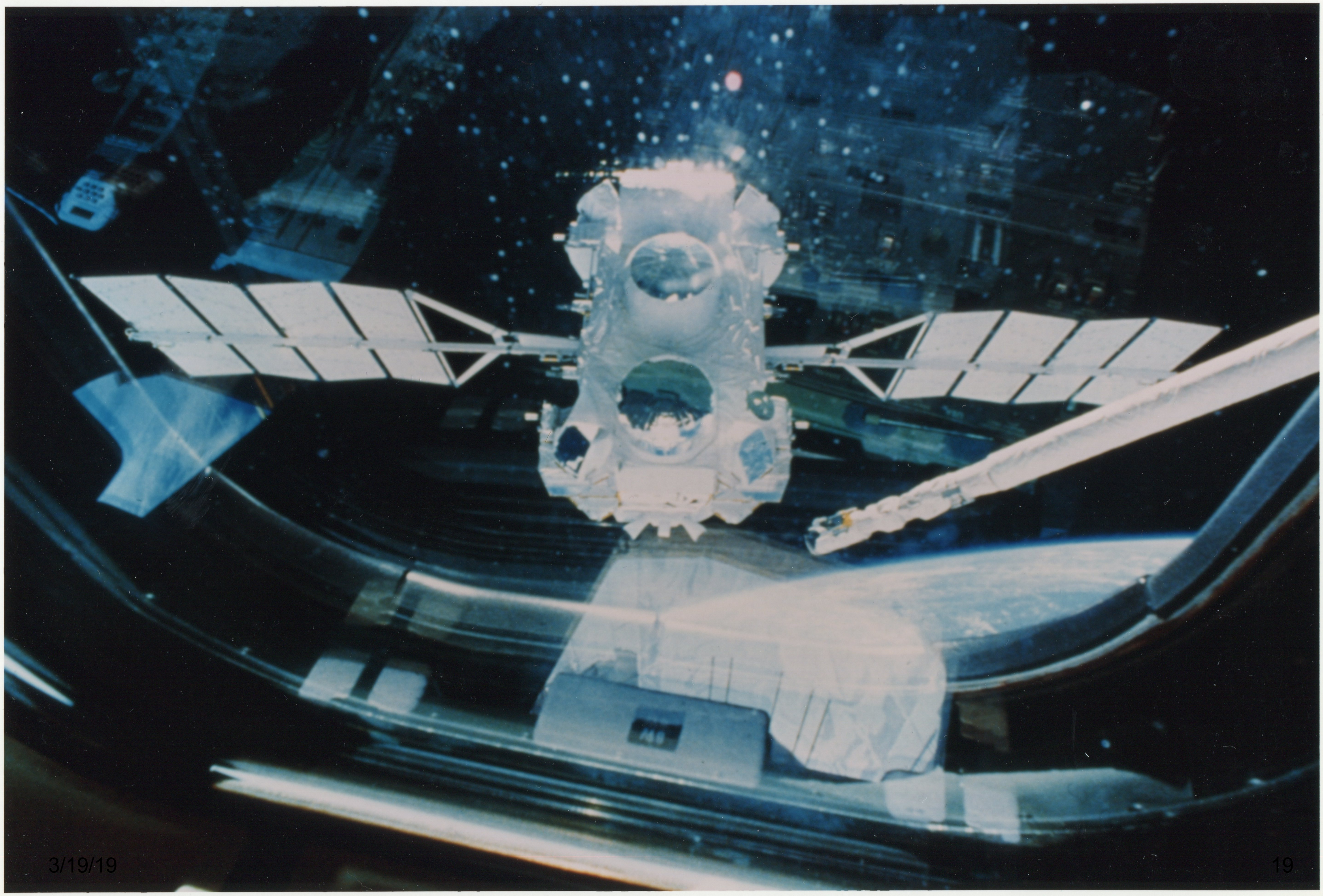
See a gamma-ray from a source,
you don't know its origin

- Need additional information to discriminate and correctly model how the sources work.
- Possible discriminators are
  - Radio waves result from electrons spiraling in magnetic fields
  - p + nuclear interactions produce neutrinos

A gamma-ray telescope



EGRET launch

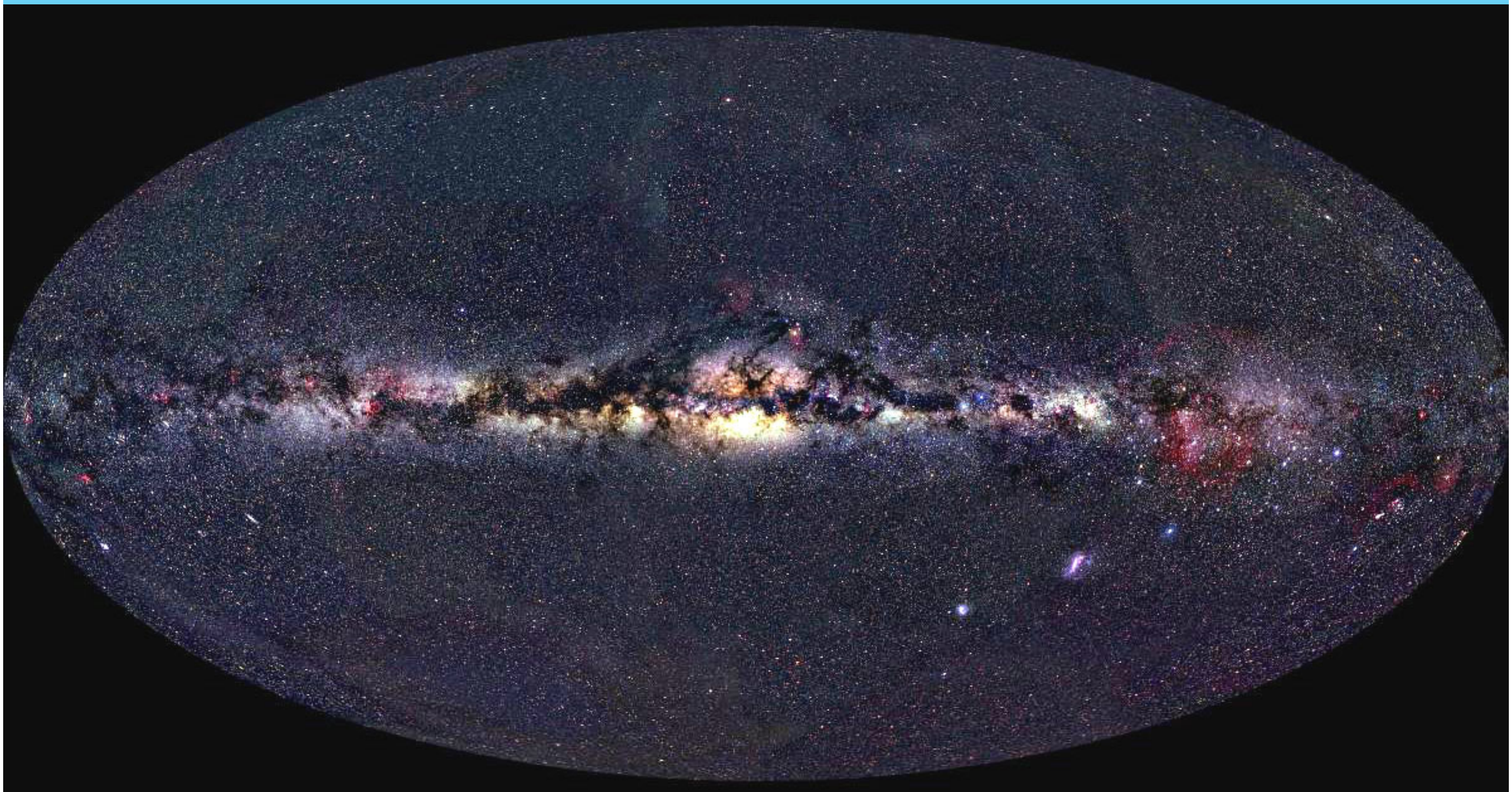


Compton Gamma-ray Observatory

Launched from Space Shuttle

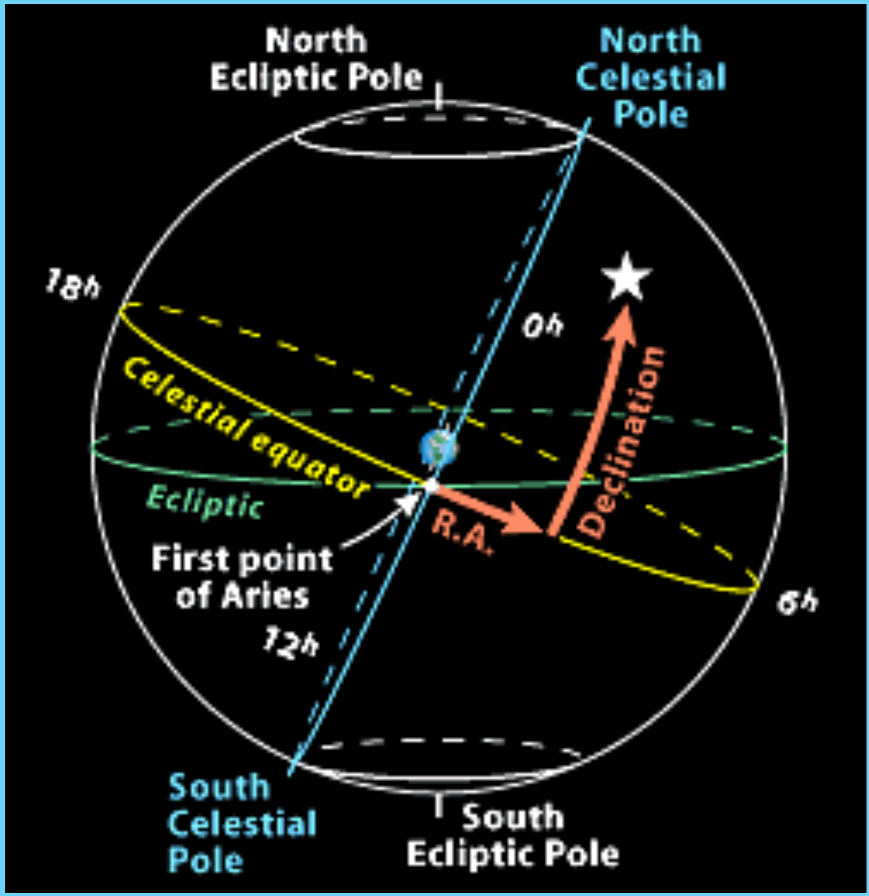
The first of 4 *Great Observatories*.

Milky Way: Aitoff projection



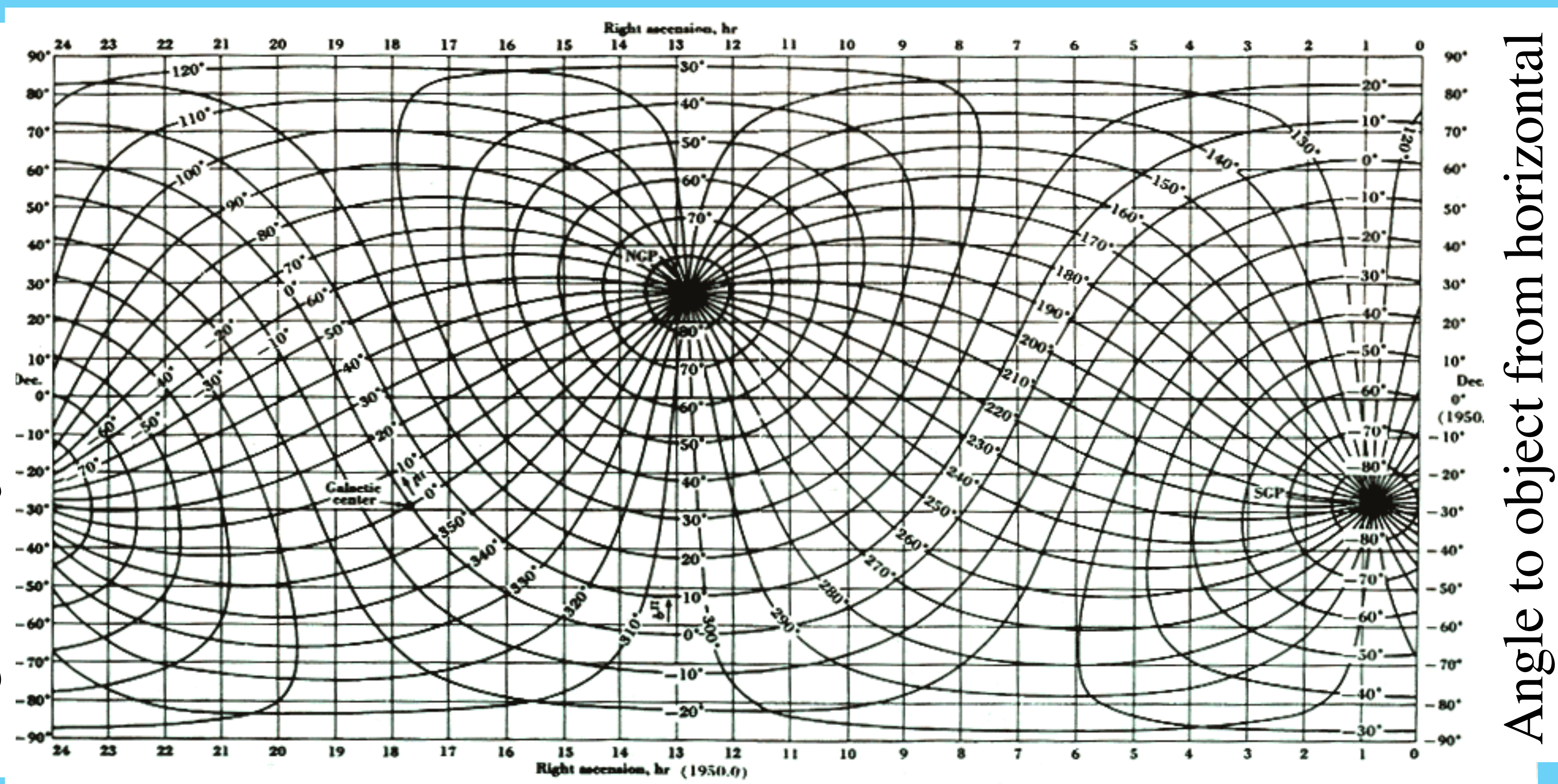
Optical wavelengths

Earth based observer coordinates Right ascension (RA) and declination 24 hours and 180 deg (+/-)



Transformation to galactic coordinates

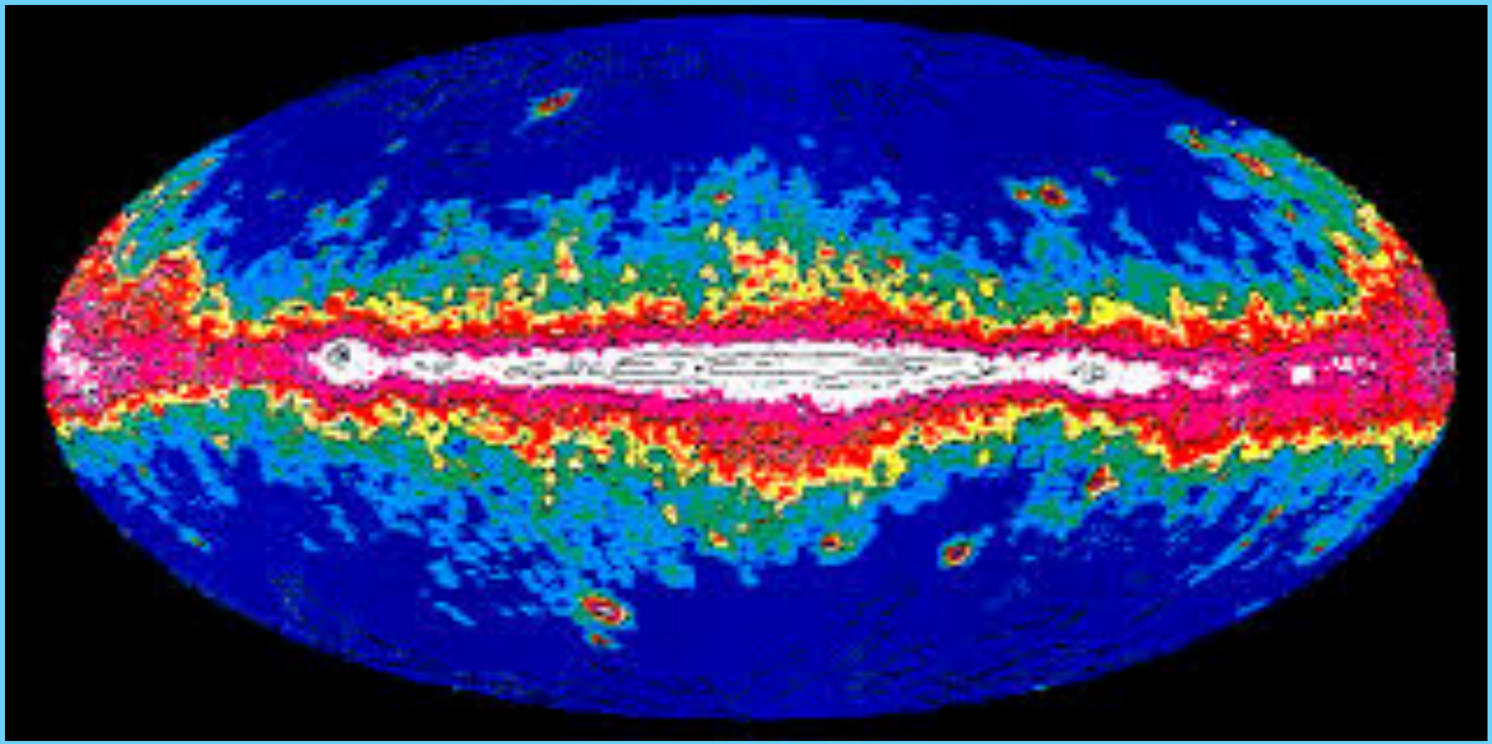
Angle to object from horizontal



Angle to object from horizontal

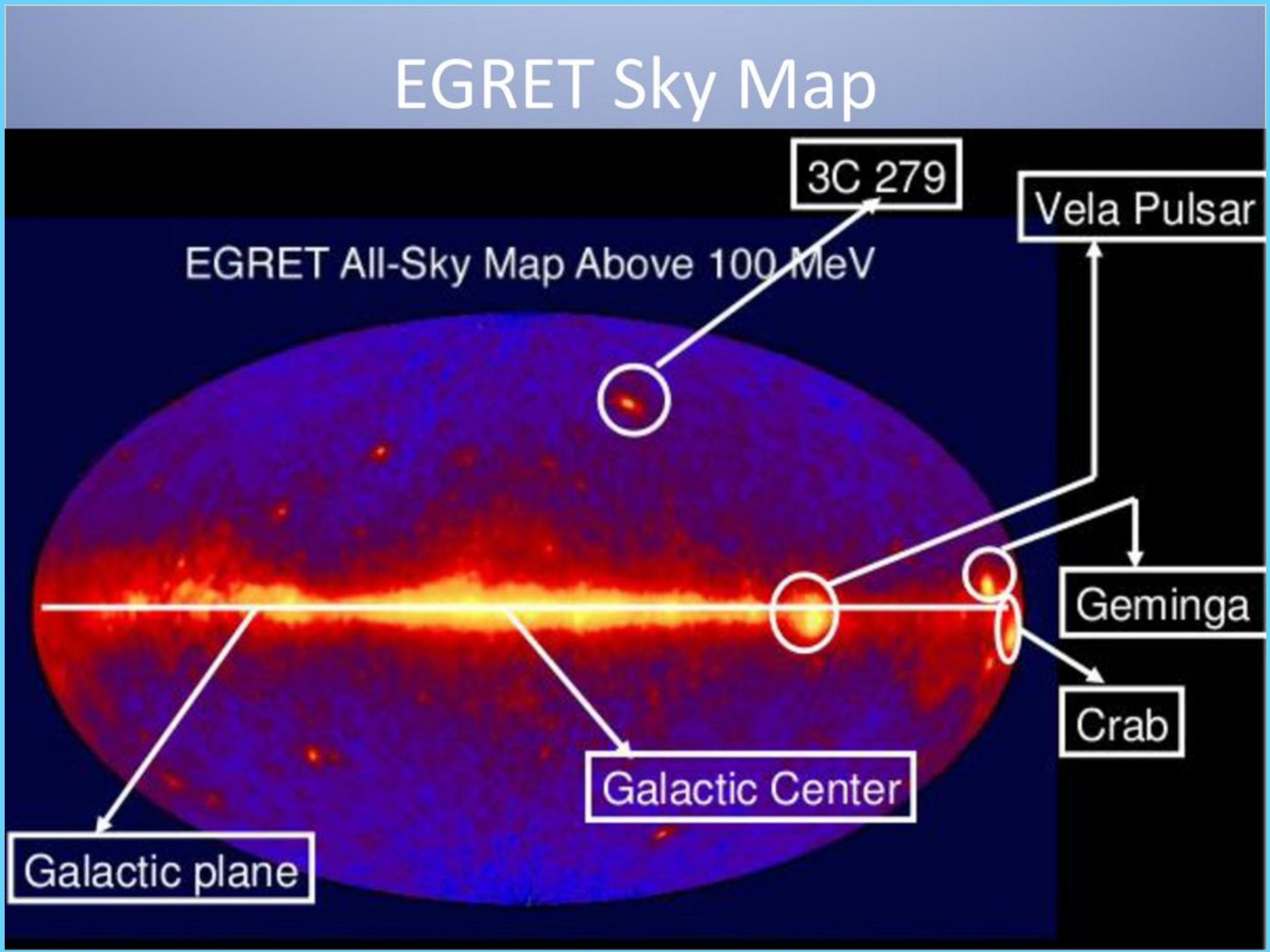
← 24 hr day →

Measuring γ–rays we can trace the gas and dust in the Milky Way.

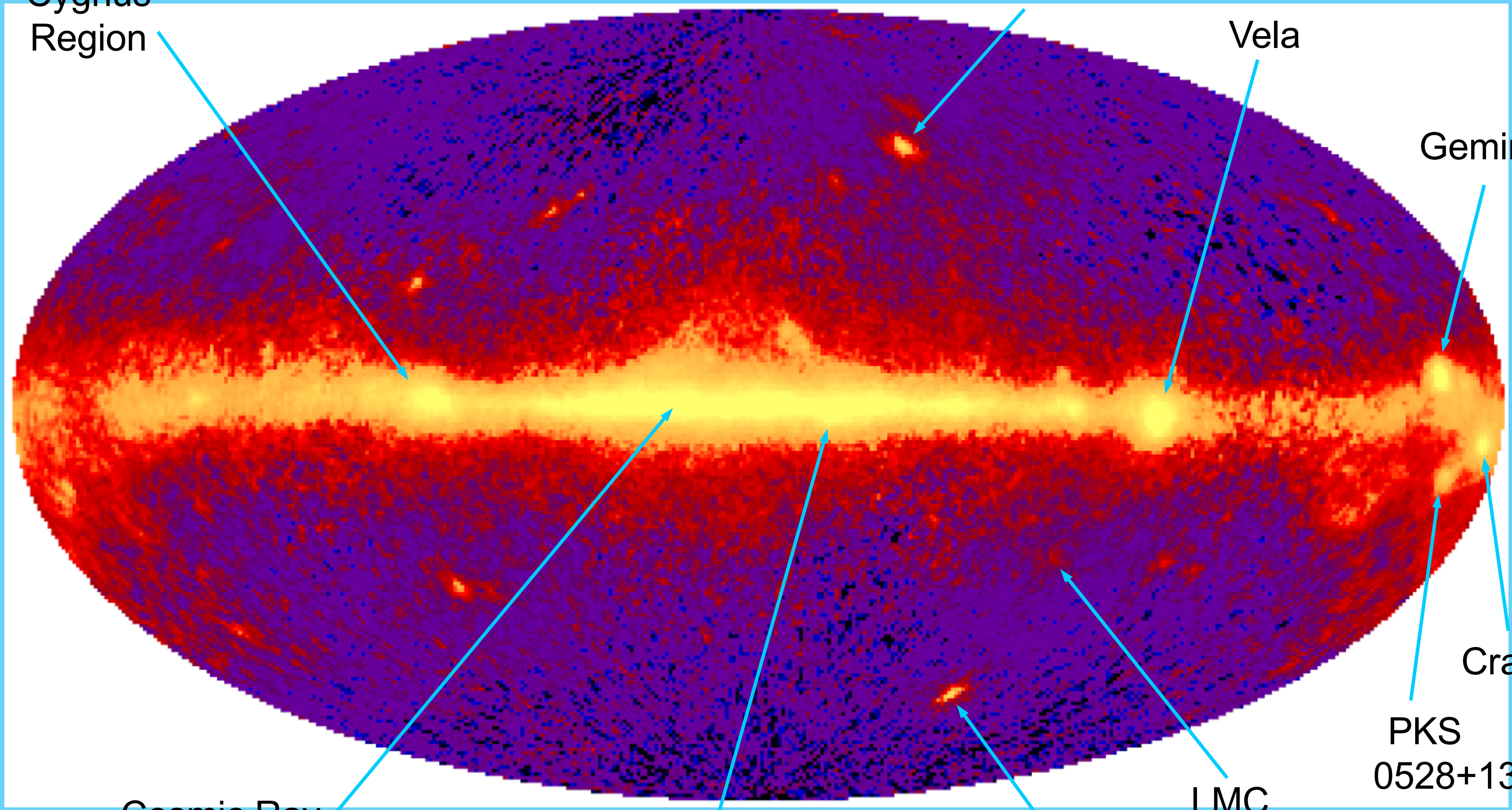


Plane of the Milky Way galaxy.
Peak gamma-ray intensity shown in white.

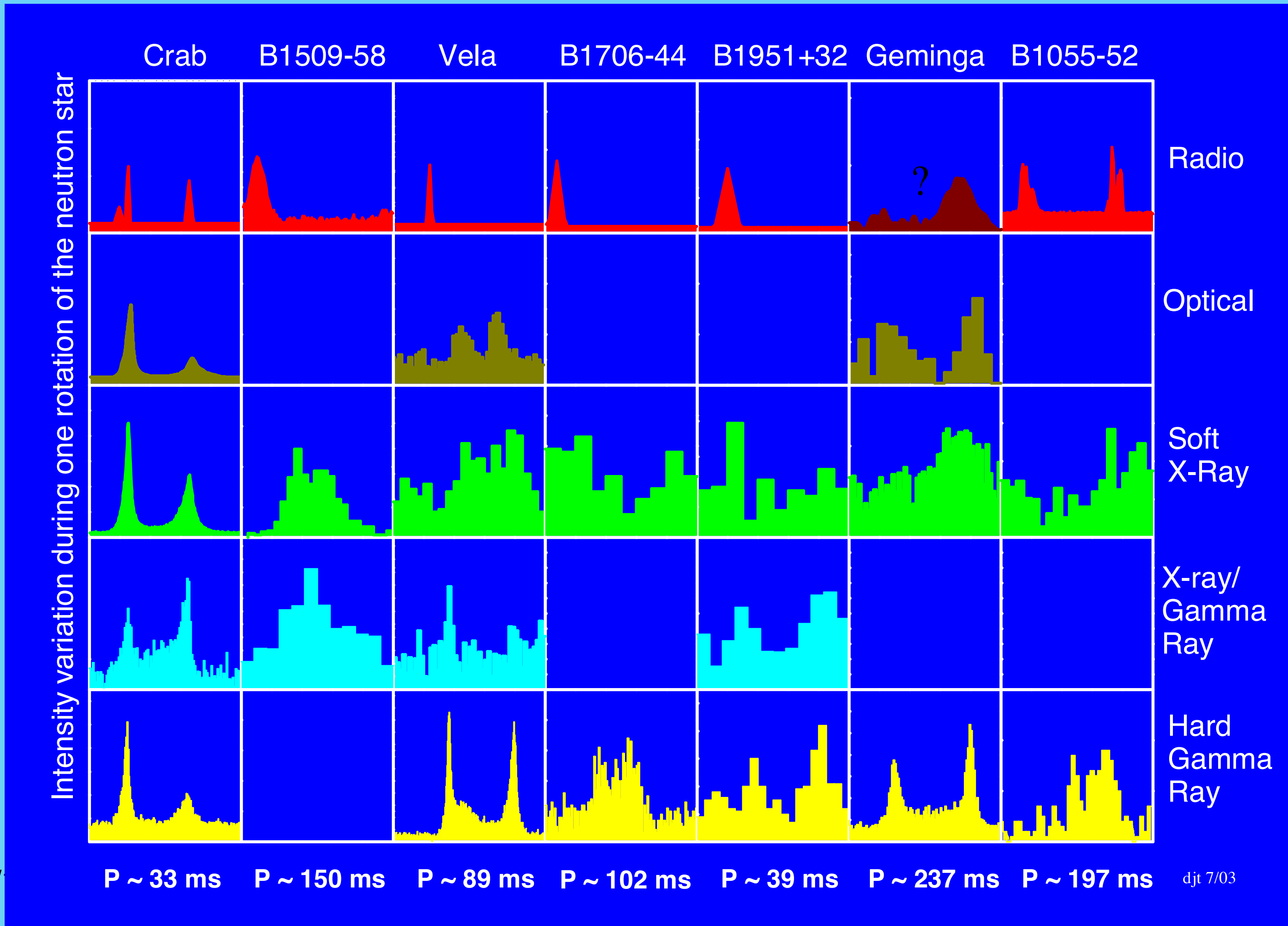
EGRET discovers Gamma ray sources



EGRET All Sky Map (>100 MeV)



EGRET pulsar time profiles



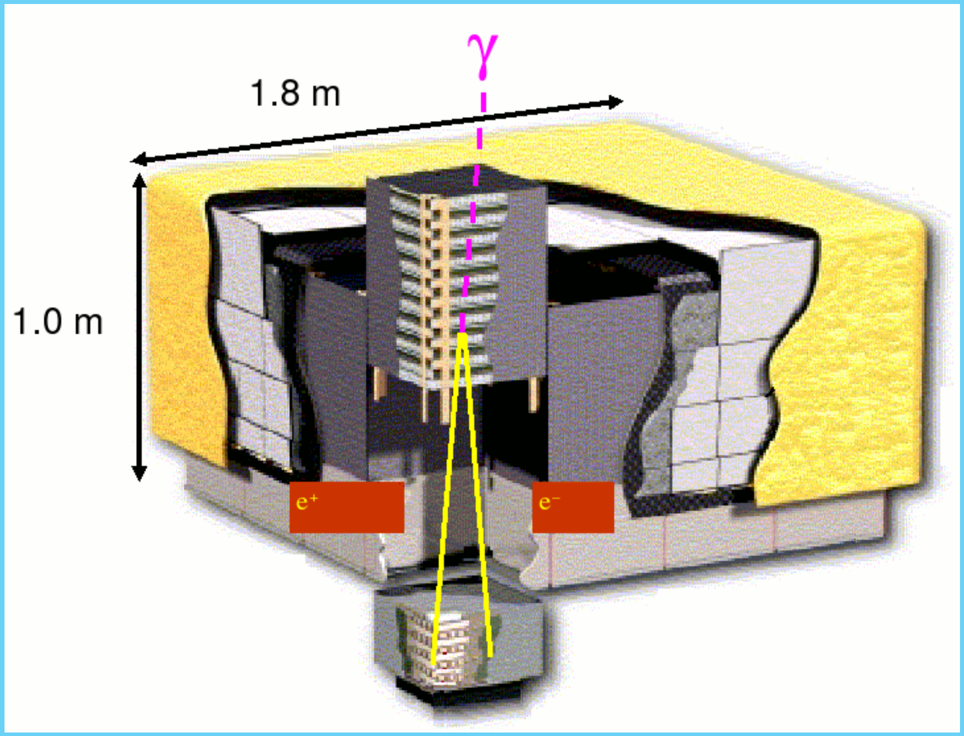
What's new?

- Discovered quasars, known to radio astronomy, were also gamma-ray sources with tremendous outputs of energy
  - Came to be known as blazers, a subset of Active Galactic Nuclei, objects powered by massive black holes
- Pulsars, also previously known to radio astronomers, were also commonly emitters of gamma rays
- Maybe EGRET could see supernova remnants, but they were often obscured by the gamma-ray background

Next generation gamma-ray telescope

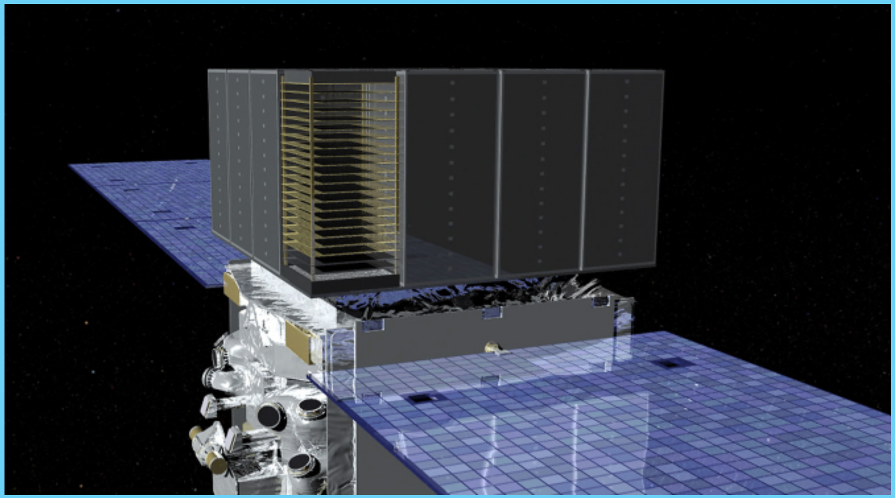
GLAST -> Fermi

- Monitor the high energy gamma-ray sky to study the time variations of AGN
- Develop statistical patterns of pulsars
- Monitor the gamma-ray sky looking for transients
- New discoveries with improved sensitivity



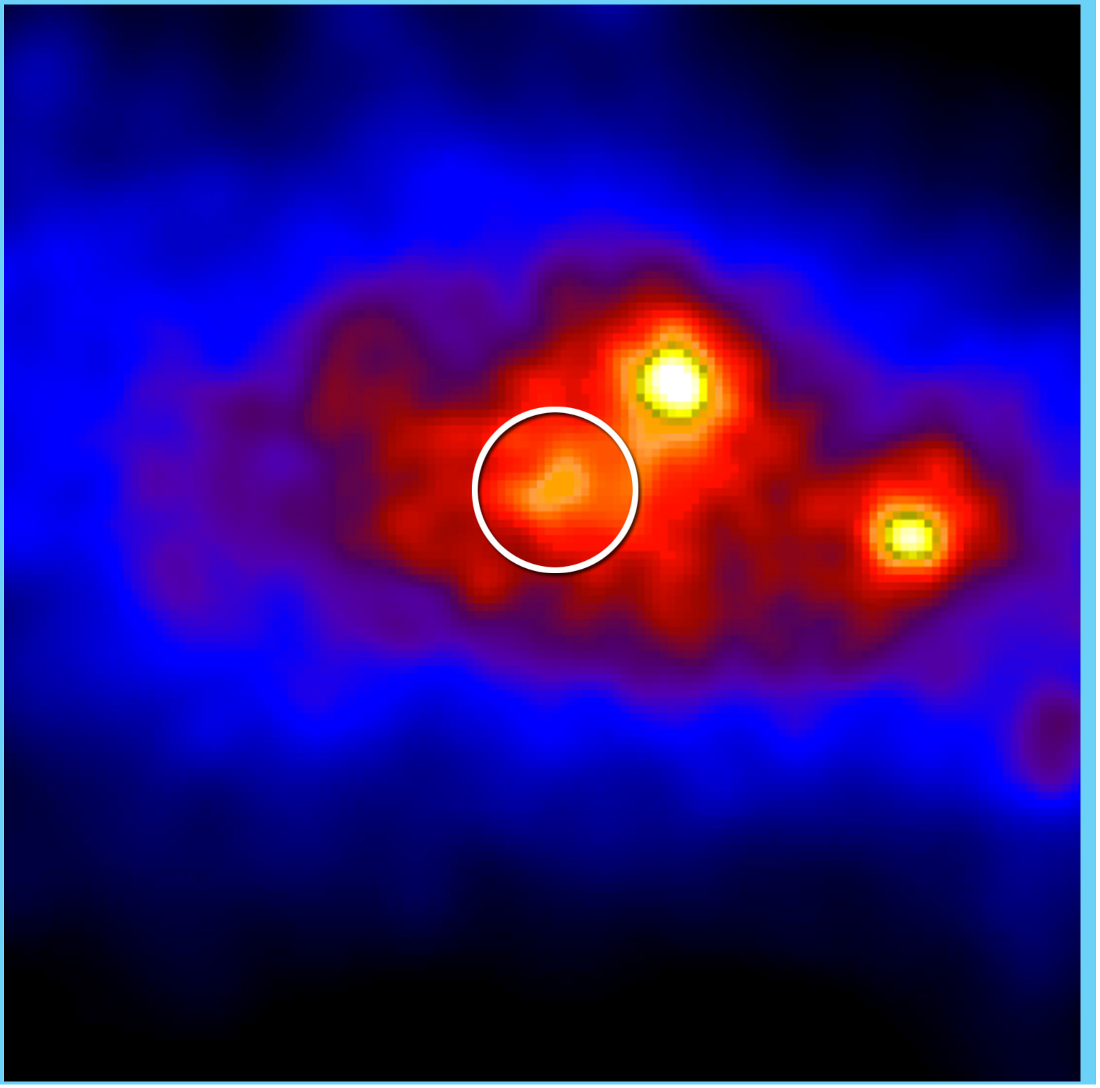
GLAST: Gamma-ray
Large Area Space Telescope

-> Fermi Space Telescope



Gamma-ray sky near Cygnus X-3

Close to the limit of resolving nearby sources.



Cygnus X-3
Microquasar: a hot massive Wolf-Rayet star in a binary system with either a NS or a BH.

Our measurement of excess ^{22}Ne has been traced to cosmic rays coming from such stars.

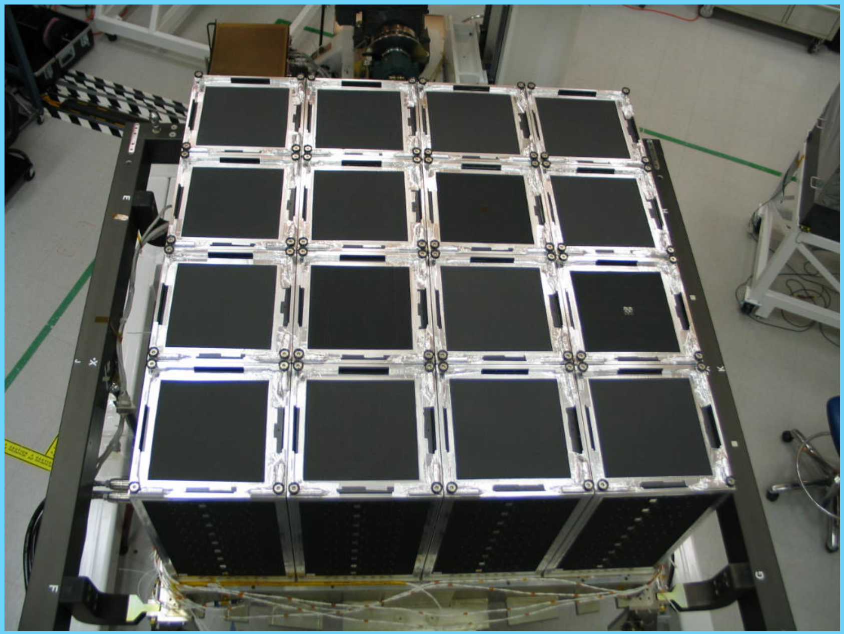
Satellite named after Enrico Fermi

- Fermi had written two papers with ideas about how the cosmic rays might be accelerated
- One of the GLAST objectives was to understand the origin of cosmic rays

Nobel Prize 1938

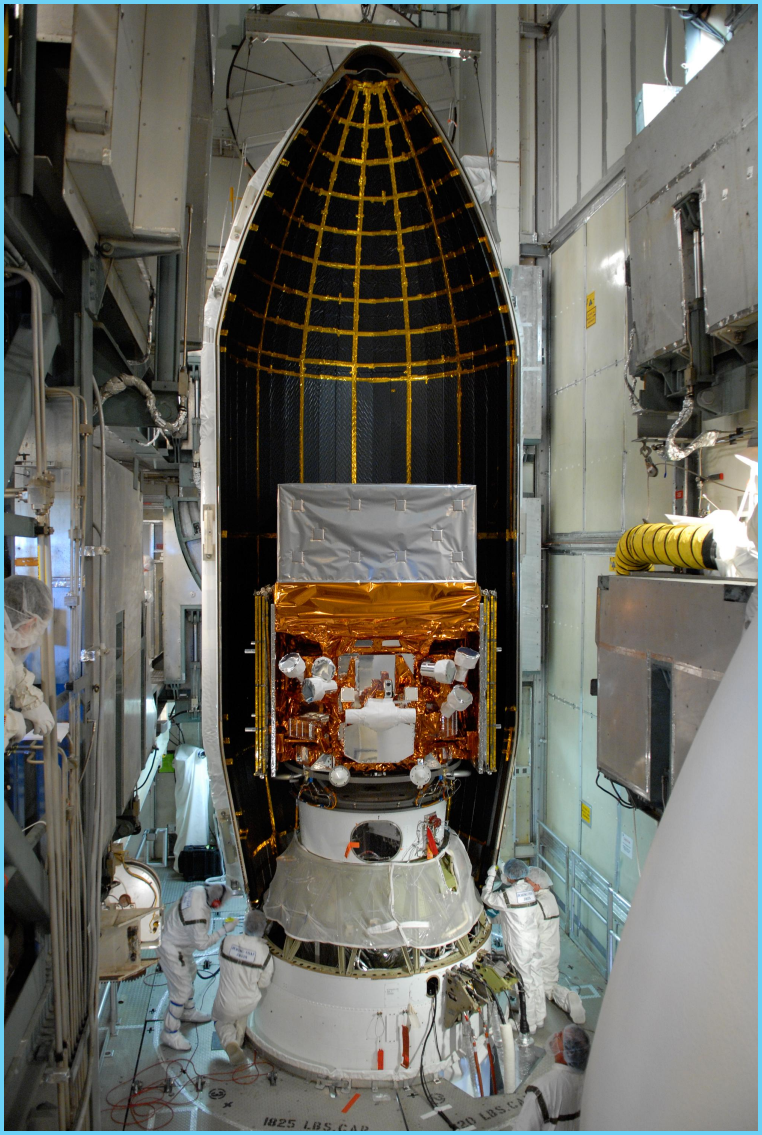
Role of neutrons in nuclear binding, work that led to nuclear reactors

I designed a segmented anti-coincidence detector to help identifying the gamma-rays among the enormous cosmic ray background



Background proportional to area: divide and conquer

Fermi launch ignition



Getting the eyes above the sky

- If you have worked on a project for many years, this is indeed an exciting moment.
  - Launch delays are frequent

GLAST launch closeup

GLAST launch from beach

The Fermi LAT Collaboration

A. A. Abdo1,2, M. Abry3, M. Ackermann4, M. Ajello4, Y. Akrami5,6, A. Allafort4, B. Anderson7, E. Antolini8,9, K. Asano10, W. B. Atwood7, T. Aune7, M. Axelsson5,11, M. Balbo12,13, L. Baldini14, J. Ballet15, E. A. Baltz4,16, D. L. Band17,18,19, G. Barbiellini20,21, M. G. Baring22, D. Bastieri12,13, M. Battelino5,23, B. M. Baughman24, K. Bechtol4, A. Belfiore25, R. Bellazzini14, B. Berenji4, L. Bergstr¨om5,6, D. Bernard26, G. F. Bignami27, E. Bissaldi28, R. D. Blandford4, P. Blasi29, E. D. Bloom4, M. Boeck30, E. Bonamente8,9, J. Bonnell19, A. W. Borgland4, A. Bouvier4, T. J. Brandt24, J. Bregeon14, A. Brez14, M. Brigida31,32, P. Bruel26, T. H. Burnett33, G. Busetto12,13, S. Buson13, G. A. Caliandro31,32, R. A. Cameron4, B. Canadas34,35, A. Cannon19,36, P. A. Caraveo25, S. Carius37, P. Carlson5,23, S. Carrigan13, J. M. Casandjian15, E. Cavazzuti38, C. Cecchi8,9, O¨ . C¸ elik19, A. Celotti39, C. S. Chang40, E. Charles4, S. Chaty15, A. Chekhtman2,41, A. W. Chen25, C. C. Cheung19, J. 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Otte7, M. Ozaki67, B. Pancrazi68, D. Paneque4, J. H. Panetta4, D. Parent55,56, V. Pavlidou79, T. J. Pearson79, V. Pelassa3, G. Pelletier54, M. Pepe8,9, M. Pesce-Rollins14, V. Petrosian4, G. Piano34,35, P. Picozza34,35, M. Pierbattista15, S. Piranomonte86, F. Piron3, C. Pittori38, A. Pohl37, M. Pohl87, T. A. Porter7, M. Prest20,88, J. R. Primack7, S. Profumo7, S. Rain`o31,32, E. Ramirez-Ruiz69, R. Rando12,13, P. S. Ray2, M. Razzano14, S. Razzaque1,2, N. Rea89,90, A. Readhead79, A. Reimer4, O. Reimer4,91, T. Reposeur55,56, L. C. Reyes92, J. L. Richards79, J. Ripken5,6, S. Ritz19, S. Robinson33,93, L. S. Rochester4, A. Y. Rodriguez90, R. W. Romani4, M. Roth33, J. J. Russell4, F. Ryde5,23, S. Sabatini34,35, T. Sada59, H. F.-W. Sadrozinski7, A. Saggion12,13, R. Sambruna19, D. Sanchez26, A. Sander24, R. Sato67, P. M. Saz Parkinson7, J. D. Scargle94, T. L. Schalk7, J. Schmitt15, P. Scott5,6, A. Sellerholm5,6, C. Sgr`o14, G. H. Share2,95, M. S. Shaw4, C. Shrader17, J. Siegal-Gaskins24, A. 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F. Wu80,105,106, R. Yamazaki59, H. Yasuda59, Y. Yatsu73, T. Ylinen5,23,37, T. Yuasa75, G. Zaharijas5,6, S. Zalewski7, J. A. Zensus40, M. Ziegler7

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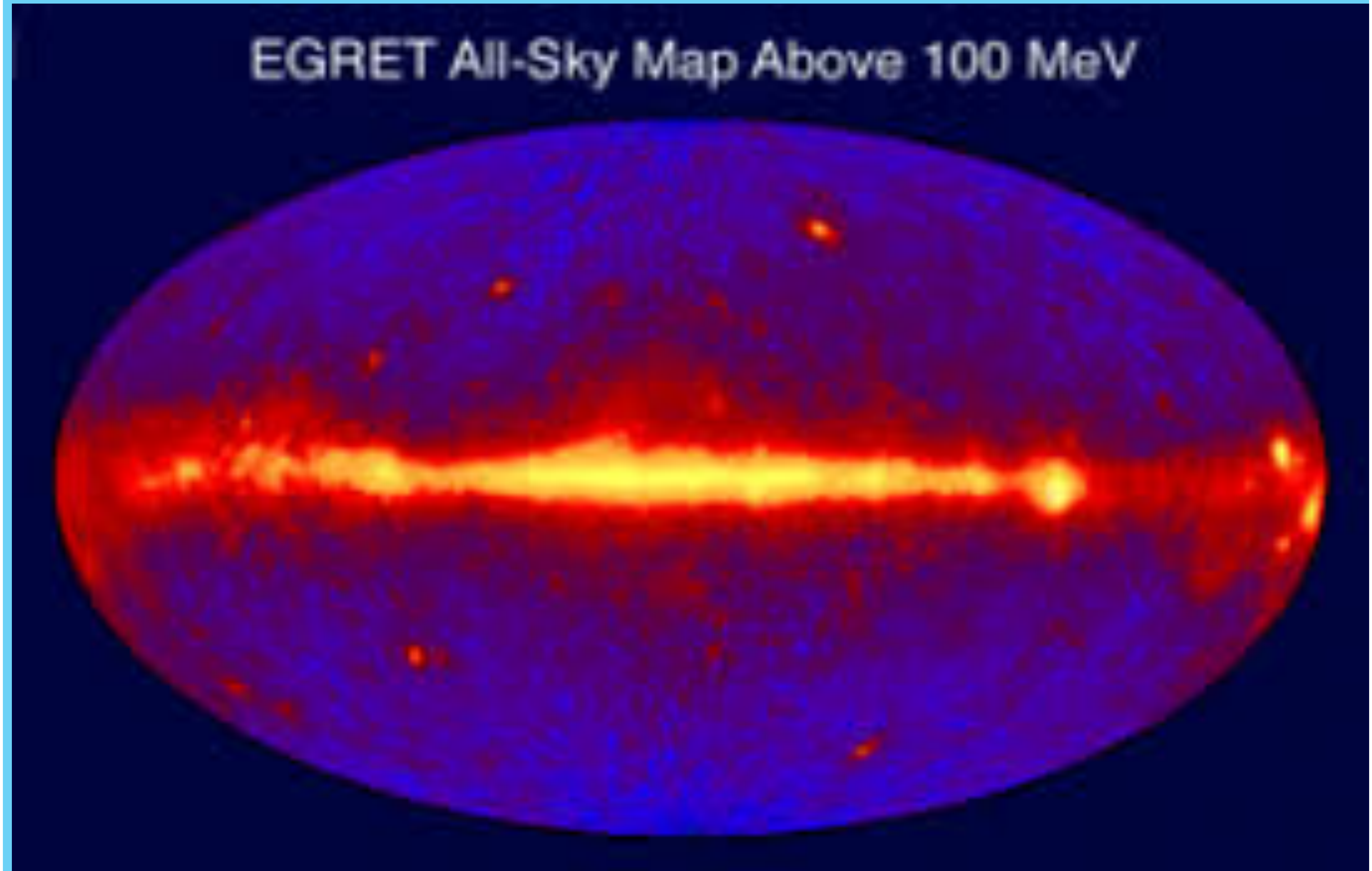
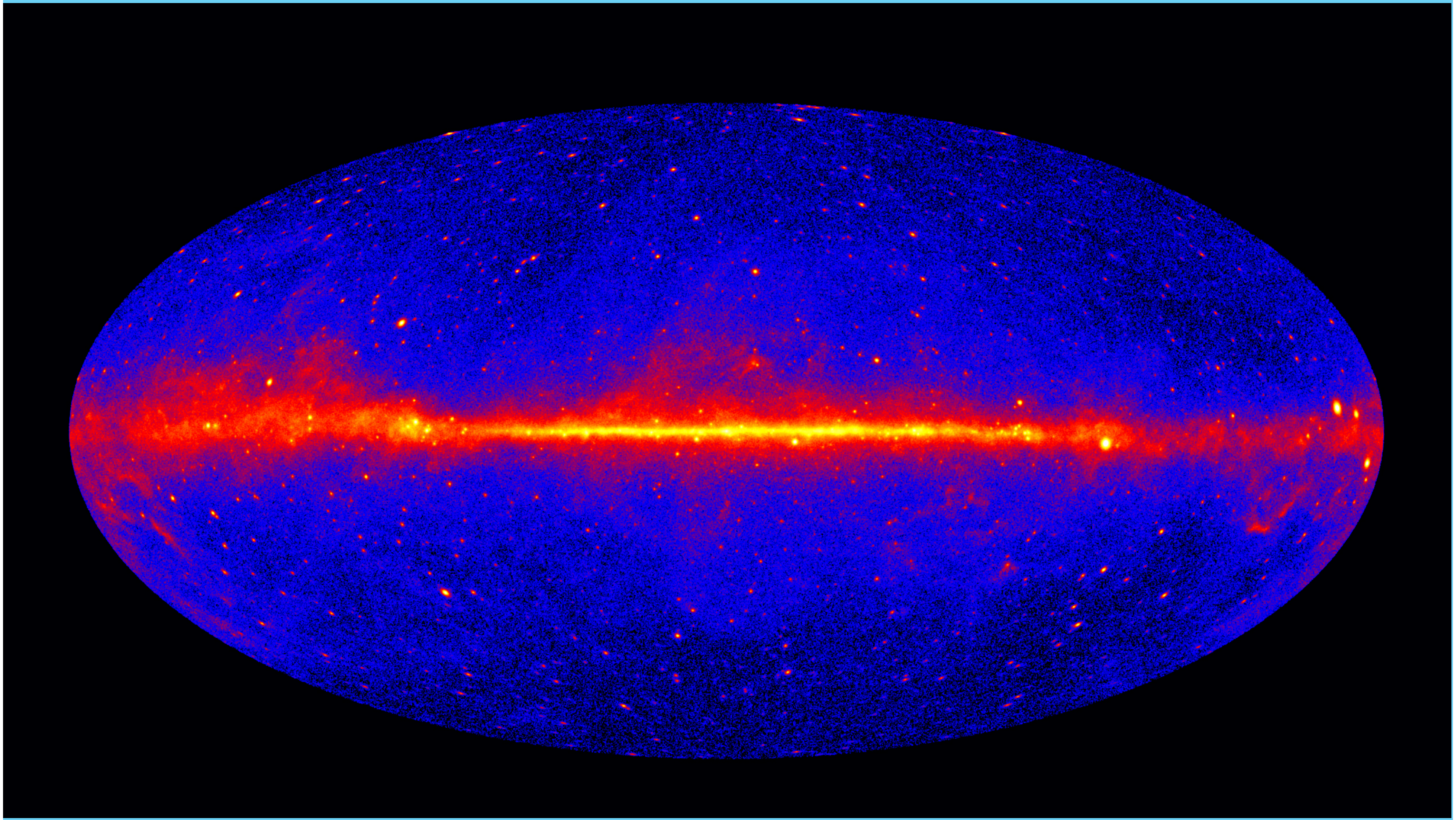
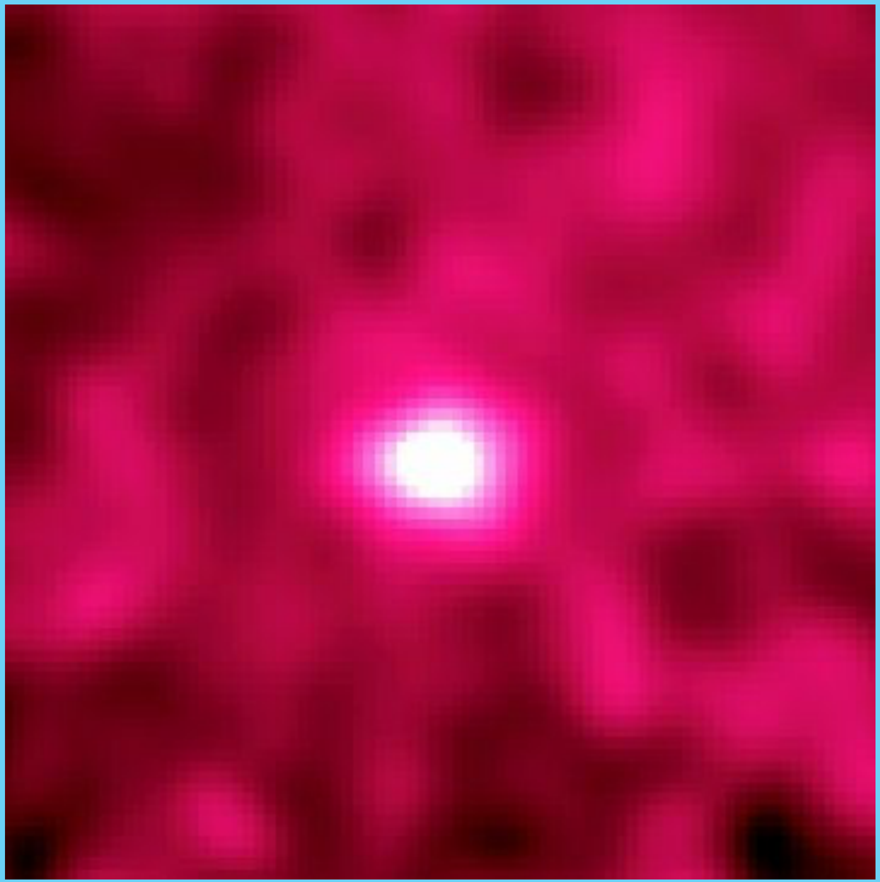

EGRET All-Sky Map Above 100 MeV

Fermi all-sky 5 years of data



The moon in gamma-rays



Cosmic rays strike the moon,
$p + p \rightarrow \pi^o \qquad \pi^o \rightarrow 2\gamma$

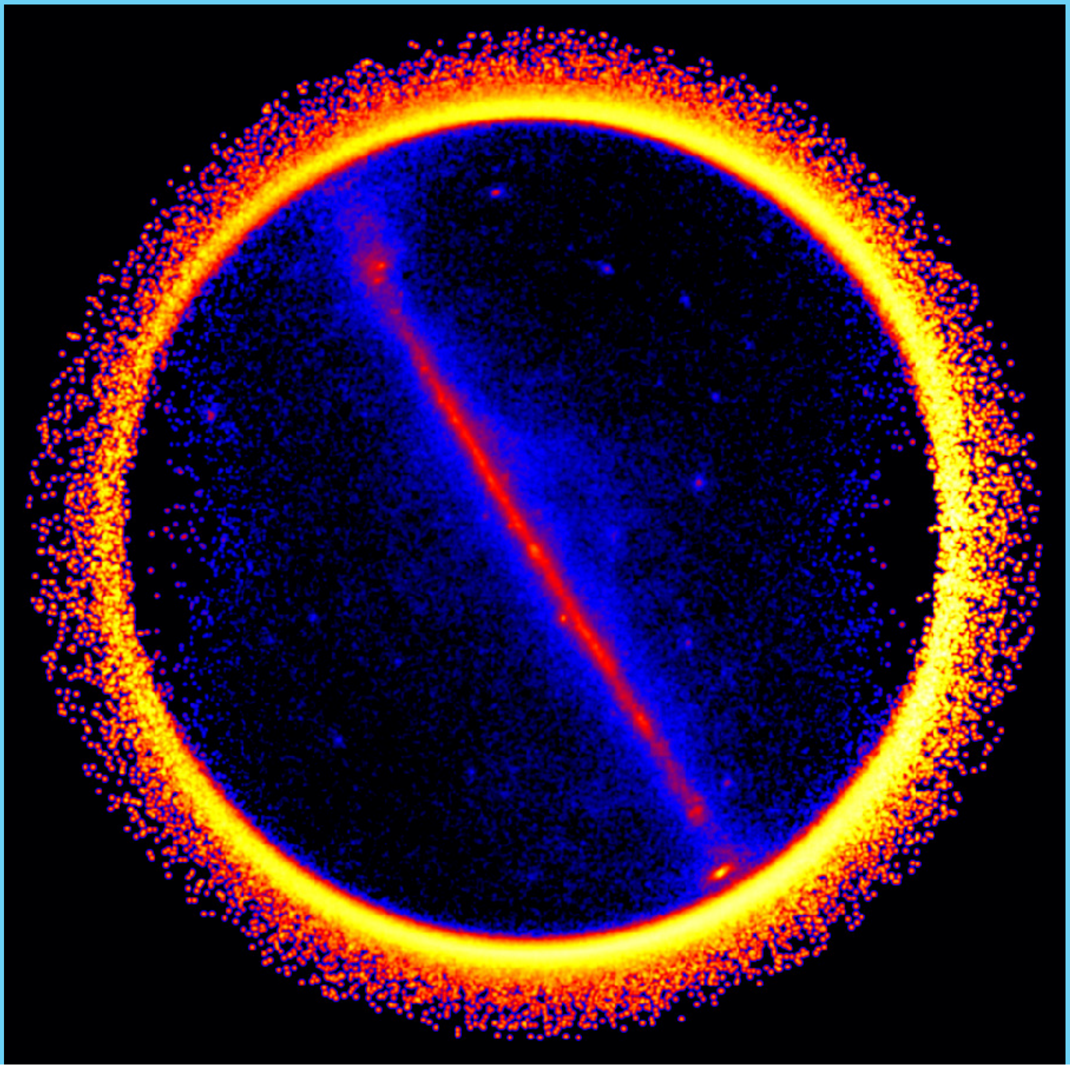
In principle, all the matter in the solar system can be mapped by gamma rays.

The problem is to separate all the diffferant contributors.

As seen from the satellite pointing towards the galactic center.

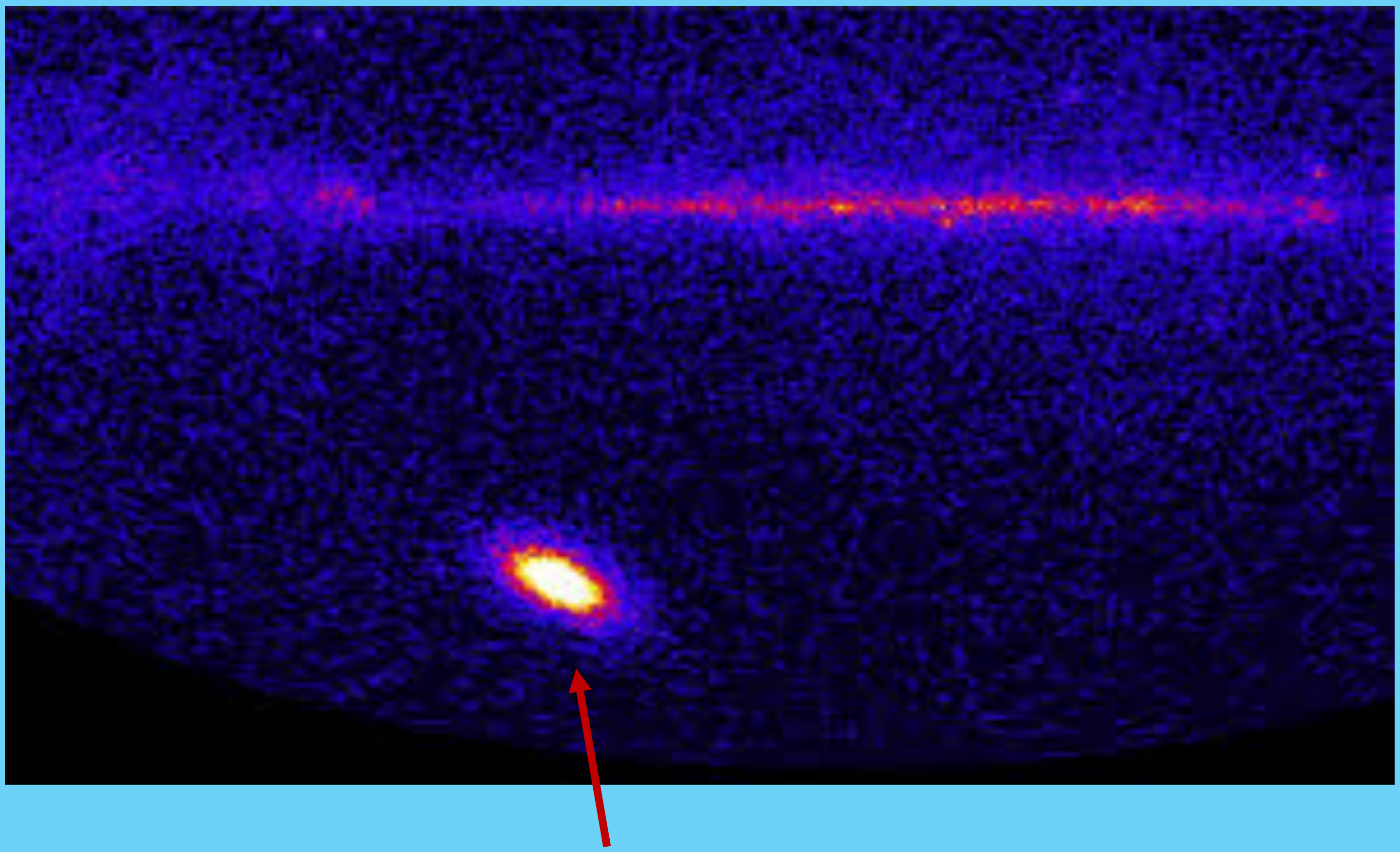
Colors represent brightness, yellow high to red low.

We are seeing cosmic ray interacting in the Earth's atmosphere.



A solar flare observed by Fermi

https://www.youtube.com/watch?v=mc-wQwaUh_Q

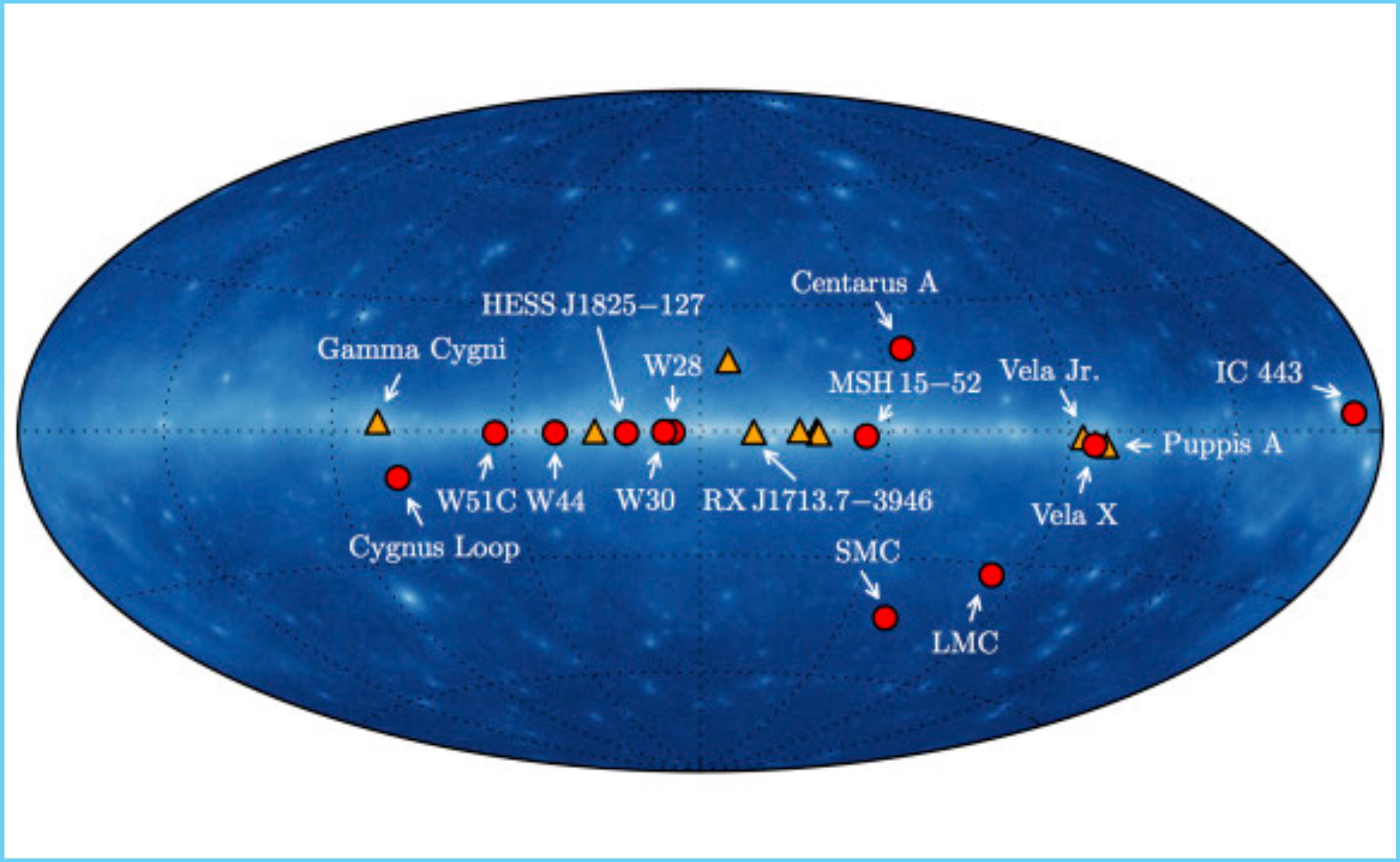


Galactic plane

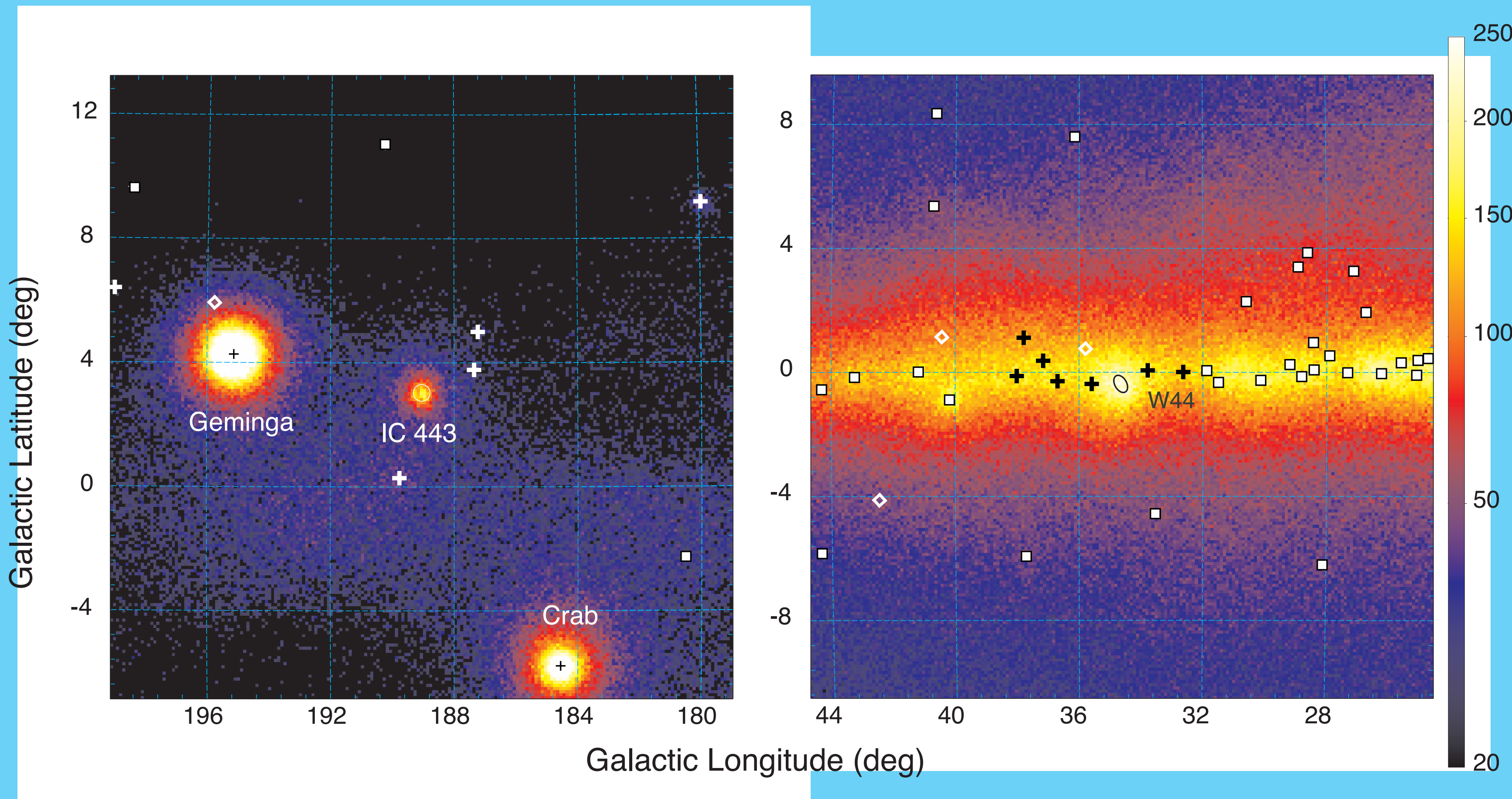
Location of the sun at the time of the flare.

Solar flare seen by Fermi

Extended sources



SNR with π^o spectra

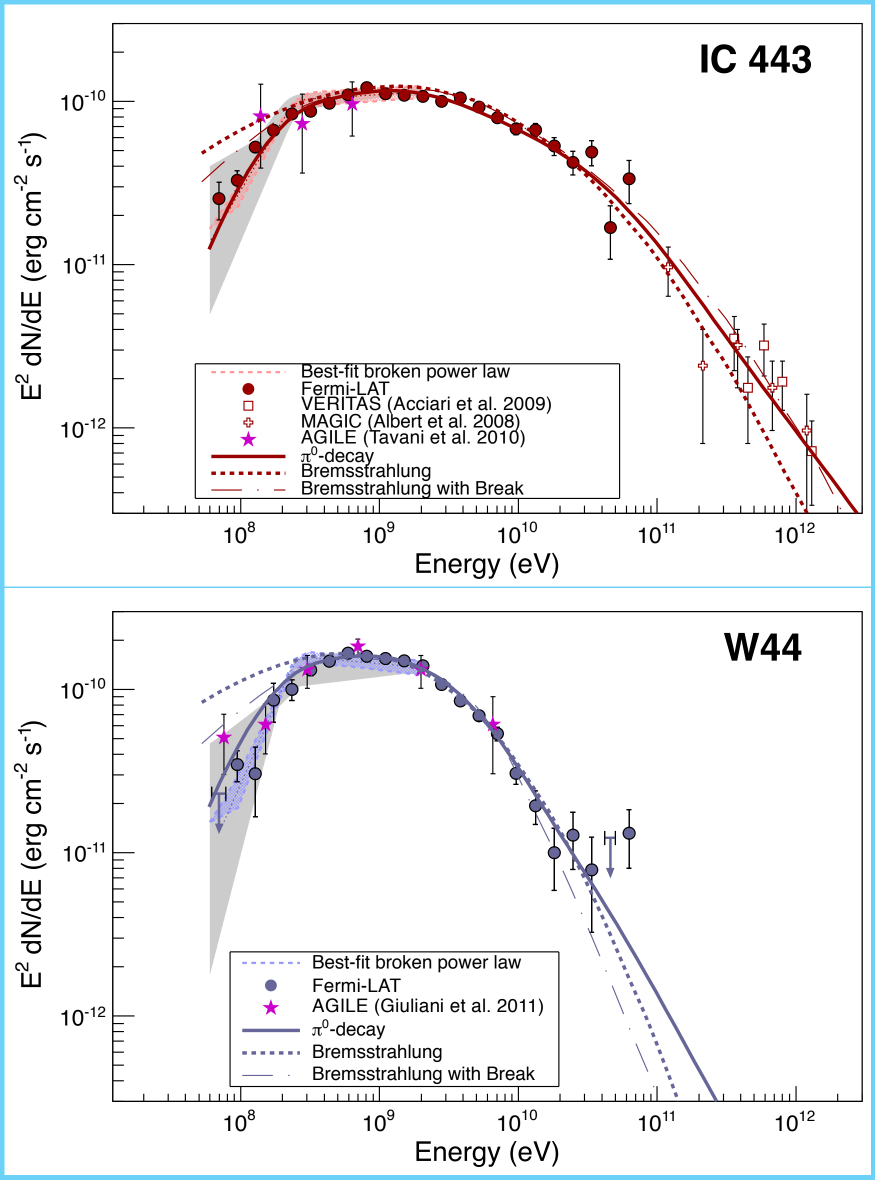


SNR with π^o spectra

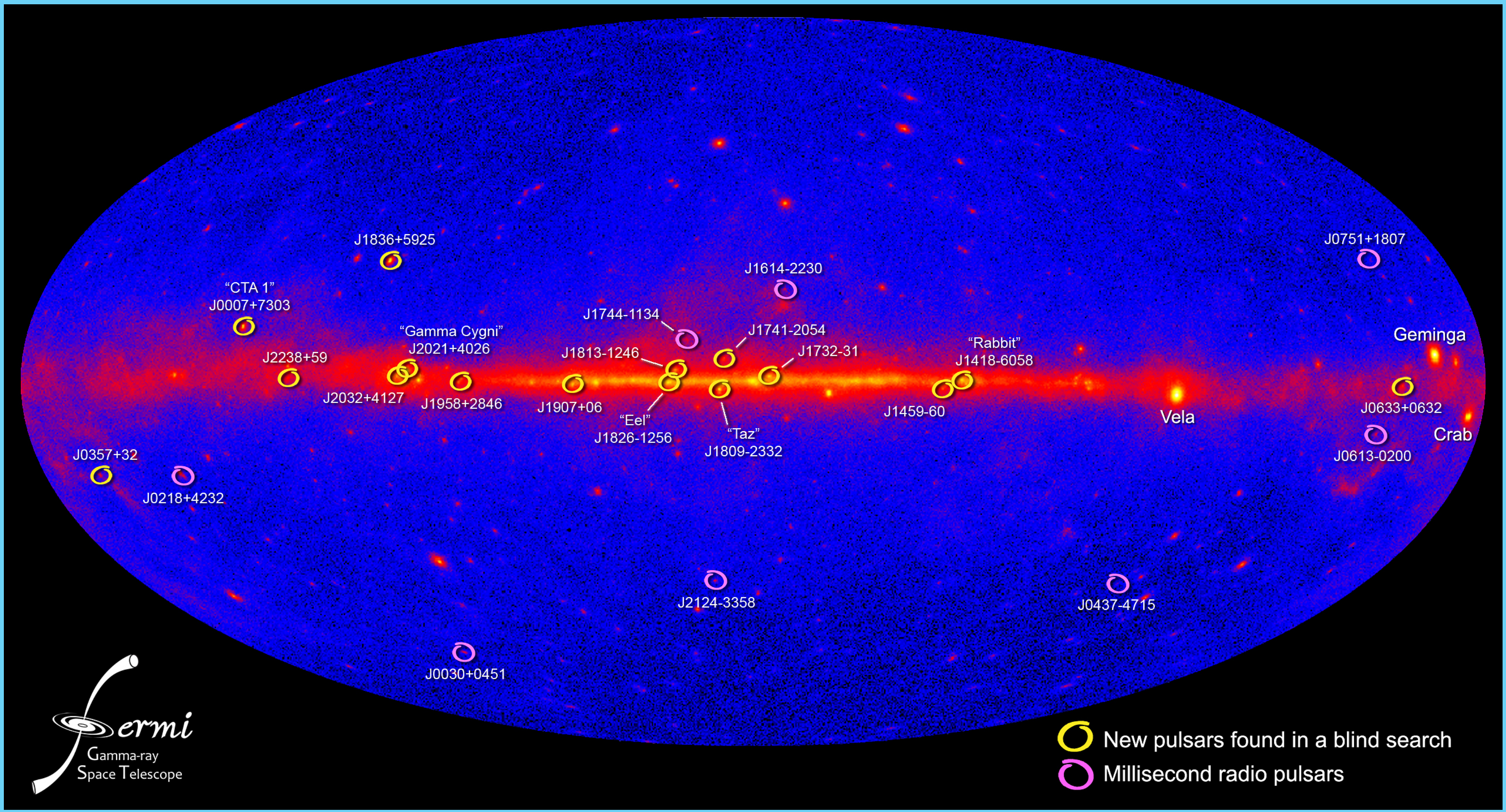
Finding peak just below 1 GeV was difficult. Other processes make gamma-rays in same energy band but without spectral peak.

Also have to find and subtract the diffuse background.

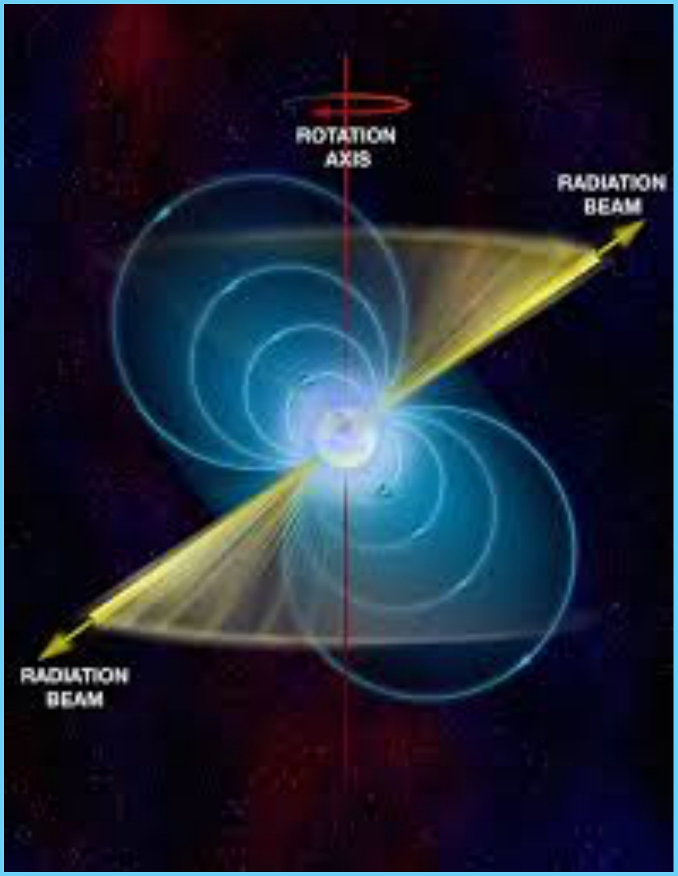
Smoking gun for SNR being the source of cosmic rays.

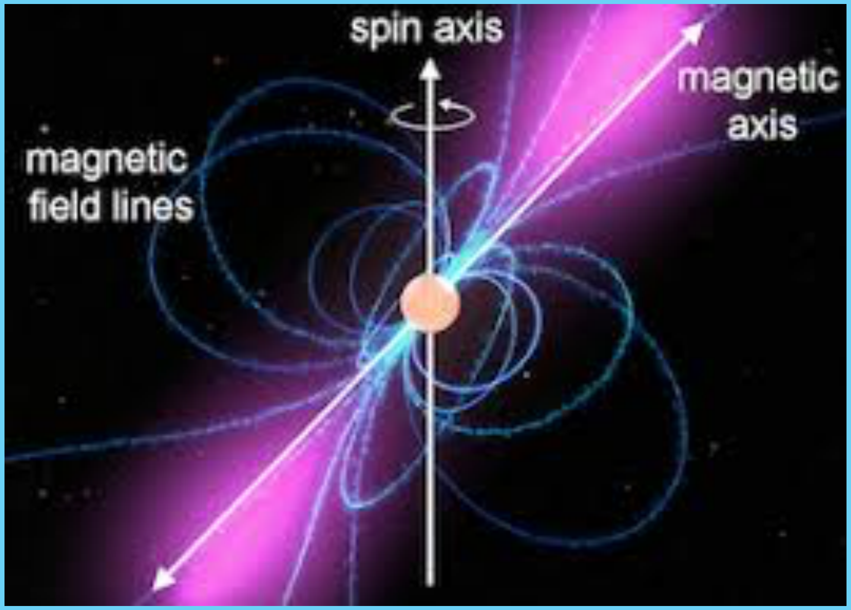


Fermi LAT pulsars

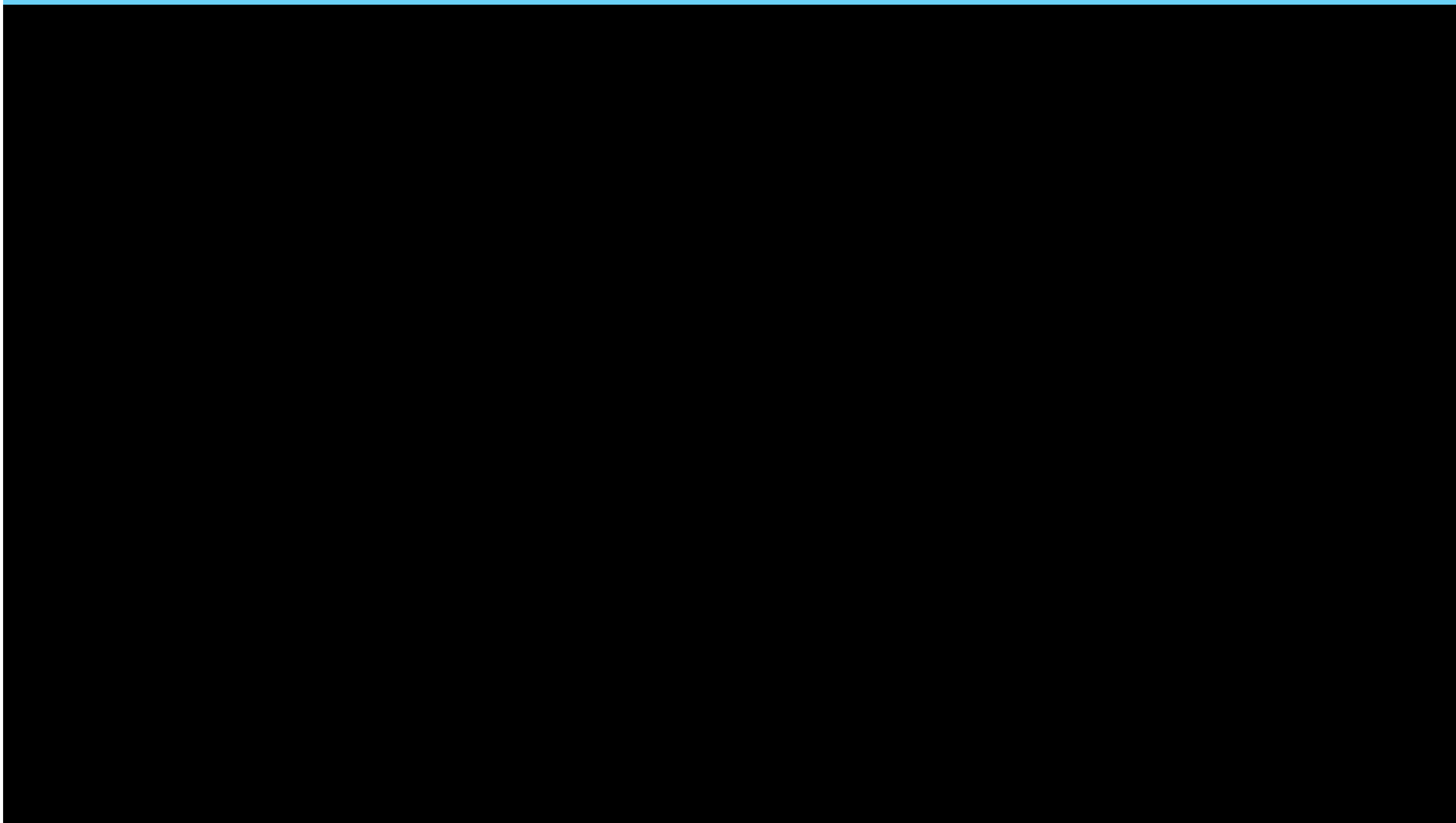


Pulsars


ROTATION AXIS
RADIATION BEAM
RADIATION BEAM


spin axis
magnetic axis
magnetic field lines

What are pulsars



Collapsed stars and densities

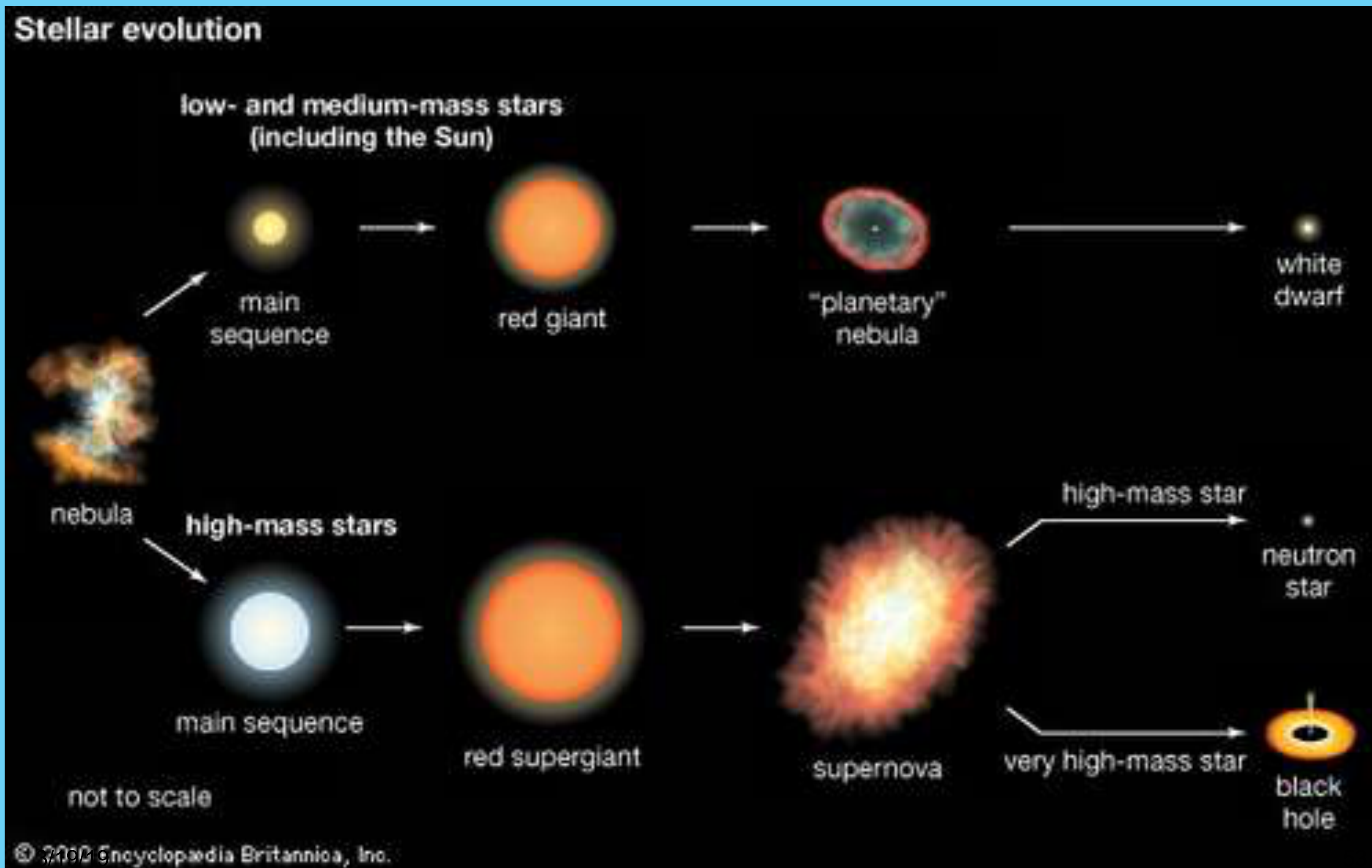
- Water 1 g/cm^3
- Earth 5 g/cm^3

- White dwarfs 10^6 g/cm^3
- Neutron stars 10^{14} g/cm^3
  - Pulsars
- Black holes $4x10^{14}$ g/cm^3

Collapsed stars

- White dwarfs
  - M_o about the size of Earth
- Neutron stars
  - 1.4 M_o is about 14 miles in diameter
- Black holes
  - 3.8 M_o up to 3 x 10^{10} M_o (30 billion)
  - 4 miles diameter to 100 AU (10 x Pluto's orbit), the edge of the solar system

What happens to old stars?



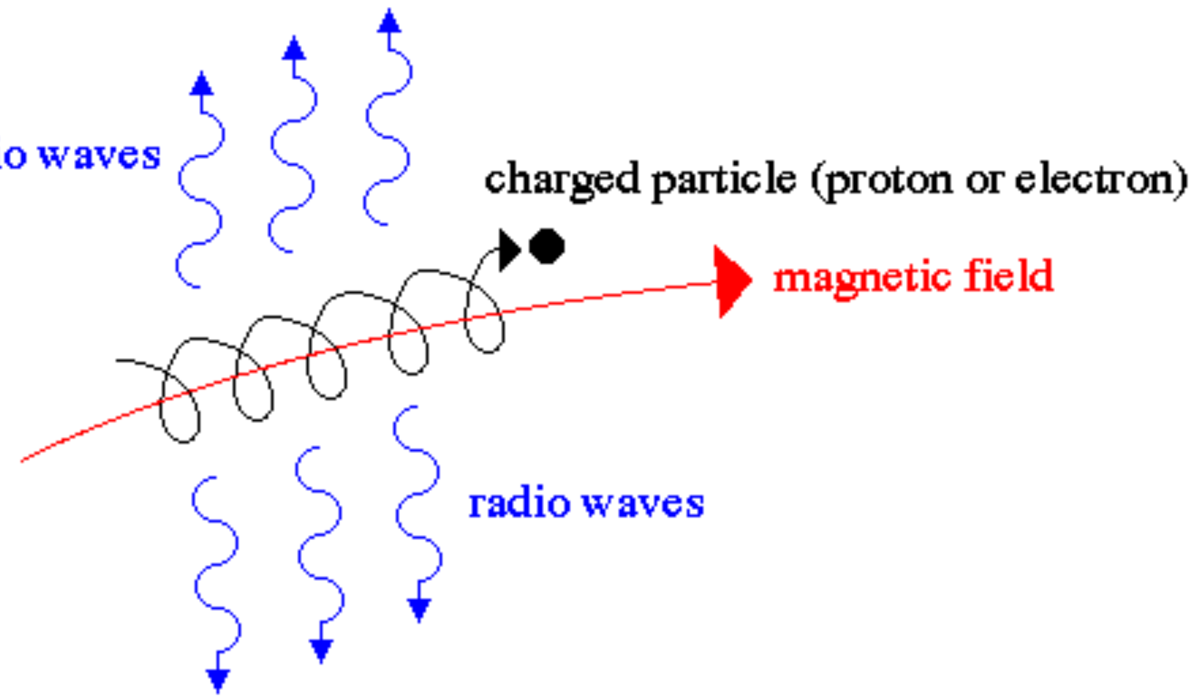
Mass ranges

- We use the Sun's mass as a unit for studying stars
- We designate it as M_o; we say the mass of our sun is $M_{sun} = 1\ M_o$

- $M_{dwarf} < 1.39\ M_o$ => white dwarf
- $1.39\ M_o < M_{ns} < 3.2\ M_o$ => neutron star
- $M_{BH} > 3.2\ M_o$ => black hole
  - stellar sized black holes
  - The original stars lose blow off a lot of mass in their explosions
- Black hole at the center of our galaxy $M = 10^6\ M_o$
- Supermassive Black holes $10^9\ M_o$

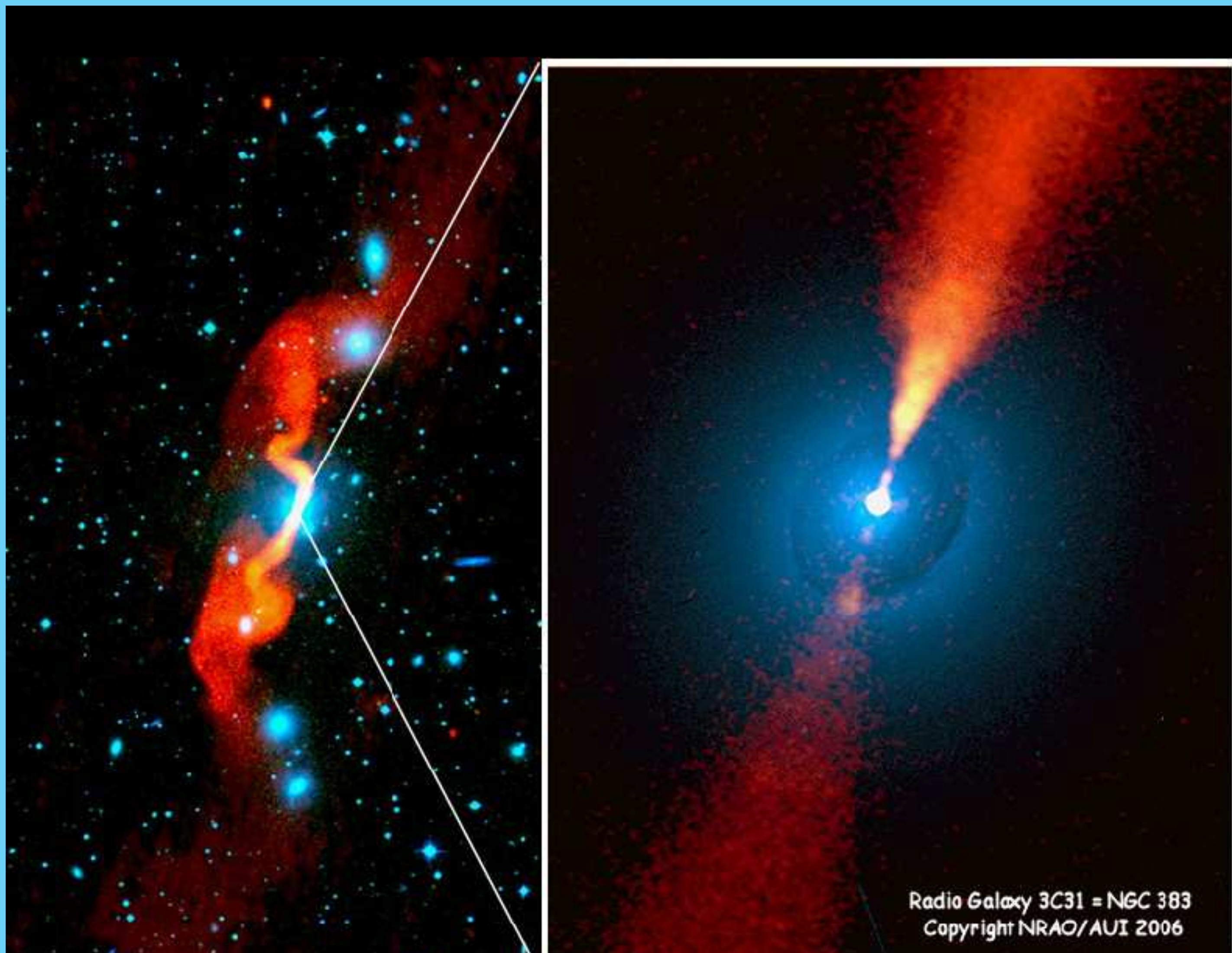
Synchrotron radiation

Synchrotron radiation

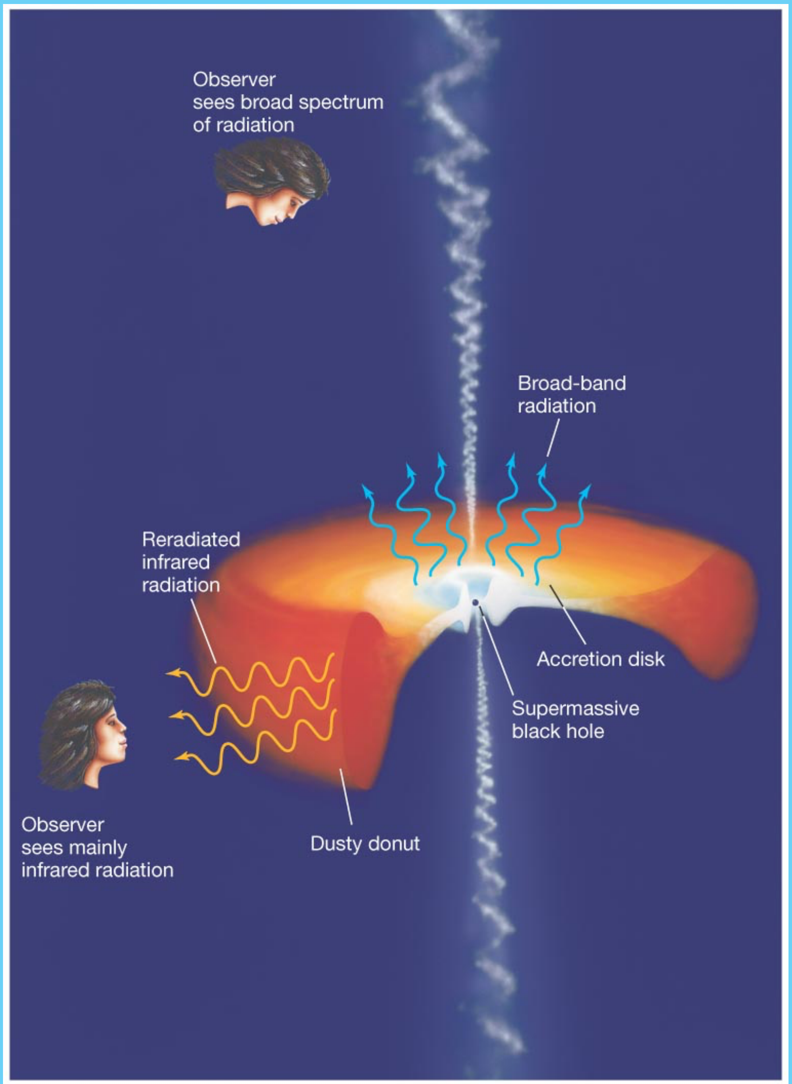


synchrontron radiation occurs when a charged particle encounters a strong magnetic field – the particle is accelerated along a spiral path following the magnetic field and emitting radio waves in the process – the result is a distinct radio signature that reveals the strength of the magnetic field

Radio galaxy 3C31, aka NGC383



What you see depends on where you see it from



Supermassive black holes

Accretion disk – see x-rays from the hot gas

Radio observations of the beams

Class of objects are called Active Galactic Nuclei

Blazars: beam points to Earth gamma-rays beamed at us

- What particles make the gamma-rays, e- or p?

Active galaxies: thumbnail sketch

- Presumably all active galaxies have the same basic ingredients: they are all powered by a flow of material onto a supermassive black hole

- When the relativistically boosted jet points close to the line of sight, it is so bright that its emission masks the isotropically emitting "central engine".

- Importantly, the radiating particles must be accelerated to multi-GeV energies to provide the "radiating agent".

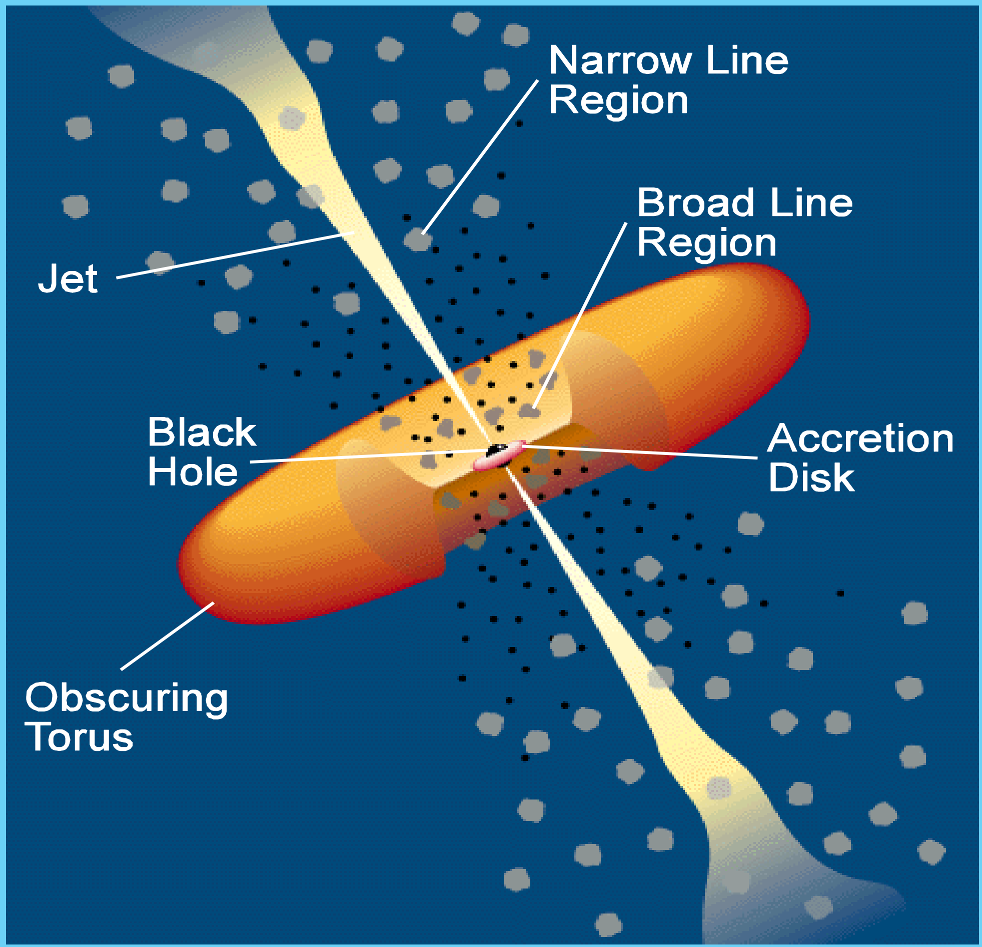


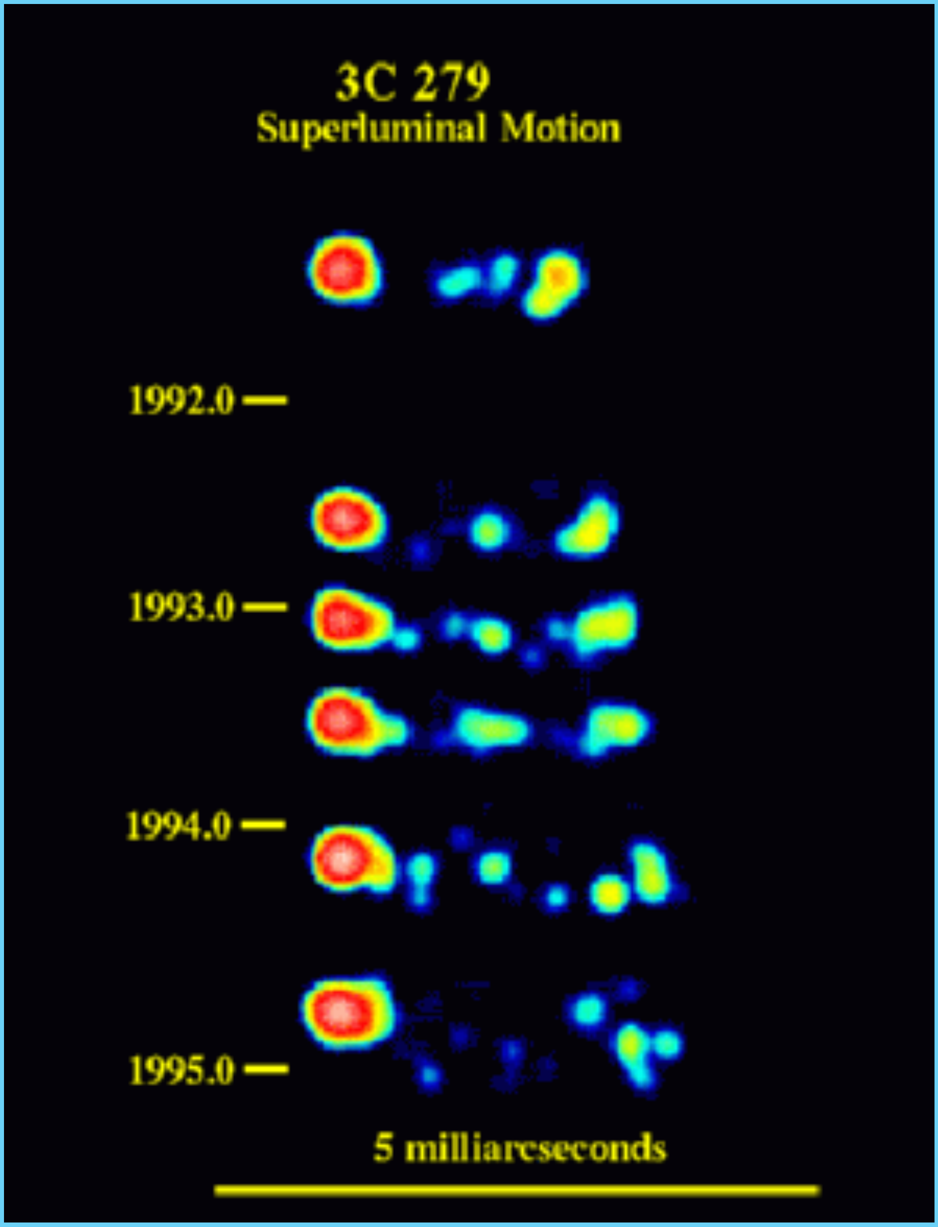
Diagram from Padovani and Urry

Active Galaxies always show relativistic jets

* How do we know a jet is relativistic? Mainly because the structures change with time, showing apparent "superluminal" expansion

* This is easily explained as just a geometrical effect, but the velocity has to be close to *c* (Lorentz factor Γ_j ~ 10) and the angle to the line of sight – small

* Very strong Doppler-boost!



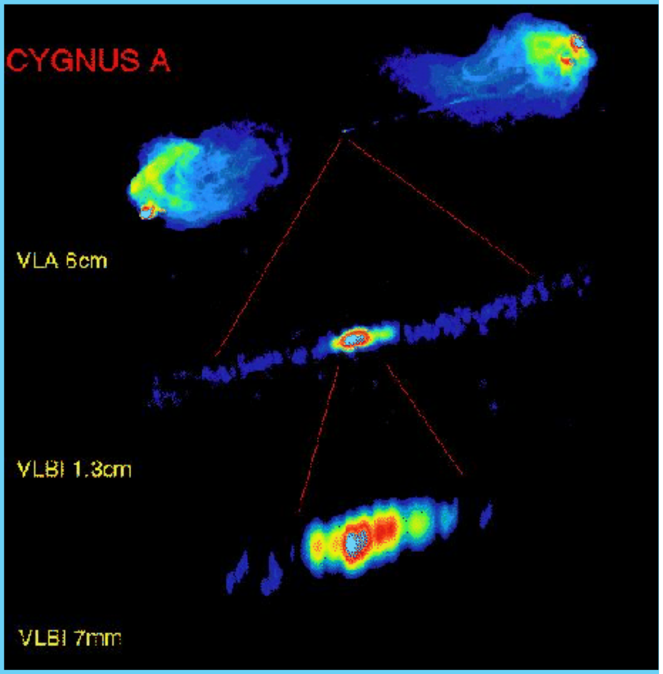
Credit: Very Large Array Image Archive

How do these sources work?

* How is the jet formed? What is the connection of the jet to the accretion process? (electromagnetic processes - unipolar inductor?)

* How is the jet so precisely collimated, over many decades of distance?

- How are radiating particles accelerated to multi-GeV energies? (=conversion of “bulk” to “random”)



- Role of hadronic processes (p vs. e)?
- What is the jet content?
- e+/e- pairs, or e-/p+ ?

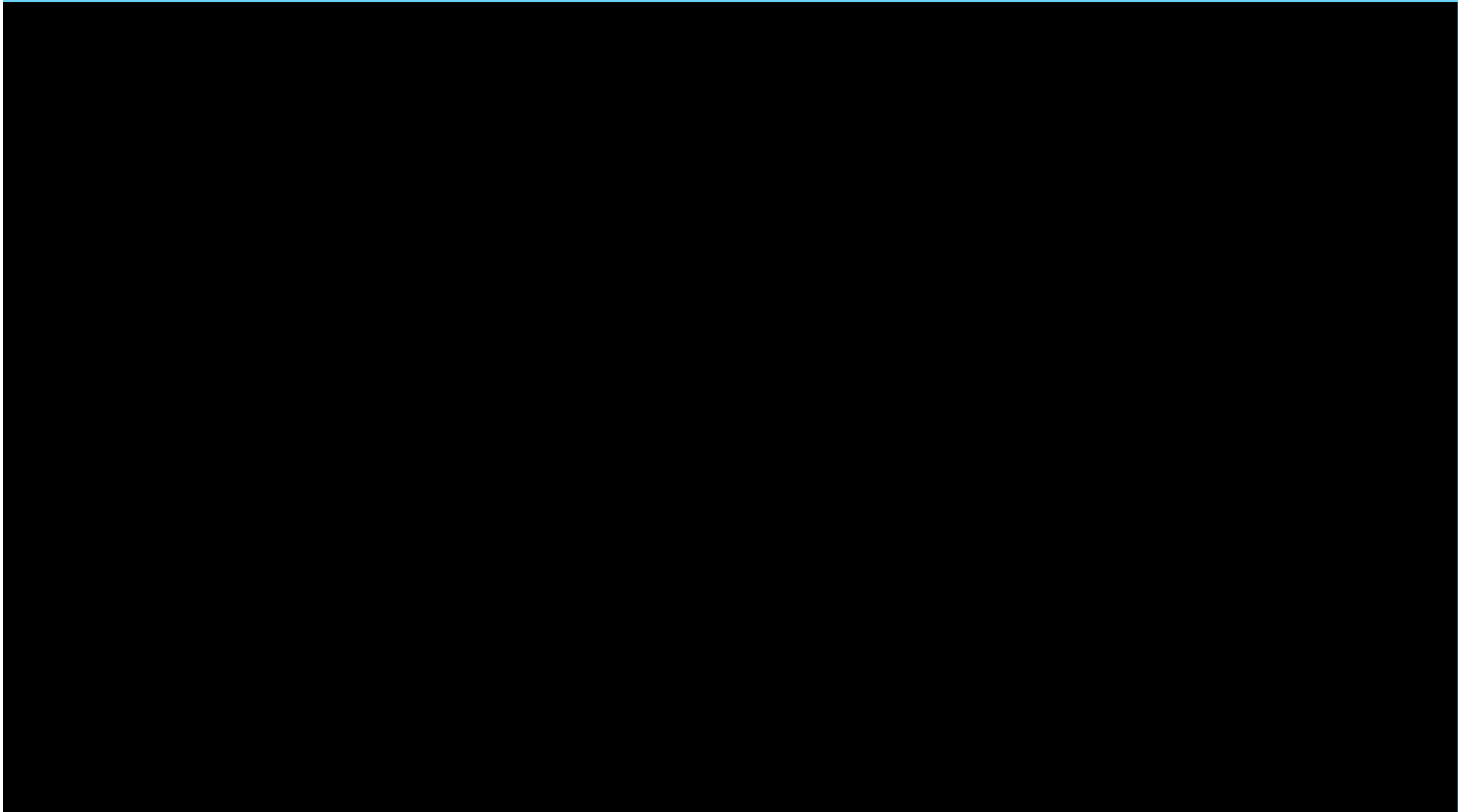
Fermi-LAT sees blazar TXS 0506+056

https://www.youtube.com/watch?v=cbWATaQx33s

Source visualized accumulating

https://www.youtube.com/watch?v=pCA47Fo5Yvk

Blazar neutrino

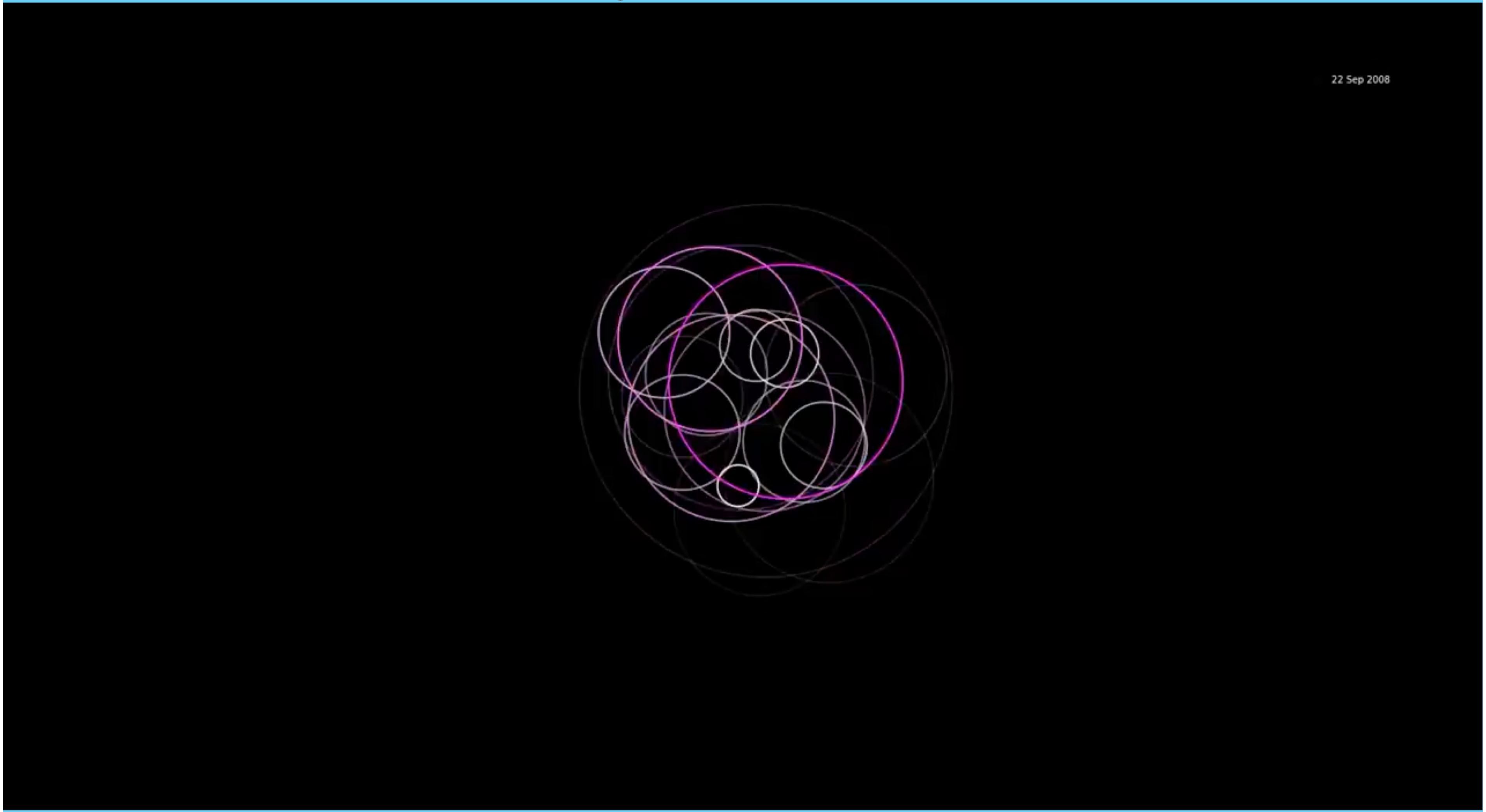


Gamma-ray rain from 3C 279

https://www.youtube.com/watch?v=9Rl4l6tuHGg

Image is about 5 degrees wide

Gamma-ray flare from blazar



Blazar physics