



FROM COLD WAR SATELLITES TO MODERN GAMMA-RAY ASTRONOMY

by Milena Crnogorčević



Scientifika
20 March 2026



What is the most energetic photon* we have ever detected?

(a) 1,000x the energy
of a Sun photon

(b) 1,000,000x

(c) 1,000,000,000x

(d) 1,000,000,000,000x

(e) 1,000,000,000,000,000x

[Photon: unit of light.]

[Note: A single green photon from the Sun: ~2eV]

What is the most energetic photon we have ever detected?

(e) 1,000,000,000,000,000,000x

→ In 2024, LHAASO announced the detection of a 2.5 PeV gamma ray! **Over a quadrillion times more energetic!**

LHAASO



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What is the most energetic photon we have ever detected?

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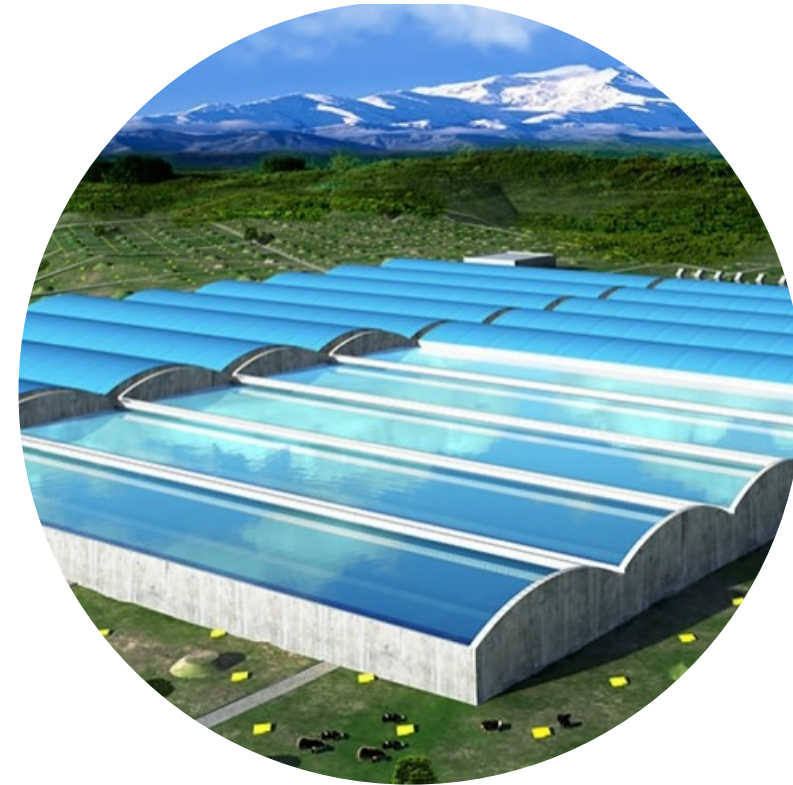
→ In 2024, LHAASO announced the detection of a 2.5 PeV gamma ray! **Over a quadrillion times more energetic!**

how big is a quadrillion?

Energy of a ping pong ball lobbed gently across the room

Energy of a baseball thrown at 99.99% the speed of light

LHAASO



[Note: A single green photon from the Sun: ~2eV]

What is the most energetic photon we have ever detected?

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→ In 2024, LHAASO announced the detection of a 2.5 PeV gamma ray! **Over a quadrillion times more energetic!**

how big is a quadrillion?

Price of a chewing gum

US national debt in dollars

LHAASO



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What is the most energetic photon we have ever detected?

(e) 1,000,000,000,000,000x

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The LHC comparison

LHC accelerates particles up to 0.01 PeV (per particle)

250x in a ***single*** photon

LHAASO



[Note: A single green photon from the Sun: ~2eV]

Side note on units (energy)

We talk in **electron-volts (eV)**.

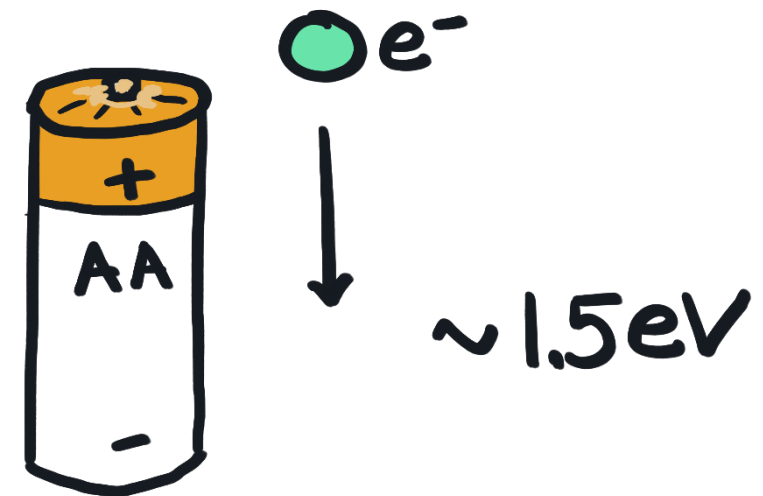
Radio astronomers: 2.4×10^{14} Hz (242 THz)

Optical/IR astronomers: 1240 nm (near-IR)

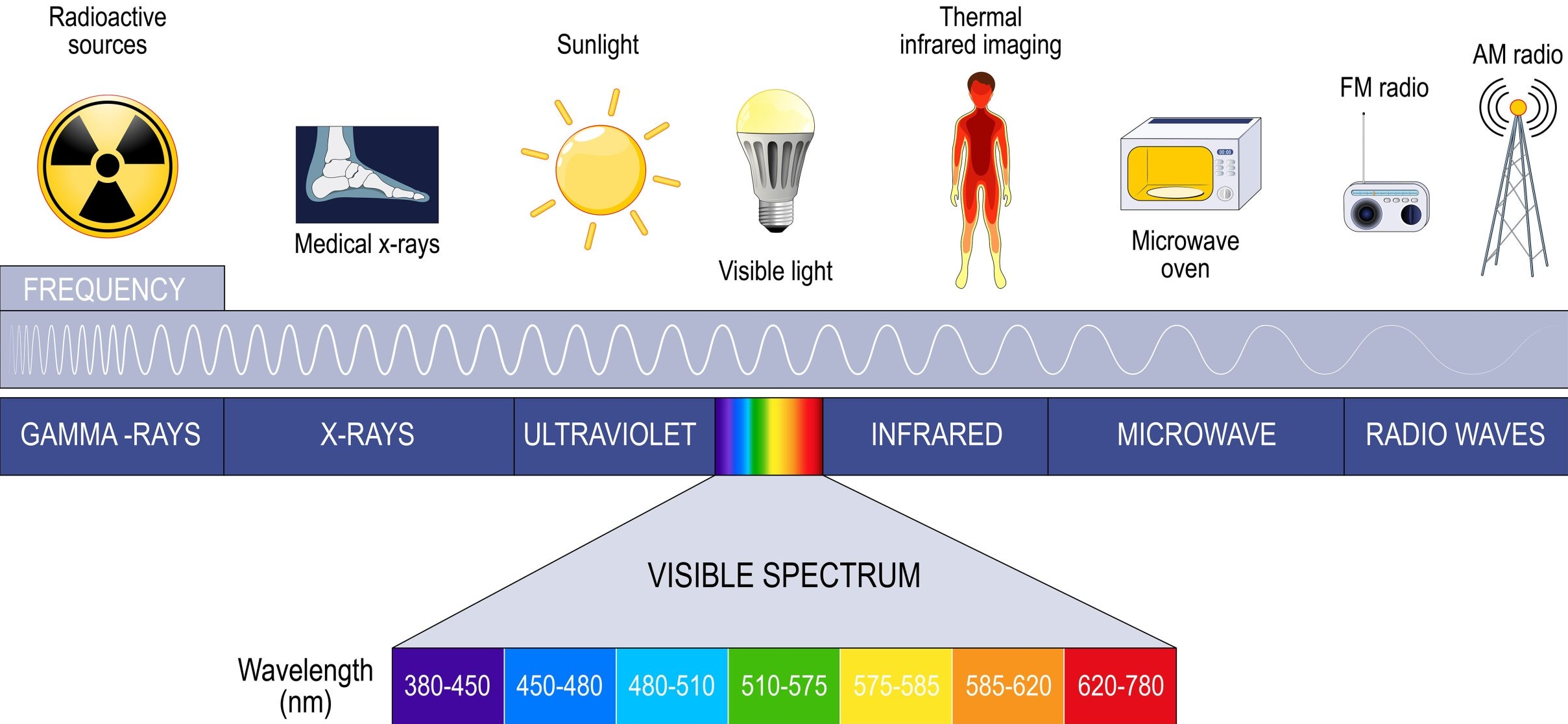
Stellar/plasma physicists: 11,600 K

Joules? 1.6×10^{-19} J

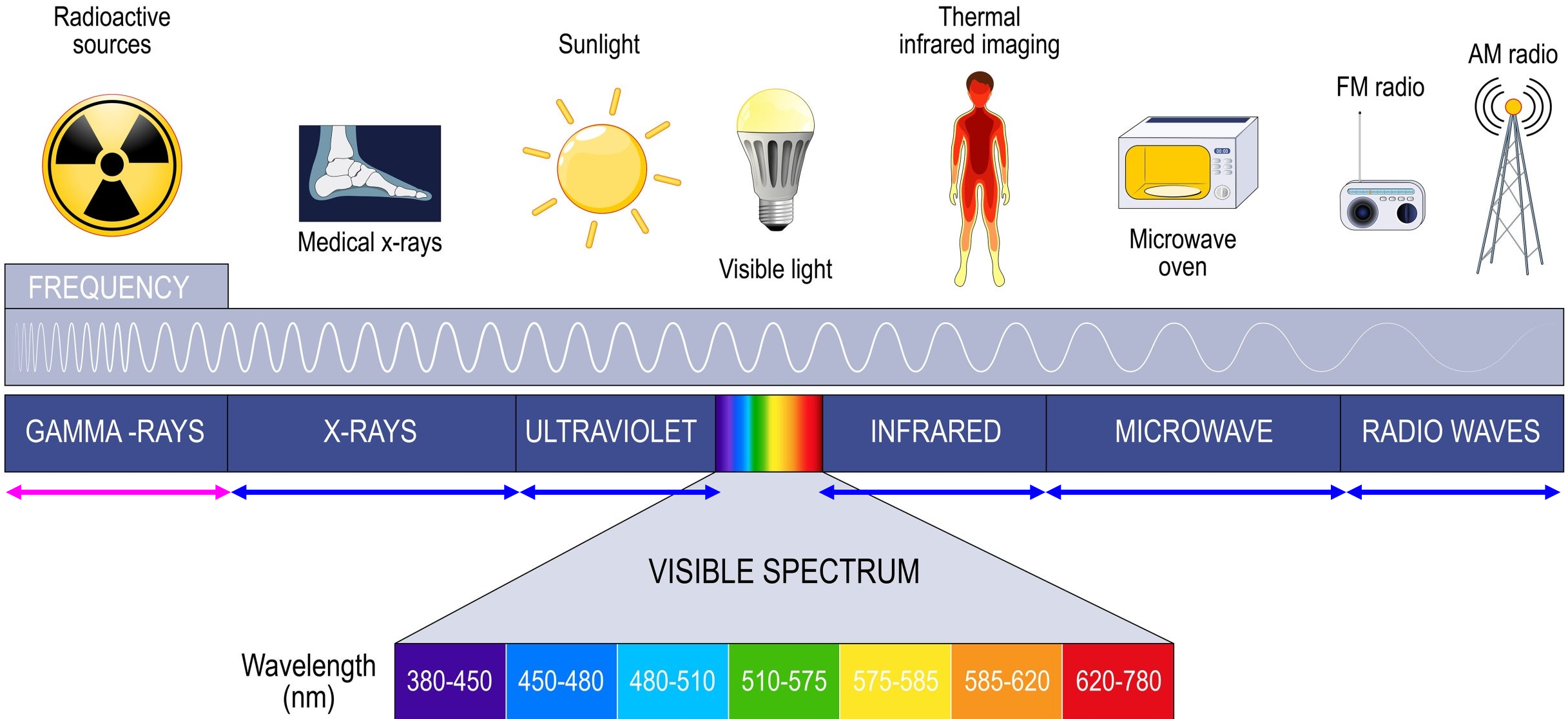
X-ray astronomer/particle physicists: 1 eV



Electromagnetic spectrum



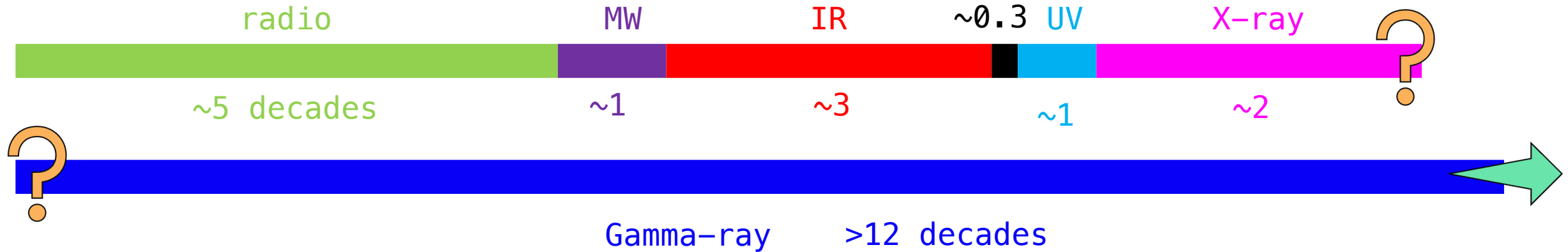
Electromagnetic spectrum



The true electromagnetic spectrum

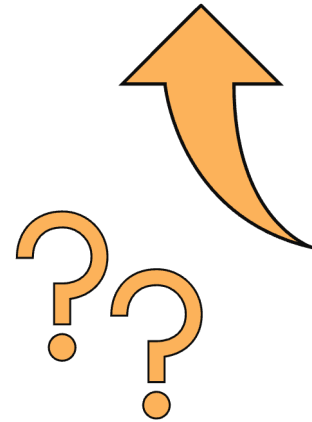


The true electromagnetic spectrum



- **Upper bound:** no limit (except those implied by detection techniques)
- **Lower bound:** endless (?) but instructive – debate on the boundary between X-rays and gamma rays

The true electromagnetic spectrum



Question: at which energy ends the X-ray and begins the gamma-ray domain?

The true electromagnetic spectrum

A plausible answer:
20 keV.
Why?

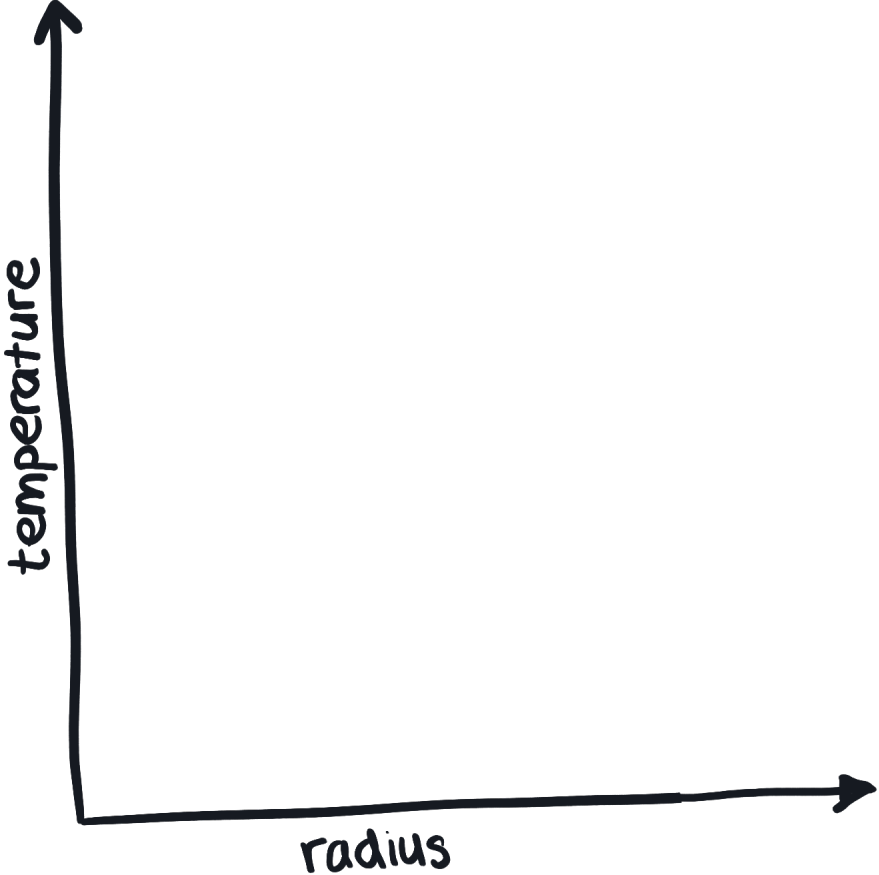
...energy ends
the X-ray and begins the
gamma-ray domain?

The true electromagnetic spectrum

A plausible answer:
20 keV.
Thermal emission.

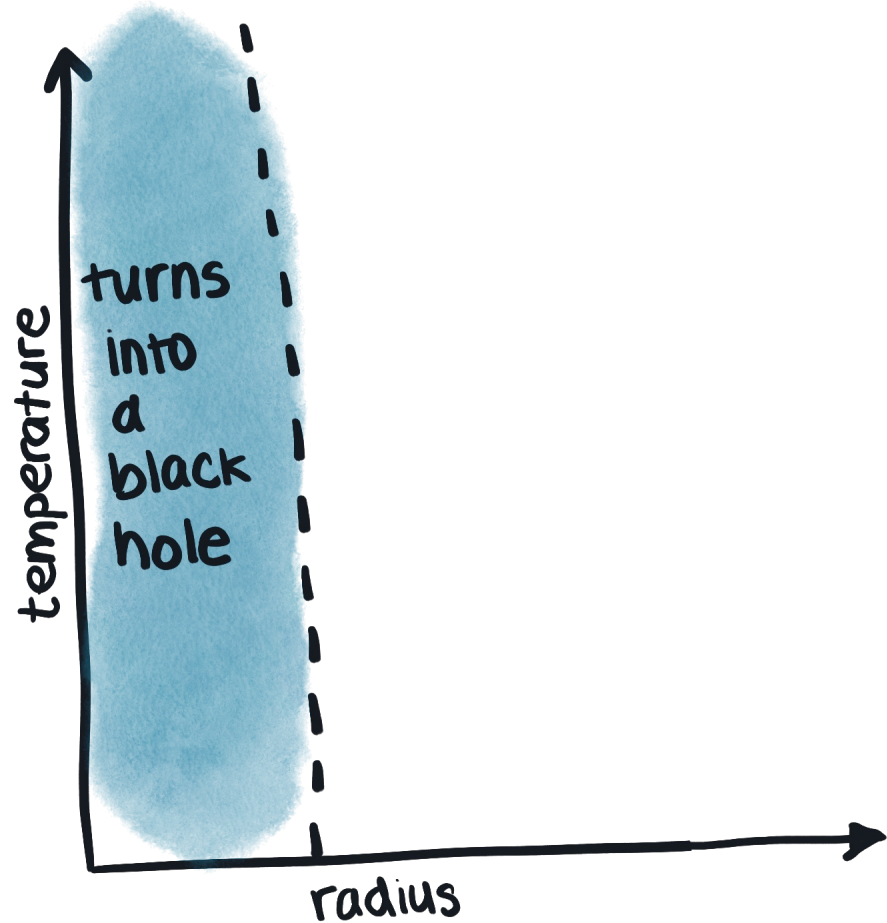
...energy ends
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Astrophysics: How hot can a glowing object be?



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Step 1: you can't be infinitely small



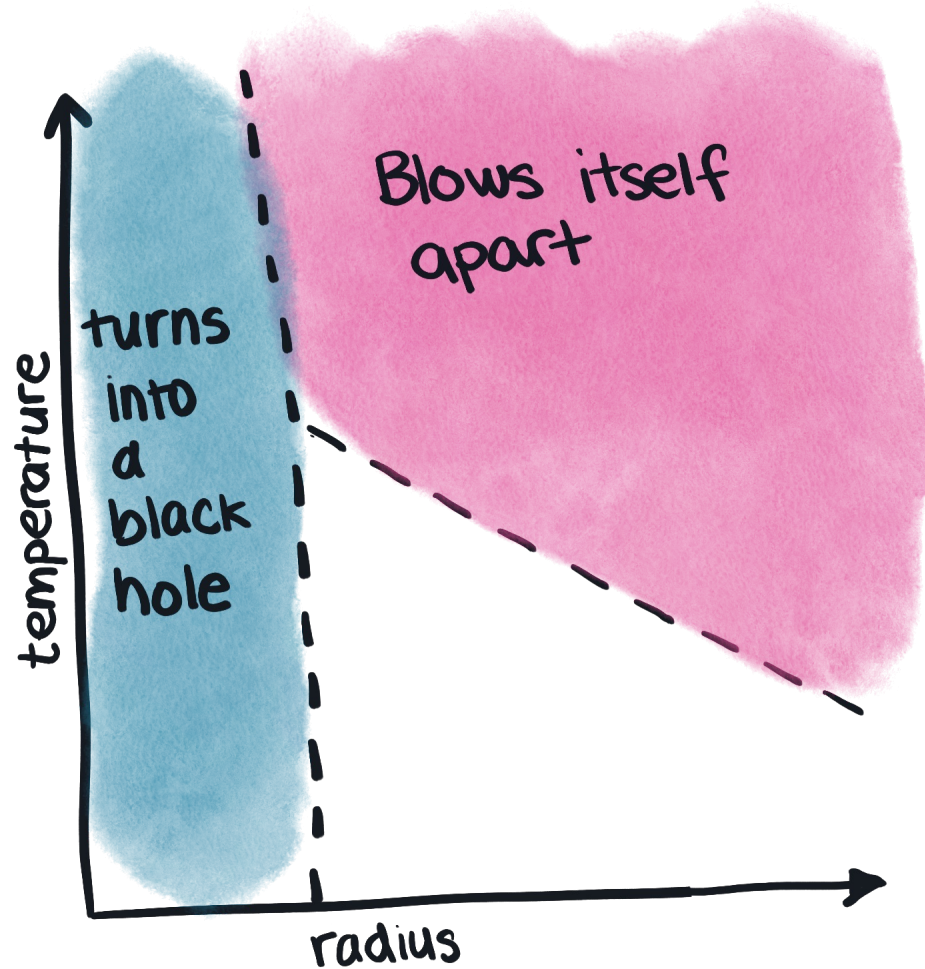
Black hole



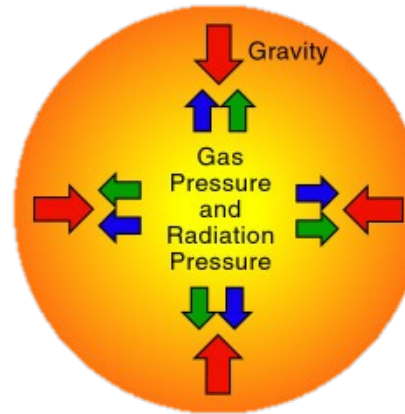
$$R \geq r_s$$

Astrophysics: How hot can a glowing object be?

Step 2: you can't be infinitely bright



Stable star



$$R^2 T^4 \leq \text{const} \times \text{mass}$$

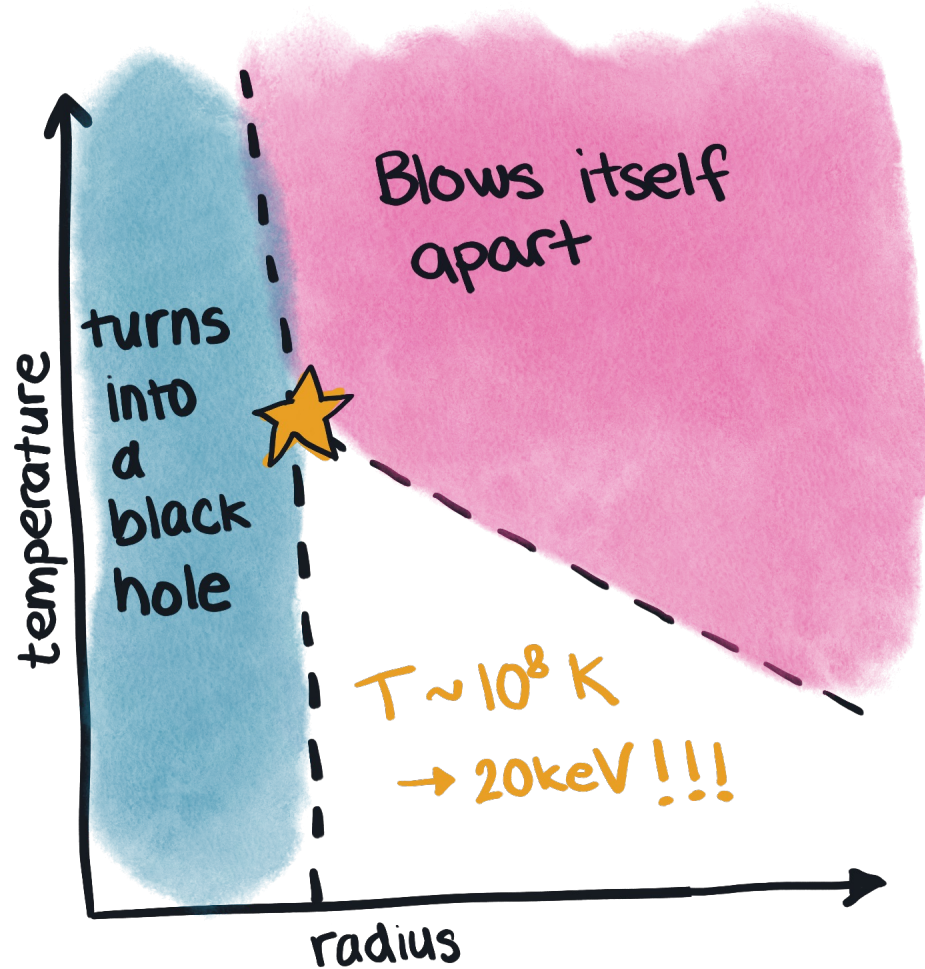
Black hole



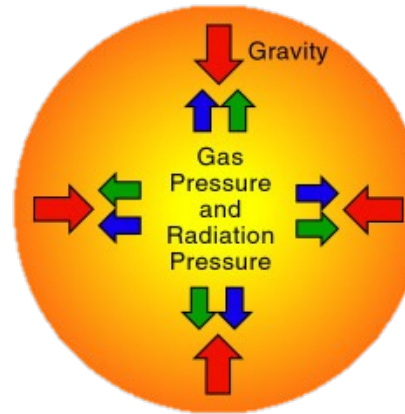
$$R \geq r_s$$

Astrophysics: How hot can a glowing object be?

Step 3: combine the two (for some macro mass)



Stable star



$$R^2 T^4 \leq \text{const} \times \text{mass}$$

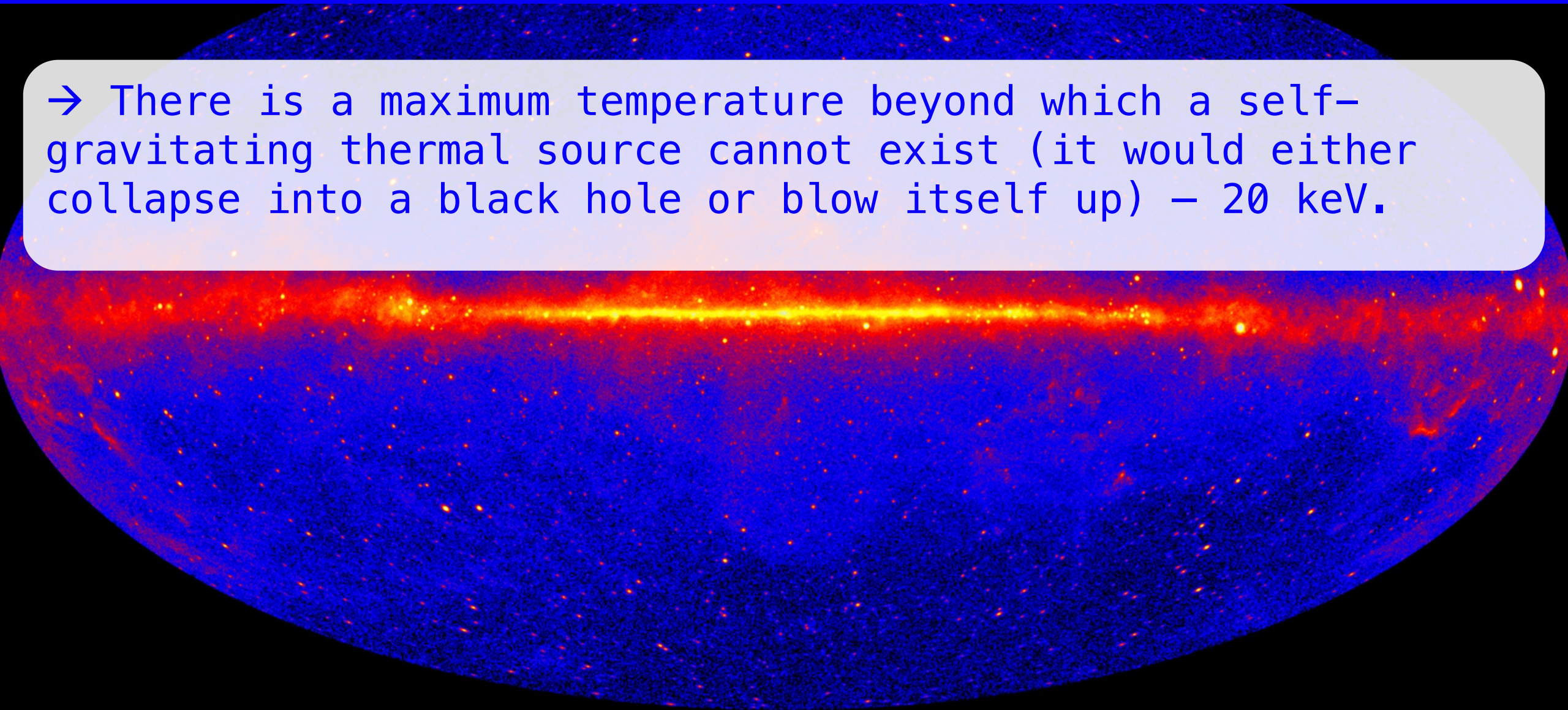
Black hole



$$R \geq r_s$$

Astrophysics: How hot can a glowing object be?

→ There is a maximum temperature beyond which a self-gravitating thermal source cannot exist (it would either collapse into a black hole or blow itself up) – 20 keV.



Astrophysics: How hot can a glowing object be?

→ There is a maximum temperature beyond which a self-gravitating thermal source cannot exist (it would either collapse into a black hole or blow itself up) – 20 keV.

→ If you see a photon with energy > 20 keV, you need **non-thermal physics**.

Non-thermal physics = proxy of gamma-ray astronomy.

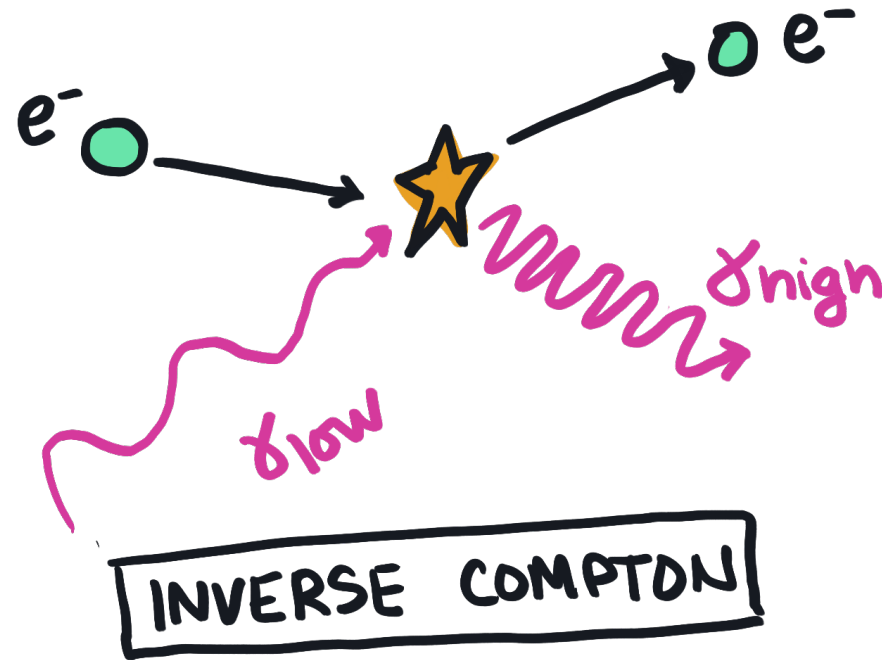
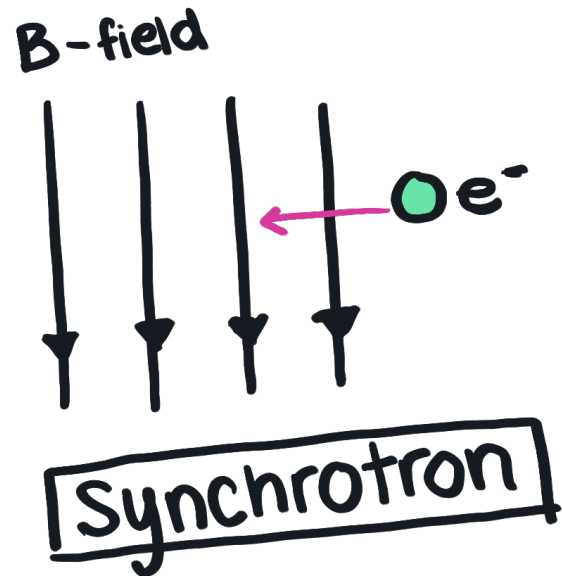
So...

Gamma rays are signatures of:

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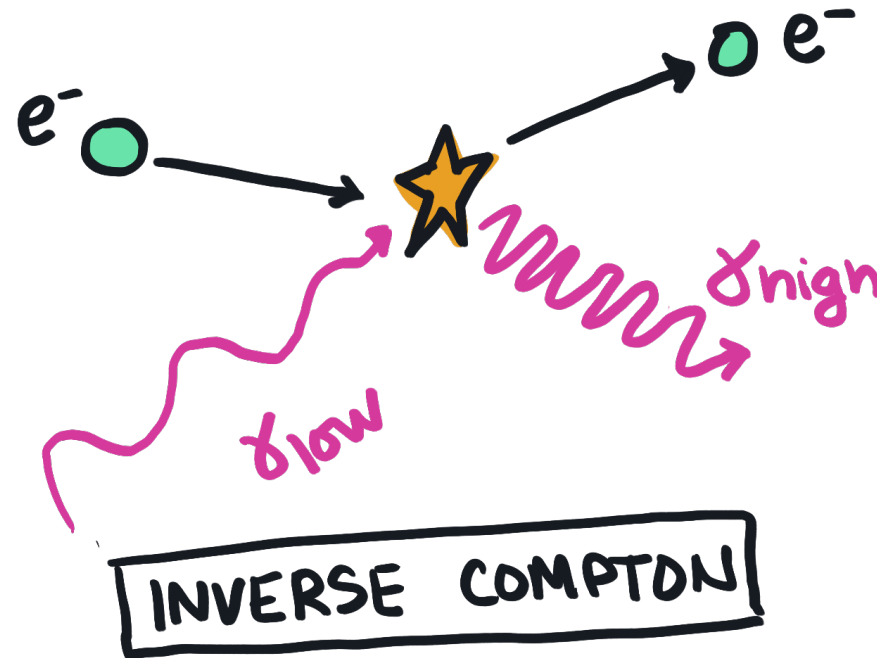
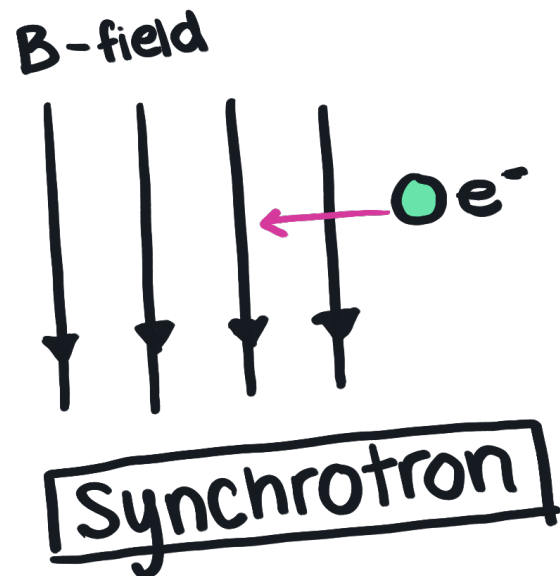
1. Particle acceleration (synchrotron, inverse Compton)



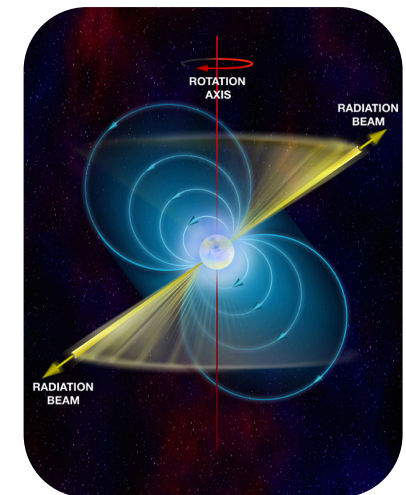
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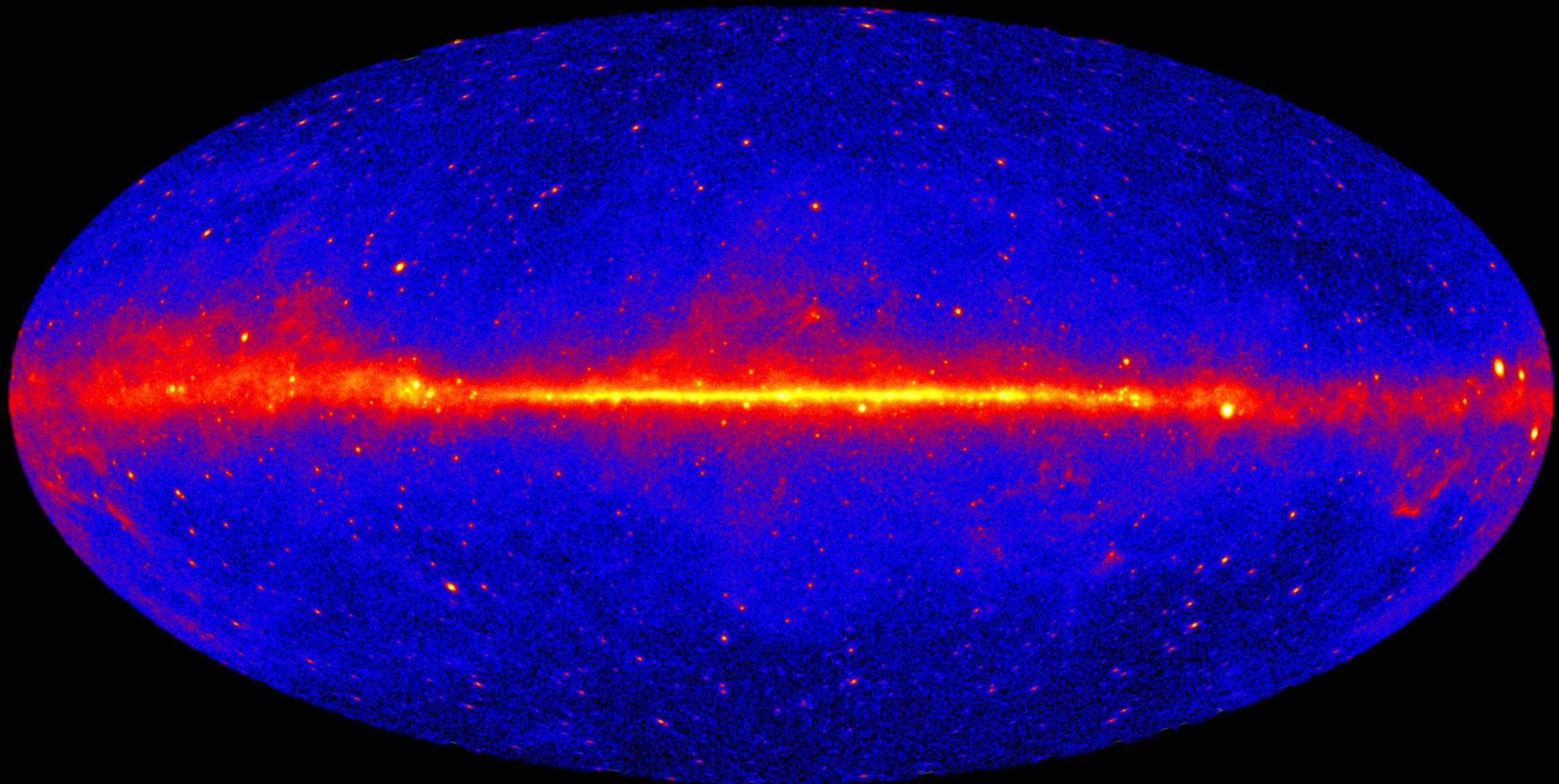
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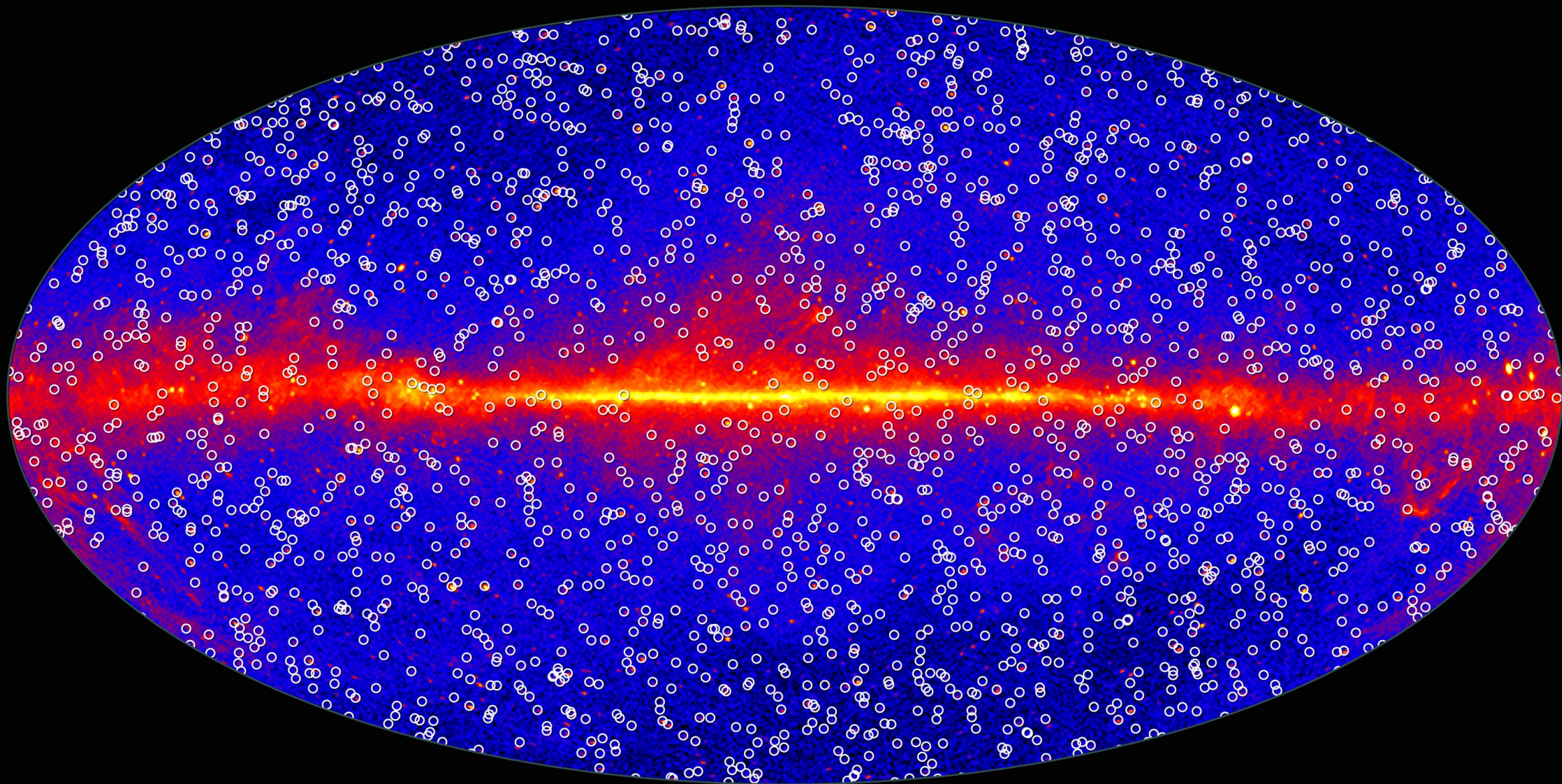
blazars



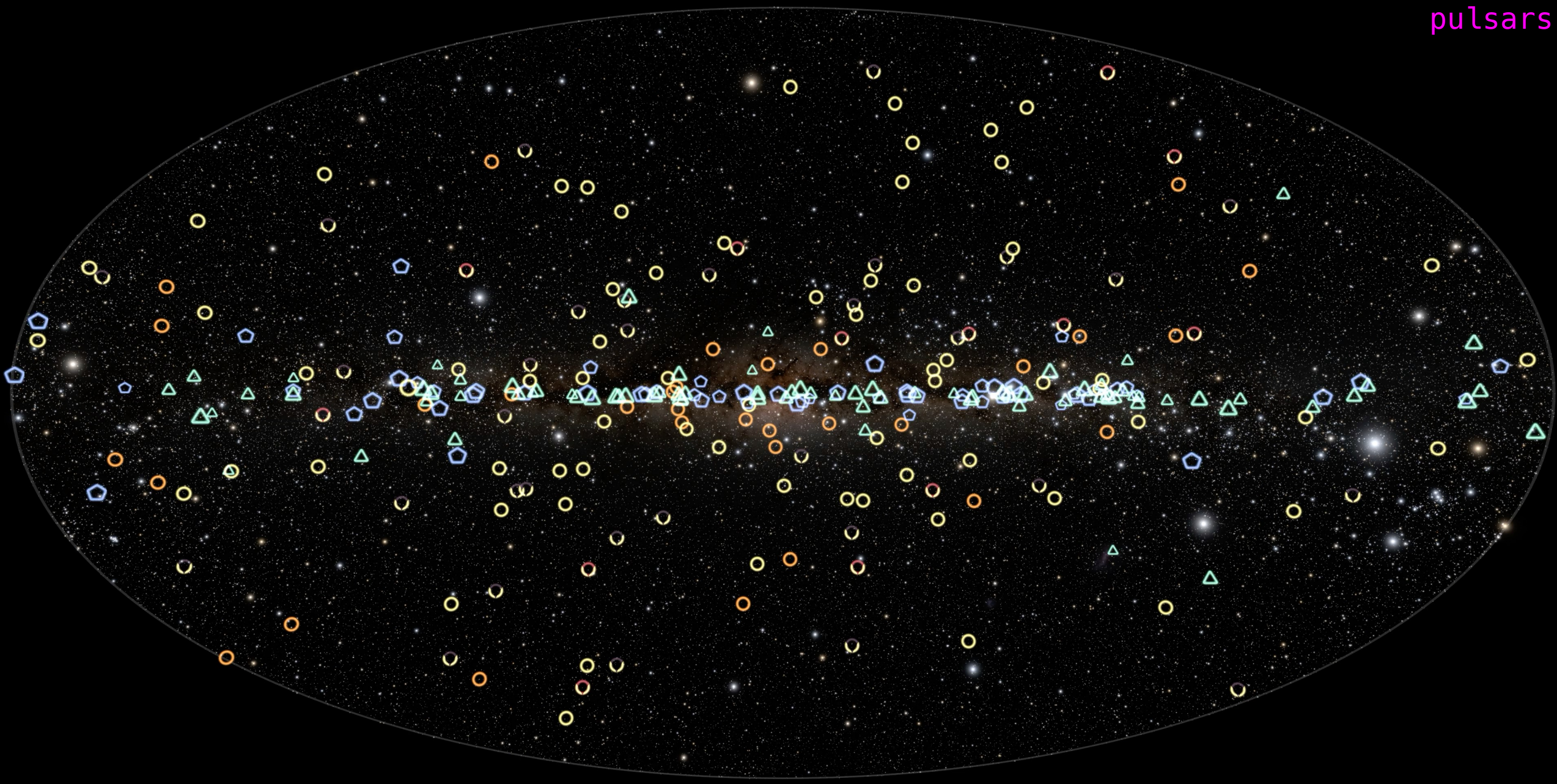
pulsars



blazars



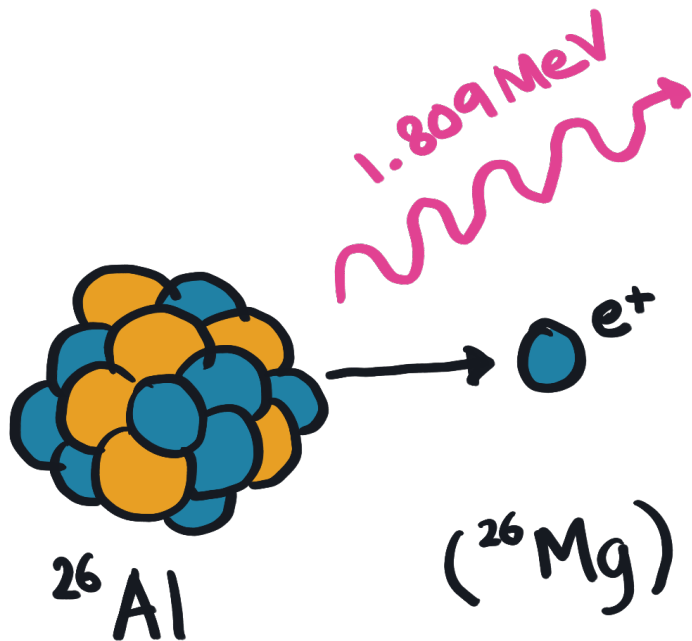
pulsars



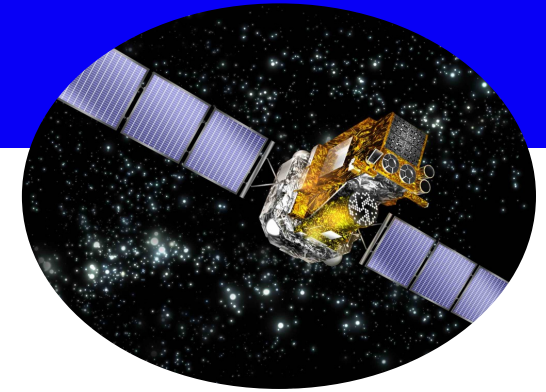
So...

Gamma rays are exclusive signatures of:

1. **Particle acceleration** (synchrotron, inverse Compton)
2. **Nuclear transitions** (radioactive decay lines)

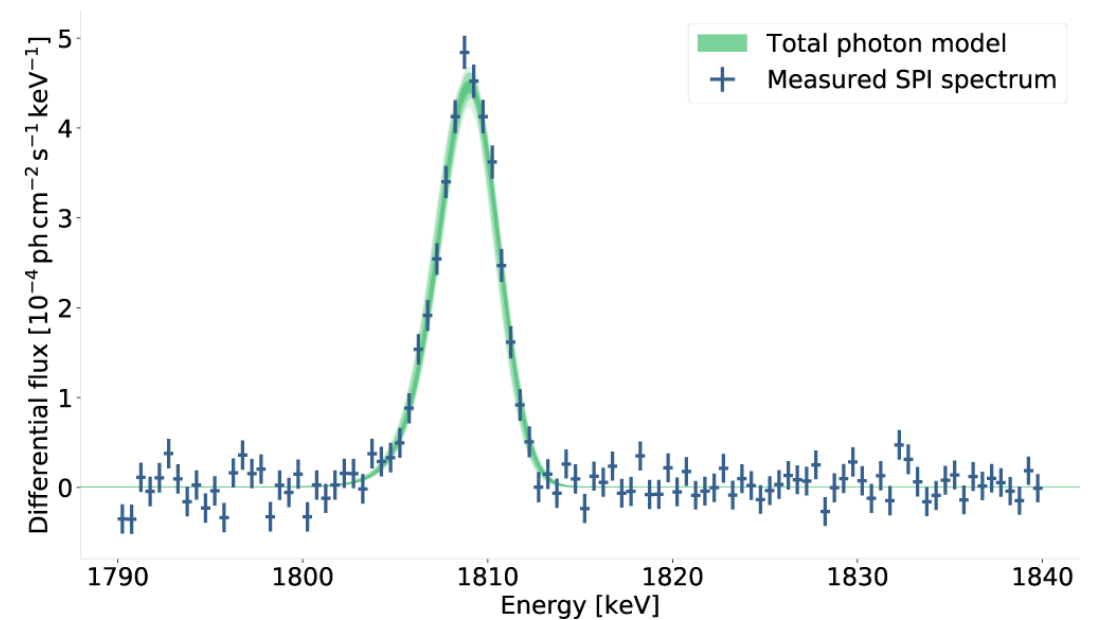
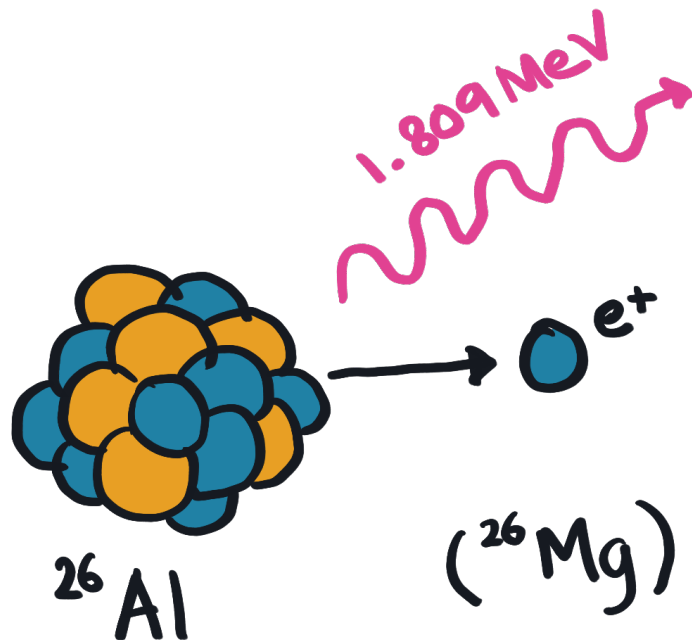


So...



Gamma rays are exclusive signatures of:

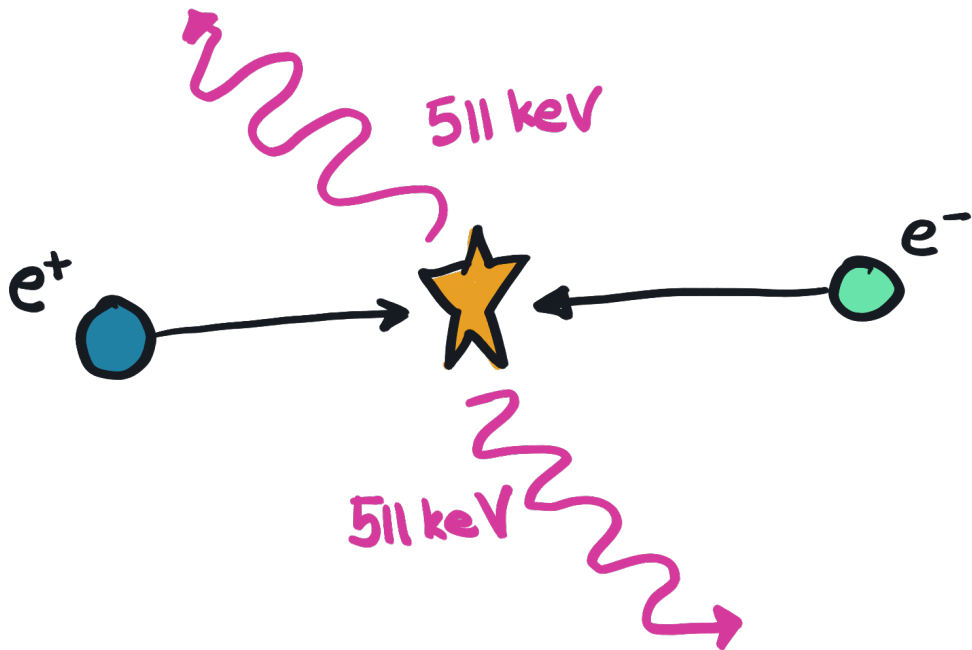
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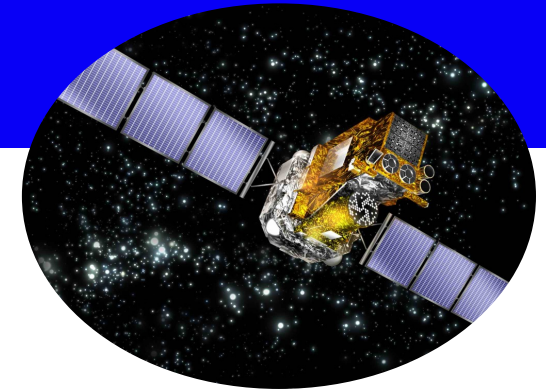
So...

Gamma rays are exclusive signatures of:

1. **Particle acceleration** (synchrotron, inverse Compton)
2. **Nuclear transitions** (radioactive decay lines)
3. **Matter-antimatter annihilation** (511 keV line)

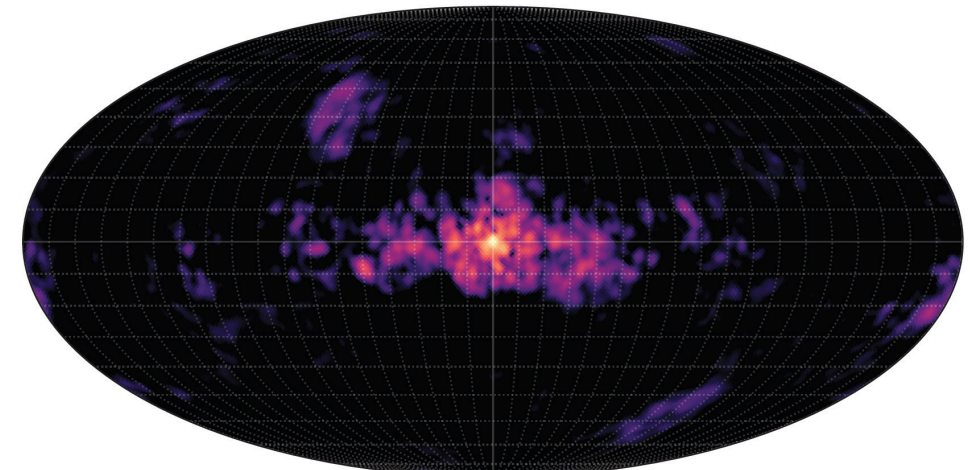
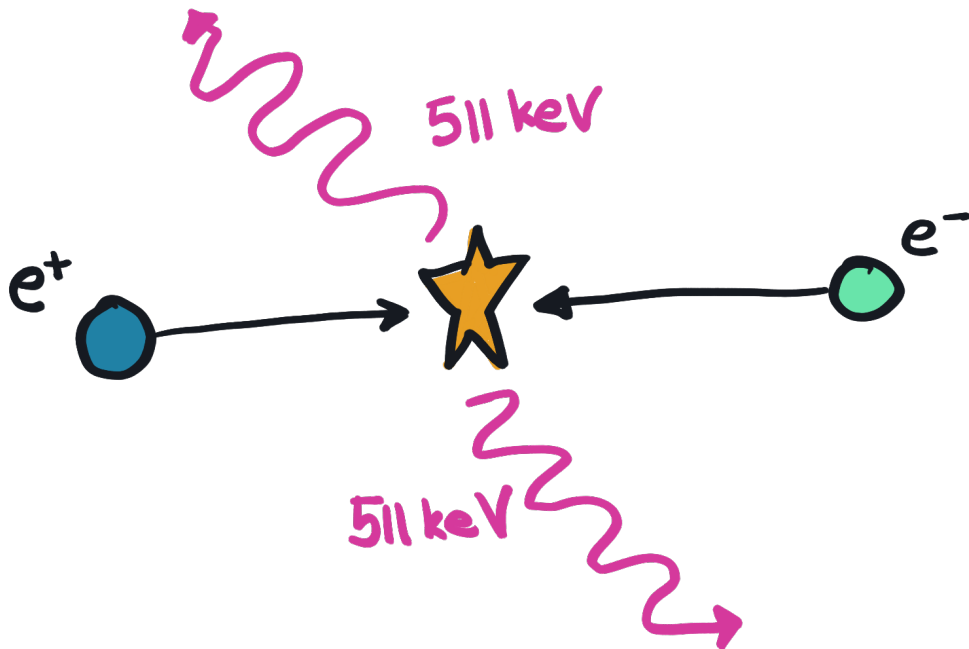


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1 / (cm² s sr)
0.0001 0.001 0.01 0.08

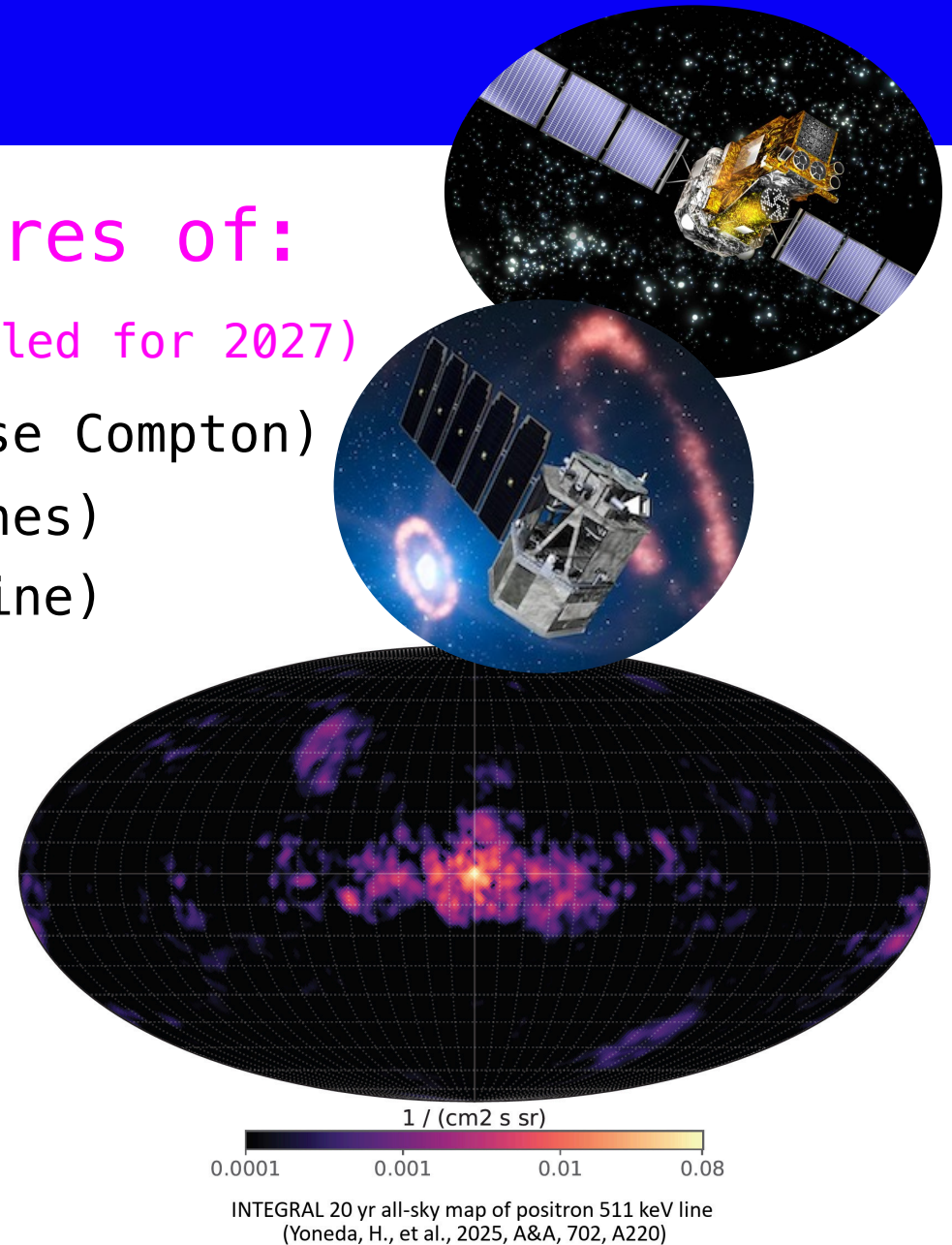
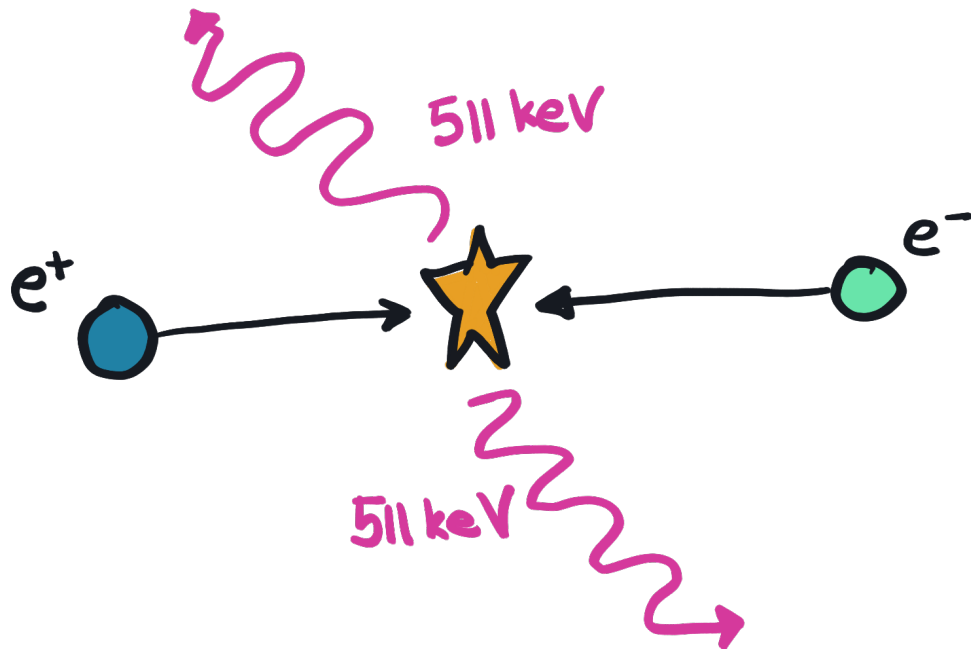
INTEGRAL 20 yr all-sky map of positron 511 keV line
(Yoneda, H., et al., 2025, A&A, 702, A220)

So...

Gamma rays are exclusive signatures of:

COSI (scheduled for 2027)

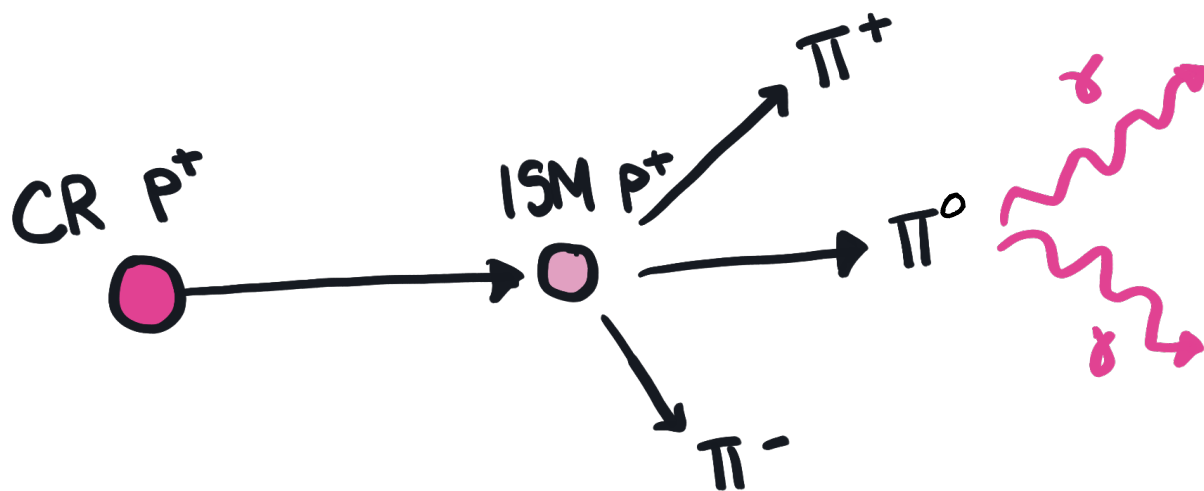
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So...

Gamma rays are exclusive signatures of:

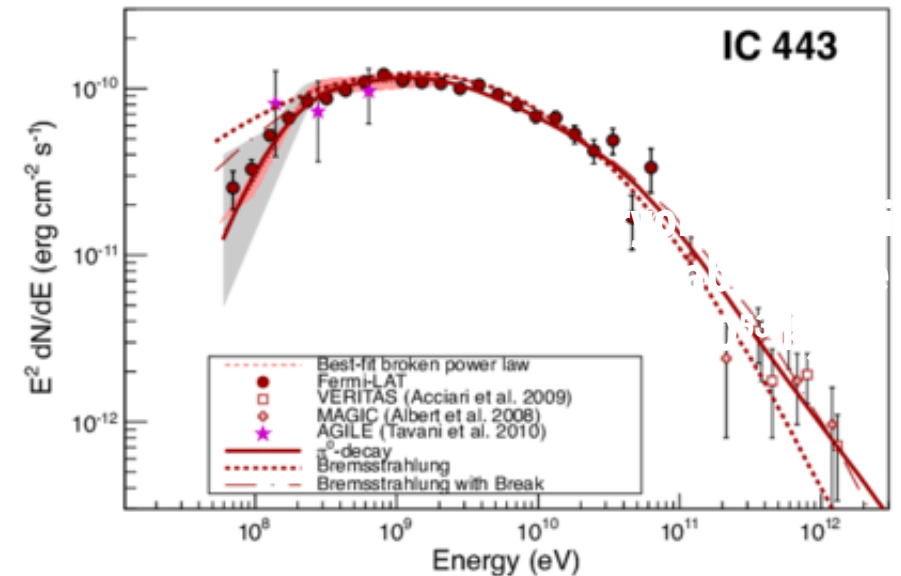
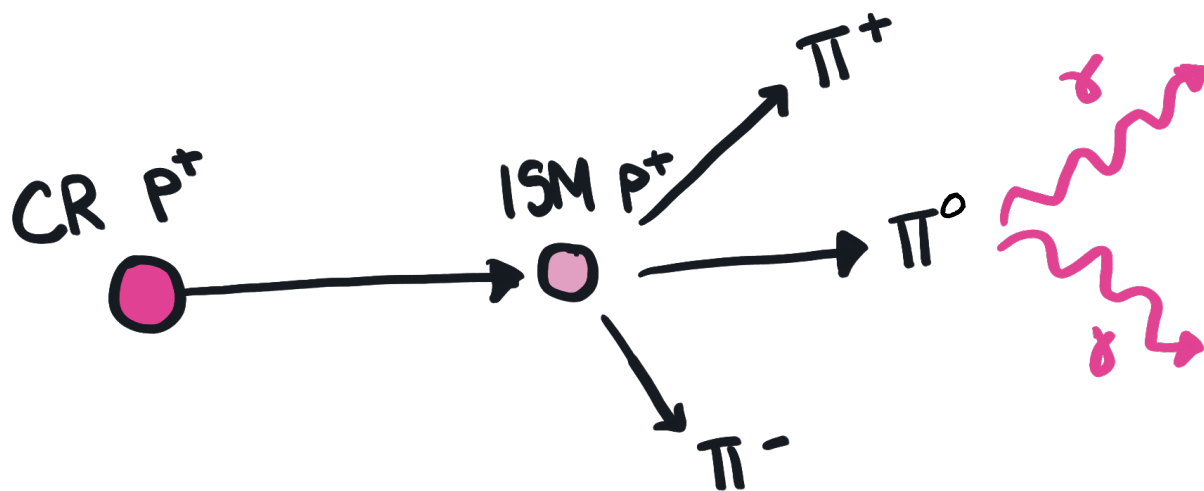
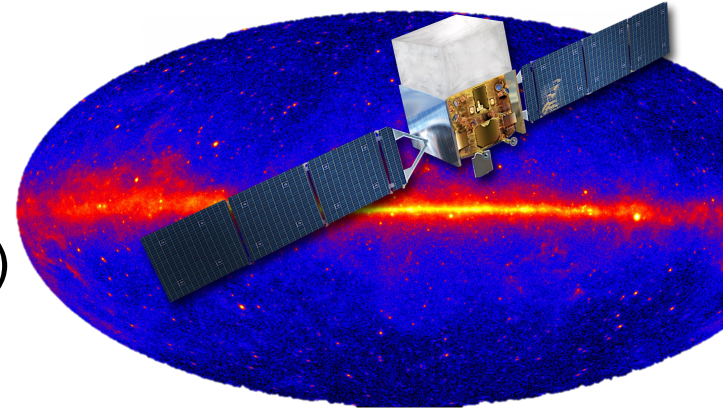
1. **Particle acceleration** (synchrotron, inverse Compton)
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4. **Pion decay** from cosmic ray interactions with matter



So...

Gamma rays are exclusive signatures of:

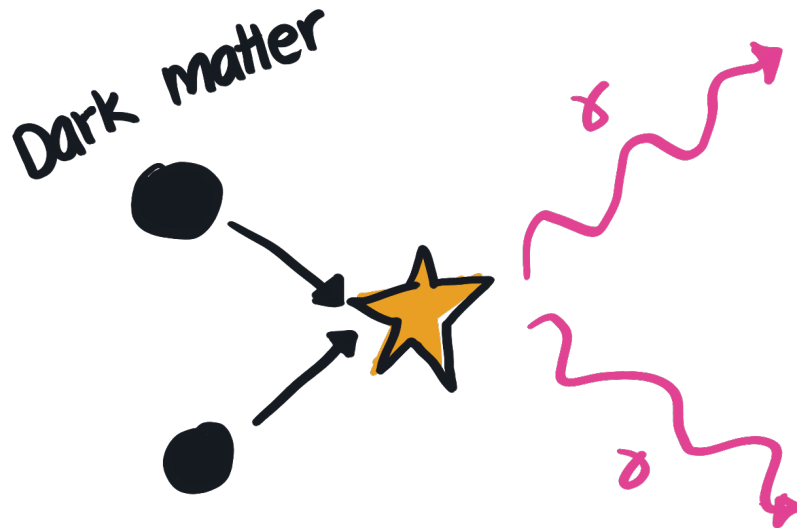
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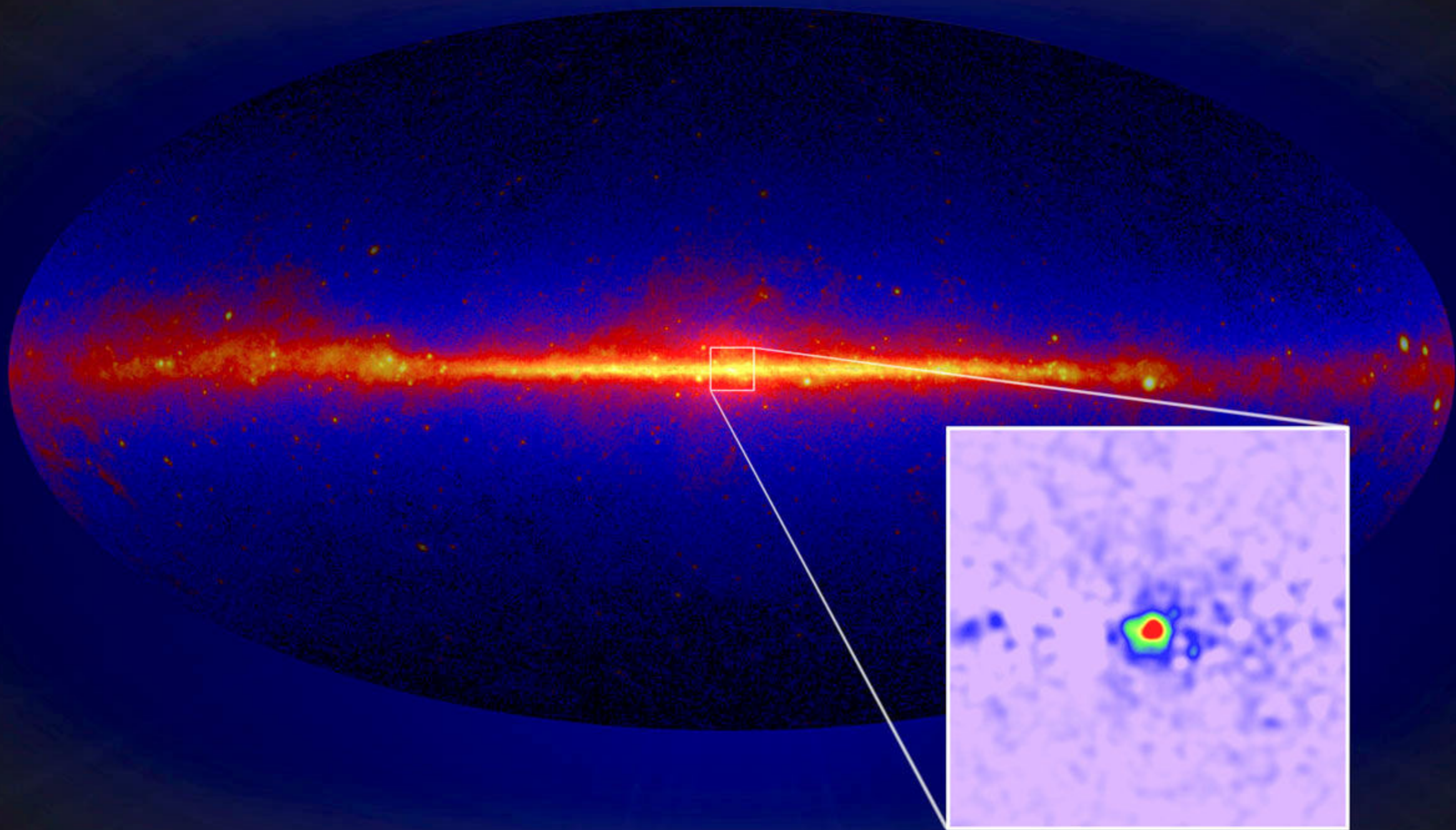


So...

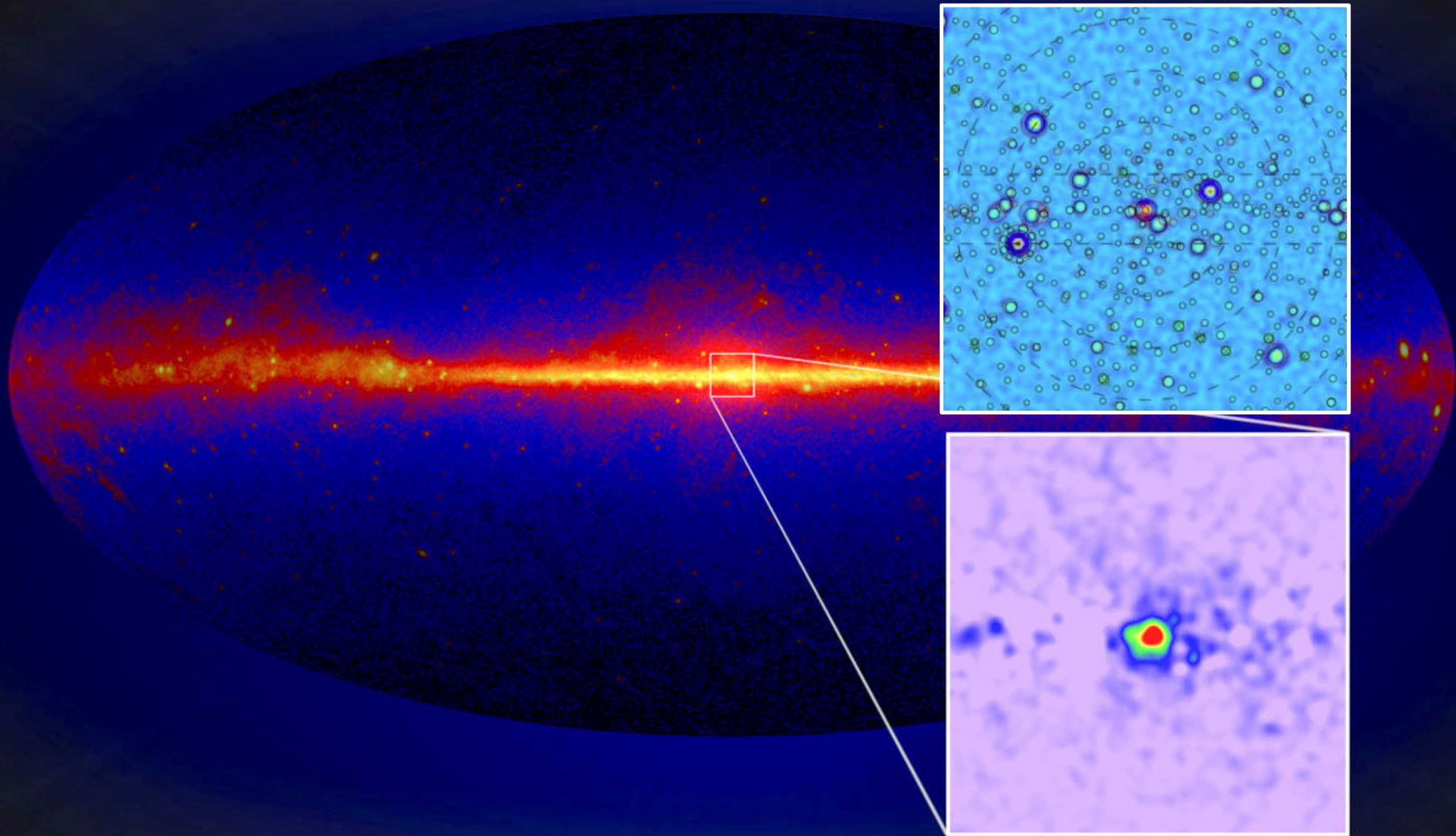
Gamma rays are exclusive signatures of:

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4. **Pion decay** from cosmic ray interactions with matter
5. And potentially: **dark matter annihilation or decay**

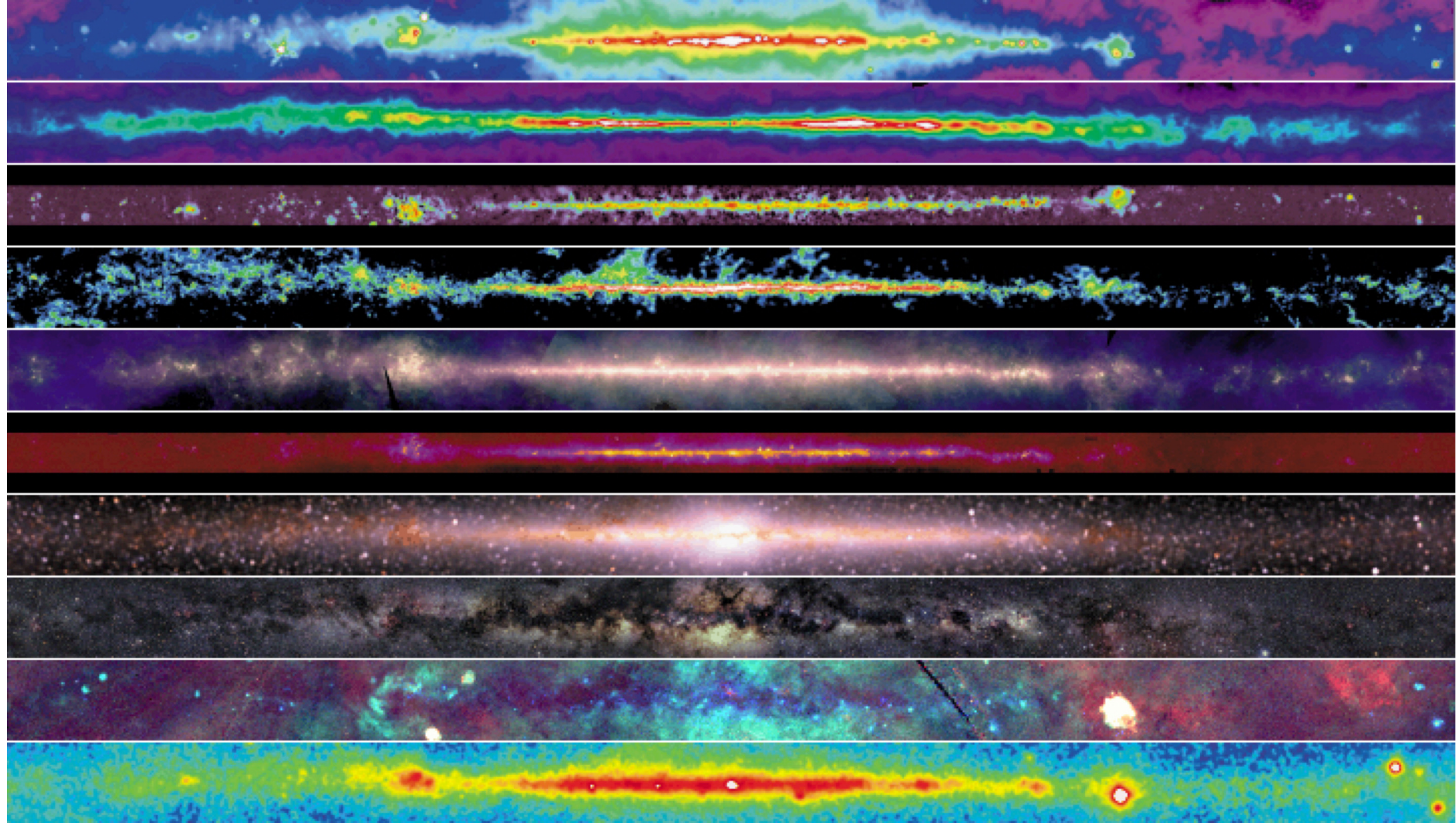


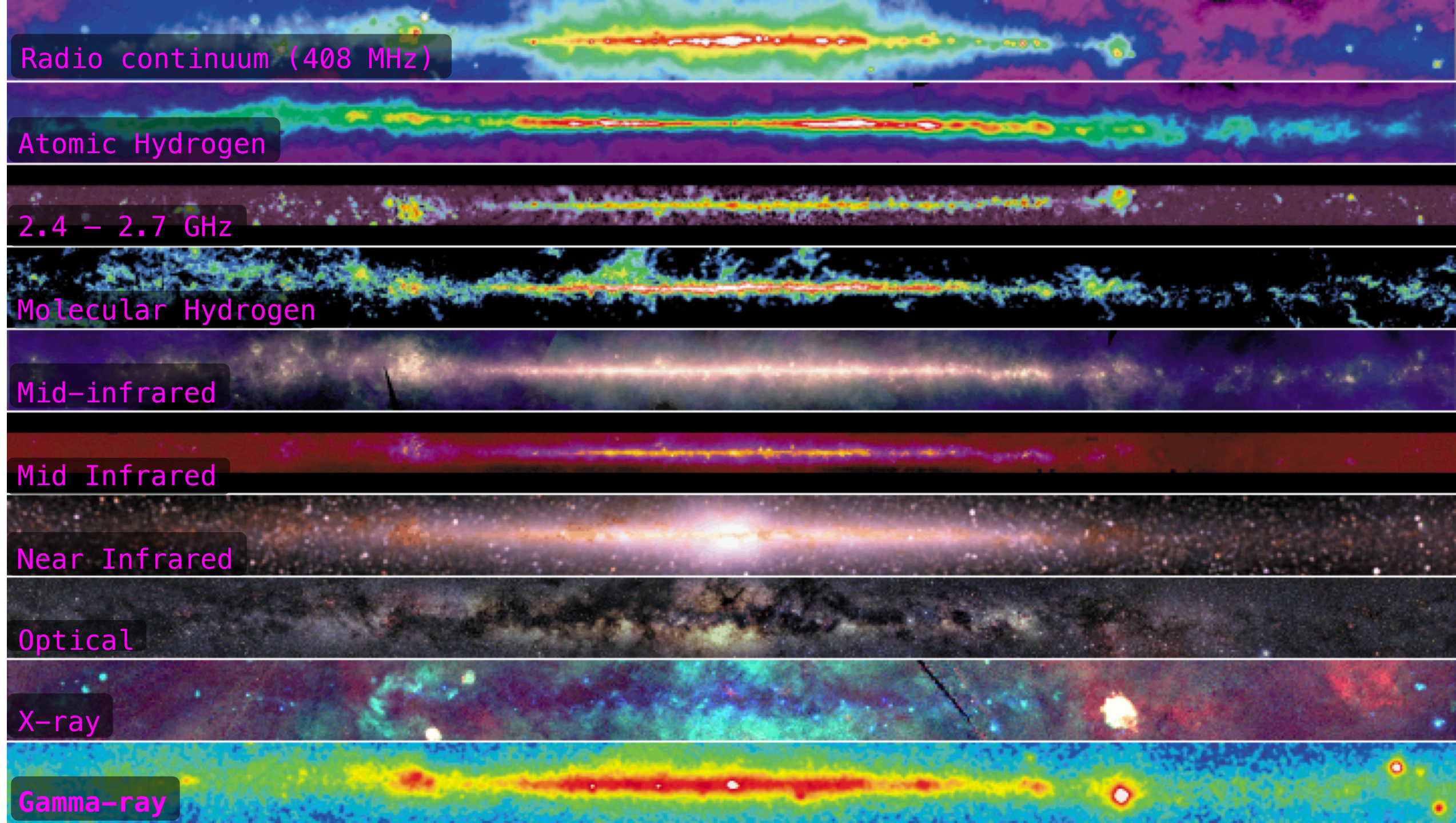


Credit: NASA/DOE/FERMI LAT COLLABORATION; T. LINDEN

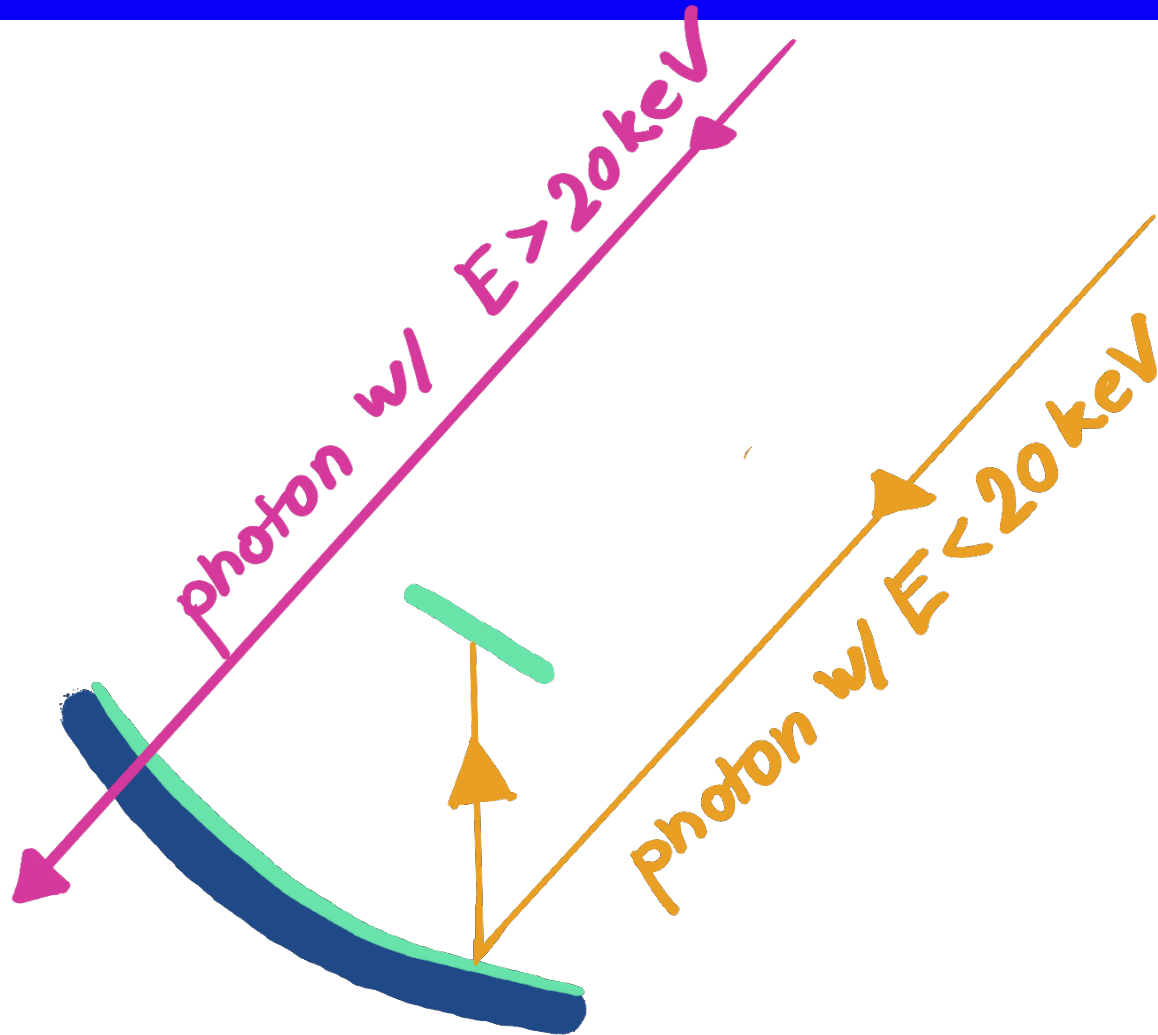


Credit: NASA/DOE/FERMI LAT COLLABORATION; T. LINDEN





Observing techniques



Problem: you cannot focus gamma rays.

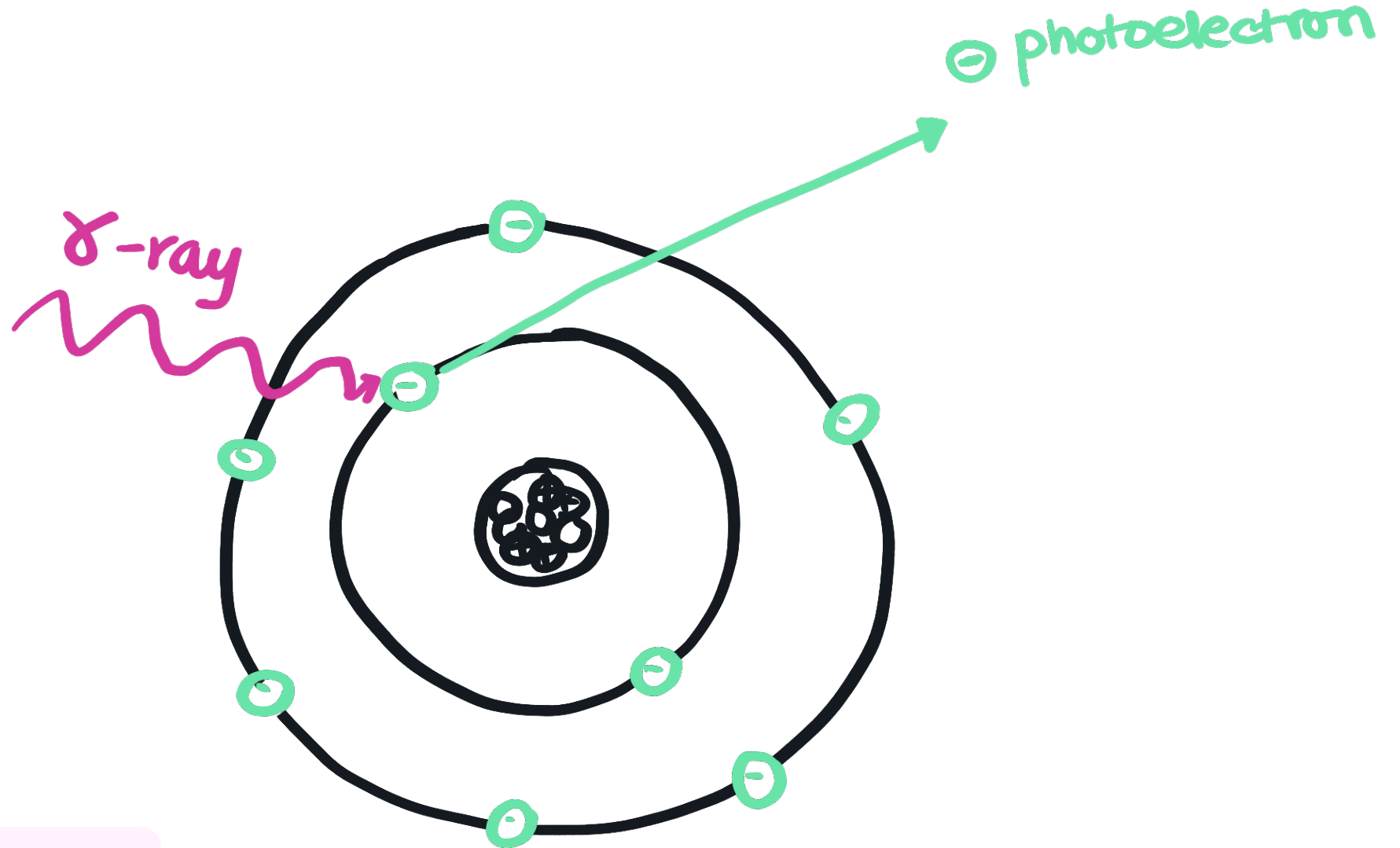
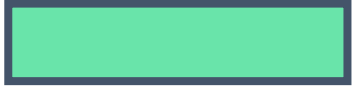
- their wavelength is smaller than any inter-atomic distances in any solid \rightarrow they pass right through

Solution:

exploit the ways gamma rays ***destroy themselves*** when they interact with matter.

Collimators and Coded Masks

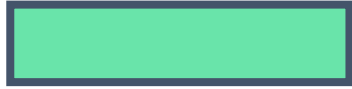
20 keV – 1 MeV



dominating interaction:
photoelectric absorption

Collimators and Coded Masks

20 keV – 1 MeV



Collimators

- Put your detector inside a dense cube

dominating interaction:
photoelectric absorption

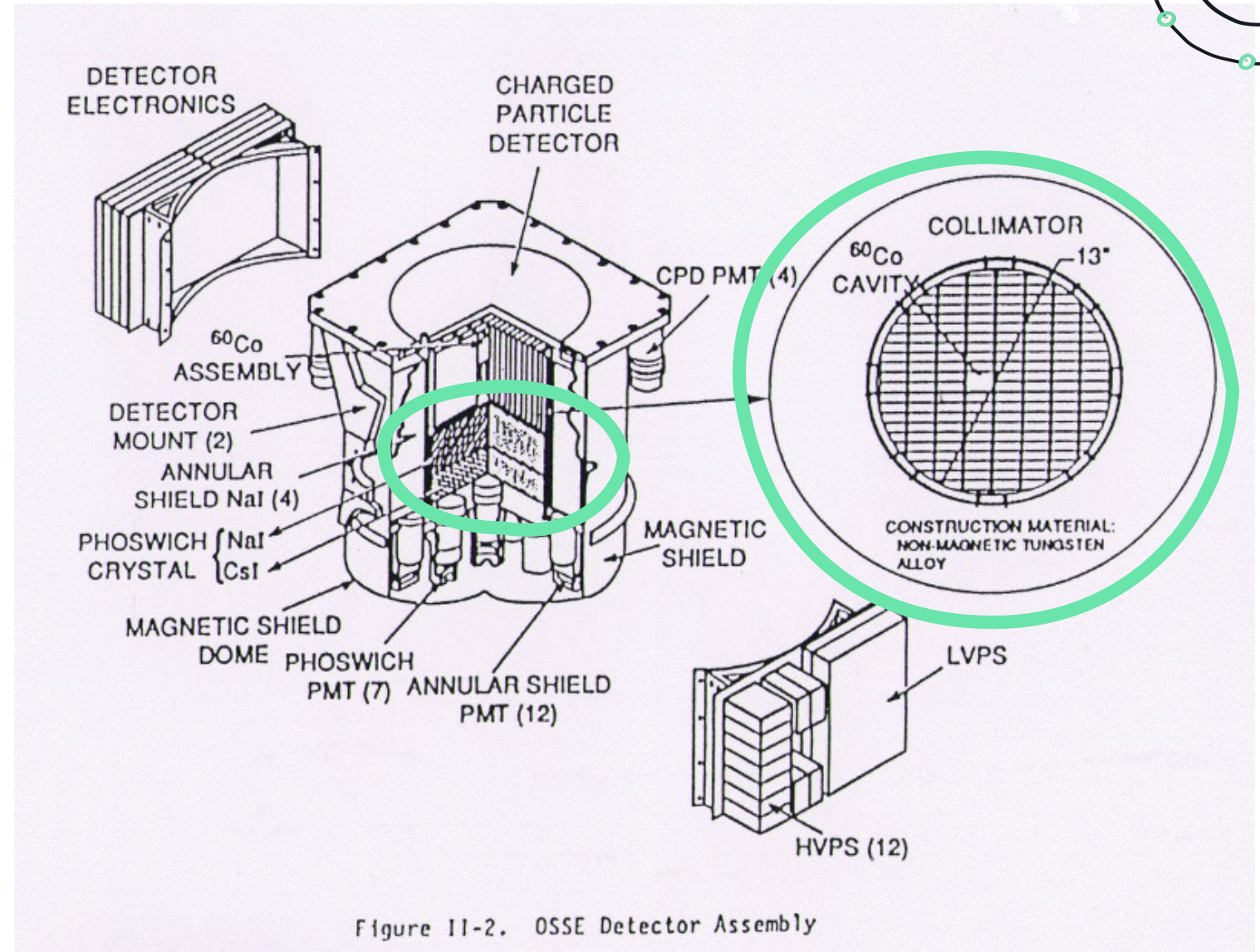
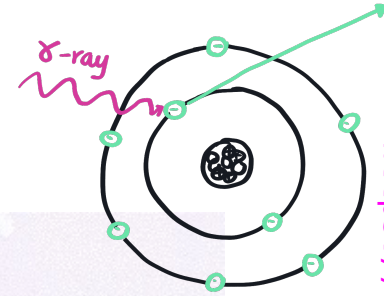
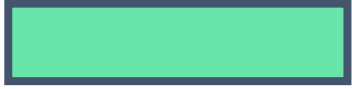


Figure 11-2. OSSE Detector Assembly

Collimators and Coded Masks

20 keV – 1 MeV



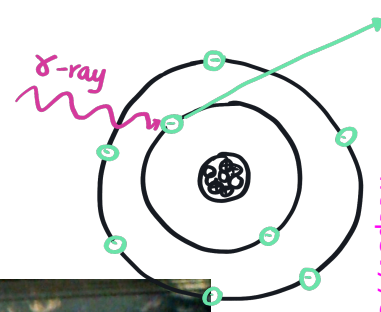
Collimators

- Put your detector inside a dense cube

Coded masks

- Put the detector inside a pattern of holes!

dominating interaction:
photoelectric absorption



Collimators and Coded Masks

20 keV – 1 MeV



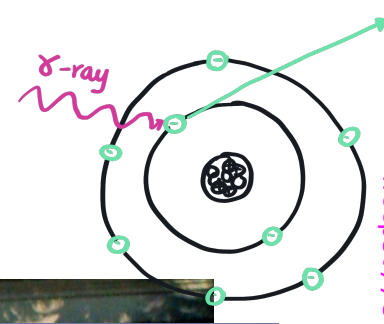
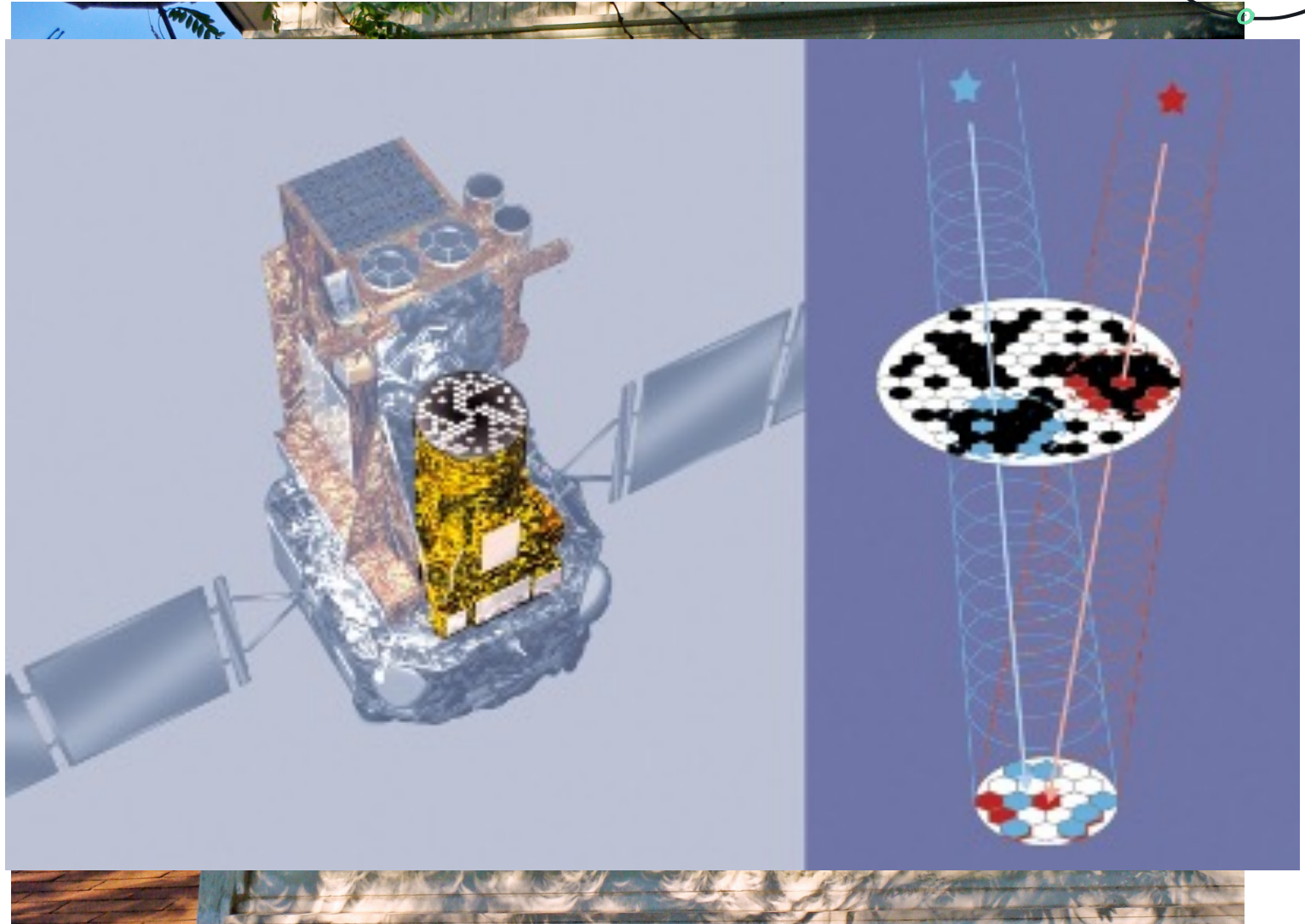
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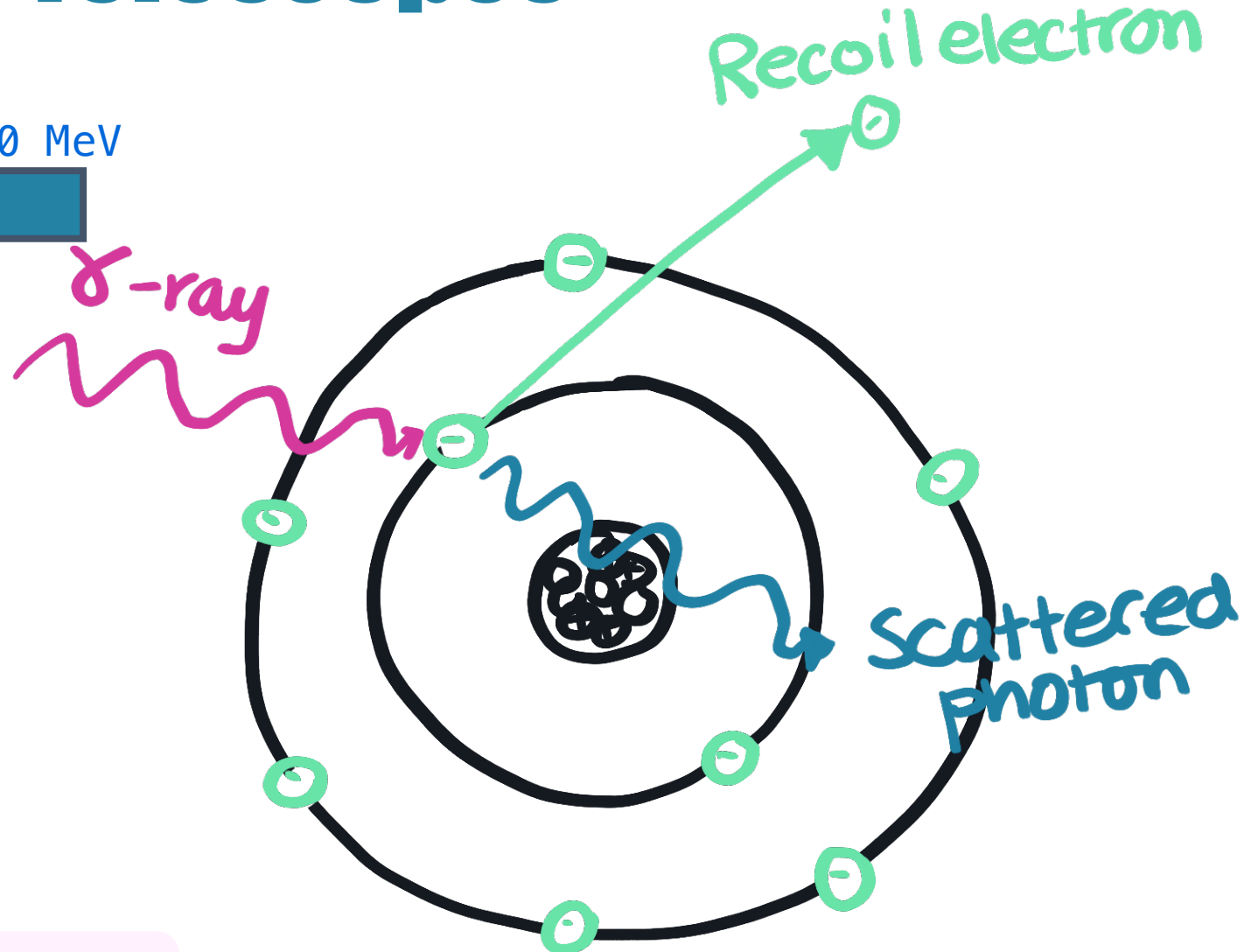
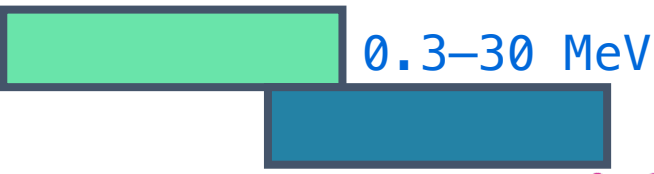
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Compton Telescopes

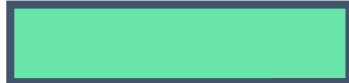
20 keV – 1 MeV



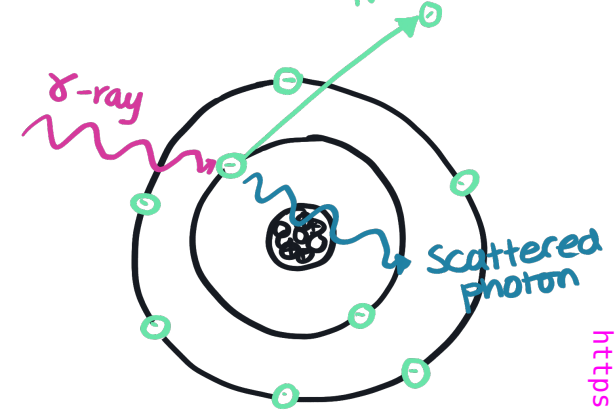
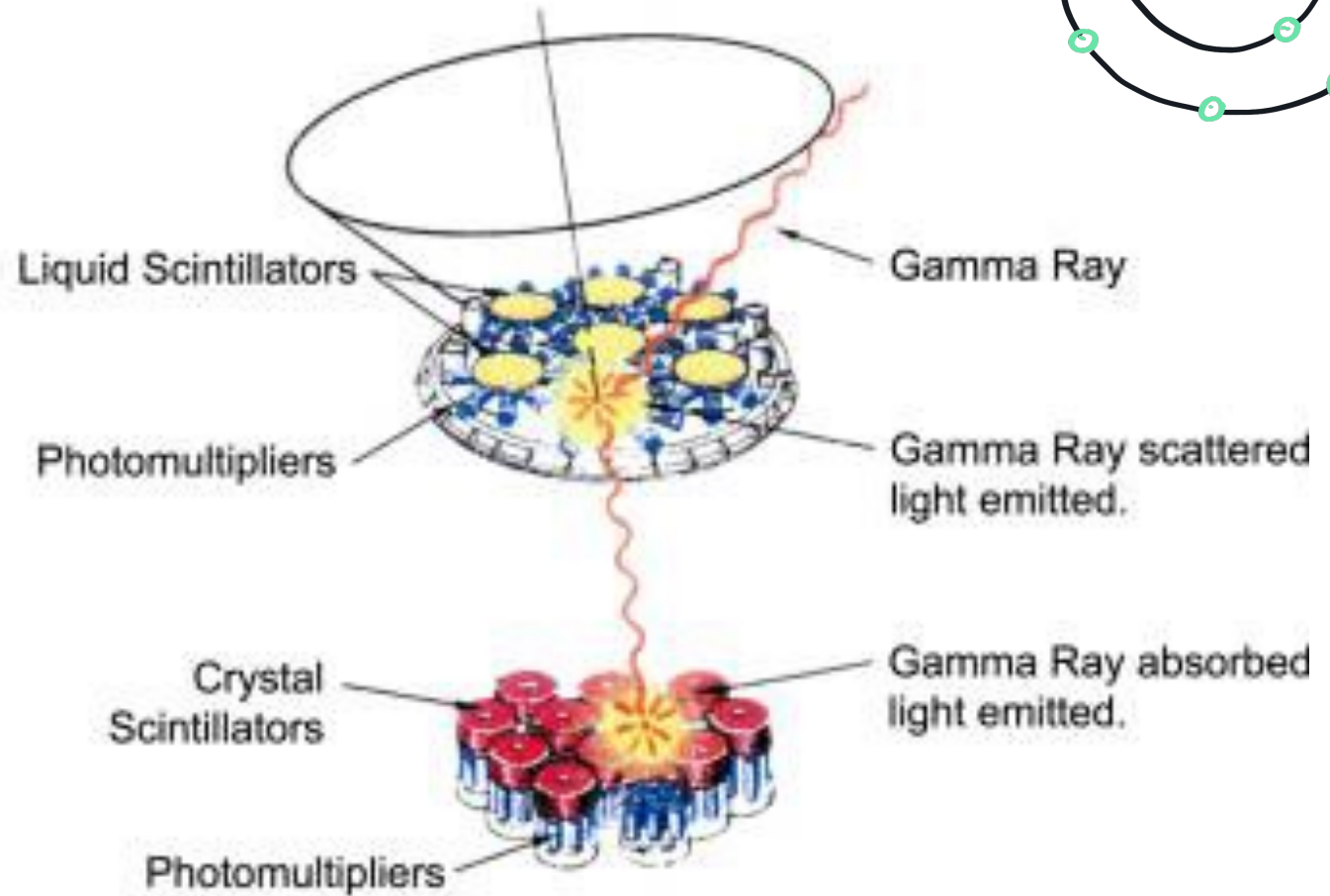
dominating interaction:
Compton scattering

Compton Telescopes

20 keV – 1 MeV



0.3–30 MeV



dominating interaction:
Compton scattering

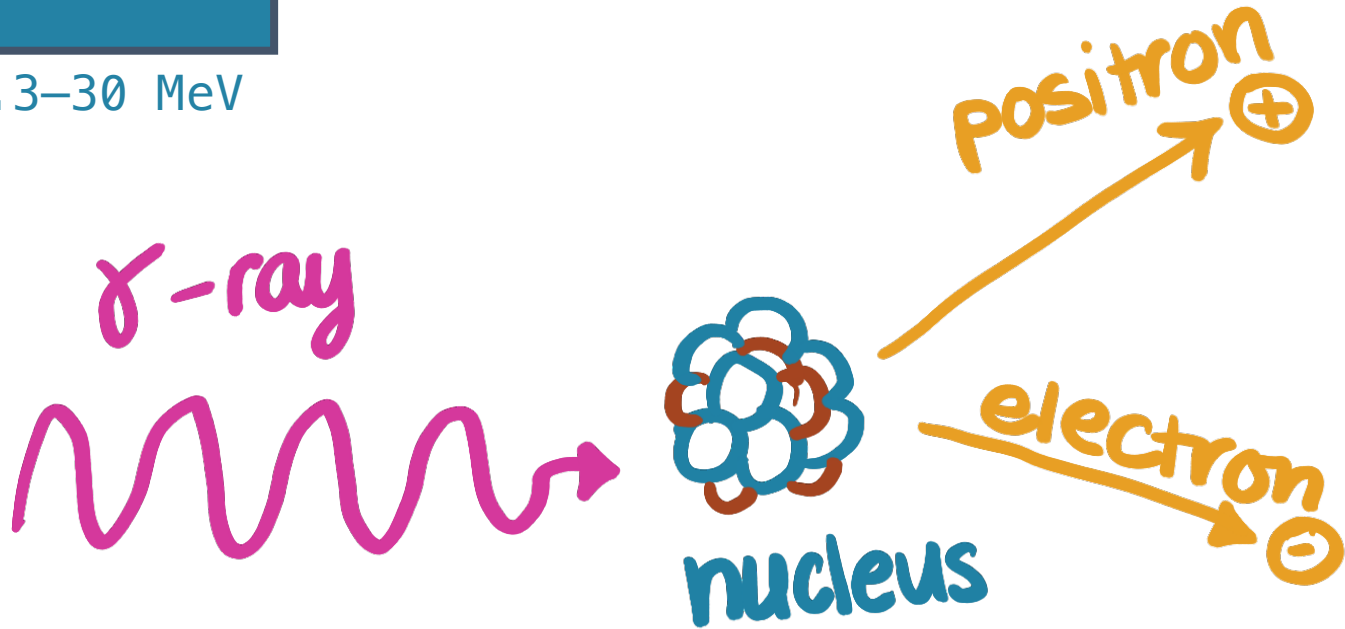
Pair Production Telescopes

20 keV – 1 MeV

20 MeV – 300 GeV



0.3–30 MeV



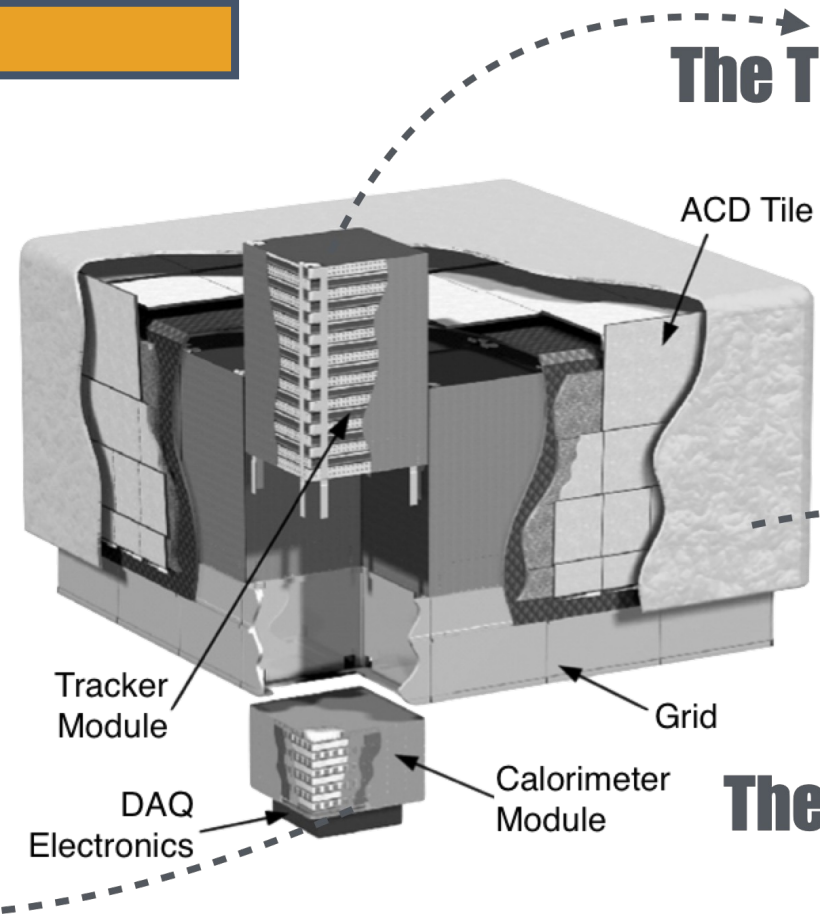
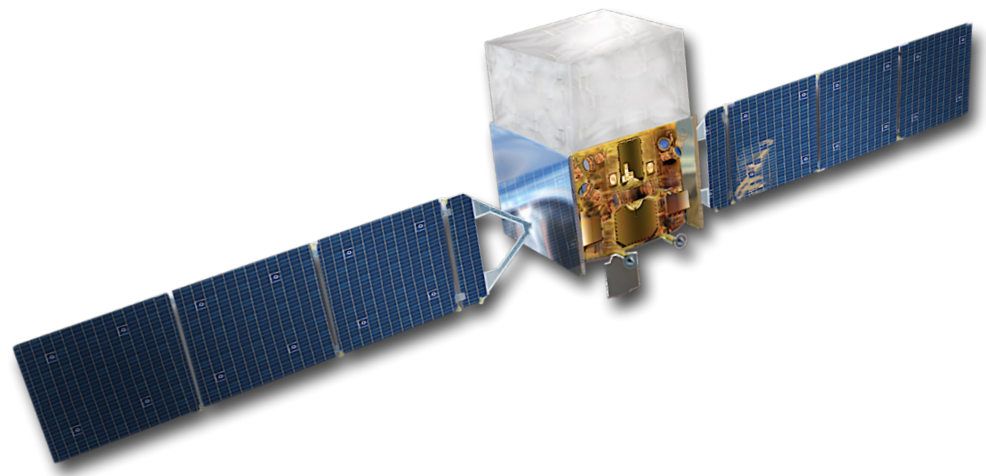
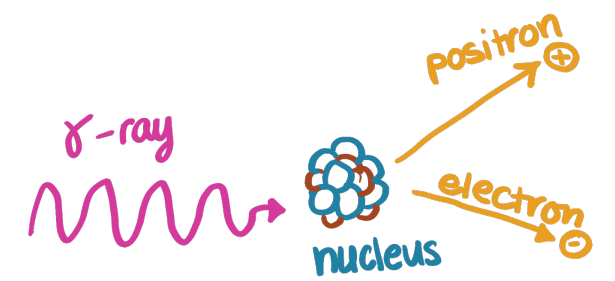
dominating interaction:
Pair production

Pair Production Telescopes

20 keV – 1 MeV

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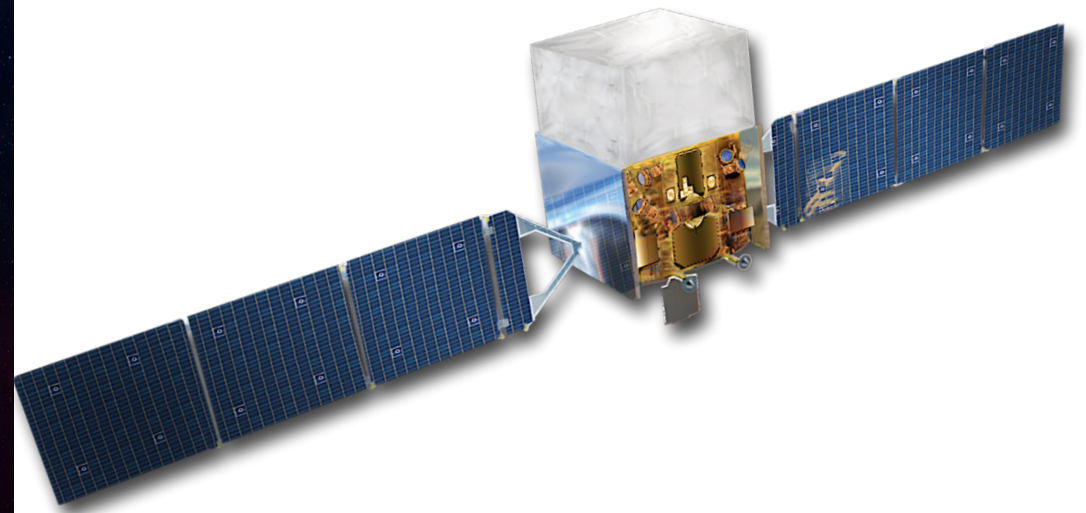
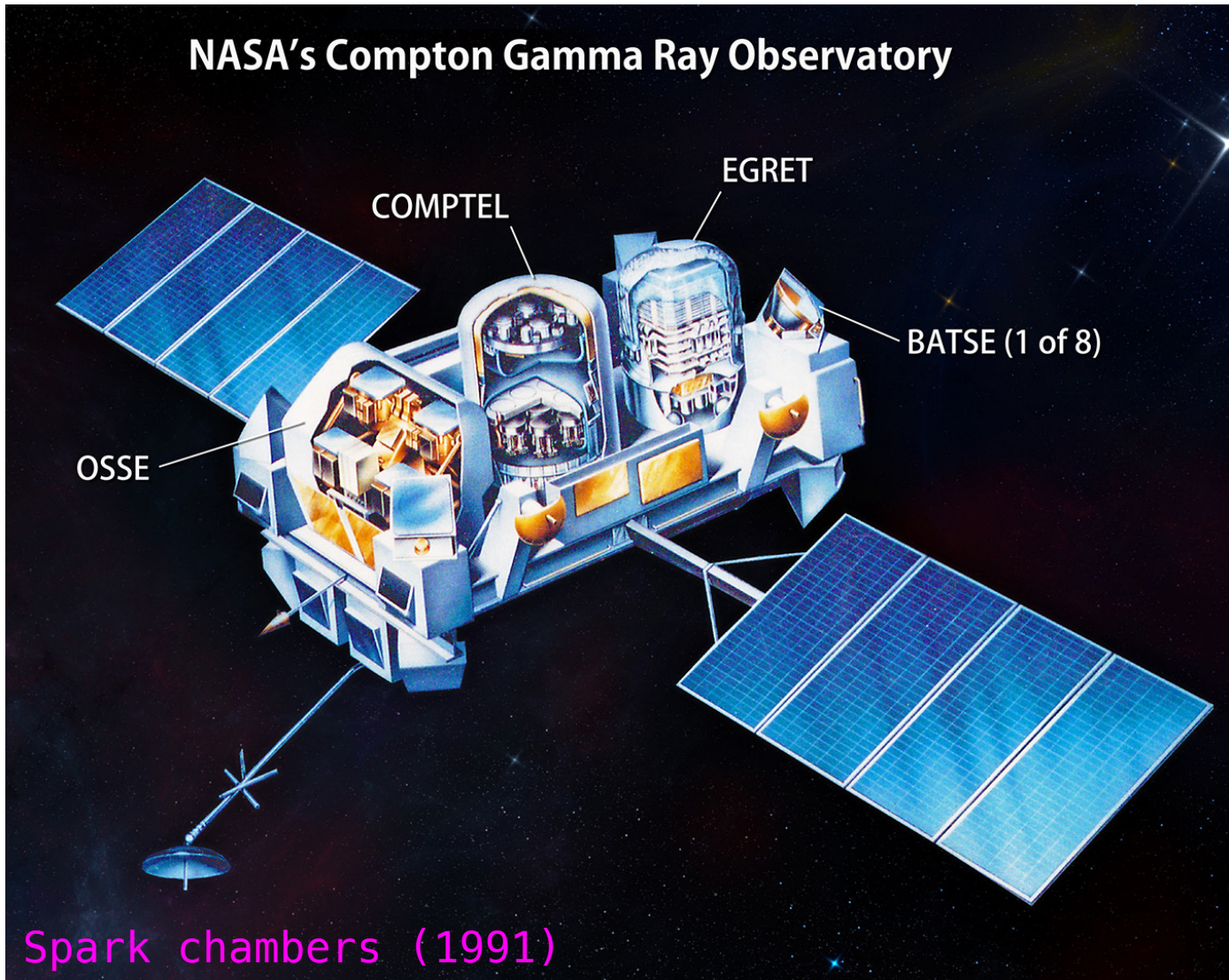
The Tracker-converter

The Calorimeter

The Anti-coincidence Detector

dominating interaction:
Pair production

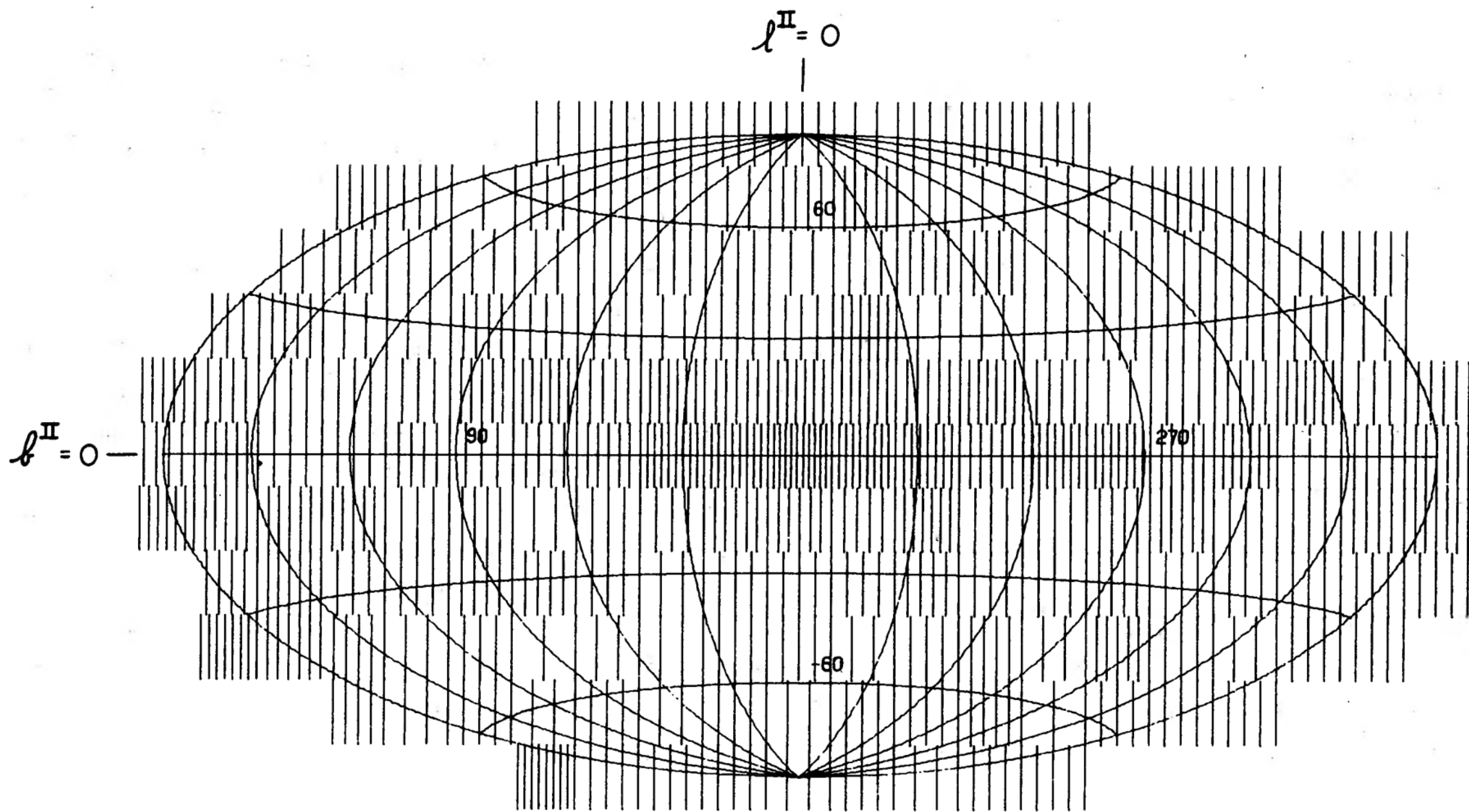
Pair Production Telescopes



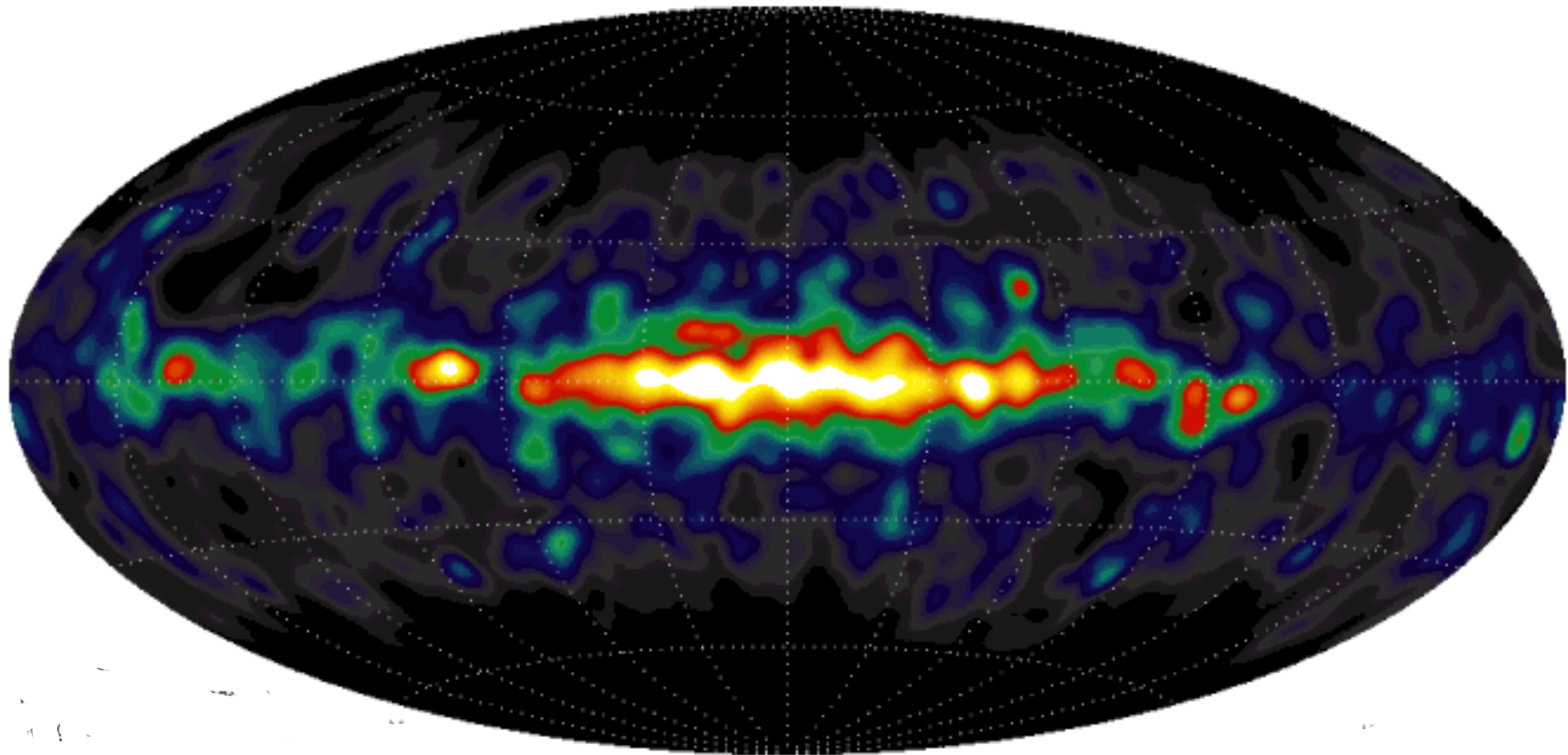
Pair Production Telescopes



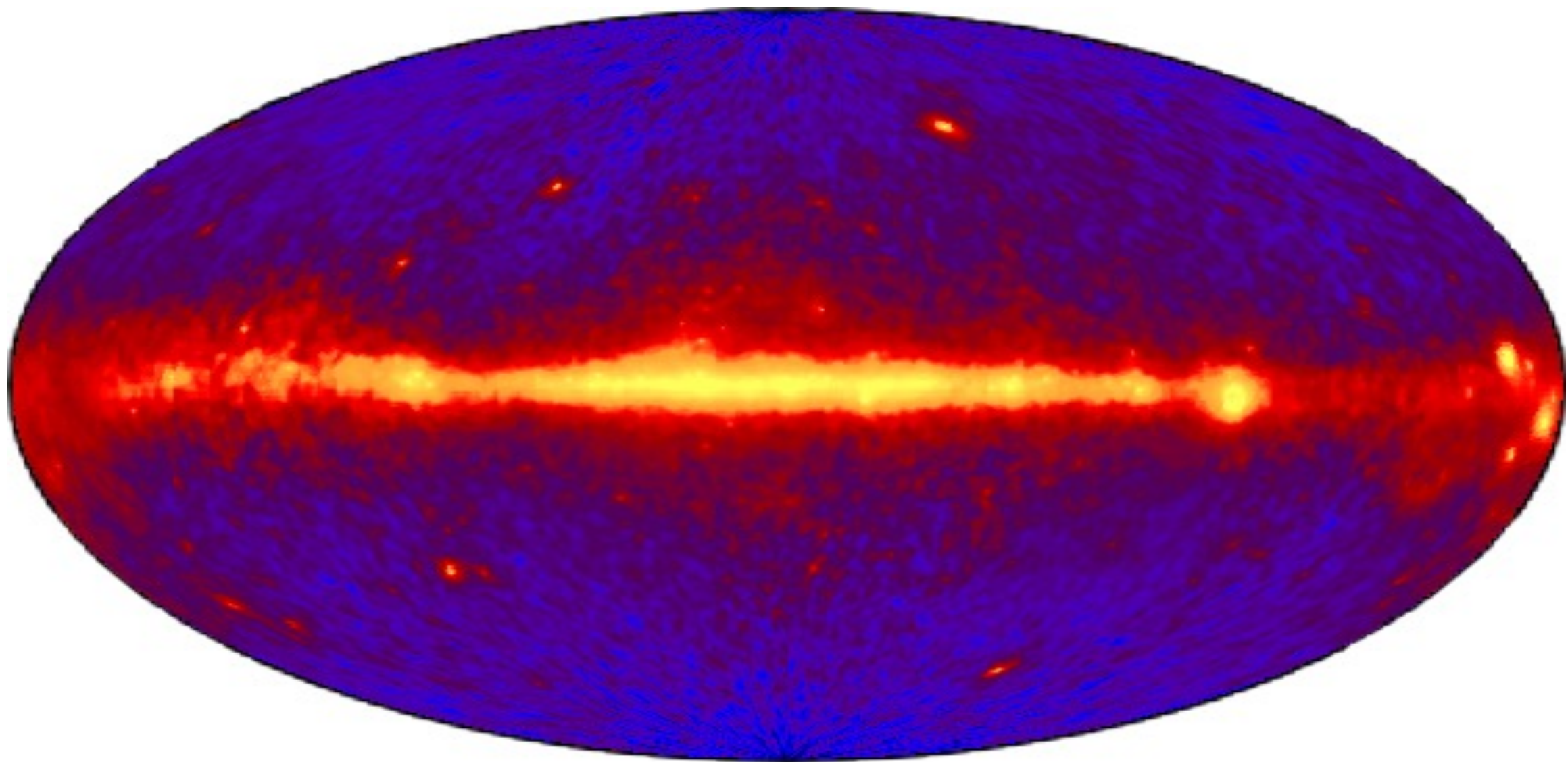
1. From left: Fermi/LAT Principle Investigator **Peter Michelson**, Fermi/LAT co-creator **Bill Atwood** and **Steven Ritz**, project scientist at NASA. (Credit: Steven Ritz/UC Santa Cruz.) **2.** **Fermi Operations team** sporting their colorful unofficial uniforms. (Courtesy Jana Thayer.) **3.** Putting the Large Area Telescope together. (Photo courtesy SLAC Communications.) **4.** The view of the launch from Cocoa Beach. (Courtesy SLAC Communications.) **5.** **The team** that put the Large Area Telescope together at SLAC. (Courtesy SLAC Communications.)



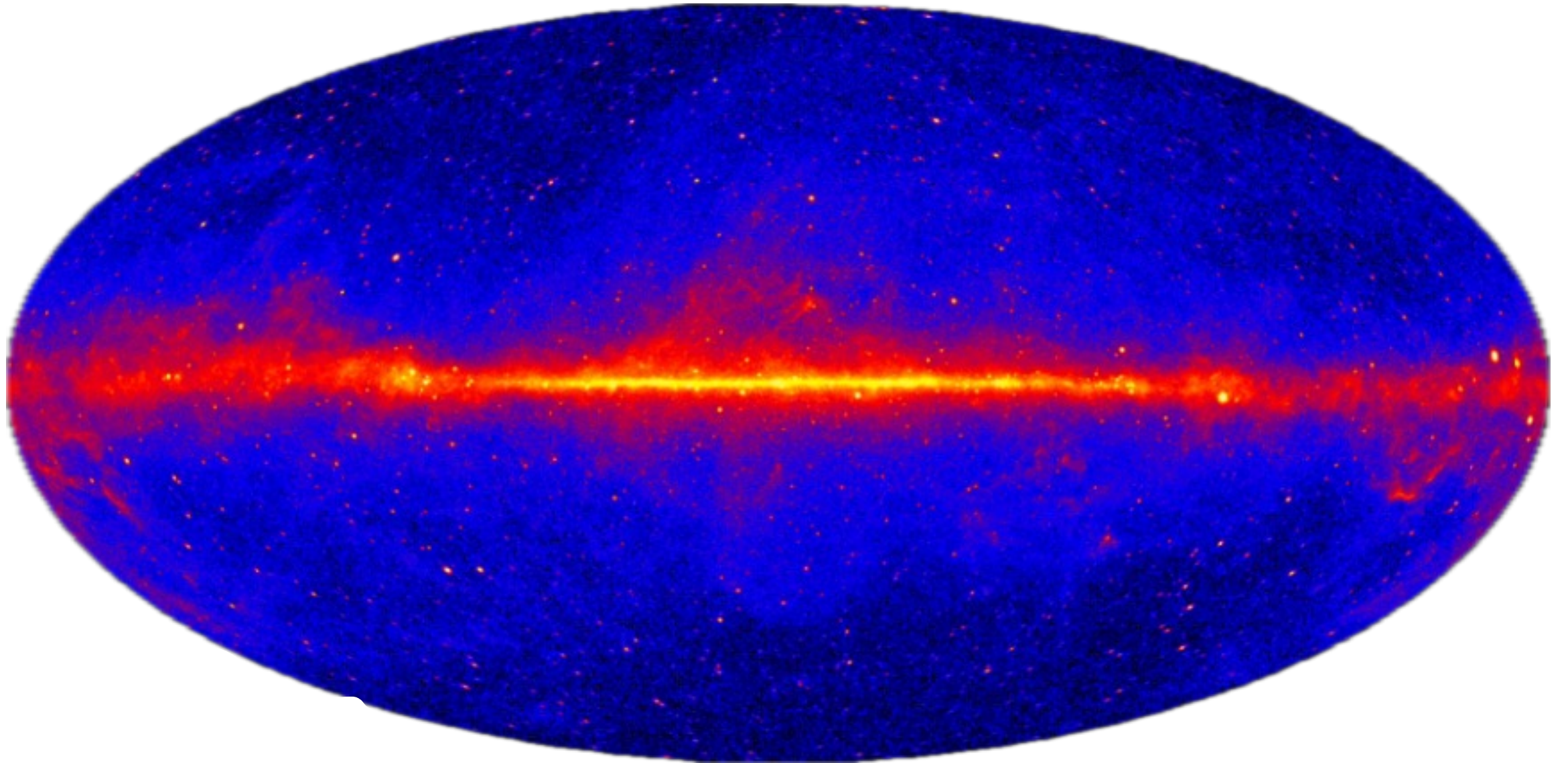
1968, Orbiting Solar Observatory, OSO-3 (~50 MeV)



2000, COMPTEL (onboard CGRO), 1–30 MeV



2000, EGRET (onboard CGRO), above 100 MeV

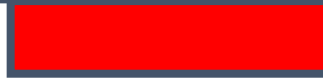


2000, LAT (onboard *Fermi*), above 500 MeV

Ground-based Observations

20 keV – 1 MeV

20 MeV – 300 GeV



0.3–30 MeV

Whipple Telescope 1986



dominating interaction:
Electromagnetic cascades

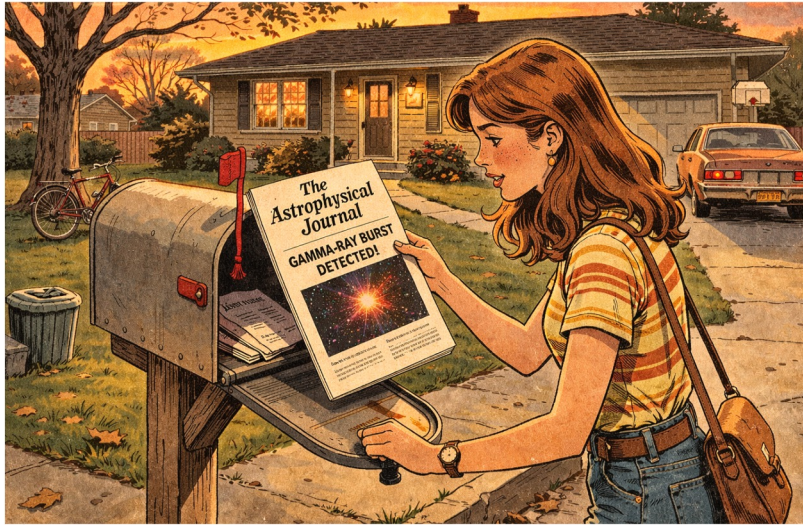


0.1 km² "light pool", a few photons per m².

It's 1973.

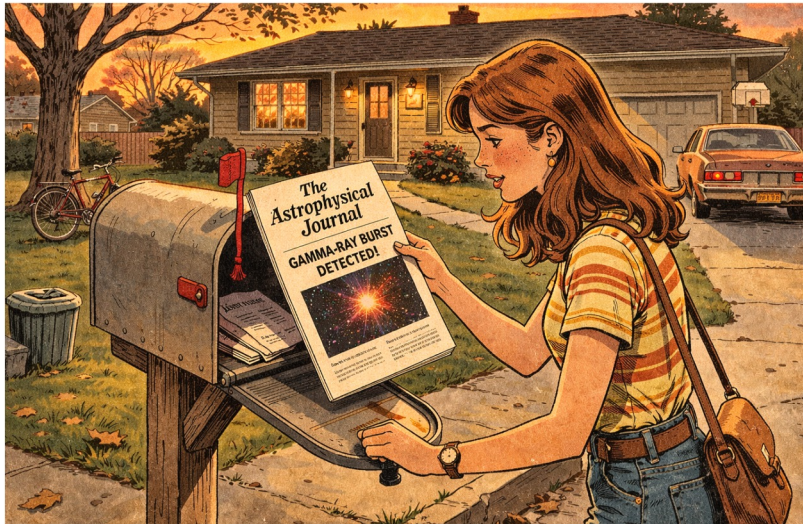
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produced with AI.



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OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Received 1973 March 16; revised 1973 April 2

ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~ 30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

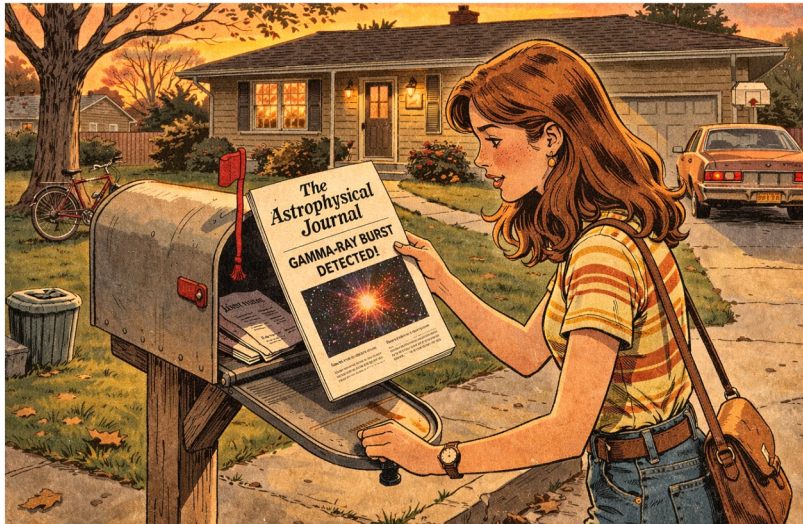
Subject headings: gamma rays — X-rays — variable stars

I. INTRODUCTION

On several occasions in the past we have searched the records of data from early *Vela* spacecraft for indications of gamma-ray fluxes near the times of appearance of supernovae. These searches proved uniformly fruitless. Specific predictions of gamma-ray emission during the initial stages of the development of supernovae have since been made by Colgate (1968). Also, more recent *Vela* spacecraft are equipped with much improved instrumentation. This encouraged a more general search, not restricted to specific time periods. The search covered data acquired with almost continuous coverage between 1969 July and 1972 July, yielding records of 16 gamma-ray bursts distributed throughout that period. Search criteria and some characteristics of the bursts are given below.

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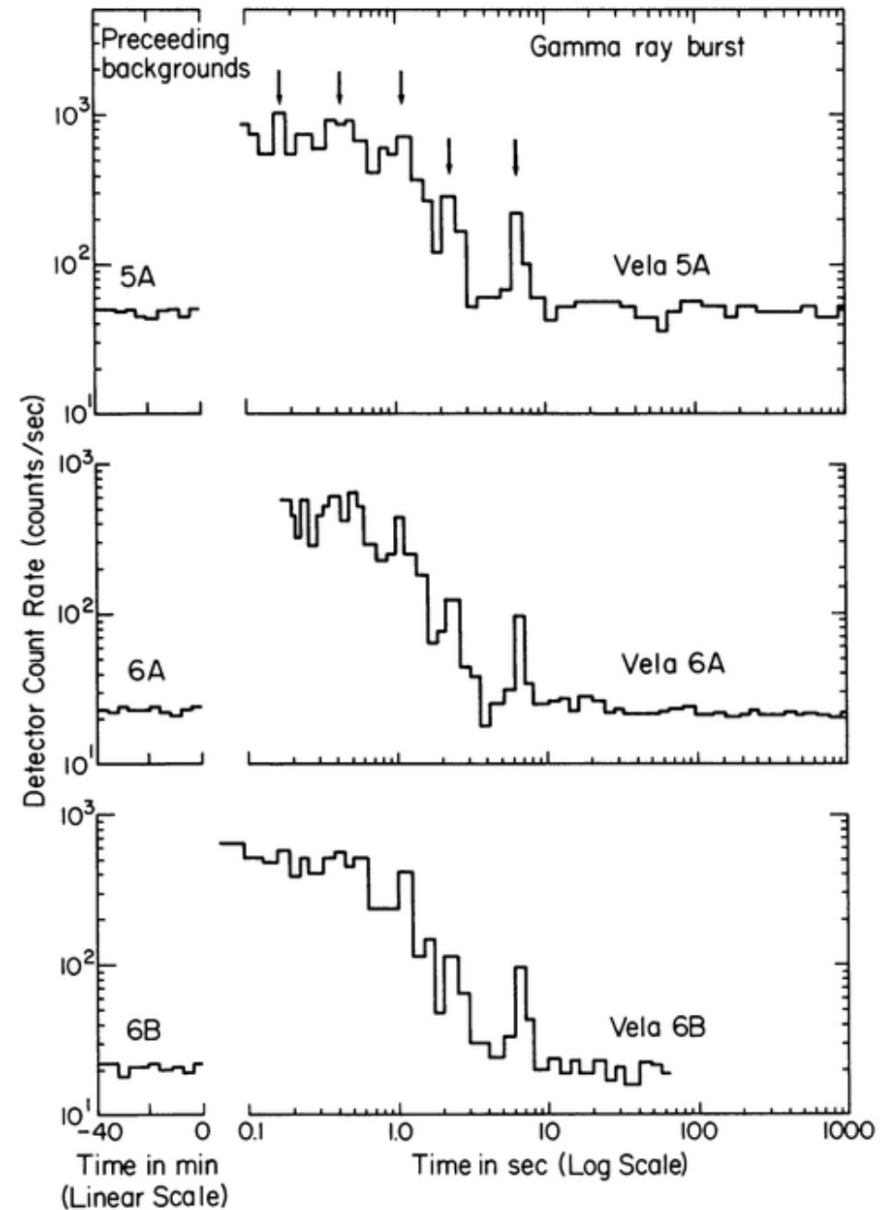
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1994: A **Century** of Gamma Ray Burst Models

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2.	Colgate	1974	ApJ, 187, 333			ST	COS	Type II SN shock brom, inv Comp scat at stellar surface	76.	Melia	1988	ApJ, 335, 965	NS	DISK	Be/X-ray binary sys evolves to NS accretion GRB with recurrence					
3.	Stecker et al.	1973	Nature, 245, P570			ST	DISK	Stellar superflare from nearby star	77.	Ruderman et al.	1988	ApJ, 335, 306	NS	DISK	e+ e- cascades by aligned pulsar outer-mag-sphere reignition					
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6.	Lamb et al.	1973	Nature, 246, P552		ST	DISK	DISK	Accretion onto WD from flare in companion	80.	Melia	1988	Nature, 336, 658	NS	DISK	NS + accretion disk reflection explains GRB spectra					
7.	Lamb et al.	1973	Nature, 246, P552		ST	DISK	DISK	Accretion onto NS from flare in companion	81.	Blaes et al.	1989	ApJ, 343, 839	NS	DISK	NS seismic waves couple to magnetospheric Alfen waves					
8.	Lamb et al.	1973	Nature, 246, P552		BH	ST	DISK	Accretion onto BH from flare in companion	82.	Trofimenko et al.	1989	Ap & SS, 152, 105	WH	COS	Kerr-Newman white holes					
9.	Zwicky	1974	Ap & SS, 28, 111			NS	HALO	NS chunk contained by external pressure escapes, explodes	83.	Sturrock et al.	1989	ApJ, 346, 950	NS	DISK	NS E-field accelerates electrons which then pair cascade					
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12.	Schlovskii	1974	SovAstron, 18, 390		COM	DISK	DISK	Comet from system's cloud strikes WD	86.	Pineault et al.	1989	ApJ, 347, 1141	NS	COM	Fast NS wanders though Oort clouds, fast WD bursts only optical					
13.	Schlovskii	1974	SovAstron, 18, 390		COM	DISK	DISK	Comet from system's cloud strikes NS	87.	Melia et al.	1989	ApJ, 346, 378	NS	DISK	Episodic electrostatic accel and Comp scat from rot high-B NS					
14.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23		ST	COS	COS	Absorption of neutrino emission from SN in stellar envelope	88.	Trofimenko	1989	Ap & SS, 159, 301	WH	COS	Different types of white, "grey" holes can emit GRBs					
15.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23		SN	COS	COS	Thermal emission when small star heated by SN shock wave	89.	Eichler et al.	1989	Nature, 340, 126	NS	NS	COS	NS - NS binary members collide, coalesce				
16.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23		NS	COS	COS	Ejected matter from NS explodes	90.	Wang et al.	1989	PRL, 63, 1550	NS	DISK	Cyclo res & Raman scat fits 20, 40 keV dips, magnetized NS					
17.	Pacini et al.	1974	Nature, 251, 399		NS	DISK	DISK	NS crustal starquake glitch; should time coincide with GRB	91.	Alexander et al.	1989	ApJ, 344, L1	NS	DISK	QED mag resonant opacity in NS atmosphere					
18.	Narlikar et al.	1974	Nature, 251, 590		WH	COS	COS	White hole emits spectrum that softens with time	92.	Melia	1990	ApJ, 351, 601	NS	DISK	NS magnetospheric plasma oscillations					
19.	Tygan	1975	A&A, 44, 21		NS	HALO	HALO	NS corequake excites vibrations, changing E & B fields	93.	Ho et al.	1990	ApJ, 348, L25	NS	DISK	Beaming of radiation necessary from magnetized neutron stars					
20.	Channugam	1974	ApJ, 193, L75		WD	DISK	DISK	Convection inside WD with high B field produces flare	94.	Mitrofanov et al.	1990	Ap & SS, 165, 137	NS	COM	Interstellar comets pass through dead pulsar's magnetosphere					
21.	Prihutski et al.	1975	Ap & SS, 34, 395		AGN	ST	COS	Collapse of supermassive body in nucleus of active galaxy	95.	Dermer	1990	ApJ, 360, 197	NS	DISK	Compton scattering in strong NS magnetic field					
22.	Narlikar et al.	1975	Ap & SS, 35, 321		WH	COS	COS	WH excites synchrotron emission, inverse Compton scattering	96.	Blaes et al.	1990	ApJ, 363, 612	NS	ISM	Old NS accretes from ISM, surface goes nuclear					
23.	Piran et al.	1975	Nature, 256, 112		BH	DISK	DISK	Inv Comp scat deep in ergosphere of fast rotating, accreting BH	97.	Paczynski	1990	ApJ, 363, 218	NS	NS	COS	NS-NS collision causes neutrino collisions, drives super-Ed wind				
24.	Fabian et al.	1976	Ap & SS, 42, 77		NS	DISK	DISK	NS crustquake shocks NS surface	98.	Zdziarski et al.	1991	ApJ, 366, 343	RE	MBR	COS	Scattering of microwave background photons by rel e-s				
25.	Chanugam	1976	Ap & SS, 42, 83		WD	DISK	DISK	Magnetic WD suffers MHD instabilities, flares	99.	Pineault	1990	Nature, 345, 233	NS	COM	DISK	Young NS drifts through its own Oort cloud				
26.	Mullan	1976	ApJ, 208, 199		WD	DISK	DISK	Thermal radiation from flare near magnetic WD	100.	Trofimenko et al.	1991	Ap & SS, 178, 217	WH	HALO	HALO	White hole supernova gave simultaneous burst of g-waves from 1987A				
27.	Woolsey et al.	1976	Nature, 263, 101		NS	DISK	DISK	Carbon detonation from accreted matter onto NS	101.	Melia et al.	1991	ApJ, 373, 198	NS	DISK	DISK	NS B-field undergoes resistive tearing, accelerates plasma				
28.	Lamb et al.	1977	ApJ, 217, 197		NS	DISK	DISK	Mag grating of accreted disk around NS causes sudden accretion	102.	Holcomb et al.	1991	ApJ, 378, 682	NS	DISK	DISK	Alfen waves in non-uniform NS atmosphere accelerate particles				
29.	Piran et al.	1977	ApJ, 214, 268		BH	DISK	DISK	Instability in accretion onto rapidly rotating BH	103.	Haensel et al.	1991	ApJ, 375, 209	SS	COS	COS	Strange stars emit binding energy in grav rad and collide				
30.	Dasgupta	1979	Ap & SS, 63, 517		DG	SOL	SOL	Charged intergal rel dust grain enters sol sys, breaks up	104.	Blaes et al.	1991	ApJ, 381, 210	NS	ISM	DISK	Slow interstellar accretion onto NS, e- capture starquakes result				
31.	Tygan	1980	A&A, 87, 224		WD	DISK	DISK	WD surface nuclear burst causes chromospheric flares	105.	Frank et al.	1992	ApJ, 385, L45	NS	DISK	DISK	Low mass X-ray binary evolve into GRB sites				
32.	Tygan	1980	A&A, 87, 224		NS	DISK	DISK	NS surface nuclear burst causes chromospheric flares	106.	Woolsey et al.	1992	ApJ, 391, 228	NS	HALO	HALO	Accreting WD collapsed to NS				
33.	Ramaty et al.	1981	Ap & SS, 75, 193		NS	DISK	DISK	NS vibrations heat atm to pair produce, annihilate, synch cool	107.	Dar et al.	1992	ApJ, 388, 164	WD	COS	COS	WD accretes to form naked NS, GRB, cosmic rays				
34.	Newman et al.	1980	ApJ, 242, 319		NS	AST	DISK	Asteroid from interstellar medium hits NS	108.	Hanami	1992	ApJ, 389, L71	NS	PLAN	COS	NS - planet magnetospheric interaction unstable				
35.	Ramaty et al.	1980	Nature, 287, 122		NS	HALO	HALO	NS core quake caused by phase transition, vibrations	109.	Meszaros et al.	1992	ApJ, 397, 570	NS	NS	COS	NS - NS collision produces anisotropic fireball				
36.	Howard et al.	1981	ApJ, 249, 302		NS	AST	DISK	Asteroid hits NS, B-field confines mass, creates high temp	110.	Carter	1992	ApJ, 391, L67	BH	ST	COS	Normal stars tidally disrupted by galactic nucleus BH				
37.	Mitrofanov et al.	1981	Ap & SS, 77, 469		NS	DISK	DISK	Helium flash cooled by MHD waves in NS outer layers	111.	Usov	1992	Nature, 357, 472	NS	COS	COS	WD collapses to form NS, B-field brakes NS rotation instantly				
38.	Colgate et al.	1981	ApJ, 248, 771		NS	AST	DISK	Asteroid hits NS, tidally disrupts, heated, expelled along B lines	112.	Narayan et al.	1992	ApJ, 395, L83	NS	NS	COS	NS - NS merger gives optically thick fireball				
39.	van Duren	1981	ApJ, 249, 297		NS	AST	DISK	Asteroid enters NS B field, dragged to surface collision	113.	Narayan et al.	1992	ApJ, 395, L83	BH	NS	COS	BH - NS merger gives optically thick fireball				
40.	Kuznetsov	1982	CosRes, 20, 72		MG	SOL	SOL	Magnetic reconnection at heliopause	114.	Brainerd	1992	ApJ, 394, L33	AGN	JET	COS	Synchrotron emission from AGN jets				
41.	Katz	1982	ApJ, 260, 371		NS	DISK	DISK	NS flares from pair plasma confined in NS magnetosphere	115.	Meszaros et al.	1992	MNRAS, 257, 29P	BH	NS	COS	BH-NS have neutrinos collide to gammas in clean fireball				
42.	Woolsey et al.	1982	ApJ, 258, 716		NS	DISK	DISK	Magnetic reconnection after NS surface He flash	116.	Meszaros et al.	1992	MNRAS, 257, 29P	NS	NS	COS	NS-NS have neutrinos collide to gammas in clean fireball				
43.	Fryxell et al.	1982	ApJ, 258, 733		NS	DISK	DISK	He fusion runaway on NS B-pole helium lake	117.	Cline et al.	1992	ApJ, 401, L57	BH	DISK	DISK	Primordial BHs evaporating could account for short hard GRBs				
44.	Hameury et al.	1982	A&A, 111, 242		NS	DISK	DISK	e- capture triggers H flash triggers He flash on NS surface	118.	Rees et al.	1992	MNRAS, 258, 41P	NS	ISM	COS	Relativistic fireball reconverted to radiation when hits ISM				
45.	Mitrofanov et al.	1982	MNRAS, 200, 1033		NS	DISK	DISK	B induced cyclc res in rad absorp giving rel e-s, inv C scat												
46.	Fenimore et al.	1982	Nature, 297, 665		NS	DISK	DISK	BB X-rays inv Comp scat by hotter overlying plasma												
47.	Lipunov et al.	1982	Ap & SS, 85, 459		NS	ISM	DISK	ISM matter accum at NS magnetopause then suddenly accretes												
48.	Baan	1982	ApJ, 261, L71		WD	HALO	HALO	Nonexplosive collapse of WD into rotating, cooling NS												
49.	Ventura et al.	1983	Nature, 301, 491		NS	ST	DISK	NS accretion from low mass binary companion												
50.	Bisnovatyi- et al.	1983	Ap & SS, 89, 447		NS	DISK	DISK	Neutron rich elements to NS surface with quake, undergo fission												
51.	Bisnovatyi- et al.	1984	SovAstron, 28, 62		NS	DISK	DISK	Thermonuclear explosion beneath NS surface												
52.	Ellison et al.	1983	A&A, 128, 102		NS	HALO	HALO	NS corequake + uneven heating yield SGR pulsations												
53.	Hameury et al.	1983	A&A, 128, 369		NS	DISK	DISK	B field contains matter on NS cap allowing fusion												
54.	Bonazzola et al.	1984	A&A, 136, 89		NS	DISK	DISK	NS surface nuc explosion causes small scale B reconnection												
55.	Michel	1985	ApJ, 290, 721		NS	DISK	DISK	Remnant disk ionization instability causes sudden accretion												
56.	Liang	1984	ApJ, 283, 121		NS	DISK	DISK	Resonant EM absorp during magnetic flare gives hot sync e-s												
57.	Liang et al.	1984	Nature, 310, 121		NS	DISK	DISK	NS magnetic fields get twisted, recombine, create flare												
58.	Mitrofanov	1984	Ap & SS, 105, 245		NS	DISK	DISK	NS magnetosphere excited by starquake												
59.	Epstein	1985	ApJ, 291, 822		NS	DISK	DISK	Accretion instability between NS and disk												
60.	Schlovskii et al.	1985	MNRAS, 212, 545		NS	HALO	HALO	Old NS in Galactic halo undergoes starquake												
61.	Tygan	1984	Ap & SS, 106, 199		NS	DISK	DISK	Weak B field NS spherically accretes, Comptonizes X-rays												
62.	Usov	1984	Ap & SS, 107, 191		NS	DISK	DISK	NS flares result of magnetic convective-oscillation instability												
63.	Hameury et al.	1985	ApJ, 293, 56		NS	DISK	DISK	High Landau e-s beamed along B lines in cold atm of NS												
64.	Rappaport et al.	1985	Nature, 314, 242		NS	DISK	DISK	NS + low mass stellar companion gives GRB + optical flash												
65.	Tremaine et al.	1986	ApJ, 301, 155		NS	COM	DISK	NS tides disrupt comet, debris hits NS next pass												
66.	Muslimov et al.	1986	Ap & SS, 120, 27		NS	HALO	HALO	Radially oscillating NS												
67.	Sturrock	1986	Nature, 321, 47		NS	DISK	DISK	Flare in the magnetosphere of NS accelerates e-s along B-field												
68.	Paczynski	1986	ApJ, 308, L43		NS	COS	COS	Cosmo GRBs: rel e- e+ opt thick plasma outflow indicated												
69.	Bisnovatyi- et al.	1986	SovAstron, 30, 582		NS	DISK	DISK	Chain fission of superheavy nuclei below NS surface during SN												
70.	Alcock et al.	1986	PRL, 57, 2088		SS	SS	DISK	SN ejects strange mat lump craters rotating SS companion												
71.	Vahia et al.	1988	A&A, 207, 55		ST	DISK	DISK	Magnetically active stellar system gives stellar flare												
72.	Babul et al.	1987	ApJ, 316, L49		CS	COS	COS	GRB result of energy released from cusp of cosmic string												
73.	Livio et al.	1987	Nature, 327, 398		NS	COM	DISK	Oort cloud around NS can explain soft gamma-repeaters												
74.	McBreen et al.	1988	Nature, 332, 234		GAL	AGN	COS	G-wave bkgrd makes BL Lac wiggle across galaxy lens caustic												

1994: A Century of Gamma Ray Burst Models

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46.	Fenimore et al.	1982	Nature, 297, 665		NS	DISK	DISK	BB X-rays inv Comp scat by hotter overlying plasma	110.	Carter	1992	ApJ, 391, L67	BH	ST	COS	Normal stars tidally disrupted by galactic nucleus BH
47.	Lipunov et al.	1982	Ap & SS, 85, 459		NS	ISM	DISK	ISM matter accum at NS magnetopause then suddenly accretes	111.	Usov	1992	Nature, 357, 472	NS	COS	COS	WD collapses to form NS, B-field brakes NS rotation instantly
48.	Baan	1982	ApJ, 261, L71		WD	HALO	HALO	Nonexplosive collapse of WD into rotating, cooling NS	112.	Narayan et al.	1992	ApJ, 395, L83	NS	NS	COS	NS - NS merger gives optically thick fireball
49.	Ventura et al.	1983	Nature, 301, 491		NS	ST	DISK	NS accretion from low mass binary companion	113.	Narayan et al.	1992	ApJ, 395, L83	BH	NS	COS	BH - NS merger gives optically thick fireball
50.	Bisnovatyi et al.	1983	Ap & SS, 89, 447		NS	DISK	DISK	Neutron rich elements to NS surface with quake, undergo fission	114.	Brainerd	1992	ApJ, 394, L33	AGN	JET	COS	Synchrotron emission from AGN jets
51.	Bisnovatyi et al.	1984	SovAstron, 28, 62		NS	DISK	DISK	Thermonuclear explosion beneath NS surface	115.	Meszaros et al.	1992	MNRAS, 257, 29P	BH	NS	COS	BH-NS have neutrinos collide to gammas in clean fireball
52.	Ellison et al.	1983	A&A, 128, 102		NS	HALO	HALO	NS corequake + uneven heating yield SGR pulsations	116.	Meszaros et al.	1992	MNRAS, 257, 29P	NS	NS	COS	NS-NS have neutrinos collide to gammas in clean fireball
53.	Hameury et al.	1983	A&A, 128, 369		NS	DISK	DISK	B field contains matter on NS cap allowing fusion	117.	Cline et al.	1992	ApJ, 401, L57	BH	DISK	DISK	Primordial BHs evaporating could account for short hard GRBs
54.	Bonazzola et al.	1984	A&A, 136, 89		NS	DISK	DISK	NS surface nuc explosion causes small scale B reconnection	118.	Rees et al.	1992	MNRAS, 258, 41P	NS	ISM	COS	Relativistic fireball reconverted to radiation when hits ISM
55.	Michel	1985	ApJ, 290, 721		NS	DISK	DISK	Remnant disk ionization instability causes sudden accretion								
56.	Liang	1984	ApJ, 283, L21		NS	DISK	DISK	Resonant EM absorp during magnetic flare gives hot sync e-s								
57.	Liang et al.	1984	Nature, 310, 121		NS	DISK	DISK	NS magnetic fields get twisted, recombine, create flare								
58.	Mitrofanov	1984	Ap & SS, 105, 245		NS	DISK	DISK	NS magnetosphere excited by starquake								
59.	Epstein	1985	ApJ, 291, 922		NS	DISK	DISK	Accretion instability between NS and disk								
60.	Schlovskii et al.	1985	MNRAS, 212, 545		NS	HALO	HALO	Old NS in Galactic halo undergoes starquake								
61.	Tryggv	1984	Ap & SS, 106, 199		NS	DISK	DISK	Weak B field NS spherically accretes, Comptonizes X-rays								
62.	Guo	1984	Ap & SS, 107, 191		NS	DISK	DISK	NS flares result of magnetic convective-oscillation instability								
63.	Hameury et al.	1985	ApJ, 293, 56		NS	DISK	DISK	High Landau e-s beamed along B lines in cold atm of NS								
64.	Rappaport et al.	1985	Nature, 314, 242		NS	DISK	DISK	NS + low mass stellar companion gives GRB + optical flash								
65.	Tremaine et al.	1986	ApJ, 301, 155		NS	COM	DISK	NS tides disrupt comet, debris hits NS next pass								
66.	Muslimov et al.	1986	Ap & SS, 120, 27		NS	HALO	HALO	Radially oscillating NS								
67.	Sturrock	1986	Nature, 321, 47		NS	DISK	DISK	Flare in the magnetosphere of NS accelerates e-s along B-field								
68.	Paczynski	1986	ApJ, 308, L43		NS	COS	COS	Cosmo GRBs: rel e+ e- opt thk plasma outflow indicated								
69.	Bisnovatyi et al.	1986	SovAstron, 30, 582		NS	DISK	DISK	Chain fission of superheavy nuclei below NS surface during SN								
70.	Alcock et al.	1986	PRL, 57, 2088		SS	SS	SS	SN ejects strange matter lump creates rotating SS companion								
71.	Vahia et al.	1988	A&A, 207, 55		ST	DISK	DISK	Magnetically active stellar system gives stellar flare								
72.	Babul et al.	1987	ApJ, 316, L49		CS	COS	COS	GRB result of energy released from cusp of cosmic string								
73.	Livio et al.	1987	Nature, 327, 398		NS	COM	DISK	Oort cloud around NS can explain soft gamma-repeaters								
74.	McBreen et al.	1988	Nature, 332, 234		GAL	AGN	COS	G-wave bkgrd makes BL Lac wiggle across galaxy lens caustic								

“For theorists who may wish to enter this broad and growing field, I should point out that there are a considerable number of combinations, for example, comets of antimatter falling onto white holes, not yet claimed.”

- M. Ruderman¹

It's 1995.

We've been detecting gamma-ray bursts for over twenty years, and we still don't know what they are.

This is one of the biggest open questions in astrophysics.



Are gamma-ray bursts galactic or extragalactic?

**The Distance Scale to Gamma-Ray Bursts
Great Debate in 1995**

Baird Auditorium, Smithsonian Natural History Museum, April 20, 1995.

Are gamma-ray bursts galactic or extragalactic?

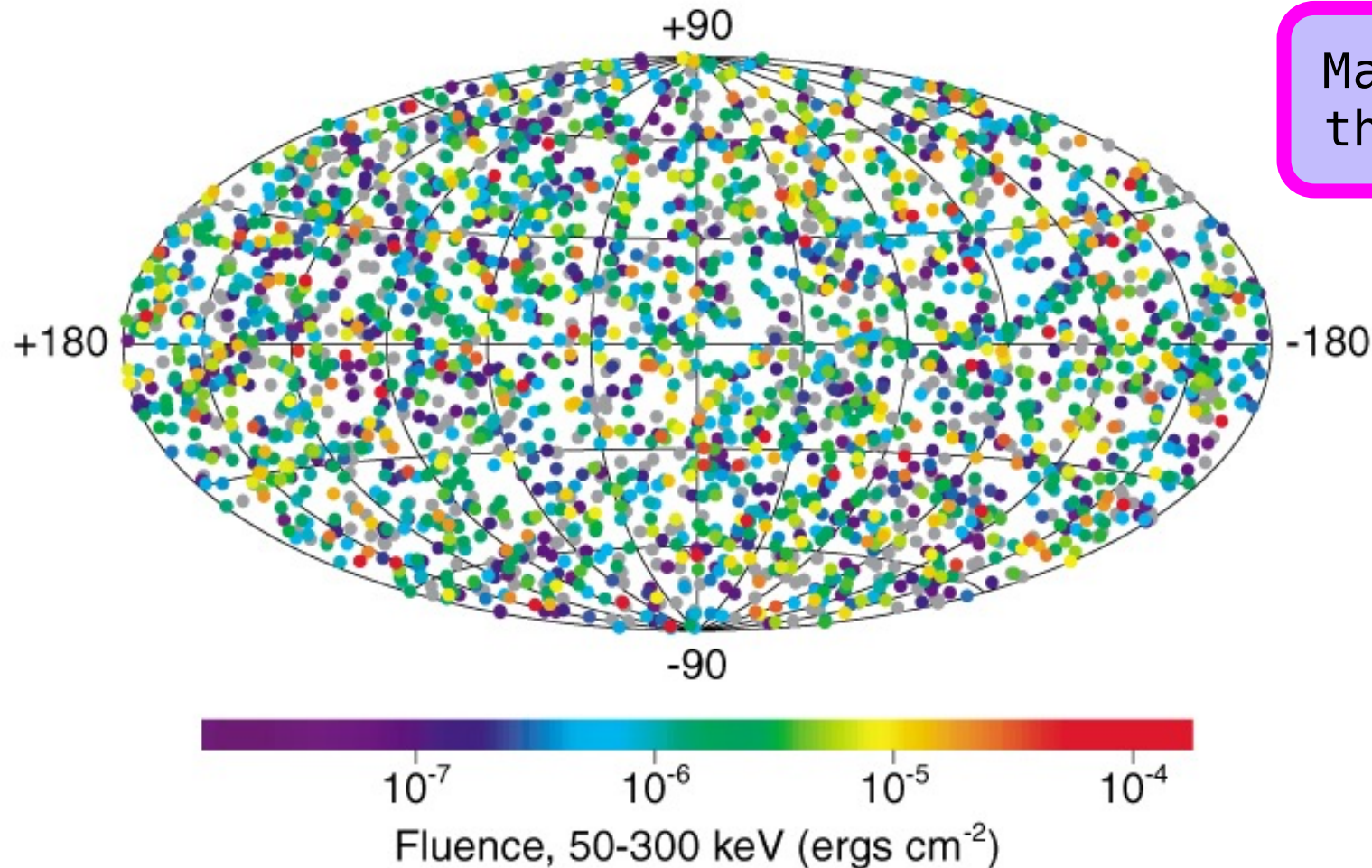


The Distance Scale to Gamma-Ray Bursts
Great Debate in 1995

Baird Auditorium, Smithsonian Natural History Museum, April 20, 1995.

Exhibit 1: The BATSE Sky Map

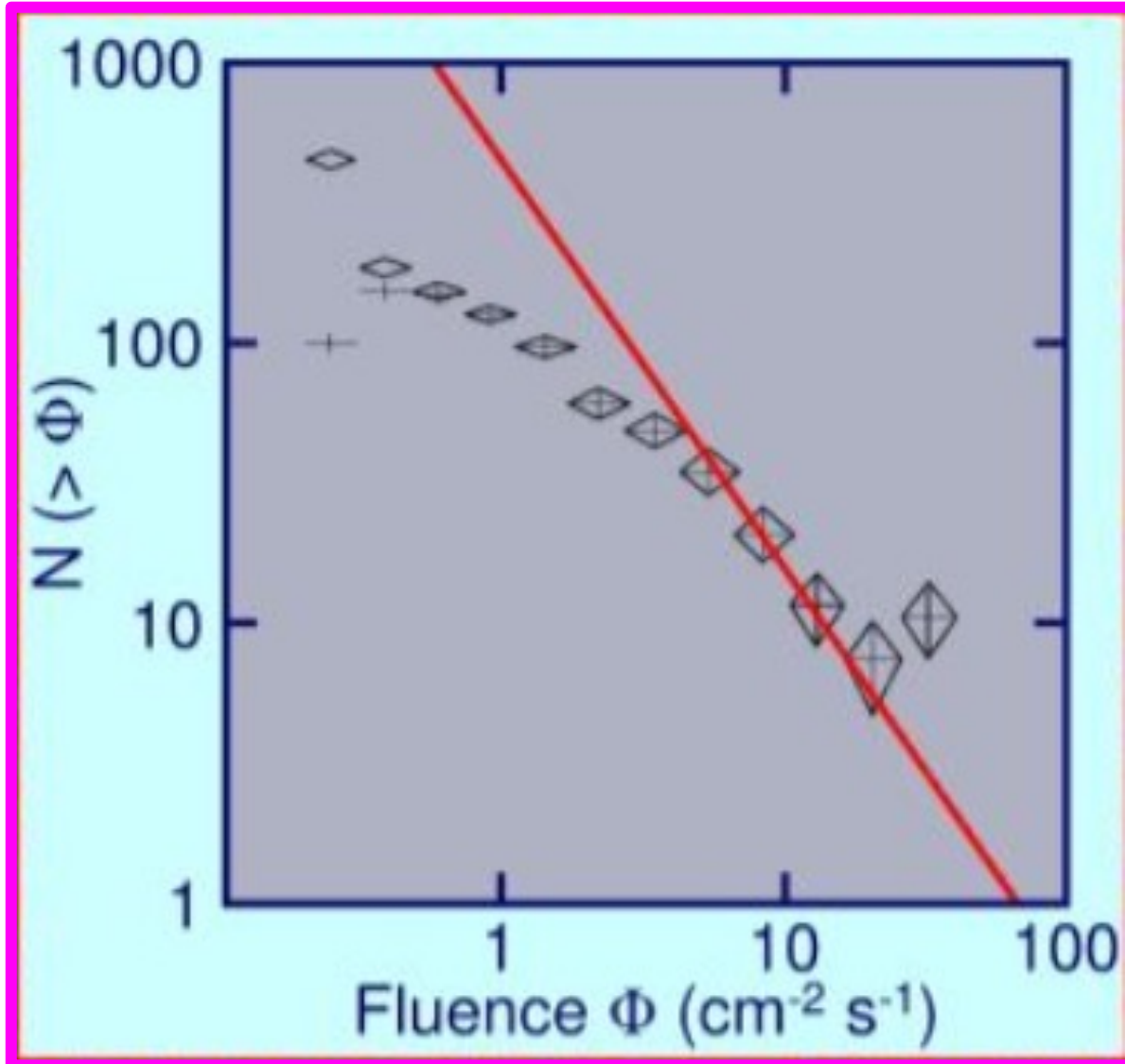
2704 BATSE Gamma-Ray Bursts



Main argument: we should see this in Andromeda. We don't.

Cosmology: 1
Galaxy: 0

Exhibit 2: The Log N – Log S



Main arguments:

- **(cosmological)** at large distances, cosmological effects (redshift, time dilation, non-Euclidian geometry) naturally suppress the number of faint sources
- **(galactic)** we're seeing the edge of the halo – sources beyond $\sim 200\text{--}400$ kpc simply don't exist, so the faint end drops off.

Cosmology: 1
Galaxy: 0

Exhibit 3: The energy problem

If GRBs are cosmological, say at $z = 1$, how much energy does a typical burst release?

Typical burst fluence: $\sim 10^{-6}$ erg/cm²

Luminosity distance: $\sim 2 \times 10^{28}$ cm

$$E \sim 4\pi d^2 \times \text{fluence} \\ \sim \mathbf{10^{51} \text{ erg}}$$

Galactic halo only requires $10^{38} - 10^{42}$ erg per burst

Cosmology: 1
Galaxy: 1

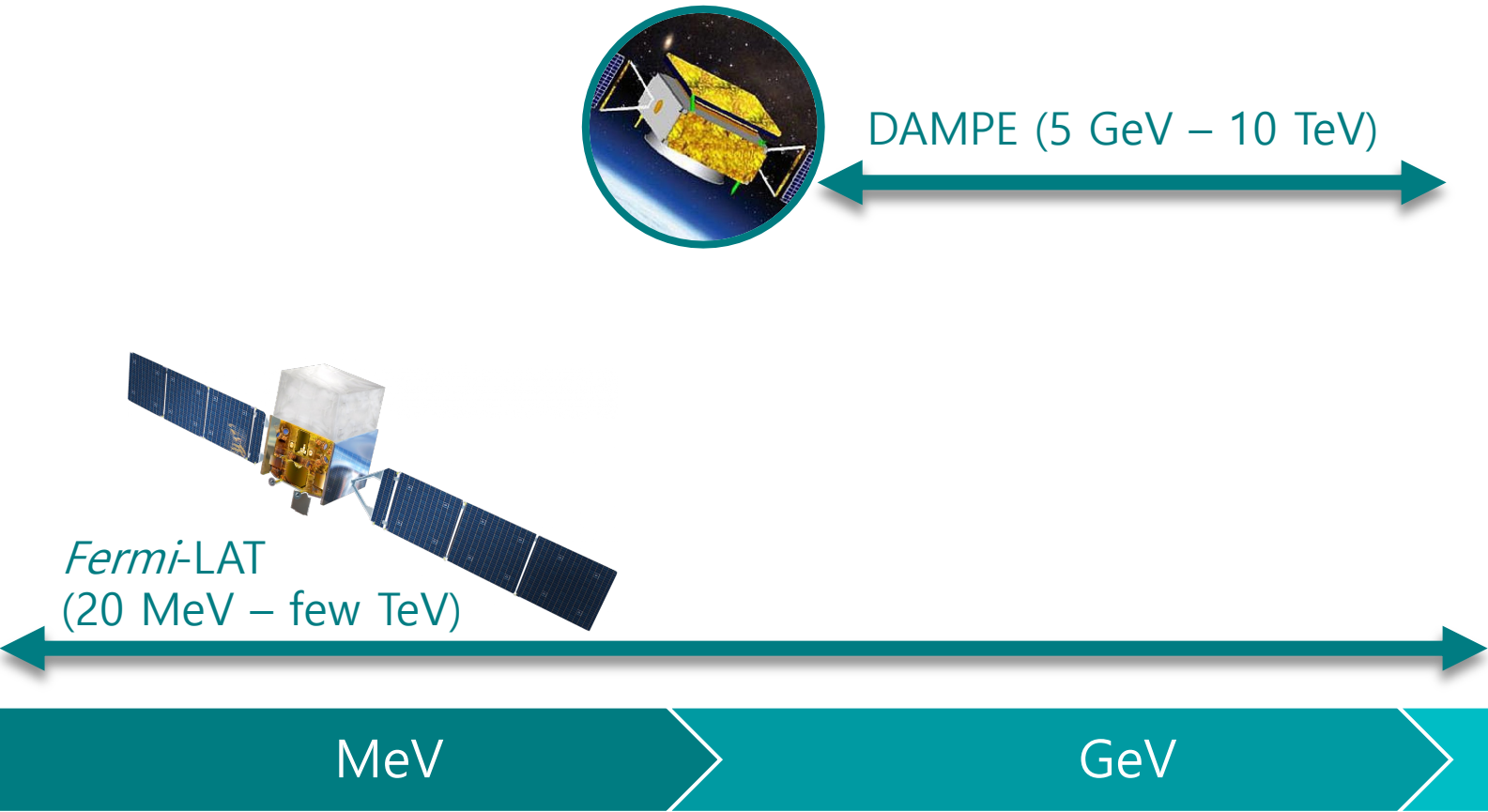
Galactic

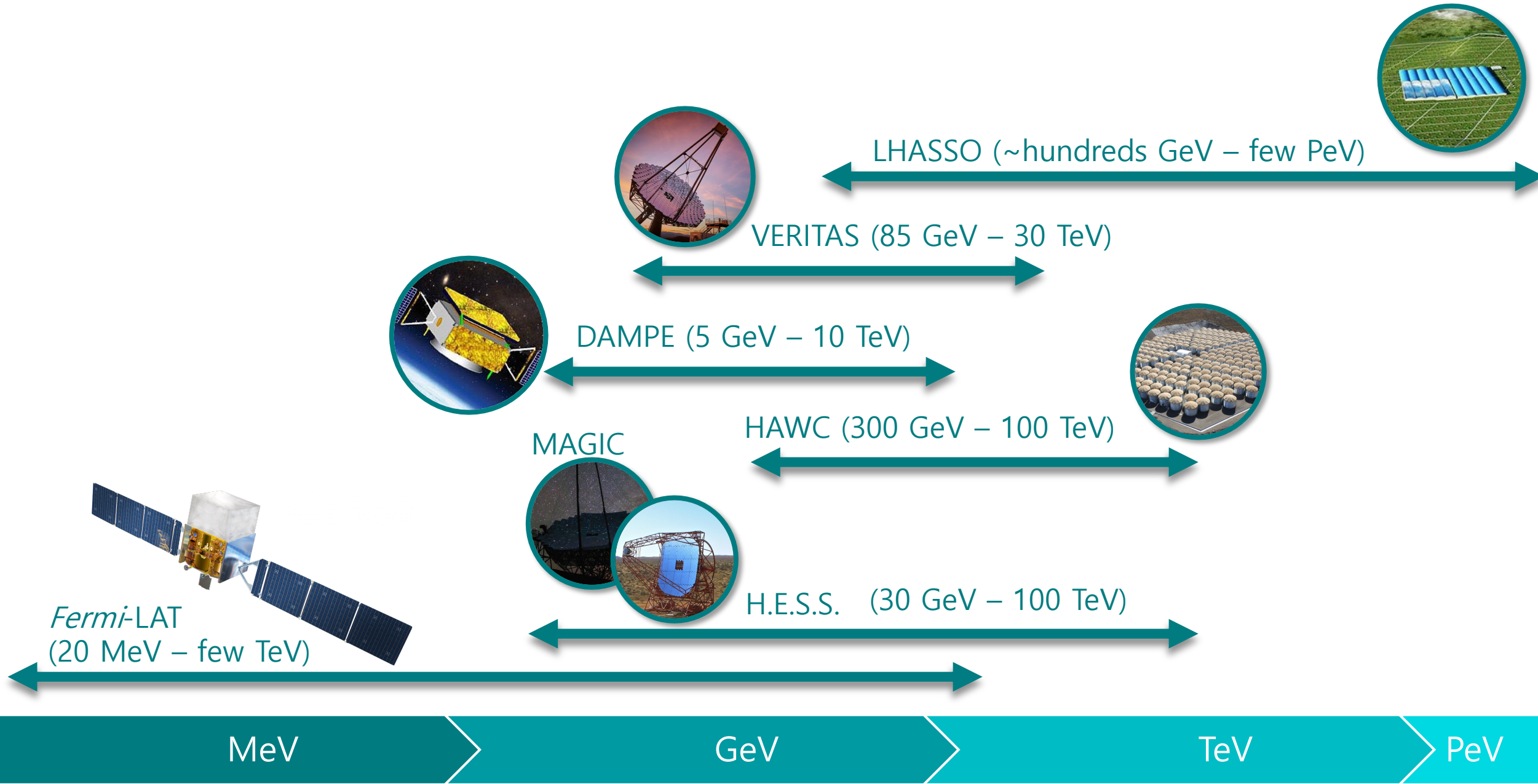
Extragalactic

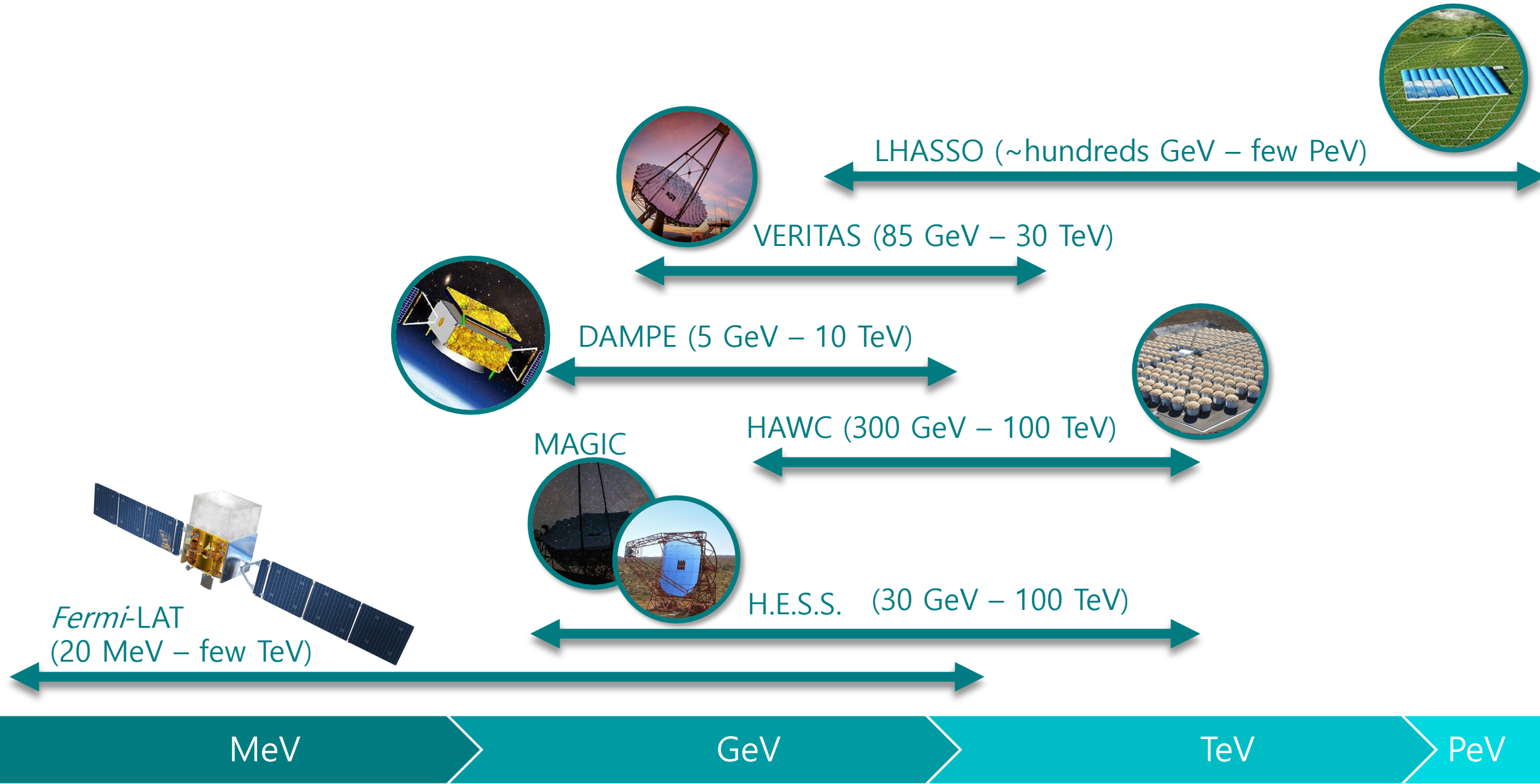
The resolution

- Two years after this debate, on February 28, 1997, the Italian–Dutch satellite BeppoSAX detected GRB 970228 and its fading X-ray afterglow.
- Ground-based telescopes found an optical counterpart sitting on a faint, distant galaxy.
- Three months later, GRB 970508 gave us the first spectroscopic redshift: $z = 0.835$.

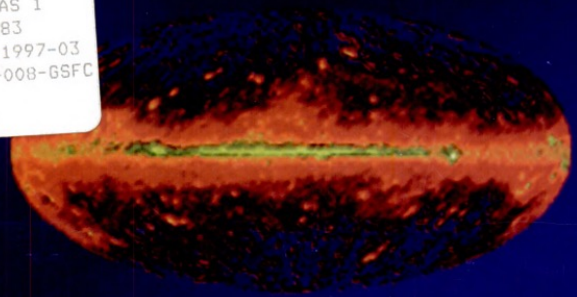
Cosmological. Case closed. It took 24 years from the first detection to settle the question





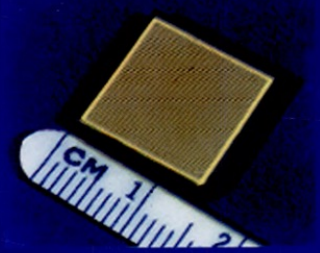


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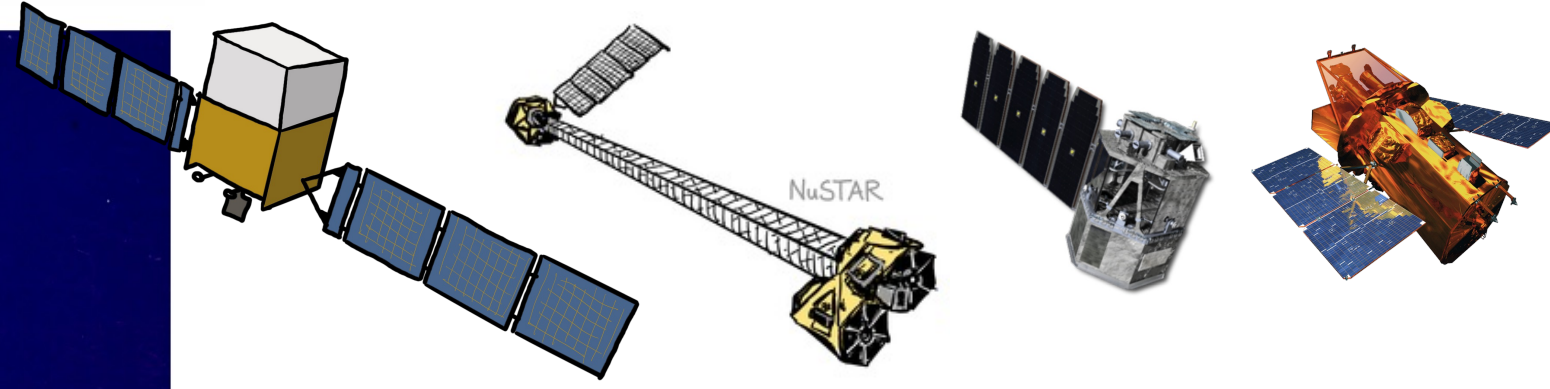


RECOMMENDED PRIORITIES FOR NASA'S GAMMA RAY ASTRONOMY PROGRAM 1996-2010

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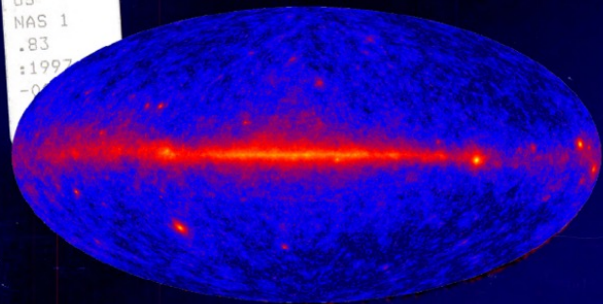


Report of the Gamma Ray Astronomy Program Working Group
April, 1997



- Intermediate Missions: Fermi, NuSTAR and now COSI
- MIDEX and SMEX: Swift and NICER
- Technology: a robust technology development program (SiPMs, new scintillators, upgraded silicon detectors, etc)
- Balloons (+ CubeSats!): long duration balloons enabled COSI, LEAP, etc.
- Data Analysis & Theory: mainly supported through GI programs
- TeV Astronomy: VERITAS, HESS, HAWC, and MAGIC.

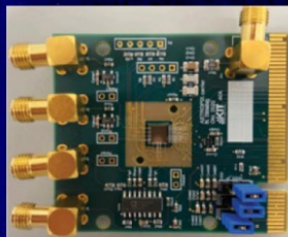
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RECOMMENDED PRIORITIES FOR NASA'S
GAMMA RAY ASTRONOMY PROGRAM
2025 - 2040



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Report of the Gamma Ray Astronomy Program Working Group
April, 2025

Submitted to the NASA Astrophysics Advisory Committee by
The Future Innovations in Gamma Ray Science Analysis Group

Future Innovations in Gamma Rays SAG: A Report on Gamma-ray Science Objectives Beyond 2025

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