Time-domain astronomy

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Rough outline

Day 1: Intro

How are gamma rays produced? What do we learn from them?

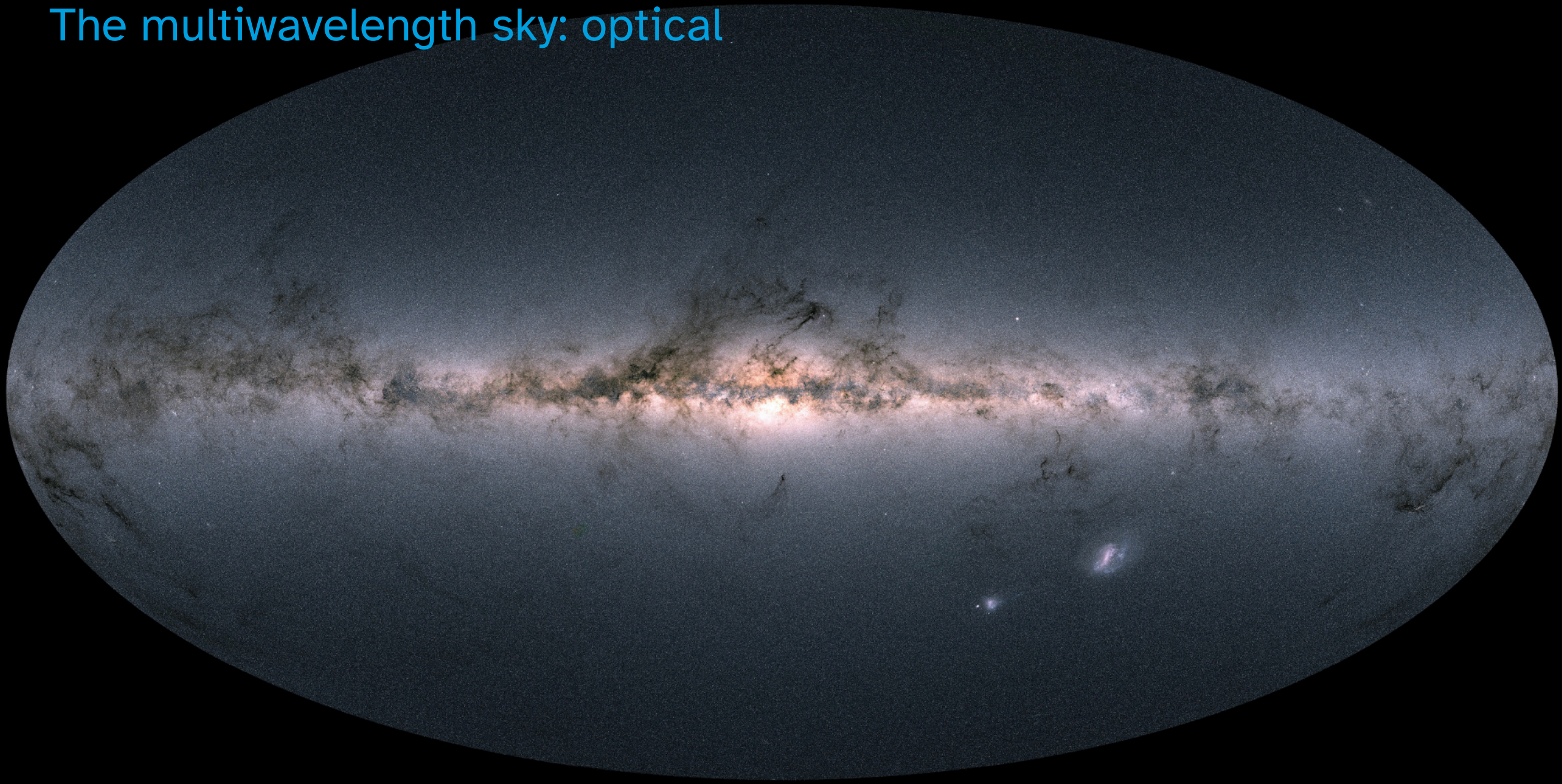
Day 2: Observations

How do we detect gamma rays? How do we decide what/when to observe?

Day 3 + 4: Sources

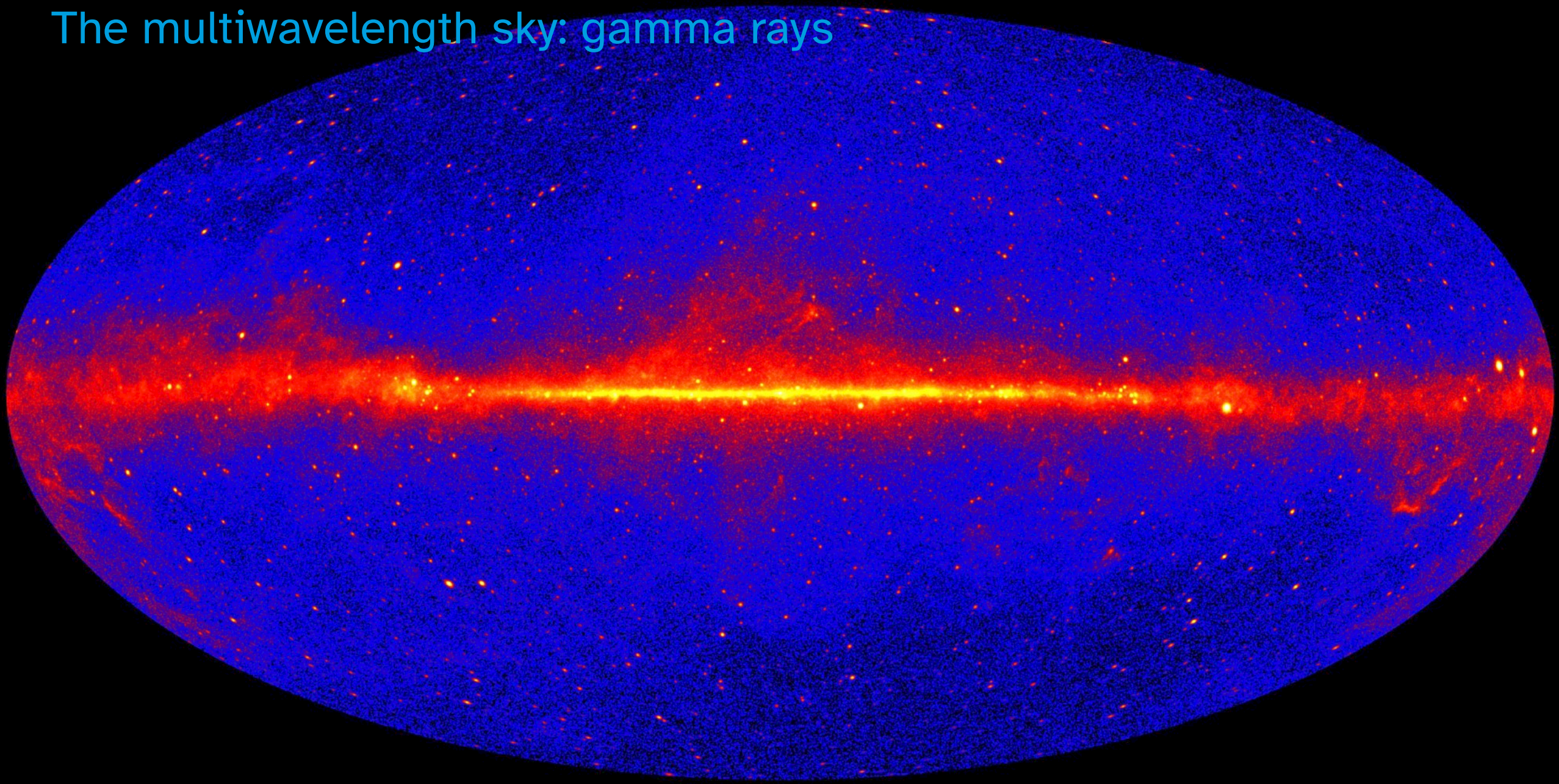
What astronomical objects do we observe in the time domain?

The multiwavelength sky: optical



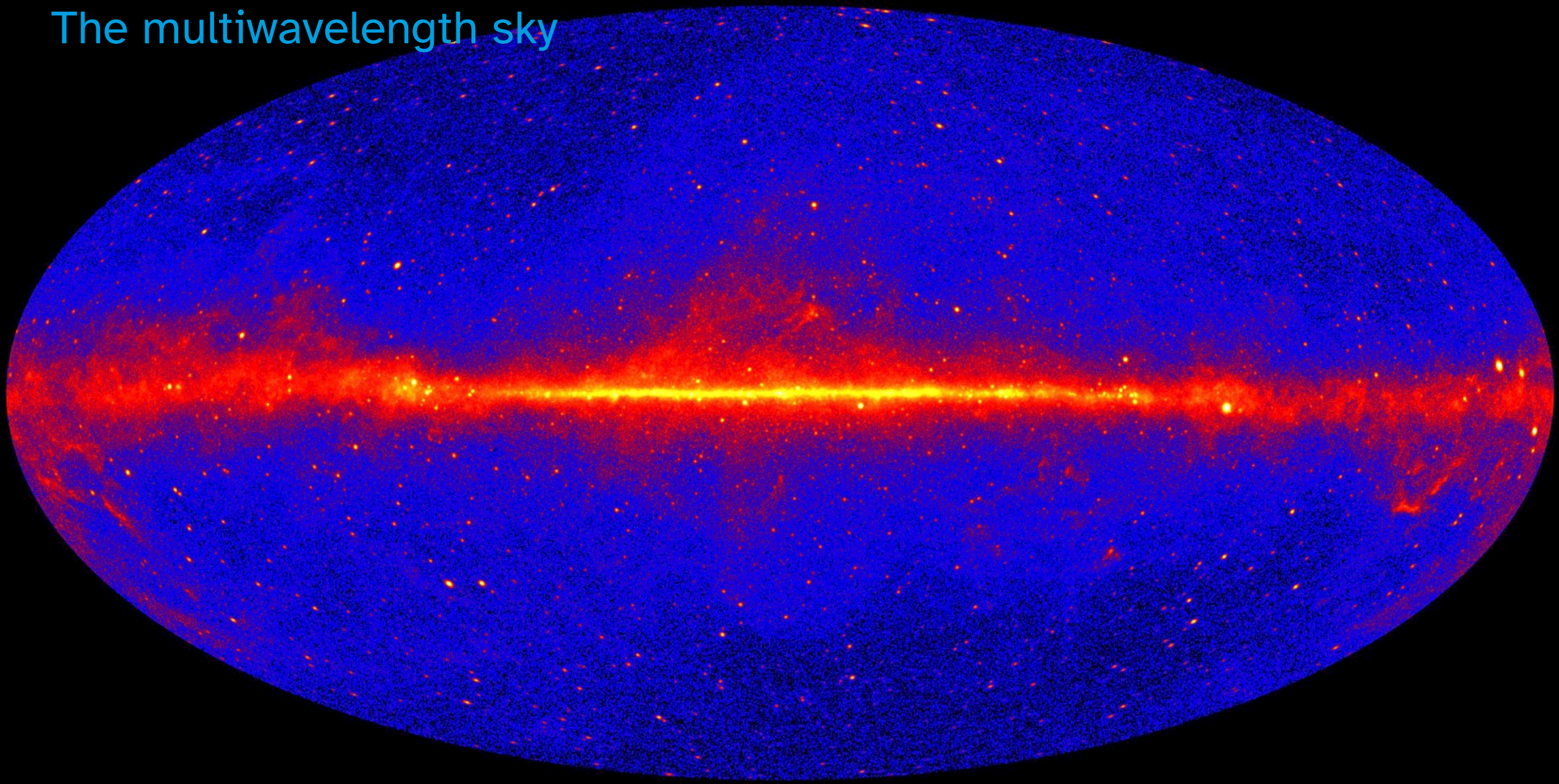
[ESA/Gaia/DPAC]

The multiwavelength sky: gamma rays



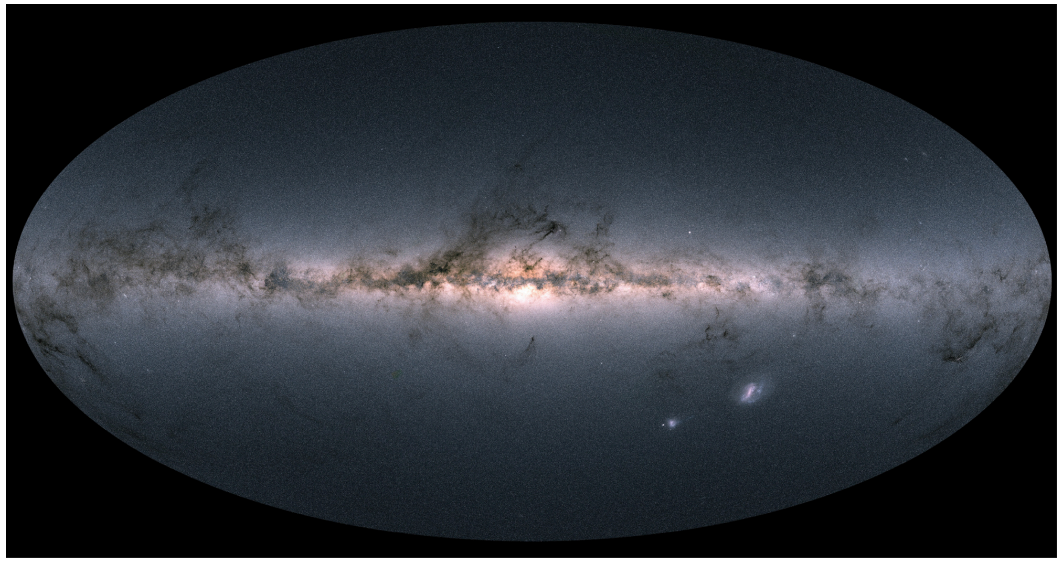
[NASA/DOE/Fermi-LAT Collaboration]

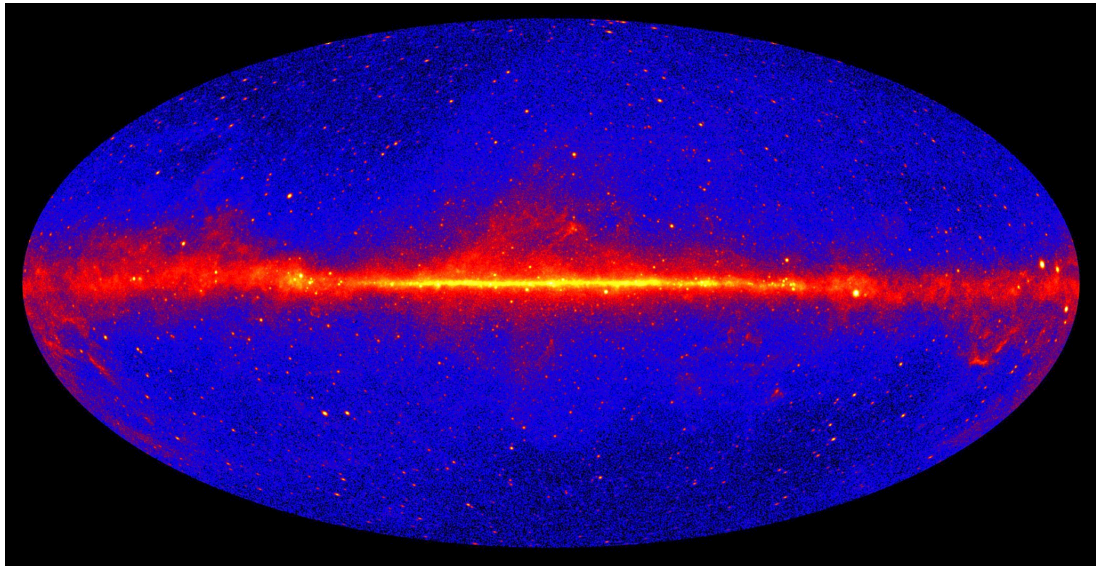
The multiwavelength sky



[NASA/DOE/Fermi-LAT Collaboration]

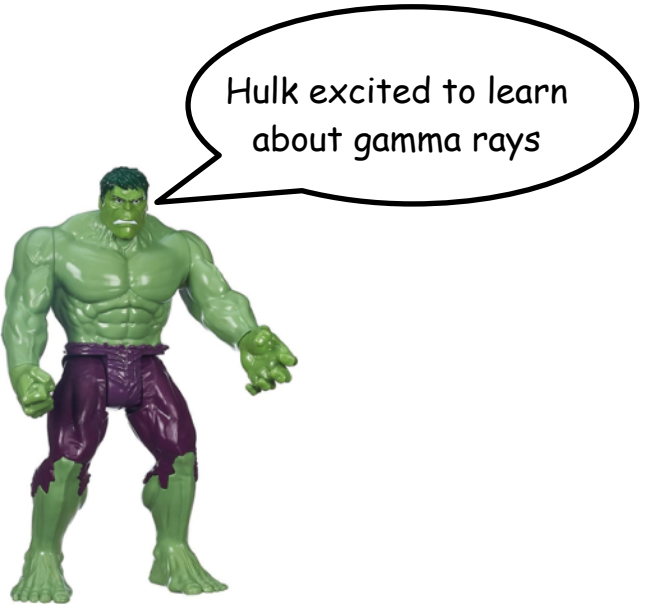
we basically just did multiwavelength analysis





Why are some sources bright over a wide energy range, while others are only bright in a narrow range?
How are the photons being produced by these sources?
Are there sources that don't show up on these maps?
How do we detect these sources?

Part 1. What are gamma rays and why do we care?



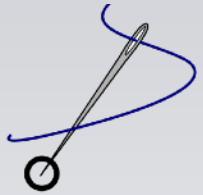
The electromagnetic spectrum

wavelength scales:

Buildings

Humans

Butterflies



Needle Point

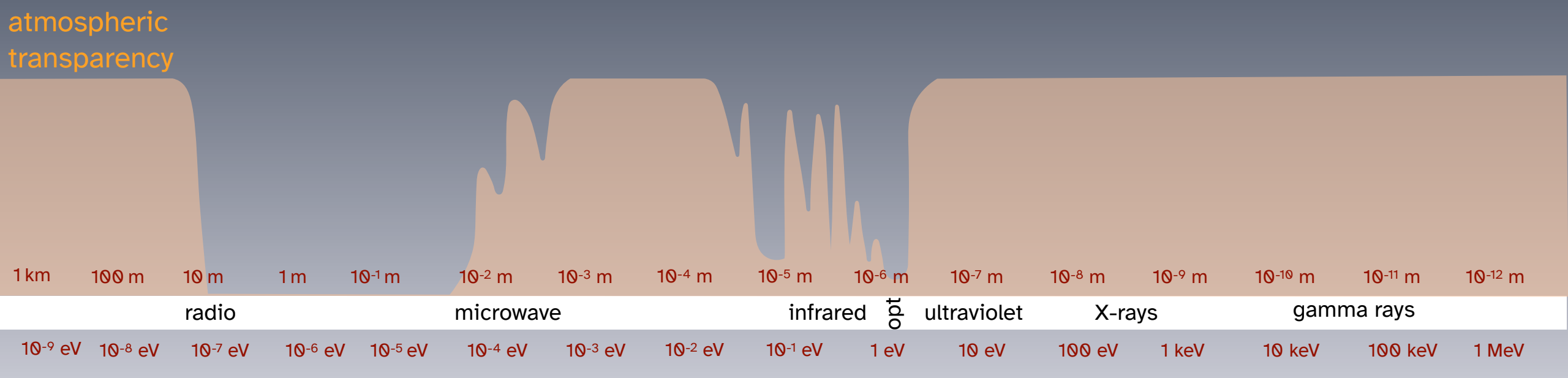
Molecules

Atoms

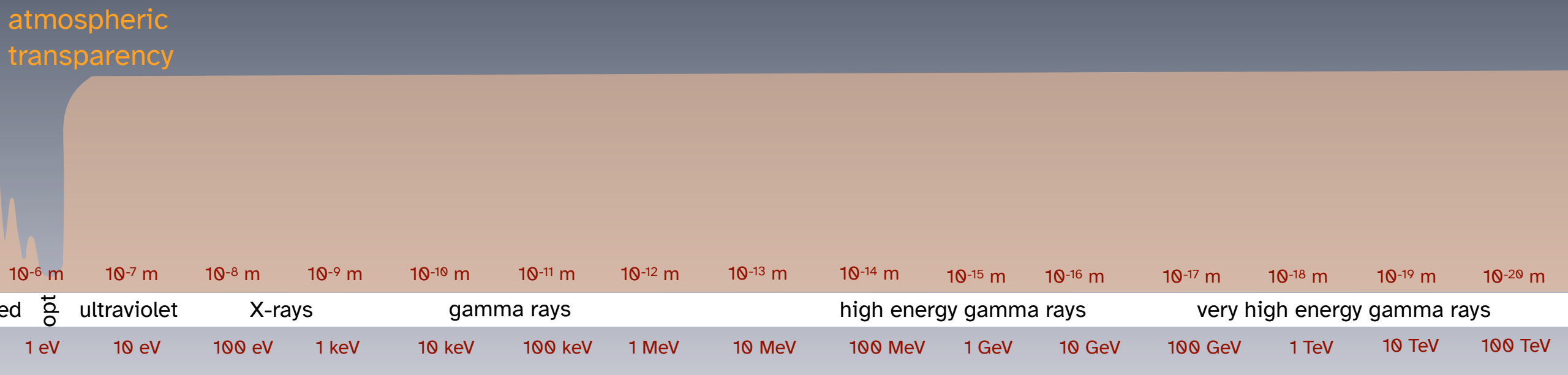
Atomic Nuclei

1 km	100 m	10 m	1 m	10^{-1} m	10^{-2} m	10^{-3} m	10^{-4} m	10^{-5} m	10^{-6} m	10^{-7} m	10^{-8} m	10^{-9} m	10^{-10} m	10^{-11} m	10^{-12} m
		radio			microwave			infrared	opt	ultraviolet		X-rays			gamma rays
10^{-9} eV	10^{-8} eV	10^{-7} eV	10^{-6} eV	10^{-5} eV	10^{-4} eV	10^{-3} eV	10^{-2} eV	10^{-1} eV	1 eV	10 eV	100 eV	1 keV	10 keV	100 keV	1 MeV

The electromagnetic spectrum



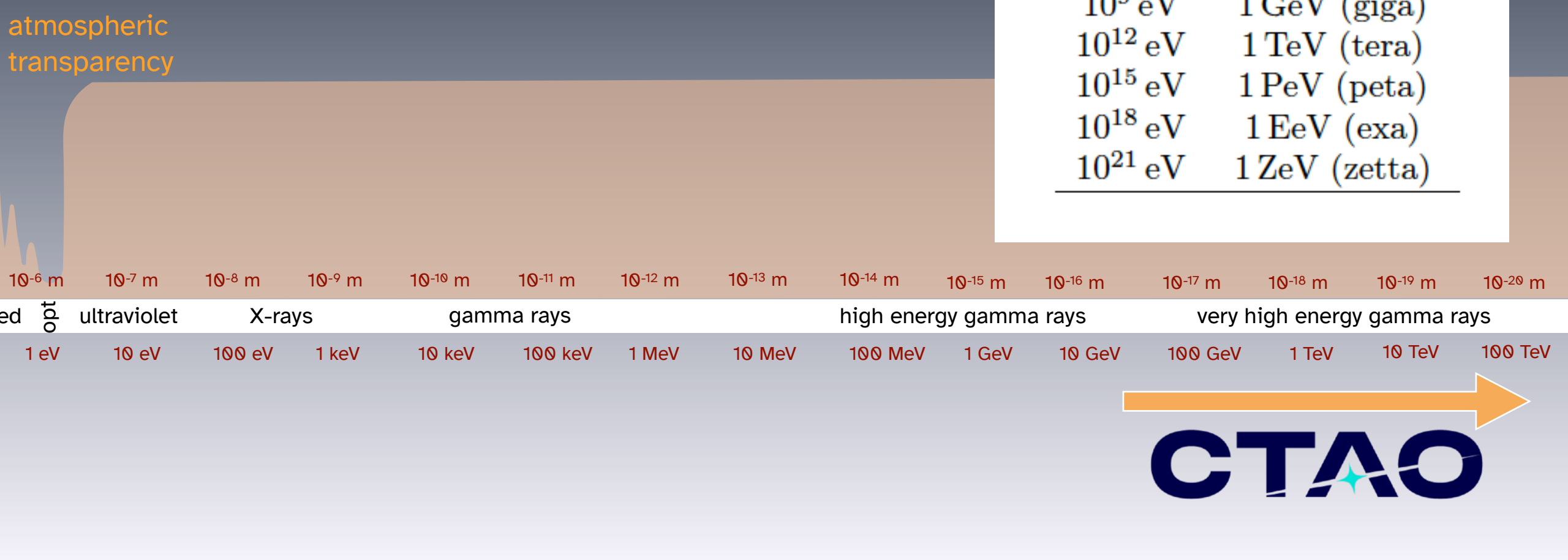
The electromagnetic spectrum, continued



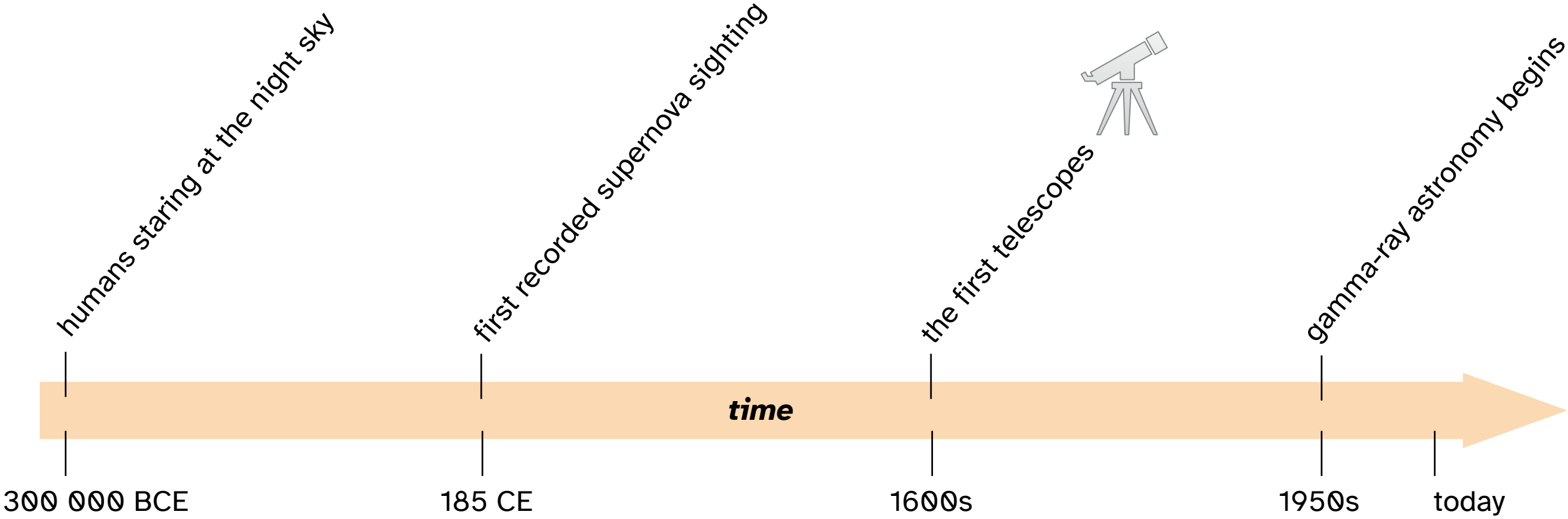
10^{-6} m	10^{-7} m	10^{-8} m	10^{-9} m	10^{-10} m	10^{-11} m	10^{-12} m	10^{-13} m	10^{-14} m	10^{-15} m	10^{-16} m	10^{-17} m	10^{-18} m	10^{-19} m	10^{-20} m
ed opt	ultraviolet	X-rays		gamma rays				high energy gamma rays			very high energy gamma rays			
1 eV	10 eV	100 eV	1 keV	10 keV	100 keV	1 MeV	10 MeV	100 MeV	1 GeV	10 GeV	100 GeV	1 TeV	10 TeV	100 TeV

The electromagnetic spectrum, continued

10^3 eV	1 keV (kilo)
10^6 eV	1 MeV (mega)
10^9 eV	1 GeV (giga)
10^{12} eV	1 TeV (tera)
10^{15} eV	1 PeV (peta)
10^{18} eV	1 EeV (exa)
10^{21} eV	1 ZeV (zetta)



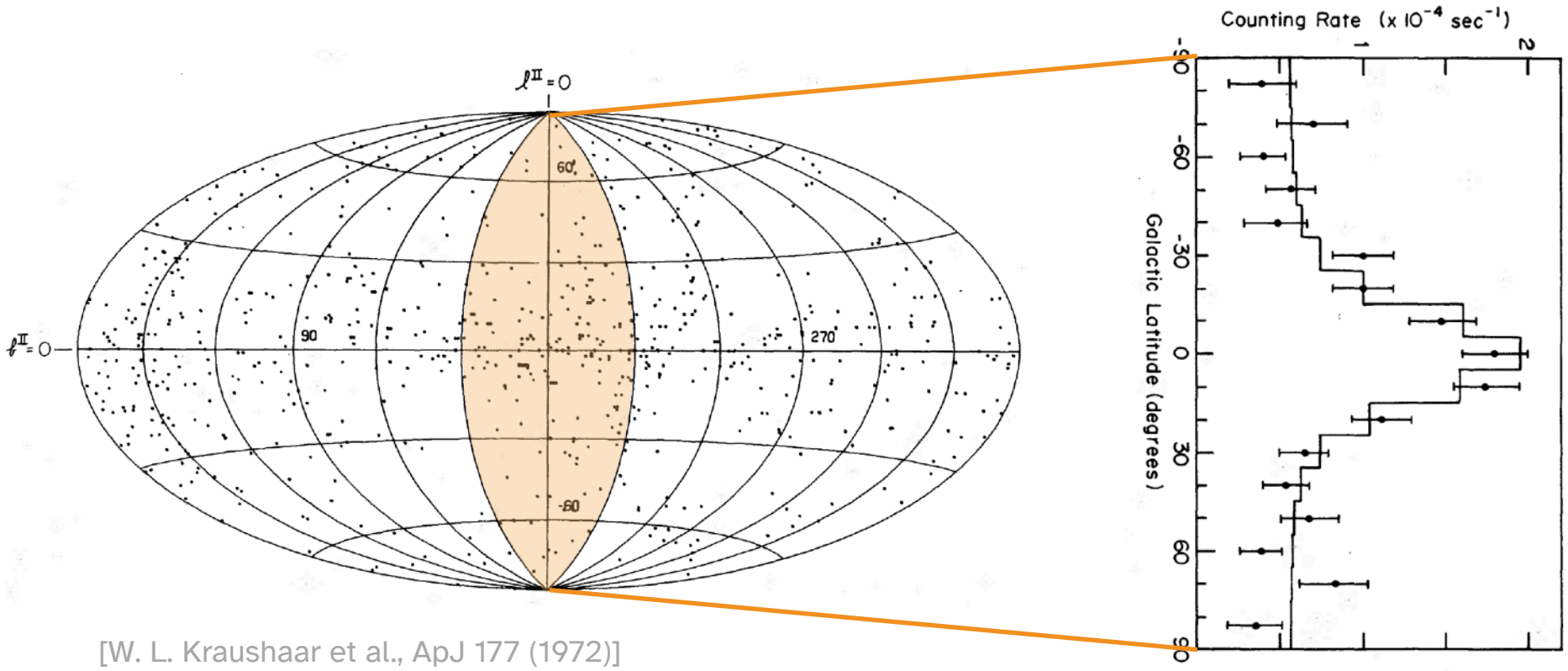
A very brief history of astronomy



A very brief history of gamma-ray astronomy

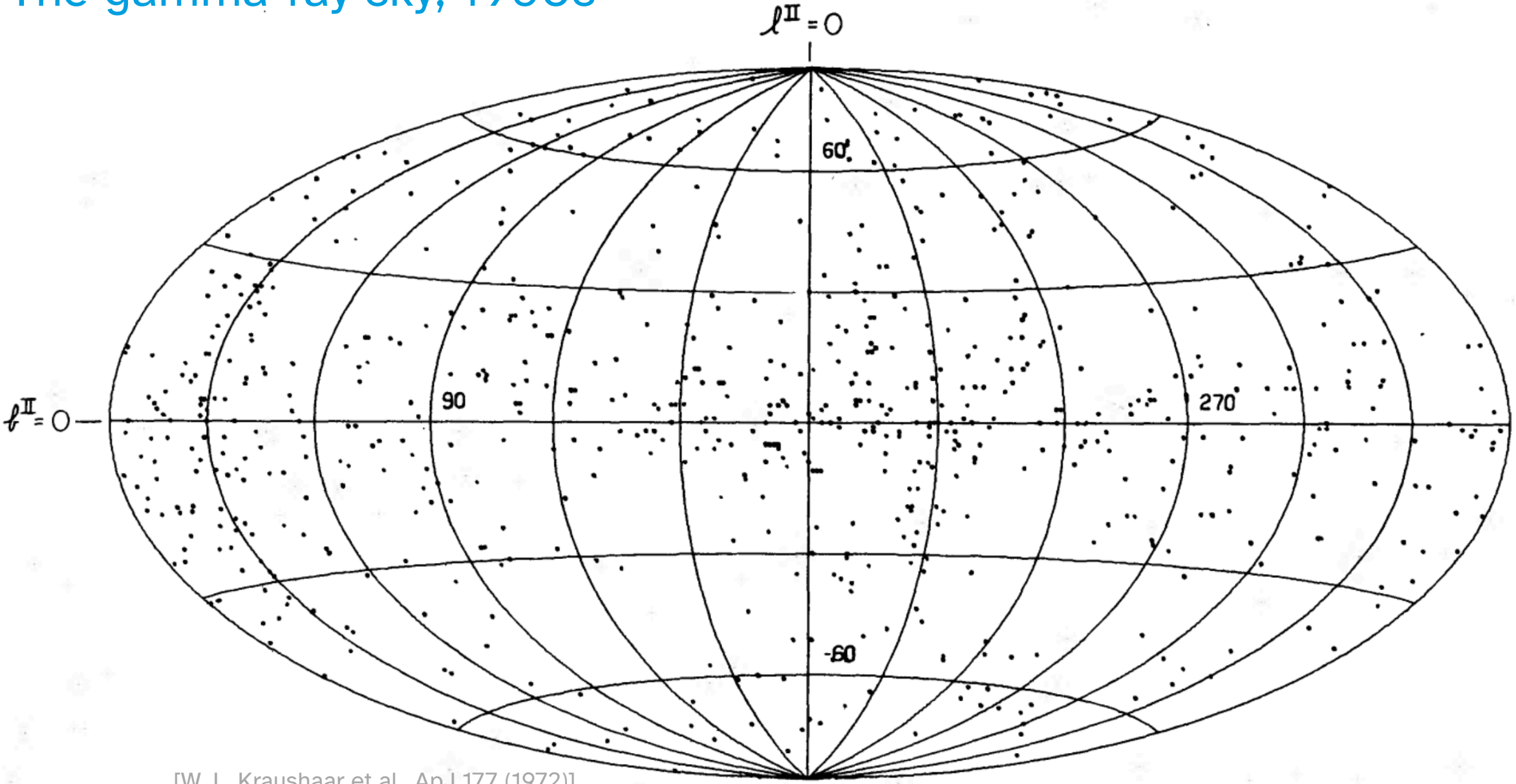
Observational gamma-ray astronomy began when we started to launch satellites

The first astrophysical gamma-ray sky (OSO-3, 1967-1968):



[W. L. Kraushaar et al., ApJ 177 (1972)]

The gamma-ray sky, 1960s

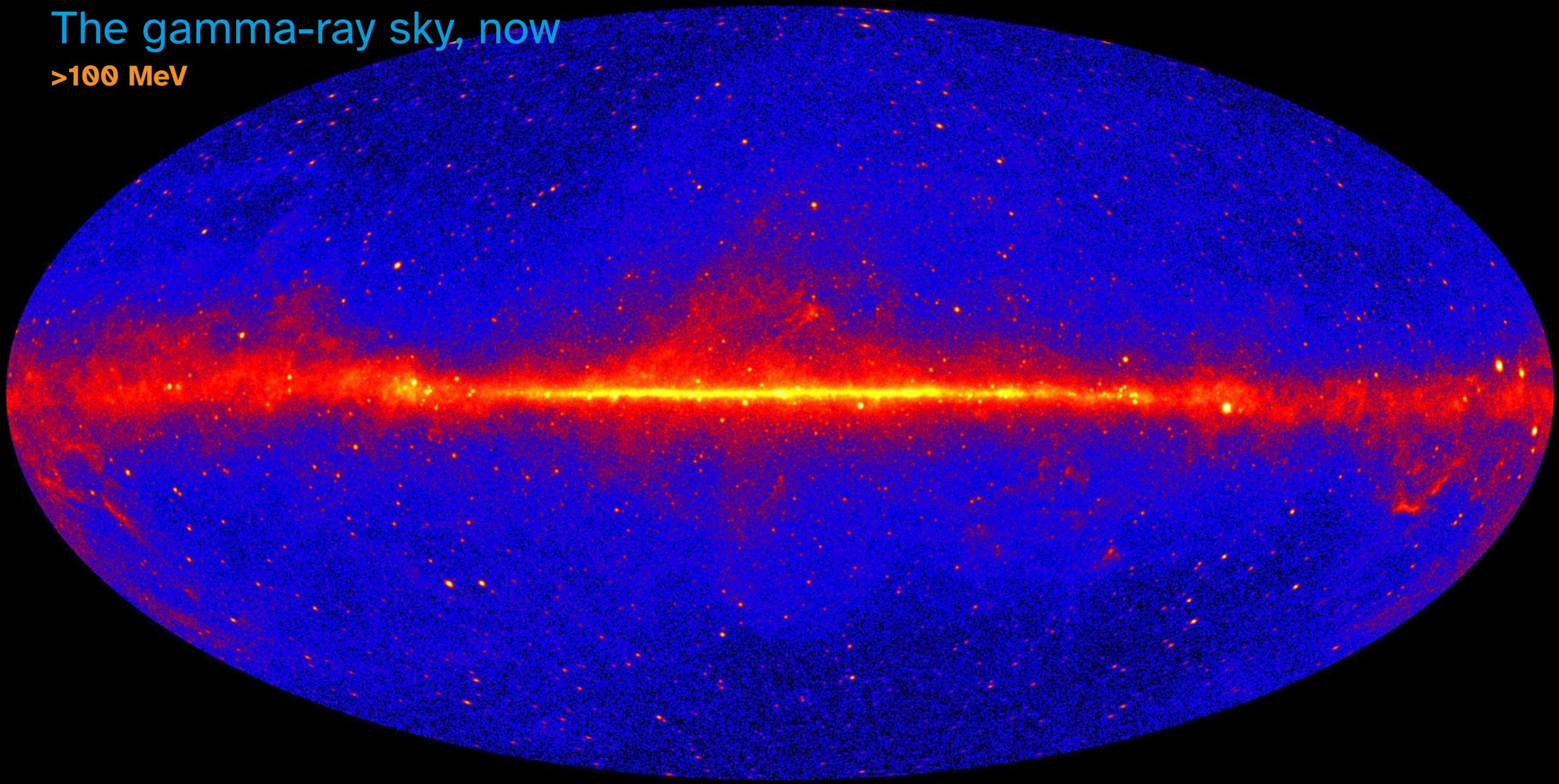


[W. L. Kraushaar et al., ApJ 177 (1972)]

[NASA/DOE/Fermi-LAT Collaboration]

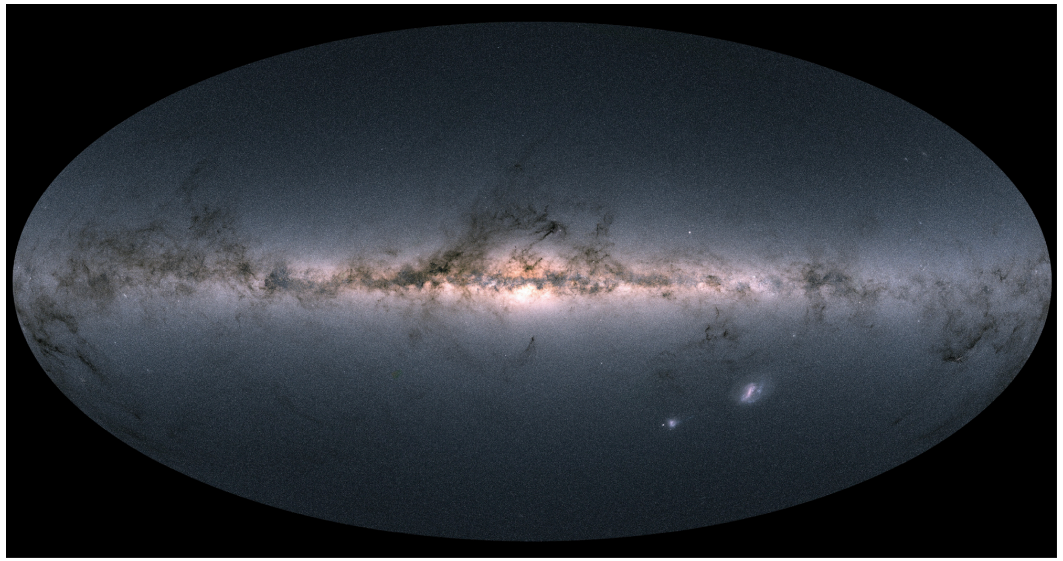
The gamma-ray sky, now

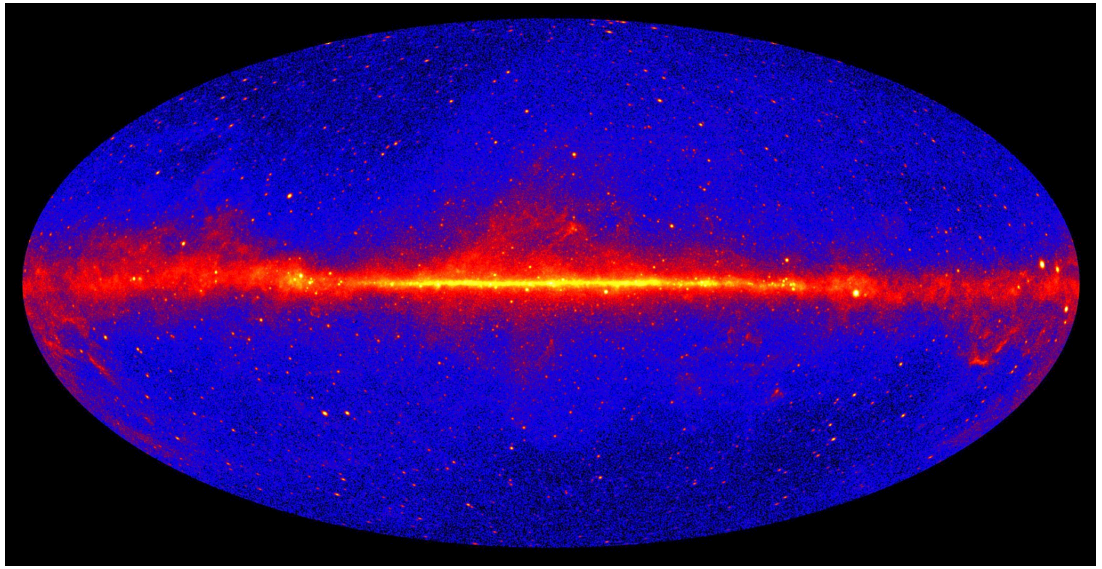
>100 MeV



Returning to the questions

How do we start to find the answers?





Why are some sources bright over a wide energy range, while others are only bright in a narrow range?

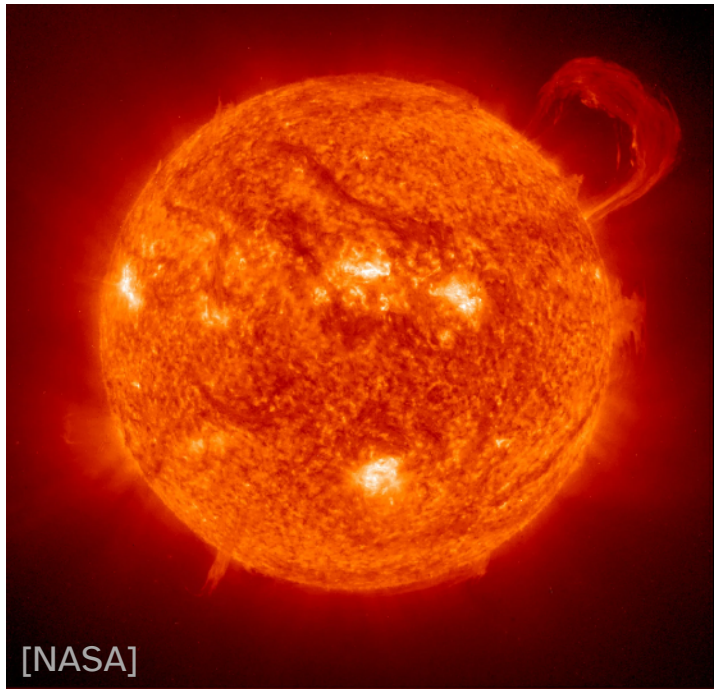
How are the photons being produced by these sources?

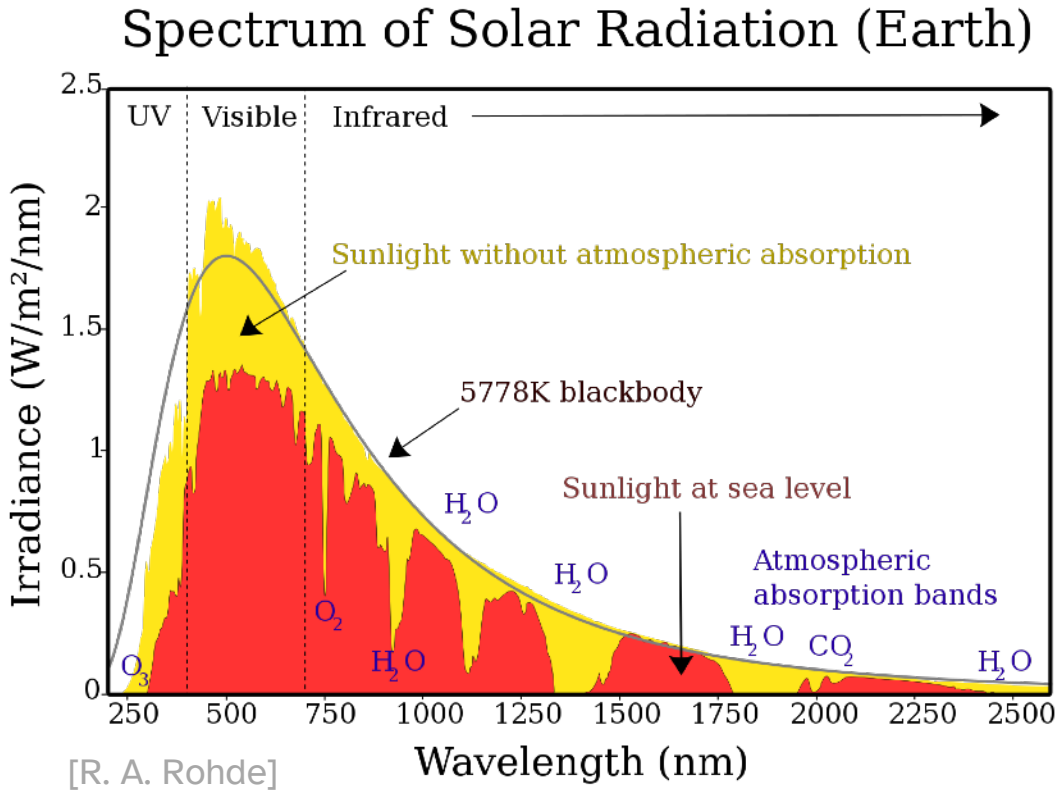
Are there sources that don't show up on these maps?

How do we detect these sources in the first place?

Most of the sources in the optical sky are thermal sources

Thermal emission can be described solely by a temperature

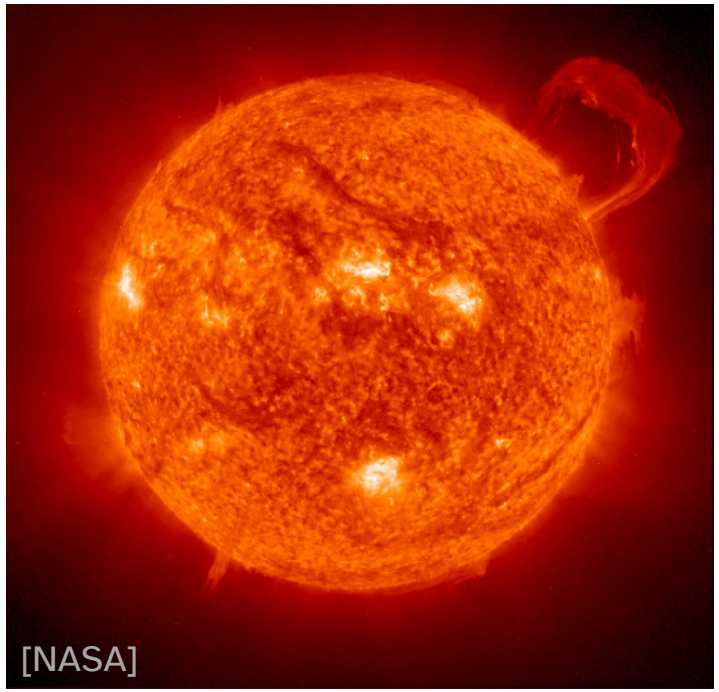


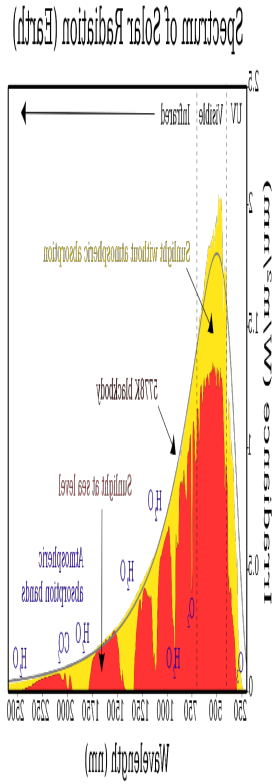


[R. A. Rohde]

Most of the sources in the optical sky are thermal sources

Thermal emission can be described solely by a temperature and is a narrow spectrum





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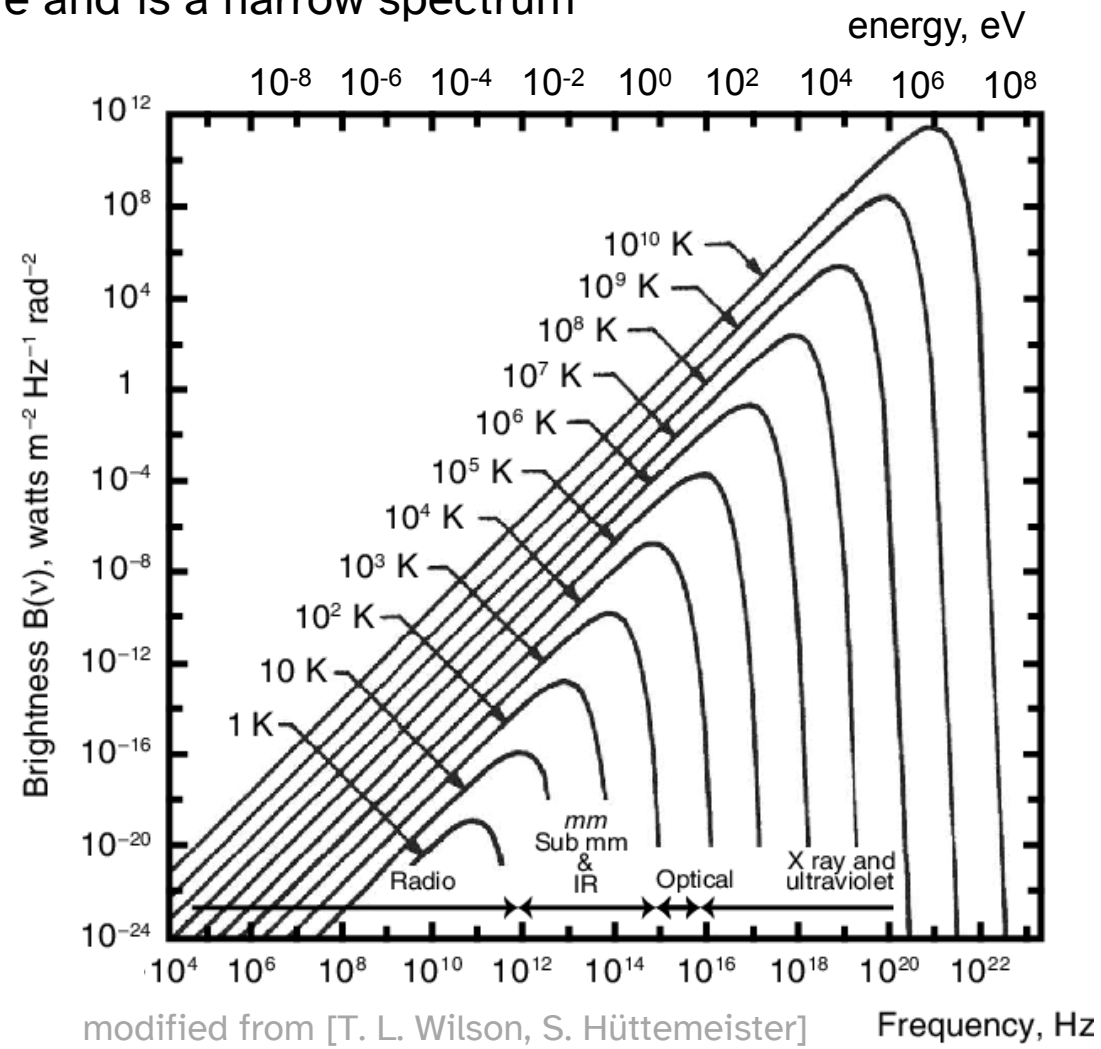
The gamma-ray sky is mostly **nonthermal**

Thermal emission can be described solely by a temperature and is a narrow spectrum

To get gamma rays, need at least T ~ 10^9 K
-> hard (although not impossible) to reach
-> nonthermal processes dominate gamma rays

usually we mean: charged particles are accelerated and then radiate photons

nonthermal processes often have broader spectra
-> multiwavelength sources



modified from [T. L. Wilson, S. Hüttemeister]

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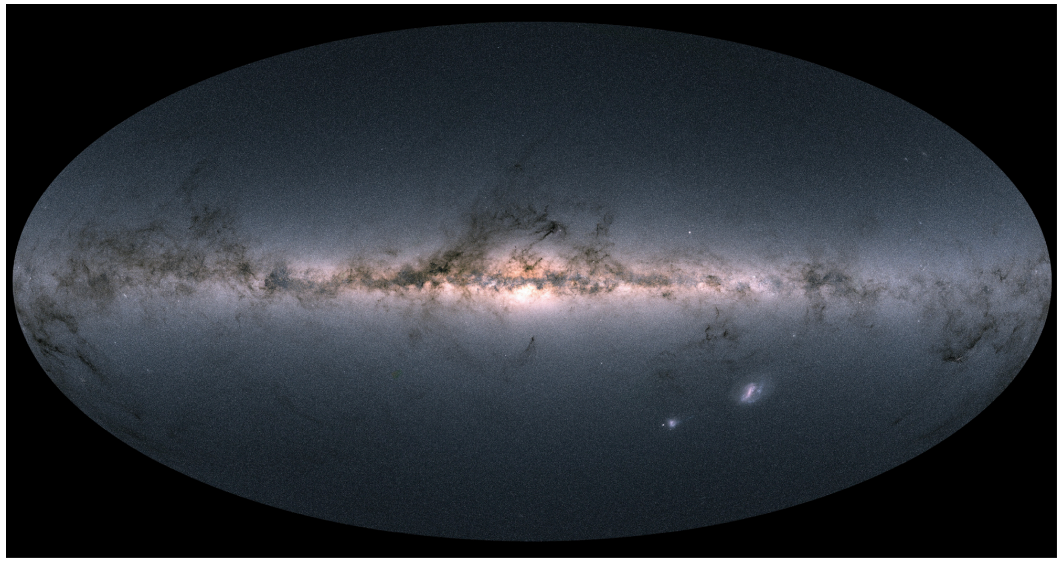

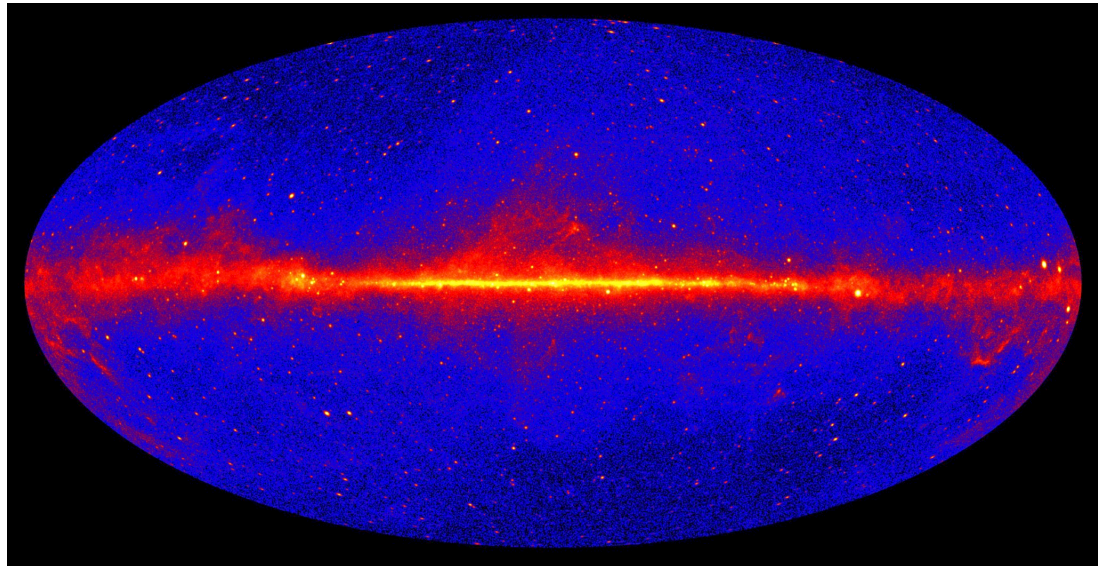

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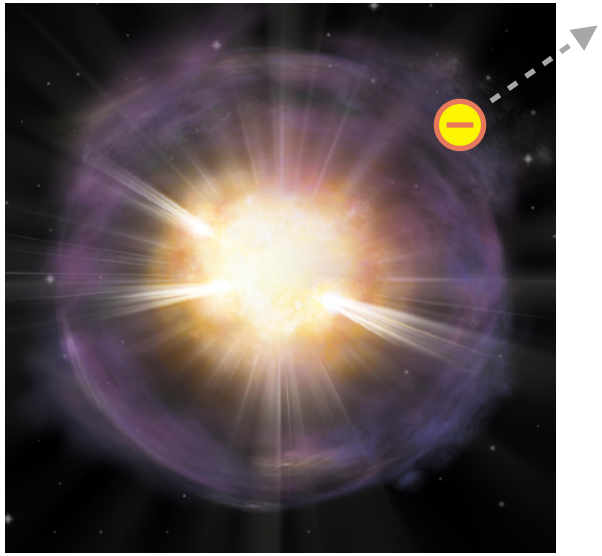
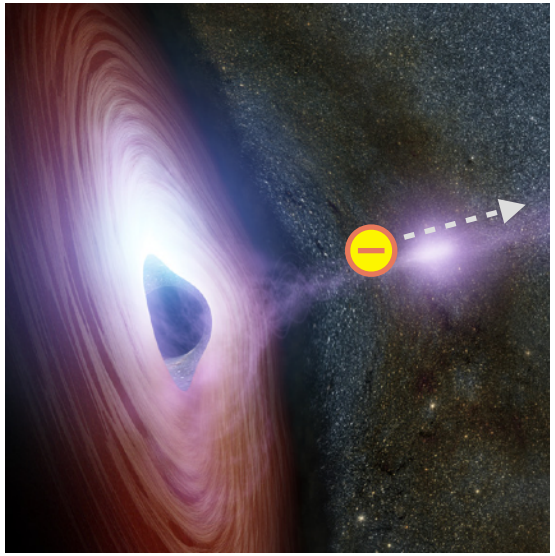
How do we get gamma rays?

Nonthermal emission

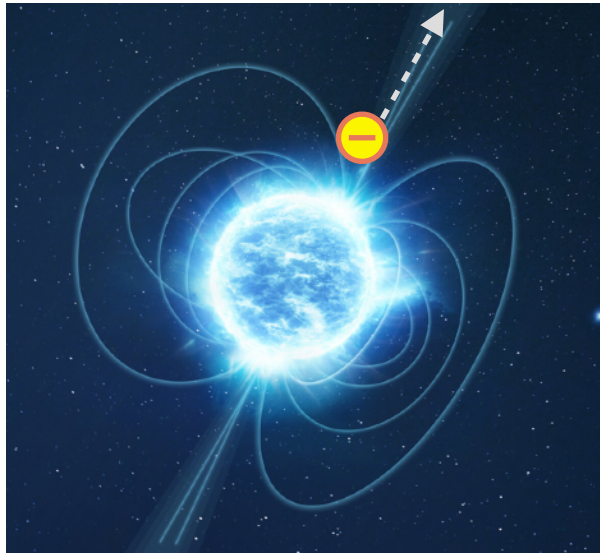
Charged particles are **accelerated** to high energies before radiating photons



[A. M. Geller/Northwestern/CTIO/SOAR/NOIRLab/NSF/AURA]



[NASA/JPL-Caltech]



[ESA]

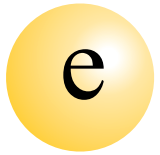
need an **energy source** and a way to **transfer this energy** to charged particles
(e.g., kinetic, gravitational, magnetic fields ...)

How do we get gamma rays?

Nonthermal emission

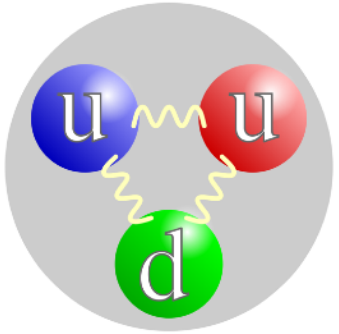
Charged particles are **accelerated** to high energies before radiating photons
The charged particles can be **leptons** (e.g., electrons) or **hadrons** (e.g., protons)
-> the radiation processes can be **leptonic** and/or **hadronic**

electron



leptons are elementary particles

proton



[A. Horvath]

hadrons are made of quarks
-> can form other particles

How do we get gamma rays?

Nonthermal emission

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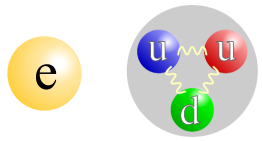
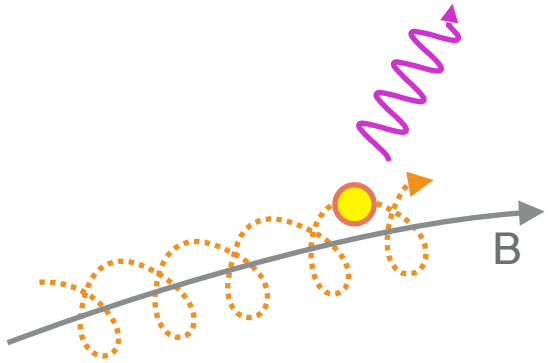
e.g., synchrotron





How do we get gamma rays?

Nonthermal emission

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e.g., inverse Compton

How do we get gamma rays?

Nonthermal emission

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The charged particles can be **leptons** (e.g., electrons) or **hadrons** (e.g., protons)
-> the radiation processes can be **leptonic** and/or **hadronic**

e.g., Bremsstrahlung

How do we get gamma rays?

Nonthermal emission

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The charged particles can be **leptons** (e.g., electrons) or **hadrons** (e.g., protons)
-> the radiation processes can be **leptonic** and/or **hadronic**

e.g., pion decay

How do we get gamma rays?

Nonthermal emission

(coloring indicates what is relevant to these lectures)

Charged particles are **accelerated** to high energies before radiating photons
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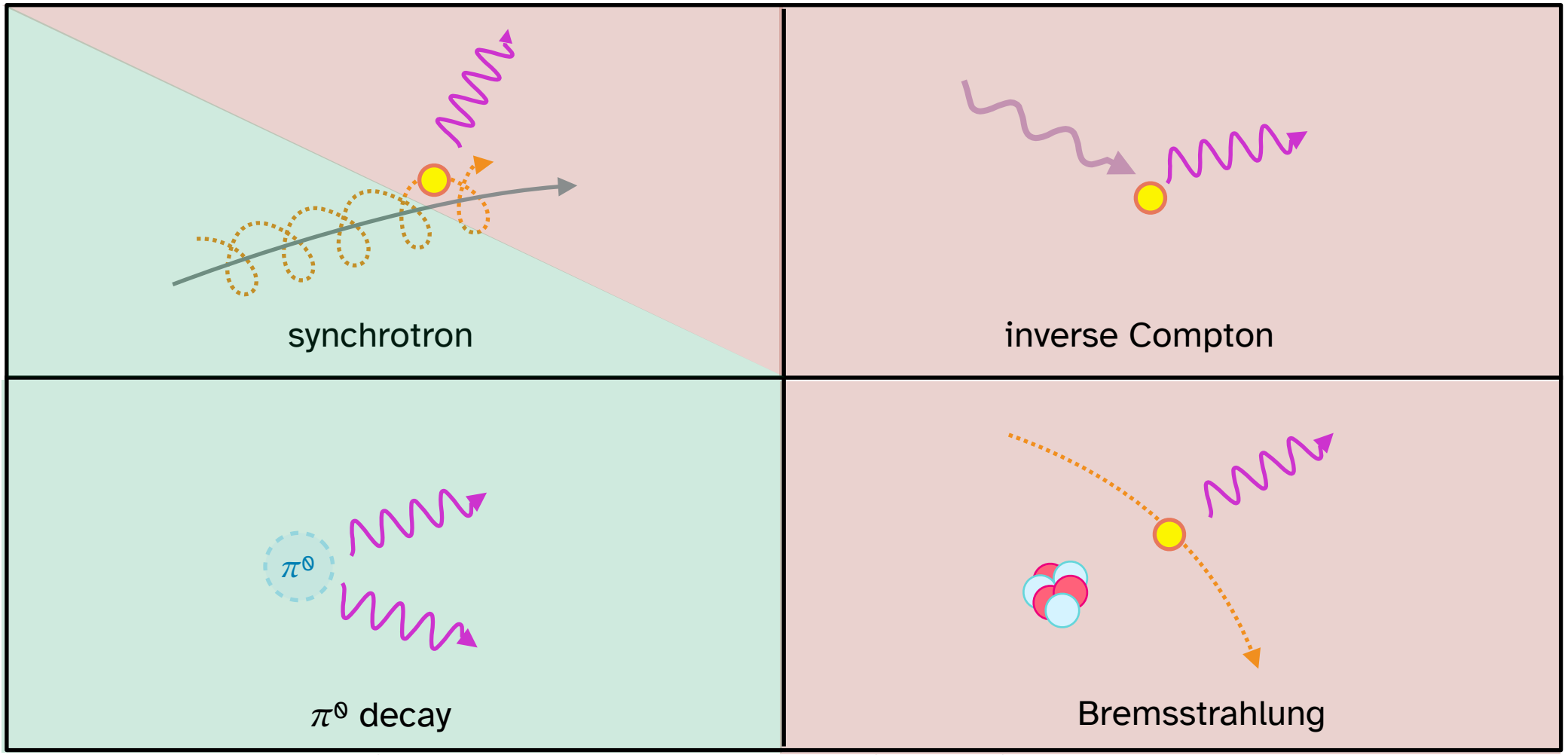

How do we get gamma rays?

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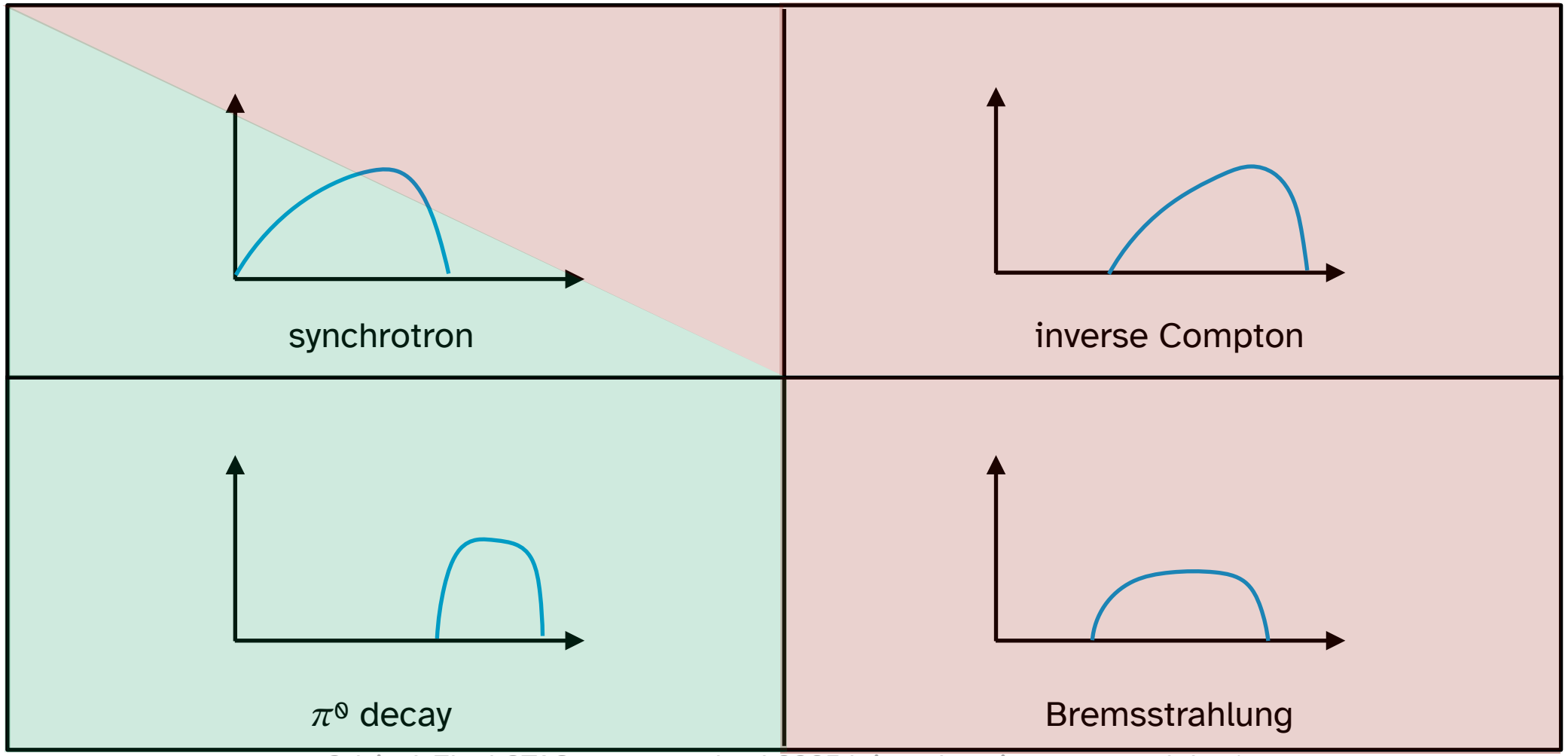

How do we get gamma rays?

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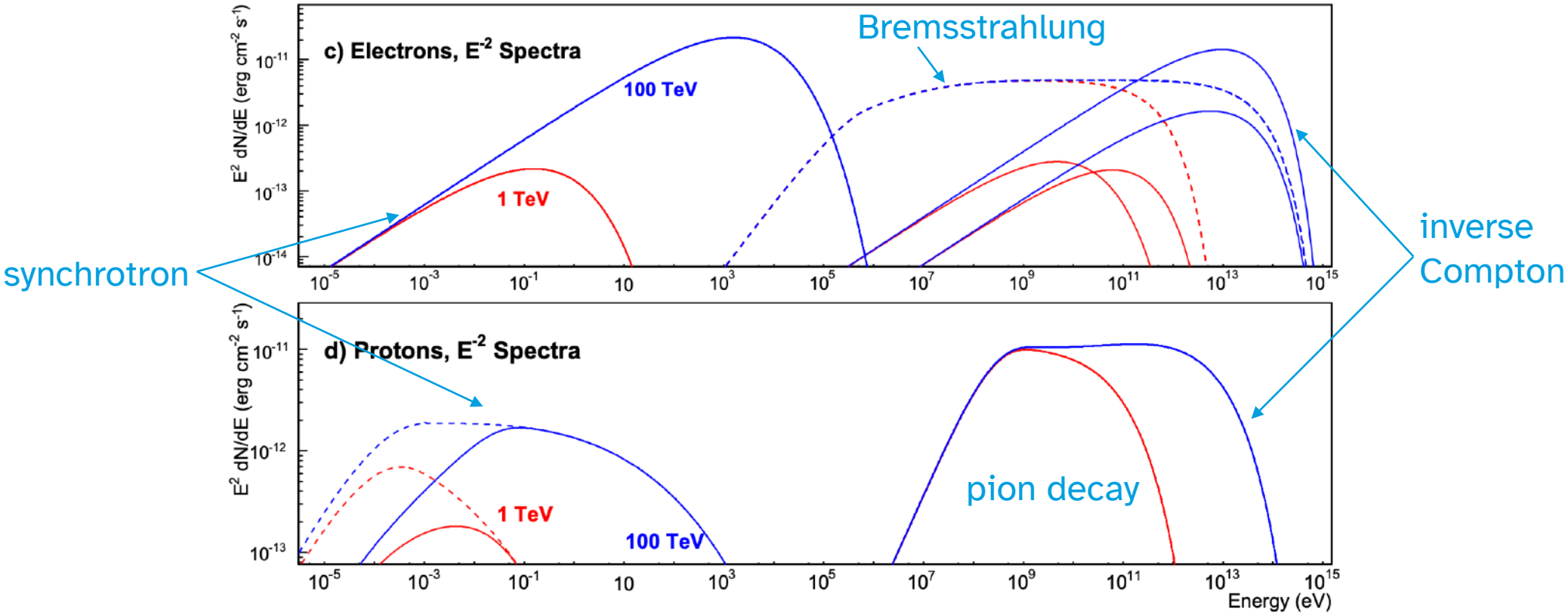
[J. A. Hinton & W. Hofmann, ARA&A 47 (2009)]

example spectra in common conditions

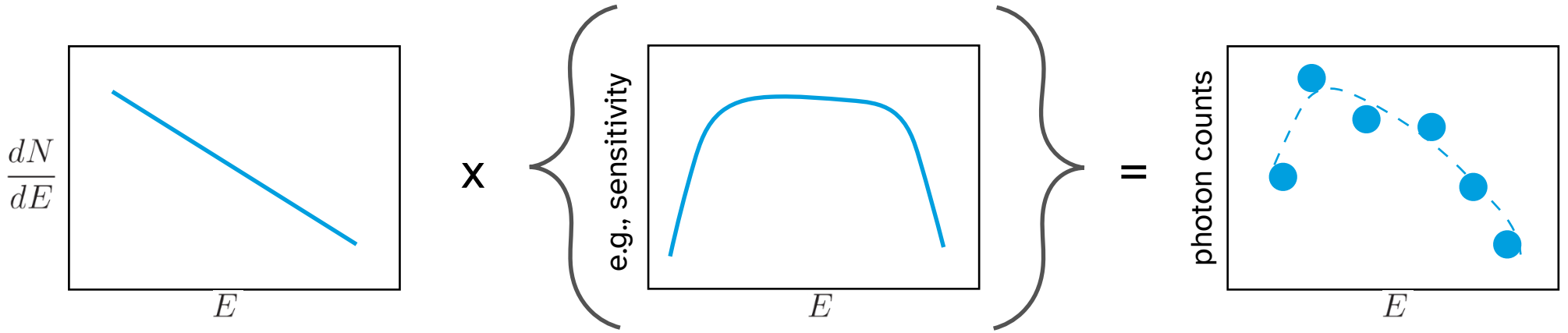


What exactly do we mean by “spectra”?

how much is emitted vs photon energy

$\frac{dN}{dE}$: number of photons per unit time*area*energy

example units: ph cm^{-2} s^{-1} keV^{-1}



spectrum at the detector

detector properties

observation

observation

analysis

What exactly do we mean by “spectra”?

how much is emitted vs photon energy

$\frac{dN}{dE}$: number of photons per unit time*area*energy

example units: ph cm^{-2} s^{-1} keV^{-1}

$E\frac{dN}{dE}$ tells us at what photon energy the largest number of photons is emitted

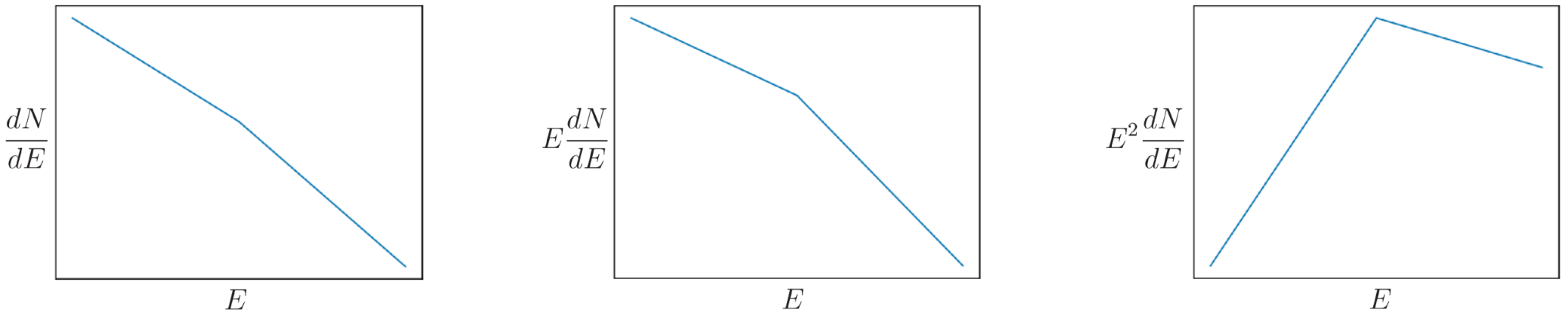
example units: ph cm^{-2} s^{-1}

$E^2\frac{dN}{dE}$ tells us at what photon energy the largest amount of energy is emitted

equivalently: νF_ν

example units: erg cm^{-2} s^{-1}

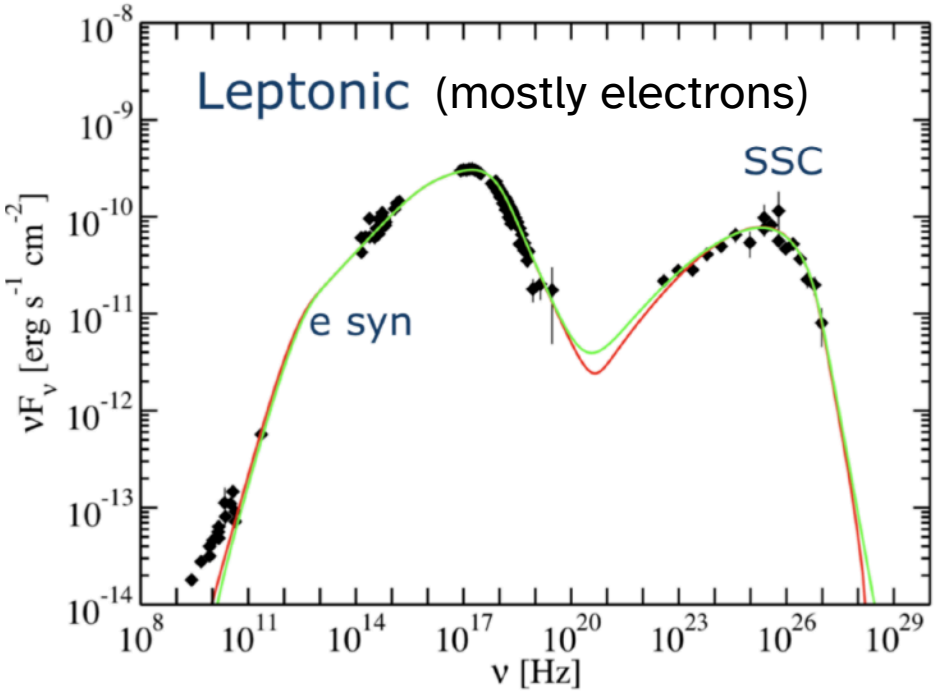
e.g.:

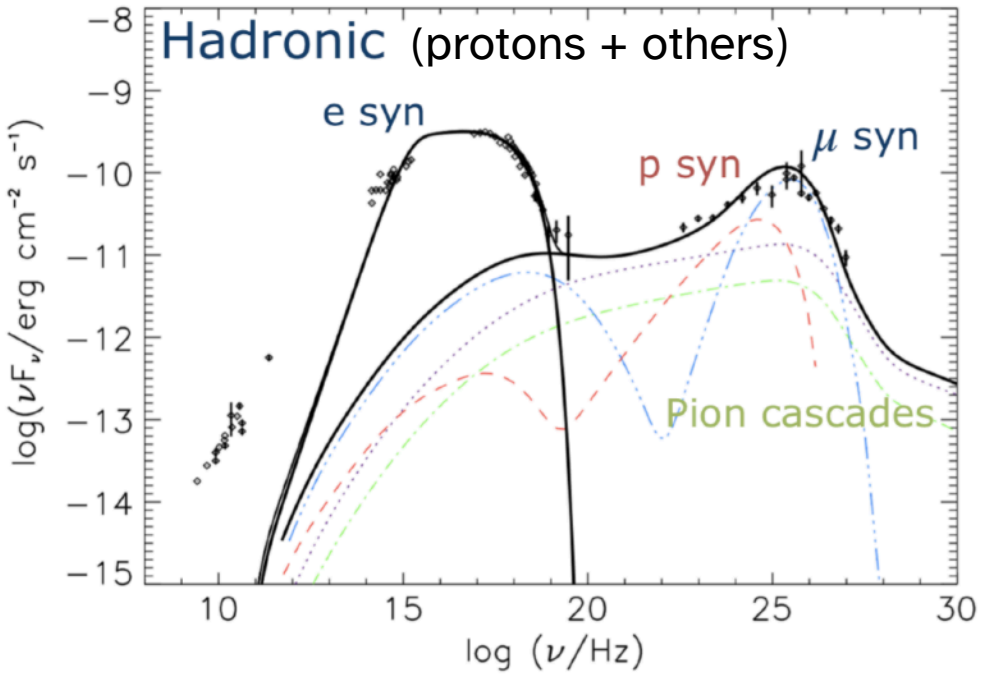


Multiwavelength spectra

Combining the spectra across a wide range of photon energies allows us to better understand the photon emission mechanisms

[M. Cerruti, TAUP 2019] Markarian 421, an active galaxy

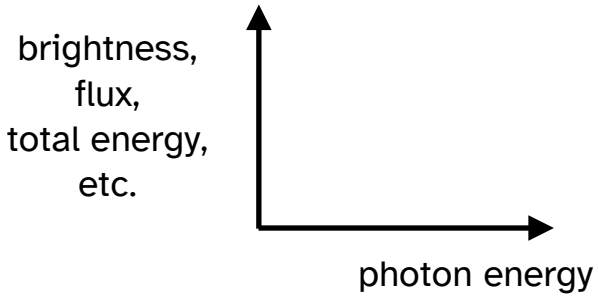


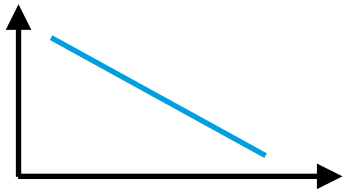


Spectra

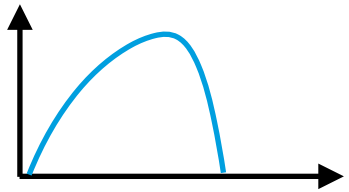
how much is emitted vs photon energy

The spectrum tells you something about the photon emission mechanism

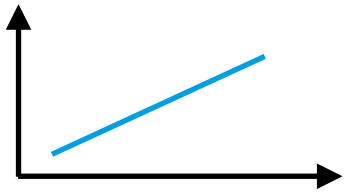




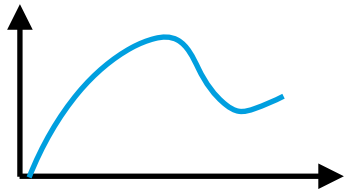
more energy emitted at lower photon energies (“soft spectrum”)



there is a “peak” photon energy



more energy emitted at higher photon energies (“hard spectrum”)

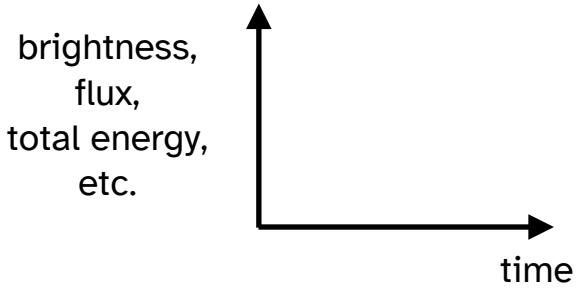


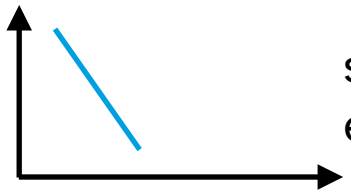
there are multiple emission mechanisms

Light curves

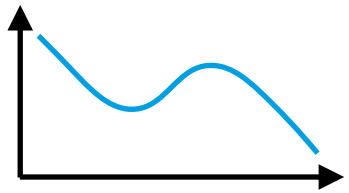
how much is emitted vs time

The lightcurve tells you about how the emission source is changing

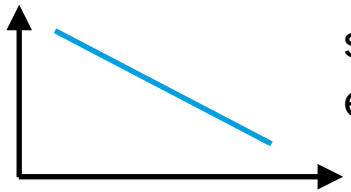




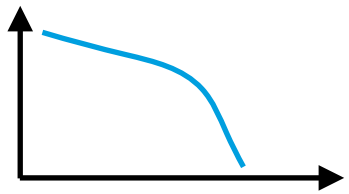
source is losing energy quickly



something has added additional energy into the system



source is losing energy slowly

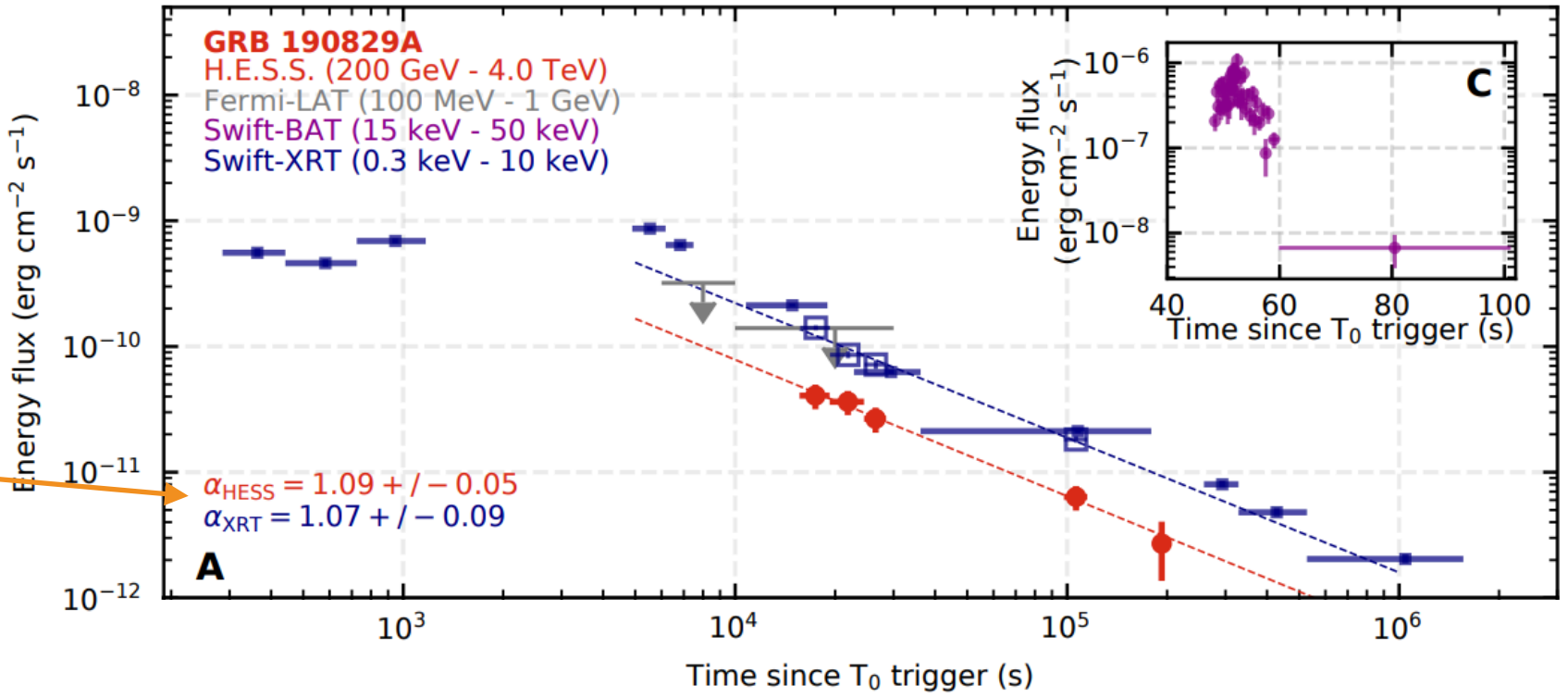


something that was providing energy is no longer doing so

Multiwavelength lightcurves

Comparing the lightcurves at different wavelengths gives information about how the system is evolving

X-ray and gamma-ray flux are decaying at the same rate
-> the same mechanism is likely producing both



modified from [H. Abdalla et al., Science 372 (2021)]

Light curves

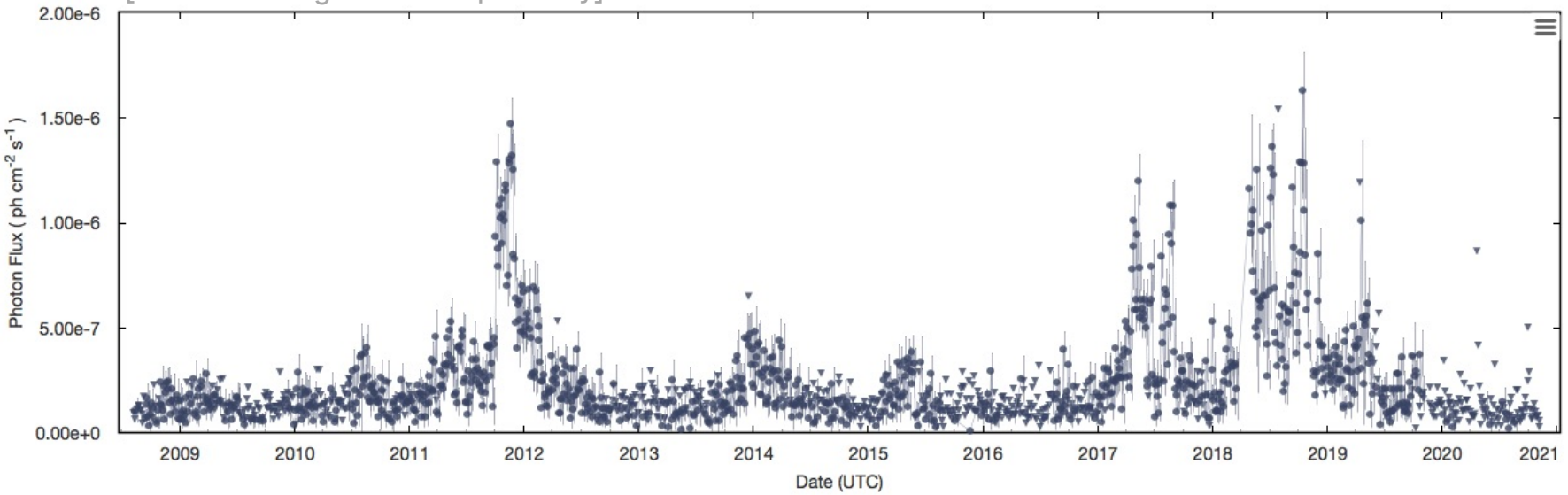
how much is emitted vs time

What if I want to see how the emission changes with time?

$$\int_{E_1}^{E_2} \left(\frac{dN}{dE}\right) dE$$: "(integral) photon flux," total number of photons detected over a photon energy range

$$\int_{E_1}^{E_2} E \left(\frac{dN}{dE}\right) dE$$: "(integral) energy flux," total energy detected over a photon energy range

[Fermi-LAT lightcurve repository]



Light curves

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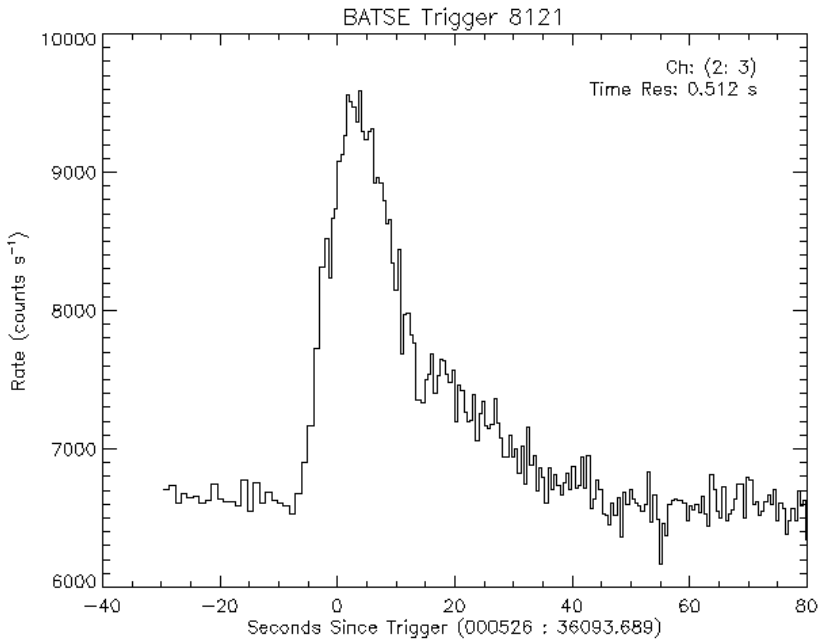
Or you can also simply plot the photon count rate over time



Light curves

how much is emitted vs time

What if I want to see how the emission changes with time?

$$\int_{E_1}^{E_2} \left(\frac{dN}{dE}\right) dE$$

$$\int_{E_1}^{E_2} E \left(\frac{dN}{dE}\right) dE$$

Takes into account instrumental factors like changing detector sensitivity, but assumes a spectral model, and will change for different assumed spectra

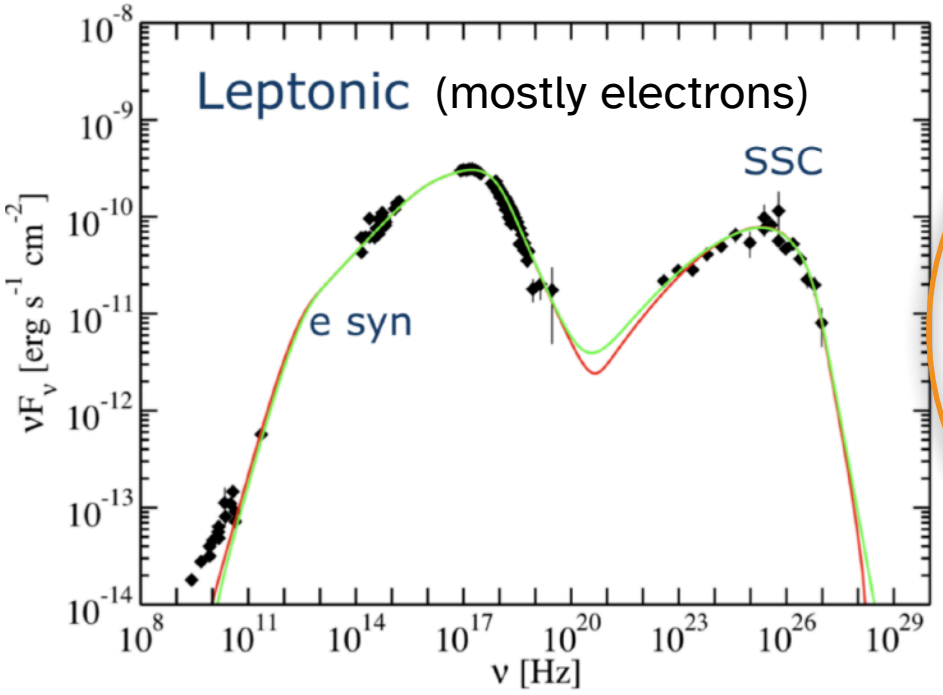
Or you can also simply plot the photon count rate over time

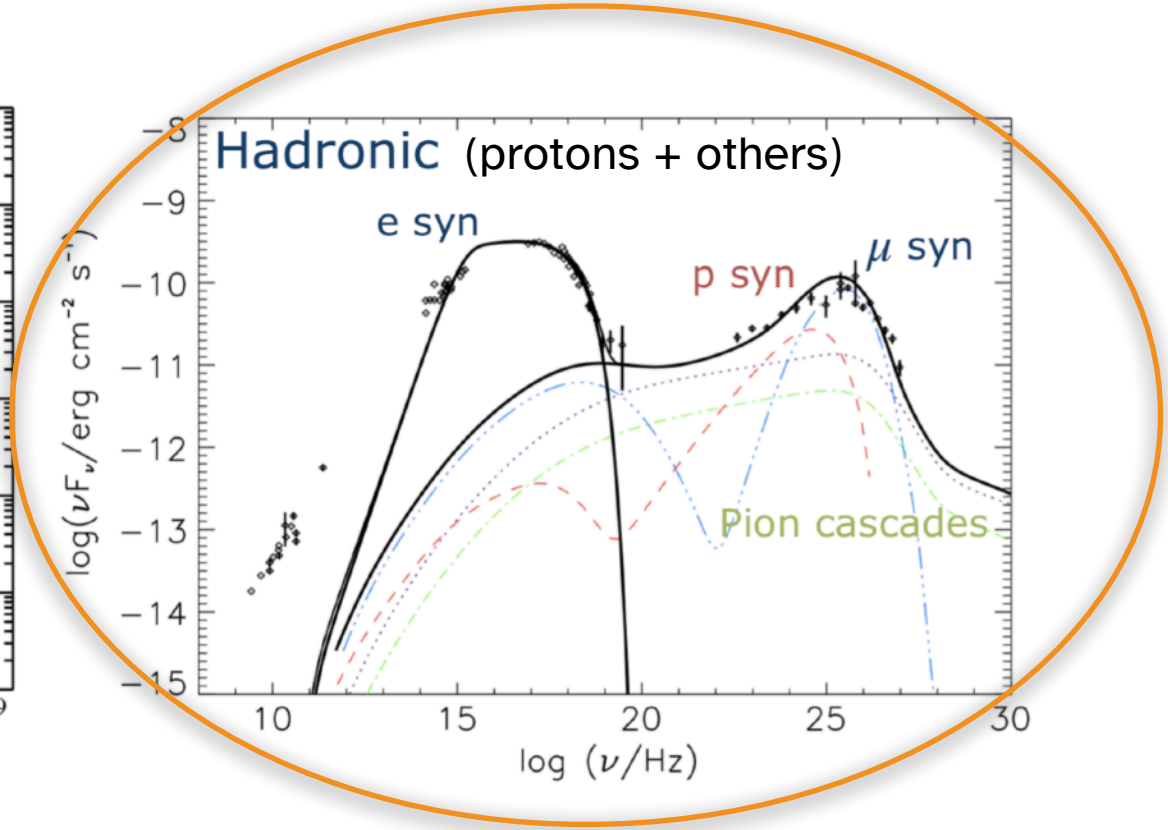
Does not require any additional assumptions — except for the implicit assumption that the detector sensitivity is not greatly changing during this time

Multiwavelength spectra

Combining the spectra across a wide range of photon energies allows us to better understand the photon emission mechanisms

[M. Cerruti, TAUP 2019]

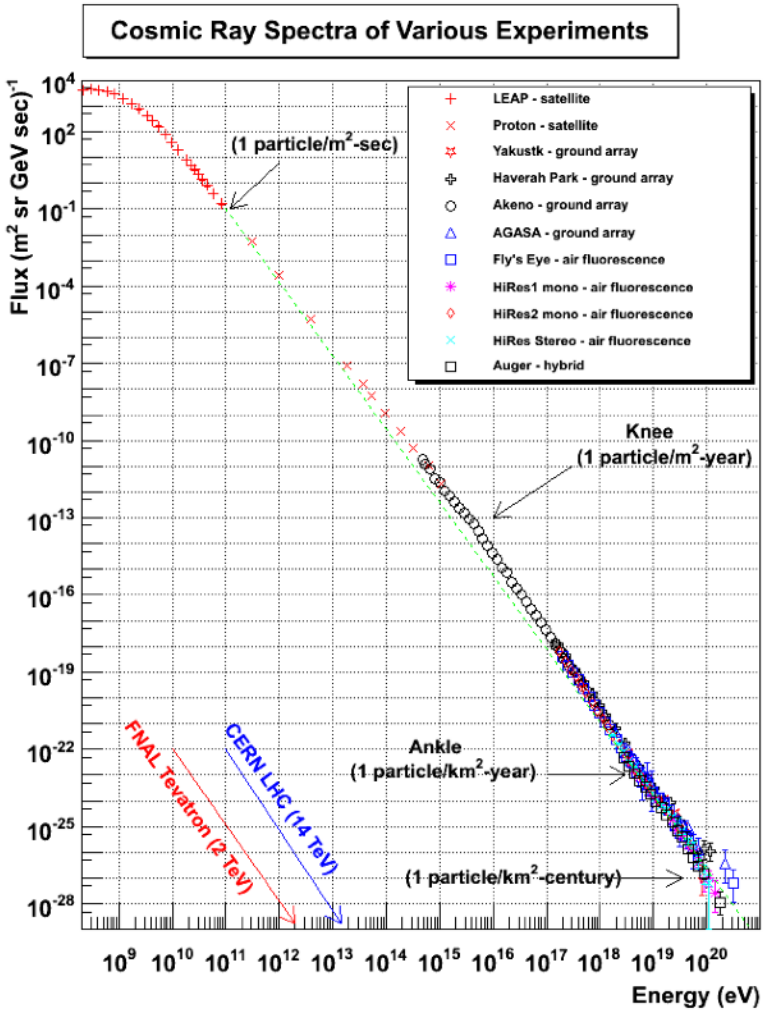




plotted here: Markarian 421, an active galaxy

The connection to cosmic rays

tbh I thought David was going to cover this ……



[M. Duldig, Science 314 (2006)]

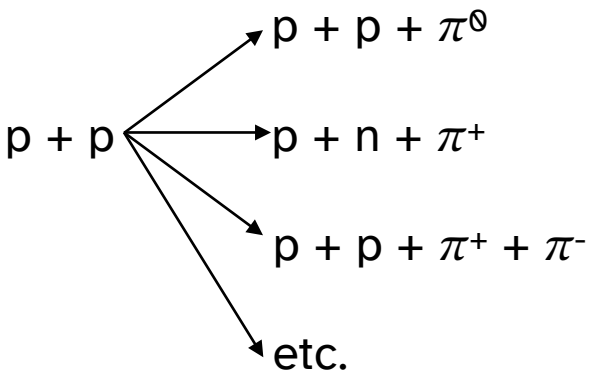
cosmic rays are charged particles -> deflected by magnetic fields

→ mostly nuclei, a few % electrons

→ 89% protons,
10% He,
1% heavier

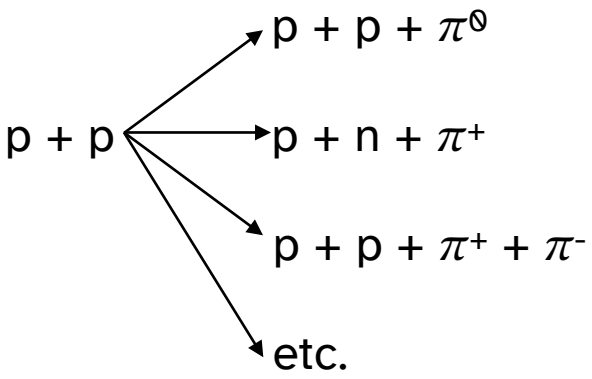
How exactly do we go from cosmic rays to gamma rays?

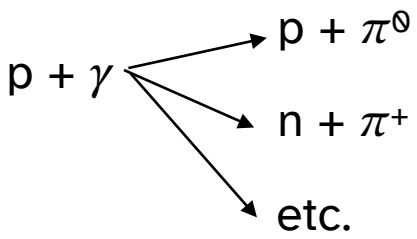
Cosmic rays to gamma rays



p	proton	**hadrons**
n	neutron	
π	pion (pi meson)	
γ	photon	
μ	muon	**leptons**
ν	neutrino	

Cosmic rays to gamma rays





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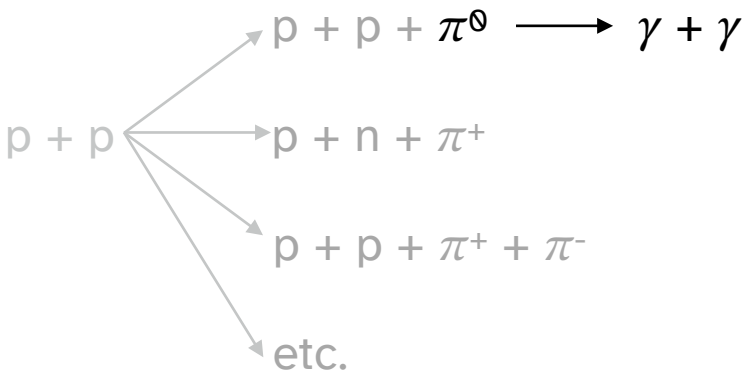
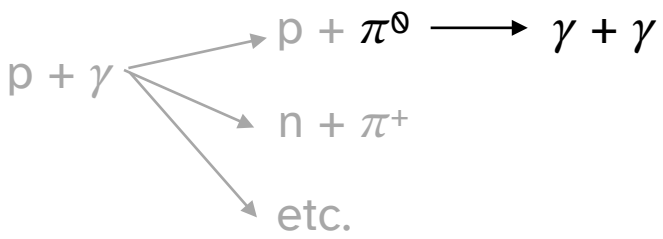
Cosmic rays to gamma rays



π^0 decays in 10^{-16} s

$\pi^{+/-}$ decays in 10^{-8} s



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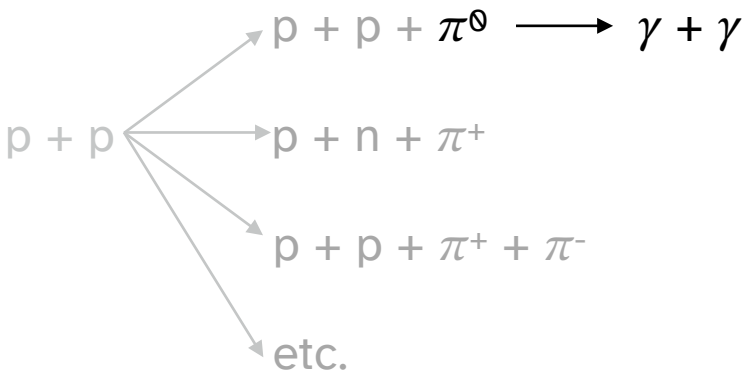
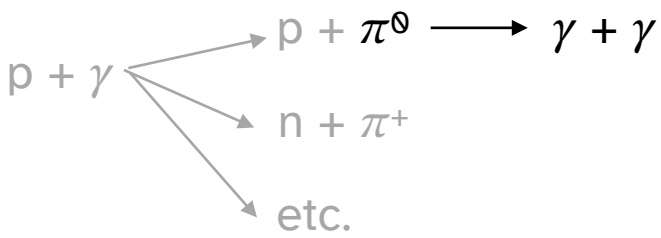
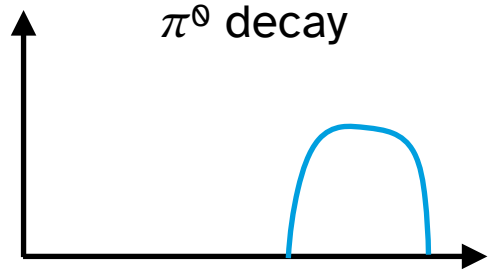
Cosmic rays to gamma rays







gamma rays can be produced by hadronic interactions, and the spectrum would be a characteristic “pion bump”

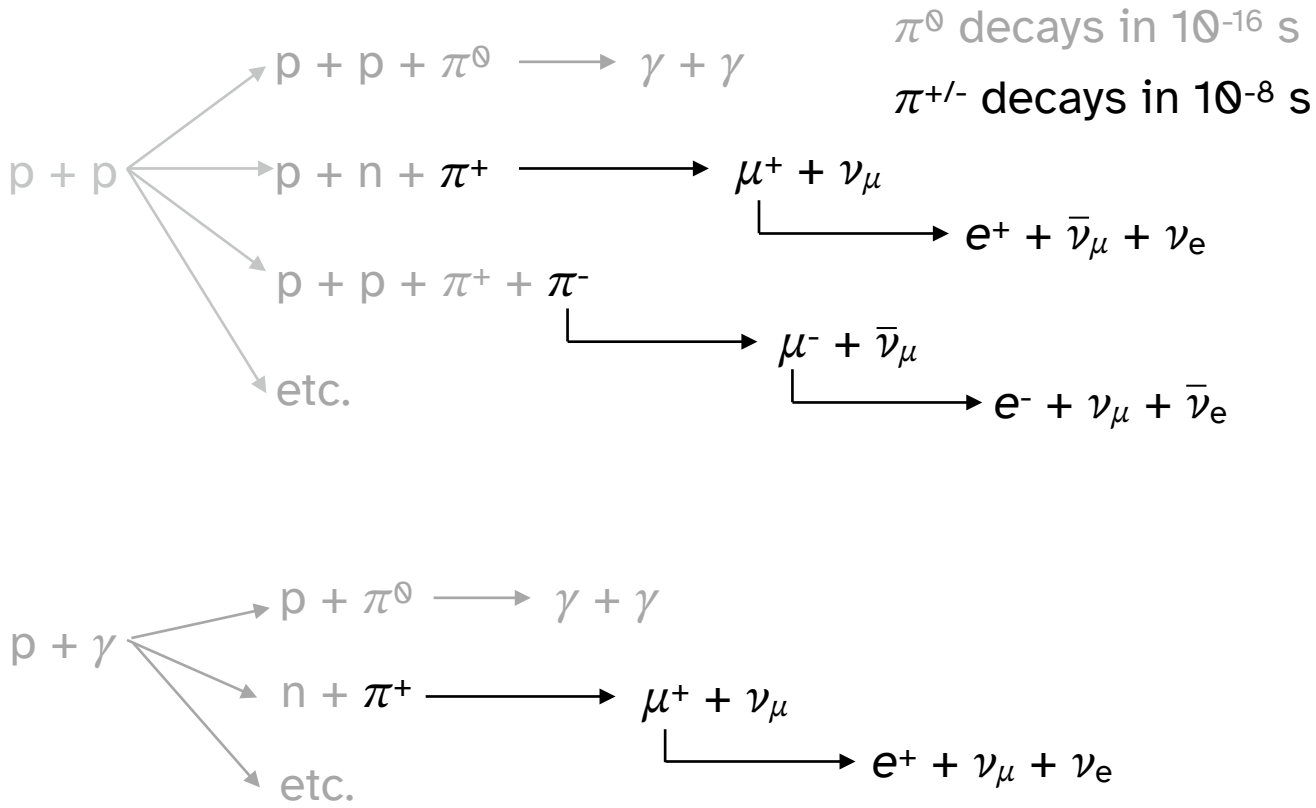
~10% of the original proton energy is transferred to the gamma rays

e.g., detect gamma rays with E_γ = 100 TeV

+ pion bump

= source can produce cosmic rays with E_{CR} = 1 PeV

Cosmic rays to gamma rays



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Gamma-ray sources are multimessenger sources

TXS 0506+056 [IceCube et al., Science 361 (2018)]

Neutrinos are the smoking gun for hadronic processes

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

[IceCube et al., Science 361 (2018)]

[IceCube/NASA]

Gamma-ray sources are multimessenger sources

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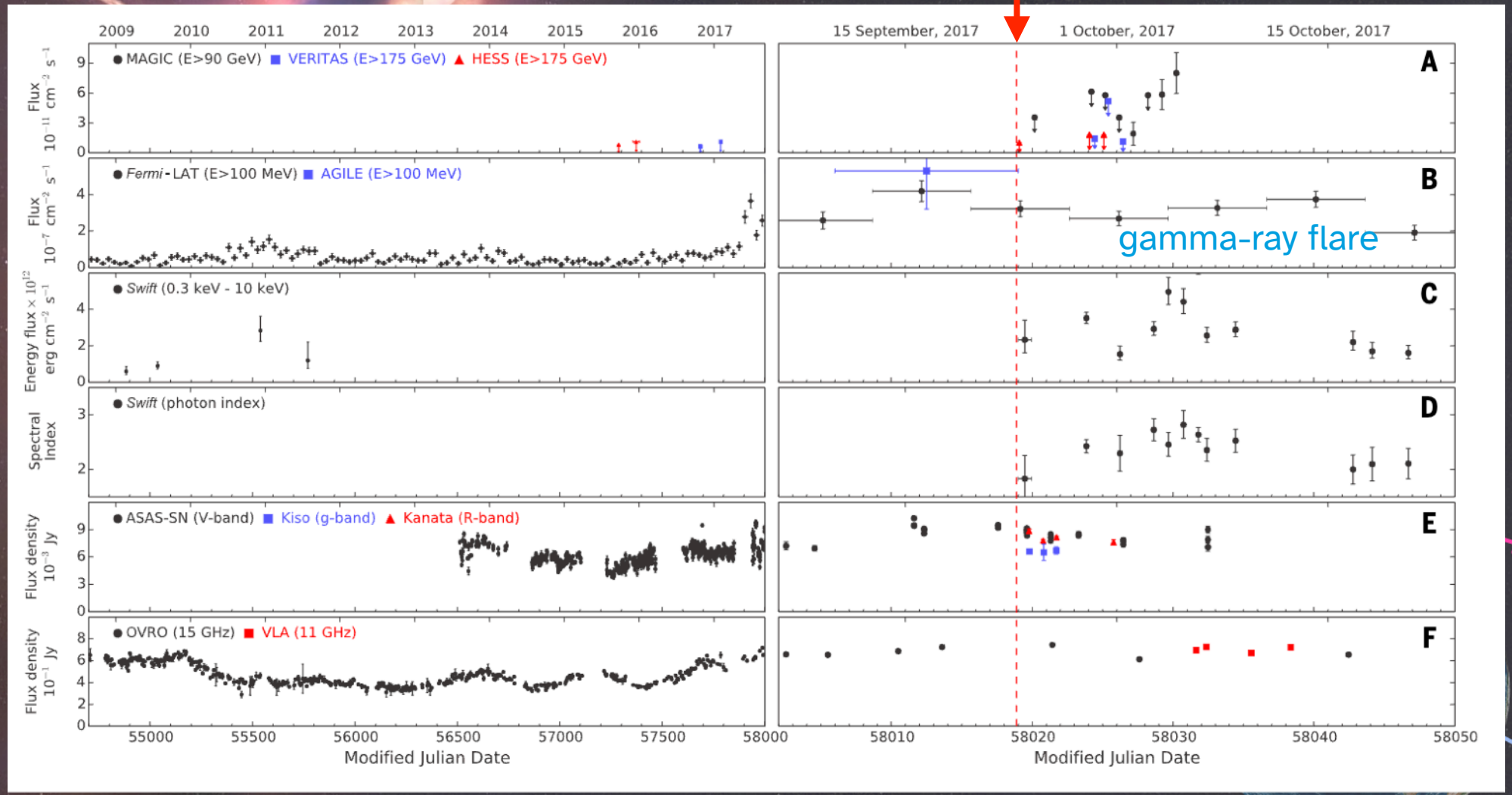


γ

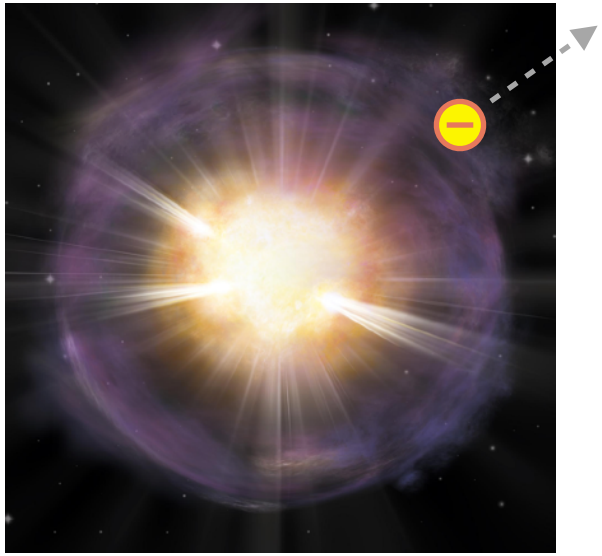
ν_μ

ask Matteo if you want to know more

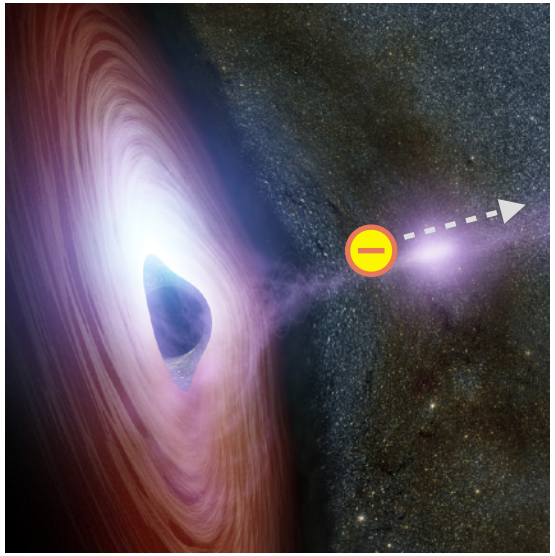
[IceCube/NASA]

Gamma-ray sources are multimessenger sources

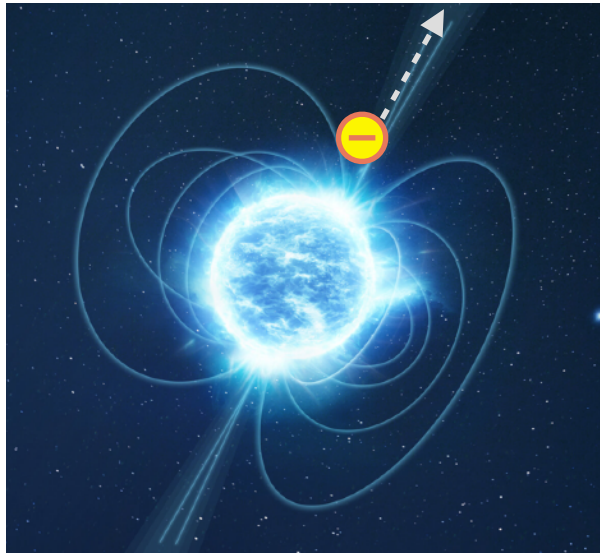
Charged particles are **accelerated** to high energies before radiating photons



[A. M. Geller/Northwestern/CTIO/SOAR/NOIRLab/NSF/AURA]



[NASA/JPL-Caltech]

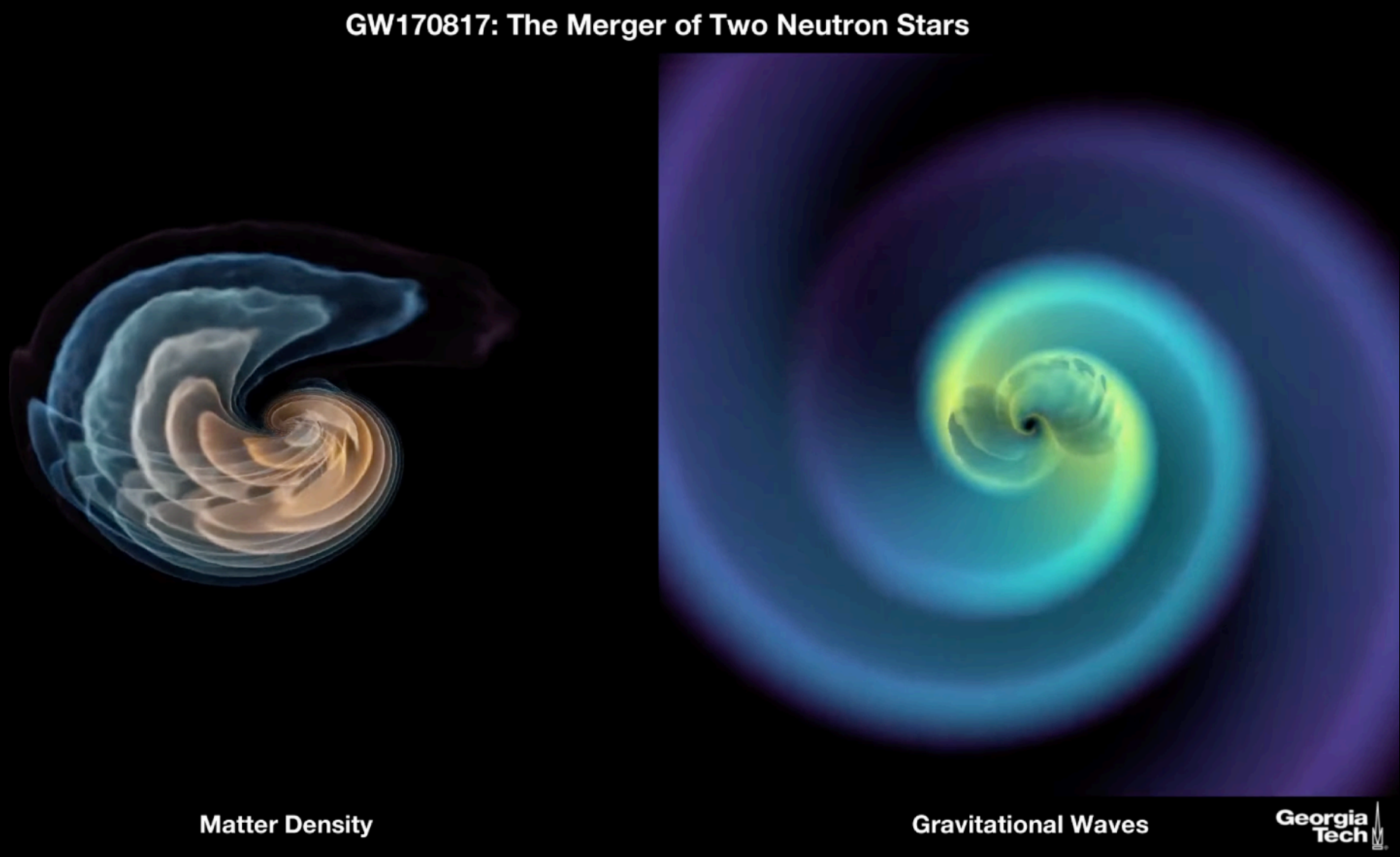


[ESA]

need a **large energy source** and a way to **transfer energy** to charged particles

=> **gamma-ray sources are often related to compact objects: black holes, neutron stars**

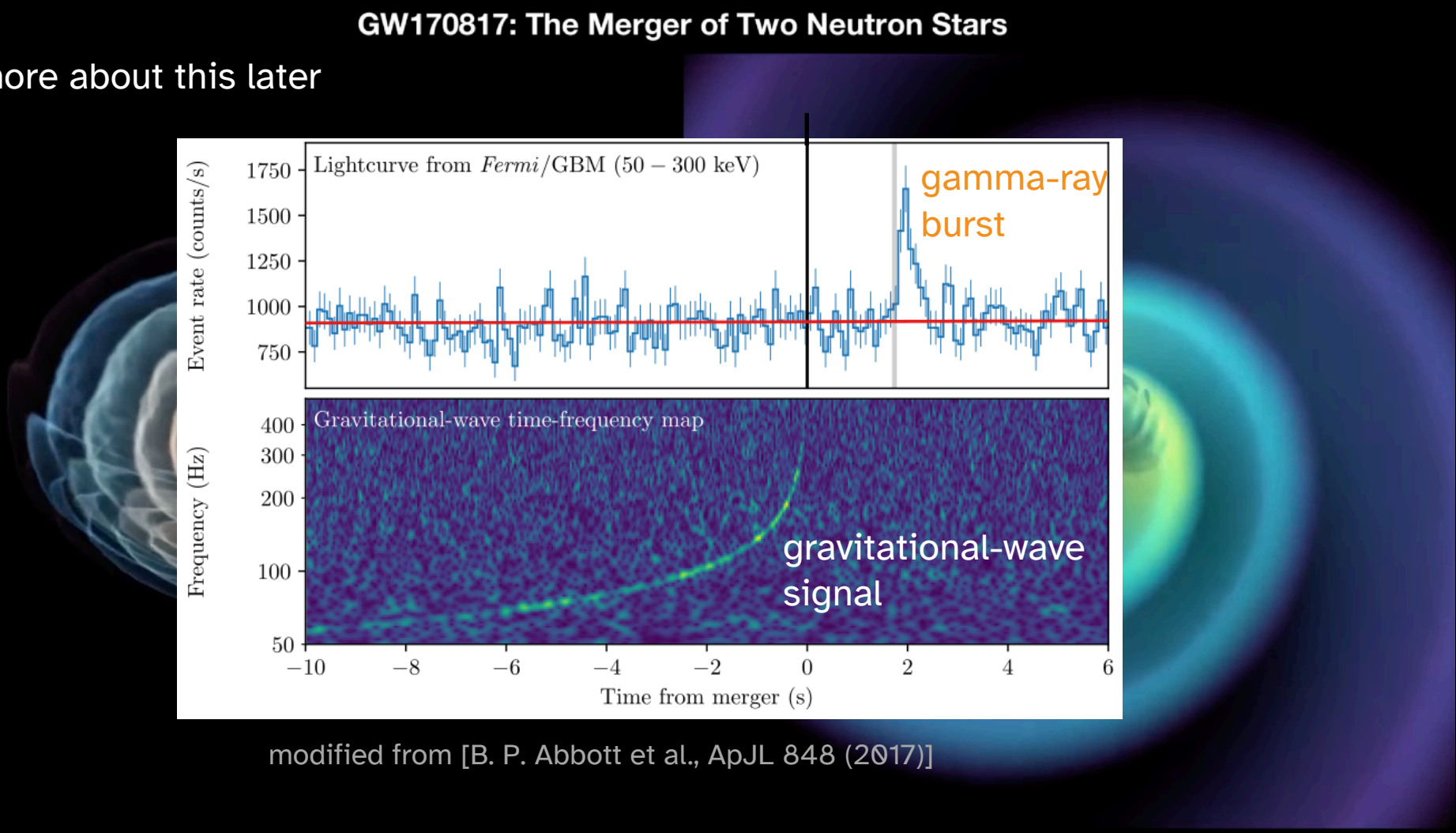
Gamma-ray sources are multimessenger sources



[Christopher W. Evans / Georgia Tech]

Gamma-ray sources are multimessenger sources

We'll talk more about this later

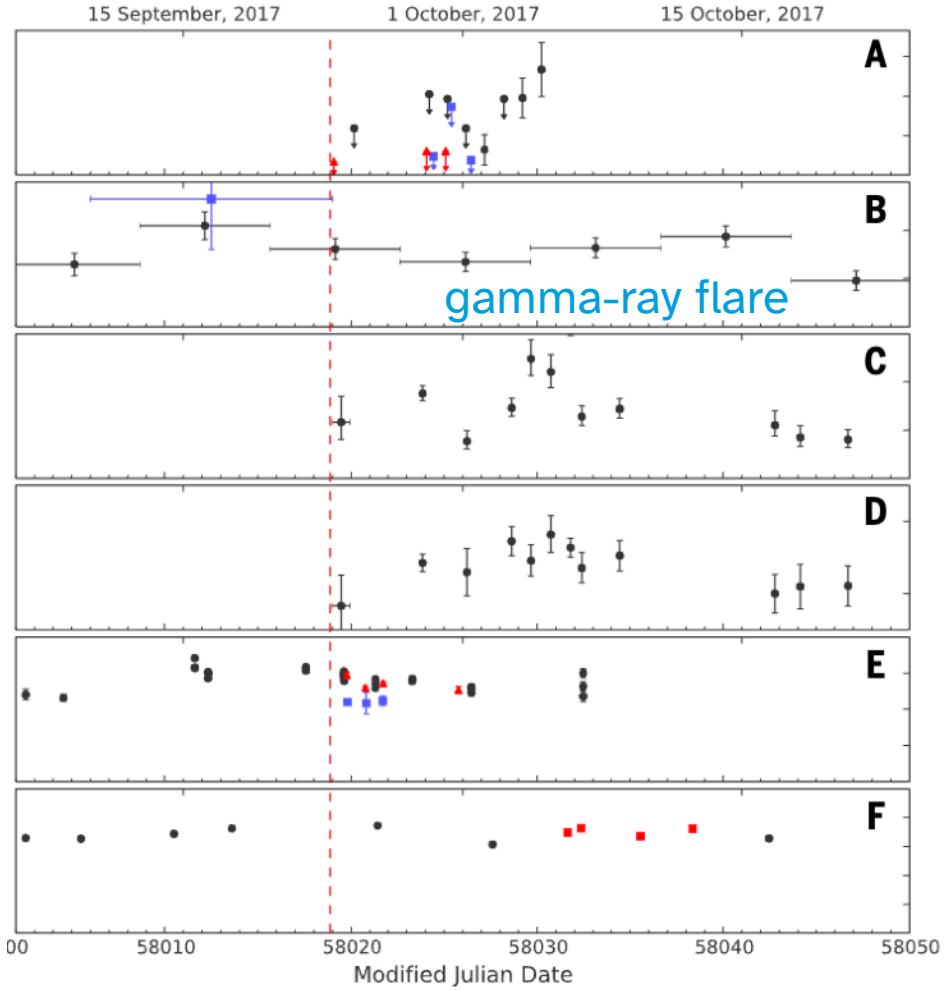


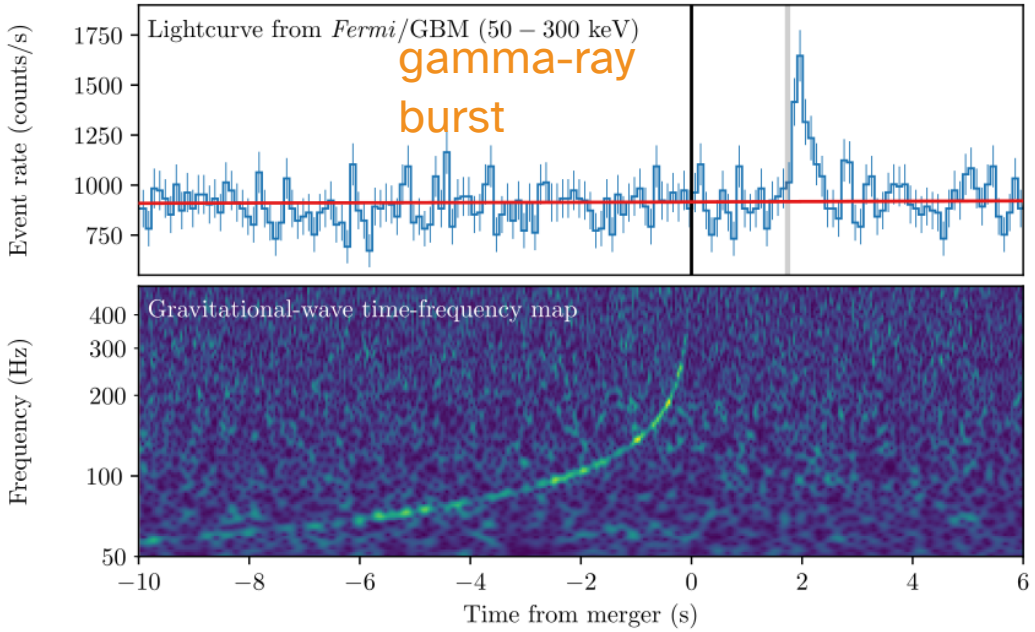
modified from [B. P. Abbott et al., ApJL 848 (2017)]

[Christopher W. Evans / Georgia Tech]

Gamma-ray sources are multimessenger sources

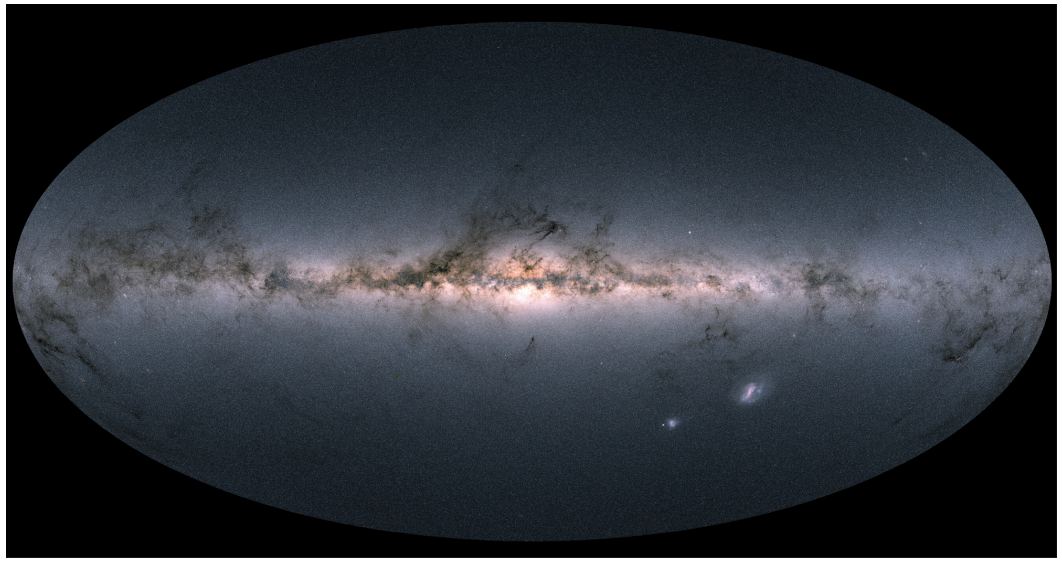
hmm we've reached that "time domain" part already

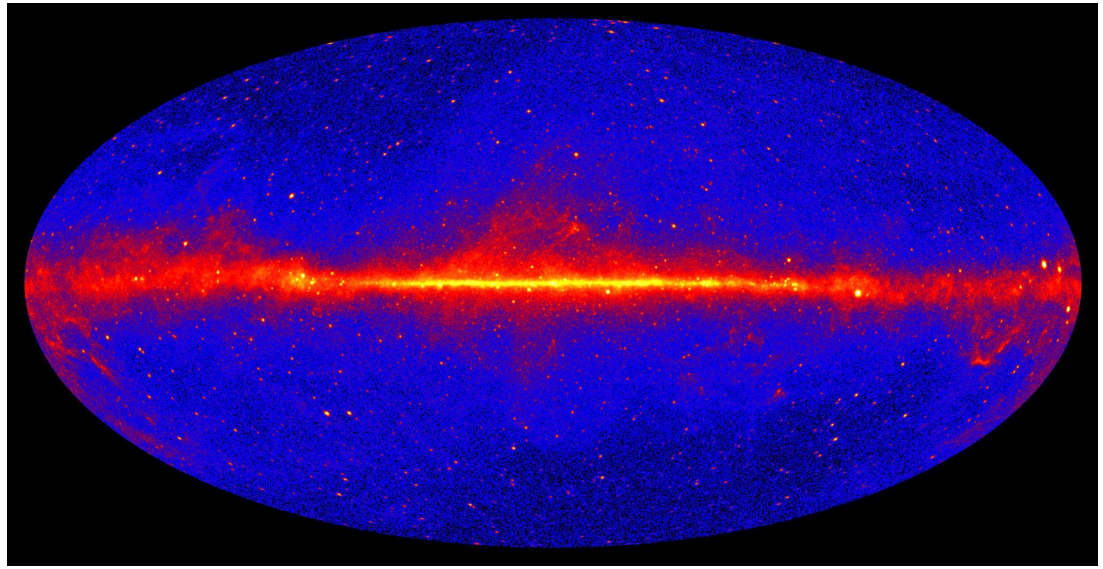




Returning to the questions

How do we start to find the answers?



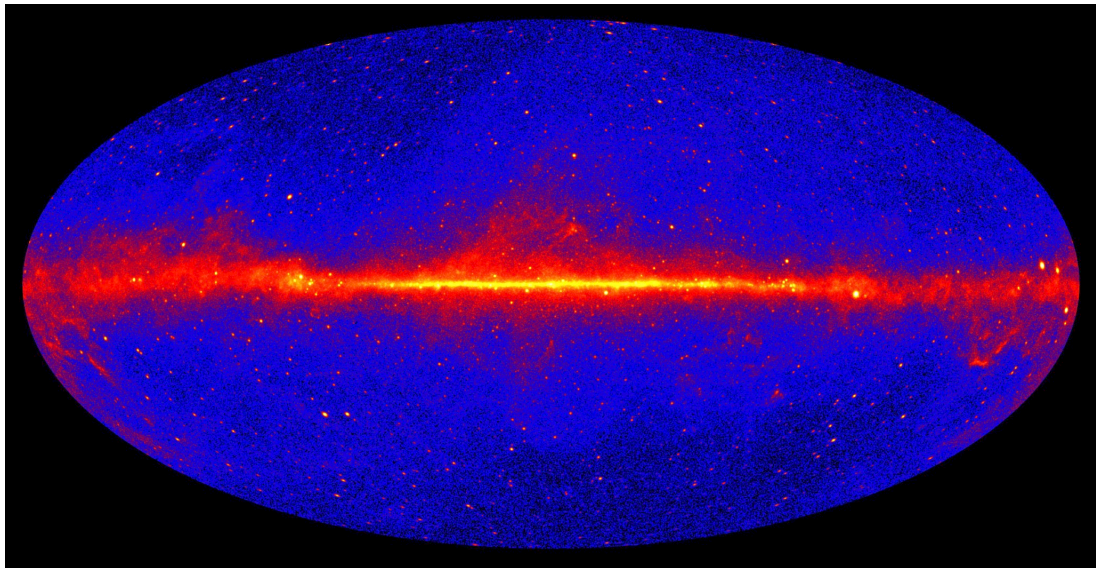


Why are some sources bright over a wide energy range, while others are only bright in a narrow range?
How are the photons being produced by these sources?
Are there sources that don't show up on these maps?
How do we detect these sources in the first place?

Returning to the questions

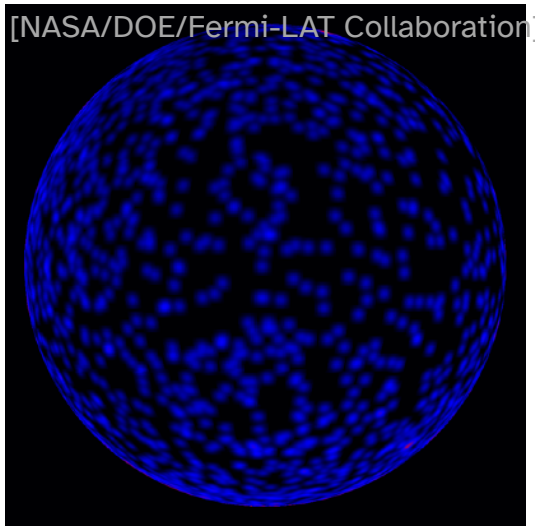
How do we start to find the answers?

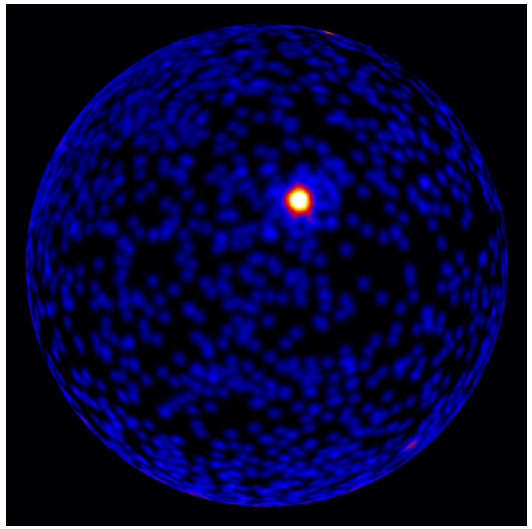
≳5000 sources in this map (GeV) ⟶
~10 years of data



[NASA/DOE/Fermi-LAT Collaboration]

The gamma-ray sky can look very different on hour-timescales

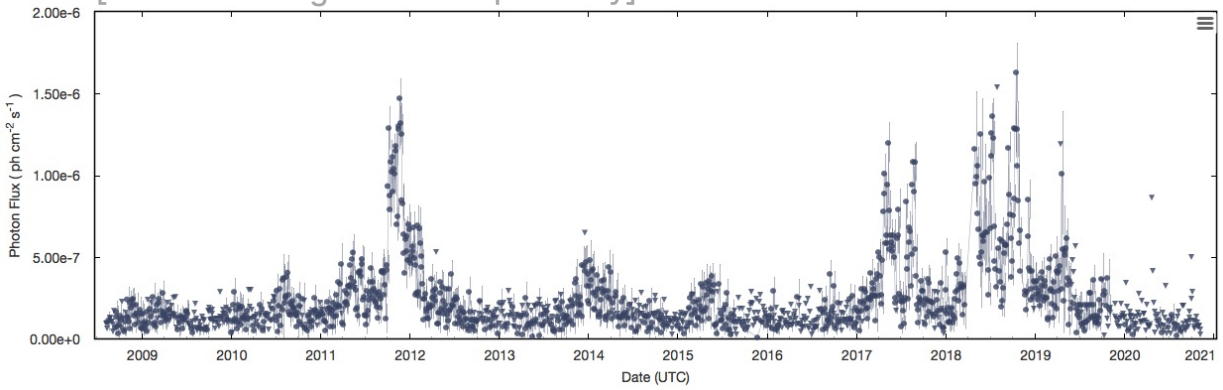




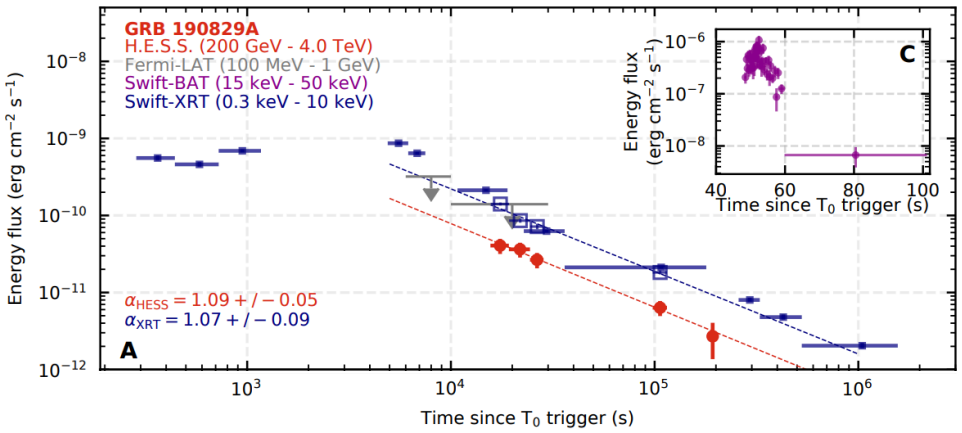
Light curves are especially important in time domain astronomy

how much is emitted vs time

[Fermi-LAT lightcurve repository]



vs



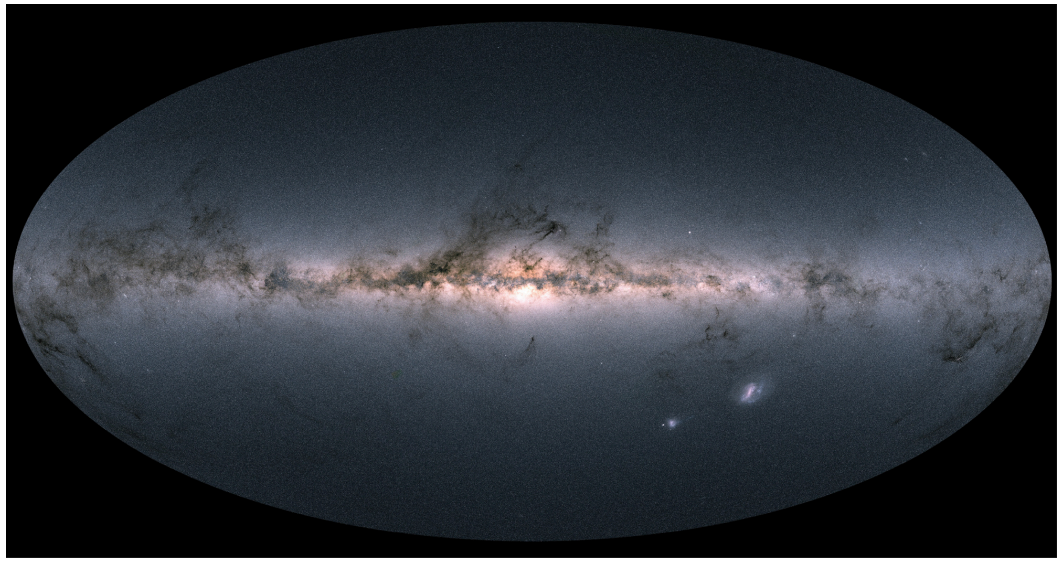
modified from [H. Abdalla et al., Science 372 (2021)]

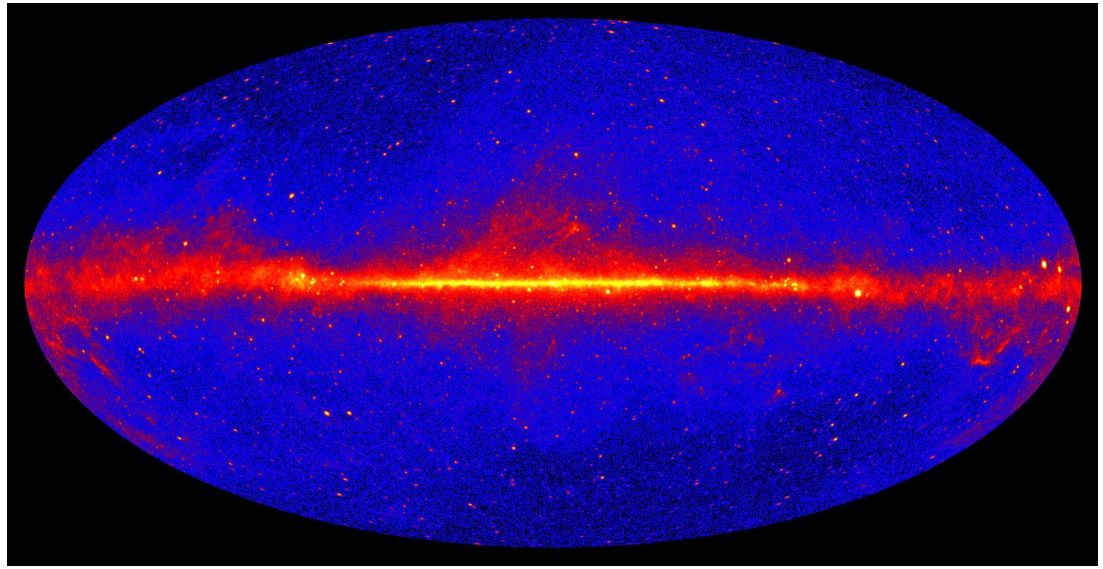
Some sources have **flares** or are **recurring** (non-catastrophic)

Others are truly **transient** (catastrophic)

Returning to the questions

How do we start to find the answers?





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