Gamma-ray astronomy

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

so what are we going to talk about

Rough outline

today (intro)
- What are gamma rays
- What do we learn from gamma rays

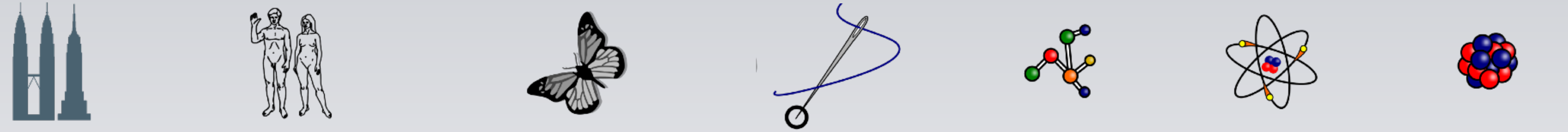
tomorrow (detectors)
- What are some ways we can detect gamma rays

the day after tomorrow (sources)
- What objects produce astrophysical gamma rays
- What can we learn from these objects

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

The electromagnetic spectrum

wavelength scales:



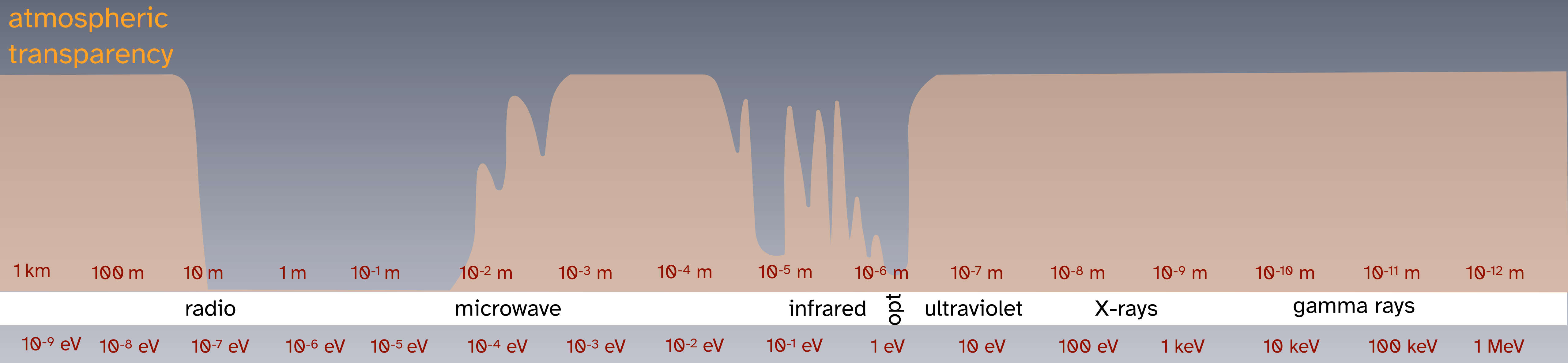
1 km	100 m	10 m	1 m	10^{-1} m	10^{-2} m	10^{-3} m	10^{-4} m	10^{-5} m	10^{-6} m	10^{-7} m	10^{-8} m	10^{-9} m	10^{-10} m	10^{-11} m	10^{-12} m

radio | microwave | infrared | opt | ultraviolet | X-rays | gamma rays

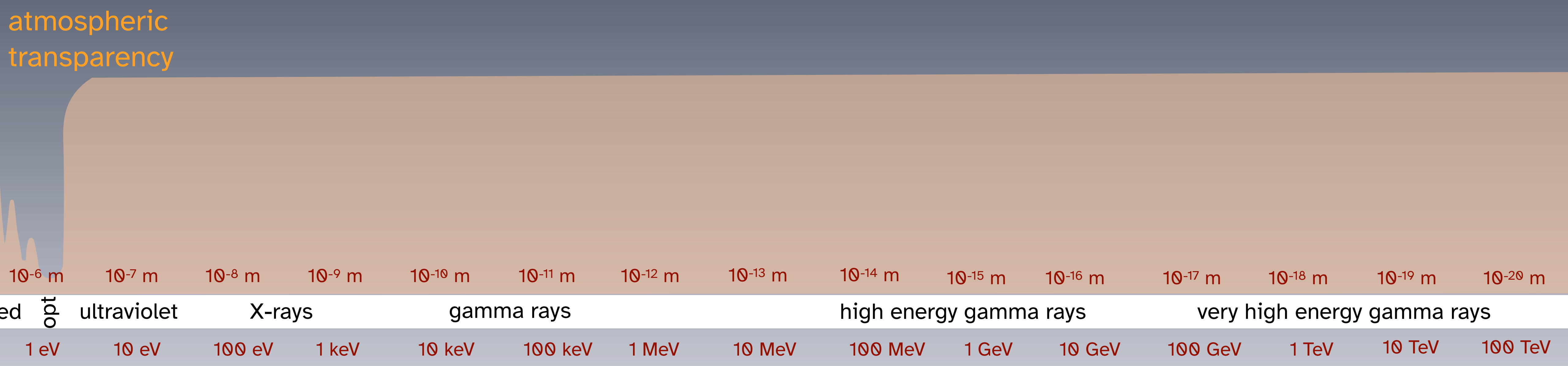
10^{-9} eV	10^{-8} eV	10^{-7} eV	10^{-6} eV	10^{-5} eV	10^{-4} eV	10^{-3} eV	10^{-2} eV	10^{-1} eV	1 eV	10 eV	100 eV	1 keV	10 keV	100 keV	1 MeV

[InductiveLoad]

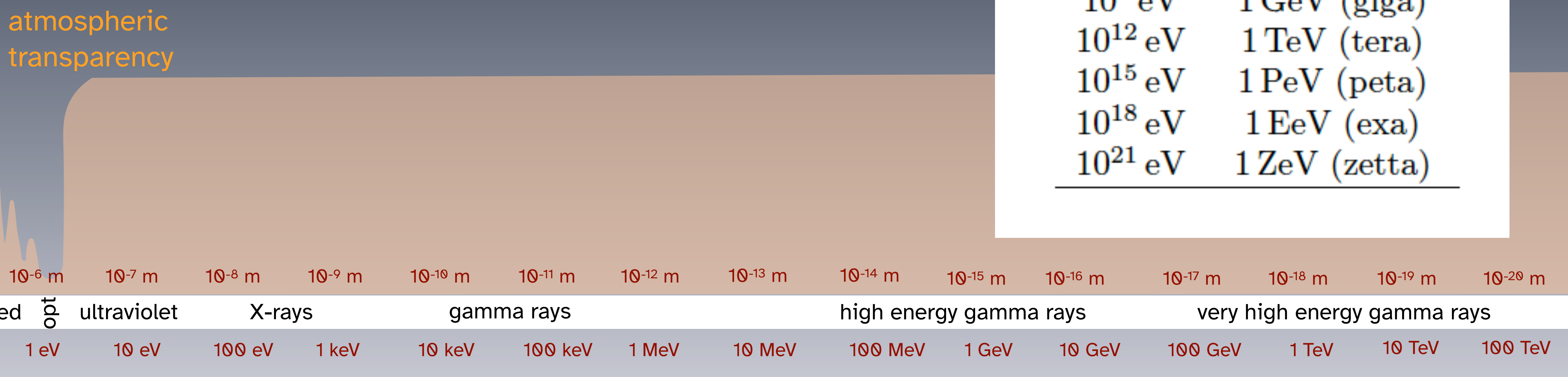
The electromagnetic spectrum



The electromagnetic spectrum, continued

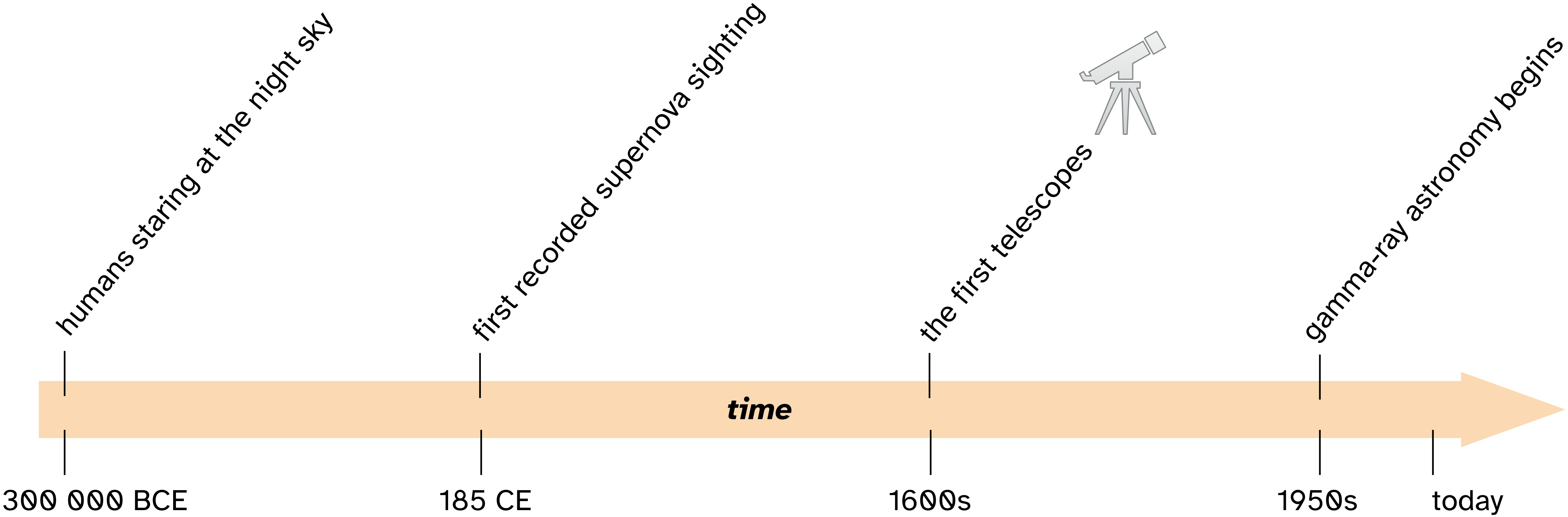


The electromagnetic spectrum, continued



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)

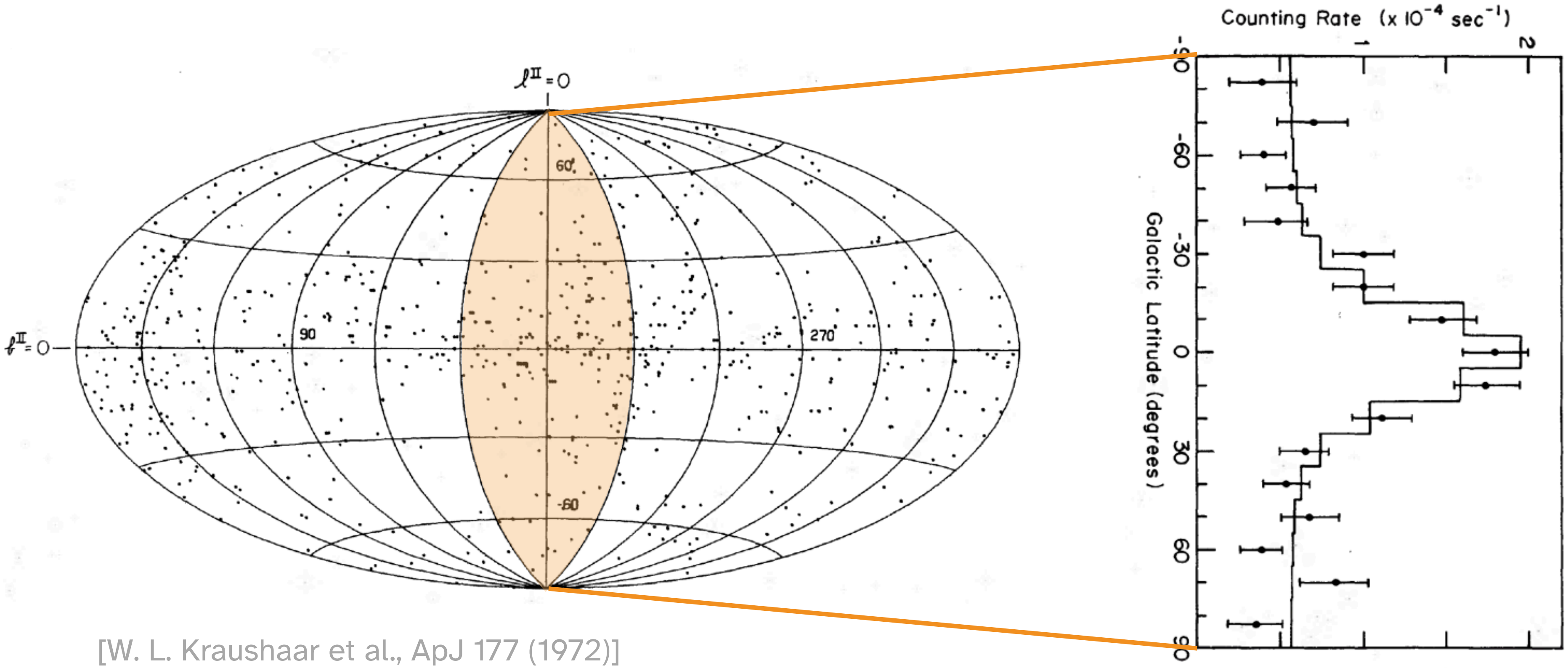
A very brief history of astronomy



A very brief history of gamma-ray astronomy

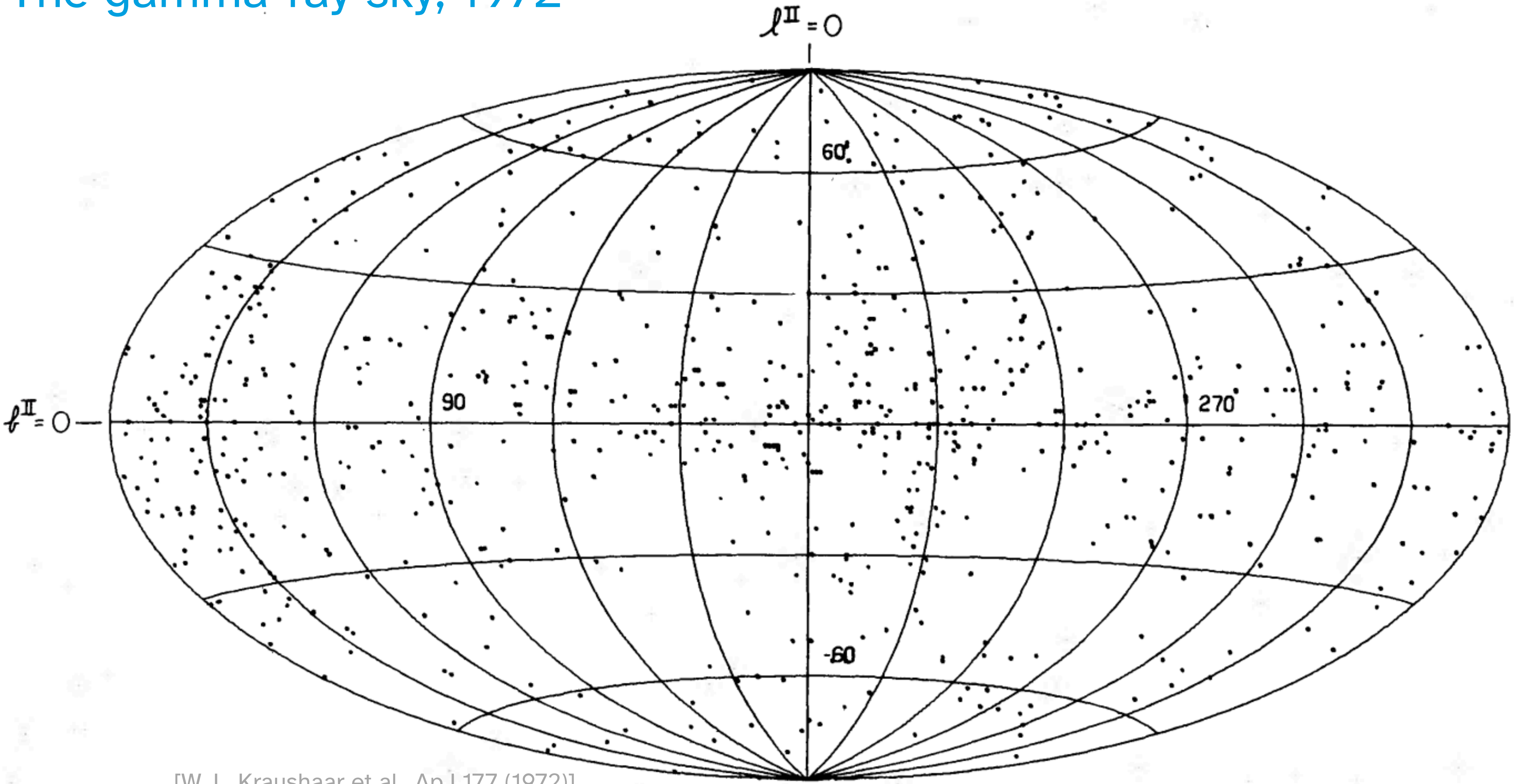
Observational gamma-ray astronomy began when we started to launch satellites

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



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

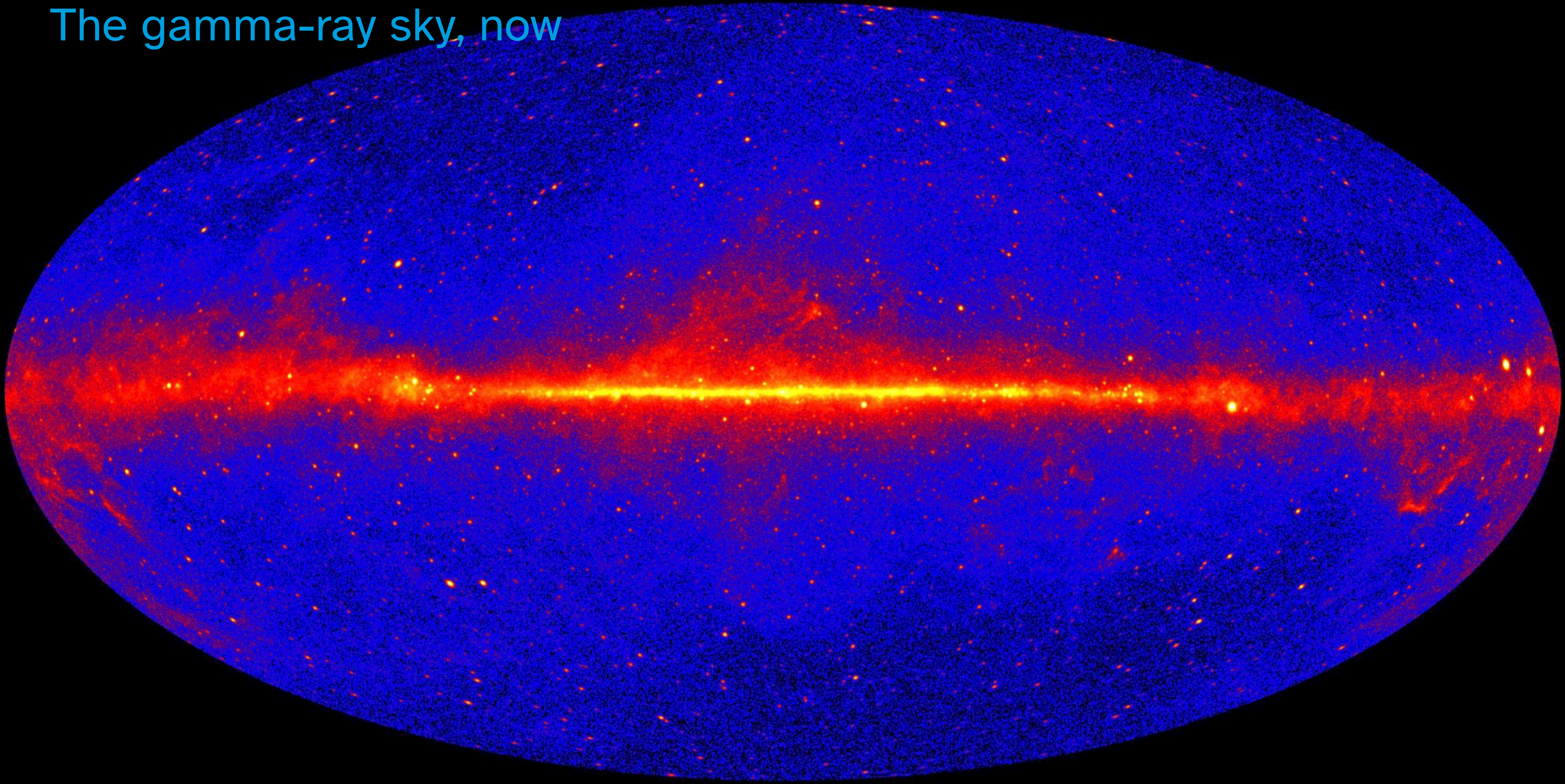
The gamma-ray sky, 1972



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

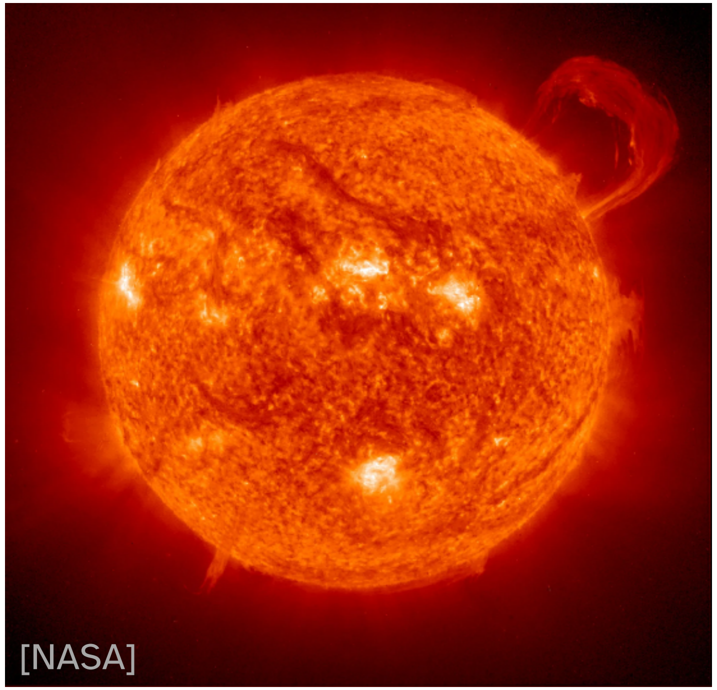
The gamma-ray sky, now

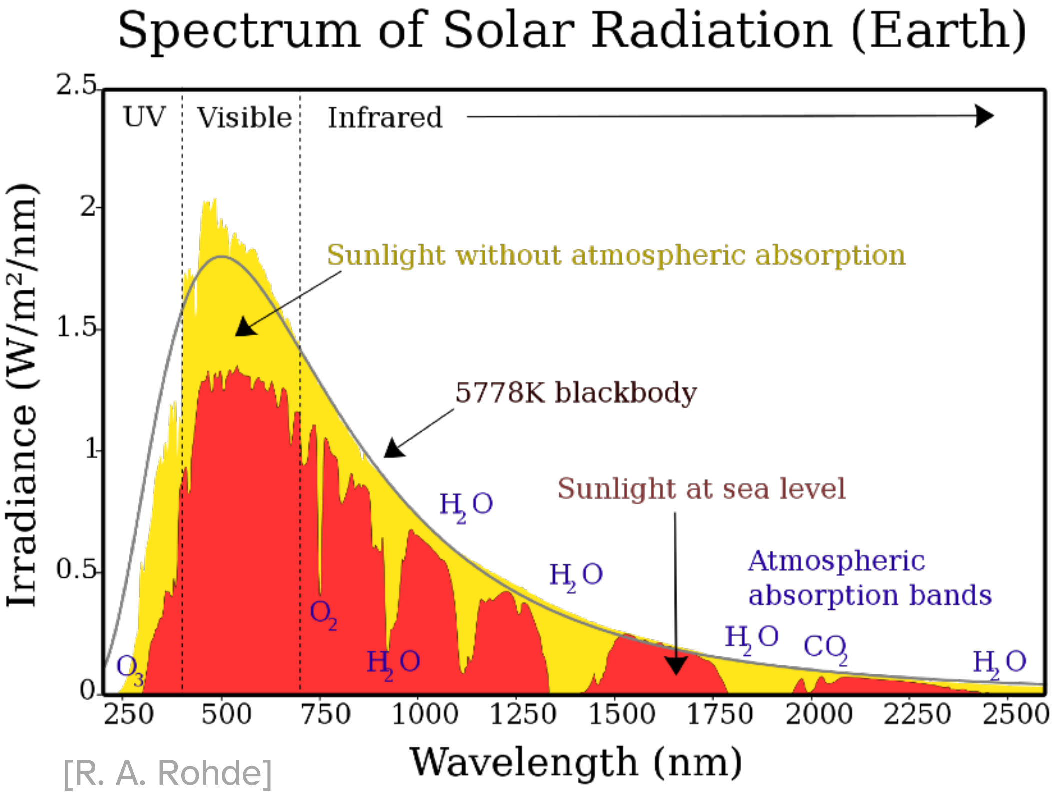
[NASA/DOE/Fermi-LAT Collaboration]



Most of the optical (visible) Universe produce thermal emission

Thermal emission can be described solely by a temperature

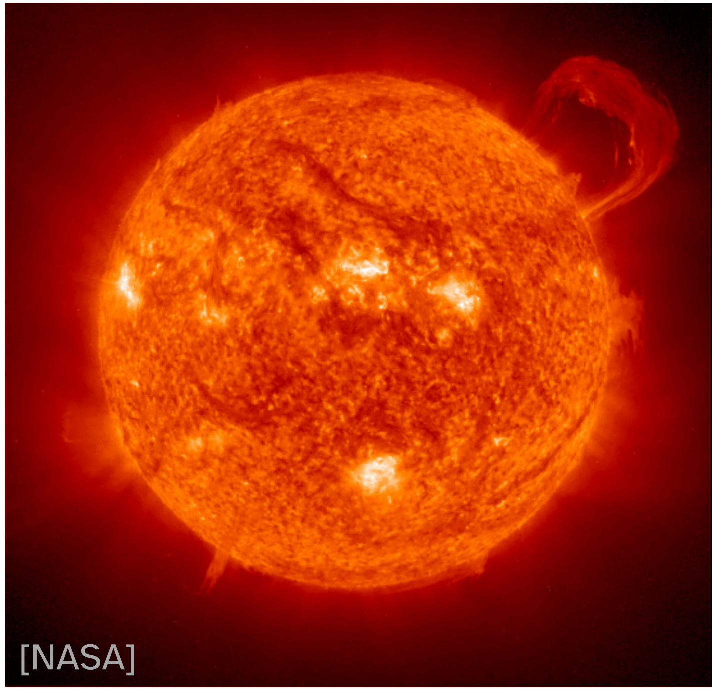


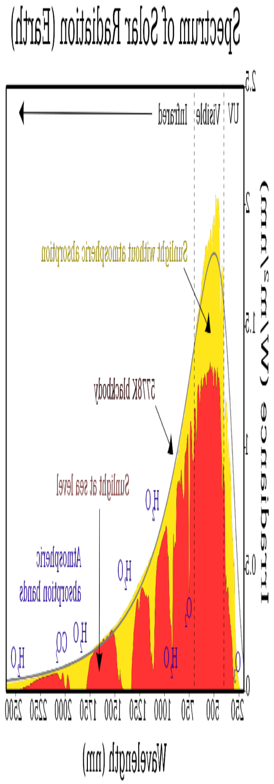


[R. A. Rohde]

Most of the optical (visible) Universe produce thermal emission

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





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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

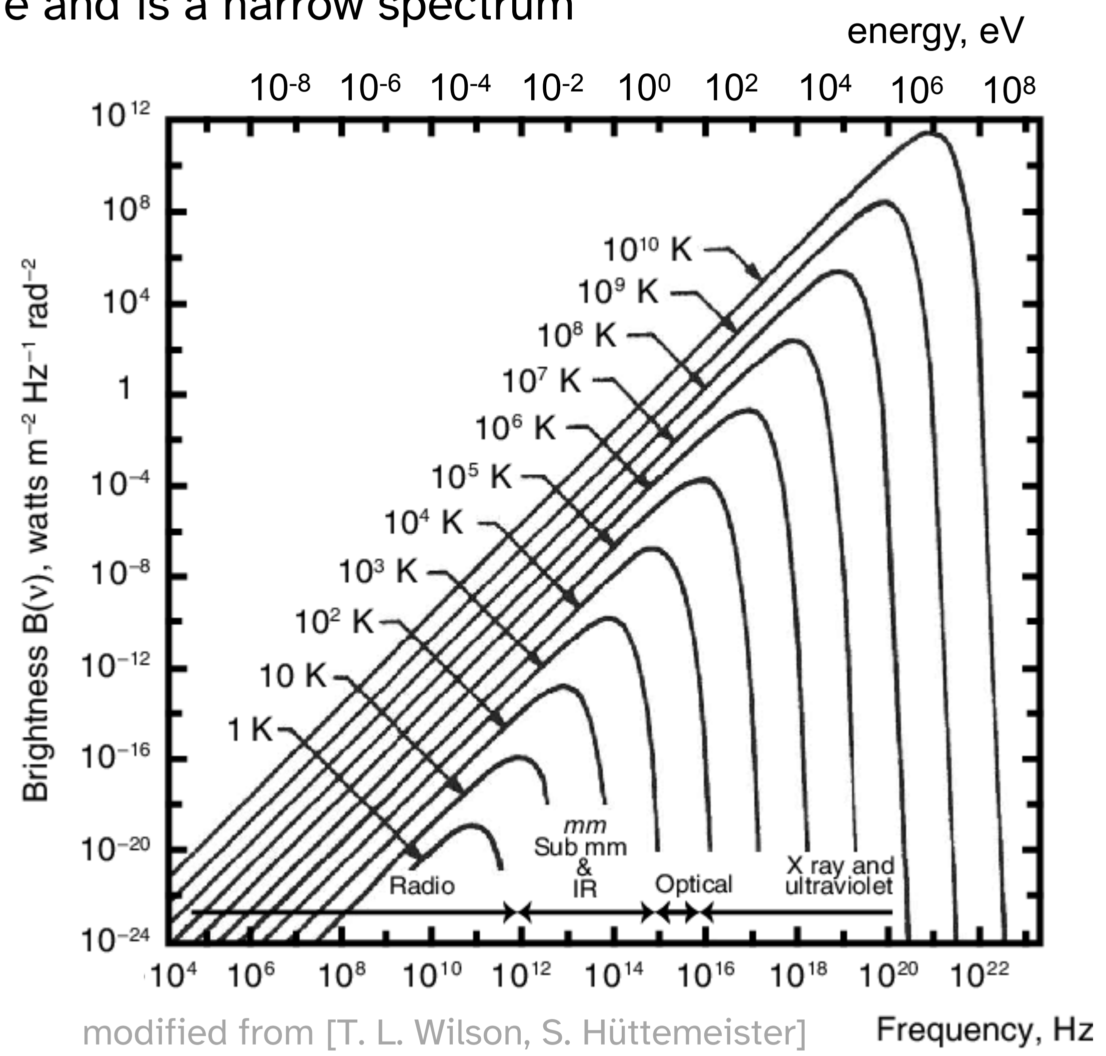
The gamma-ray sky is **nonthermal**

with a few exceptions

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

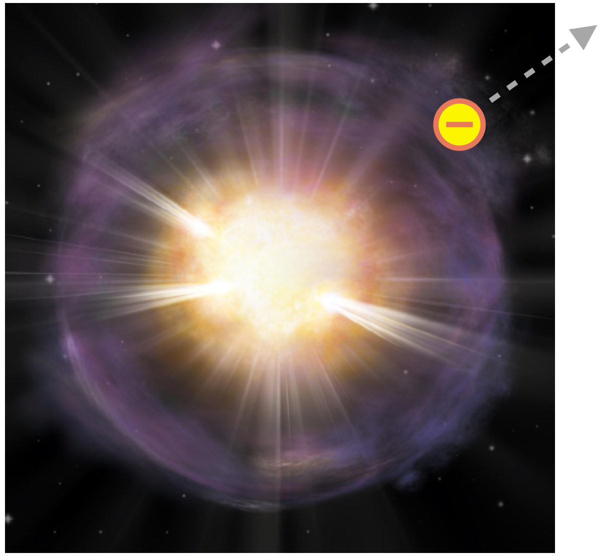


modified from [T. L. Wilson, S. Hüttemeister]

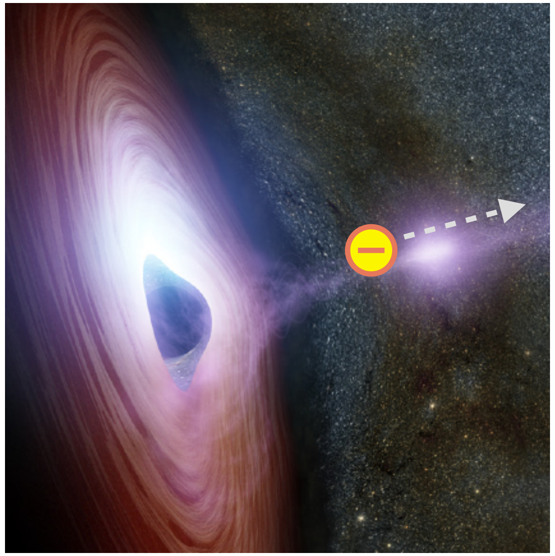
How do we get gamma rays?

Nonthermal emission

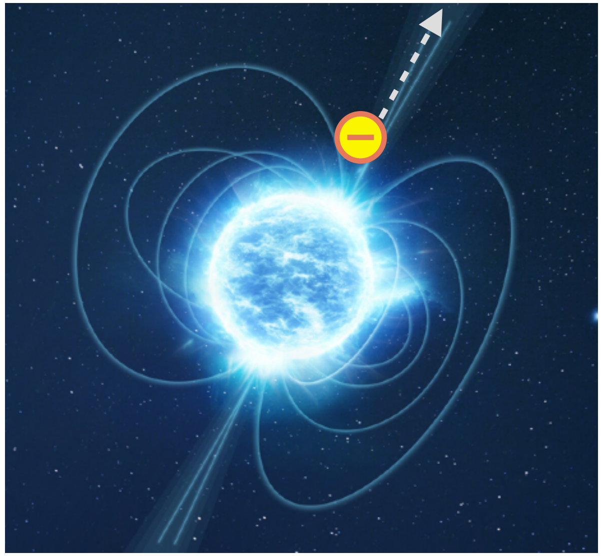
Charged particles are **accelerated** to high energies before radiating photons



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



[NASA/JPL-Caltech]



[ESA]

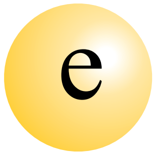
need an **energy source** and a way to **transfer this energy** to charged particles
(e.g., kinetic, gravitational, magnetic fields …)

How do we get gamma rays?

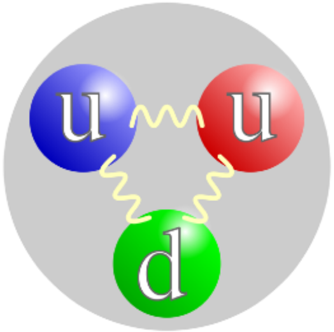
Nonthermal emission processes

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



proton



[A. Horvath]

leptons are elementary particles

hadrons are made of quarks
-> can convert into other particles

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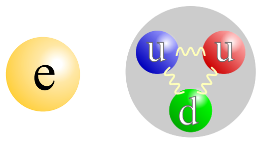
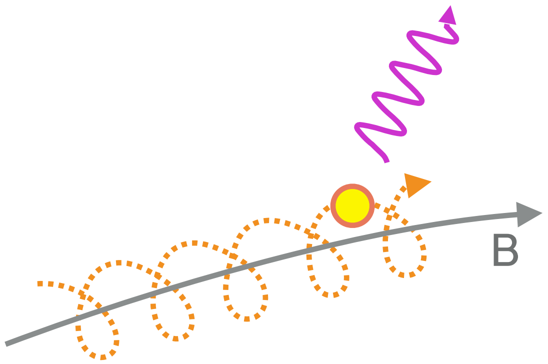
e.g., synchrotron





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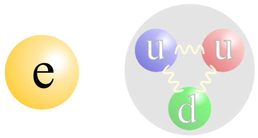
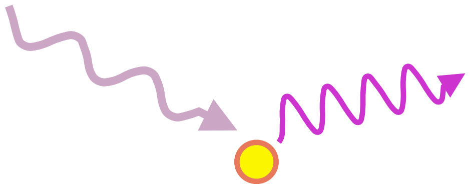
e.g., inverse Compton





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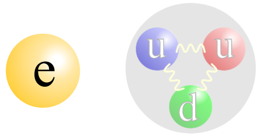
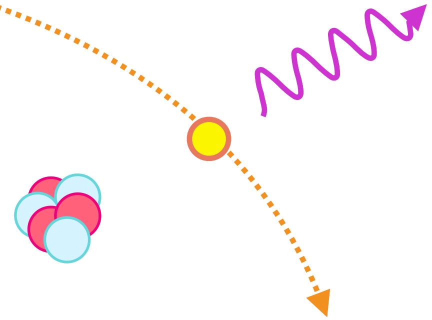
e.g., Bremsstrahlung





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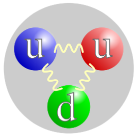
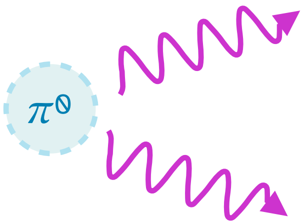
e.g., pion decay





What processes produce gamma rays?

Nonthermal emission processes

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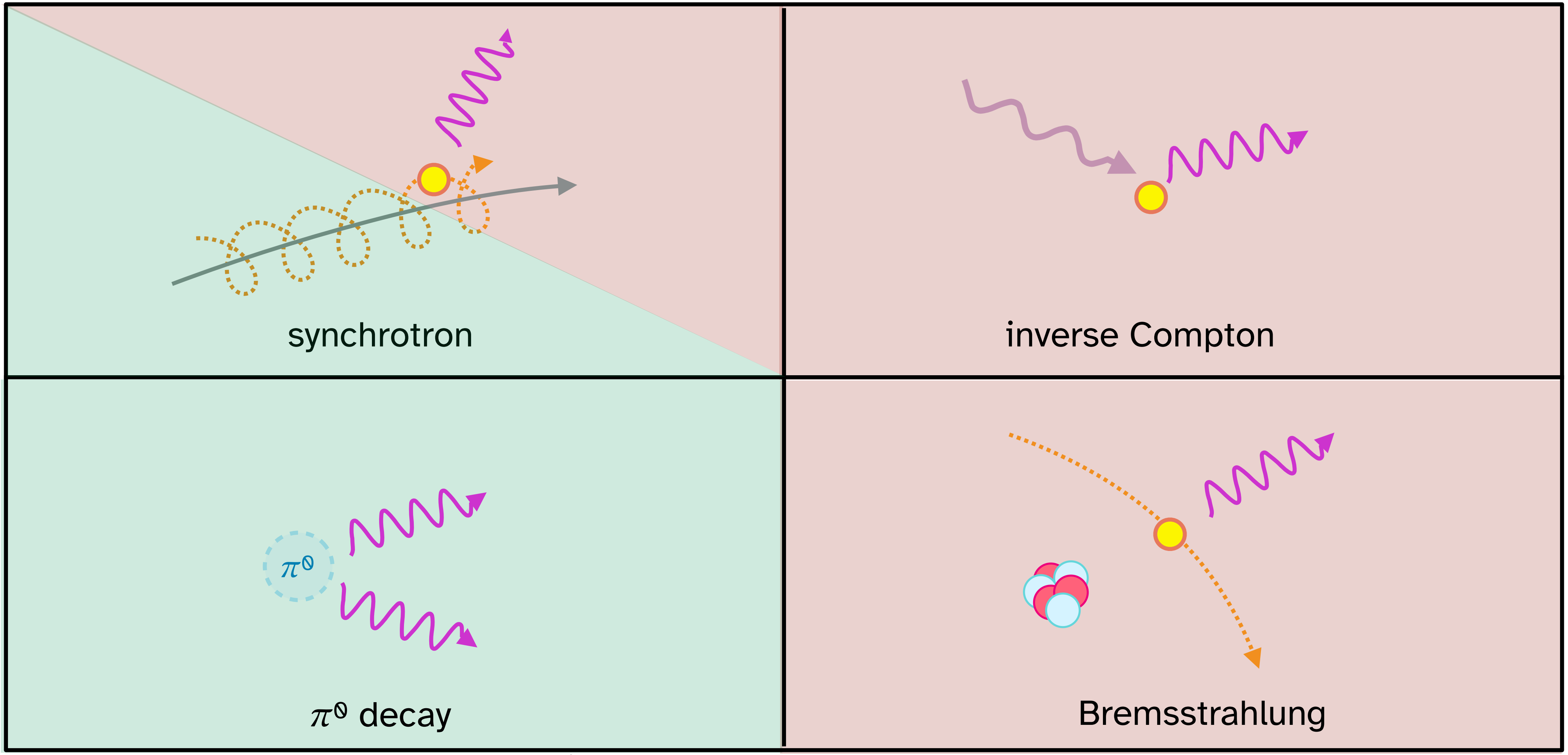
(coloring indicates what is relevant to these lectures)



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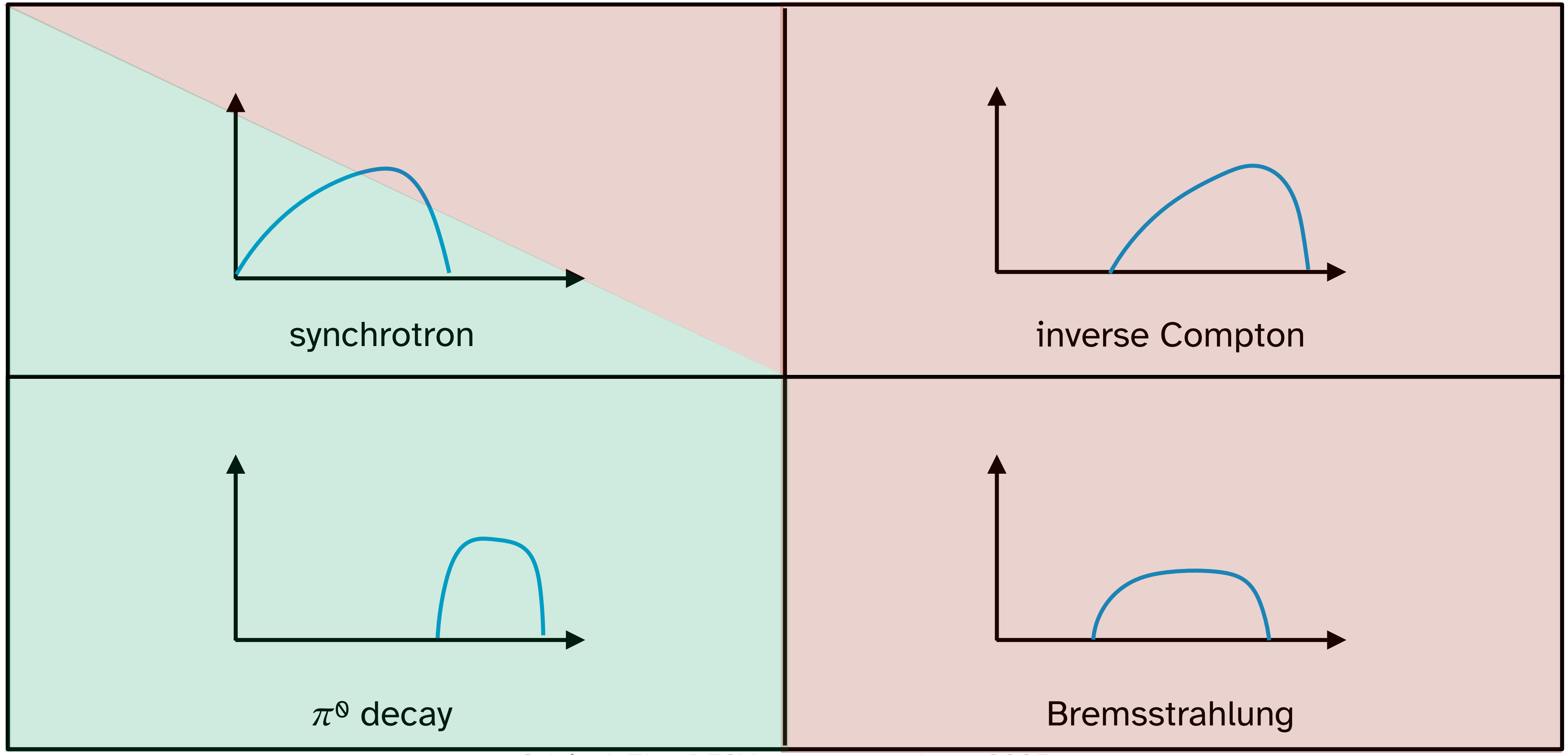

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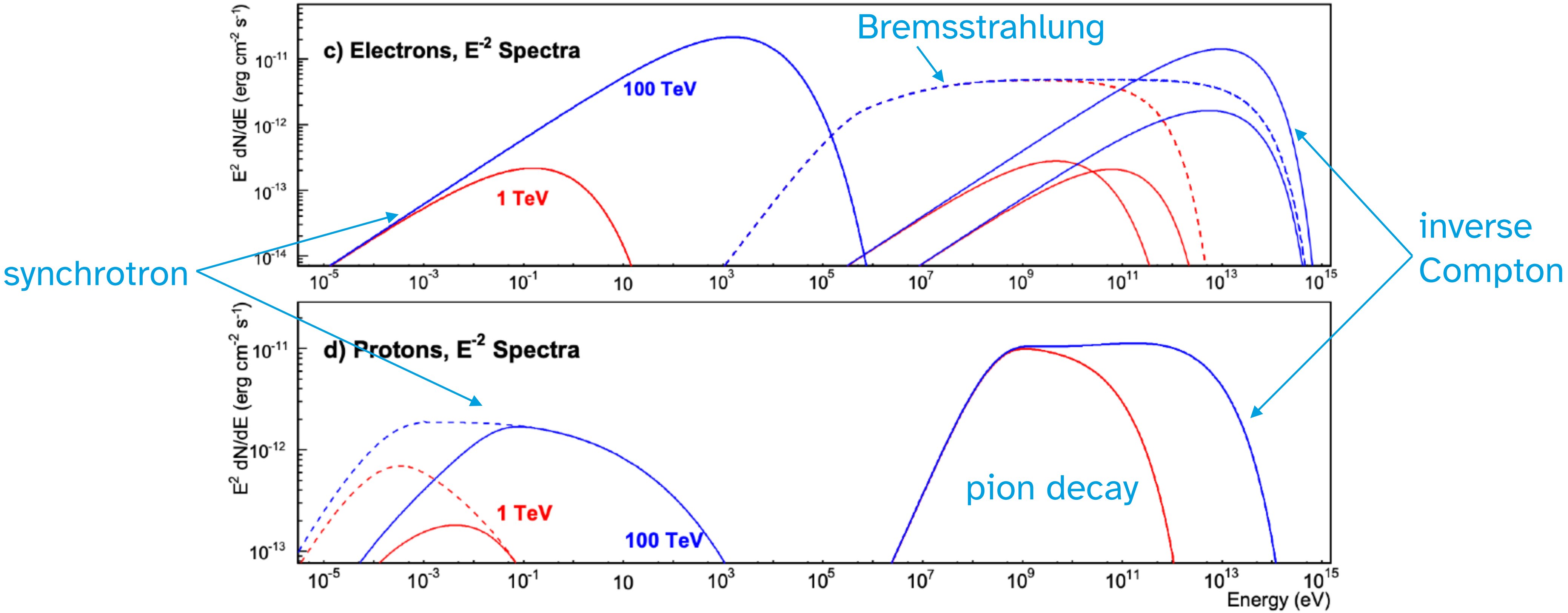
[J. A. Hinton & W. Hofmann, ARA&A 47 (2009)]

example spectra under common conditions

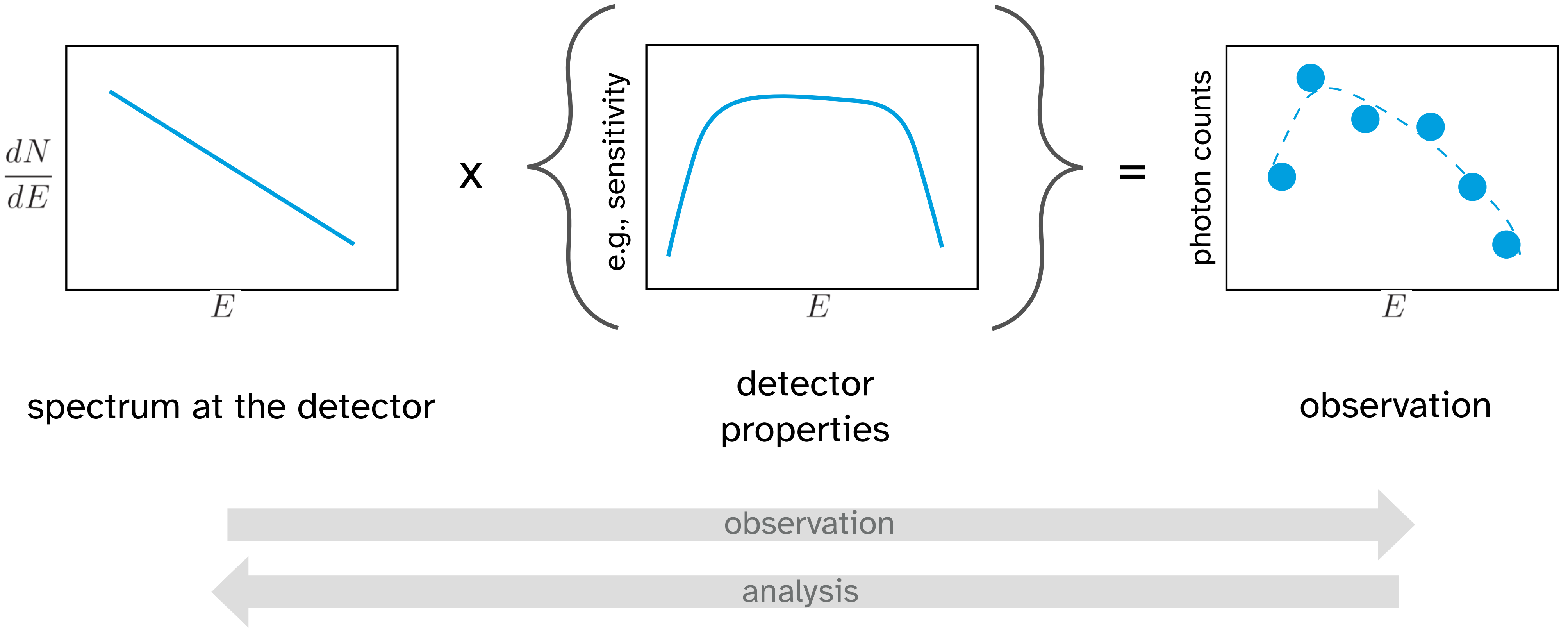


What exactly do we mean by “spectra”?

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}



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

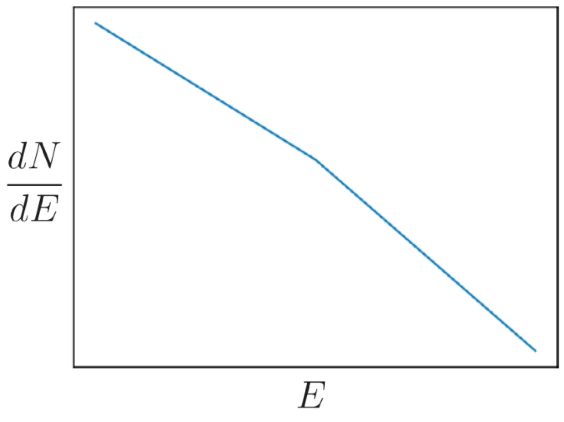
example units: ph cm^{-2} s^{-1}

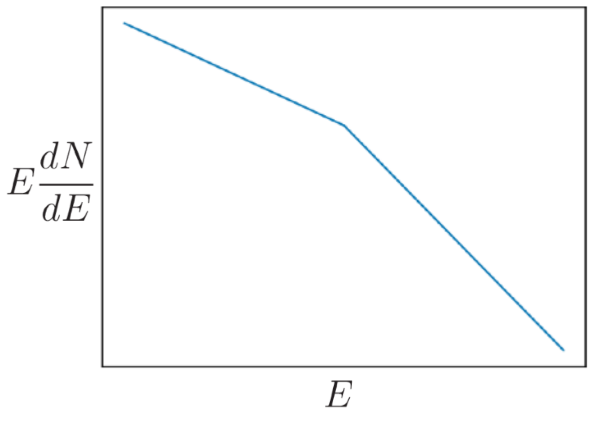
$E^2\frac{dN}{dE}$ tells us at what photon energy the largest amount of energy is emitted

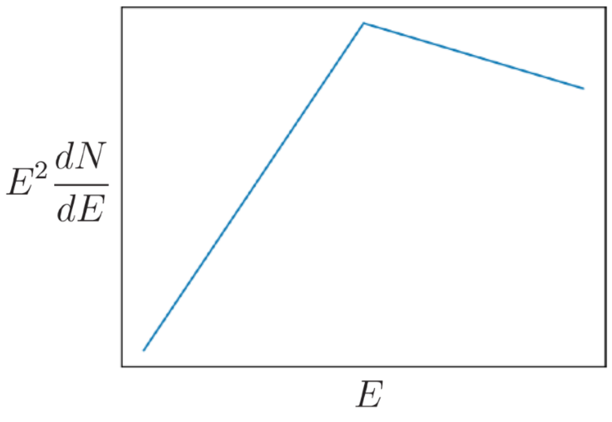
equivalently: νF_ν

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

e.g.:



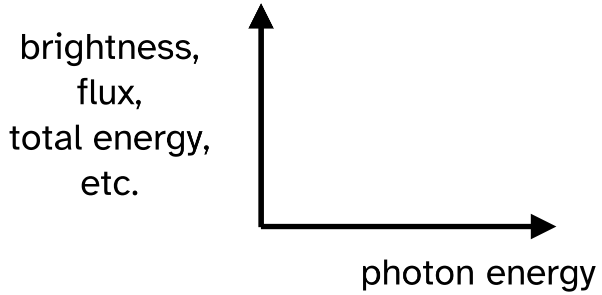


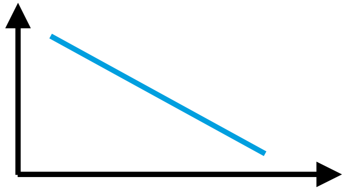


Spectra

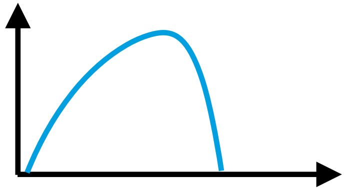
how much is emitted vs photon energy

The spectrum tells you something about the photon emission processes

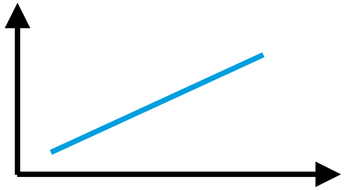




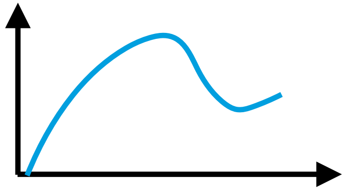
more energy emitted at lower photon energies (“soft spectrum”)



there is a “peak” photon energy



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



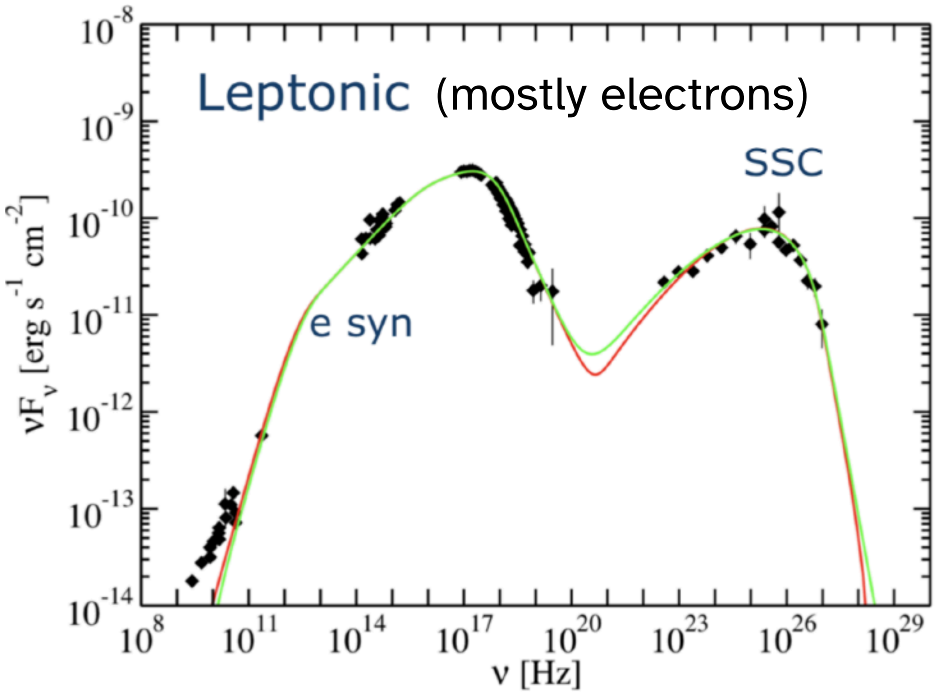
there are multiple emission mechanisms

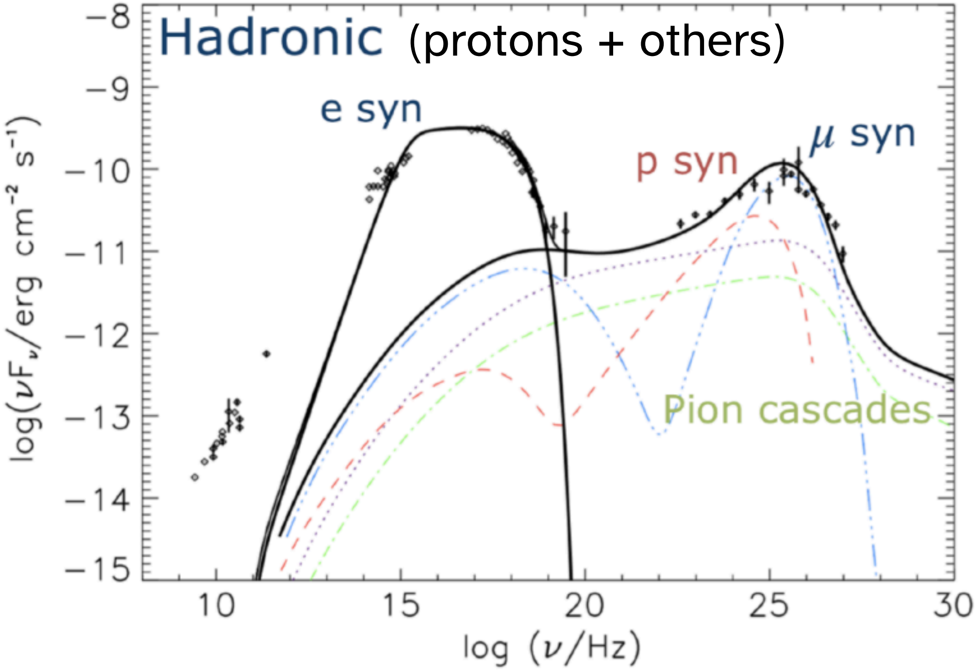
Multiwavelength spectra

how much is emitted vs photon energy

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





Light curves

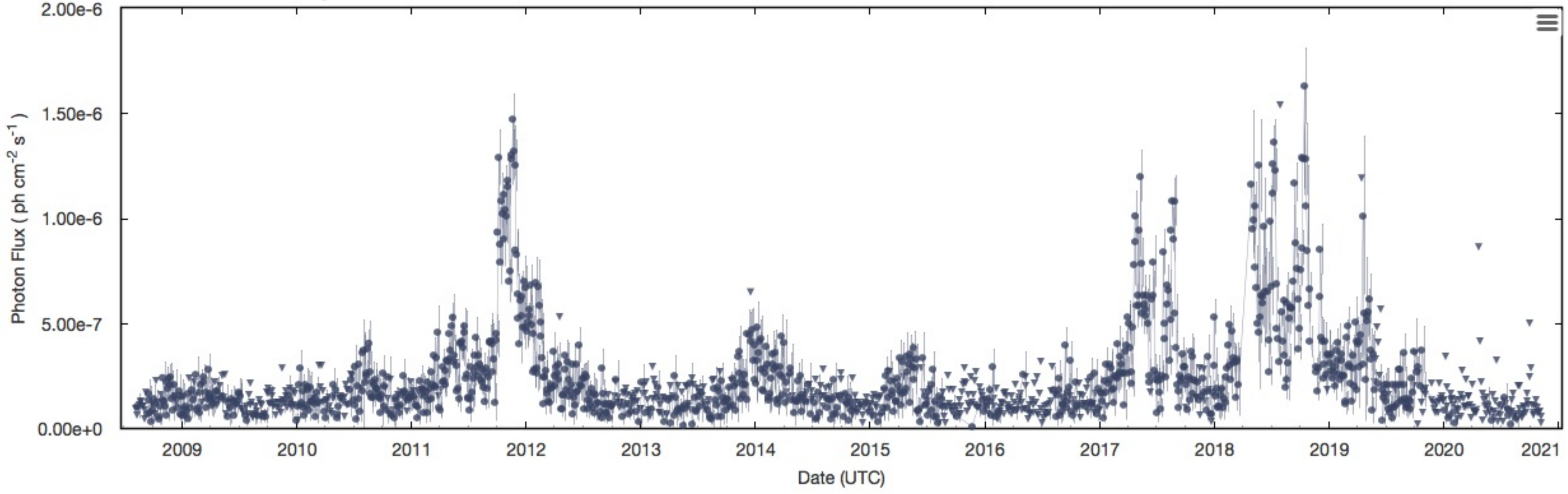
how much is emitted vs time

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]



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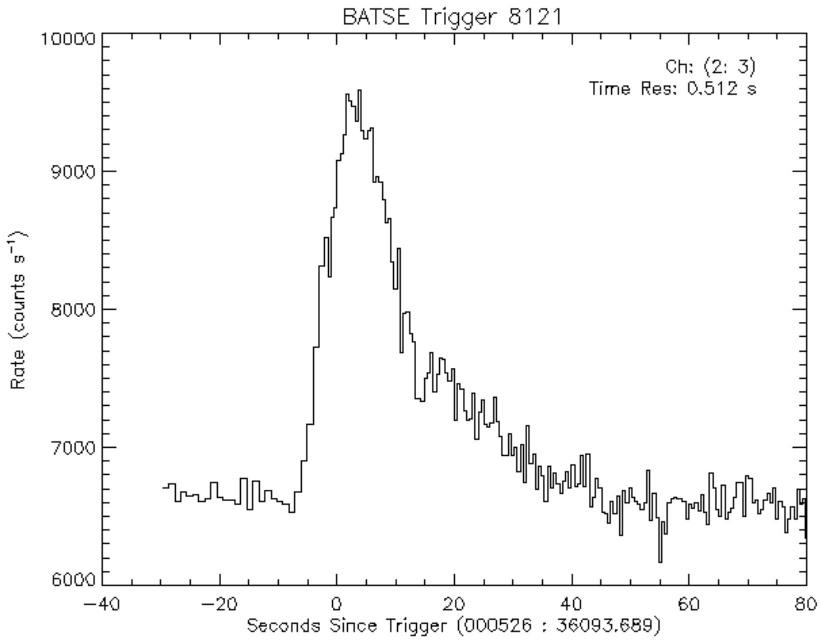
$$\int_{E_1}^{E_2} E \left(\frac{dN}{dE}\right) dE$$

: “(integral) energy flux,” total energy detected over a photon energy range

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



Light curves

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

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

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

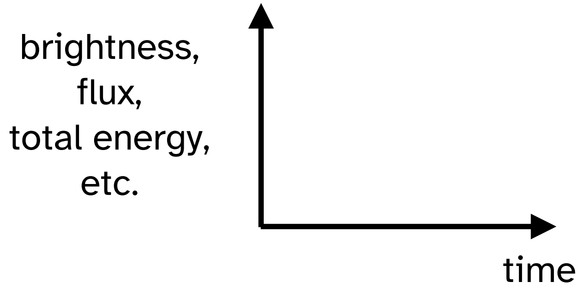
Or you can also simply plot the photon count rate over time

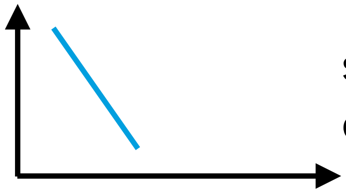
Does not require any additional assumptions — except for the implicit assumption that the detector sensitivity is not greatly changing during this time

Light curves

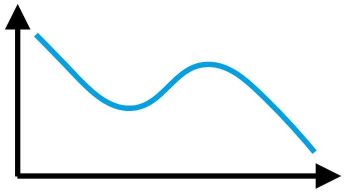
how much is emitted vs time

The lightcurve tells you about how the emission source is changing

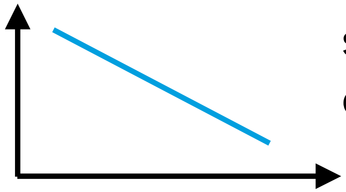




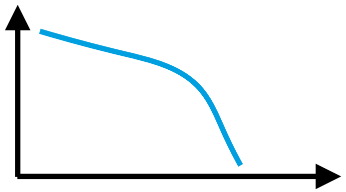
source is losing energy quickly



something has added additional energy into the system



source is losing energy slowly



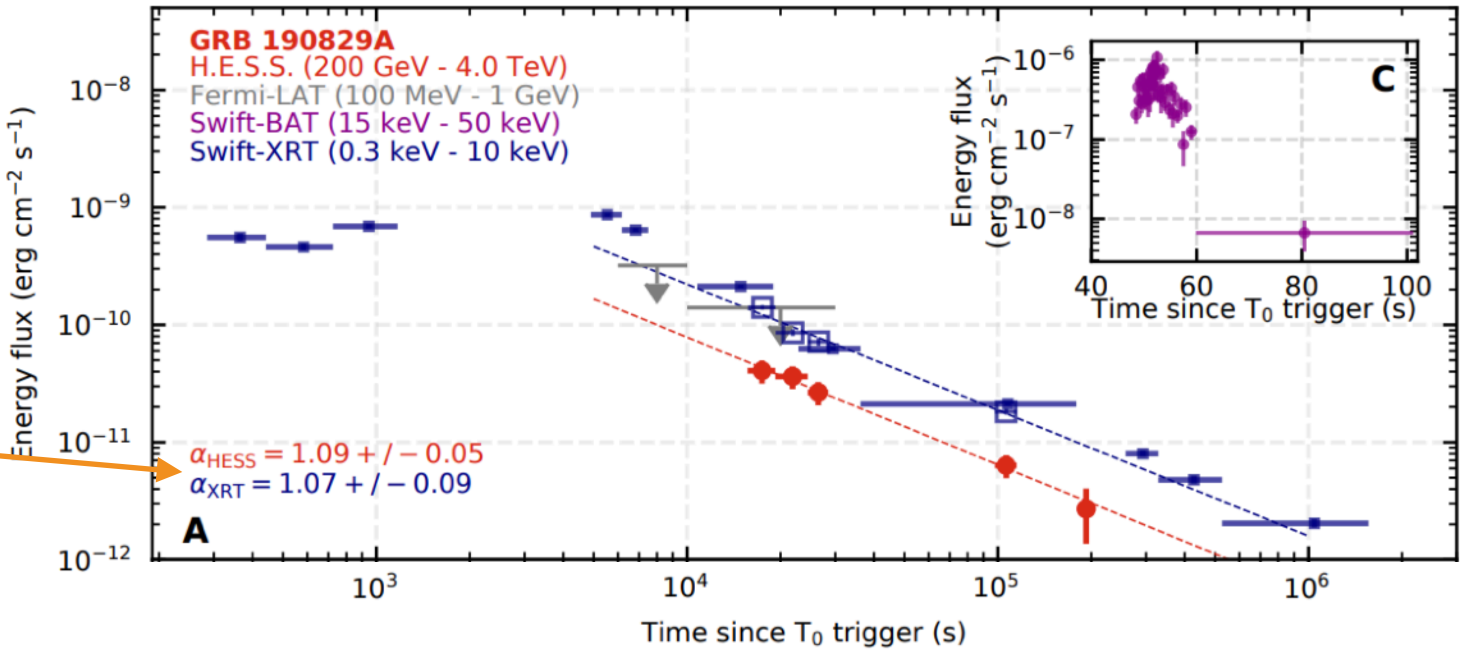
something that was providing energy is no longer doing so

What do we learn from gamma rays?

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)]

Multiwavelength spectra

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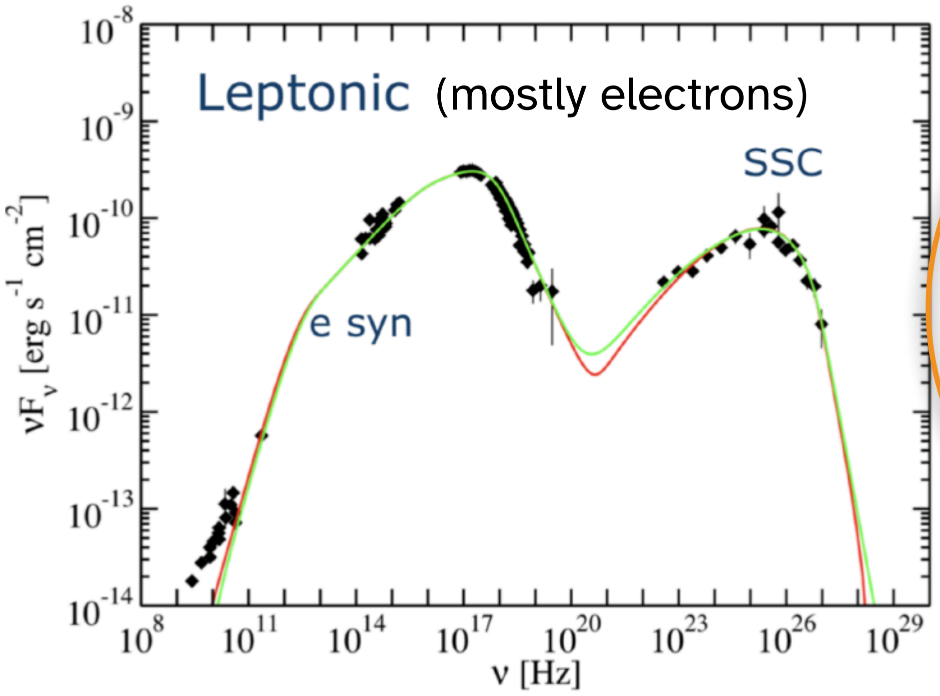
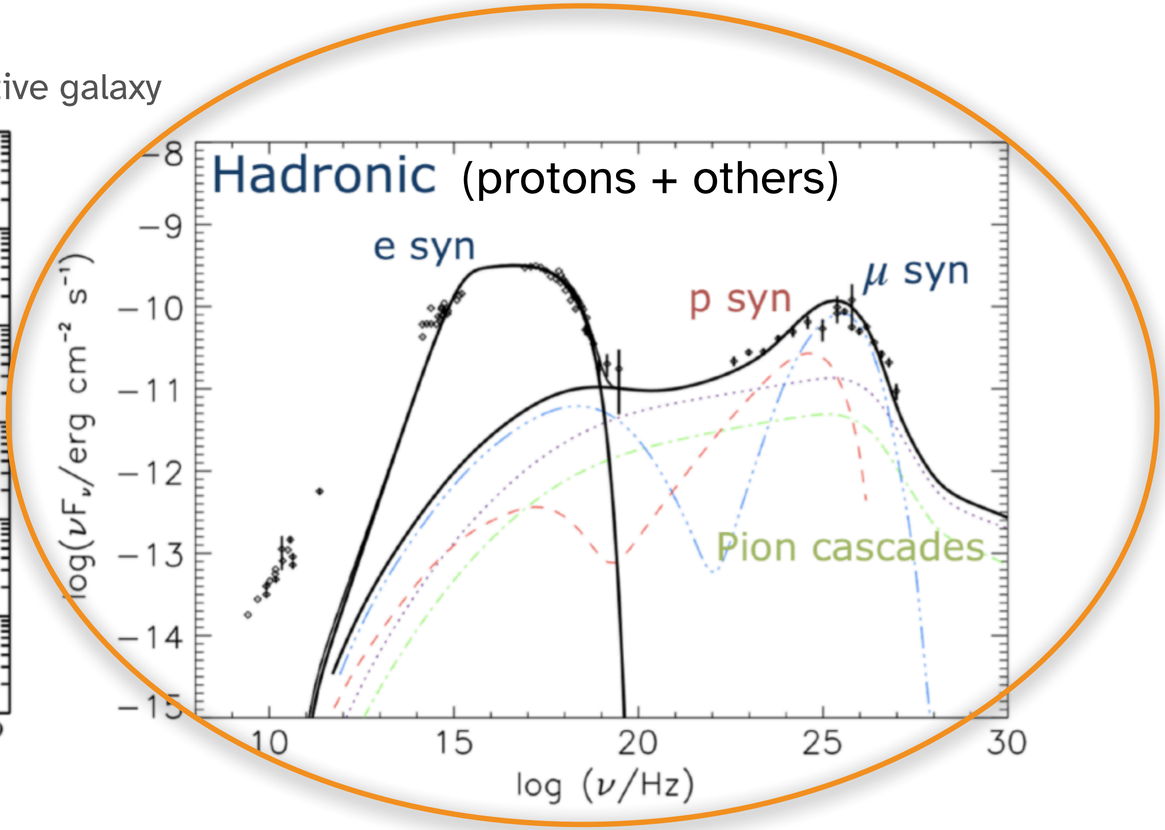
[M. Cerruti, TAUP 2019] Markarian 421, an active galaxy



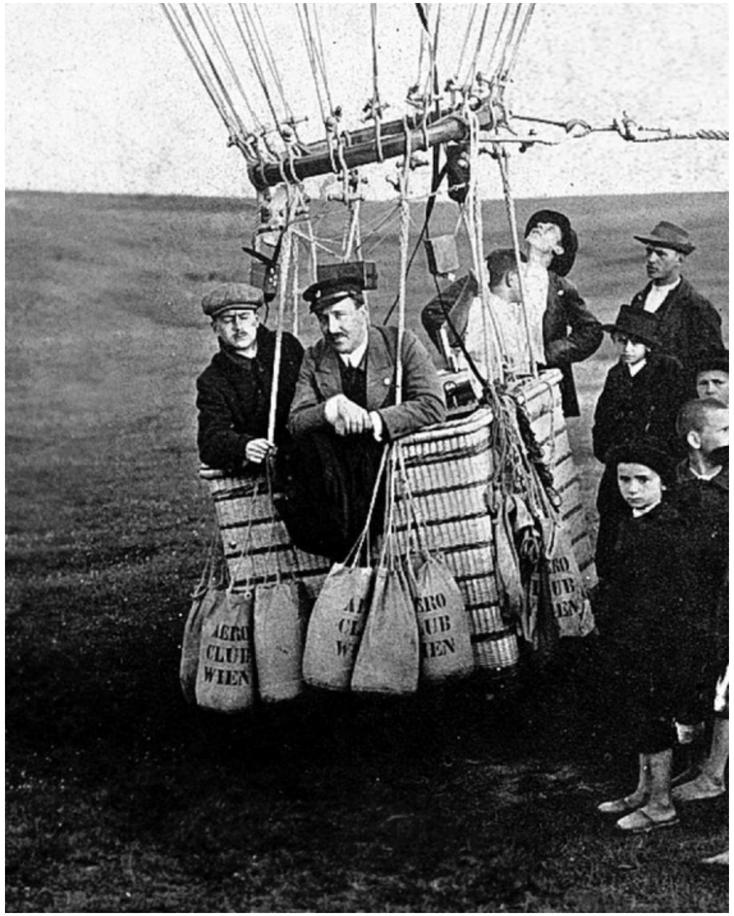


=> hadronic sources are sources of *cosmic rays*

ok great but what are cosmic rays

controversial: I kind of hate this term ...

Historical term, meaning: any kind of ionizing radiation from space



[Uni Wien]

In the 1900s, people started detecting ionizing radiation in the atmosphere

The rate did not decrease w/ altitude in the way that would be expected if the source of radiation was terrestrial

← From 1911 to 1913, Victor Hess made a series of balloon flights, and found that the amount of radiation increases at high altitudes

-> it is coming from space

The radiation was termed **cosmic rays**

Note: the actual story about the discovery of cosmic rays is more complex; see, e.g., [P. Carlson & A. de Angelis, EPJ H (2010)]

ok great but what are cosmic rays

controversial: I kind of hate this term …

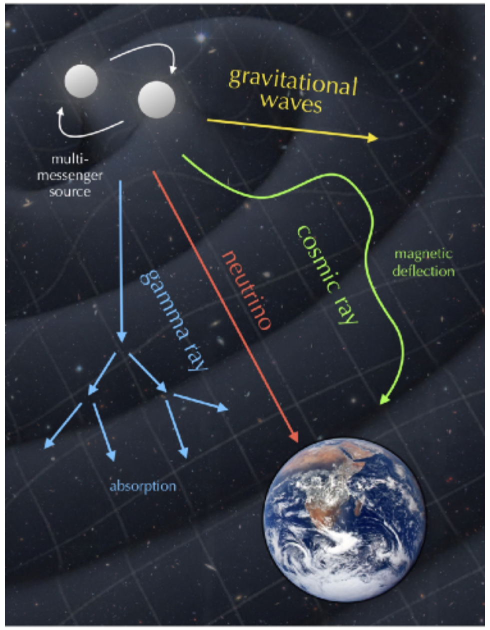
Historical term, meaning: any kind of ionizing radiation from space

nowadays we usually mean charged particles (protons, atomic nuclei, electrons/positrons)

but “cosmic ray” can also mean neutral particles + the secondary particles produced by the ones listed above

which in principle encompasses pretty much everything????   (╯°□°)╯︵ ┻━┻

Oftentimes we see some diagram like the following examples:

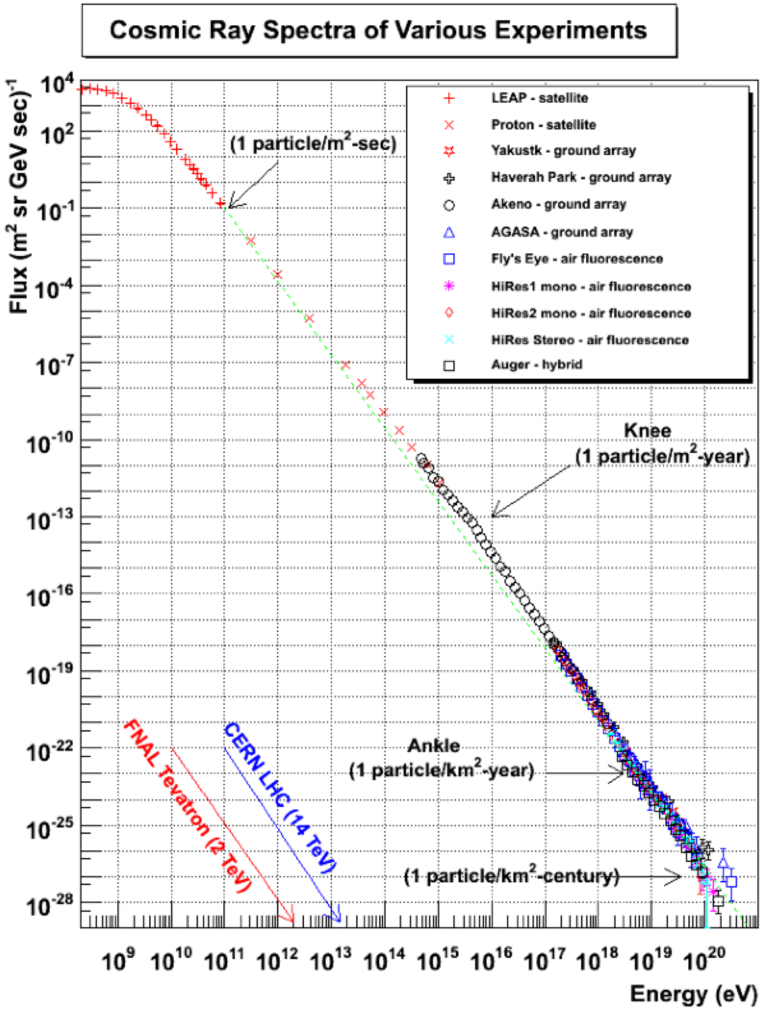


[Niels Bohr Institute]

so for astro purposes, most of the time we mean “charged particles”

Cosmic rays: Flux measured on Earth

Almost featureless spectrum over >11 orders of magnitude in particle energy



[W. F. Hanlon]

mostly

cosmic rays are charged particles -> deflected by magnetic fields

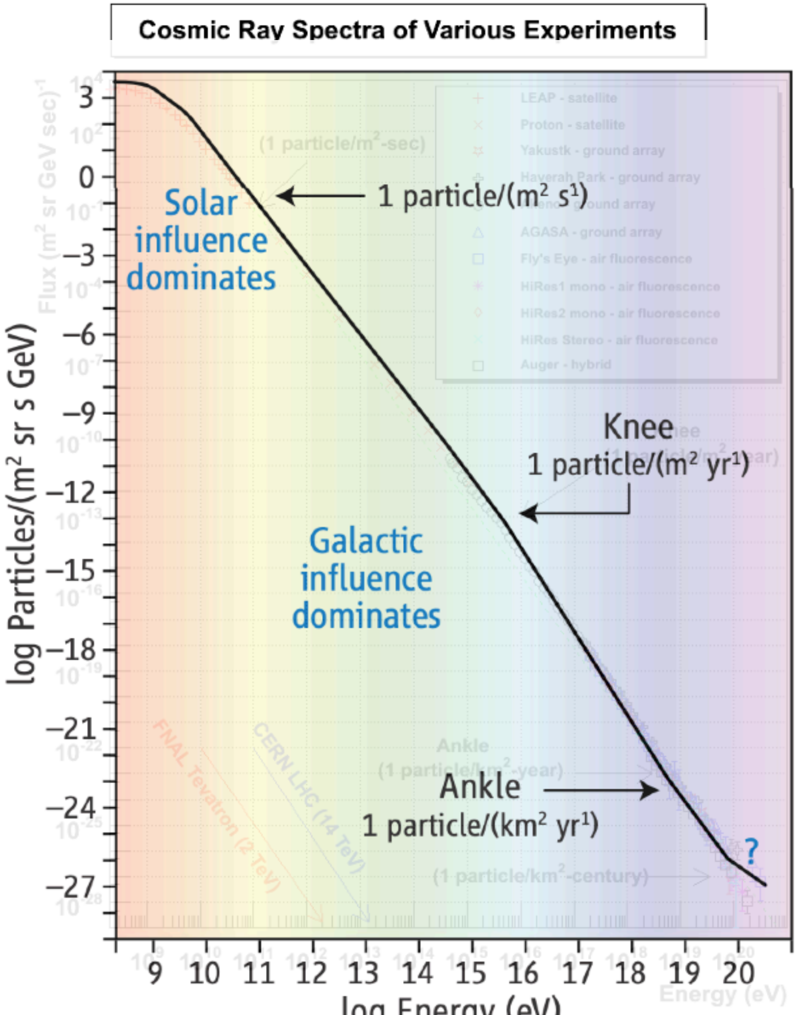
mostly nuclei, a few % electrons

89% protons,
10% He,
1% heavier

One of the oft-cited motivations in this field is "to find the origin of cosmic rays" or "to explain the cosmic-ray spectrum"

Cosmic rays: Flux measured on Earth

Almost featureless spectrum over >11 orders of magnitude in particle energy



[W. F. Hanlon]

[M. Duldig, Science 314 (2006)]

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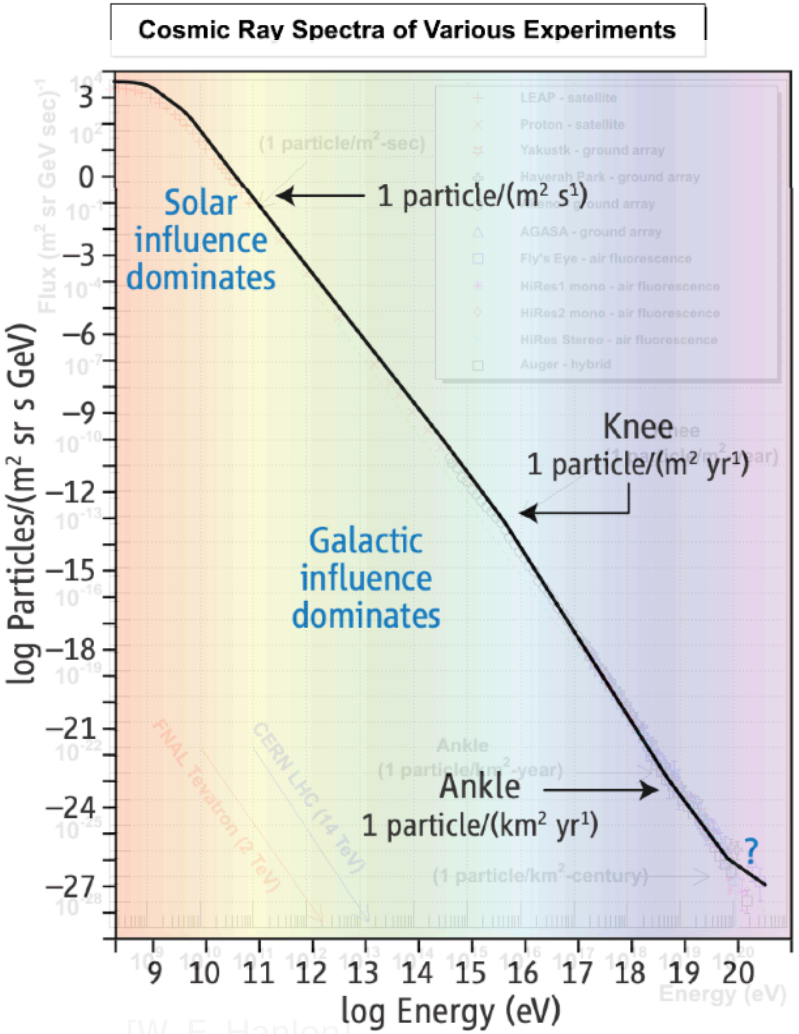

[W. F. Hanlon]

[M. Duldig, Science 314 (2006)]

mostly

cosmic rays are charged particles -> deflected by magnetic fields

they don't point back to their origins

-> we need (mostly) indirect methods of determining what is producing them

- Can this type of source accelerate particles to this energy?
- Is this type of source common enough to account for the cosmic rays?

From cosmic rays to gamma rays

$p + p \rightarrow p + p + \pi^0$

$p + p \rightarrow p + n + \pi^+$

$p + p \rightarrow p + p + \pi^+ + \pi^-$

$p + p \rightarrow$ etc.

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

From cosmic rays to gamma rays

$p + p \rightarrow p + p + \pi^0$

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$p + p \rightarrow$ etc.

$p + \gamma \rightarrow p + \pi^0$

$p + \gamma \rightarrow n + \pi^+$

$p + \gamma \rightarrow$ etc.

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

From cosmic rays to gamma rays

$p + p \rightarrow$
- $p + p + \pi^0 \longrightarrow \gamma + \gamma$
- $p + n + \pi^+$
- $p + p + \pi^+ + \pi^-$
- etc.

$p + \gamma \rightarrow$
- $p + \pi^0 \longrightarrow \gamma + \gamma$
- $n + \pi^+$
- etc.

π^0 decays in 10^{-16} s

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

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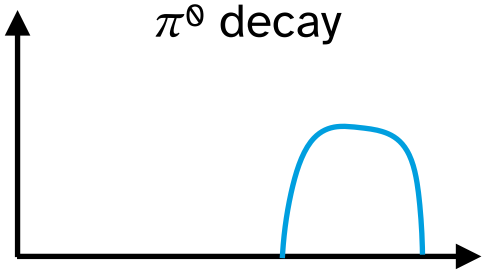


gamma rays can be produced by hadronic interactions, and the spectrum would be a characteristic “pion bump”

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

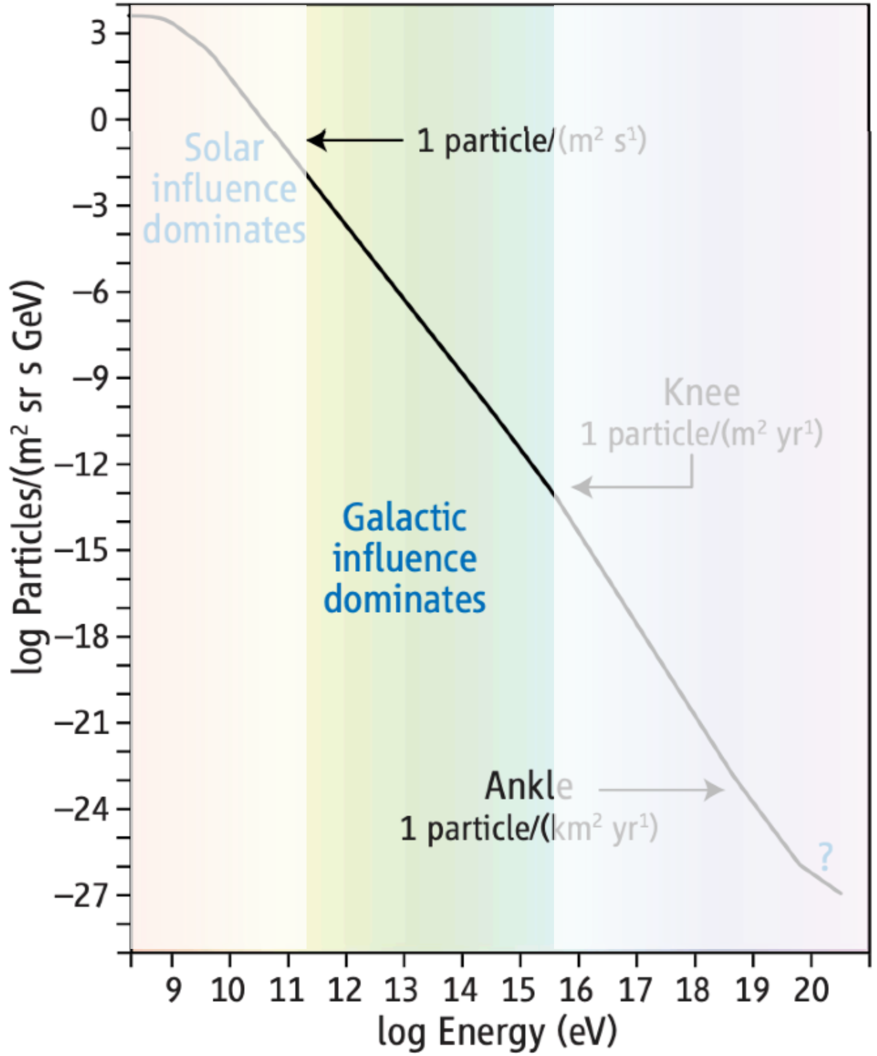
e.g., detect gamma rays with E_γ = 100 TeV

+ pion bump

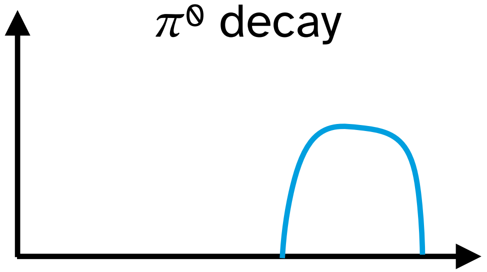
= source can produce cosmic rays with E_{CR} = 1 PeV

Sources of cosmic rays?

What gamma rays tell us about the cosmic-ray spectrum



[M. Duldig, Science 314 (2006)]



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"PeVatrons"

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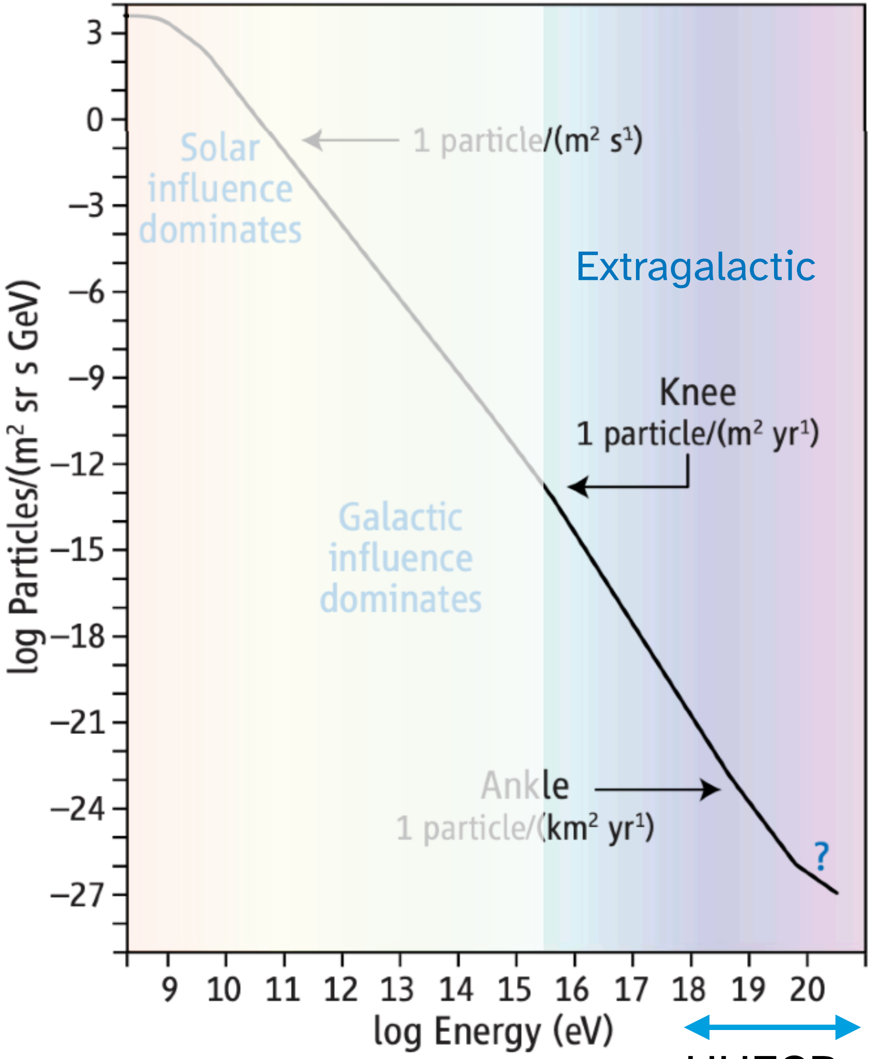


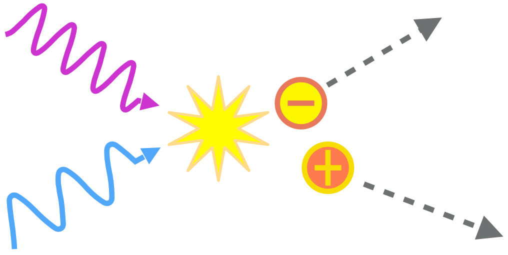
[M. Duldig, Science 314 (2006)]

UHECRs Ultra High-Energy Cosmic Ray

We are extremely unlikely to detect gamma rays at >PeV energies, especially from extragalactic sources

Extragalactic background light (EBL)

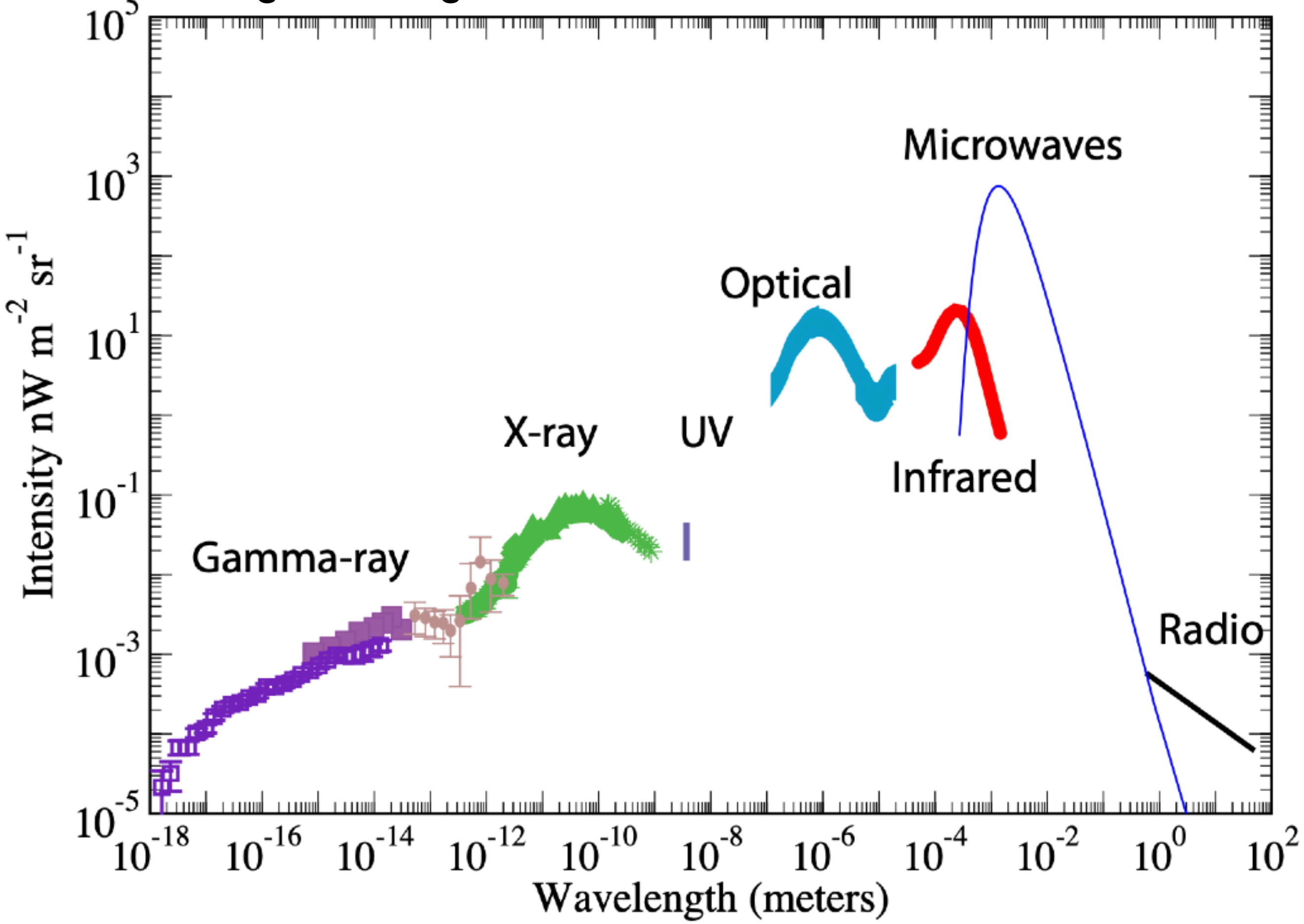
Gamma rays pair produce with other photons



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

Gamma rays ≳100 GeV pair produce with the optical/infrared background (from star formation, active galaxies)

Background light in the Universe



[A. Cooray, R. Soc. Open Sci., Vol. 3 (2016)]

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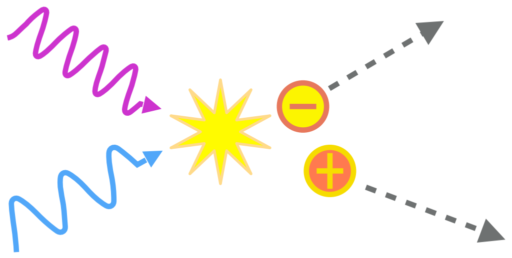
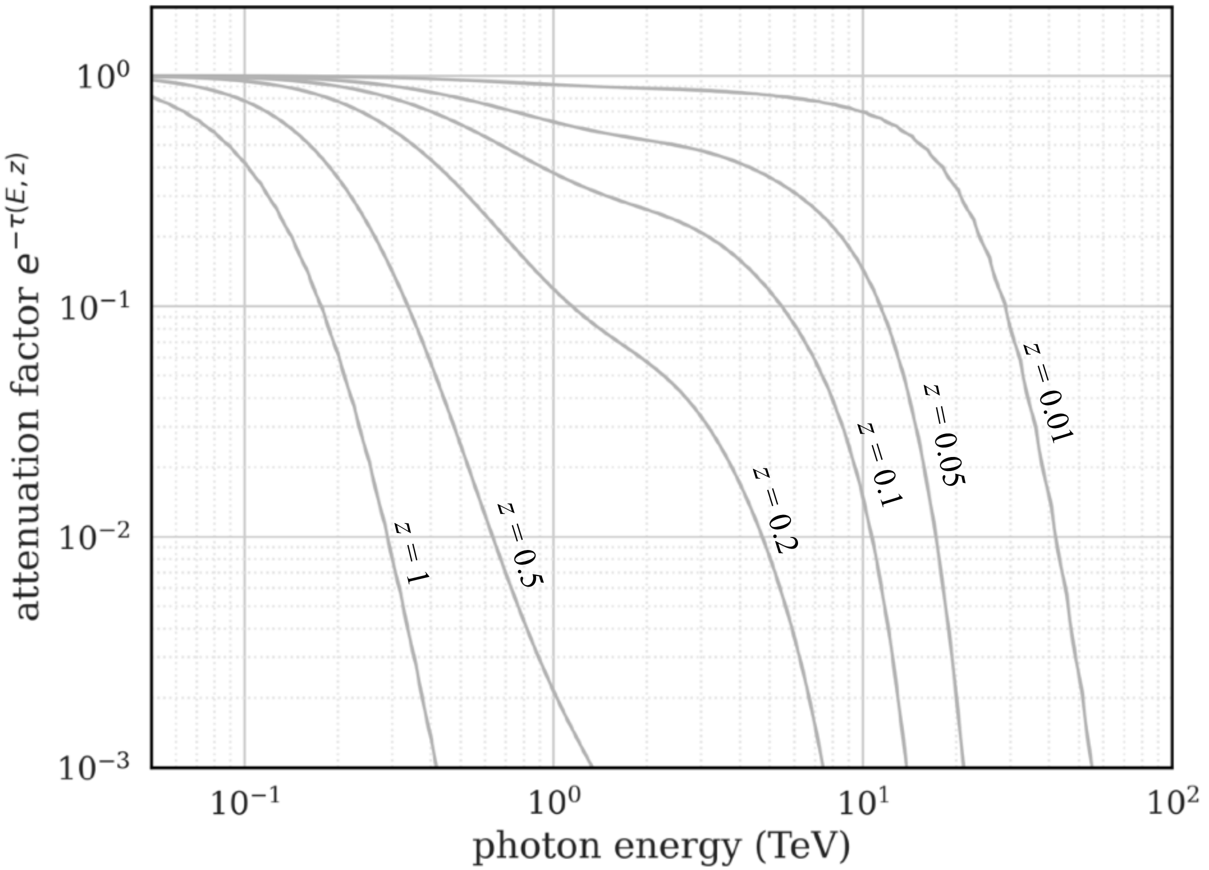


$\gamma + \gamma \longrightarrow e^{+} + e^{-}$

Gamma rays ≳100 GeV pair produce with the optical/infrared background (from star formation, active galaxies)

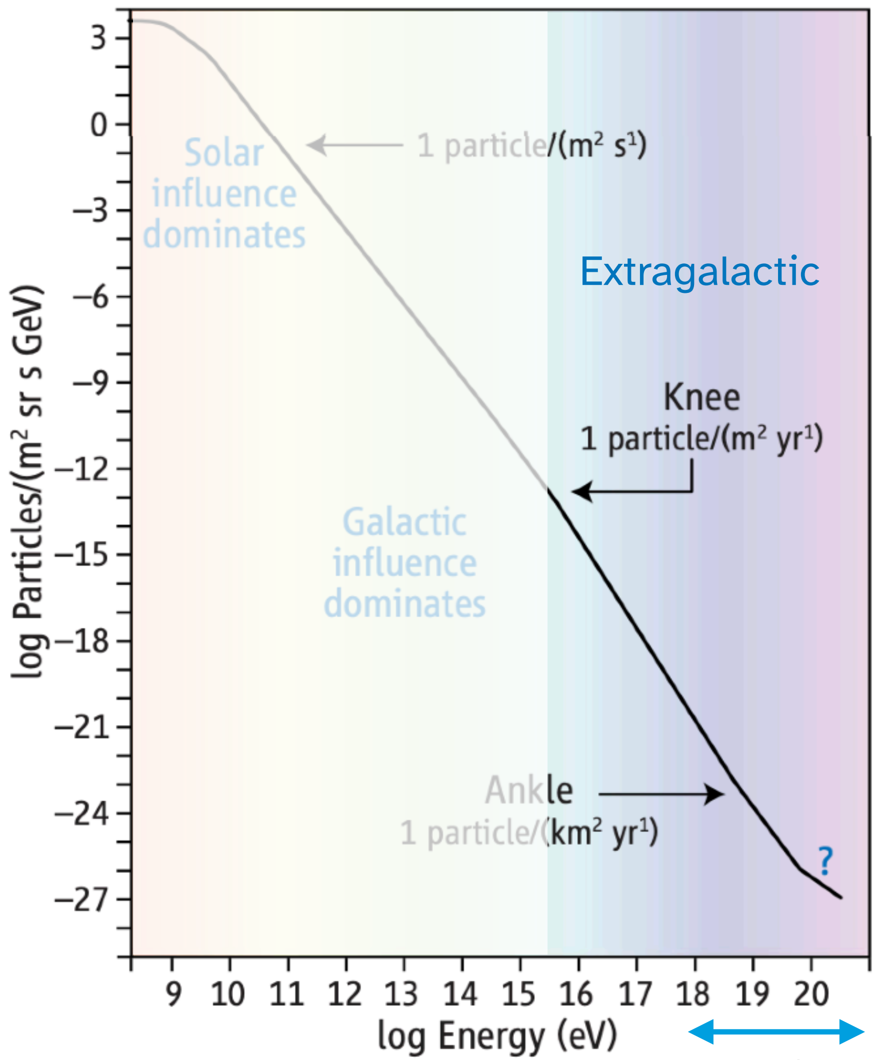
Photons with higher energies are increasingly absorbed before reaching us

EBL model: A. Saldana-Lopez et al., MNRAS, 507 (2021)



Sources of cosmic rays?

The connection to neutrinos



[M. Duldig, Science 314 (2006)]

UHECRs Ultra High-Energy Cosmic Ray

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High-energy neutrinos are a better tracer of UHECR sources

Cosmic rays: Sources

The connection to neutrinos

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Cosmic rays: Sources

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$p + p \rightarrow$
- $p + p + \pi^0 \rightarrow \gamma + \gamma$
- $p + n + \pi^+ \rightarrow \mu^+ + \nu_\mu$
  - $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$
- $p + p + \pi^+ + \pi^-$
  - $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
    - $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$
- etc.

$p + \gamma \rightarrow$
- $p + \pi^0 \rightarrow \gamma + \gamma$
- $n + \pi^+ \rightarrow \mu^+ + \nu_\mu$
  - $\mu^+ \rightarrow e^+ + \nu_\mu + \nu_e$
- etc.

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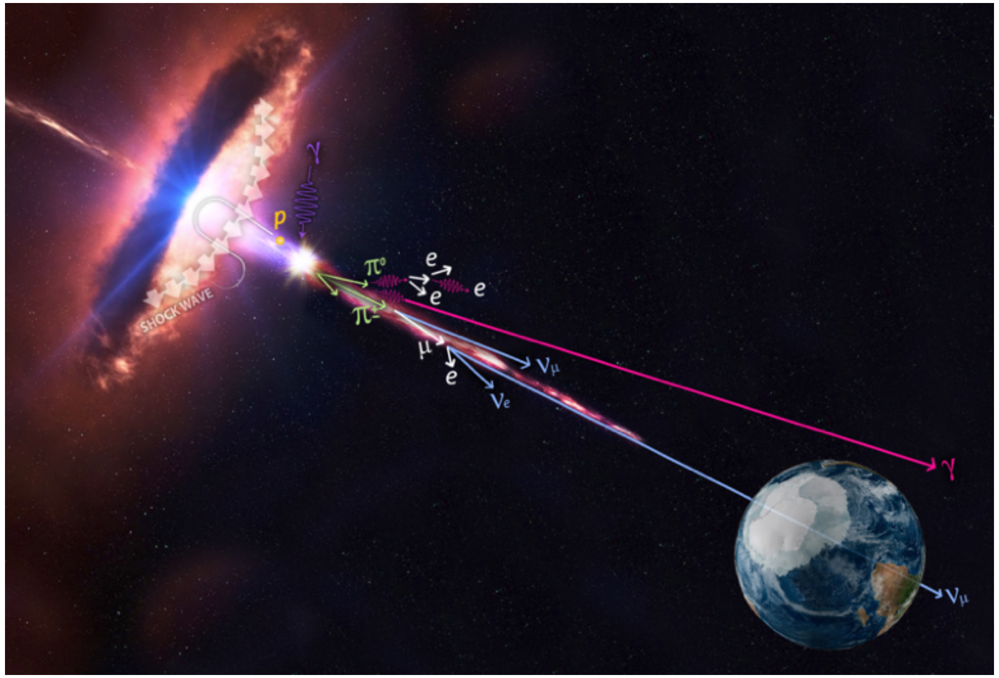
Gamma-ray sources are multimessenger sources

Neutrinos from gamma-ray sources



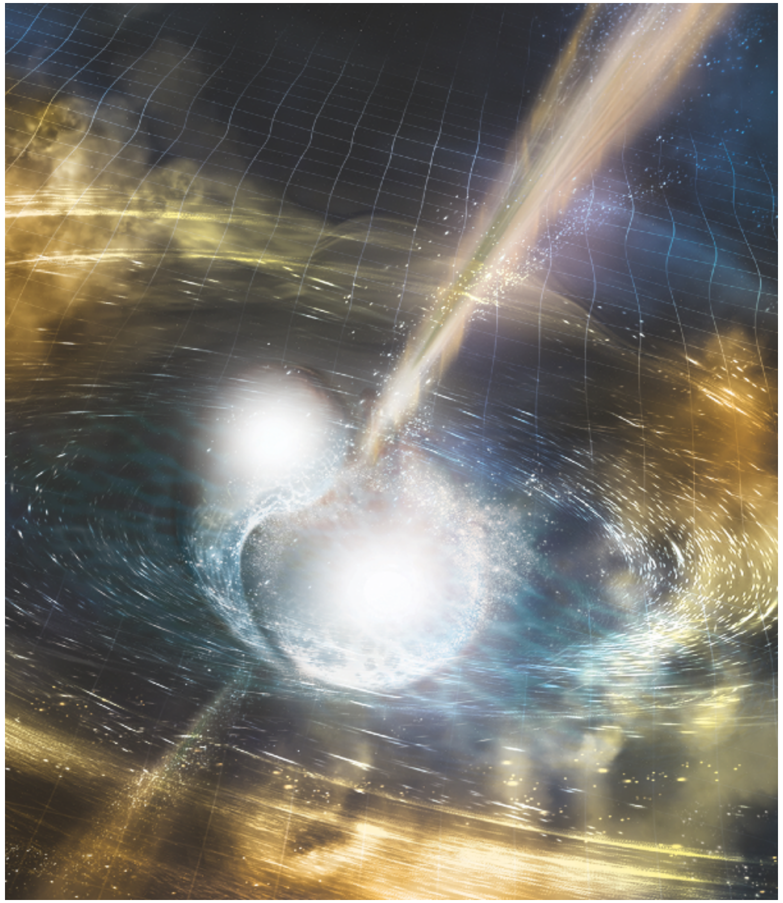
[Roen Kelly/IceCube/NASA]

IceCube has found some neutrino events and hotspots that seem to be correlated with blazars (active galaxies w jets pointed at us)

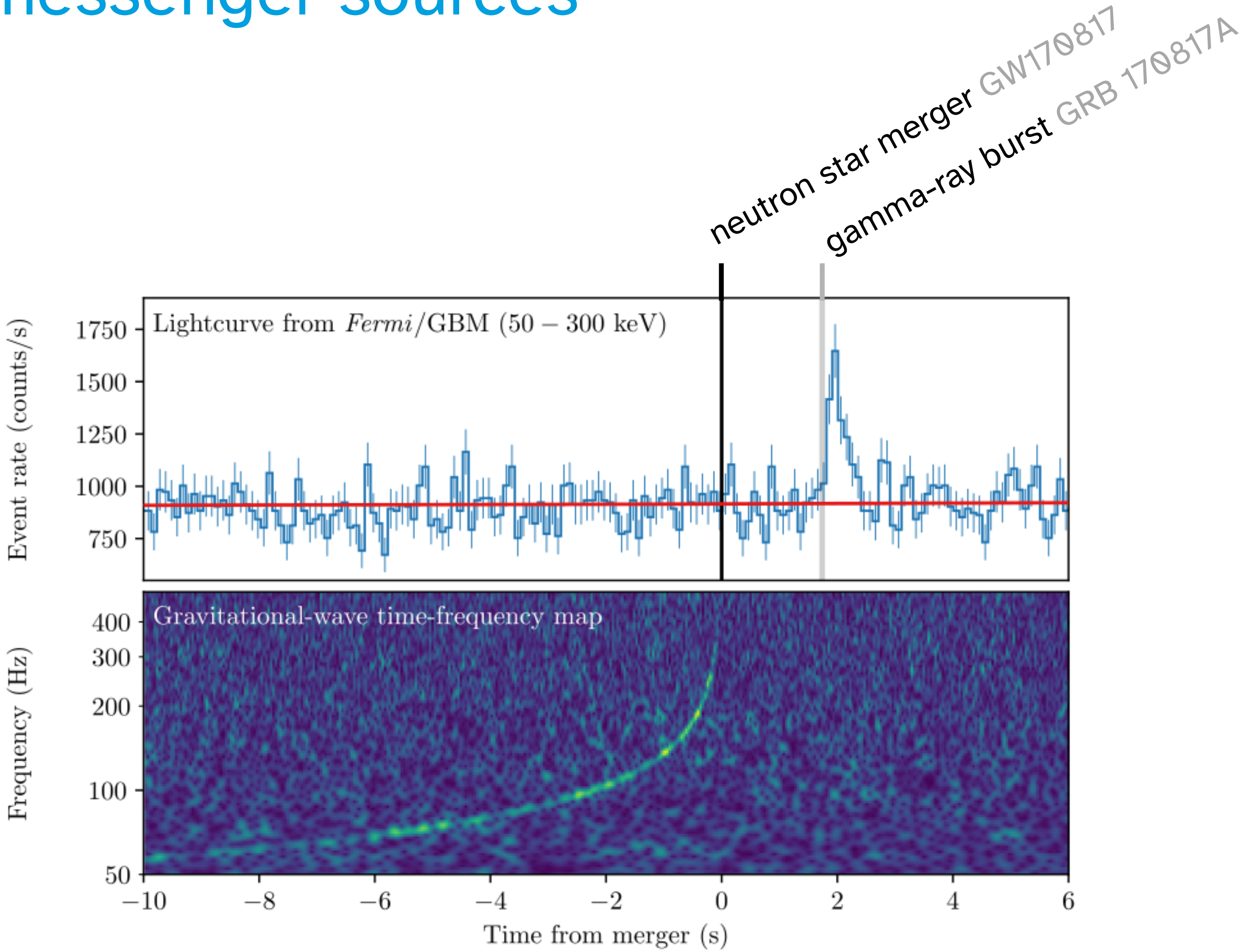
You might hear more about this in Walter’s lectures. If not, you should ask your friendly local neutrino astrophysicist

Gamma-ray sources are multimessenger sources

Gravitational waves from gamma-ray sources



[NSF/LIGO/Sonoma State University/A. Simonnet]



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

(we'll discuss this a bit on day 3)