ASTROPHYSICS DATA CAMP
SHAPING A WORLD CLASS UNIVERSITY

Introduction to gamma-ray astronomy with a focus on Active Galactic Nuclei

PADOVA 25.09.2023

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UNIVERSITÀ DEGLI STUDI DI PADOVA

Few words about myself

- I am a researcher at the **Physics and Astronomy department** of the Padova U.
- Main field of research: **gamma-ray blazar** emission in a **multi-wavelength** context
- Active outreacher
- Experiments: **MAGIC, CTA, SWGO**
- Contact: elisa.prandini@unipd.it

Welcome!

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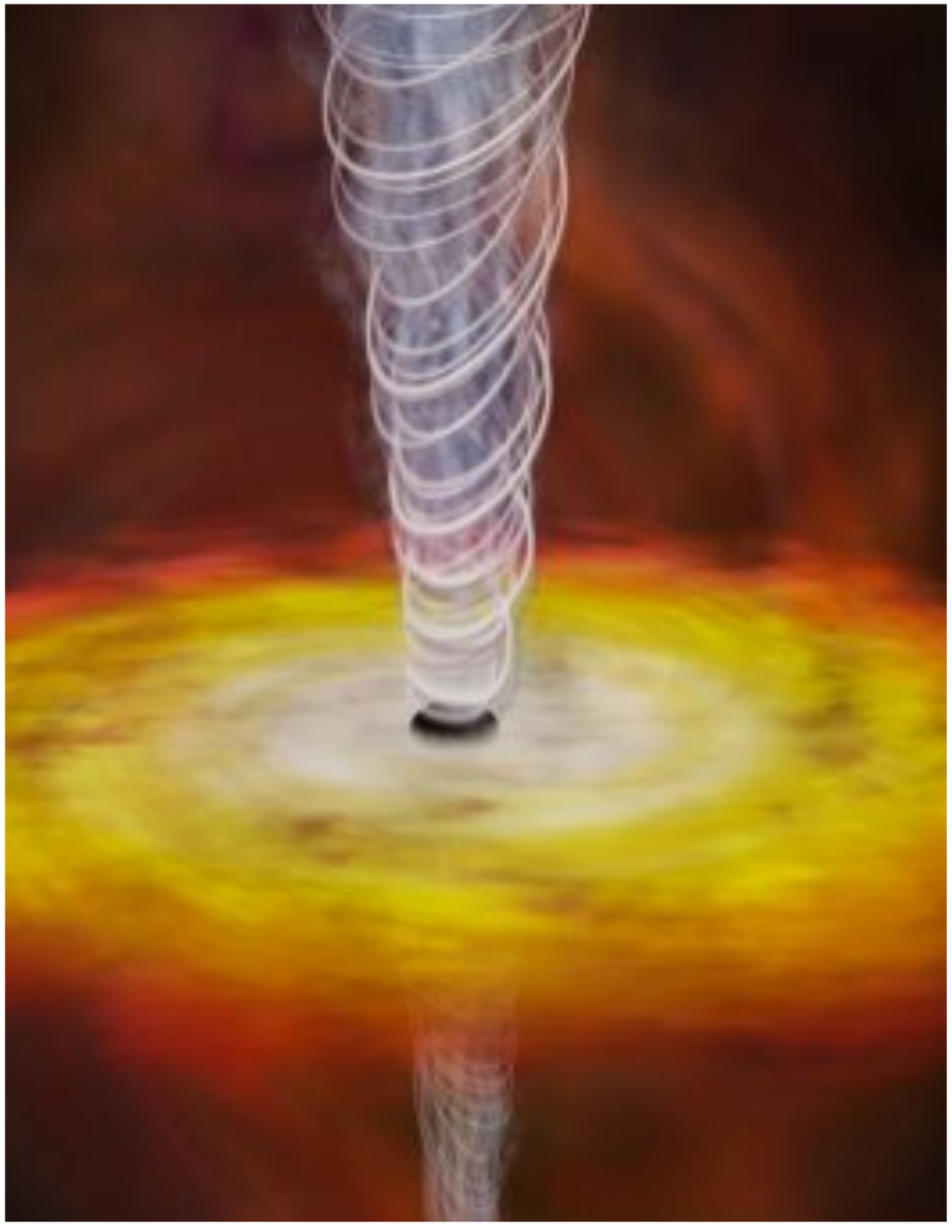
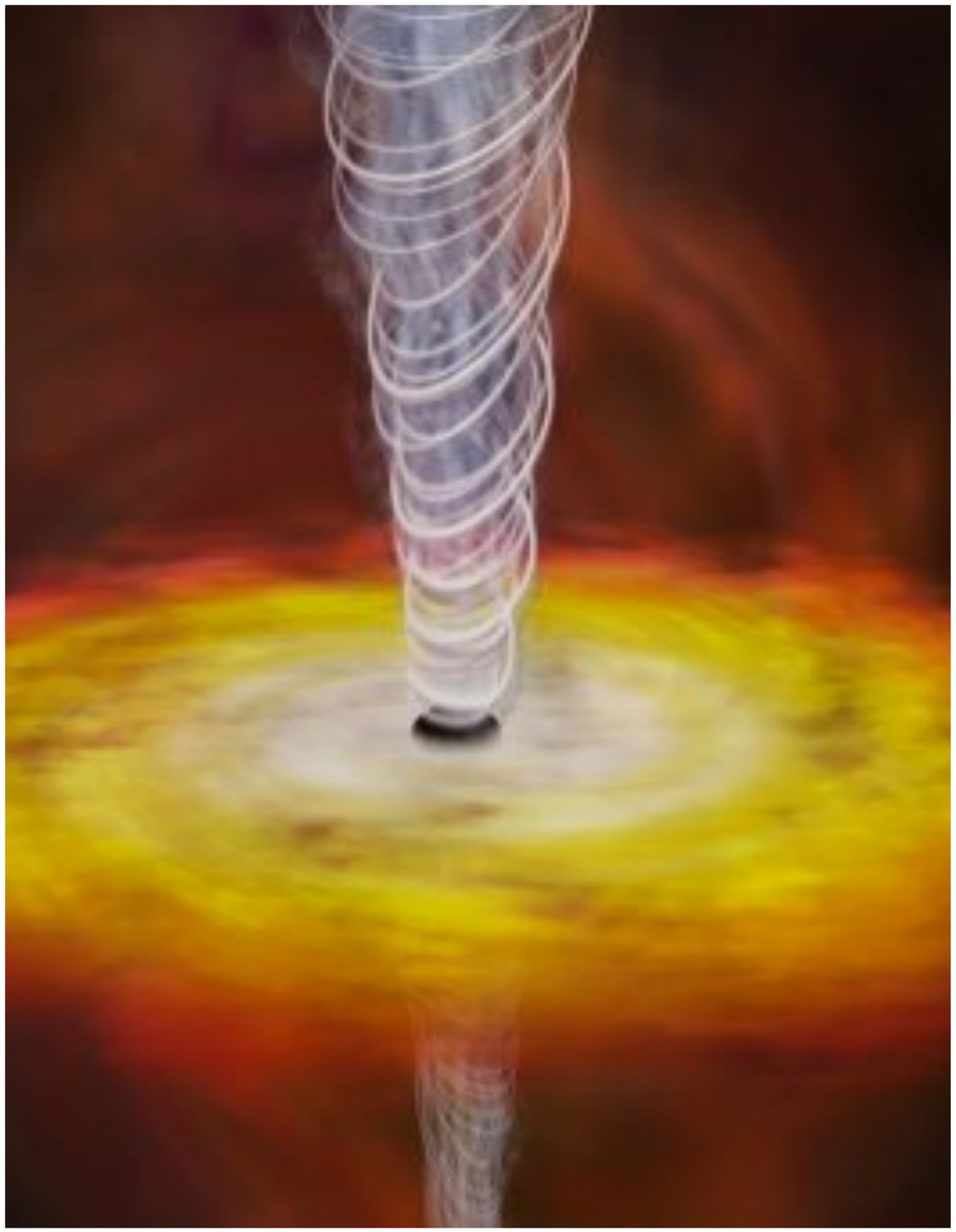
Event code
RLYHLJ

Daily schedule



- **Lectures**
- **Practical** sessions in small groups
- **Article** reading in small groups

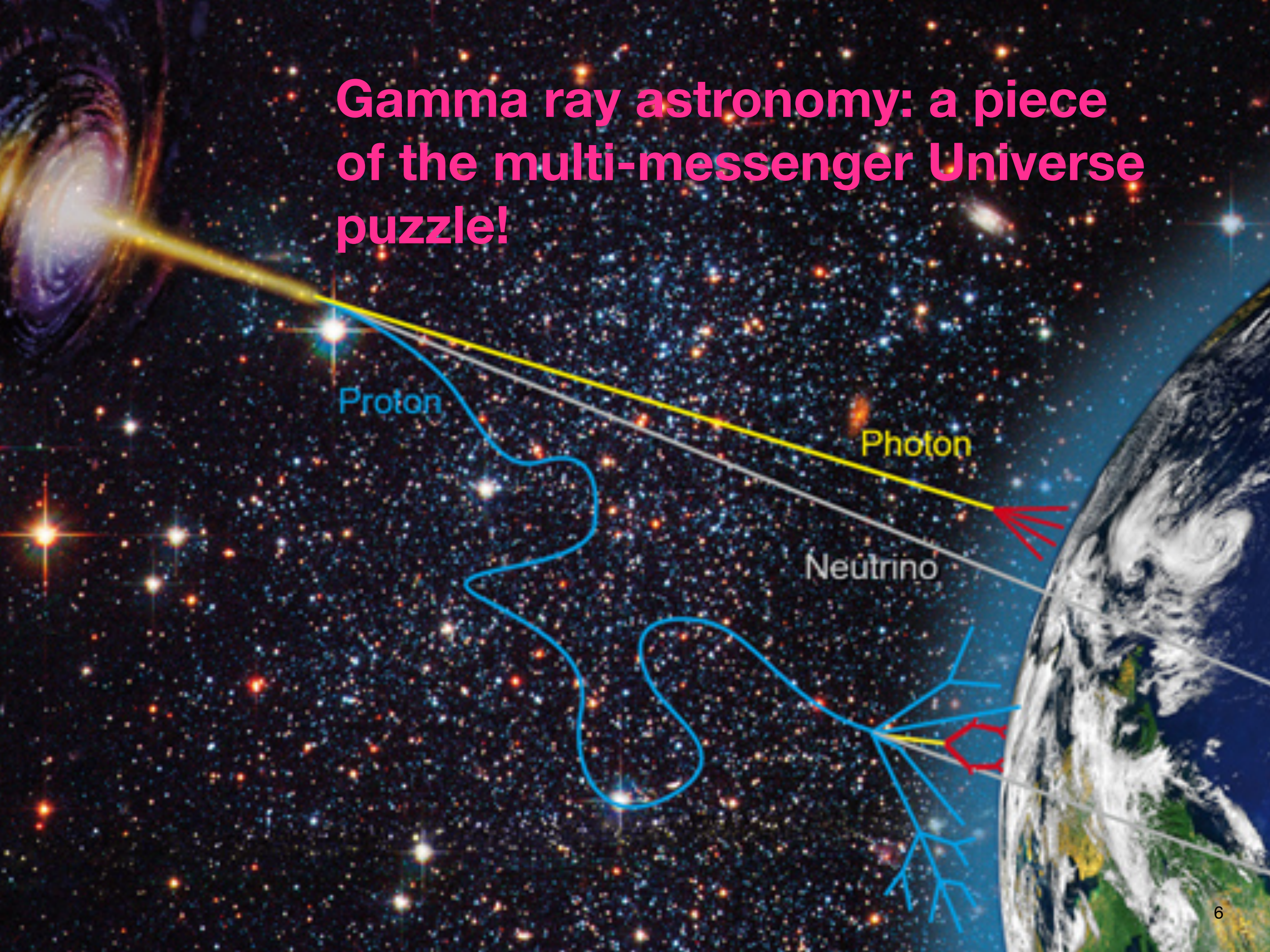
About this lecture



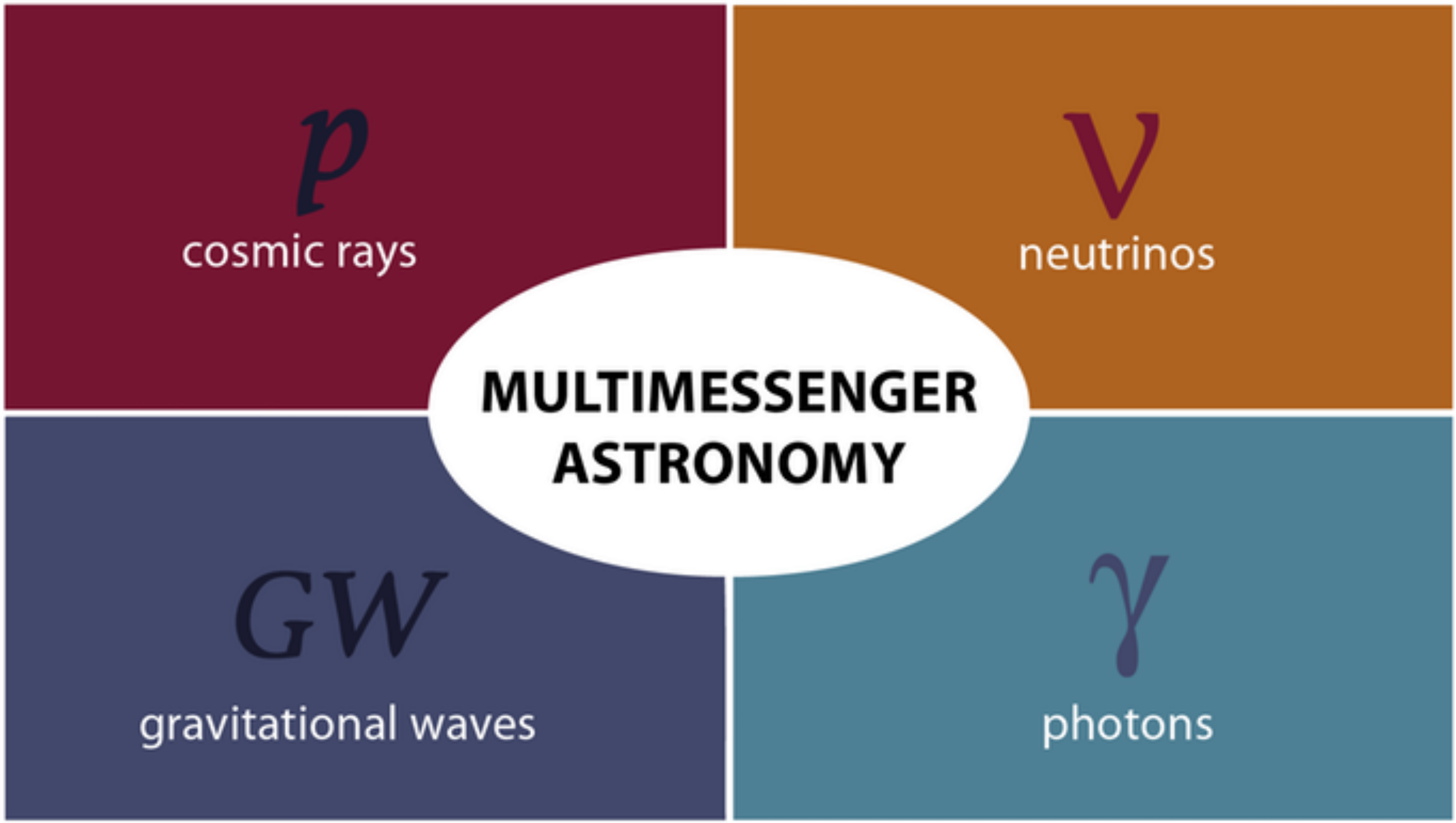
Introduction to gamma-ray astronomy

This will be also an opportunity to introduce many concepts that you will hear this week. Please interrupt me for questions!

Gamma ray astronomy: a piece of the multi-messenger Universe puzzle!

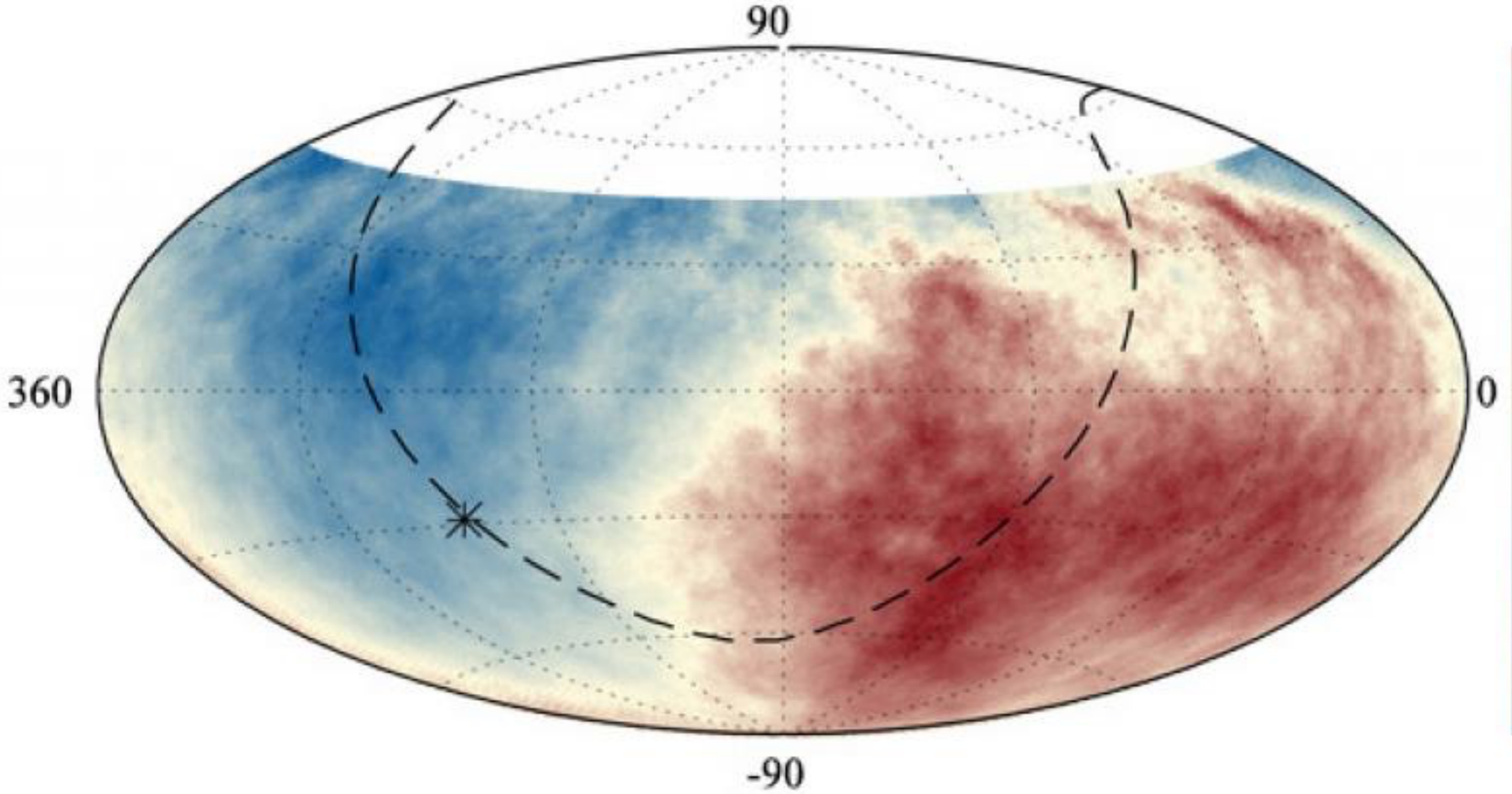


Today we focus on cosmic rays and photons!



Why do we need multi-messengers?

- Main reason: we do not have a *perfect messenger*
  - **Cosmic Rays:** are deflected in their path
  - **Photons**: are absorbed in their path
  - **Neutrinos:** very difficult to measure
  - **Gravitational Waves:** detectable only for a small class of objects



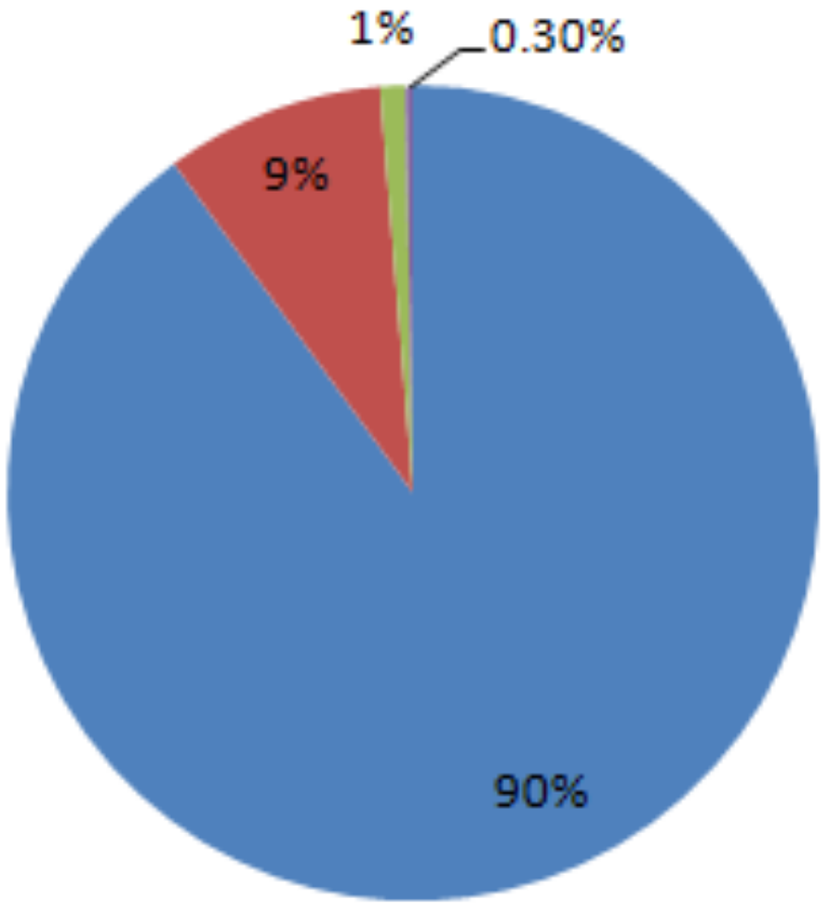
The cosmic-ray Universe

Messenger 1: Cosmic Ray

Cosmic Rays for non-physicists:
a powerful and dangerous weapon

What are cosmic rays?

- Cosmic rays are energetic particles impinging the Earth atmosphere
  - ~99% are **ionised atoms** (H, He, Fe nuclei)
    - **90% protons**
    - ~9% heavier nuclei
  - ~ 1% **electrons**
  - <1% **antiparticles** (anti-proton and positron)



Paper #1 (measurement of cosmic rays)

Being mostly **charged particles** they are **deflected** by magnetic fields and cannot point to their generator (i.e. the astrophysical source)!

When a charged cosmic ray enters the atmosphere…

proton

other elementary particles

other elementary particles

MUONS

Cosmic Rays: detection and first studies

- **Beginning of 20th century** - electroscopes were found to discharge slowly even in the absence of radioactive matter

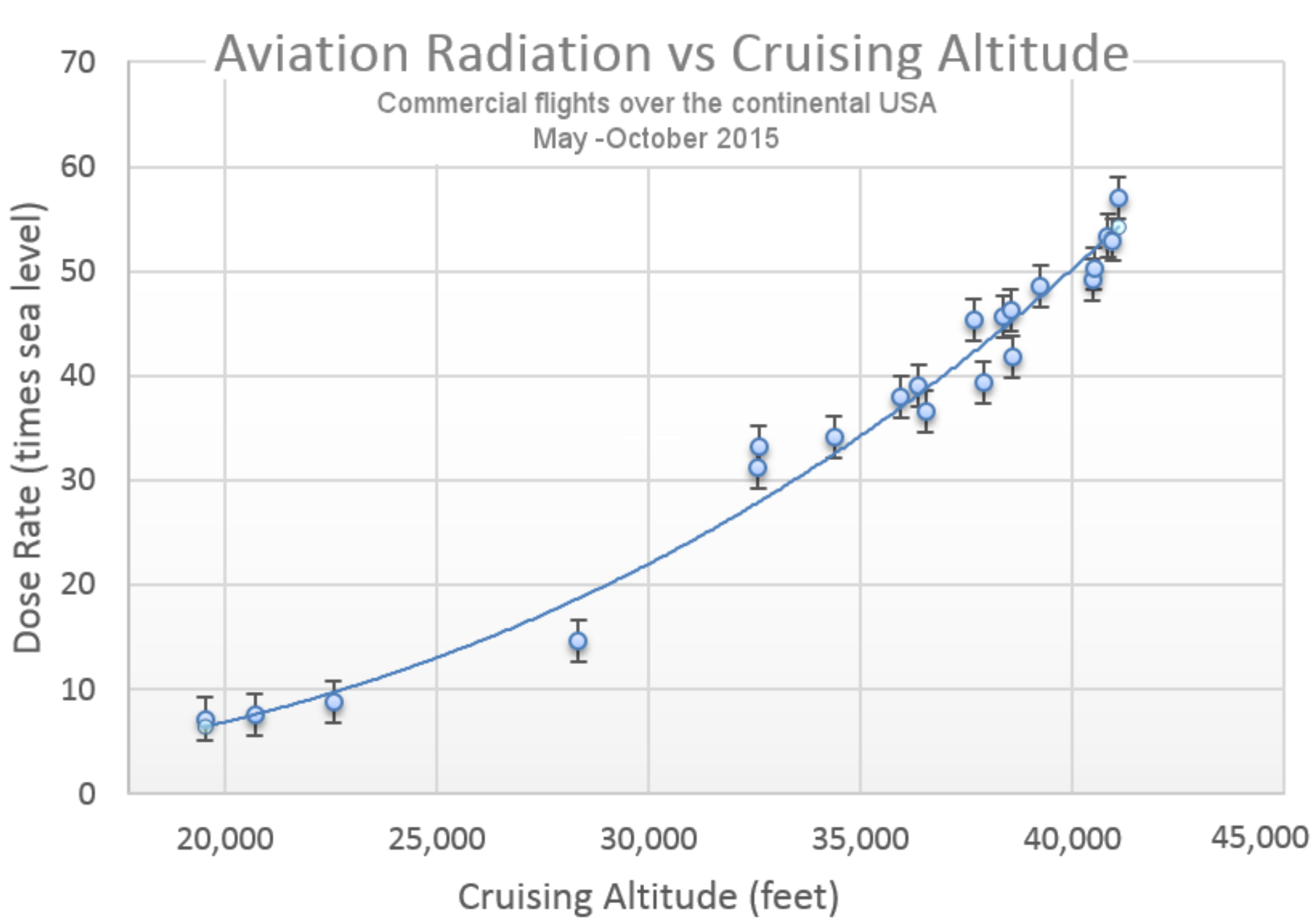
- **1909** - Father Wulf: measure the ionisation rate with increasing altitude (**Eiffel tower**)

- **1911** - Domenico Pacini: same measurement but underwater (**lake and sea**)

- **1912** - Victor Hess measures radioactivity in a balloon flight and finds that radiation levels increase with altitude -> these particle comes from outside Earth! (Nobel prize)

- **from 1920 to 1950** - Identification and discovery of new particles. Actors: Ernest Rutherford, Robert Millikan, Jacob Clay, Bruno Rossi, Pierre Auger…

Radiation on Earth from **secondary** cosmic rays

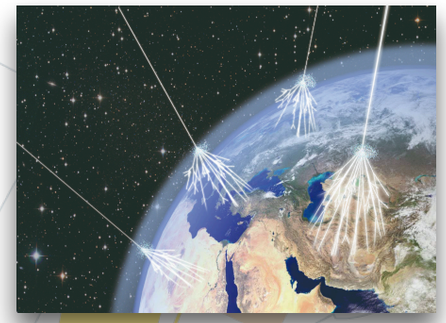


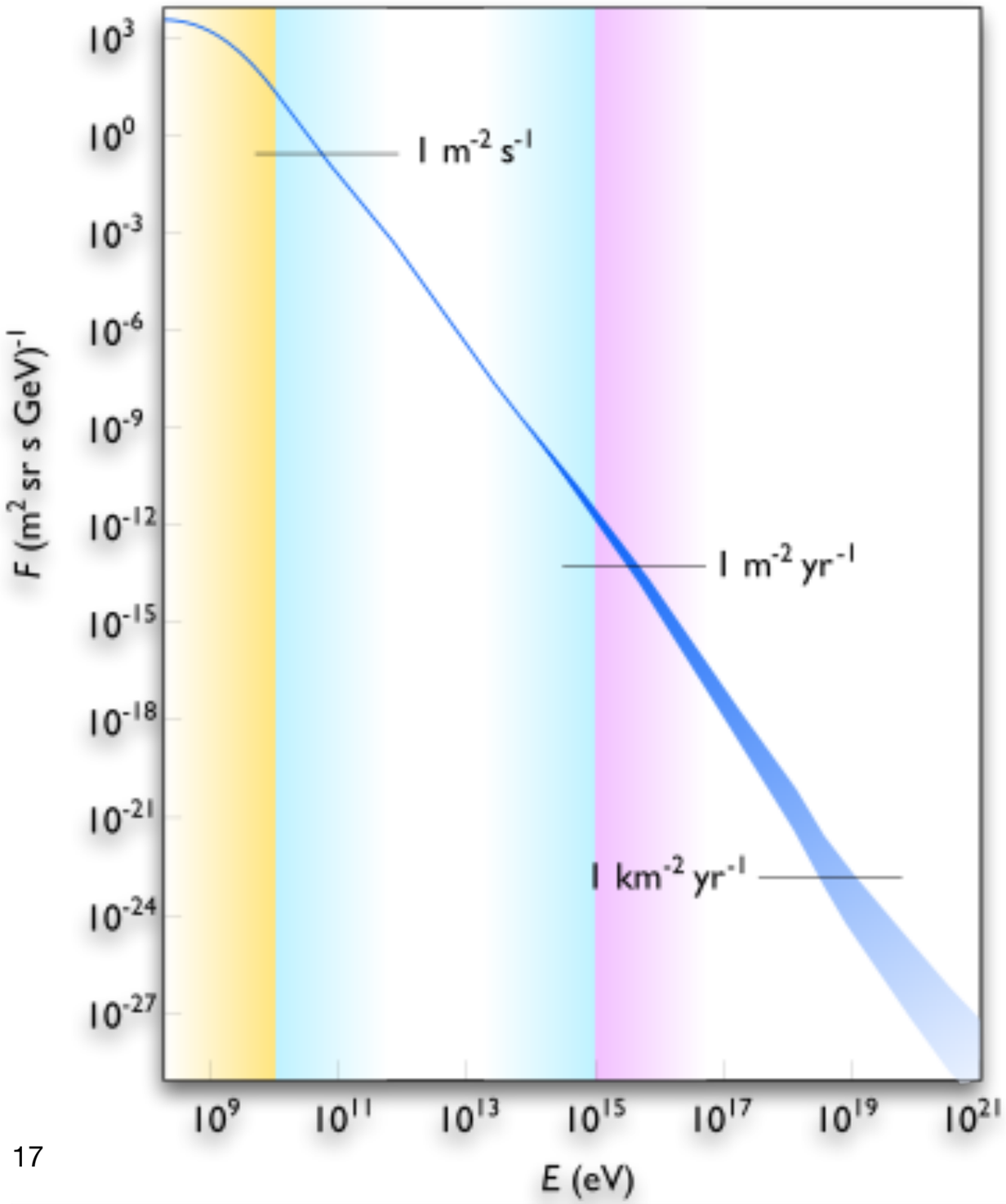
Radiation from **primary** cosmic rays

- Strongly affects **space-born** instrumentation

- It is one of the problems that we have to face when planning a human travel to **Mars**

The **spectrum** of (primary) cosmic ray

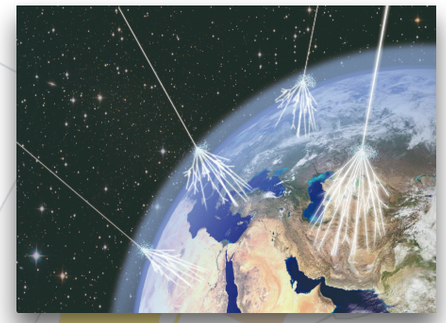


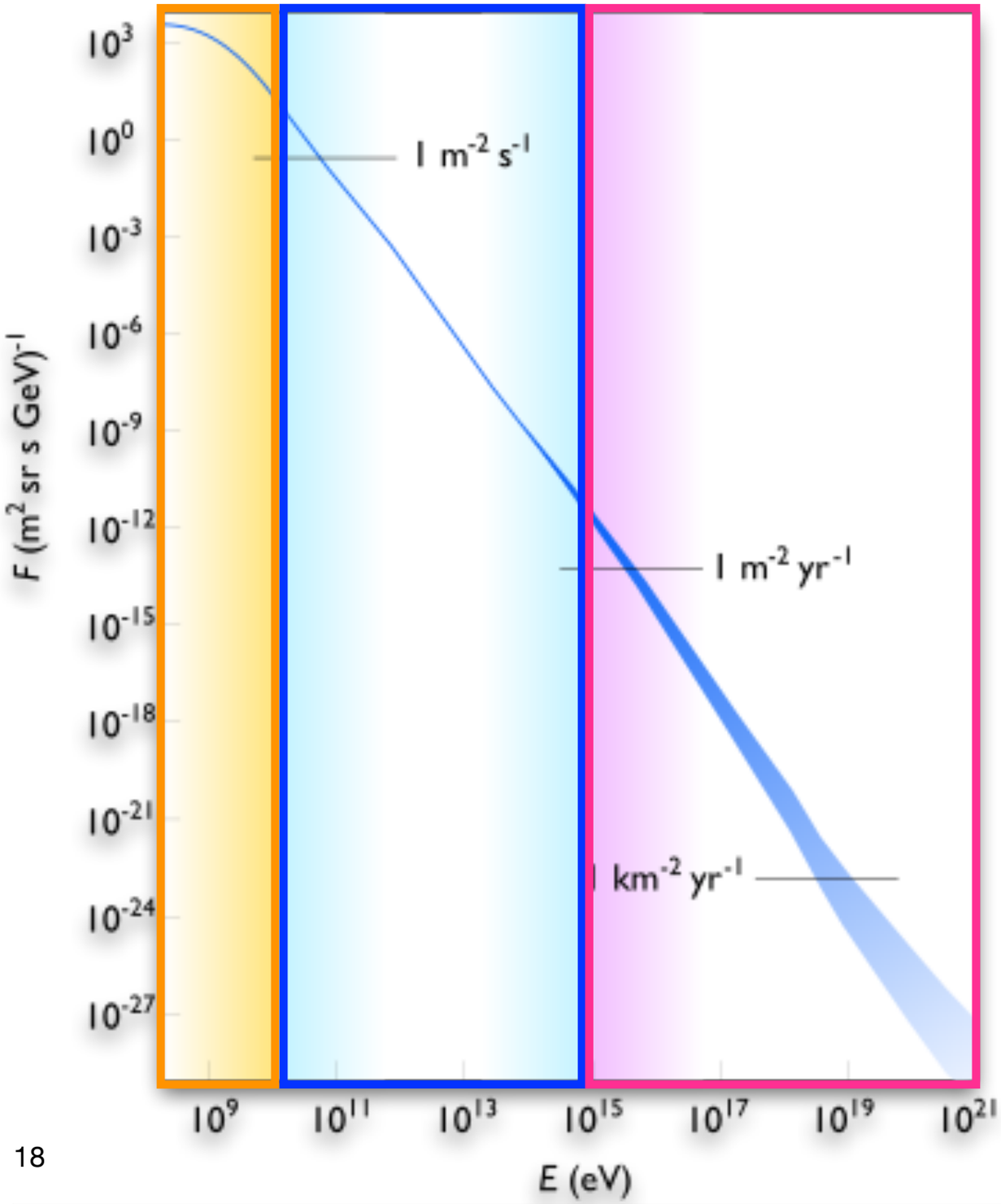


- Spectrum is a plot correlating **photon flux density** F(y) with the **energy** E(x)
- F = dN / (dA dt dE dΩ)
- **Spectrum**: how many particles per area, energy, time, and solid angle as a function of energy
- The cosmic ray spectrum is approximately a **power law: $F = F_0 \times E^{-\Gamma}$**

Why in the plot the spectrum follows approximately a straight line?

The **spectrum** of (primary) cosmic ray





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Thee regimes:

low energies

medium energies

high energies

Astro-particle physics and cosmic rays

- Comic rays are the **most energetic particles** of the Universe (reaching an energy much larger that that of particle accelerators, e.g. CERN!)

- **Astroparticle physics** is the study of this cosmic radiation with the purpose of investigating the physical condition of the emitting region, the emission processes, and the propagation:

  - **Strong magnetic fields**
  - **Strong gravity**
  - **Explosions** Paper #2 (gamma ray burst)
  - **Acceleration in shock waves propagating in the medium**
  - **Exotic physics** Paper #3 (dark matter)
    Paper #4 (physics beyond the standard model)

Where are cosmic rays coming from?

Where are cosmic rays coming from?

The Sun

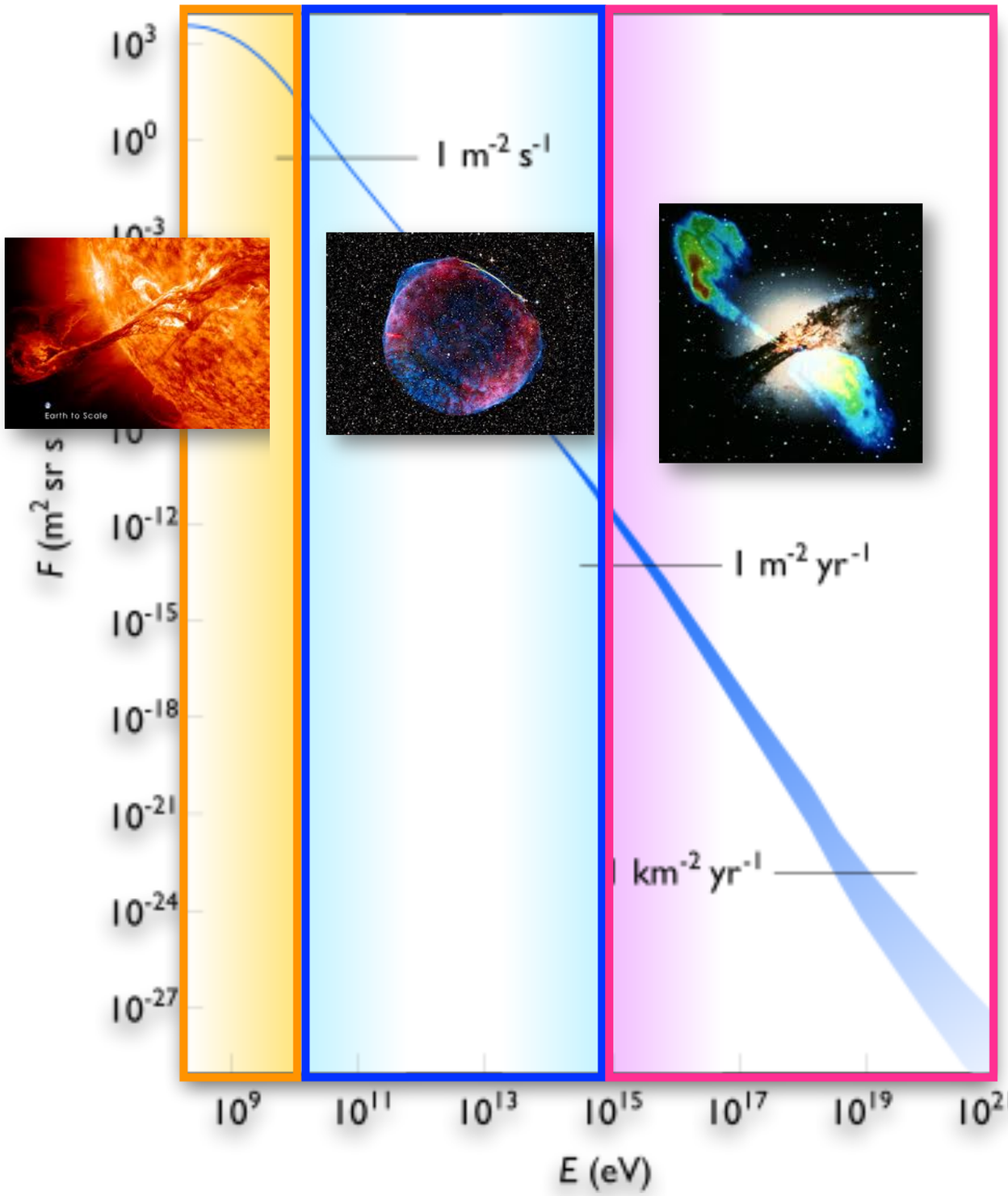
From our Galaxy (*galactic*):

- supernova explosions
- supernova remnants
- pulsar
- microquasars

From outside our galaxy (*extragalactic*):

- **active galaxies**
- gamma-ray burst
- cluster of galaxies
- starburst galaxies

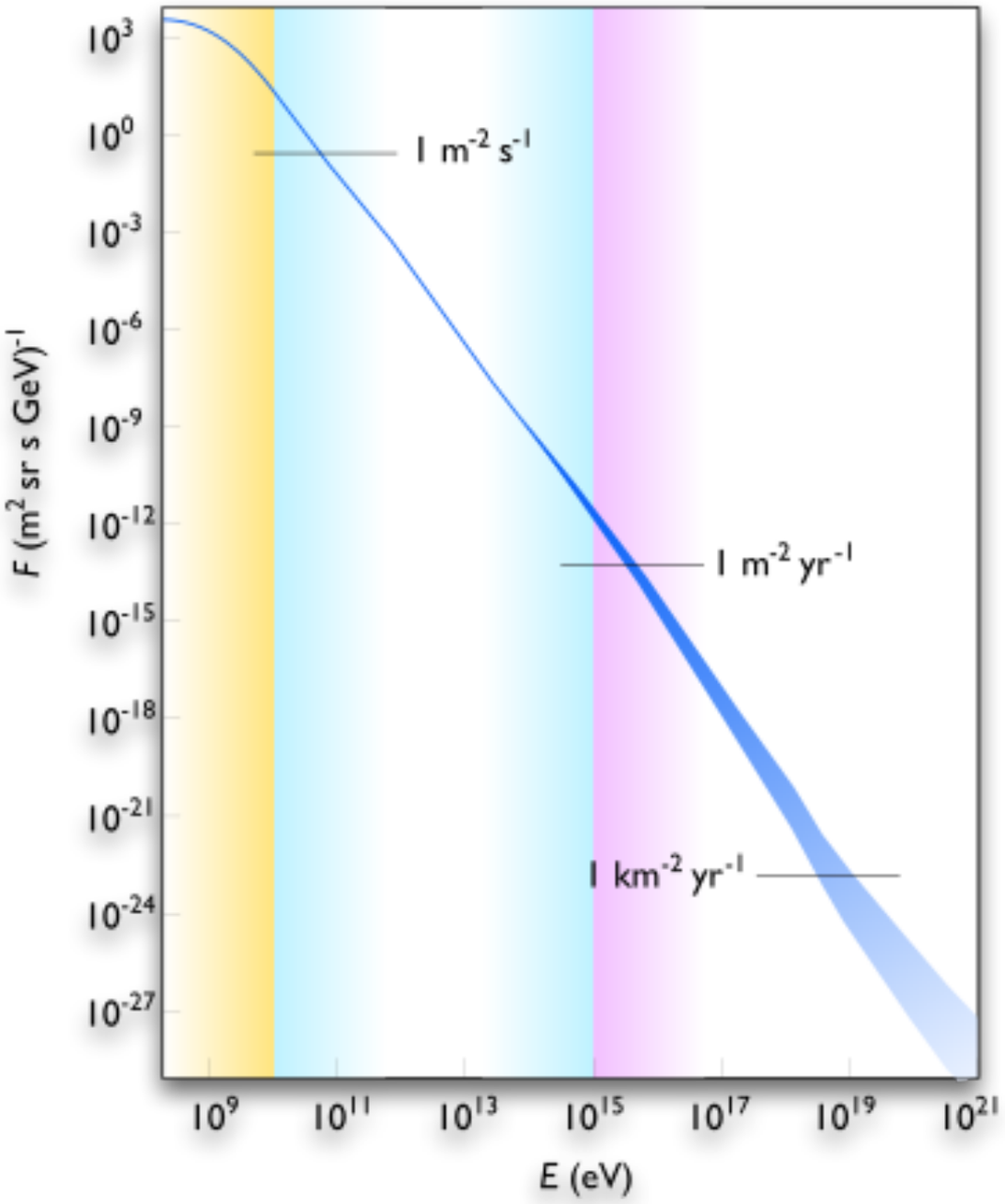
The spectrum of cosmic ray



Thee regimes:

1. **low energies**: solar cosmic rays
2. **medium energies**: galactic cosmic rays
3. **high energies**: extragalactic cosmic rays

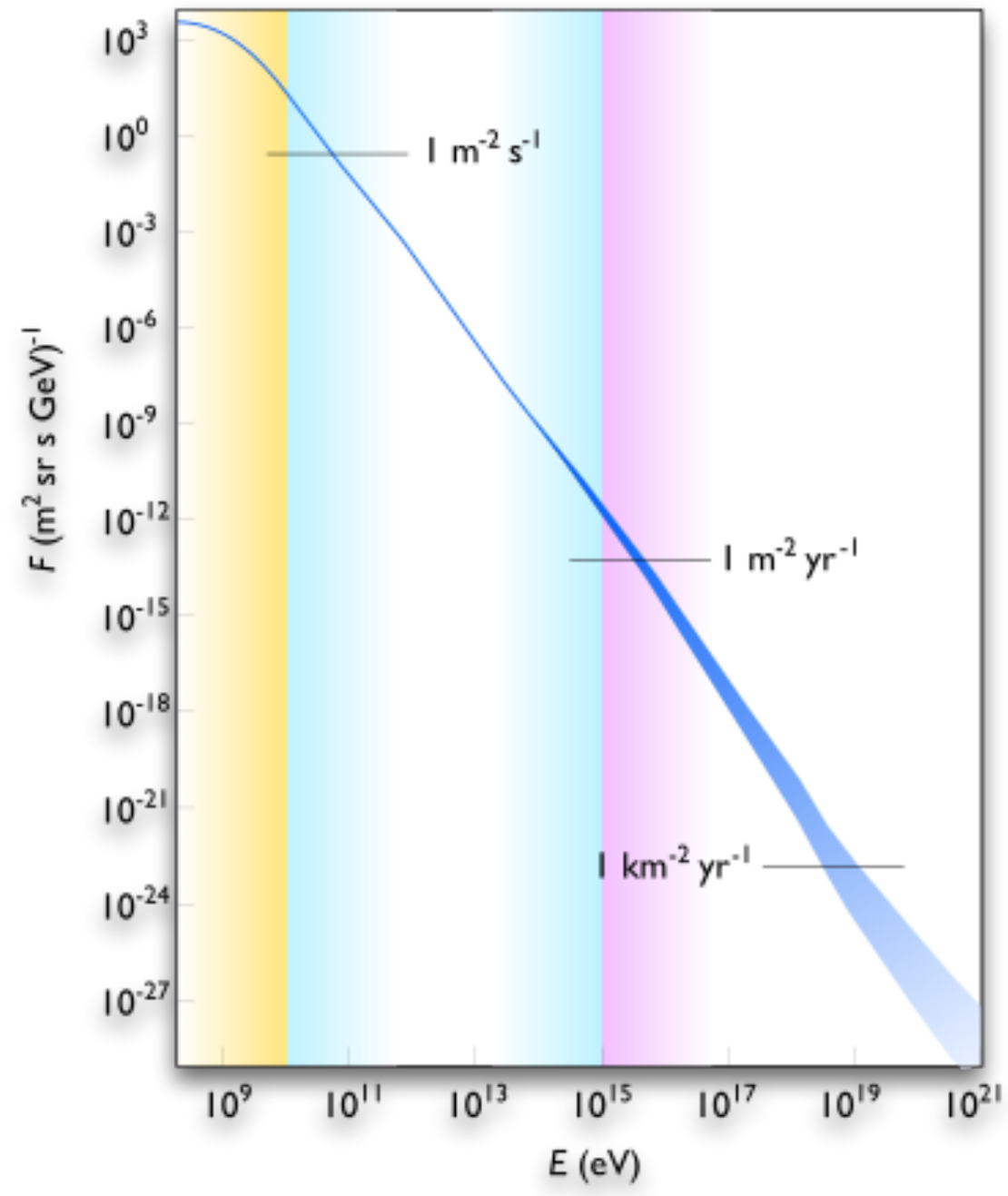
Rate of Cosmic Rays



Try to estimate the flux of cosmic rays as a function of its energy

Particle energy (eV)
1×10^{9} (GeV)
1×10^{12} (TeV)
1×10^{16} (10 PeV)
1×10^{20} (100 EeV)

Rate of Cosmic Rays



Try to estimate the flux of cosmic rays as a function of its energy

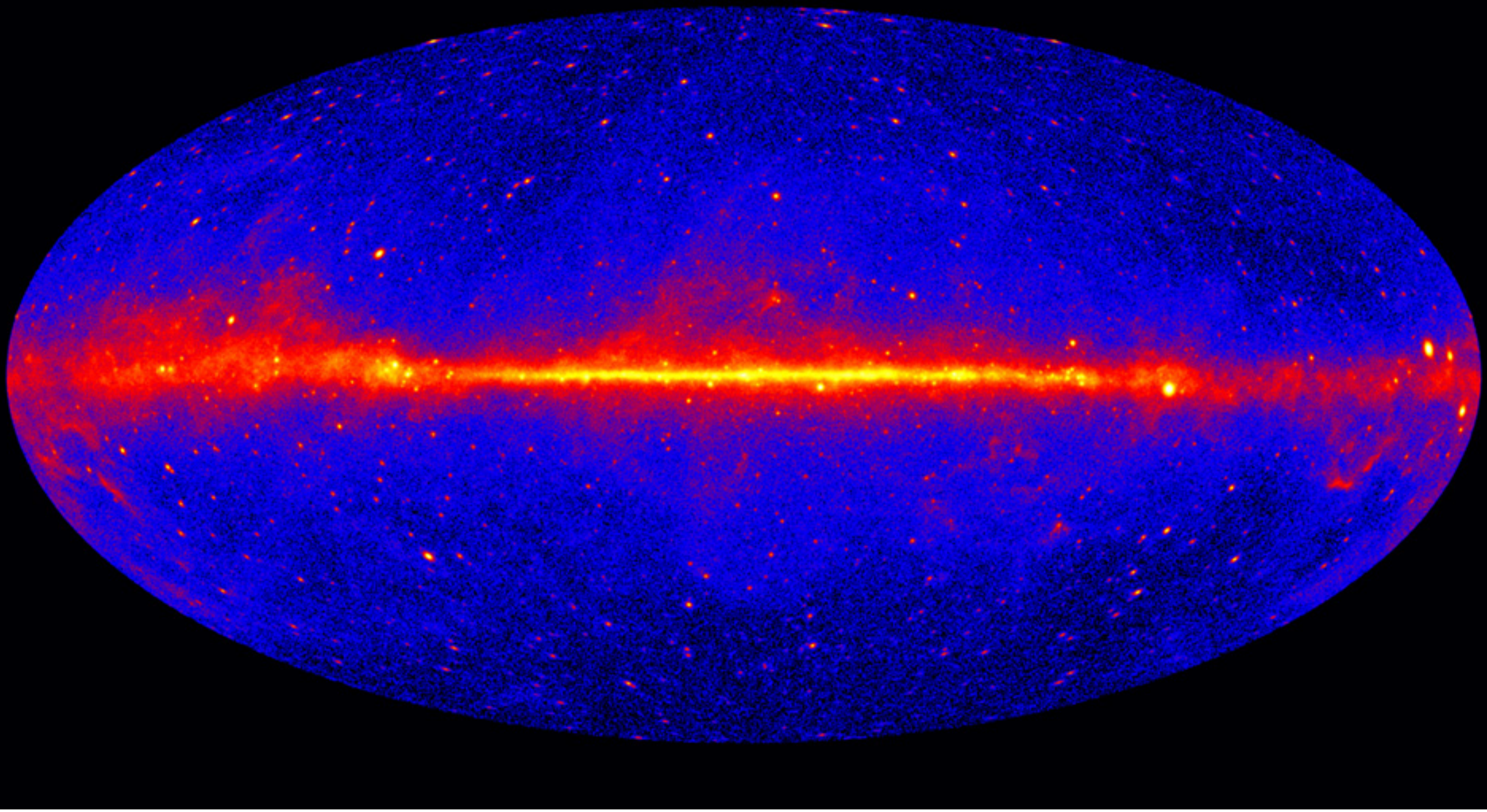
Particle energy (eV)	Particle rate ($m^{-2}s^{-1}$)
1×10^{9} (GeV)	1×10^{4}
1×10^{12} (TeV)	1
1×10^{16} (10 PeV)	1×10^{-7} (a few times a year)
1×10^{20} (100 EeV)	1×10^{-15} (once a century)

BUT...

Proton

Photon

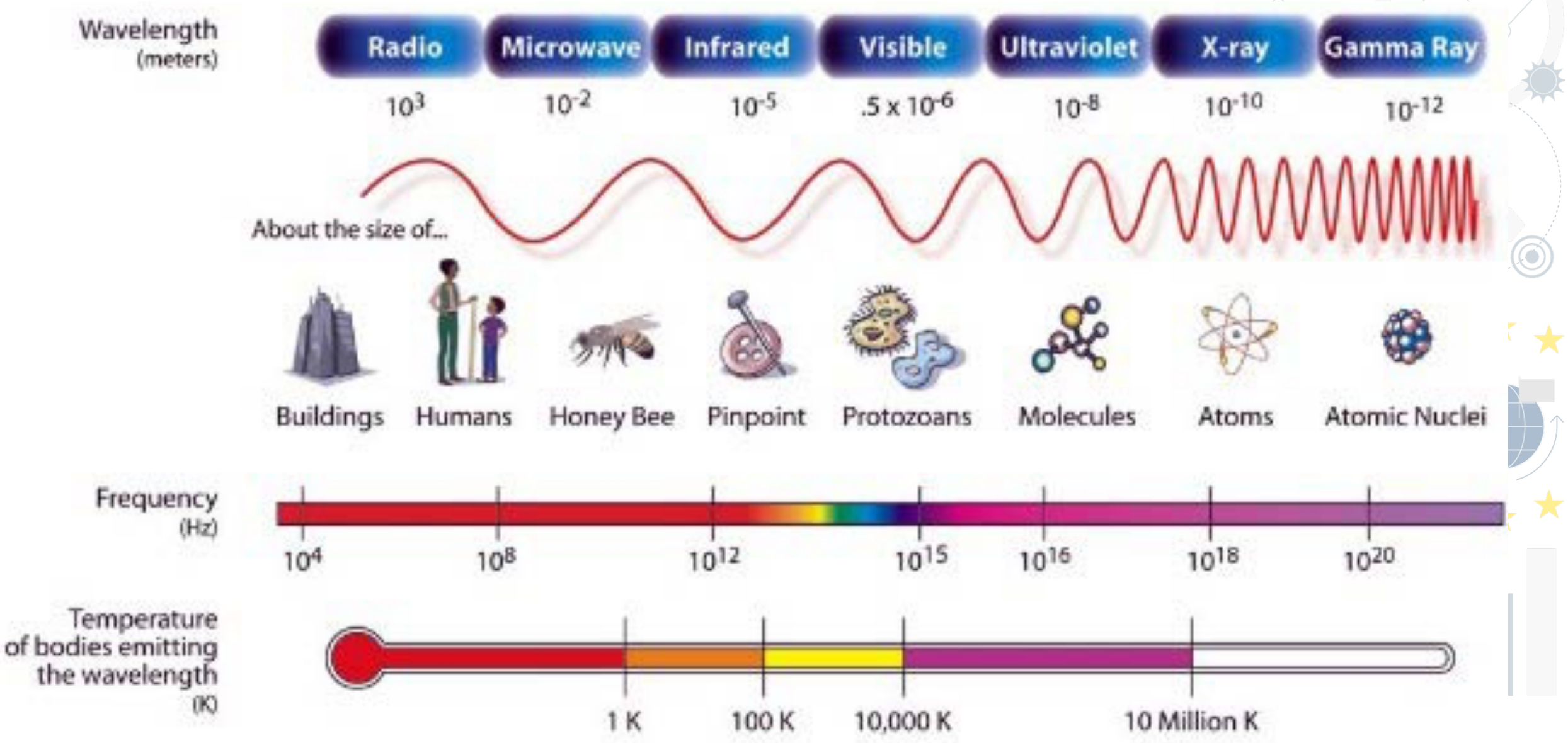
Neutrino



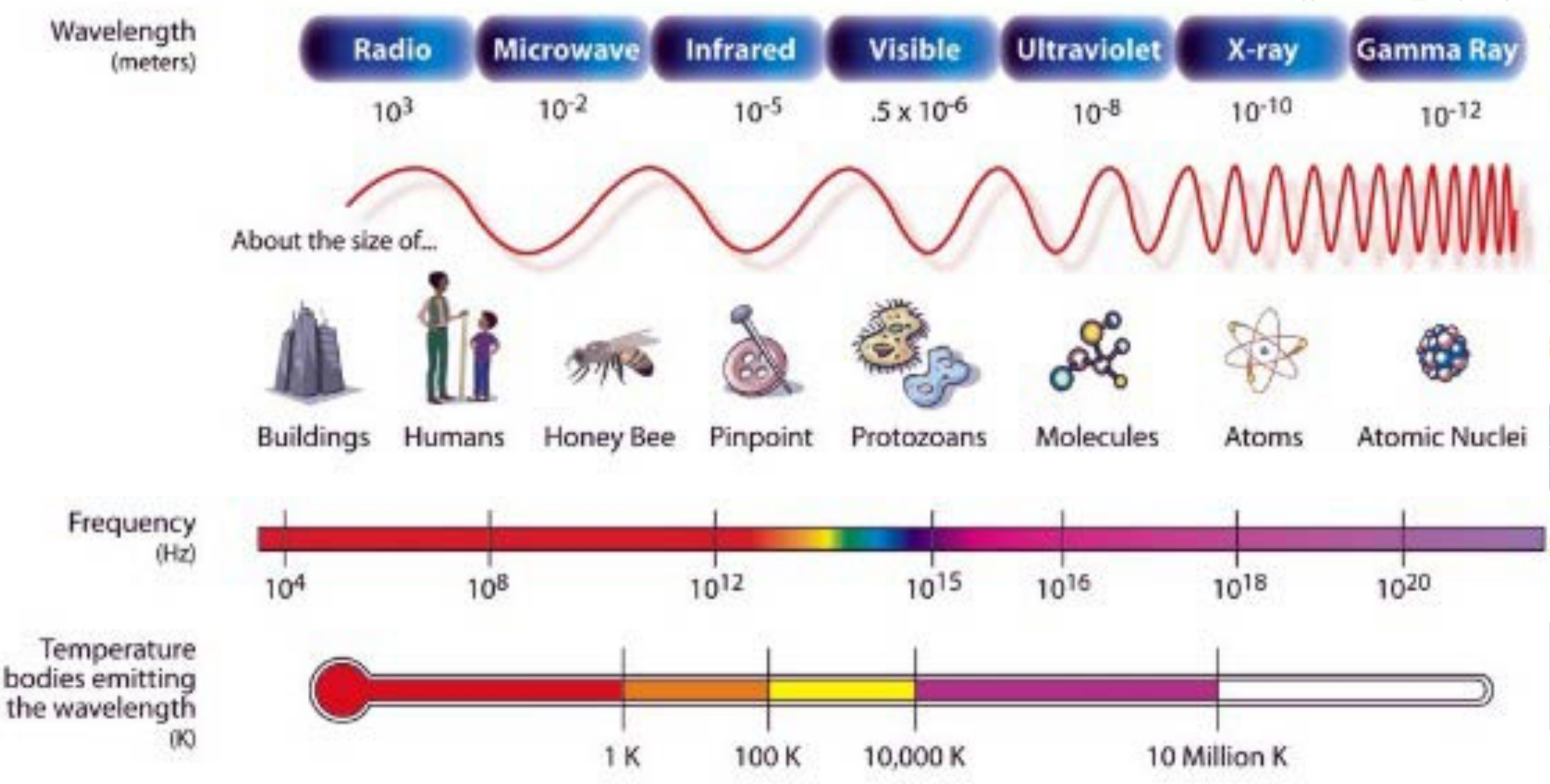
The electromagnetic Universe

Messenger 2: Photon

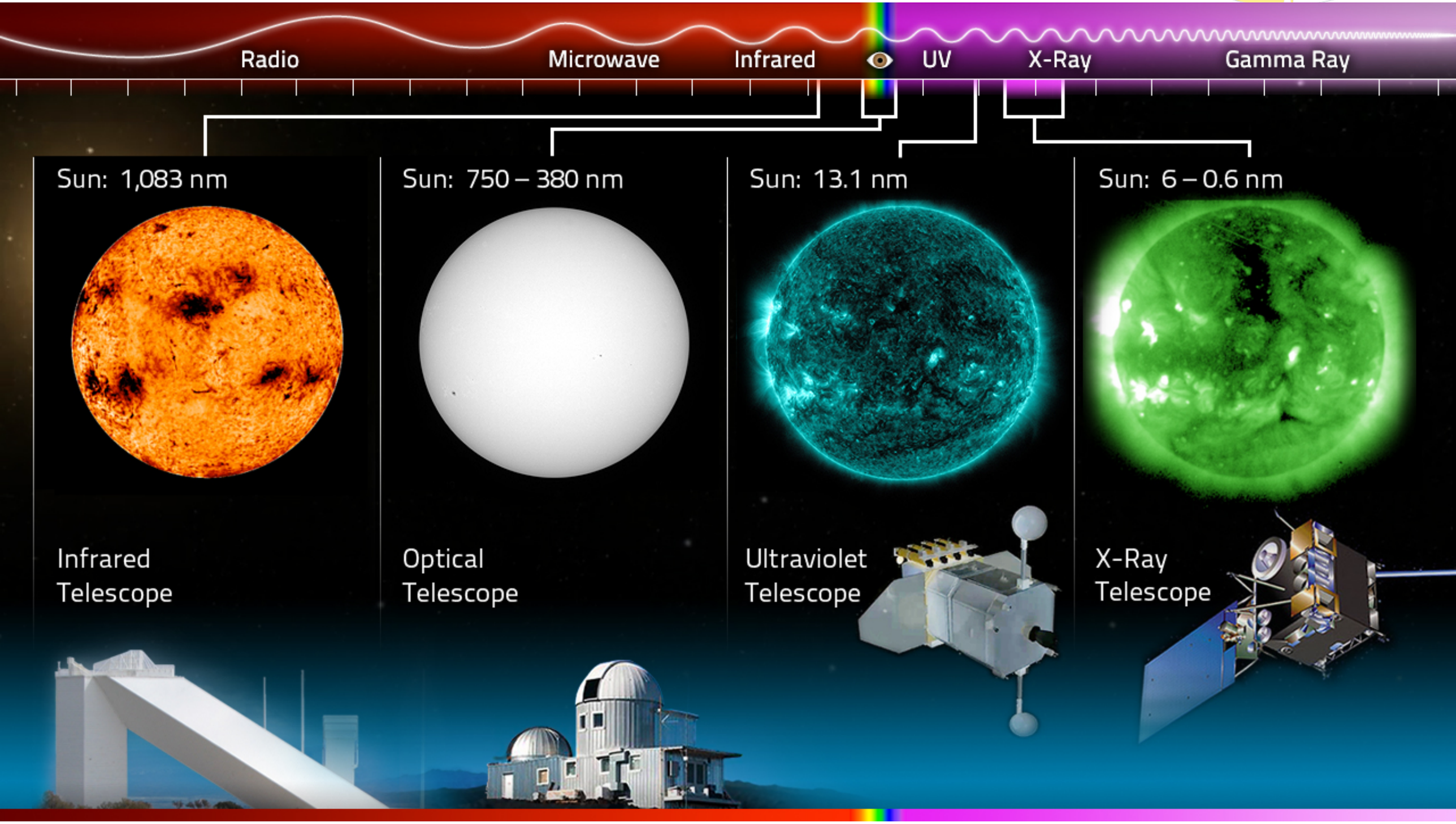
Looking at the Universe through the electromagnetic spectrum



Let's play a game: looking at this room through the electromagnetic bands…



A nearby example: the Sun



radio continuum (408 MHz)

atomic hydrogen

radio continuum (2.5 GHz)

molecular hydrogen

infrared

mid-infrared

near infrared

optical

x-ray

gamma ray

Multiwavelength Milky Way

http://adc.gsfc.nasa.gov/mw

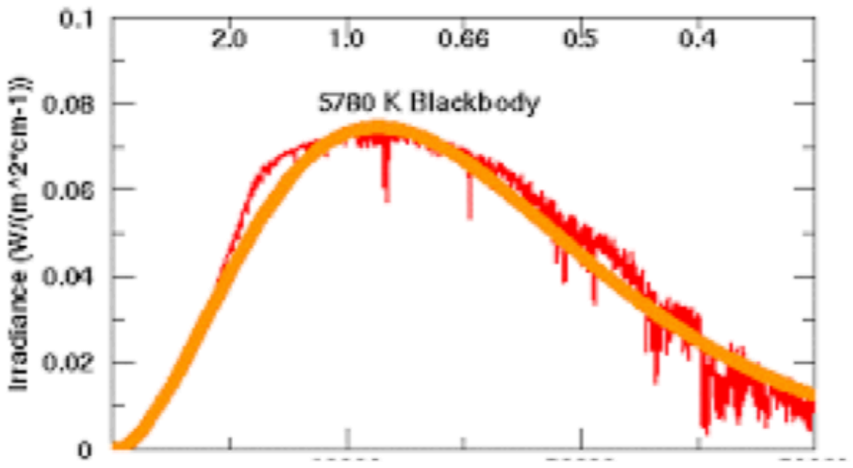
Photon emission: the **thermal emission**

- A body at a certain temperature and thermal equilibrium emits electromagnetic radiation following the Plank's law of **black body** radiation

Our body also emits (in the IR band)

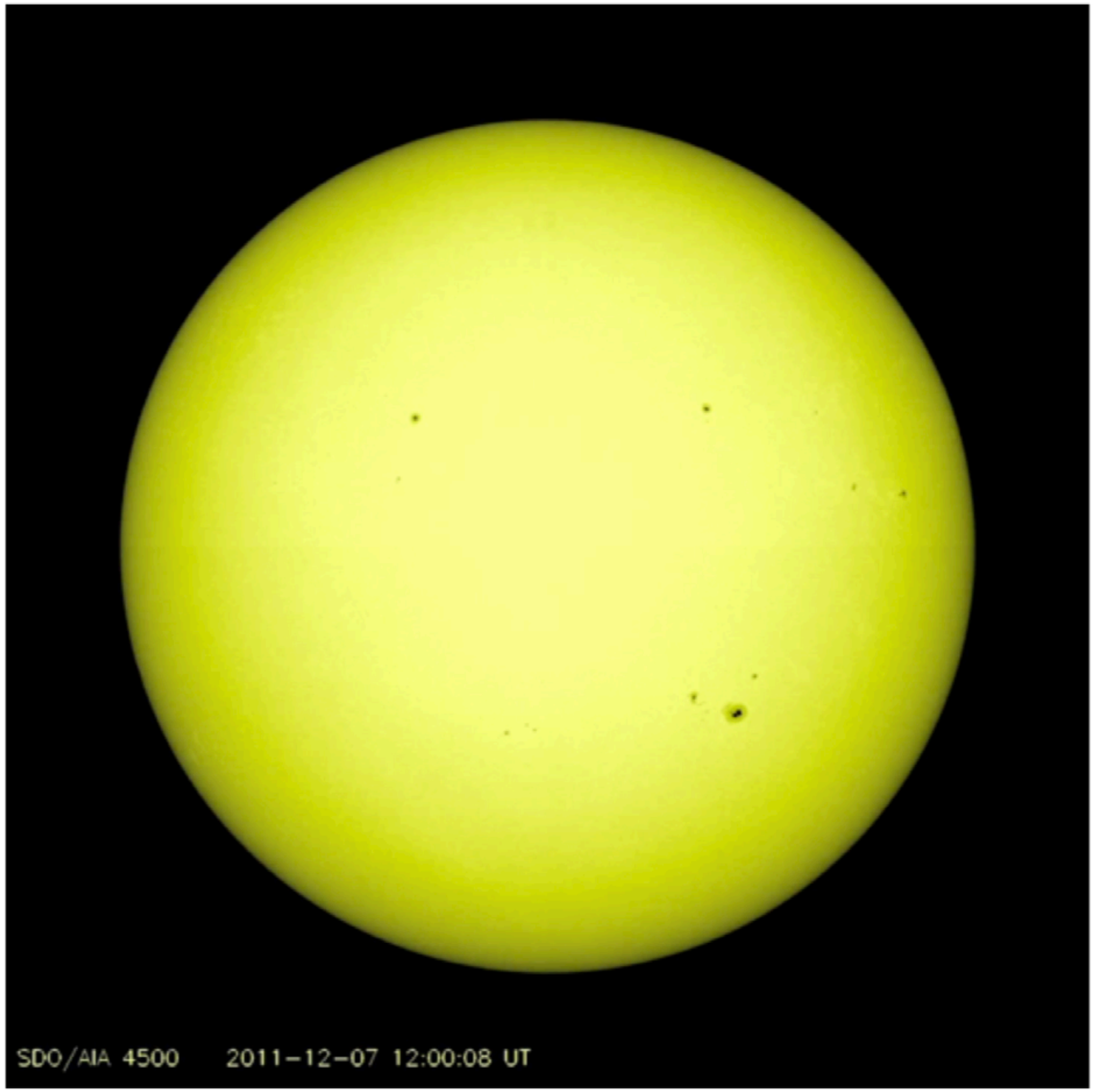
Thermal emission: examples

- The sun
  - T_{phot} = 5770 K



frequency

L_{sun}= 3.8x10^{26} W = 3.8x10^{33} erg/s



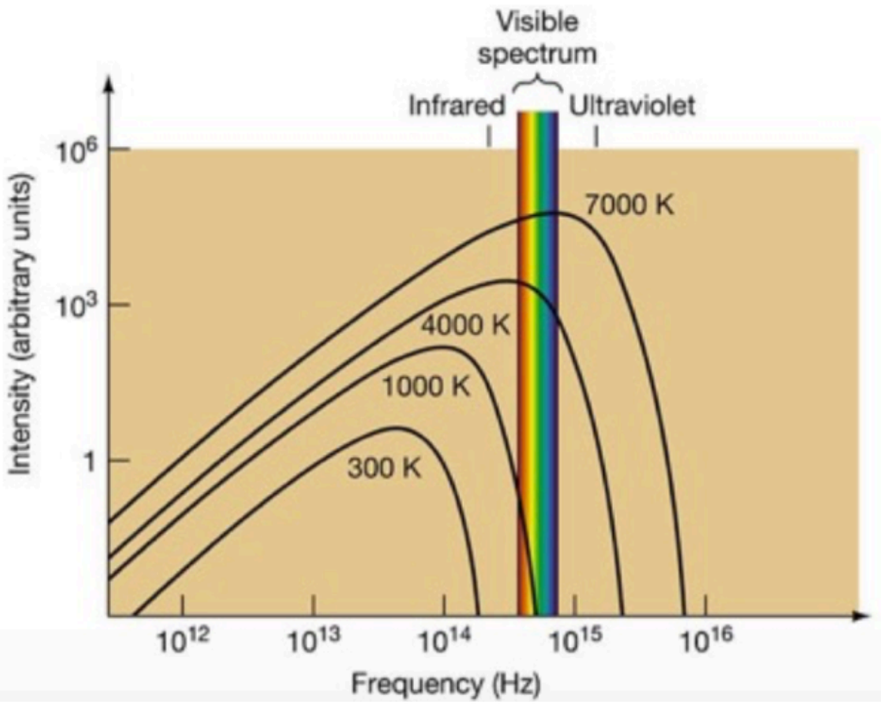
courtesy of A. Stamerra

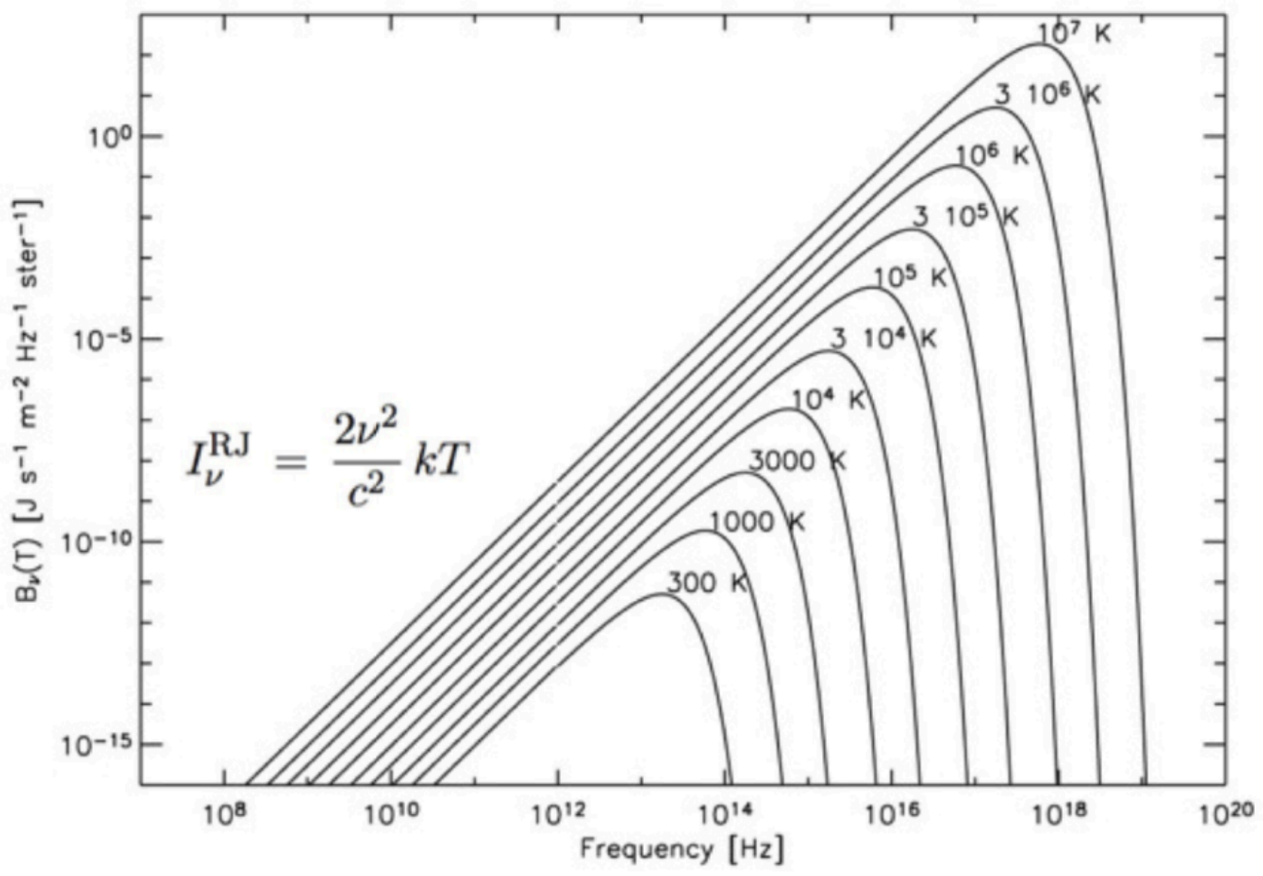
Thermal emission: examples

- The sun

$$B_\nu = \frac{8\pi h\nu^3}{c^2}\frac{1}{\mathrm{e}^{\frac{h\nu}{kT}}-1}$$

$$[\mathrm{J\,s^{-1}\,m^{-2}\,Hz^{-1}}]$$





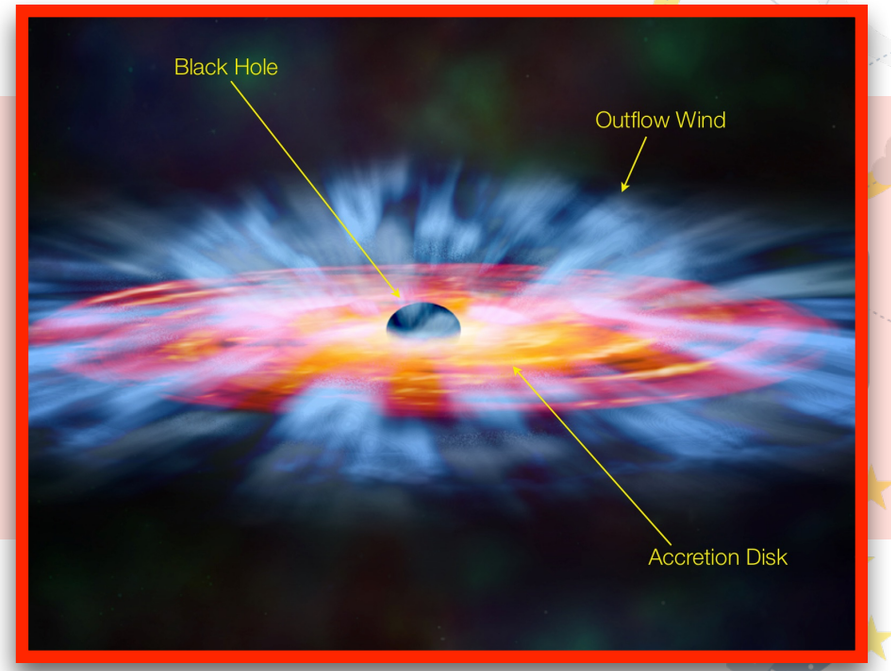
μm IR optical UV X-ray

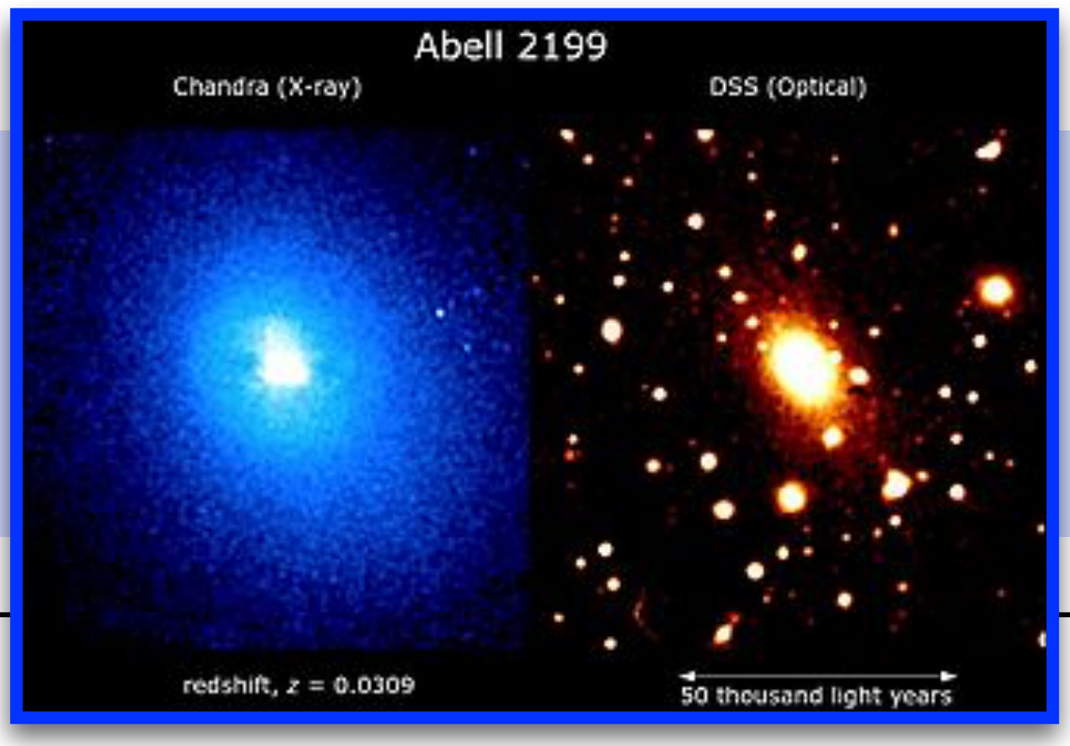
courtesy of A. Stamerra

Thermal emission: examples

- Maximum photon energy in astrophysics from thermal emission

Accretion disk in active galactic nuclei T ~ 10^7 K





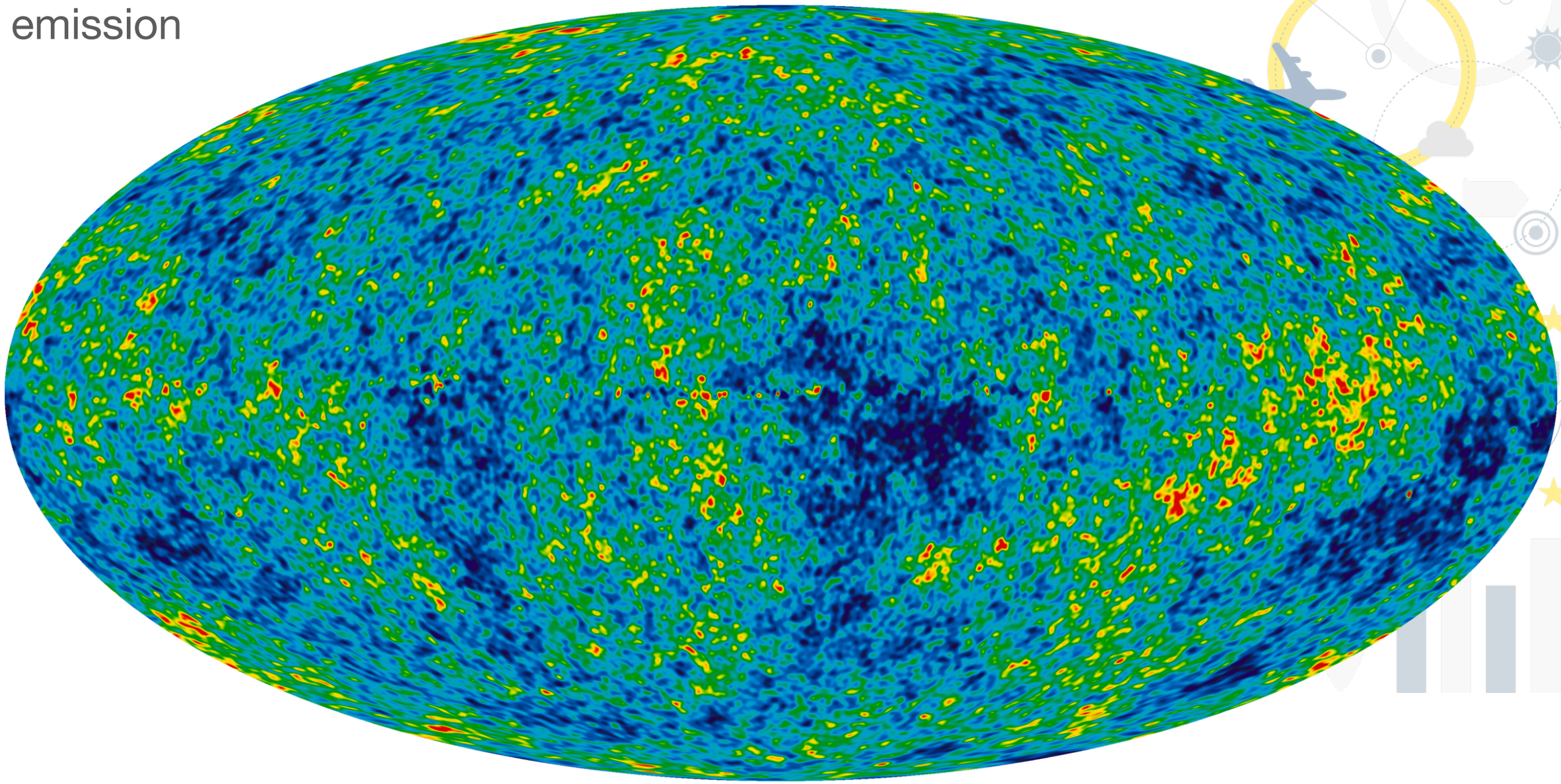
Galaxy cluster T ~ 10^7 K

very bright in X-ray

Thermal emission: examples

- Minim photon energy in astrophysics from thermal emission

CMB T ~ 2.7 K —>
microwave radiation



Thermal emission: examples

Key concepts:

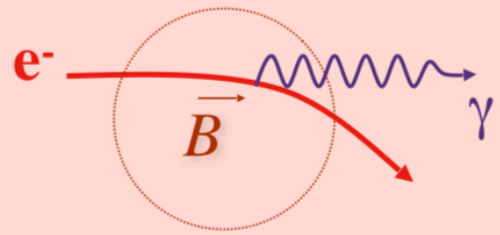
Thermal emission is not only related to infrared radiation!

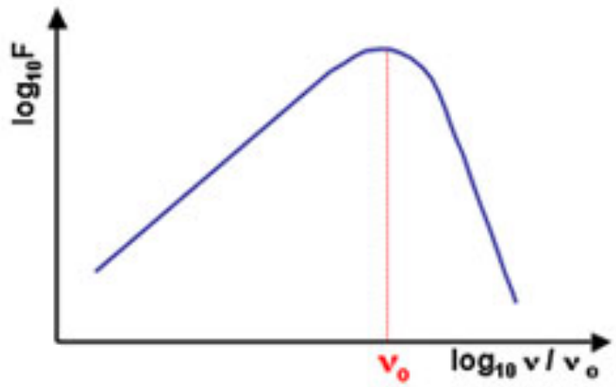
But as far as we know, it does not reach *gamma rays.*

Therefore: ***looking in gamma rays means looking at the non-thermal Universe*** *particle acceleration —> cosmic rays!*

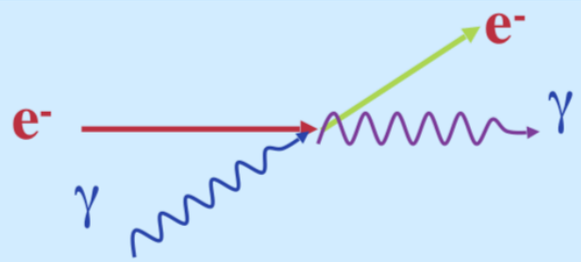
Photon emission: main **non-thermal** processes

- Synchron radiation

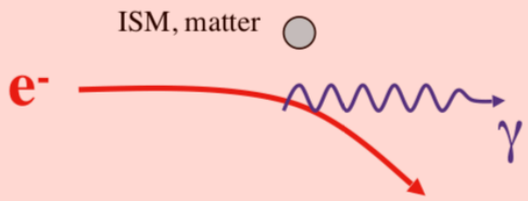


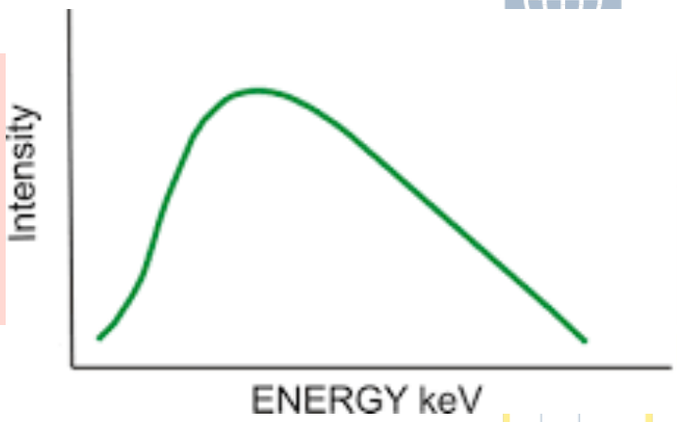


- Inverse Compton

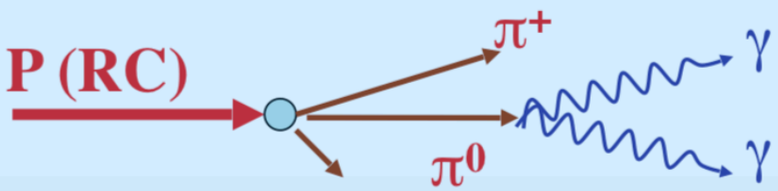


- Bresstrahlung

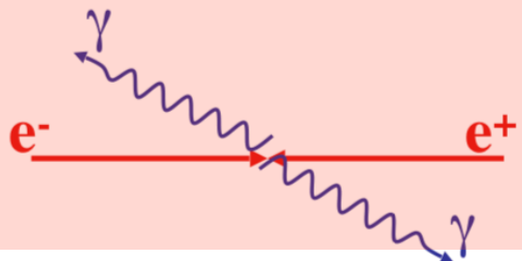


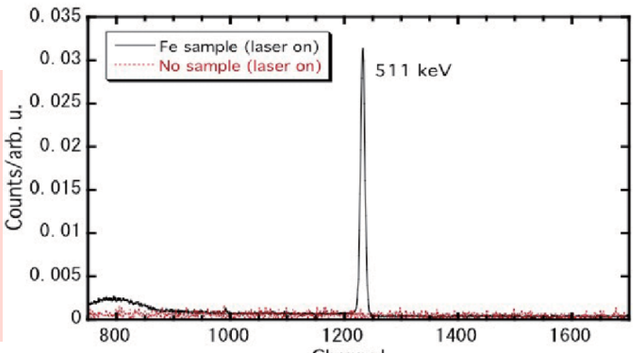


- Particle collision



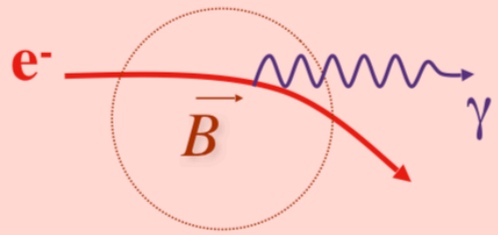
- Annihilation

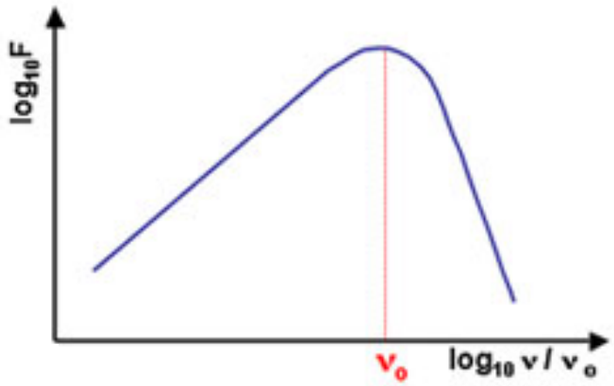




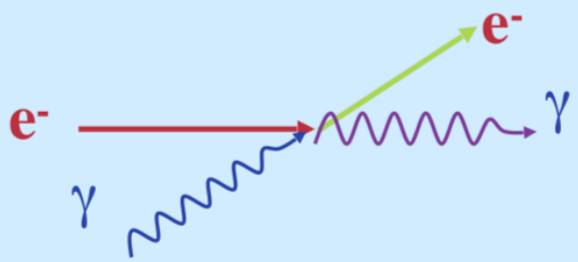
Photon emission: main **non-thermal** processes

- **Synchron radiation**





- **Inverse Compton**



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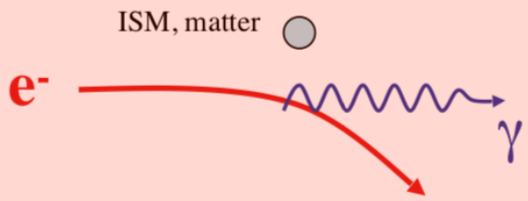
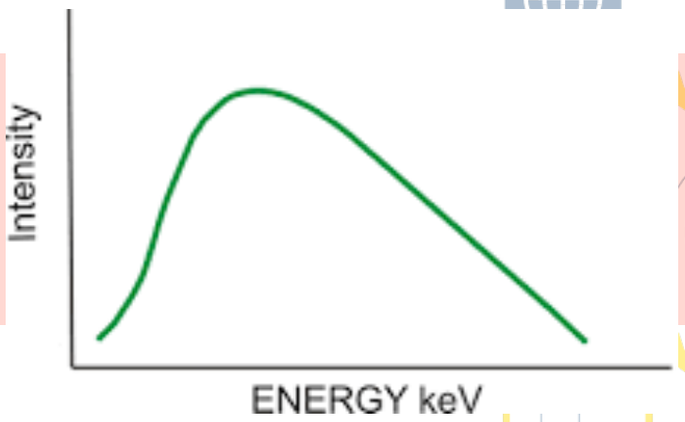
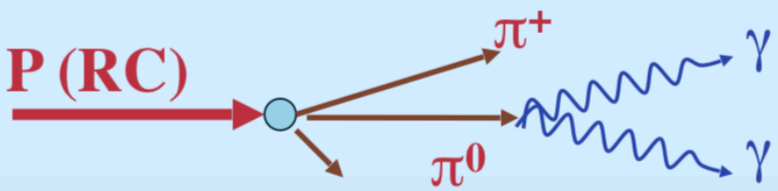
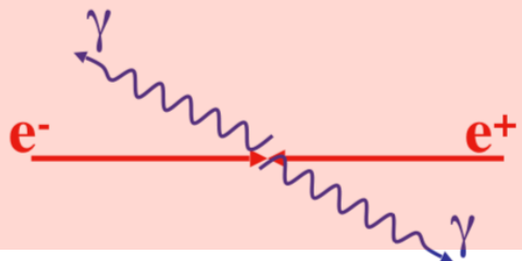


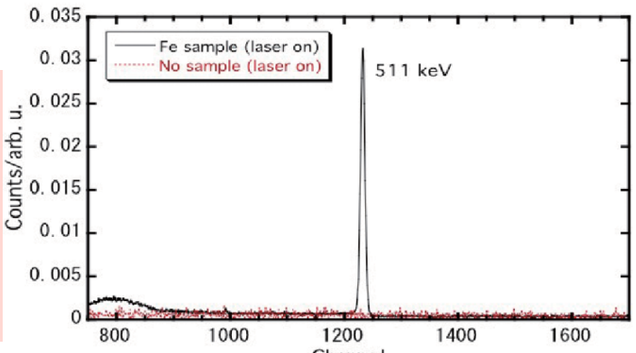


- Particle collision

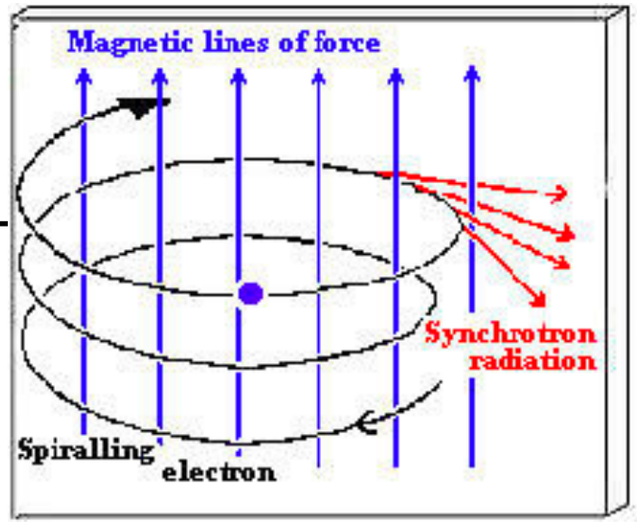


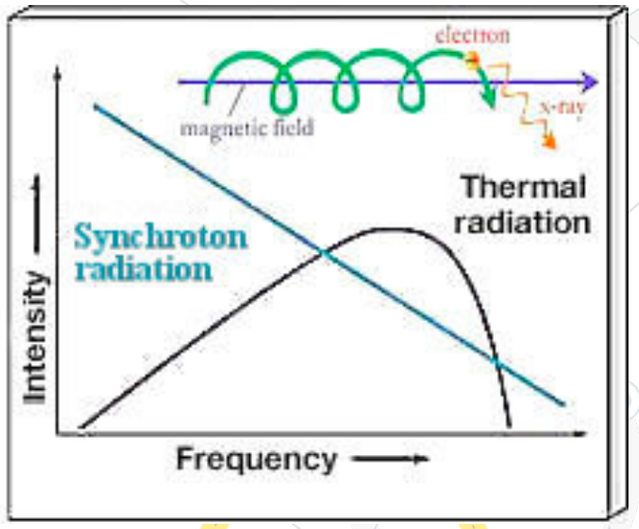
- Annihilation

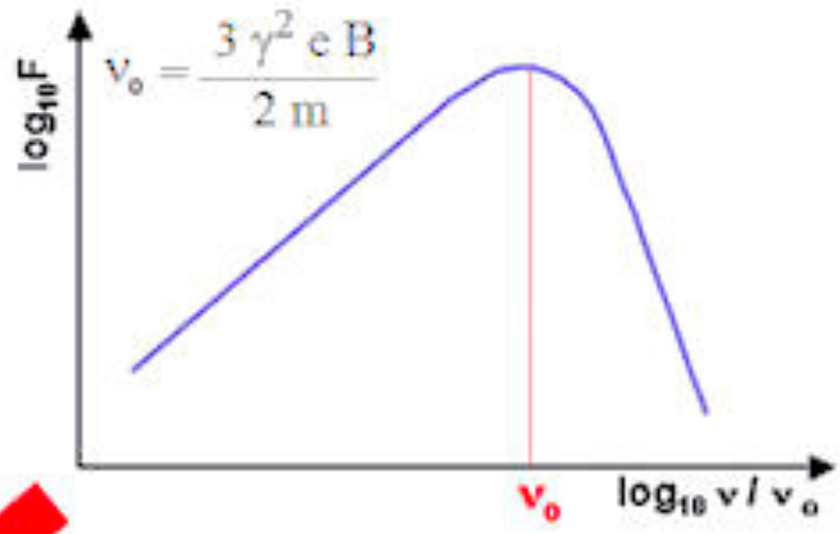


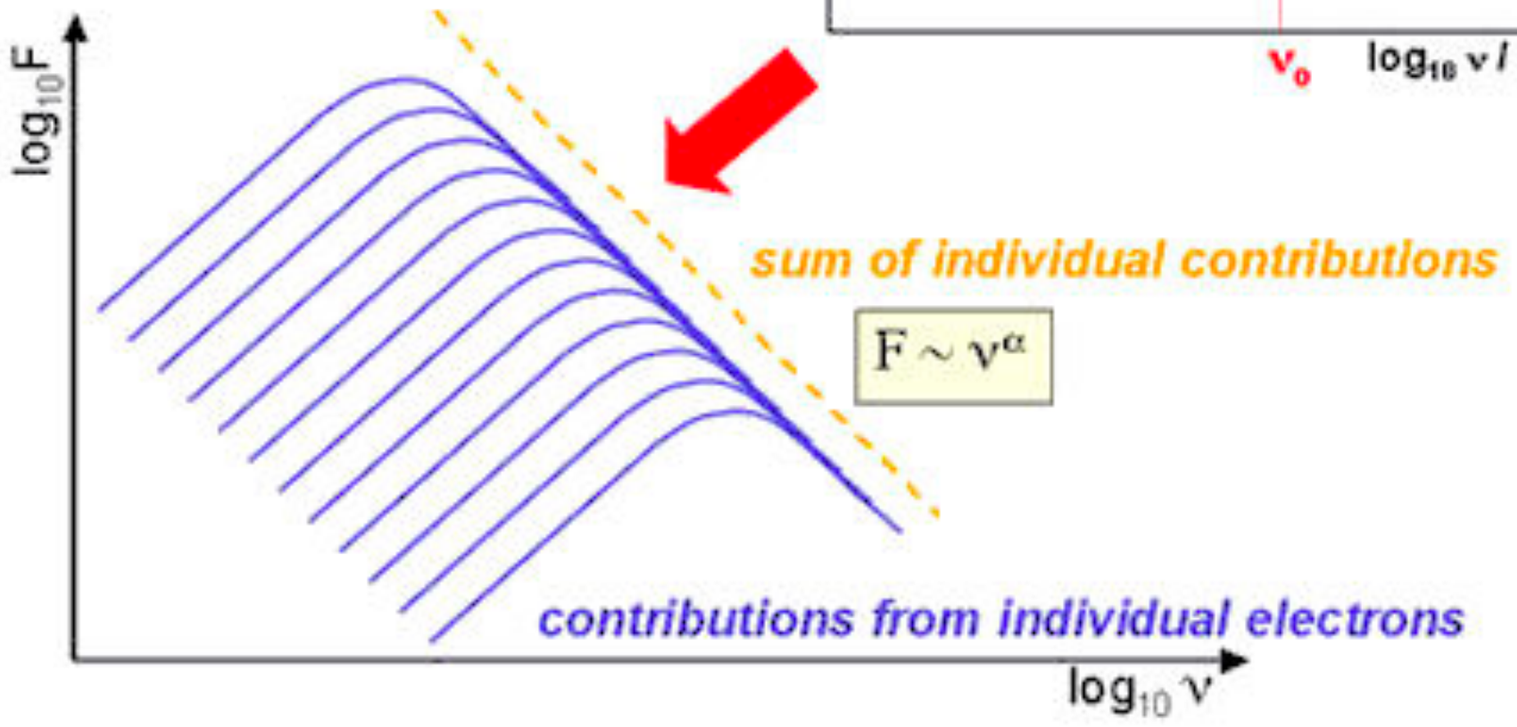


Synchrotron radiation









Nebulae

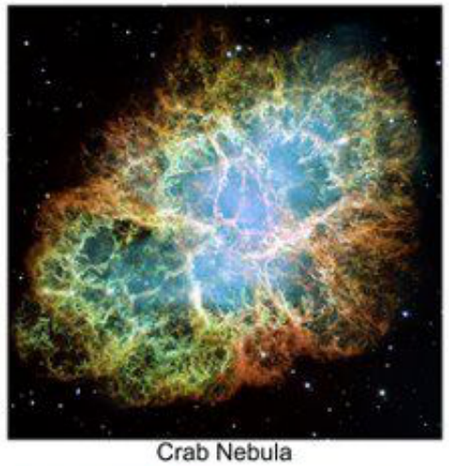
Emission is mainly **non-thermal**


Bubble Nebula

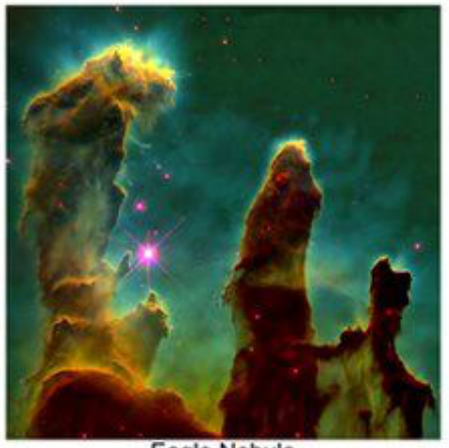

Butterfly Nebula

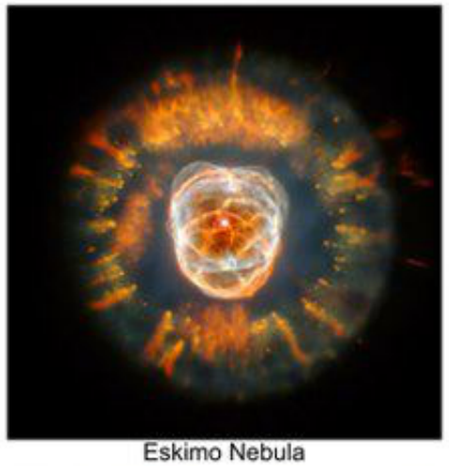

Carina Nebula


Catseye Nebula


Crab Nebula


Dumbbell Nebula


Eagle Nebula


Eskimo Nebula

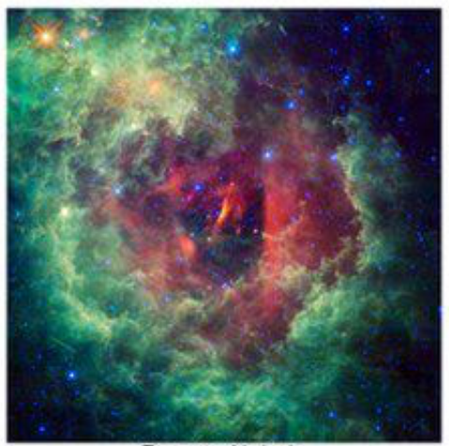

Helix Nebula

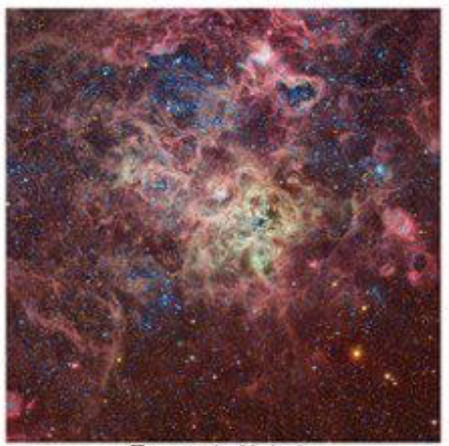

Horsehead Nebula


Hourglass Nebula


Medusa Nebula


Orion Nebula

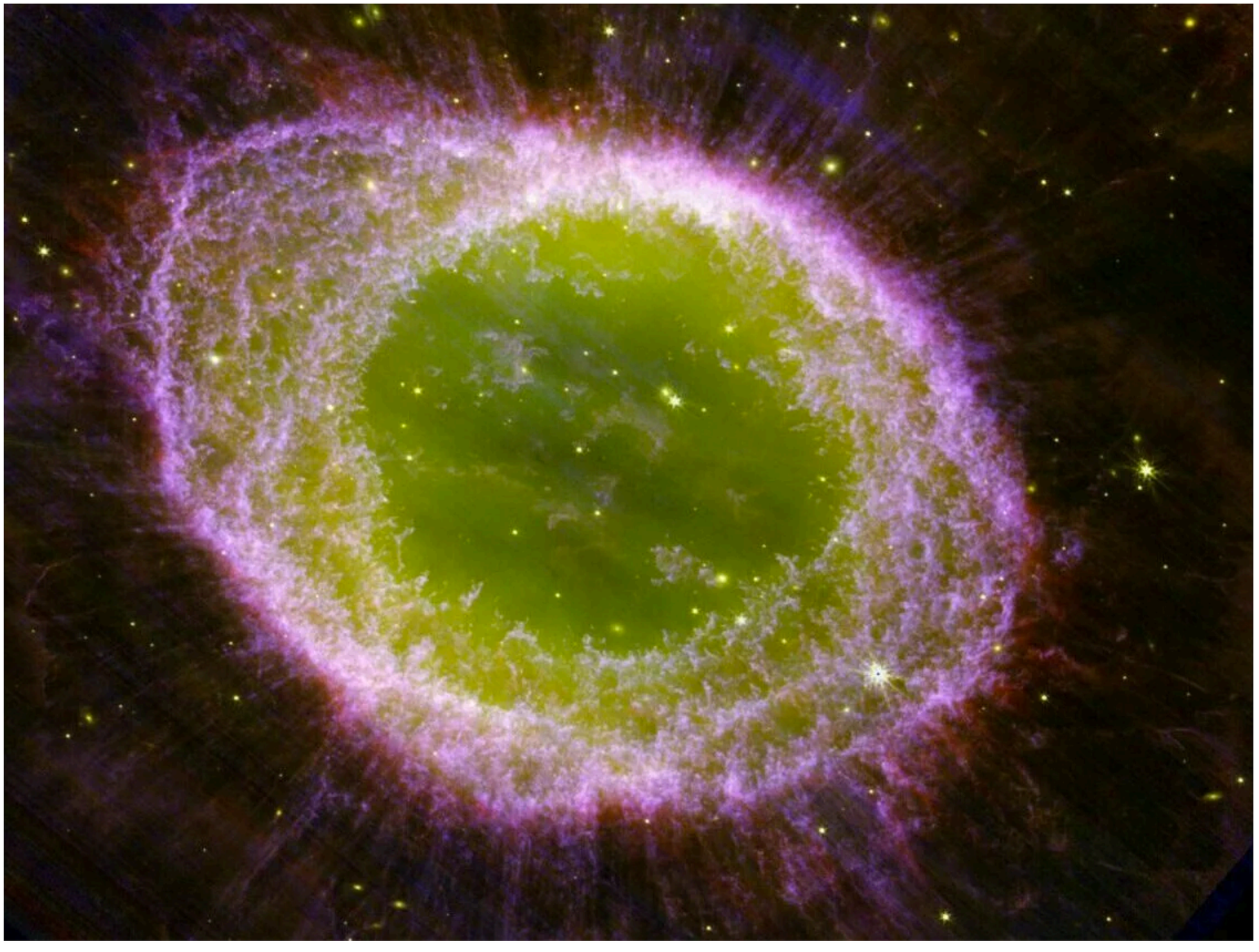

Rosette Nebula


Tarantula Nebula


Trifid Nebula

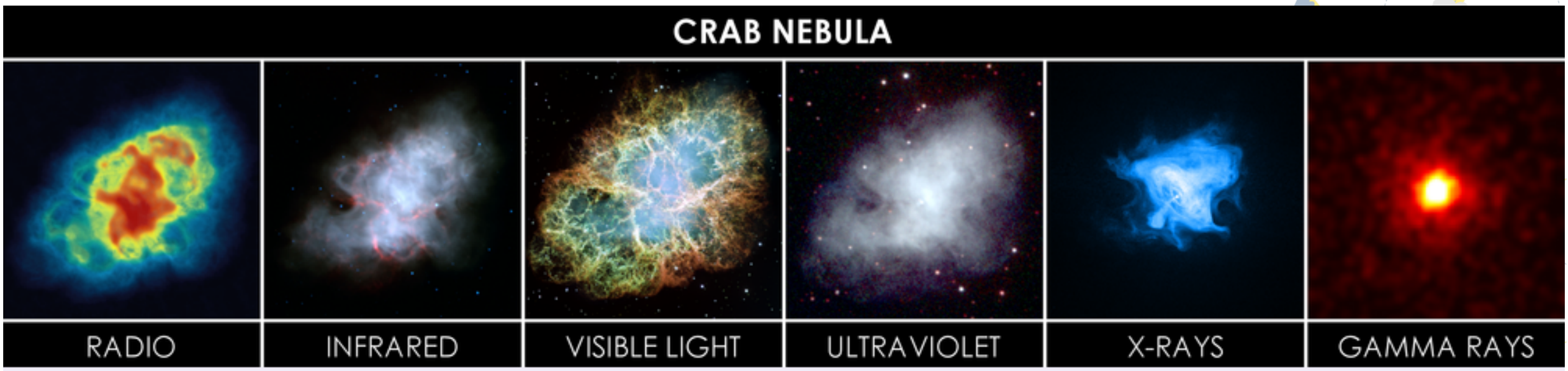
These are <u>galactic</u> sources

A nebula with James Webb's eyes:



Multi-wavelength emission from the Crab Nebula

Wikipedia: The Crab Nebula is an expanding remnant of a **star's supernova explosion**. Japanese and Chinese astronomers recorded this violent event nearly 1,000 years ago in **1054 AD**, as did likely the Native Americans. The **glowing relic has been expanding** since the star exploded, and it is now approximately 11 light-years in width.



The crab nebula in radio, infrared, visible, ultraviolet, x-ray and gamma-ray wavelengths.

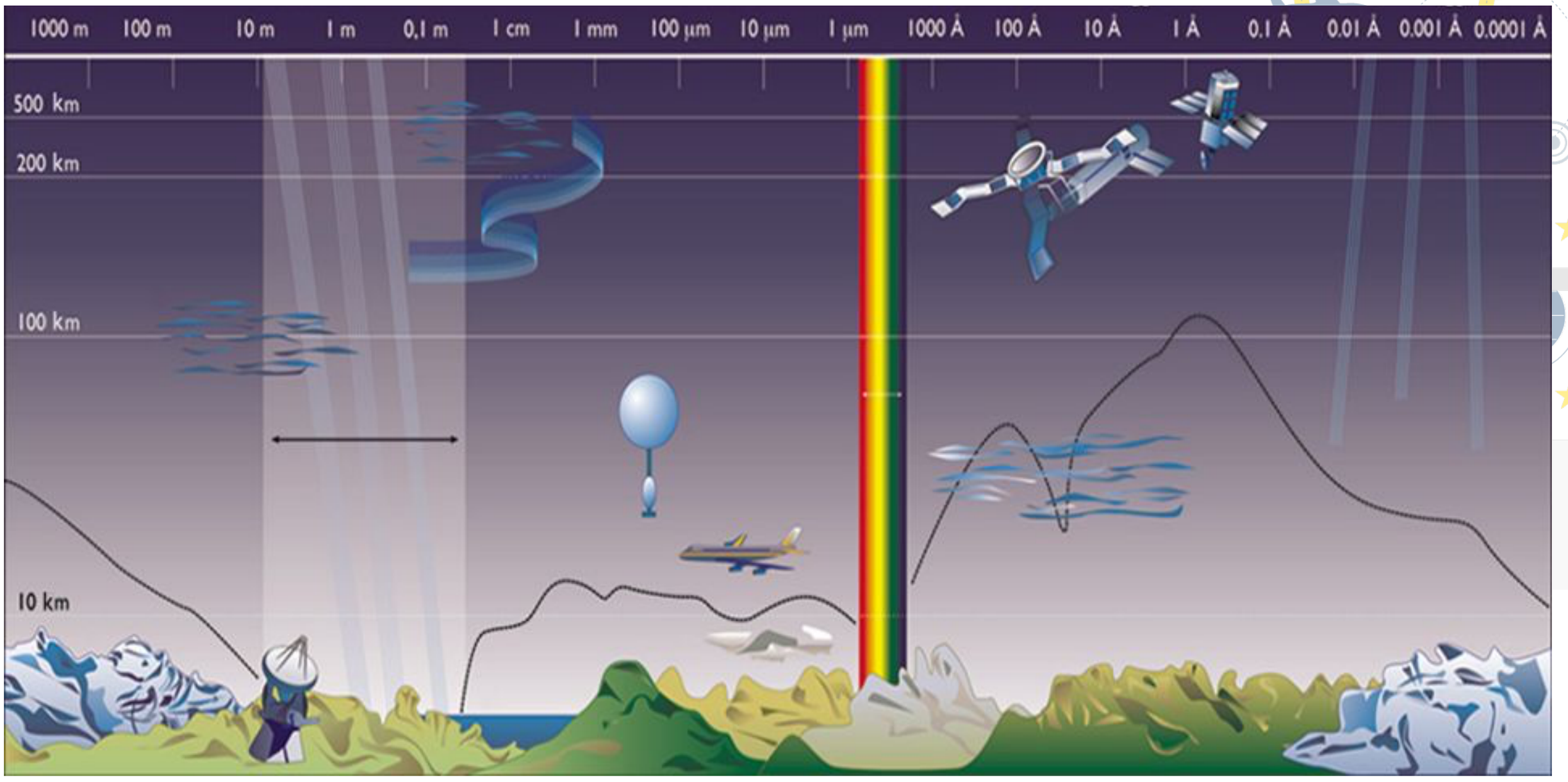
Sources: Radio: NRAO/AUI and M. Bietenholz, J.M. Uson, T.J. Cornwell; Infrared: NASA/JPL-Caltech/R. Gehrz (University of Minnesota); Visible: NASA, ESA, J. Hester and A.Loll (Arizona State University); Ultraviolet: NASA/Swift/E. Hoversten, PSU, X-ray: NASA/CXC/SAO/F. Seward et al.; Gamma: NASA/DOE/Fermi LAT/R. Buehler

Each band tells us something different!

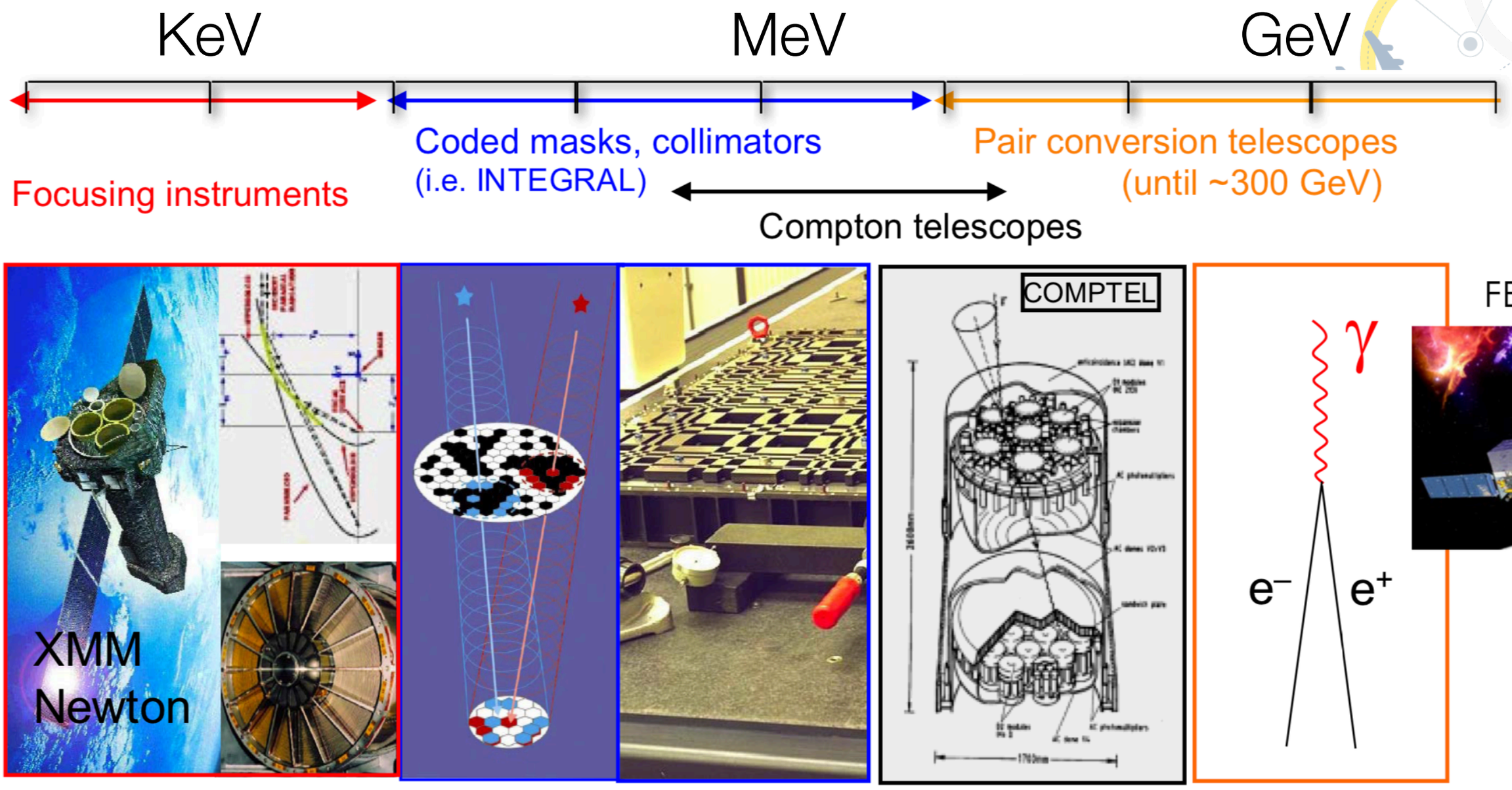
Paper #5 (Crab nebula)

The opacity of the atmosphere

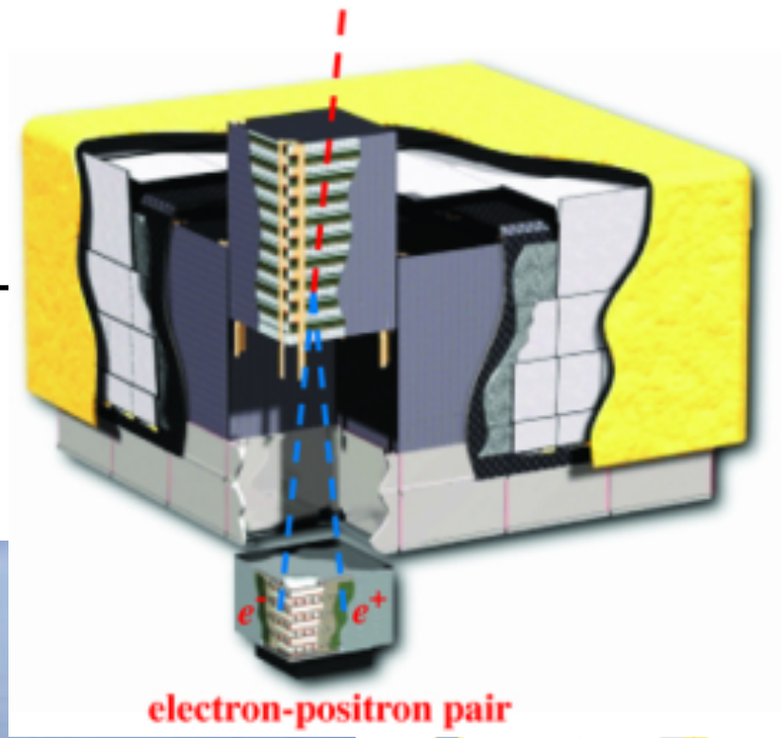
look at the black line:



Space detectors of high-energy photons



Gamma ray instrumentation: The *Fermi* satellite



At higher energies: Ground-based detectors of gamma rays

Looking for **electromagnetic showers** induced by **photons** coming from a specific **direction**

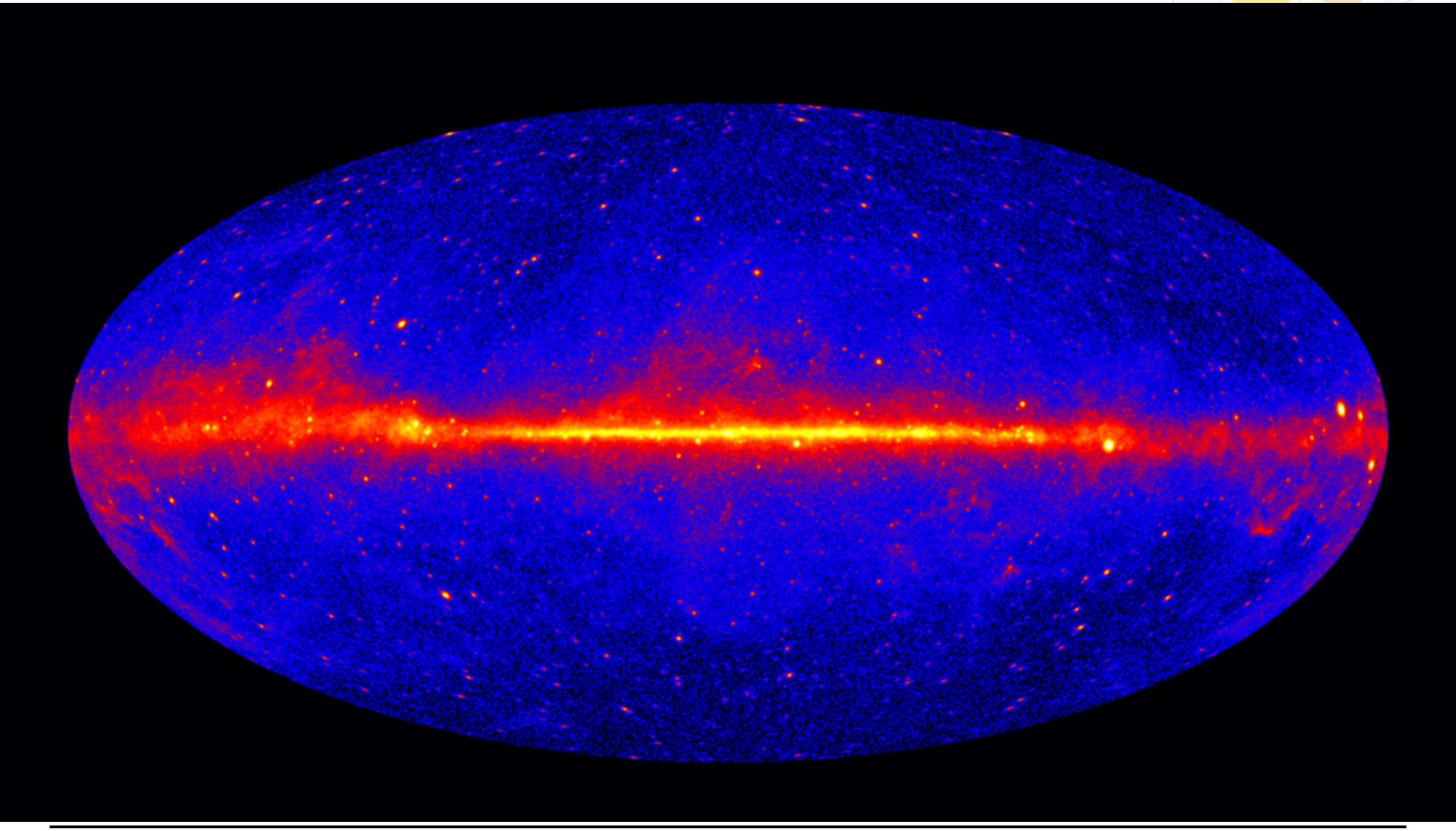
Direct detection of **shower particles**

water Cherenkov detectors

Indirect detection of shower particles

Imaging Atmospheric Cherenkov telescopes

The Universe in gamma-rays seen by *Fermi*-LAT



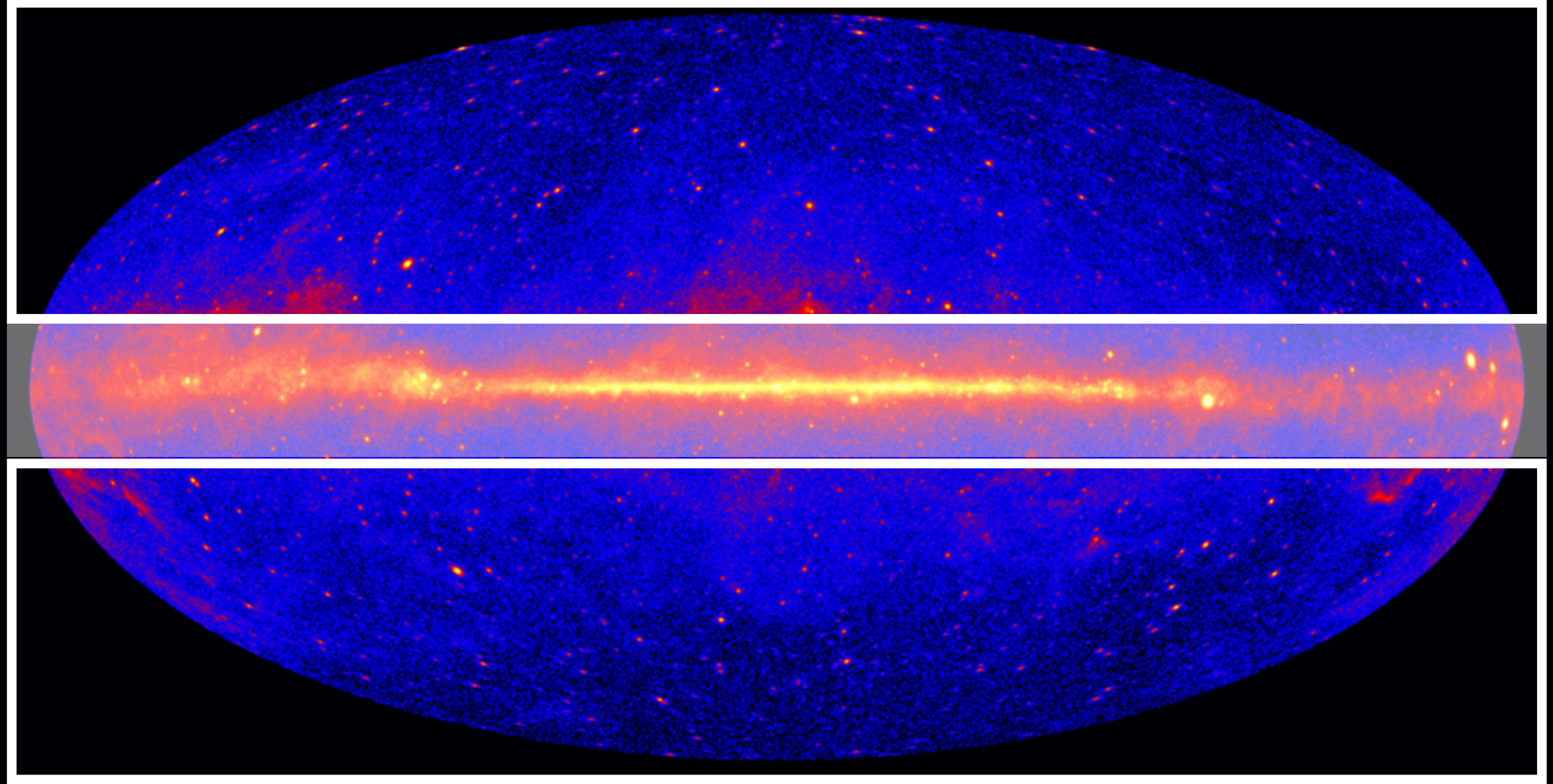
The Universe in gamma-rays seen by *Fermi*-LAT

galactic sources

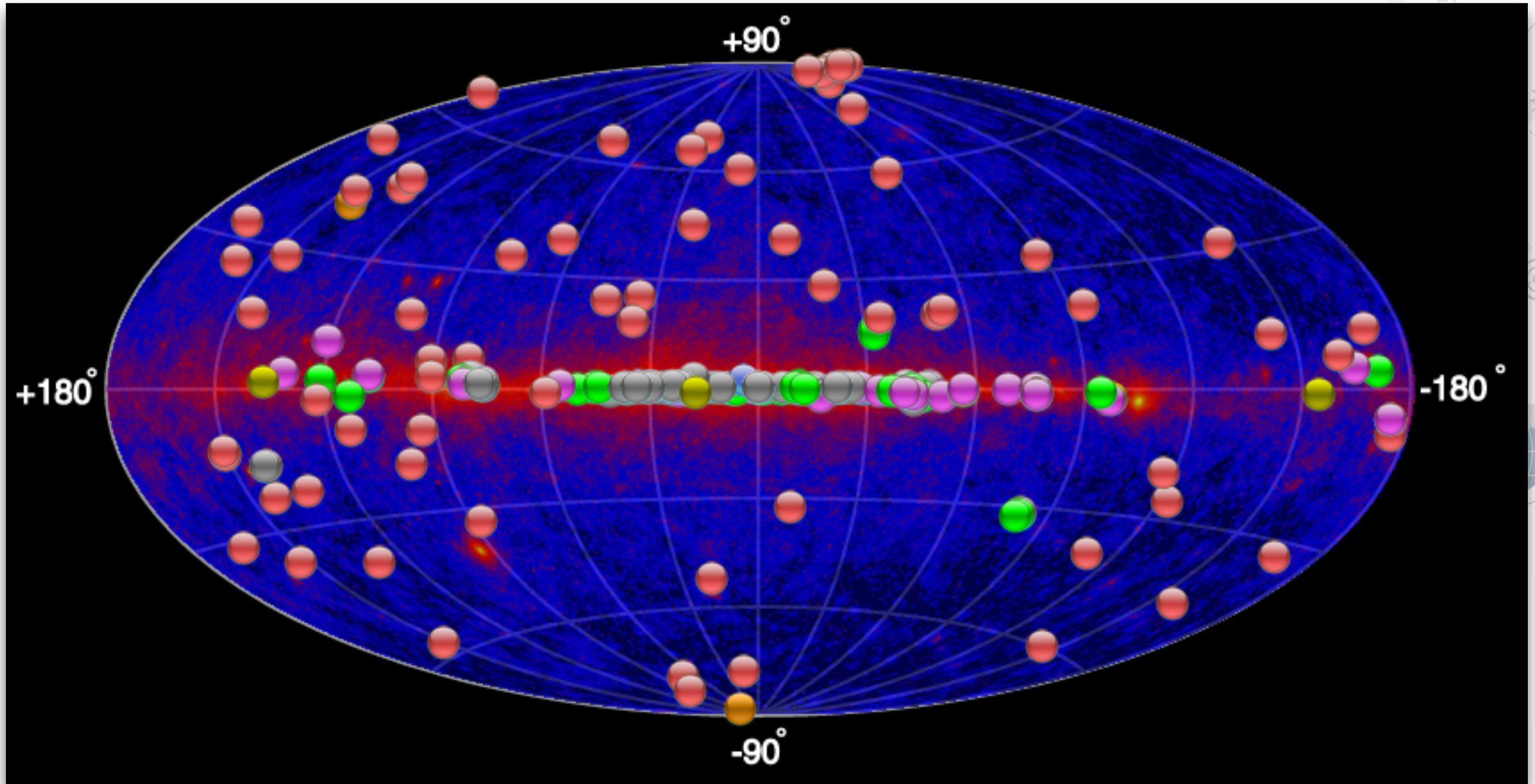
Paper #6 (Pulsars)

The Universe in gamma-rays seen by *Fermi*-LAT

extra-galactic sources



At higher energies (Very high energy gamma rays, from ground based instruments)

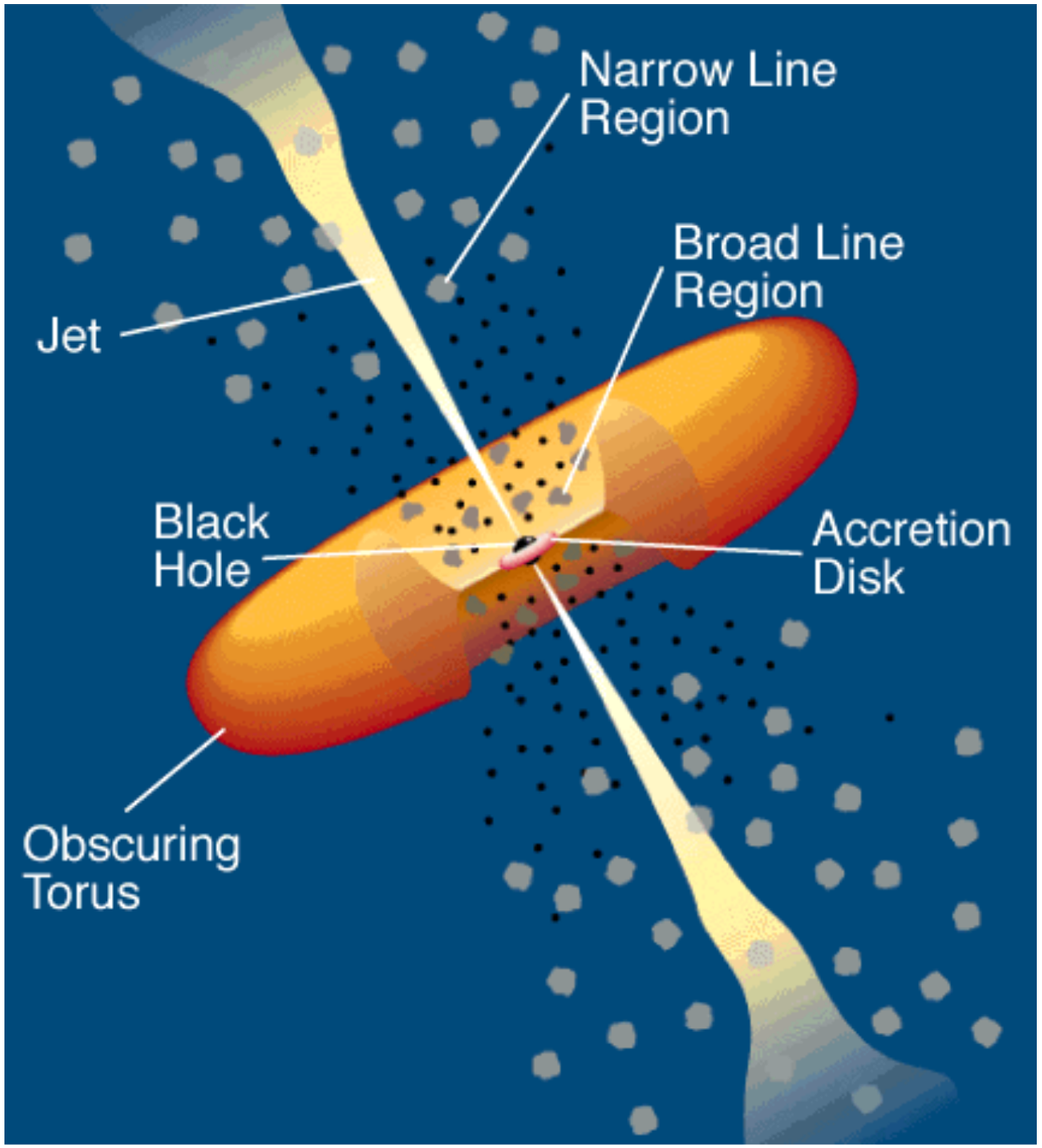


Tutorial of this morning

- How many extragalactic sources (non transient) has seen *Fermi* up to now?
- And how many extragalactic sources have been detected at the highest energies (TeV)?
- For comparison: how many galaxies have we detected in optical wavelength?

At gamma rays, the large majority of the detected sources are (jetted) **Active Galactic Nuclei**

Jetted active galactic nucleus (AGN)

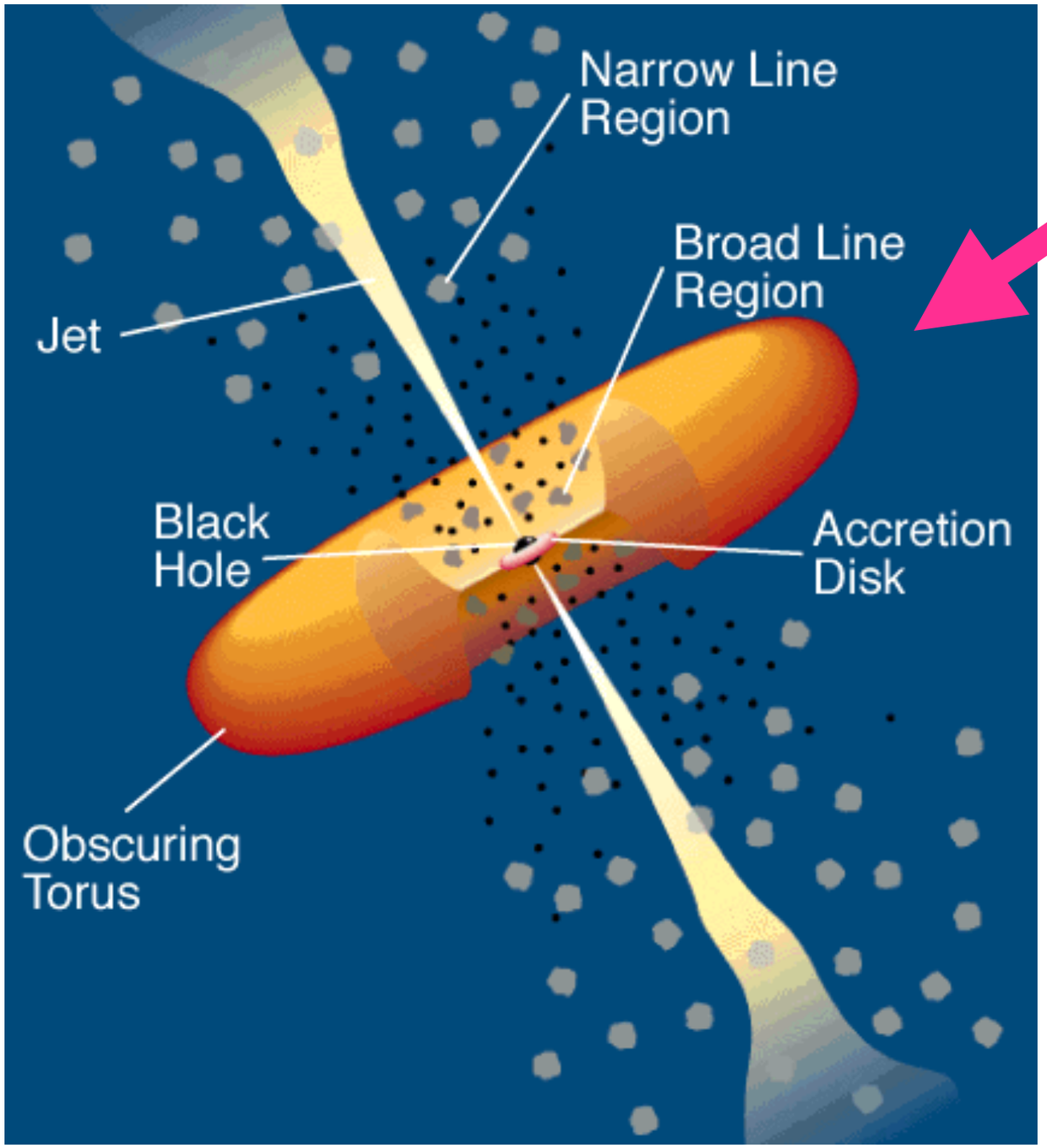


- Central, supermassive black hole ($10^{7\text{-}9}$ solar masses)
- Energy from *accretion*
- Jet of ultra-relativistic particles extending for several *kiloparsec*

1 parsec = 1pc = 3,26 light years

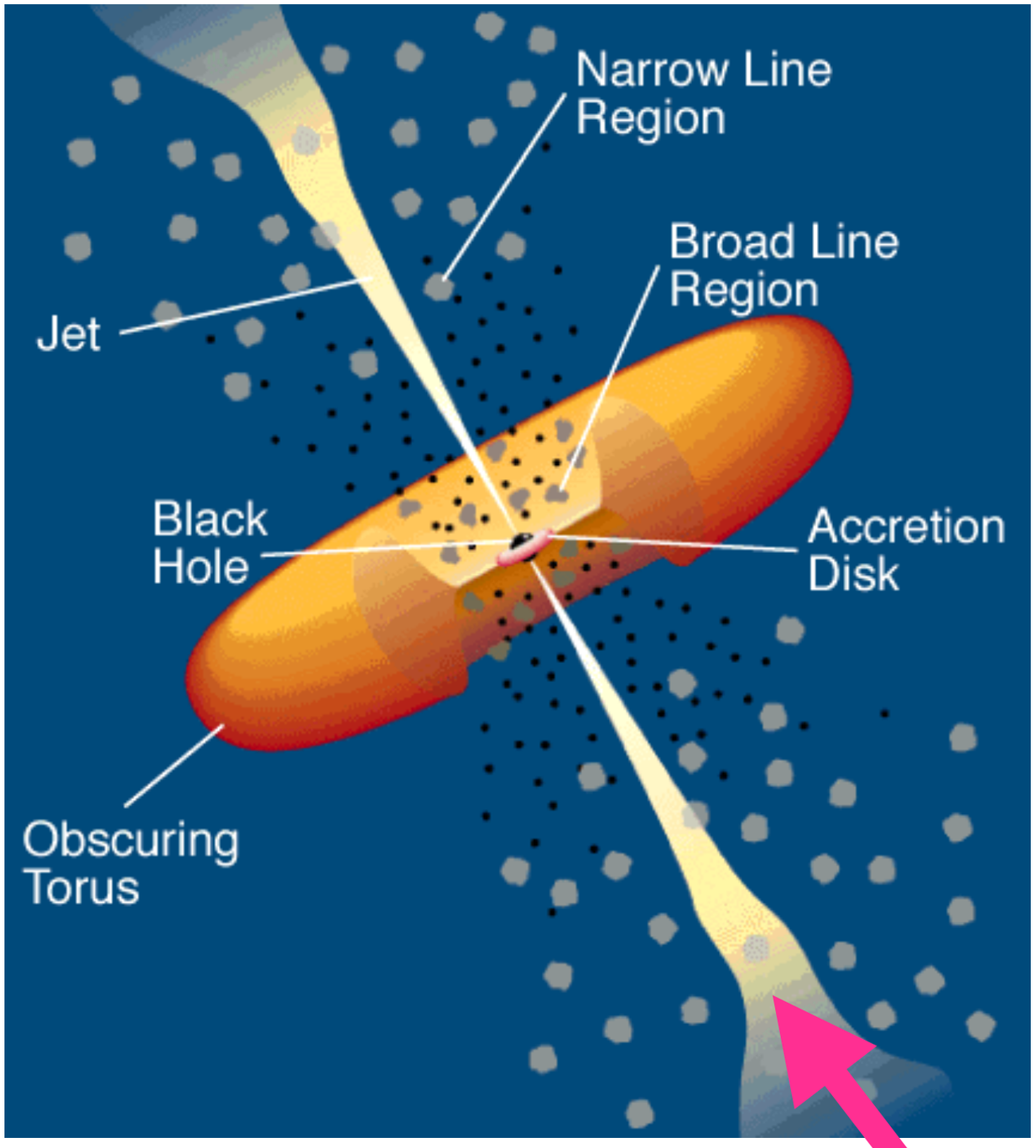
Where do cosmic rays (and gamma rays) come from?

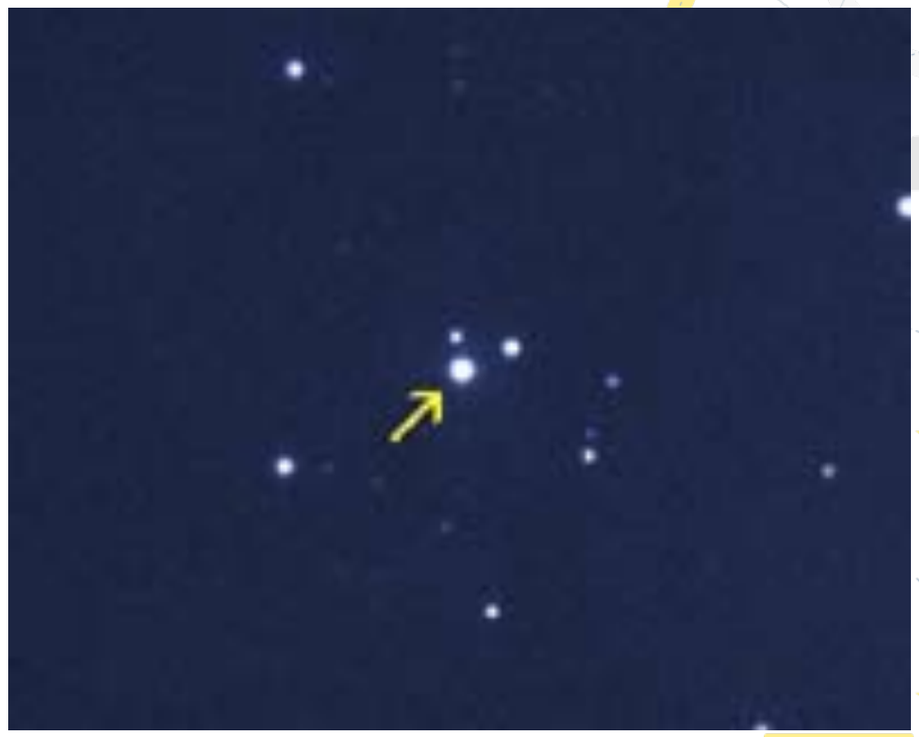
jetted-AGN from one side



This is a radiogalaxy

jetted-AGN from the other perspective





This is called a blazar!

Paper #7 (Mkn 421)

Paper #8 (Neutrino blazar)

Active galaxies: historical perspective

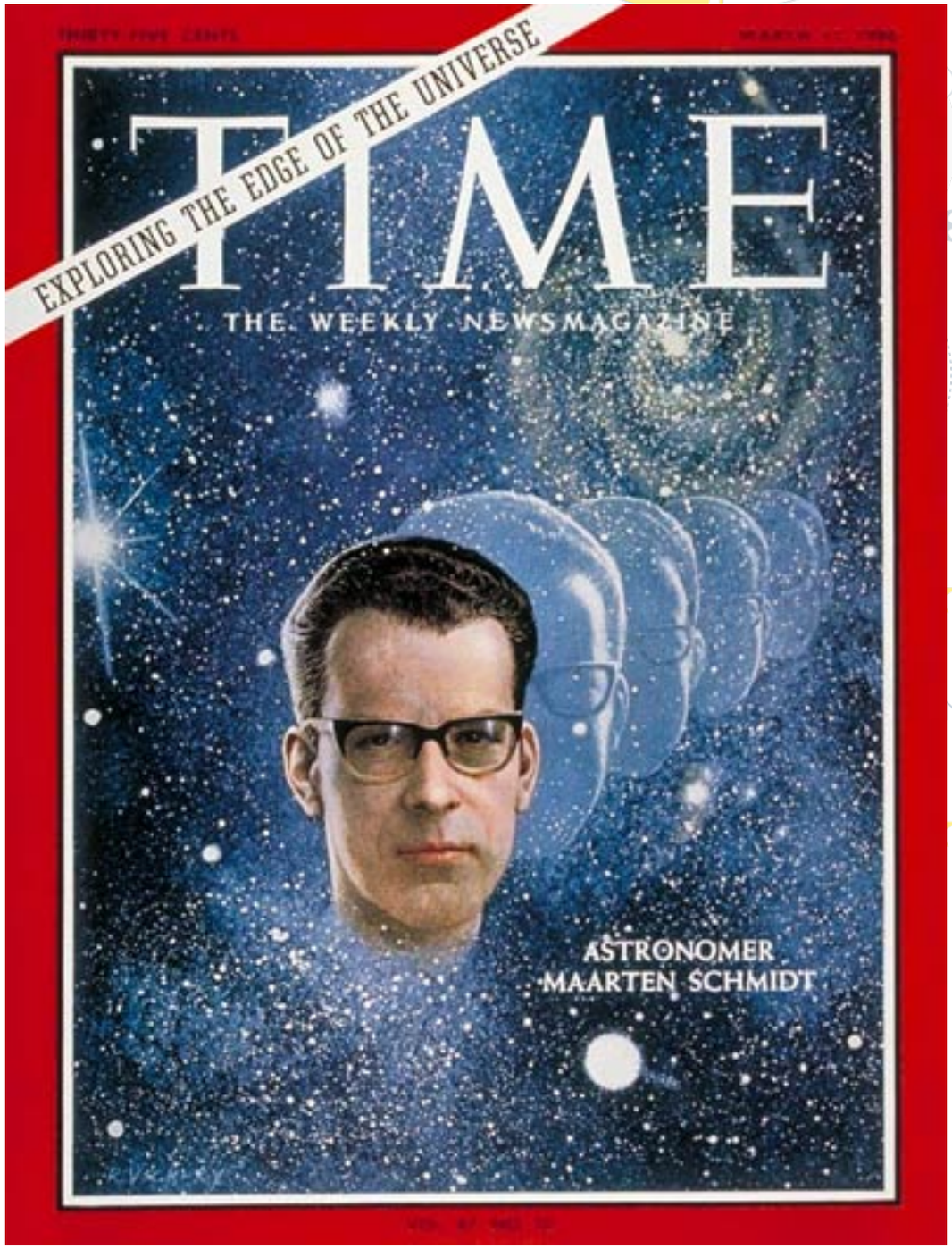
beginning of 1900 - systematic star's spectral studies and classification (**Annie Jump Cannon** among others). Also nebula spectra are investigated and show evident emission lines.

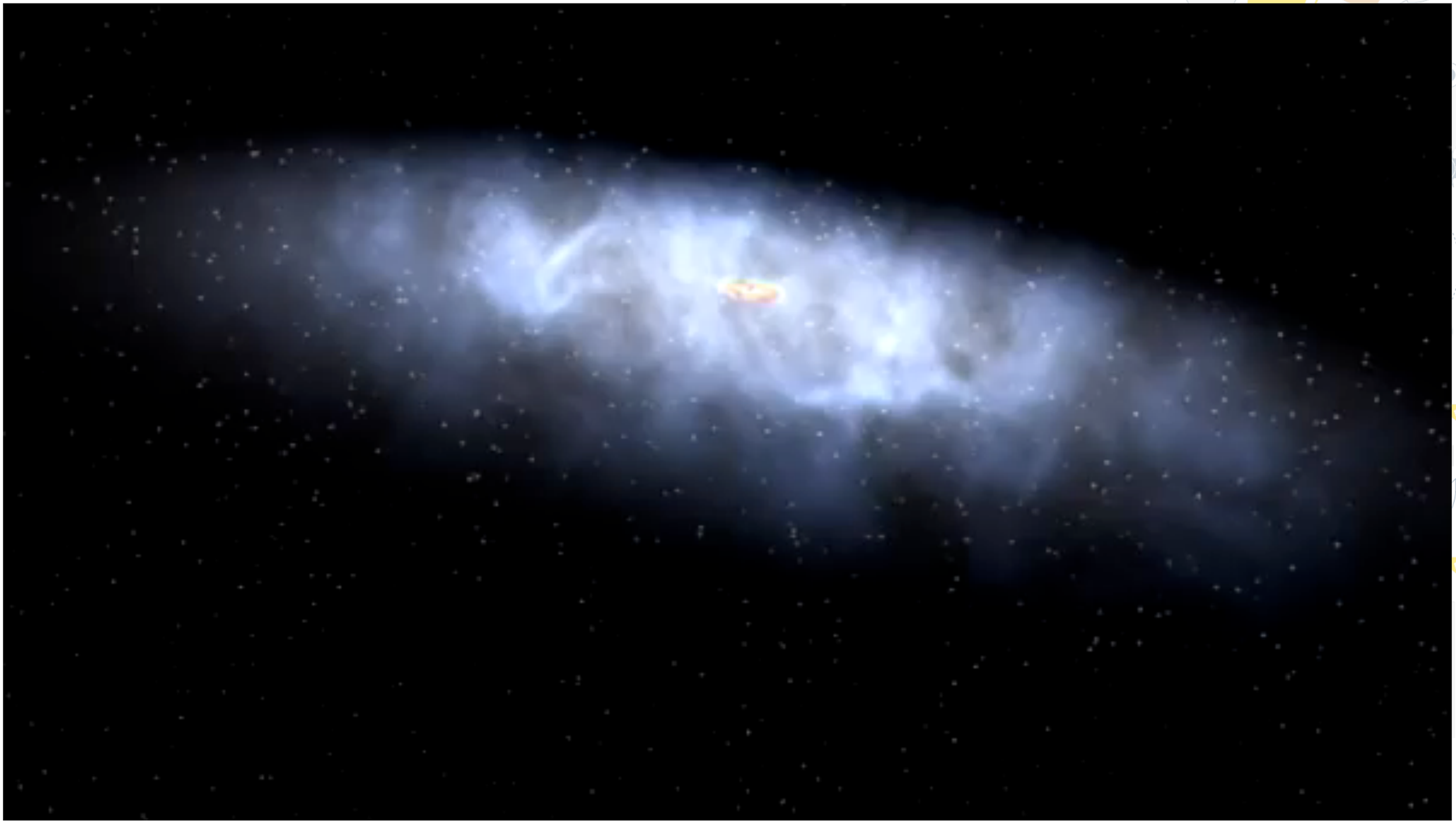
1908 - **Edward Fath** discover emission lines from the galaxy NGC 1068

1926 - **Edwin Hubble** obtains nebula-like spectra from 3 galaxies

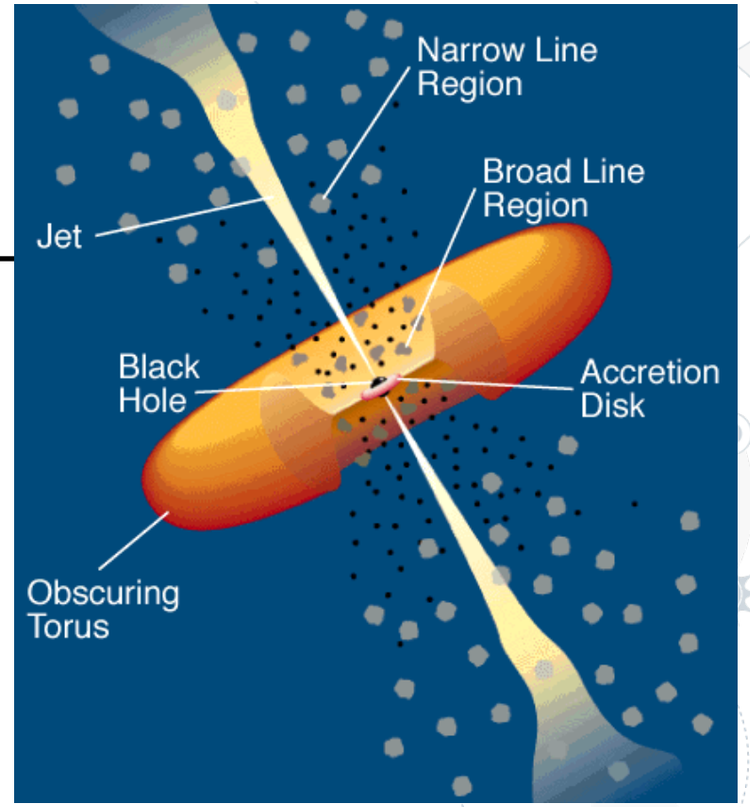
1943 - **Carl Seyfert** starts a systematic study of galactic nuclei with emission lines (later on named Seyfert galaxies)

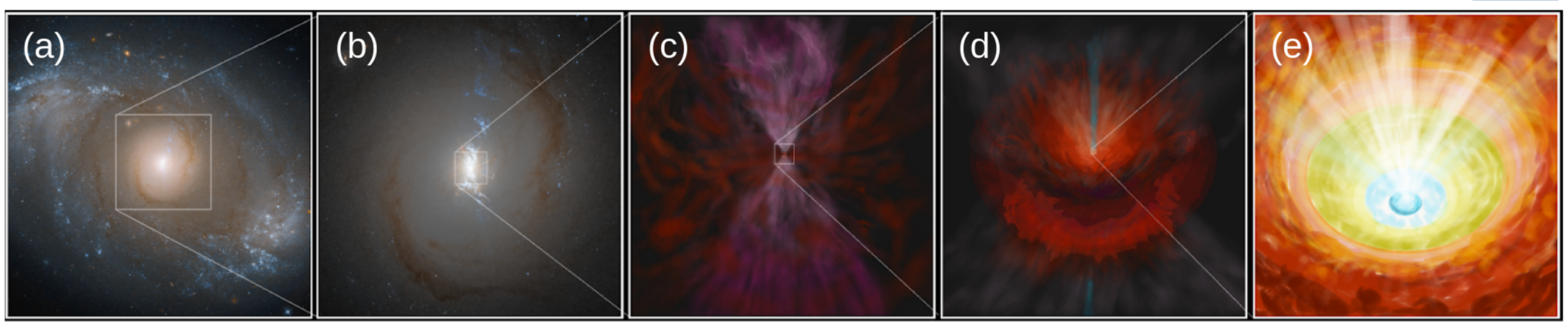
1963 – **Maarten Schmidt** recognises the hydrogen lines in the optical spectrum of the radio source 3C 273 and estimated its incredible distance: almost 3 billions light years!





Non-jetted active galaxy: zooming into its heart





~10-100 kpc whole galaxy	~1-10 kpc galactic nuclei region	~0.1-1 kpc NLR/polar dust	~1-100 pc dusty torus	~0.01-1 pc dust sublimation zone
near- to far-IR	near- to far-IR	mid- to far-IR	near- to mid-IR	near-IR

Jetted active galaxy:
zooming into its heart with a multi-wavelength approach

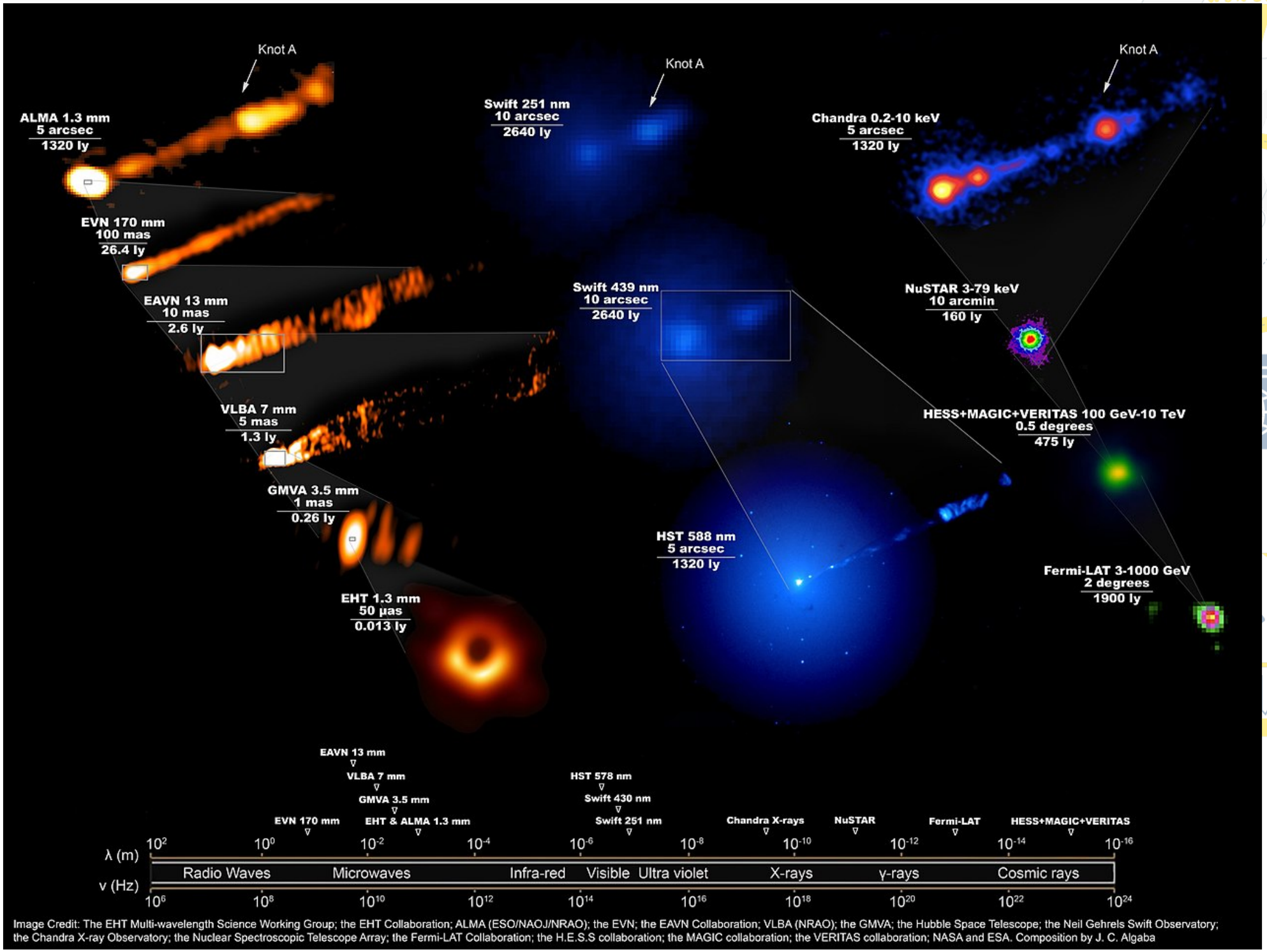
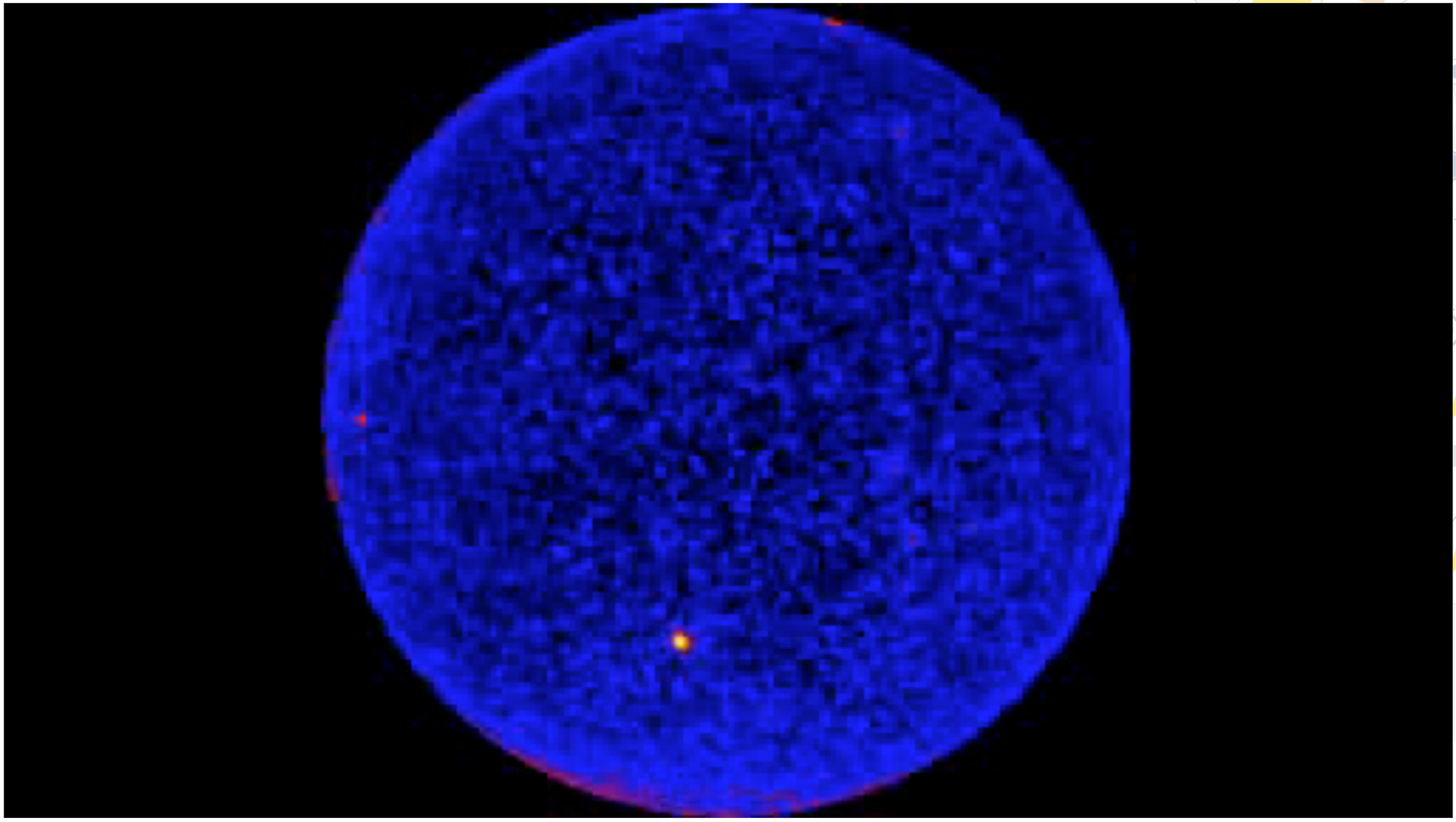


Image Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope; the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array; the Fermi-LAT Collaboration; the H.E.S.S collaboration; the MAGIC collaboration; the VERITAS collaboration; NASA and ESA. Composition by J. C. Algaba

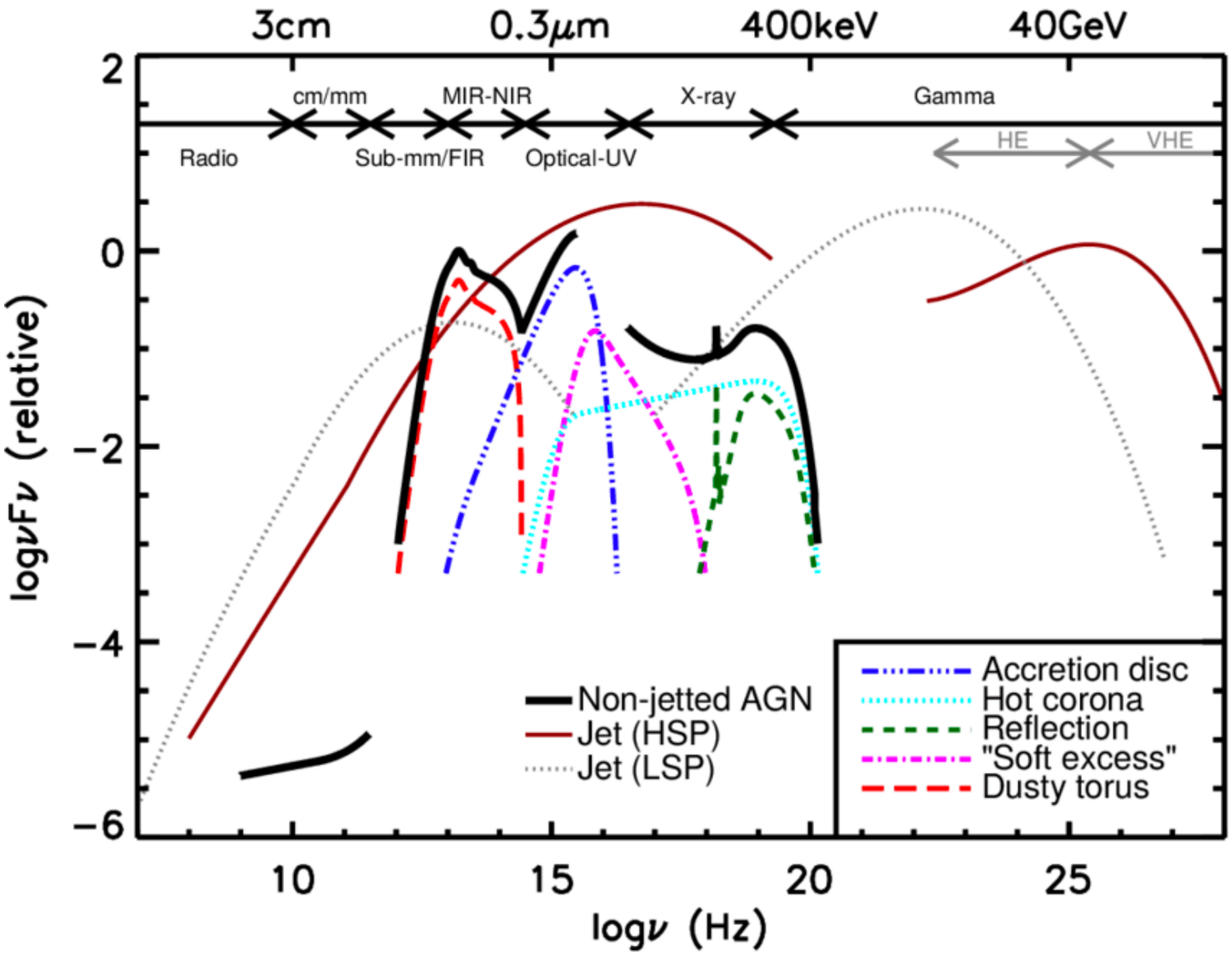
A **movie** of the **gamma ray sky** as seen by the *Fermi* satellite

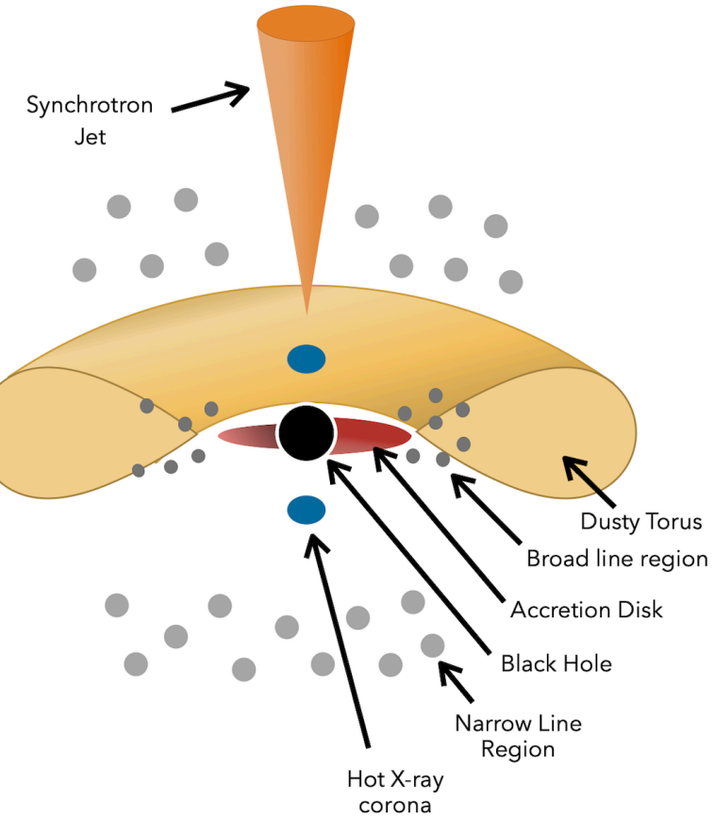


Key points

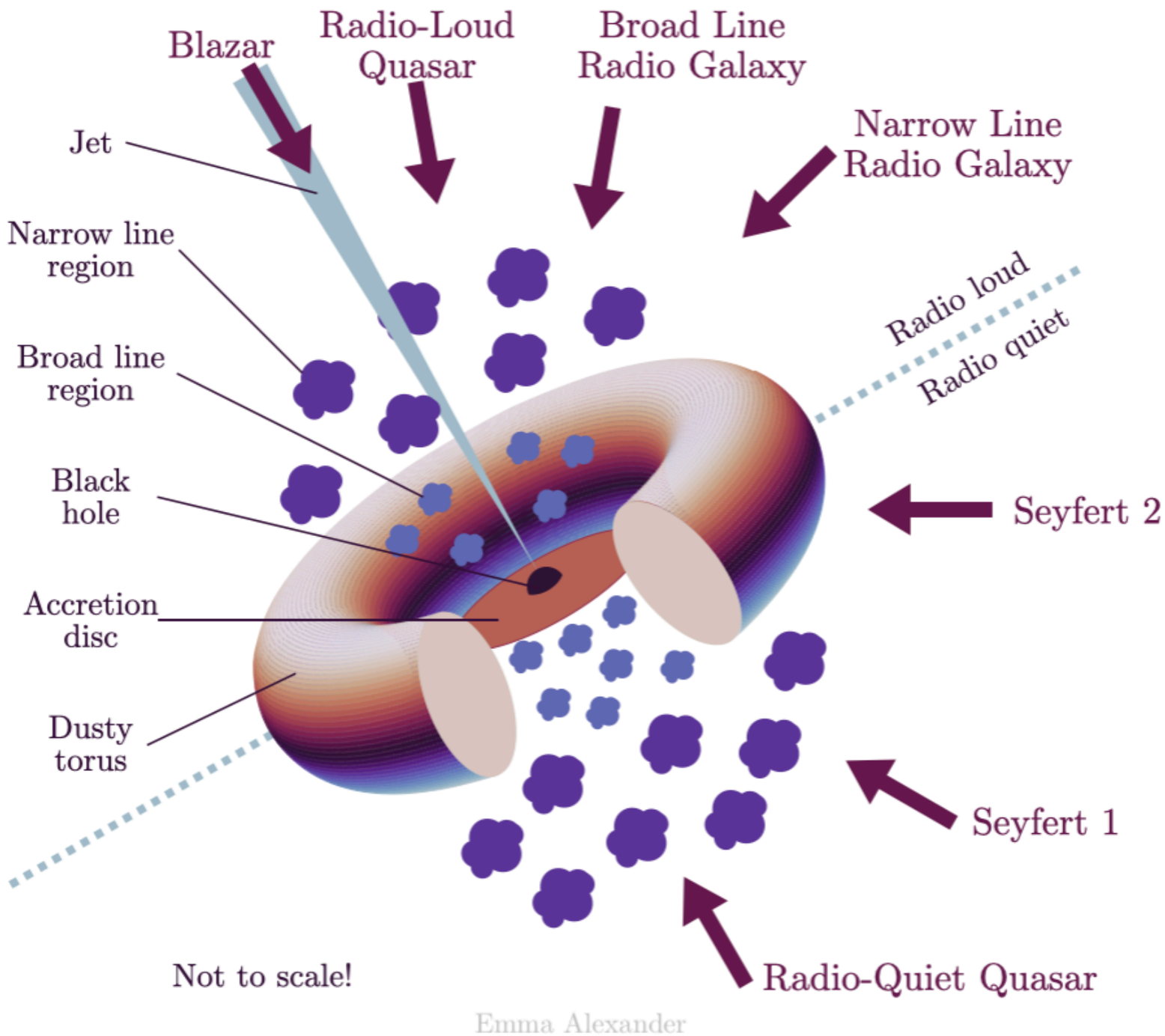
- Active galaxies are **particle accelerators** in the sky
- They are objects outside our galaxy: **extragalactic**
- The **jet of active galaxies** is where we think that particles (protons, electrons, …) are accelerated
- Also **gamma rays** are expected to be produced in the jet via non-thermal processes
- The study of gamma rays allows us to investigate the **origin of cosmic rays** since they point to their generator
- However, active galaxies are **variable emitters**, and this makes things quite complex!

Let's play astrophysics! Active galaxies emission





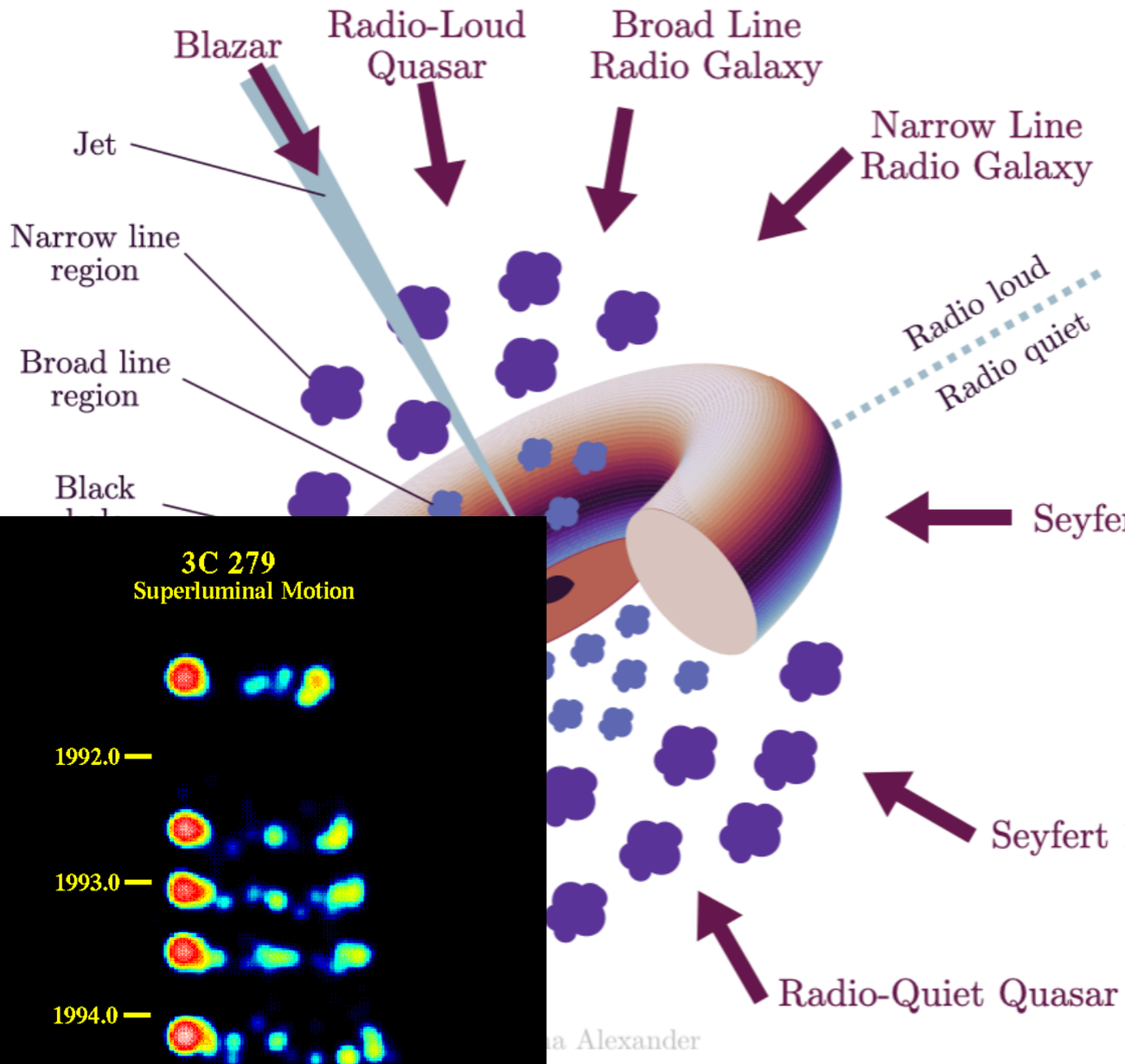
Let's play astrophysics!
Active galaxies emission - **jetted case**



Now imagine that you can change the orientation of the observer. Which is in your opinion the **easiest object** to study?

(not easy… try!)

Let's play astrophysics!
Active galaxies emission - **jetted case**



Blazars: dominated by the **relativistic boost**!

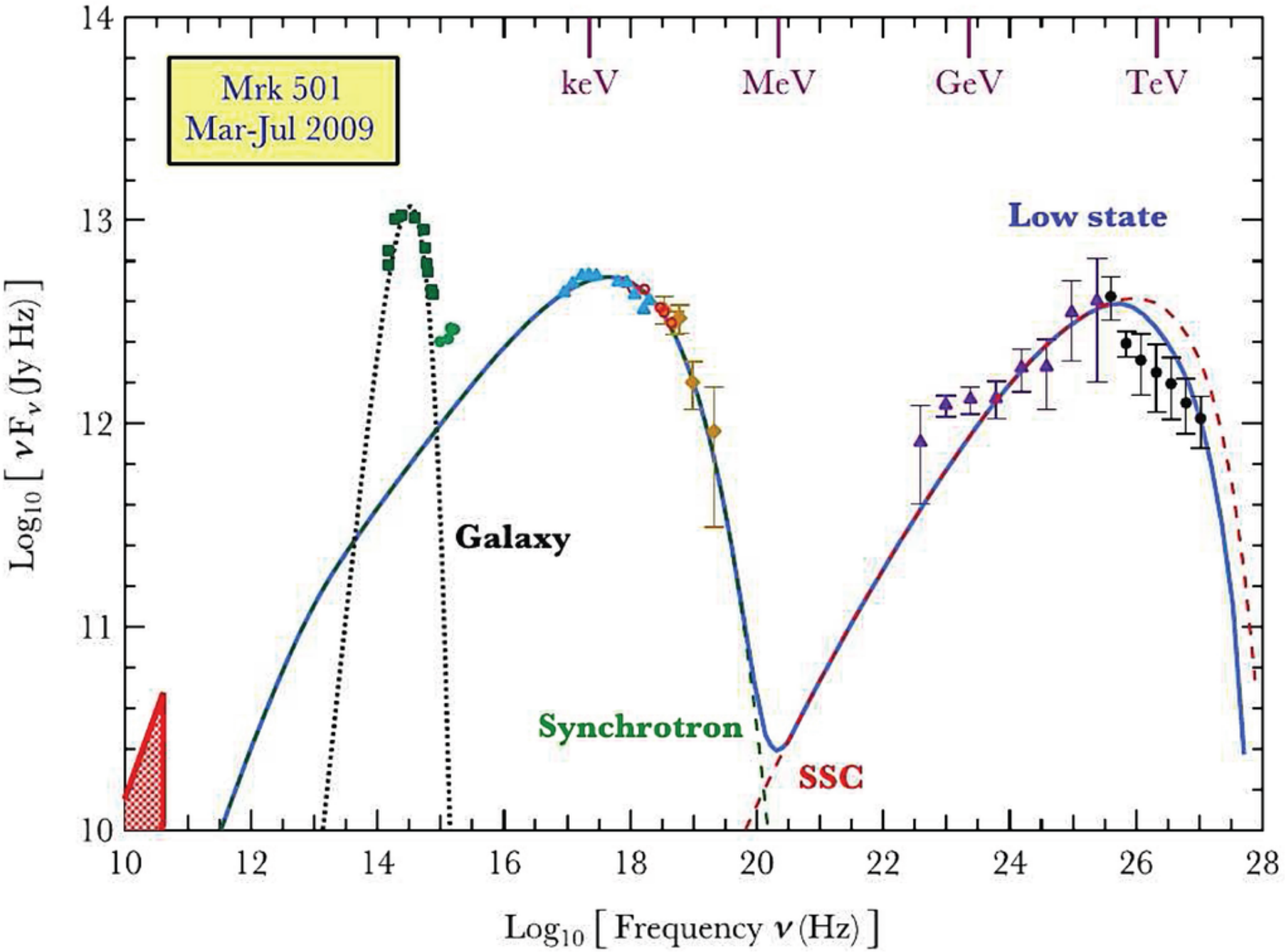
- **Time** is contracted

- **Luminosity is highly enhanced**

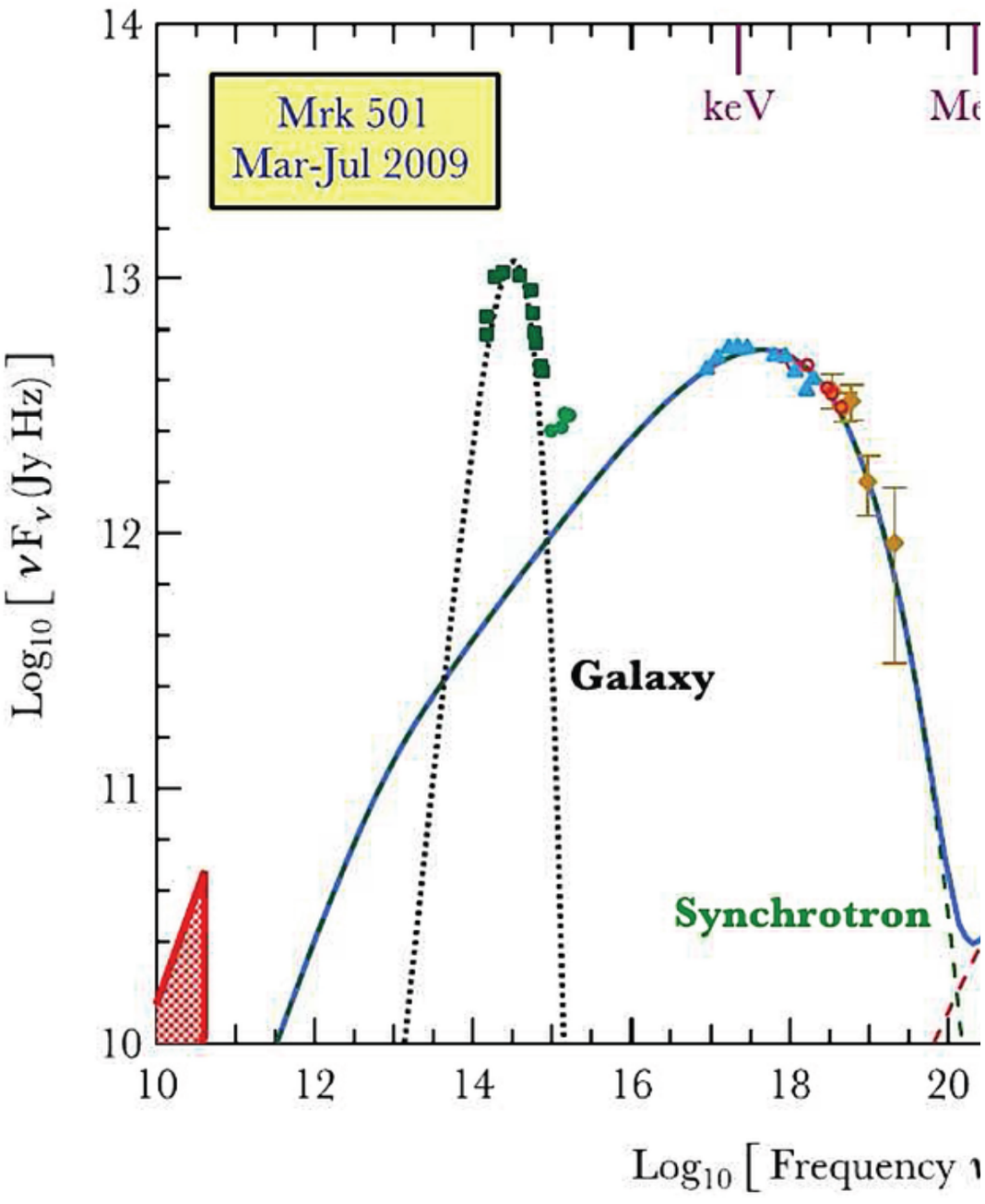
- Explaination of **superluminal motion** detected in some blazars (example: 3C 279)

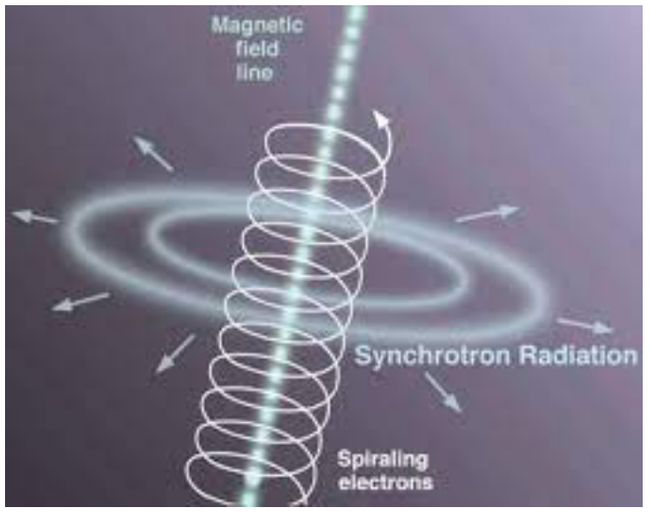
From a blazar you 'see' almost only the jet!

Let's play astrophysics!
Blazars: **a PICTURE**



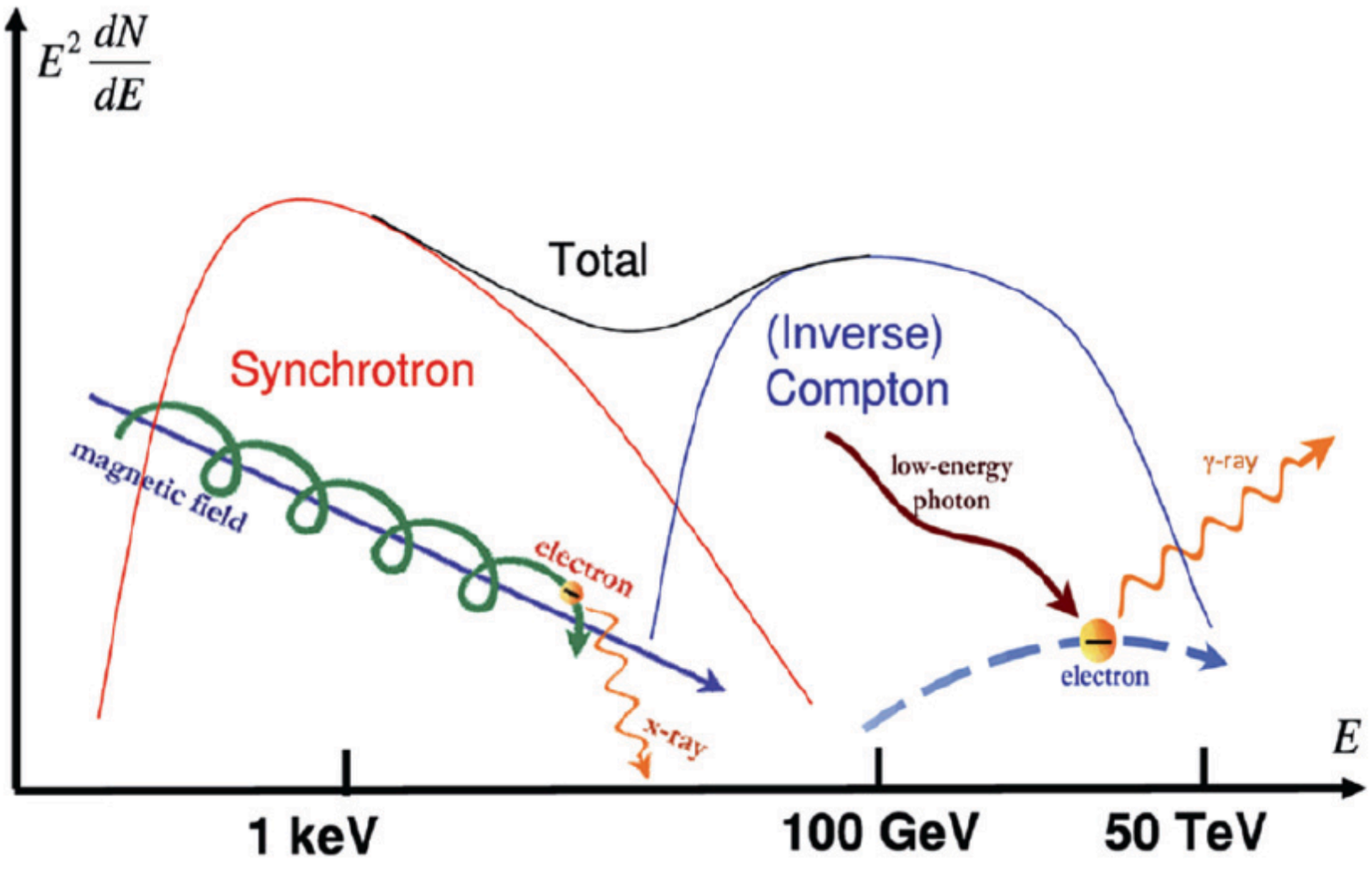
Let's play astrophysics!
Blazars: **a PICTURE**





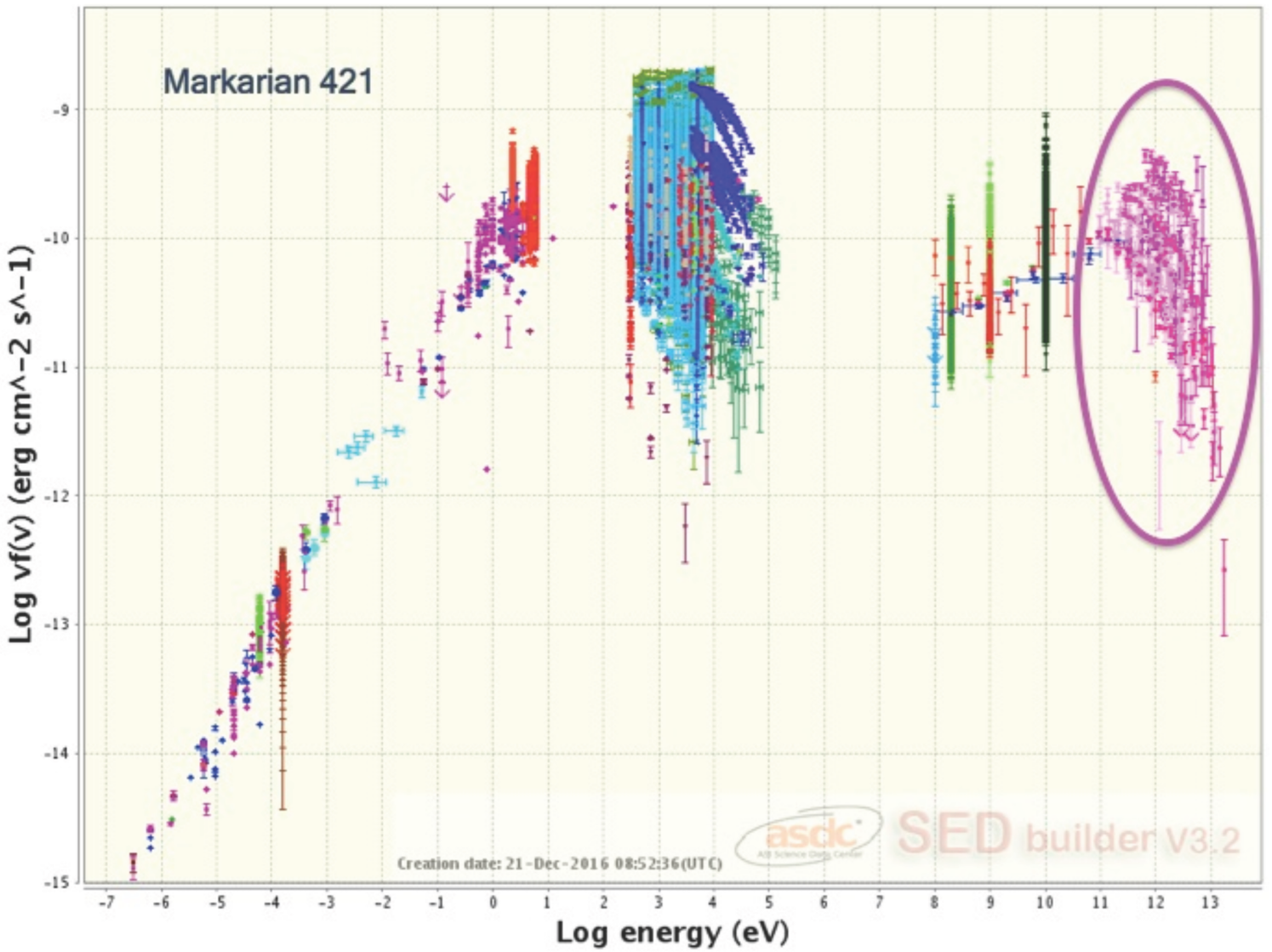
Let's play astrophysics!
Blazars: **a PICTURE**

- **Inverse Compton emission**



Let's play astrophysics!
Blazars: **a (sort of) MOVIE**

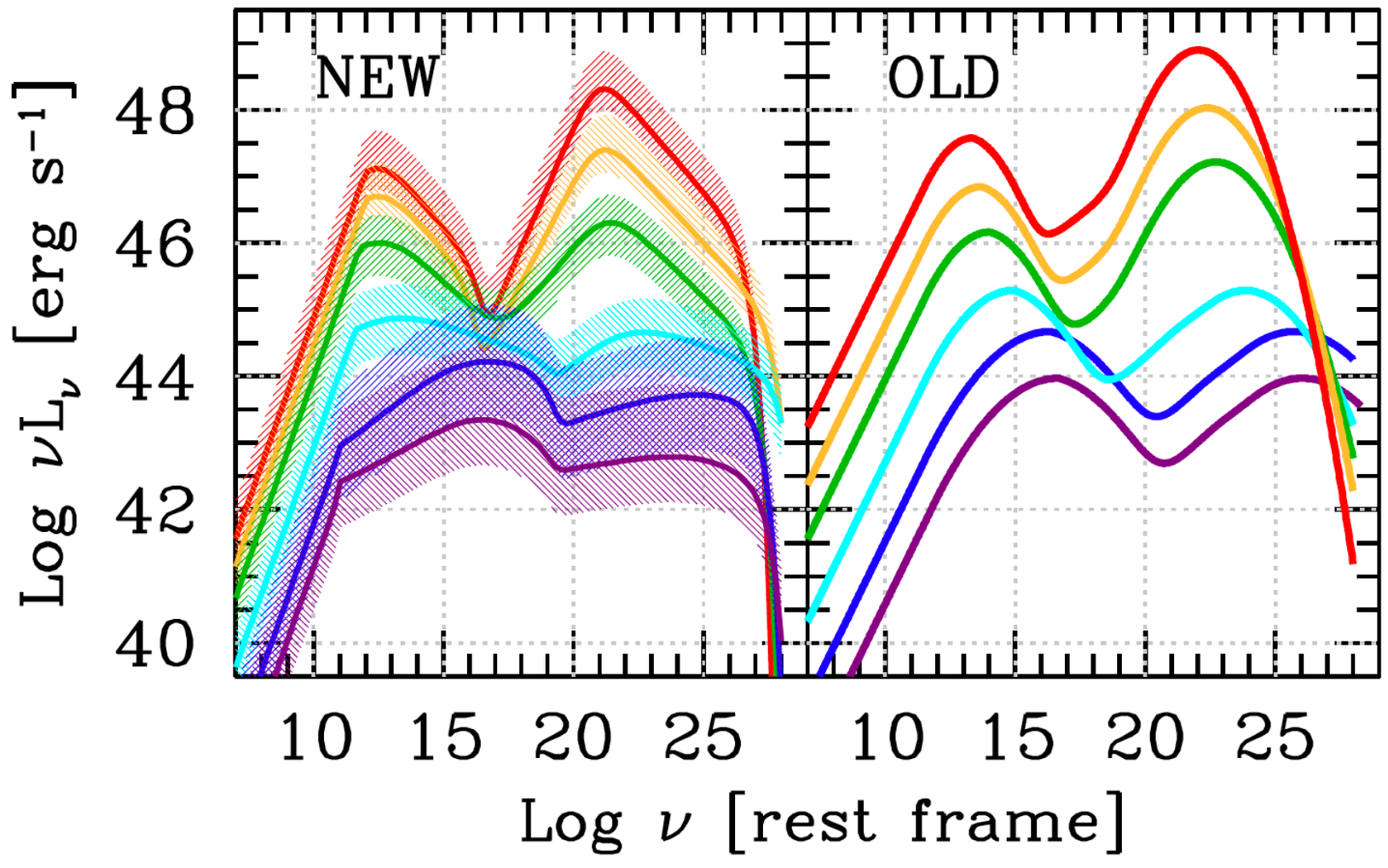
- Synchrotron emission
- Inverse Compton emission
- Large variability!



Can you estimate by eye the location of the peaks? Can you tell which wavelength is that?

The blazar sequence

Anti-correlation between the synchrotron peak position and the source luminosity

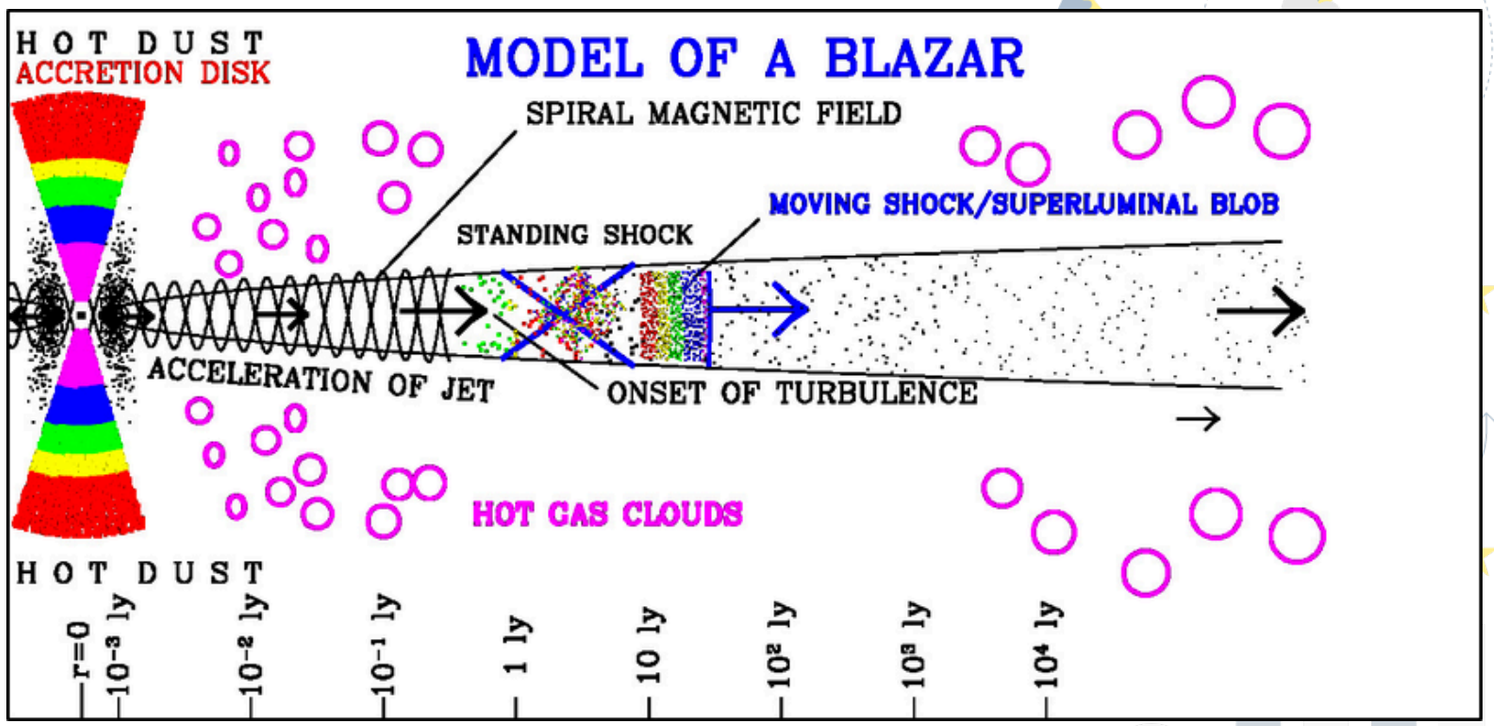


Hands-on:
Let's build the spectral energy distribution of a few sources and verify the blazar sequence

Fossati+ 1998, Ghisellini 2018

Blazars: from observations to models

- Purpose of multi-band observations of blazar is that of providing a set of data to be **modelled**
  - Acceleration mechanism
  - Physical conditions of the emitting region
- Very exciting and developing field! Also very complex!



Thursday lectures dedicated on this topic

Strongly connected with cosmic ray physics

In conclusion

- Broad overview of some of the key topic of astroparticle physics
  - Cosmic rays
  - Gamma rays as tracer of non-thermal processes
- The extragalactic sky at gamma rays is dominated by blazars
- The blazar broadband emission is relatively simple (two-peak structure) but it changes with time


Thanks