Gamma-ray astronomy

Sylvia J. Zhu
sylvia.zhu@desy.de

Astroparticle School 2025

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

hello!! I’m Sylvia, you can talk to me about:

👋

gamma rays

Fermi
Gamma-ray
Space Telescope

H.E.S.S.

gamma-ray bursts

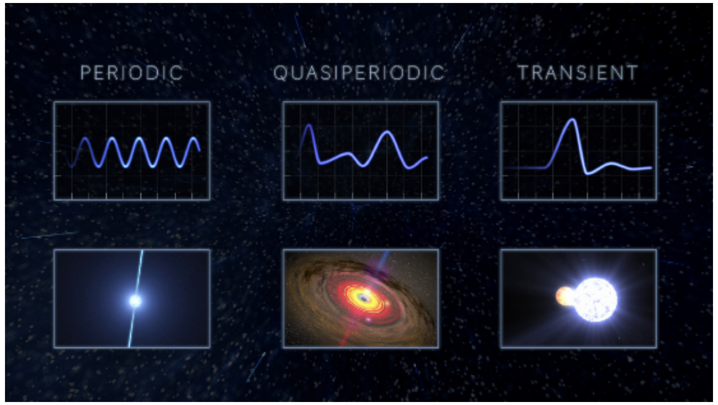
[ESO / A. Roquette]

gen 1 Pokémon

gravitational waves

LSC
LIGO
Scientific
Collaboration

time-domain astronomy



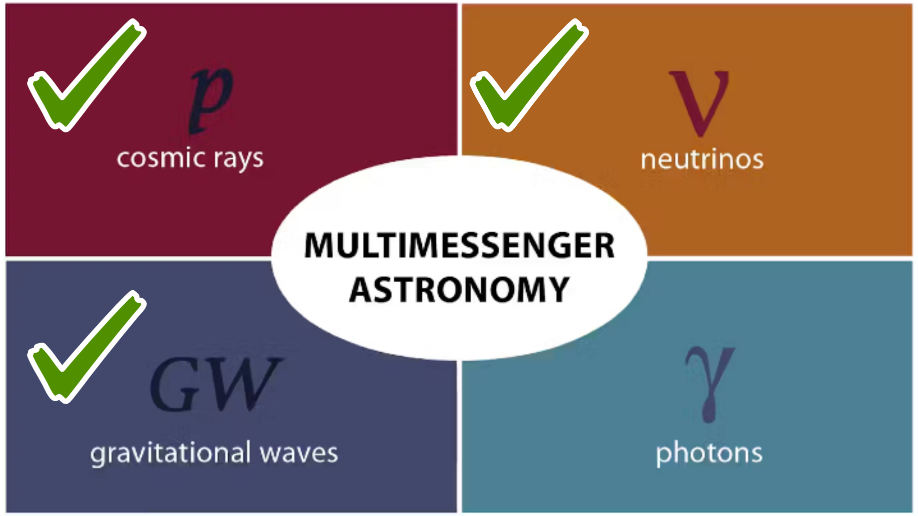
Here's roughly what we're going to discuss in the next 90 min

with a break in between or whatever

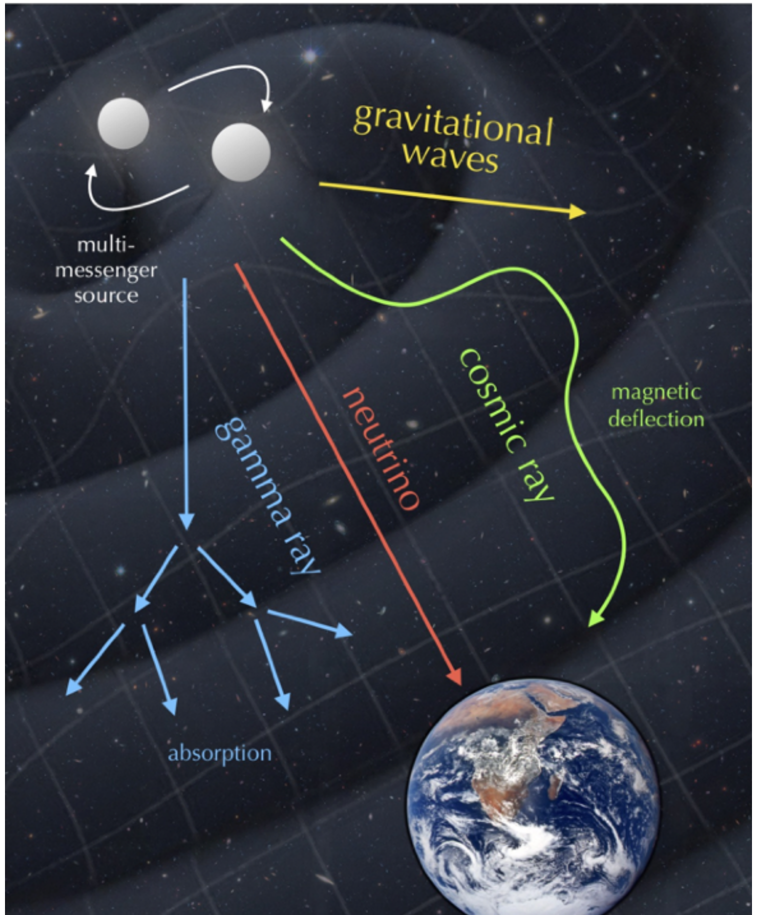
1. How does gamma-ray astronomy connect to the other lectures/talks you've had?
2. How do we detect gamma-ray photons?
3. What kind of physics do we learn from gamma-ray astronomy?

The four astroparticle messengers

You might have seen some diagram like one of these



[The Conversation, adapted from IceCube]

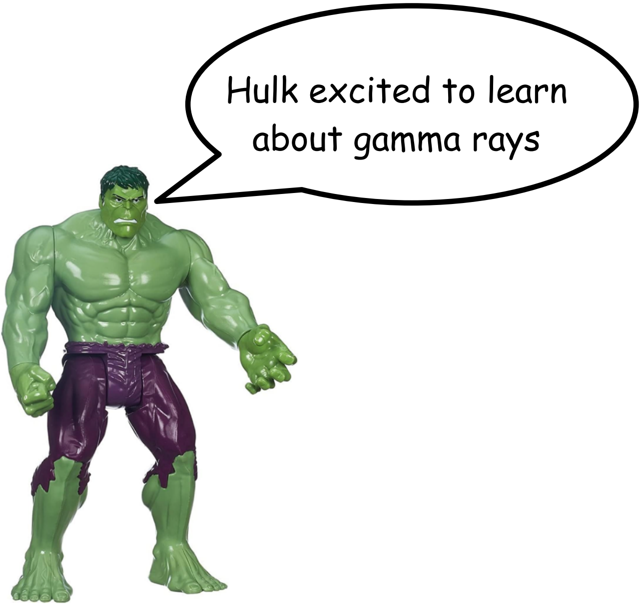


[Niels Bohr Institute]

You've already learned about three of these,
I'm going to talk about (a subset of) the fourth one
and how it connects to the other three

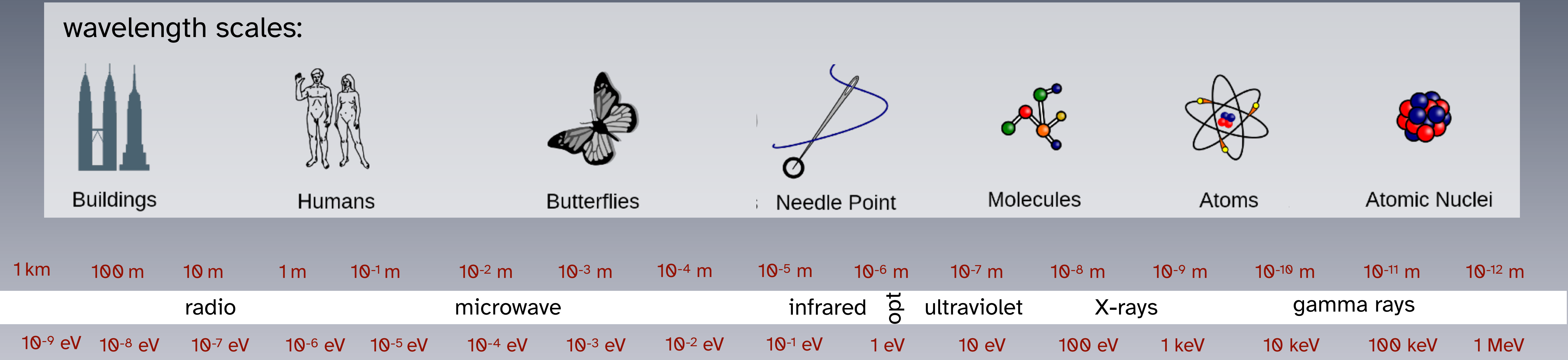
Part 1. Gamma-ray astronomy is multimessenger astronomy

Connecting the astroparticle messengers



The electromagnetic spectrum

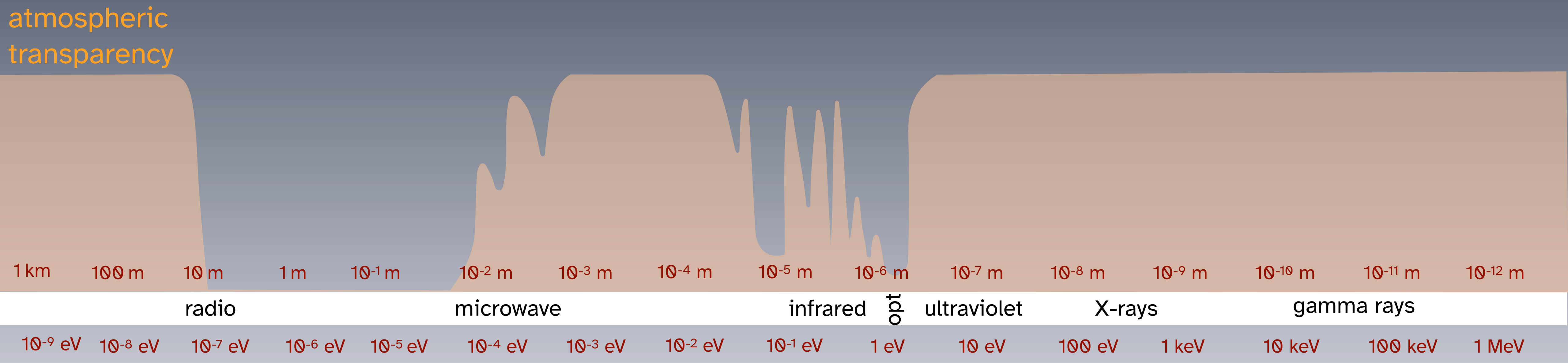
All gamma rays are photons but not all photons are gamma rays



[InductiveLoad]

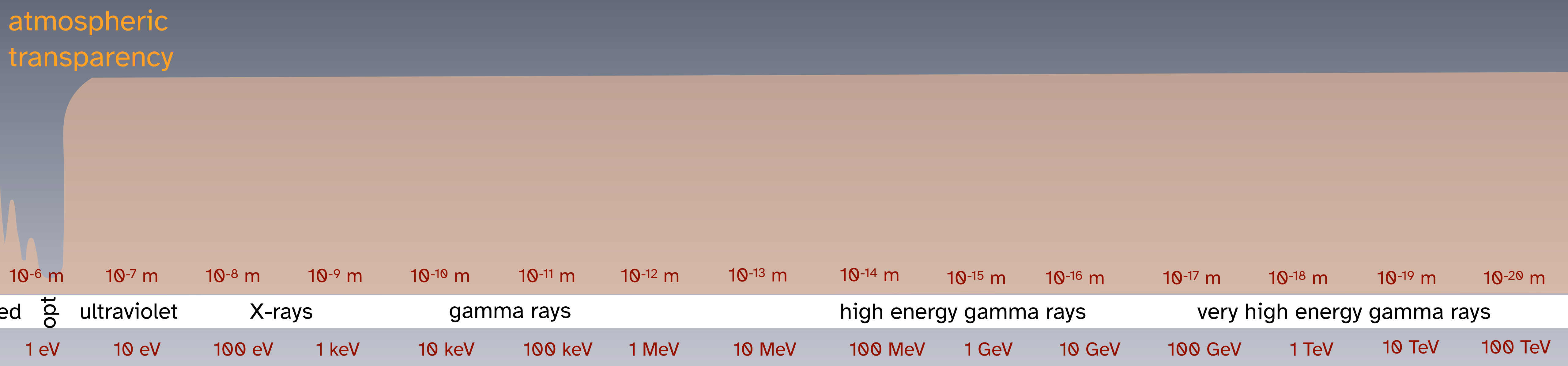
The electromagnetic spectrum

All gamma rays are photons but not all photons are gamma rays



The electromagnetic spectrum, continued

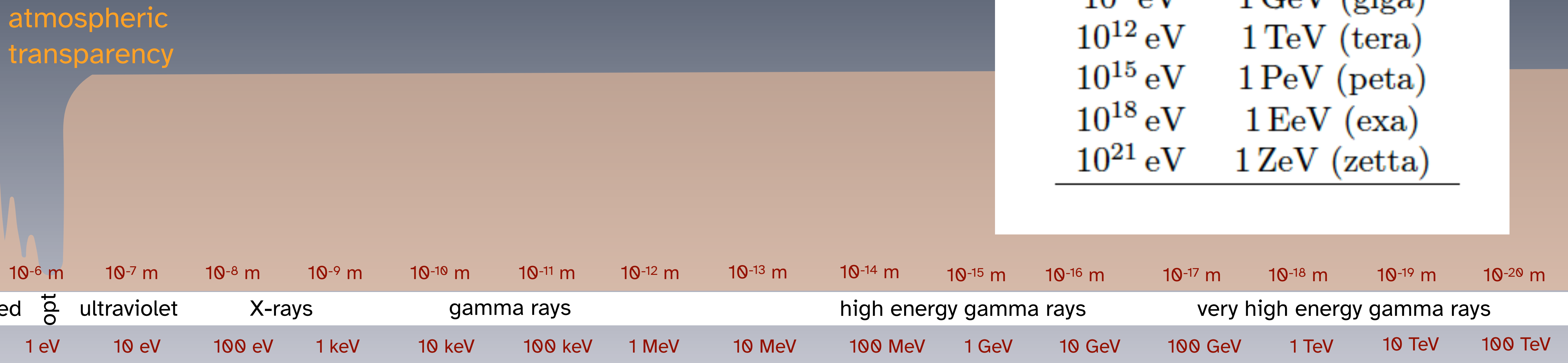
All gamma rays are photons but not all photons are gamma rays



The electromagnetic spectrum, continued

All gamma rays are photons but not all photons are gamma rays

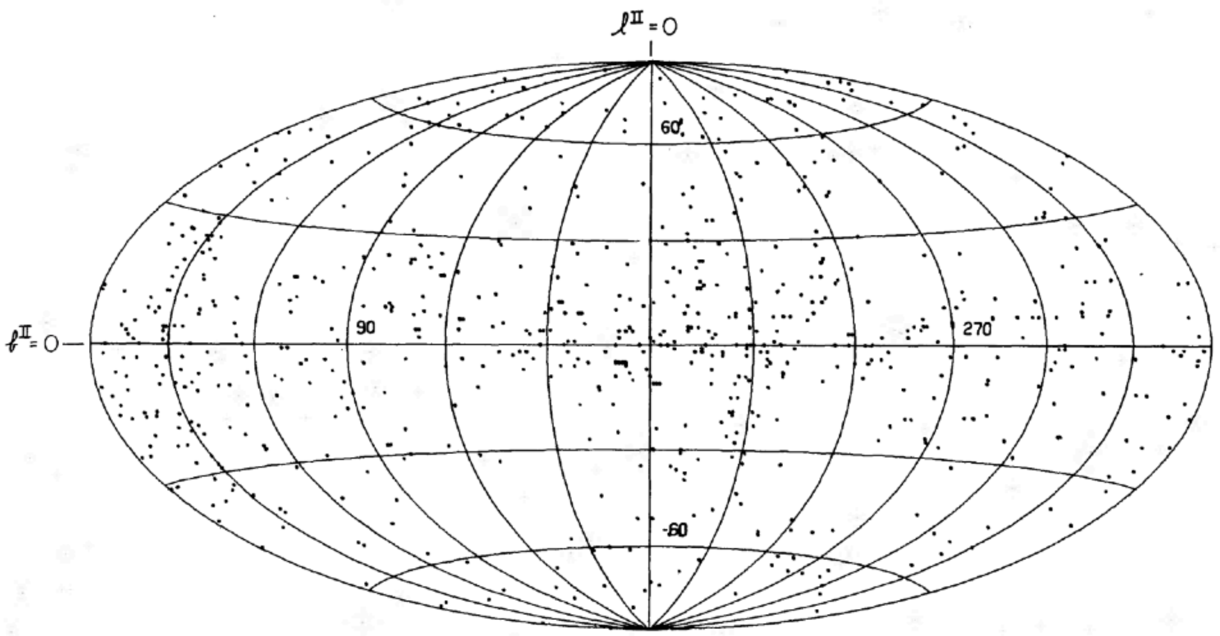
10^3 eV	1 keV (kilo)
10^6 eV	1 MeV (mega)
10^9 eV	1 GeV (giga)
10^{12} eV	1 TeV (tera)
10^{15} eV	1 PeV (peta)
10^{18} eV	1 EeV (exa)
10^{21} eV	1 ZeV (zetta)



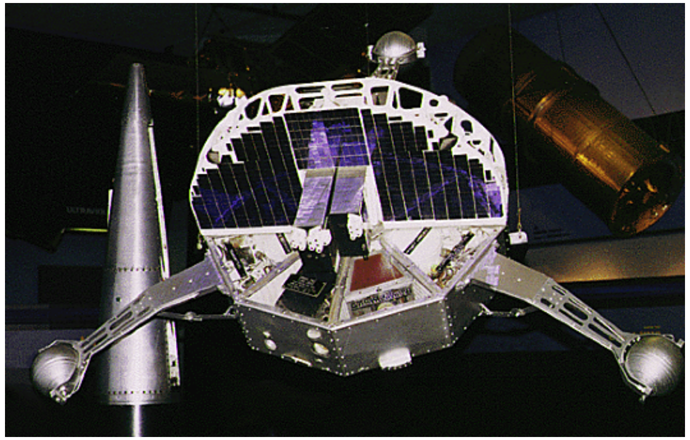
A very brief history of gamma-ray astronomy

Gamma-ray astronomy began when we started to launch satellites

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

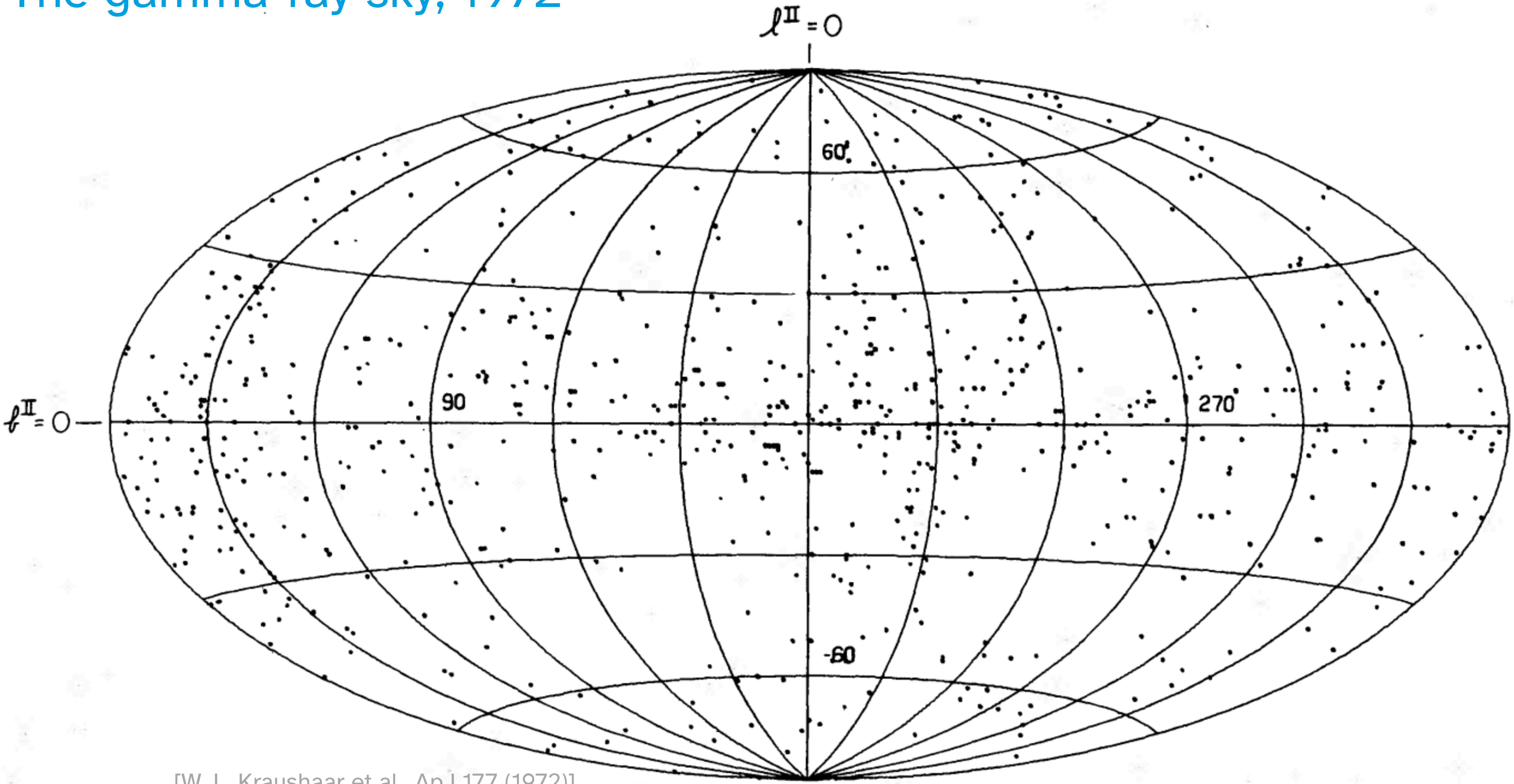


[W. L. Kraushaar et al., ApJ 177 (1972)]



[NASA]

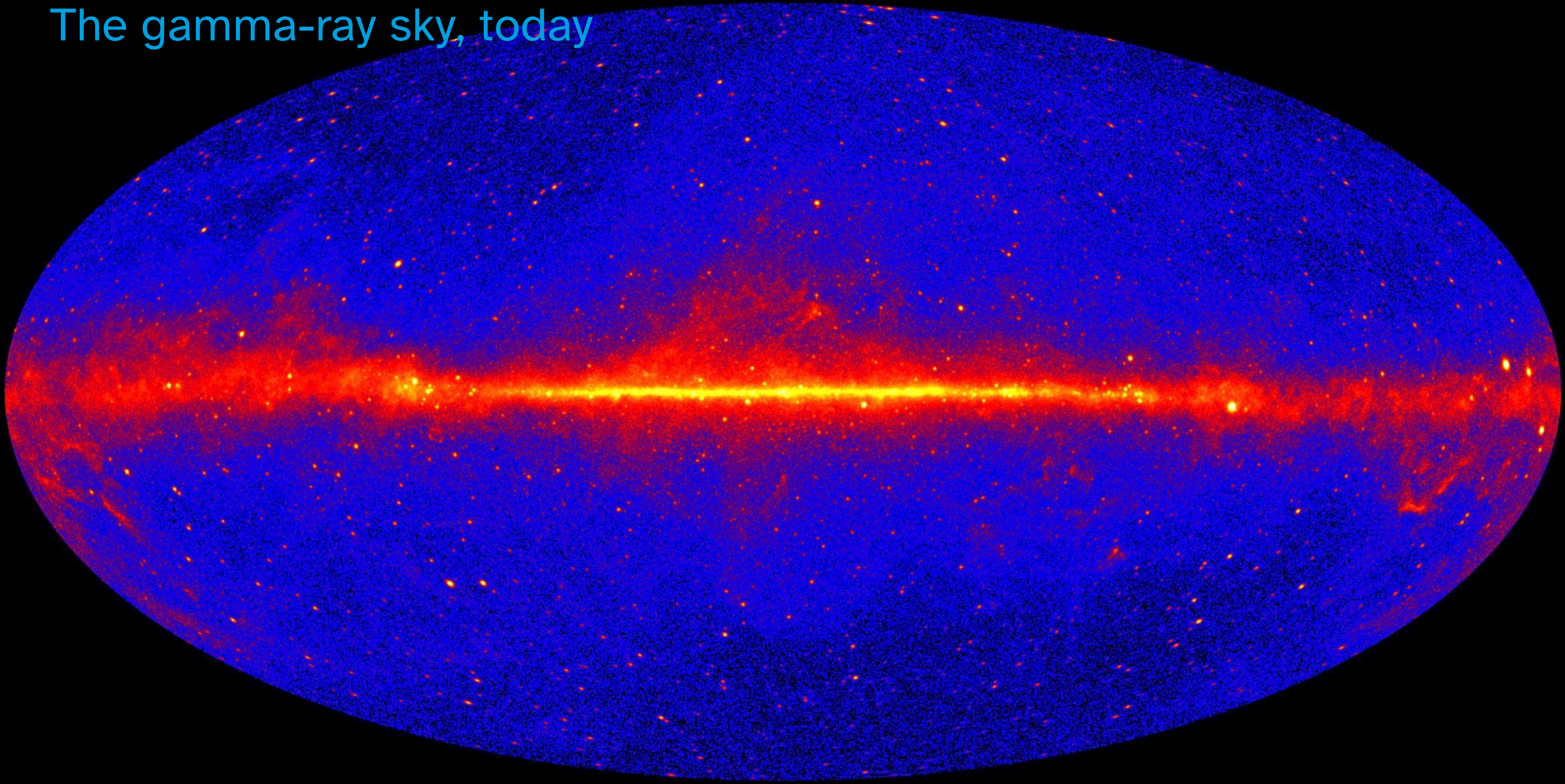
The gamma-ray sky, 1972



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

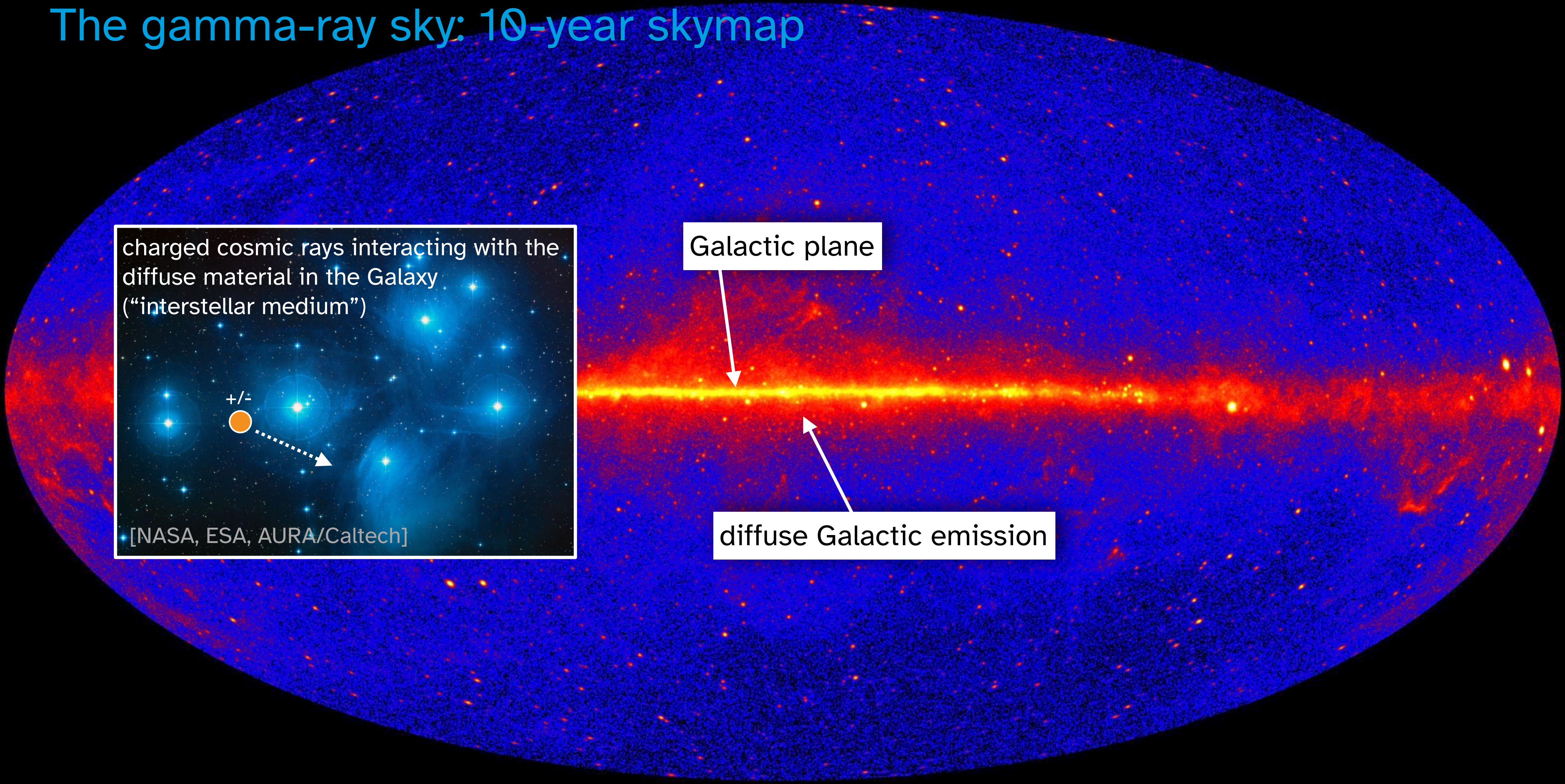
[NASA/DOE/Fermi-LAT Collaboration]

The gamma-ray sky, today



[NASA/DOE/Fermi-LAT Collaboration]

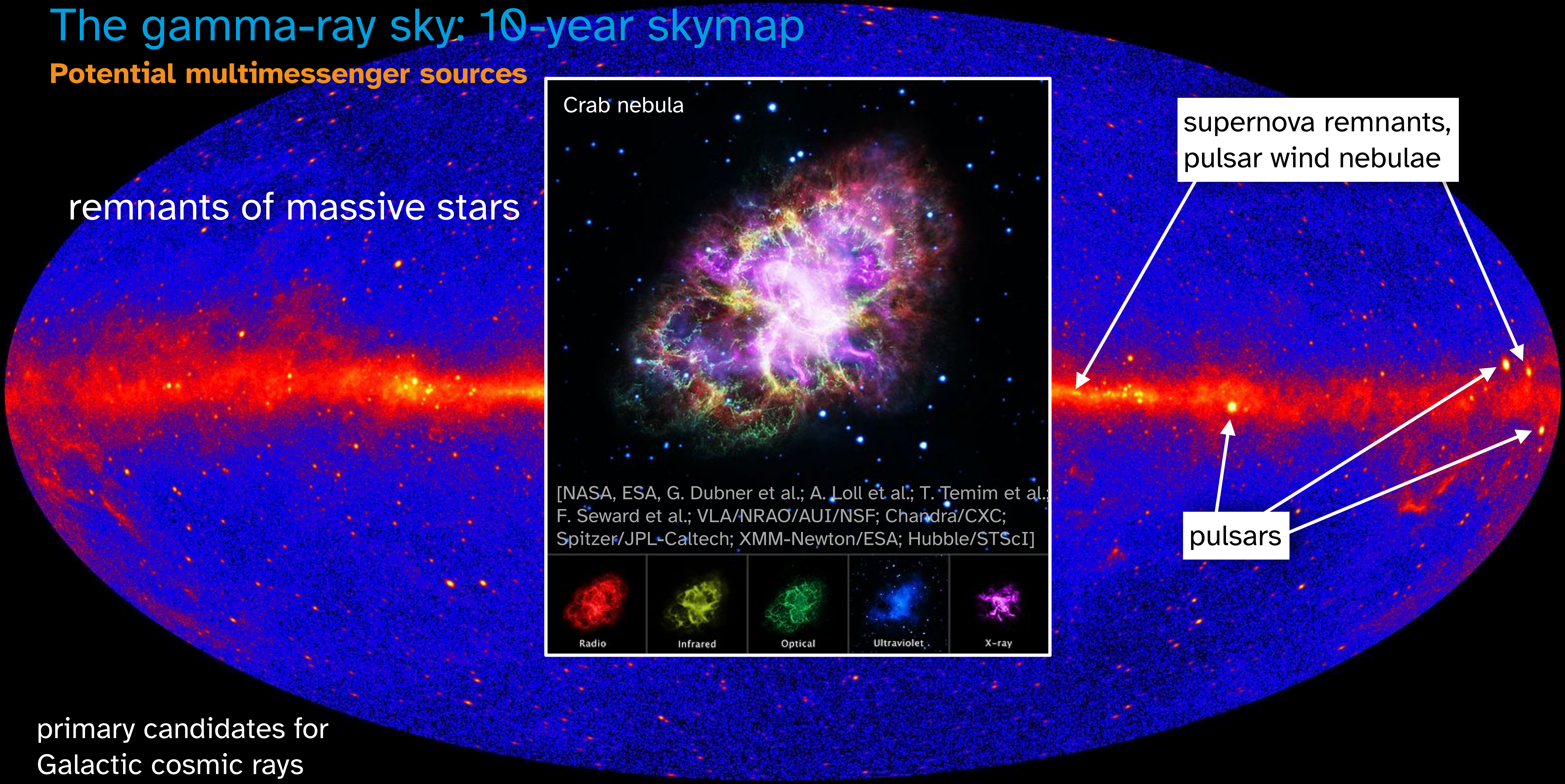
The gamma-ray sky: 10-year skymap



[NASA/DOE/Fermi-LAT Collaboration]

The gamma-ray sky: 10-year skymap

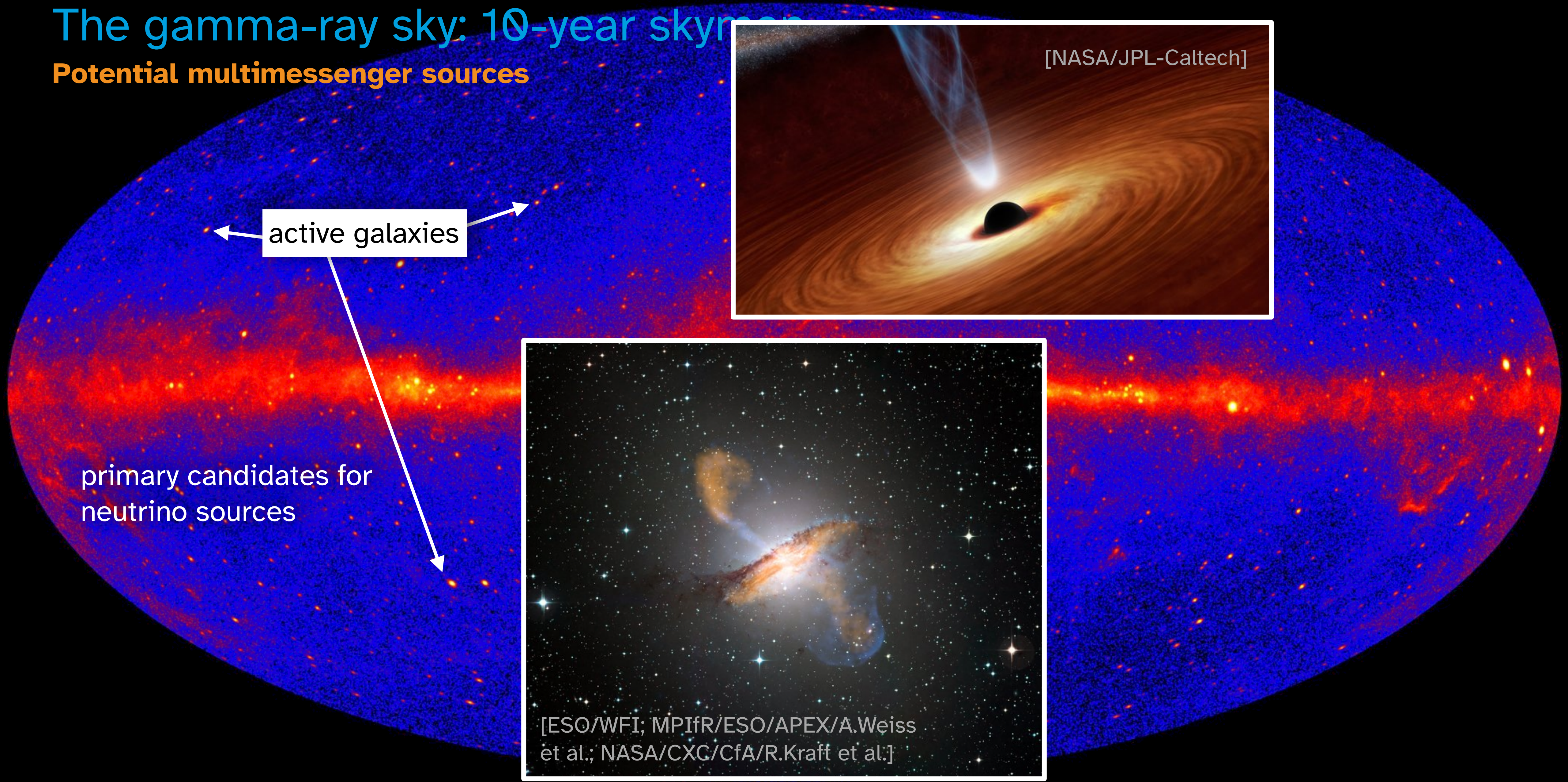
Potential multimessenger sources



The gamma-ray sky: 10-year skymap

Potential multimessenger sources

[NASA/DOE/Fermi-LAT Collaboration]

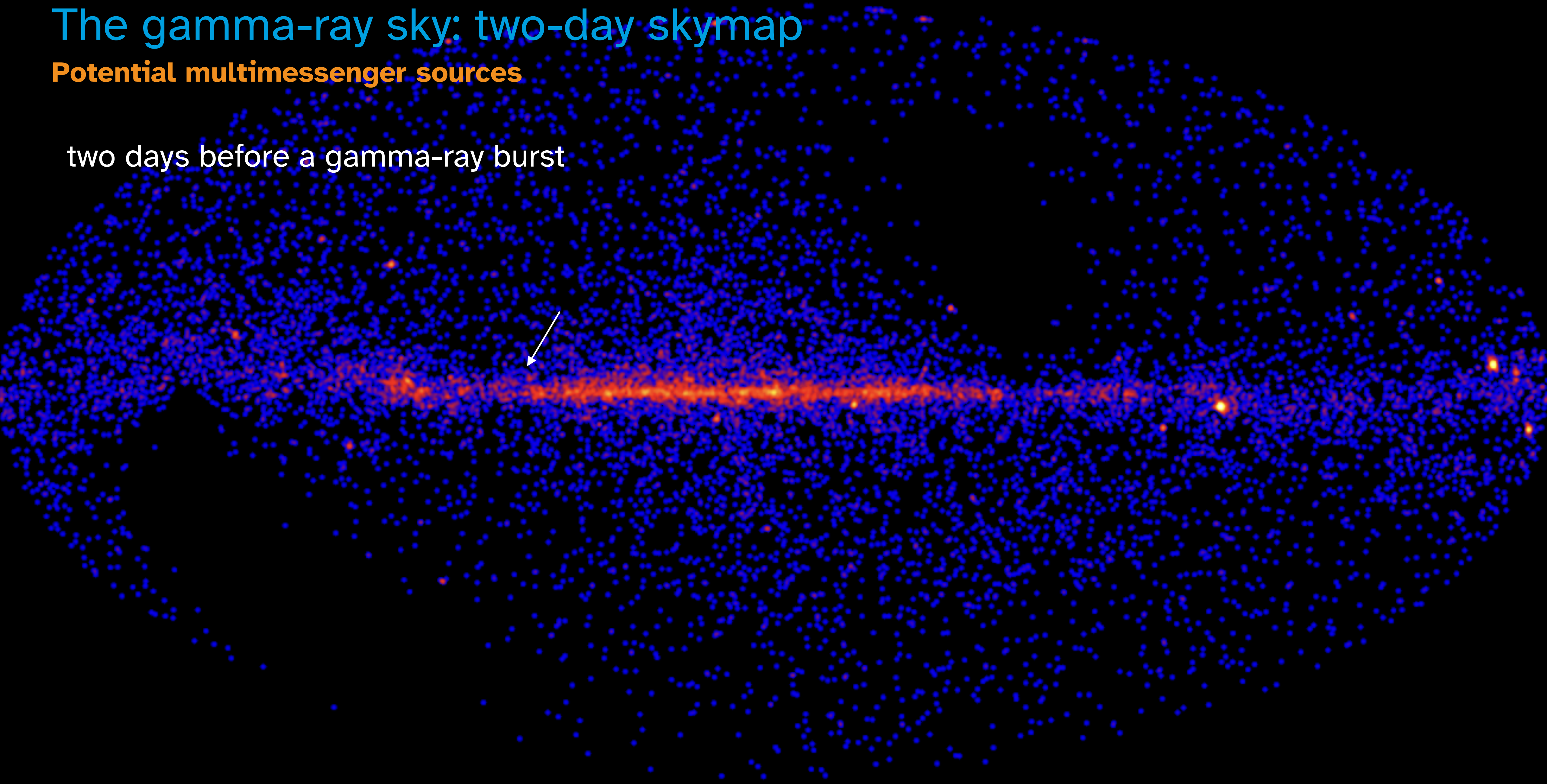


[NASA/JPL-Caltech]

[ESO/WFI; MPIfR/ESO/APEX/A.Weiss et al.; NASA/CXC/CfA/R.Kraft et al.]

The gamma-ray sky: two-day skymap

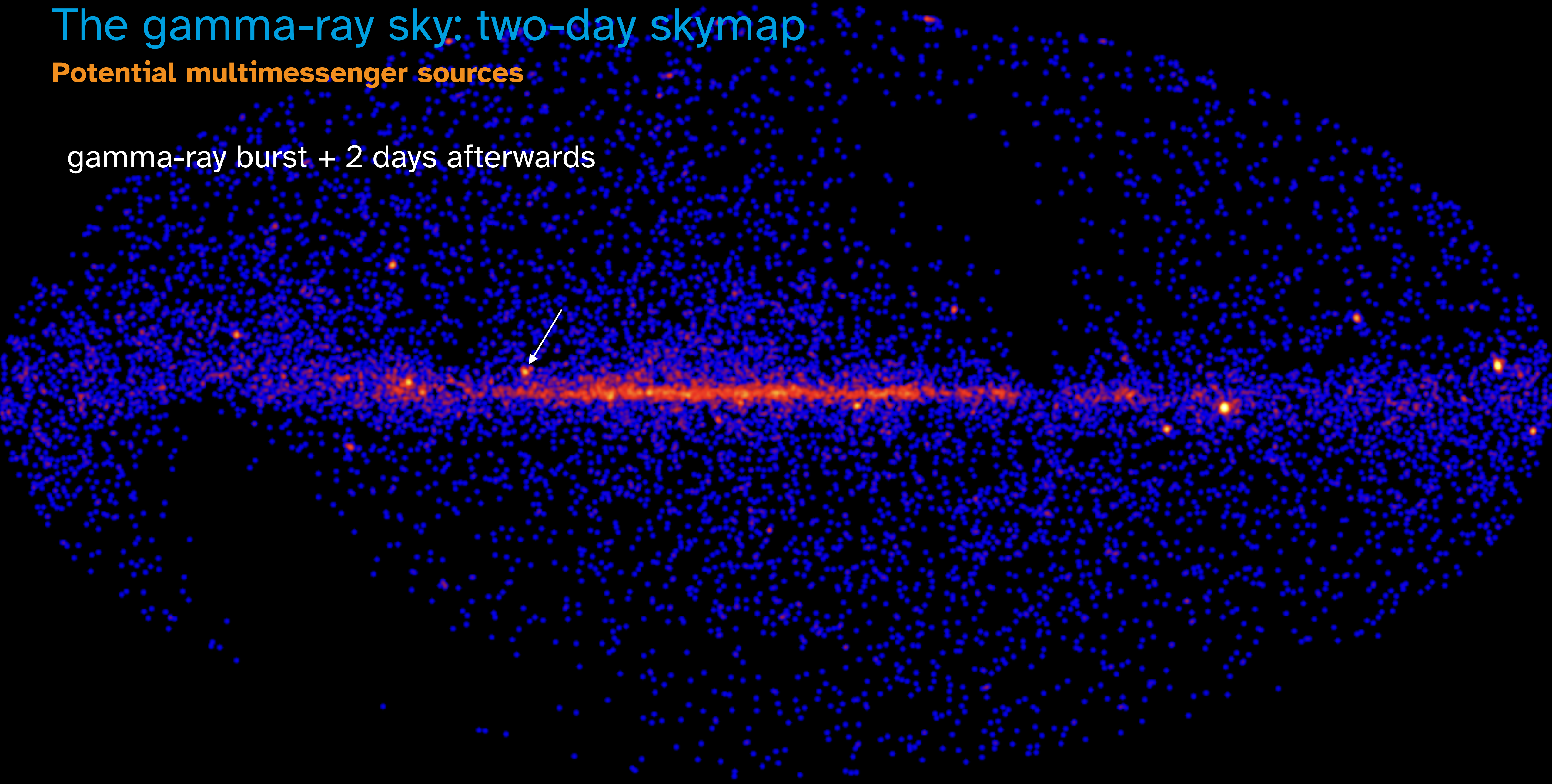
Potential multimessenger sources



[D. Green]

The gamma-ray sky: two-day skymap

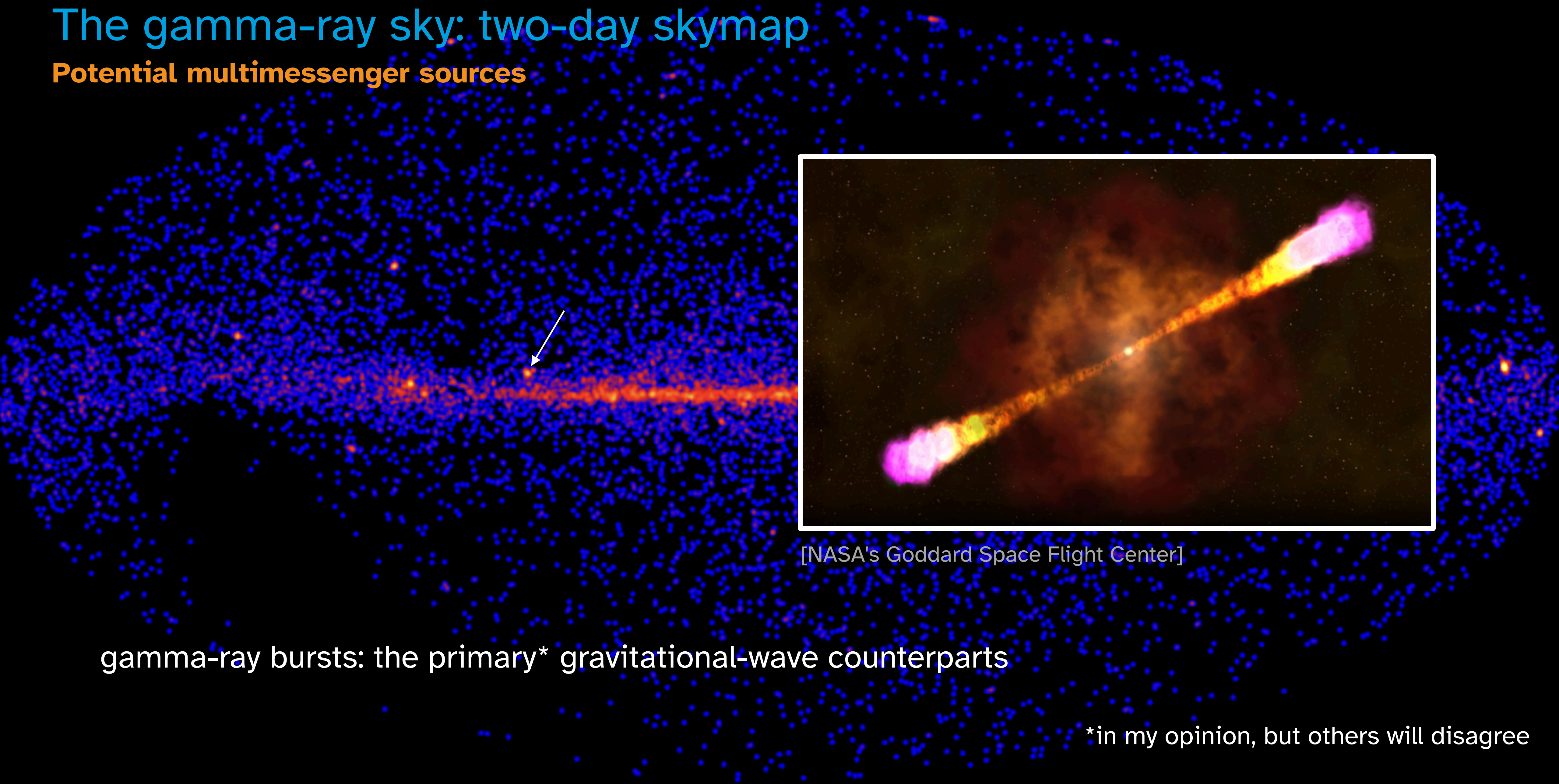
Potential multimessenger sources



[D. Green]

The gamma-ray sky: two-day skymap

Potential multimessenger sources



[NASA's Goddard Space Flight Center]

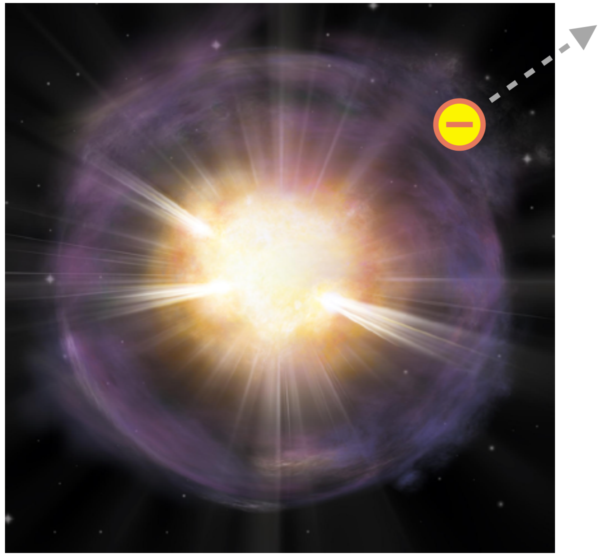
gamma-ray bursts: the primary* gravitational-wave counterparts

*in my opinion, but others will disagree

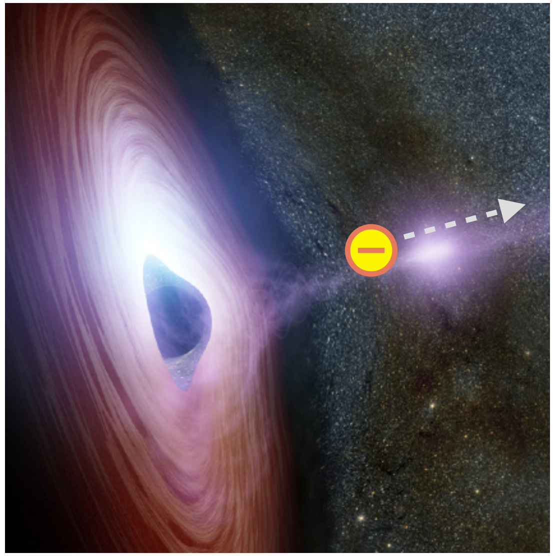
How do we get gamma rays?

Nonthermal emission processes

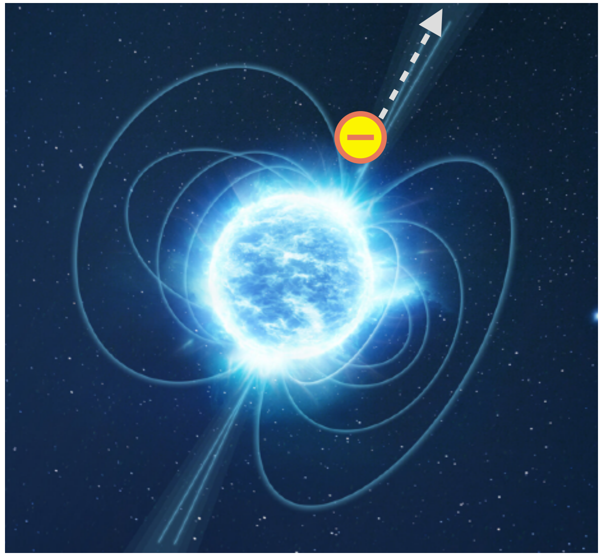
In general: Charged particles are **accelerated** to high energies before radiating photons



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



[NASA/JPL-Caltech]



[ESA]

We need an **energy source** and a way to **transfer this energy** to charged particles

kinetic, gravitational, magnetic fields ...

How do we get gamma rays?

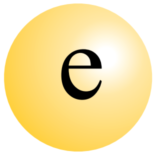
Nonthermal emission processes

In general: Charged particles are **accelerated** to high energies before radiating photons

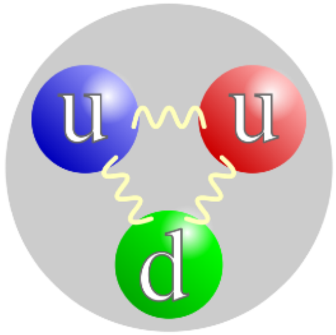
The charged particles can be **leptons** (e.g., electrons) or **hadrons** (e.g., protons)

-> the radiation processes can be **leptonic** and/or **hadronic**

electron



proton



[A. Horvath]

leptons are elementary particles

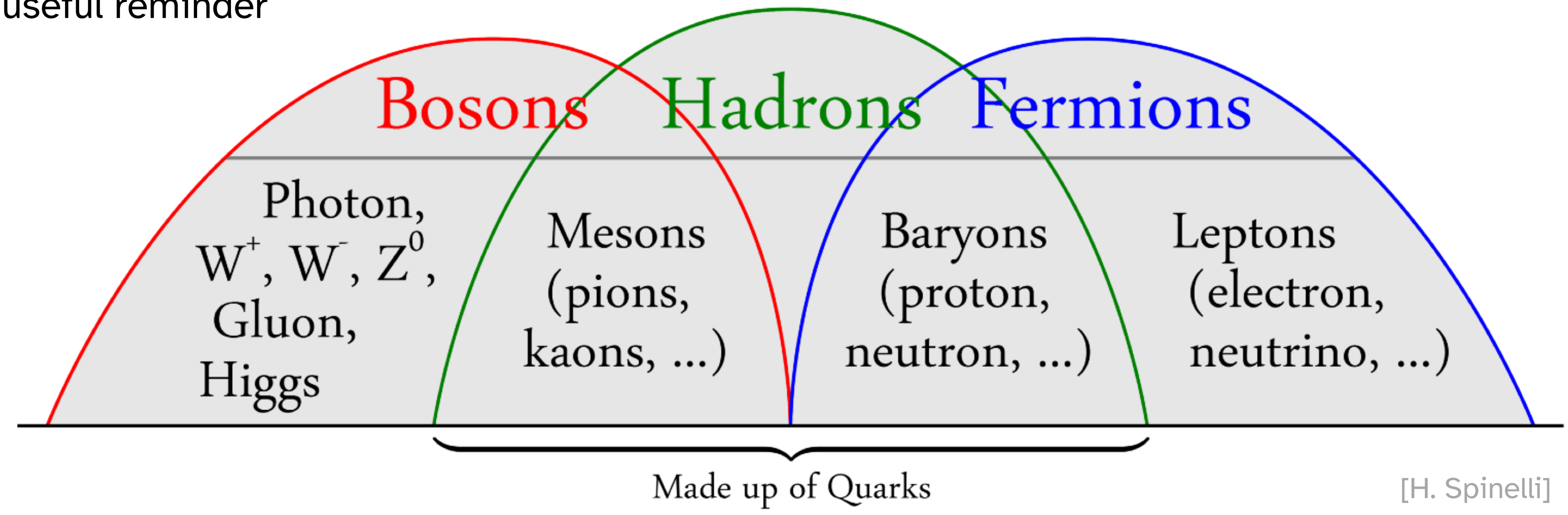
hadrons are made of quarks
-> can convert into other particles

How do we get gamma rays?

Nonthermal emission processes

In general: 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**

useful reminder

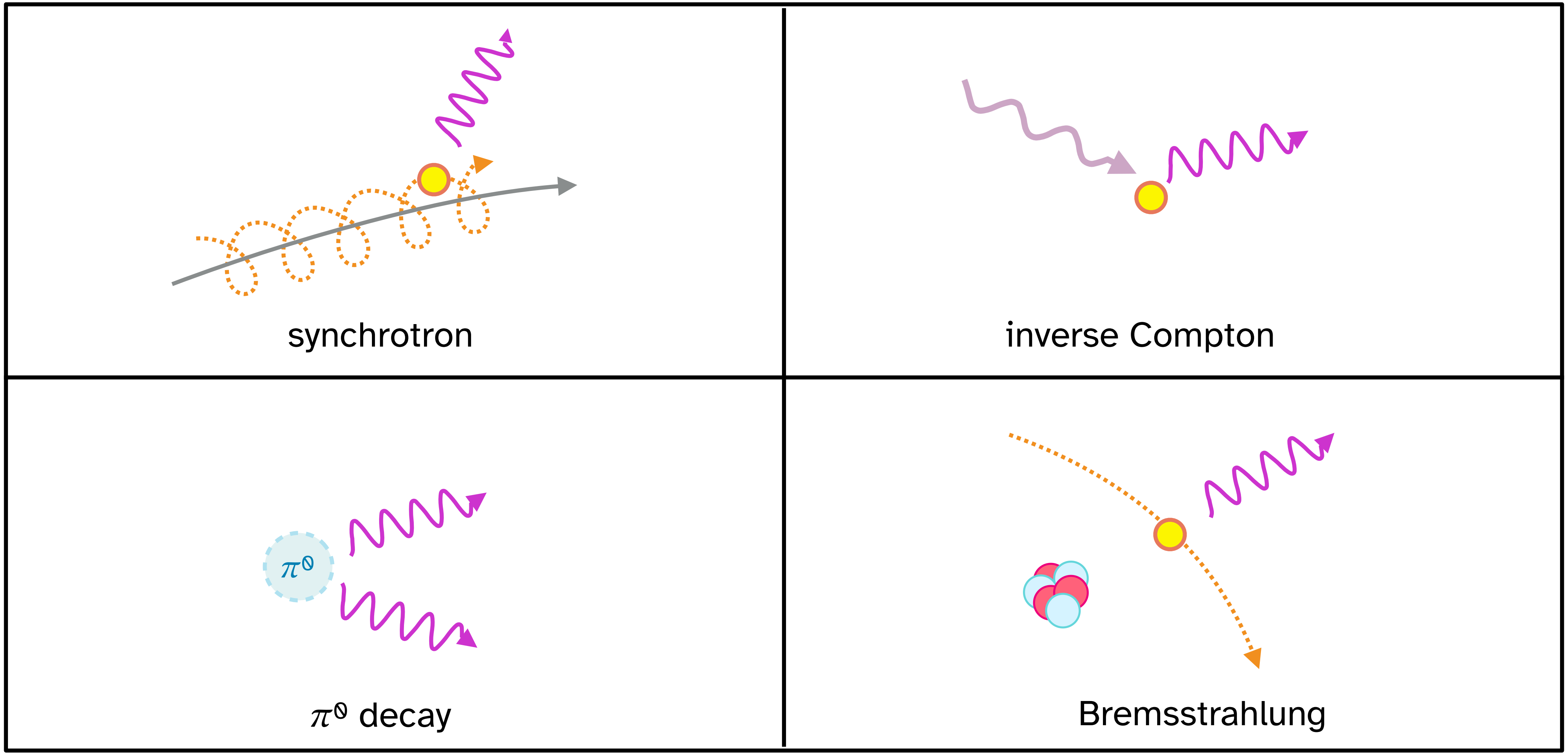


[H. Spinelli]

How do we get gamma rays?

Nonthermal emission processes

In general: Charged particles are **accelerated** to high energies before radiating photons
The charged particles can be **leptons** (e.g., electrons) or **hadrons** (e.g., protons)

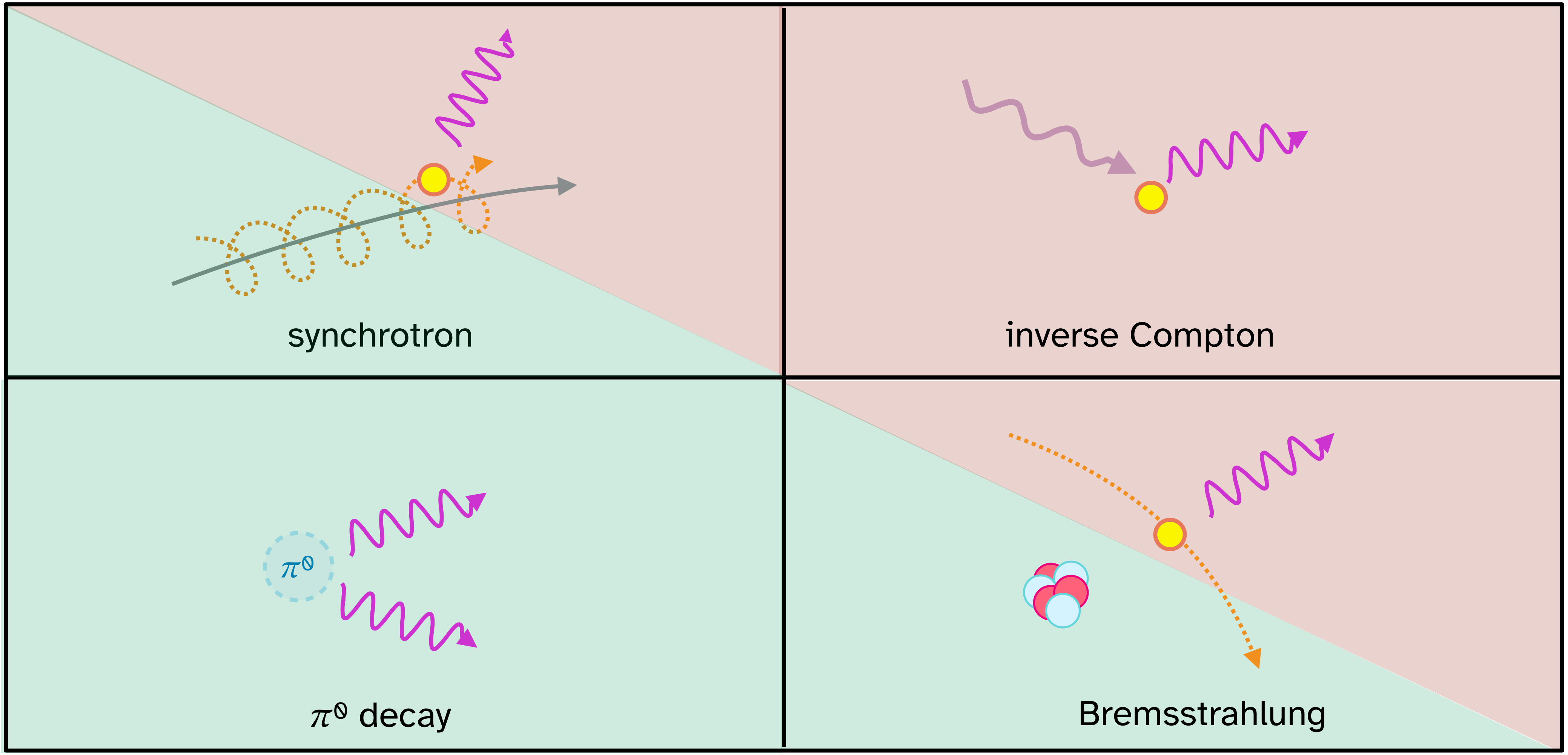


How do we get gamma rays?

Nonthermal emission processes

In general: Charged particles are **accelerated** to high energies before radiating photons
The charged particles can be **leptons** (e.g., electrons) or **hadrons** (e.g., protons)

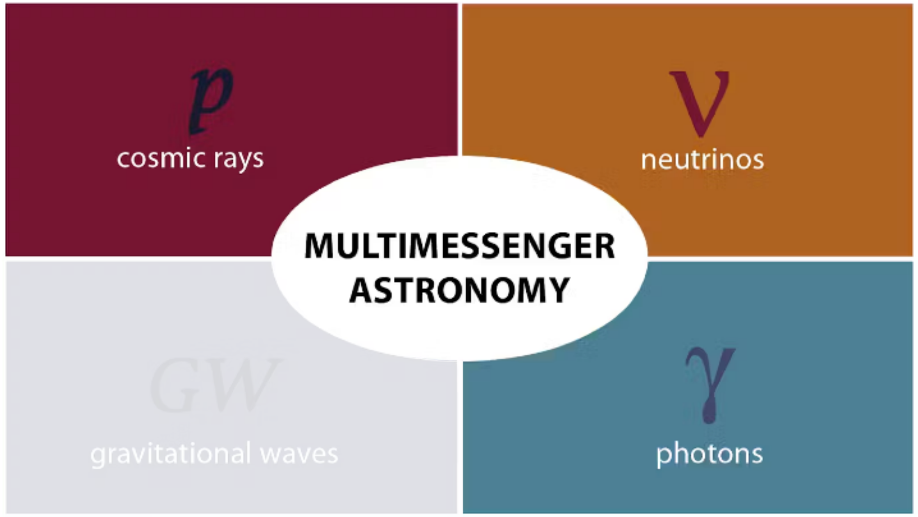
(coloring indicates what is **relevant** to our topic)



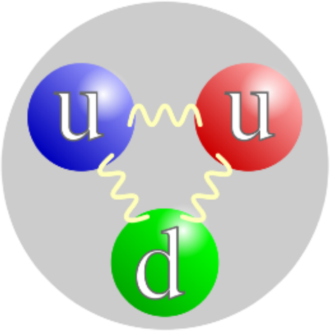
How do we get gamma rays?

Nonthermal emission processes

In general: 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**
Hadronic processes also produce **cosmic rays** and **neutrinos**



proton



[A. Horvath]

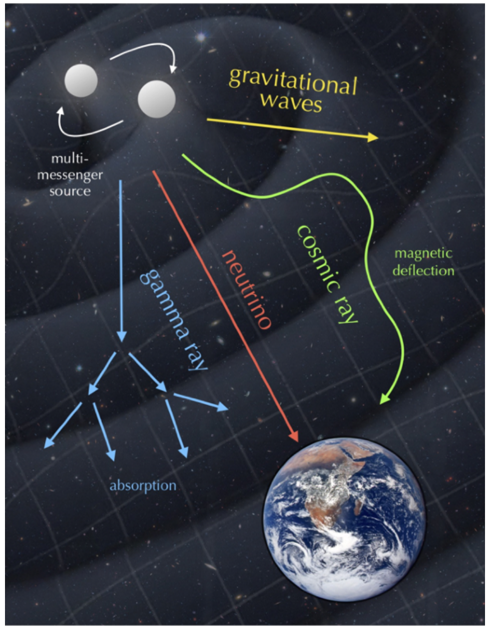
hadrons are made of quarks
-> can convert into other particles

ok controversial opinion: I hate the term "cosmic rays"

fight me

Historical term, meaning: any kind of ionizing radiation from space (which technically includes gamma rays)
- nowadays we usually mean charged particles (protons, atomic nuclei, electrons/positrons)
  - but "cosmic ray" can also be neutrons + the secondary particles produced by the ones listed above
    - and as soon as we acknowledge cosmic-ray neutrons, then why not neutrinos too
      - so cosmic rays in principle encompass pretty much everything???? (╯°□°)╯︵ ┻━┻

Practically speaking, often we see some diagram like this ⟶

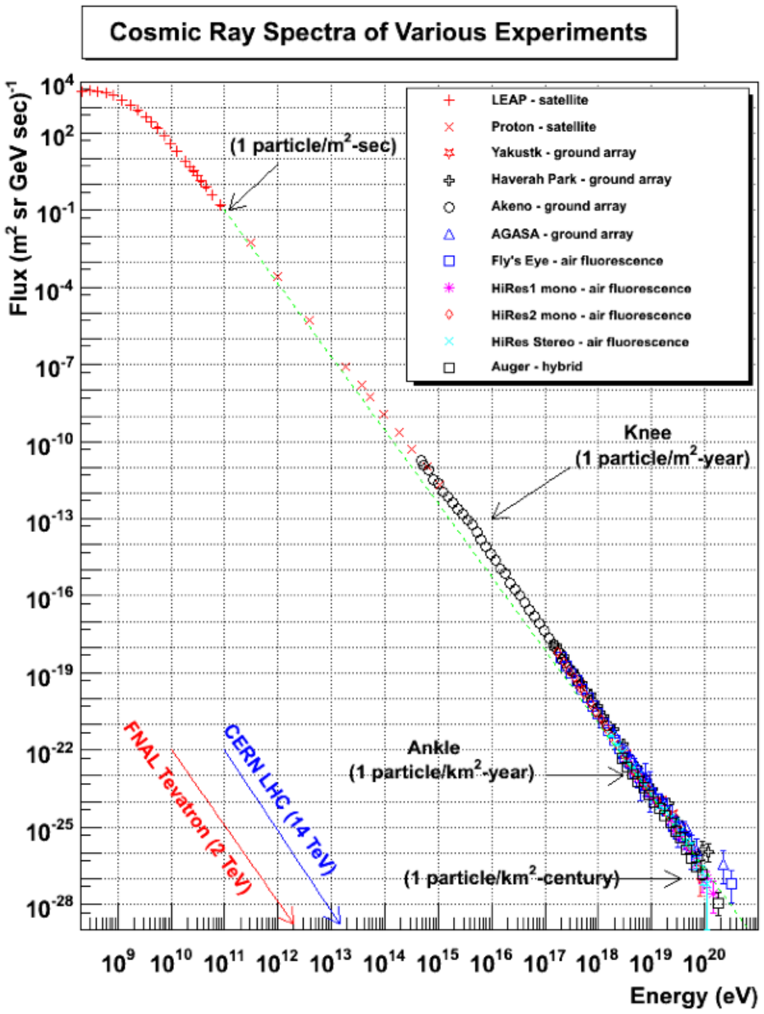


[Niels Bohr Institute]

so for gamma-ray purposes, sometimes we mean "charged particles"
and usually we mean "charged hadrons" in particular
¯_(ツ)_/¯

Cosmic rays: Flux measured on Earth

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



[W. F. Hanlon]

The cosmic rays detected at Earth:

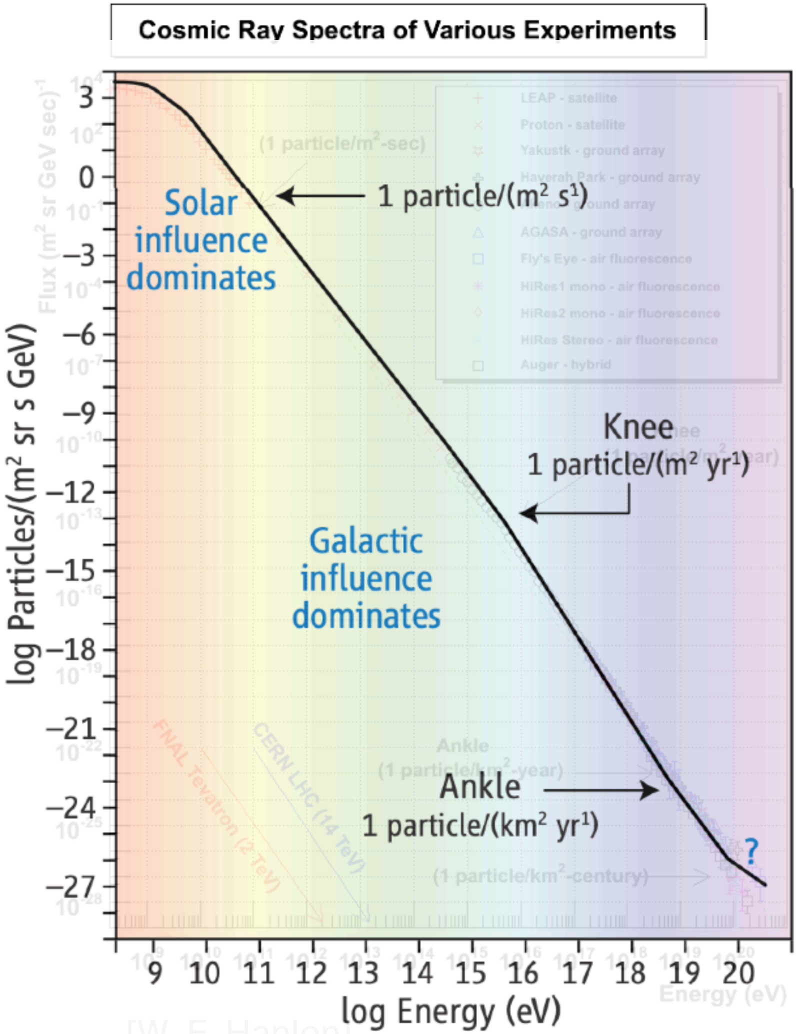
Mostly charged particles -> deflected by magnetic fields

→ mostly nuclei, a few % electrons

→ 89% protons,
10% He,
1% heavier

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)]

The cosmic rays detected at Earth:

Mostly charged particles -> deflected by magnetic fields

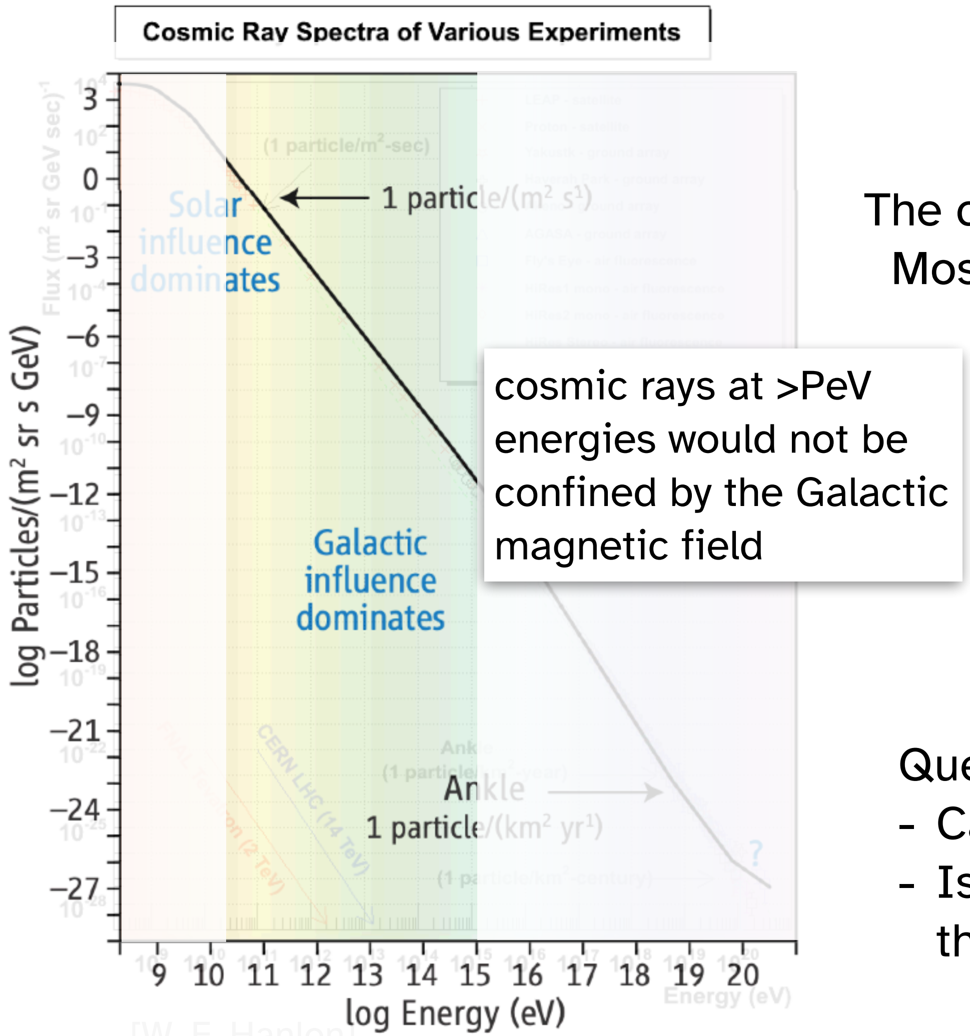
→ mostly nuclei, a few % electrons

→ 89% protons,
10% He,
1% heavier

One of the oft-cited motivations in gamma-ray astronomy 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)]

The cosmic rays detected at Earth:

Mostly charged particles -> deflected by magnetic fields

↓

they don't point back to their origins

-> we need (mostly) indirect methods of determining their sources

Questions we ask:

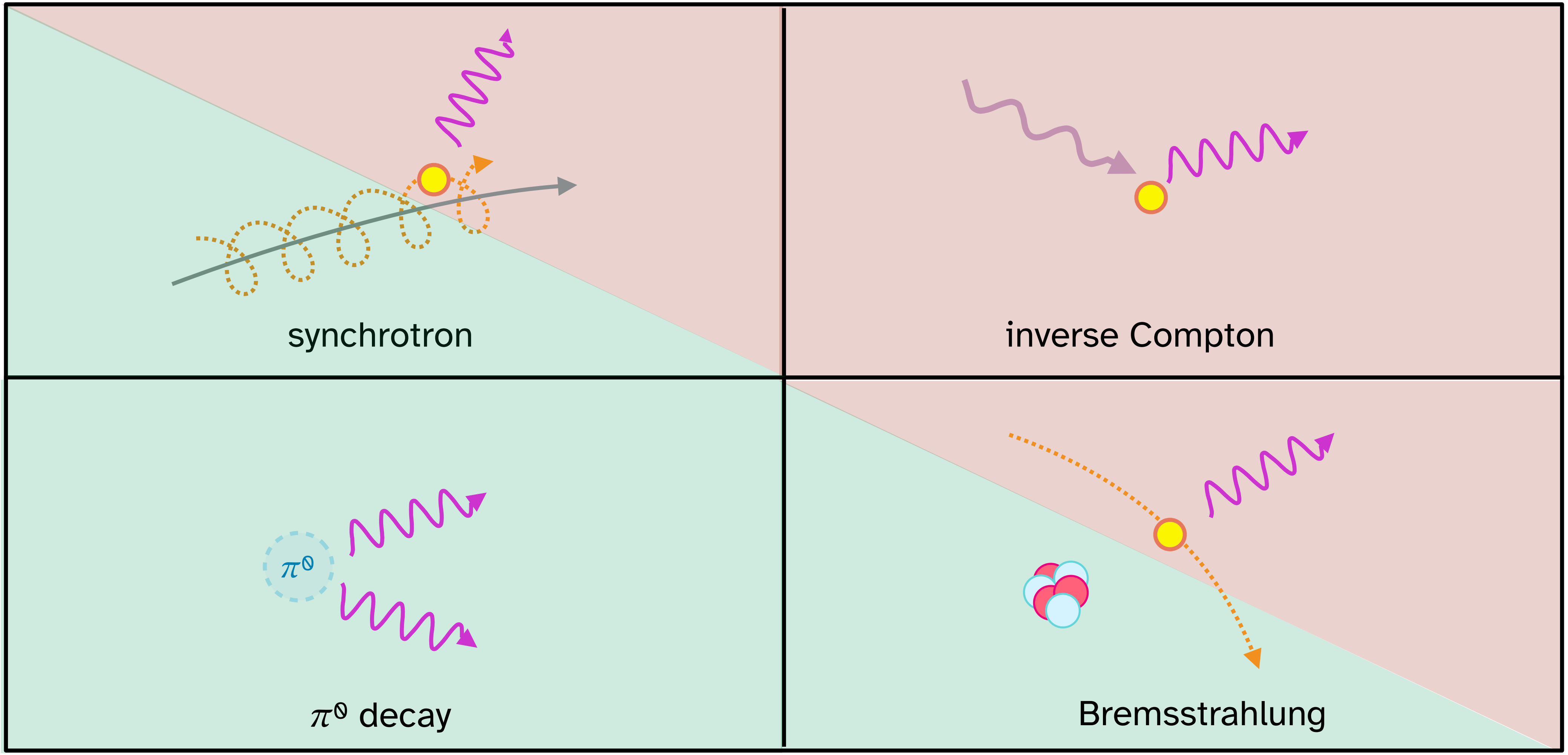
- Can this type of source accelerate ~~particles~~ hadrons to this energy?
- Is this type of source common enough to account for all of the cosmic-ray flux at this energy?

How do we get gamma rays?

Nonthermal emission processes

In general: Charged particles are **accelerated** to high energies before radiating photons
The charged particles can be **leptons** (e.g., electrons) or **hadrons** (e.g., protons)

(coloring indicates what is relevant to our topic)



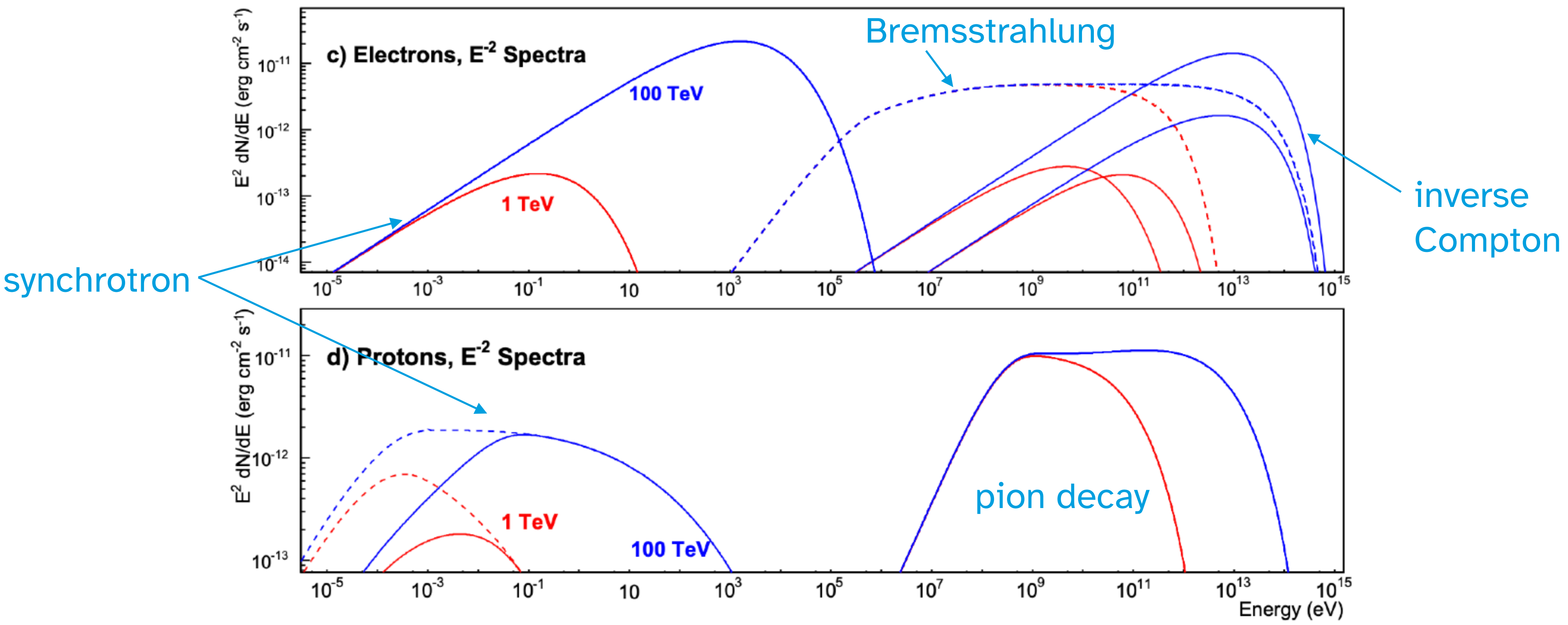
How do we get gamma rays?

Nonthermal emission processes

In general: Charged particles are **accelerated** to high energies before radiating photons
The charged particles can be **leptons** (e.g., electrons) or **hadrons** (e.g., protons)

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

example spectra under common conditions



From cosmic rays to gamma rays

what happens if you smash protons into things

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

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

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

$p + p \rightarrow$ etc.

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

From cosmic rays to gamma rays

what happens if you smash protons into things

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

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

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

$p + p \rightarrow$ etc.

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

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

$p + \gamma \rightarrow$ 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

what happens if you smash protons into things

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

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

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

$p + p \rightarrow$ etc.

π^0 decays in 10^{-16} s

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

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

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

$p + \gamma \rightarrow$ etc.

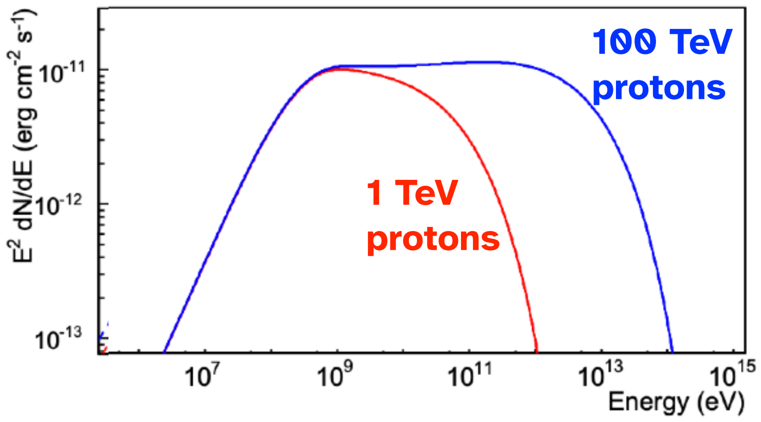
p	proton	hadrons
n	neutron	hadrons
π	pion (pi meson)	hadrons
γ	photon	
μ	muon	leptons
ν	neutrino	leptons

From cosmic rays to gamma rays

what happens if you smash protons into things

p + p → p + p + π^0 → $\gamma + \gamma$
p + p → p + n + π^+
p + p → p + p + π^+ + π^-
p + p → etc.

p + γ → p + π^0 → $\gamma + \gamma$
p + γ → n + π^+
p + γ → etc.



π^0 decay produces a characteristic “pion bump” in the spectrum

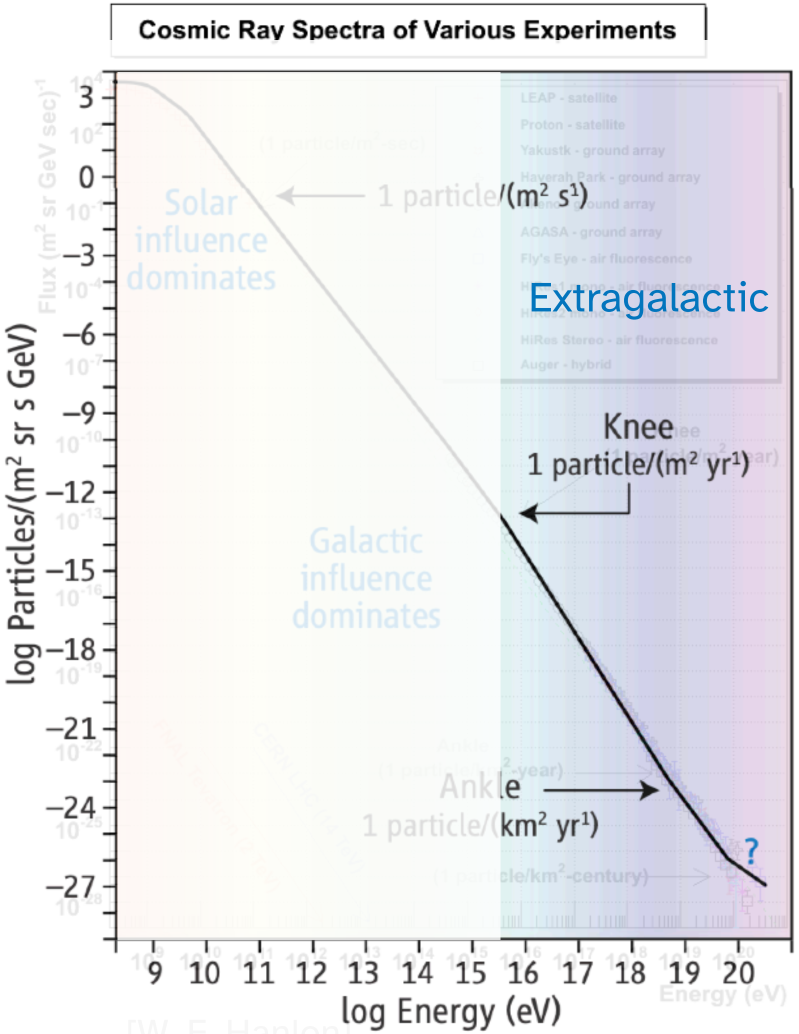
~10% of the original proton energy is transferred to the gamma rays

e.g., detect gamma rays with E_γ = 100 TeV
+ pion bump (or some other hadronic signature)
= source can produce cosmic rays with E_{CR} = 1 PeV

Galactic “Pevatrons”

Cosmic rays: Flux measured on Earth

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



[W. F. Hanlon]

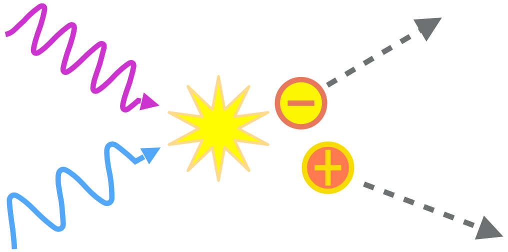
[M. Duldig, Science 314 (2006)]

Can we play this same game for the extragalactic cosmic rays?

We would need to detect gamma rays at >PeV energies from outside the Galaxy; can we do so?

Extragalactic background light (EBL)

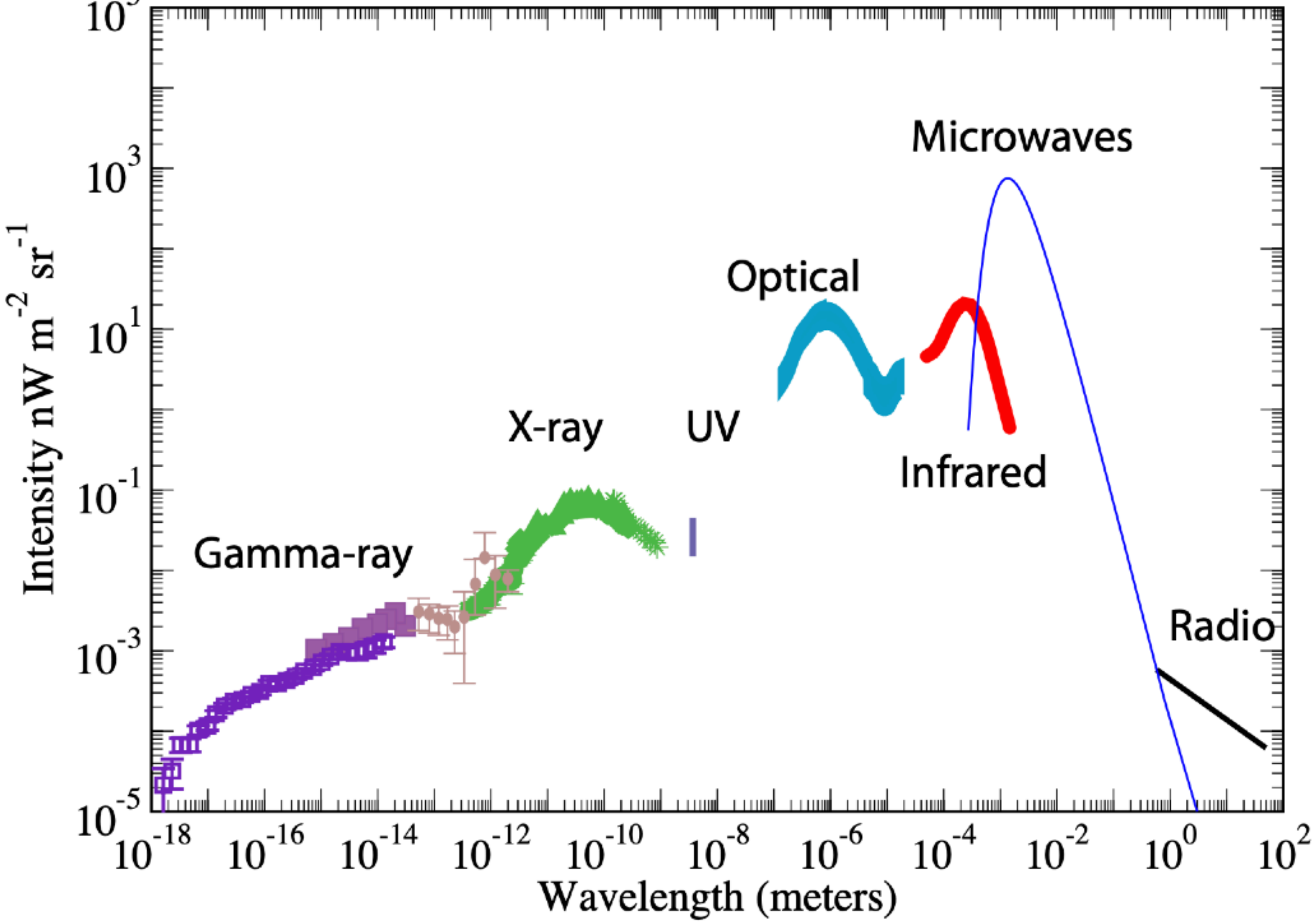
Gamma rays pair produce with other photons



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

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

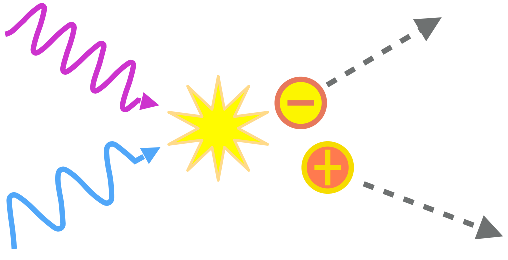
Background light in the Universe



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

Extragalactic background light (EBL)

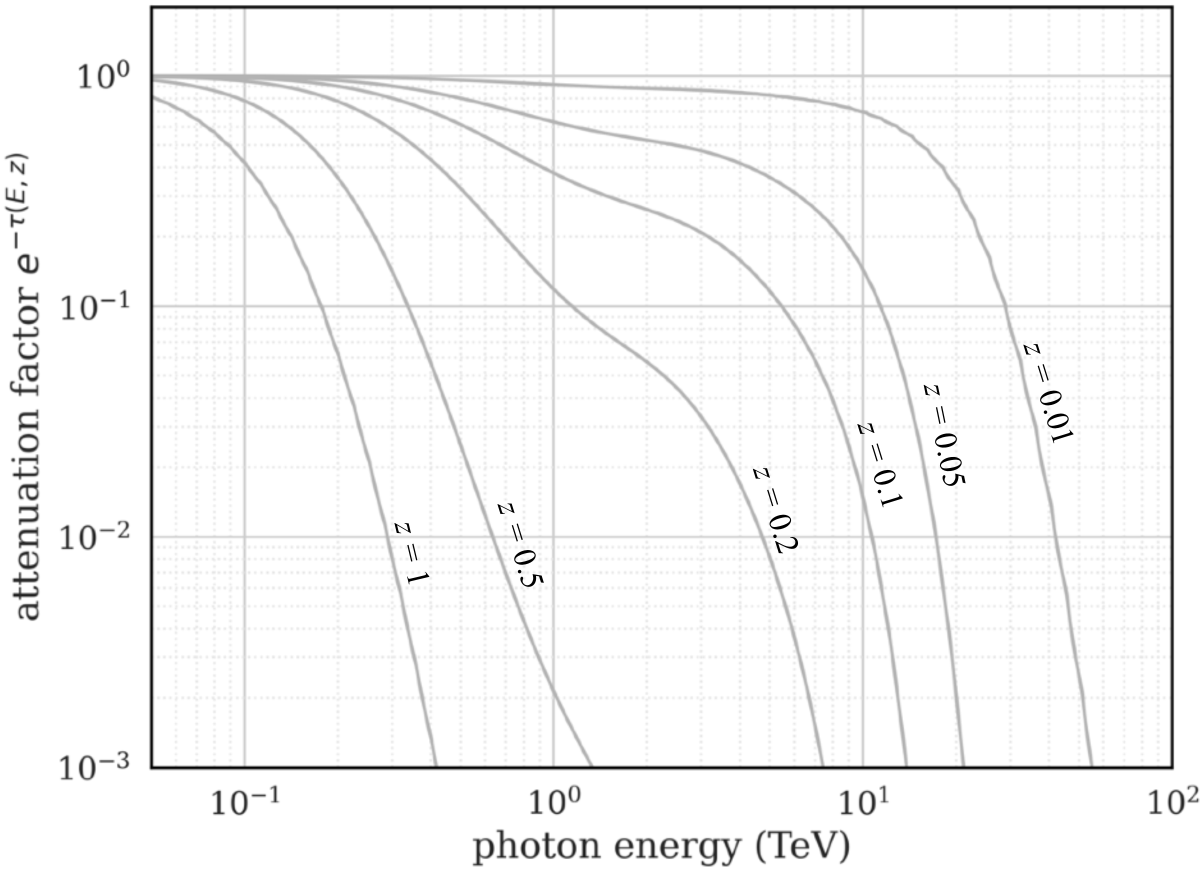
Gamma rays pair produce with other photons



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)

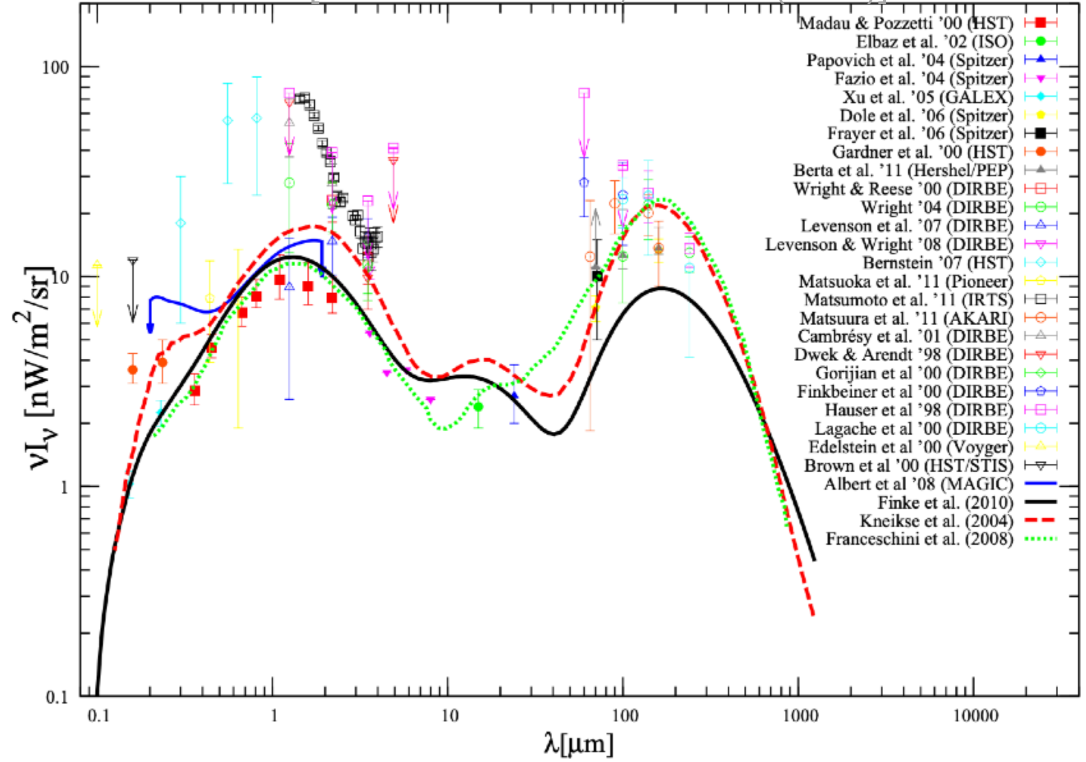


Extragalactic background light (EBL)

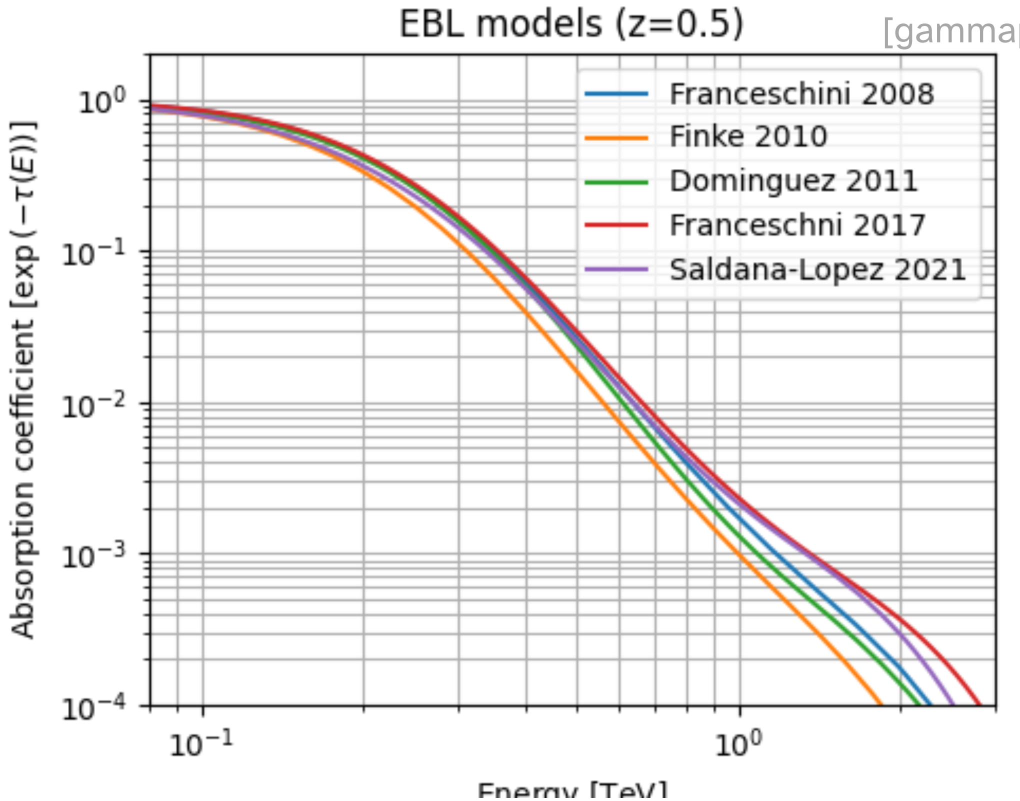
Gamma rays pair produce with other photons

There is a lot of uncertainty in the EBL spectrum itself

[Y. Inoue & K. Ioka, PRD 86 (2012)]



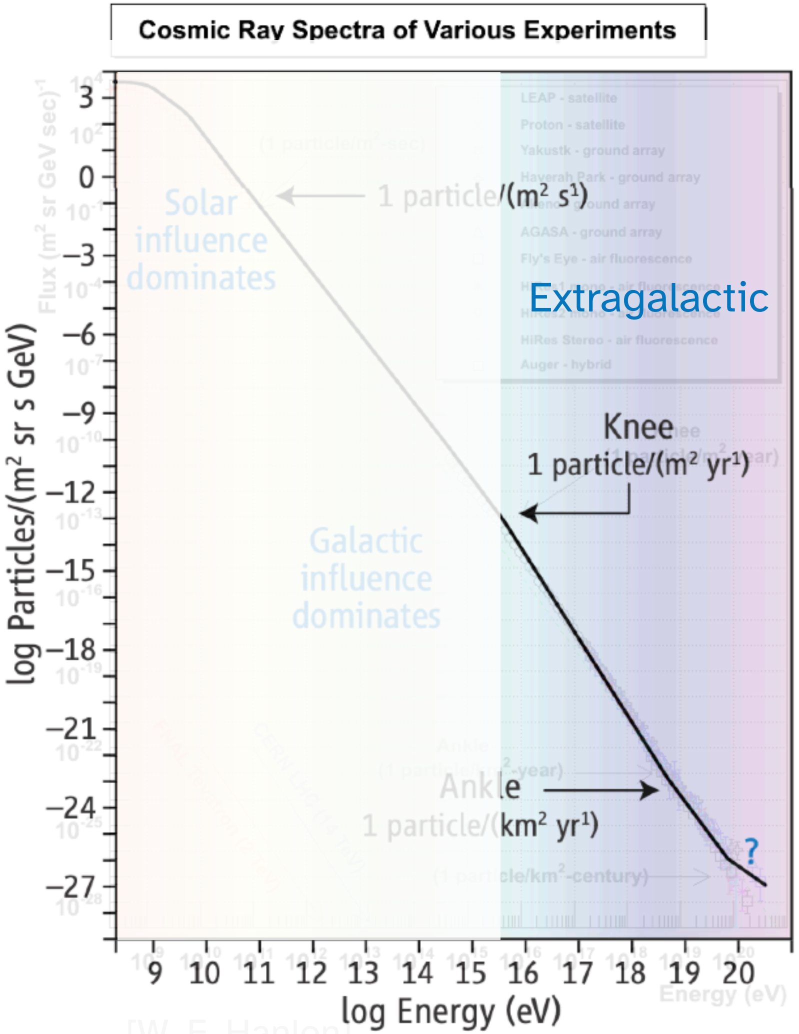
[gammapy]



=> EBL is a major limiting factor in extragalactic sources, for both the **detection** and the **analysis**

Cosmic rays: Flux measured on Earth

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



[M. Duldig, Science 314 (2006)]

Can we play this same game for the extragalactic cosmic rays?

We would need to detect gamma rays at >PeV energies from outside the Galaxy; can we do so?

(no)

High-energy neutrinos are a better tracer of extragalactic cosmic rays

Cosmic rays: Sources

The connection to neutrinos

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

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

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

$p + p \rightarrow$ etc.

π^0 decays in 10^{-16} s

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

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

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

$p + \gamma \rightarrow$ etc.

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

Cosmic rays: Sources

The connection to neutrinos

π^0 decays in 10^{-16} s

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

$p + p \rightarrow$

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

$p + \gamma \rightarrow$

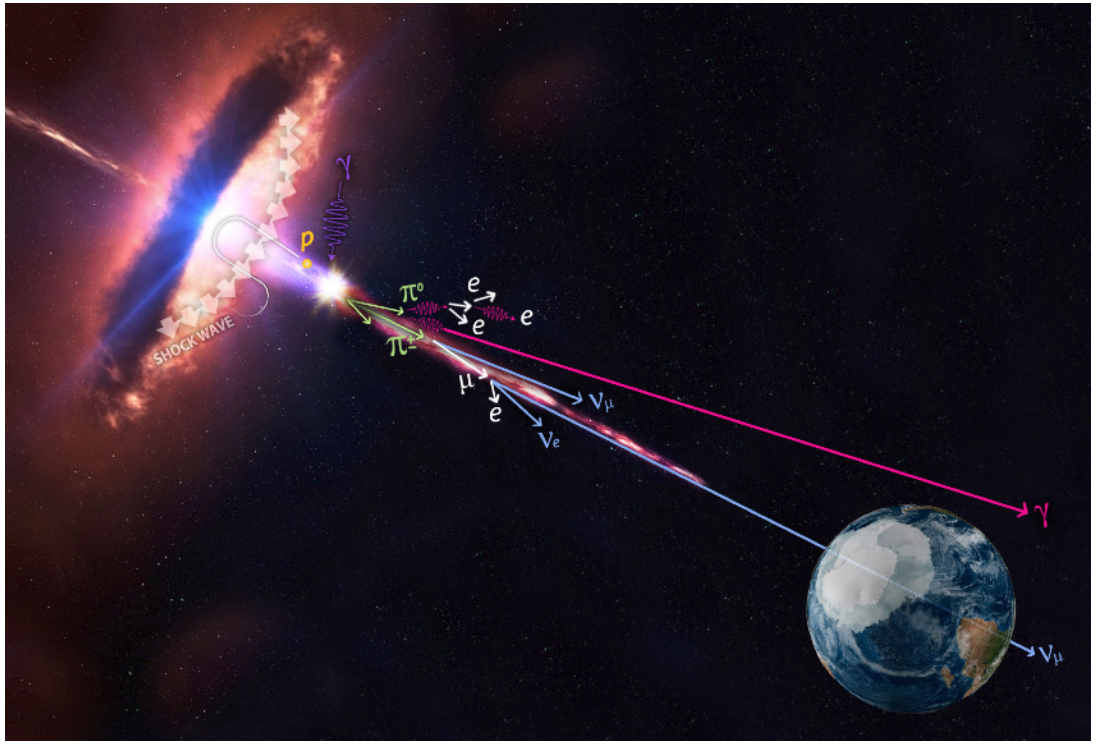
- $p + \pi^0 \rightarrow \gamma + \gamma$
- $n + \pi^+ \rightarrow \mu^+ + \nu_\mu$
  - $\mu^+ \rightarrow e^+ + \nu_\mu + \nu_e$
- etc.

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

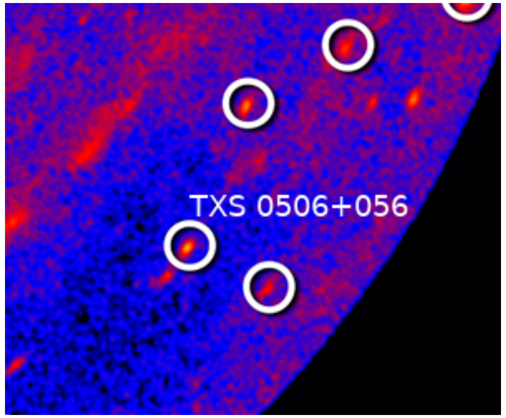
Gamma-ray sources are multimessenger sources

Neutrinos from active galaxies

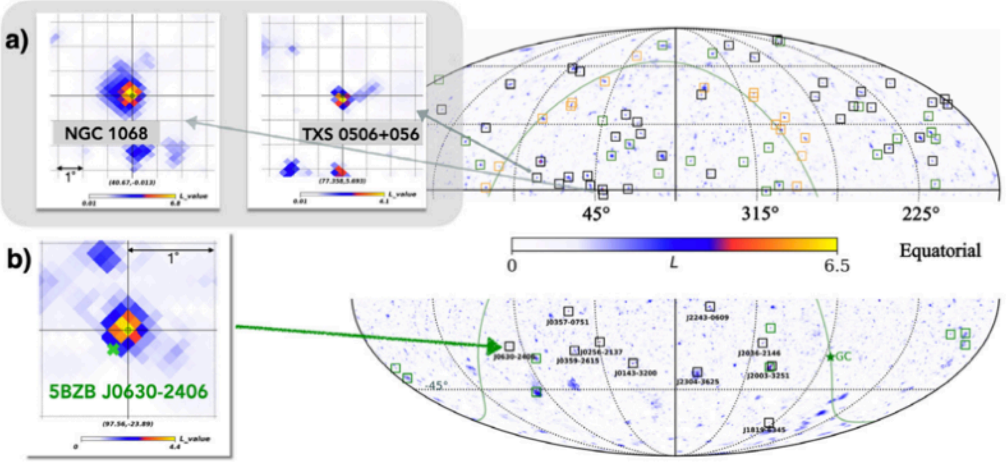
Blazars (jetted active galaxies w/ the jets pointed at us) are ~~the primary~~ candidates for neutrino counterparts



[Roen Kelly/IceCube/NASA]



[Nealmcb / Fermi]

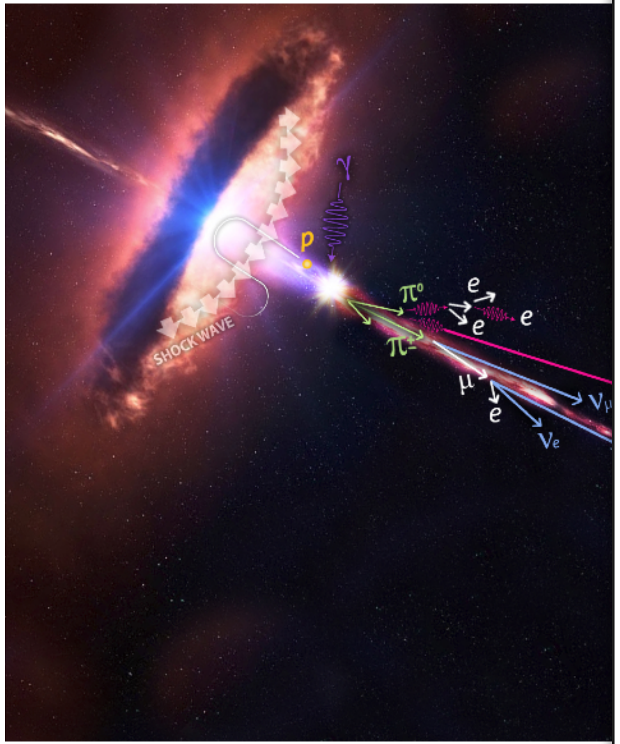


[S. Buson et al., EPJ Web Conf (2025)]

Gamma-ray sources are multimessenger sources

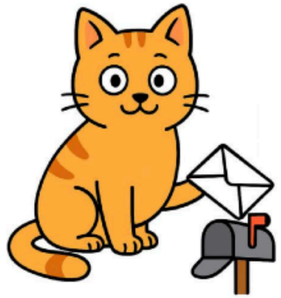
Neutrinos from active galaxies

Blazars (jetted active galaxies w/ the jets pointed at us) are ~~the primary~~ candidates for neutrino



[Roen Kelly/IceCube/NASA]

although …

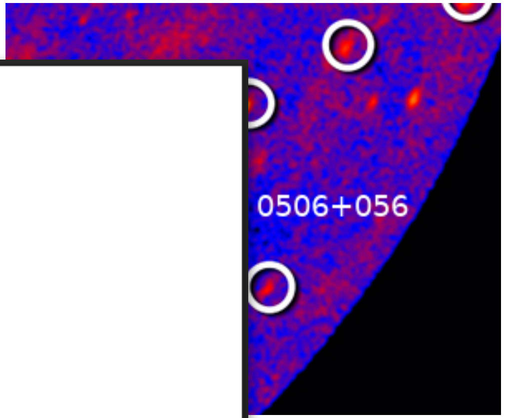


Take home message

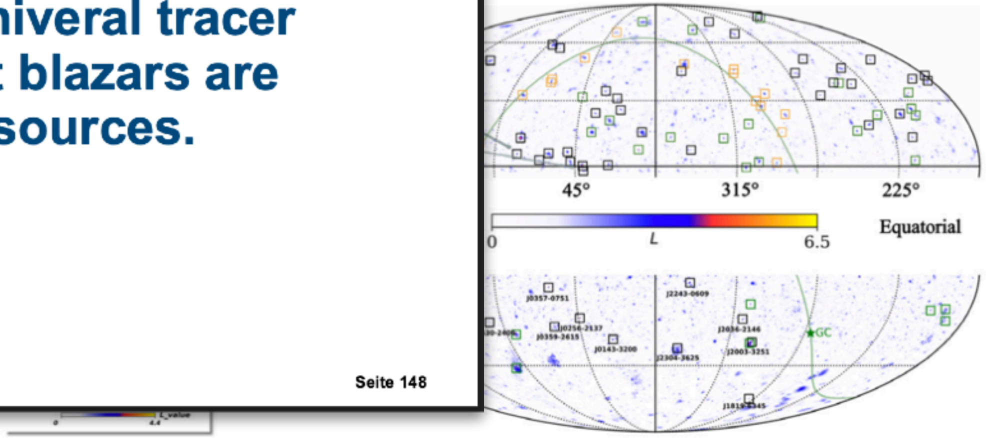
Gamma-ray emission in blazars could not be established as a univeral tracer for neutrino emission, but blazars are not ruled out as neutrino sources.

RUB

Seite 148



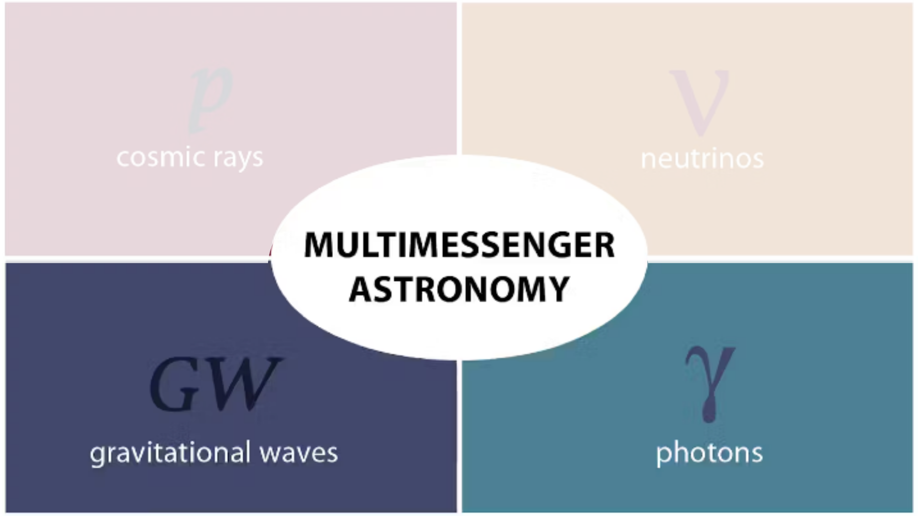
rmi]

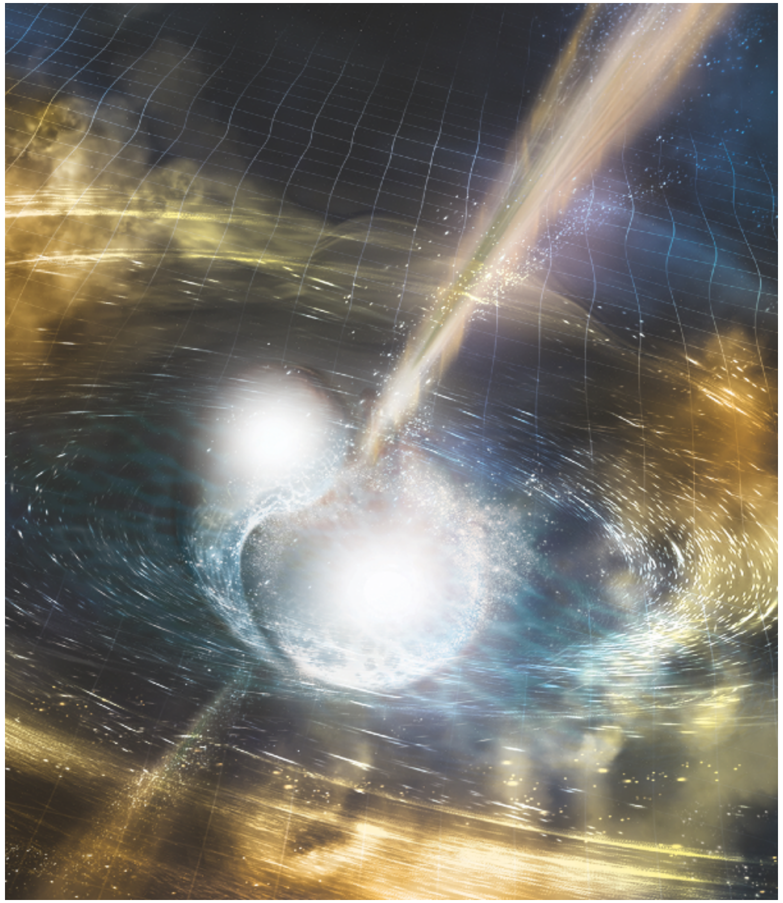


[S. Buson et al., EPJ Web Conf (2025)]

Gamma-ray sources are multimessenger sources

Gravitational waves from neutron star mergers



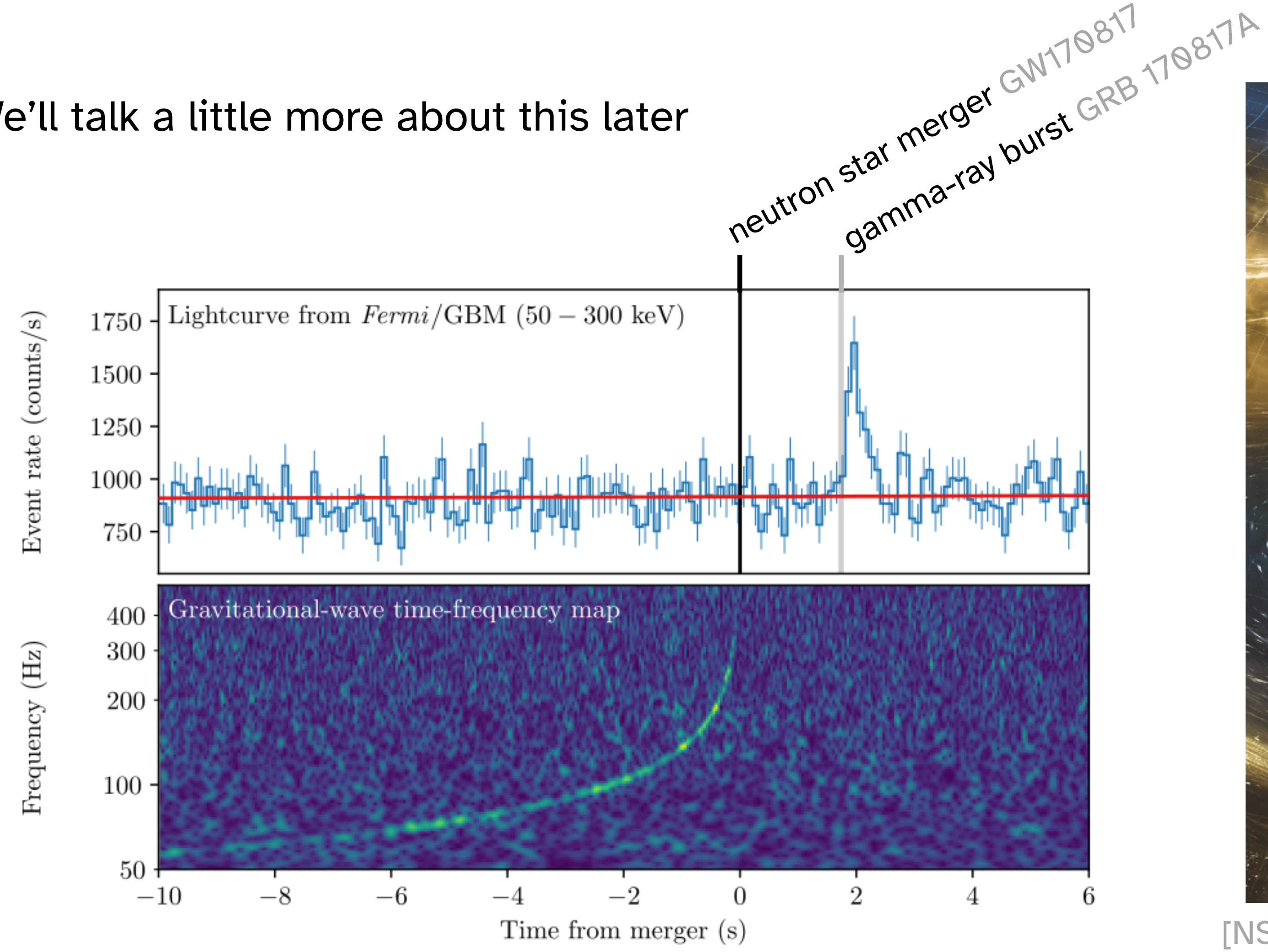


[NSF/LIGO/Sonoma State University/A. Simonnet]

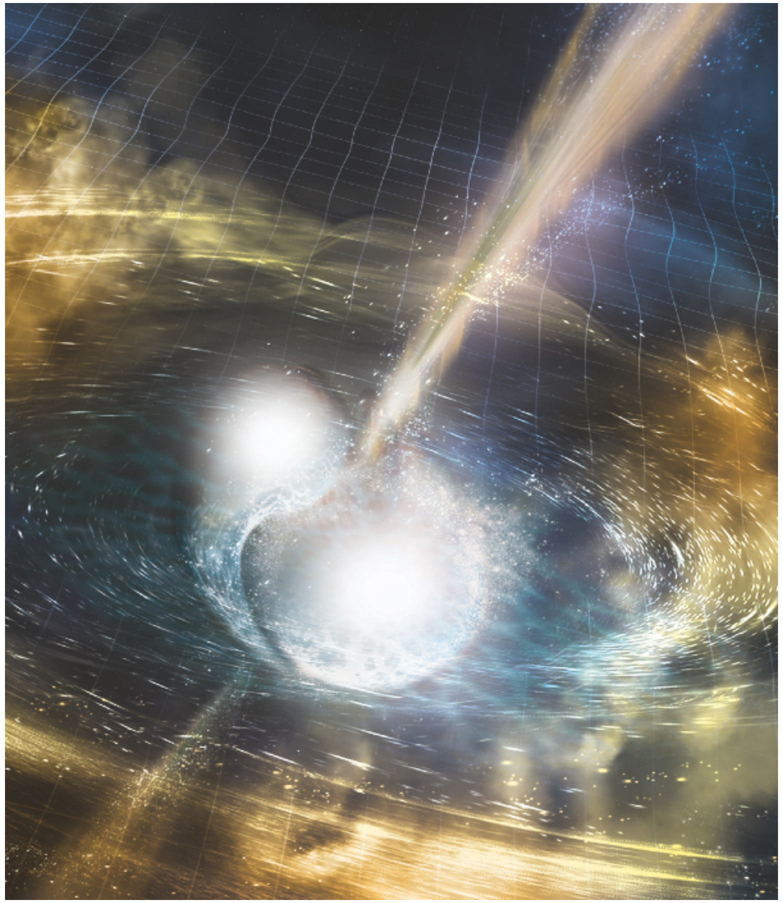
Gamma-ray sources are multimessenger sources

Gravitational waves from neutron star mergers

We'll talk a little more about this later

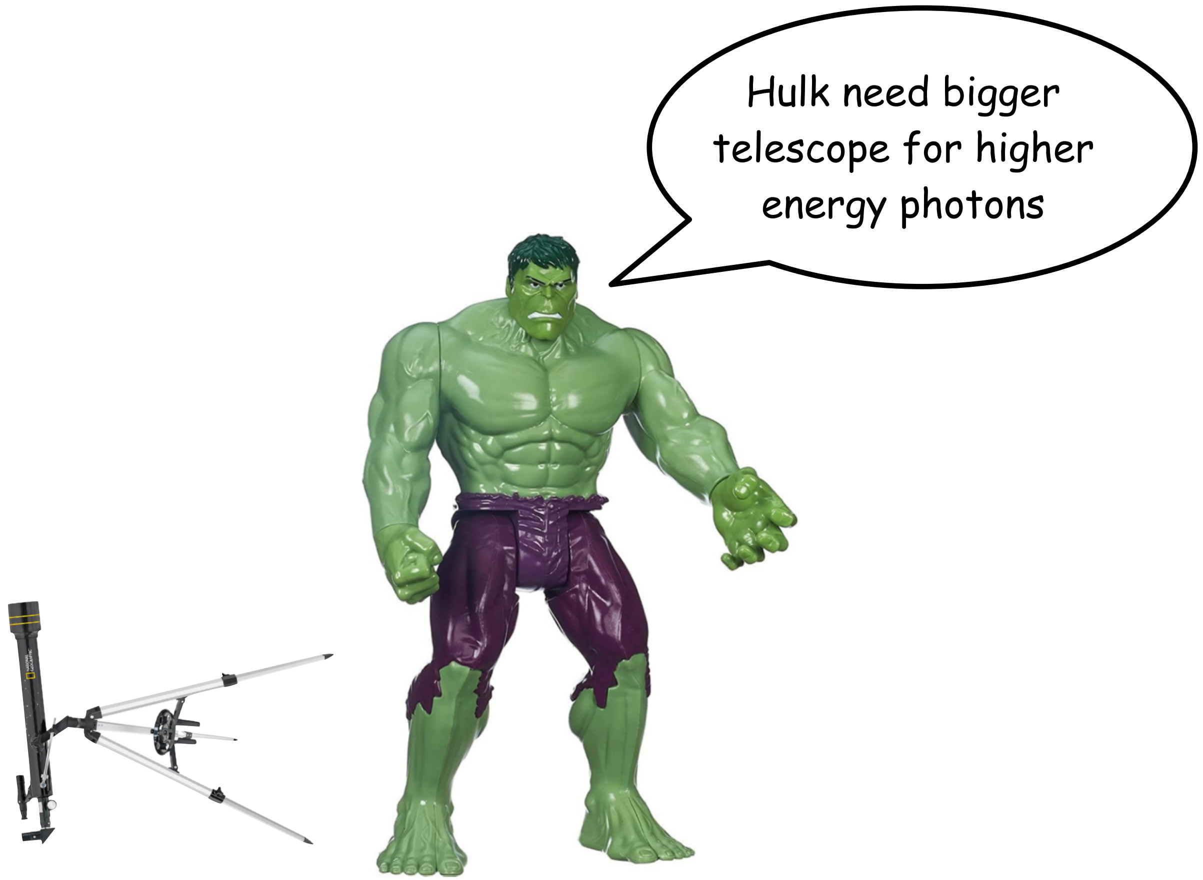


modified from [B. P. Abbott et al., ApJL 848 (2017)]



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

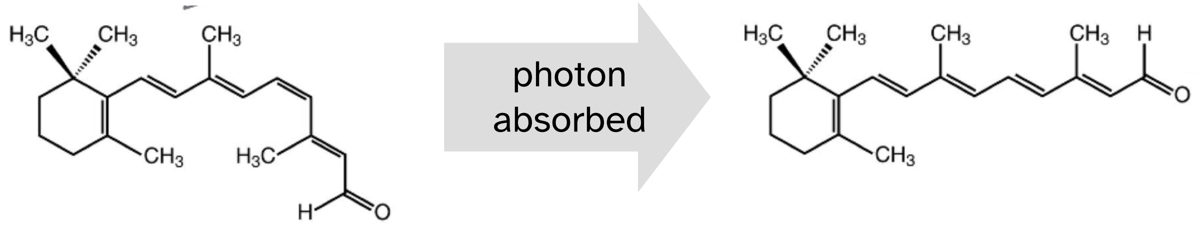
Part 2. How do we detect gamma rays?



How optical photons interact with matter

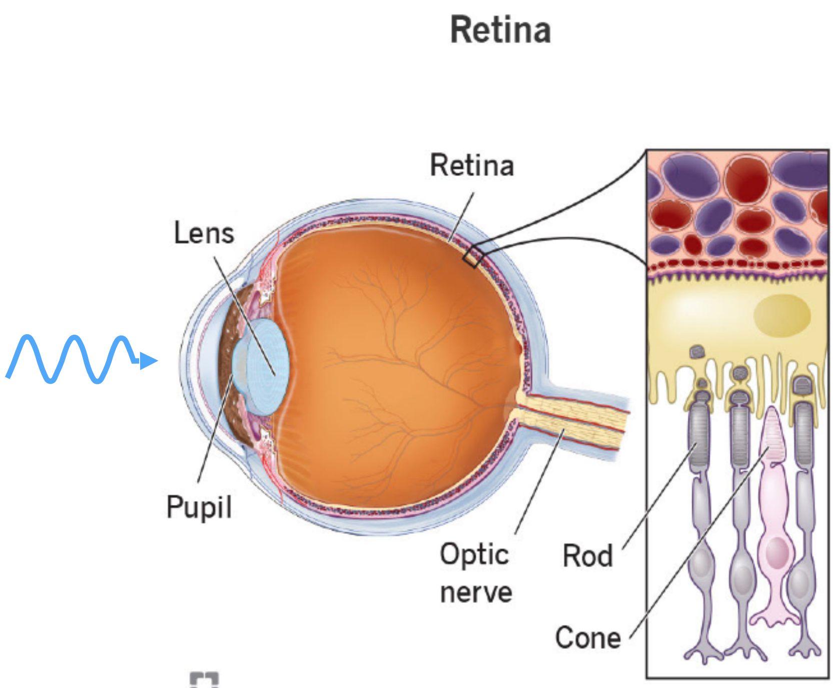
photons -> electric signals

The back of the human eye has photoreceptors that directly **absorb photons** at optical/visible wavelengths and convert them into electric signals



(a) 11-*cis*-retinal (b) all-*trans*-retinal

[Anatomy & Physiology, Connexions]



Cleveland Clinic ©2022

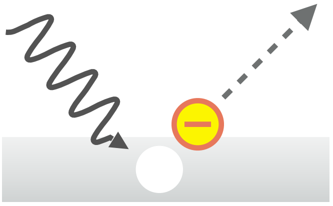
[Cleveland Clinic]

How do we do this for gamma rays?

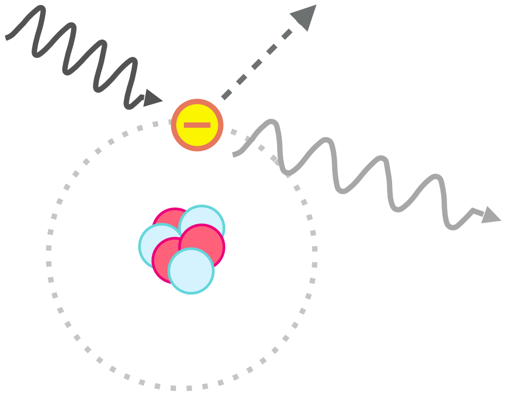
How gamma rays interact with matter

photons -> electric signals

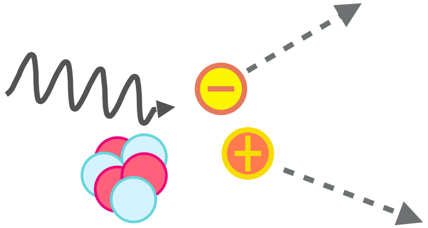
Gamma rays are hard to measure directly, but *electrons* (and positrons) are easy



photoelectric effect



Compton scattering

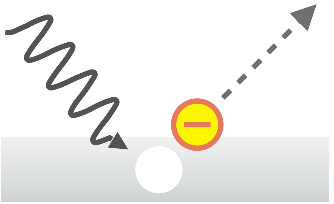


pair production

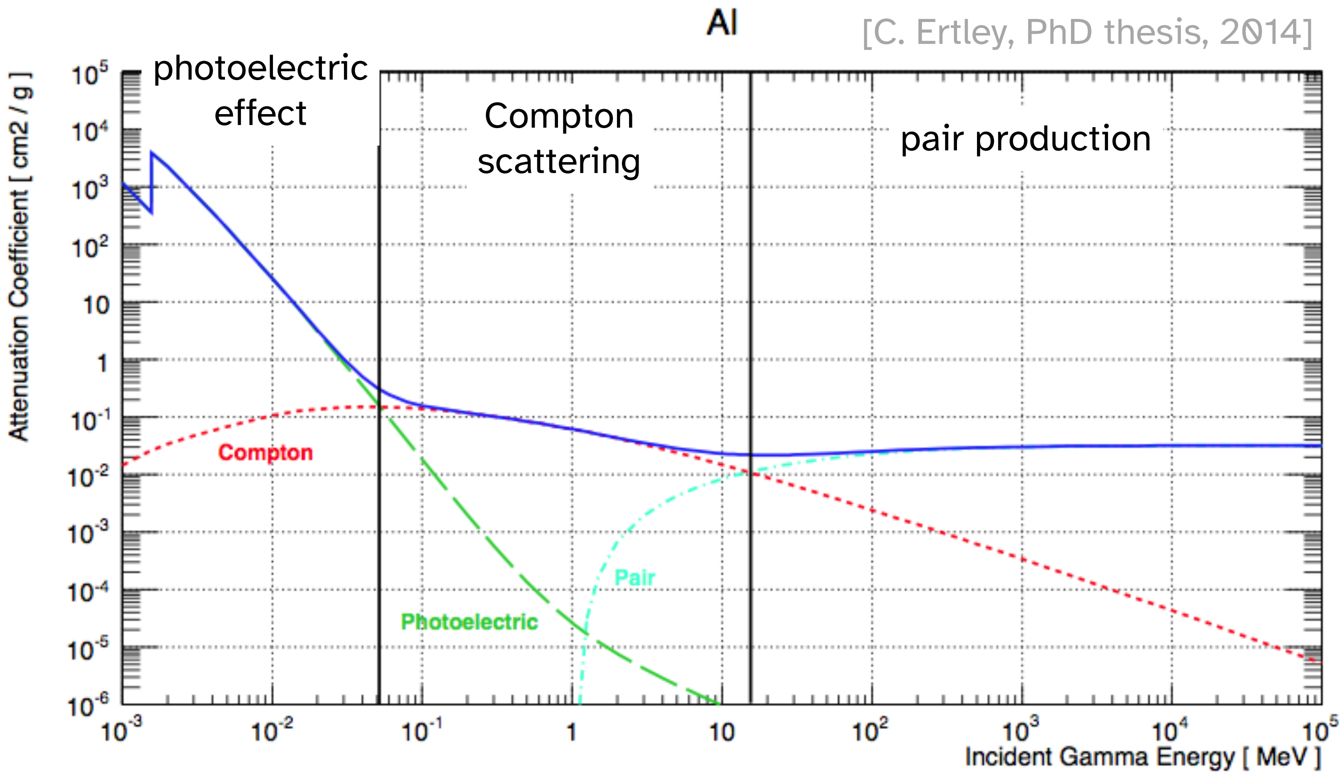
How gamma rays interact with matter

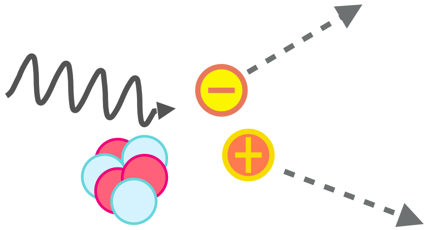
photons -> electric signals

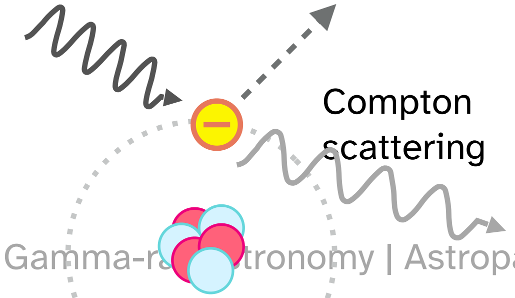
Note: The exact shapes of these curves depend on the target material



photoelectric effect





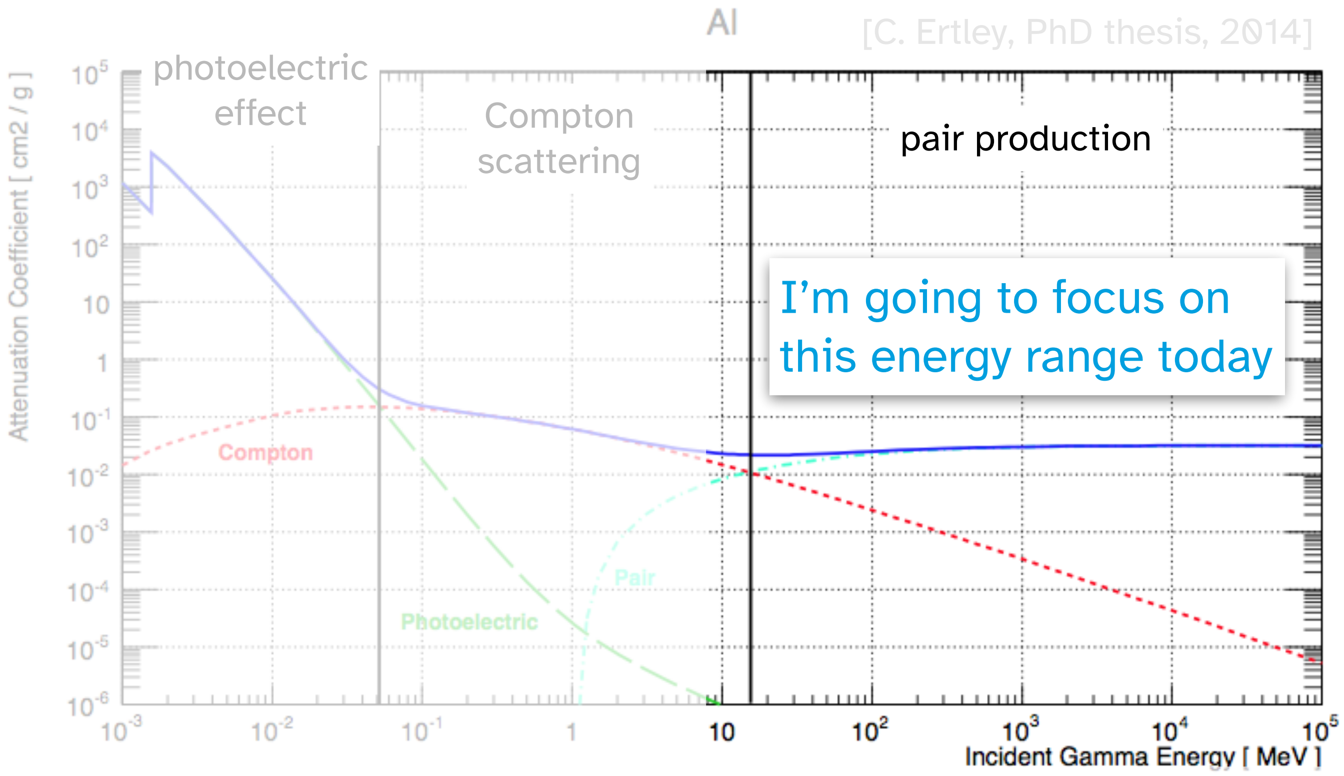


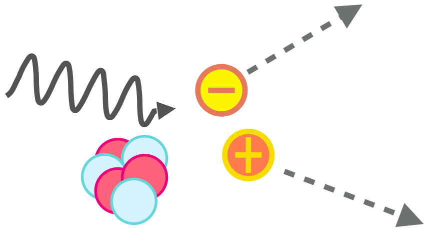
Compton scattering

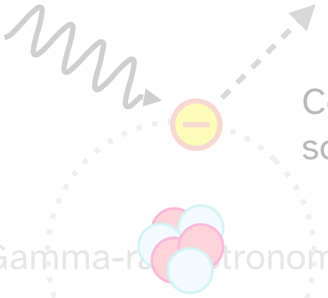
How gamma rays interact with matter

photons -> electric signals

Note: The exact shapes of these curves depend on the target material

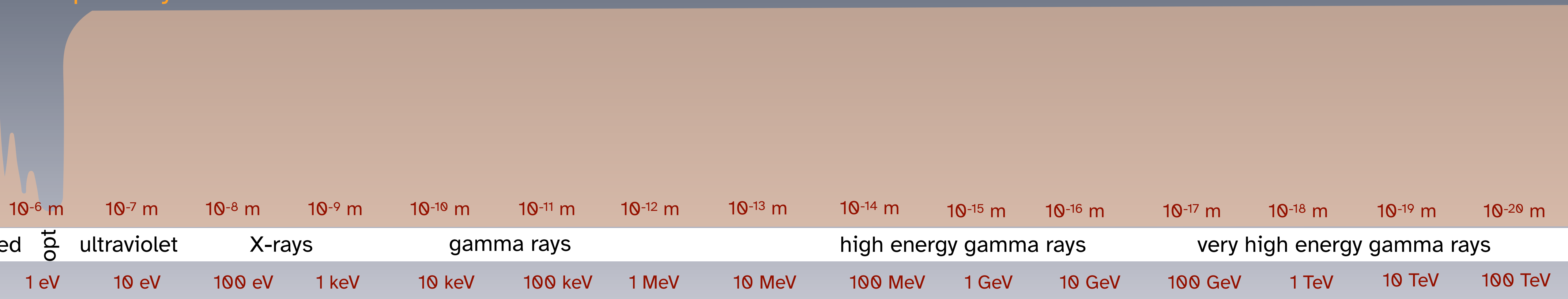






The electromagnetic spectrum, continued

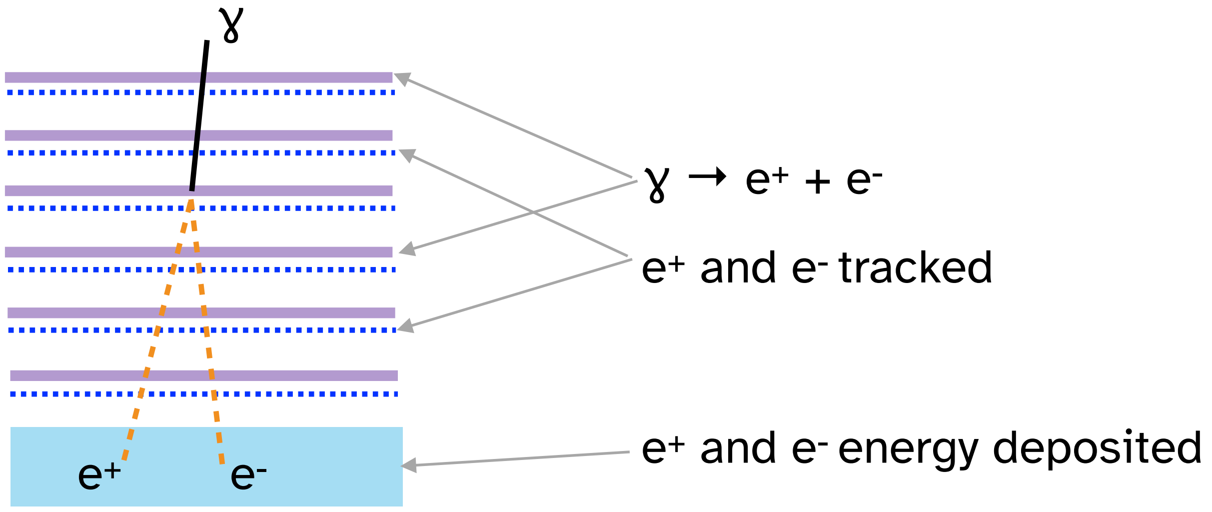
The atmosphere is opaque to gamma rays,
so let's go to space first

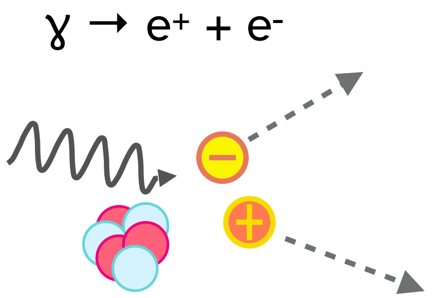


How gamma rays interact with matter: pair production

Pair-conversion telescopes

Gamma rays are hard to measure directly, but *electrons* (and positrons) are easy



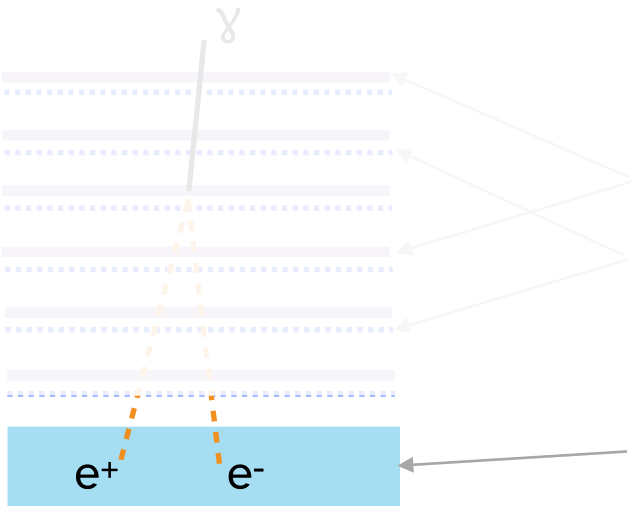


In pair-conversion telescopes, the gamma rays are converted into electron-positron pairs, whose trajectories are tracked and energies are measured

How gamma rays interact with matter: pair production

Pair-conversion telescopes

Gamma rays are hard to measure directly, but *electrons* (and positrons) are easy



$\gamma \rightarrow e^+ + e^-$

e^+ and e^- tracked

e^+ and e^- energy deposited

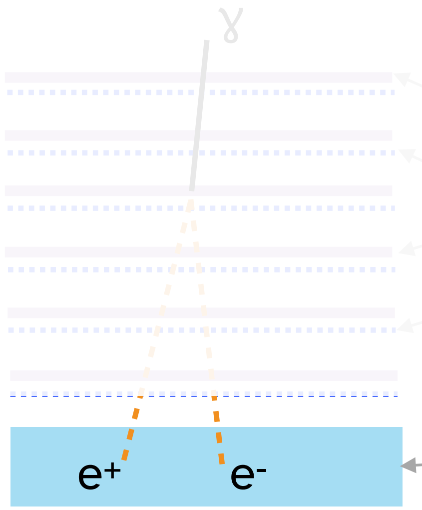
What exactly is happening here?

In pair-conversion telescopes, the gamma rays are converted into electron-positron pairs, whose trajectories are tracked and energies are measured

How gamma rays interact with matter: pair production

Pair-conversion telescopes

Gamma rays are hard to measure directly, but *electrons* (and positrons) are easy



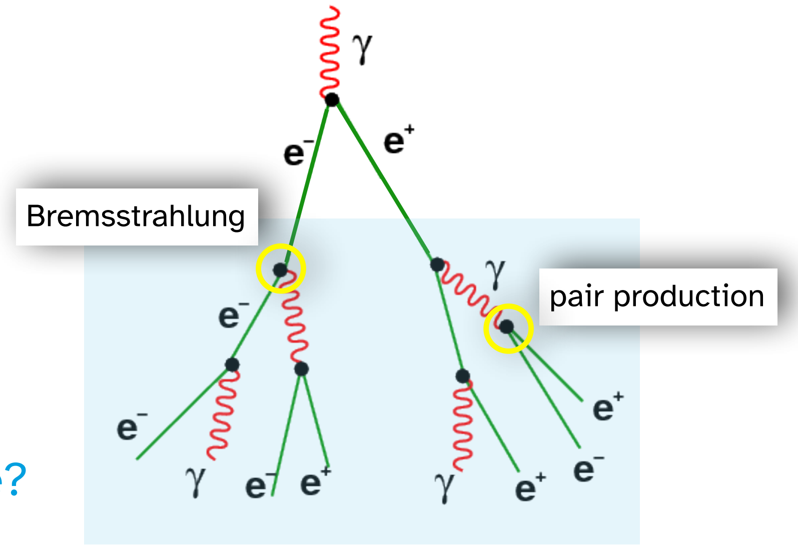
γ → e+ + e-

e+ and e- tracked

e+ and e- energy deposited

What exactly is happening here?

electromagnetic shower



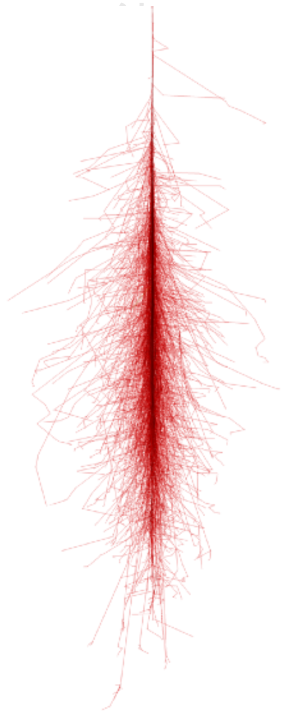
In pair-conversion telescopes, the gamma rays are converted into electron-positron pairs, whose trajectories are tracked and energies are measured

How gamma rays interact with matter: pair production

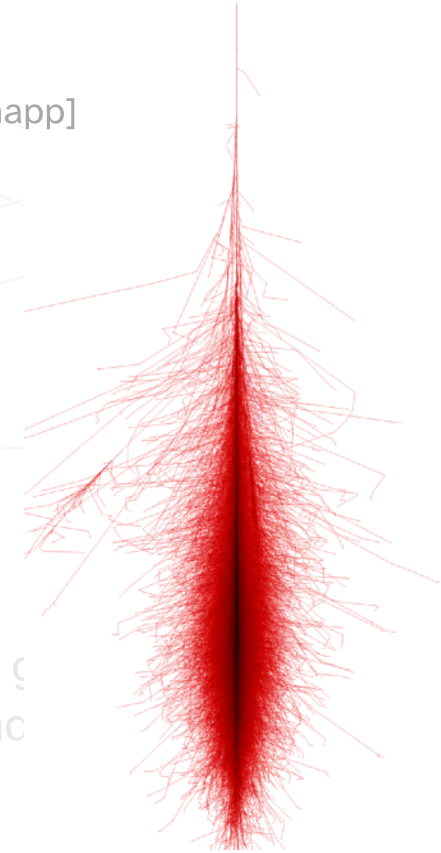
Pair-conversion telescopes

Gamma rays are hard to measure directly, but *electrons* (and positrons) are easy

lower energy γ



higher energy γ



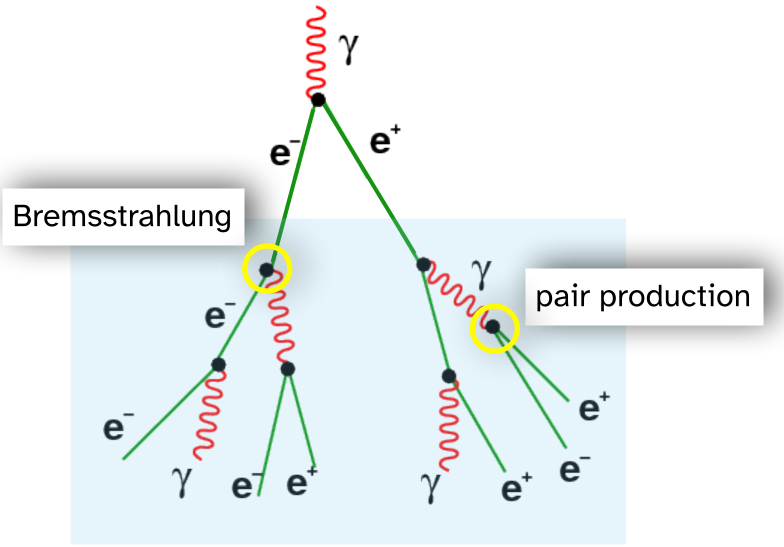
[J. Knapp]

d

/ deposited

In pair-conve the (/erted into electron-positron pairs, whose traje d anc ured

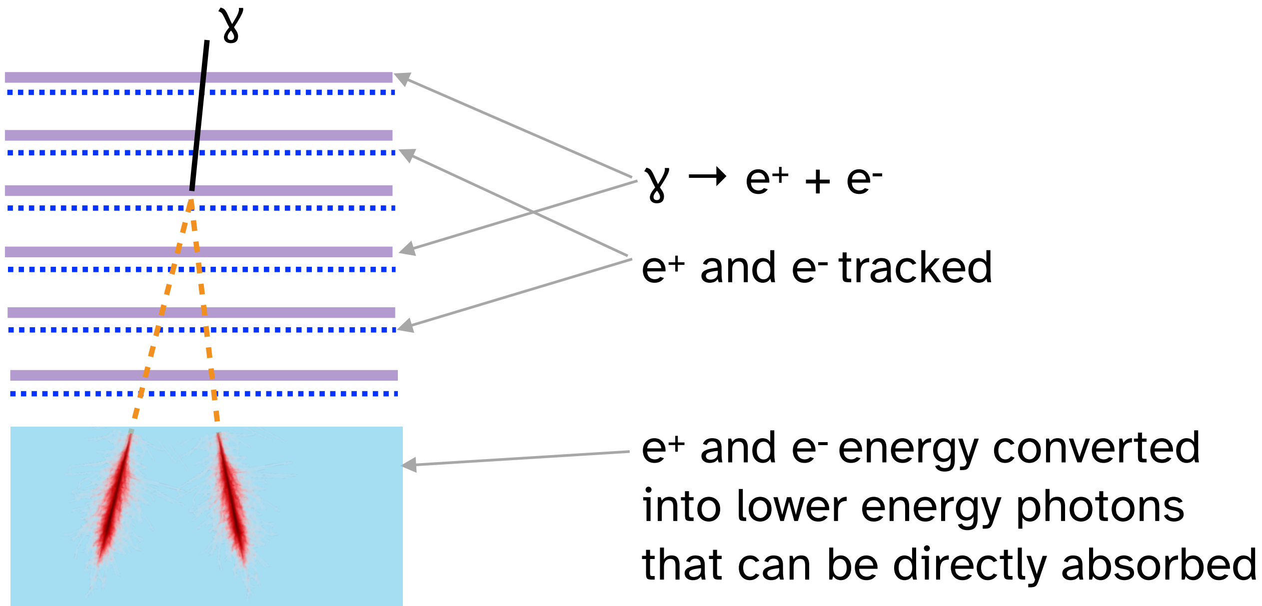
electromagnetic shower

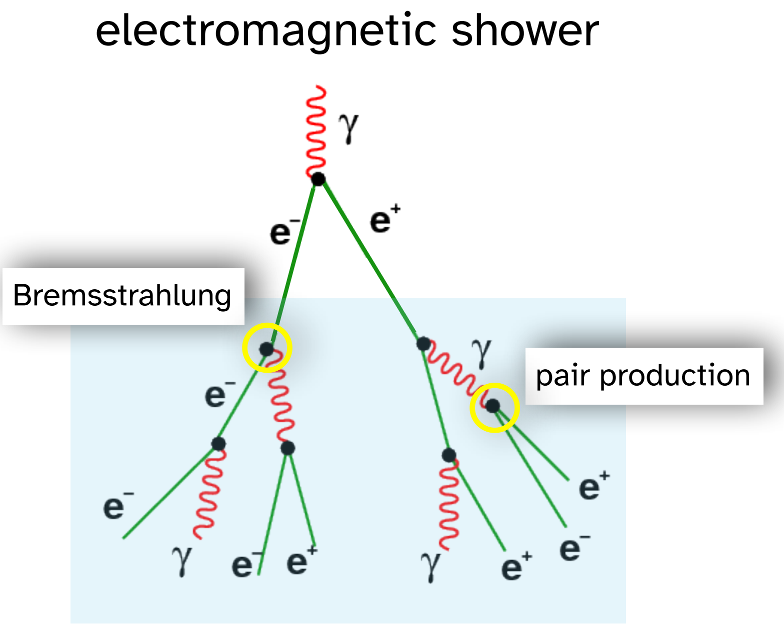


How gamma rays interact with matter: pair production

Pair-conversion telescopes

Gamma rays are hard to measure directly, but *electrons* (and positrons) are easy



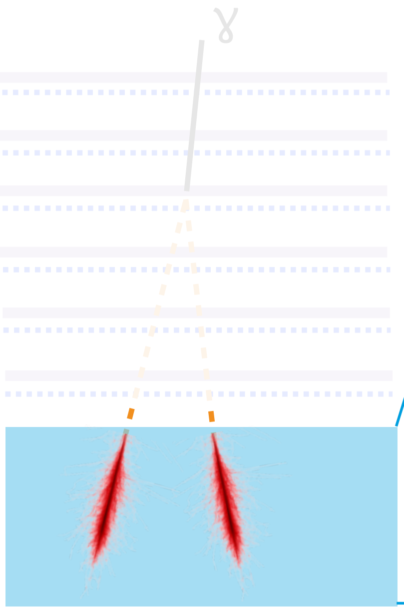


In pair-conversion telescopes, the gamma rays are converted into electron-positron pairs, whose trajectories are tracked and energies are measured

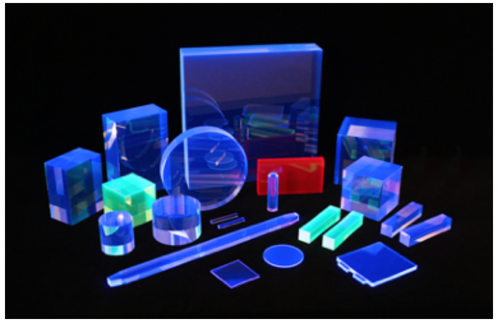
How gamma rays interact with matter: pair production

Pair-conversion telescopes

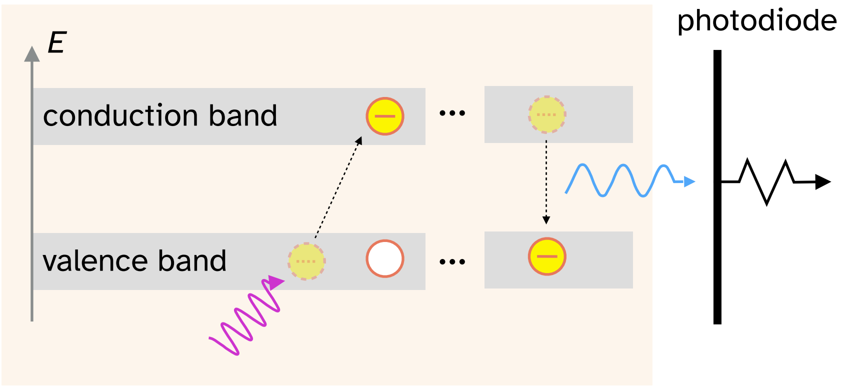
Gamma rays are hard to measure directly, but *electrons* (and positrons) are easy



Scintillators absorb higher energy photons or charged particles, then reemit the energy in lower energy (UV, optical) photons



[Eljen Technology]

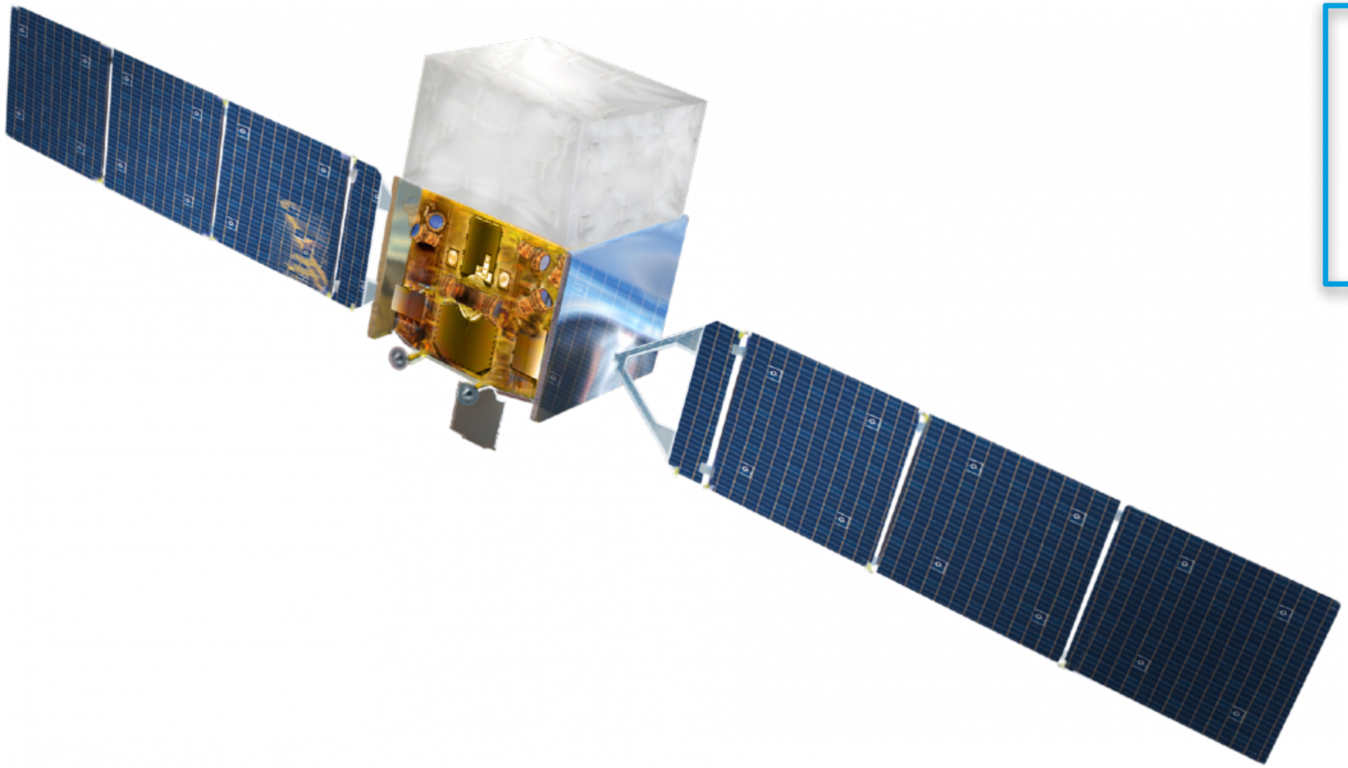


inorganic crystal scintillator

In pair-conversion telescopes, the gamma rays are converted into electron-positron pairs, whose trajectories are tracked and energies are measured

How gamma rays interact with matter: pair production

Pair-conversion telescopes



[NASA/DOE/Fermi-LAT]

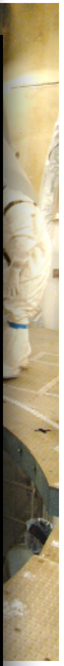
Fermi Large Area Telescope

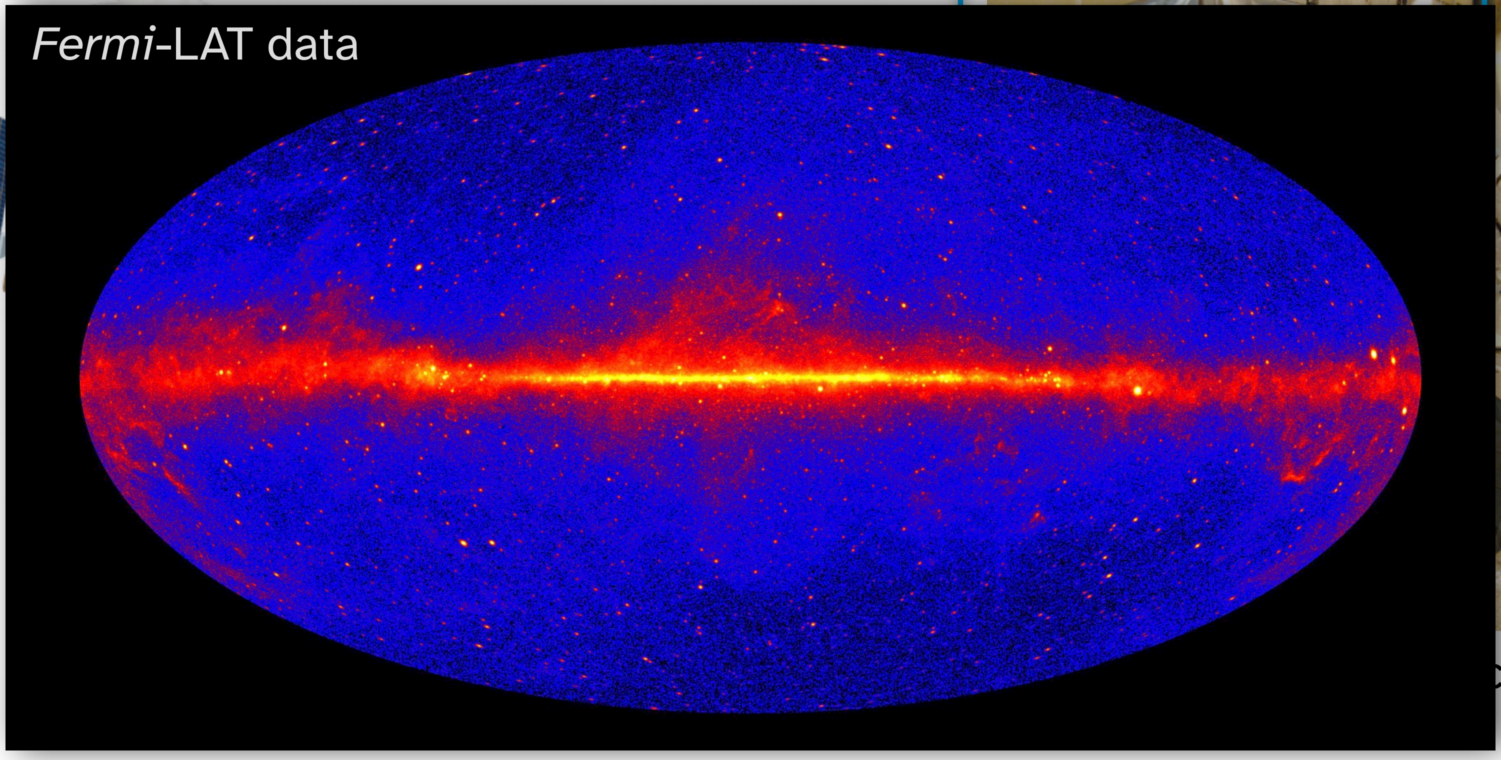
In pair-conversion telescopes, the gamma rays are converted into electron-positron pairs, whose trajectories are tracked and energies are measured

How gamma rays interact with matter: pair production

Pair-conversion telescopes

[NASA/DOE/Fermi-LAT]

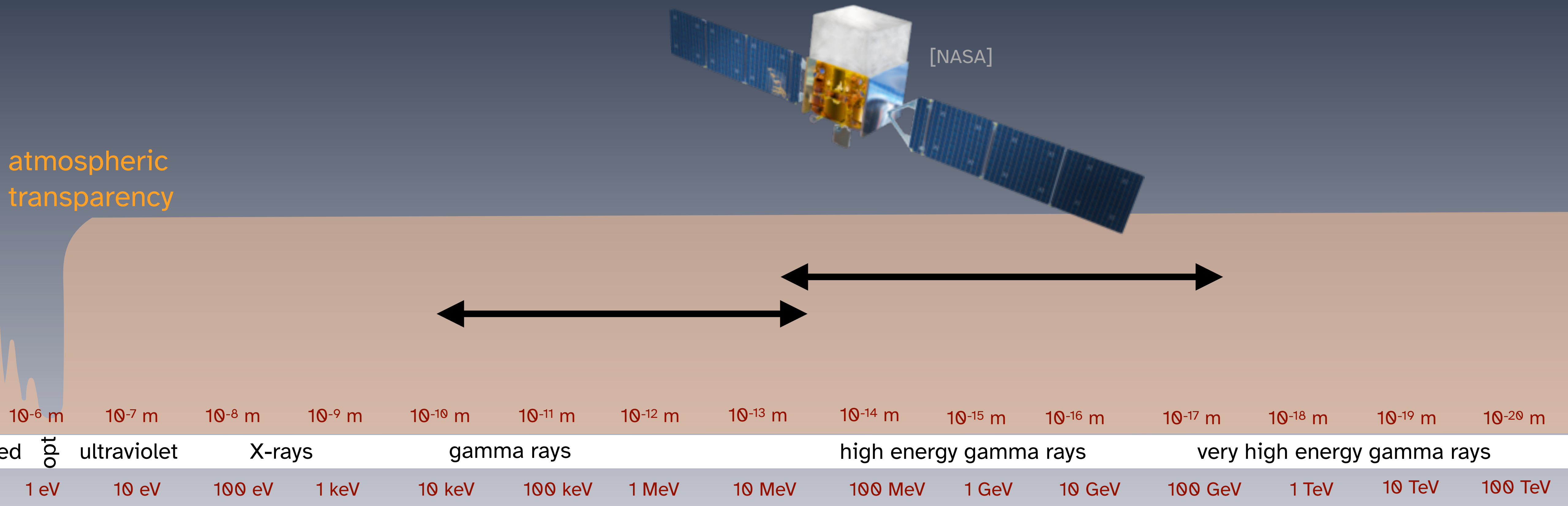




cope

In pair-conversion telescopes, the gamma rays are converted into electron-positron pairs, whose trajectories are tracked and energies are measured

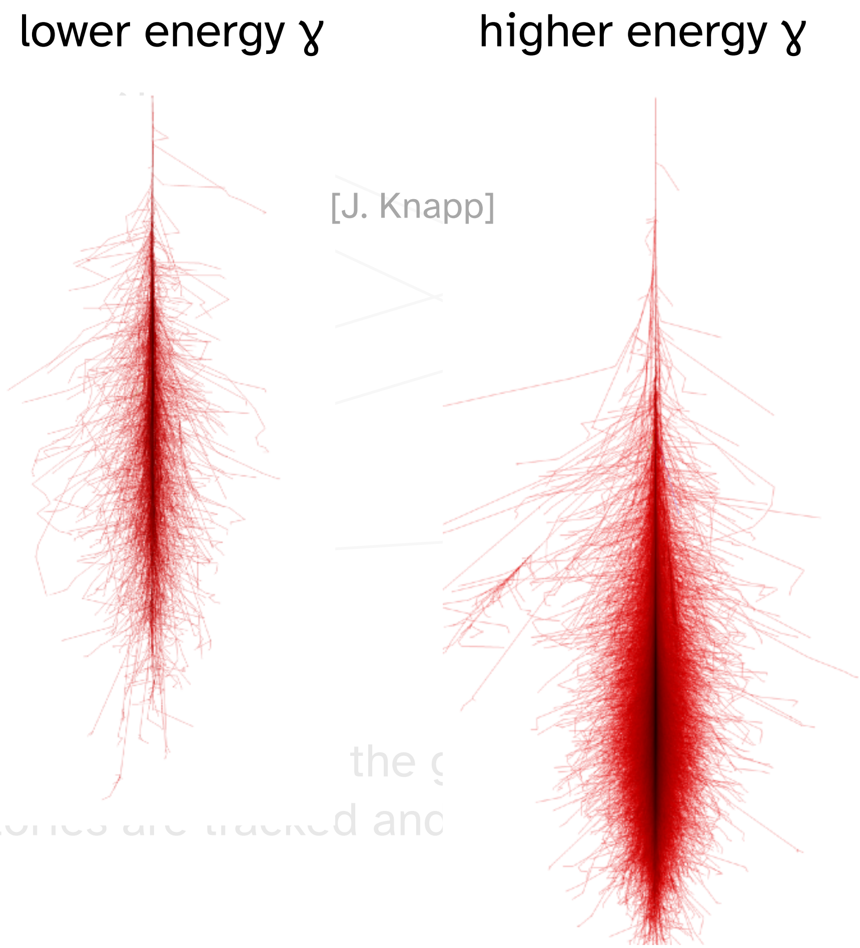
The electromagnetic spectrum, continued



How gamma rays interact with matter: pair production

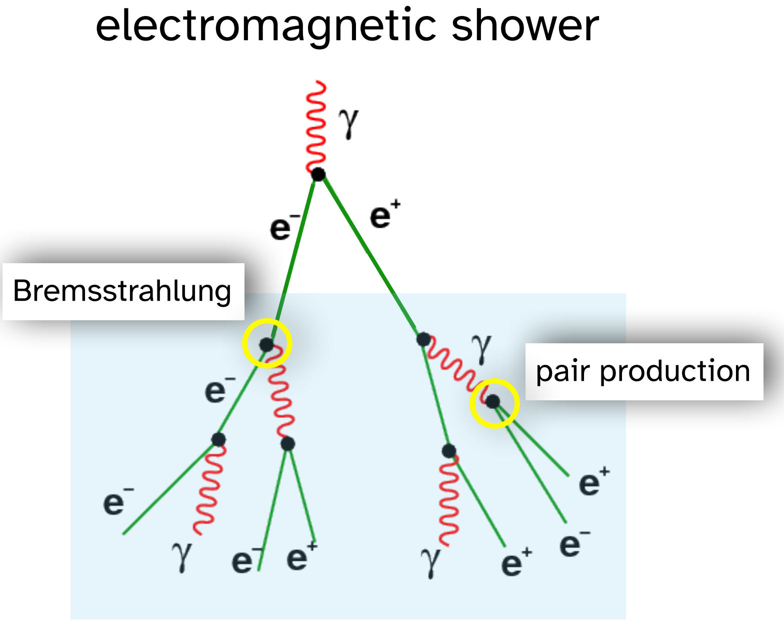
Pair-conversion telescopes

Gamma rays are hard to measure directly, but *electrons* (and positrons) are easy



d

/ deposited

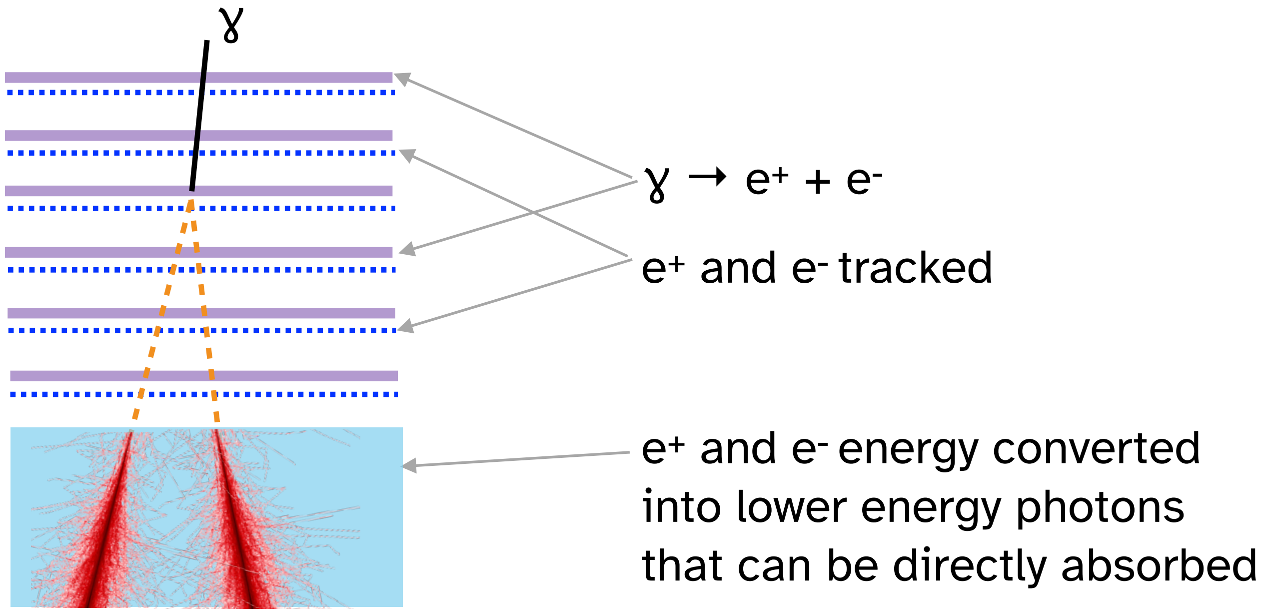


In pair-conve … the ɡ … /erted into electron-positron pairs,
whose traje… …d anc … ıred

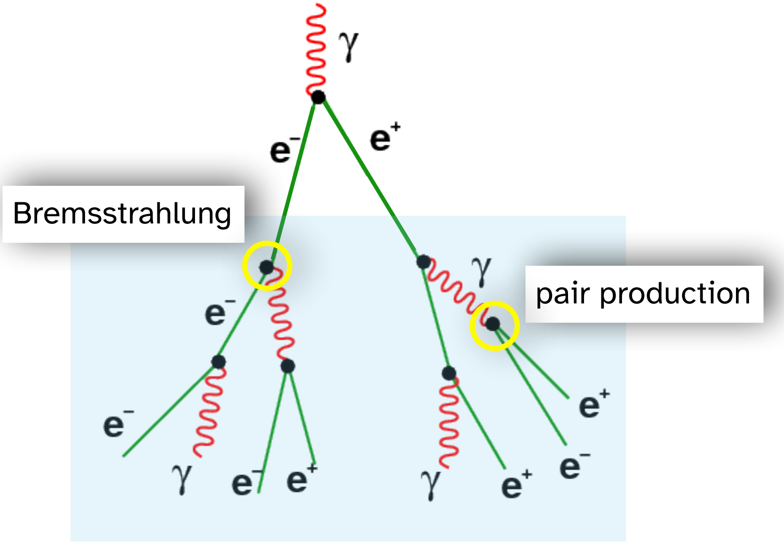
How gamma rays interact with matter: pair production

Pair-conversion telescopes

Gamma rays are hard to measure directly, but *electrons* (and positrons) are easy



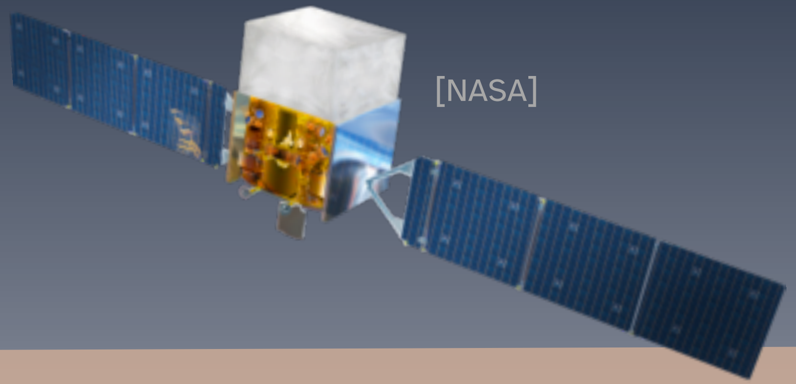
electromagnetic shower



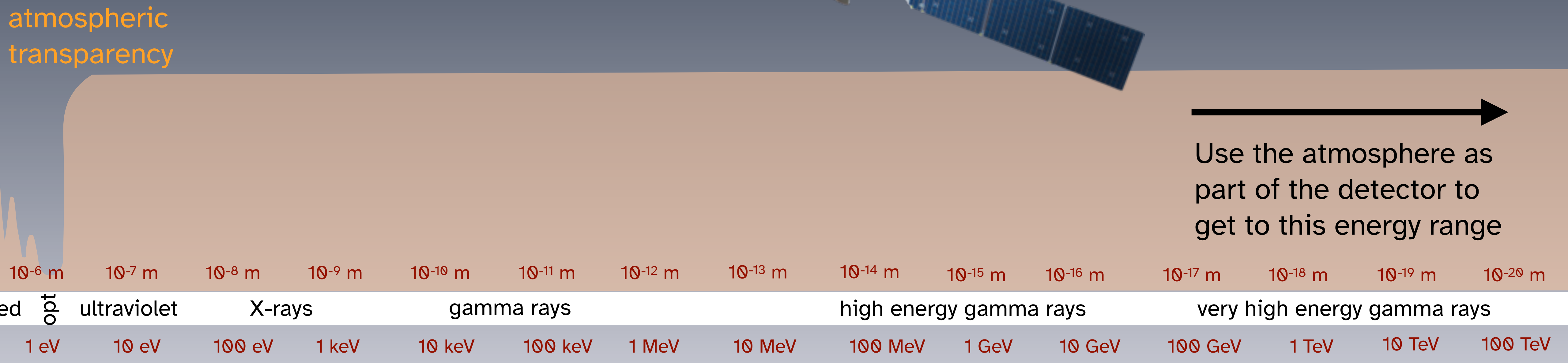
When the initial photon energy is too high, the shower can't be contained within the detector

-> space-based telescopes can't go above ~100s of GeV

The electromagnetic spectrum, continued



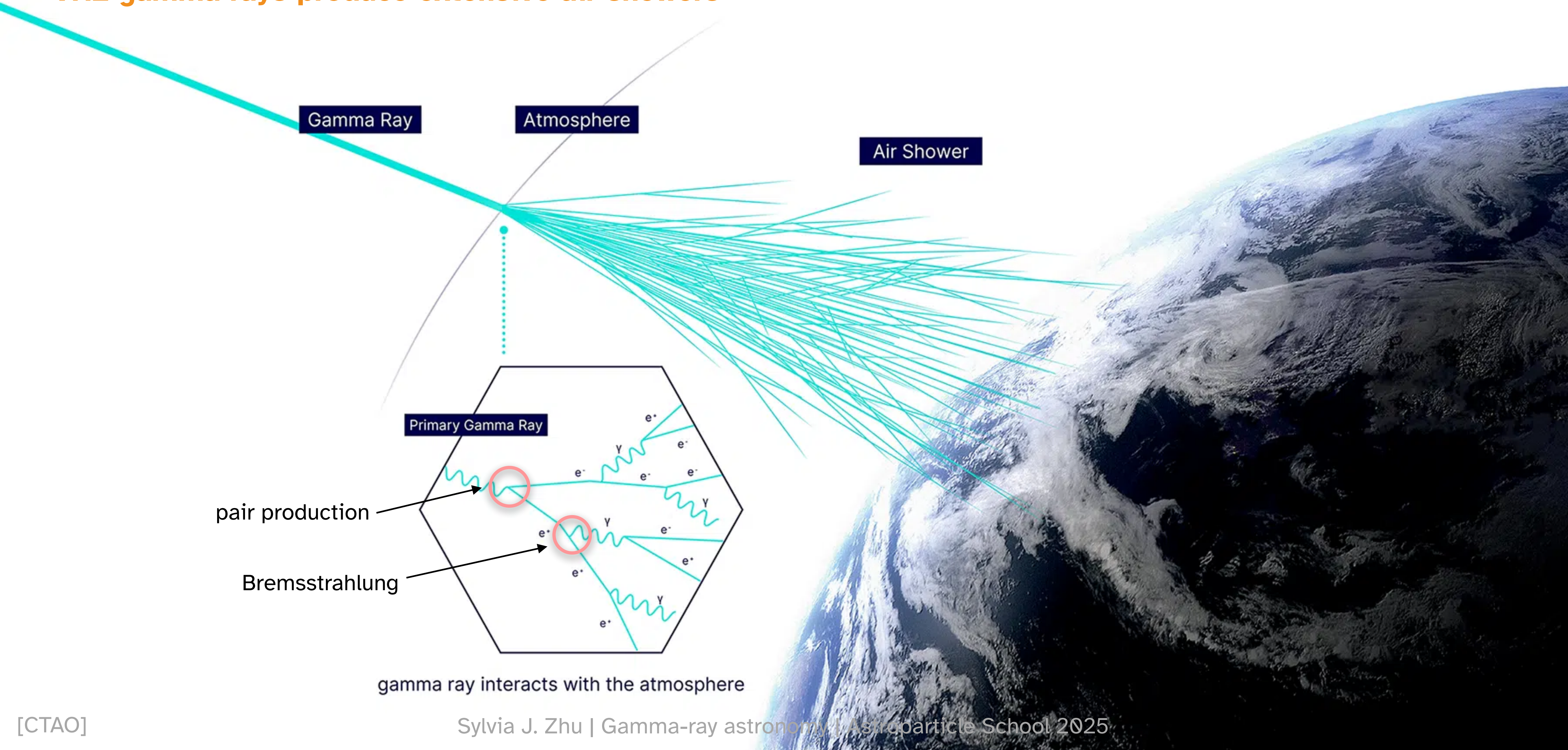
[NASA]



Use the atmosphere as part of the detector

VHE gamma rays produce extensive air showers

VHE: Very High Energy
(>100 GeV)

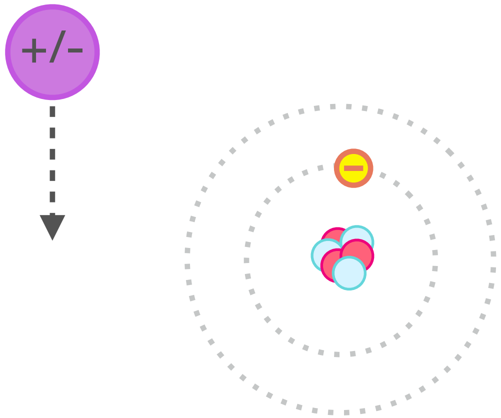


[CTAO]

Use the atmosphere as part of the detector

Particles in the air shower produce Cherenkov radiation

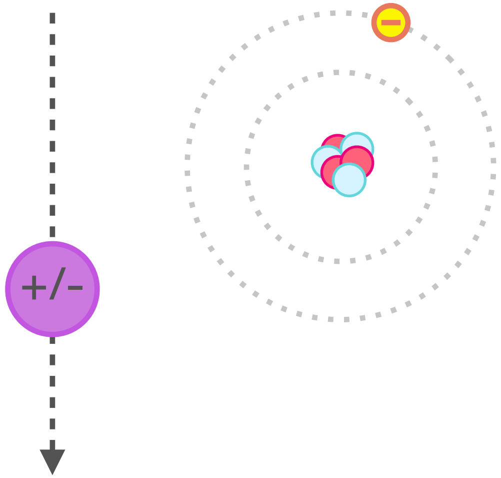
electromagnetic equivalent to a sonic boom



Use the atmosphere as part of the detector

Particles in the air shower produce Cherenkov radiation

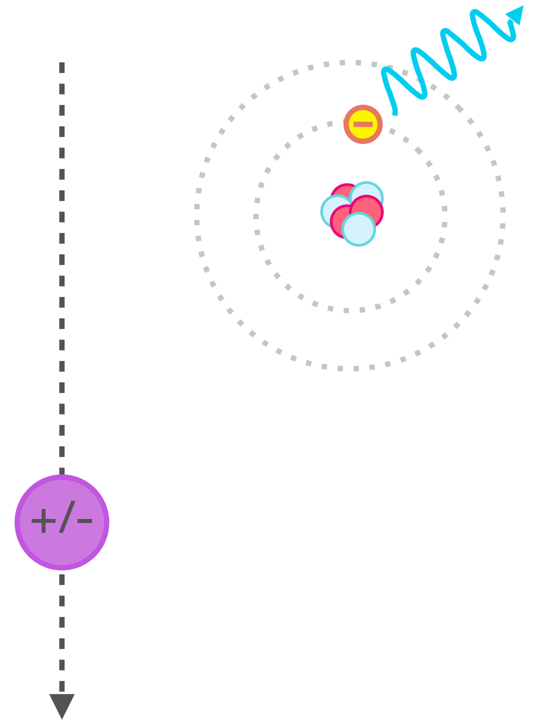
electromagnetic equivalent to a sonic boom



Use the atmosphere as part of the detector

Particles in the air shower produce Cherenkov radiation

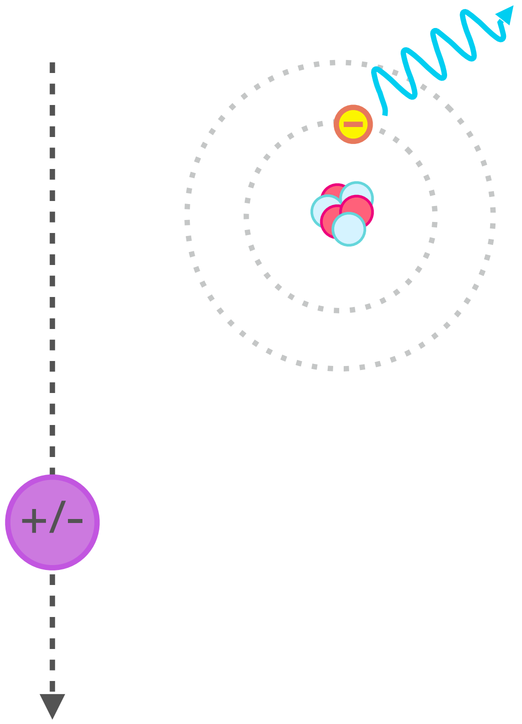
electromagnetic equivalent to a sonic boom



Use the atmosphere as part of the detector

Particles in the air shower produce Cherenkov radiation

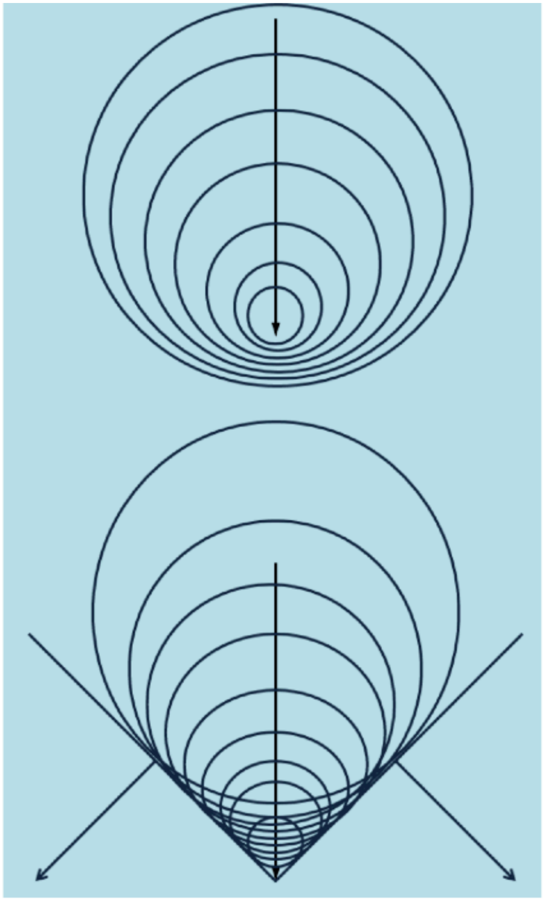
electromagnetic equivalent to a sonic boom



v < c/n:
no wavefront

v > c/n:
wavefront

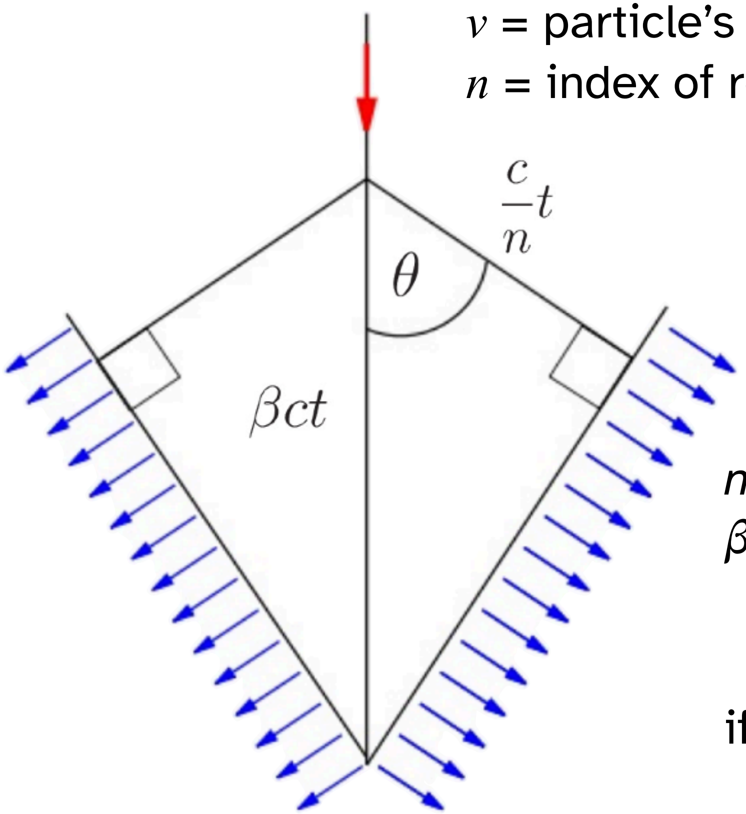
[J. Eckhard]



Use the atmosphere as part of the detector

Particles in the air shower produce Cherenkov radiation

electromagnetic equivalent to a sonic boom



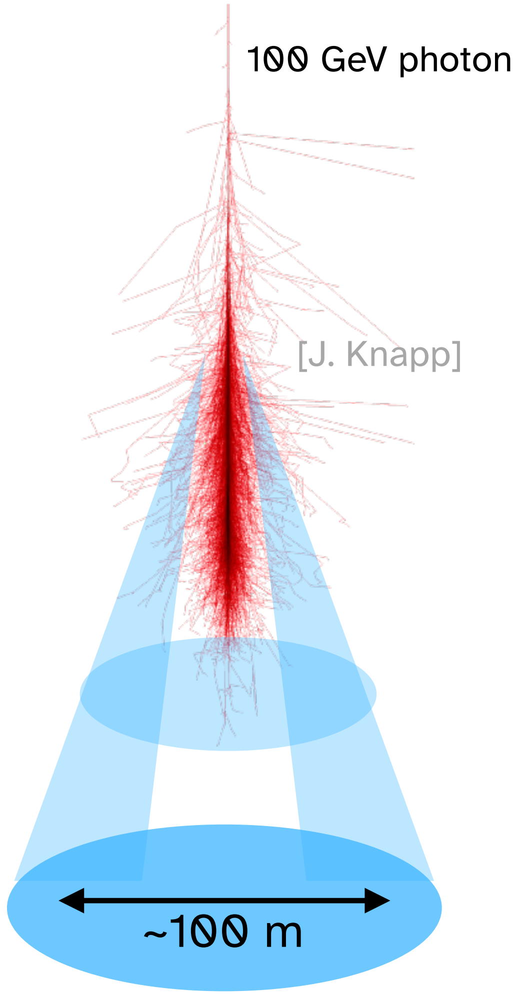
v = particle's speed
n = index of refraction of air

$$\beta = \frac{v}{c}$$

$$\theta = \arccos \frac{1}{\beta n}$$

n ~ slightly larger than 1
β ~ 1
=> θ ~ 1°

if shower starts 10 km above ground,
Cherenkov light cone size will be ~100 m
-> place your detectors on the ground to cover this

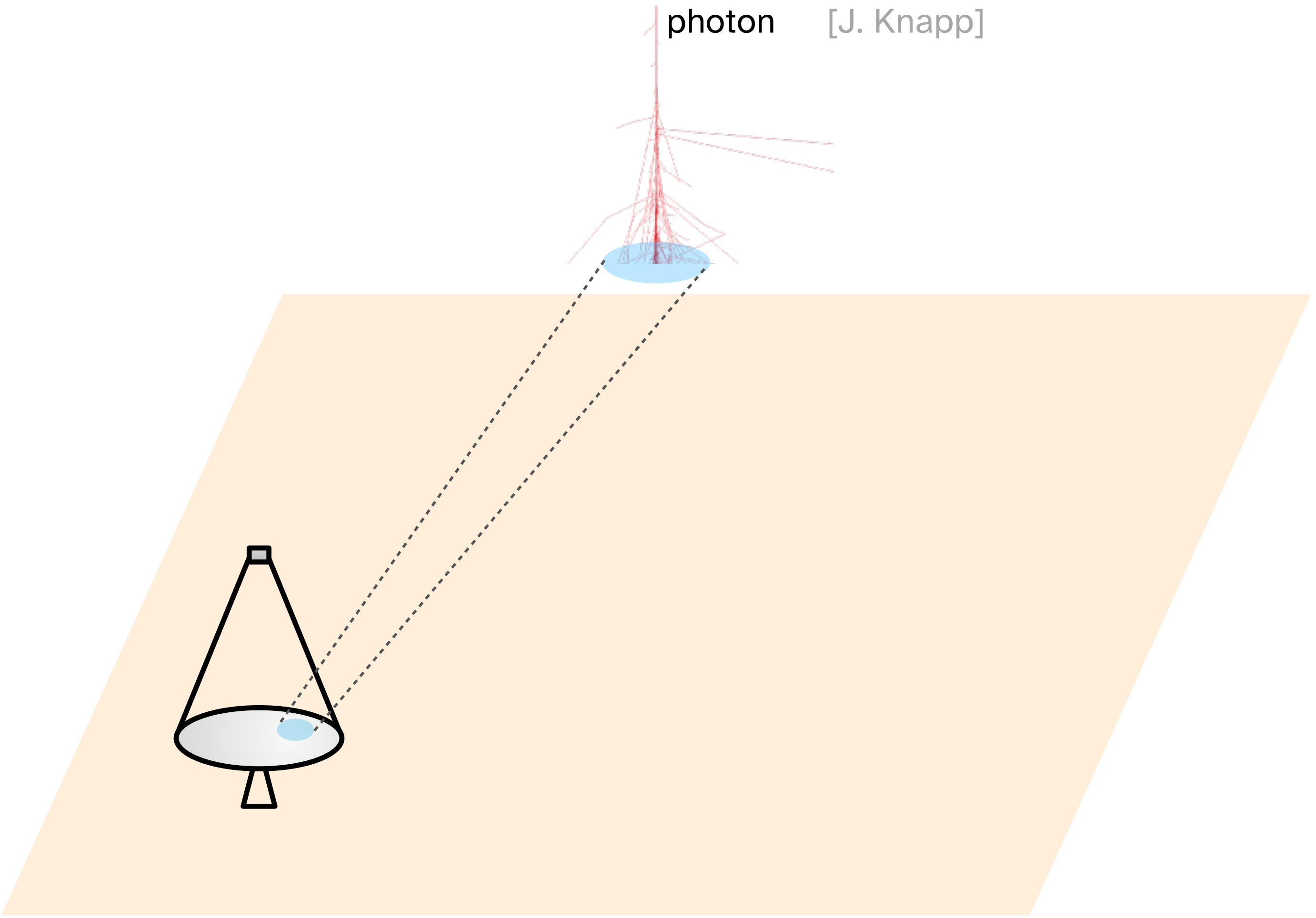


[J. Knapp]

modified from [J. Eckhard]

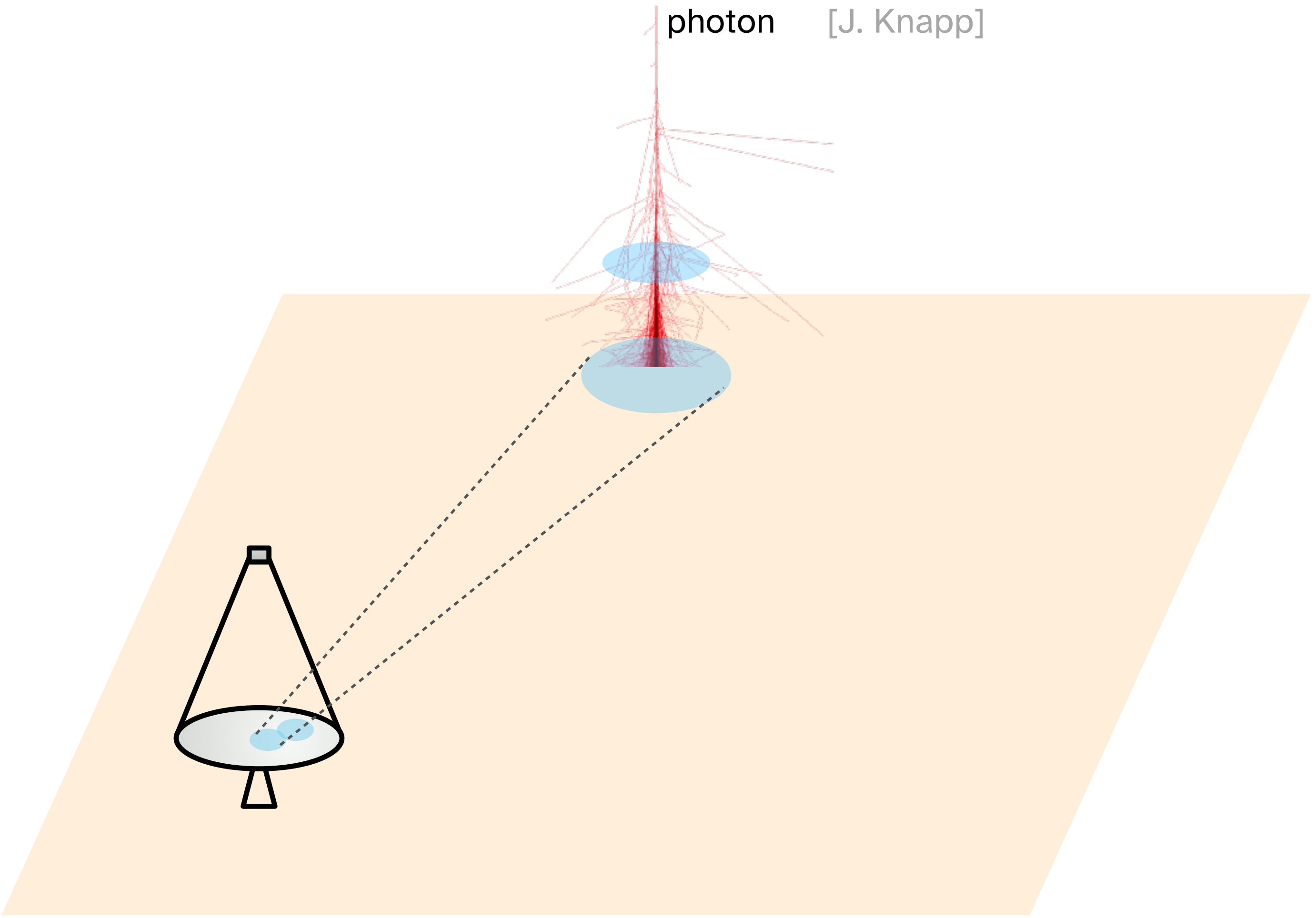
Imaging Atmospheric Cherenkov Telescopes (IACTs)

Take a "snapshot" of the pool of Cherenkov light



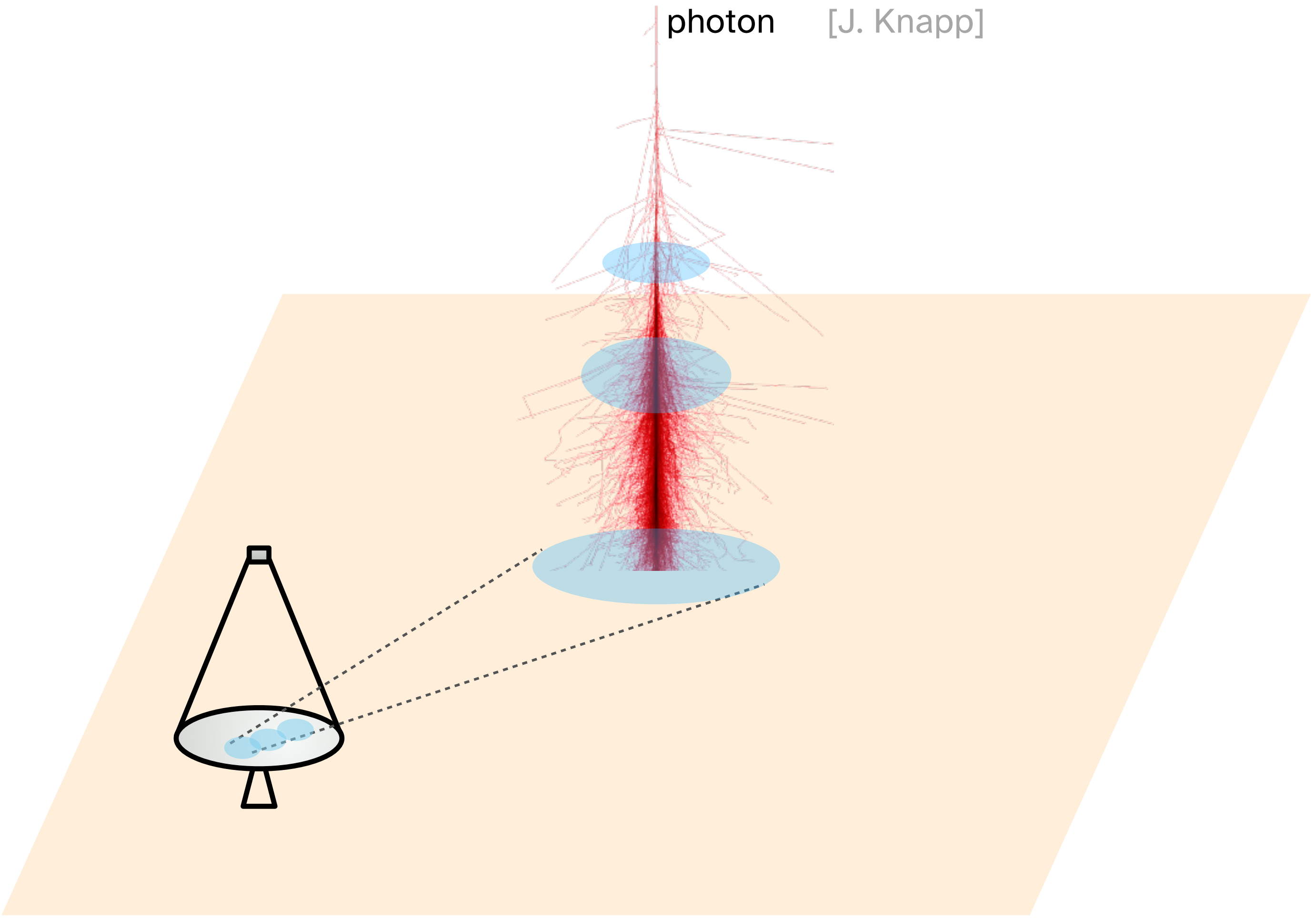
Imaging Atmospheric Cherenkov Telescopes (IACTs)

Take a “snapshot” of the pool of Cherenkov light



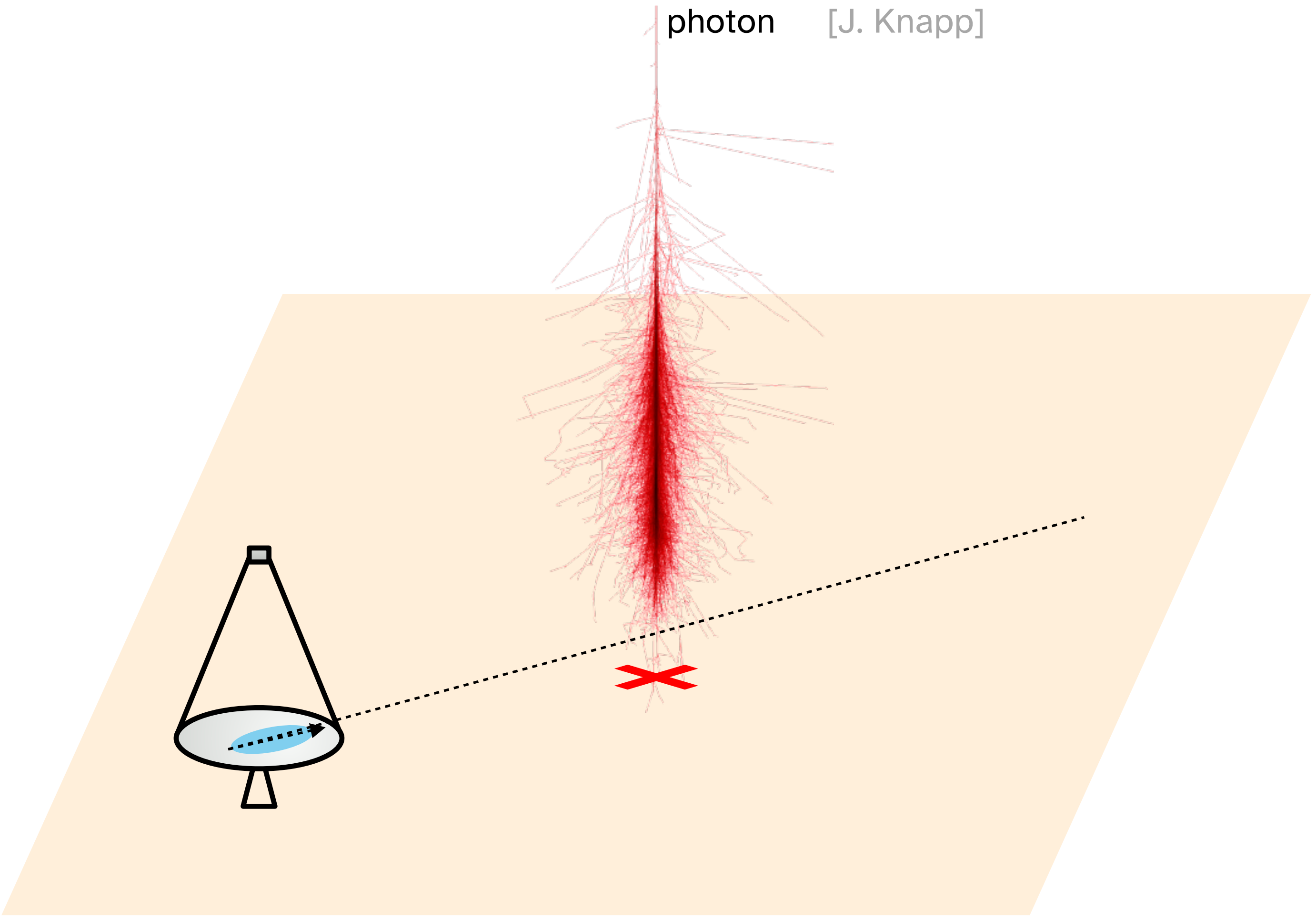
Imaging Atmospheric Cherenkov Telescopes (IACTs)

Take a "snapshot" of the pool of Cherenkov light



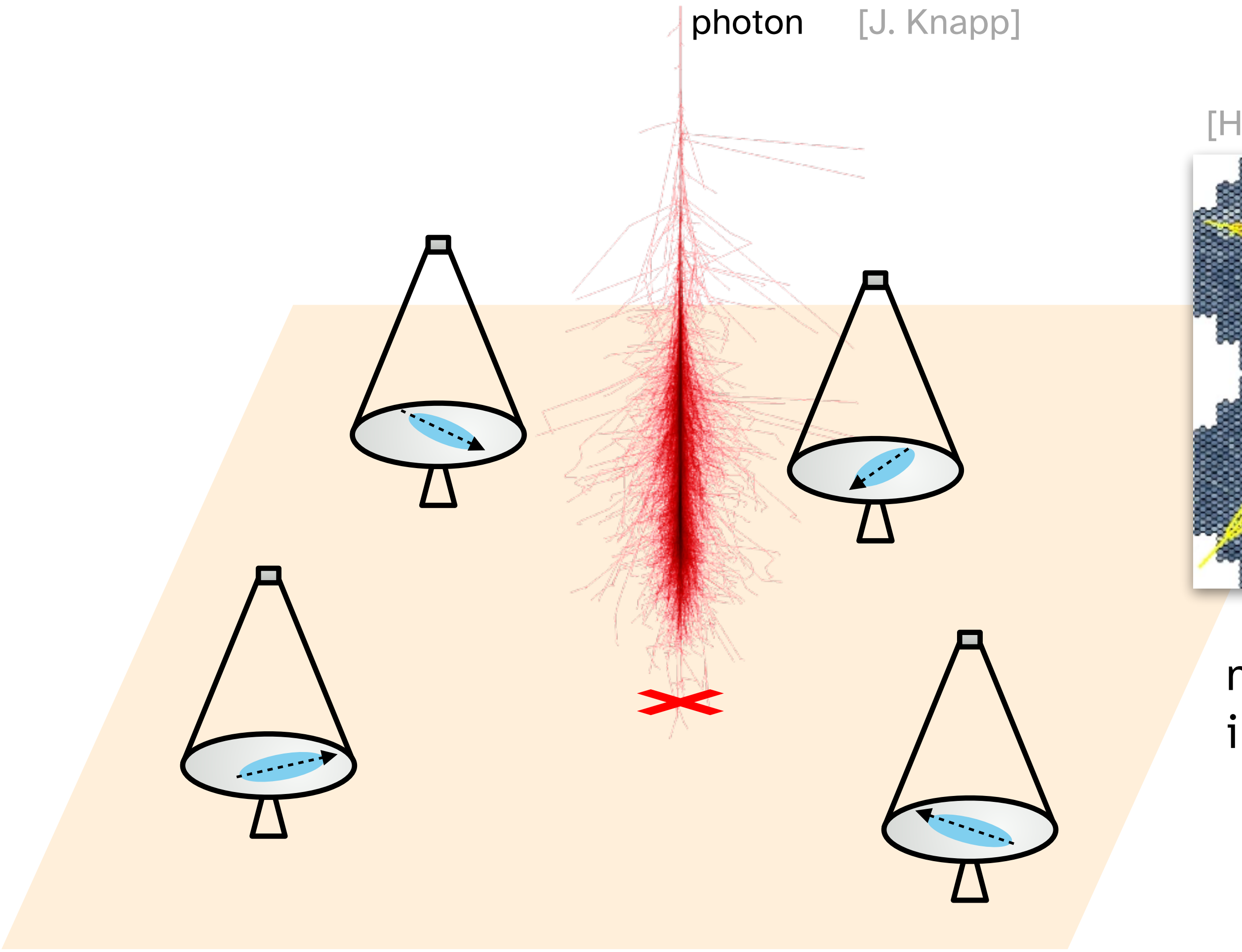
Imaging Atmospheric Cherenkov Telescopes (IACTs)

Take a “snapshot” of the pool of Cherenkov light

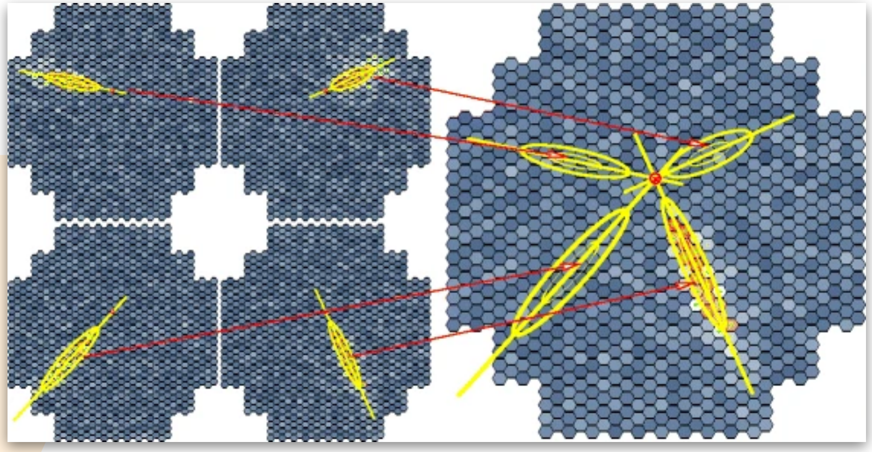


Imaging Atmospheric Cherenkov Telescopes (IACTs)

Take a "snapshot" of the pool of Cherenkov light



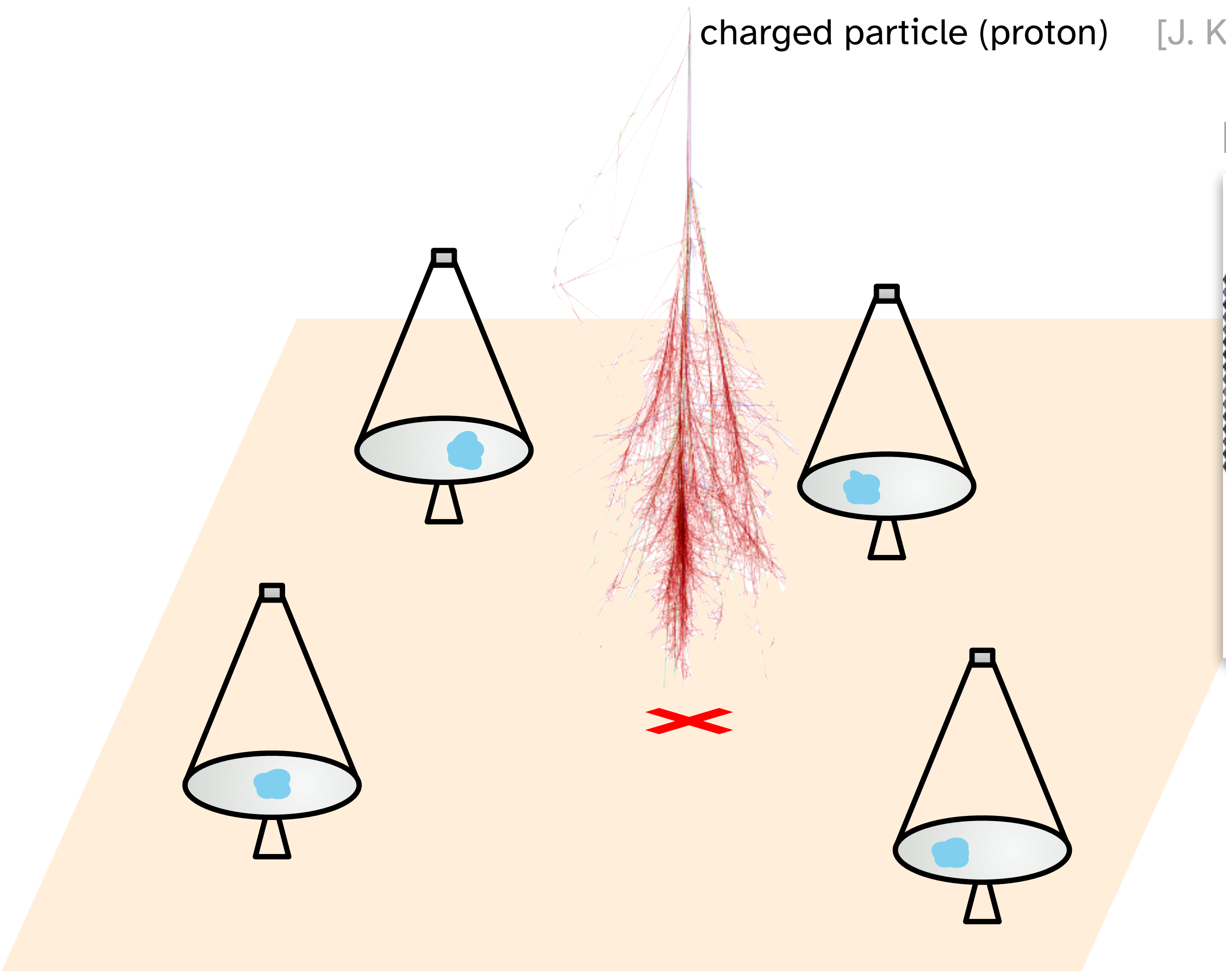
[H. Völk & K. Bernlöhr, ExA 25 (2009)]



main axes -> photon direction
image intensity + geometry -> energy

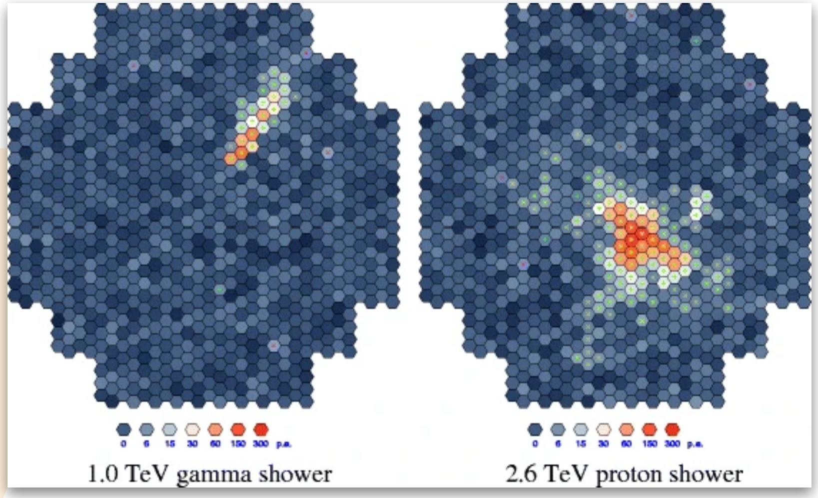
Imaging Atmospheric Cherenkov Telescopes (IACTs)

Take a “snapshot” of the pool of Cherenkov light



[J. Knapp]

[H. Völk & K. Bernlöhr, ExA 25 (2009)]



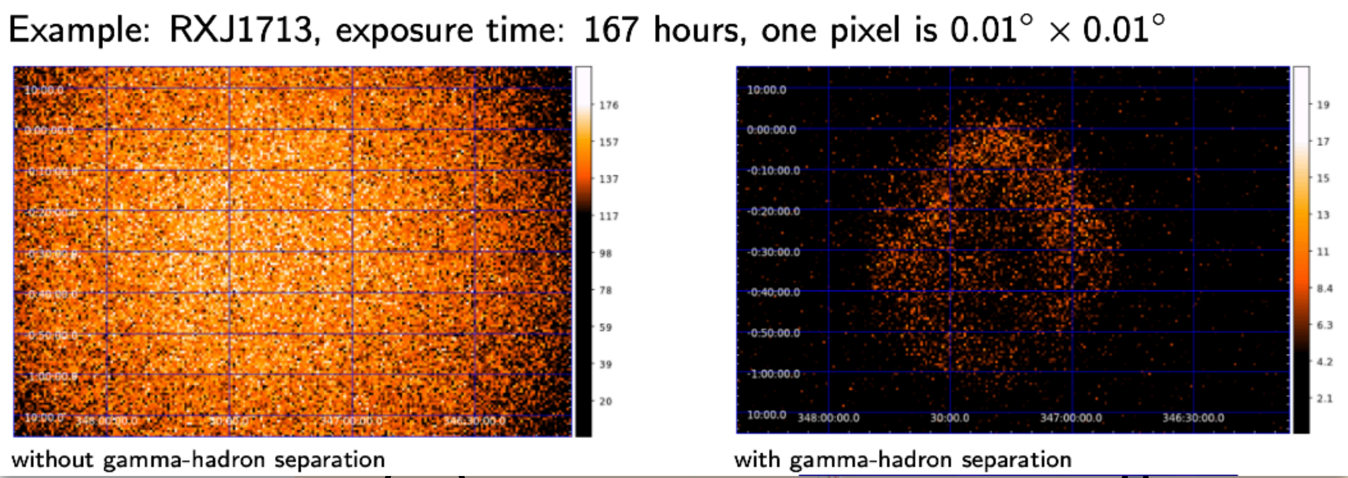
main axes -> photon direction
image intensity + geometry -> energy
shape -> charged particle rejection
“gamma-hadron separation”

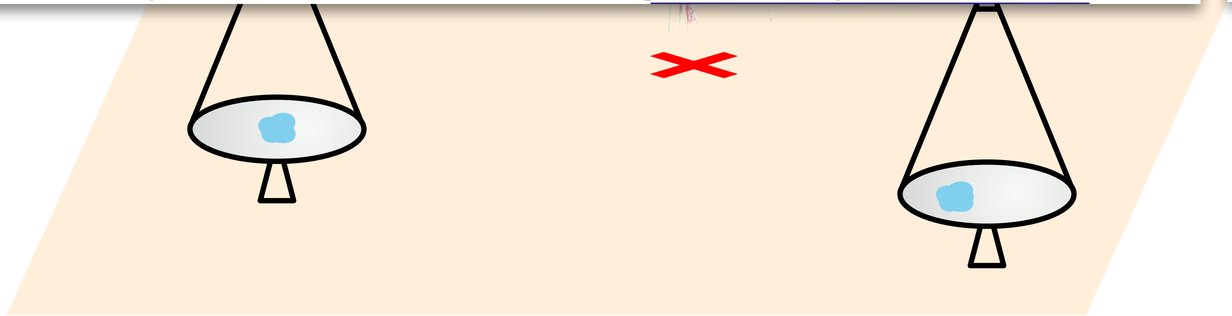
Imaging Atmospheric Cherenkov Telescopes (IACTs)

Take a “snapshot” of the pool of Cherenkov light

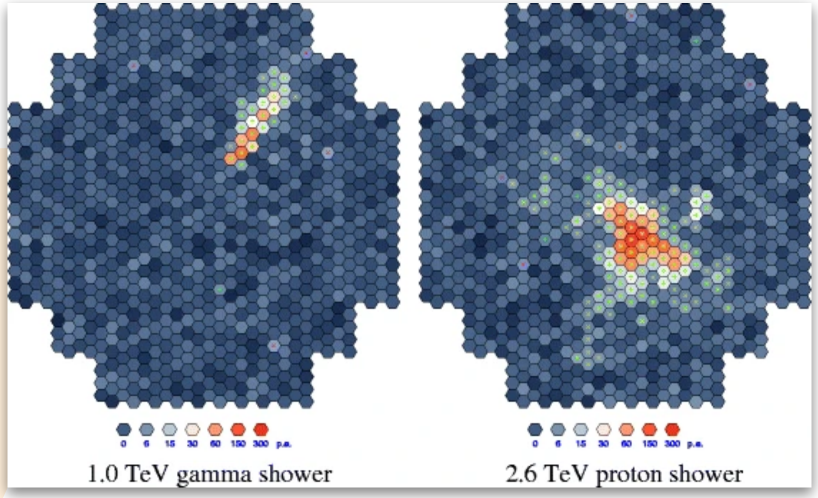
charged particle (proton) [J. Knapp]

[R. Marx]





[H. Völk & K. Bernlöhr, ExA 25 (2009)]



main axes -> photon direction
image intensity + geometry -> energy
shape -> charged particle rejection
“gamma-hadron separation”

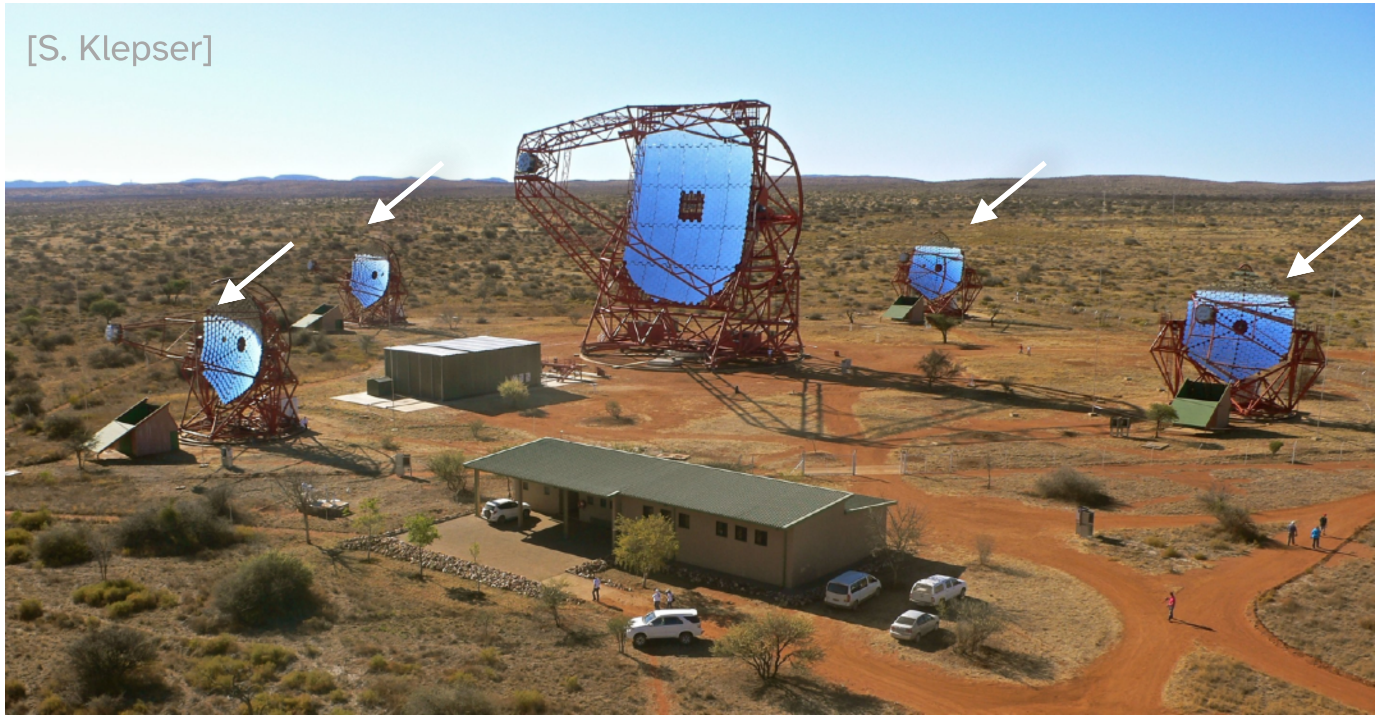
IACT arrays

[Daniel R. Strebe]

Telescope structure: Steel frames

Very stable, but very heavy

H.E.S.S. small telescopes



60 tons, ~25 m at tallest

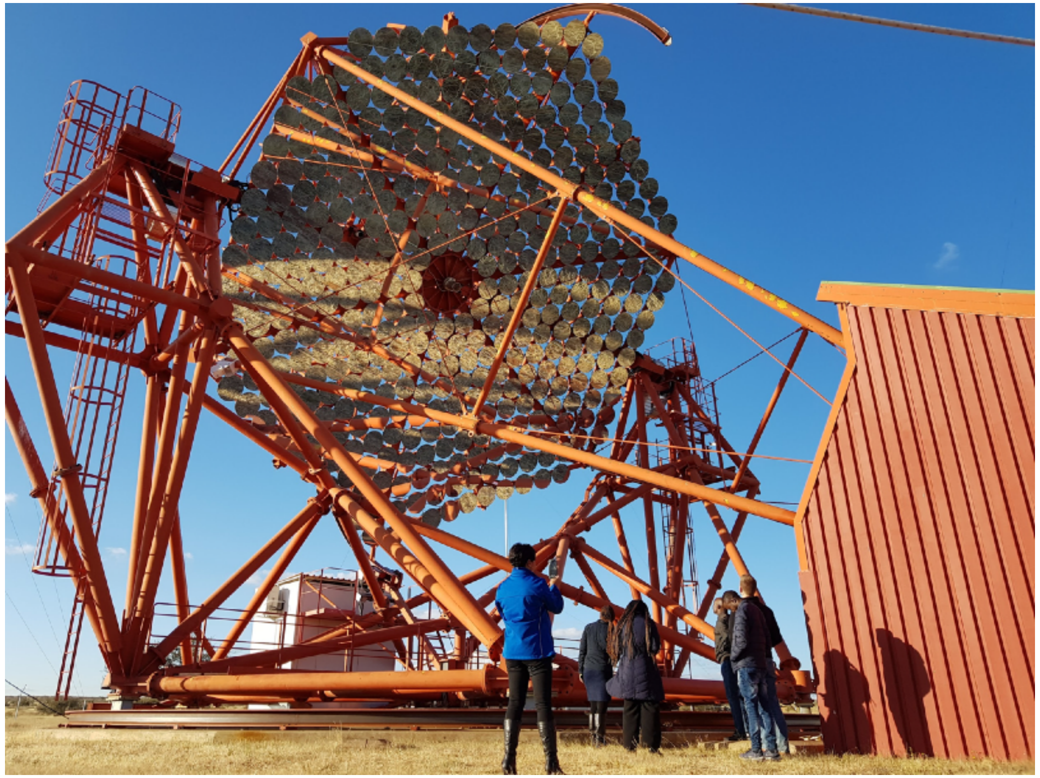
H.E.S.S. big telescope

600 tons, ~60 m at tallest

Telescope structure: Steel frames

Very stable, but very heavy

H.E.S.S. small telescopes



108 m^2 total mirror area (a large apartment in Berlin)

H.E.S.S. big telescope

614 m^2 mirrors (1.5 basketball courts / 3 tennis courts)

Telescope structure: Steel frames

Very stable, but very heavy

[Helmholtz Alliance for Astroparticle Physics / A. Chantelauze]

Telescope structure: Carbon fiber frames

Much more agile but less rigid

MAGIC telescopes ~40 tons, ~30 m at tallest

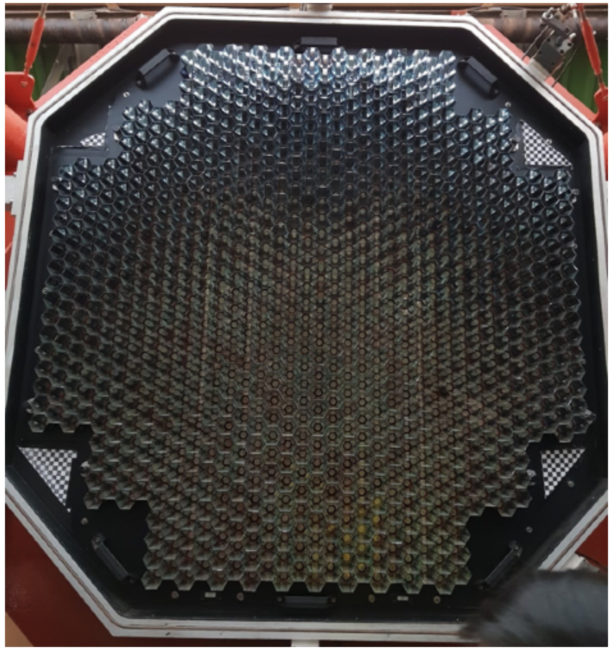
[MAGIC collaboration]

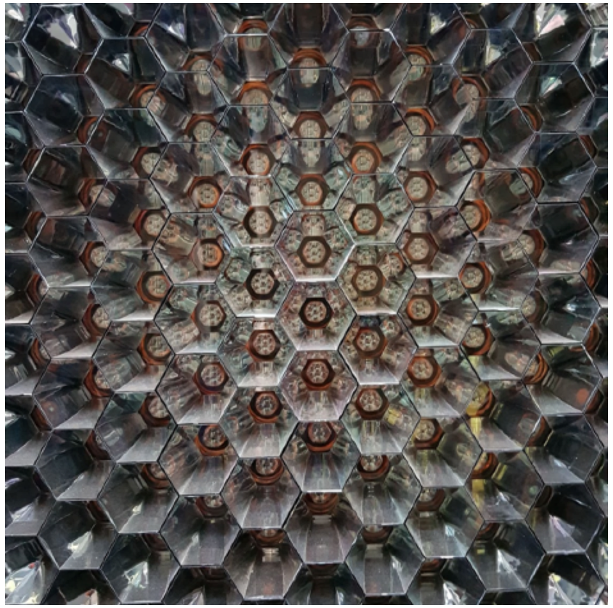
[S. Schurig]

Cameras: Photomultiplier tubes (PMTs)

Mature technology but sensitive to light damage

H.E.S.S. small telescopes

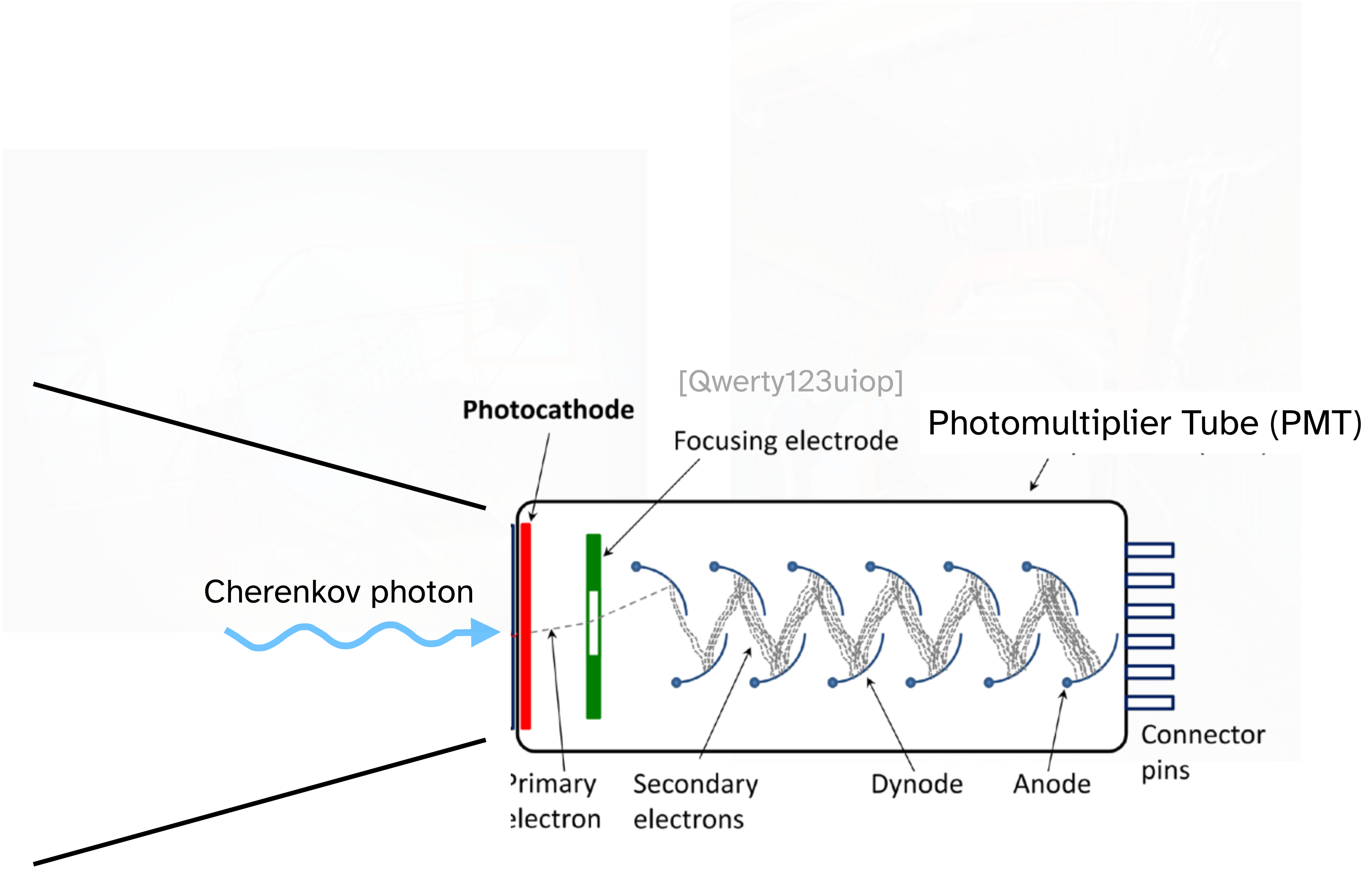


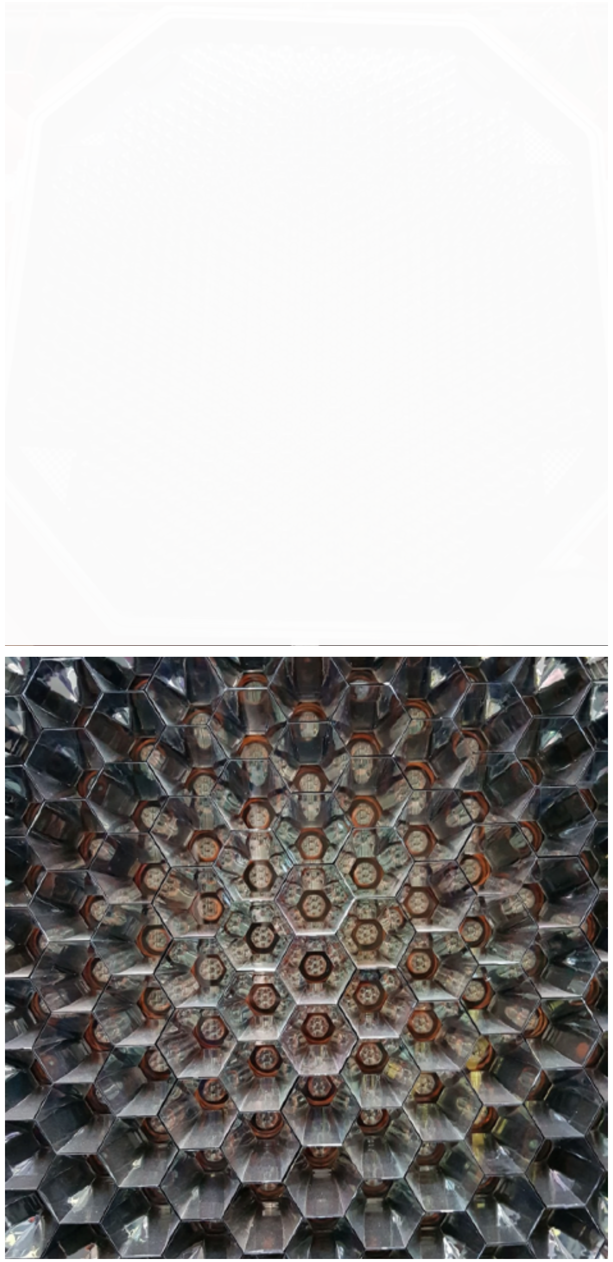


Cameras: Photomultiplier tubes (PMTs)

Mature technology but sensitive to light damage

PMTs are also used by MAGIC and VERITAS



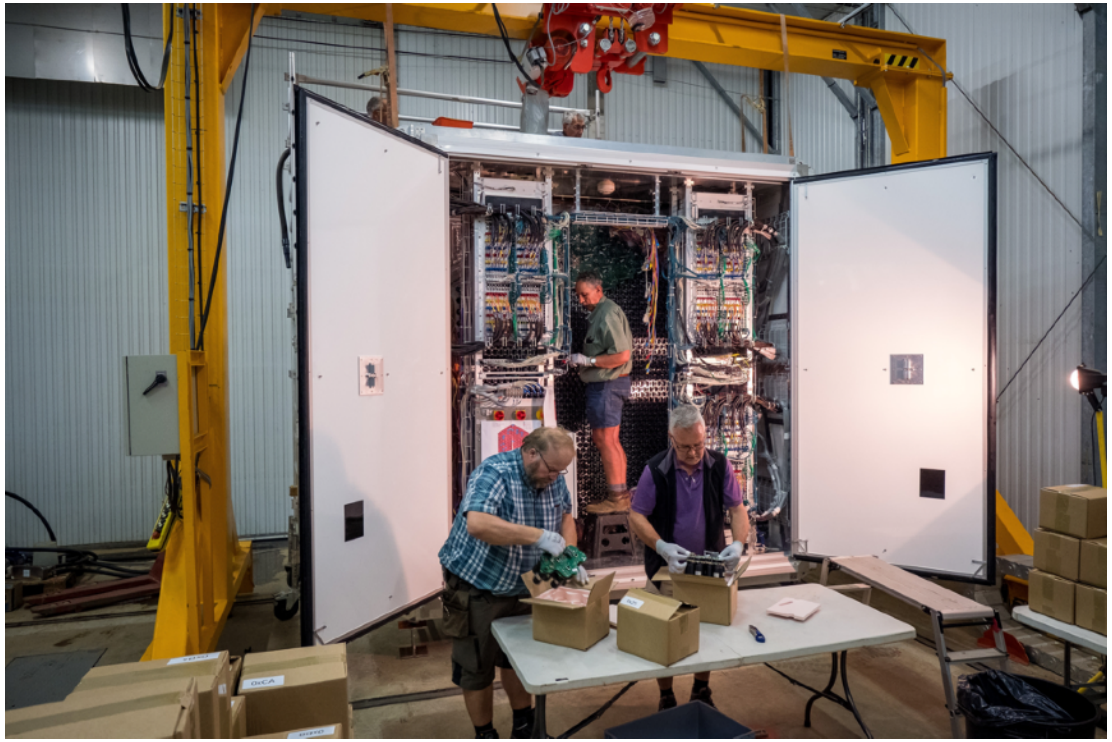


Cameras: Photomultiplier tubes (PMTs)

Mature technology but sensitive to light damage

PMTs are also used by MAGIC and VERITAS

[C. Föhr (MPIK)]

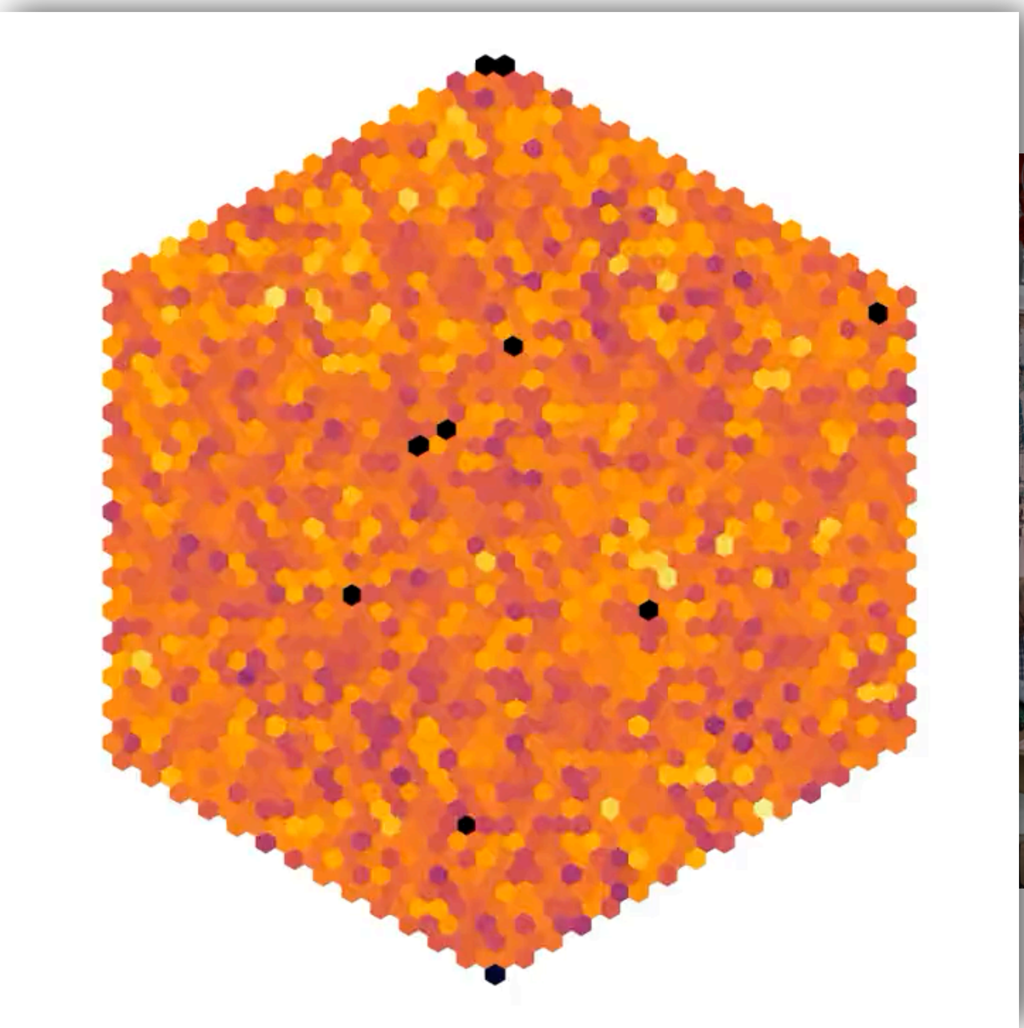


Cameras: Photomultiplier tubes (PMTs)

Mature technology but sensitive to light damage

PMTs are also used by MAGIC …

[C. Föhr (MPIK)]



IACT arrays

When can they observe?

Best for observations | OK for observations | **Can't observe** | OK for observations | Best for observations

Cherenkov flashes are dim while the moon is very bright
If there is too much ambient light, air showers can't be detected
+ PMT cameras can get damaged

=> IACT arrays observe ≳25 nights during every 28 day moon cycle (**when weather is good**)

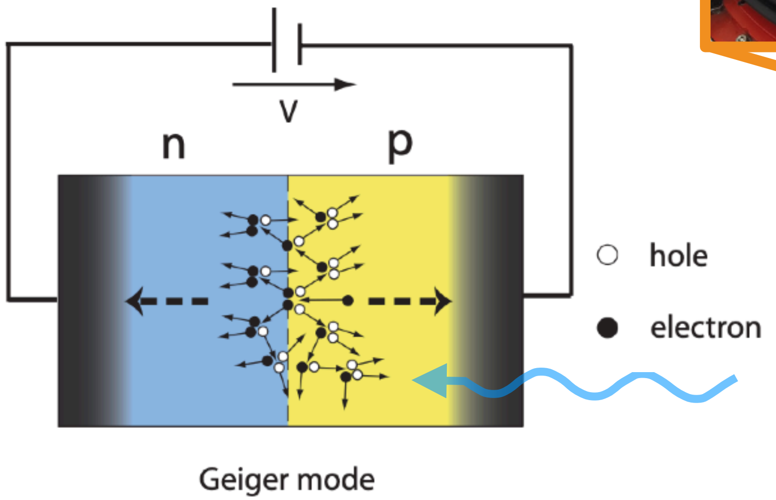
IACT telescopes

[Daniel R. Strebe]

Cameras: Silicon photomultipliers (SiPMs)

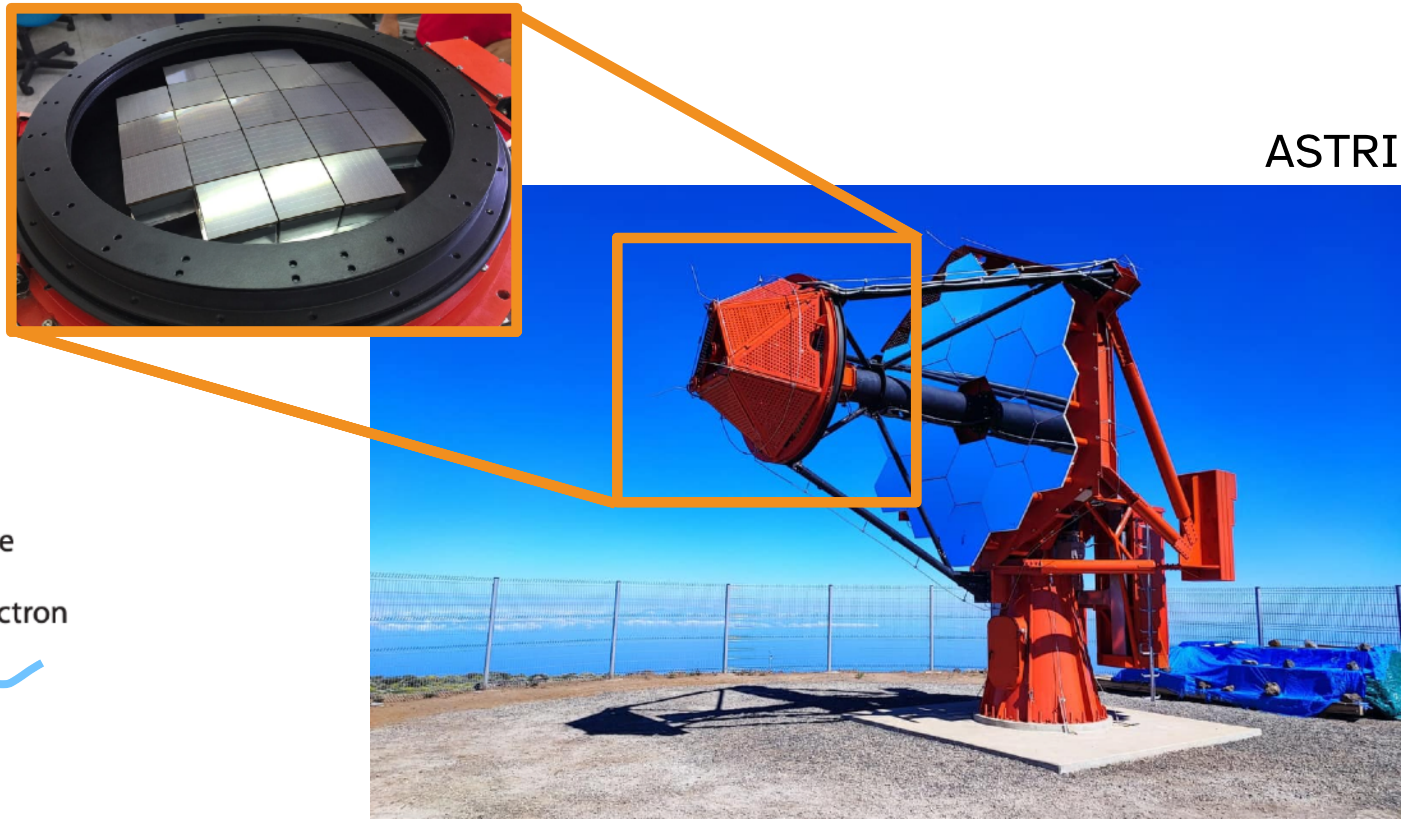
Higher quantum efficiency but relatively recently developed

SiPMs are also used by FACT



[A. N. Otte, PhD Thesis (2007)]

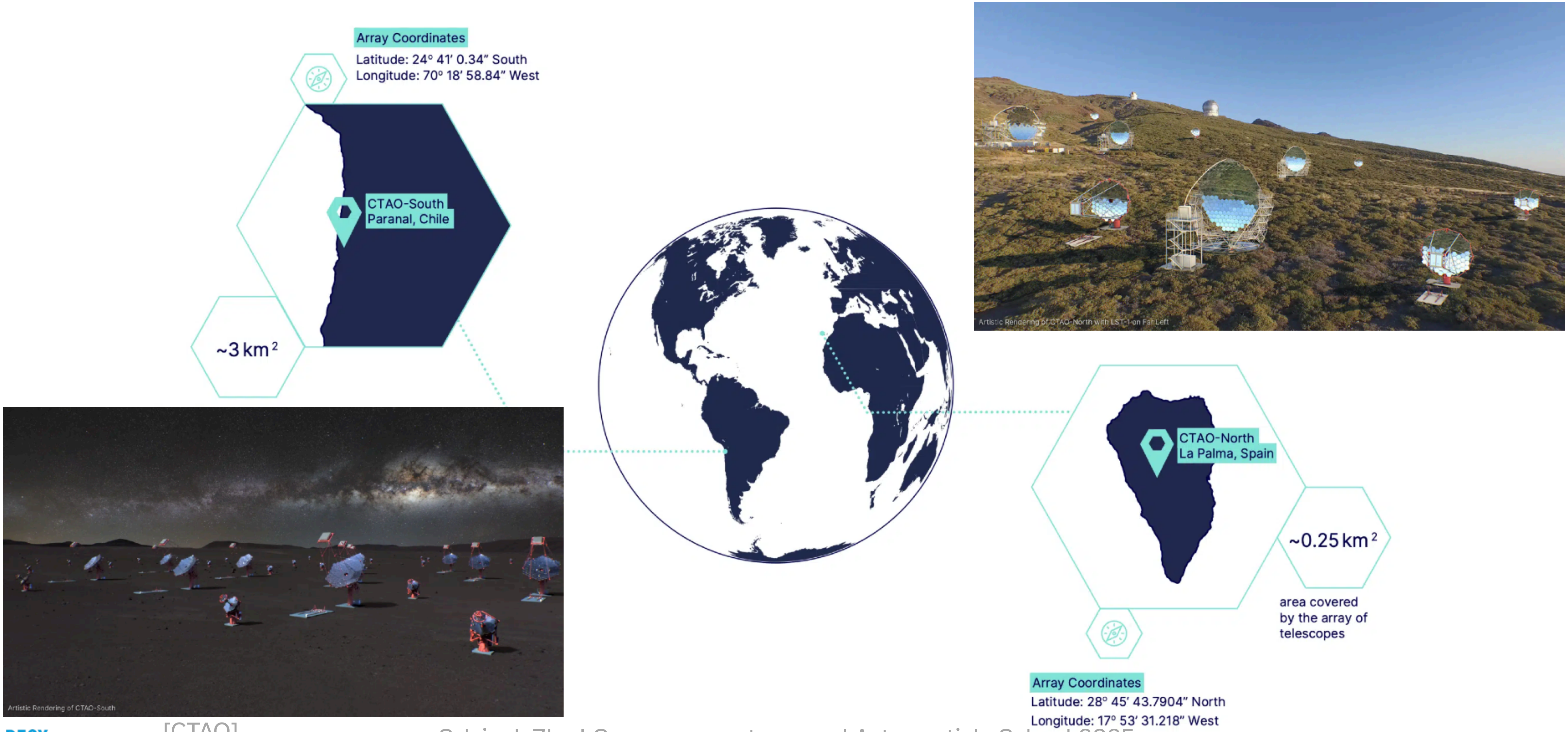
ASTRI



[INAF]

Cherenkov Telescope Array Observatory (CTAO)

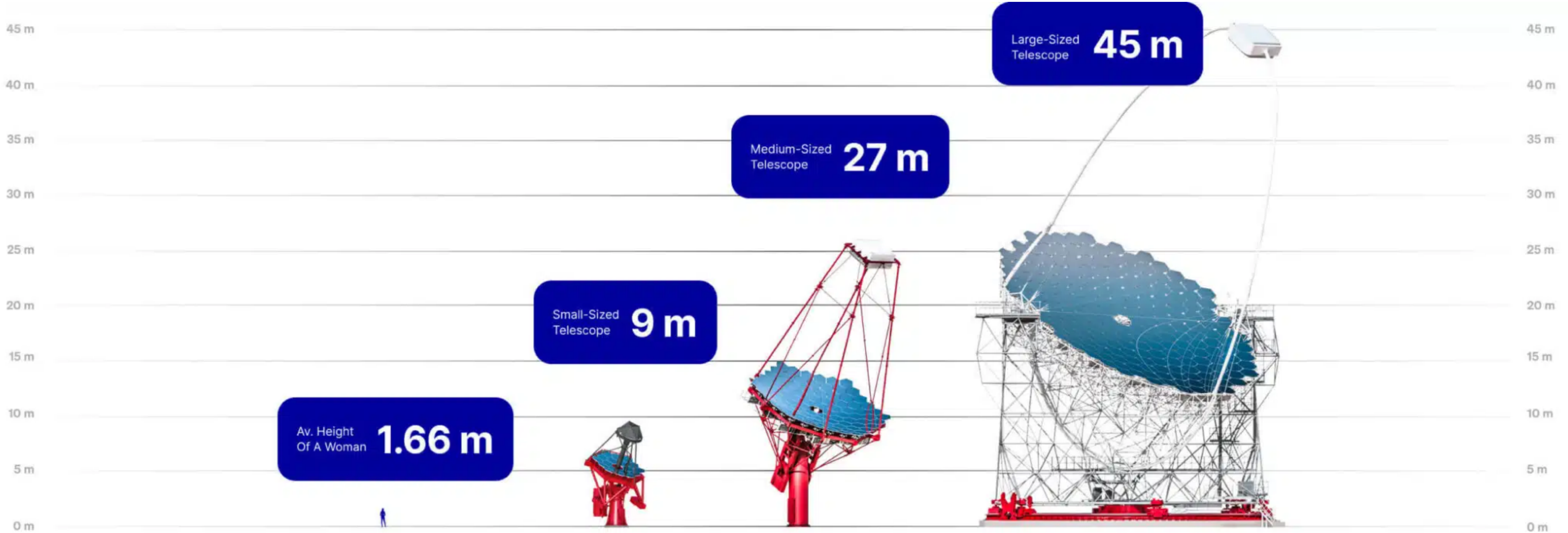
Next generation IACT array



[CTAO]

Cherenkov Telescope Array Observatory (CTAO)

Next generation IACT array



person	SSTs	MSTs	LSTs
eyeballs	SiPM cameras	PMT cameras	PMT cameras
bones	steel structure	steel structure	carbon fiber structure

[CTAO]

IACT arrays

[Daniel R. Strebe]

Cherenkov Telescope Array Observatory (CTAO)

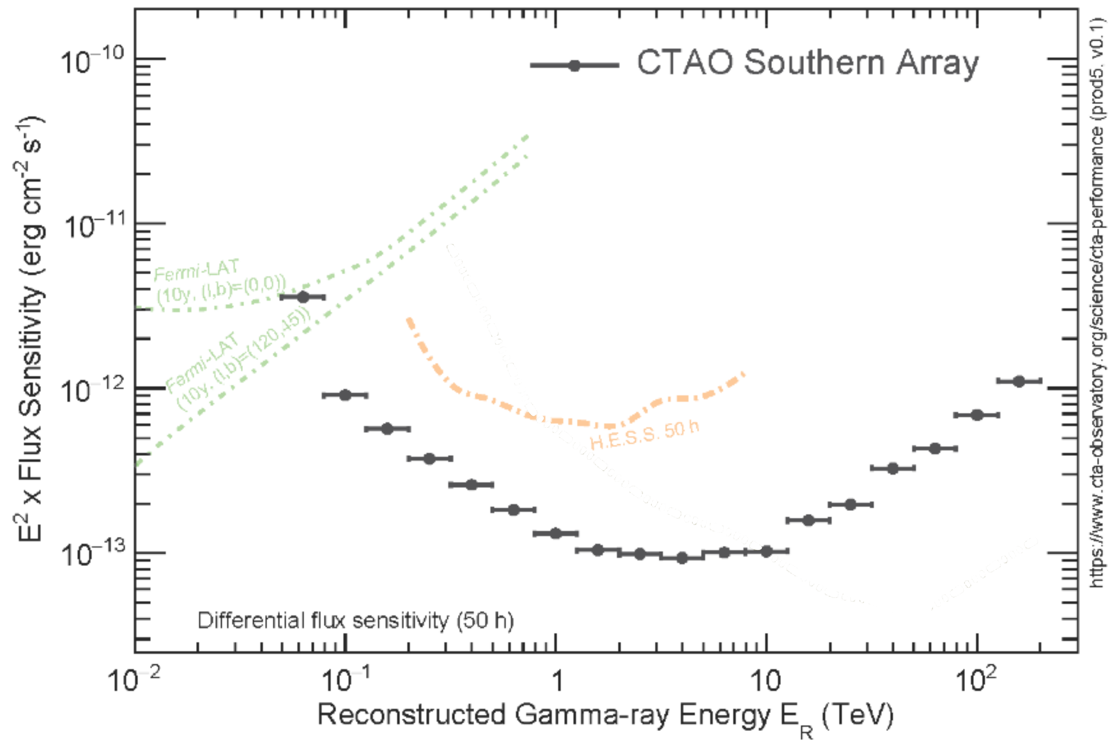
LST-1

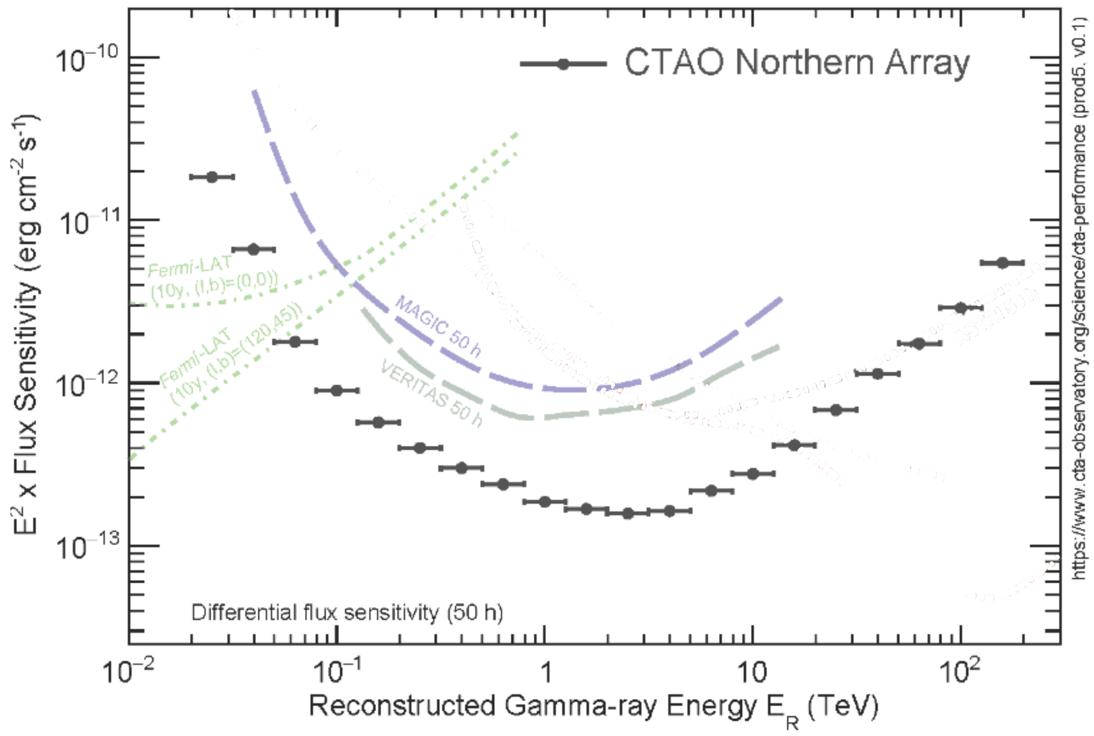
[CTAO]

Cherenkov Telescope Array Observatory (CTAO)

Next generation IACT array

CTAO will be 10x more sensitive than the current generation of IACT arrays





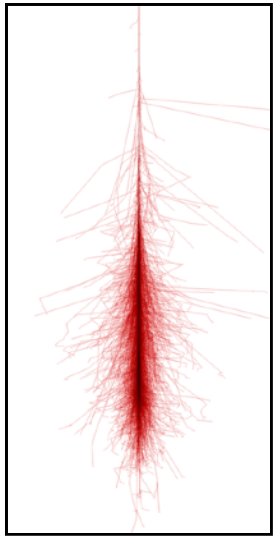
But how do we get to even higher energies?

modified from [CTAO]

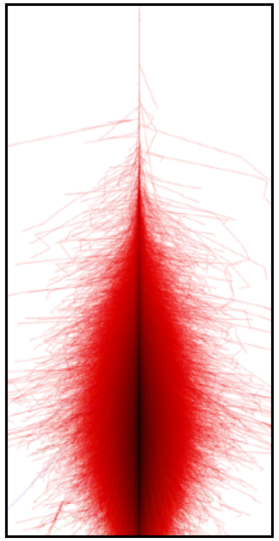
Use the atmosphere as part of the detector

VHE gamma rays produce extensive air showers

100 GeV gamma ray vs 100 TeV gamma ray



[J. Knapp]



[J. Knapp]

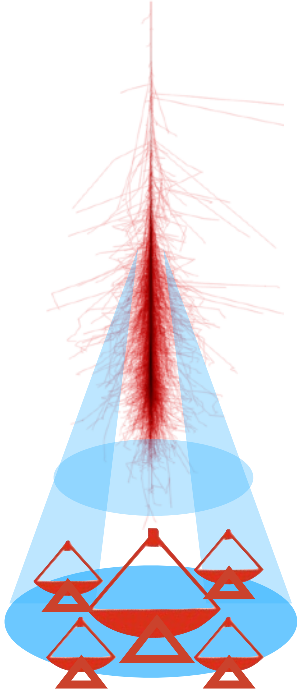
- most shower particles don't reach the ground
- detect them via Cherenkov light in air

- many shower particles reach the ground
- detect them directly in your telescope

Use the atmosphere as part of the detector

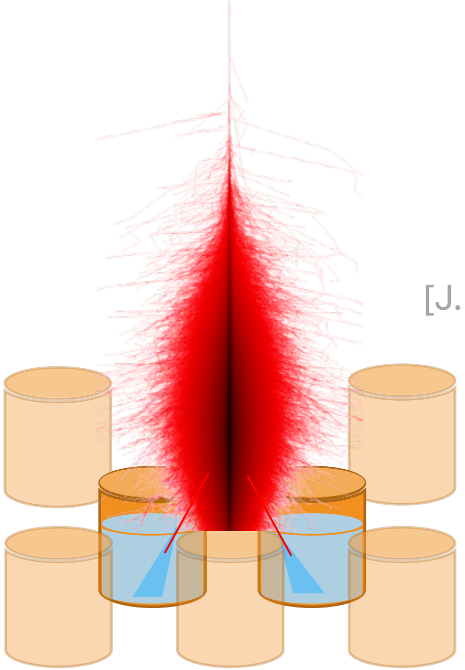
VHE gamma rays produce extensive air showers

100 GeV gamma ray — vs — 100 TeV gamma ray



[J. Knapp]

- most shower particles don't reach the ground
- detect them via Cherenkov light in air



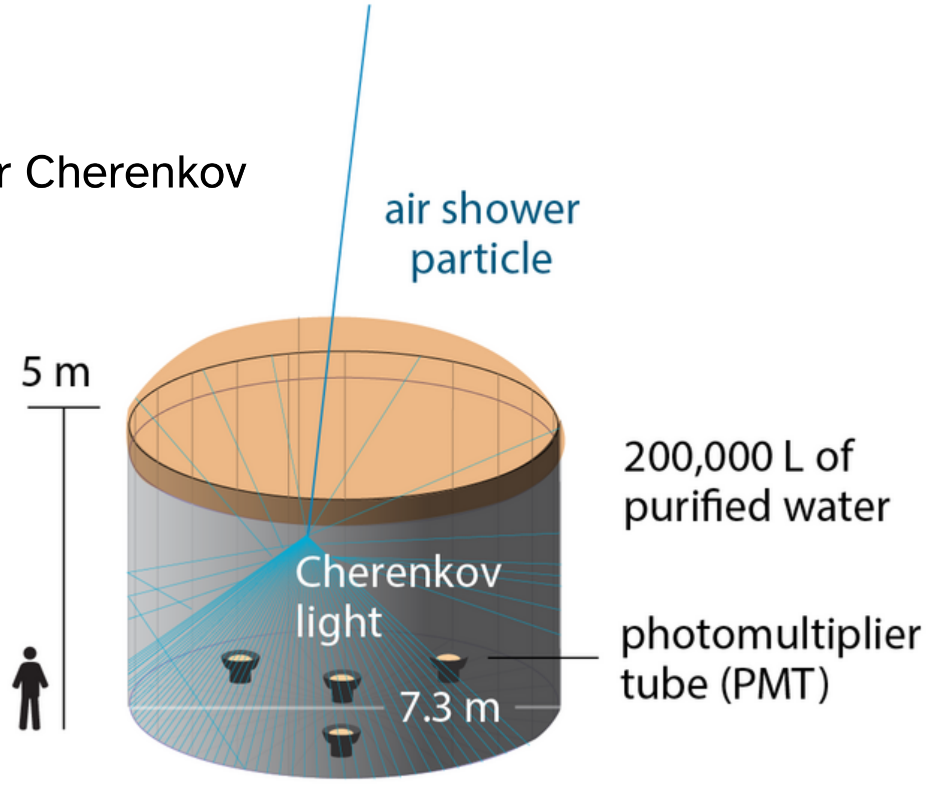
[J. Knapp]

- many shower particles reach the ground
- detect them directly in your telescope

Particle detector arrays

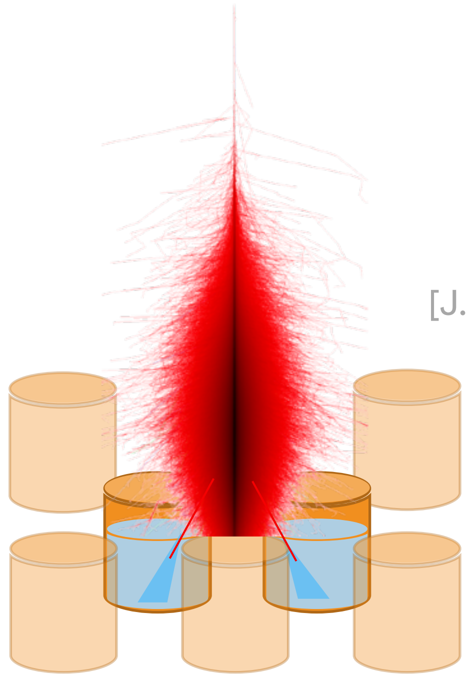
Charged particle detectors

e.g., water Cherenkov detectors



[U. M. Nisa, HAWC]

100 TeV gamma ray



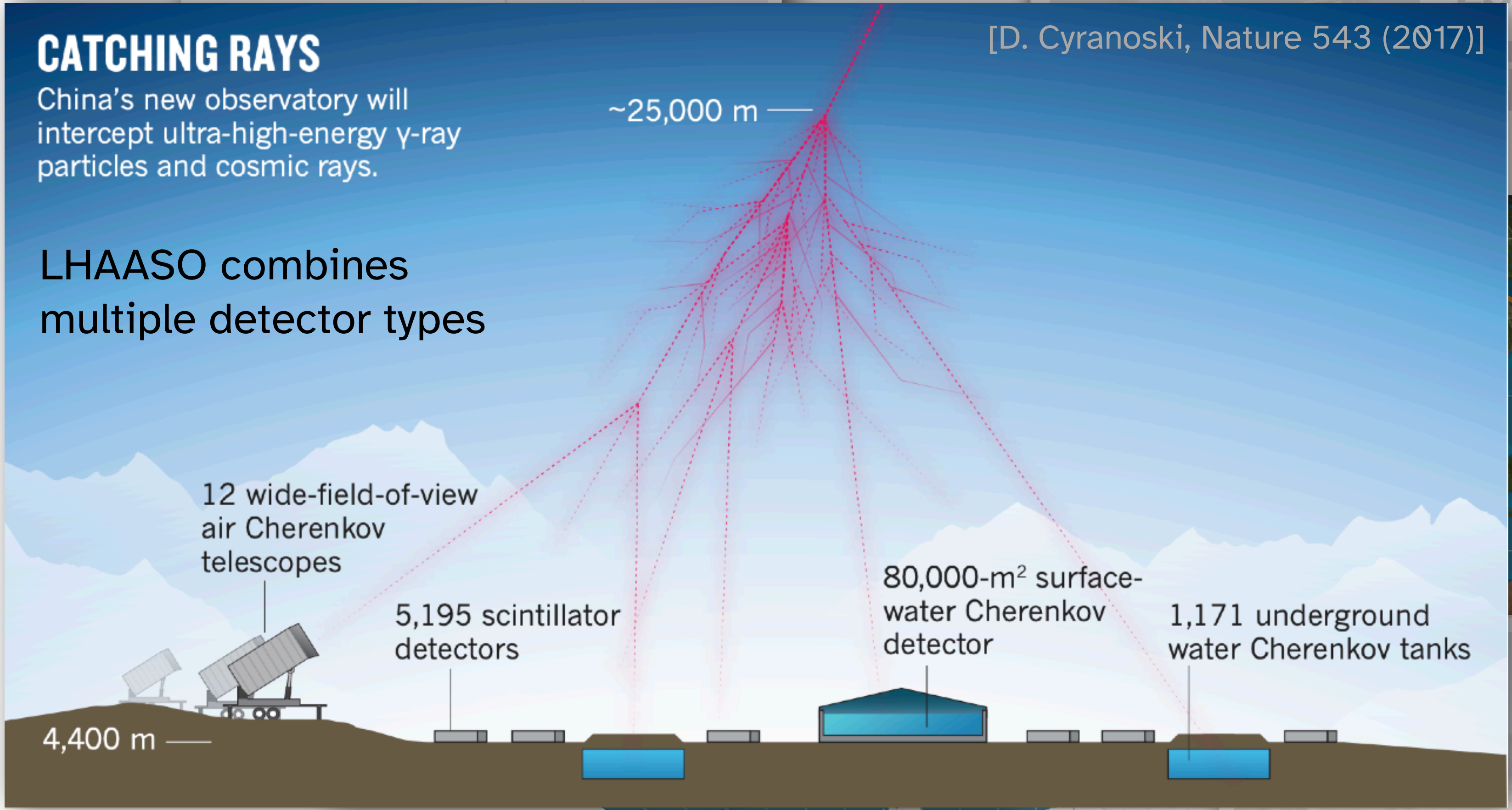
[J. Knapp]

- many shower particles reach the ground
- detect them directly in your telescope

Particle detector arrays

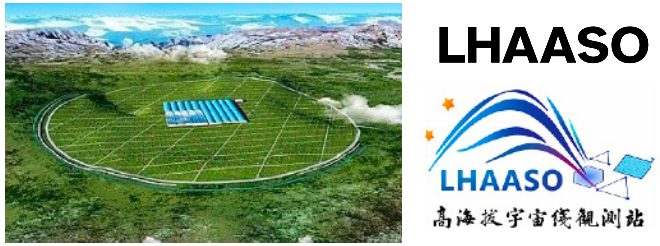
[Daniel R. Strebe]

Particle detector arrays



[D. Cyranoski, Nature 543 (2017)]

LHAASO combines multiple detector types



[IHEP]

MAGIC

LST-1

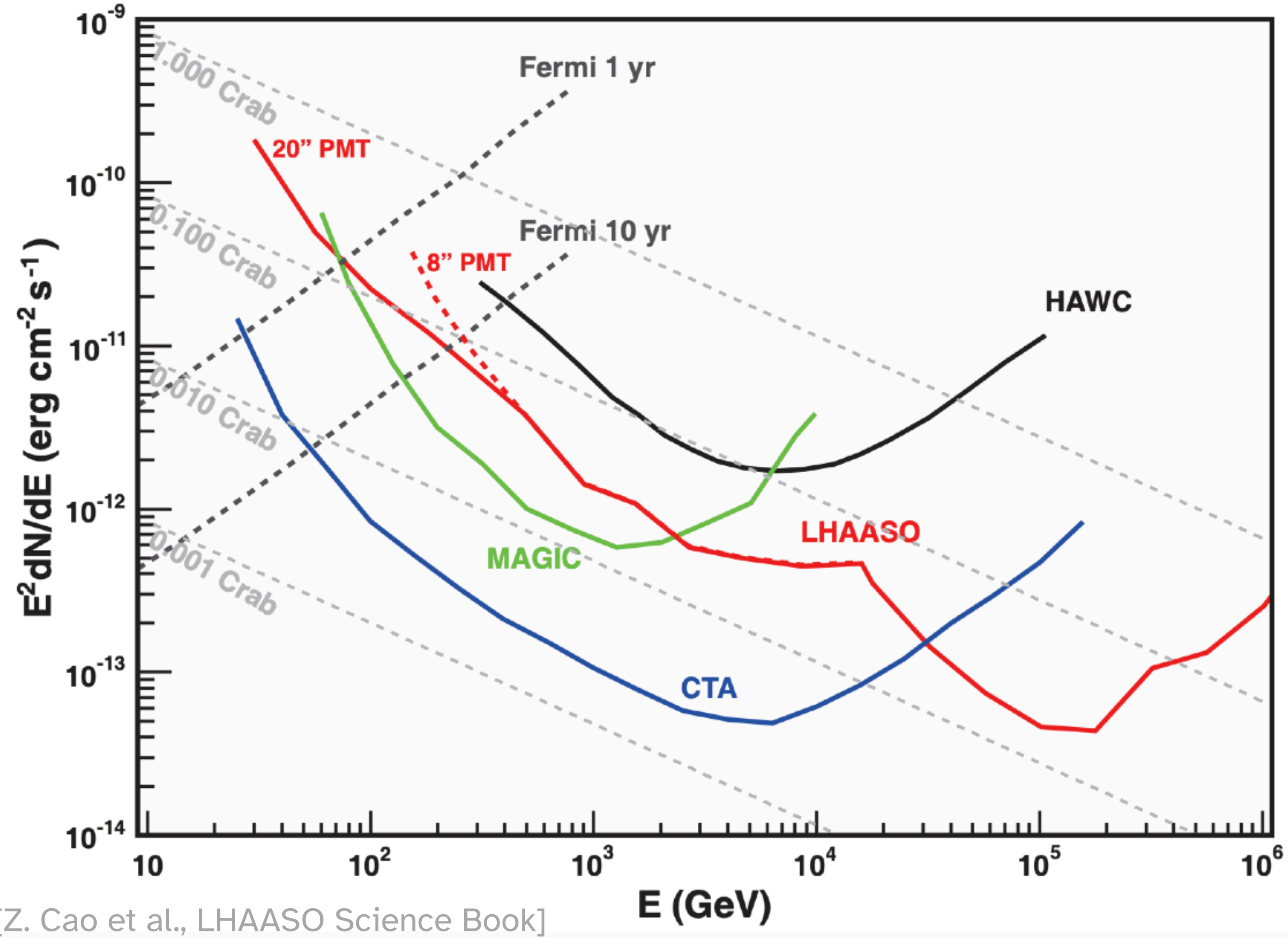
H.E.S.S.

[H.E.S.S., MPIK/Christian Föhr]

[Daniel R. Strebe]

Gamma-ray detectors

Comparing sensitivities

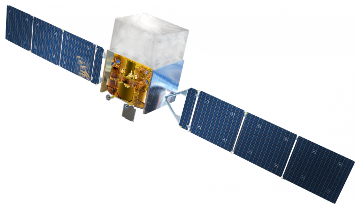


[Z. Cao et al., LHAASO Science Book]

Gamma-ray detectors

Complementary capabilities

	Fermi-LAT	IACT arrays (current gen)	CTAO	particle detector arrays
duty cycle	~95%	~15%	~15%	~90%
energy range	[10s of MeV, 100s of GeV]	[~25 to 100 GeV, 100 TeV]	[~20 GeV, >300 TeV]	[100s of GeV, >PeV]
field of view	>2 sr	~ 5°	~ 5°	>2 sr
angular resolution	~0.1° - 1°	< 0.1°	< 0.05°	~0.1° - 2°
energy resolution	~5 - 20%	~10 - 15%	~5%	~30 - 50%



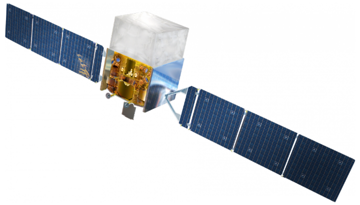
Gamma-ray detectors

Complementary capabilities

survey instruments:
large field of view, good duty cycle;
resolution not as precise

pointed instruments:
good resolution and sensitivity;
limited duty cycle, small field of view

	Fermi-LAT	IACT arrays (current gen)	CTAO	particle detector arrays
duty cycle	~95%	~15%	~15%	~90%
energy range	[10s of MeV, 100s of GeV]	[~25 to 100 GeV, 100 TeV]	[~20 GeV, >300 TeV]	[100s of GeV, >PeV]
field of view	>2 sr	~ 5°	~ 5°	>2 sr
angular resolution	~0.1° - 1°	< 0.1°	< 0.05°	~0.1° - 2°
energy resolution	~5 - 20%	~10 - 15%	~5%	~30 - 50%



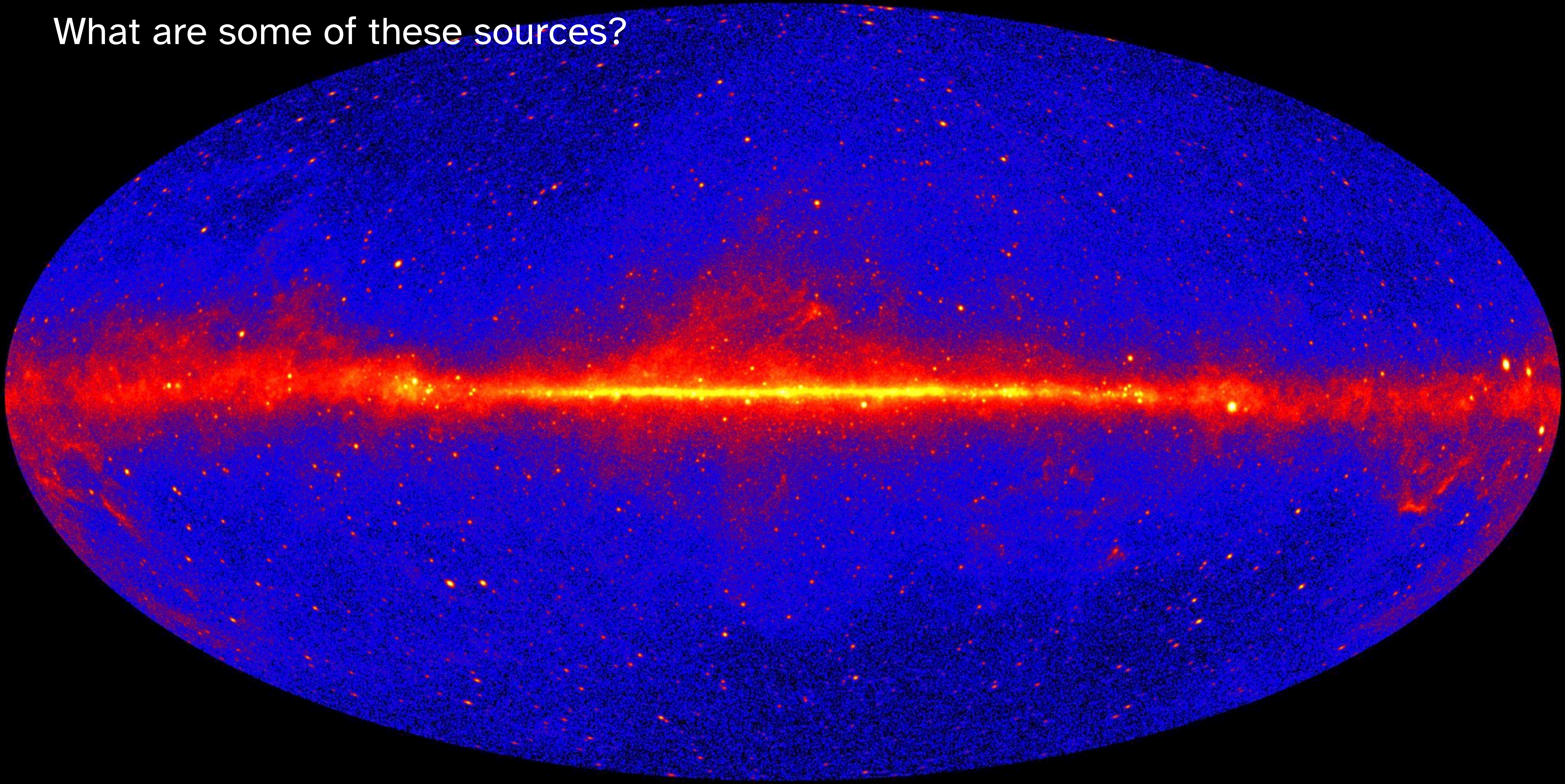
H.E.S.S.

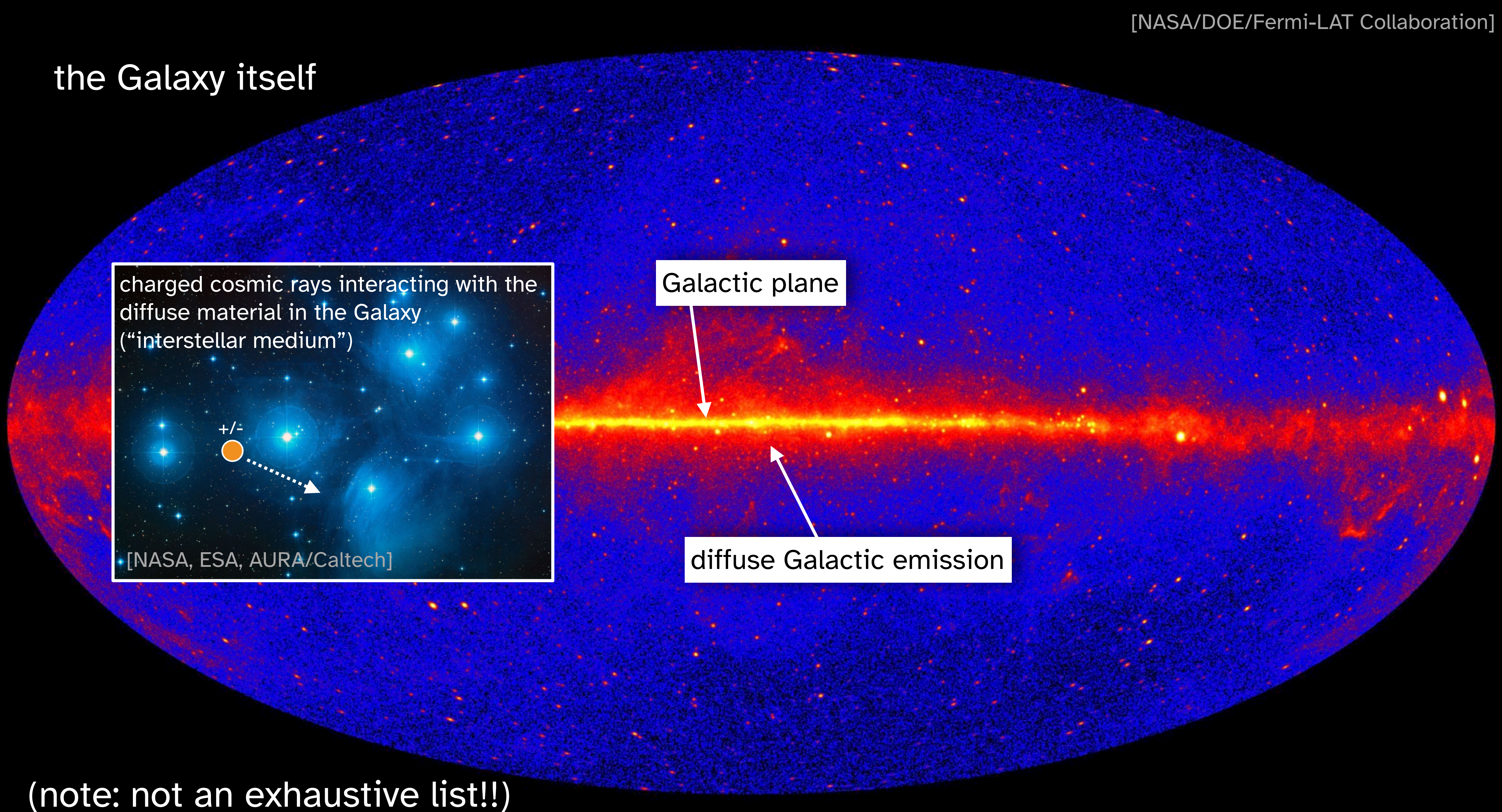
CTAO

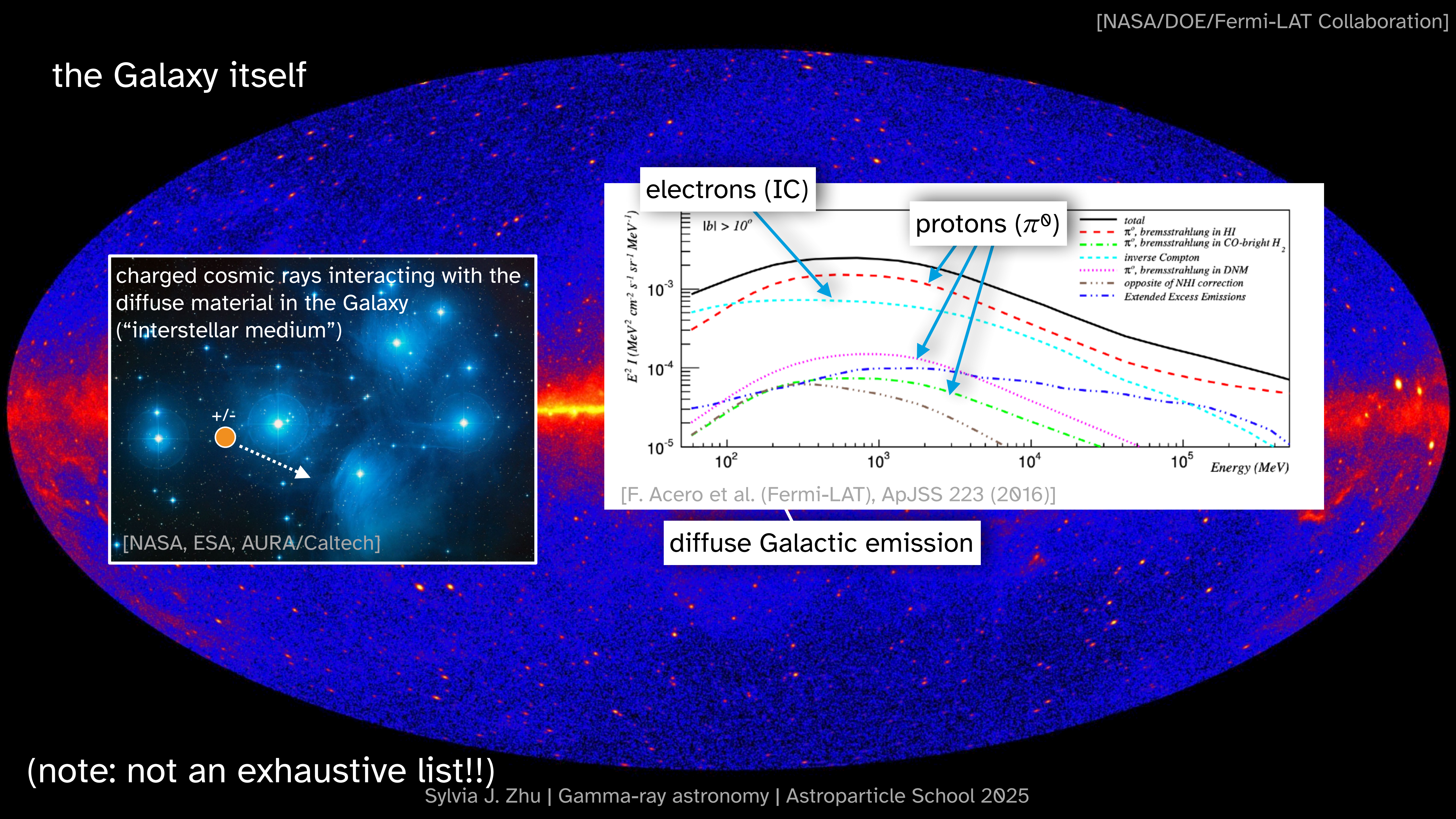
Gamma-ray sources

Note: The rest of these lectures will have a bias toward what I find interesting :)

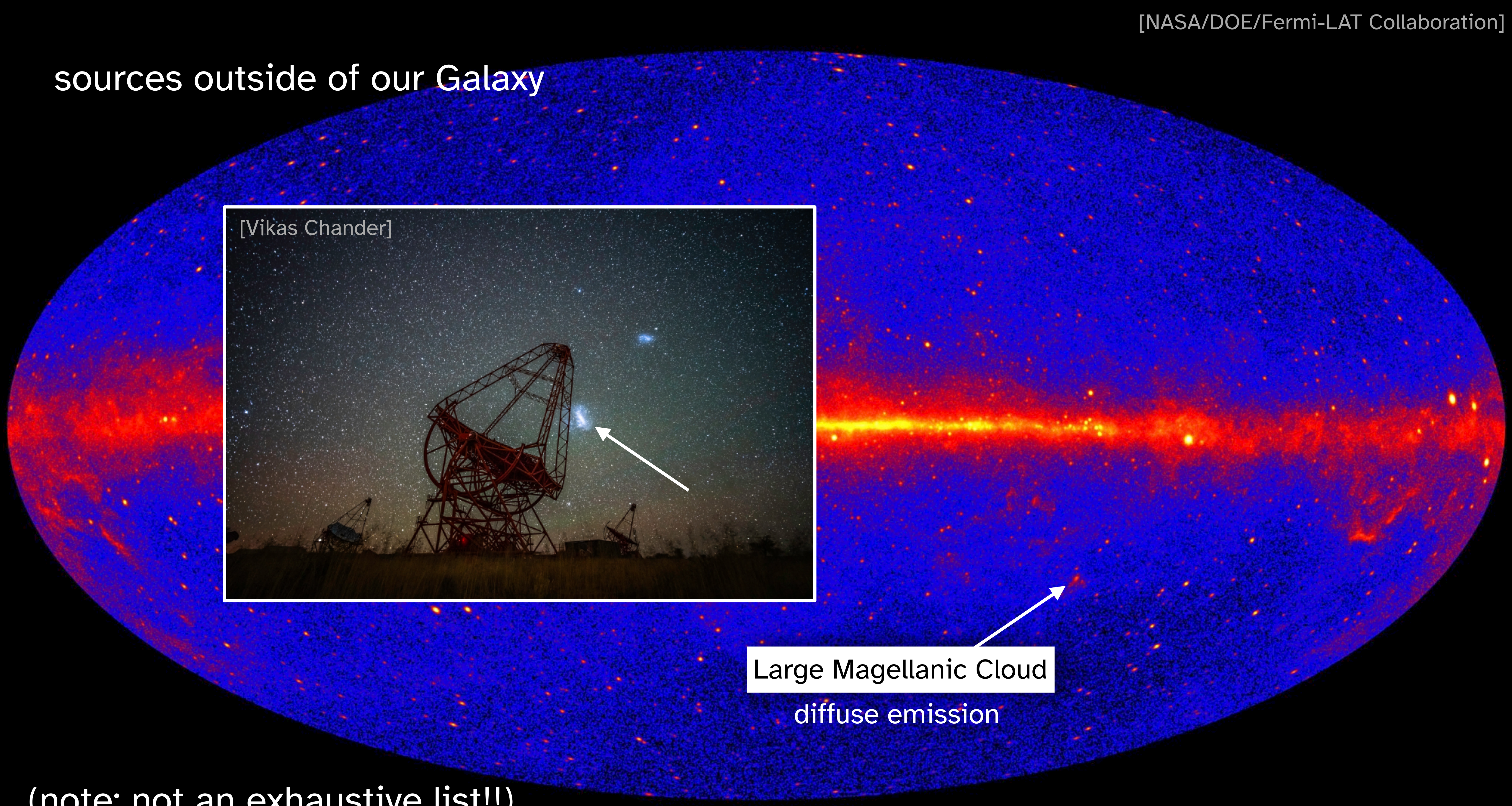
What are some of these sources?




[NASA/DOE/Fermi-LAT Collaboration]
the Galaxy itself
charged cosmic rays interacting with the diffuse material in the Galaxy ("interstellar medium")
+/-
[NASA, ESA, AURA/Caltech]
Galactic plane
diffuse Galactic emission
(note: not an exhaustive list!!)

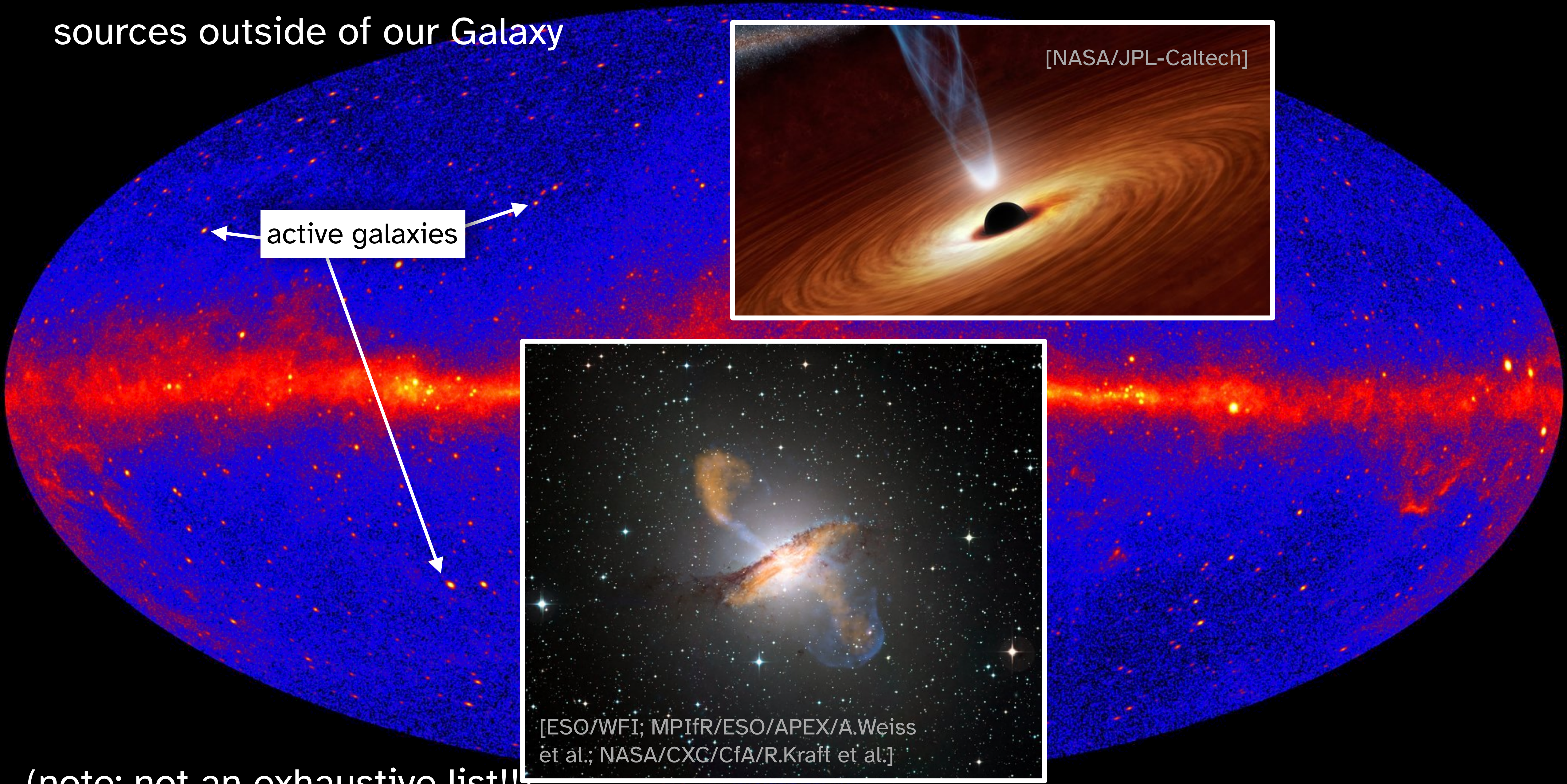

[NASA/DOE/Fermi-LAT Collaboration]
the Galaxy itself
charged cosmic rays interacting with the diffuse material in the Galaxy ("interstellar medium")
+/-
[NASA, ESA, AURA/Caltech]
electrons (IC)
protons (π^0)
|b| > 10°
$E^2\ I\ (MeV^2\ cm^{-2}\ s^{-1}\ sr^{-1}\ MeV^{-1})$
10^{-3}
10^{-4}
10^{-5}
10^2
10^3
10^4
10^5
Energy (MeV)
total
π^0, bremsstrahlung in HI
π^0, bremsstrahlung in CO-bright H_2
inverse Compton
π^0, bremsstrahlung in DNM
opposite of NHI correction
Extended Excess Emissions
[F. Acero et al. (Fermi-LAT), ApJSS 223 (2016)]
diffuse Galactic emission
(note: not an exhaustive list!!)

sources outside of our Galaxy



(note: not an exhaustive list!!)

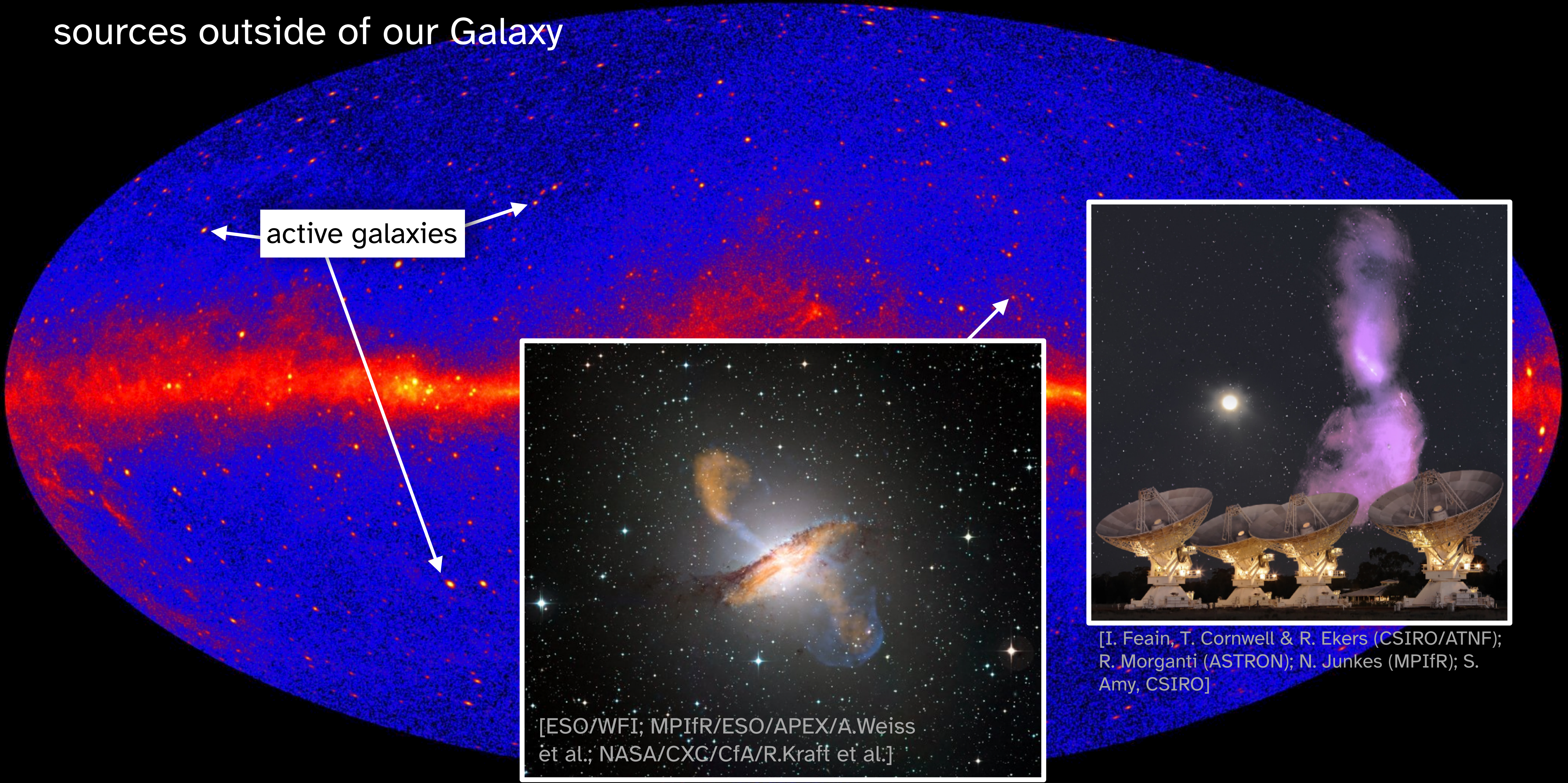
sources outside of our Galaxy



(note: not an exhaustive list!!)

sources outside of our Galaxy

[NASA/DOE/Fermi-LAT Collaboration]

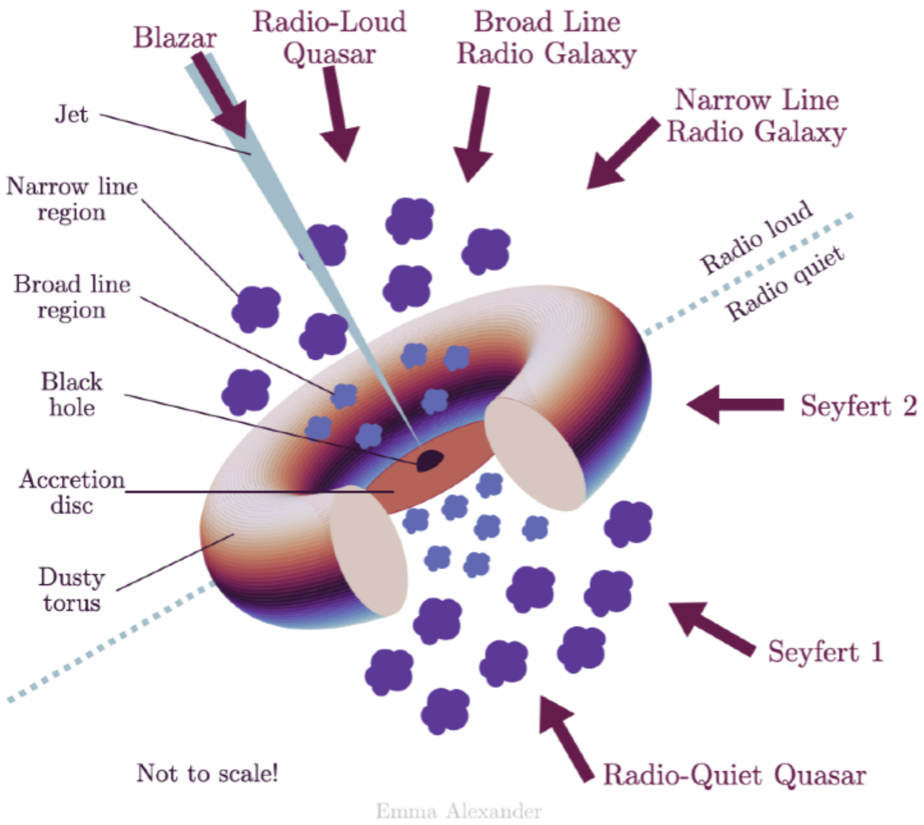


[ESO/WFI; MPIfR/ESO/APEX/A.Weiss et al.; NASA/CXC/CfA/R.Kraft et al.]

[I. Feain, T. Cornwell & R. Ekers (CSIRO/ATNF); R. Morganti (ASTRON); N. Junkes (MPIfR); S. Amy, CSIRO]

Active galaxies in a nutshell

I'm not the expert here tho 😬 ask Anna if you have ?s



[Emma Alexander]

Most galaxies have a supermassive black hole in the center

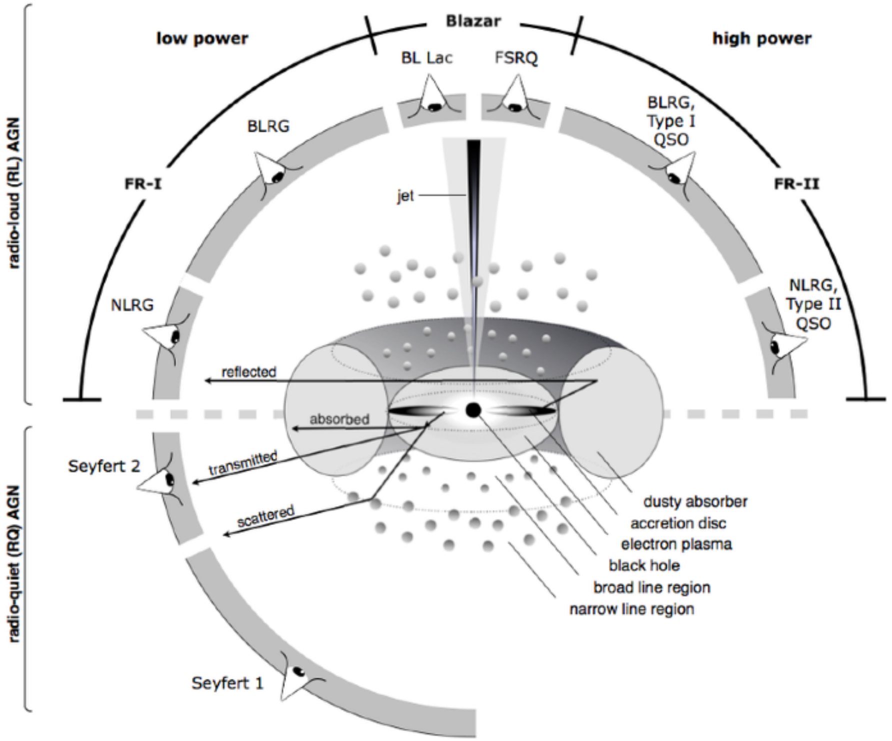
If the black hole is accreting matter, it can emit across the electromagnetic spectrum

How we name it depends on the viewing angle and the properties of the system

e.g., Centaurus A is a radio galaxy

Active galaxies in a nutshell

I'm not the expert here tho 😬 ask Anna if you have ?s



[Marie-Luise Menzel]

Most galaxies have a supermassive black hole in the center

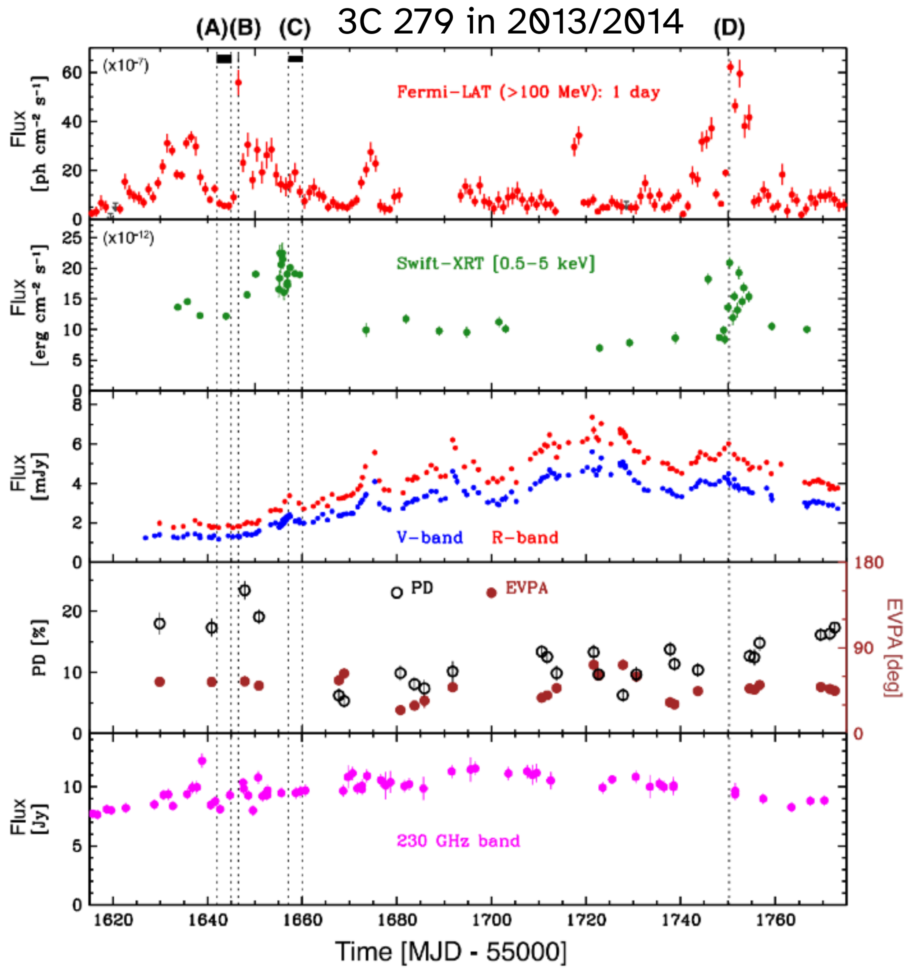
If the black hole is accreting matter, it can emit across the electromagnetic spectrum

How we name it depends on the viewing angle and the properties of the system

e.g., Centaurus A is a radio galaxy

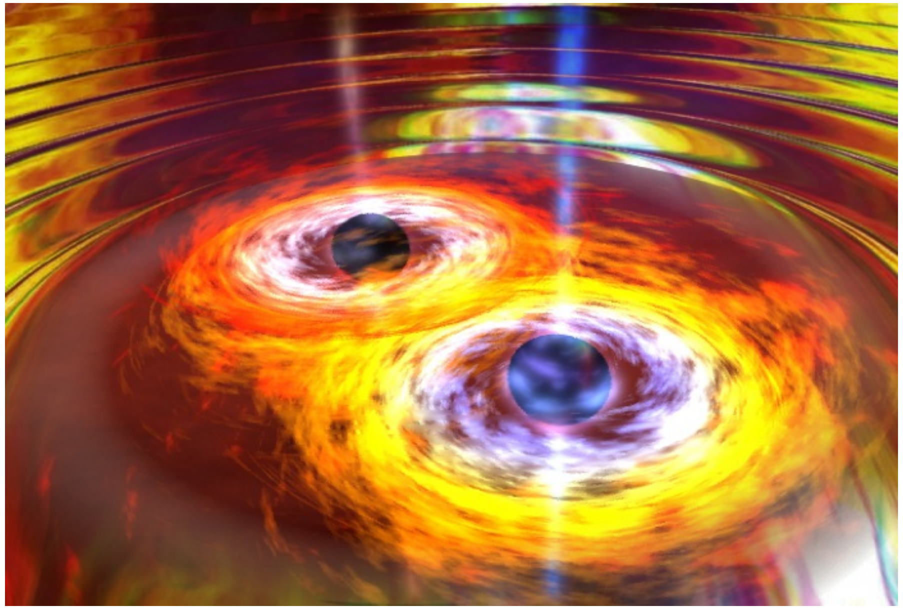
Active galaxies often show variability

I'm not the expert here tho 😬 ask Anna if you have ?s



[M. Hayashida et al., ApJ 807 (2015)]

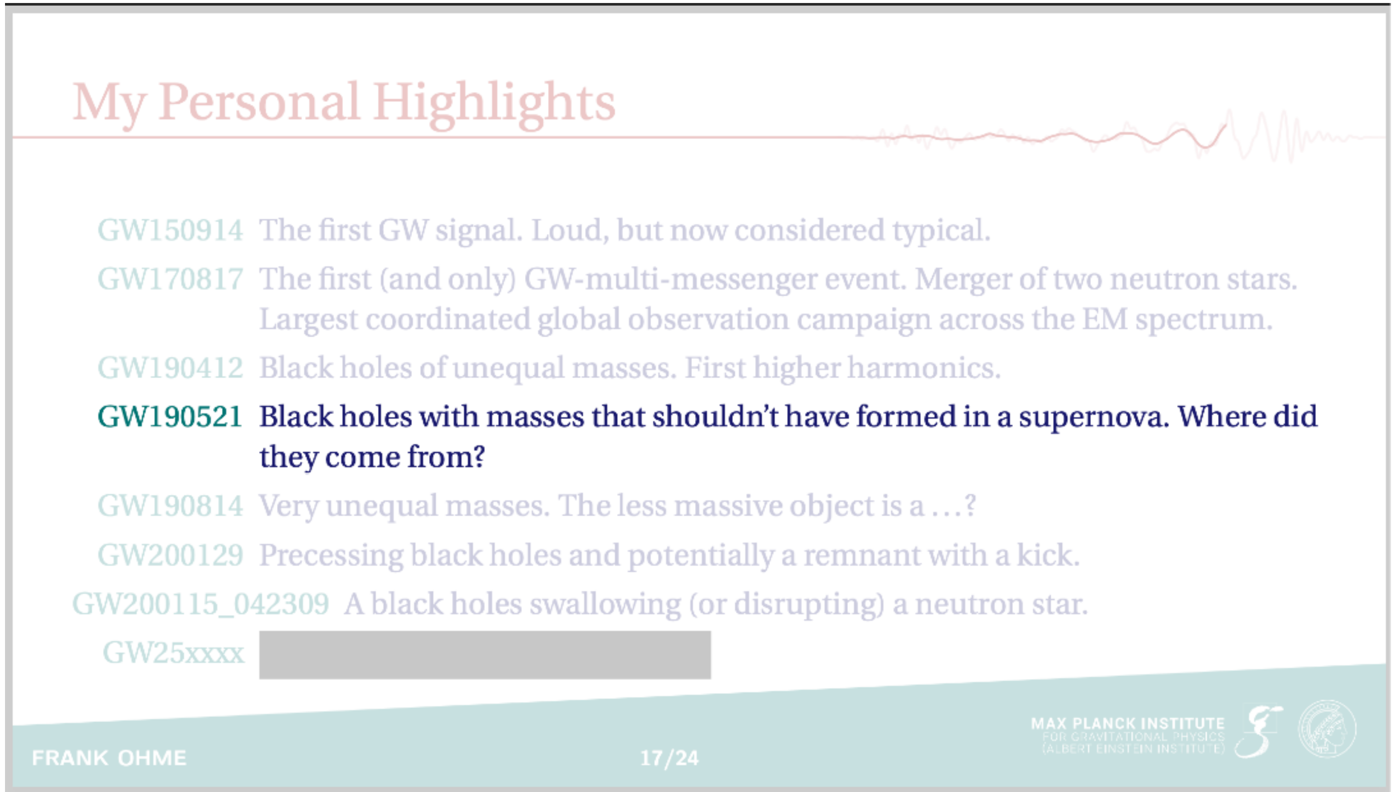
Flaring activity can be (often is?) multiwavelength
-> accretion/disruption of a stellar-mass object?
-> changes in the magnetic field?
-> evidence for a binary supermassive black hole companion?



[NASA]

AGN as GW counterparts?

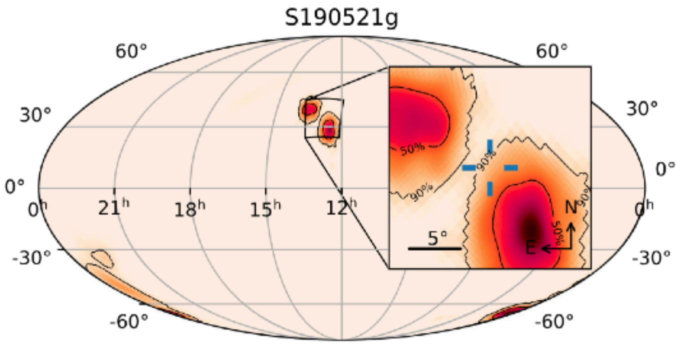
not exactly gamma rays, but still …

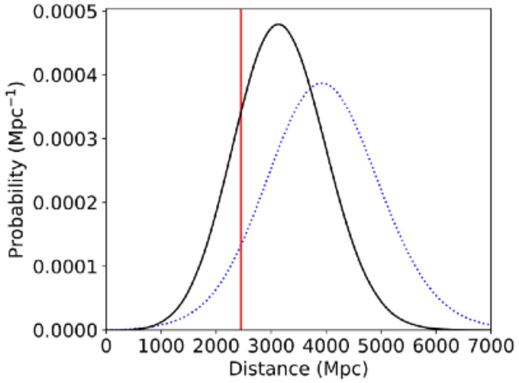


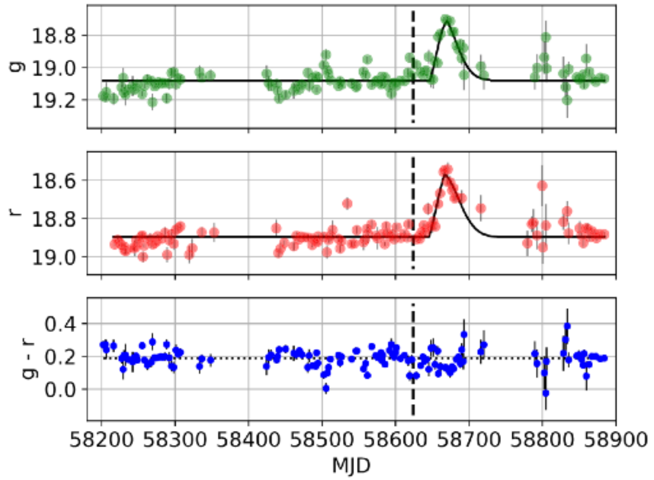
[D. Ferguson, K. Jani, D. Shoemaker, P. Laguna, Georgia Tech, MAYA Collaboration]

AGN as GW counterparts?

not exactly gamma rays, but still ...







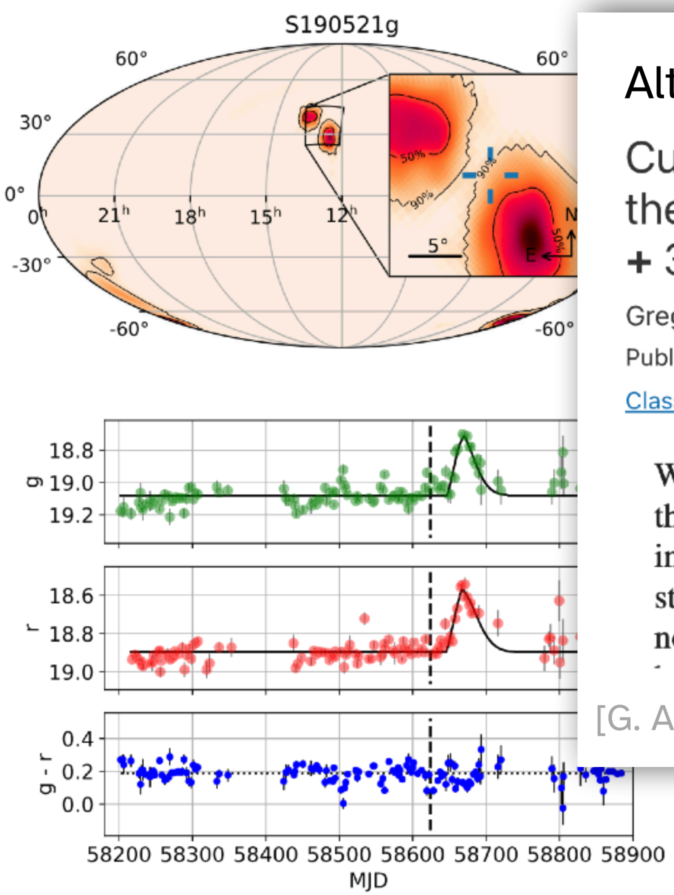
[M. J. Graham et al., PRL 124 (2020)]

An AGN flare in optical light (ZTF) was temporally and spatially in coincidence with the BBH GW190521
-> merger occurred in an AGN accretion disk and kicked up material?

[D. Ferguson, K. Jani, D. Shoemaker, P. Laguna, Georgia Tech, MAYA Collaboration]

AGN as GW counterparts?

not exactly gamma rays, but still …

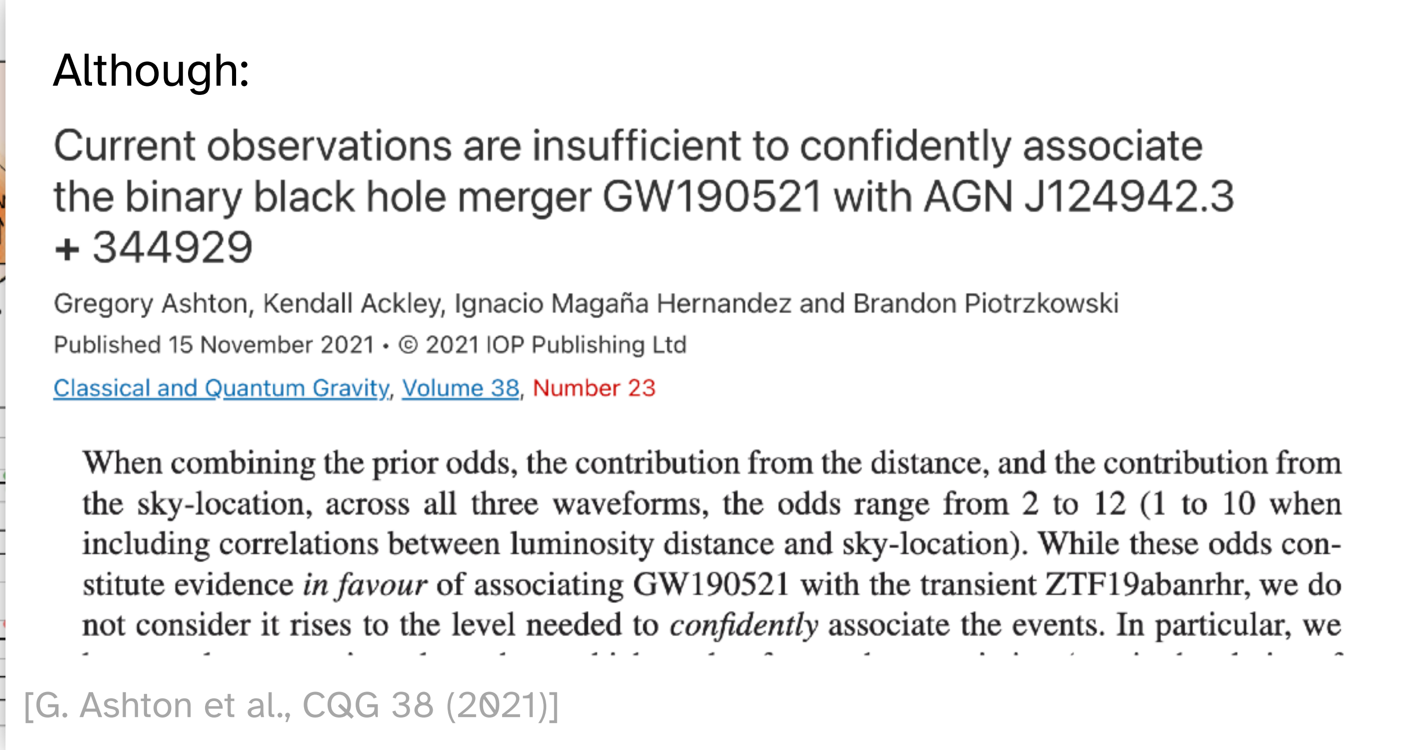


[M. J. Graham et al., PRL 124 (2020)]

AGN accretion disk and kicked up material?

[D. Ferguson, K. Jani, D. Shoemaker, P. Laguna, Georgia Tech, MAYA Collaboration]

Although:



Current observations are insufficient to confidently associate the binary black hole merger GW190521 with AGN J124942.3 + 344929

Gregory Ashton, Kendall Ackley, Ignacio Magaña Hernandez and Brandon Piotrzkowski

Published 15 November 2021 • © 2021 IOP Publishing Ltd

Classical and Quantum Gravity, Volume 38, Number 23

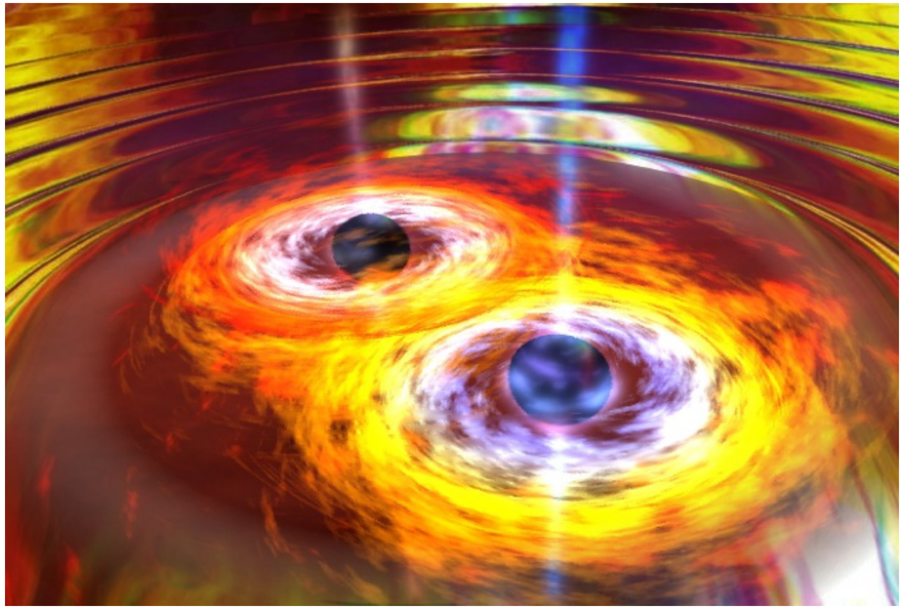
When combining the prior odds, the contribution from the distance, and the contribution from the sky-location, across all three waveforms, the odds range from 2 to 12 (1 to 10 when including correlations between luminosity distance and sky-location). While these odds constitute evidence *in favour* of associating GW190521 with the transient ZTF19abanrhr, we do not consider it rises to the level needed to *confidently* associate the events. In particular, we

[G. Ashton et al., CQG 38 (2021)]

AGN as GW counterparts? pt II

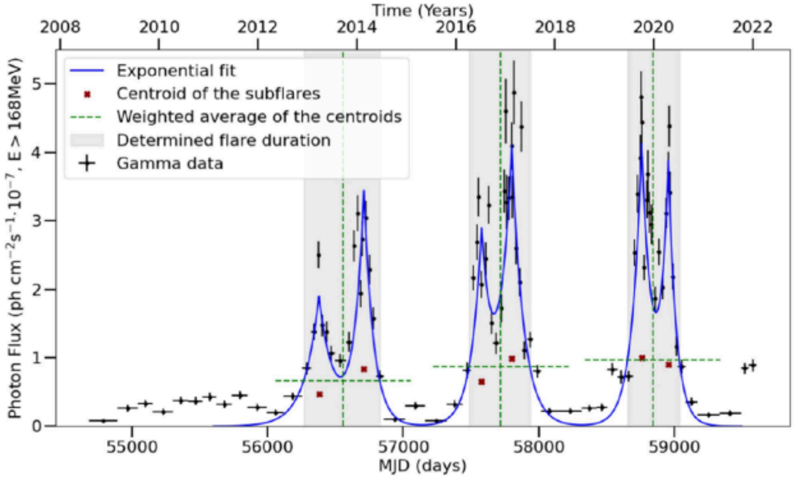
ok we're back to gamma rays now

J1048 + 7143

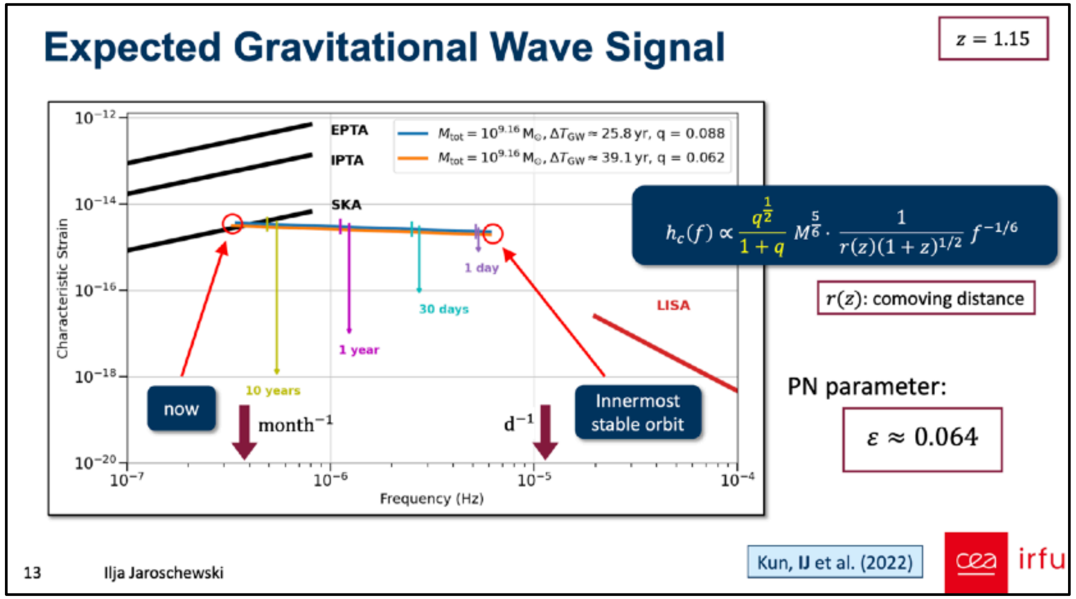


[NASA]

Model: Jets precess when the supermassive black holes are close to merger
-> Periodic AGN flares?



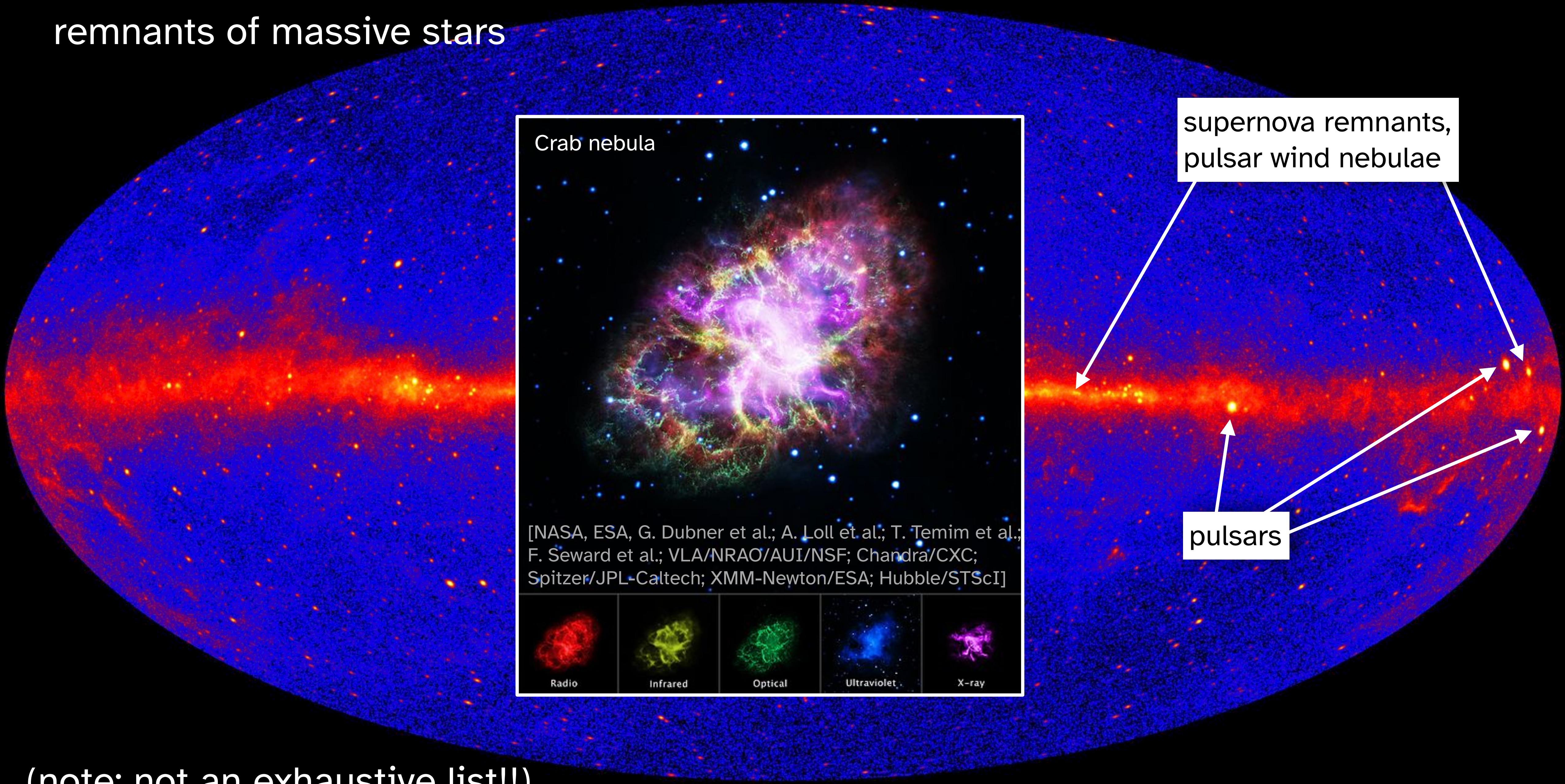
[E. Kun et al., ApJ 940 (2022)]



[I. Jaroschewski, first ACME workshop (2025)]

[NASA/DOE/Fermi-LAT Collaboration]

remnants of massive stars

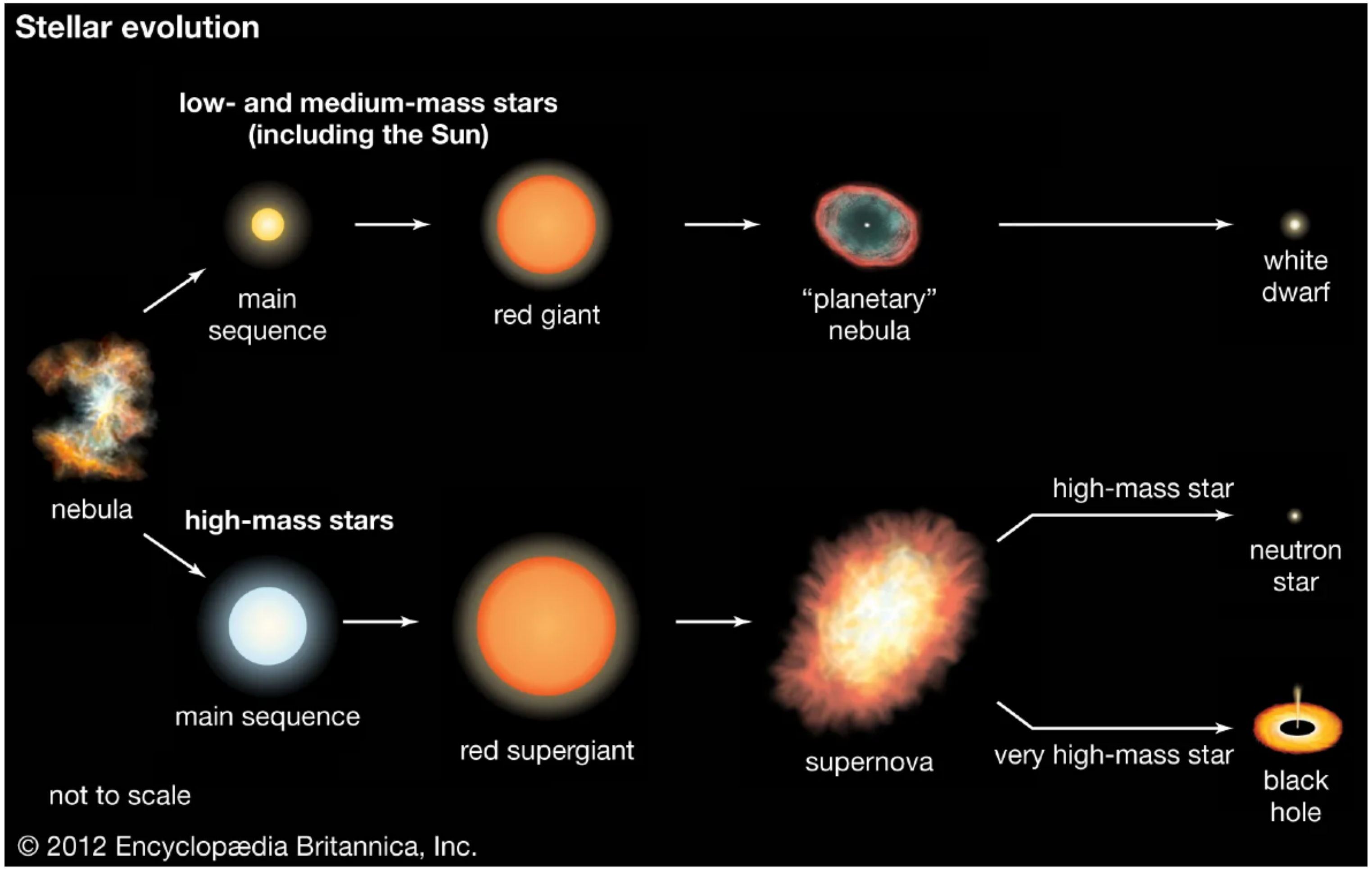


(note: not an exhaustive list!!)

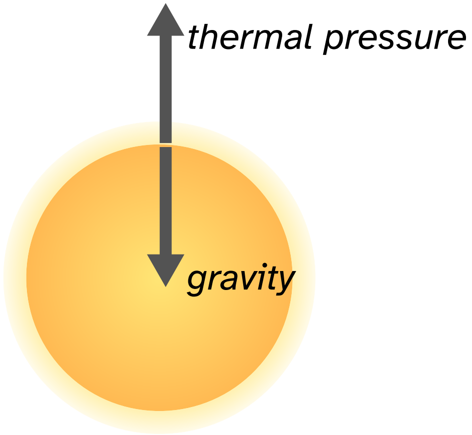
What happens at the end of a massive star’s life?

core-collapse supernovae

A star’s evolution depends primarily on its initial mass



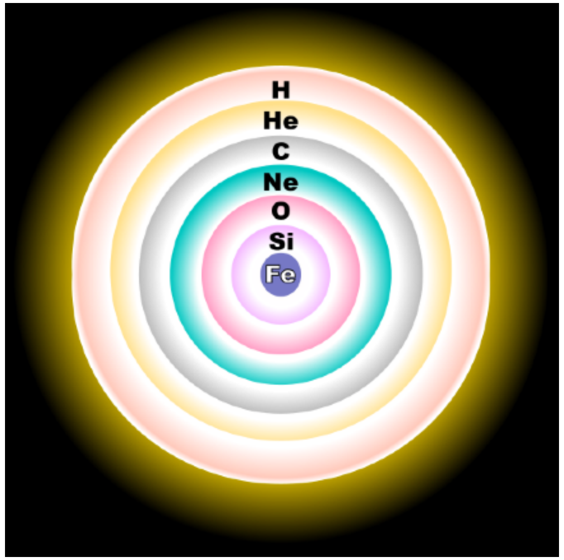
Outward support provided by thermal energy from nucleosynthesis (fusion)



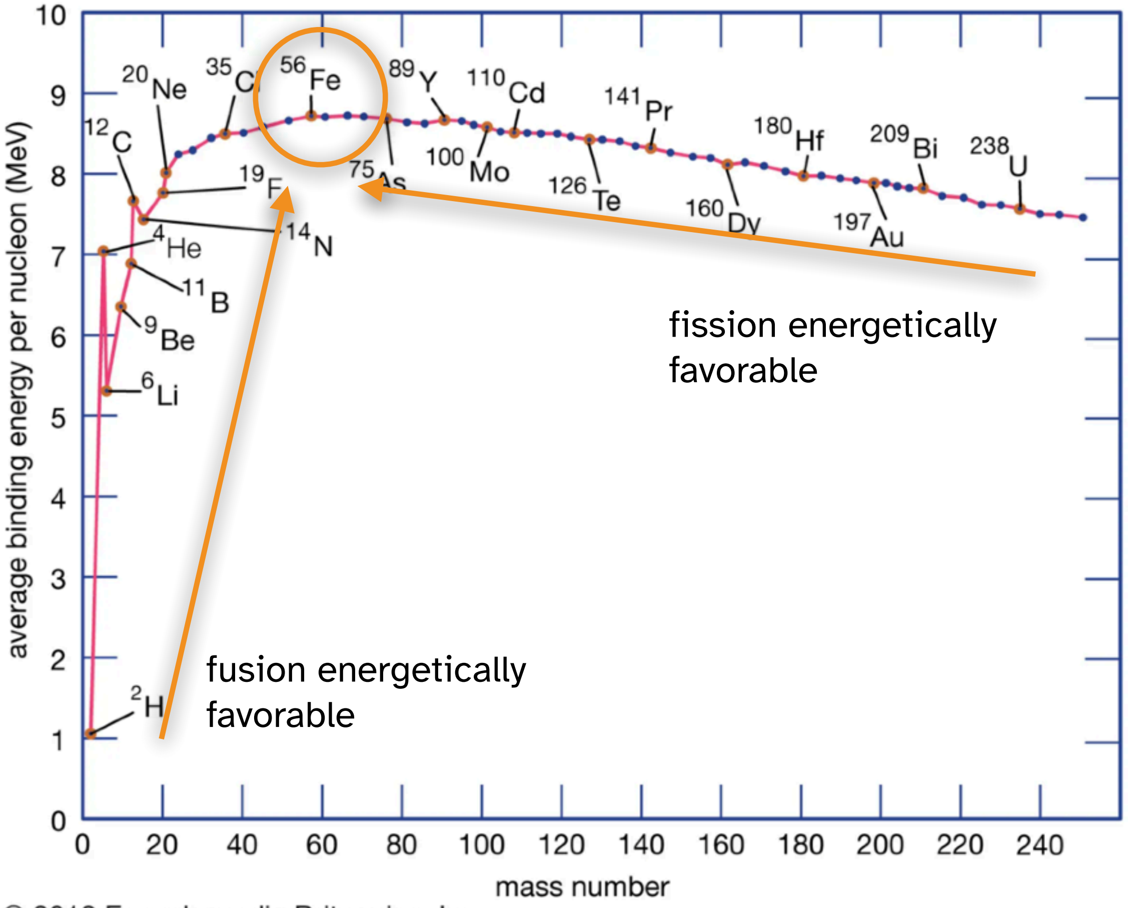
What happens at the end of a massive star's life?

core-collapse supernovae

Massive stars fuses successively heavier elements until iron



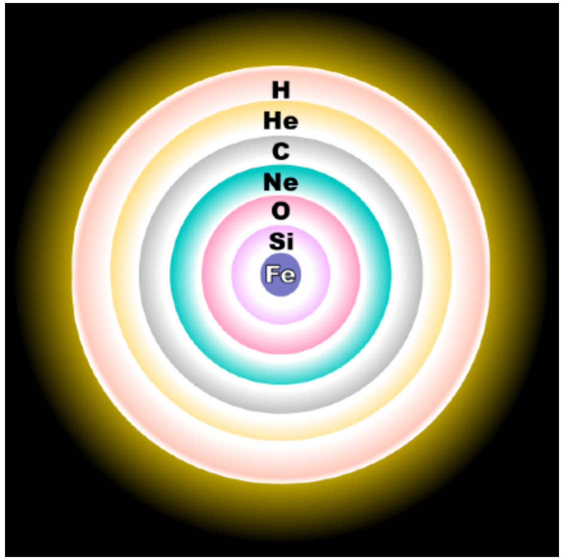
R. J. Hall



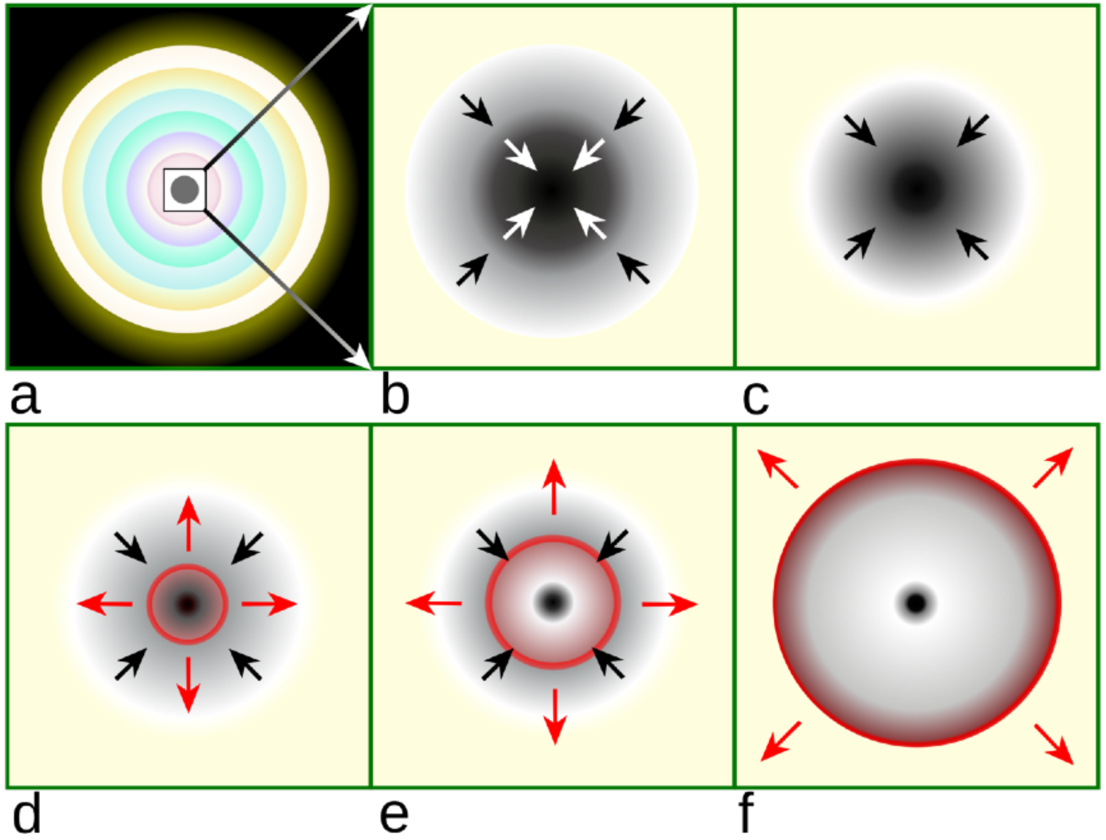
What happens at the end of a massive star's life?

core-collapse supernovae

Fusion no longer energetically favorable -> thermal pressure is gone, outer layers collapse and rebound



R. J. Hall

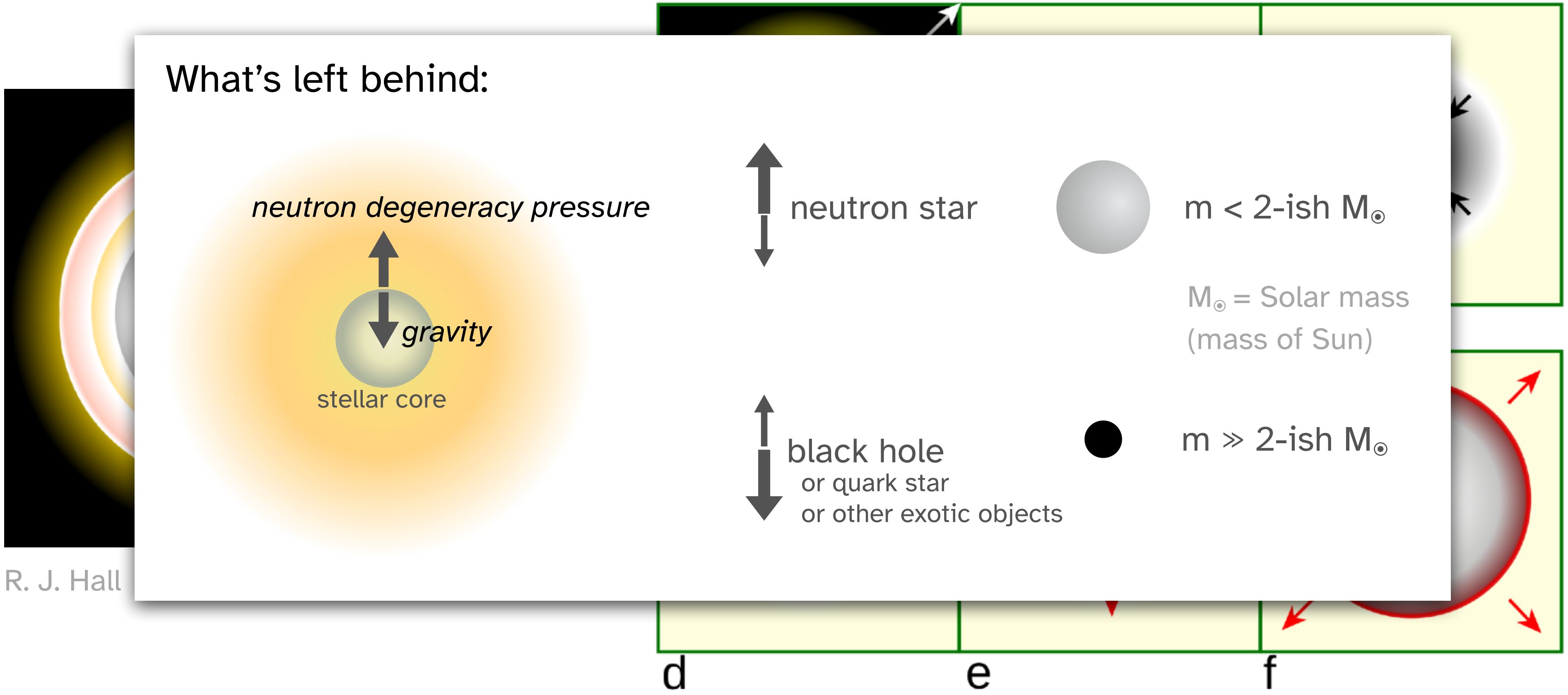


R. J. Hall

What happens at the end of a massive star's life?

core-collapse supernovae

Fusion no longer energetically favorable -> thermal pressure is gone, outer layers collapse and rebound



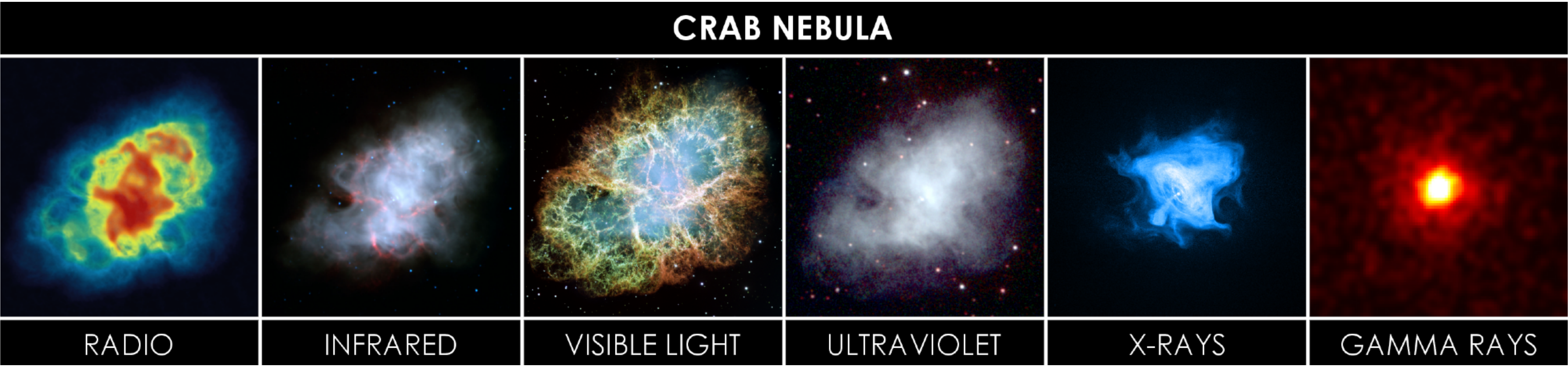
R. J. Hall

R. J. Hall

Crab nebula

a composite system: supernova remnant + pulsar wind nebula + pulsar

Emission at different wavelengths suggests multiple physical processes / components

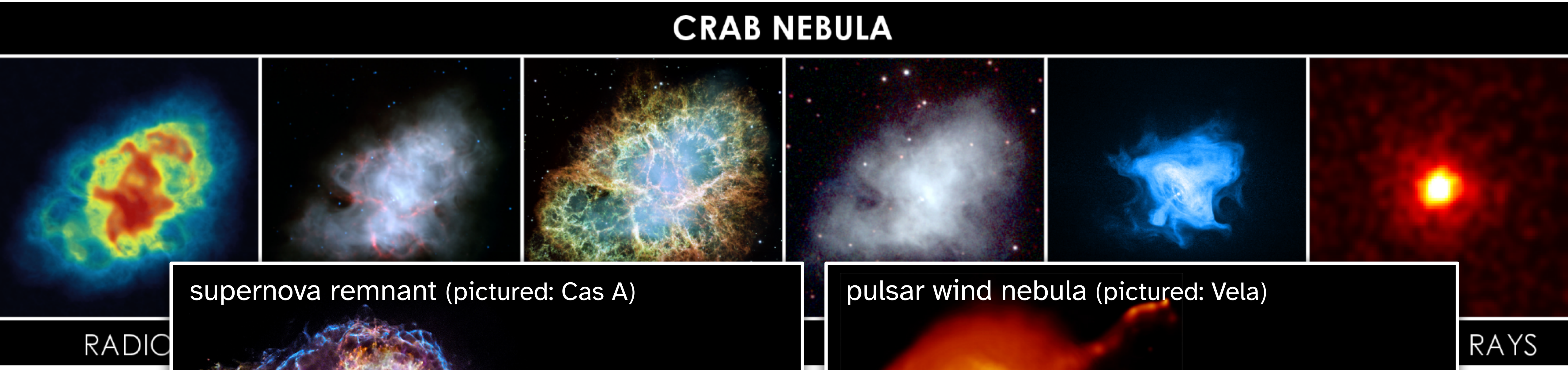


[NRAO/AUI, M. Bietenholz, J.M. Uson, T.J. Cornwell; NASA/JPL-Caltech/R. Gehrz (University of Minnesota); NASA, ESA, J. Hester and A. Loll (Arizona State University); NASA/Swift/E. Hoversten, PSU; NASA/CXC/SAO/F.Seward et al.; NASA/DOE/Fermi LAT/R. Buehler]

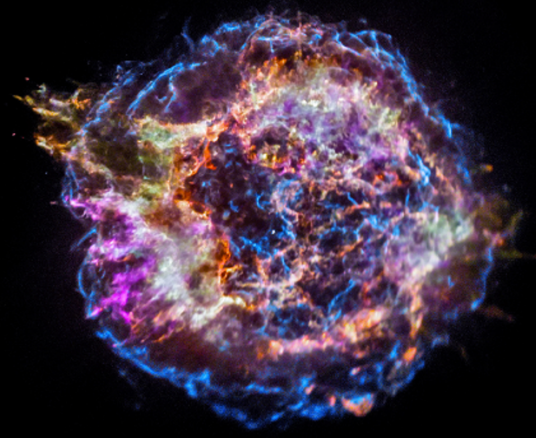
Crab nebula

a composite system: supernova remnant + pulsar wind nebula + pulsar

Emission at different wavelengths suggests multiple physical processes / components



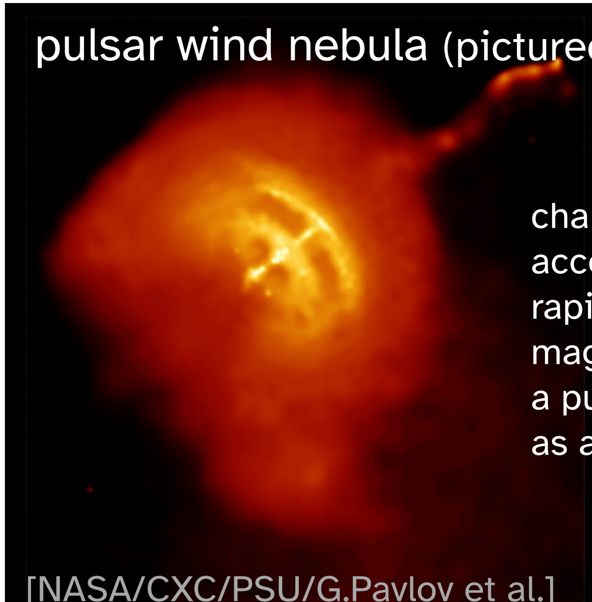
supernova remnant (pictured: Cas A)



material from original supernova explosion encounters and interacts with the surrounding environment

[NASA/CXC/SAO]

pulsar wind nebula (pictured: Vela)



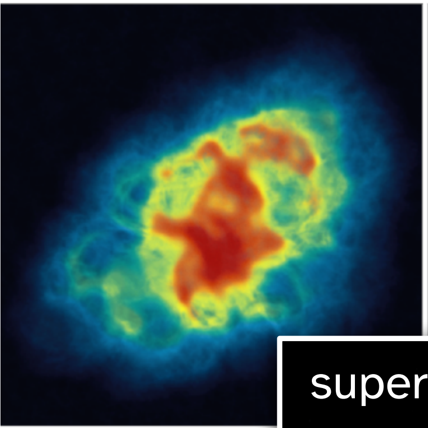
charged particles are accelerated by the rapidly rotating magnetic fields around a pulsar and stream out as a wind

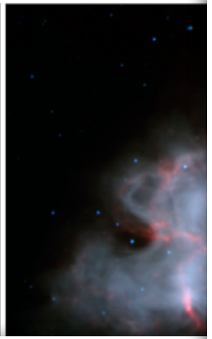
[NASA/CXC/PSU/G.Pavlov et al.]

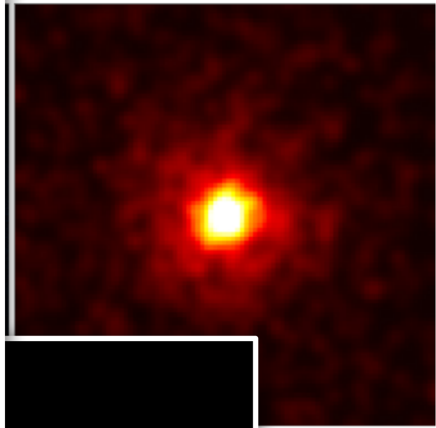
Crab nebula

a composite system: su

Emission at different wav







RADIO

RAYS

[NRAO/AUI, M
NASA/CXC/S

SU;

supernova rem

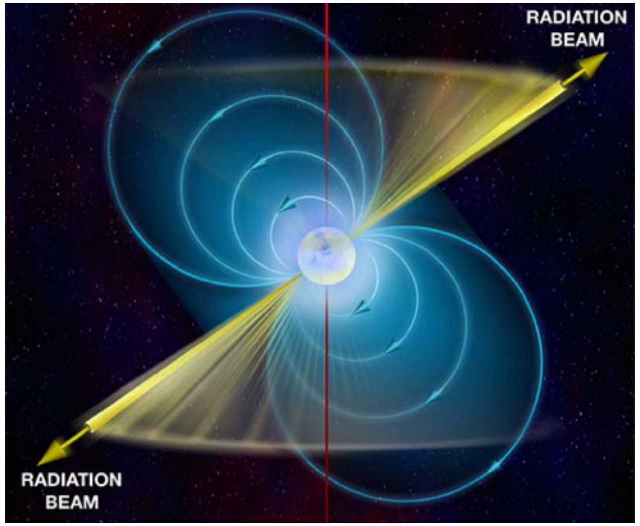
[NASA/CXC/SAO]

es are
the

around
eam out

[NASA/CXC/PSU/G.Pavlov et al.]

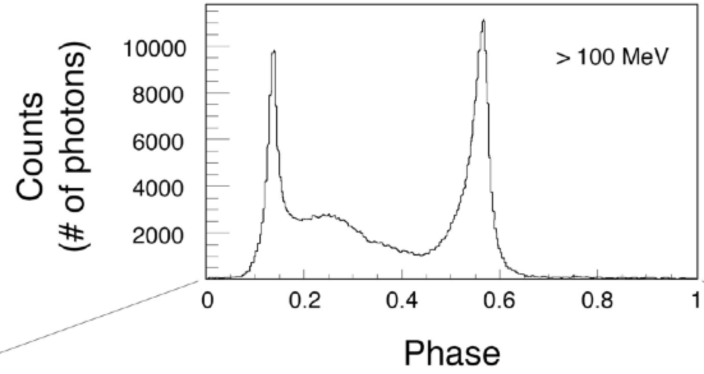
Pause: What is a pulsar?

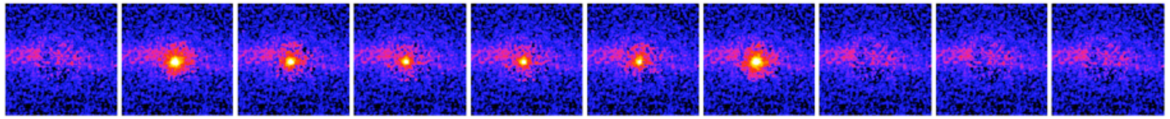


[NRAO]

The core of a pulsar is a neutron star, usually with a strong magnetic field

Pulsars are often described as lighthouses: beams of radiation that sweep across the sky





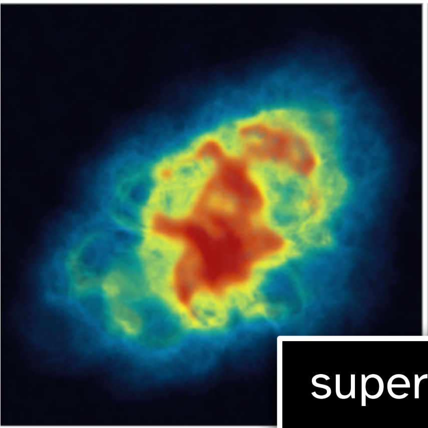
[Grodin et al. 2013 ApJ, NASA/DOE/Fermi-LAT]

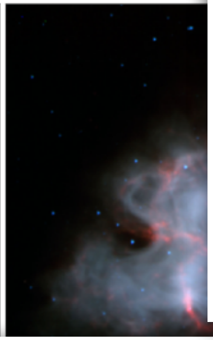
DESY.

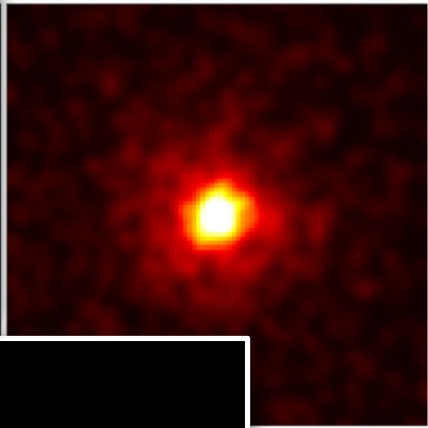
Crab nebula

a composite system: su

Emission at different wave







RADIO

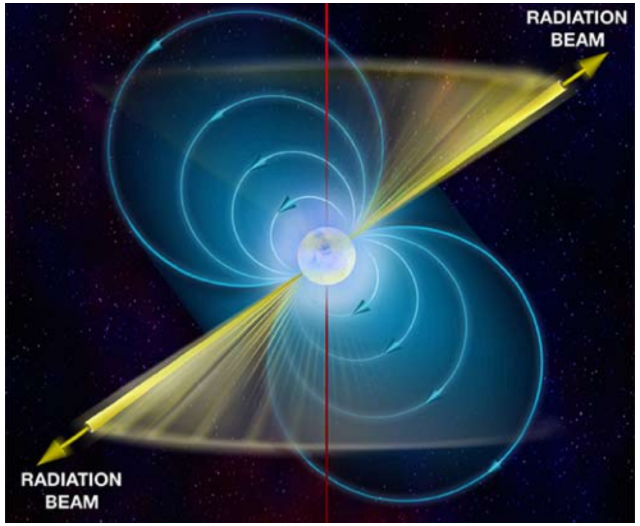
RAYS

[NRAO/AUI, M
NASA/CXC/S

ota]

SU;

Pause: What is a pulsar?

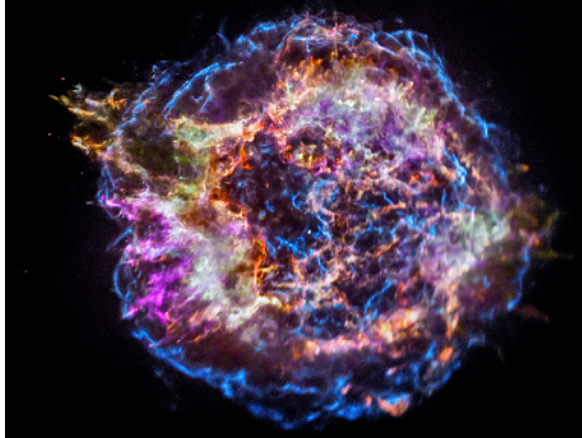


[NRAO]

The core of a pulsar is a neutron star, usually with a strong magnetic field

Pulsars are often described as lighthouses: beams of radiation that sweep across the sky

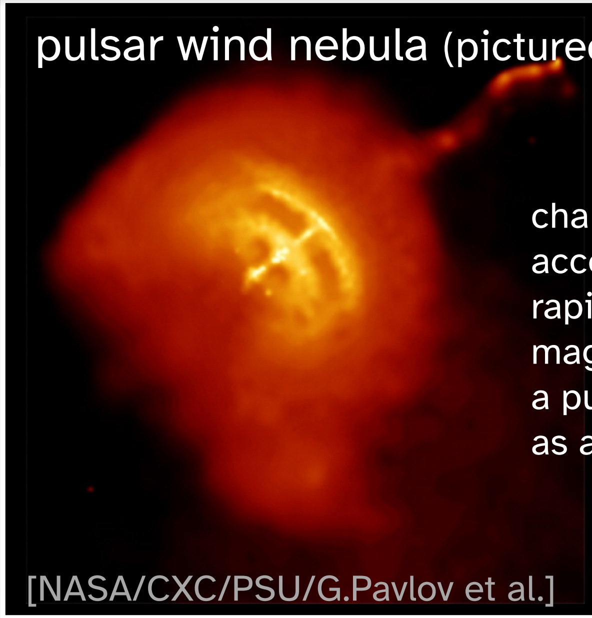
supernova remnant (pictured: Cas A)



material from original supernova explosion encounters and interacts with the surrounding environment

[NASA/CXC/SAO]

pulsar wind nebula (pictured: Vela)



charged particles are accelerated by the rapidly rotating magnetic fields around a pulsar and stream out as a wind

[NASA/CXC/PSU/G.Pavlov et al.]

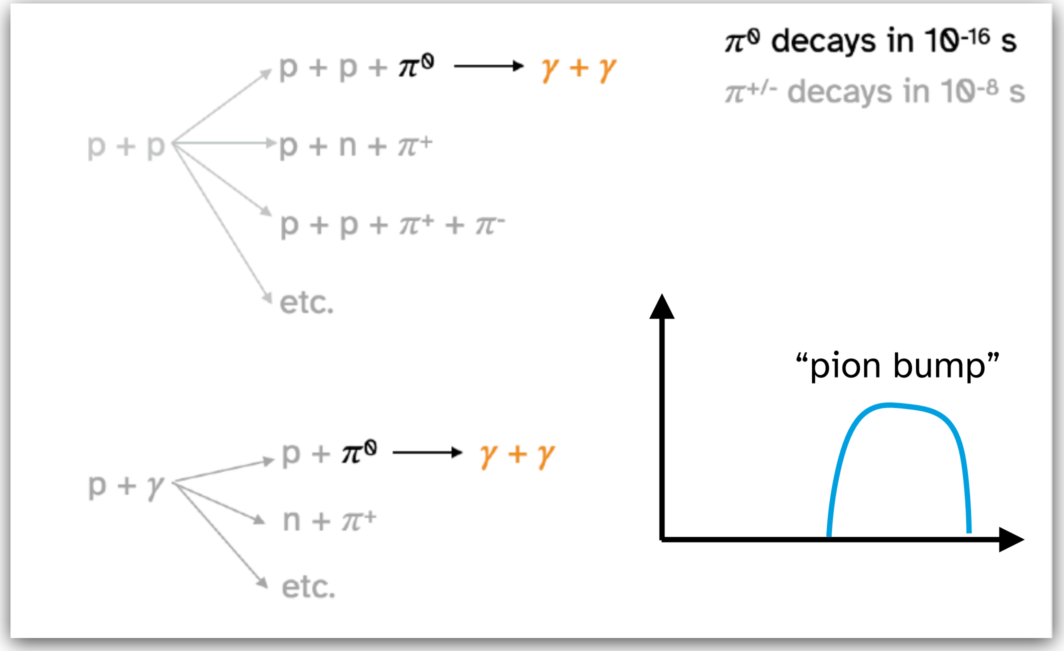
my

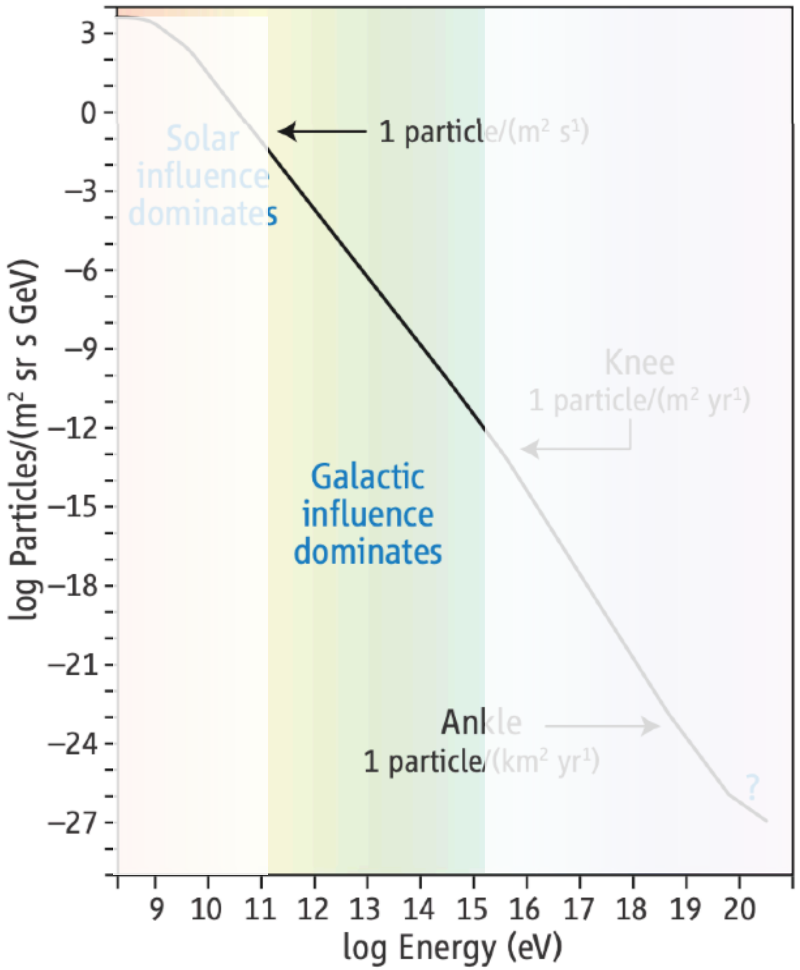
A common goal in Galactic gamma-ray astronomy

Looking for Pevatrons

Reminder: a nice summary: presentation by [H. Fleischhack]

- Cosmic-ray hadrons up to ~PeV energies should be Galactic
- Their sources are hard to pinpoint directly
- Instead we ask questions like:
  - -> What sources produce ~100 TeV gamma rays?
  - -> Are these gamma rays from *hadronic* processes?





[M. Duldig, Science 314 (2006)]

A common goal in Galactic gamma-ray astronomy

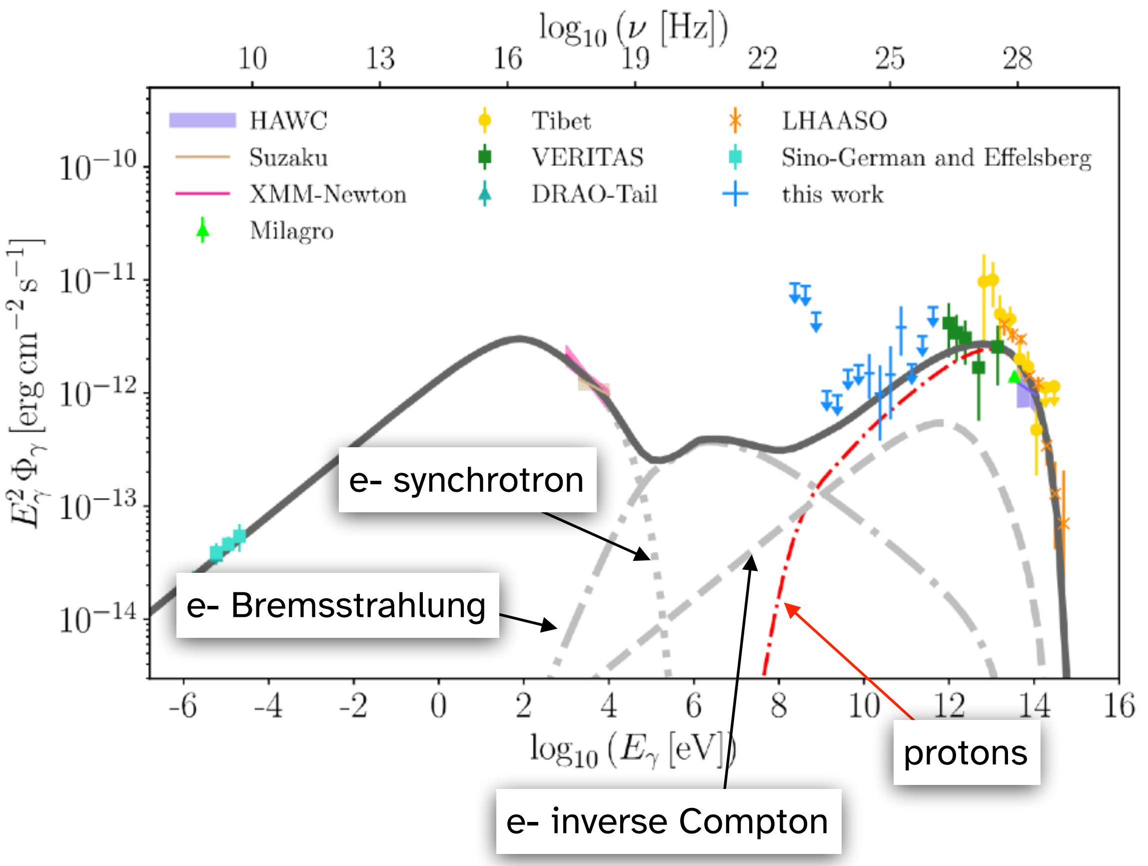
Looking for Pevatrons

Are these gamma rays from *hadronic* processes?

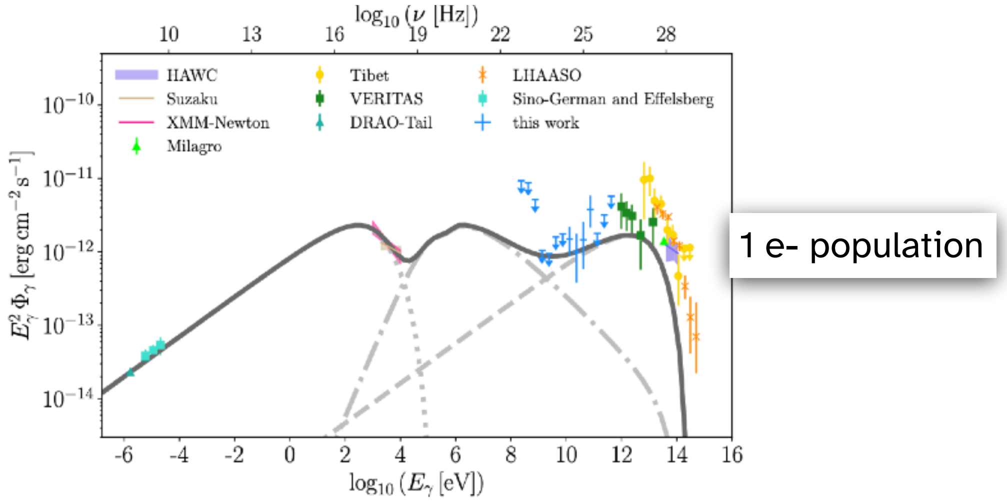
[K. Fang et al., PRL 129 (2022)]

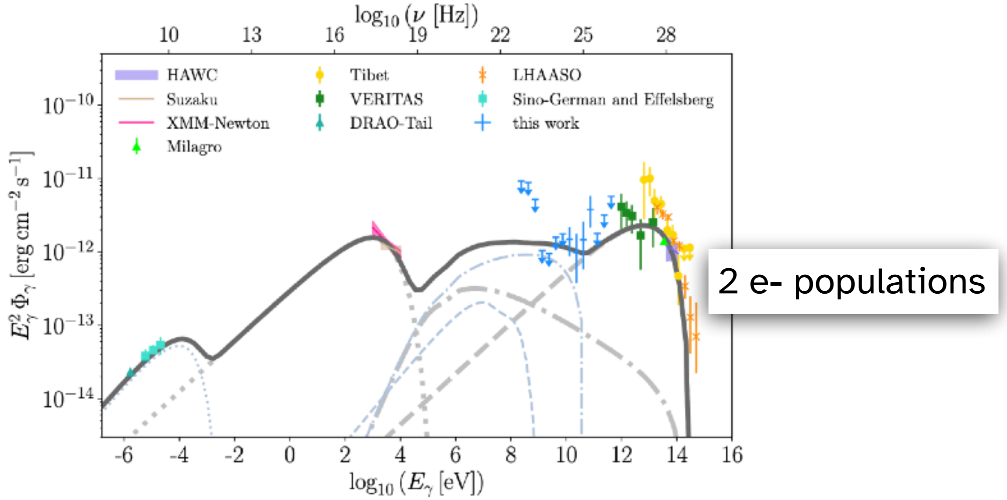
examples for a supernova remnant (G 106.3 +2.7):

(lepto-)hadronic scenario



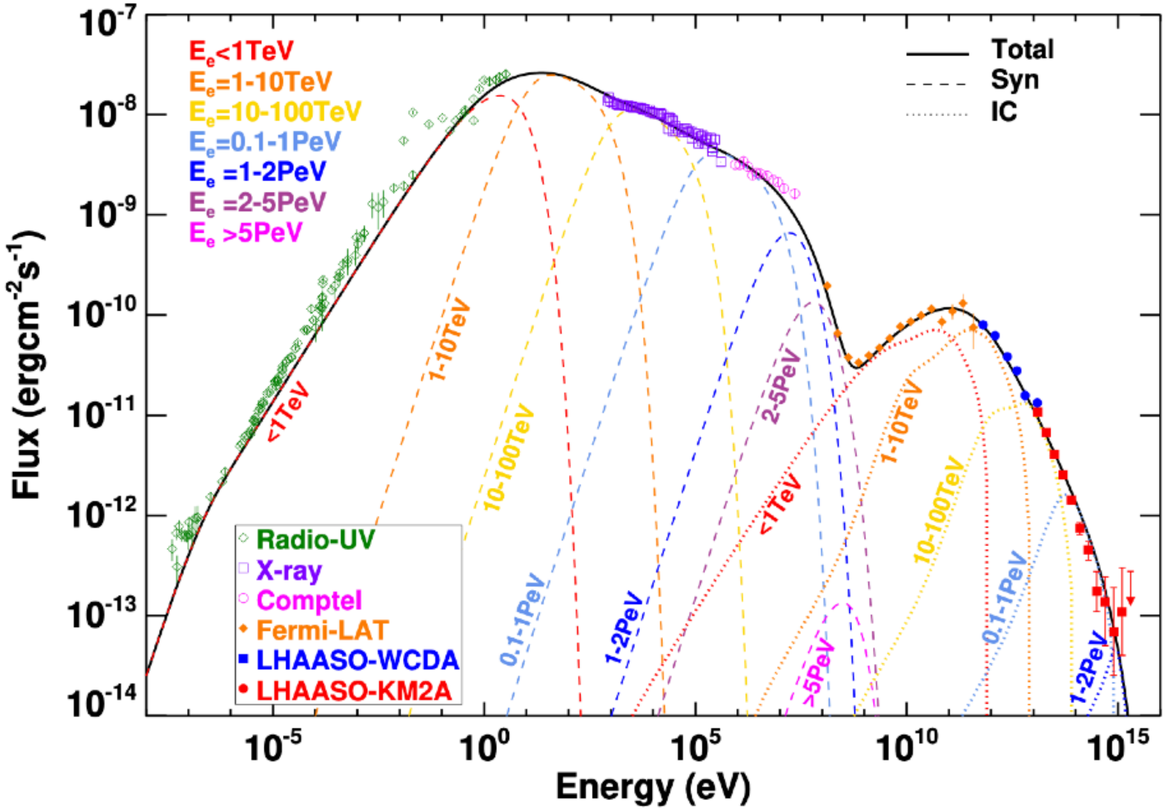
leptonic scenarios





Is the Crab a Pevatron?

Looking for Pevatrons



[LHAASO Collaboration, Science 373 (2021)]

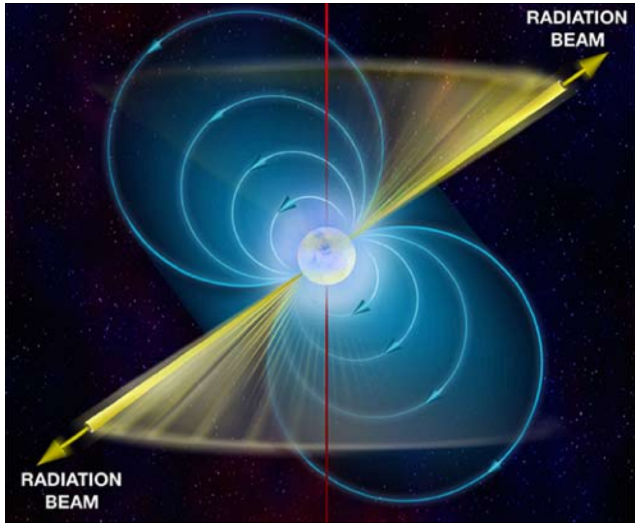
Yes **but** it is a leptonic one

=> The Crab is not a producer of PeV-energy hadrons
=> Does this generalize to other systems?
=> What about the individual components in these systems?

etc.

Pulsars

Nature's lighthouses?

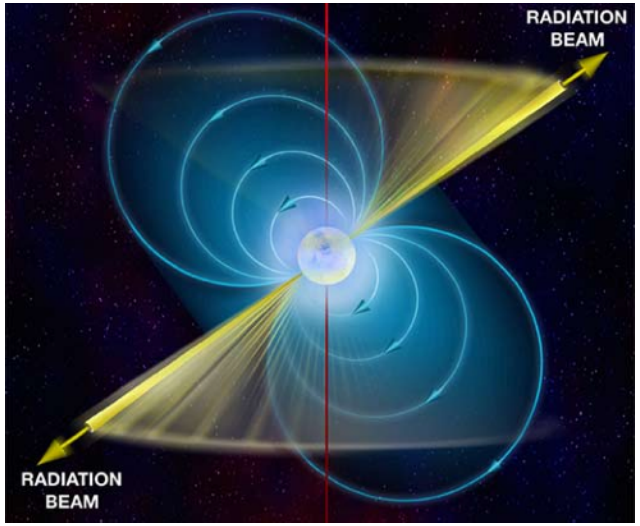


[NRAO]

Pulsars are often described as lighthouses
-> charged particles funnelled along magnetic field lines to the poles, produce relativistically beamed radiation

Pulsars

Nature's lighthouses?



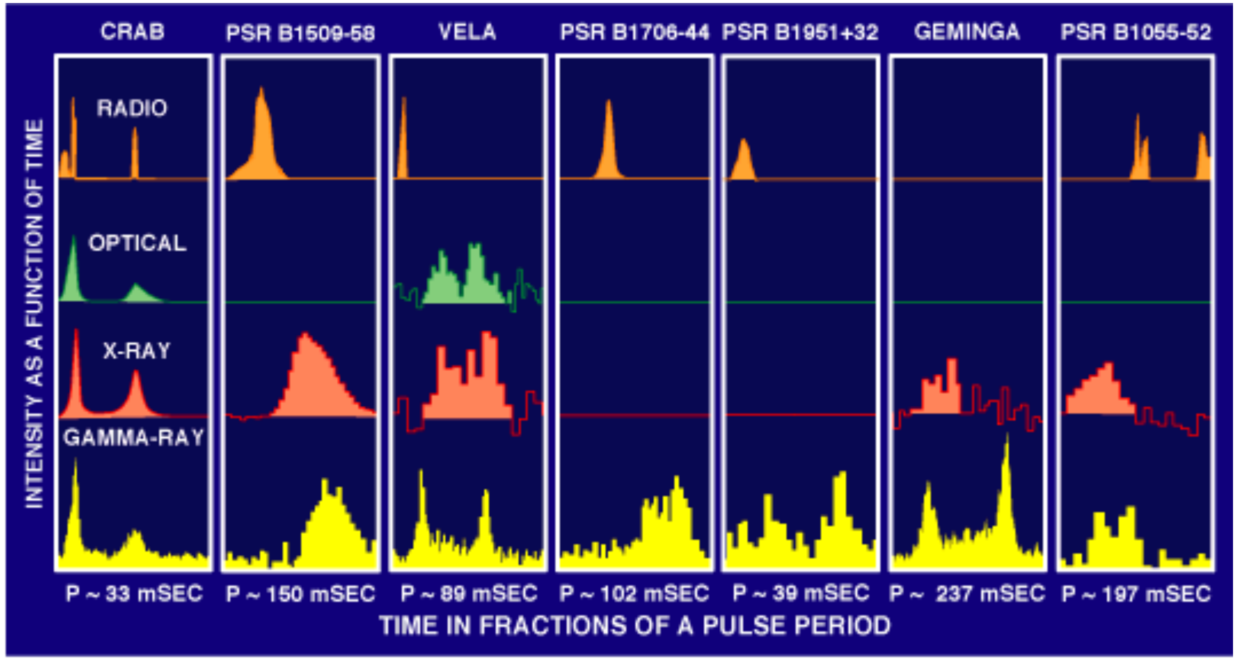
[NRAO]

Pulsars are often described as lighthouses
-> charged particles funnelled along magnetic field lines to the poles, produce relativistically beamed radiation

[D.J. Thompson (NASA/GSFC)]

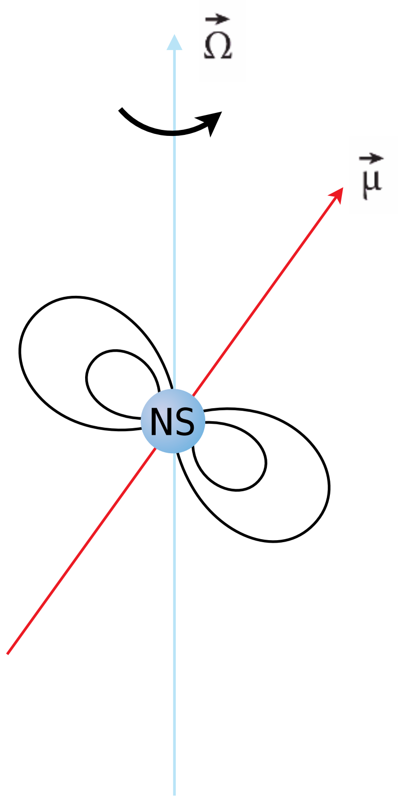
But it's been known for a while that the emission is more complex

compare lightcurves at different wavelengths



Pulsars

So where *are* the photons being produced?



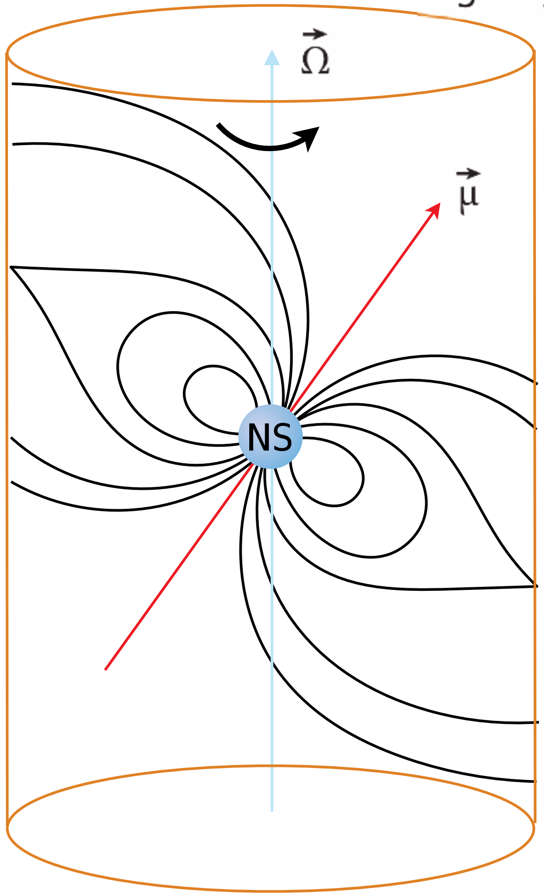
[A. Philippov & M. Kramer, Annu Rev Astron & Astrophys 60 (2022)]

Pulsars

So where *are* the photons being produced?

Light cylinder = where the magnetic field lines would be rotating at the speed of light

$R_{LC} = c/\Omega$

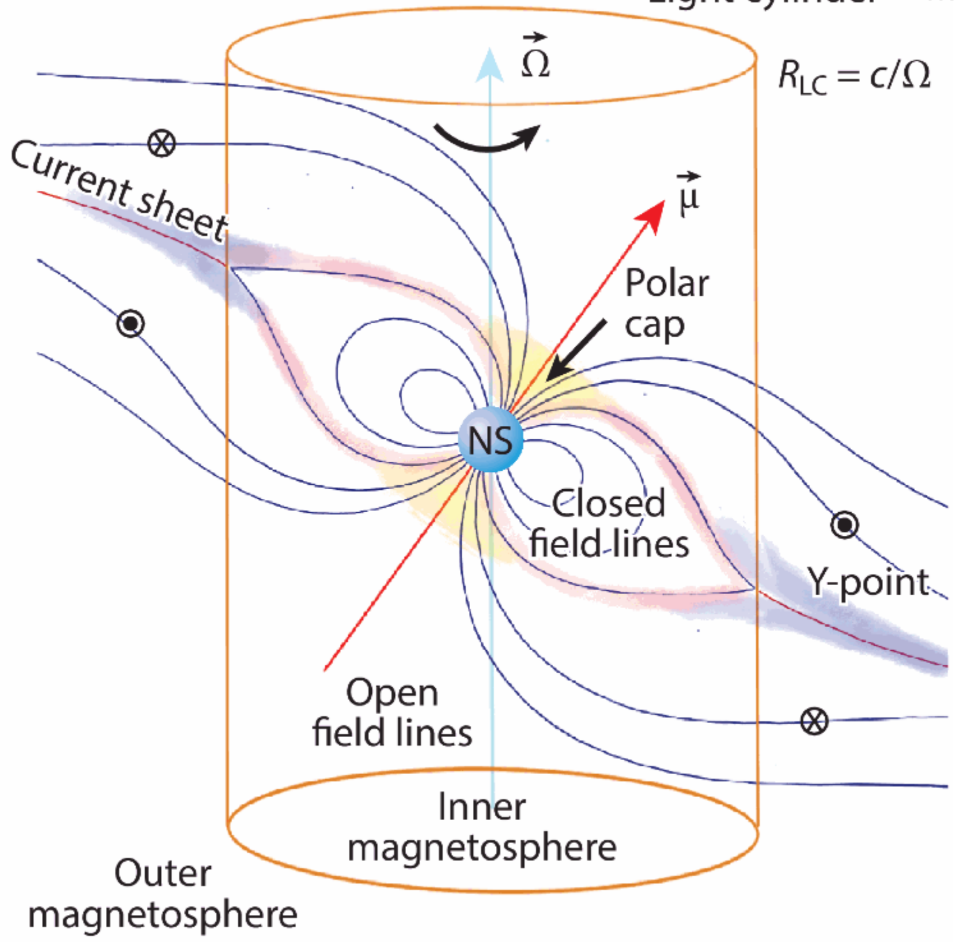


[A. Philippov & M. Kramer, Annu Rev Astron & Astrophys 60 (2022)]

Pulsars

So where *are* the photons being produced?

Light cylinder = where the magnetic field lines would be rotating at the speed of light

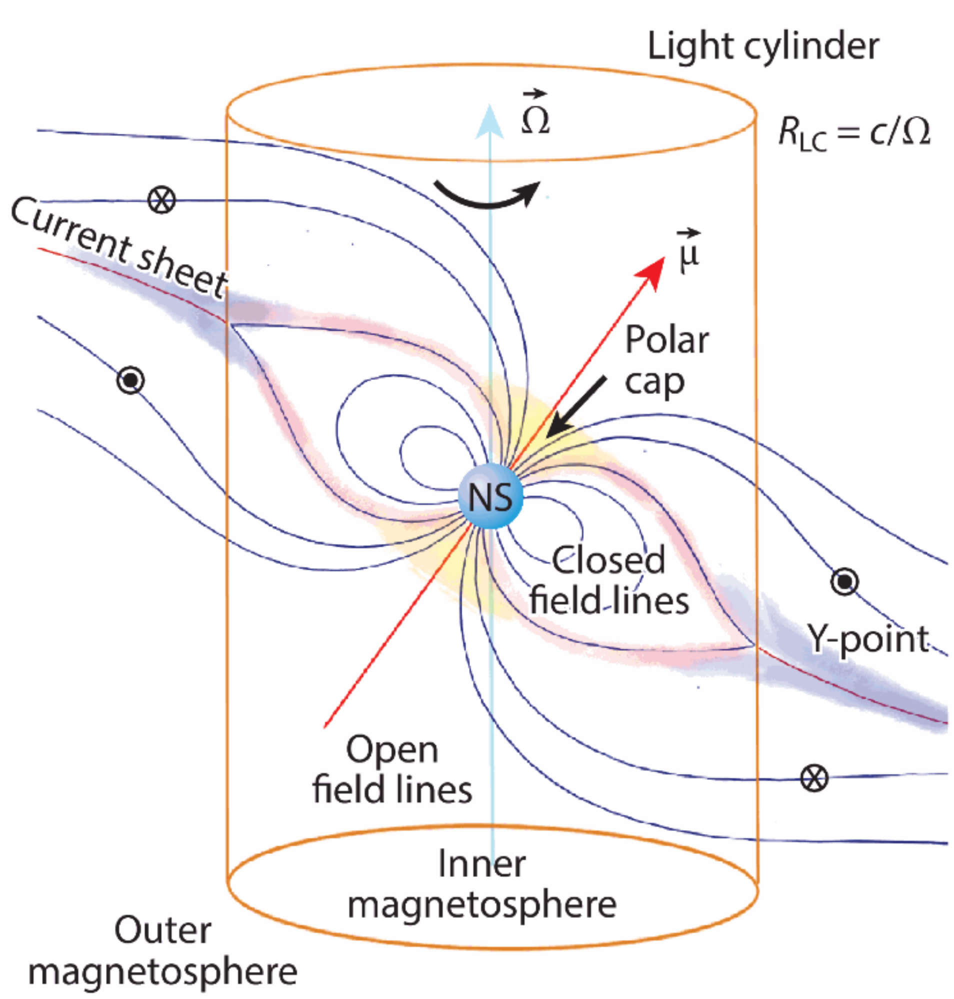


[A. Philippov & M. Kramer, Annu Rev Astron & Astrophys 60 (2022)]

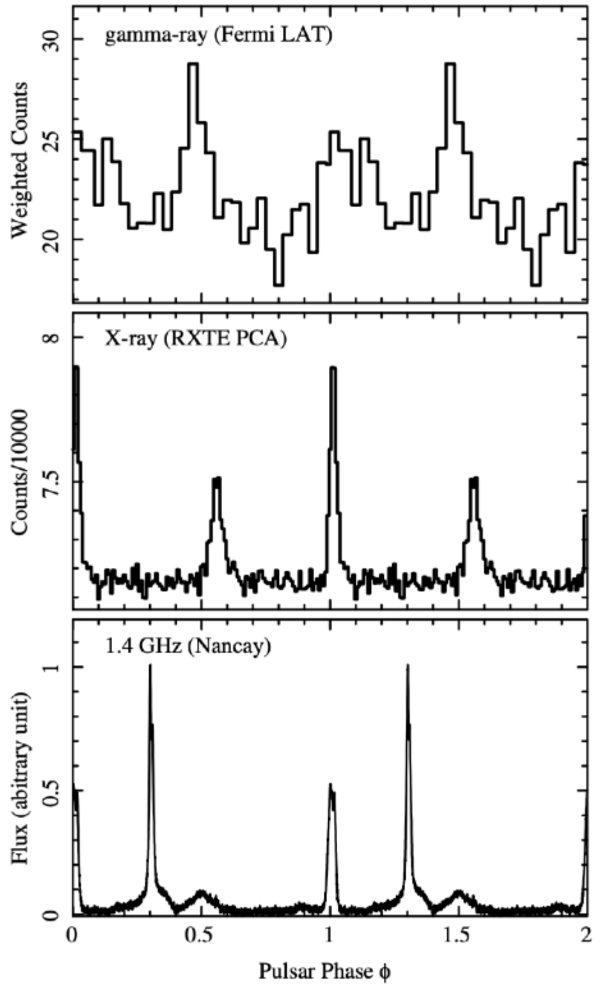
There are multiple regions in the magnetosphere that could be the sources of (gamma-ray) emission

Pulsars

So where *are* the photons being produced?



[A. Philippov & M. Kramer, Annu Rev Astron & Astrophys 60 (2022)]



[Y. Du et al., ApJ 801 (2015)]

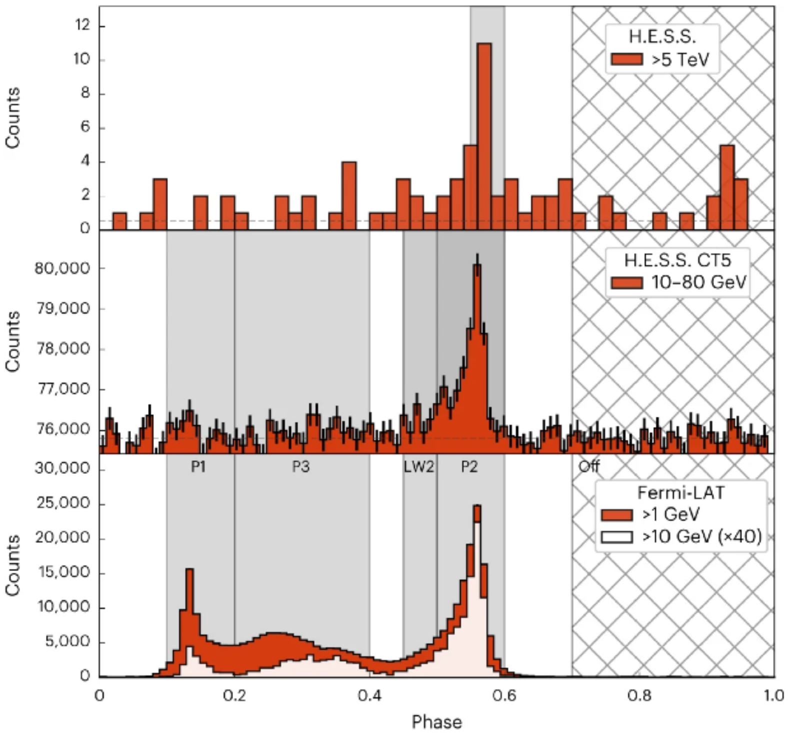
if the peaks are not aligned, likely the emission is coming from different regions

=> pulsar modelling is a very active field

Pulsars

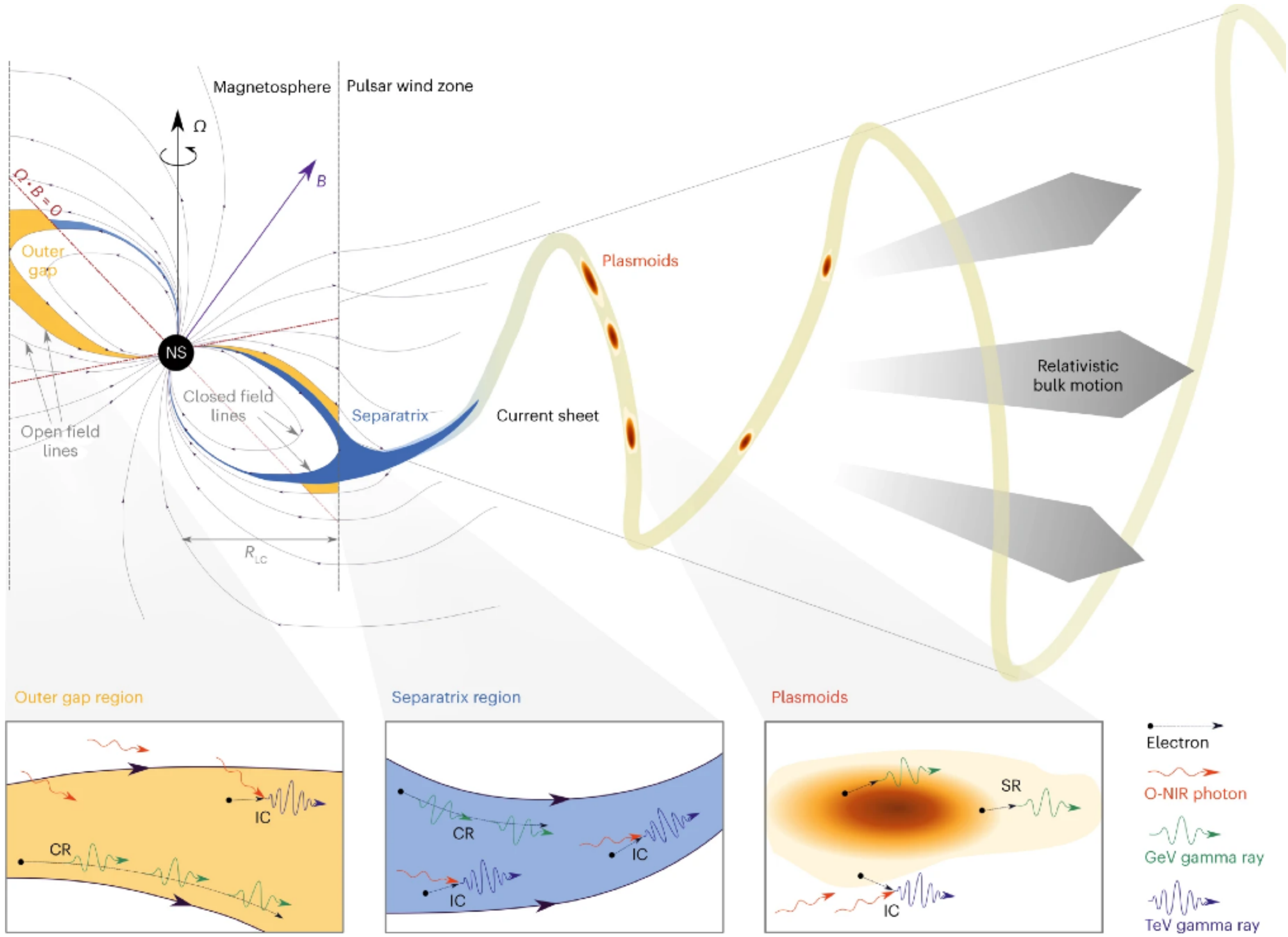
TeV emission

H.E.S.S. detected pulsations >5 TeV from the Vela pulsar



[H.E.S.S. Collaboration, Nature Astro 7 (2023)]

This allows for more detailed investigations of how and where pulsars accelerate charged particles



Scientists discover
the highest energy gamma-rays
from a pulsar

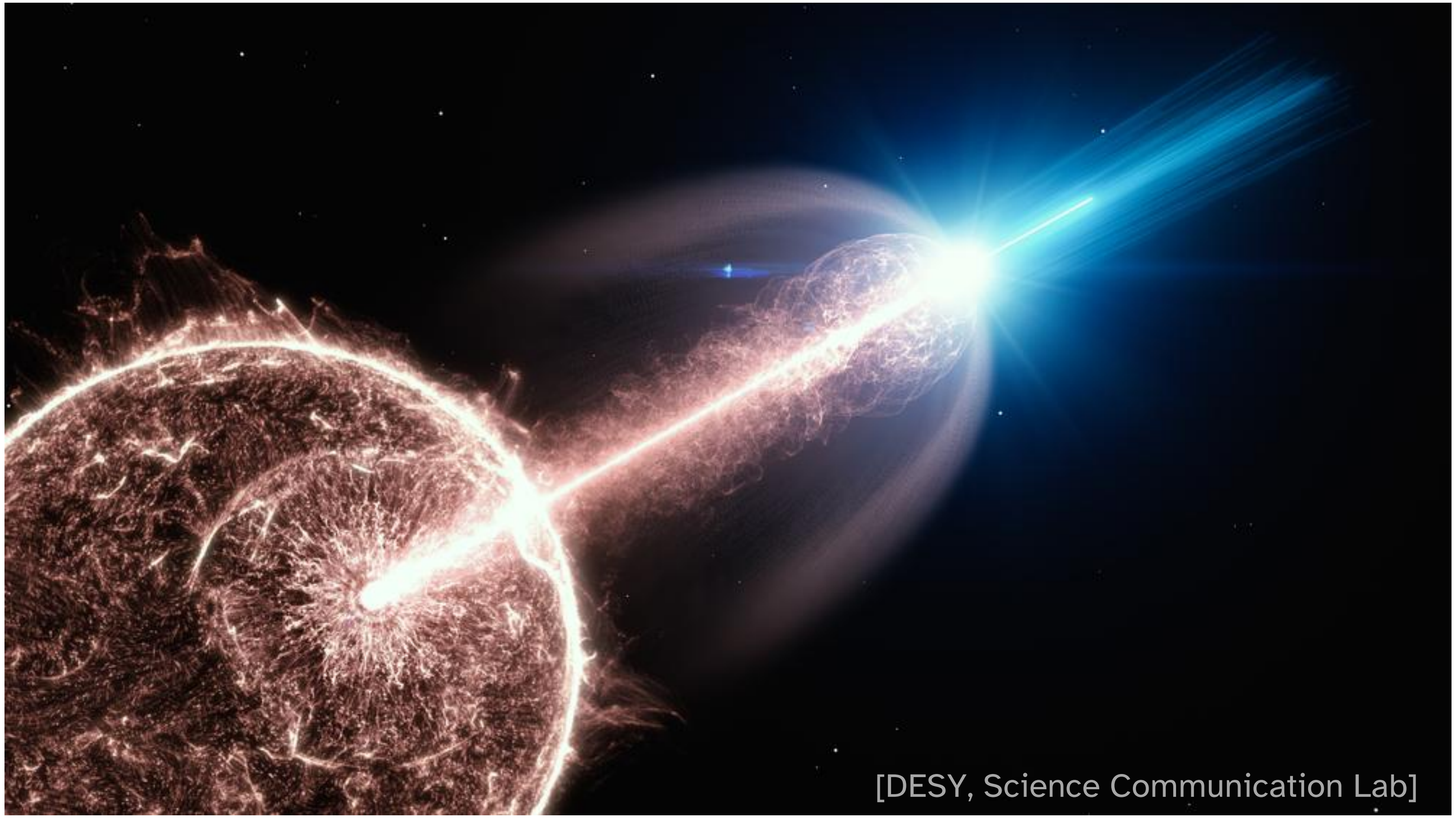
DESY.

H.E.S.S.

[Science Communication Lab for DESY]

now I'm going to focus on gamma-ray bursts

because I study them and like them

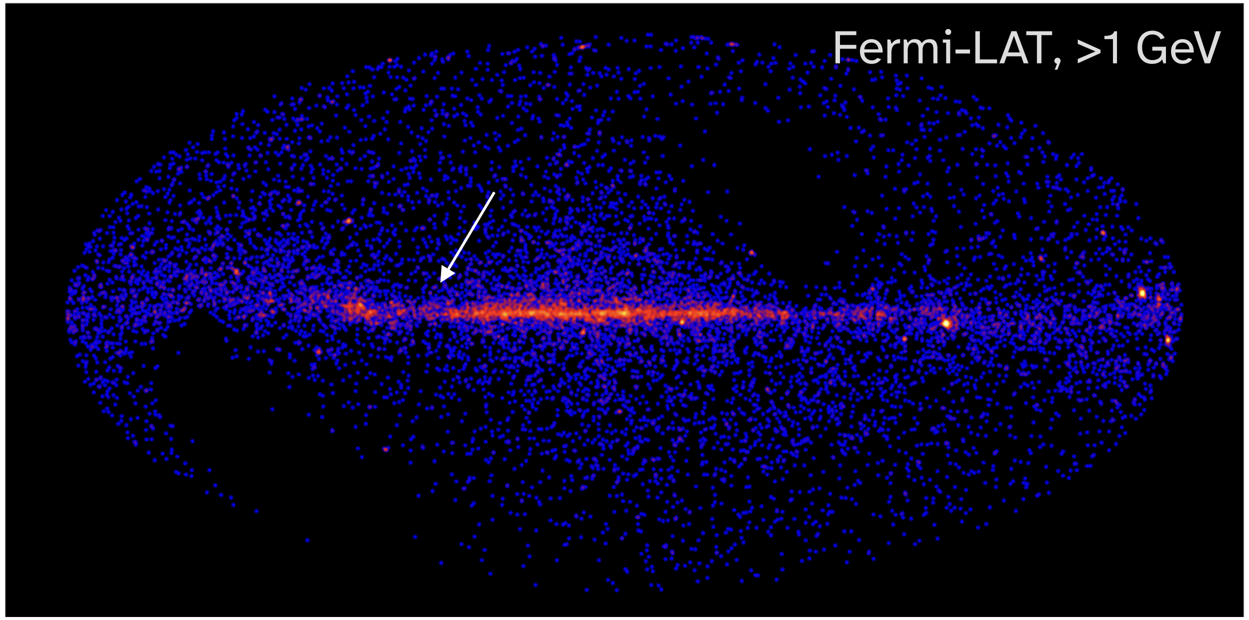


[DESY, Science Communication Lab]

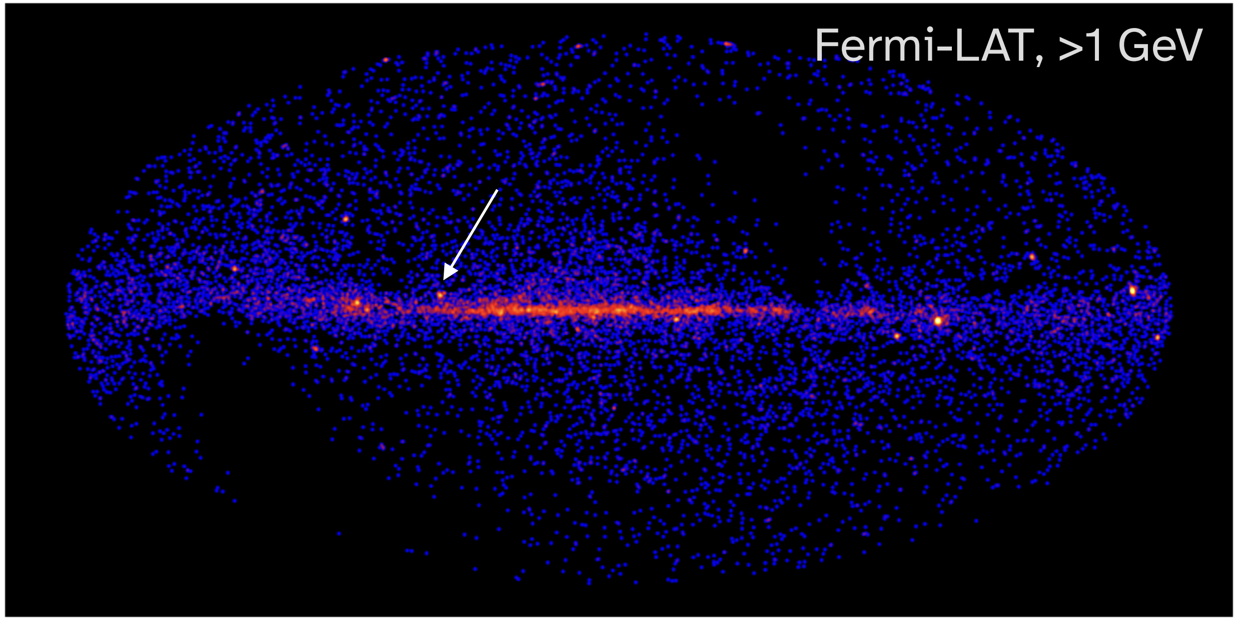
ok but what exactly is a “gamma-ray burst”?

Literally, a burst of gamma rays that easily outshines the rest of the gamma-ray sky for their brief existence

D. Green



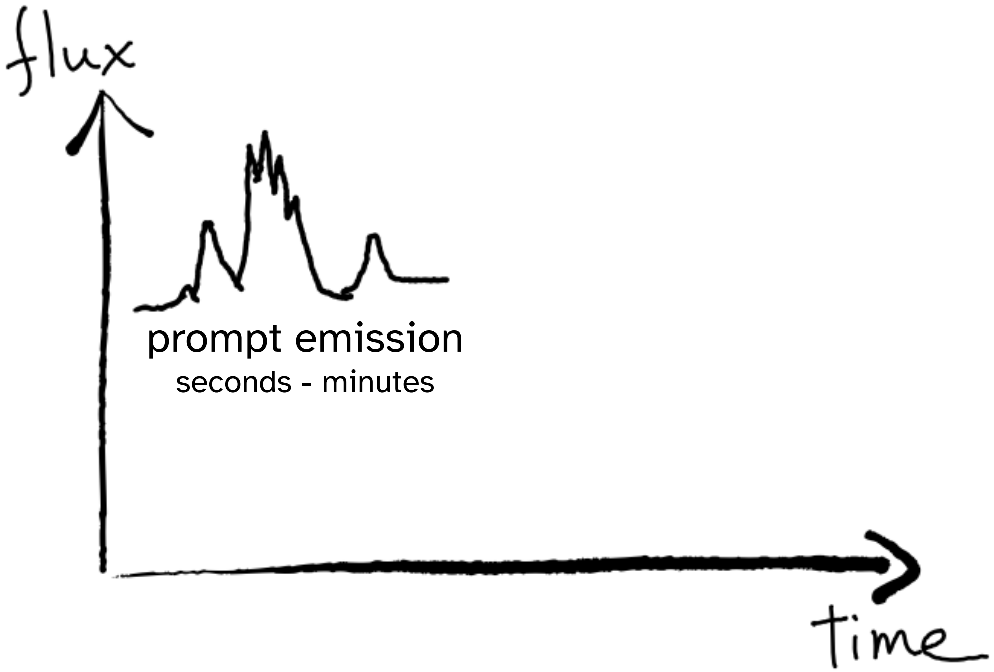
2 days before GRB

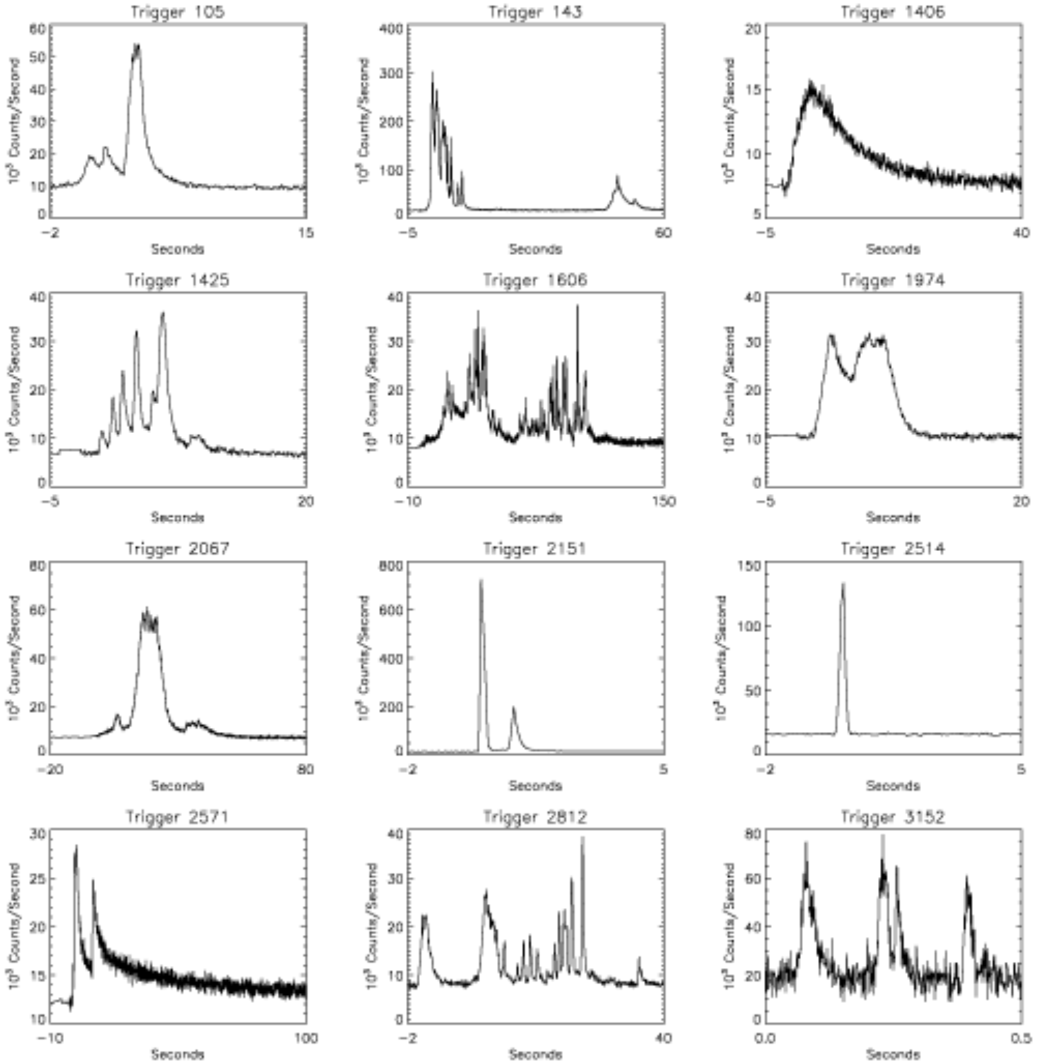


GRB + 2 days after

Gamma-ray bursts

What causes them, and how do we know?



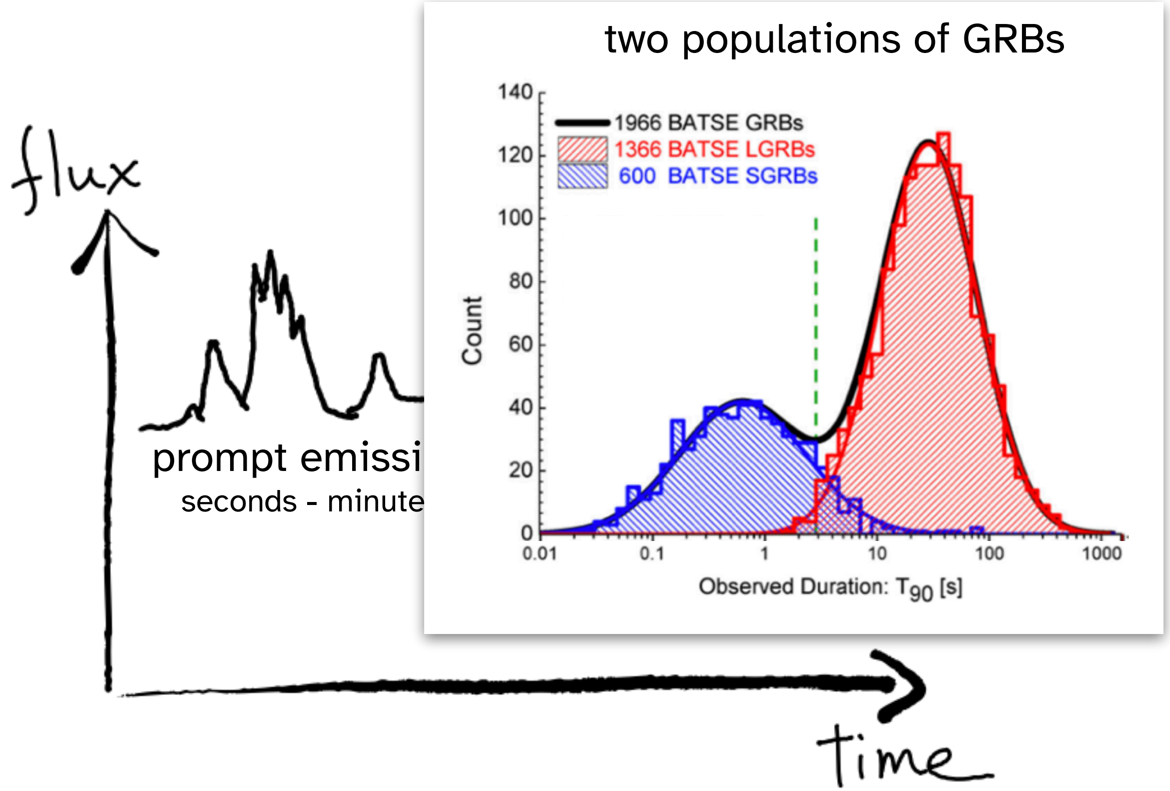


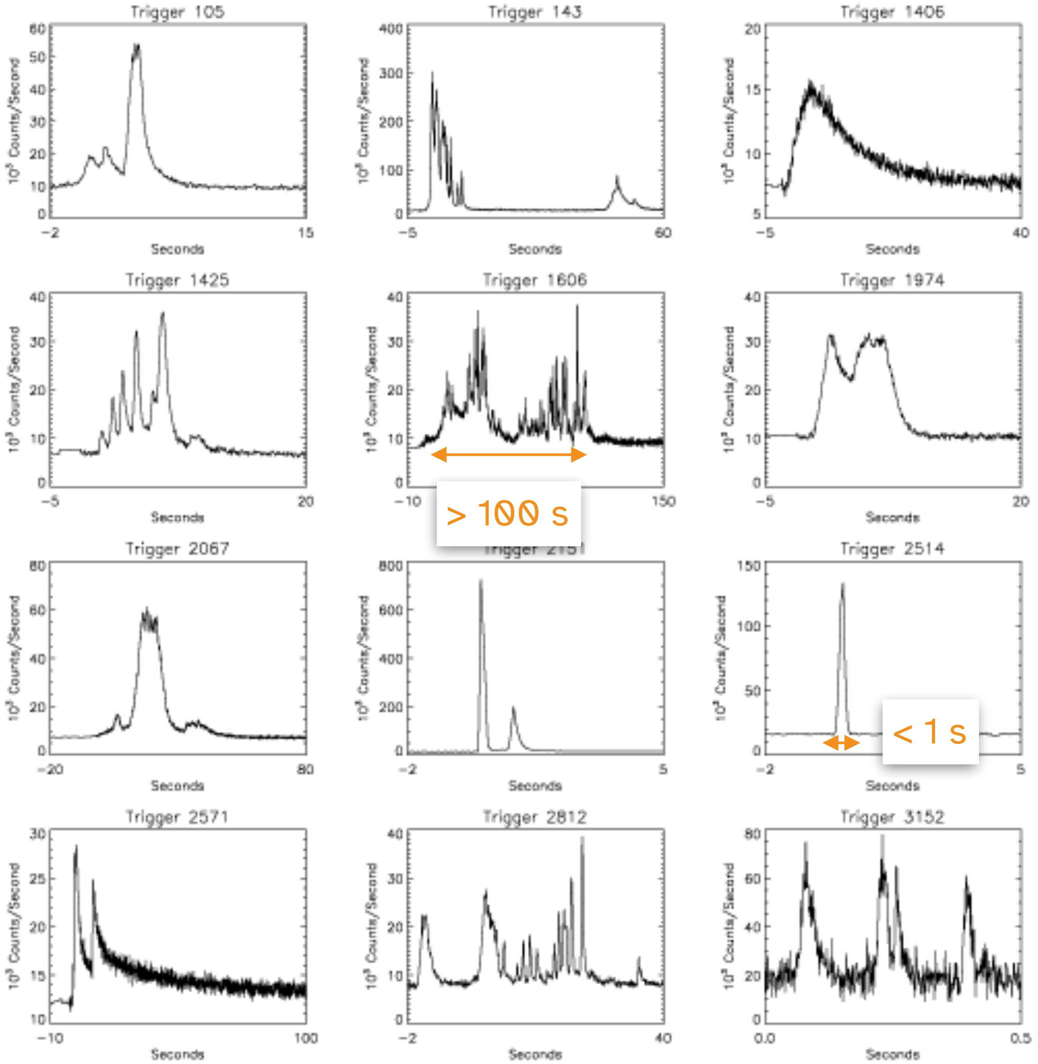
[J. T. Bonnell (NASA/GSFC)]

Gamma-ray bursts

What causes them, and how do we know?

[A. Shahmoradi & R. J. Nemiroff, MNRAS 451 (2015)]

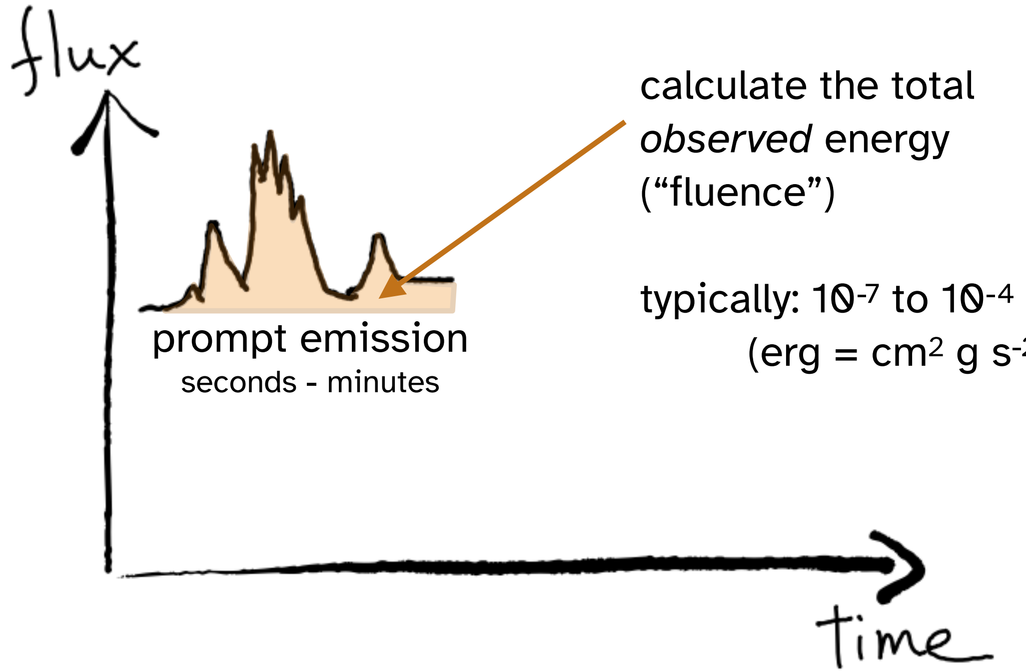




[J. T. Bonnell (NASA/GSFC)]

Gamma-ray bursts

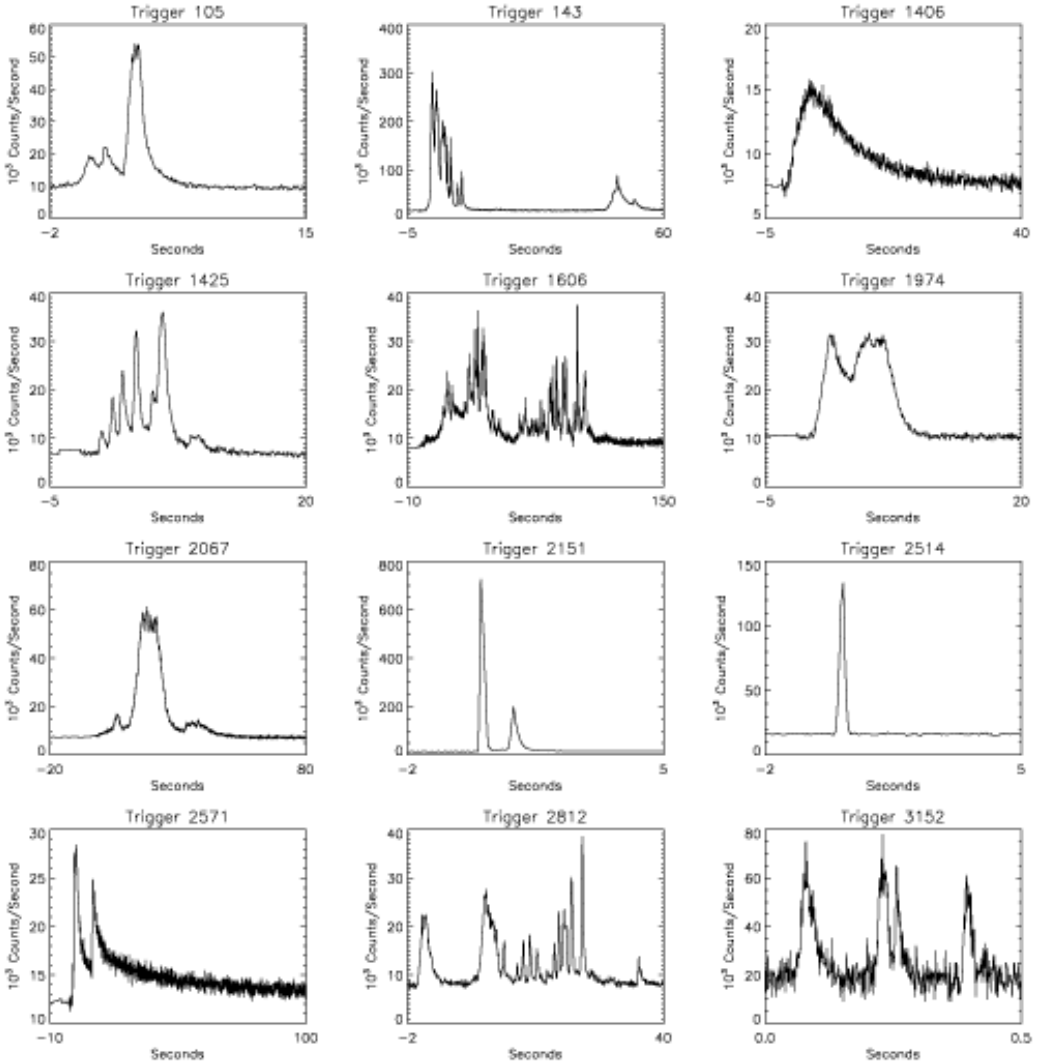
What causes them, and how do we know?



calculate the total *observed* energy ("fluence")

typically: 10^{-7} to 10^{-4} erg

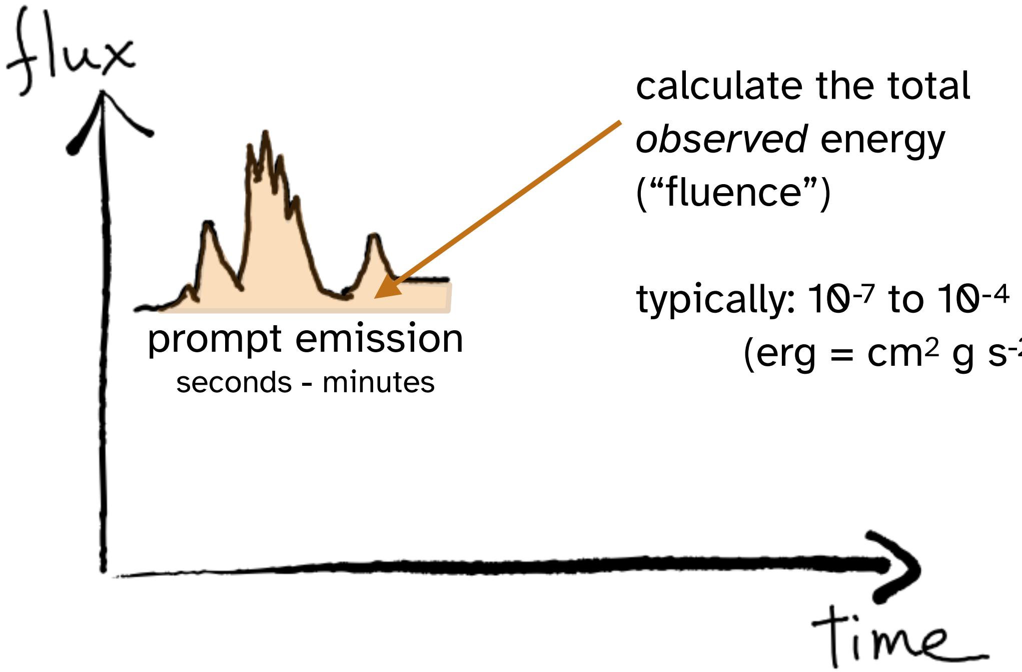
($\text{erg} = \text{cm}^2\ \text{g}\ \text{s}^{-2}$)



[J. T. Bonnell (NASA/GSFC)]

Gamma-ray bursts

What causes them, and how do we know?

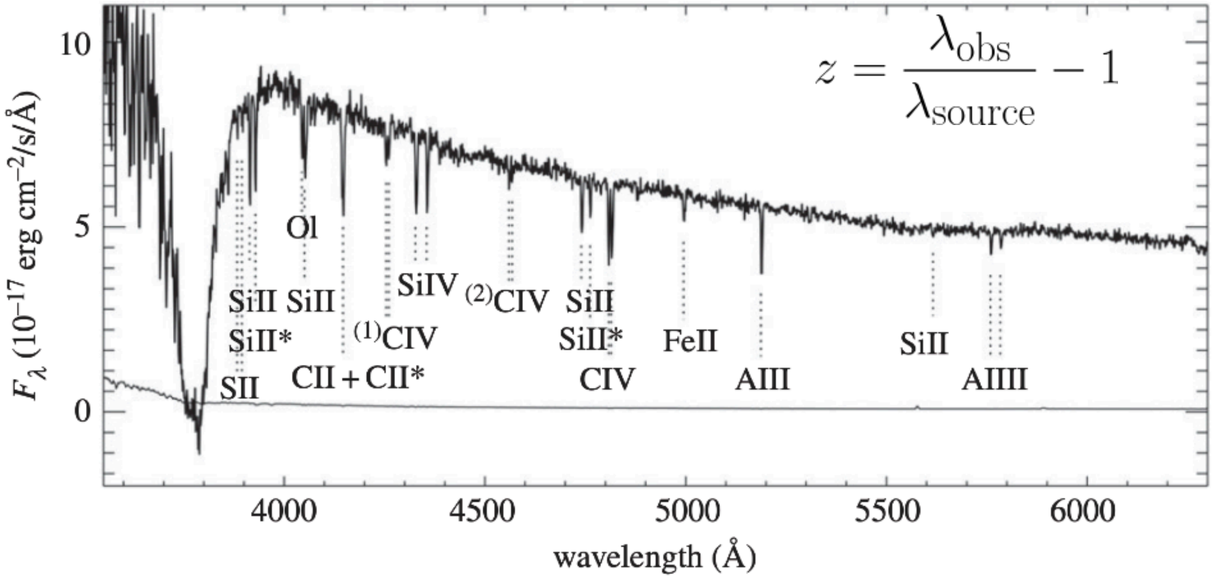


prompt emission
seconds - minutes

calculate the total *observed* energy ("fluence")

typically: 10^{-7} to 10^{-4} erg
($erg = cm^2\ g\ s^{-2}$)

[A. Rau et al., ApJ 720 (2010)]



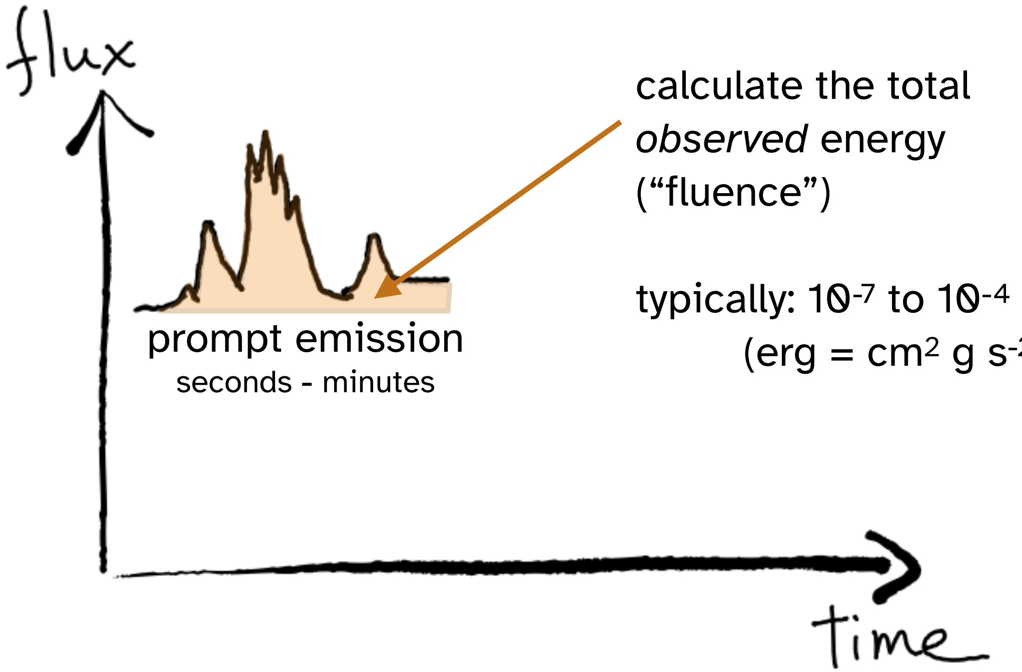
e.g., OI line: 4050 Å here
1356 Å rest frame

} z ~ 2 ~ 16 Gpc

Very useful: [Cosmology Calculator]
BUT be careful about default cosmology values

Gamma-ray bursts

What causes them, and how do we know?



calculate the total *observed* energy ("fluence")

typically: 10^{-7} to 10^{-4} erg
(erg = cm^2 g s^{-2})

fluence S: 10^{-4} erg/cm^2
distance r: 16 Gpc

energy emitted by the source (assuming isotropic):

$$E_{\rm iso} = 4\pi r^2 S \sim 10^{54}\,{\rm erg}$$

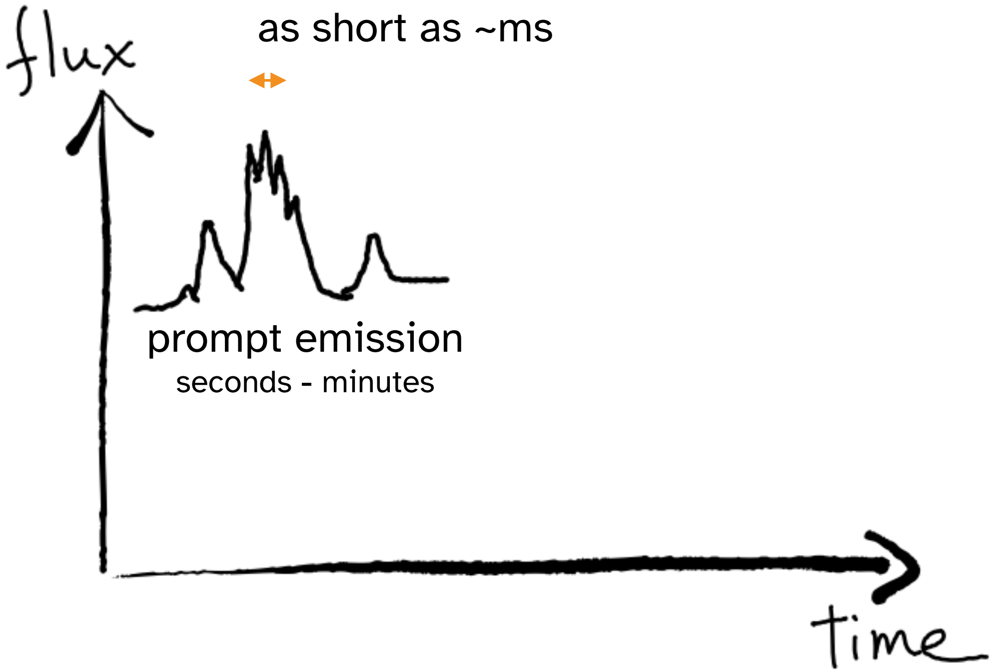
by comparison, the rest energy of the Sun:

$$E_\odot = 10^{54}\,{\rm erg}$$

So: GRBs are stellar-sized phenomena (not, e.g., galaxy-sized)
release as much energy in minutes as the Sun will in its entire lifetime

Gamma-ray bursts

What causes them, and how do we know?



variability timescale Δt
as short as ~ms

prompt emission
seconds - minutes

size of emitting region:

$$d = c\Delta t \sim 10^5\,\mathrm{m}$$

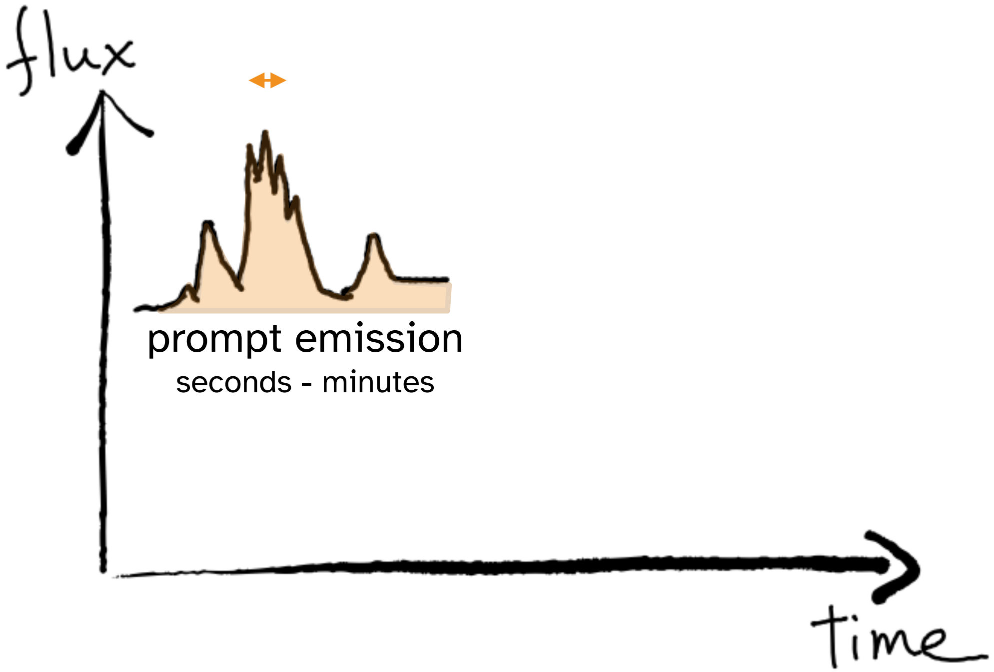
compare to the radius of Earth:

$$R_\oplus = 6 \times 10^6\,\mathrm{m}$$

so, emission is occurring in regions smaller than the Earth

Gamma-ray bursts

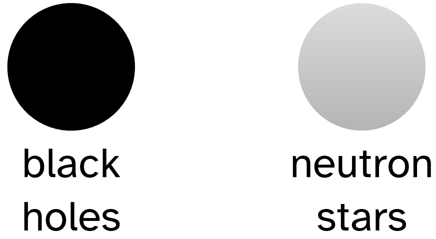
What causes them, and how do we know?



Combining these facts:

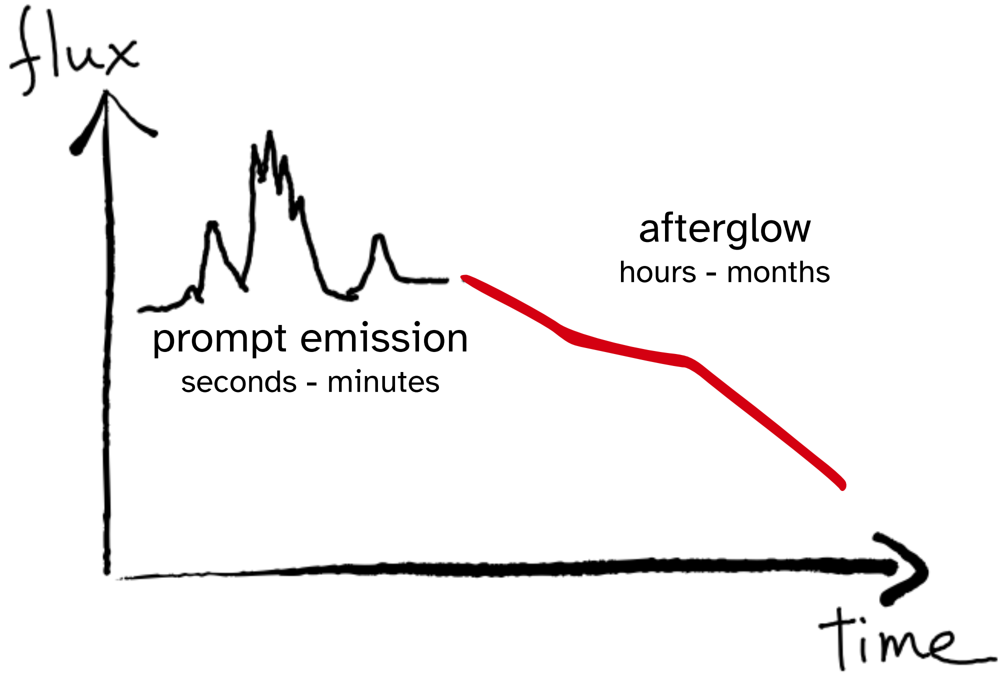
GRBs are stellar-sized phenomena
release $M_{\odot}c^2$ within minutes
emission occurring in regions smaller than the Earth

=> stellar-mass compact objects must be involved

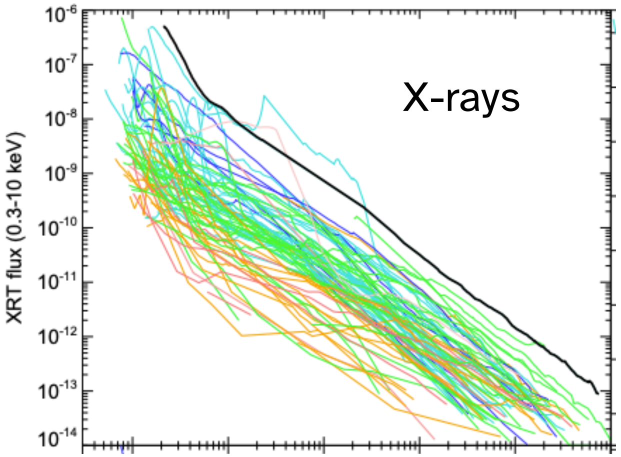


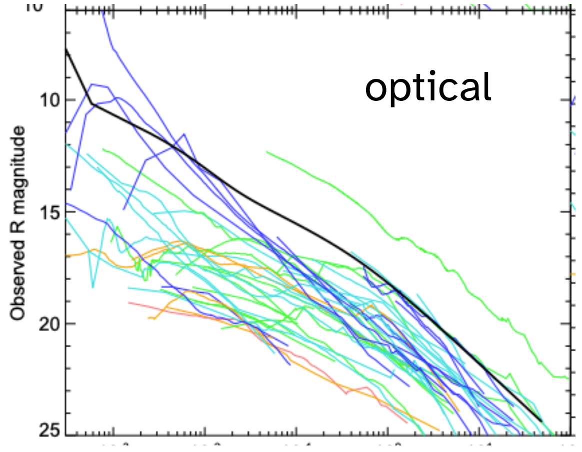
Gamma-ray bursts

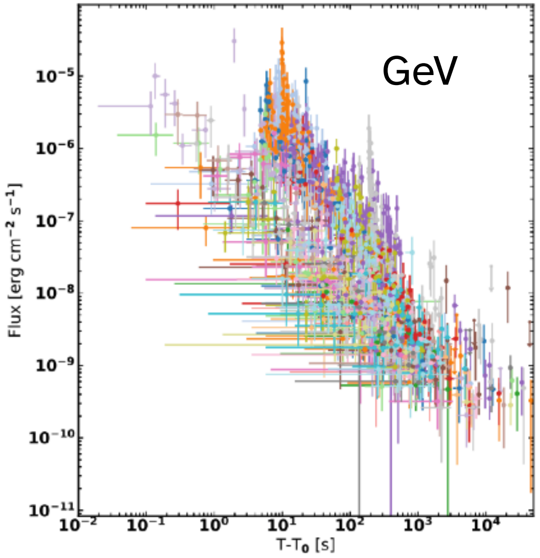
What causes them, and how do we know?



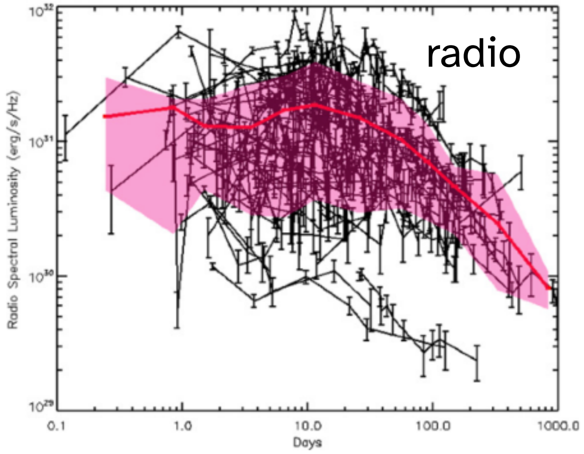
D. A. Perley et al., ApJ 781 (2014)







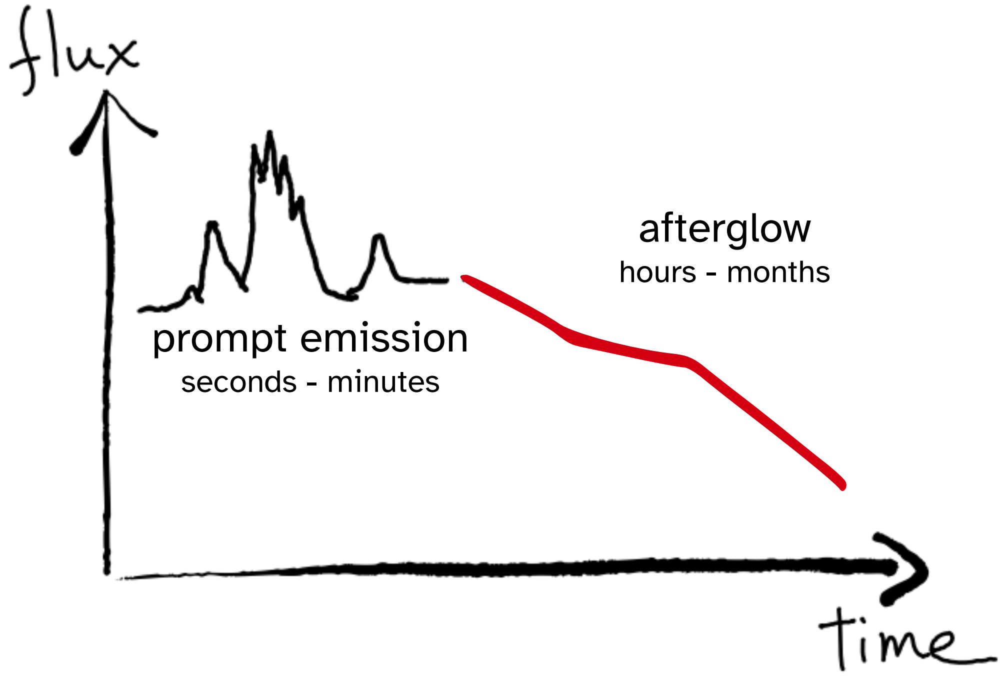
M. Ajello et al., ApJ 878 (2019)



P. Chandra & D. A. Frail, ApJ 746 (2012)

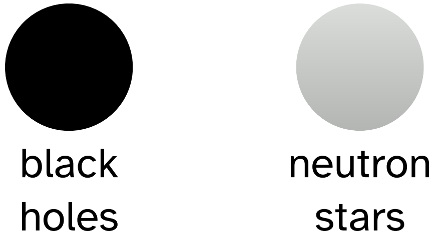
Gamma-ray bursts

What causes them, and how do we know?



Putting all the clues together:

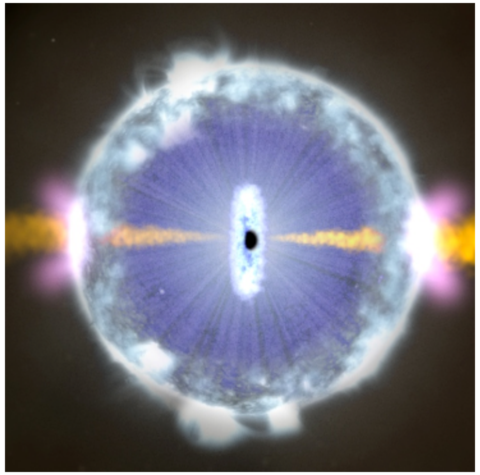
GRBs are stellar-sized phenomena (not, e.g., galaxy-sized)
release $M_{\odot}c^2$ within minutes
emission occurring in regions smaller than the Earth
emission starts out highly variable but then evolves slowly and fades
stellar-mass compact objects are involved



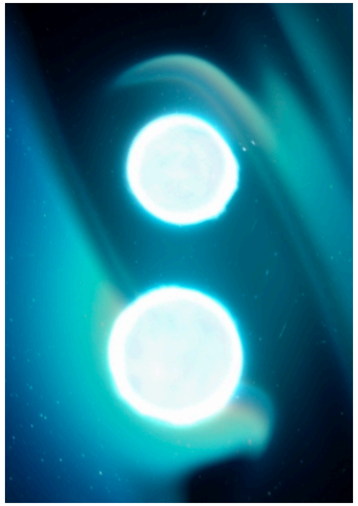
Gamma-ray bursts

What causes them, and how do we know?

[NASA's Goddard Space Flight Center]



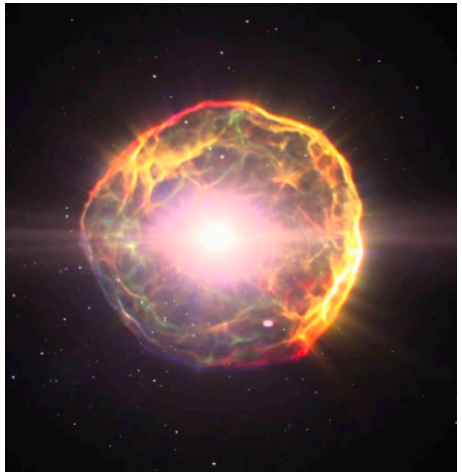
NASA's Goddard Space Flight Center/CI Lab



two neutron stars merge
(probably)

or

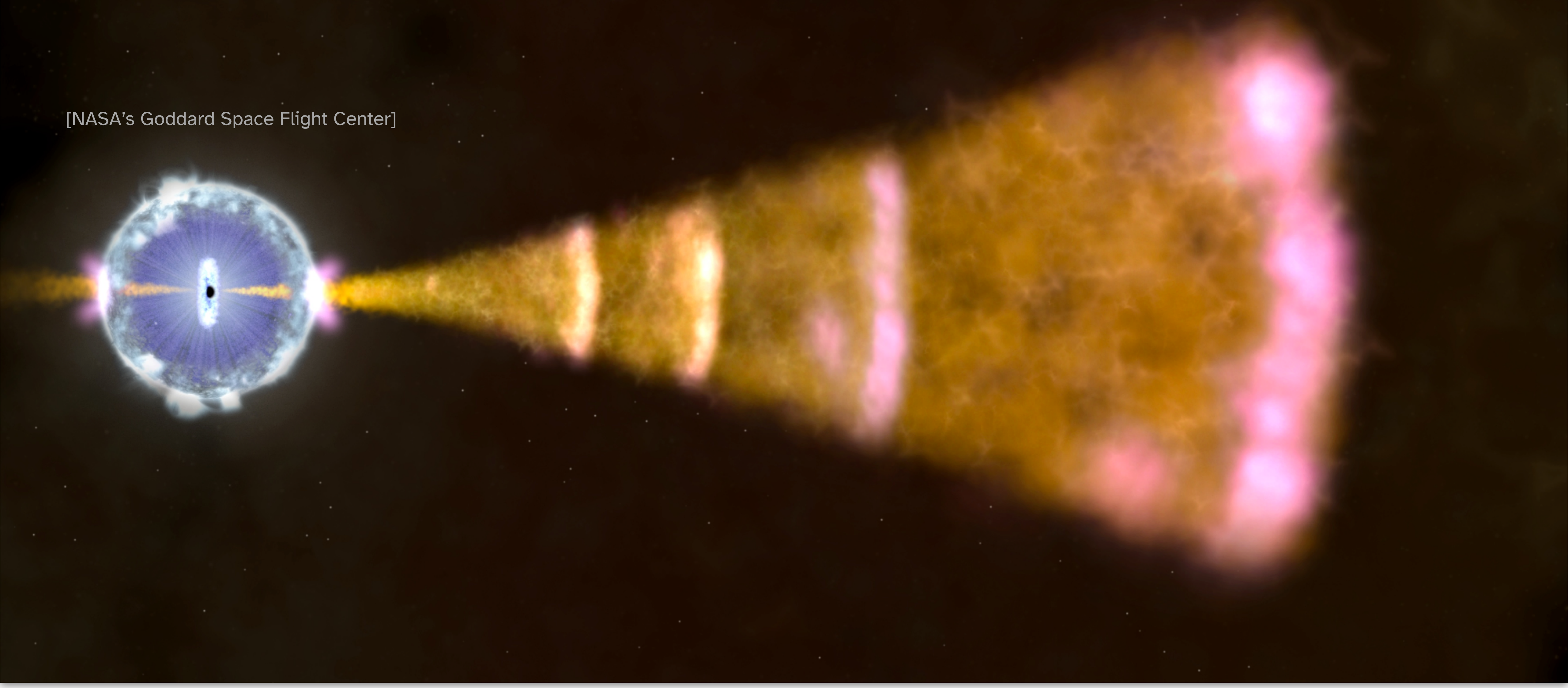
ESO/L Calçada



a massive star collapses

Gamma-ray bursts

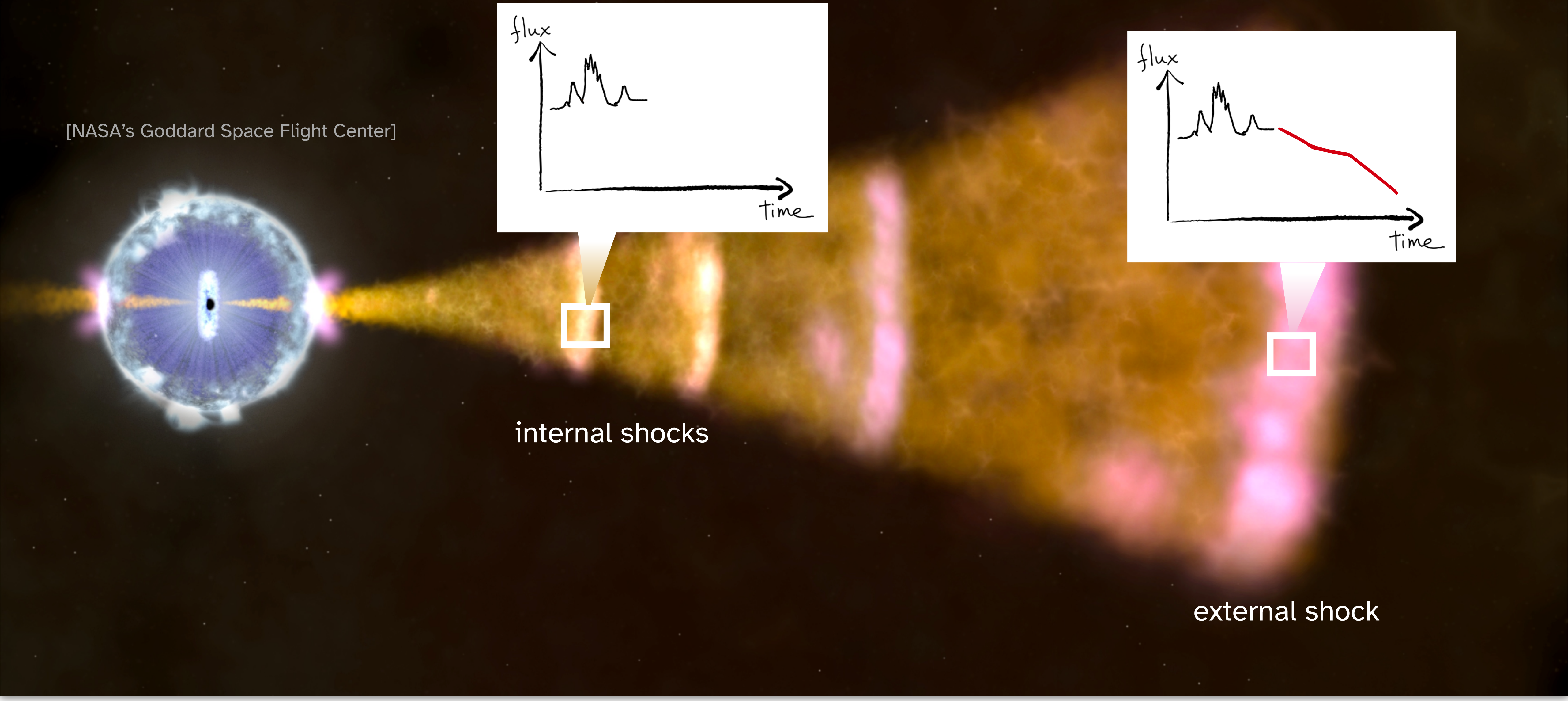
What causes them, and how do we know?



[NASA’s Goddard Space Flight Center]

Gamma-ray bursts

What causes them, and how do we know?



[NASA's Goddard Space Flight Center]

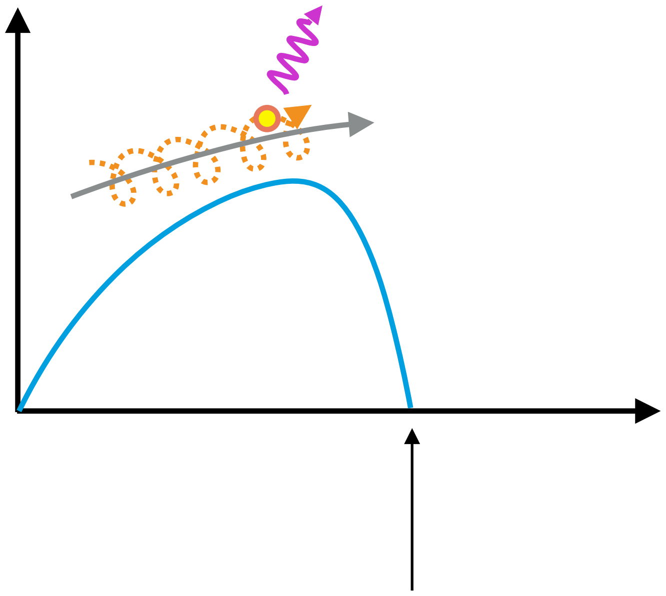
Gamma-ray bursts

How the photons are emitted

[DESY, Science Communication Lab]

Gamma-ray bursts

VHE gamma-ray observations



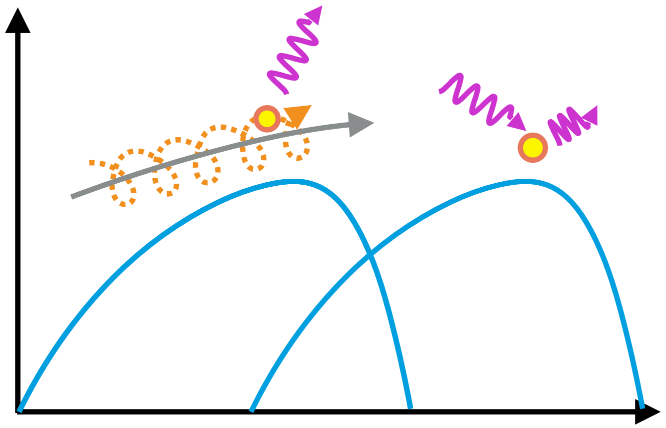
Multiwavelength observations have shown that the afterglow is well described by electron synchrotron

Assuming a **single magnetic field strength** well describes the region (“one-zone”), there is a theoretical maximum synchrotron photon energy, from balancing energy gains and losses

$E_{\max} \sim \mathcal{O}(100)\,\mathrm{MeV}$

Gamma-ray bursts

VHE gamma-ray observations

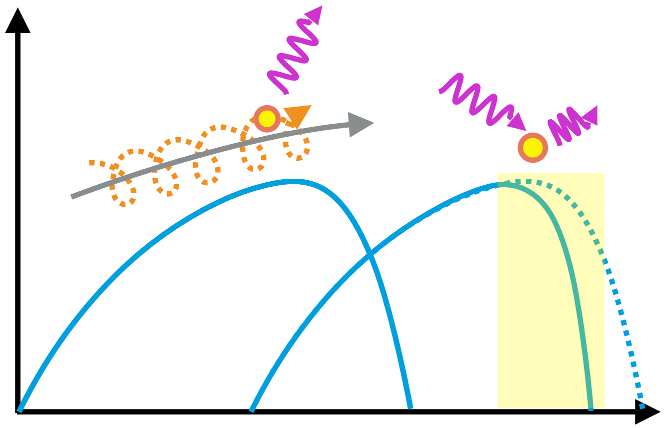


Multiwavelength observations have shown that the afterglow is well described by electron synchrotron

A synchrotron self-Compton component is also expected to exist, would be at >GeV energies

Gamma-ray bursts

VHE gamma-ray observations



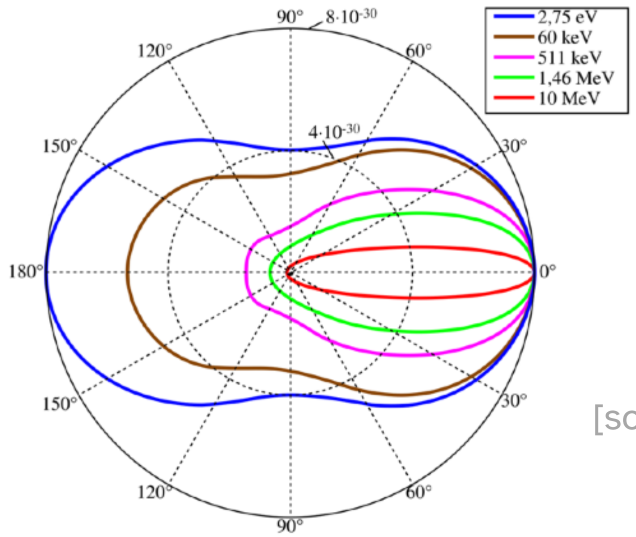
“Klein-Nishina regime”

Multiwavelength observations have shown that the afterglow is well described by electron synchrotron

A synchrotron self-Compton component is also expected to exist, would be at >GeV energies

At TeV energies, we expect a very **steep** spectrum as the interaction cross section greatly decreases

interaction cross section for (inverse) Compton scattering:

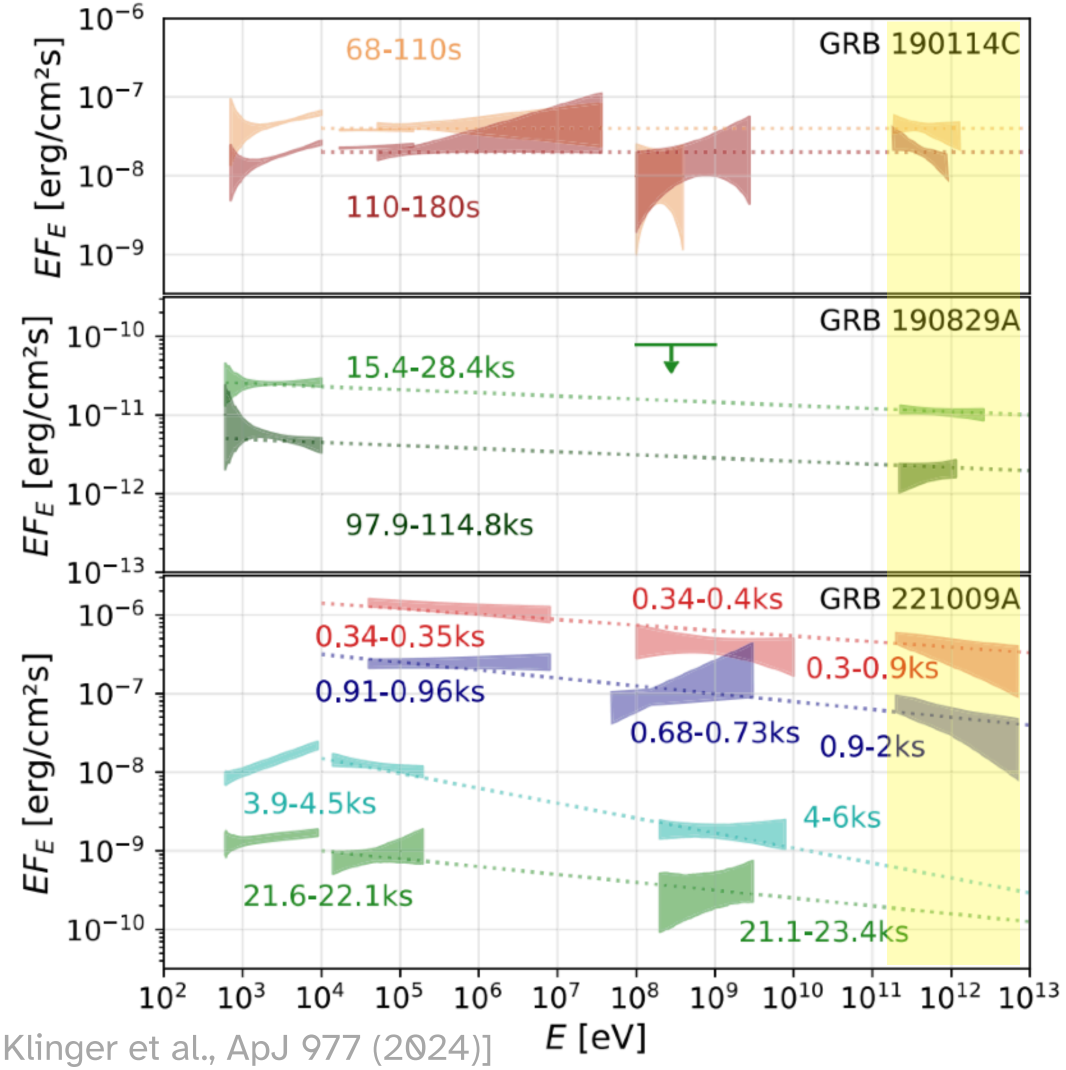


photon energy

[source]

Gamma-ray bursts

Do we see the inverse Compton component?

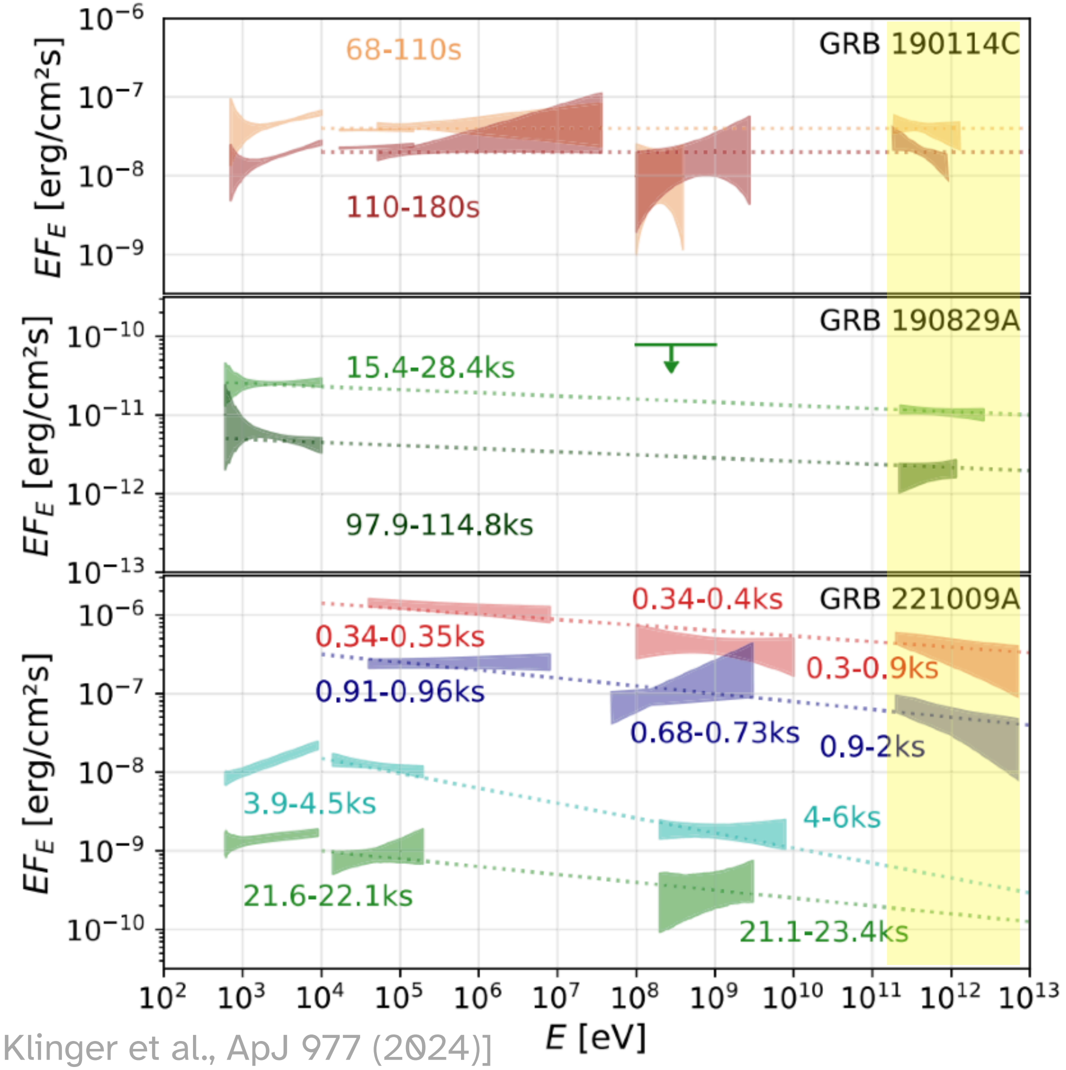


[M. Klinger et al., ApJ 977 (2024)]

no smoking gun so far

Gamma-ray bursts

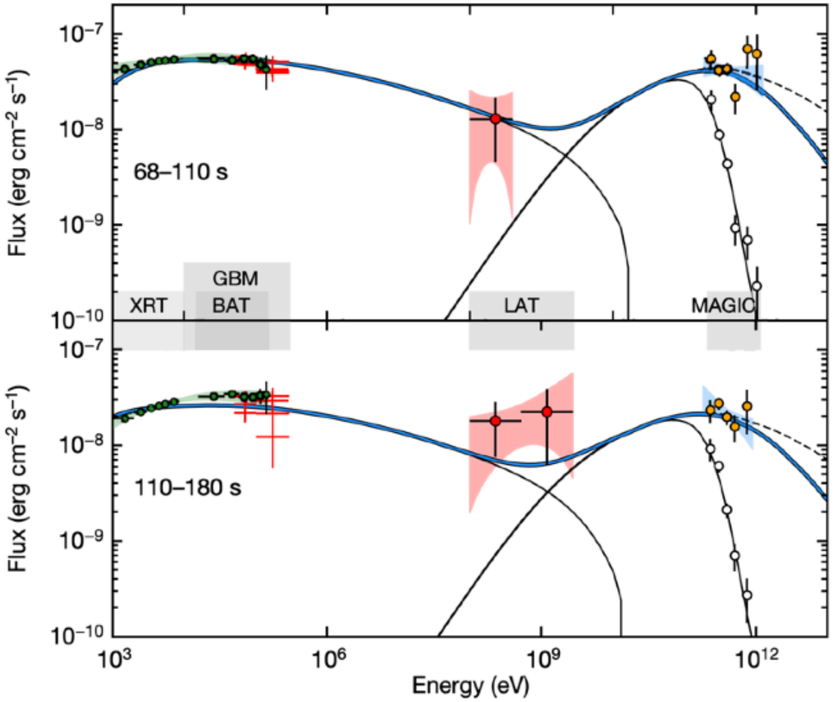
Do we see the inverse Compton component?



[M. Klinger et al., ApJ 977 (2024)]

no smoking gun so far

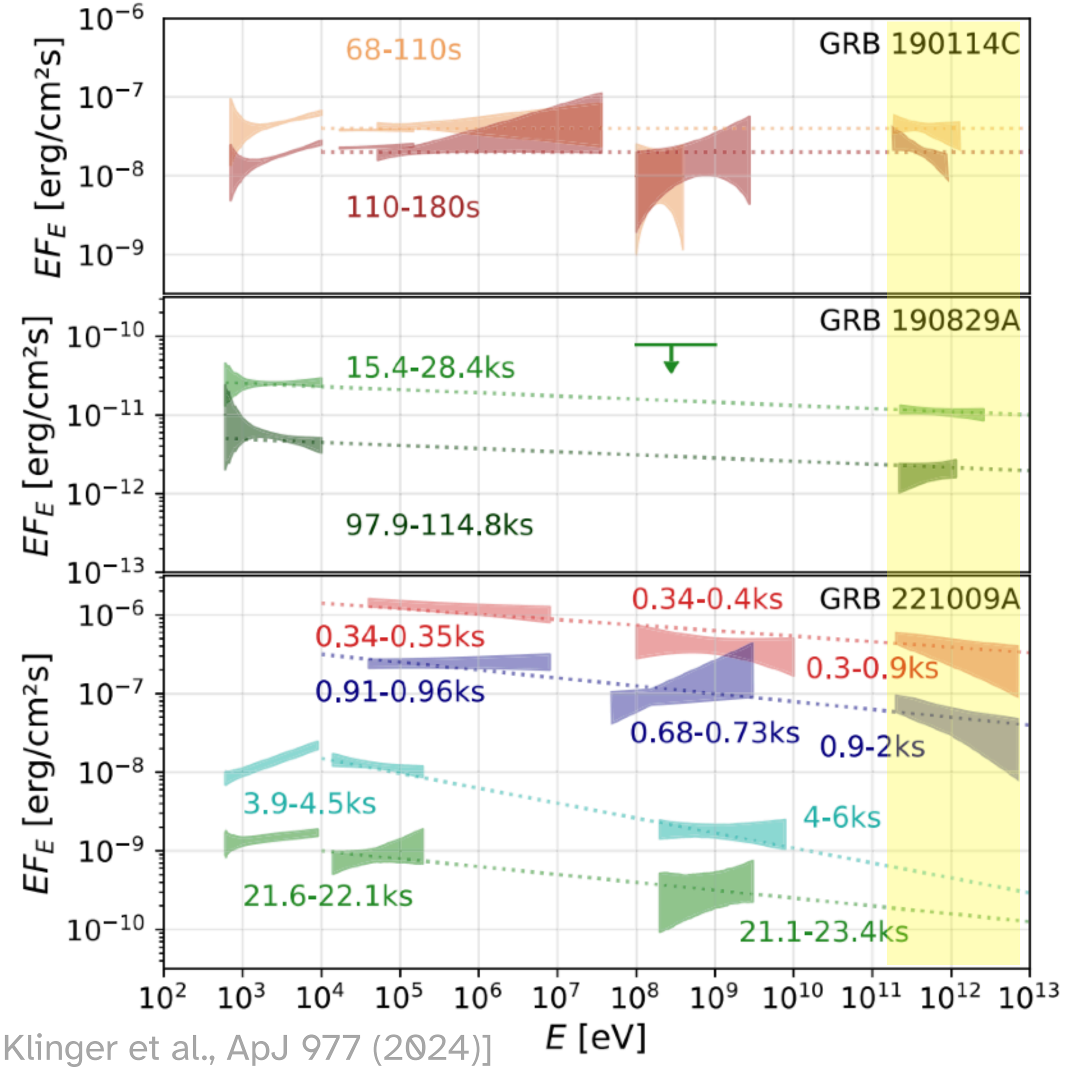
(although there is disagreement)



[MAGIC, Nature 575 (2019)]

Gamma-ray bursts

Do we see the inverse Compton component?

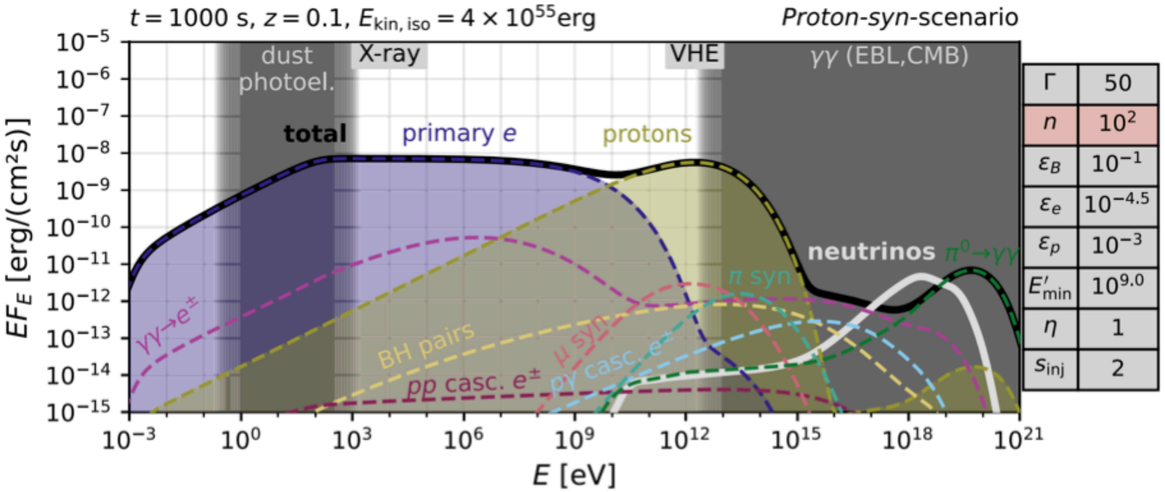


[M. Klinger et al., ApJ 977 (2024)]

How do we get flat spectra across such a wide energy range?

Possibilities:

- structure in the magnetic field (multi-zone)
- exploring more complex single-zone scenarios



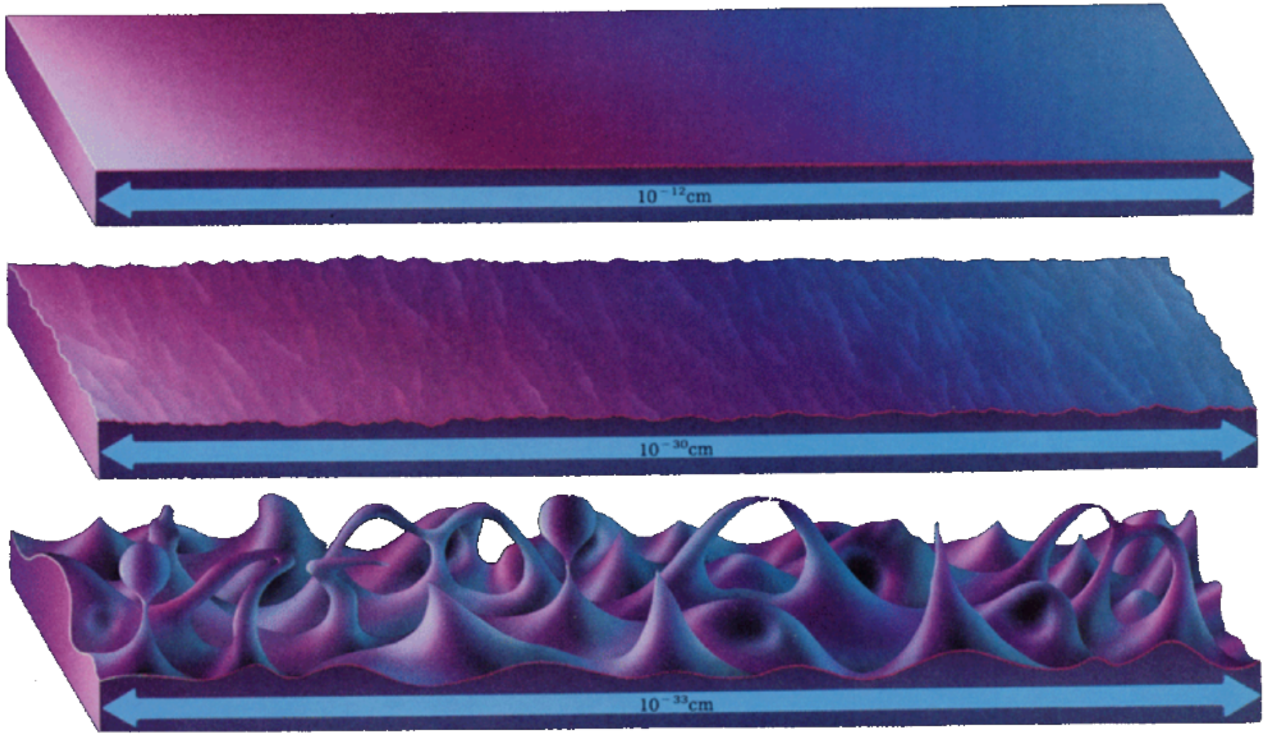
Physics with gamma-ray bursts

Testing Lorentz invariance

Lorentz invariance (special relativity):

The laws of physics are the same for all observers in inertial reference frames

One test is whether the speed of light is the same for photons of different energies



at the Planck scale ($E > 10^{19}$ GeV), quantum gravity effects could make spacetime “foamy”

-> photons at different energies could be affected differently

Physics with gamma-ray bursts

Testing Lorentz invariance

Lorentz invariance (special relativity):

The laws of physics are the same for all observers in inertial reference frames

One test is whether the speed of light is the same for photons of different energies

e.g.:

$$v \simeq c$$

e.g., [H. Song & B.-Q. Ma, ApJ 983 (2025)]

Physics with gamma-ray bursts

Testing Lorentz invariance

Lorentz invariance (special relativity):

The laws of physics are the same for all observers in inertial reference frames

One test is whether the speed of light is the same for photons of different energies

e.g.:

photon momentum

$$v \simeq c \left[1 - s_n \frac{n+1}{2} \left(\frac{pc}{E_{\mathrm{LV},n}} \right)^n \right]$$

±1

Lorentz invariance violation energy scale

σ = -1: higher-energy photons are faster than c

σ = +1: higher-energy photons are slower than c

e.g., [H. Song & B.-Q. Ma, ApJ 983 (2025)]

Physics with gamma-ray bursts

Testing Lorentz invariance

Lorentz invariance (special relativity):

The laws of physics are the same for all observers in inertial reference frames

One test is whether the speed of light is the same for photons of different energies

e.g.:

photon momentum

$$v \simeq c\left[1 - s_n \frac{n+1}{2}\left(\frac{pc}{E_{\mathrm{LV},n}}\right)^n\right]$$

±1

Lorentz invariance violation energy scale

σ = -1: higher-energy photons are faster than c

σ = +1: higher-energy photons are slower than c

> energy photons are emitted earlier than low-energy photons at the source. By evaluating 17 high-energy photons from 10 GRBs observed by FGST, MAGIC, and LHAASO, we estimate the LV energy scale to be $E_{LV} \simeq 3.00 \times 10^{17}$ GeV. The null hypothesis of dispersion-free vacuum $E = pc$ (or, equivalently, the constant light speed $v_\gamma = c$) is rejected at a significance level of 3.1σ or higher.

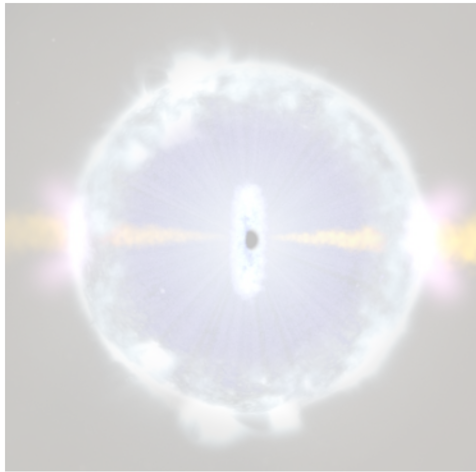
although this is just one study, and there seems to be a wide range in conclusions among studies in the field ¯_(ツ)_/¯

e.g., [H. Song & B.-Q. Ma, ApJ 983 (2025)]

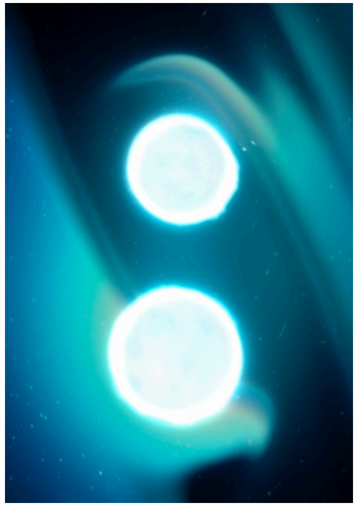
Gamma-ray bursts

What causes them, and how do we know?

[NASA's Goddard Space Flight Center]



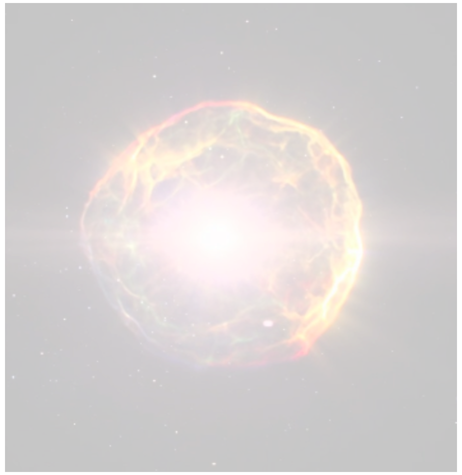
NASA's Goddard Space Flight Center/CI Lab



two neutron stars merge
(probably)

or

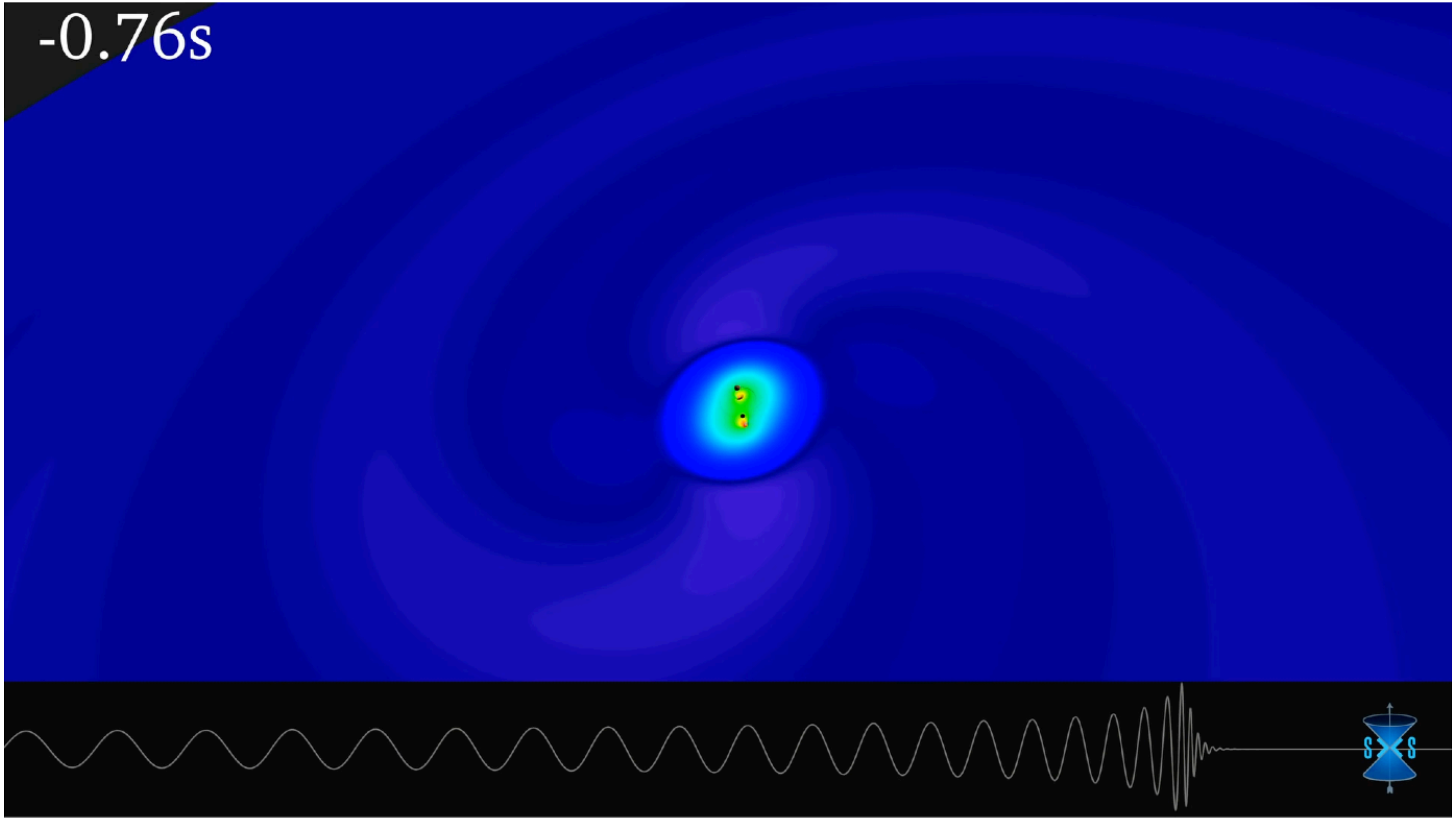
ESO/L. Calçada



a massive star collapses

Neutron star mergers

What do the signals look like?

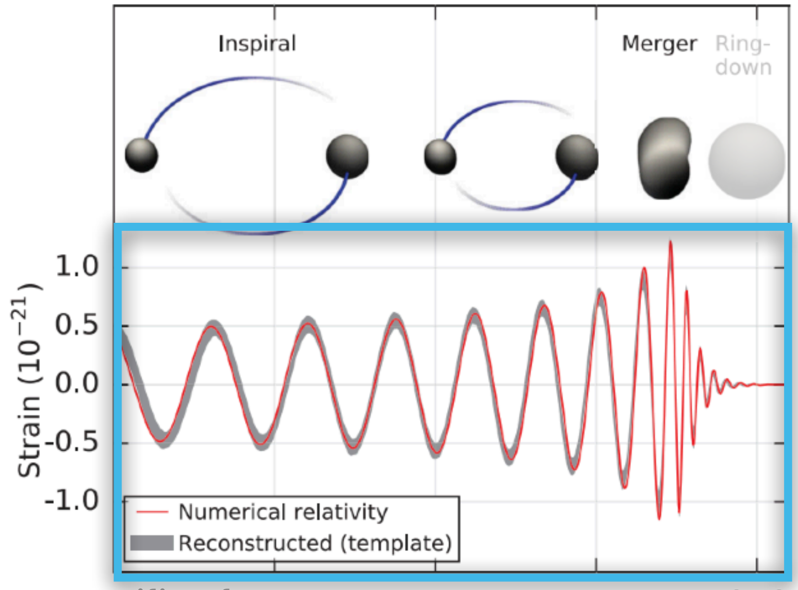


Animation created by SXS, the Simulating eXtreme Spacetimes (SXS) project (http://www.black-holes.org)
Video and explanation: https://www.ligo.caltech.edu/video/ligo20160211v10

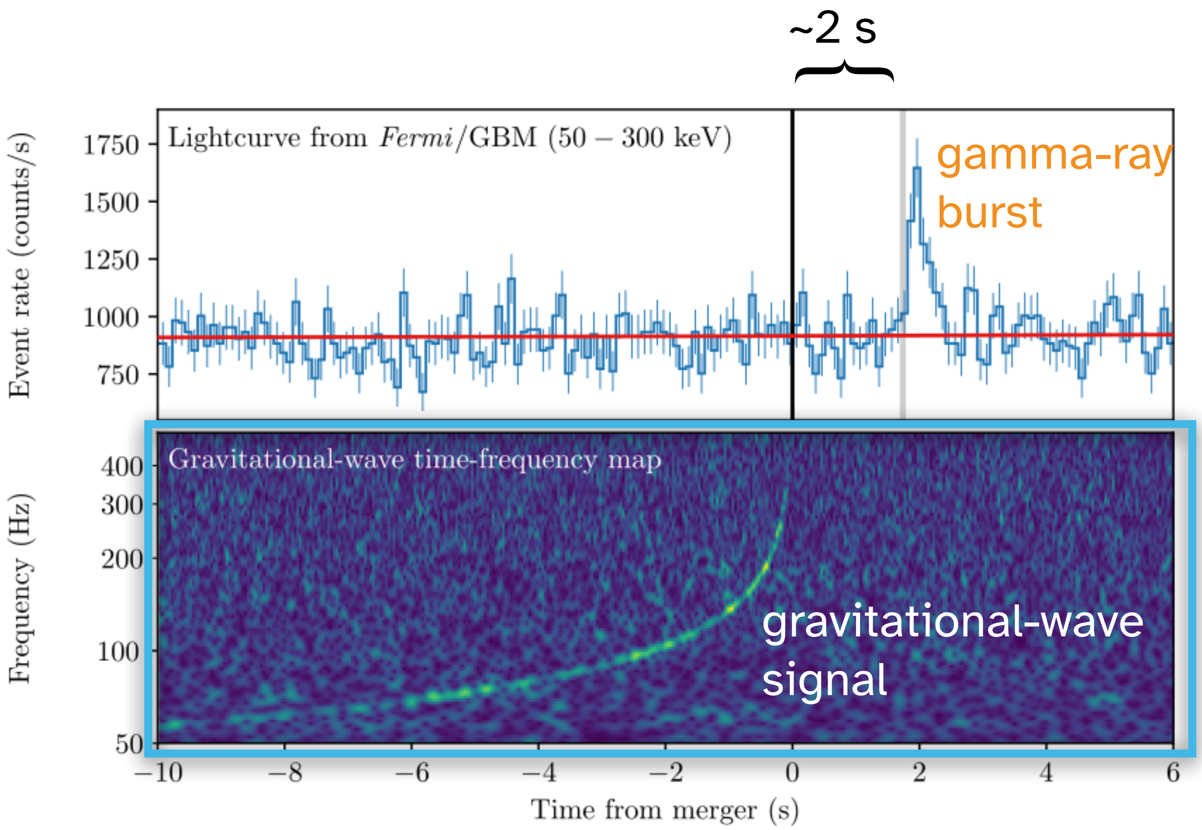
Neutron star mergers

What do the signals look like?

gravitational-wave signal



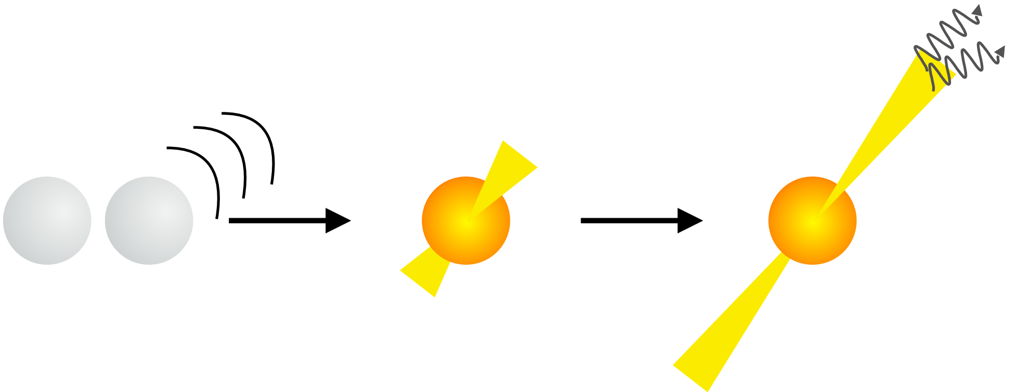
modified from [B. P. Abbott et al., PRL 116 (2016)]

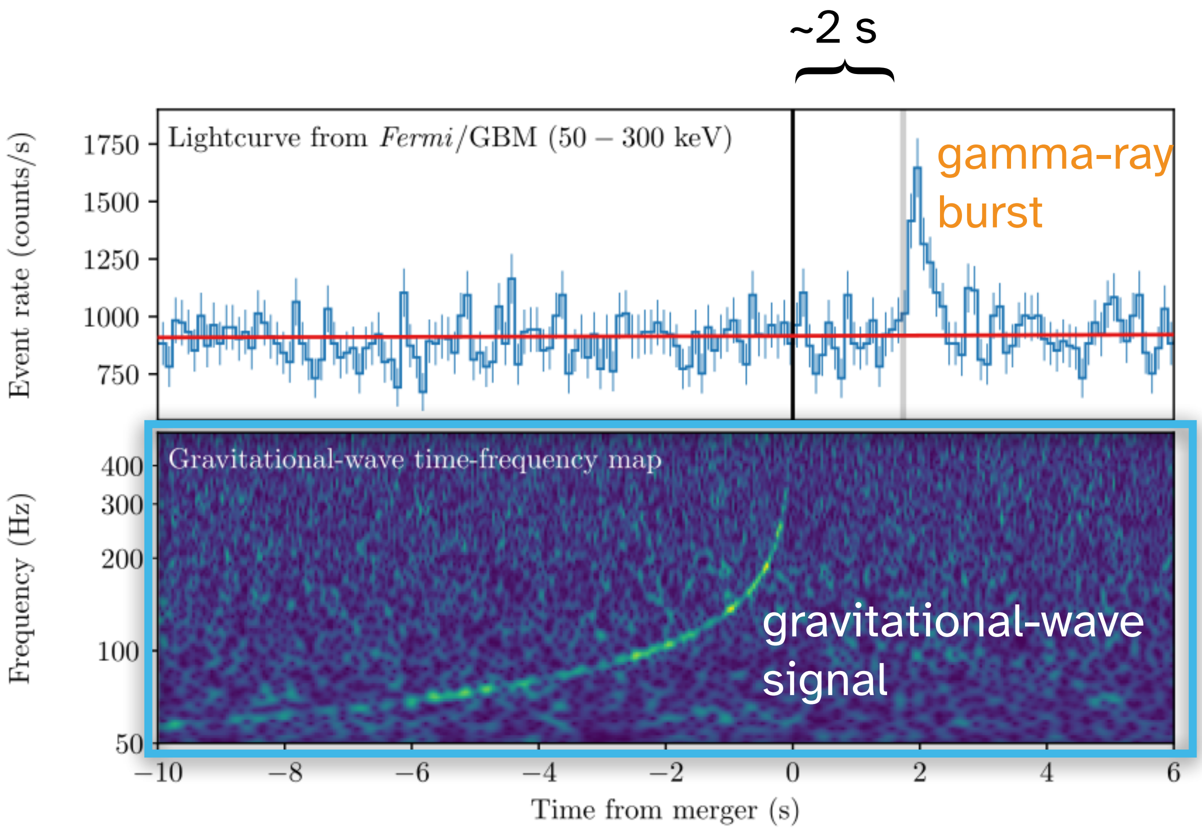


modified from [B. P. Abbott et al., ApJL 848 (2017)]

Neutron star mergers

What do the signals look like?





2-second delay is probably all due to the time necessary to merge -> launch jet -> produce photons … but what if it's not?

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

Physics with neutron star mergers

Speed of light vs speed of gravity

gamma-ray signal came 1.75 seconds after gravitational-wave signal

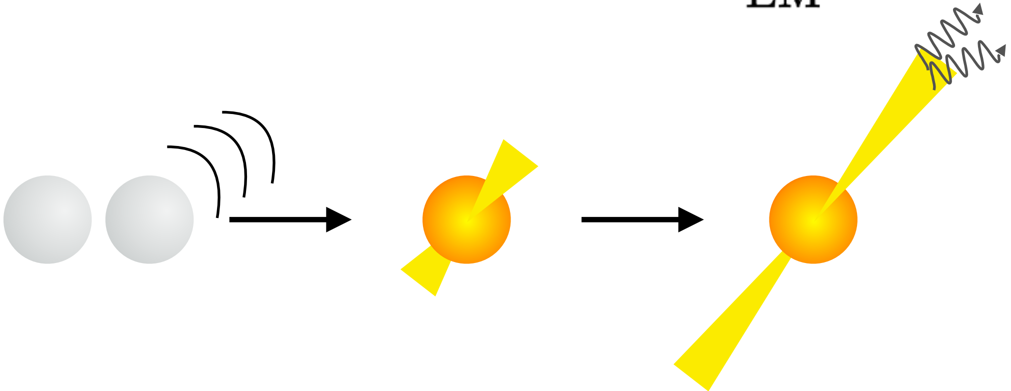
take the distance to source to be 26 Mpc (conservative estimate) = 8e23 m

If the photons and gravitational waves were released at the same time, then gravity travels faster than light

$$\frac{v_{\mathrm{GW}} - v_{\mathrm{EM}}}{v_{\mathrm{EM}}} \leq +7 \times 10^{-16}$$

If it actually took *longer* than 2 seconds for the source to produce the photons (e.g., 10 seconds), then gravity travels slower than light

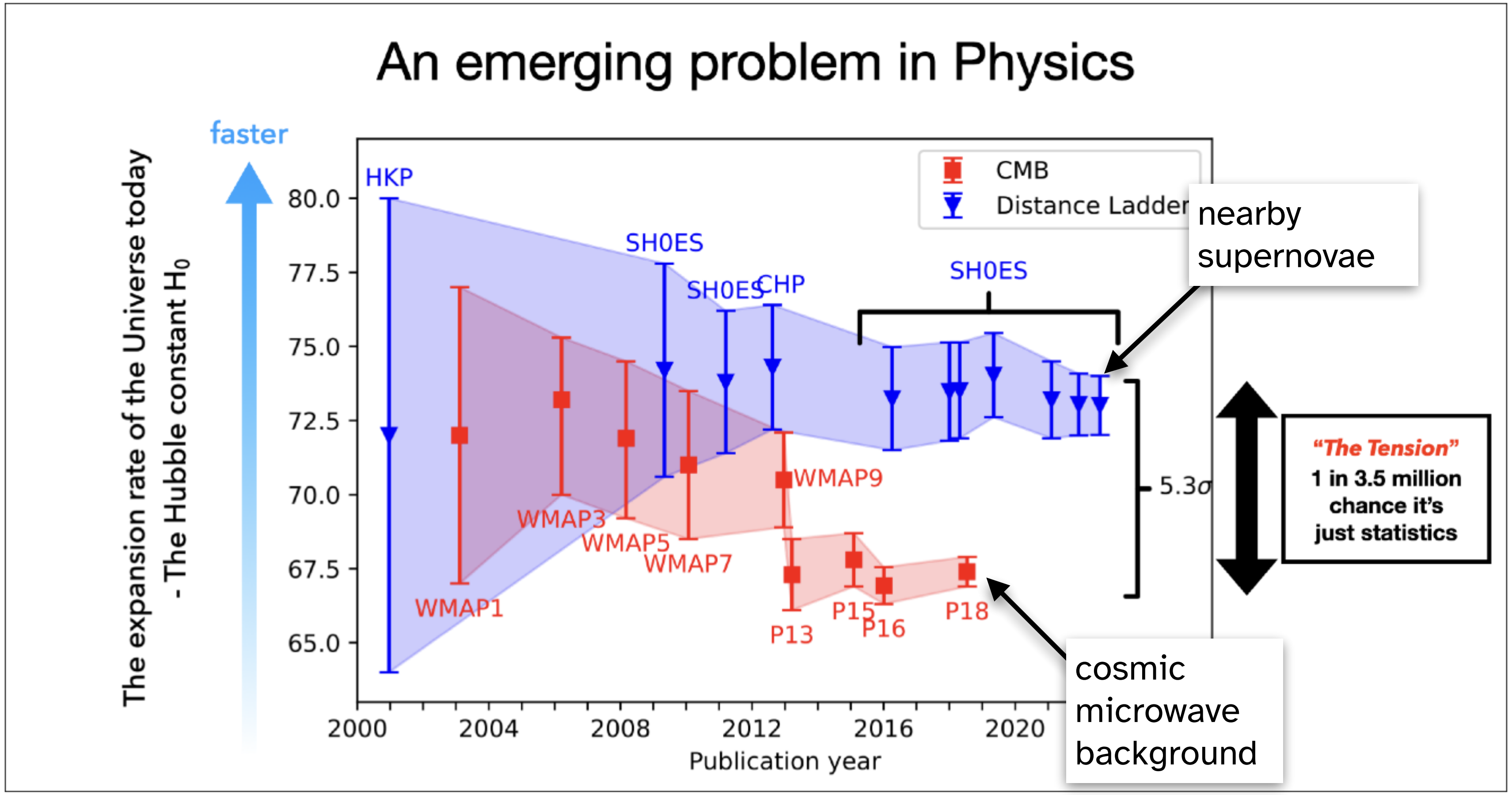
$$\frac{v_{\mathrm{GW}} - v_{\mathrm{EM}}}{v_{\mathrm{EM}}} \geq -3 \times 10^{-15}$$



Cosmology with neutron star mergers

Resolving the Hubble tension?

Hubble constant H_0 describes how fast the Universe is currently expanding -> there is a *Hubble tension*

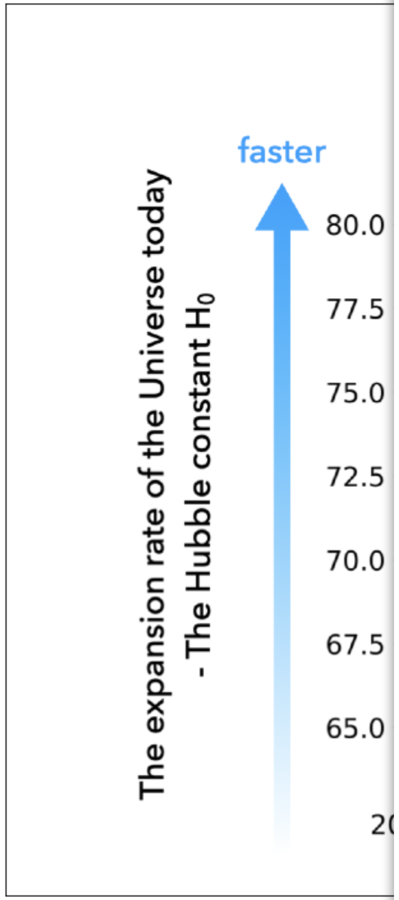


[D. Kenworthy]

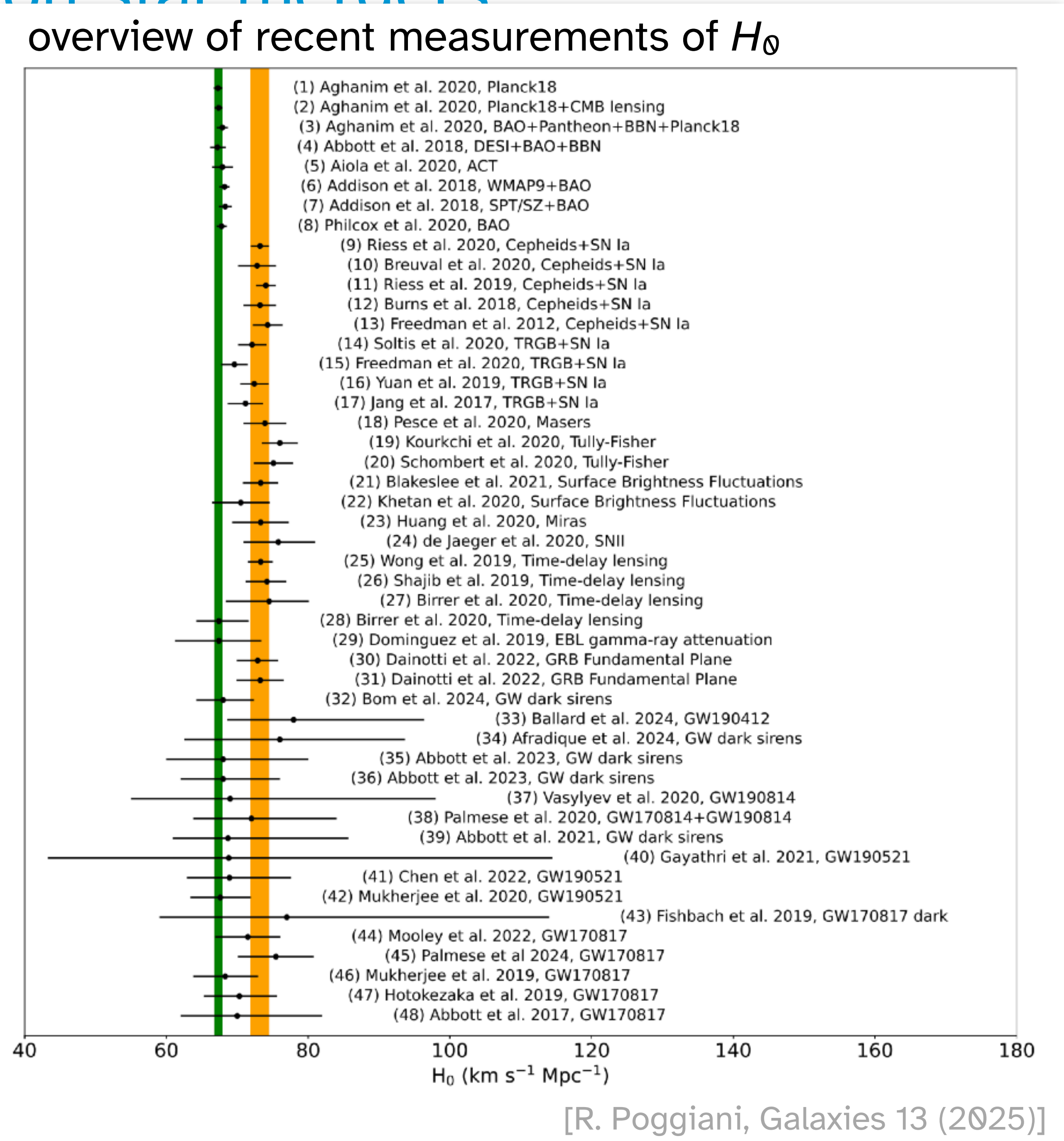
Cosmology with neutron star mergers

Resolving the Hubble tension?

Hubble constant H_0 describes how … *ubble tension*



[D. Kenworthy]



[R. Poggiani, Galaxies 13 (2025)]

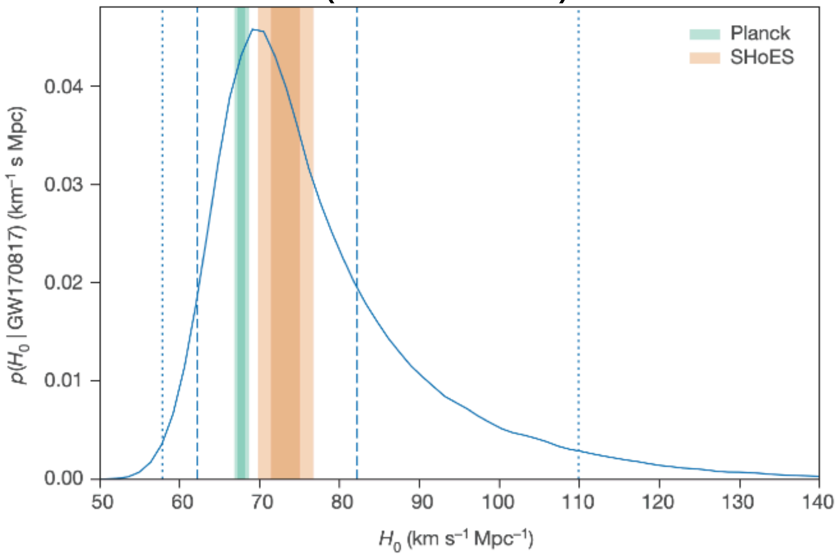
Cosmology with neutron star mergers

Resolving the Hubble tension?

Hubble constant H_0 describes how fast the Universe is currently expanding -> there is a *Hubble tension*
Multimessenger observations of neutron star mergers can give an independent measure of H_0
GW-only measurements can also be used by including host galaxies in a probabilistic way

for nearby objects: $\mathrm{v} = \mathrm{H_0 d}$ d from GW observation, v from electromagnetic

one event (GW170817)



[B. P. Abbott et al., Nature 551 (2017)]

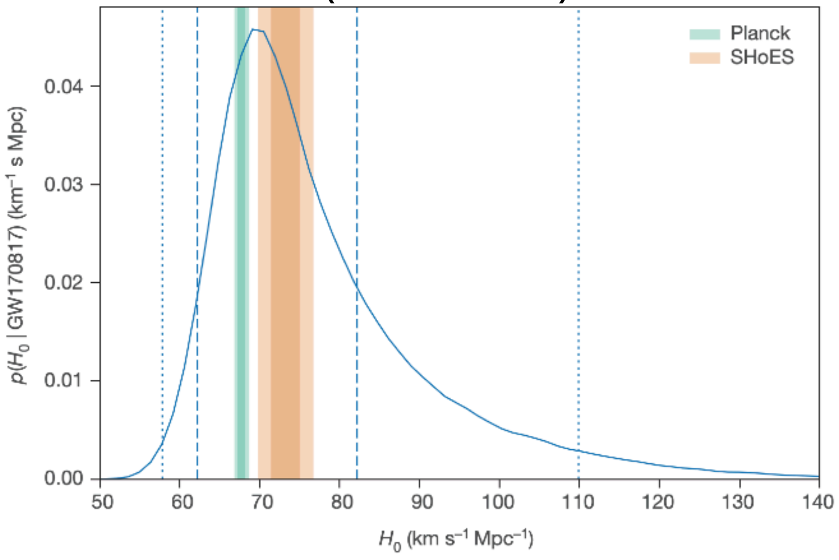
Cosmology with neutron star mergers

Resolving the Hubble tension?

Hubble constant H_0 describes how fast the Universe is currently expanding -> there is a *Hubble tension*
Multimessenger observations of neutron star mergers can give an independent measure of H_0
GW-only measurements can also be used by including host galaxies in a probabilistic way

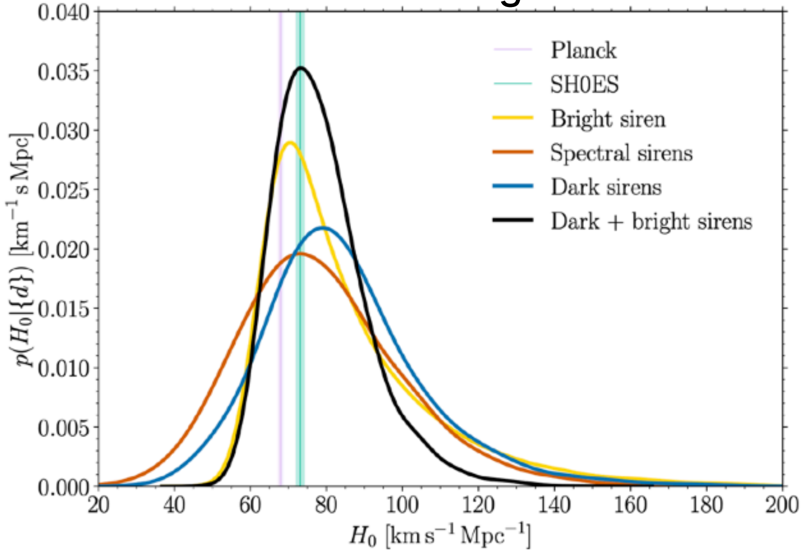
for nearby objects: $\mathrm{v} = \mathrm{H_0 d}$ d from GW observation, v from electromagnetic

one event (GW170817)



[B. P. Abbott et al., Nature 551 (2017)]

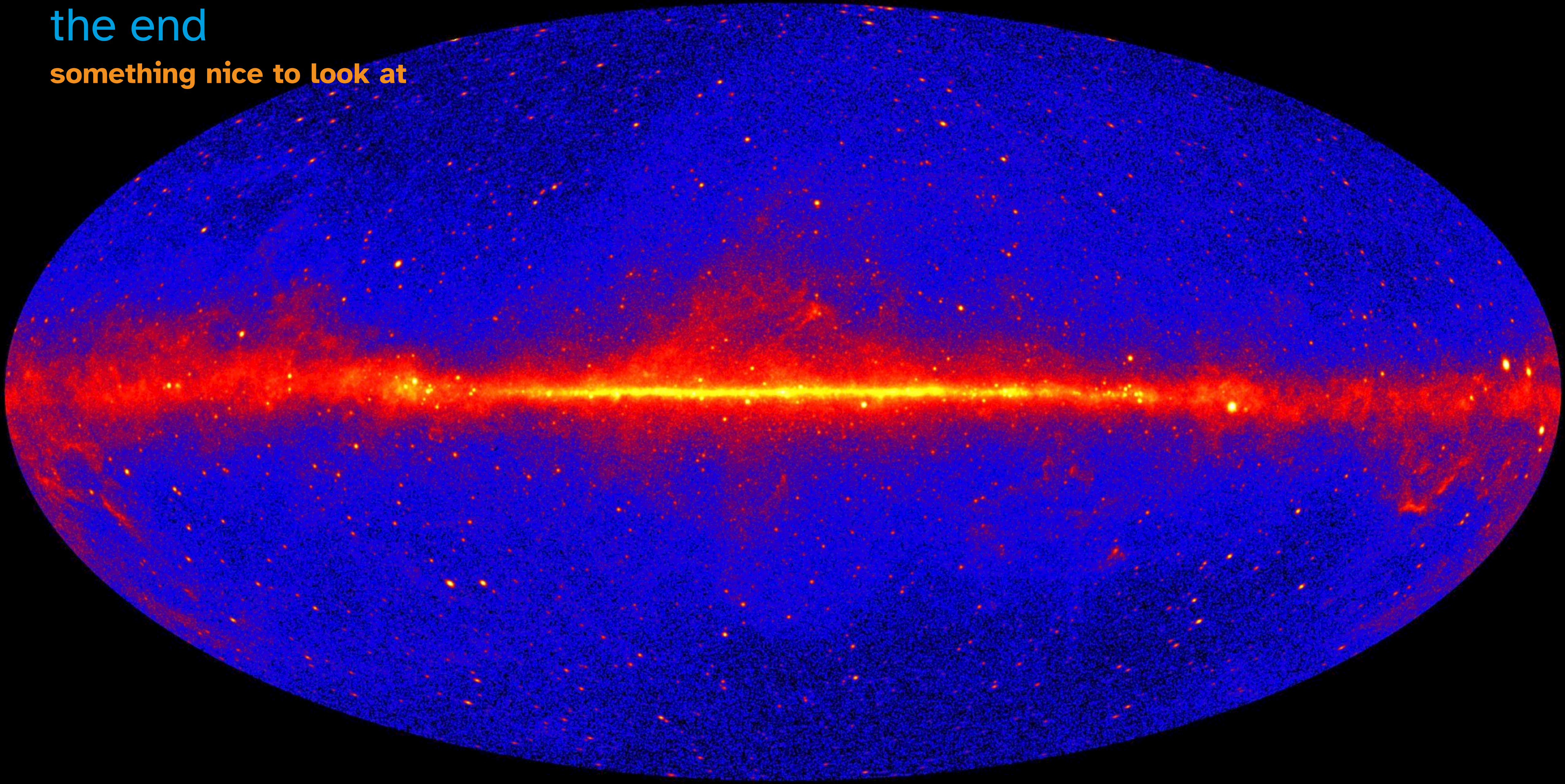
most recent catalog



[LVK, arXiv:2509.04348]

the end

something nice to look at



[NASA/DOE/Fermi-LAT Collaboration]