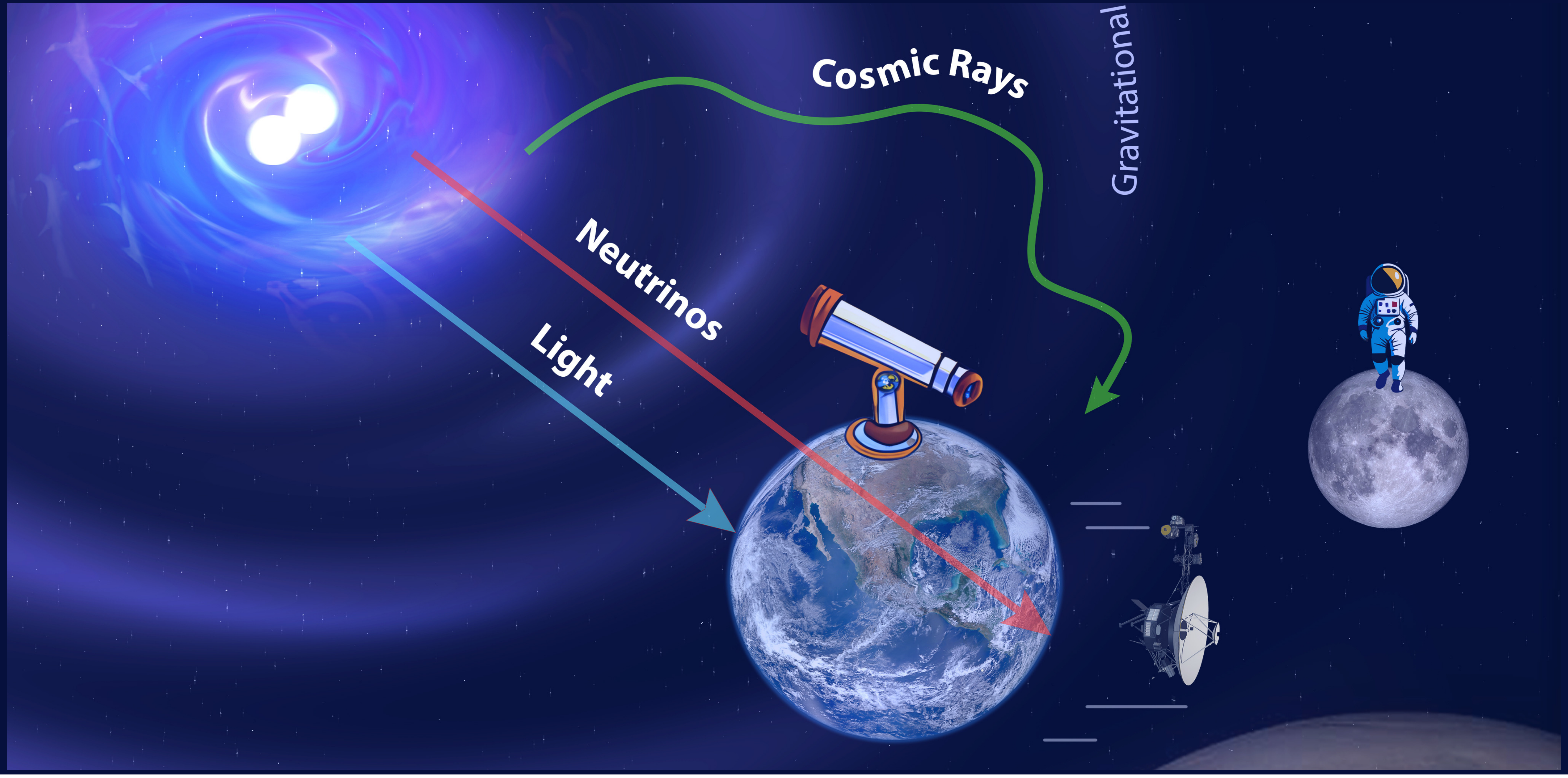
IDPASC

IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

cnrs université PARIS-SACLAY Université Paris Cité

15-25 July 2025

Salle des conseils
Bâtiment 100



Multi-Messenger Astrophysics in the high energy domain: gamma rays and gravitational waves

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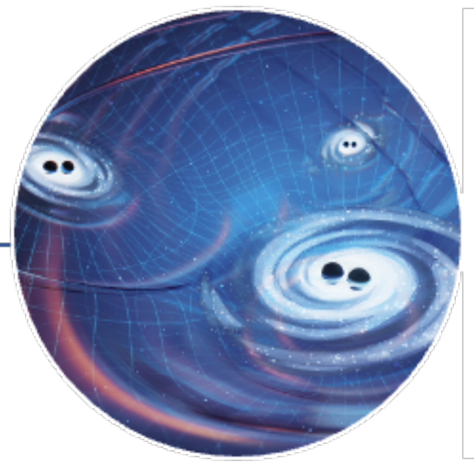


Multimessenger Astrophysics

Instrumentation for Gamma-ray Astrophysics

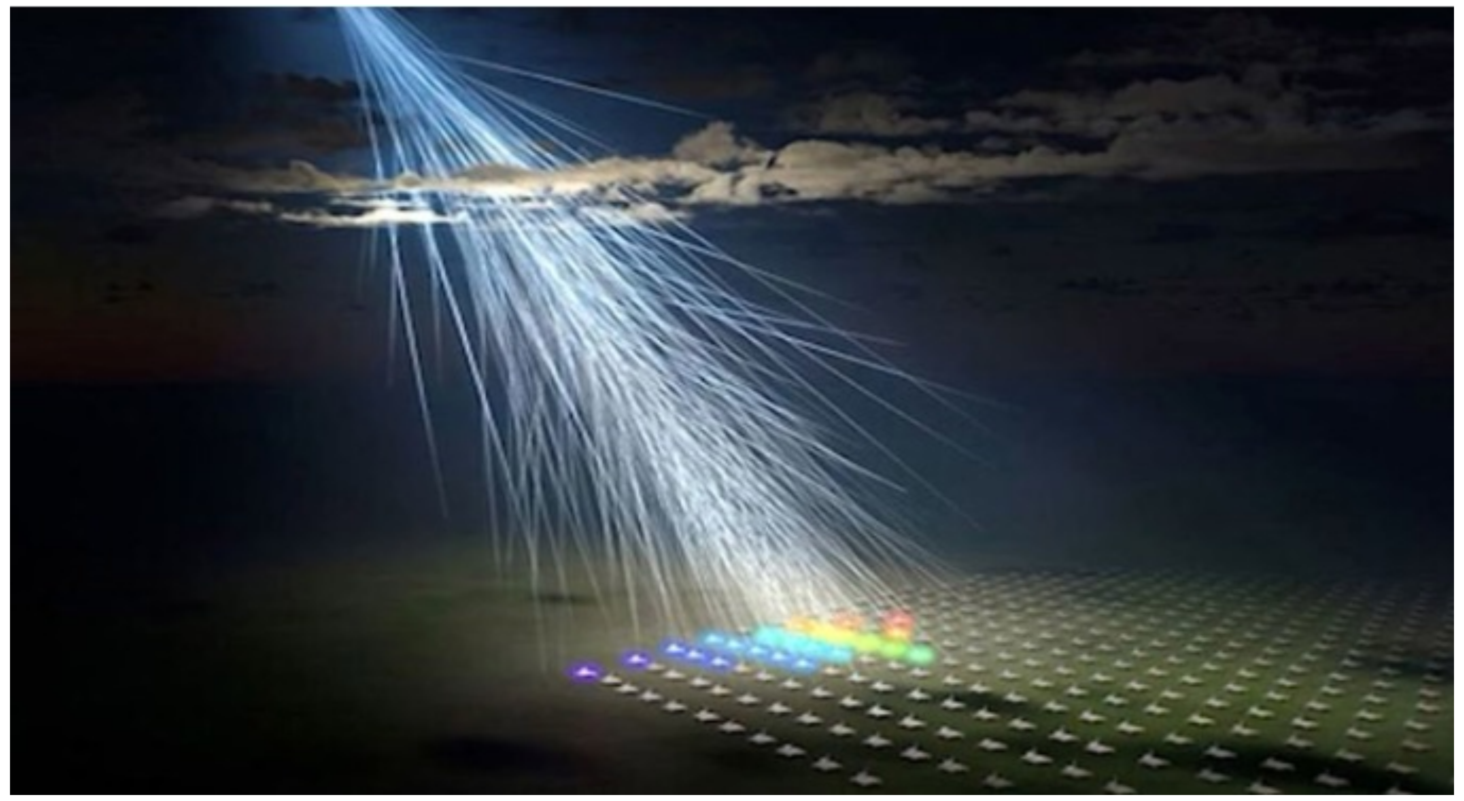
High-energy Astrophysics

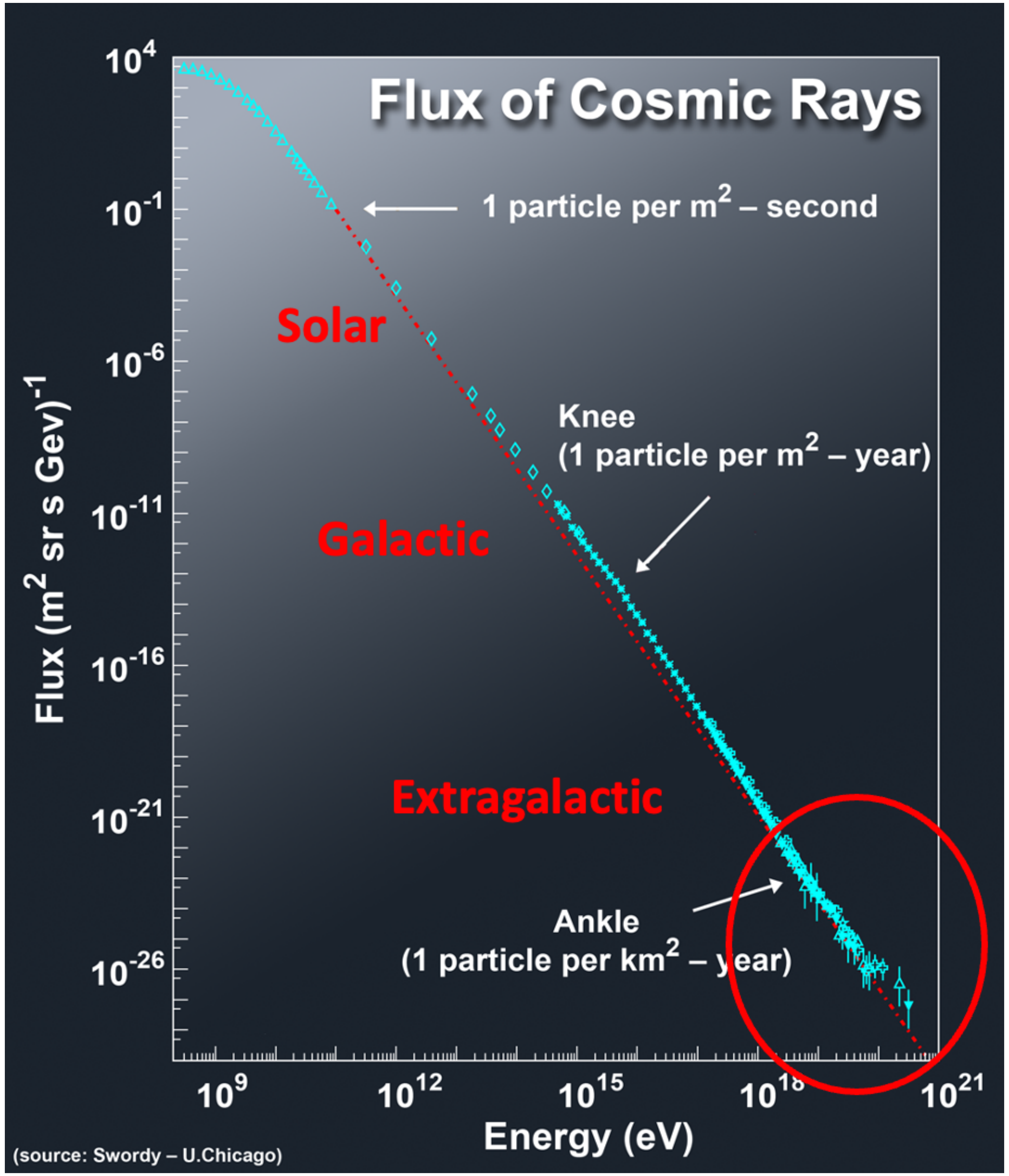
tilepy

CTAO

H.E.S.S.

The biggest question in Astroparticle Physics: The origin of Cosmic Rays





What are the sources of CRs?

Most energetic and violent events can produce high energy CRs

- Necessary condition for a source to accelerate cosmic rays
- Particle must stay confined:

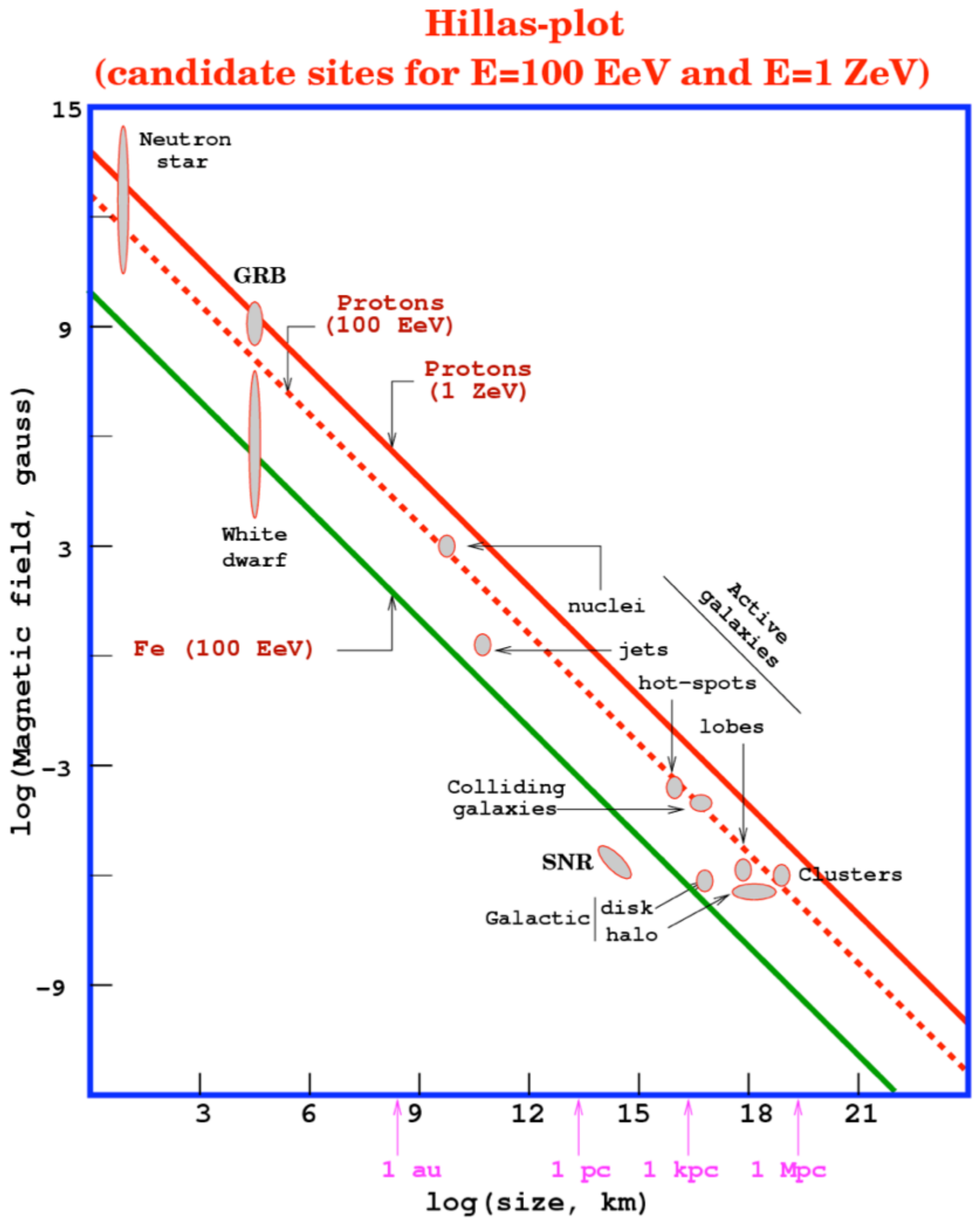
$$R_{\mathrm{Larmor}} = \frac{E}{ZeB} < R_{\mathrm{source}}$$

- Maximum energy:

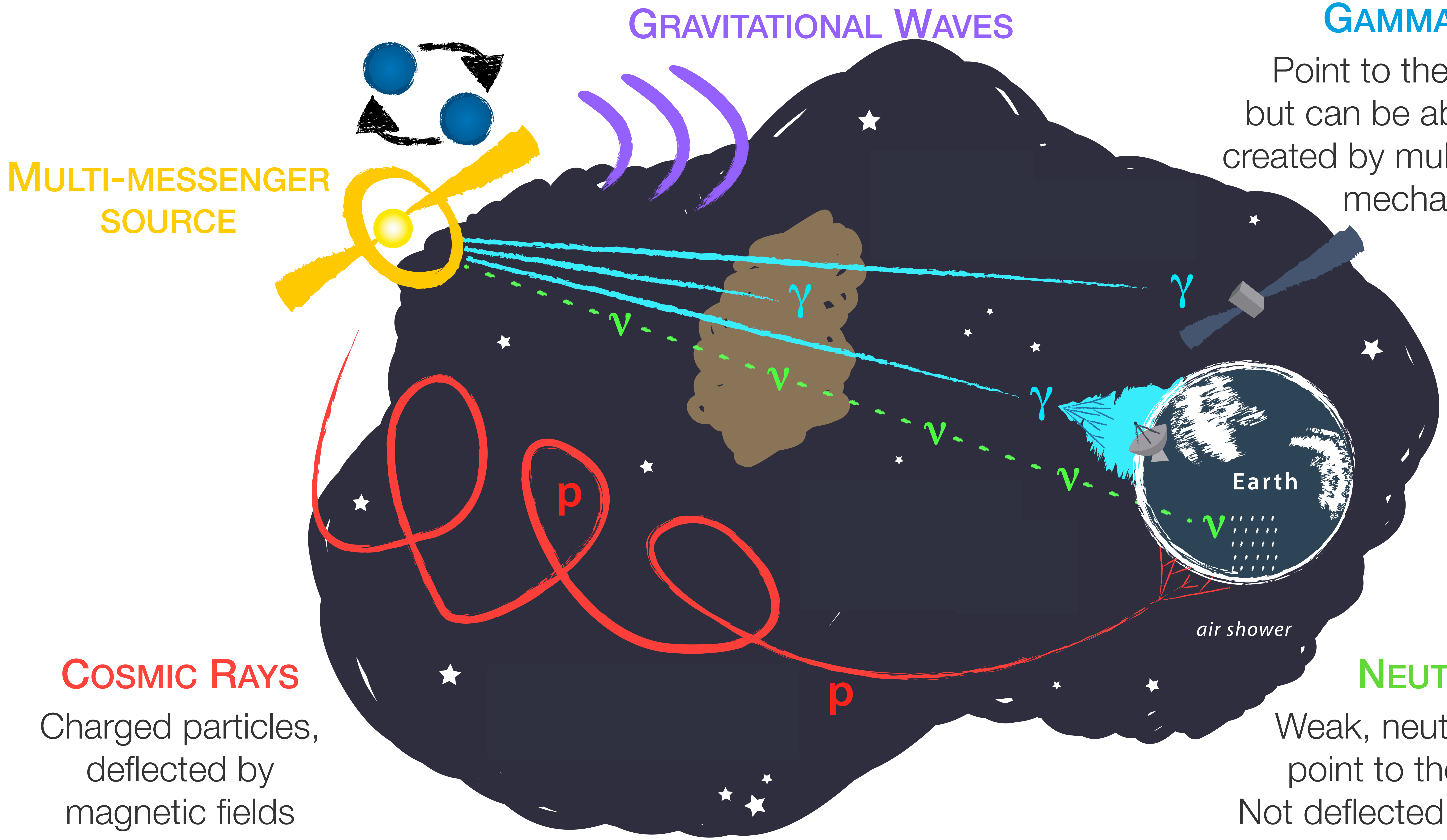
$$E_{\mathrm{max}} = \beta_{\mathrm{sh}} Z \left(\frac{B}{\mu\mathrm{G}}\right)\left(\frac{R}{\mathrm{kpc}}\right) \mathrm{EeV}$$

Velocity of the shock front (β_{sh})

Charge number of CR particle (Z)



Multi-Messenger Astrophysics



GAMMA RAYS

Point to their sources, but can be absorbed and created by multiple emission mechanisms

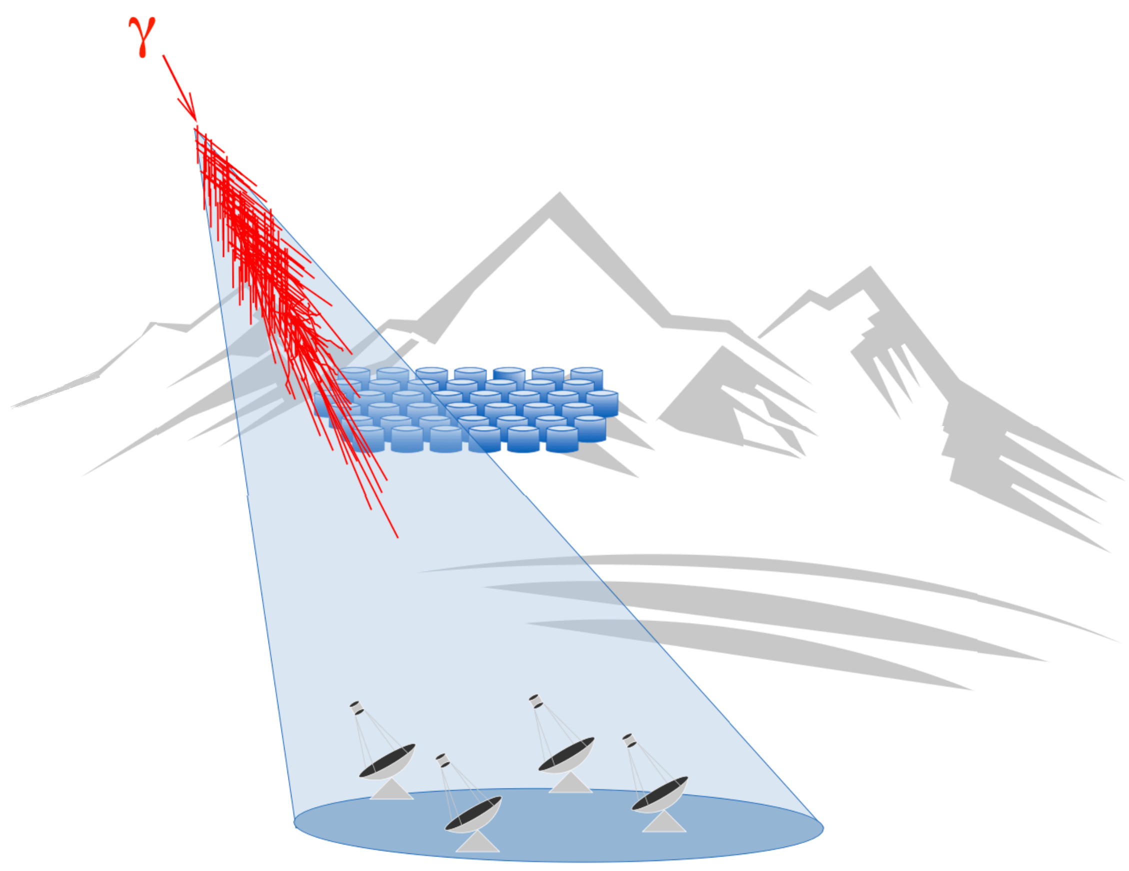
COSMIC RAYS

Charged particles, deflected by magnetic fields

NEUTRINOS

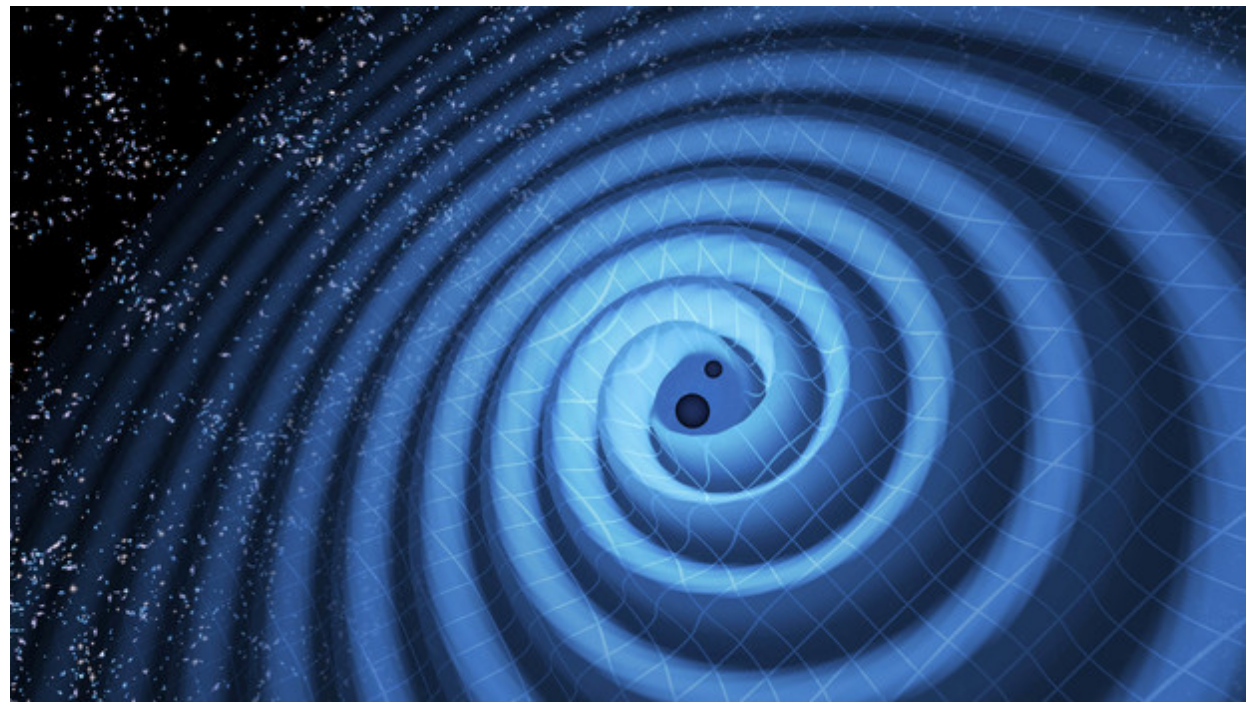
Weak, neutral particles, point to their sources, Not deflected, not absorbed

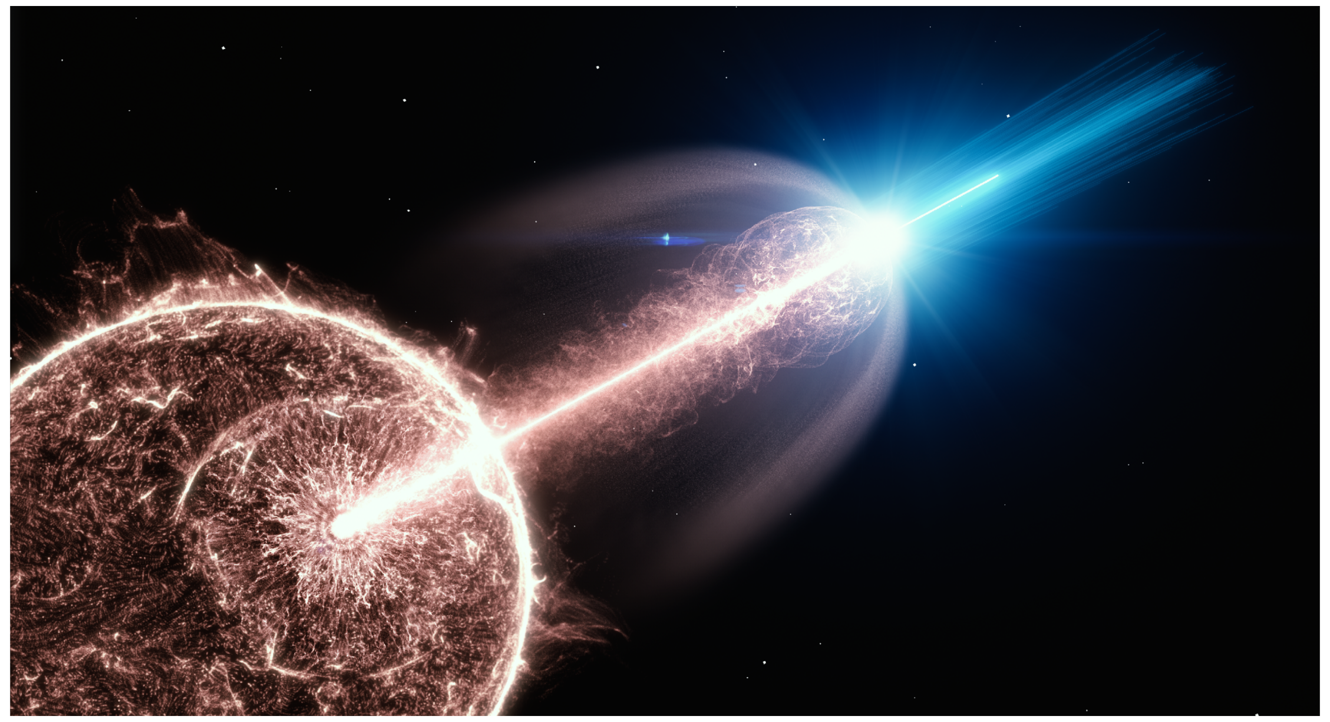
Outline



1. Very-High-Energy Gamma-ray Astrophysics

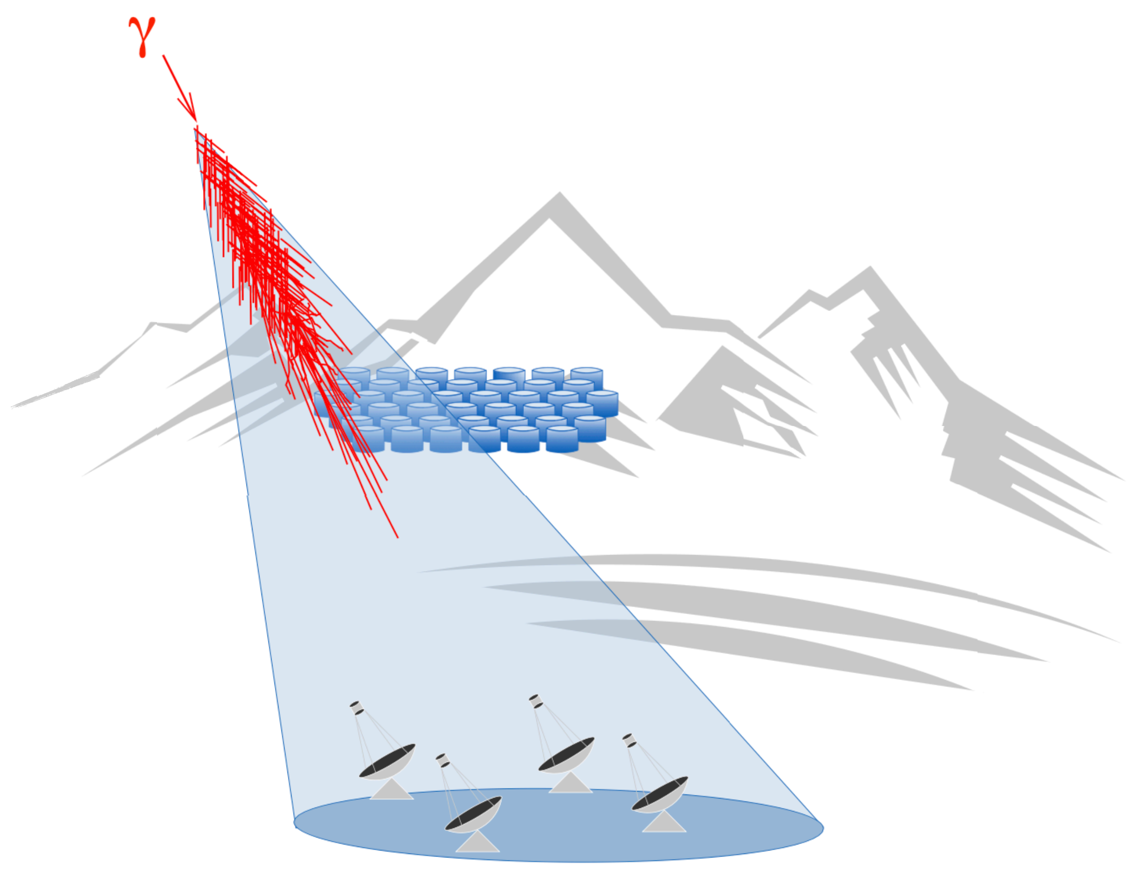
2. Gravitational Waves



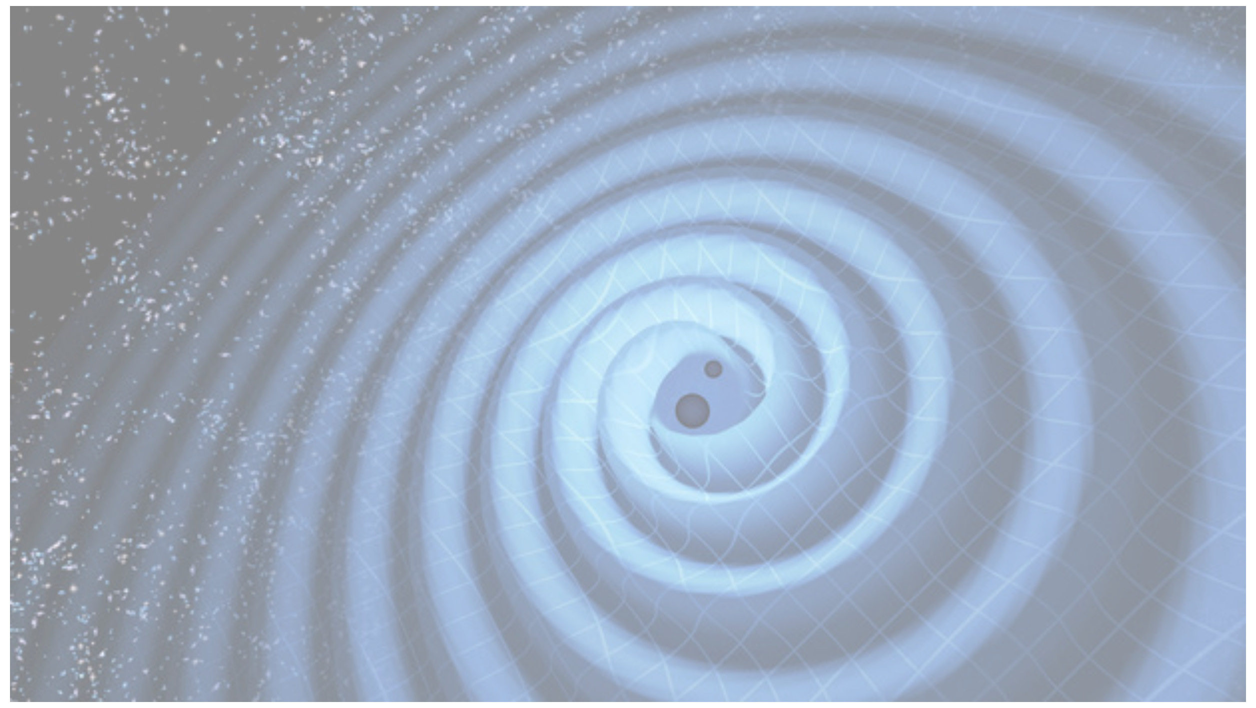


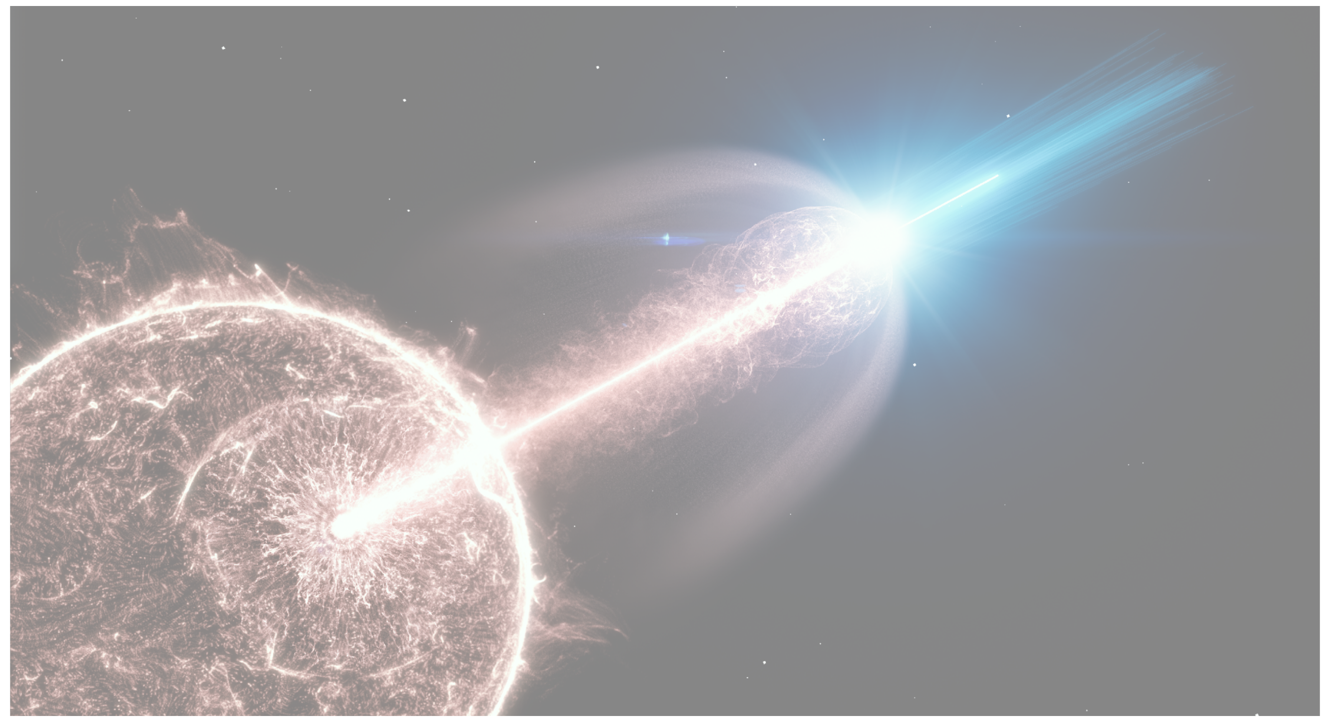
3. A multi-messenger case: Gamma-Ray Bursts

Outline

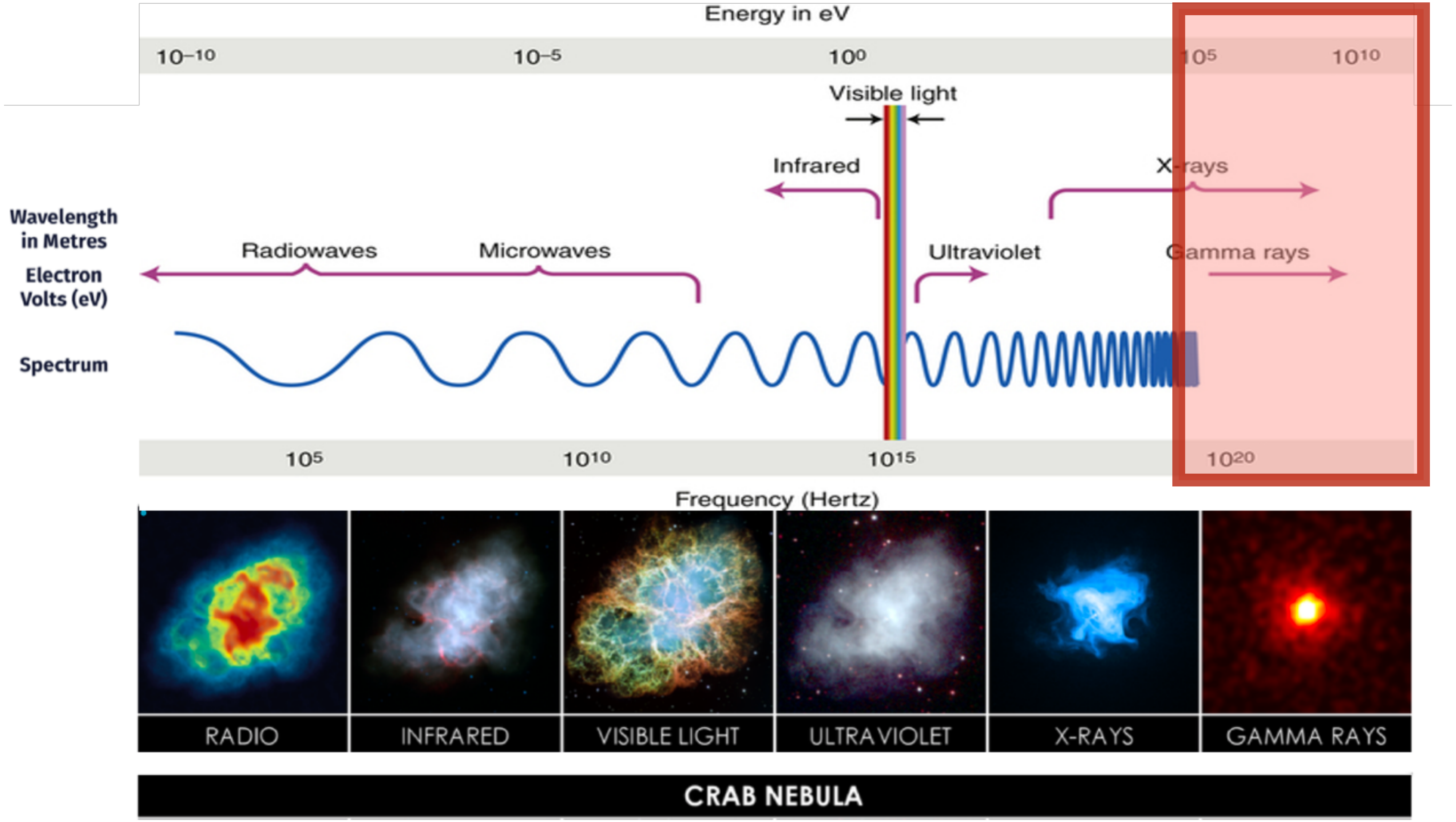


1. Very-High-Energy Gamma-ray Astrophysics



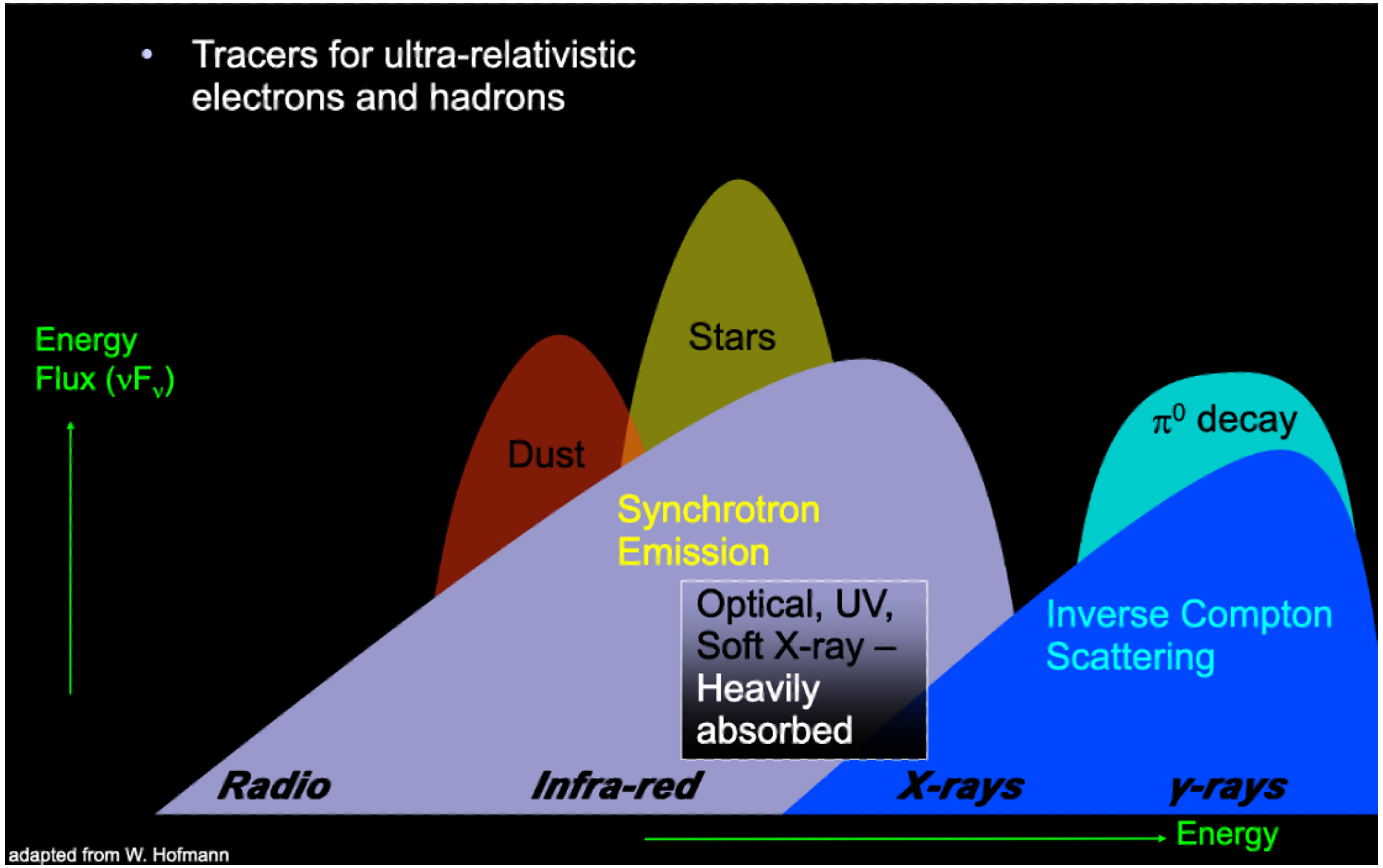


Electromagnetic spectrum



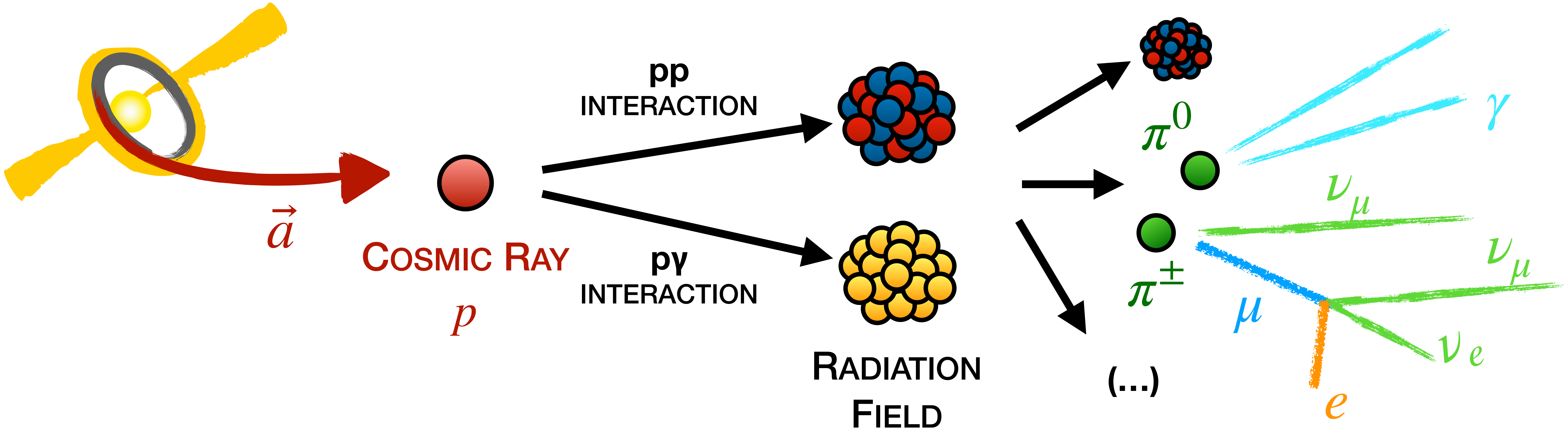
γ-rays: why to study them?

- Indicate the presence of a parental population of high-energy massive particles
- Little effect from absorption in the galaxy
- Carry information directly from the sites of acceleration

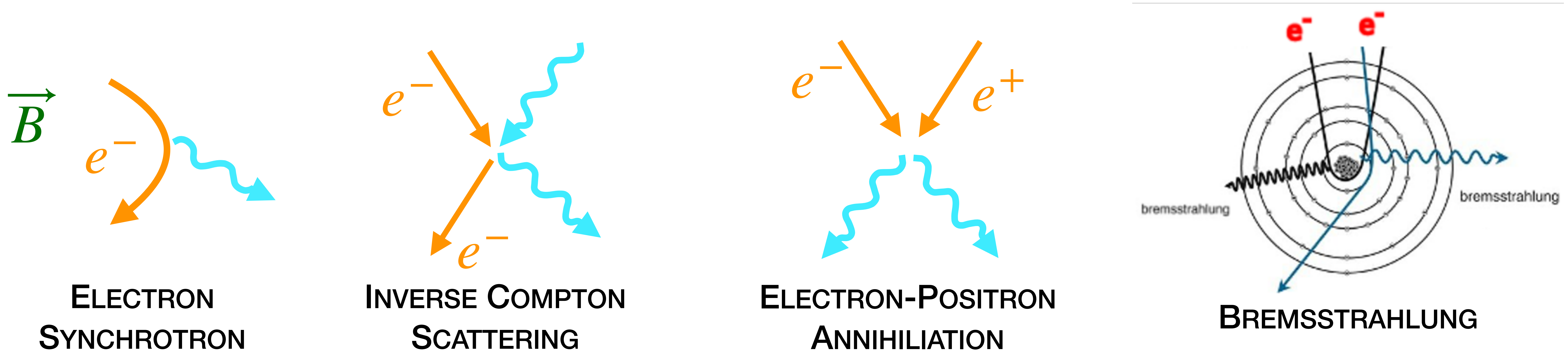


γ-rays: how are they produced?

HADRONIC PROCESSES



LEPTONIC PROCESSES

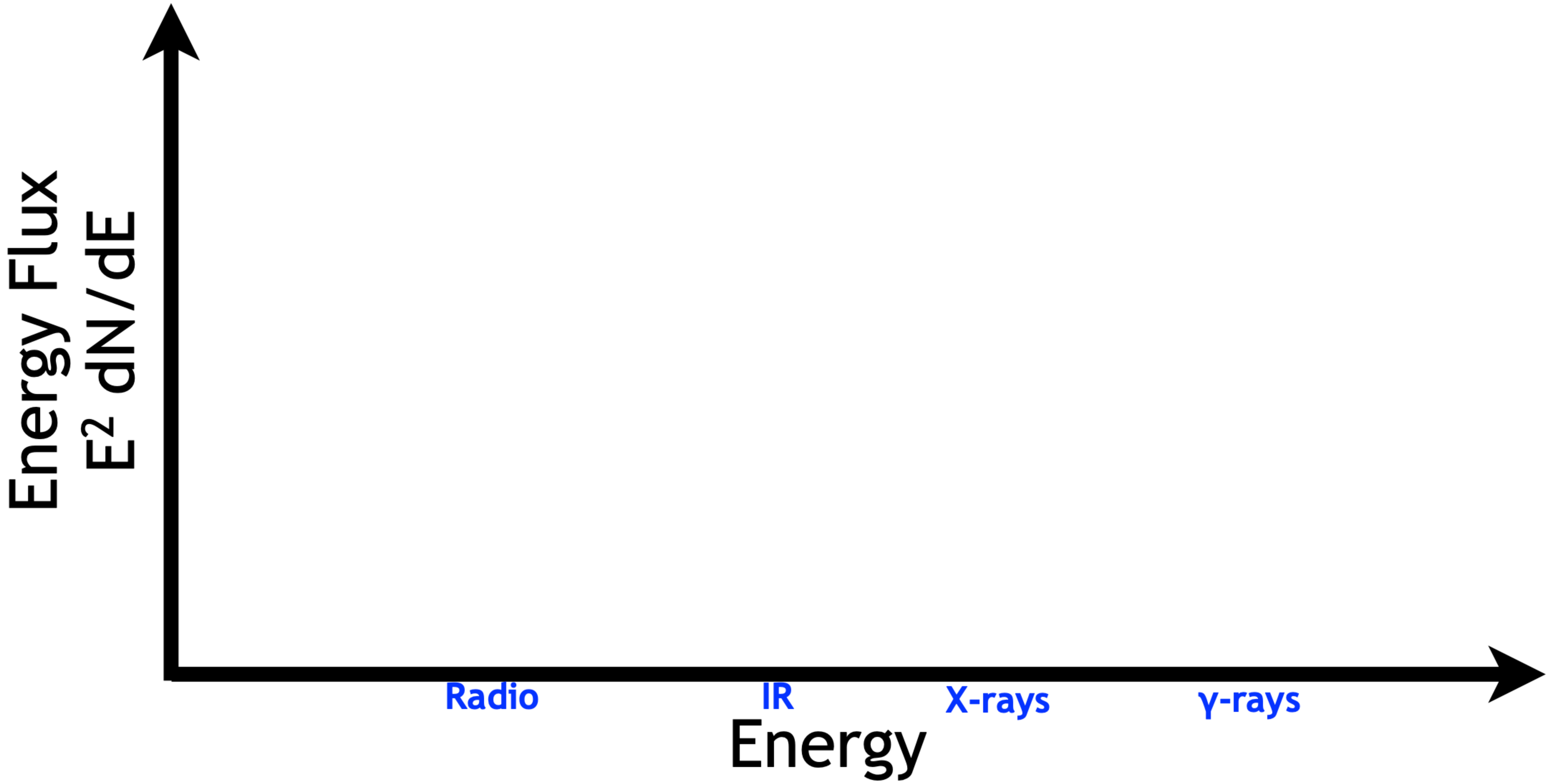


γ-rays: how are they produced?

Only produced by non-thermal processes

ELECTRON POPULATION

PROTON POPULATION

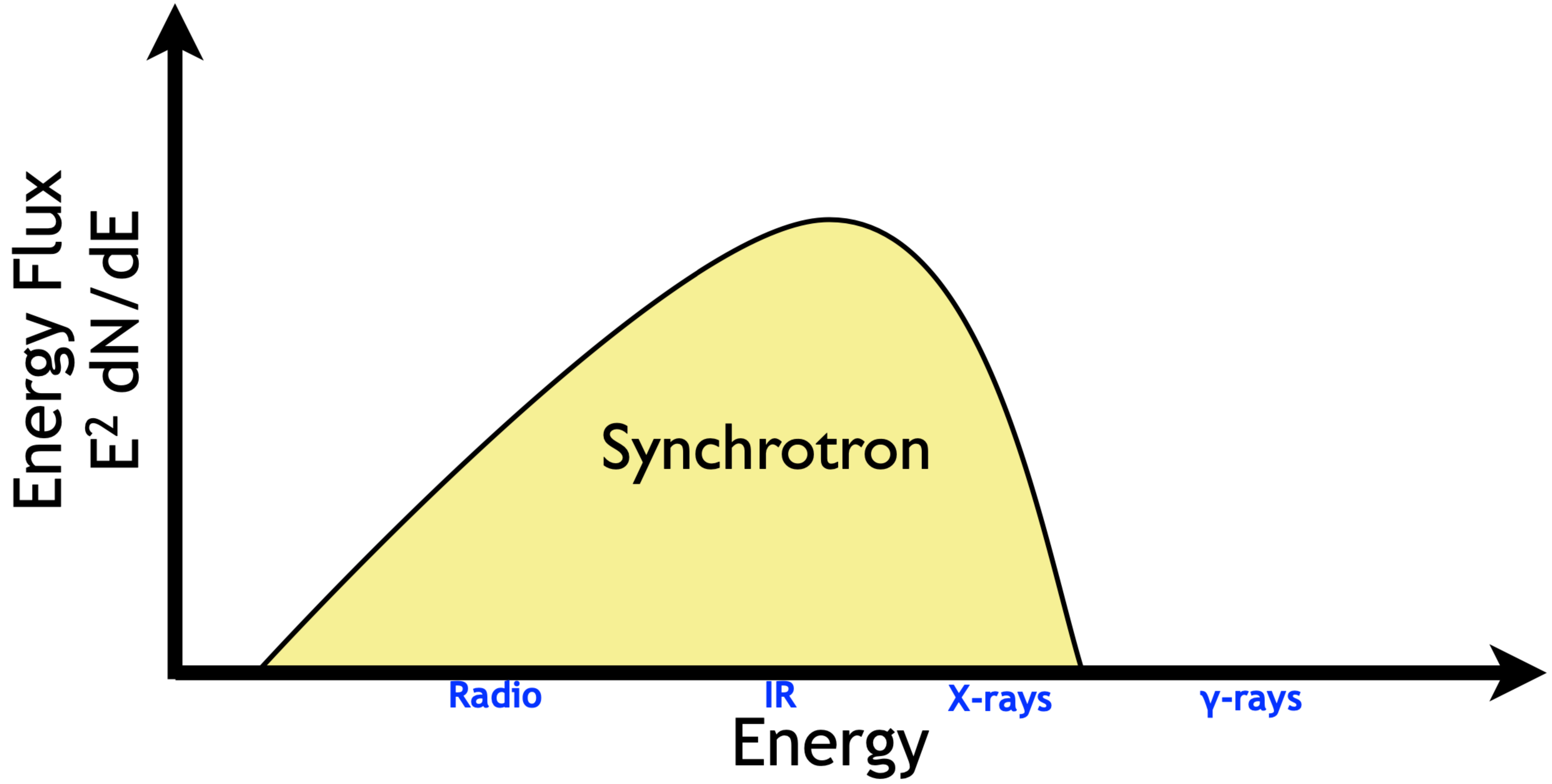


γ-rays: how are they produced?

Only produced by non-thermal processes

ELECTRON POPULATION
+ $\overrightarrow{B}$ FIELD

PROTON POPULATION



γ-rays: how are they produced?

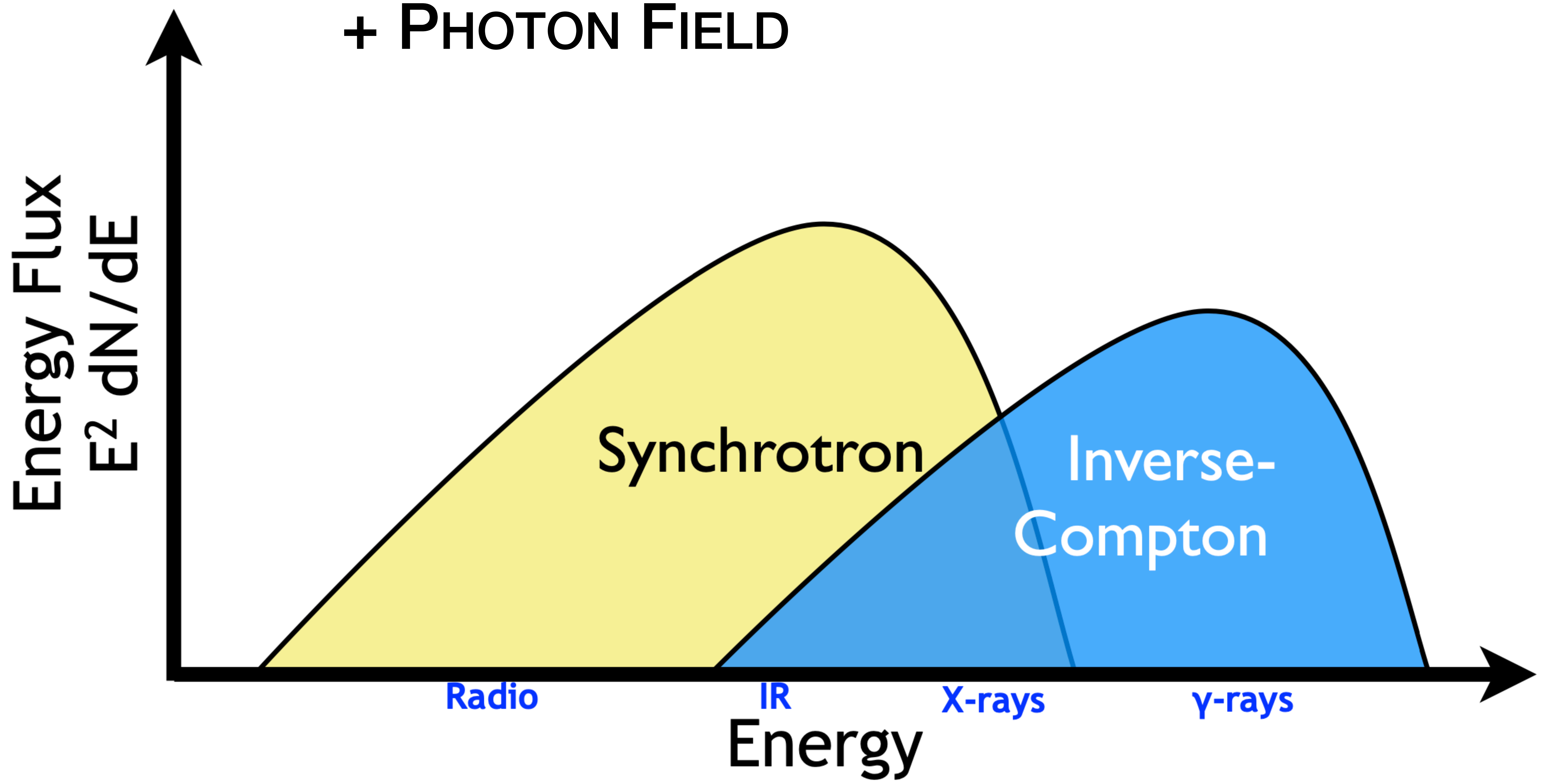
Only produced by non-thermal processes

ELECTRON POPULATION

$+\vec{B}$ FIELD

+ PHOTON FIELD

PROTON POPULATION



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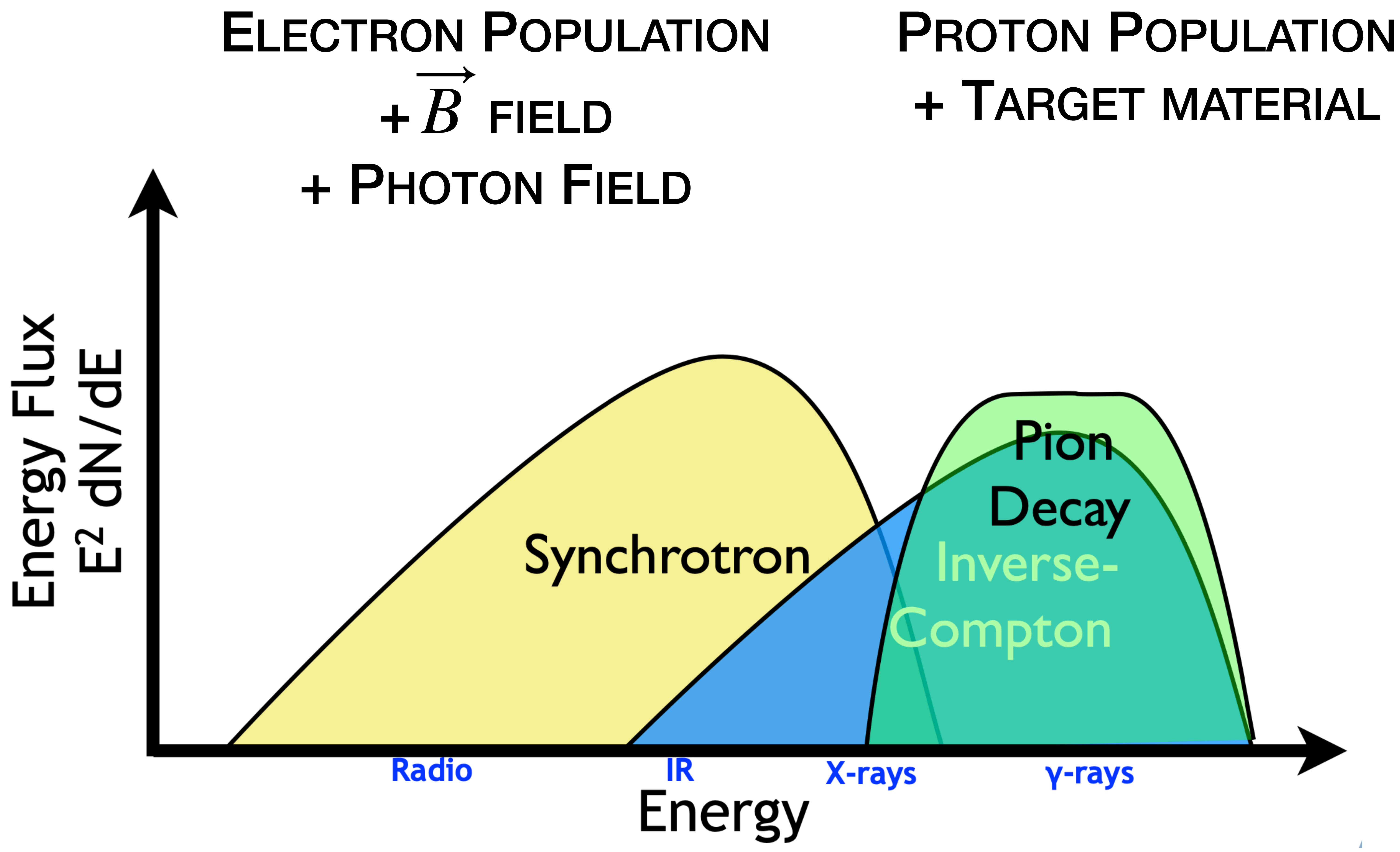


γ-rays: how to detect them?

- Medium-Energy Gamma Rays (MeV)

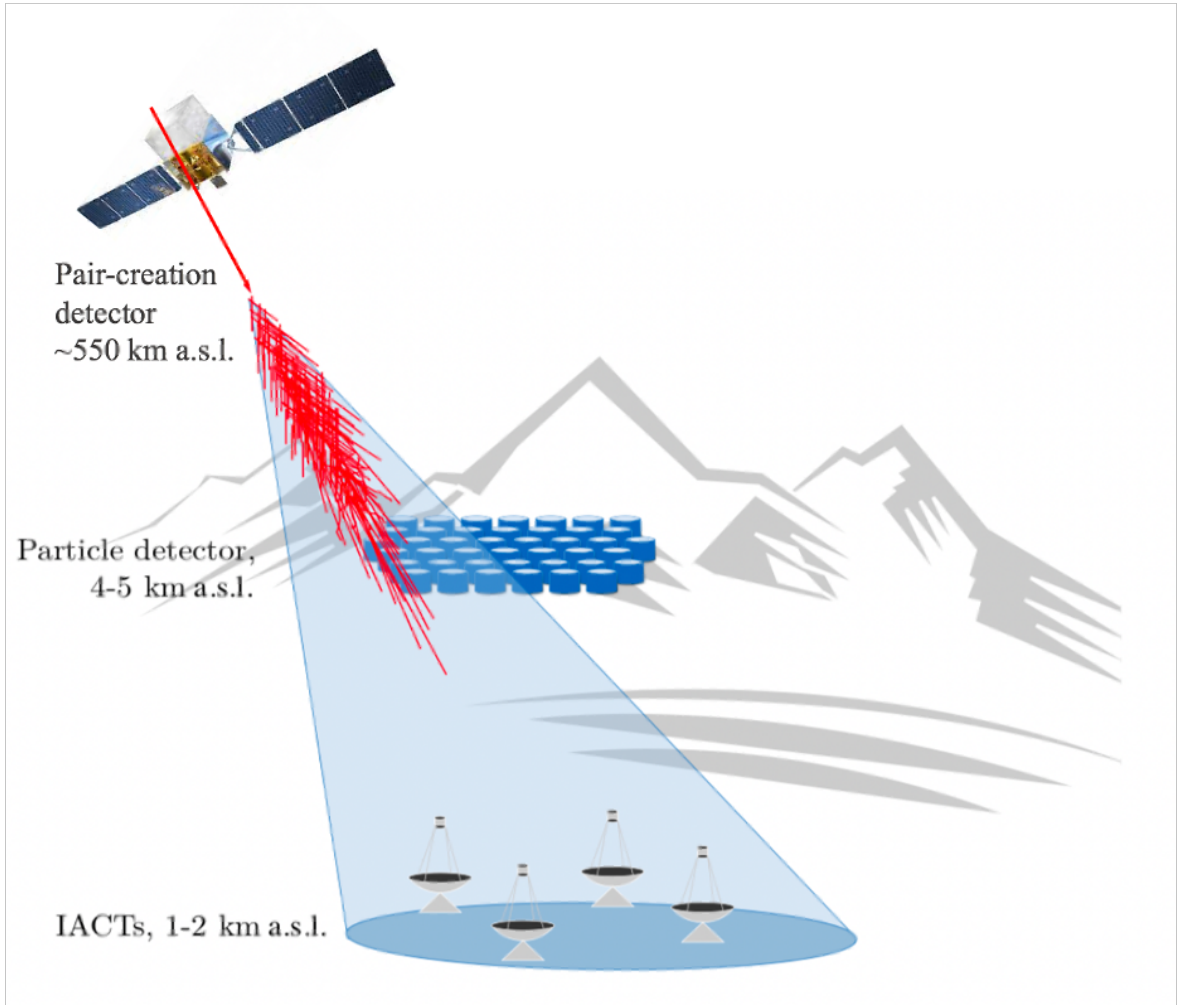
  → 🛰 Detected from space

- High-Energy (HE) Gamma Rays (100 MeV — 50 GeV)

  → 🛰 & 🌍 Detected from space ground-based experiments

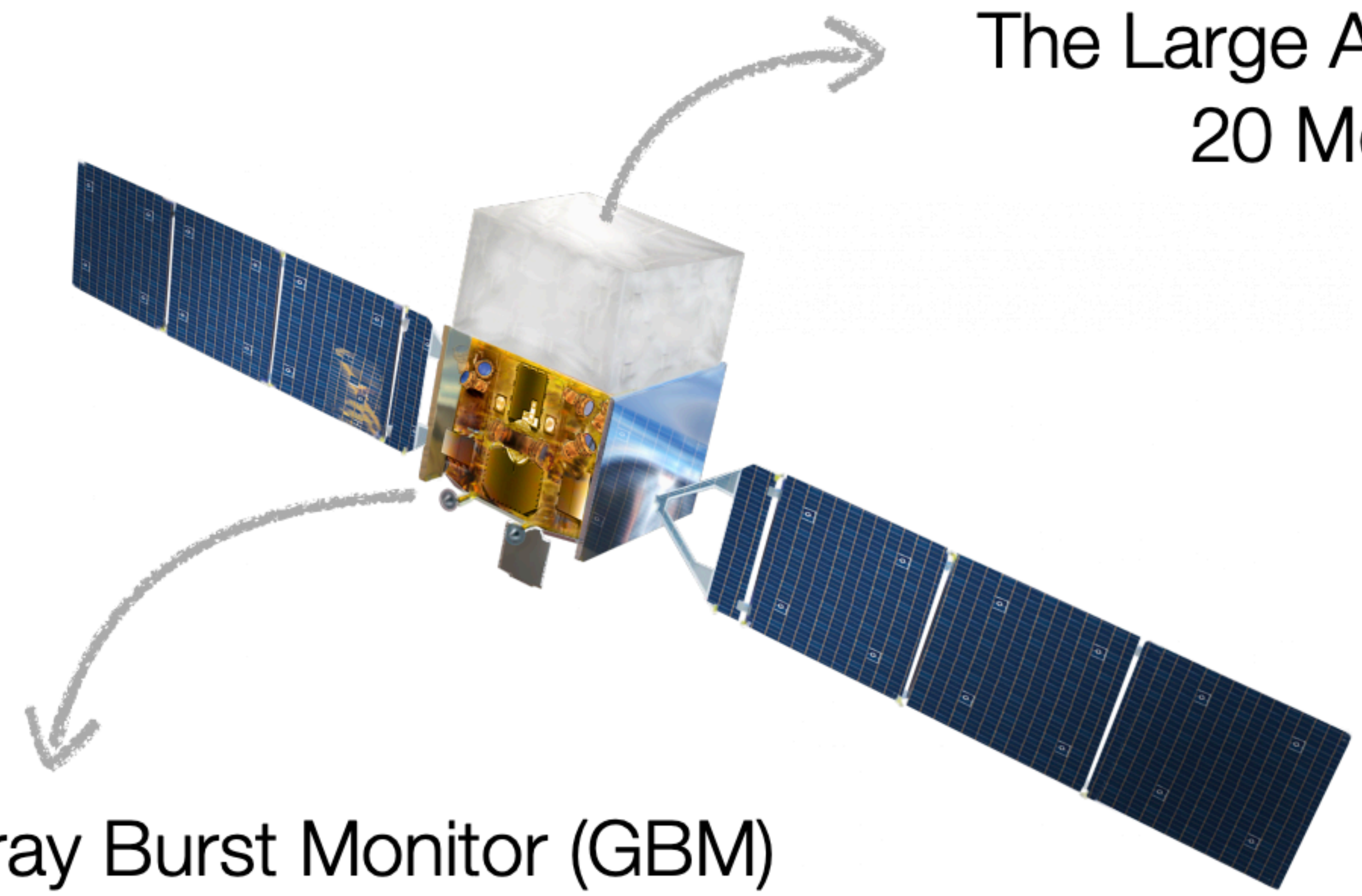
- Very-High-Energy (VHE) Gamma Rays (50 GeV — 100 TeV)

  → 🌍 Detected from ground-based experiments

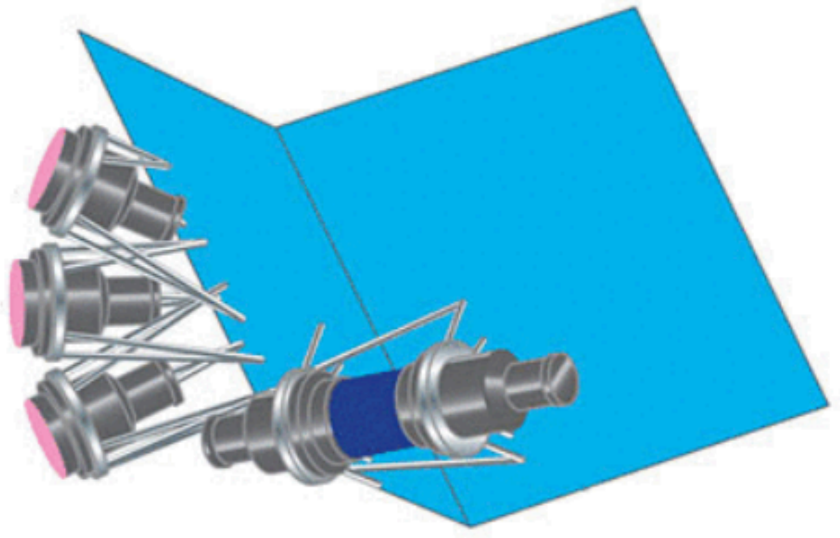


γ-rays in space: *Fermi*-LAT

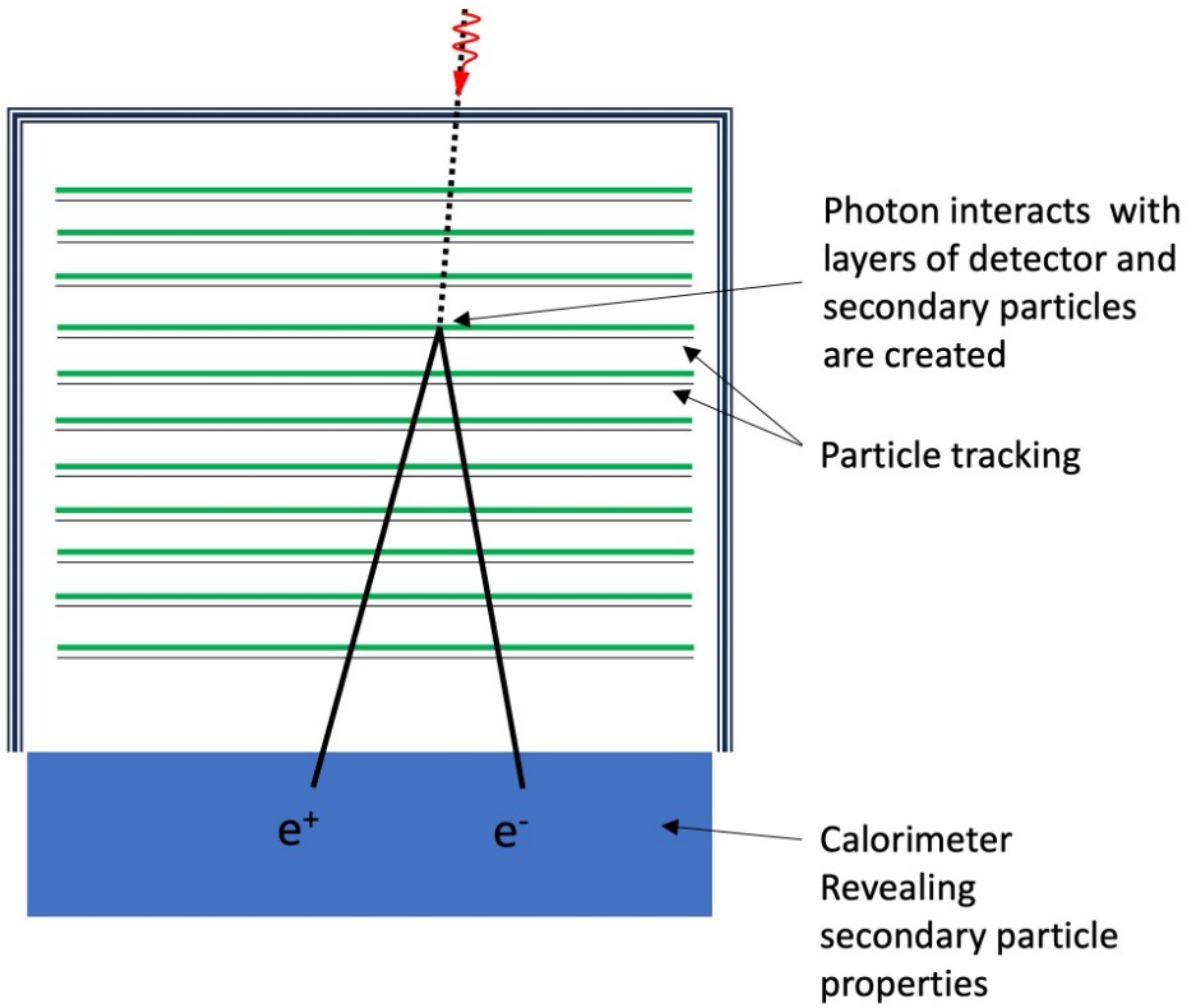
The Large Area Telescope (LAT)
20 MeV - 400 GeV



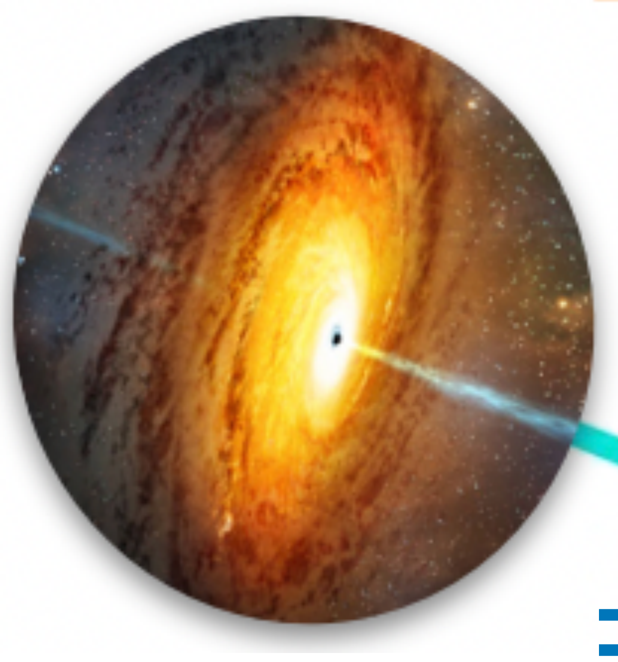
The Gamma ray Burst Monitor (GBM)
8 keV - 30 MeV



Scintillation detectors are distributed around the spacecraft with different viewing angles in order to determine the direction of a burst by comparing the count rates of different detectors

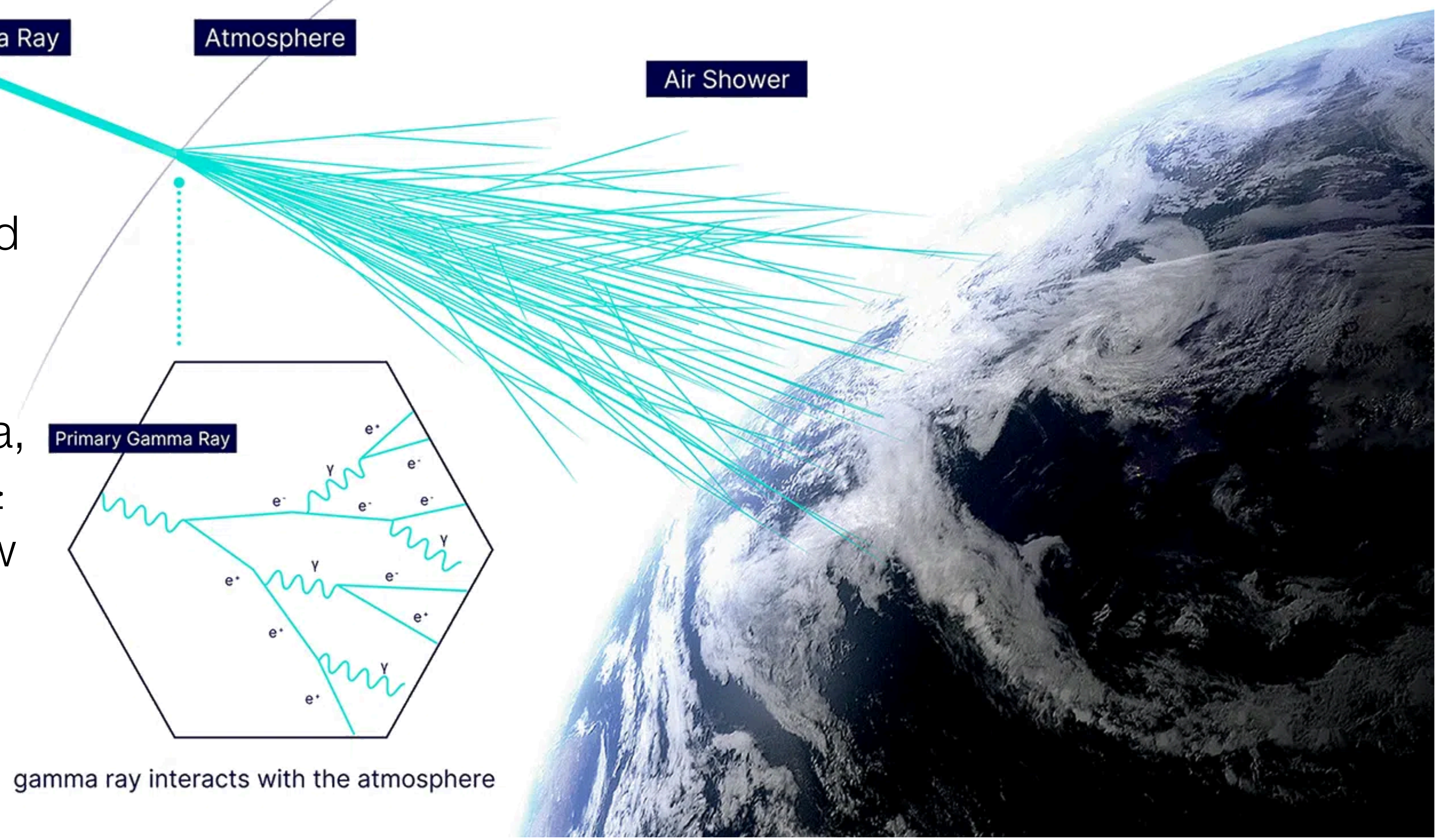


Credit: Liz Hays and Judy Racusin (Fermi school 2021)



VHE γ-rays

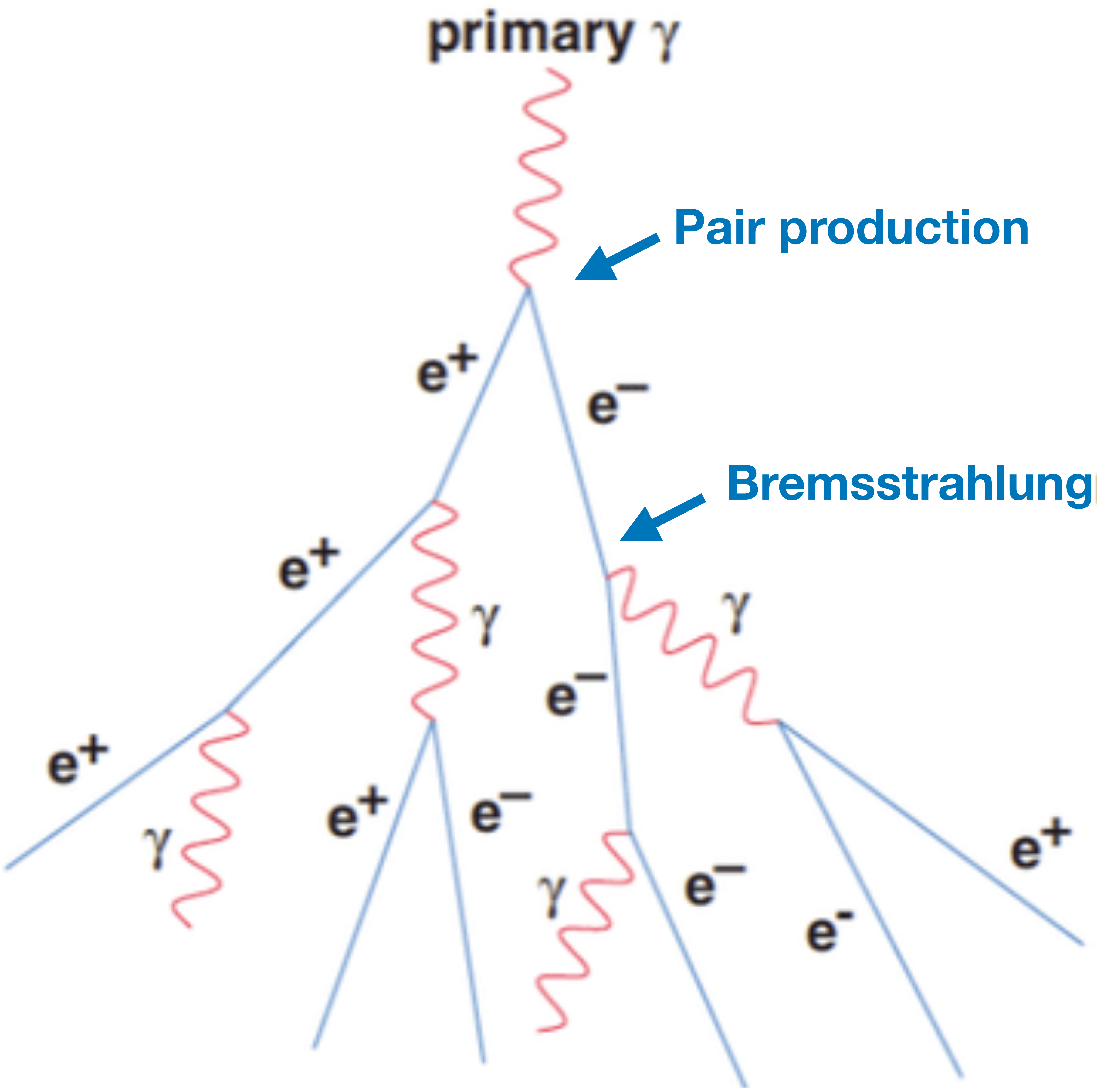
Interaction of primary particle in the high atmosphere ⇒ showers of secondary particles (Extensive Air Showers)

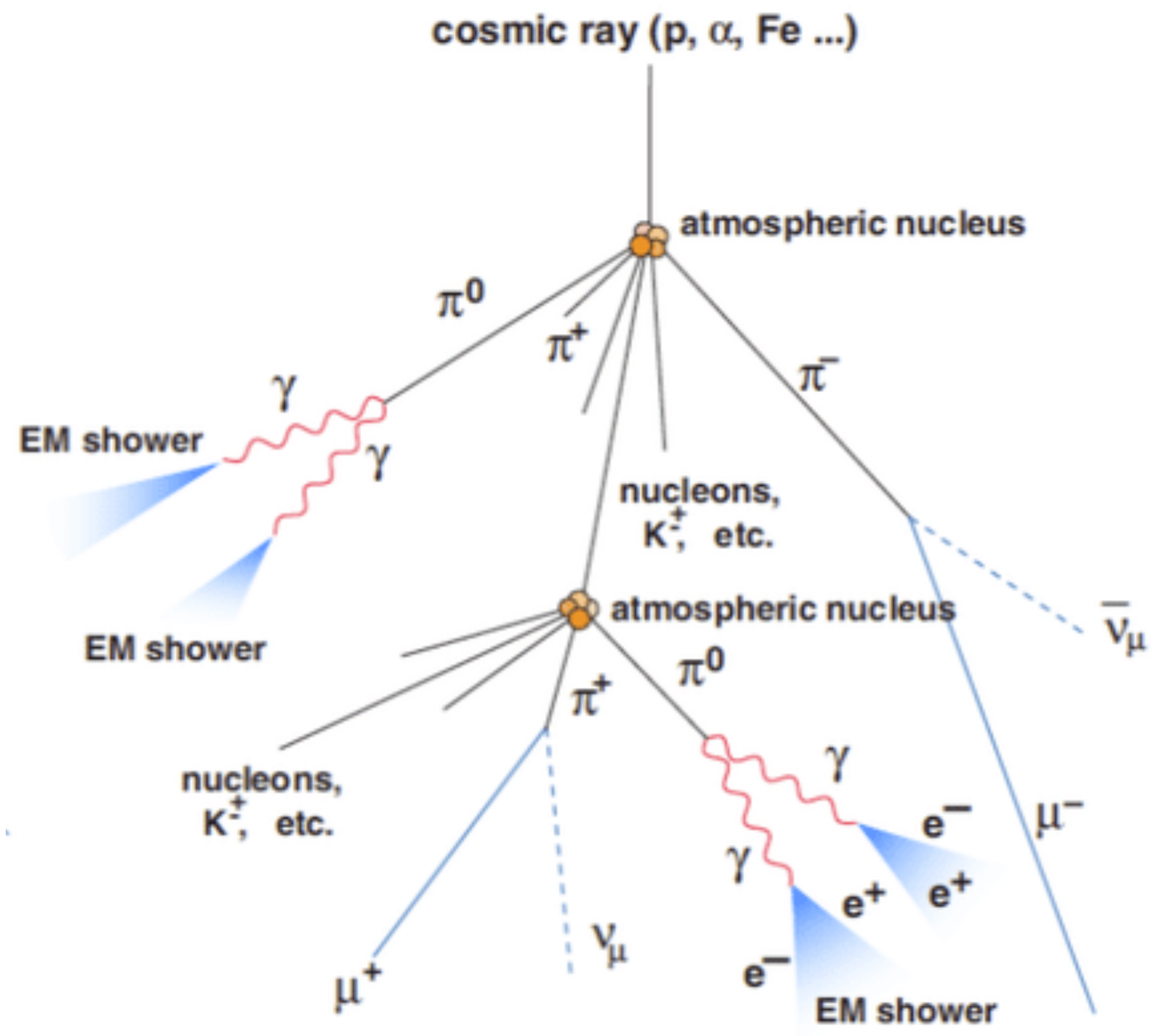


- Atmosphere acts as an inhomogeneous calorimeter and a tracking medium
- Spread on a wide area, distant detection ⇒ large effective area, can be used at high energies (≥ 100 TeV) where flux are very low
- Cascades initiated by:
  - Photons
  - Charged particles

Extensive Air Showers

Electromagnetic vs Hadronic showers

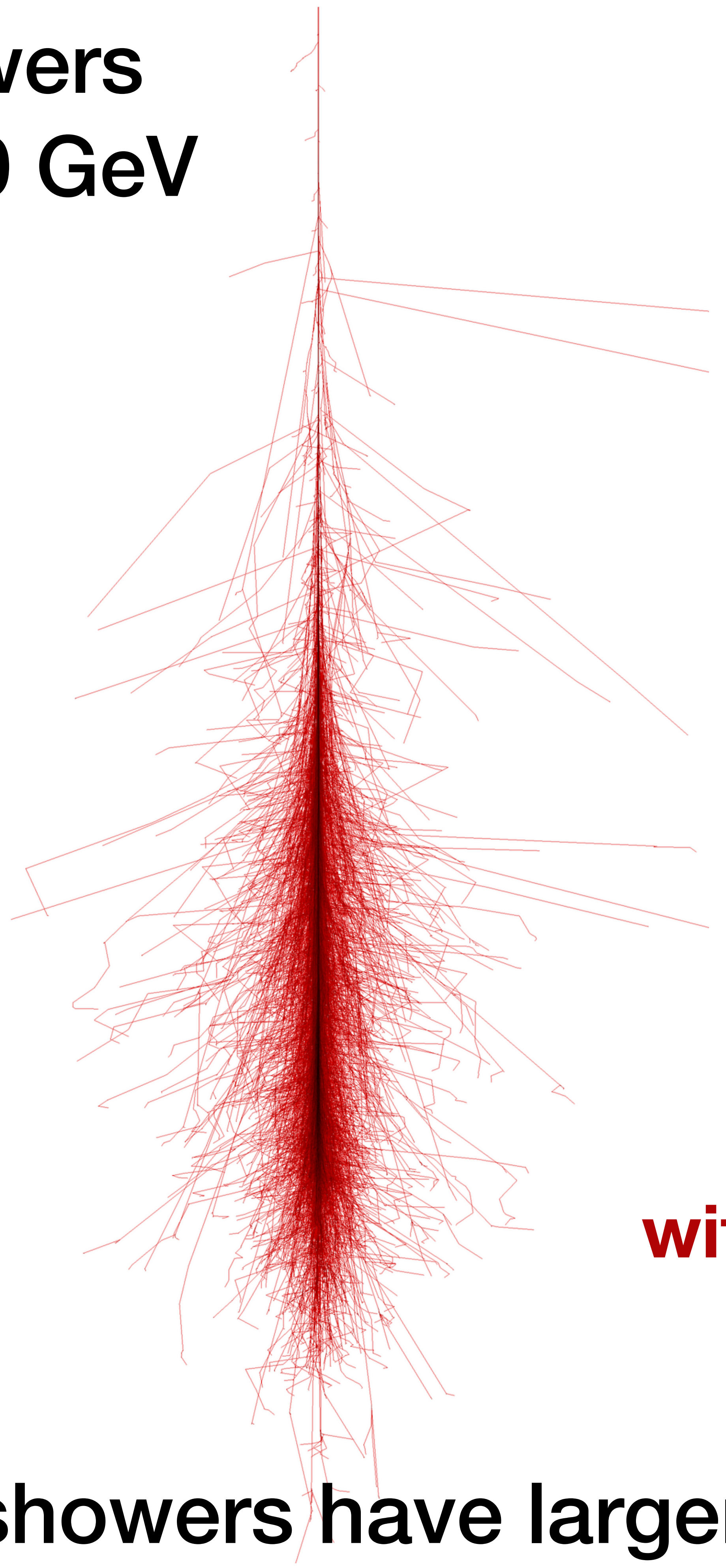




Extensive Air Showers

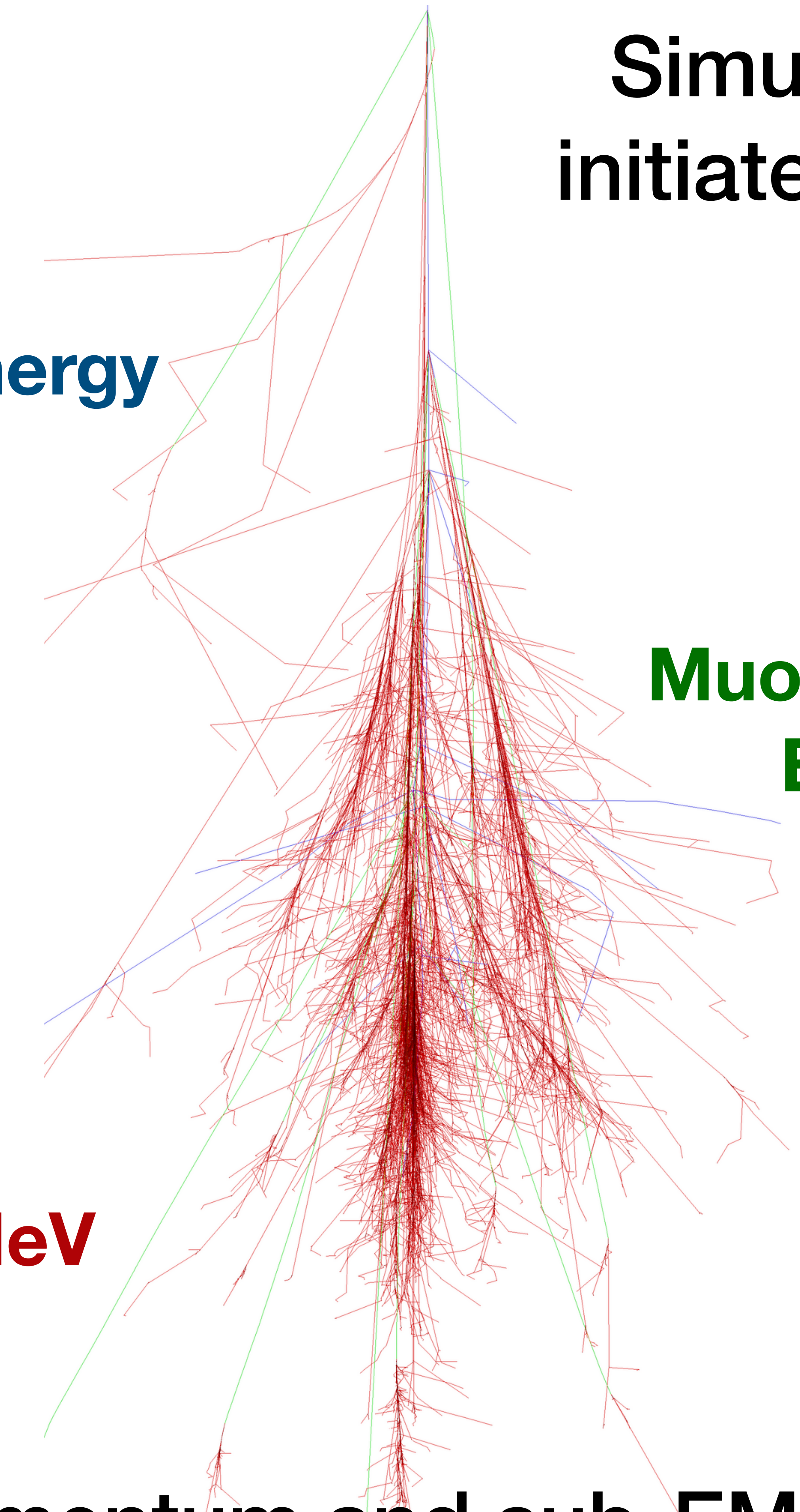
Electromagnetic vs Hadronic showers

Simulated showers initiated by a 100 GeV gamma ray



Hadrons with energy E > 0.1 GeV

e^+, e^-, γ with energy E>0.1 MeV



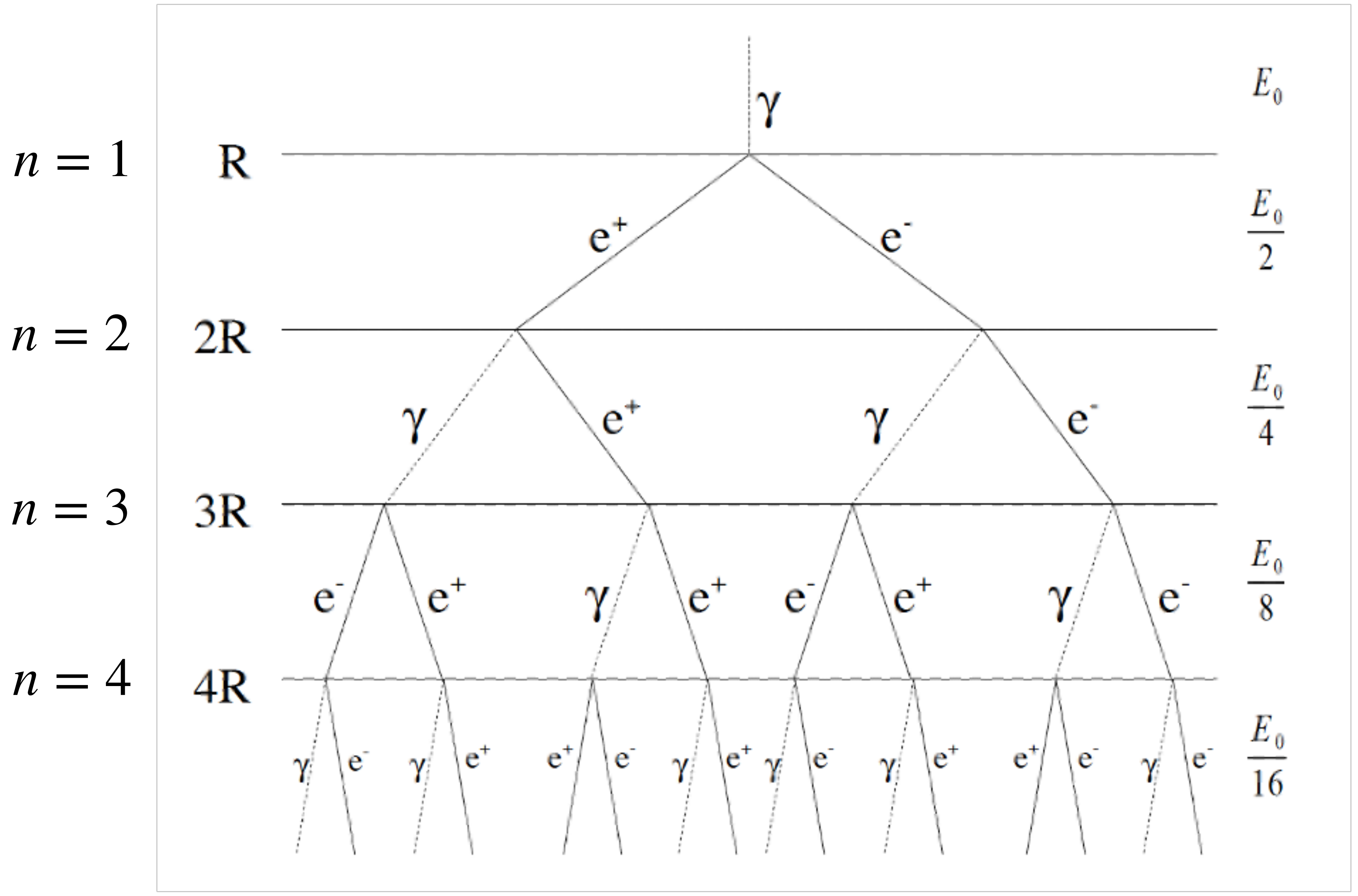
Simulated showers initiated by a 100 GeV proton

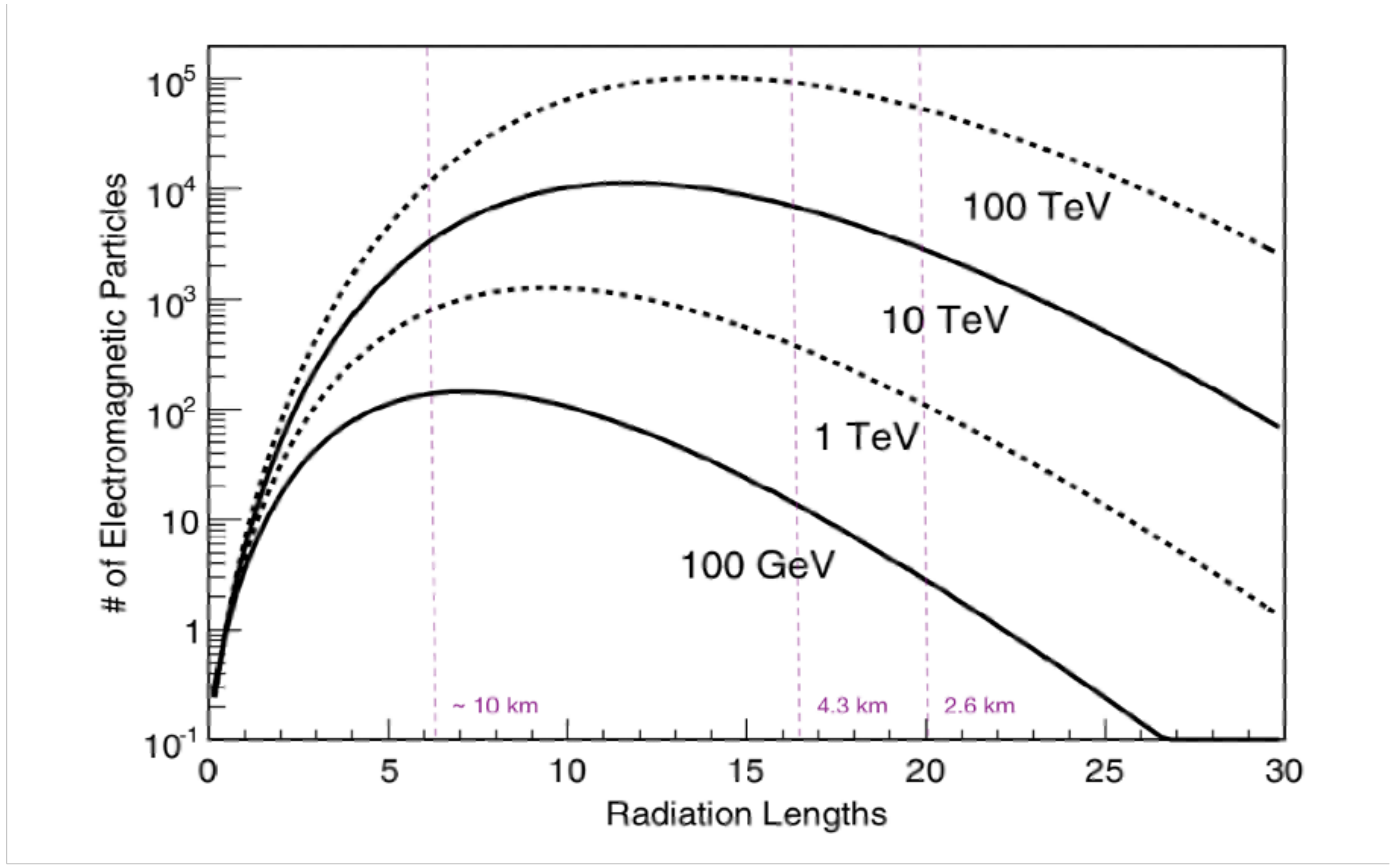
Muons with energy E > 0.1 GeV

Hadronic showers have larger transverse momentum and sub-EM showers

Extensive Air Showers

The Heitler model



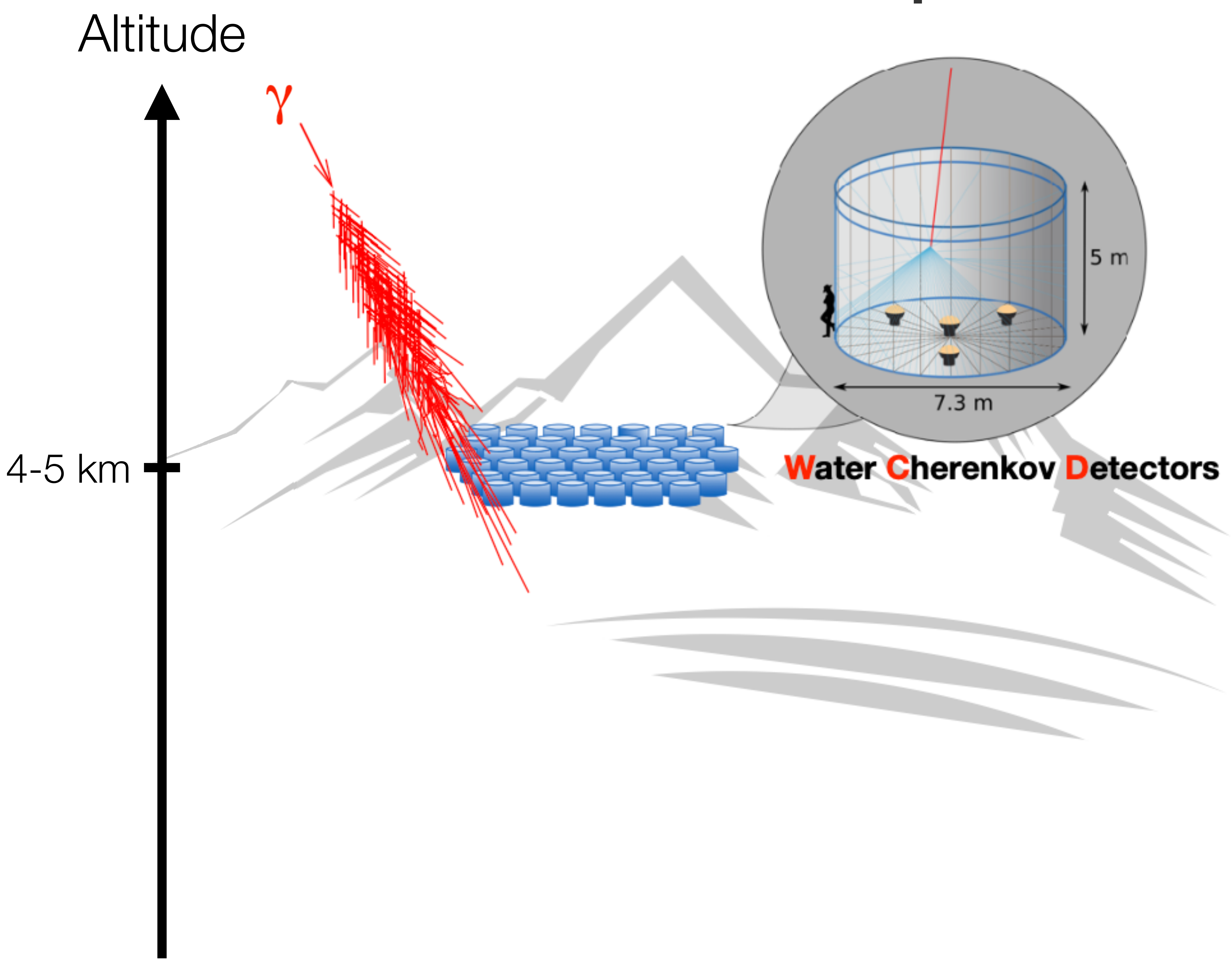


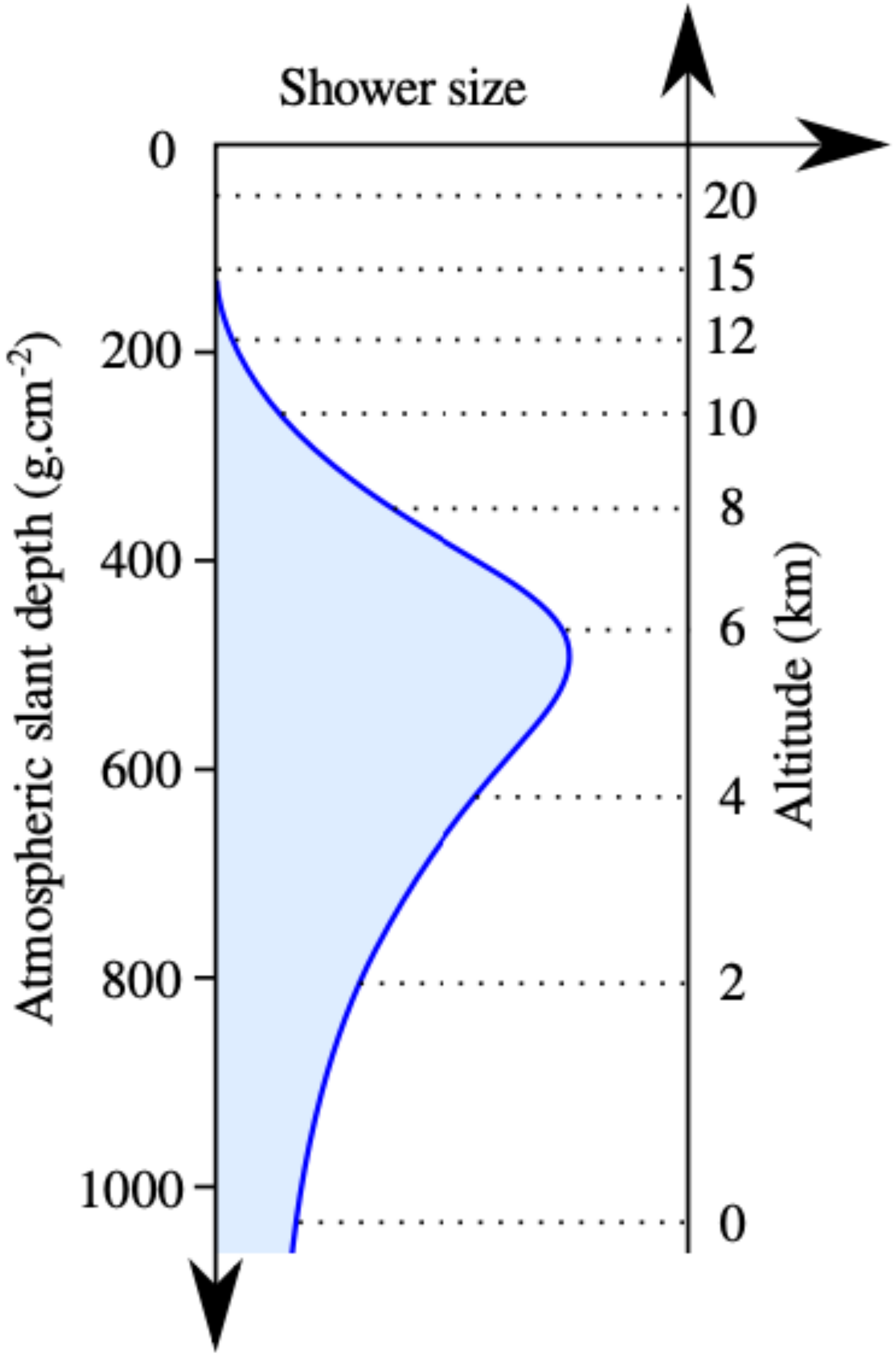
Radiation length: X_0

$$x = nR = nX_0 \ln 2$$
$$N = 2^n = e^{x/X_0}$$
$$N_{\max} = E_0/E_{\text{crit}}$$
$$\Rightarrow x_{\max} = X_0 \ln\left(\frac{E_0}{E_{\text{crit}}}\right)$$

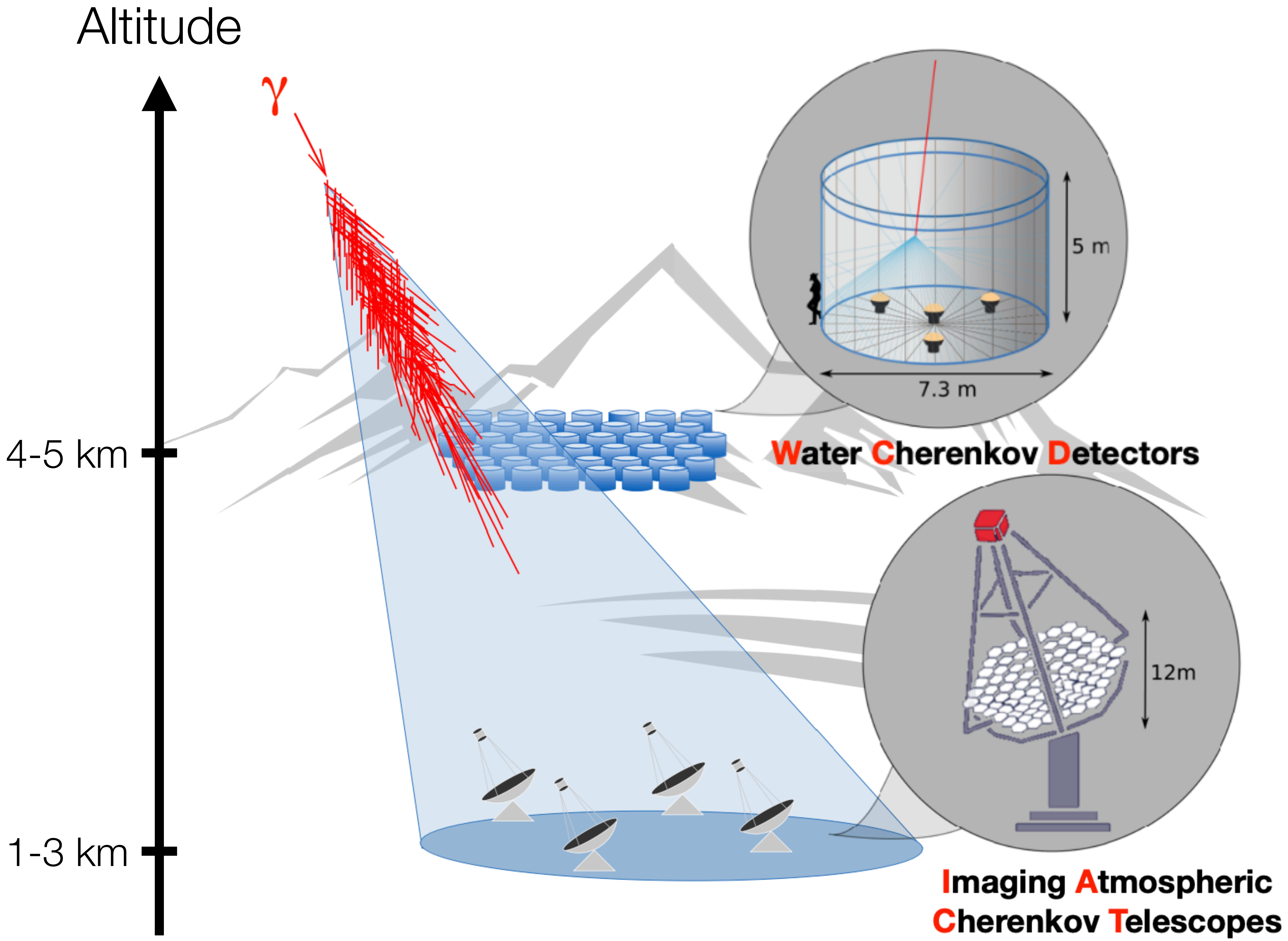
- The shower is dominated by Bremsstrahlung and pair creation
- Electromagnetic showers start to develop at an altitude around 25 km

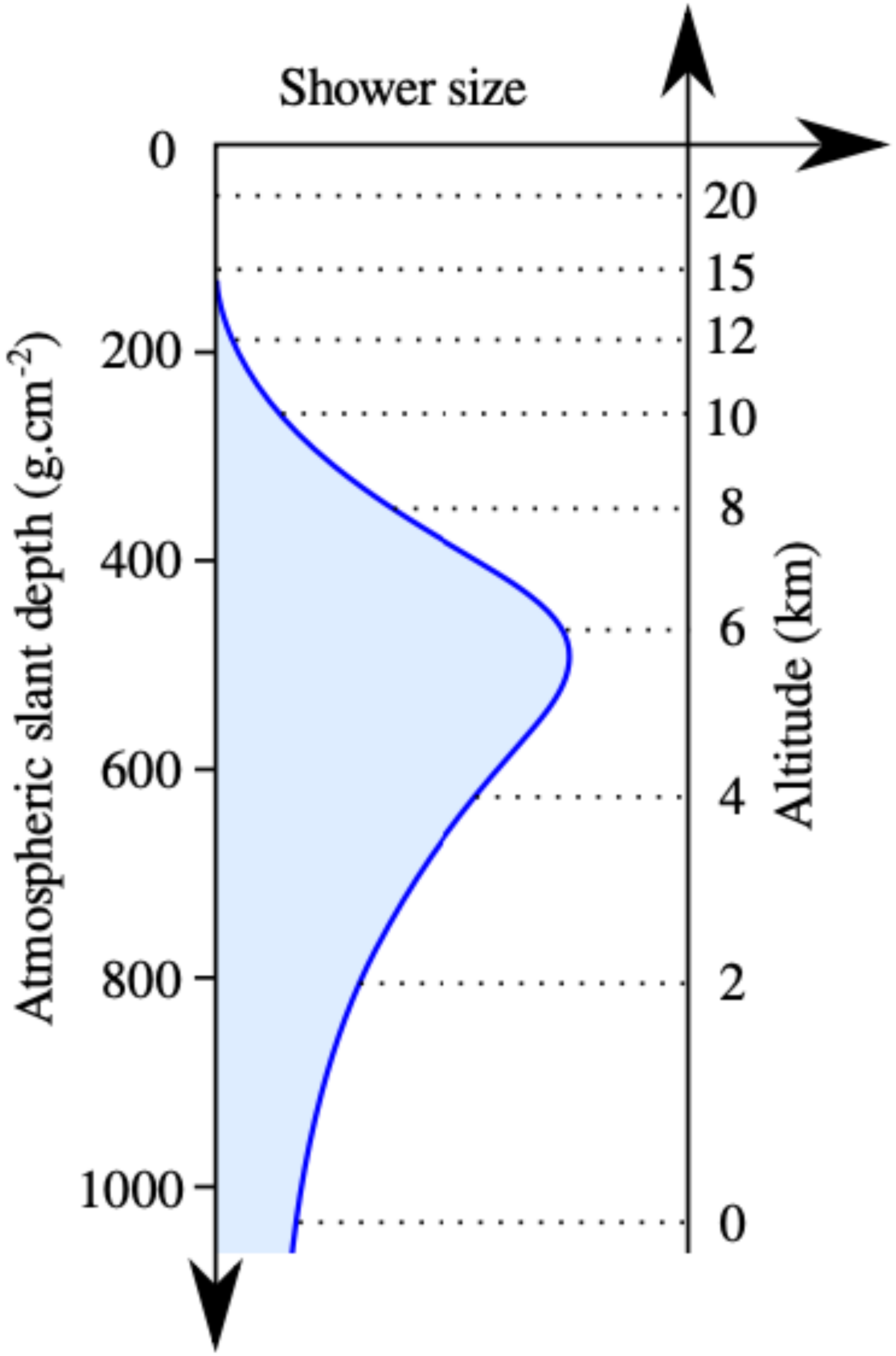
Ground particle arrays



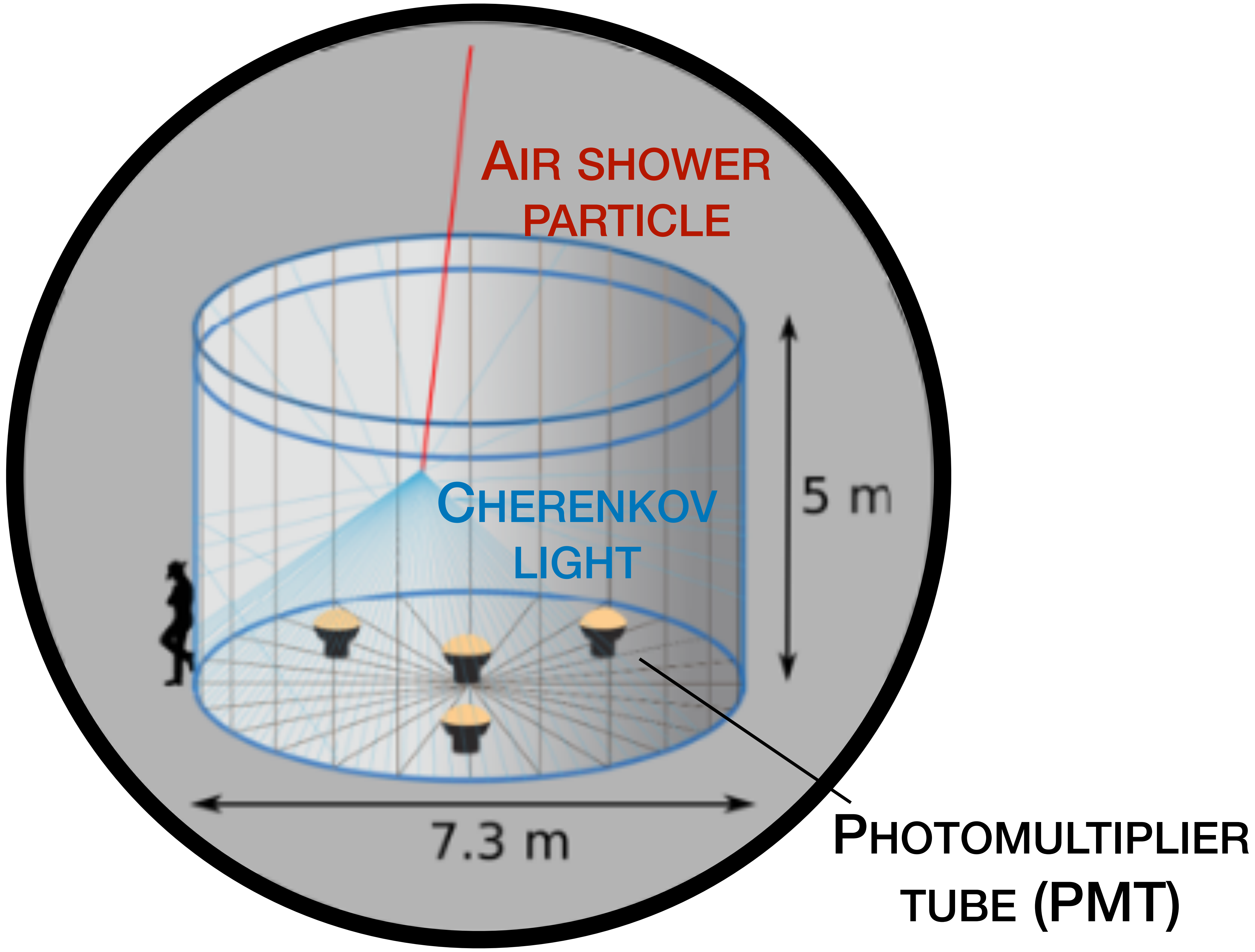


Ground particle arrays





Water Cherenkov Detectors



Detecting method: showers particles reaching the ground ($\mu^{\pm}, e\pm, \gamma, \nu$), in water, ground-based

Field of View (FOV): 50°

Duty cycle: 100% (operates in daylight too)

Angular resolution: $[0.1, 1]^{\circ}$

Energy resolution: ~30%

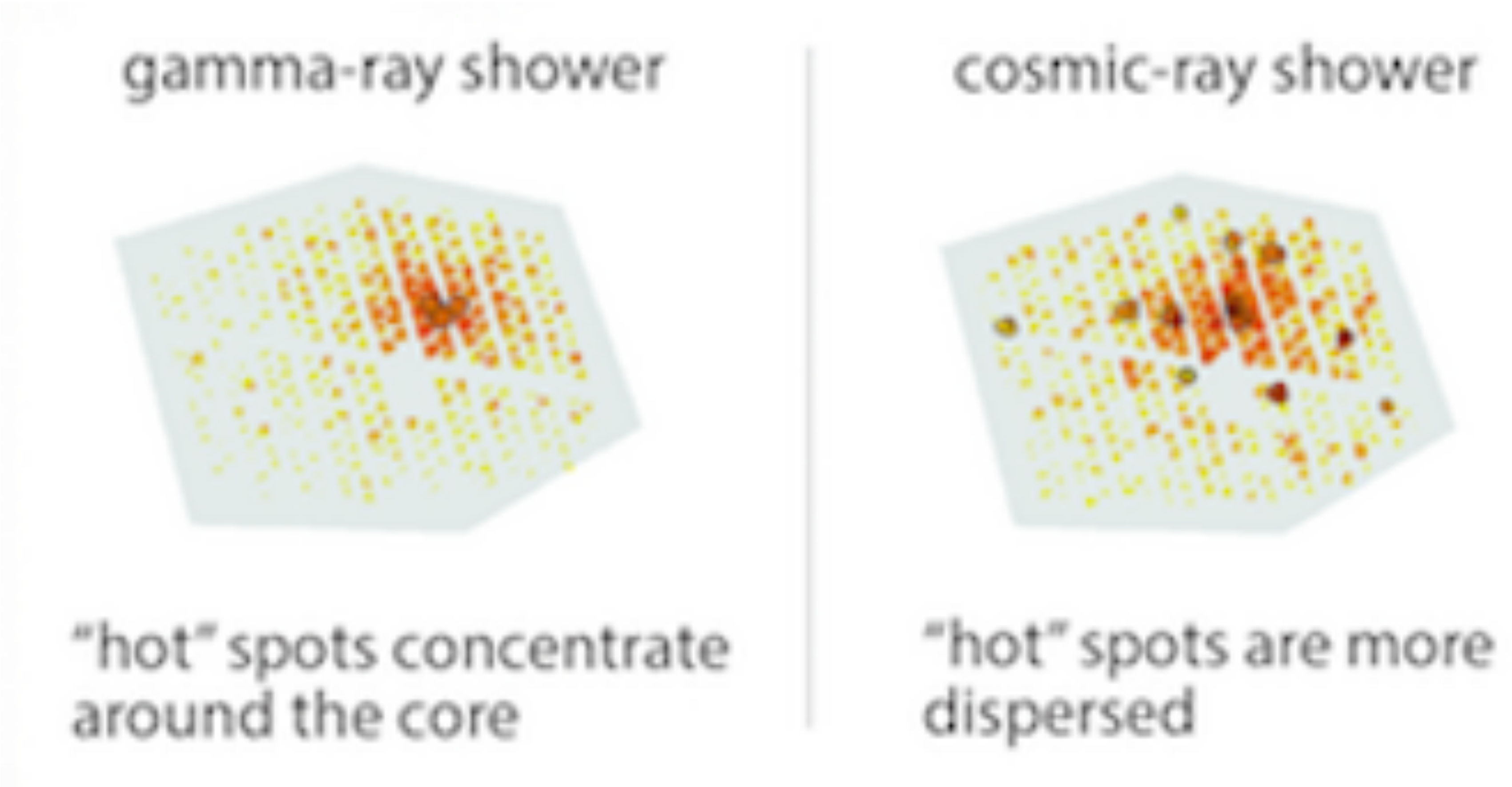
Effective aerea: ~10^5 m^2

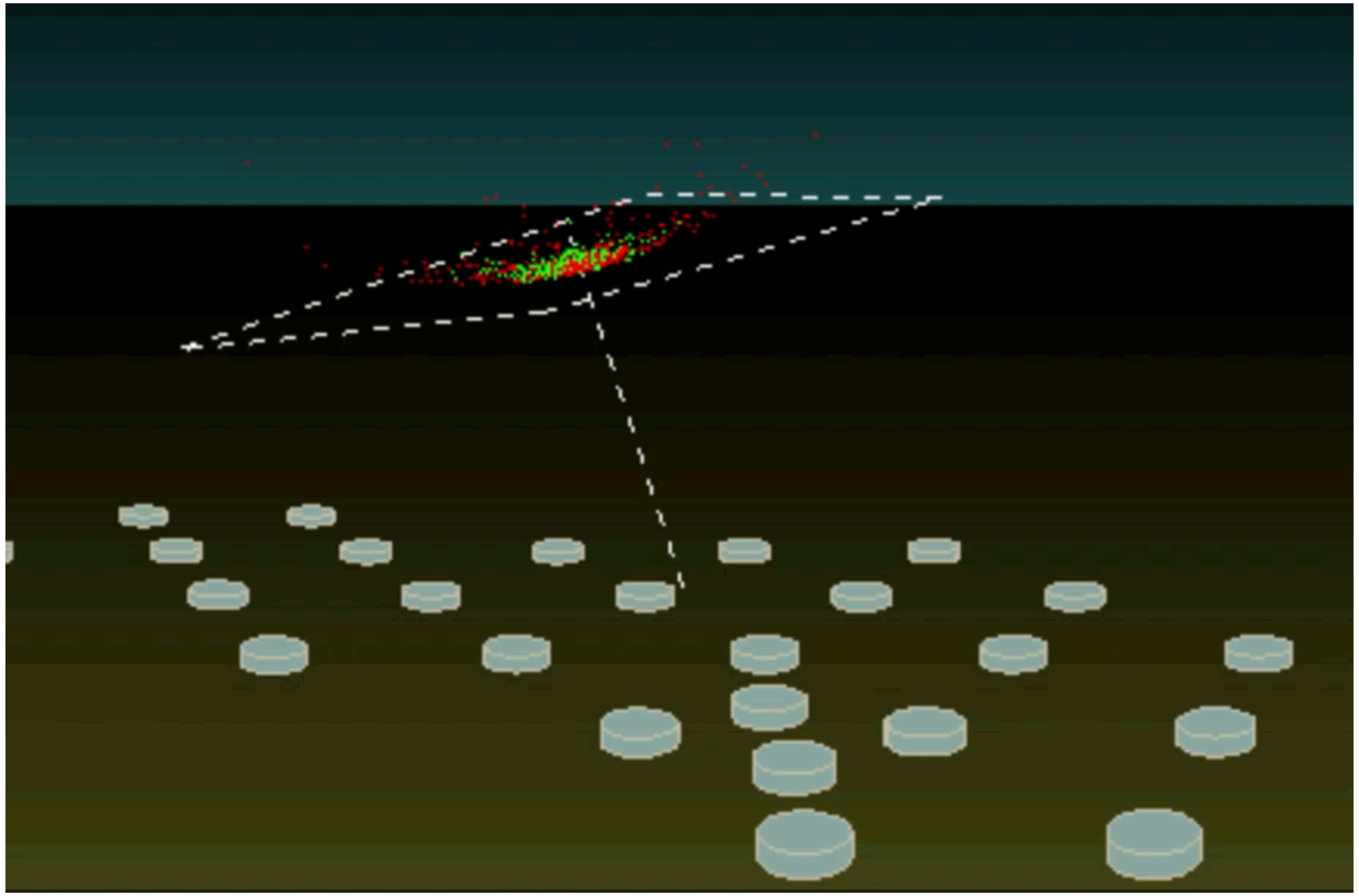
Energy range: ultra-high-energy regime (UHE, E > 100 TeV)

Water Cherenkov Detectors

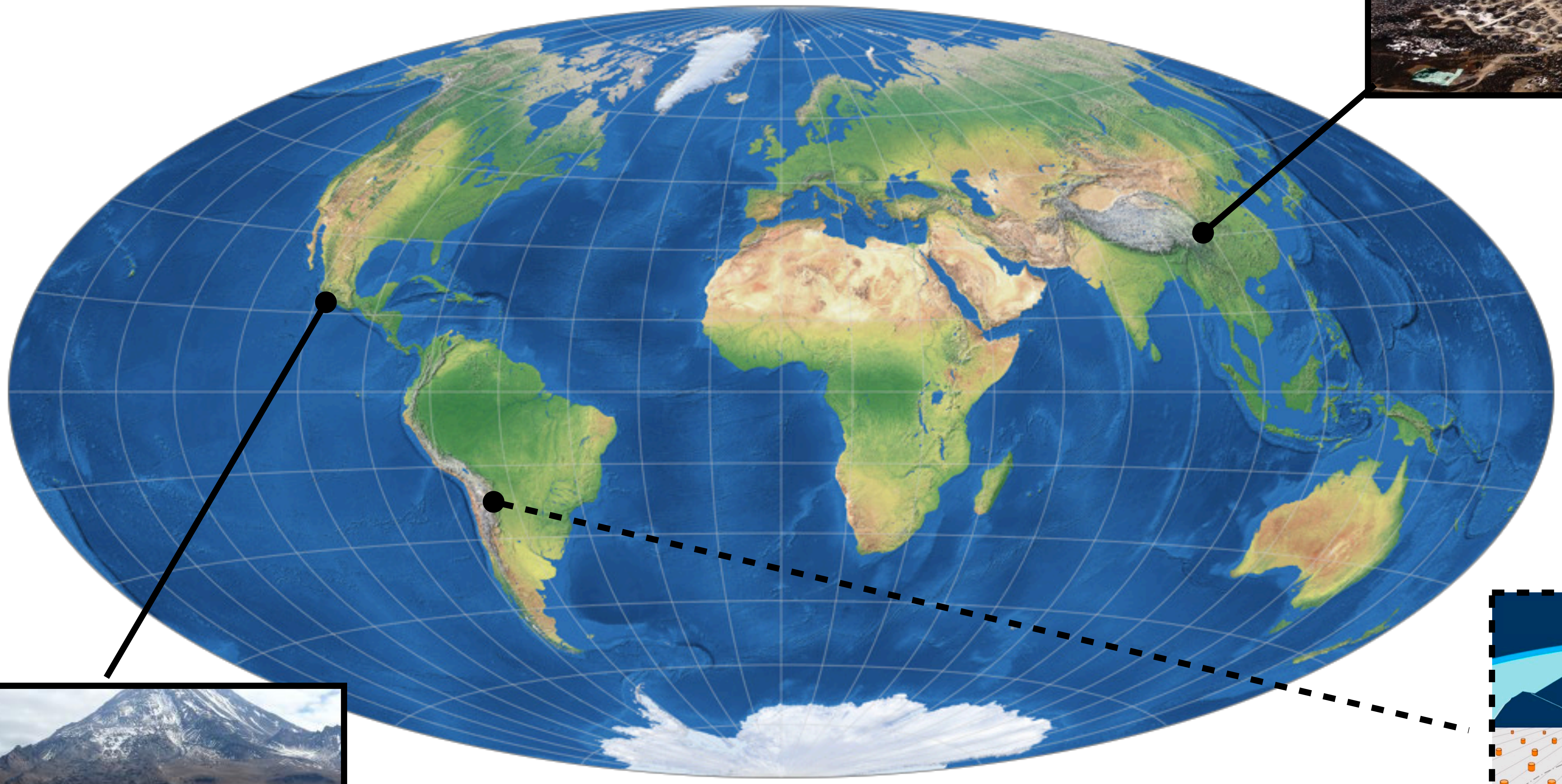
Reconstruction

- **Timing** → Direction
- **Shape** → Nature
- **Size** → Energy



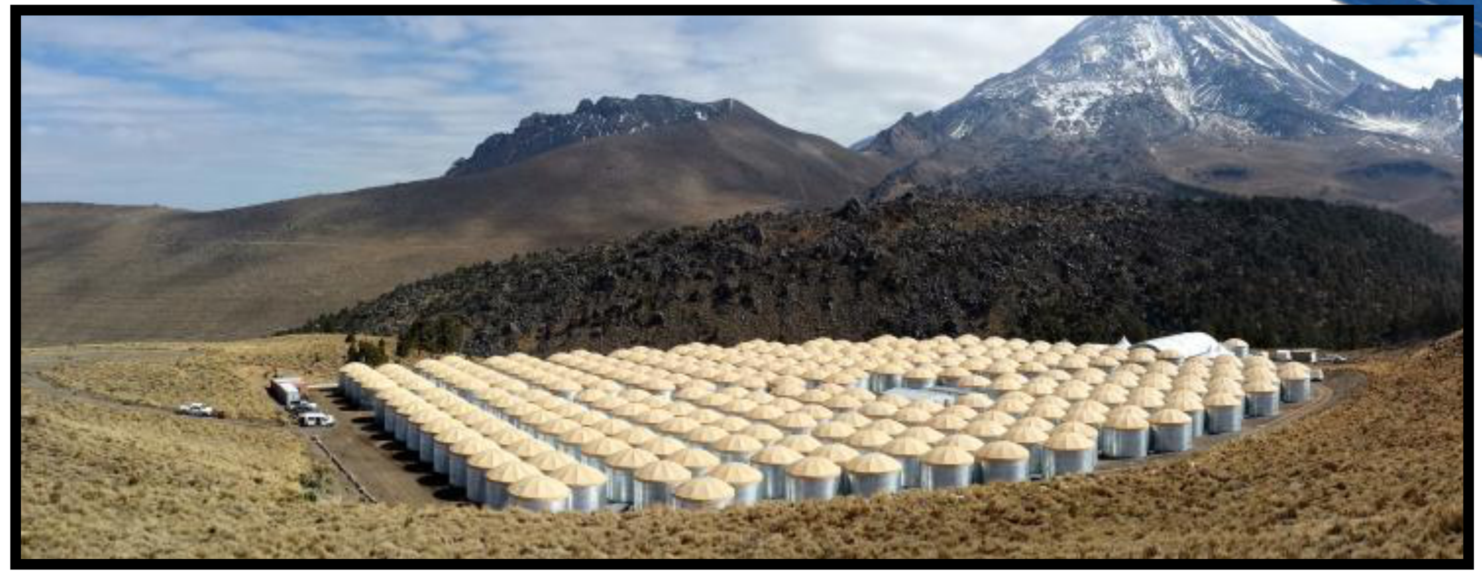


Current and future generation of WCDs

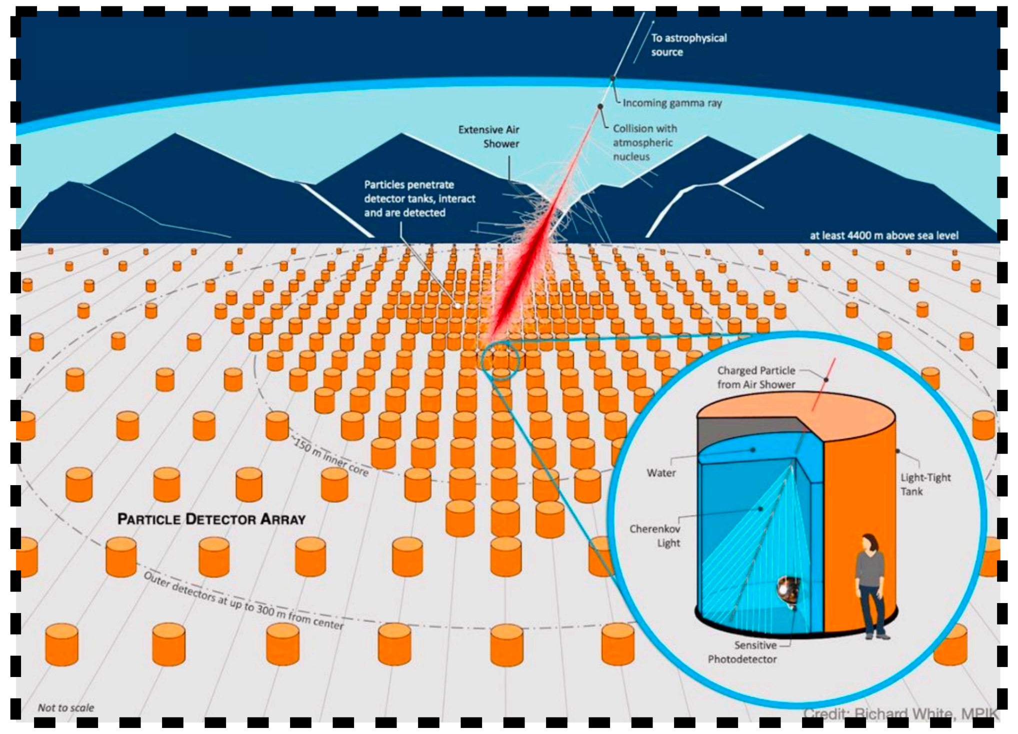


LHASSO (2021)
Daocheng, China
(4410 m)

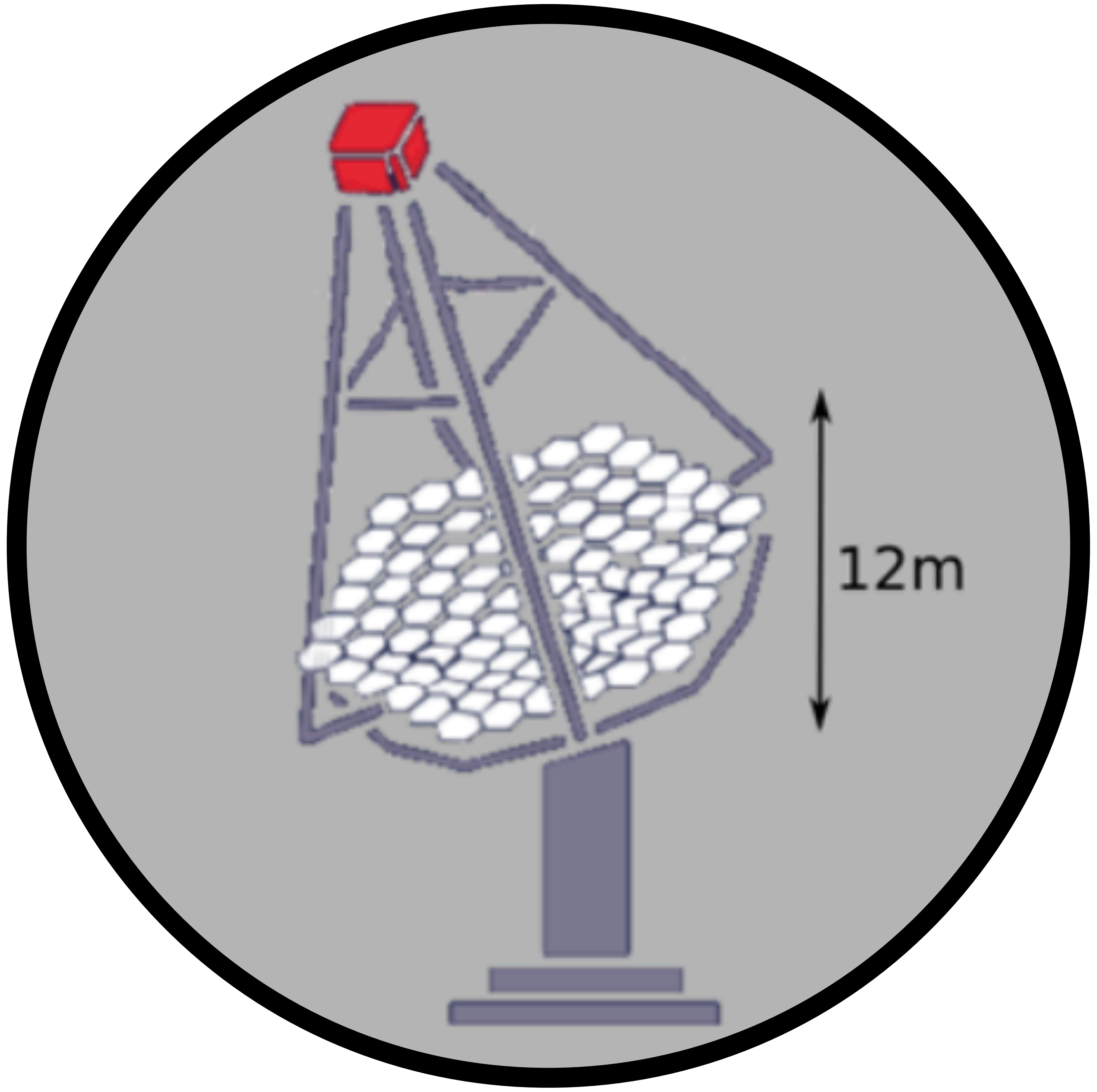
HAWC (2015)
Puebla, Mexico
(4100 m)



SWGO
Atacama, Chile
(4770 m)



Imaging Atmospheric Cherenkov Telescopes (IACTs)



Detecting method: Cherenkov radiation induced by EAS in atmosphere, ground-based, pointing

Field of View (FOV): 2-6°

Duty cycle: 10-15% (clear, moonless nights)

Angular resolution: $[0.04, 1]^{\circ}$

Energy resolution: ~15%

Effective aerea: ~10^5 m^2

Energy range: wide (50-100 TeV)

IACTs: detection techniques

Shower maximum:

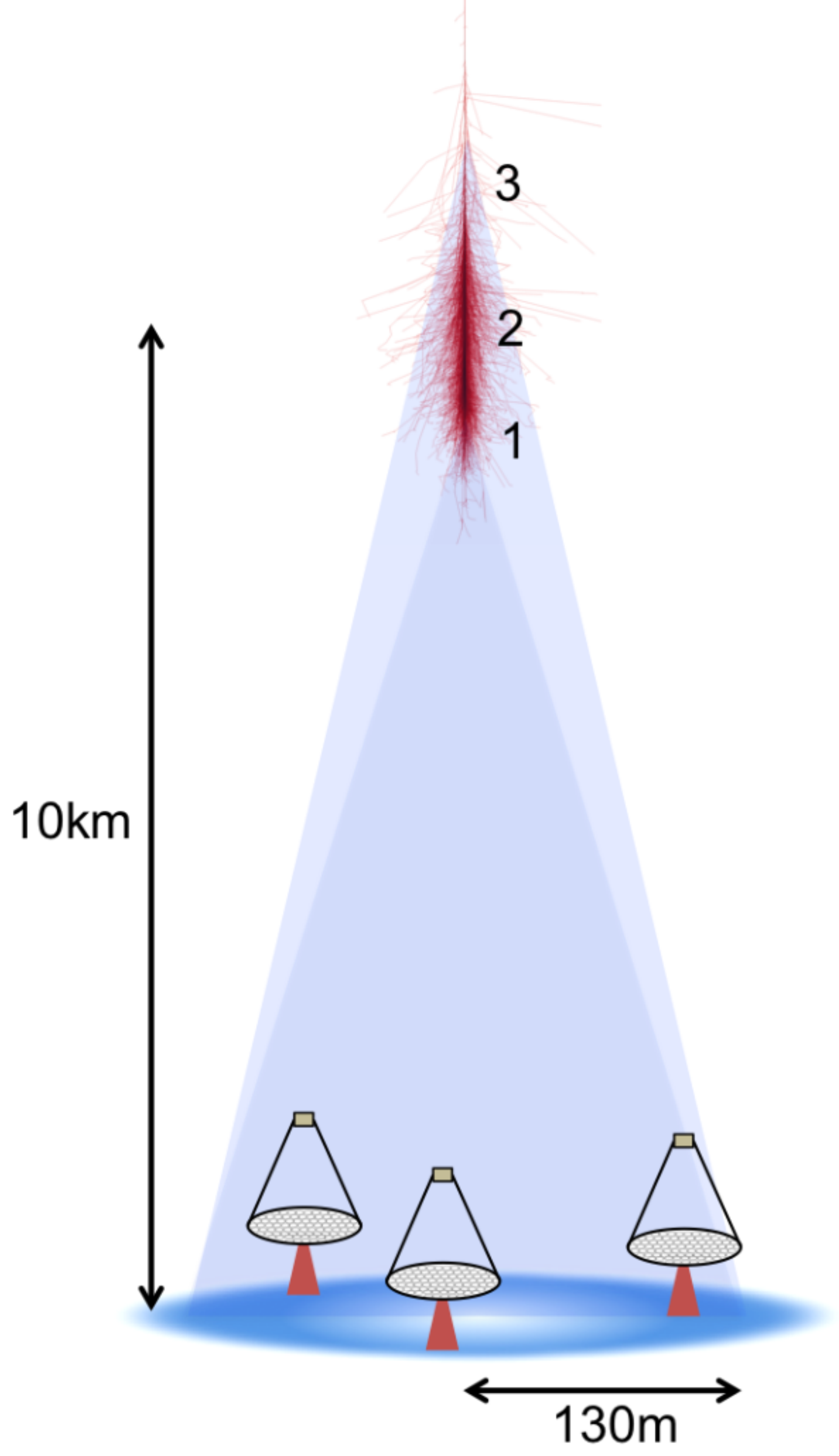
- Altitude ~10 km
- ~10^3 charged particles

Cherenkov emission:

- Altitude $\theta_{Cherenkov}$ ~1°
- Duration < 10 ns
- UV light

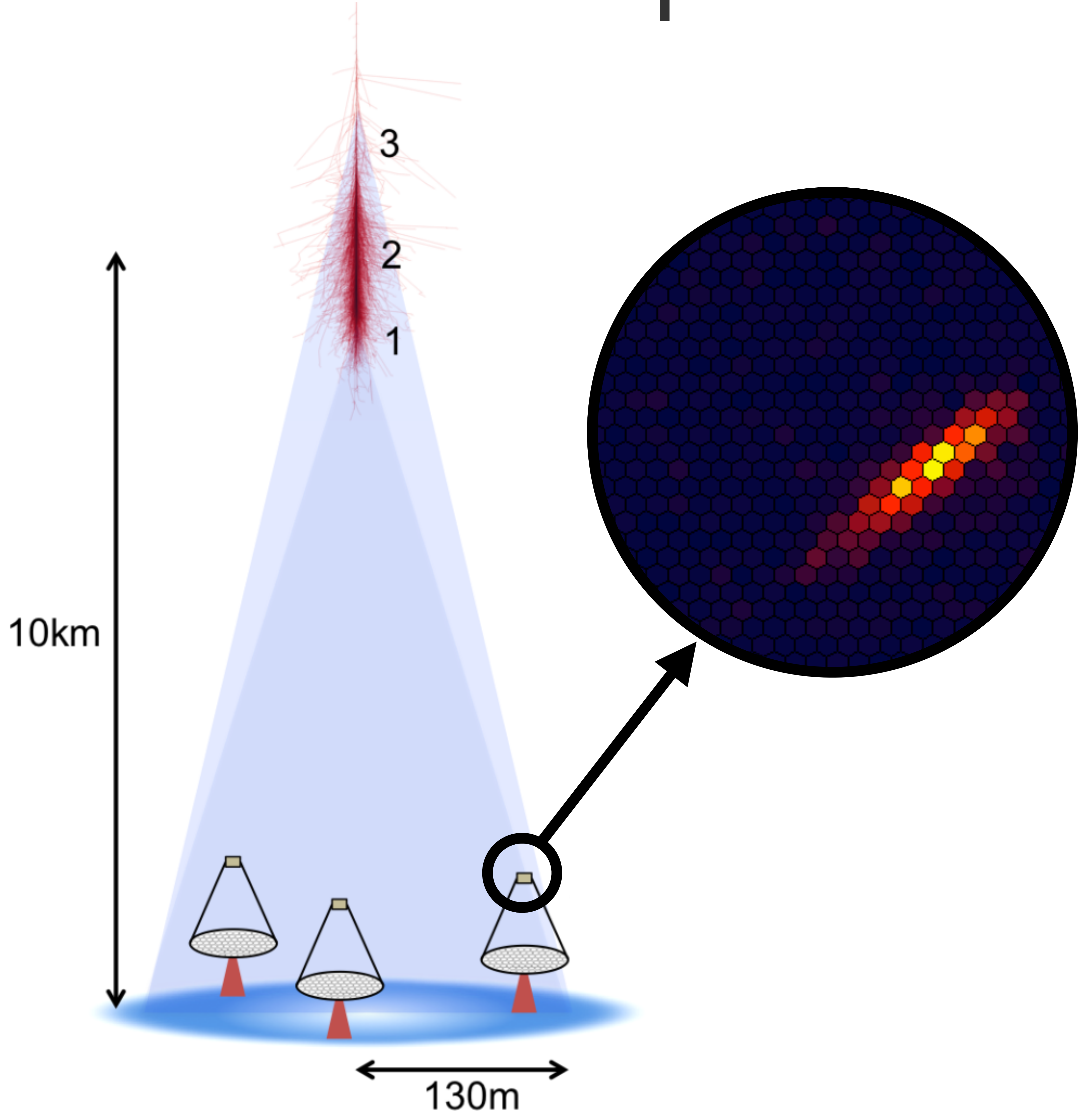
Cherenkov light-pool on ground:

- R ~100 m
- ~100 $\gamma_{Cherenkov}/m^2$



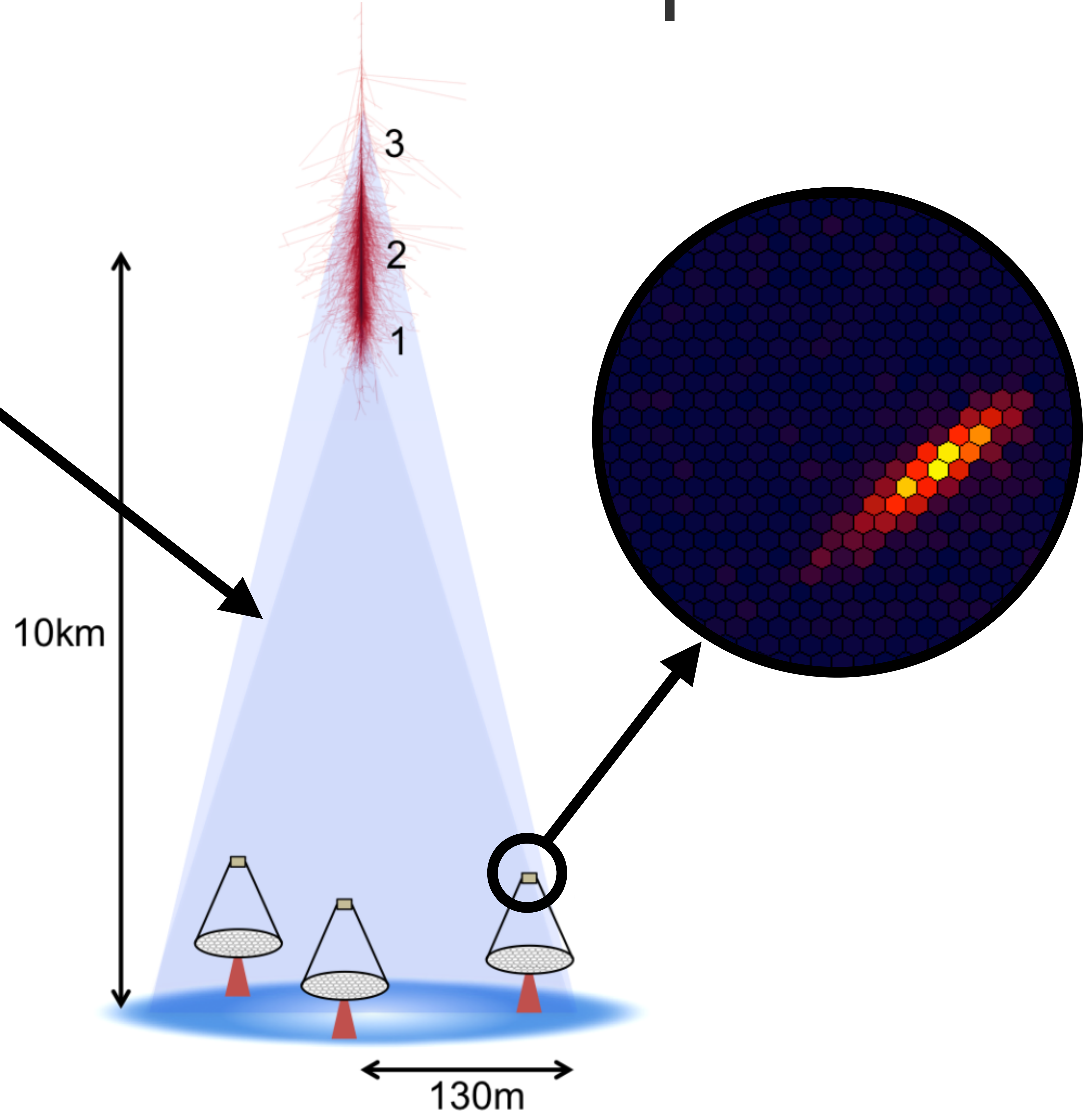
IACTs: detection techniques

- Cherenkov light-pool ~120 m
- Image the shower on a fast camera (Δt ~2ns)
- Large effective area (10^5 m^2) even with modest reflector
- Change in Cherenkov angle + multiple Coulomb-scattering washes out the ring shape of the Cherenkov light → faint elliptical shaft of UV light



IACTs: detection techniques

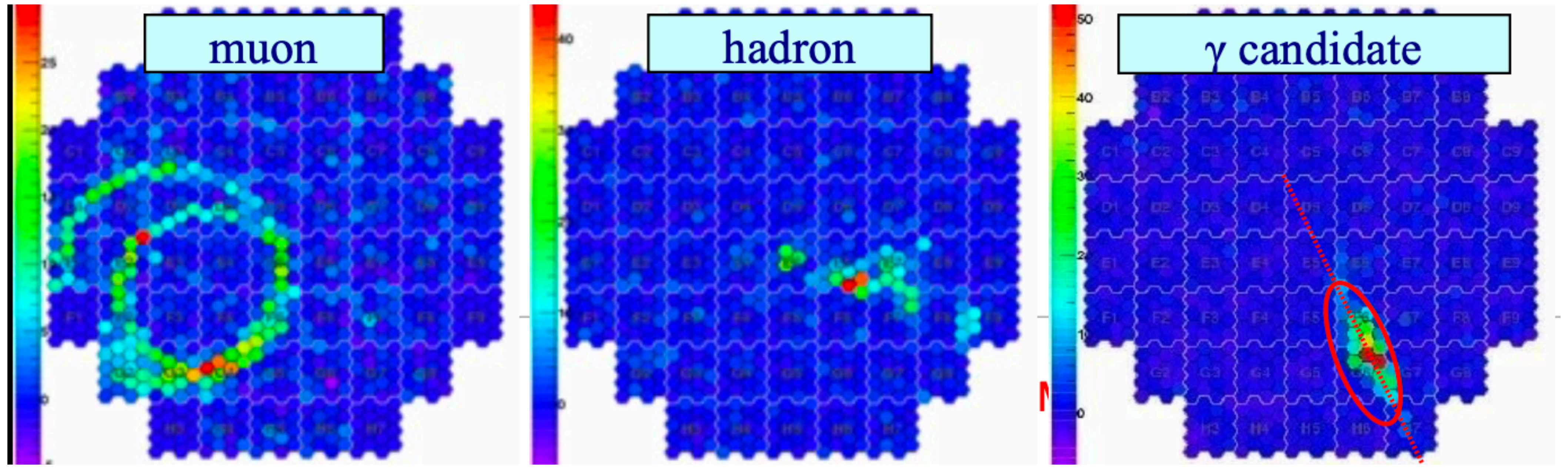
Energy: amount of Cherenkov light (calorimeter)



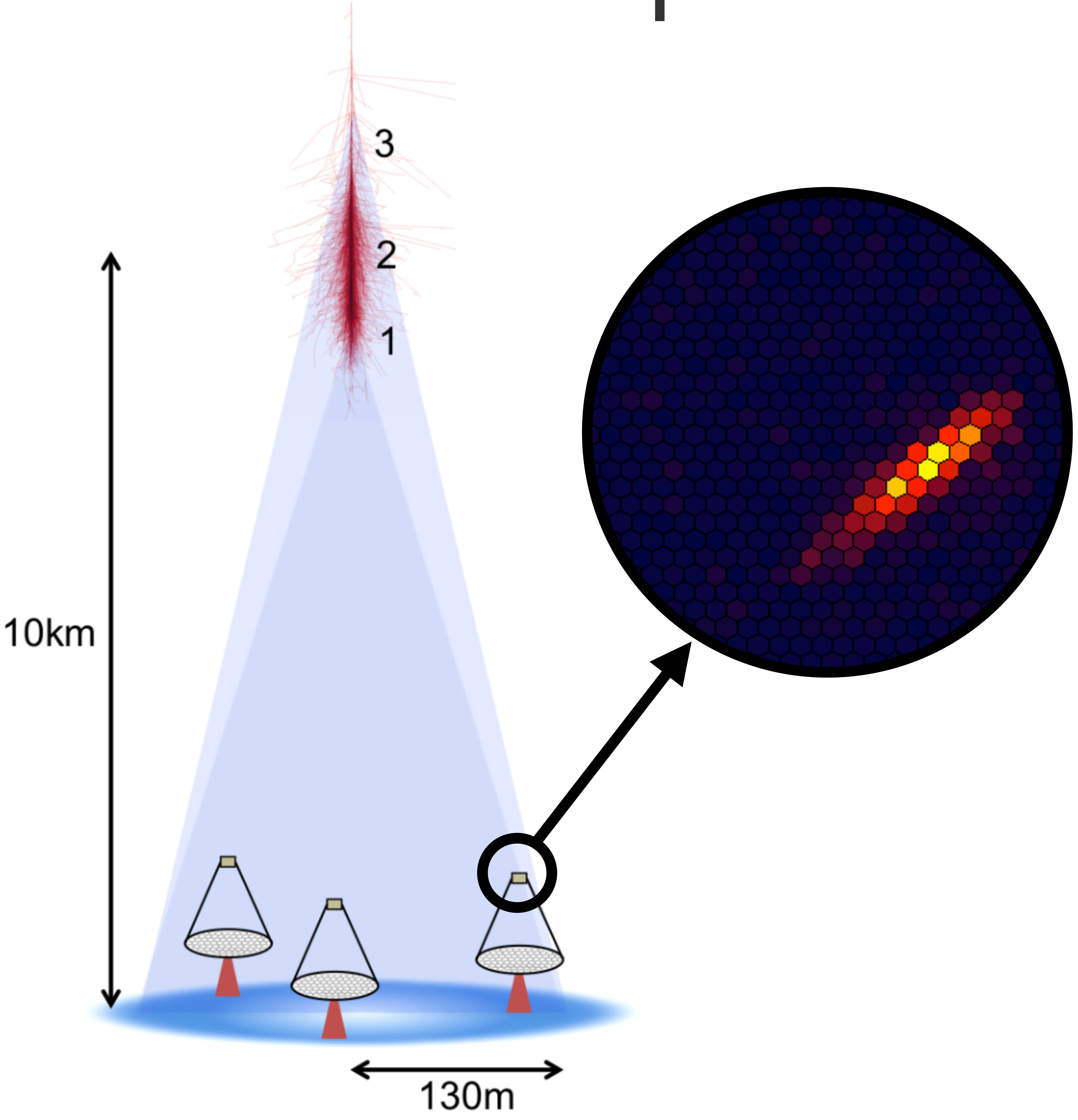
IACTs: detection techniques

Energy: amount of Cherenkov light (calorimeter)

Nature: shape of the shower



With every gamma-ray around 1000 cosmic rays enter the atmosphere at the same time making a significant background noise



IACTs: detection techniques

Energy: amount of Cherenkov light (calorimeter)

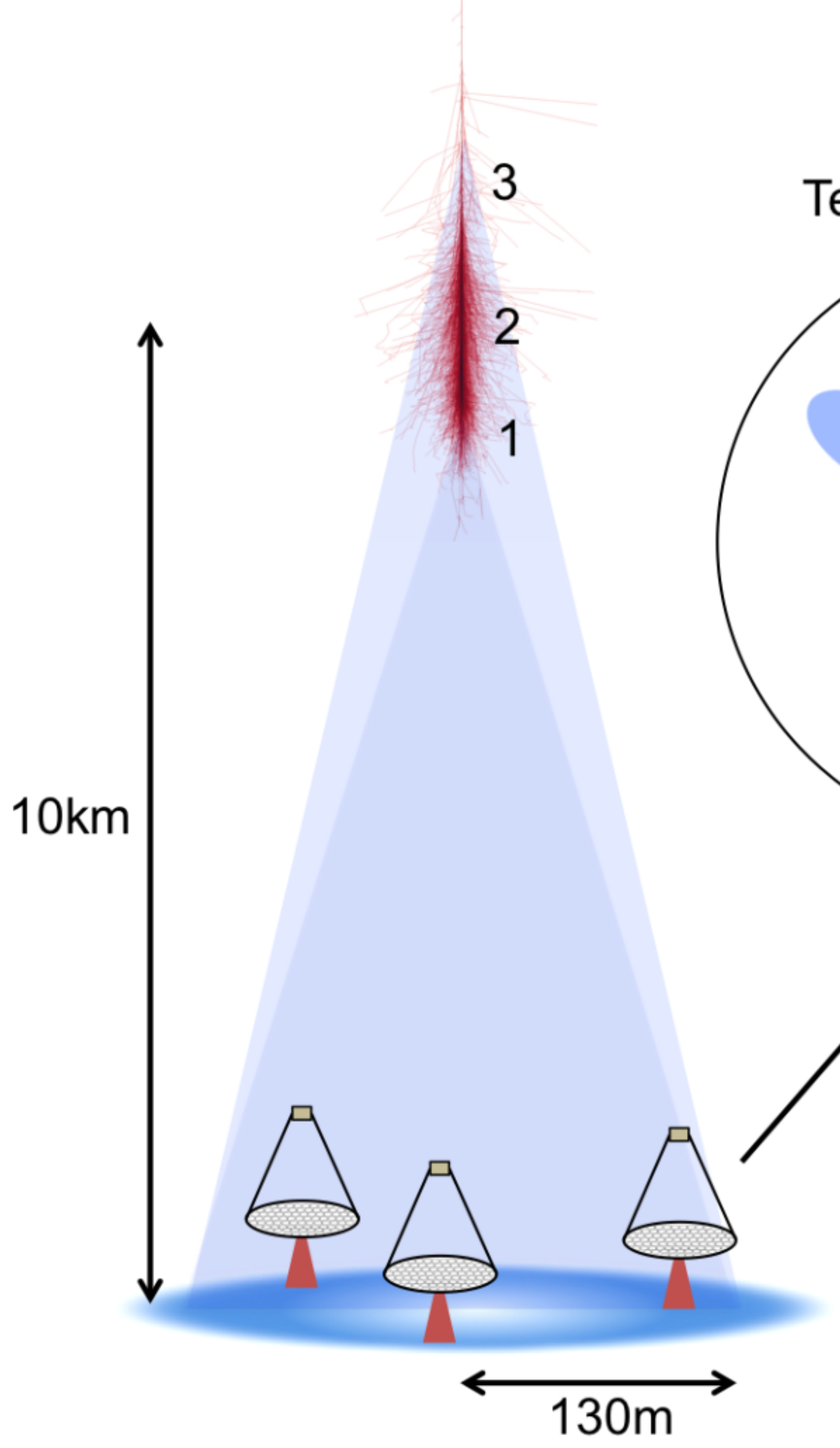
Nature: shape of the shower

Direction: stereoscopic observation

↓

Directional reconstruction by geometrical intersection of image main axes

- Greatly reduces the background at the trigger level (requiring 2-tel coincidence)
- Significantly improves shower reconstruction, PSF, etc



IACTs: detection techniques

Energy: amount of Cherenkov light (calorimeter)

Nature: shape of the shower

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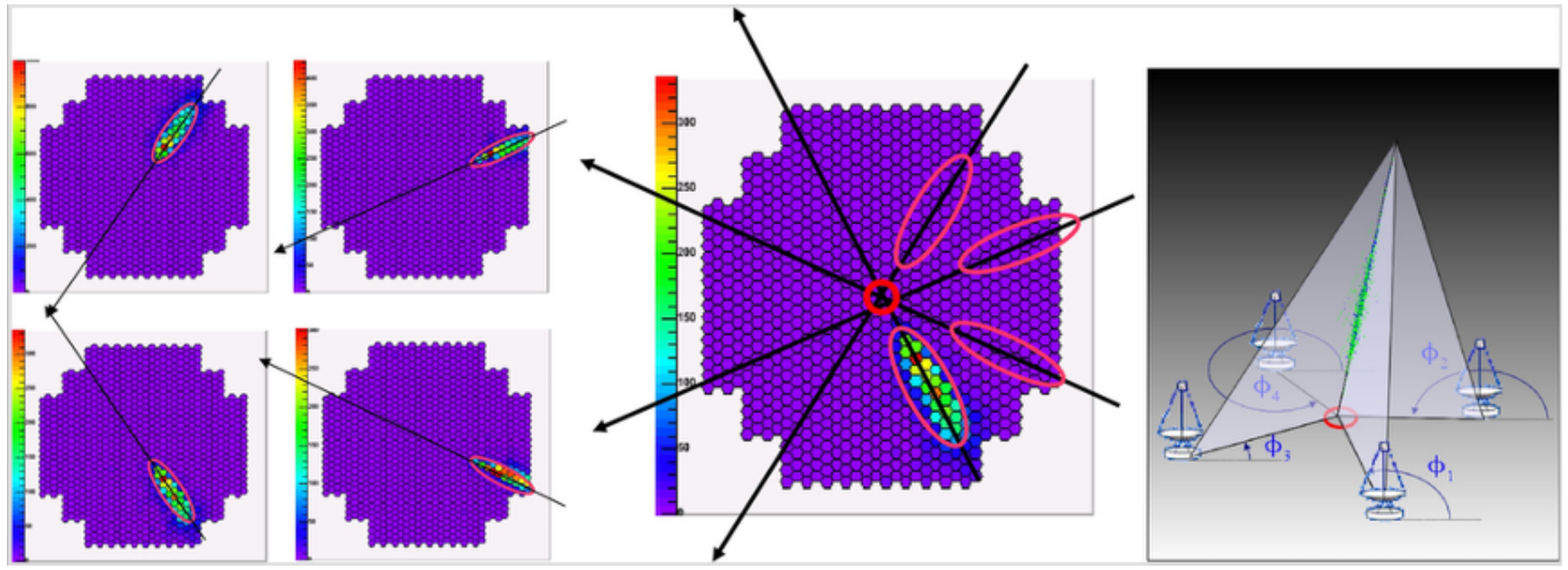
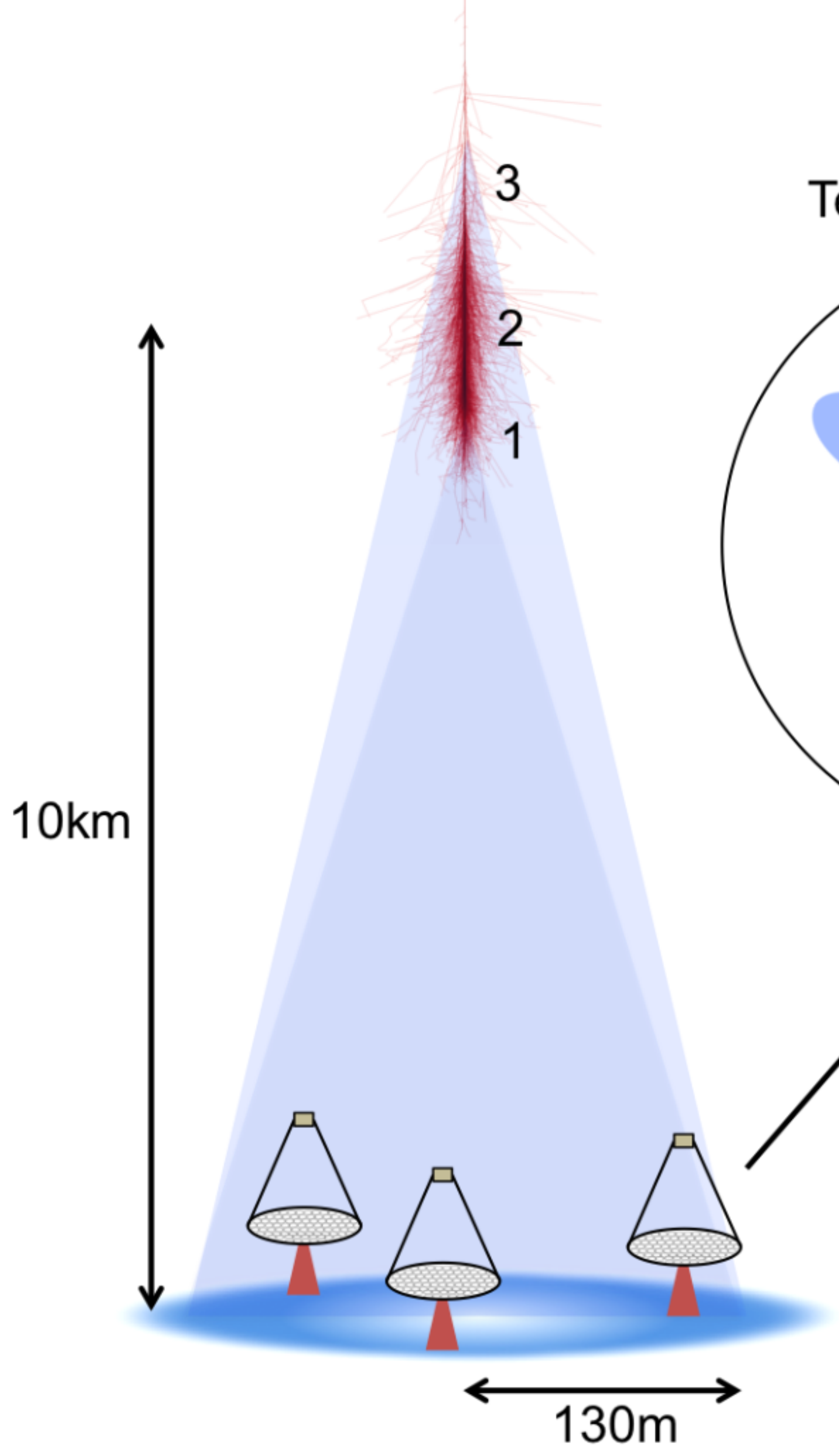
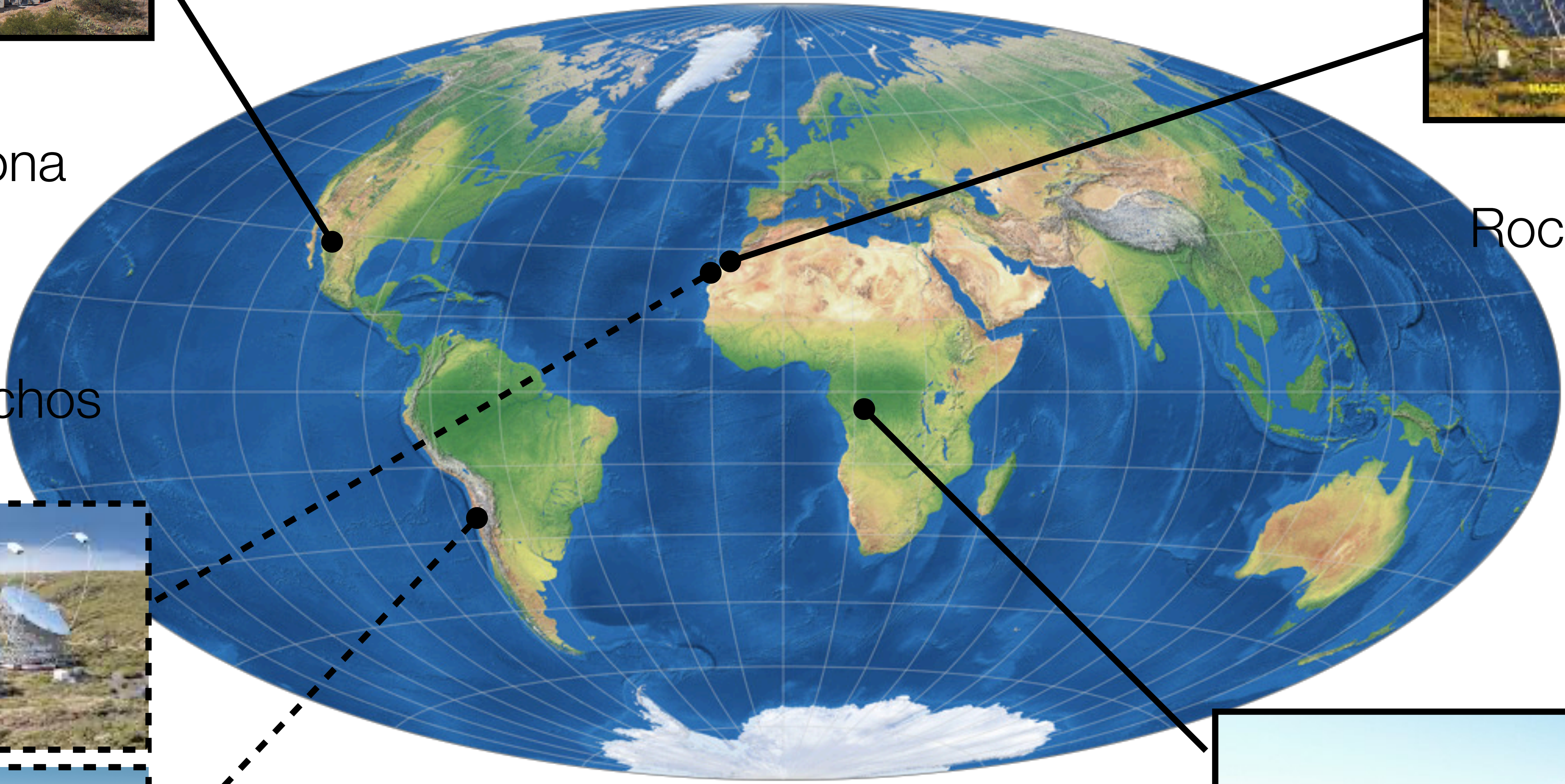




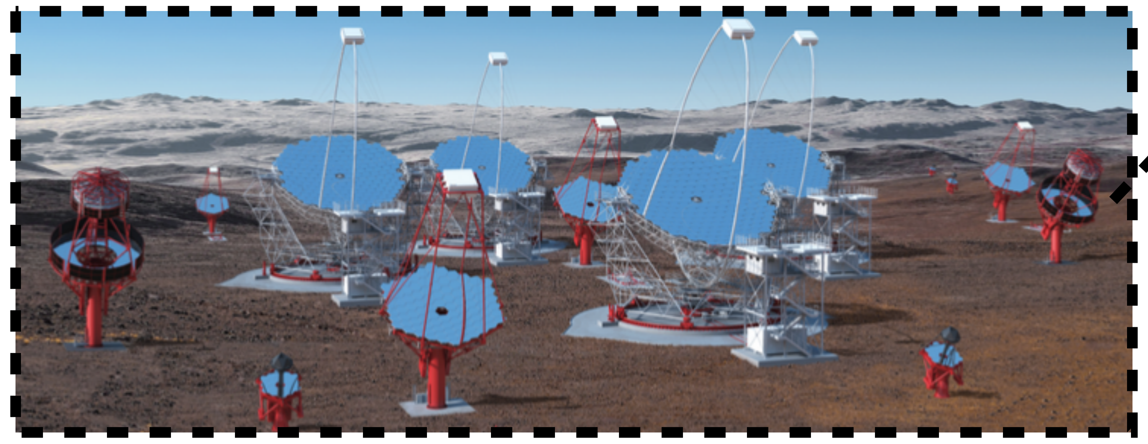
Current and future generation of IACTs

VERITAS
Mount Hopkins, Arizona

MAGIC
Roche de los Muchachos
Canary Island

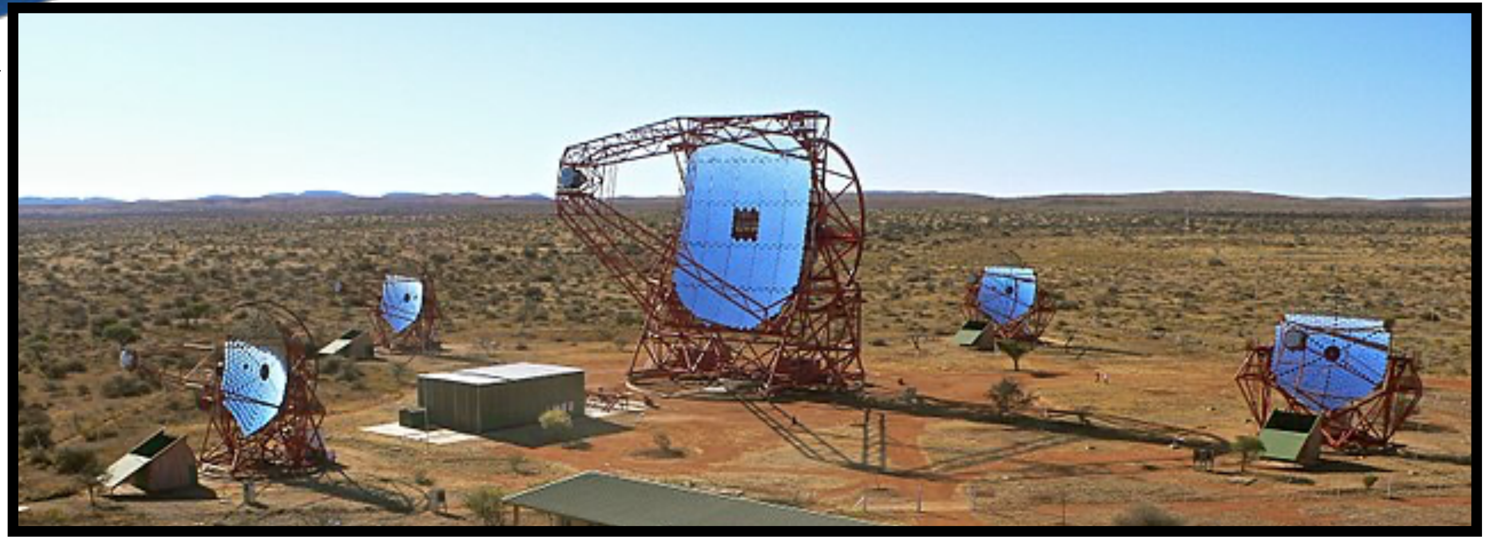


CTAO - North
Roche de los Muchachos
Canary Island

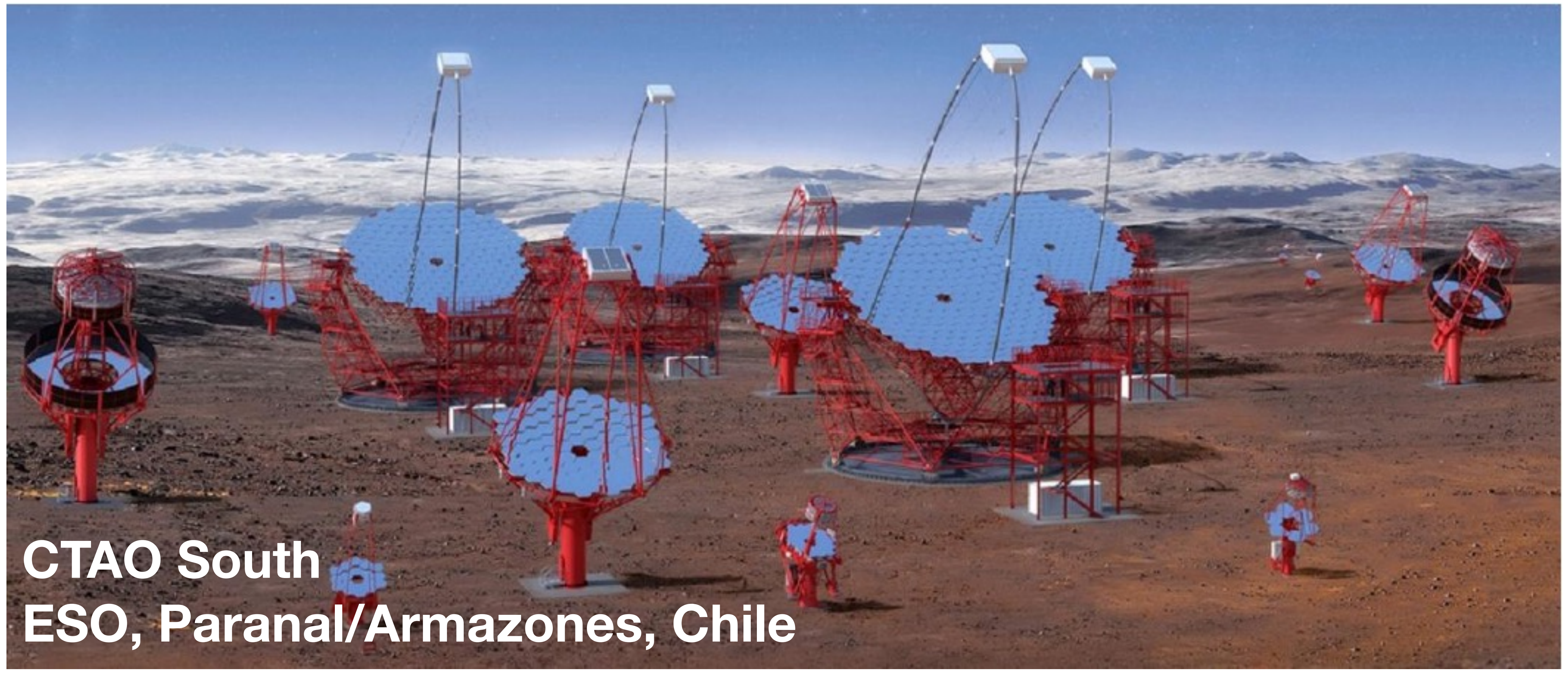


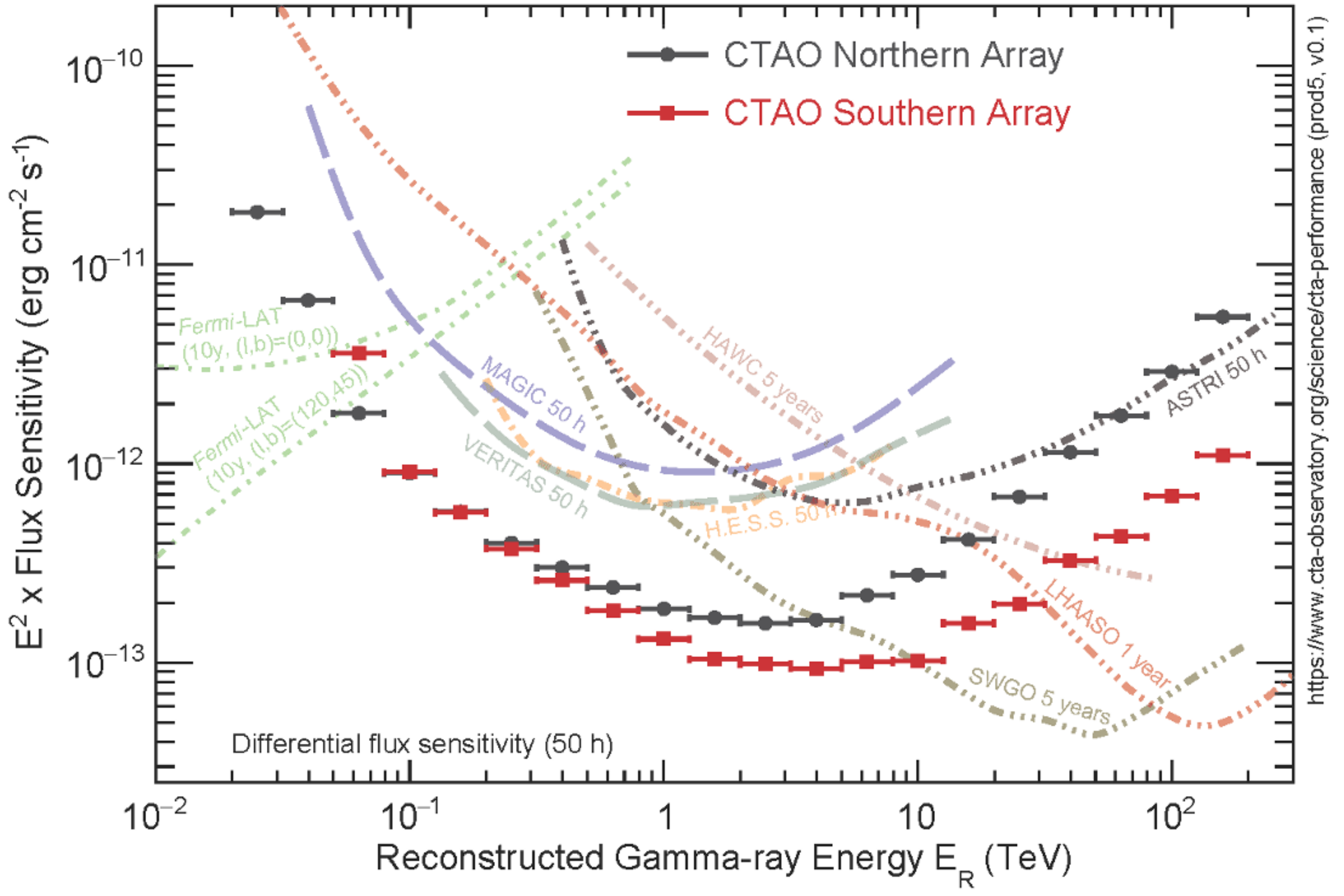
CTAO - South
Atacama, Chile

H.E.S.S. (2002)
Khomas Highland,
Namibia

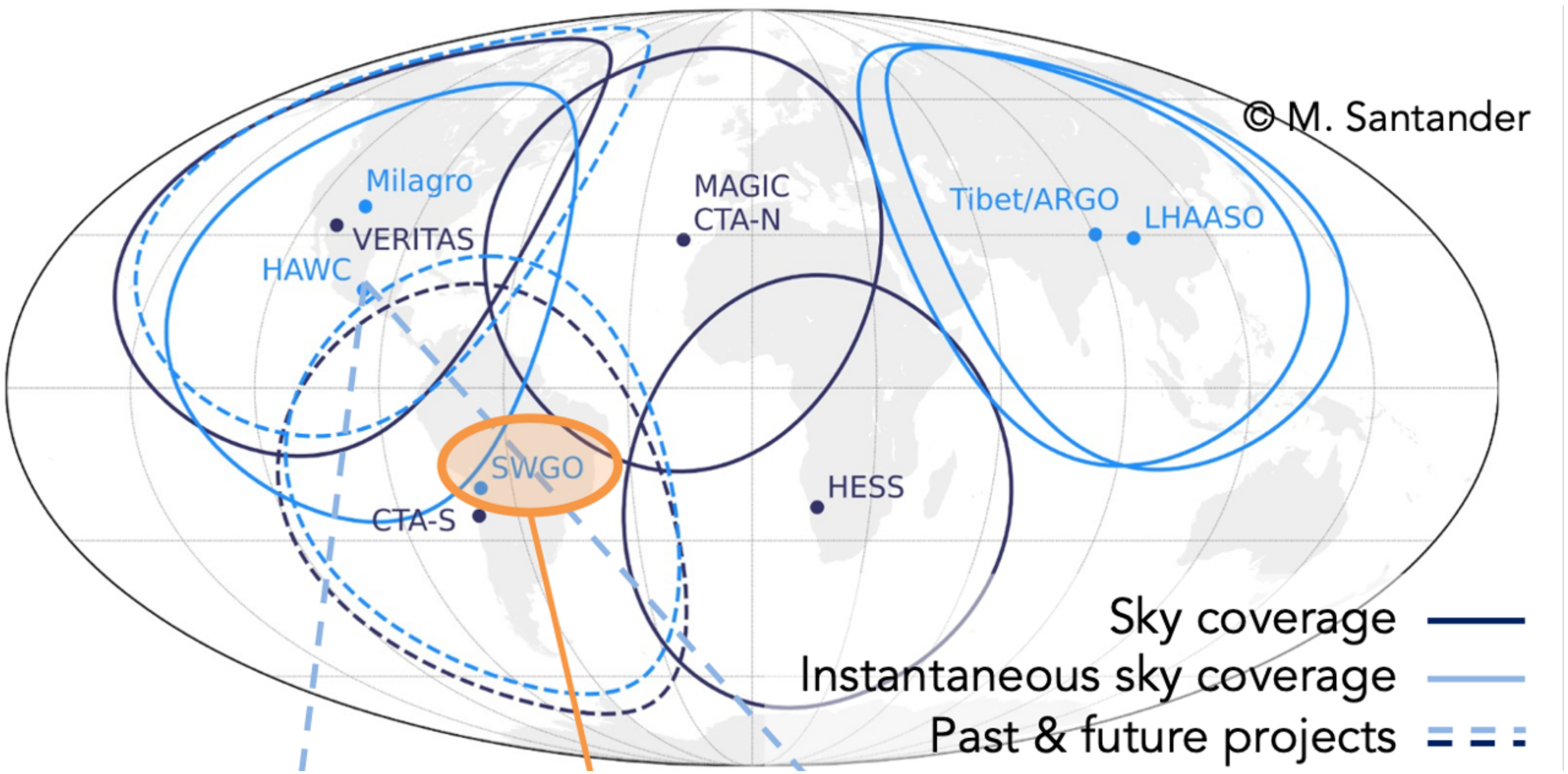


Future IACTs: The Cherenkov Telescope Array Observatry (CTAO)



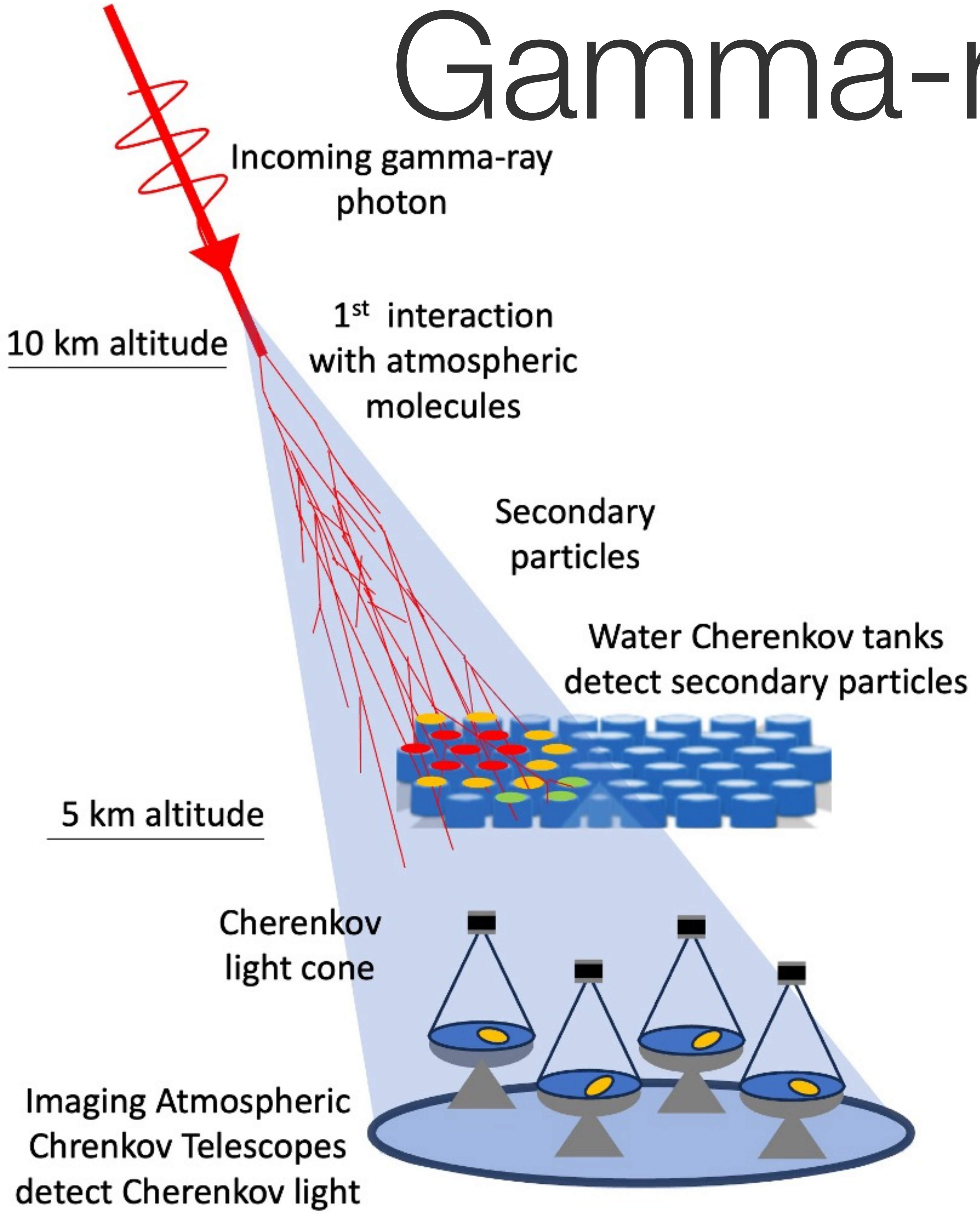


Current and future generation of WCT and IACTs



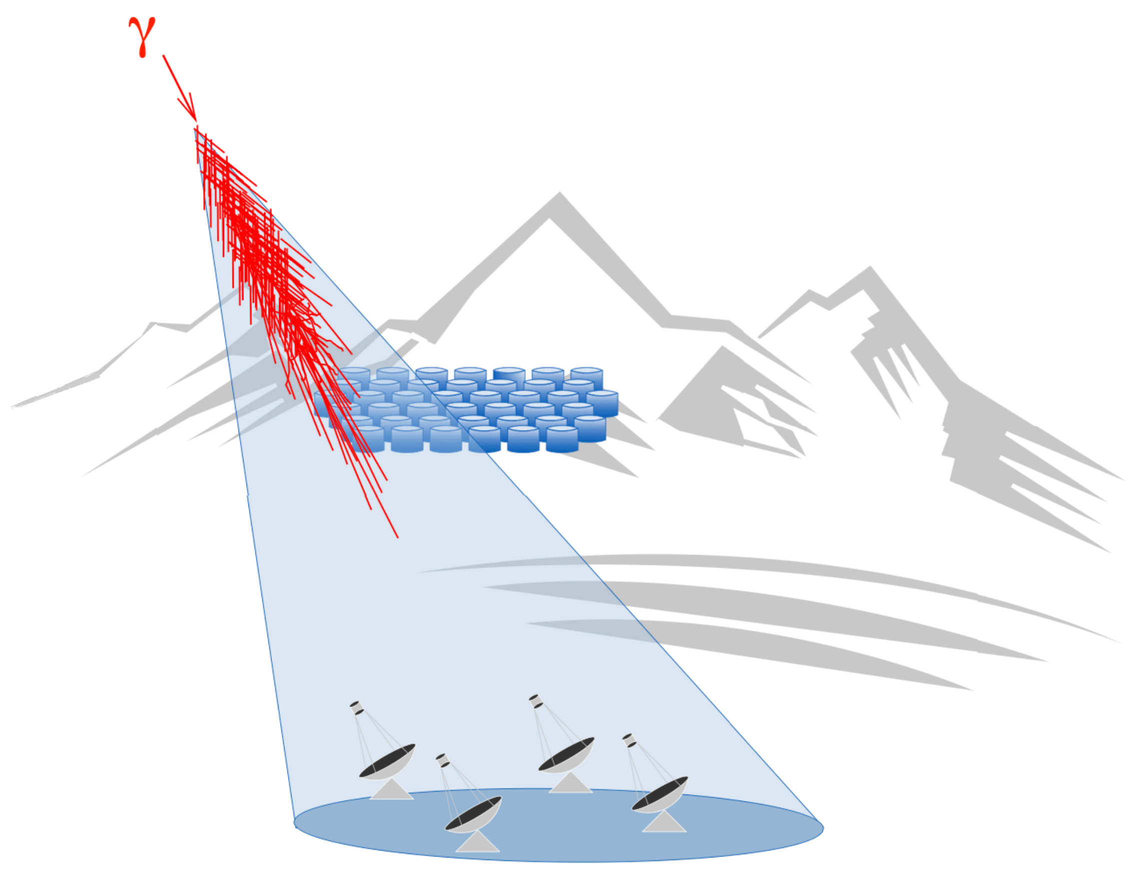
Gamma-ray Astrophysics

Summary

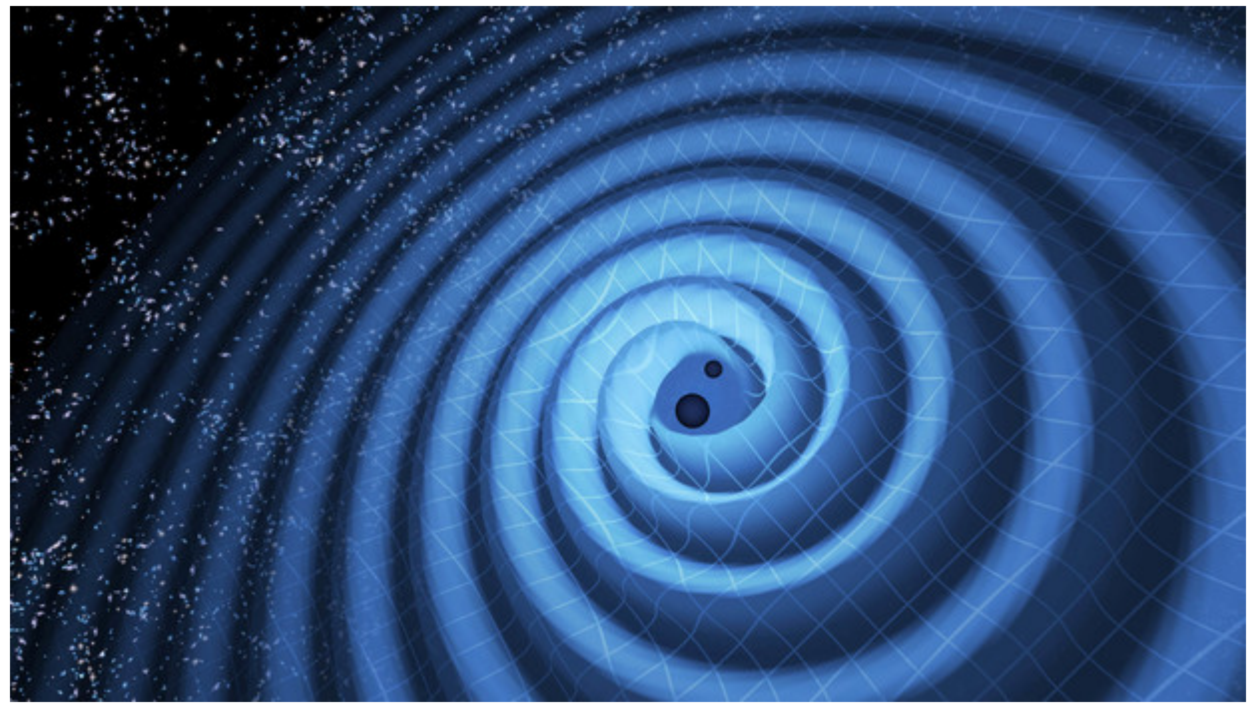


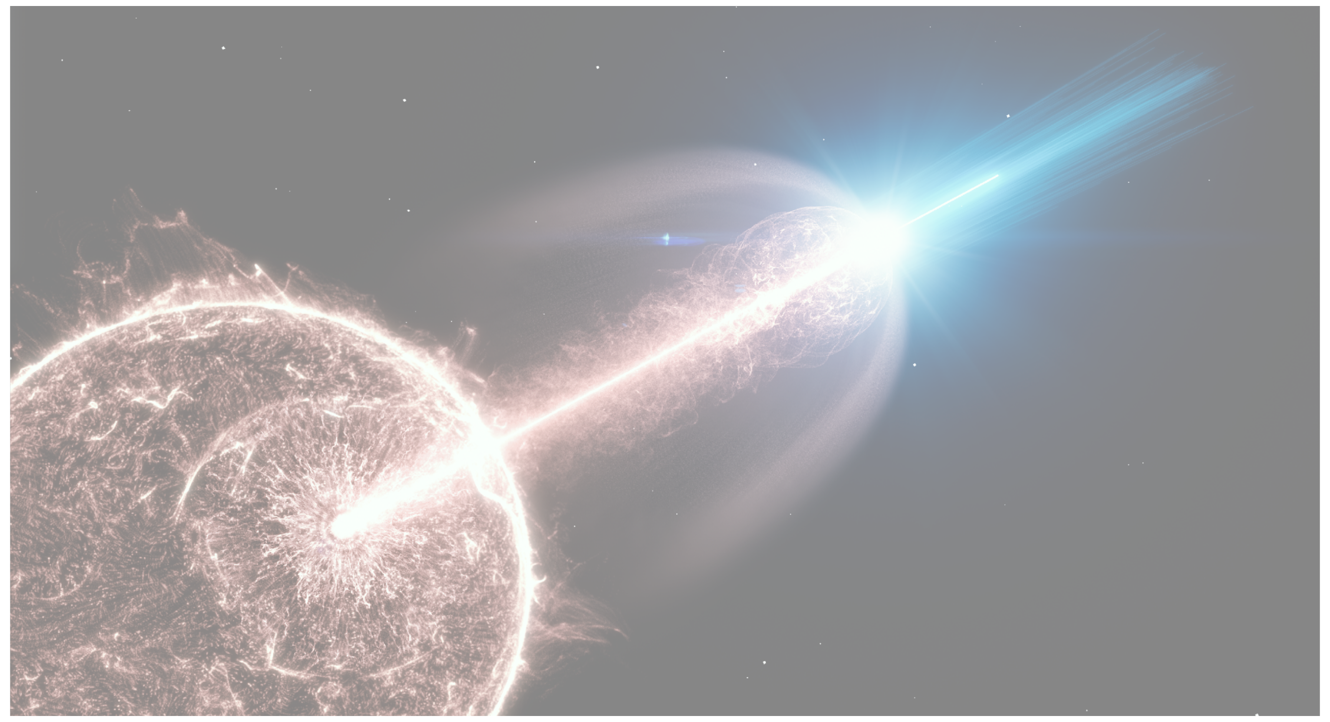
	Space-based (Fermi-LAT)	Ground-particle arrays	IACTs
Field of view	$\sim$137°	90°	3°-10°
Duty cycle	$>$95%	$>$95%	10-30%
Energy range	20 MeV - $>$ 300 GeV	$\sim$500 GeV - $>$100 TeV	30 GeV - $>$100 TeV
Angular resolution	0.15°($>$ 10GeV)	0.4°-0.1°	0.05-0.02°
Energy resolution	15% $>$ (100 MeV)	60% - 20%	$\sim$7%
Background rejection	$<$ 10%	90% – 99.8%	$>$95%
Effective area	0.8 m^2	several 10^4 m^2	several 10^4 m^2

Outline



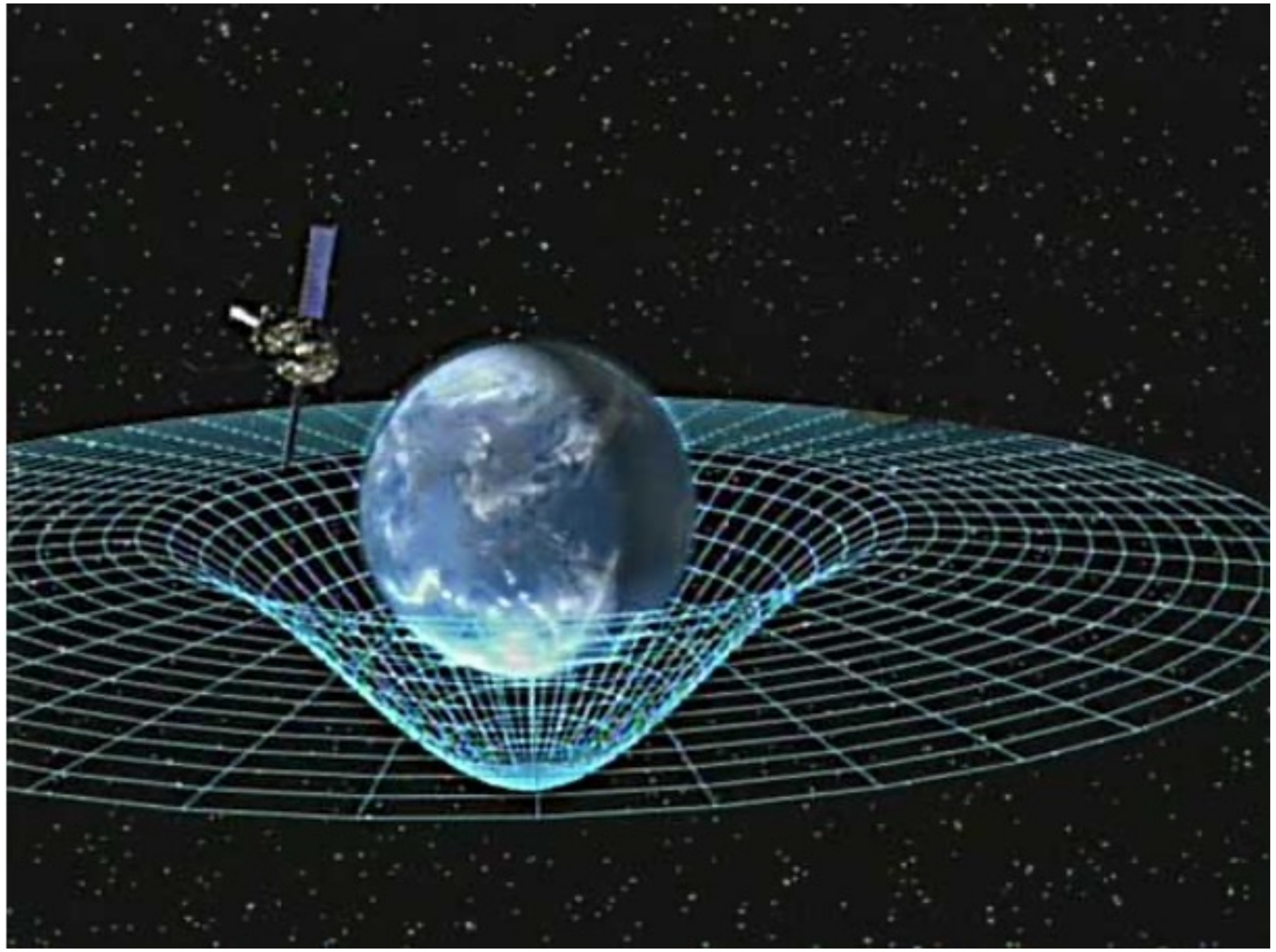
2. Gravitational Waves





Gravitational Waves

- Gravitational waves are '**ripples**' in space-time caused by some of the most violent and energetic processes in the Universe
- Albert Einstein predicted their existence in 1916 in his general theory of relativity
- They travel at the speed of light (300,000 km per second)
- These waves squeeze and stretch anything in their path as they pass by



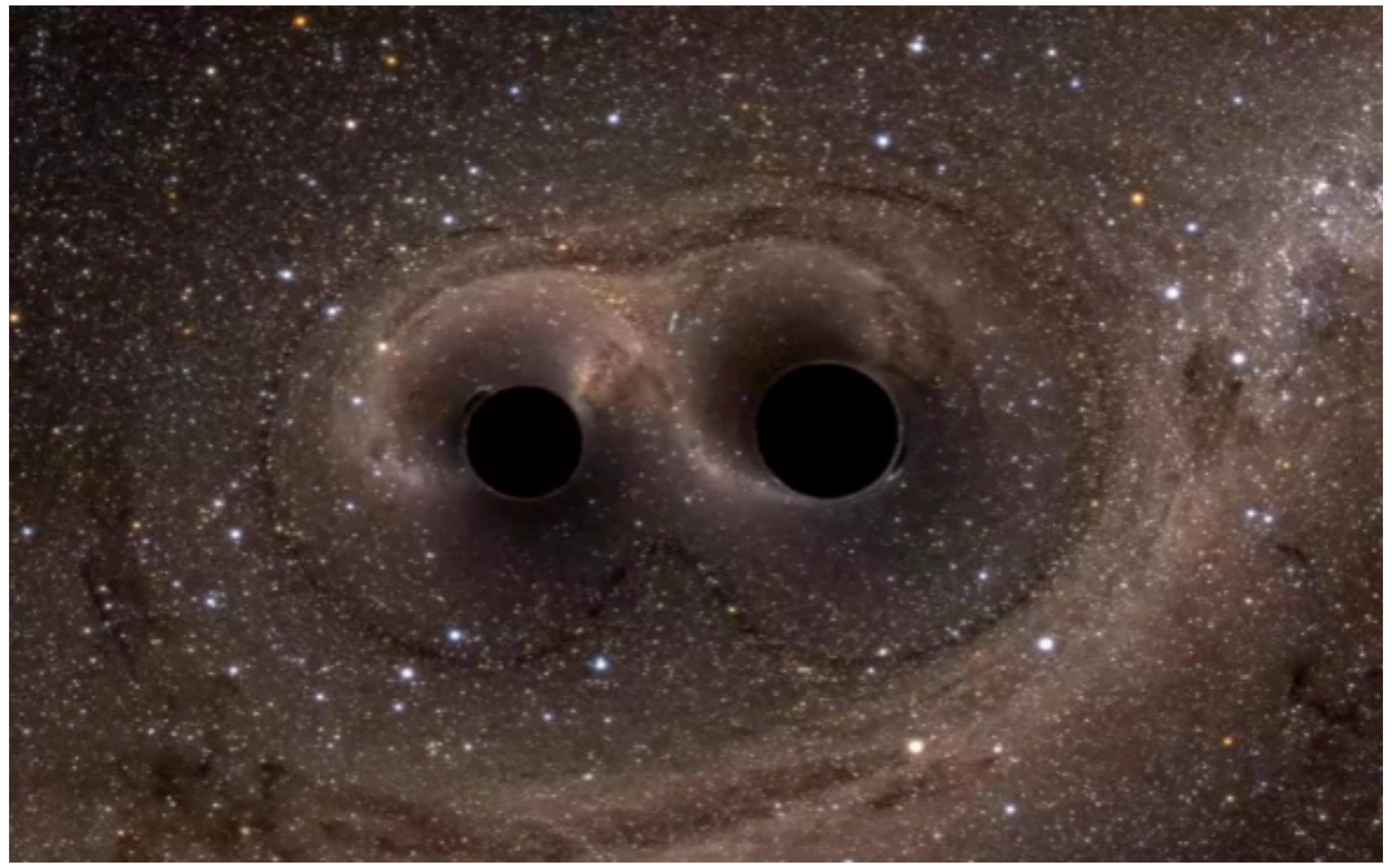
What causes gravitational waves?

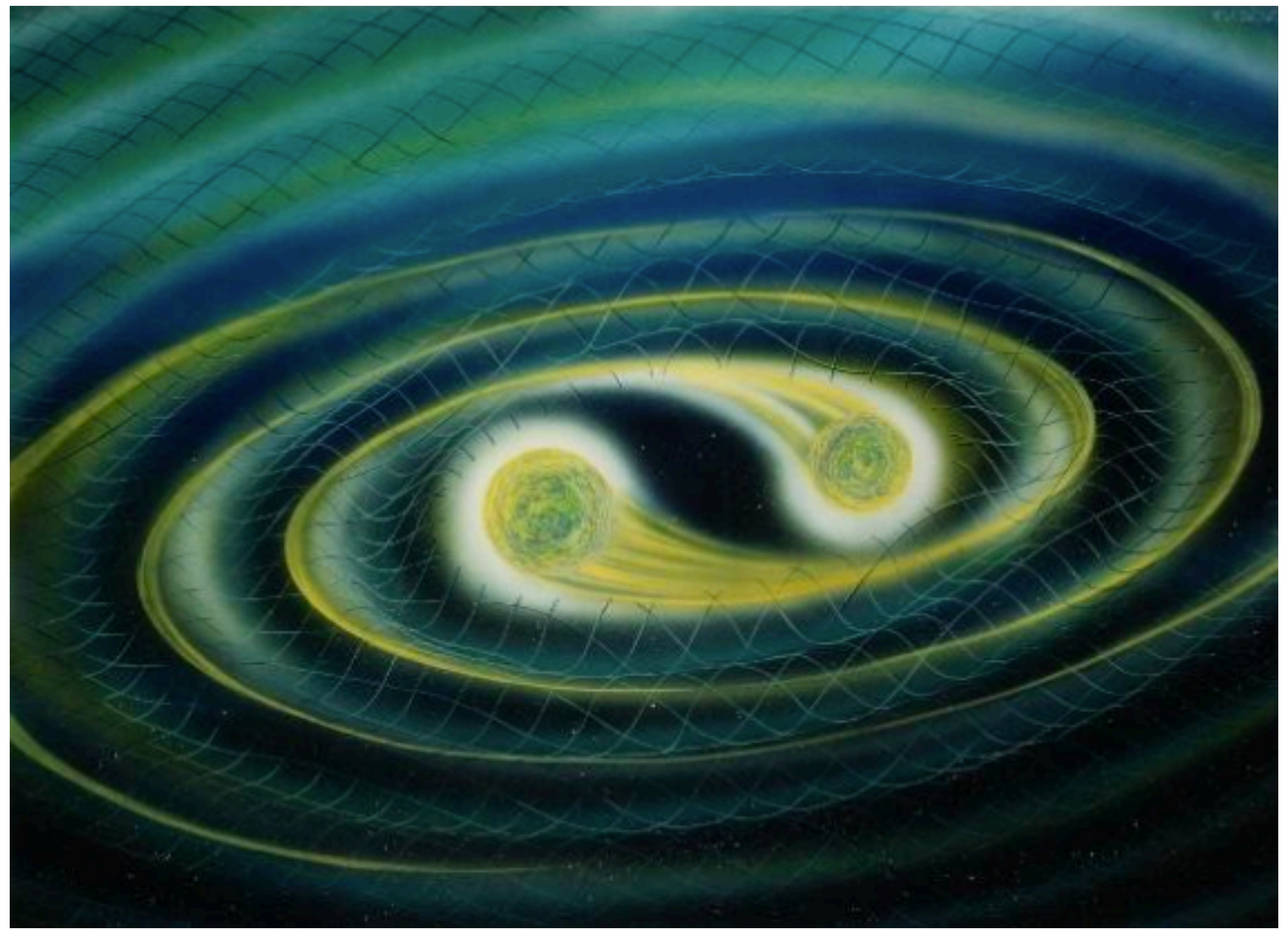
- In theory, all accelerating objects emit gravitational waves, but most are too weak to detect
- The most powerful gravitational waves are created when objects move at very high speeds
- Only massive and fast cosmic events produce detectable waves

Two black holes orbiting each other and merging

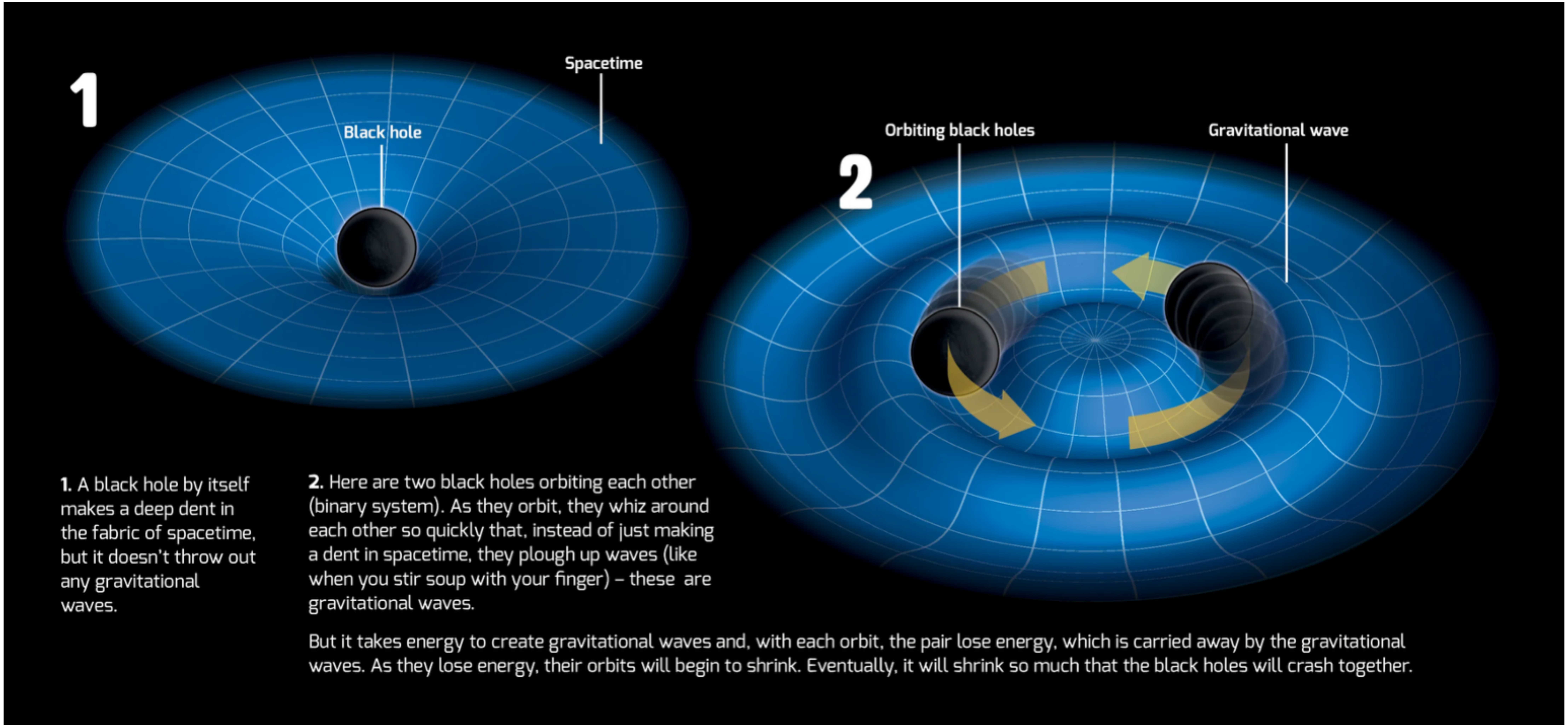
Two big stars orbiting each other

A star exploding asymmetrically (Supernova)





How gravitational waves are generated

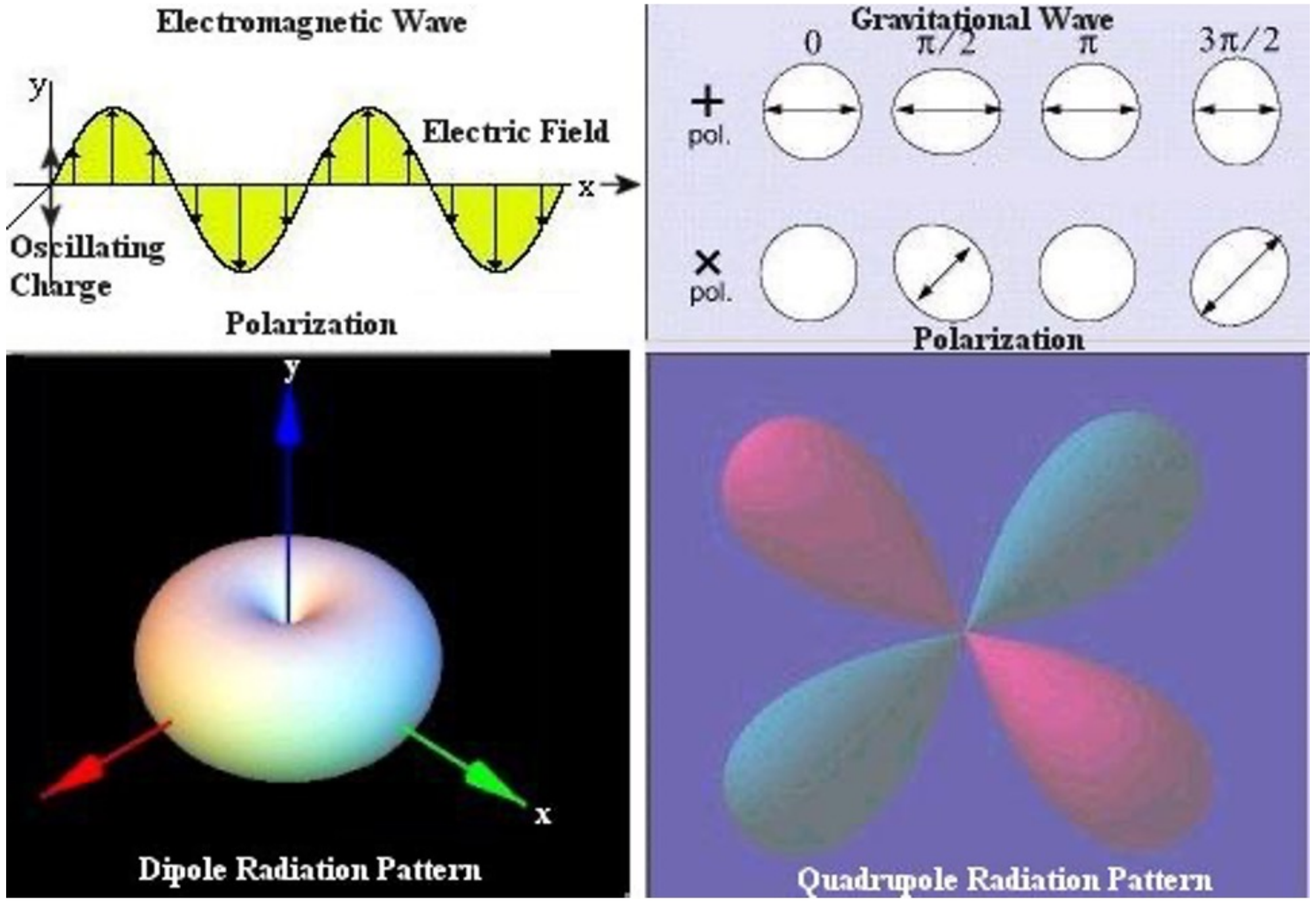


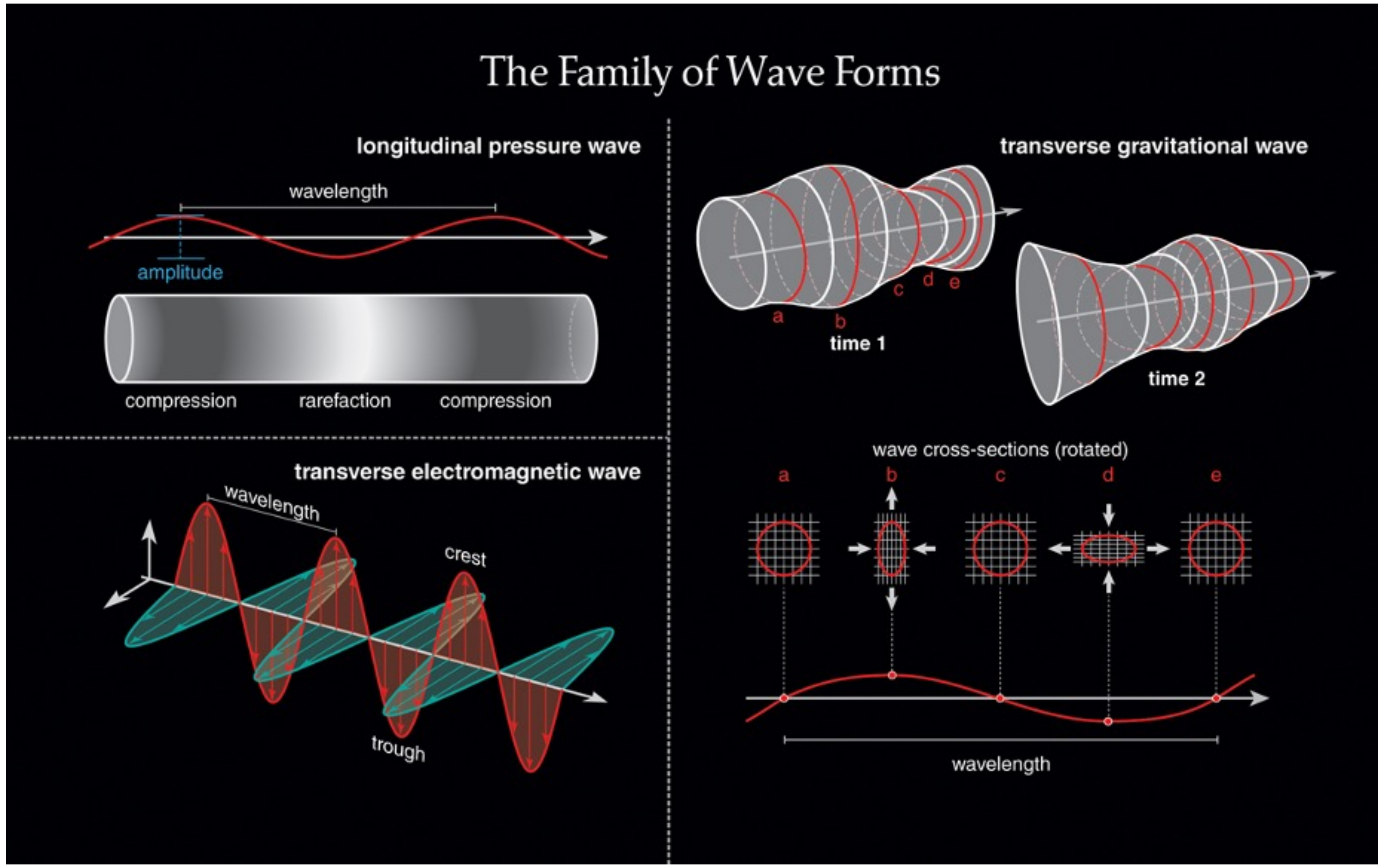
How gravitational waves are generated

Solution of Einstein's equation of general relativity:

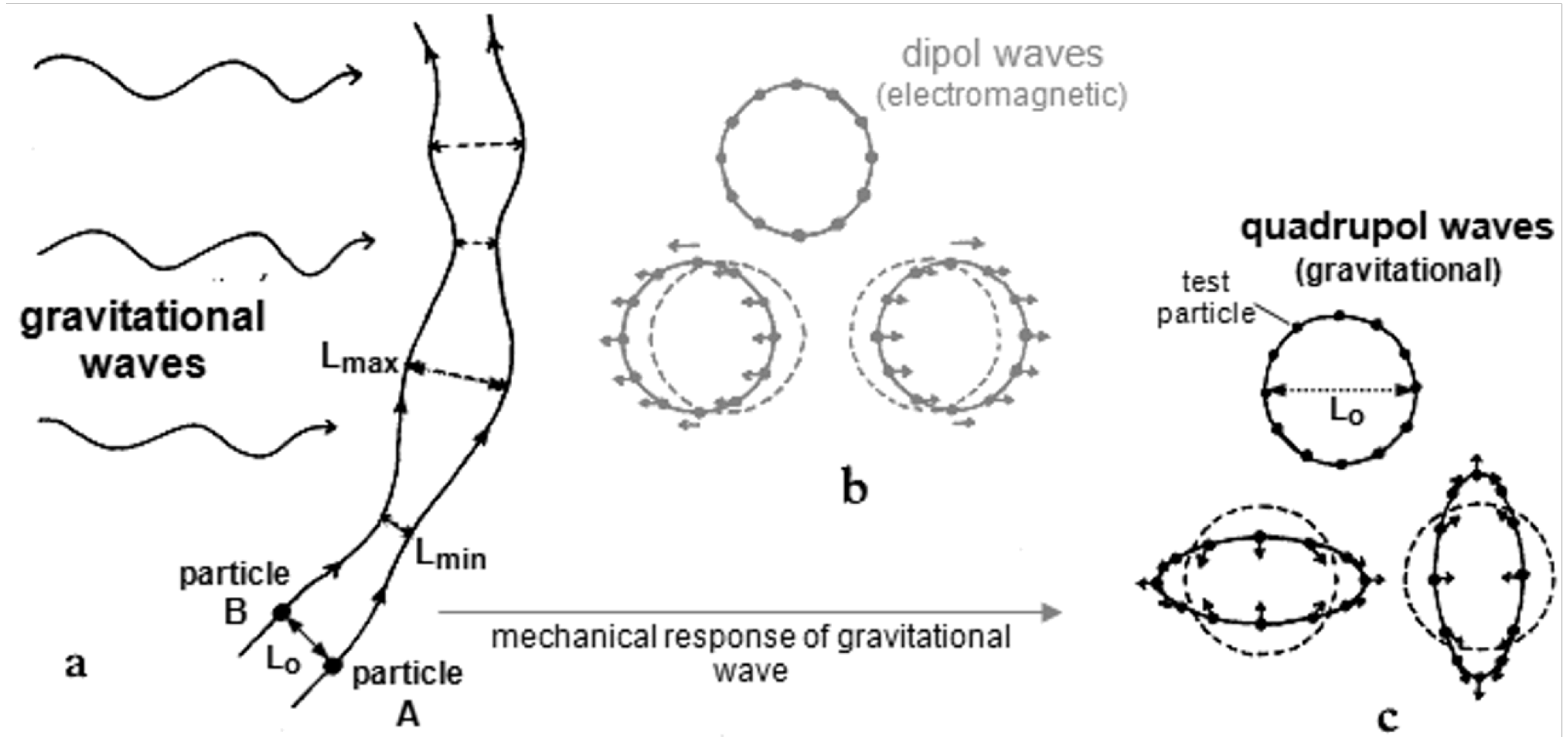
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

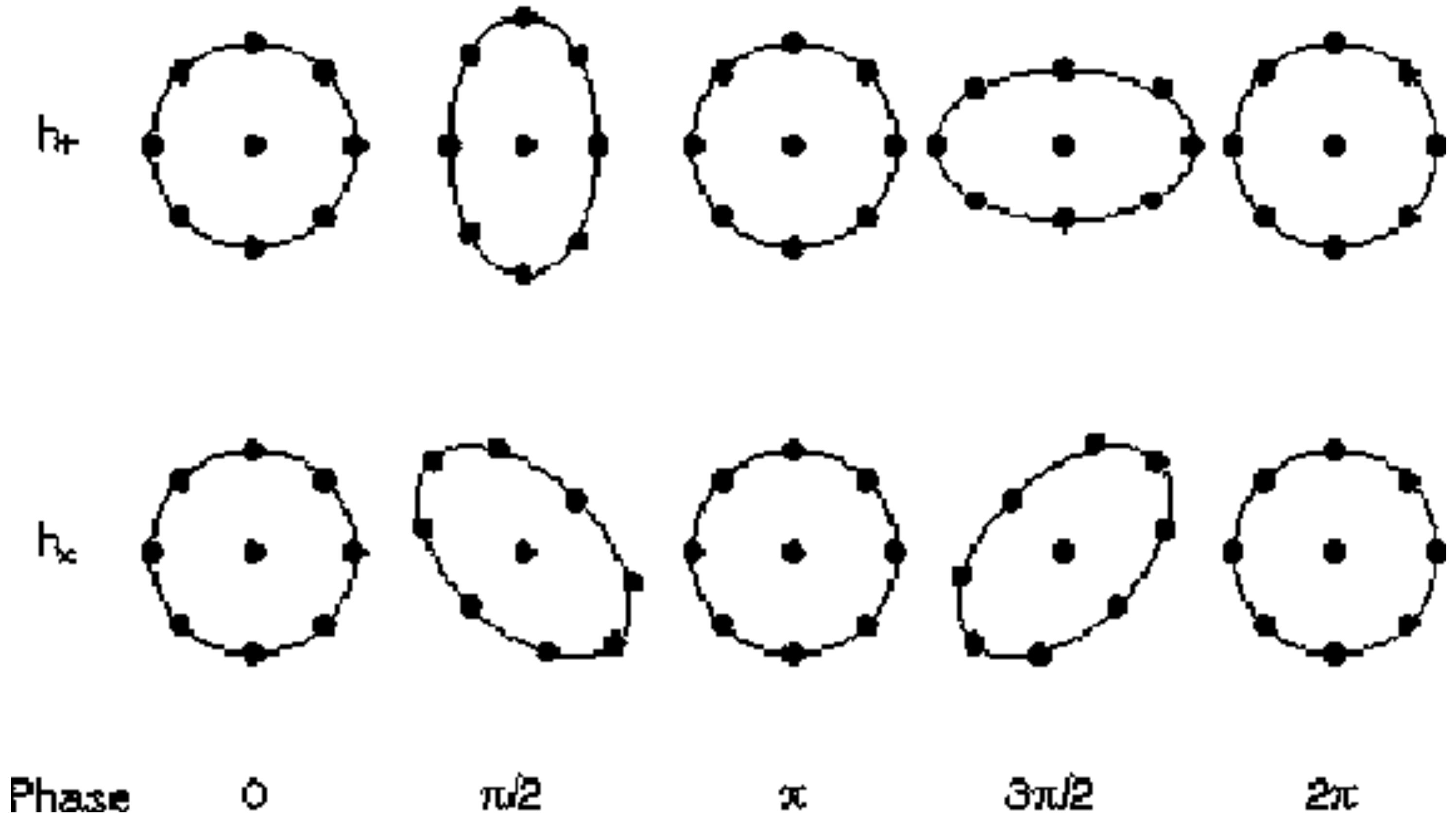
Gravitational Waves happen here





Gravitational waves deform spacetime





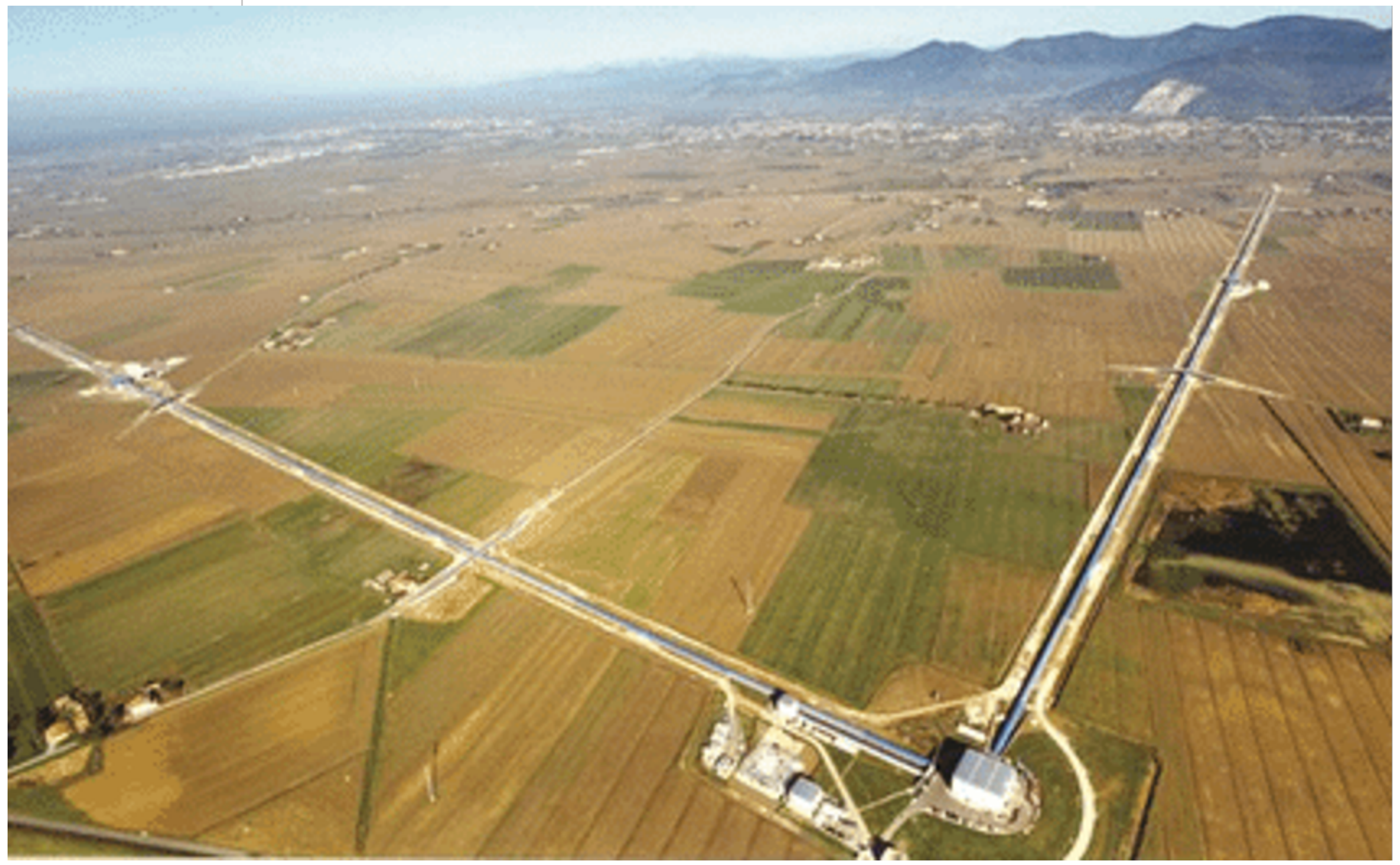
The effect of a GW

$$h \approx \frac{4G^{5/3}}{c^4}\frac{(\pi f)^{2/3}\mathcal{M}^{5/3}}{D} \sim 10^{-22} \quad \Rightarrow \quad \frac{\Delta L}{L} \simeq h \sim 10^{-22}$$

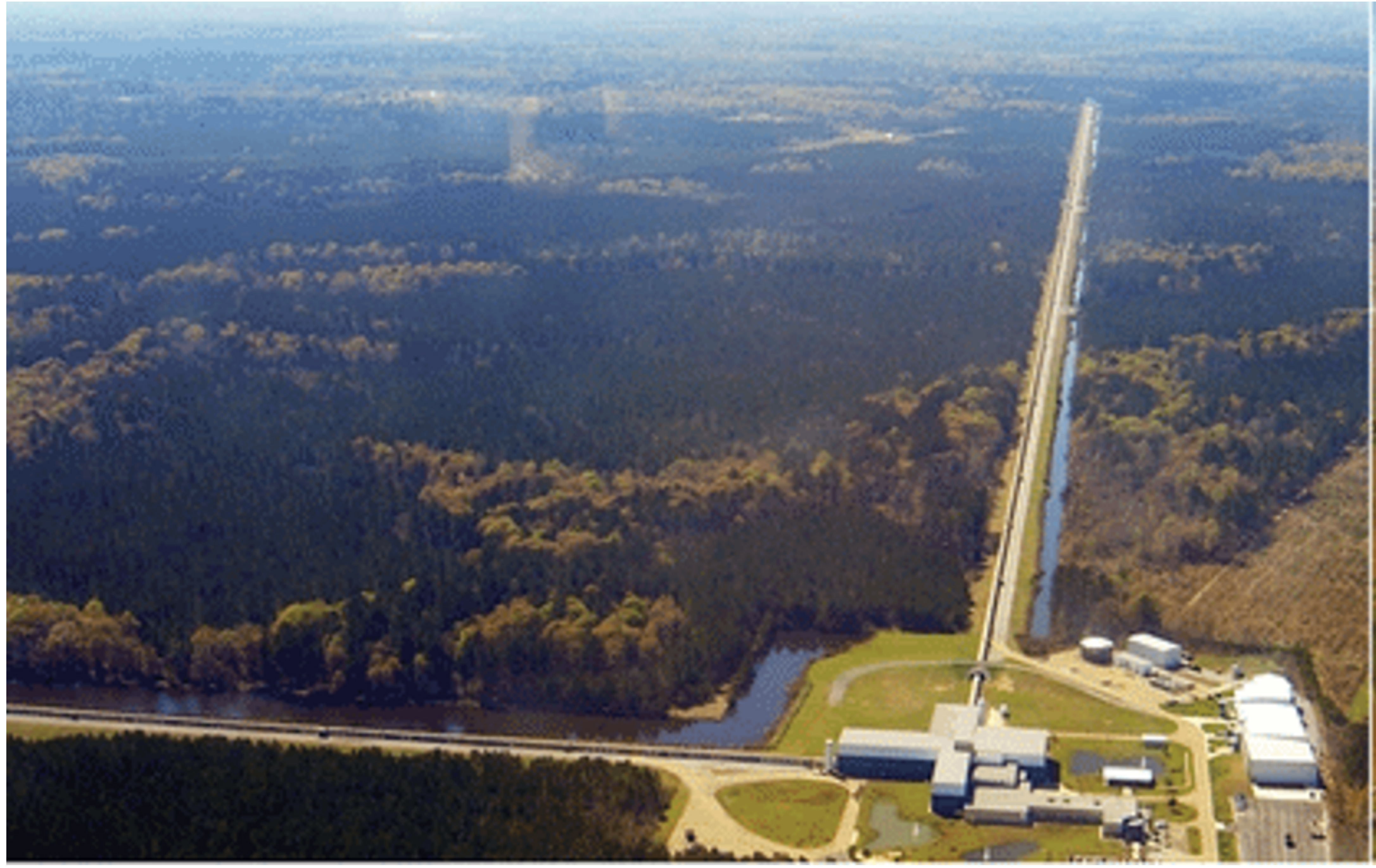
The strain *h* is the ration of the deformation in the arm length to the arm length. Usually smaller than an atom.

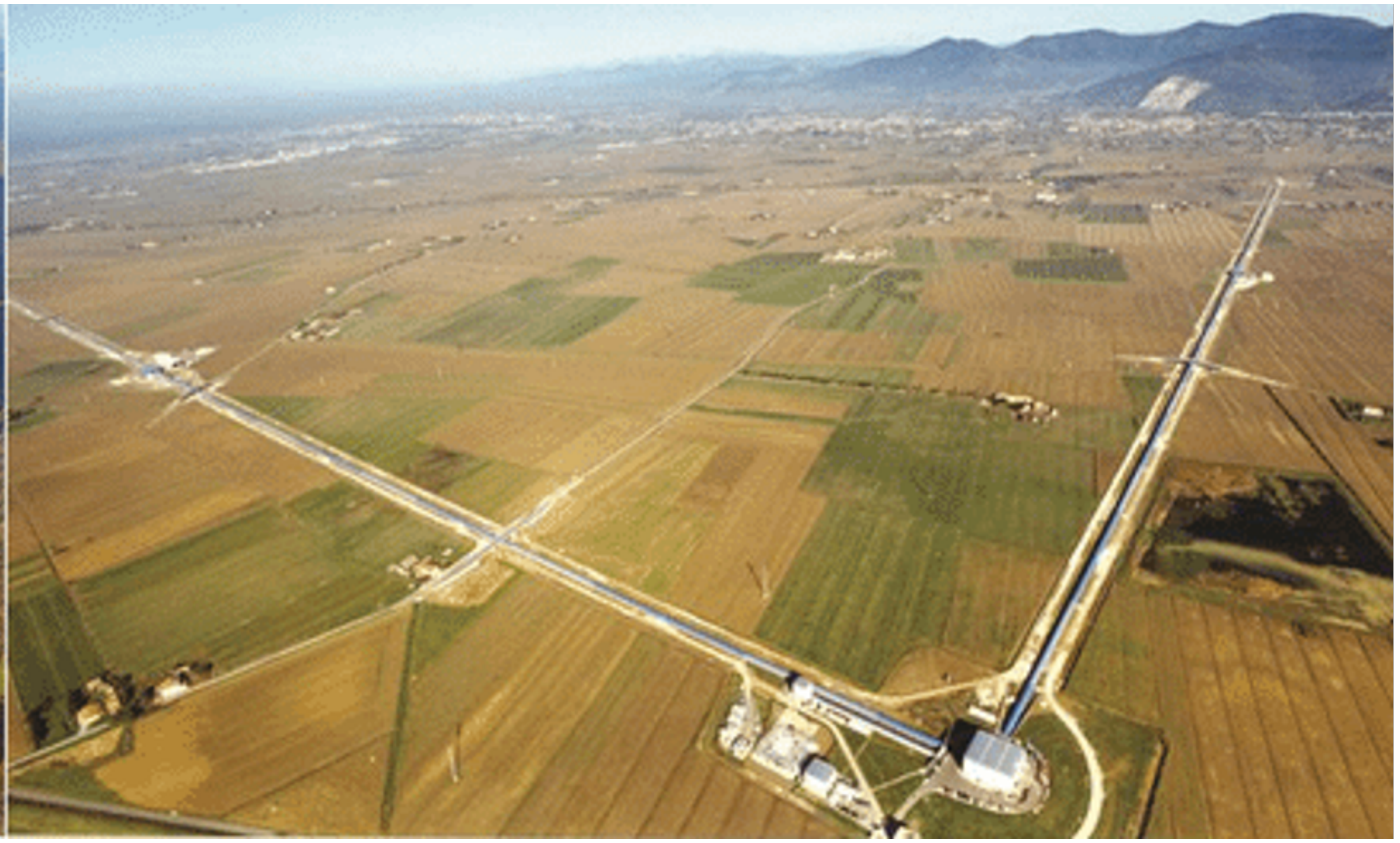
Where:

- $\mathcal{M} = \frac{(M_1 M_2)^{3/5}}{(M_1+M_2)^{1/5}}$ is the **chirp mass**
- f is the **GW frequency** = twice the orbital frequency
- D is the distance to the source
- For circular orbits: $f = \frac{1}{\pi}\sqrt{\frac{G(M_1+M_2)}{r^3}}$



GW interferometers

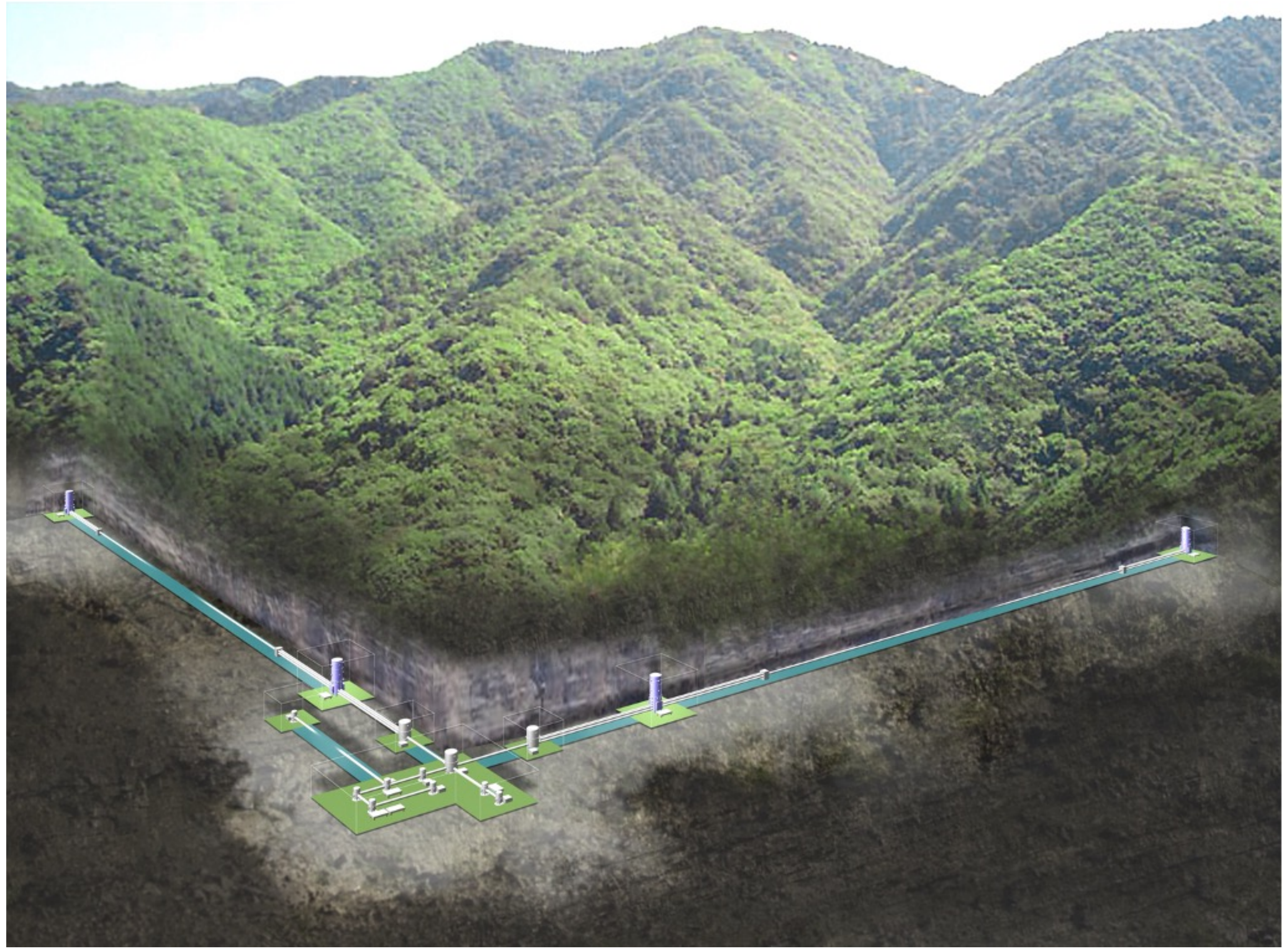




LIGO - Livingston (USA)
4km arms

LIGO - Handford (USA)
4km arms

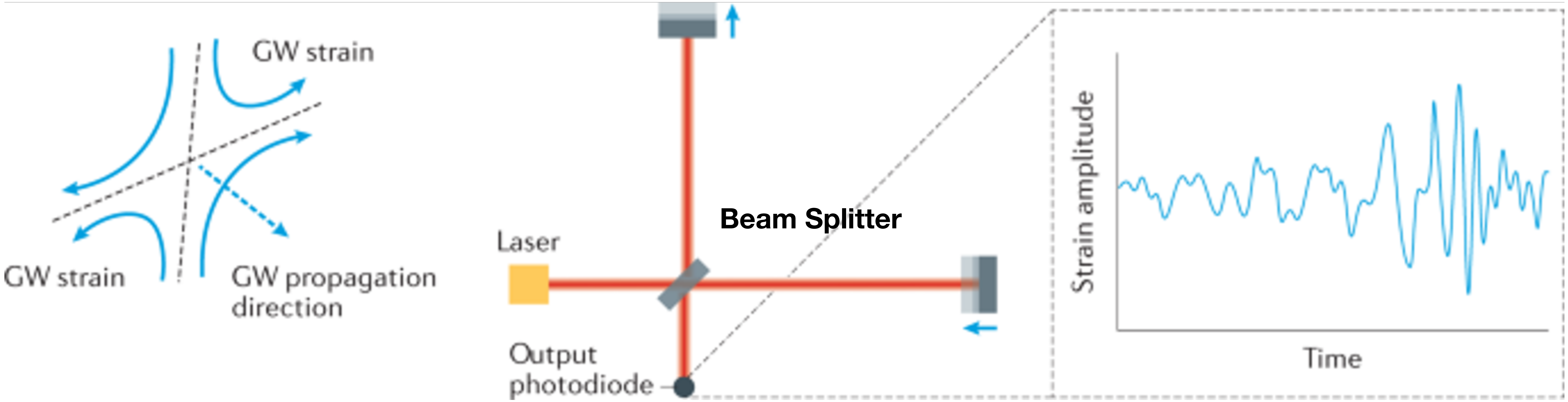
GW interferometers



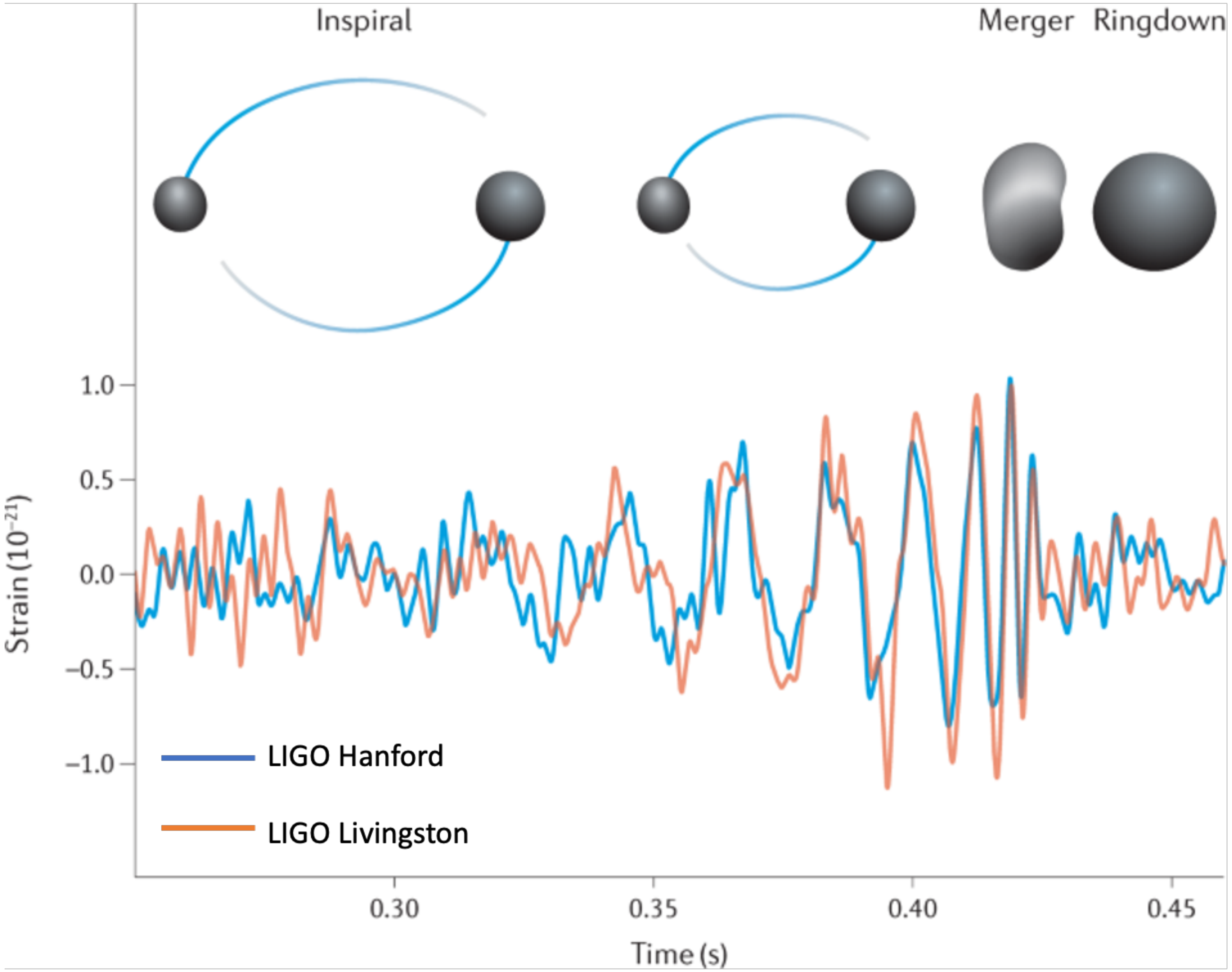
KAGRA - Japan
3 km arms

VIRGO - Italy
3 km arms

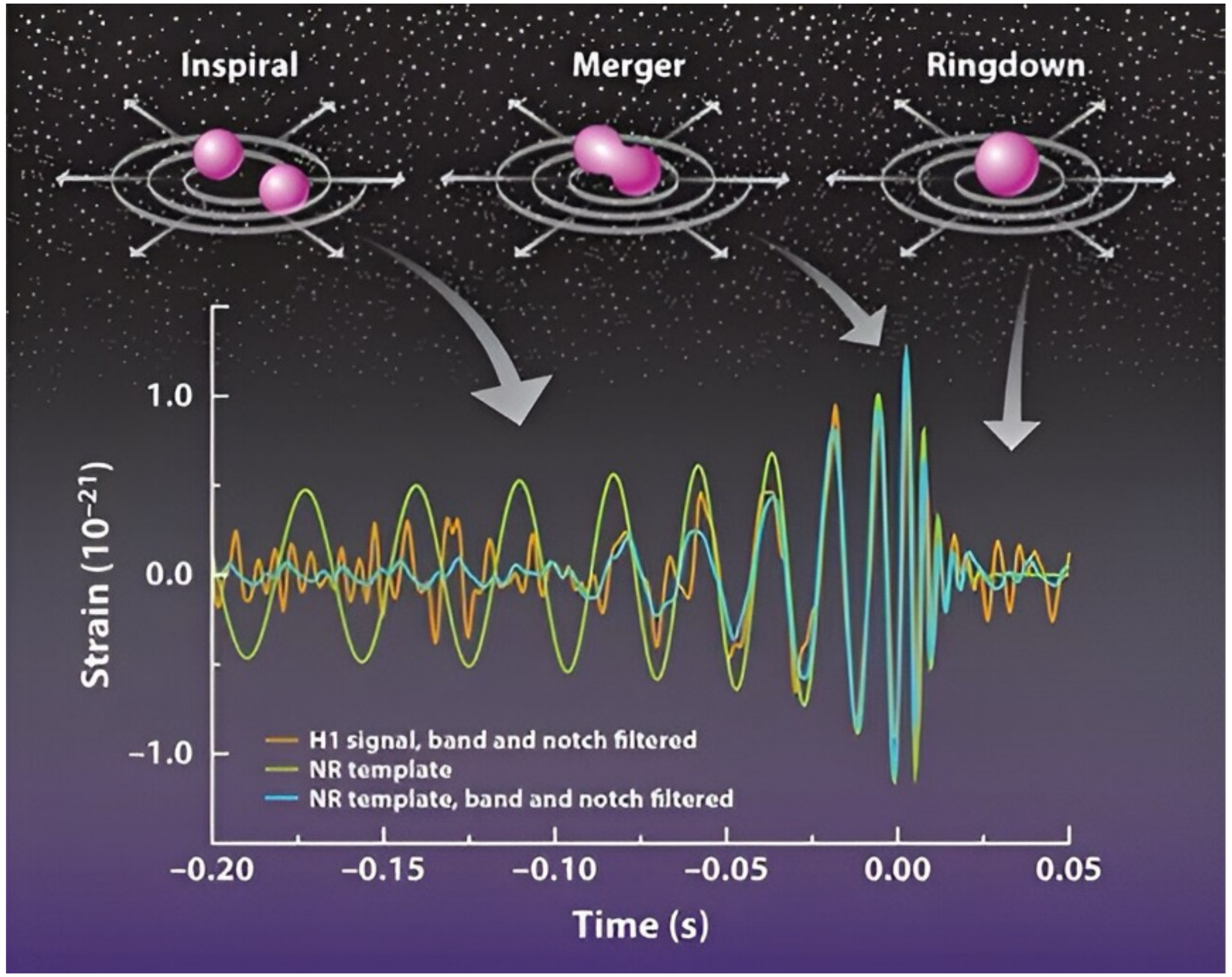
GW detection



GW detection



GW detection

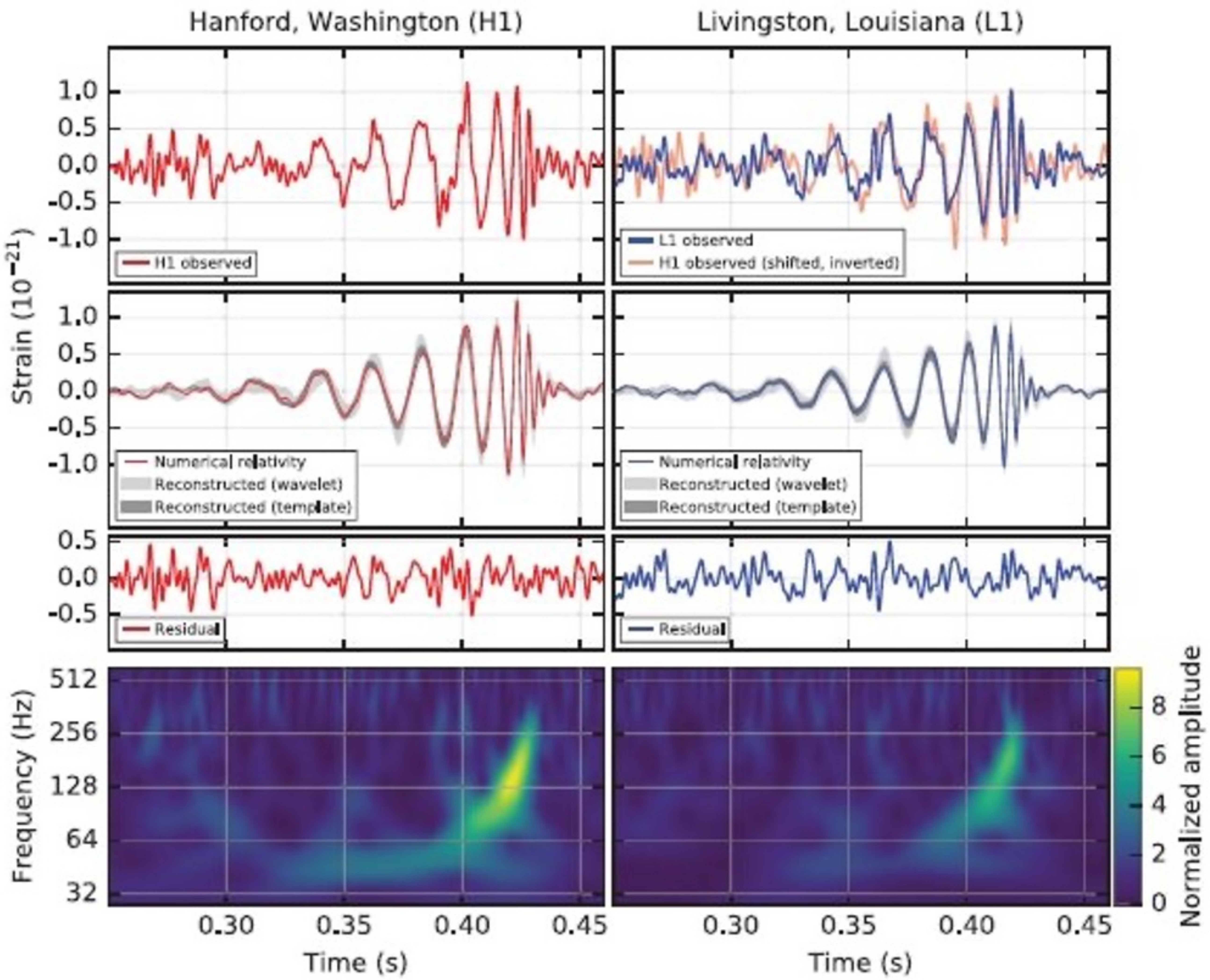


The signal is compared to a set of templates

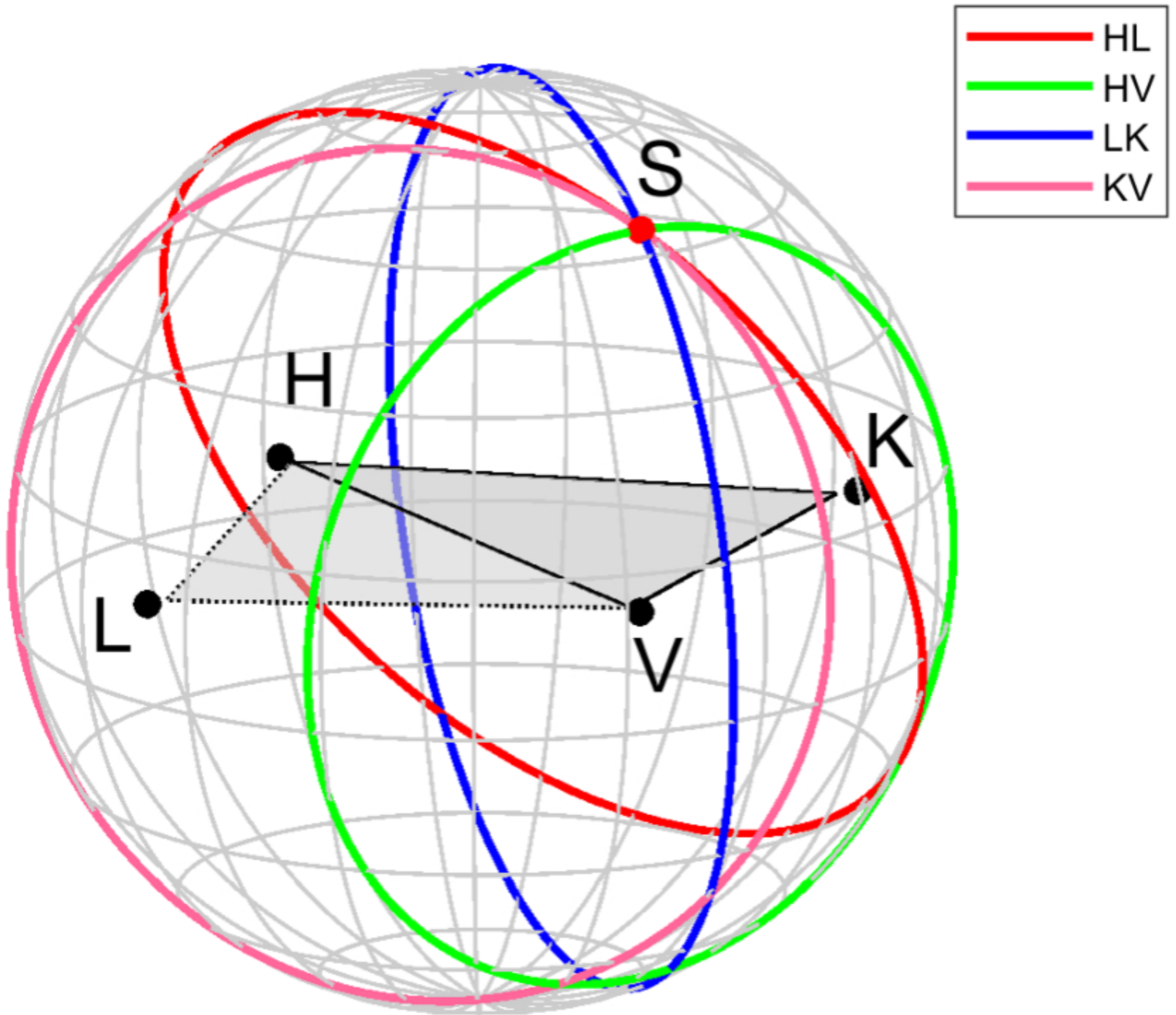
Template bank (milions):

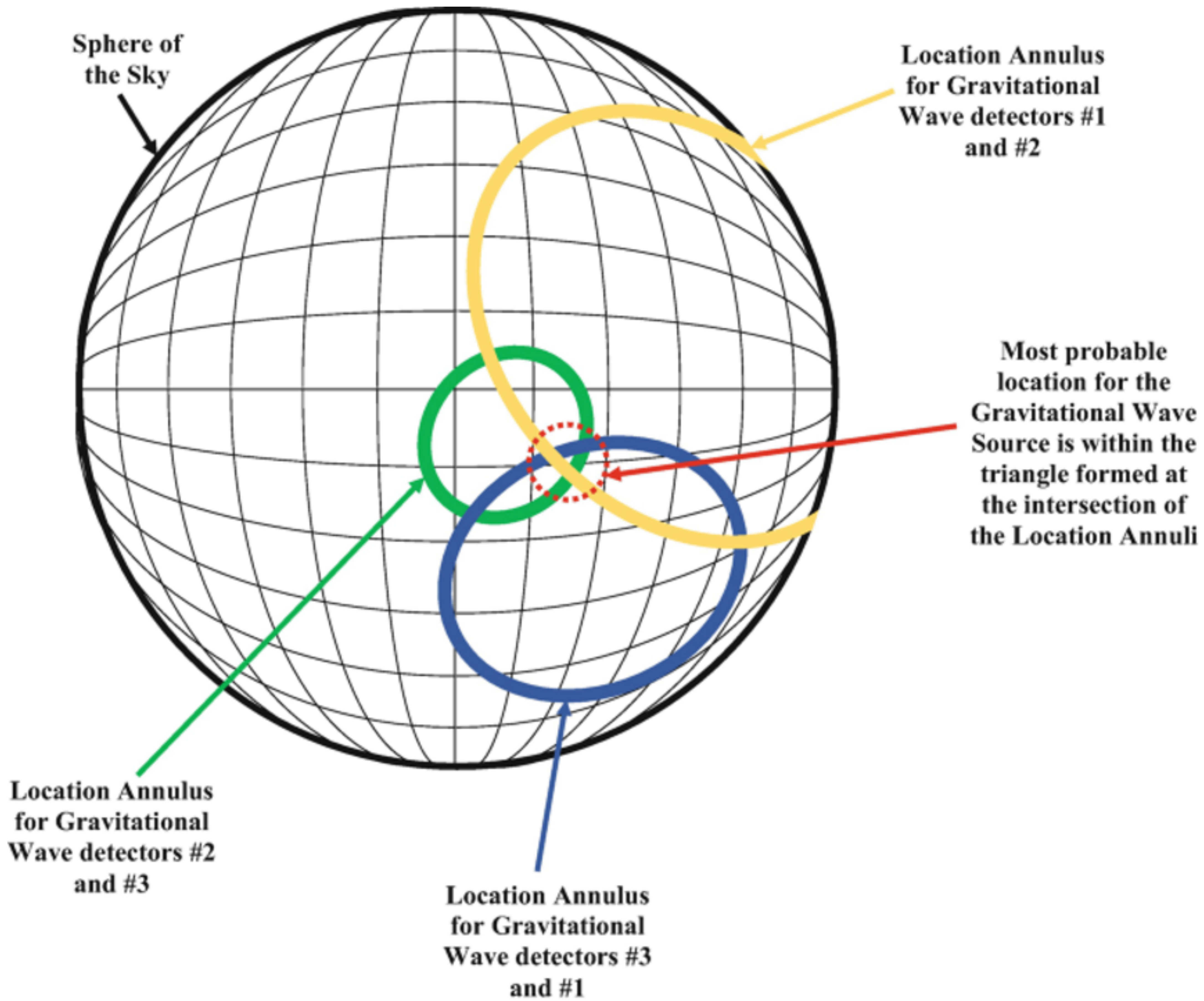
- Built from numerical relativity and post Newton expansions
- Each template is for specific source properties (mass, inclination, spin etc…)
- Obtained apriori
- Cross match the data with template

GW 150914: First binary black hole merger



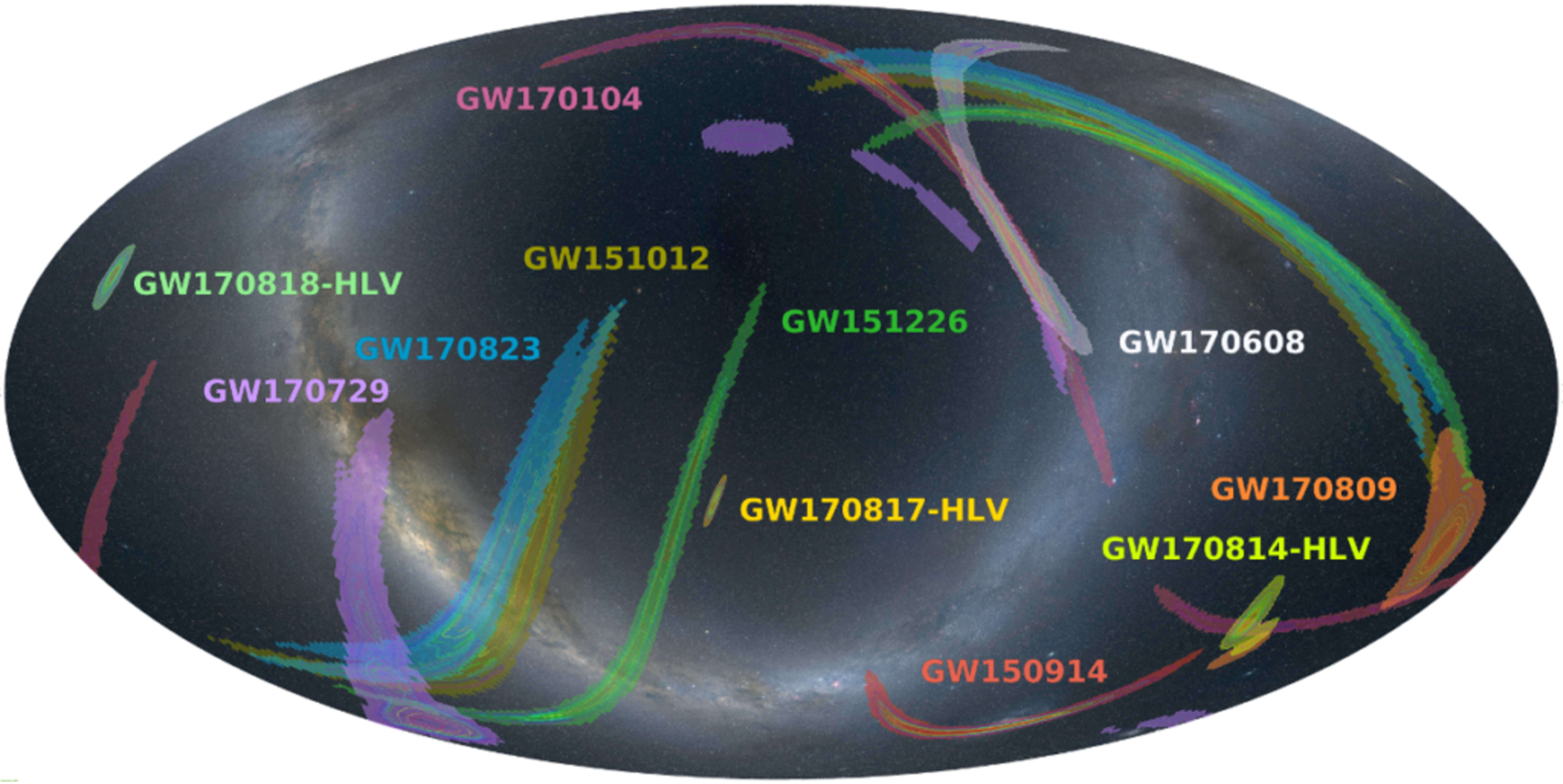
GW localization



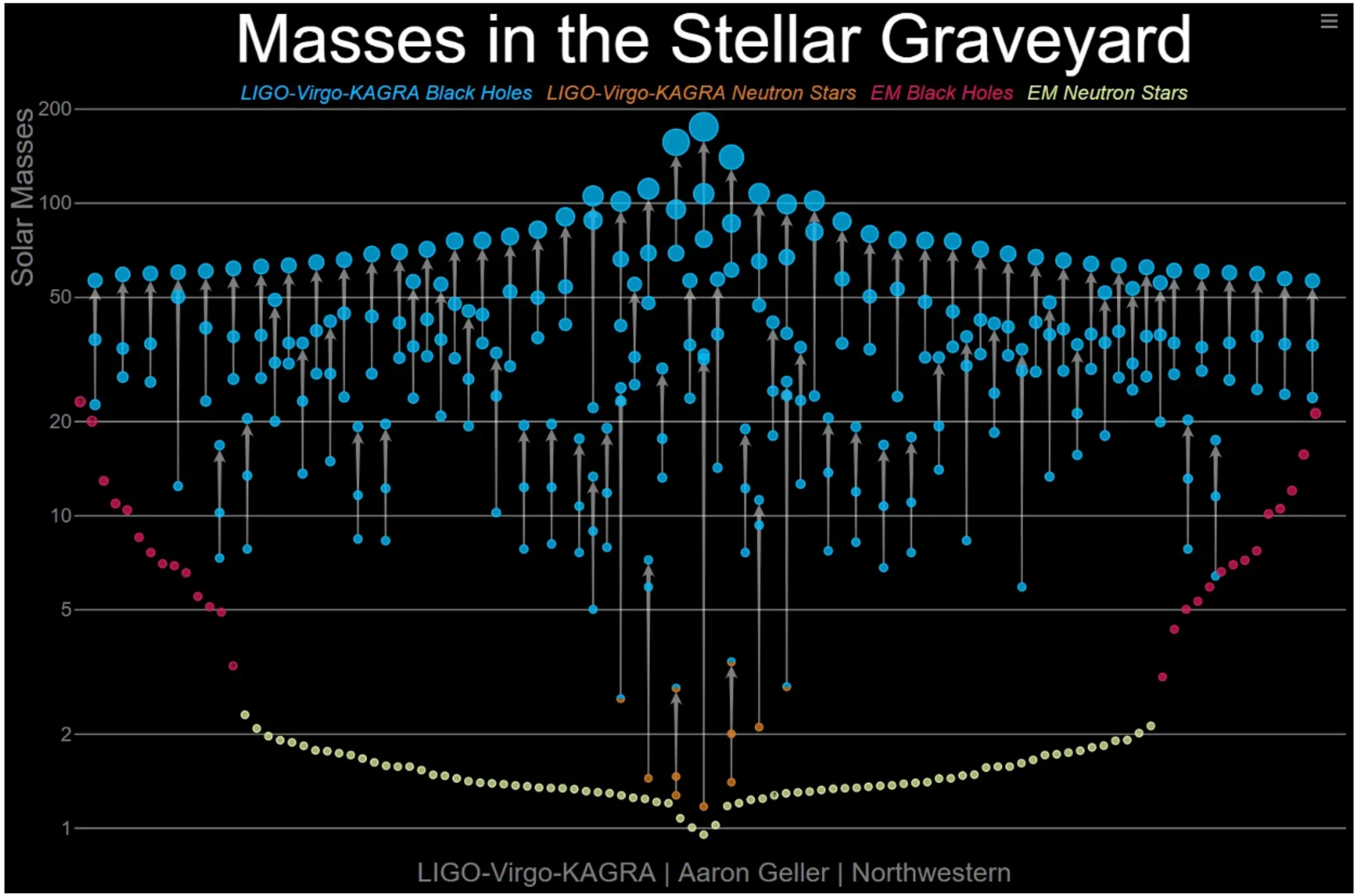


Based on timing triangulation: More interferometers → more accuracy

GW localization

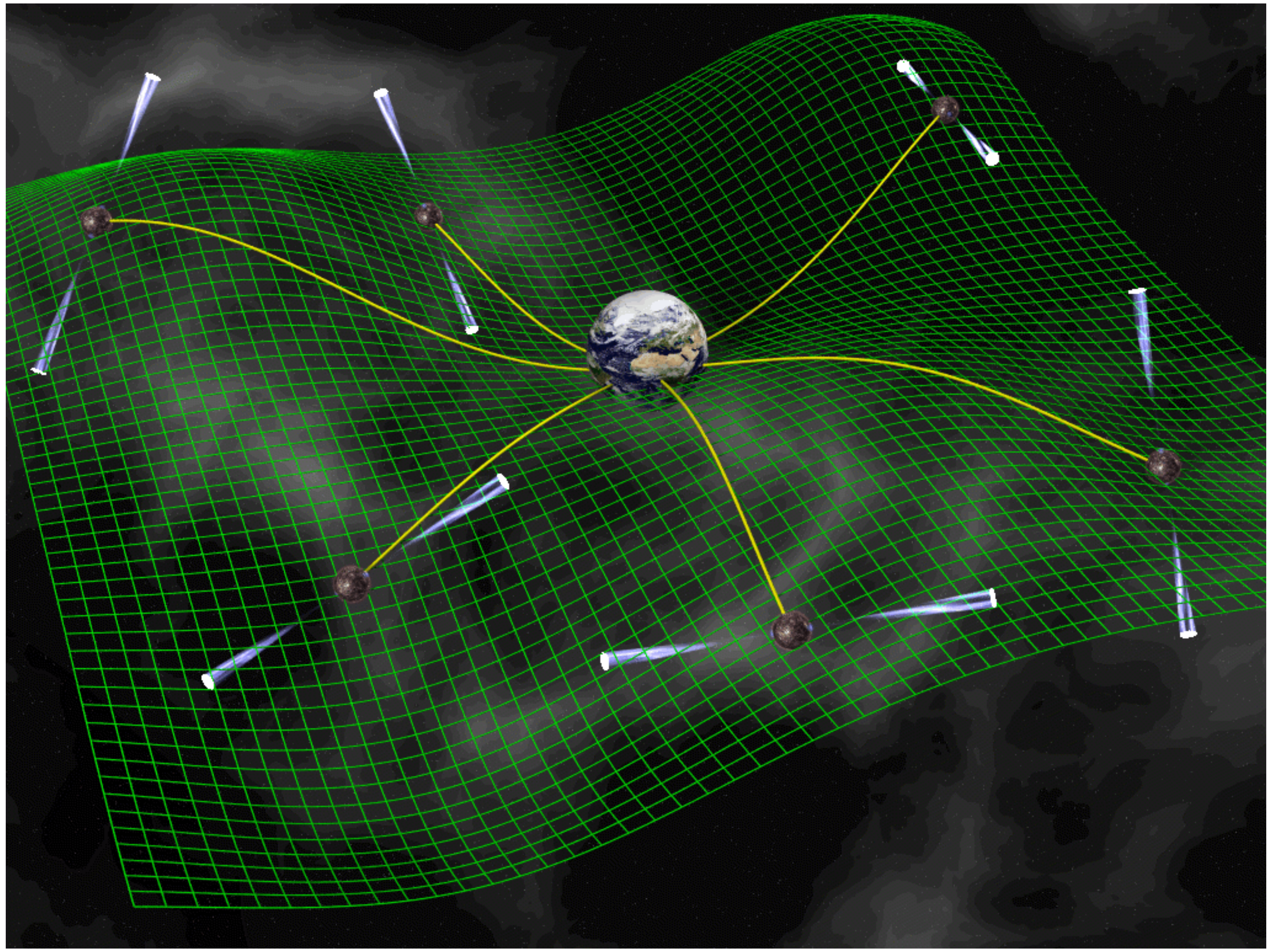


We can now “observe” black holes with GWs



GWs: another way

A Pulsar Timing Array (PTA) is a network of highly stable millisecond pulsars monitored over time to detect tiny variations in their arrival times.



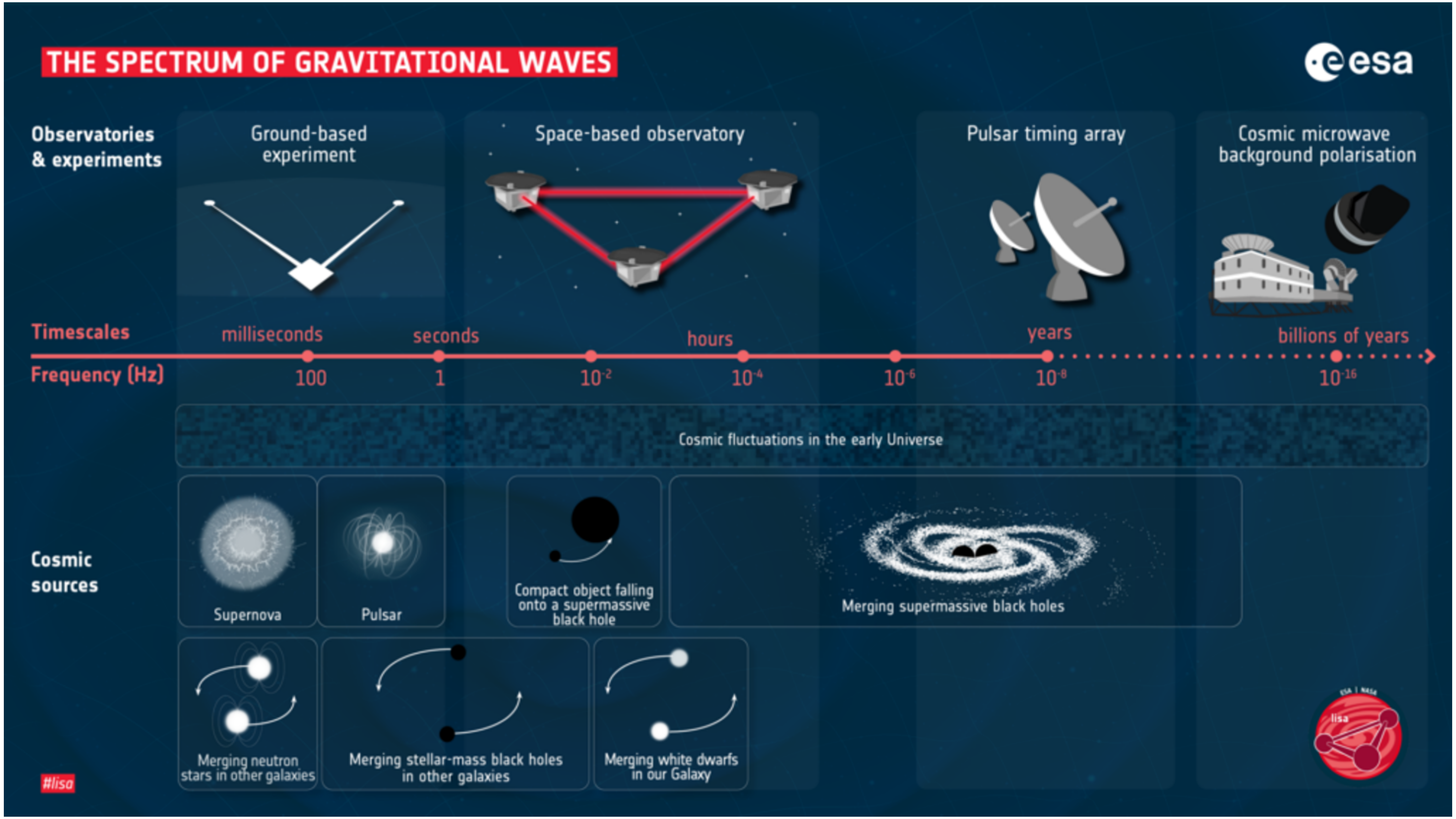
Sensitive to **very low-frequency GWs**

$$f \sim 10^{-9} - 10^{-7}\ \mathrm{Hz}$$

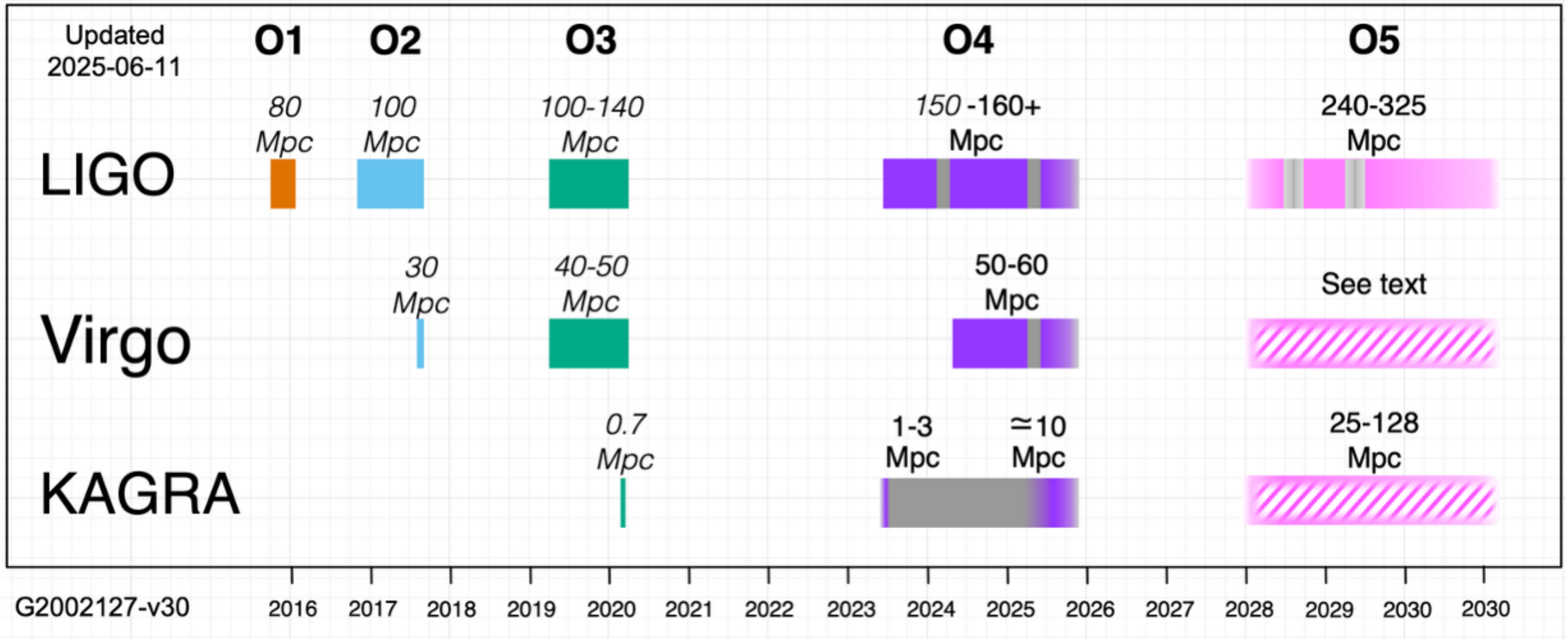
This corresponds to:

- **Supermassive black hole binaries** (SMBHBs) in galaxy mergers
- Possibly a **stochastic GW background** from many unresolved sources

The GW spectrum

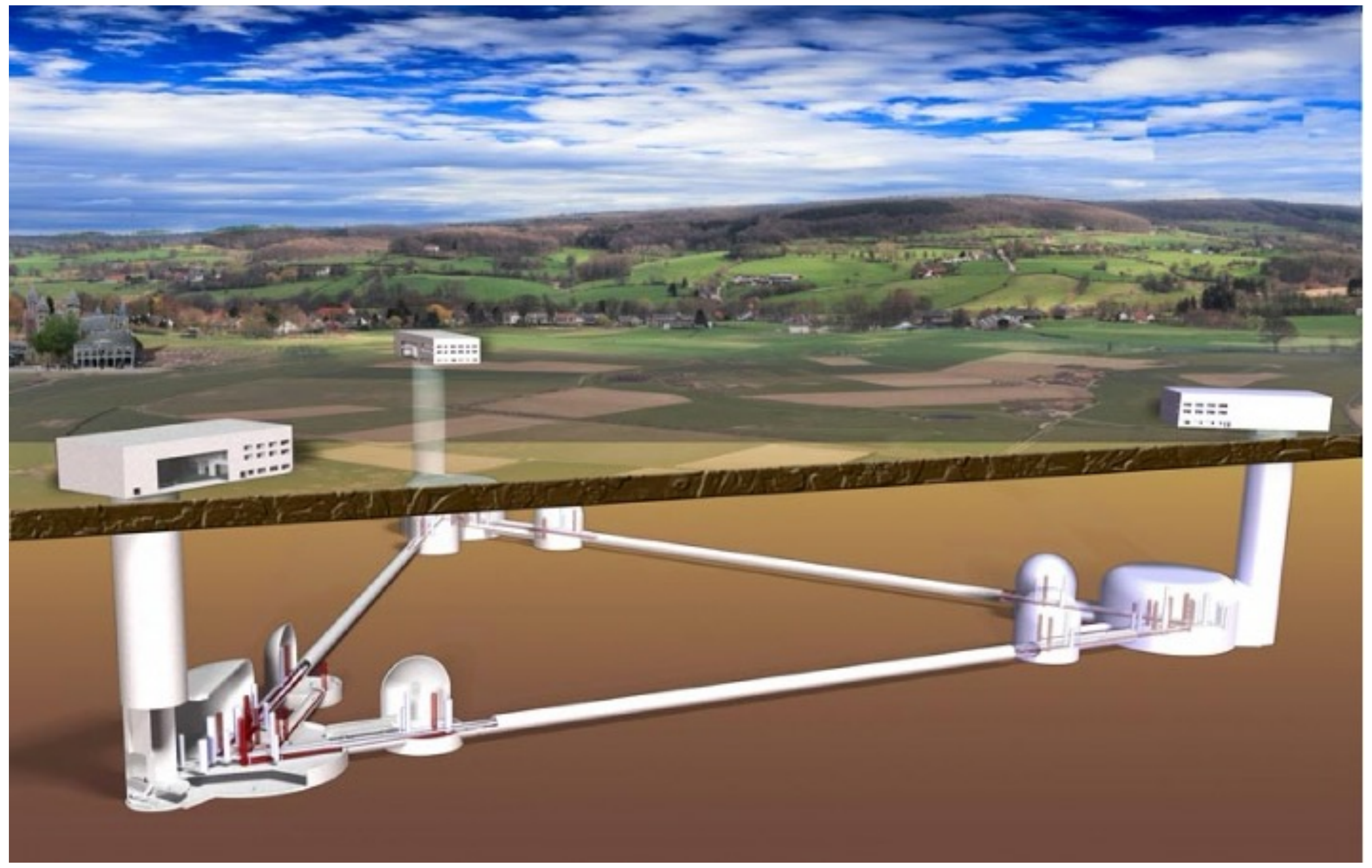


GWs: near future



Upgrades to LIGO, Virgo and Especially KAGRA

GWs: far future

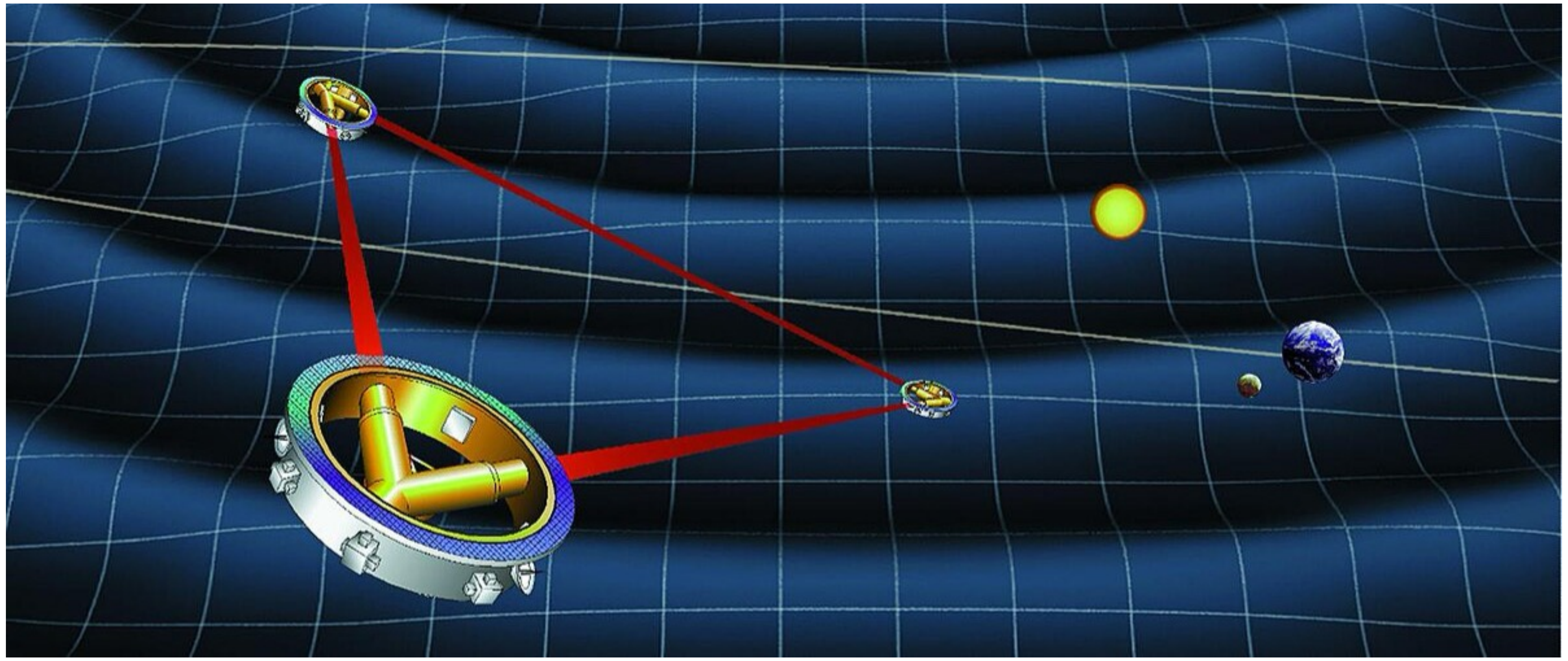


Einstein Telescope (ET):

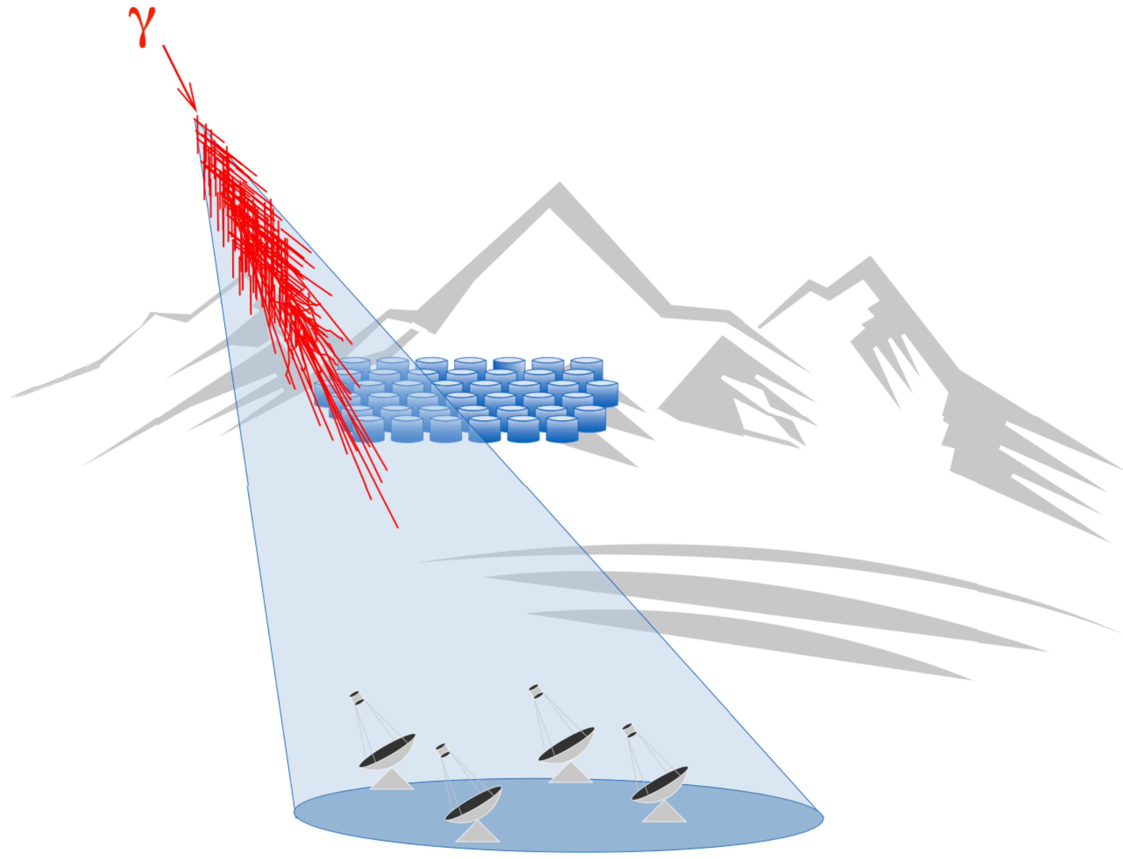
- Triangular shape
- 10 km arms
- Installed in Europe

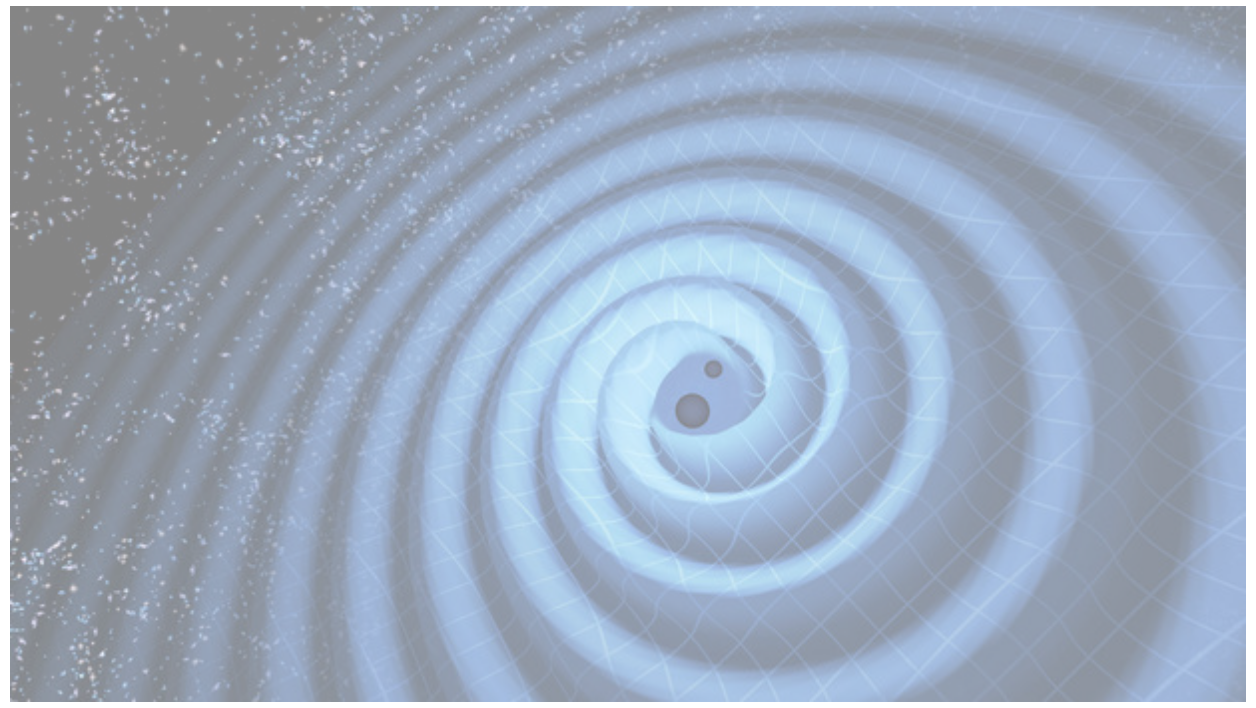
LISA:

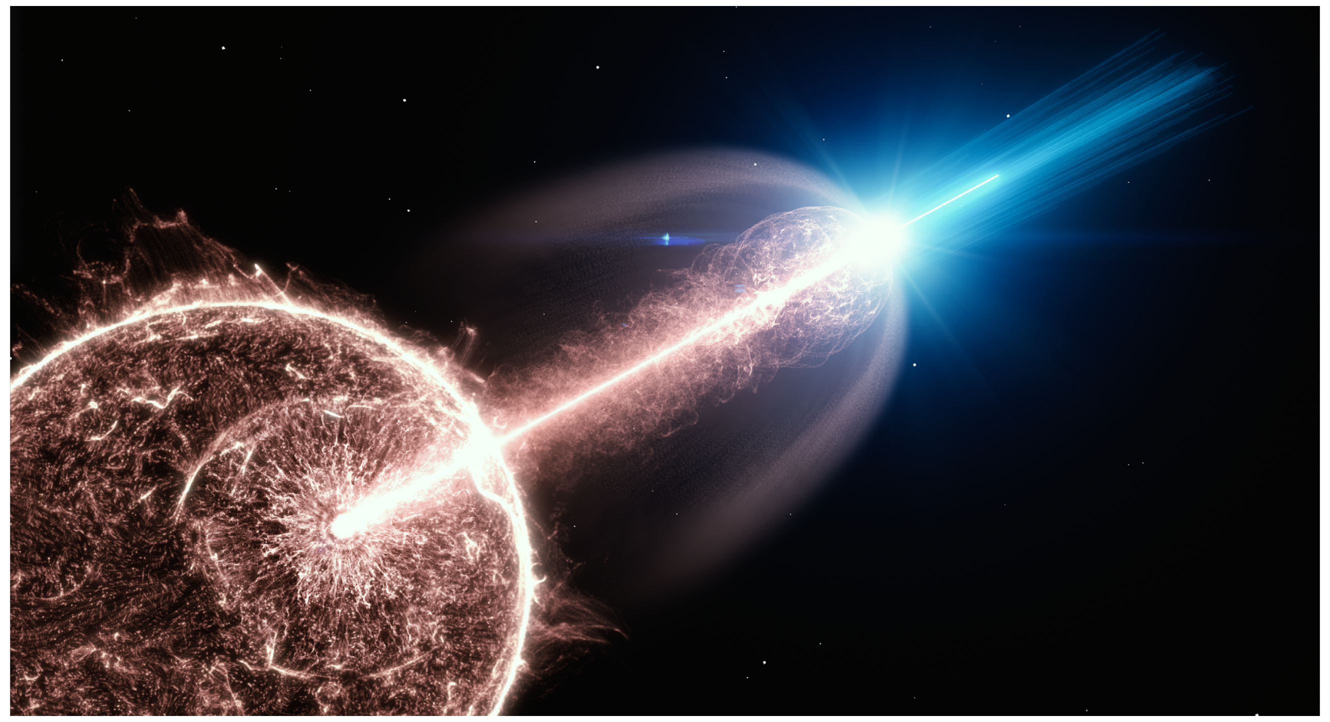
- Triangular shape
- 2.5 million km arms
- Space based



Outline

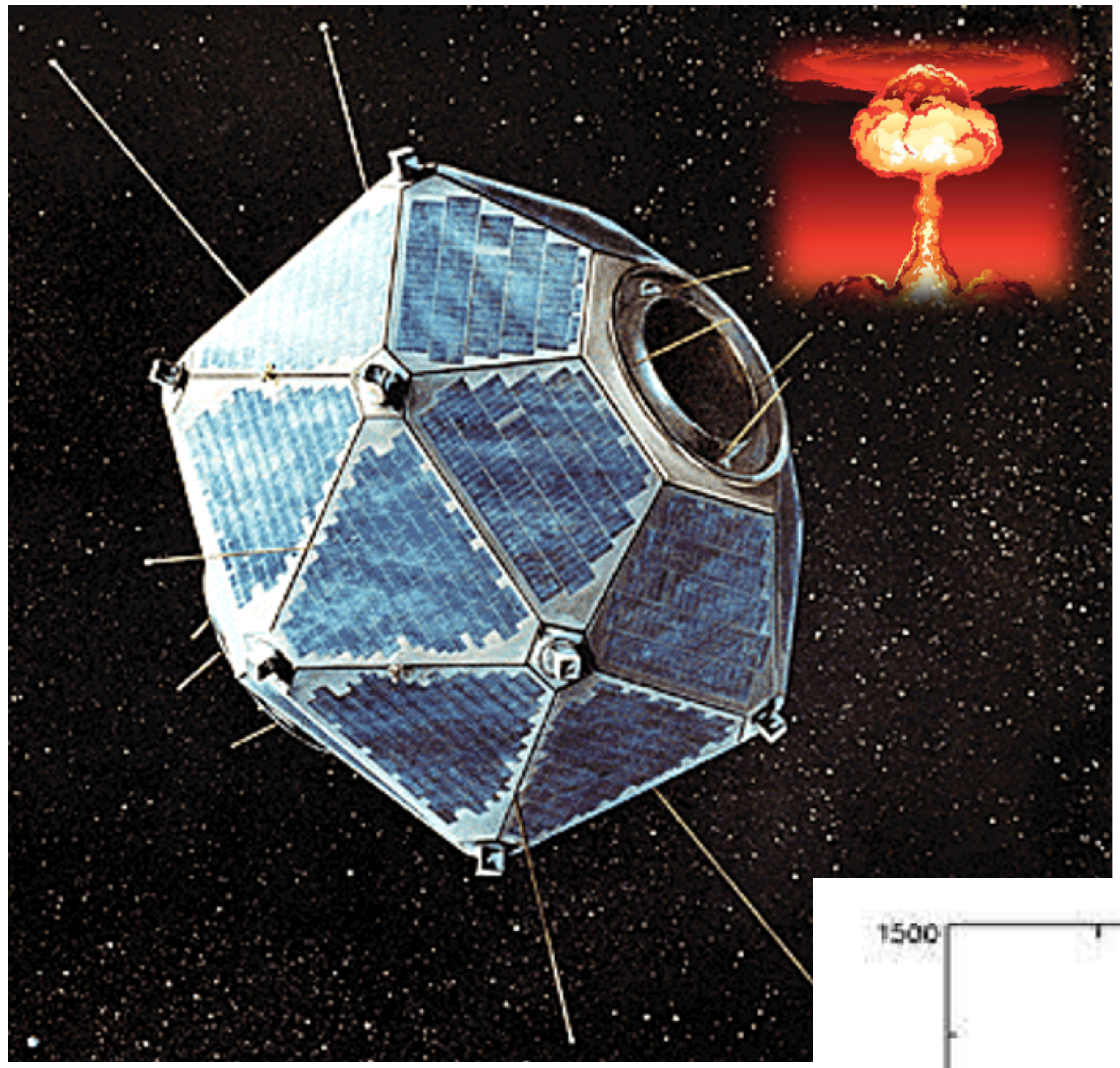


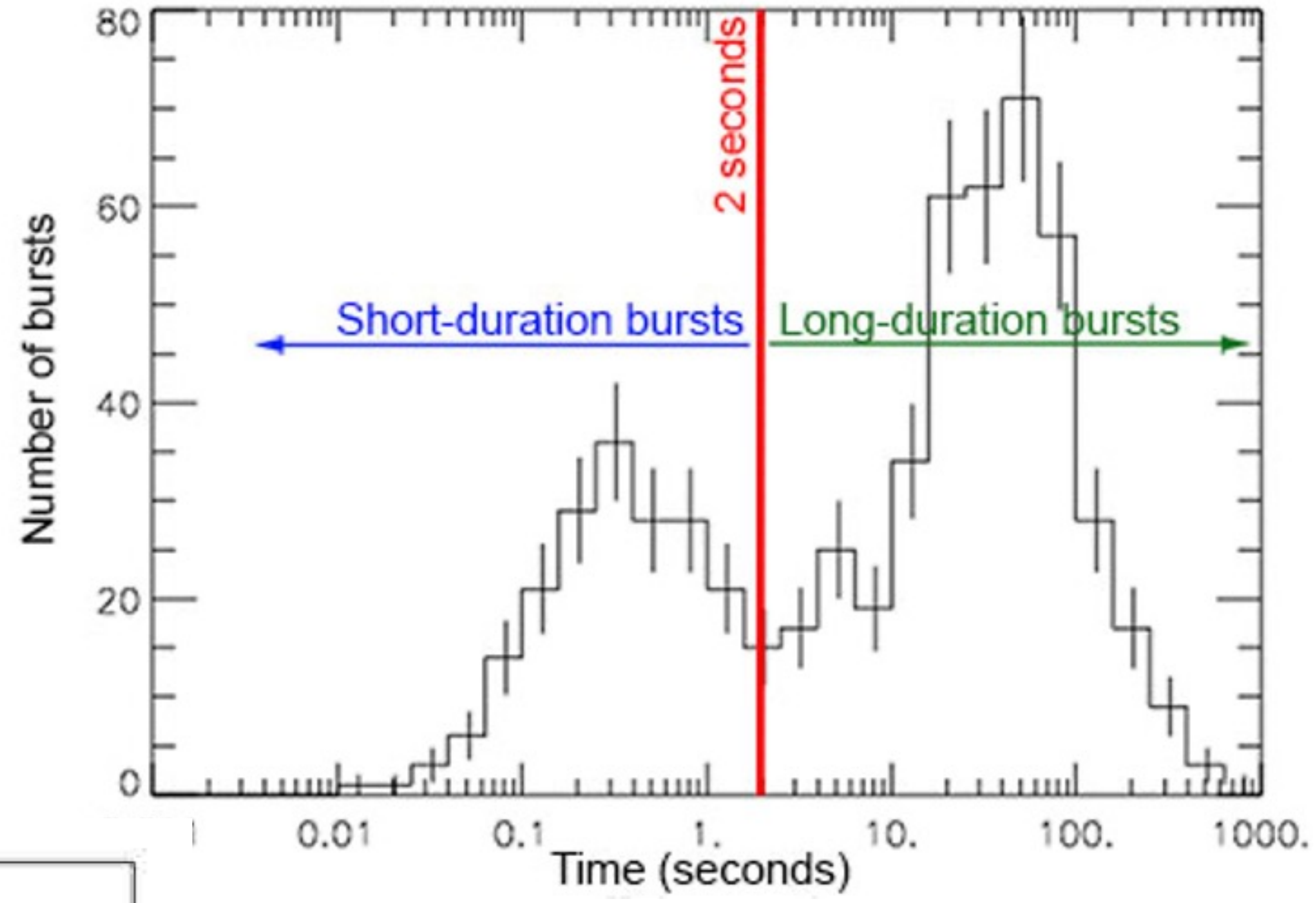


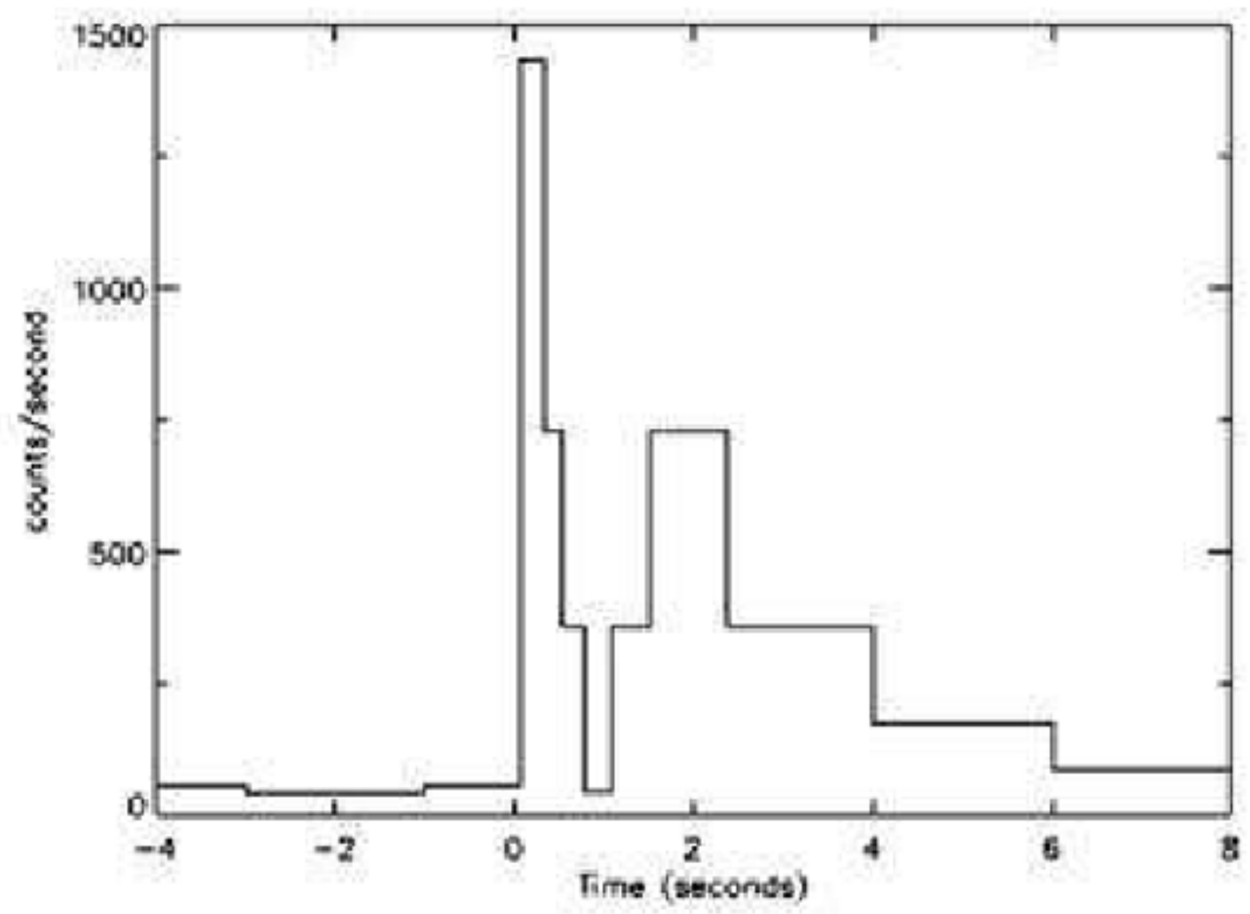


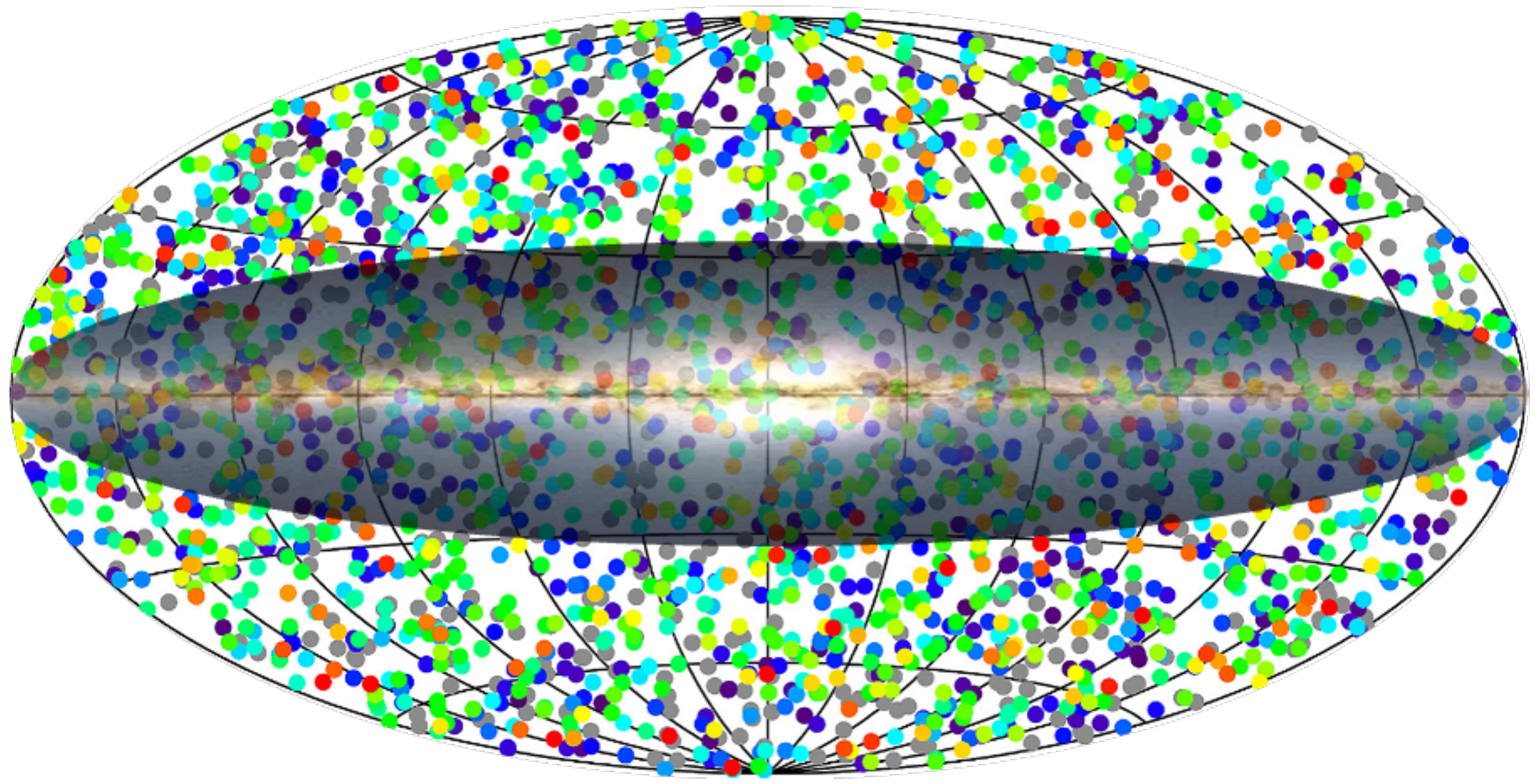
3. A multi-messenger case: Gamma-Ray Bursts

Gamma-Ray Bursts







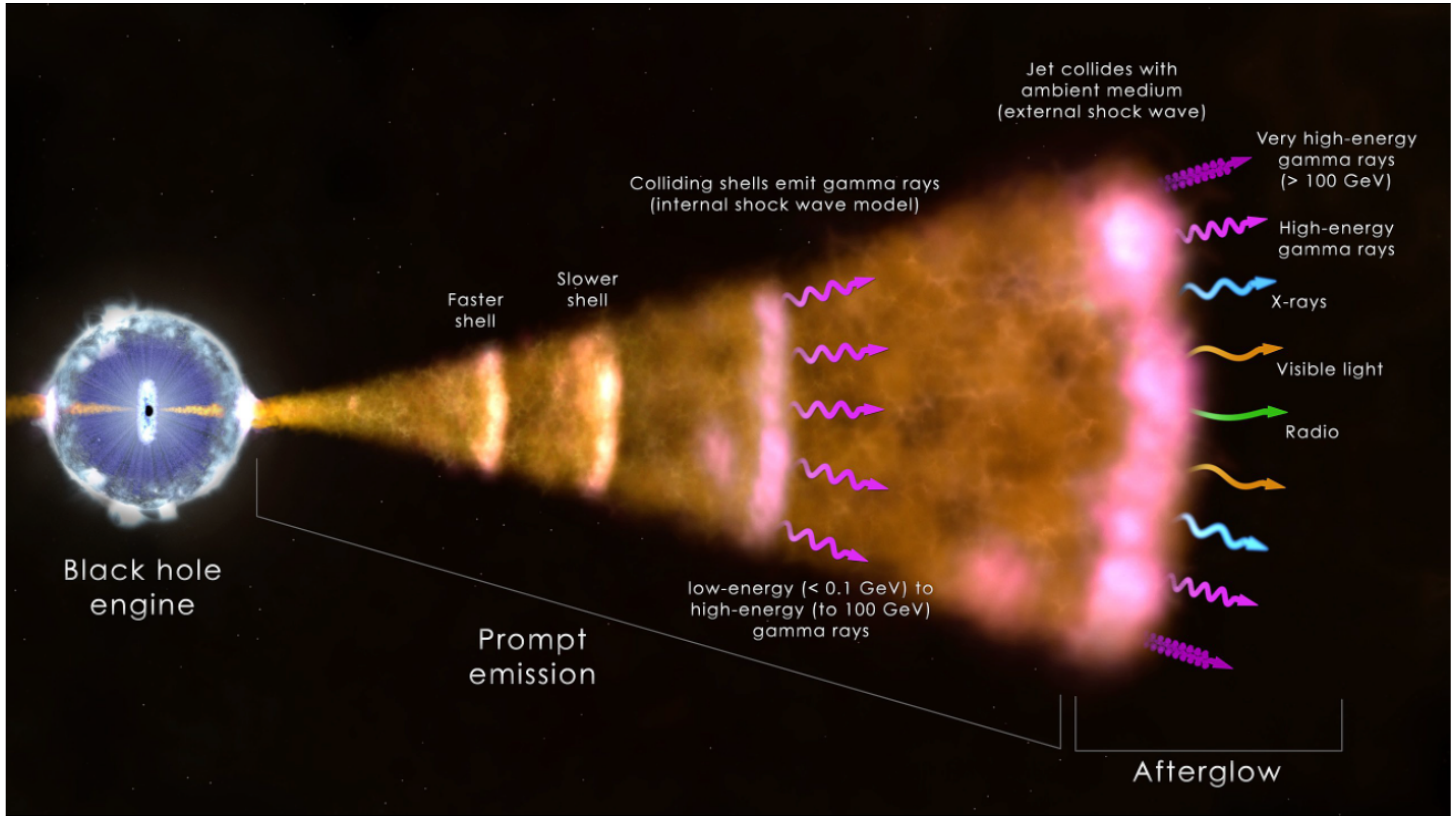


Gamma-Ray Bursts

Brightest electromagnetic transient (10^{51-53} erg released)

- Distinction into short and long GRBs:
  - **short**, $T_{90} < 2$ s;
  - **long**, $T_{90} > 2$ s (**core collapse of massive stars**)

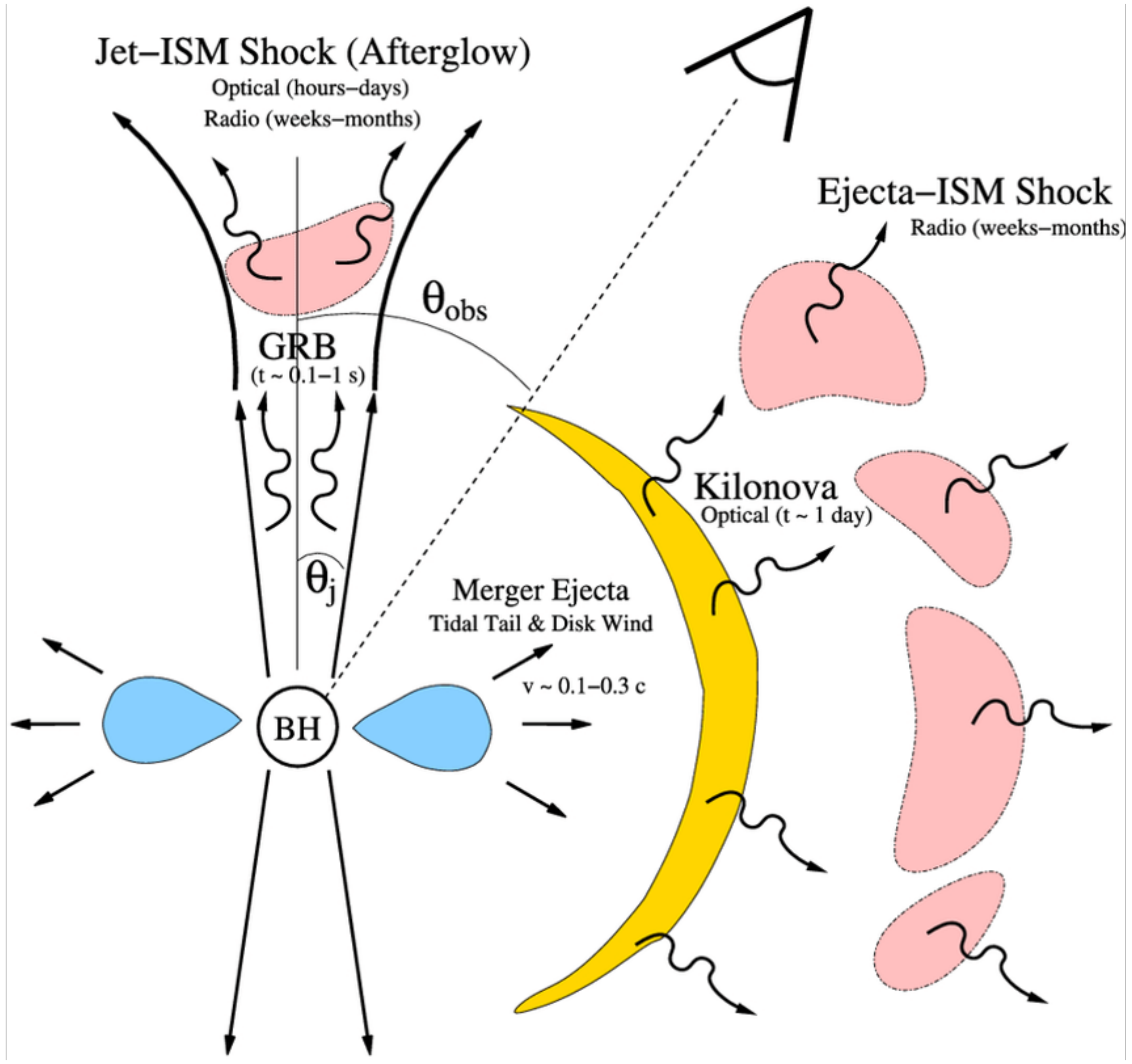
The Long GRBs and short GRBs have similar emission mechanisms whith short GRBs being scaled down



GRBs and GWs, what is the relation ?

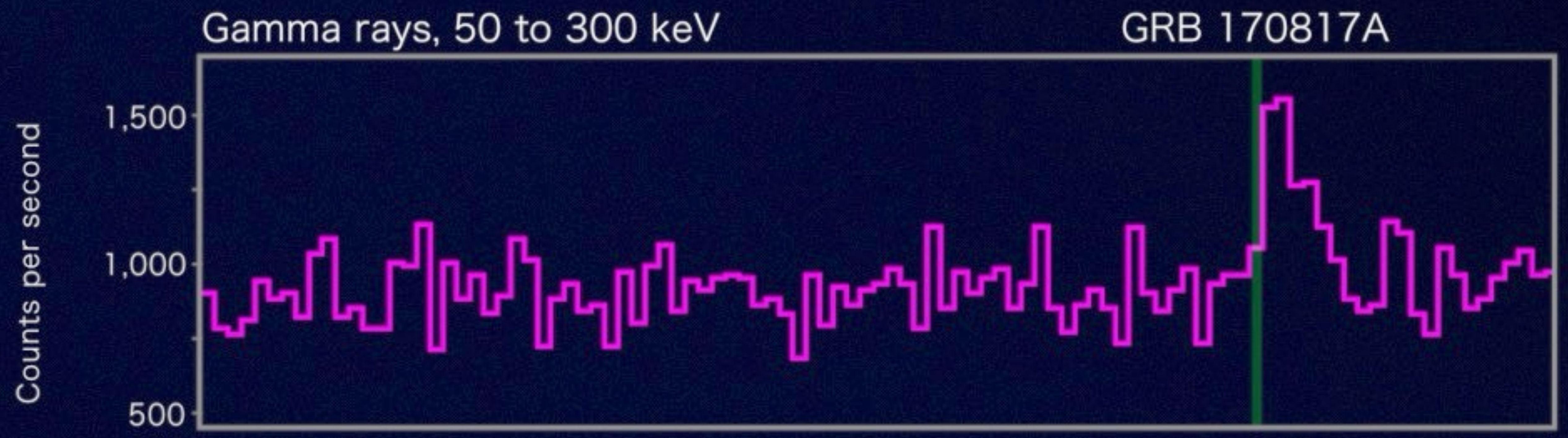
Where do short GRBs come from?

Merger of neutron stars are responsible for short GRBs. These same mergers can also create GWs



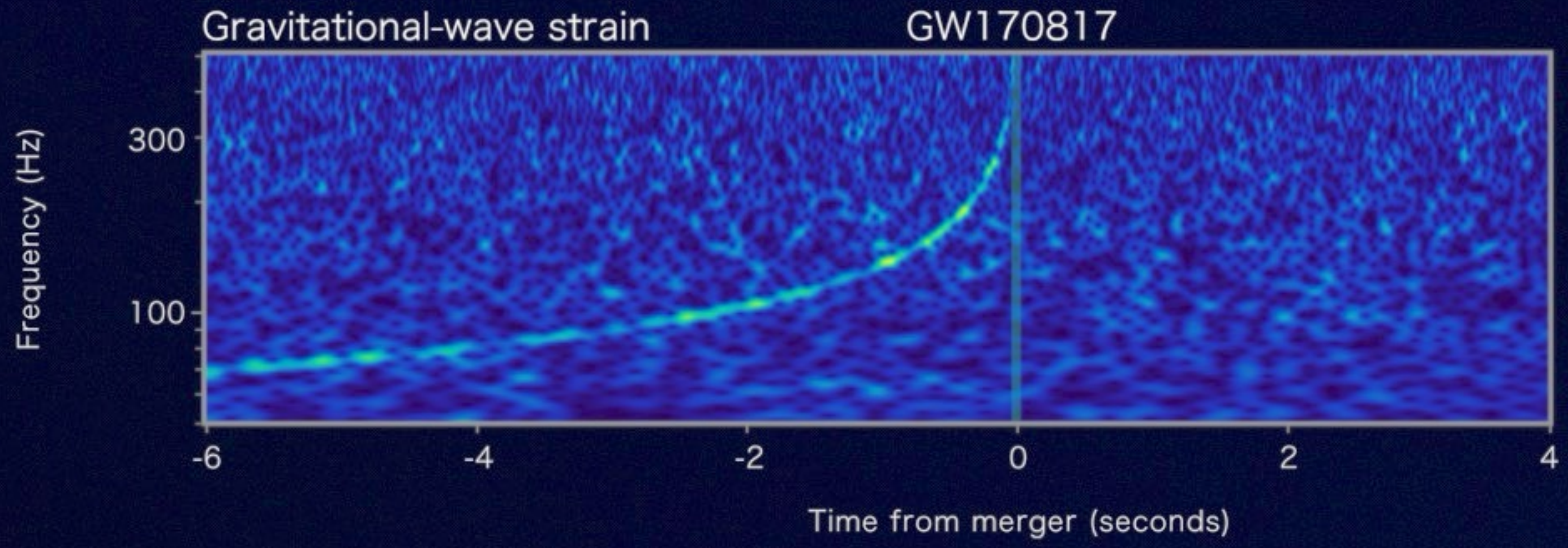
Fermi

Reported 16 seconds after detection



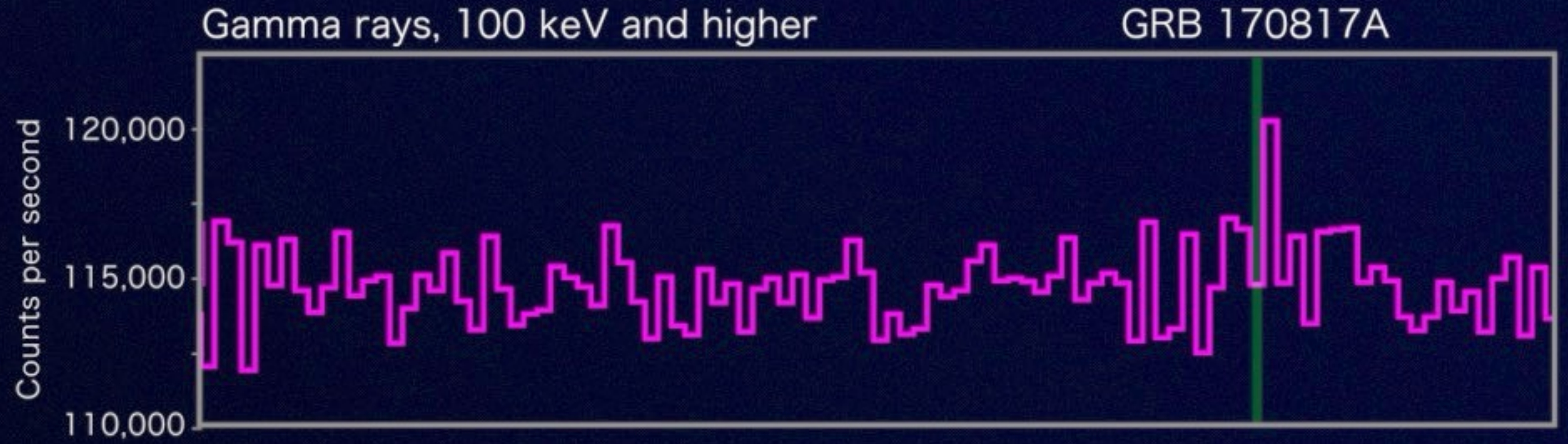
LIGO-Virgo

Reported 27 minutes after detection

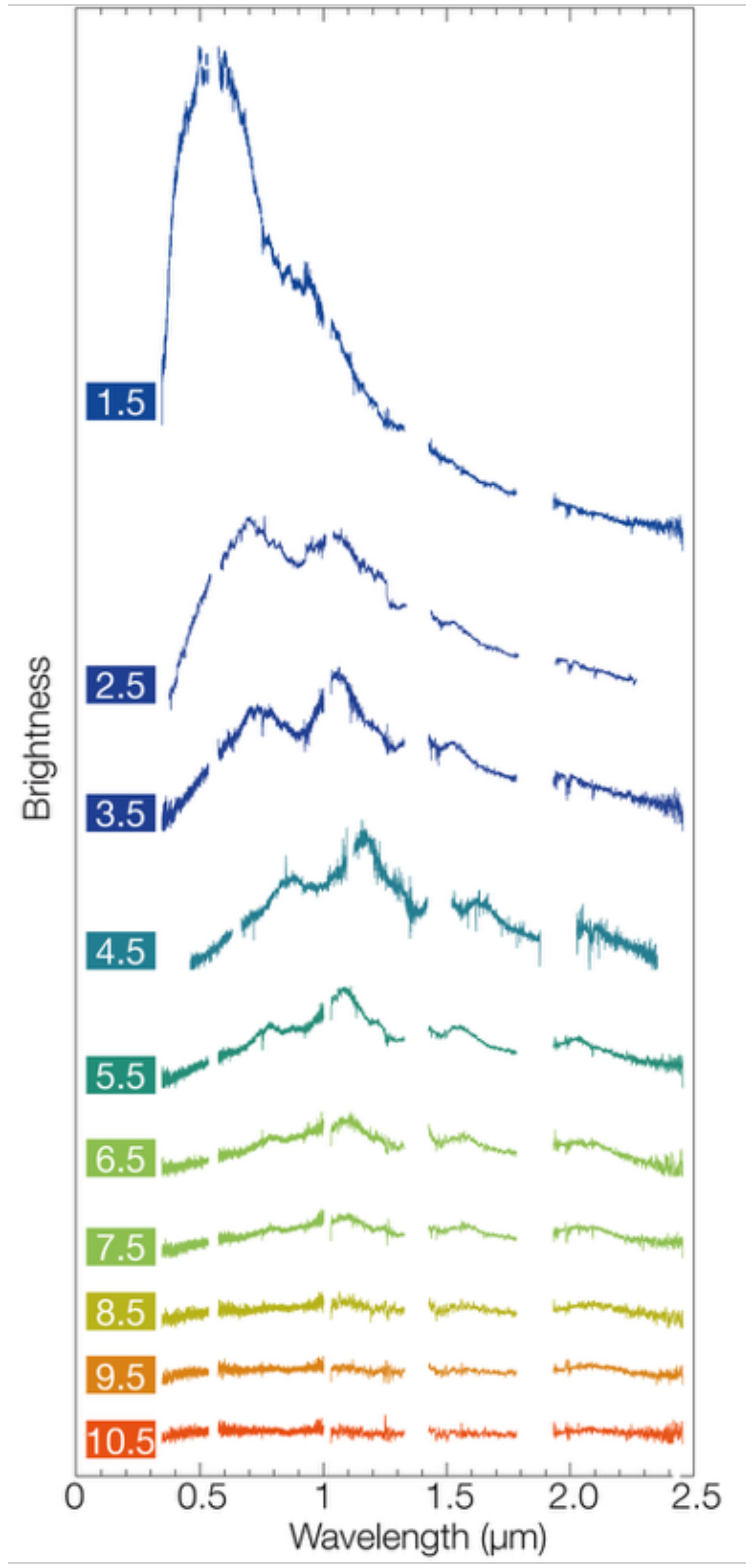


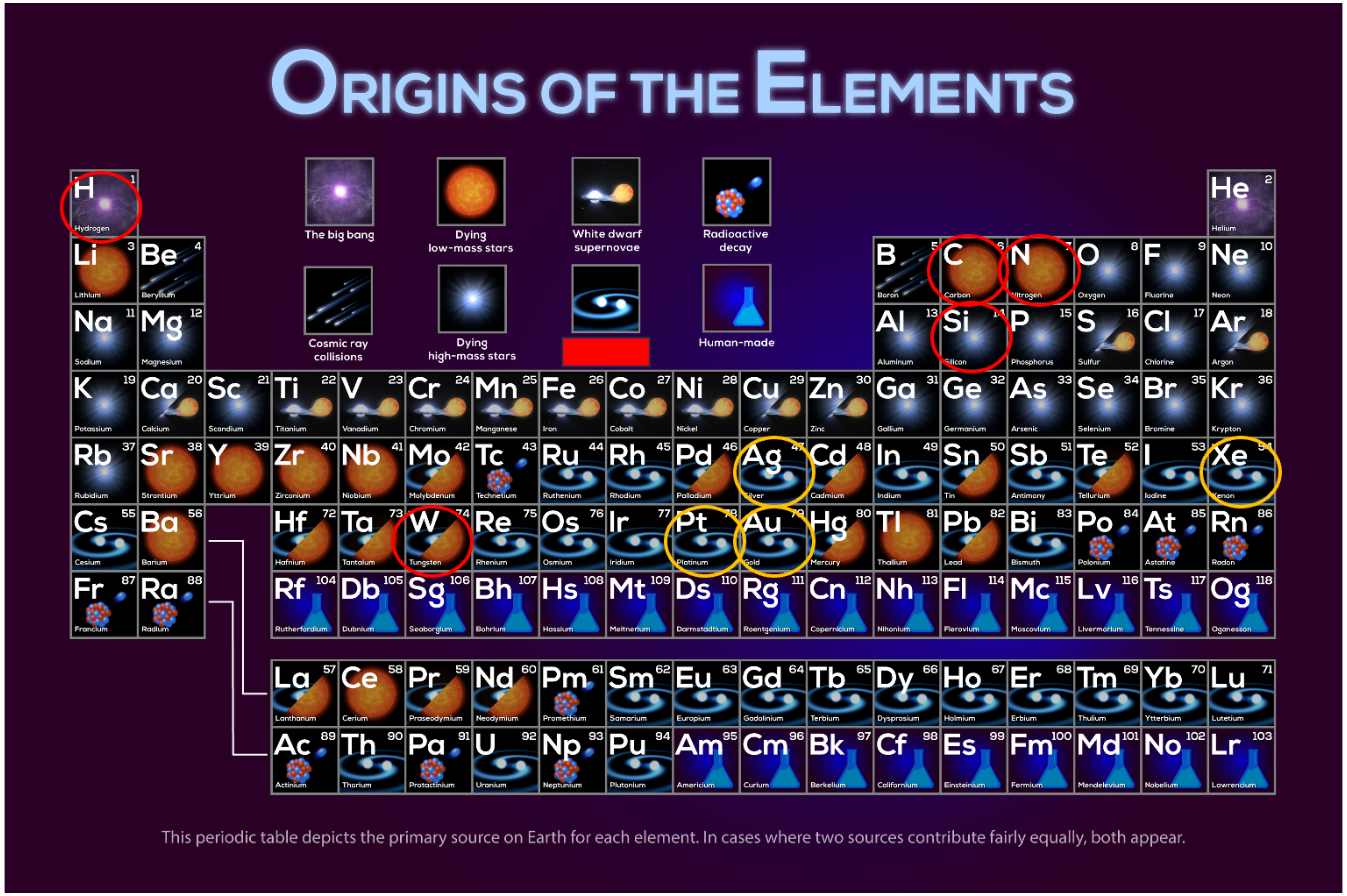
INTEGRAL

Reported 66 minutes after detection



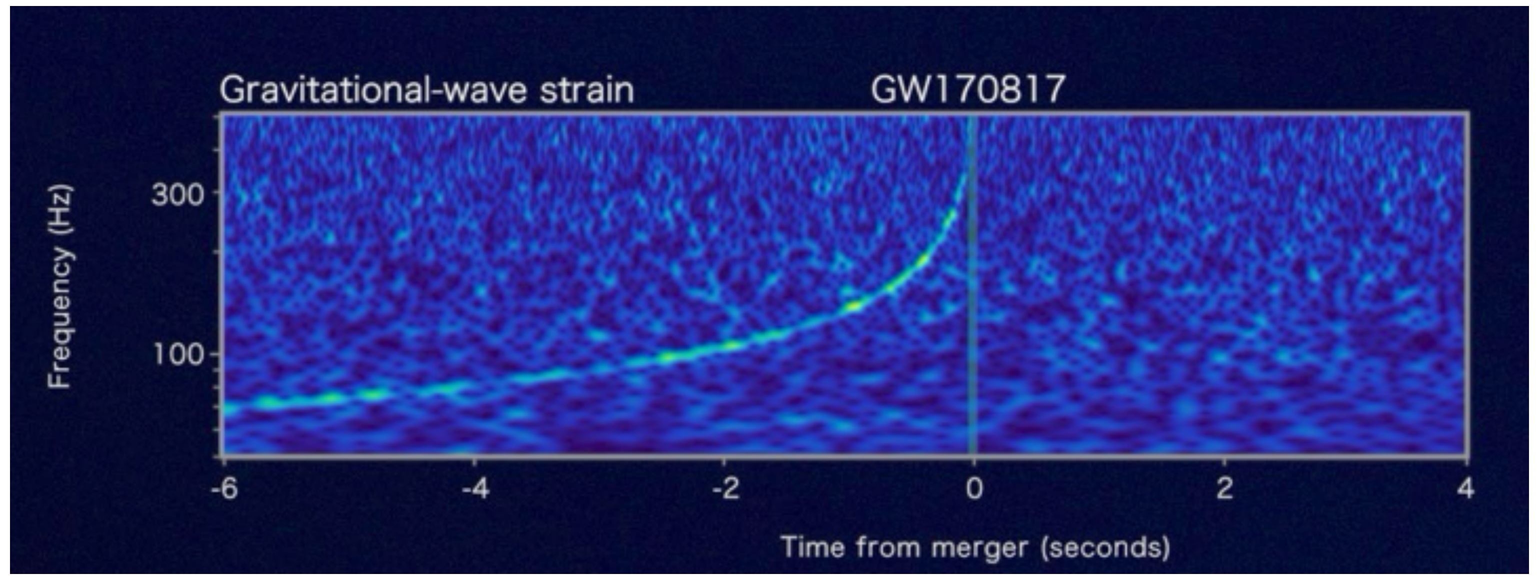
What can we learn from the Kilonova



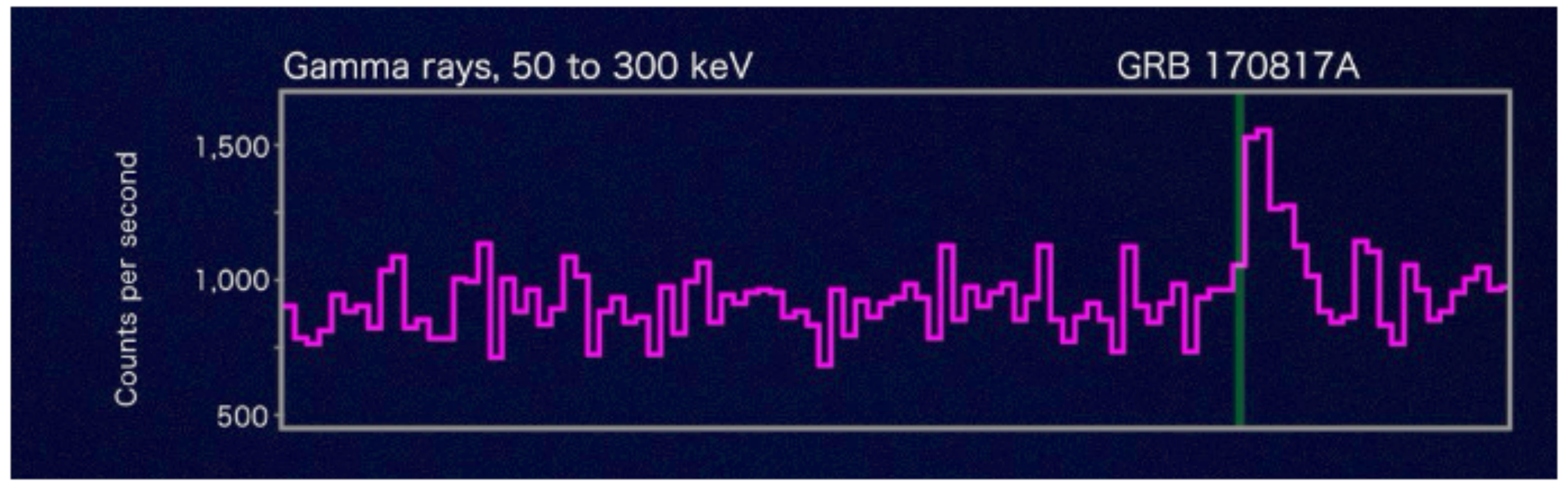


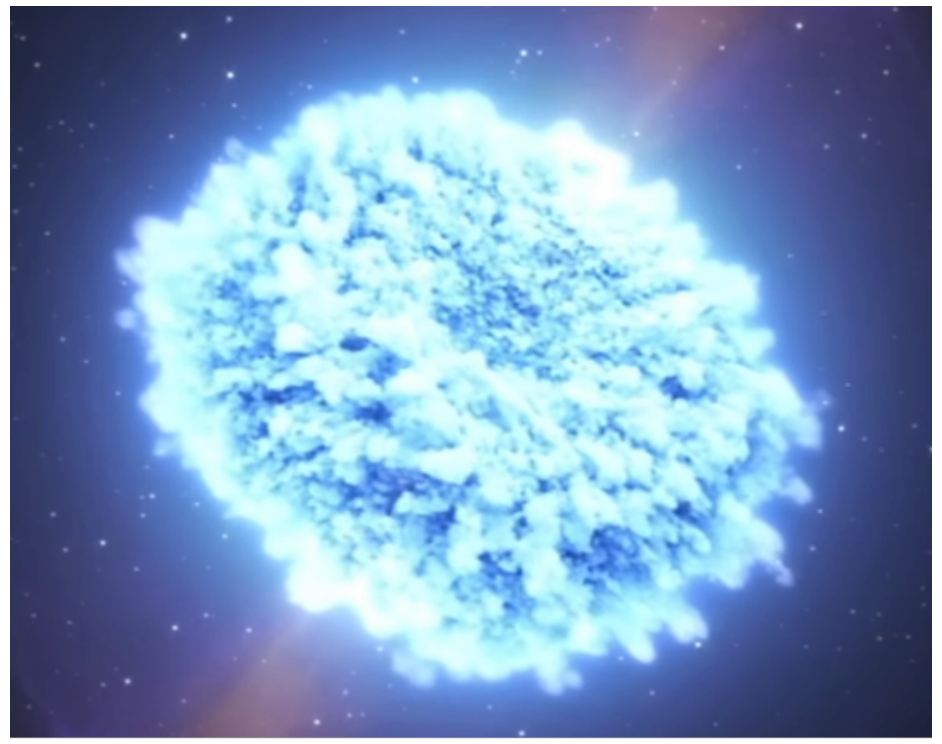
Few seconds, many discoveries

Gravitational Waves
→ **Neutron star merger**

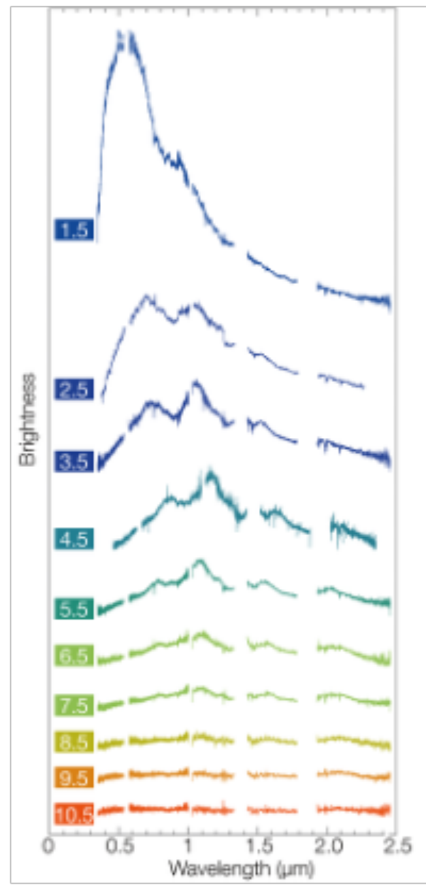


Formation of a jet
of highly relativistic particles
→ **Short Gamma-Ray Bursts**





Nucleosynthesis process: rapid
neutron-capture process (r-process)
— radioactive decay → **Kilonova &**
formation of heavy elements



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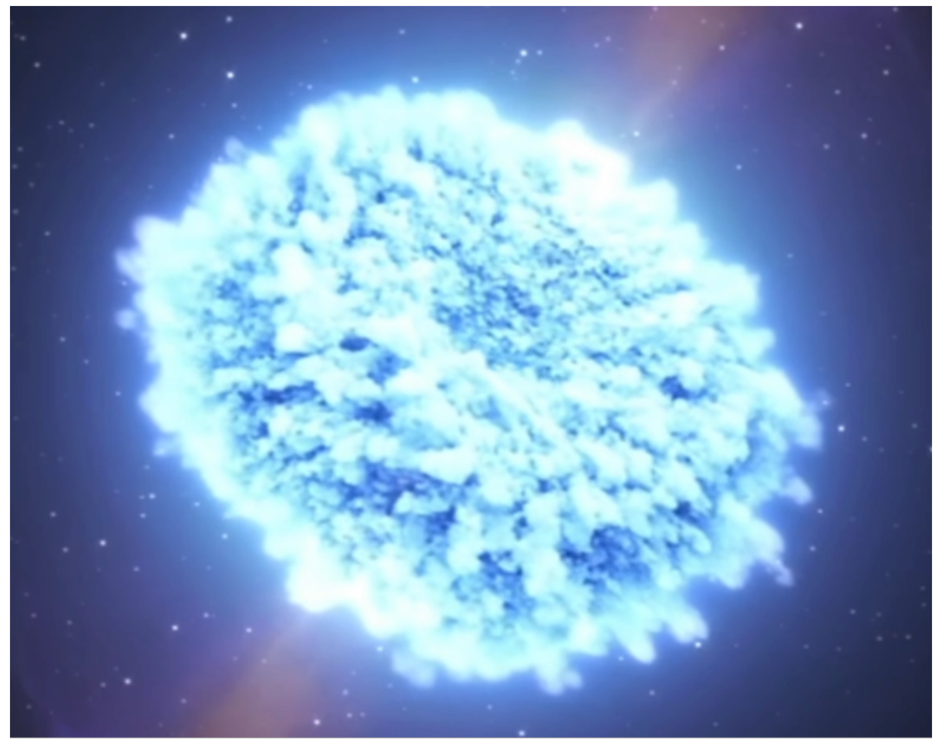


Gravitational Waves

→ **Neutron star merger**

Formation of a jet
of highly relativistic particles

→ **Short Gamma-Ray Bursts**

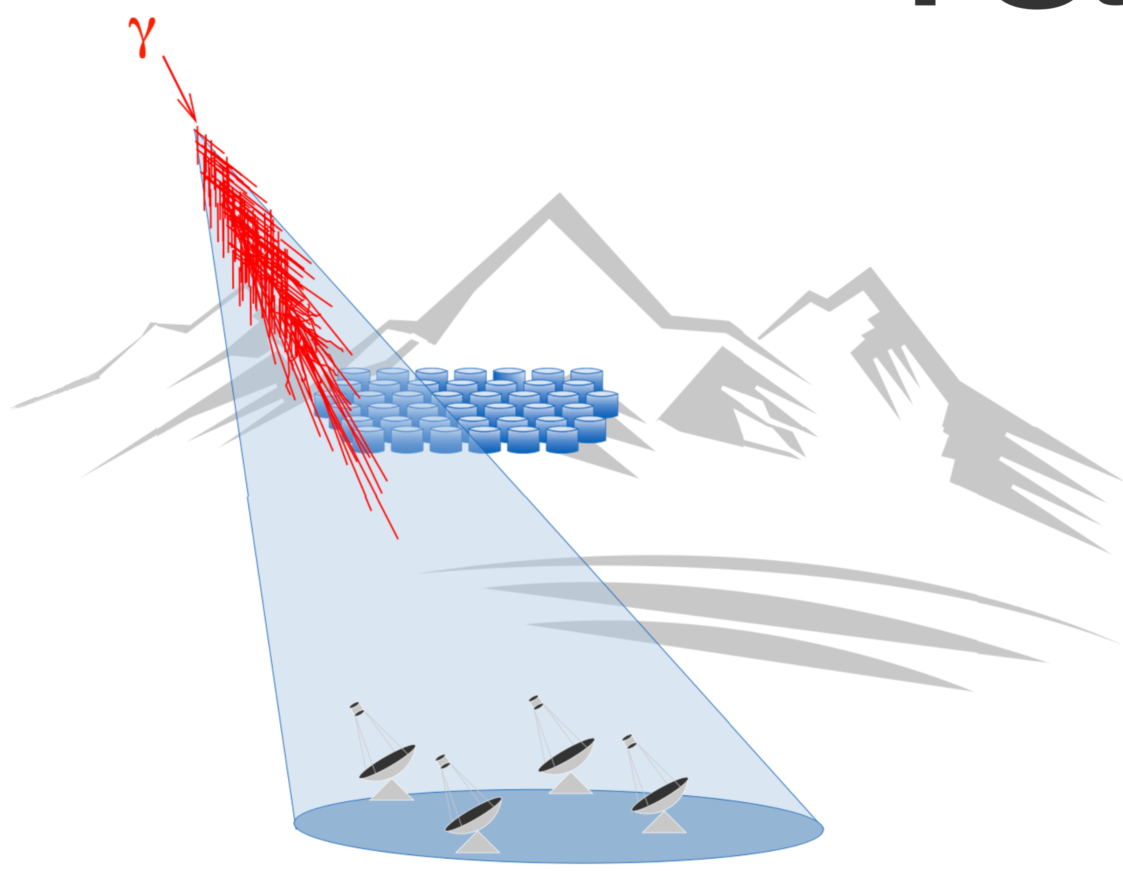
Nucleosynthesis process: rapid
neutron-capture process (r-process)

— radioactive decay → **Kilonova &
formation of heavy elements**

GW170817 and its electromagnetic counterparts

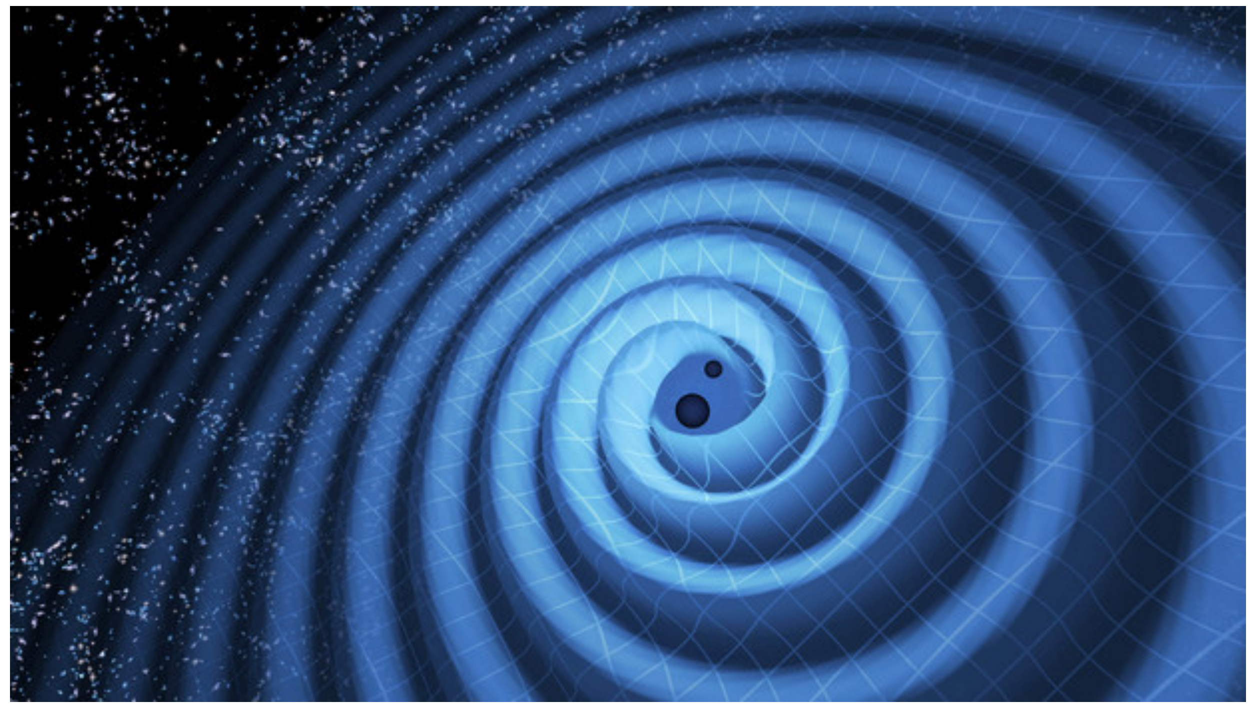
- Confirmed neutron star mergers as a source of gravitational wave
- Proved that neutron star mergers produce short gamma-ray bursts
- Revealed that heavy elements (like gold and platinum) form via r-process nucleosynthesis in kilonovae
- Enabled precise localization of a gravitational wave source using light
- Provided a new independent way to measure the Hubble constant
- Showed that gravitational waves travel at the speed of light to high precision
- Tested general relativity in the strong-field, dynamical regime
- Constrained alternative theories of gravity by confirming gravitational wave speed and polarization
- Placed tight limits on violations of Lorentz invariance and the equivalence principle
- Provided constraints on the neutron star equation of state from merger dynamics and tidal effects

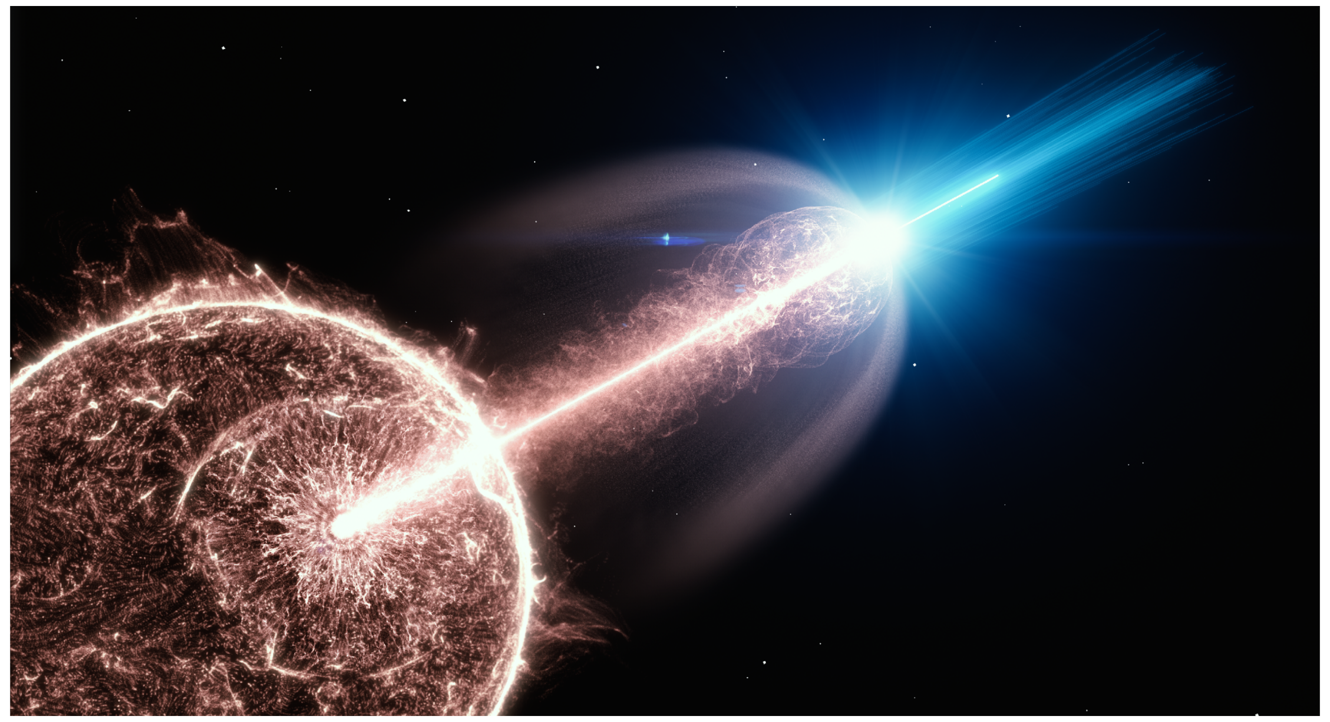
Take home messages



1. γ-ray astronomy is a *mature* field, but it's about to level up with new instruments like CTAO, which will bring better sensitivity and resolution.

2. Gravitational Waves are a *new* tool (first detection in 2015). This field is still young, and the most exciting discoveries are still ahead.





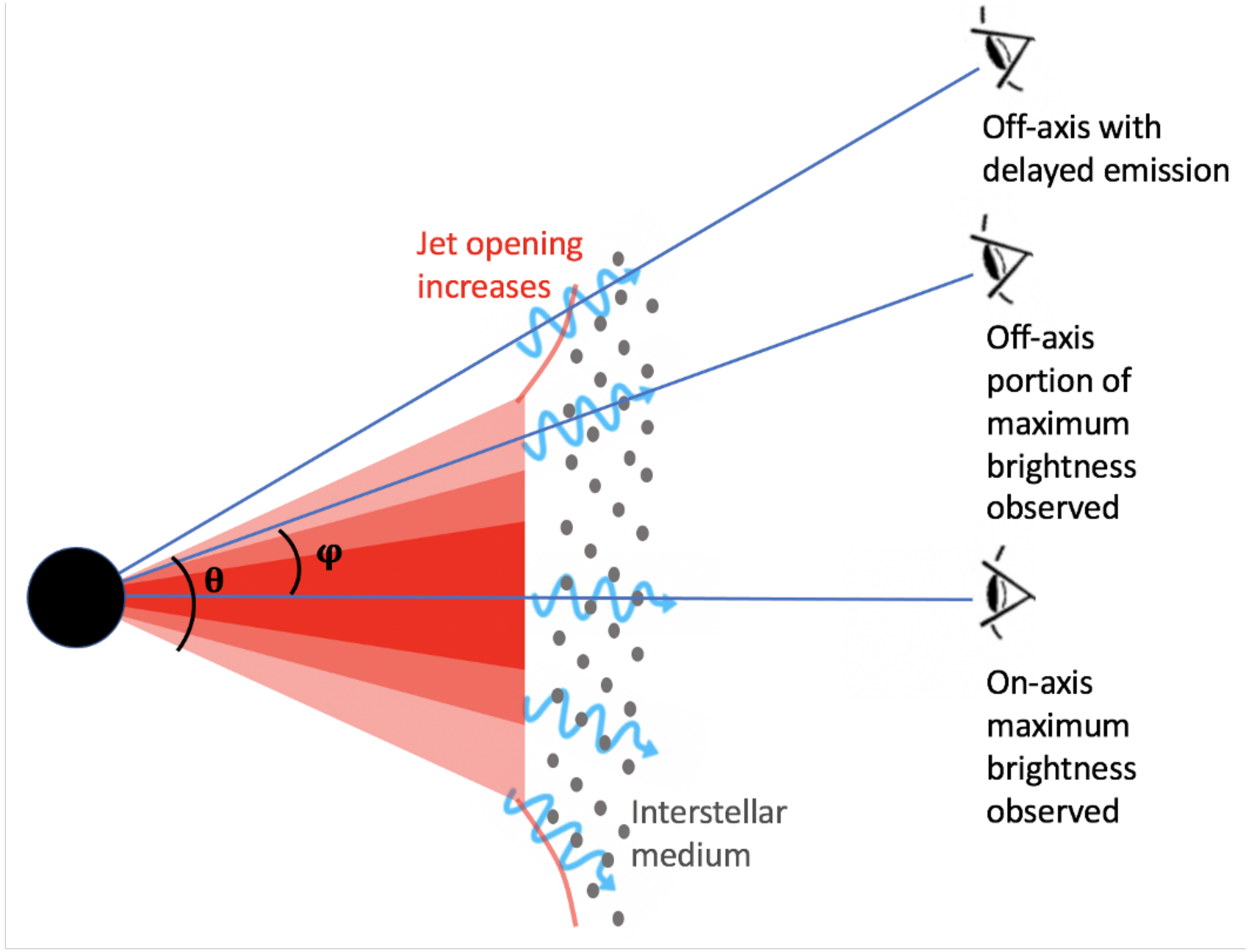
3. Multi-messenger astrophysics combines signals like GWs, γ rays, and ν to reveal a more complete picture of the Universe, making it essential for understanding extreme cosmic events and driving future discoveries.


Cosmic Rays
Gravitational Waves
Neutrinos
Light

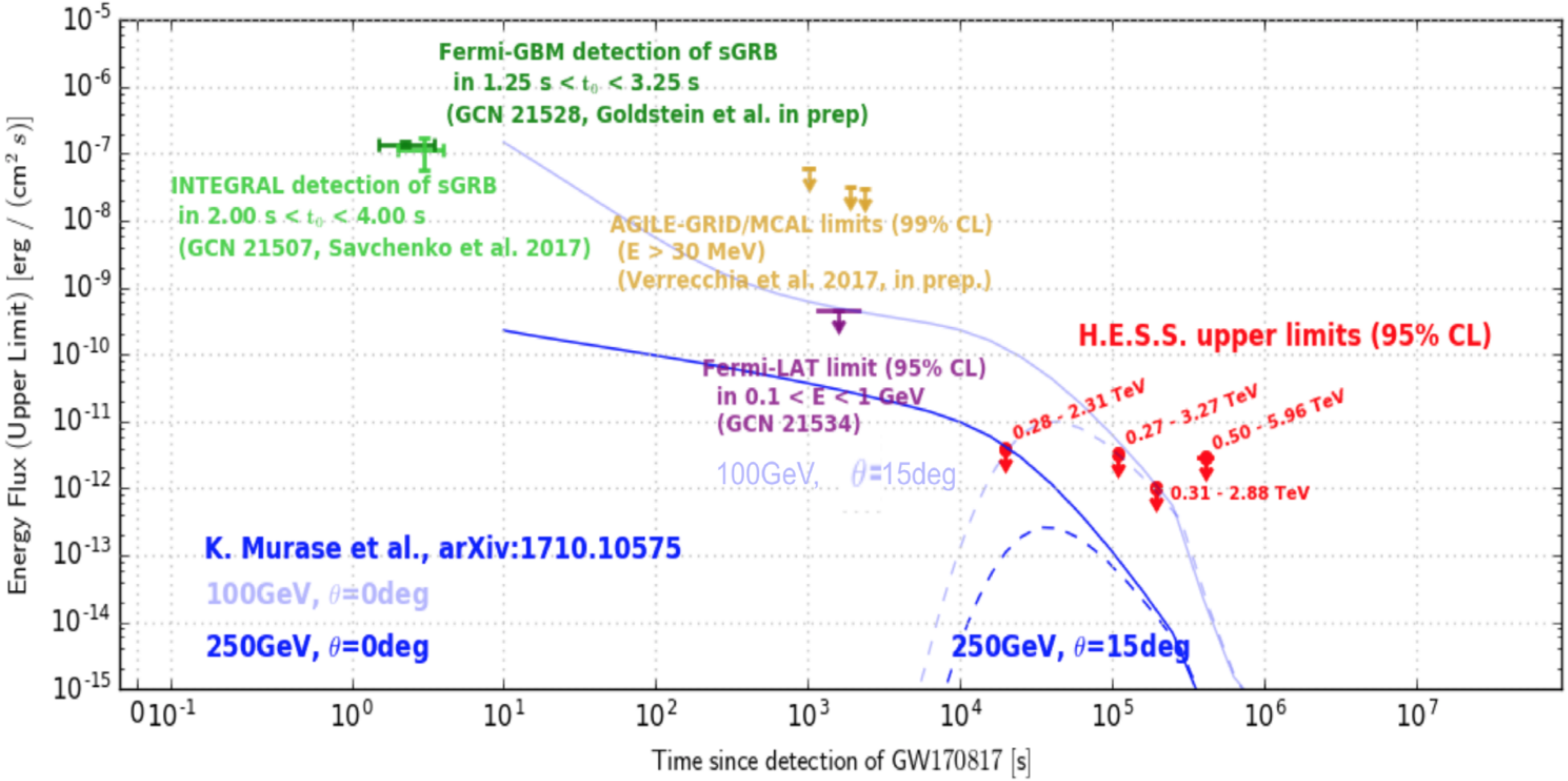
Gamma-Ray Burst

GRBs detected directly are usually on-axis

But GRBs resulting from GW events might be off-axis, adding to the complecity of the problem



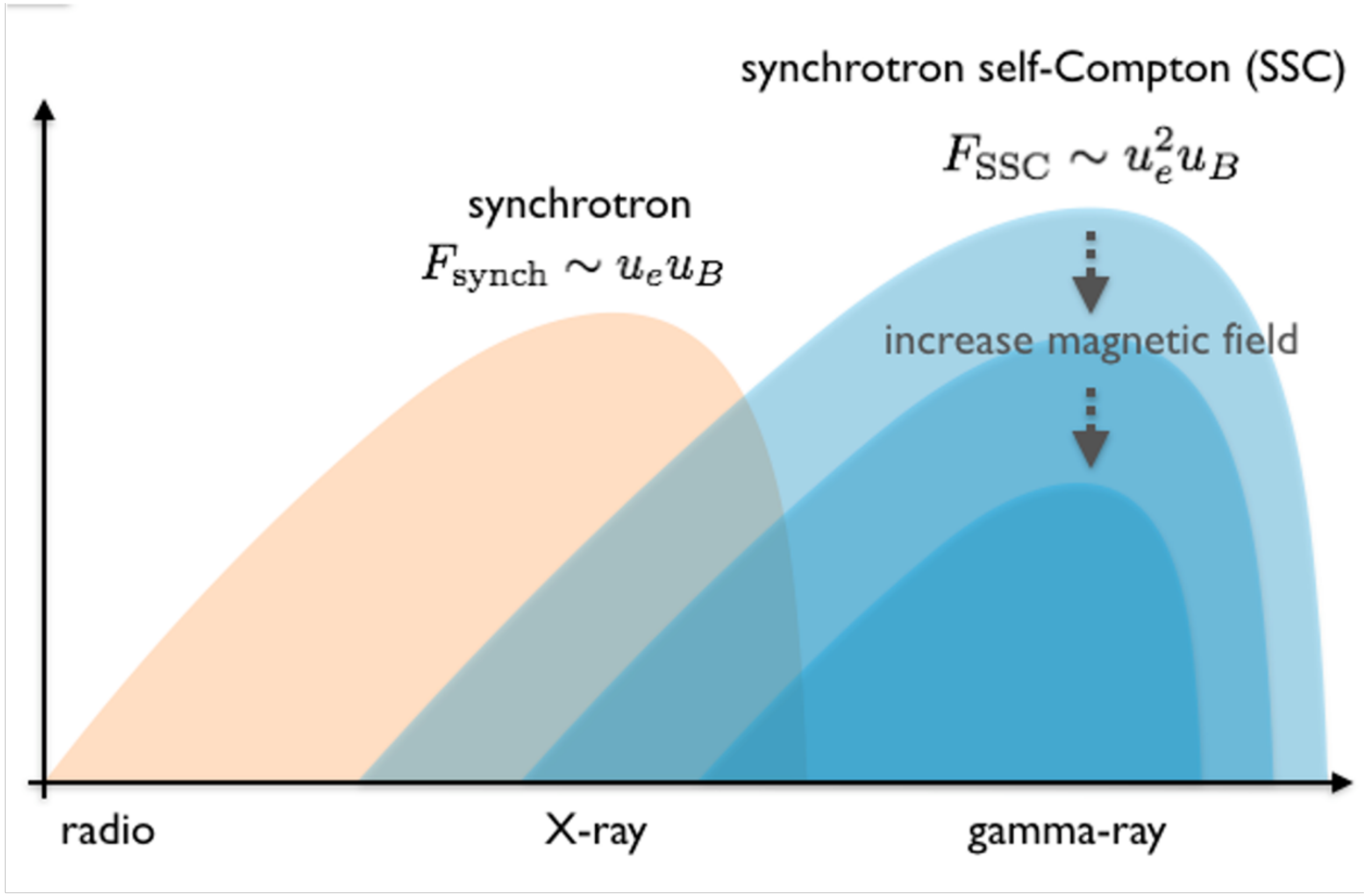
Example: contraining viewing angle with VHE γ-rays



Example: constraining magnetic fields

Synchrotron alone cannot disantangle between the energy ins the particles and the enegy in the magnetic field. An additional measurement is needed.

Synchrotron self-Compton is when the synchroton photons are also the photon fileds for inverse-Compton



Example: constraining magnetic fields