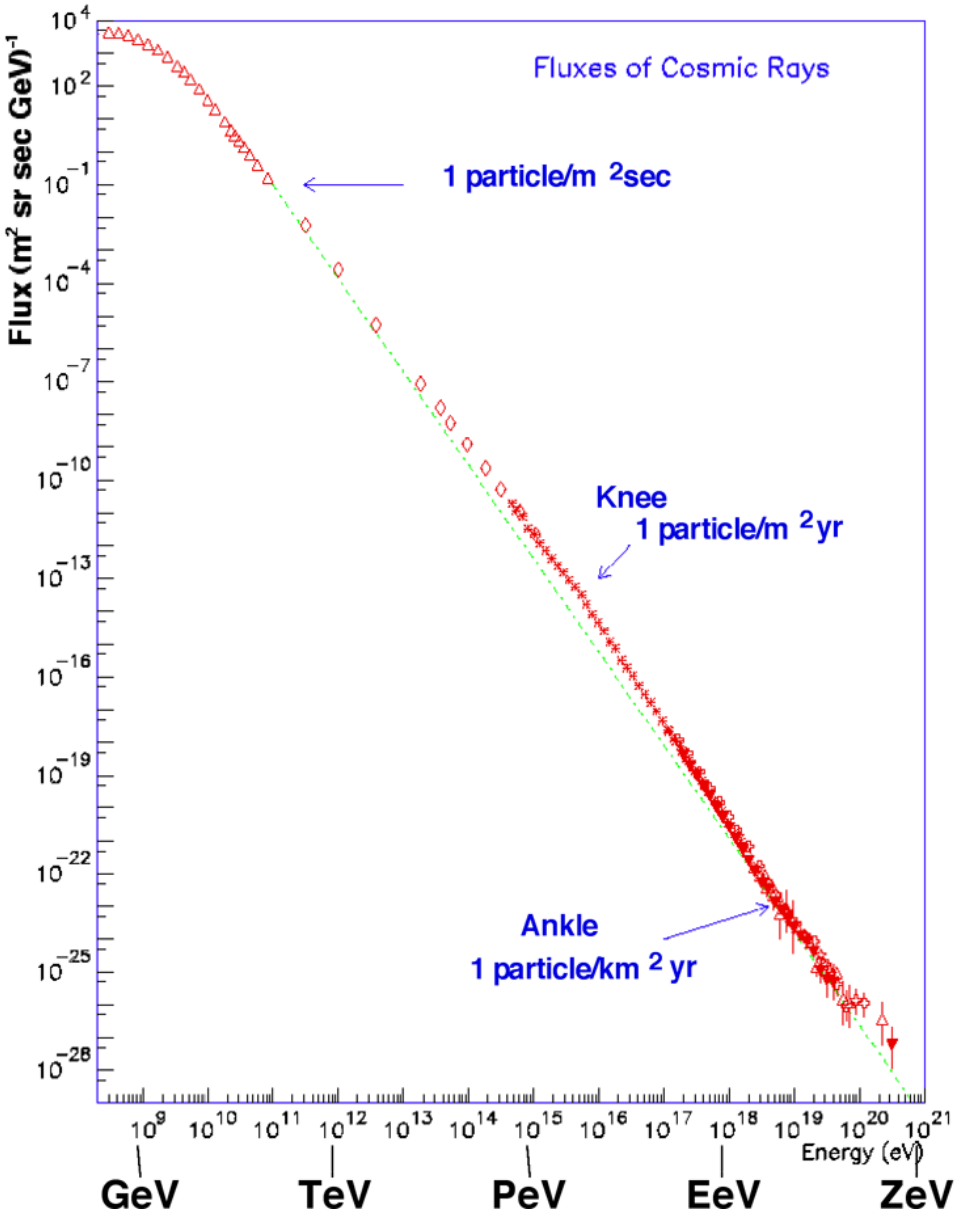
Lecture 1:
Cosmic Rays

i) What are Cosmic Rays (CRs)?
ii) CR Sources
iii) Detection Techniques
iv) Ultra High-Energy Cosmic Rays (UHECRs)
v) Other messengers

Lukasz Stawarz
Obserwatorium Astronomiczne UJ

High Energy Astrophysics, 2024/25

Cosmic Ray Energy Spectrum



Victor Hess, 1912

cosmic rays (CRs): charged high-energy particles

Note:

- huge range in particles' energies
- huge range in fluxes rapidly decreasing with energy
- approximately a single power-law energy spectrum $N(E) \propto E^{-2.7}$

Thermal vs. Non-thermal

non-relativistic vs. ultra-relativistic

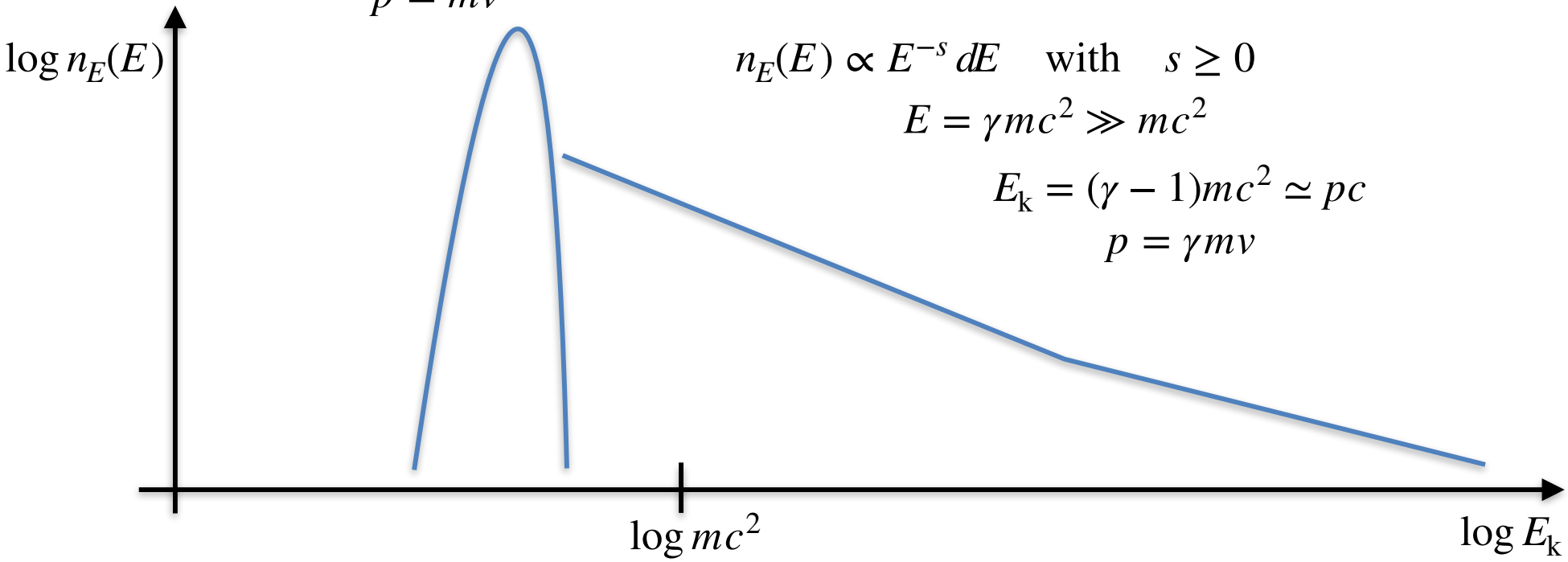
total number (density) of particles $N = \int dE\, n_E(E) = \int d^3\vec{p}\, n_{\vec{p}}(\vec{p}) \overset{\text{iso}}{\rightarrow} 4\pi \int dp\, p^2 n_p(p)$

$$n_E(E) \propto E^{1/2}\, e^{-E/kT}\, dE$$

$$\langle E_\mathrm{k} \rangle \simeq kT \ll mc^2$$

$$E_\mathrm{k} = p^2/2m$$

$$p = mv$$



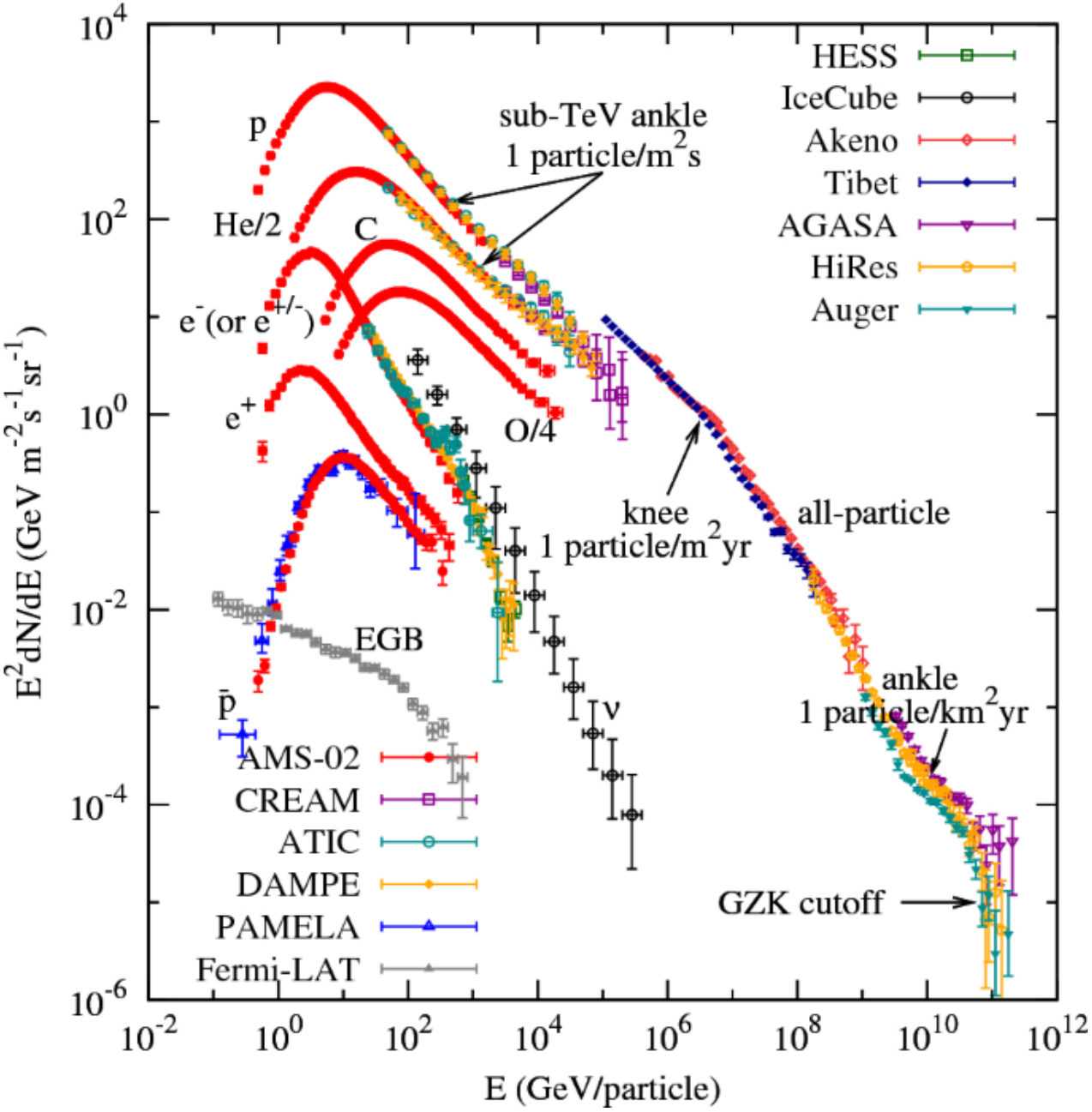
$$n_E(E) \propto E^{-s}\, dE \quad \text{with} \quad s \geq 0$$

$$E = \gamma mc^2 \gg mc^2$$

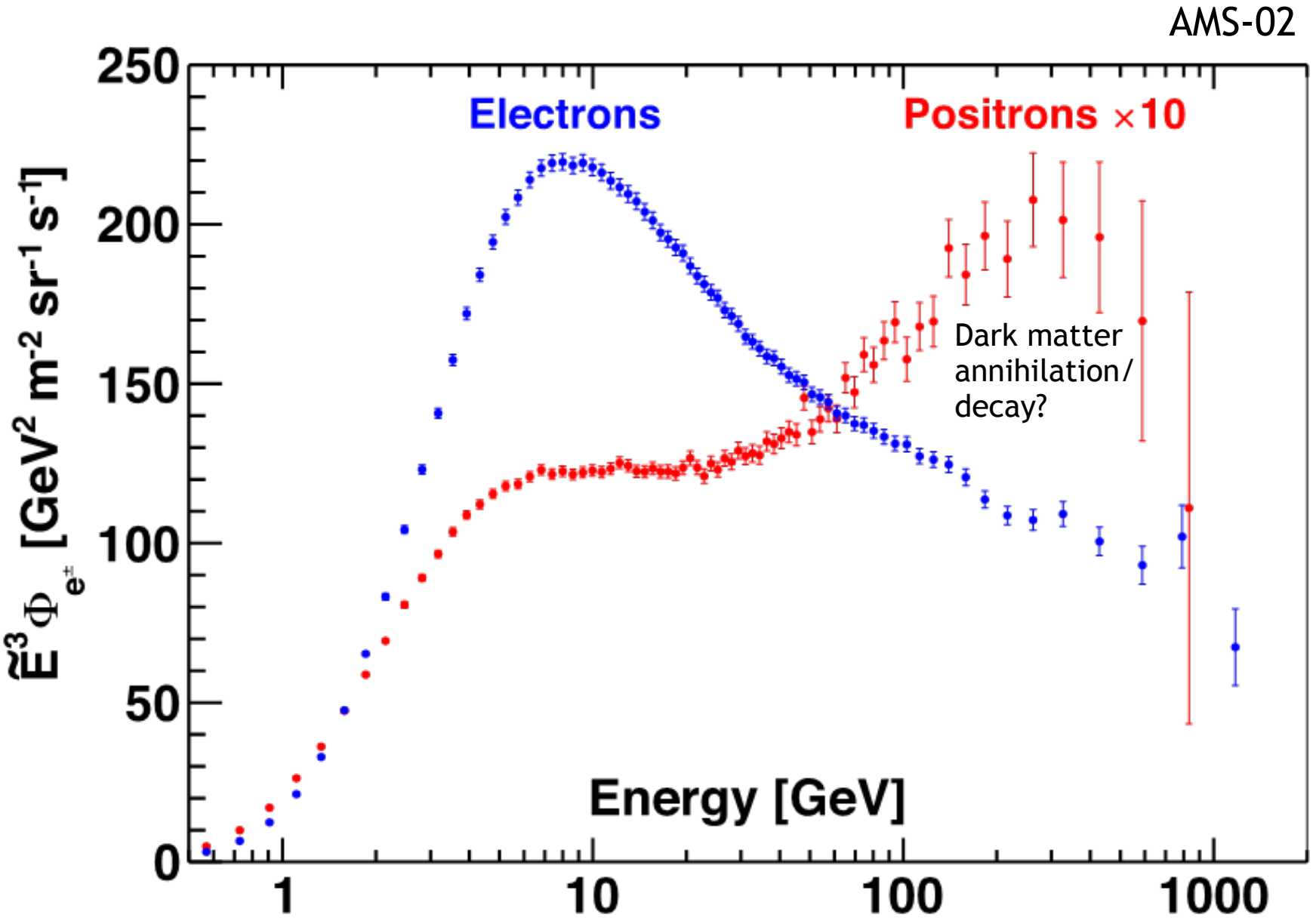
$$E_\mathrm{k} = (\gamma - 1)mc^2 \simeq pc$$

$$p = \gamma mv$$

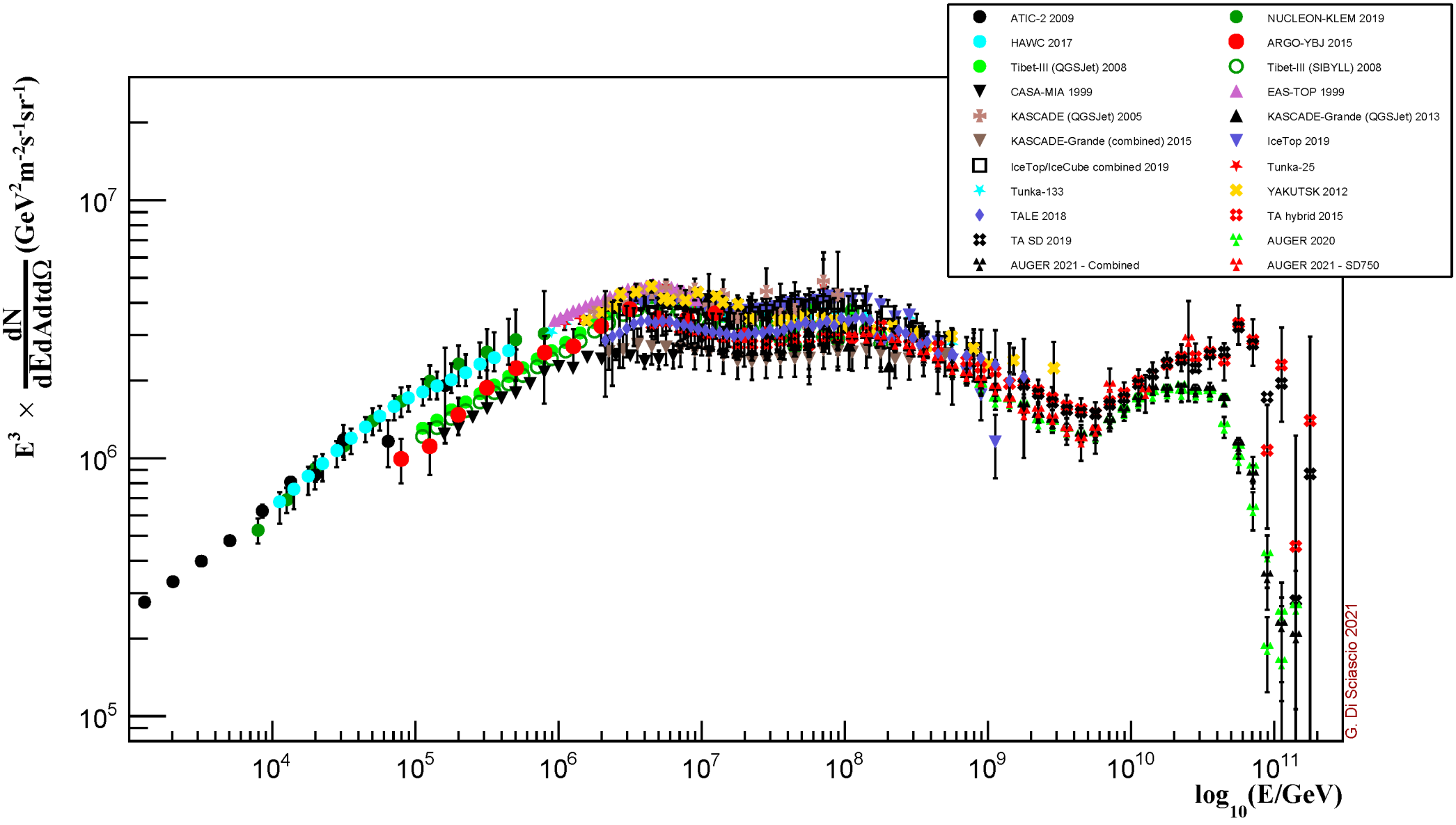
Composition



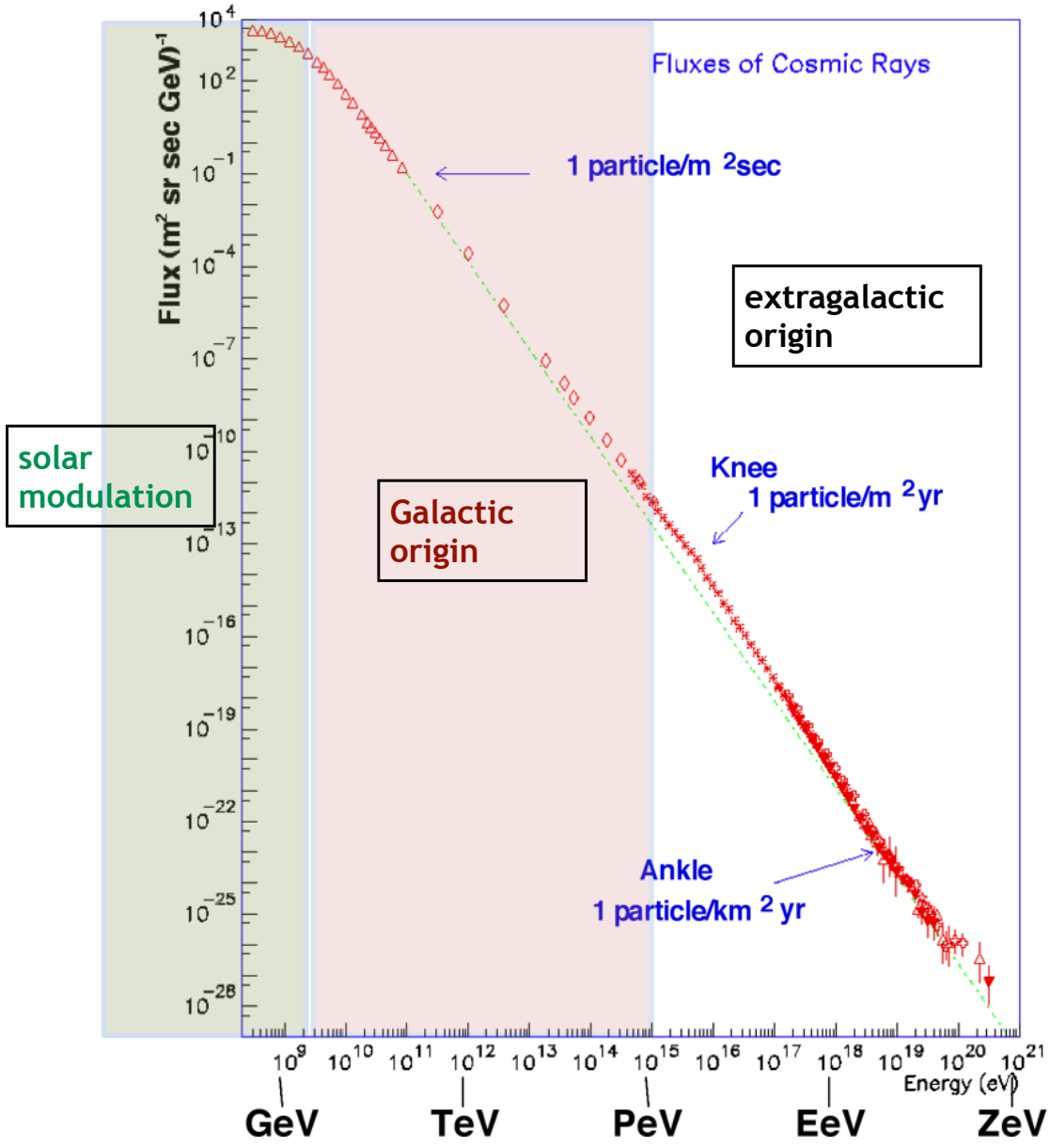
Cosmic-ray Electrons and Positrons



High and Ultra High-Energy Cosmic Rays



Cosmic Ray Origin



Victor Hess, 1912

cosmic rays (CRs): charged high-energy particles

Note:

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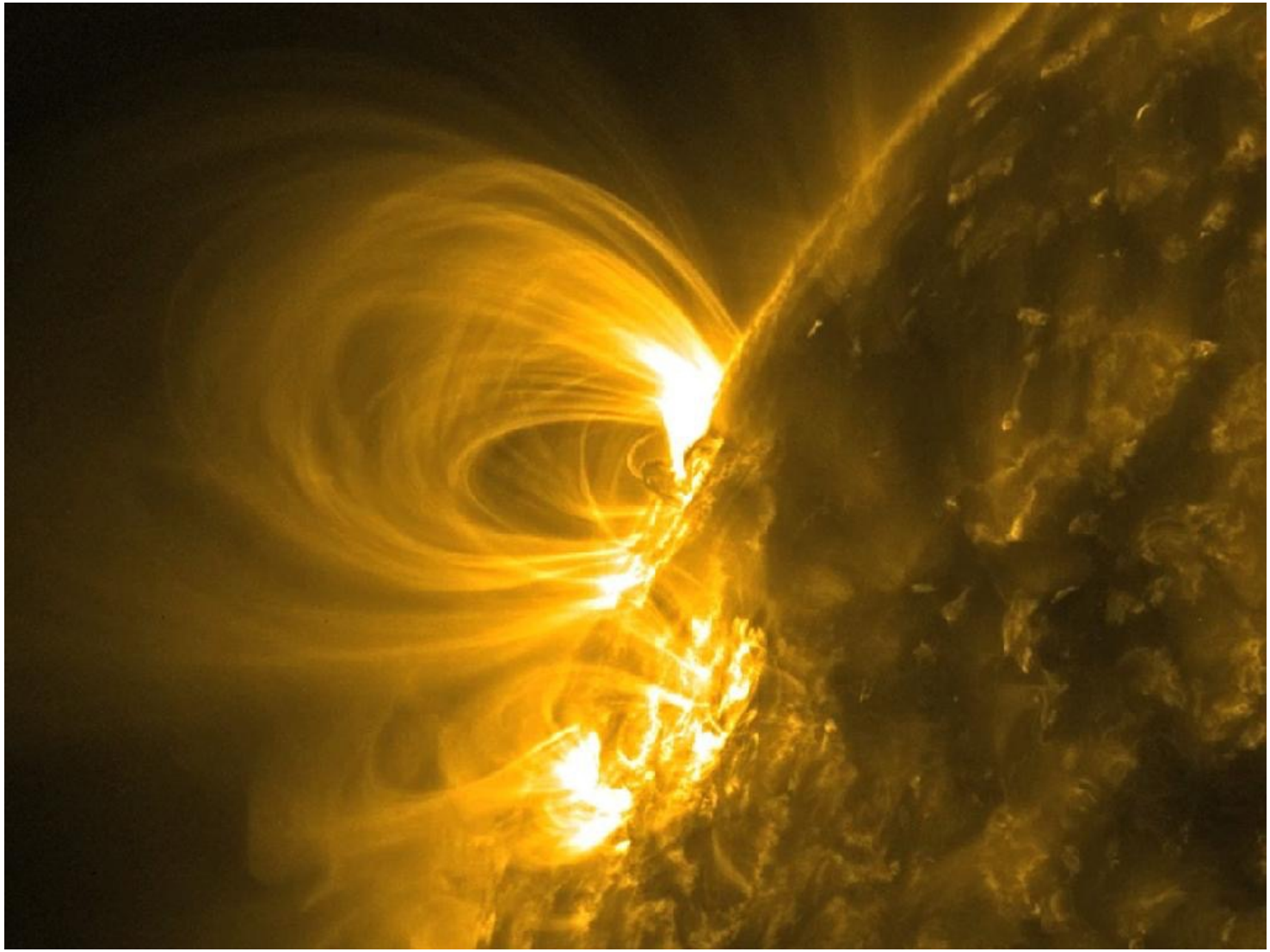
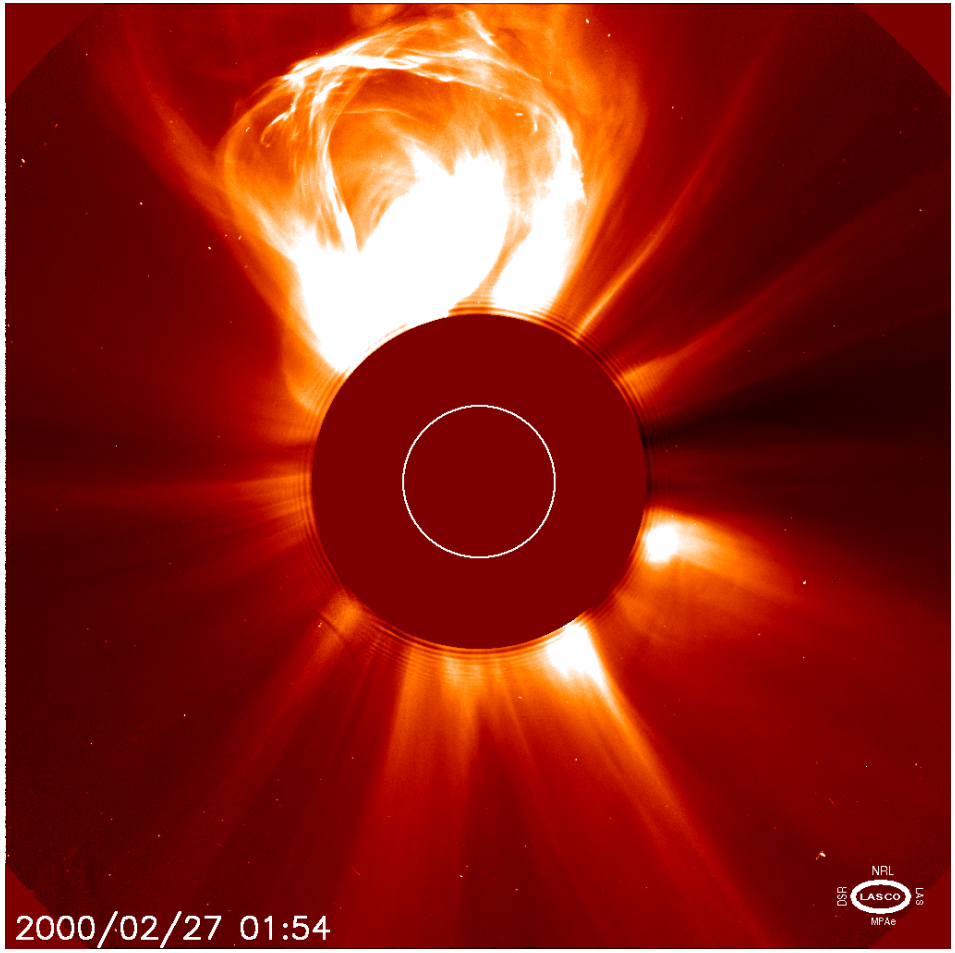
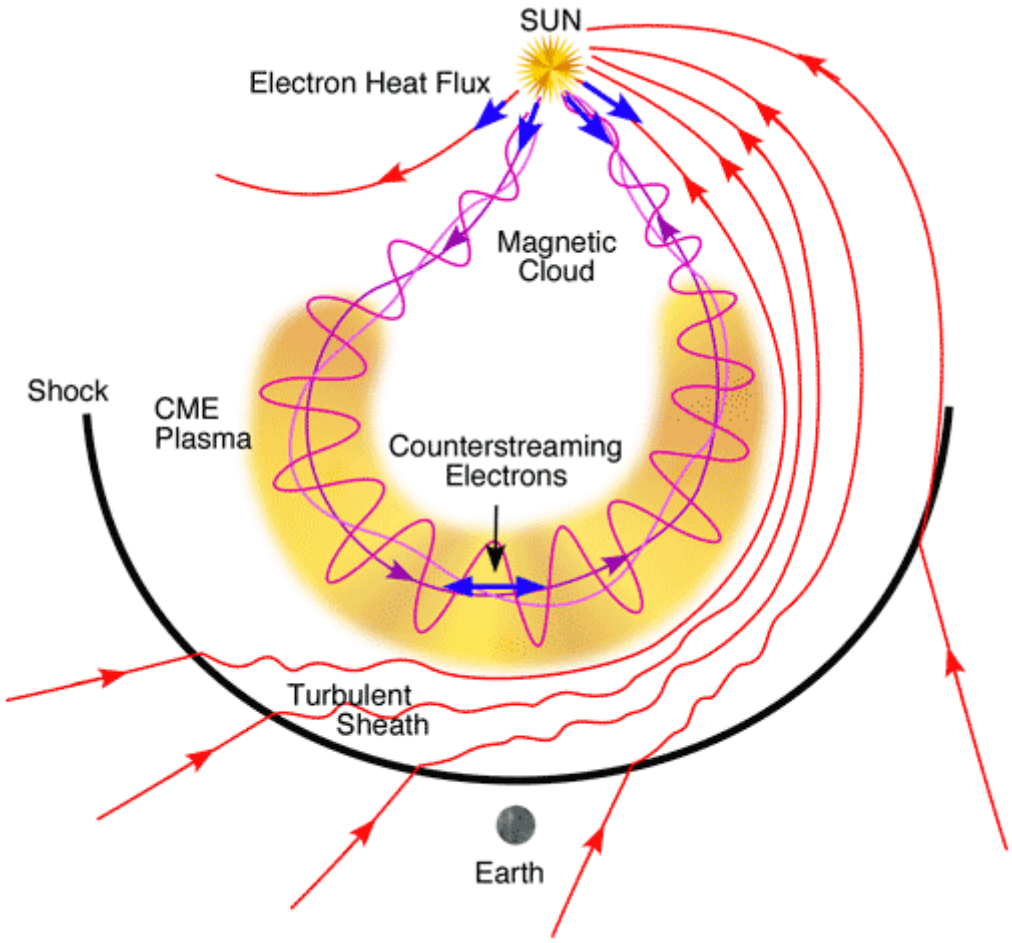
Solar Flares



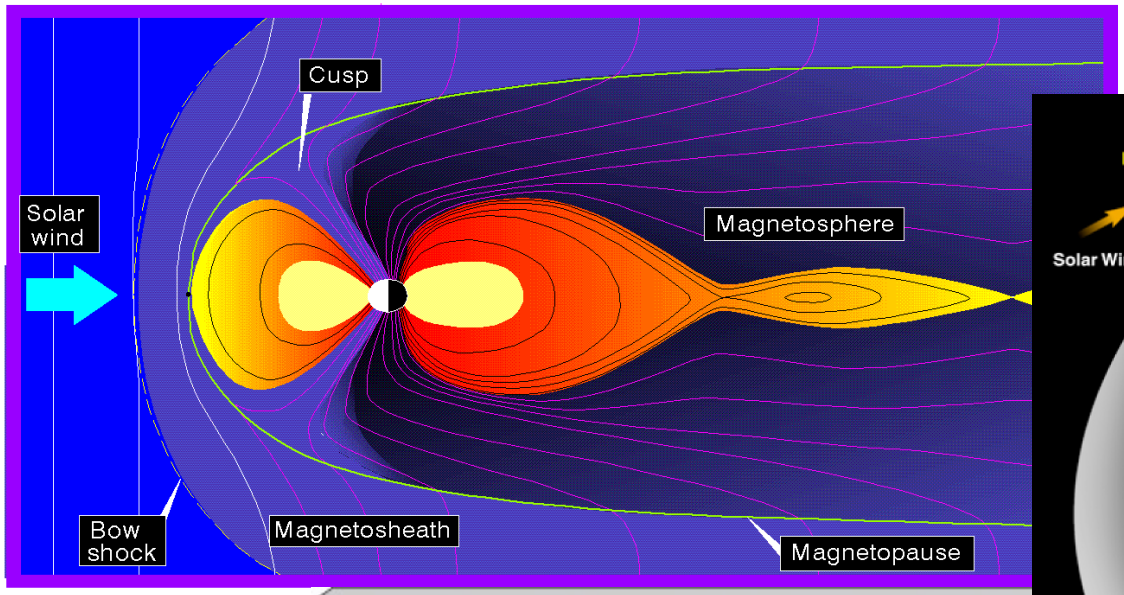
Discovered in optical in 1859 by Richard Carrington,
in radio in 1943 by Grote Reber,
and in UV/X-rays in the 1970s

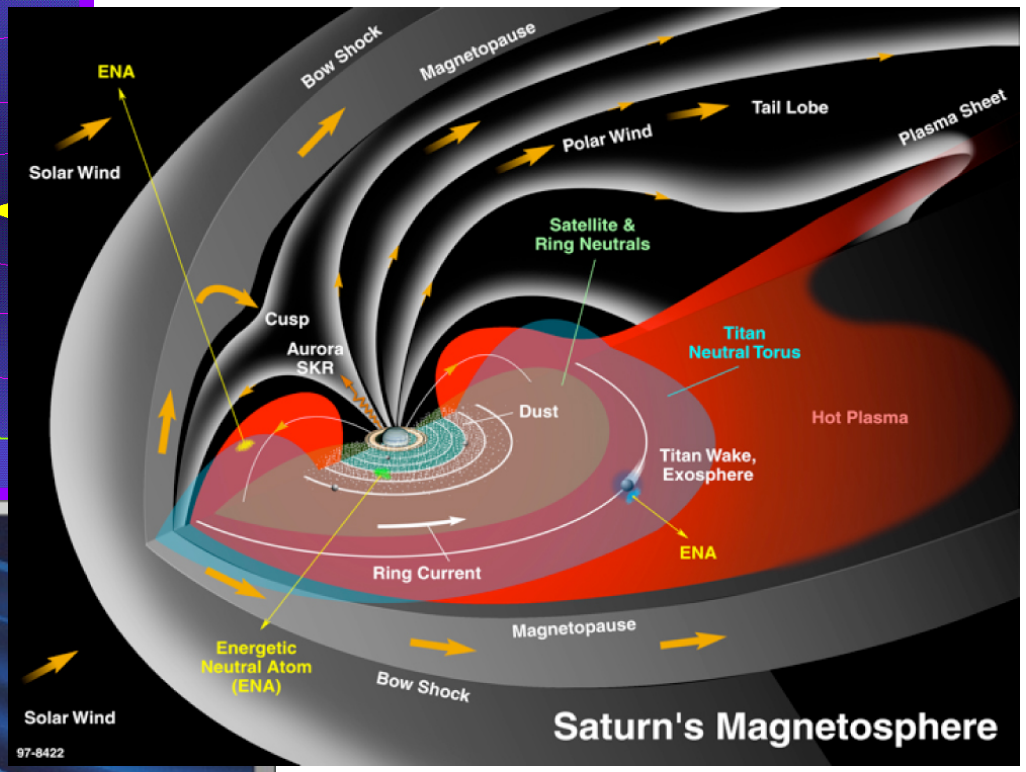
Coronal Mass Ejections

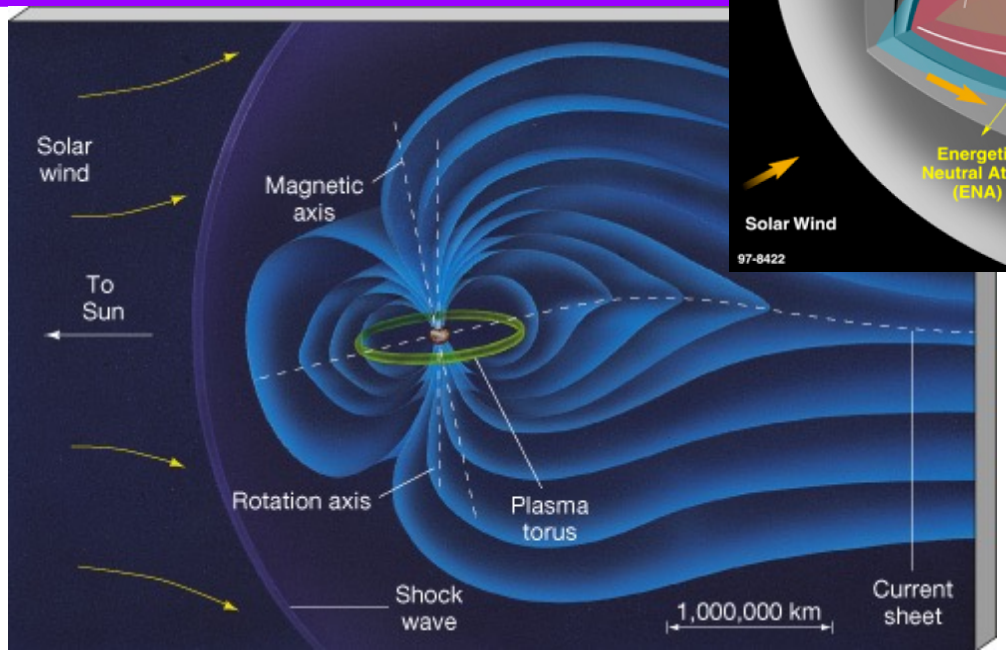




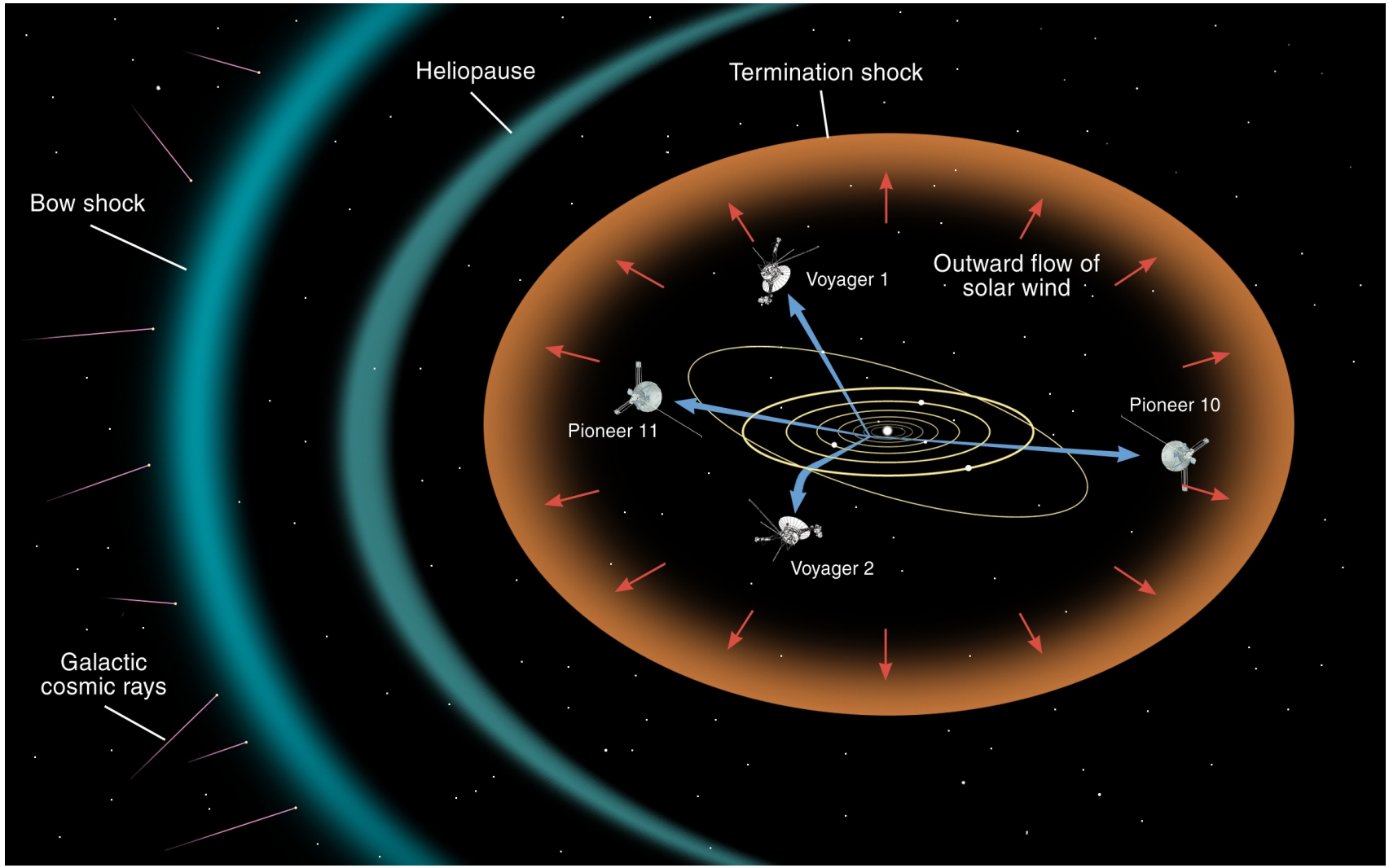
Planetary Magnetospheres



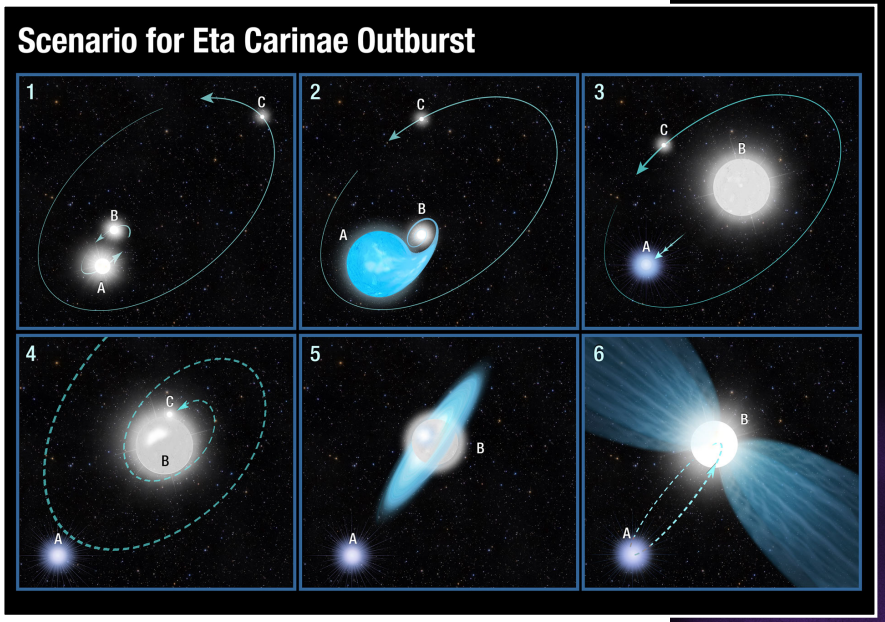


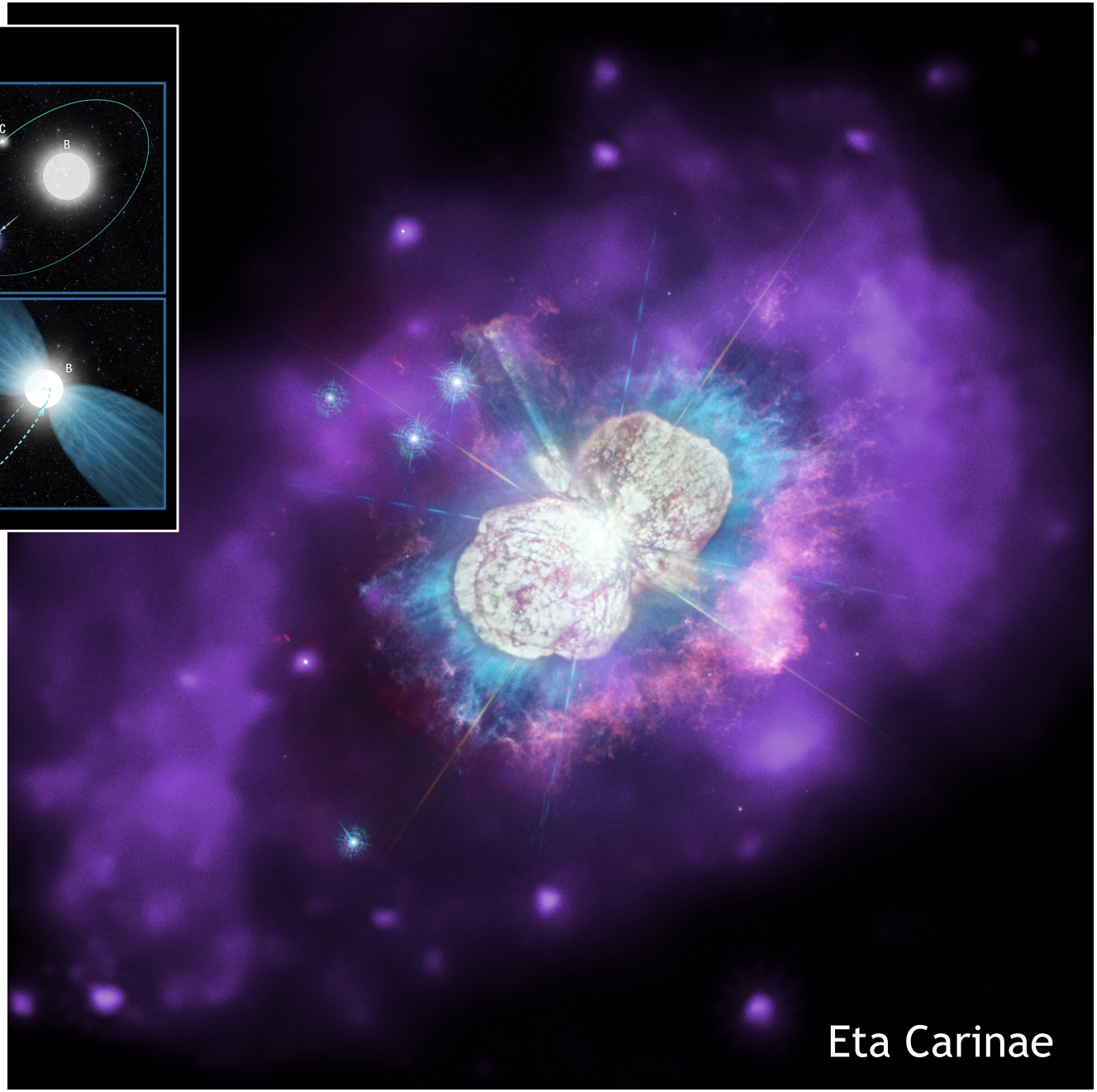


Termination Shock

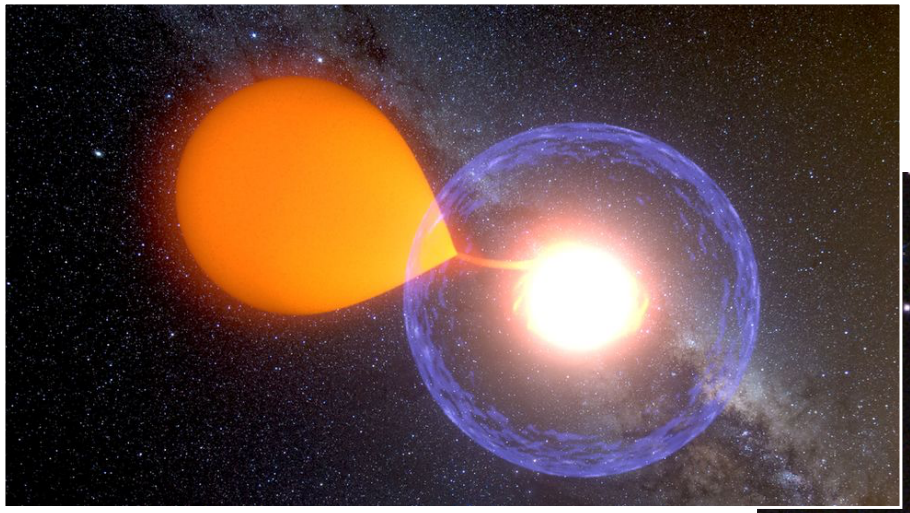


High-mass Binary Stars



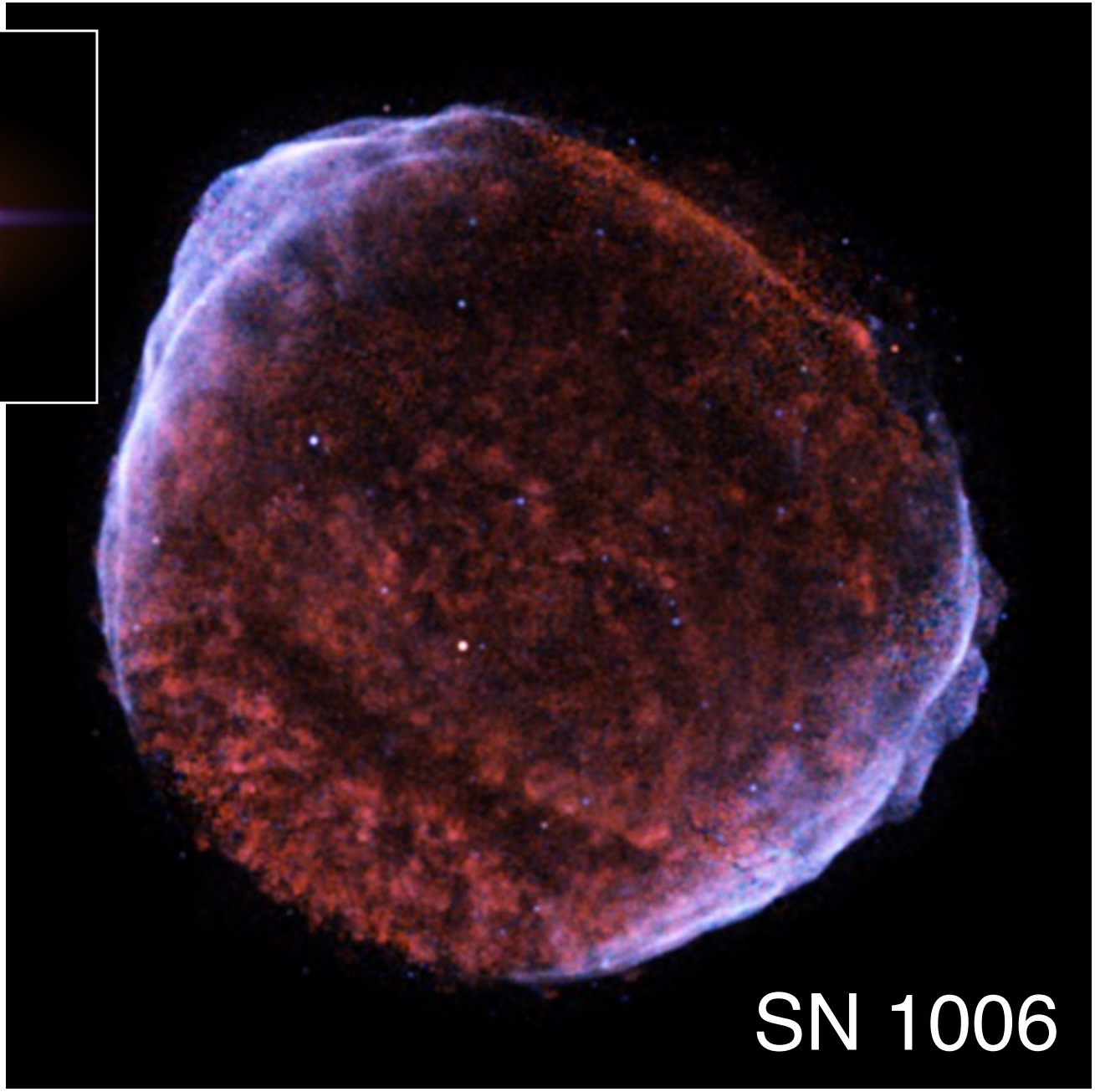


Novae

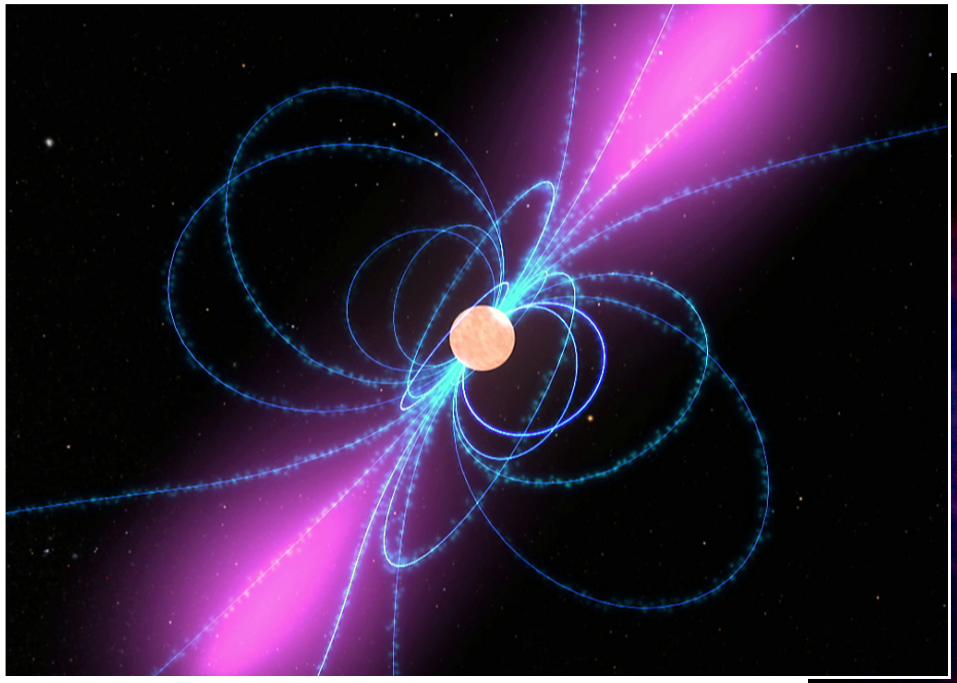


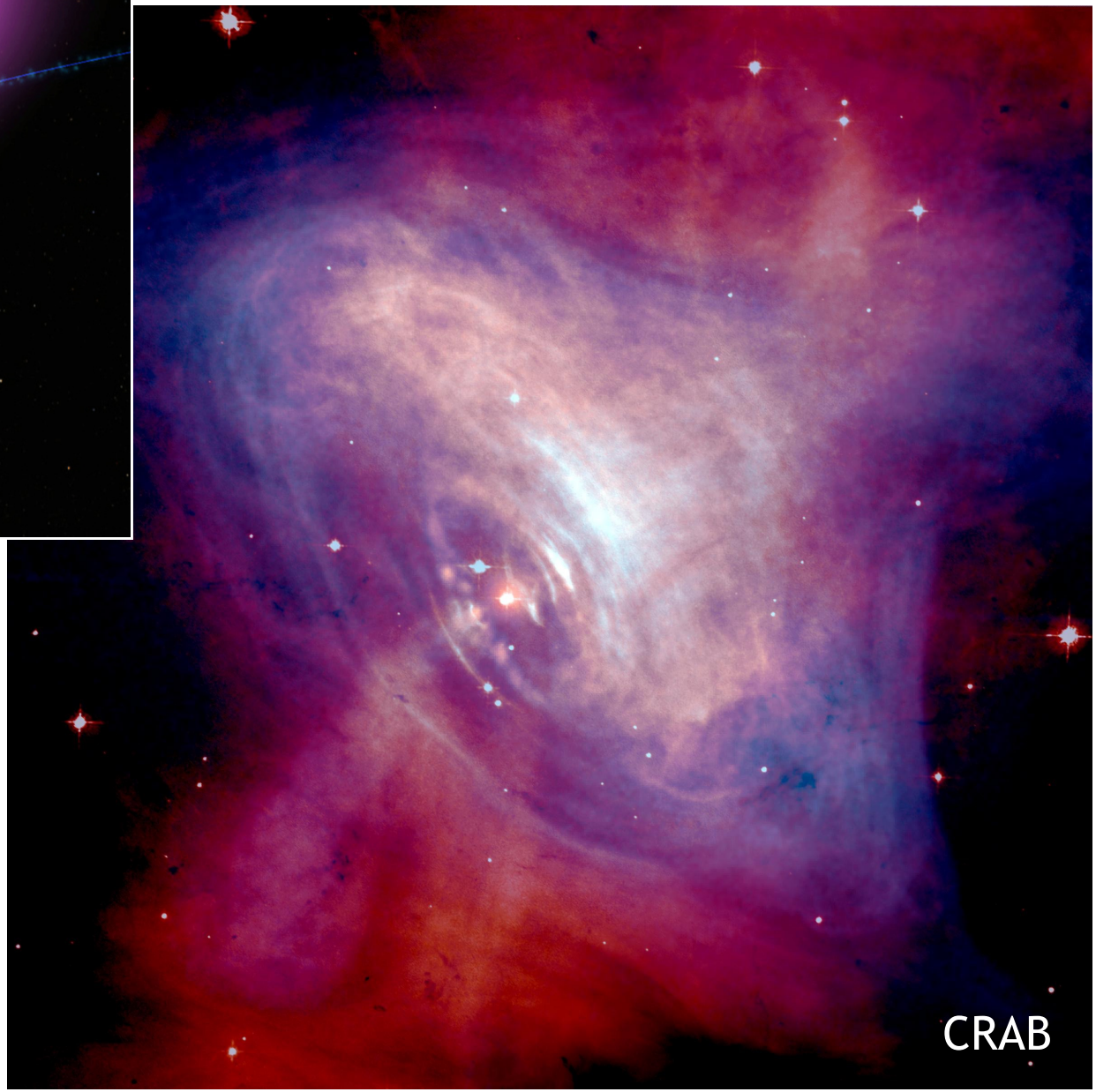
V838 Monocerotis

Supernovae & Supernova Remnants

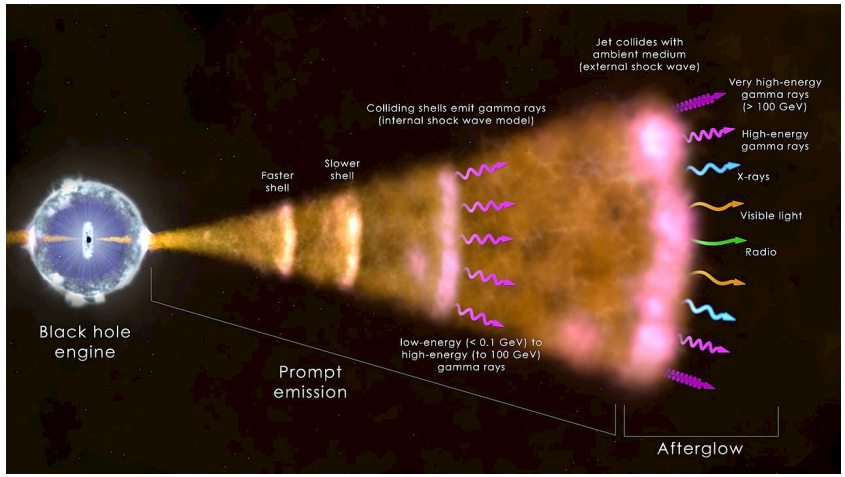


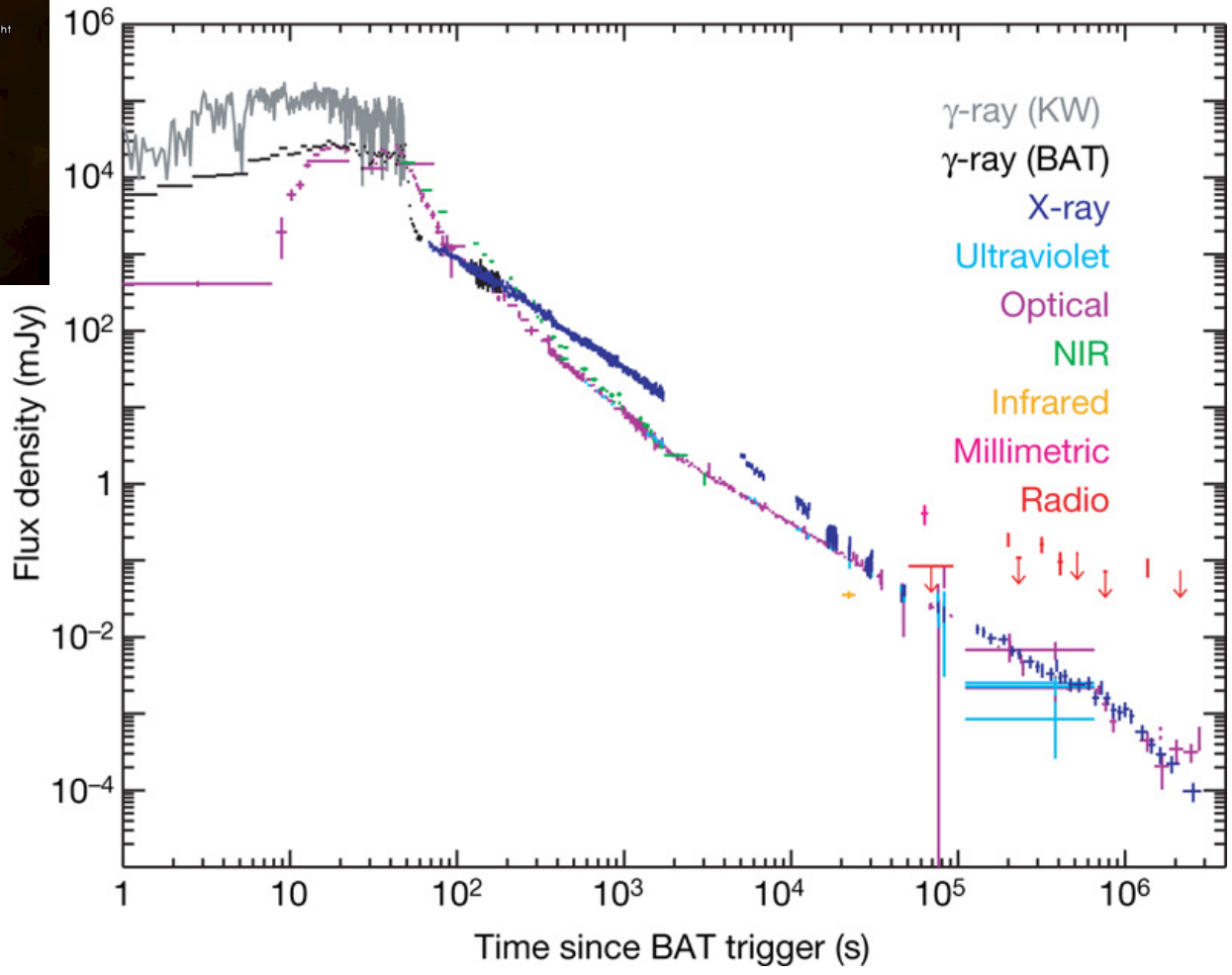
Pulsars & Their Wind Nebulae



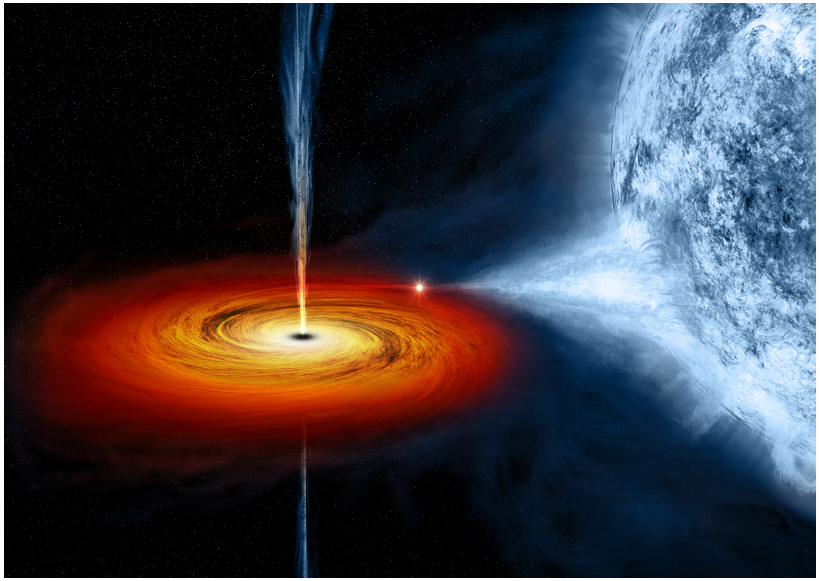


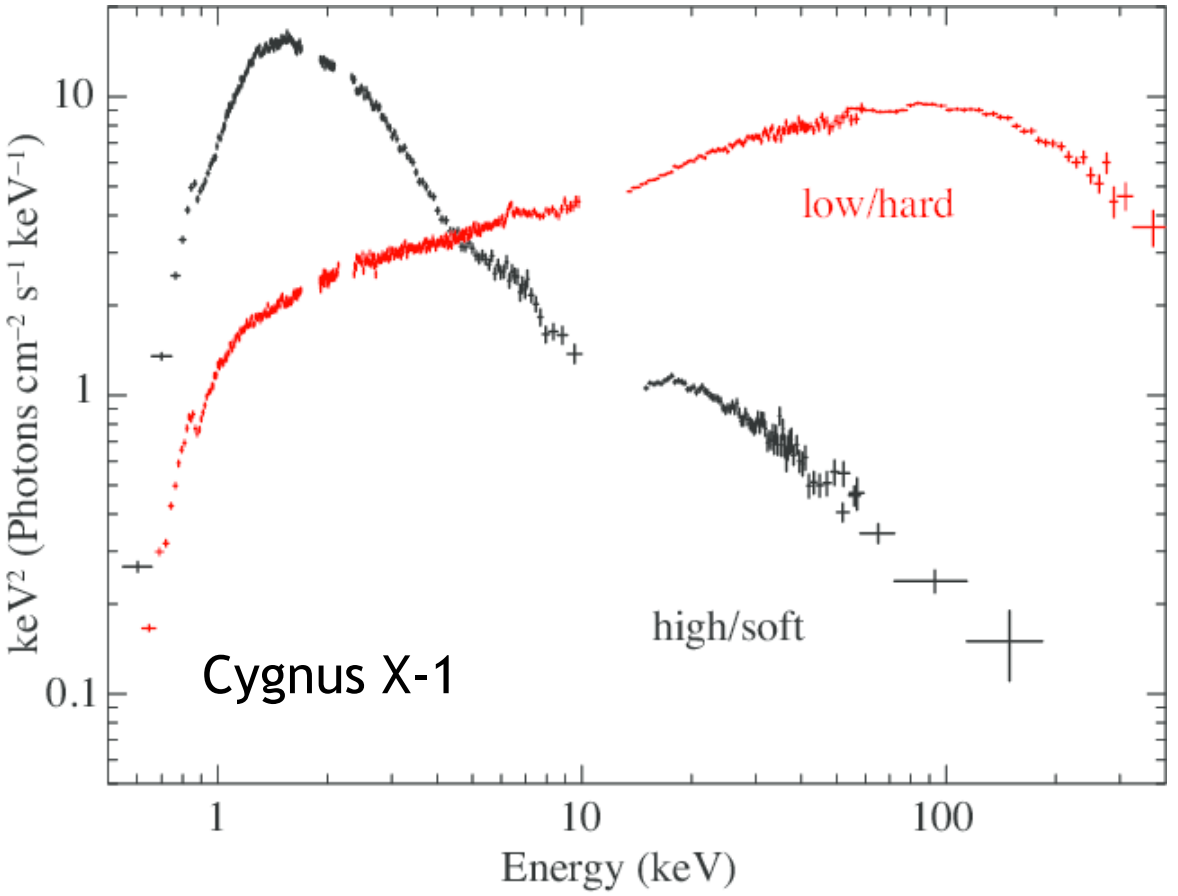
(Long) Gamma Ray Bursts



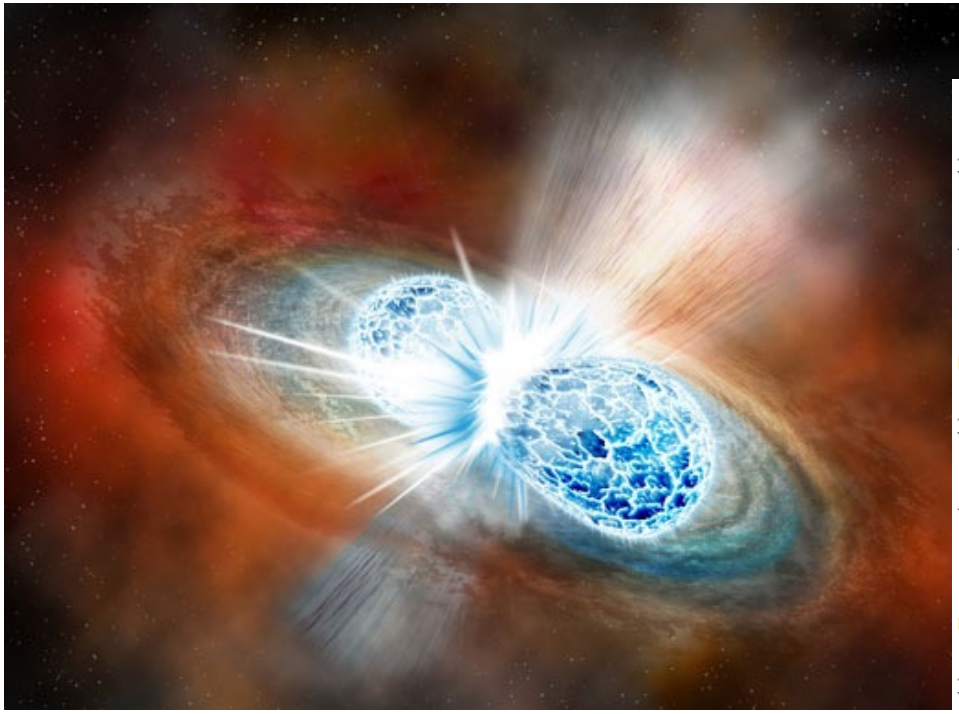


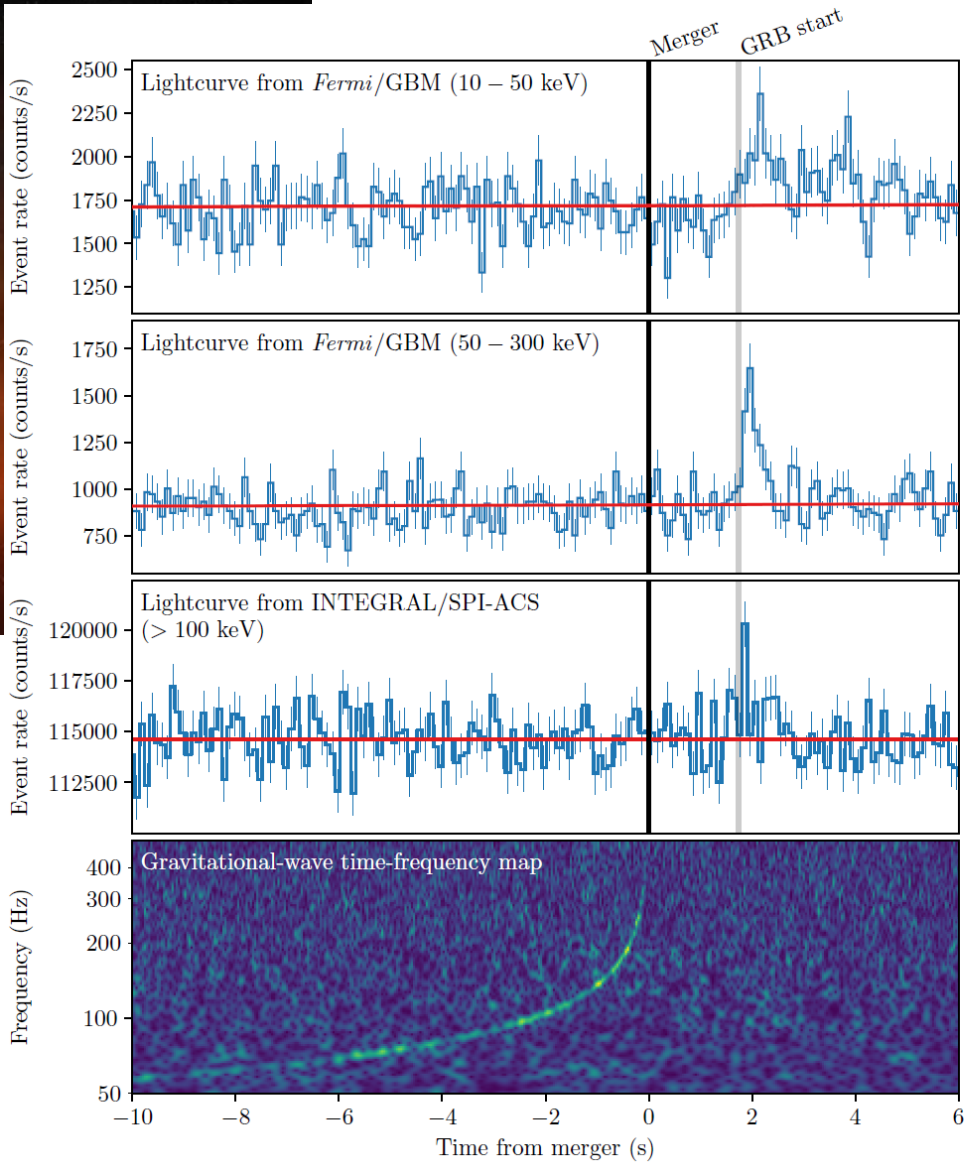
X-ray Binaries



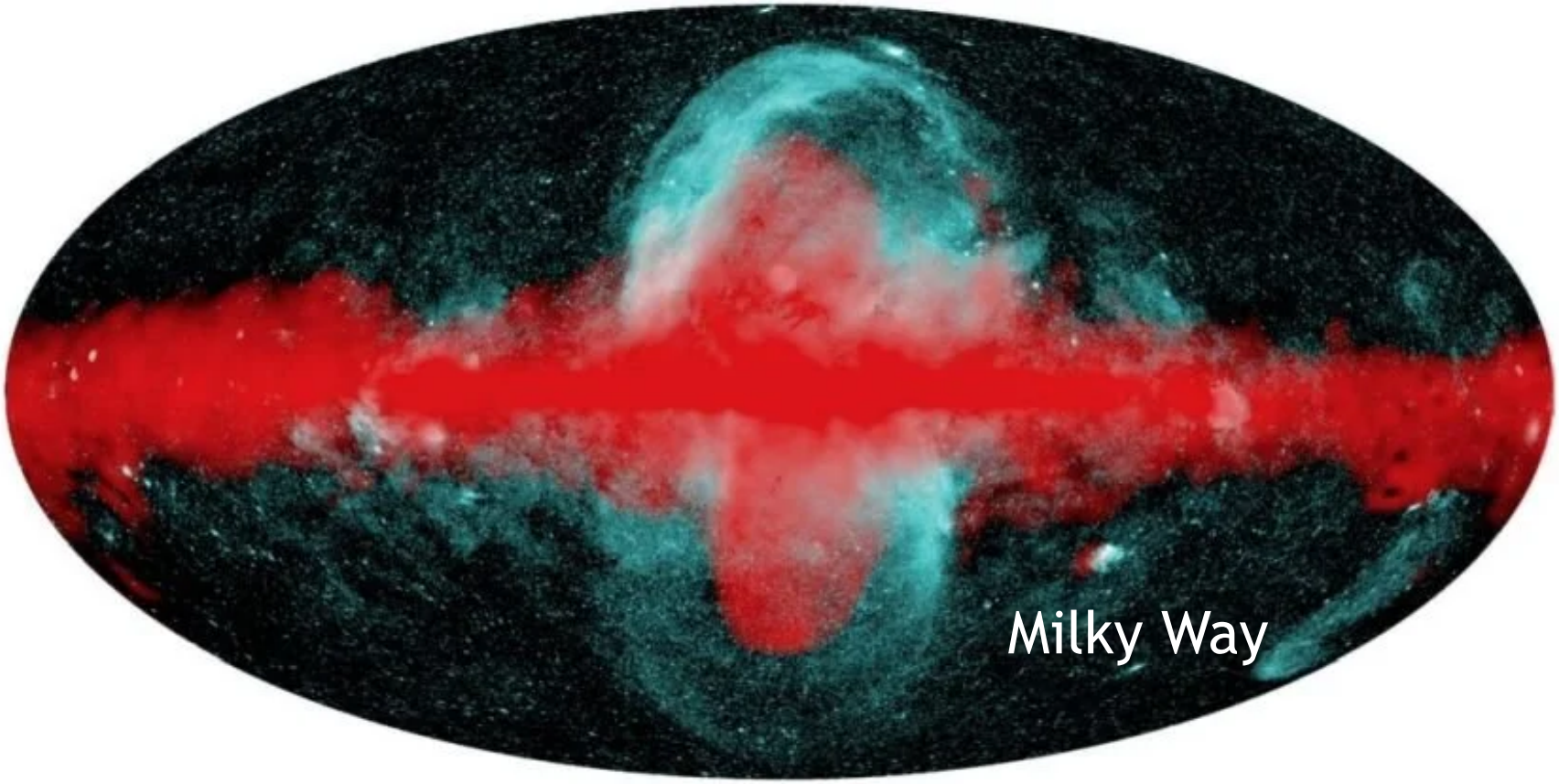


Merging Neutron Stars



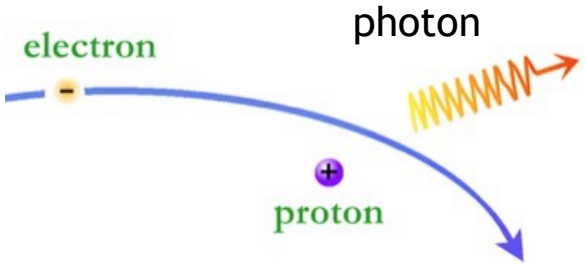


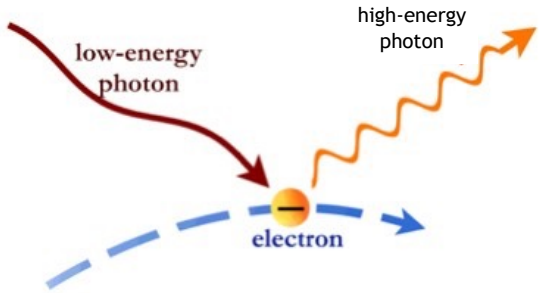
Galactic Disk and Halo



Cosmic Ray Interactions

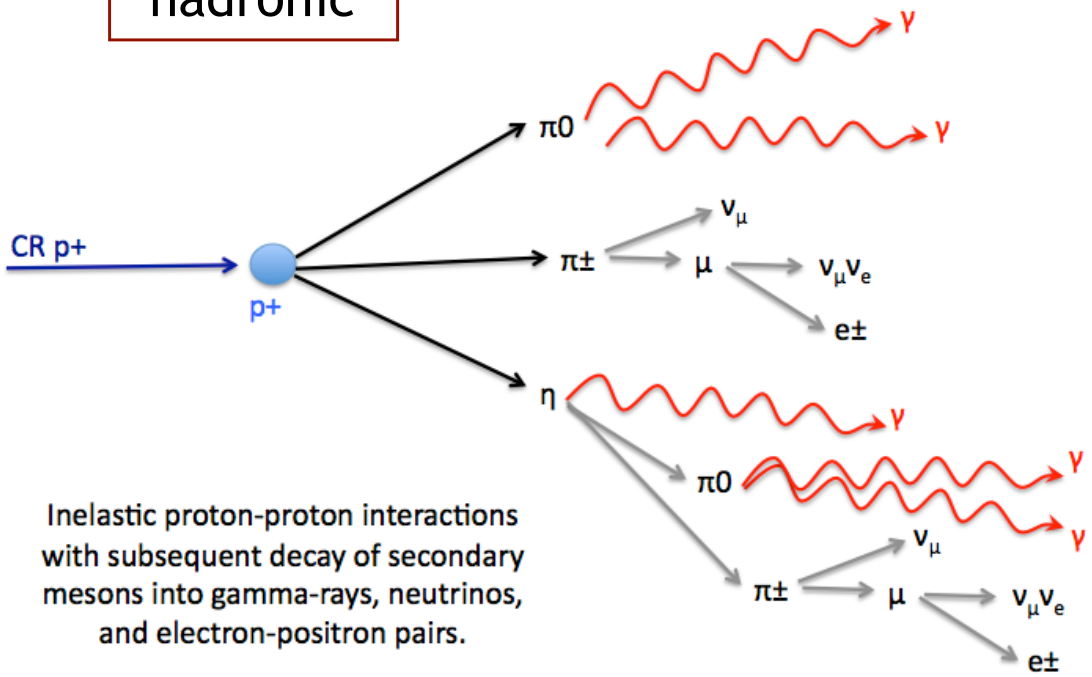
"leptonic"





Interactions of a charged particle with electromagnetic field

"hadronic"



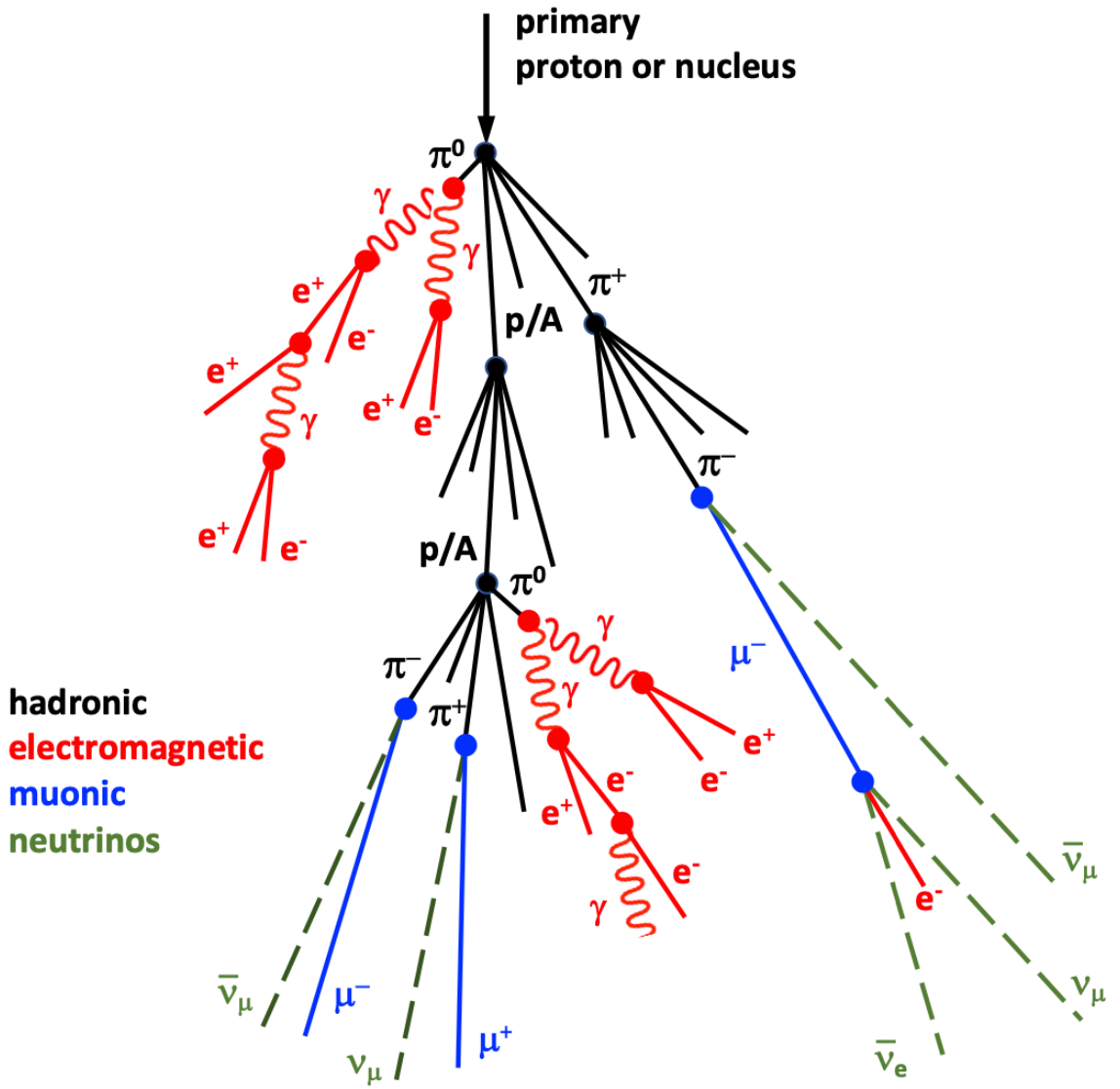
Inelastic proton-proton interactions with subsequent decay of secondary mesons into gamma-rays, neutrinos, and electron-positron pairs.

also "photo-meson production"

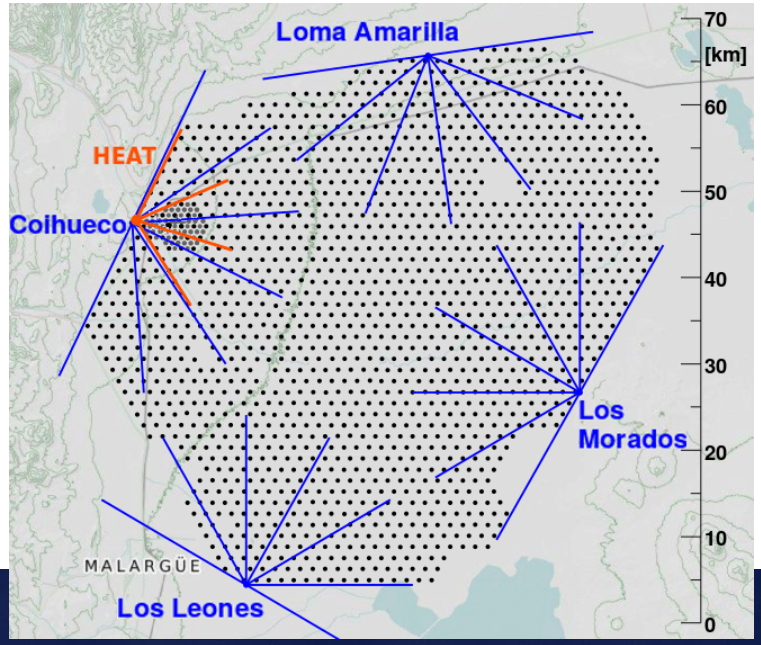
$$\mathrm{CR} + \gamma \rightarrow n + \pi^{+}$$
$$\mathrm{CR} + \gamma \rightarrow p + \pi^{0}$$

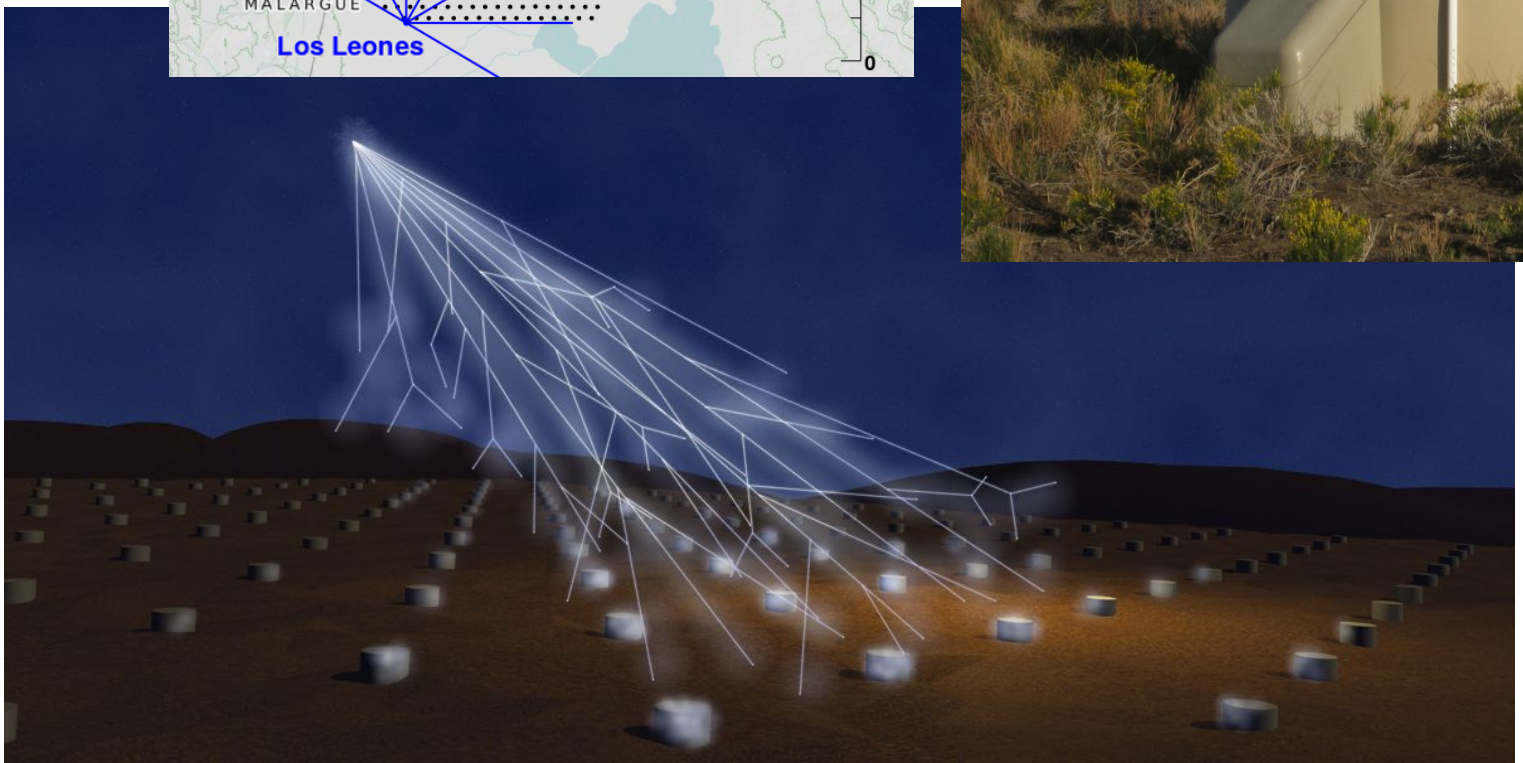
etc.

Detection: Atmospheric Showers



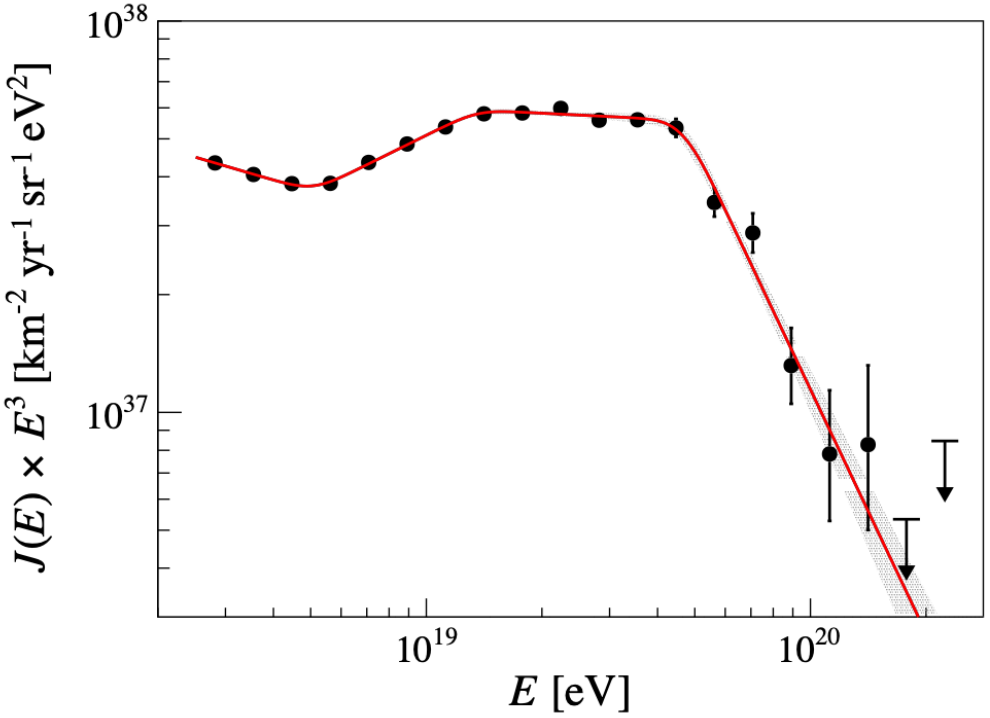
UHECR Observatories

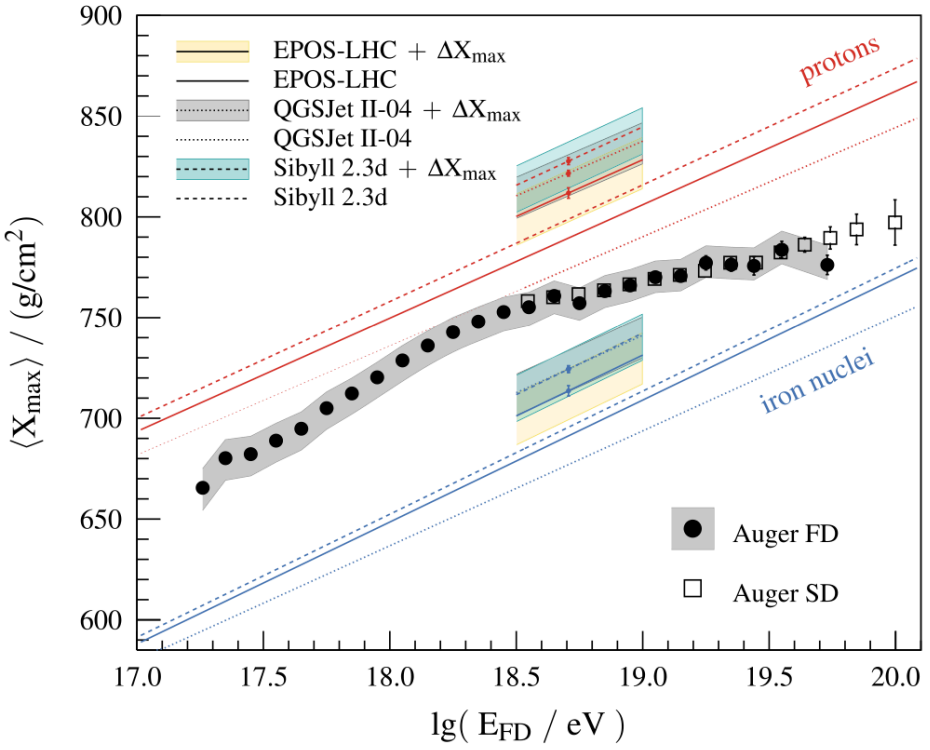




P. Auger Observatory

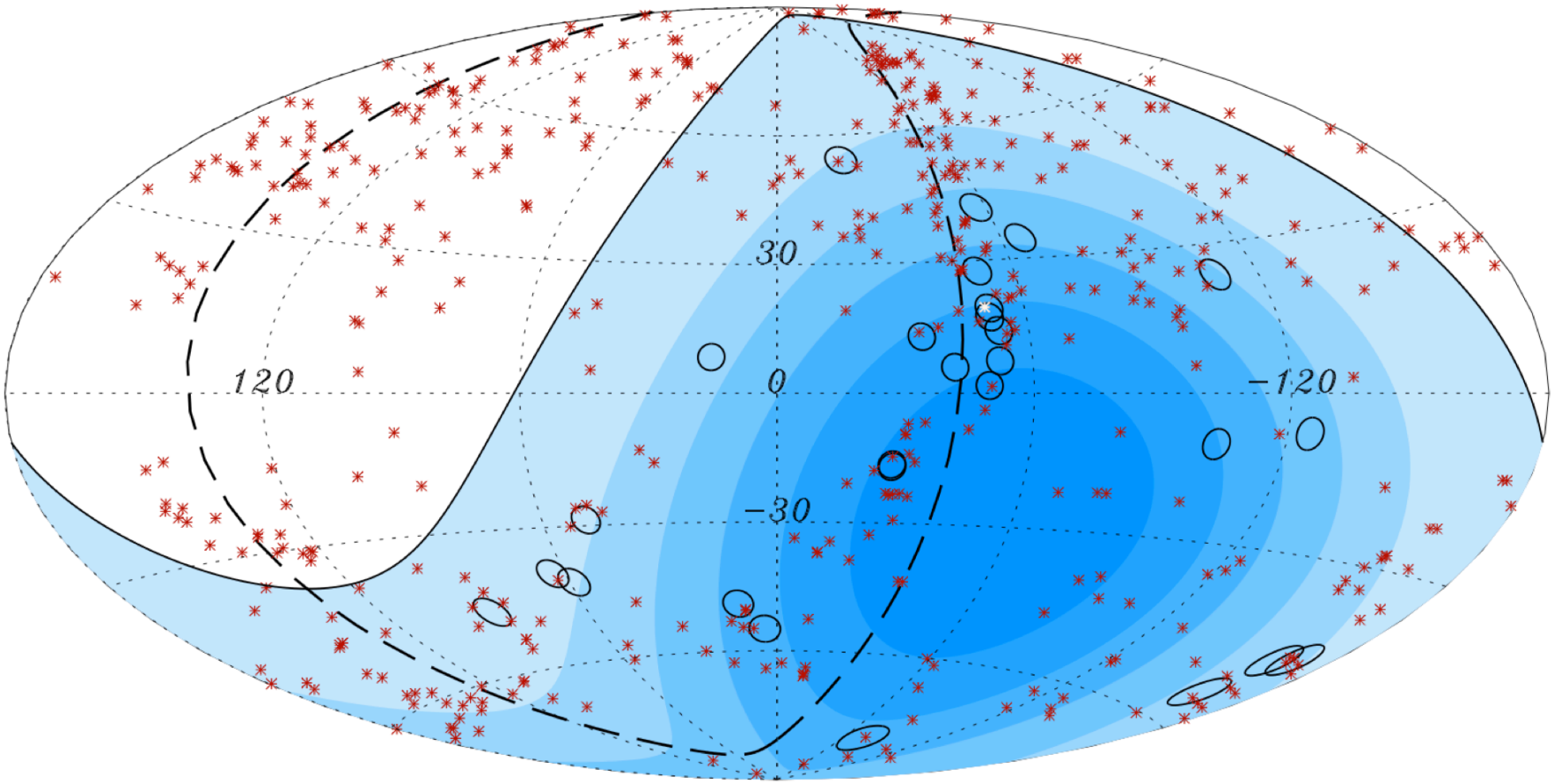
UHECR Spectrum and Composition





The Pierre Auger Collaboration,
Phys. Rev. D 102, 062005 (2020)

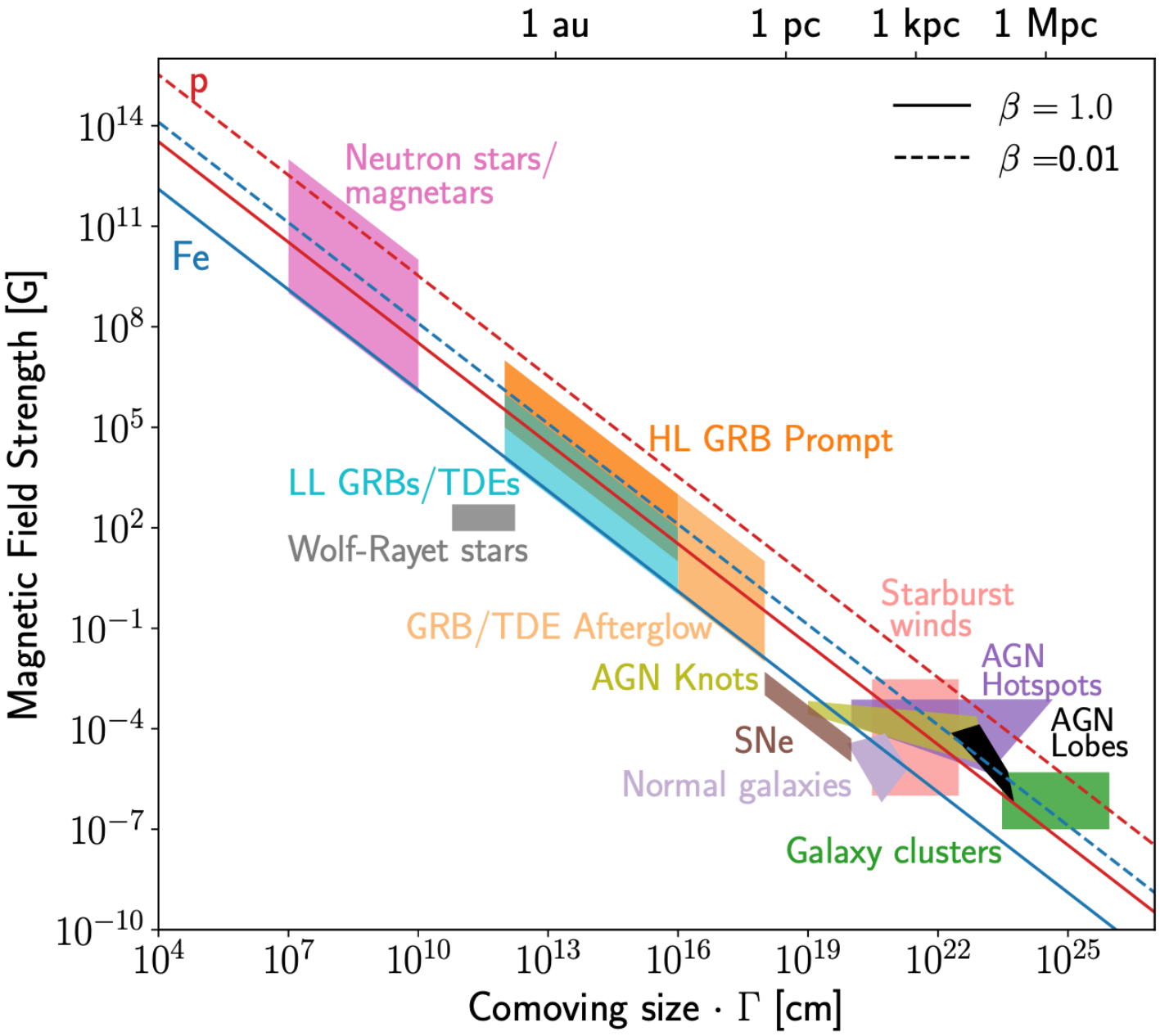
UHECR Sources: Nearby AGN?



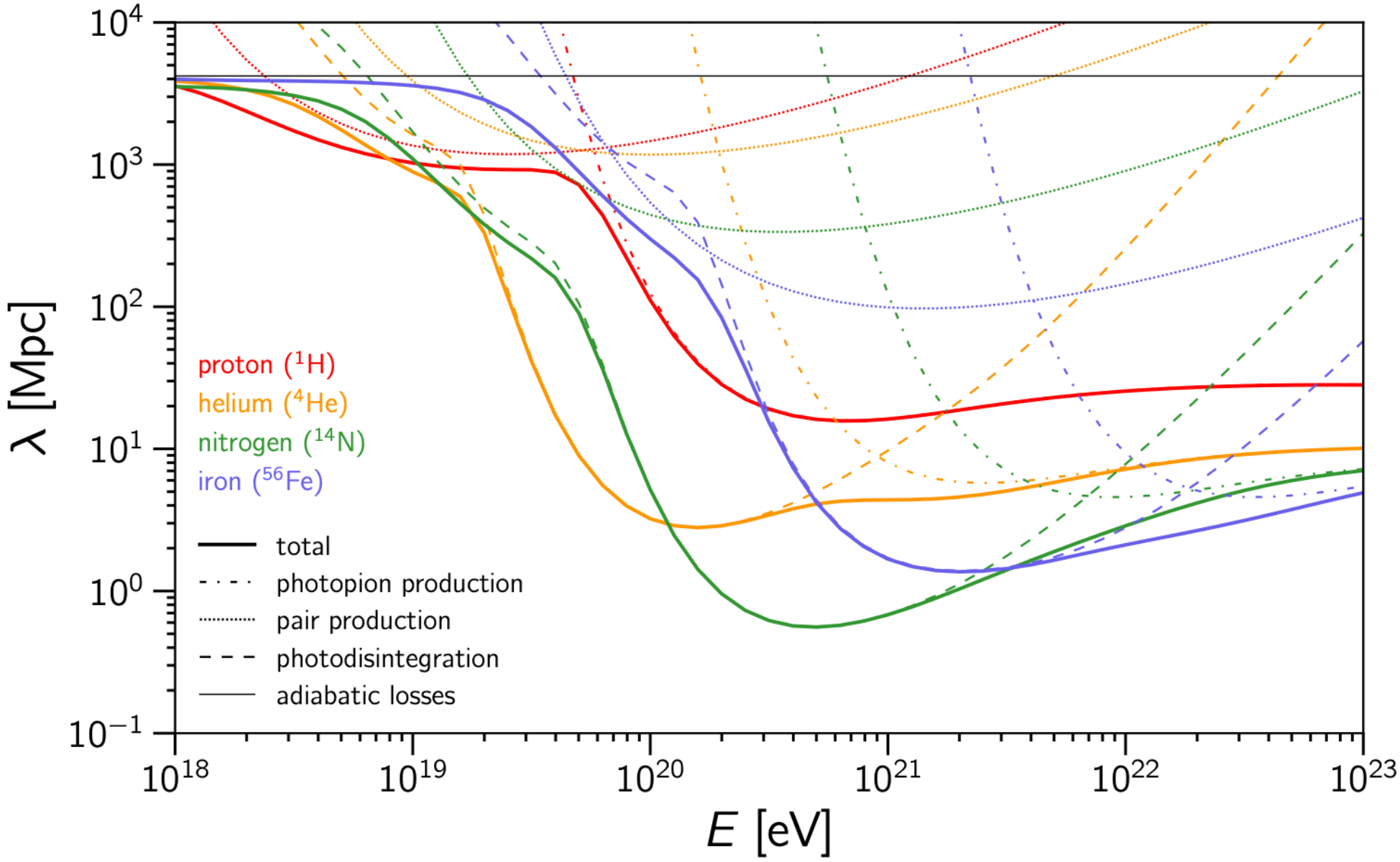
Pierre Auger Collaboration, Science 318 (2007) 938

circles of radius 3.1° centered at the arrival directions of the 27 cosmic rays with highest energy detected by the Pierre Auger Observatory. The positions of the 472 AGN (318 in the field of view of the Observatory) with redshift z ≤ 0.018 (D < 75 Mpc) are indicated by red asterisks. The solid line represents the border of the field of view (zenith angles smaller than 60°). Darker color indicates larger relative exposure. Each colored band has equal integrated exposure. The dashed line is the supergalactic plane. Centaurus A, one of our closest AGN, is marked in white.

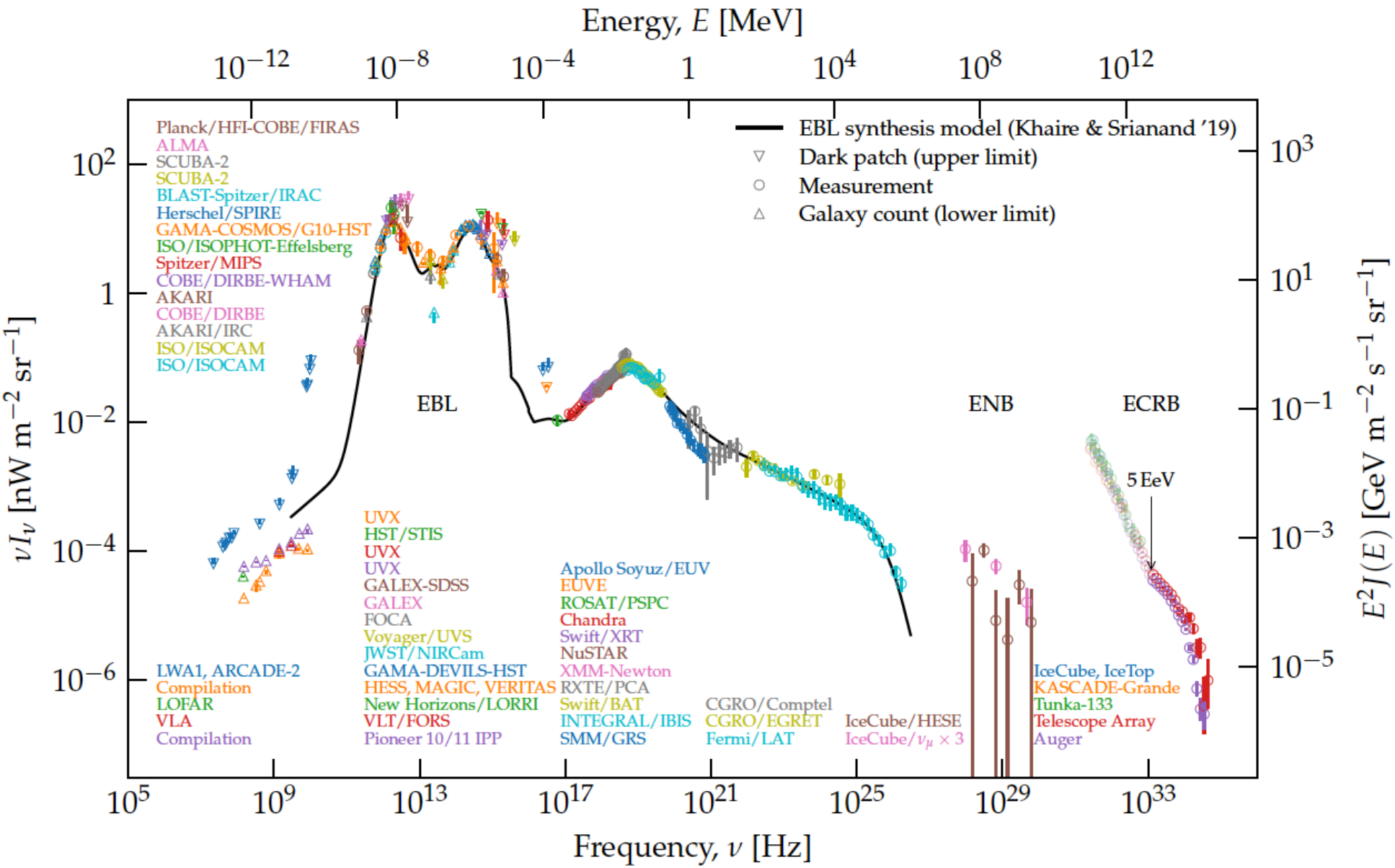
Problem #1: Powerful Accelerator Needed



Problem #2: Energy Loss Length



Cosmic Background Emission (and Particles)



Problem #3: Cosmic Magnetic Field

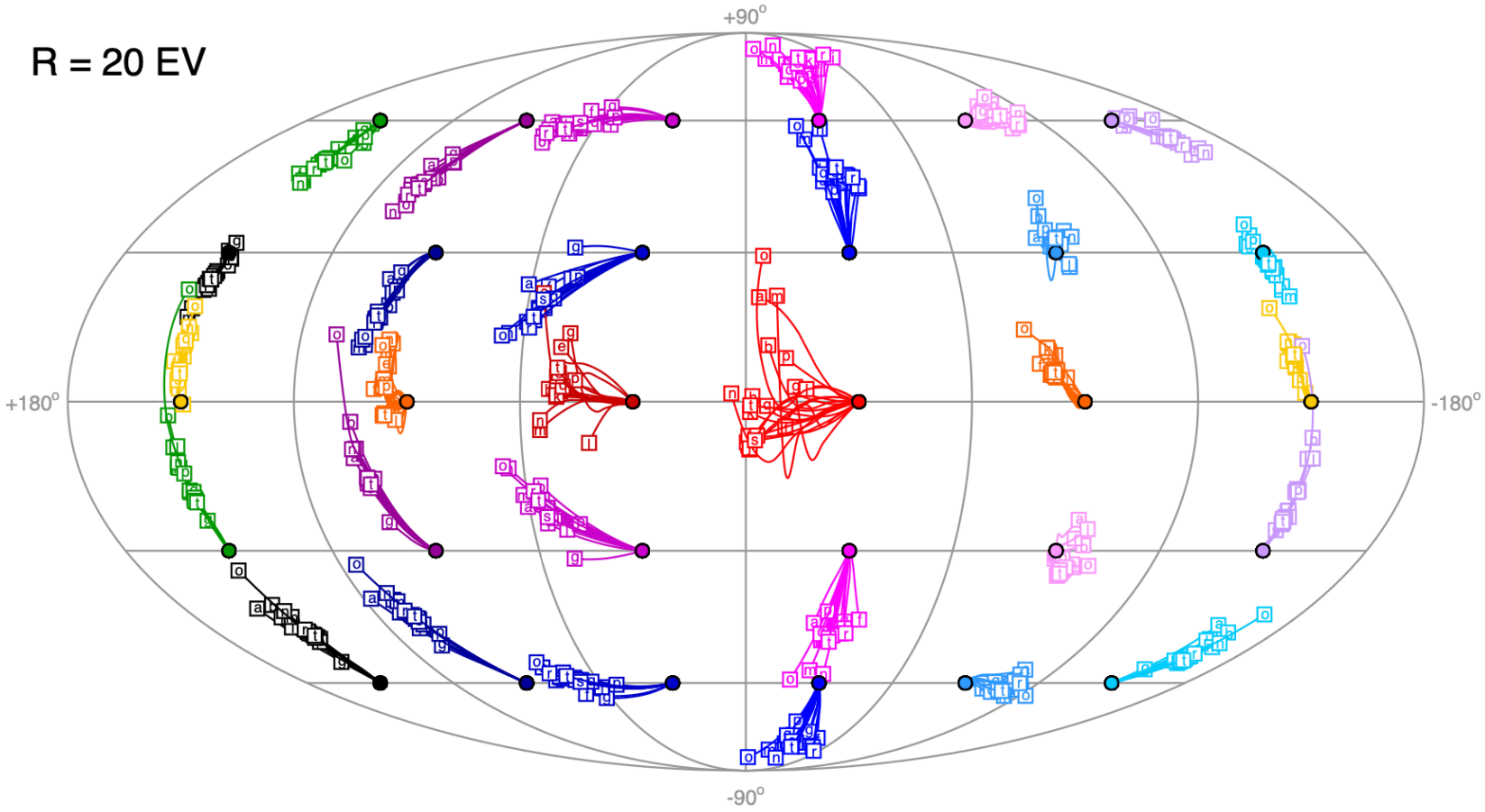


Figure 4. Backtracking of charged particles through the Galaxy starting from a regular grid of initial directions (dots). The resulting directions outside of the Galaxy for particles with a rigidity of 20 EV are denoted by squares and the lines connecting the initial and final positions were constructed by performing backtracking at higher rigidities. Each of the letters (a)-(t) denotes a different GMF model that describes the synchrotron and RM data.

Origin: Supergalactic Plane?

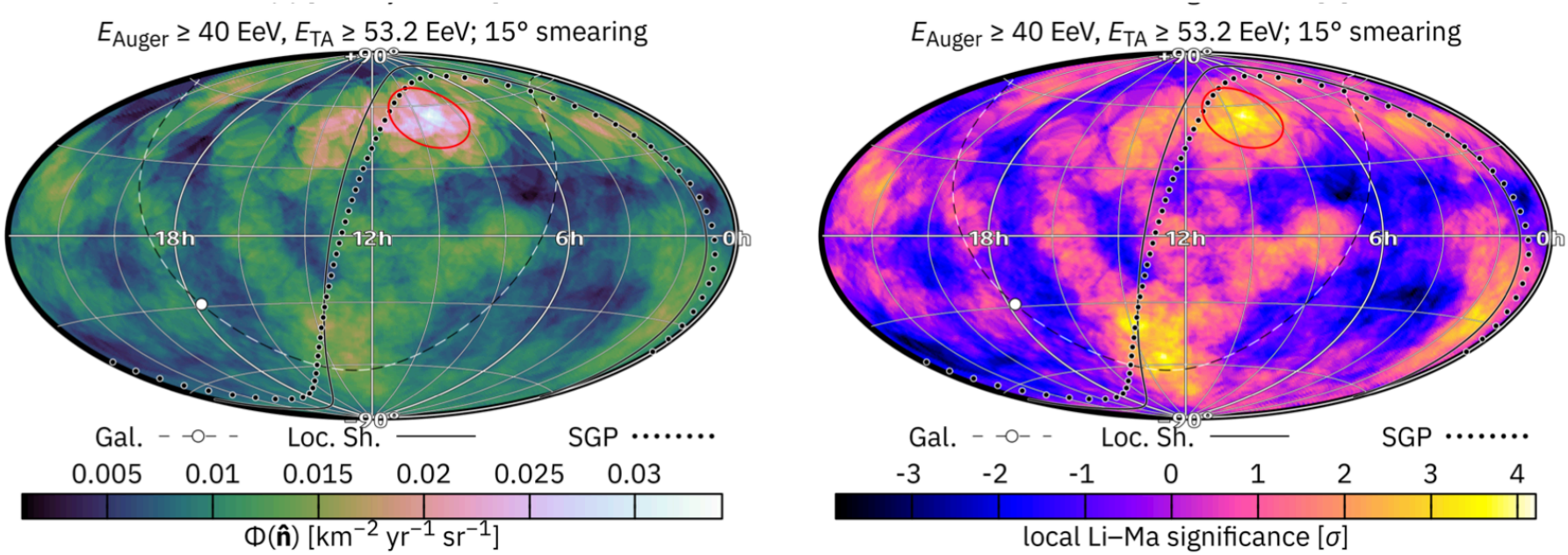
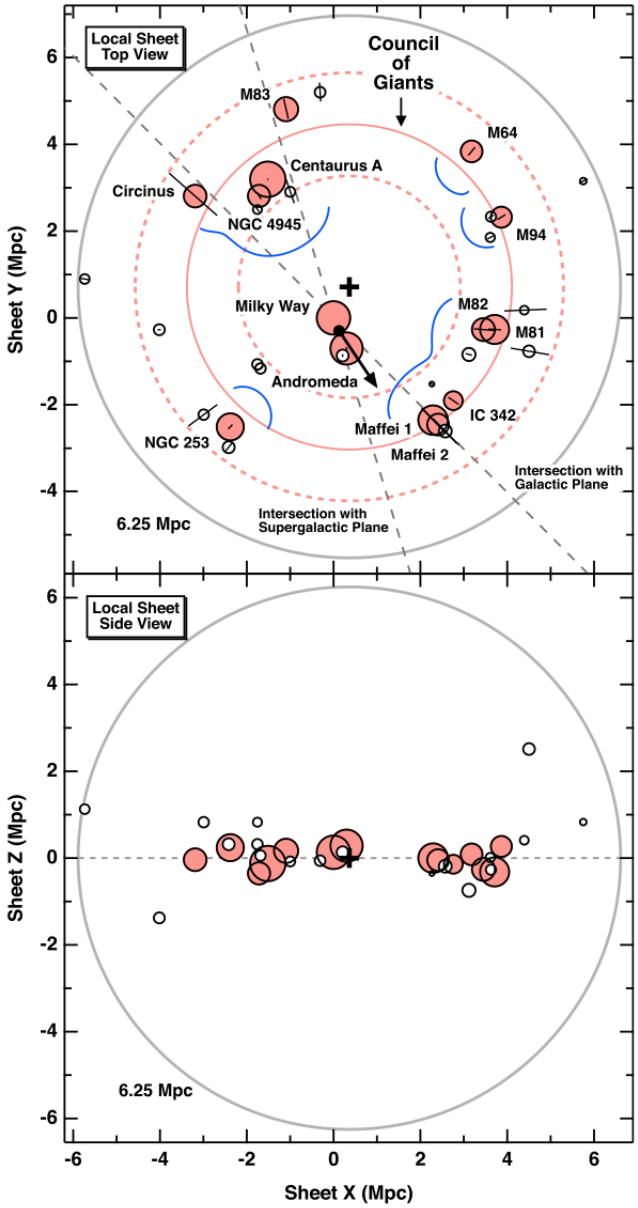


Figure 4: Left: Flux of cosmic rays from the higher-energy dataset smoothed in 20°-radius (top) and 15°-radius (bottom) circular windows (Hammer projection, equatorial coordinates), with the most significant excess highlighted (red circle). Right: Corresponding local statistical significances against the isotropic null hypothesis.

Di Matteo et al. for the P. Auger Collab. & TA Collab., ICRC 2019

“A Council of Giants”



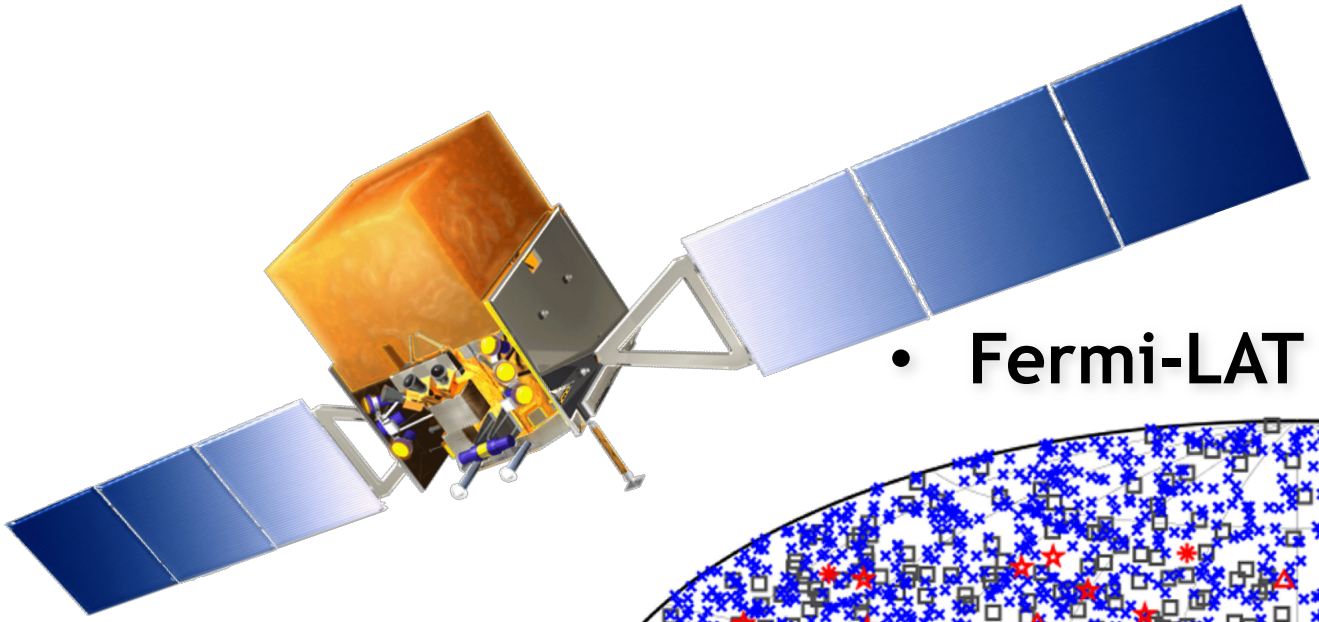
Supergalactic plane is a well-known structure along which galaxy clusters within several tens of Mpc of us are preferentially located.

Local Sheet is a planar structure about 0.5Mpc thick and 10Mpc across tilted by only 8° with respect to the SGP and including nearly all galaxies within about 6 Mpc of us, including NGC 4945, Cen A and Circinus. The Local Sheet consists of the Local Group (the Milky Way and M31, plus their satellites) near the center and the Council of Giants (twelve more large galaxies and their satellites) in a ring surrounding it.

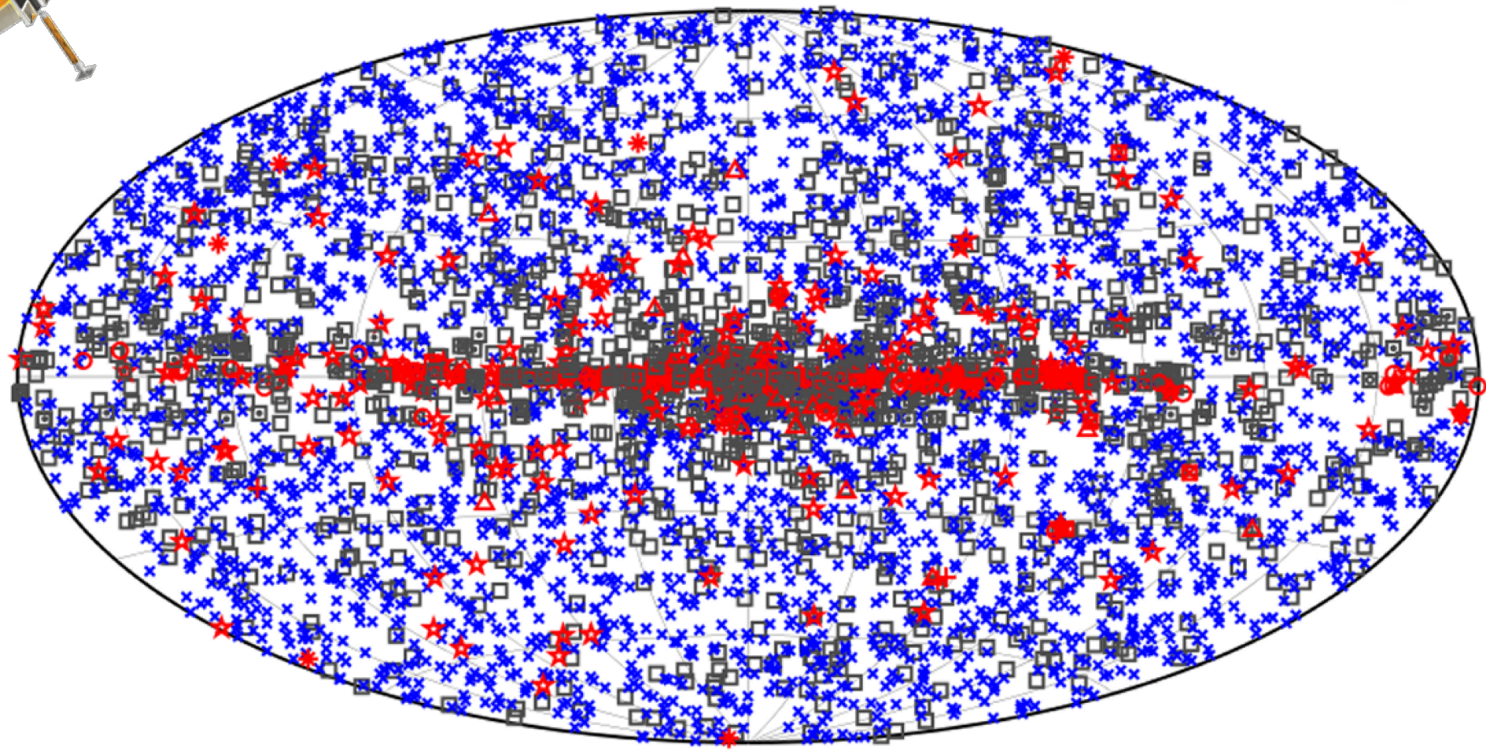
McCall 2014:

“Local Sheet is both geometrically and dynamically distinct from the Local Supercluster and the evolution of the Sheet and Local Group were probably interconnected. The Sheet is inclined by 8° with respect to the Local Supercluster, and the dispersion of giant members about the mid-plane is only 230 kpc. A ‘Council of Giants’ with a radius of 3.75 Mpc encompasses the Local Group, demarcating a clear upper limit to the realm of influence of the Local Group. “

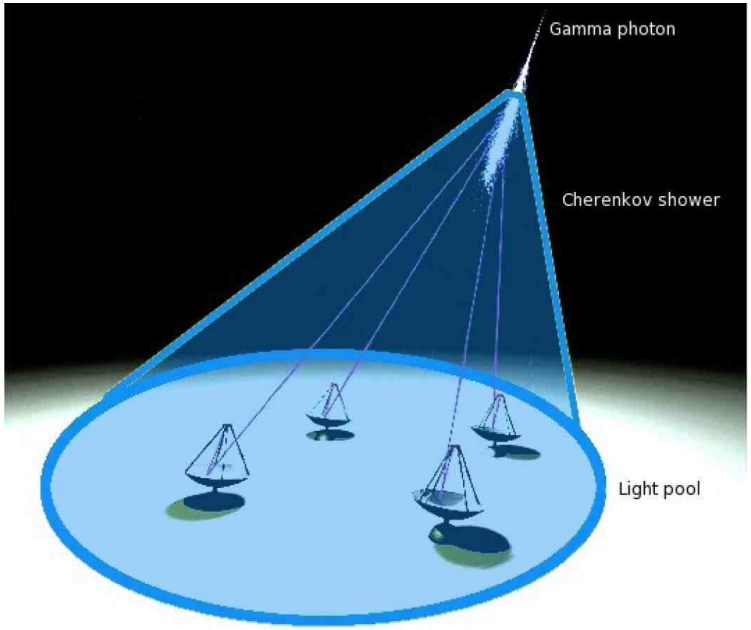
High-Energy Gamma-rays



- **Fermi-LAT (20 MeV – 300 GeV)**



Very High-Energy Gamma-rays

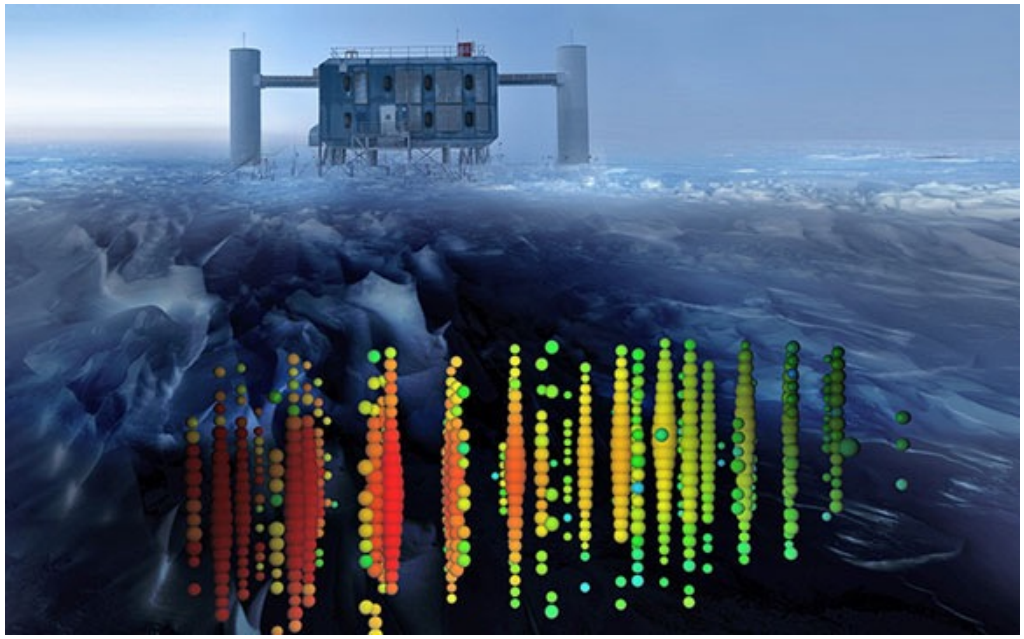


Cherenkov Telescopes:
>100 GeV

- Now: **H.E.S.S., MAGIC, VERITAS**
- Soon: **CTA**

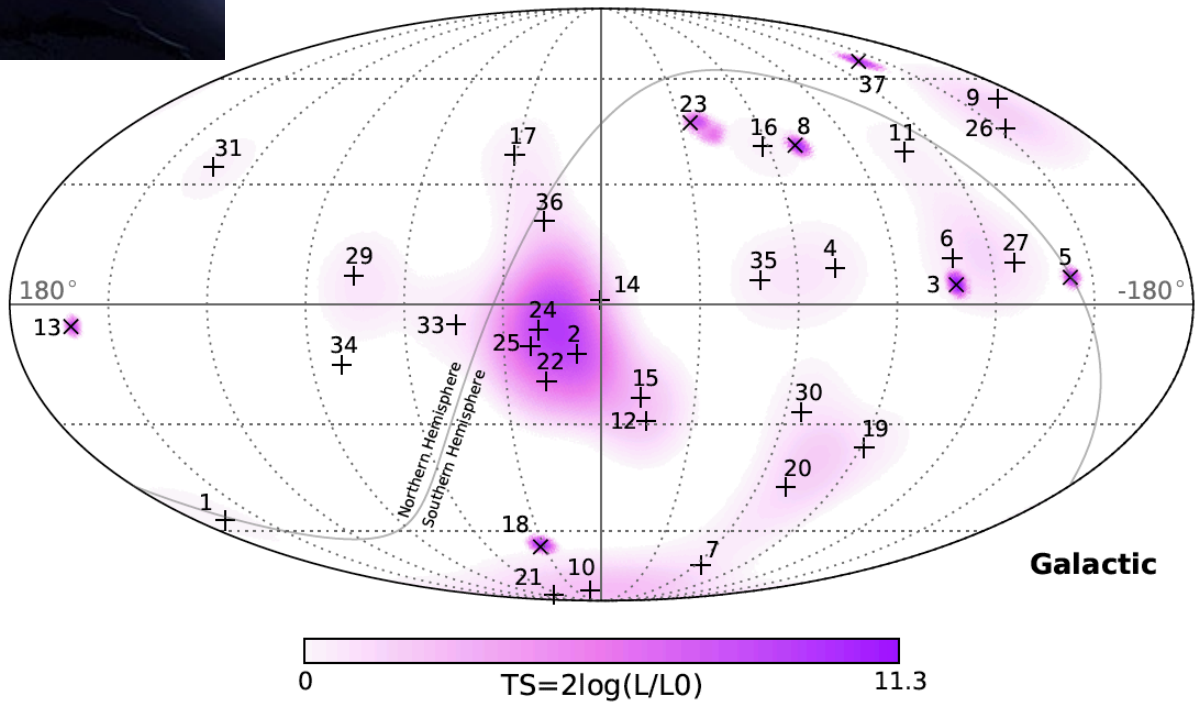
High-Energy Neutrinos

IceCube Detector

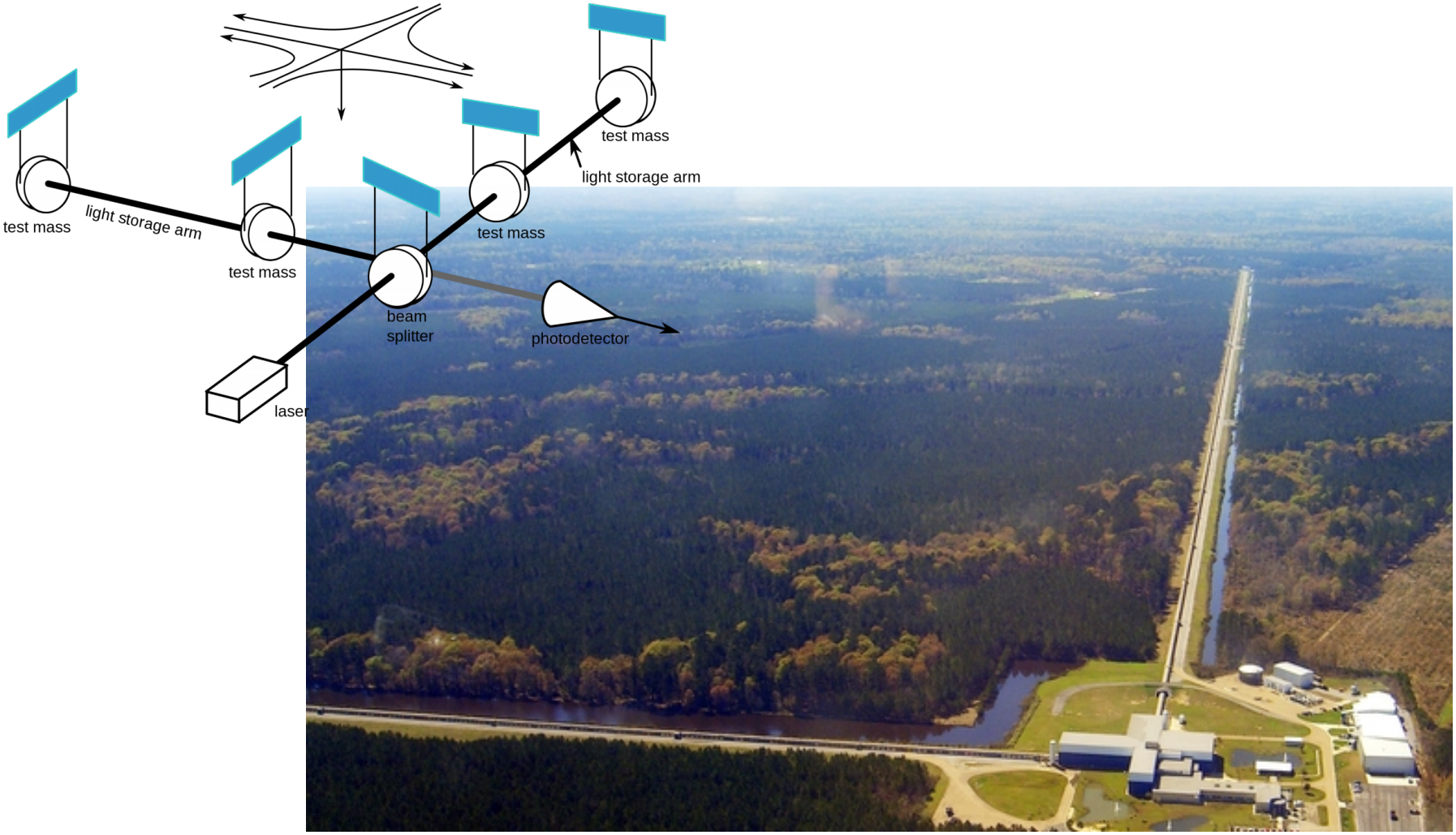


M. G. Aartsen et al. [IceCube Collaboration],
Phys. Rev. Lett. 113, 101101 (2014)

Sky map of 37 events from the search for starting events in IceCube



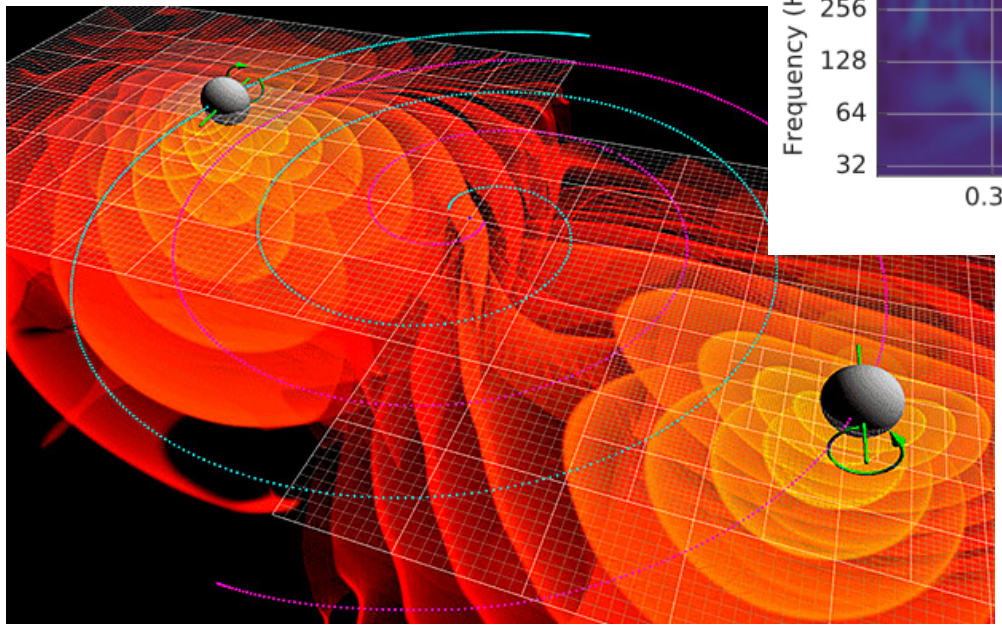
Gravitational Waves

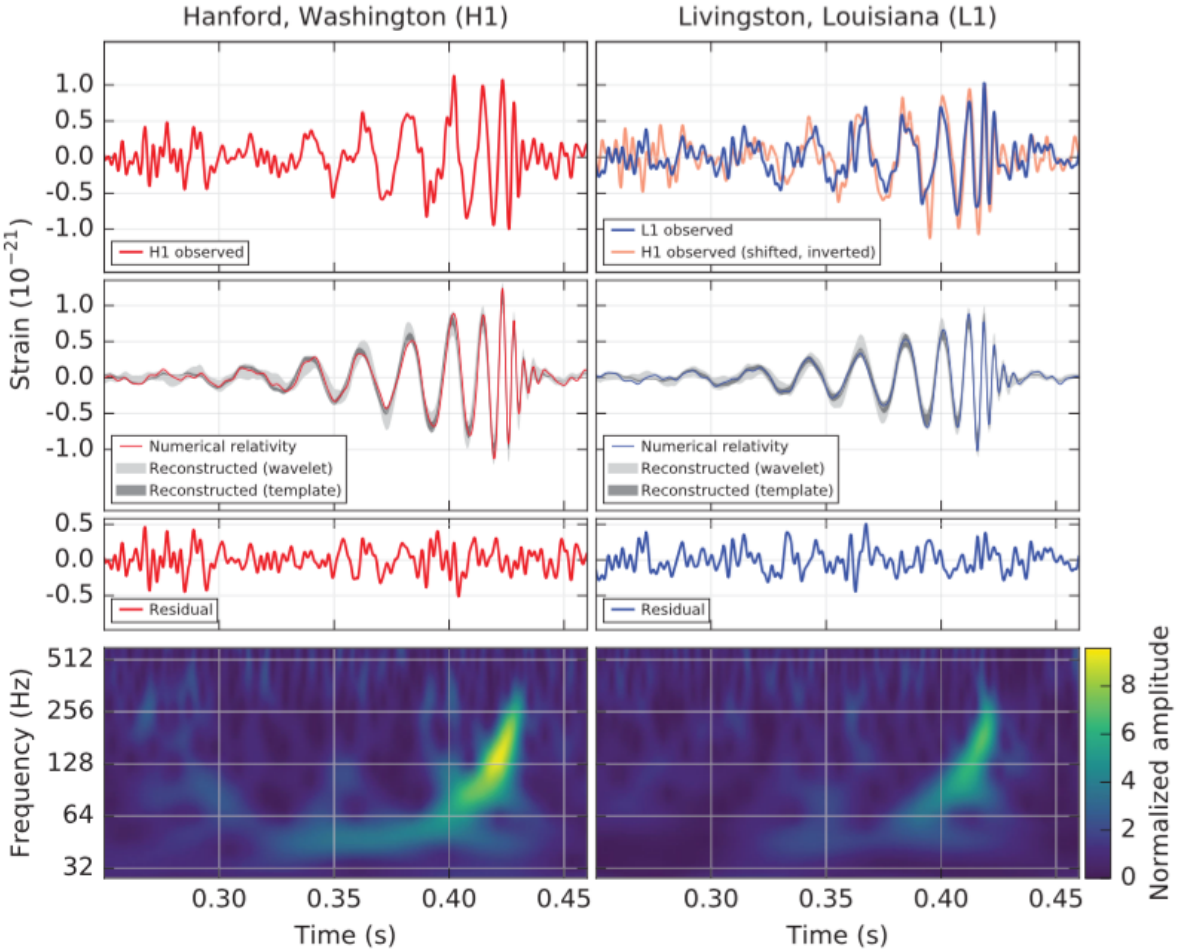


LIGO

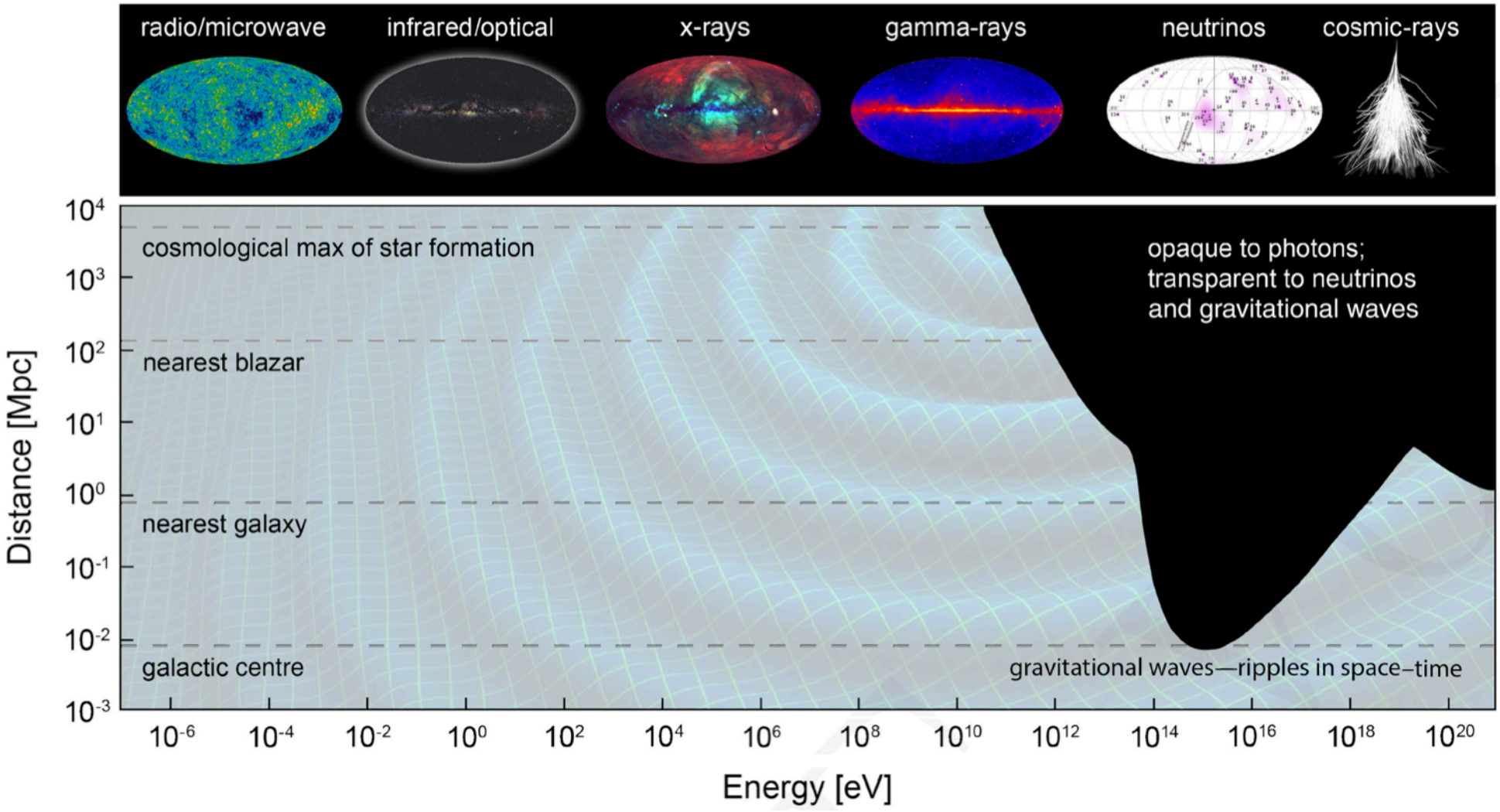
Merging Black Holes

GW150914

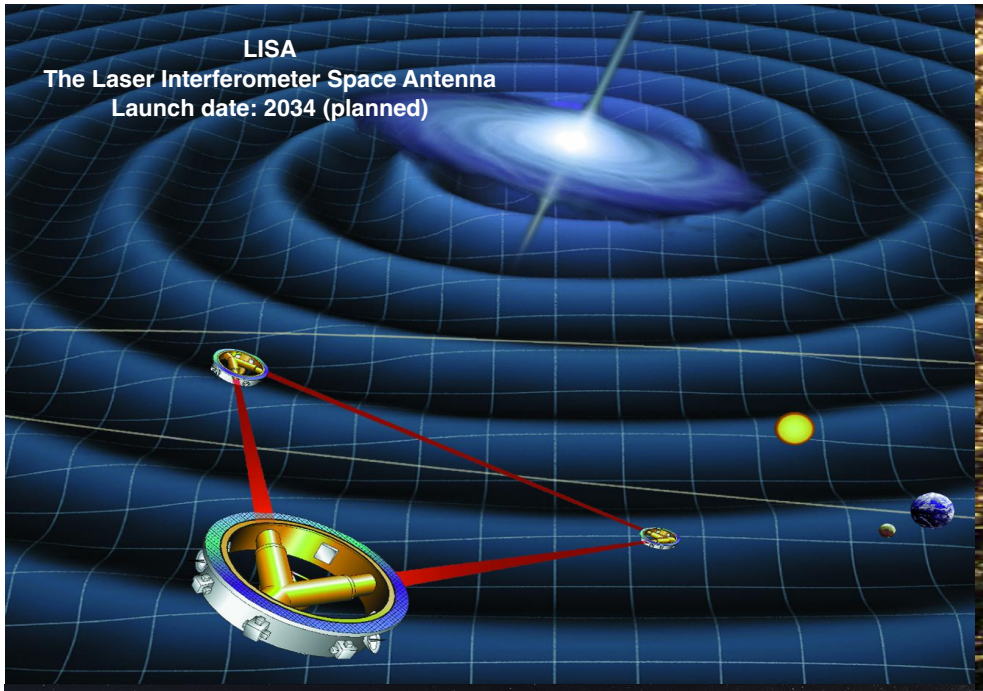


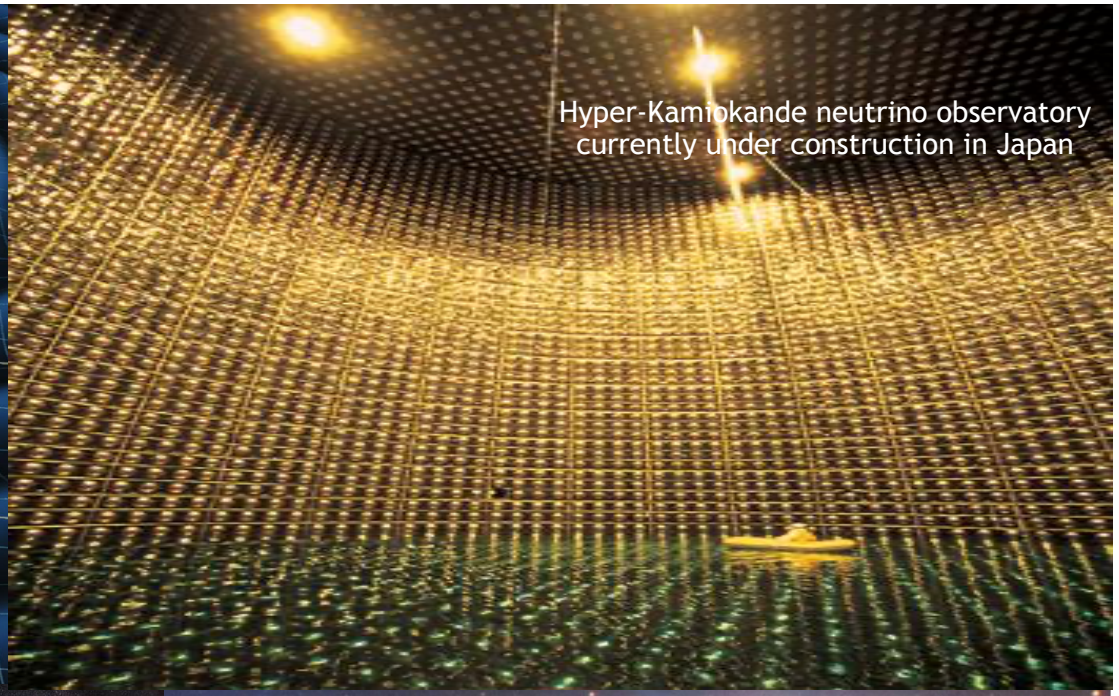


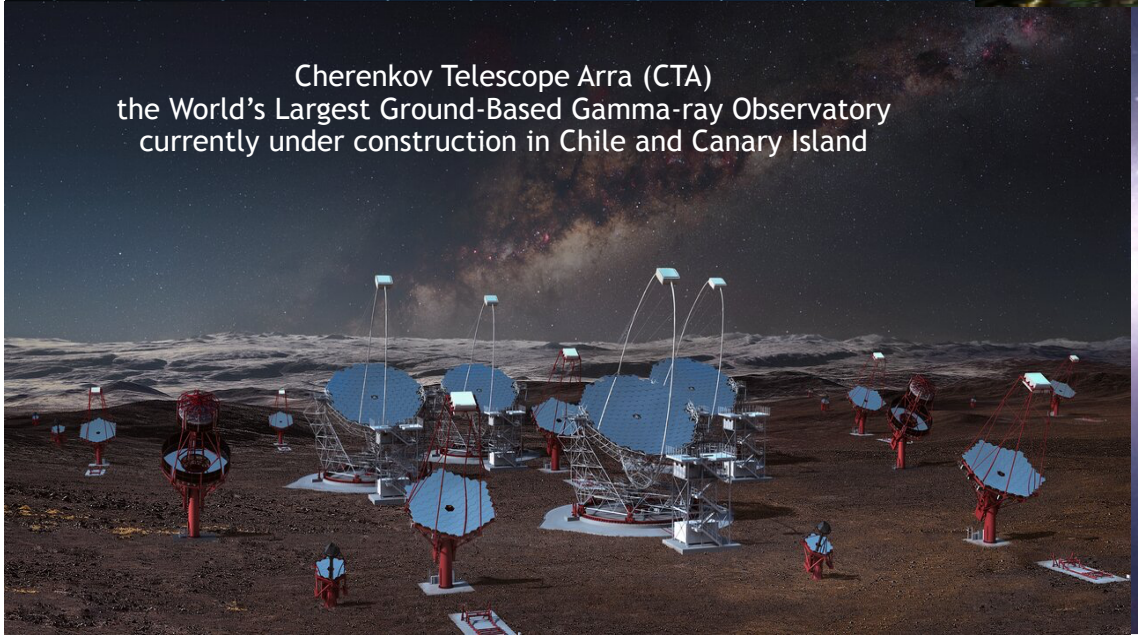
Cosmic Horizon



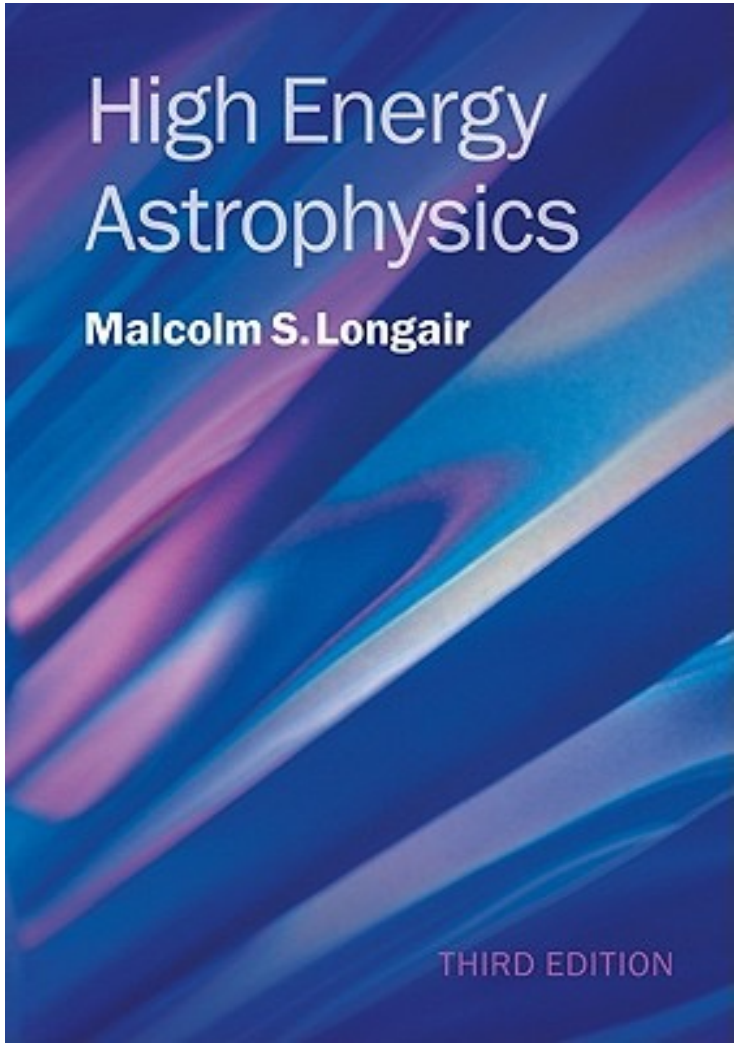
The Future Is Exciting!

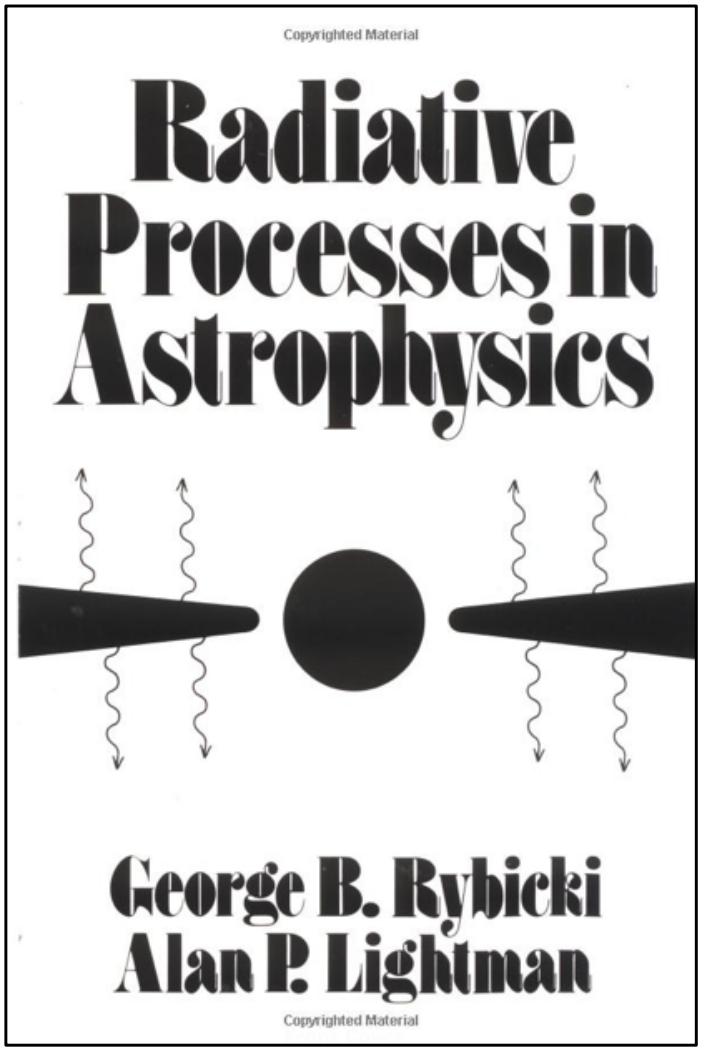




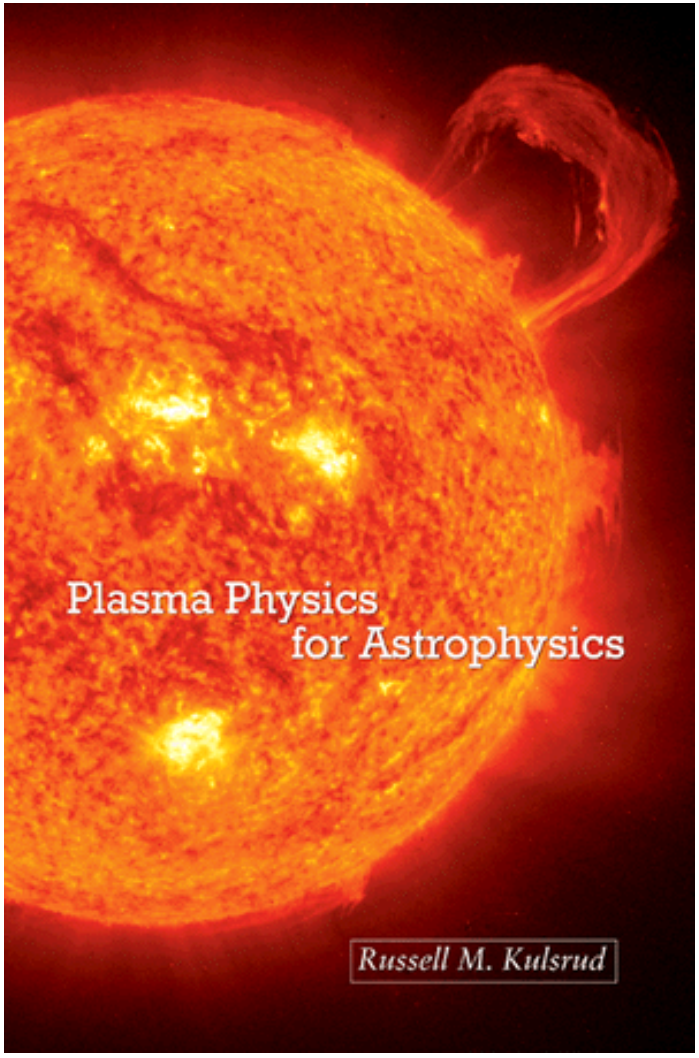


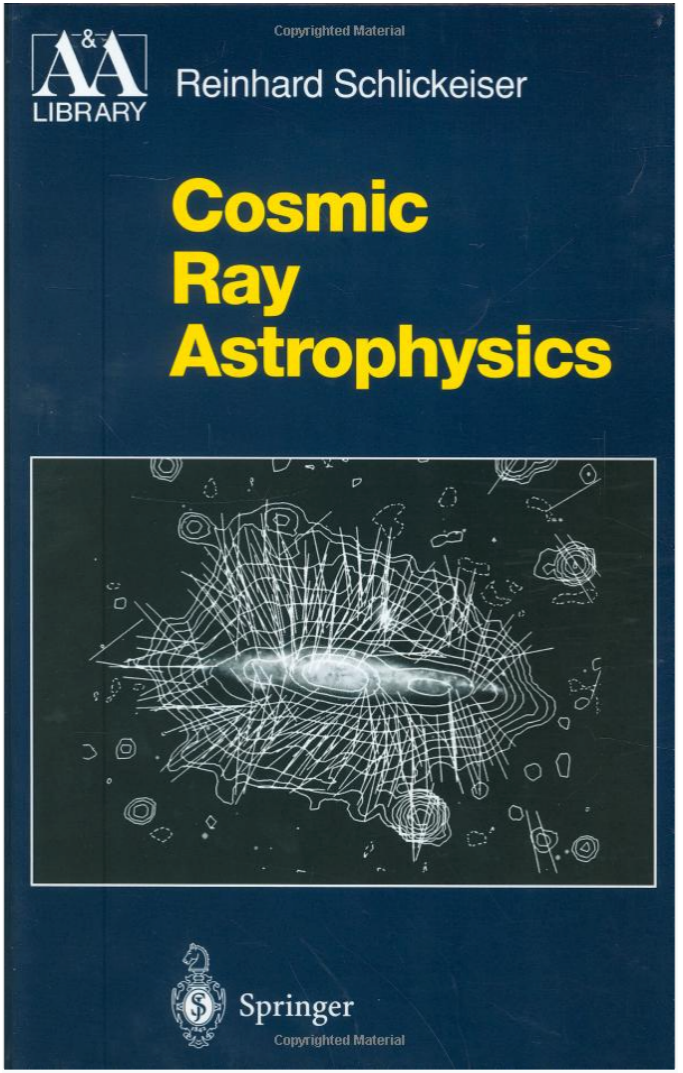
Literature: Radiative Processes





Literature: Plasma Physics, CRs





Literature: Active Galactic Nuclei