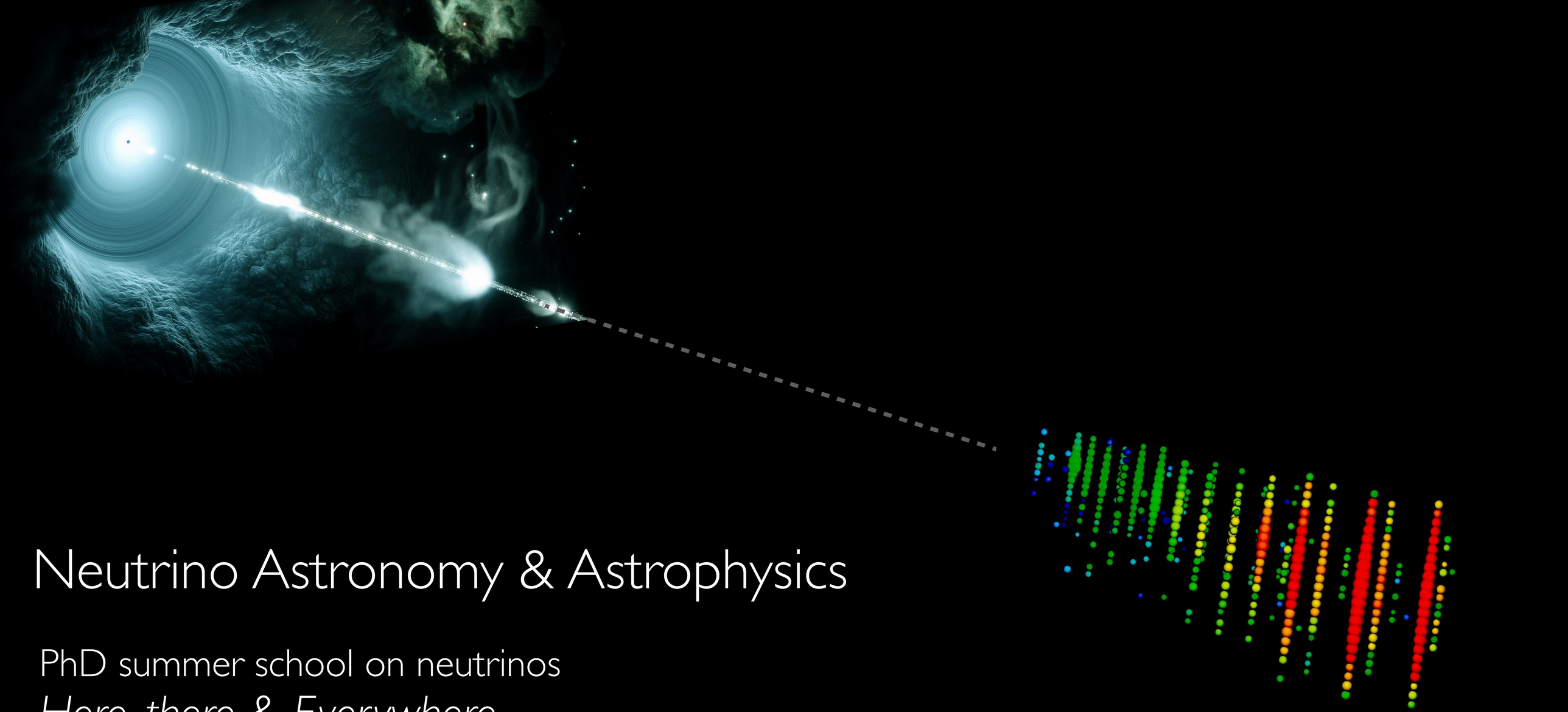


Neutrino Astronomy & Astrophysics

PhD summer school on neutrinos

Here, there & Everywhere

NBI, Copenhagen

Foteini Oikonomou

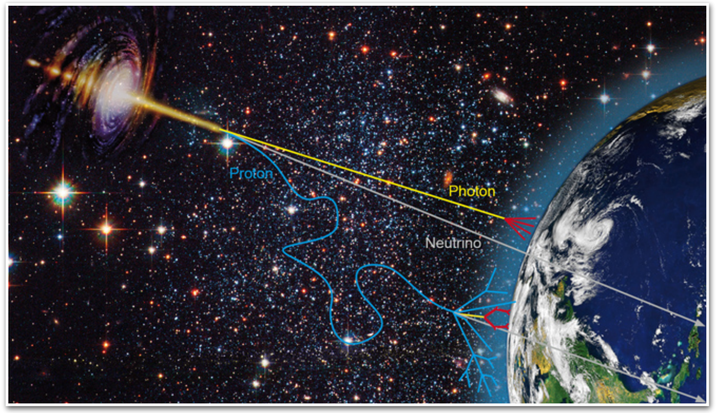
Norwegian University of Science and Technology

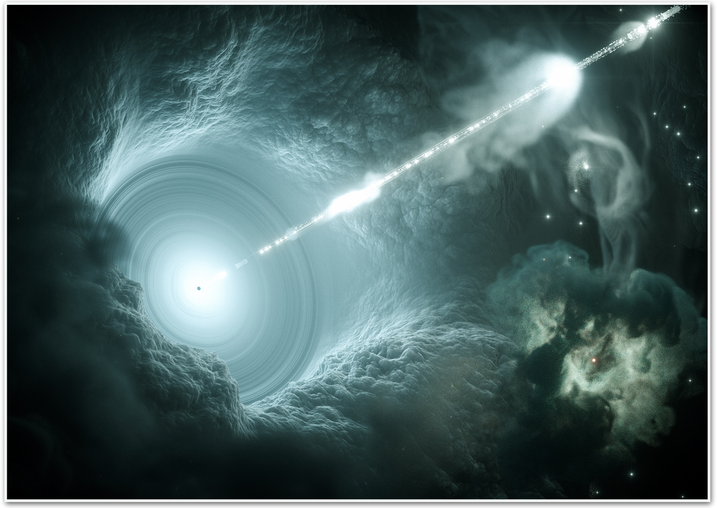
July 5th-9th

About me

foteini.oikonomou@ntnu.no

- NTNU Trondheim
- Main research interests:
  - Ultra-high energy cosmic rays (sources, phenomenology)
  - Astrophysical sources of high-and ultra-high energy neutrinos
  - Active-galactic nuclei as cosmic accelerators





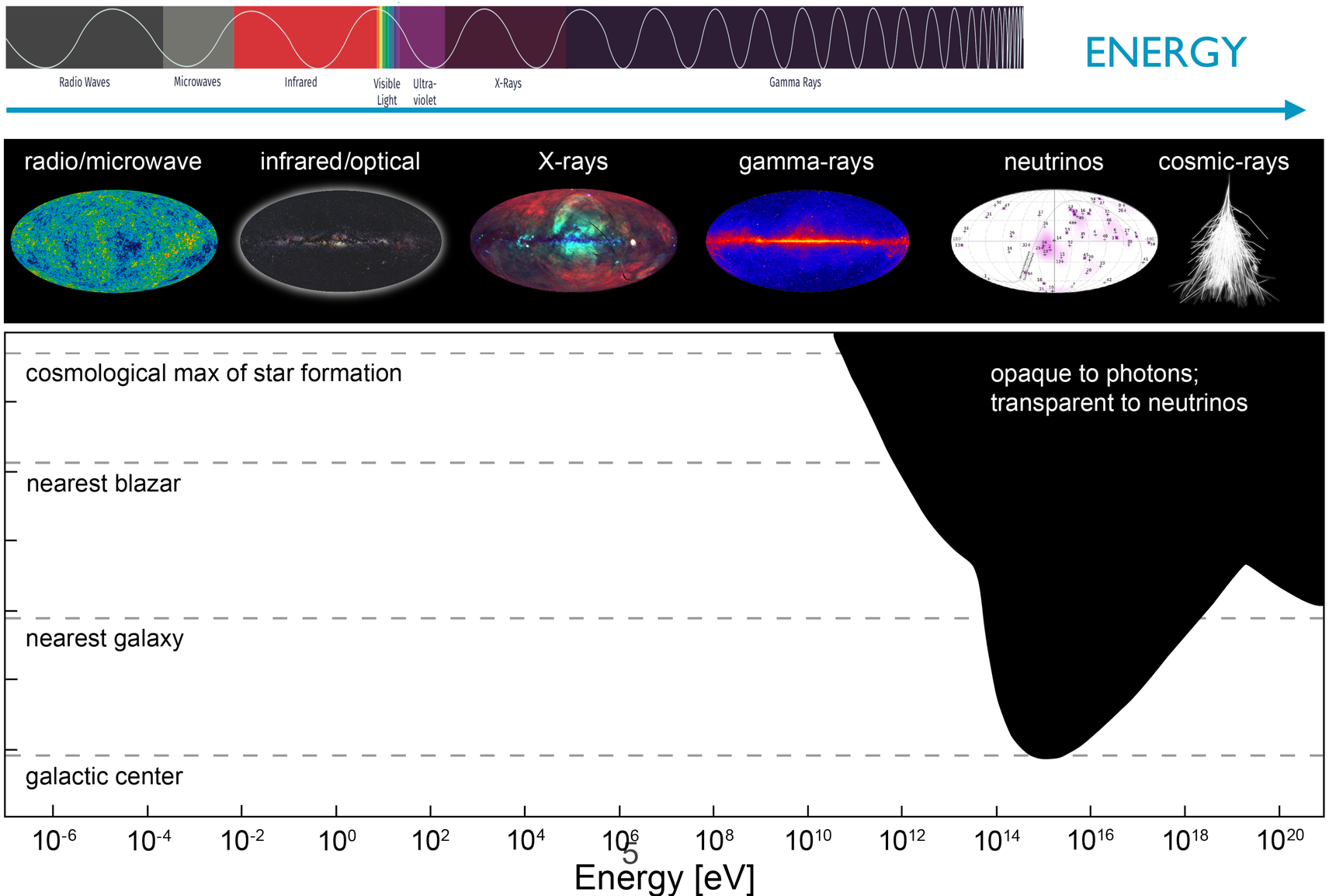
Lecture plan

- Experimental facts and basic theoretical concepts
- Requirements for astrophysical accelerators of high-energy cosmic rays/ high-energy neutrinos (generic source properties)
- Overview of candidate astrophysical sources (Active Galactic Nuclei/ Starburst Galaxies/Gamma ray bursts/Pulsars/Tidal Disruption Events) constraints and prospects

Resources

- T.K. Gaisser, R. Engel & E. Resconi: Cosmic Rays and Particle Physics, Cambridge University Press (2016)
- C. Dermer & G. Menon: High-energy radiation from black holes: Gamma-rays, Cosmic Rays, and Neutrinos, Princeton University Press (2009)
- G. Ghisellini: Radiative processes in High Energy Astrophysics, Springer (2012) https://arxiv.org/abs/1202.5949
- Many excellent reviews

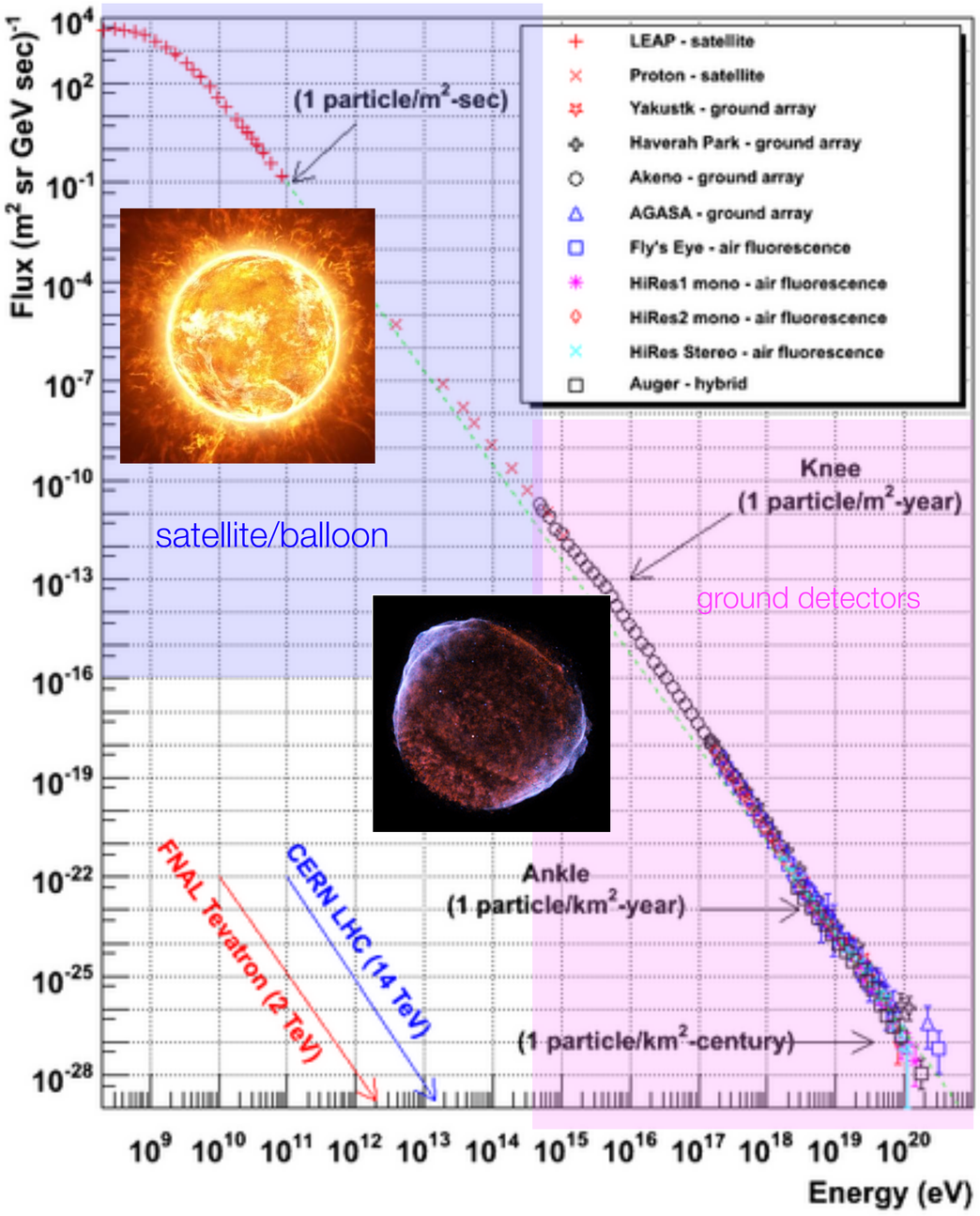
High-energy messengers of the non-thermal Universe



Cosmic rays

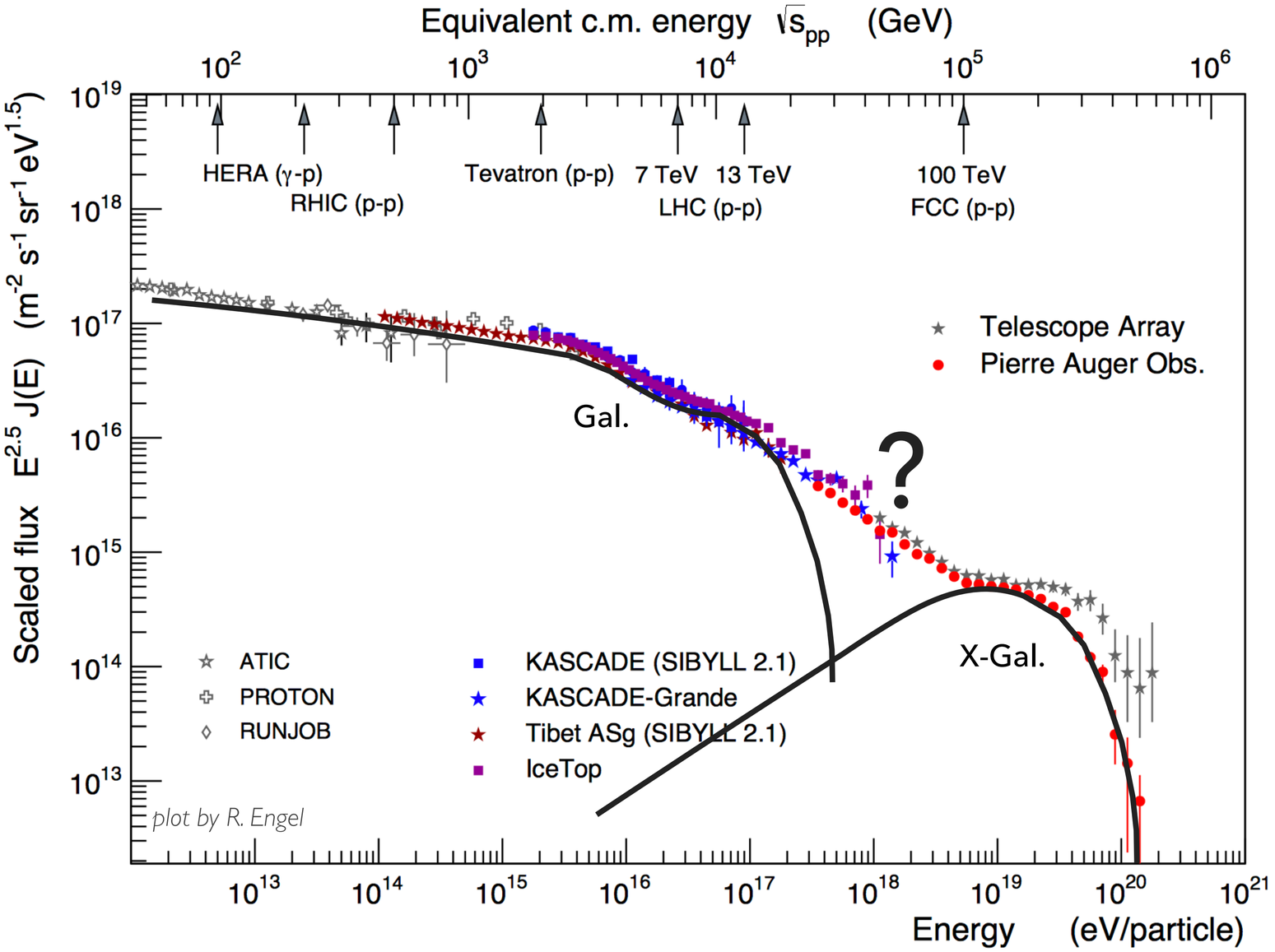
- In early 1900s electroscopes detected radiation in atmosphere;
- In 1912, Hess rode a balloon with improved equipment to 5km altitude;
- He found that above 1 km, the radiation intensity steadily increased
- Hess was awarded the 1936 Nobel Prize in Physics for this discovery.

Cosmic rays



plot originally by M. Swordy

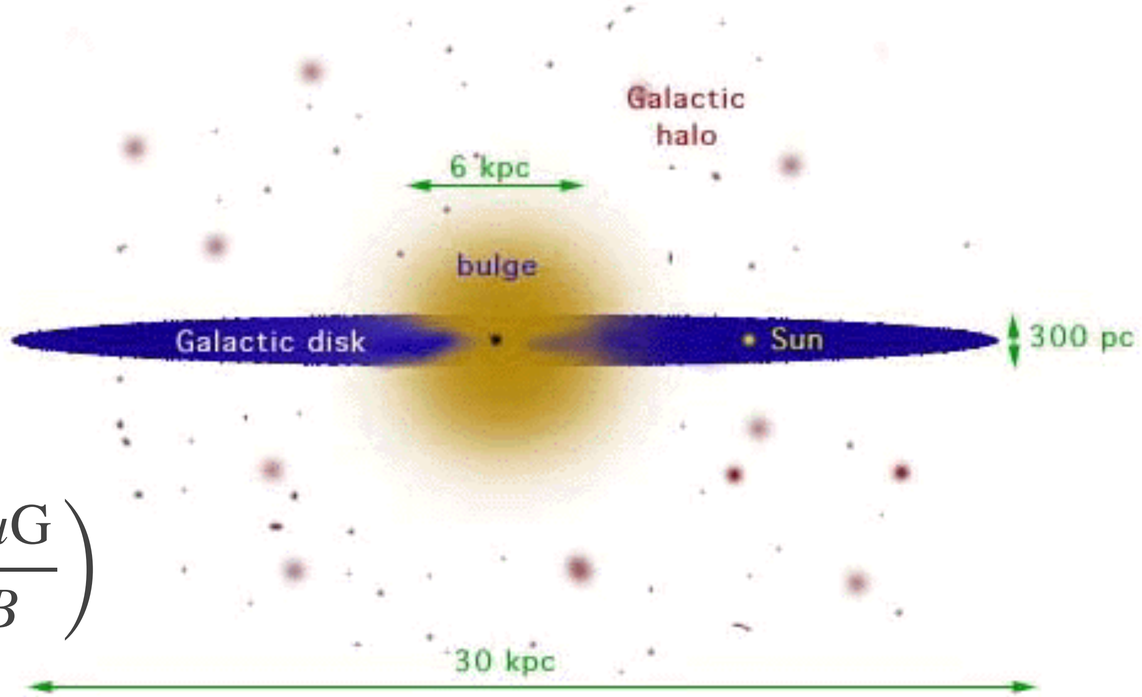
Highest-energy cosmic rays



Extragalactic origin

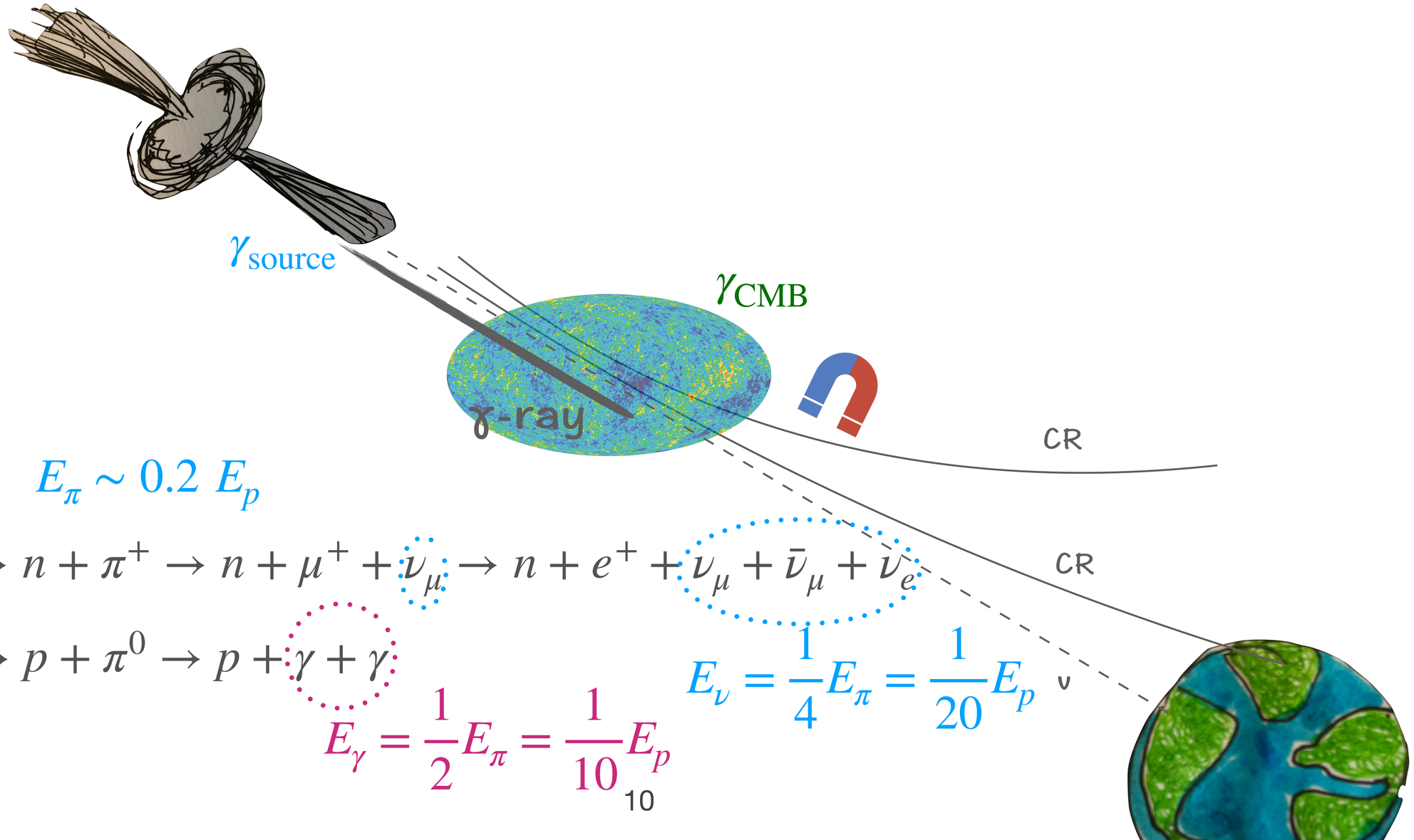
- Size of the Milky Way ~ kpc [10^8 AU]
- Galactic B-field ~ 3 μG
- Larmor radius of cosmic rays

$$R_{\mathrm{Larmor}} = \frac{E \cdot c}{e \cdot ZB} \sim \frac{1}{\mathrm{kpc}} \left(\frac{1}{Z}\right) \left(\frac{E}{10^{18.5}\ \mathrm{eV}}\right) \left(\frac{3\mu\mathrm{G}}{B}\right)$$



[+ Observational evidence: No anisotropy from the Galaxy]

Secondary messengers



$$E_\pi \sim 0.2\ E_p$$

$$p + \gamma \rightarrow n + \pi^+ \rightarrow n + \mu^+ + \nu_\mu \rightarrow n + e^+ + \nu_\mu + \bar{\nu}_\mu + \nu_e$$

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

$$E_\nu = \frac{1}{4}E_\pi = \frac{1}{20}E_p$$

$$E_\gamma = \frac{1}{2}E_\pi = \frac{1}{10}E_p$$

Cosmic-ray accelerators

Minimum requirement: Confinement

$$R_{\text{source}} > r_{\text{Larmor}} = \frac{E}{ZBec}$$

Maximum energy,

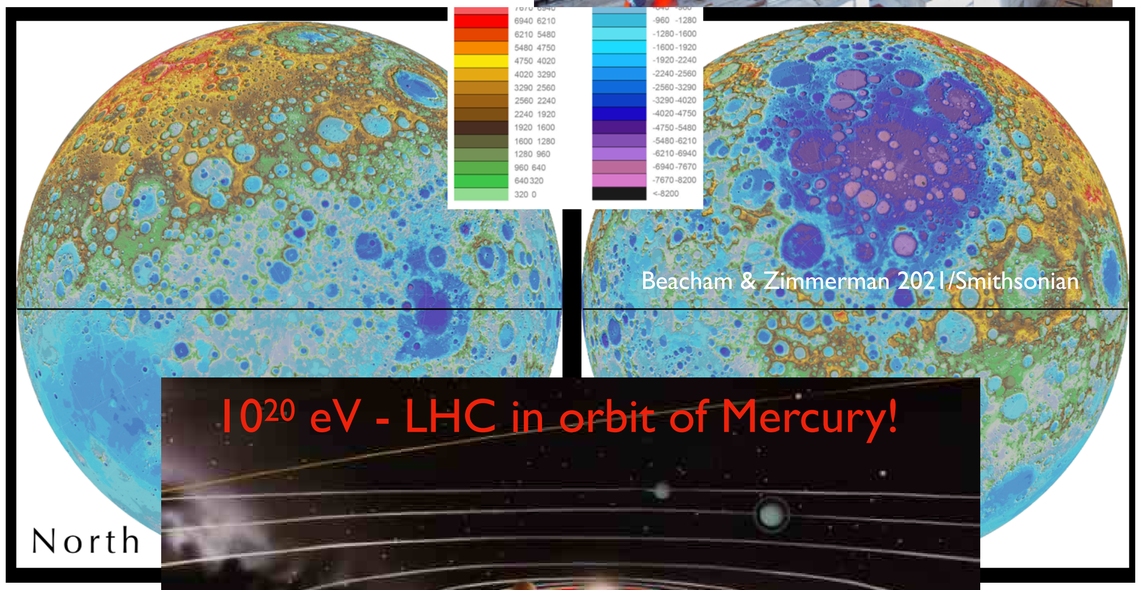
$$E_{\text{max}} = ZecBR_{\text{source}}$$

$$E_{\text{max}} \sim 1 \text{ EeV } Z \left(\frac{B}{1\,\mu\text{G}}\right)\left(\frac{R_{\text{source}}}{1 \text{ kpc}}\right)$$

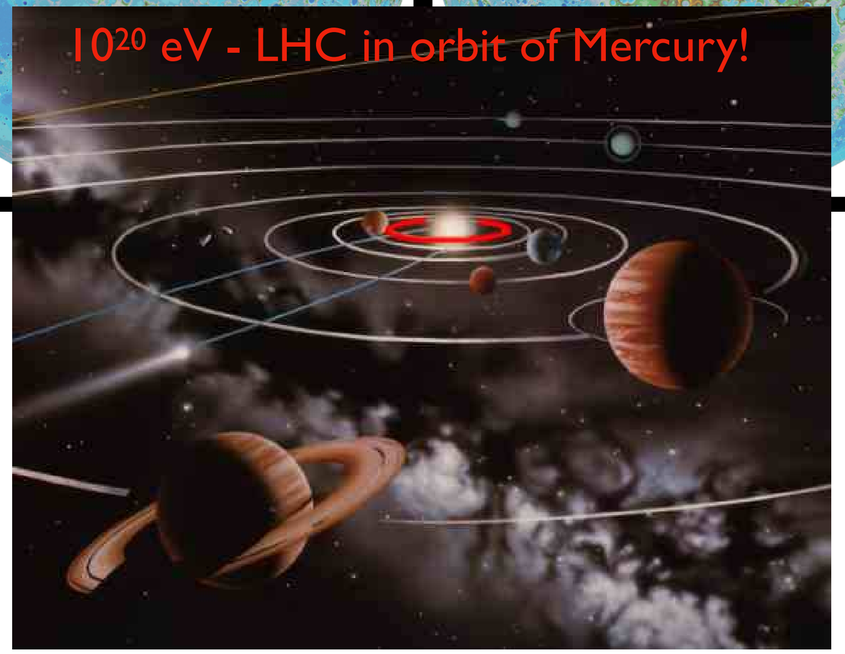
EeV = 10^{18} eV, ZeV = 10^{21} eV

TeV = 10^{12} eV

PeV = 10^{15} eV

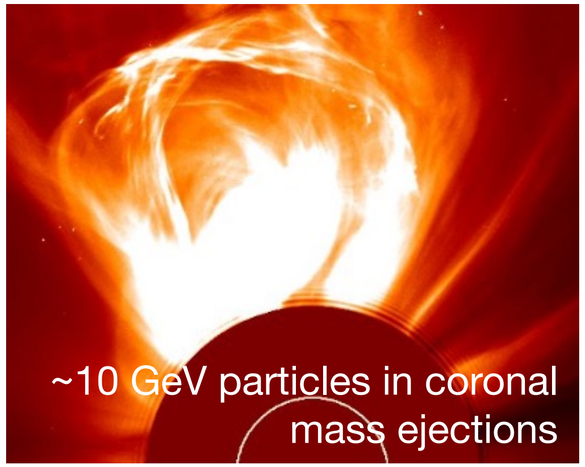


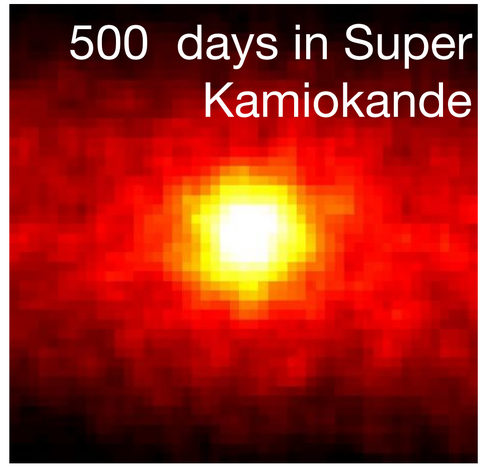
10^{20} eV - LHC in orbit of Mercury!

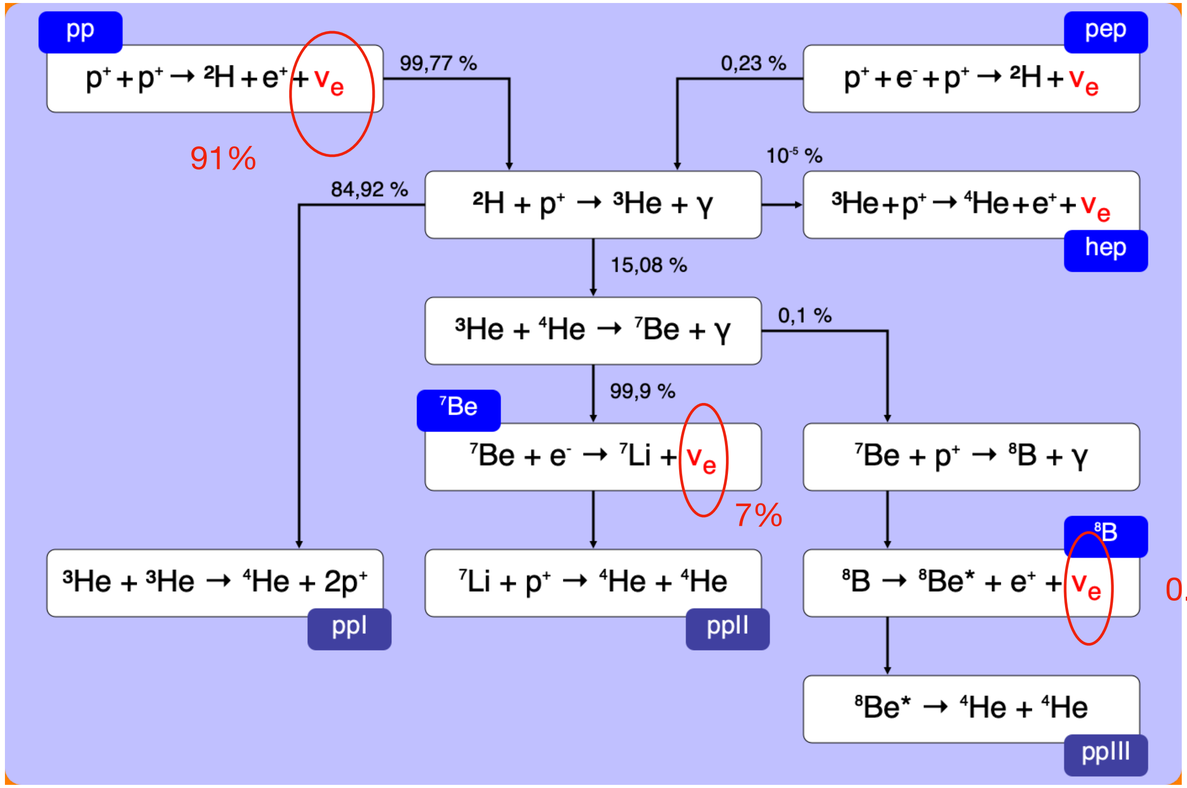


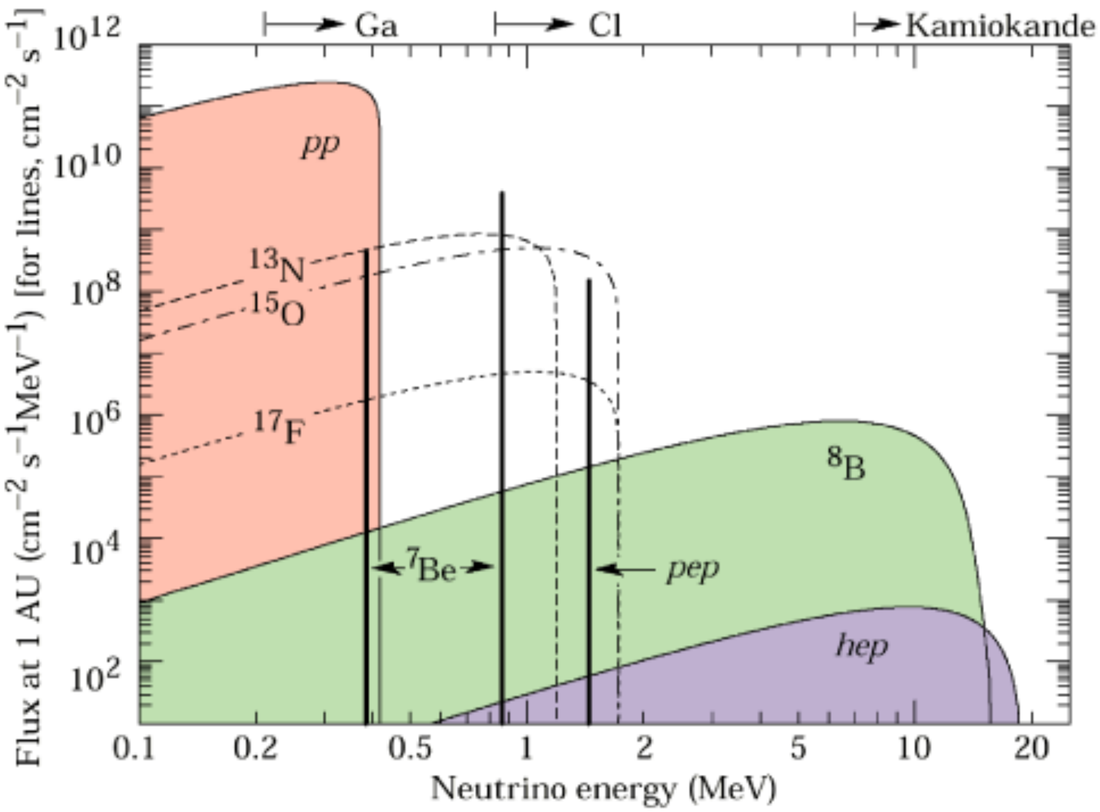
The Sun

The first astrophysical neutrino source

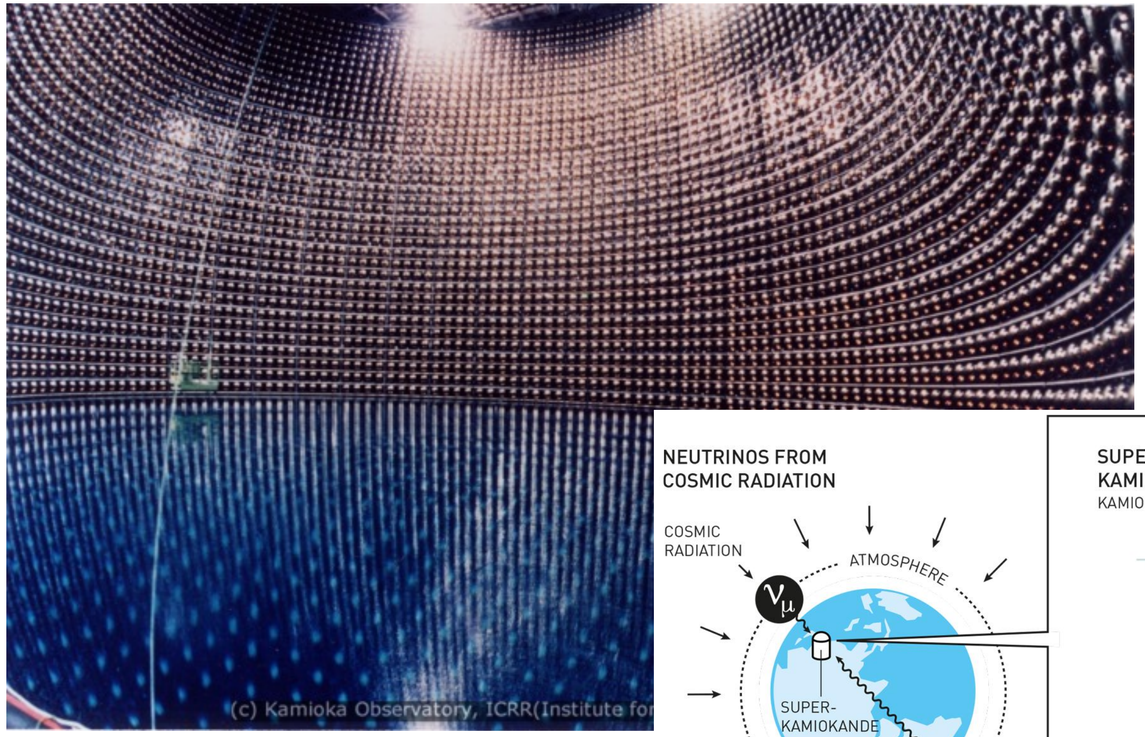


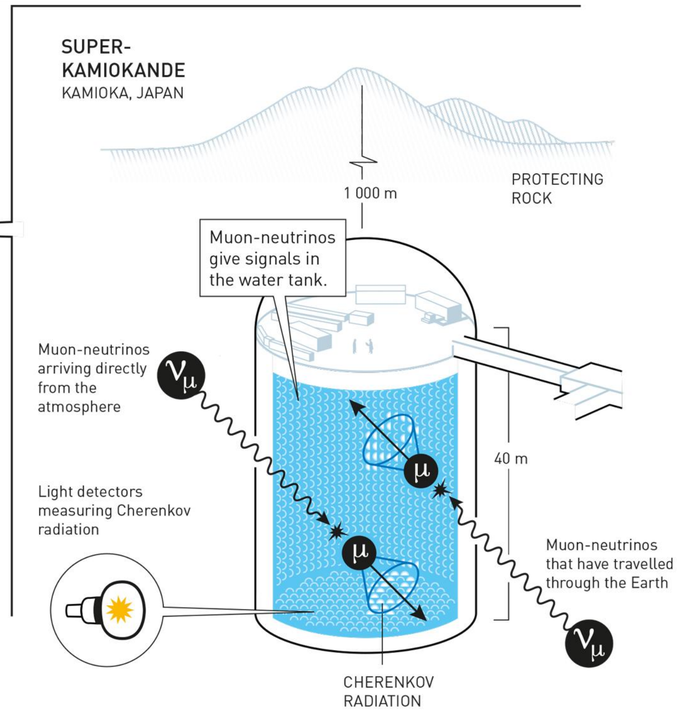


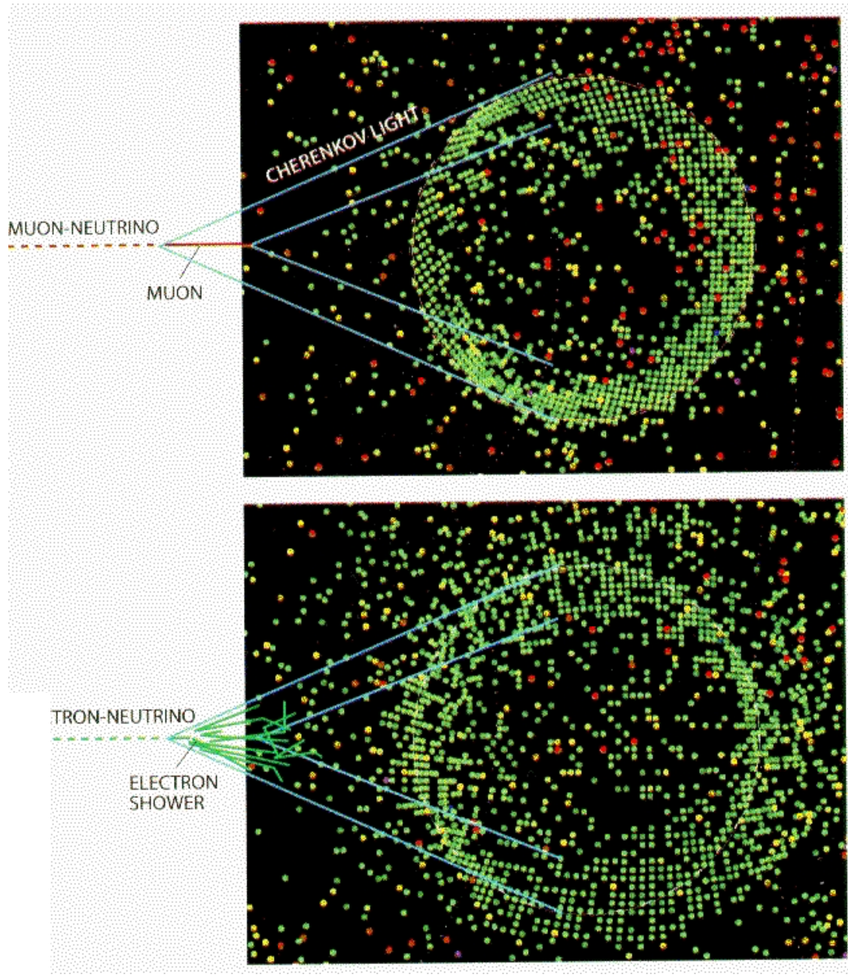




(Super)-Kamiokande





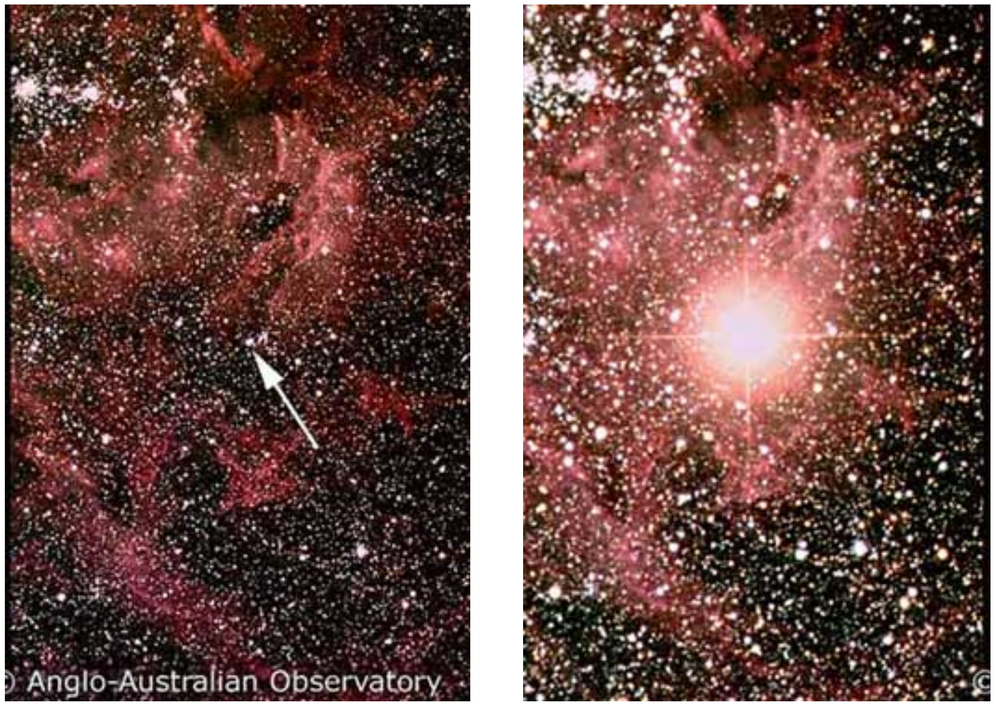


50,000 ton water Cherenkov detector
2700 meters underground in Kamioka, Mount Ikeno, Japan

as well as Sudbury Neutrino Observator Borexino etc.

Supernova1987A

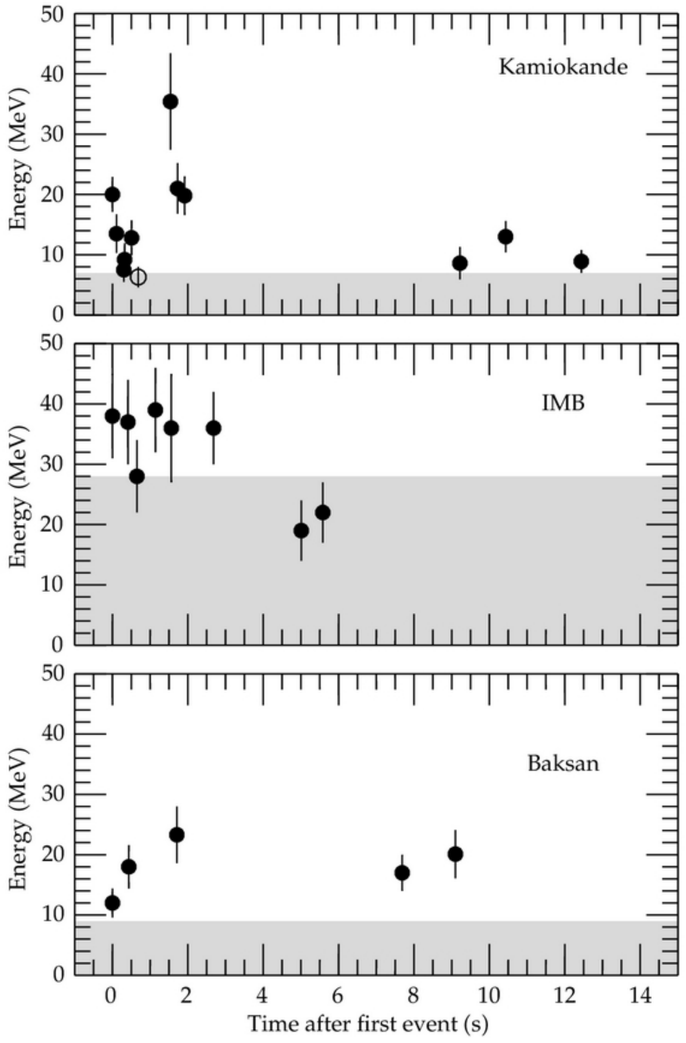
The second astrophysical neutrino source



51.4 kpc away in the Small Magellanic Cloud

Nobel prize 2002

Annual Reviews 1999

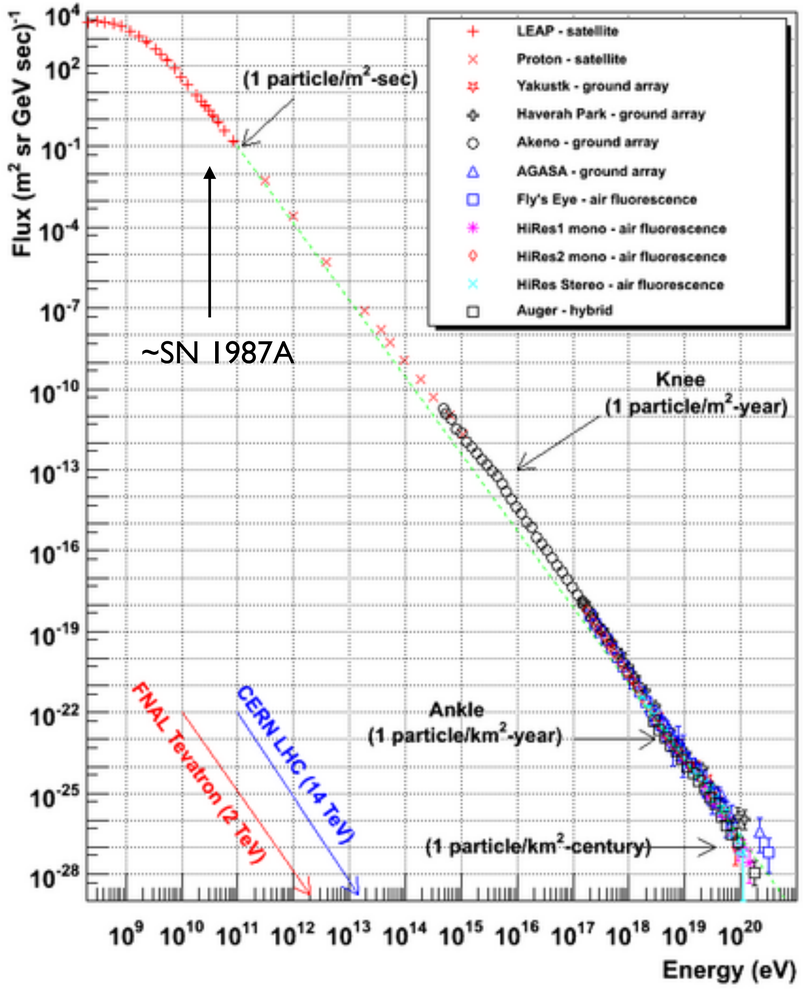


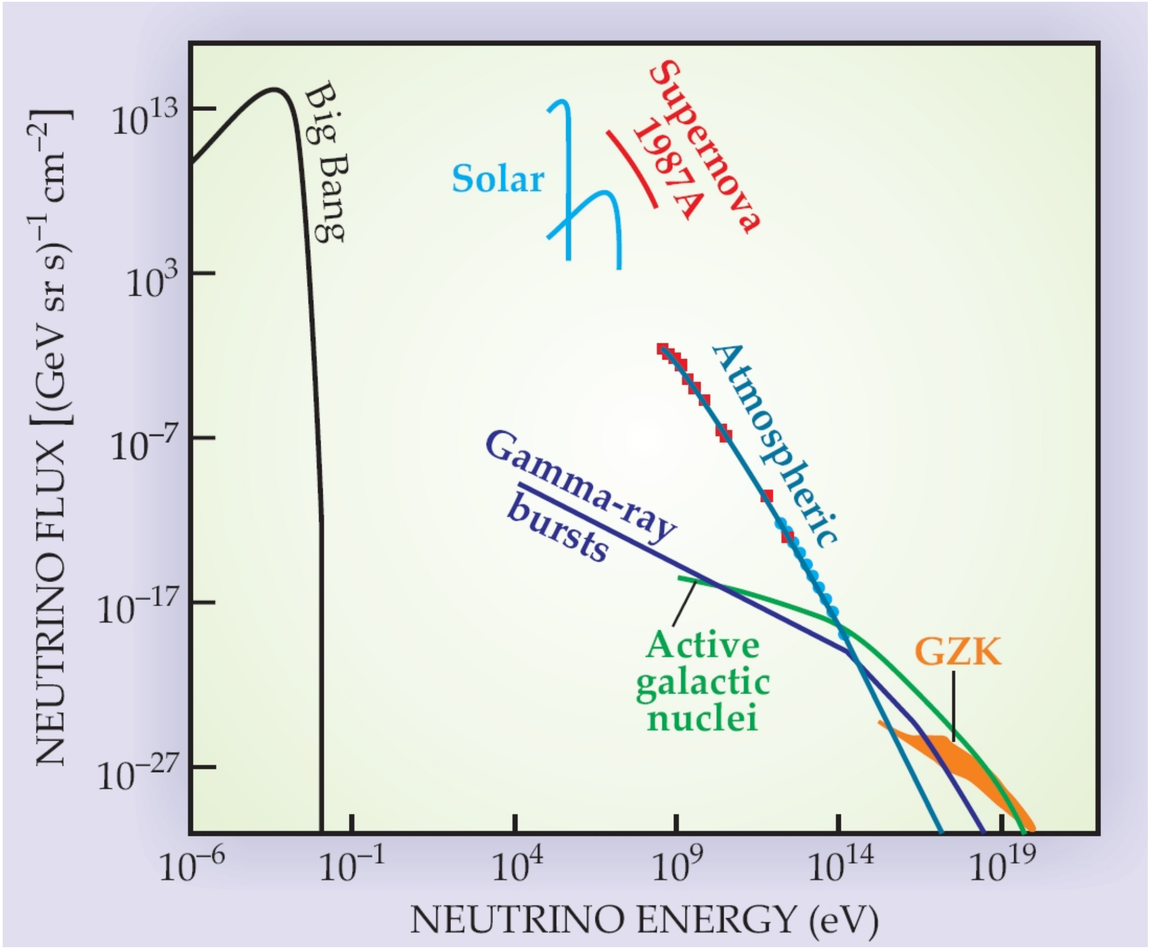
Kamiokande-II (Japan)
Water Cherenkov detector

Irvine-Michigan-Brookhaven
Water Cherenkov detector

Baksan Scintillator Telescope

What happens at higher energies?

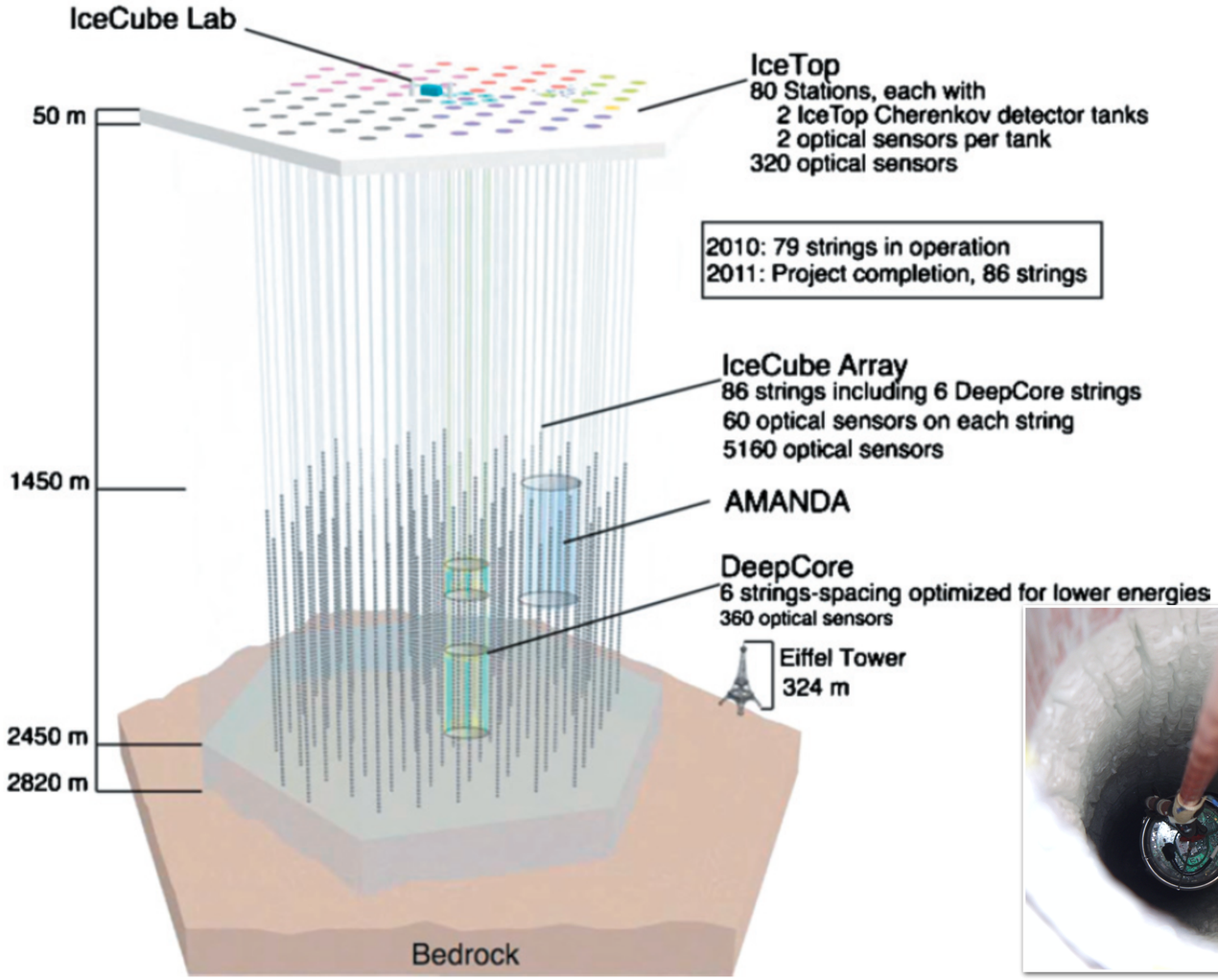




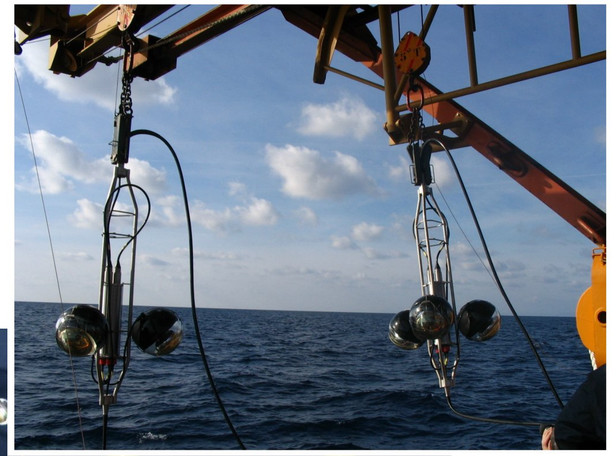
High-energy neutrino detection

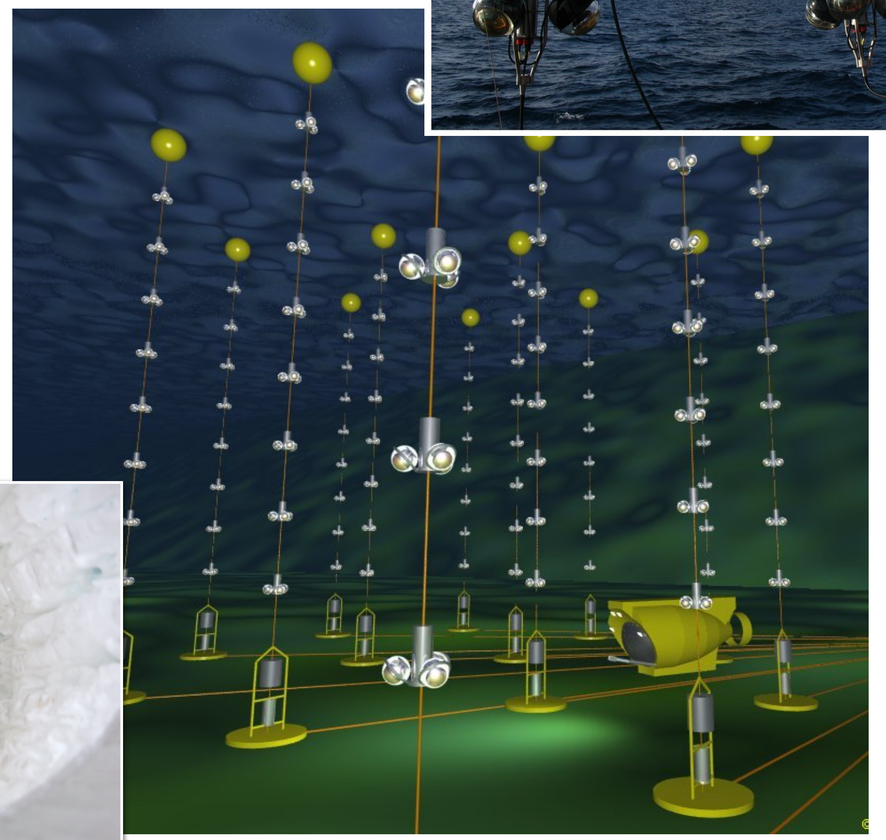
Huge volumes needed: water/in-ice Cherenkov detection

IceCube - South Pole



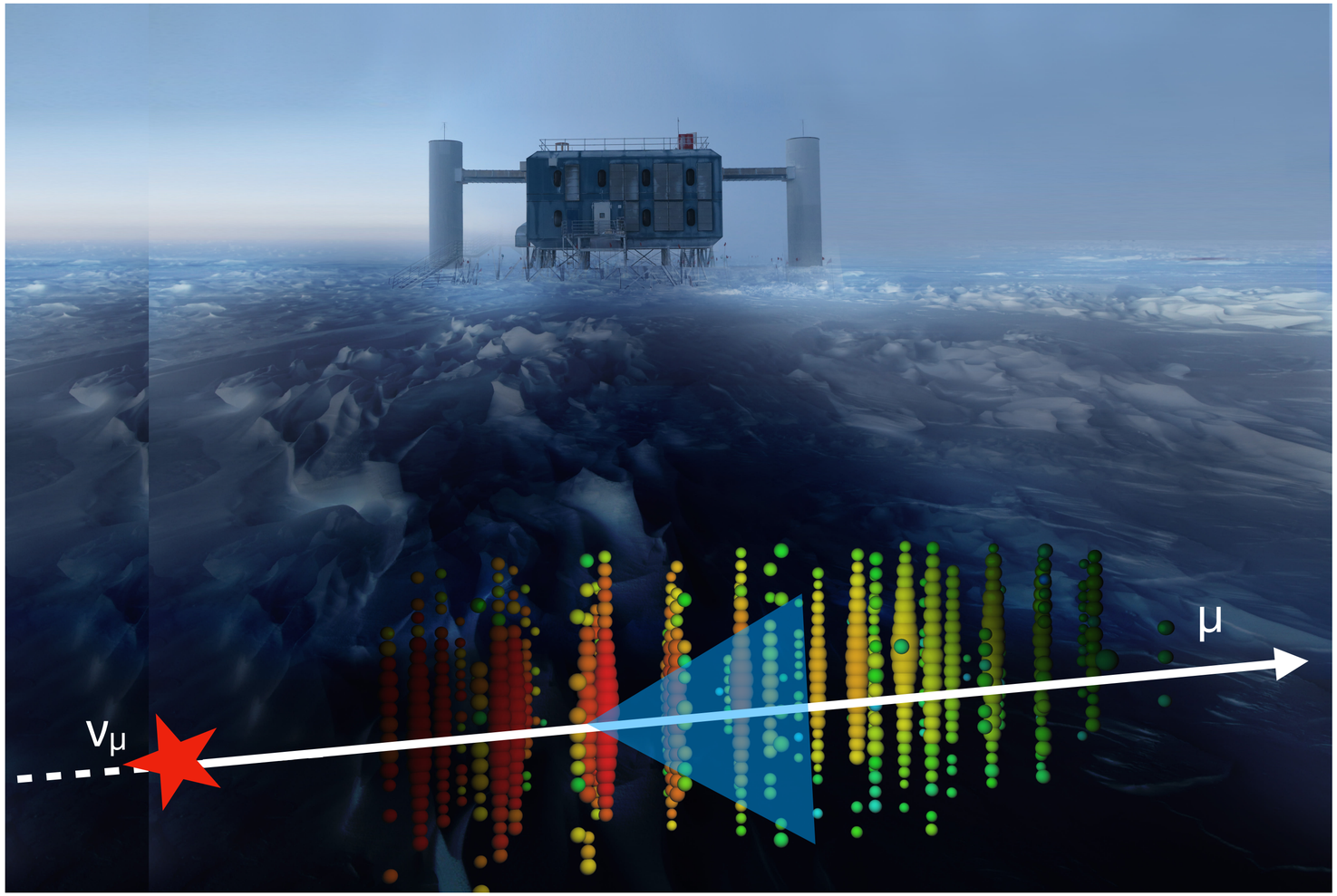
ANTARES (2.5 km under the Mediterranean Sea)





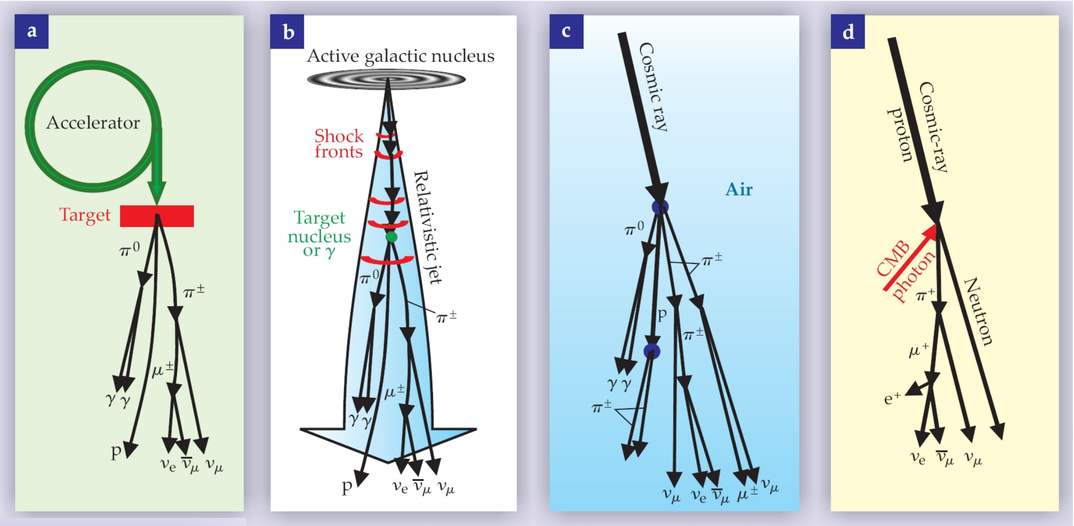
High-energy neutrino detection

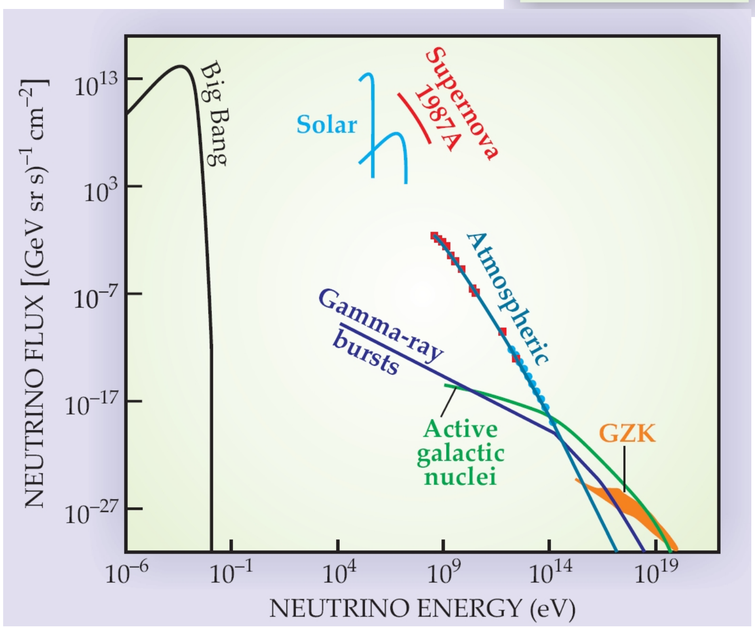
Water/in-ice Cherenkov detection



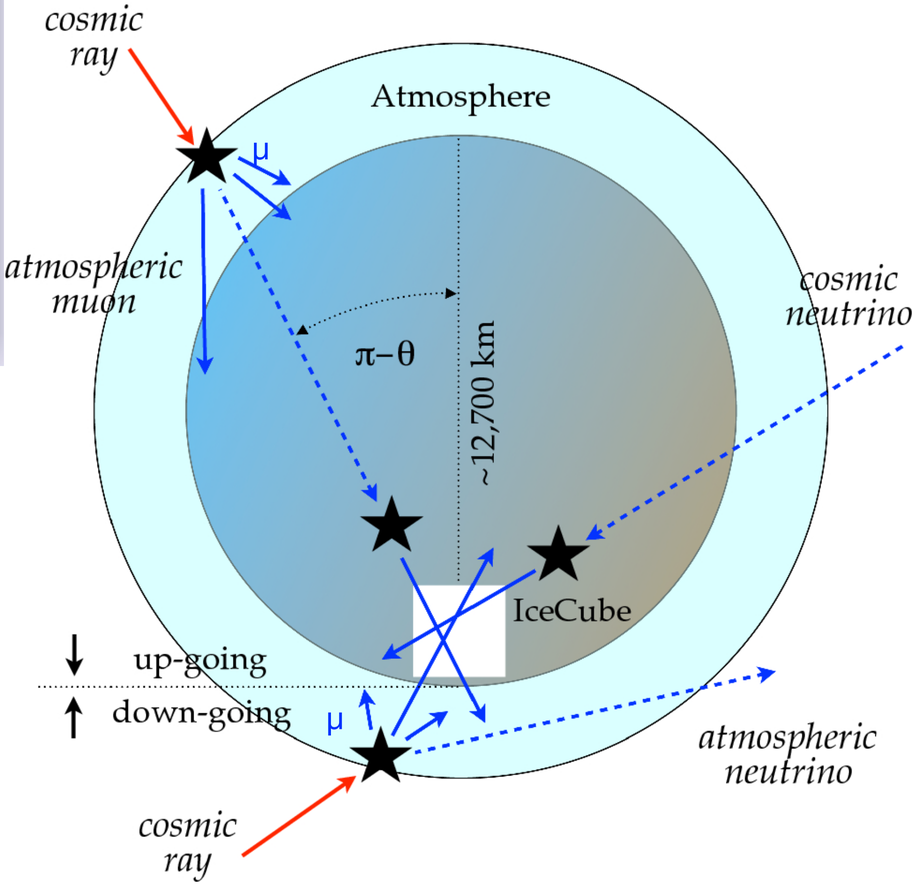
High-energy neutrino detection

Backgrounds

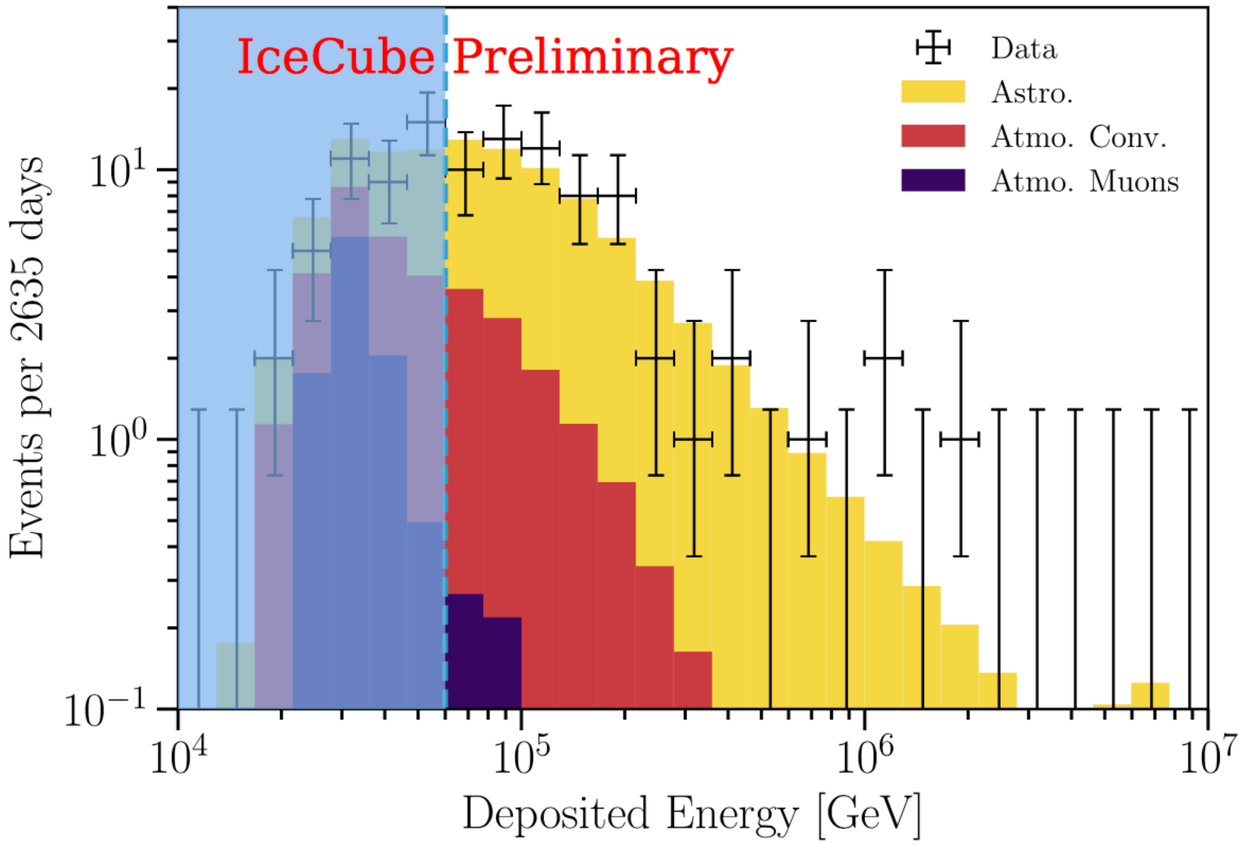


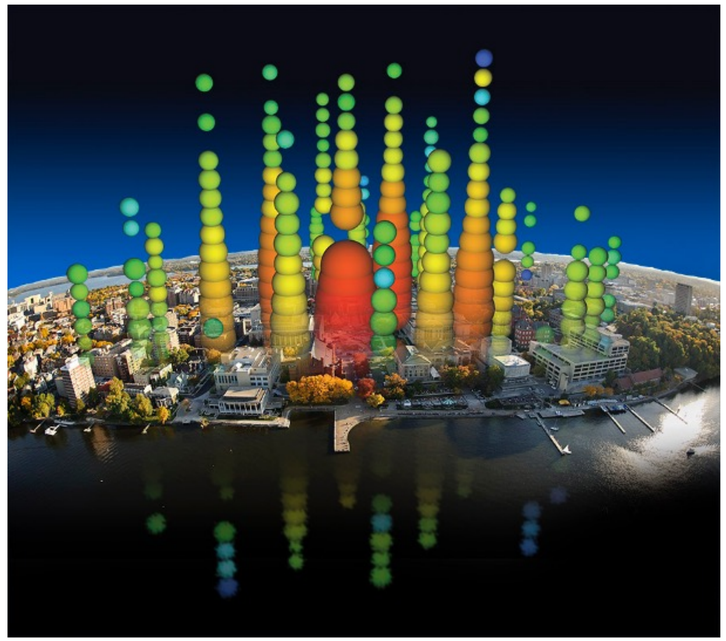


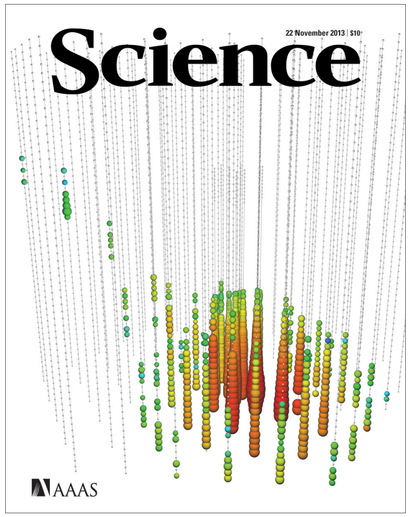
Ahlers, Helbing, Perez de los Heros, 2018, EPJC



IceCube detects astrophysical neutrinos

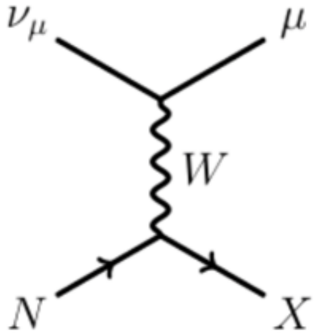






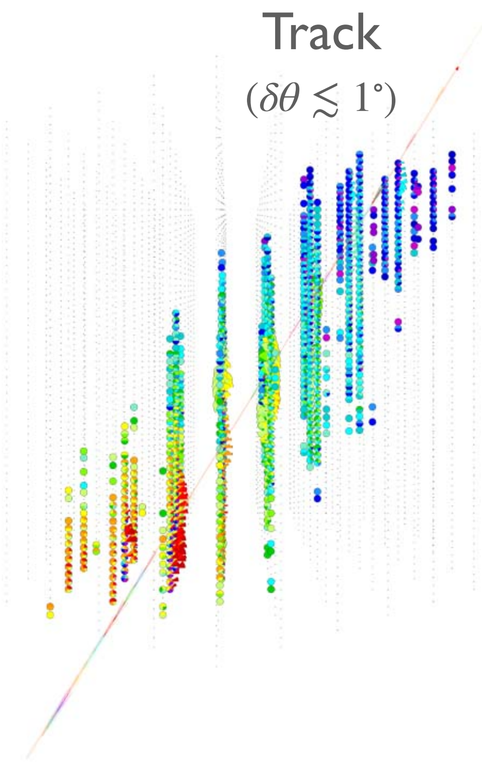
IceCube, Science 342, 1242856 (2013)
IceCube, Phys. Rev. Lett. (2015)

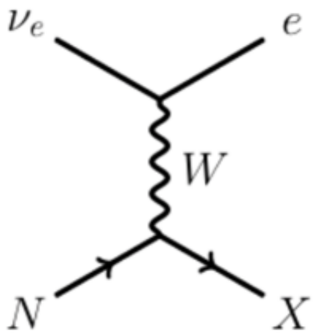
Flavour identification



Track

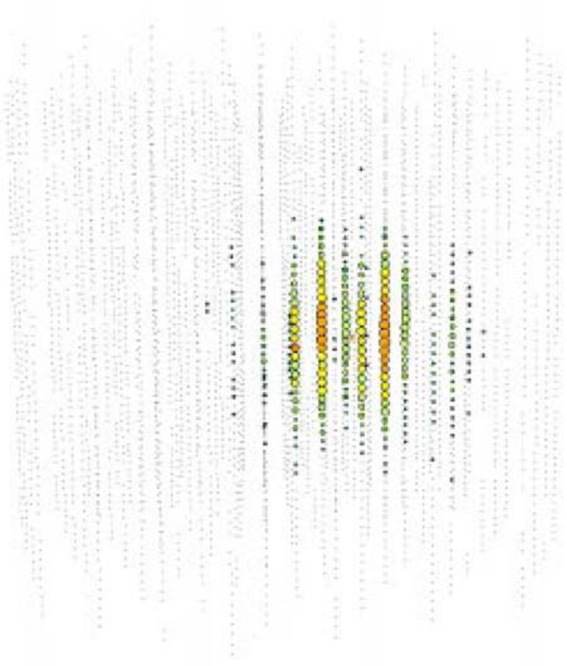
($\delta\theta \lesssim 1°$)

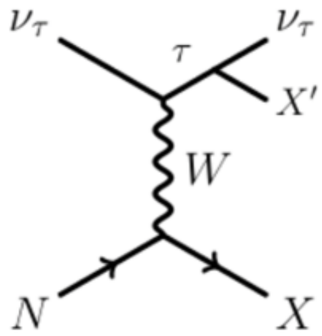




Cascade

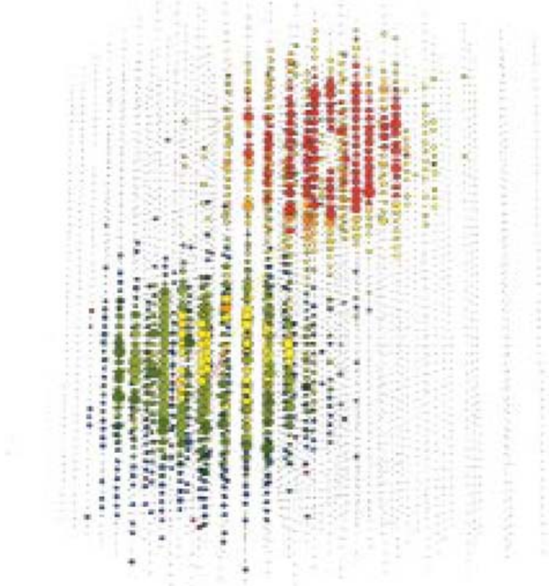
also NC ν_i ($\delta\theta \gtrsim 10°$)





Double Bang

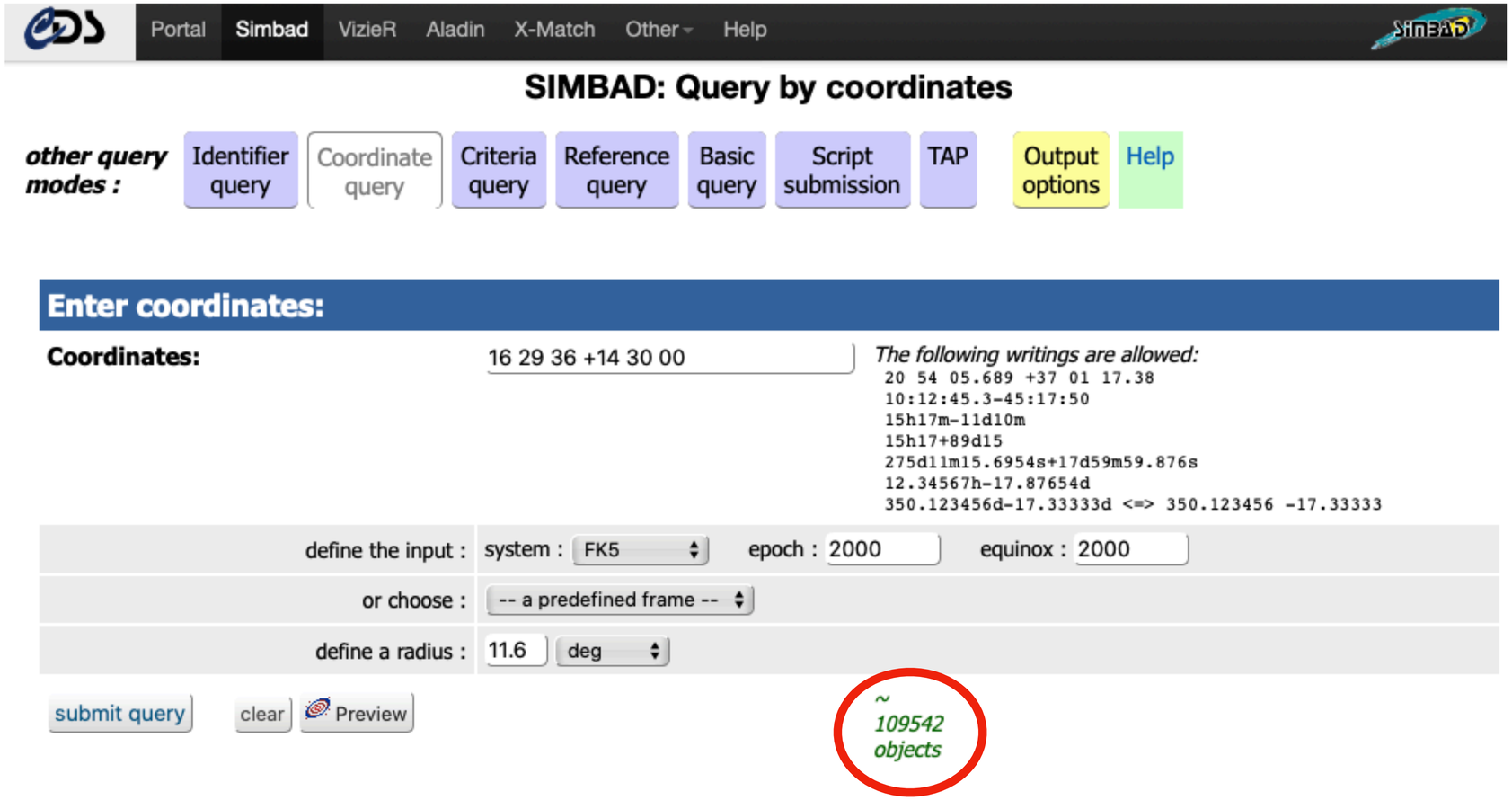
($\delta\theta \lesssim$ cascade)



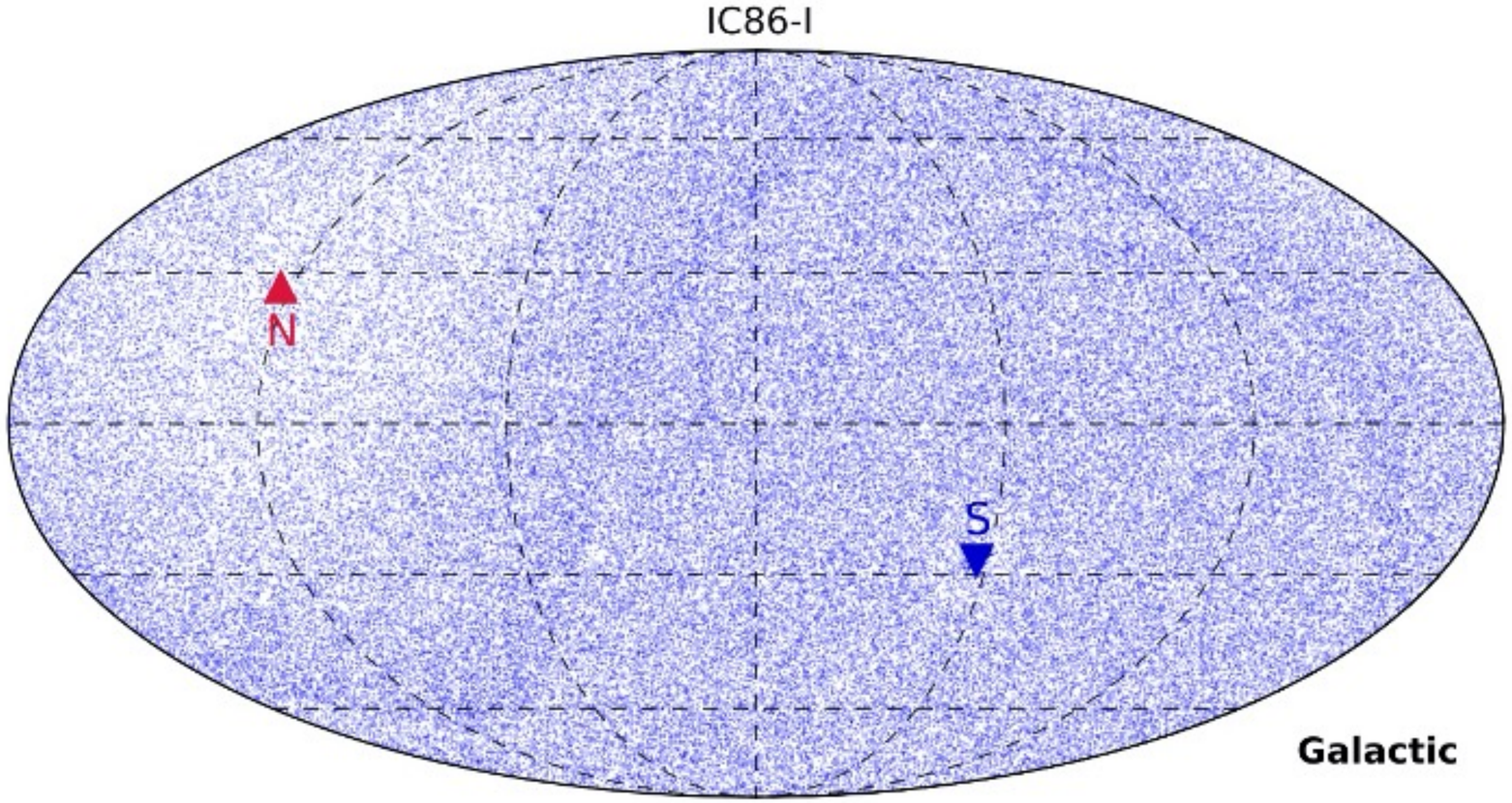
*tau decay length ~ 50m per PeV

For astronomy we need high angular resolution

Example, IC-17 (cascade):

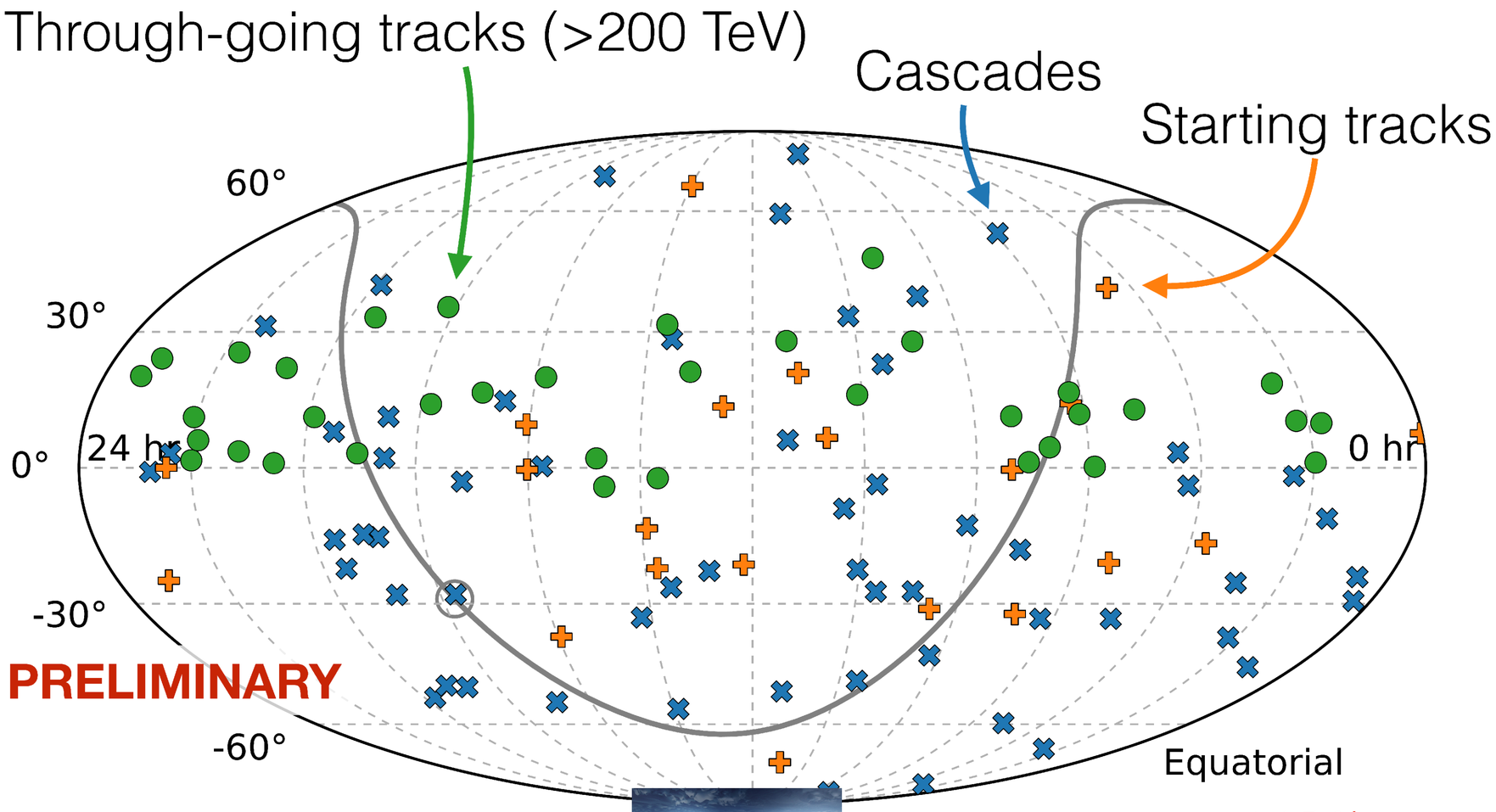


Sky distribution of the neutrinos



~100000 neutrinos per year
~100 astrophysical
~10 neutrinos with energy E> 60 TeV (high probability of being astrophysical)

Sky distribution of the neutrinos

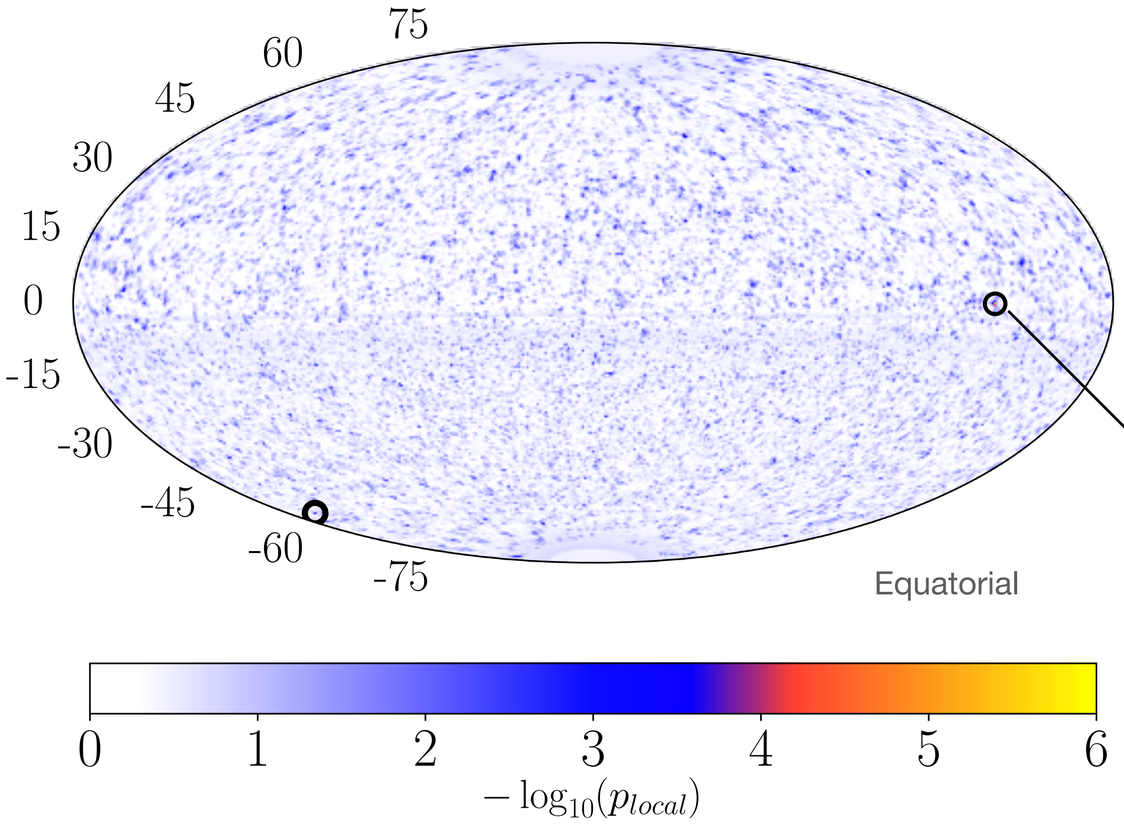


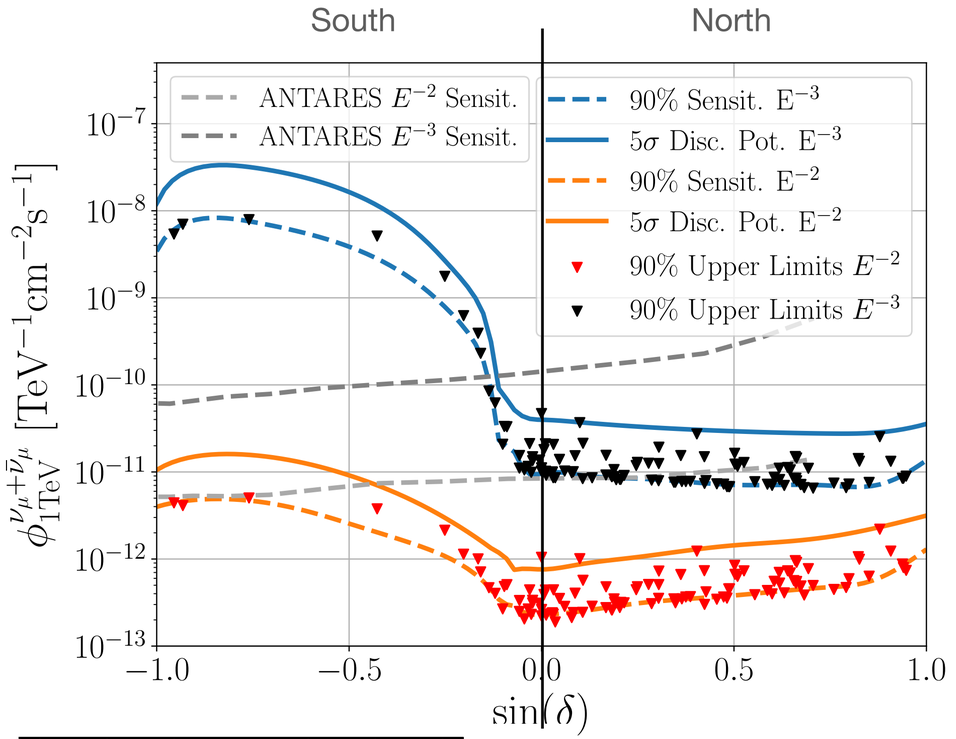
Galactic fraction $\lesssim 15\,\%$

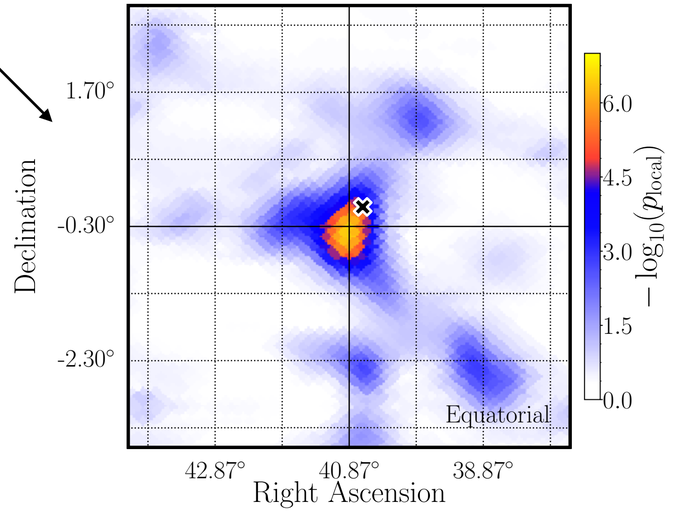
No very strong association signal (few ~3σ analyses)

Neutrino Point Sources?

IceCube 10 year "Point-Source" search



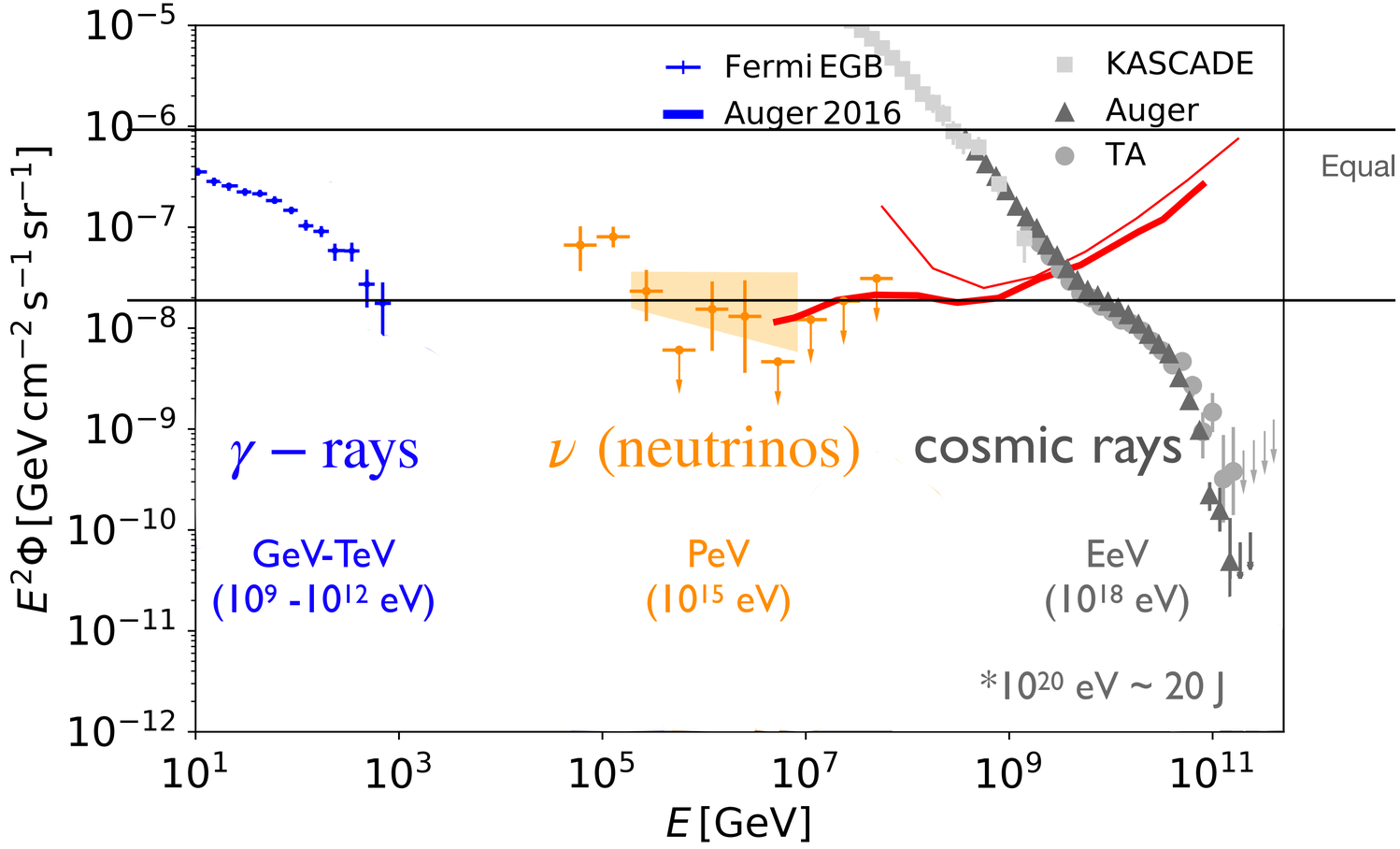




Isotropy not unexpected. Universe homogeneous and isotropic at large scales

NGC 1068 (AGN/starburst galaxy), 2.9σ (i.e. chance probability 0.187%, or 1 in ~500)

Energy flux



Equal energy content per decade

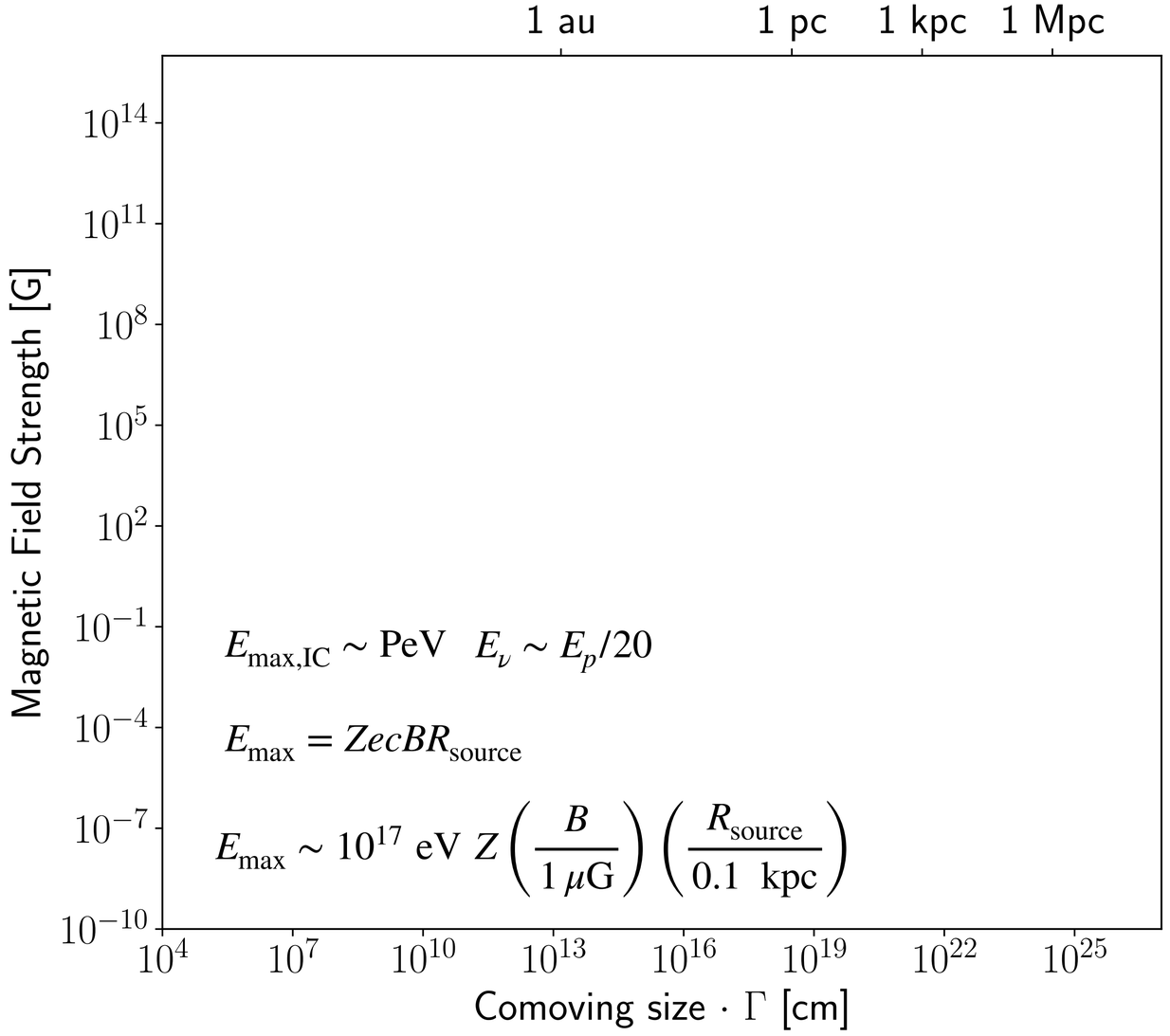
Lecture plan

- Experimental facts and basic theoretical concepts
- Requirements for astrophysical accelerators of high-energy cosmic rays/ high-energy neutrinos (generic source properties)
- Overview of candidate sources (Active Galactic Nuclei/Starburst Galaxies/Gamma ray bursts/Pulsars/Tidal Disruption Events) constraints and prospects

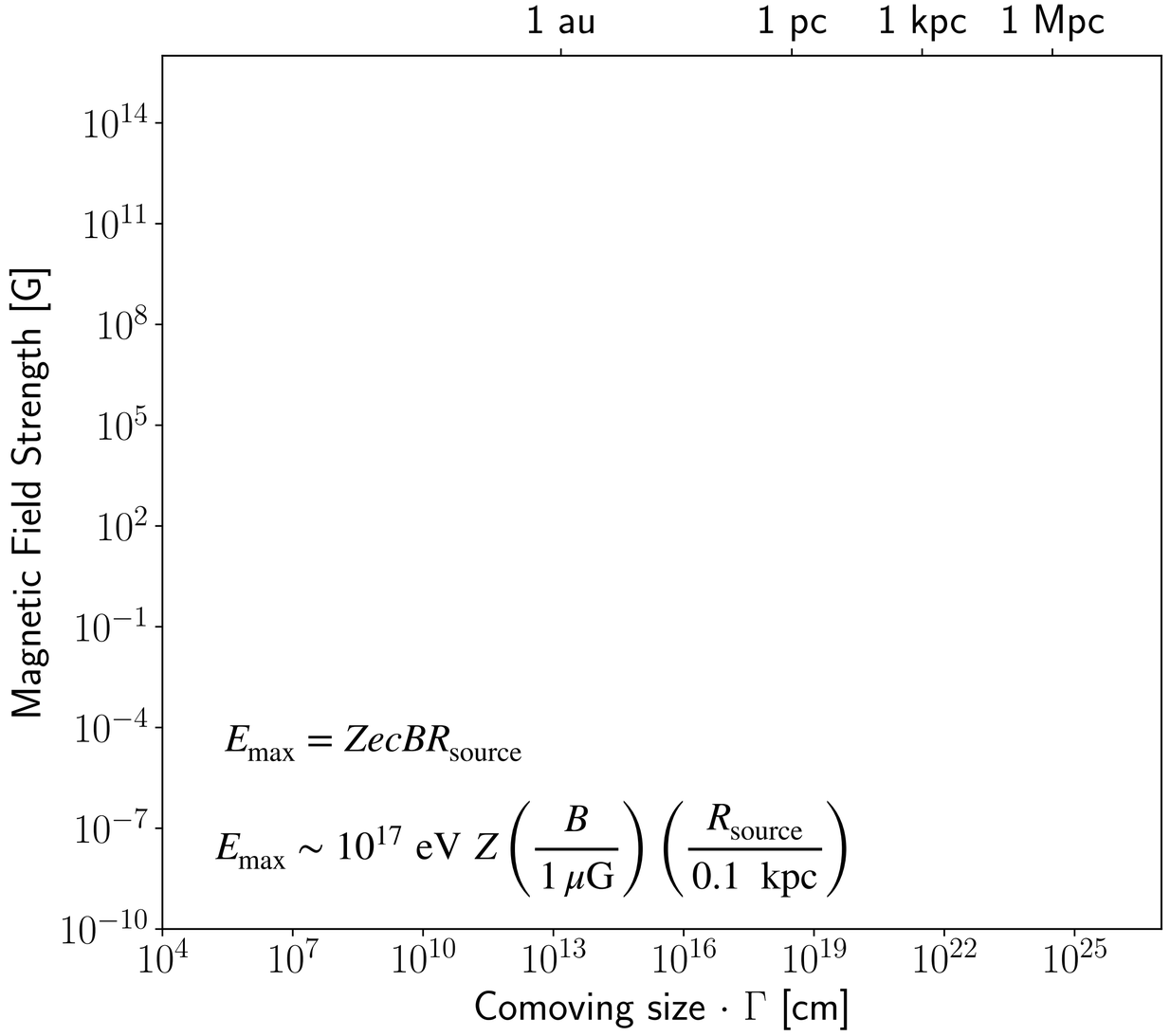
Generic source properties/requirements

- Hillas criterion for acceleration and plausible sources
- Waxman & Bahcall neutrino bound (possible connection to UHECRs)
- Neutrino source energy budget
- Neutrino source number density

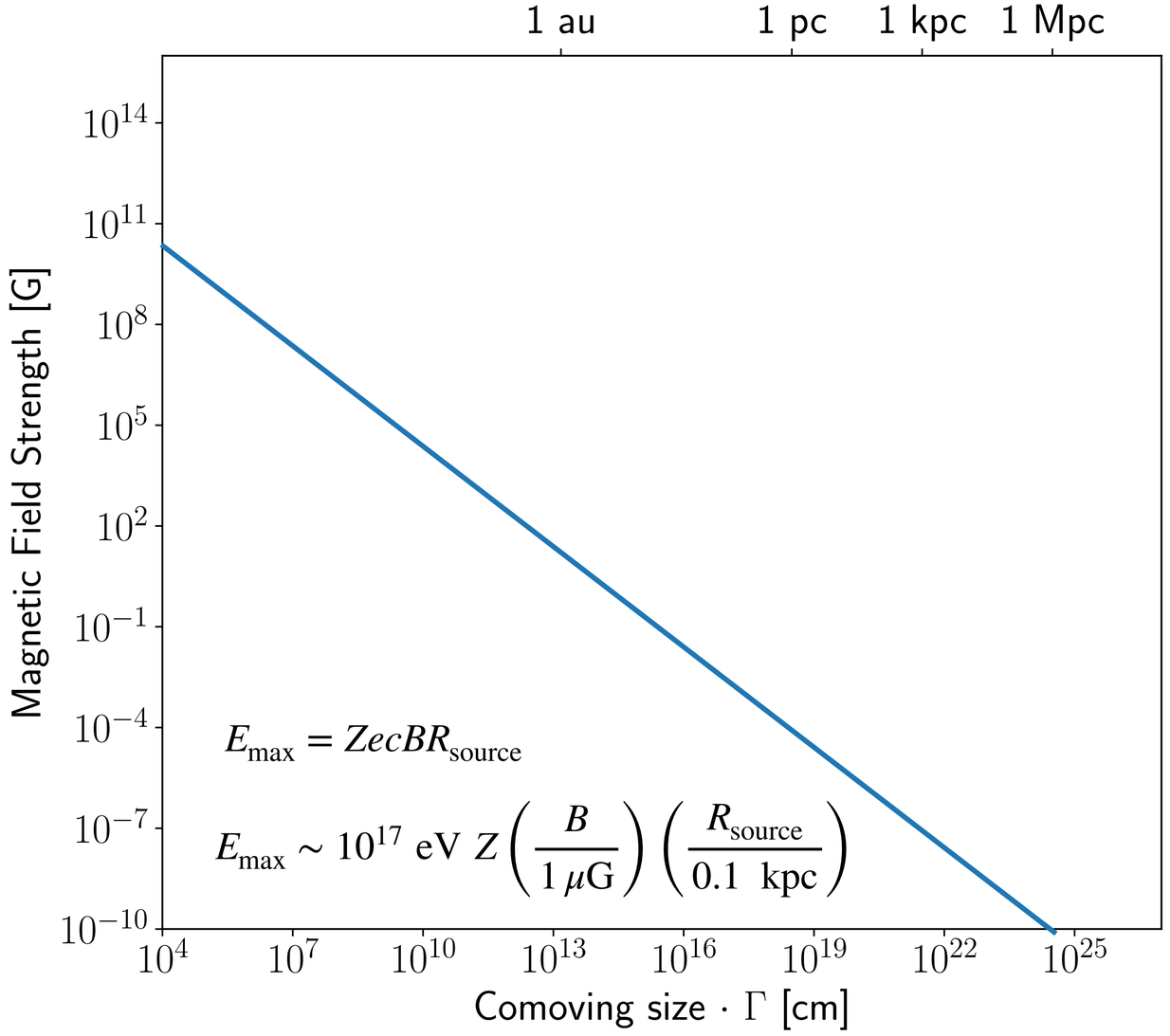
Hillas criterion



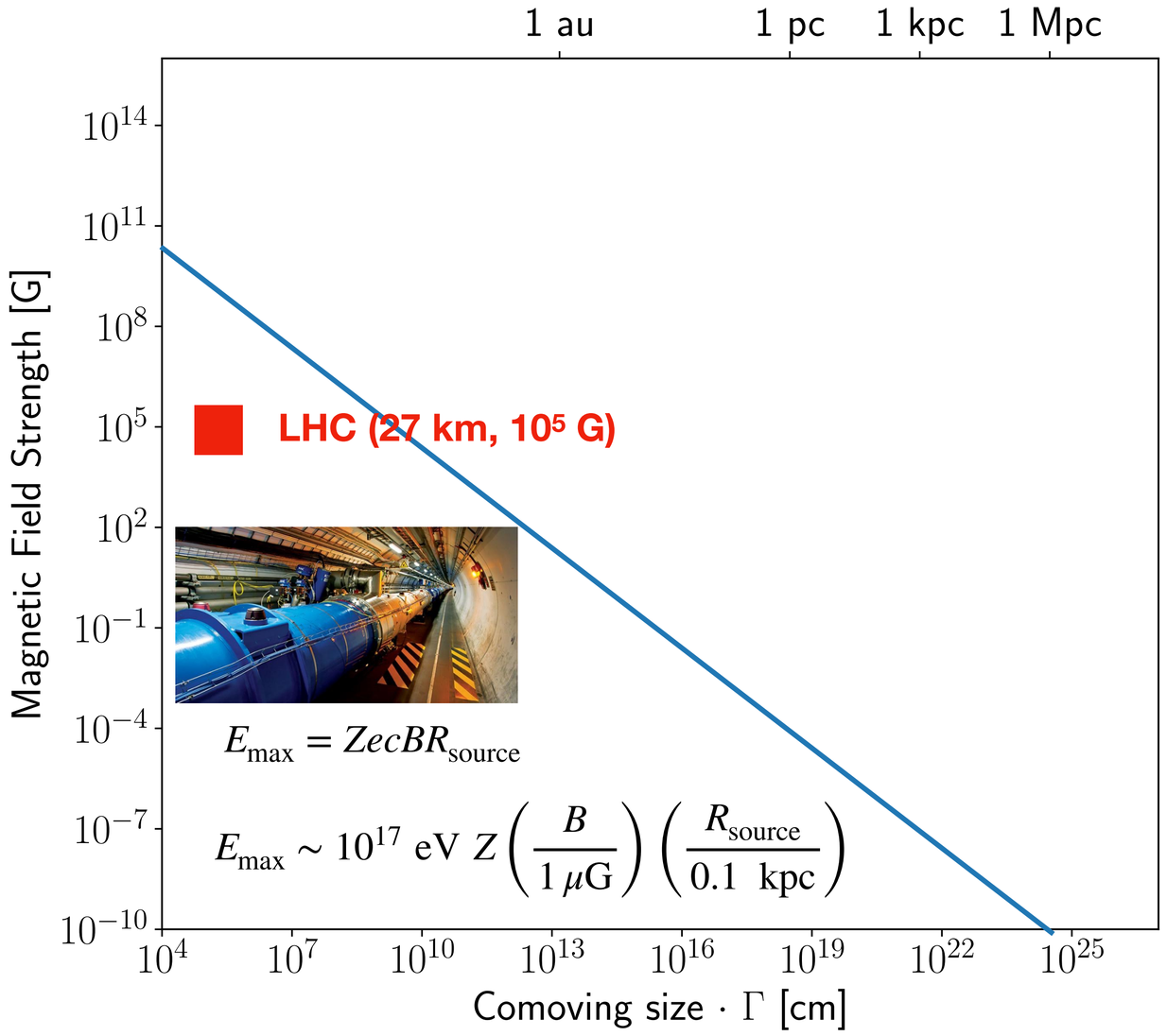
Hillas criterion



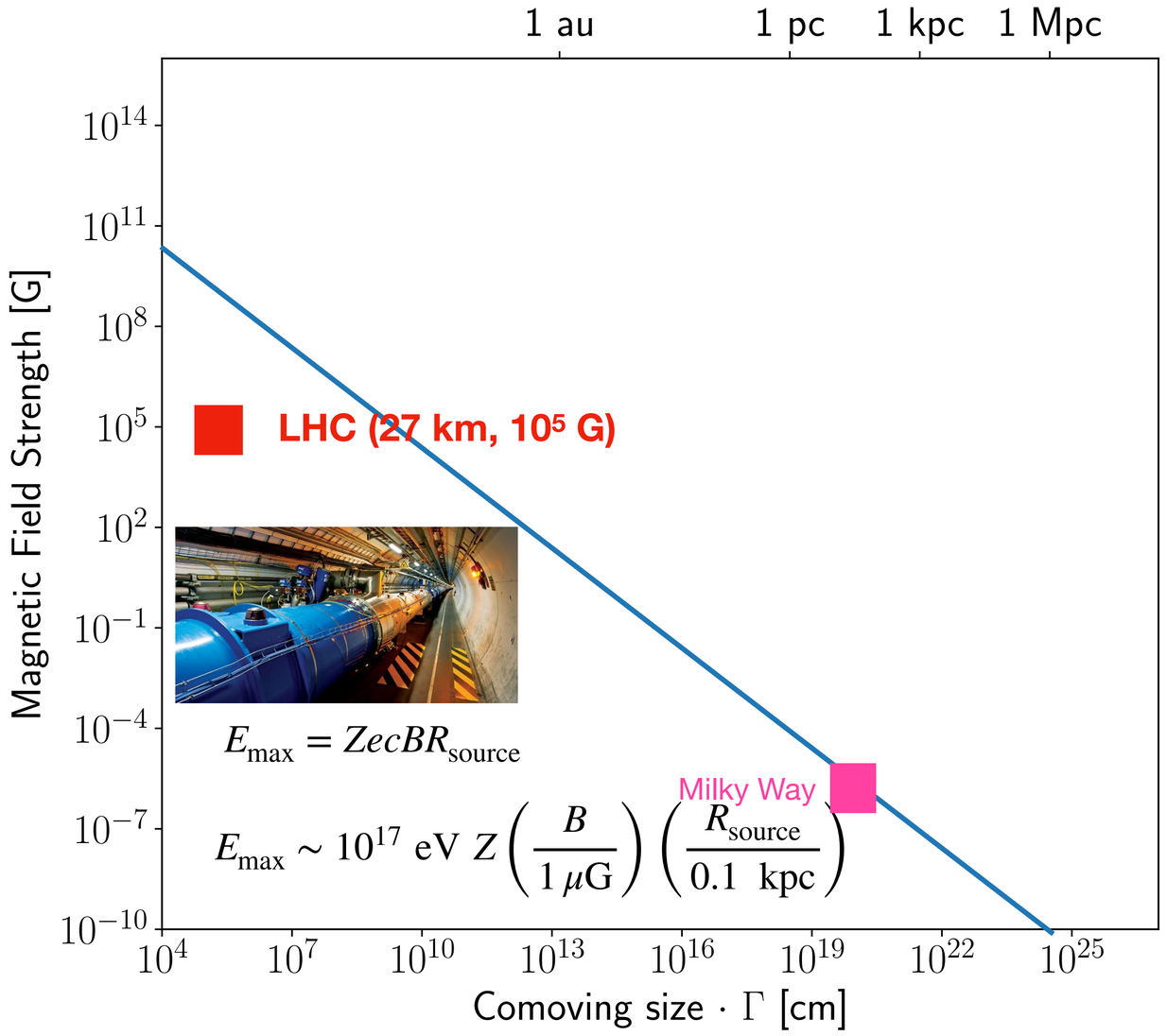
Hillas criterion



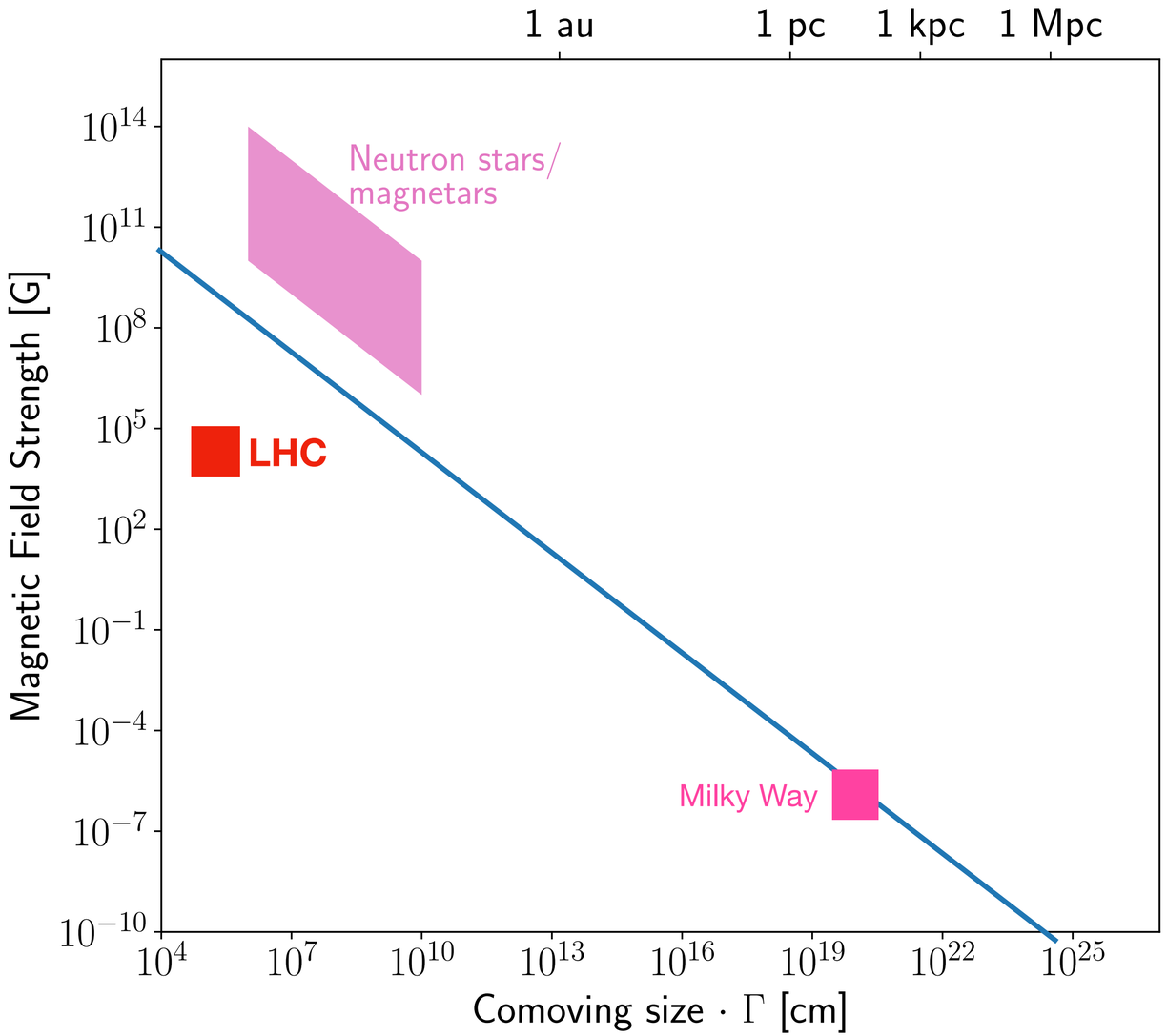
Hillas criterion



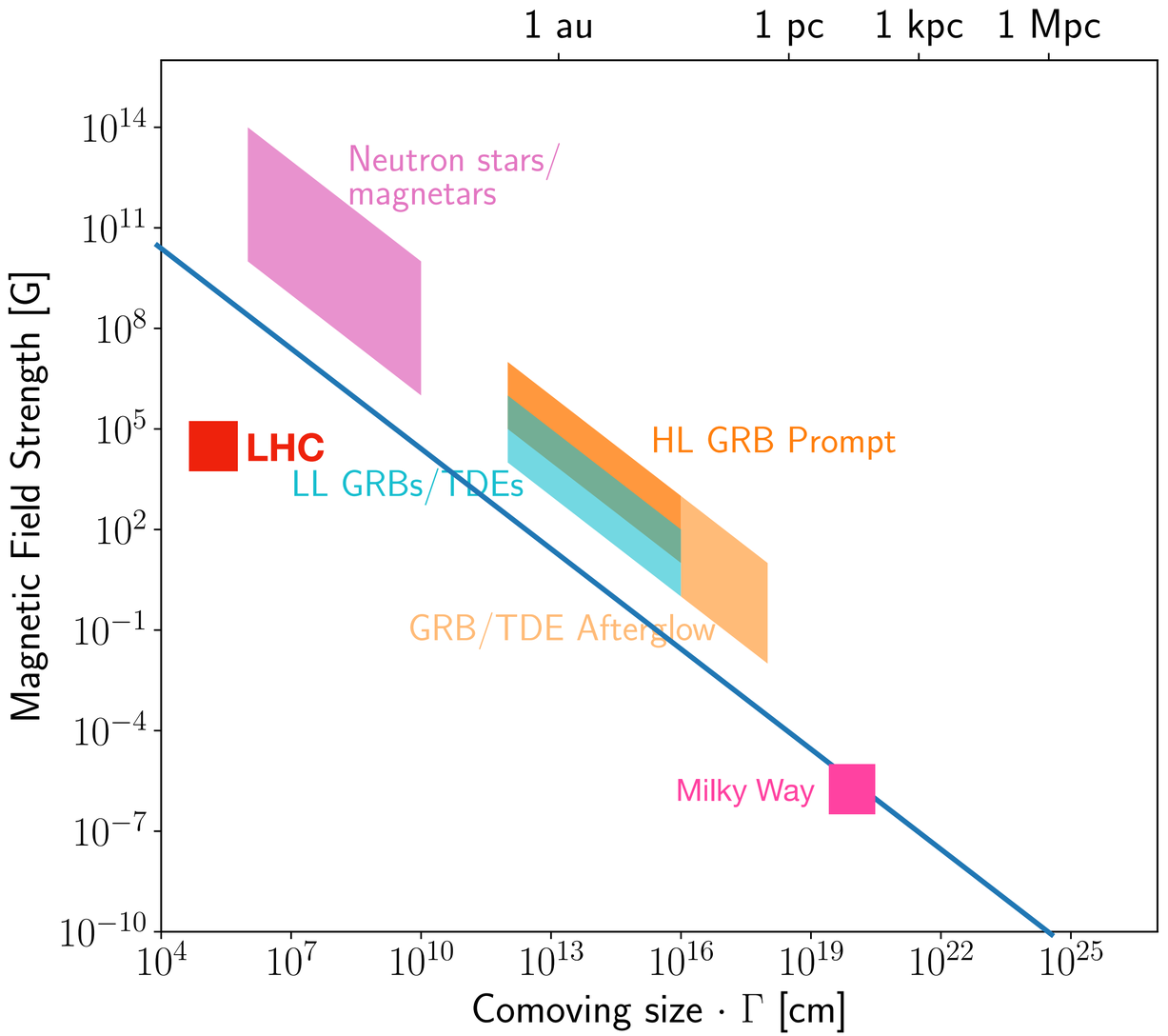
Hillas criterion

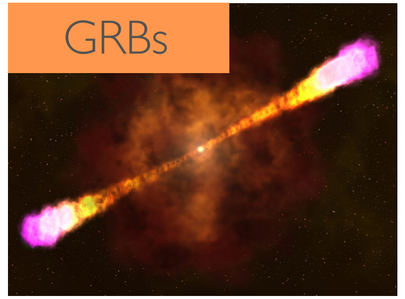


Hillas criterion



Hillas criterion





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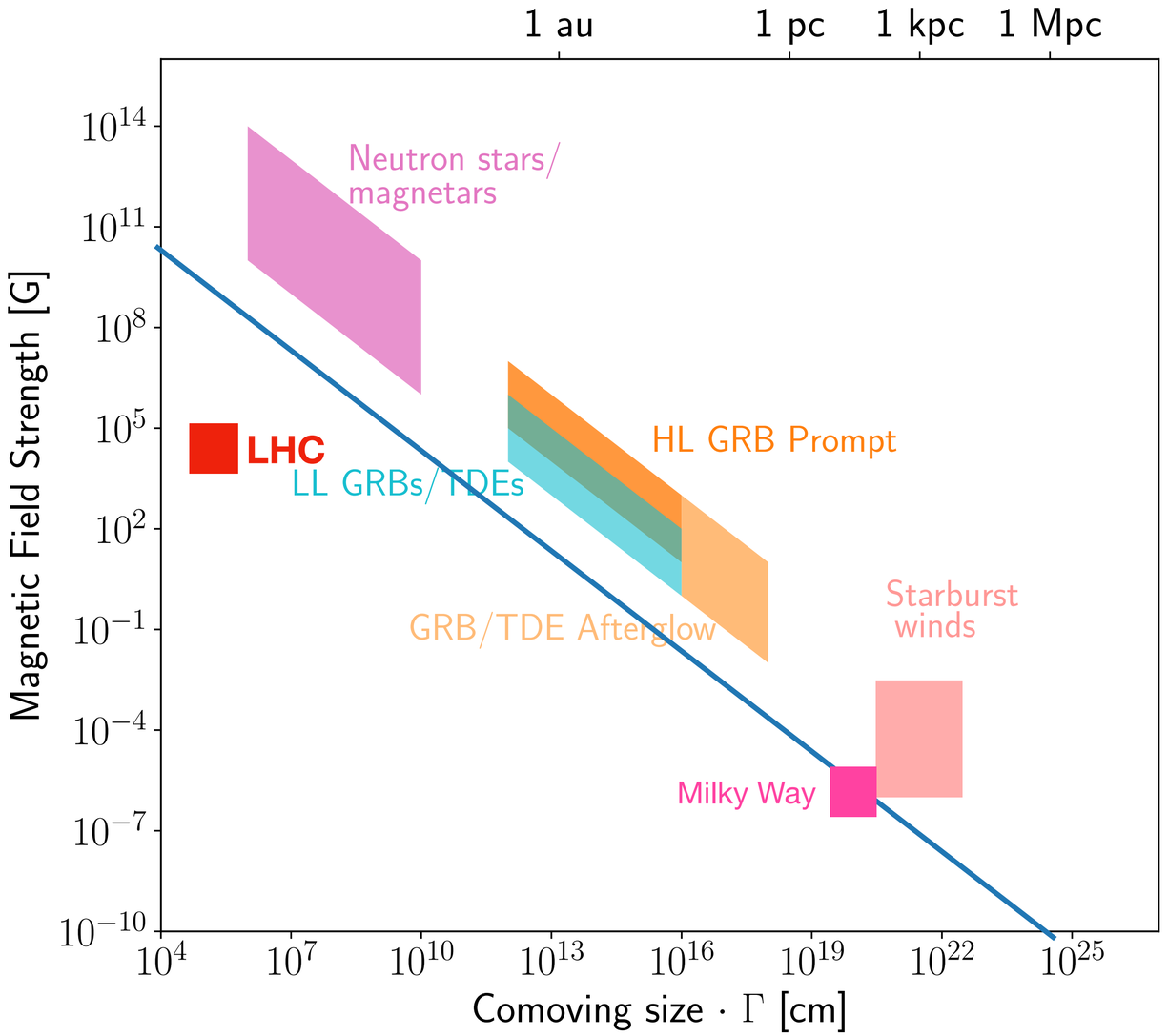
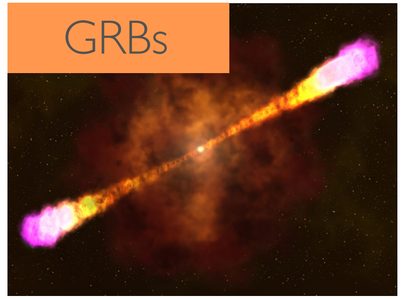
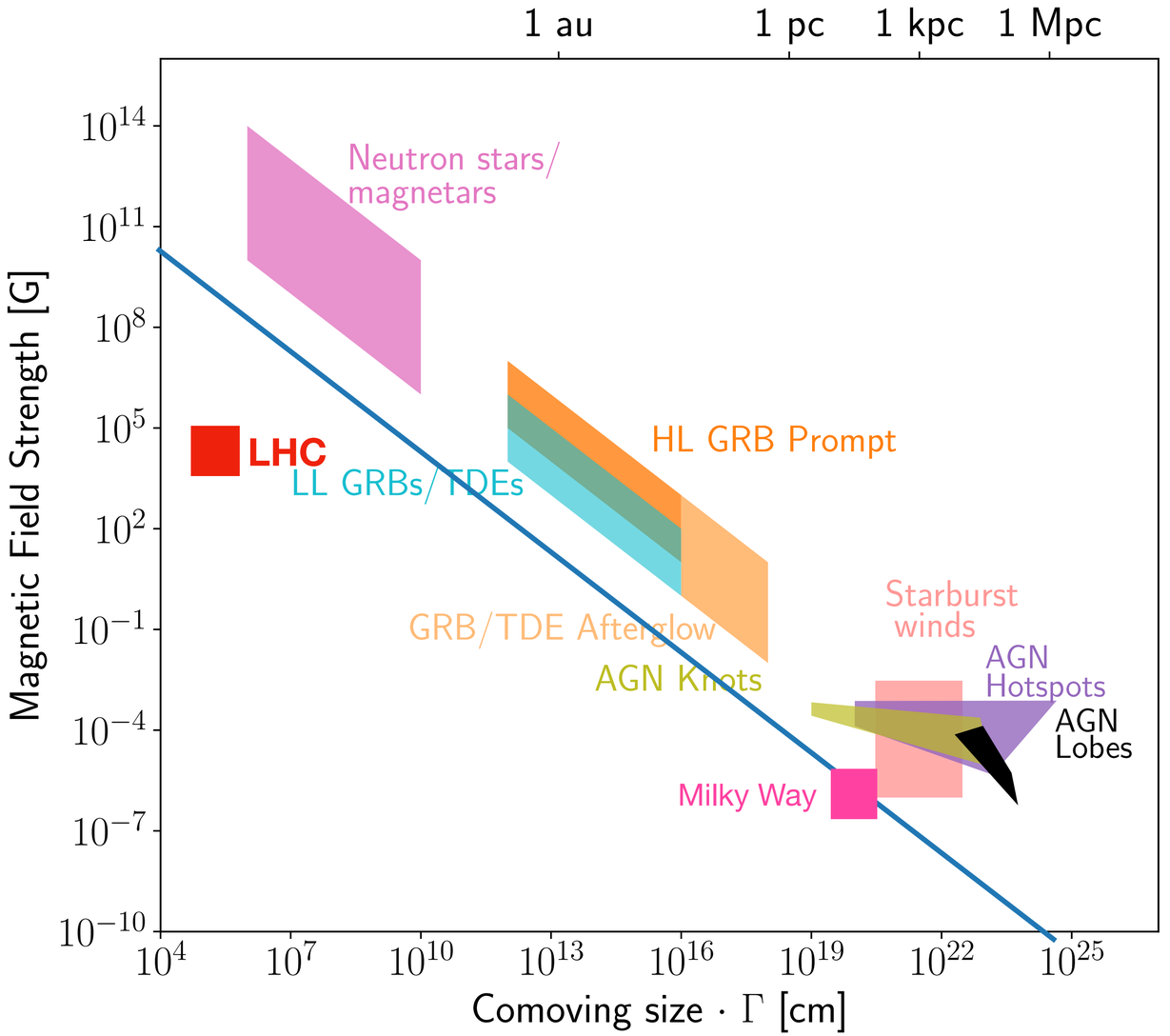
Hillas criterion

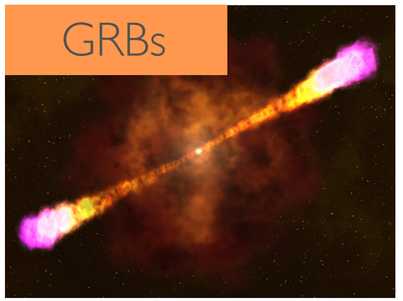


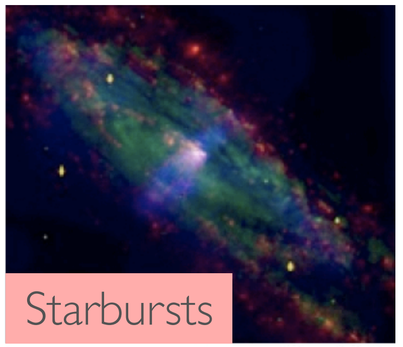


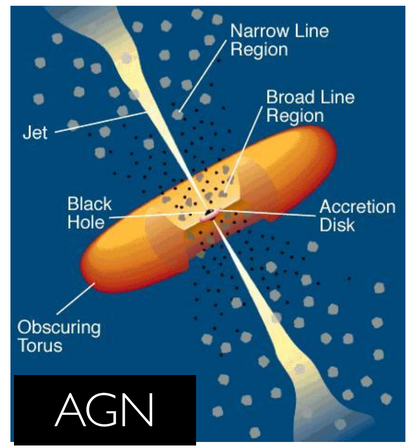
FO for MIAPP UHECR Review, 2019, FrASS, 6, 23

Hillas criterion

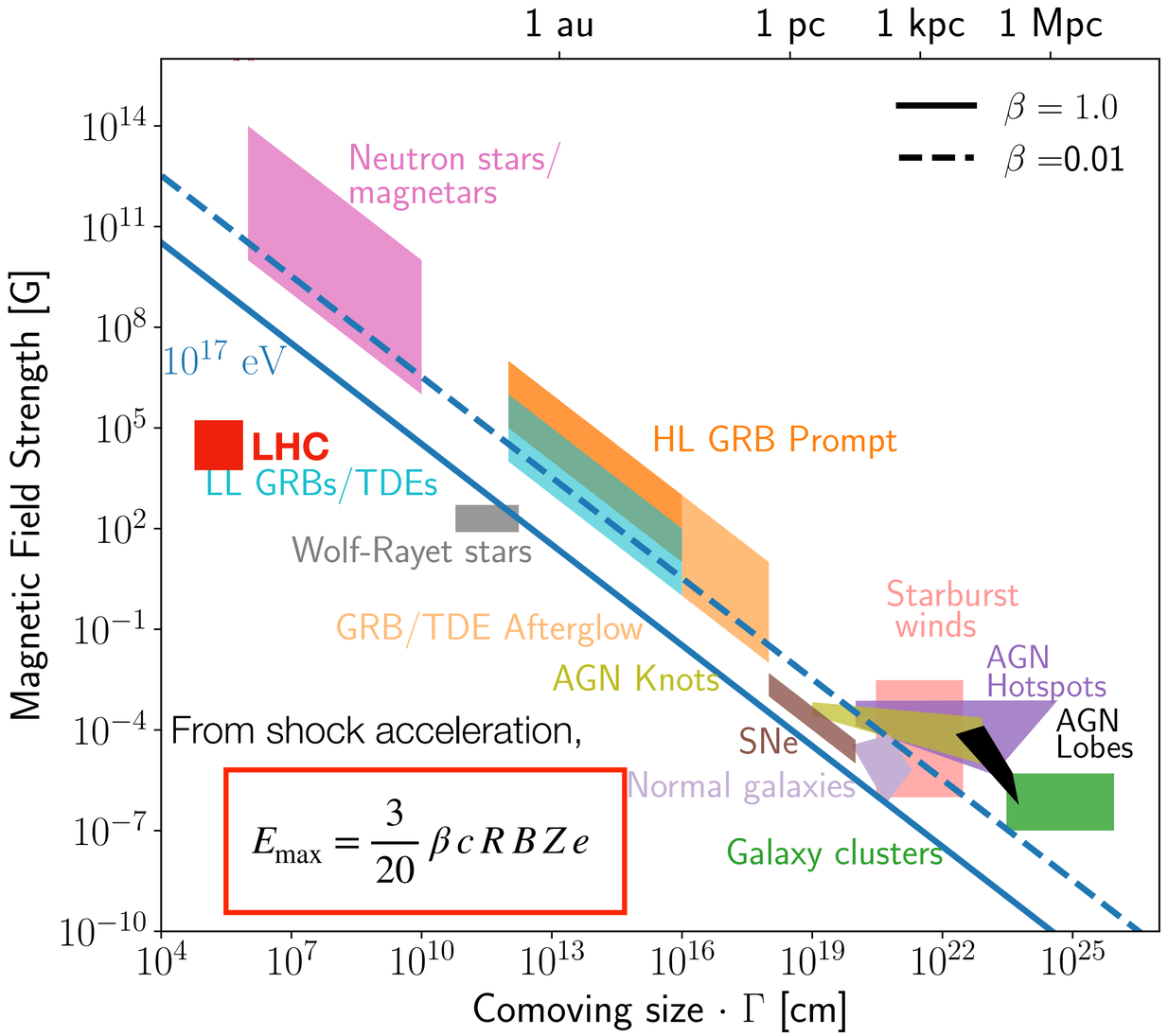


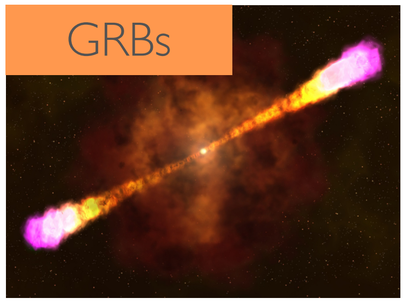


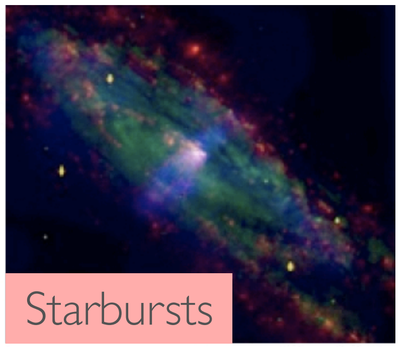


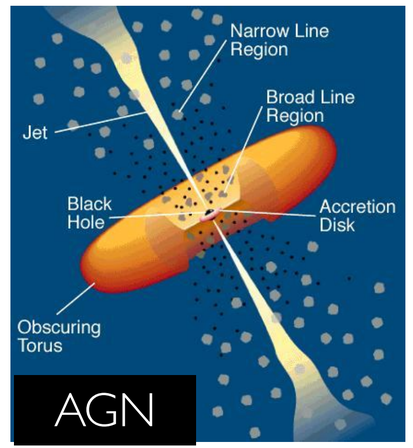


Hillas criterion

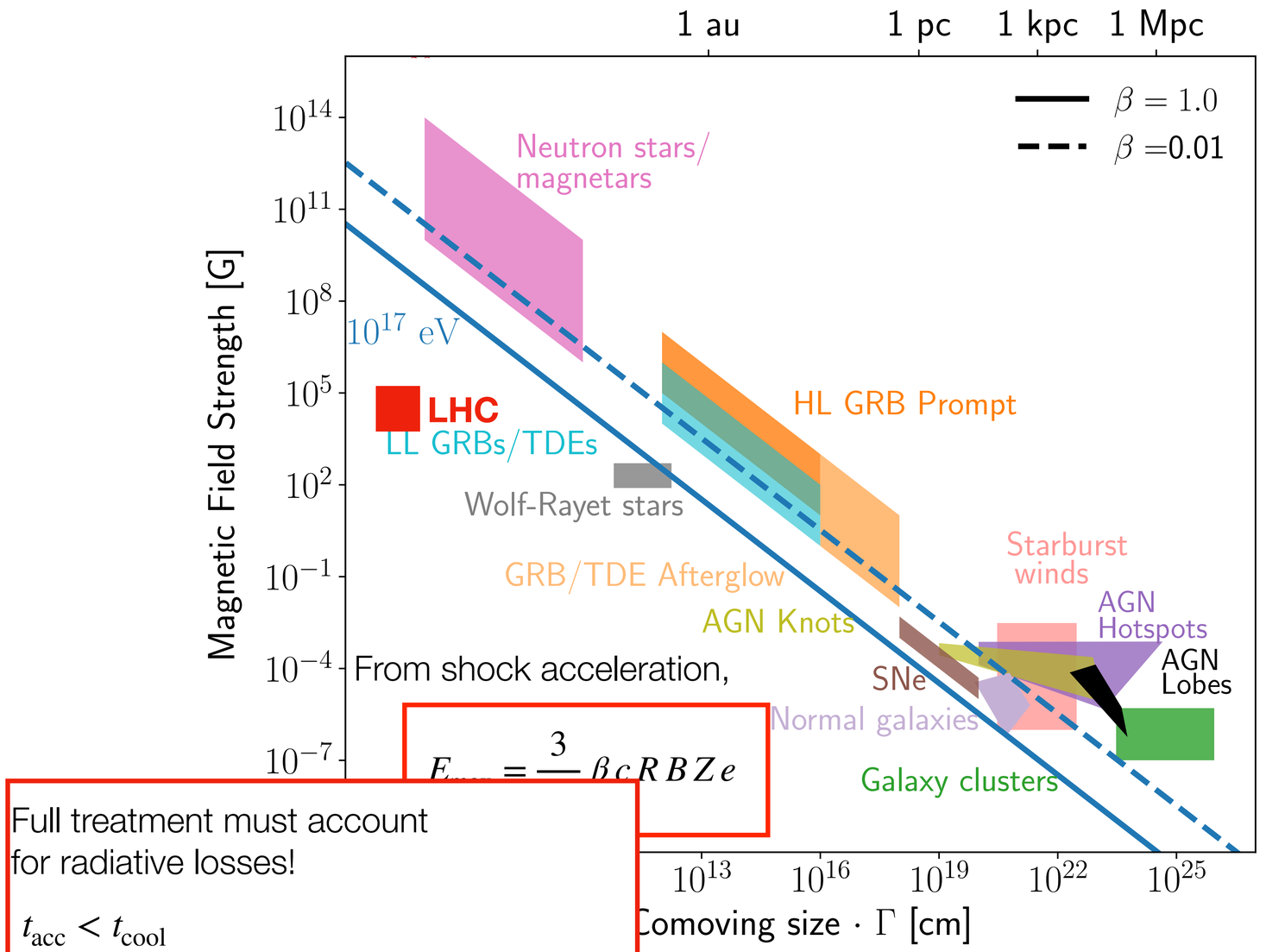








Hillas criterion



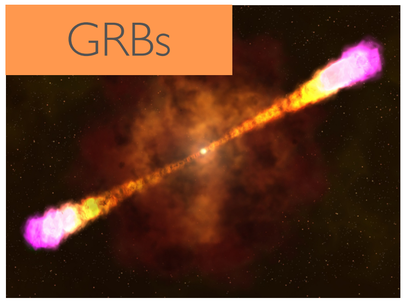
From shock acceleration,

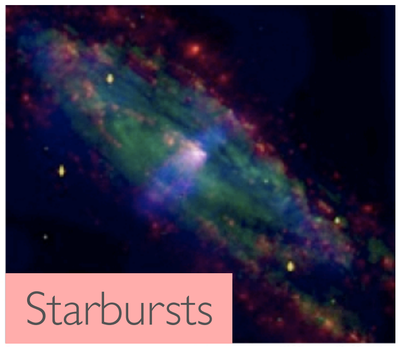
$$E_{max} = \frac{3}{\beta} \beta c R B Z e$$

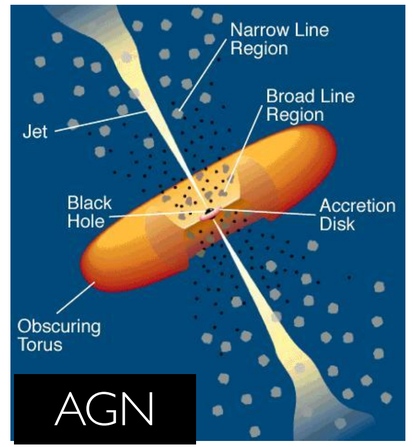
Full treatment must account for radiative losses!

$t_{acc} < t_{cool}$

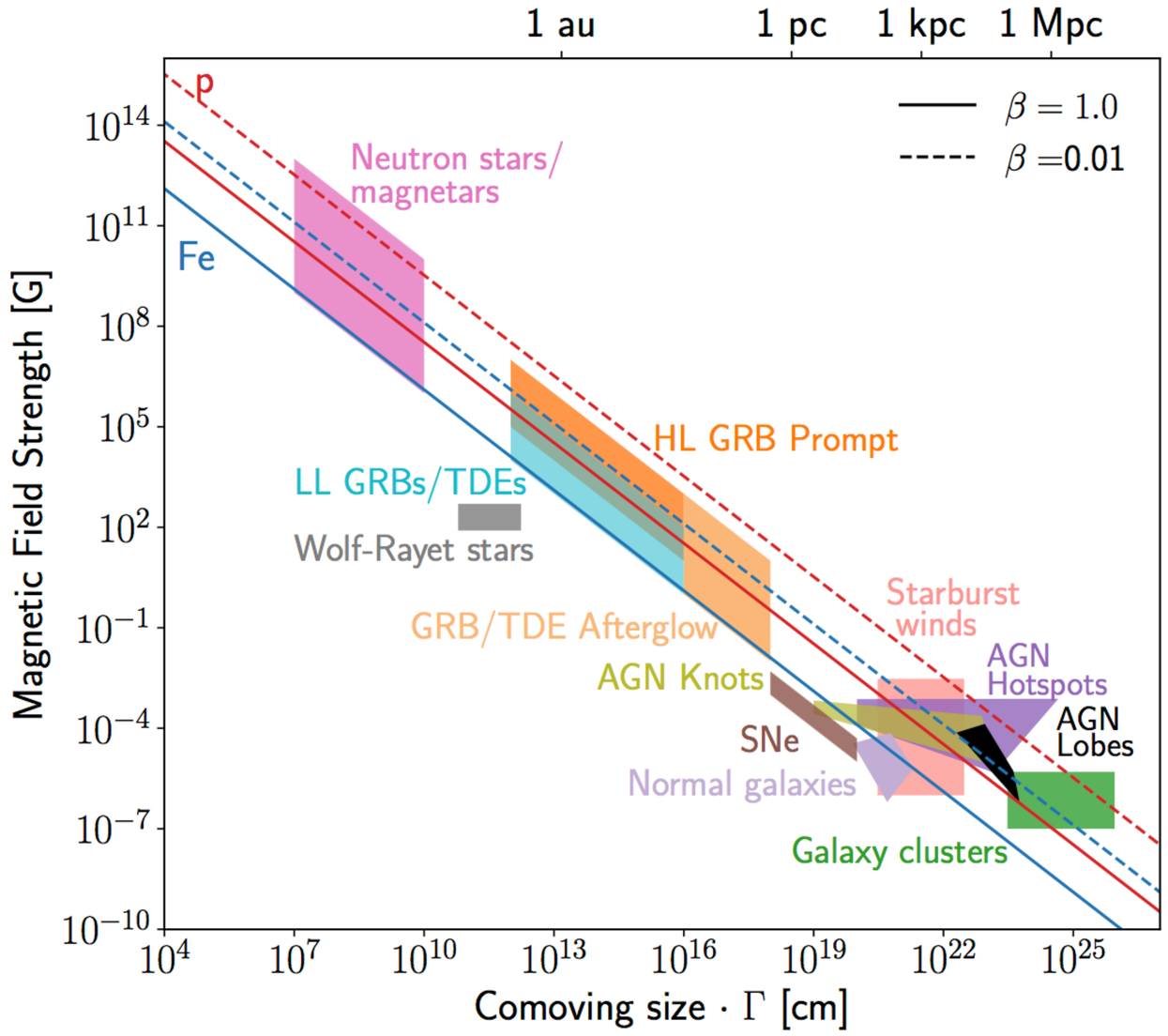
$t_{cool} = (t_{Synchrotron} + t_{escape} + t_{interaction})^{-1}$

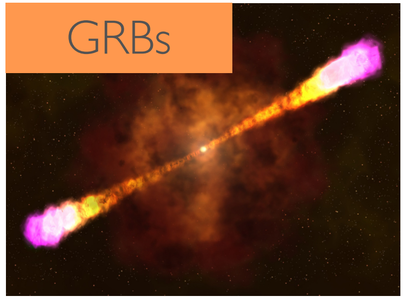


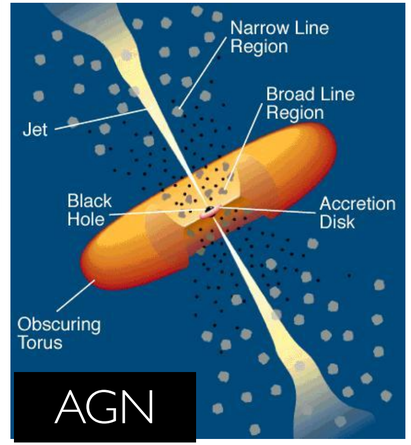




Hillas criterion for 10^{20} eV CRs







Take home messages

- Two known astrophysical neutrino sources: Sun & SN 1987A
- IceCube has revealed an extra-Galactic (cosmic) neutrino flux but not the sources yet
- Many different source classes can possibly accelerate neutrinos in the IceCube energy range
- Fewer if we require a connection to ultra-high energy cosmic rays