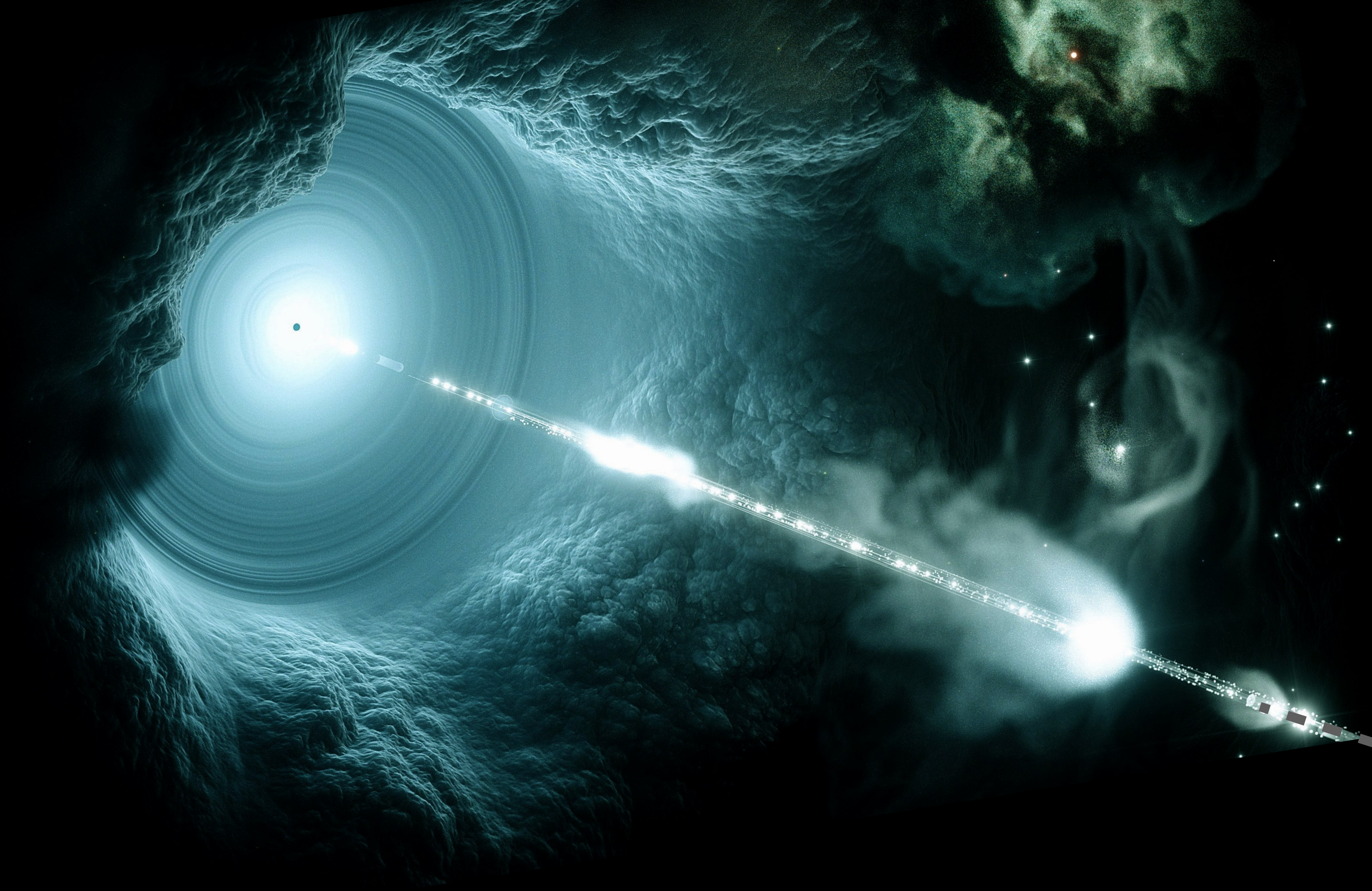
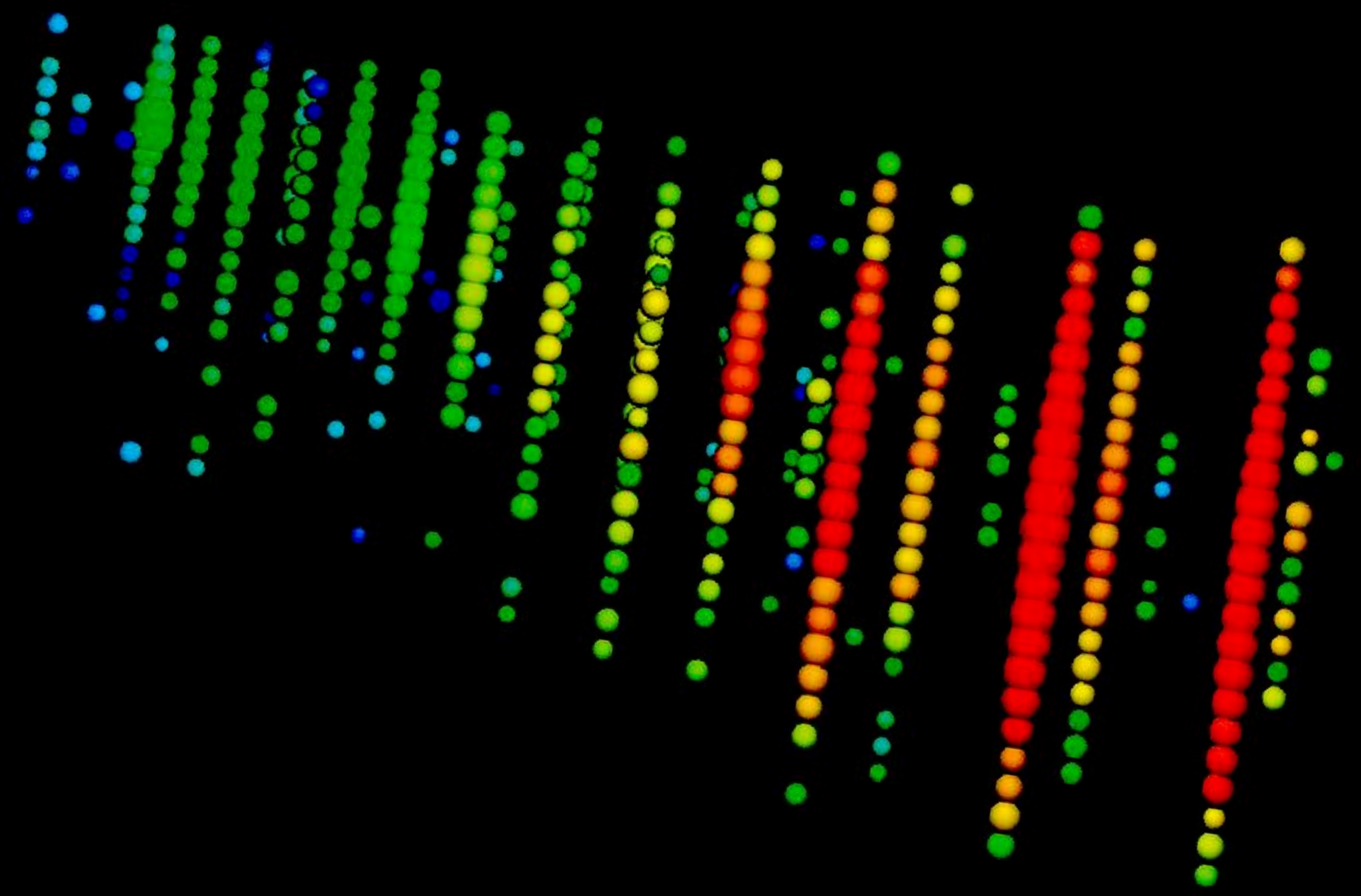




Neutrino Astronomy & Astrophysics

Summer school on neutrinos

Here, there & Everywhere

NBI, Copenhagen

Foteini Oikonomou

July 11th-15th

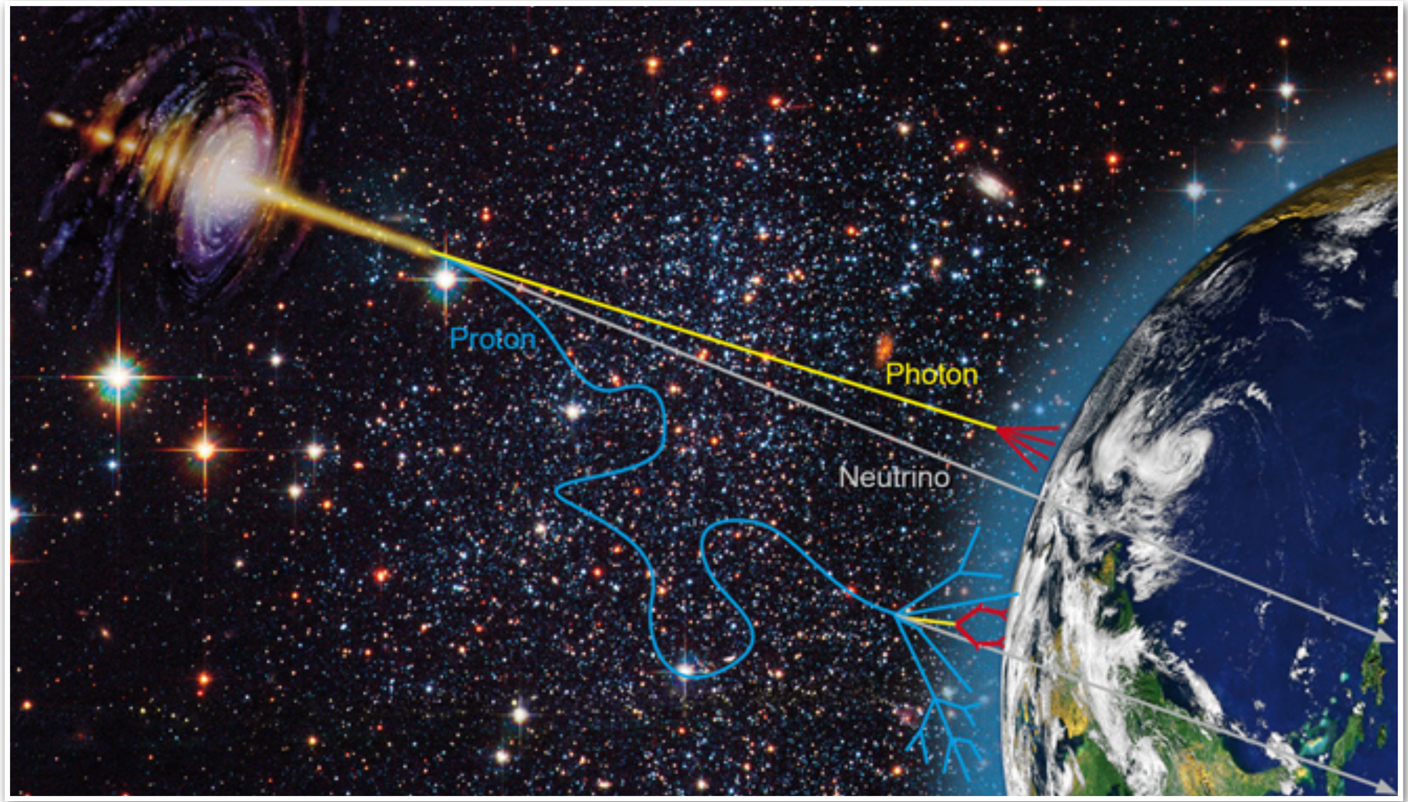
NTNU

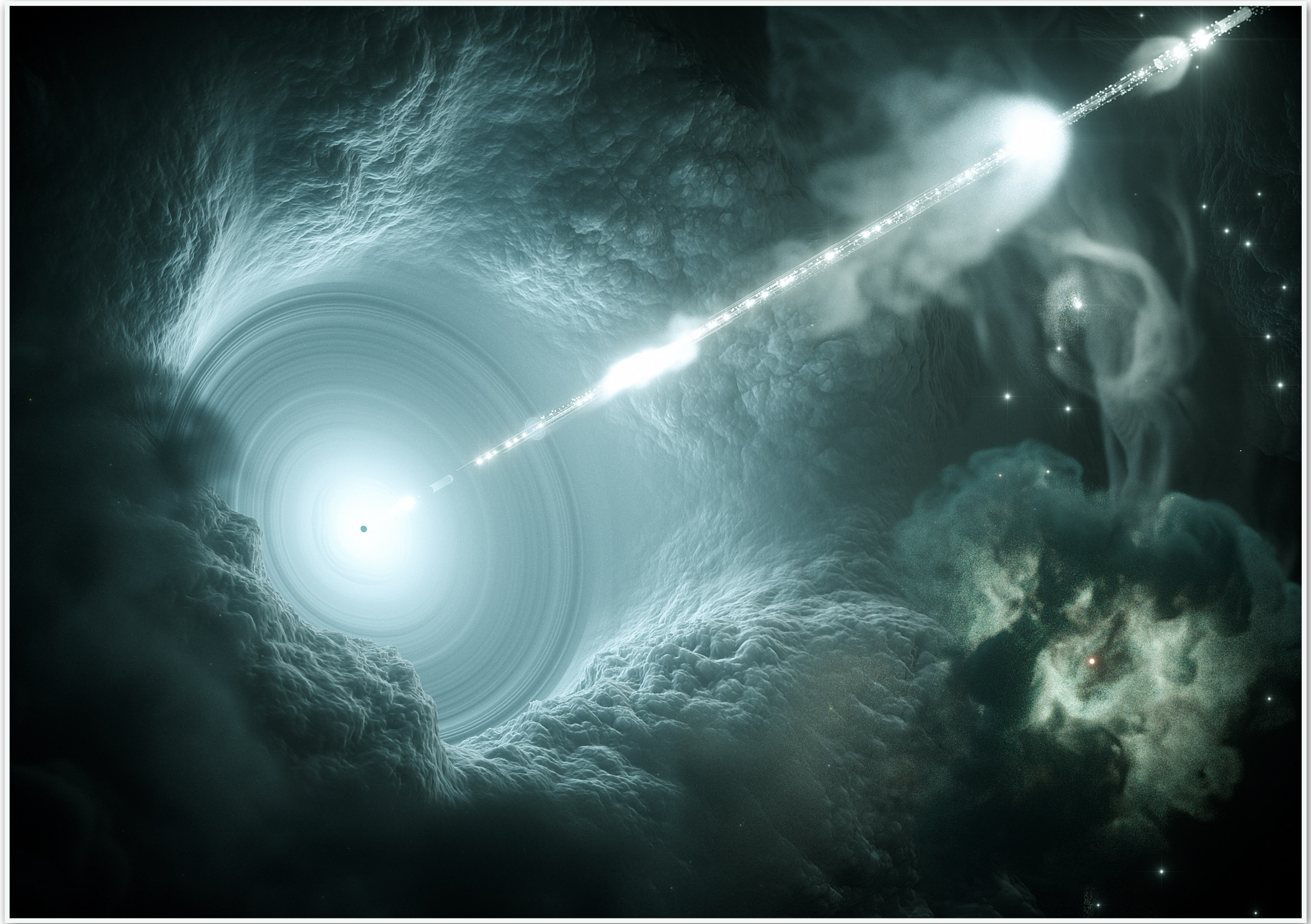
Norwegian University of
Science and Technology

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

- Overview of astrophysical neutrino sources, experimental facts and basic theoretical concepts

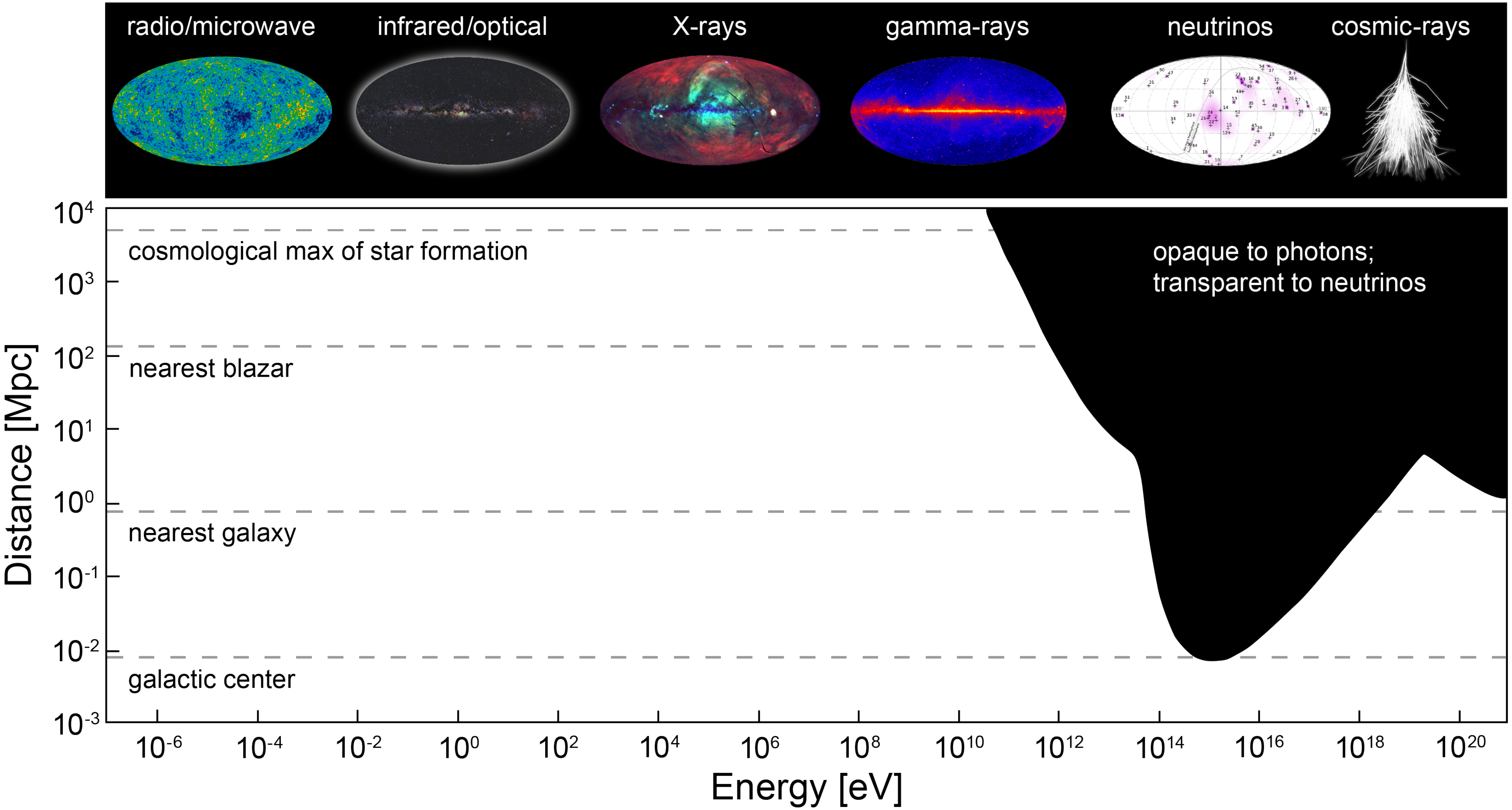
- Requirements for astrophysical accelerators of high-energy cosmic rays/ high-energy neutrinos (generic source properties)

- Overview of candidate high-energy astrophysical sources (Active Galactic Nuclei/Starburst Galaxies/Gamma ray bursts/Pulsars/Tidal Disruption Events). Constraints and prospects for source identification.

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

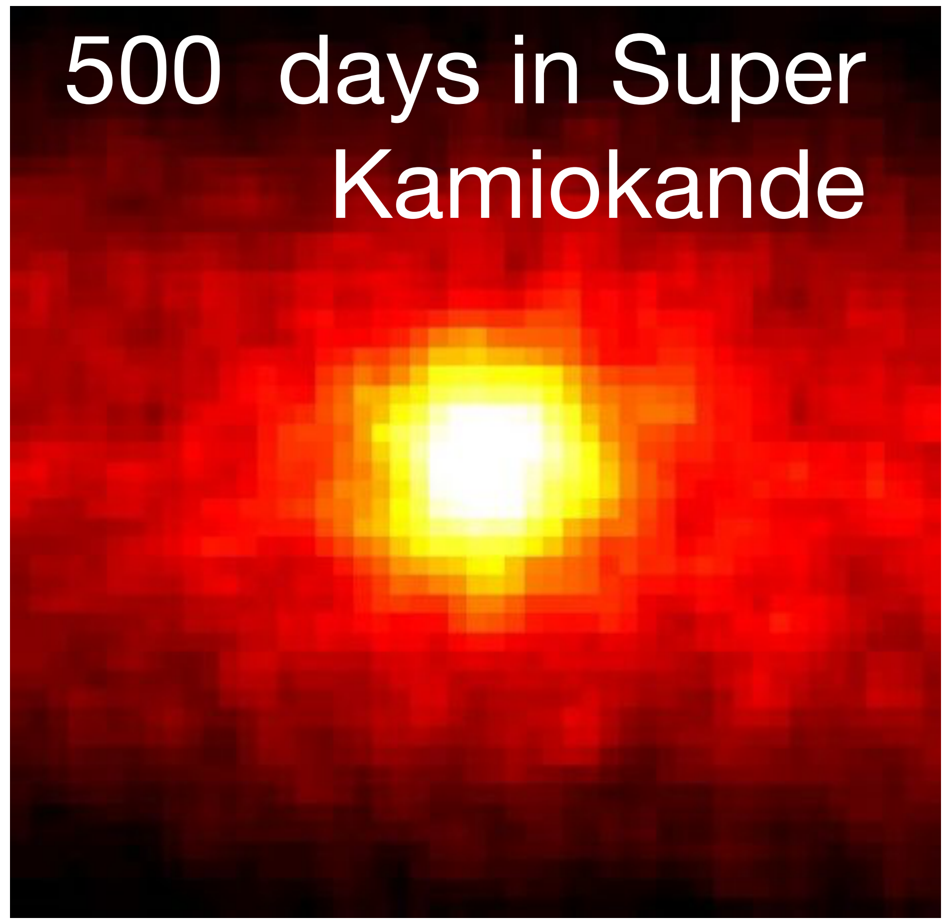
High-energy messengers of the non-thermal Universe

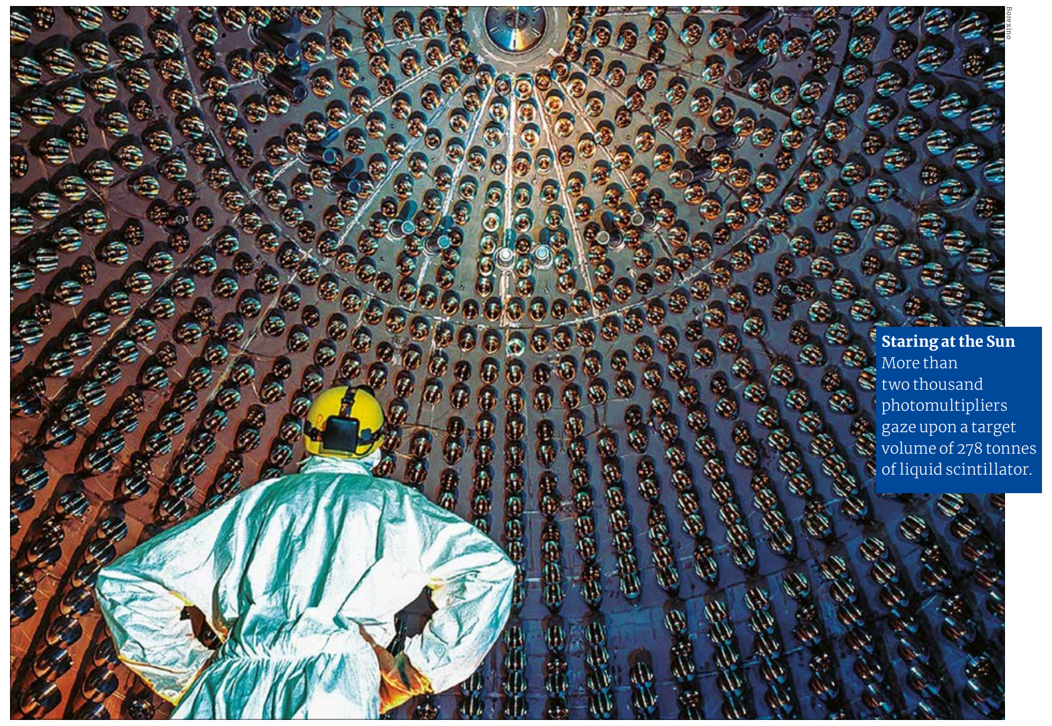


Sources of astrophysical neutrinos

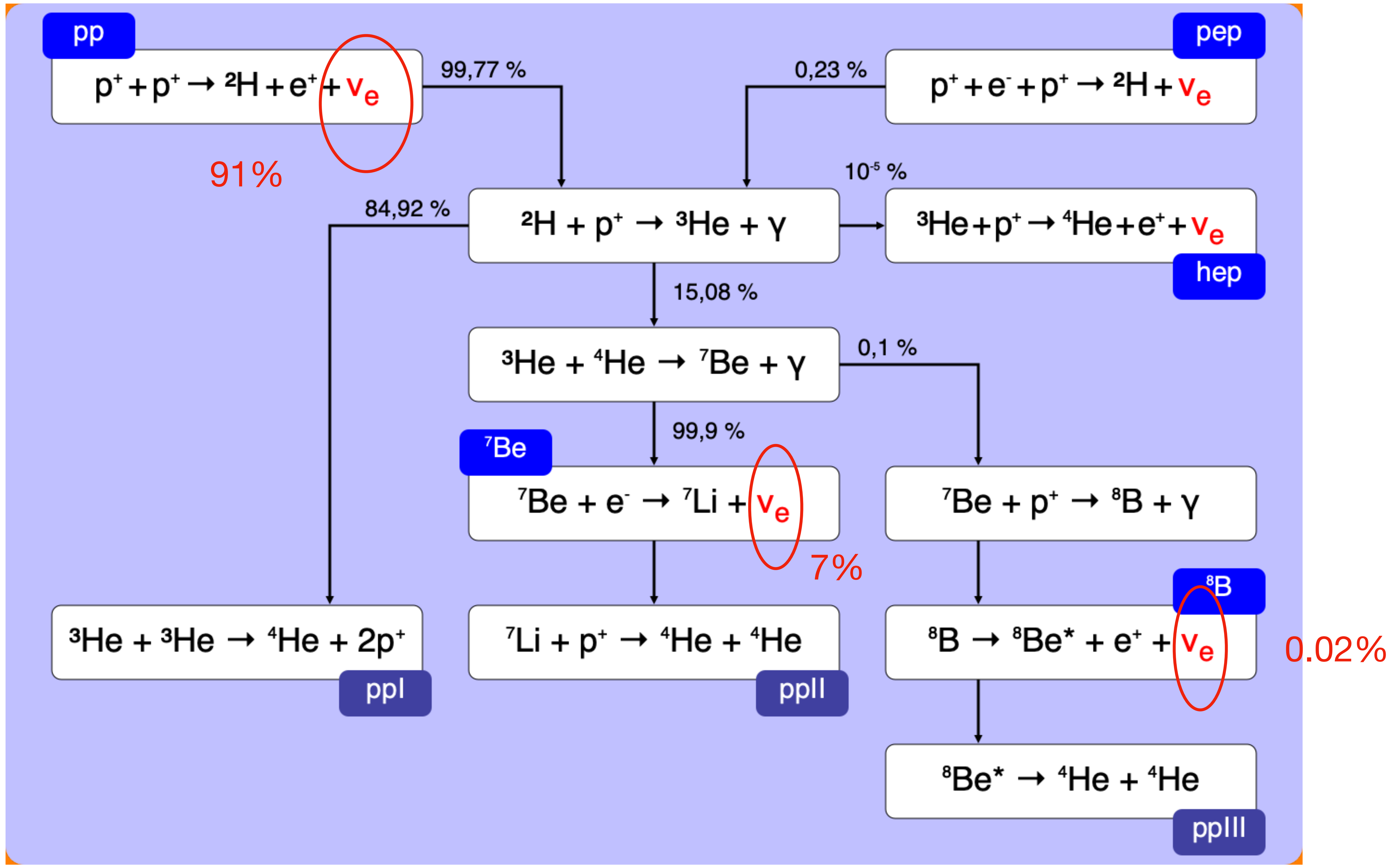
The Sun

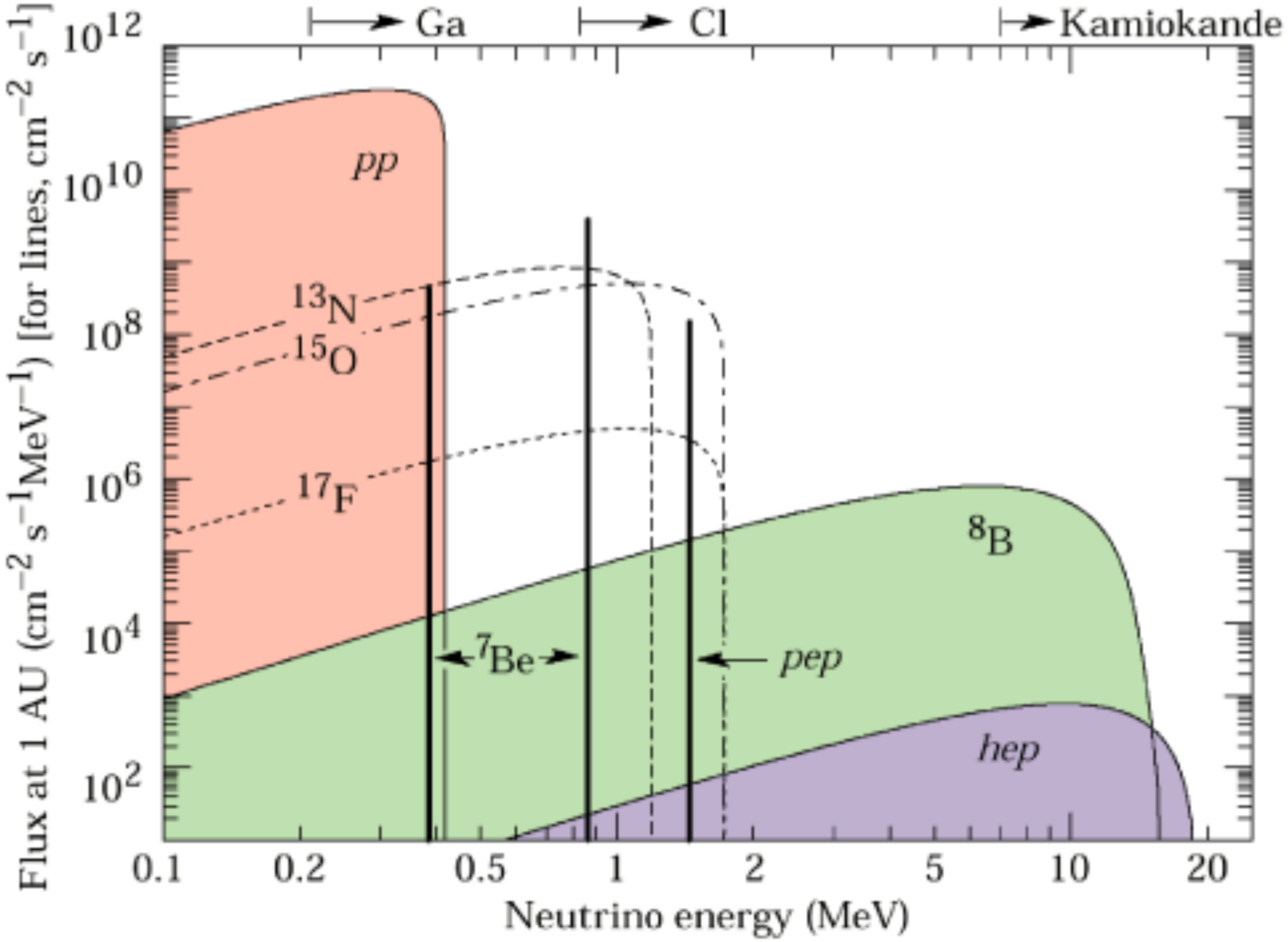
The first astrophysical neutrino source





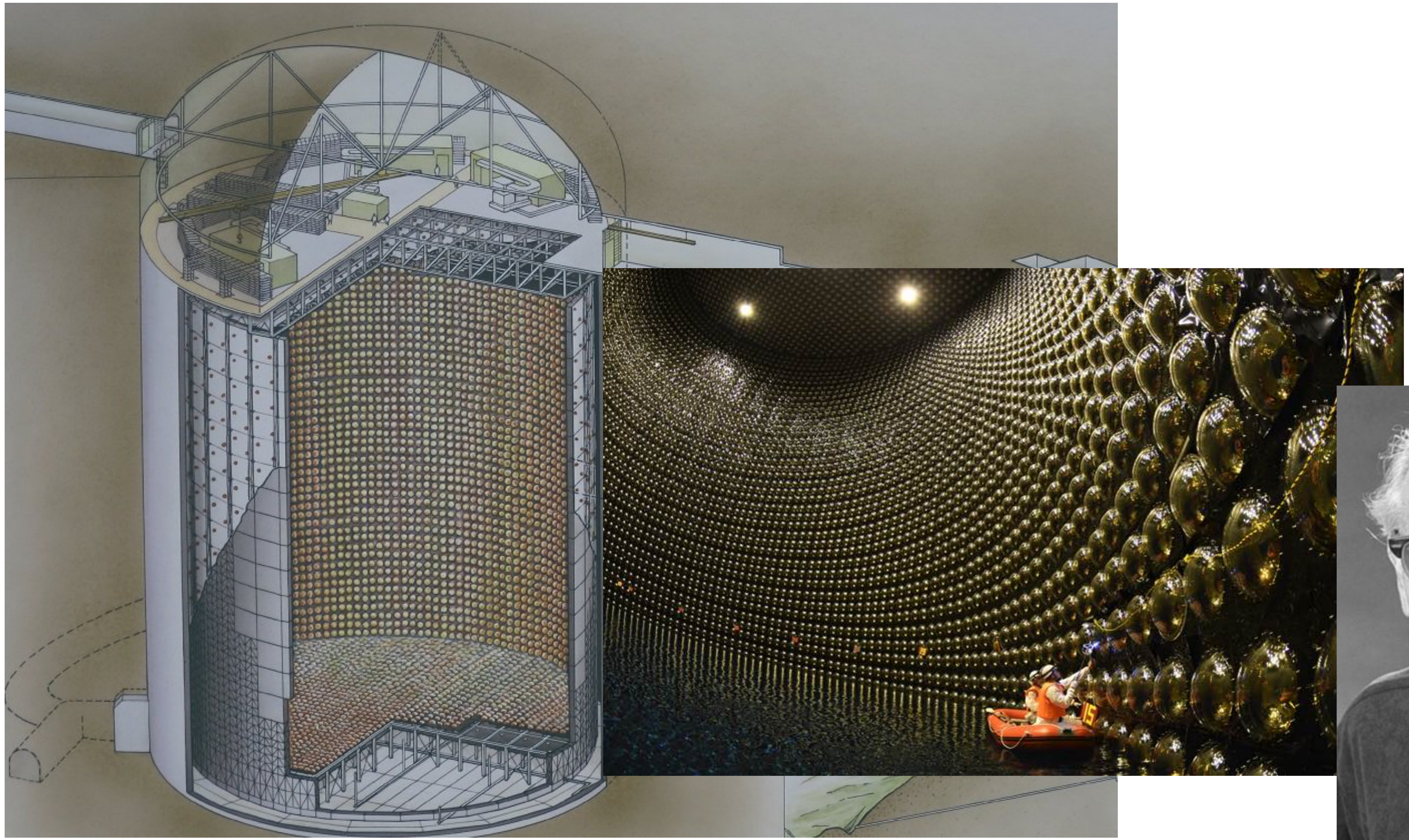
HOW THE SUN AND STARS SHINE

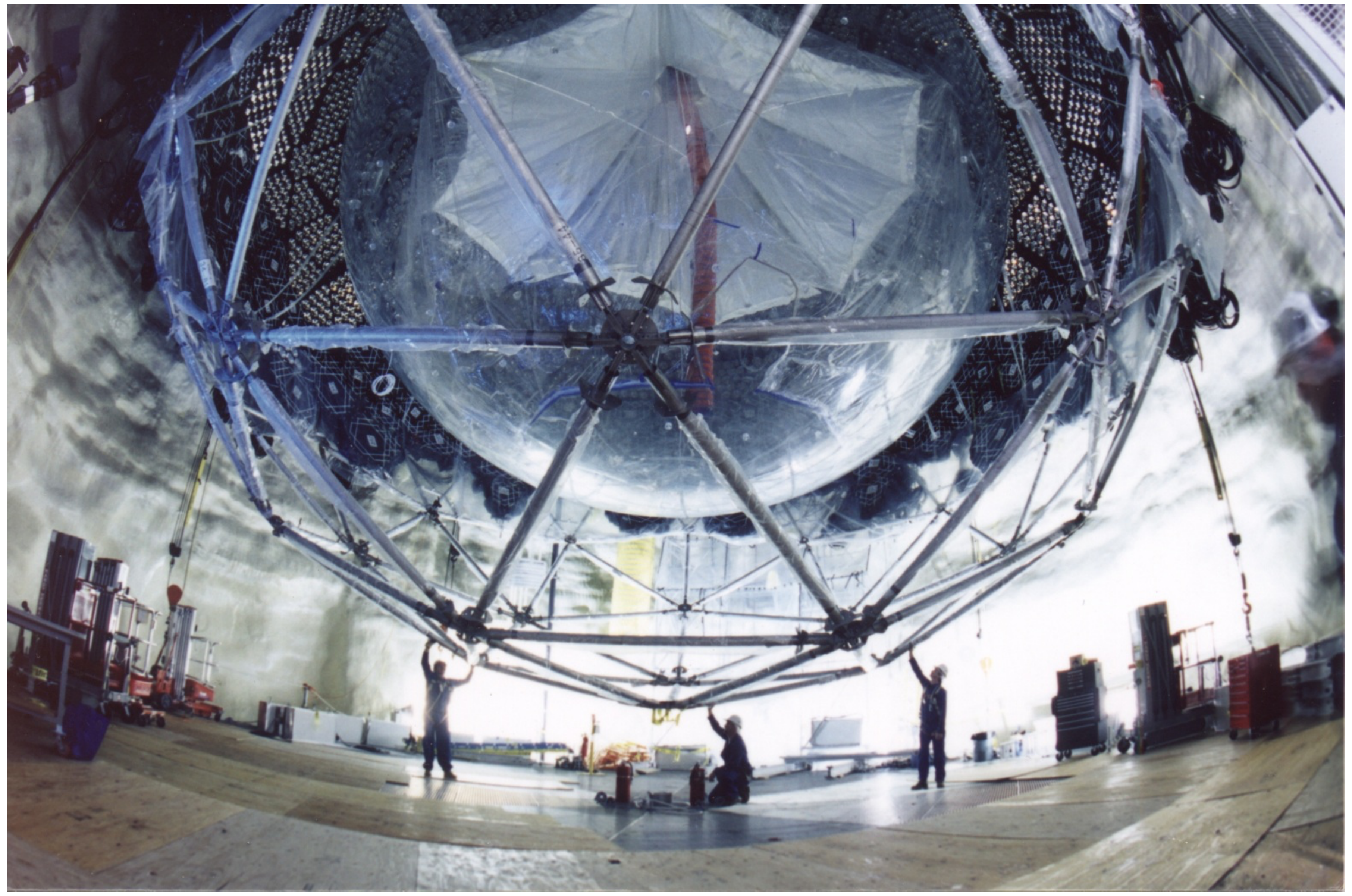


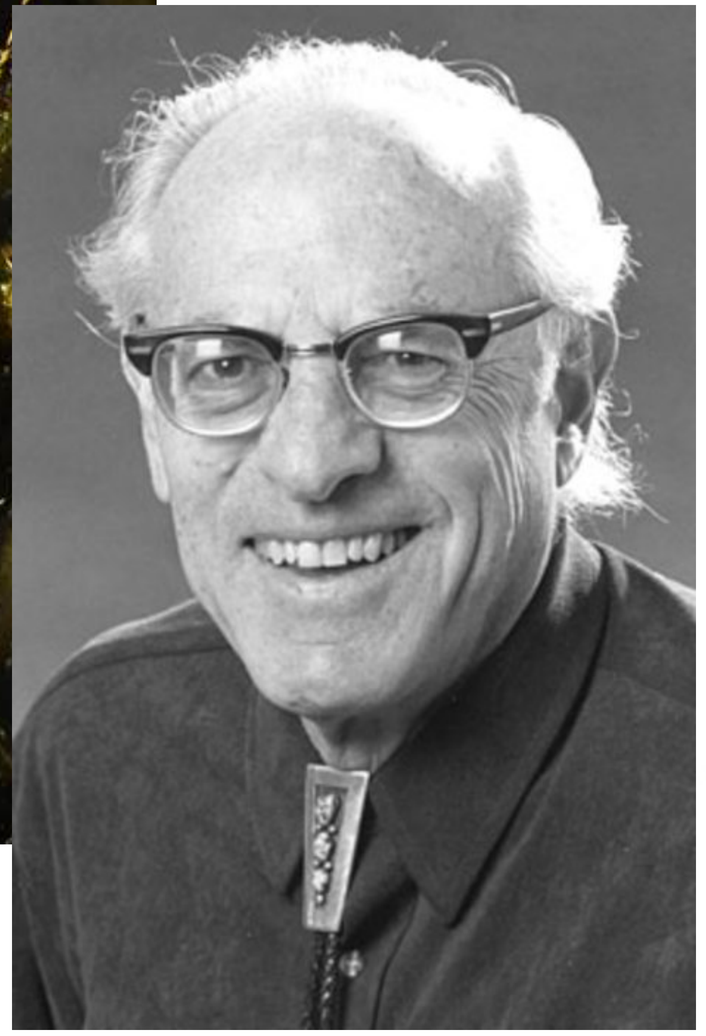


see results of Borexino Coll 2020 Nature

Solar Neutrino Oscillations

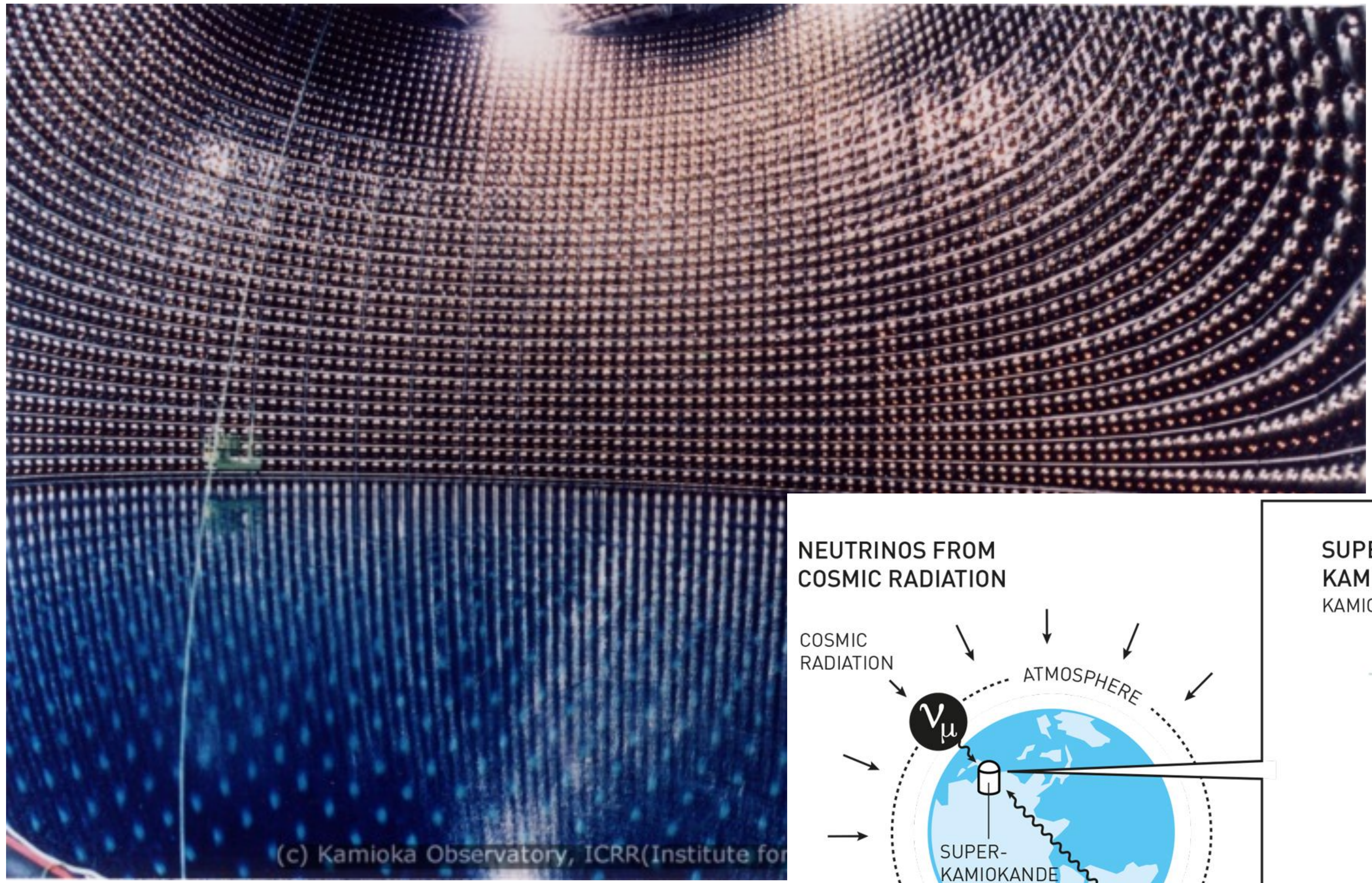


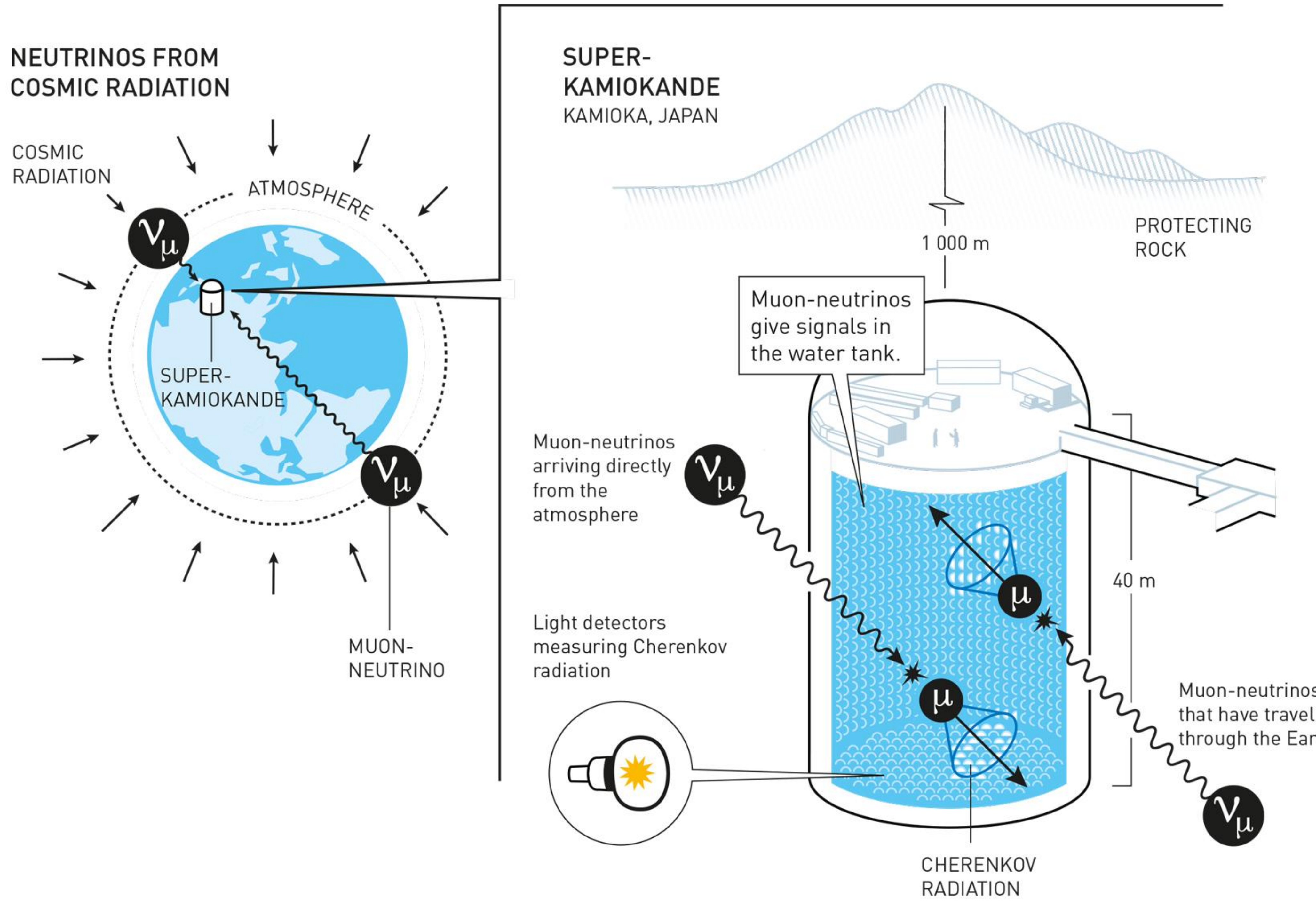


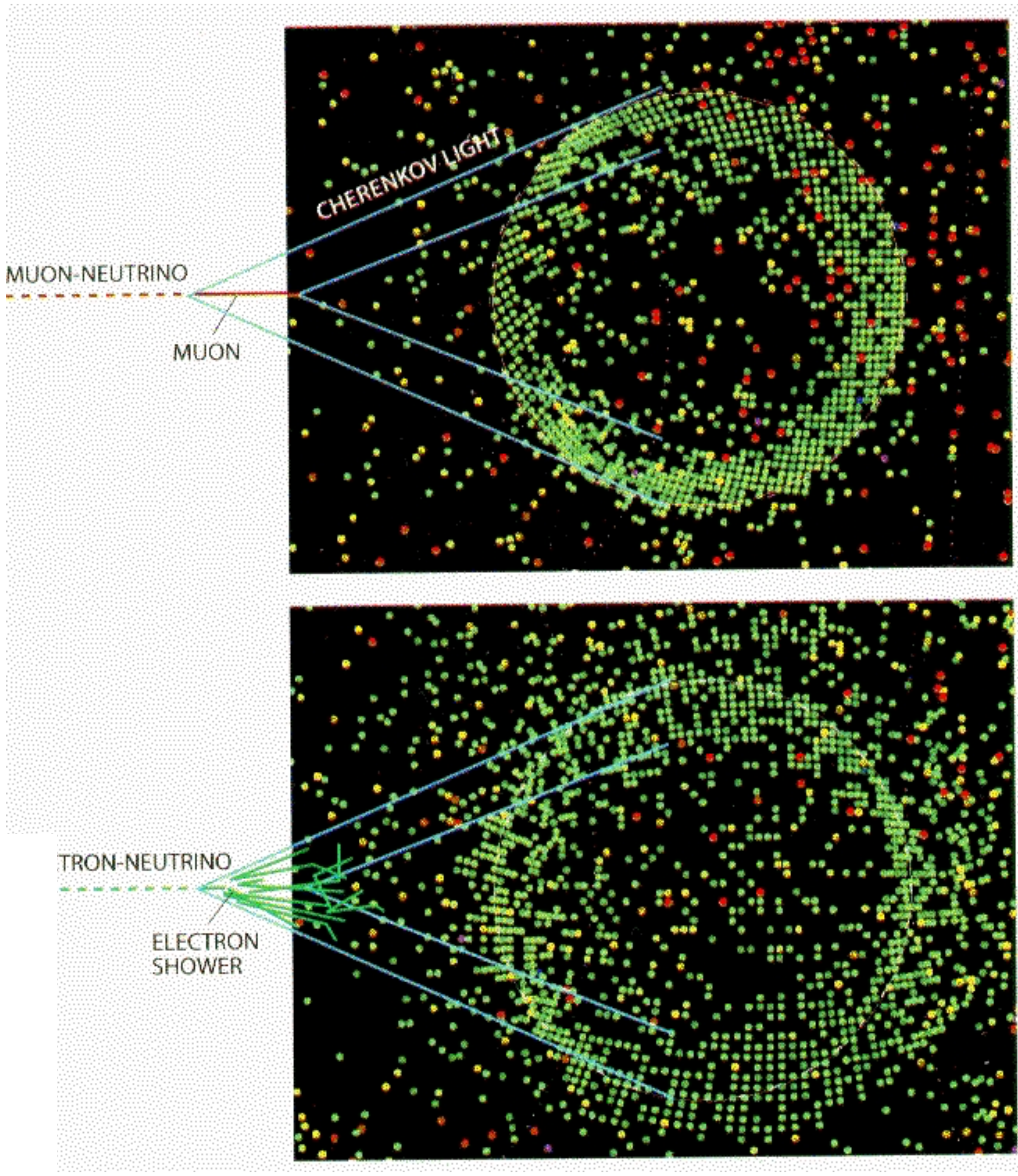


1995 Reines for the detection of the neutrino

(Super)-Kamiokande







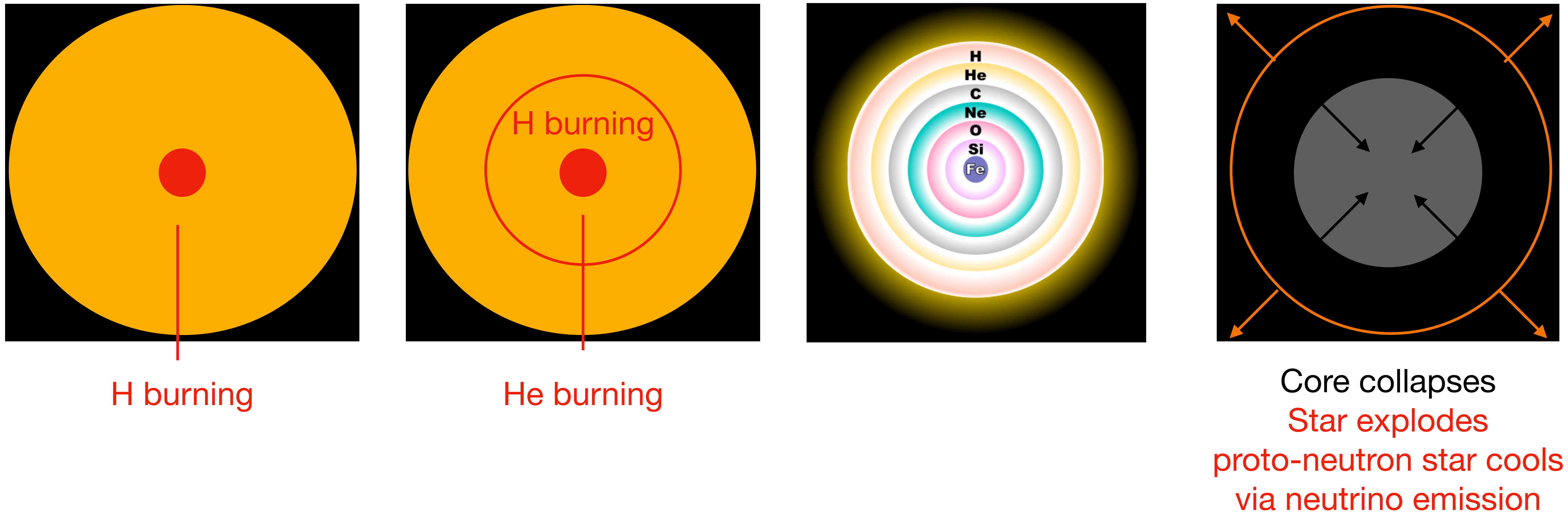
50,000 ton water Cherenkov detector
2700 meters underground in Kamioka,
Mount Ikeno, Japan

as well as Sudbury Neutrino Observator
Borexino etc.

Supernovae

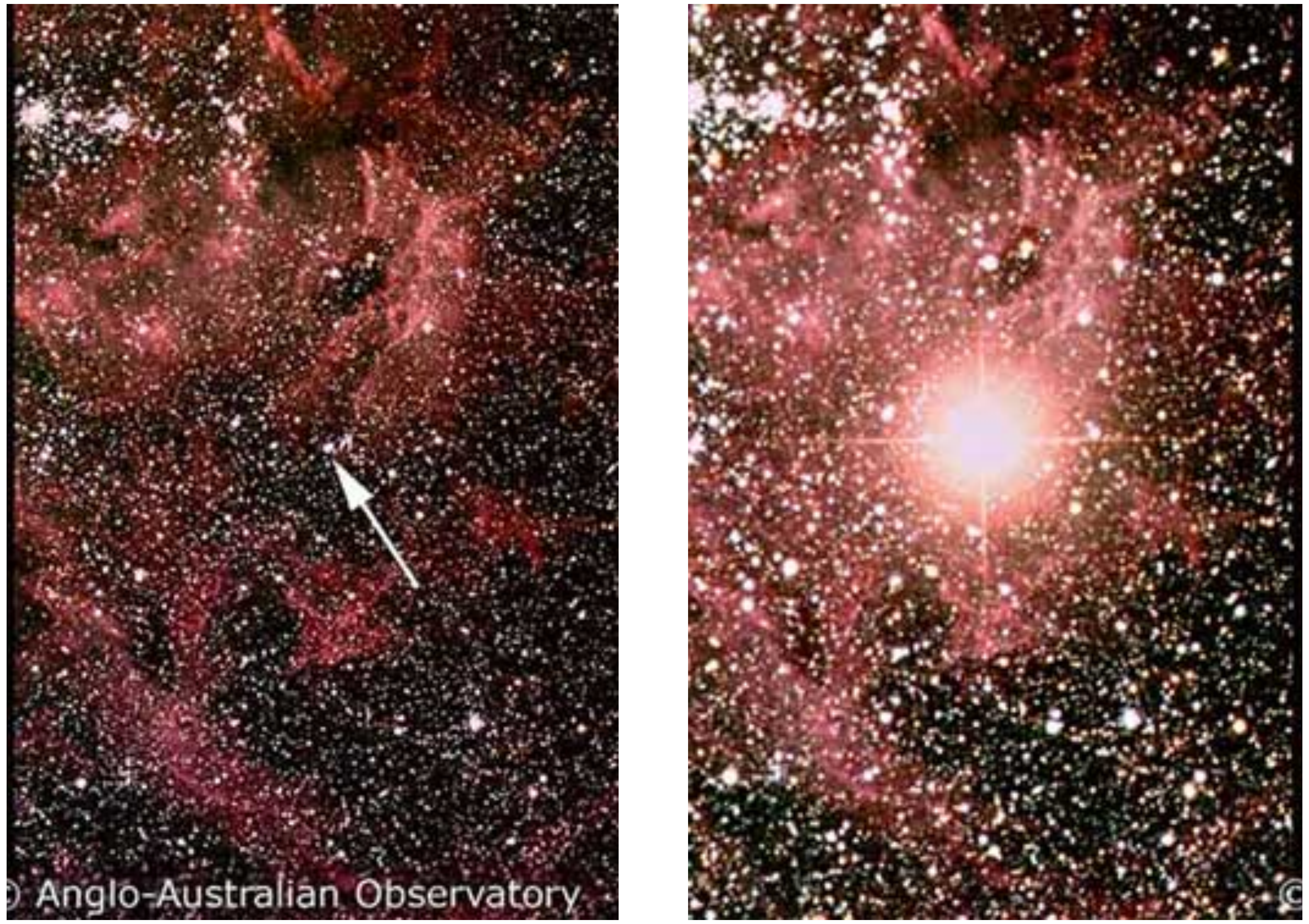
Supernova in 1994D in NGC 4526

Massive star



Supernova1987A

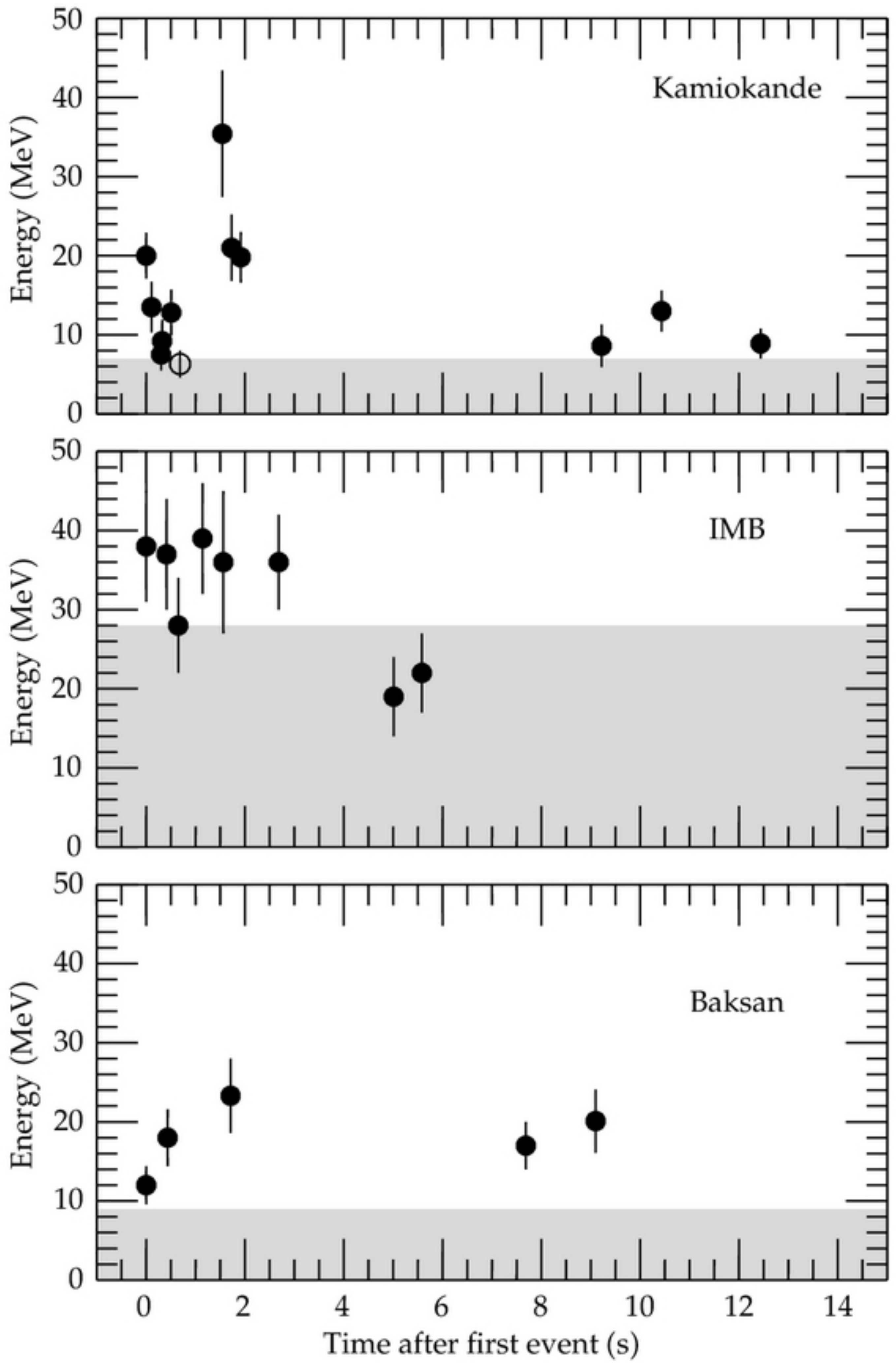
The second astrophysical neutrino source



51.4 kpc away in the Small Magellanic Cloud

Nobel prize 2002

Annual Reviews 1999

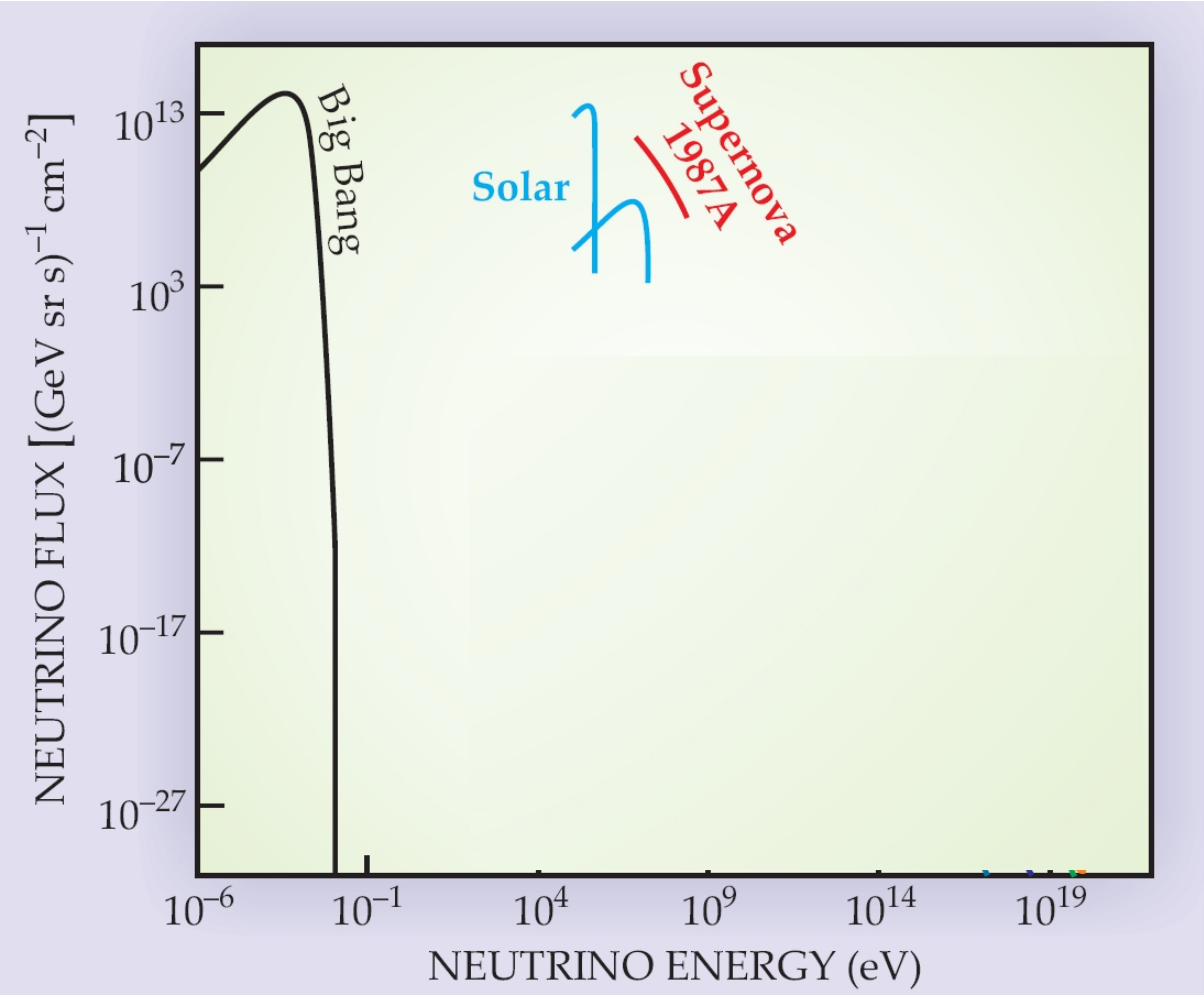


Kamiokande-II (Japan)
Water Cherenkov detector

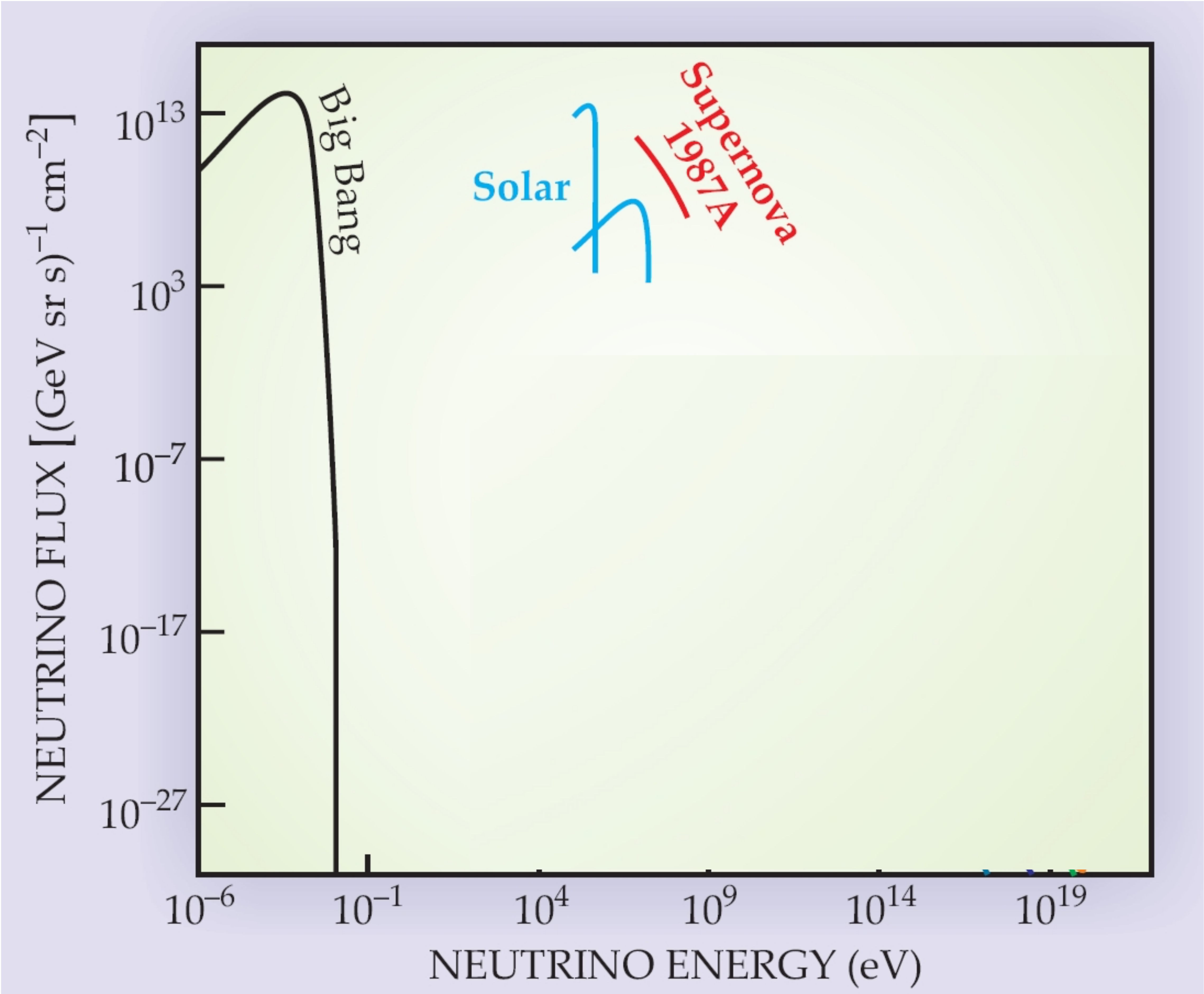
Irvine-Michigan-Brookhaven
Water Cherenkov detector

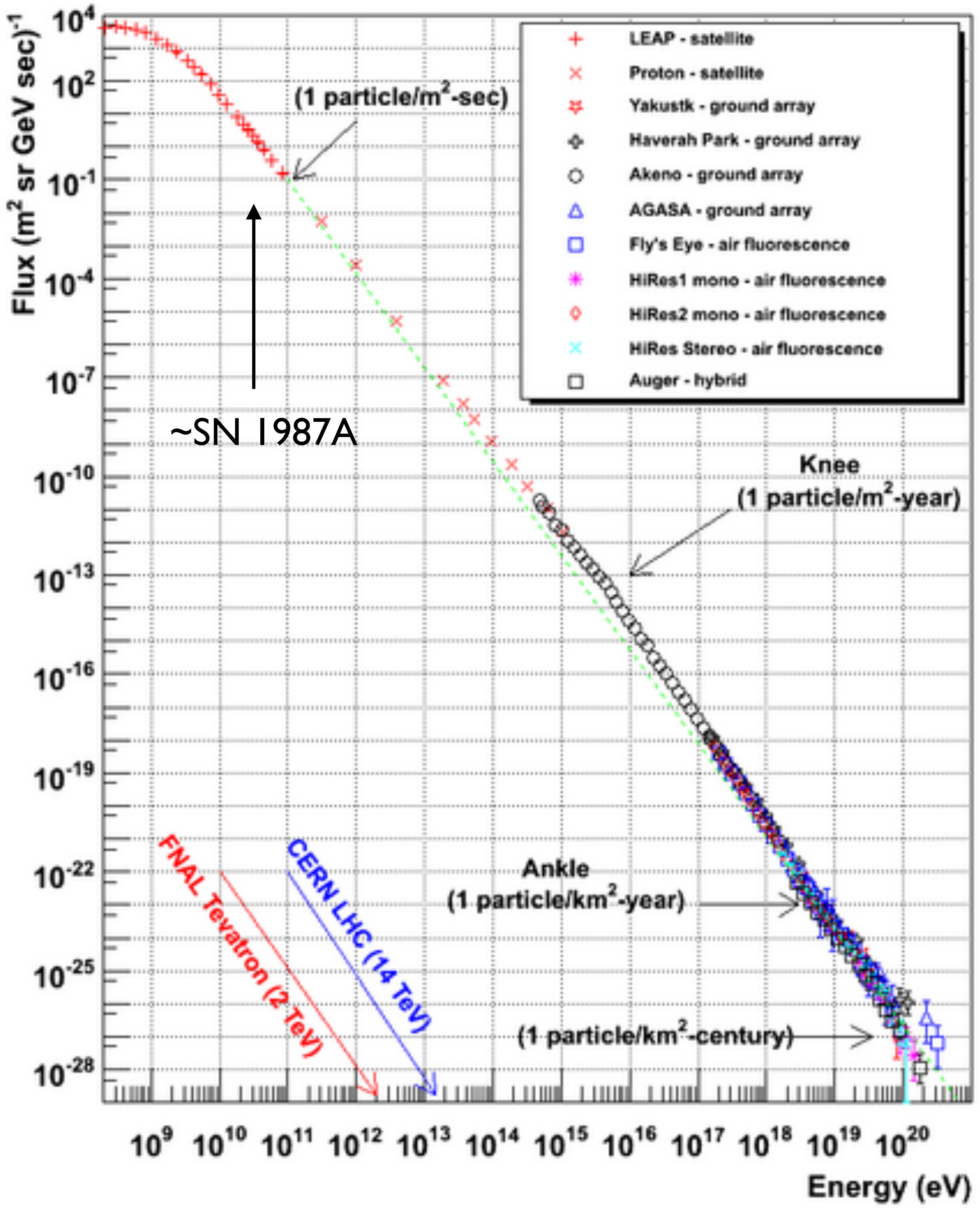
Baksan Scintillator Telescope

What happens at higher energies?

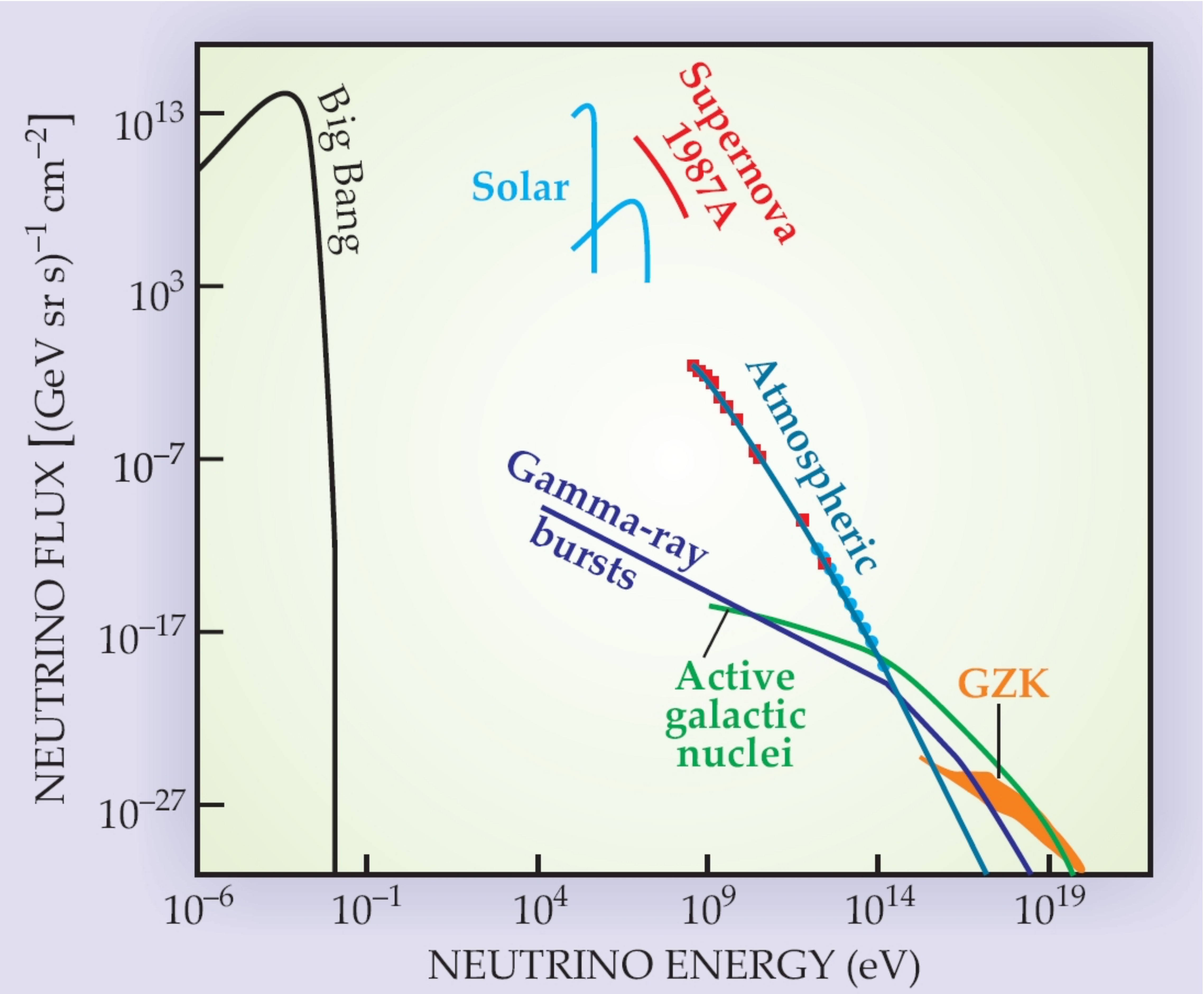


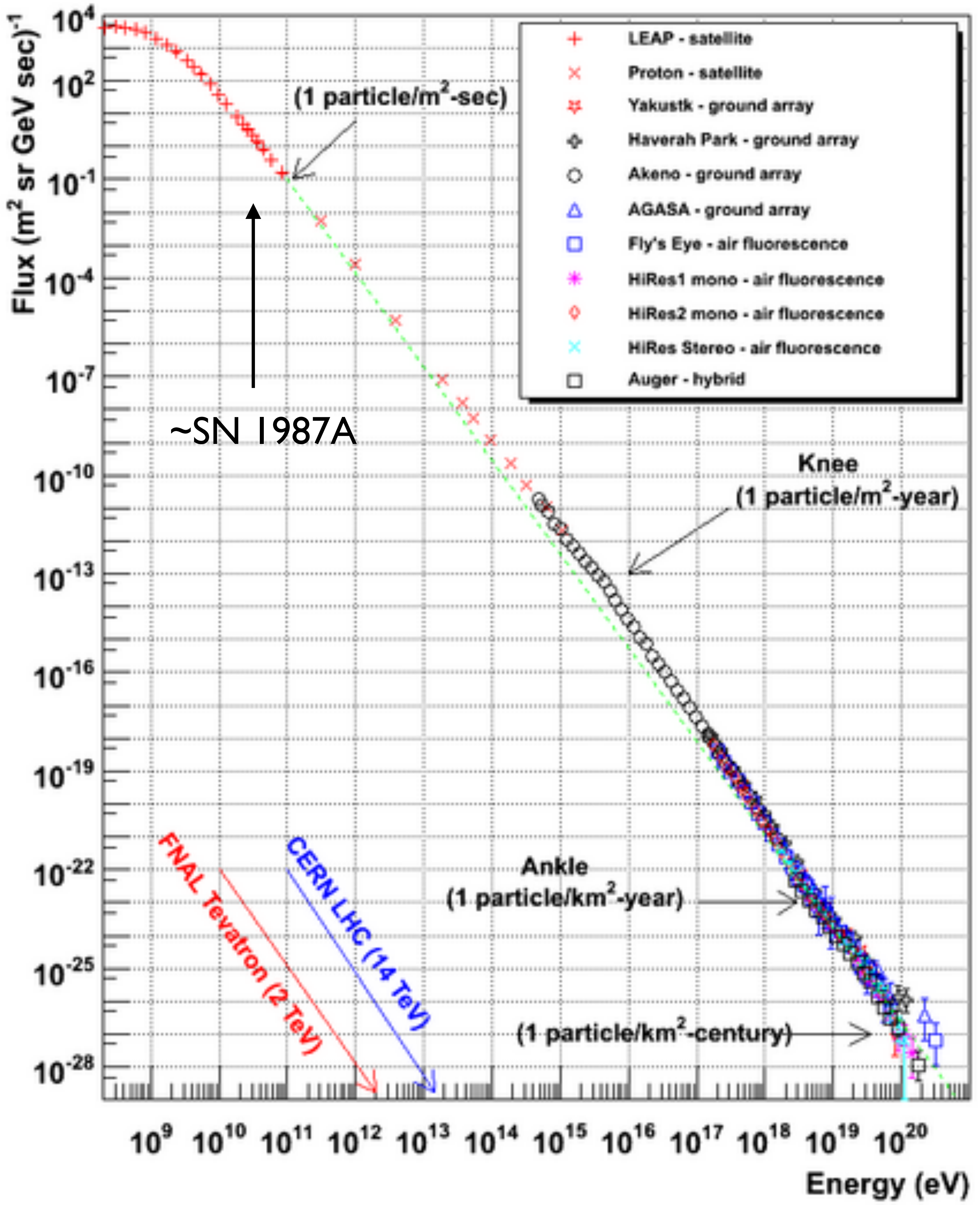
What happens at higher energies?



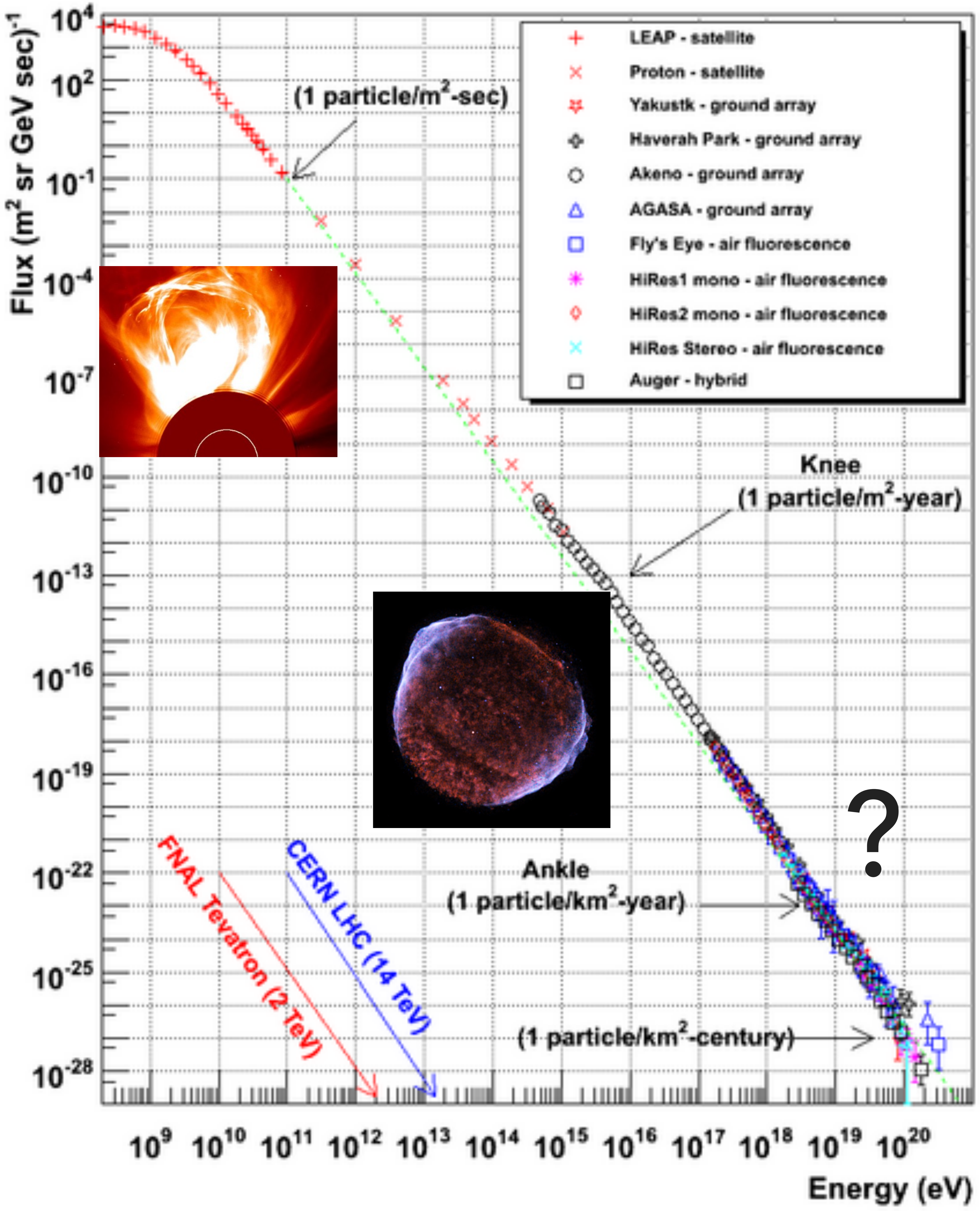


What happens at higher energies?



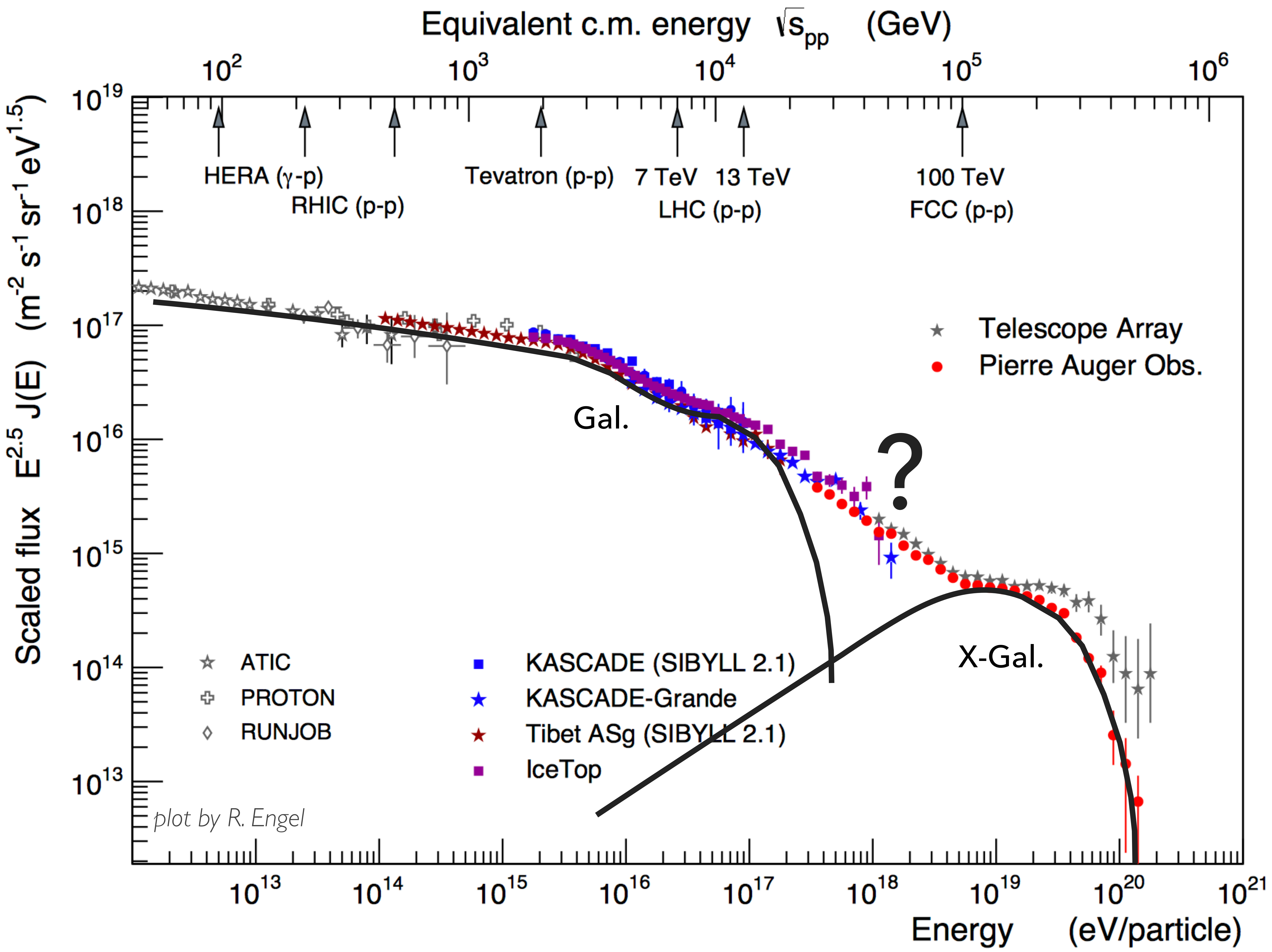


Cosmic rays



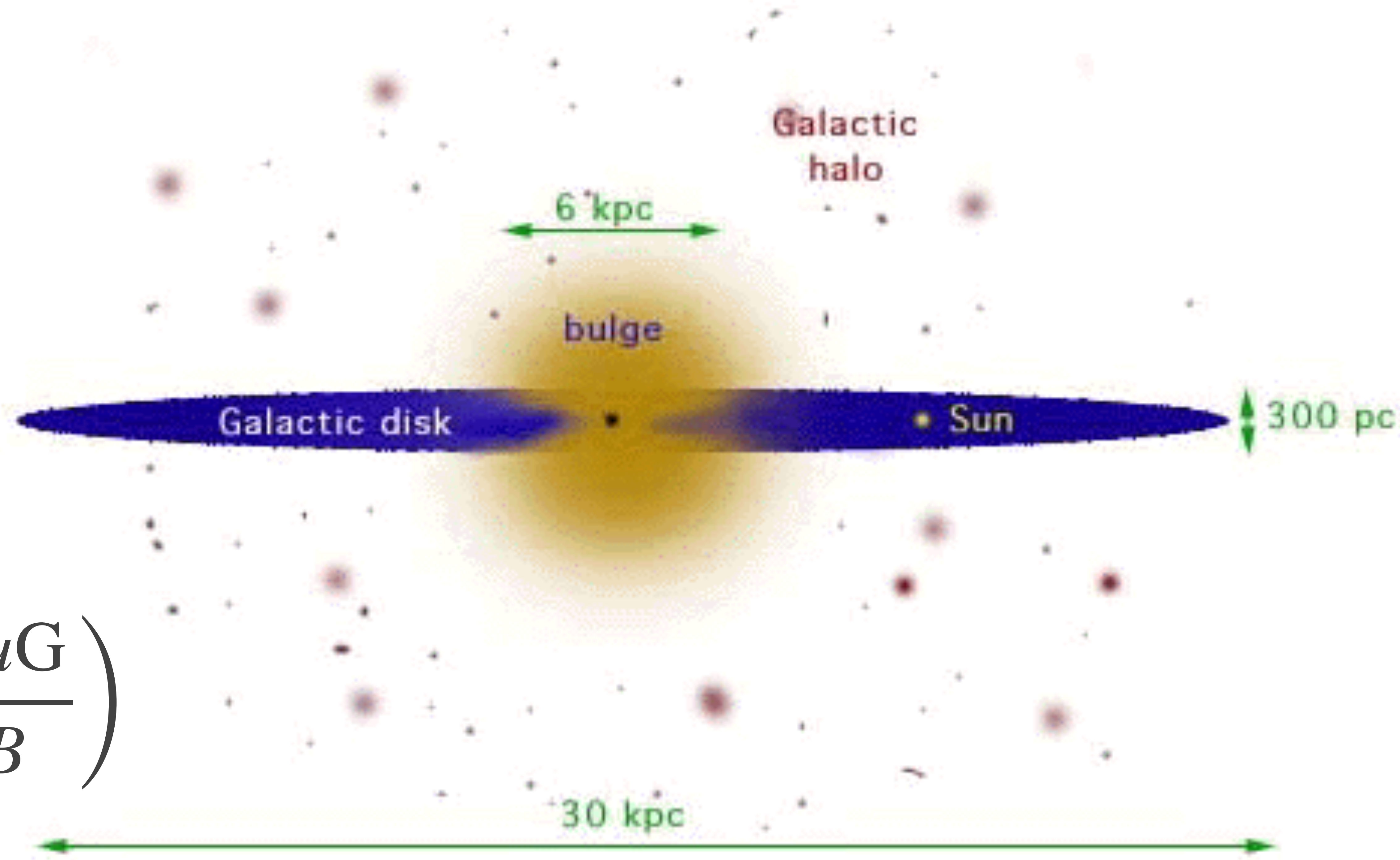
plot originally by M. Swordy

Highest-energy cosmic rays



Extragalactic origin

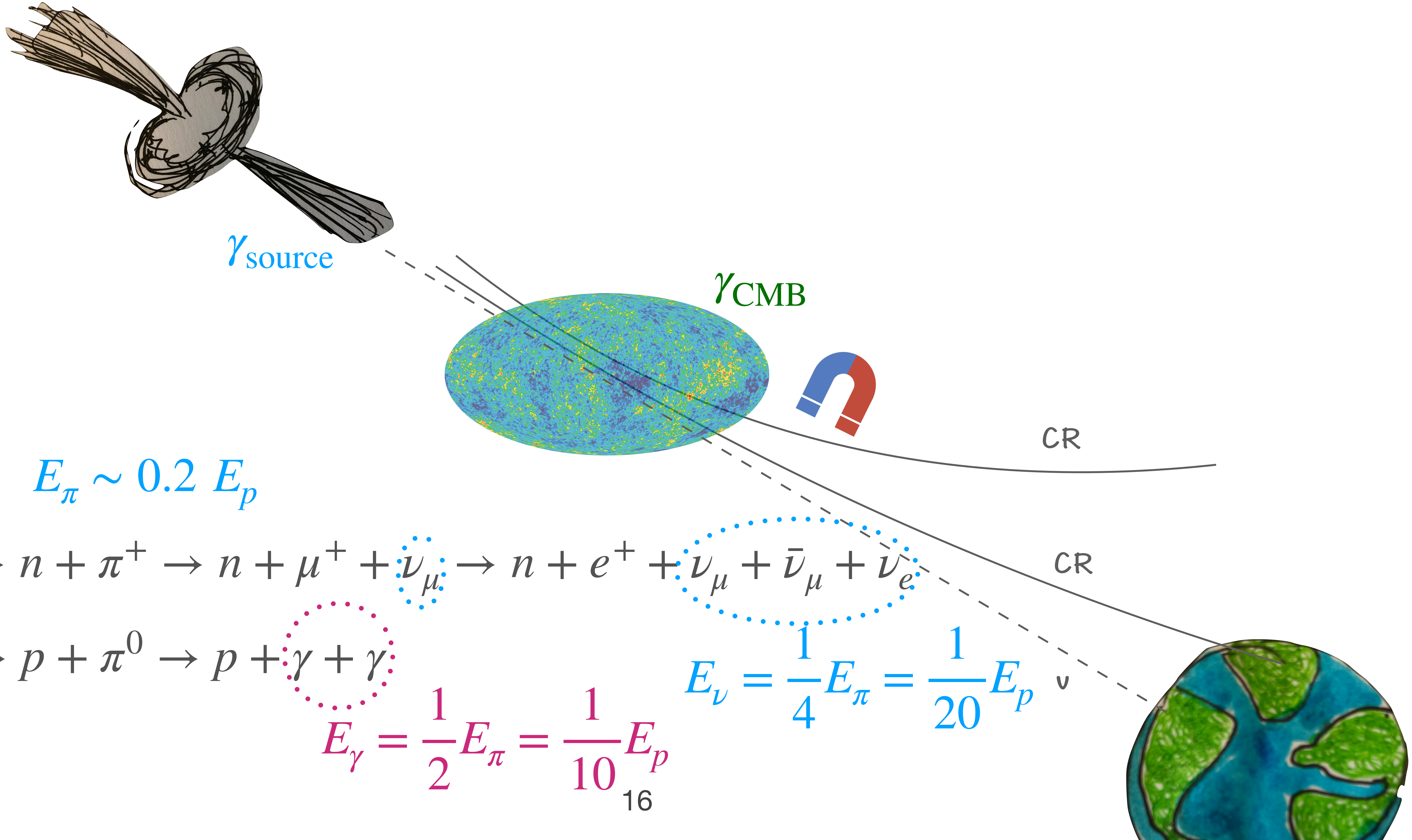
- Size of the Milky Way ~ kpc [10^8 AU]
- Galactic B-field ~ 3 μG
- Larmor radius of cosmic rays



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

[+ Observational evidence: No anisotropy from the Galaxy]

Secondary messengers



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

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

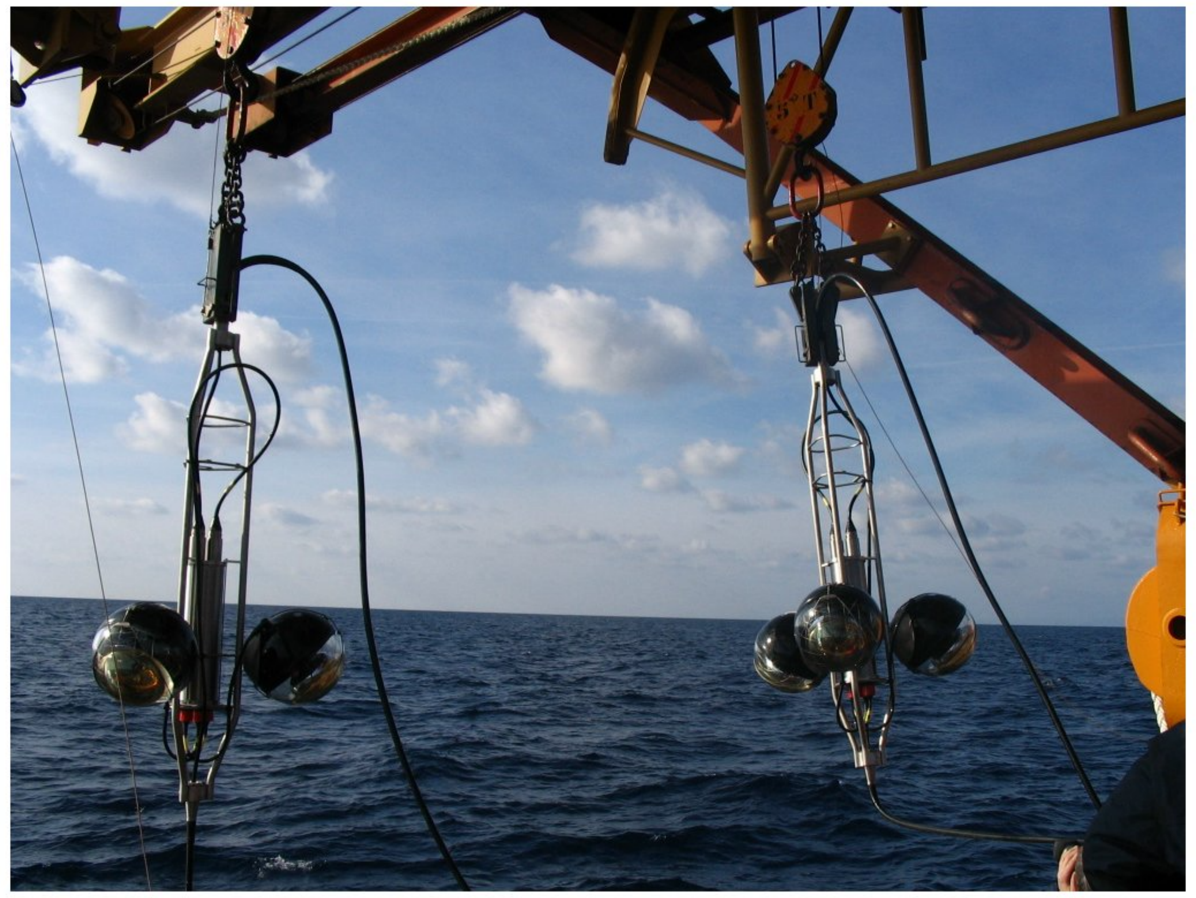
$$p + \gamma \to p + \pi^0 \to p + \gamma + \gamma$$

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

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

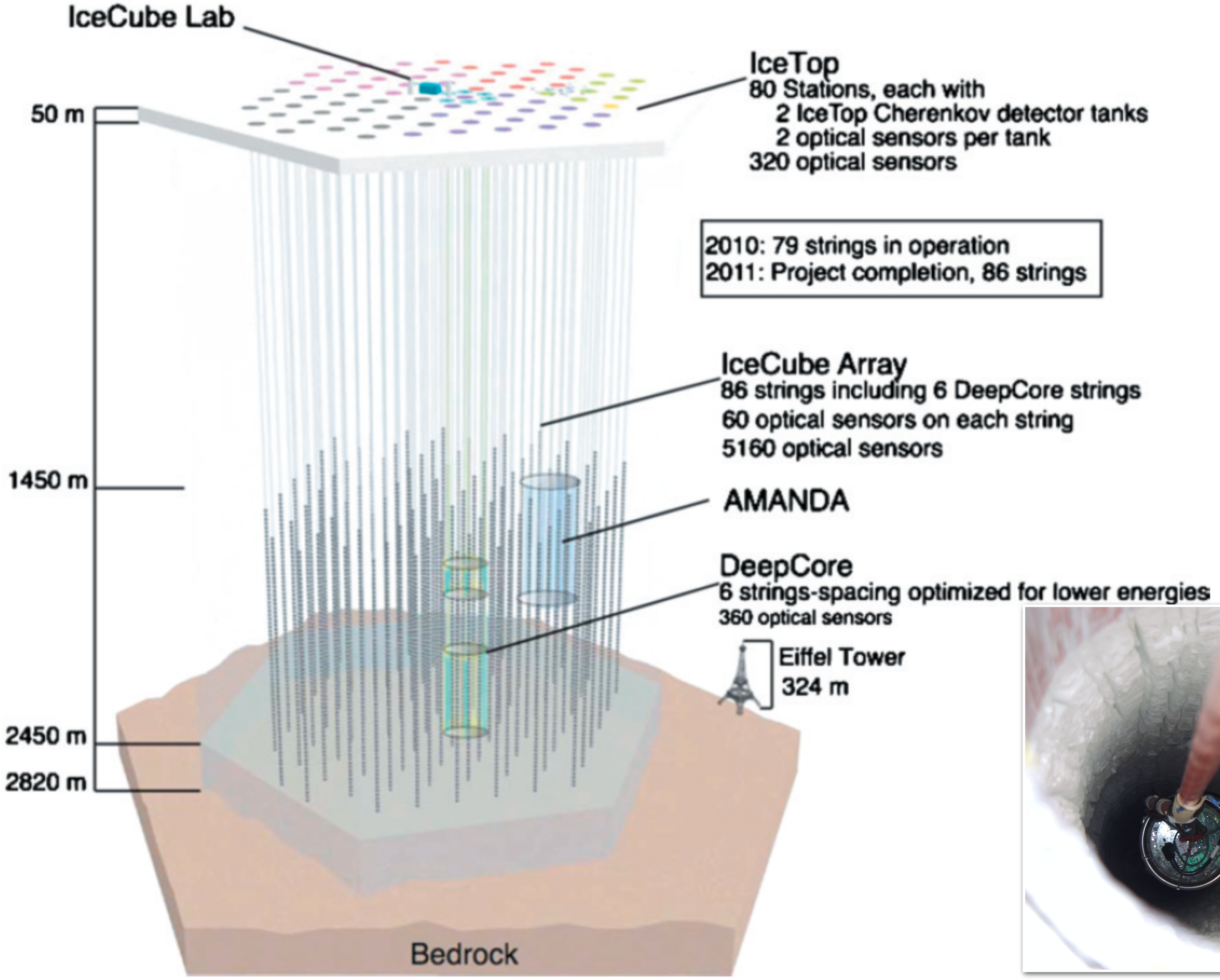
High-energy neutrino detection

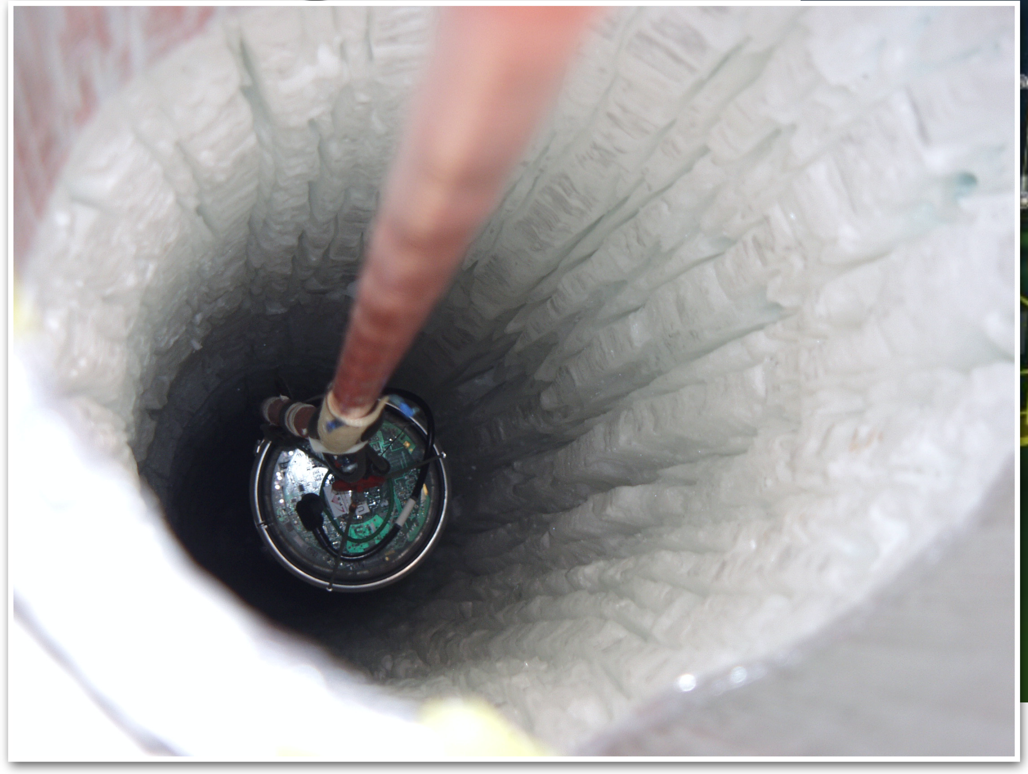
ANTARES (2.5 km under the Mediterranean Sea)

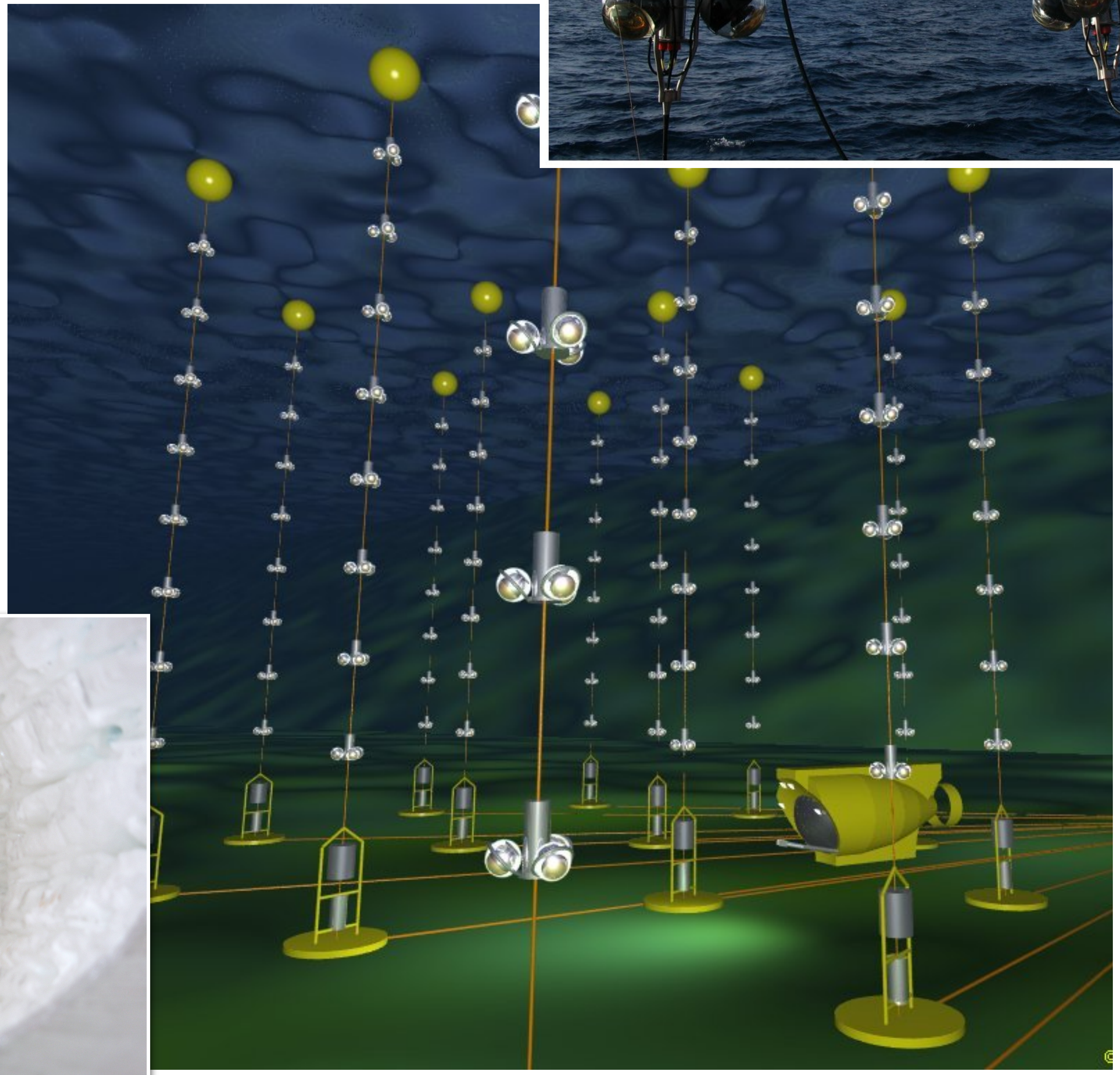


Huge volumes needed: water/in-ice Cherenkov detection

IceCube - South Pole

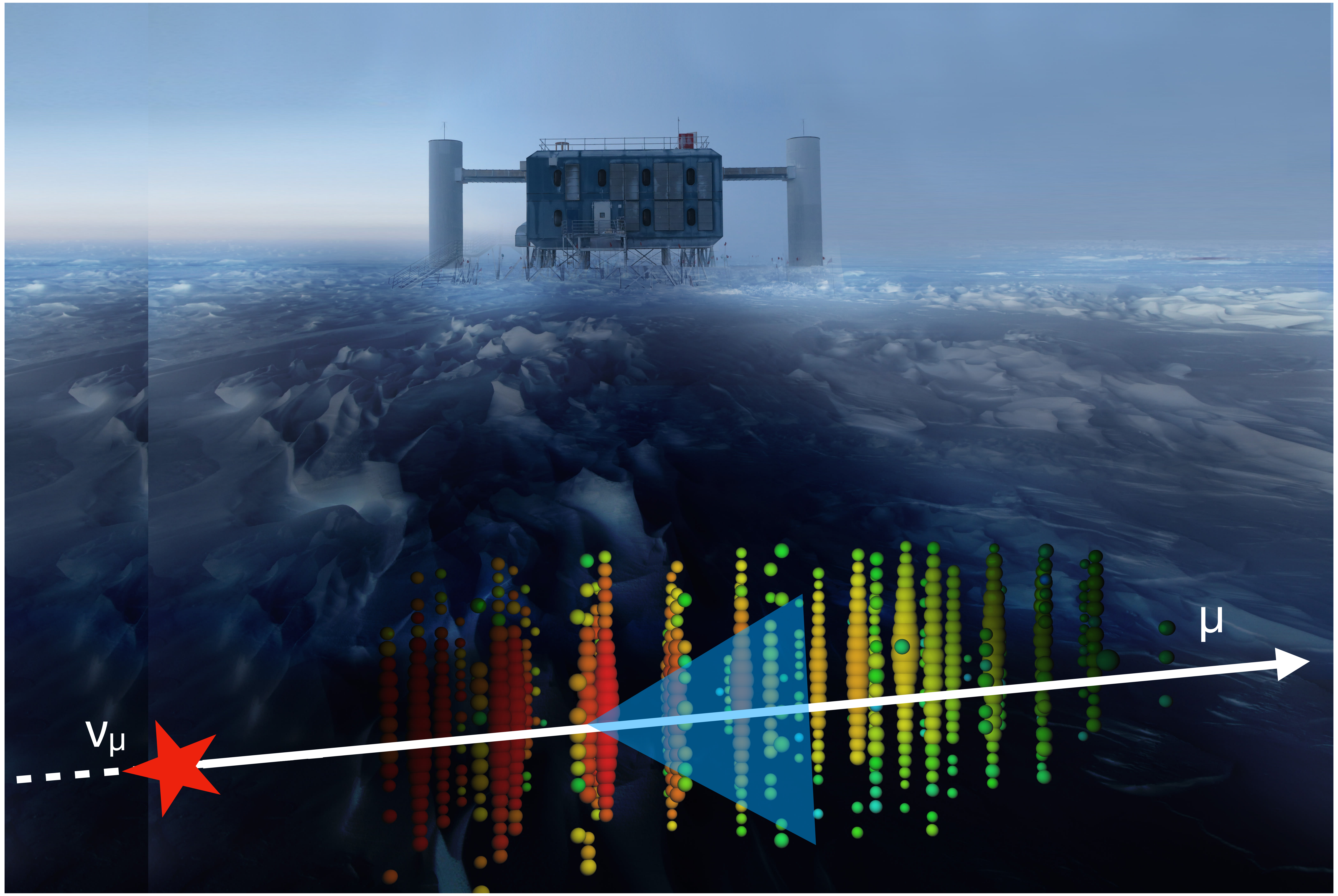






High-energy neutrino detection

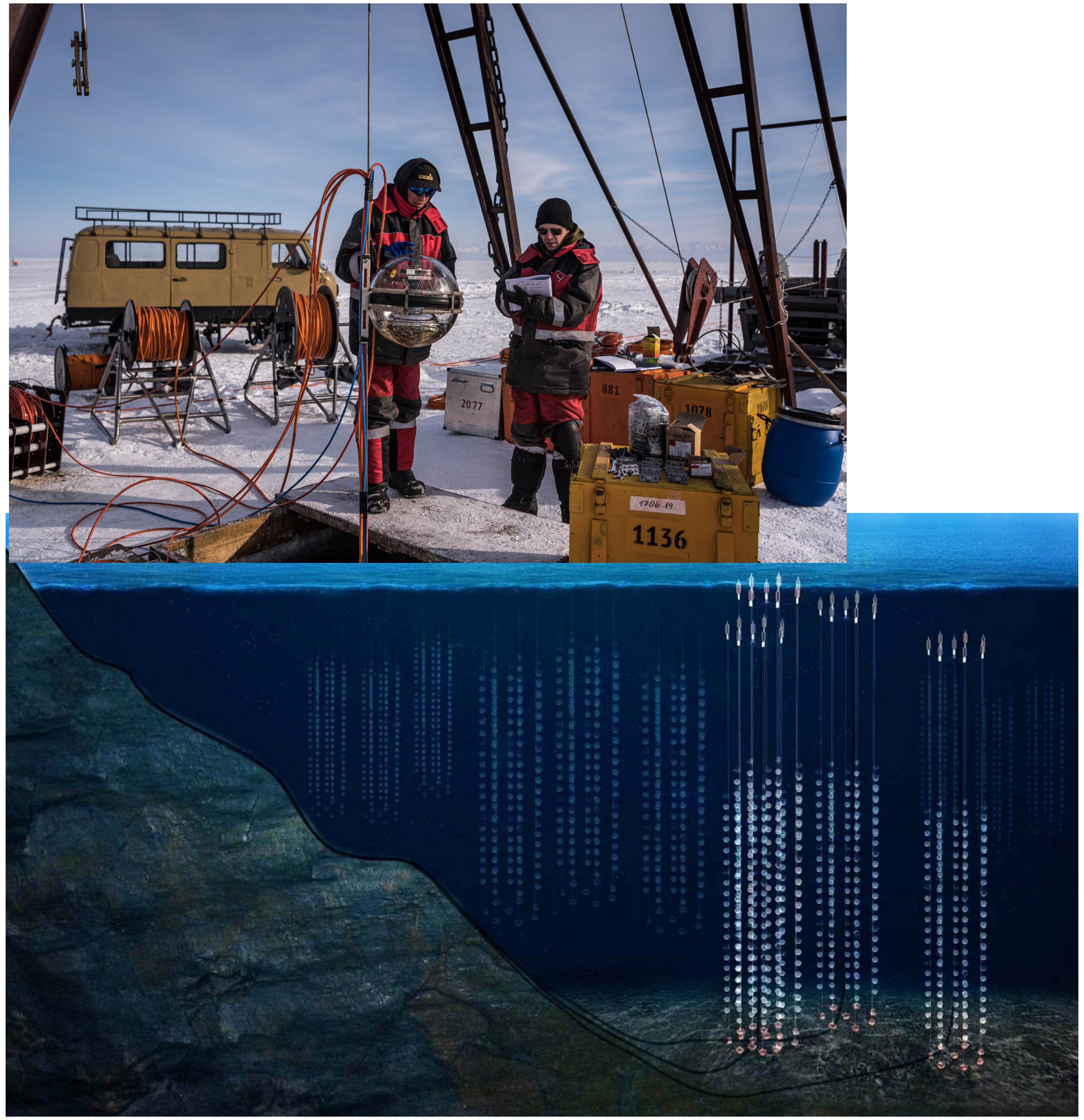
Water/in-ice Cherenkov detection



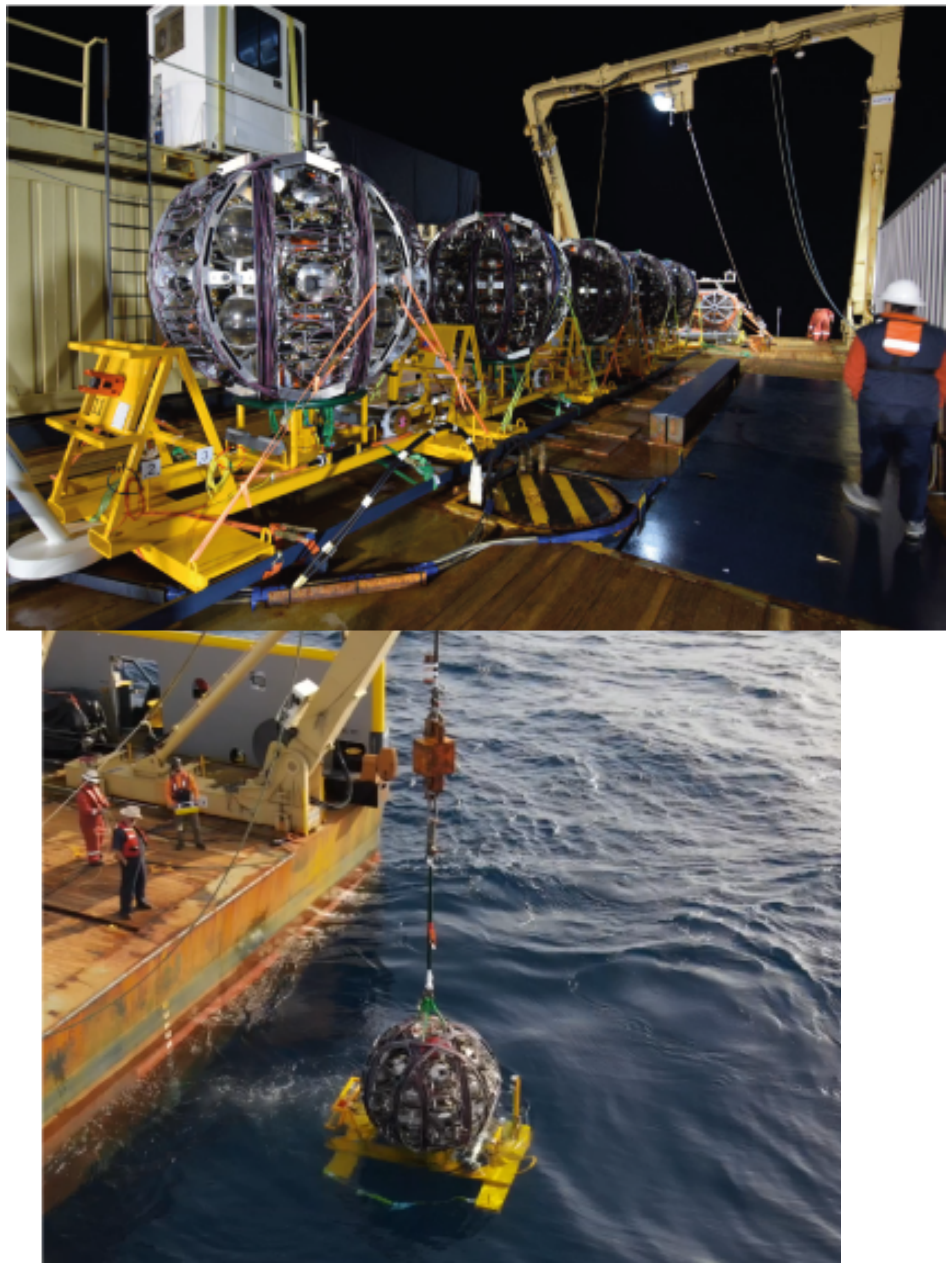
High-energy neutrino detection

+several in preparation!

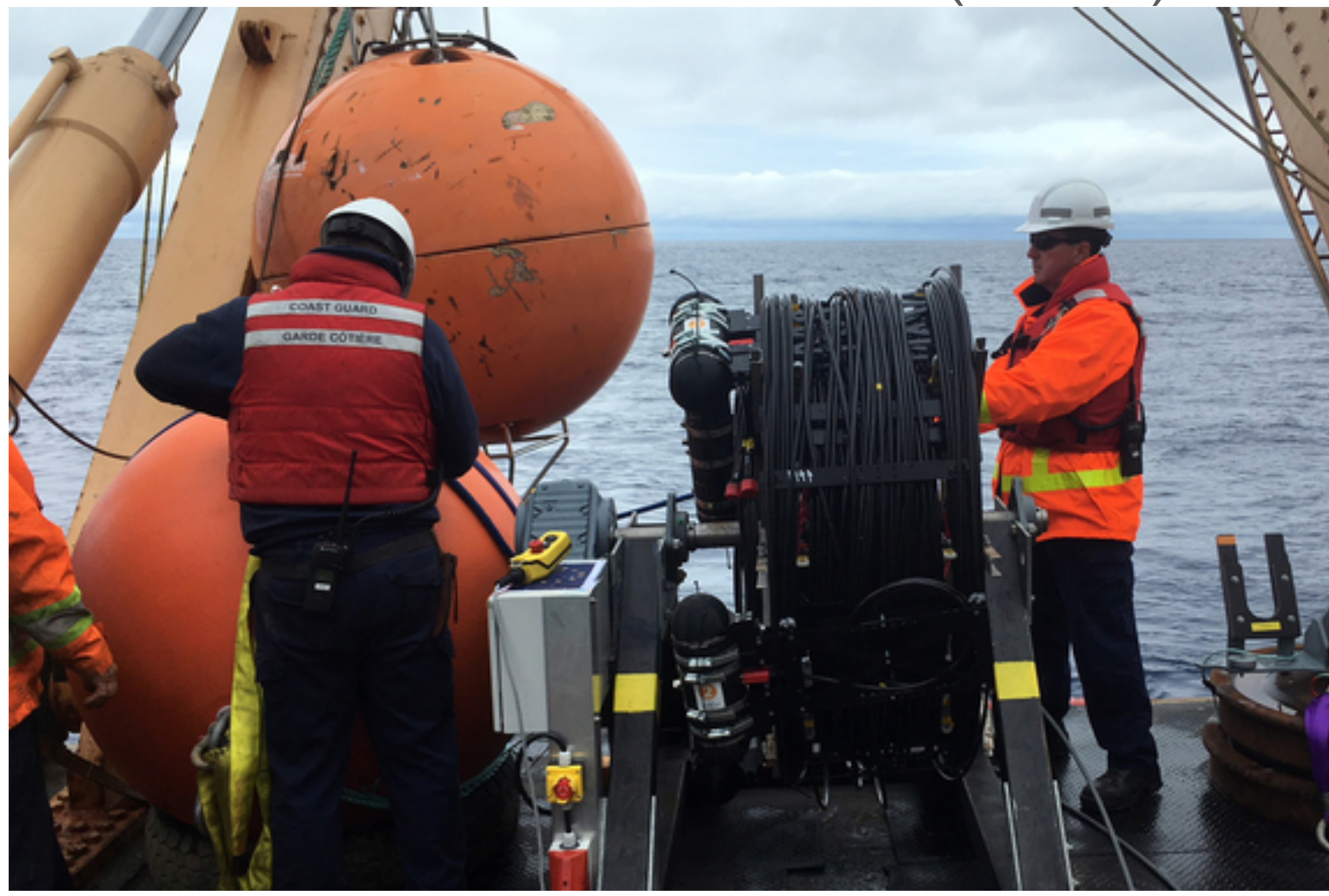
GVD - Lake Baikal

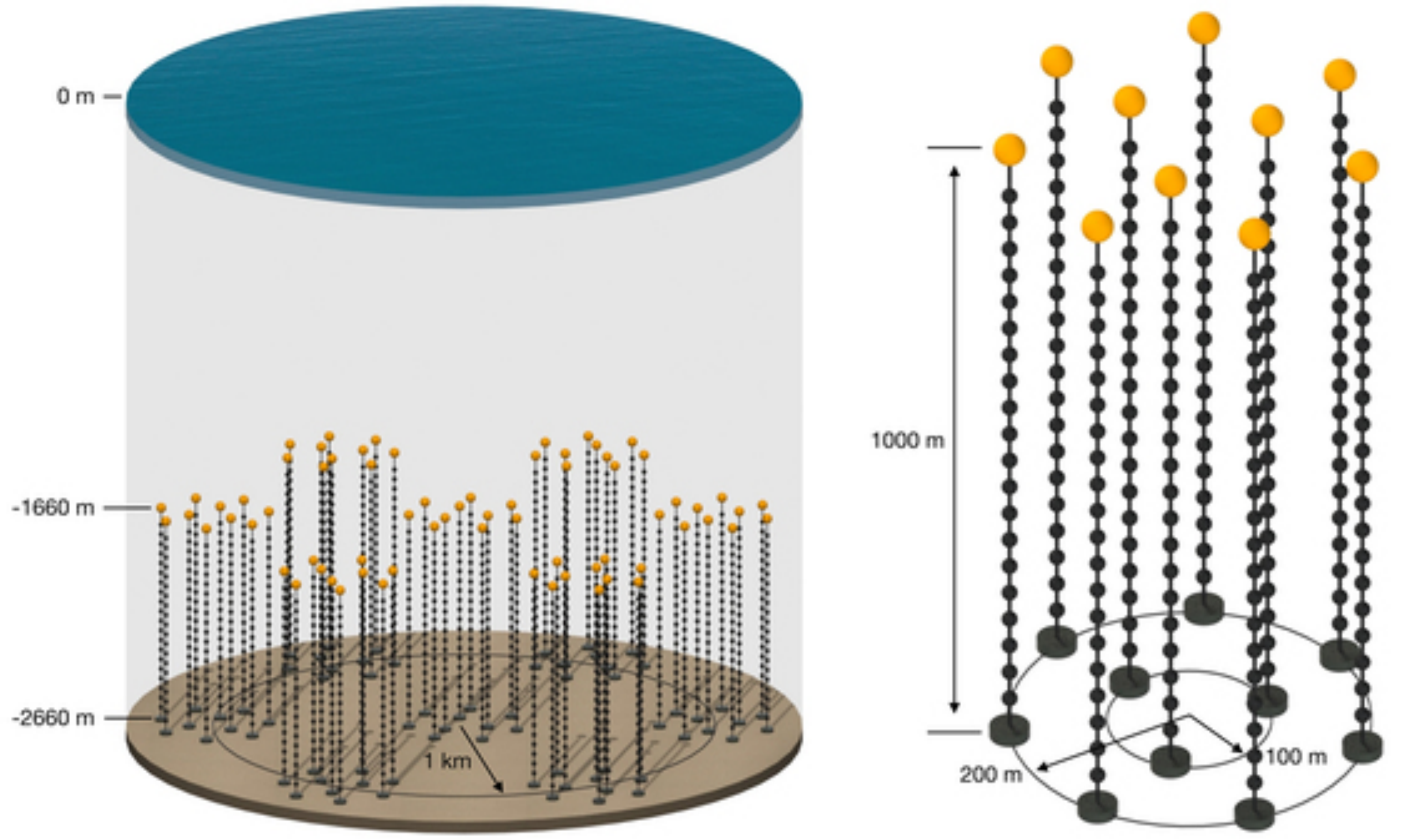


KM3NeT - France/Italy



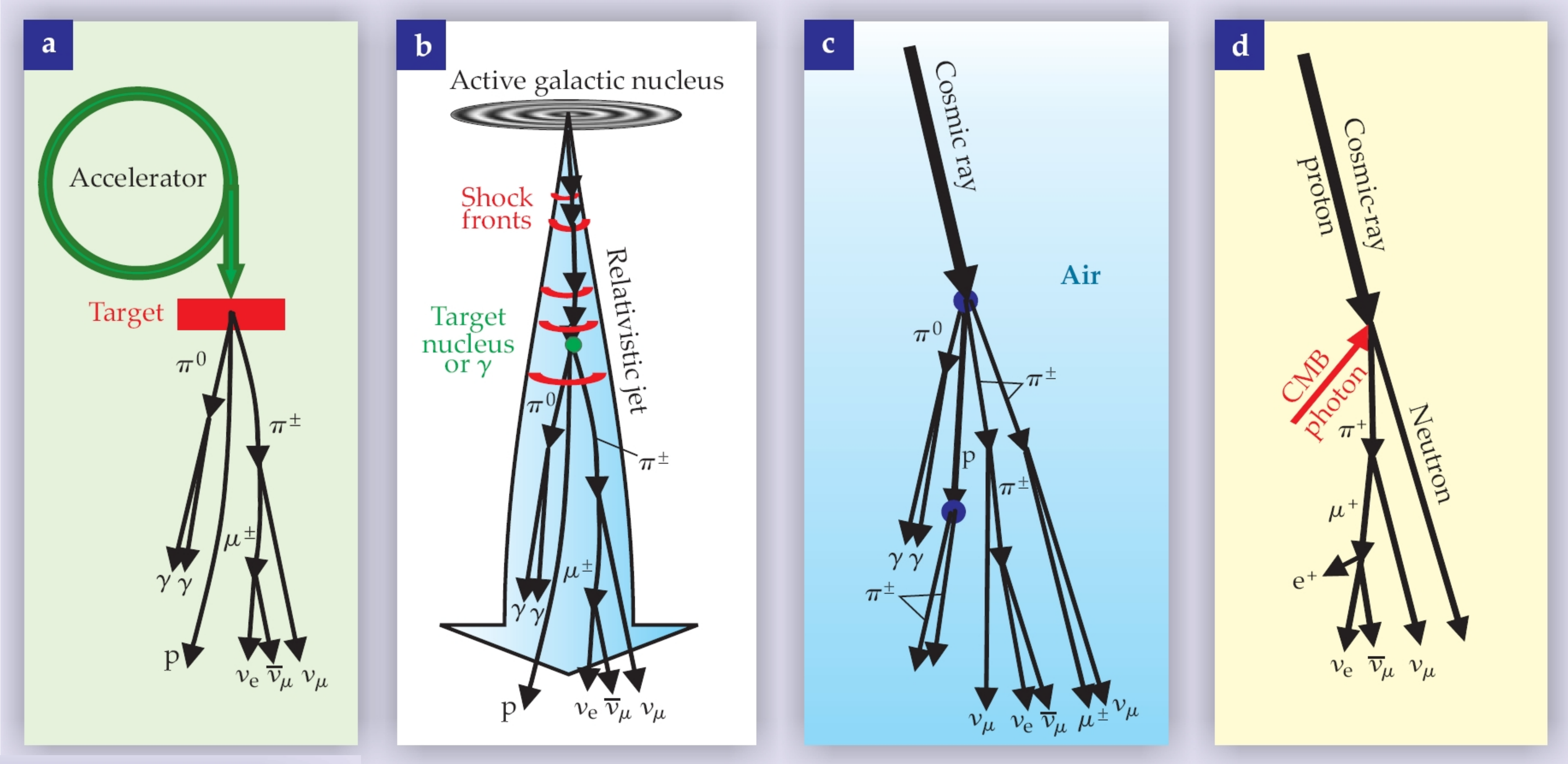
P-ONE - Canada (Pacific)

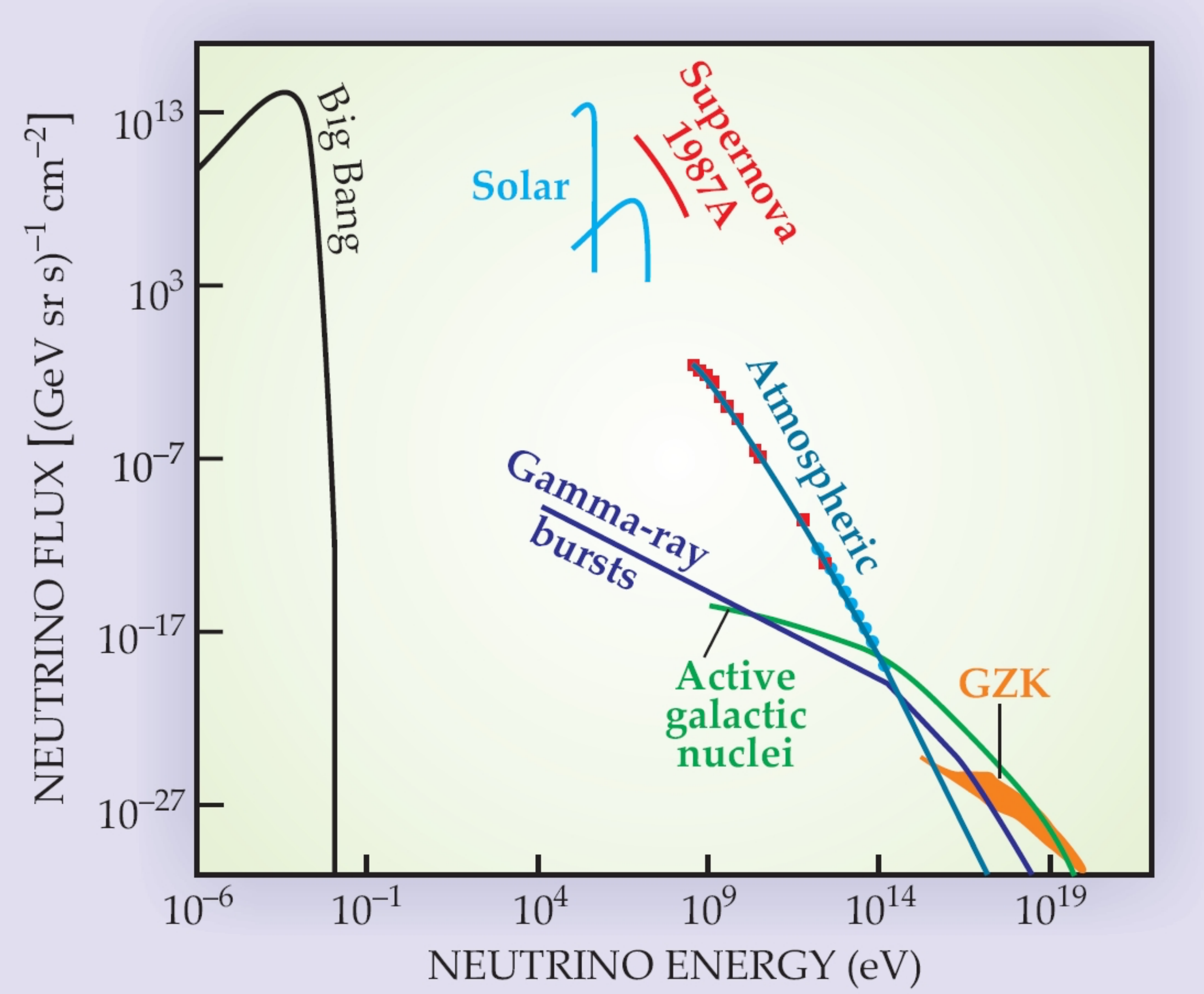




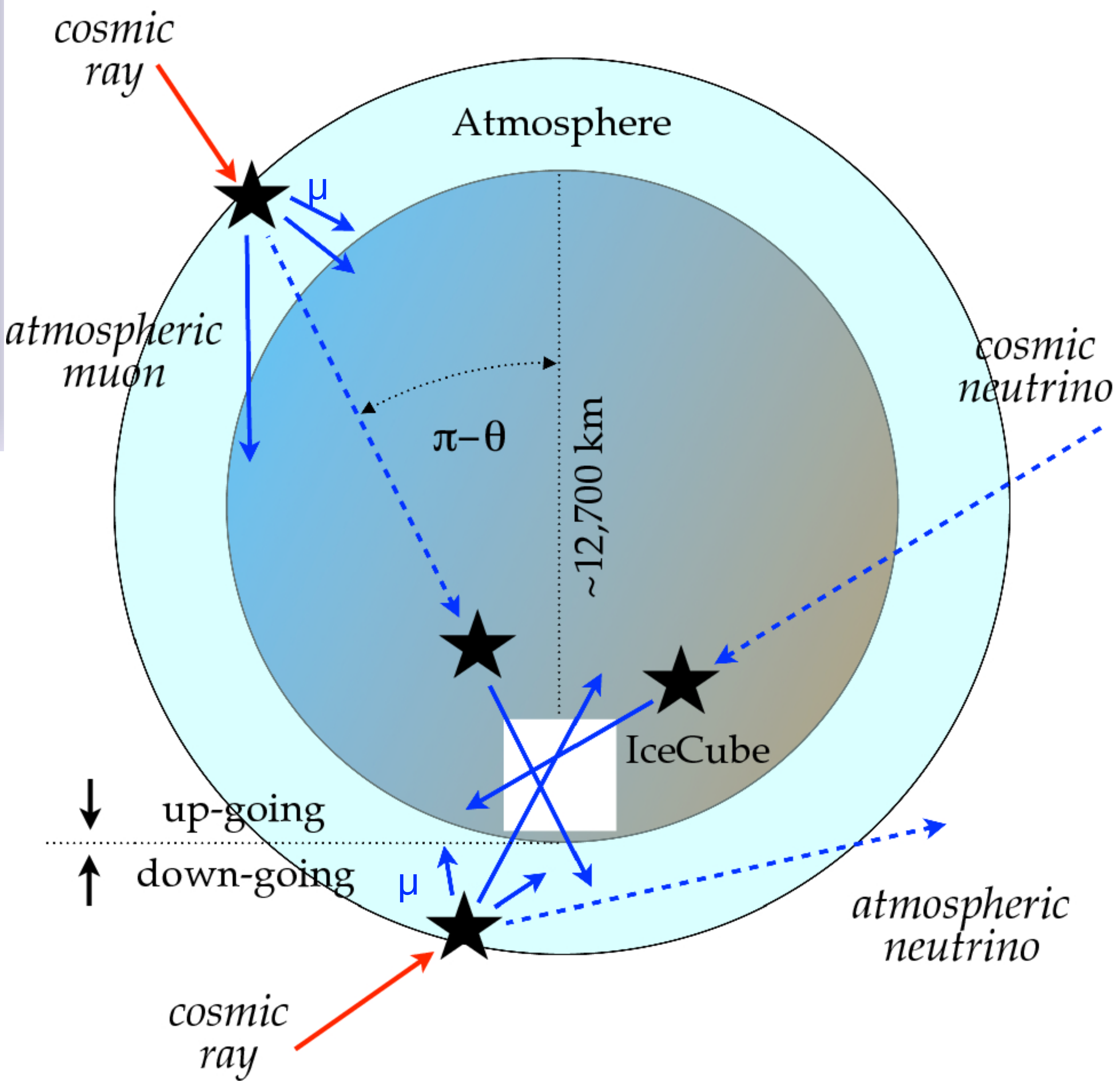
High-energy neutrino detection

Backgrounds

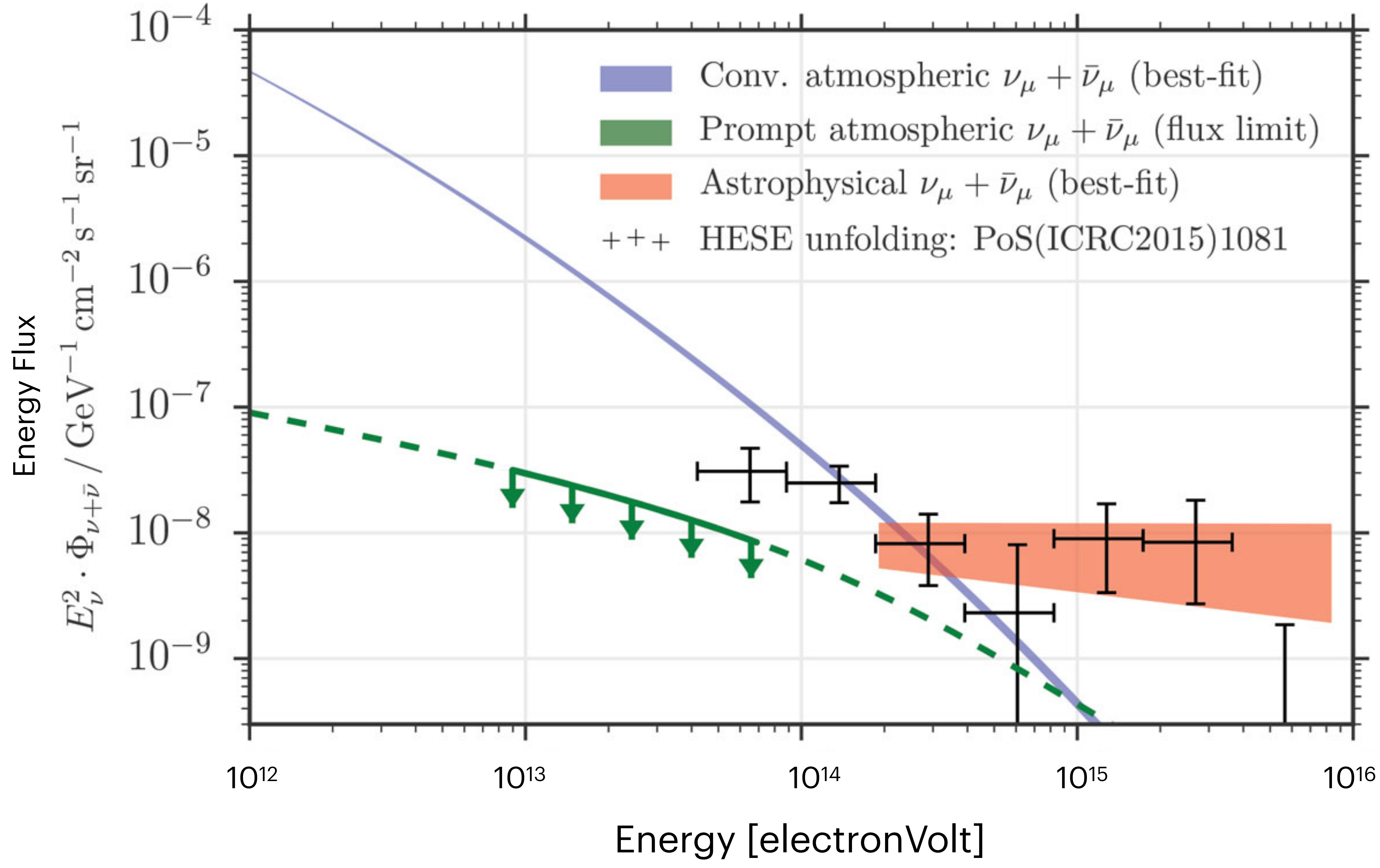


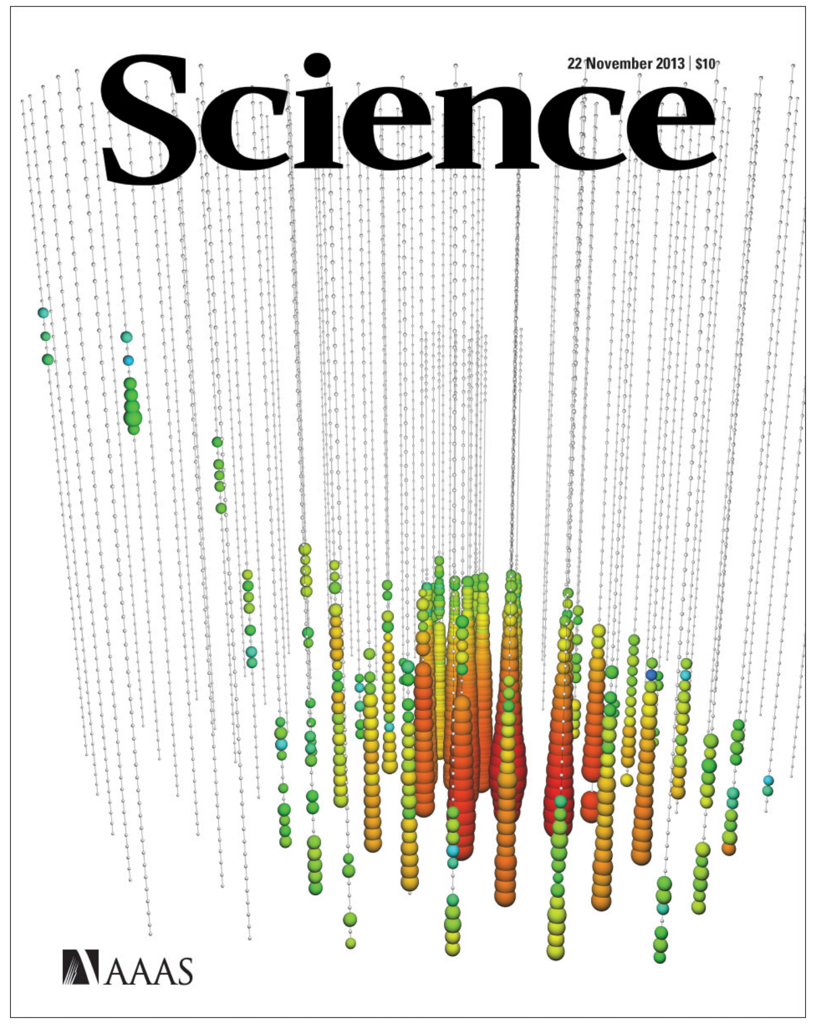


Ahlers, Helbing, Perez de los Heros, 2018, EPJC

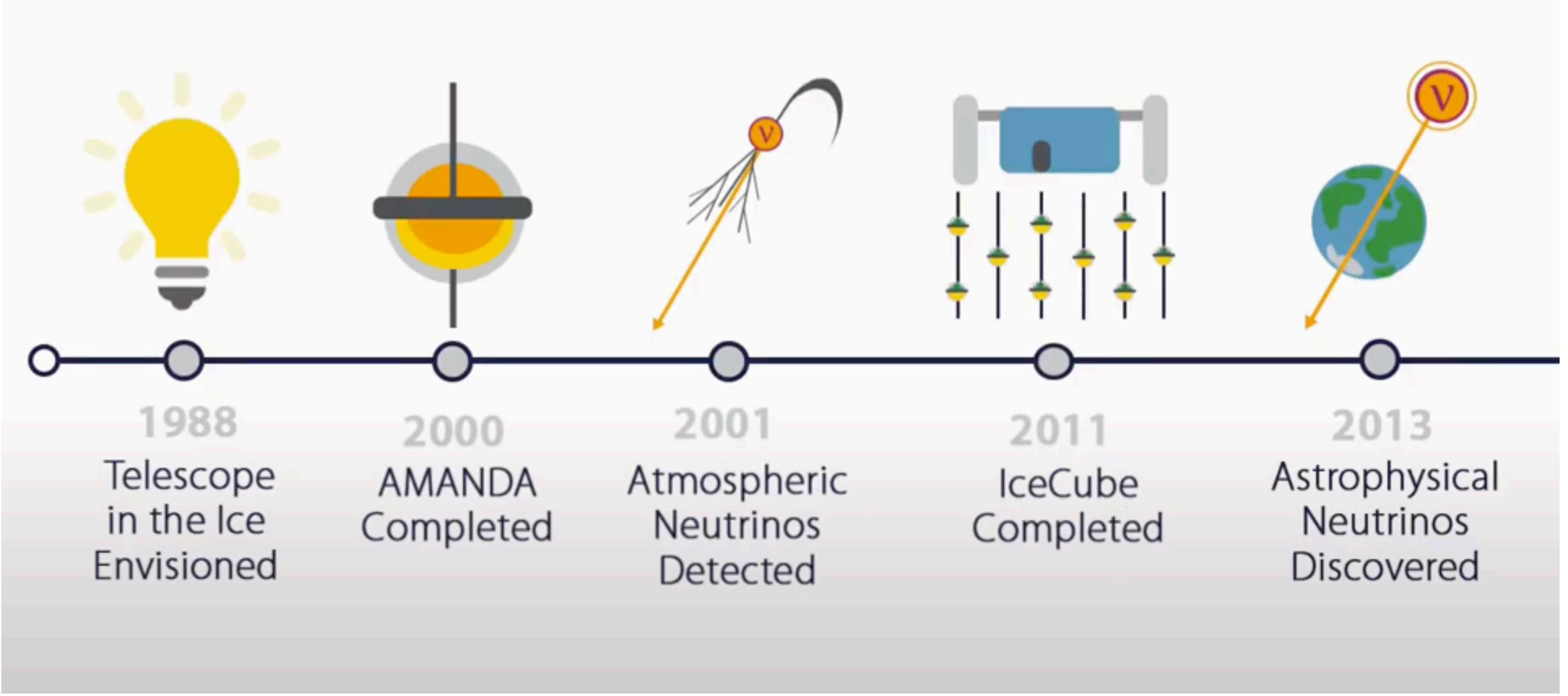


Discovery of astrophysical neutrinos



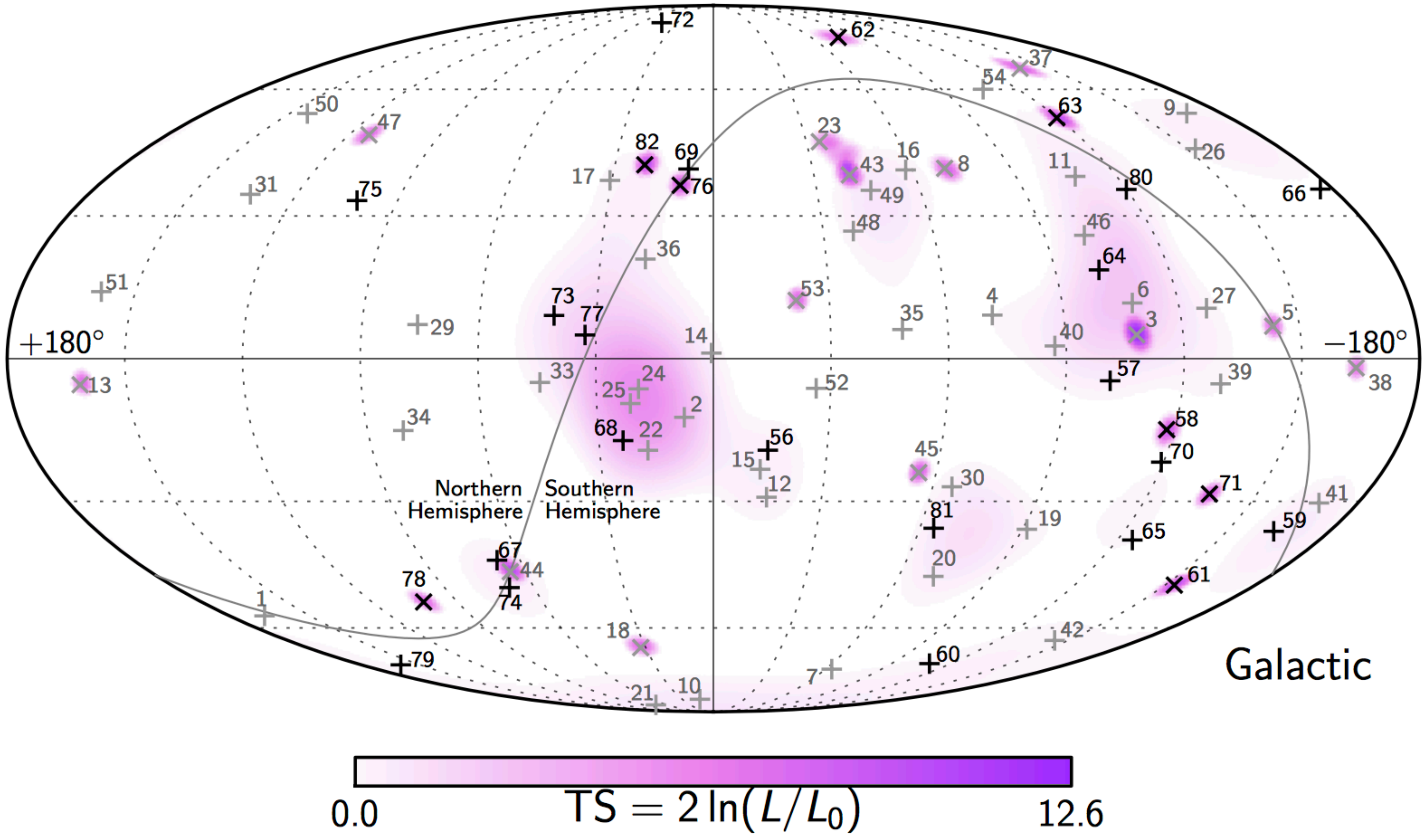


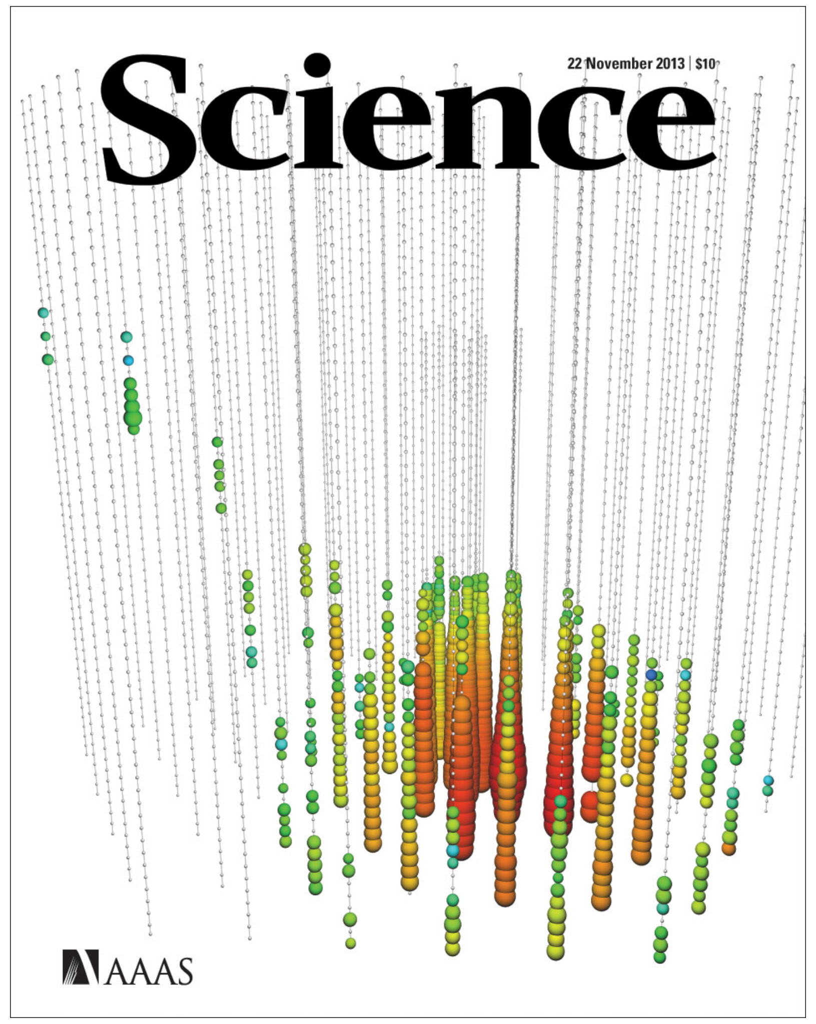
IceCube, Science 342, 1242856 (2013)
IceCube, Phys. Rev. Lett. (2015)



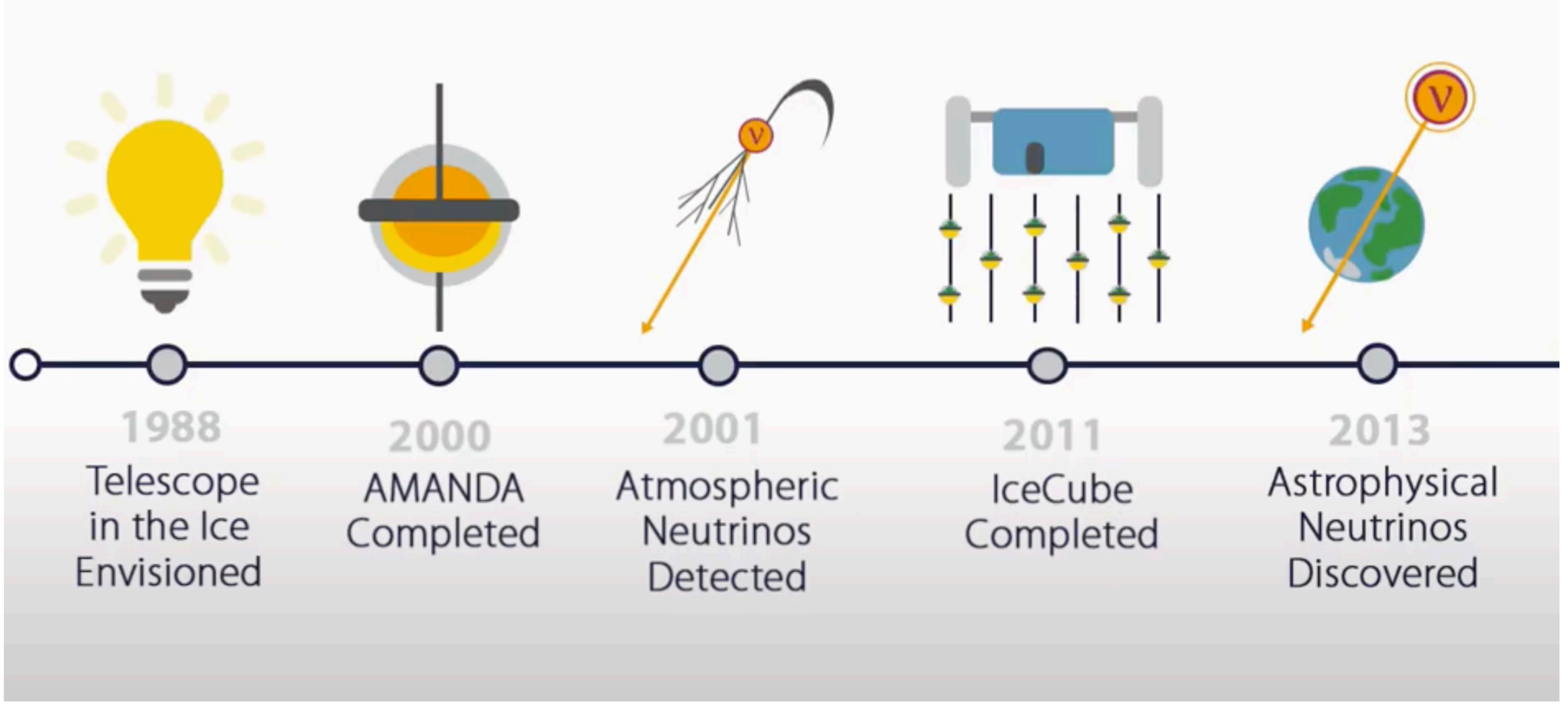
Discovery of astrophysical neutrinos

IceCube Coll. PoS(ICRC2017)981

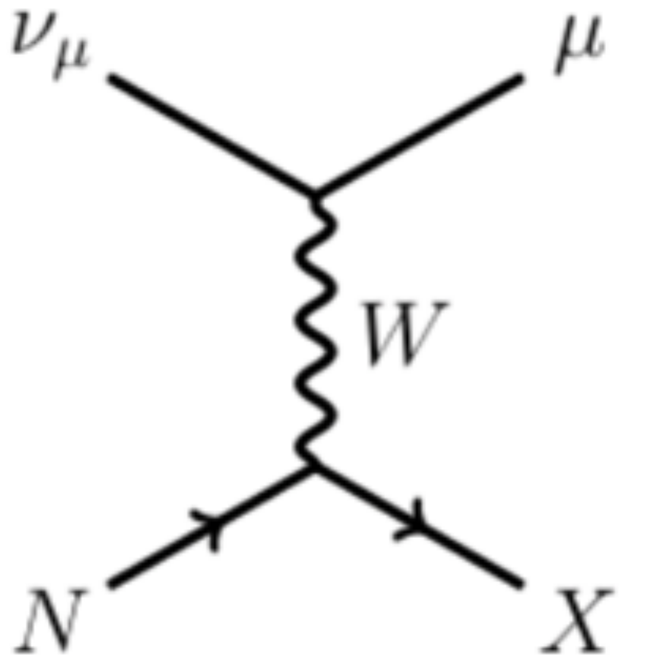


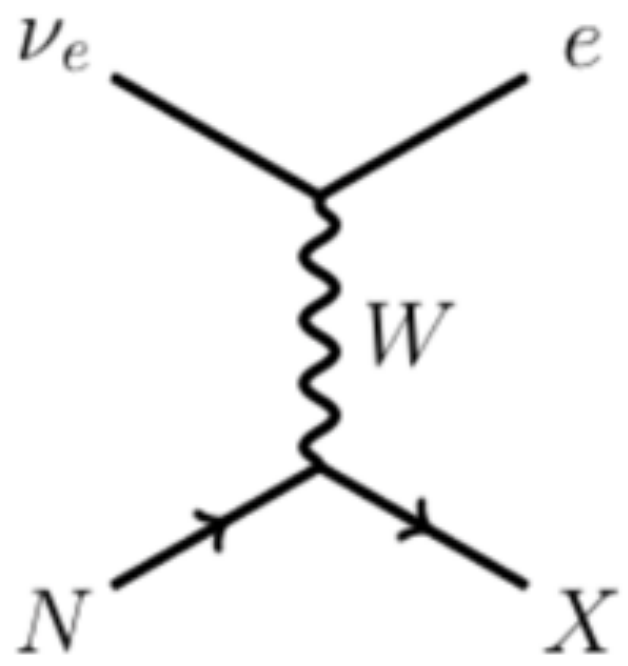


IceCube, Science 342, 1242856 (2013)
IceCube, Phys. Rev. Lett. (2015)



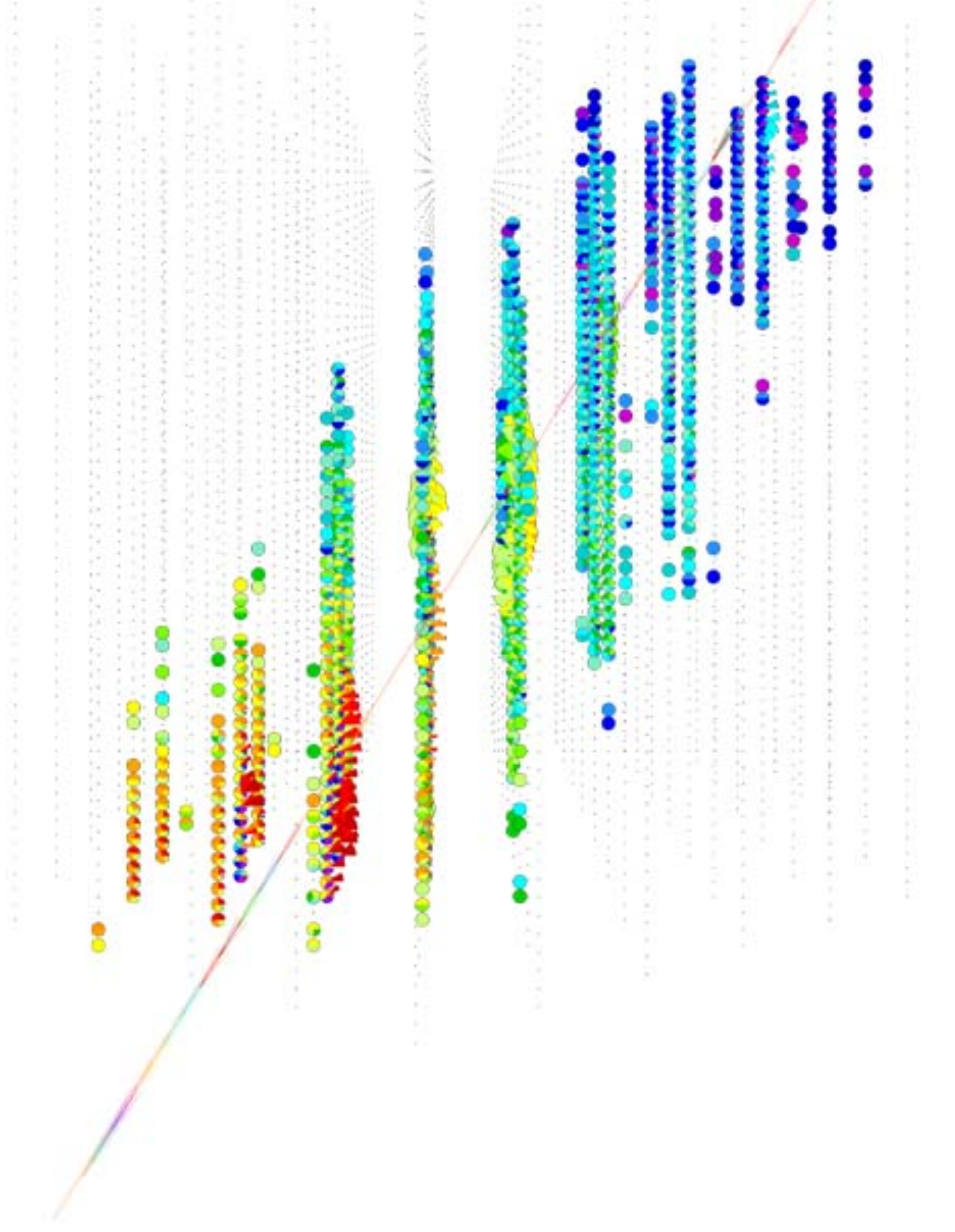
Flavour identification





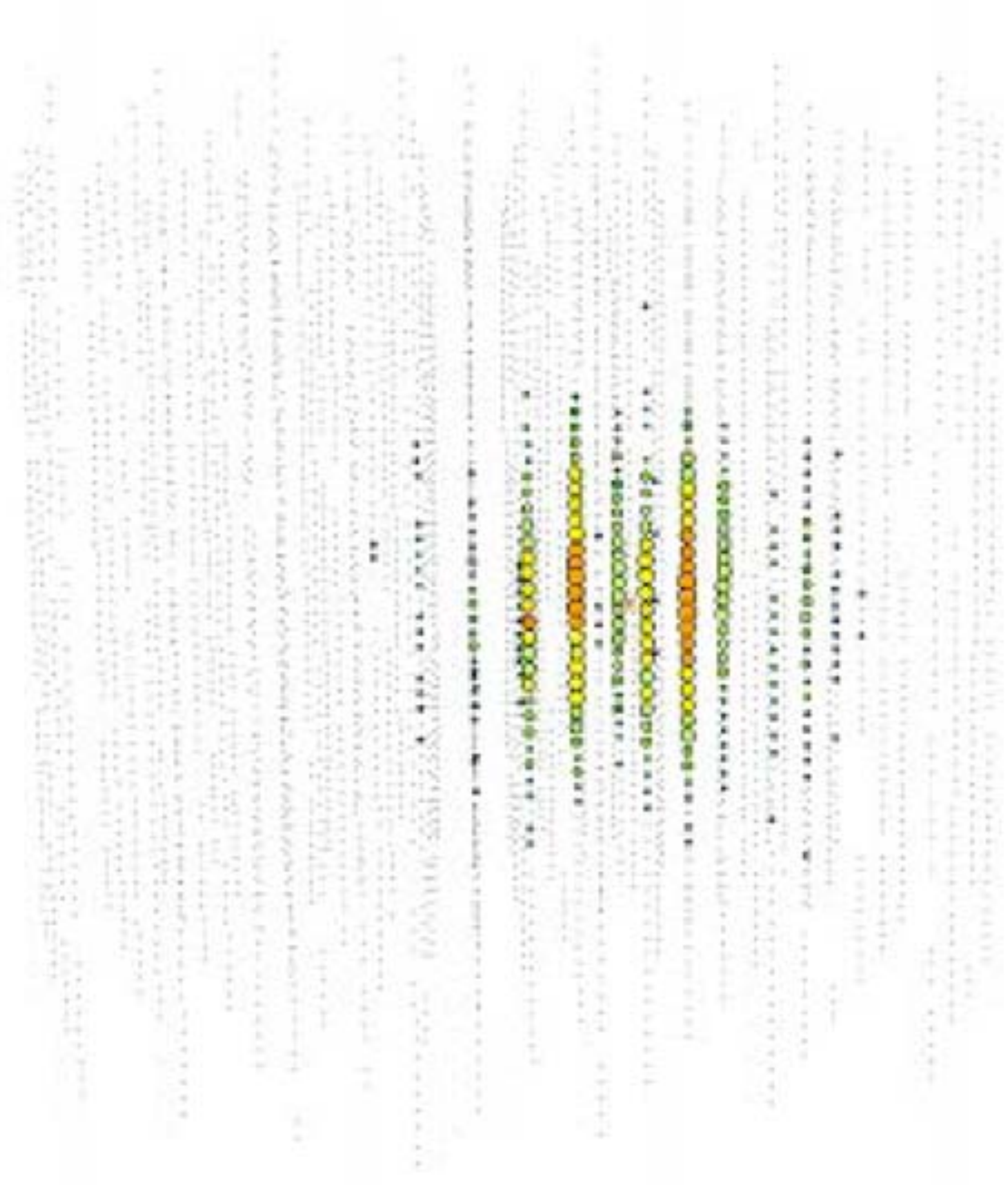
Track

($\delta\theta \lesssim 1^\circ$)



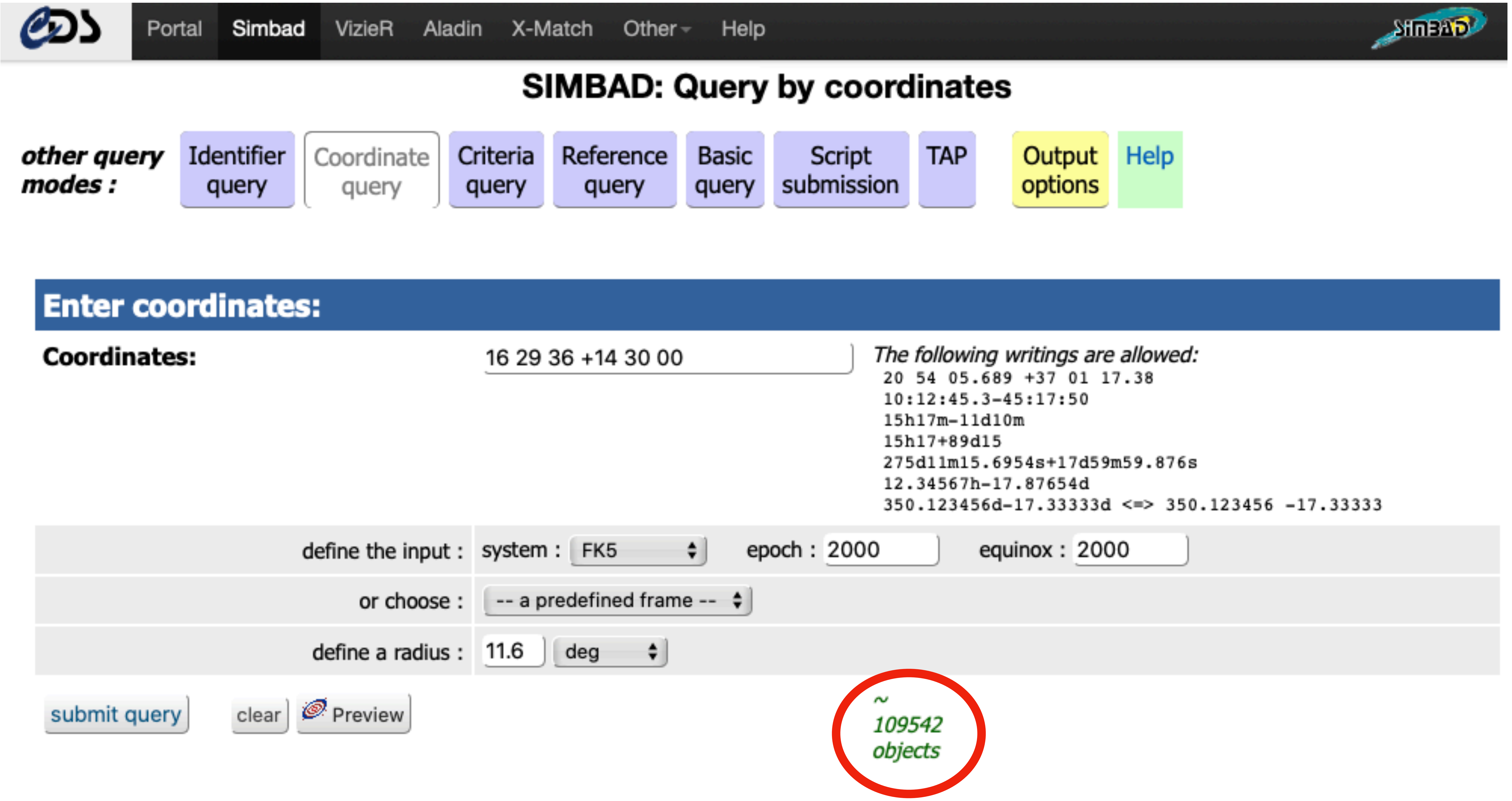
Cascade

also NC ν_i ($\delta\theta \gtrsim 10^\circ$)



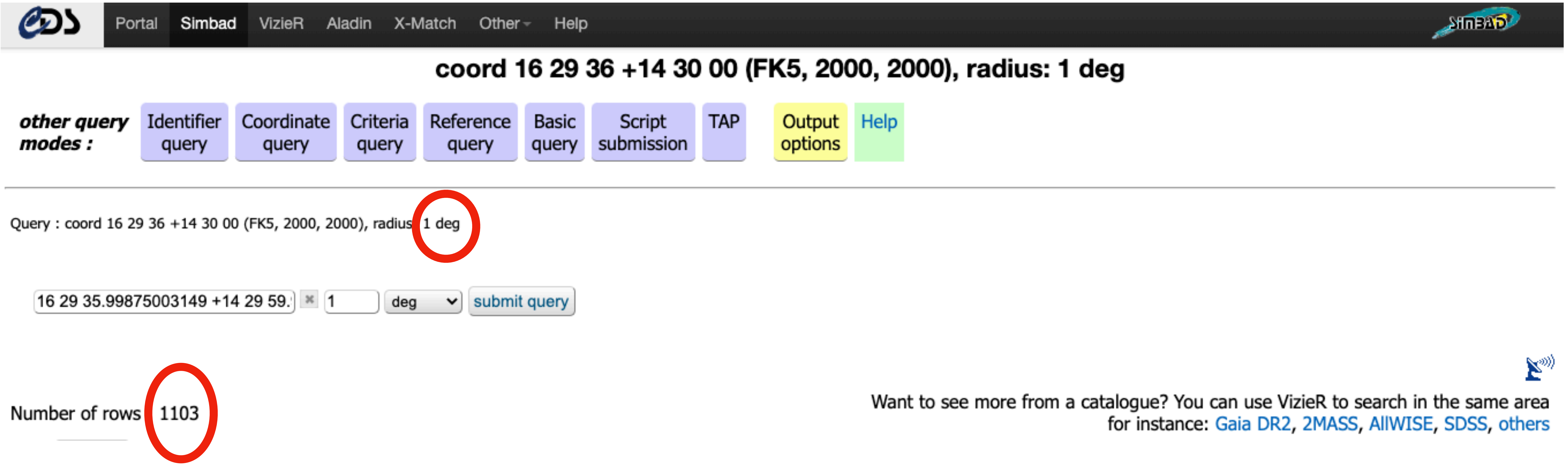
For astronomy we need high angular resolution

Example, IC-17 (cascade):

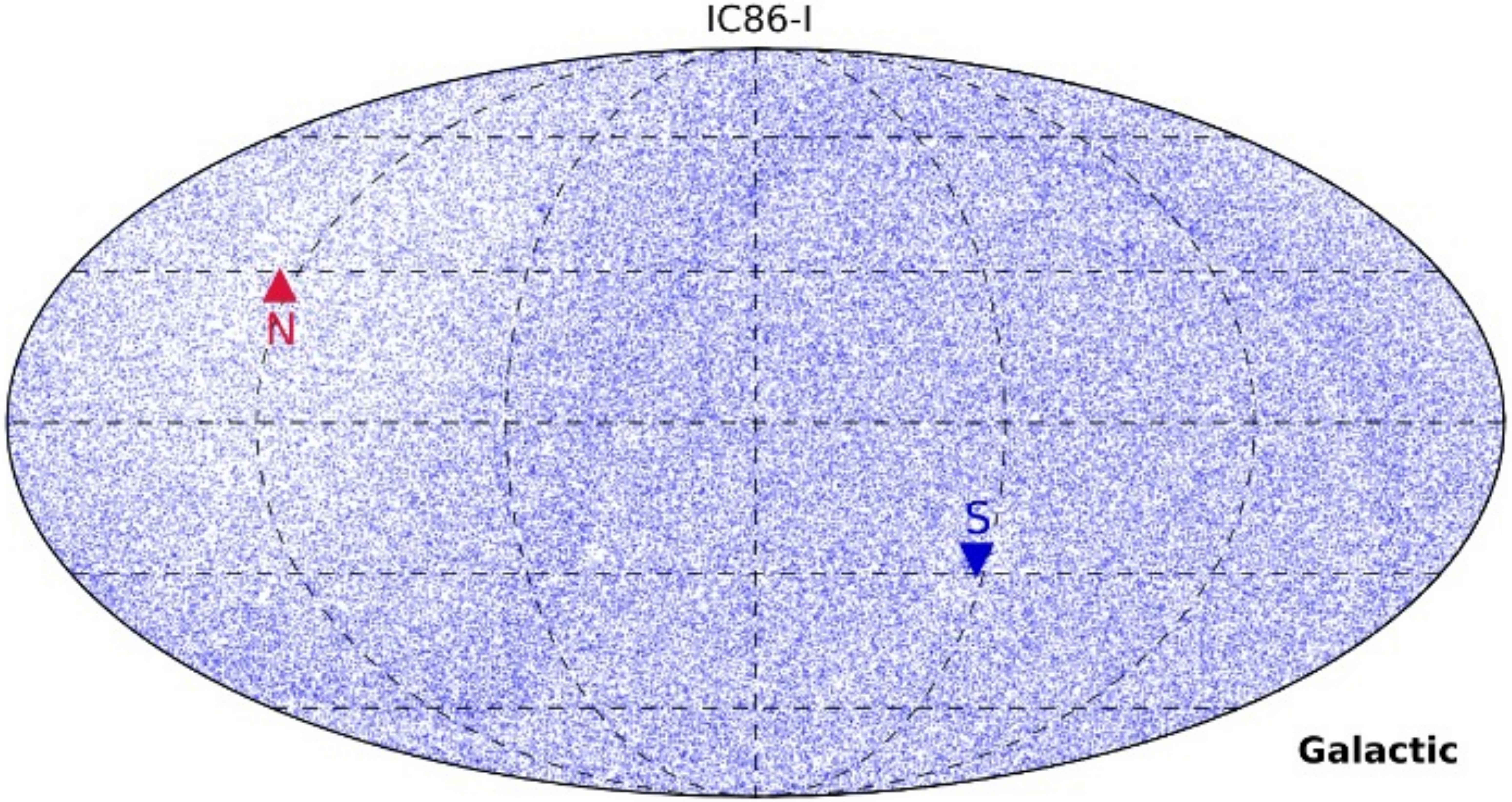


For astronomy we need high angular resolution

Even with tracks neutrino astronomy is hard…

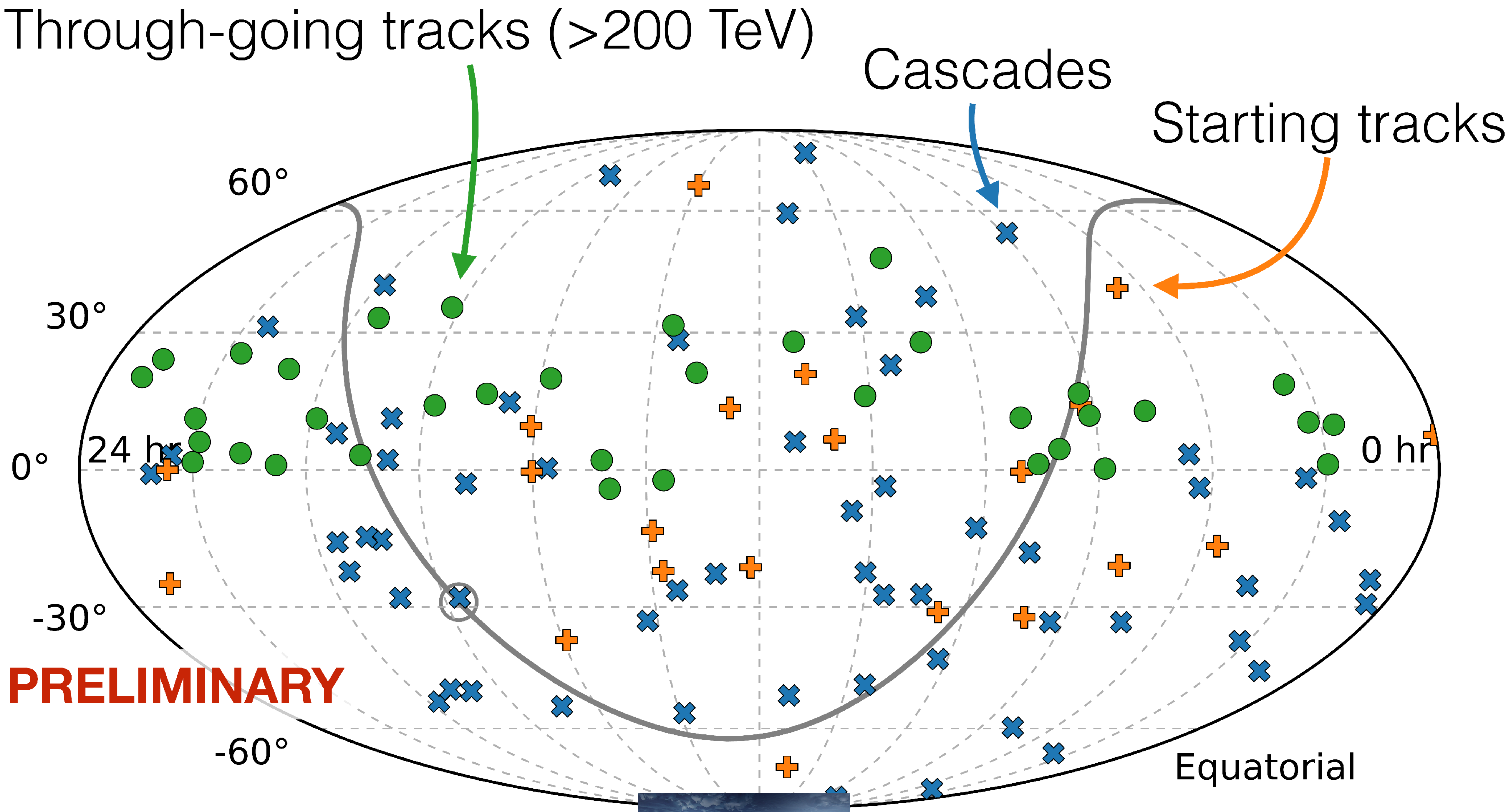


Sky distribution of the neutrinos

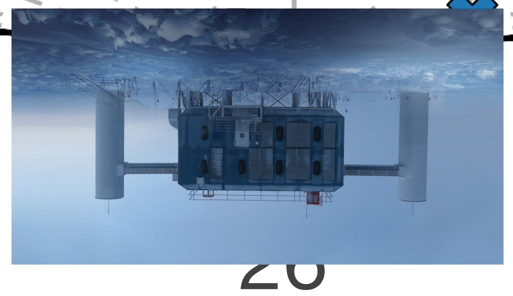


~100000 neutrinos per year
~100 astrophysical
~10 neutrinos with energy E> 60 TeV (high probability of being astrophysical)

Sky distribution of the neutrinos



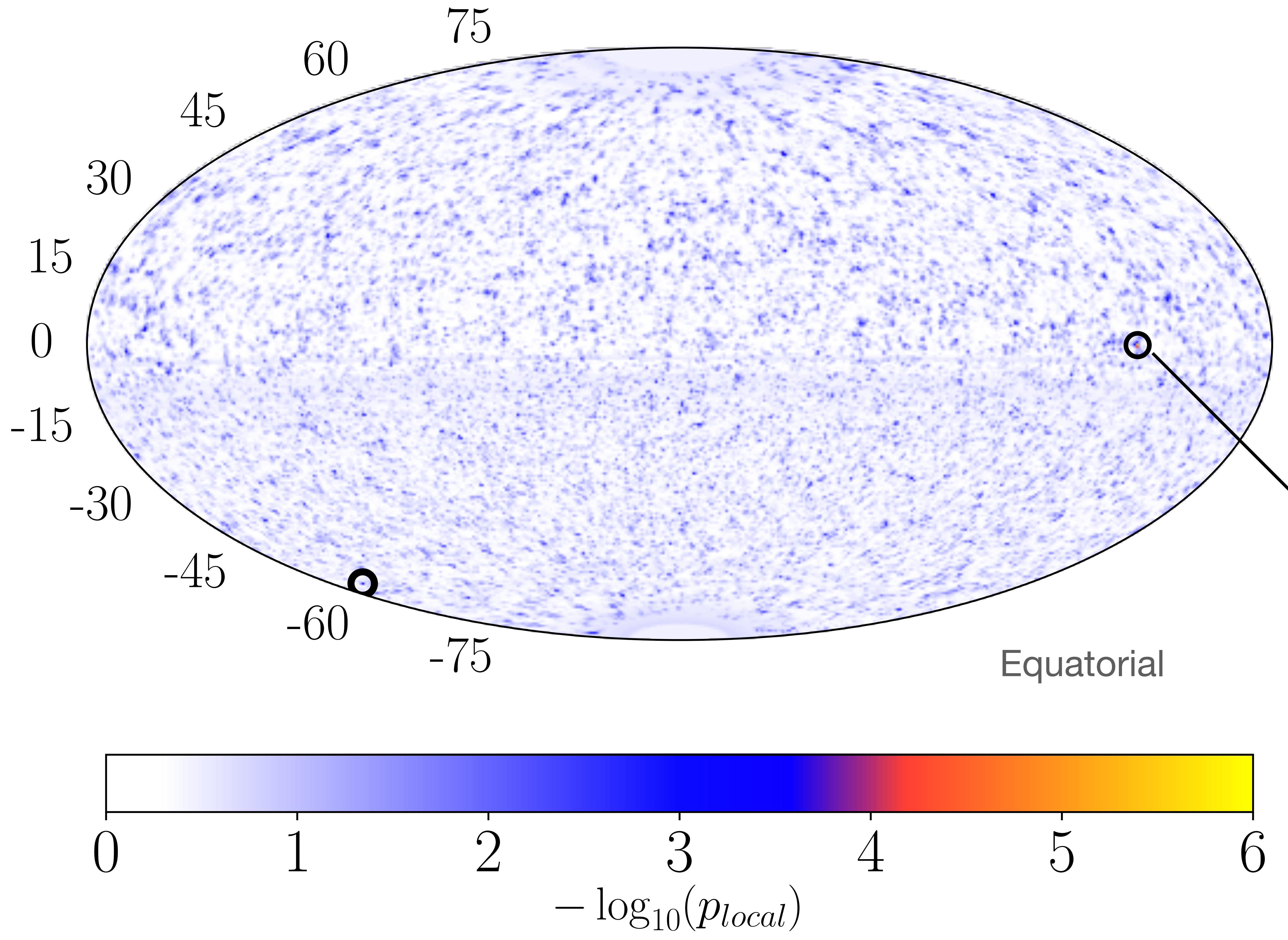
ICECUBE PRELIMINARY

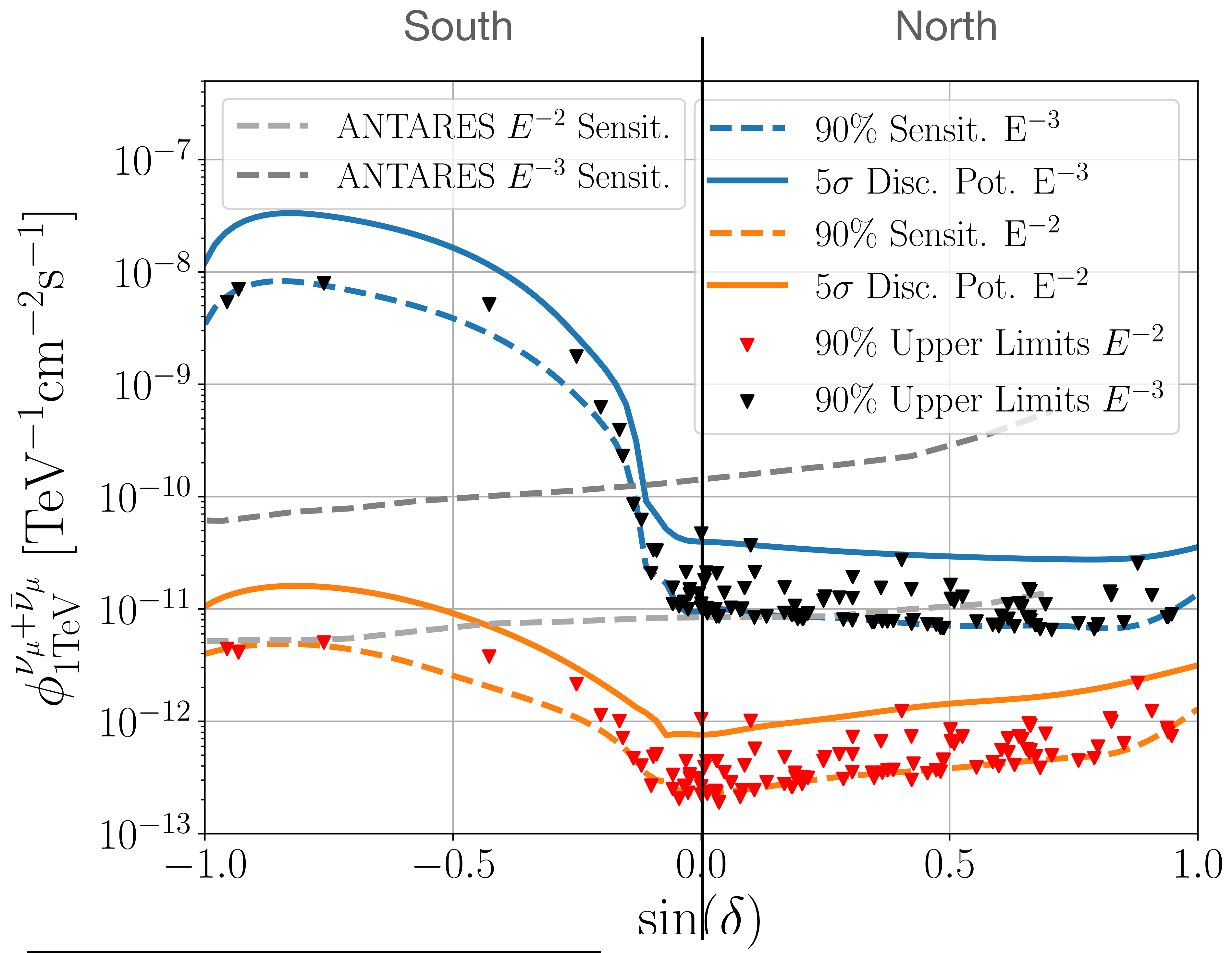


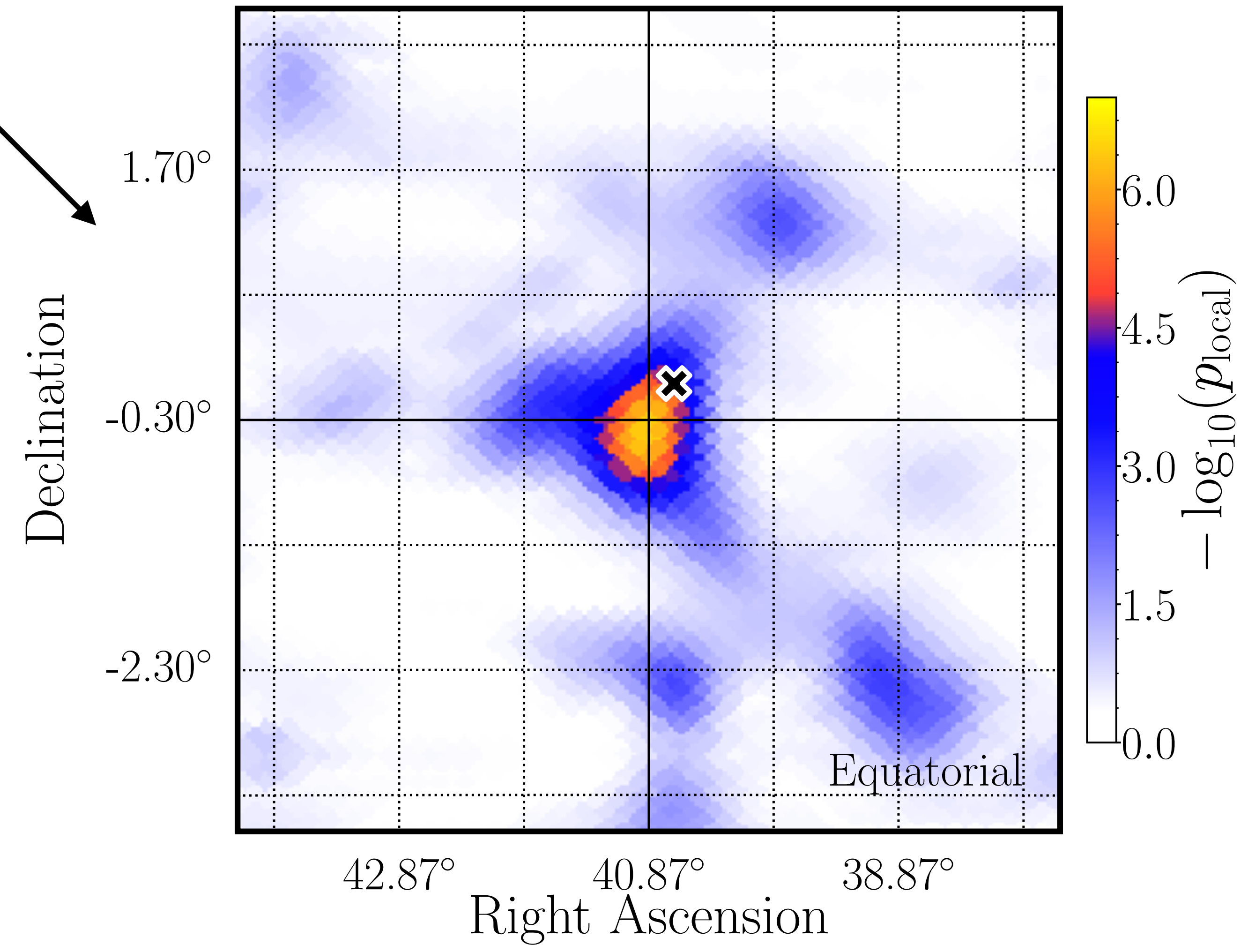
Galactic fraction $\lesssim 15\,\%$
No very strong association signal (few ~3σ analyses)

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)

Summary

- Two known astrophysical neutrino sources: Sun & SN 1987A
- IceCube has revealed an extra-Galactic (cosmic) neutrino flux but not the sources yet

Lecture plan

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

Generic source properties

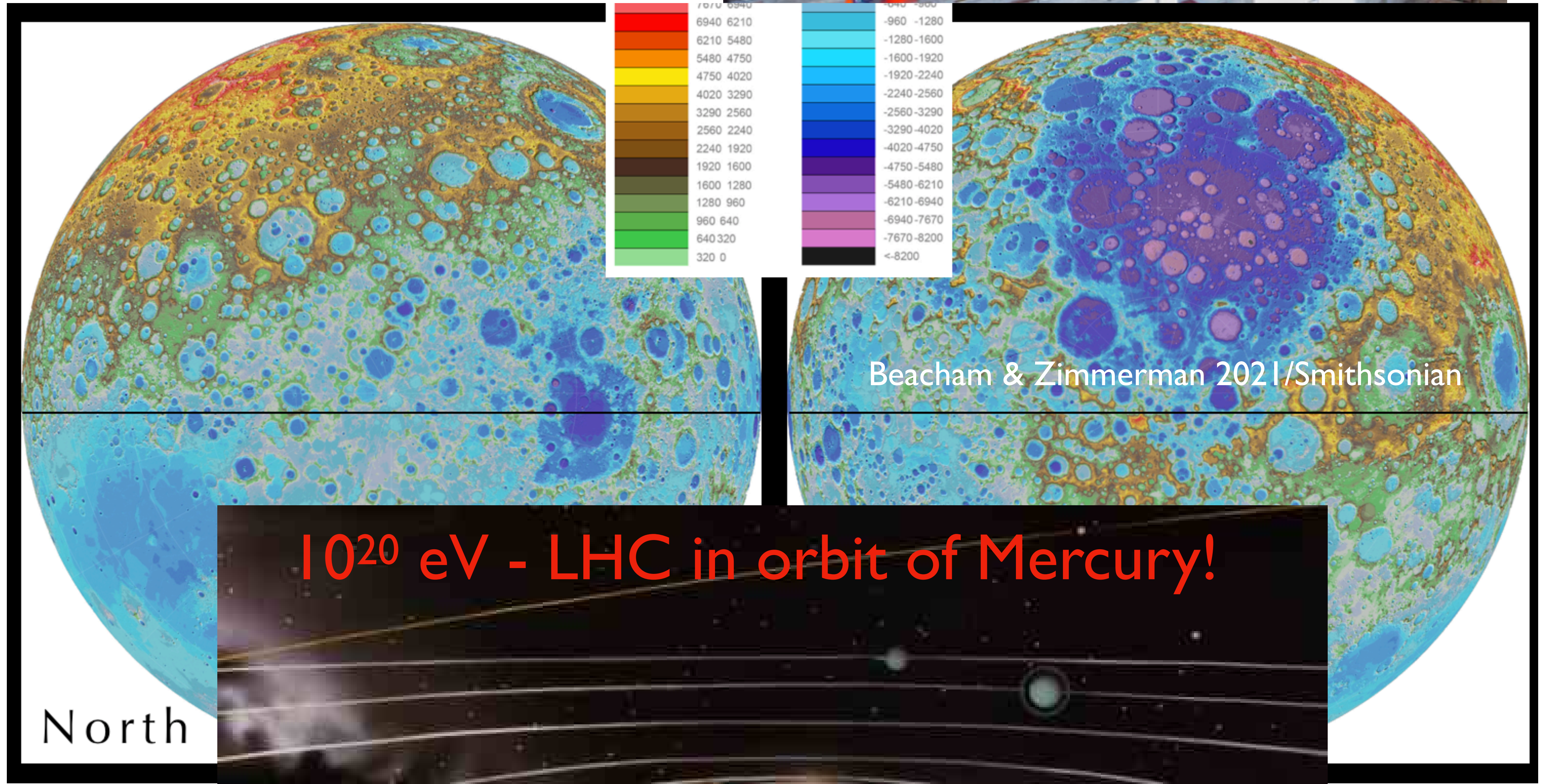
- Hillas criterion for acceleration and plausible sources
- Waxman & Bahcall neutrino bound (possible connection to UHECRs)
- Neutrino source emissivity
- Neutrino source number density

Cosmic-ray accelerators

Minimum requirement: Confinement (Hillas 1984)

TeV = 10^{12} eV

PeV = 10^{15} eV

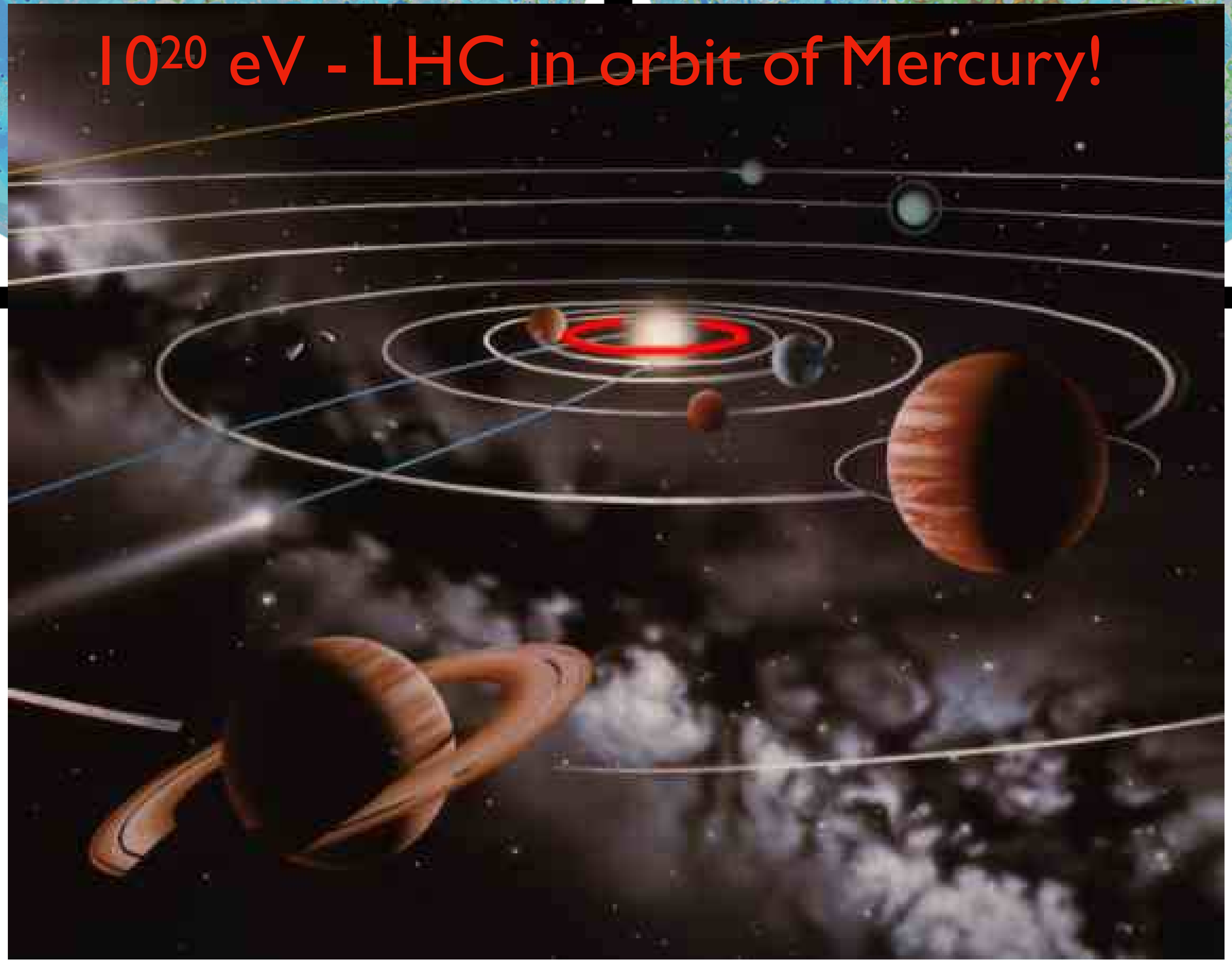


$$R_{\text{source}} > r_{\text{Larmor}} = \frac{E}{ZBec}$$

Maximum energy,

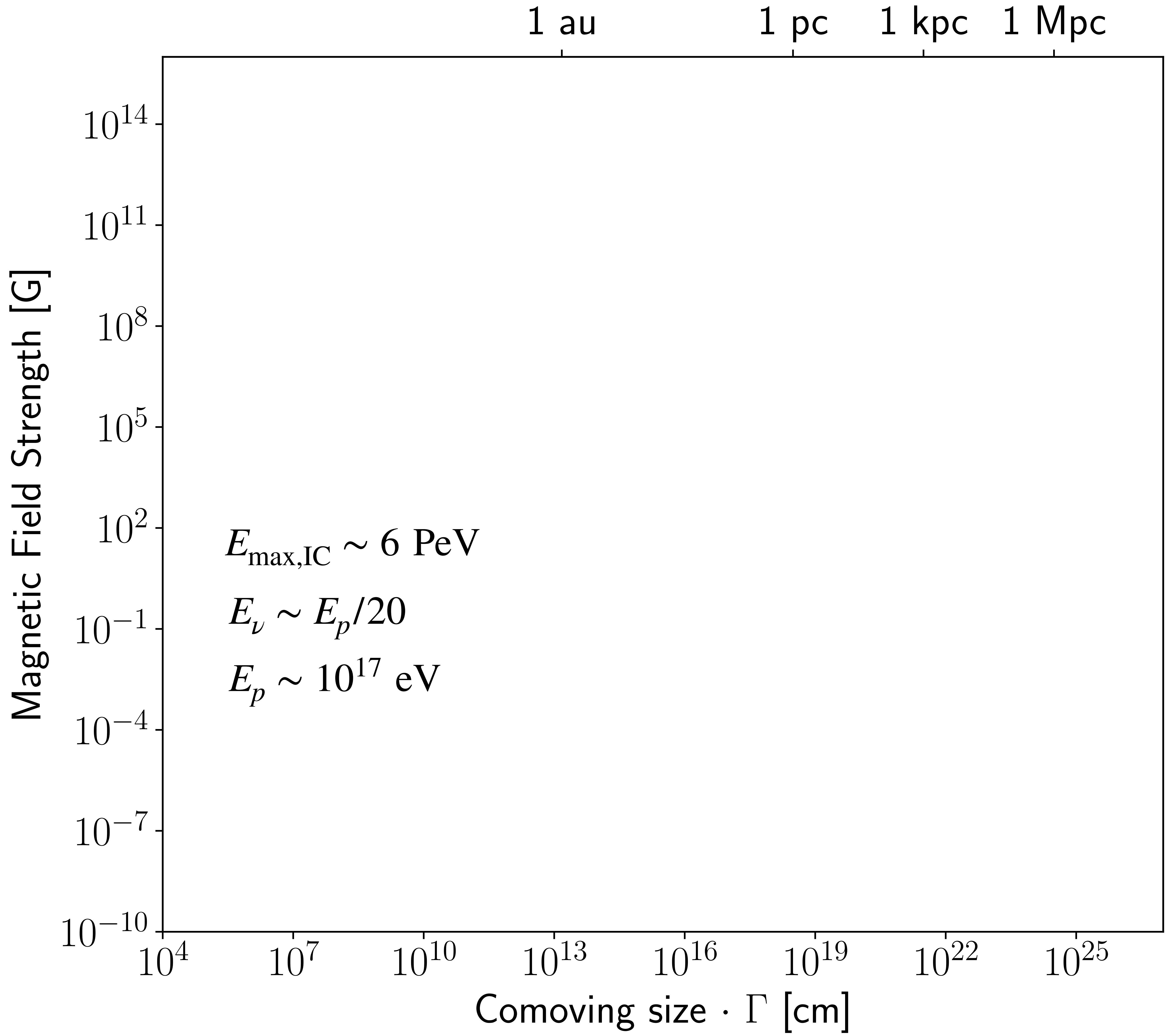
$$E_{\max} = ZecBR_{\text{source}}$$

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

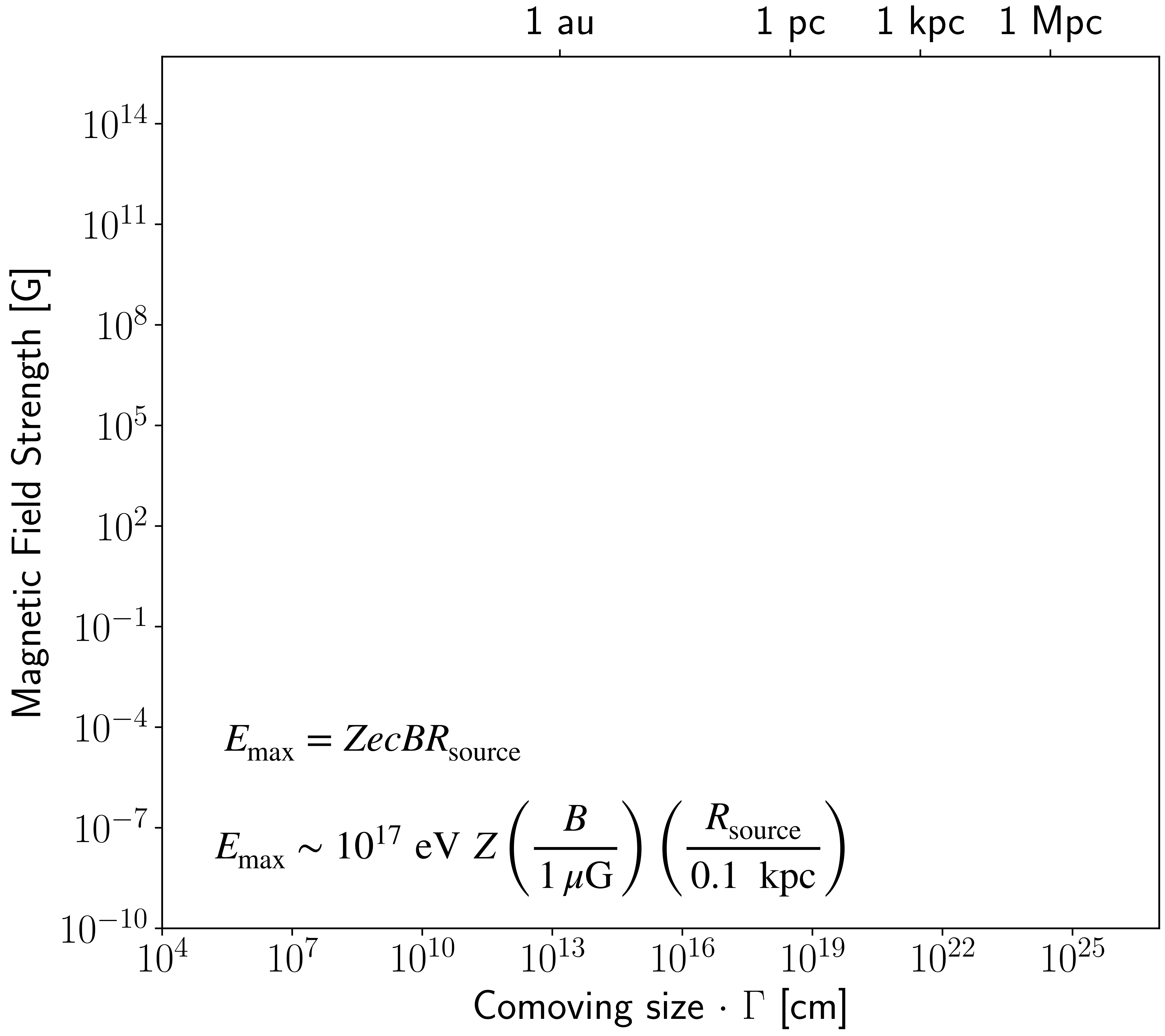


EeV = 10^{18} eV, ZeV = 10^{21} eV

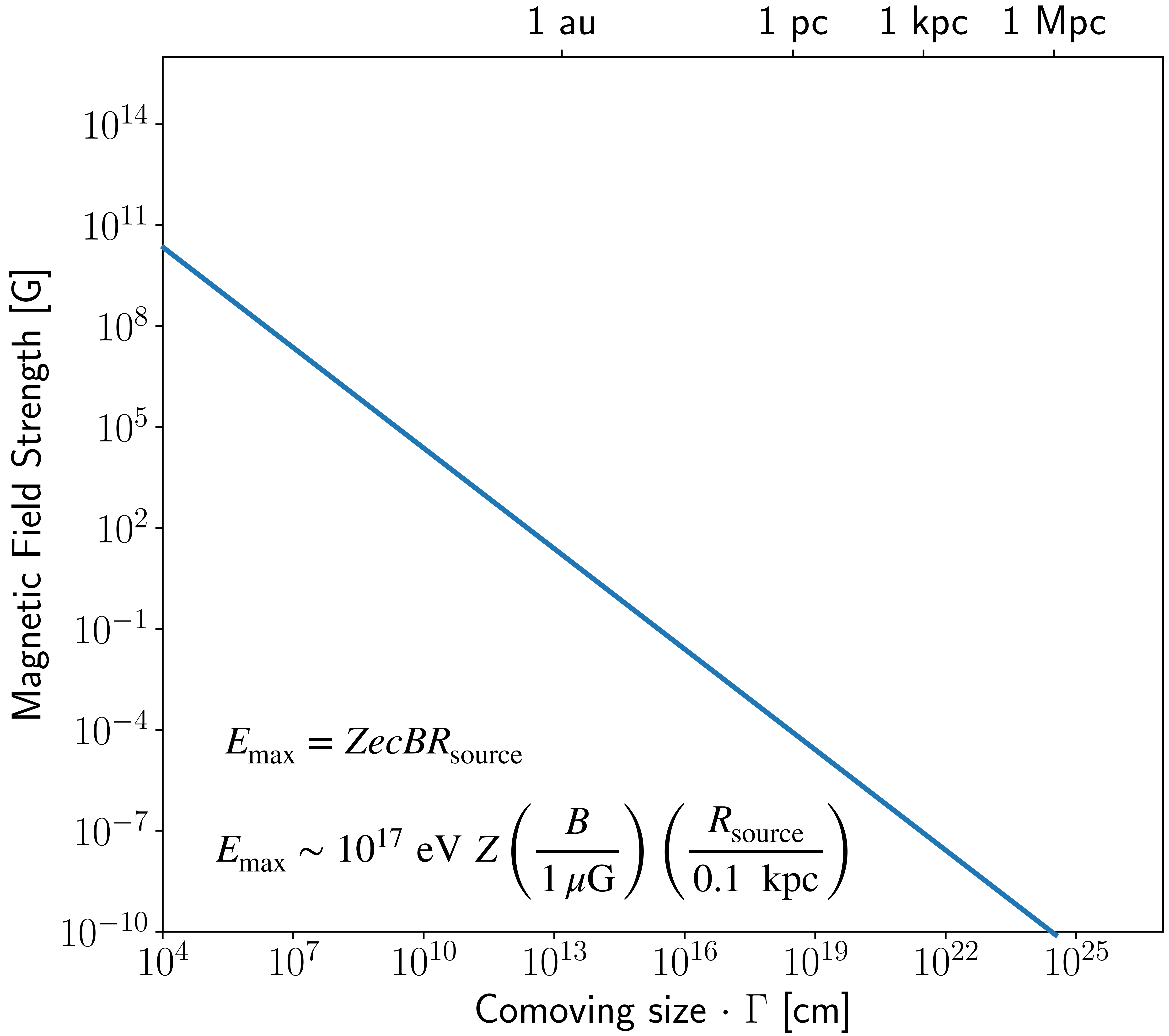
Cosmic-ray accelerators that satisfy the confinement requirement



Cosmic-ray accelerators that satisfy the confinement requirement (10^{17} eV)



Cosmic-ray accelerators that satisfy the confinement requirement (10^{17} eV)



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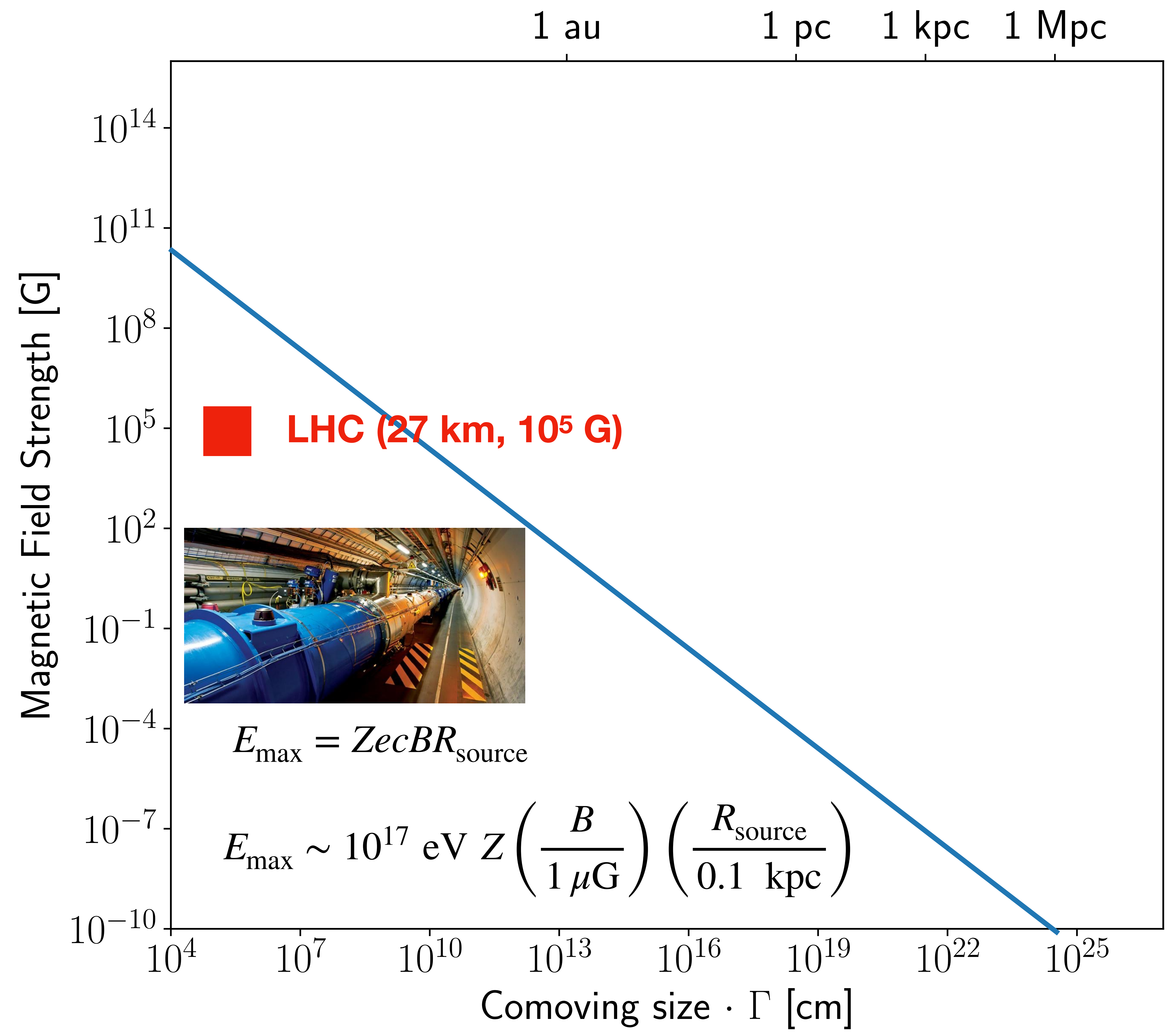

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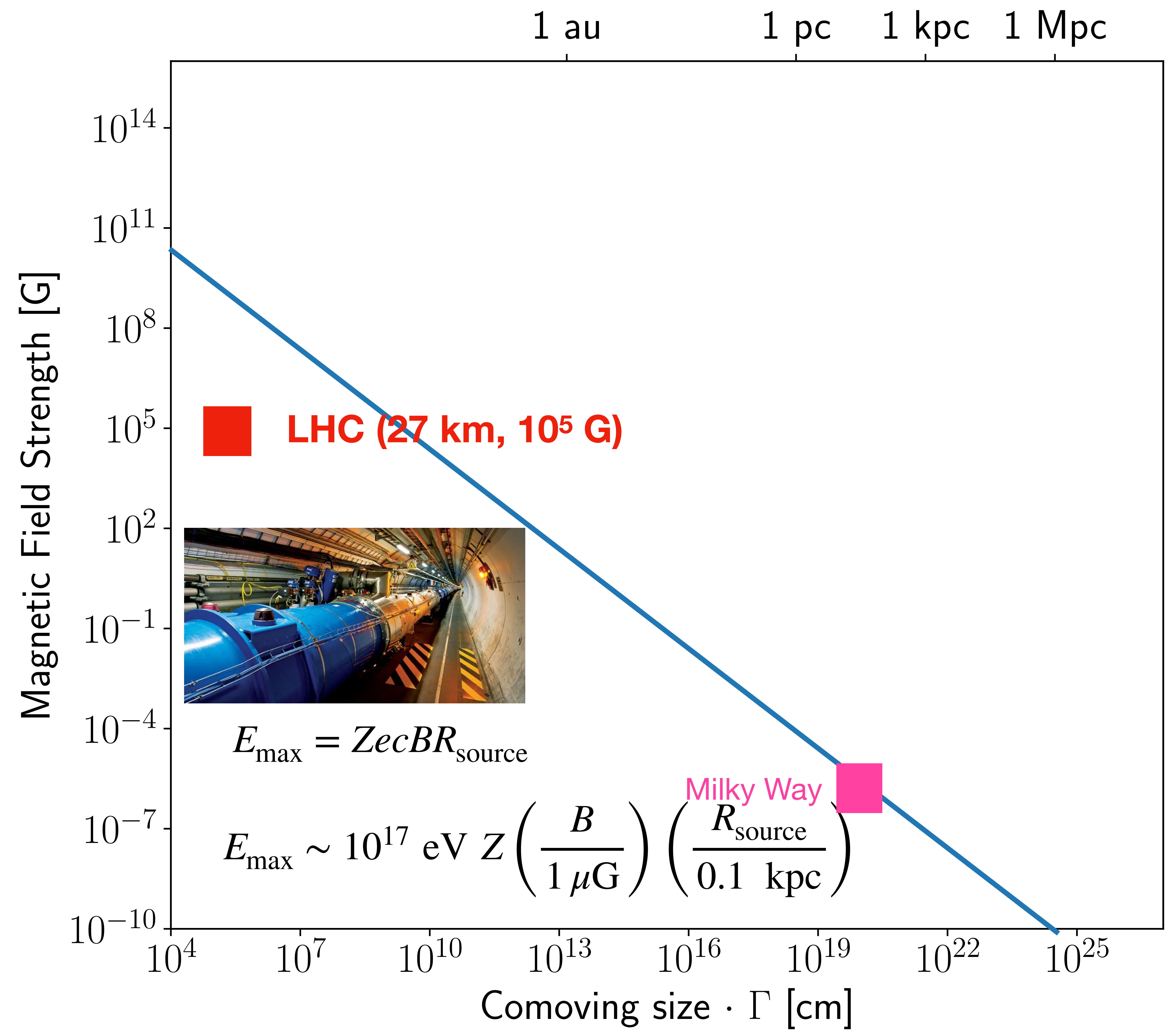
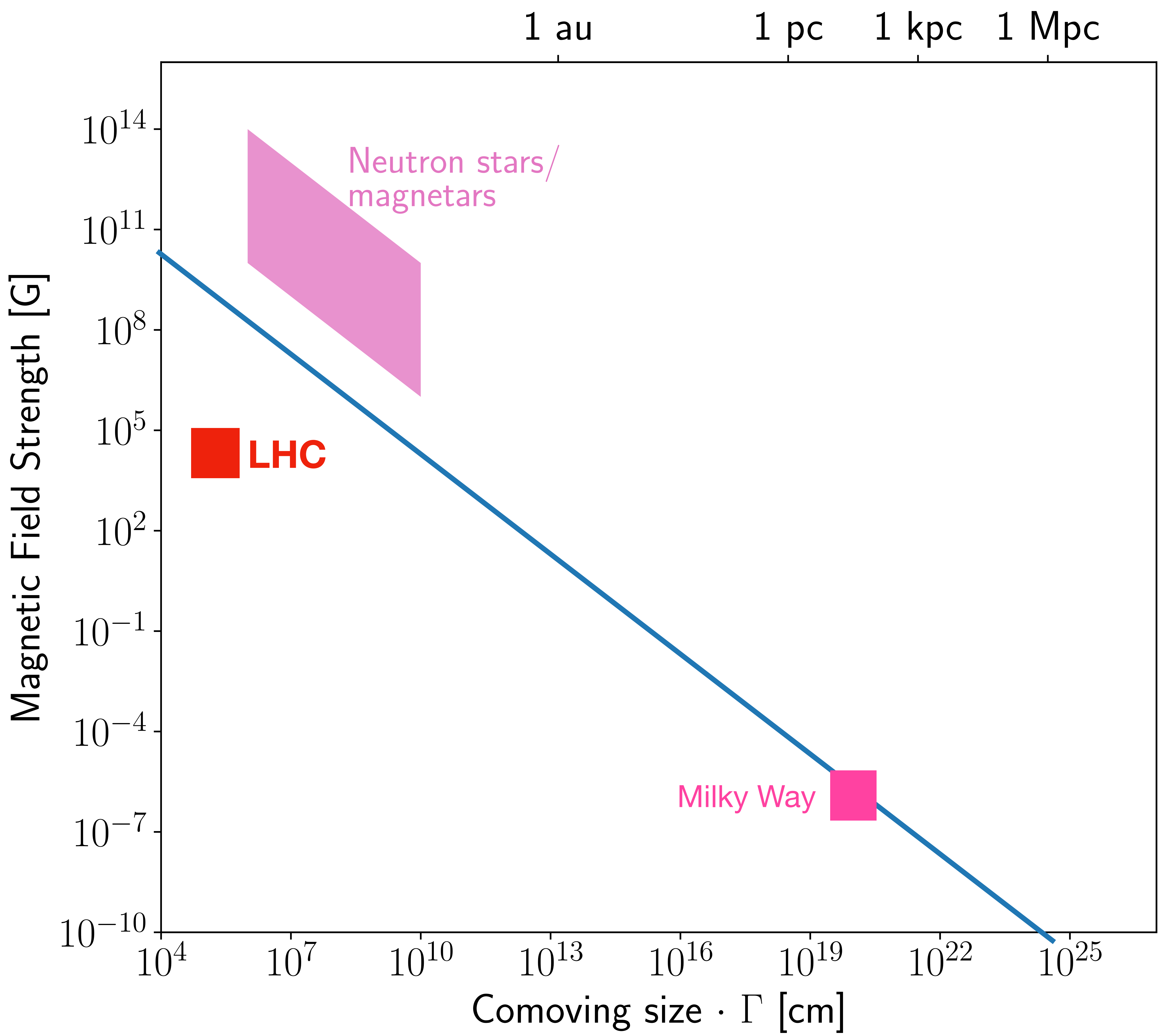


Cosmic-ray accelerators that satisfy the confinement req 17 eV)



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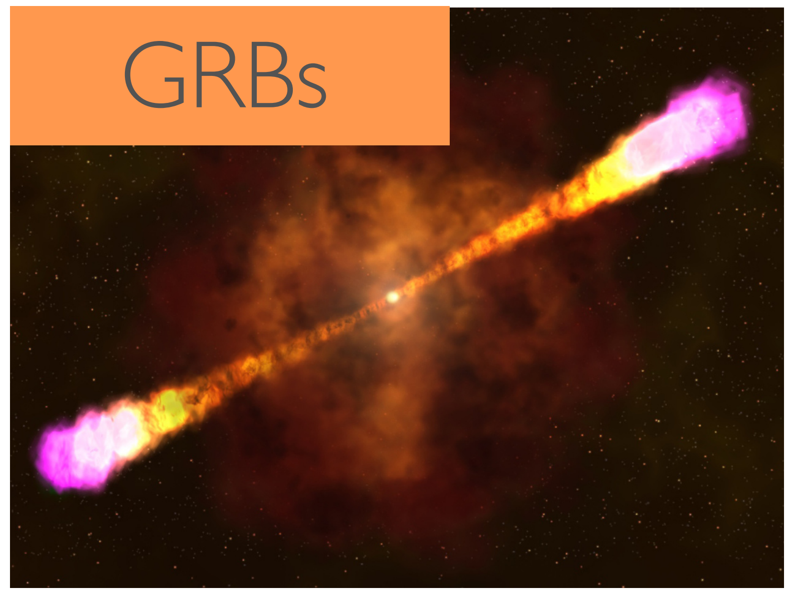

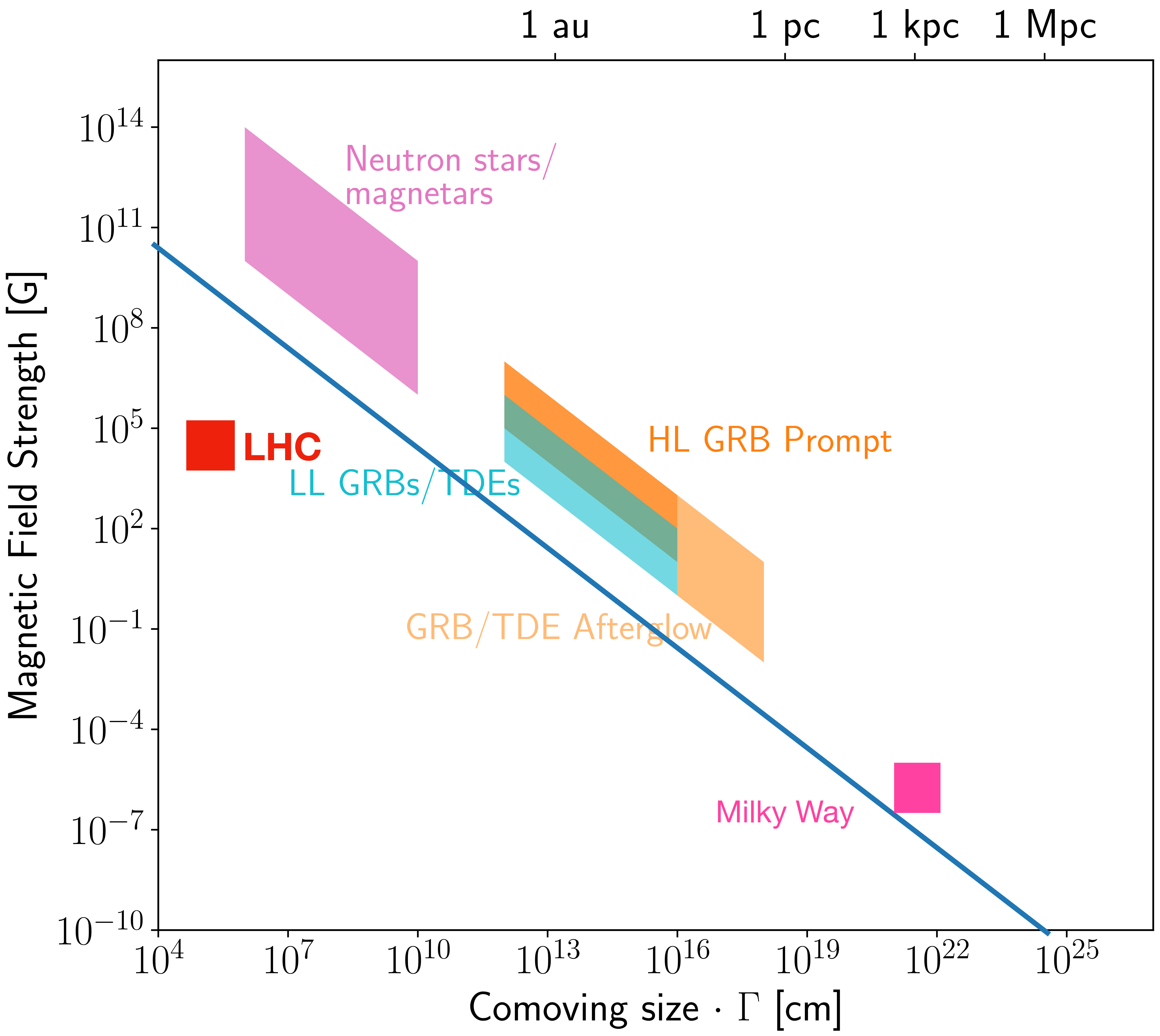

FO for MIAPP UHECR Review, 2019, FrASS, 6, 23

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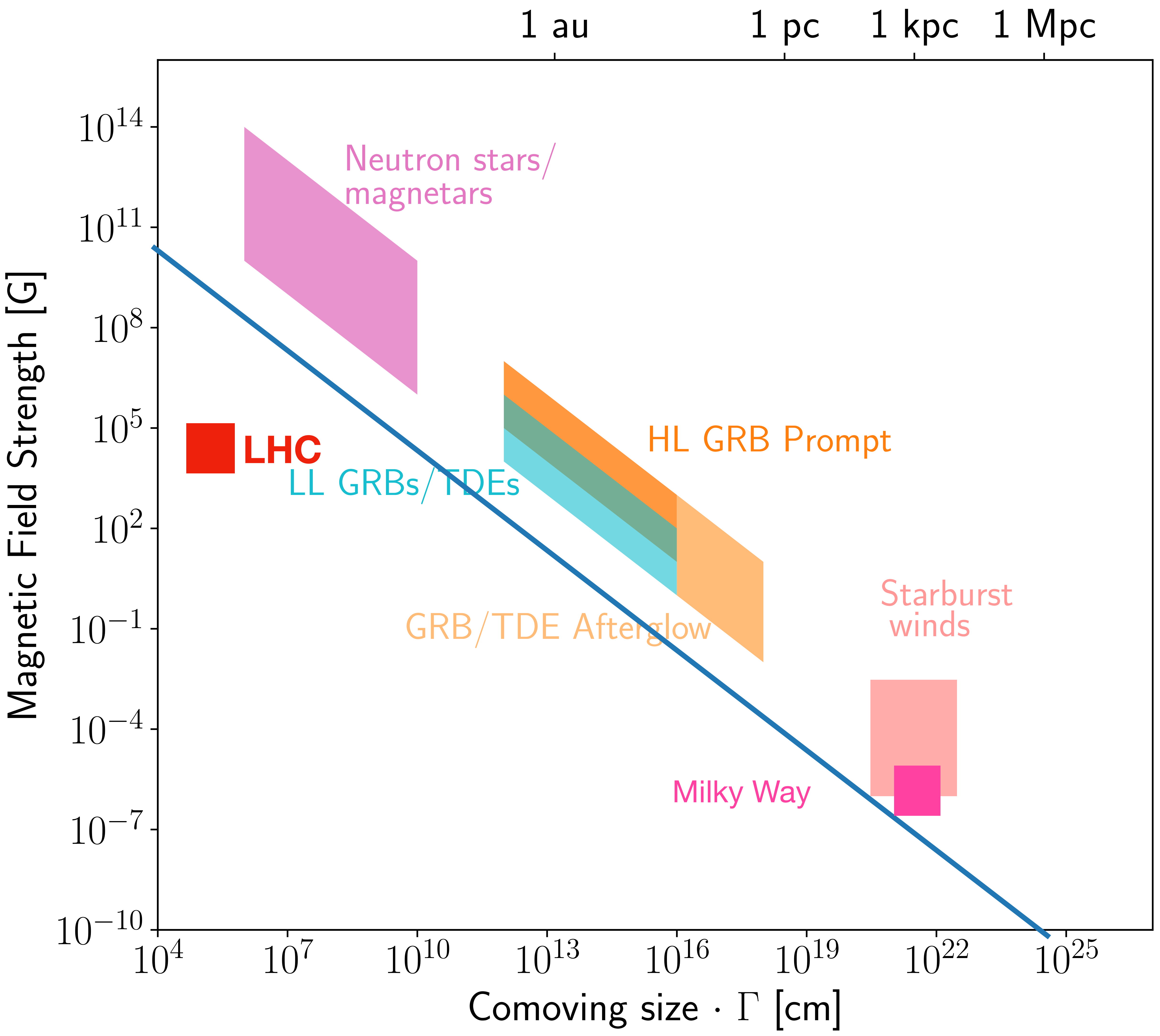

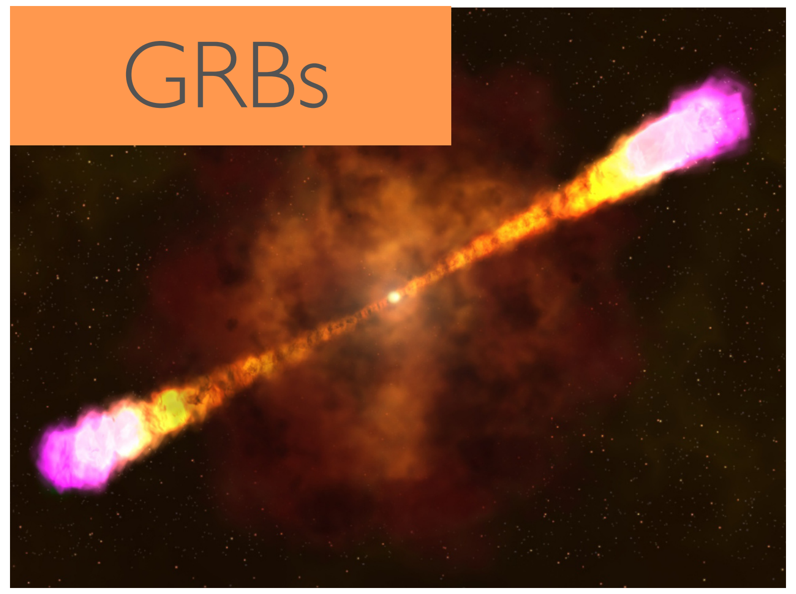

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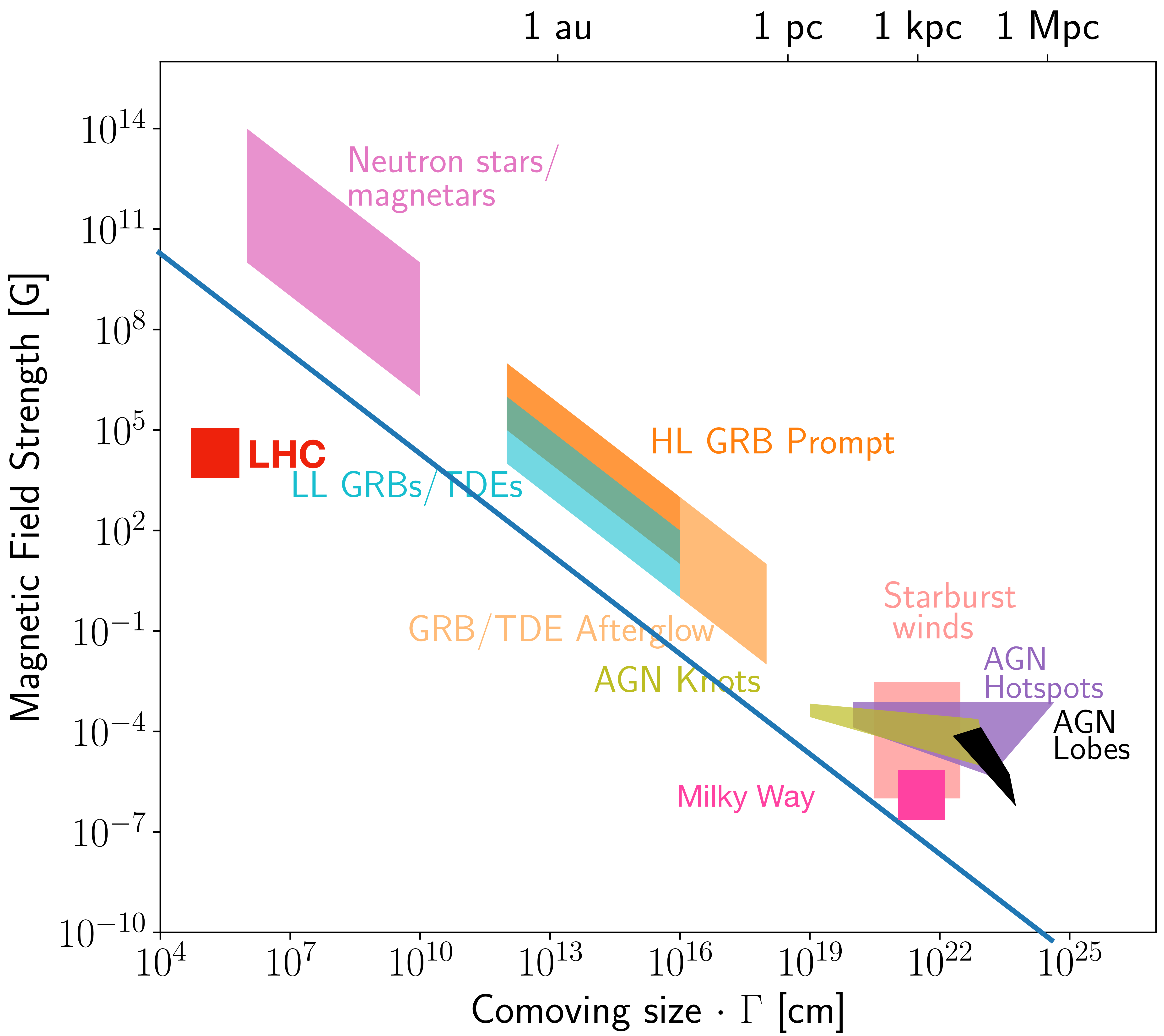

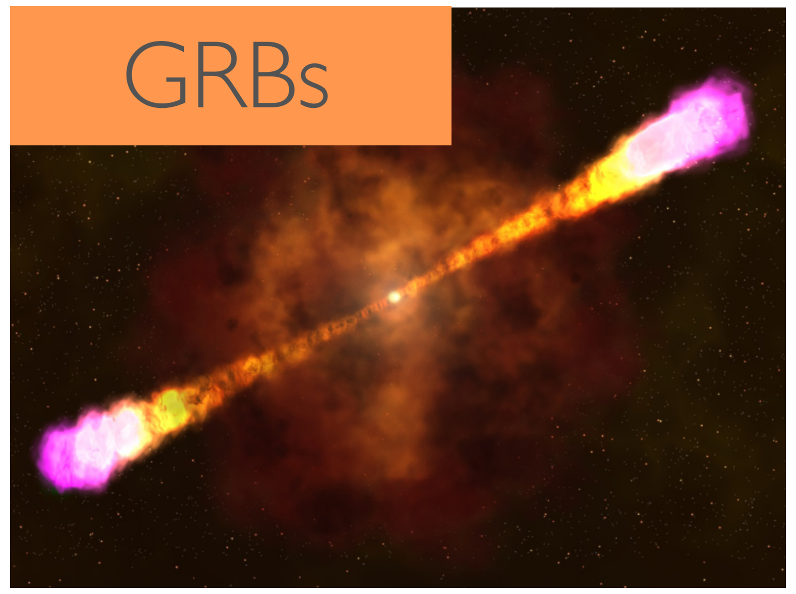

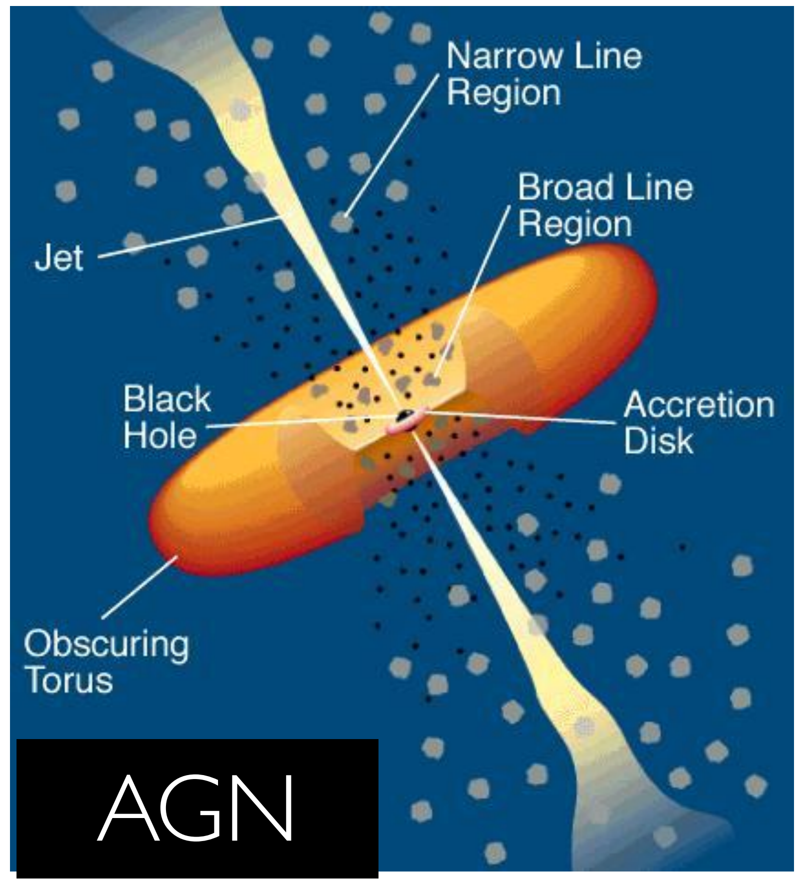

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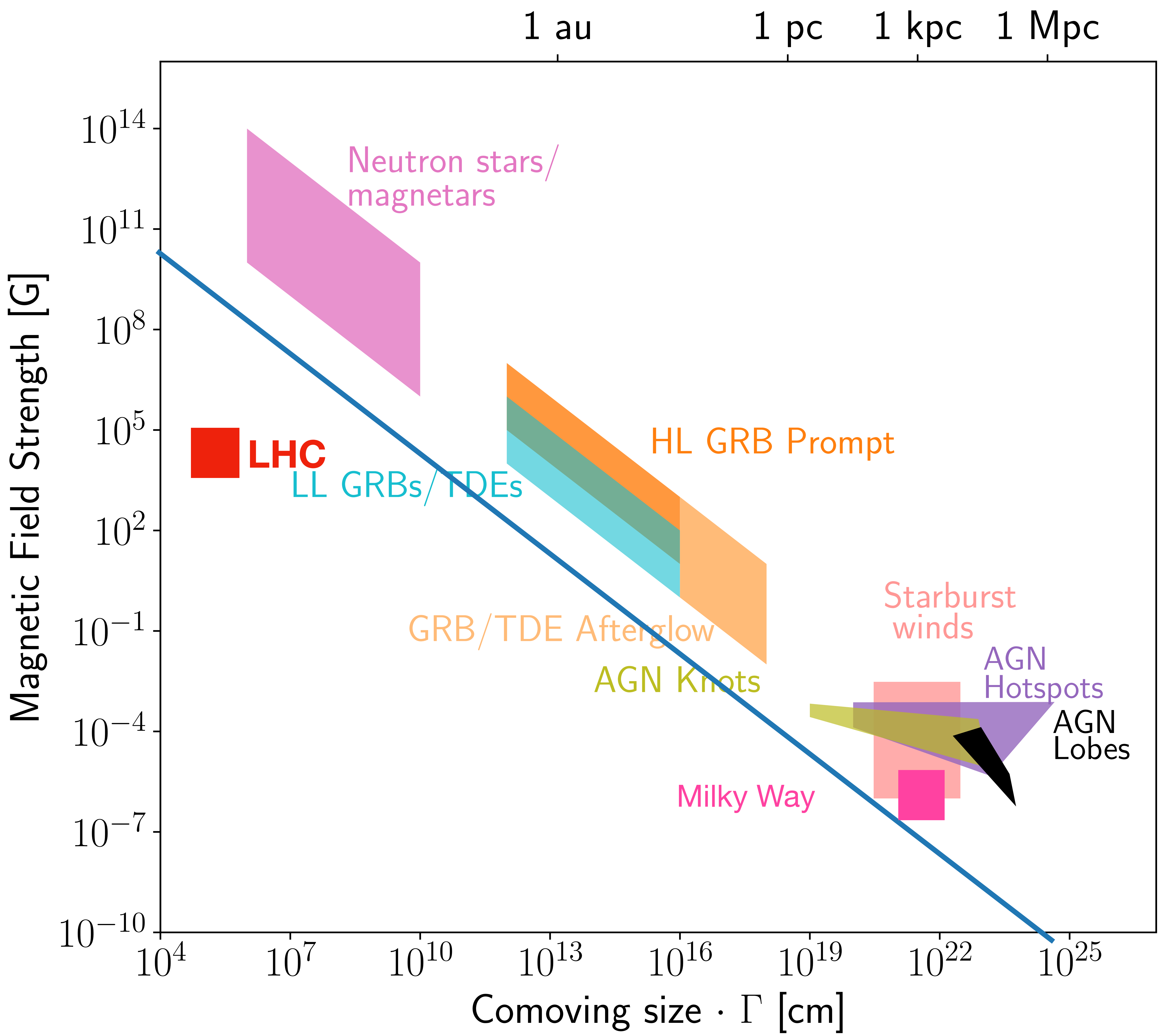

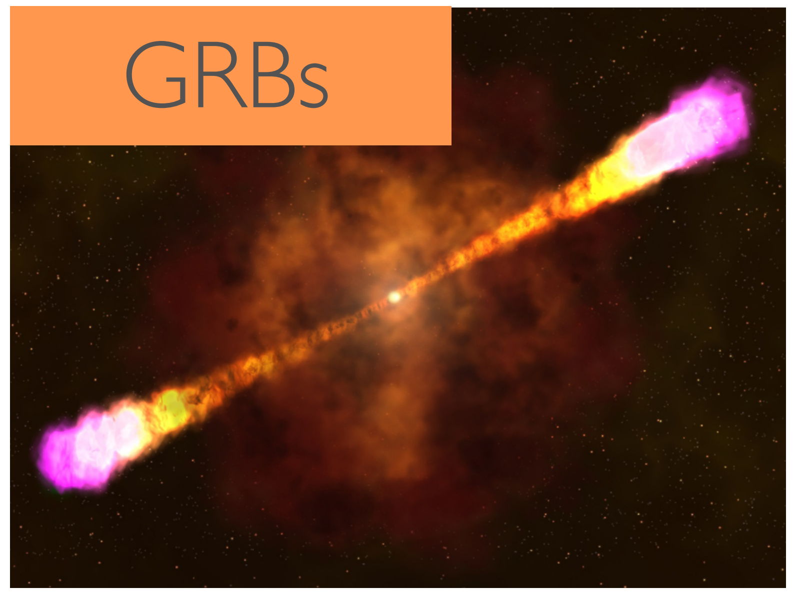

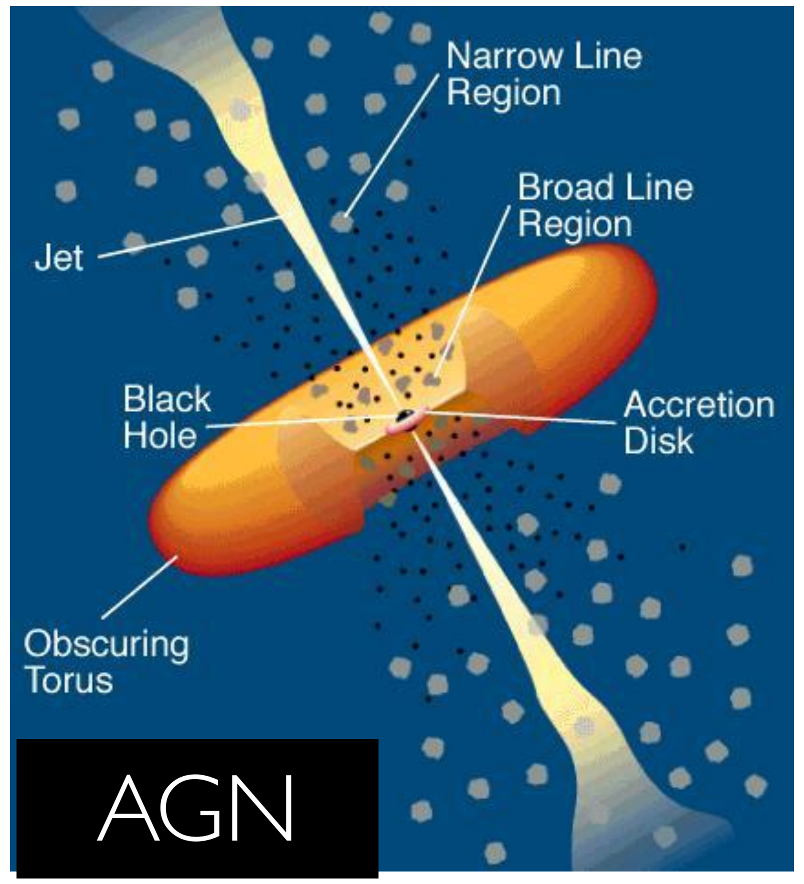

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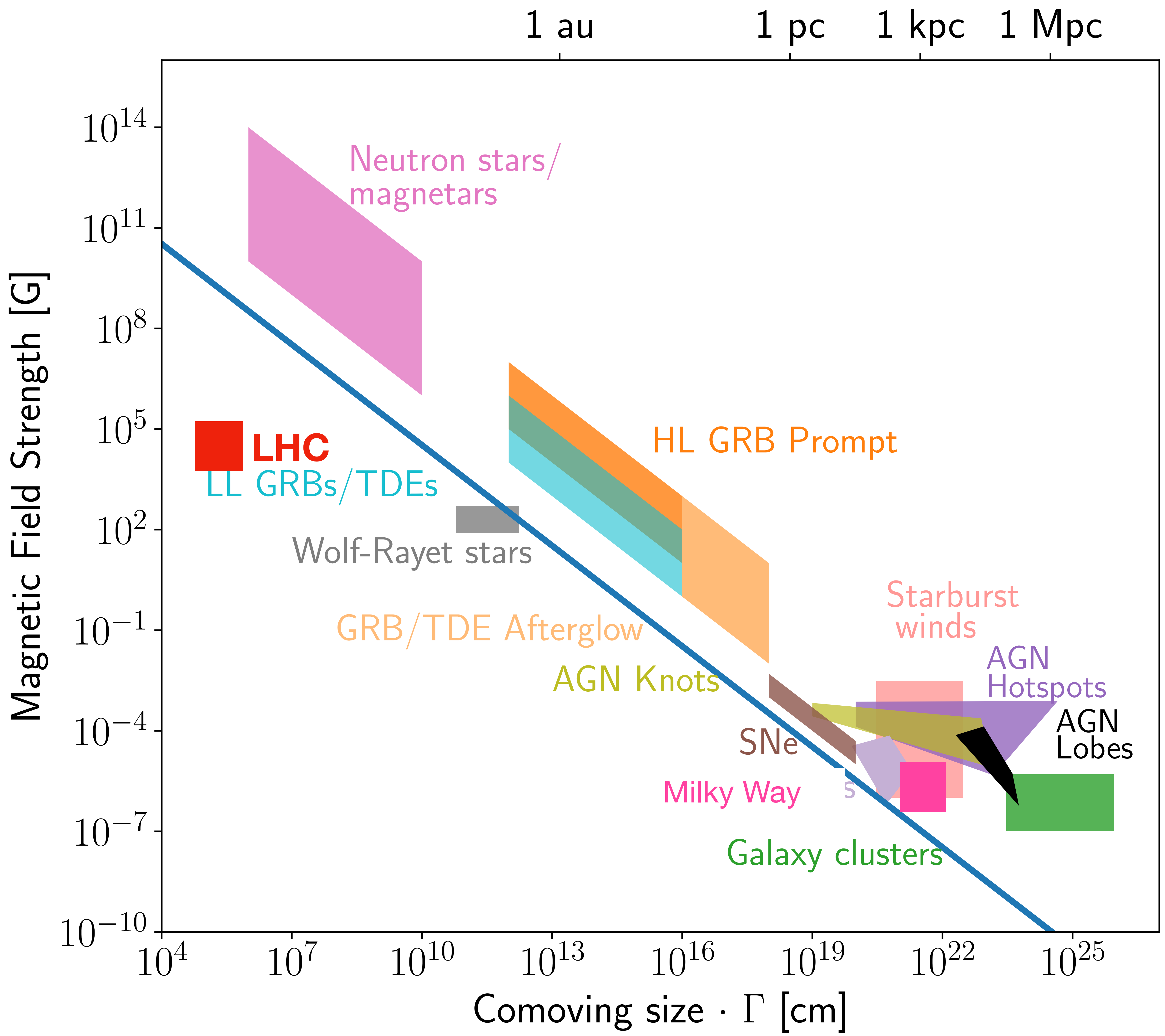

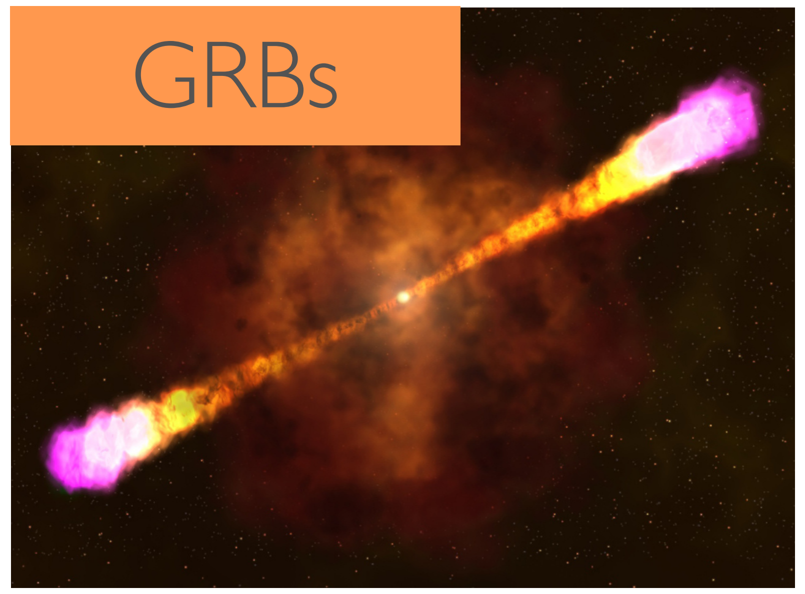

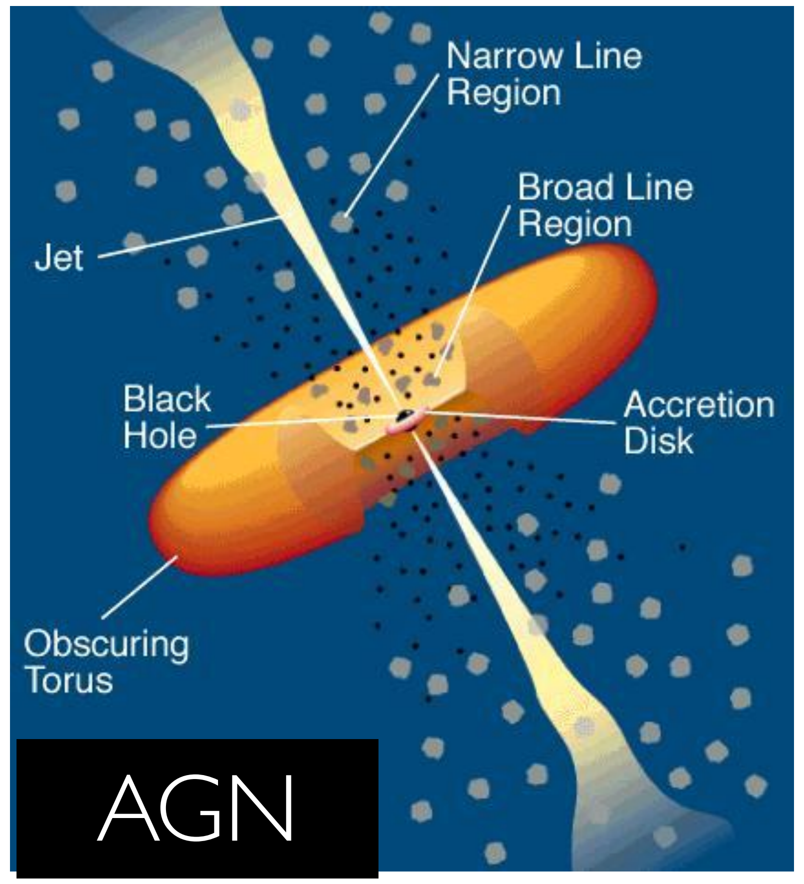

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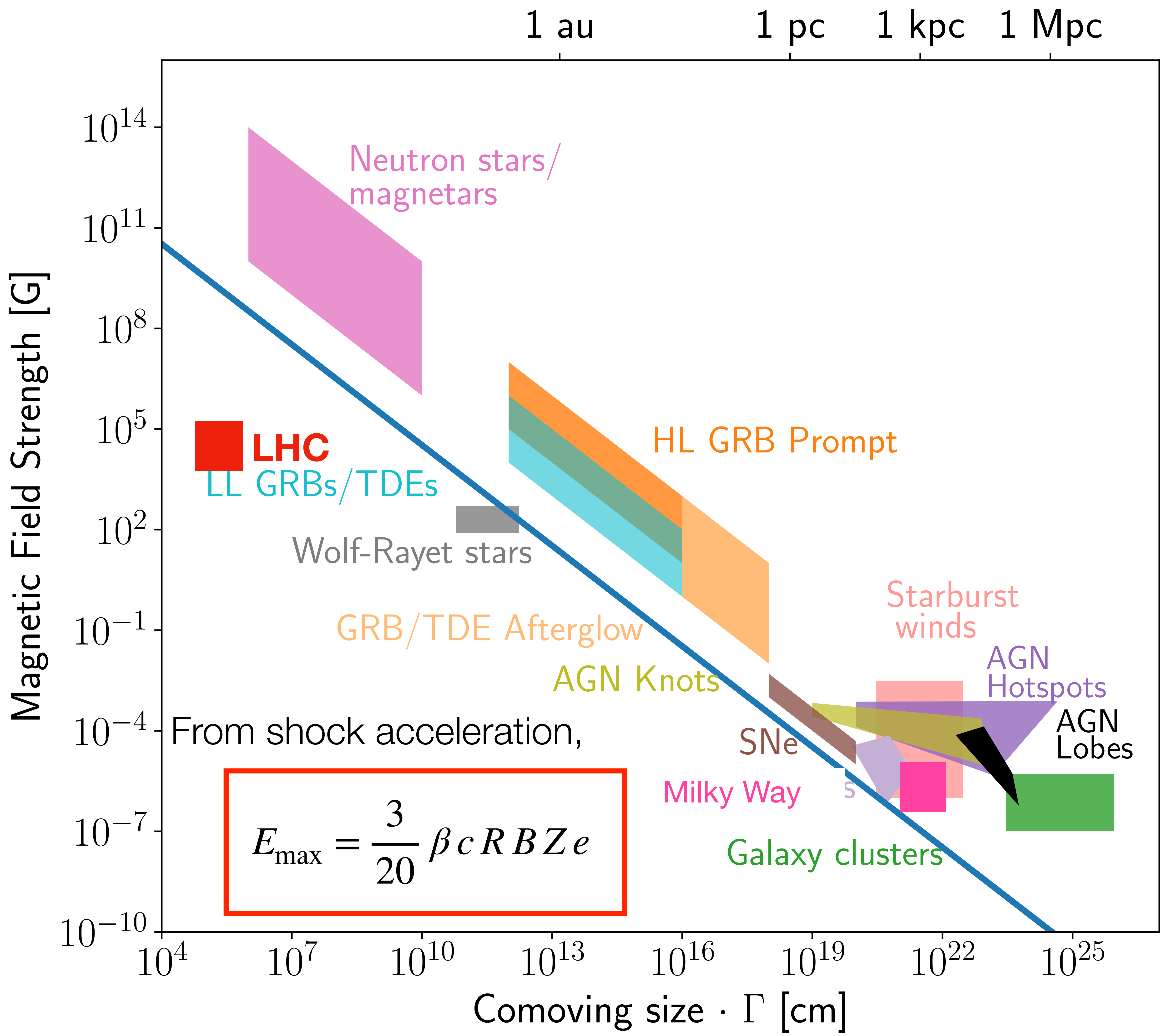

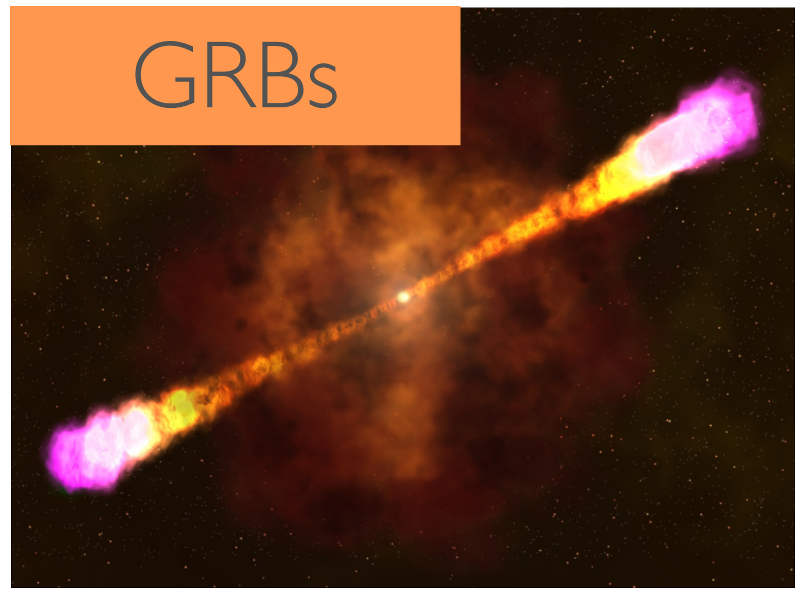

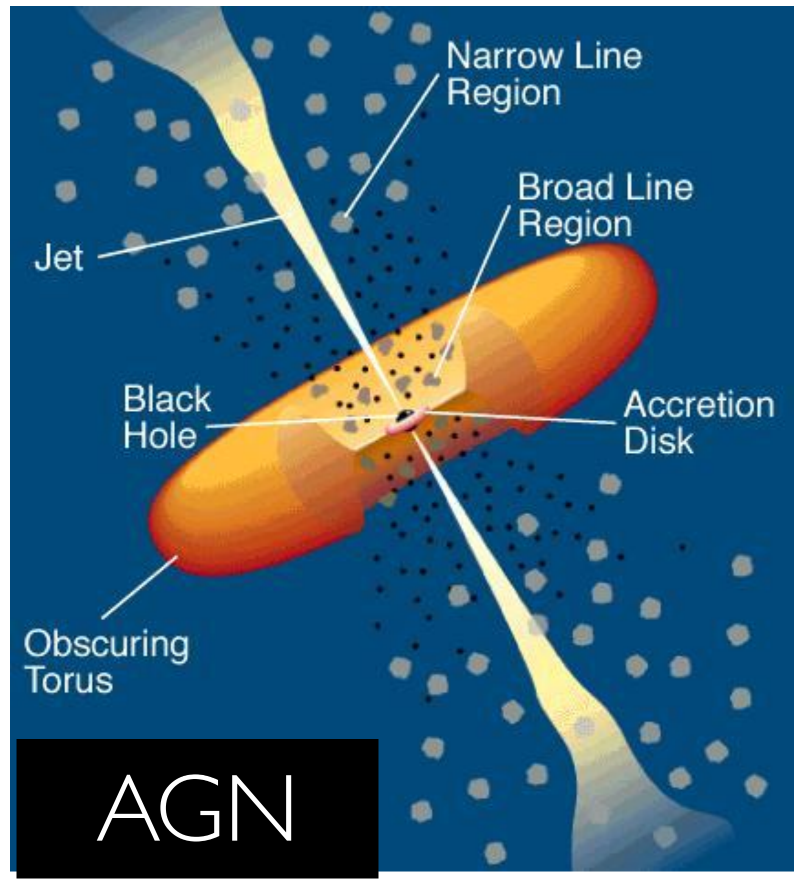

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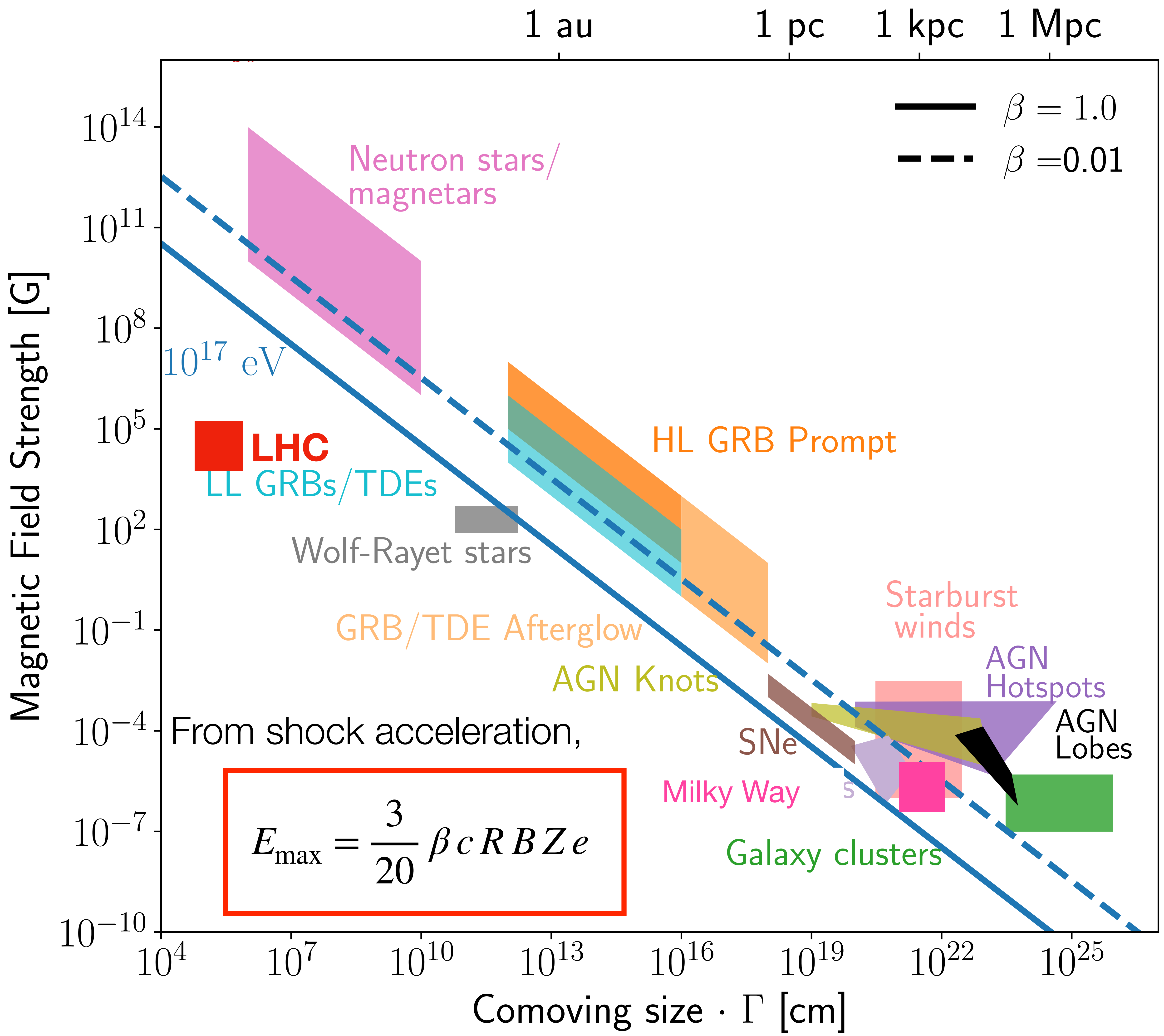

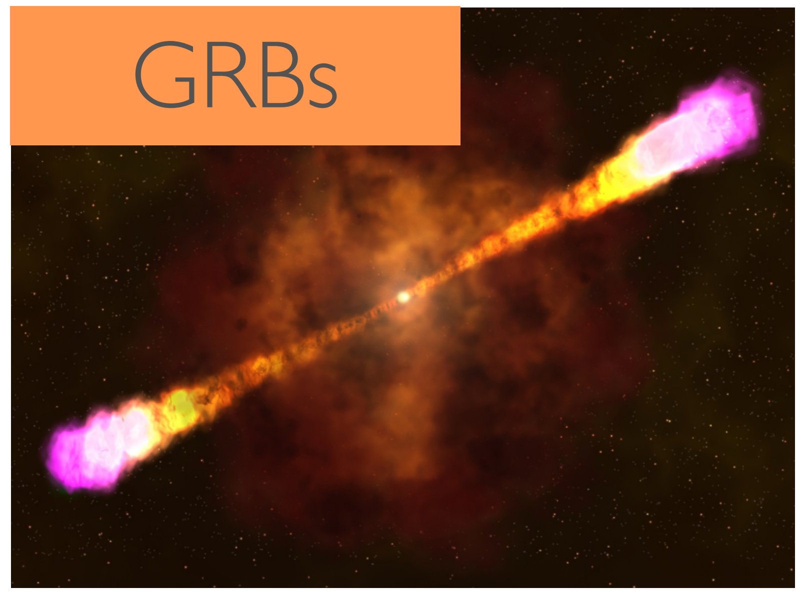

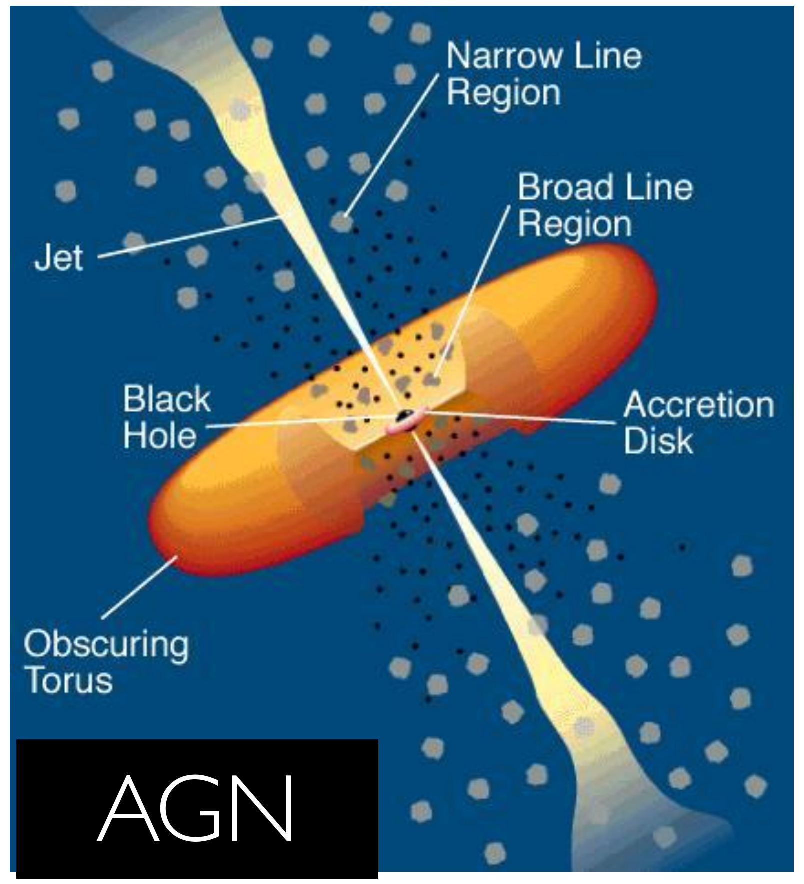

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- Hillas criterion for acceleration and plausible sources
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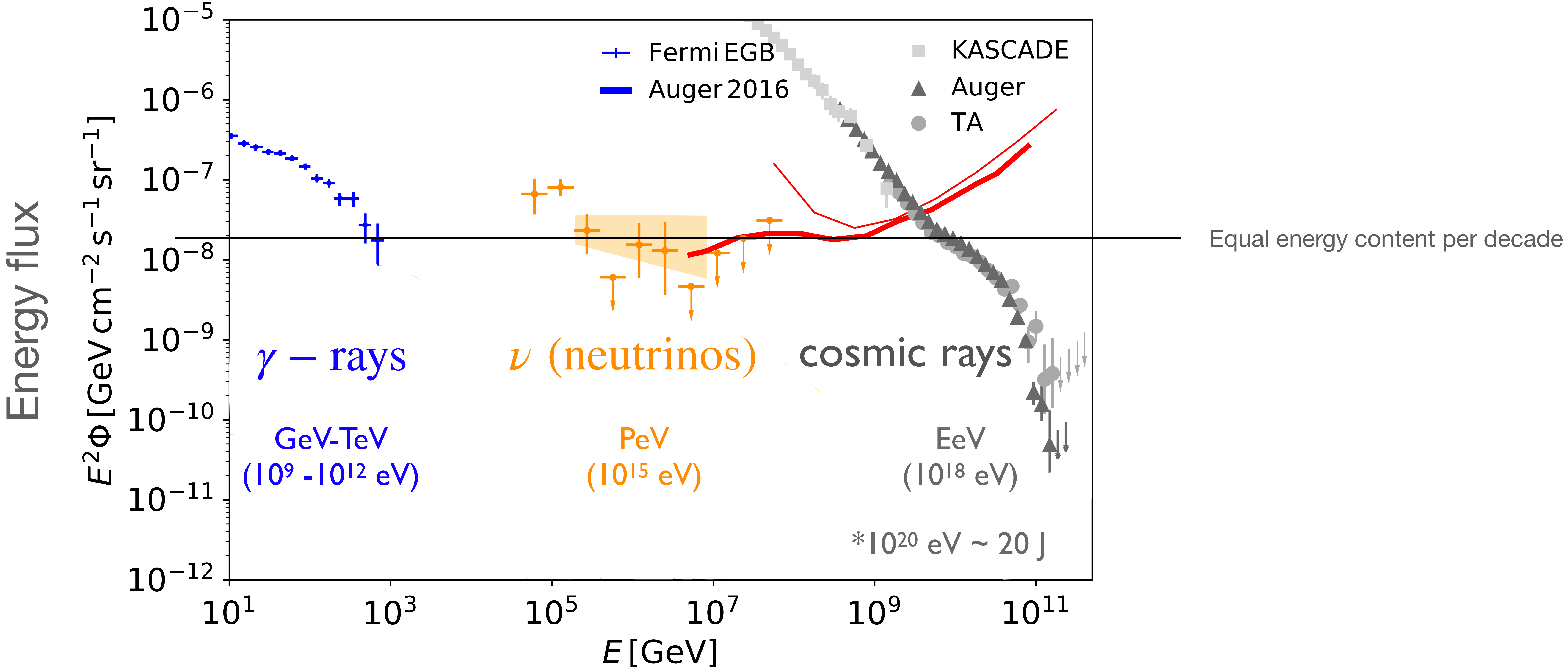
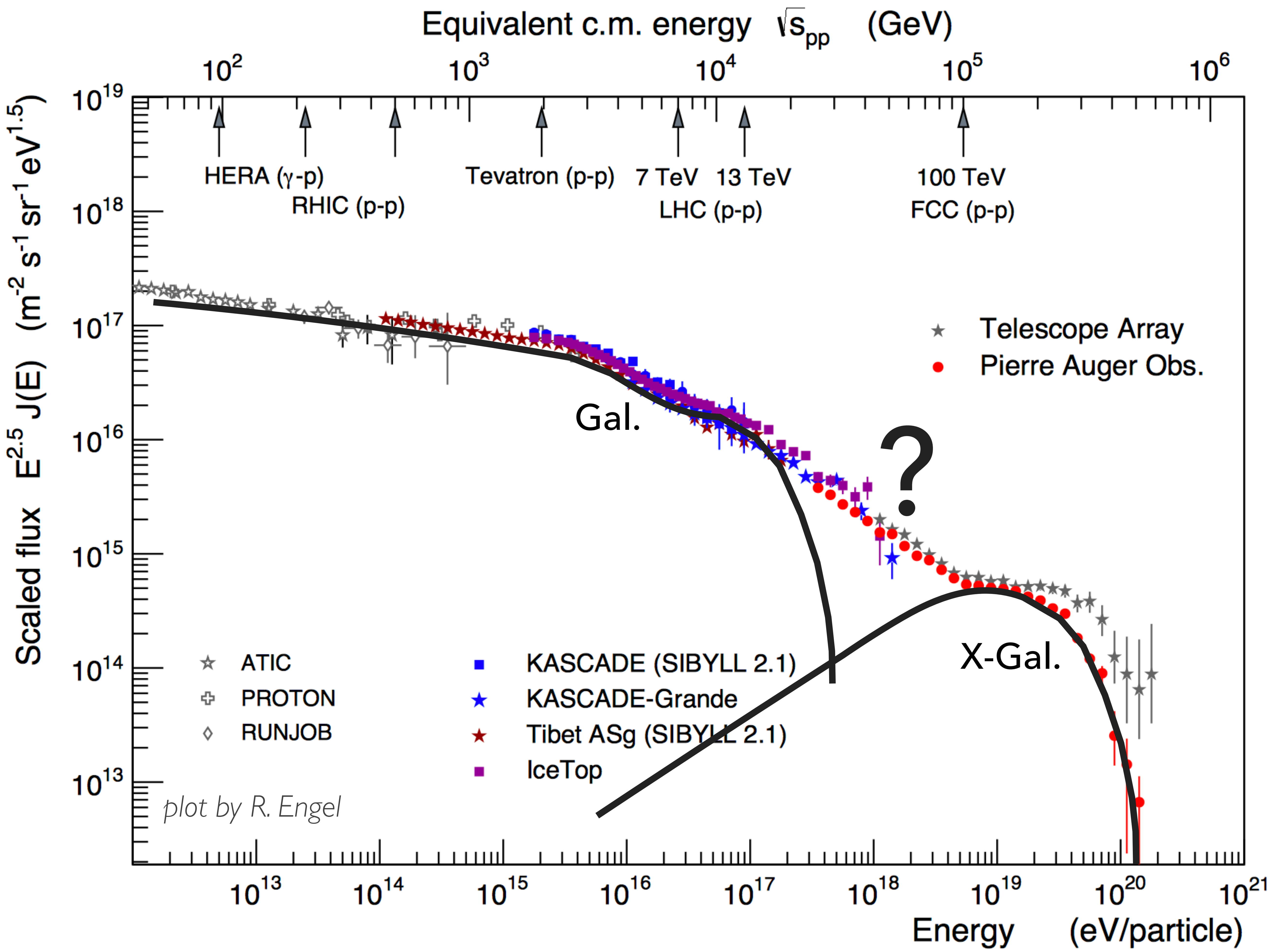
Neutrino energy flux and multimessenger connections



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

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

Highest energy cosmic rays and multimessenger connections



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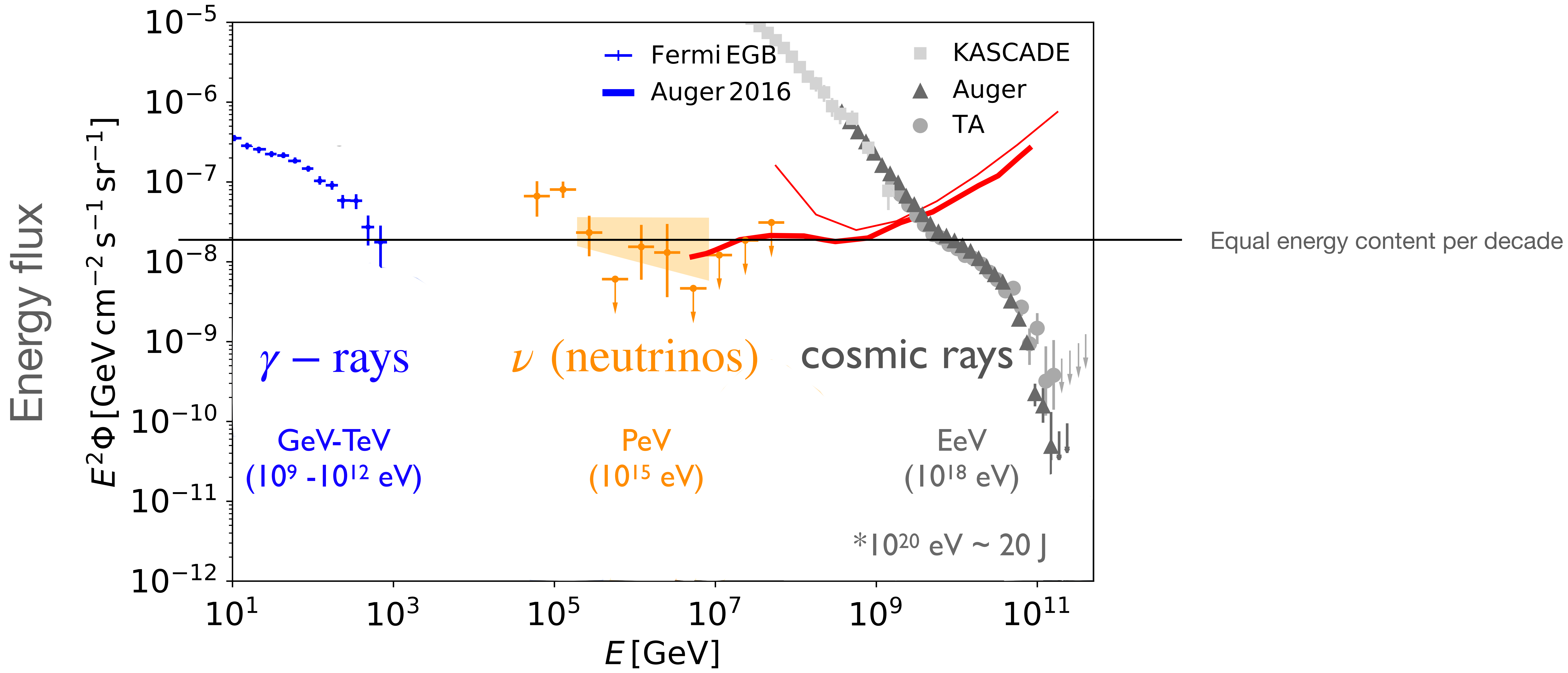
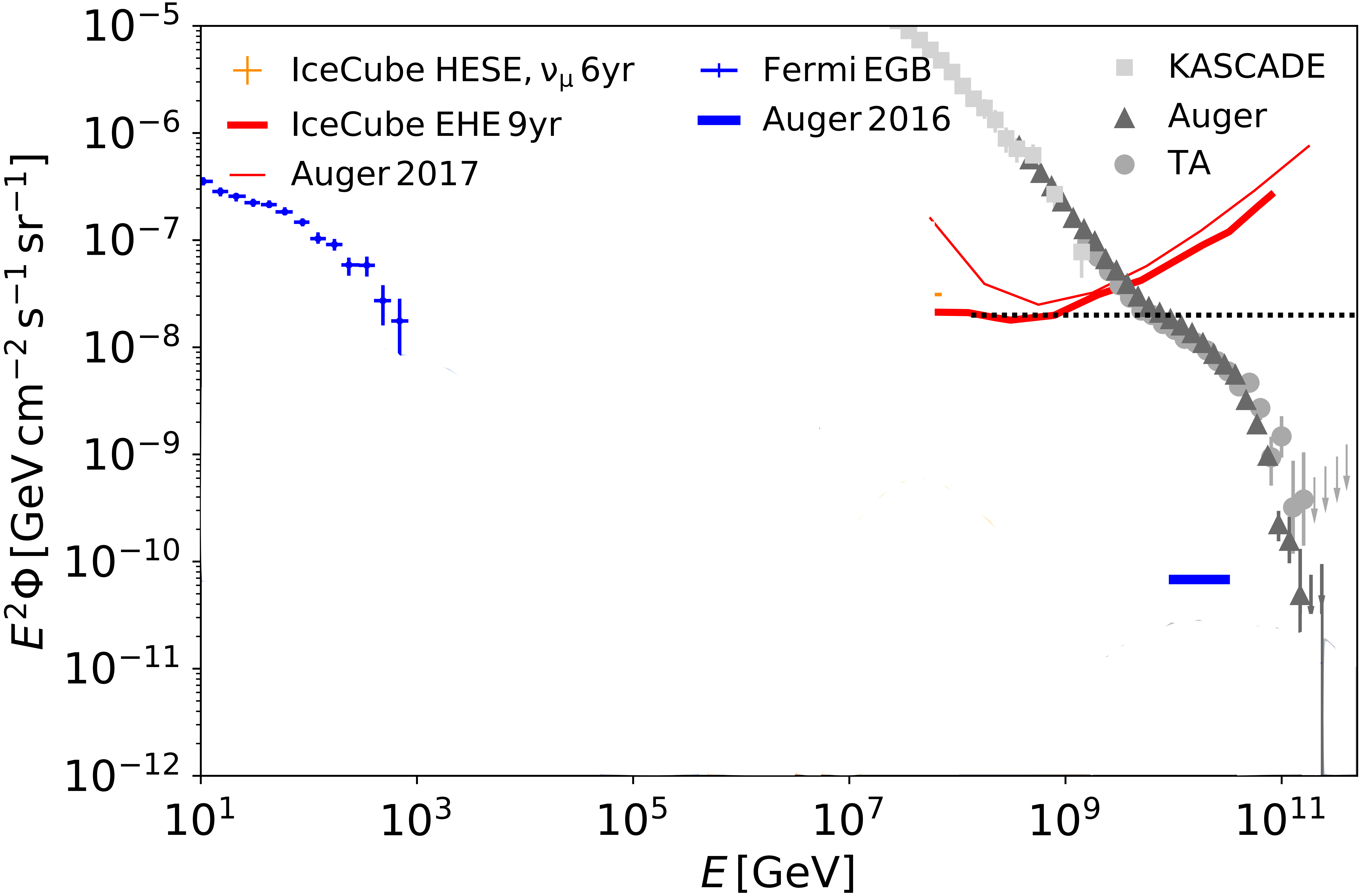


Waxman-Bahcall bound

E. Waxman, J. Bahcall, PRD 1998



1. UHECR energy loss length

Mean free path = 1/ (number density of targets x cross-section)

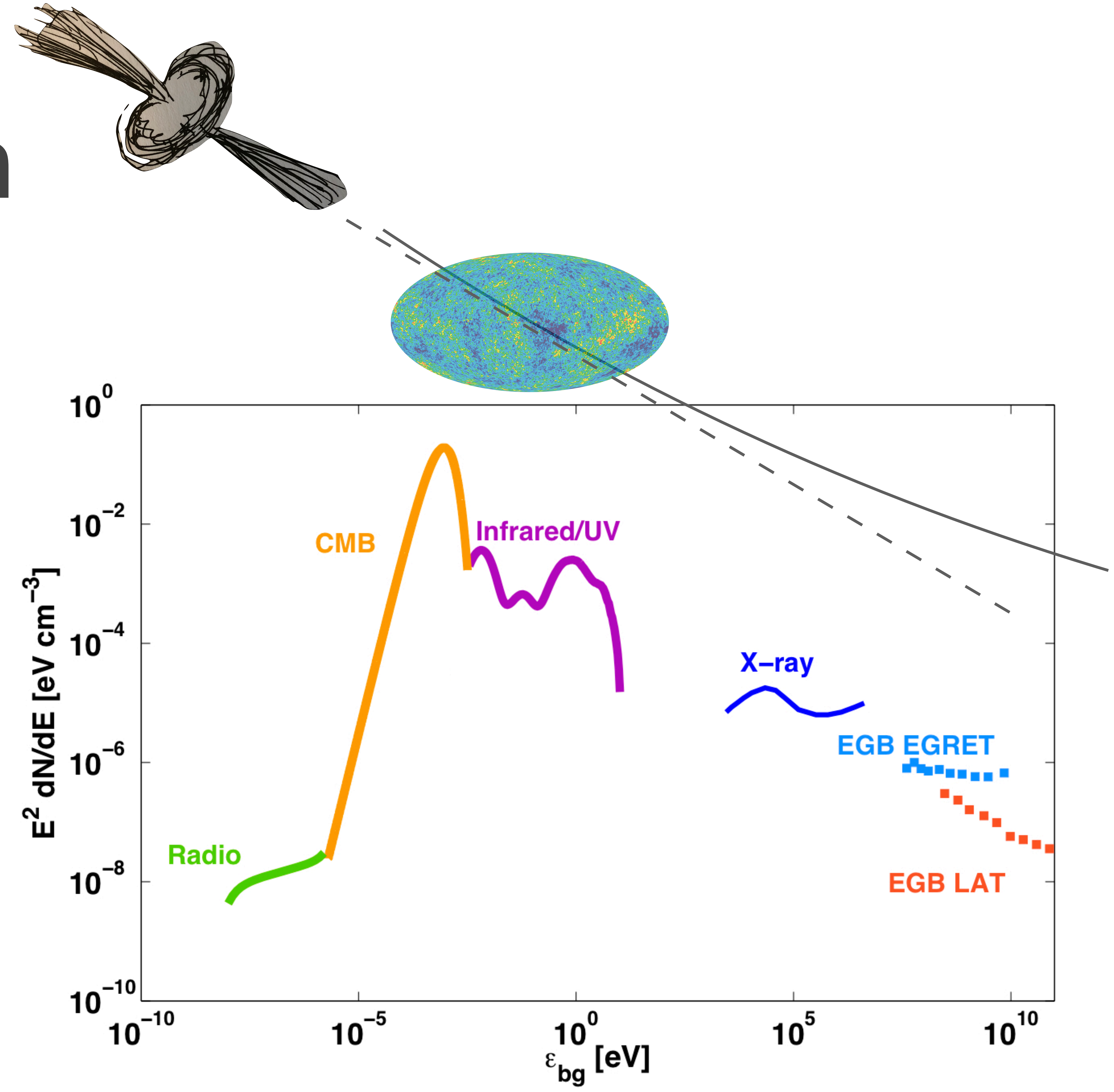
$$\lambda = 1/n\sigma$$

Relative energy loss per unit time:

$$\left| -\frac{1}{E}\frac{\mathrm{d}E}{\mathrm{d}t} \right| = \left\langle \kappa \sigma n_\gamma c \right\rangle, \kappa = \frac{\Delta E}{E} = \text{inelasticity}$$

Energy loss length:

$$\chi_{\mathrm{loss}} = c \cdot \left| \frac{1}{E}\frac{\mathrm{d}E}{\mathrm{d}t} \right|^{-1}$$



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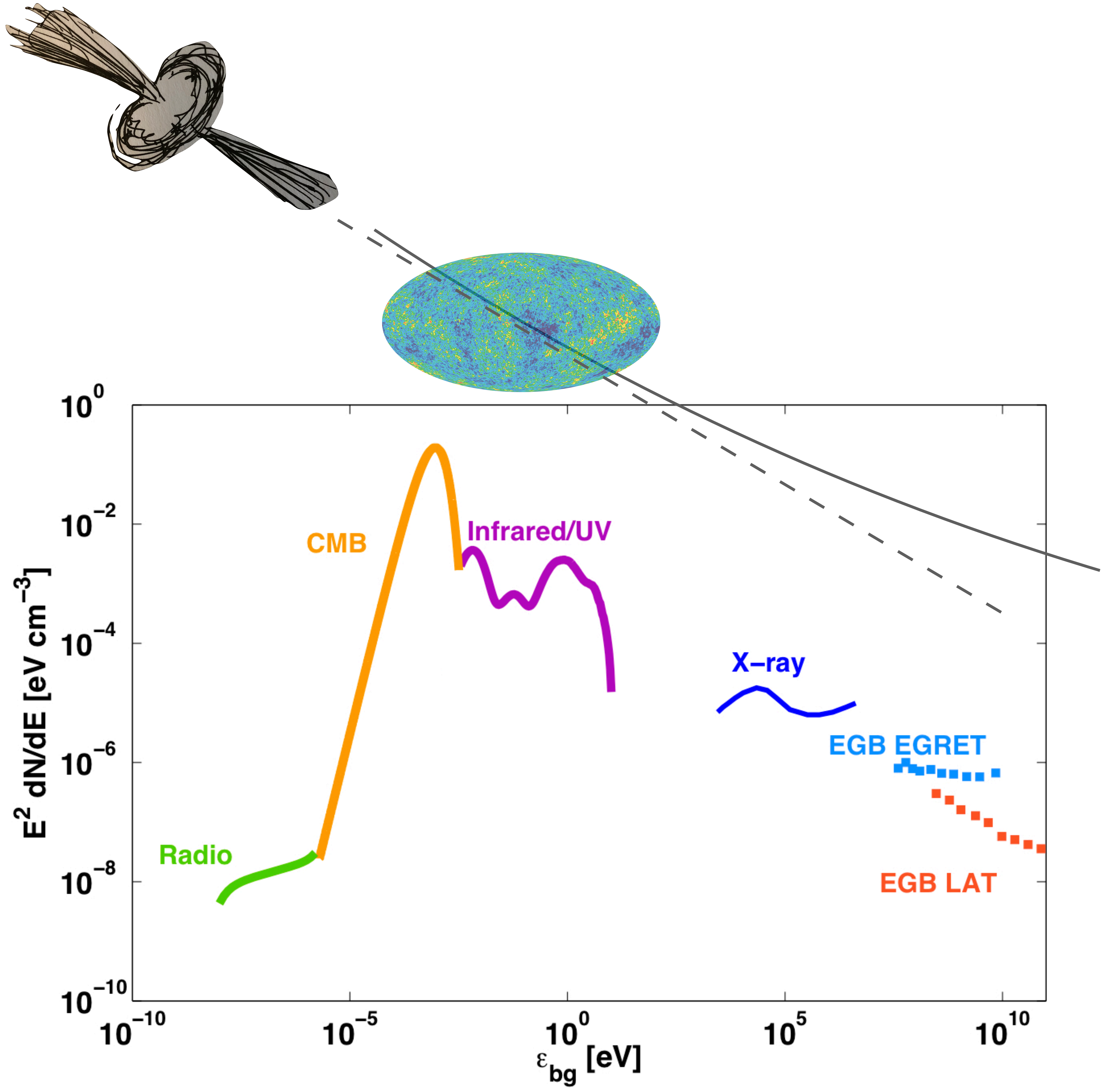


Photo-pair production (Bethe-Heitler process):

$$p + \gamma_{\rm bg} \rightarrow p + e^+ + e^-$$

$$[\kappa_{p\gamma}^{ee} = 2m_e/m_p \approx 10^{-3}, \sigma_{p\gamma,\rm thresh}^{ee} \approx 1.2 \cdot 10^{-27}\,\mathrm{cm}^2, n_{\rm CMB} \approx 411\,\mathrm{cm}^{-3}]$$

$$E_p \gtrsim 10^{19}\,\mathrm{eV} \left(\frac{\varepsilon_\gamma}{6 \times 10^{-4}\,\mathrm{eV}} \right)^{-1}$$

$$\lambda_{p\gamma}^{ee} \sim 1/(n_{\rm CMB} \cdot \sigma_{p\gamma}^{ee}) \sim 1\,\mathrm{Mpc}$$

$$\chi_{\rm BH,loss} \sim \lambda_{p\gamma}^{ee}/\kappa \sim 1\mathrm{Gpc}$$

1. UHECR energy loss length

Photo-pion production

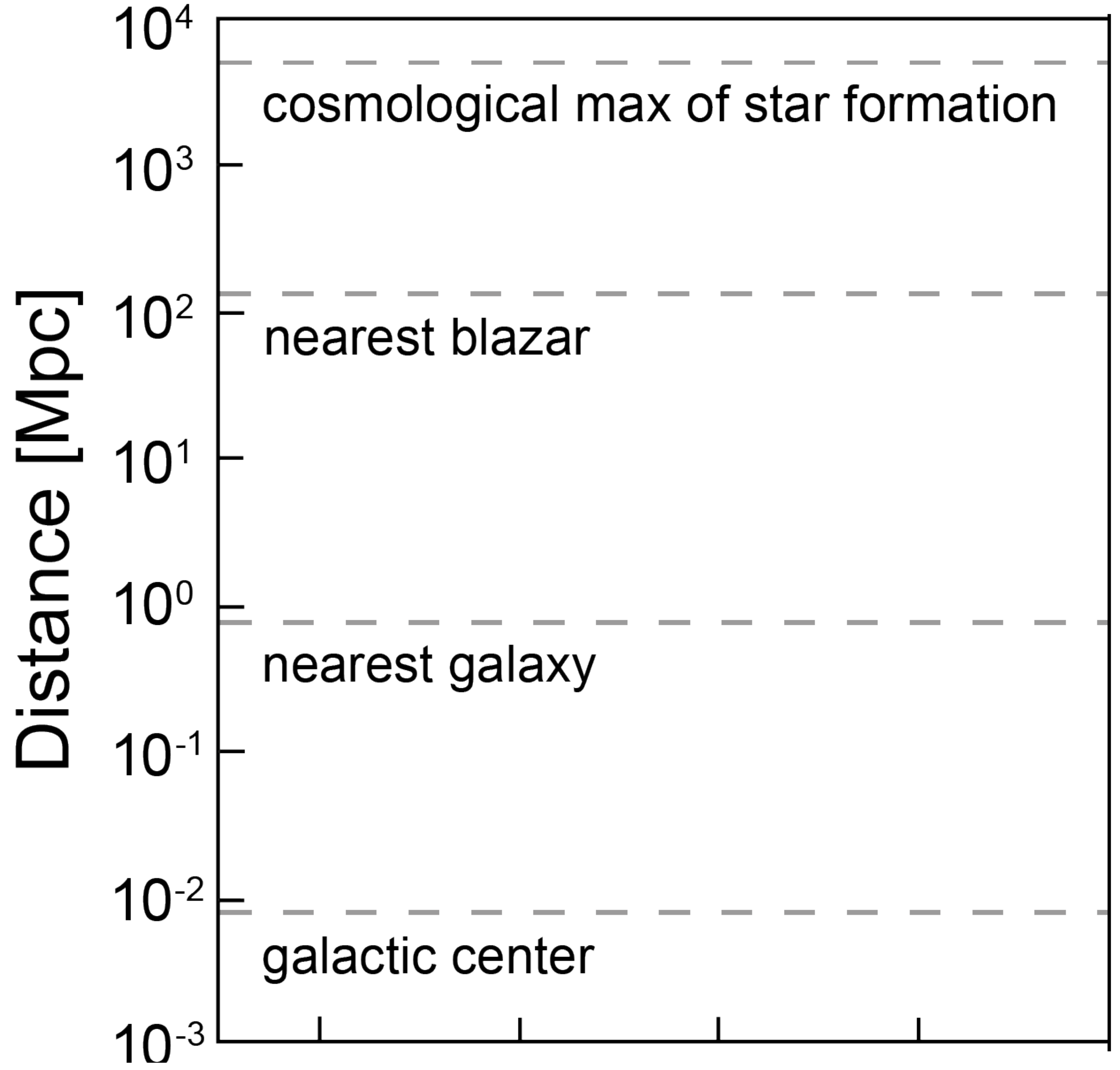
Photo-pion production:

$$p + \gamma_{\rm CMB} \rightarrow \Delta^+ \rightarrow n/p + \pi^+/\pi^0$$

$$E_{\rm p} \gtrsim 10^{20}\,{\rm eV}\left(\frac{\varepsilon_{\gamma,{\rm cmb}}}{6\cdot 10^{-4}\,{\rm eV}}\right)^{-1}, n_{\rm cmb} \sim 411\,{\rm cm}^{-3}$$

$$\left[\kappa \approx m_\pi/m_p \approx 0.2, \sigma_{p\gamma} \approx 5\cdot 10^{-28}\,{\rm cm}^2\right]$$

$$\lambda_{p\gamma,{\rm CMB}} = 1/n\sigma \sim 6\,{\rm Mpc},\ \chi_{\rm loss} = \lambda/\kappa \sim 50\,{\rm Mpc}$$



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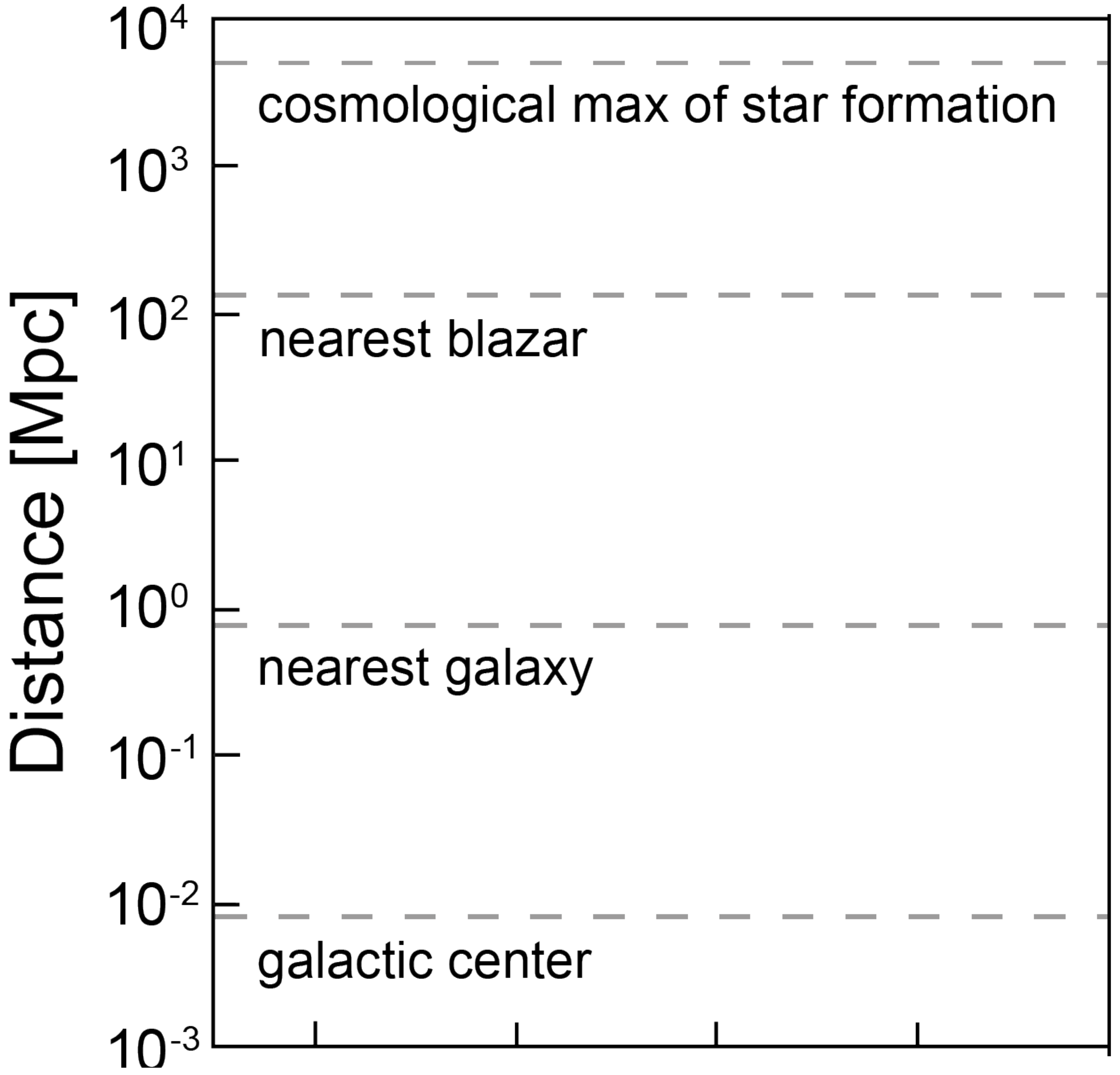
$$E_{\rm p} \gtrsim 7\cdot 10^{17}\,{\rm eV}\left(\frac{\varepsilon_{\gamma,{\rm IR}}}{0.1\,{\rm eV}}\right)^{-1}, n_{\rm EBL} \sim 10^{-2}\,{\rm cm}^{-3}$$

$$\left[\kappa \approx m_\pi/m_p \approx 0.2, \sigma_{p\gamma} \approx 5\cdot 10^{-28}\,{\rm cm}^2\right]$$

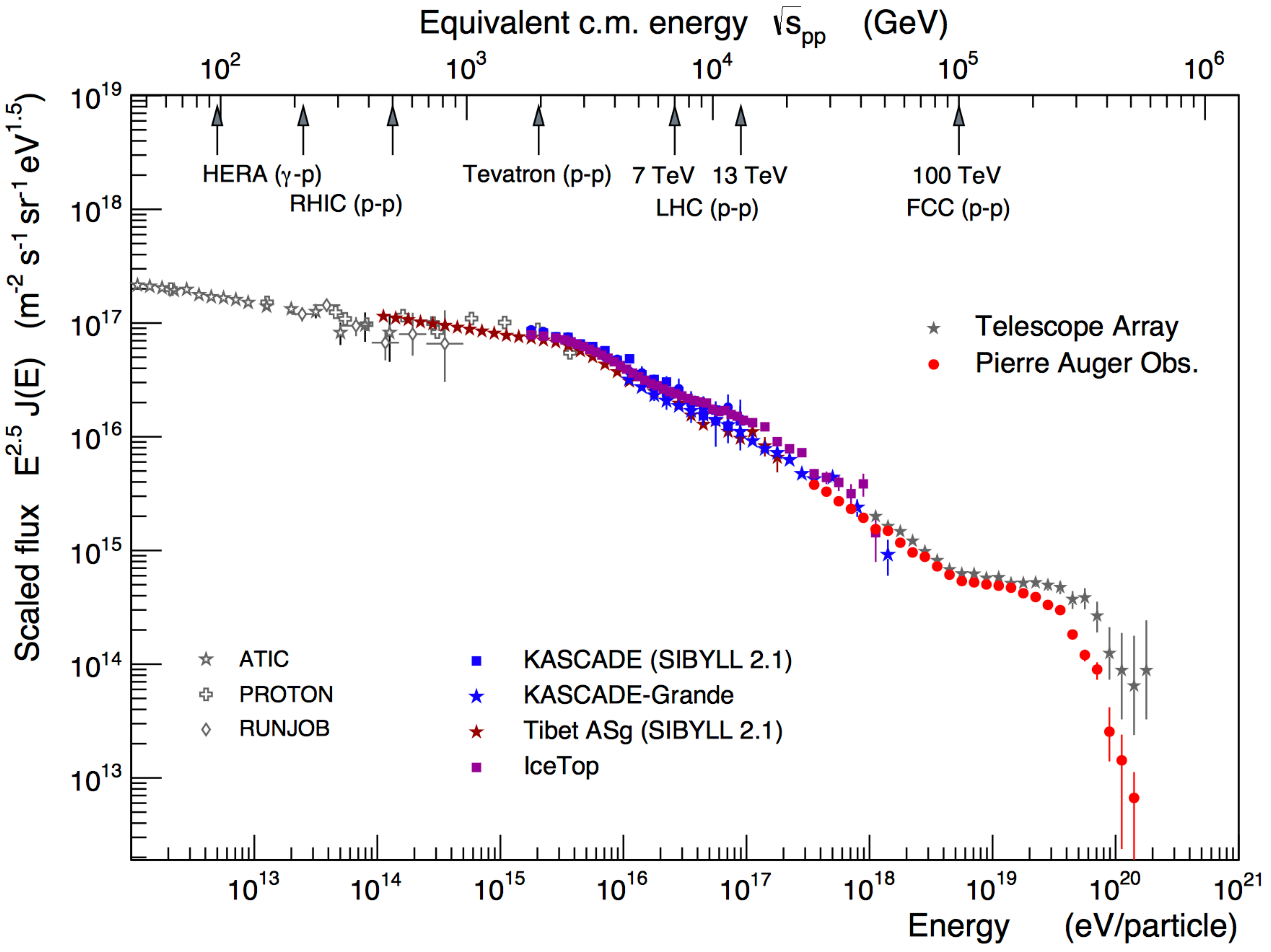
$$\lambda_{p\gamma,{\rm CMB}} = 1/n\sigma \sim 6\,{\rm Mpc}, \chi_{\rm loss} = \lambda/\kappa \sim 50\,{\rm Mpc}$$

Expansion of the Universe:

$$\chi_{\rm expansion,loss} \sim c/H_0 \sim 4{\rm Gpc}$$



2. UHECR energy density



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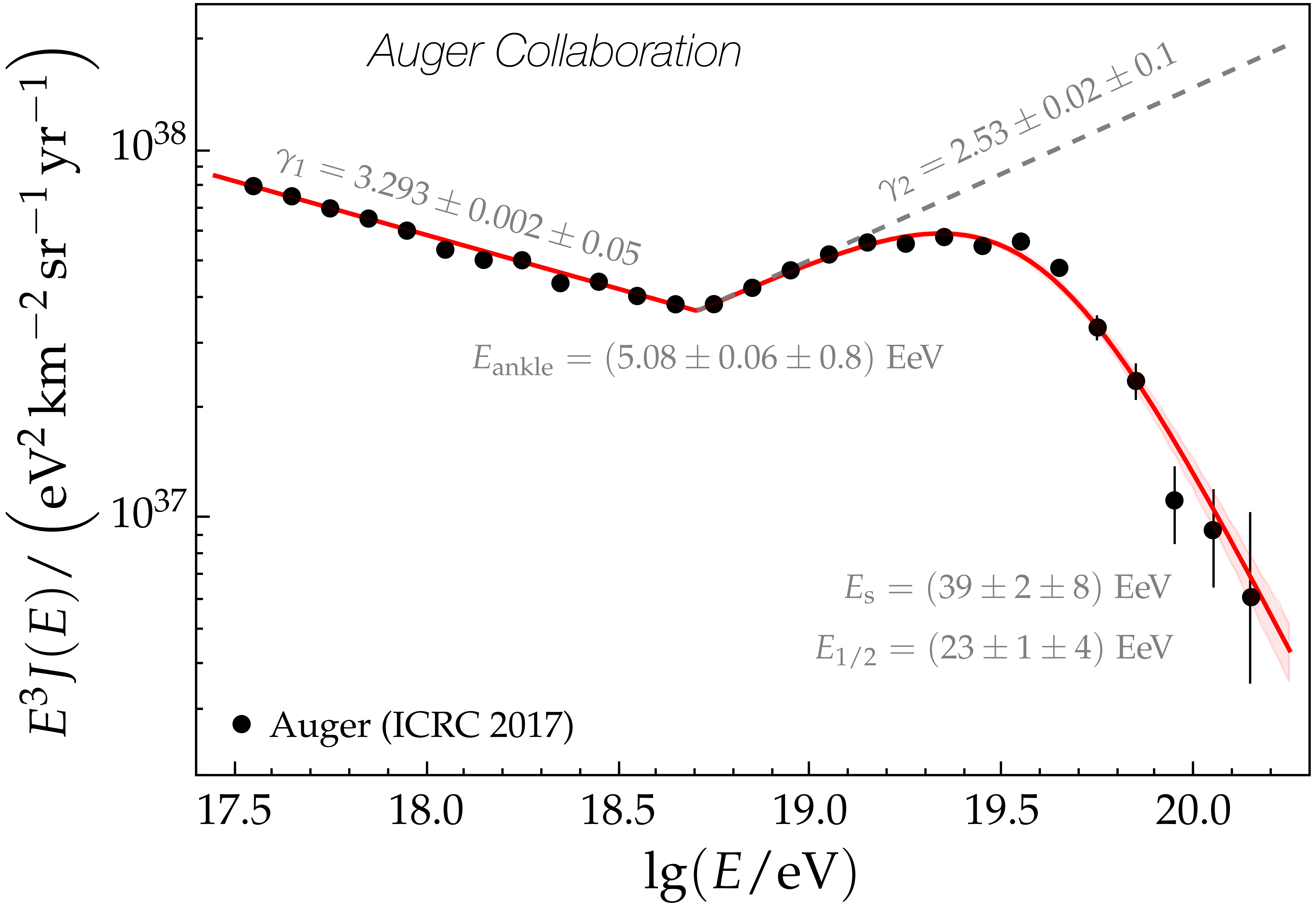

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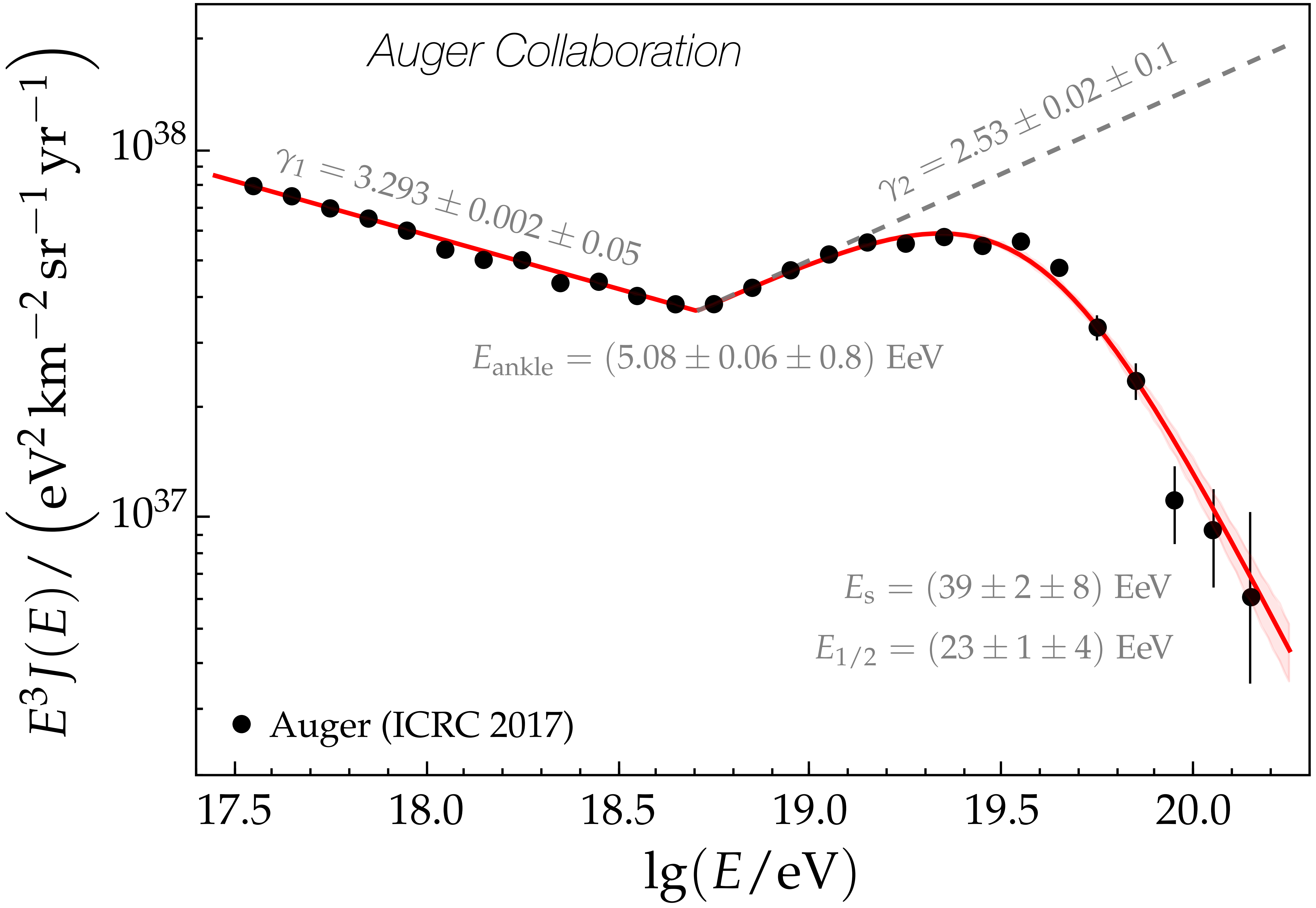


J(E) is the measured number of particles per unit energy, per unit area, per unit time, per unit solid angle

$$J(E) = \frac{\mathrm{d}N}{\mathrm{d}E\mathrm{d}A\mathrm{d}t\mathrm{d}\Omega}$$

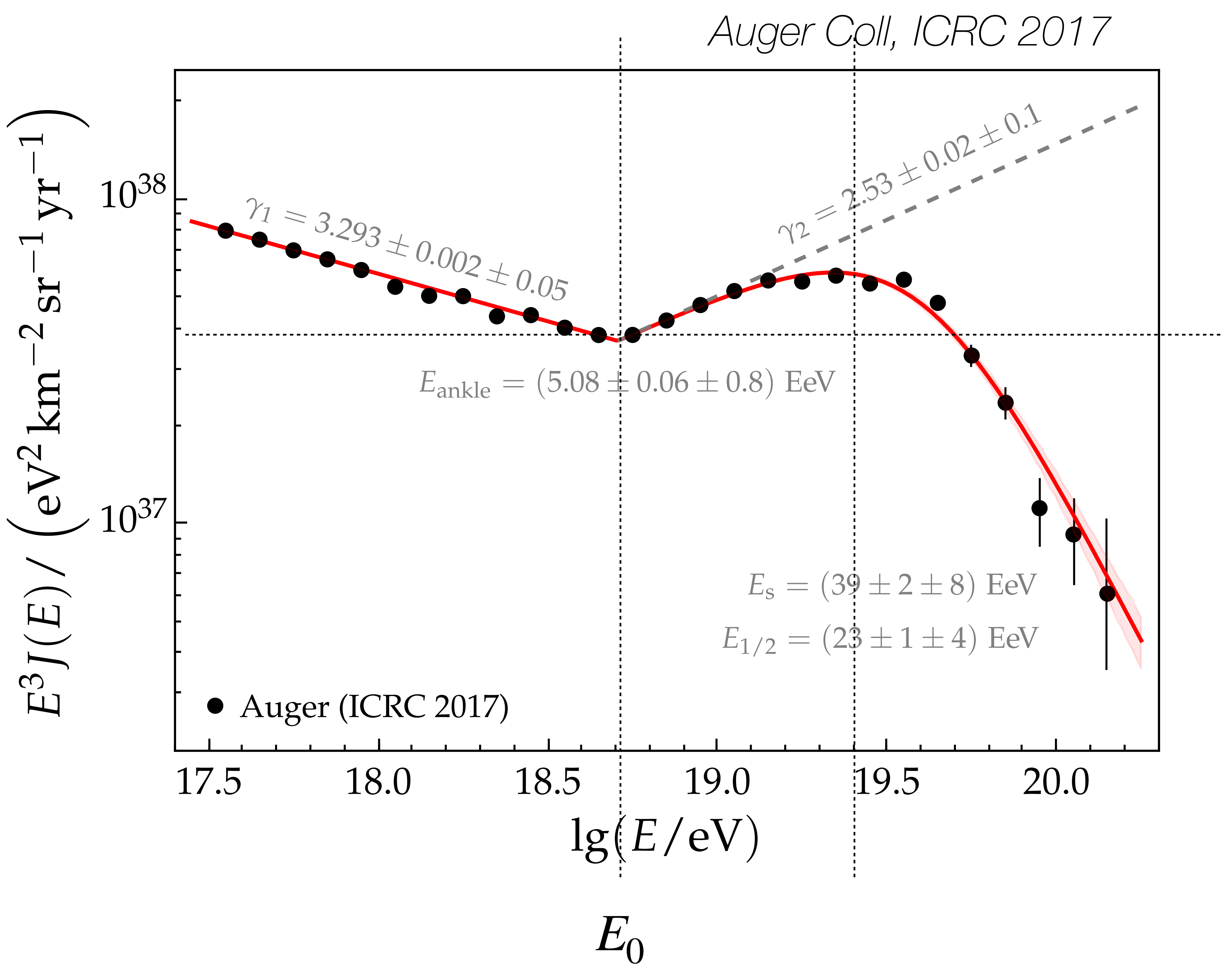
The number density of particles is

$$n(E) = \frac{\mathrm{d}N}{\mathrm{d}E\mathrm{d}^3x} = \frac{\mathrm{d}N}{\mathrm{d}E\ \mathrm{d}l\ \mathrm{d}A} = \frac{\mathrm{d}N}{\mathrm{d}E\ c\mathrm{d}t\ \mathrm{d}A} = \frac{4\pi}{c}J(E)$$

and the energy density is

$$U_E = \int E\ n(E)\ \mathrm{d}E = \frac{4\pi}{c}\int E\ J(E)\ \mathrm{d}E$$

3. UHECR emissivity



At 5 EeV we measure,

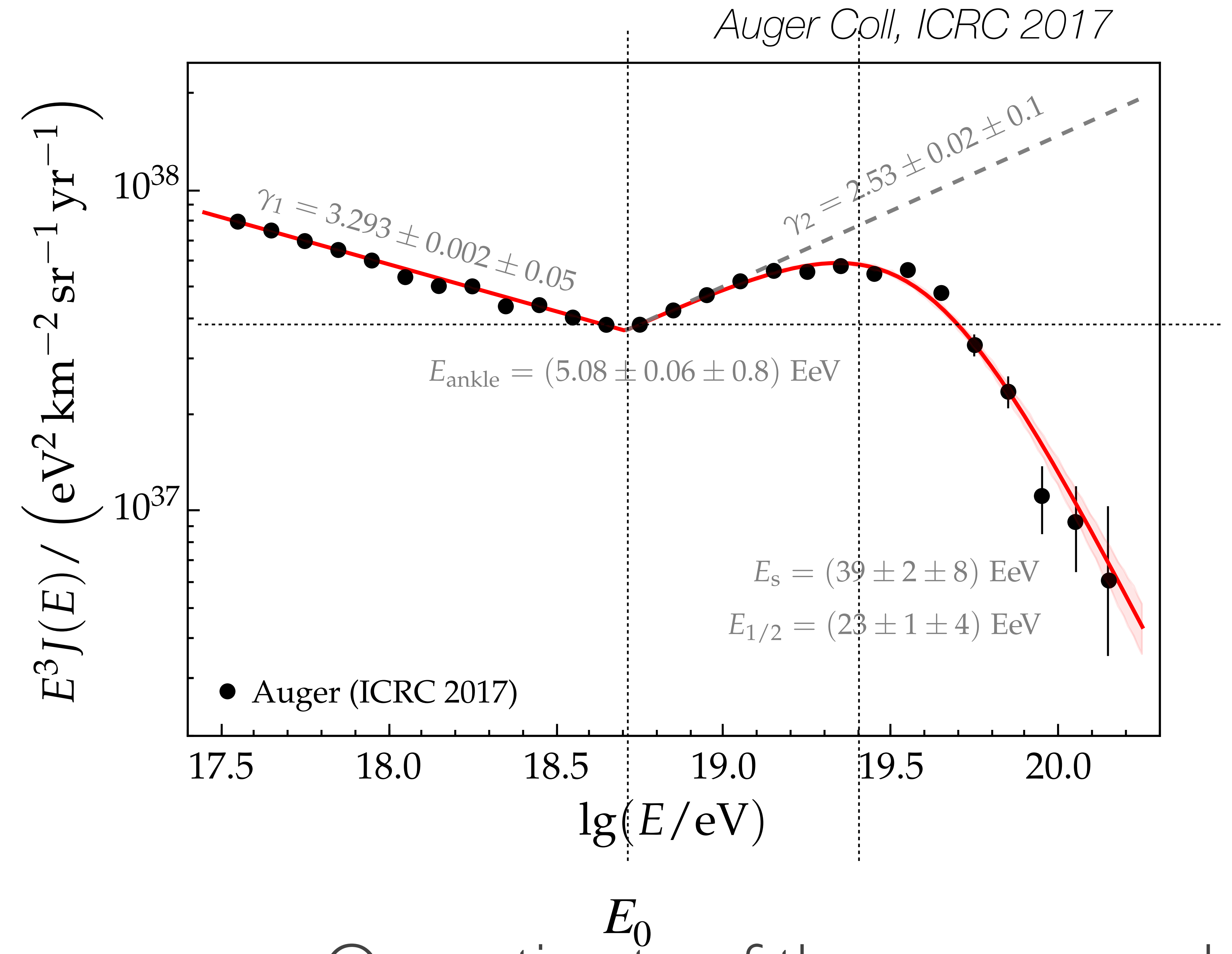
$$E_0^3 \cdot J_0 = 10^{37.3}\ \mathrm{eV^2\ km^{-2}\ sr^{-1}\ yr^{-1}}$$

which corresponds to (for an E^{-2} spectrum),

$$U_{\rm UHECR} \approx \frac{4\pi}{c} E_0^2 J_0 \ln(E_{\rm max}/E_{\rm min}) \sim \frac{4\pi}{c} E_0^2 J_0 \ln(10)$$

$$\approx 10^{-8}\ \mathrm{eV\ cm^{-3}} \quad \approx 6 \times 10^{53}\ \mathrm{erg\ Mpc^{-3}}$$

3. UHECR emissivity



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1 erg ~ 1 TeV!

Our estimate of the energy production rate based on the ***observed*** spectrum:

$$\dot{\varepsilon}_{\rm UHECR} \approx \frac{U_{\rm UHECR}}{t_{\rm loss,UHECR}} = \frac{U_{\rm UHECR}}{\chi_{\rm loss,UHECR}/c} = \frac{U_{\rm UHECR}}{1\ \mathrm{Gpc}/c} \approx 2 \times 10^{44}\ \mathrm{erg\ Mpc^{-3}\ year^{-1}}$$

Full derivation based on simulated ***intrinsic*** source spectra:

$$\dot{\varepsilon}_{\rm Auger\ combined\ fit} \approx 5 \times 10^{44}\ \mathrm{erg\ Mpc^{-3}\ year^{-1}}$$

Waxman-Bahcall bound

- Neutrinos from photo-meson interactions of UHECR protons in sources (AGN/GRBs)
- Optically-thin sources (protons can escape) - otherwise neutrino only sources not UHECR sources
- Fermi-type acceleration

$$E_{\rm CR}^2 {\rm d}N_{\rm CR}/{\rm d}E_{\rm CR} \sim E_{\rm CR}^{-2} \text{ (at the source)}$$

$$\dot{\varepsilon}_{\rm UHECR} \approx 10^{44} \text{ erg Mpc}^{-3} \text{ year}^{-1}$$

- Proton loses fraction, ϵ, of its energy to muon neutrinos

$$E_\nu^2 \Phi_\nu (\text{single flavour})|_{E_\nu = 0.05 E_{cr}} = \frac{c}{4\pi} \epsilon \frac{1}{2} \frac{1}{2} \xi_z t_{\rm H} \dot{\varepsilon}_{\rm UHECR}$$

we called it J before…

$$= 1.5 \times 10^{-8} \epsilon \xi_z \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

Hubble time

$$p + \gamma_{\rm CMB} \to p + \pi^0 - \text{BR } 50\,\%$$

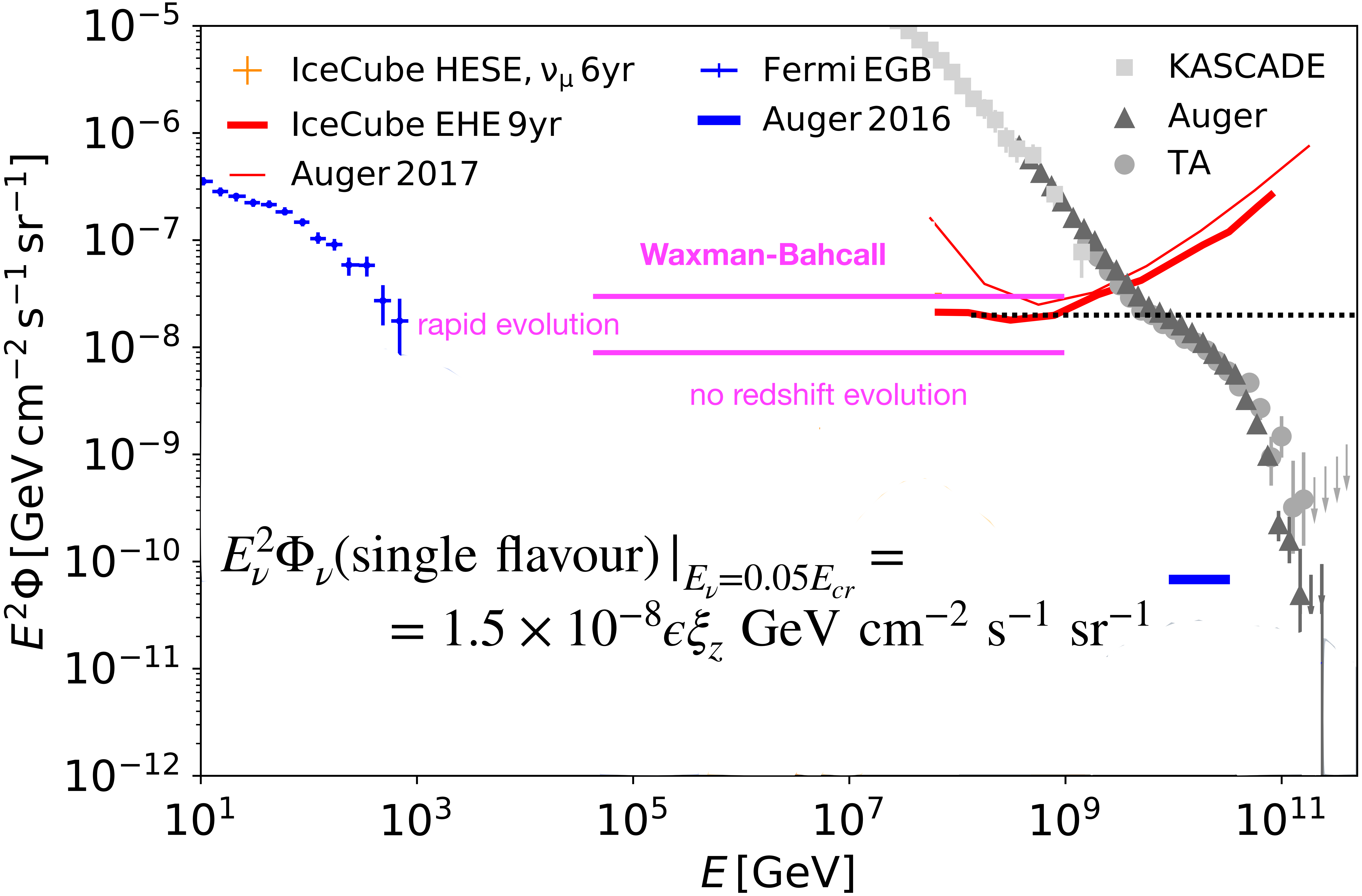
$$p + \gamma_{\rm CMB} \to n + \pi^+ - \text{BR } 50\,\%$$

$$\xi_z \sim 0.6 \text{ (no evolution)} - 10 \text{ (rapid evolution)}$$

$$\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e \quad \underbrace{\bar{\nu}_\mu \, \nu_\mu}_{}$$

50% of E_{π^+}

Waxman-Bahcall bound



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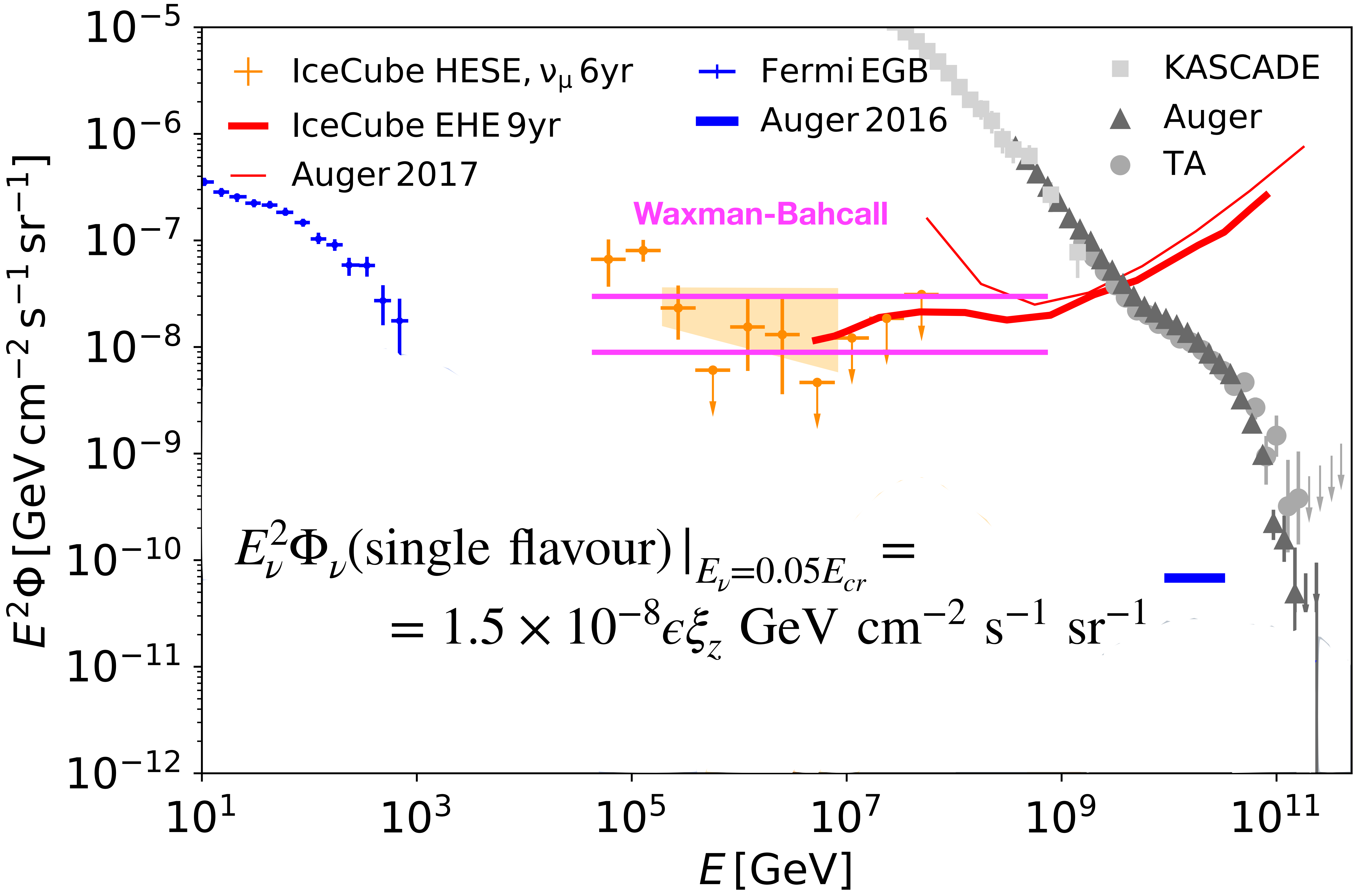

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Generic source properties

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

Neutrino source number density

The product of luminosity per source, ***L***, and source density, ***n***, corresponds to the total emission per volume and is constrained by the observed diffuse flux of neutrinos

$$\text{luminosity density} \sim L \cdot n$$

The number density gives the volume within which one source must lie is

$$V = \frac{4\pi r^3}{3} \sim \frac{1}{n}$$

Source class	Number density [Mpc^{-3}]
powerful blazars (FSRQ)	10^{-9}
weaker blazars (BL Lac)	10^{-7}
Starburst galaxies	10^{-5}
Galaxy clusters	10^{-5}
Jetted AGN	10^{-4}
Normal galaxies	10^{-2}

Neutrino source number density

- The nearest neutrino source must therefore be at distance

$$r \sim \left(\frac{4\pi n}{3}\right)^{-1/3} \quad -(1) \qquad \text{e.g. } n = 10^{-4}\mathrm{Mpc}^{-3} \quad r = 10\ \mathrm{Mpc}$$

- The flux expected from an individual source with neutrino luminosity **L** is $f \sim \dfrac{L}{4\pi r^2}$

- Sources below the IceCube point-source flux sensitivity F_{lim} must therefore satisfy

$$r > \left(\frac{L}{4\pi F_{lim}}\right)^{1/2}$$

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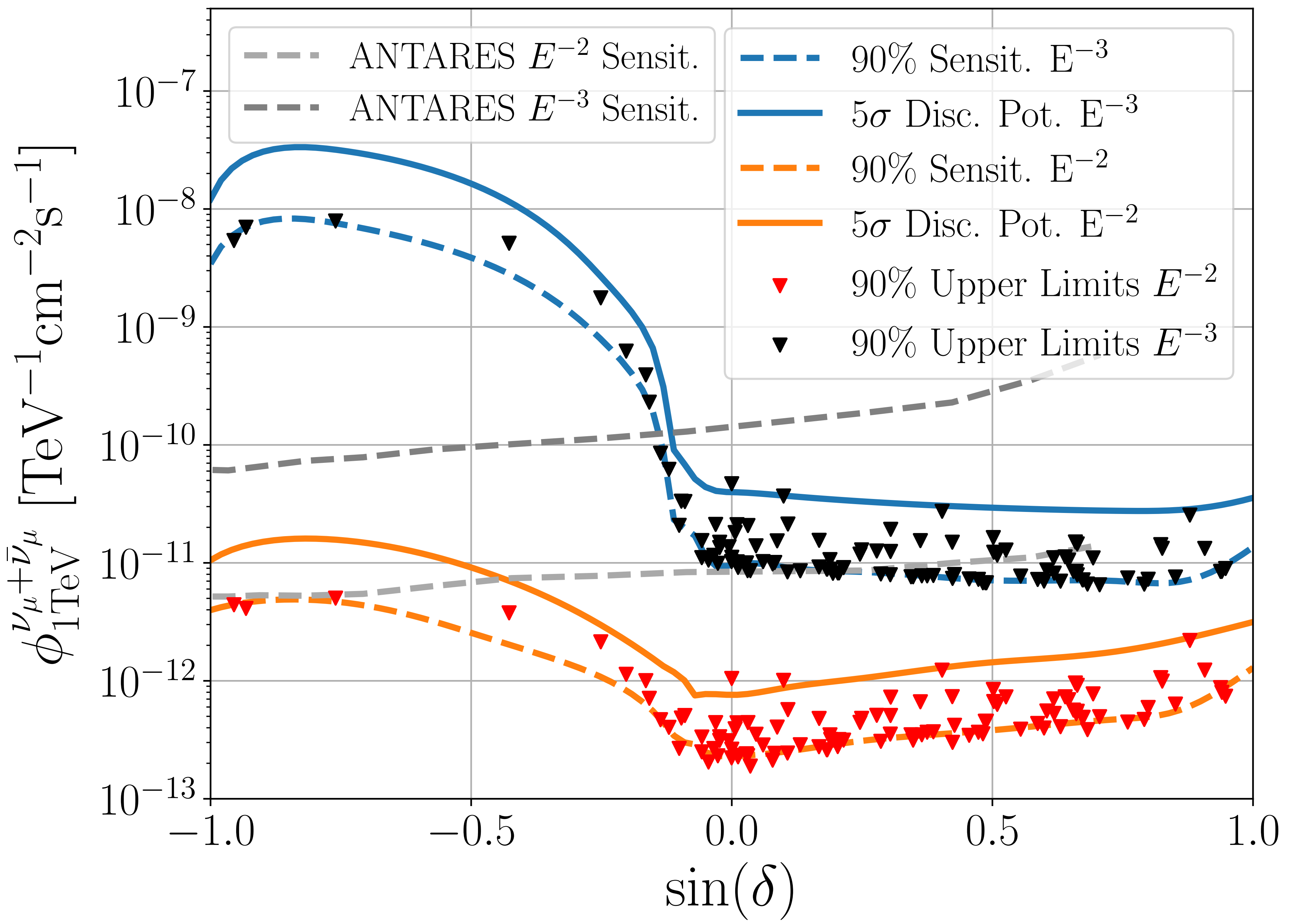

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Neutrino source number density

- Sources below the IceCube point source sensitivity must therefore satisfy.

$$r > \left(\frac{L}{4\pi F_{lim}} \right)^{1/2}$$

- which translates to a luminosity dependent upper limit on the number density

$$n \leq \frac{3}{4\pi} \left(\frac{L}{4\pi F_{lim}} \right)^{-3/2}$$

where we used Eq. (1) $r \sim \left(\frac{4\pi n}{3} \right)^{-1/3}$

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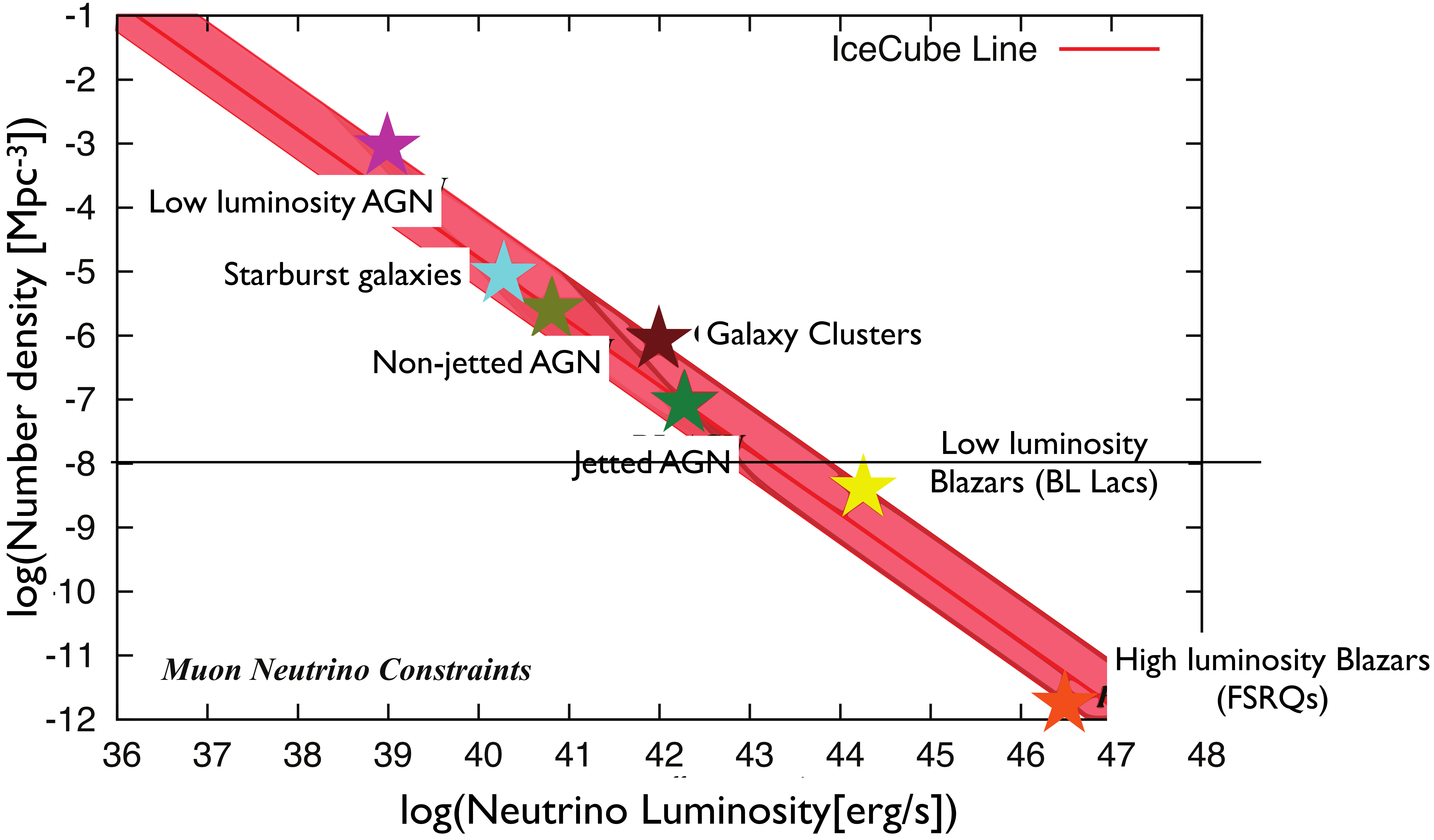
Neutrino source number density

see also Lipari PRD78(2008)083011
Ahlers & Halzen PRD90(2014)043005
Kowalski 2014,
Neronov & Semikoz 2018,
Ackermann, Ahlers et al. 2019,
Yuan et al 2019,
Capel, Mortlock, Finley 2020

Murase & Waxman 16, PRD 94 (2016) 103006



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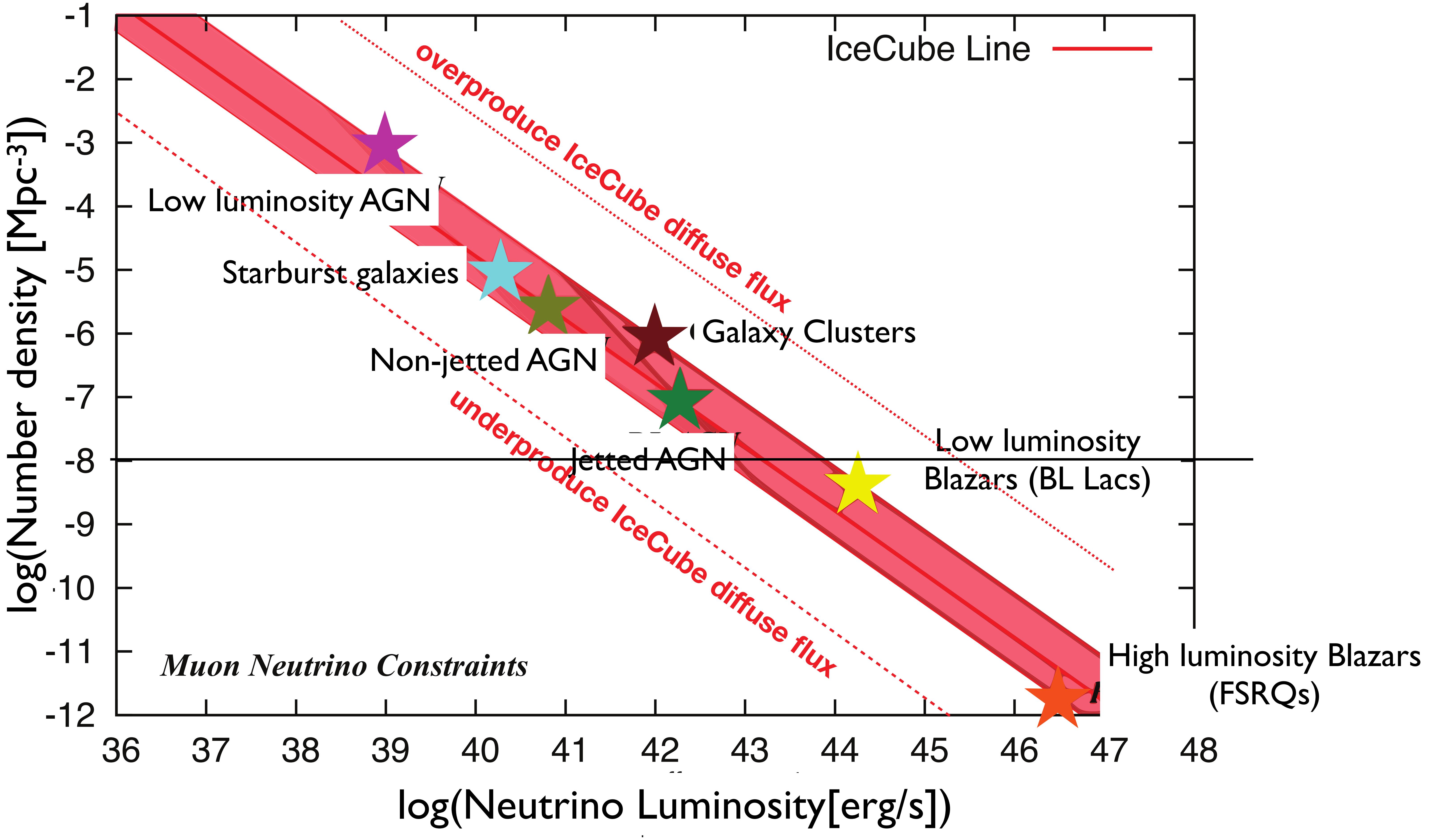

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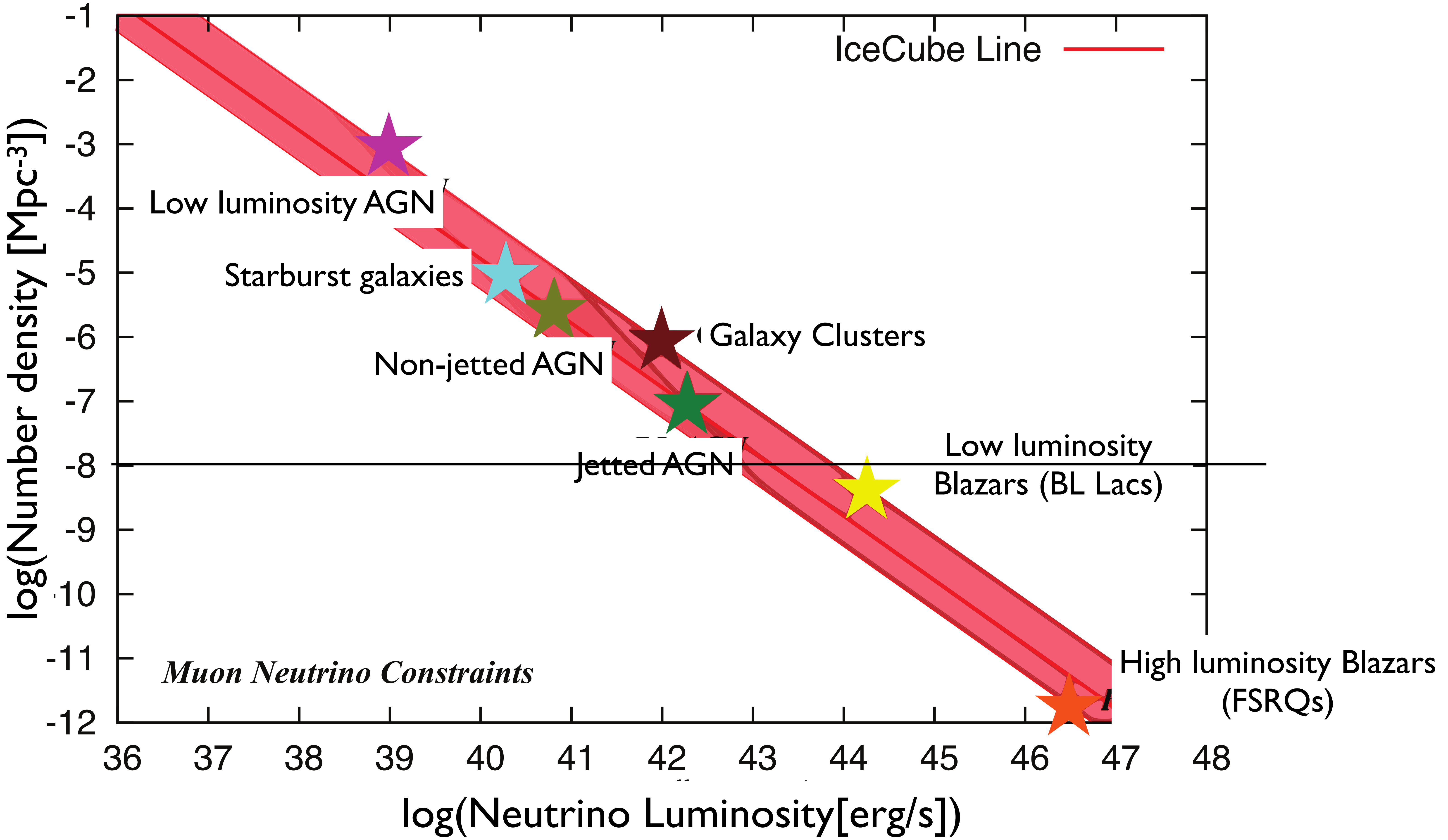

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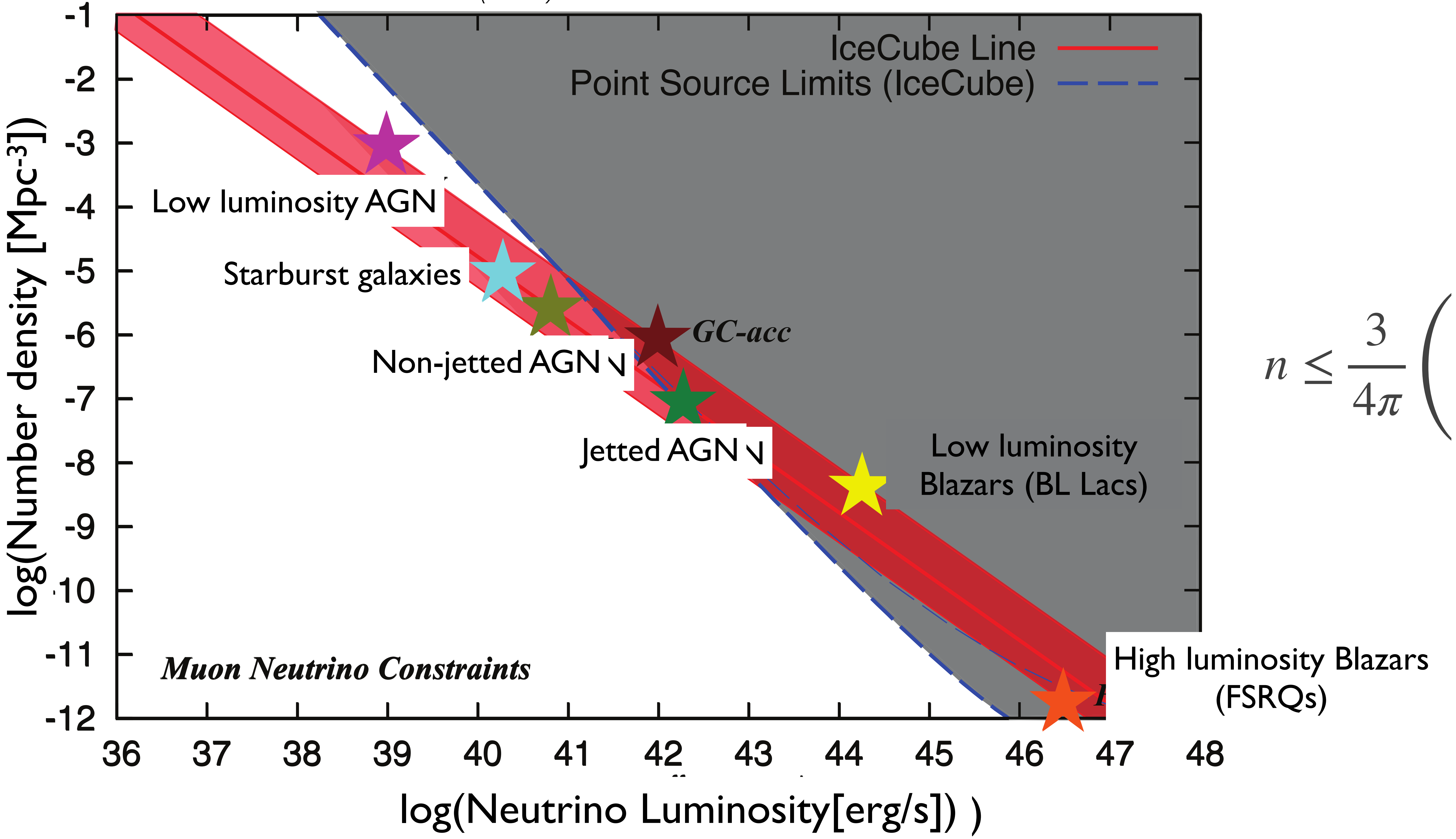

$$n \leq \frac{3}{4\pi}\left(\frac{L}{4\pi F_{lim}}\right)^{-3/2}$$

Absence of point-source detections implies that the number density is low enough that no source exists at distance low enough to produce a multiplet

Neutrino source number density

see also Lipari PRD78(2008)083011
Ahlers & Halzen PRD90(2014)043005
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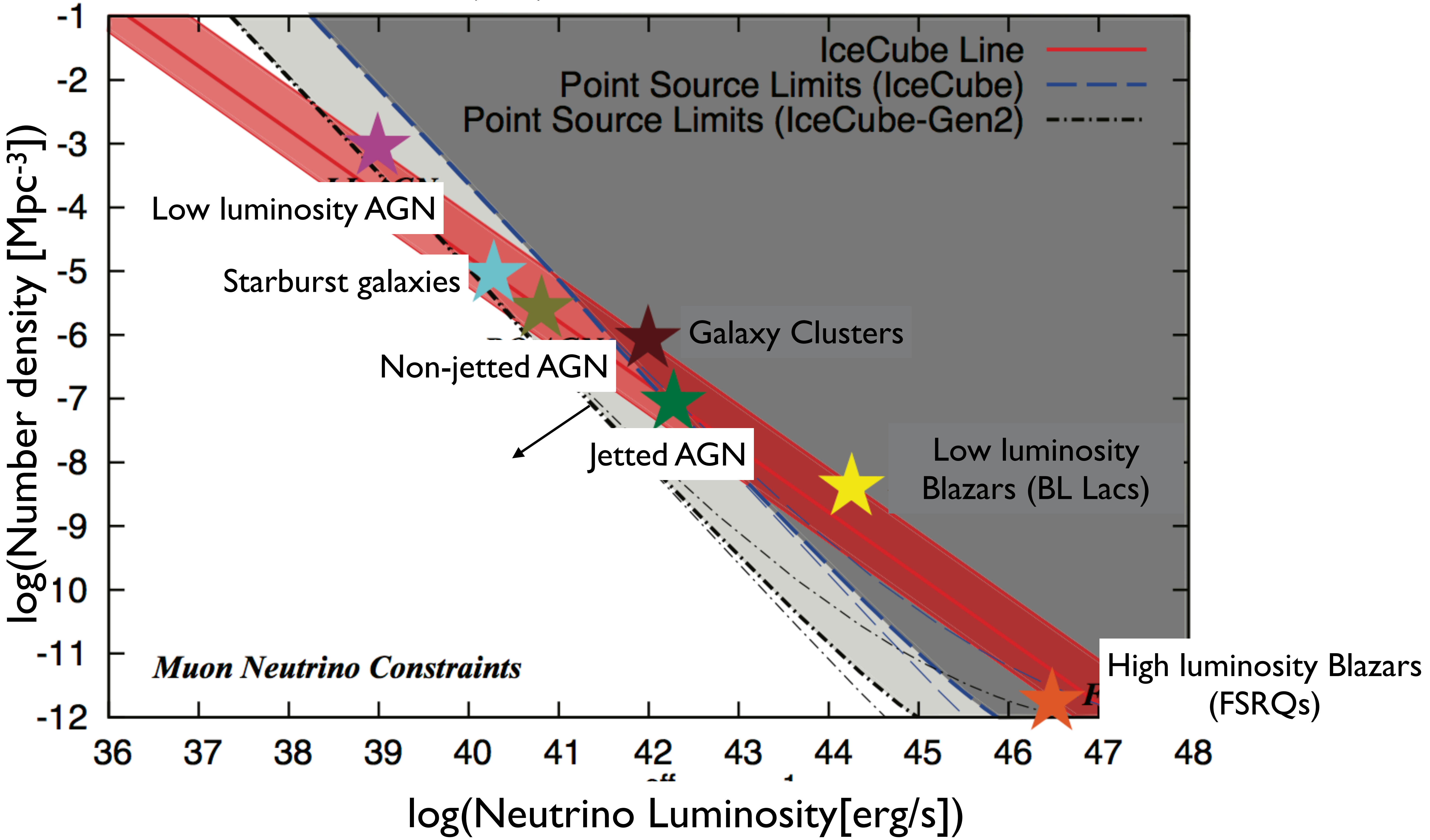


Take home messages

- Neutrino sources must have sufficient energy budget (generally ok)
- IceCube flux at the level predicted by Waxman & Bahcall (common origin of UHECRs and neutrinos or coincidence)
- Neutrino number density constraints disfavour rare and luminous source classes

Lecture plan

- Overview of astrophysical neutrino sources, experimental facts and basic theoretical concepts

- Requirements for astrophysical accelerators of high-energy cosmic rays/ high-energy neutrinos (generic source properties)

- Overview of candidate high-energy astrophysical sources (Active Galactic Nuclei/Starburst Galaxies/Gamma ray bursts/Pulsars/Tidal Disruption Events). Constraints and prospects for source identification.

Active Galactic Nuclei

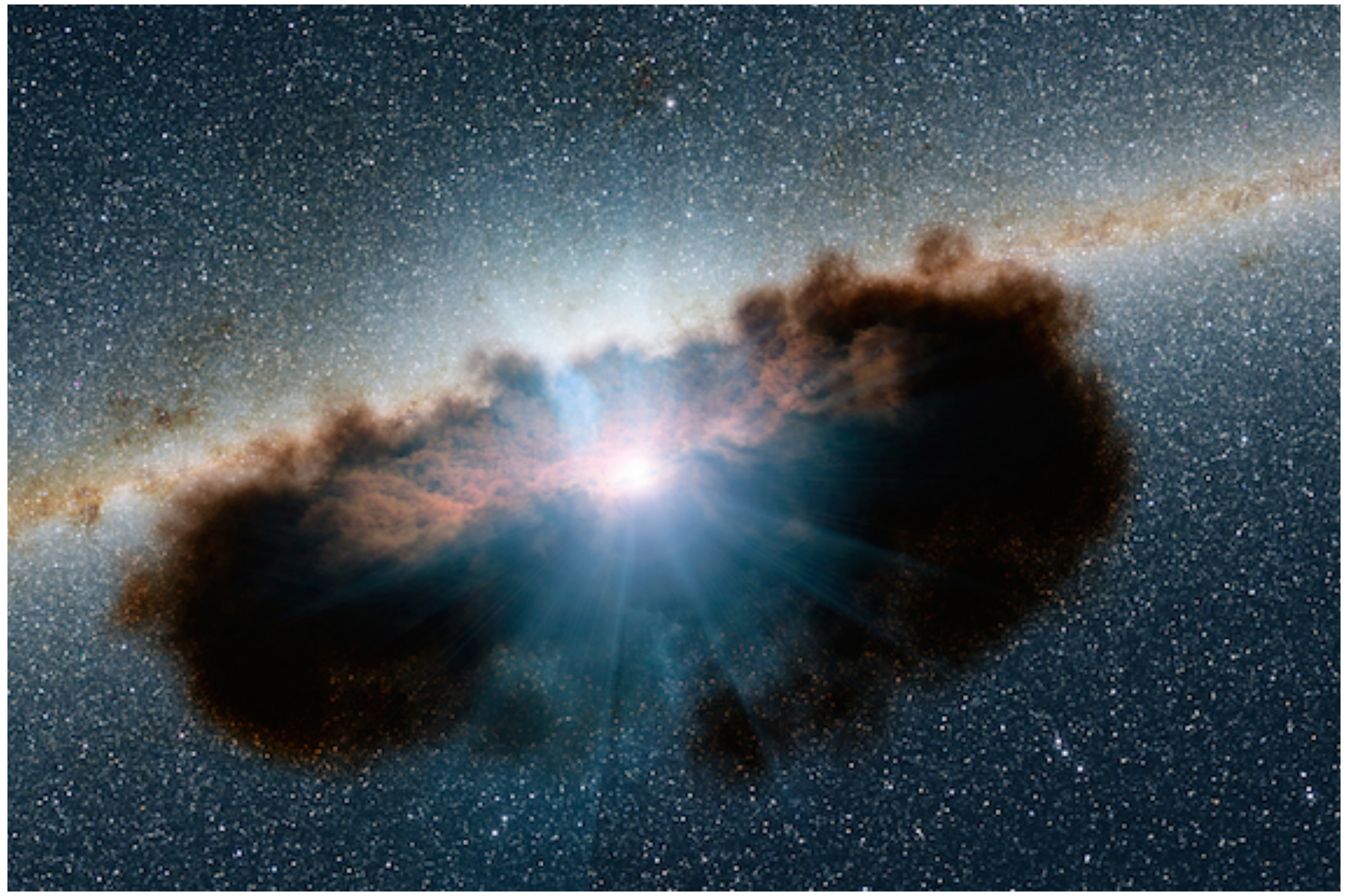
Most powerful ``steady'' sources in the Universe (L≥ 10^{47} erg/s) > 1000 bright Galaxies!

They host a super-massive black hole (SMBH) (10^{6}-10^{10} M_{sun}). ``Active'' as emission >> stars in the galaxy - accretion on to SMBH

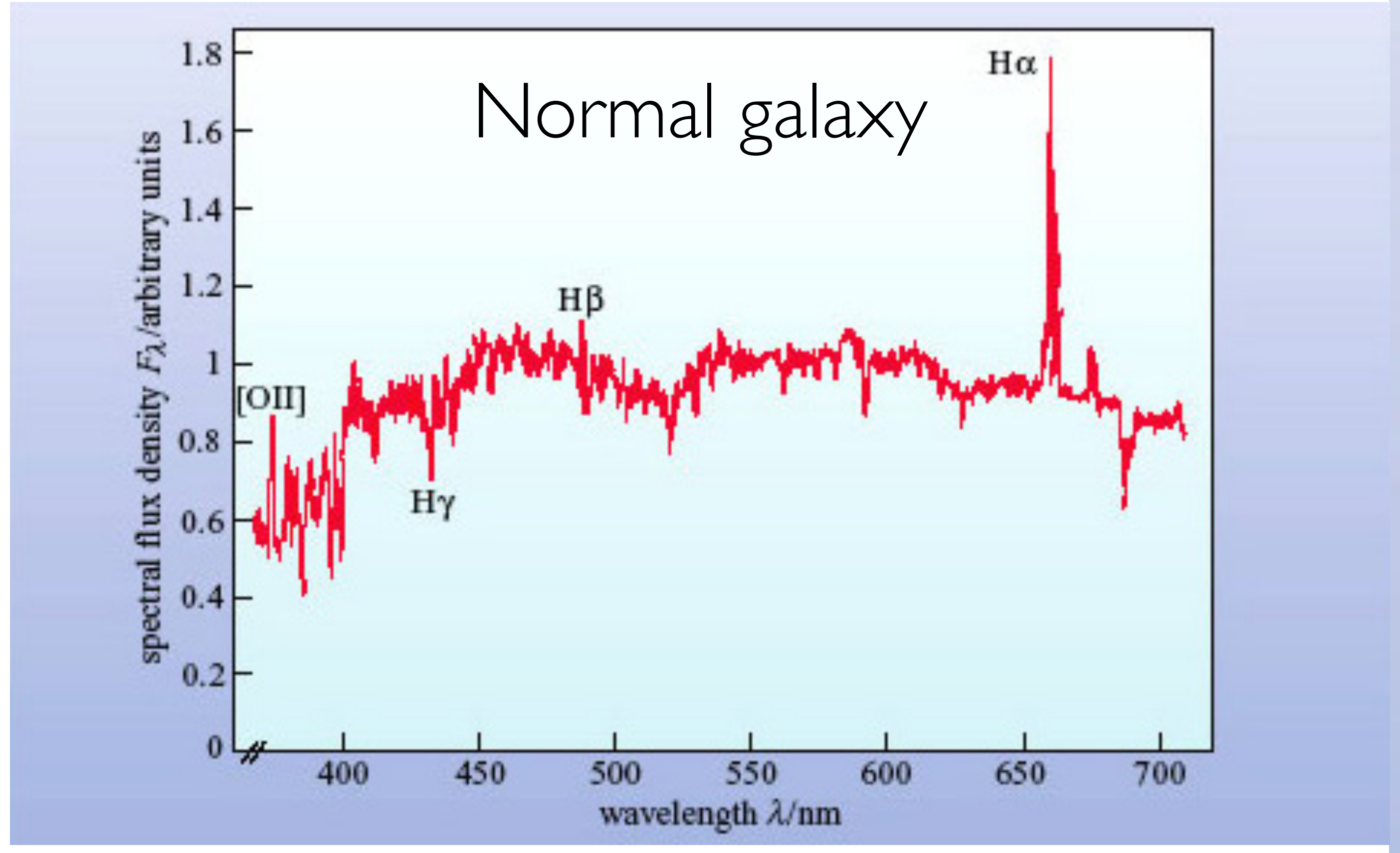
Visible to large redshifts (z > 7.5) - peak z~2 (depends on type)

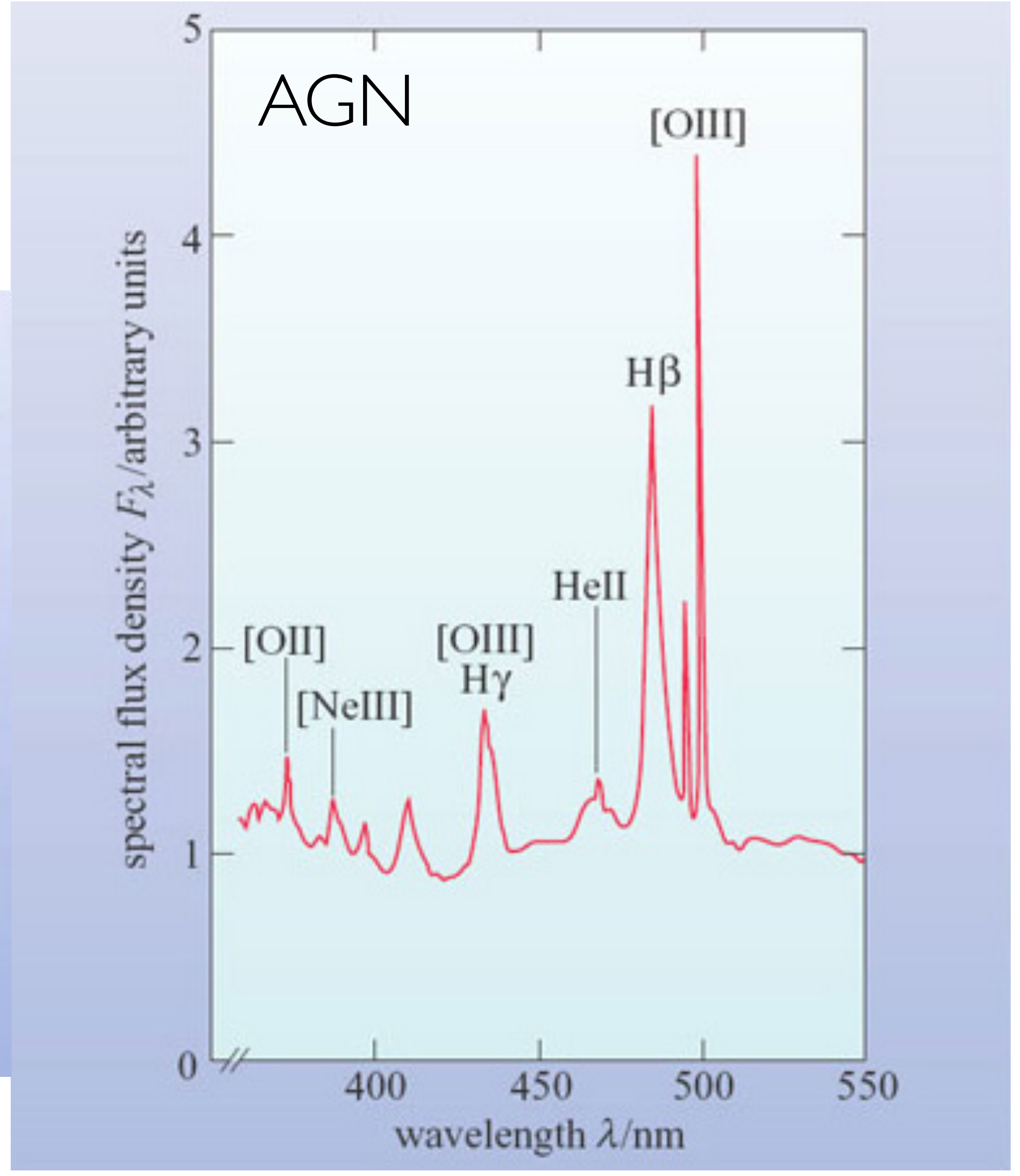
1% of galaxies active

Broad emission lines reveal rapid bulk rotation



Artist's impression of non-jetted AGN shrouded in dust [NASA/JPL]





[Spectra from: https://www.open.edu/openlearn/science-maths-technology/introduction-active-galaxies/content-section-2.2.2]

The engine

For an AGN with disk luminosity

$$L_{\rm disk} = 10^{46}\ {\rm erg/s}$$

and time variability

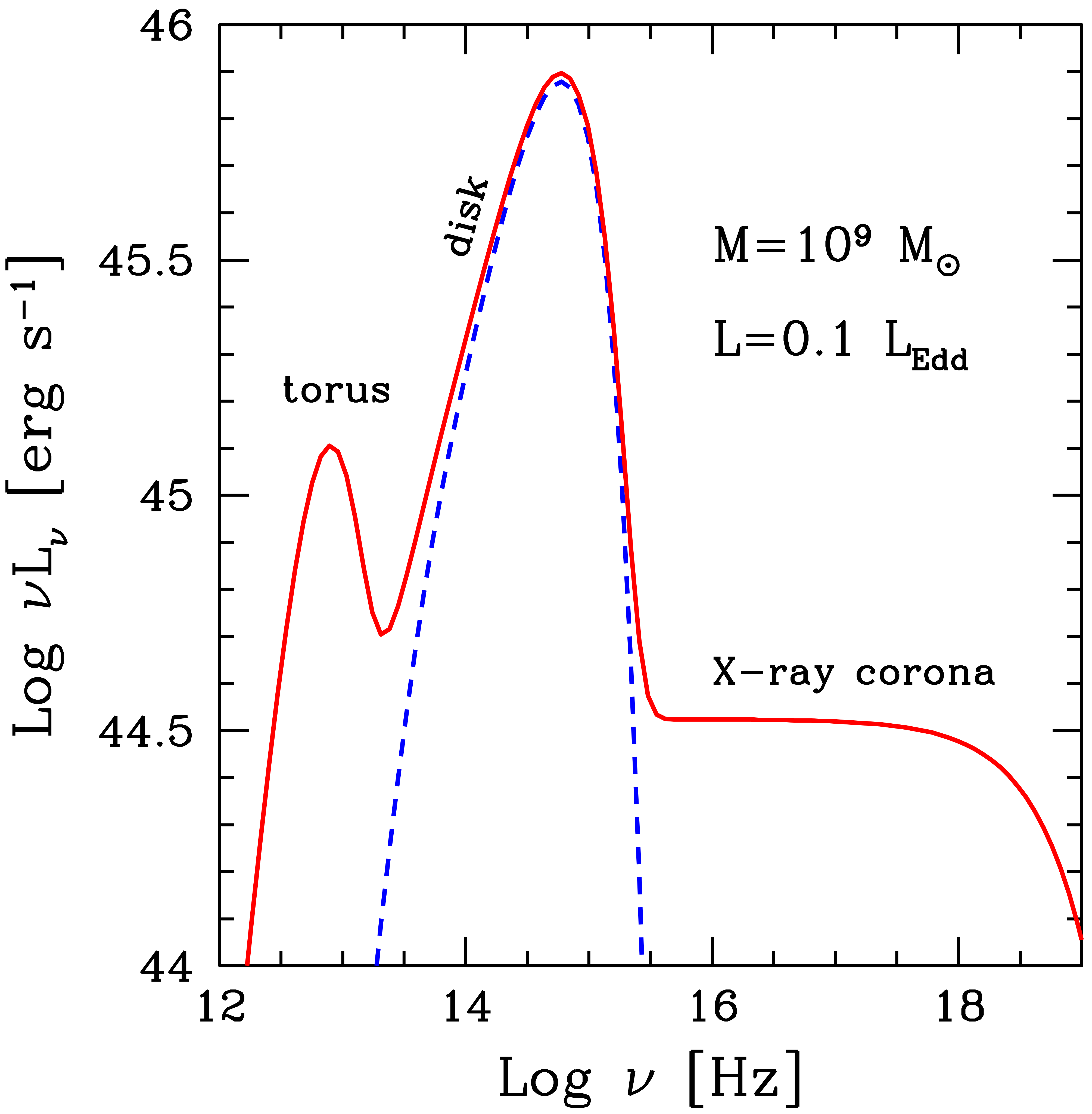
$\Delta t = 10^4$ s, causality dictates $R \sim c\Delta t = 0.01$ pc $= 20$ AU

We need a supermassive black hole due to the Eddington limit!

$$L_{\rm Edd} = \frac{4\pi G M m_p c}{\sigma_{\rm T}} = 10^{38} {\rm erg/s} \left(\frac{M}{M_{\rm Sun}}\right)$$

I.e. we need,

$$M \geq 10^8 M_{\rm Sun} \left(\frac{L_{\rm disk}}{10^{46}\ {\rm erg/s}}\right)$$

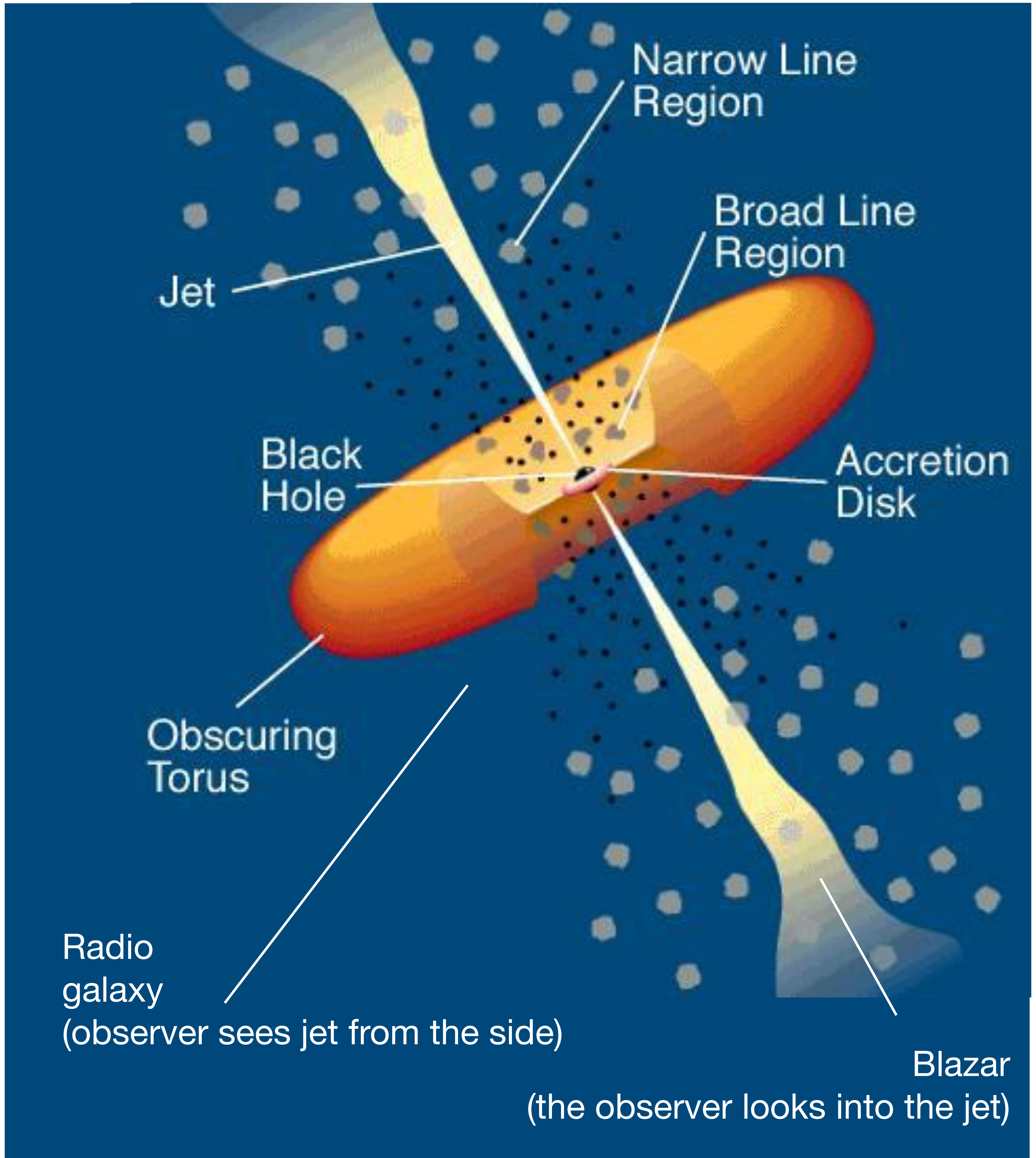


AGN Unification

The majority of AGN classes can be explained by three parameters:

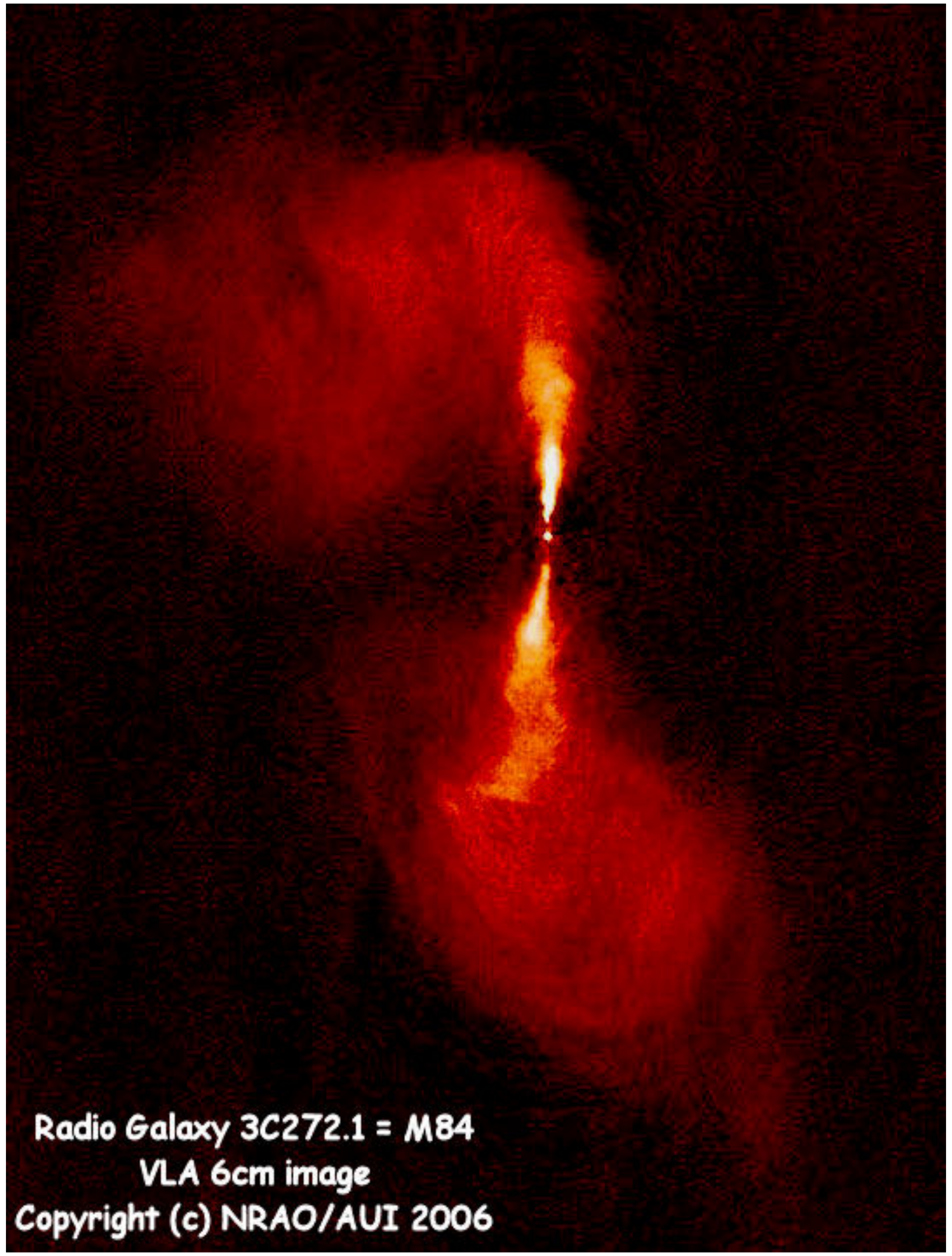
- Orientation
- Presence of jet or not (10% have it)
- Radiative efficiency

	Face on	Side-view
Jetted (radio-loud)	Blazars (BL Lac/ FSRQ)	Radio-Galaxies (FRI/II)
Non-jetted (radio-quiet)	Seyfert I	Seyfert II

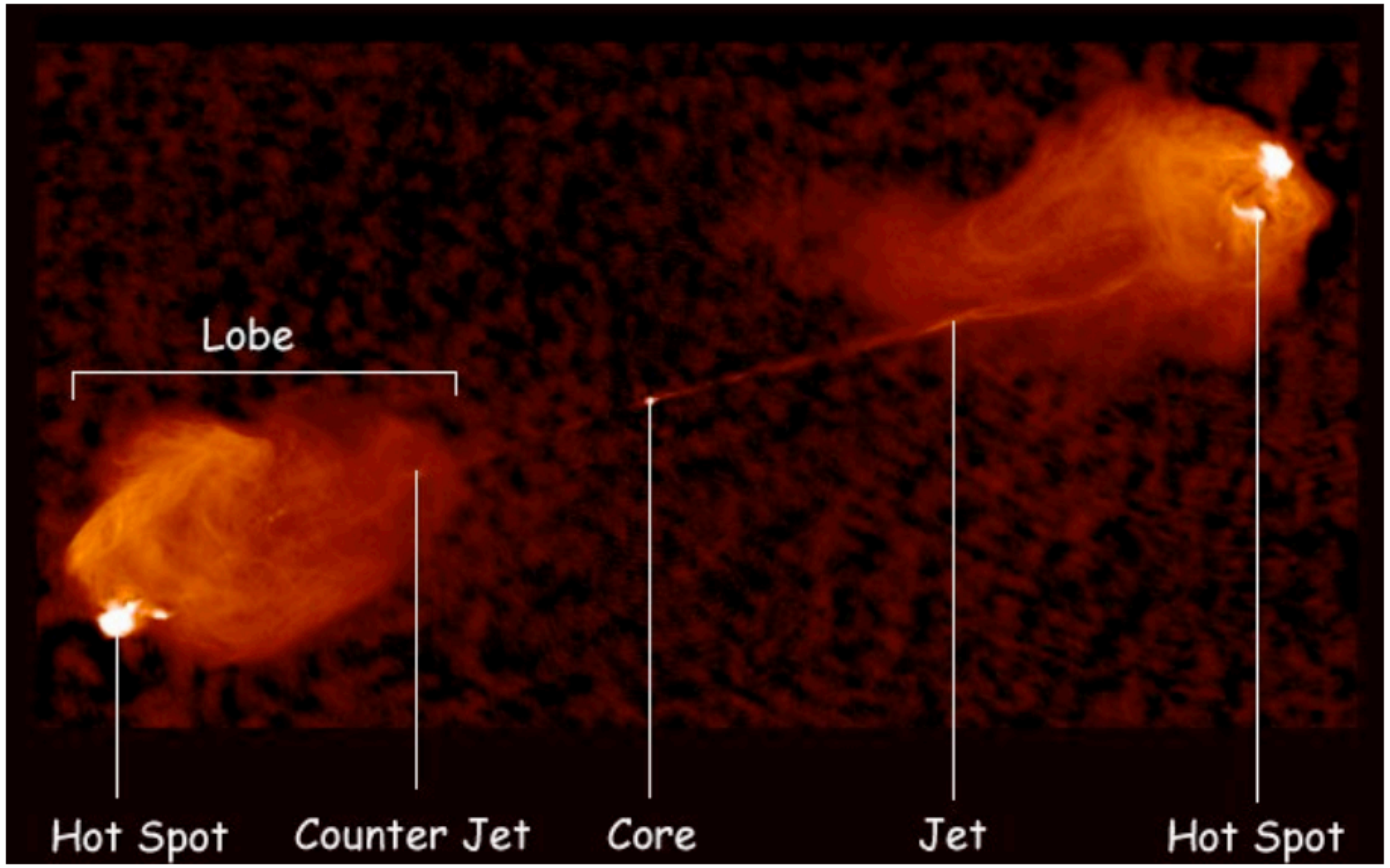


10% of AGN host jets

FRI



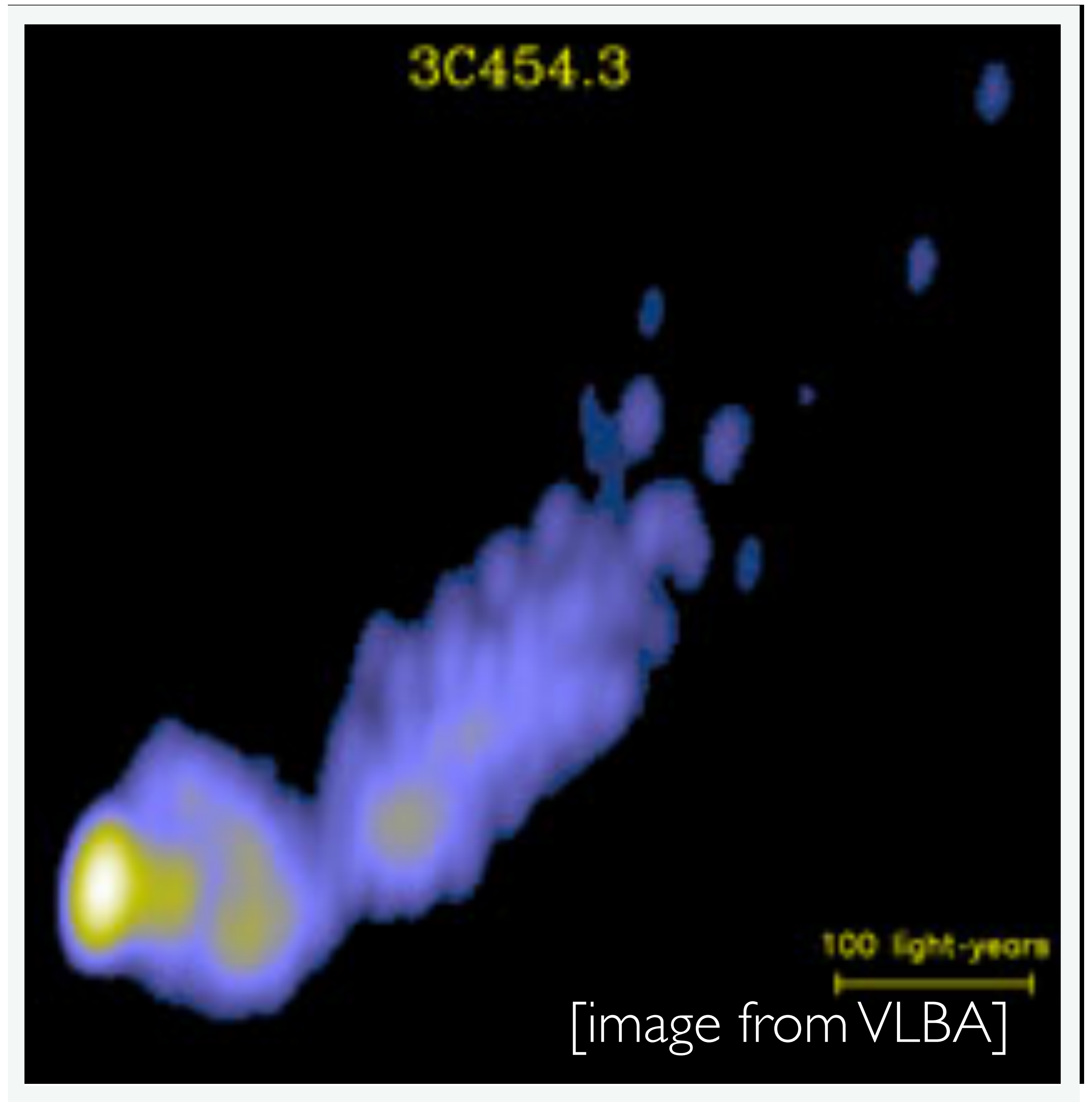
FRII



Radio galaxy Cygnus A Image credits: NRAO/AUI,A. Bridle

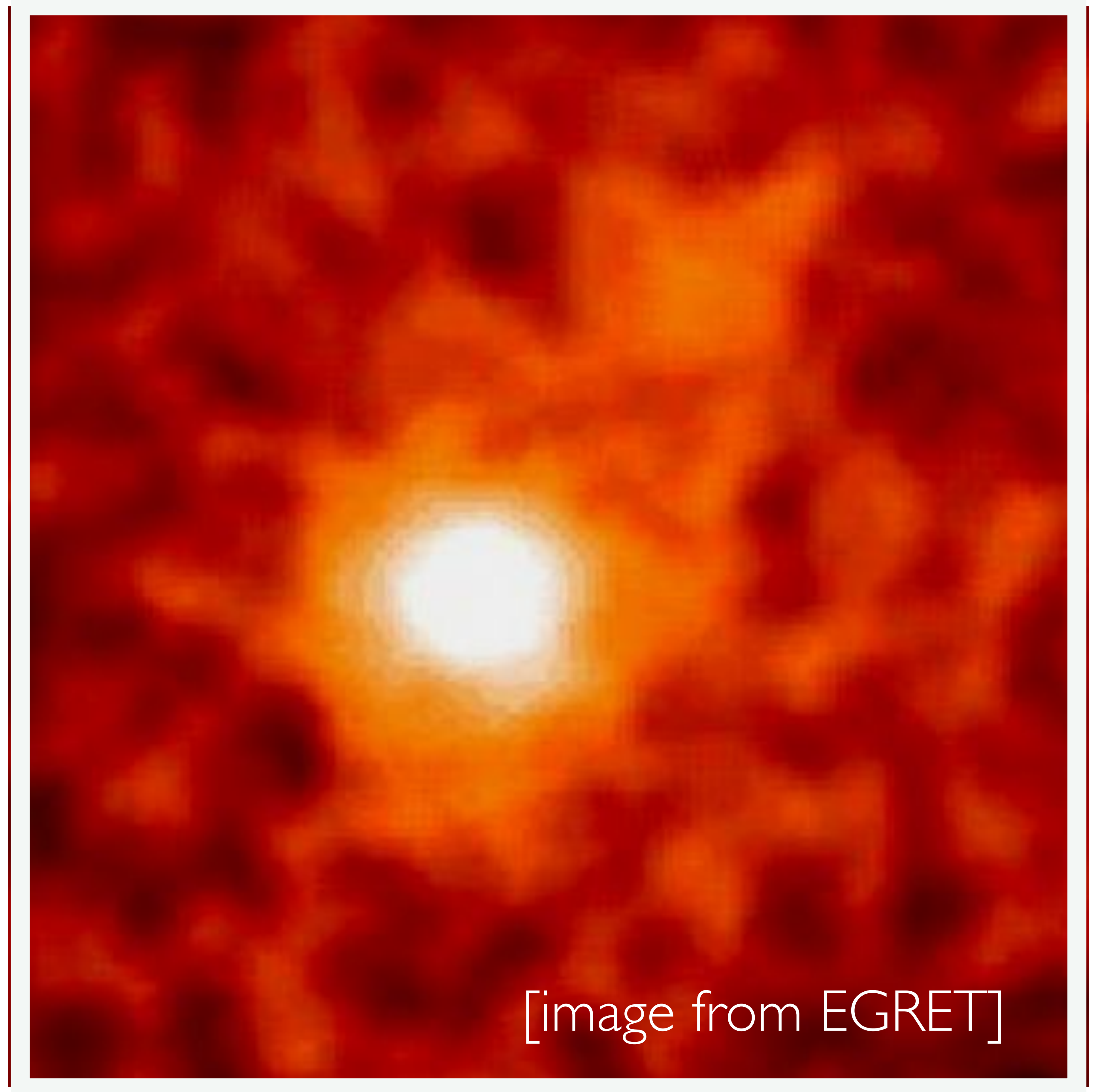
Blazars: Star-like appearance

Radio



Optical

γ-rays



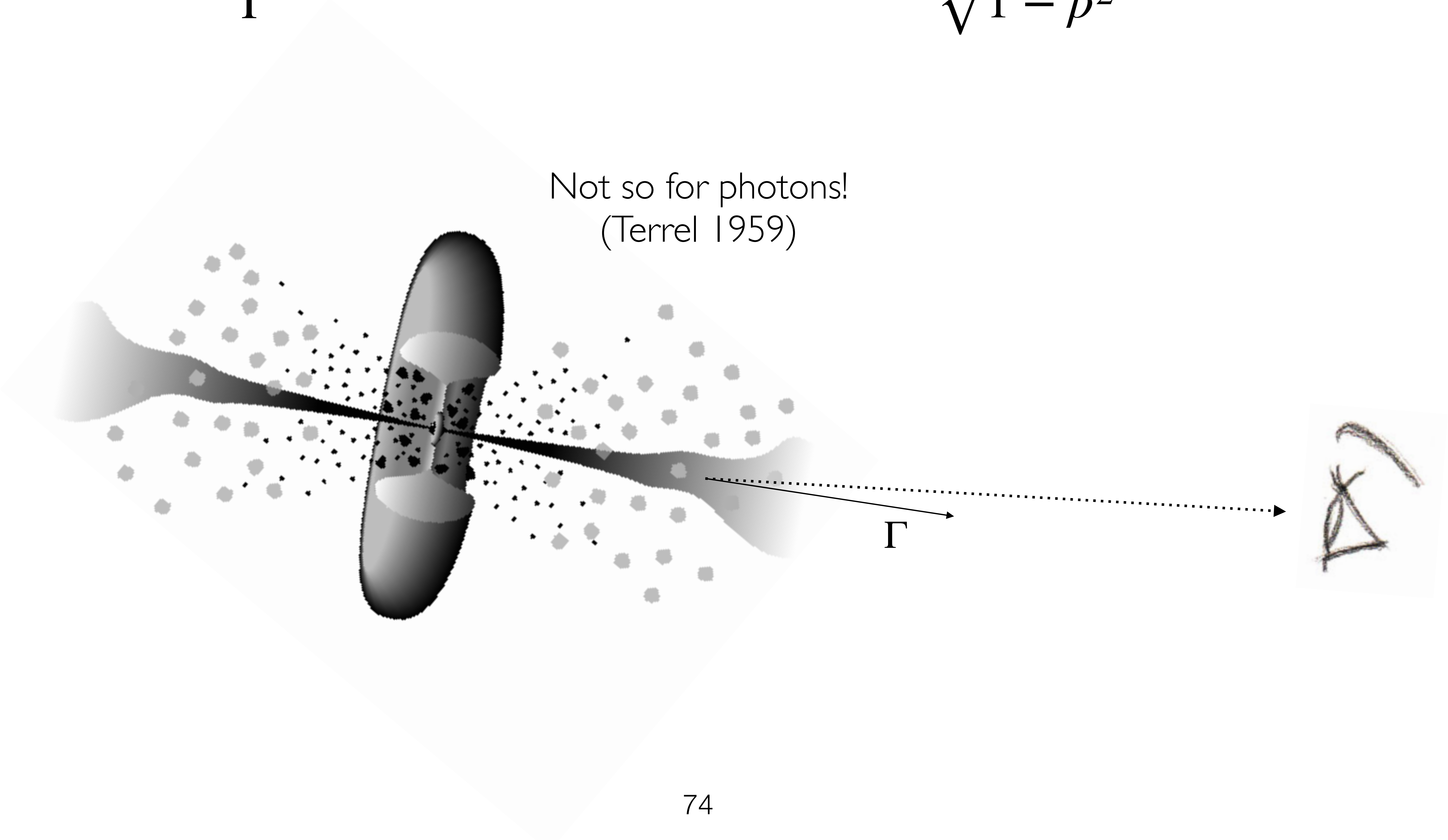
No spectacular jets…but wealth of information from timing/variability and spectra!

Relativistic beaming

Usual relativity (rulers and clocks)

$$\Delta x = \frac{\Delta x'}{\Gamma} \qquad \Delta t = \Delta t' \, \Gamma \qquad \Gamma = \frac{1}{\sqrt{1-\beta^2}}$$

Not so for photons!
(Terrel 1959)



Relativistic beaming

If the emitting region is moving relativistically, observed features appear boosted:

Doppler factor, $\delta = \dfrac{1}{\Gamma(1 - \beta\cos\theta)}$

$\Delta t = \Delta t'/\delta$ (shortening of timescales)

$\Delta x = \Delta x'\ \delta$

$\nu = \delta\nu',\ E = \delta E'$ (blueshift)

$L_{\rm obs} = \delta^4 L'$

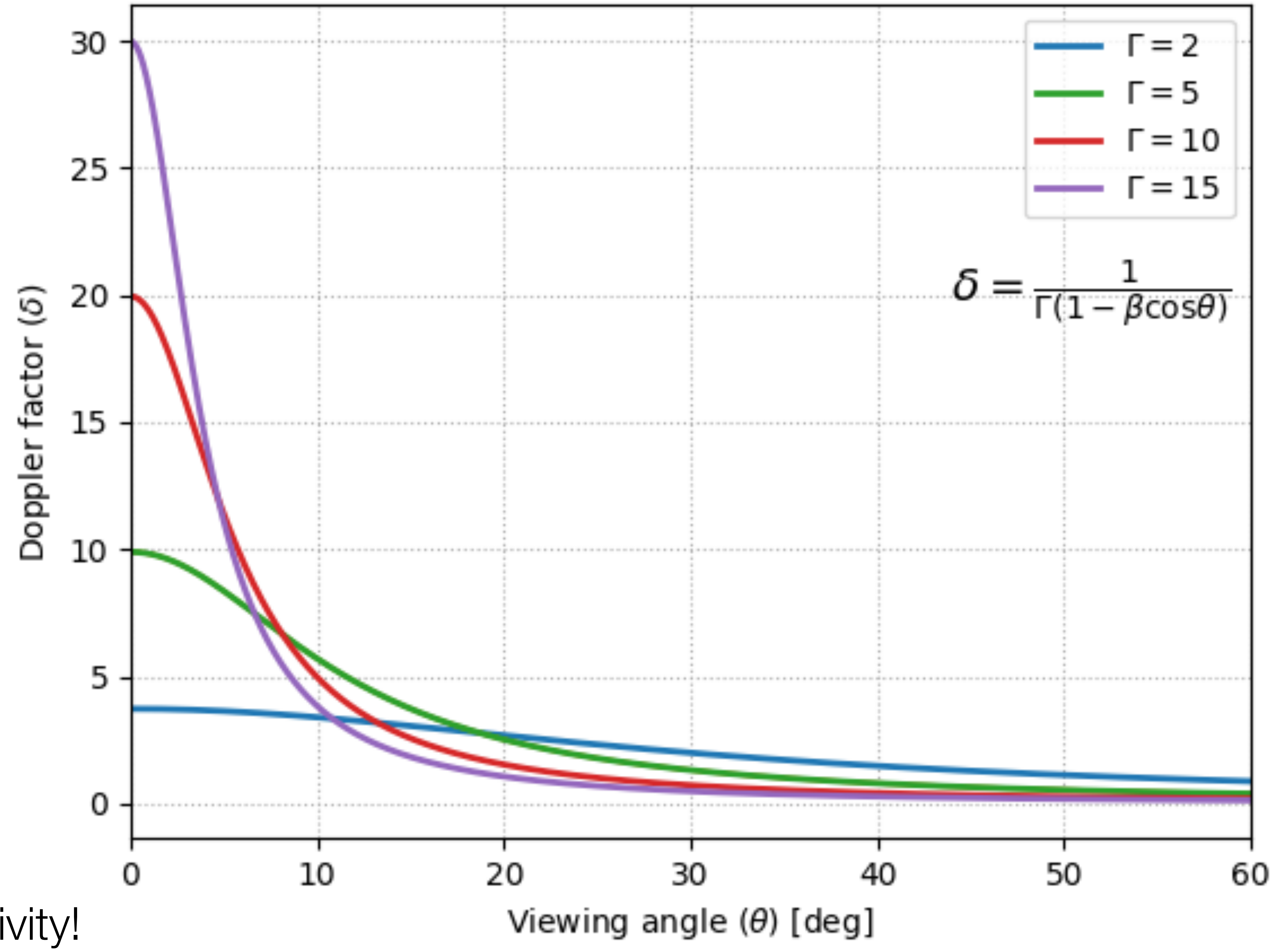
(dashes denote rest-frame quantities)

Special cases:

$\delta_{\rm max} = \delta(0^\circ) = \dfrac{1}{\Gamma(1-\beta)} = \Gamma(1+\beta) \sim 2\Gamma$

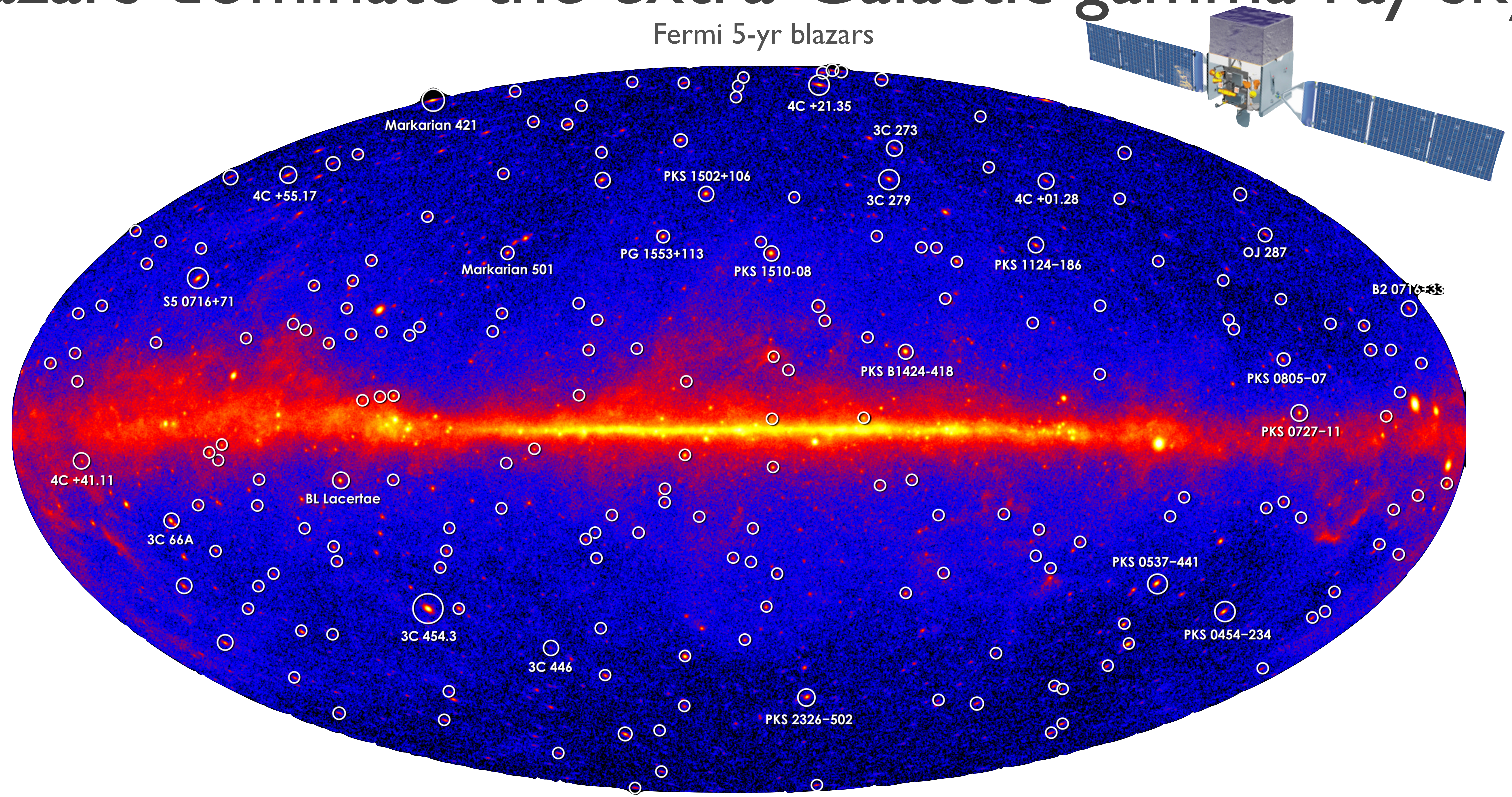
$\delta_{\rm min} = \delta(90^\circ) = 1/\Gamma$ – recover special relativity

$\theta = 1/\Gamma, \cos\theta \approx 1 - \dfrac{\theta^2}{2} \approx \beta,\ \delta = \Gamma$ – opposite of special relativity!



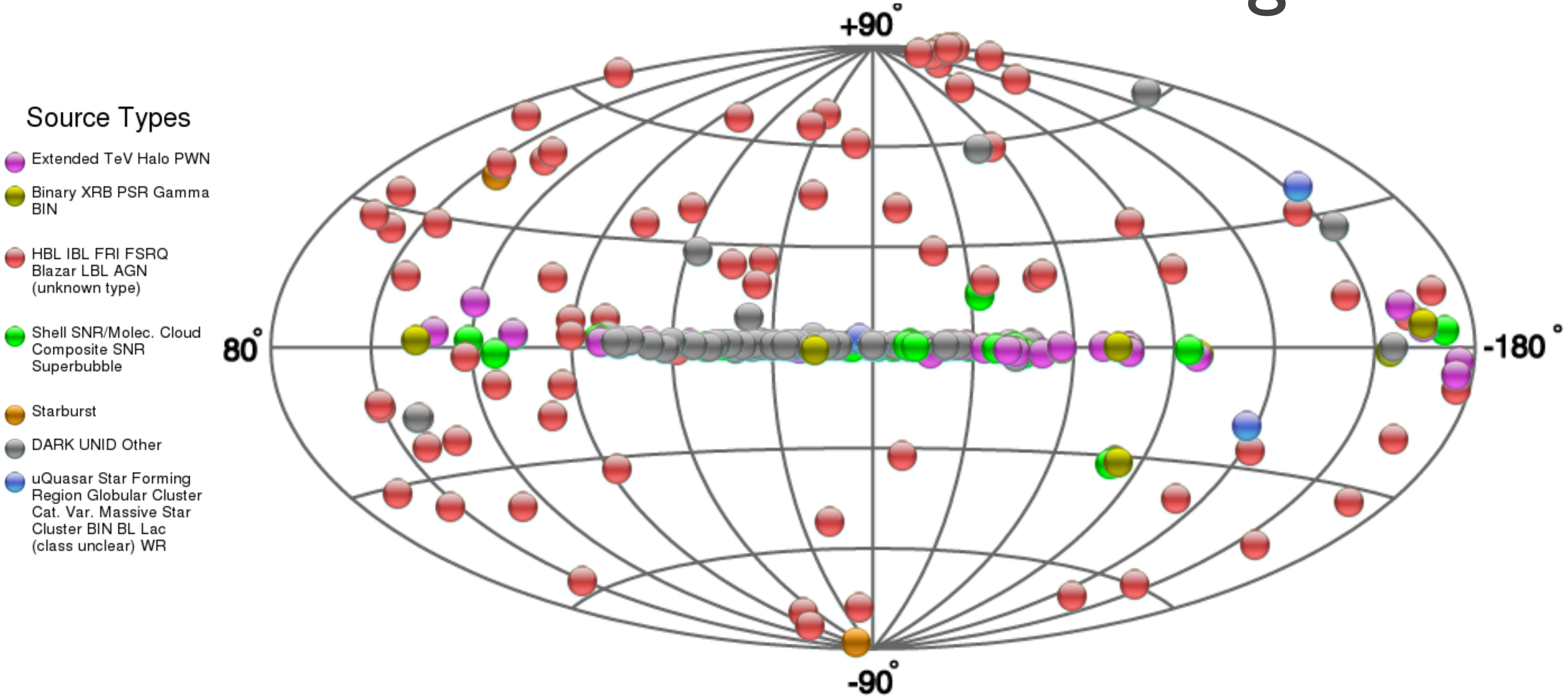
Blazars dominate the extra-Galactic gamma-ray sky

Fermi 5-yr blazars

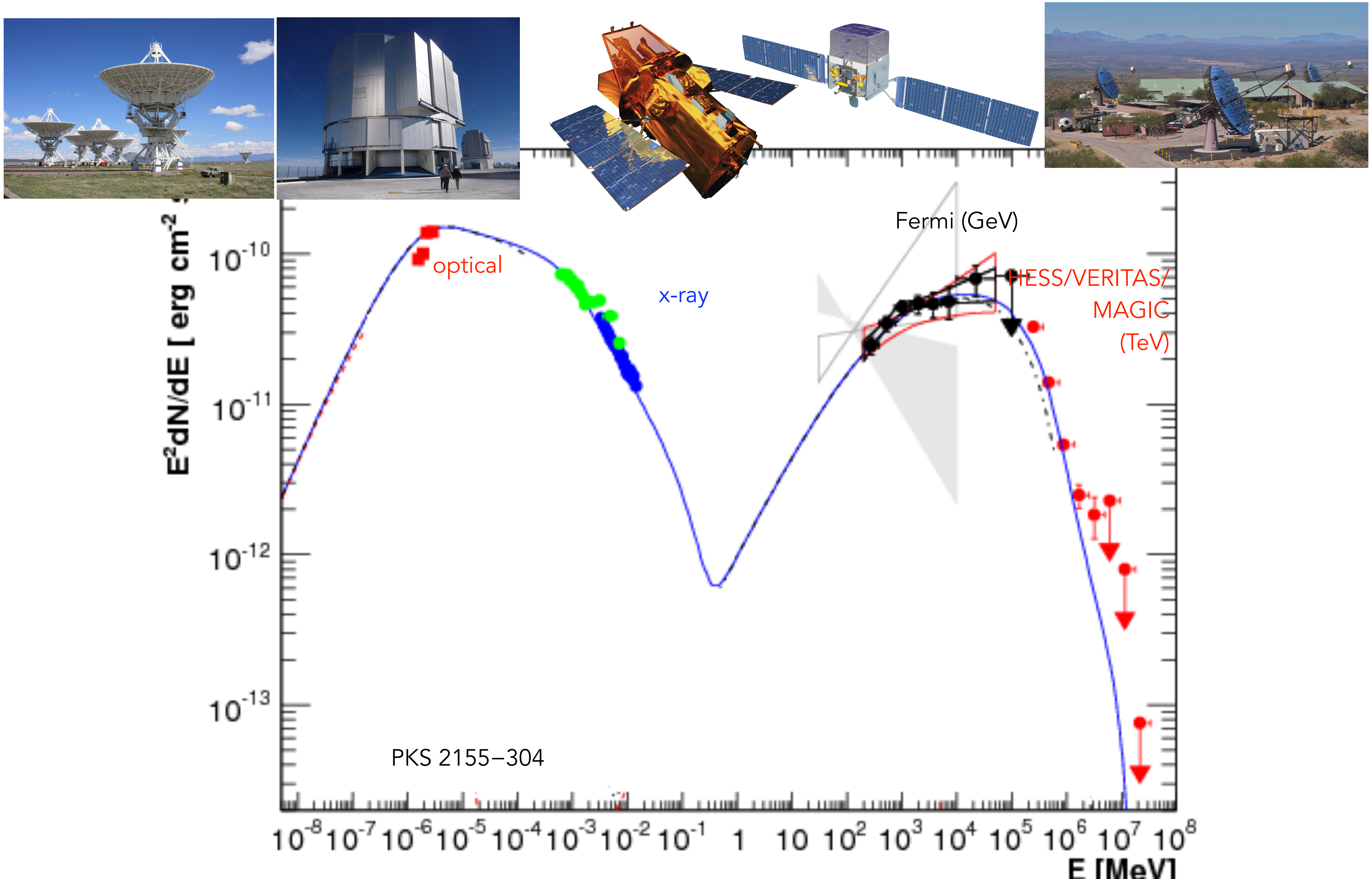


>90% of extragalactic Fermi sources (see also TeVCaT)

Blazars dominate the extra-Galactic gamma-ray sky



Blazar spectral energy distribution

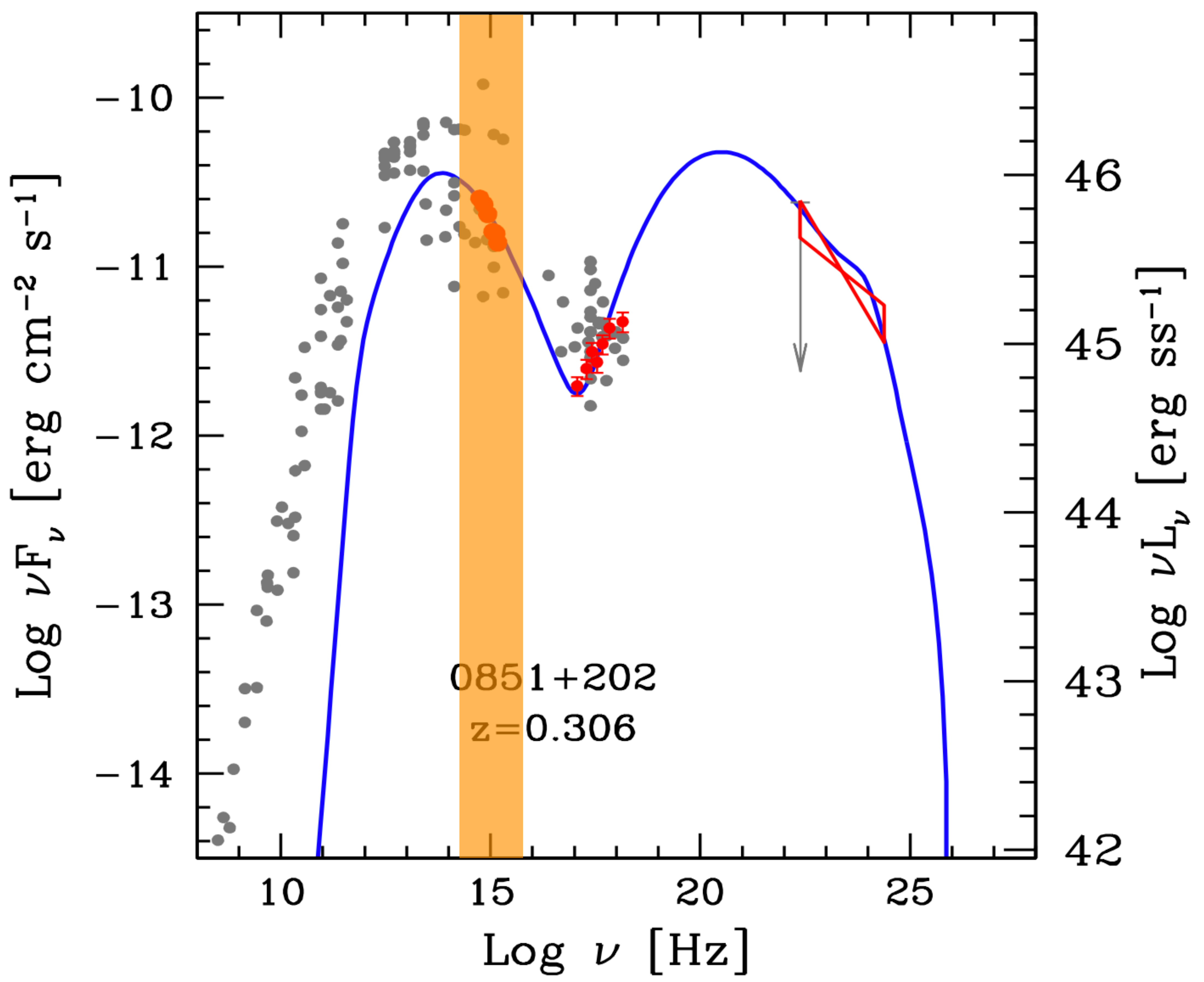


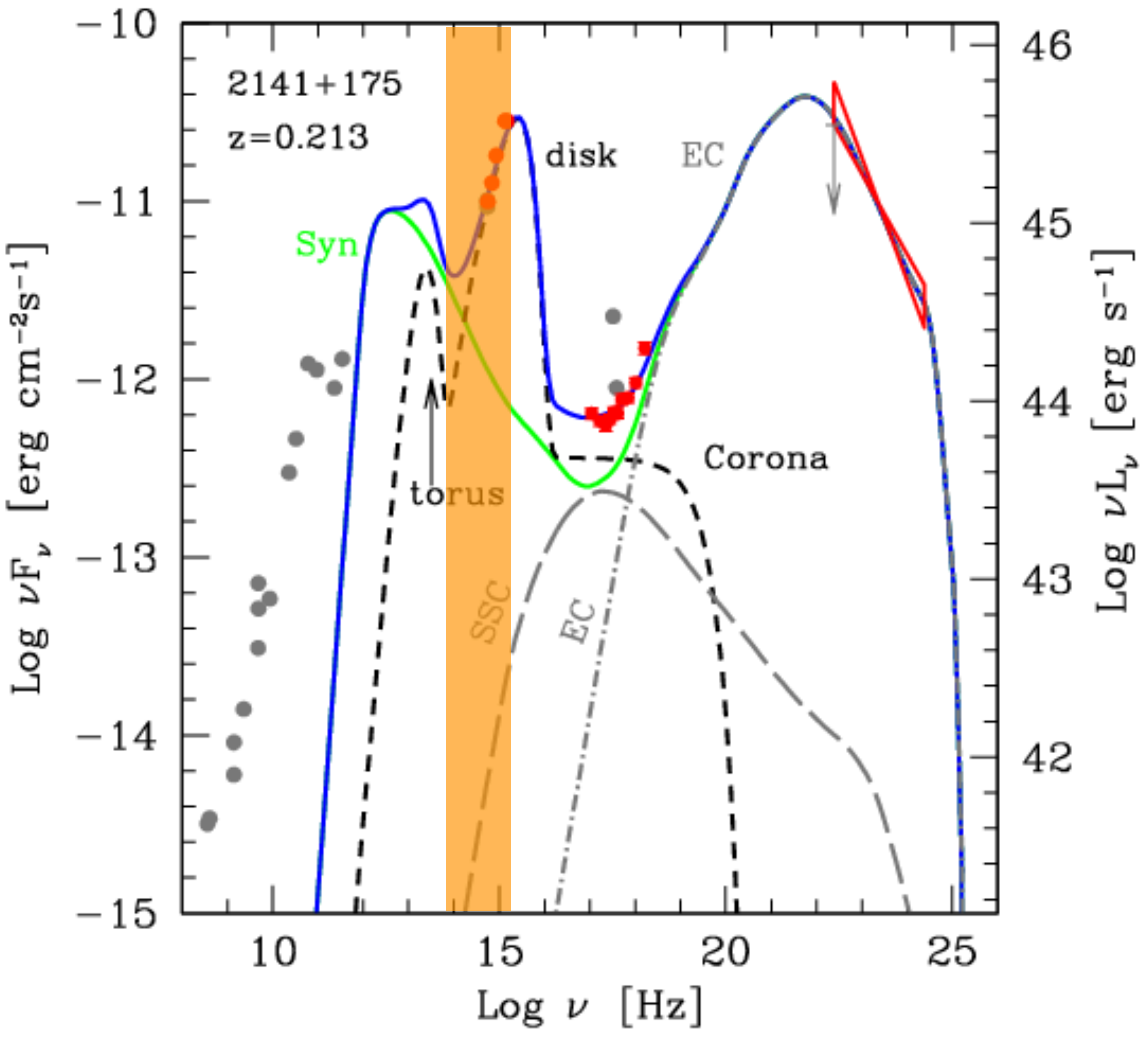
Blazar classes: BL Lac objects and FSRQs

BL Lac Object

Optical light

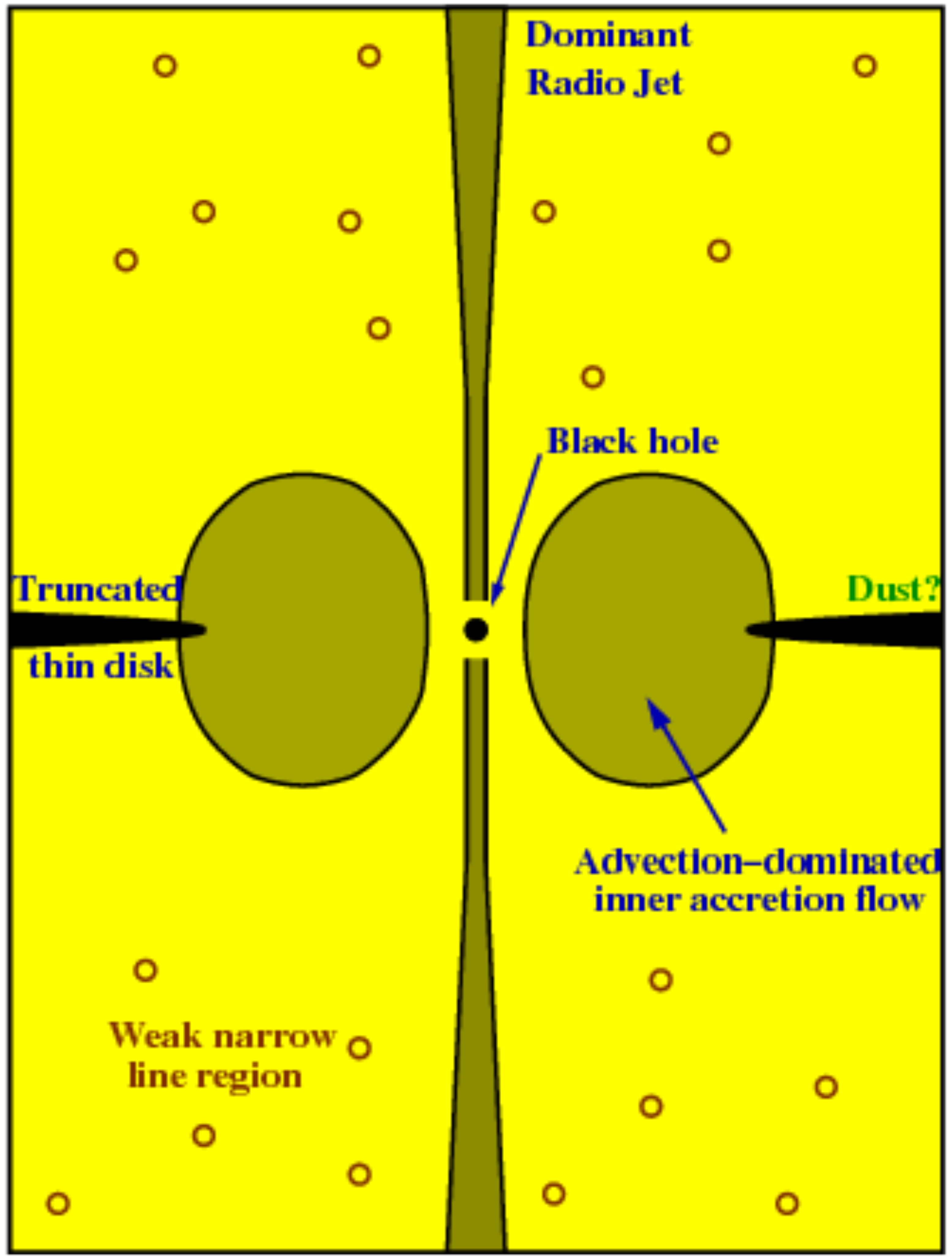
Flat spectrum radio quasar



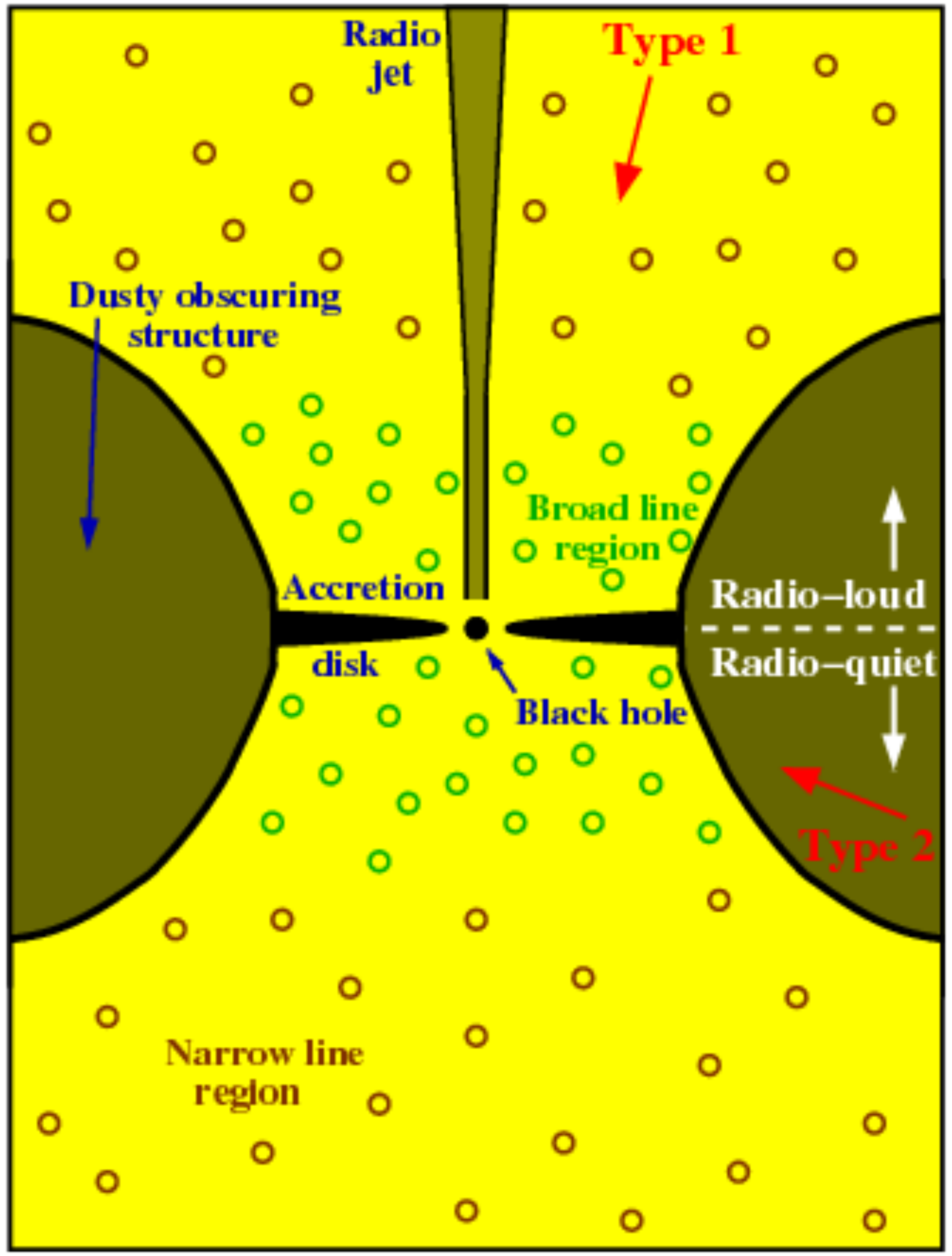


Blazar classes: BL Lac objects and FSRQs

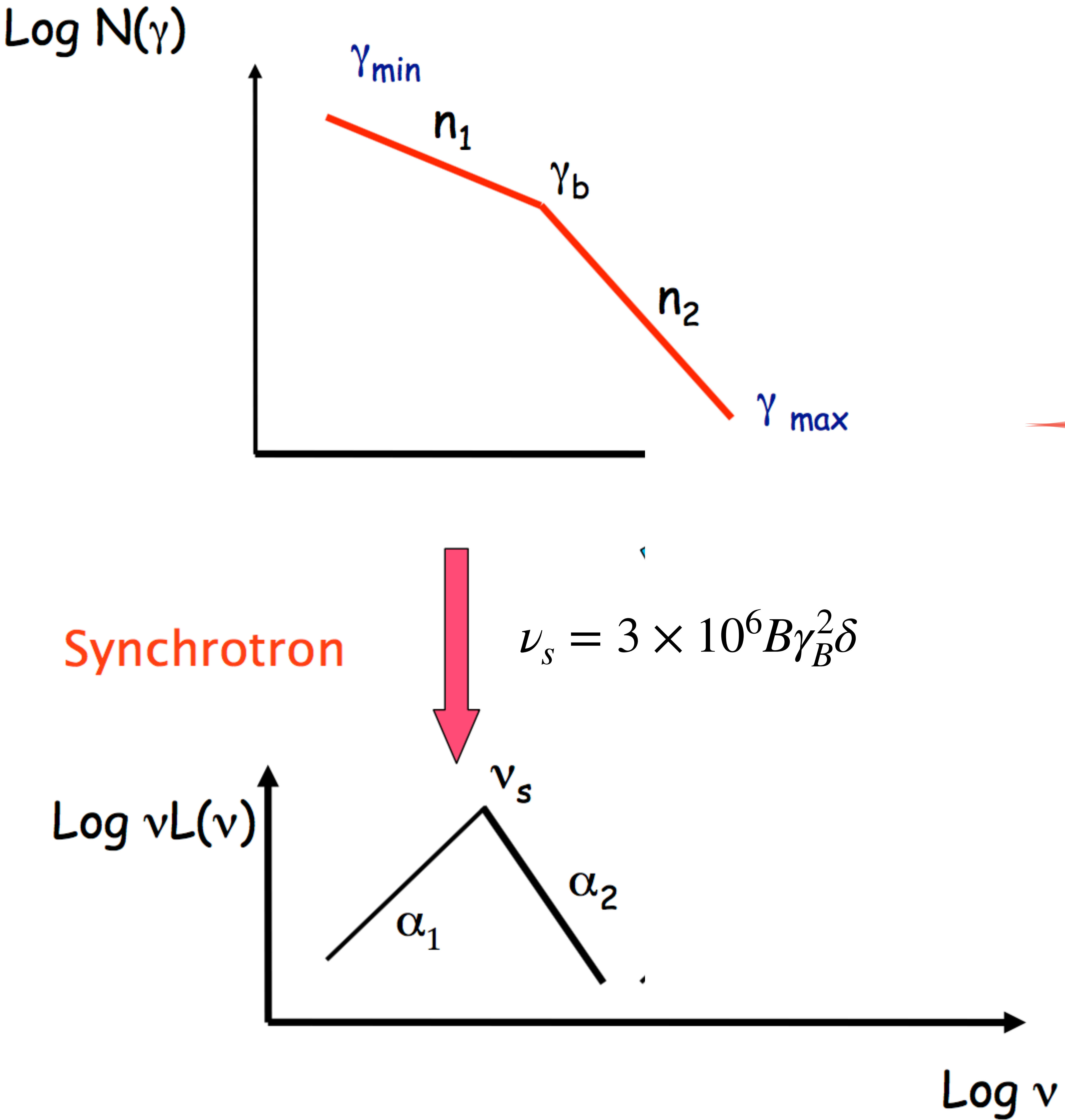
BL Lac Object



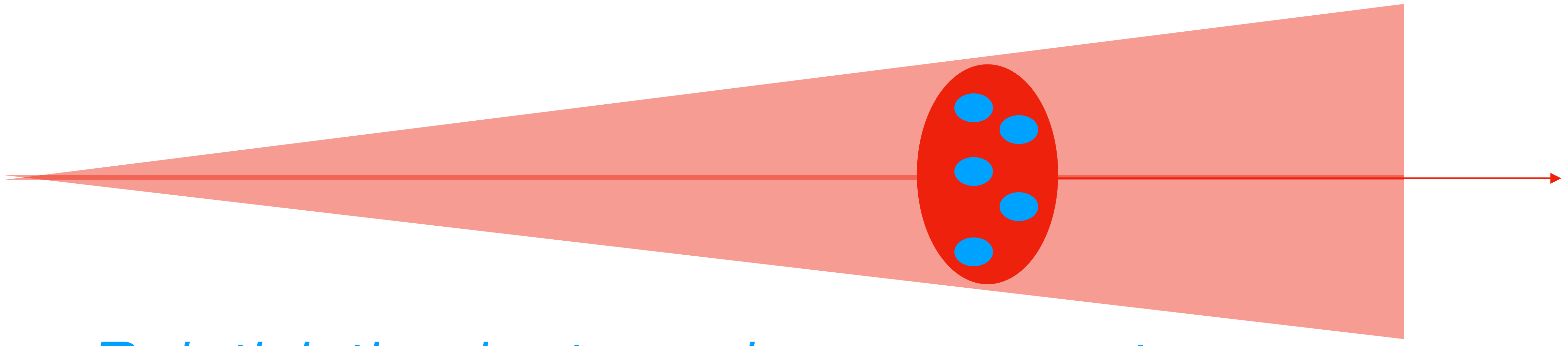
Flat spectrum radio quasar



Emission from BL Lac objects



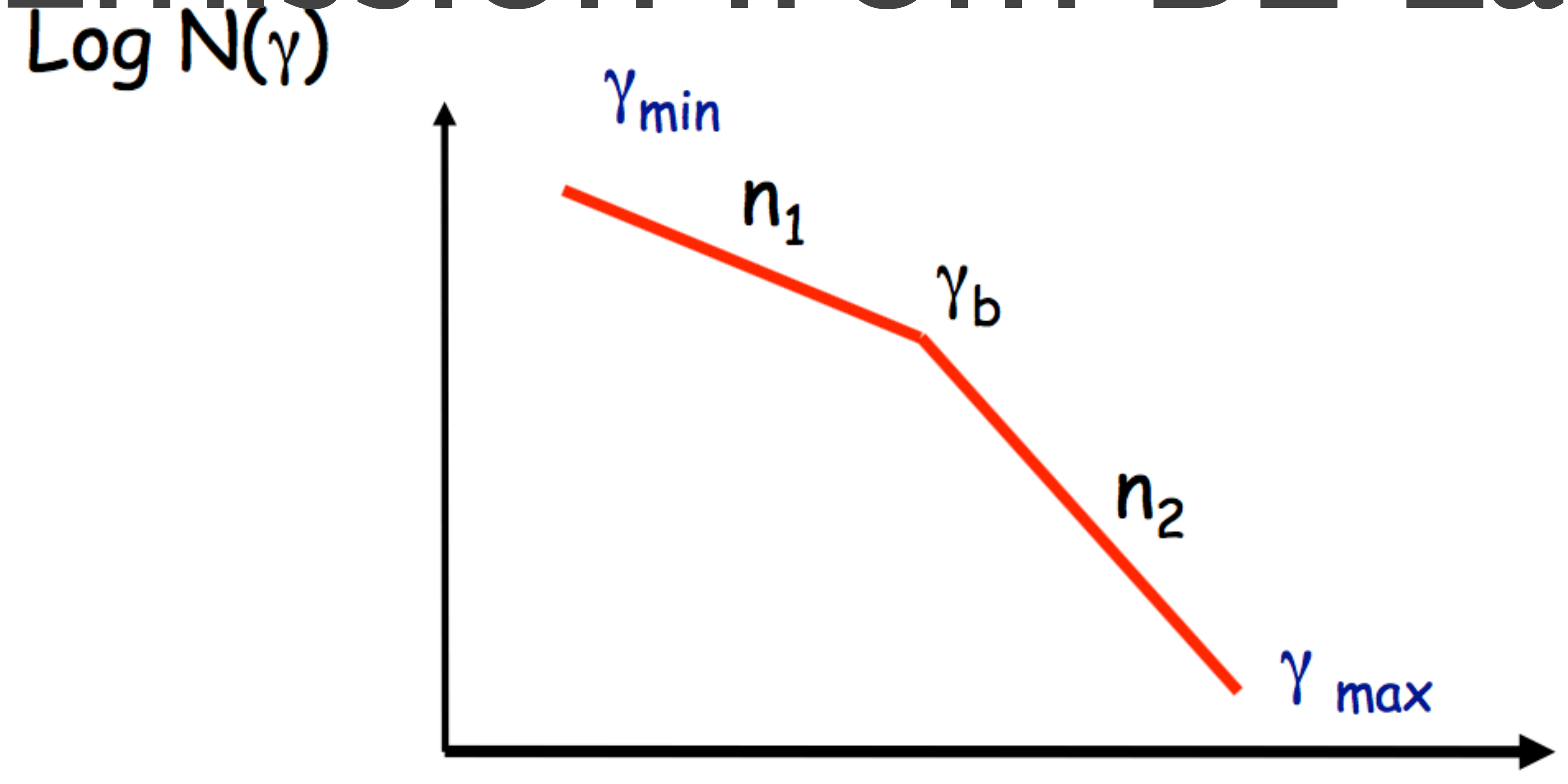
$$\nu_s = 3 \times 10^6 B \gamma_B^2 \delta$$

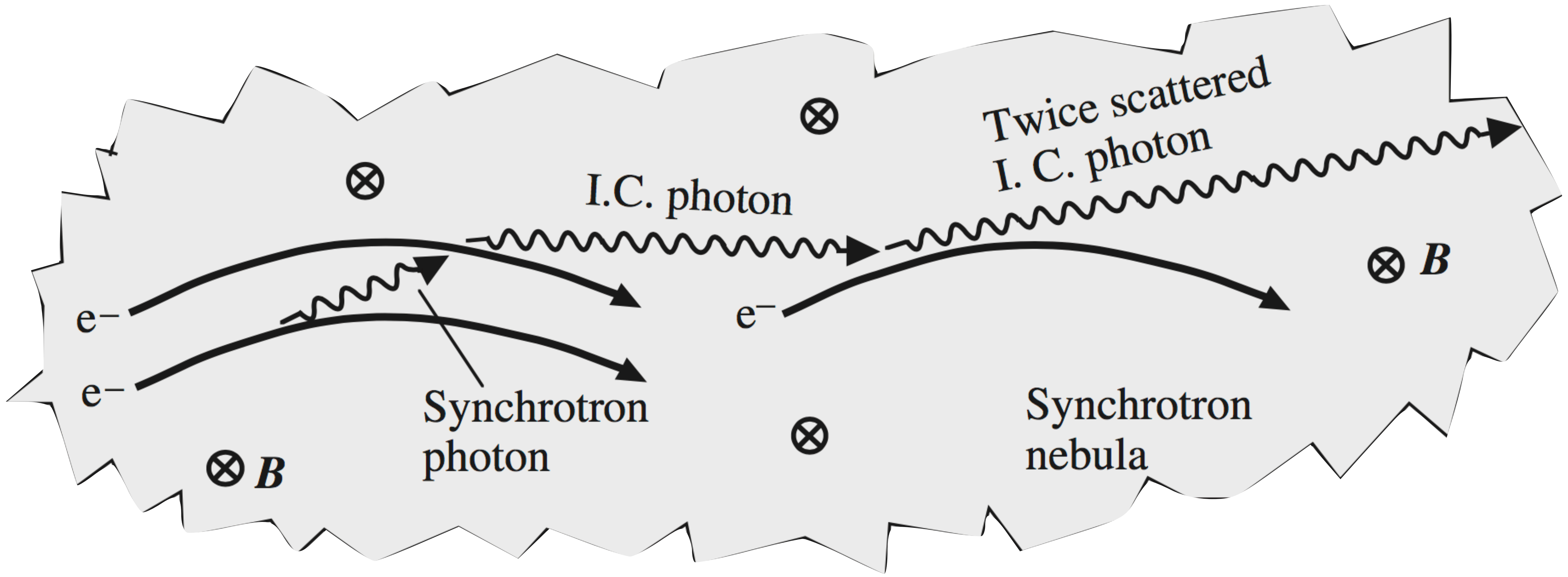


Relativistic electrons in a compact, relativistic region moving at $\beta \sim 1$

Magnetic field strength B, doppler factor δ, electron Lorentz factor γ

Emission from BL Lac objects



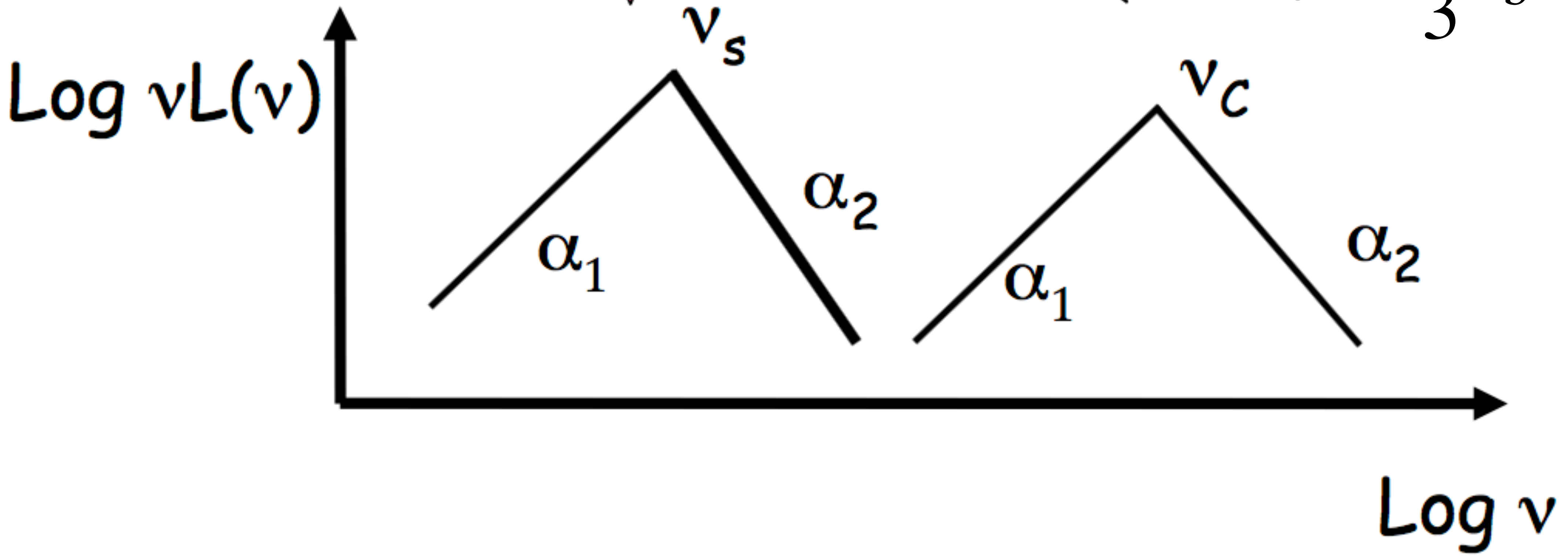


Synchrotron

$$\nu_S = \frac{4}{3}\gamma_{\mathrm{break}}^2 \nu_B \approx 3.7 \cdot 10^6 \gamma_{\mathrm{break}} B\delta$$

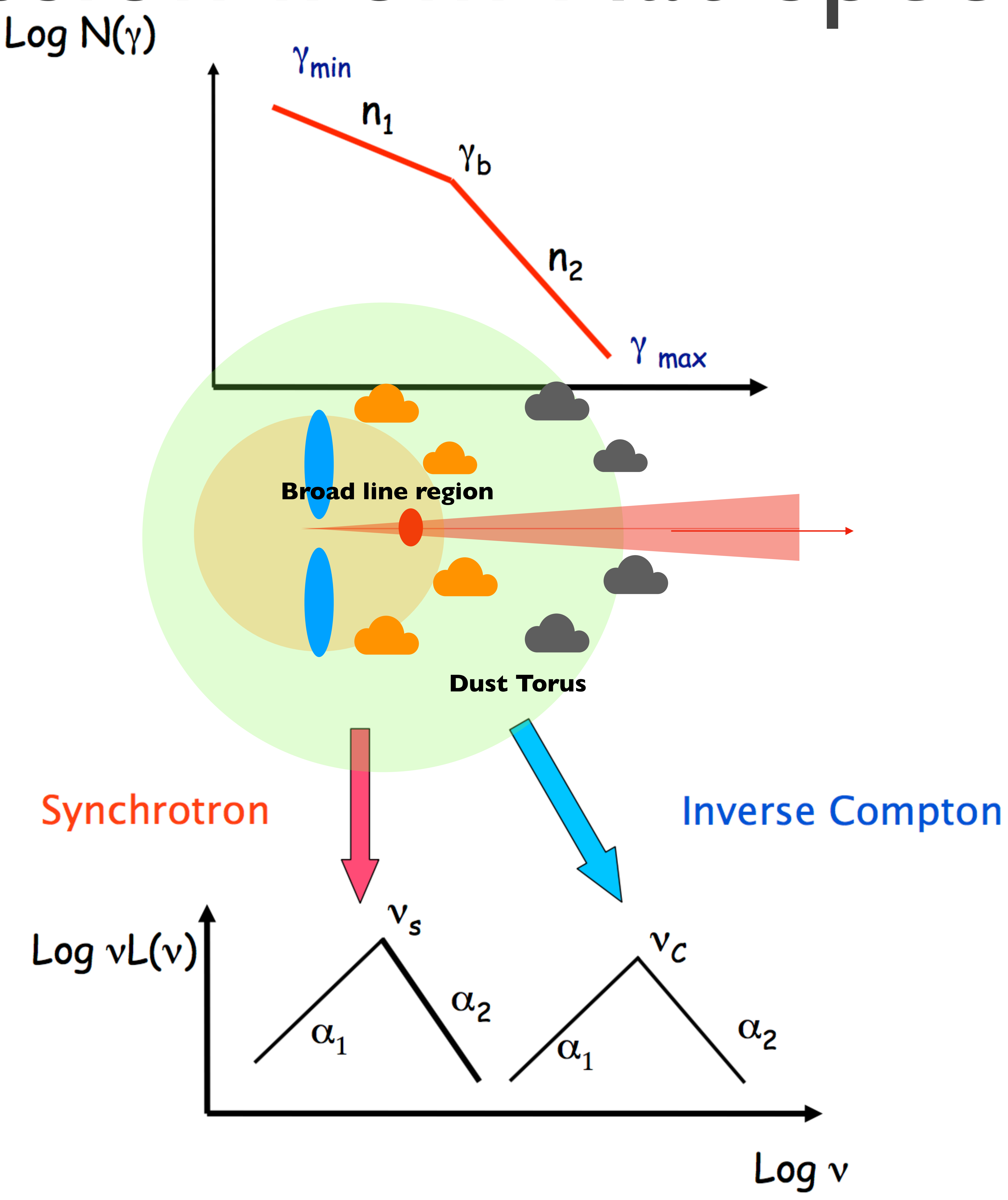
Inverse Compton

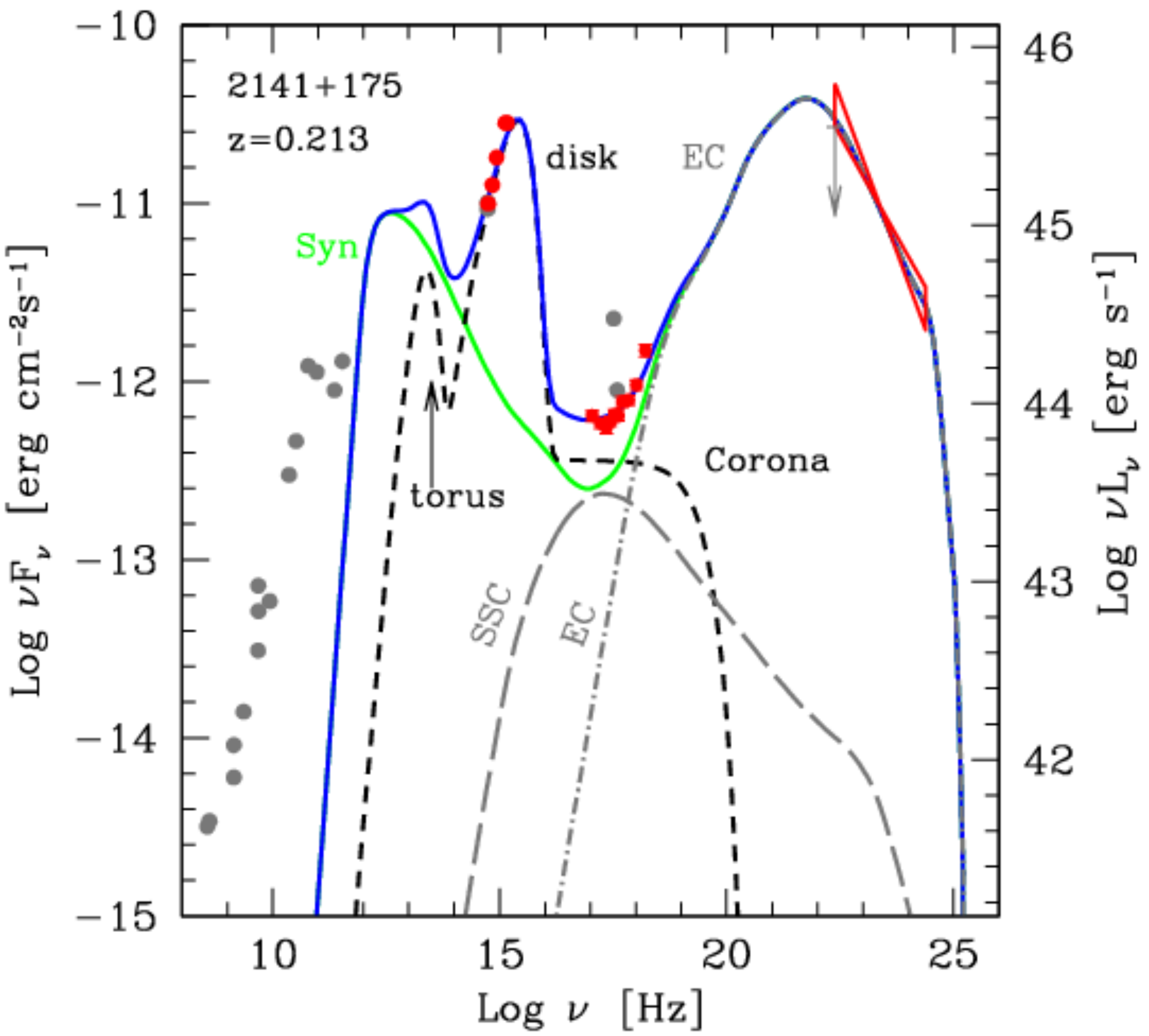
$$\nu_C = \frac{4}{3}\gamma_b^2 \nu_S$$



In this synchrotron + synchrotron self Compton (SSC) model, we can in principle determine the magnetic field strength, doppler factor, γ_b, n_1, n_2, electron density, size of emitting region from observed quantities (see back-up)

Emission from Flat Spectrum Radio Quasars





Summary

- AGN host a compact and extremely bright emission region
- The AGN ``zoo'' can be compactly described by the Unification model
- Blazars are the most luminous persistent astrophysical sources in the Universe
- Non-thermal spectra, can be easy to determine physical conditions in the sources

Back-up

Eddington luminosity reminder

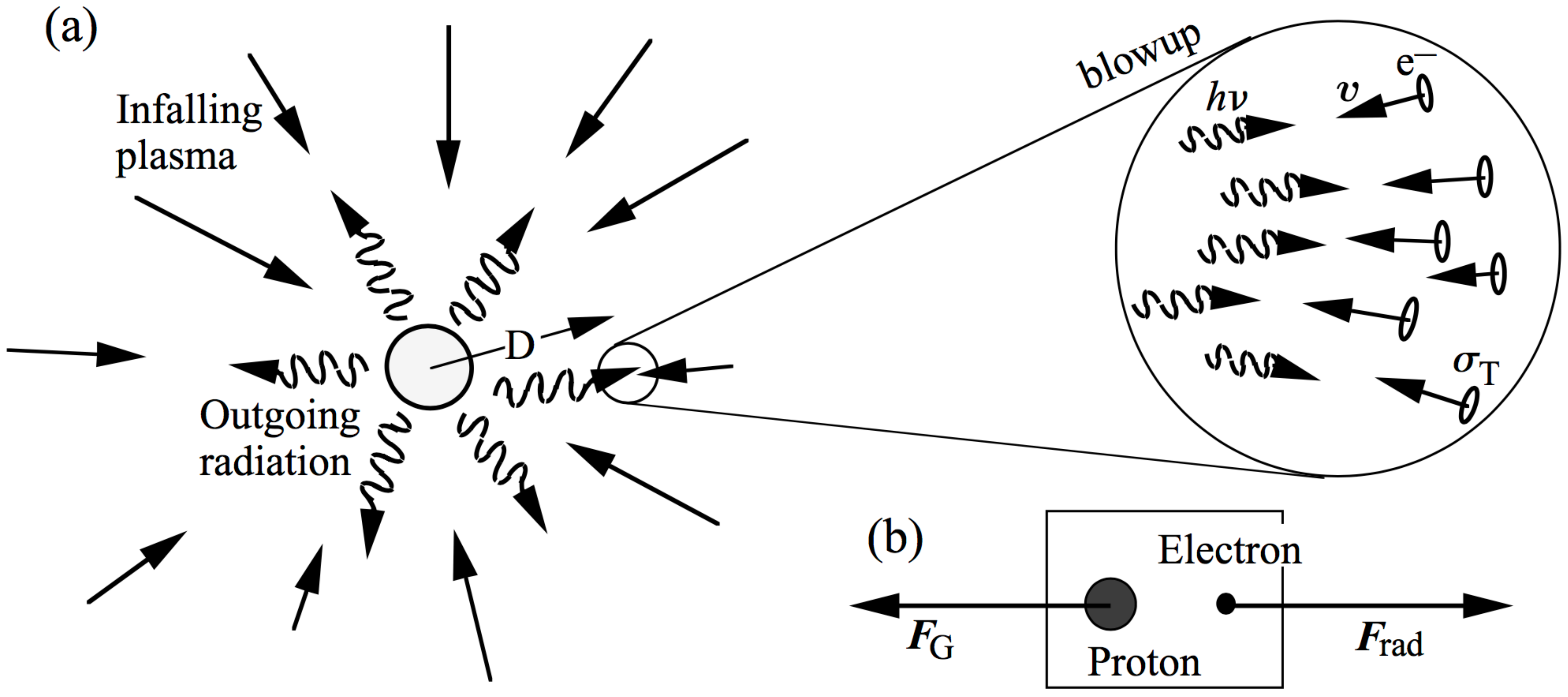


Image from H. Bradt "Astrophysical processes" 2008

Outward radiative force = Inward self-gravity

$$F_{\mathrm{rad}} = \frac{L\sigma_T}{4\pi r^2 c}\ ^{*} \qquad F_{\mathrm{Grav}} = \frac{GMm_p}{r^2}$$

$\frac{L}{4\pi r^2 c}$ is the radiation pressure since we have here, momentum per second which is a force and force per unit area.

$$L_{\mathrm{Edd}} = \frac{4\pi GMm_p c}{\sigma_{\mathrm{T}}} = 30{,}000\left(\frac{M}{M_{\mathrm{Sun}}}\right)L_{\mathrm{Sun}}$$

Photo-pion production

$p + \gamma_{\rm CMB} \rightarrow \Delta^+ \rightarrow n/p + \pi^+/\pi^0$

At threshold we want s_{min}

$$s = (\mathbf{p}_{\rm p} + \mathbf{p}_\gamma)^2 = (\mathbf{p}_{\rm p} + \mathbf{p}_\pi)^2$$

$$= (m_p + m_\pi)^2 c^2$$

$$(\mathbf{p}_{\rm p} + \mathbf{p}_\gamma)^2 = \mathbf{p}_{\rm p}{}^2 + \mathbf{p}_\gamma{}^{2*} + 2\,\mathbf{p}_{\rm p} \cdot \mathbf{p}_\gamma$$

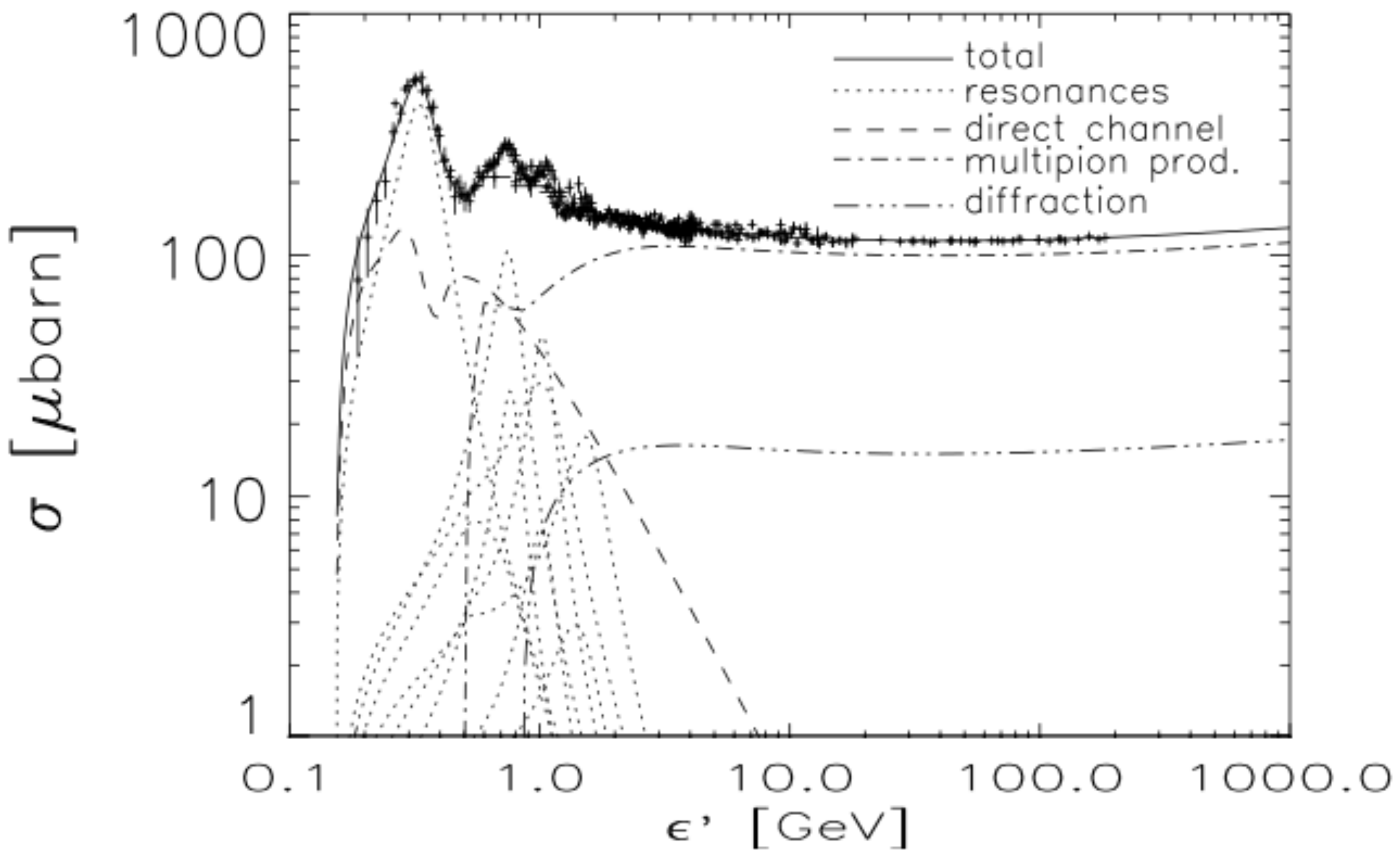
$$= m_p^2 c^2 + \cancel{\mathbf{p}_\gamma^2} + \mathbf{2}\,\mathbf{p}_{\rm p} \cdot \mathbf{p}_\gamma$$

$$= m_p^2 c^2 + 2(E_p \varepsilon_\gamma / c^2 - |\vec{p}_{\rm p}| \cdot |\vec{p}_\gamma| \cdot \cos\theta)**$$

$$= m_p^2 c^2 + 4E_p \varepsilon_\gamma / c^2$$

$$E_{\rm p} \geq \frac{m_\pi (2m_p + m_\pi)}{4\varepsilon_\gamma} c^4$$

Mücke et al 1999



$[{*}\mathbf{p}^2 = (E/c)^2 - |\vec{p}| \cdot |\vec{p}| = -m^2c^2]$ $\quad [**\,\vec{p} \approx E/c]$

$[E^2 = p^2c^2 + m^2c^4]$

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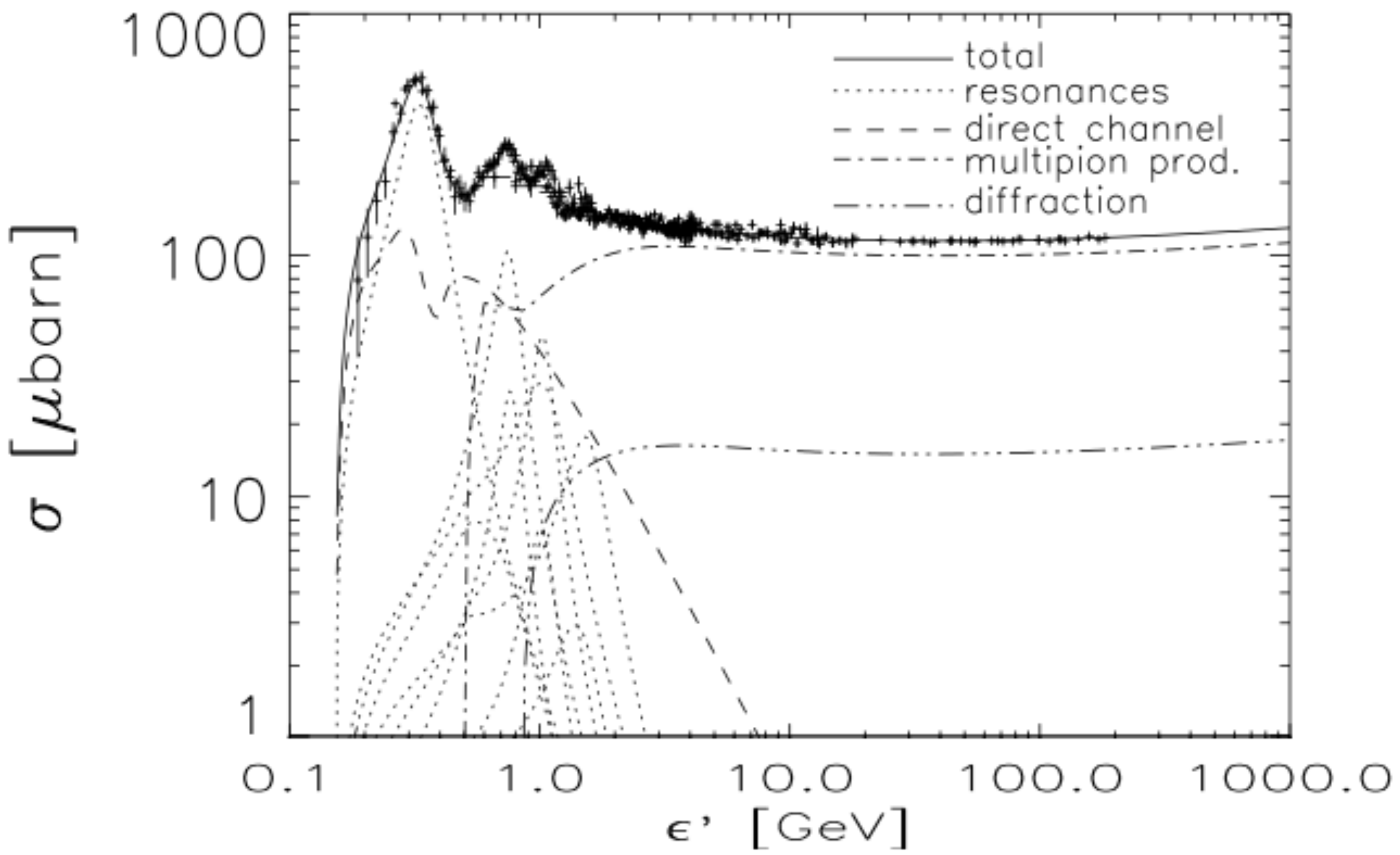
$$= m_p^2 c^2 + 2(E_p \varepsilon_\gamma / c^2 - |\vec{p}_{\rm p}| \cdot |\vec{p}_\gamma| \cdot \cos\theta)^{**}$$

$$= m_p^2 c^2 + 4 E_p \varepsilon_\gamma / c^2$$

$$E_{\rm p} \geq \frac{m_\pi (2m_p + m_\pi)}{4\varepsilon_\gamma} c^4$$

$$\left[{}^*\mathbf{p}^2 = (E/c)^2 - |\vec{p}| \cdot |\vec{p}| = -m^2 c^2\right] \quad [{}^{**}\vec{p} \approx E/c]$$
$$\left[E^2 = p^2 c^2 + m^2 c^4\right]$$

Mücke et al 1999



$$E_{\rm p} \gtrsim 10^{20}\,\text{eV} \left(\frac{\varepsilon_{\gamma,\rm cmb}}{6 \cdot 10^{-4}\,\text{eV}}\right)^{-1}, n_{\rm cmb} \sim 411\,\text{cm}^{-3}$$

$$E_{\rm p} \gtrsim 7 \cdot 10^{17}\,\text{eV} \left(\frac{\varepsilon_{\gamma,\rm IR}}{0.1\,\text{eV}}\right)^{-1}, n_{\rm EBL} \sim 10^{-2}\,\text{cm}^{-3}$$

$$\left[\kappa \approx m_\pi/m_p \approx 0.14, \sigma_{p\gamma} \approx 5 \cdot 10^{-28}\,\text{cm}^2\right]$$

$$\lambda_{p\gamma,\rm CMB} = 1/n\sigma \sim 6\,\text{Mpc}, \chi_{\rm loss} = \lambda/\kappa \sim 50\,\text{Mpc}$$