COST — EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

COST CA18108 Fourth Annual Conference - Rijeka (Croatia)
Quantum gravity phenomenology in the multi-messenger approach
11-15 July 2023

Neutrino astrophysics in the multi-messenger era

Probing the Universe through high-energy neutrinos

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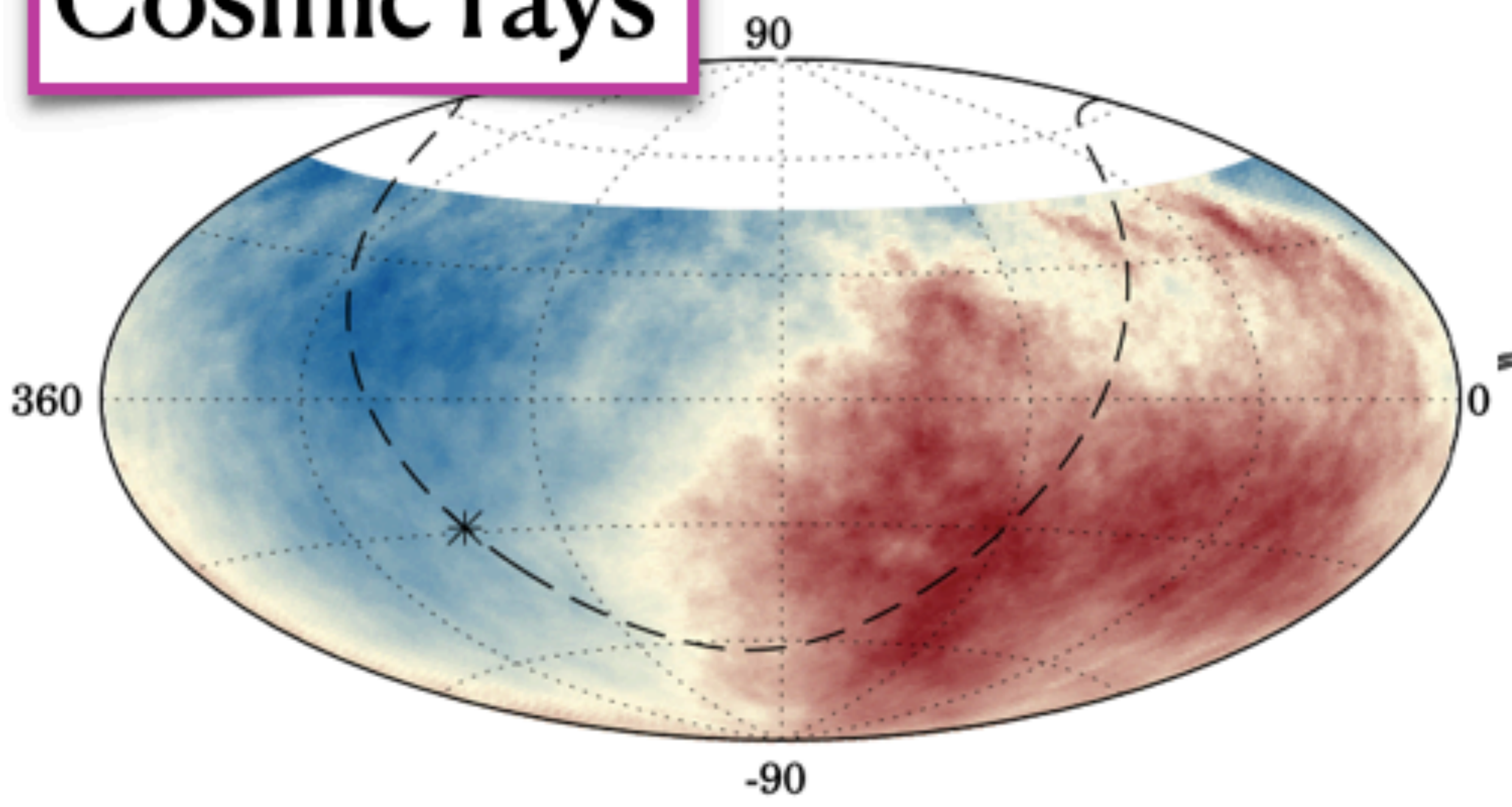
Outline

- Multi-messenger astronomy
- Neutrino astronomy
  - Neutrinos as ideal messengers
  - Neutrino telescopes
  - Neutrino science keys
- Potential high-energy astrophysical neutrino emitters
  - Gamma-Ray Bursts
  - Active Galactic Nuclei (in particular, blazars)
- State-of-the-art of neutrino astronomy: experimental results
- Summary

Multi-messenger astronomy

Cosmic rays

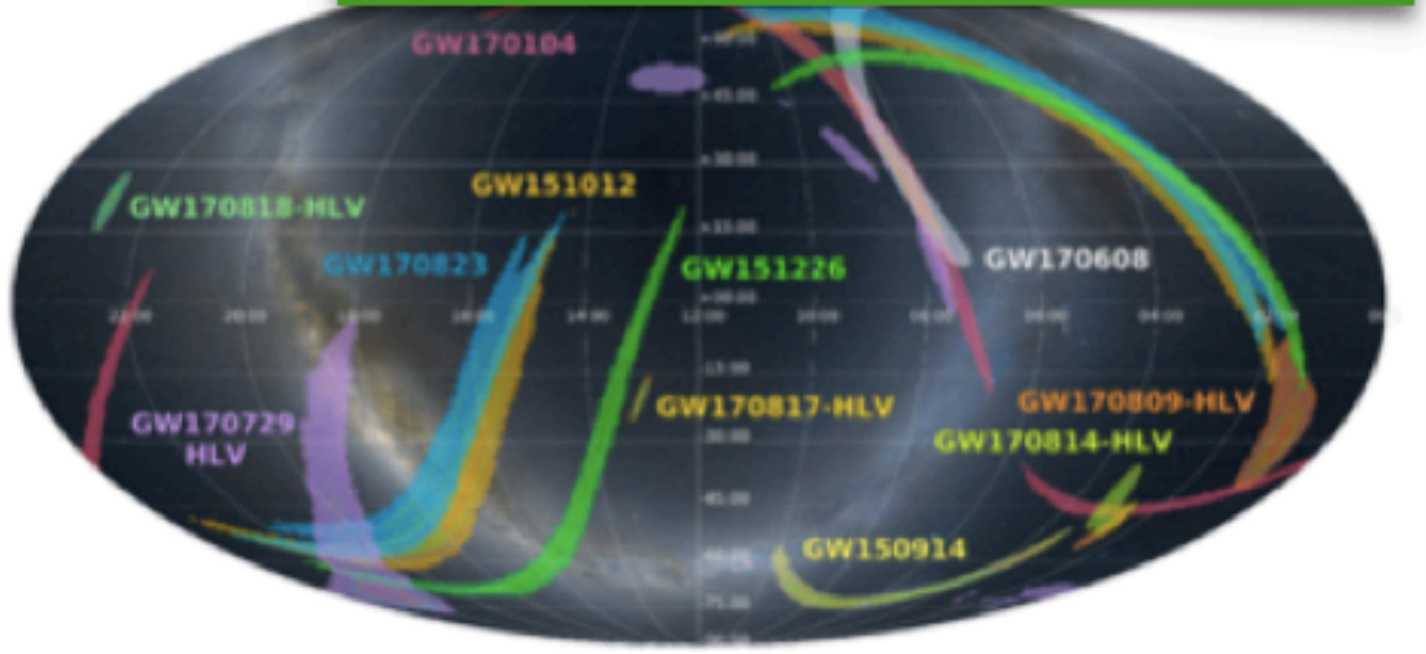


Pierre Auger Observatory

UHECRs

> EeV

Gravitational Waves

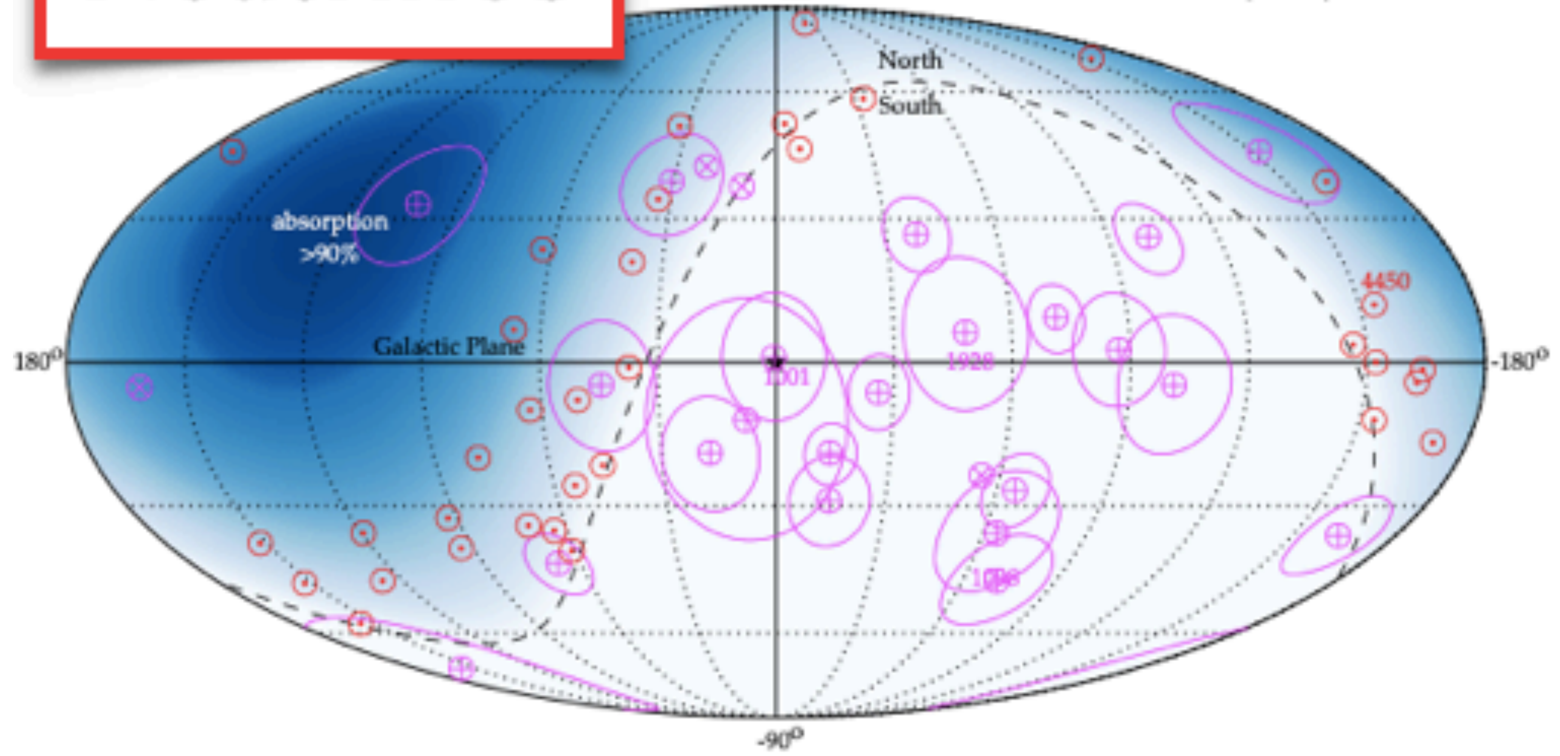


LIGO-Virgo GWs

The sky is full of messengers

Each of these signals carries a message. What can they tell us?

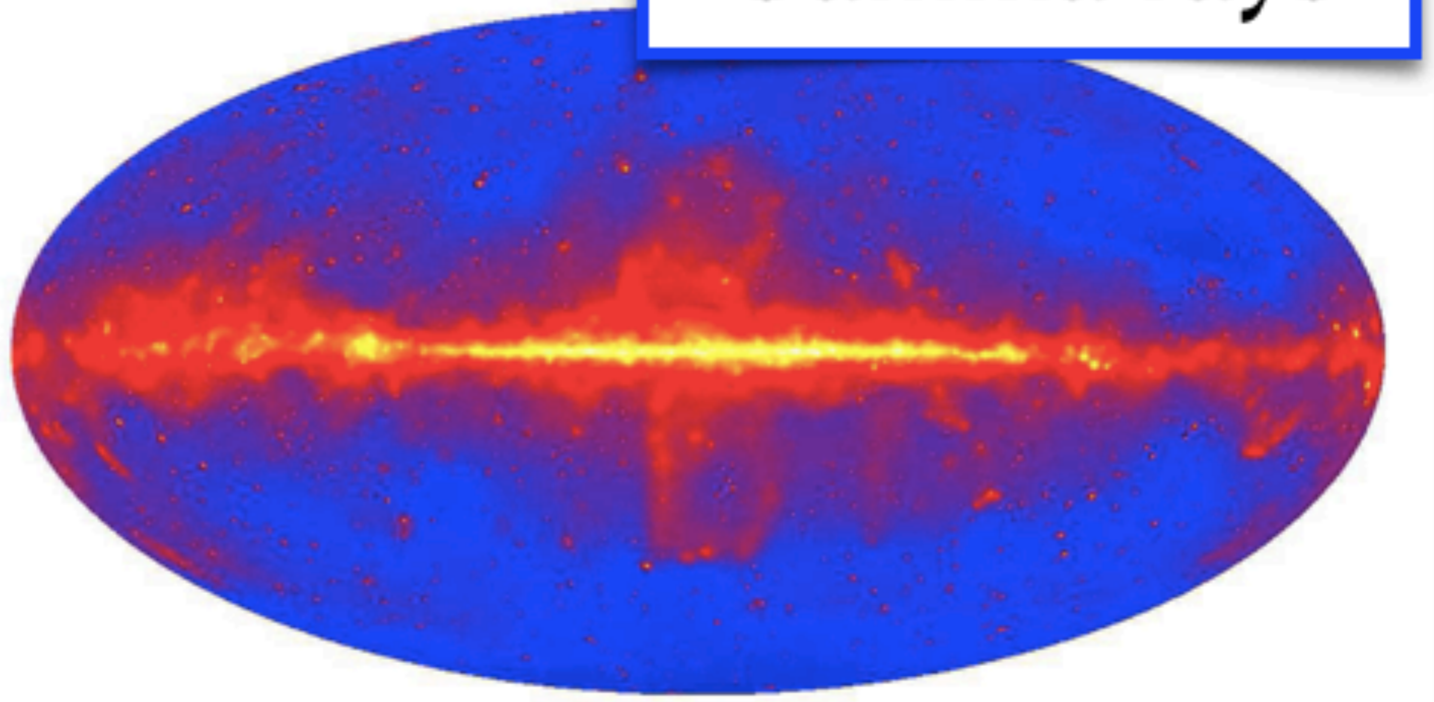
Neutrinos



IceCube astrophysical neutrino events

TeV-PeV

Gamma rays

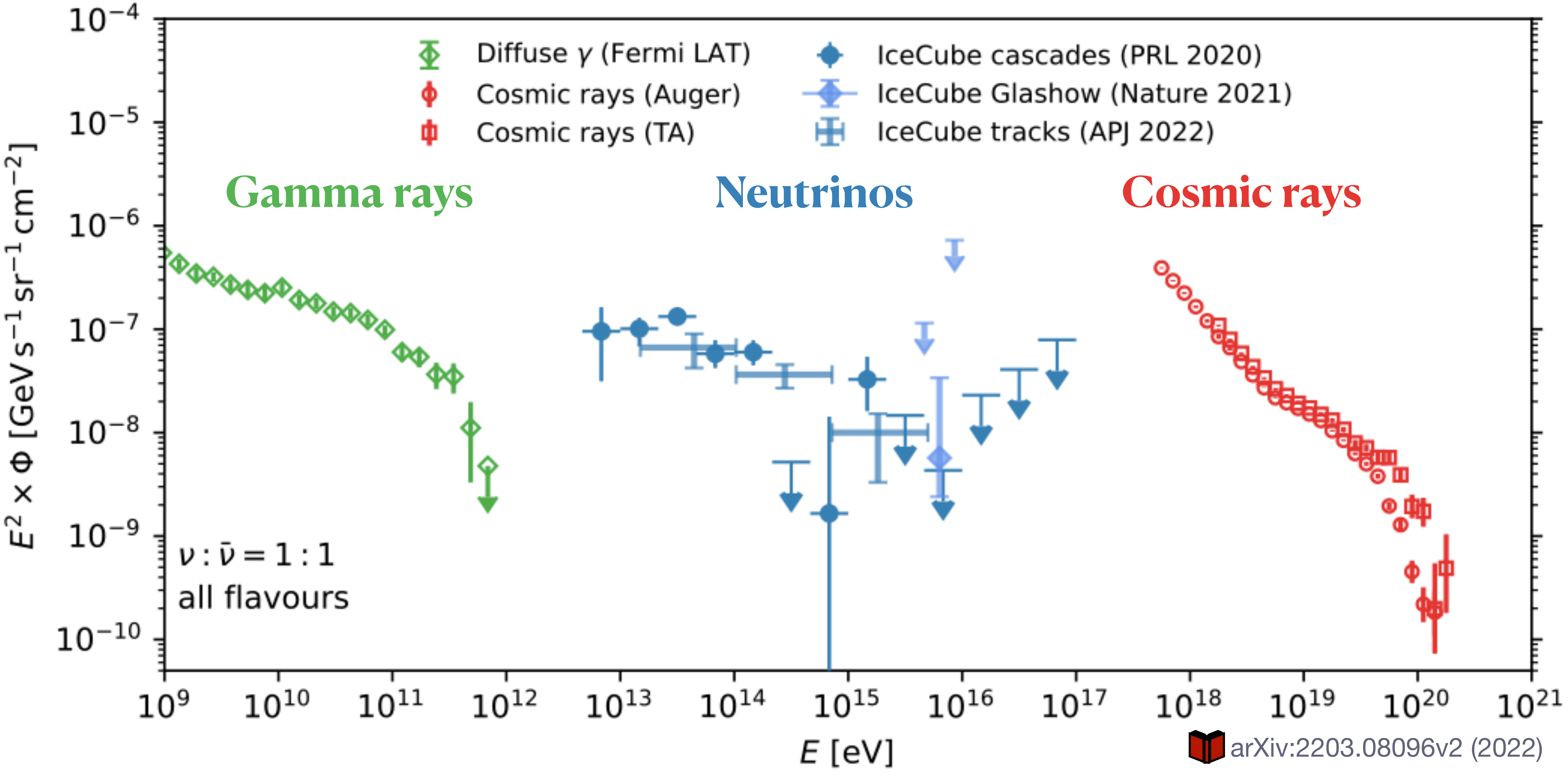


Fermi-LAT map

MeV-GeV

Observed diffuse fluxes of multiple messengers

A complete picture of the high-energy Universe is necessarily multi-messenger in nature



arXiv:2203.08096v2 (2022)

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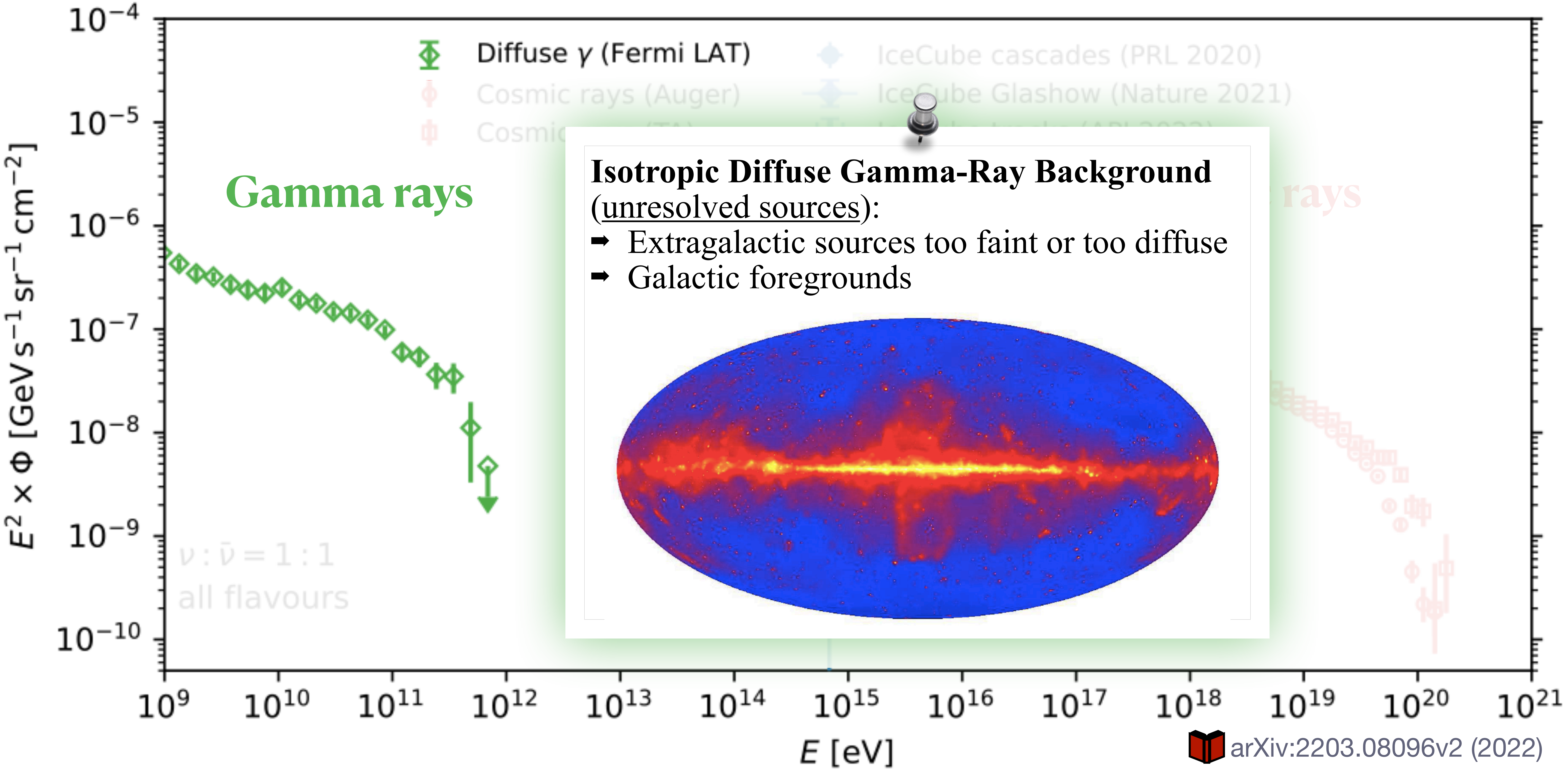

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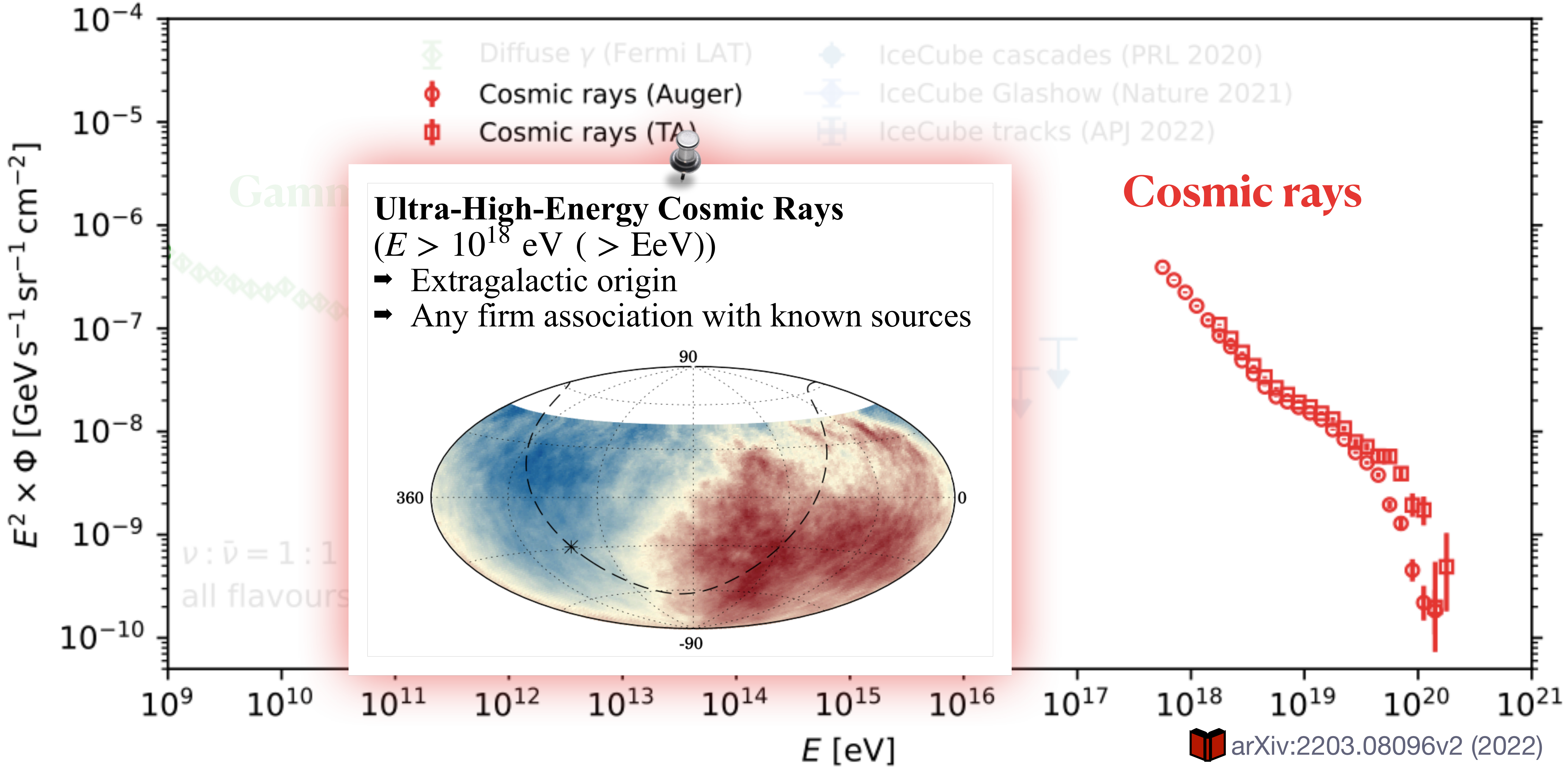


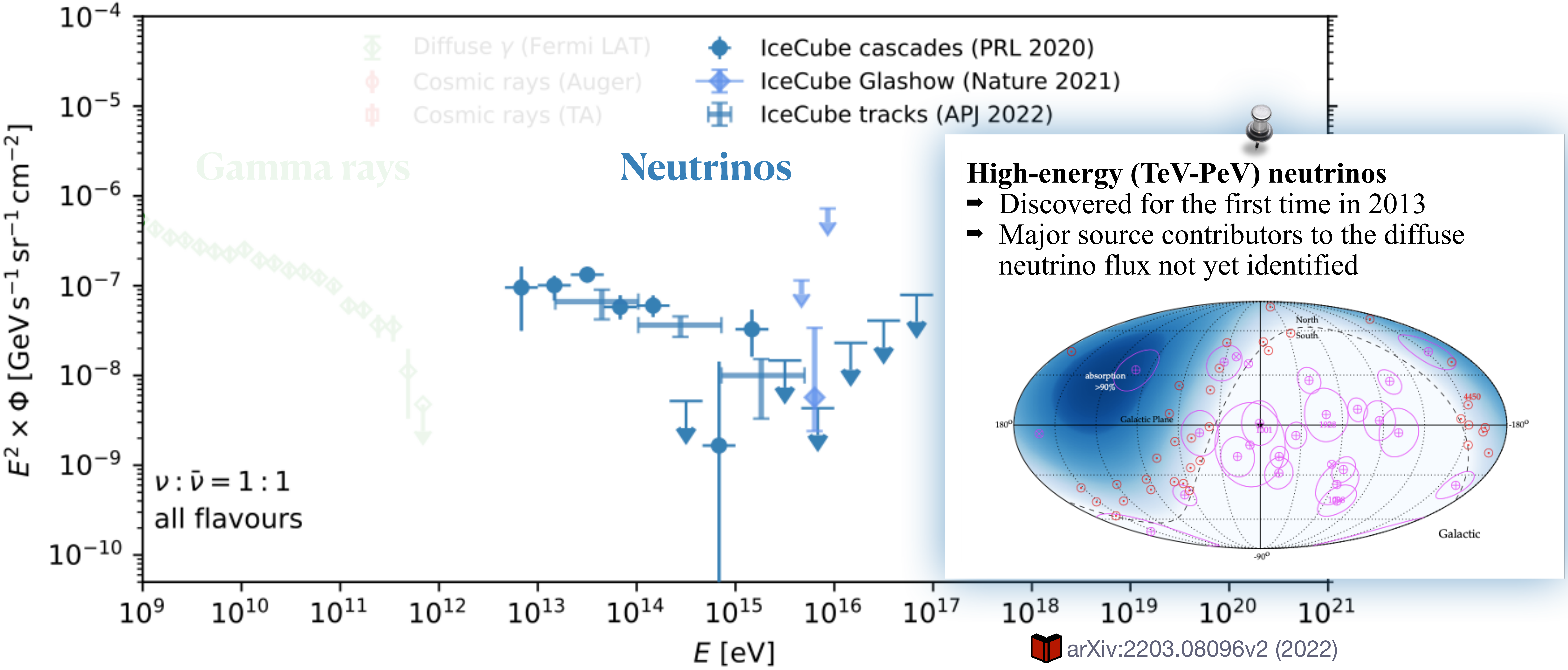
Ultra-High-Energy Cosmic Rays
($E > 10^{18}$ eV (> EeV))

➡ Extragalactic origin
➡ Any firm association with known sources

arXiv:2203.08096v2 (2022)

Observed diffuse fluxes of multiple messengers

A complete picture of the high-energy Universe is necessarily multi-messenger in nature



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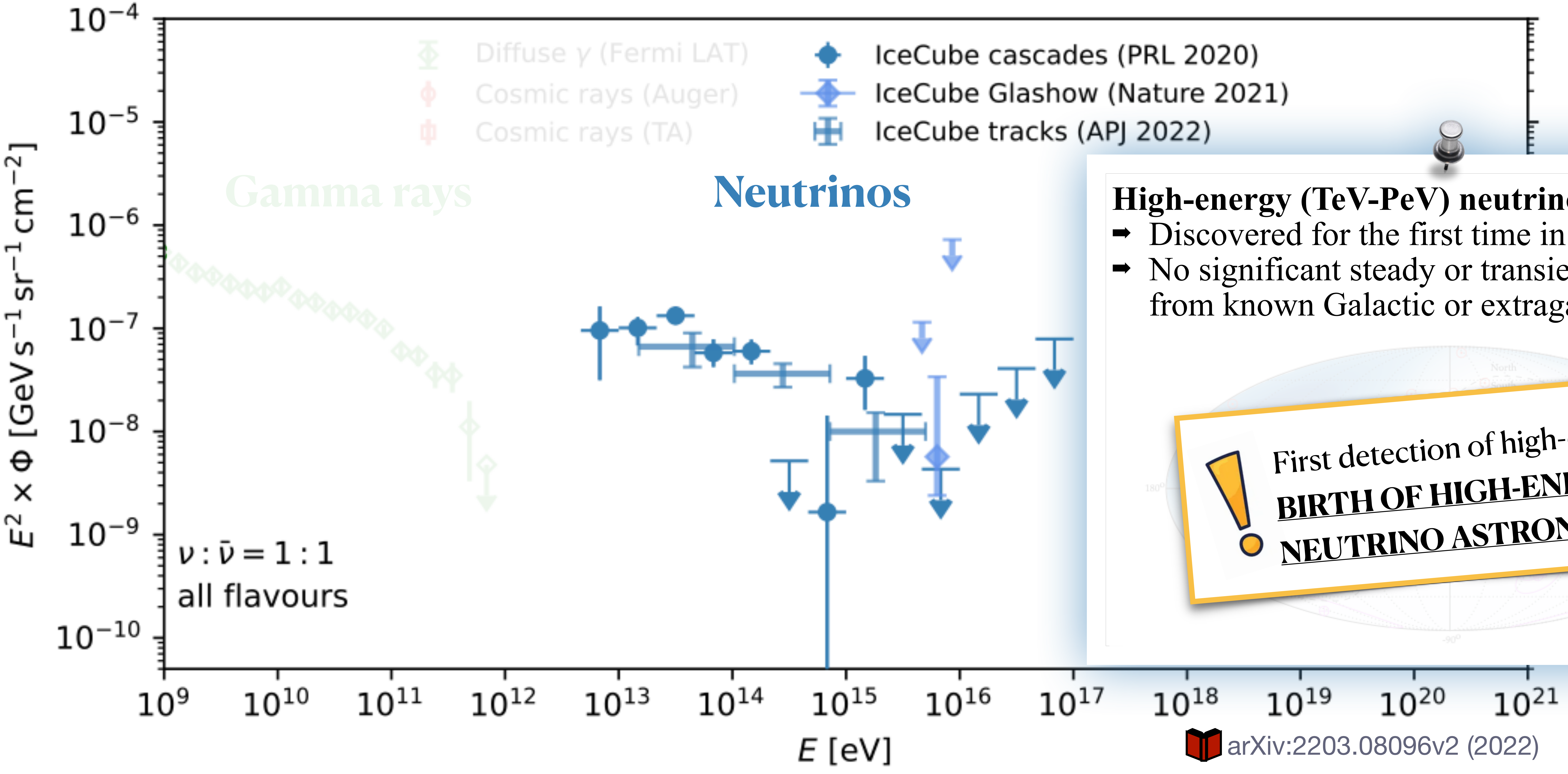


High-energy (TeV-PeV) neutrinos

- Discovered for the first time in 2013
- No significant steady or transient emission from known Galactic or extragalactic sources

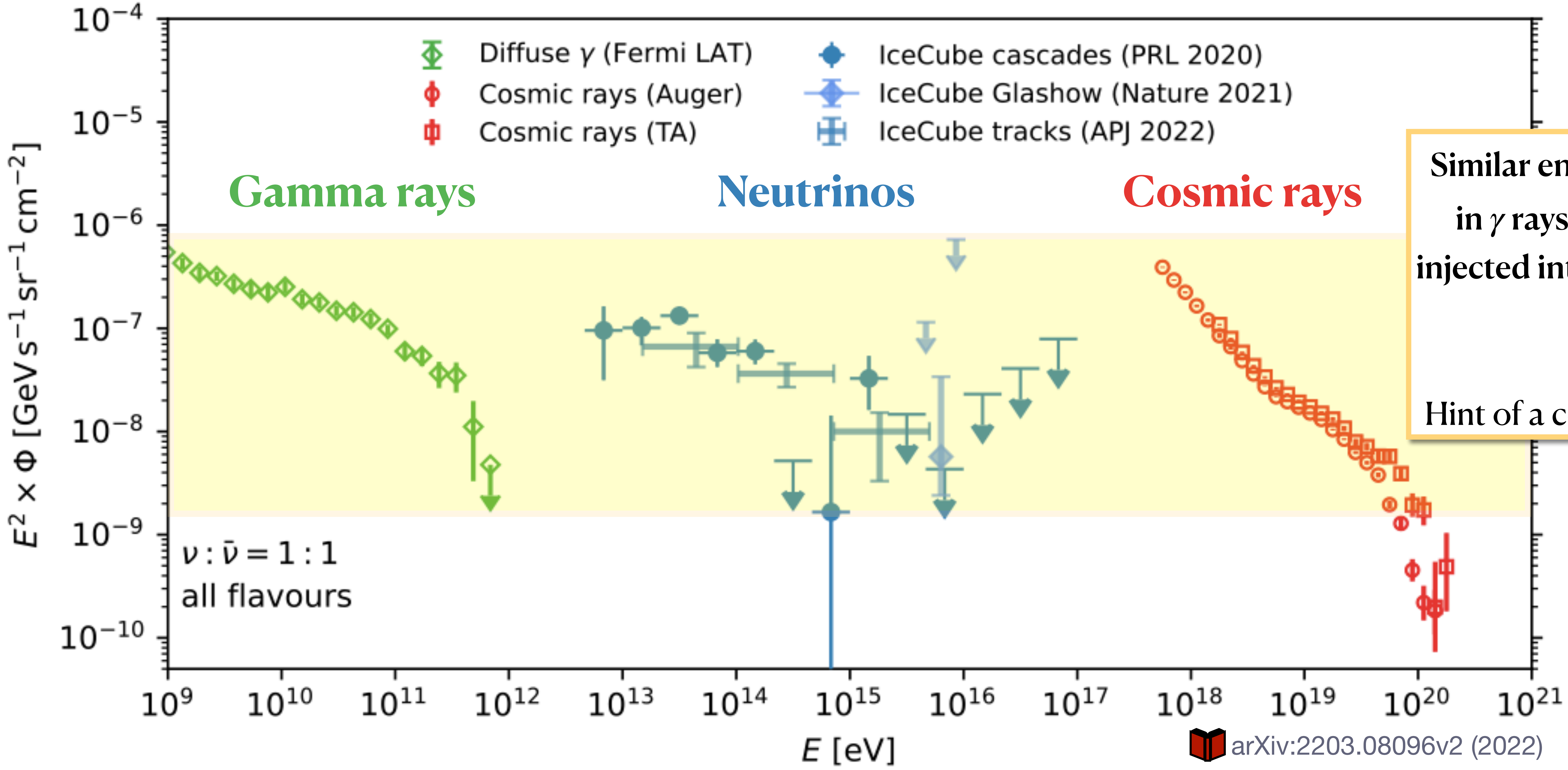
First detection of high-energy νs

BIRTH OF HIGH-ENERGY NEUTRINO ASTRONOMY

arXiv:2203.08096v2 (2022)

Observed diffuse fluxes of multiple messengers

A complete picture of the high-energy Universe is necessarily multi-messenger in nature



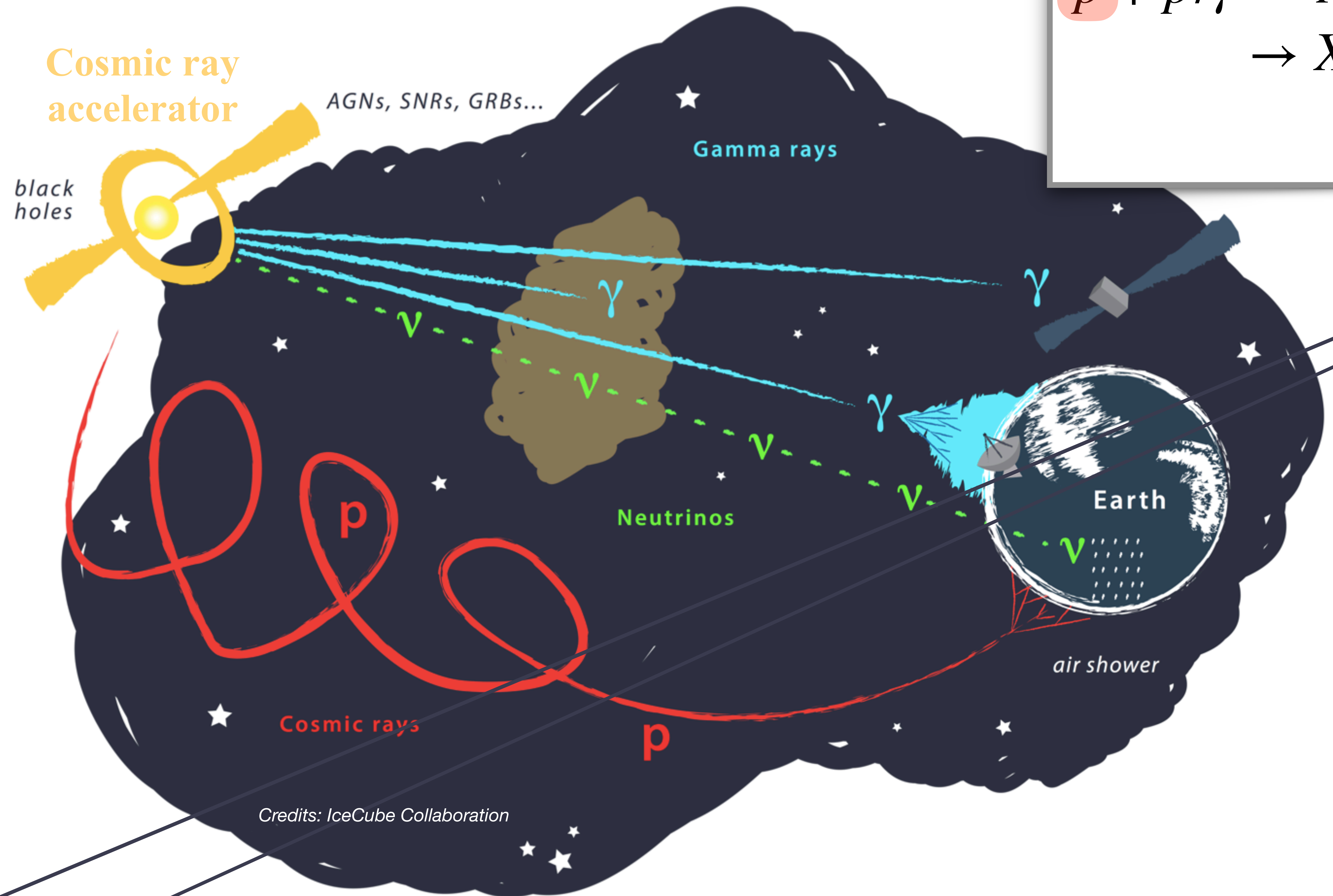
arXiv:2203.08096v2 (2022)

Similar energy densities in γ rays, νs and CRs injected into our Universe

↓

Hint of a common origin?

Messengers from cosmic accelerators



HADRON acceleration

$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^\pm \rightarrow \mu^\pm + \overset{(-)}{\nu}_\mu$$
$$\mu^\pm \rightarrow e^\pm + \overset{(-)}{\nu}_e + \overset{(-)}{\nu}_\mu$$

- Acceleration of **CRs** in astrophysical sources (especially in the aftermath of cataclysmic events), sometimes visible also in **GWs**;
- Secondary ν**s** and γ rays from pion decays.

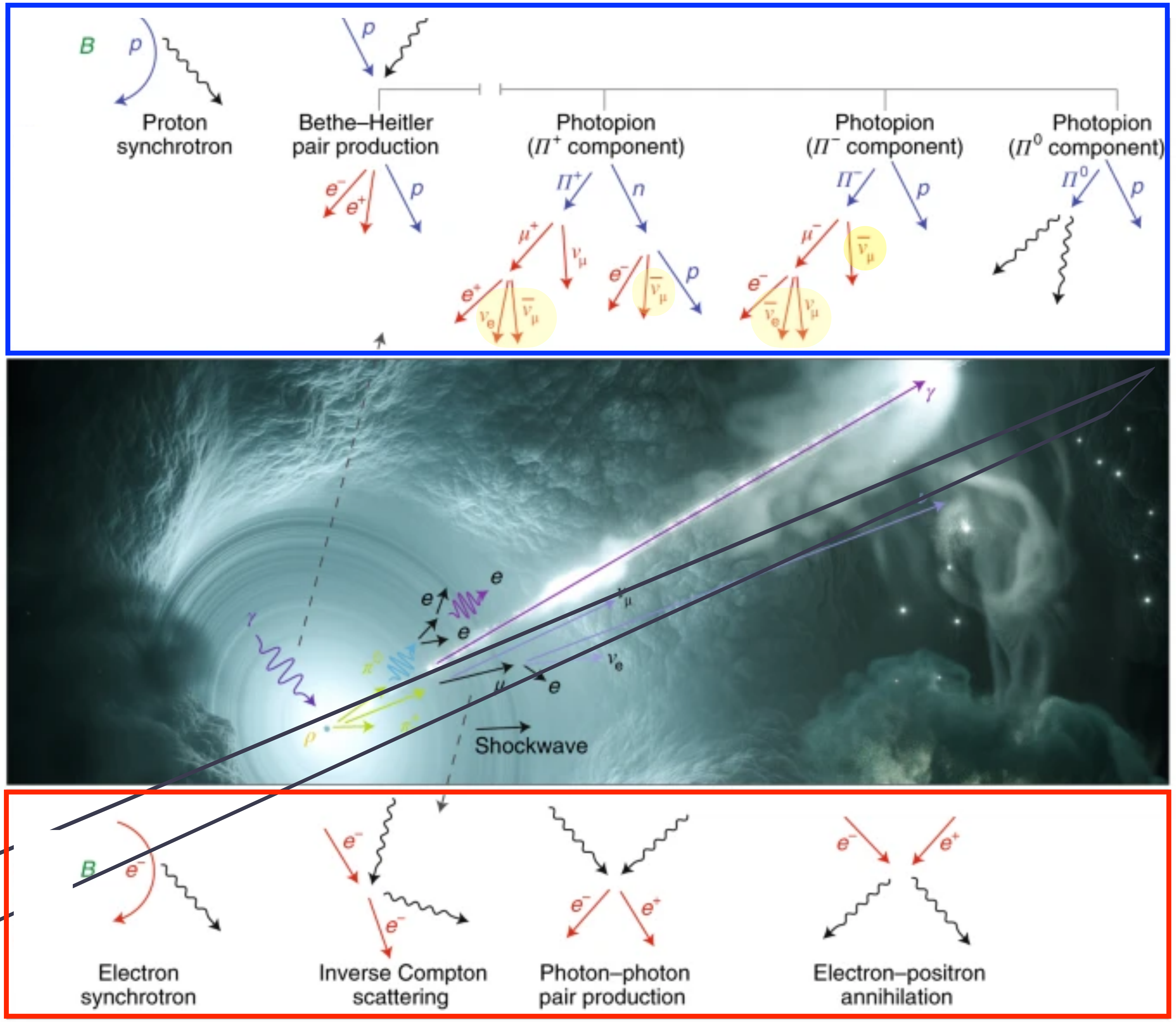
$$\langle E_\nu \rangle \simeq \frac{1}{2} \langle E_\gamma \rangle \simeq \frac{1}{20} E_p$$

e.g. Lipari, Lusignoli & Meloni '07

Why neutrinos?

Neutrinos: smoking-gun of sources of CRs

HADRONIC



LEPTONIC

Neutrinos are solely created in processes involving CRs

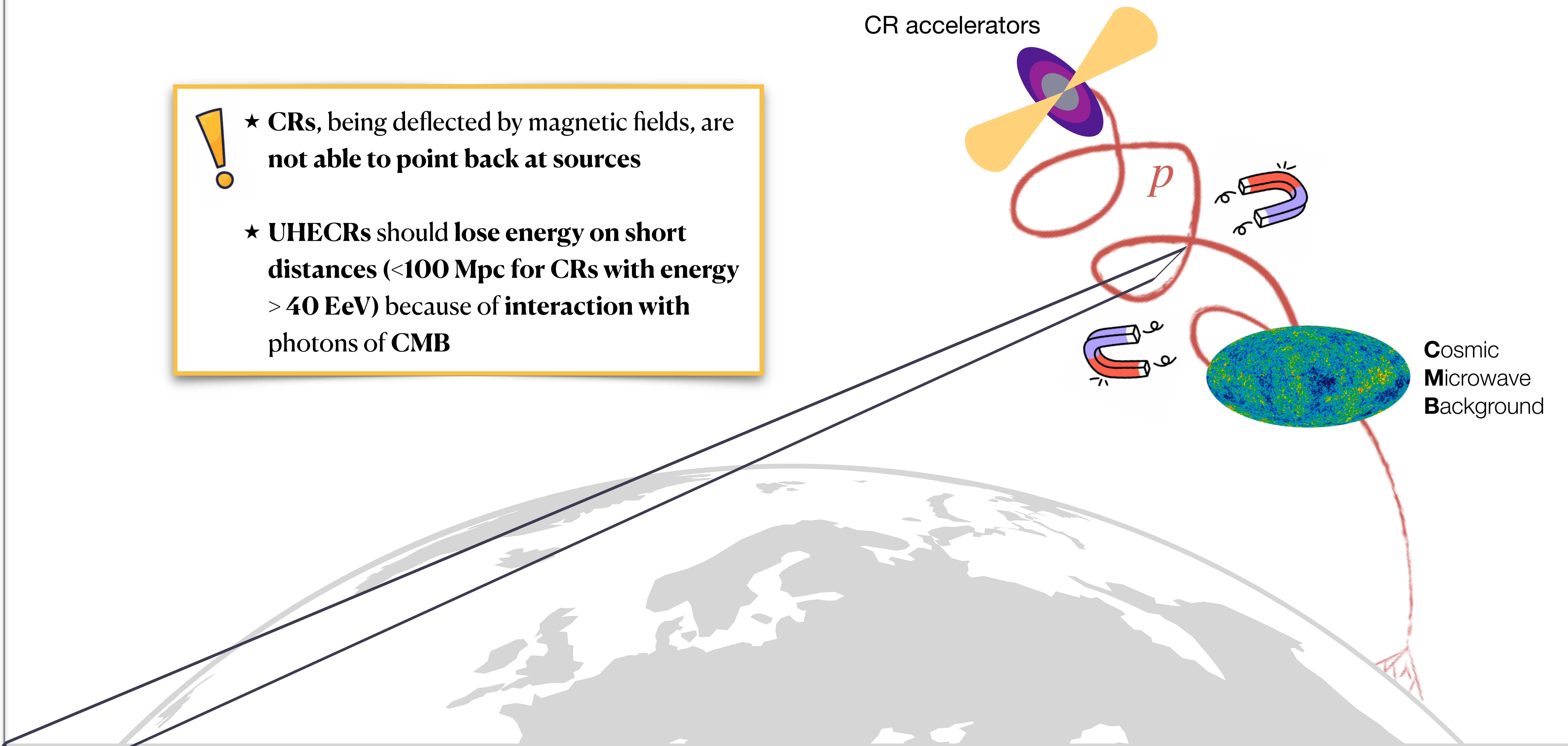
γ rays are also produced in leptonic processes (synchrotron, inverse Compton scattering, bremsstrahlung)

Credits: Nature Astronomy volume 3, pages 24–25 (2019)

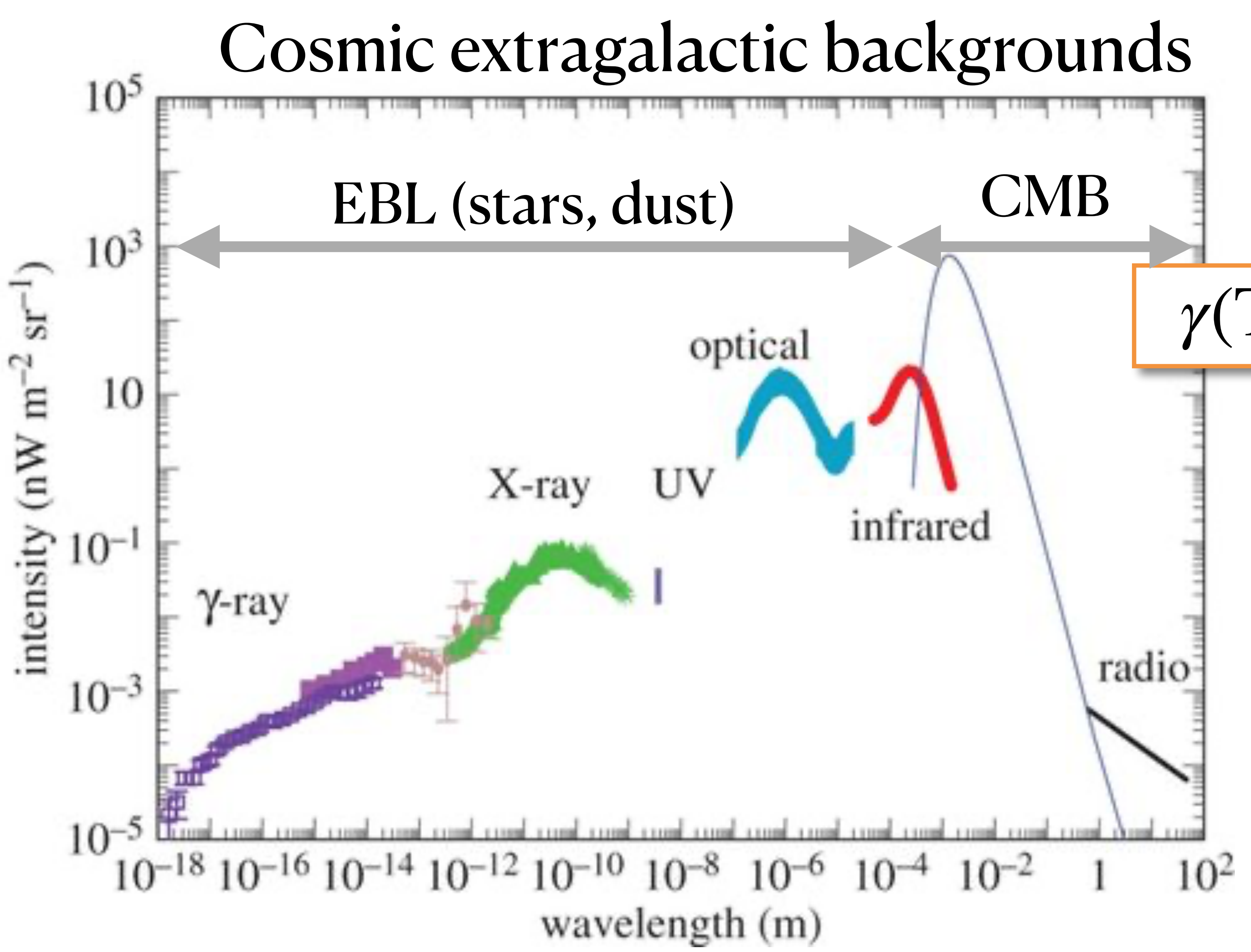
Limits of CRs

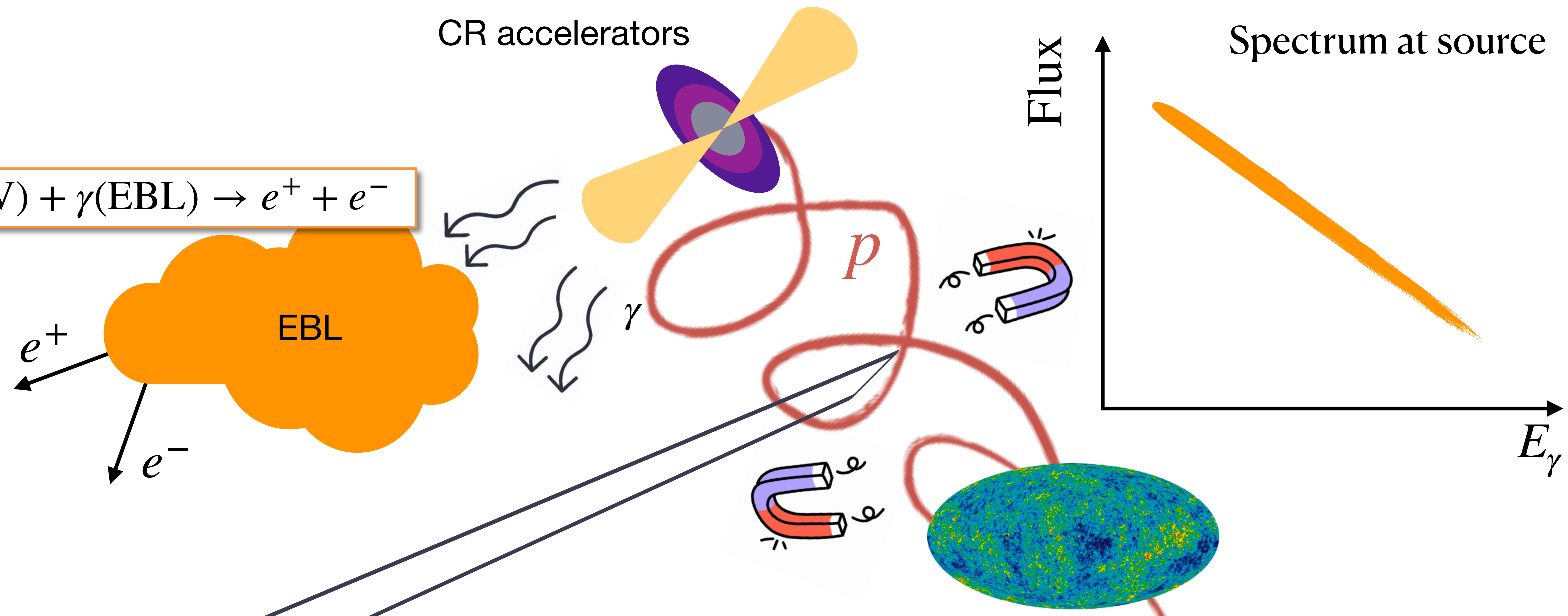
★ **CRs**, being deflected by magnetic fields, are **not able to point back at sources**

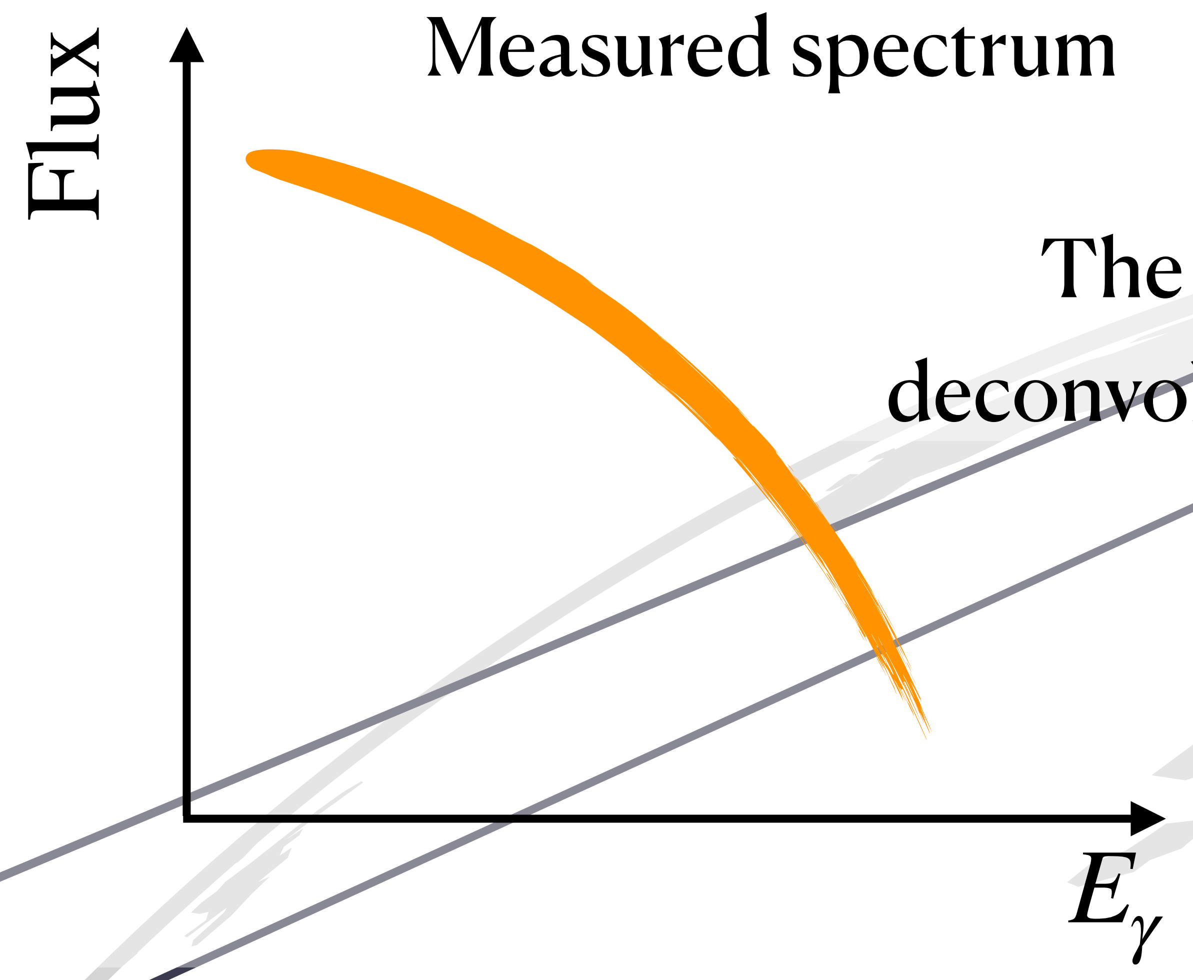
★ **UHECRs** should **lose energy on short distances (<100 Mpc for CRs with energy** > **40 EeV)** because of **interaction with** photons of **CMB**



Limits of γ rays







The γ-ray spectrum needs to be deconvolved for a specific model of EBL

- ★ γ rays point back at sources but the **γ-ray spectrum can be attenuated because of the absorption due to EBL**
- ★ Visible Universe: up to 10 Mpc (at EeV)

Neutrinos power

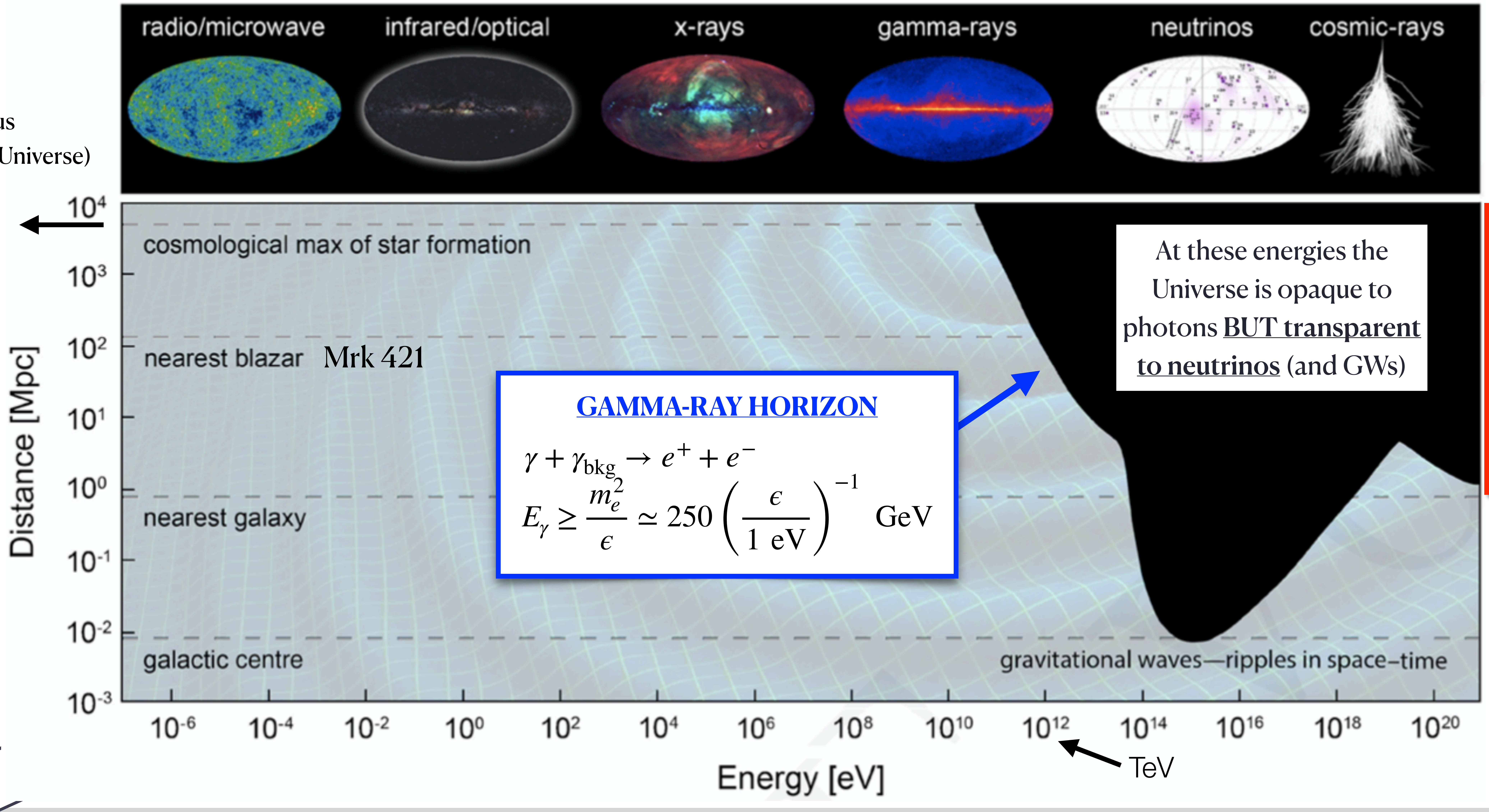
Neutrinos only suffer from energy degradation (and the **effect** is **tiny wrt CRs and gamma rays**)

$$E_{\mathrm{Earth}} = \frac{E_{\mathrm{source}}}{1+z}$$

Neutrinos to reveal the *terra incognita* of the Universe

Hubble radius (observable Universe)

$$R_H = \frac{c}{H_0}$$



GAMMA-RAY HORIZON

$$\gamma + \gamma_{\rm bkg} \rightarrow e^+ + e^-$$

$$E_\gamma \geq \frac{m_e^2}{\epsilon} \simeq 250 \left(\frac{\epsilon}{1\ \rm eV}\right)^{-1}\ \rm GeV$$

At these energies the Universe is opaque to photons **BUT transparent to neutrinos** (and GWs)

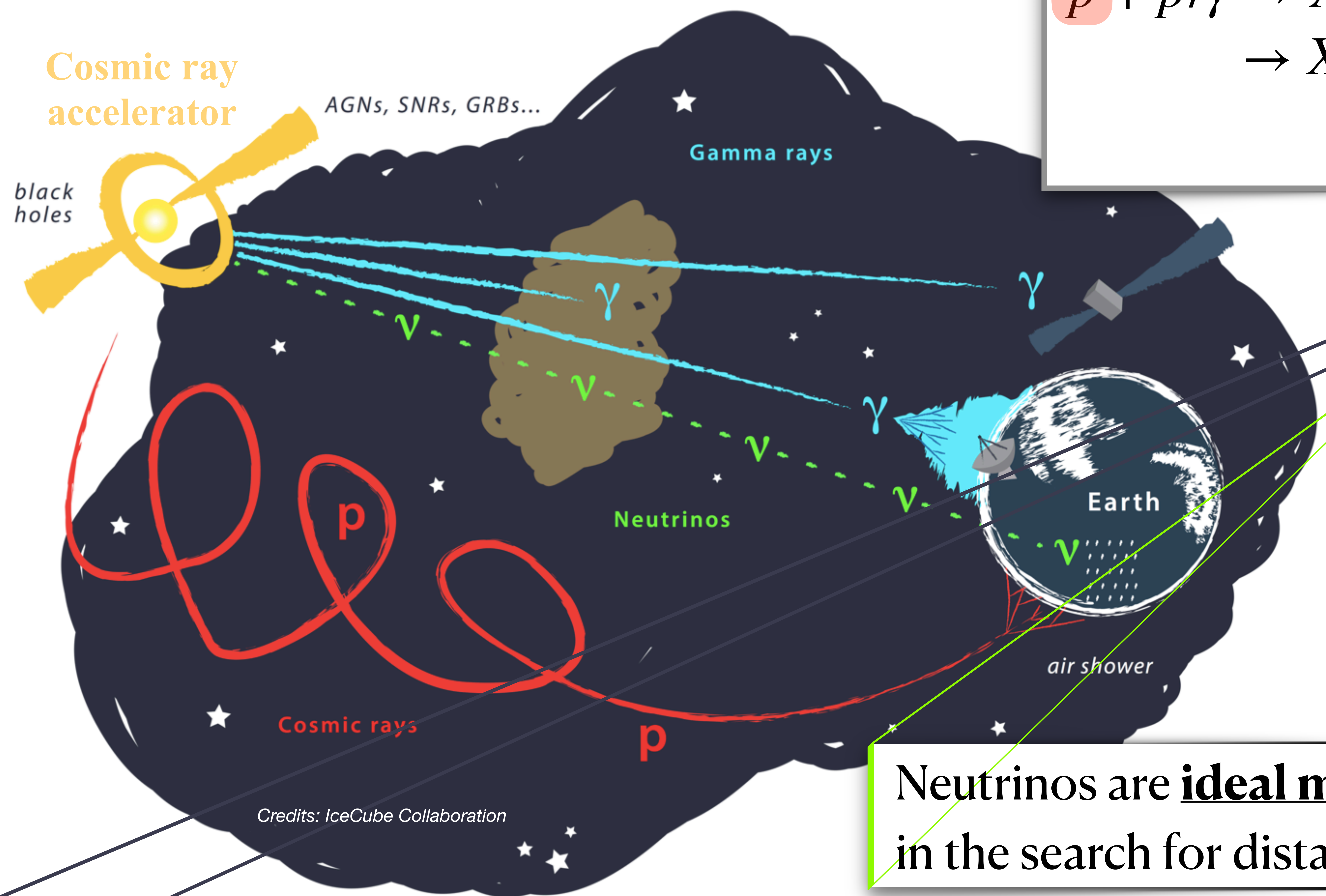
UHECRs should lose energy quickly on short distances (<100 Mpc)

$p + \gamma_{\rm CMB}$

Neutrinos: ideal messengers

$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^\pm \rightarrow \mu^\pm + \overset{(-)}{\nu}_\mu$$
$$\mu^\pm \rightarrow e^\pm + \overset{(-)}{\nu}_e + \overset{(-)}{\nu}_\mu$$

HADRON acceleration



Unique properties of **neutrinos**: electrically neutral, stable, and weakly interacting particles

- **No deflection** in magnetic field (unlike cosmic rays)
- **No absorption** in cosmic backgrounds, as Extragalactic Background Light (unlike gamma-rays)

Neutrinos are **ideal messengers** in the search for distant astrophysical objects

Neutrinos: ideal messengers

$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$
$$\mu^{\pm} \rightarrow e^{\pm} + \ldots + \overset{(-)}{\nu}_{\mu}$$

HADRON acceleration

Neutrinos are very hard to be detected!

- ➡ Low statistics
- ➡ Large background
- ➡ Low cross section (weakly interacting particles)

… in magnetic field (unlike cosmic rays)

★ **No absorption** in cosmic backgrounds, as Extragalactic Background Light (unlike gamma-rays)

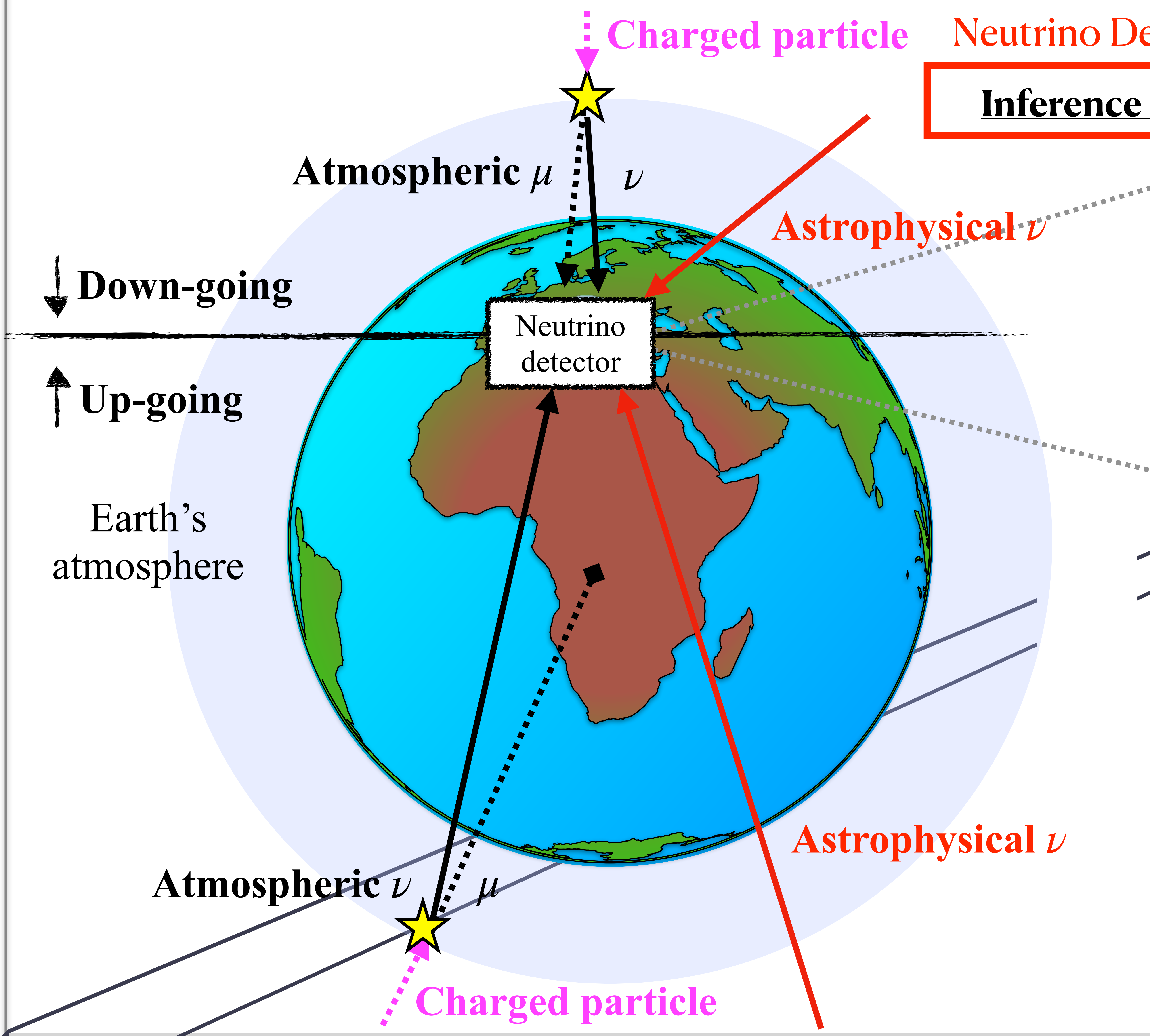
Neutrinos are **ideal messengers** in the search for distant astrophysical objects

How we detect high-energy neutrinos?

"We propose setting up apparatus in an underground lake or deep in the ocean in order to separate charged particle directions by Cherenkov radiation."

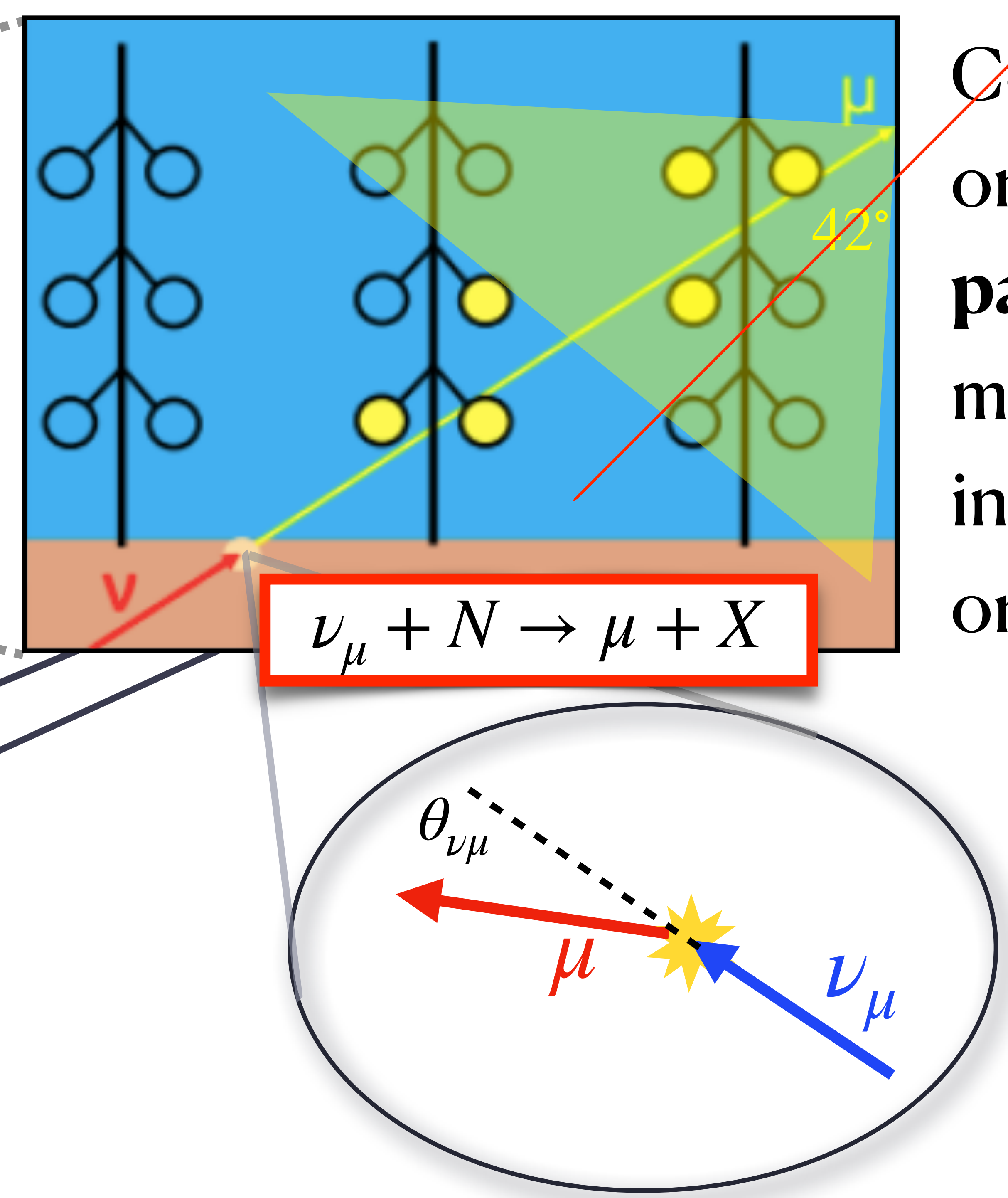
–Markov, 1960

Neutrino telescopes: detection principle



Neutrino Detectors = three-dimensional arrays of photomultiplier tubes (PMTs)

Inference of energy and direction of incoming neutrinos from hits on PMTs

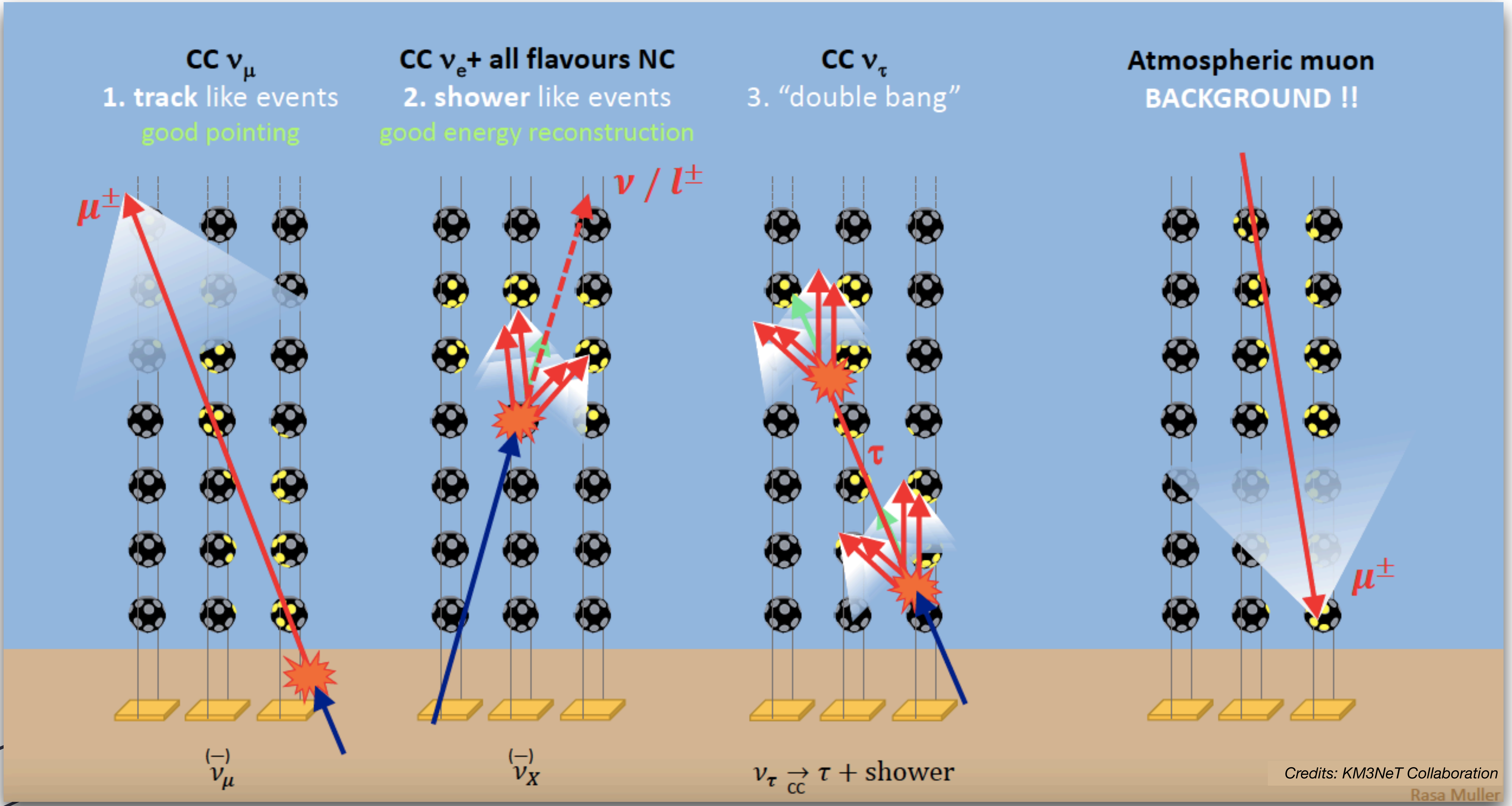


Cone of **Cherenkov light** originated **by secondary particles** produced in the medium as result of neutrino interactions with quarks inside or nearby the detector volume

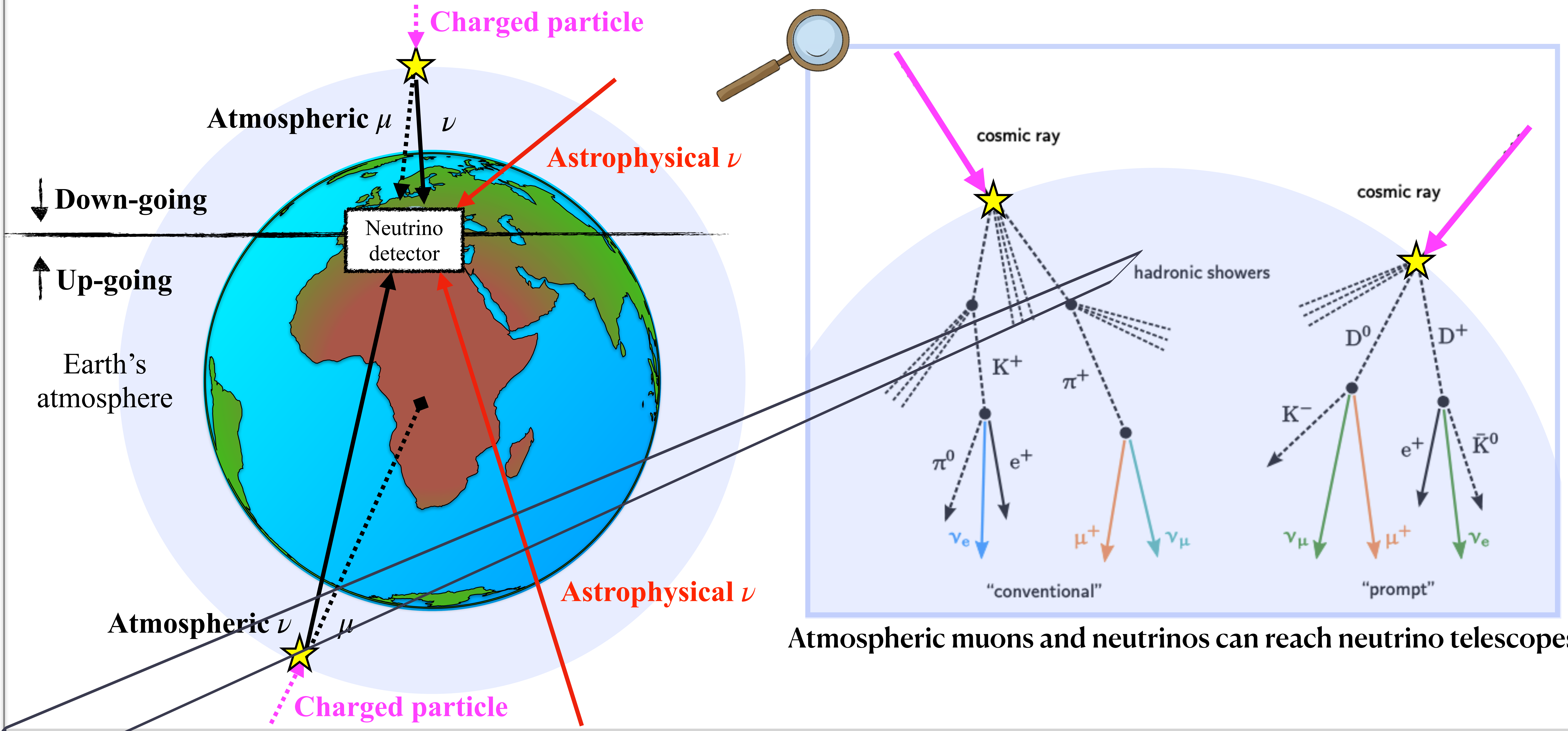
$$\theta_{\nu\mu} \simeq \frac{0.7^\circ}{[E_\nu(\text{TeV})]^{0.7}}$$

★ Main channel ⟶ charged current ν_μ interactions (**long muon path** inside the detector)

Neutrino telescopes: event topologies

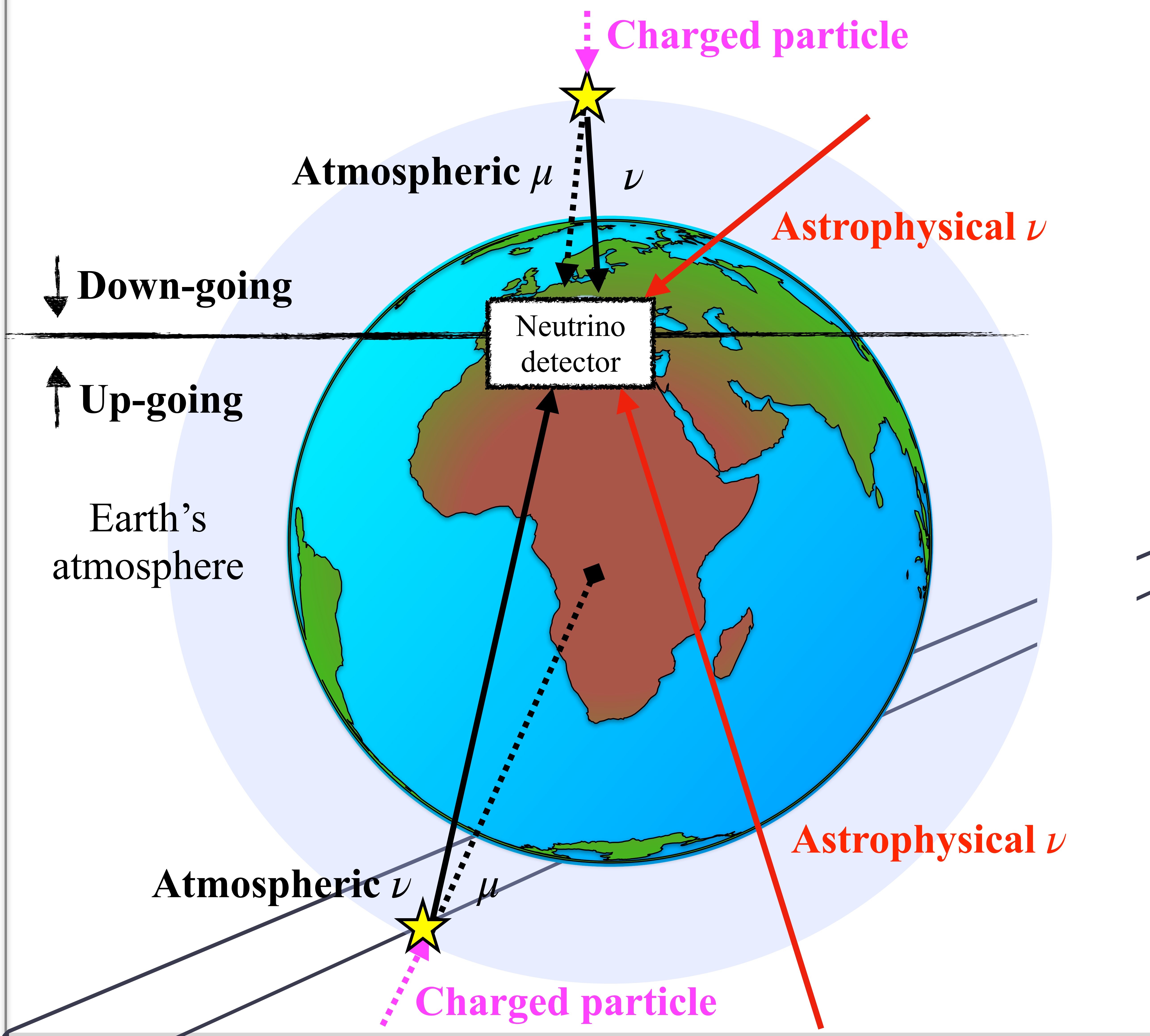


Neutrino telescopes: atmospheric background

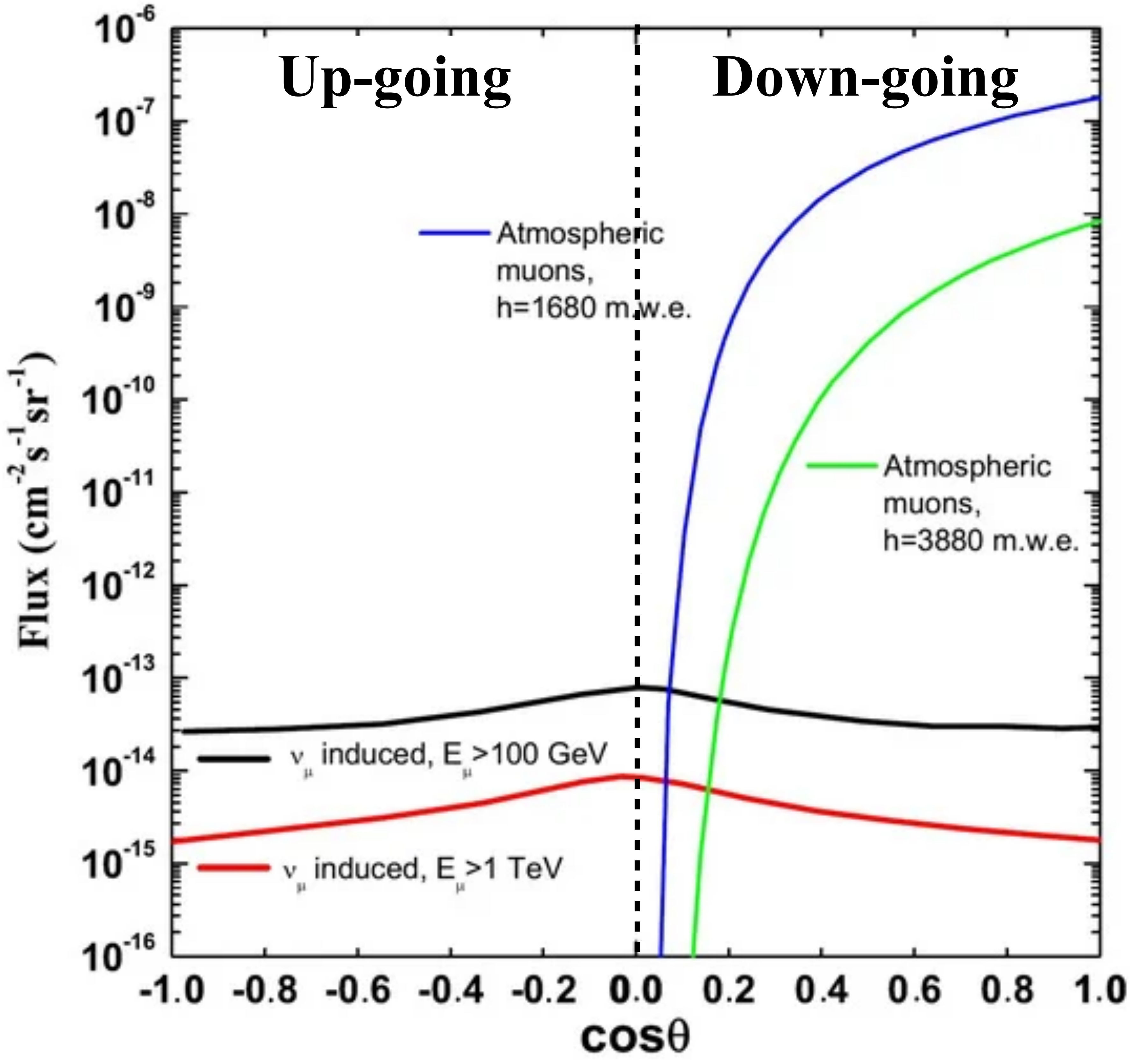


Atmospheric muons and neutrinos can reach neutrino telescopes

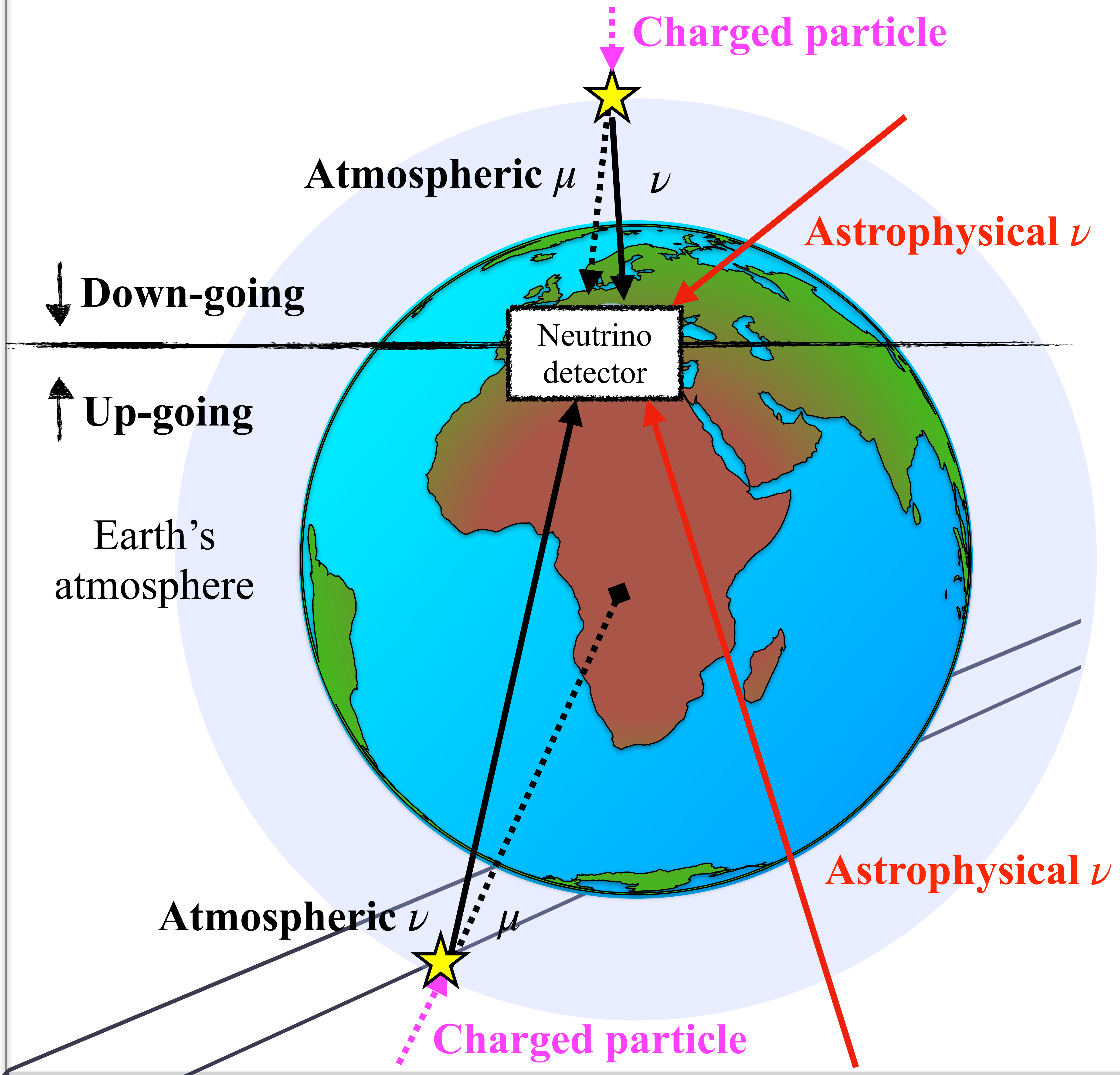
Neutrino telescopes: atmospheric background



The **Earth** is used as **screening against all particles, except neutrinos** that can traverse the Earth



Neutrino telescopes: atmospheric background



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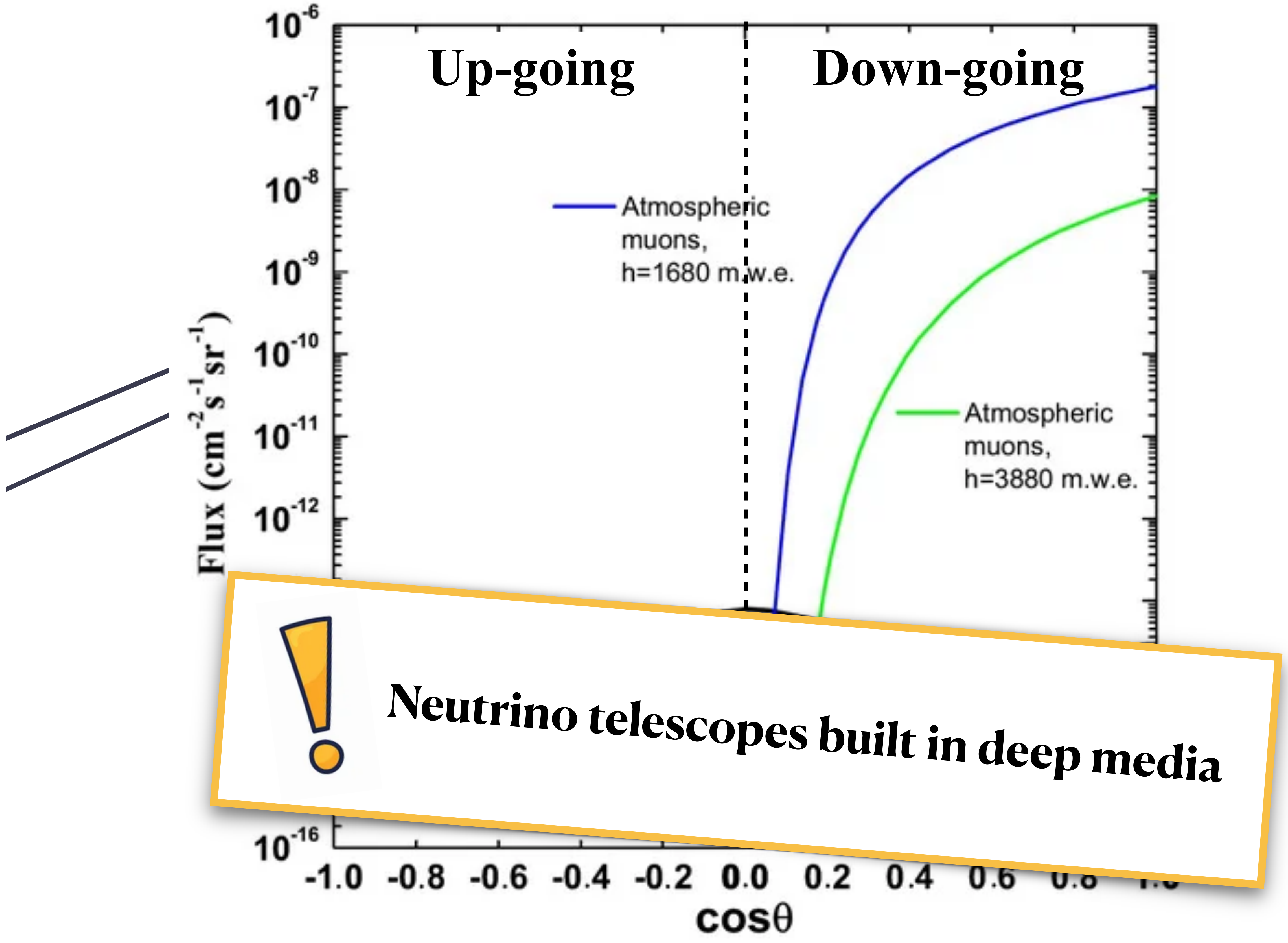
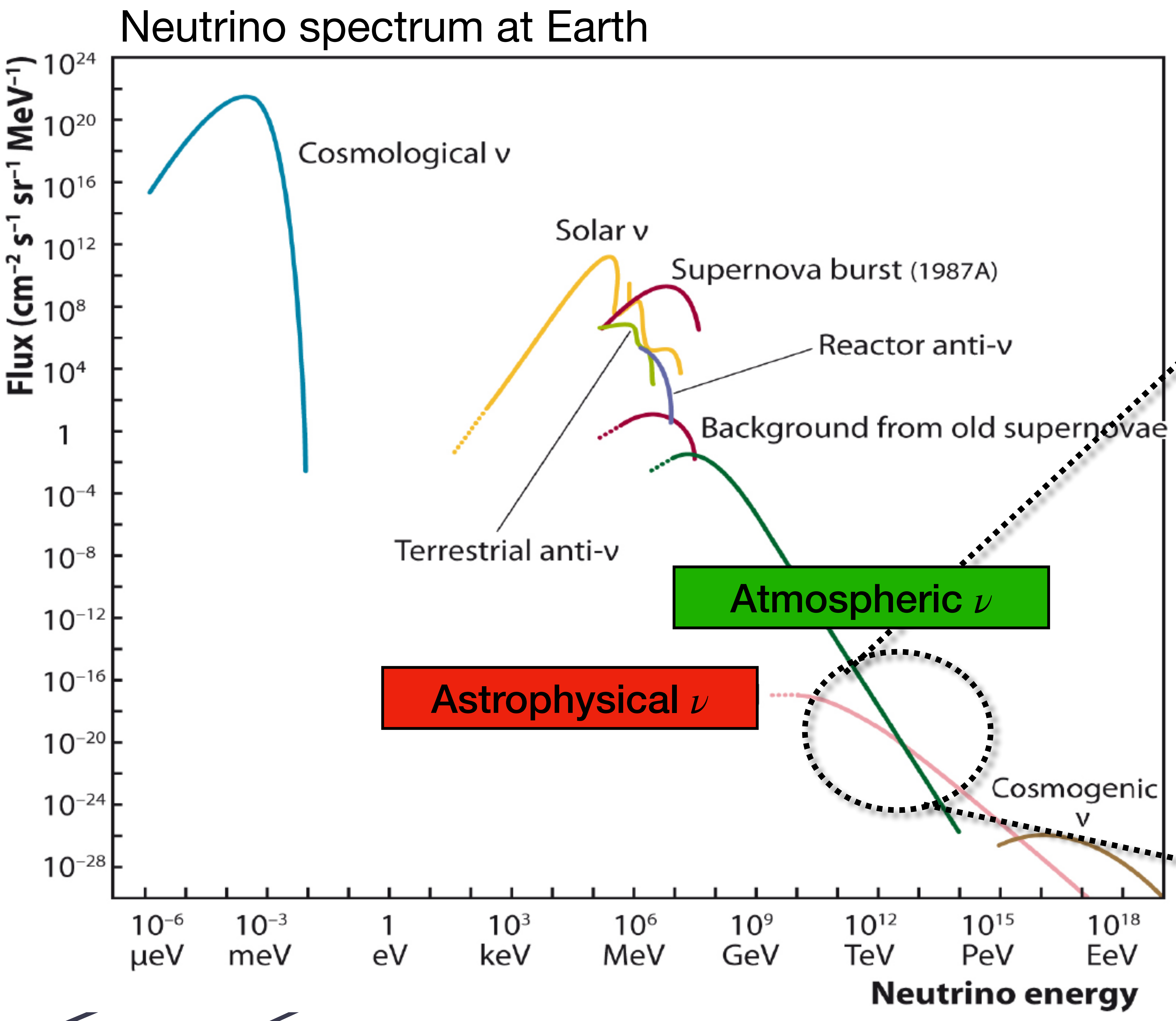
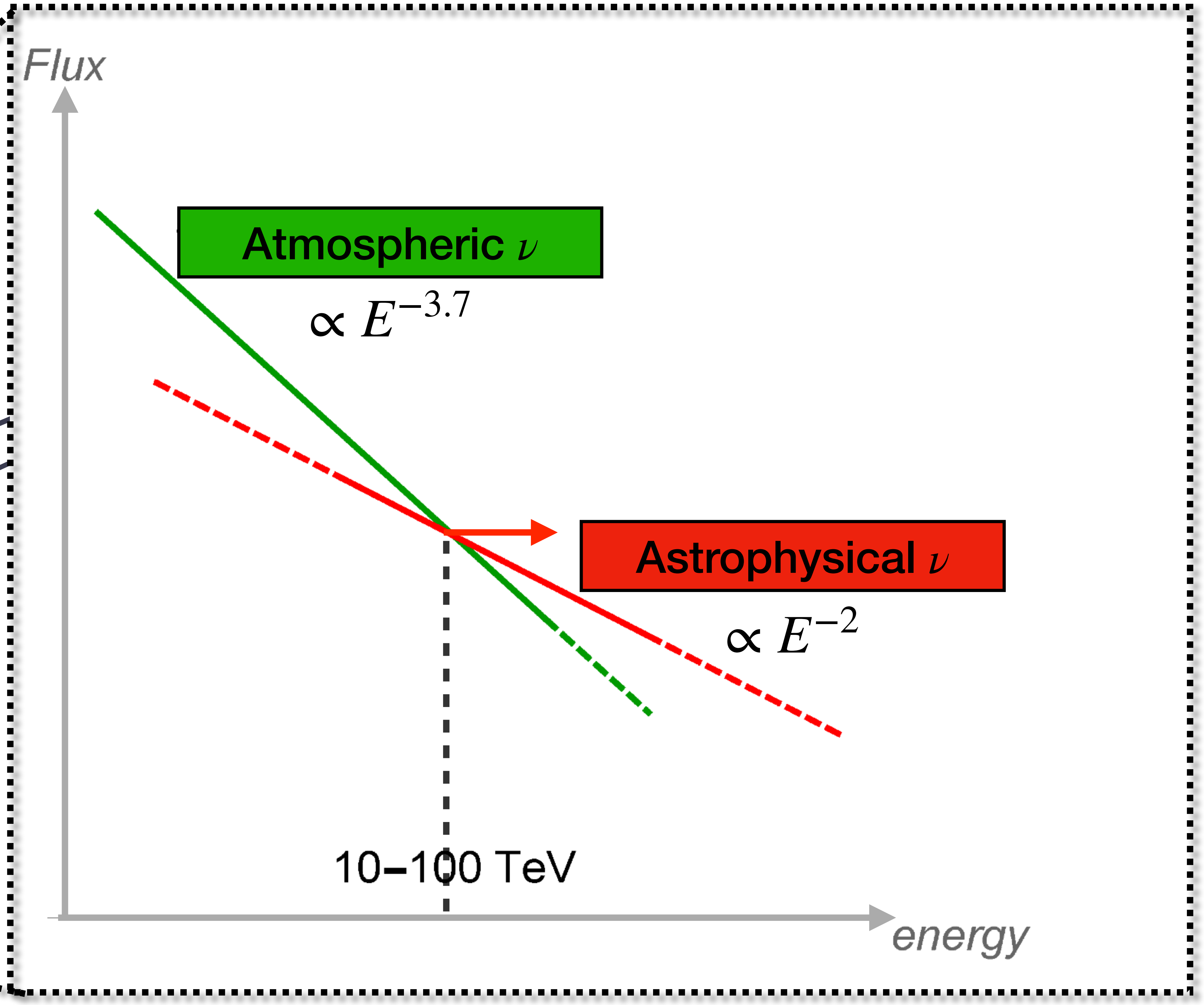


Neutrino telescopes: ν_{atm} vs ν_{astro}

High-energy neutrino telescopes with astrophysical purposes optimized for E > TeV

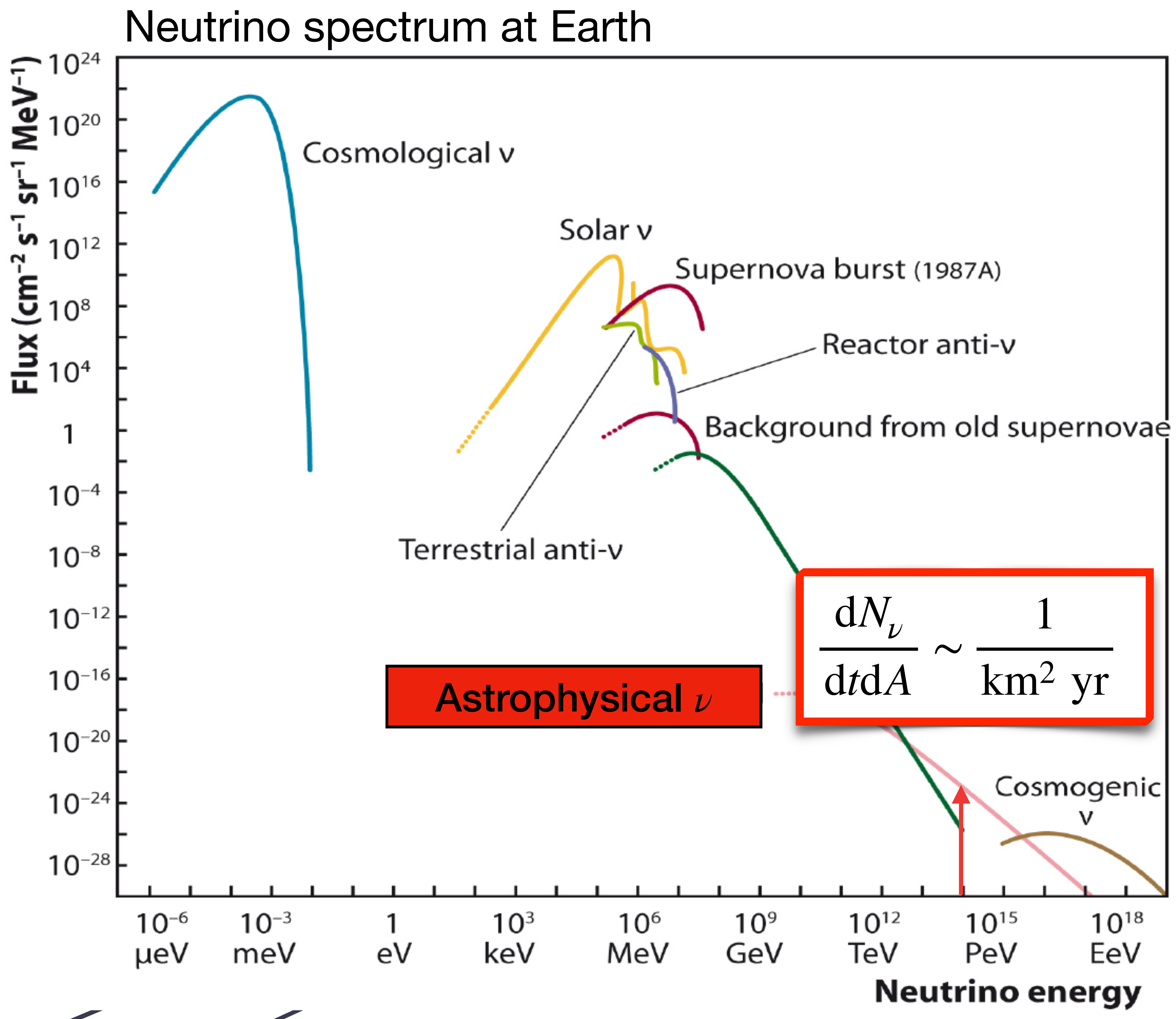
Cosmic neutrinos can stand out over the atmospheric neutrinos at high energies (>10-100 TeV), becoming observable.



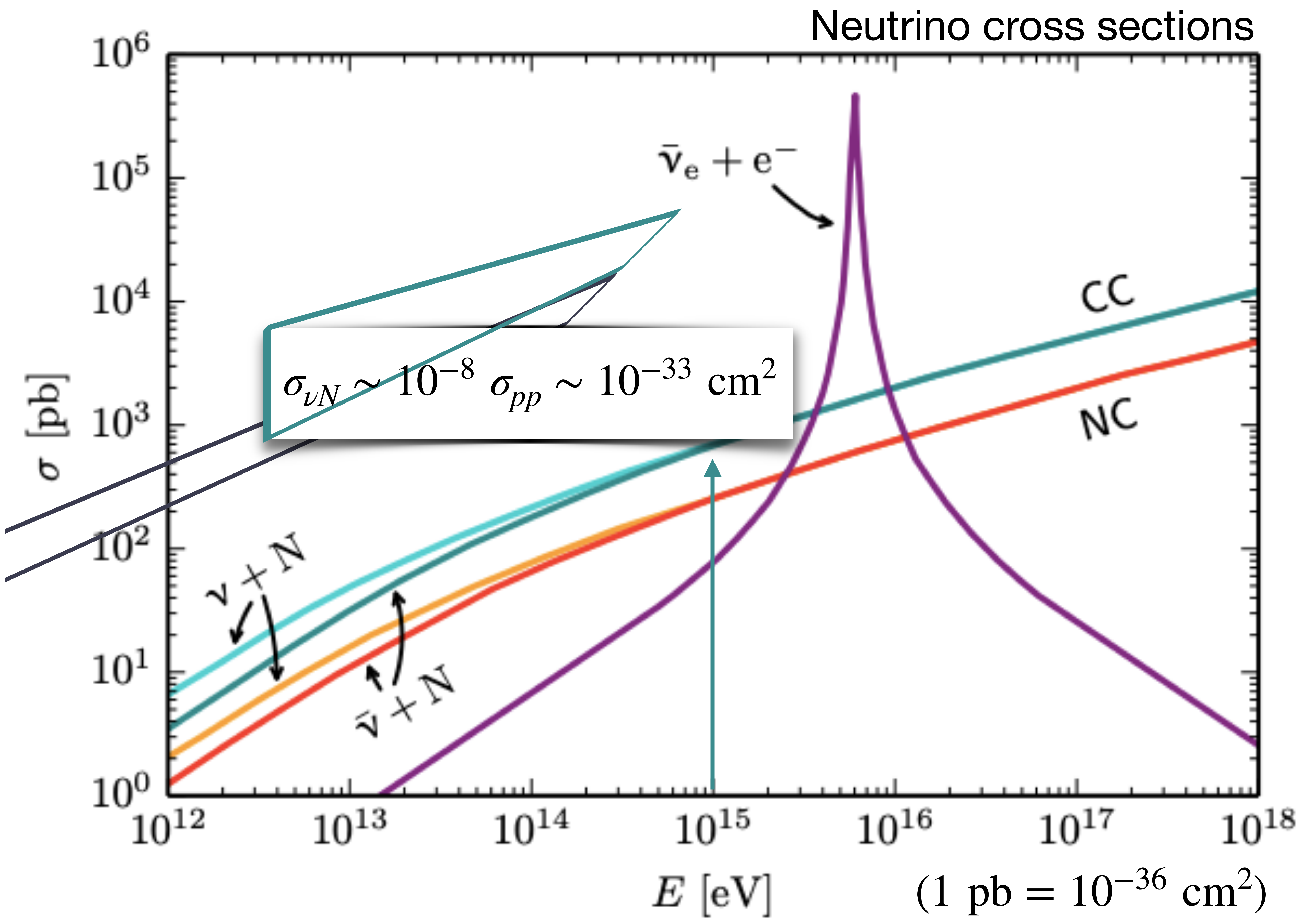


Detector requirements

For a neutrino with energy of ~ 1 PeV



$$\frac{dN_\nu}{dt\,dA} \sim \frac{1}{\text{km}^2\ \text{yr}}$$



$$\sigma_{\nu N} \sim 10^{-8}\ \sigma_{pp} \sim 10^{-33}\ \text{cm}^2$$

$(1\ \text{pb} = 10^{-36}\ \text{cm}^2)$

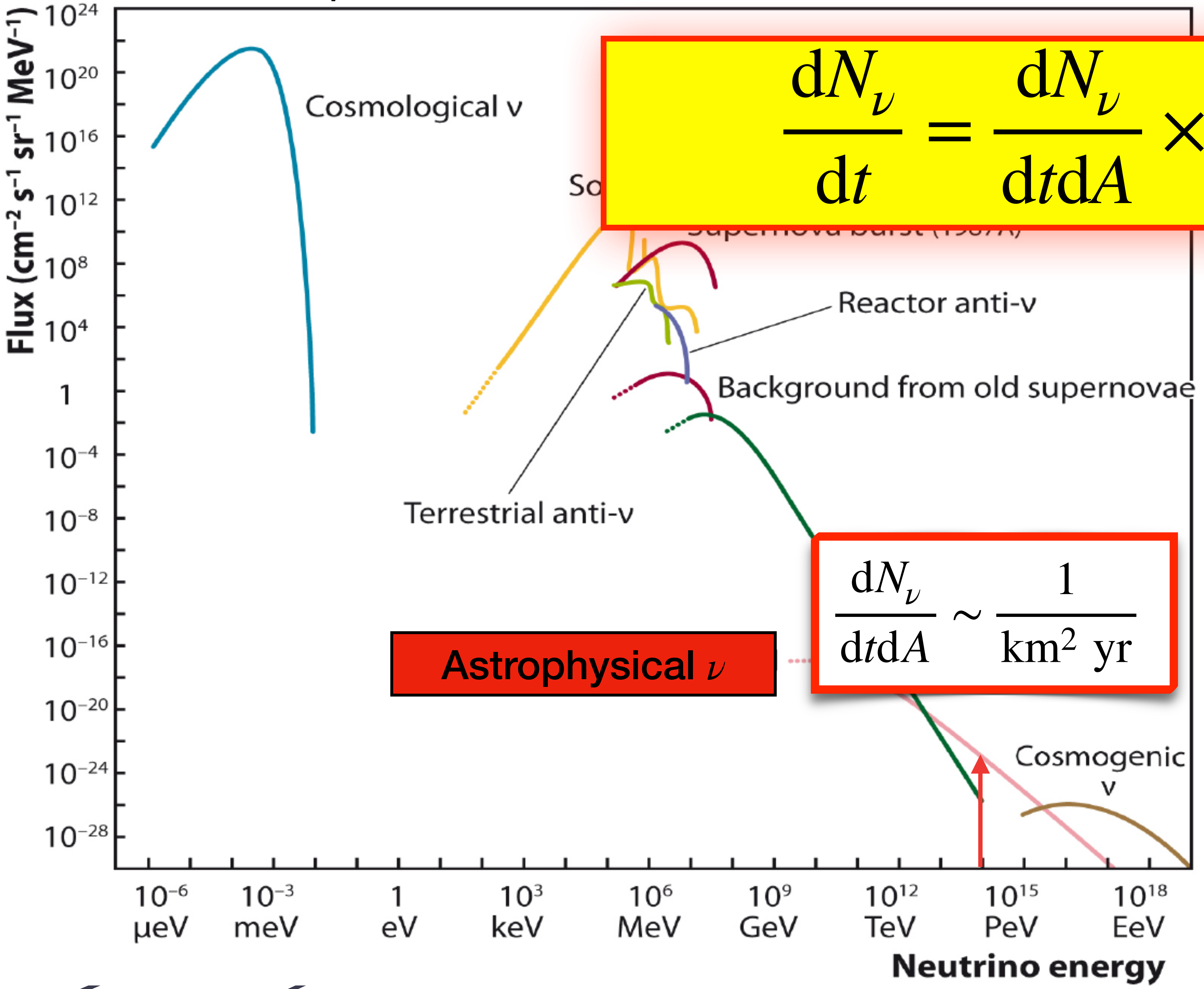
Detector requirements

Minimum detector size of $\sim 1\ \mathrm{km}^3$

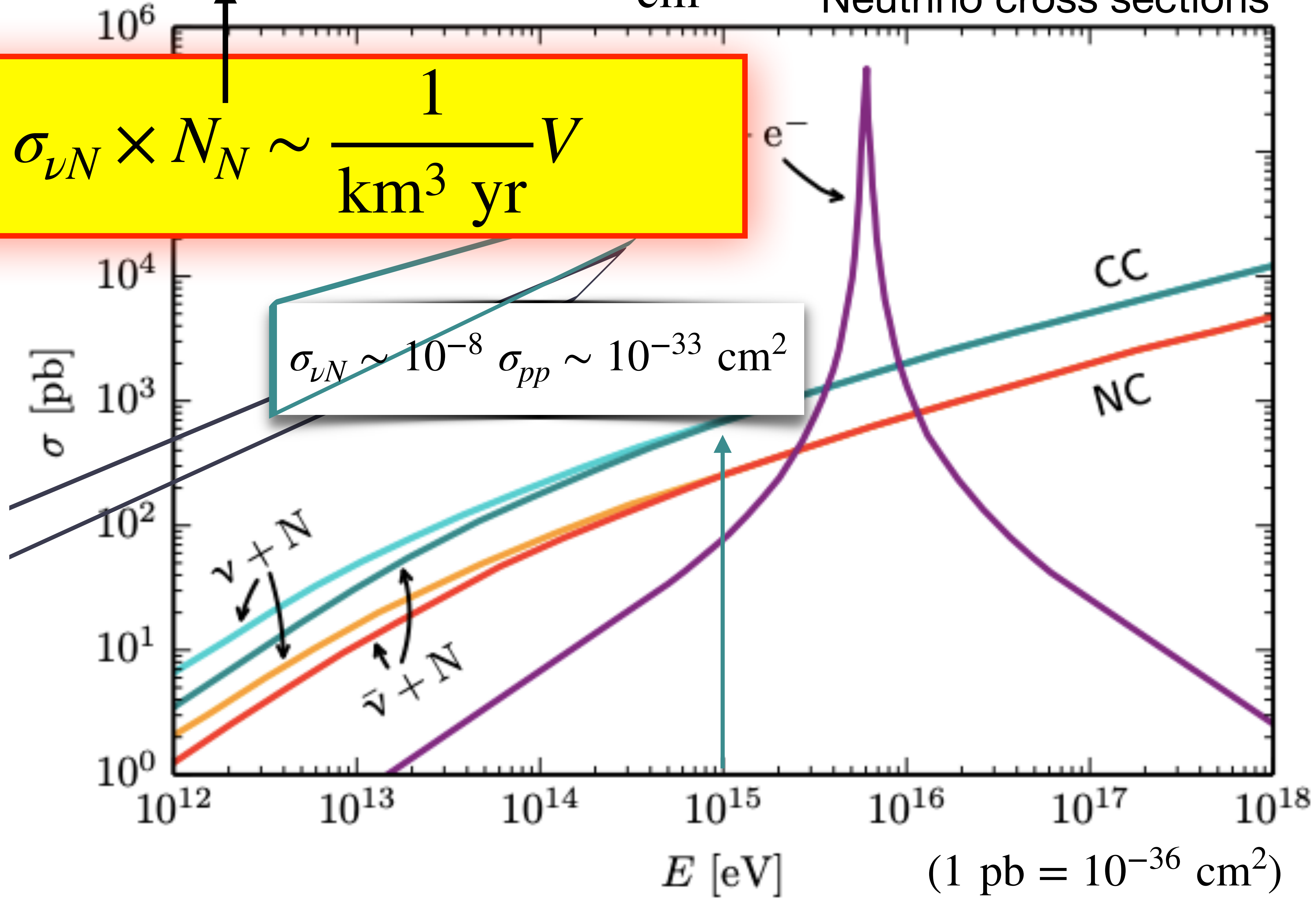
For a neutrino with energy of $\sim 1\ \mathrm{PeV}$

Nucleon targets $N_N \sim N_A \dfrac{V}{\mathrm{cm}^3}$

$$\frac{\mathrm{d}N_\nu}{\mathrm{d}t} = \frac{\mathrm{d}N_\nu}{\mathrm{d}t\mathrm{d}A} \times \sigma_{\nu N} \times N_N \sim \frac{1}{\mathrm{km}^3\ \mathrm{yr}} V$$



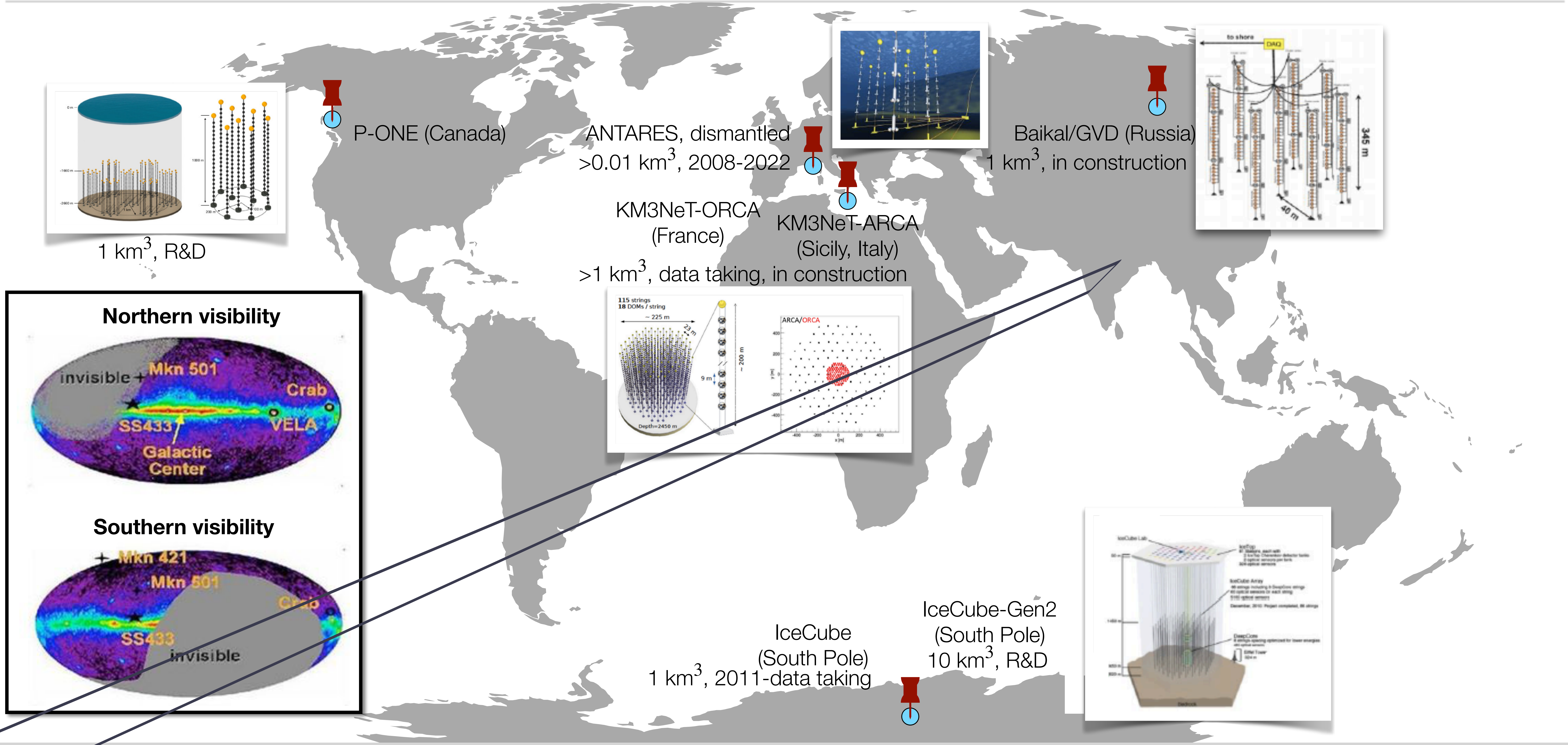
$$\frac{\mathrm{d}N_\nu}{\mathrm{d}t\mathrm{d}A} \sim \frac{1}{\mathrm{km}^2\ \mathrm{yr}}$$



$\sigma_{\nu N} \sim 10^{-8}\ \sigma_{pp} \sim 10^{-33}\ \mathrm{cm}^2$

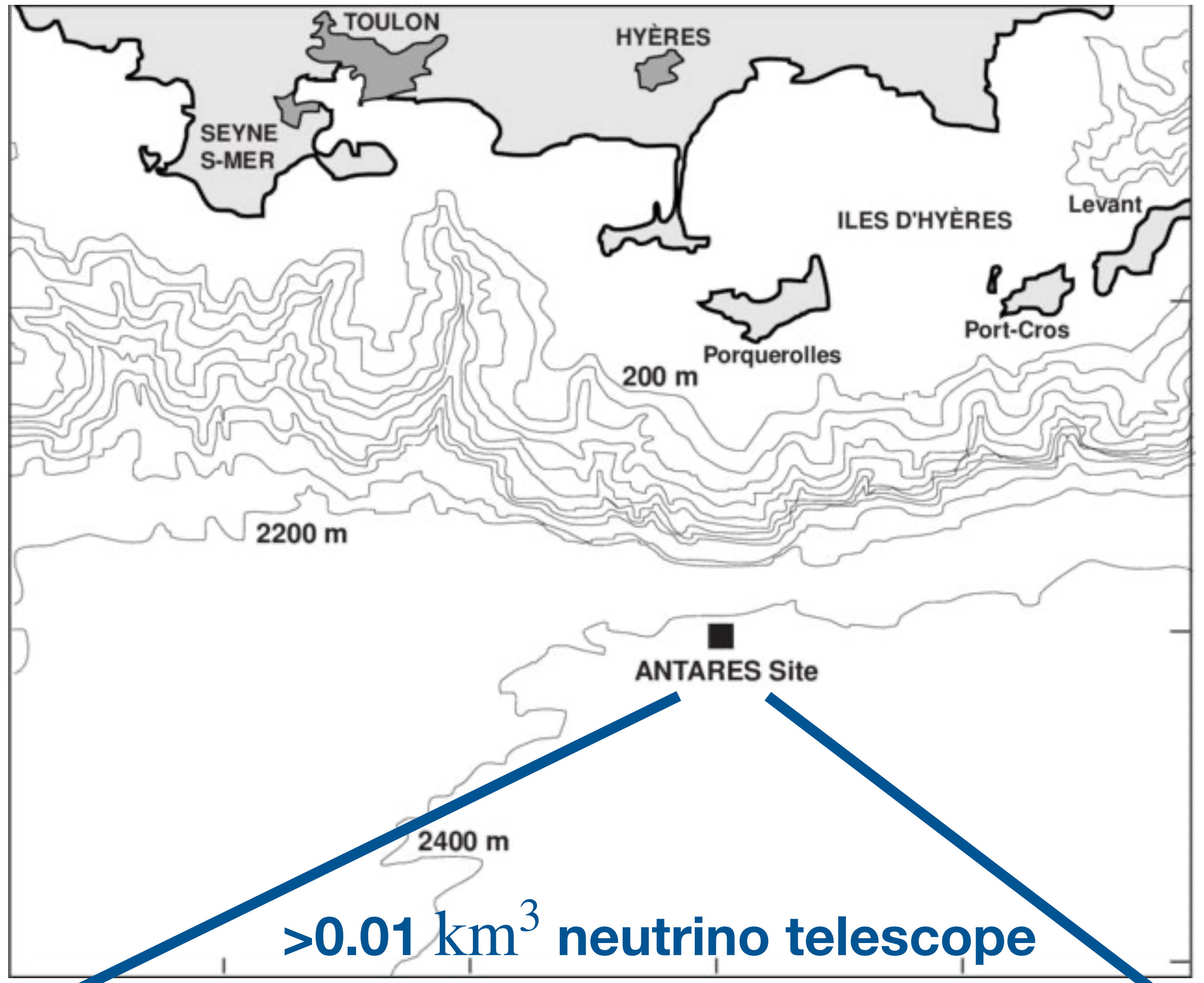
$(1\ \mathrm{pb} = 10^{-36}\ \mathrm{cm}^2)$

High-energy neutrino telescopes: World map

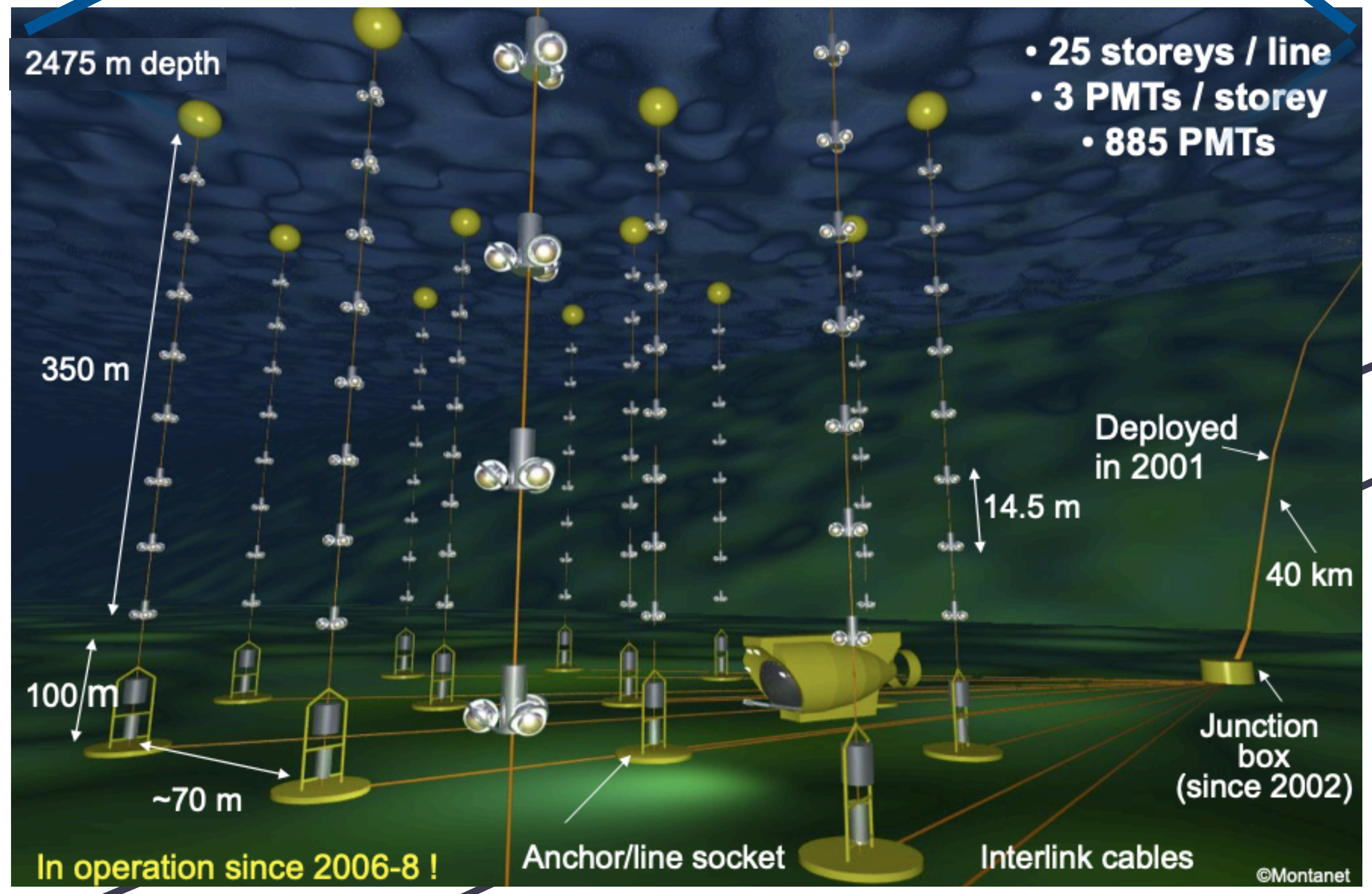


ANTARES neutrino telescope

https://antares.in2p3.fr



>0.01 km^3 neutrino telescope

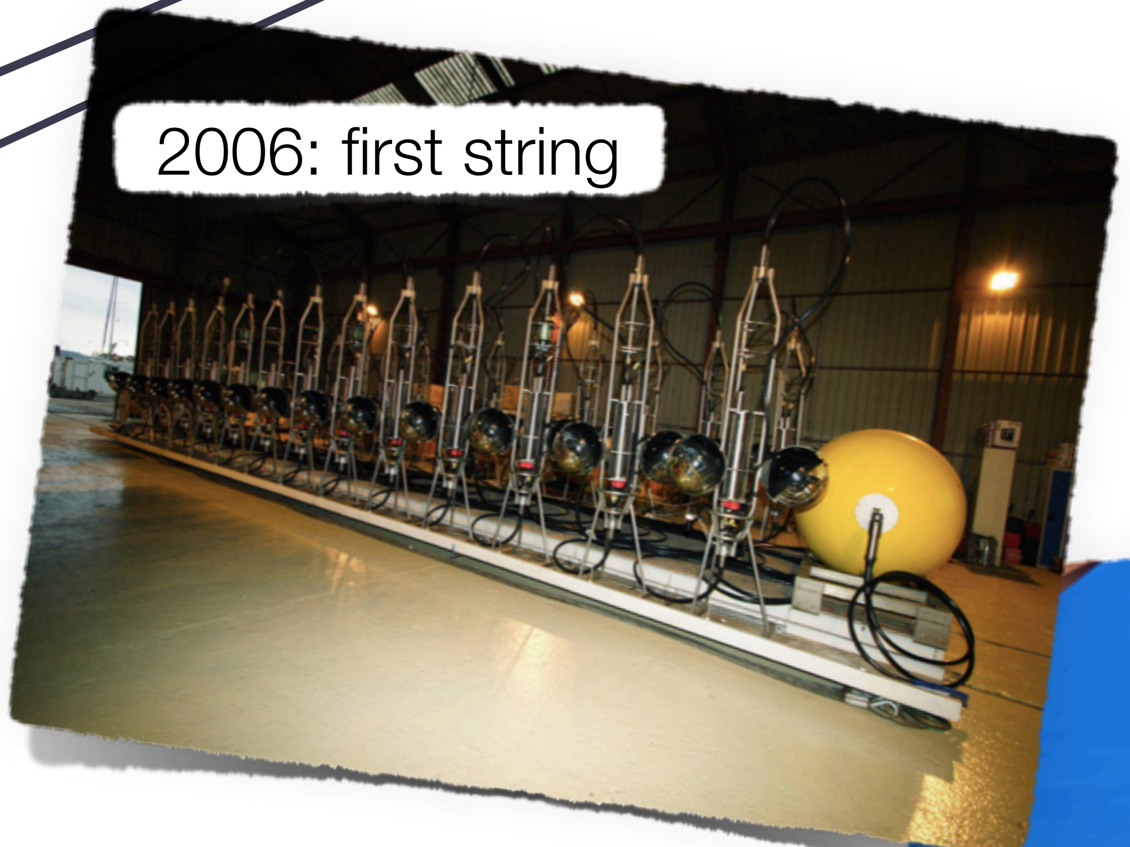


Credits: ANTARES Collaboration

First under-sea neutrino telescopes

~ 14 years of data taking

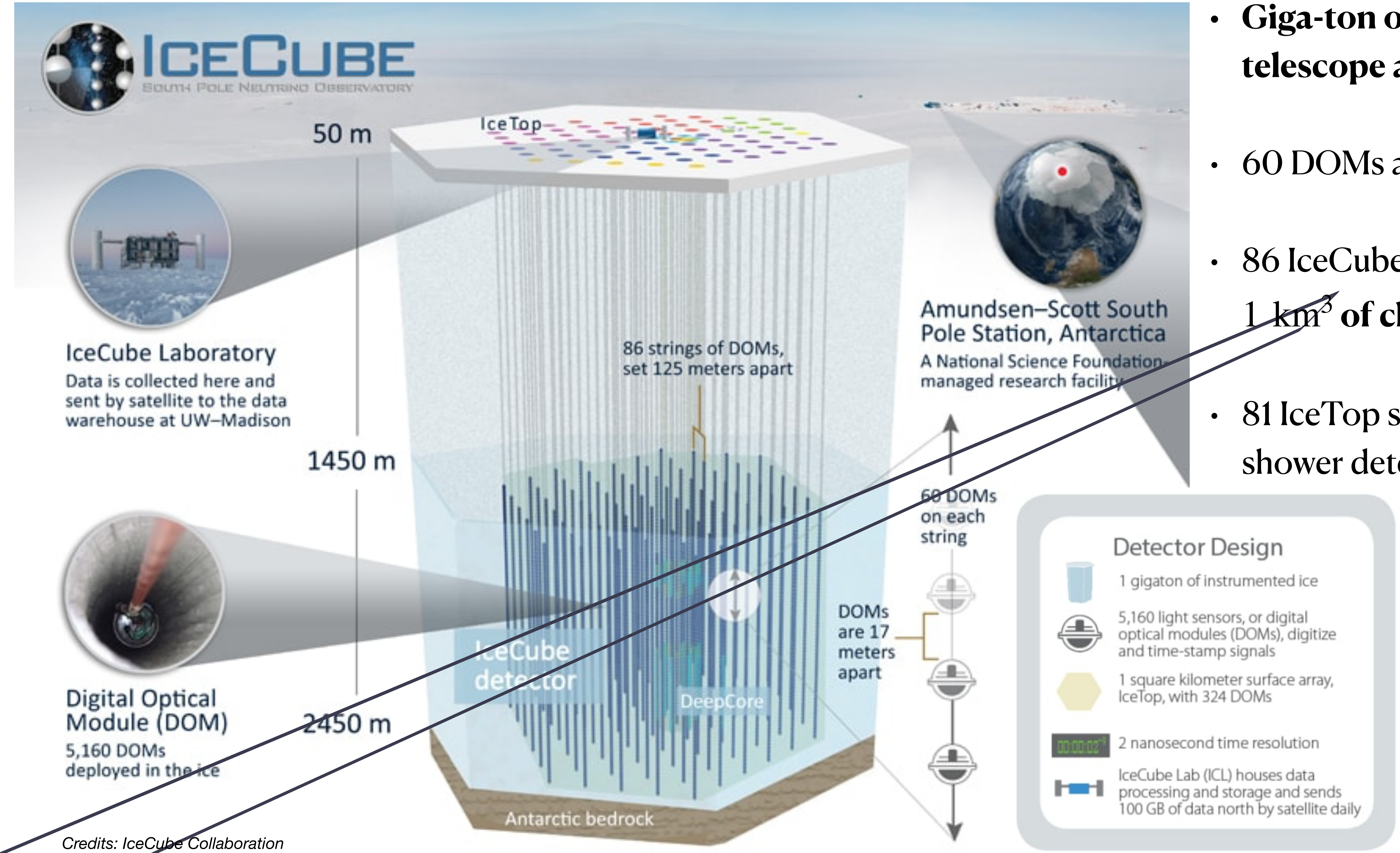
- 40 km offshore Toulon (France)
- 2006: first complete detector line
- **2008: detector with 12 lines completed**
- 2022: Data taking terminated and detector decommissioned



- 3D array of 885 PMTs
- 2475 m depth
- 12 vertical lines, 25 storeys,
- 3 PMTs per storey
- PMT facing 45° downwards

IceCube

https://icecube.wisc.edu



Credits: IceCube Collaboration

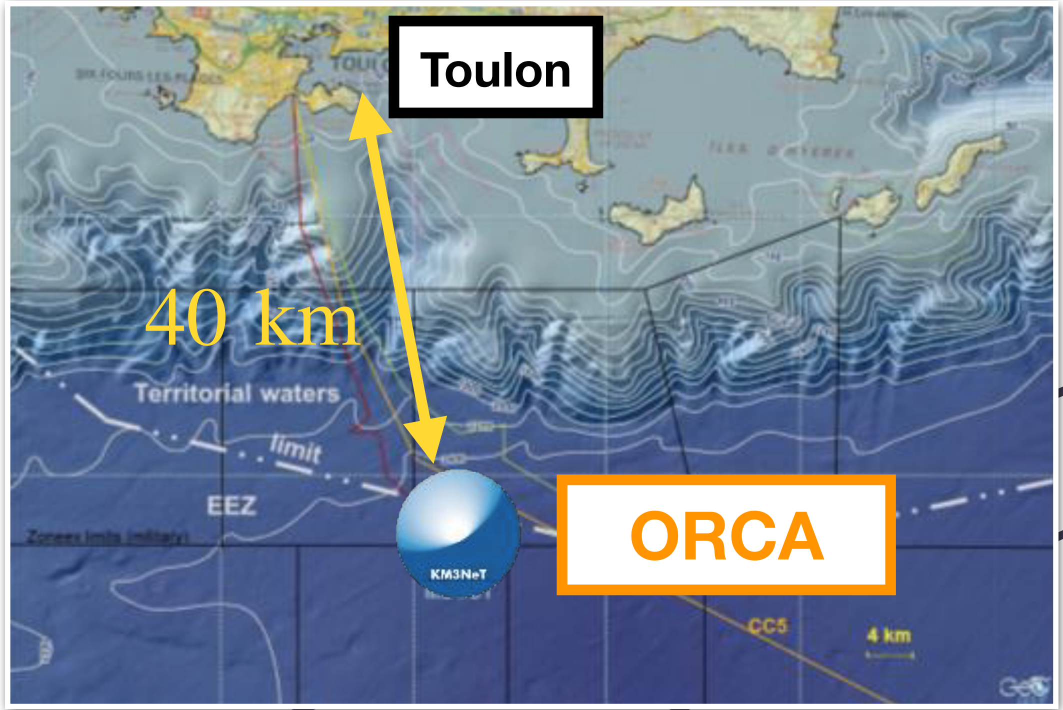
- **Giga-ton optical Cherenkov telescope at the South Pole**
- 60 DOMs attached to strings
- 86 IceCube strings instrumenting $1\ km^3$ **of clear glacial ice**
- 81 IceTop stations for cosmic ray shower detections

<u>Taking data with its full configuration since 2011</u>

KM3NeT

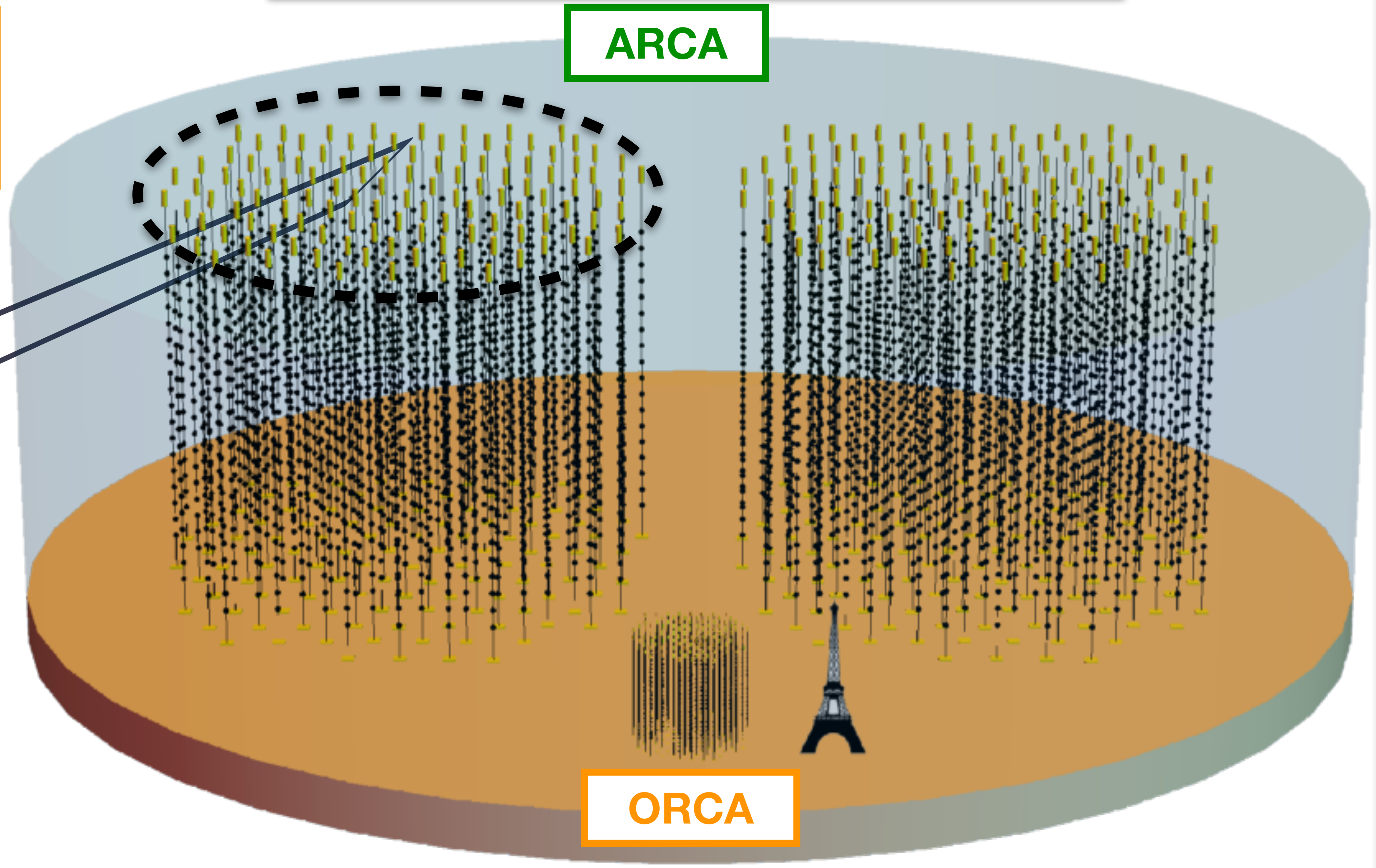
KM3NeT
www.km3net.org

- Deep infrastructure under construction in the Mediterranean Sea
- Two instrument sites: ORCA (France) and ARCA (Italy) ⟶ **Same technology** used for both detectors but **different physics**



	Astroparticle **R**esearch with **C**osmics in the **A**byss	**O**scillation **R**esearch with **C**osmics in the **A**byss
Location	Italy (Sicilian coast)	France (coast of Toulon)
Depth	3450 m	2450 m
Number of DUs	**115 x 2 (2 BB)**	**115 (1 BB)**
Instrumented volume	~ 1 Gton	~ 7 Mton

> 1 km^3 **neutrino telescope**



- Construction started in 2015
- Status at 2023: ARCA(ORCA) taking data with 21(18) DUs

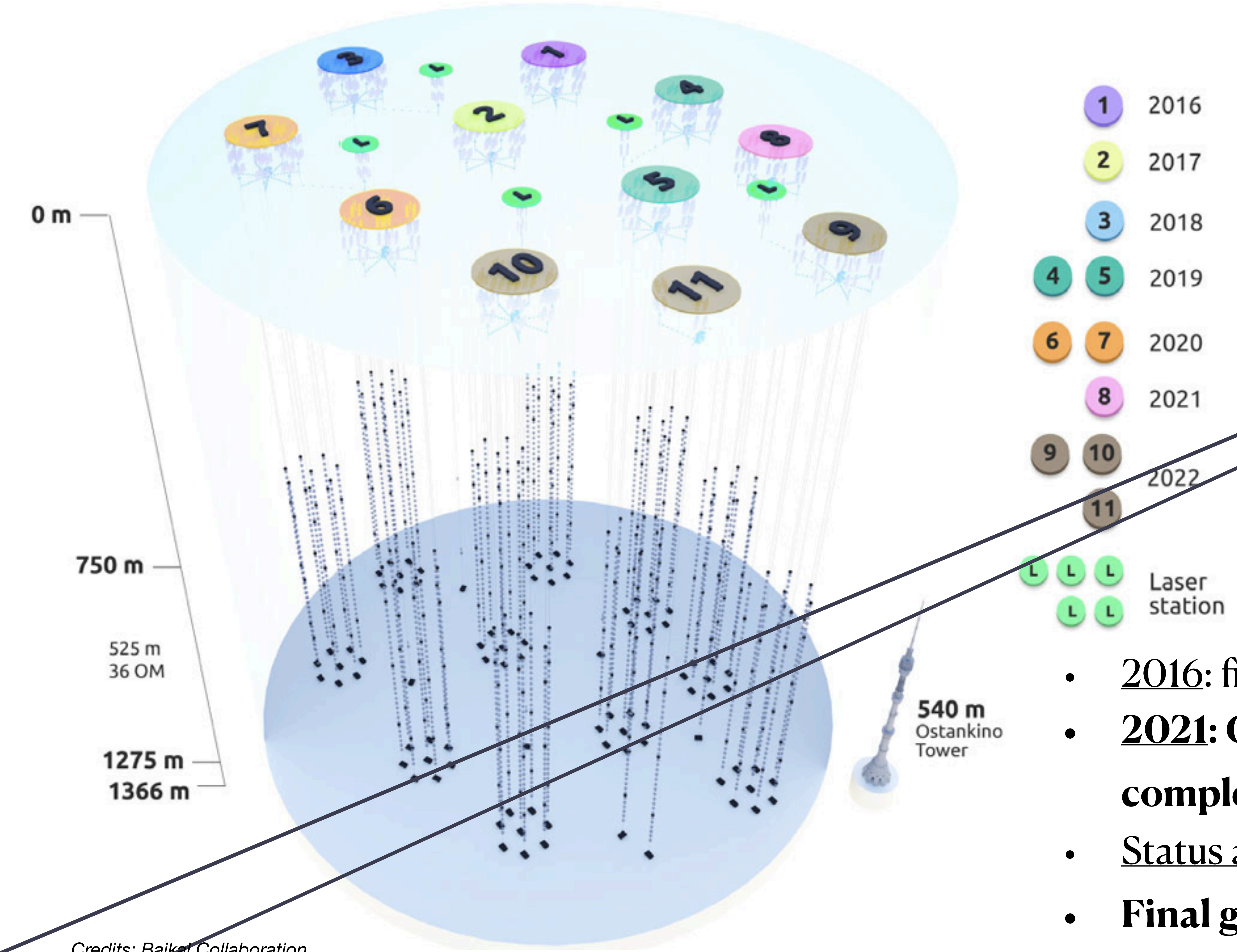
1 Building Block = 115 Detection Units
(1 BB = 115 DUs)

Credits: KM3NeT Collaboration

Baikal-GVD

https://baikalgvd.jinr.ru

BAIKAL-GVD

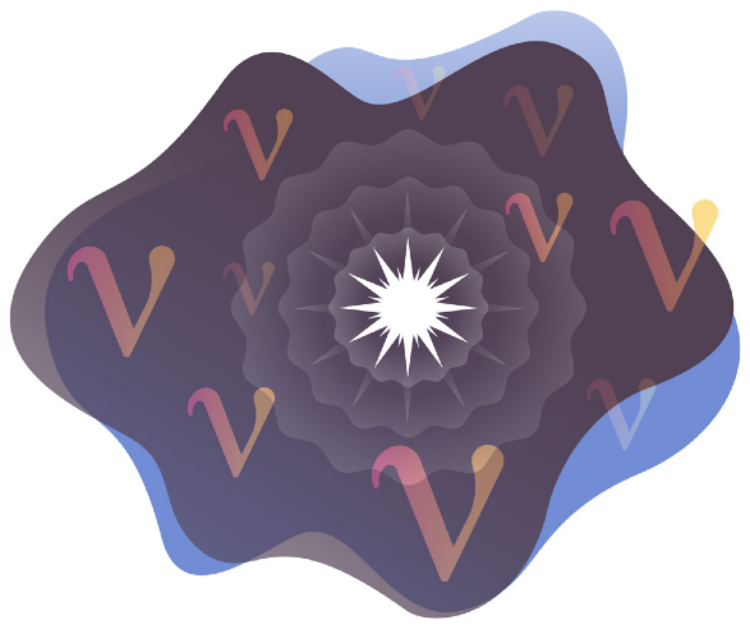


Credits: Baikal Collaboration

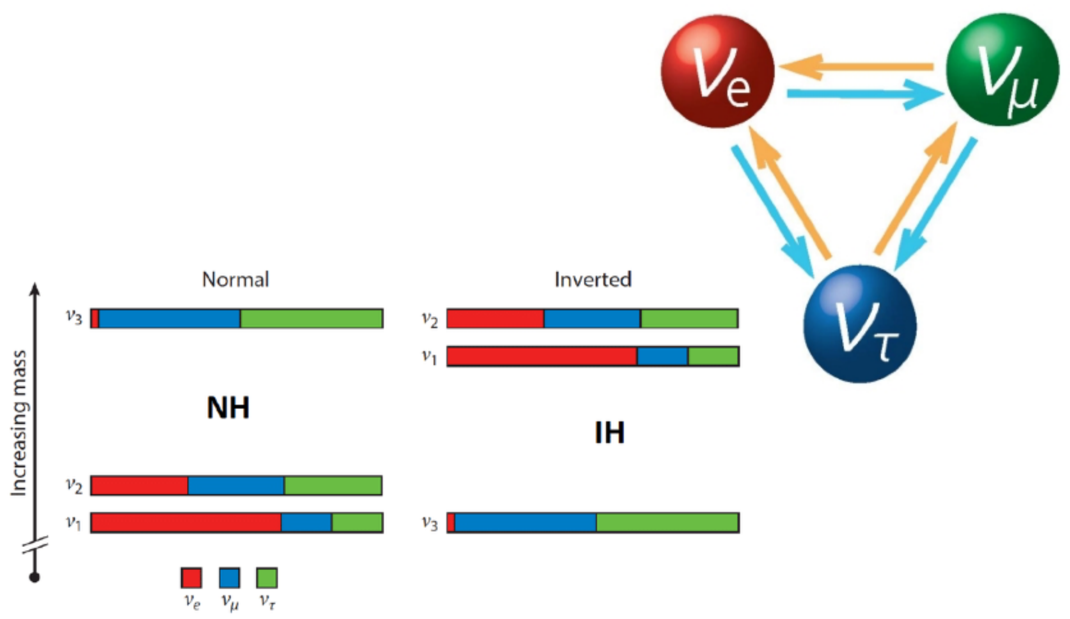
- <u>2016</u>: first cluster deployed
- **<u>2021</u>: GVD Phase 1 (8 clusters with 8 strings each) completed (volume of $\sim 0.4\ \mathrm{km}^3$)**
- <u>Status at 2023</u>: Baikal-GVD consists of 12 clusters
- **Final goal: 27 clusters ($\sim 1.4\ \mathrm{km}^3$)**

Neutrino telescopes: key science cases

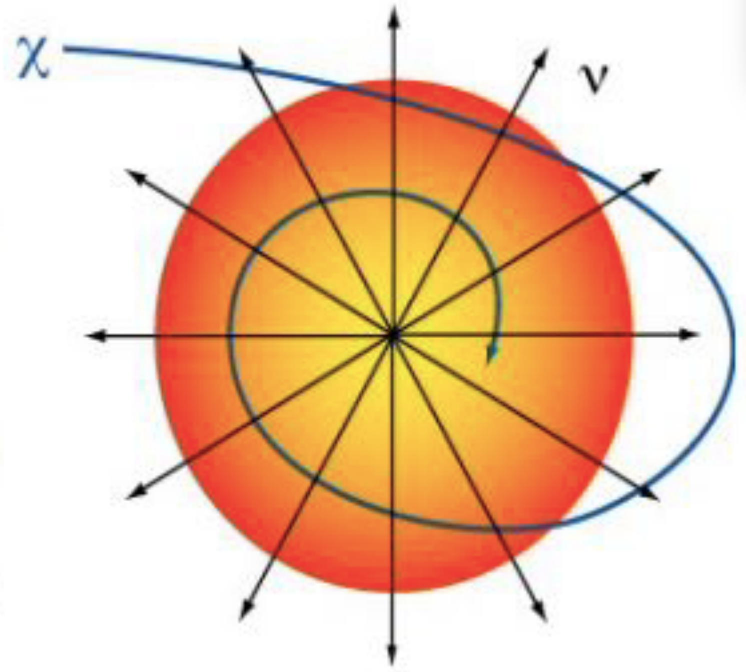
Supernova neutrinos



Neutrino mass hierarchy
Neutrino oscillations



Dark matter



High-energy neutrinos
Neutrino astronomy

Low-energy (MeV scale) | GeV | TeV | High-energy (PeV scale)

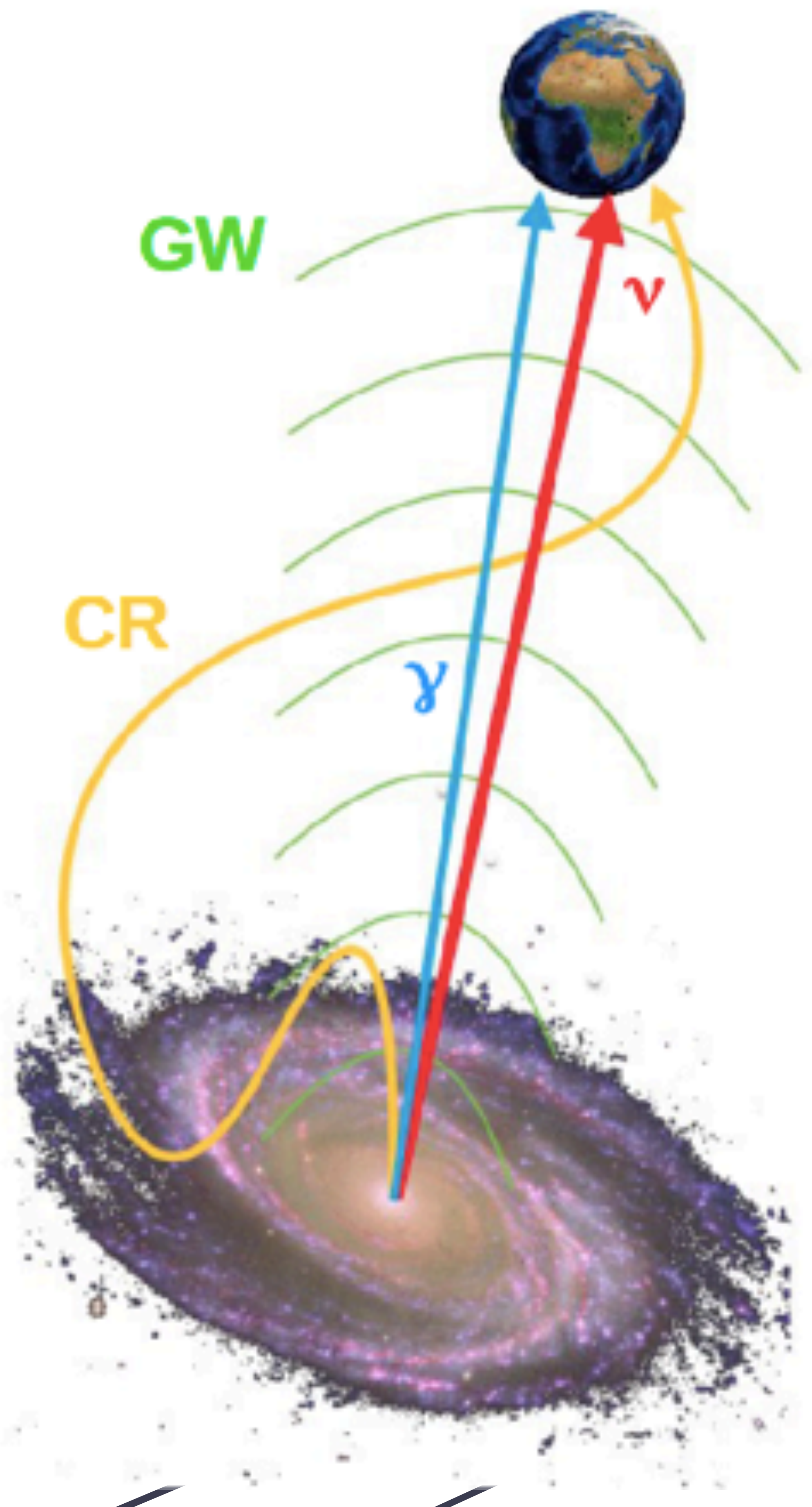
Observation of coincident hits in photomultipliers above the background

KM3NeT/ORCA
DeepCore

KM3NeT/ARCA
IceCube
Baikal-GVD

ANTARES

This talk…



- Promising extragalactic astrophysical sources of neutrinos and their characteristics
- Neutrino astronomy state-of-art

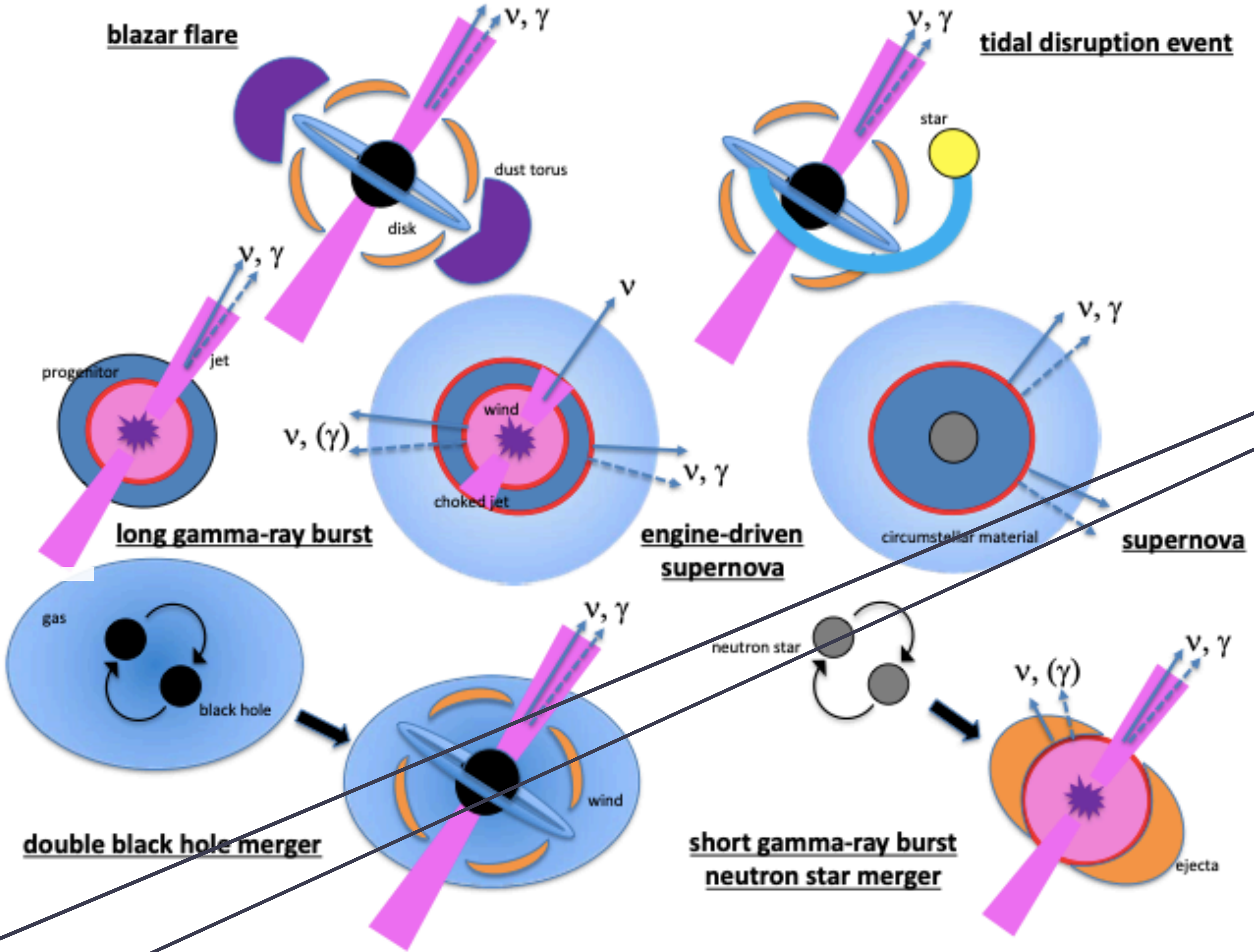
High-energy neutrinos
Neutrino astronomy

TeV ⟷ High-energy (PeV scale)

- Review talk on QG studies with IceCube: T. Katori, '*Search for Quantum-Gravity-Motivated effects in IceCube*' (today, after lunch)
- For QG studies with lower energy neutrinos see (both today, after lunch):
  - A.Domi, '*Lorentz invariance violation with KM3NeT/ORCA115*'
  - V. D'Esposito, '*Fundamental decoherence and neutrino oscillations*'
- Review talk about cosmic messengers can be used for QG studies: M. Bustamante's talk '*New physics from high-energy cosmic messengers*' (Thursday 13, morning session)

High-energy multi-messenger transients

Wide variety of transient sources potentially emitting neutrinos of astrophysical origin



- ✦ Non-thermal emission can be observed across the EM spectrum for most of these sources
- ✦ Wide variety of timescales and EM spectral features for these sources

Transients: astrophysical phenomena with duration limited in time, contrary to steady sources

[High-Energy Multimessenger Transient Astrophysics](#)
Kohta Murase and Imre Bartos
Annual Review of Nuclear and Particle Science 2019 69:1, 477-506

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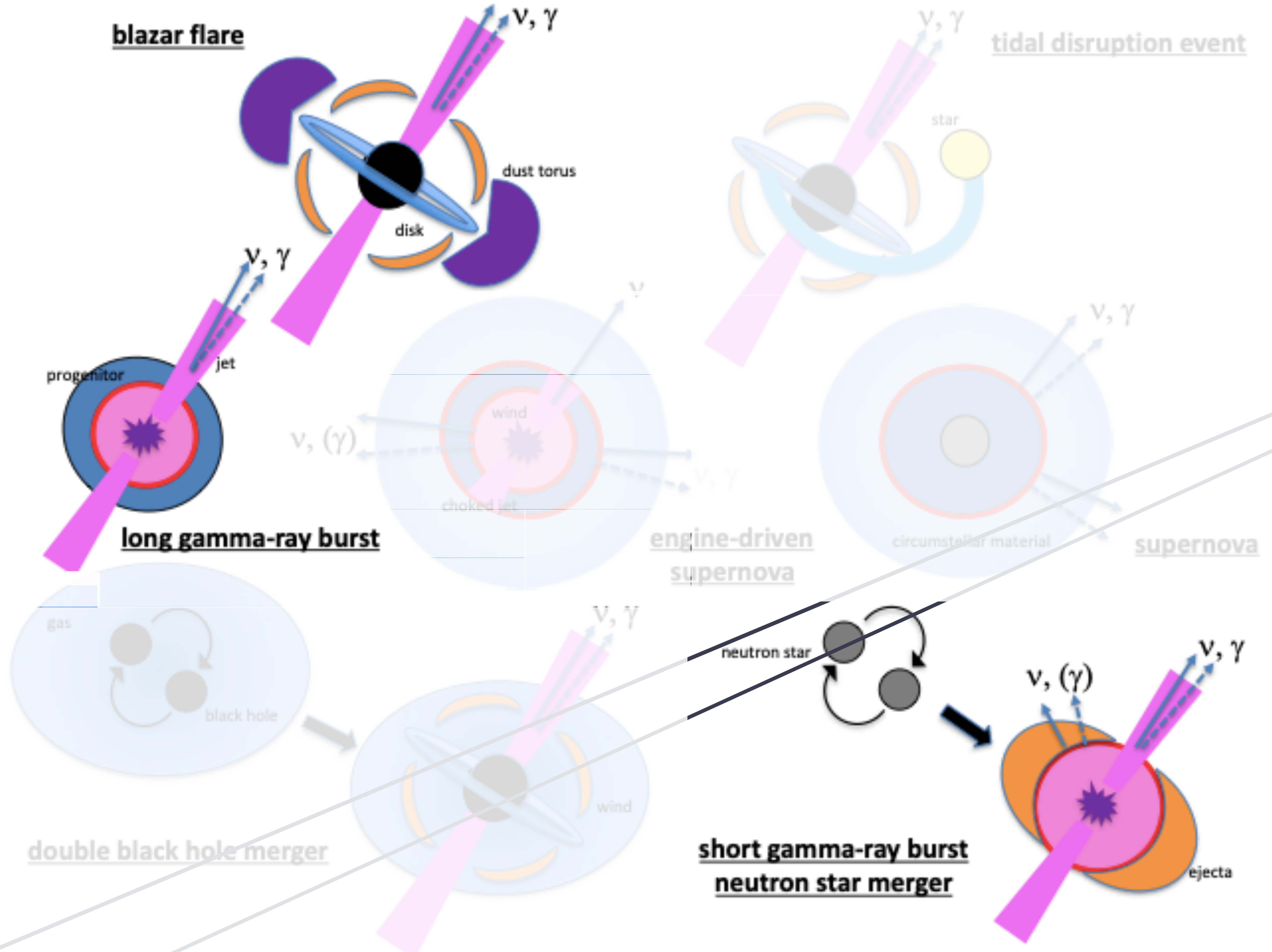

This talk

Excellent study cases both for <u>ν astronomy</u> and QG

- ✦ Gamma-Ray Bursts (GRBs)
- ✦ Blazars, namely Active Galactic Nuclei (AGNs) with relativistic jet pointing towards us

<u>Transients:</u> astrophysical phenomena with duration limited in time, contrary to steady sources

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Gamma-Ray Bursts (GRBs)

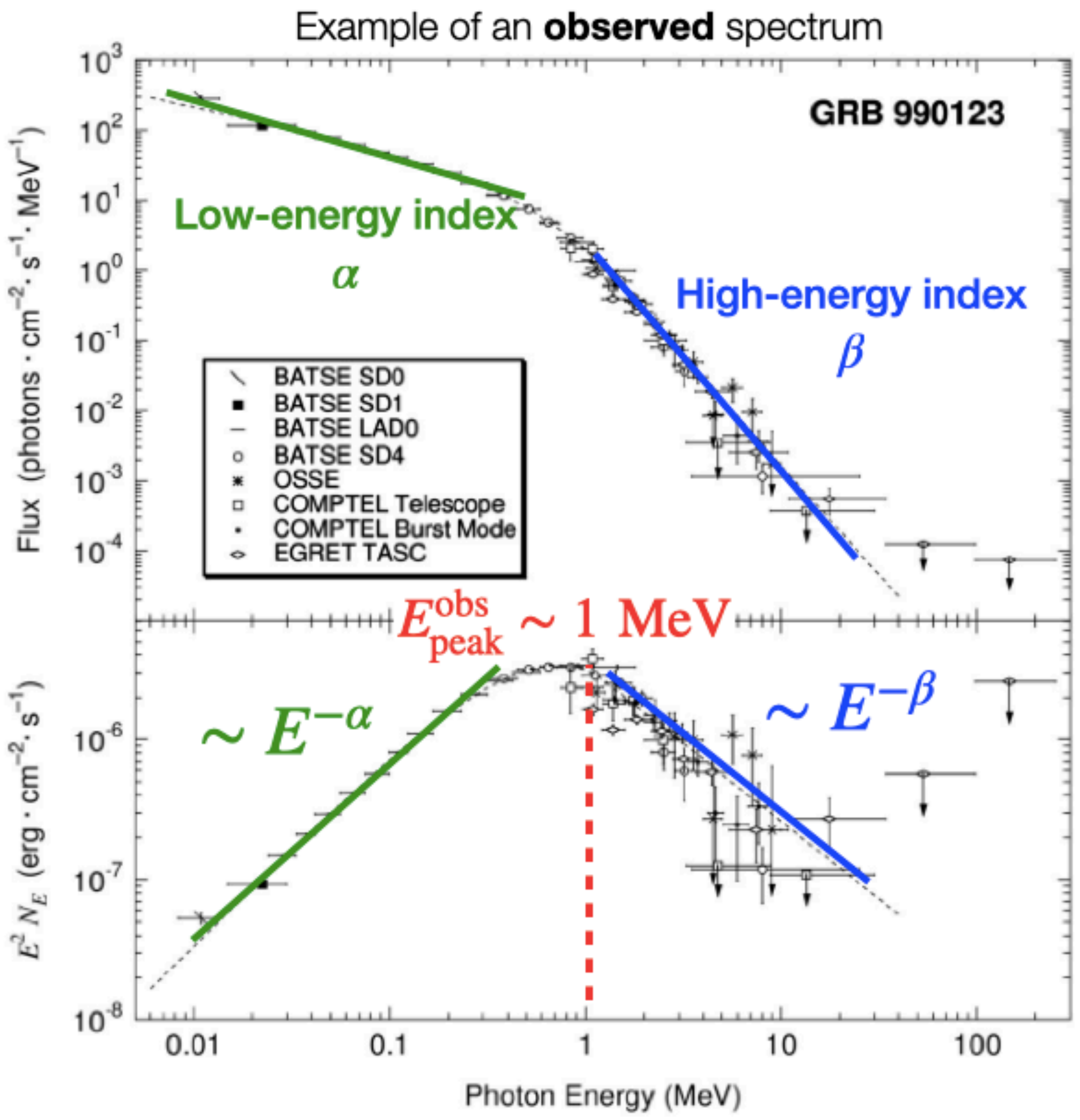
GRBs are single **short-lived radiation of γ-ray radiation** (extragalactic sources)

✦ The **brightest electromagnetic events** known to occur in the Universe

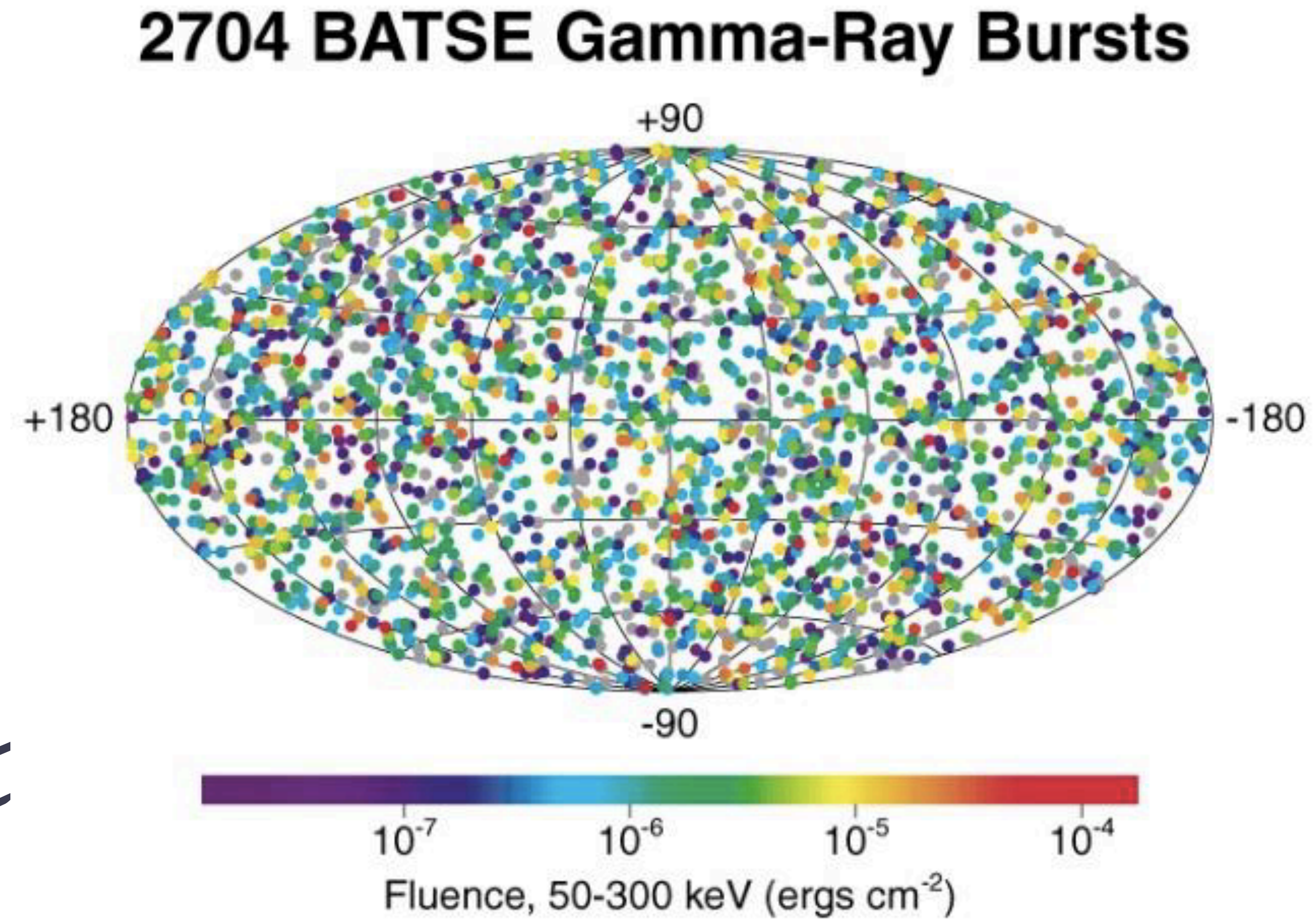
⇩

$$L_{\gamma,\mathrm{iso}} \sim 10^{54}\ \mathrm{erg/s}$$

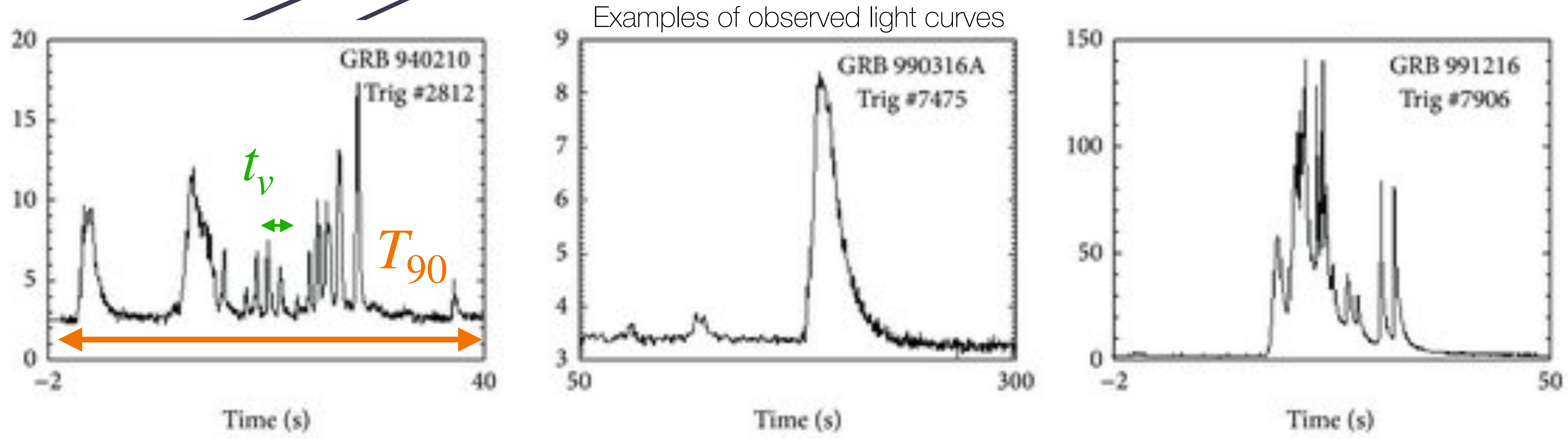
✦ **Non-thermal** γ-ray spectra



Briggs M. S., Band D. L., Kippen R. M., et al., ApJ524, 82-91, (1999)



★ Wide variety of gamma-ray light curves with **fast variability time**



Proxy of the prompt duration

Minimum variability time observed in burst light curves

Basic framework: the *fireball model*

GRBs in the multimessenger framework: ν production

$p\gamma$ interactions

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

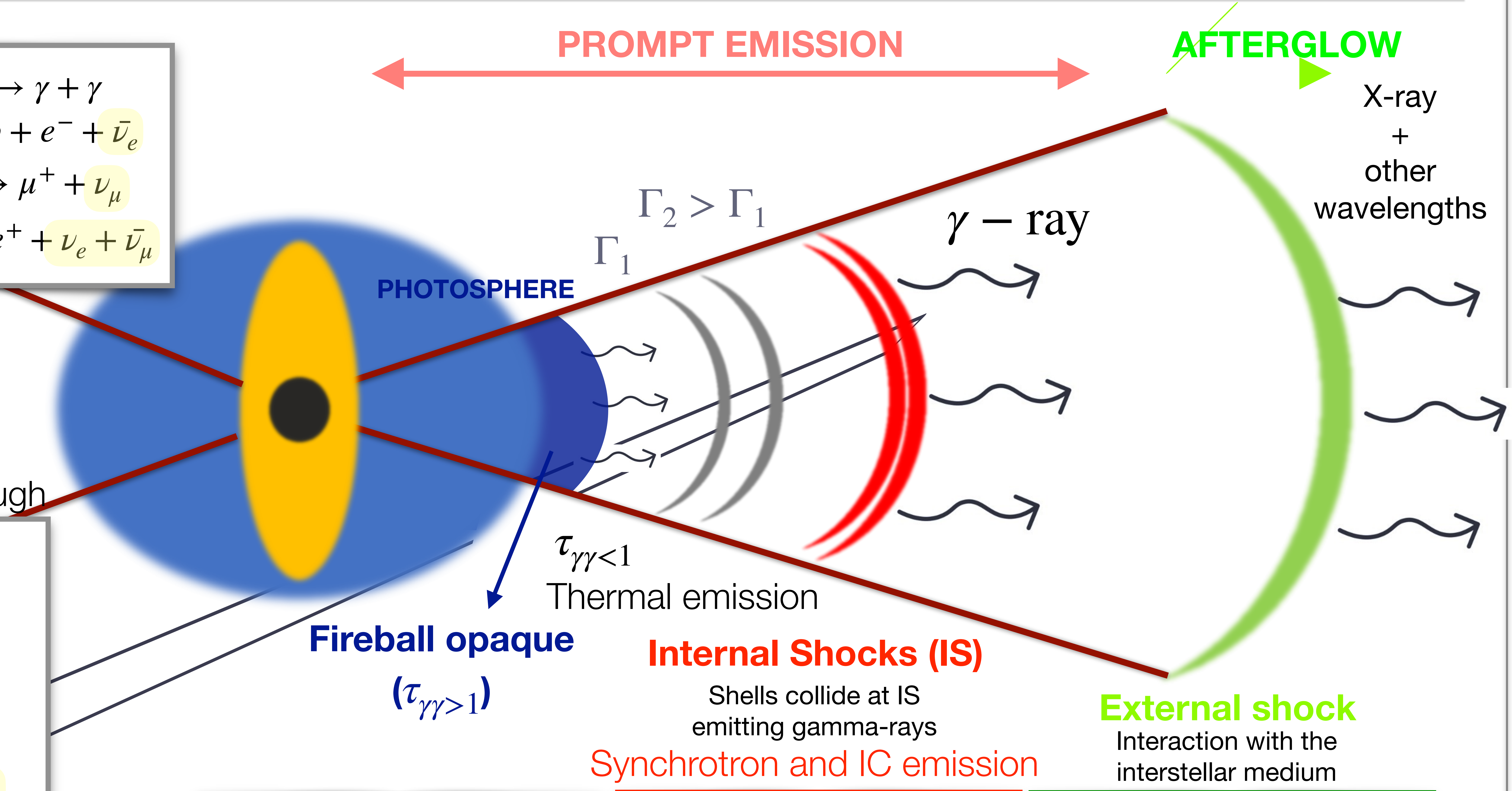
Shock acceleration of p:
1st order Fermi acceleration

***pp/pn* collisions**
If the envelope is large enough

$$\begin{cases} p + p \rightarrow p + n + \pi^+ \\ p + n \rightarrow p + p + \pi^- \\ p + p \rightarrow p + p + \pi^0 \\ n + n \rightarrow p + n + \pi^- \end{cases}$$

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu \rightarrow e^\pm + \nu_e$$

$$\pi^0 \rightarrow 2\gamma \rightarrow e^\pm$$



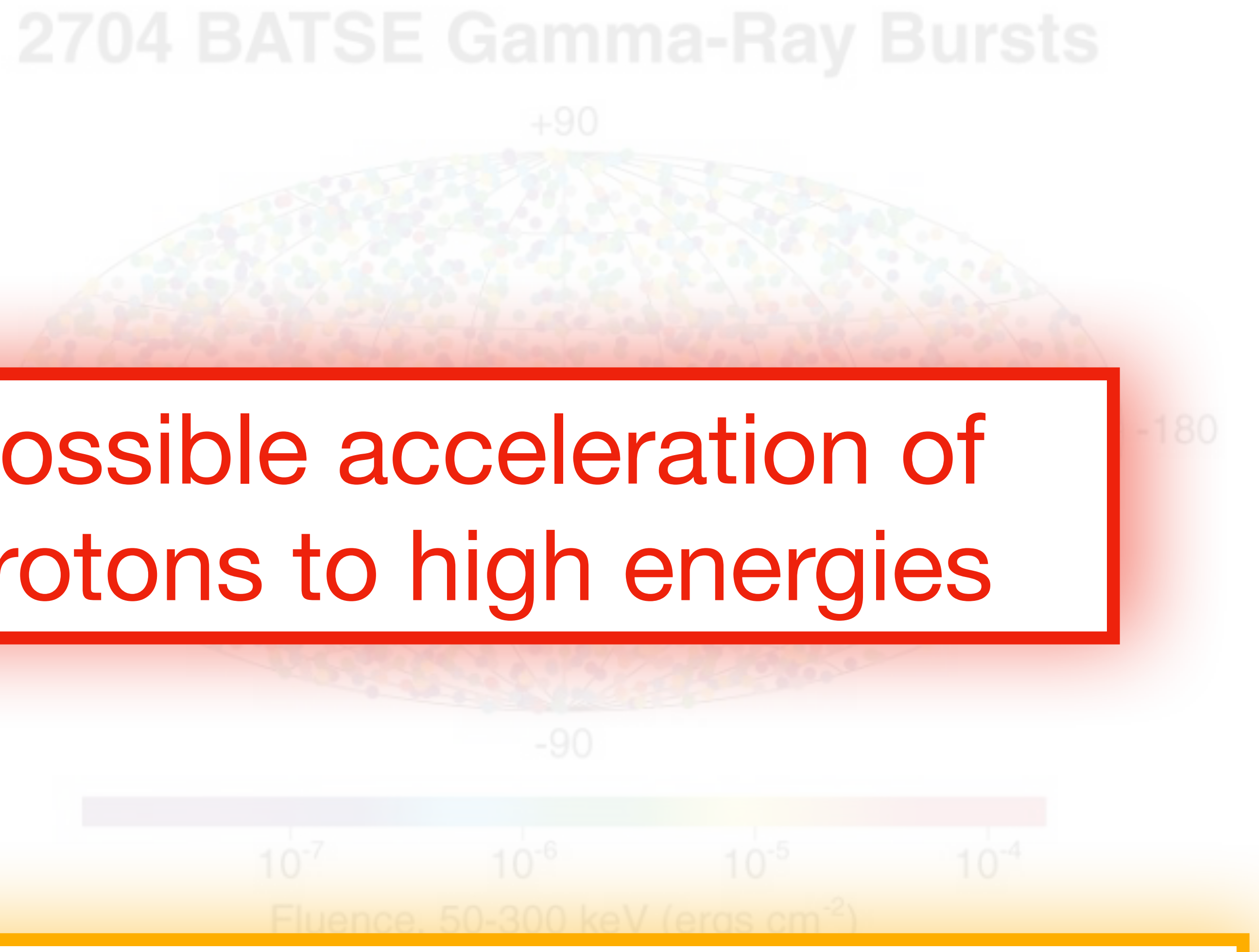
GeV-TeV neutrinos
Meszaros & Waxman 2001

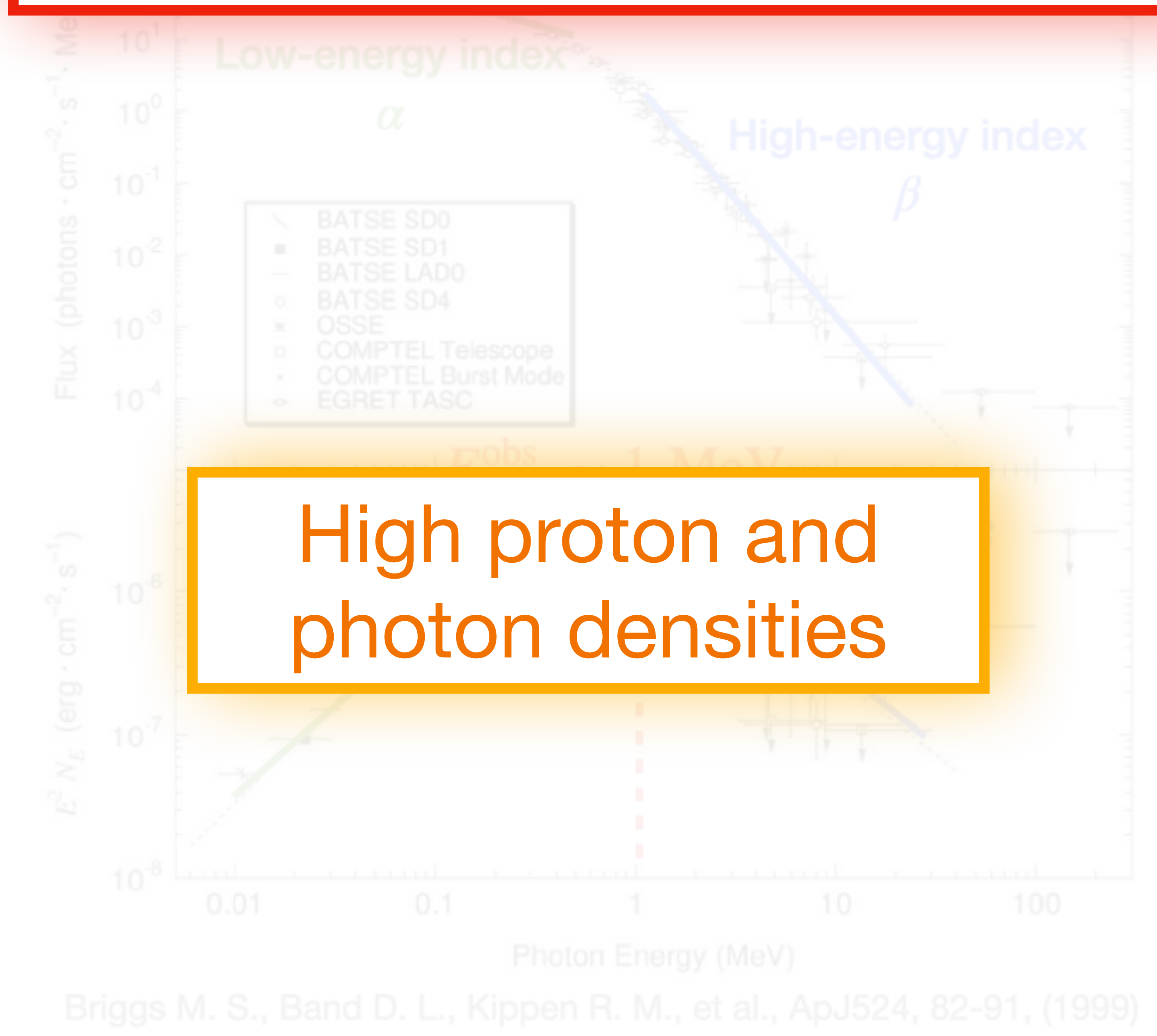
TeV-PeV neutrinos
Waxman & Bahcall 1997

PeV-EeV neutrinos
Waxman & Bahcall 2000

Why are GRBs natural sources of ν candidates?

GRBs are single **short-lived radiation of γ-ray radiation** (extragalactic sources)





✦ The **brightest electromagnetic events** known to occur in the Universe

⇩

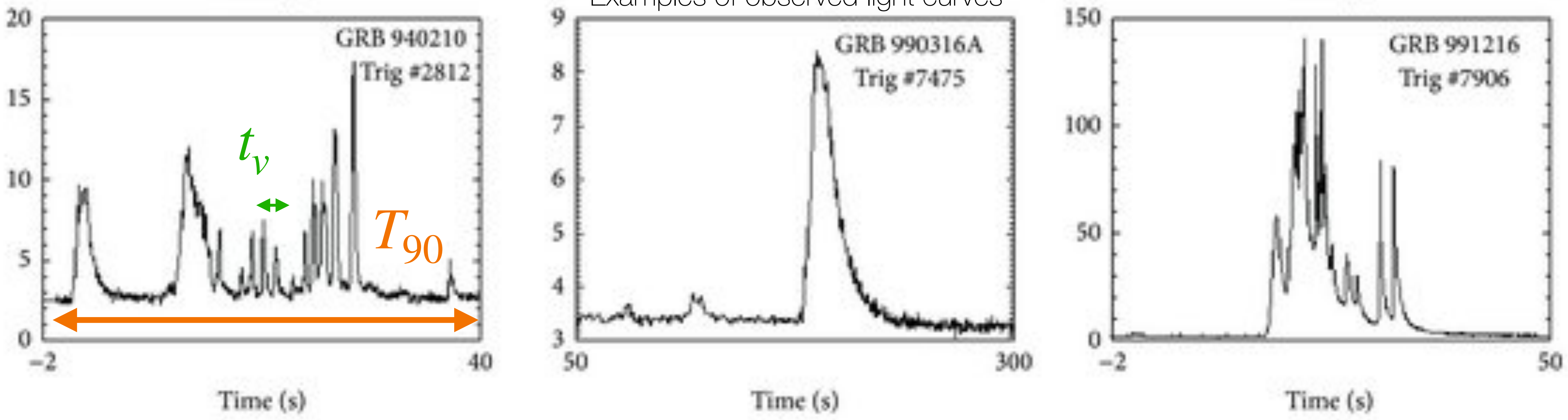
$L_{\gamma,\text{iso}} \sim 10^{54}$ erg/s

Possible acceleration of protons to high energies

High proton and photon densities

★ Wide variety of gamma-ray light curves with **fast variability time**

Examples of observed light curves



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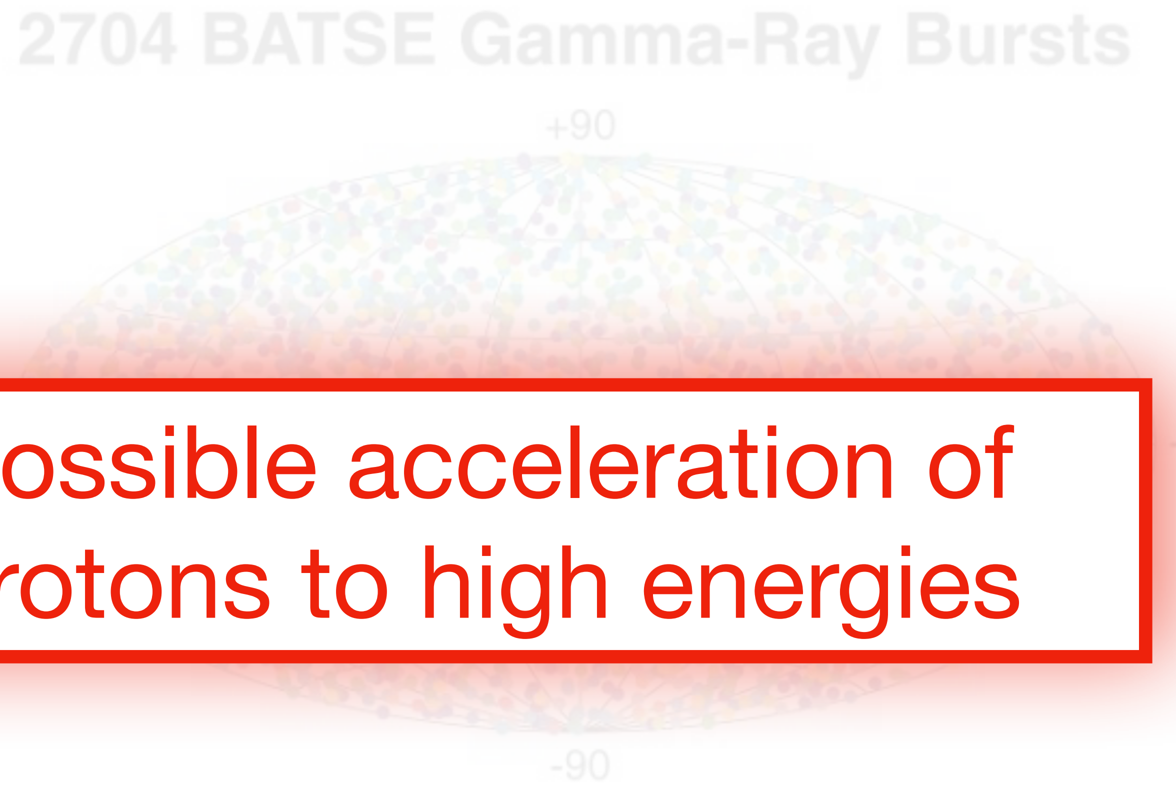


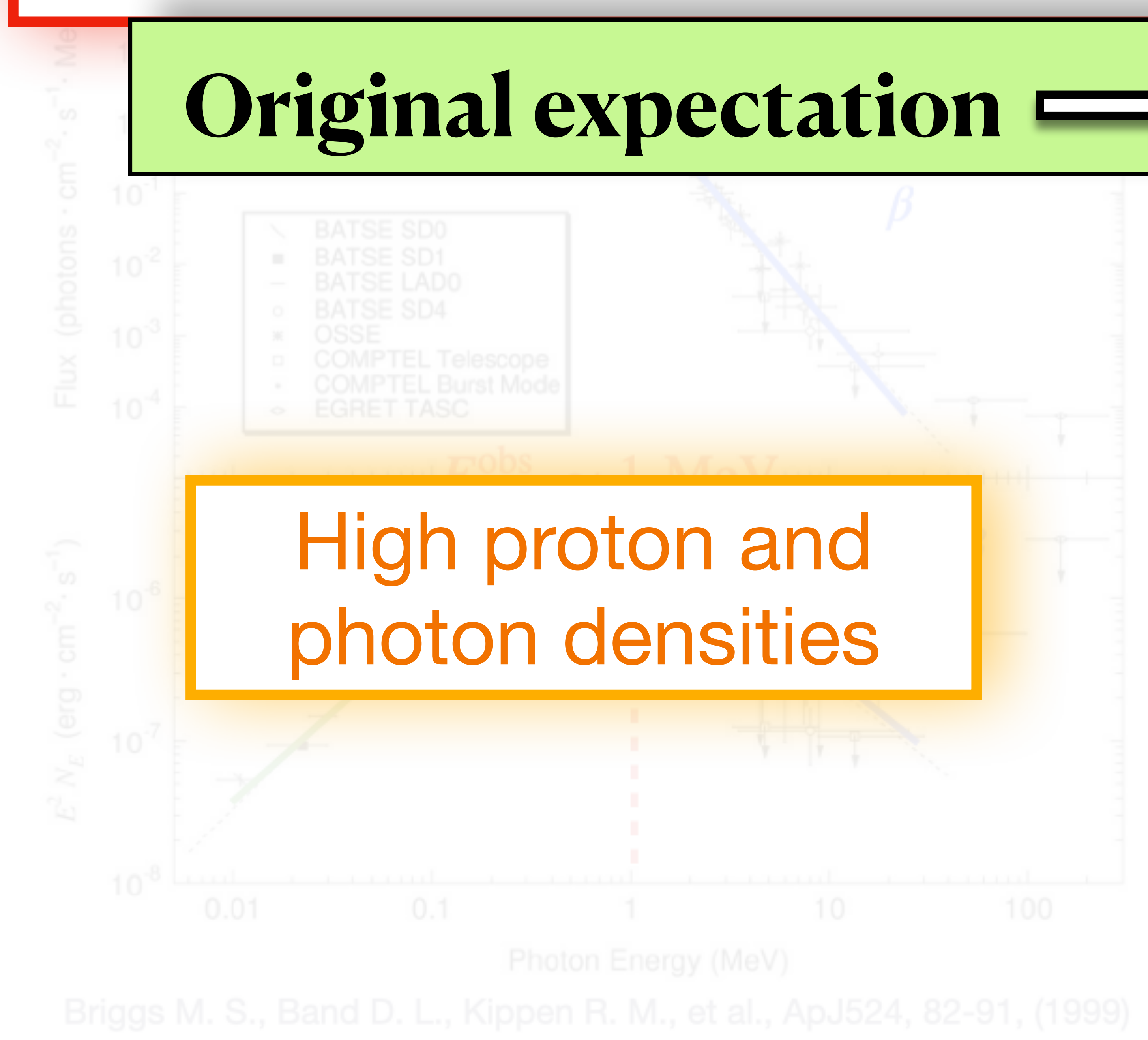
- The **brightest electromagnetic events** known to occur in the Universe

⇩

$$L_{\gamma,\mathrm{iso}} \sim 10^{54}\ \mathrm{erg/s}$$

Possible acceleration of protons to high energies

Original expectation ⟹ GRBs produce copius high-energy neutrinos via $p\gamma$ interactions



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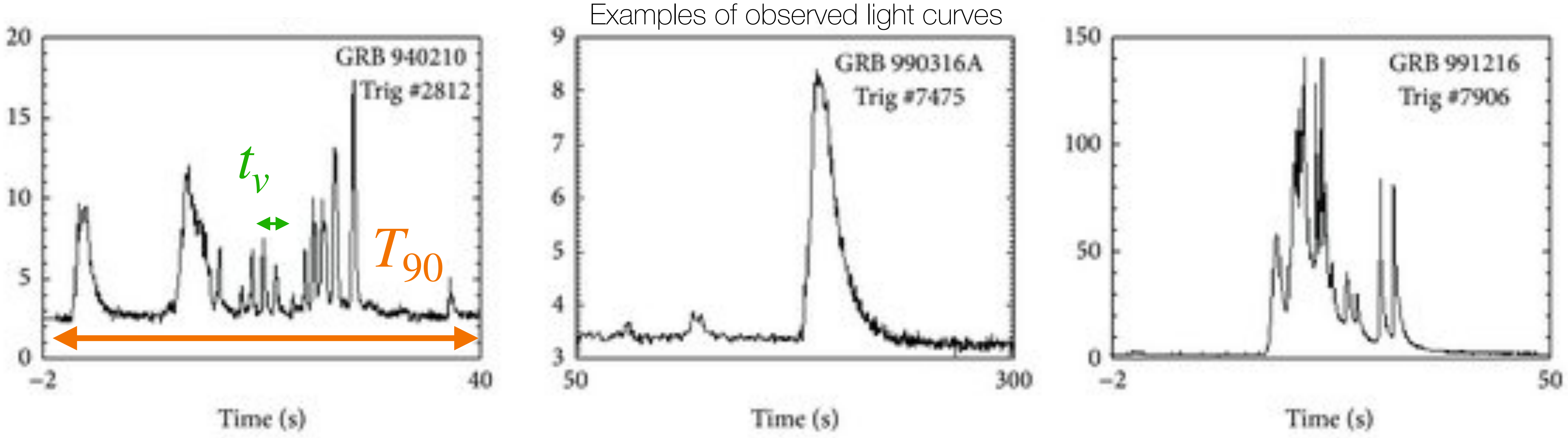


Proxy of the prompt duration

Minimum variability time observed in burst light curves

$\nu - \gamma$ relation in the IS model

For each GRB

$$\text{Energy in neutrinos} \propto \text{Energy in gamma rays}$$

Fraction of the total p energy given into pions

$$\int_0^{+\infty} E_\nu F_\nu(E_\nu) dE_\nu = \frac{1}{8} f_p \left[1 - (1 - x_{p\to\pi})^{\tau_{p\gamma}}\right] \int_{1\ \mathrm{keV}}^{10\ \mathrm{MeV}} E_\gamma F_\gamma(E_\gamma) dE_\gamma$$

$< x_{p\to\pi} > = 0.2$ Average fraction of proton energy going into a pion per interaction

$f_p = 10$ Fraction of the total energy in protons compared to the total energy in electrons (*baryonic loading*)

Optical depth to $p\gamma$

$$\tau_{p\gamma} \propto R_C \Rightarrow \tau_{p\gamma} = \left(\frac{L_{\gamma,\mathrm{iso}}}{10^{52}\mathrm{erg/s}}\right)\left(\frac{10^{2.5}}{\Gamma}\right)^4 \left(\frac{0.01\mathrm{s}}{t_\mathrm{v}}\right)\left(\frac{\mathrm{MeV}}{E_\mathrm{peak}}\right)$$

Implications of GRB stacking searches (IS model)

IceCube

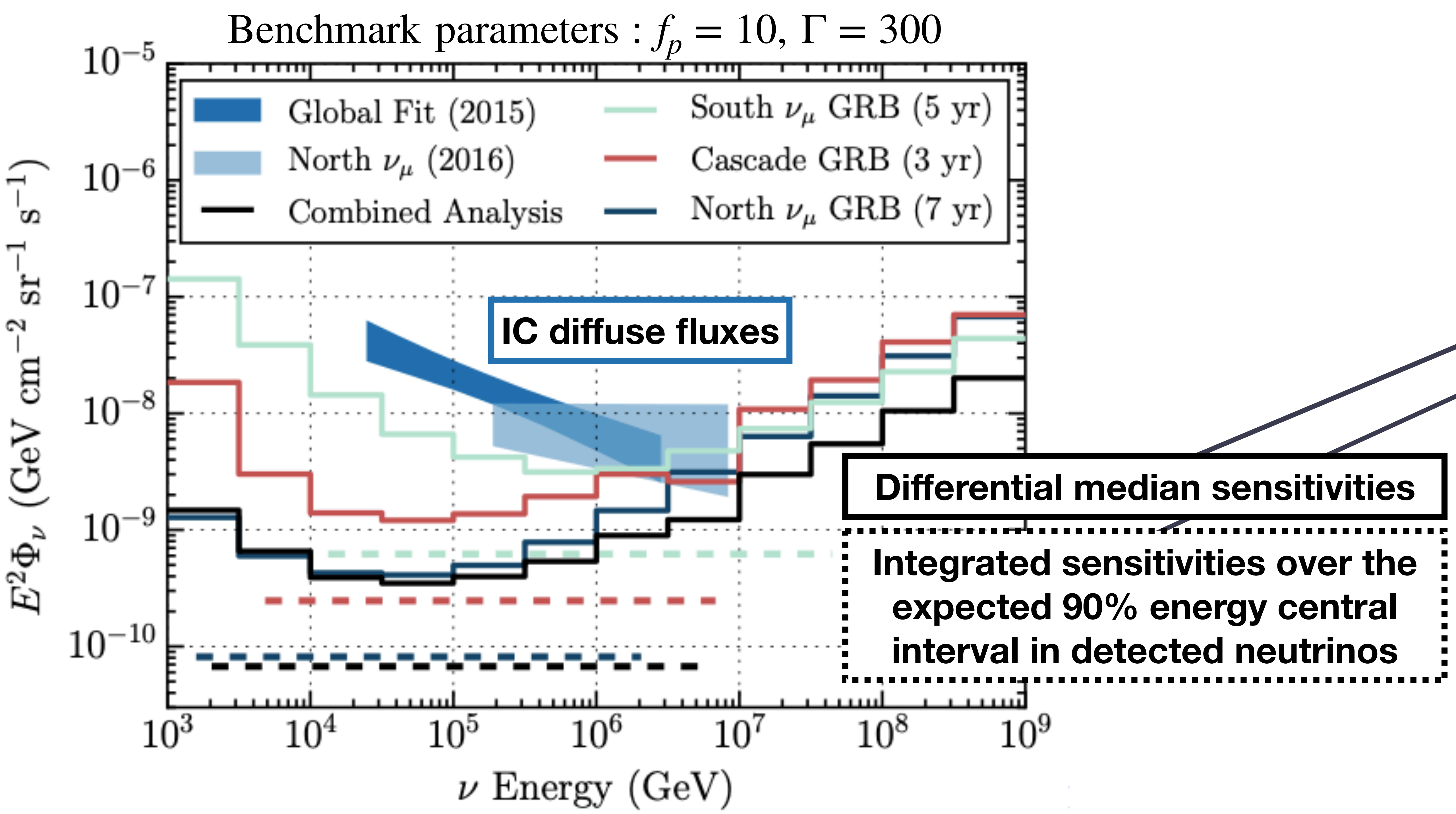
- 3 yr showers (all flavors) + 7 yr upgoing tracks + 5 yr downgoing tracks
- Stacking of 1172 GRBs

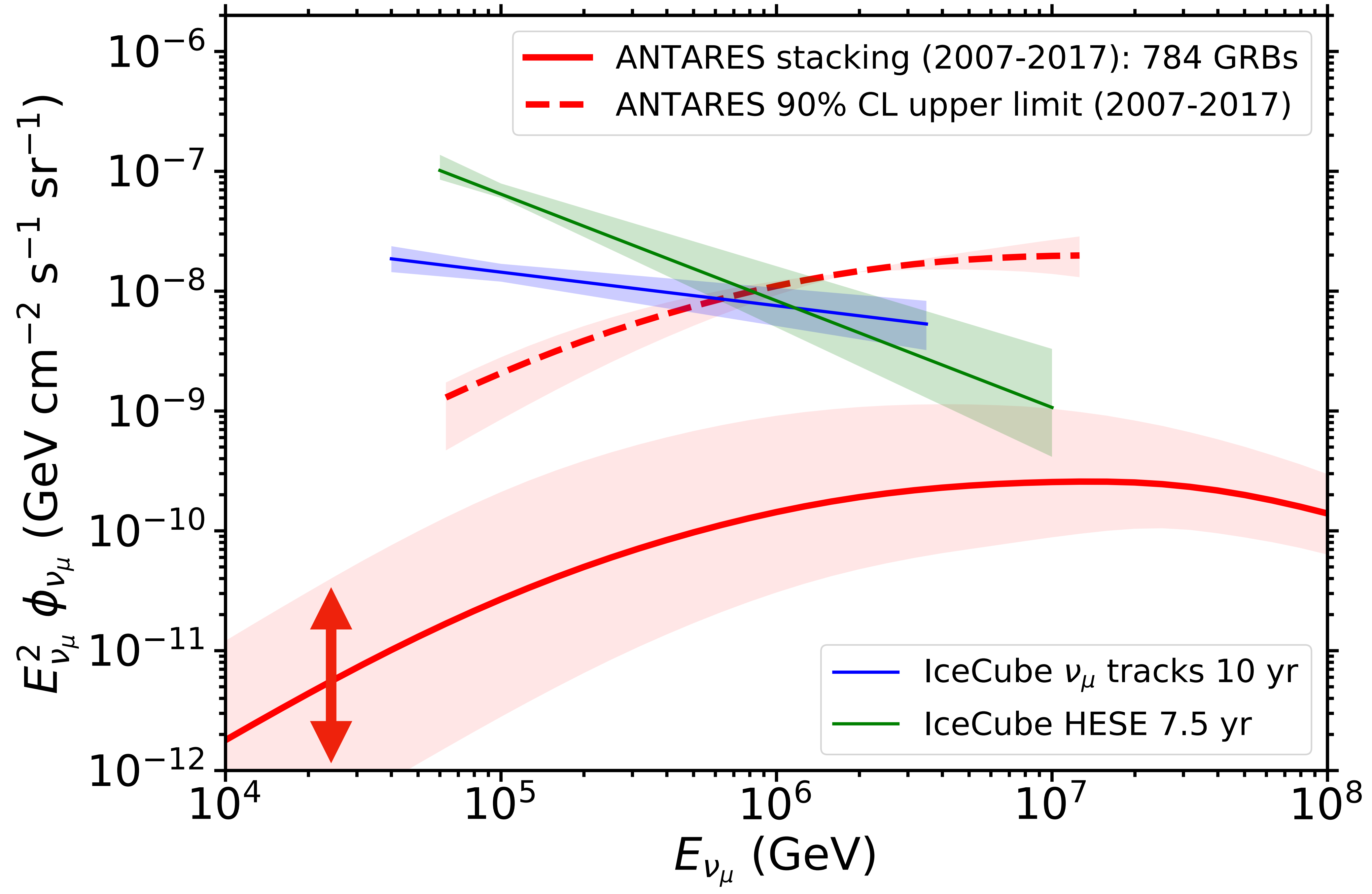
So far, no neutrinos observed in coincidence with GRBs

ANTARES

- 10 yr upgoing tracks
- Stacking analysis of 778 GRBs

Investigation of the impact of the large parameter variability (Γ, t_v, z)





<1% of the neutrino diffuse flux

IceCube Collaboration, ApJ 843 (2017) 112

Assumed GRB rate of 667 long GRB per year to compute the quasi-diffuse flux

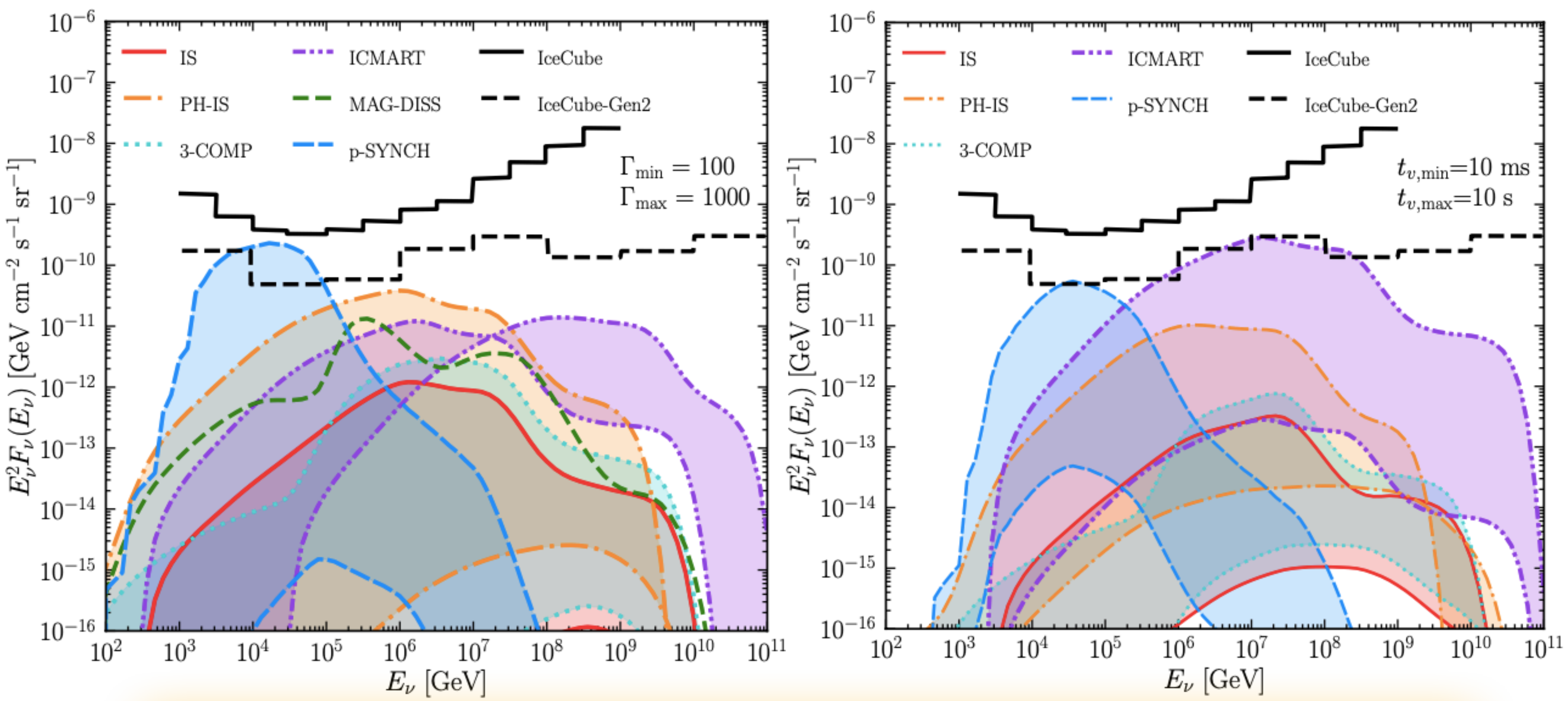
<10% of the neutrino diffuse flux

ANTARES Collaboration, MNRAS 500 (2021) 5614

Neutrino signal dependence on GRB emission mechanism

Pitik et al., JCAP 05 (2021) 034

$E_{\gamma,\mathrm{iso}} = 3.4 \times 10^{54}$ erg, $T_{90} = 100$ s, $z = 2$



Stacked neutrino fluxes from GRBs evaluated for 6 different models

$$\dot{N}_{\mathrm{GRB}} = 667\ \mathrm{yr}^{-1}$$

Matter dominated jets

- Internal Shock
- Dissipative photosphere + IS
- 3 Components (ph+IS+external shock)

Poynting flux dominated jets

- ICMART
- Magnetized jet model with gradual dissipation *(*)*

Proton-synchrotron emission *(*)*

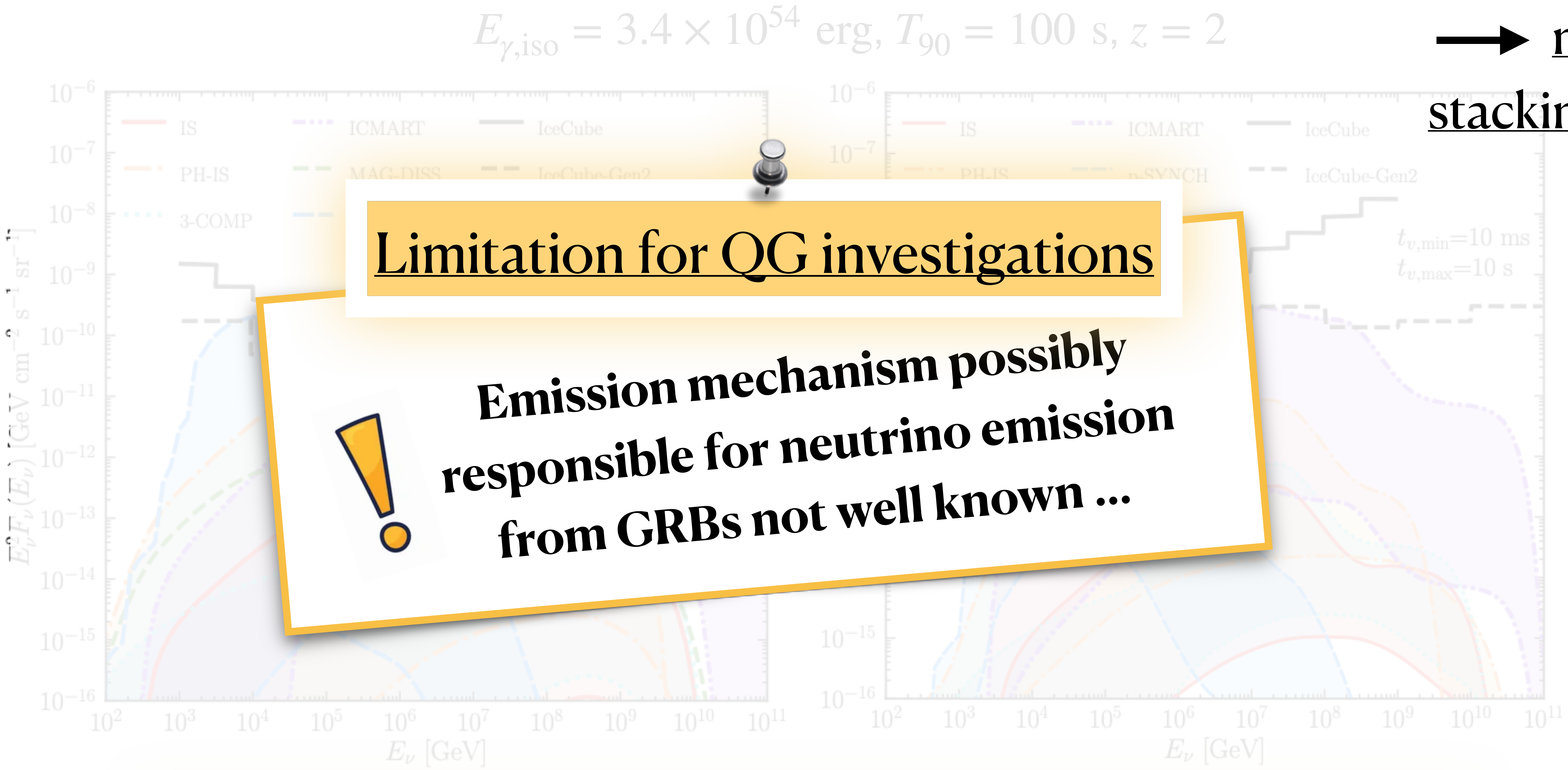
(*) Neutrino flux predicted for the first time

The neutrino production is strongly dependent on the GRB parameters used:

- Variation in neutrino flux up to few orders of magnitude
- Neutrino flux peak energy range from 10^4 GeV to 10^8 GeV

Neutrino signal dependence on GRB emission mechanism

Pitik et al., JCAP 05 (2021) 034



Limitation for QG investigations

Emission mechanism possibly responsible for neutrino emission from GRBs not well known …

The neutrino production is strongly dependent on the GRB parameters used:

- Variation in neutrino flux up to few orders of magnitude
- Neutrino flux peak energy range from 10^4 GeV to 10^8 GeV

All these models are able to explain the GRB spectrum

⟶ need to rely on a wide range of jet models in targeted stacking searches

Matter dominated jets

- Internal Shock
- Dissipative photosphere + IS
- 3 Components (ph+IS+external shock)

Poynting flux dominated jets

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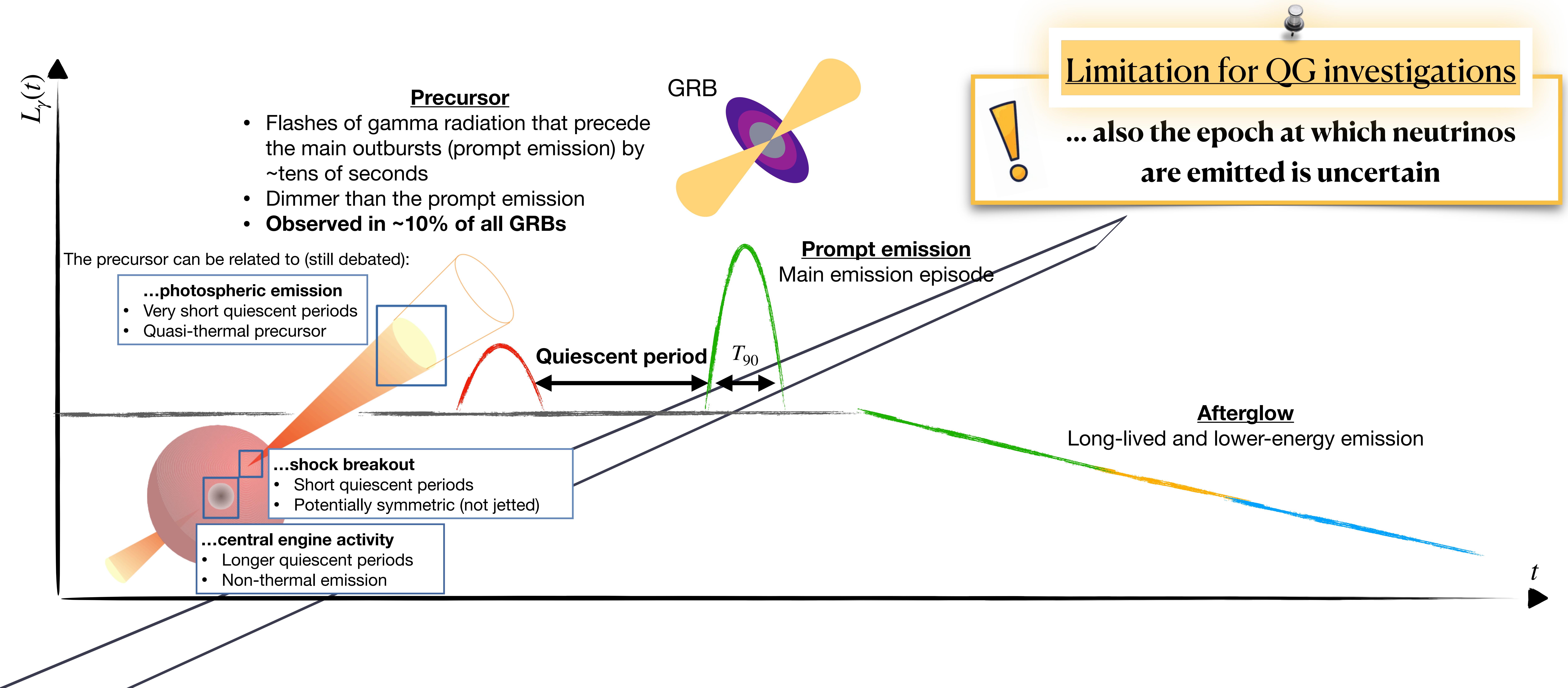
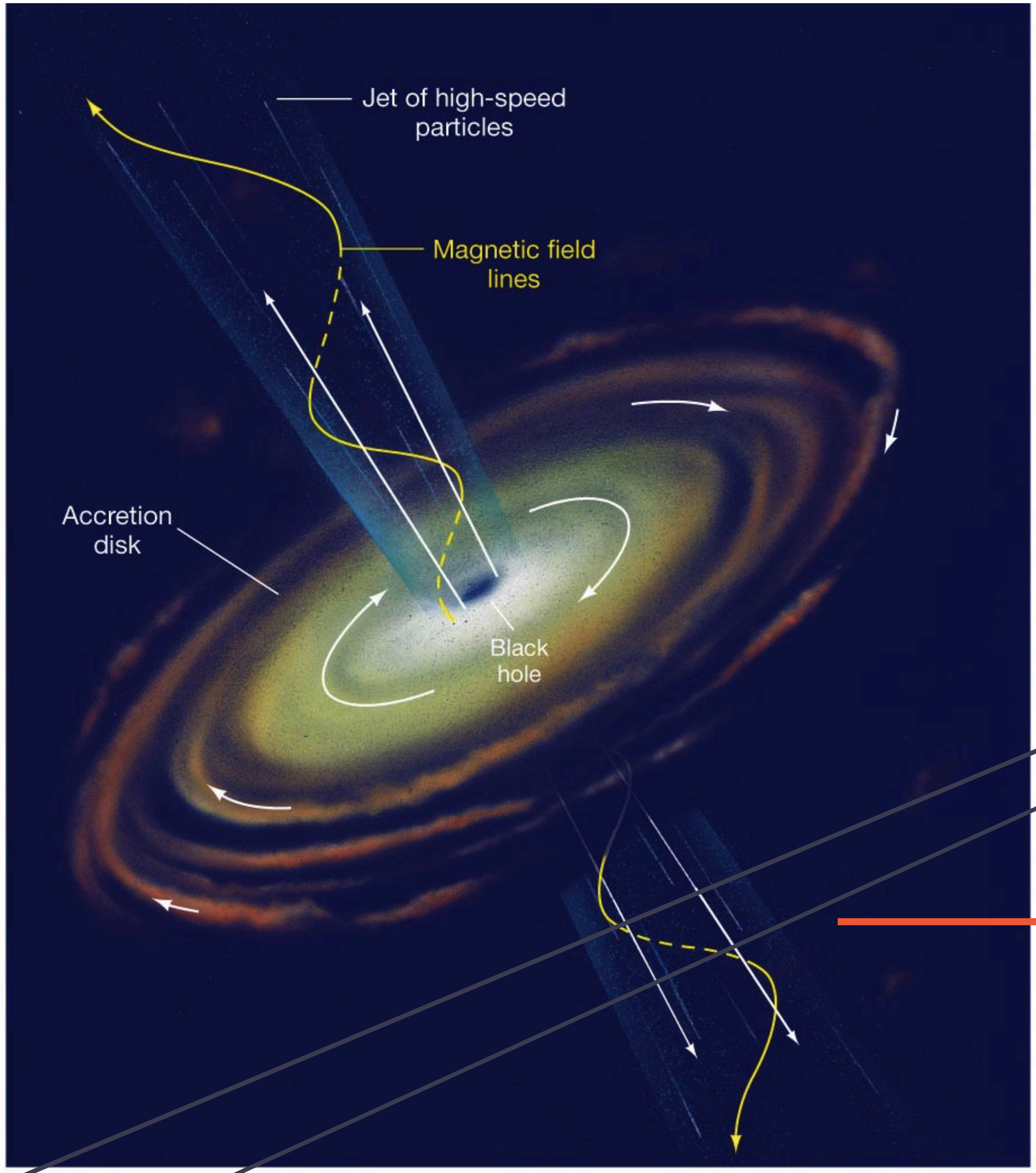
Multi-emission epochs in GRBs



Active Galactic Nuclei (AGN)



AGNs are galaxies that release an incredibly amount of energy (up to many thousand times more than a normal galaxy)

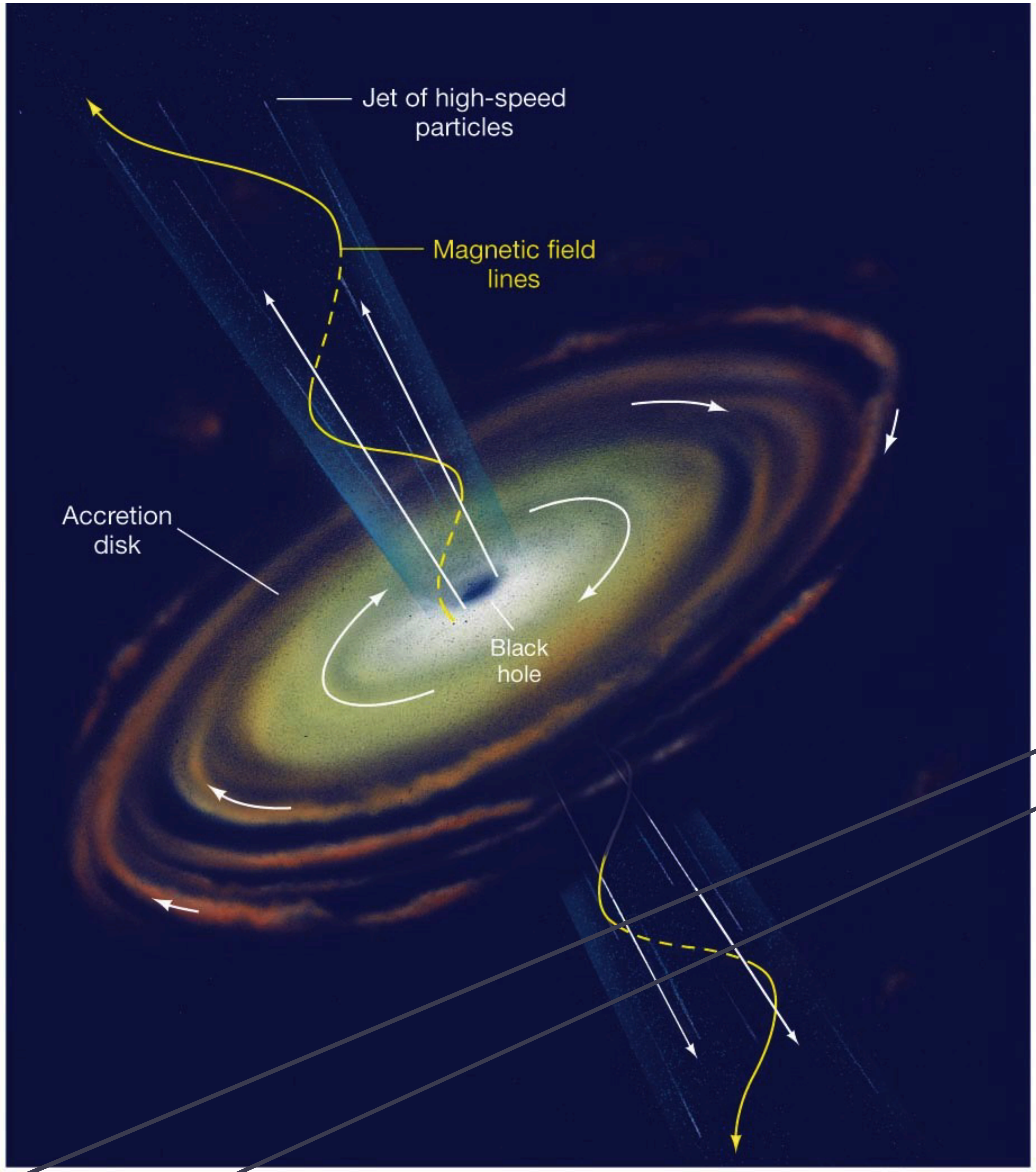
- **Most powerful sources** in the Universe (up to 10^{48} erg/s)
- Energy is generated by the conversion of gravitational energy of the infall material onto SMBH into radiation and outflows

Central region:
- SuperMassive Black Hole (SMBH)
- Accretion disk
- Broad-line region cloud surrounded by a dust torus

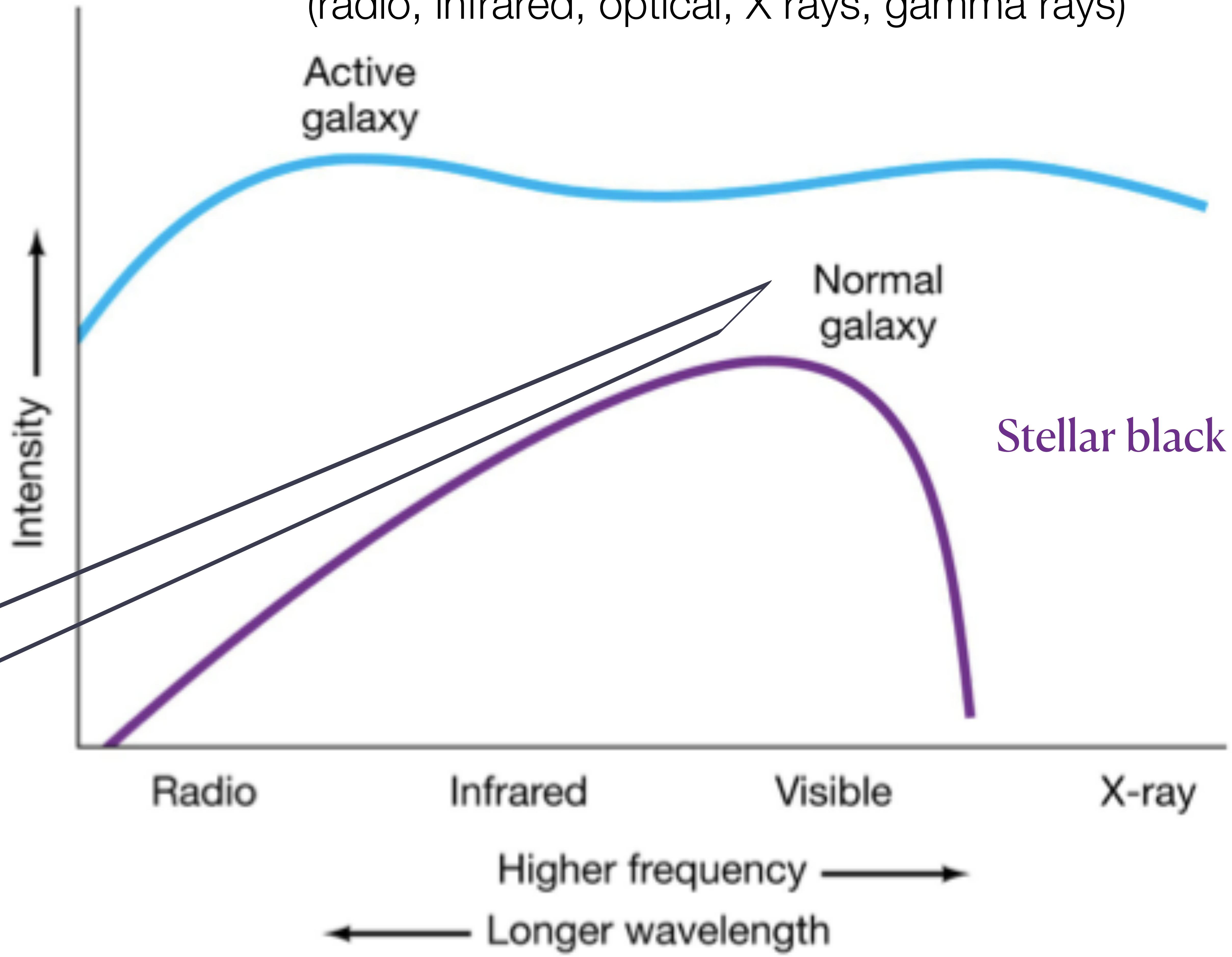
Relativistic jets
- Highly collimated relativistic outflows
- **Extreme particle accelerators**
- Note that the so-called 'jetted AGNs' constitute only the ~10% of the AGN population

Jetted AGNs of particular interest for neutrino searches

Active Galactic Nuclei (AGN)

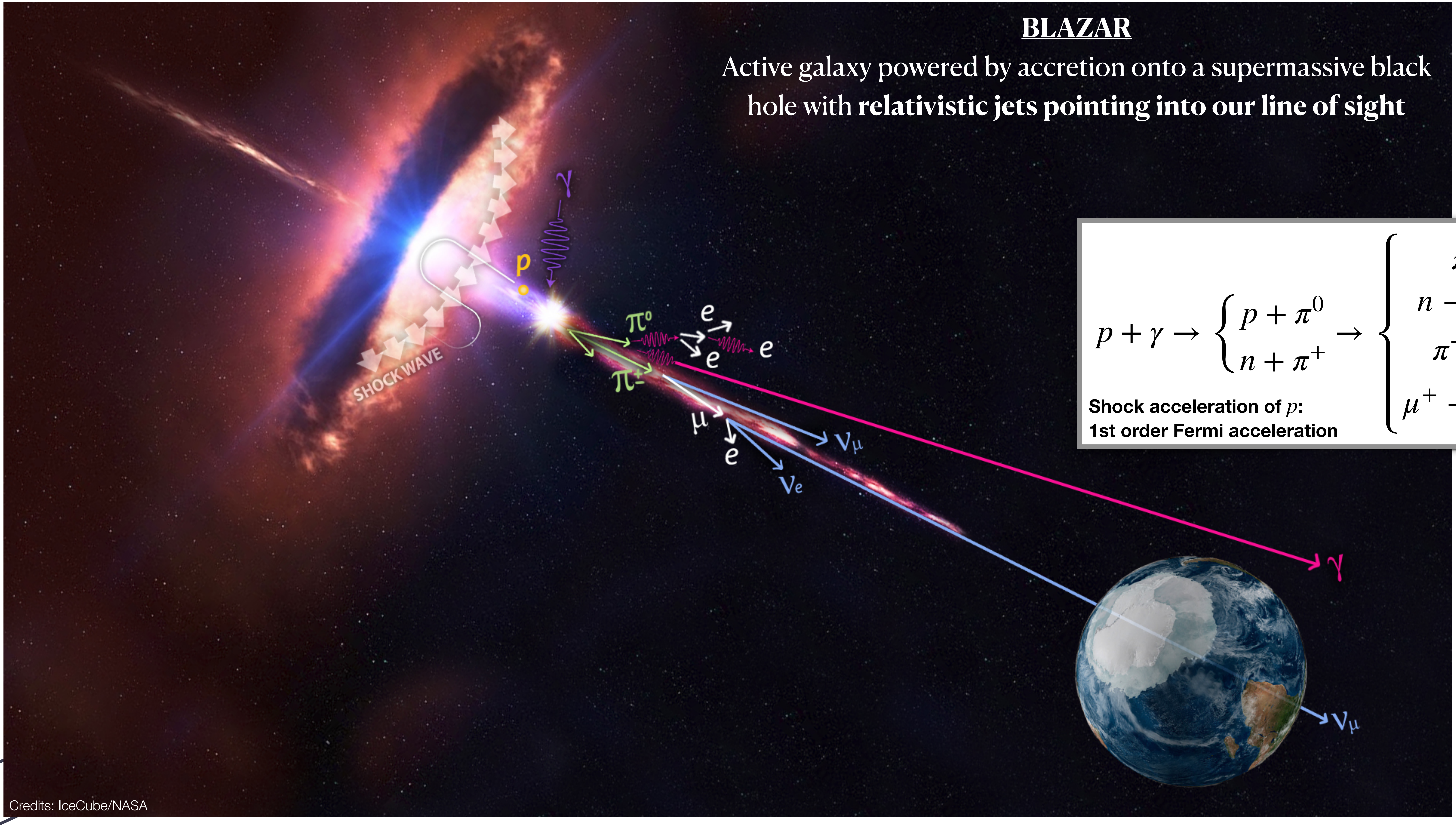


Non-thermal radiation spanning over a broad range of wavelengths
(radio, infrared, optical, X rays, gamma rays)



Stellar black body radiation

Neutrinos from blazars



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

Shock acceleration of p:
1st order Fermi acceleration

Neutrinos from blazars

Neutrinos in coincidence with a known blazar were identified!

... even if these are not the dominant sources of the diffuse astrophysical neutrino flux as well ($\lesssim 30\,\%$)

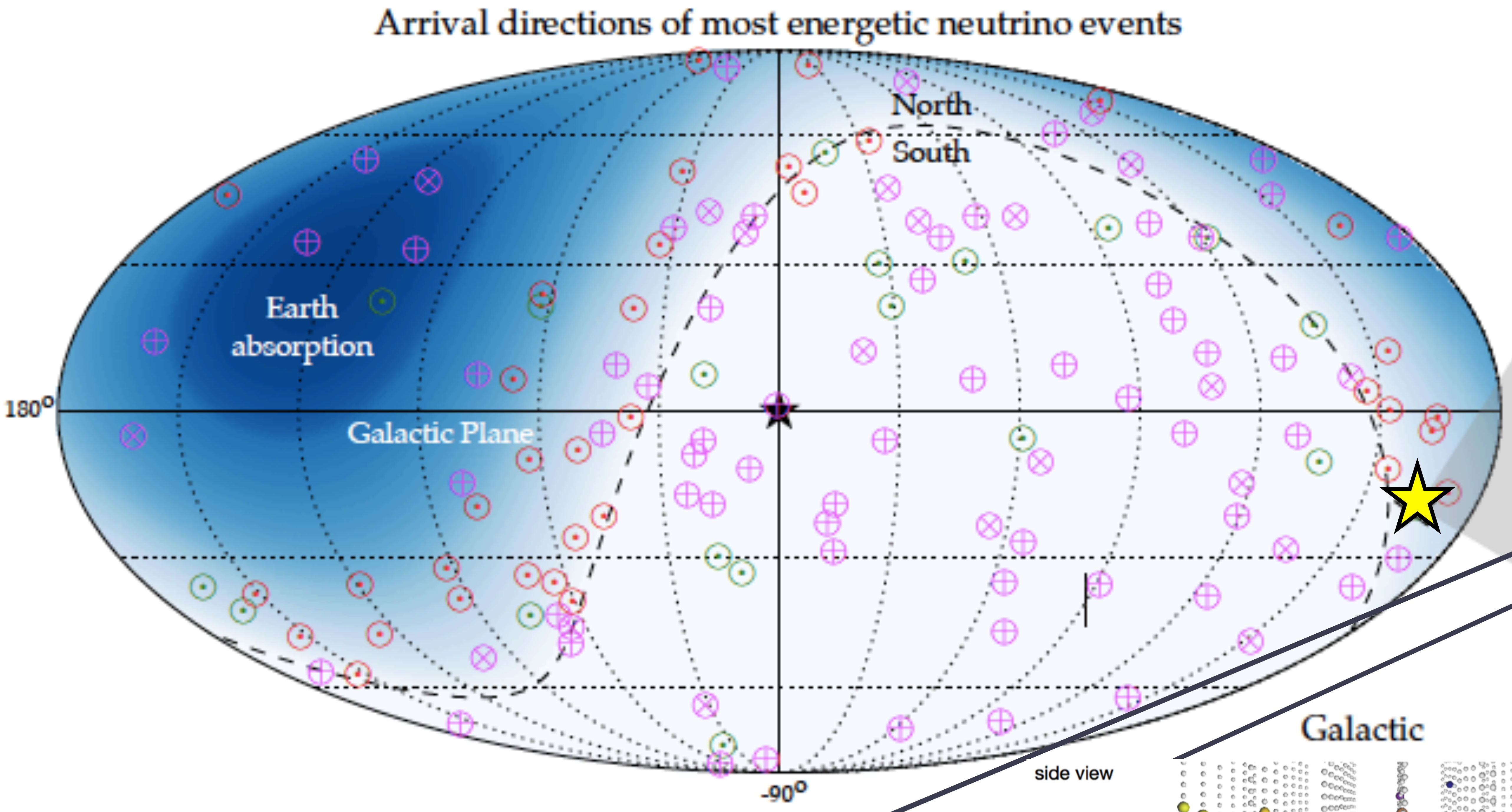
ANTARES, ApJ 911 (2021) 48
IceCube, ApJ 835 (2017) 45

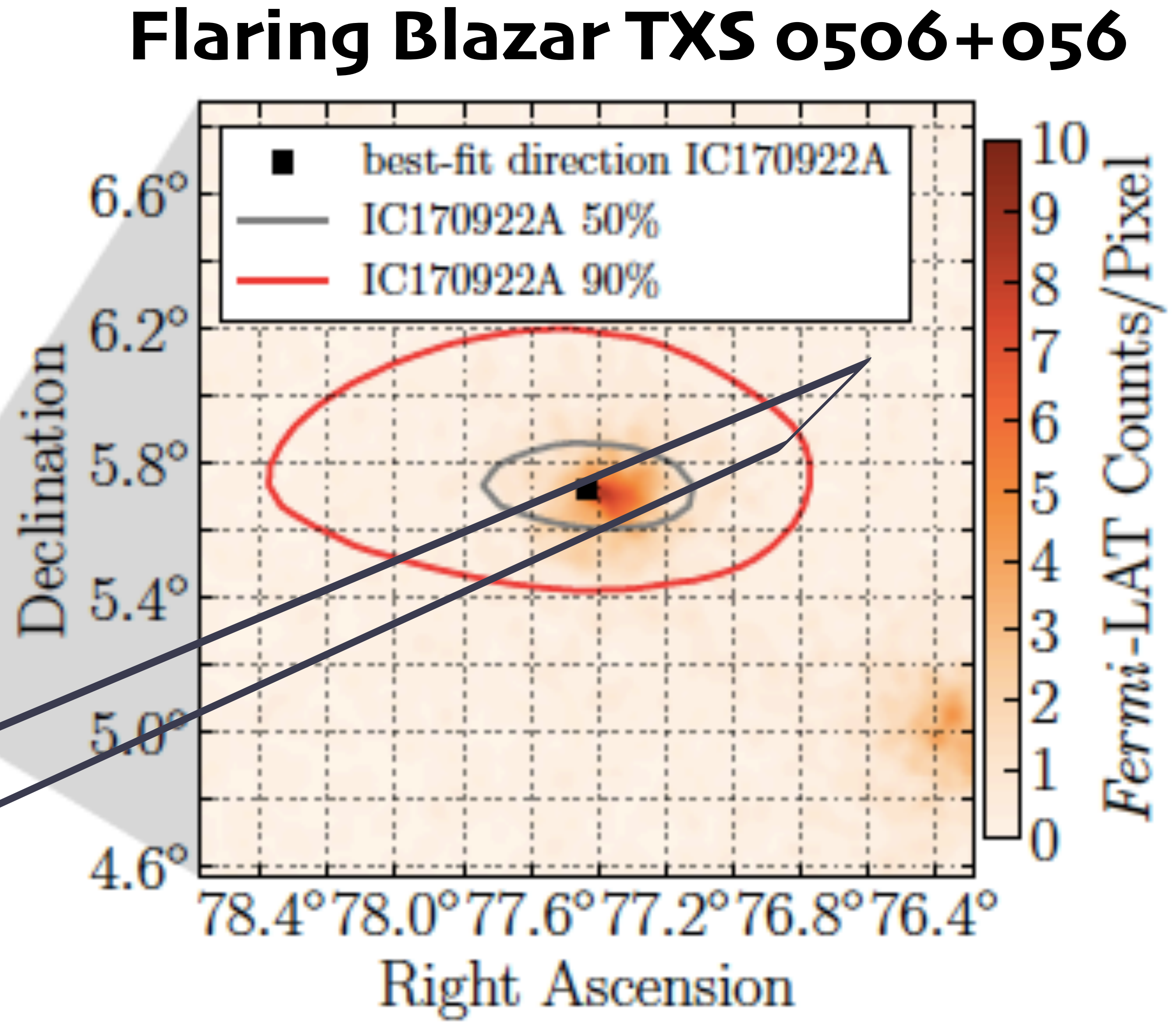
First *transient* source of high-E νs

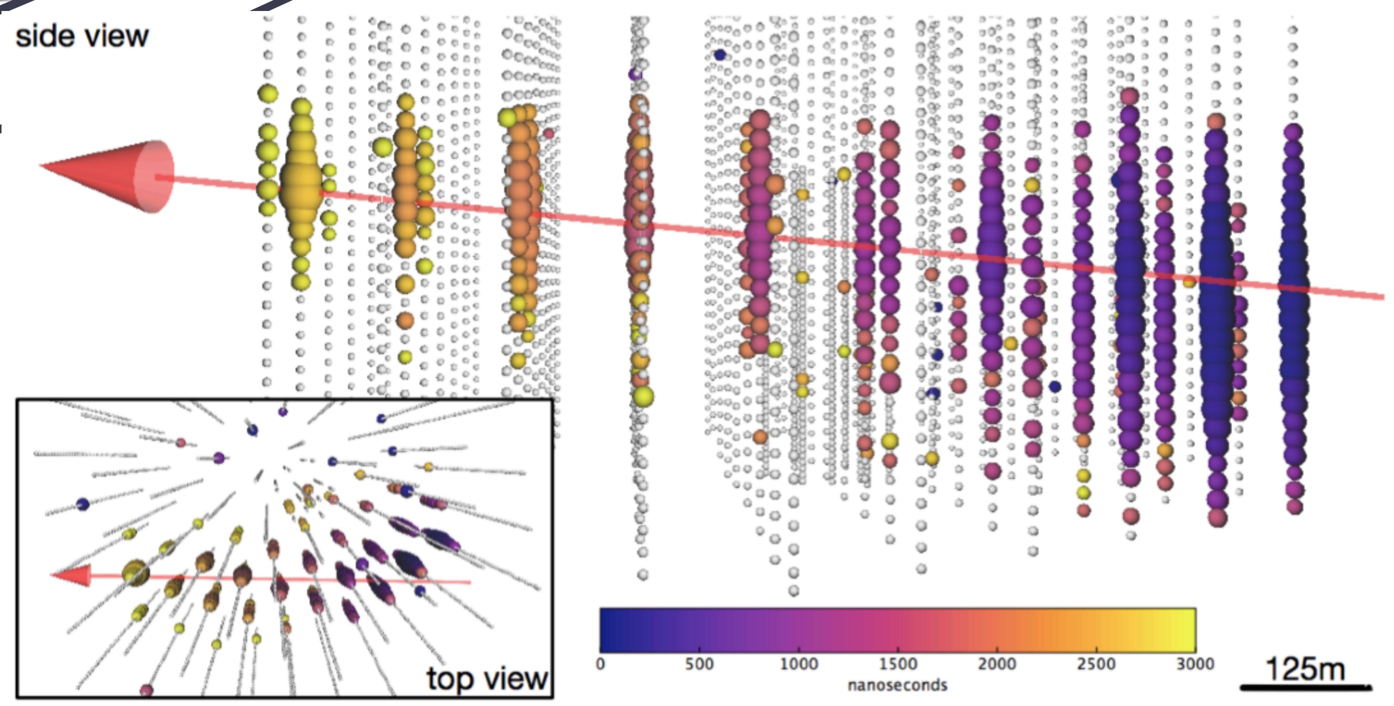
Multimessenger astrophysics neutrino breakthrough!

TXS 0506+056 & IC-170922A

2018: First source of neutrinos identified







★ Most probable energy between 250 and 300 TeV and probability of astrophysical origin 56.6%

Blazar flare observed by Fermi-LAT and MAGIC ($z = 0.3365 \pm 0.0010$)

Significance for correlation ~3σ

IceCube Coll,, Science 361, 147-151 (2018)

First *transient* source of high-E νs

Multimessenger astrophysics neutrino breakthrough!

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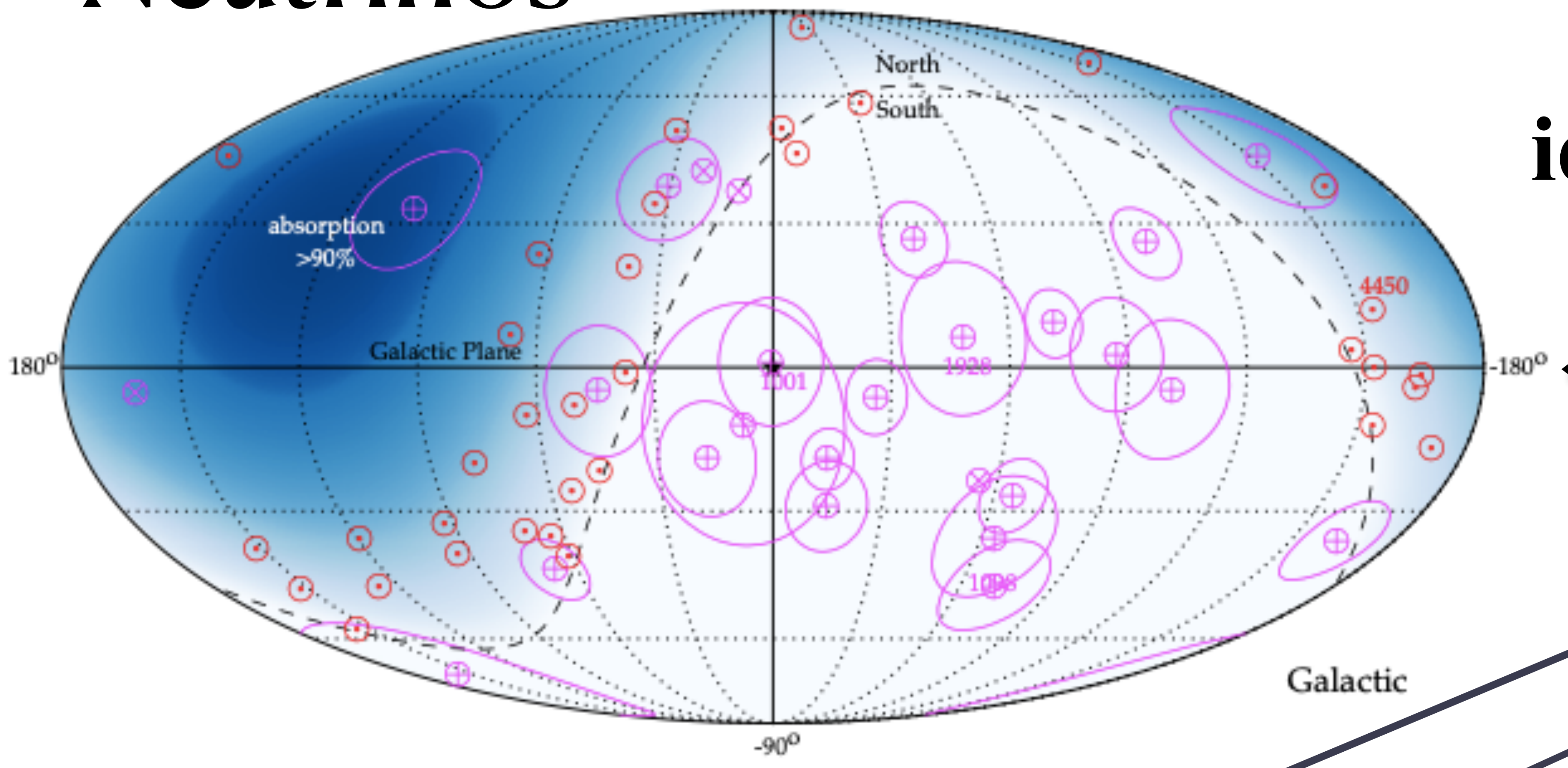
2018: First source of neutrinos identified

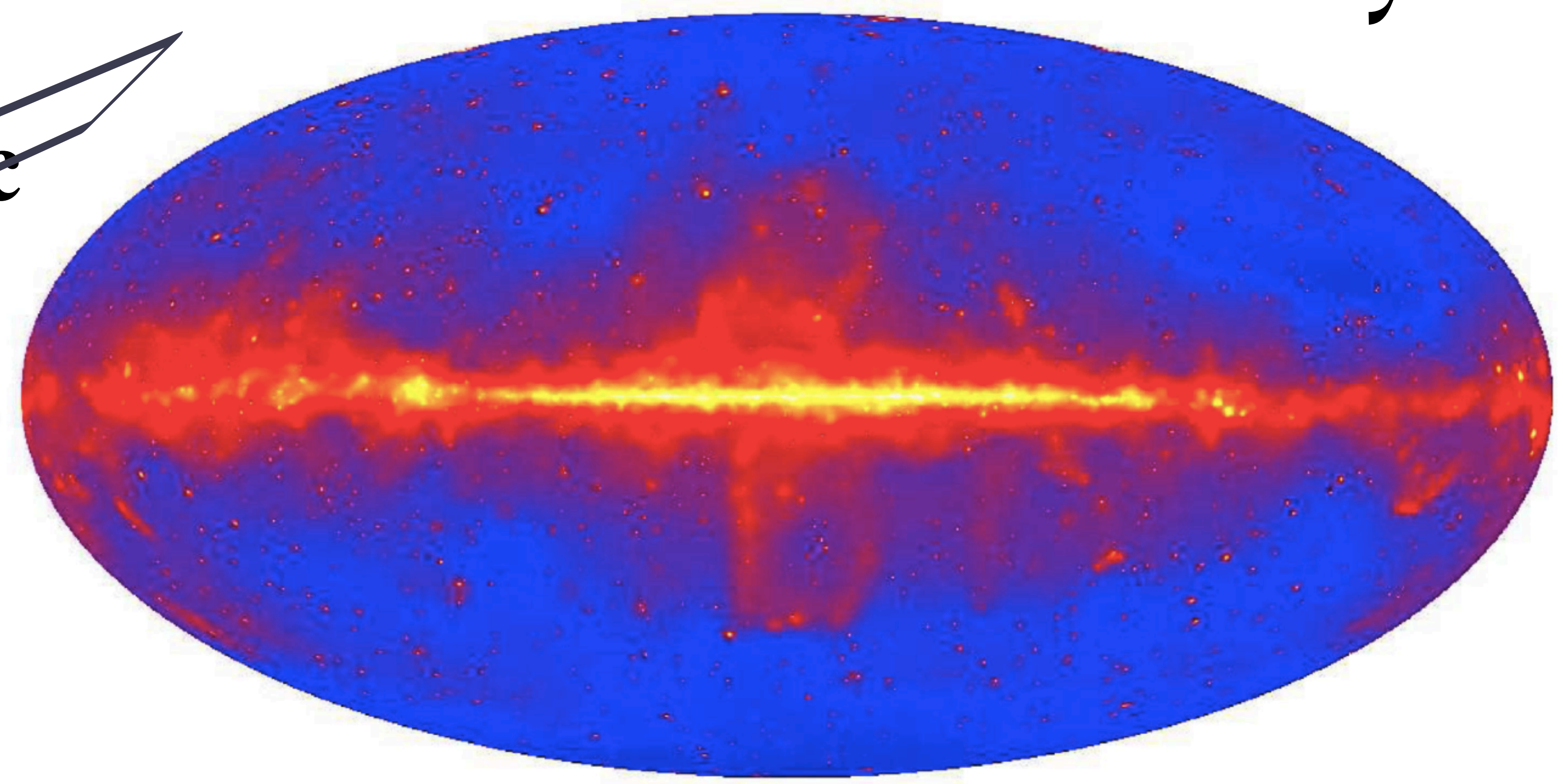
Flaring Blazar TXS 0506+056

Neutrinos



The combined info allowed the identification of a cosmic hadronic accelerator at >PeV energies

Gamma rays



★ Most probable energy between 250 and 300 TeV and probability of astrophysical origin 56.6%

($z = 0.3365 \pm 0.0010$)

Significance for correlation ~3σ

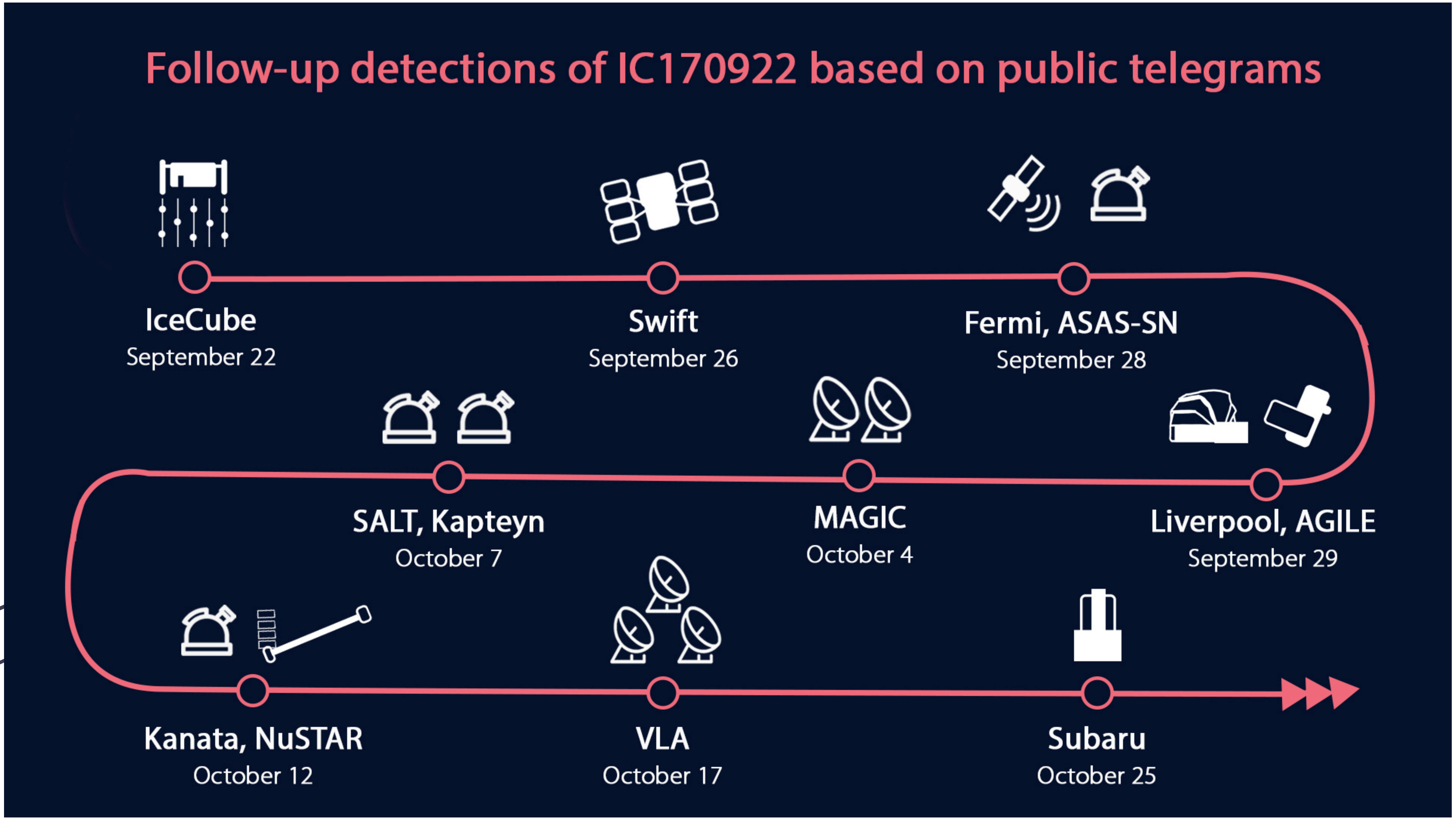
IceCube Coll., *Science* 361, 147-151 (2018)

TXS 0506+056: multi-messenger follow-up

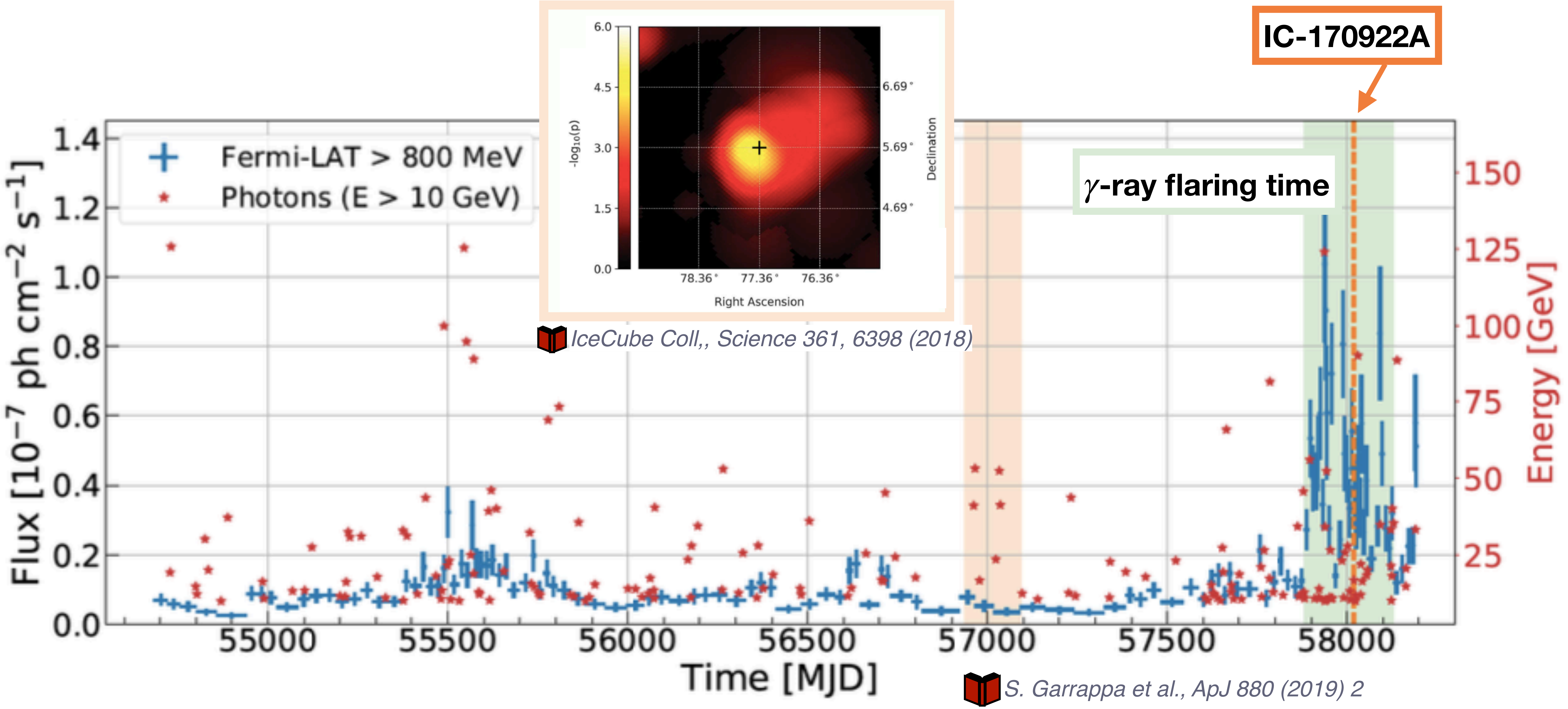
IceCube alert system implemented in **2016**

★ Publicly distributed **43 seconds after trigger**, refined direction 4 hr later

★ Neutrino direction given at 6 arc-minutes from the direction of TXS 0506+056



Neutrino flare in 2014/2015 from the direction of TXS 0506+056



IceCube Coll,, Science 361, 6398 (2018)

S. Garrappa et al., ApJ 880 (2019) 2

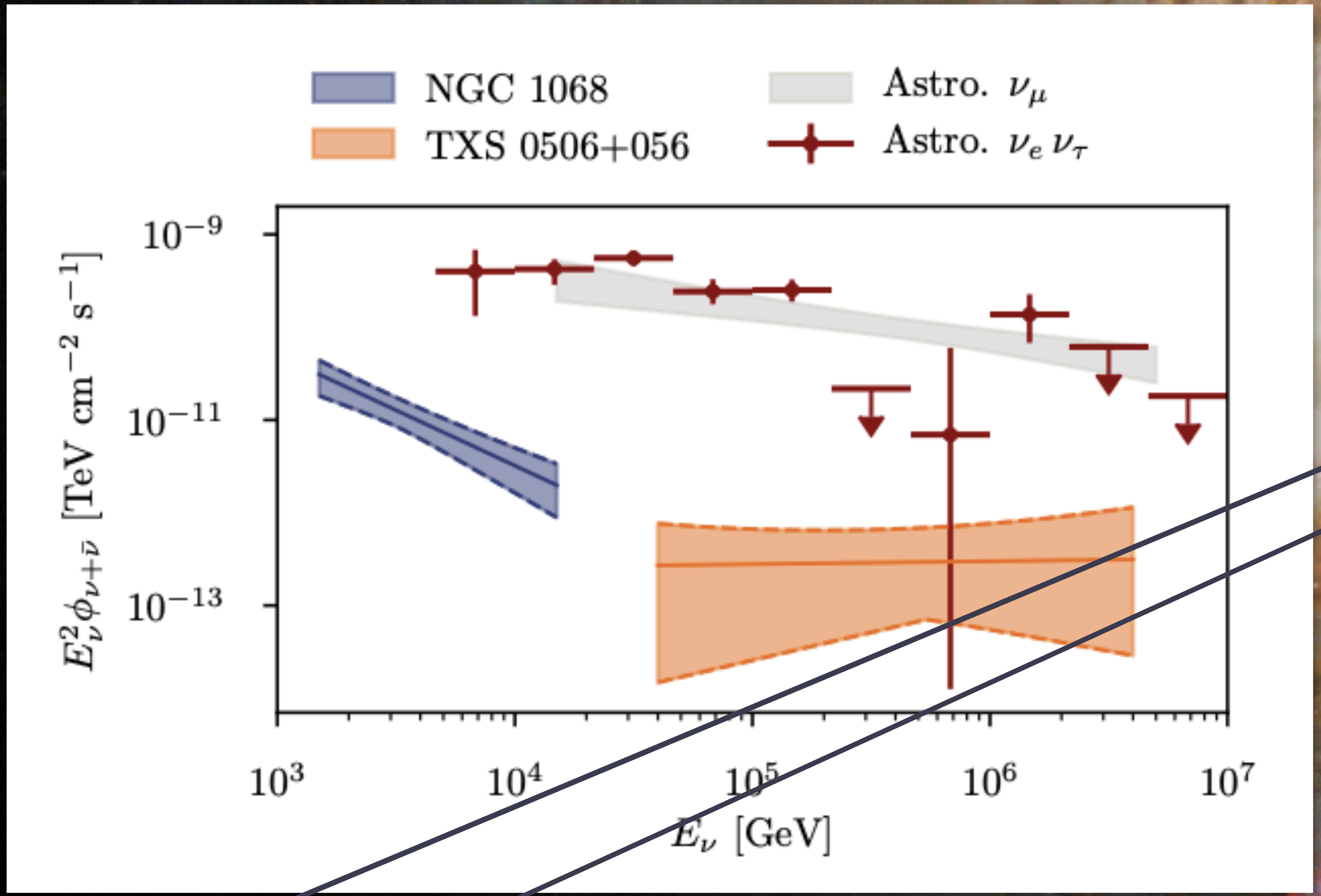
★ Independent 3.5σ evidence for a neutrino flare (13 ± 5 excess events) in 2014/2015

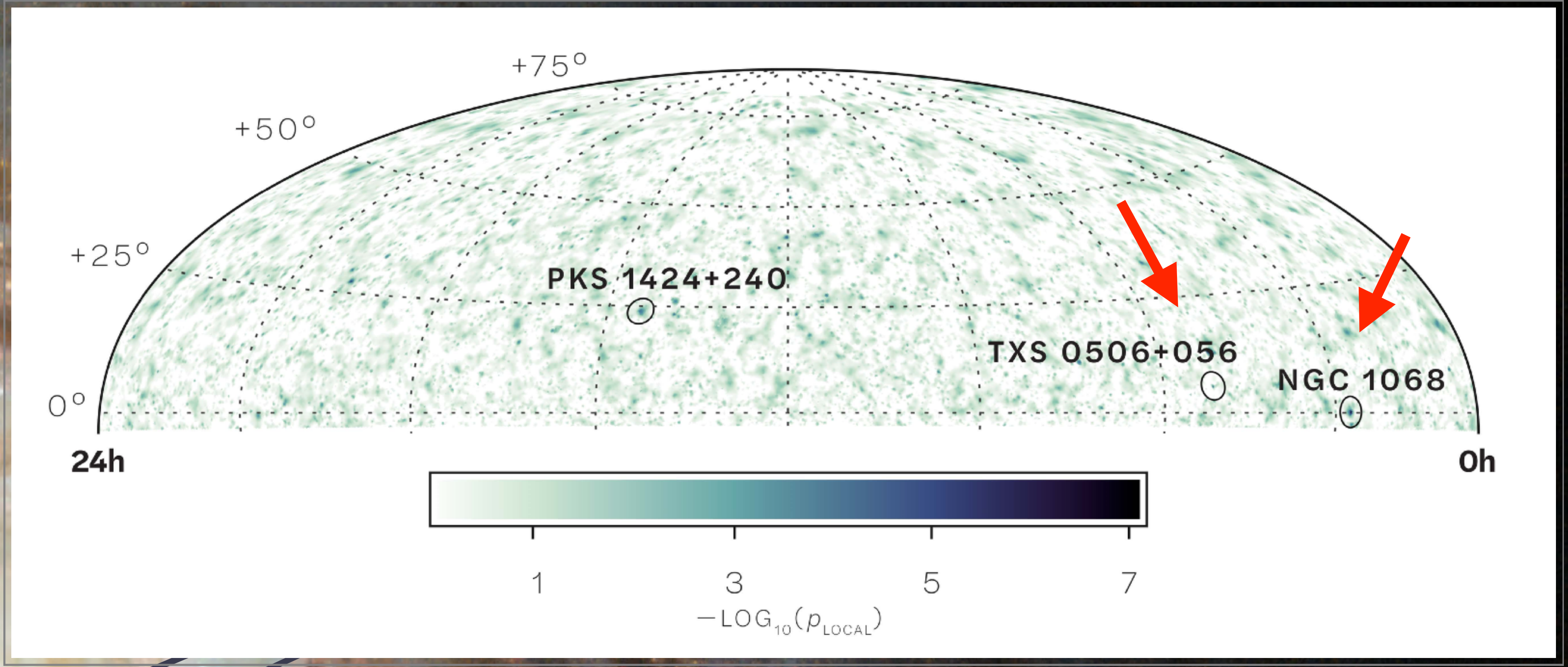
★ Neutrino luminosity over 158 days is about four times that of Fermi-LAT γ rays

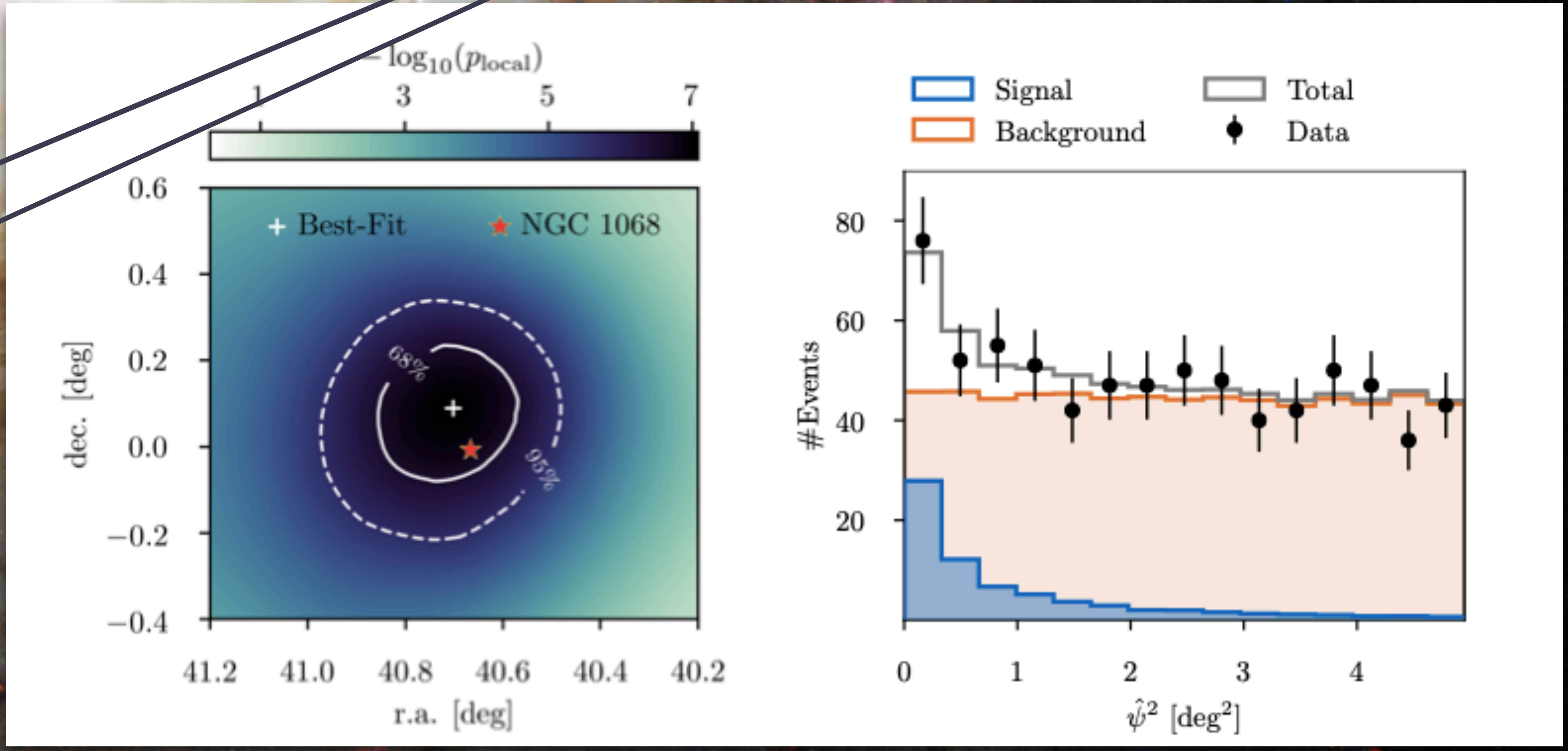
NGC 1068: the first *steady* source of high-E νs

Excess of 79^{+22}_{-20} neutrinos associated with the AGN NGC 1068

Significance of 4.2σ







IceCube Collab., *Science* 378, 538 (2022)

For QG point of view, refer to the following talks

GRBs

- Plenary talk by T. Piran, *'Gamma-ray bursts as tool to explore the Lorentz invariance violation'*
(Tuesday 11, morning session)

- D. Staicova, *'Effect of the cosmological model on LIV constraints from GRB Time-Delay datasets'*
(Wednesday 12, afternoon session)

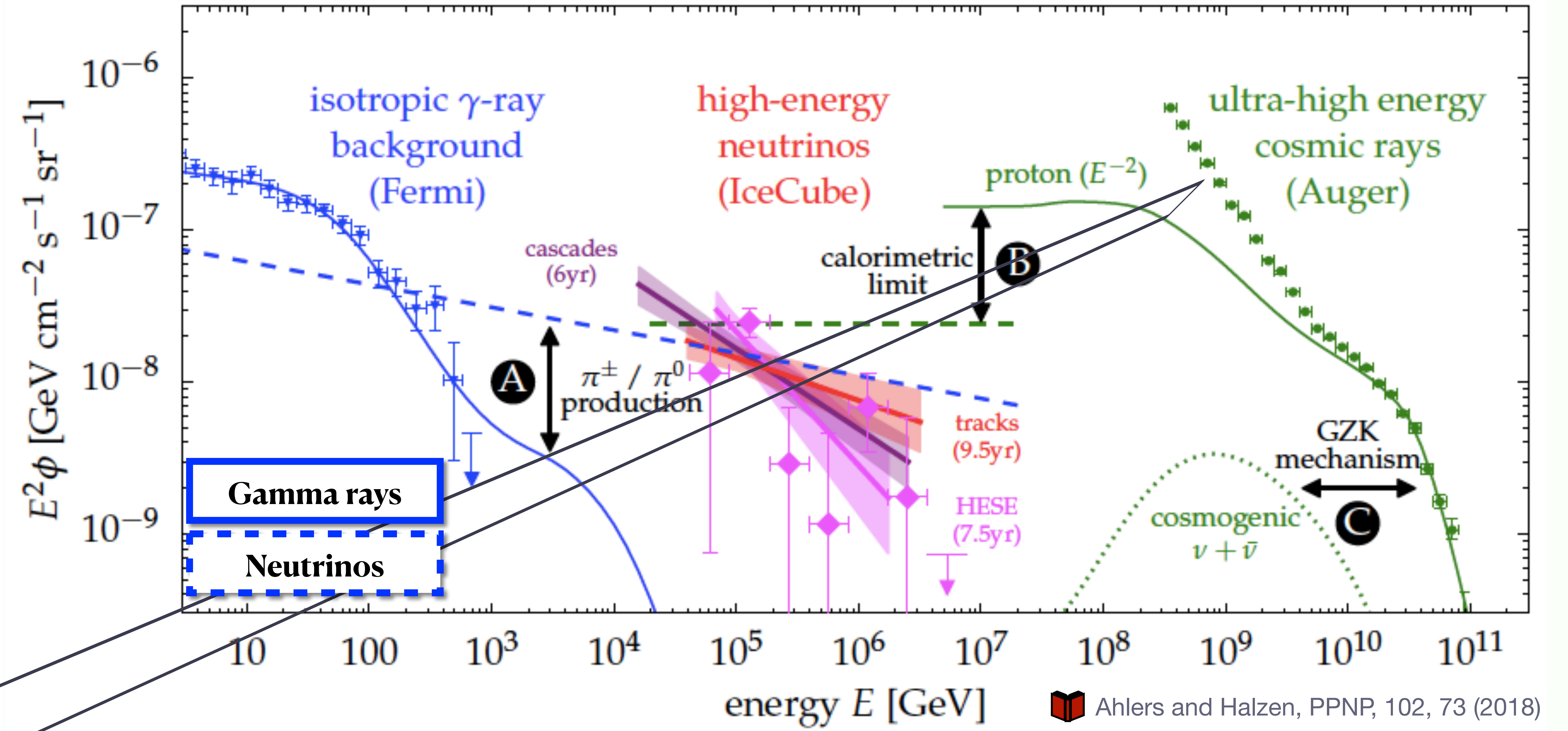
- G. Rosati, *'Testing Planck-scale in vacuo dispersion with IceCube astrophysical neutrinos'*
(Thursday 13, morning session)

AGNs

- J. Bulmont, *'Source-intrinsic energy dependent time-delays in AGNs and search for Lorentz invariance violation'*
(Tuesday 11, morning session, after the present contribution)

Hidden sources to gamma rays?

The strong constraints from the Fermi-LAT data on the isotropic gamma-ray background suggest that the neutrinos observed by IceCube might possibly come from **sources that are hidden to gamma-ray observations**

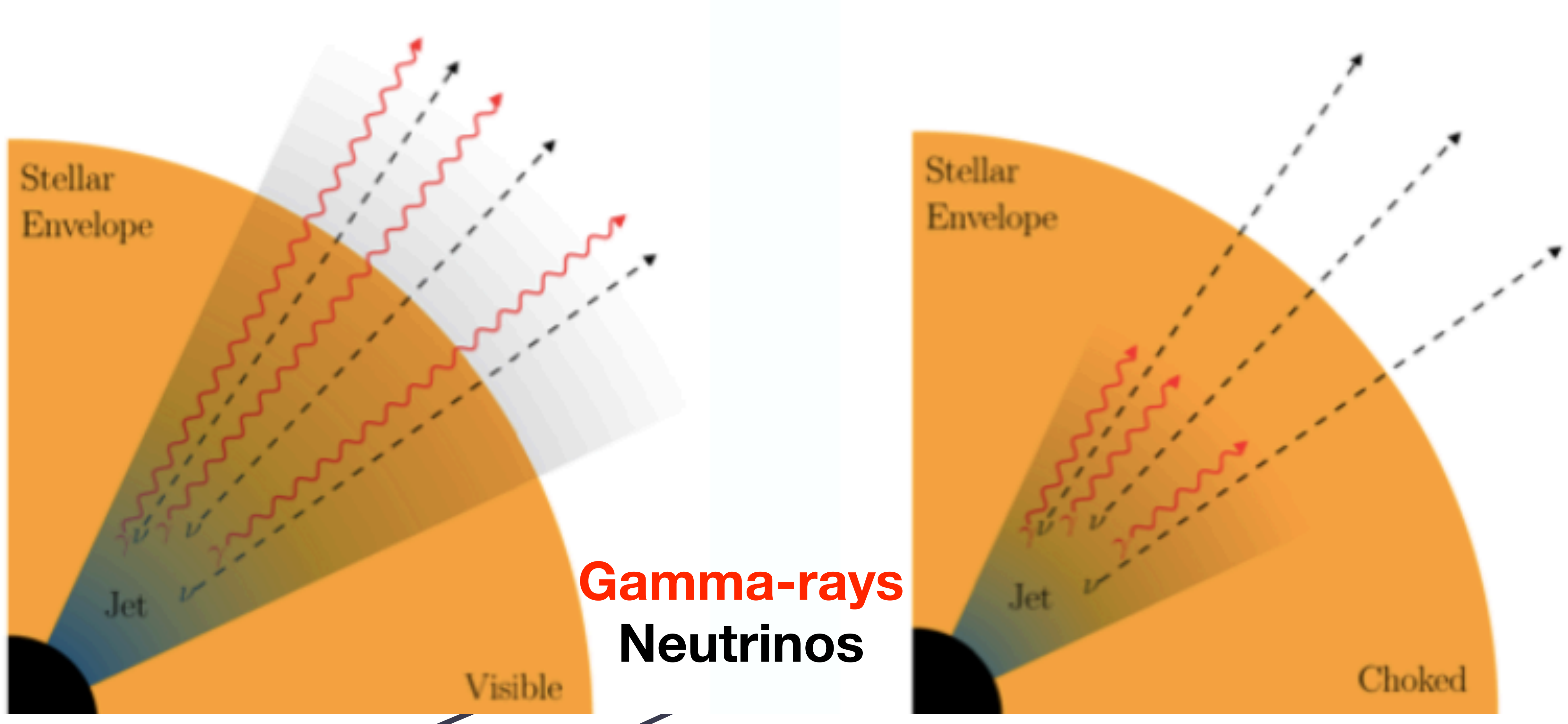


Ahlers and Halzen, PPNP, 102, 73 (2018)

High energy neutrinos from choked jets

The jet successfully accelerates particles but does not have enough energy to escape the stellar envelope; the jet will be choked:
high energy neutrinos will escape, but no electromagnetic radiation

Meszaros & Waxman 2001; Razzaque et al. 2004; Murase & Ioka 2013; Xiao & Dai 2014; Kimura et al. 2015, Senno et al. 2016; Nakar & Piran 2017; Fasano et al. 2021



***pγ* interactions**

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The identification of another observable associated signature is crucial!

See e.g, Nakar & Piran 2017

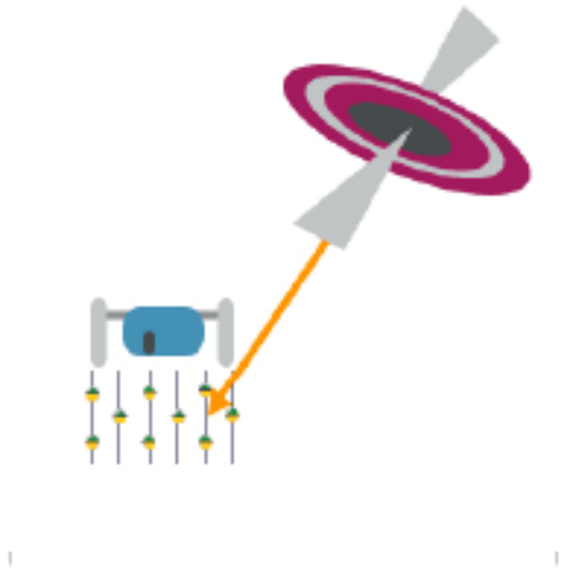
Neutrino astronomy status in a nutshell

... by the IceCube Collaboration

2013 — Astrophysical Neutrinos Discovered

Diffuse flux of astrophysical neutrinos (TeV-PeV)

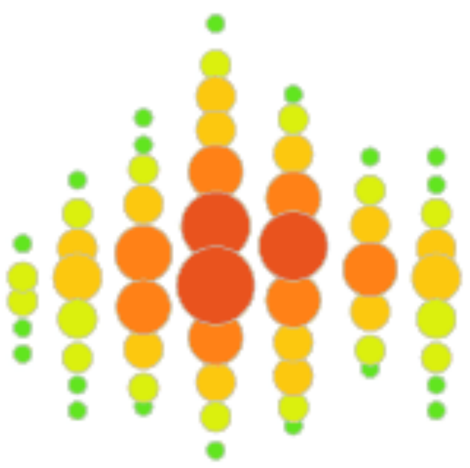
Science 342 (2013), 6161



2018 — First Source TXS 0506+056 Identified

- ★ Neutrino with energy ~260 TeV in spatial and temporal coincidence with a blazar (transient source) in a flaring state (significance $\sim 3\sigma$)
- ★ Neutrino flare from the same direction of the sky (no flare in gamma rays)

Science 361 (2018), 147

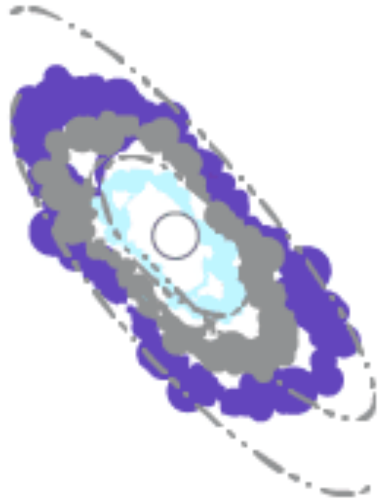


2021 — Glashow Resonance Neutrino Identified

Resonant interaction of electron anti-neutrinos with electrons at ~6.3 PeV

$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow X$$

Nature 591 (2021), 220

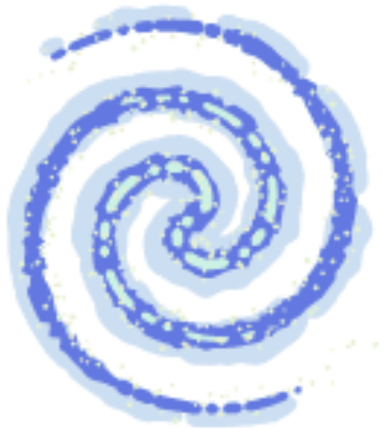


2022 — Second Source NGC 1068 Identified

Active galaxy but *steady* source

- ★ Excess of 79^{+22}_{-20} neutrinos associated with the AGN NGC 1068
- ★ Significance of 4.2σ

Science 378 (2022), 538



2023 — Third Source Milky Way Identified

Diffuse ν-flux from Milky Way

- ★ 10 years of data
- ★ Significance of 4.5σ

Science 380 (2023), 1338

Credit: Sandbox Studio, Chicago

What next?
Stay tuned ...

Summary (1)

- **Neutrinos** are **ideal** cosmic **messengers** within the context of the growing field of the multi-messenger astronomy;

- Huge efforts by several collaborations to build high-energy Cherenkov neutrino telescopes have been made over the years: the relatively small telescope **ANTARES** has taken data for almost 14 years (**from 2008 to the beginning of 2022**), the cubic-kilometer telescope **IceCube** at the South Pole is **taking data since more than 10 years**, **KM3NeT** and **Baikal-GVD** are both **under construction** in the Mediterranean Sea and Lake Baikal, respectively, and taking data with partial detector configurations (once completed, they will reach > cubic-kilometer volumes);

- **2013: birth of high-energy neutrino astronomy** with the **discovery of a diffuse flux of TeV-PeV neutrinos** (but the origin of such flux has not yet been identified);

- **2018: first source of neutrinos identified** (**blazar**; i.e. a flaring AGN) ⇨ success of multi-messenger approach (combination between gamma and neutrino information);

Summary (2)

- Among several potential astrophysical neutrino emitters, **GRBs** and **AGNs** are **not dominant sources of the observed diffuse flux of neutrinos** (contribution <10% and 30%, respectively), but are still particularly interesting for multi-messenger studies and very promising sources of high-energy neutrinos
  - ✳ **GRBs**:
    - The mechanism powering high-luminous GRBs is still subject to debate: several GRB hadronic models are able to reproduce the γ-ray spectra of GRBs and only some of them have been tested;
    - The statistic need to be increased (current constraints still not enough to exclude the neutrino production from GRBs) and, even in case of no detection, new limits help in testing different hadronic models. These models may be constrained with even deeper upper limits;
    - Searches for neutrino correlation not only related to the prompt emission (precursor, afterglow);
  - ✳ **Blazars:**
    - Discovered association between the *transient* source TXS 0506+056 (blazar) and the *steady* source NGC 1068 (not flaring AGN) and neutrinos by the IceCube Collaboration;

- Choked bursts would contribute to the astrophysical diffuse neutrino flux.


Thank you for the attention!