Ultra-high-energy neutrinos

Damiano F. G. Fiorillo

Niels Bohr Institute, Copenhagen

ν Here, There & Everywhere

PhD Summer School on Neutrinos

July 17-21, 2023

Niels Bohr Institute, Copenhagen

KØBENHAVNS UNIVERSITET
UNIVERSITY OF COPENHAGEN

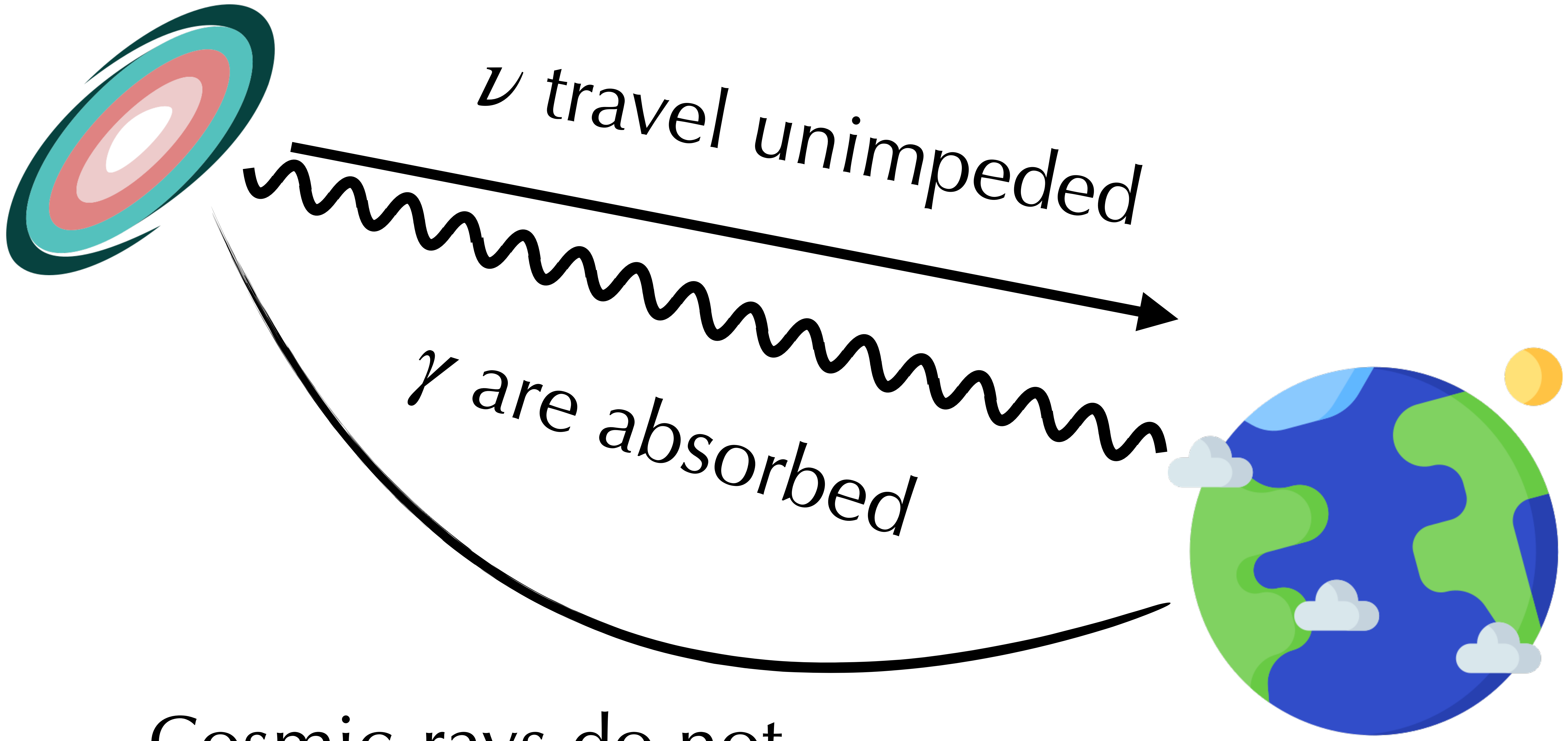
VILLUM FONDEN

Outline

- What are ultra-high-energy (UHE) neutrinos?
- How do we detect them?
- Why are they relevant?
- What do we learn from them?
    - Energy spectrum
    - Arrival direction
    - (Flavor composition)

What are UHE neutrinos?

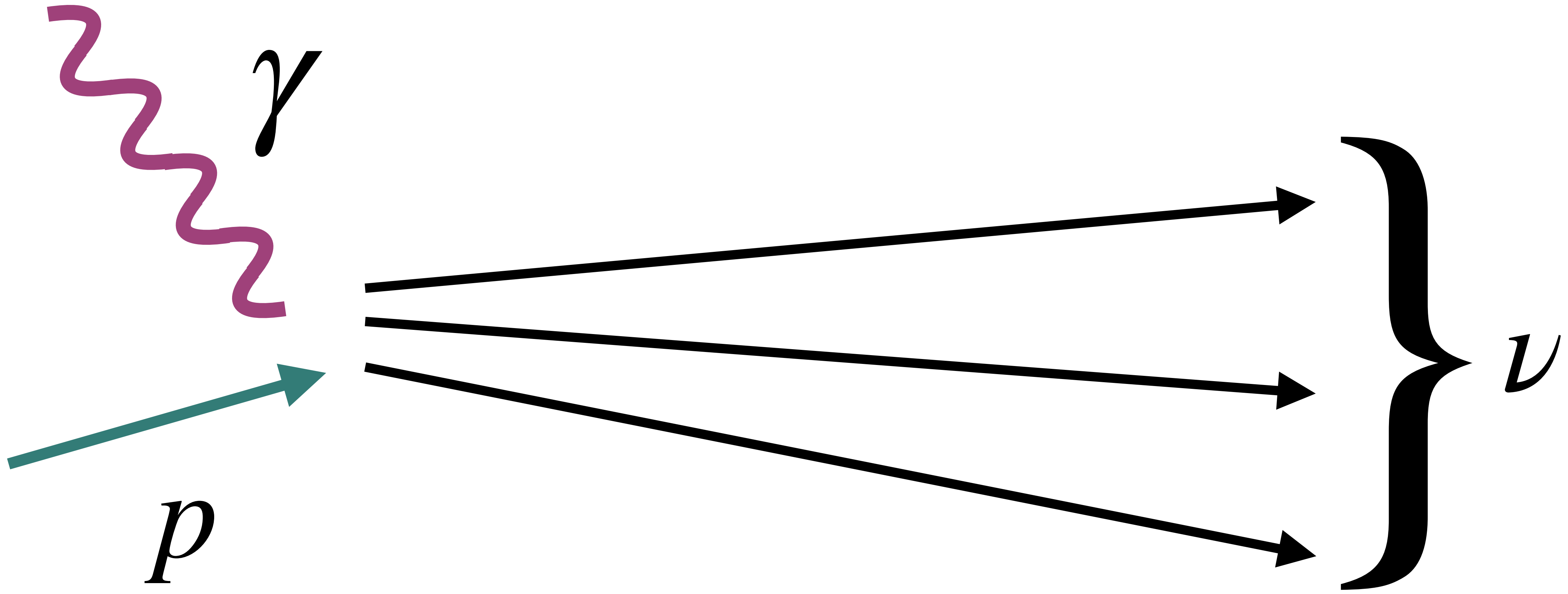
Multimessenger astrophysics

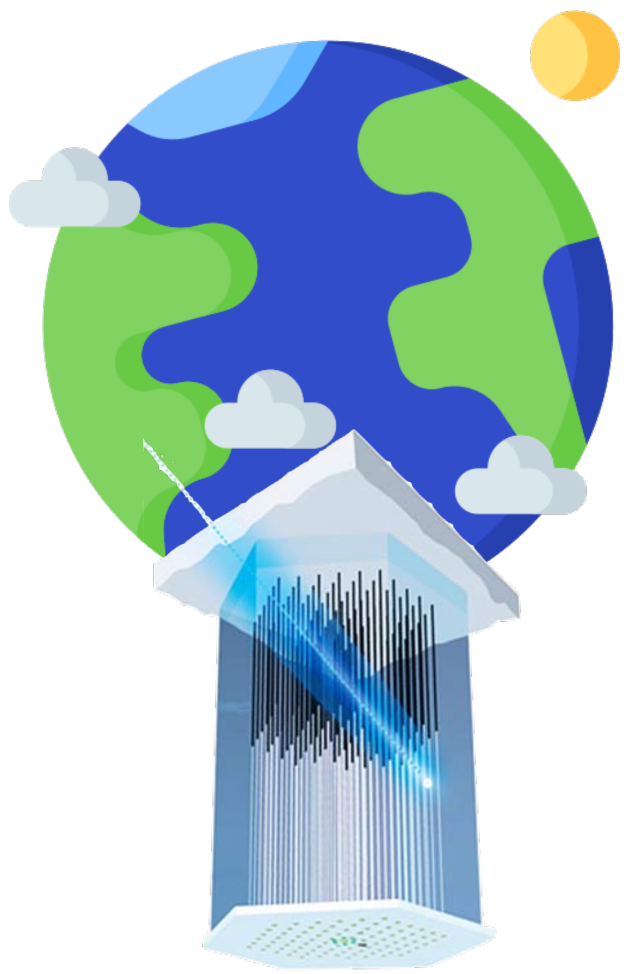


Cosmic-rays do not point back to sources

- Astrophysical neutrinos can locate cosmic-ray sources!

High-energy neutrino detection

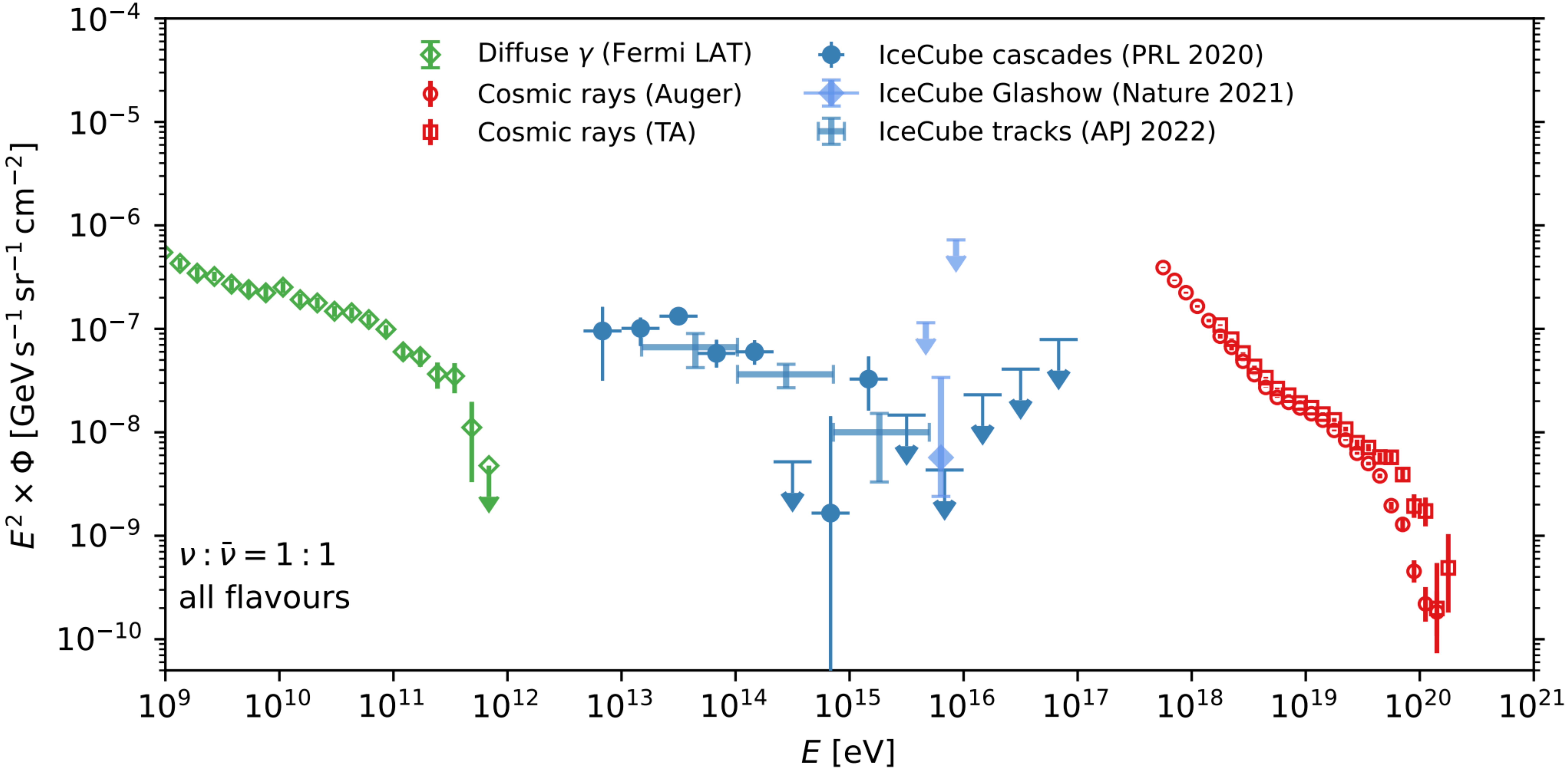




✦ IceCube detects neutrinos with TeV-PeV energies

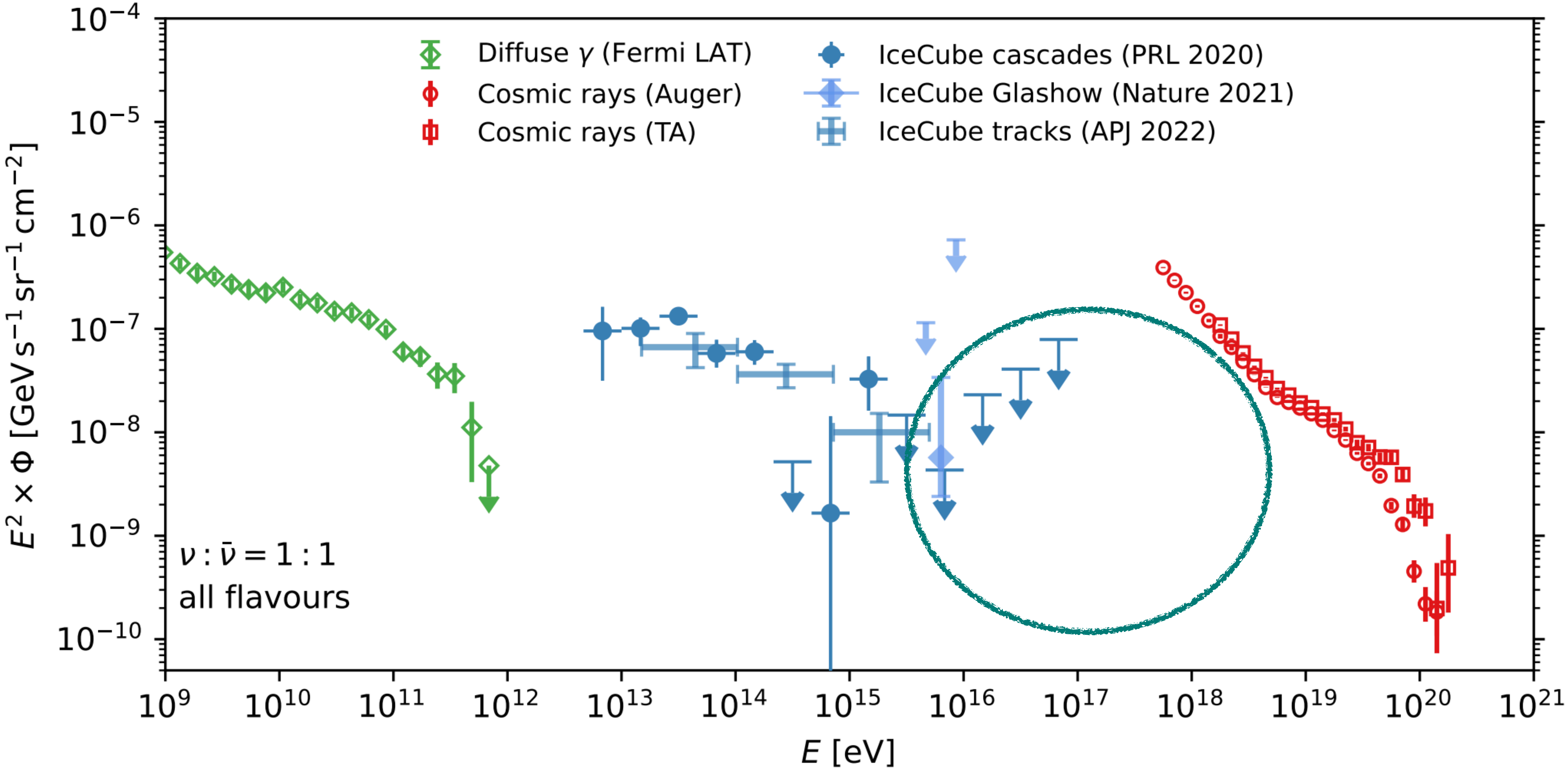
Requires km^3-sized detector!

UHE neutrino detection



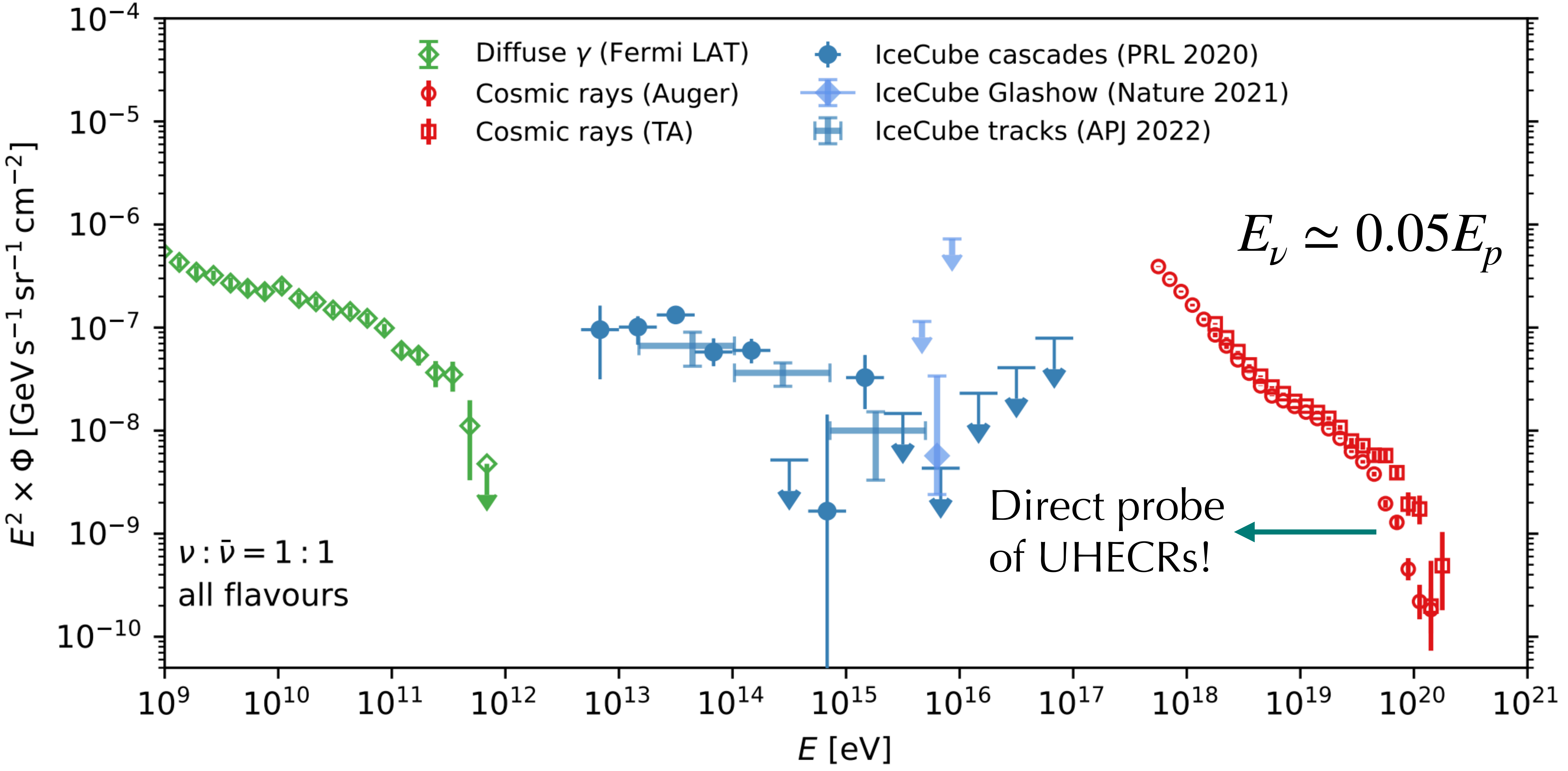
Snowmass, 2203.08096

UHE neutrino detection



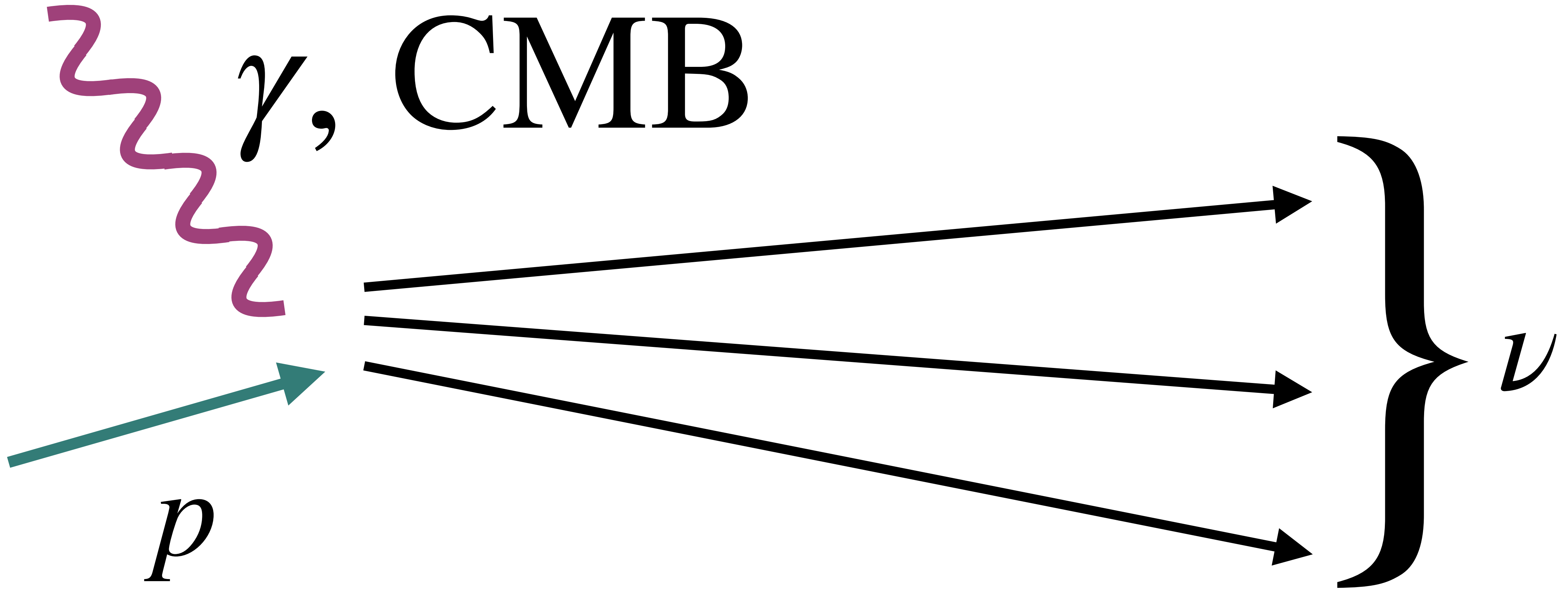
Snowmass, 2203.08096

UHE neutrino detection



Snowmass, 2203.08096

Cosmogenic neutrinos



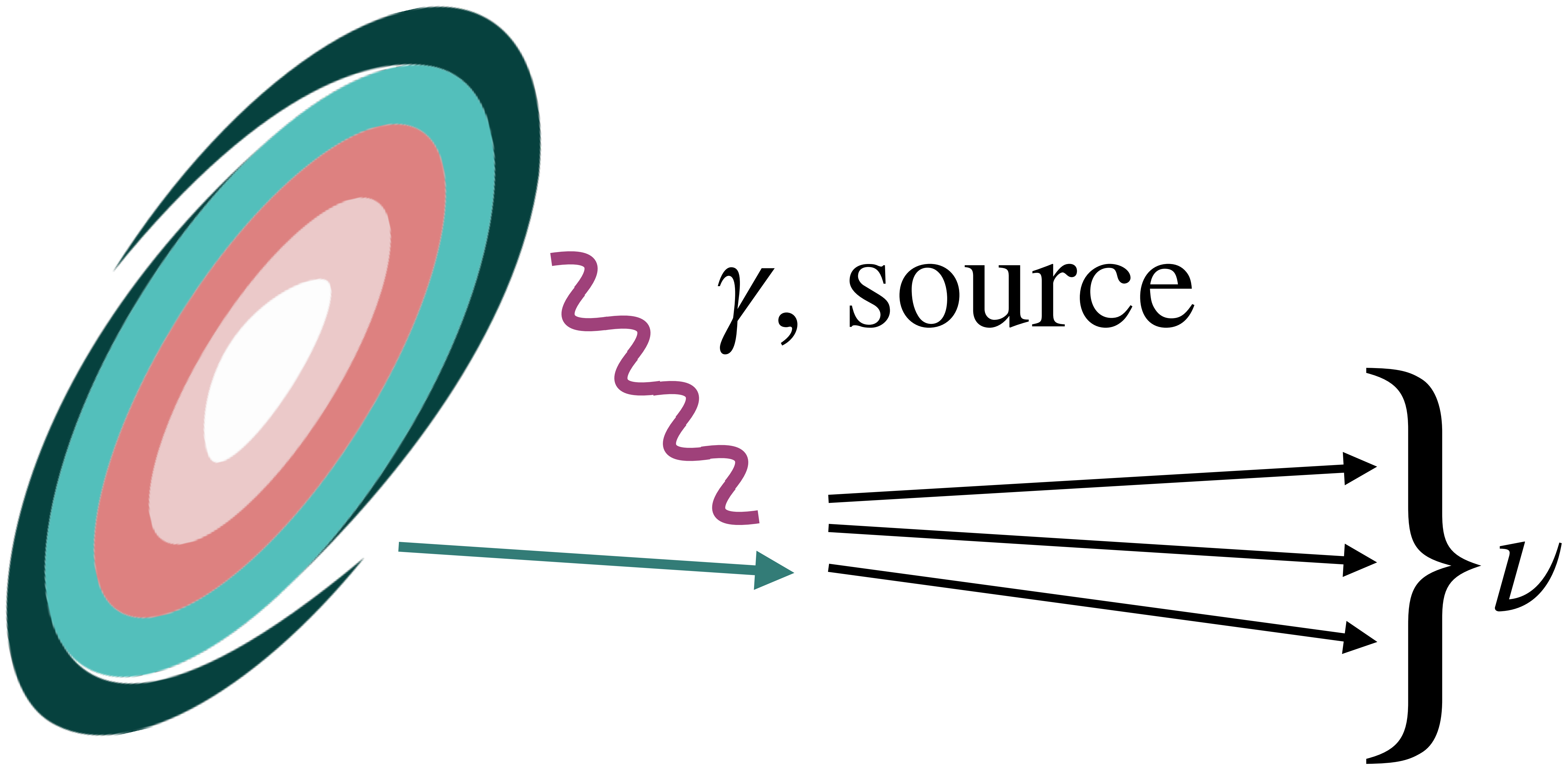
Greisen-Zatsepin-Kuzmin limit at 50 EeV

$$E_p \epsilon_\gamma \simeq m_p m_\pi$$

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

- Chemical composition
- High redshift

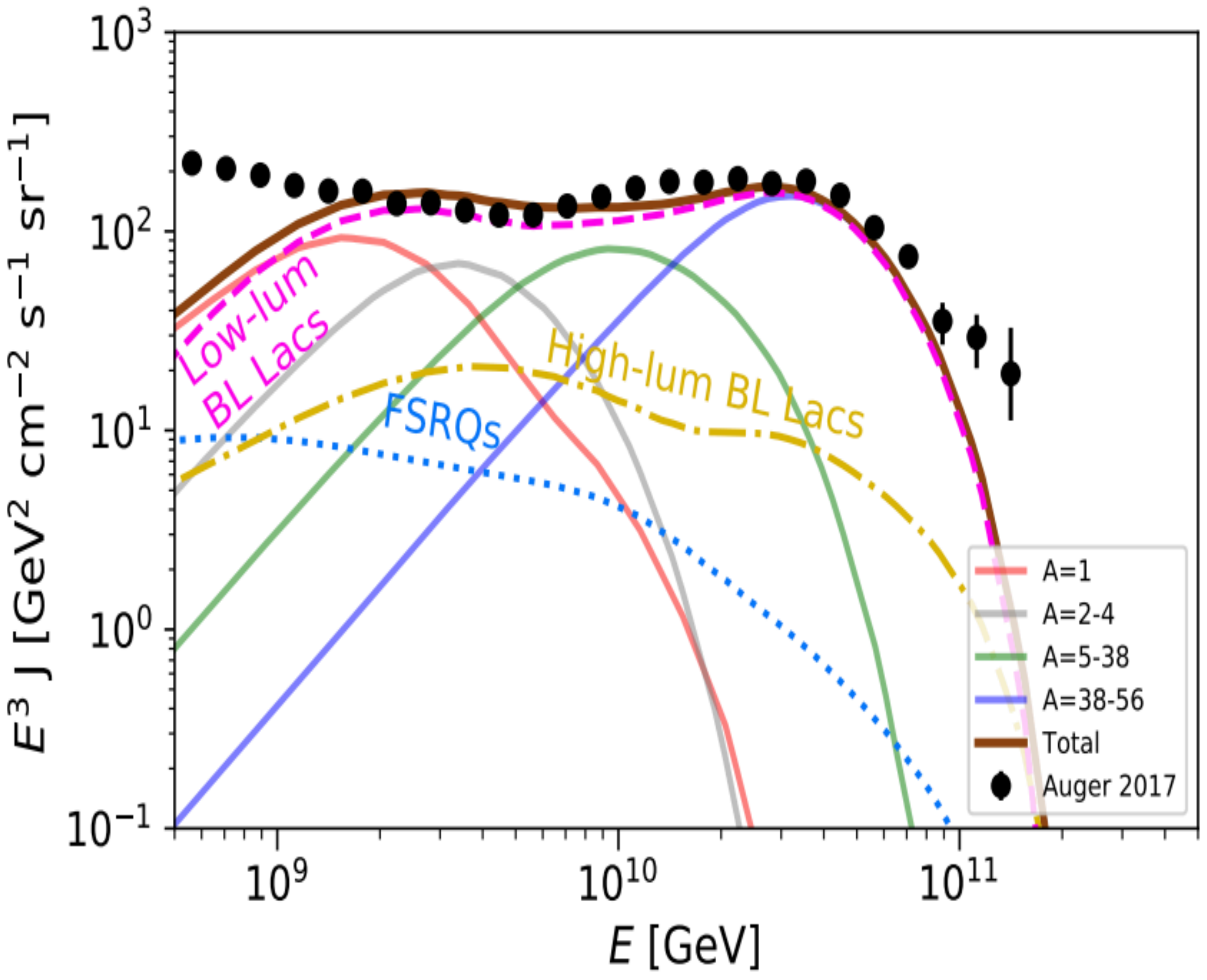
Astrophysical UHE neutrinos

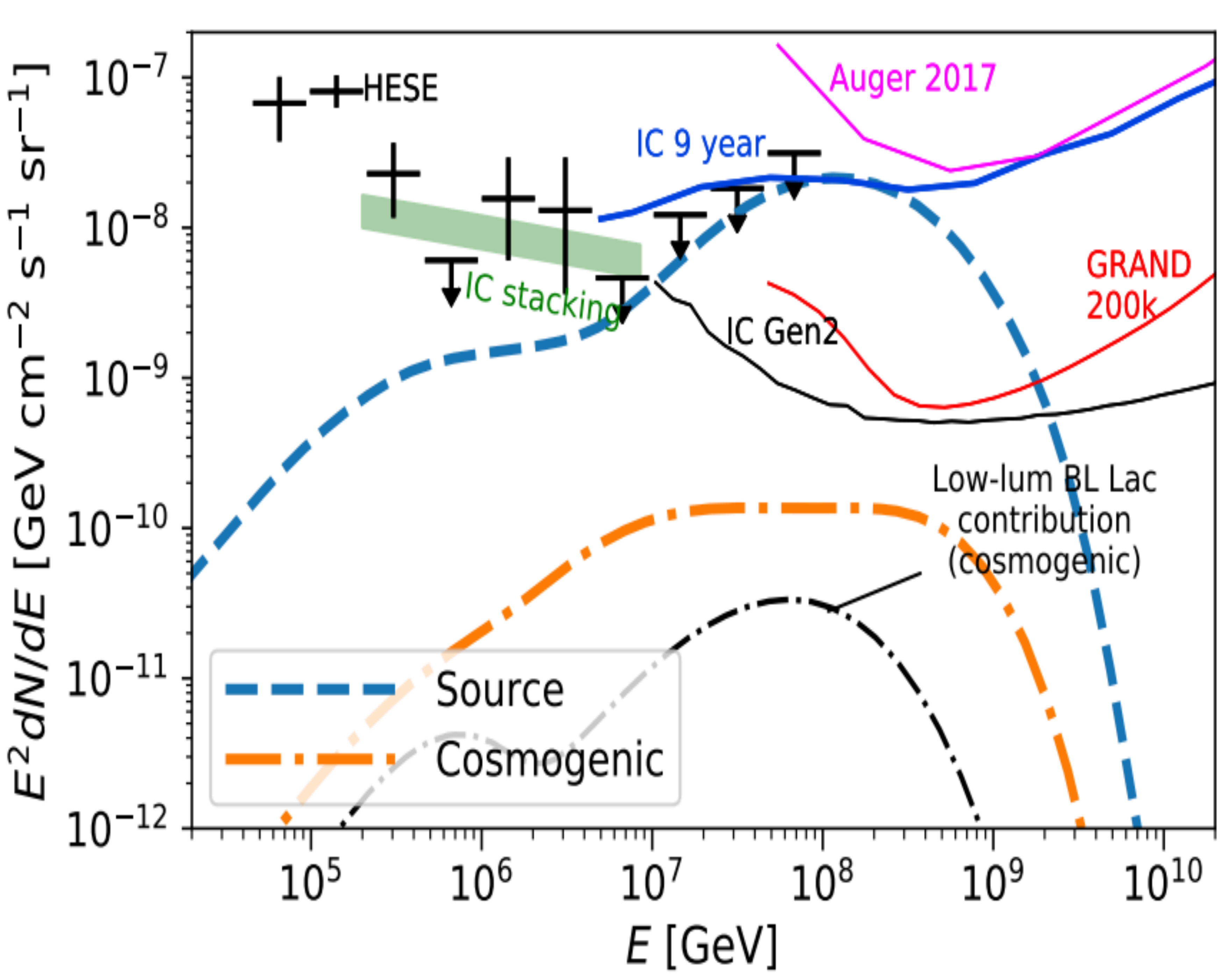


$$E_p \epsilon_\gamma \simeq m_p m_\pi$$

- ✦Requires dense target in source (model dependent)
- ✦UHE neutrino sources need not be sources of observable UHECRs

Astrophysical UHE neutrinos



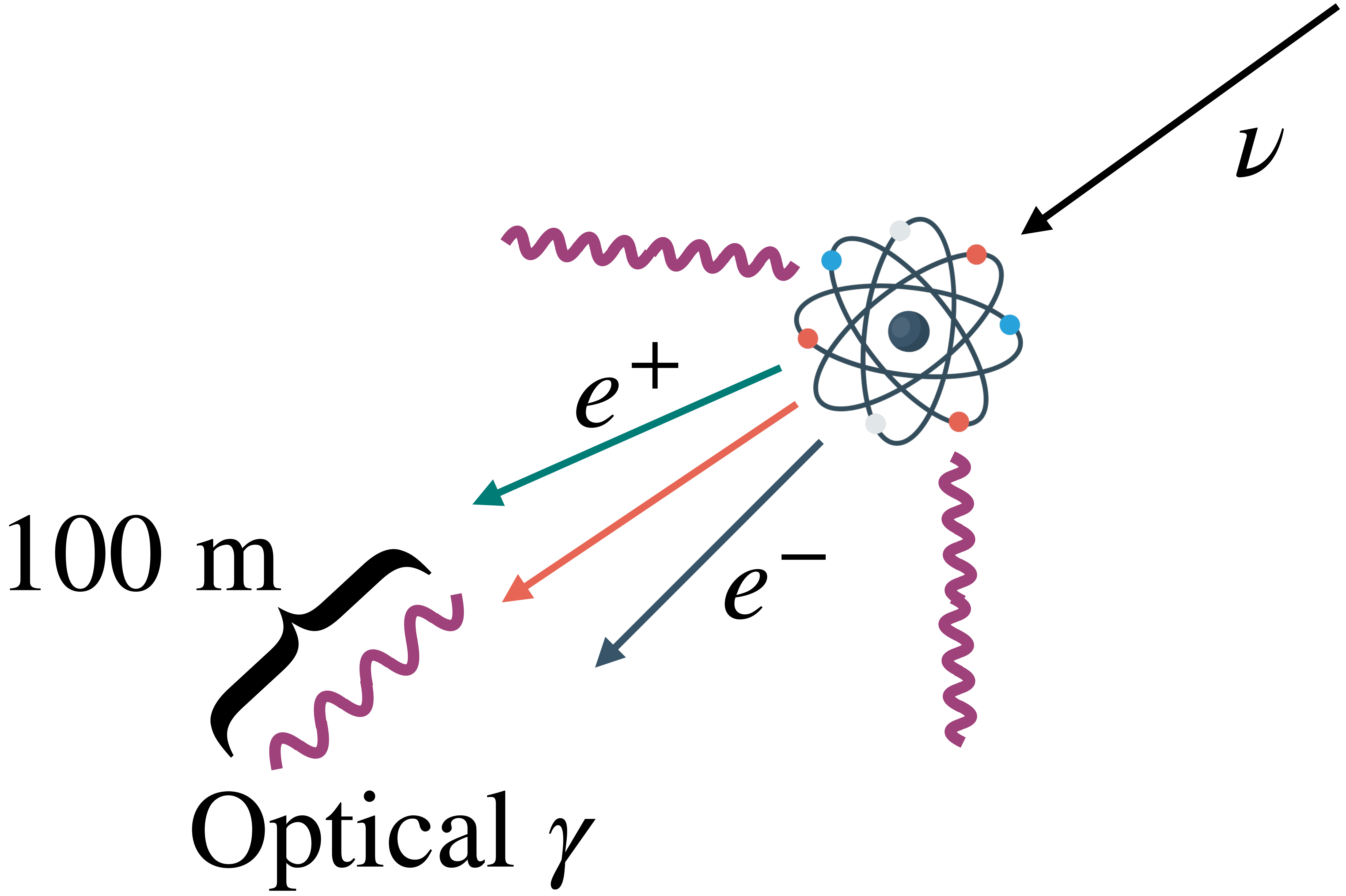


- ✦FSRQs bright, efficient UHE neutrino emitters
- ✦Low-luminosity BL Lac, efficient UHECRs emitters

Rodrigues et al., 2003.08392

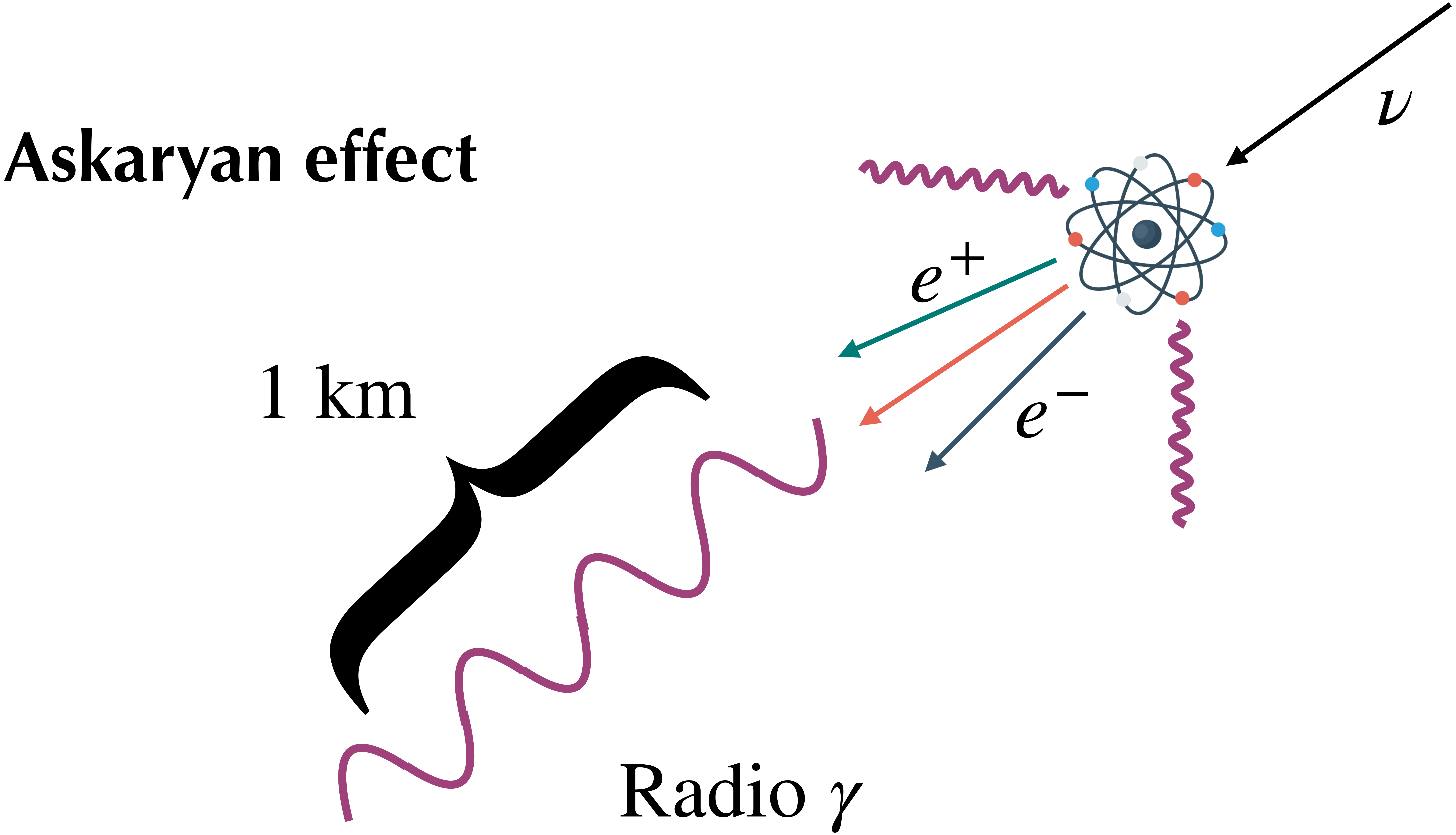
How do we detect them?

In-ice radio detection



Requires densely instrumented, huge detectors

In-ice radio detection

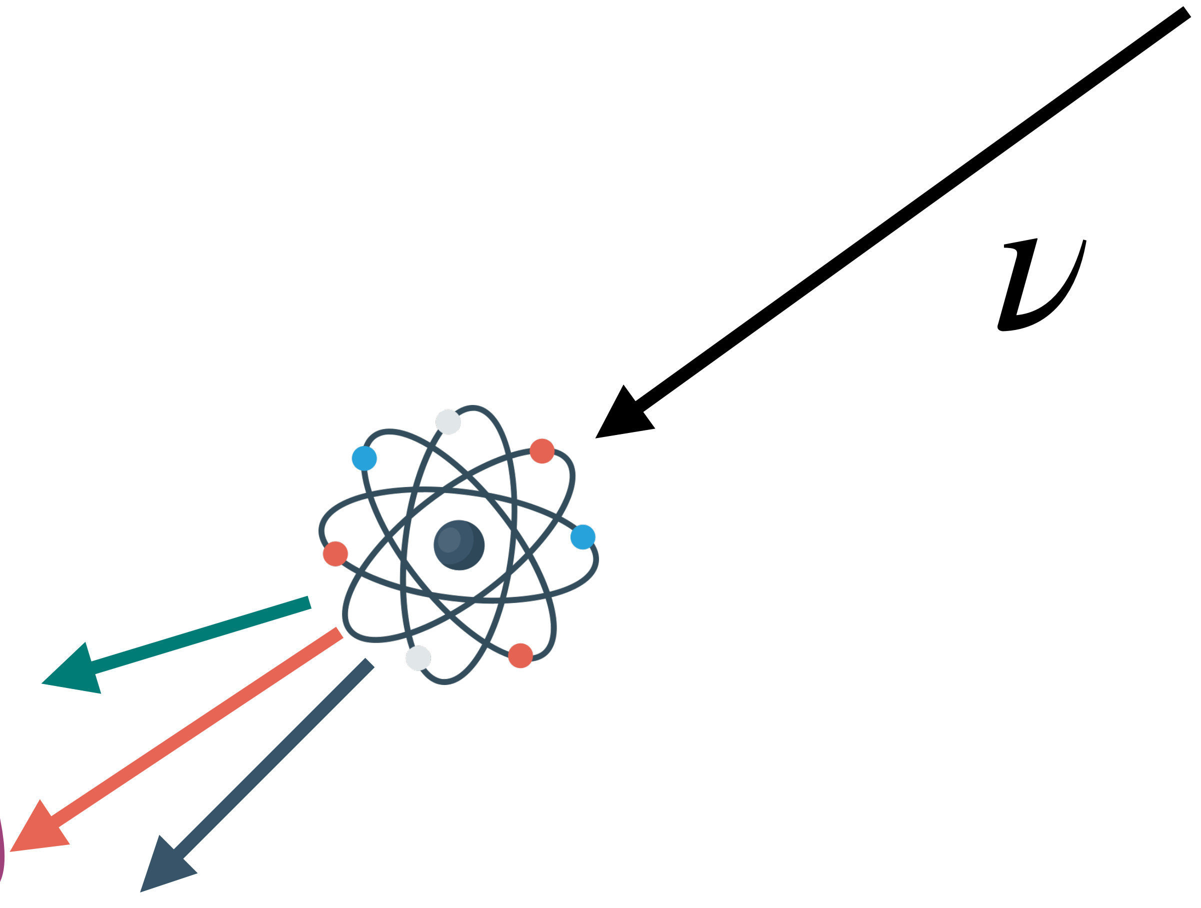


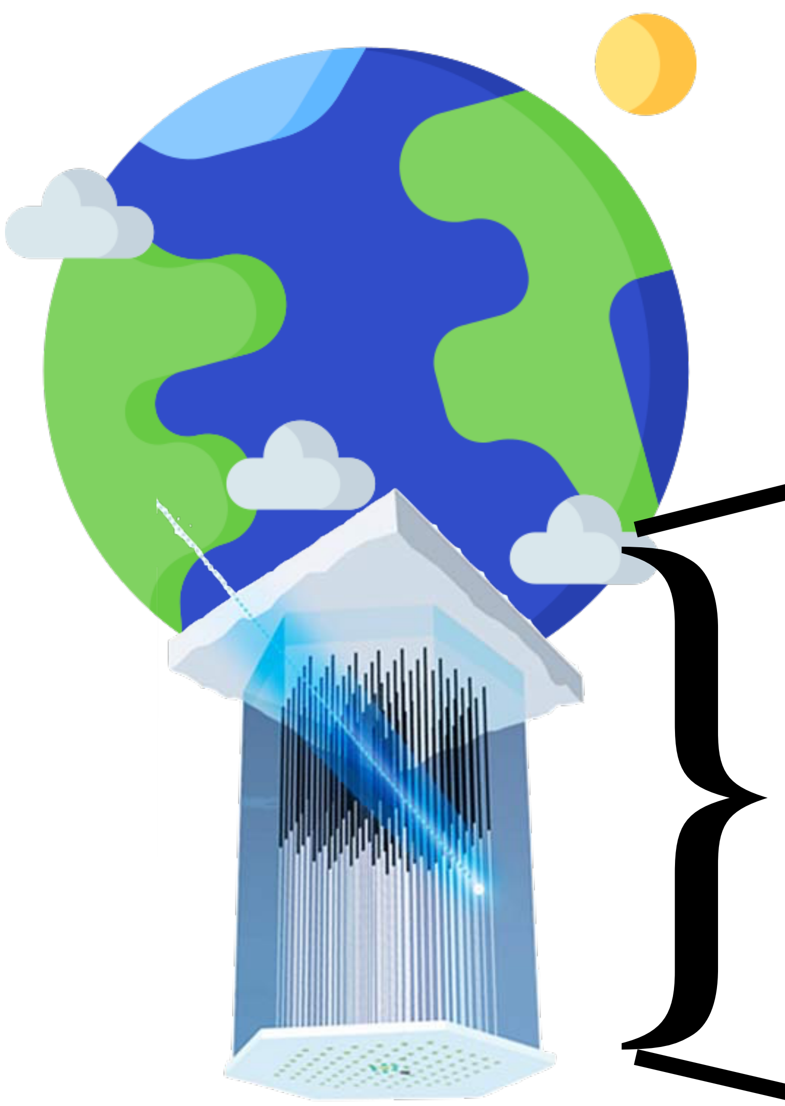
IceCube Gen2 (radio)

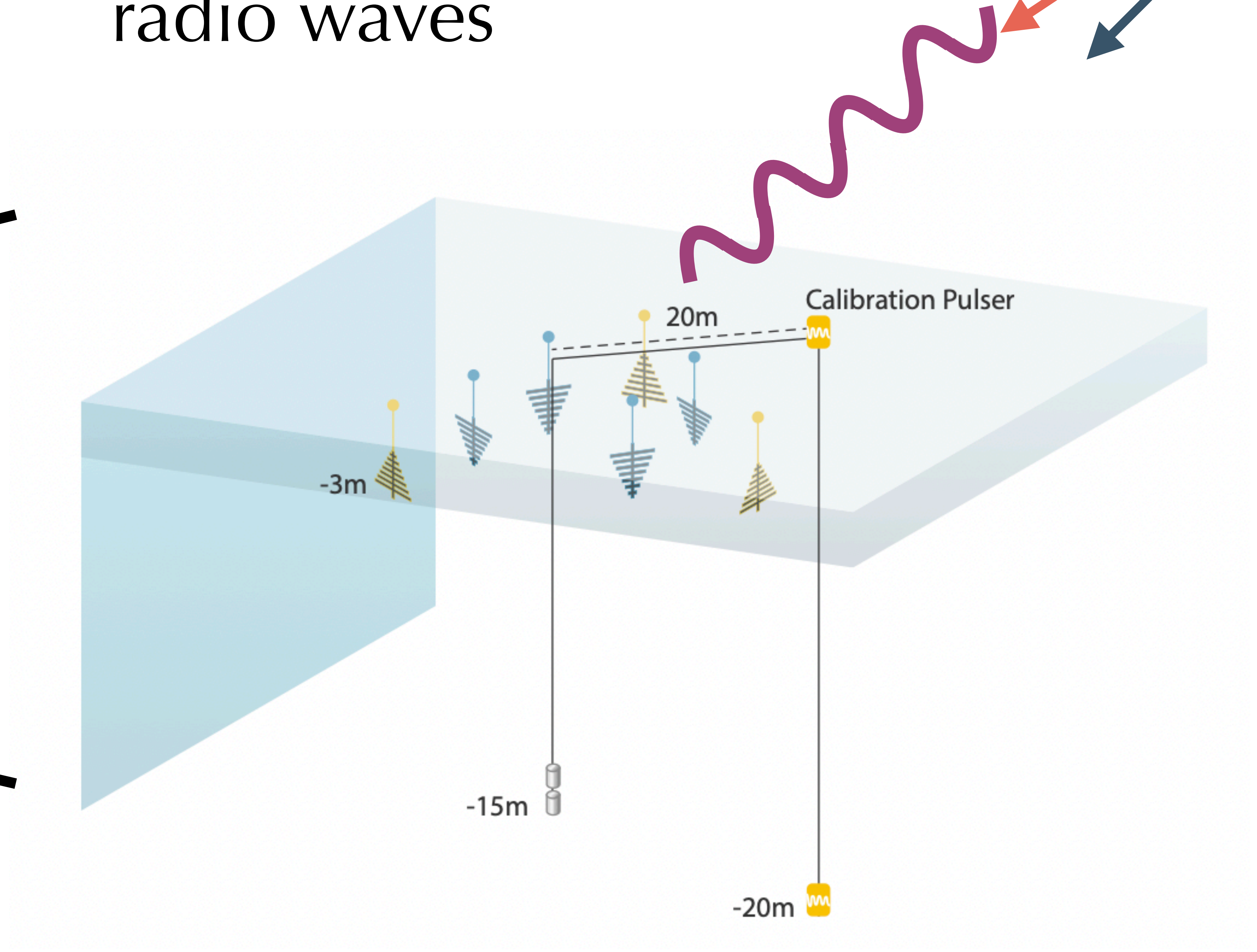
See also ARA, ARIANNA, RNO-G, …

Askaryan effect -

in-ice shower looks like a moving dipole, producing radio waves

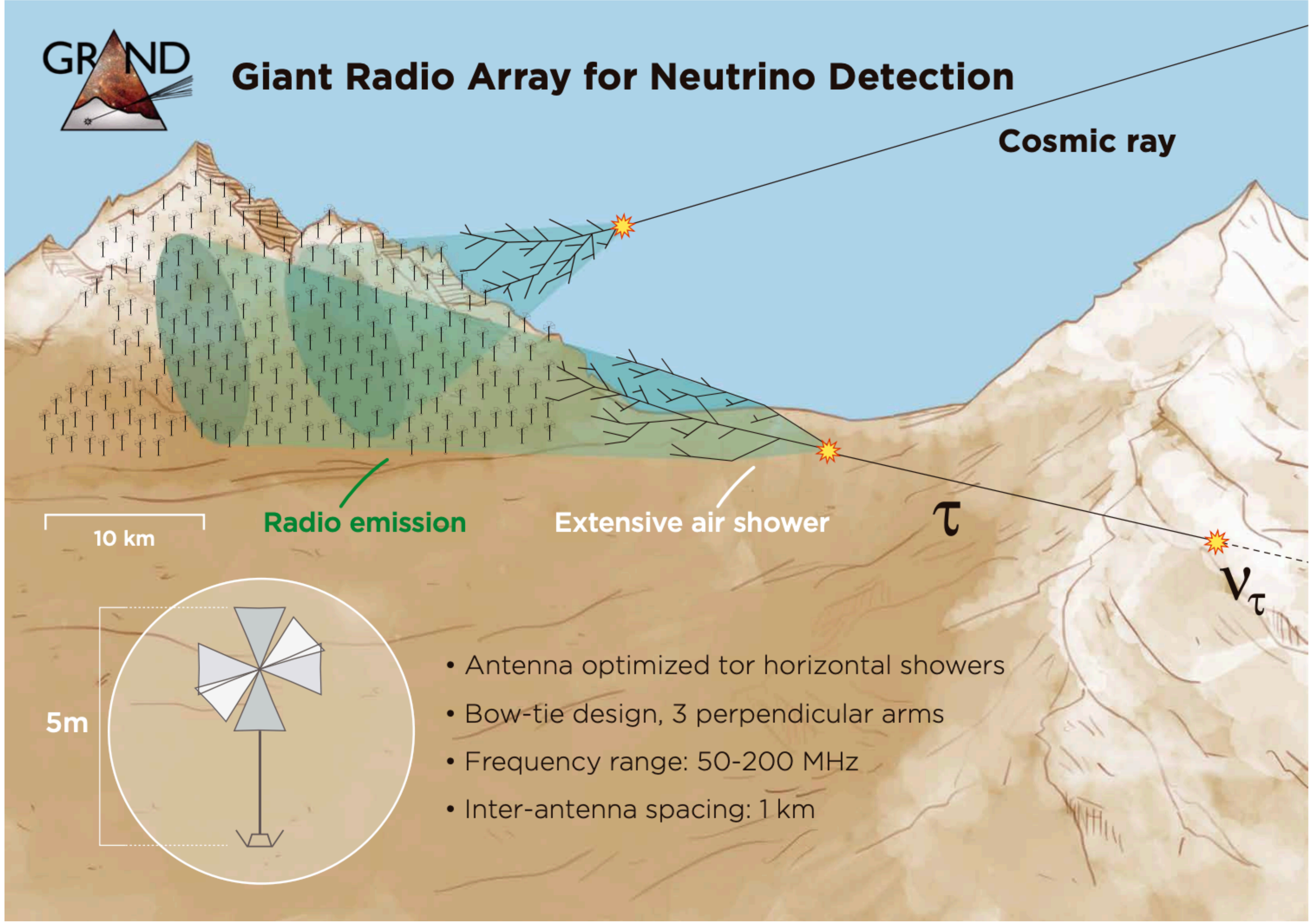






- ✦ Radio array in IceCube-Gen2 will be sensitive to UHE neutrinos
- ✦ Start taking data in 2030

Giant Radio Array for Neutrino Detection (GRAND)



- ✦ Coherent emission by geomagnetic effect
- ✦ Mostly sensitive to Earth-skimming tau neutrinos

GRAND Collaboration, 1810.09994

Why UHE neutrinos?

Astrophysics

- Smoking gun signature of UHECRs interactions
  - High-redshift UHECRs sources
  - UHECRs composition
  - Individual UHE sources

Why UHE neutrinos?

Astrophysics

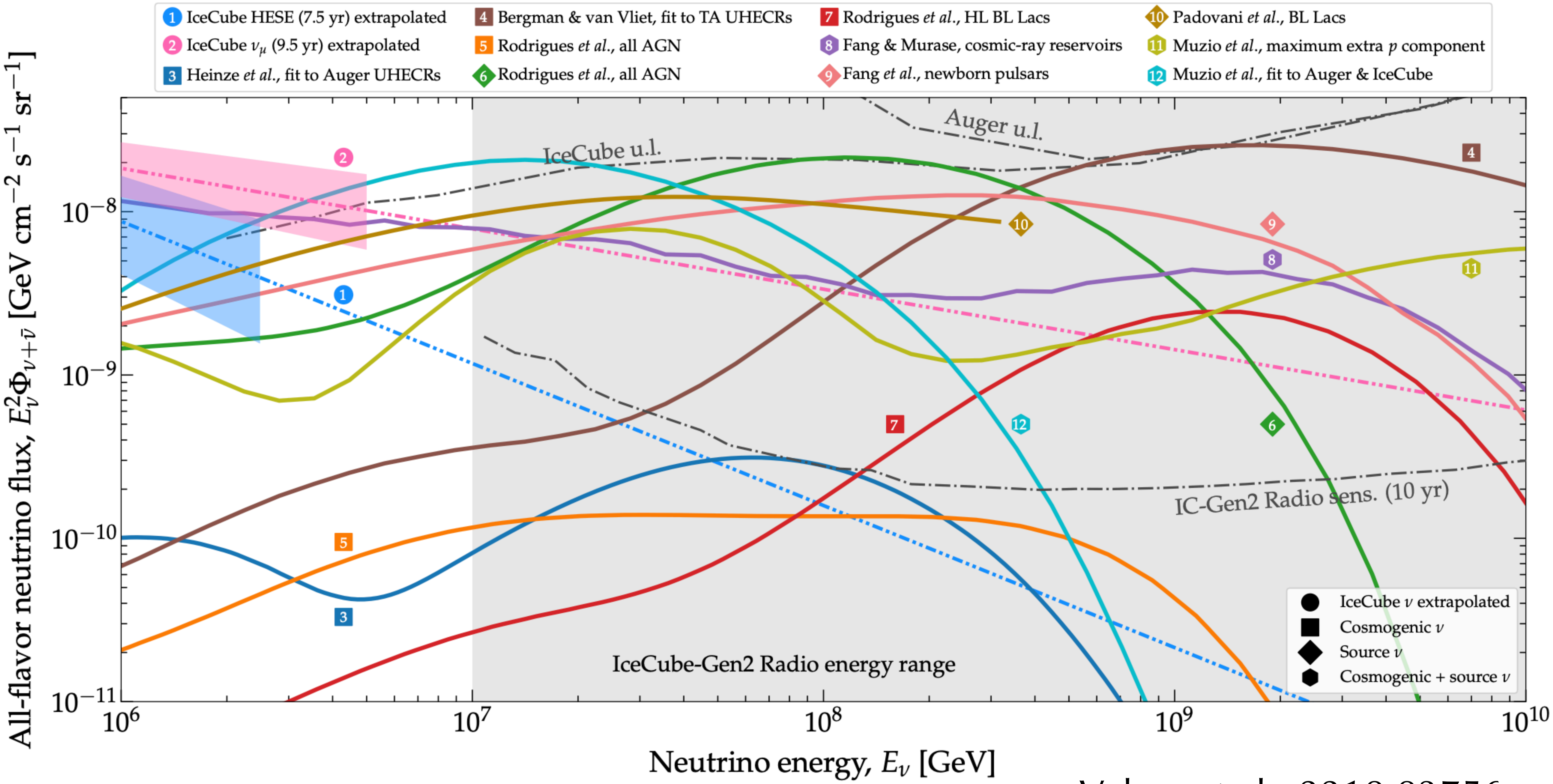
- Smoking gun signature of UHECRs interactions
  - High-redshift UHECRs sources
  - UHECRs composition
  - Individual UHE sources

Particle physics

- Testing high-energy Beyond the Standard Model (BSM) physics
  - BSM sources of UHE neutrinos (e.g. dark matter)
  - BSM neutrino oscillations
  - BSM neutrino interactions

Learning from UHE neutrinos

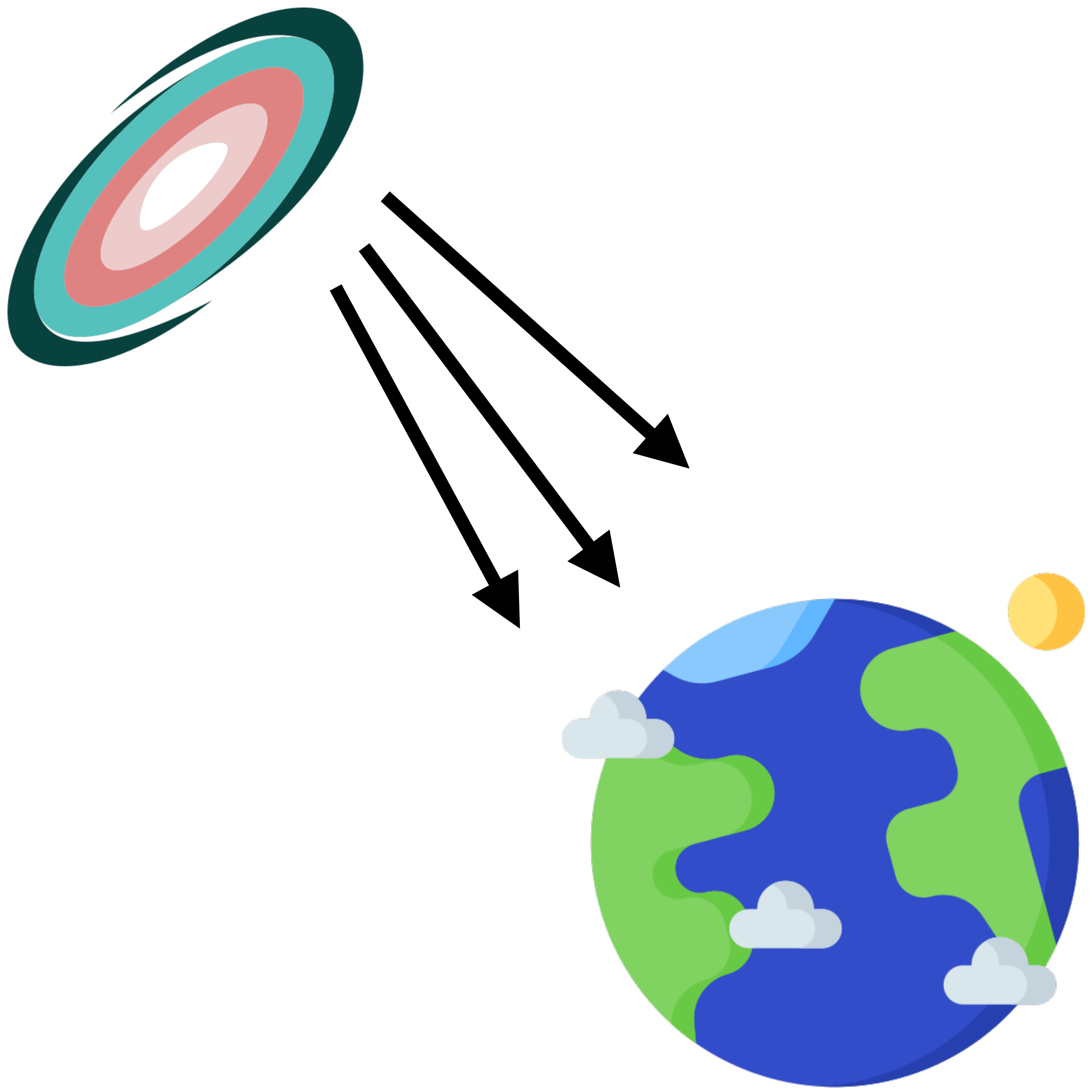
Energy spectrum



Valera et al., 2210.03756

Multiplet searches

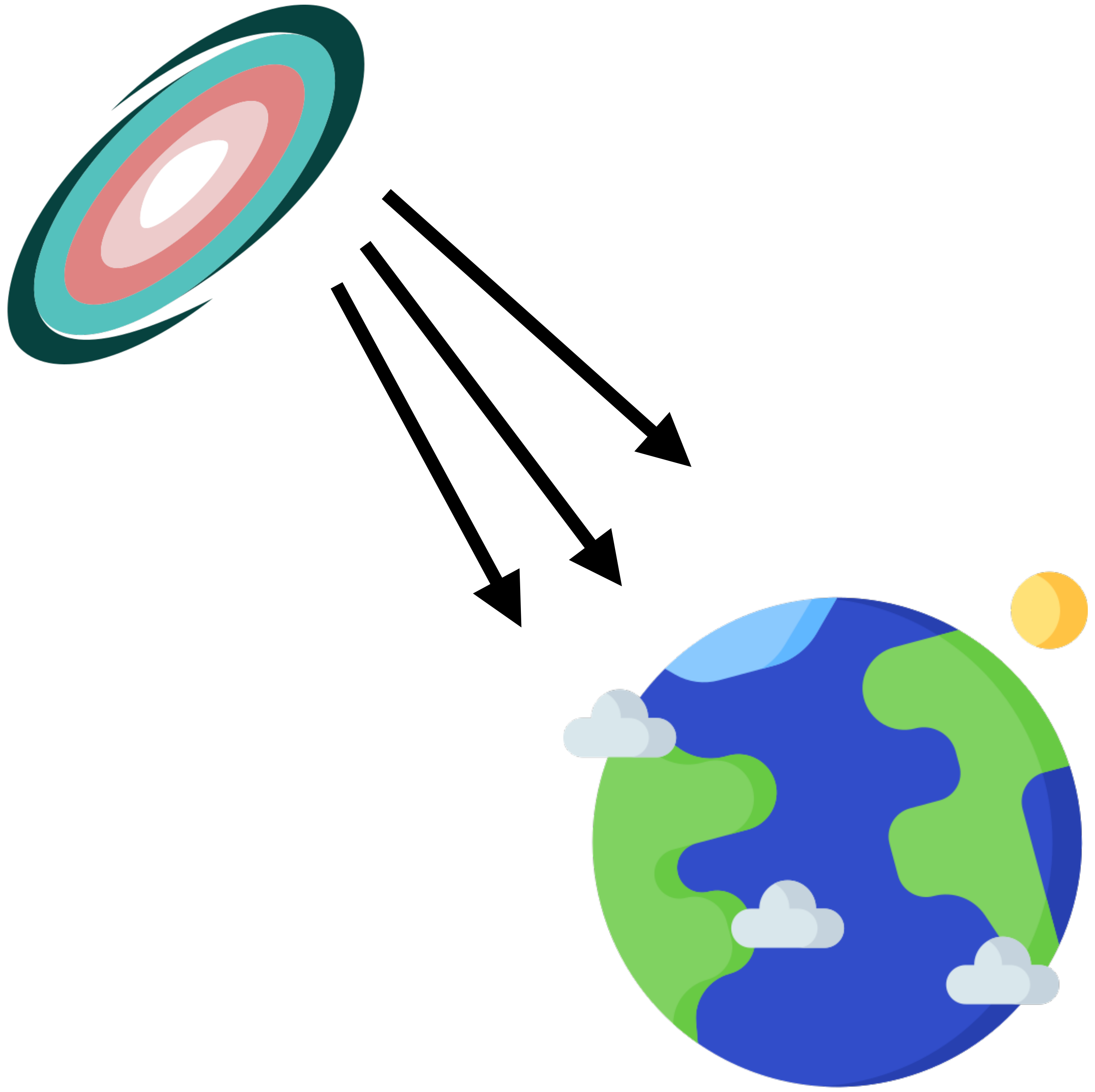
Bright sources produce excess of events (multiplets) with similar direction

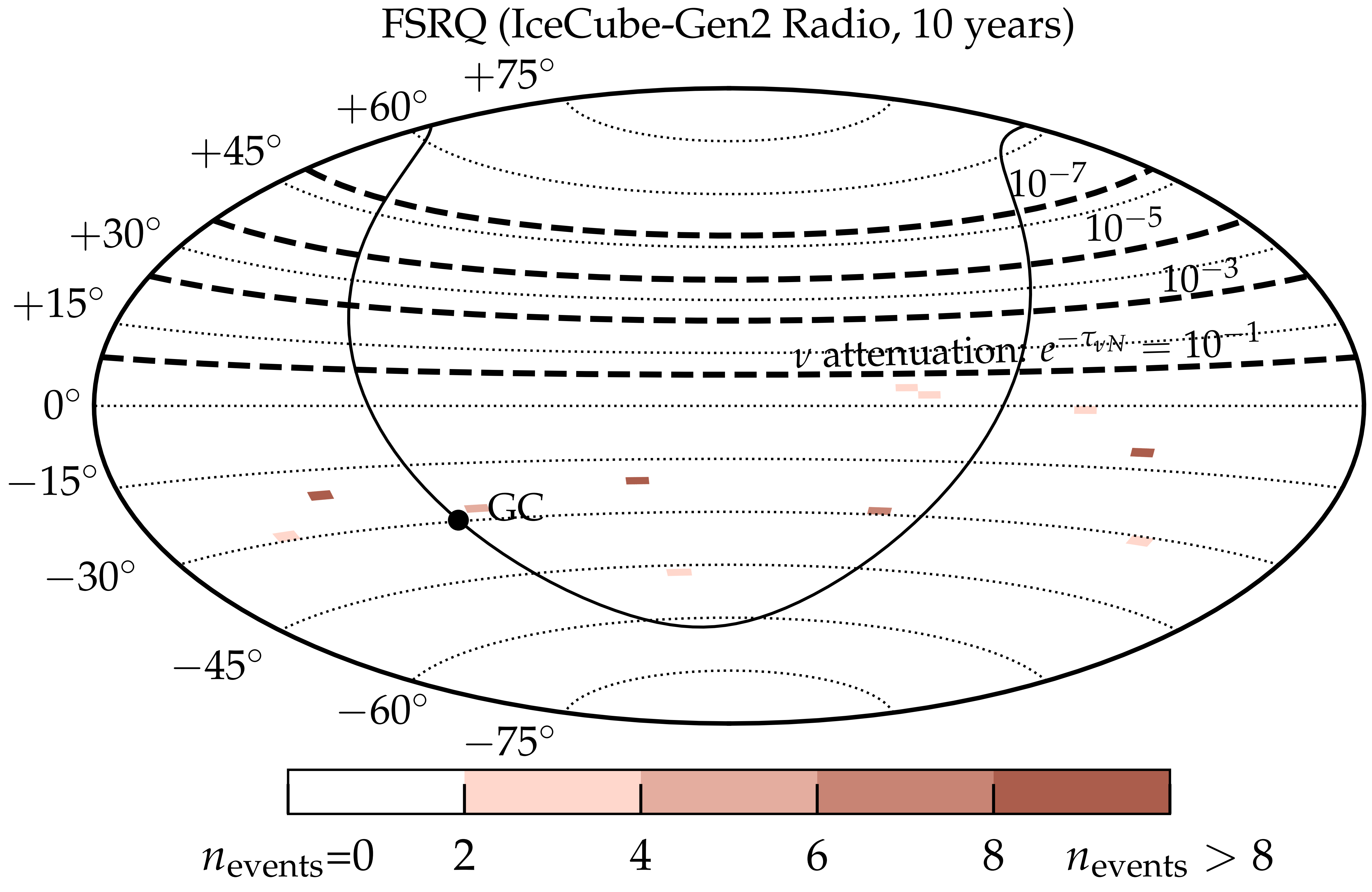


Multiplet searches

Bright sources produce excess of events (multiplets) with similar direction

Assume angular uncertainty ~ 2°, so we divide the sky in pixels of 2° × 2° solid angle





Fiorillo et al., 2205.15985, see also Fang et al., 1609.08027

Multiplet searches

- Unresolved flux could produce fictitious multiplets by Poisson fluctuations

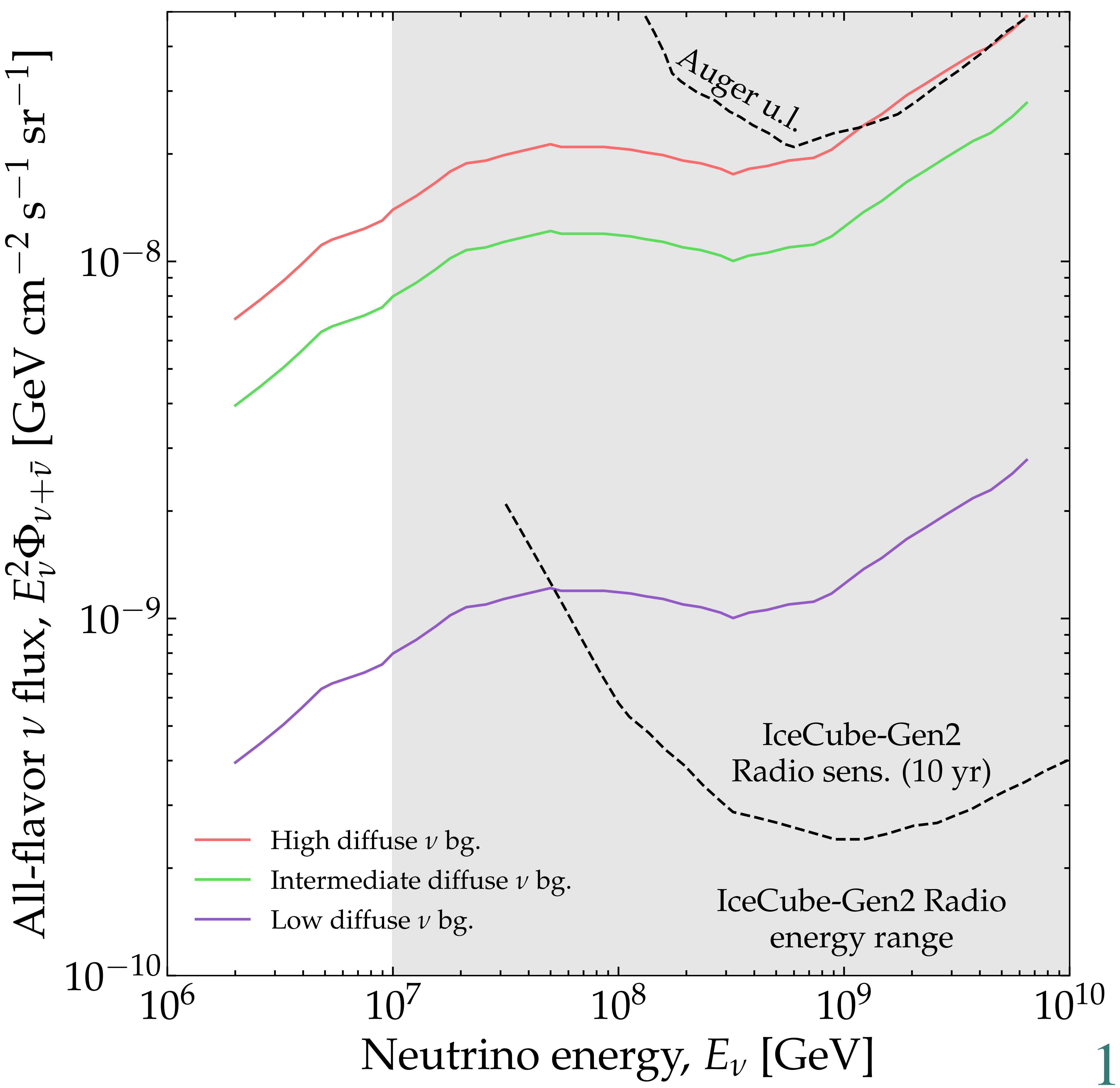
- ~ 3400 pixels make fluctuations more likely - look-elsewhere effect

Multiplet searches

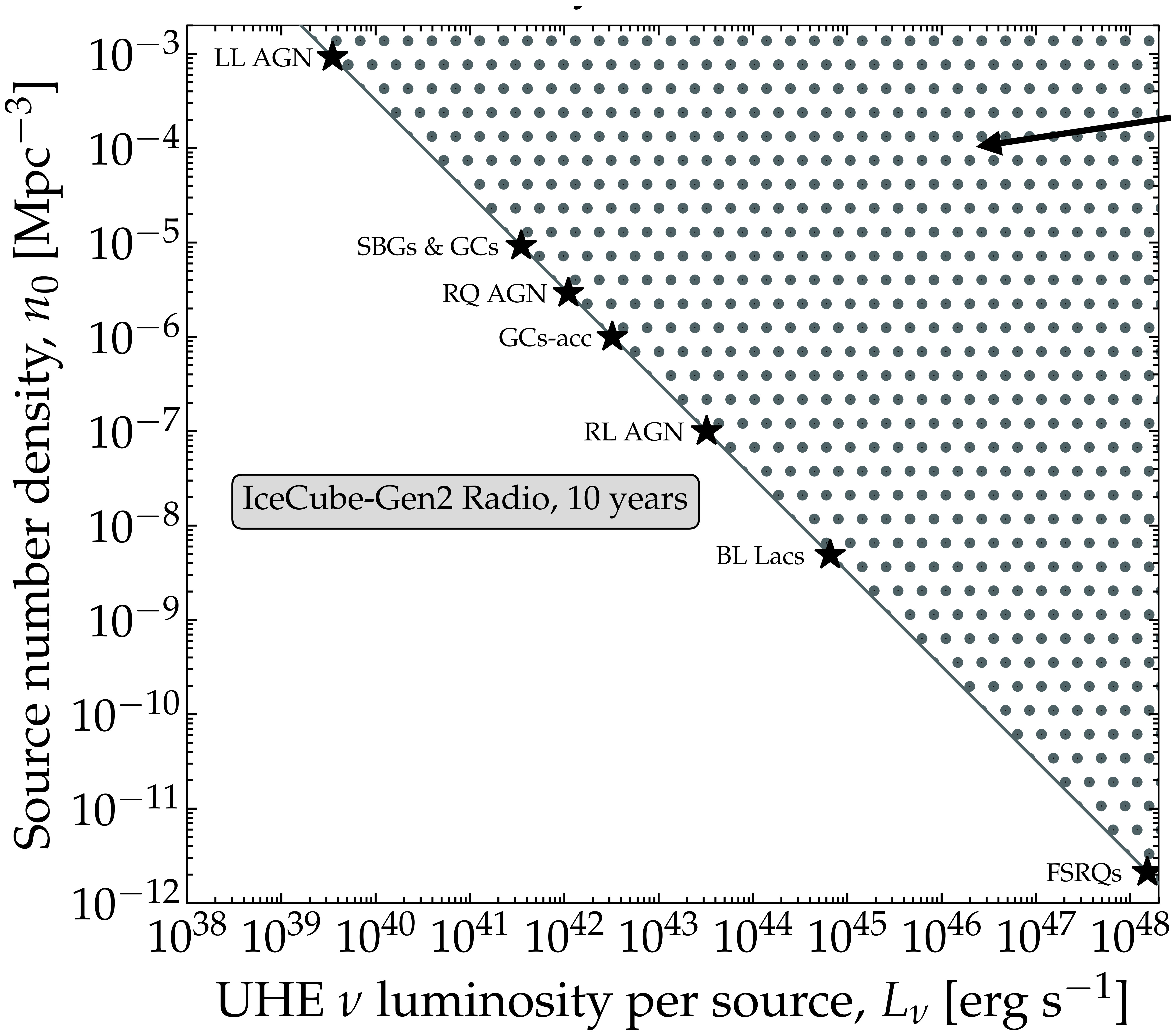
- Unresolved flux could produce fictitious multiplets by Poisson fluctuations
- ~ 3400 pixels make fluctuations more likely - look-elsewhere effect
- How large is the (background) diffuse flux?

Multiplet searches

- Unresolved flux could produce fictitious multiplets by Poisson fluctuations
- ~ 3400 pixels make fluctuations more likely - look-elsewhere effect
- How large is the (background) diffuse flux?



Steady-state sources

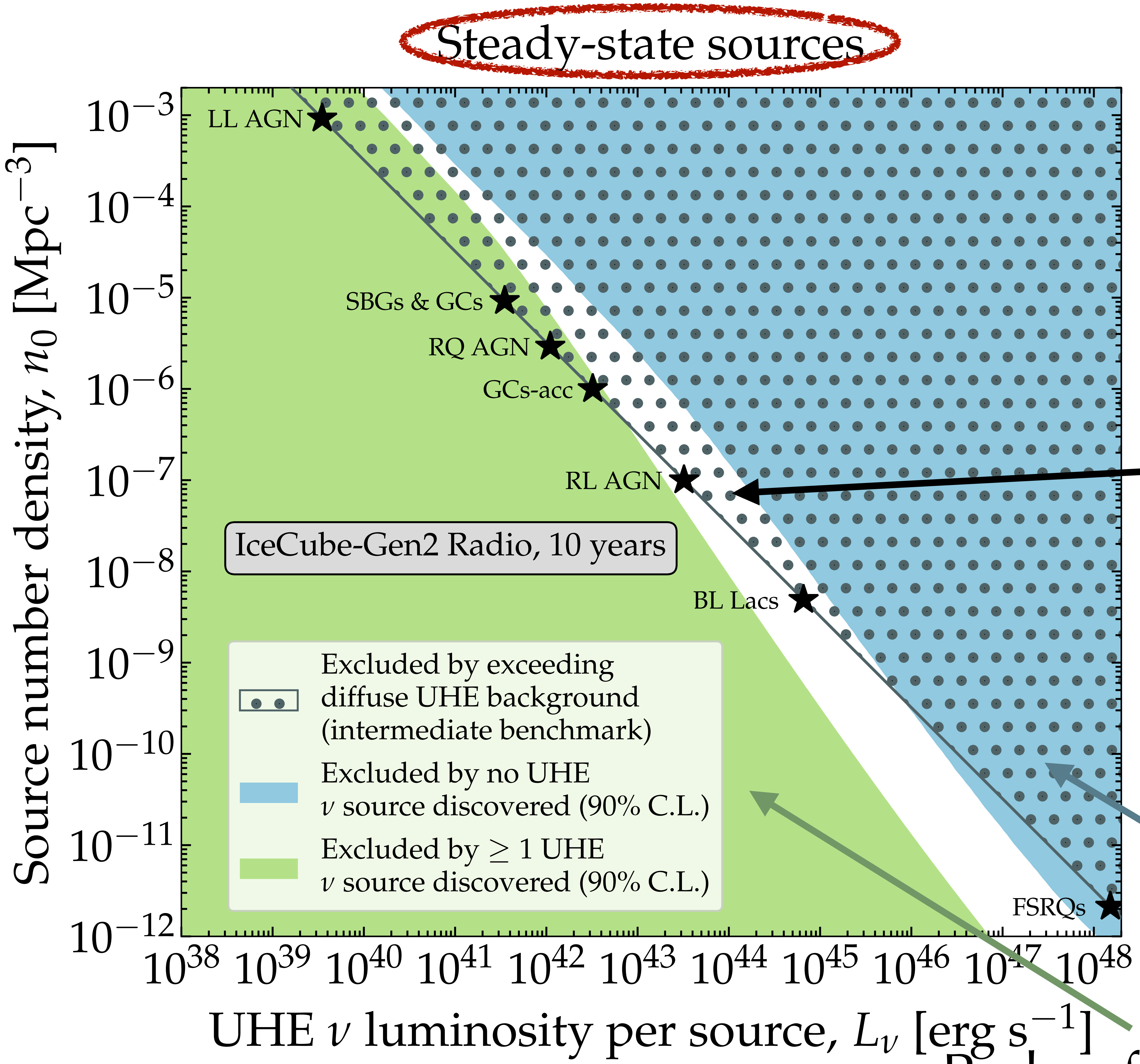


- How many sources? n_0
- How far away? Star-formation rate
- How many neutrinos from each? L_ν
- All the sources cannot exceed the diffuse neutrino flux

$$\phi_\nu^{\mathrm{diffuse}} \propto n_0 L_\nu$$

See also Murase et al., 1607.01601

Source populations



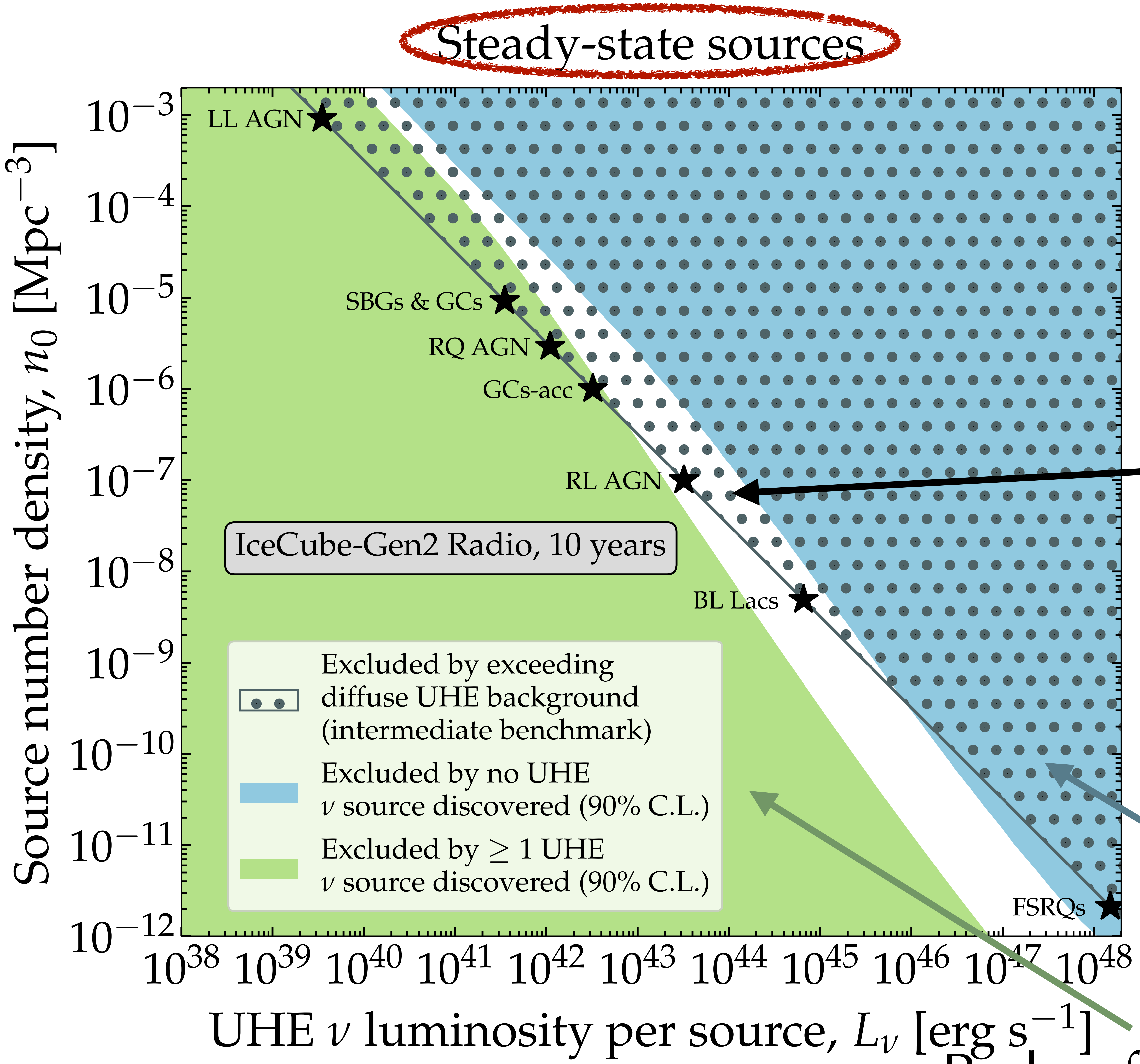
Main question: what do we learn from a (non-)detection?

Exceeds diffuse flux

Prob. of detection > 90%, excl. if no detection

Prob. of detection < 10%, excl. if at least one detection

Source populations



Main question: what do we learn from a (non-)detection?

Exceeds diffuse flux

Most steady-state sources are unlikely to be discovered

Prob. of detection > 90%, excl. if no detection

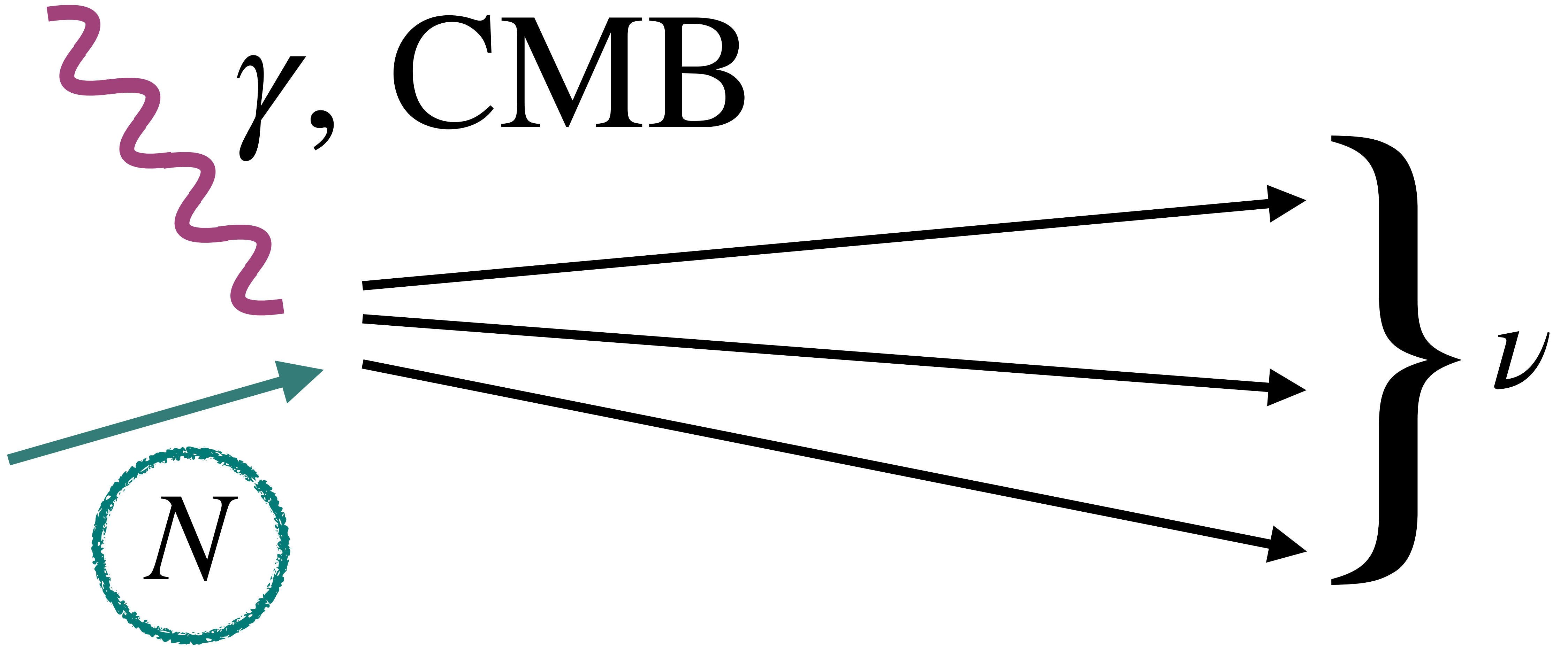
Prob. of detection < 10%, excl. if at least one detection

Conclusions

- UHE neutrinos point to UHECRs acceleration
- Energy spectrum as a probe of production mechanism
- Angular distribution as a probe of point sources
  - Very bright sources (e.g. Flat Spectrum Radio Quasars) may lead to multiplets
  - Multimessenger and catalog searches
- Flavor composition as a complementary probe

Backup slides

Cosmogenic neutrinos

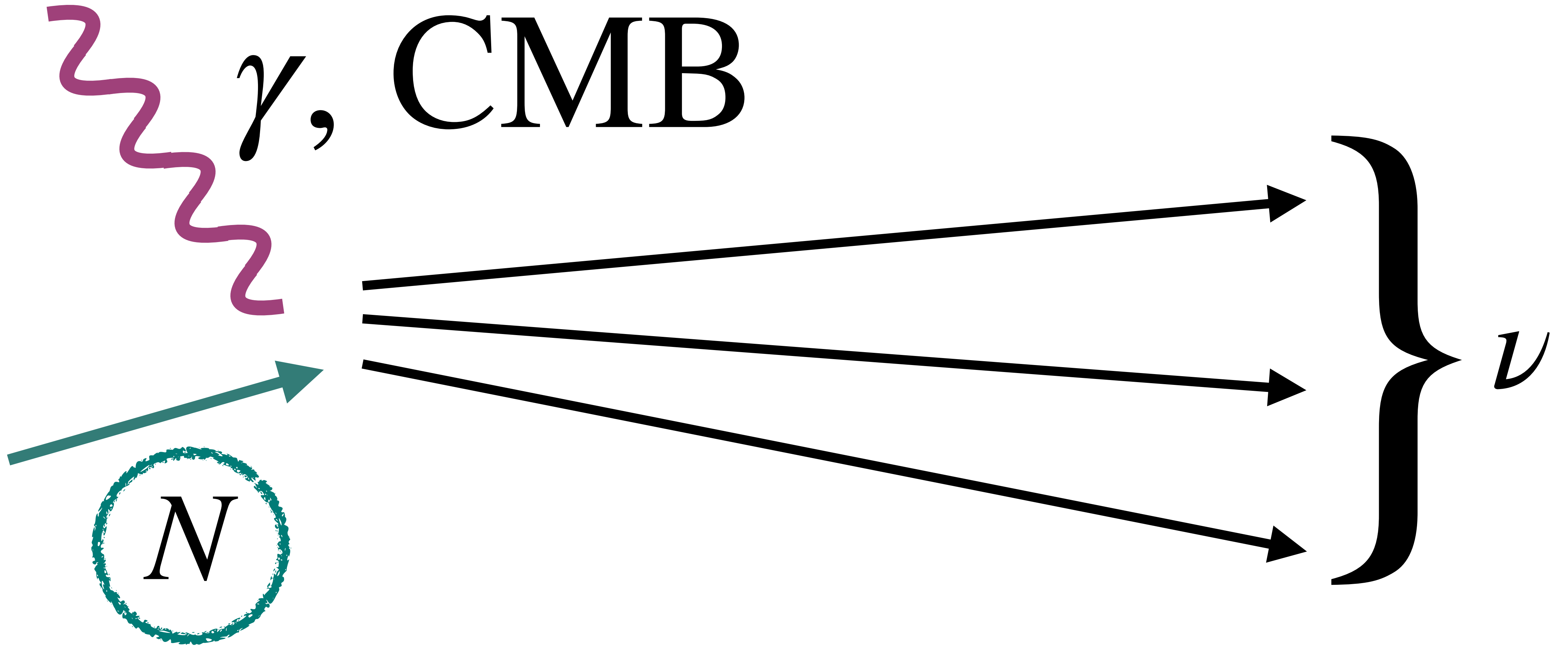


Greisen-Zatsepin-Kuzmin limit at 50 EeV

Lower efficiency of neutrino production!

$$\frac{E_N}{A}\epsilon_\gamma \simeq m_p m_\pi$$

Cosmogenic neutrinos



Greisen-Zatsepin-Kuzmin limit at 50 EeV

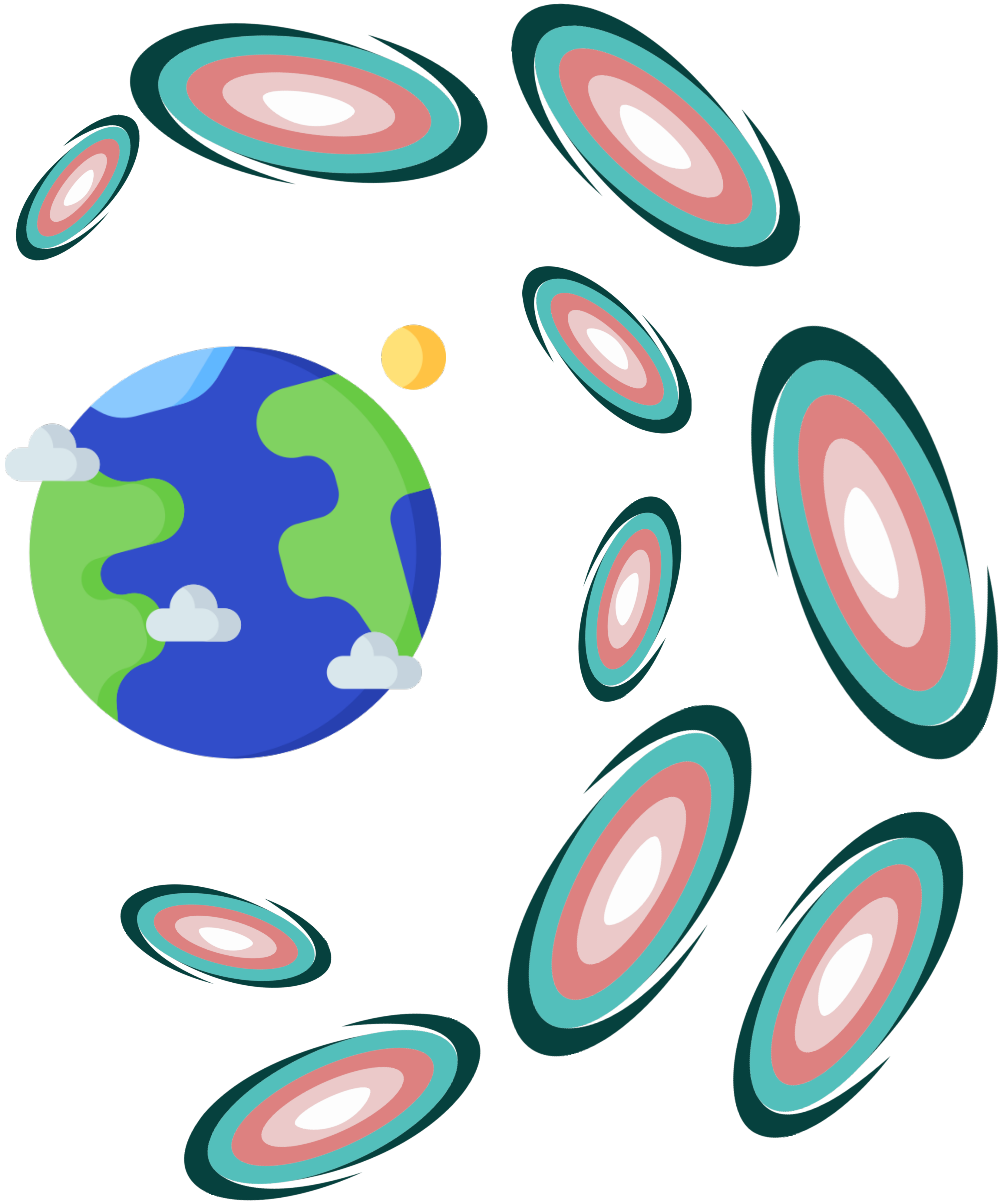
Telescope Array

lighter composition

Pierre Auger Observatory

iron-dominated composition

Cosmogenic neutrinos

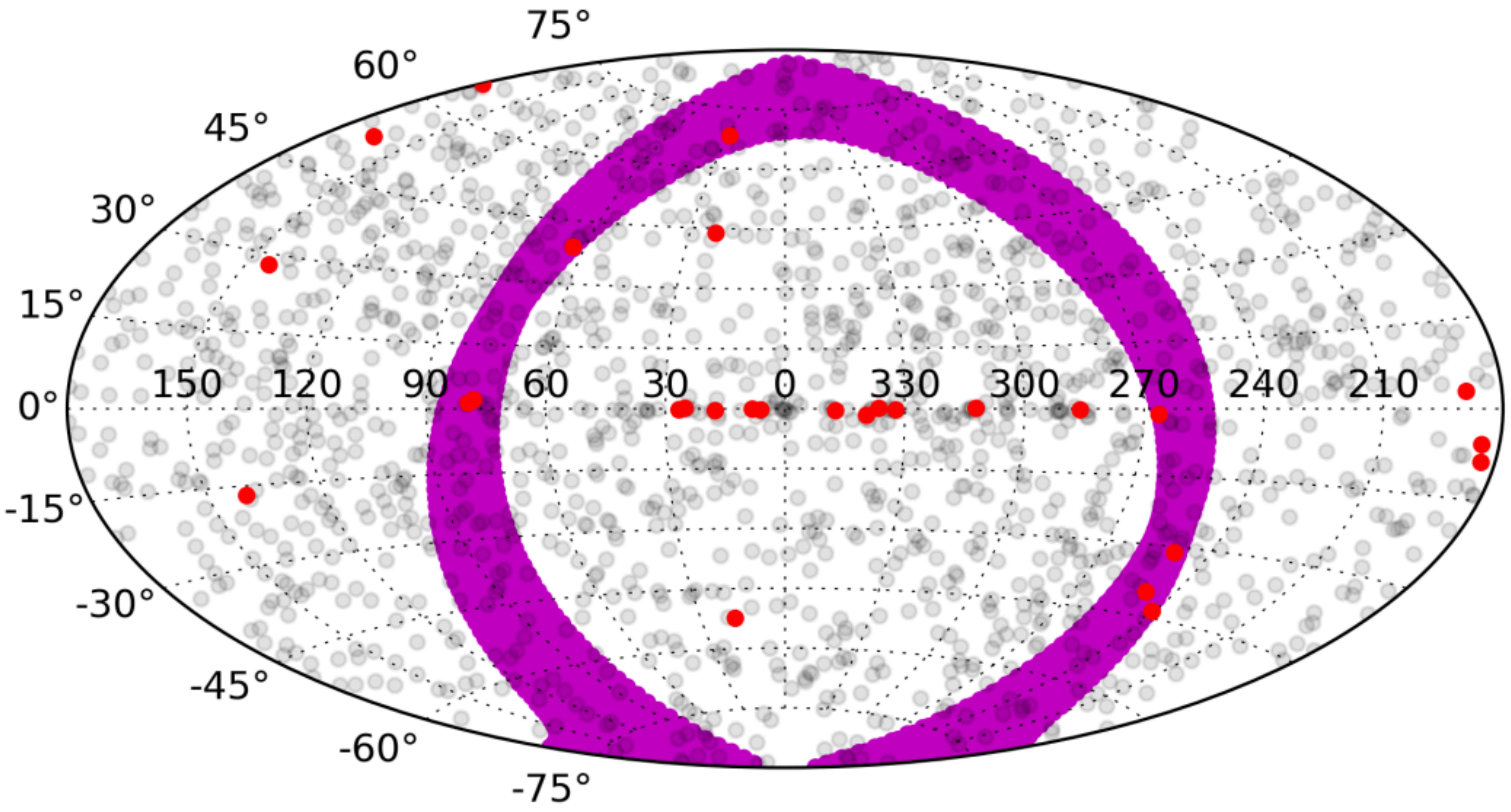


Higher redshift sources imply higher flux

$$\rho(z) \propto (1+z)^m,\ z < z_{\rm max}$$

UHECRs weakly sensitive to m or $z_{\rm max}$

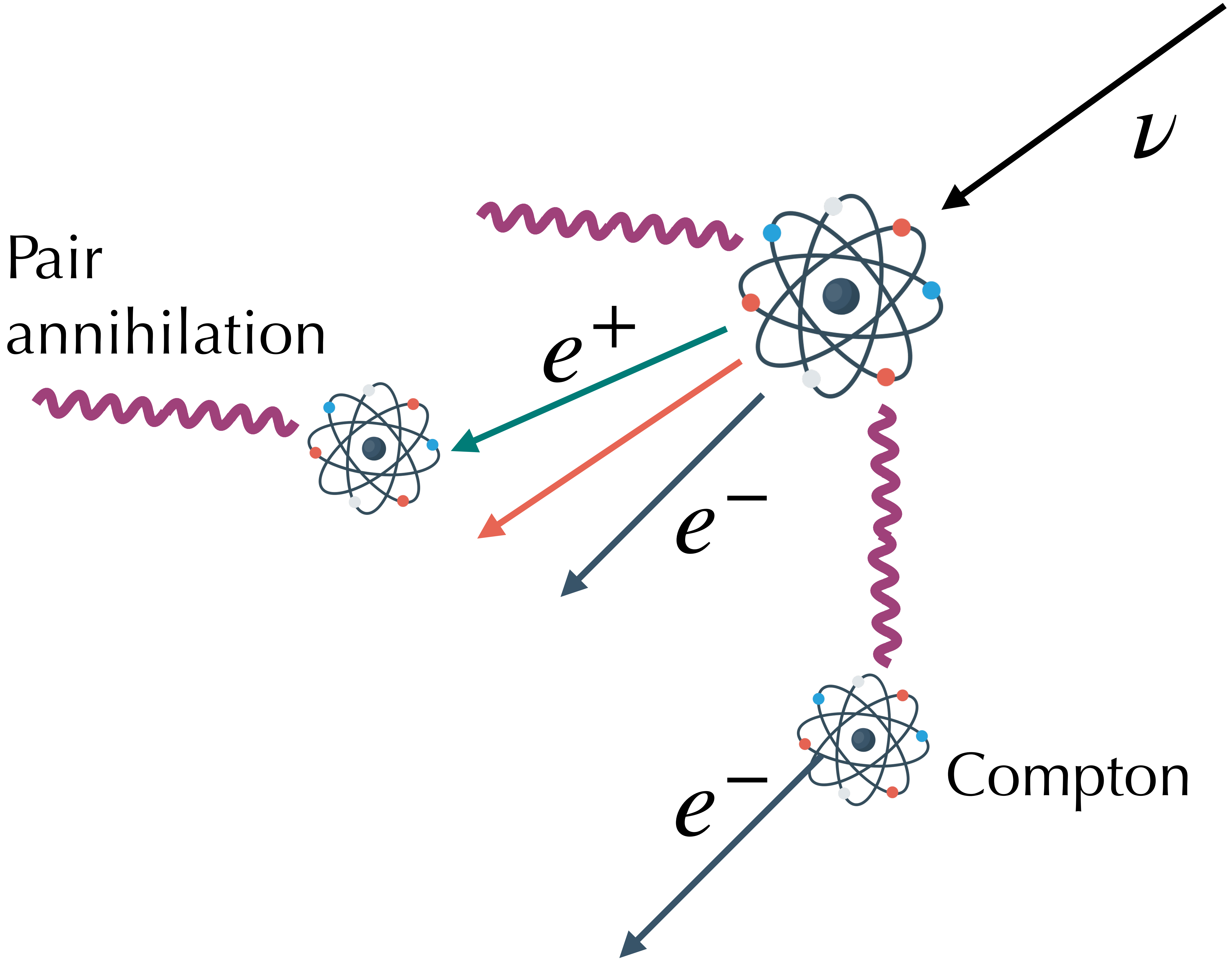
Giant Radio Array for Neutrino Detection (GRAND)



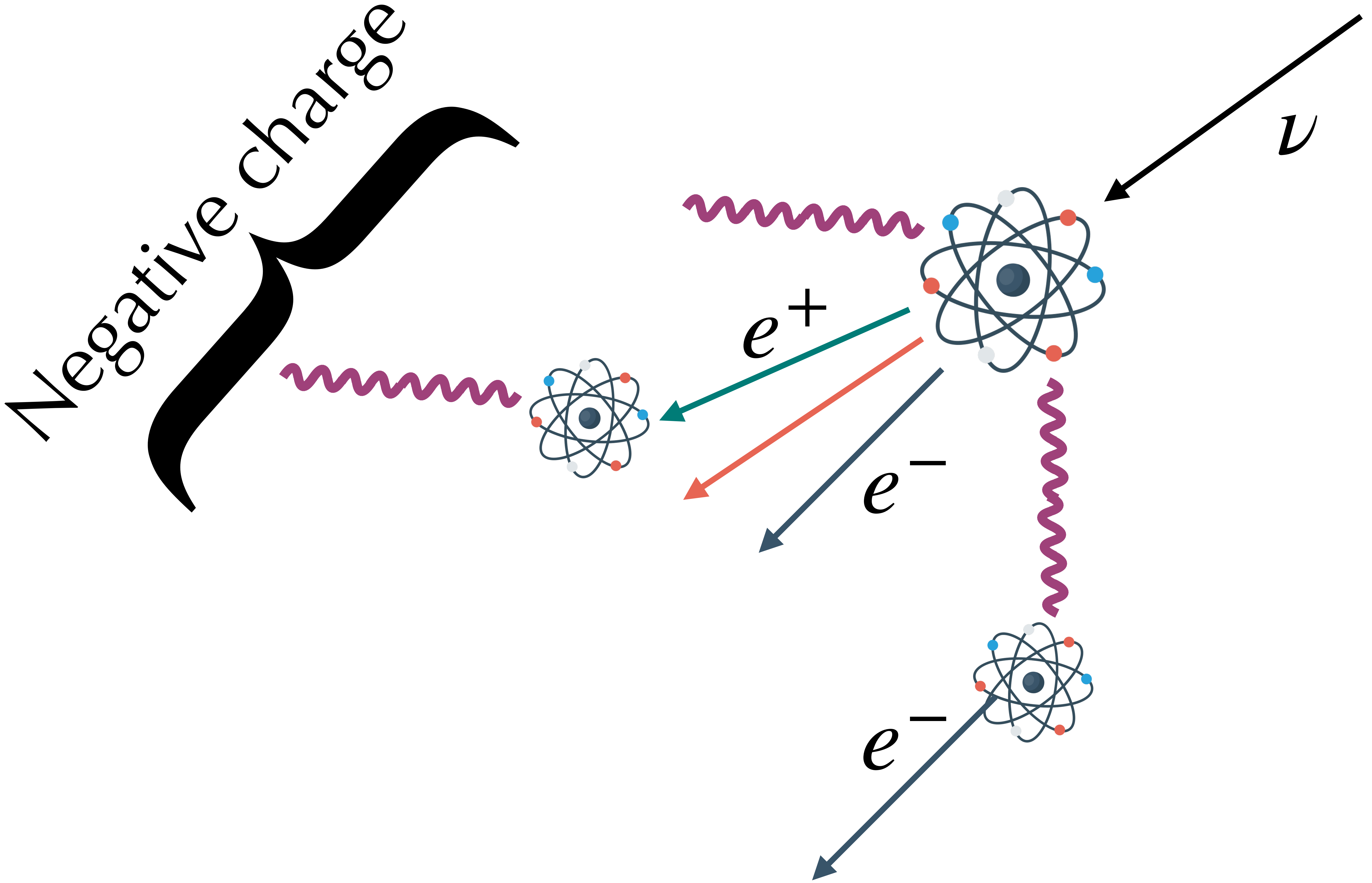
- ✦ Anisotropic instantaneous response
- ✦ Earth rotation and many geographical sites allow nearly uniform sky coverage

GRAND Collaboration, 1810.09994

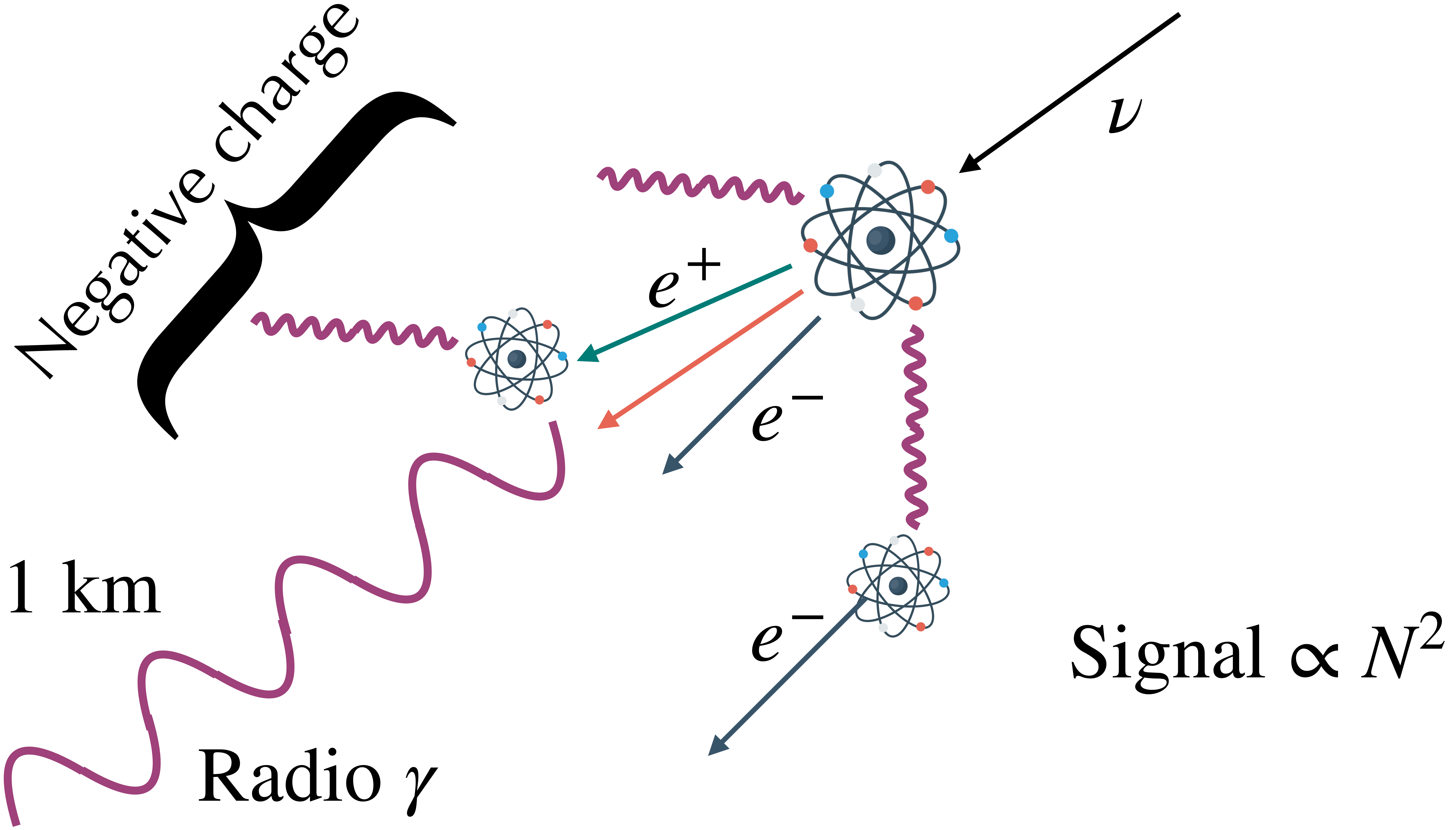
In-ice radio detection



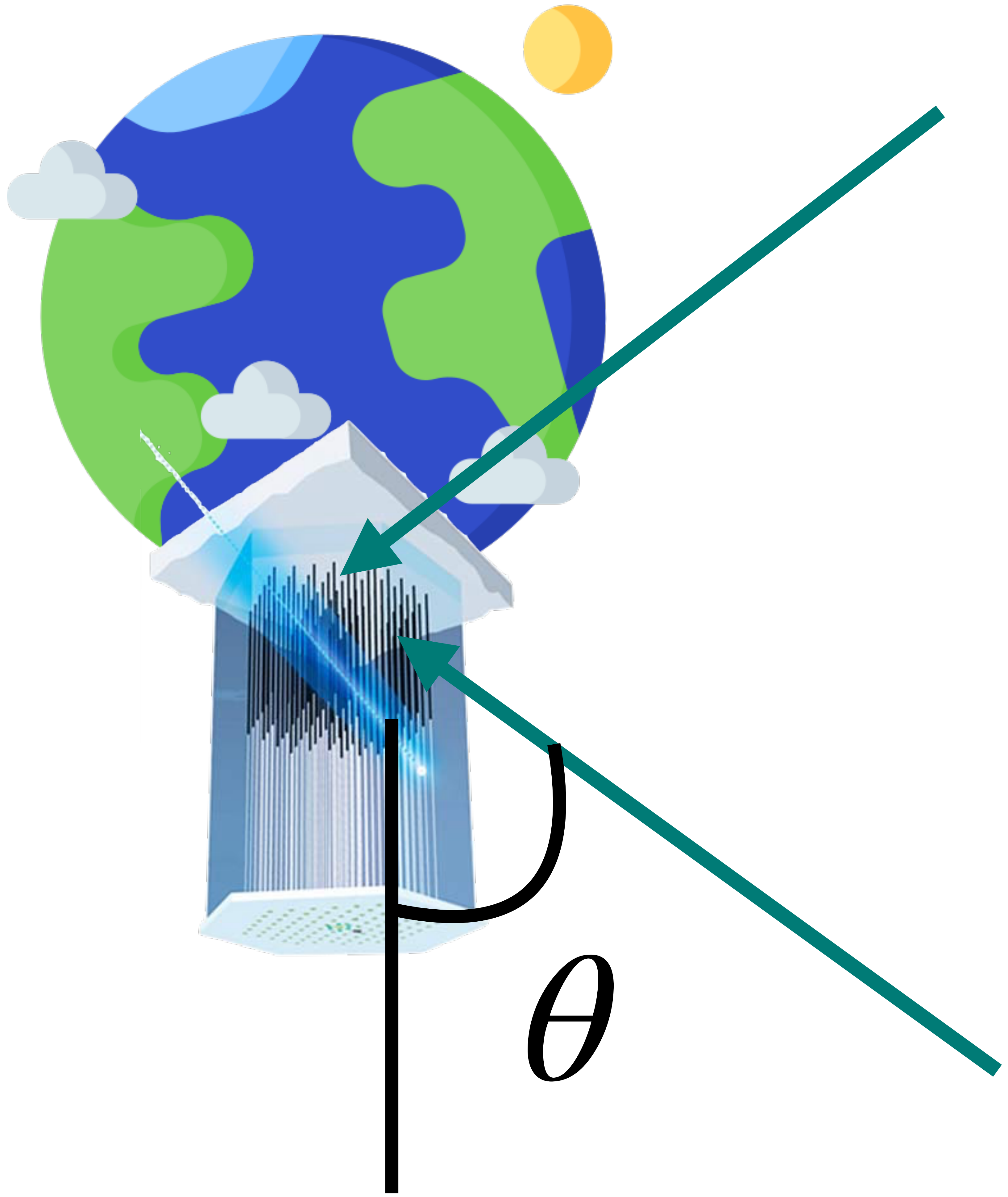
In-ice radio detection



In-ice radio detection



Energy spectrum



$$N_\nu \propto \Phi_\nu \sigma_{\nu N} \exp\left[-n\sigma_{\nu N} L(\theta)\right]$$

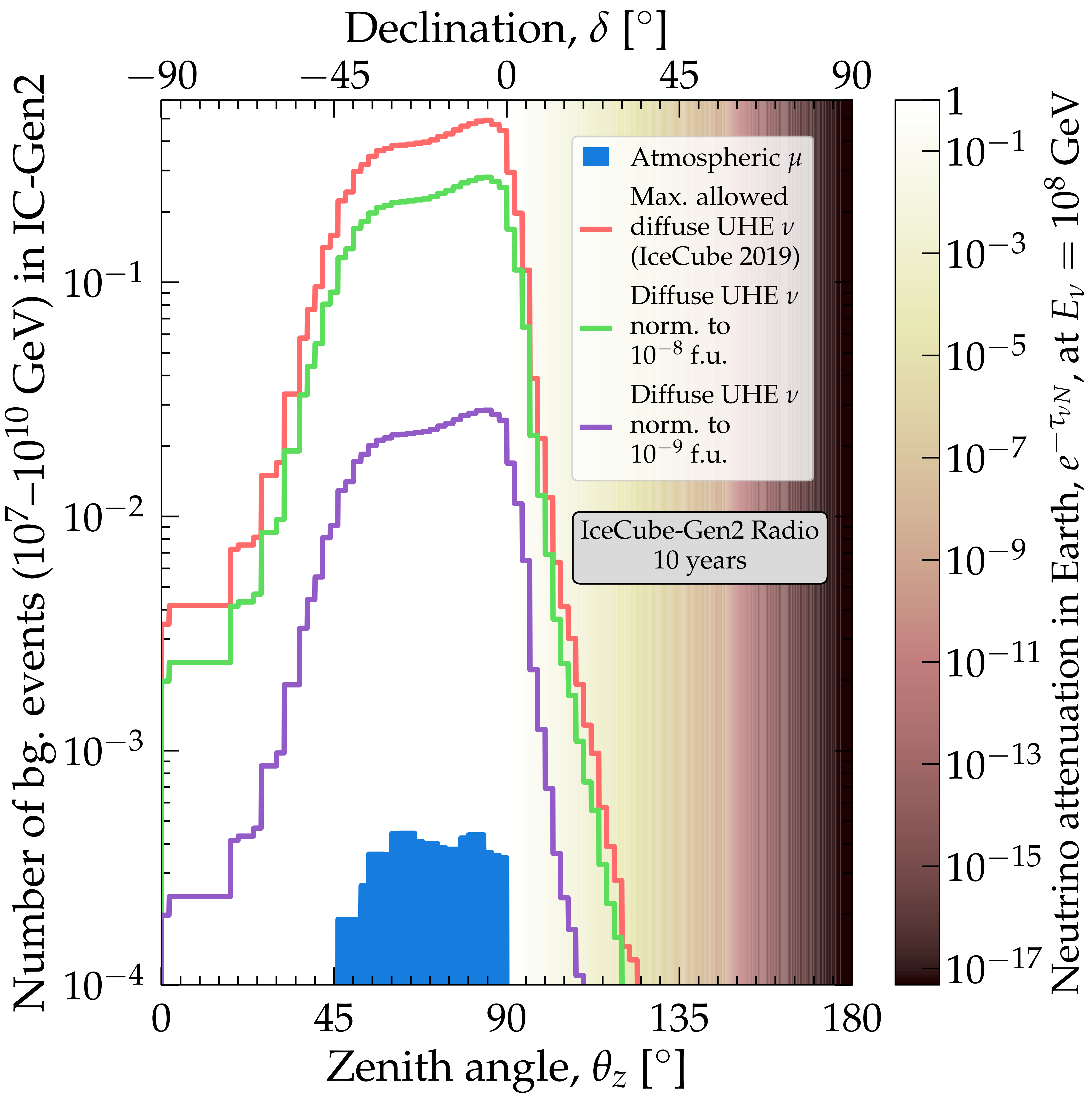
- Degeneracy among cross section and flux (resolved by Earth absorption, see Valera et al., 2204.04237)
- Energy resolution $\sim 0.1 E_\nu$
- Discriminate non-standard production mechanisms (e.g. dark matter decay, see Fiorillo et al., 2307.02538)

Multiplet searches

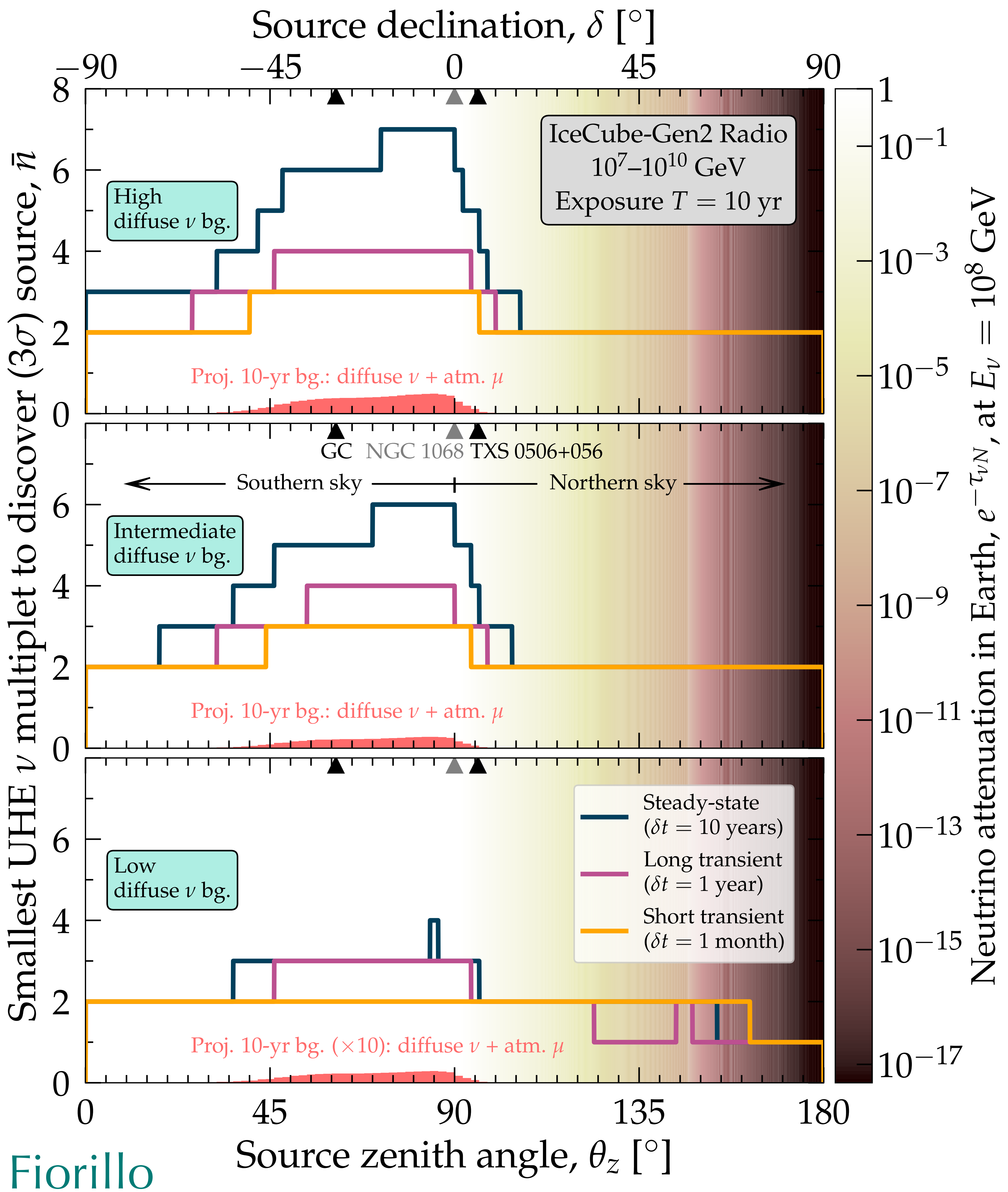
- Unresolved flux could produce fictitious multiplets by Poisson fluctuations

- ~ 3400 pixels make fluctuations more likely - look-elsewhere effect

- How large is the background?



Multiplet searches

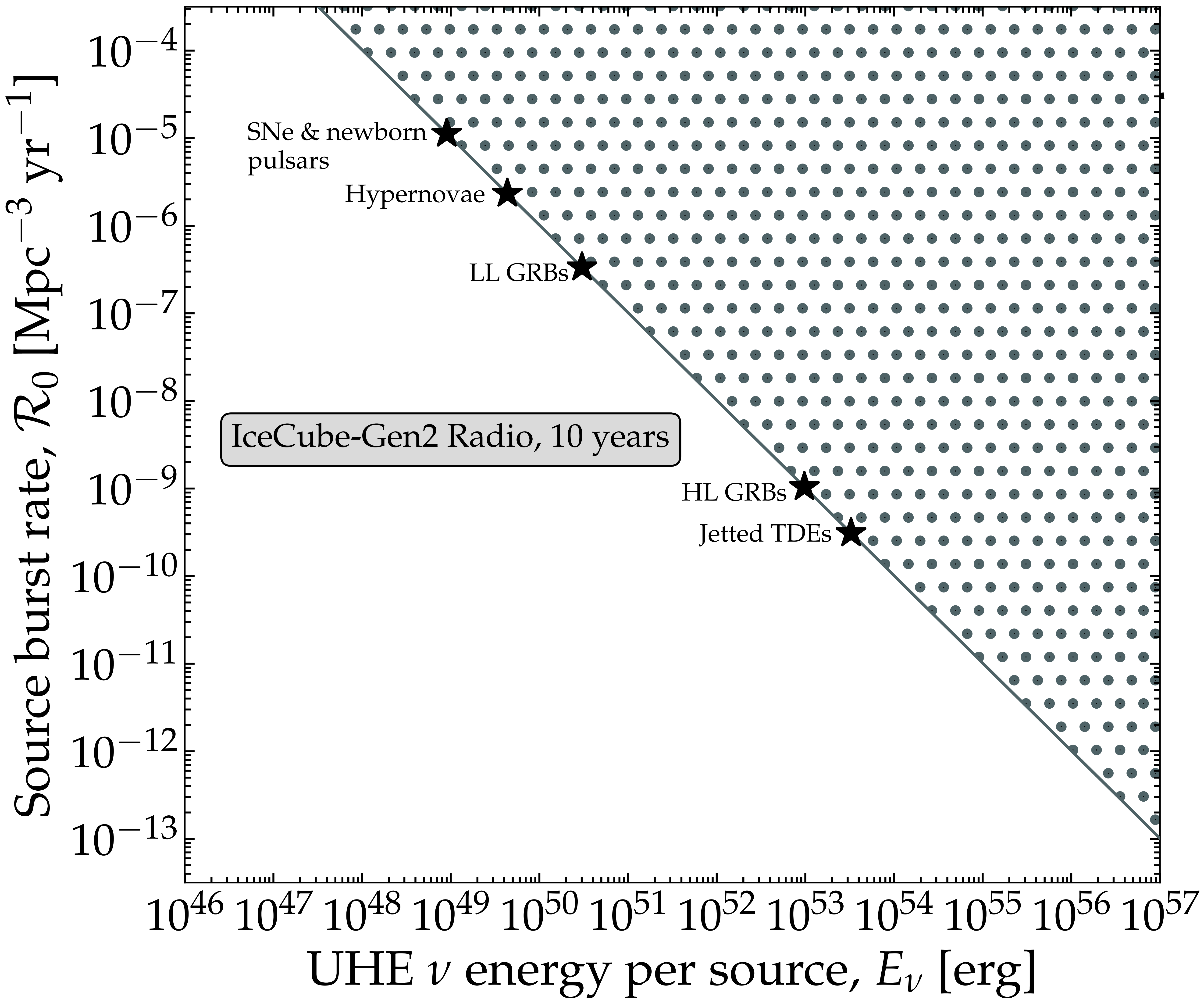


Main question: smallest multiplet size to claim a point source detection at 3σ?

- Multiplet size depends on the zenith angle because of background
- Transient sources can be identified more easily - in a short time there is less background

Damiano Fiorillo

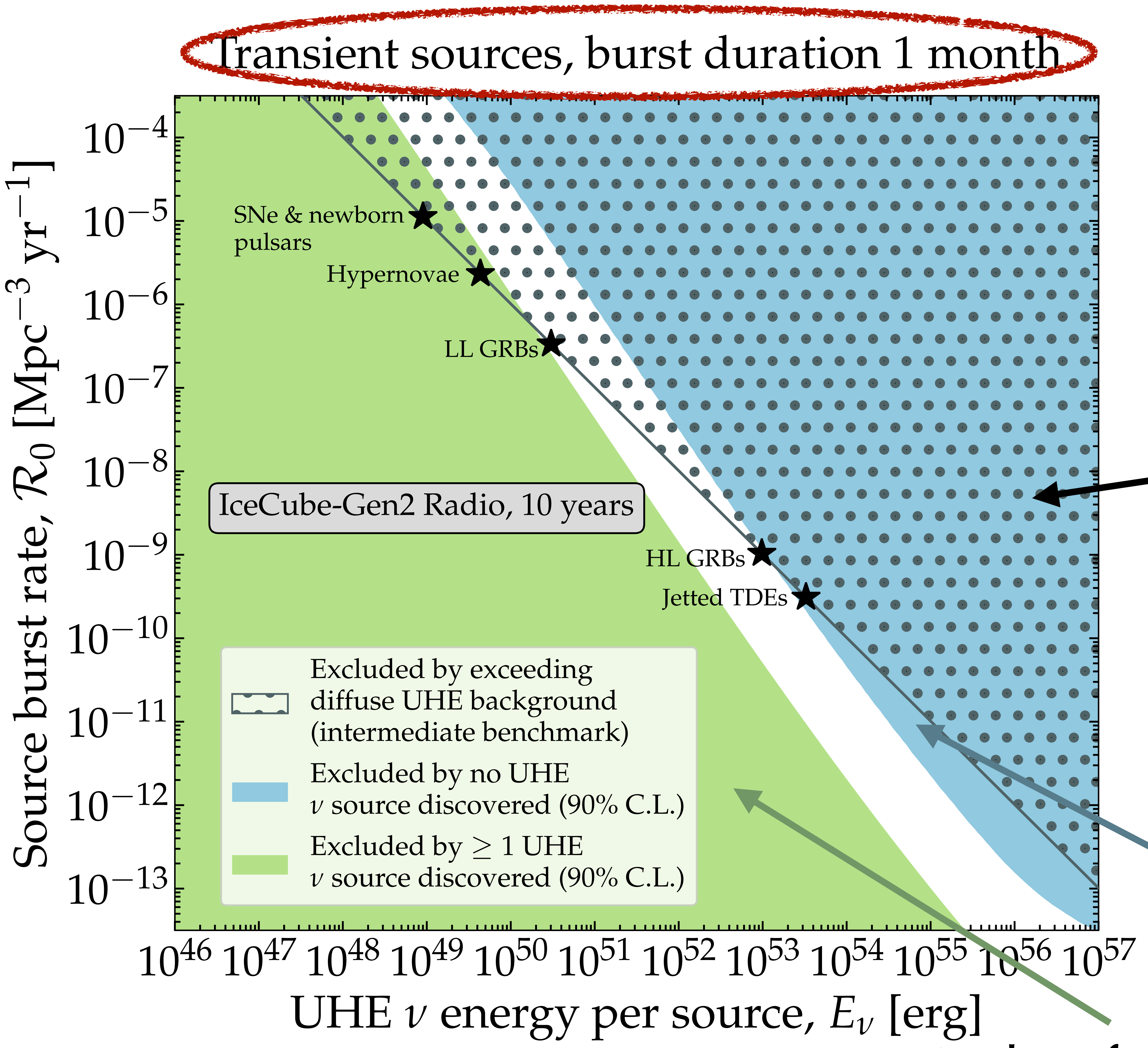
Transient sources



Exceeds diffuse flux

- How many sources explode? $\mathscr{R}_0$
- How far away? Star-formation rate
- How many neutrinos from each? E_ν
- All the sources cannot exceed the diffuse neutrino flux

Source populations



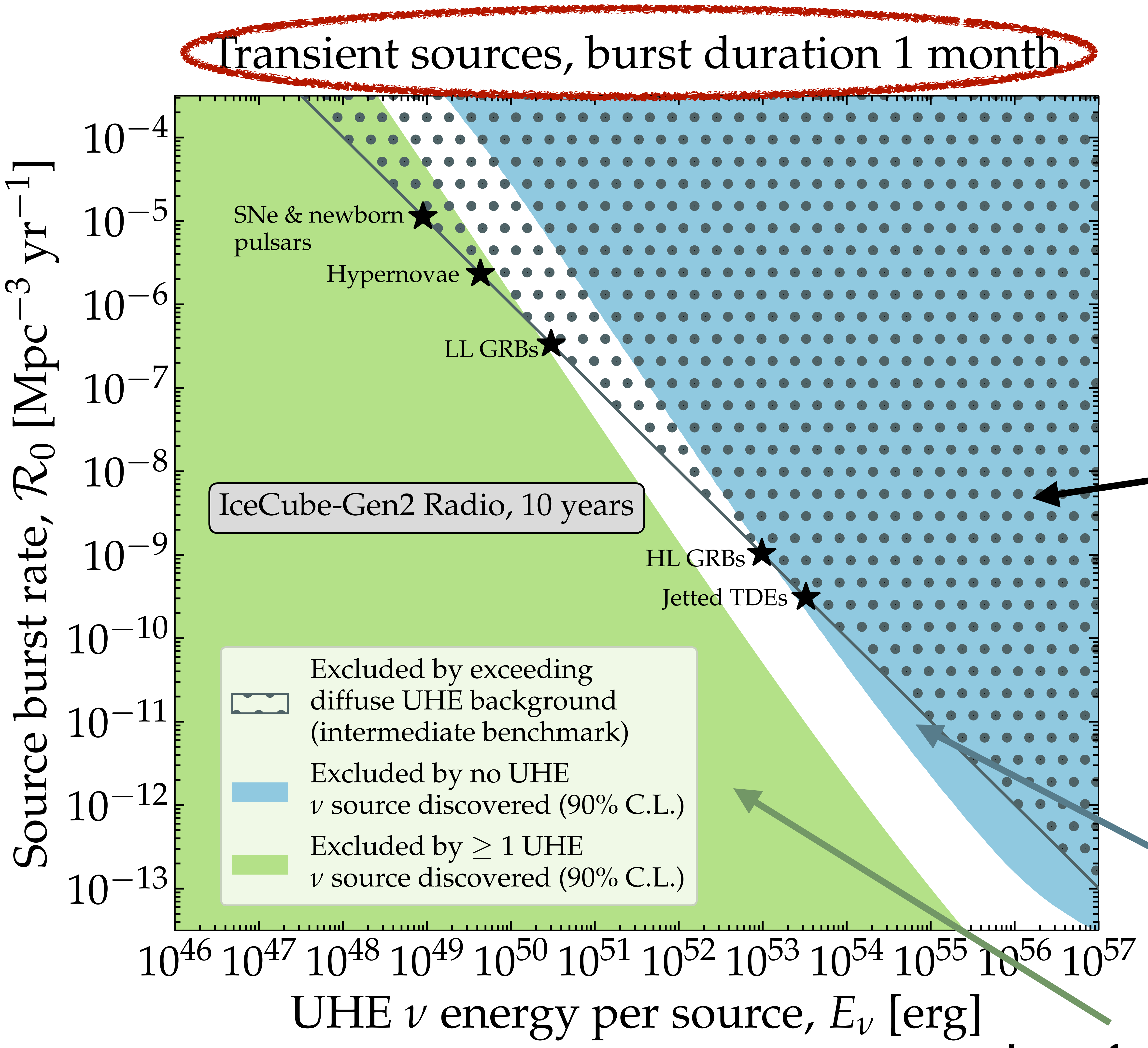
Main question: what do we learn from a (non-)detection?

Exceeds diffuse flux

Prob. of detection > 90%, excl. if no detection

Prob. of detection < 10%, excl. if at least one detection

Source populations



Main question: what do we learn from a (non-)detection?

Exceeds diffuse flux

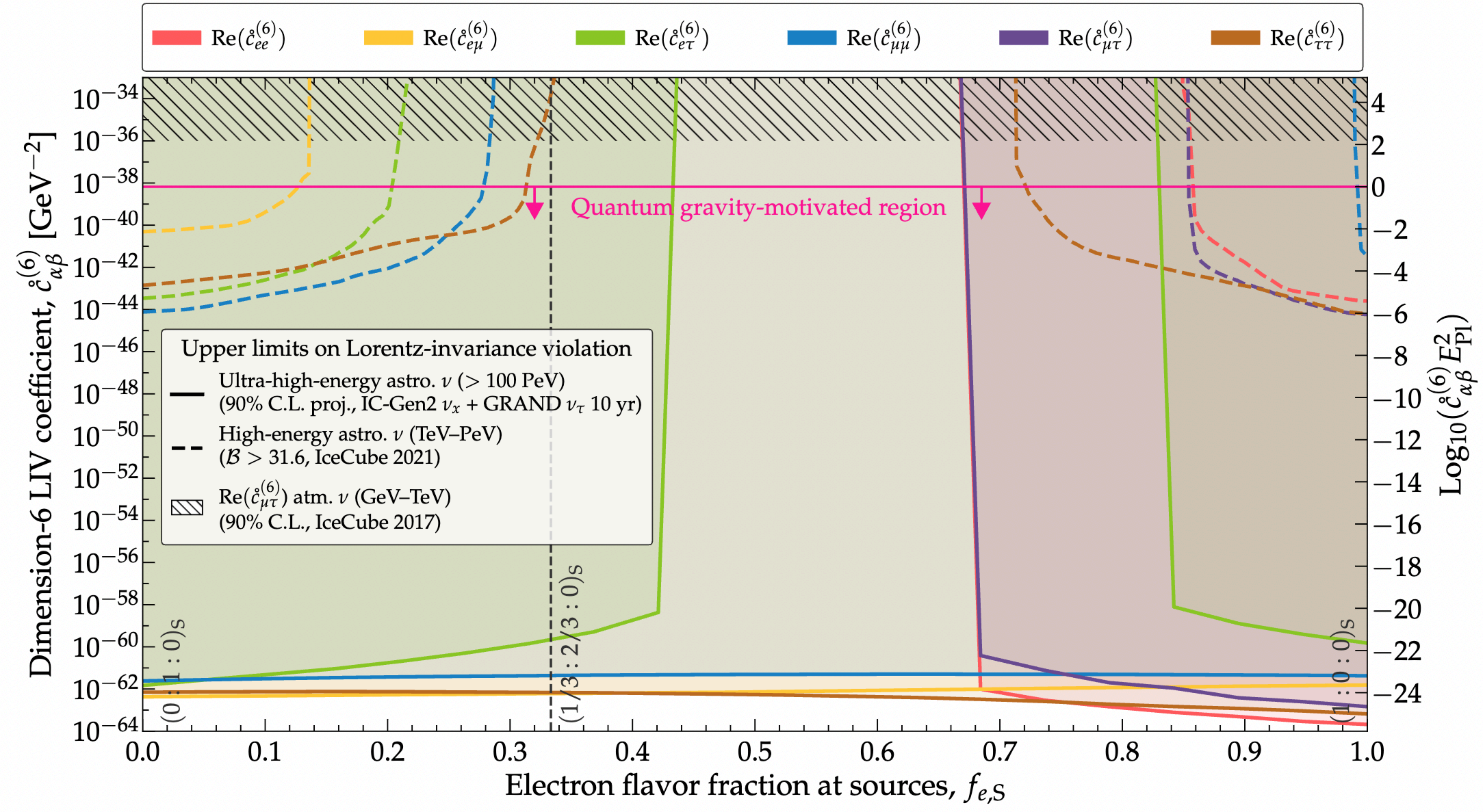
Brightest transient sources could be discovered, if they dominate diffuse flux

Prob. of detection > 90%, excl. if no detection

Prob. of detection < 10%, excl. if at least one detection

Flavor composition

$$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \ldots$$

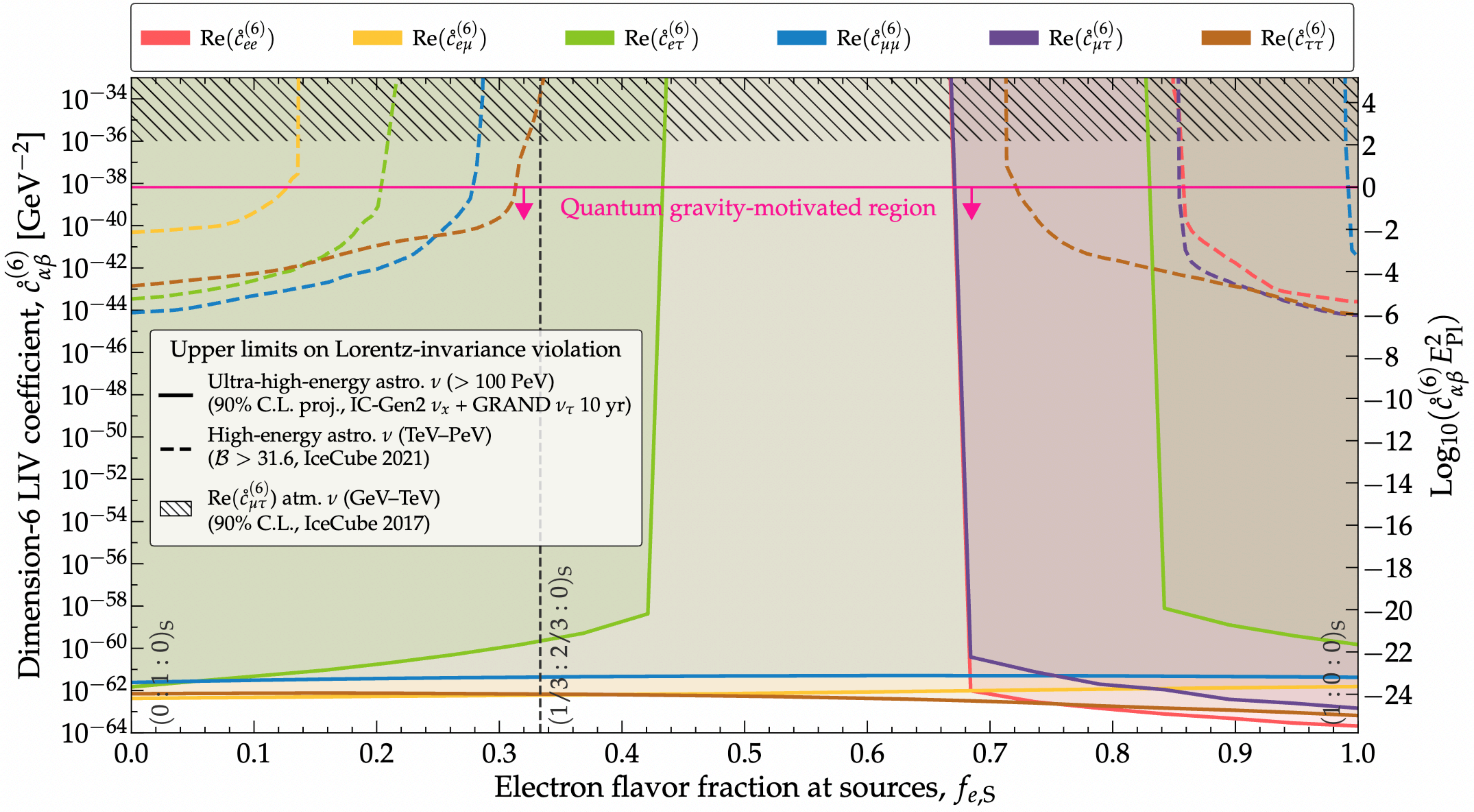


- Tau fraction from comparing GRAND and IceCube-Gen2 radio
- Individual flavor discrimination from differences in shower structure?

Testagrossa et al., work in progress

Flavor composition

$$H \sim \frac{m^2}{2E} + \overset{\circ}{a}^{(3)} - E \cdot \overset{\circ}{c}^{(4)} + E^2 \cdot \overset{\circ}{a}^{(5)} - E^3 \cdot \overset{\circ}{c}^{(6)} \ \ldots$$



- Tau fraction from comparing GRAND and IceCube-Gen2 radio
- Individual flavor discrimination from differences in shower structure?

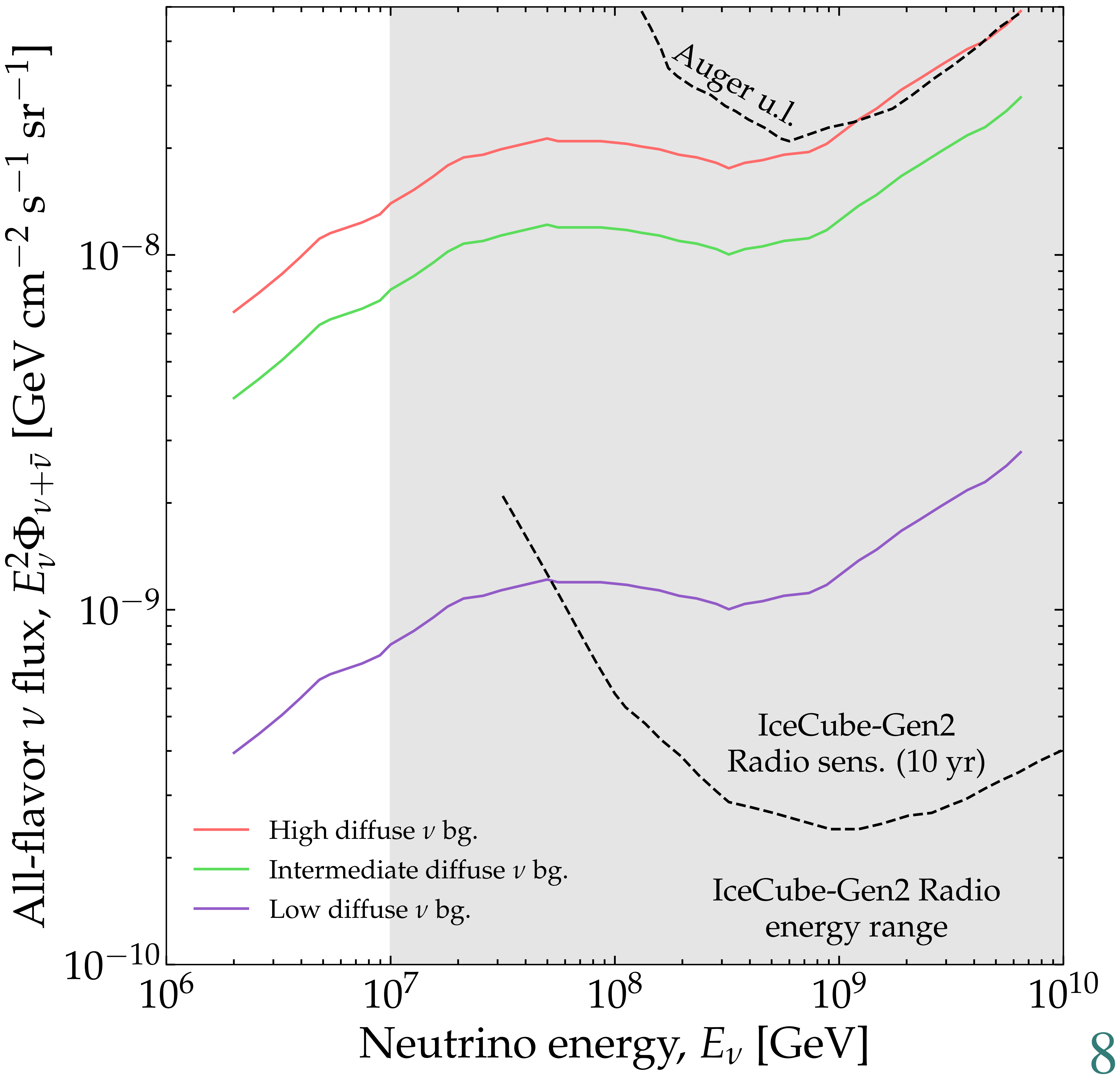
Testagrossa et al., work in progress

Multiplet searches

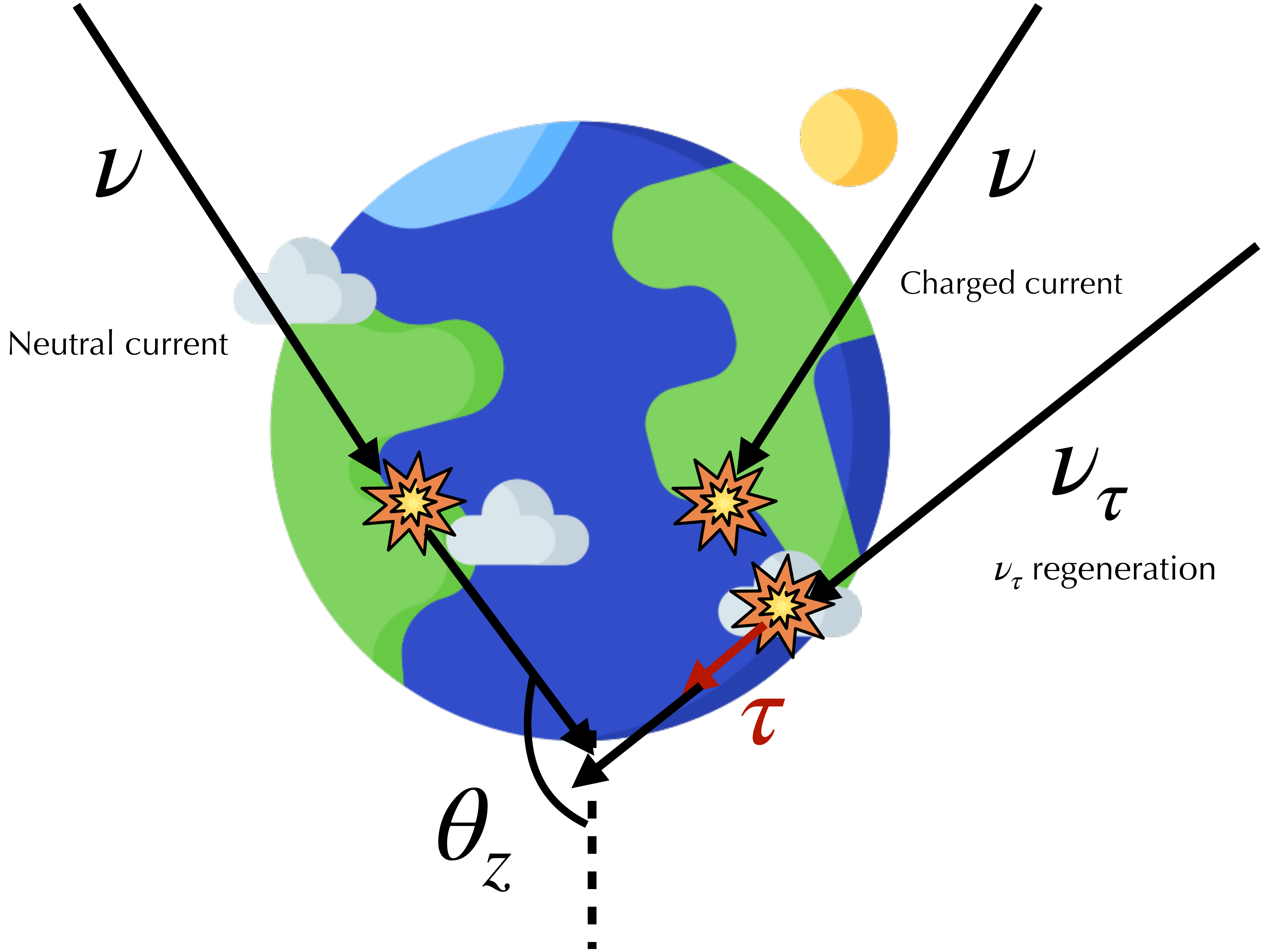
- Unresolved flux could produce fictitious multiplets by Poisson fluctuations

- ~ 3400 pixels make fluctuations more likely - look-elsewhere effect

- How large is the background?



Detector simulation



- Account for effects of Earth propagation
- Earth propagation leads to anisotropy of the signal
- Effective volume obtained in Valera et al., 2022 using NuRadioMC and NuRadioReco (Glaser et al., 2019)

Multiplet size

$$p = \sum_{k=n_i}^{+\infty} (\mu_i^k / k!) e^{-\mu_i}$$

Local p-value

↓

$$\pi_i(p) = \sum_{k=\bar{n}_i(p)}^{+\infty} \frac{\mu_i^k}{k!} e^{-\mu_i}$$

Prob. of excess in a single pixel

↓

$$P_0(p) = \prod_i (1 - \pi_i(p))$$

Prob. of no excess in any pixel

We require P_0 to be larger than the confidence level

Multiplet size - transients

$$p = \sum_{k=n_i}^{+\infty} (\mu_i^k / k!) e^{-\mu_i}$$

Local p-value

For burst duration δt and exposure T we introduce $T/\delta t$ bins in time

↓

$$\pi_i(p) = \sum_{k=\bar{n}_i(p)}^{+\infty} \frac{\mu_i^k}{k!} e^{-\mu_i}$$

Prob. of excess in a single pixel

↓

$$P_0(p) = \prod_i (1 - \pi_i(p))$$

Prob. of no excess in any pixel

We require P_0 to be larger than the confidence level

Chances of detection

$$P(n_i) = \sum_{\sigma_i} \frac{\lambda^{\sigma_i} e^{-\lambda}}{\sigma_i!} \prod_{\alpha=1}^{\sigma_i} \int p(z_\alpha) dz_\alpha \frac{(b_i + \sum_{\alpha=1}^{\sigma_i} s(z_\alpha))^{n_i}}{n_i!} e^{-b_i - \sum_{\alpha=1}^{\sigma_i} s(z_\alpha)}$$

Prob. of n_i events in a pixel

Prob. of σ_i sources in a pixel

Redshift distribution of each source - follows star formation rate

Number of events follows a Poisson distribution - expected number of events come from diff. background and sources

Chances of detection

$$P(n_i) = \sum_{\sigma_i} \frac{\lambda^{\sigma_i} e^{-\lambda}}{\sigma_i!} \prod_{\alpha=1}^{\sigma_i} \int p(z_\alpha) dz_\alpha \frac{(b_i + \sum_{\alpha=1}^{\sigma_i} s(z_\alpha))^{n_i}}{n_i!} e^{-b_i - \sum_{\alpha=1}^{\sigma_i} s(z_\alpha)}$$

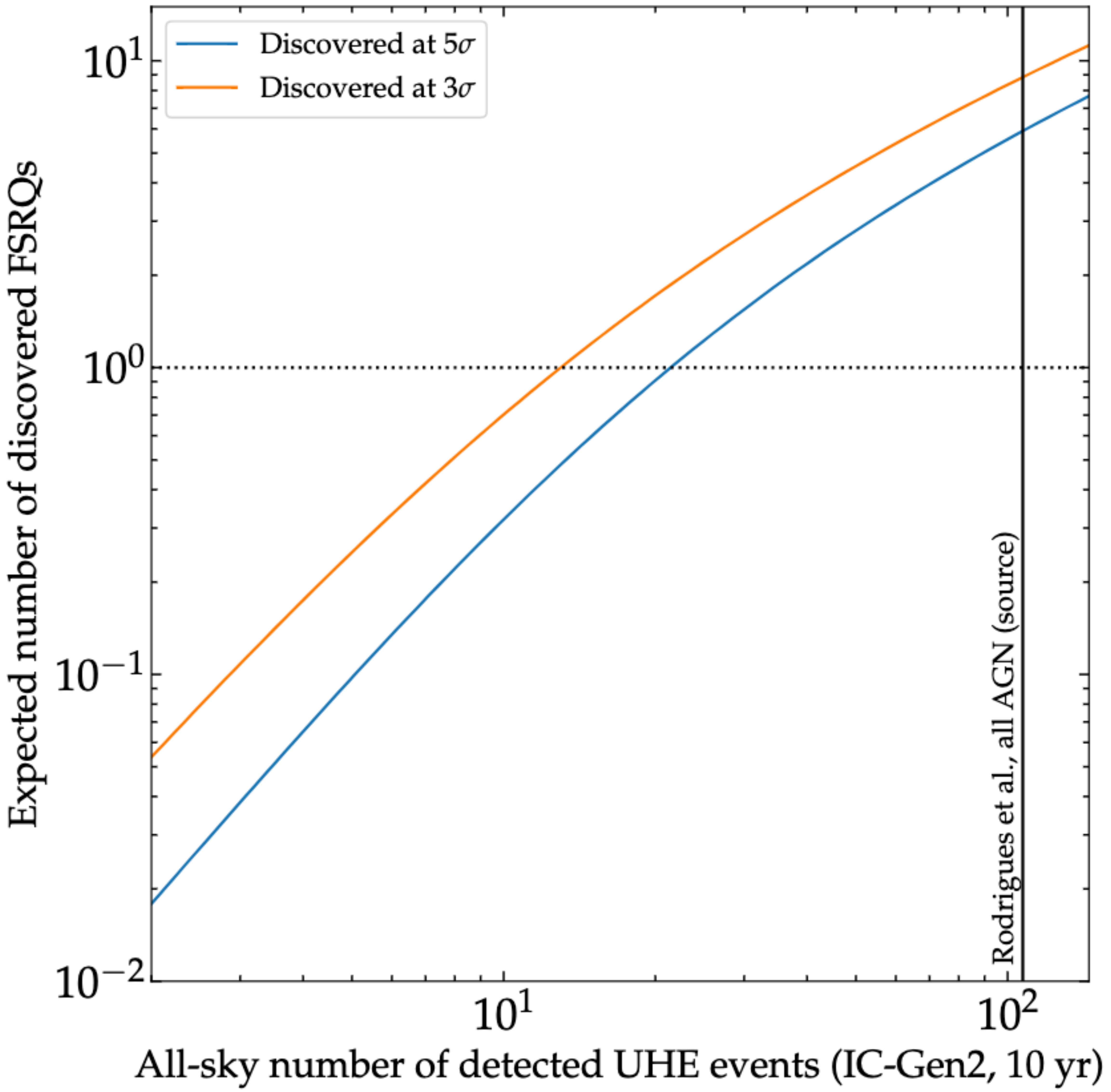
Prob. of n_i events in a pixel

Prob. of σ_i sources in a pixel

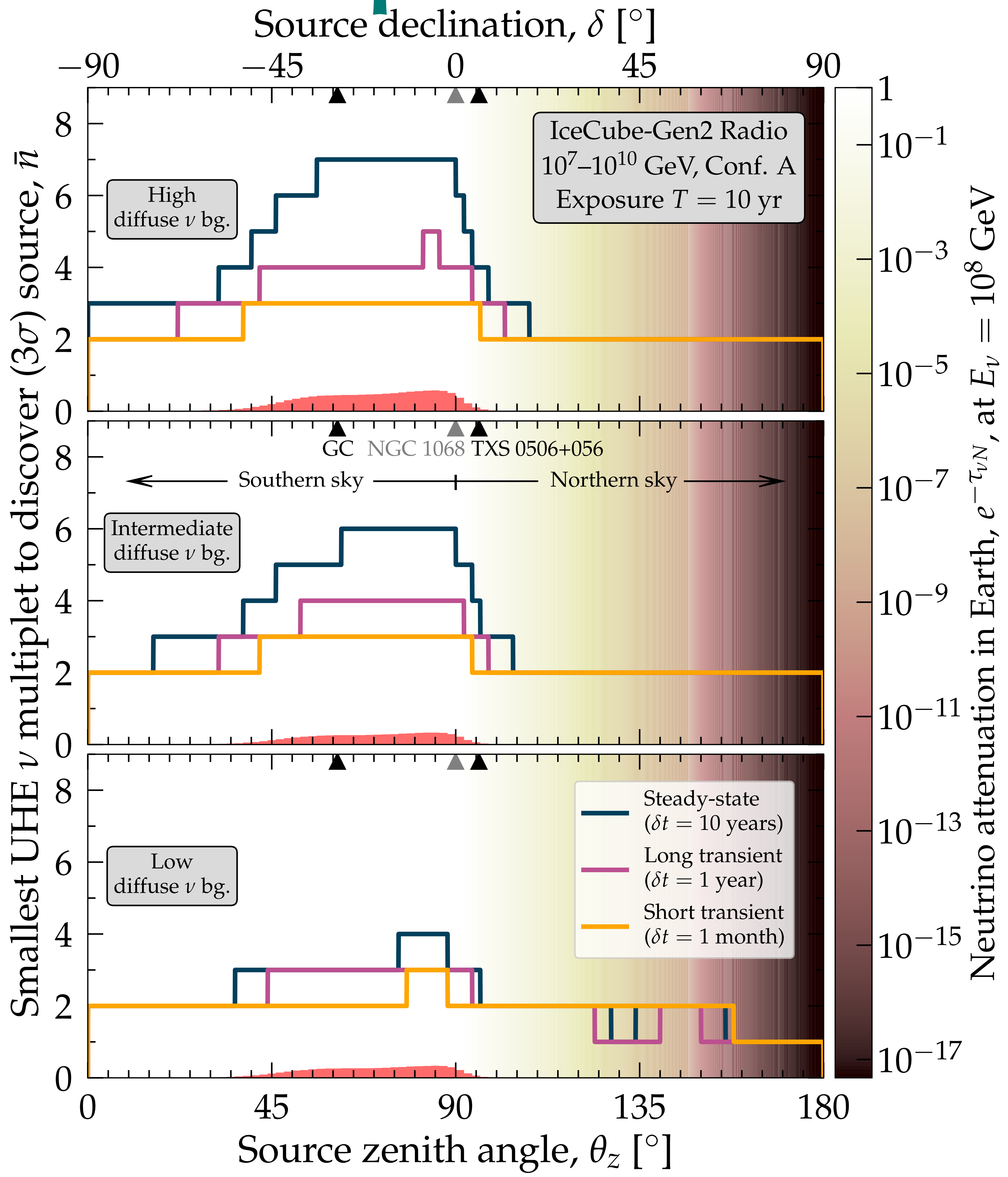
Redshift distribution of each source - follows star formation rate

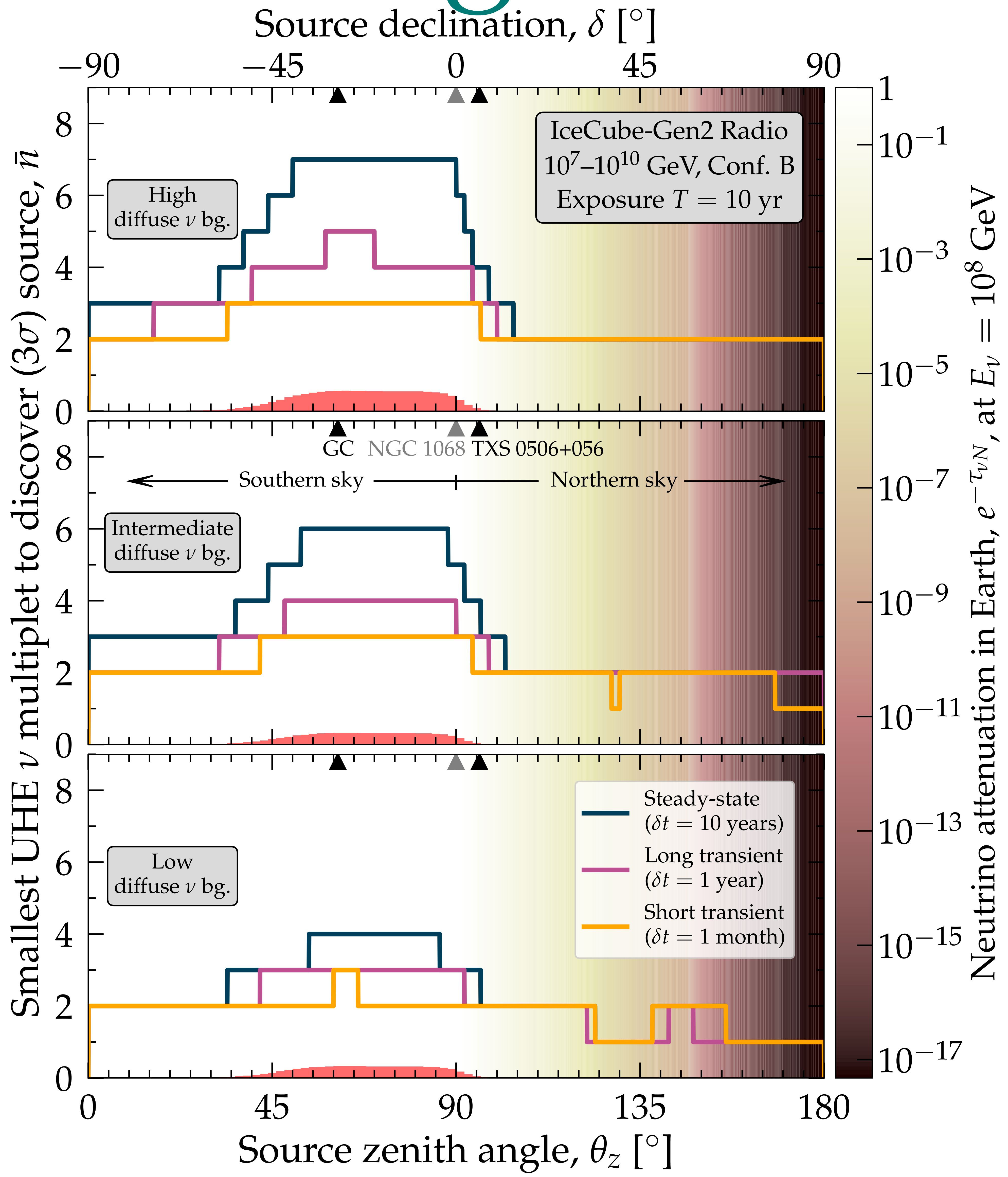
Number of events follows a Poisson distribution - expected number of events come from diff. background and sources

FSRQ expected detection

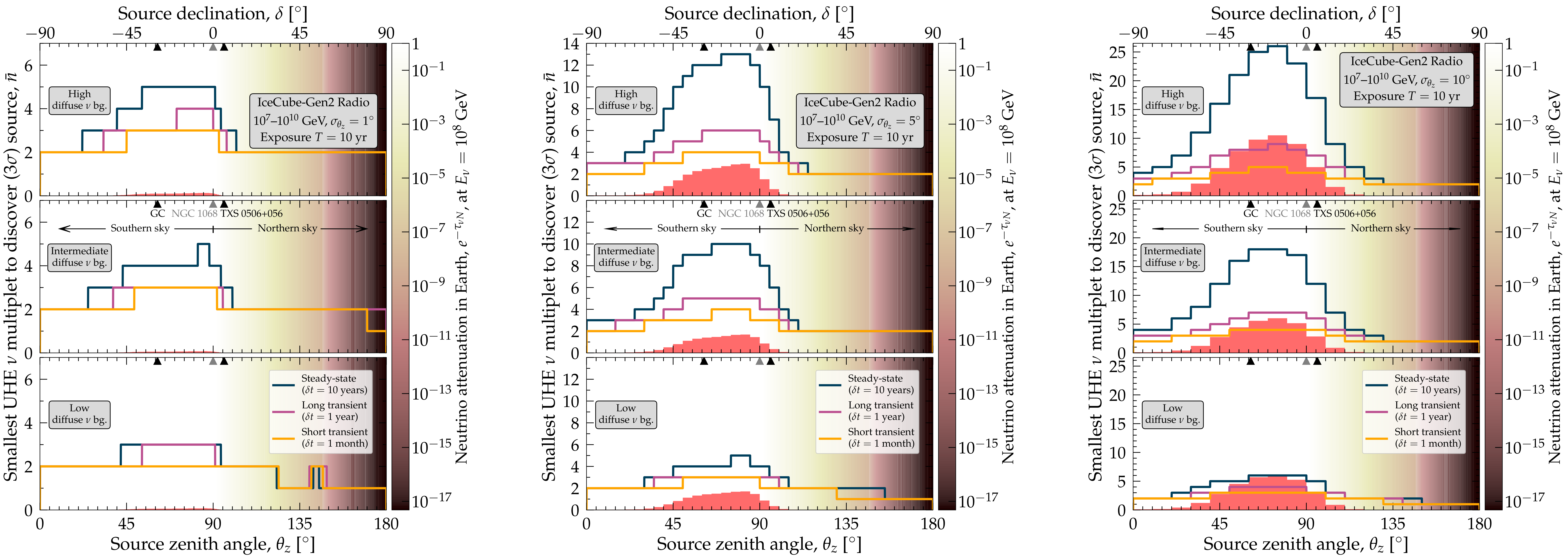


Impact of detector design



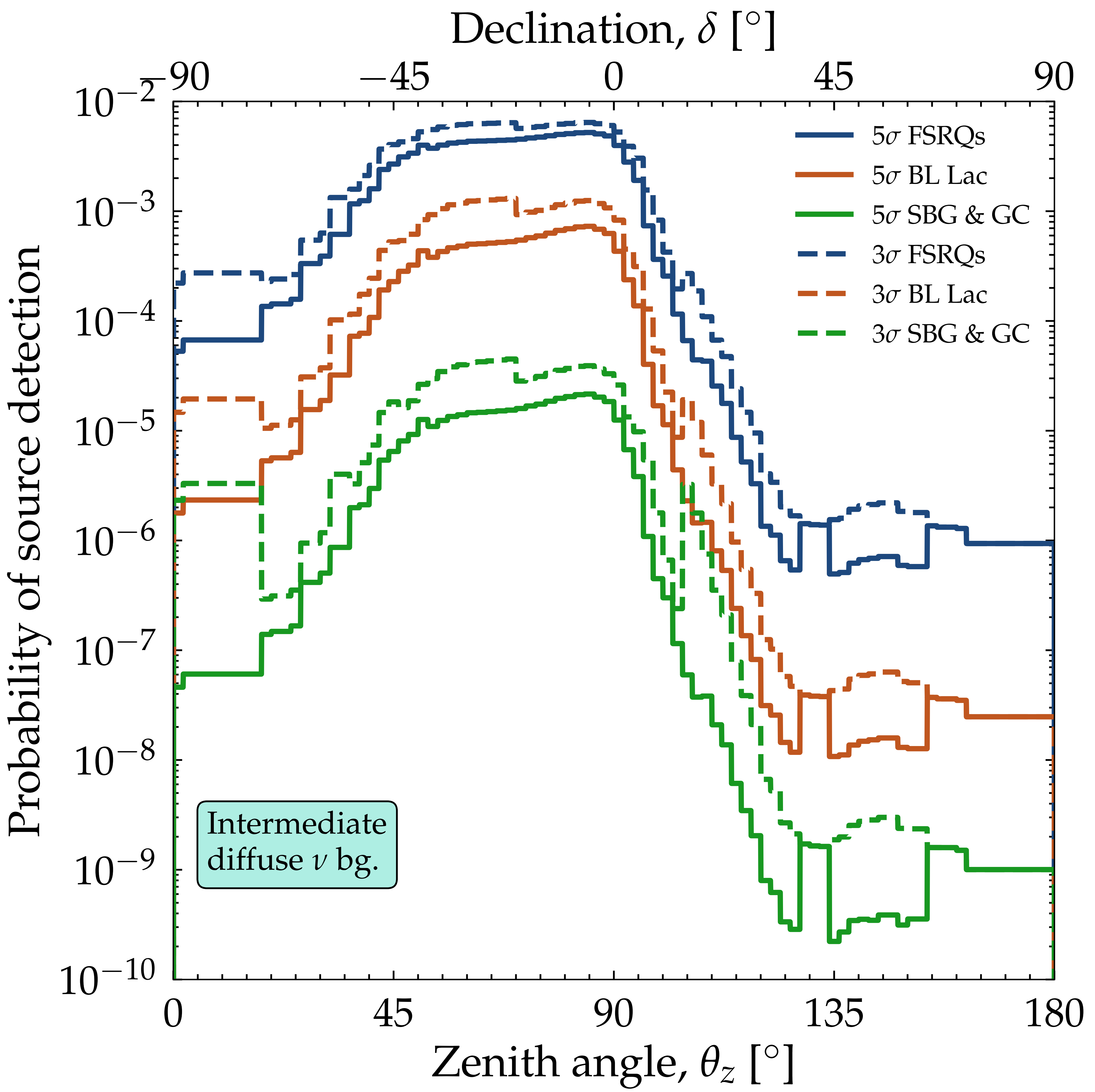


Impact of angular resolution



Damiano Fiorillo

Chances of detection



- For a given source population, three random variables:
  - Number of sources in a pixel
  - Source distance
  - Number of events from the source
- Averaging over all three, we obtain probability of significant multiplets