# Near-future discovery of point sources of ultra-high-energy neutrinos

Damiano F. G. Fiorillo

Niels Bohr Institute, Copenhagen

Based on arXiv:2205.15985,

with Mauricio Bustamante, Victor B. Valera

KØBENHAVNS UNIVERSITET
UNIVERSITY OF COPENHAGEN

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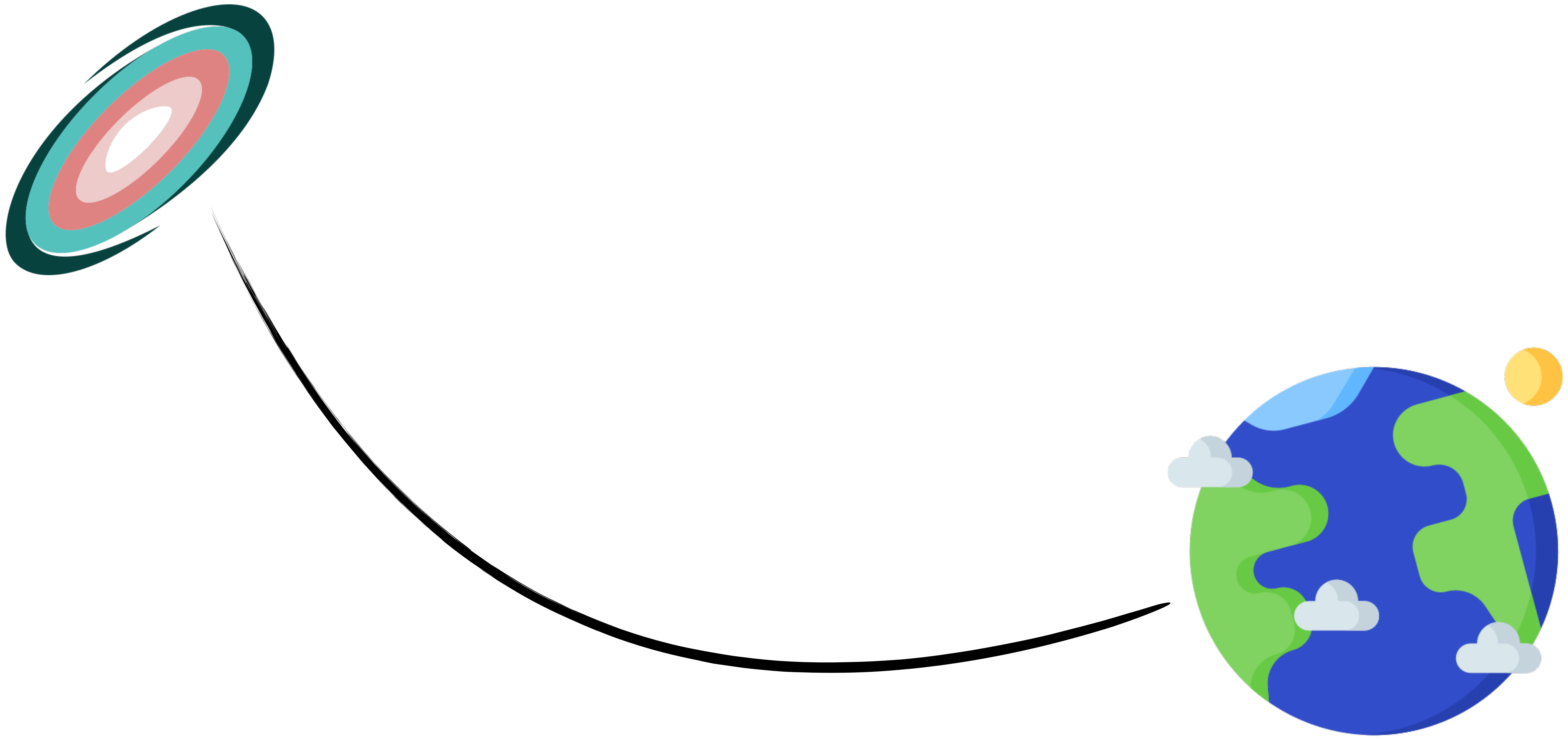
# Multimessenger astrophysics



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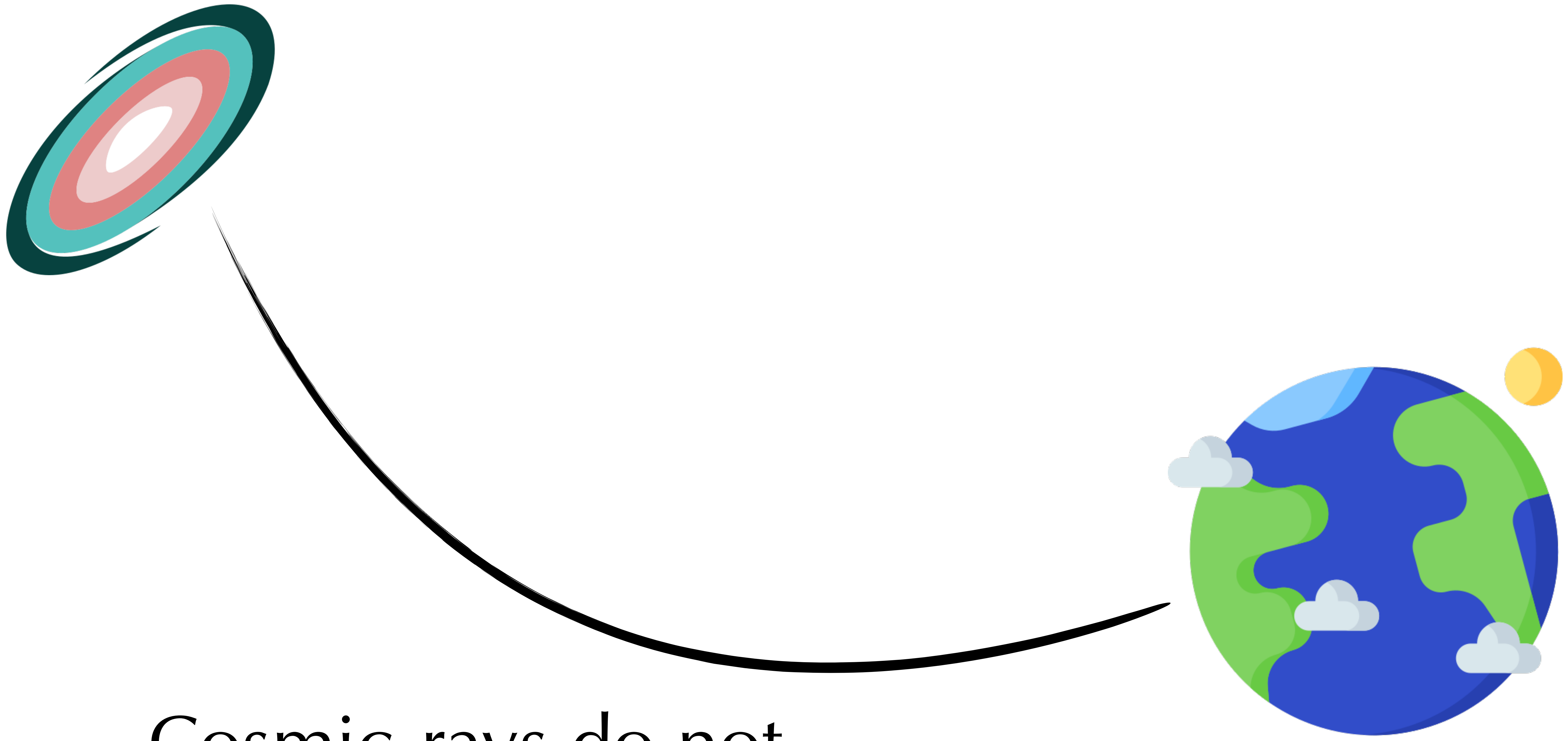
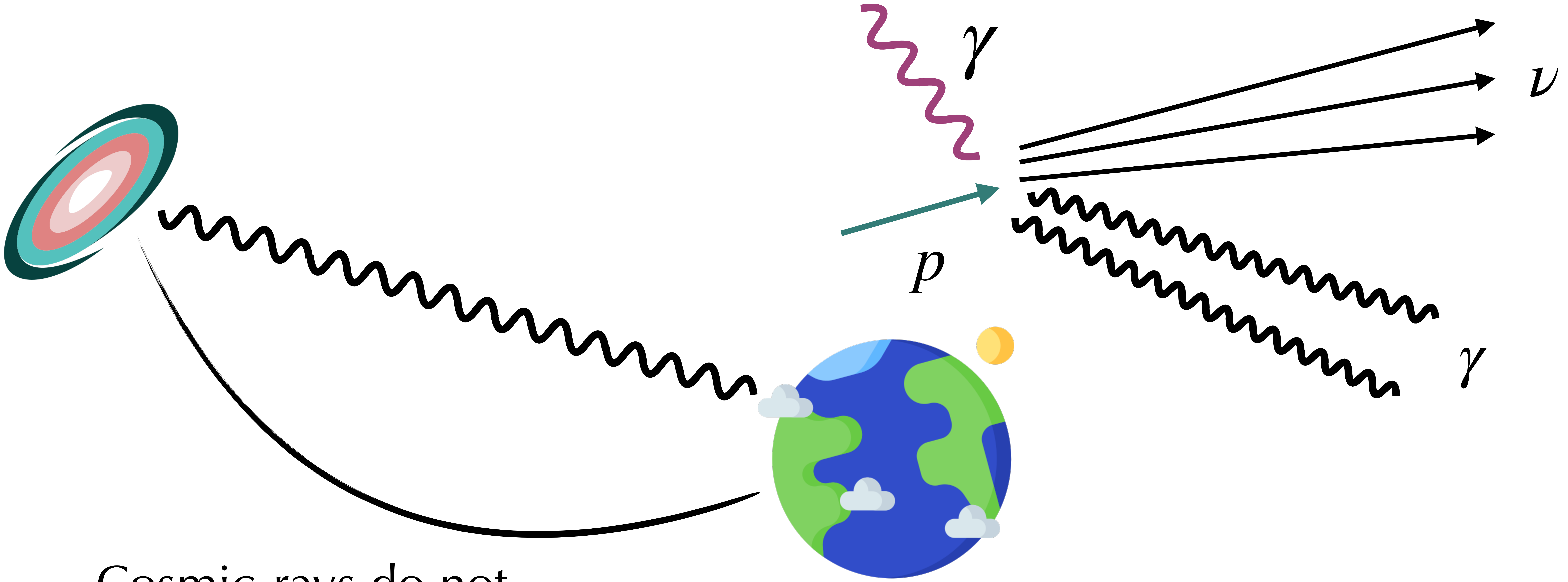


Cosmic-rays do not point back to sources

- At ultra-high energies hints of anisotropies
  - Large-scale dipolar anisotropy (Auger, 2017)
  - Small-scale anisotropies (Auger, 2018; TA, 2021)

# Multimessenger astrophysics

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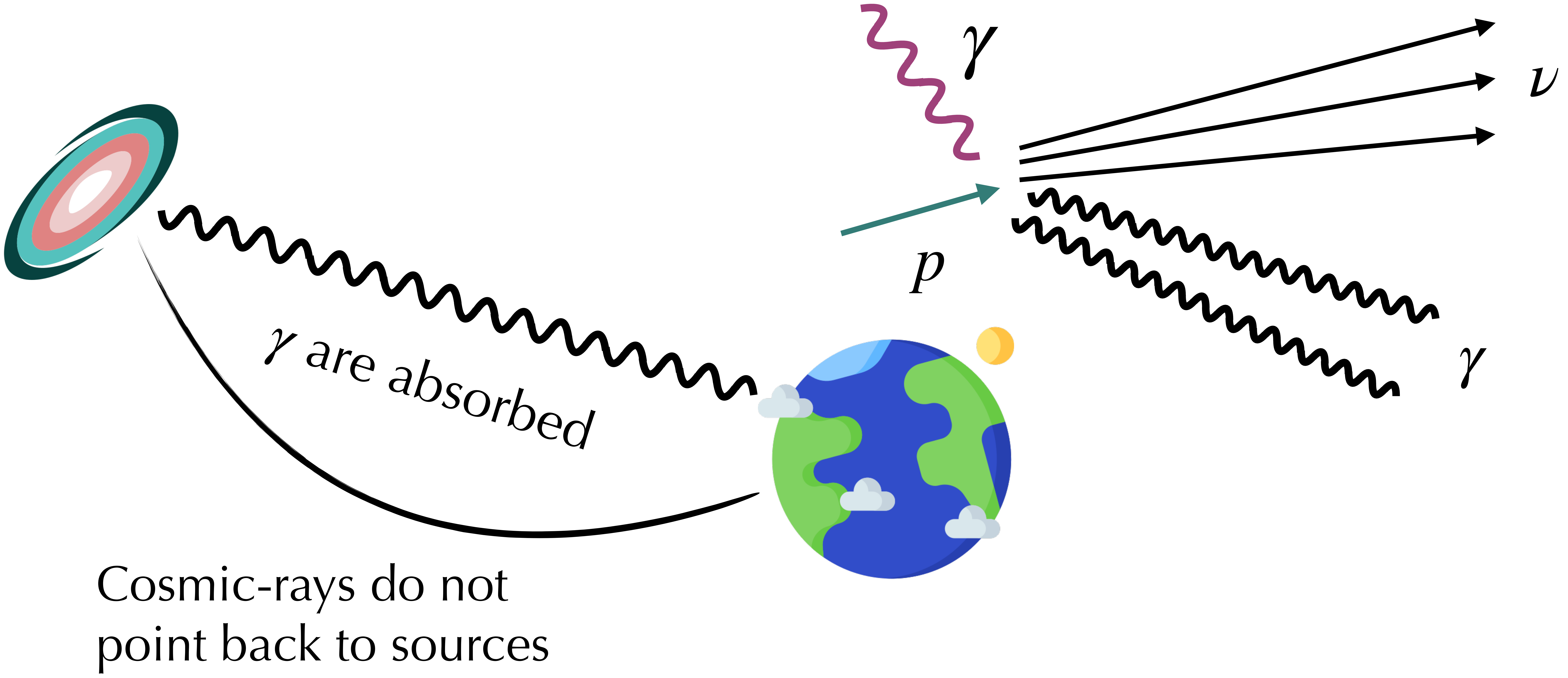

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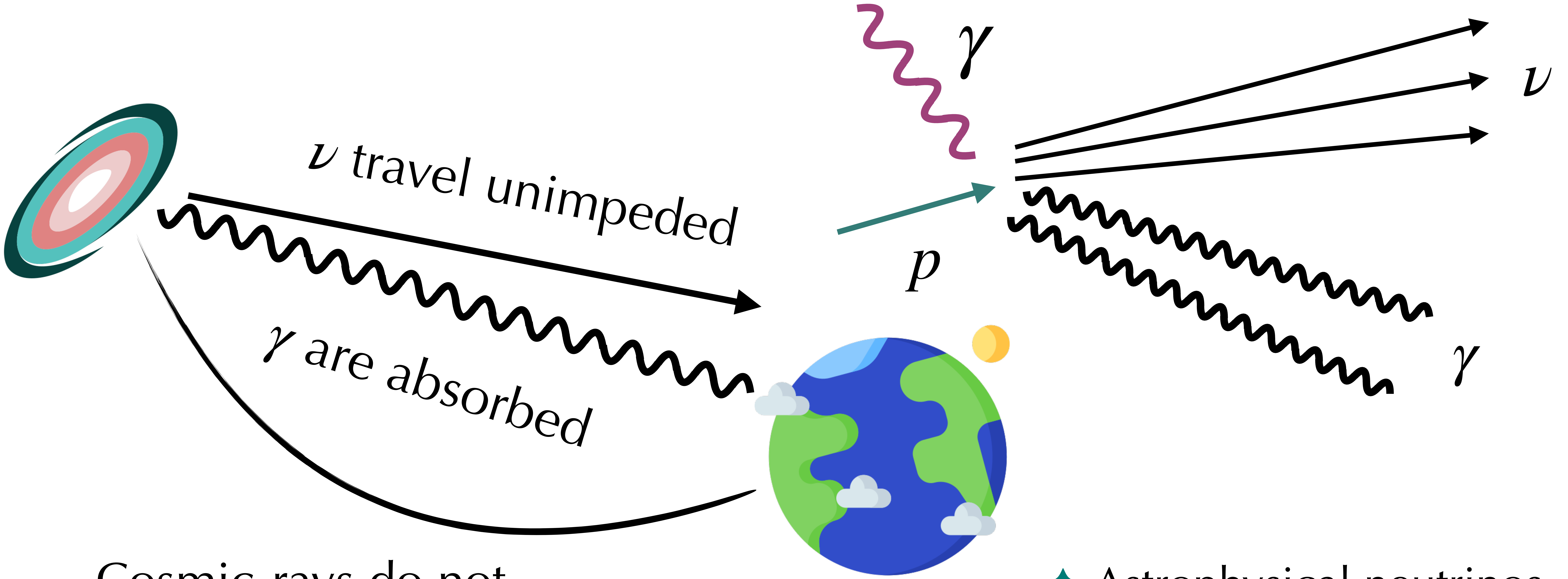
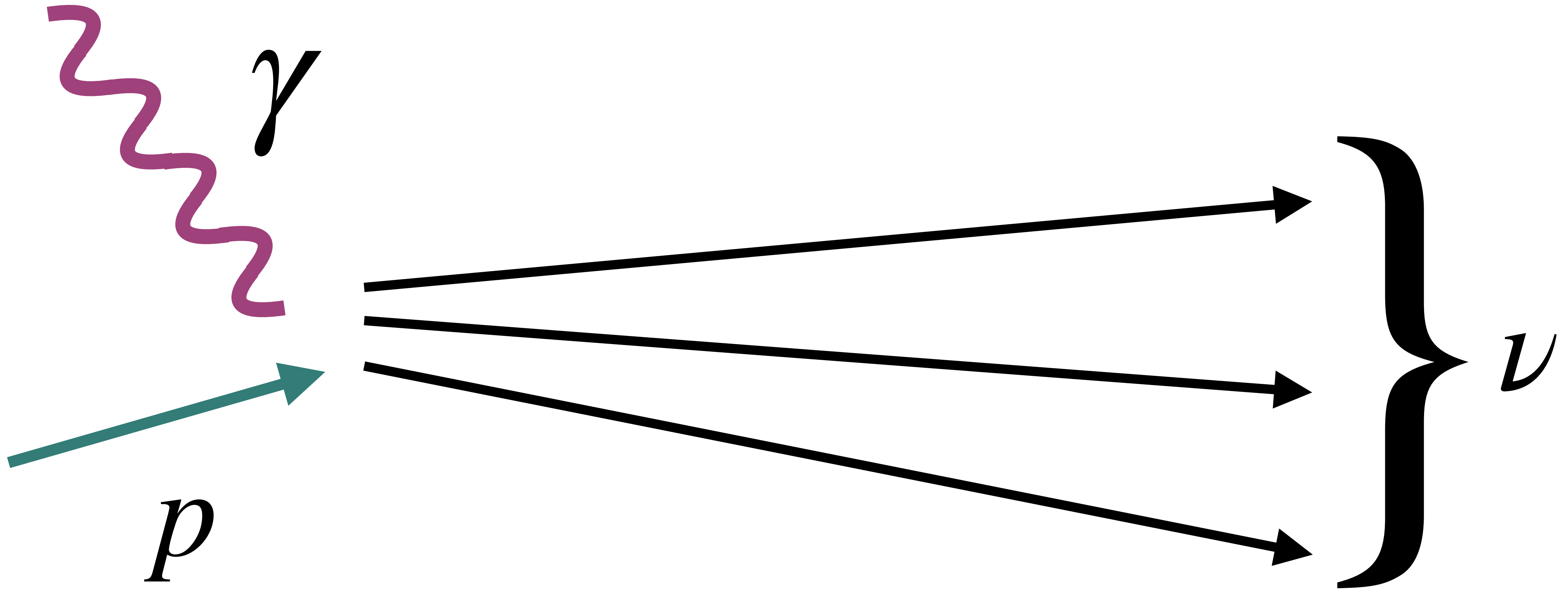


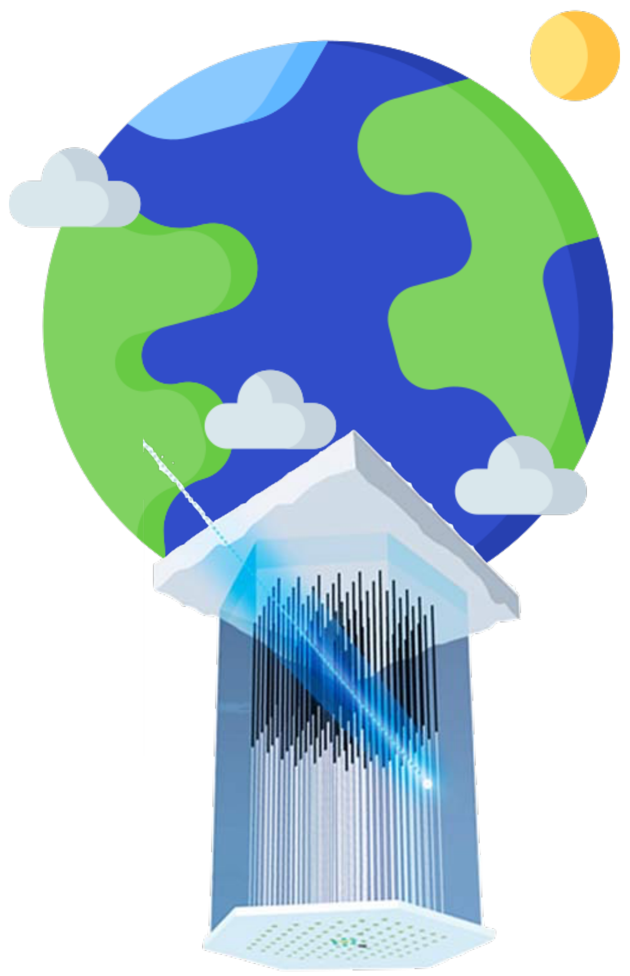

Cosmic-rays do not point back to sources

- Astrophysical neutrinos can locate point sources!

# High-energy neutrino point sources




Typically
$E_\nu \sim 0.05 E_p$



km$^3$ scale detector

IceCube-Gen2 will increase
volume by an order of magnitude

- IceCube detects neutrinos with TeV-PeV energies
- A few candidate sources reported: TXS 0506+056 (IceCube, 2018), AT2019dsg (IceCube, 2021), NGC 1068 (IceCube, 2021)
- Signature of $\sim 100$ PeV cosmic rays

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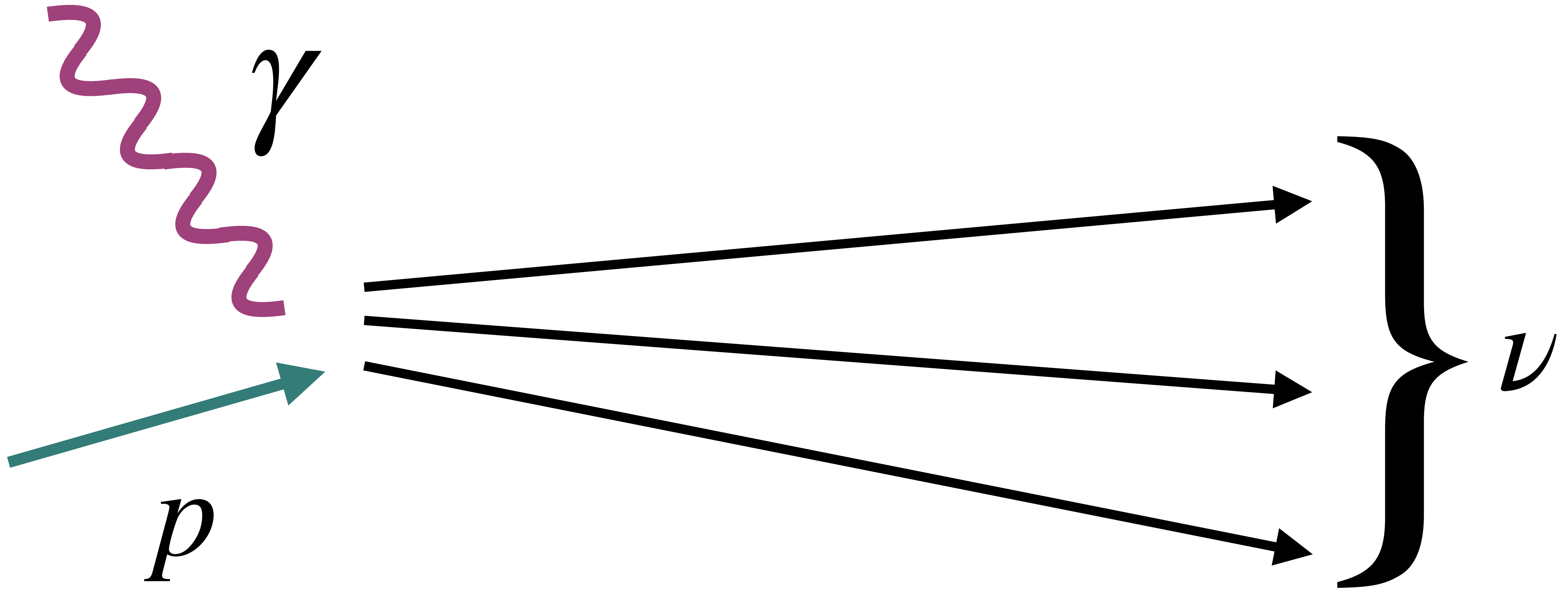


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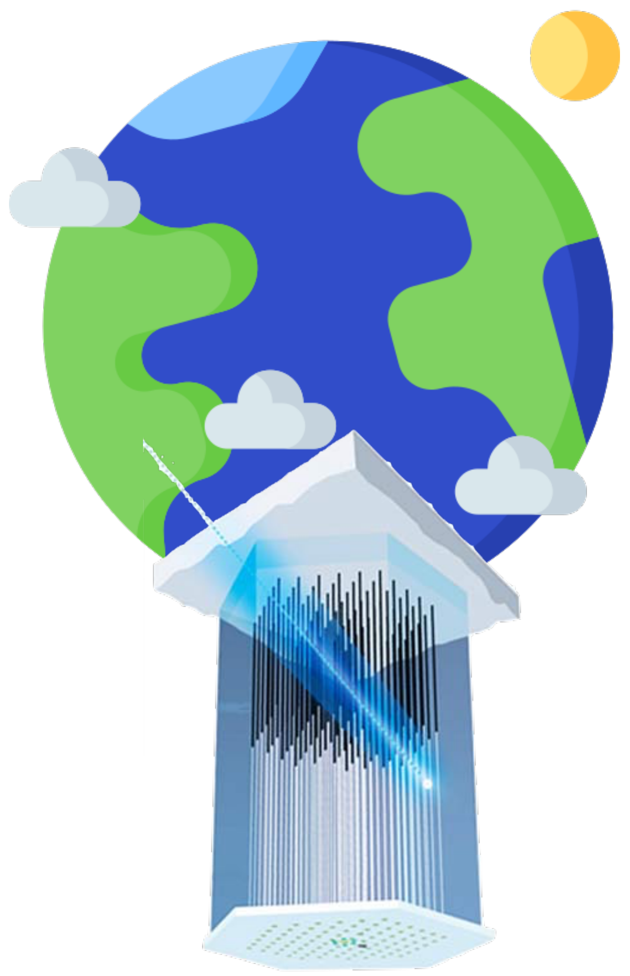

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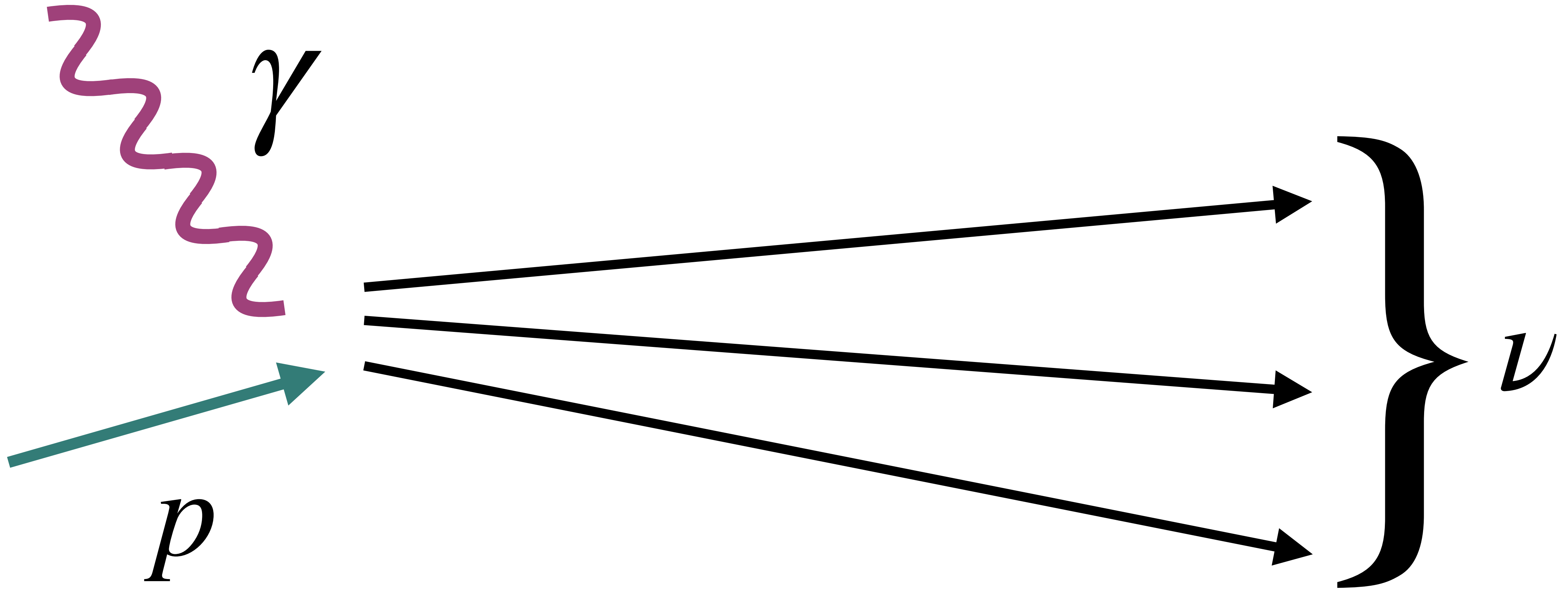


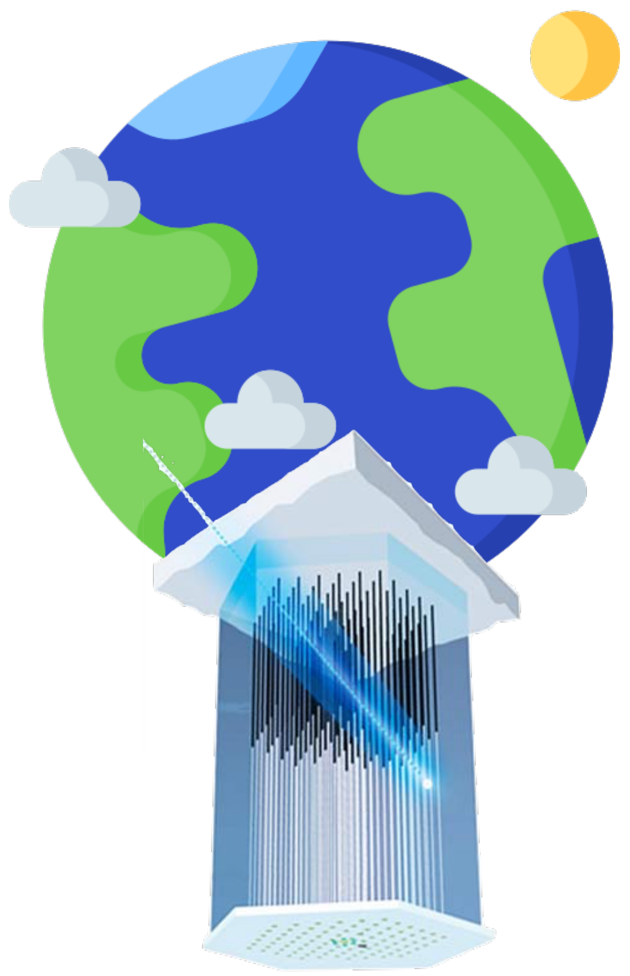

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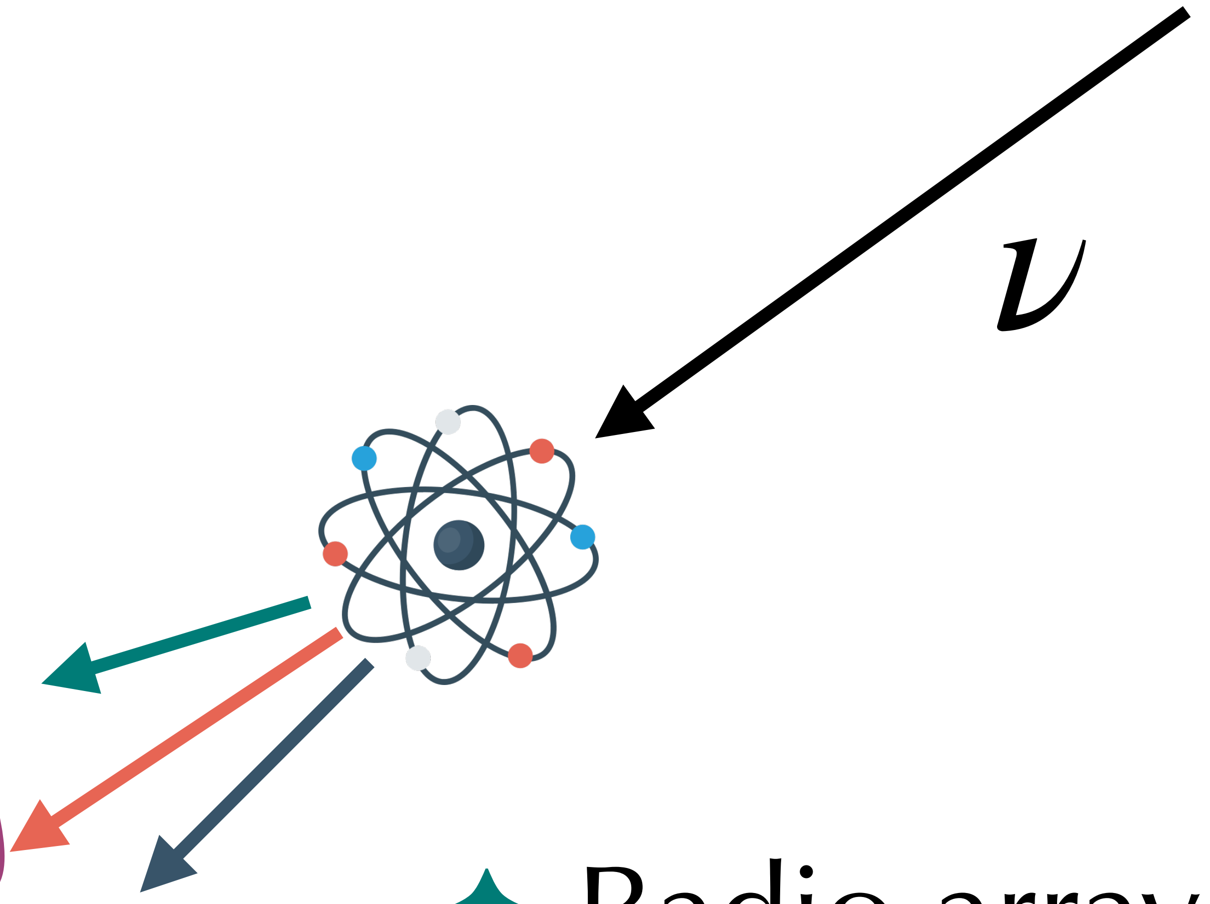
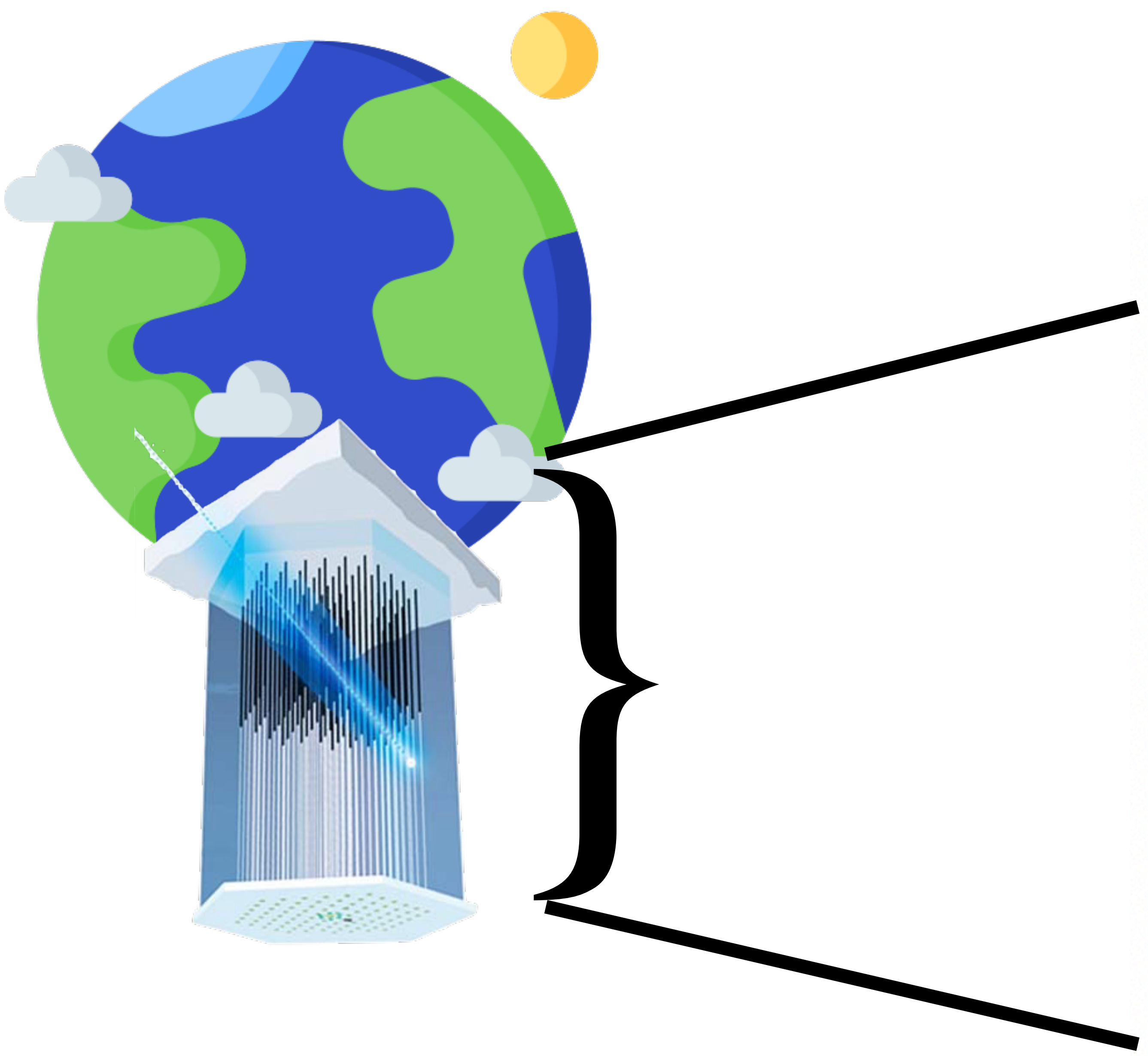
**Can we detect sources of ultra-high-energy (UHE) neutrinos?**

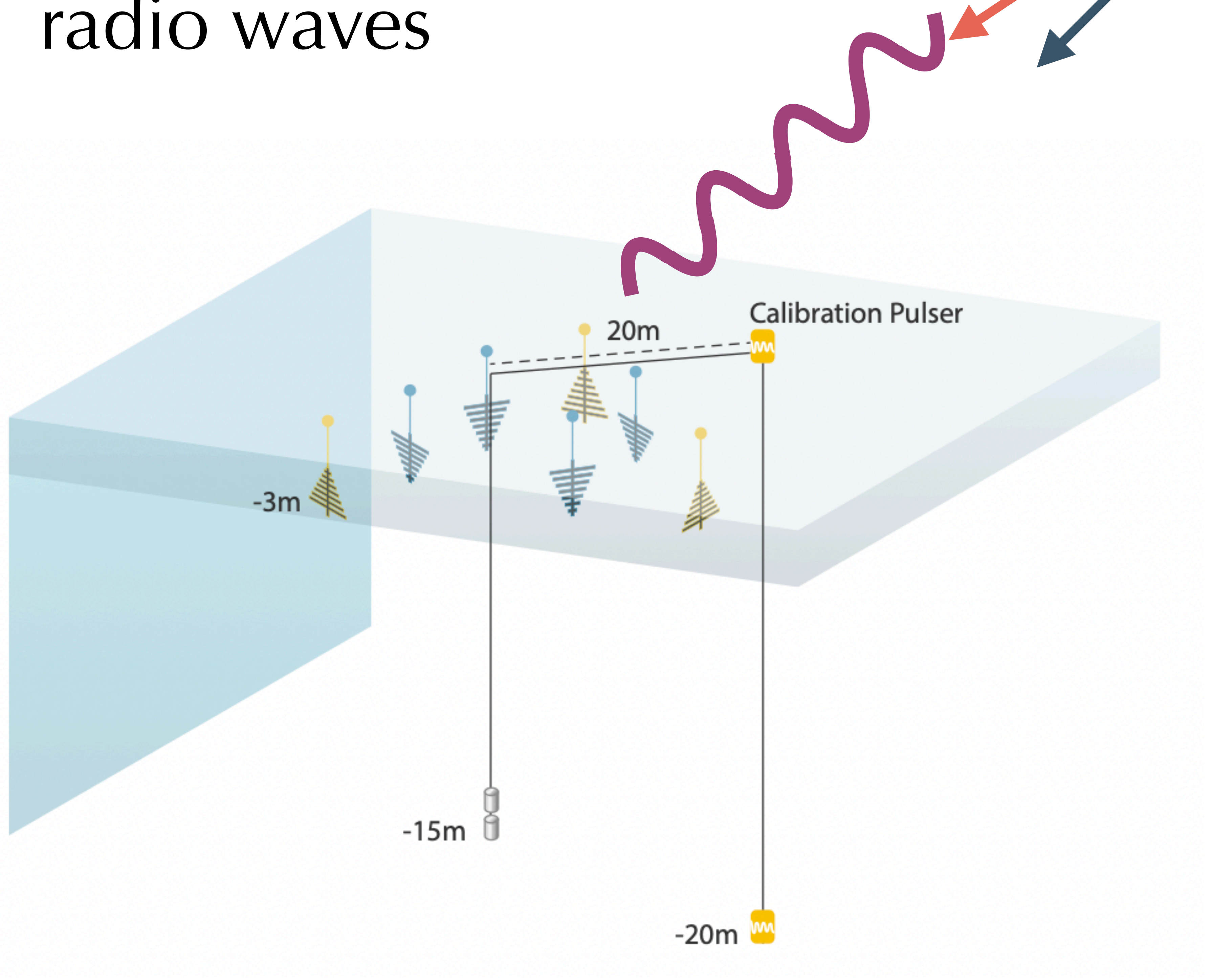
# UHE neutrino detection

**Askaryan effect** -

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



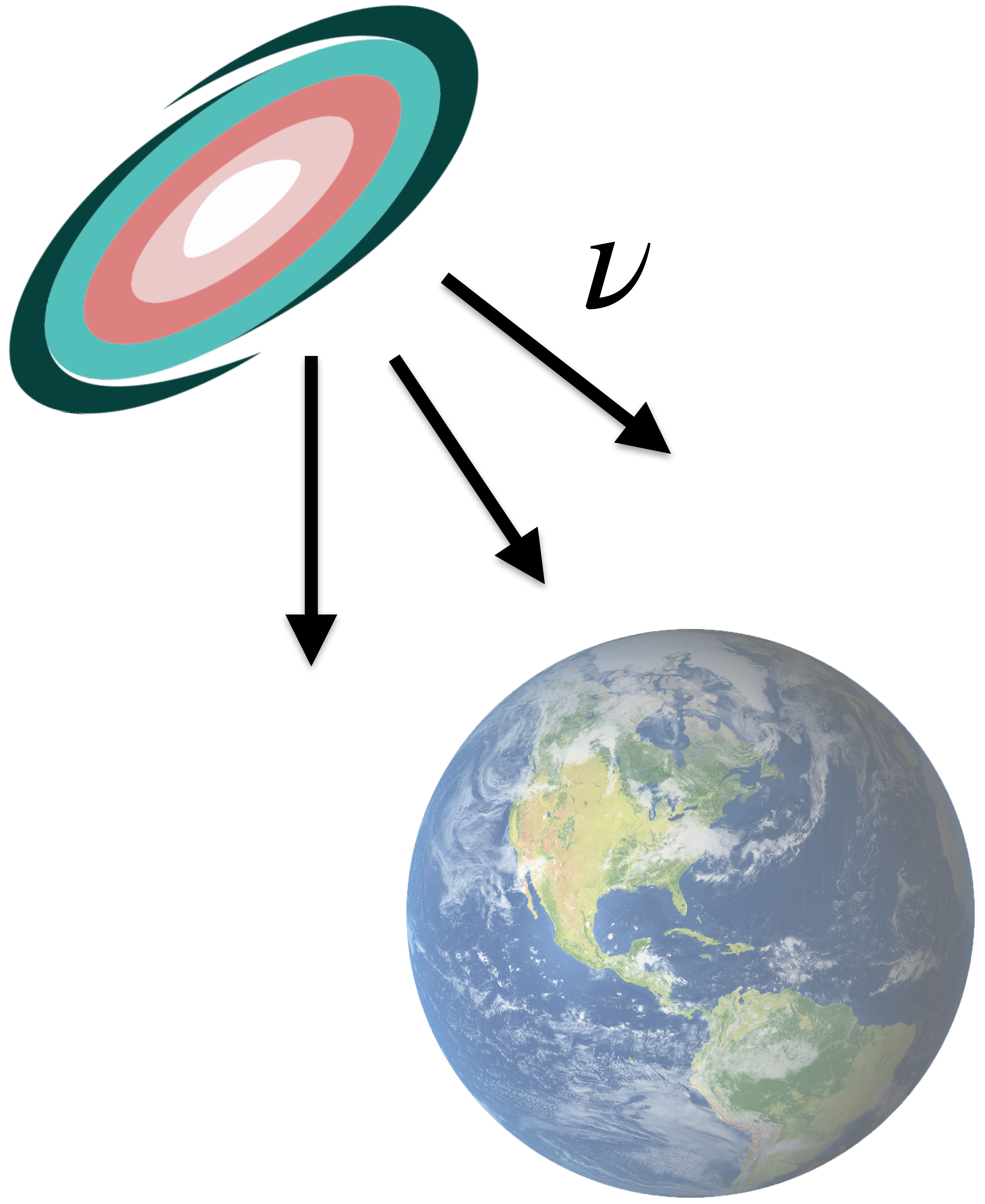





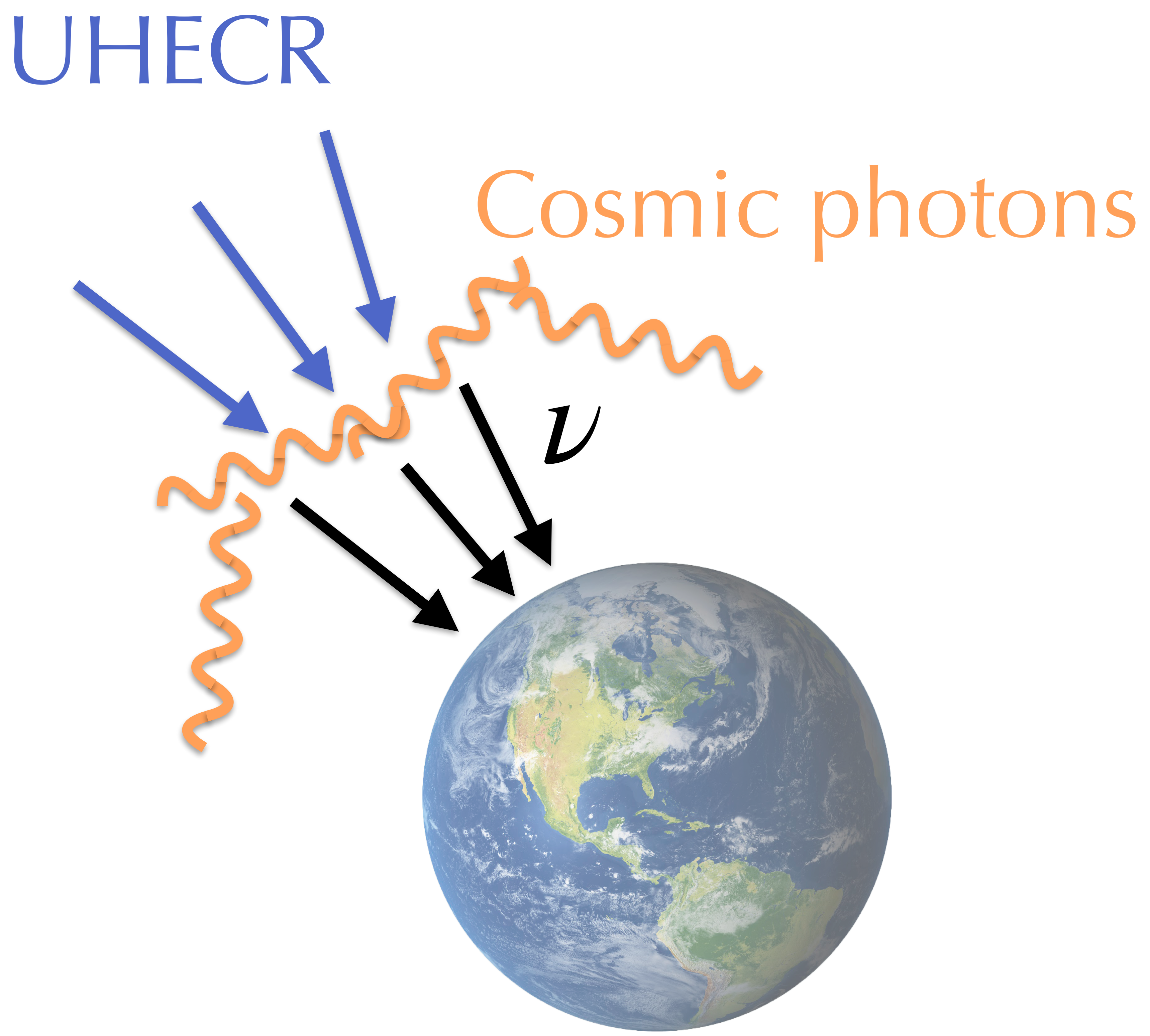

- ✦ Radio array in IceCube-Gen2 will be sensitive to UHE neutrinos
- ✦ Start taking data in 2030
- ✦ Realistic prospects for point source detection at IceCube-Gen2 radio array

# UHE neutrinos

**Source neutrinos**




**Cosmogenic neutrinos**



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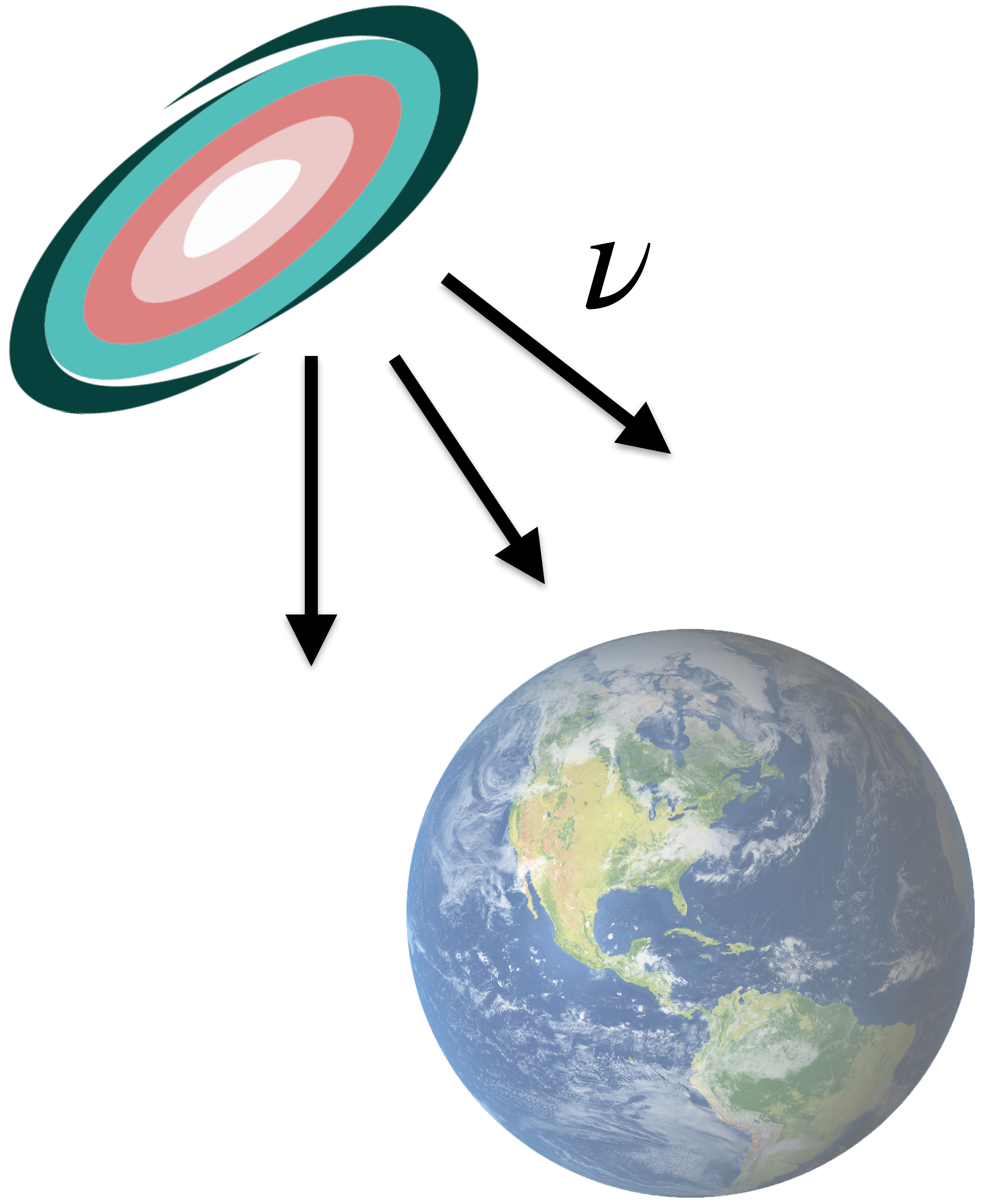


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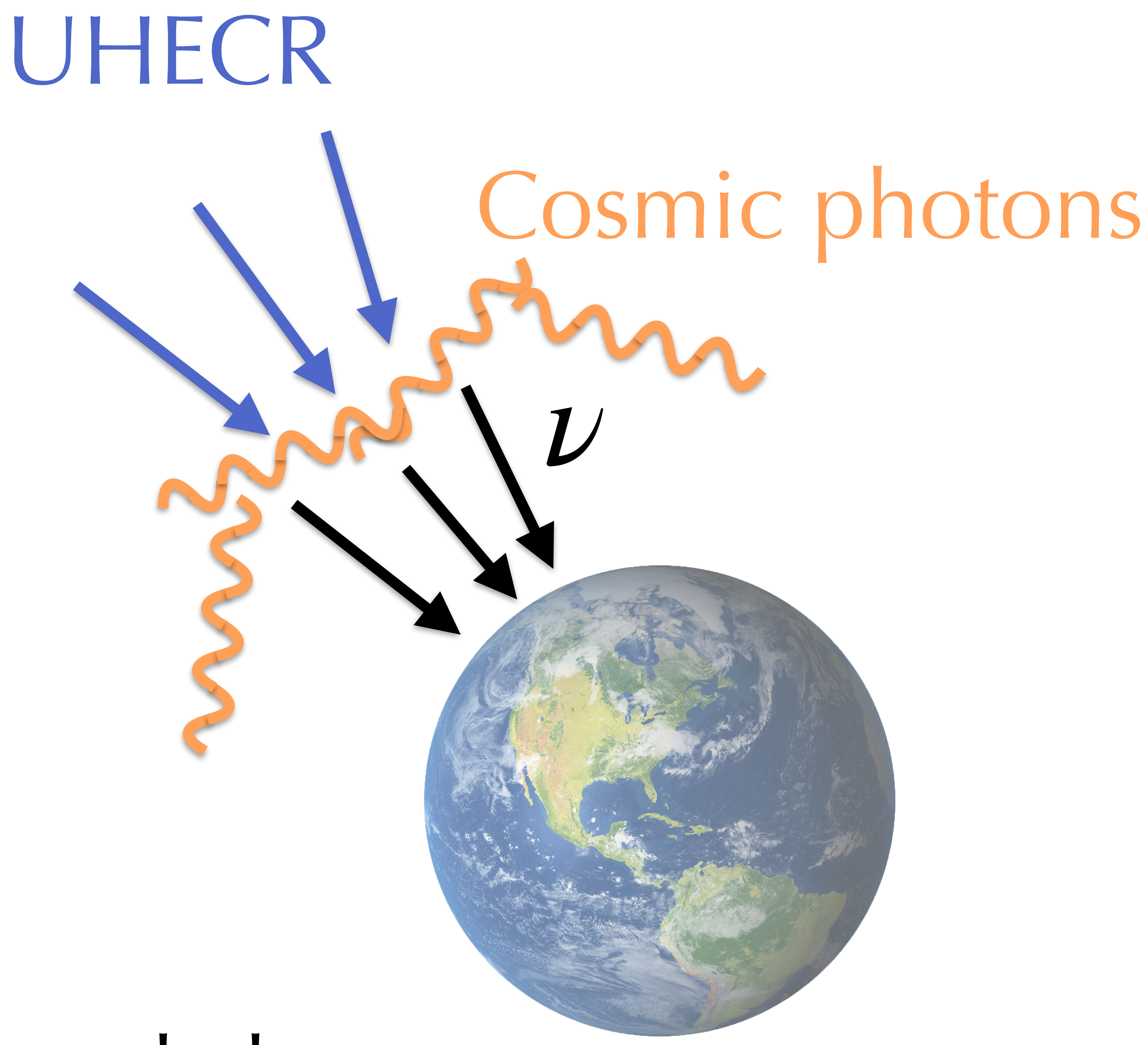
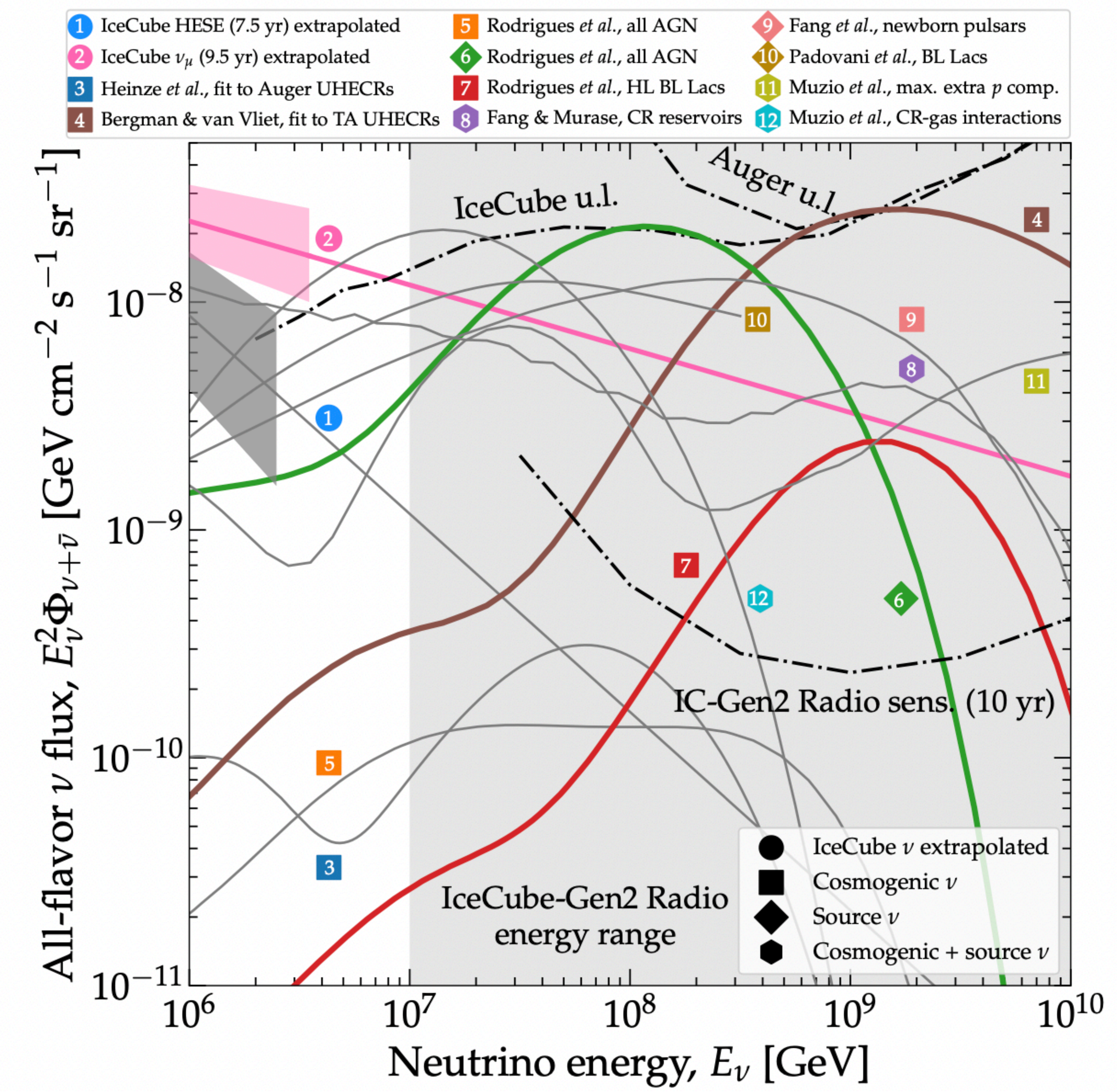



Point source discovery can help discriminate between the two!

# UHE neutrinos

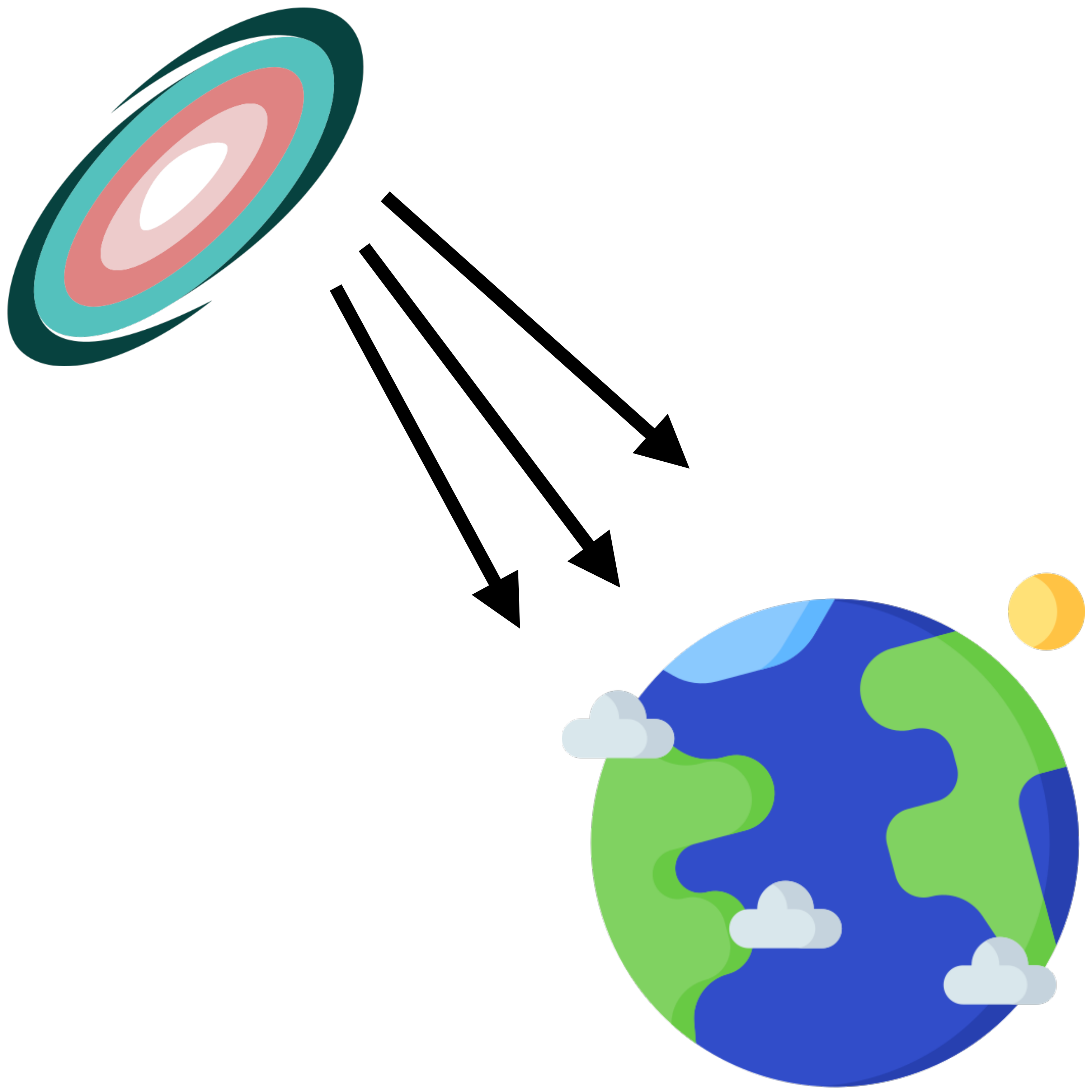



- Landscape of theoretical models for UHE neutrinos
- Huge uncertainty in the magnitude of the diffuse flux
- Either cosmogenic or source neutrinos may dominate

Valera, Bustamante, Glaser, 2022

# Multiplet searches

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



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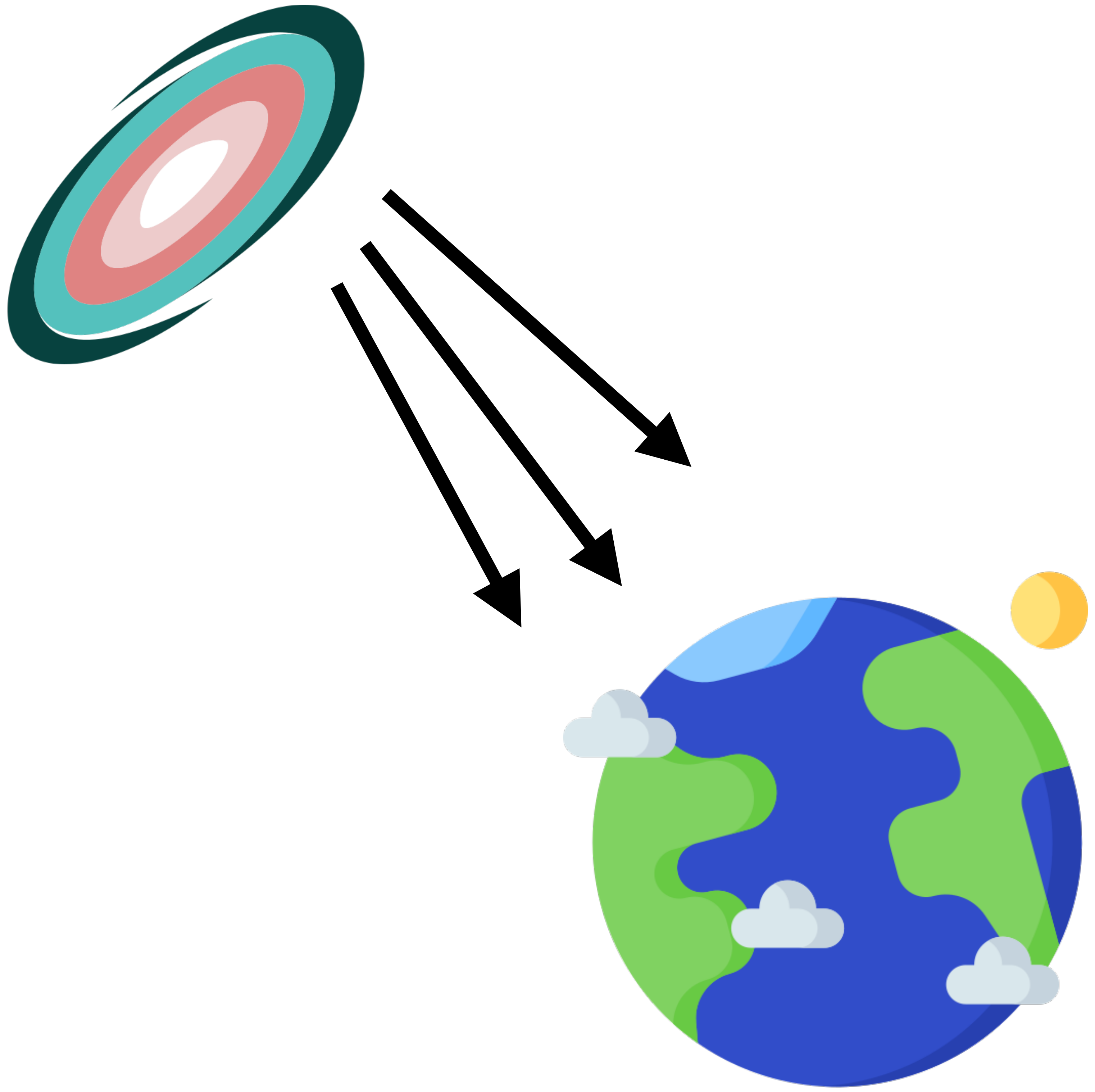
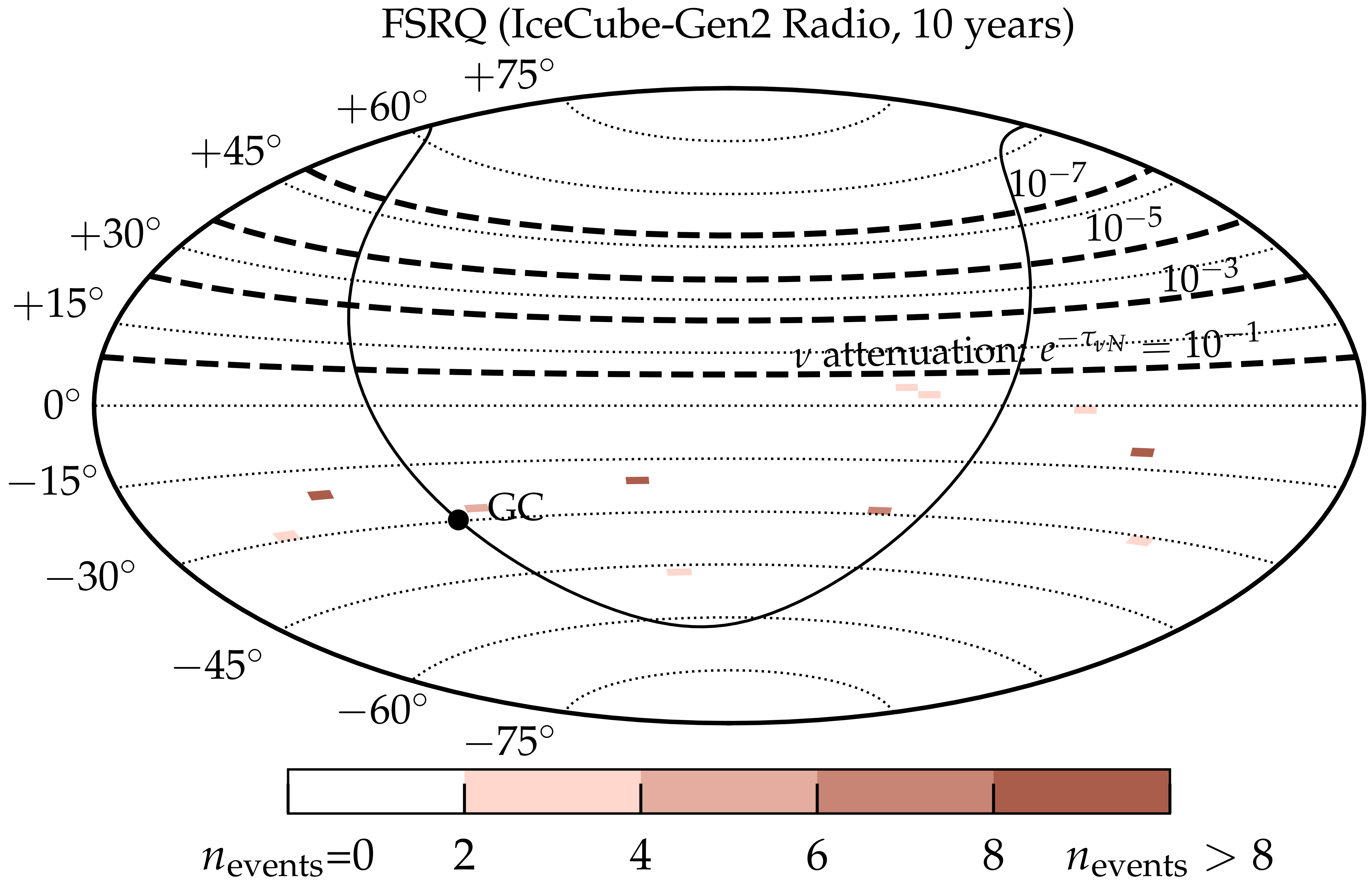


Assume angular uncertainty ~ 2°, so we divide the sky in pixels of 2° × 2° solid angle




See also Fang et al., 1609.08027

# Multiplet searches

- Unresolved flux could produce fictitious multiplets by Poisson fluctuations
- $\sim 3400$ pixels make fluctuations more likely - look-elsewhere effect

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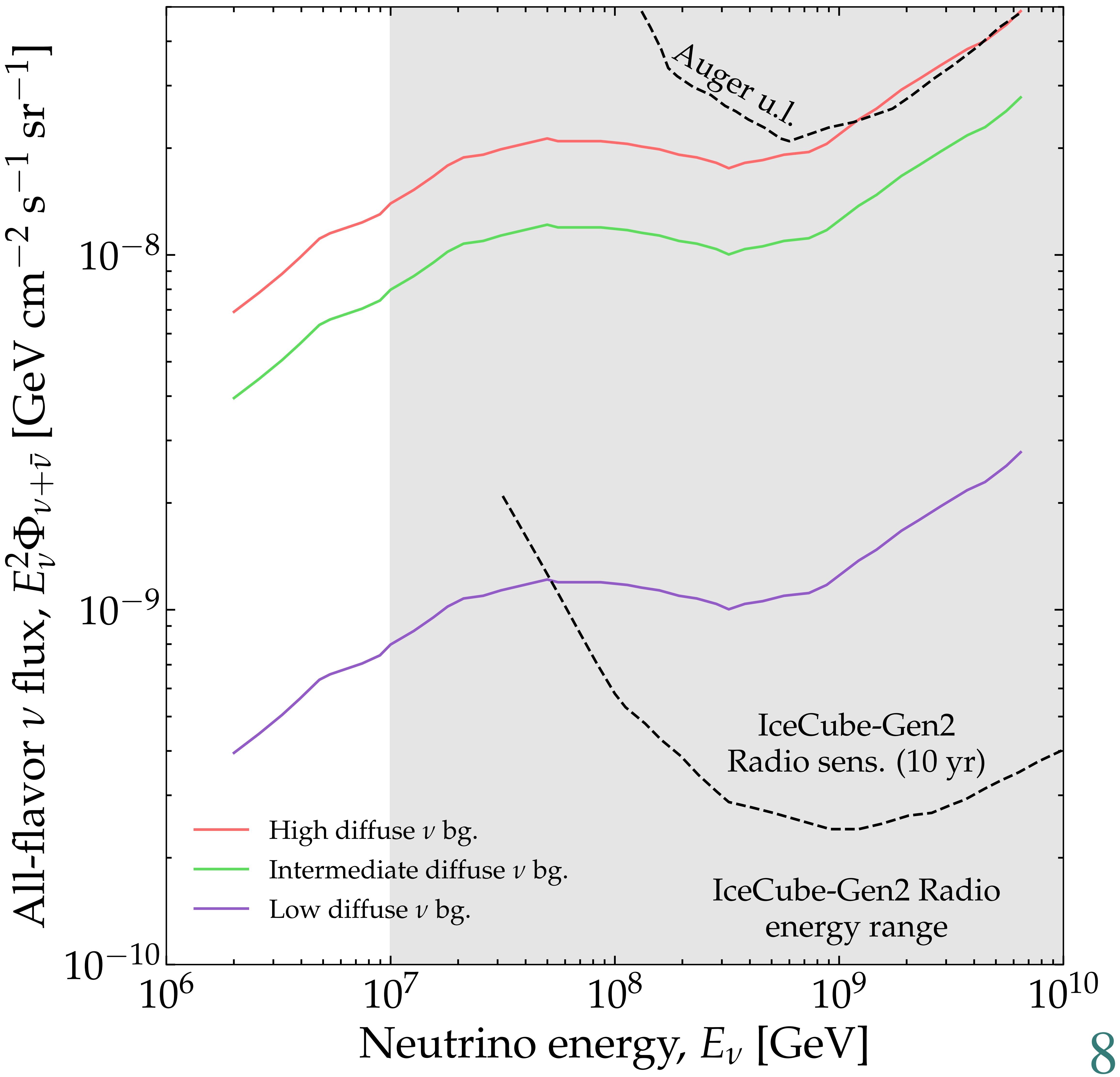
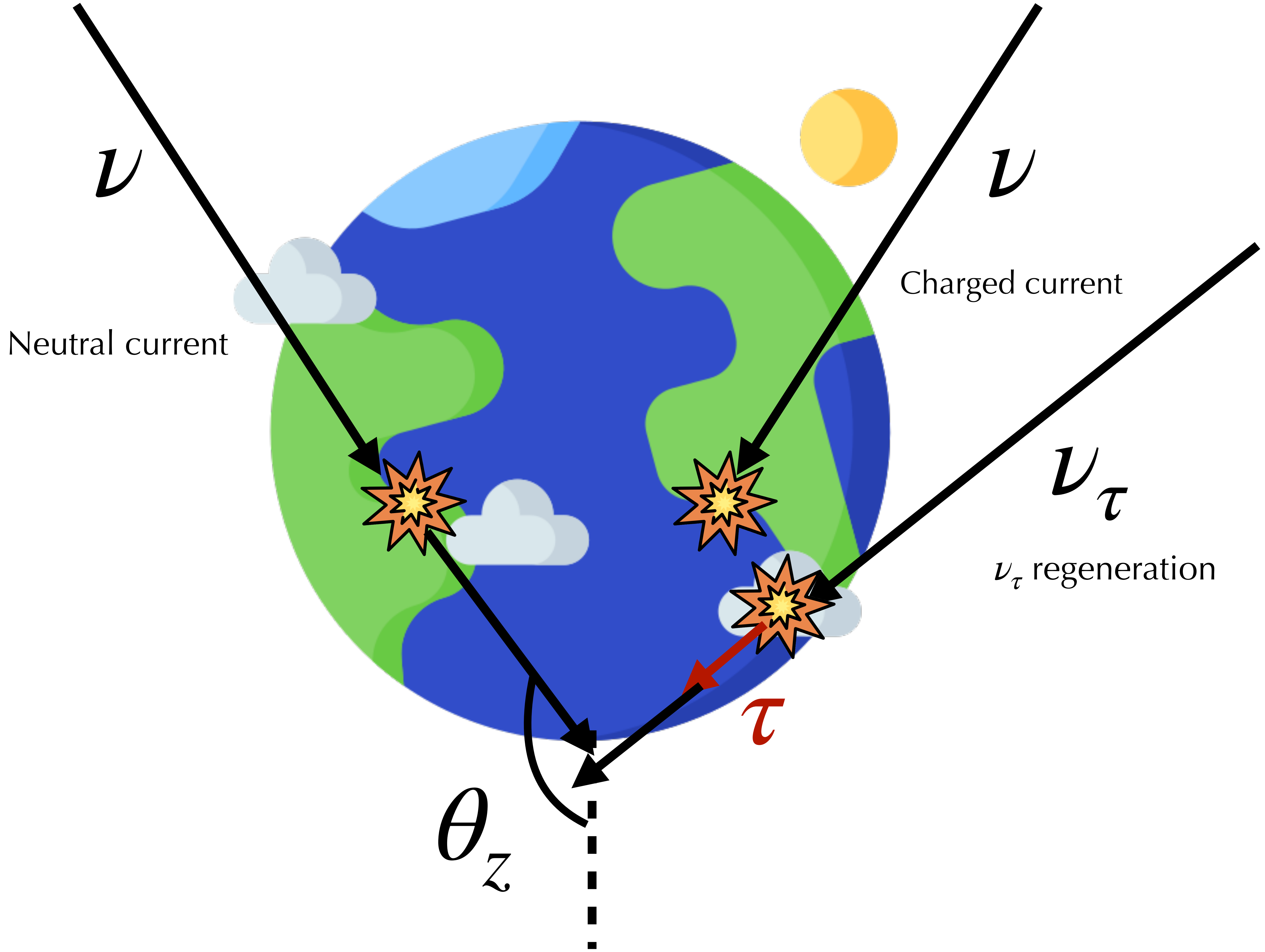


# Detector simulation




- 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)

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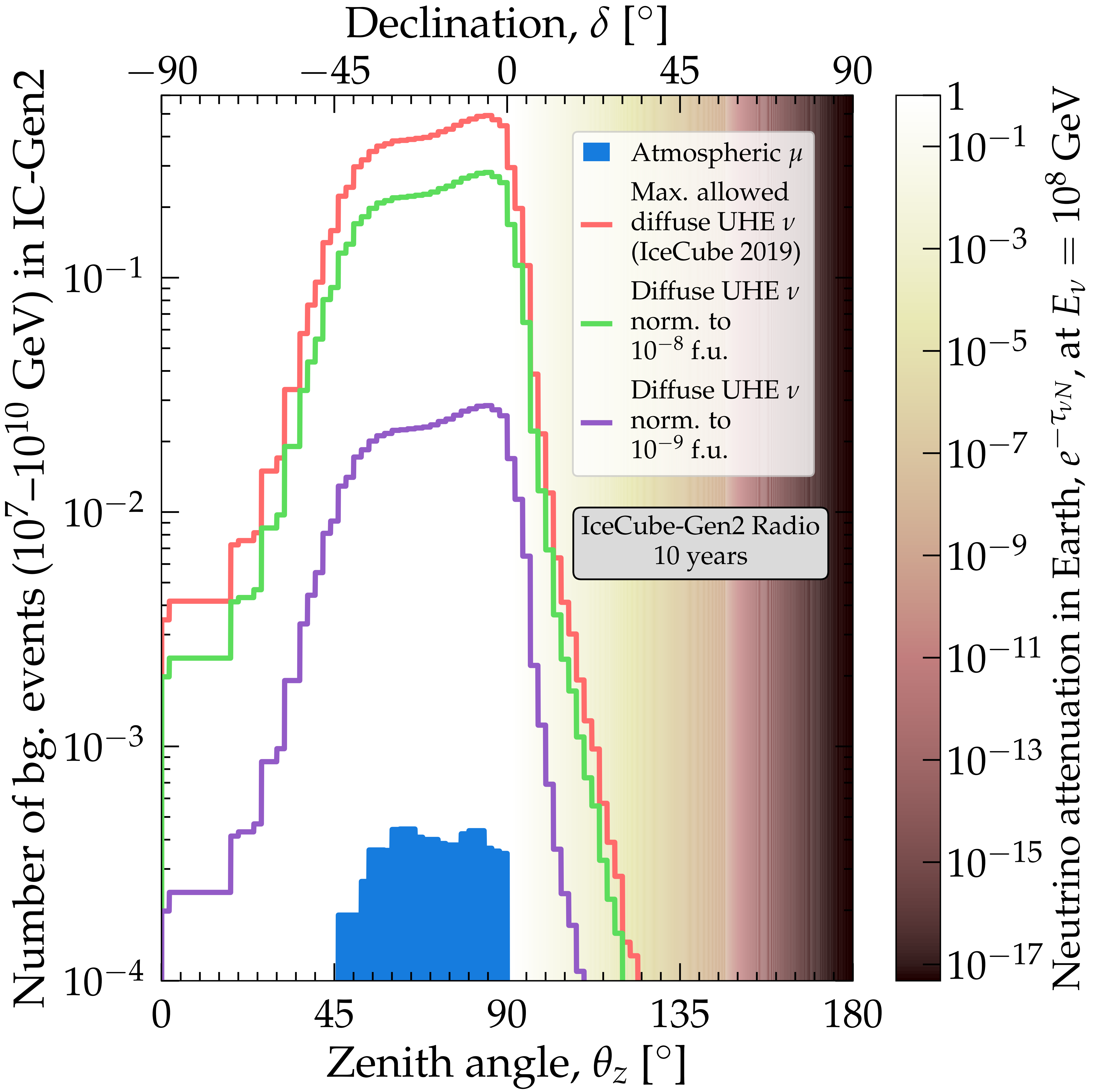

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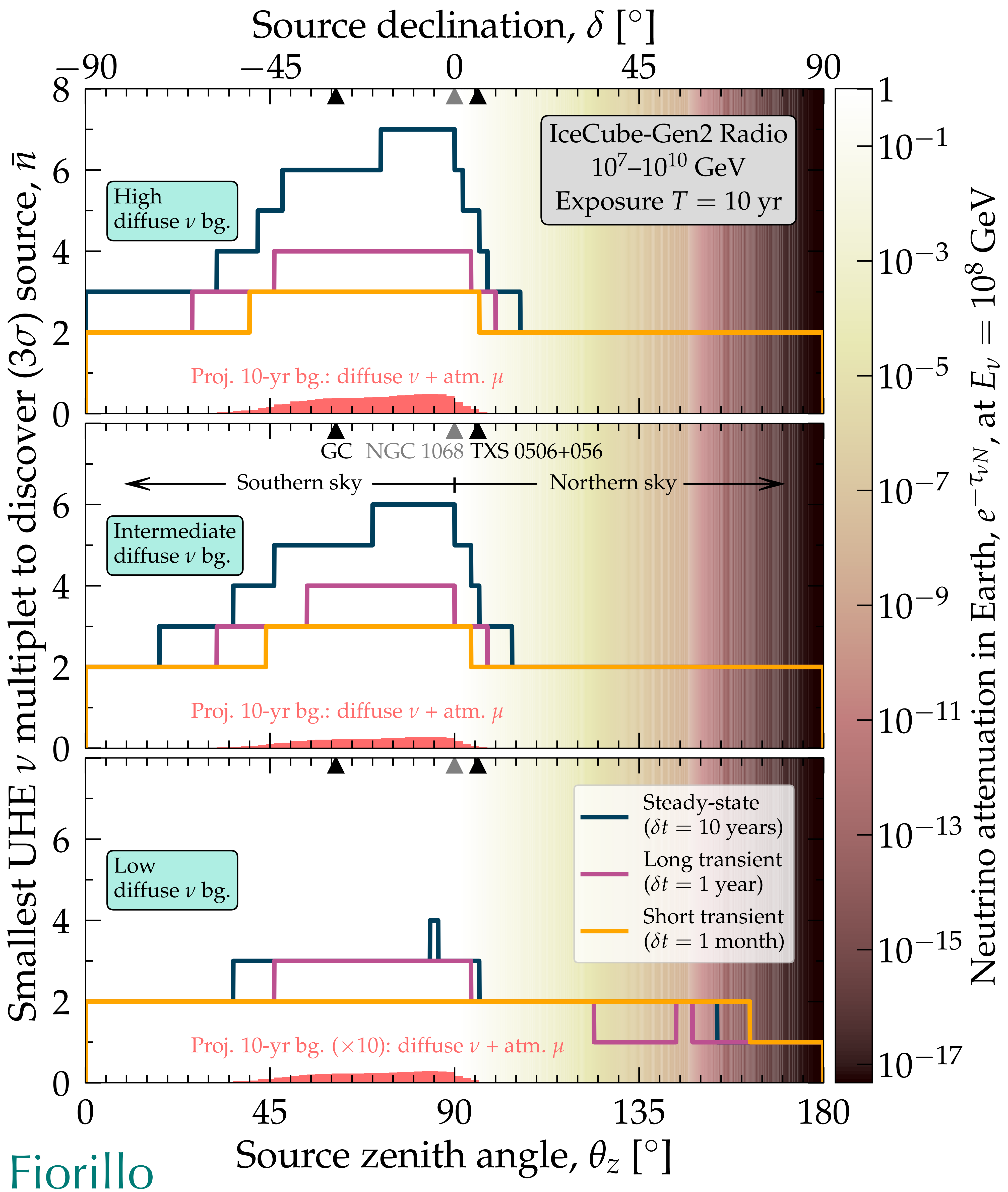
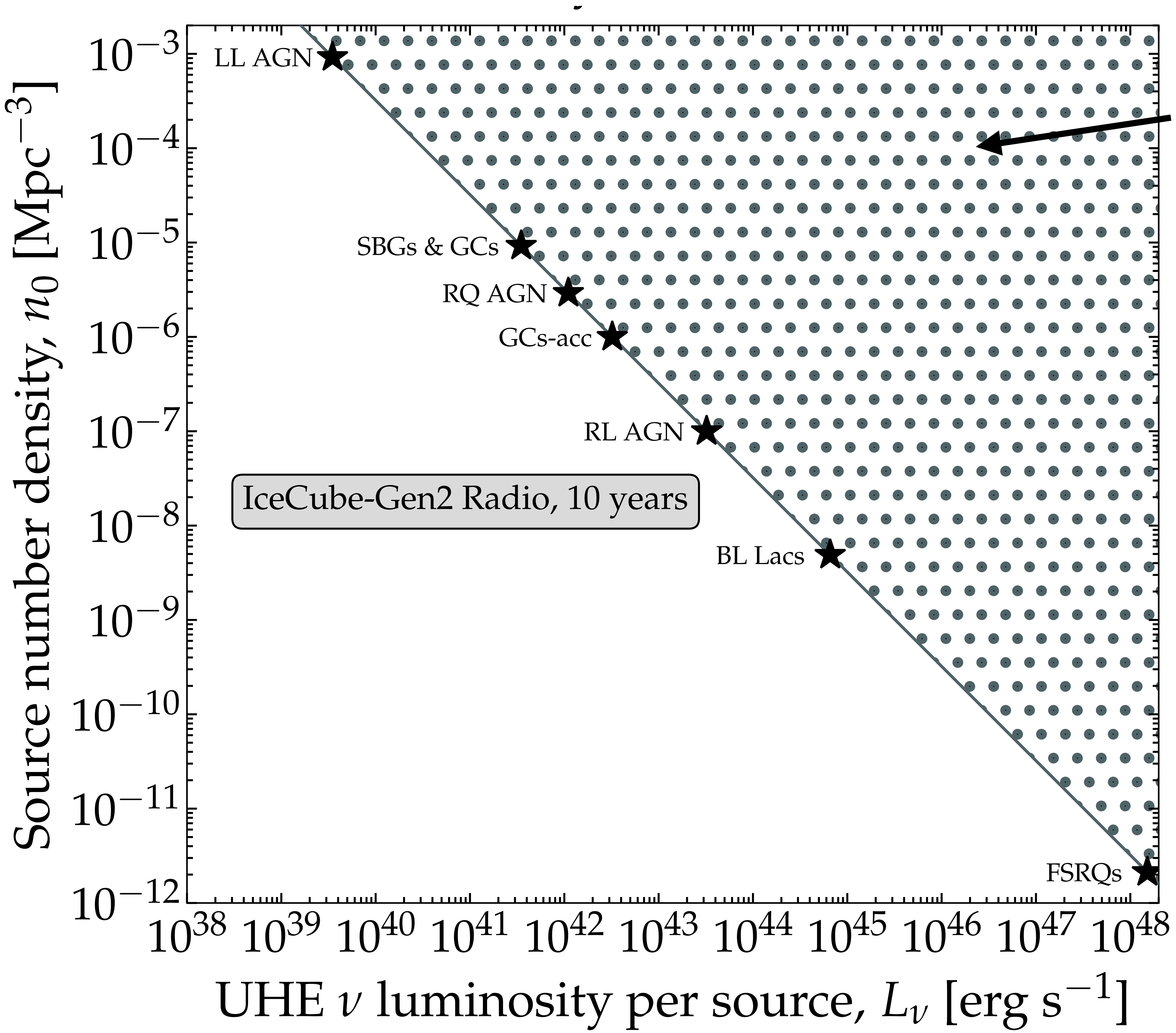



**Main question:** smallest multiplet size to claim a point source detection at 3$\sigma$?

- 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

# Steady-state sources

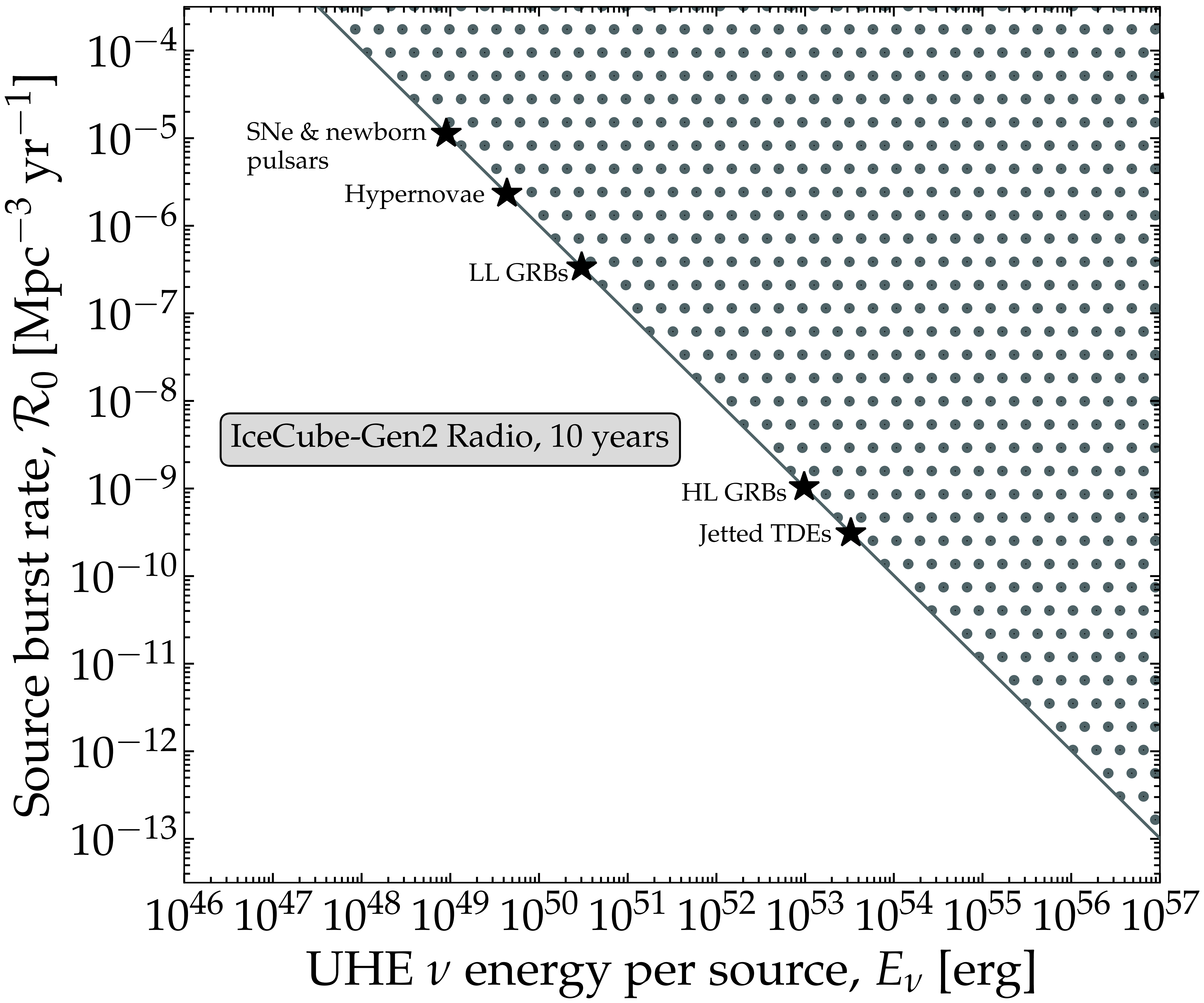



Exceeds diffuse flux

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

See also Murase et al., 1607.01601

# Transient sources




Exceeds diffuse flux

- How many sources explode? $\mathscr{R}_0$
- How far away? Star-formation rate
- How many neutrinos from each? $E_\nu$
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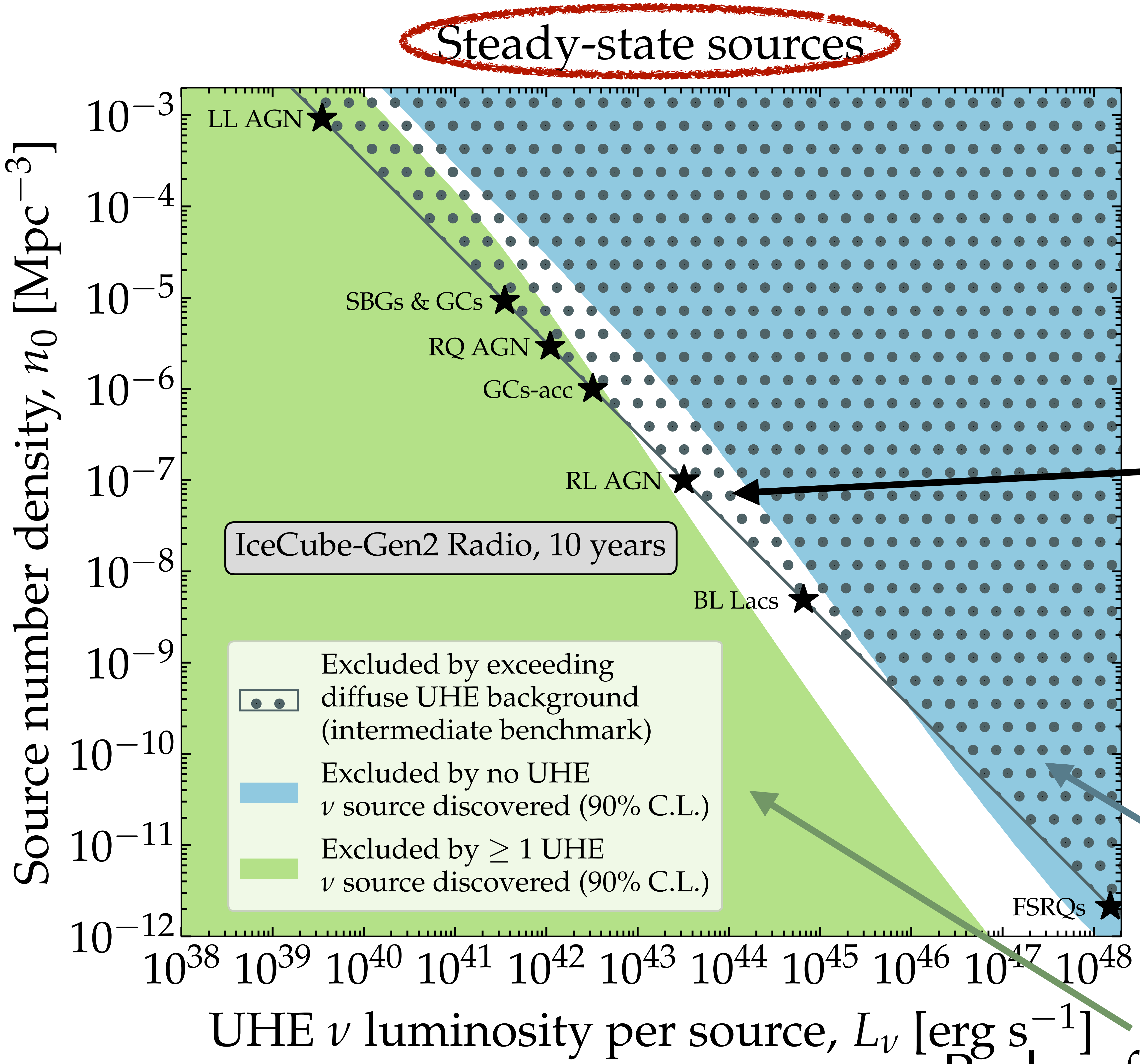
# Source populations




**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

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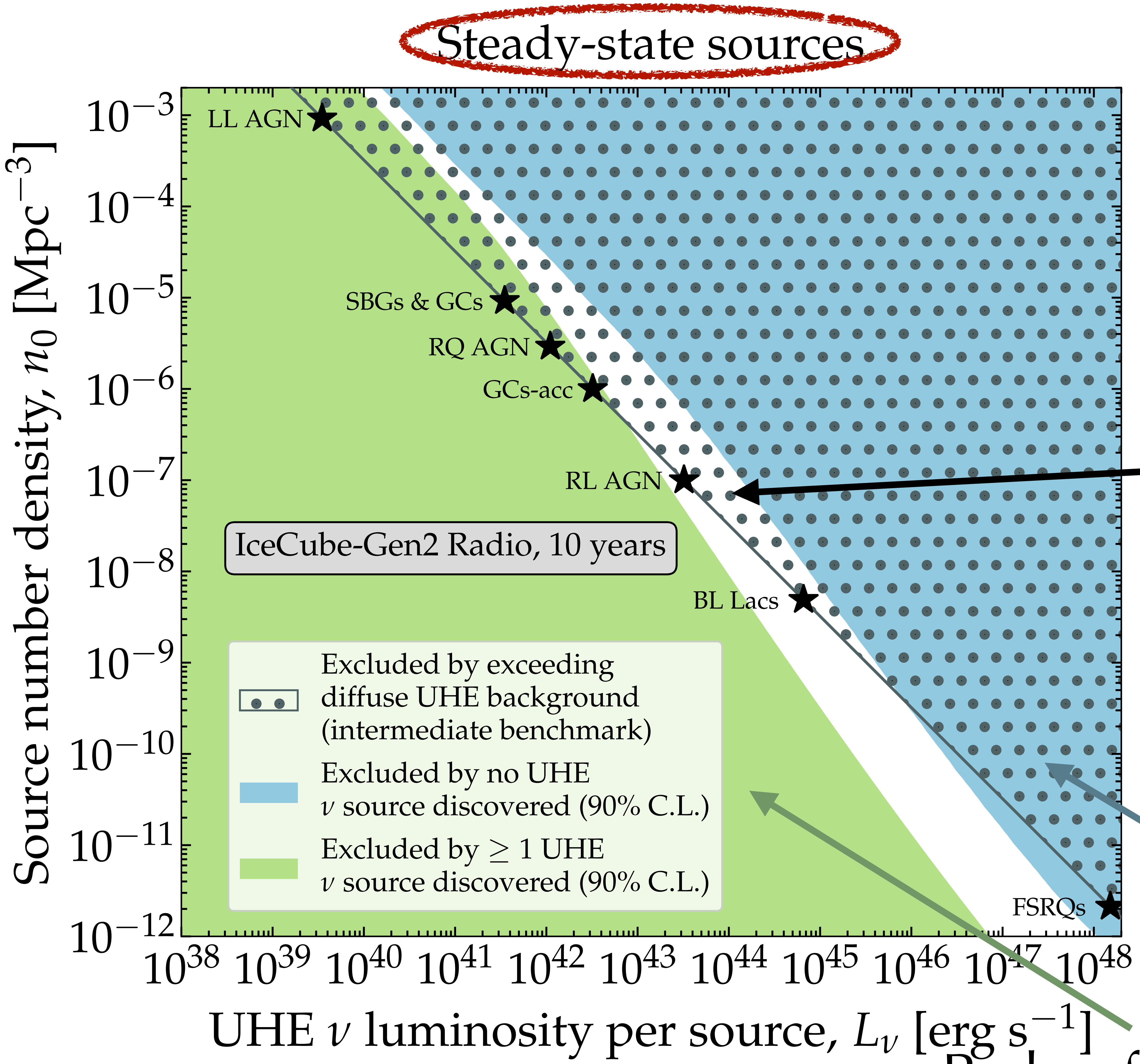


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Most steady-state sources are unlikely to be discovered

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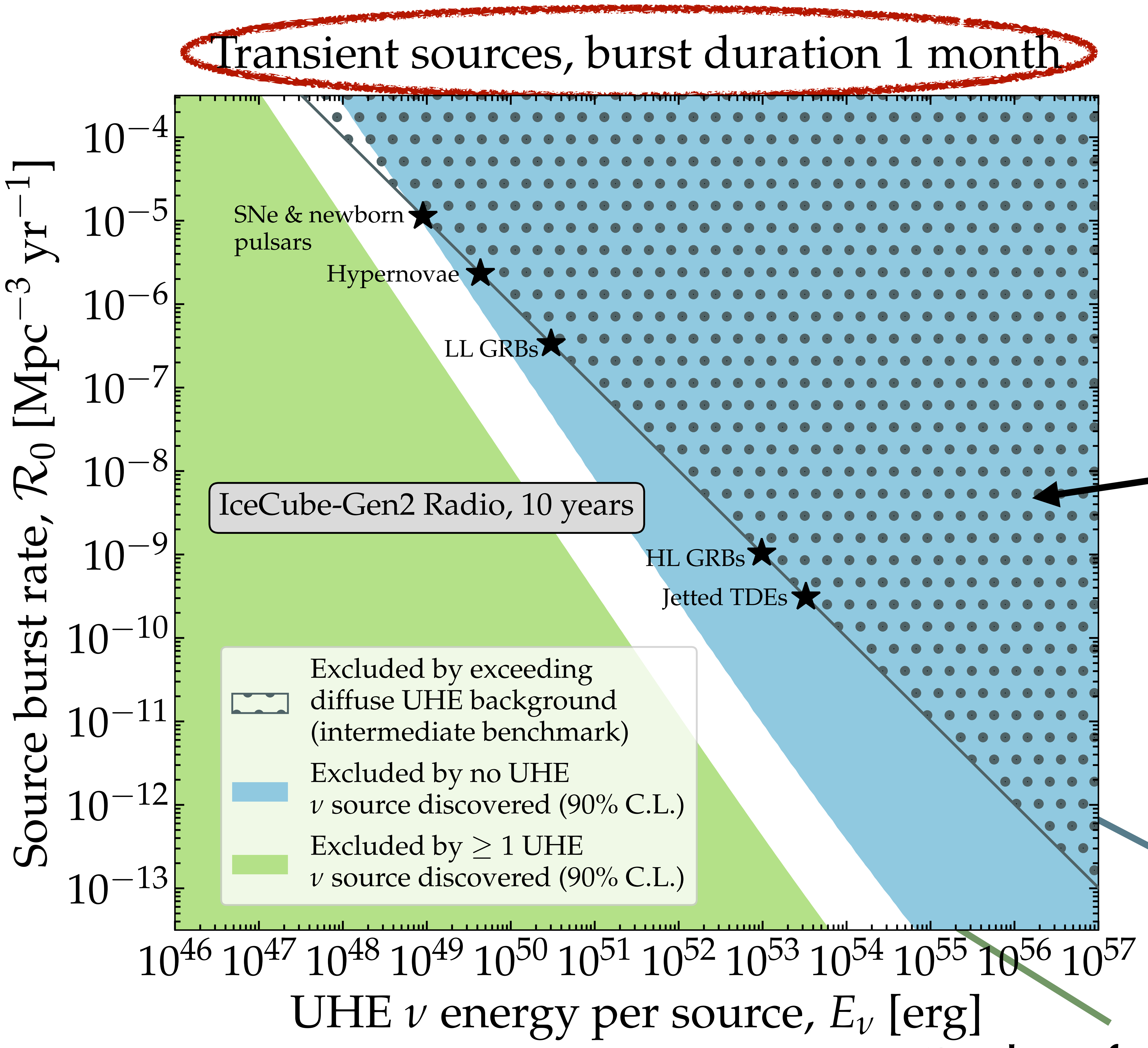


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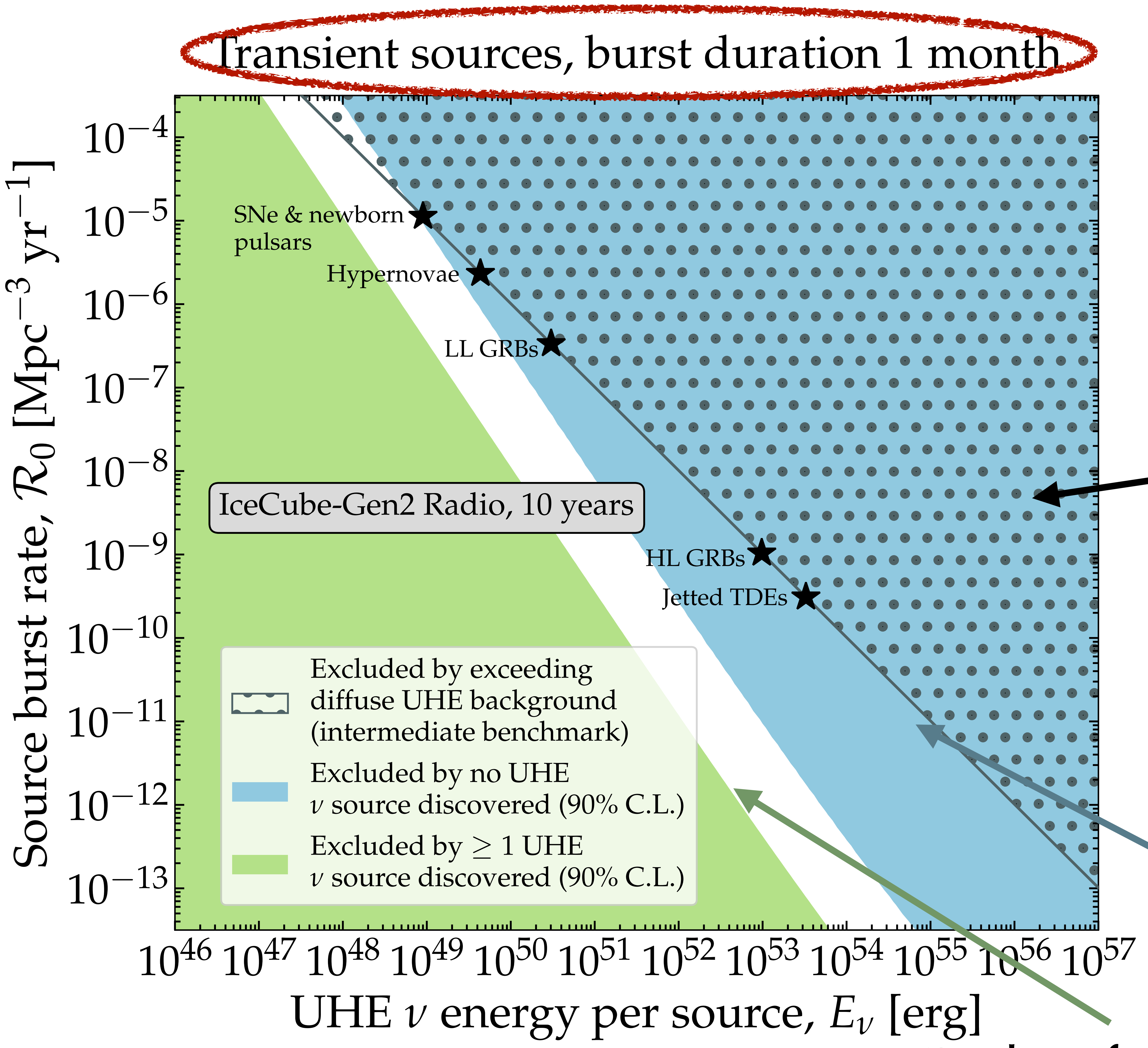


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Exceeds diffuse flux

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

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

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# Conclusions

- First quantitative prospects for detection of UHE neutrino point sources, using state-of-the-art detector simulation
- Projected constraints on source populations from multiplet searches
- Point source discovery may be within reach of IceCube-Gen2 Radio Array, especially for transient sources
- Results strongly depend on angular resolution, while slightly change with array design

# Backup slides

# 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 $\delta t$ and exposure $T$ we introduce $T/\delta t$ bins in time

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# 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 $\sigma_i$ 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

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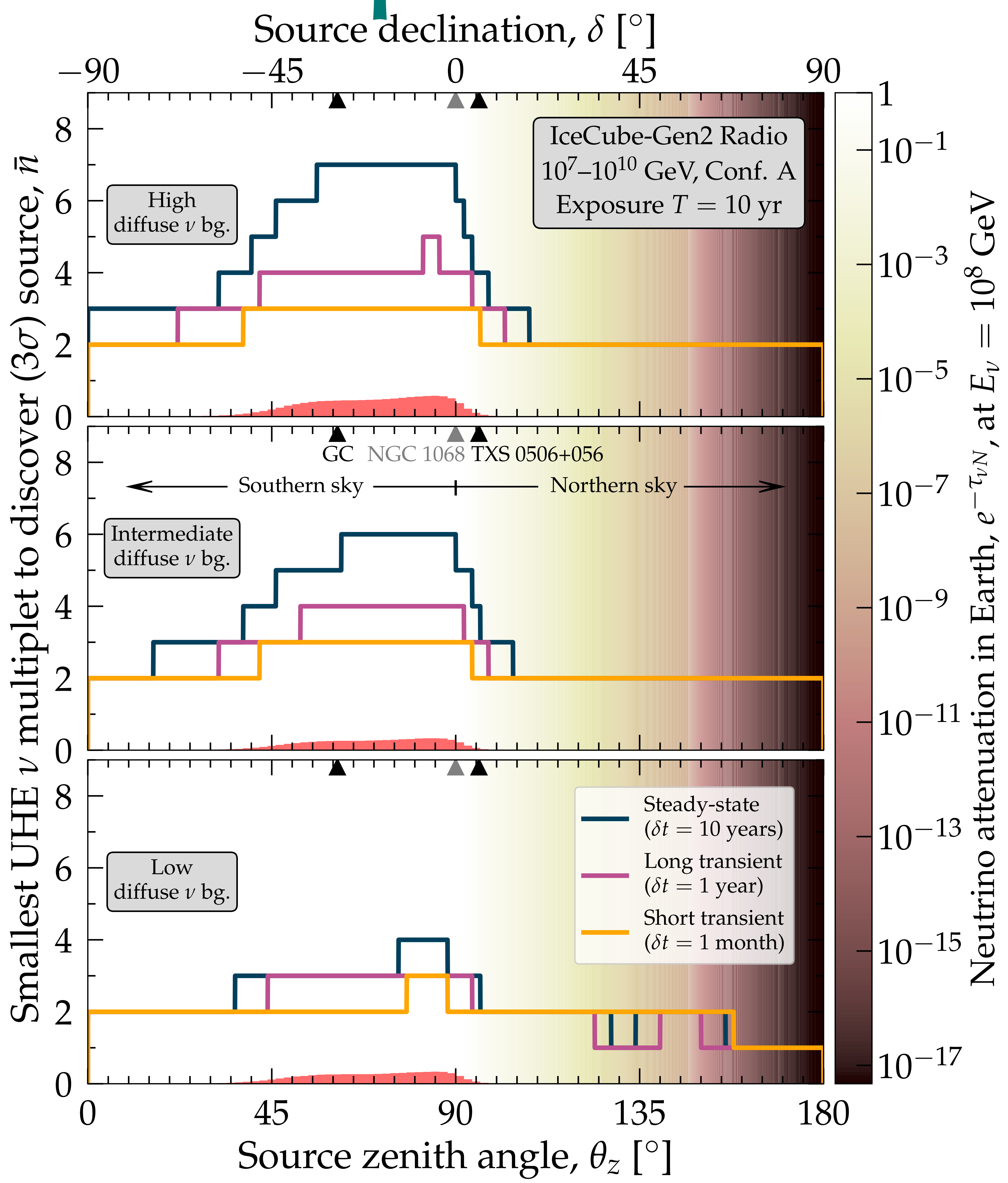
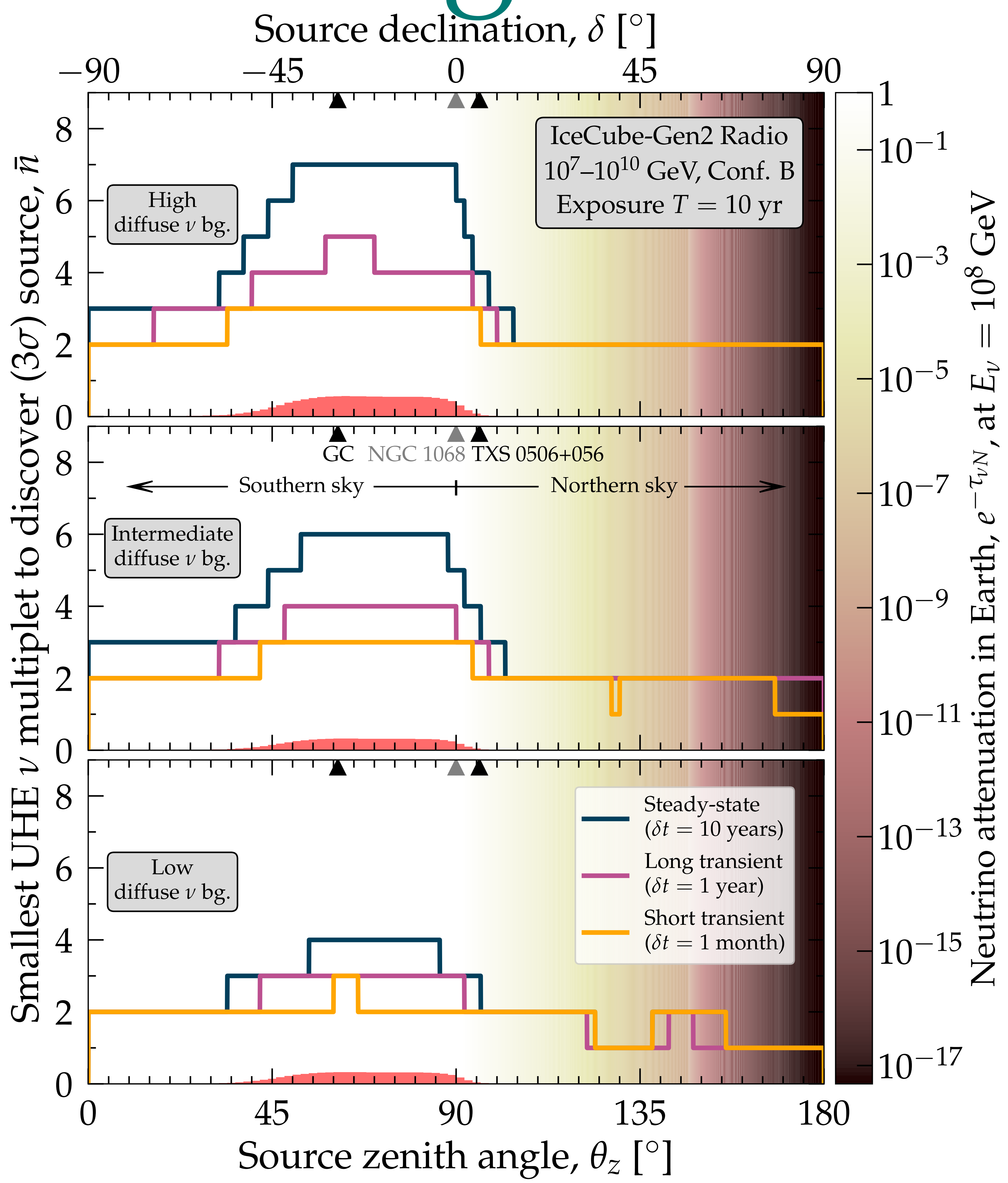
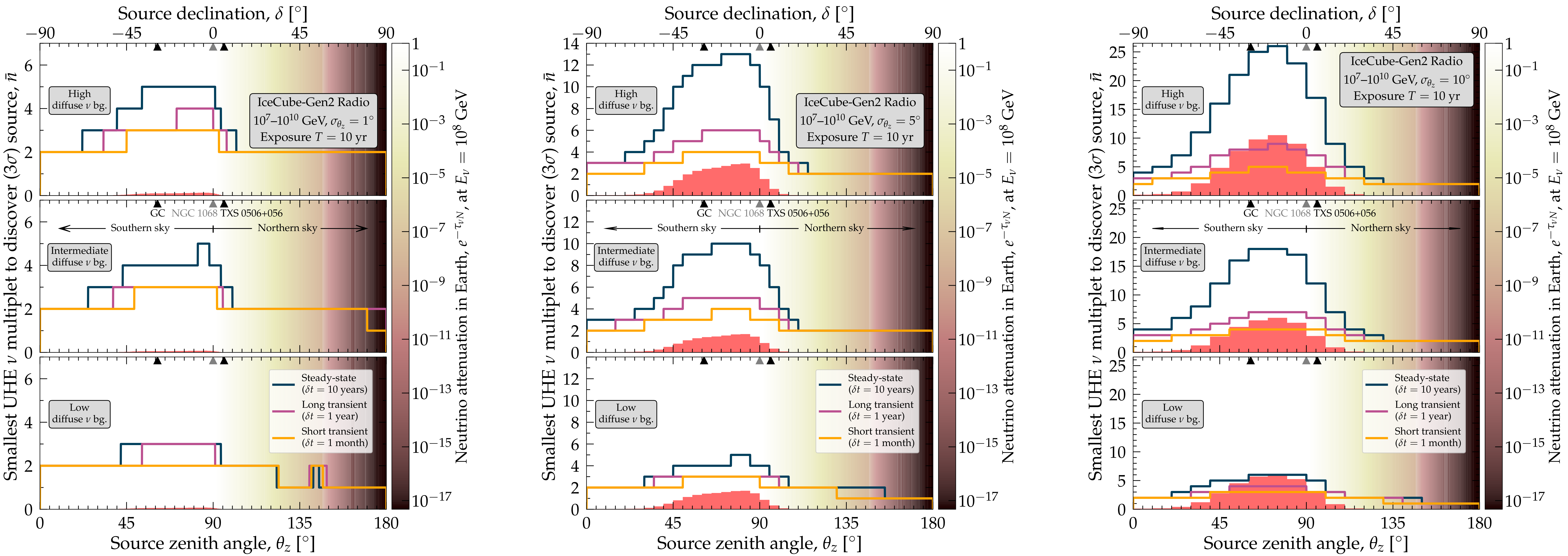
# Impact of detector design



# Impact of angular resolution

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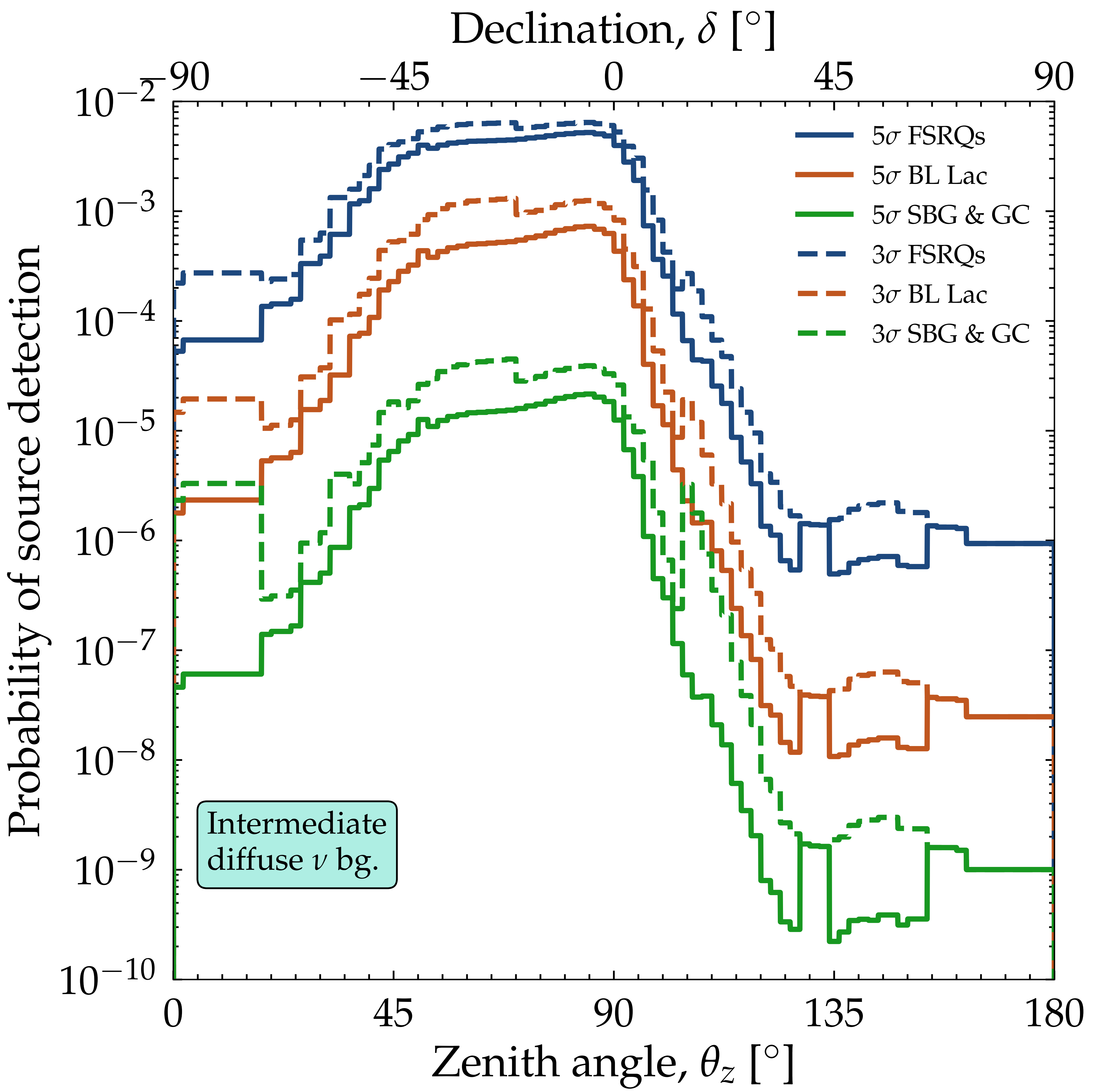
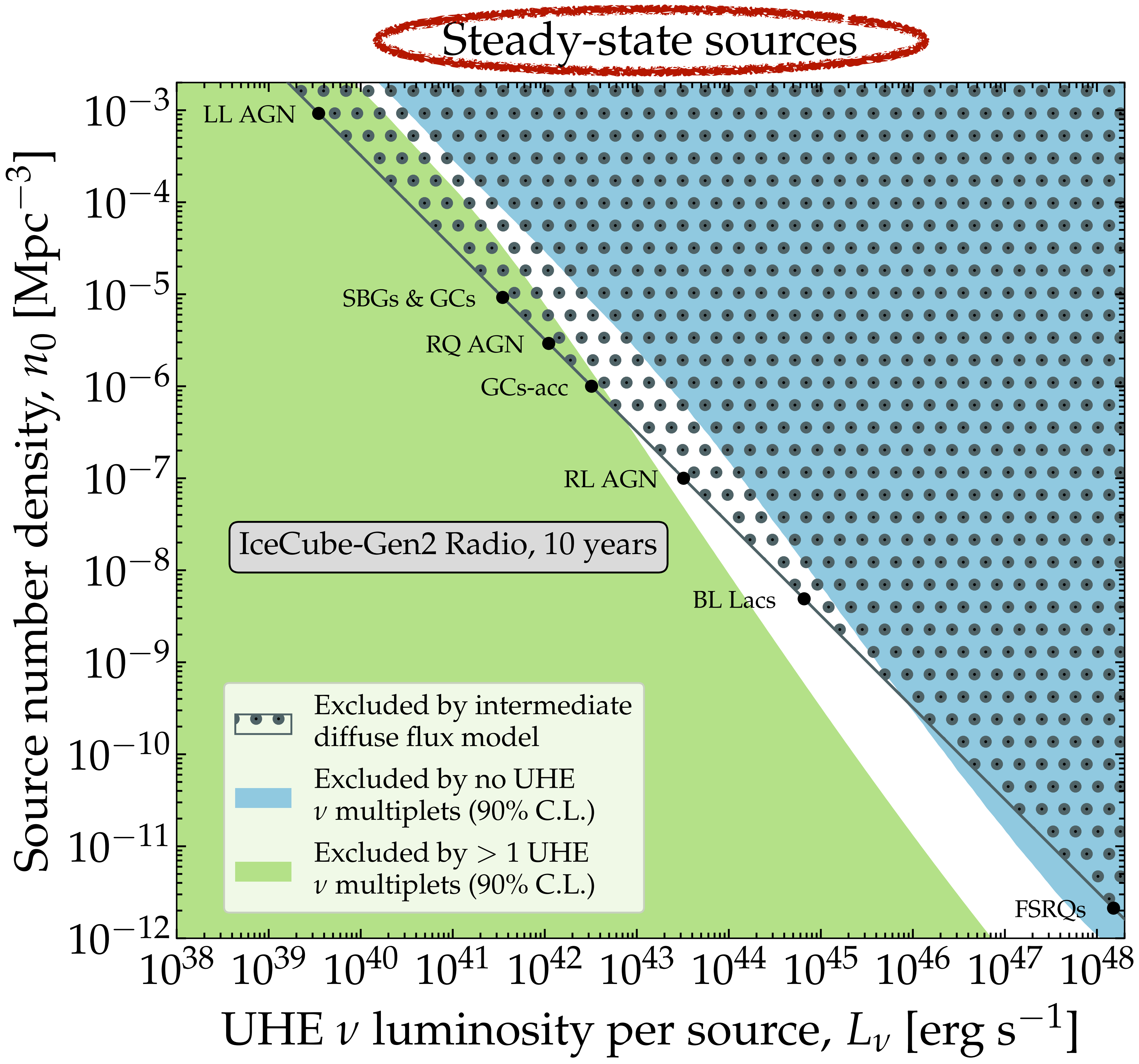



- For a given source population, three random variables:
  - Number of sources in a pixel
  - Source distance
  - Number of events from the source
- Averaging over all three, we obtain probability of significant multiplets

# Source populations

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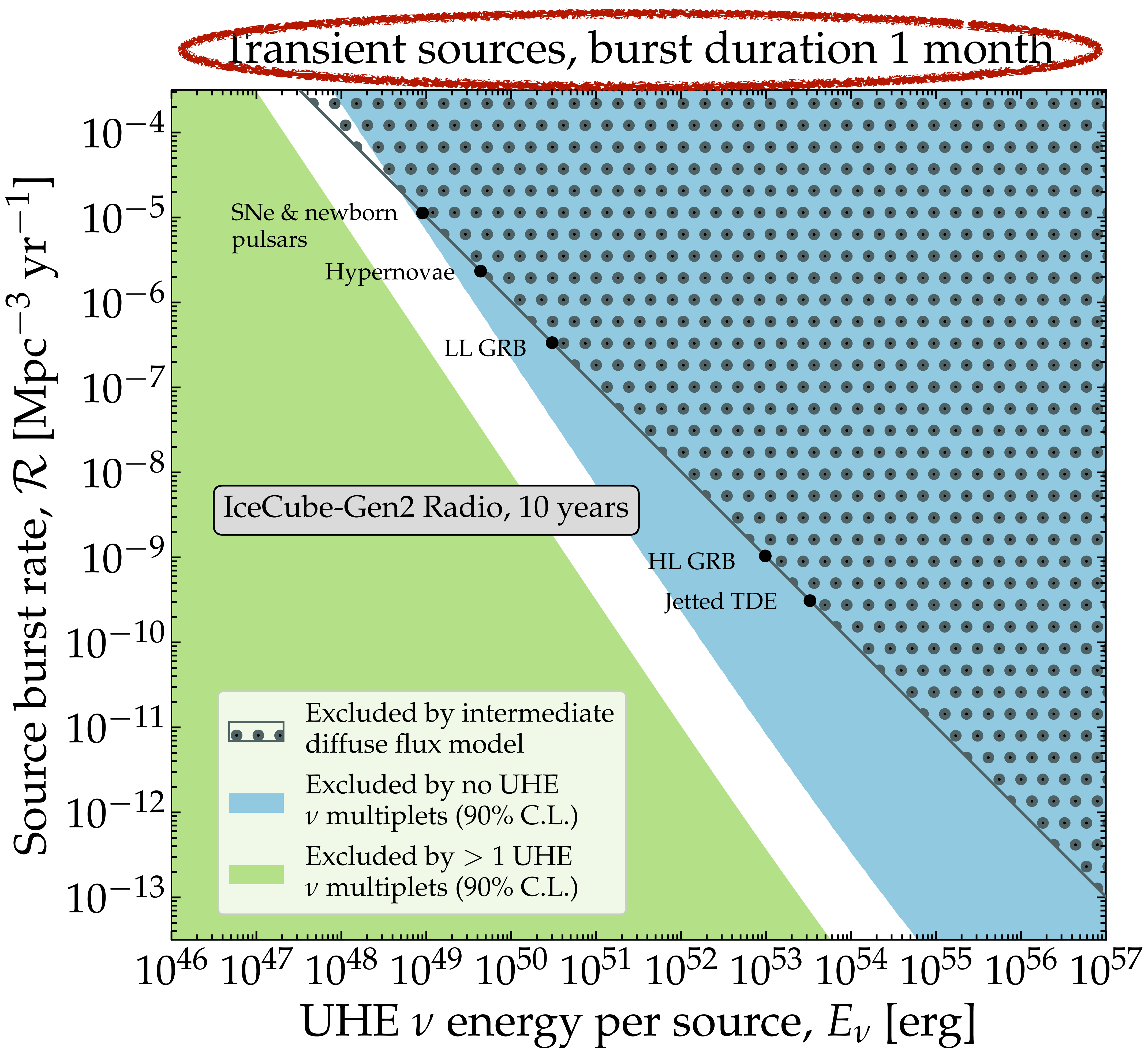


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