

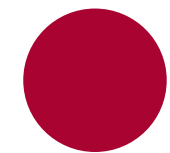
Near-future discovery of point sources of ultra-high-energy neutrinos

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Niels Bohr Institute, Copenhagen

Based on arXiv:2205.15985,

with Mauricio Bustamante, Victor B. Valera



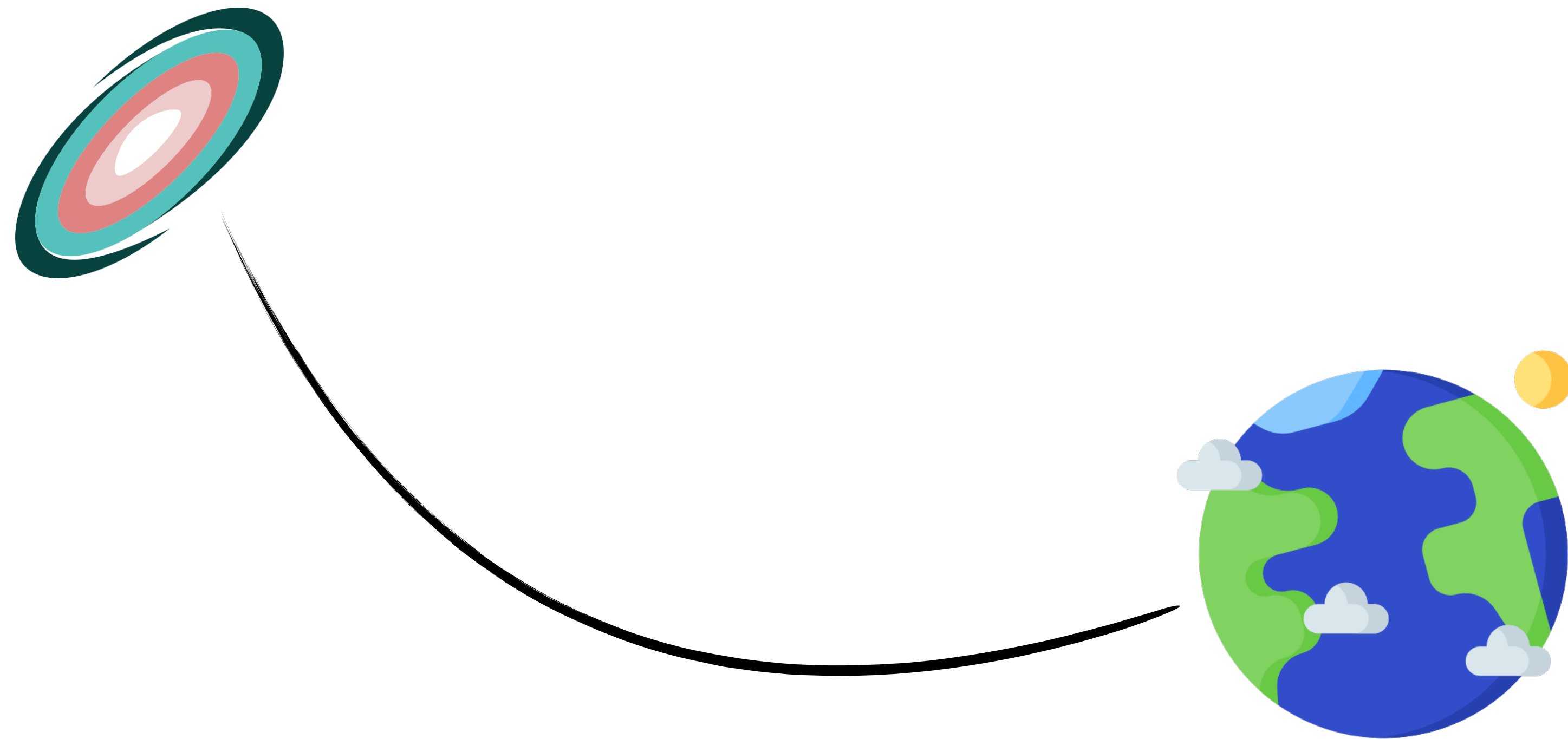
KØBENHAVNS UNIVERSITET
UNIVERSITY OF COPENHAGEN



VILLUM FONDEN

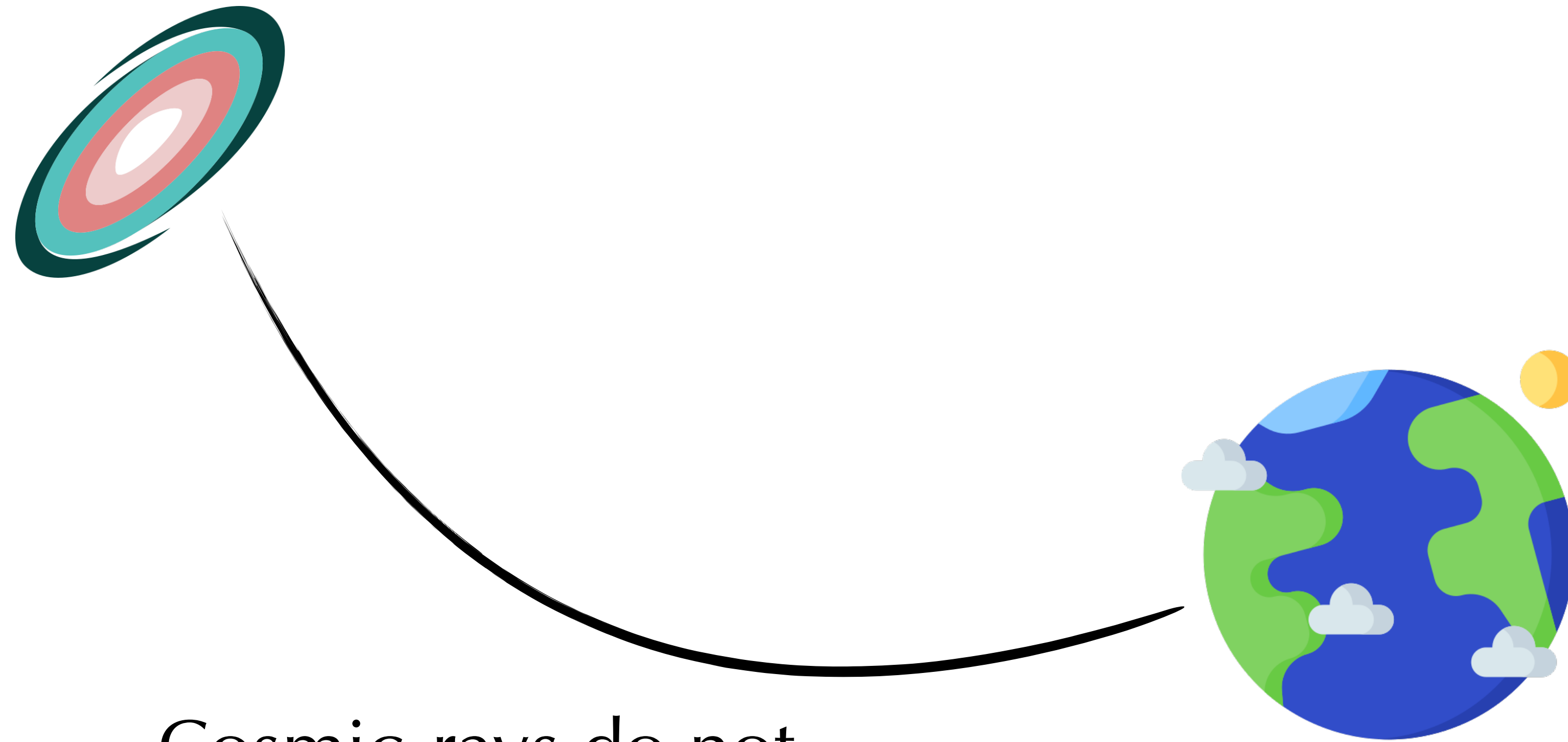


Multimessenger astrophysics



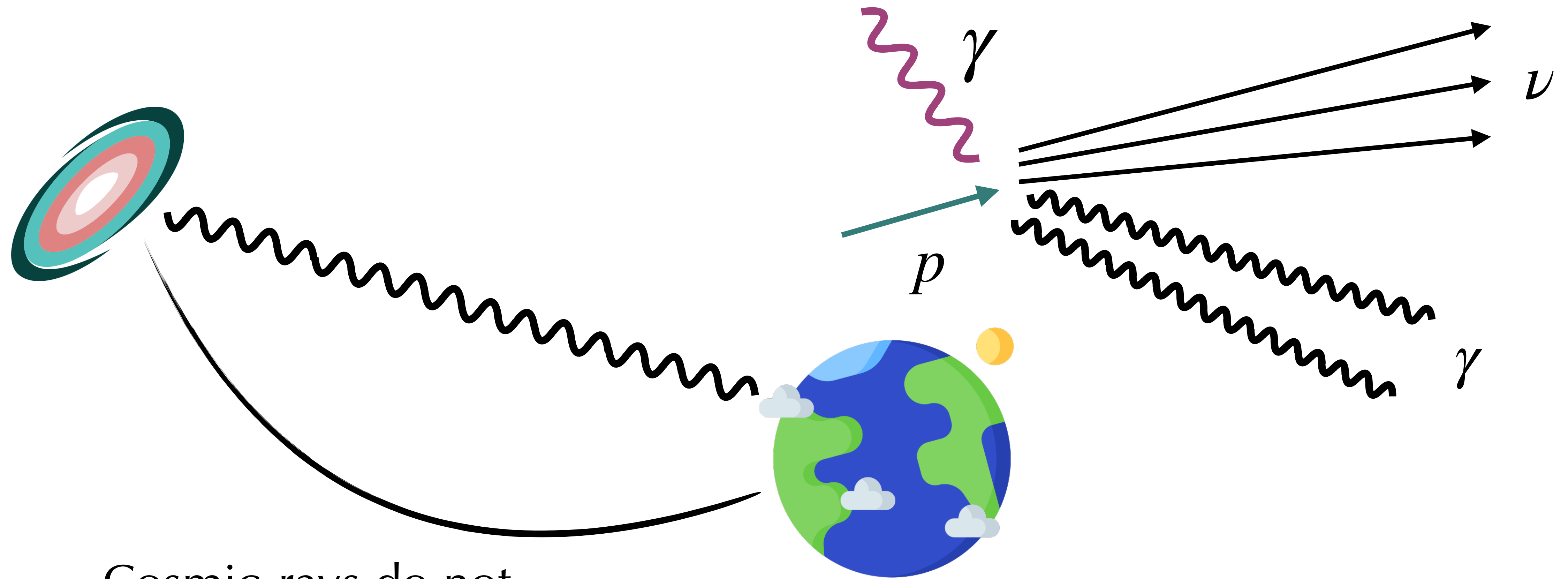
Multimessenger astrophysics

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



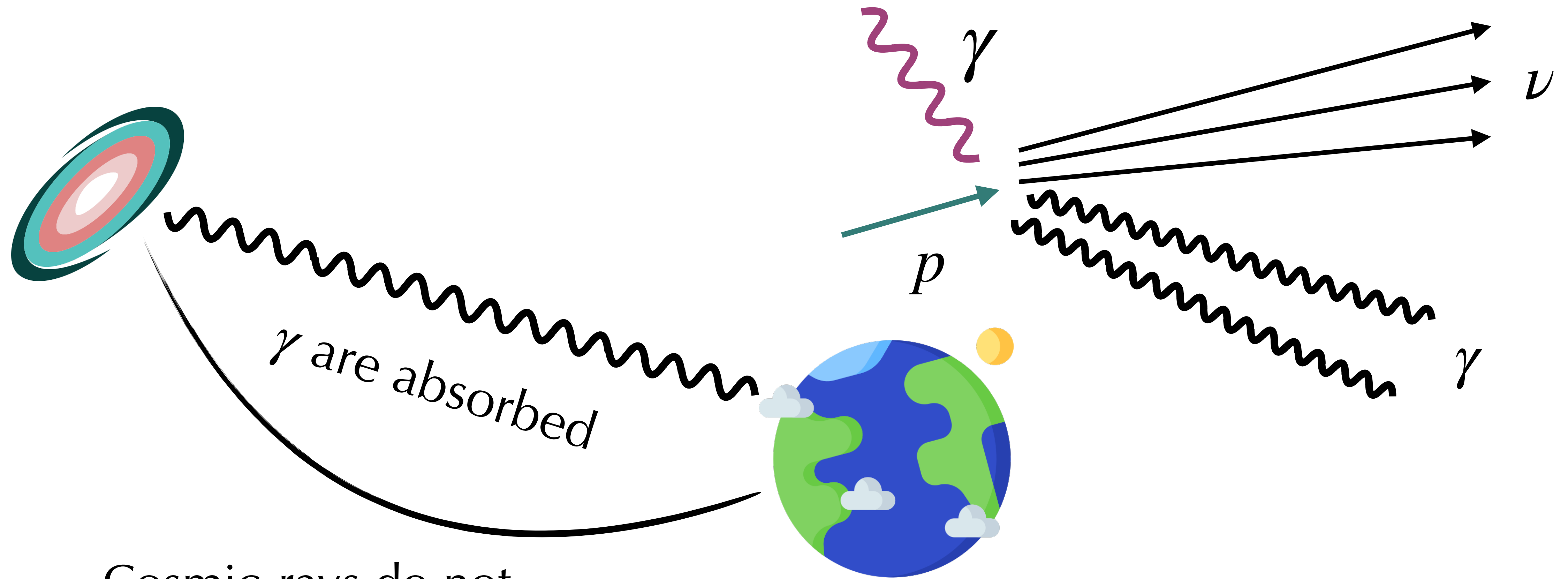
Cosmic-rays do not point back to sources

Multimessenger astrophysics



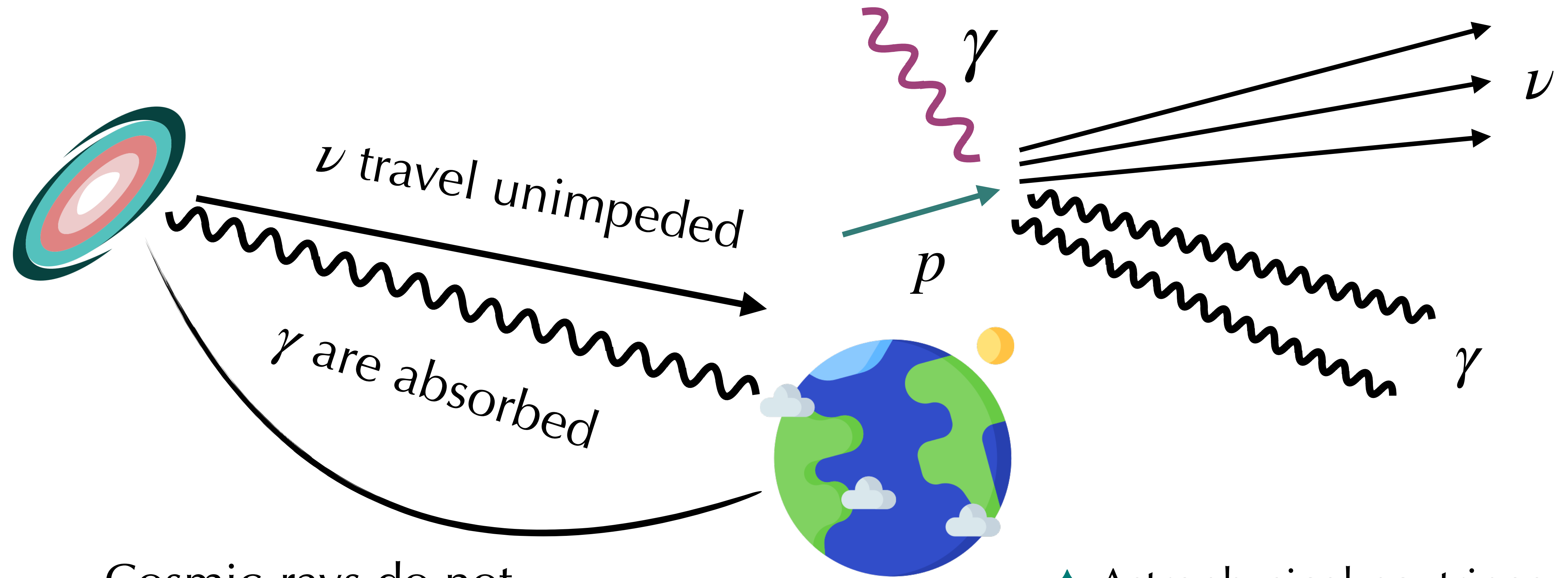
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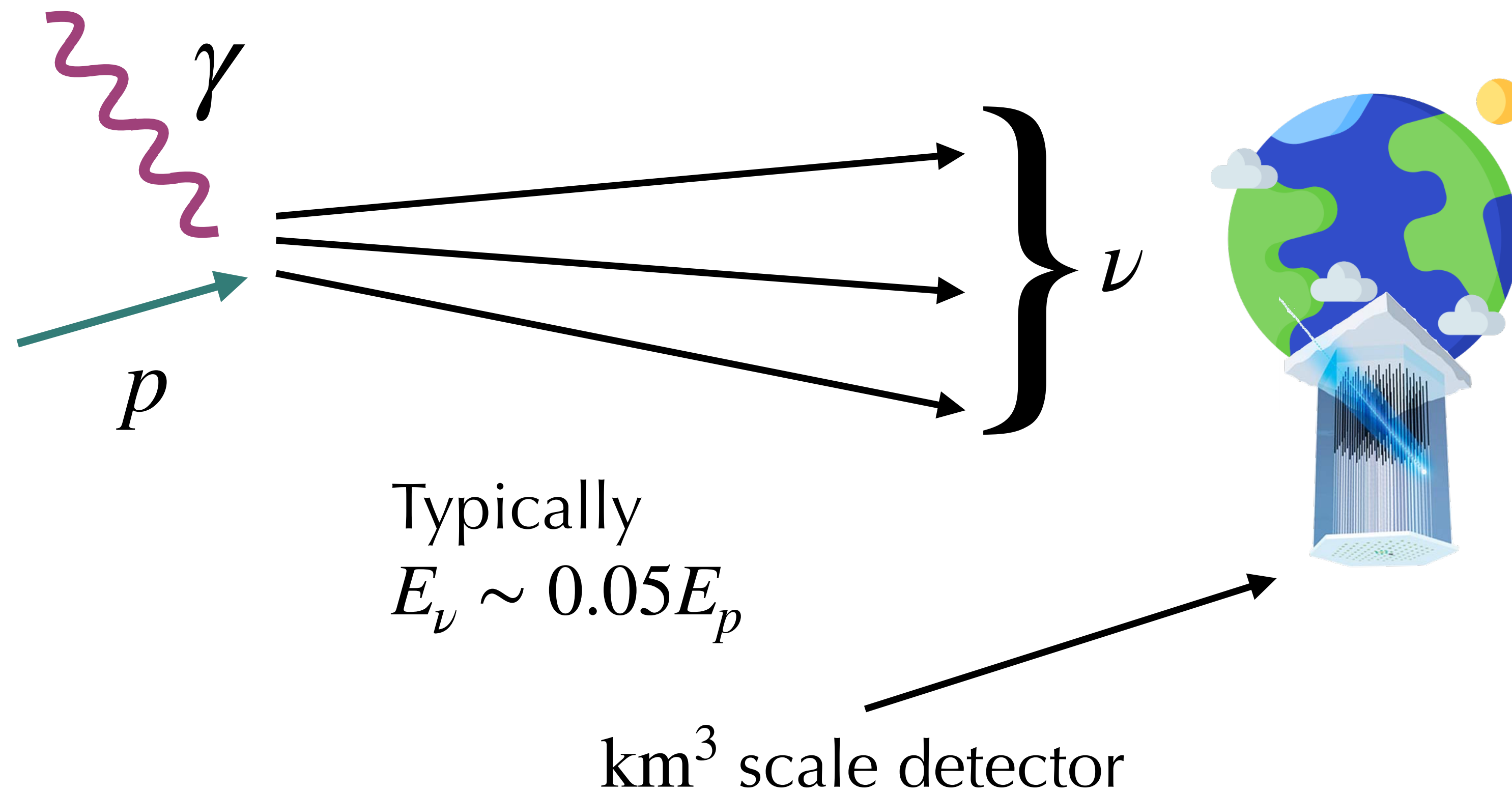
Multimessenger astrophysics



Cosmic-rays do not point back to sources

◆ Astrophysical neutrinos can locate point sources!

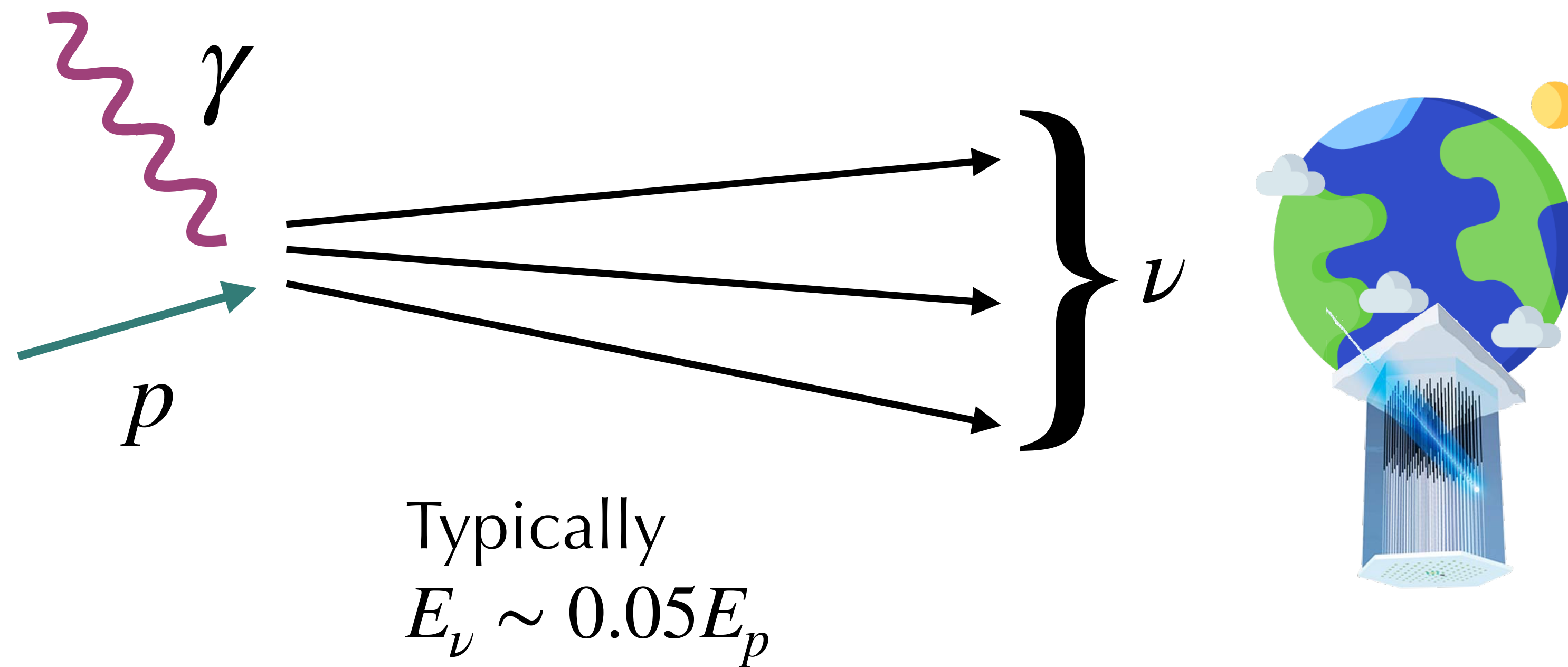
High-energy neutrino point sources



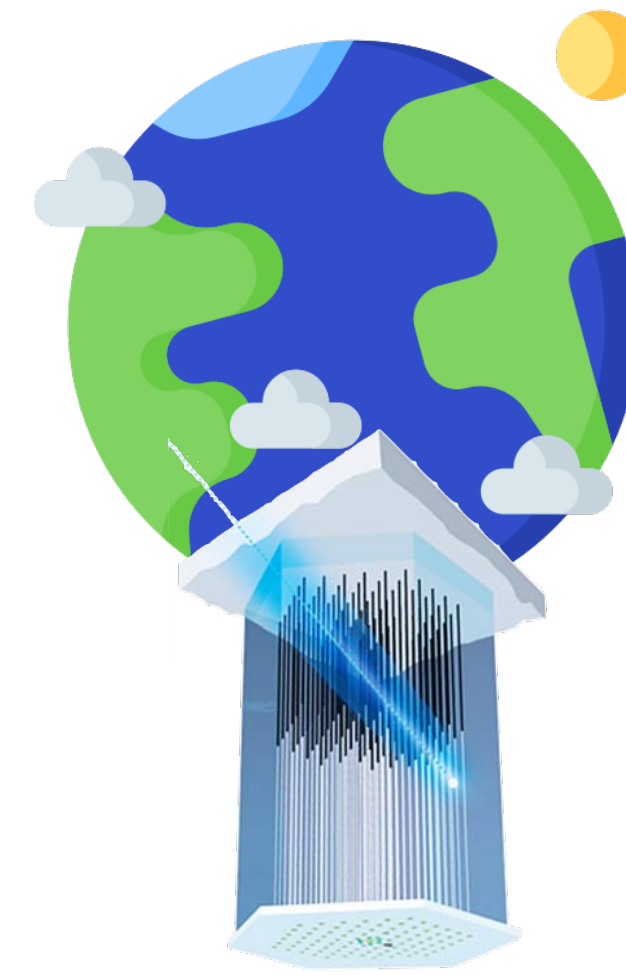
- ◆ IceCube detects neutrinos with TeV-PeV energies
- ◆ A few candidate sources reported: TXS 0506+056 (IceCube, 2018), AT2019dsg (IceCube, 2021), NGC 1068 (IceCube, 2021)
- ◆ Signature of ~ 100 PeV cosmic rays

IceCube-Gen2 will increase volume by an order of magnitude

High-energy neutrino point sources

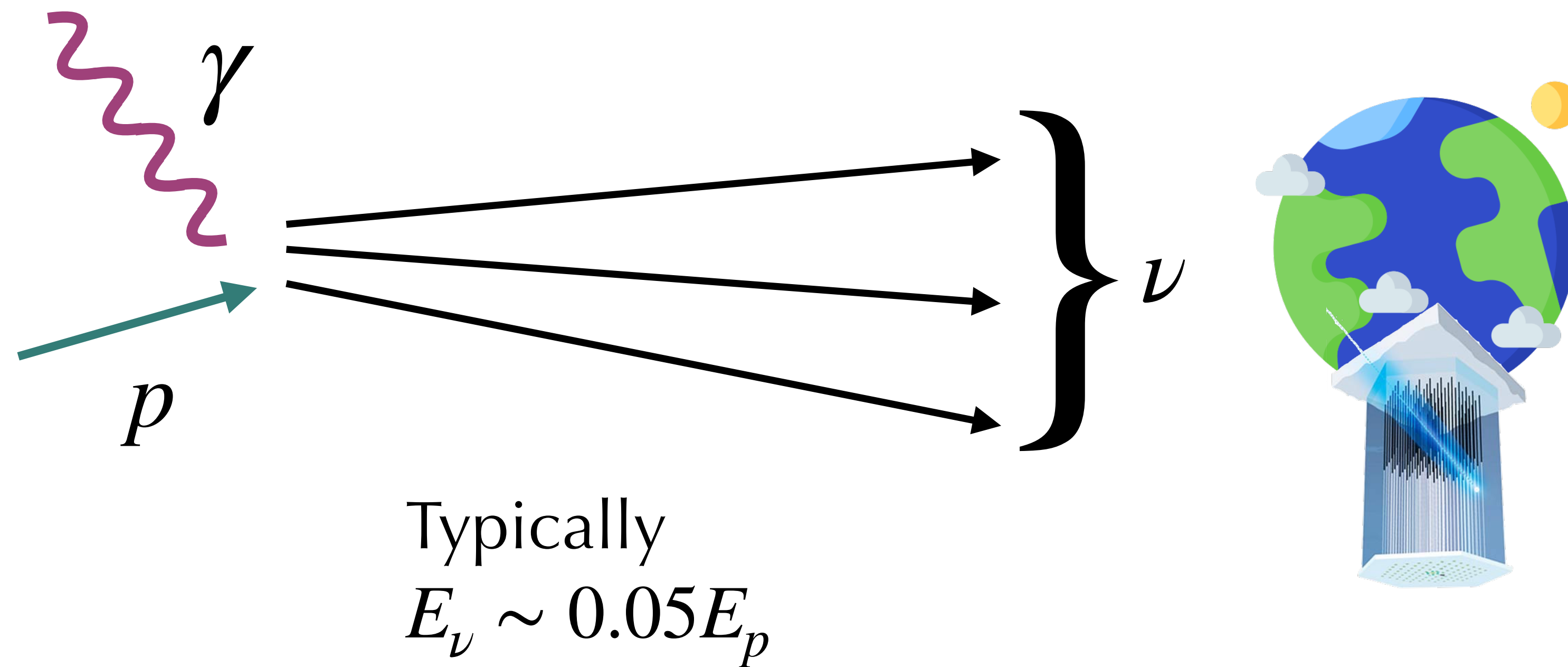


To probe UHECRs (~ 10 EeV) we need UHE neutrinos (~ 100 PeV)



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High-energy neutrino point sources



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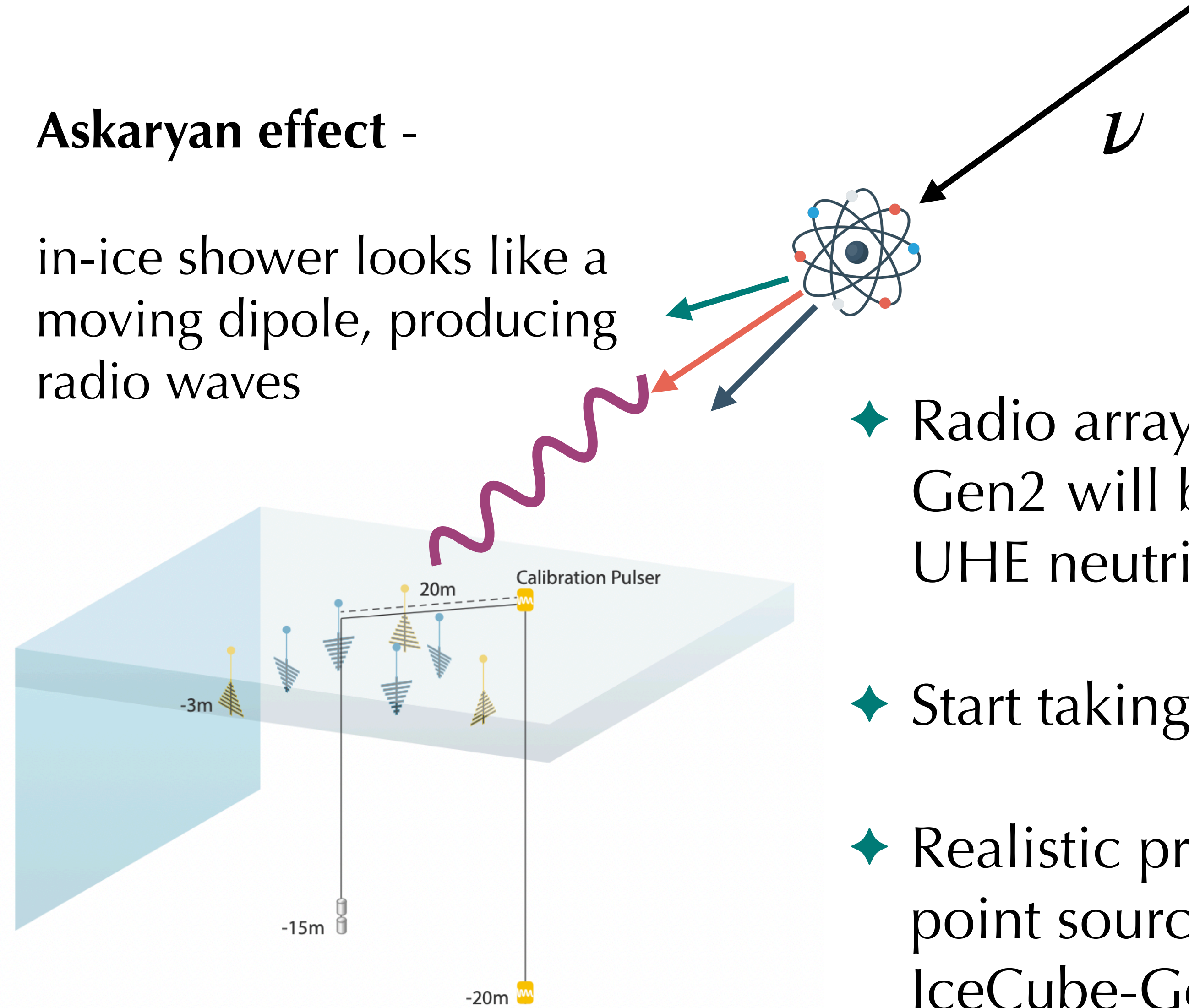
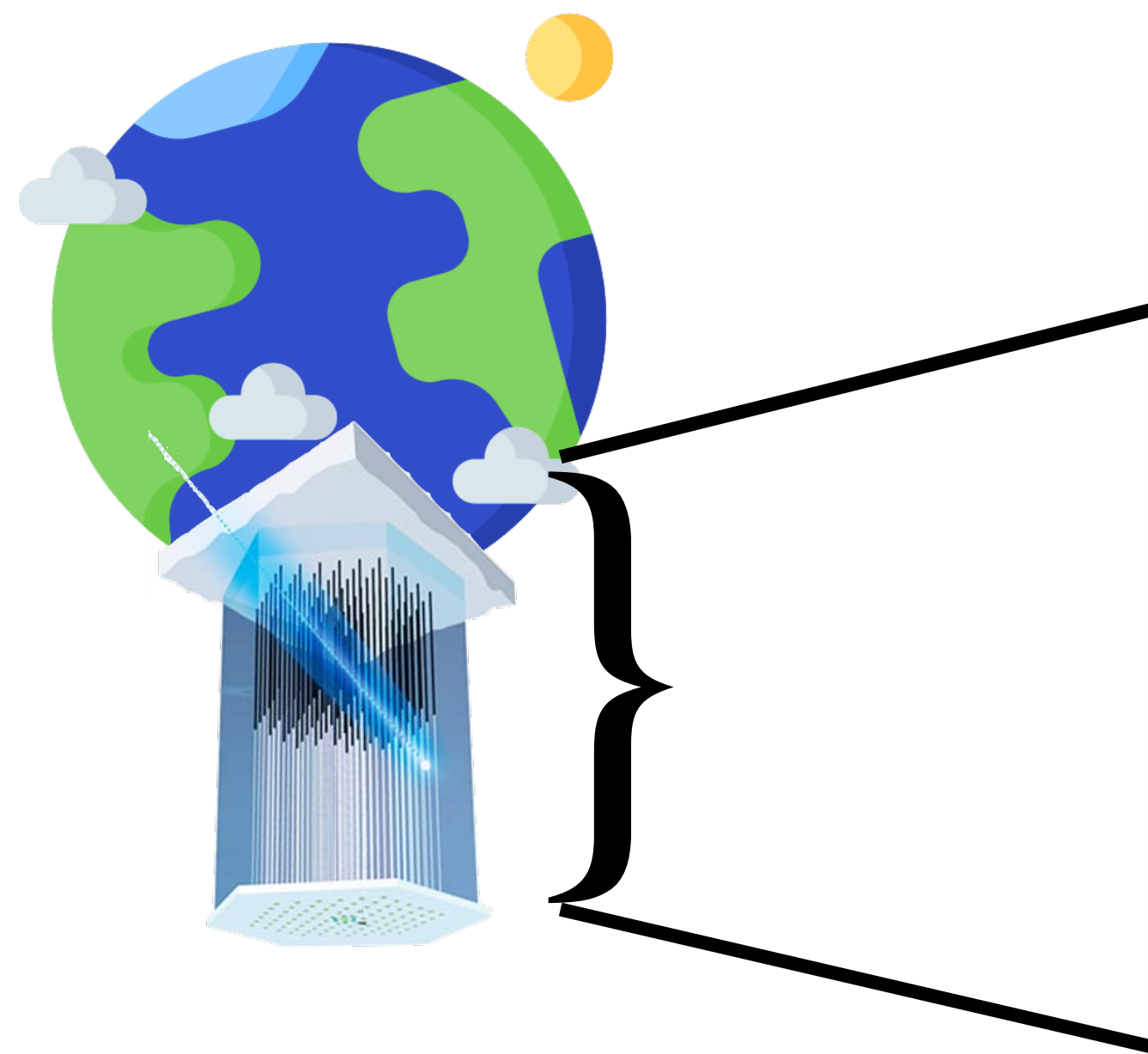
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Can we detect sources of ultra-high-energy (UHE) neutrinos?

UHE neutrino detection

Askaryan effect -

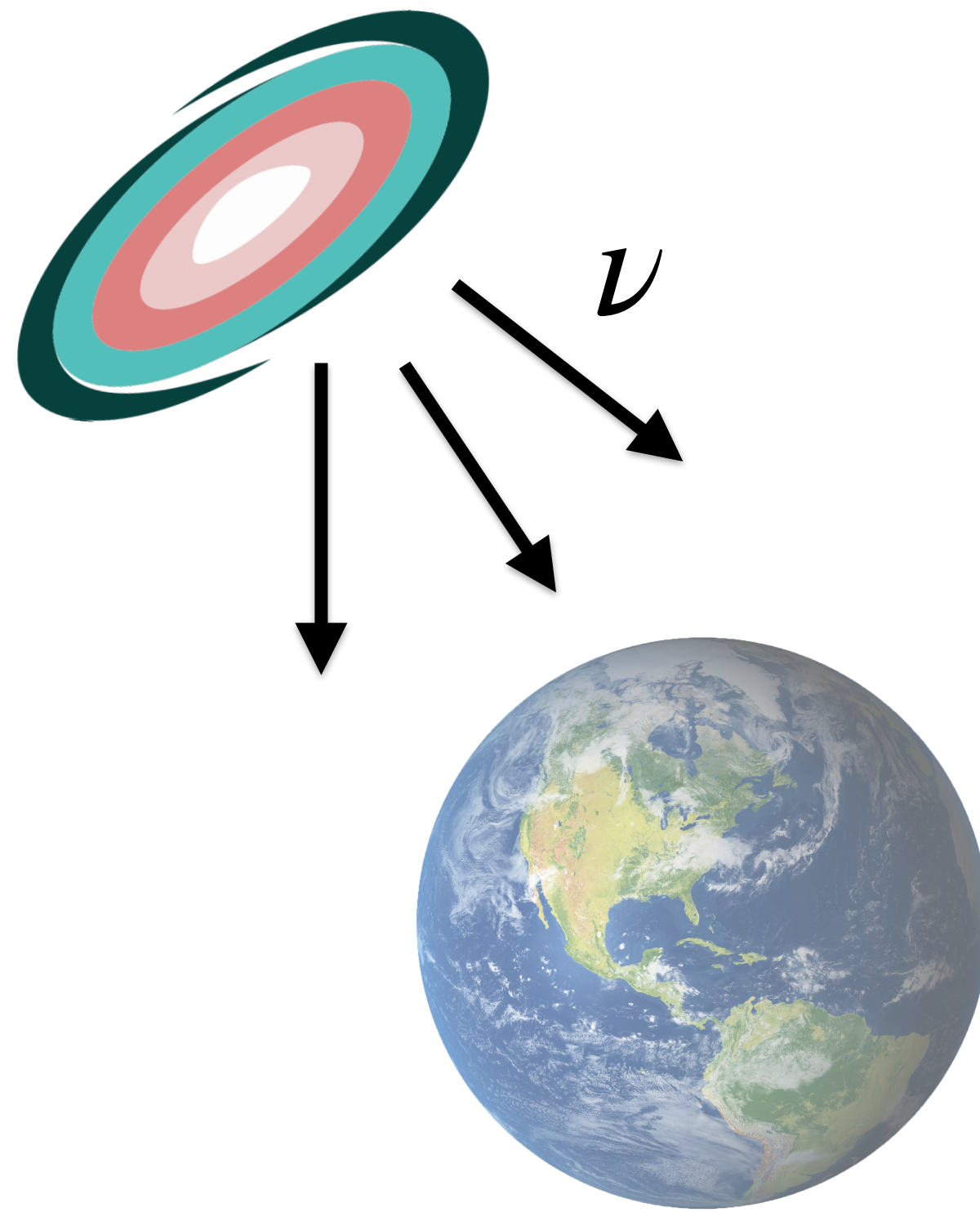
in-ice shower looks like a moving dipole, producing radio waves



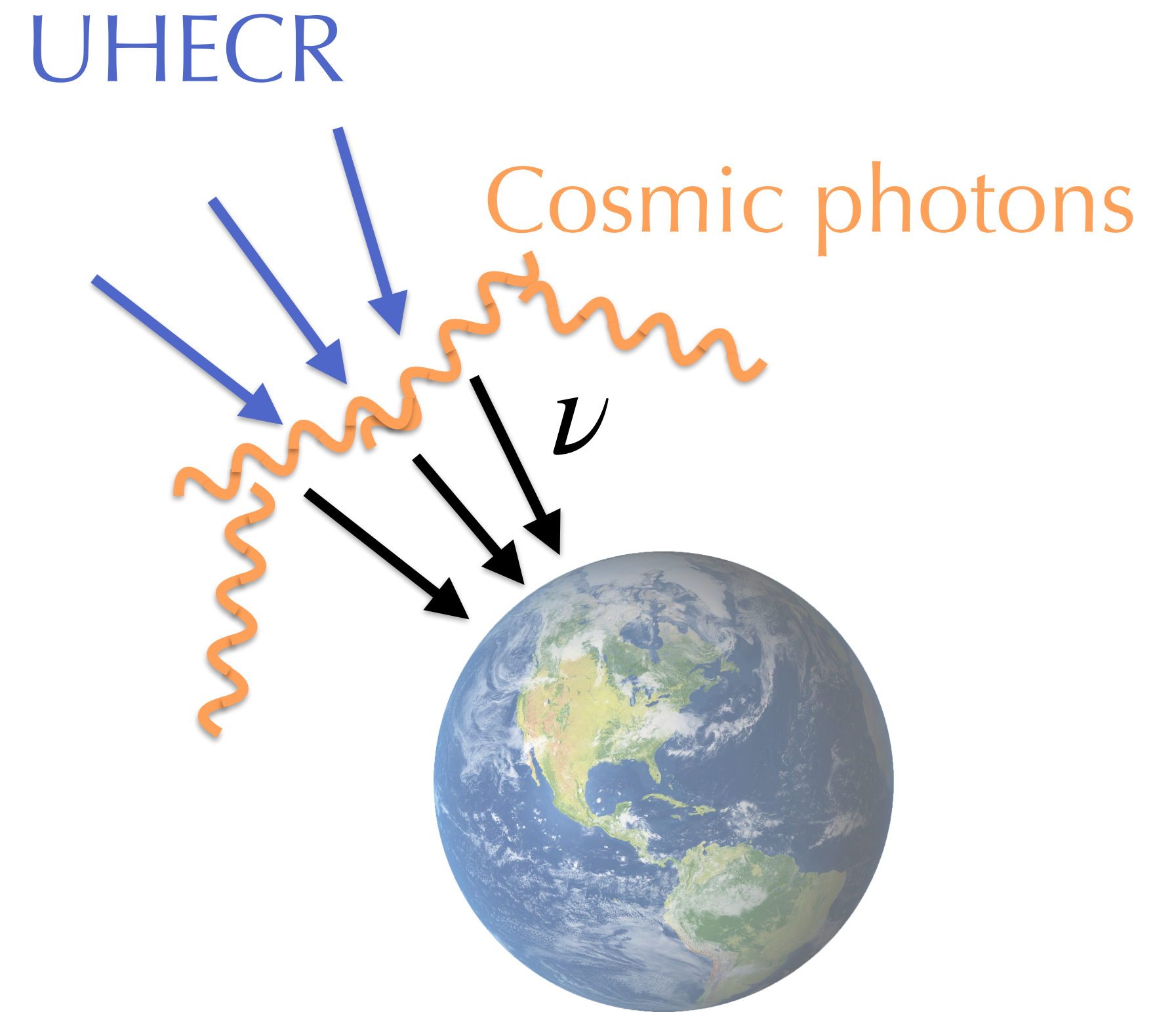
- ◆ Radio array in IceCube-Gen2 will be sensitive to UHE neutrinos
- ◆ Start taking data in 2030
- ◆ Realistic prospects for point source detection at IceCube-Gen2 radio array

UHE neutrinos

Source neutrinos

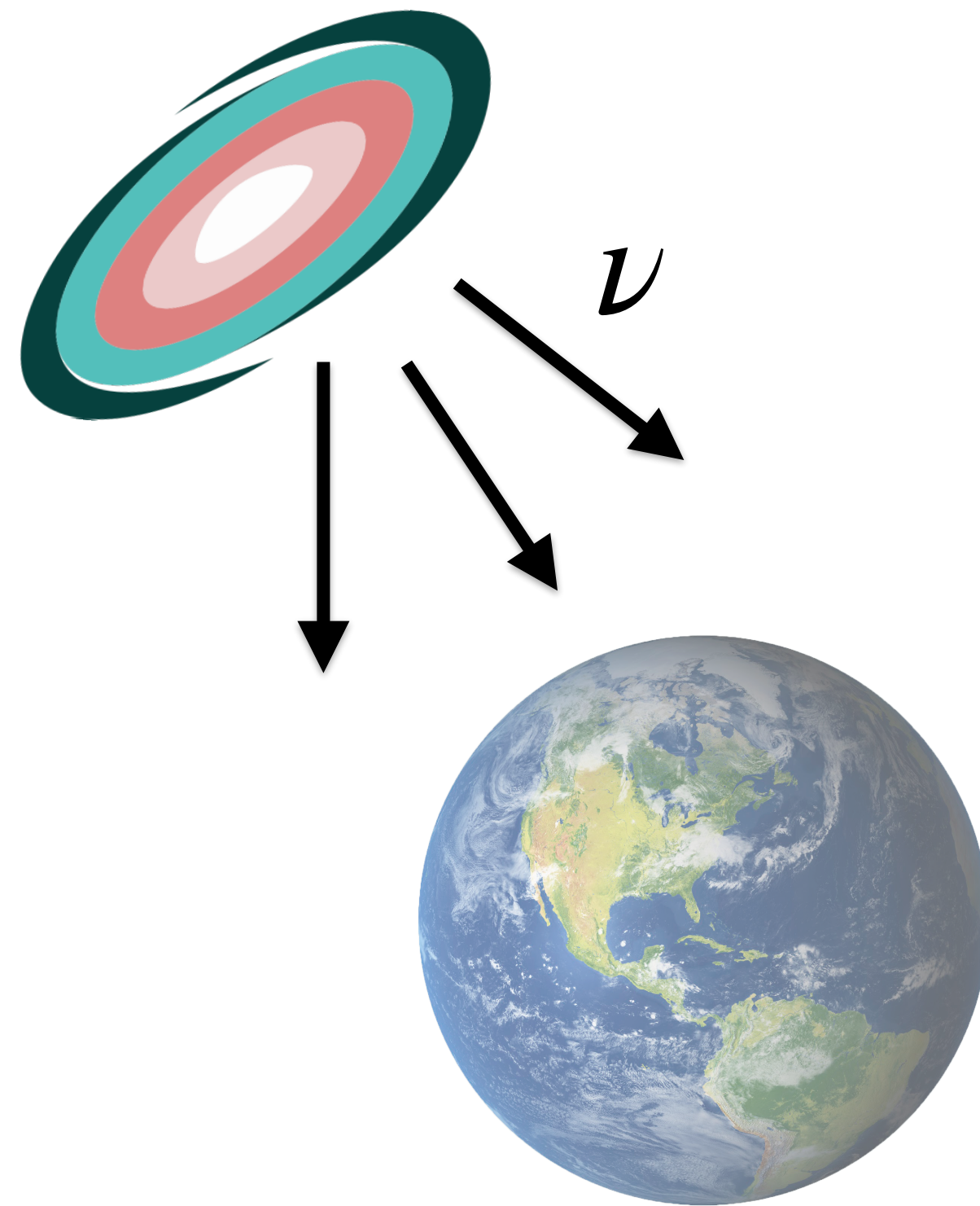


Cosmogenic neutrinos

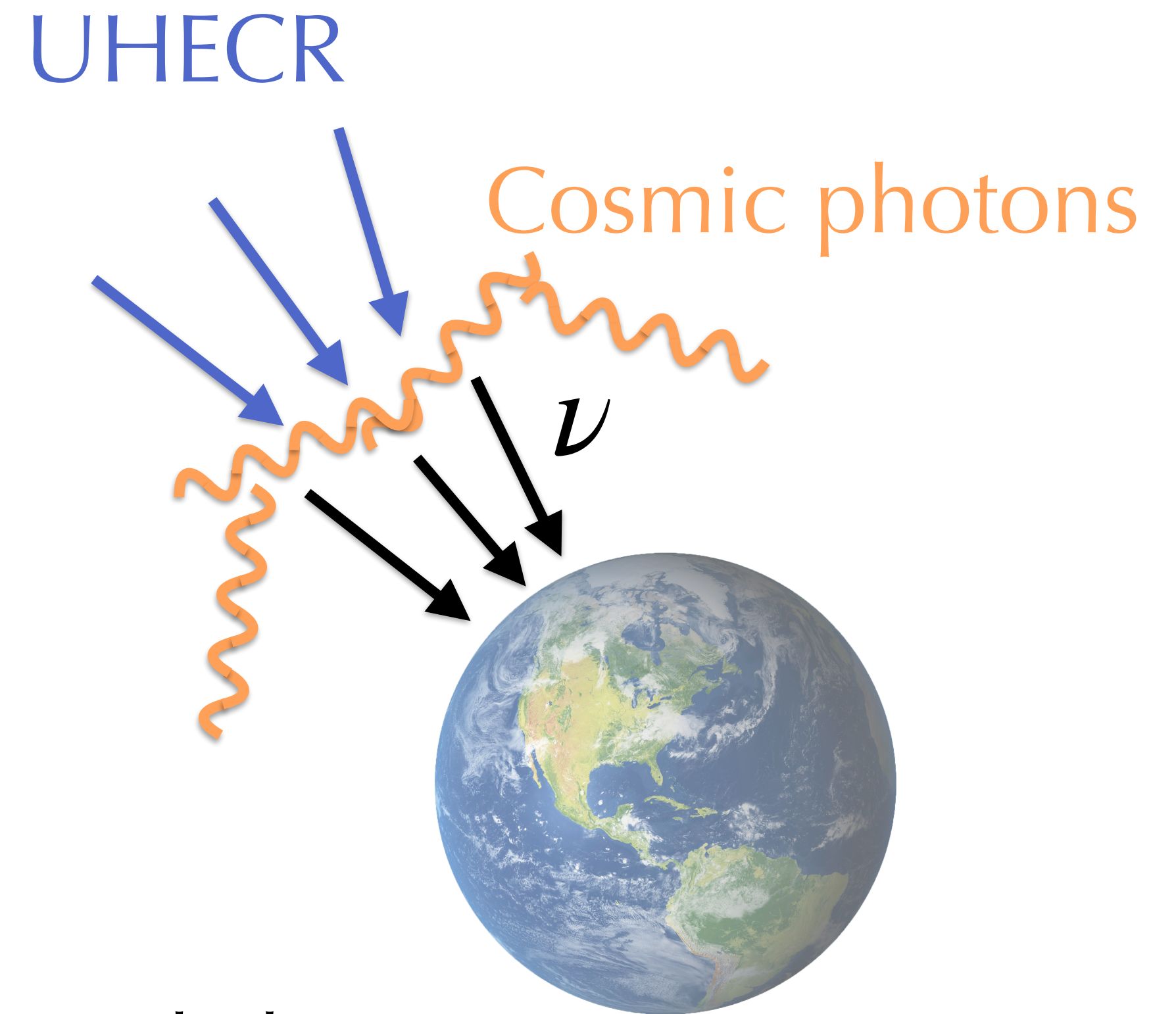


UHE neutrinos

Source neutrinos

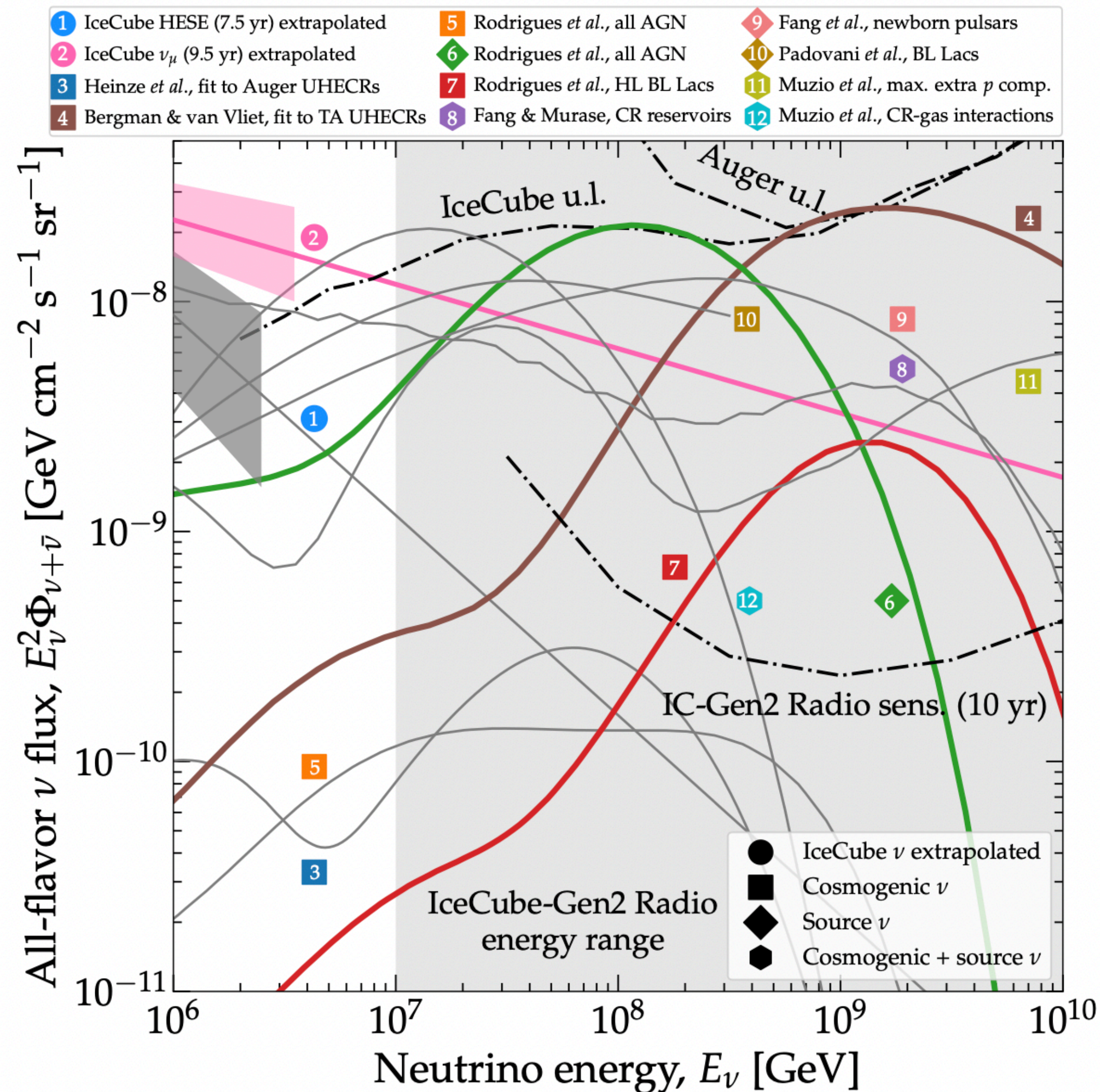


Cosmogenic neutrinos



Point source discovery can help discriminate between the two!

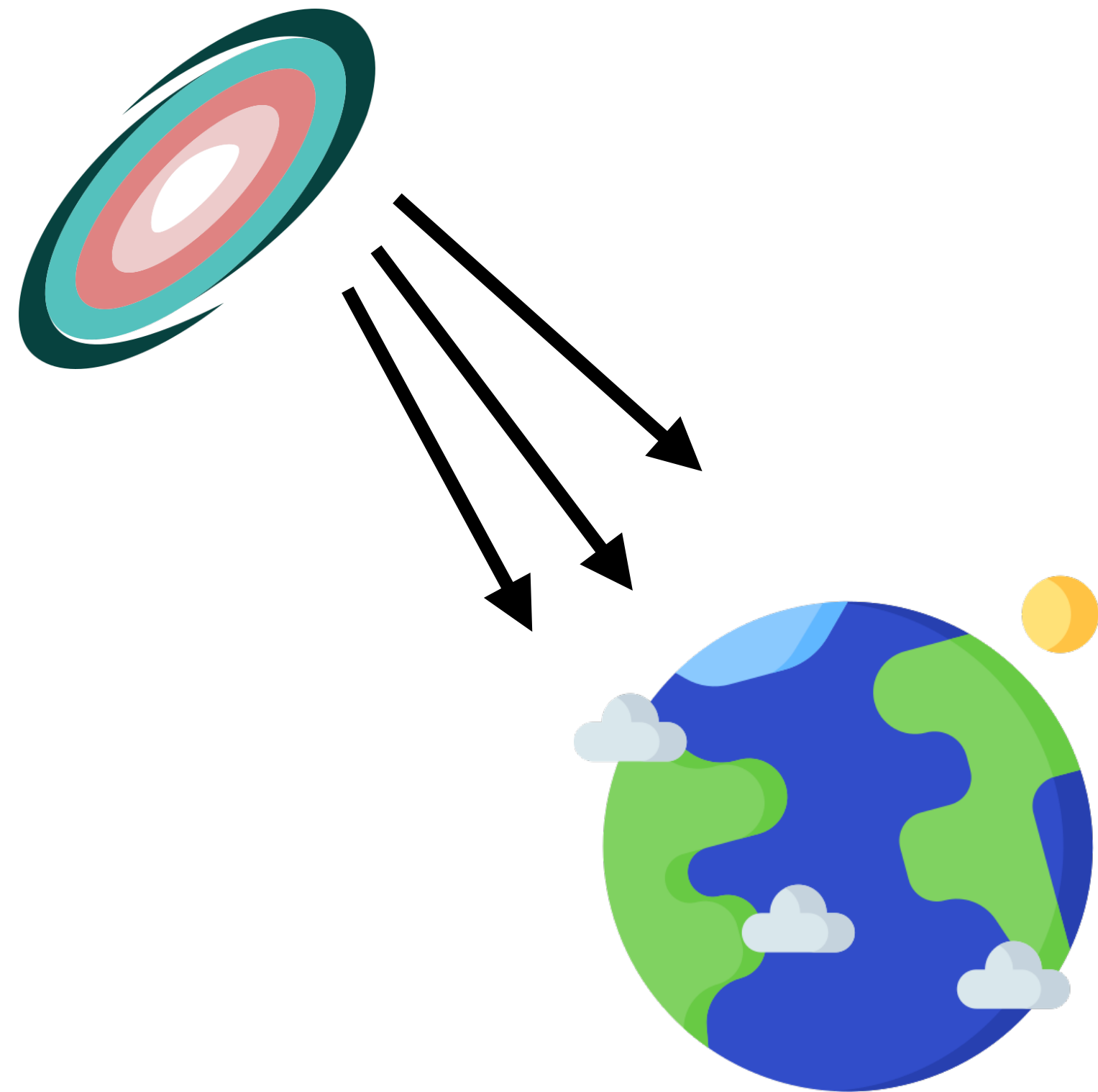
UHE neutrinos



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

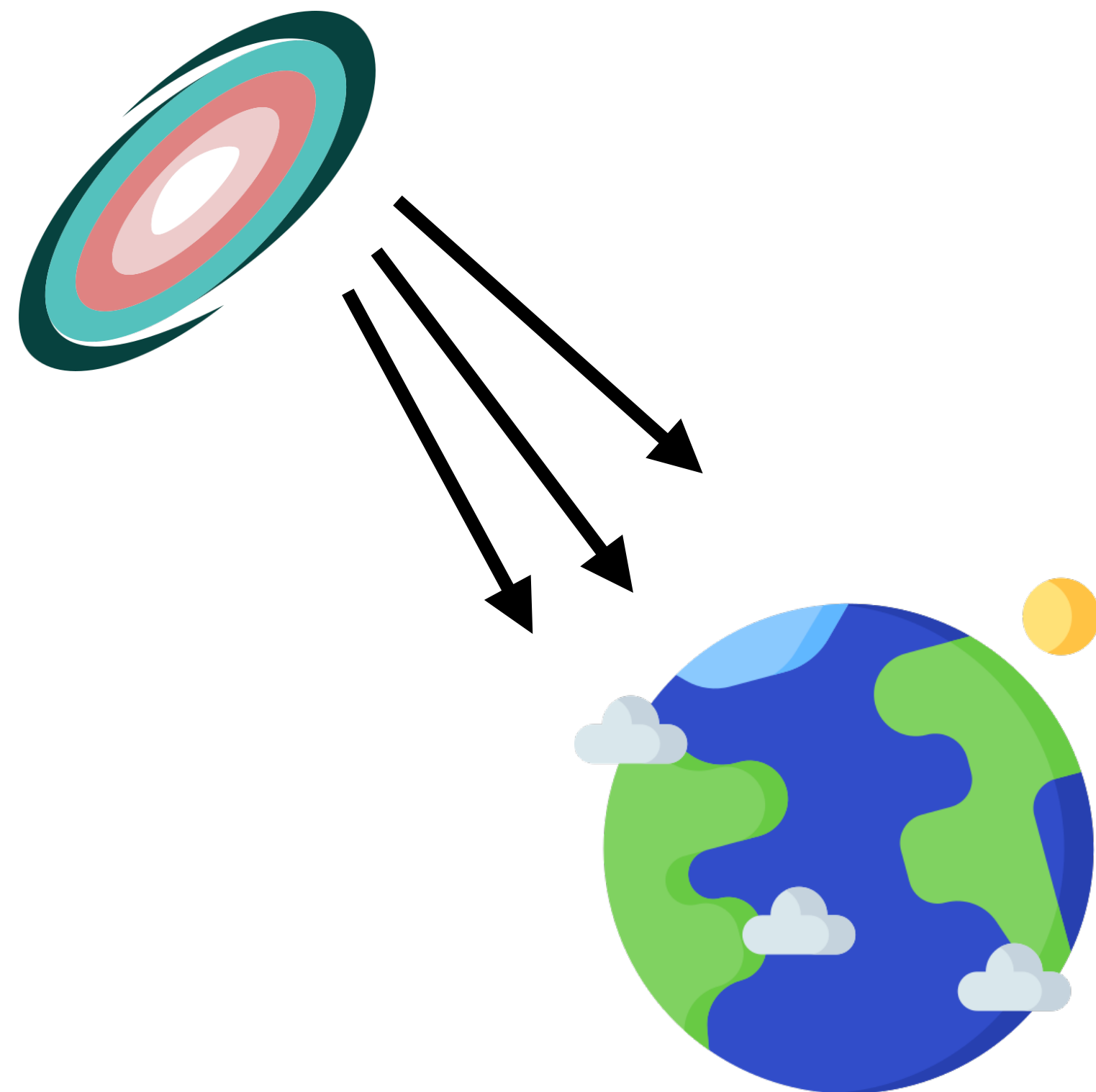
Multiplet searches

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

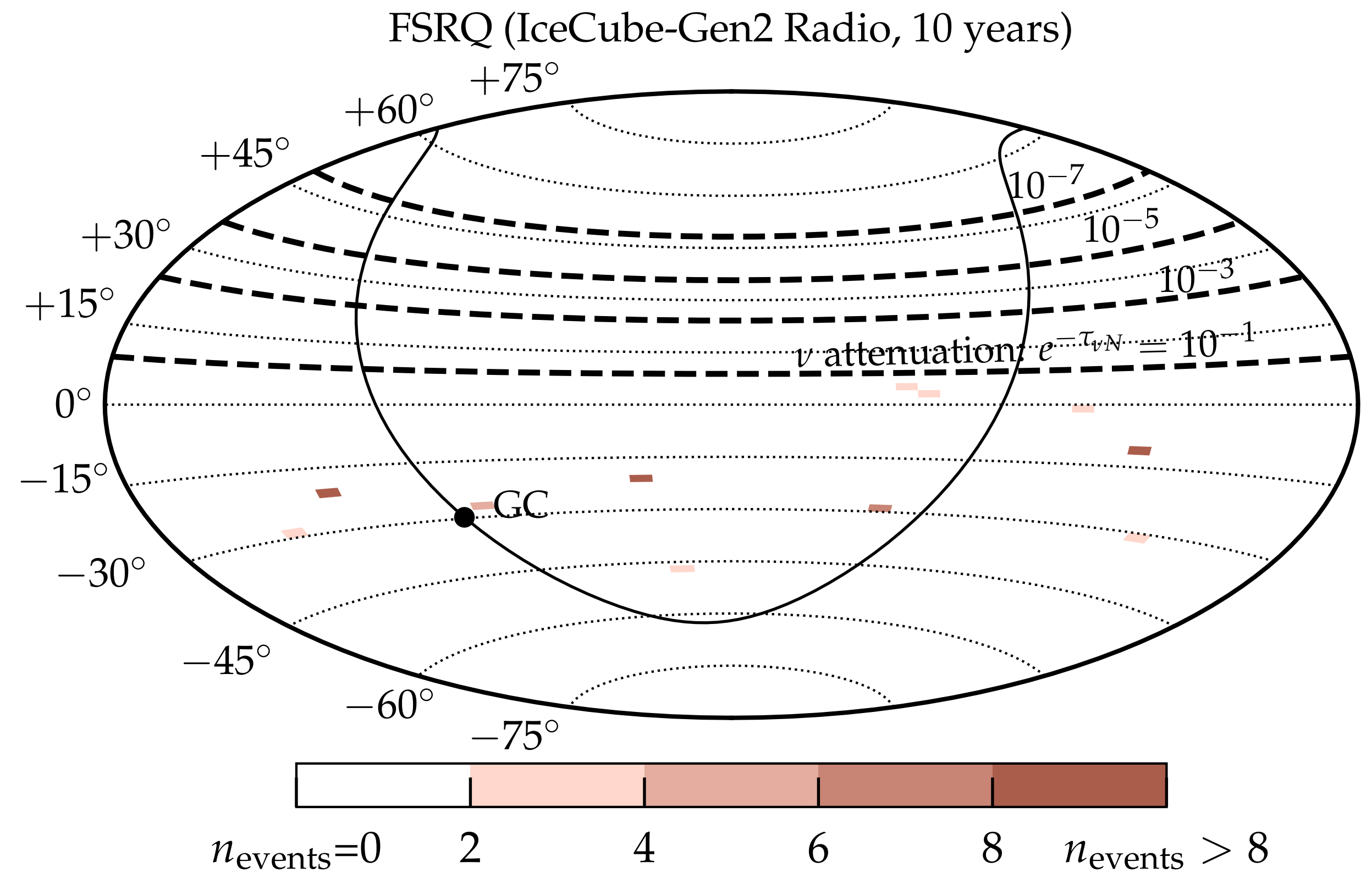


Multiplet searches

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



Assume angular uncertainty $\sim 2^\circ$, so we divide the sky in pixels of $2^\circ \times 2^\circ$ solid angle



See also Fang et al., 1609.08027

Multiplet searches

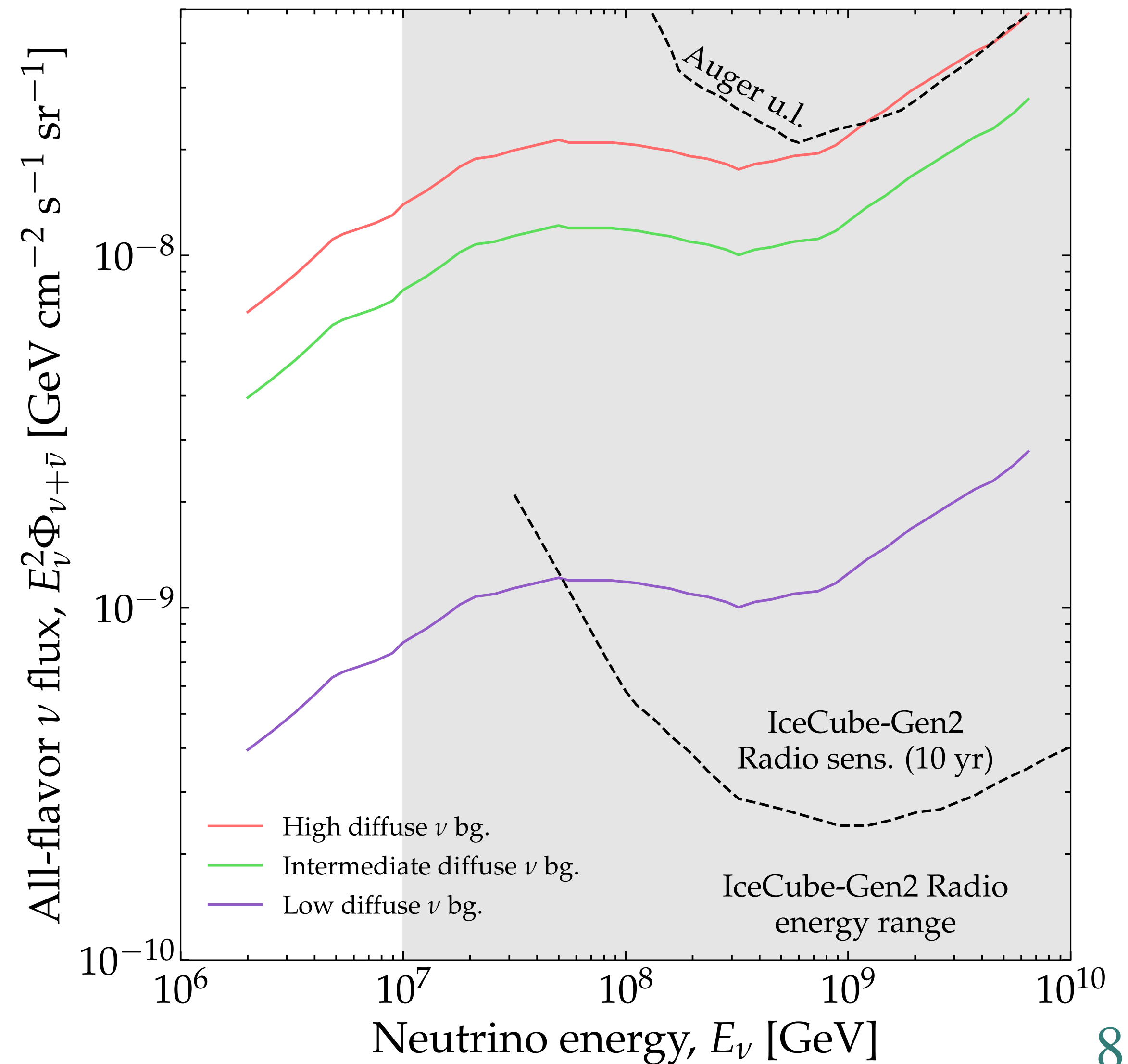
- ◆ Unresolved flux could produce fictitious multiplets by Poisson fluctuations
- ◆ ~ 3400 pixels make fluctuations more likely - look-elsewhere effect

Multiplet searches

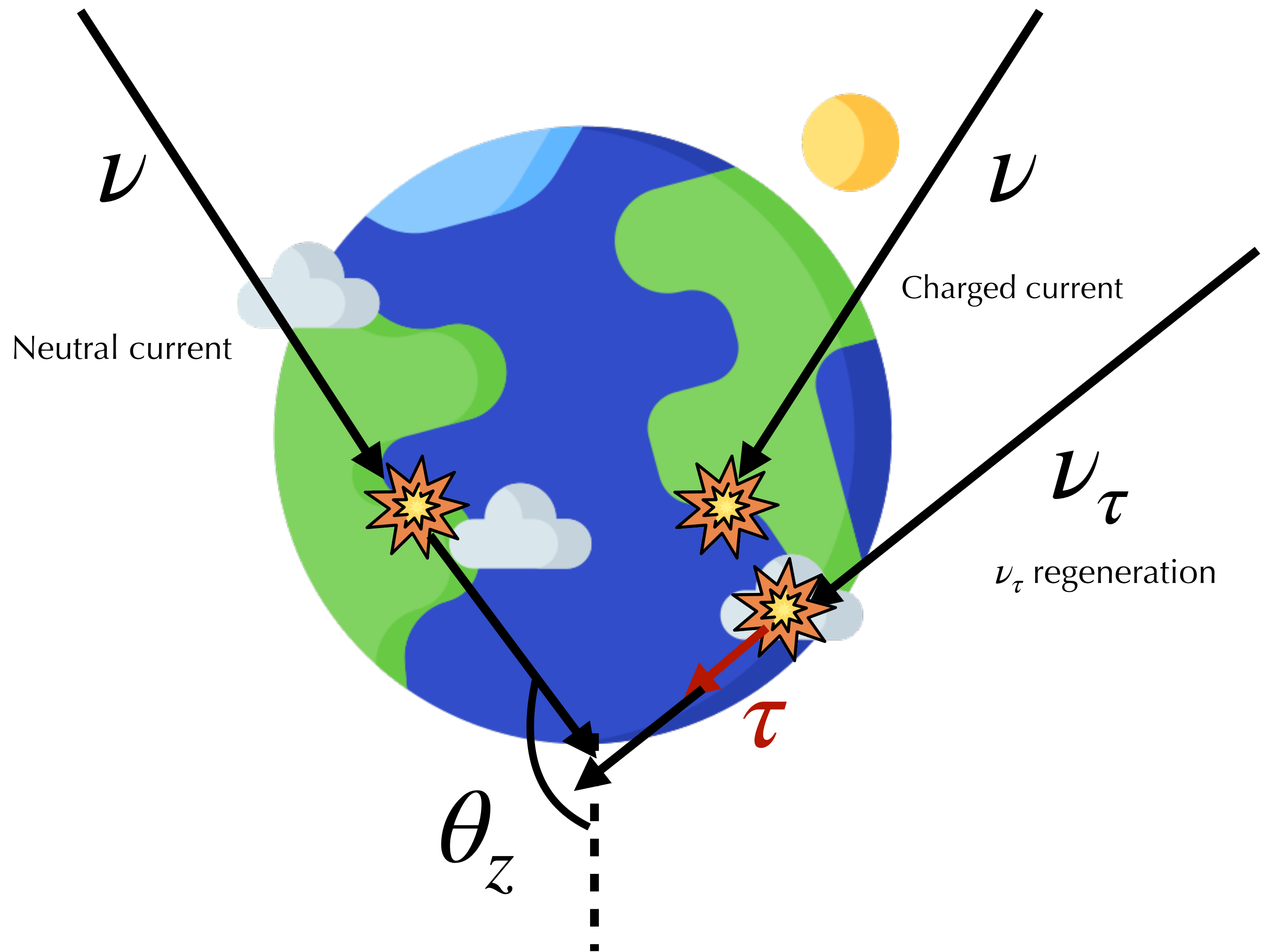
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- ◆ How large is the background?

Multiplet searches

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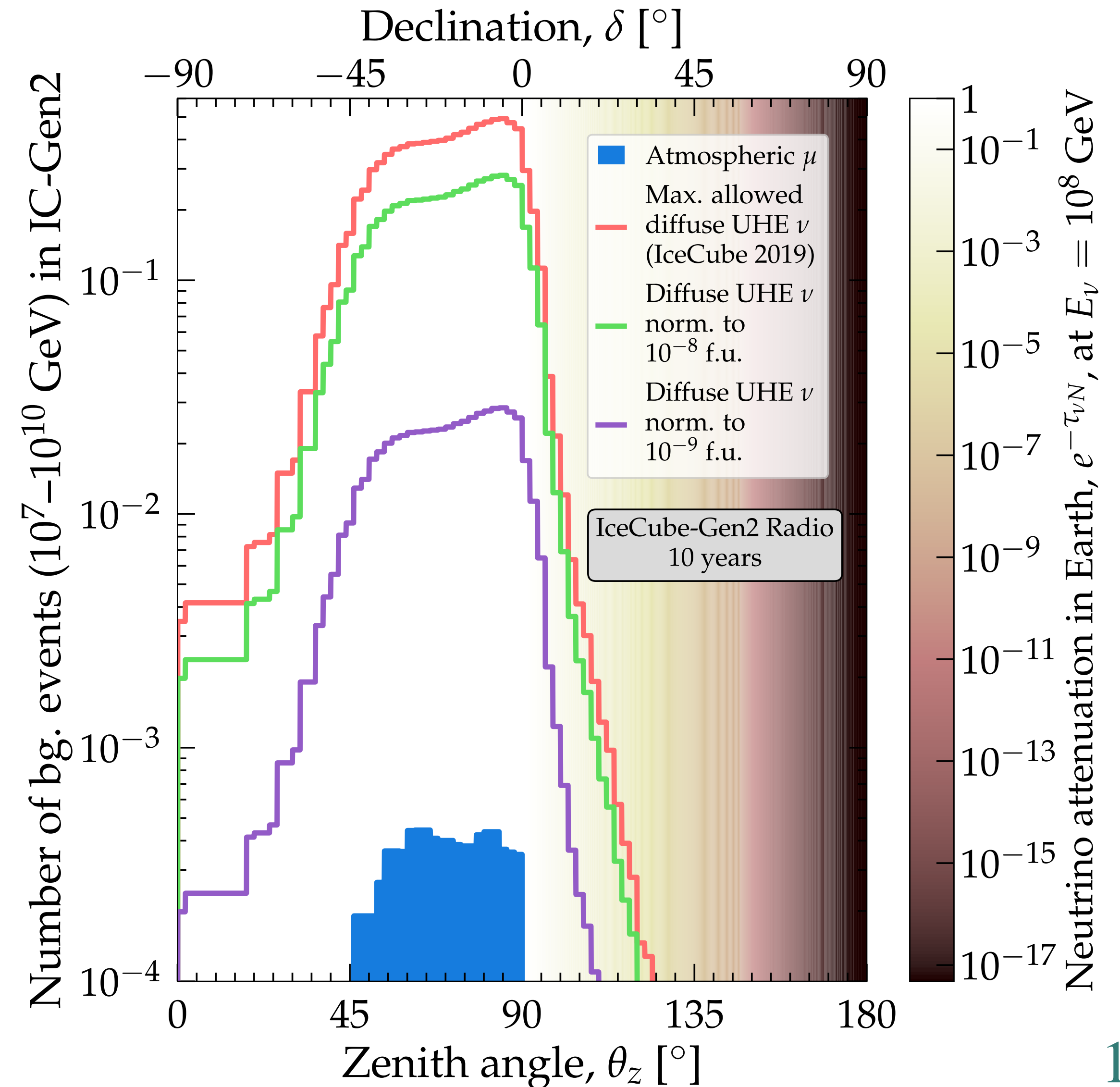
Detector simulation



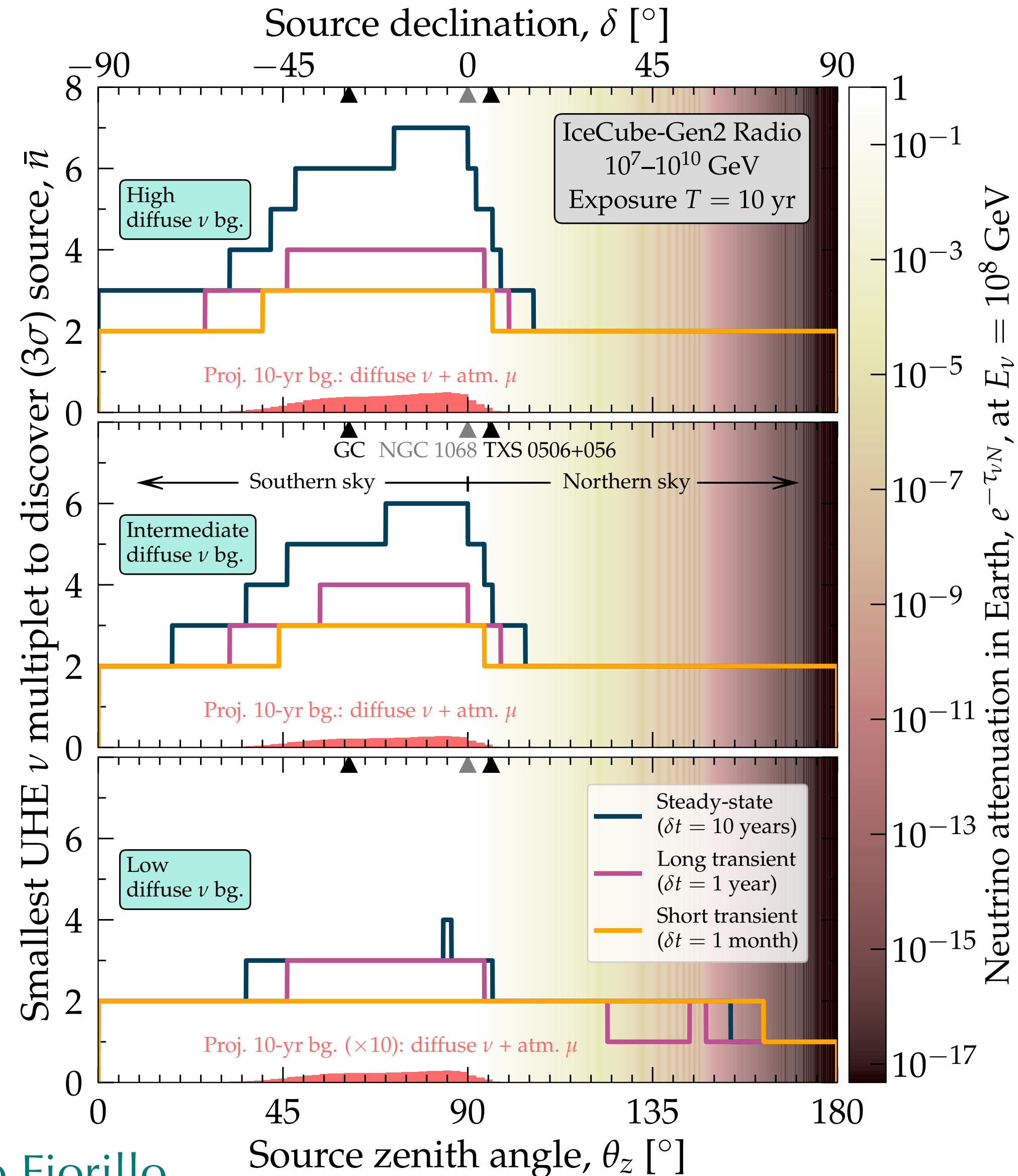
- ◆ Account for effects of Earth propagation
- ◆ Earth propagation leads to anisotropy of the signal
- ◆ Effective volume obtained in Valera et al., 2022 using NuRadioMC and NuRadioReco (Glaser et al., 2019)

Multiplet searches

- ◆ Unresolved flux could produce fictitious multiplets by Poisson fluctuations
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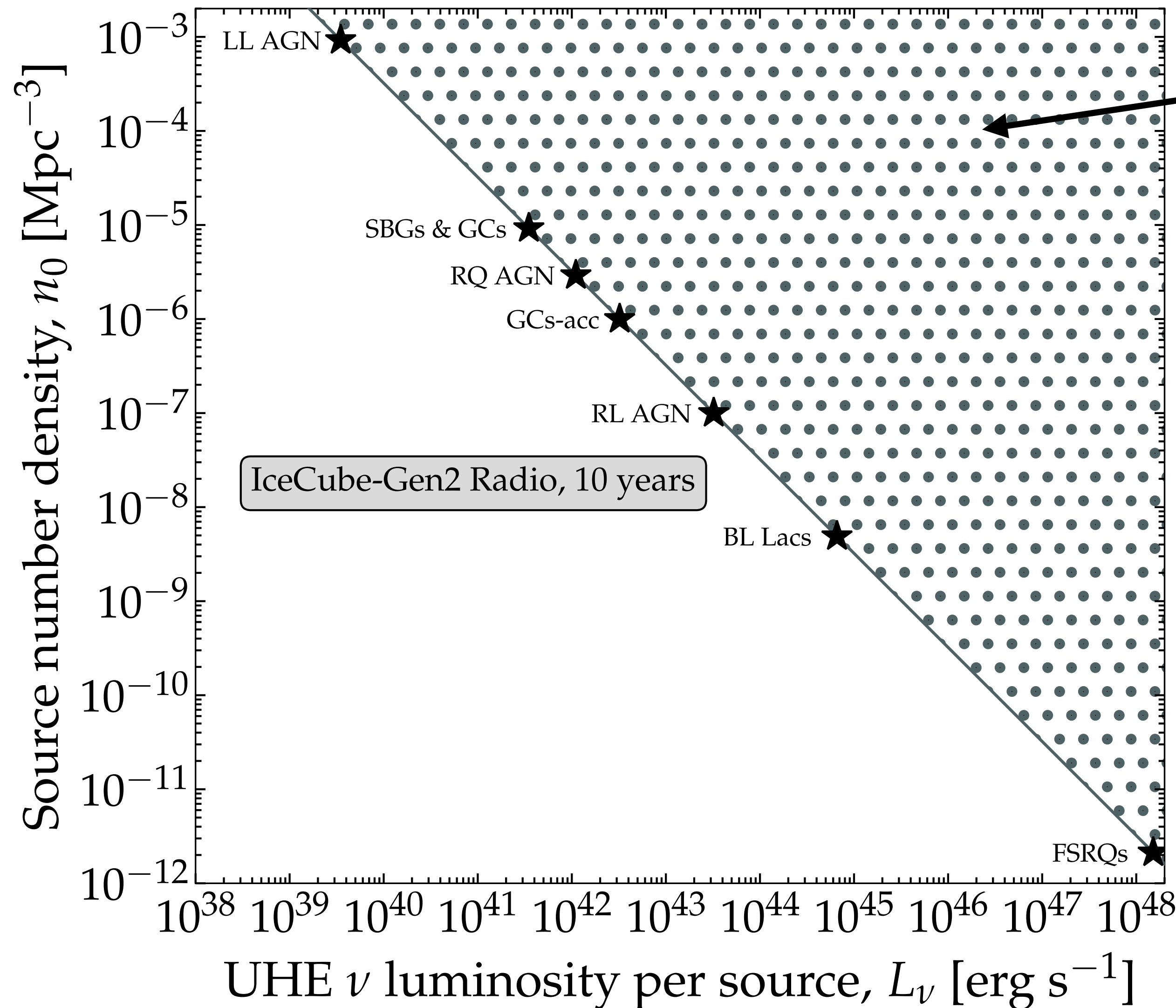
Multiplet searches



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

Steady-state sources

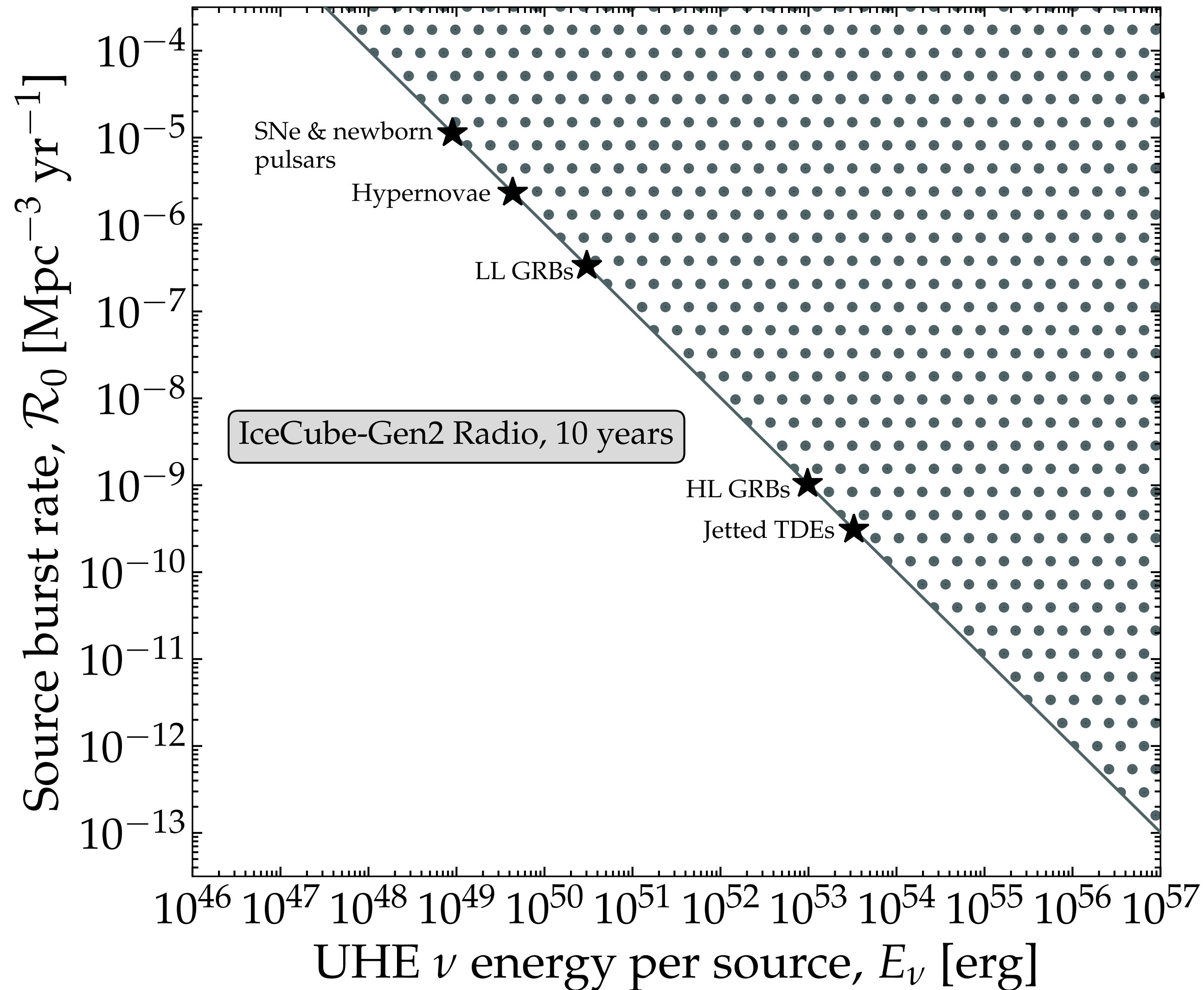


Exceeds diffuse flux

- ◆ 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

See also Murase et al., 1607.01601

Transient sources

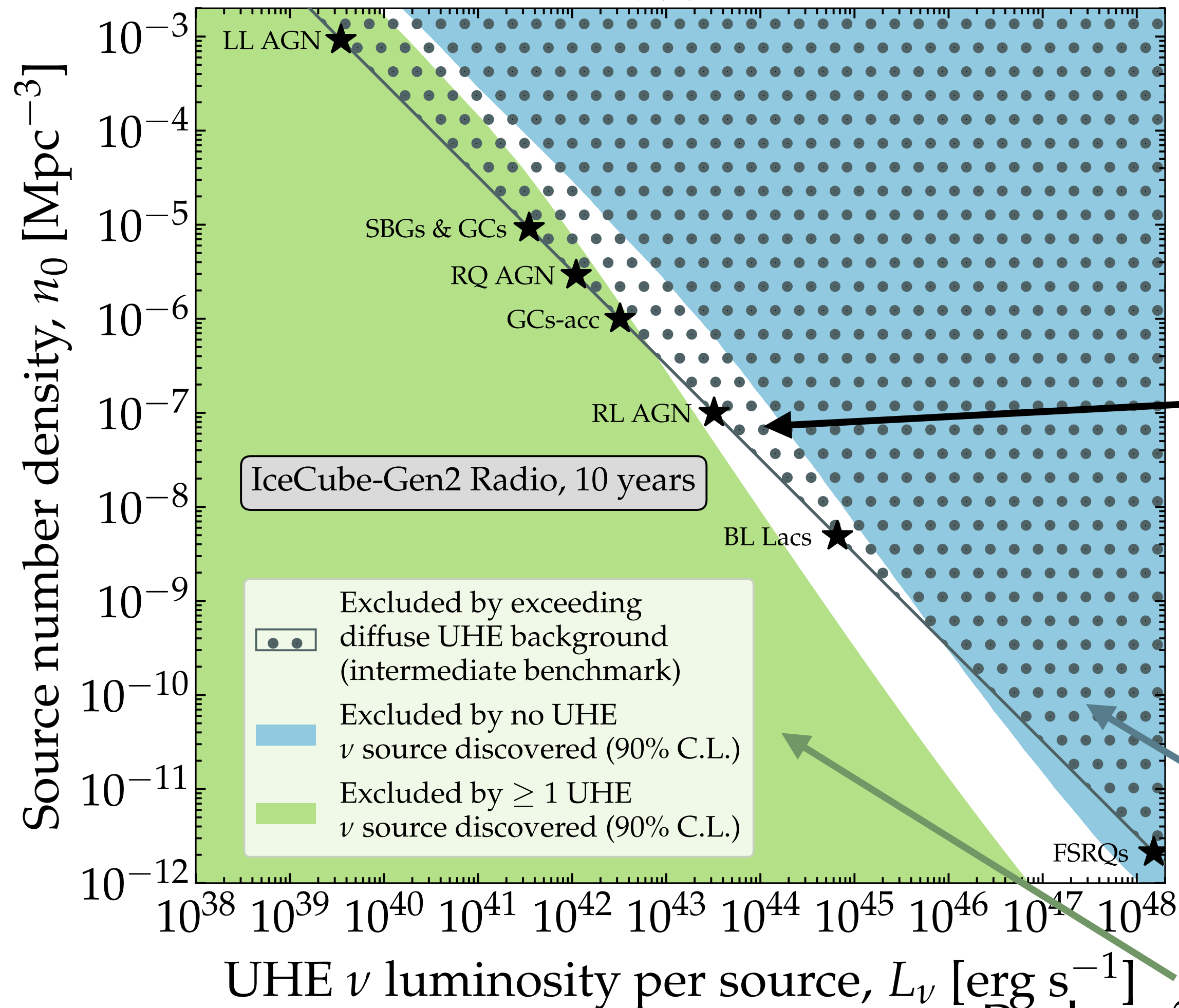


Exceeds diffuse flux

- ◆ How many sources explode? \mathcal{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

Steady-state sources



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

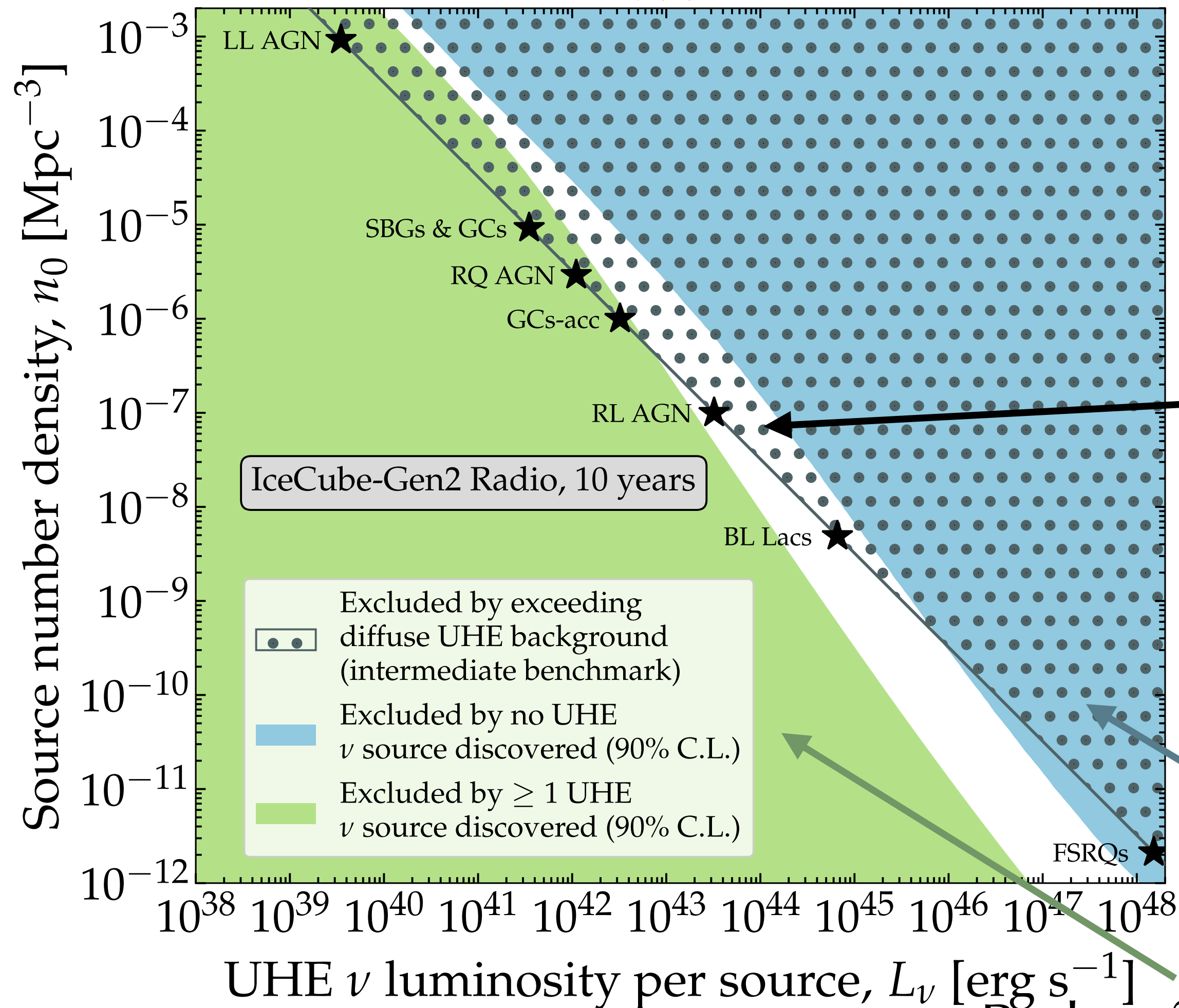
Exceeds diffuse flux

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

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

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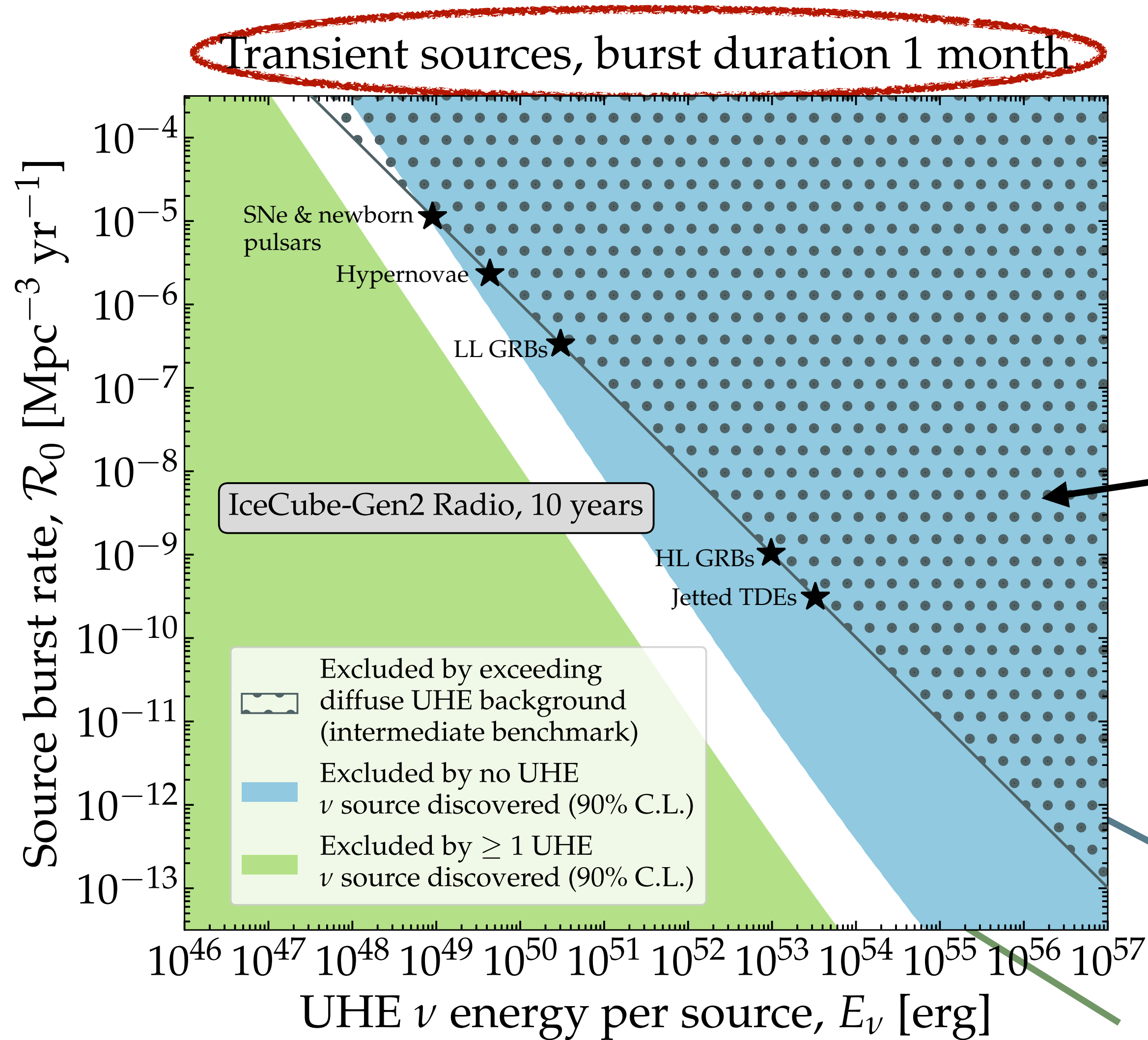
Exceeds diffuse flux

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

Source populations



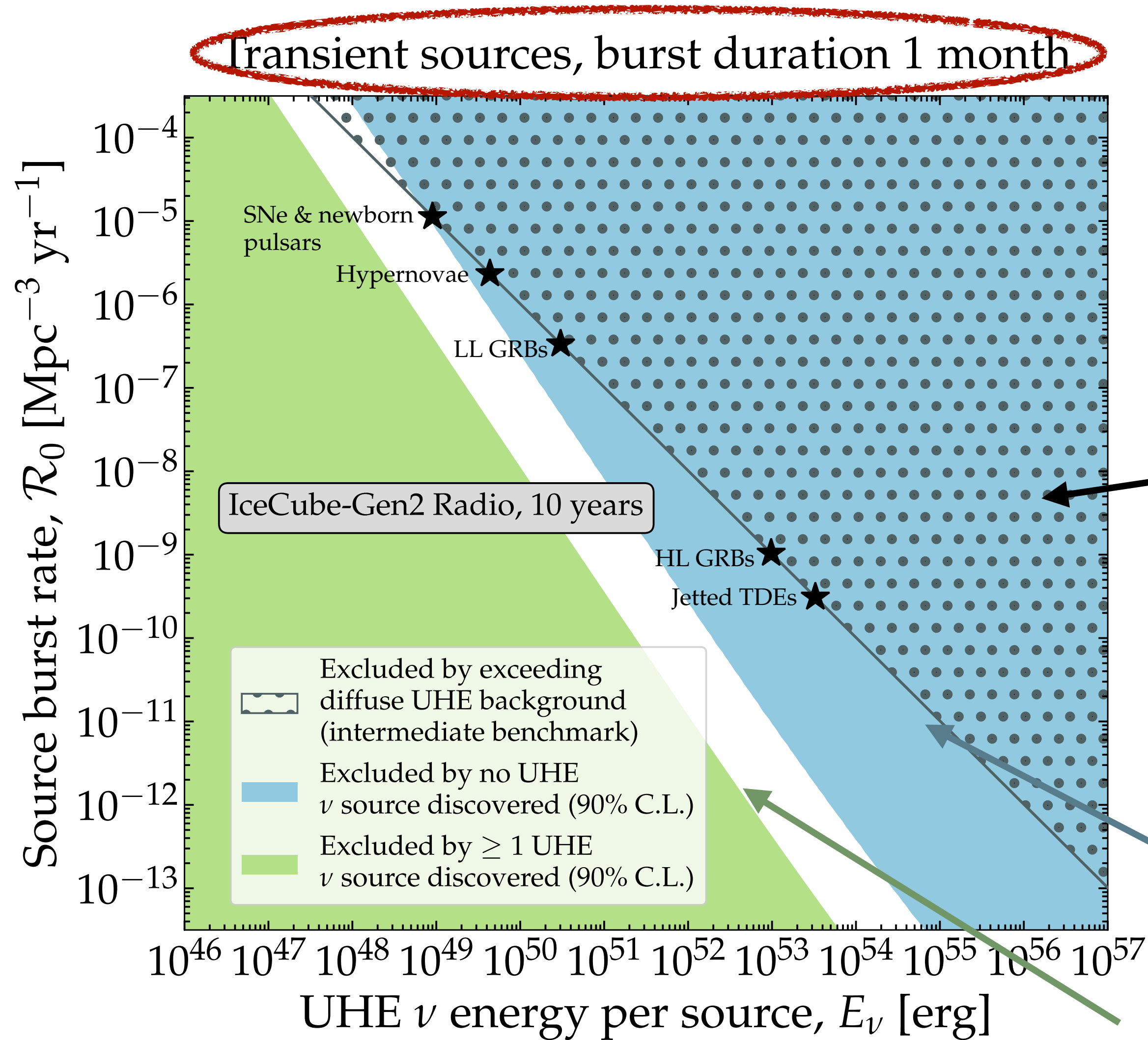
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Source populations



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

Exceeds diffuse flux

Most 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

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

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

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

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

Local p-value



Prob. of excess in a single pixel



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

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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 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.
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sources

Chances of detection

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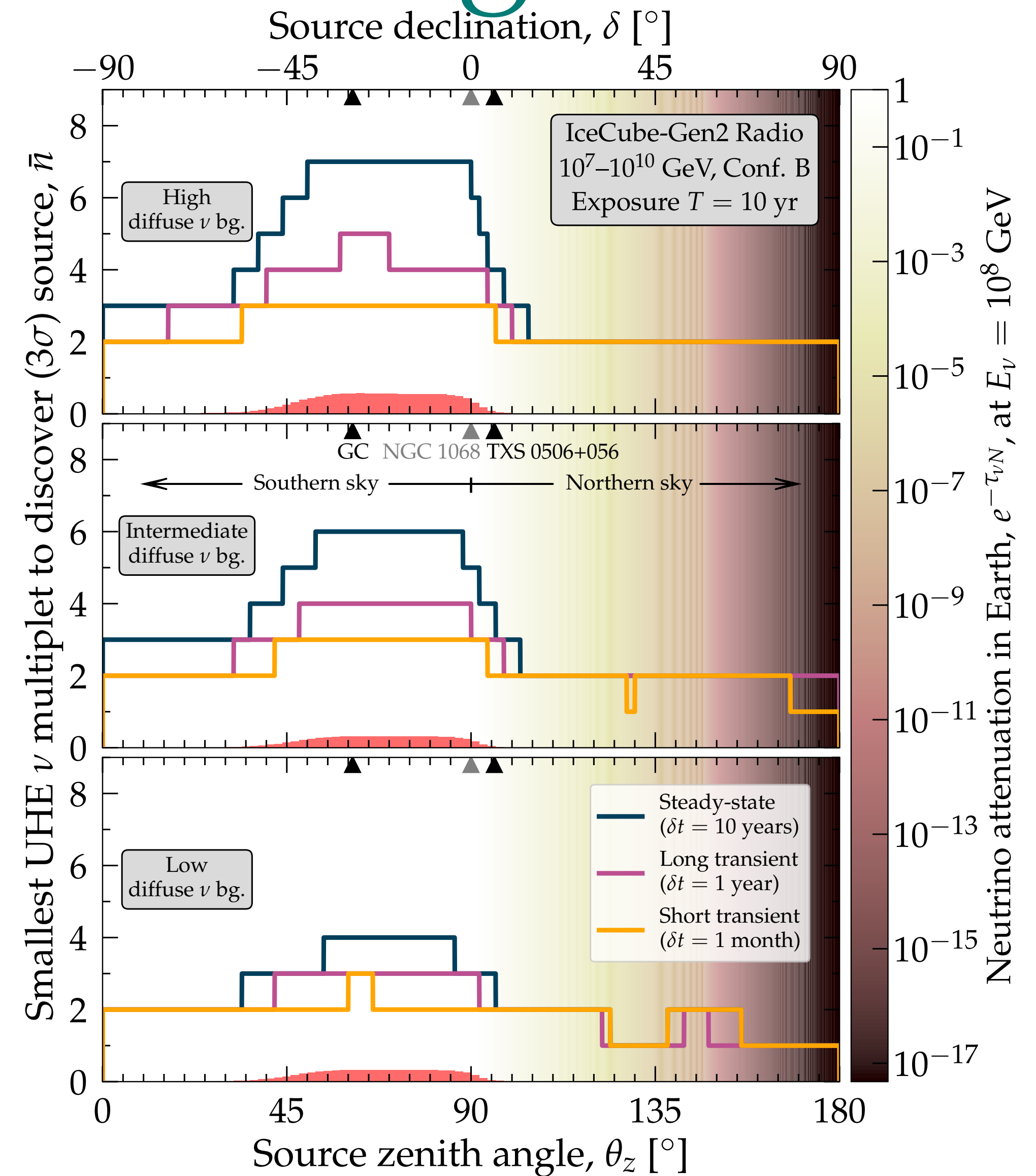
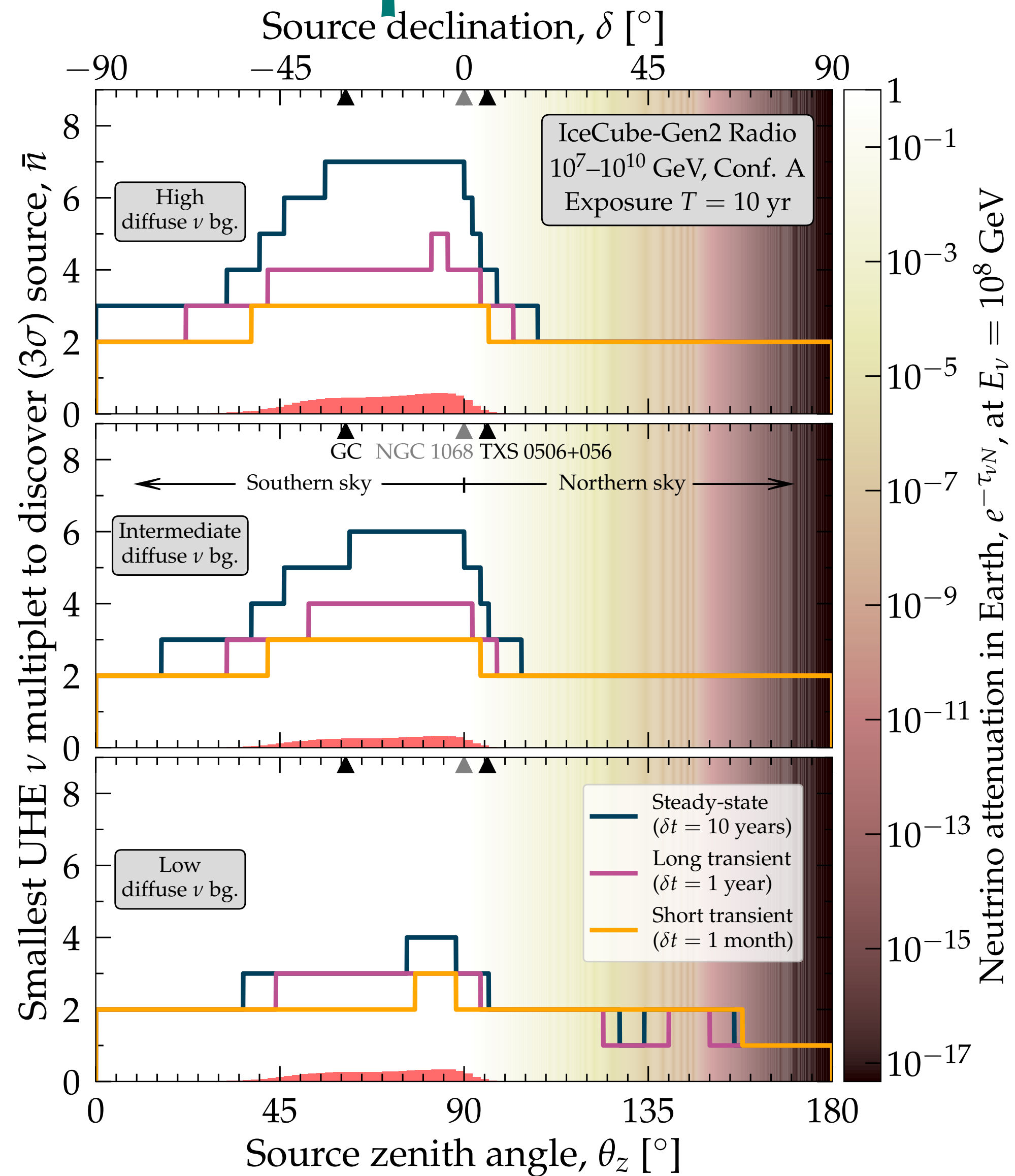
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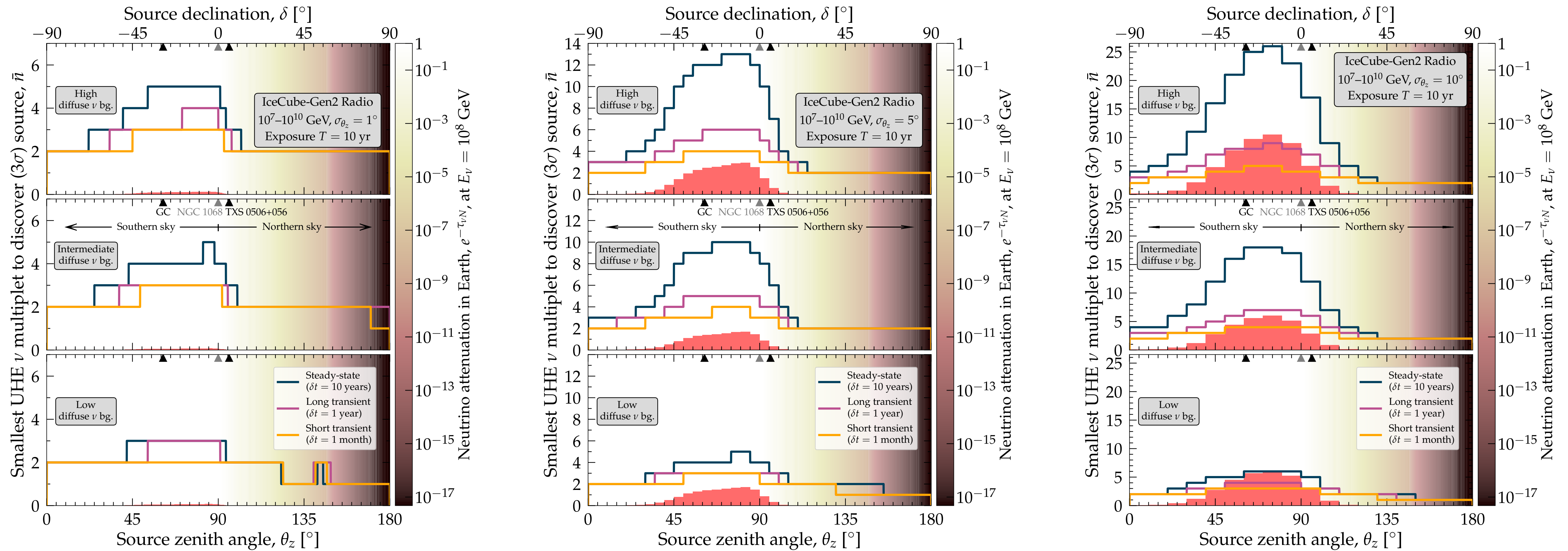
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Impact of detector design

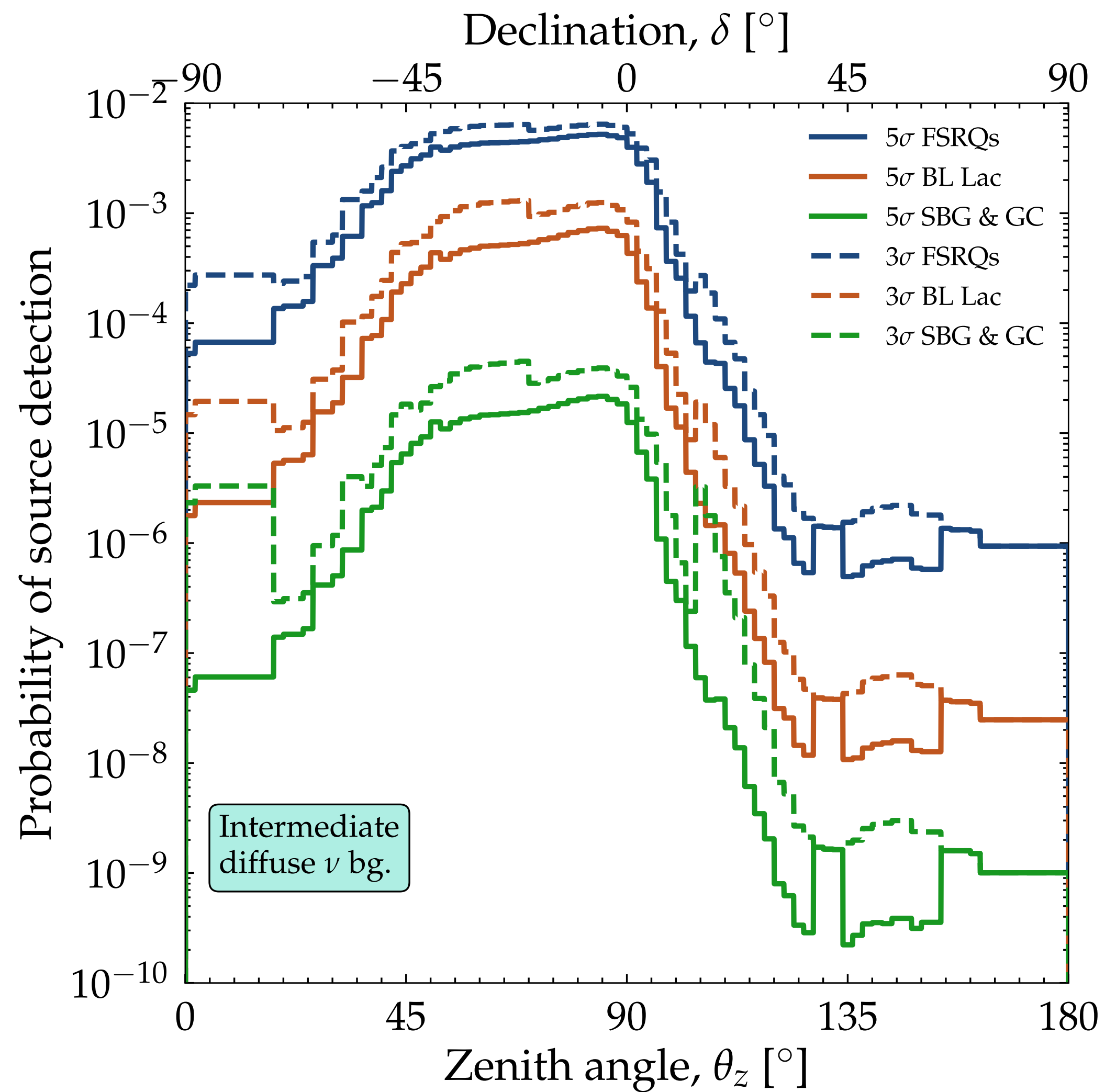


Impact of angular resolution



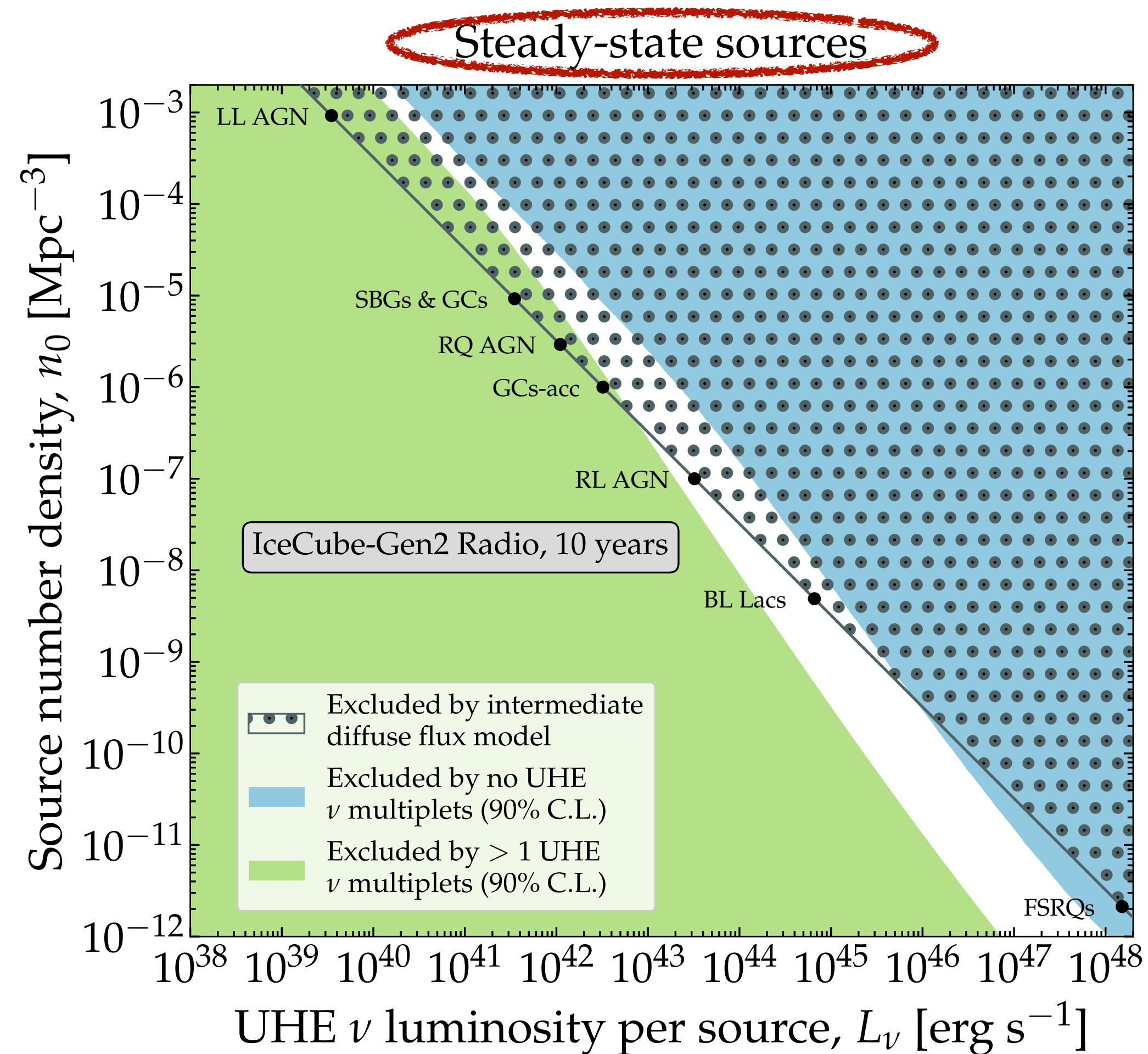
Chances of detection

- ◆ 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



Source populations

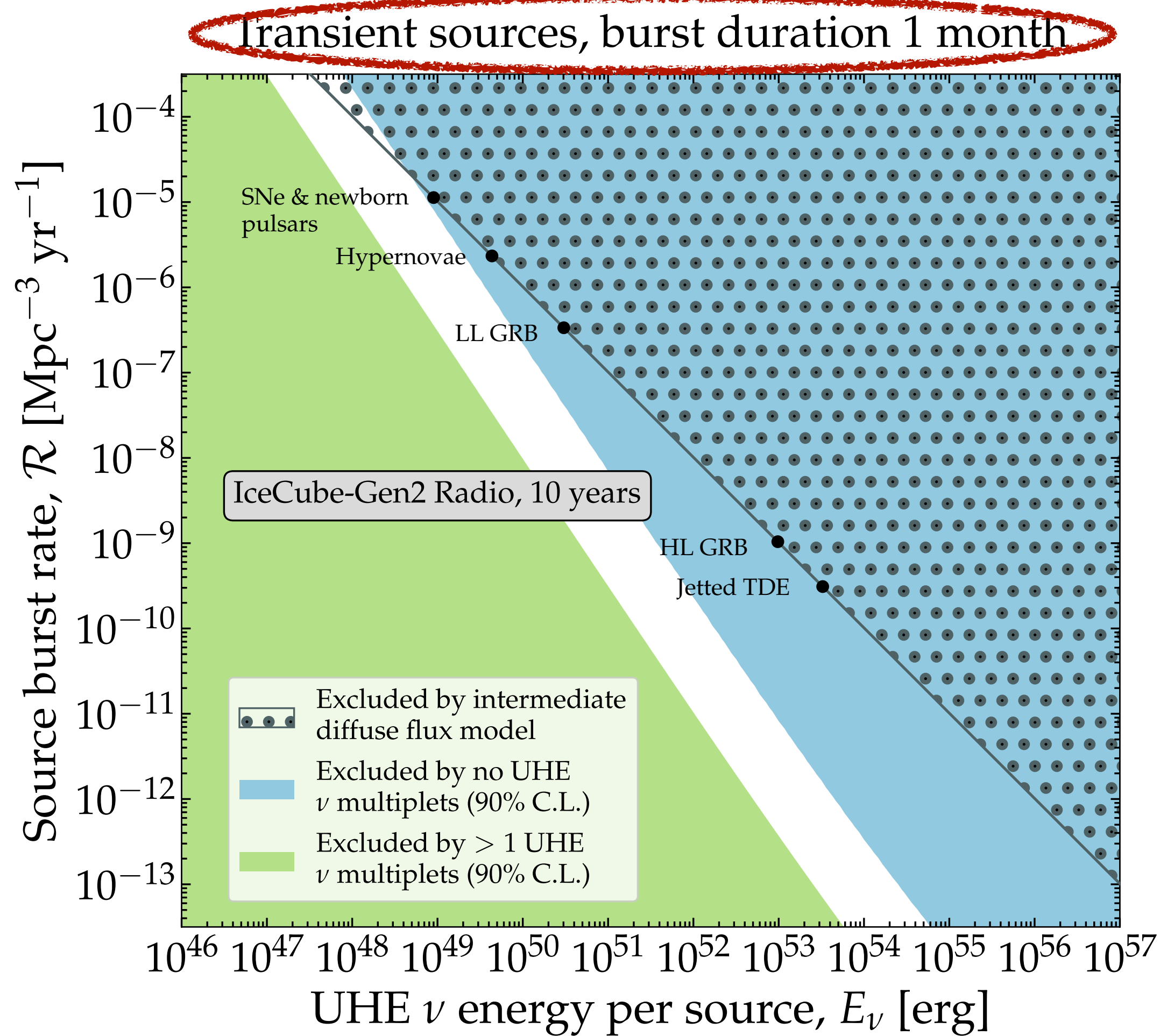
Main question: what do we learn from a (non-)detection?



- ◆ No detection excludes very bright sources
- ◆ At least one detection excludes dim sources
- ◆ Most steady-state sources not expected to be discovered

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