

A First Look at Sky Anisotropies of High-Energy Neutrino Flavours

Bernanda Telalovic, Mauricio Bustamante

What are the astrophysical neutrino flavour arrival directions?

Could we see new physics if they come from different directions?



EuCAPT



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IceCube has seen a flux of high-energy astrophysical neutrinos!



Which new physics?

Say that ν_e , ν_μ and ν_τ have different arrival directions.

What could cause this?

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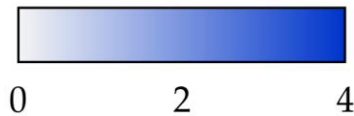
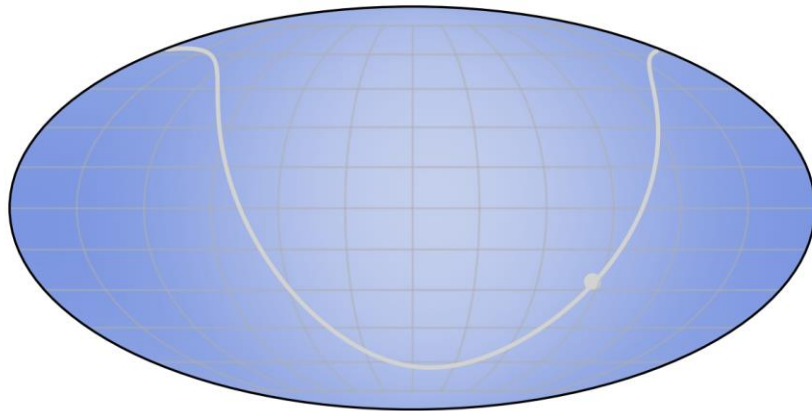
- **Astrophysics:** the high-energy neutrino production mechanisms are different and directional, or
- **Fundamental physics:** neutrino flavour oscillations are affected in a directionally-dependent manner.

Different production mechanisms from different directions... seems unlikely

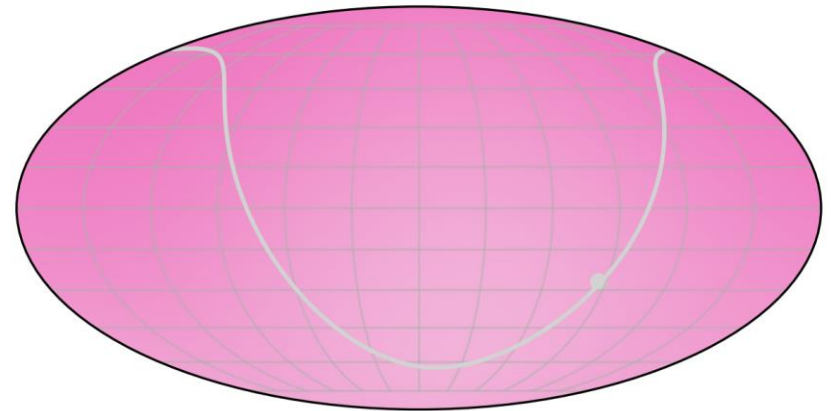
Ok, but are they the same?

We used 7.5 year HESE data to **recover arrival directions of flavours.**

$$\Phi^e = \Phi^\tau$$



$$\Phi^\mu$$

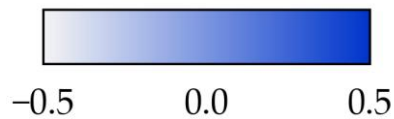
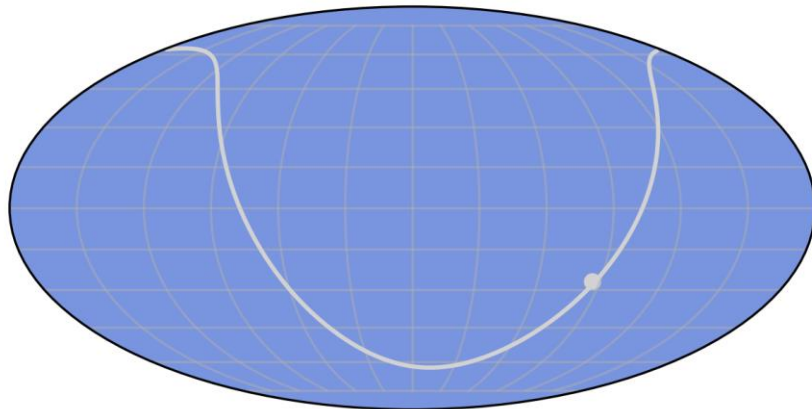


Equatorial

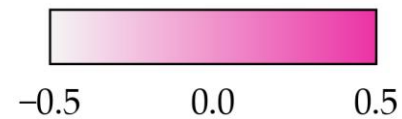
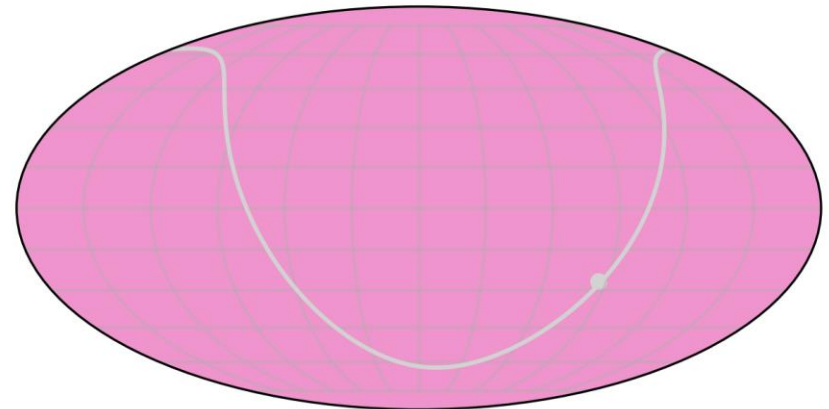
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If the distributions were isotropic:

$$\Delta\Phi^e = \Delta\Phi^\tau$$



$$\Delta\Phi^\mu$$

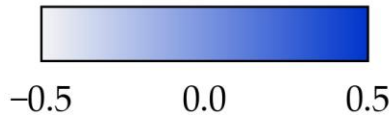
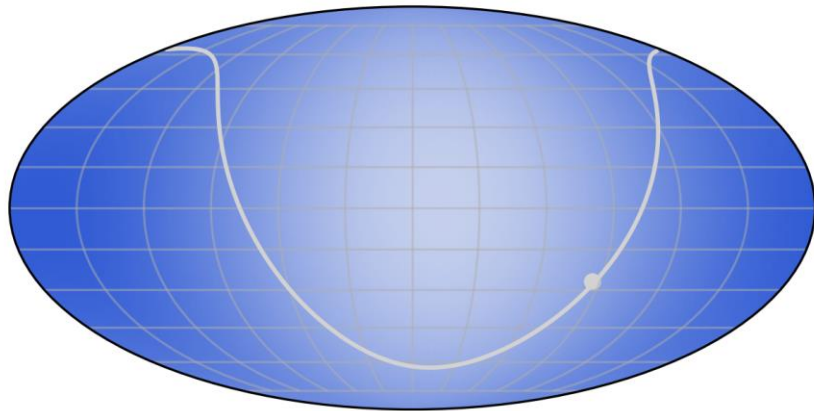


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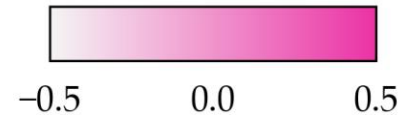
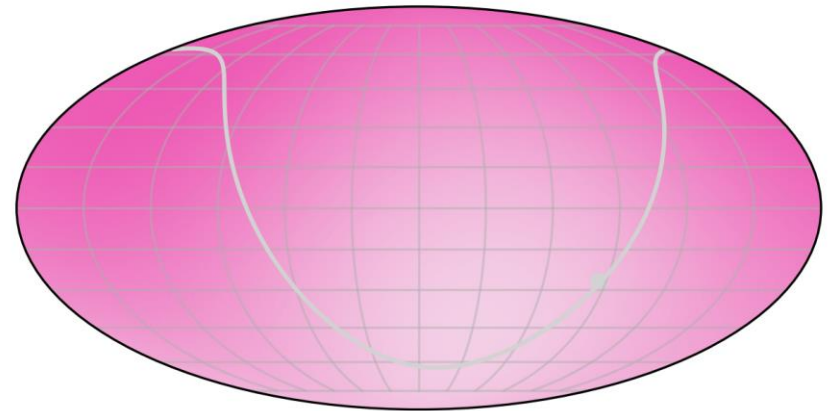
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The flavour all-sky-average current **dipole** anisotropy best fits:

$$\Delta\Phi^e = \Delta\Phi^\tau$$



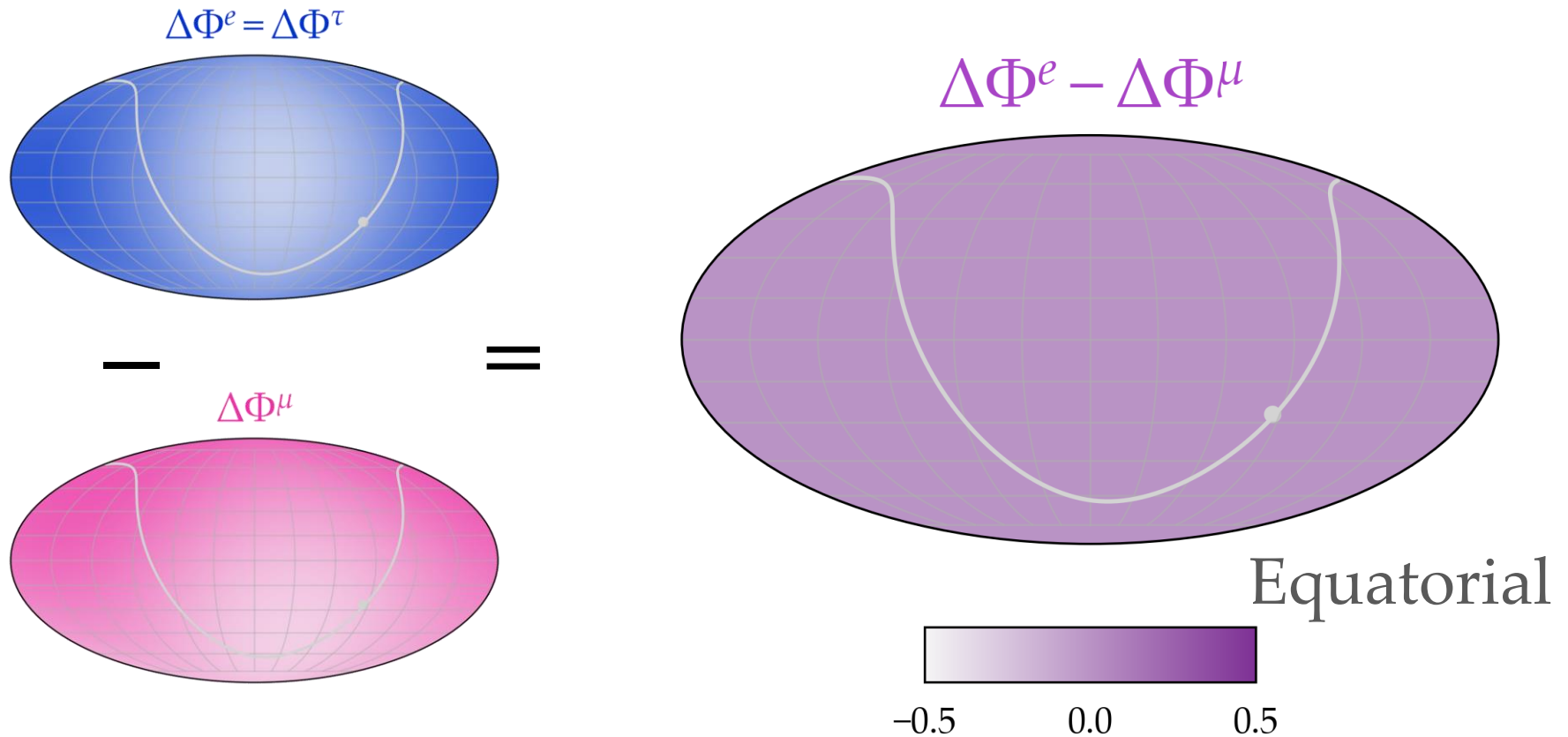
$$\Delta\Phi^\mu$$



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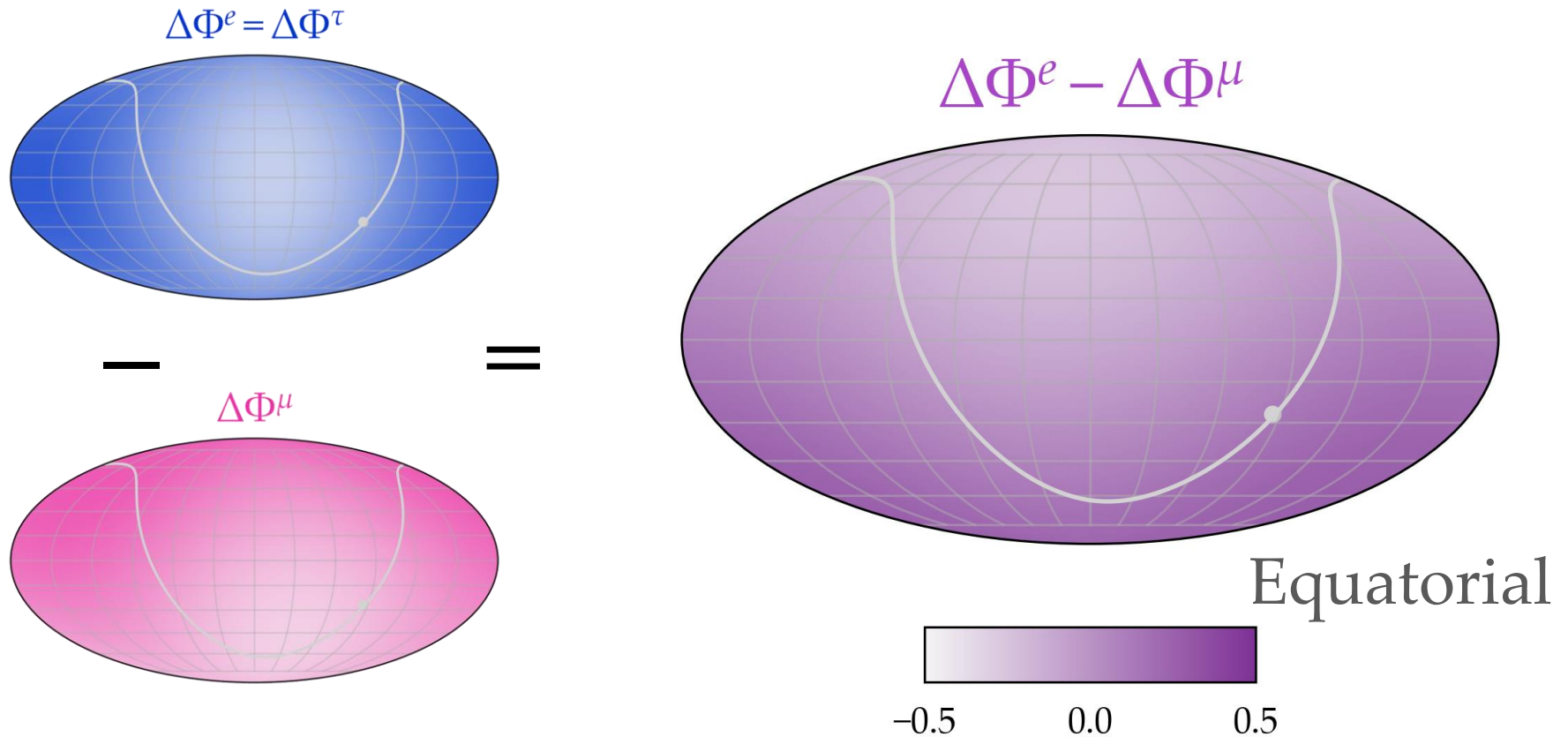
Currently large uncertainties—compatible with isotropy at 1σ .

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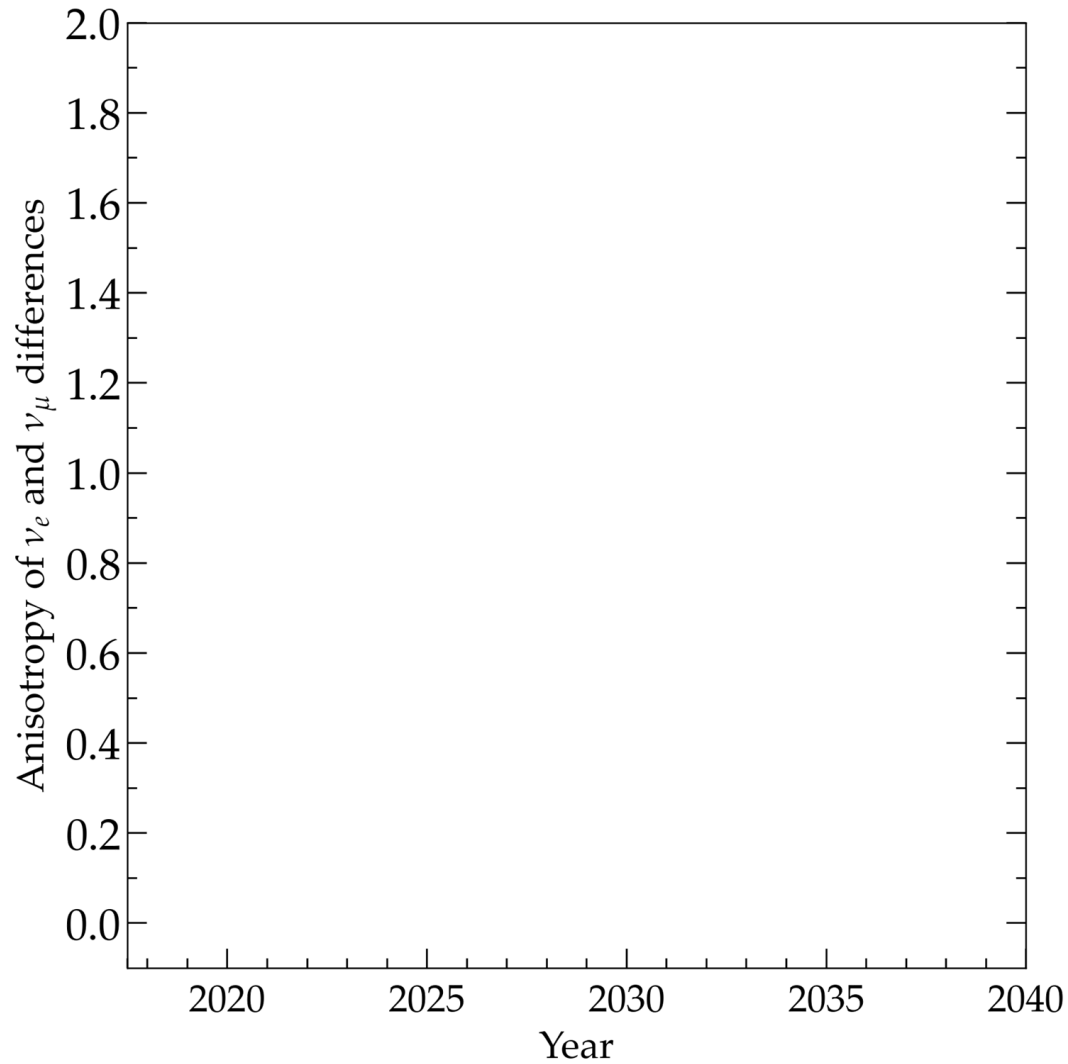
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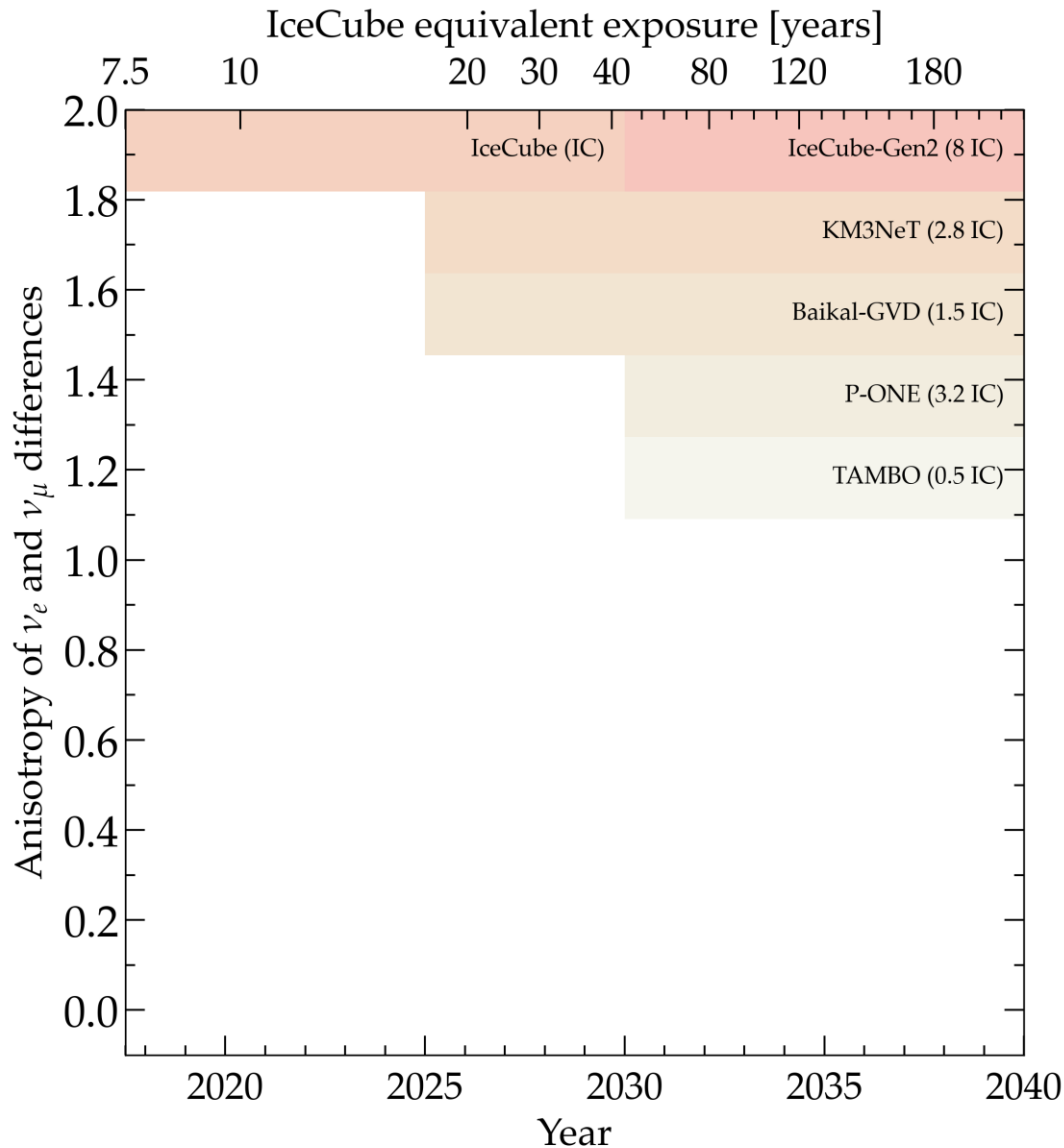


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How well can we constrain isotropy over time?



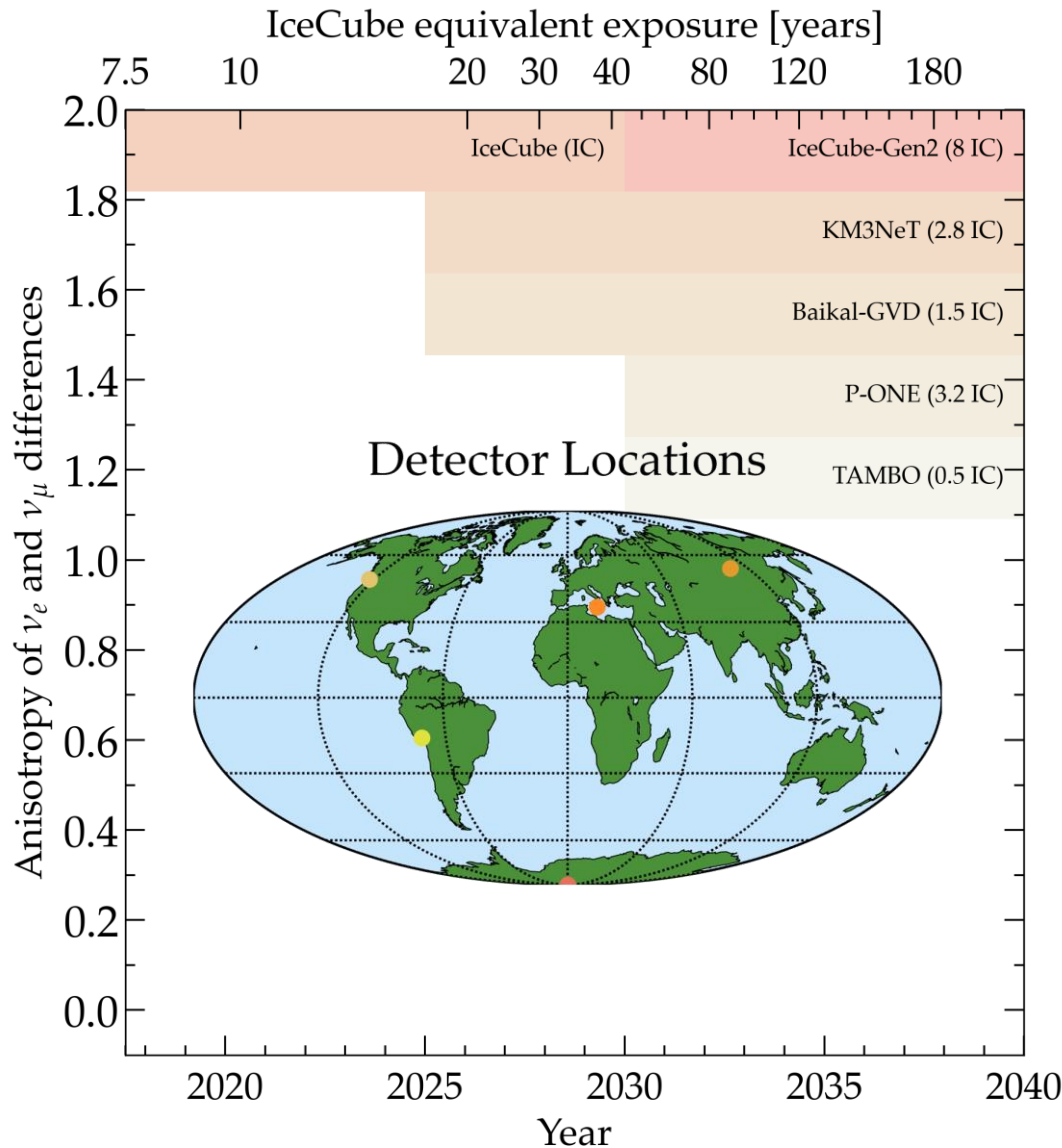
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More detectors – better:

- Statistics
- Angular resolution (KM3NeT)
- Sky coverage

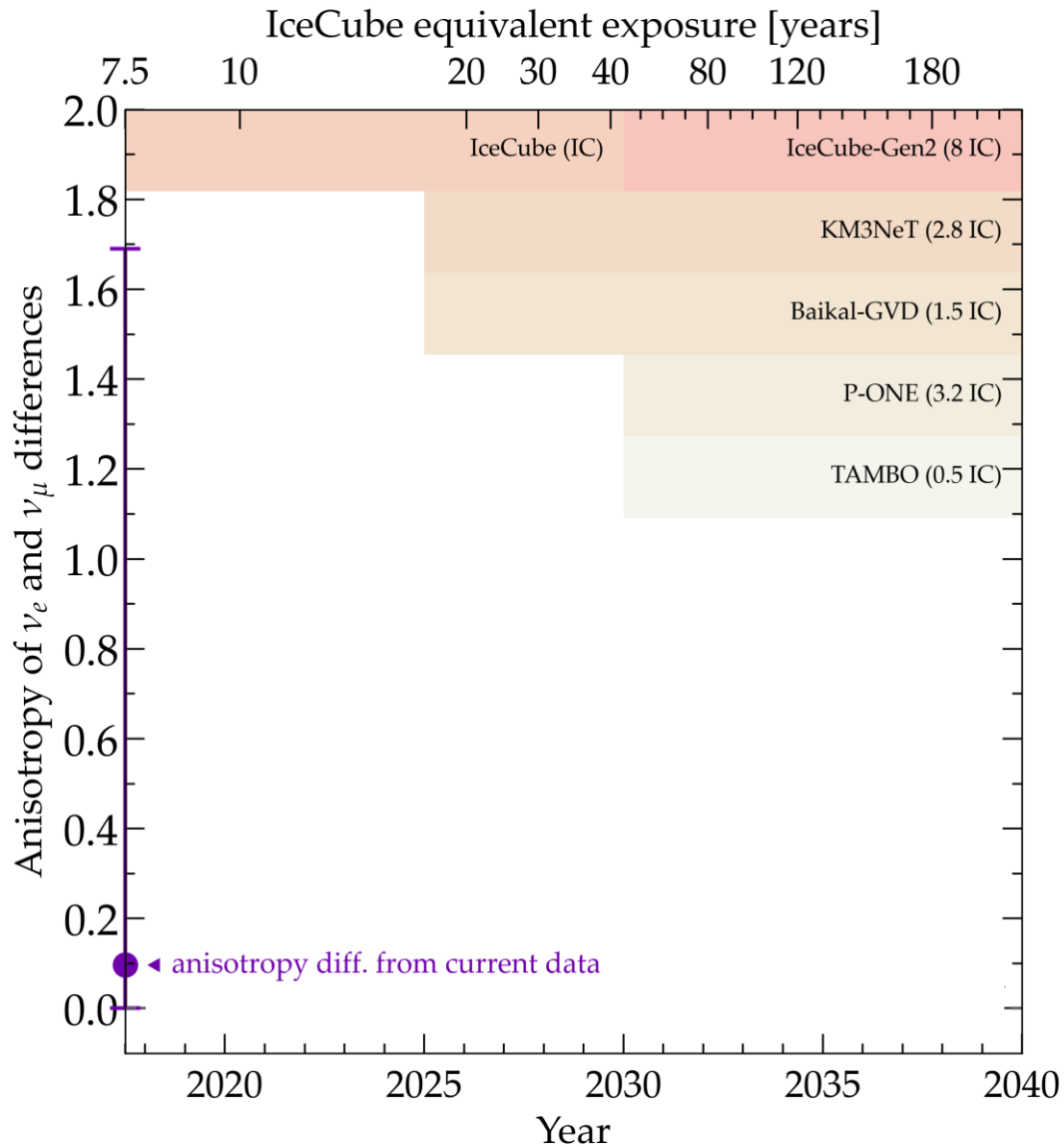
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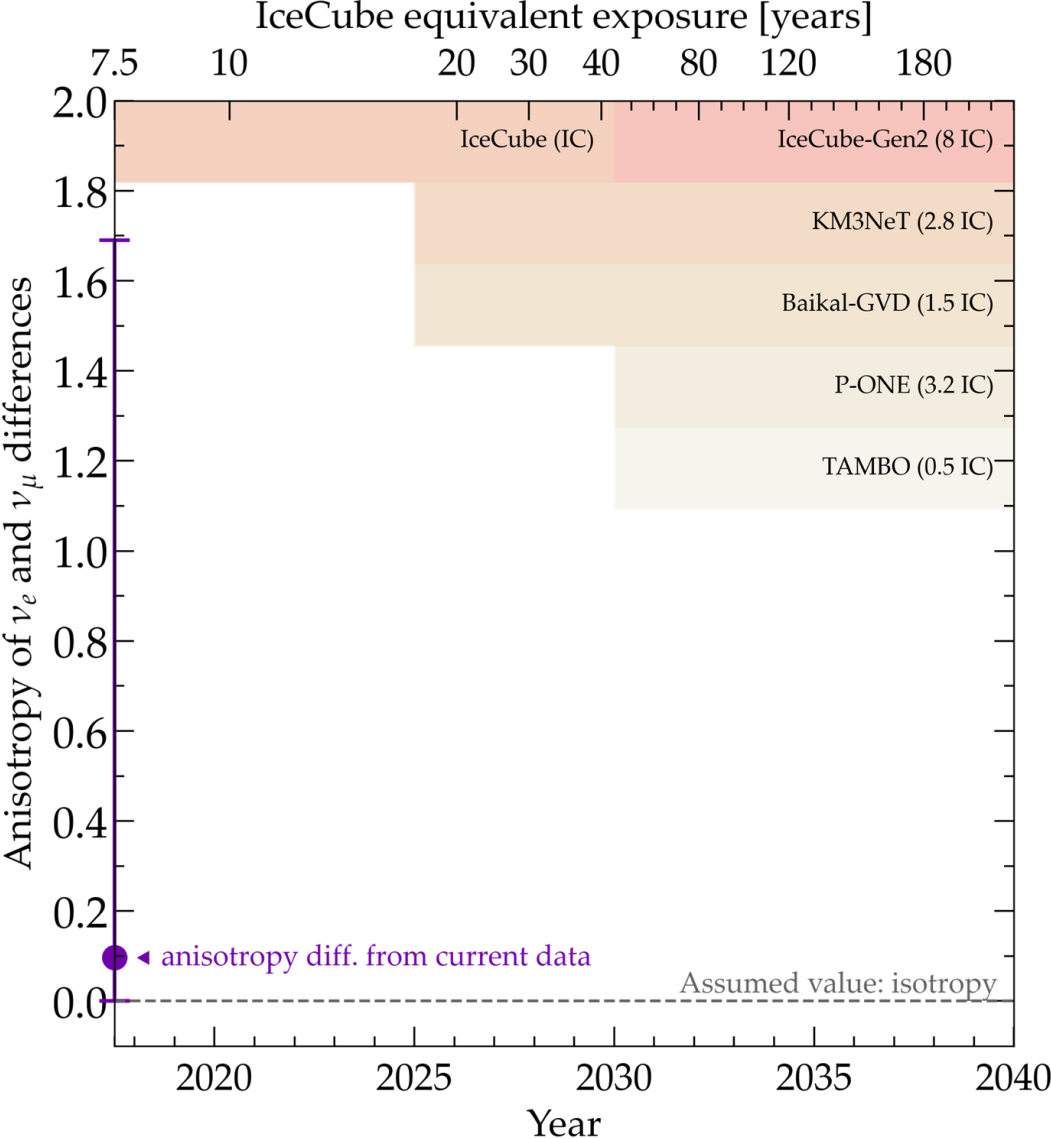
More detectors – better:

- Statistics
 - Angular resolution (KM3NeT)
 - Sky coverage
- IceCube + Gen2 (current/2030)
 - KM3NeT (2025)
 - Baikal-GVD (2025)
 - P-ONE (2030)
 - TAMBO (2030)

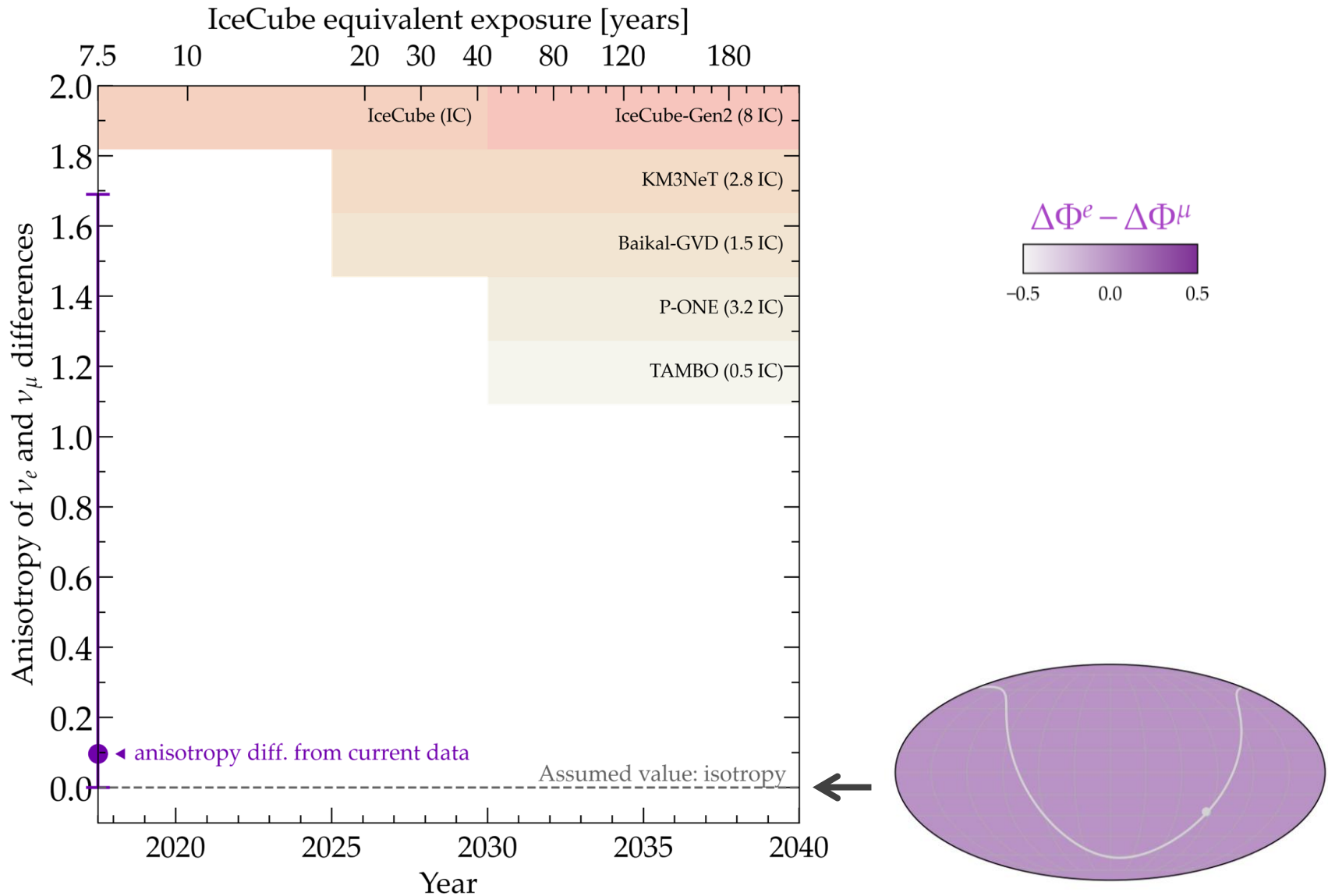
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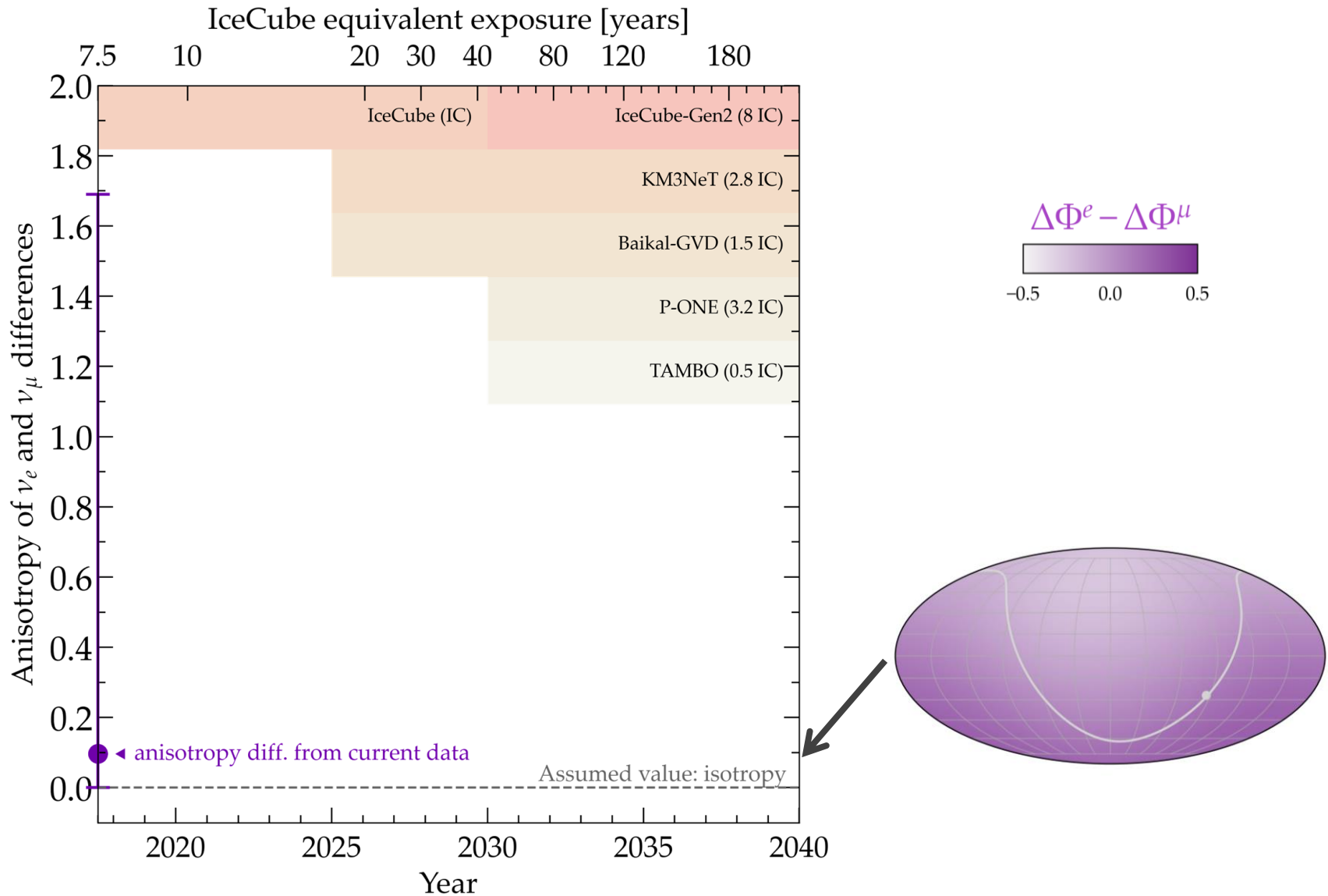
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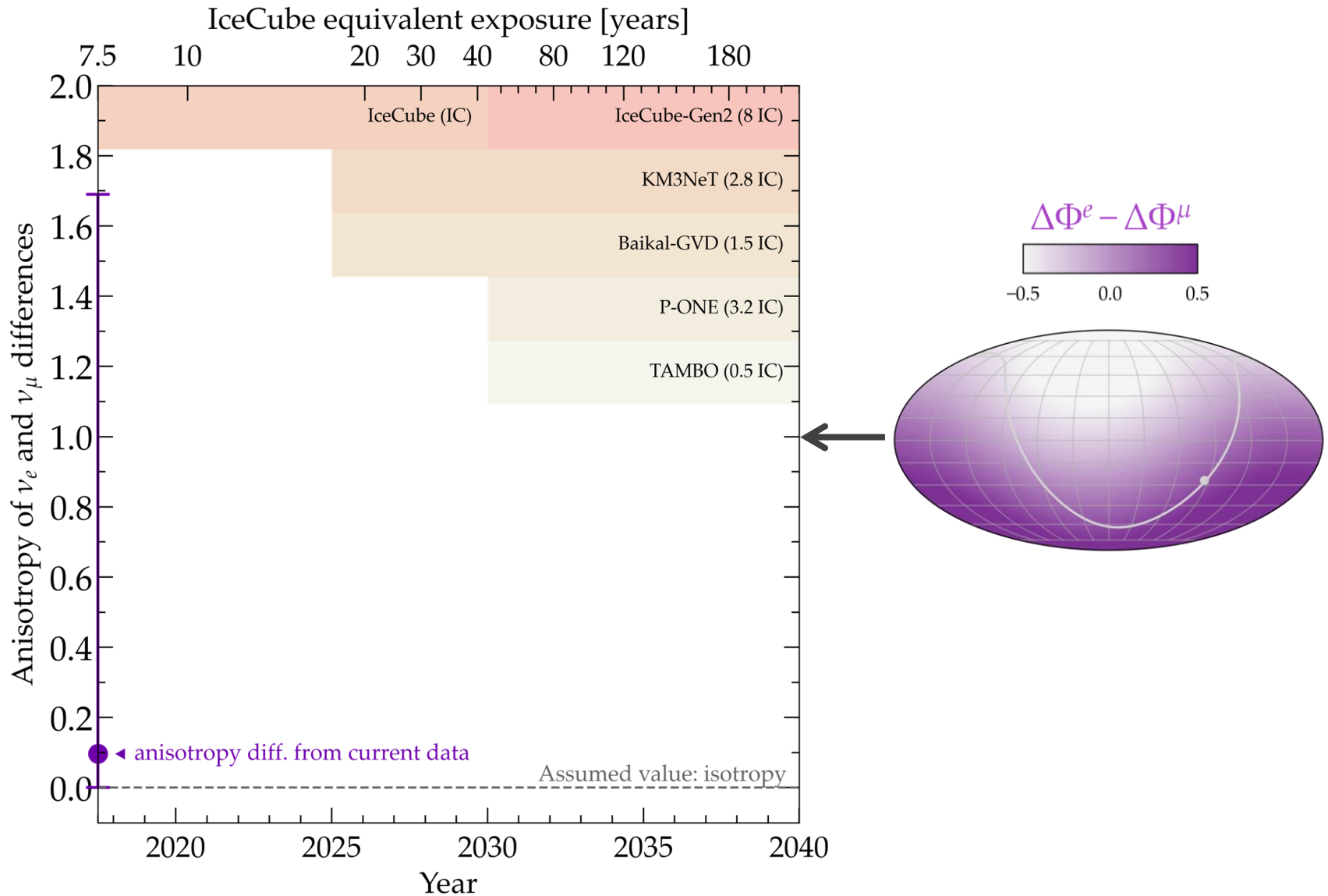
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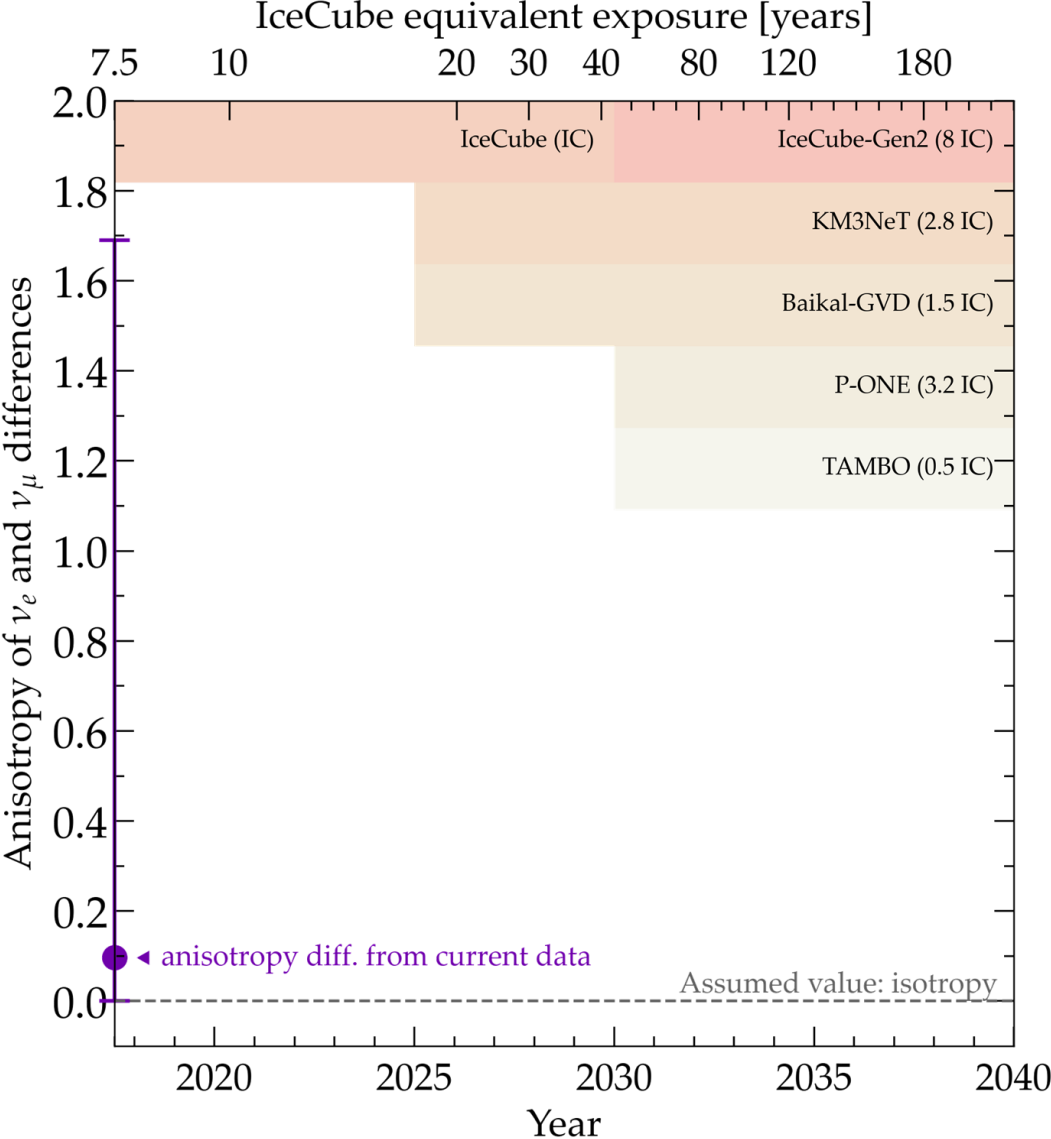
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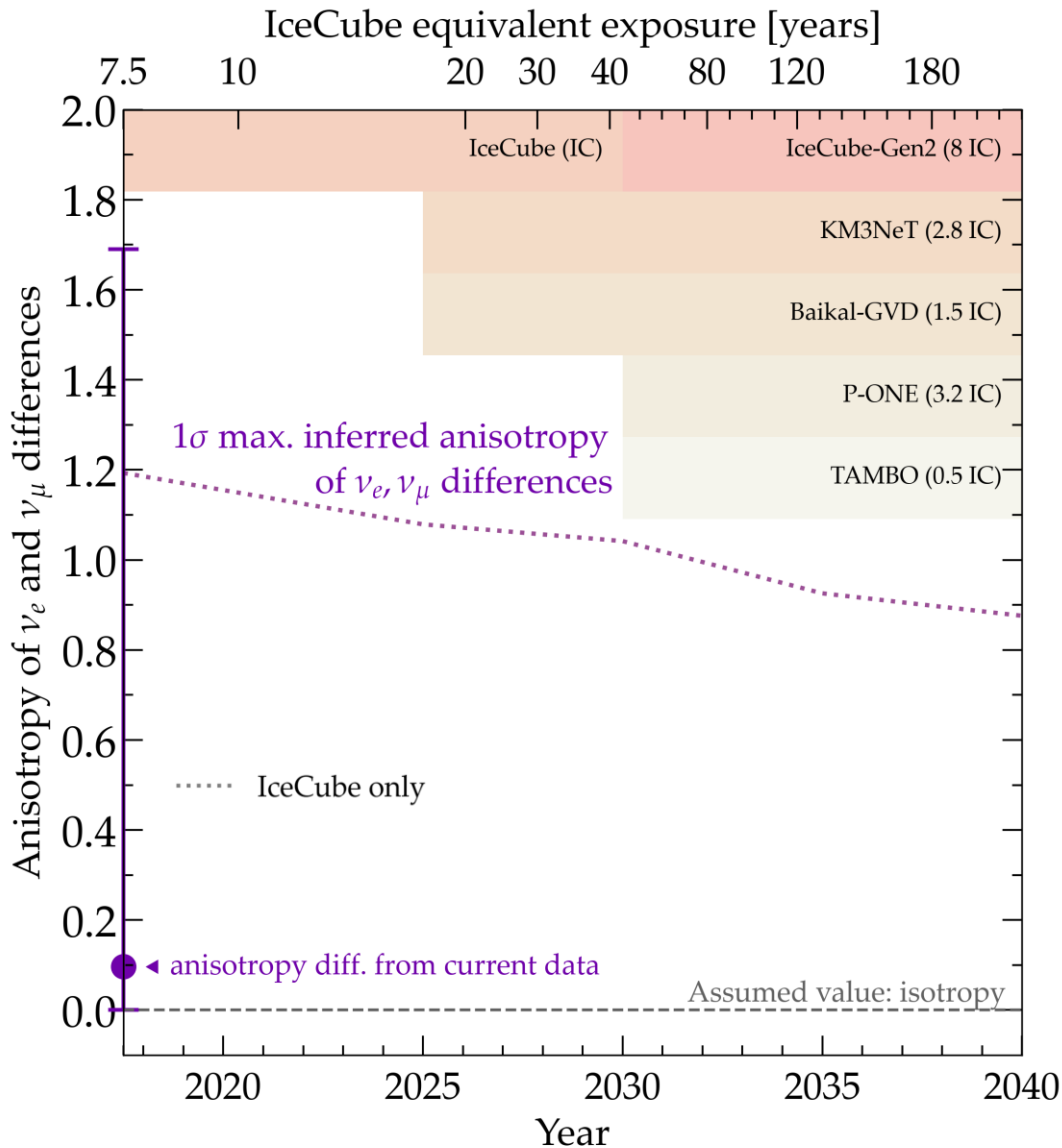
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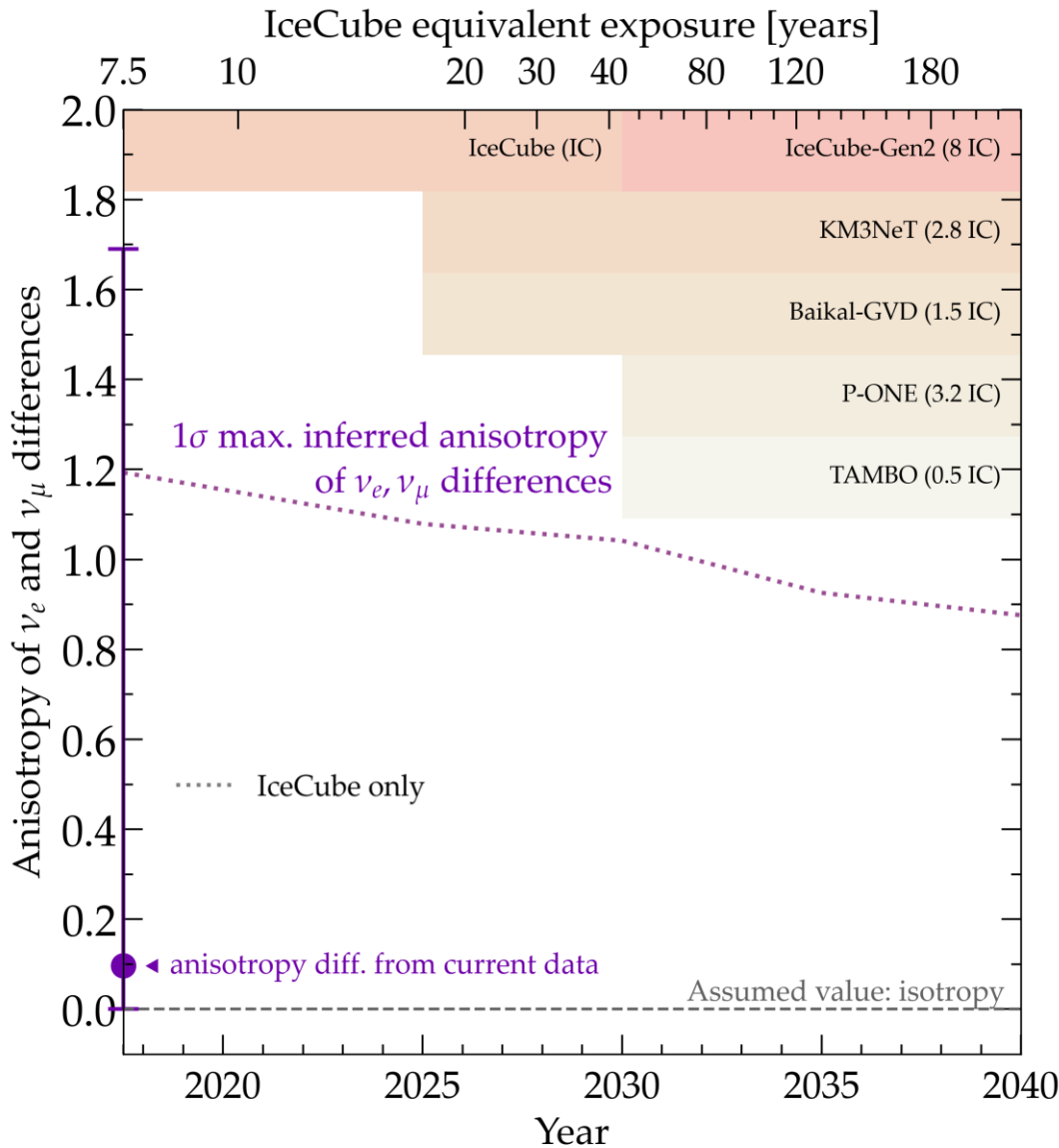
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Improvement by 2040:

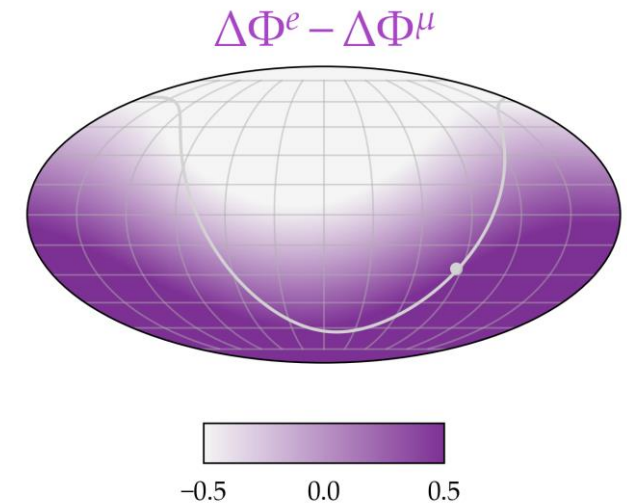
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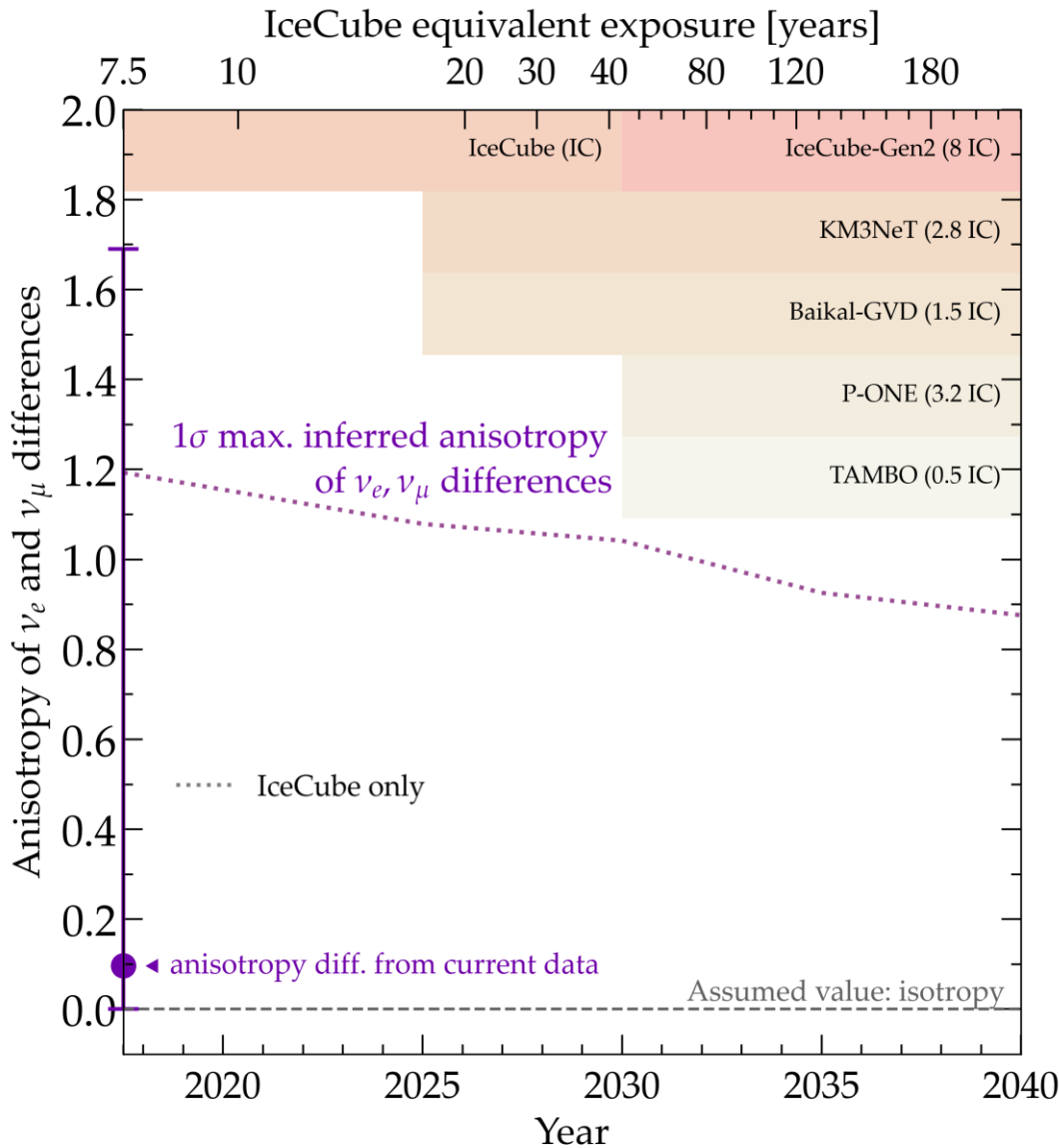


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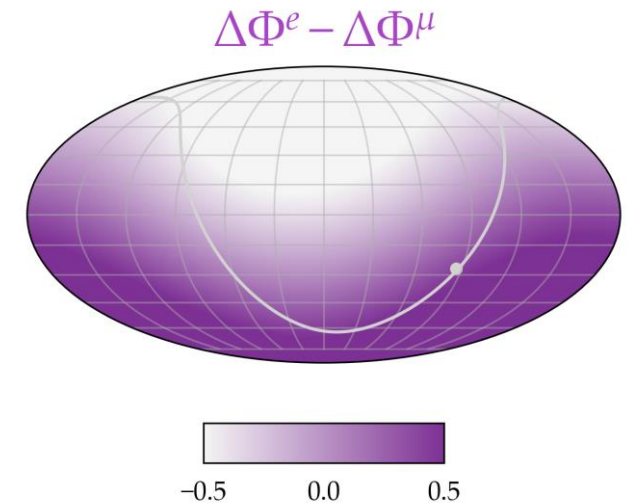


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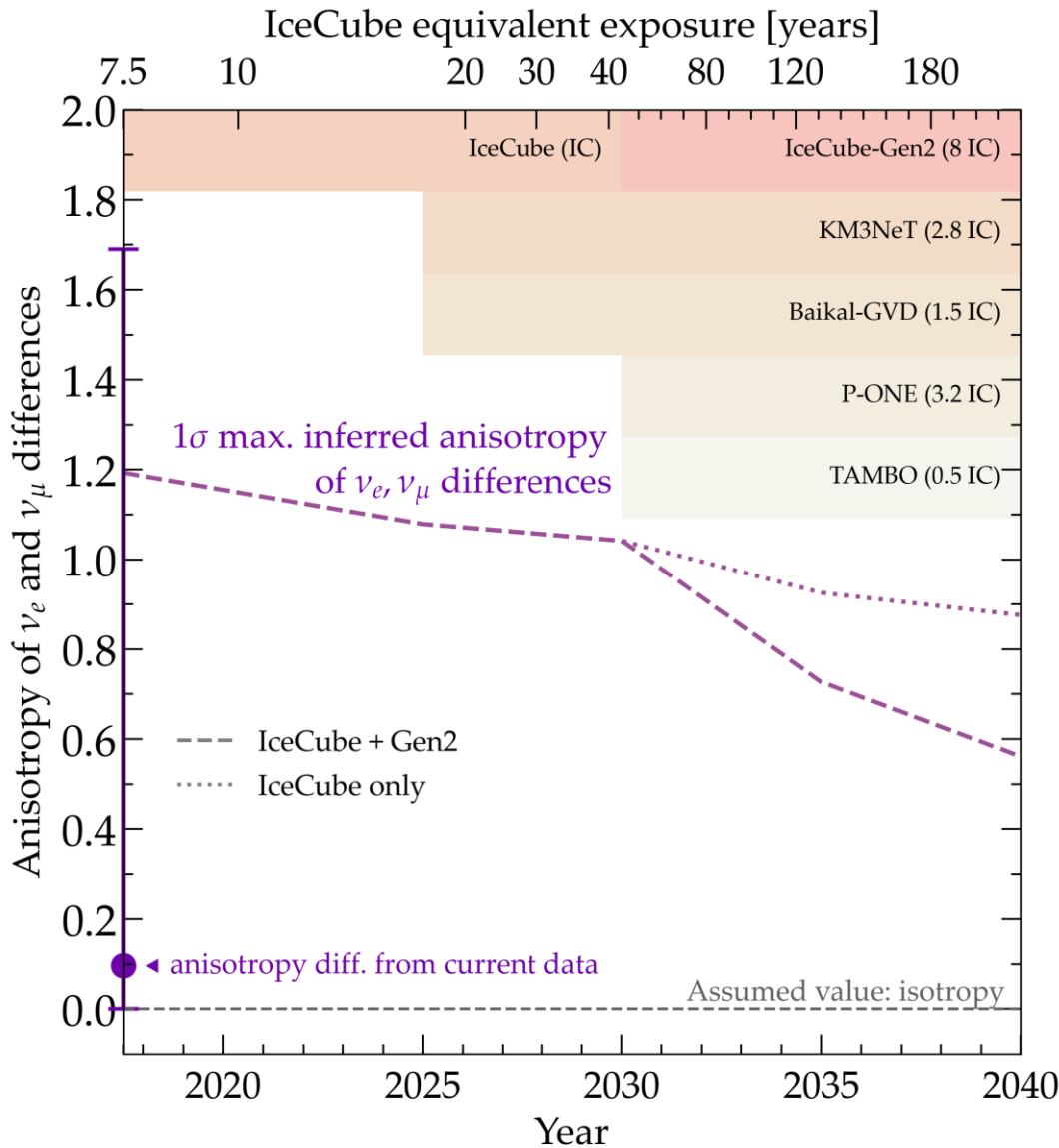


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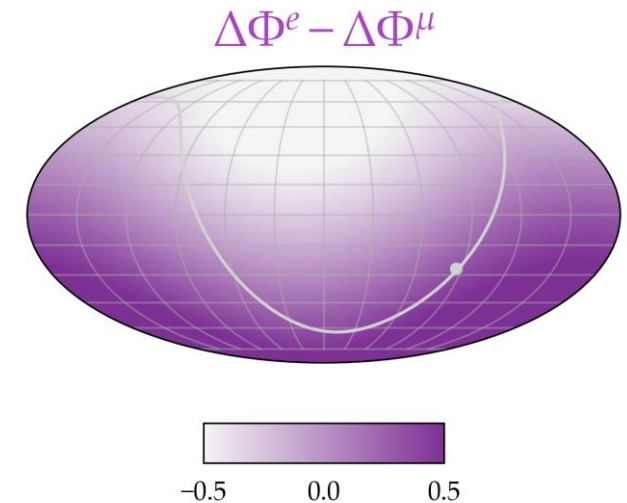


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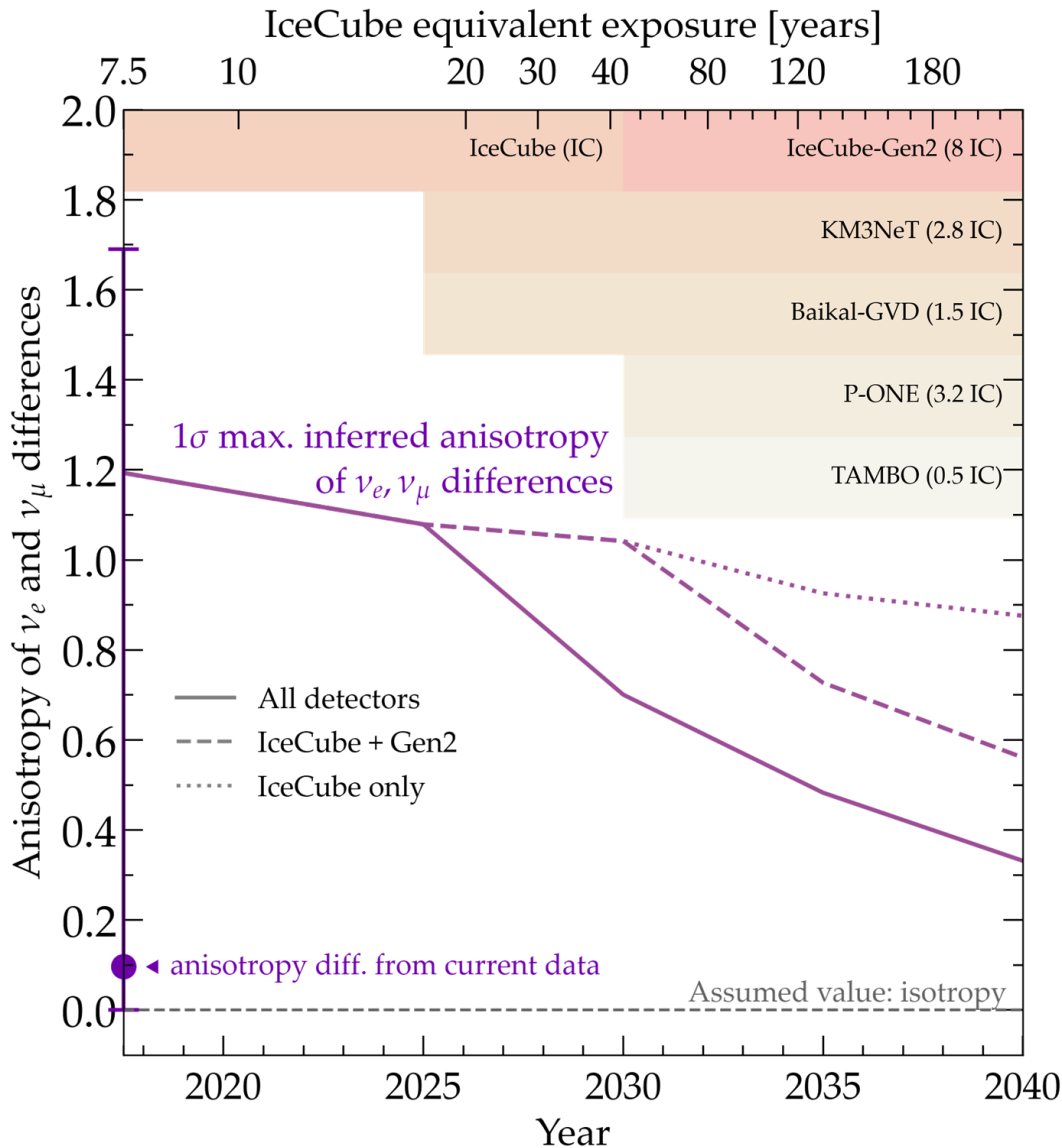


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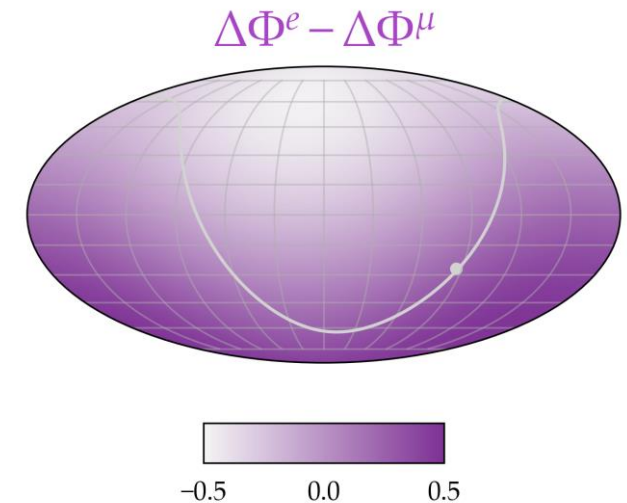


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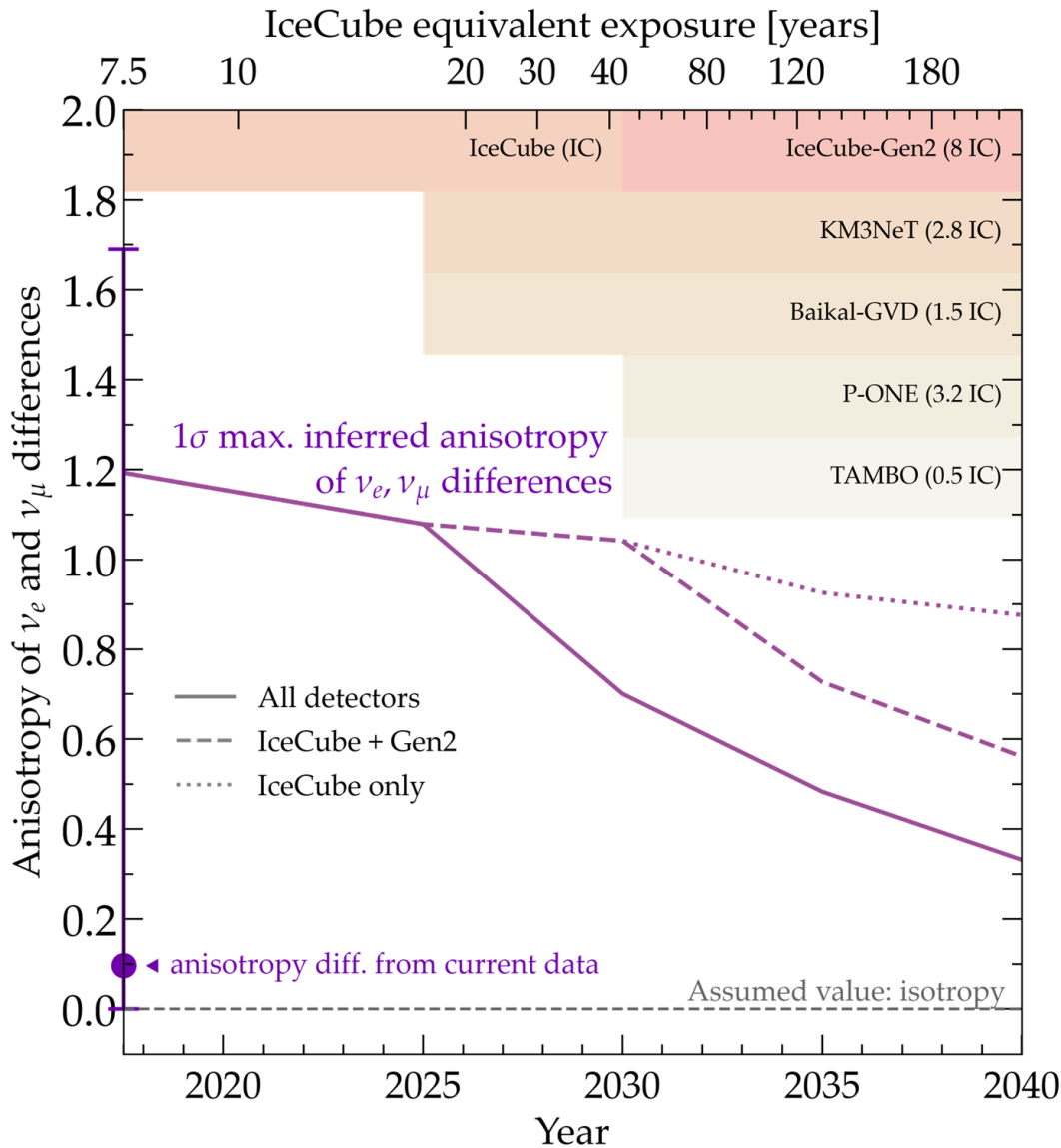


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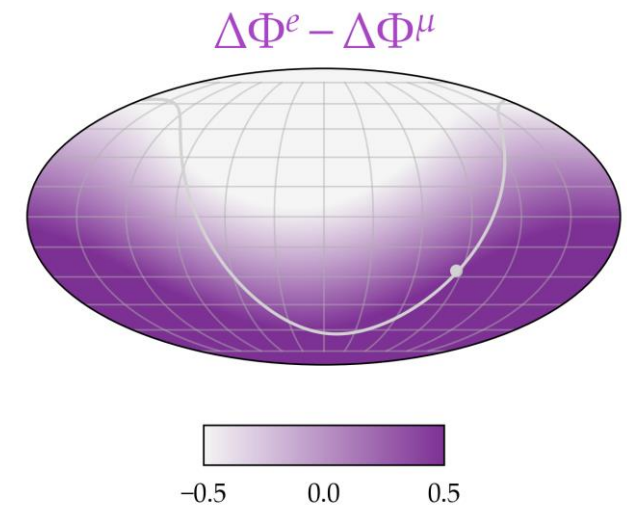


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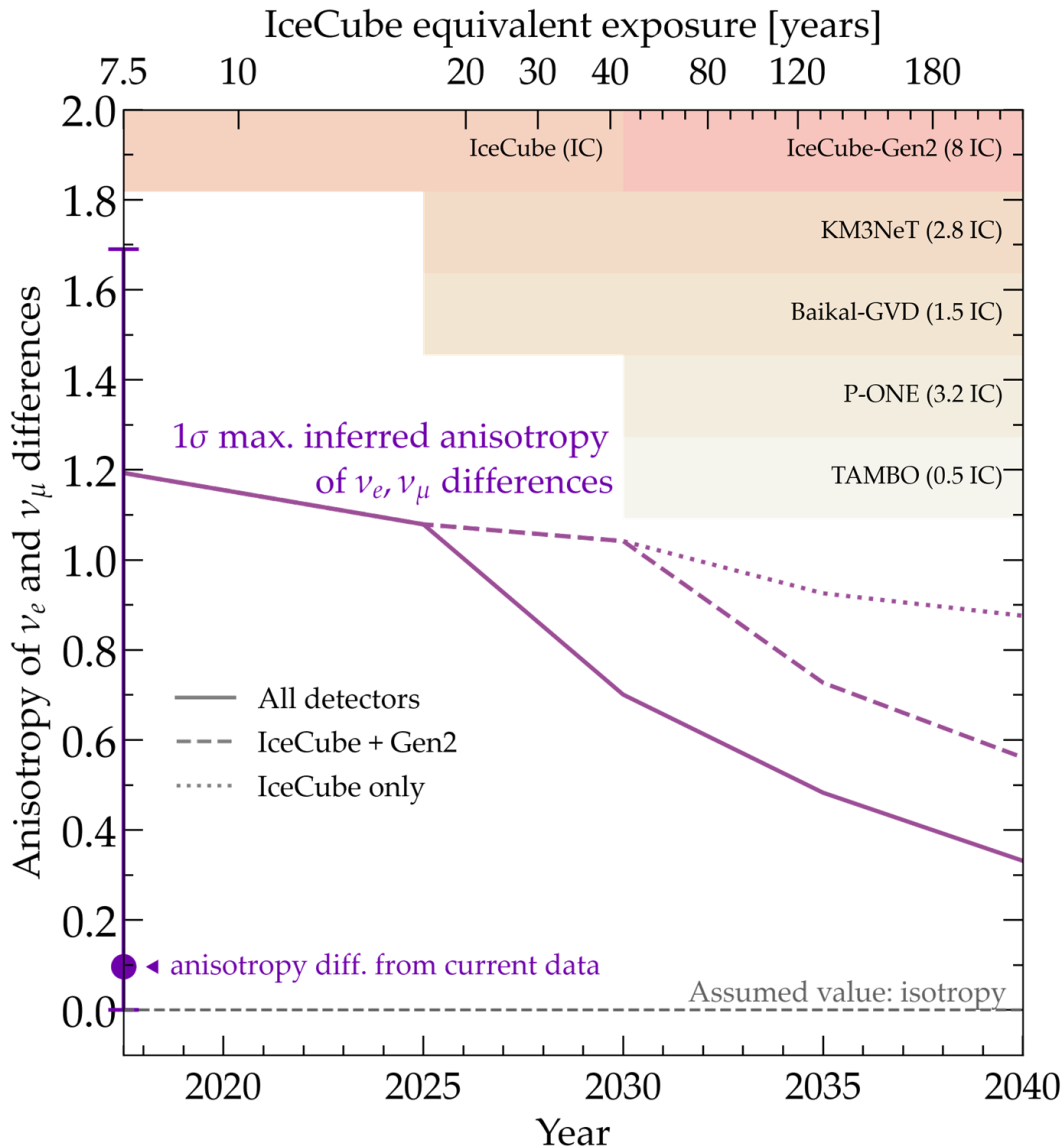


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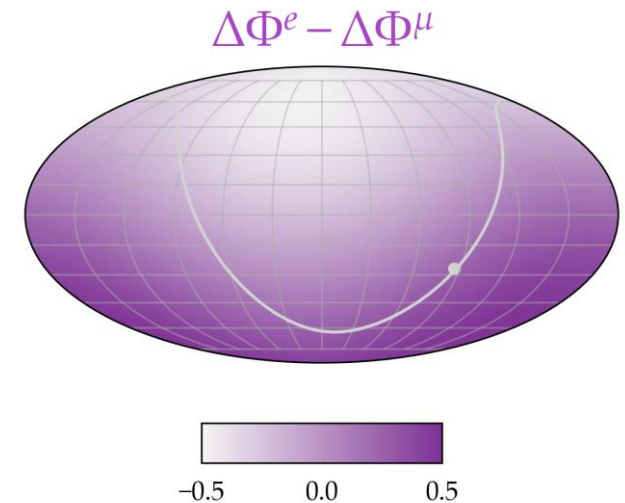


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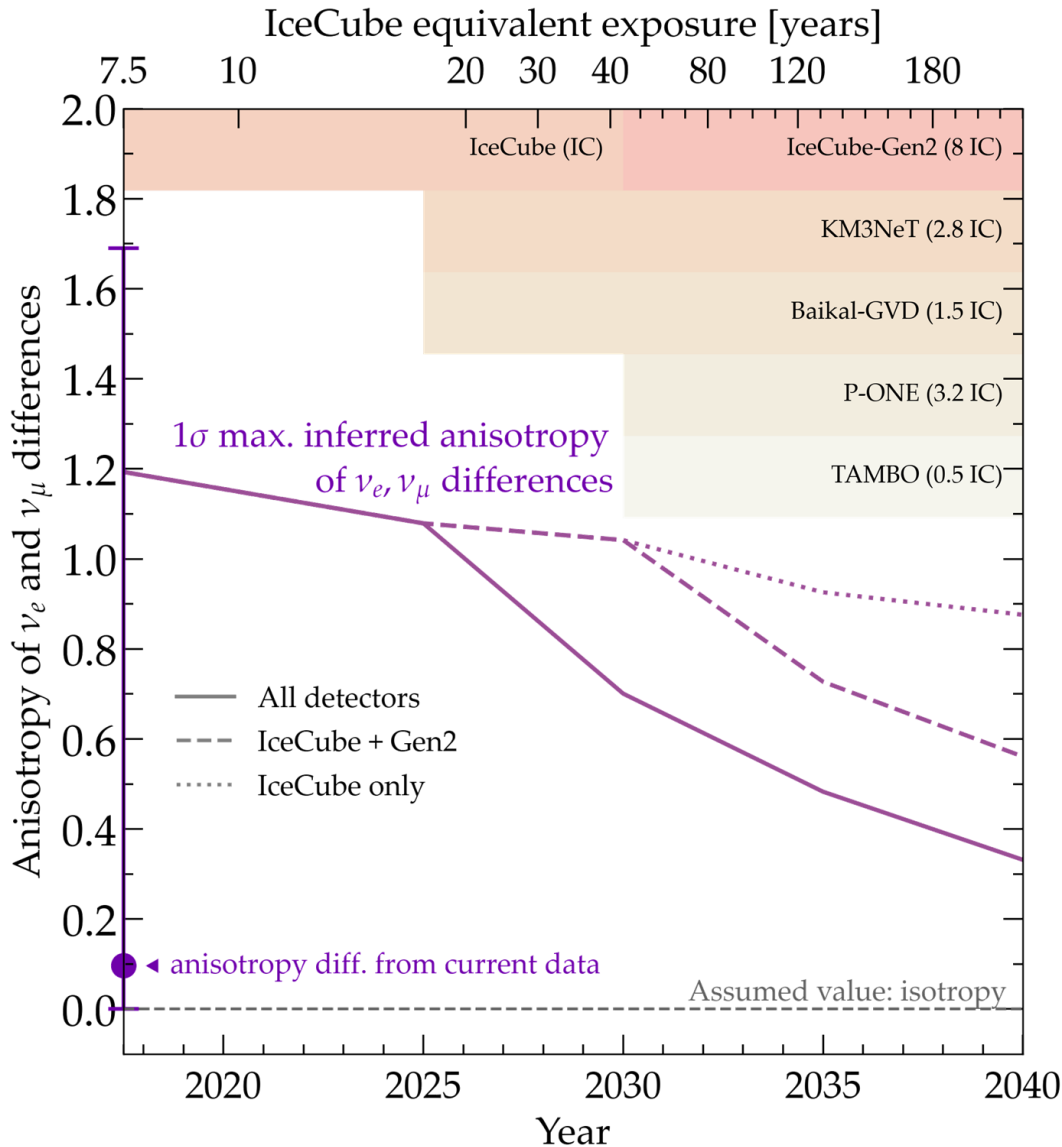


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Assuming IC-like sensitivity

Now we use these for... (ongoing work)

Constraining anisotropy-generating parameters in beyond-Standard Model physics:

- **Lorentz-invariance violation** as a mechanism of anisotropy,



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Anisotropy-generating parameters not yet explored with high energies (TeV-PeV)

Now we use these for... (ongoing work)

Constraining anisotropy-generating parameters in beyond-Standard Model physics:

- **Lorentz-invariance violation** as anisotropy,
- **Neutrino-dark matter interactions** with flavour-dependent couplings.

Anisotropy-generating parameters not yet explored with high energies (TeV-PeV)

Thanks!

Questions?

Interested? – come see me at the poster session!

A First Look at Sky Anisotropies of High-Energy Neutrino Flavours

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What are the neutrino flavour arrival directions?

Could they come from different directions?

Neutrino arrival distributions and their flavour differences are a novel potential probe into new physics (see bottom). We use IceCube high-energy ($>10^6$ GeV) astrophysical neutrino data and simulate upcoming worldwide neutrino observatories to predict how well we can recover arrival directions of differently flavoured neutrinos.



- IceCube (IC)
- IceCube-Gen2 (ICG2)
- IceCube-Upgrade (ICU)
- POGO (POGO)
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Flux Model

The flux of ν_{α} ($\alpha = \mu, \tau$) at Earth is:

$$\Phi_{\nu_{\alpha}} = \int_{\text{Flavour}} \int_{\text{Direction}} \int_{\text{Energy}} \frac{d\Phi_{\nu_{\alpha}}}{dE dA dt d\Omega dA} dE d\Omega dA dt$$

The difference of the harmonic moments:

$$\Delta C_{lm}^{\nu_{\alpha}} = C_{lm}^{\nu_{\alpha}} - C_{lm}^{\nu_{\beta}}$$

is independent of the sky-averaged flavour.

The anisotropy measure is the power spectrum:

$$C_l^{\nu_{\alpha}} = \frac{1}{2l+1} \sum_{m=-l}^l |\Delta C_{lm}^{\nu_{\alpha}}|^2$$

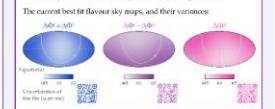
and the power spectrum of the flavour difference:

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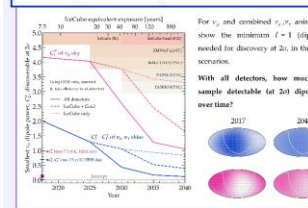
We restricted our analysis to $l=1$ (dipole).

Analysis and Current Best Fits

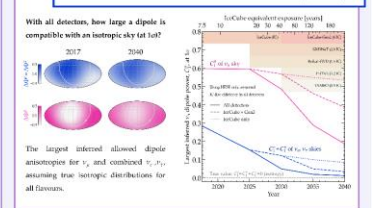
- IceCube (IC) 7.5 year public High-Energy Starting event sample (HSES) data and Monte Carlo (MC) [1,2].
- IC detects three event morphologies correlated to the three neutrino flavours.
- Scaled HSES MC to model exposure and angular resolution of upcoming detectors.
- Set equal τ_{μ}, τ_{τ} moments due to detection degeneracy.
- Used Bayesian forward folding to fit flux model parameters.



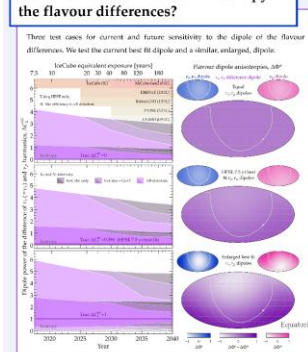
How large flavour dipoles can we discover?



How well can we constrain an isotropic sky?



How well can we discover anisotropy in the flavour differences?



Why do we expect isotropy in the flavour difference distributions?

If ν_{μ}, ν_{τ} and ν_{τ} have different arrival directions, normalized to their all-sky flavour ratios, then:

- Astrophysics: the high-energy neutrino production mechanisms are different and directionally-dependent or
- Fundamental physics: neutrino flavour oscillations are affected in a directionally-dependent manner.

We don't expect astrophysical processes to induce different anisotropies for different flavours. So, any observed difference is likely due to flavour-dependent effects during neutrino propagation.

Ongoing Work:

- Constraining anisotropy-generating parameters in beyond Standard Model physics.
- Lepton number violation as a mechanism of anisotropy.
- Flavour-dependent couplings in neutrino-dark matter interactions.

Take-home message...

Today, observations are compatible with isotropy for all flavours and flavour differences.

Future neutrino telescopes might either confirm isotropy, or discover differences in the arrival directions of different neutrino flavours.



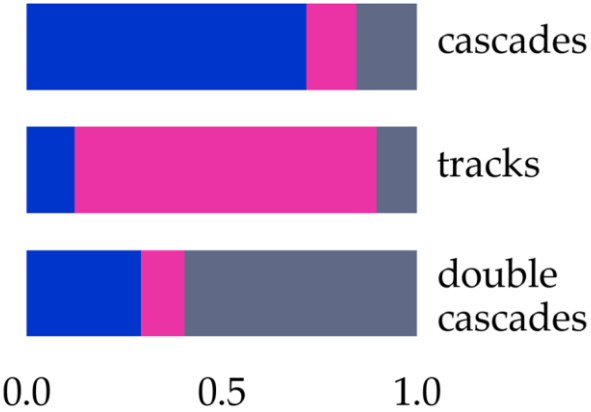
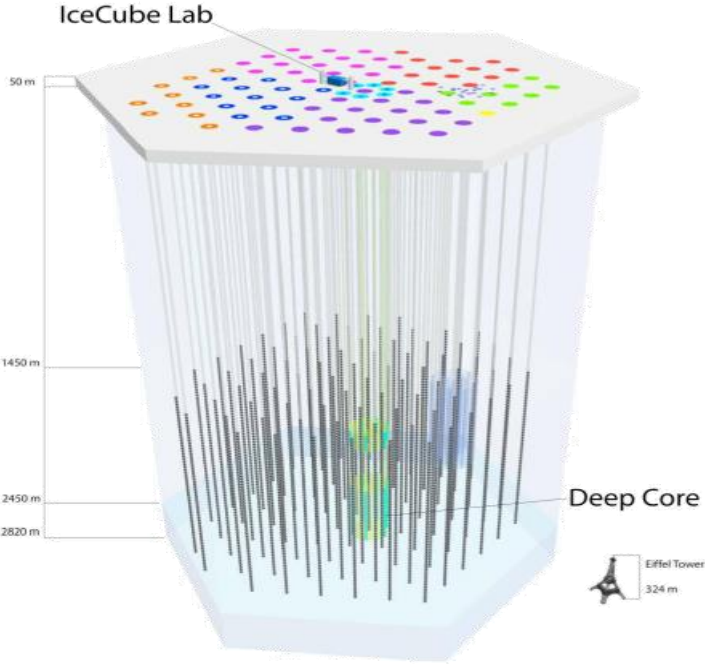
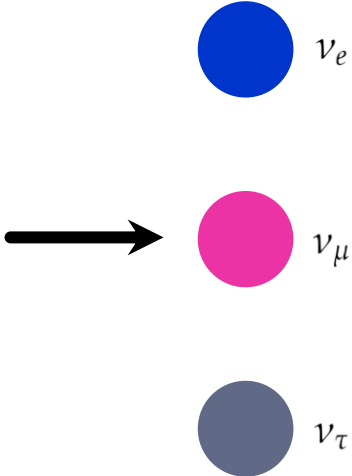
- R. Abbasi *et al.* (IceCube), The IceCube high-energy starting event sample: Description and flux characterization with 7.5 years of data, *Phys. Rev. D* **104**, 022002 (2021), [arXiv:2011.03545](https://arxiv.org/abs/2011.03545) [astro-ph.HE].
- IceCube Collaboration, HESE 7.5 year data release, <https://icecube.wisc.edu/data-releases/2021/12/hese-7-5-year-data/> (2021).

IceCube detection

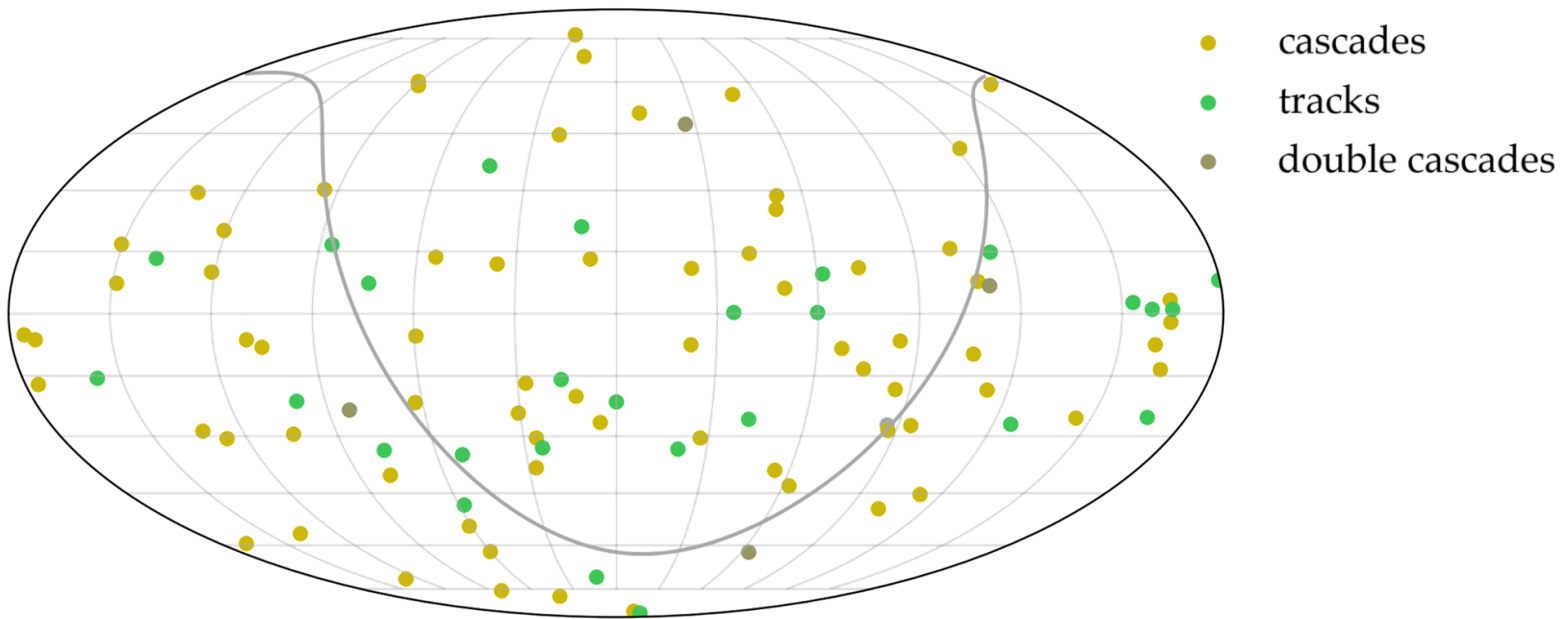
Neutrino

detected in IceCube

as morphology:



IceCube HESE 7.5 year event sample – best fit locations (102 events)



The Flux Model

The flavour-flux:

$$\Phi_\alpha = \frac{\Phi_0}{4\pi} f_\alpha (1 + \Delta\Phi_\alpha) \quad \Delta\Phi_\alpha = \sum_{\ell>0,m} a_{\ell,m}^\alpha Y_{\ell,m}$$

The anisotropy measure (power spectrum):

$$C_\ell^\alpha = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell,m}^\alpha|^2$$
$$\Delta C_\ell^{\alpha,\beta} = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |\delta a_{\ell,m}^{\alpha,\beta}|^2 \quad \delta a_{\ell,m}^{\alpha,\beta} = a_{\ell,m}^\alpha - a_{\ell,m}^\beta$$

