Sky Anisotropies of High-Energy Neutrino Flavours

Bernanda Telalovic, Mauricio Bustamante

What are the astrophysical neutrino flavour ratio directions?

Could we see new physics if they're different?

NIELS BOHR INSTITUTE

VILLUM FONDEN

UNIVERSITY OF COPENHAGEN

What?

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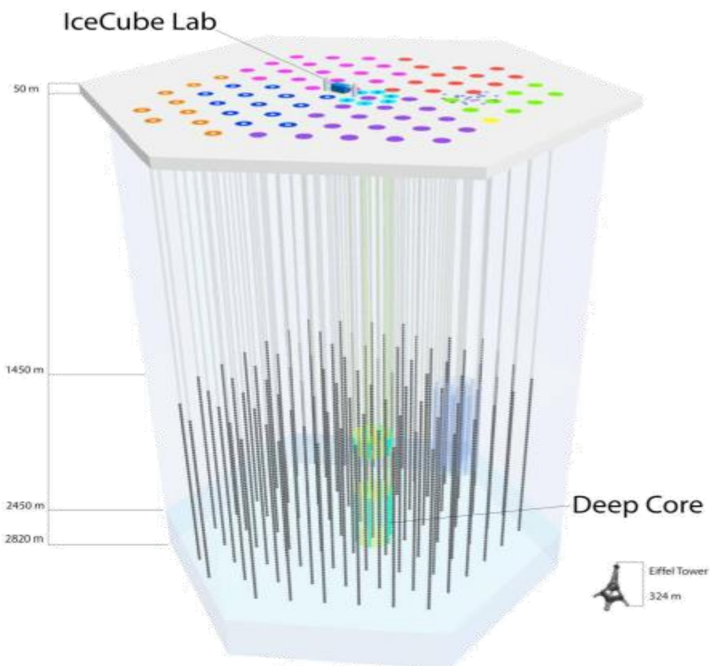
IceCube has seen a flux of high-energy astrophysical neutrinos!

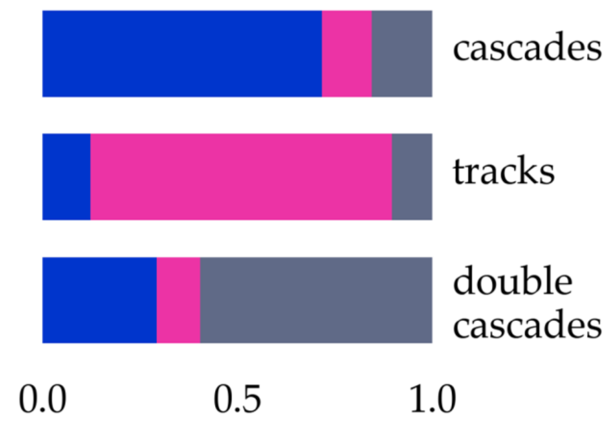
Neutrino detected in IceCube as morphology:

ν_e

ν_μ

ν_τ

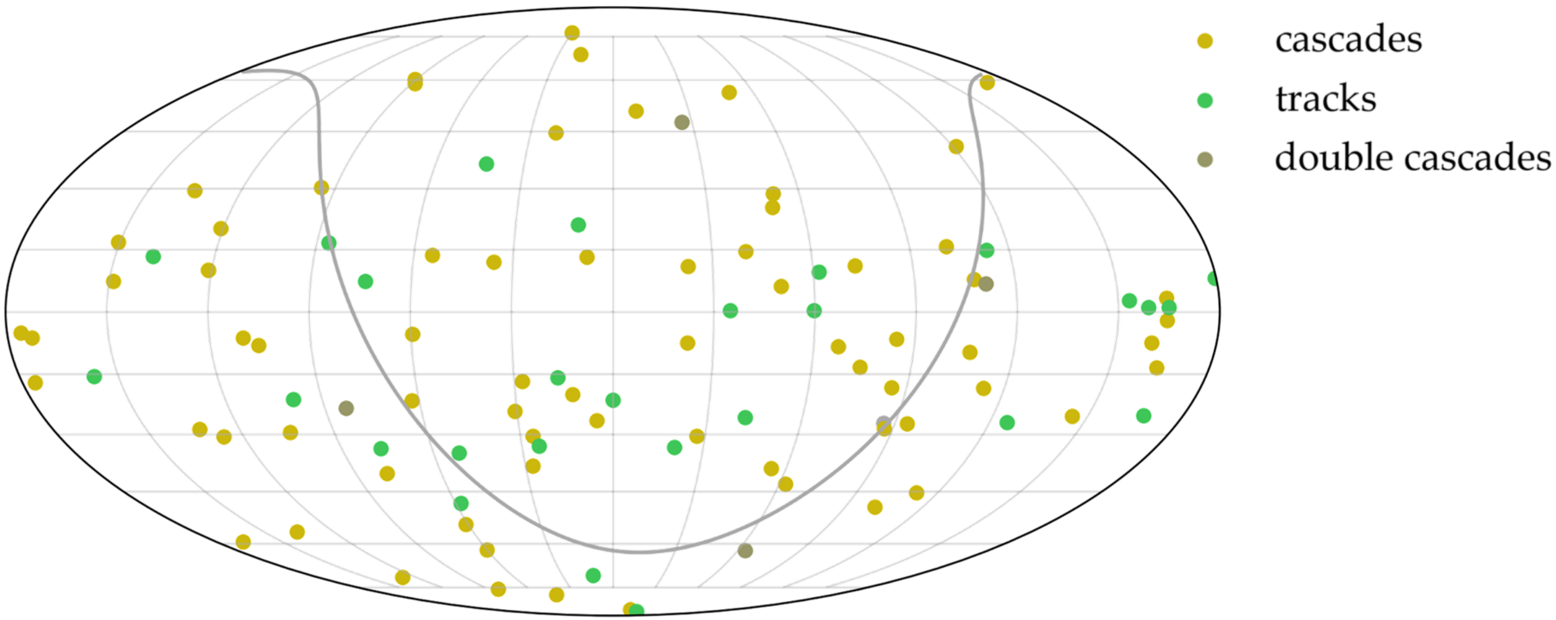




interacts as flavour

HESE dataset

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



The flavour-flux at Earth:

$$\Phi_\alpha = \frac{\Phi_0}{4\pi} f_\alpha \left(1 + \Delta\Phi_\alpha\right)$$

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all-flavour flux
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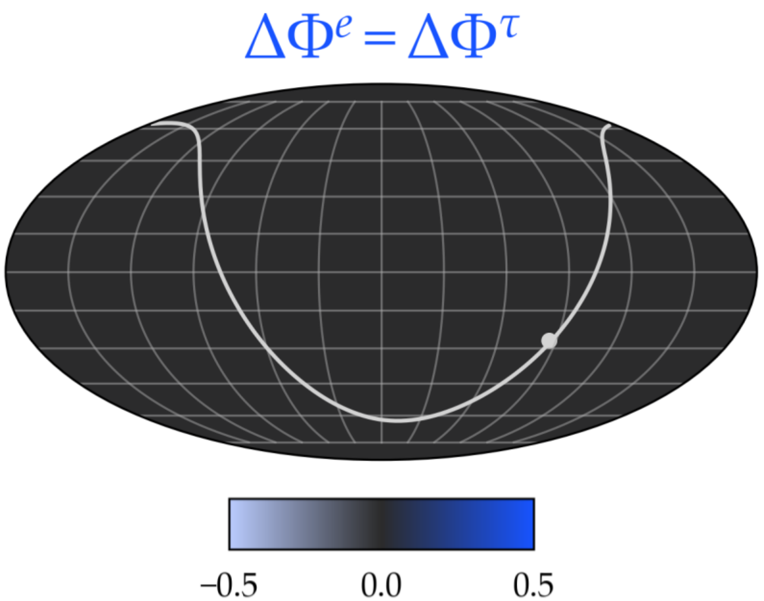

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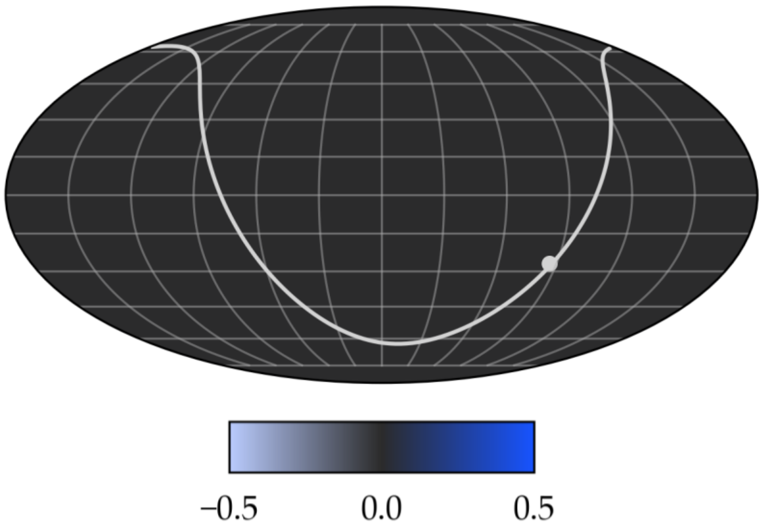

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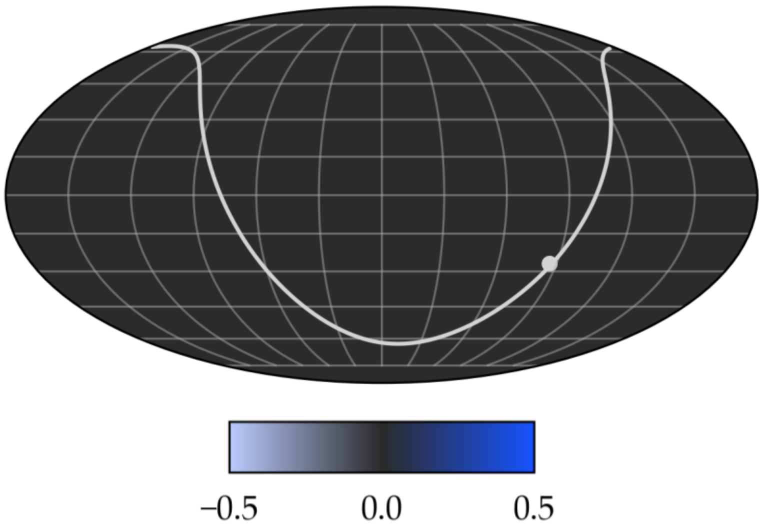

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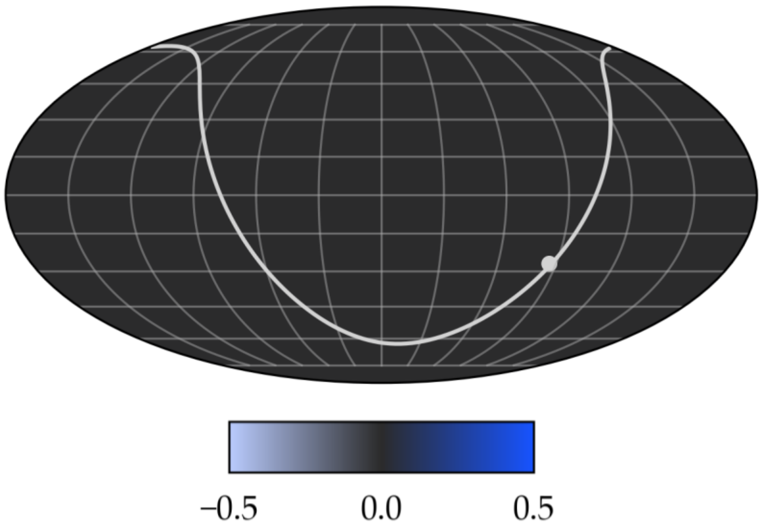

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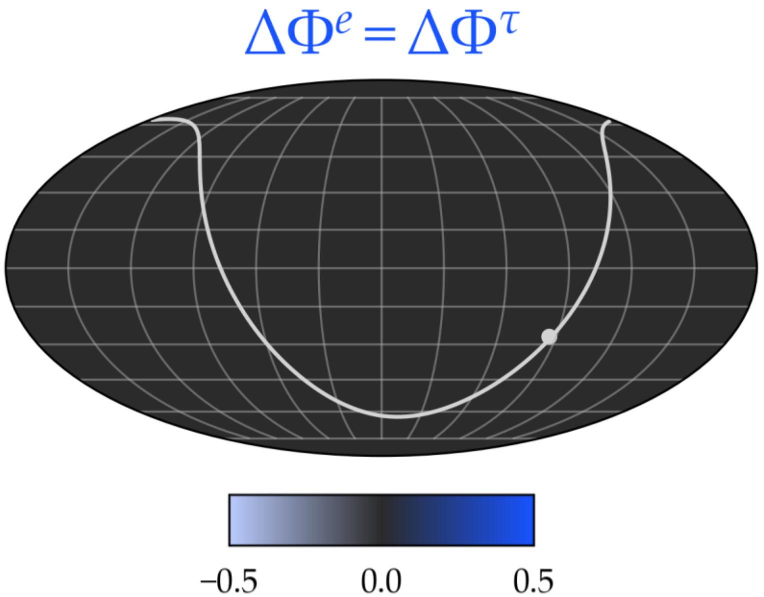

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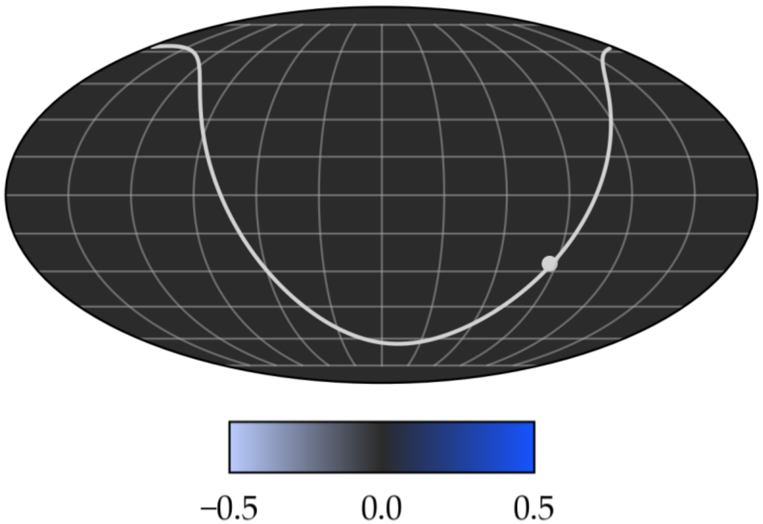

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new physics?

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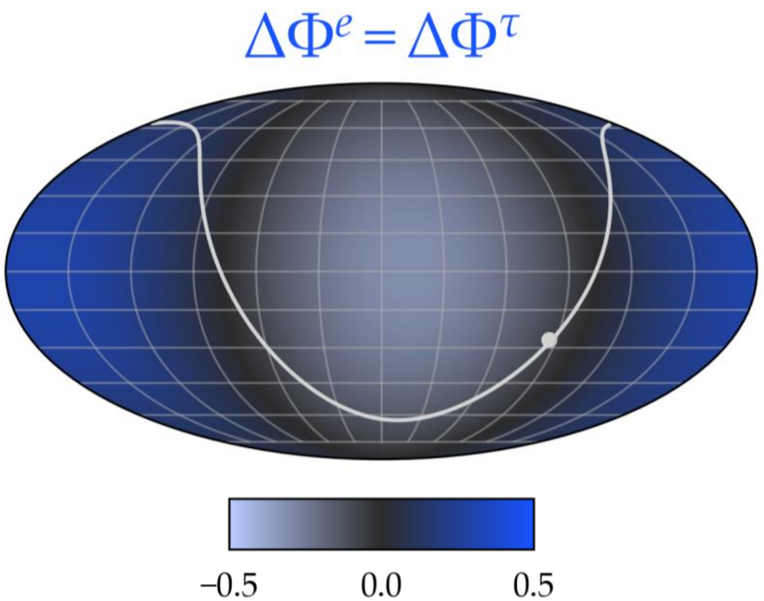

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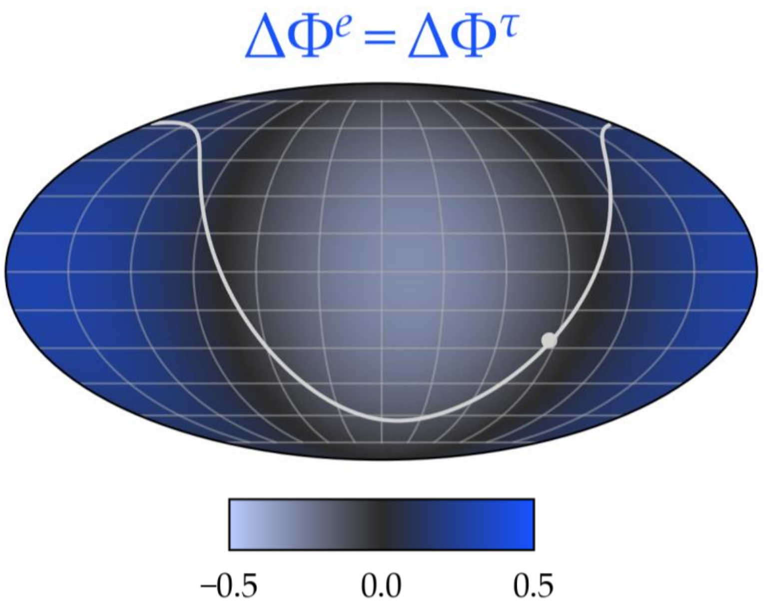

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Are flavour ratios directionally-dependent?

real spherical harmonics

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Why new physics?

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

What could cause this?

Detection

Lots of stuff

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Assume we've all done a good job...

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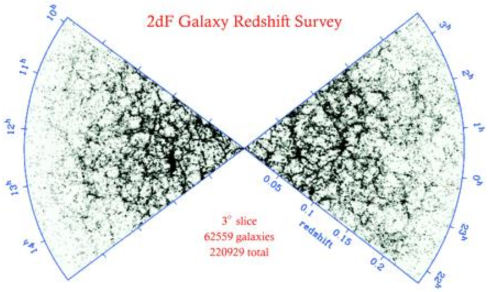

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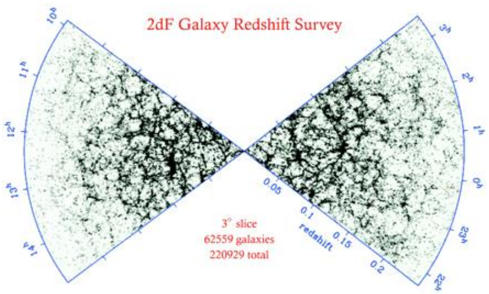

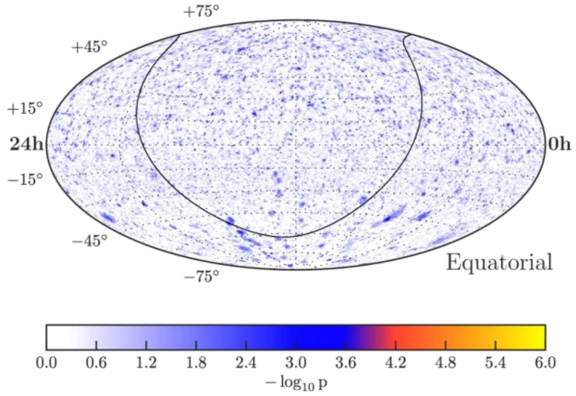

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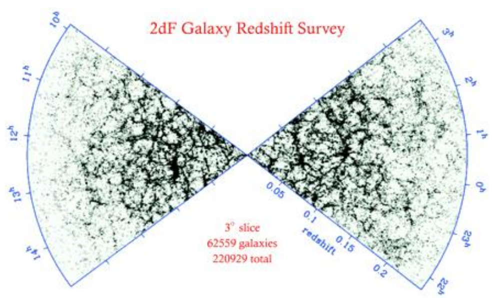

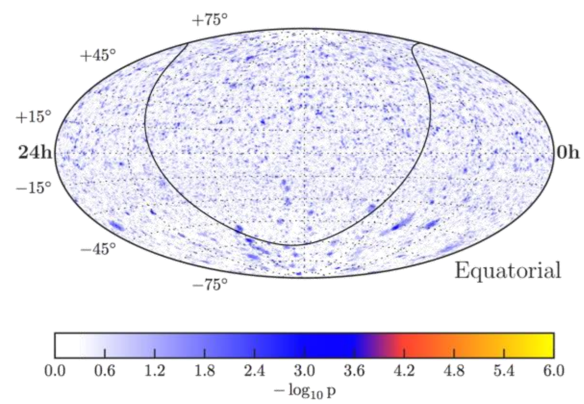

But we care about flavour ratios

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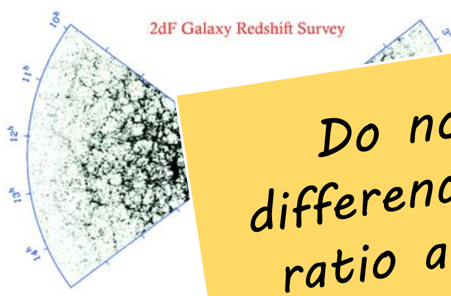

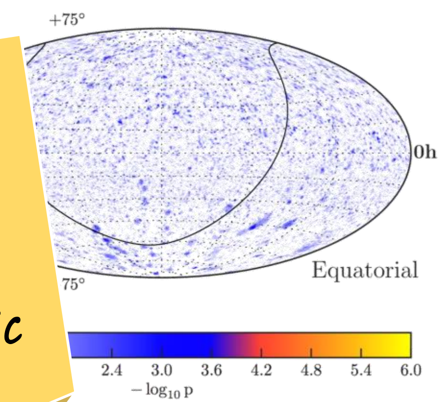

Do not expect differences in flavour ratio anisotropies...

even with anisotropic production

flavour ratios

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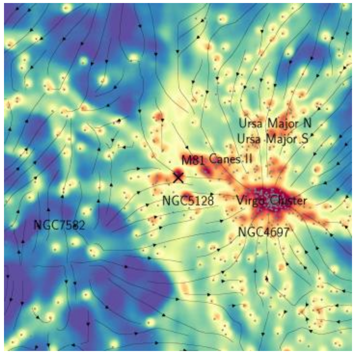

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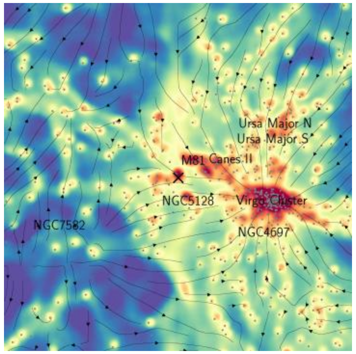

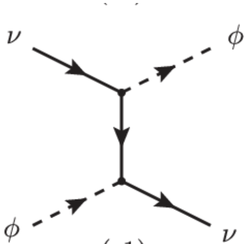

(c1)

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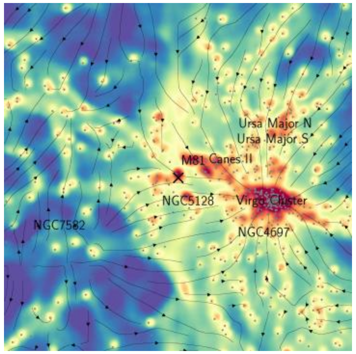

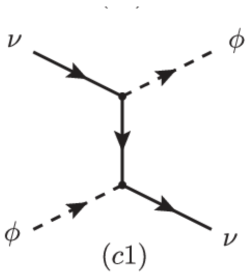

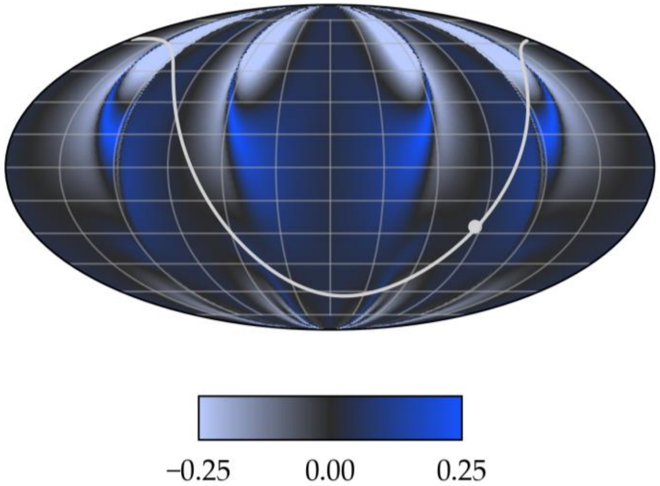

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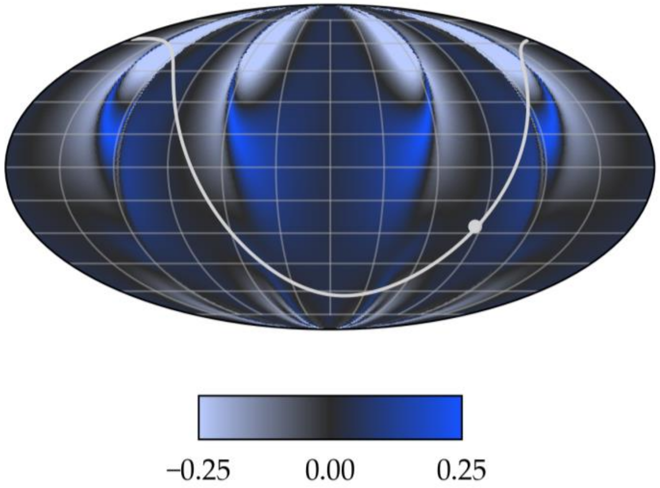

Lorentz Invariance Violation (LIV)

$$H_{\text{tot}} = H_{\text{vac}} + H_{\text{LIV}}$$

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couples to momentum 4-vector
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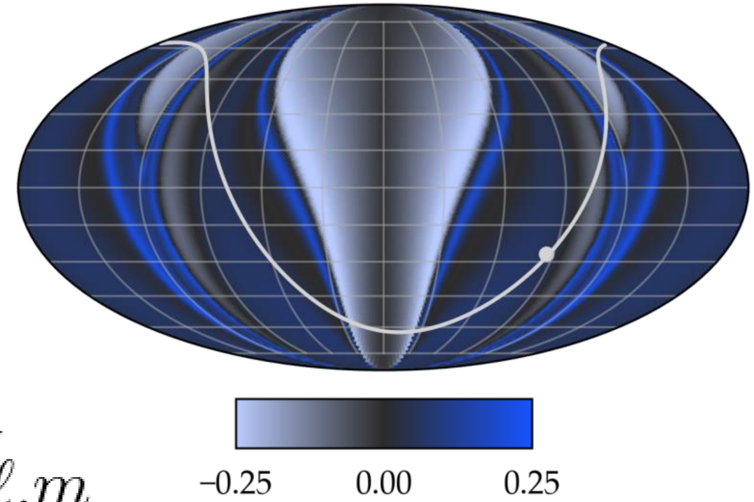

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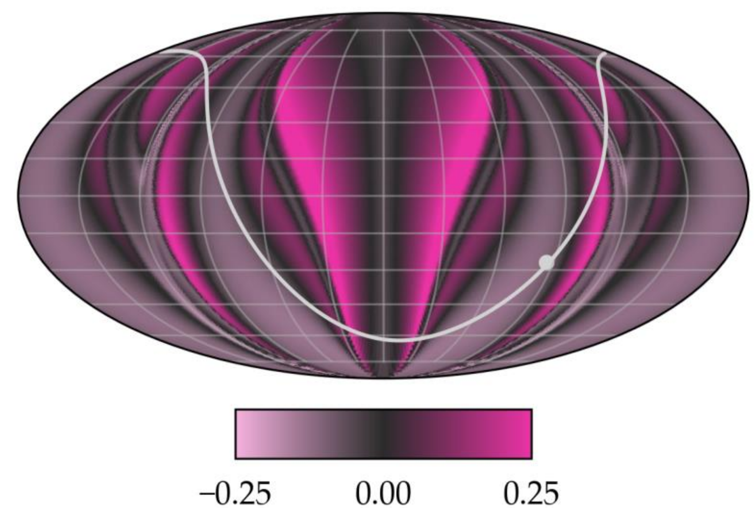

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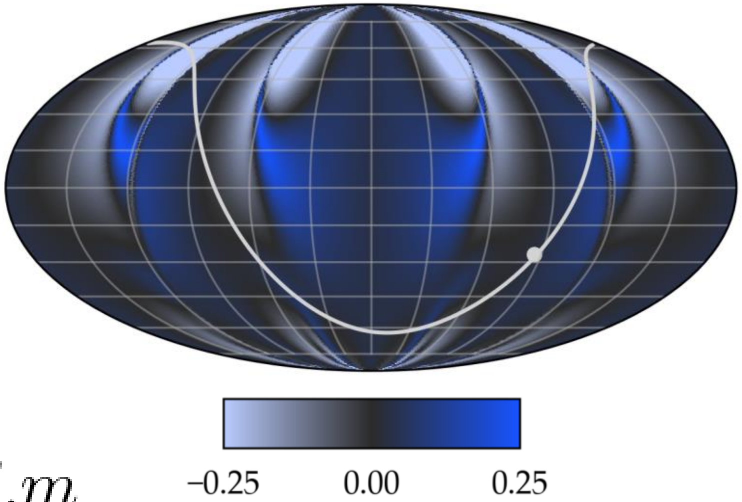
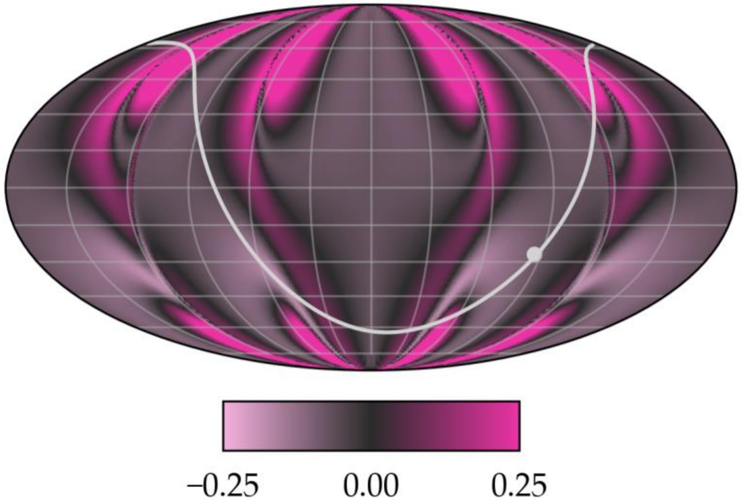
When:

$$d = 5 \quad \wedge \quad \hat{\mathbf{a}}_{1,0} \neq 0$$



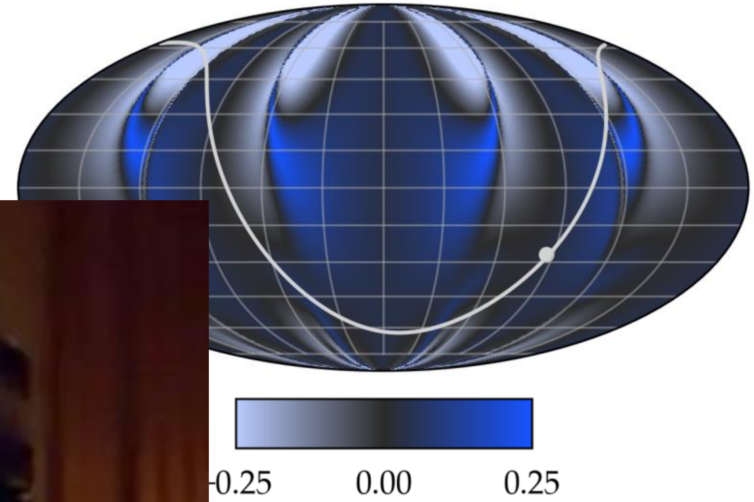


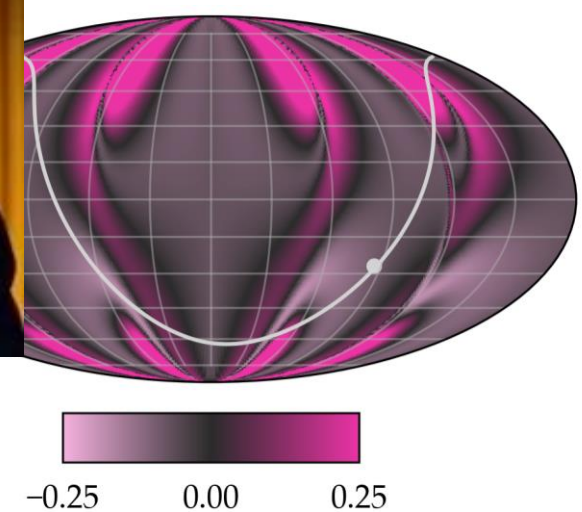
$$H_{\rm tot} = \ldots$$

$$H_{\rm LIV} = \sum_{d} \ldots$$

When:

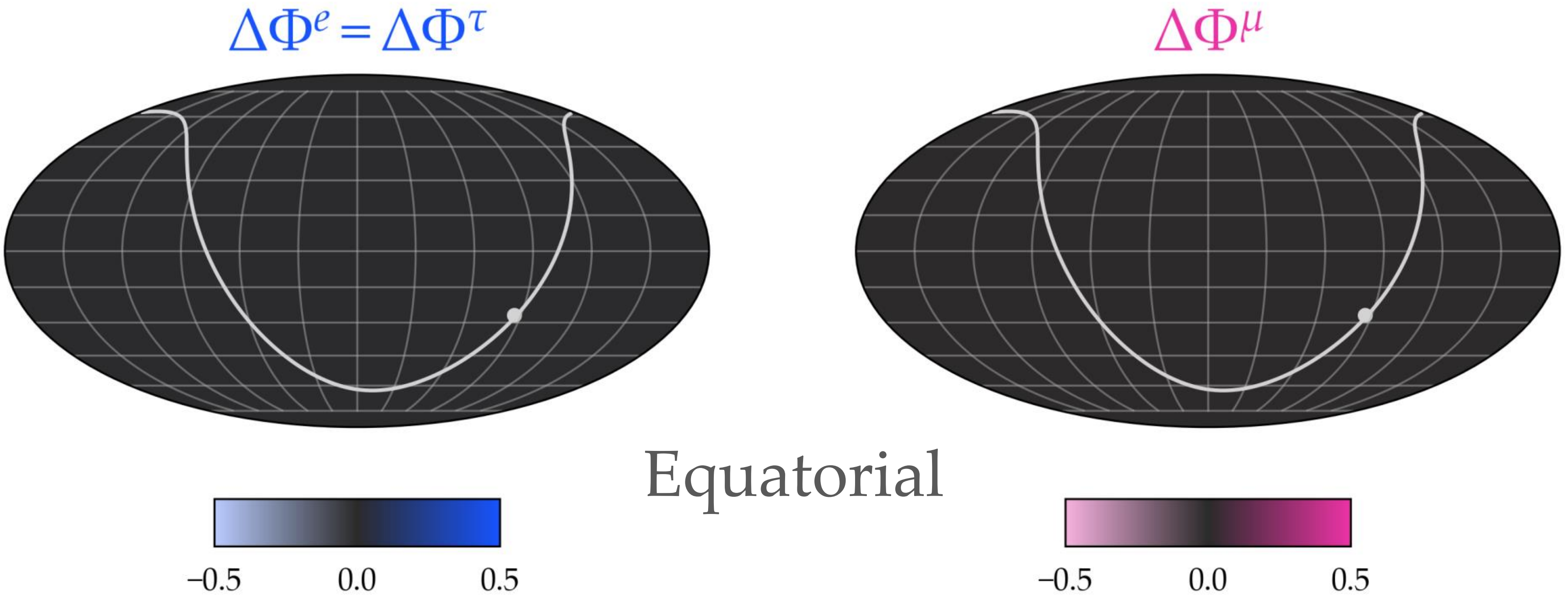
$$d = \ldots$$





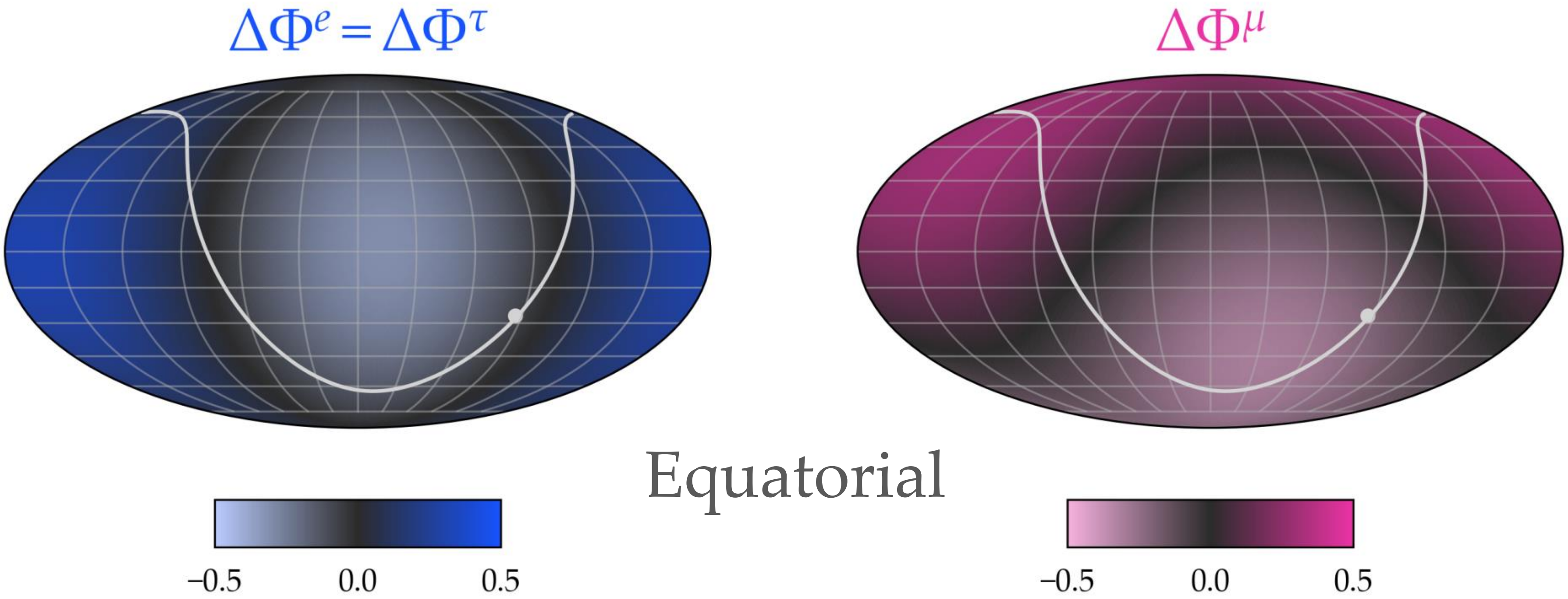
Ok, but are they the same?

If the distributions were isotropic:



Ok, but are they the same?

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



Currently large uncertainties–compatible with isotropy at 1σ.

“We don’t expect different anisotropies in flavour ratios”

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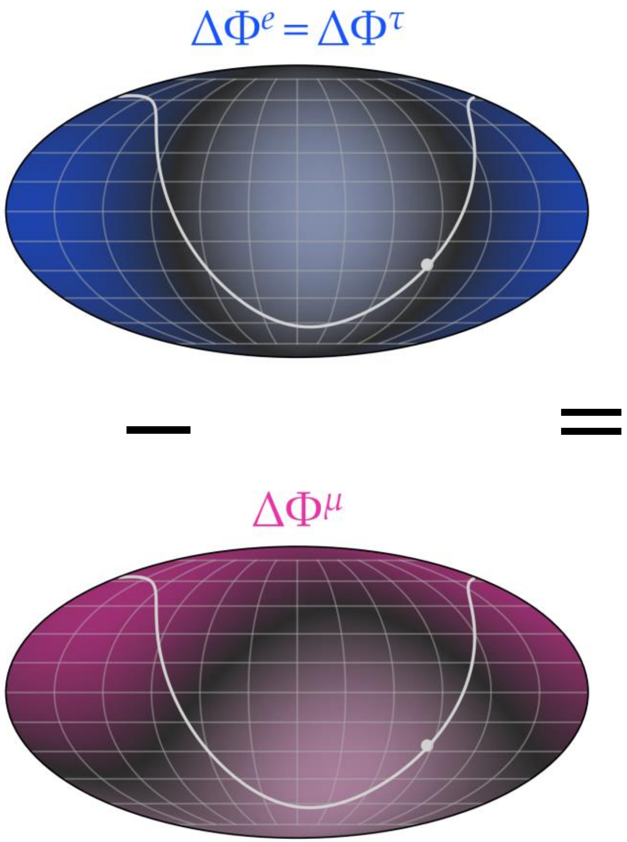

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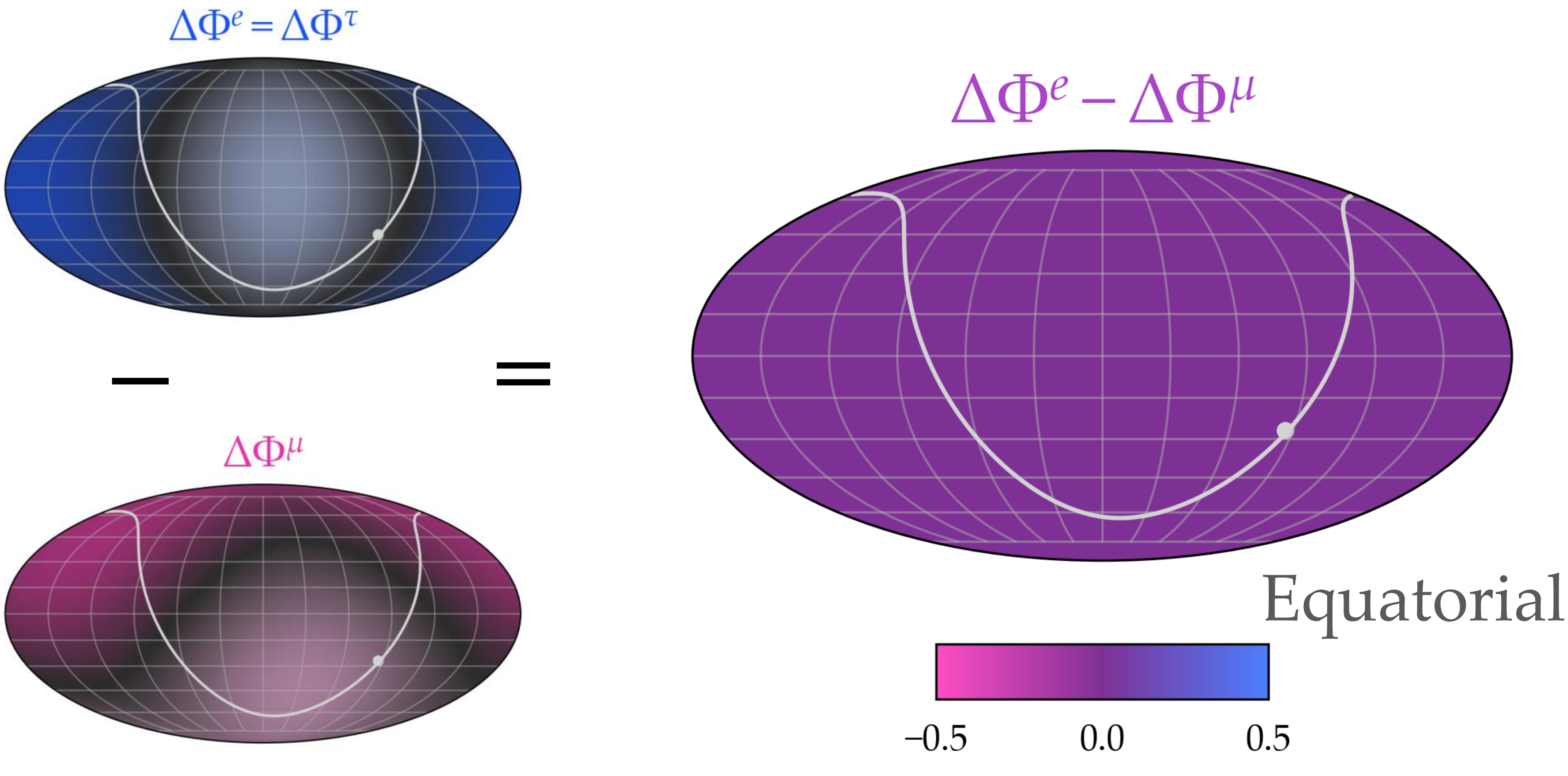

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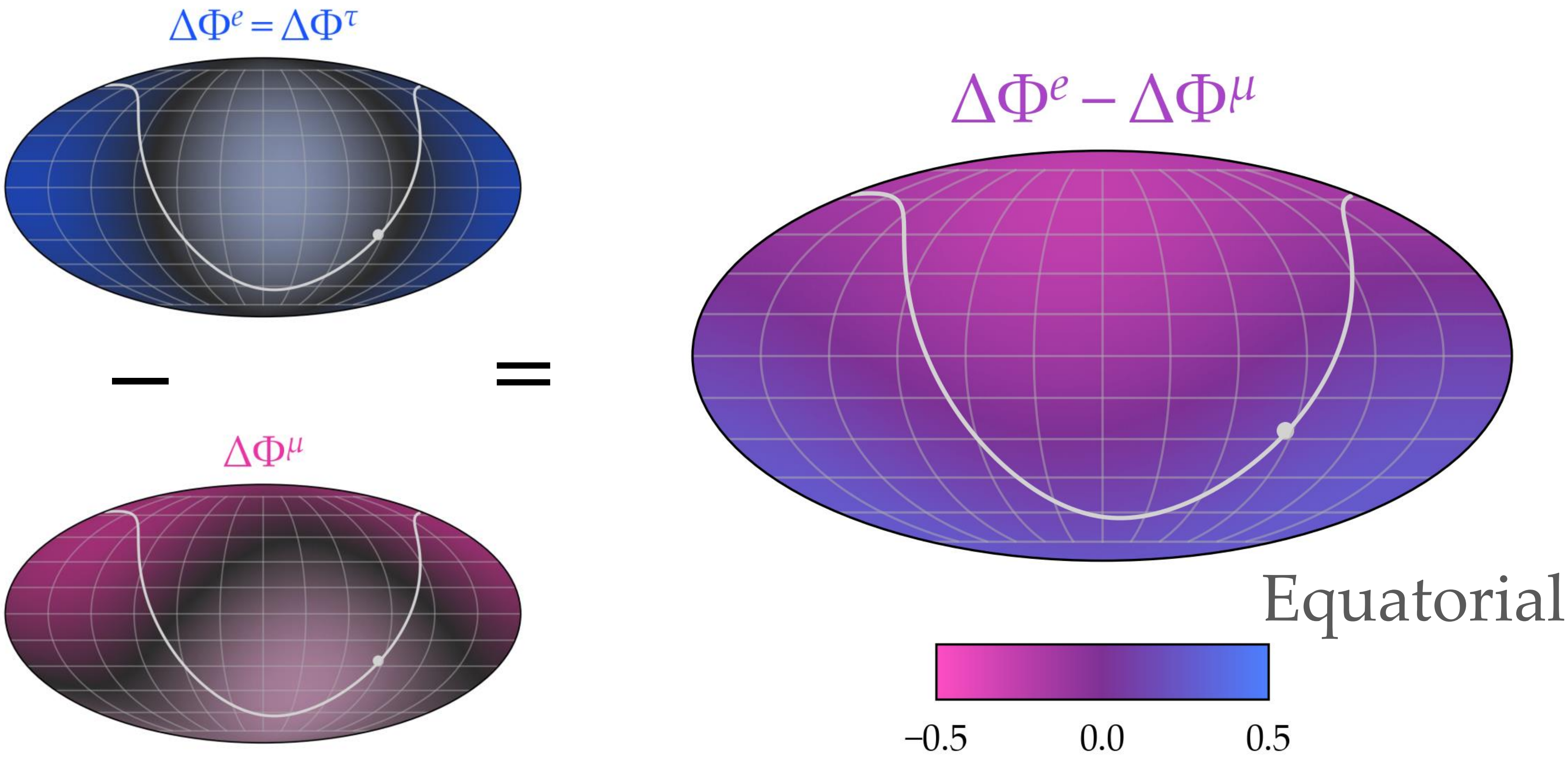

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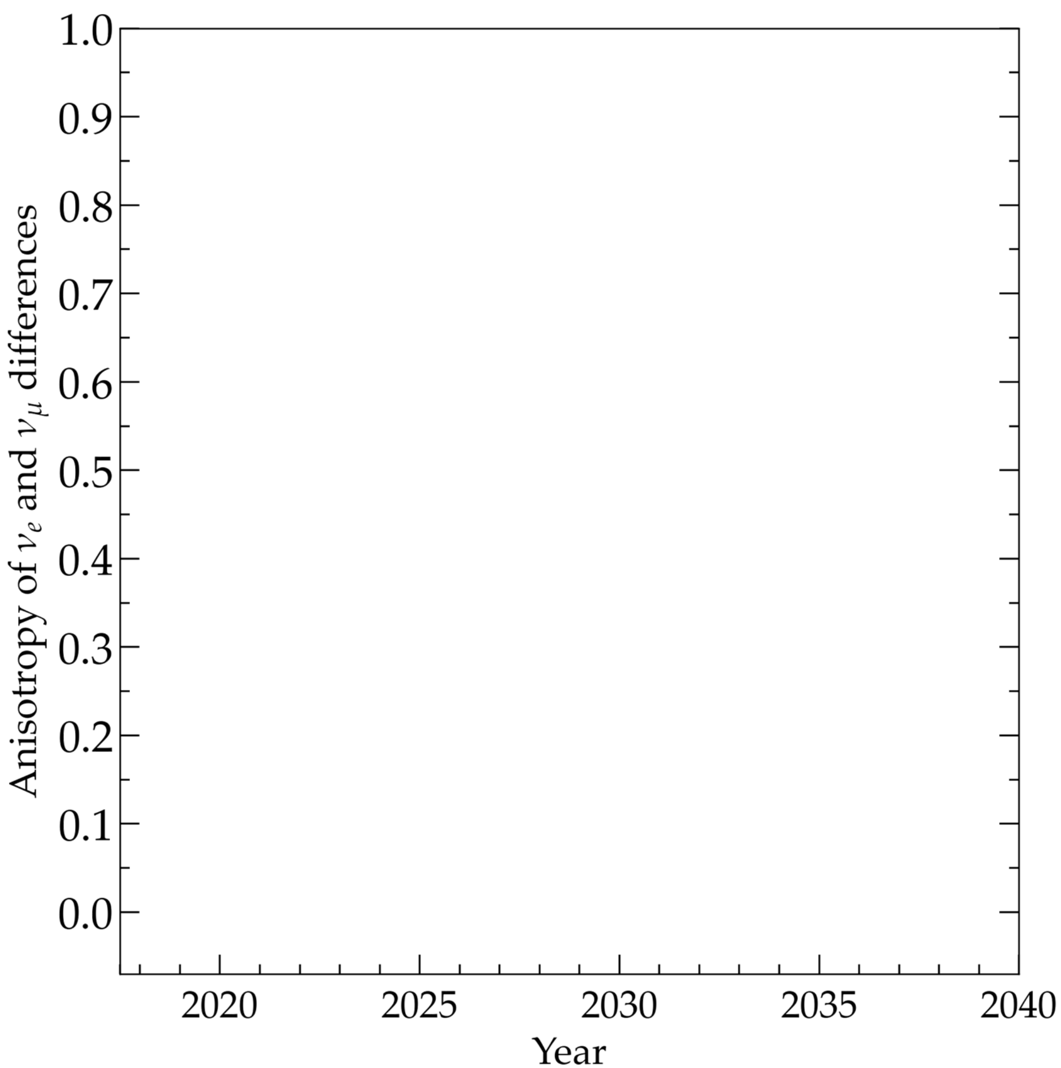

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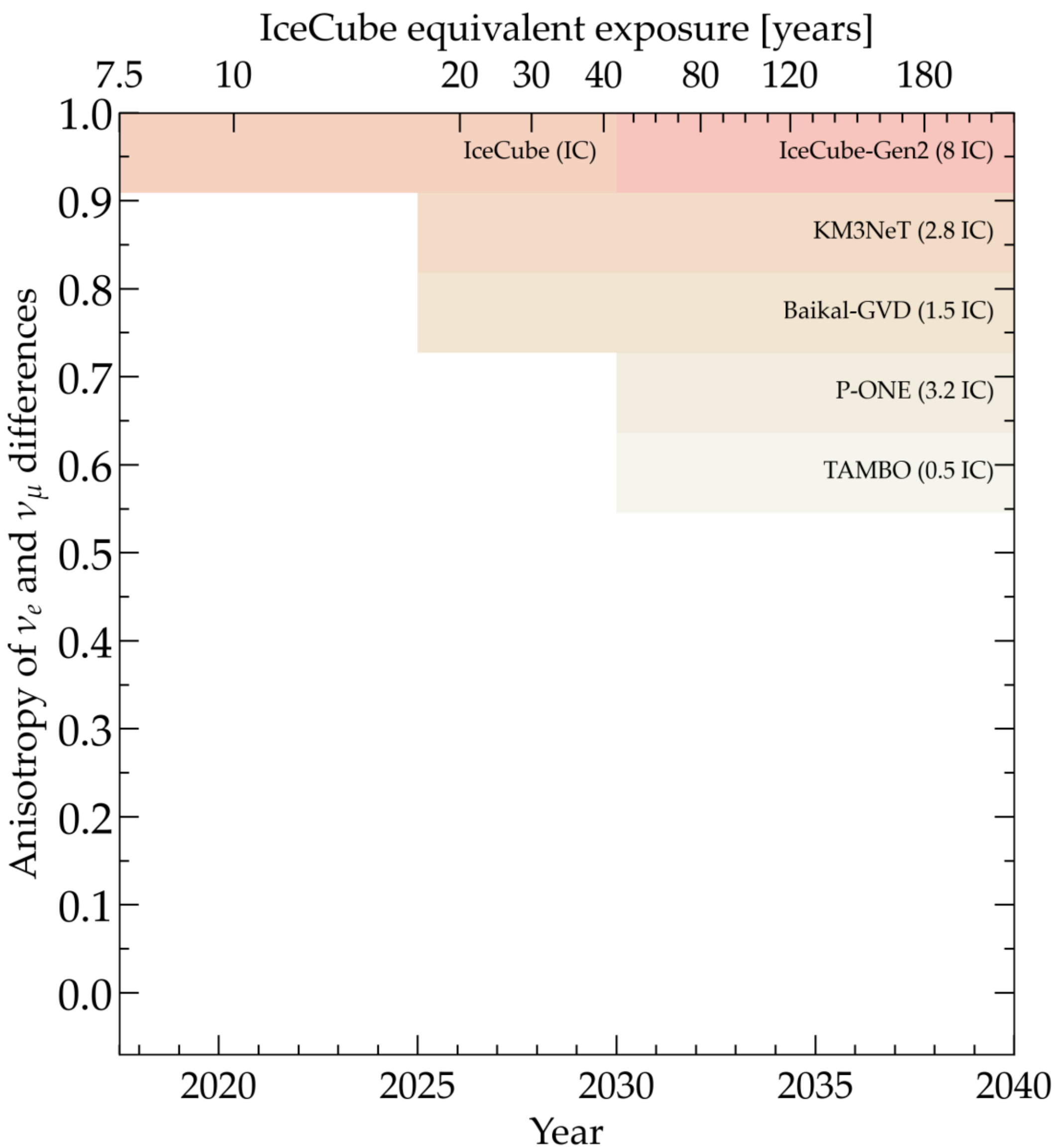

More detectors – better:

- Statistics
- Angular resolution (KM3NeT)
- Sky coverage

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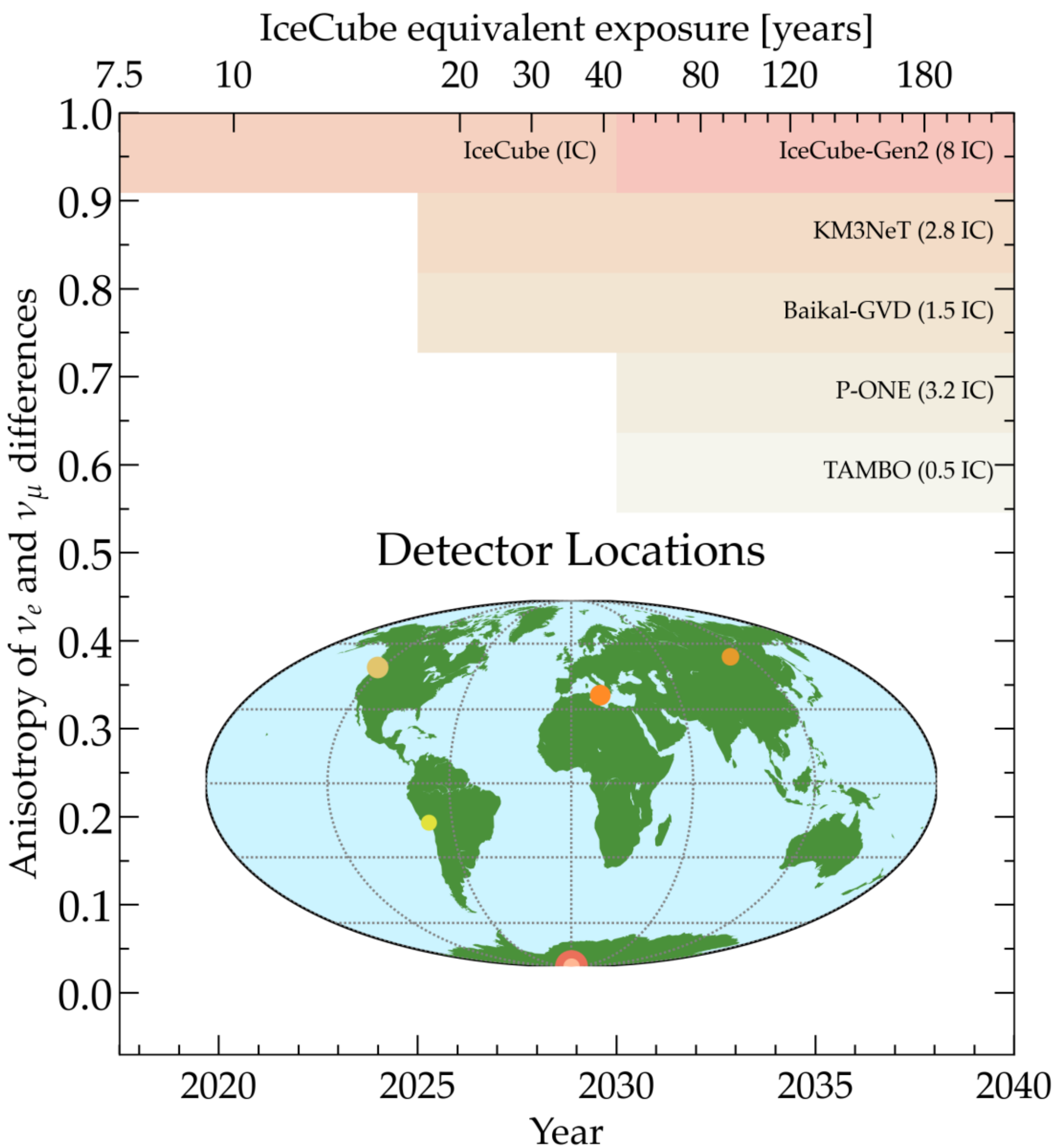

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- IceCube (current)
- KM3NeT (2025)
- Baikal-GVD (2025)
- IceCube Gen2 (2030)
- P-ONE (2030)
- TAMBO (2030)

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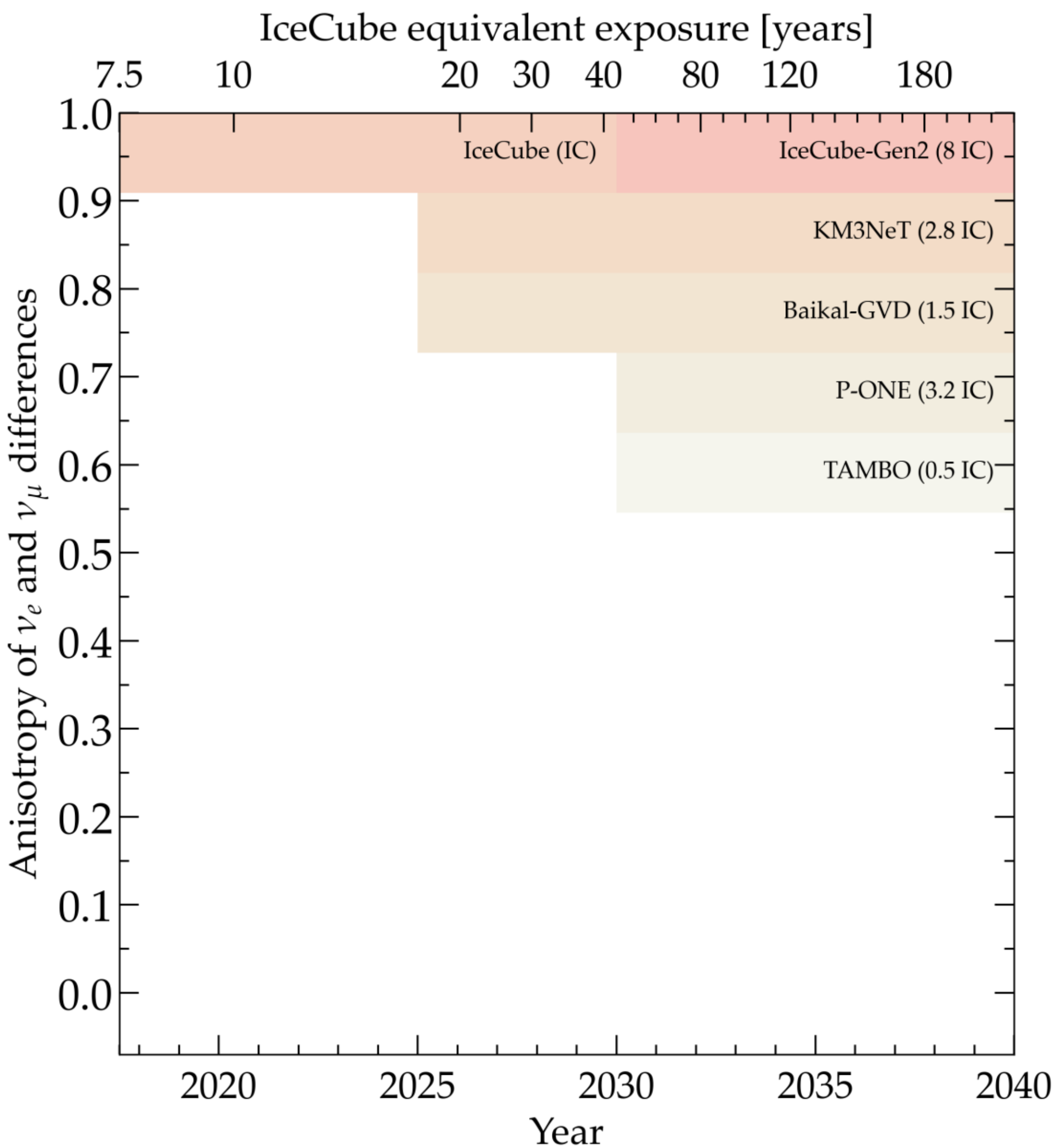

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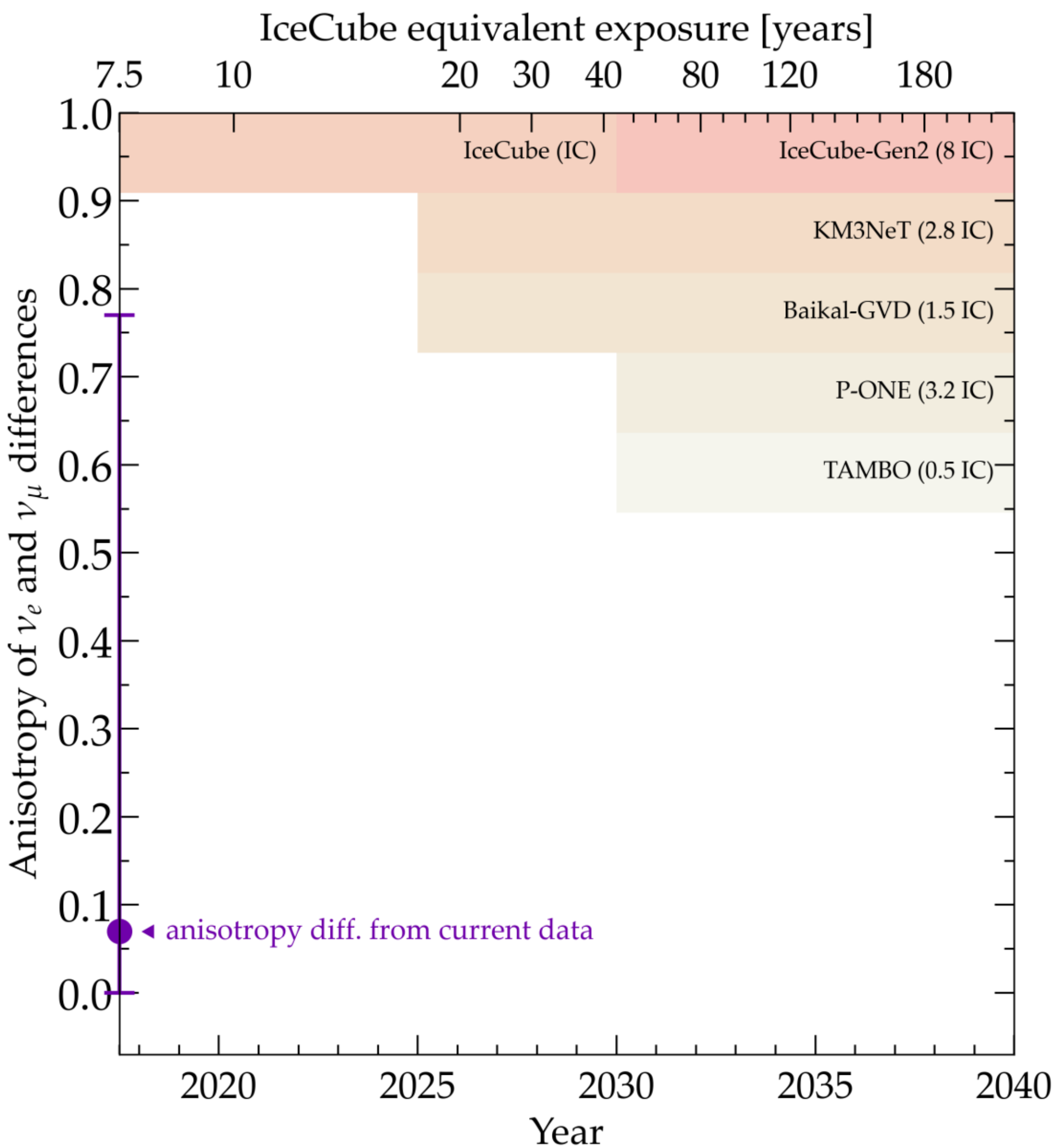

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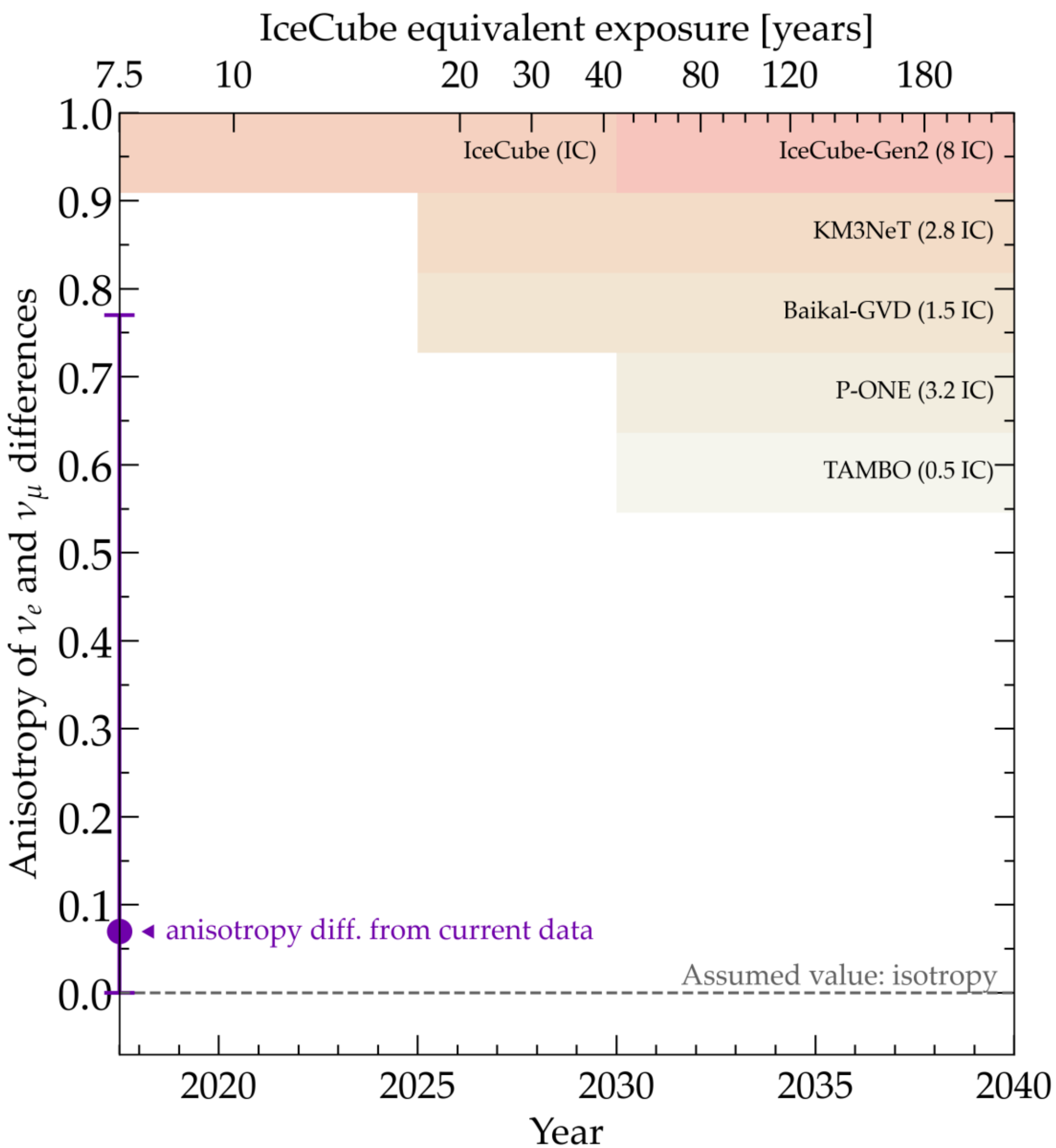

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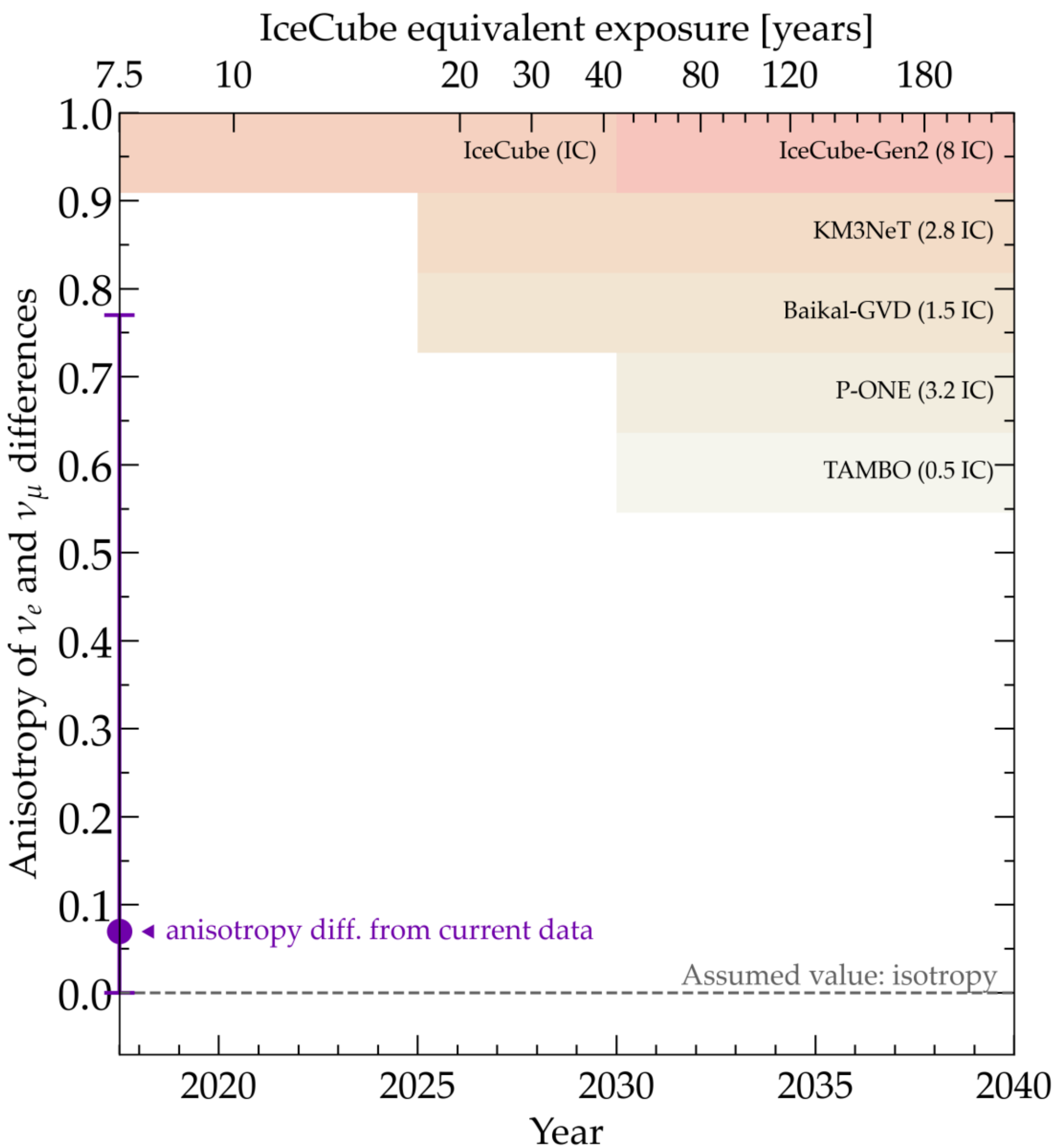

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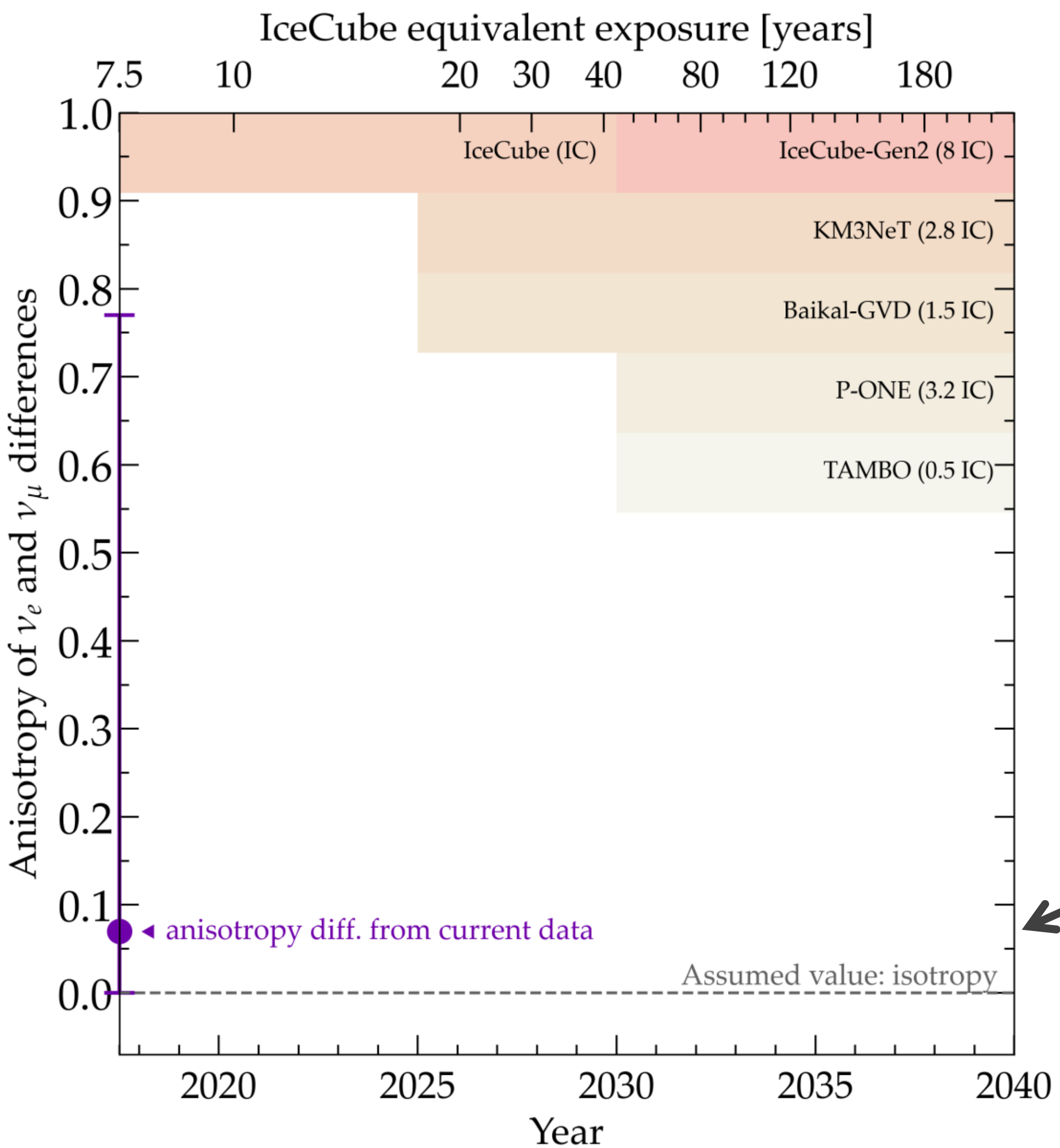

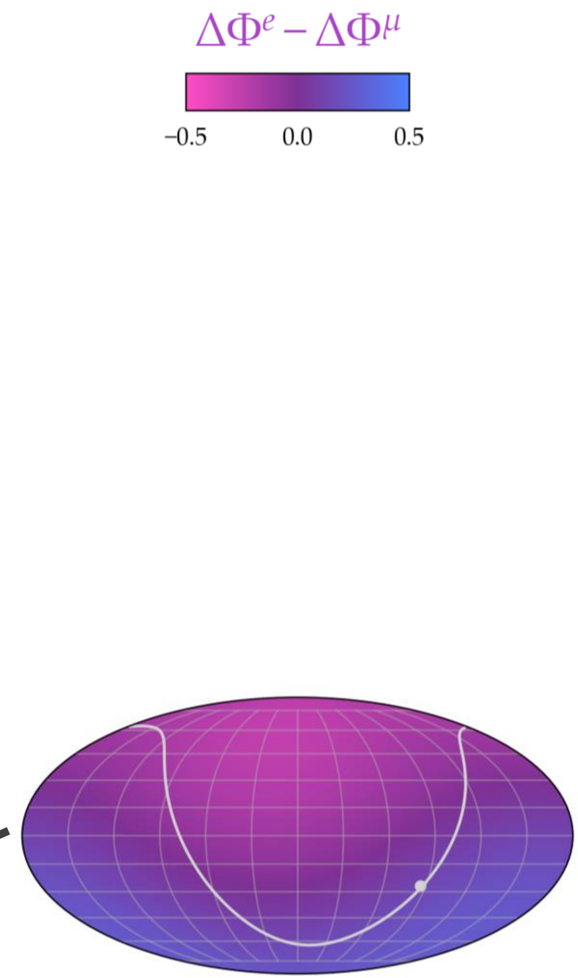

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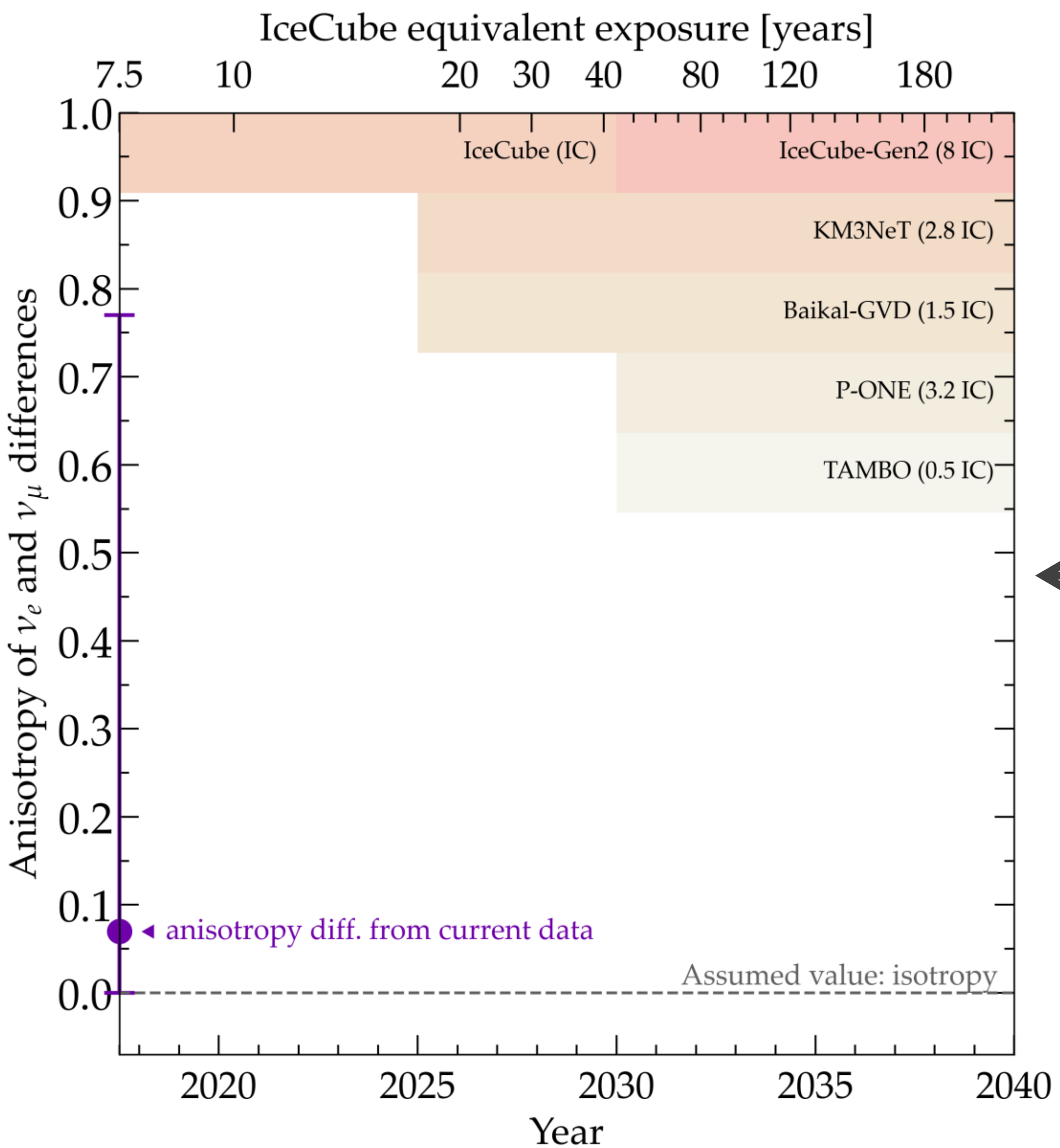

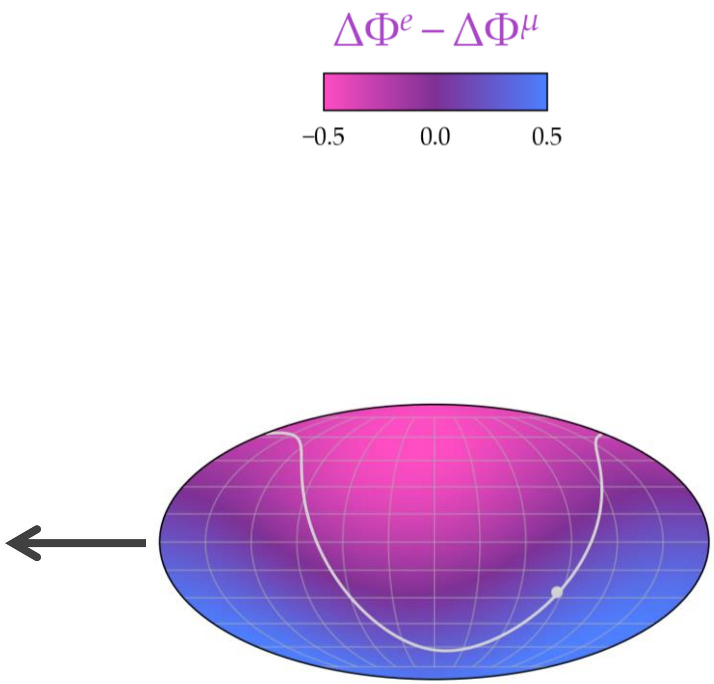

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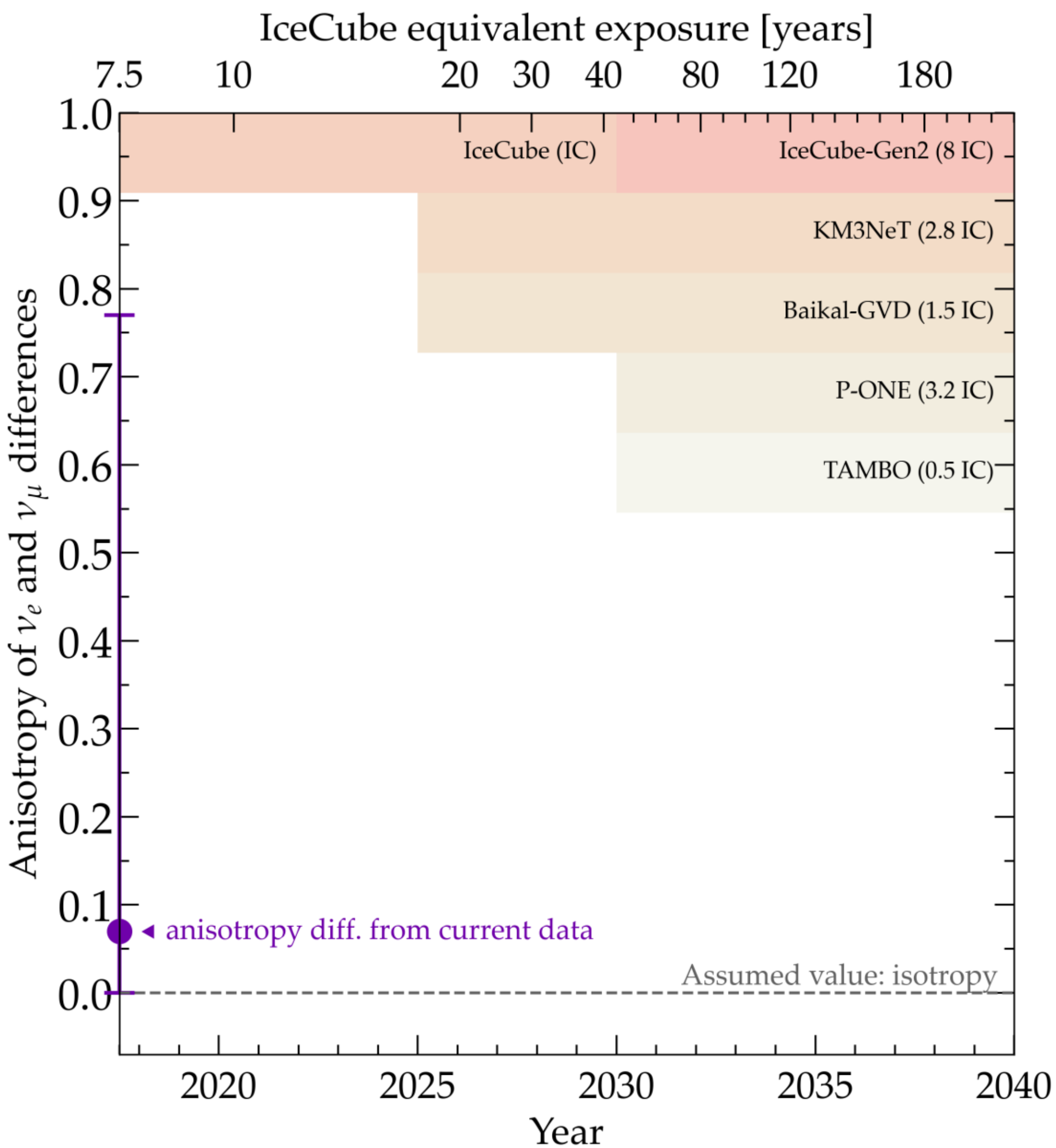

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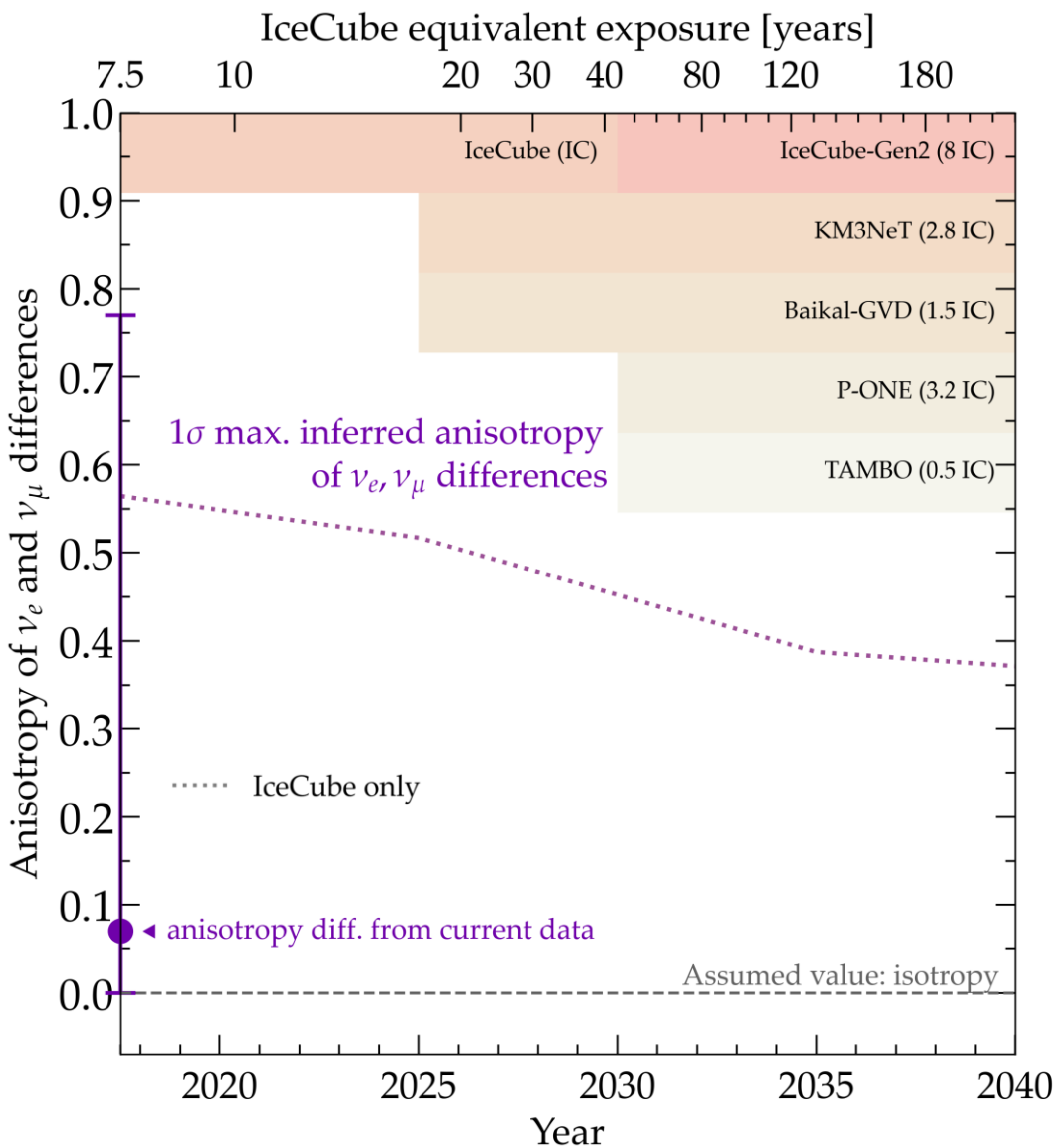

Improvement by 2040:

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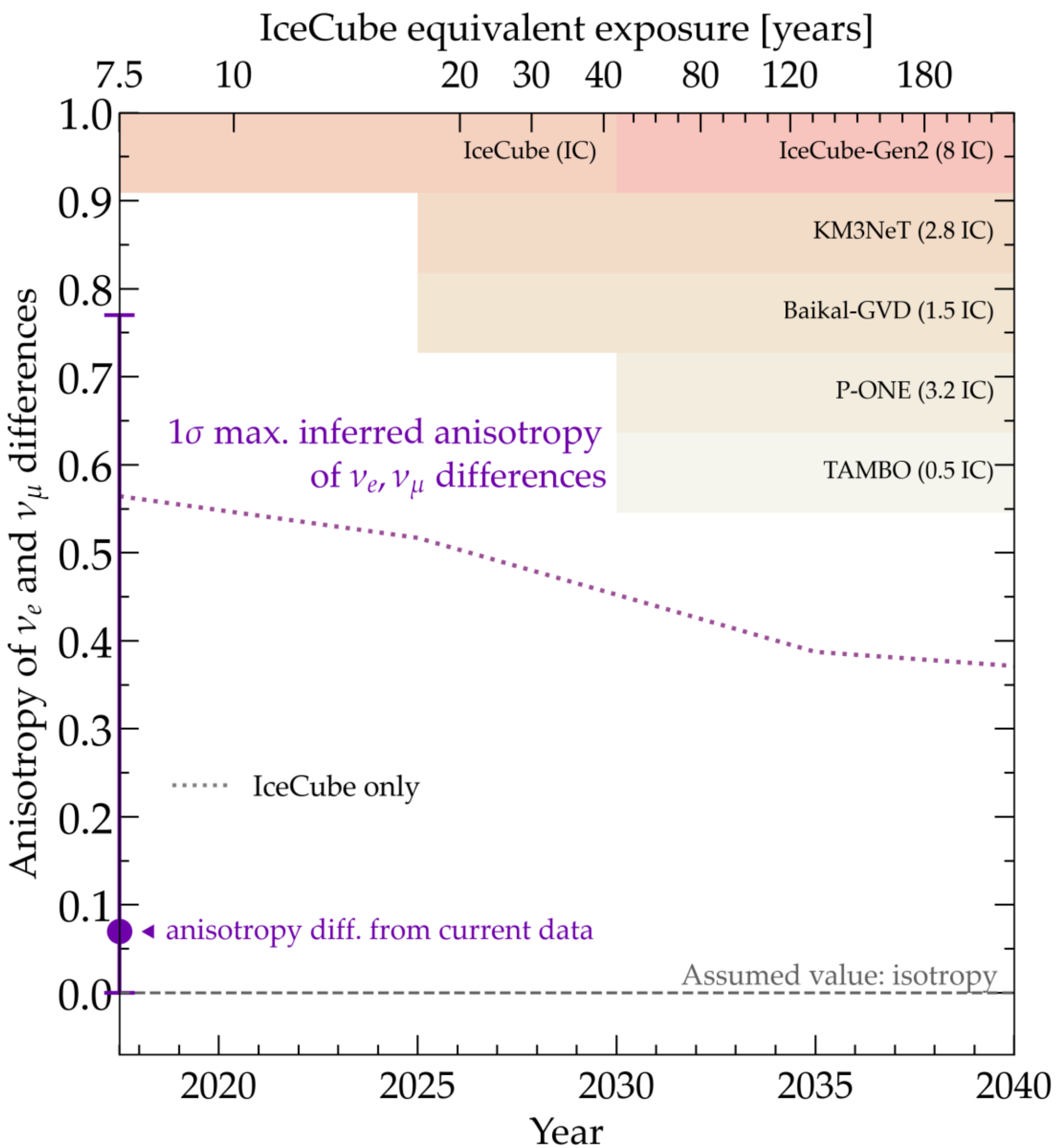

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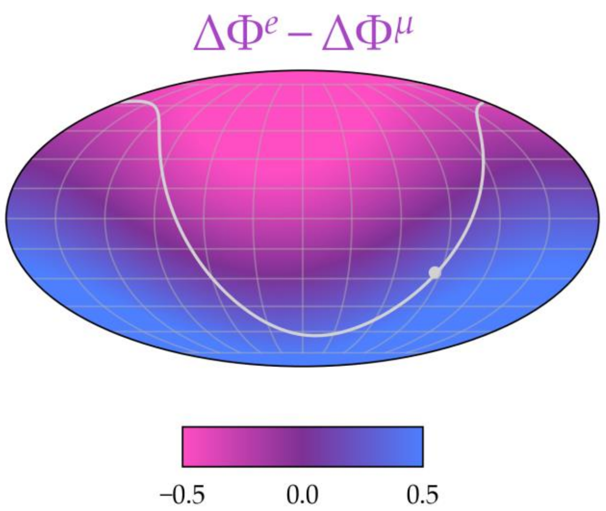
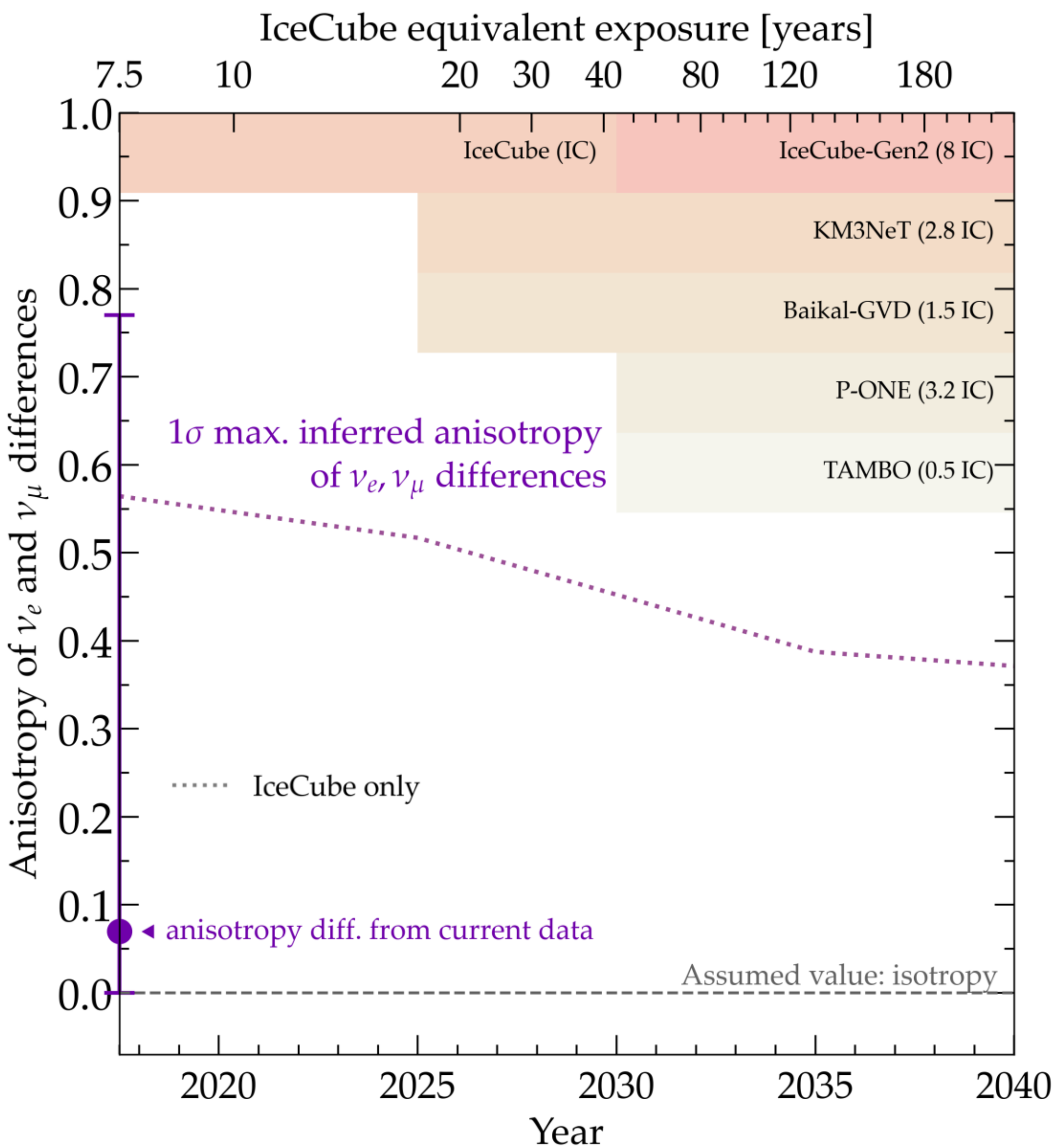


How well can we constrain isotropy over time?



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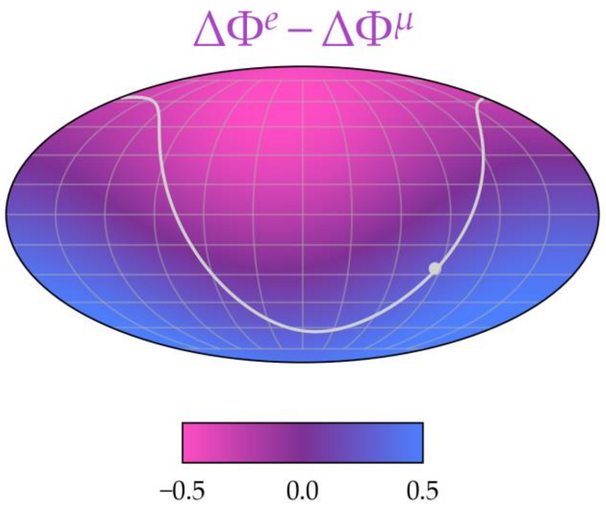

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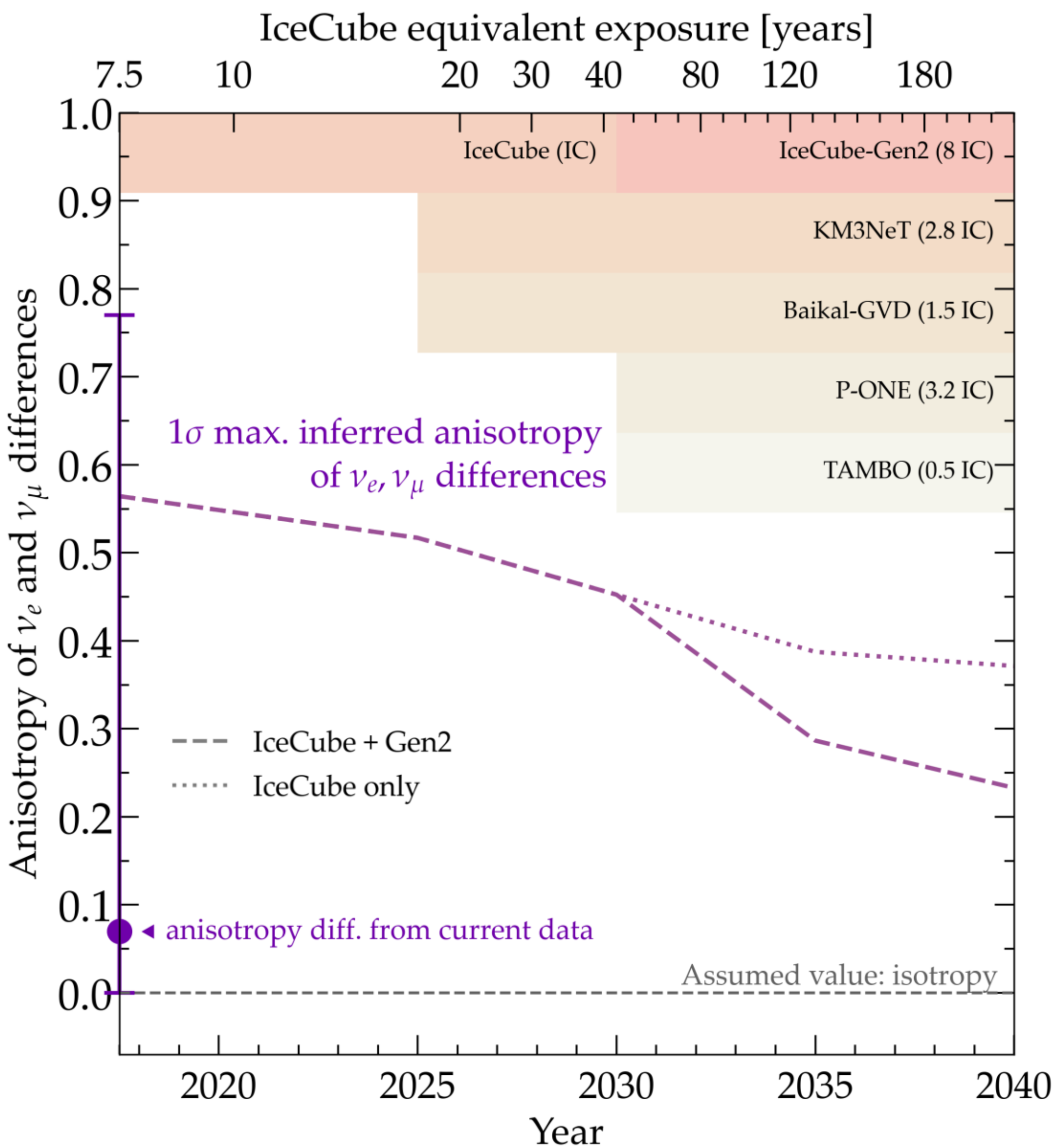
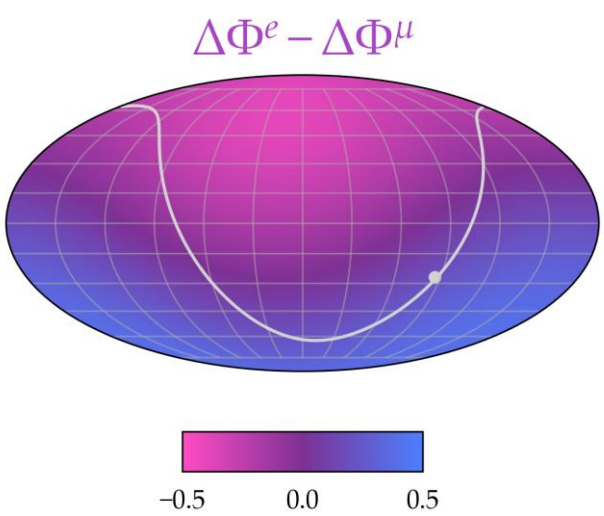


Improvement by 2040:

- IC only: 25%
- IC + Gen2: 55%



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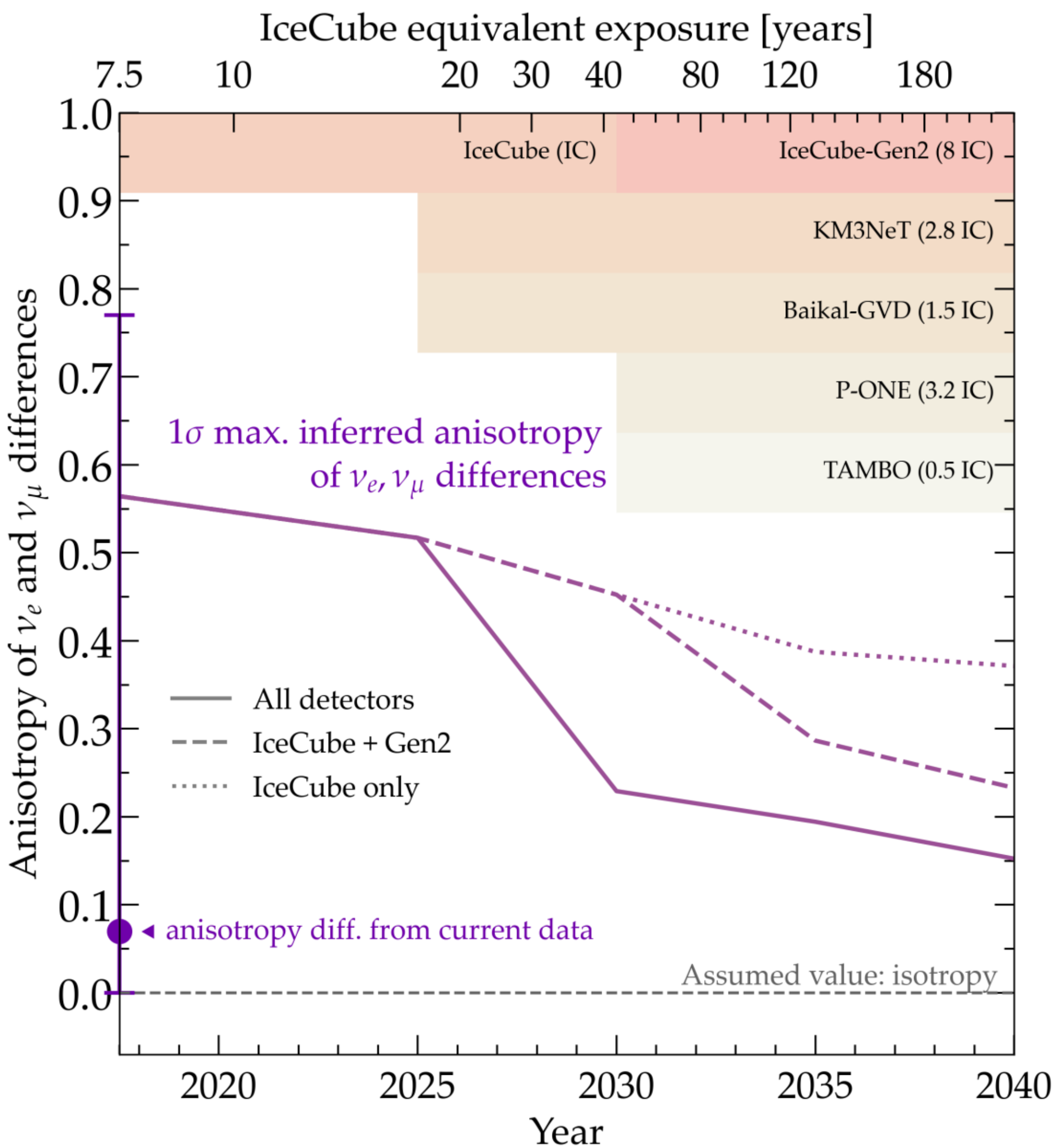
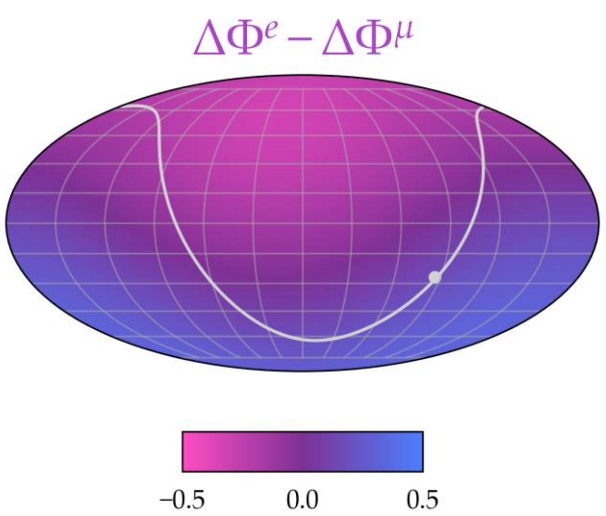
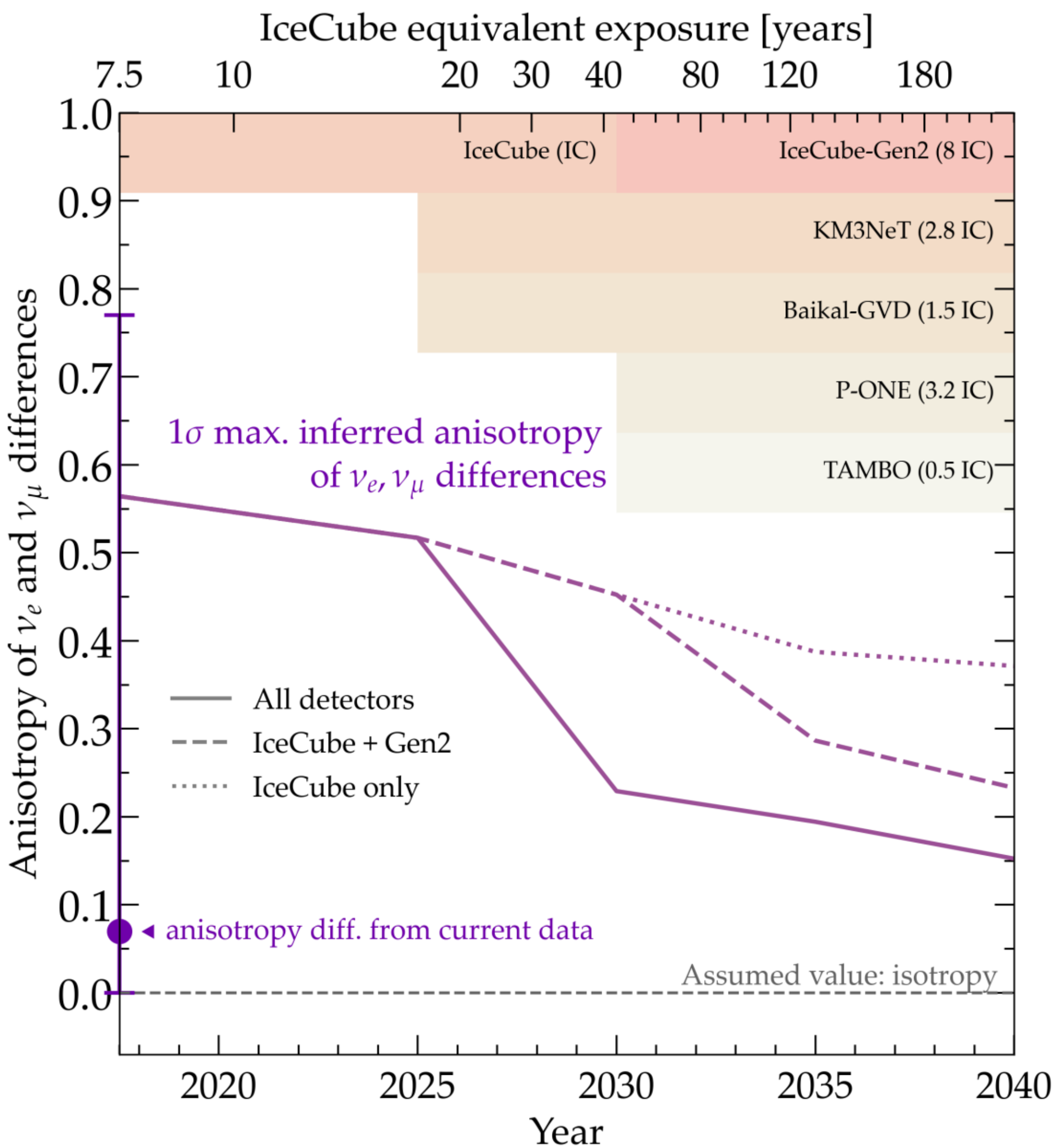


Improvement by 2040:

- IC only: 25%
- IC + Gen2: 55%
- All detectors: 73%





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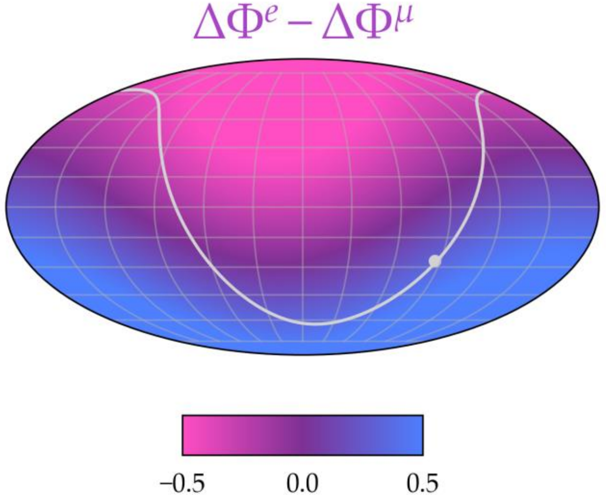

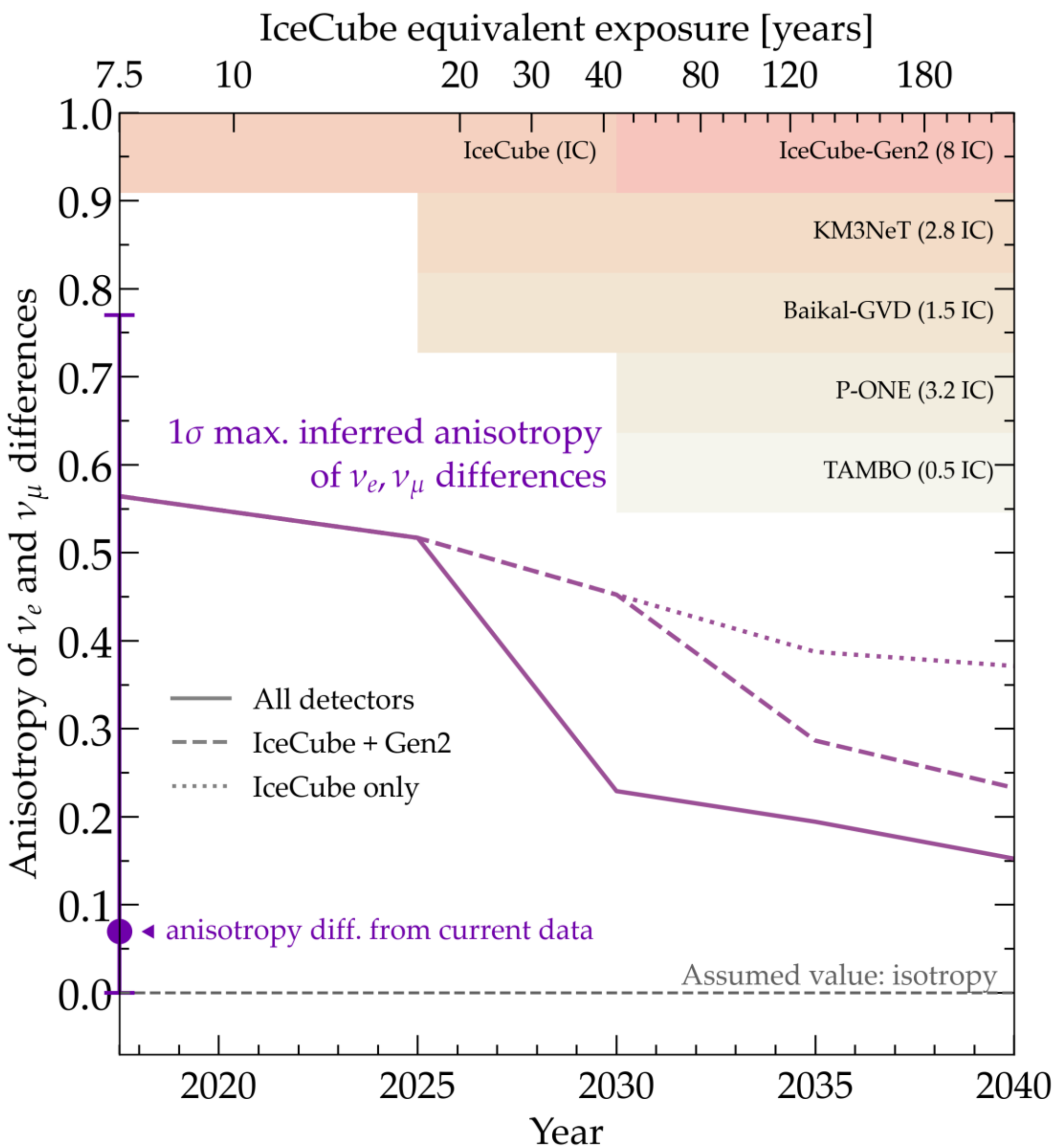

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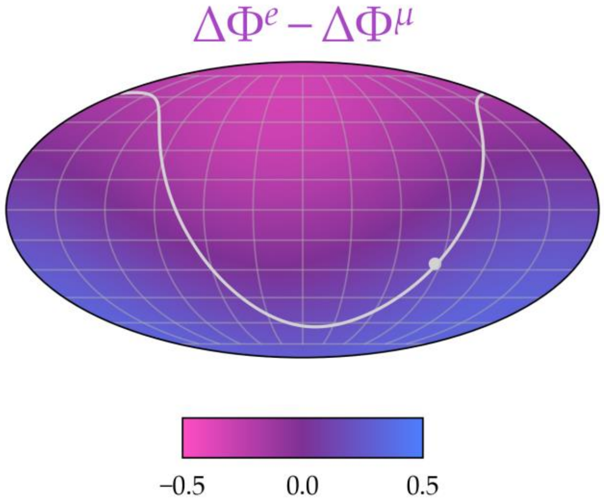

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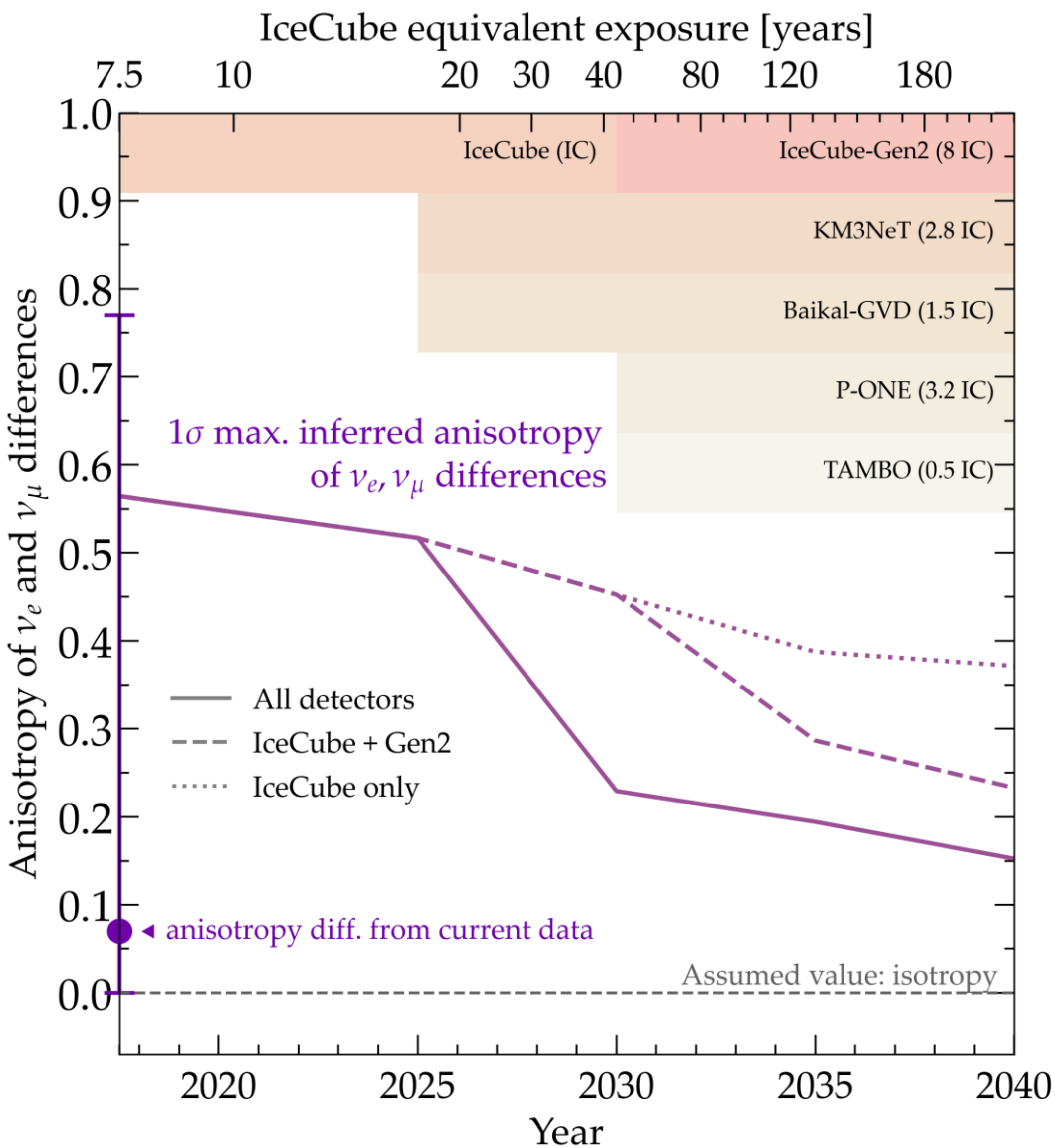

Improvement by 2040:

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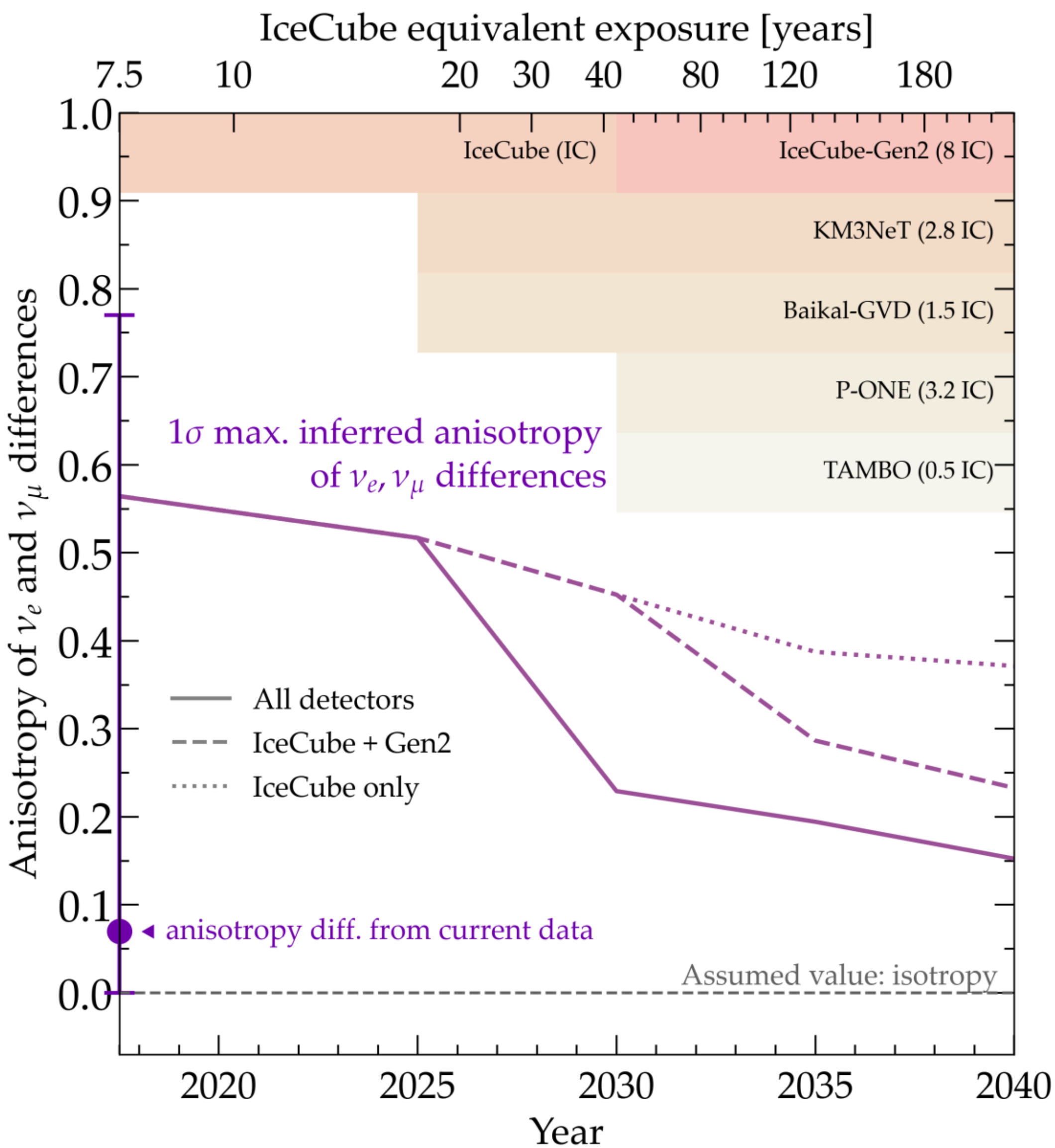
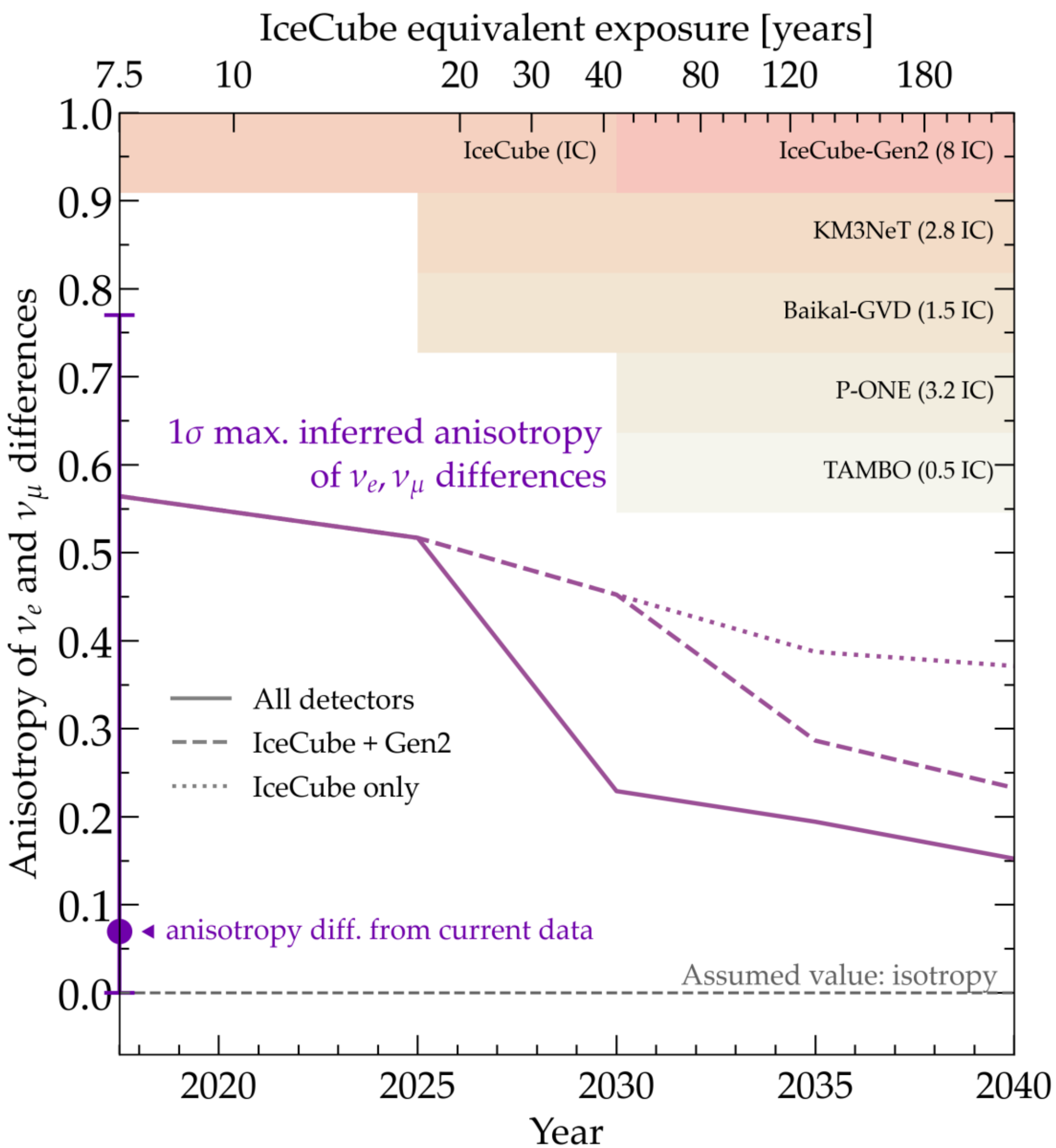
Assuming IC-like sensitivity

How well can we constrain isotropy over time?



How anisotropic is LIV?

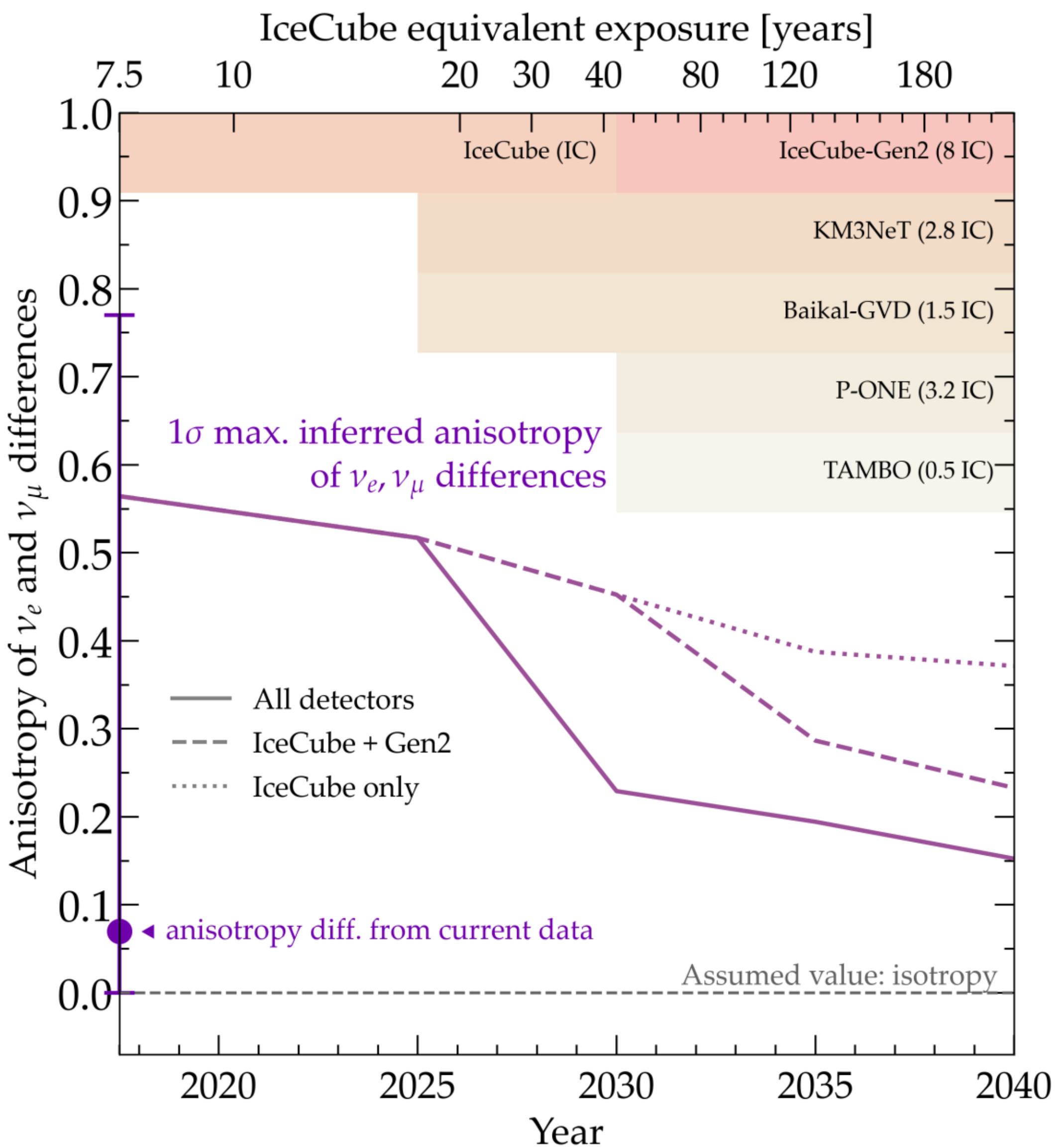
How well can we constrain isotropy over time?



How anisotropic is LIV?

What about other BSM anisotropies?

How well can we constrain isotropy over time?

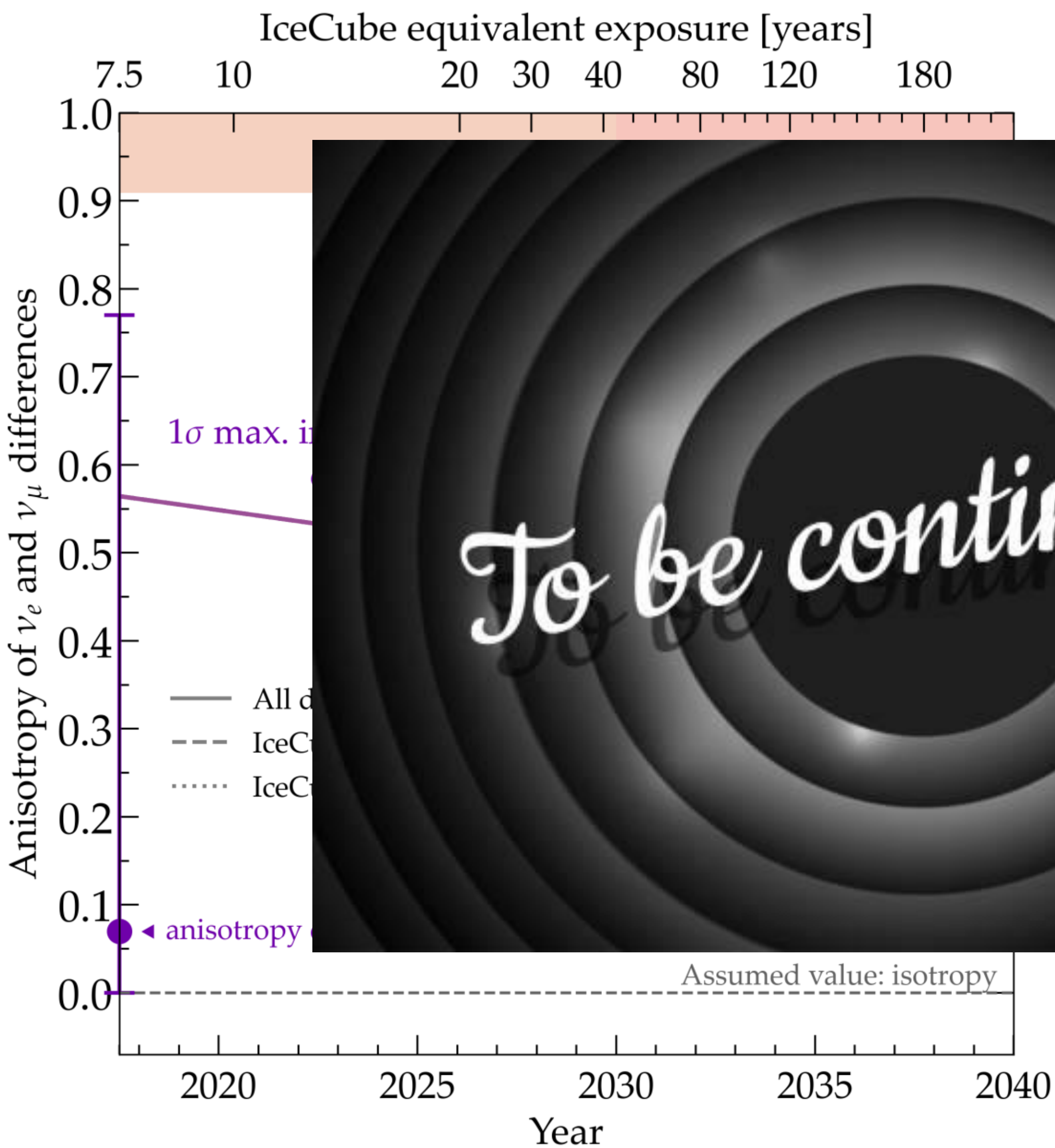


How anisotropic is LIV?

What about other BSM anisotropies?

How well can we constrain them with flavour ratios?

How well can we constrain isotropy over time?



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Thanks!

Questions?

References

- 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 [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).

- Sungwook E. Hong *et al.*, Revealing the Local Cosmic Web from Galaxies by Deep Learning, Astrophys.J. **913**, 1, 76 (2021), arXiv:2008.01738 [astro-ph.CO]

"We don't expect anisotropies in flavour ratios"

$$\Delta\Phi_\alpha = \sum_{\ell>0,m} a^\alpha_{\ell,m} Y_{\ell,m}$$

Take the difference:

$$\delta a^{\alpha,\beta}_{\ell,m} = a^\alpha_{\ell,m} - a^\beta_{\ell,m}$$

Quantifying anisotropy

$$\Delta\Phi_\alpha = \sum_{\ell>0,m} a^{\alpha}_{\ell,m} Y_{\ell,m}$$

The anisotropy measure (power spectrum):

Quantifying anisotropy

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The anisotropy measure (power spectrum):

$$C^{\alpha}_{\ell} = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a^{\alpha}_{\ell,m}|^2$$

Quantifying anisotropy

$$\Delta\Phi_\alpha = \sum_{\ell>0,m} a^\alpha_{\ell,m} Y_{\ell,m}$$

The anisotropy measure (power spectrum):

$$C^\alpha_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a^\alpha_{\ell,m}|^2$$

$$\Delta C^{\alpha,\beta}_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |\delta a^{\alpha,\beta}_{\ell,m}|^2$$

How do we recover the flux?

Using Ice Cube Monte Carlo. We need:

Data

Model

Monte Carlo

Model parameters

Repetition

How do we recover the flux?

We do: