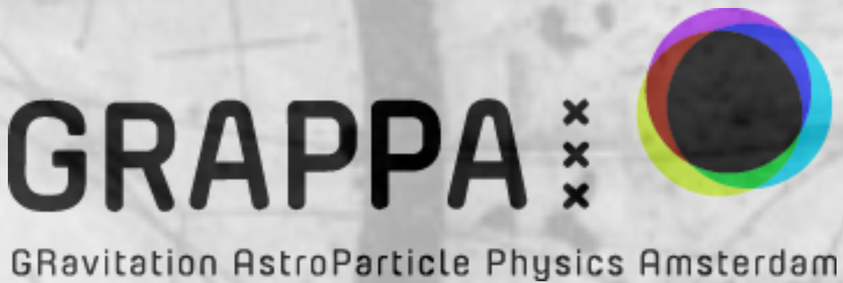
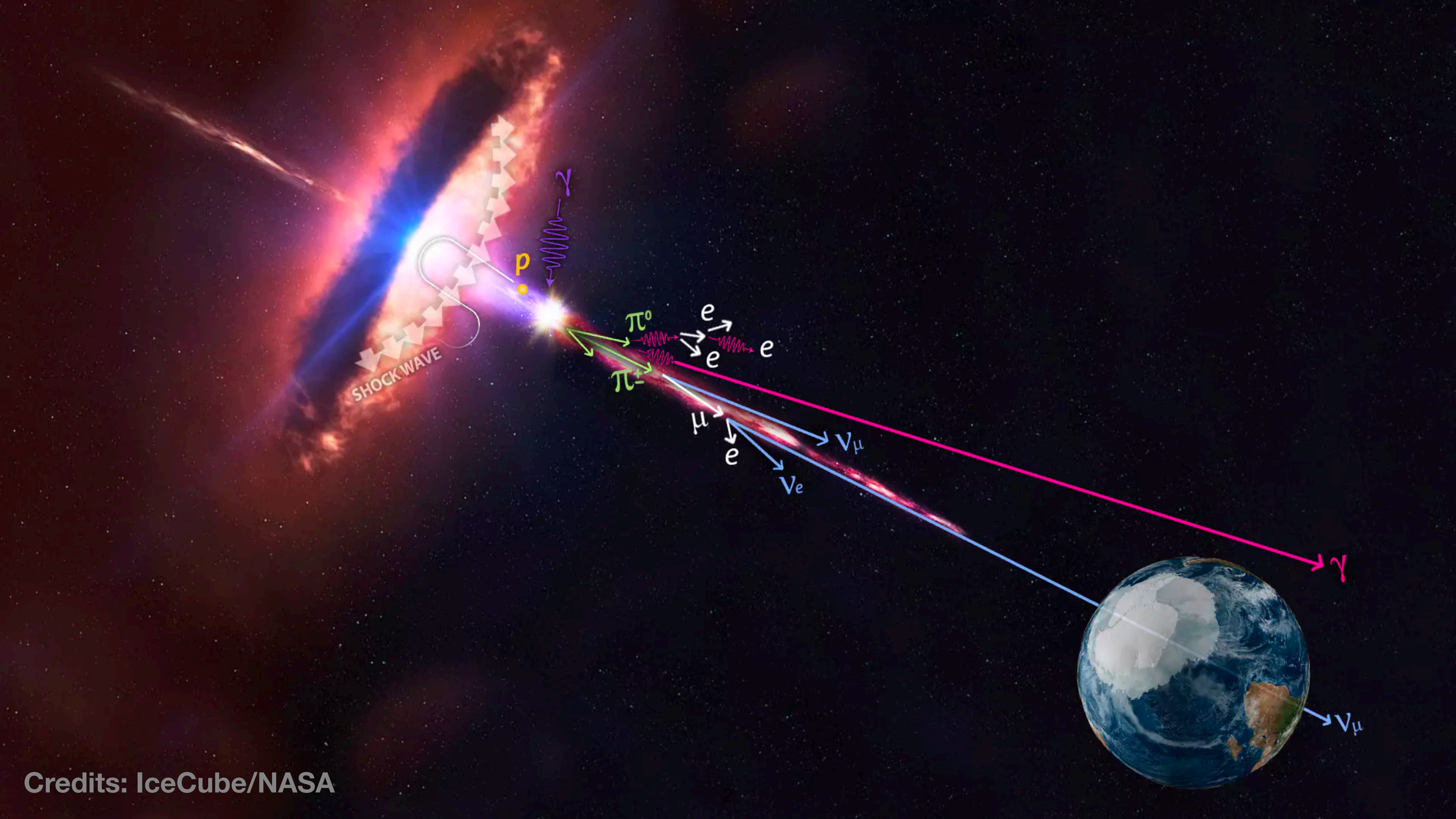
Angular power spectrum analysis on current and future high-energy neutrino data

Ariane Dekker

PALS 2019



A. Dekker, S. Ando, JCAP 02 (2019) 002
A. Dekker, M. Chianese, S. Ando, arXiv:1910.XXXXX



Credits: IceCube/NASA

Astrophysical Sources

p-γ

Photo-hadronic interactions

Active Galactic Nuclei

Blazars (4 — 6 %)

Gamma-Ray Bursts

p-p

Hadro-nuclear interactions

Starburst Galaxies

Galaxy clusters

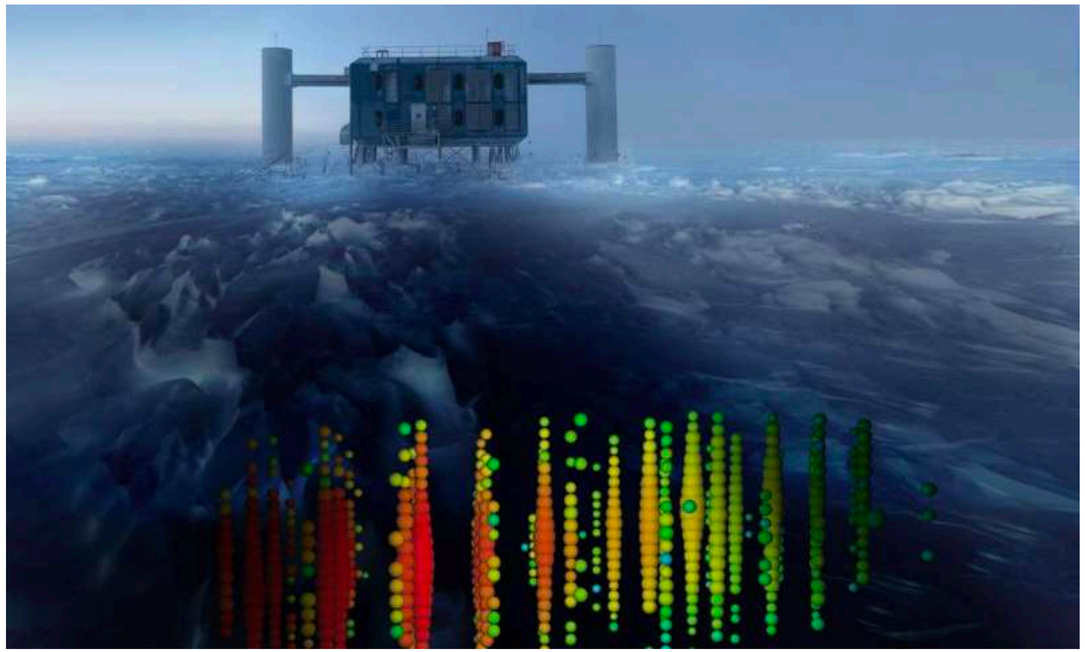
Astrophysical Sources

p-γ	p-p
Photo-hadronic interactions	**Hadro-nuclear interactions**
Active Galactic Nuclei	Starburst Galaxies
Blazars (4 — 6 %)	Galaxy clusters
Gamma-Ray Bursts	

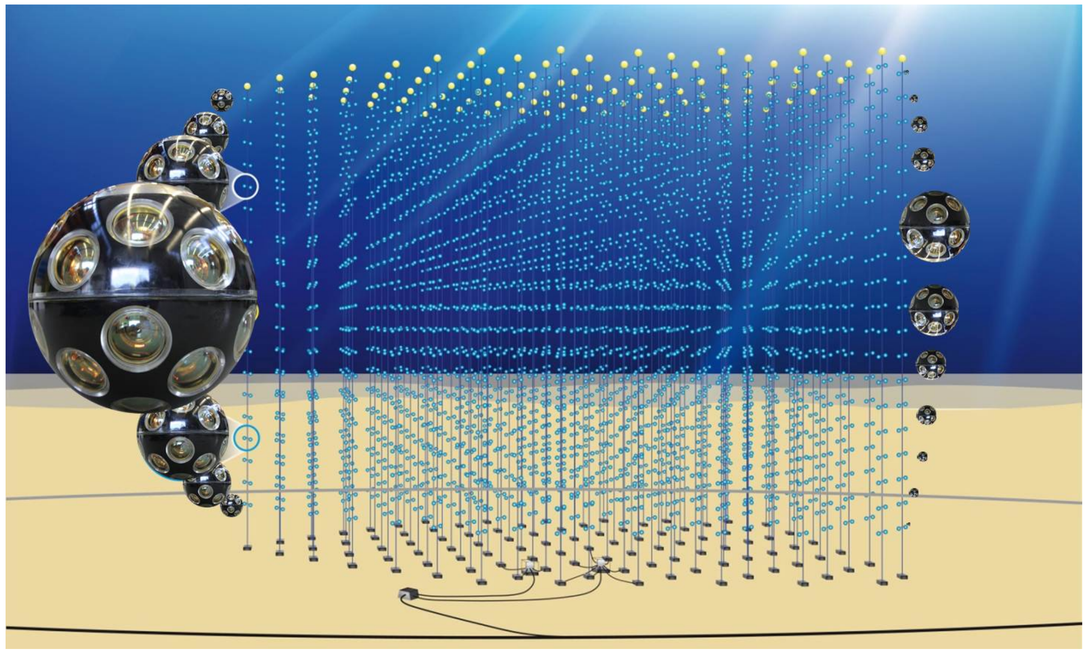
Dark Matter

Neutrino detectors

IceCube

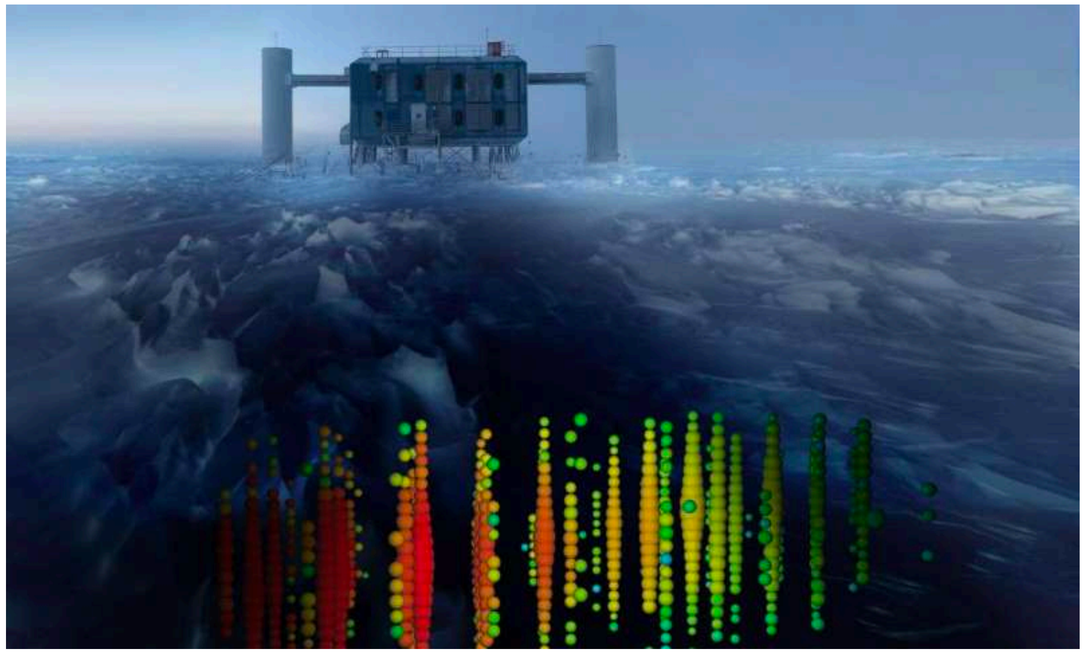


KM3NeT



Neutrino detectors

IceCube



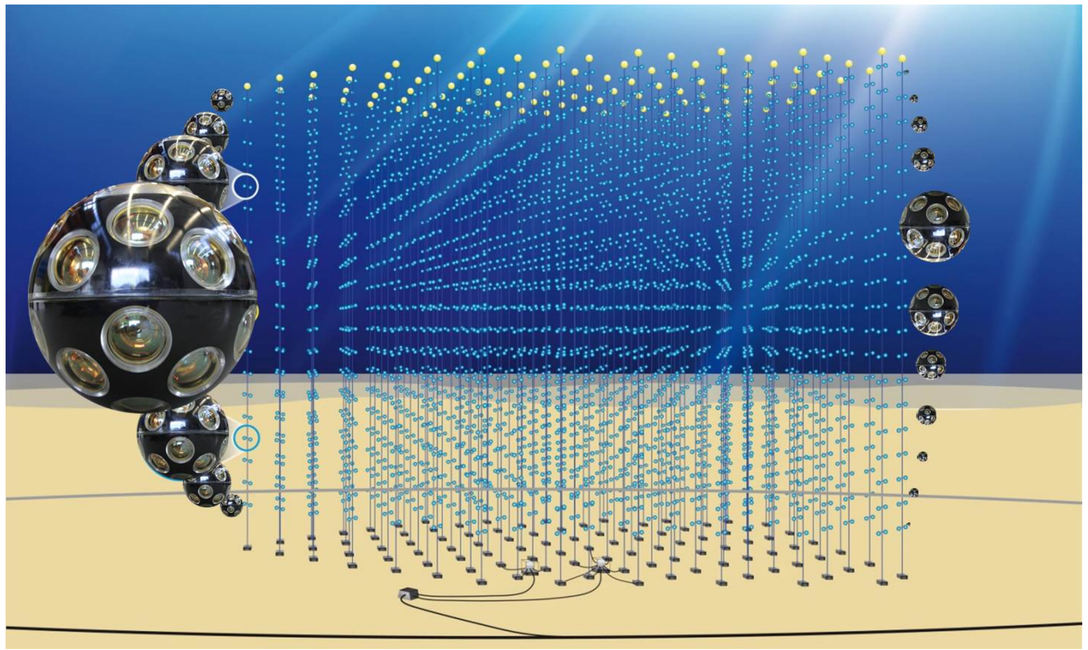
- Cubic km of Antarctic ice
- Isotropic distribution
- TXS 0506+056
- Sources unknown
- IceCube-Gen2

IceCube Collaboration

Neutrino detectors

- **Situated in the Mediterranean Sea -> Observes Galactic centre**
- **Construction phase**

KM3NeT

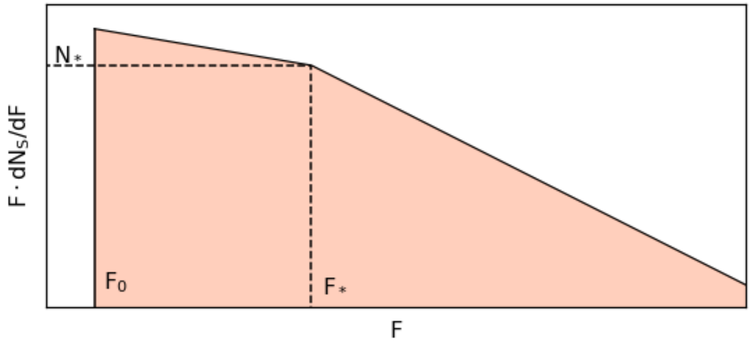


Method

Angular power spectrum analysis

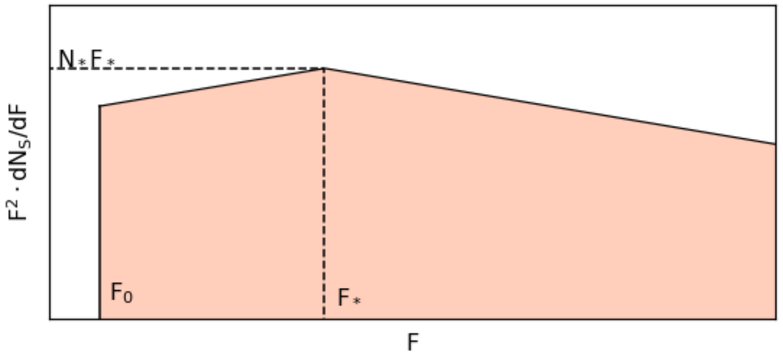
Monte Carlo method

Statistical distribution flux



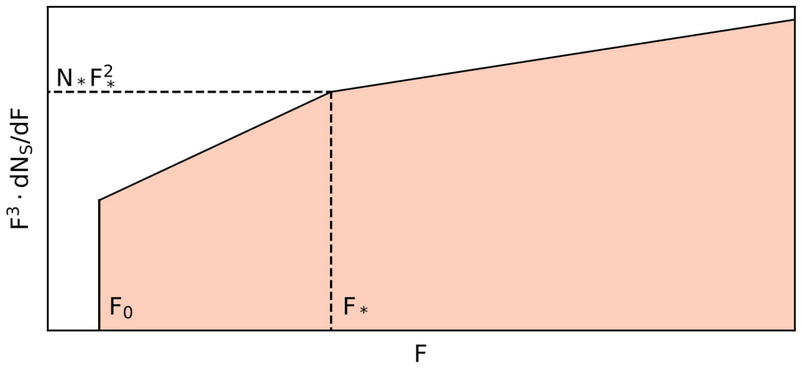
$$\frac{dN_s}{dF} \propto \begin{cases} F^{-2.5} & F_\star < F \\ F^{-1.5} & F_0 < F < F_\star \end{cases}$$

Source-flux distribution



$$4\pi I_\nu = \langle F \rangle \propto N_\star F_\star$$

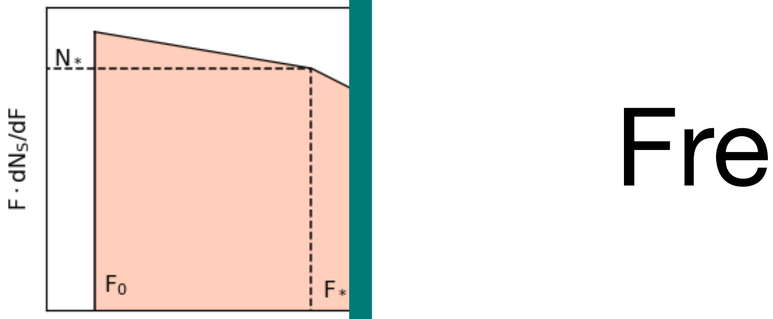
1st moment



$$\left\langle (F - < F >)^2 \right\rangle$$

2nd moment

Angular Power Spectrum

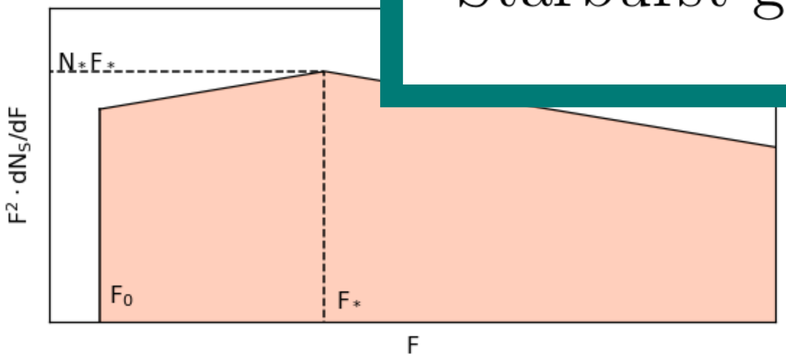


Free parameter: $N_\star \propto \dfrac{I_\nu}{F_\star}$

stribution

Blazars: $N_\star = 6 \cdot 10^2$

Starburst galaxies: $N_\star = 10^7$



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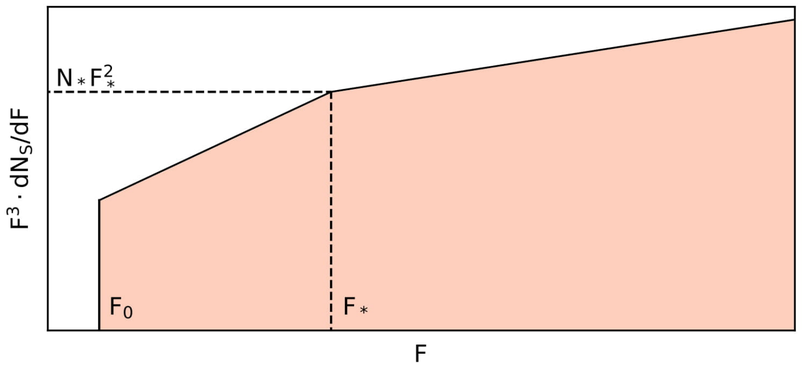
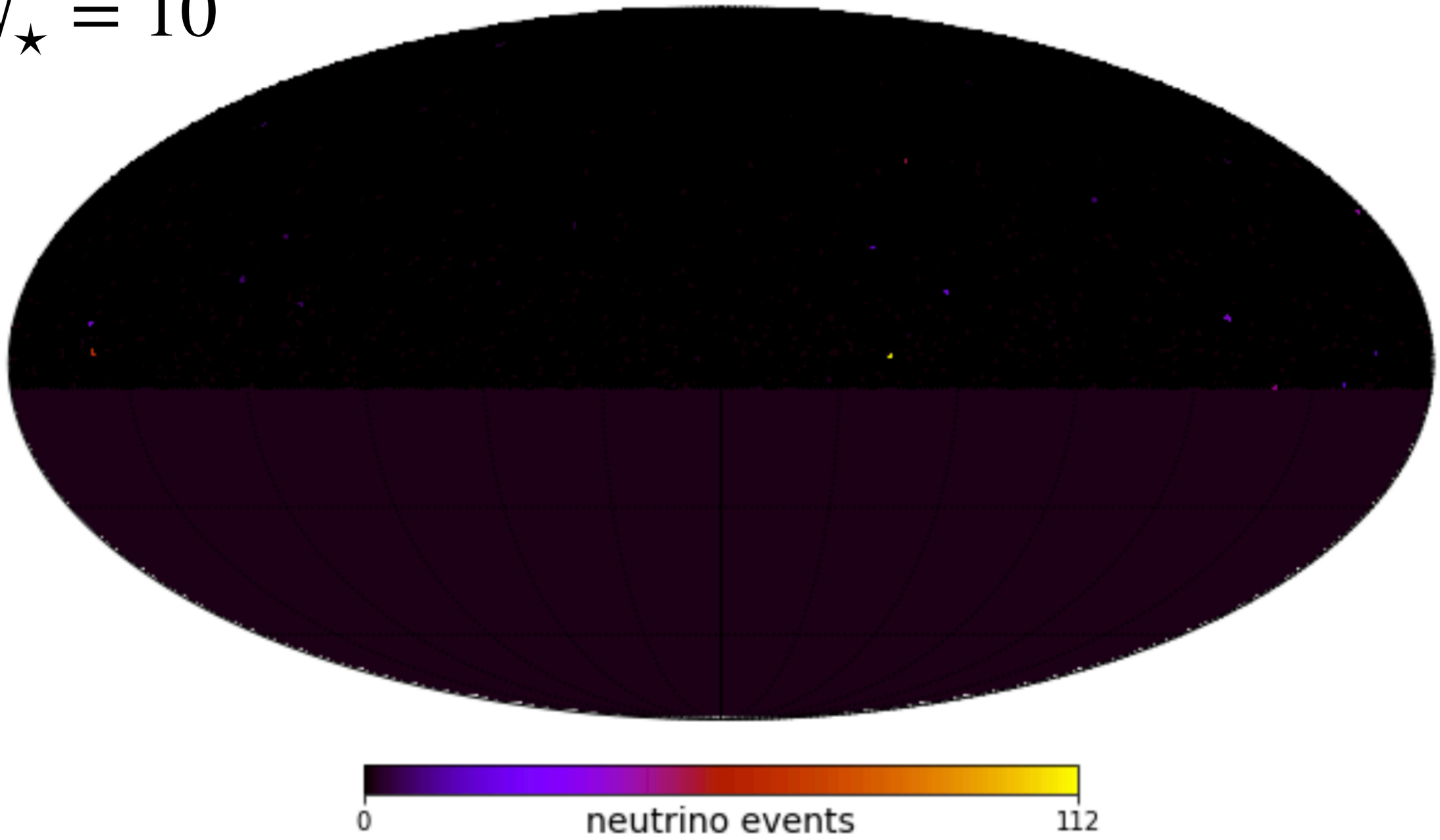


$$\left\langle (F - < F >)^2 \right\rangle$$

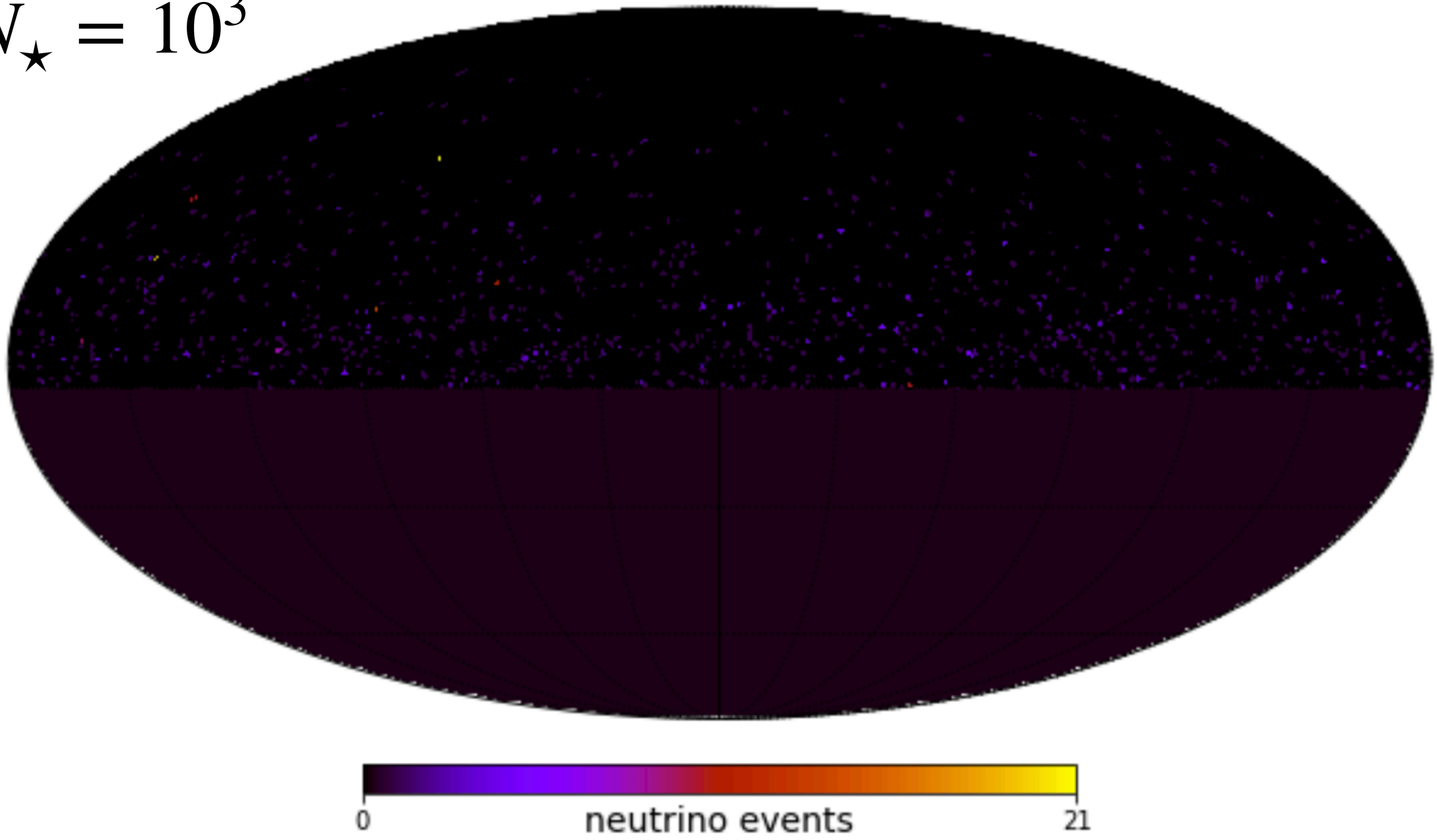
2nd moment

Angular Power Spectrum

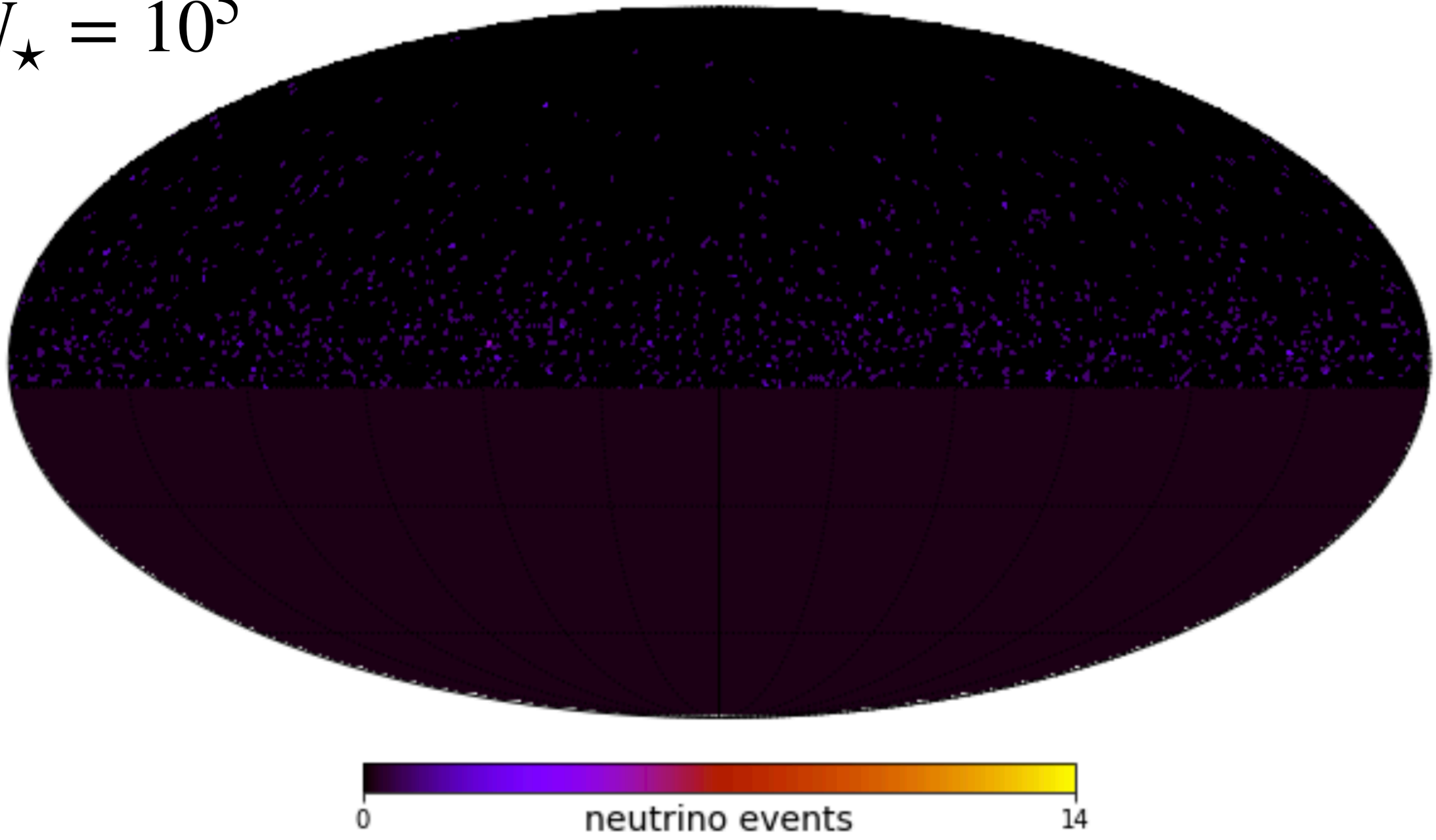
$N_\star = 10$



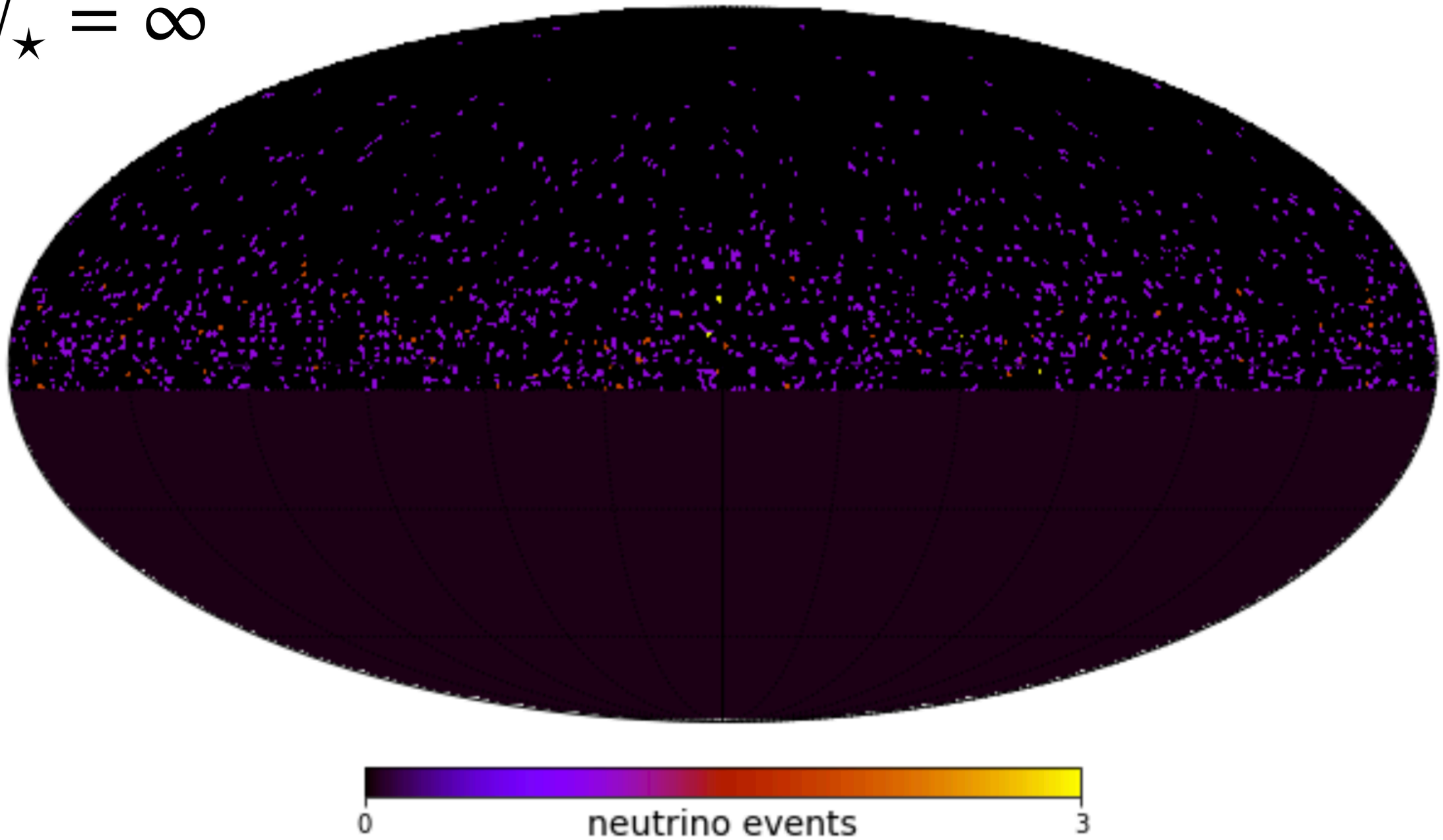
$N_\star = 10^3$



$N_\star = 10^5$



$N_\star = \infty$

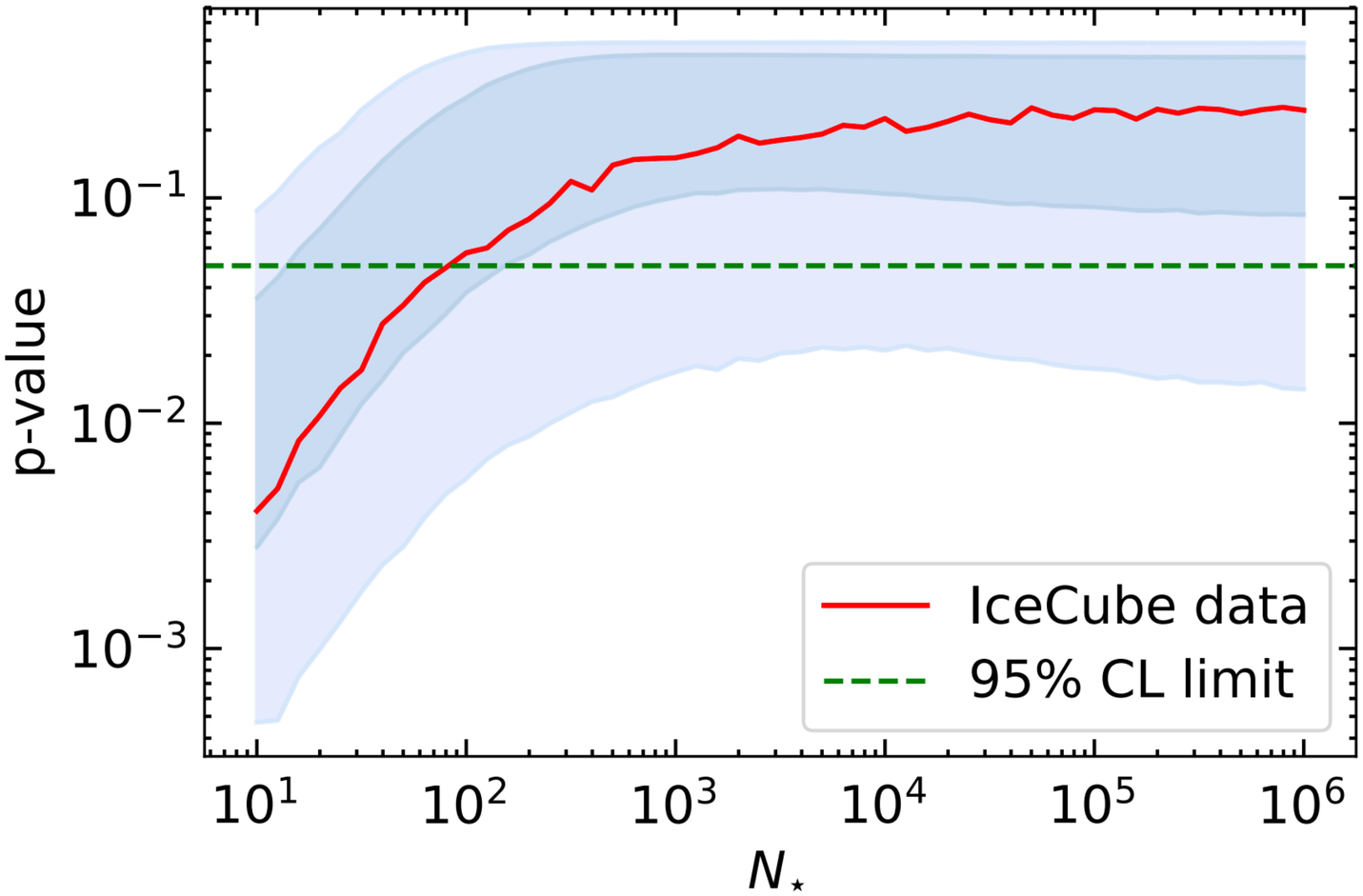


P-value 2-year IceCube

21 observed events

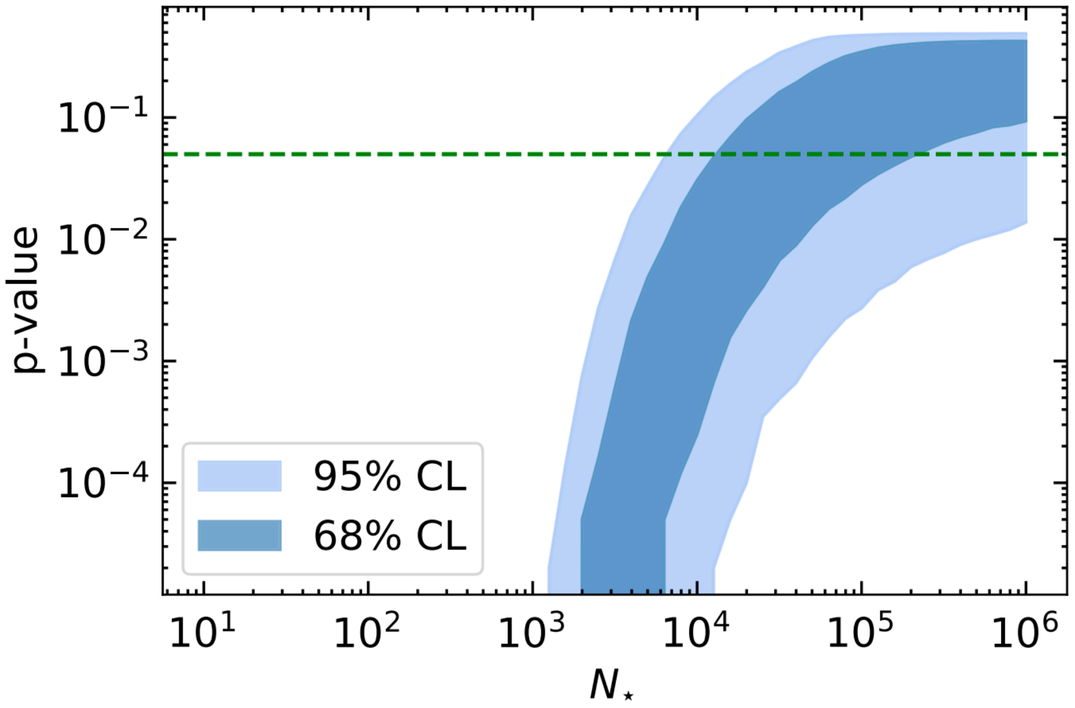
$E_\nu > 50\,\mathrm{TeV}$

$N_\star > 82$

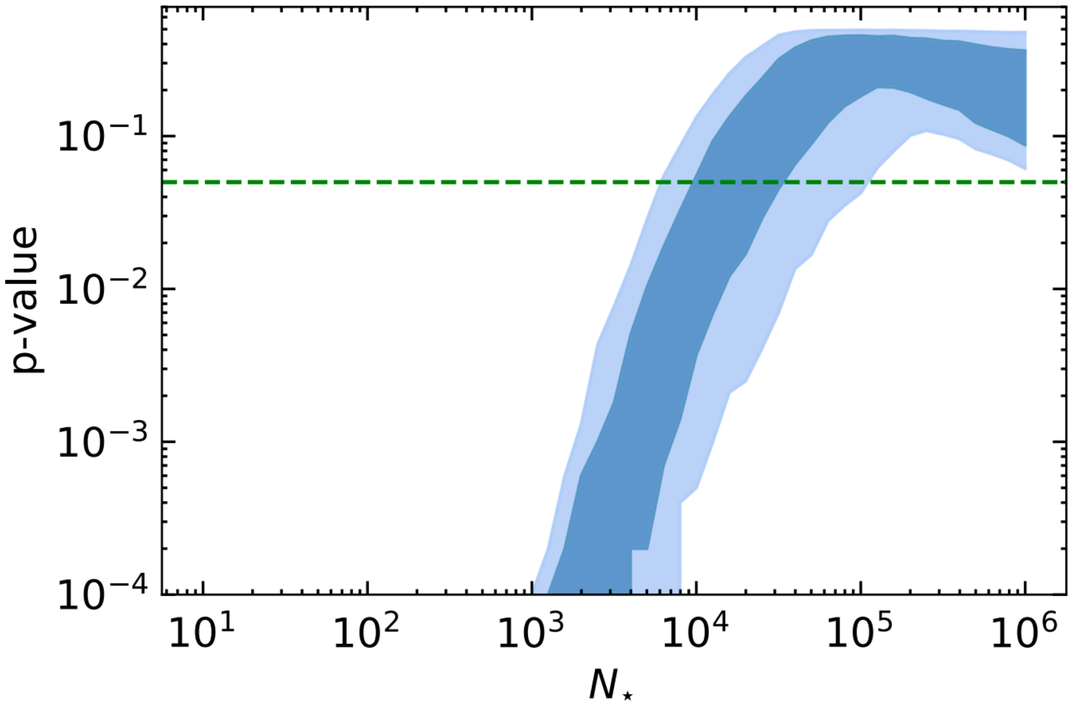


10-year exposure assuming $N_\star = \infty$

IceCube-Gen2



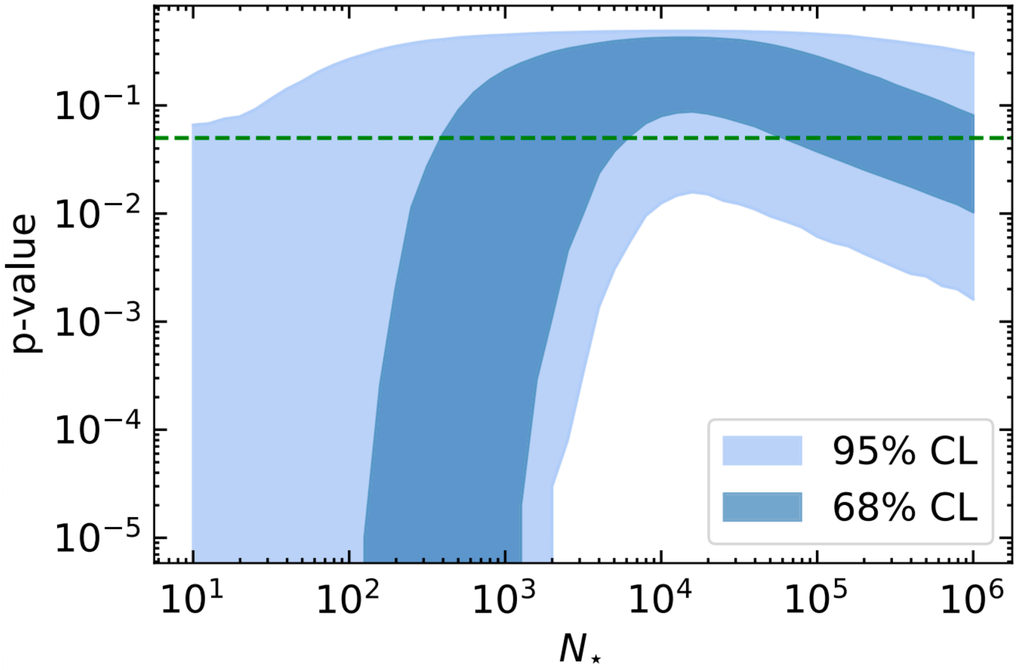
KM3NeT



$$\text{Blazars: } N_\star = 6 \cdot 10^2$$

10-year exposure assuming $N_\star = 10^4$

IceCube-Gen2



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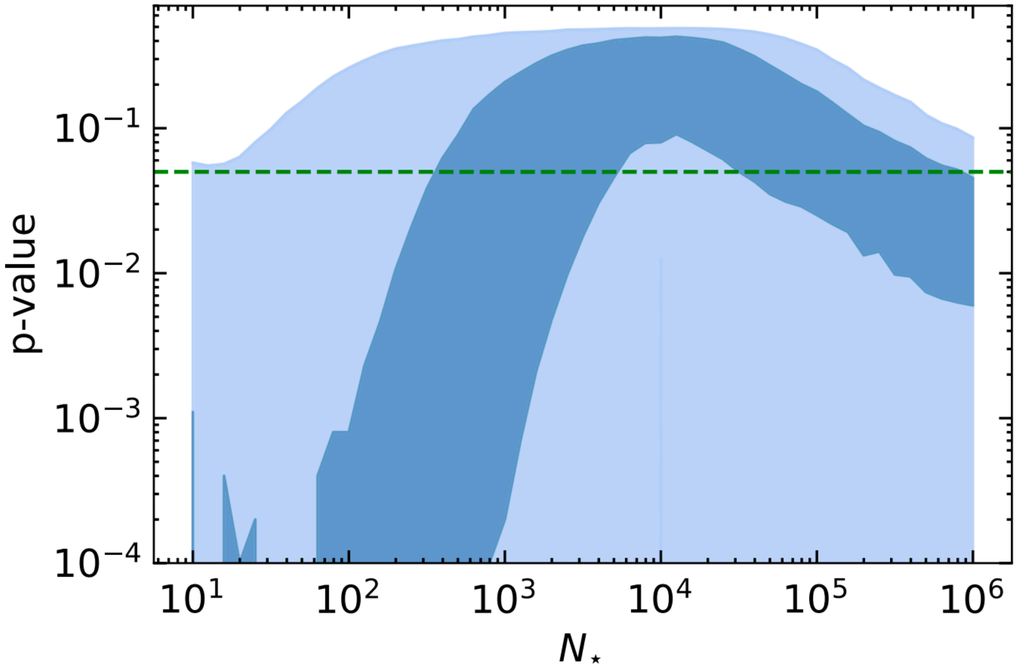

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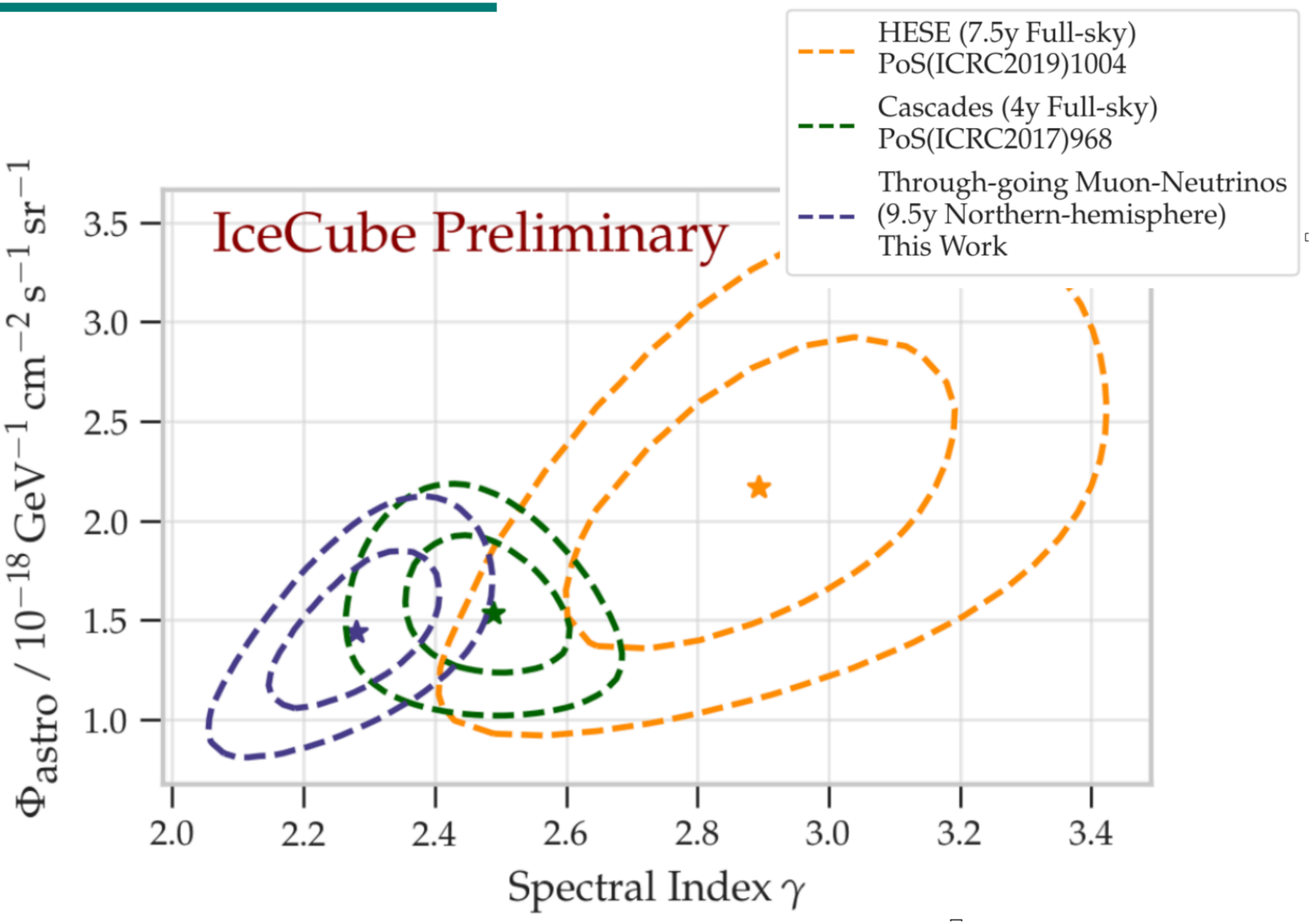
Heavy Dark Matter

J. Stettner, 2019

Heavy Dark Matter

- **Tension between HESE (full sky) and Through-Going (Northern hemisphere)**



J. Stettner, 2019

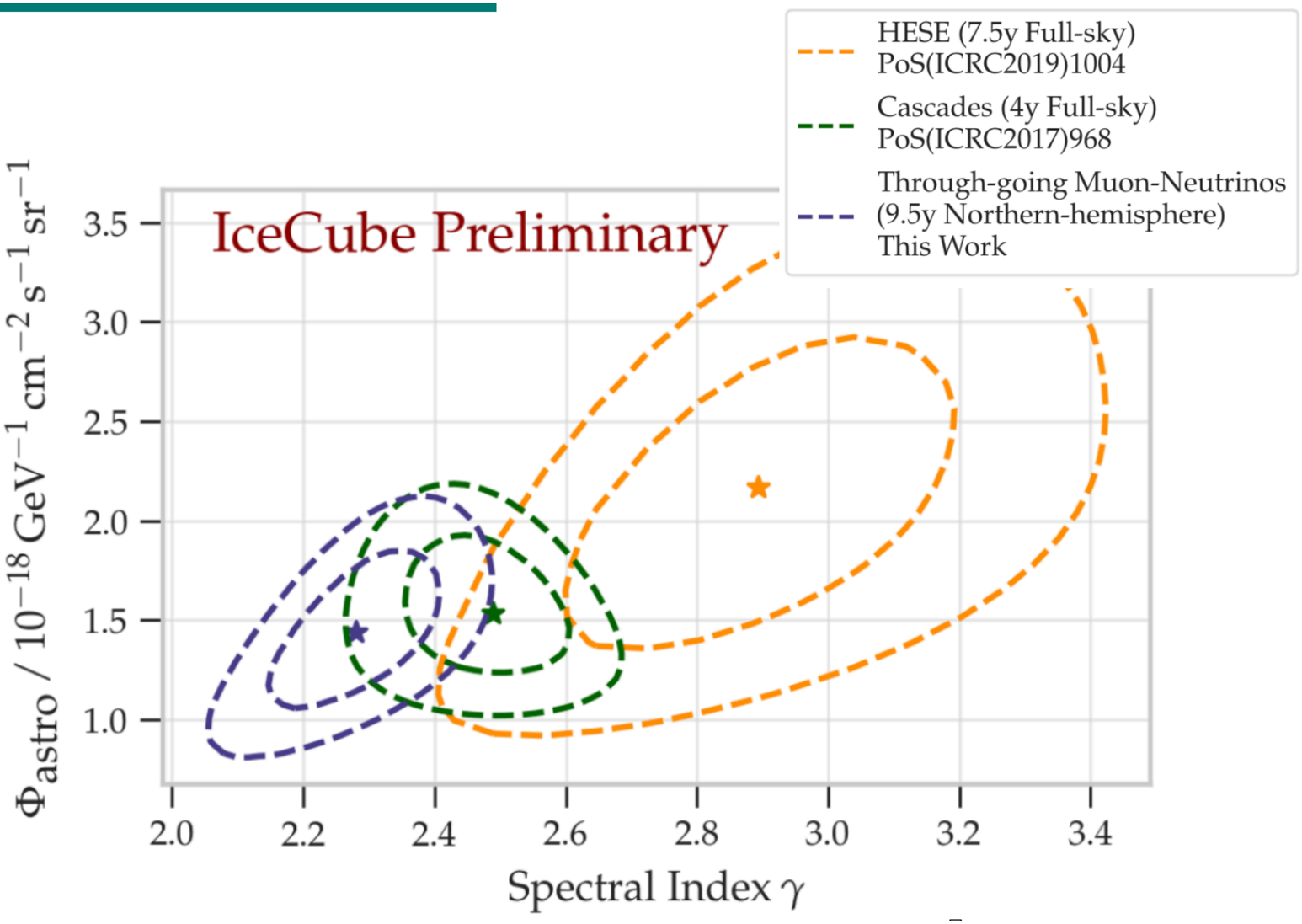
Heavy Dark Matter

- **Tension between HESE (full sky) and Through-Going (Northern hemisphere)**

- **HESE best-fit** $\gamma = 2.89$
- **1st order Fermi-acceleration** $\gamma = 2$
- **2nd order**

  p—p: $\gamma \lesssim 2.2$

- **Excess of events for single component (IC & ANTARES)**
- **2-component**



J. Stettner, 2019

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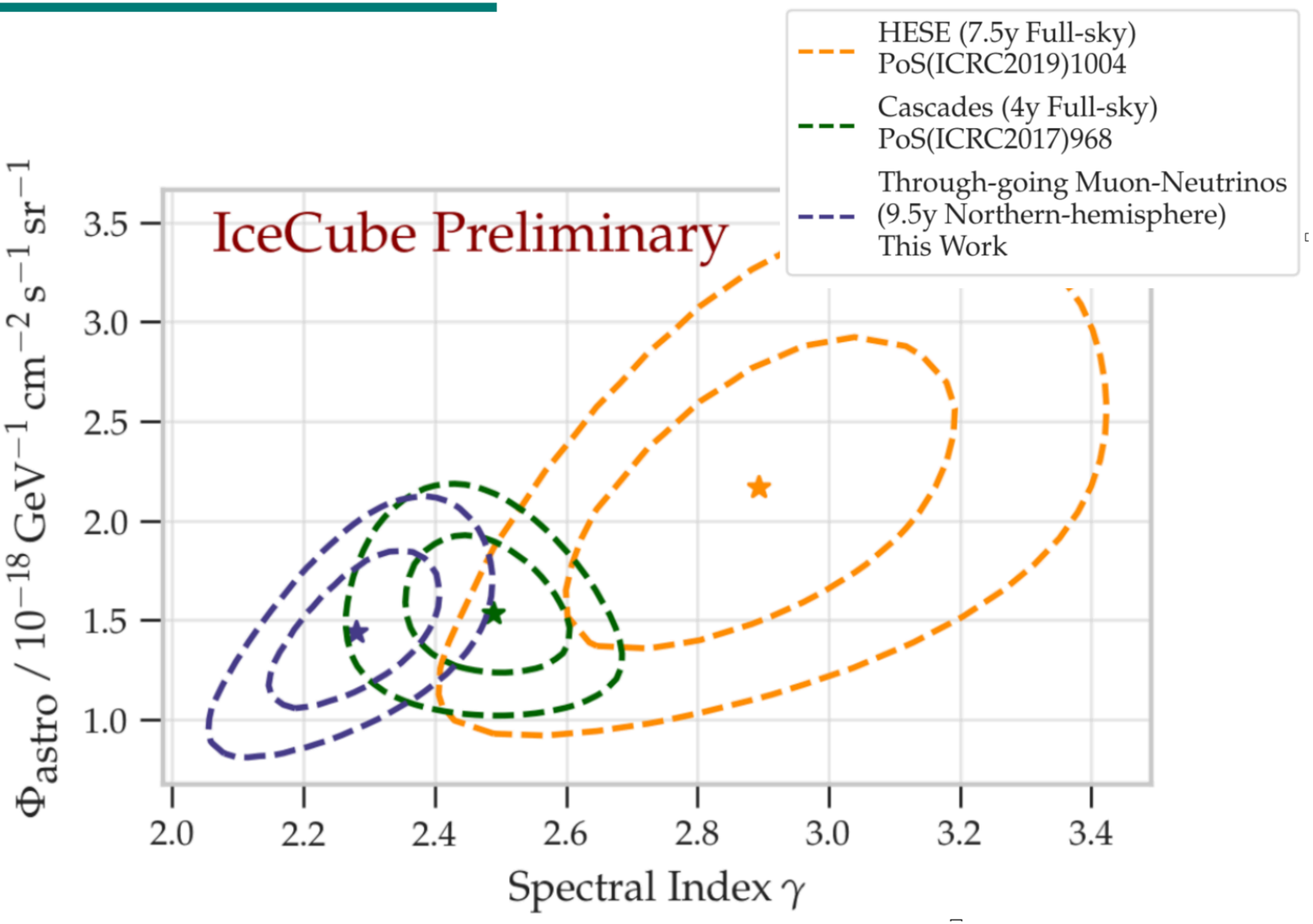
- **Excess of events for single component (IC & ANTARES)**
- **2-component**
- **DM contributing to Extra-Galactic and Galactic emission**
- **Cannot produce anisotropy -> constrain DM parameters**



J. Stettner, 2019

Null hypothesis

- **Isotropic astrophysical flux:** 7.5-yr HESE

$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE} = \frac{6.45}{3} \cdot \left(\frac{E}{100\mathrm{TeV}}\right)^{-2.89} \cdot 10^{-18}\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

Model

- **Isotropic astrophysical flux:** 10-yr Through-going

$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE} = 1.44 \cdot \left(\frac{E}{100\mathrm{TeV}}\right)^{-2.28} \cdot 10^{-18}\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

- **Dark matter flux**

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- **Dark matter flux**

Decay

NFW/isothermal

$\chi \to t\bar{t}$

$\chi \to \tau^+\tau^-$

$m_{\mathrm{DM}} = 400\,\mathrm{TeV}, 4\,\mathrm{PeV}$

Annihilation

NFW/isothermal

Clumpiness

$\chi\chi \to t\bar{t}$

$\chi\chi \to \tau^+\tau^-$

$m_{\mathrm{DM}} = 200\,\mathrm{TeV}, 2\,\mathrm{PeV}$

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- **Dark matter flux**

$$N_\nu^{tot} = \underbrace{N_\nu^{Astr} + N_\nu^{Atm} + N_\nu^{DM,EG}}_{\text{Isotropic}} + \underbrace{N_\nu^{DM,Gal}}_{\text{Anisotropic}}$$

P-value 6-year IceCube HESE

33 Observed events [60-200 TeV]

Model

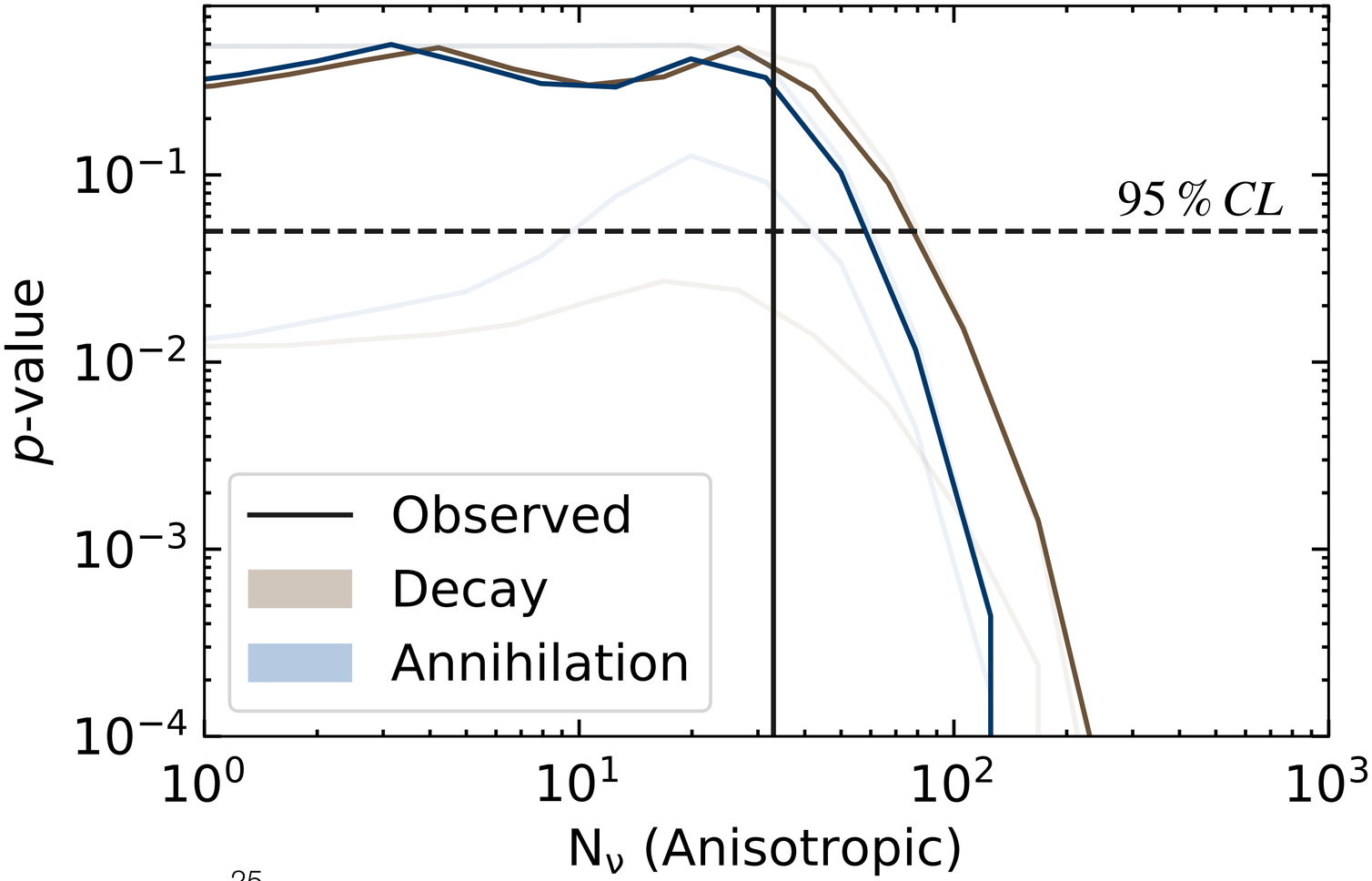
$\chi \to \tau^+\tau^-,\ m_{\rm DM} = 400\,{\rm TeV}$

$\chi\chi \to \tau^+\tau^-,\ m_{\rm DM} = 200\,{\rm TeV}$

NFW density profile

Free parameters:

Cross section & Lifetime



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NFW density profile

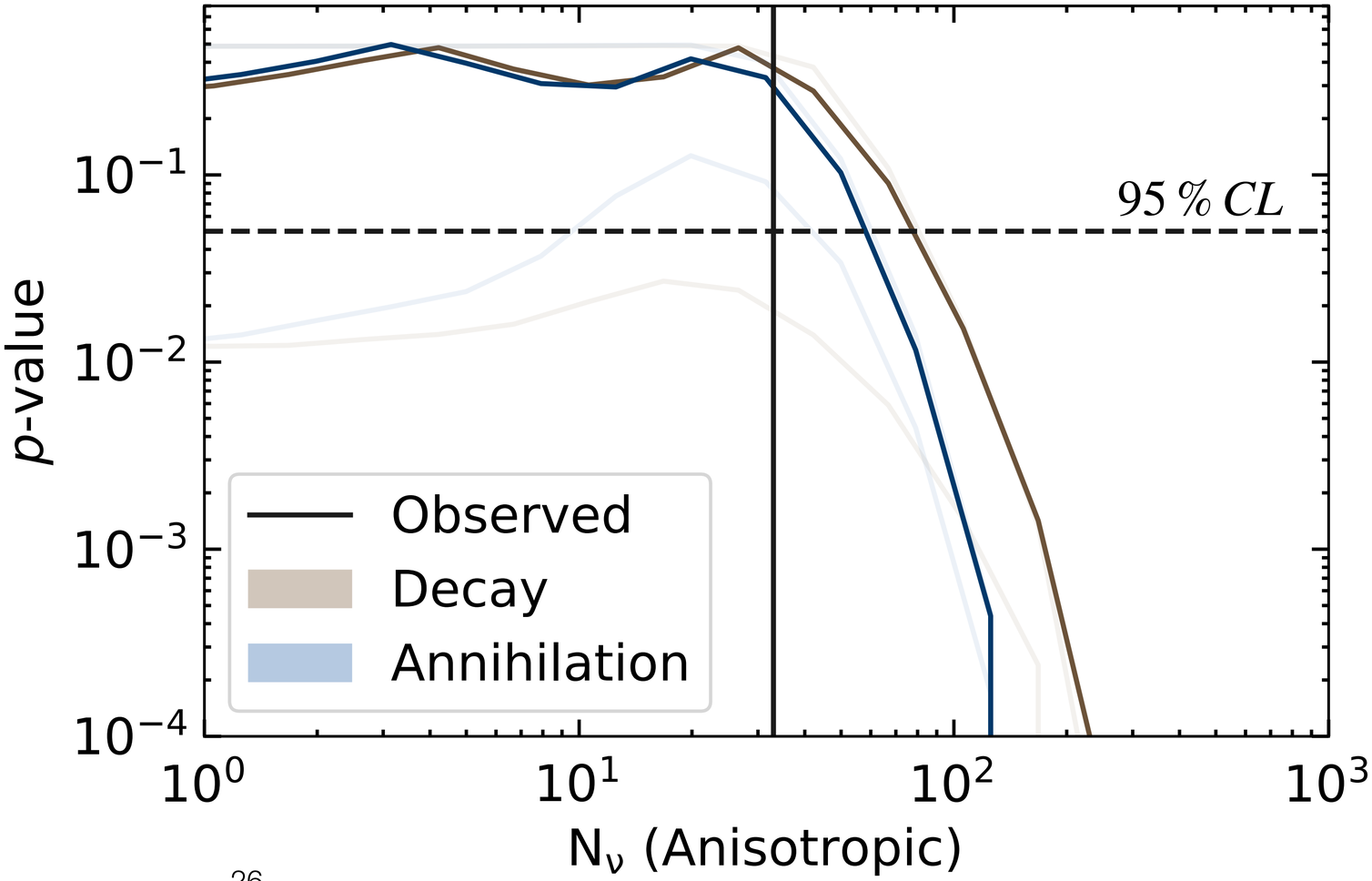
Constraints

$\tau_{\rm DM} = 4.7 \cdot 10^{28}$ [s]

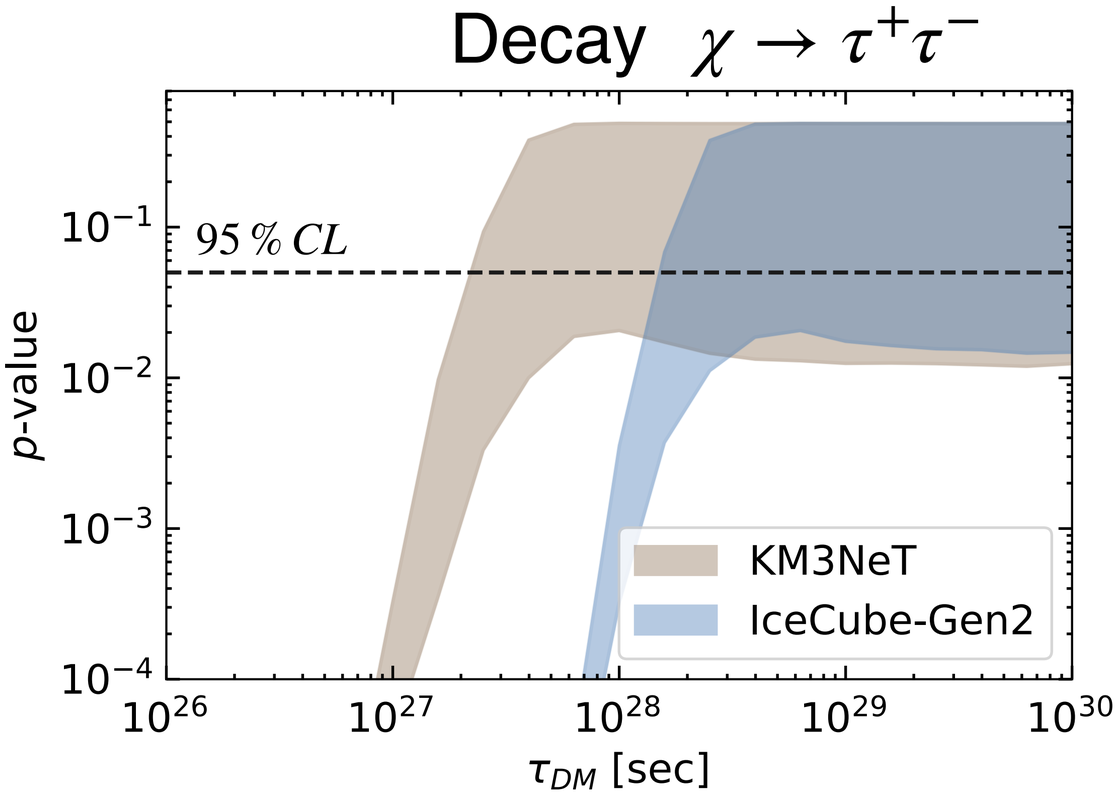
$< \sigma v > = 1.2 \cdot 10^{-22}$ [cm^3/s]

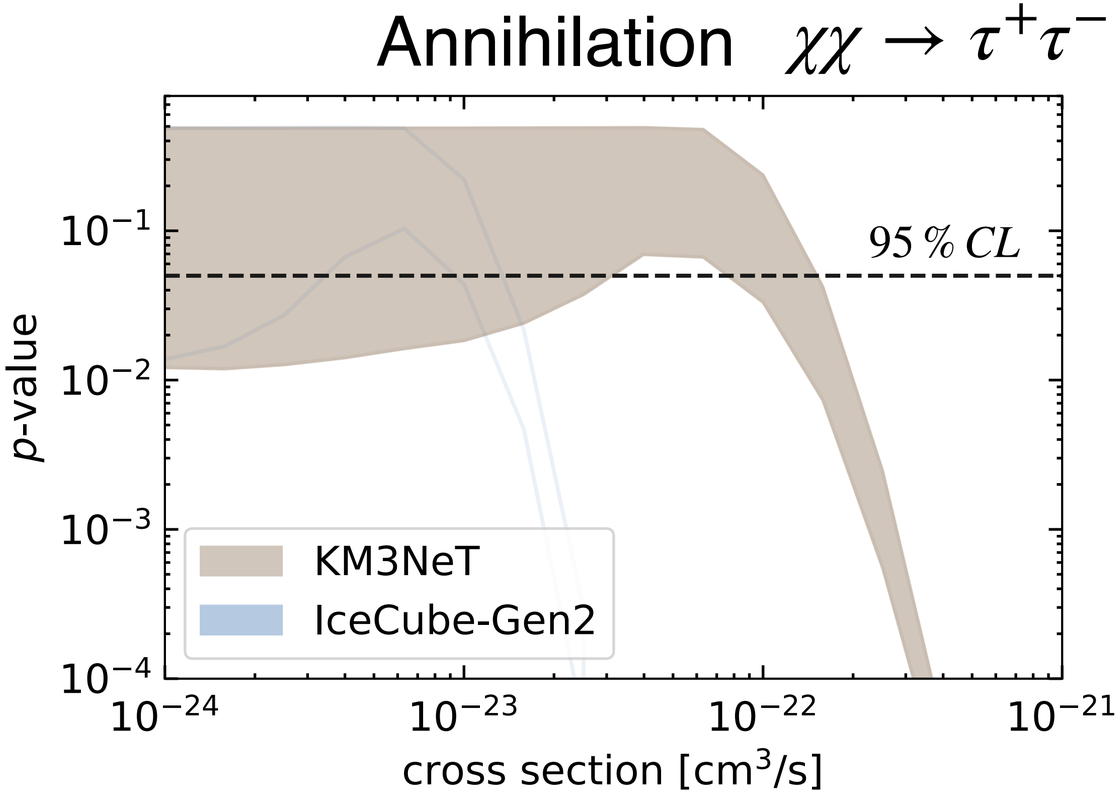
$N^{ann} \propto \rho^2$

$N^{dec} \propto \rho$

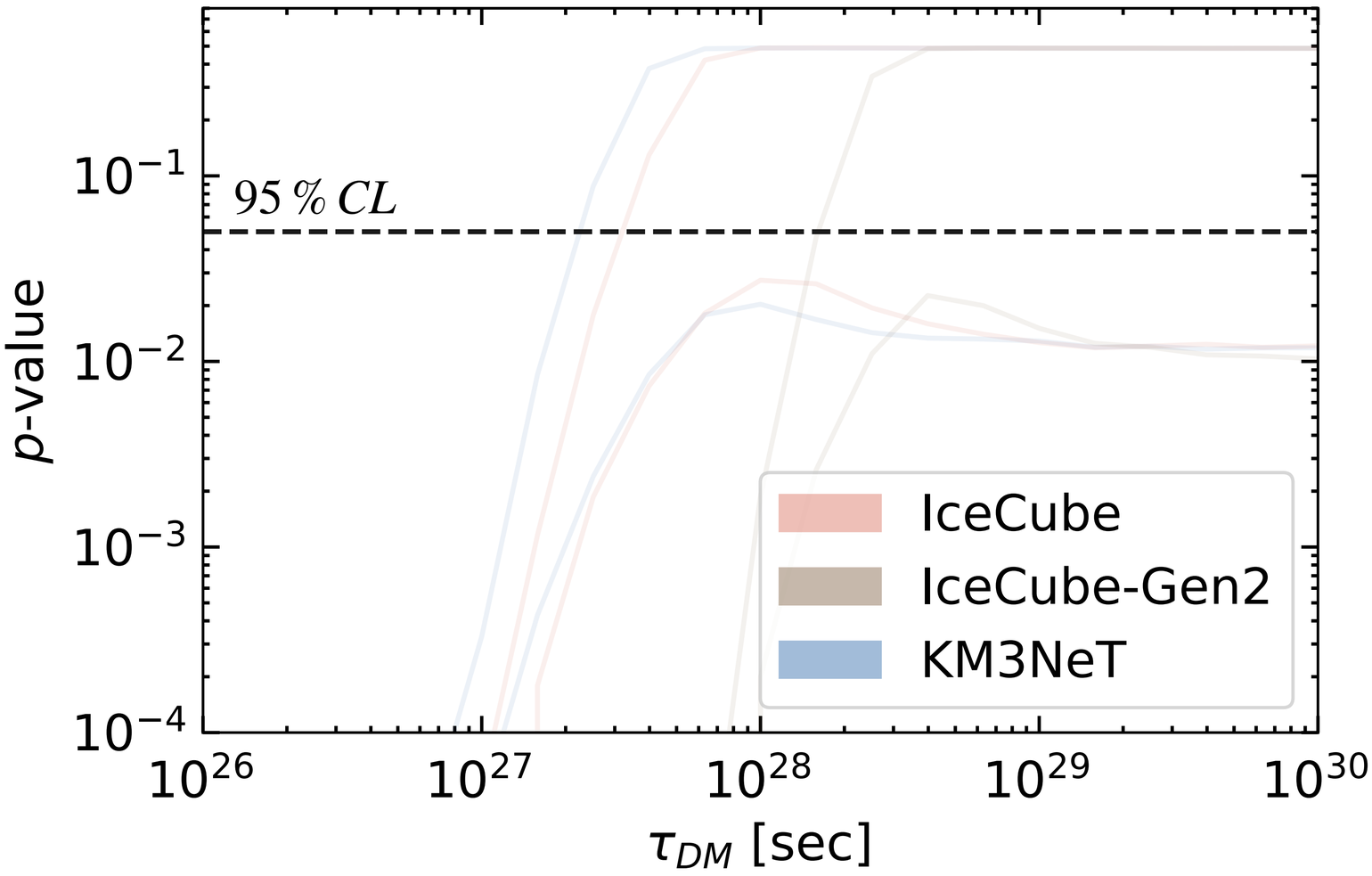


P-value 10-year IceCube-Gen2 and KM3NeT

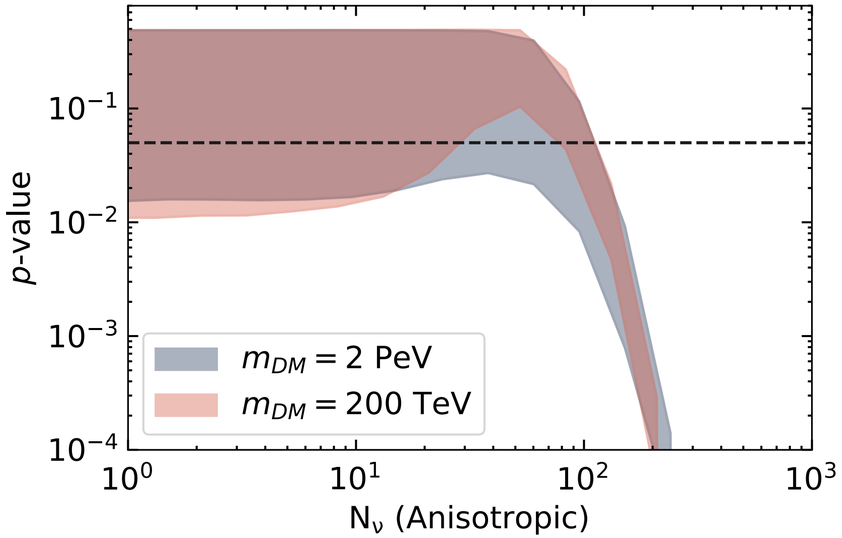


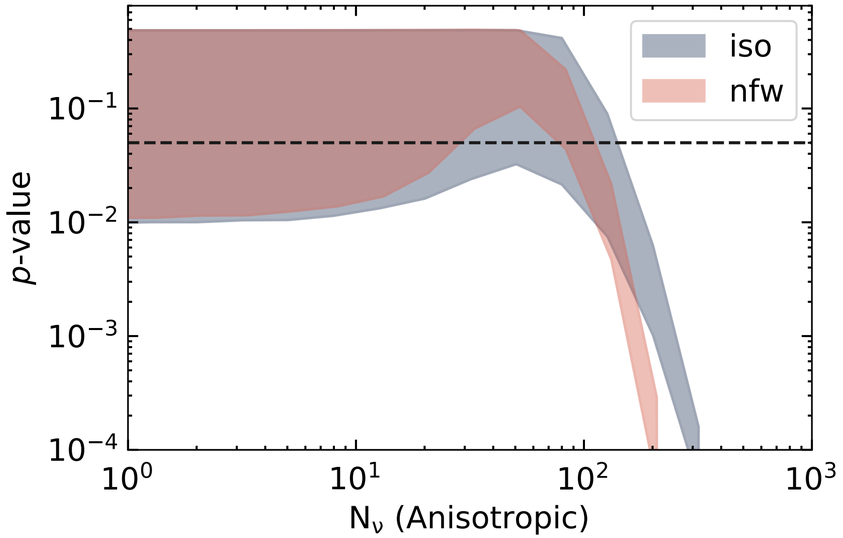


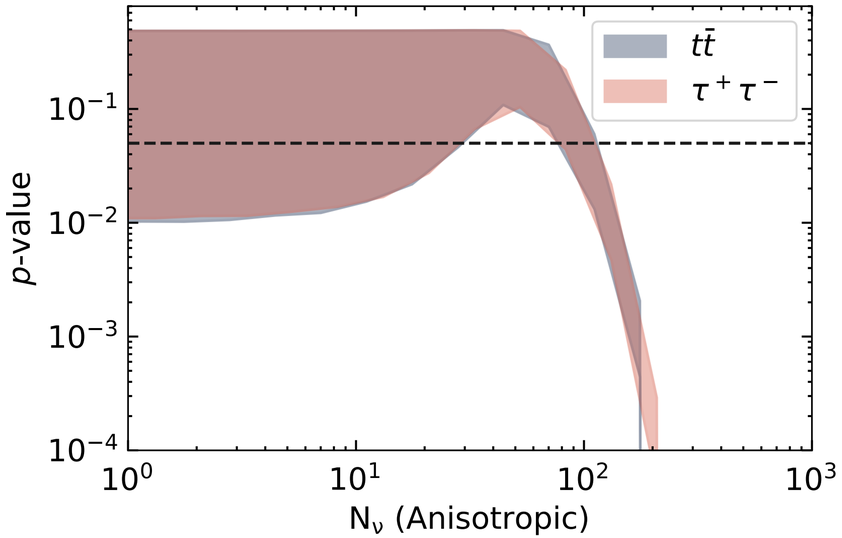
P-value 10-year IceCube-Gen2, IceCube, KM3NeT

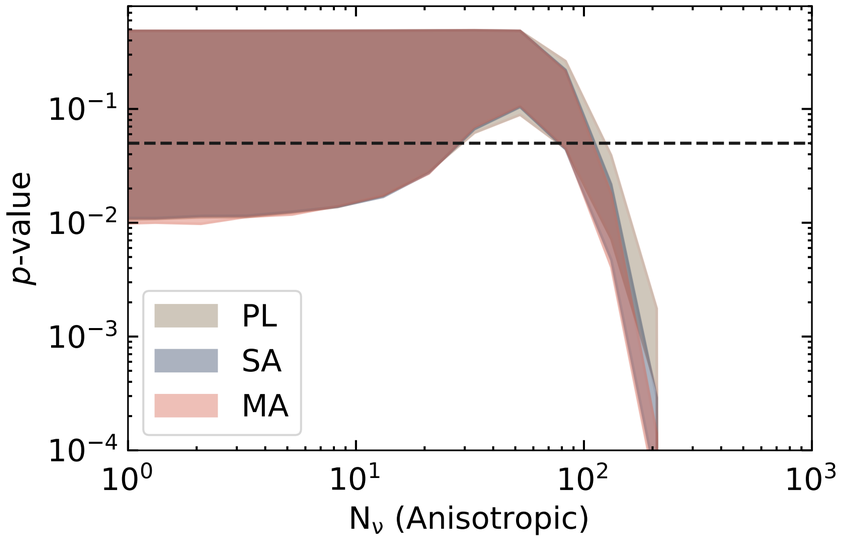


P-value 10-year IceCube-Gen2 Annihilation

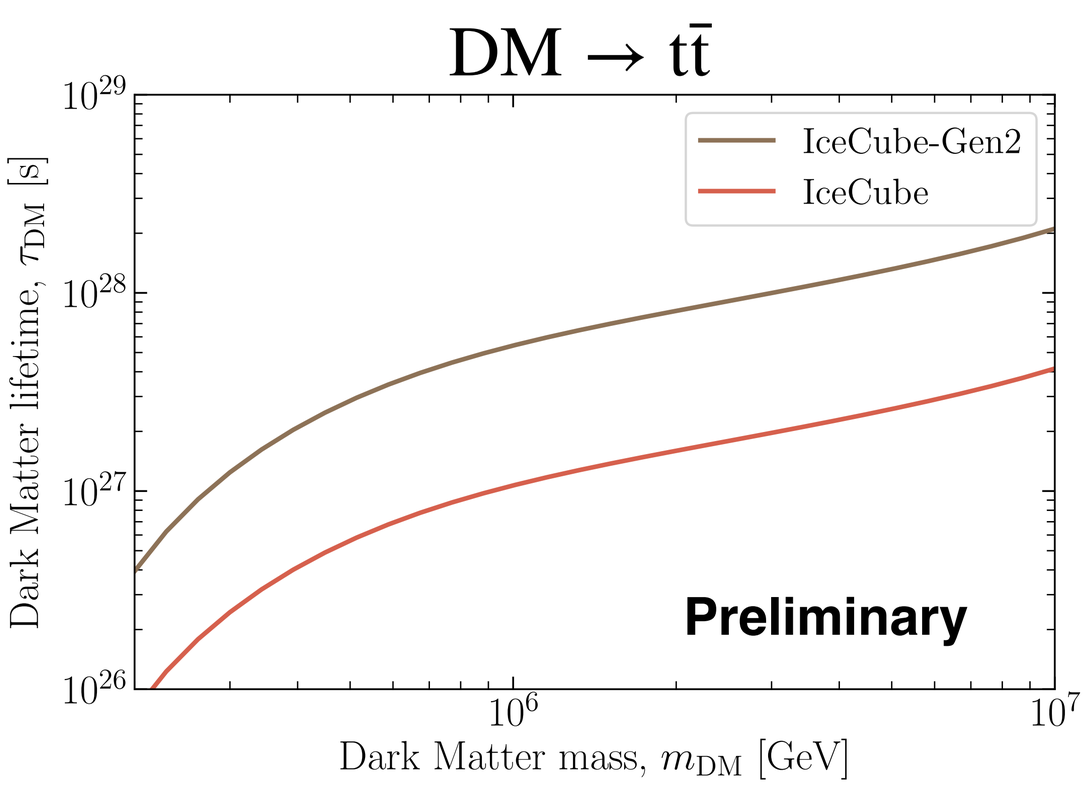


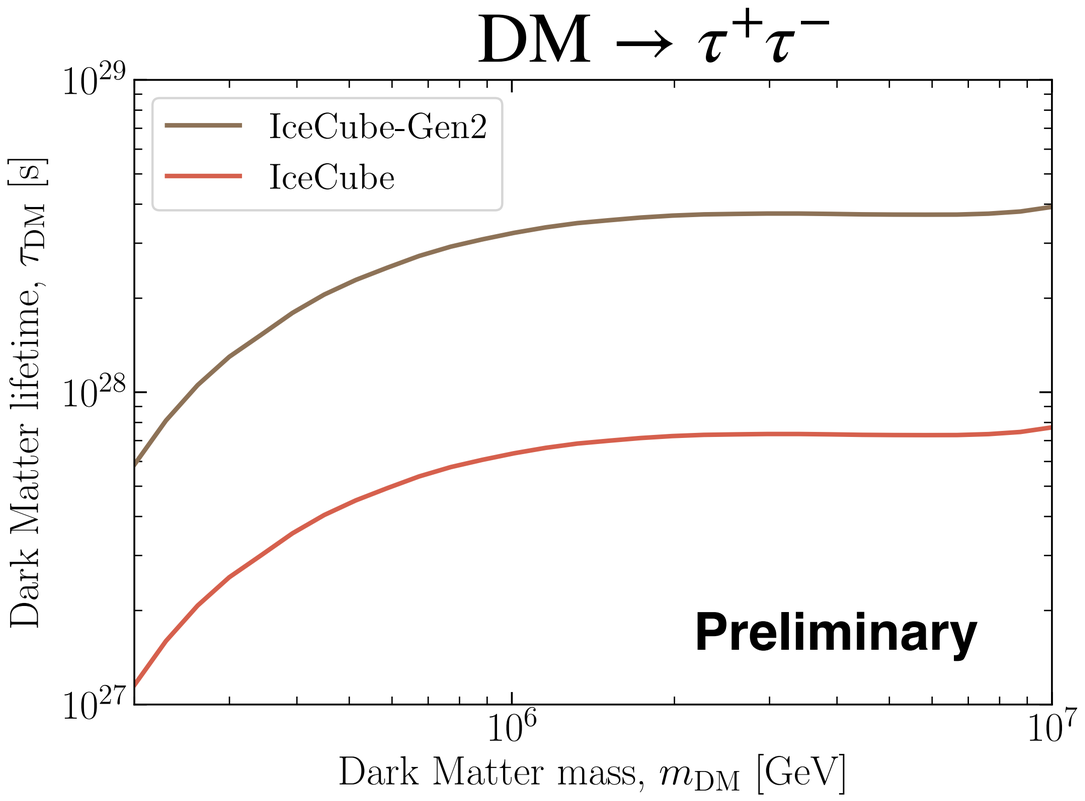






Decay constraints 10-yr IceCube-Gen2, IceCube





Summary

- Angular Power Spectrum powerful probe
- 2-year of IceCube data with 21 events already constrains $N_\star > 82$
- With 10-yr IceCube-Gen2 & KM3NeT exposure we can constrain bright sources
- The tension between HESE and Through-Going datasets
- Constrain DM parameters using IceCube HESE and TG KM3NeT exposure

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Thank you for your attention

Backup slides

Source-flux distribution

Olber's paradox

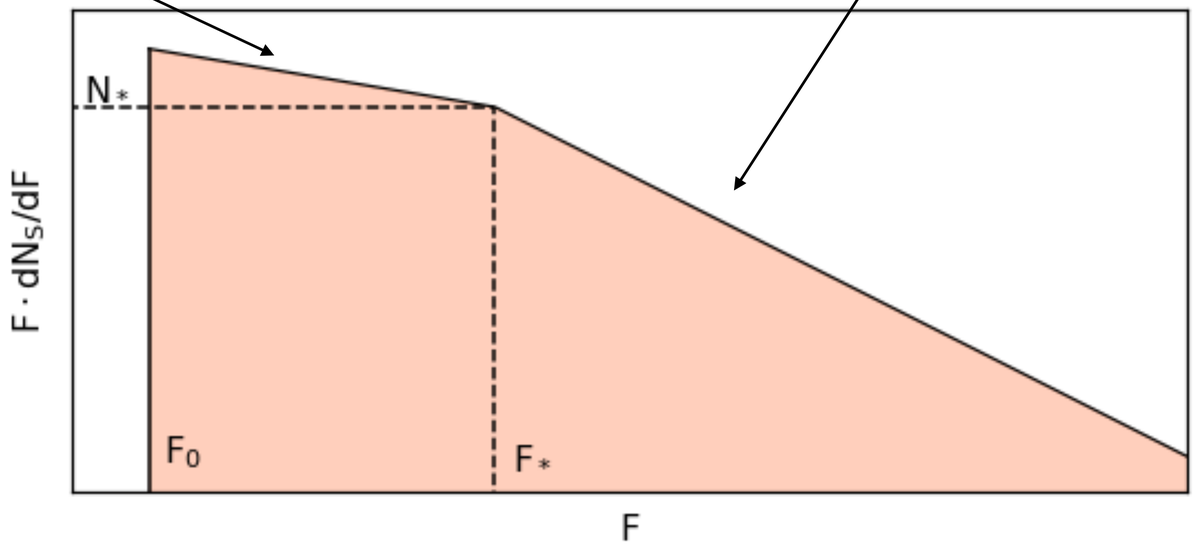
$$\beta = 1.5$$

Homogeneous Univers, Euclidean space

$$F = \frac{L}{4\pi r^2},\ \rho = \frac{N}{V}$$

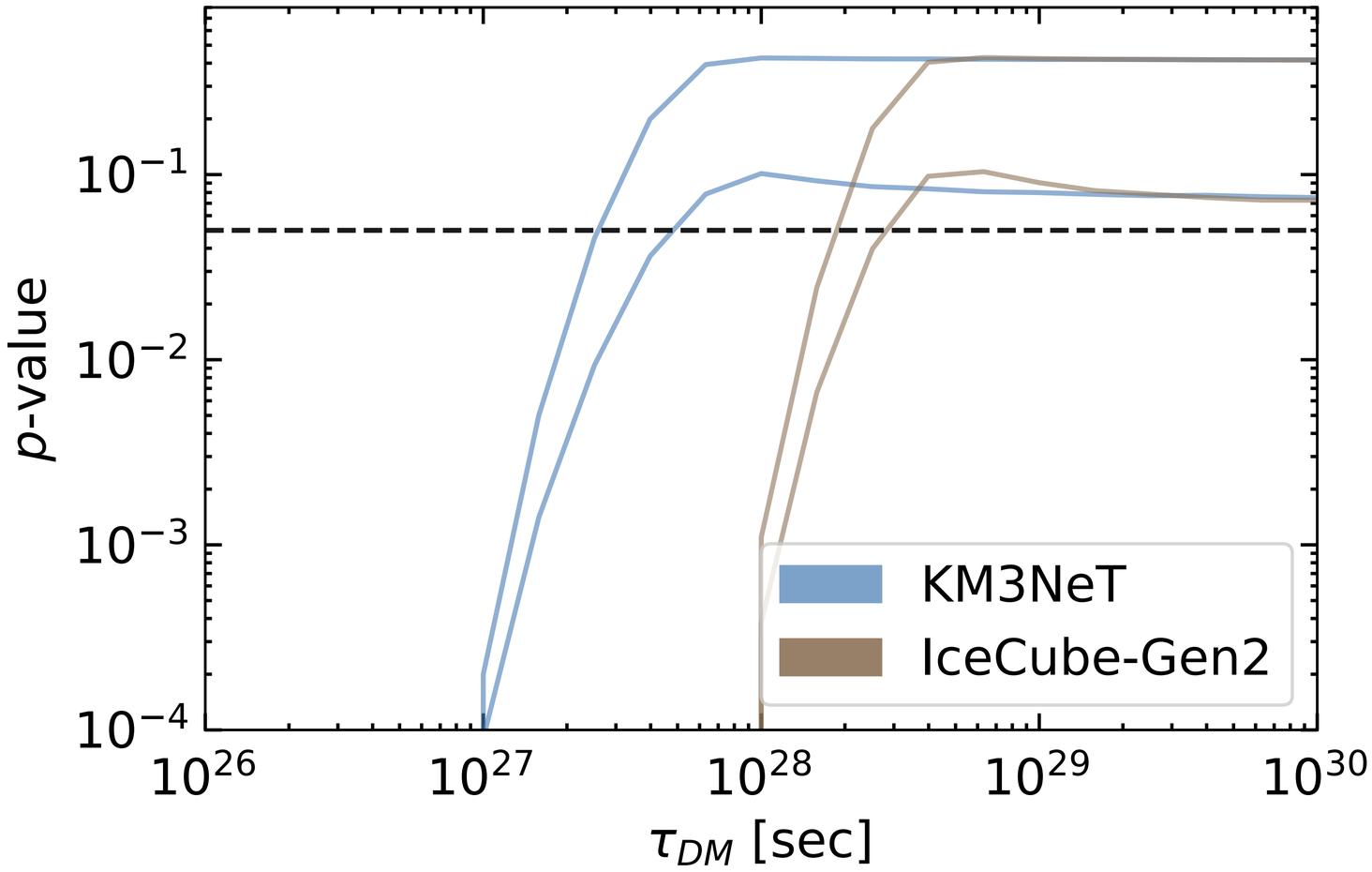
$$\frac{d\mathrm{N}}{d\mathrm{F}} = \frac{d\mathrm{N}}{d\mathrm{r}}\frac{d\mathrm{r}}{d\mathrm{F}} = F^{-5/2}$$

$$\alpha = 2.5$$

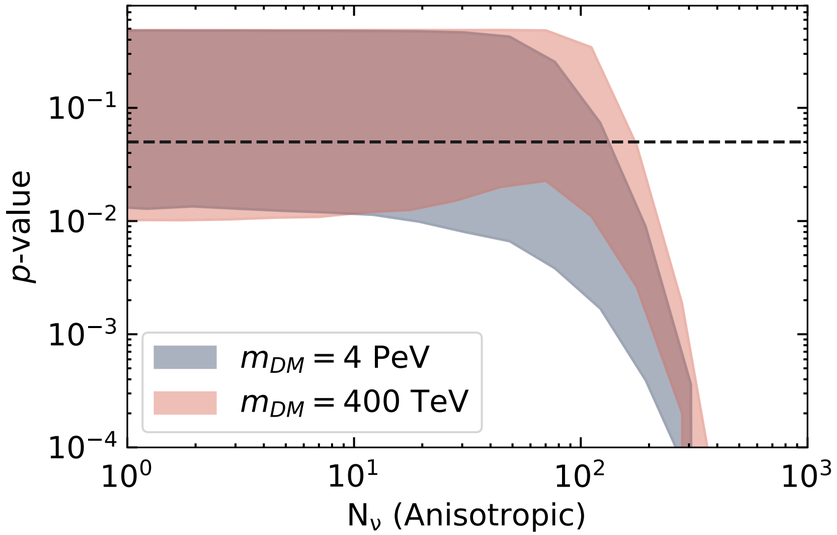


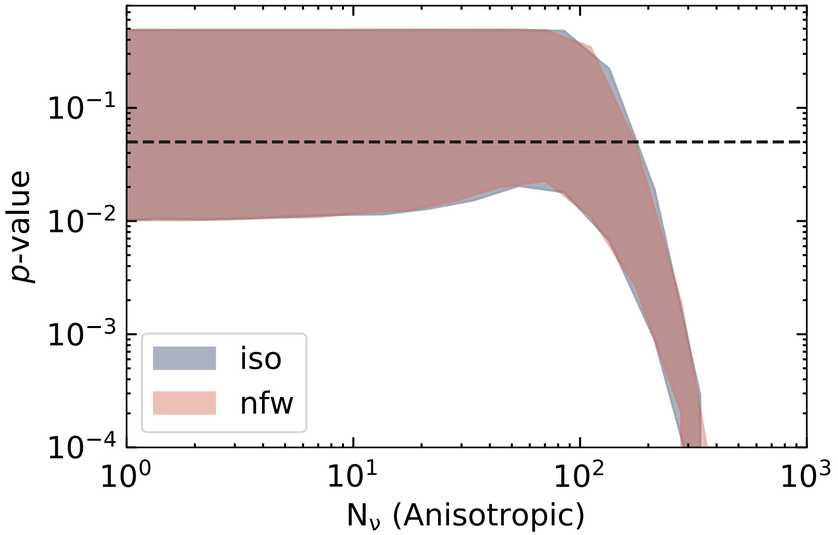
$$\frac{d\mathrm{N_s}}{d\mathrm{F}} \propto \begin{cases} F^{-\alpha} & F_\star < F \\ F^{-\beta} & F_0 < F < F_\star \end{cases}$$

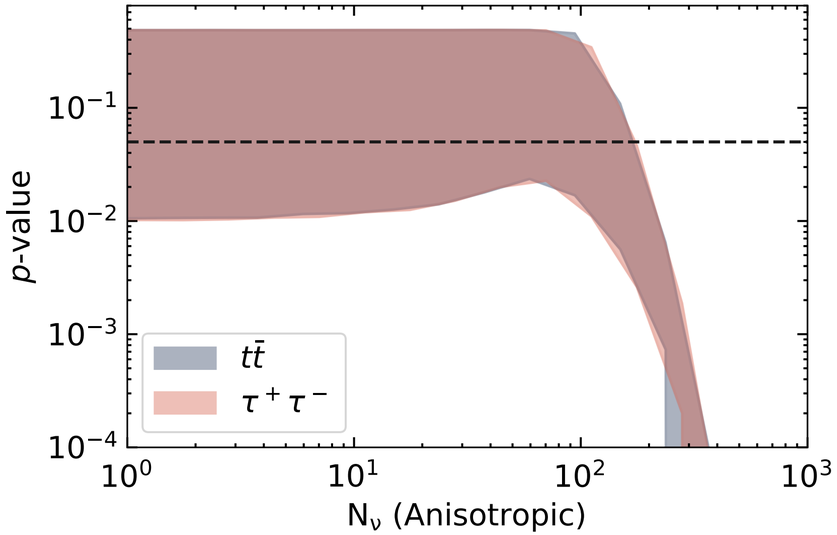
P-value 10-year IceCube-Gen2,KM3NeT

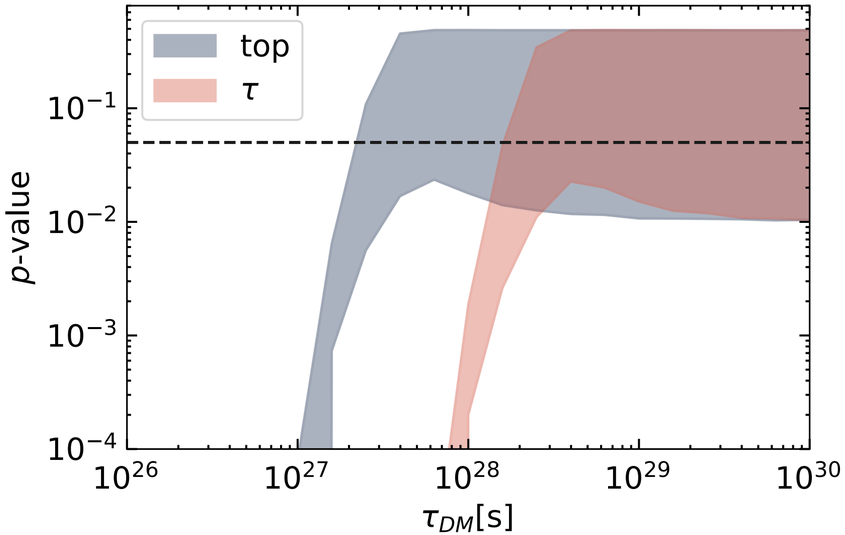


P-value 10-year IceCube-Gen2 Decay



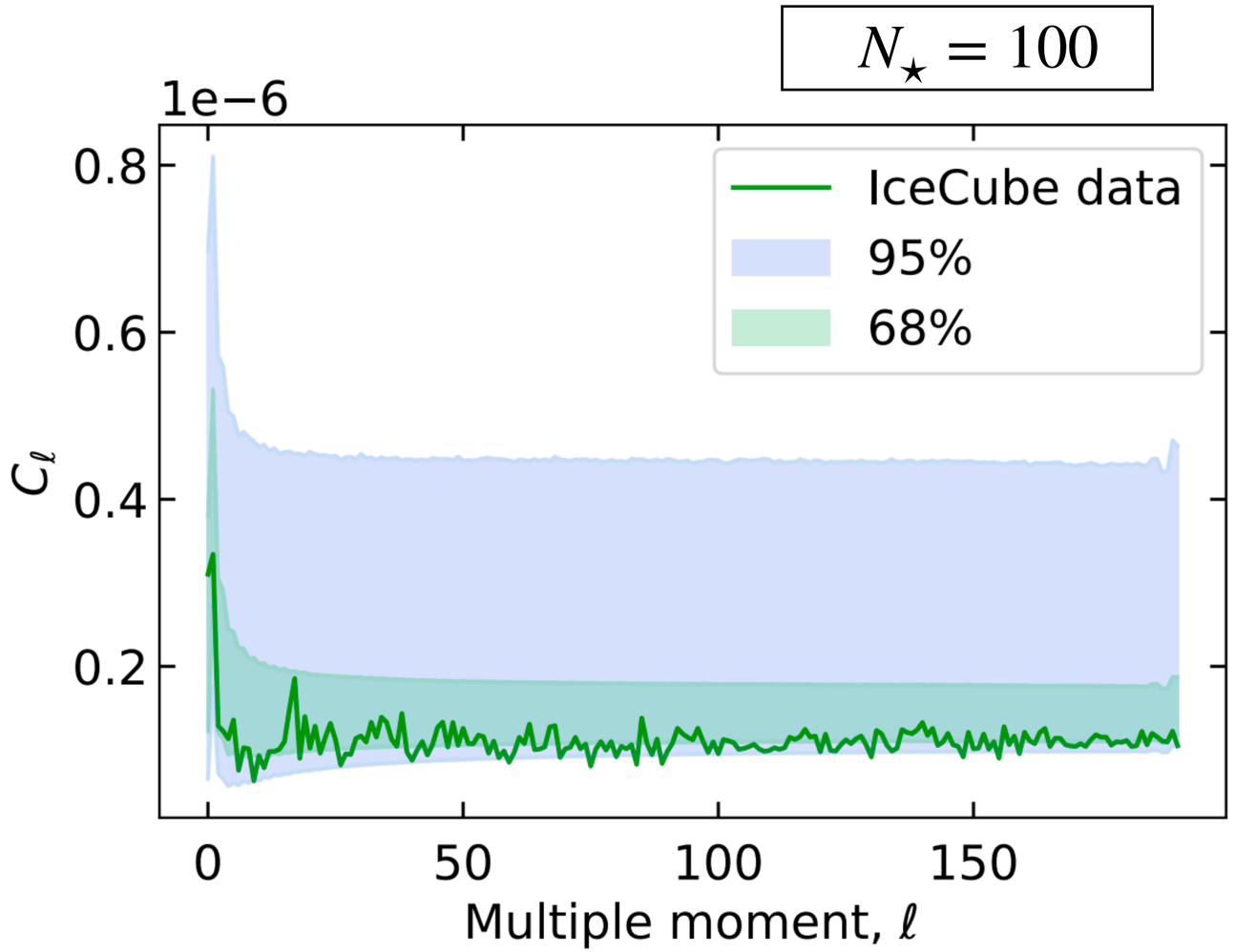




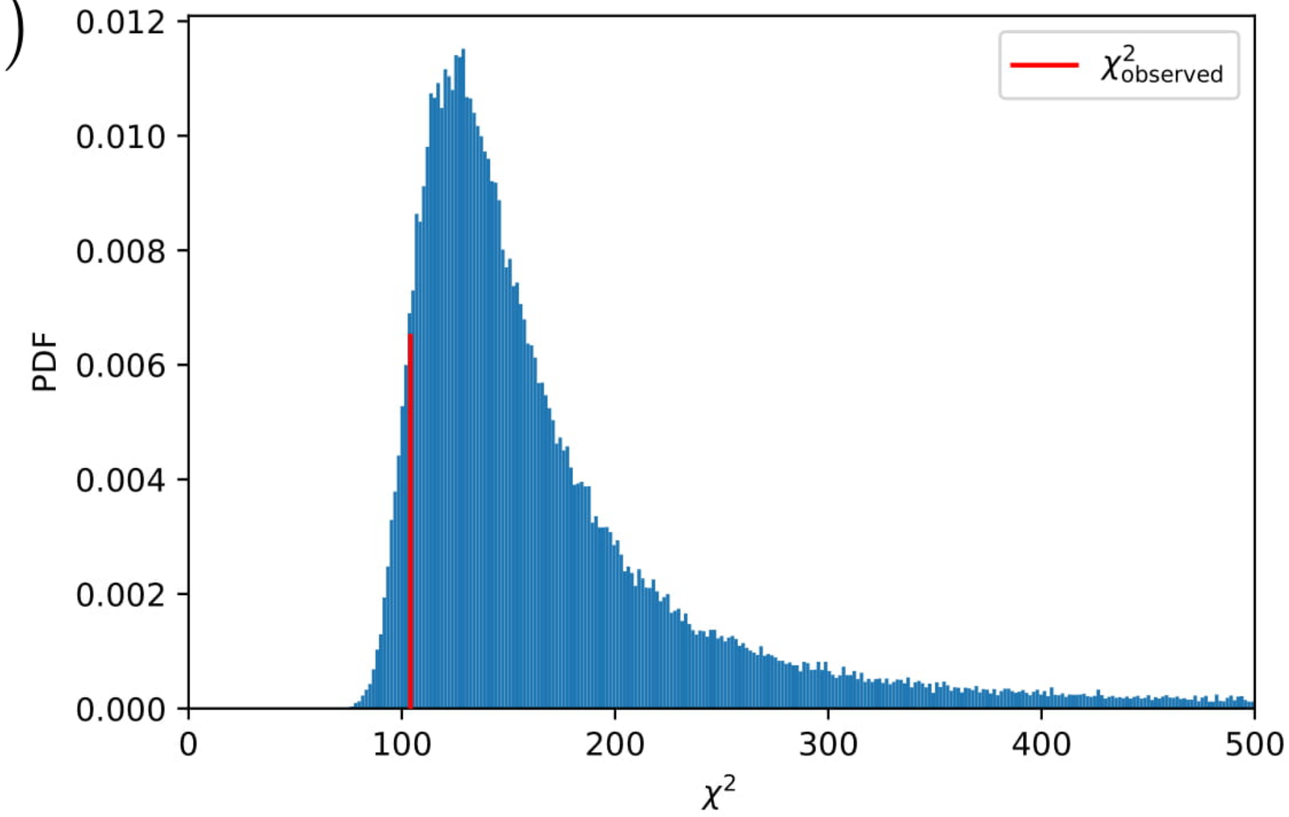


Angular power spectrum

$$C_l = \frac{1}{2l+1} \sum_m |a_l^m|^2$$



Analysis

$$\chi^2(C_l) = \sum_l (C_l - C_l^{\mathrm{mean}})^{\mathrm{T}} \mathrm{cov}^{-1} (\mathrm{C_l} - \mathrm{C_l^{mean}})$$

$$\mathrm{p-value} = \mathrm{CDF}\left(\langle \chi^2 \rangle - \langle \chi^2_{\mathrm{observed}} \rangle\right)$$