

Ultra-High-Energy Neutrino Anomaly across ANITA-IV, KM3NeT, and IceCube

Dibya S. Chattopadhyay, Oklahoma State University

Based on:

arXiv:2502.21299, Phys. Rev. Lett. **136**, 081001 [V. Brdar, D. S. Chattopadhyay]

arXiv:2607.19487, “*Four, One, and None: Quantifying the Ultra-High-Energy Neutrino Anomaly Across ANITA-IV, KM3NeT, and IceCube*” [C. Argüelles, V. Brdar, D. S. Chattopadhyay]

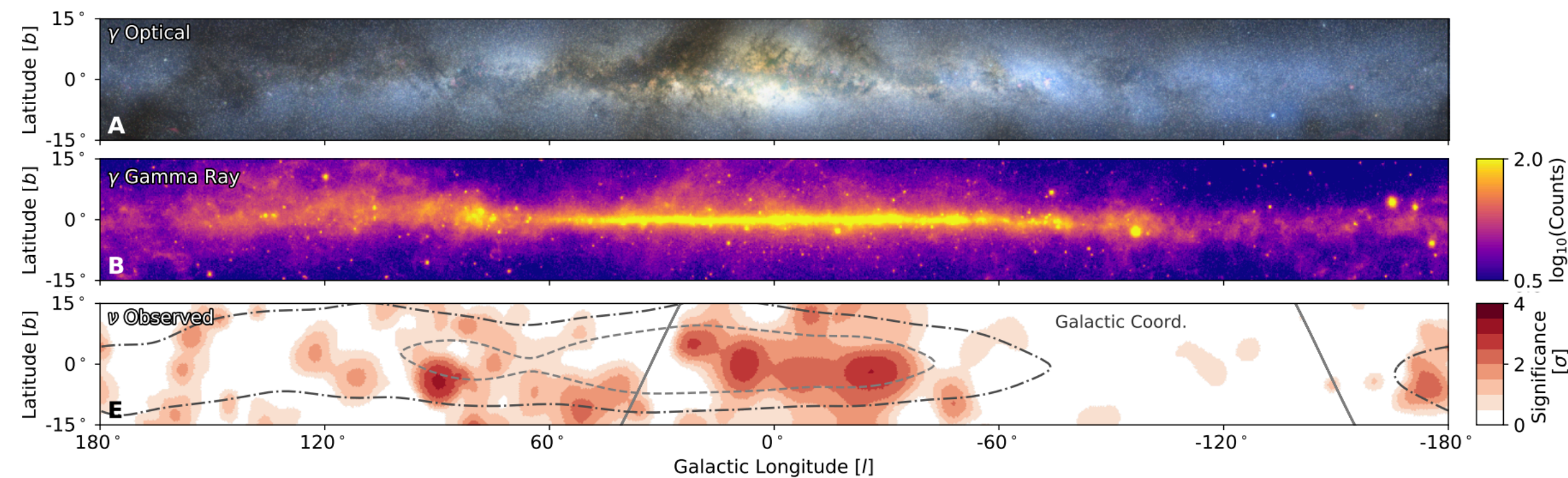
 **CETUP* 2026, Lead/Deadwood Middle School, SD**

7 July, 2026



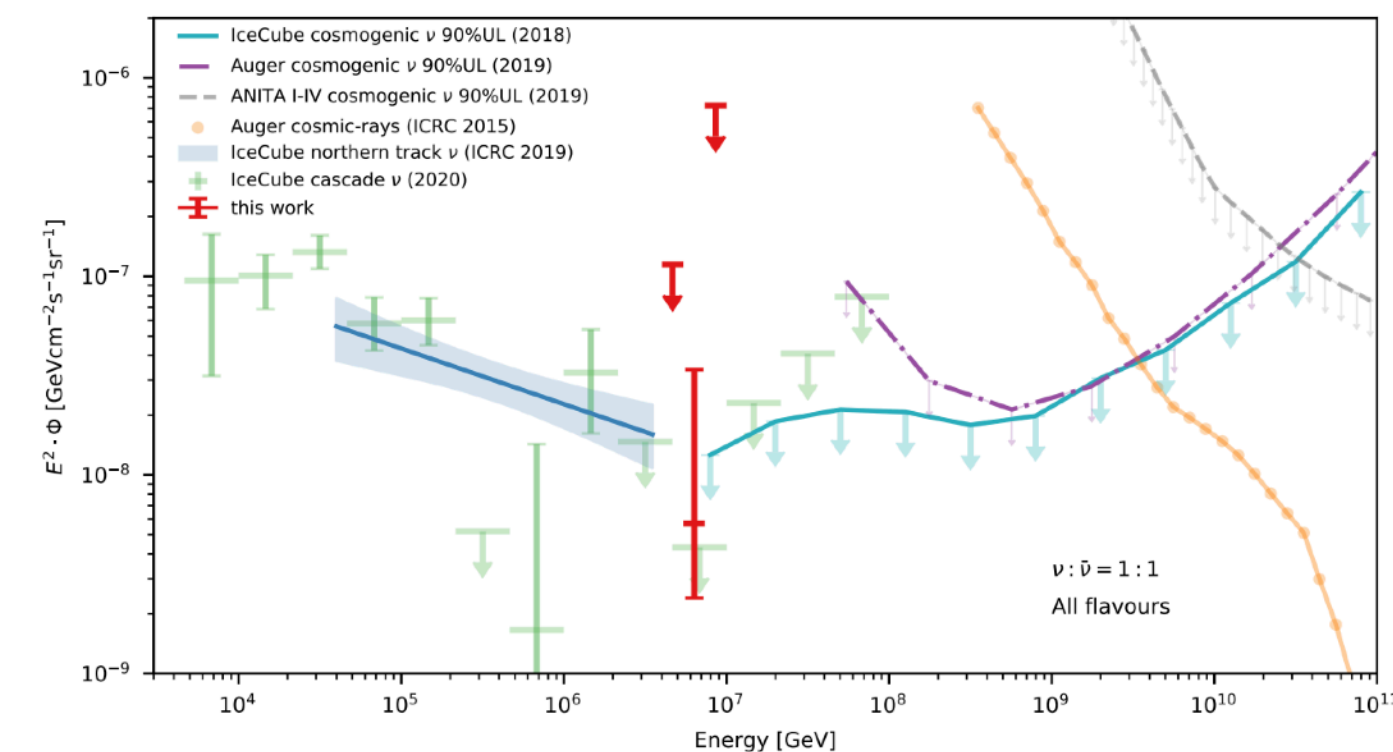
Ultra-high-energy neutrino astronomy...

- High energy neutrino astronomy with energies above 0.1 PeV, from 2013 at the **IceCube** detector, Antarctica.
- Including observation of a **Glashow Resonance** event (6.05 ± 0.72 PeV)
- **Milky Way** observed in neutrinos, neutrinos from **distant blazars** detected...
- ANTARES → **KM3NeT** (ARCA + ORCA)

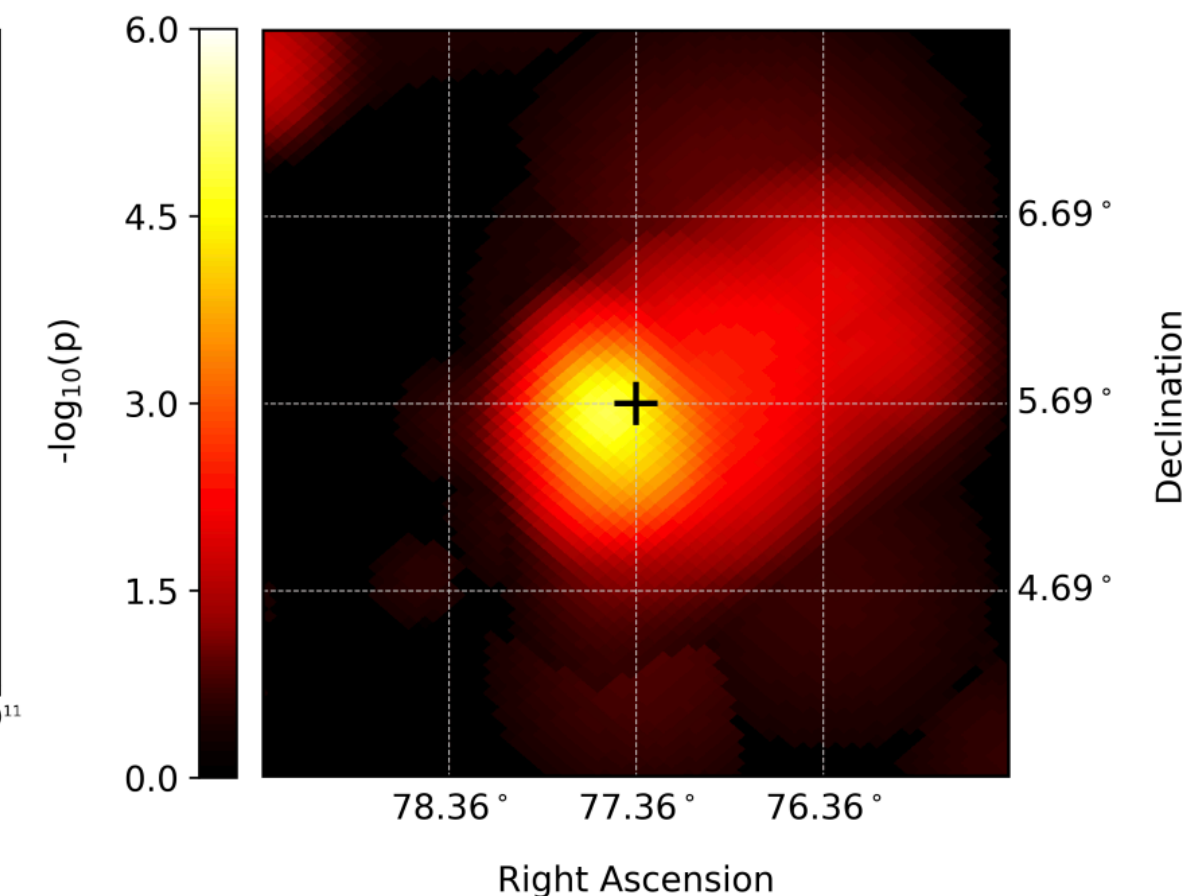


MW observed in neutrinos, arXiv:2307.04427 [astro-ph.HE]

Glashow Resonance at IceCube,
arXiv:2110.15051 [hep-ex]



Blazar TXS 0506+056 (1.75 Gpc),
arXiv:1807.08794 [astro-ph.HE]



Four, one, and none, the anomaly...

- **KM3-230213A:** 13 February, 2023
— a **220 PeV** neutrino at KM3NeT



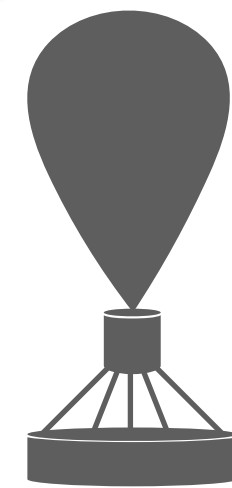
KM3NeT

Cubic Kilometre
Neutrino Telescope

- **ANITA-IV anomaly:** 4 upgoing
neutrino like events at $\mathcal{O}(1 - 10)$ EeV

- ANITA I & III events

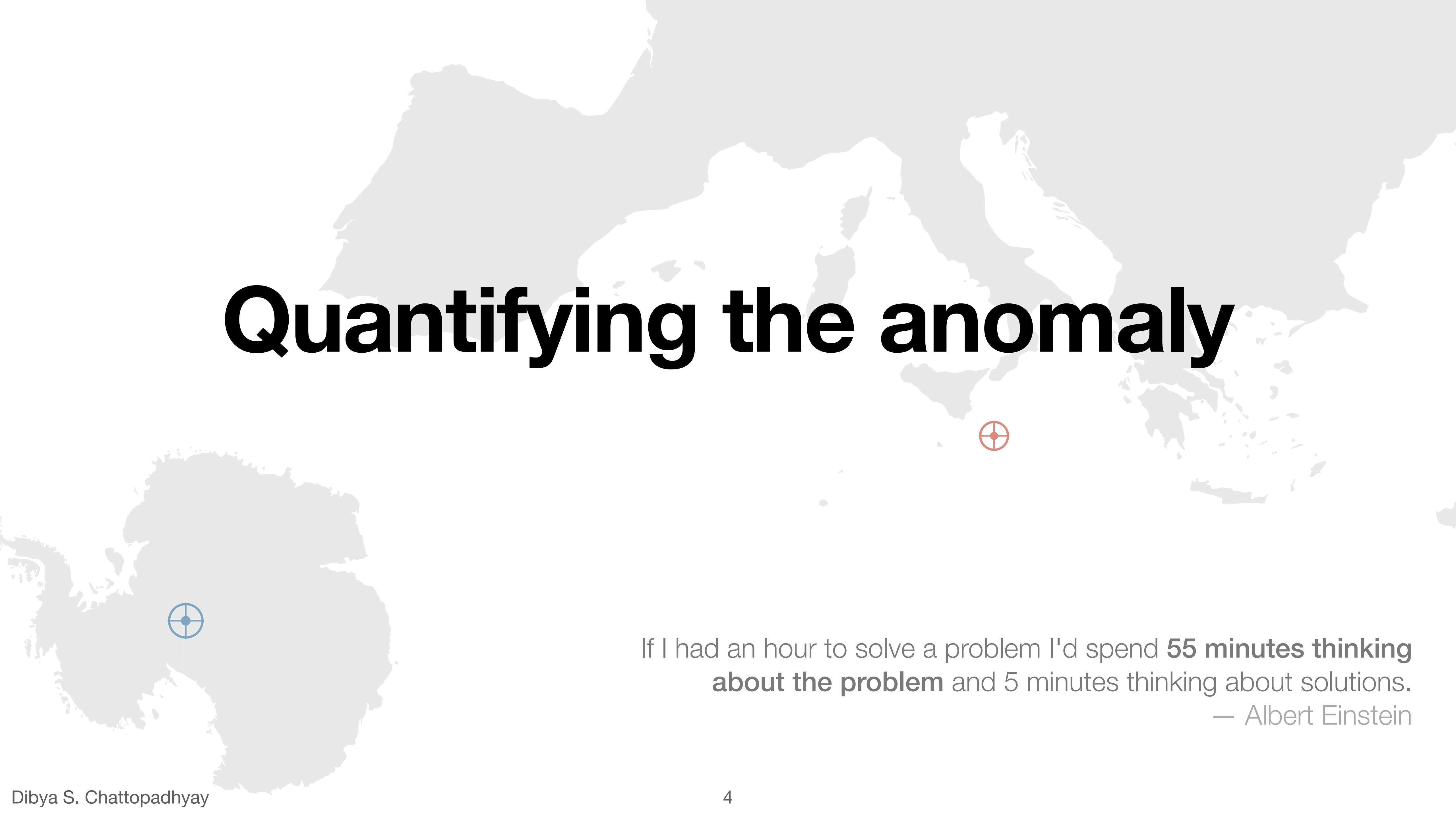
ANITA



Antarctic Impulsive
Transient Antenna



IceCube



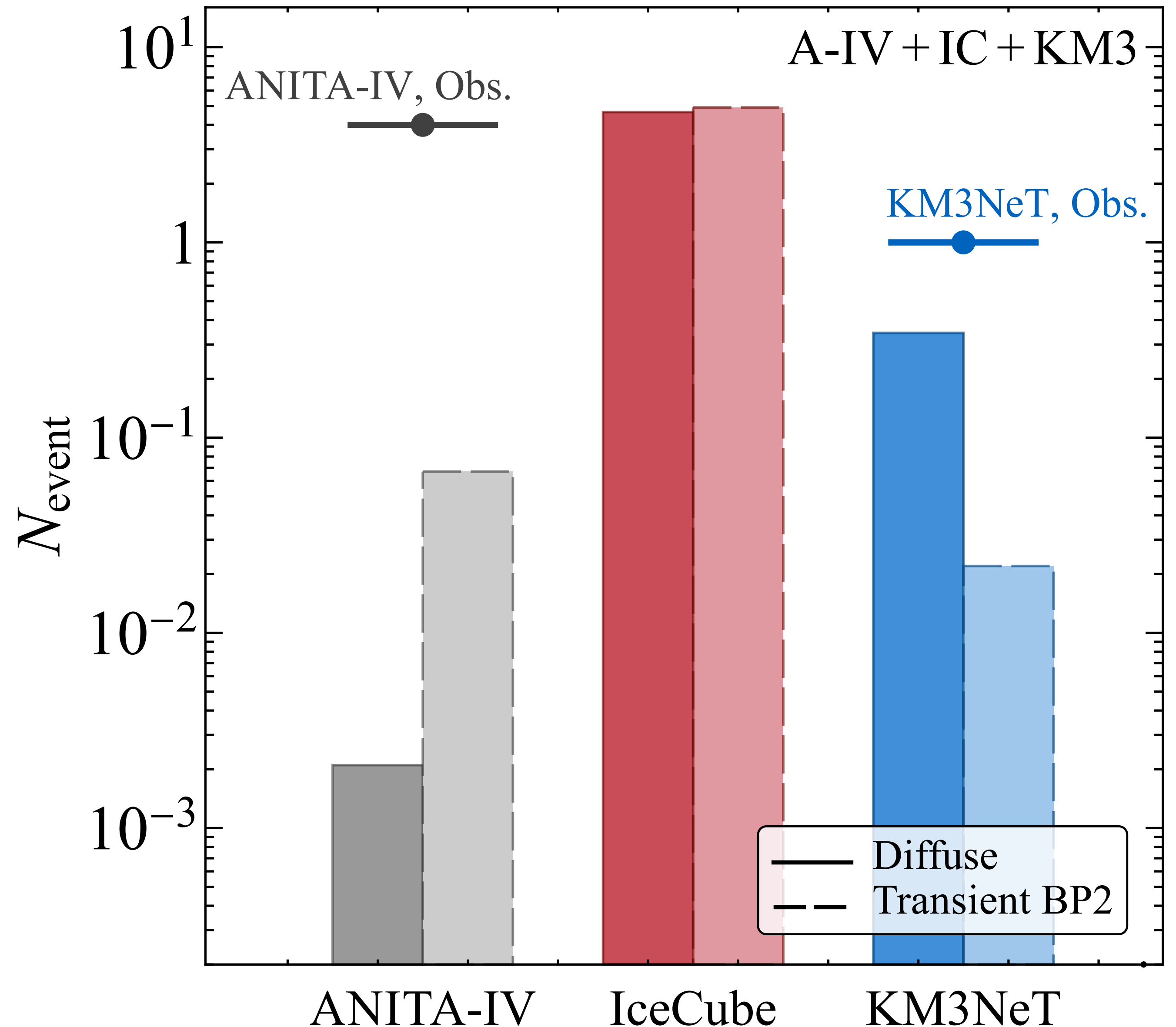
Quantifying the anomaly

If I had an hour to solve a problem I'd spend **55 minutes thinking about the problem** and 5 minutes thinking about solutions.

— Albert Einstein

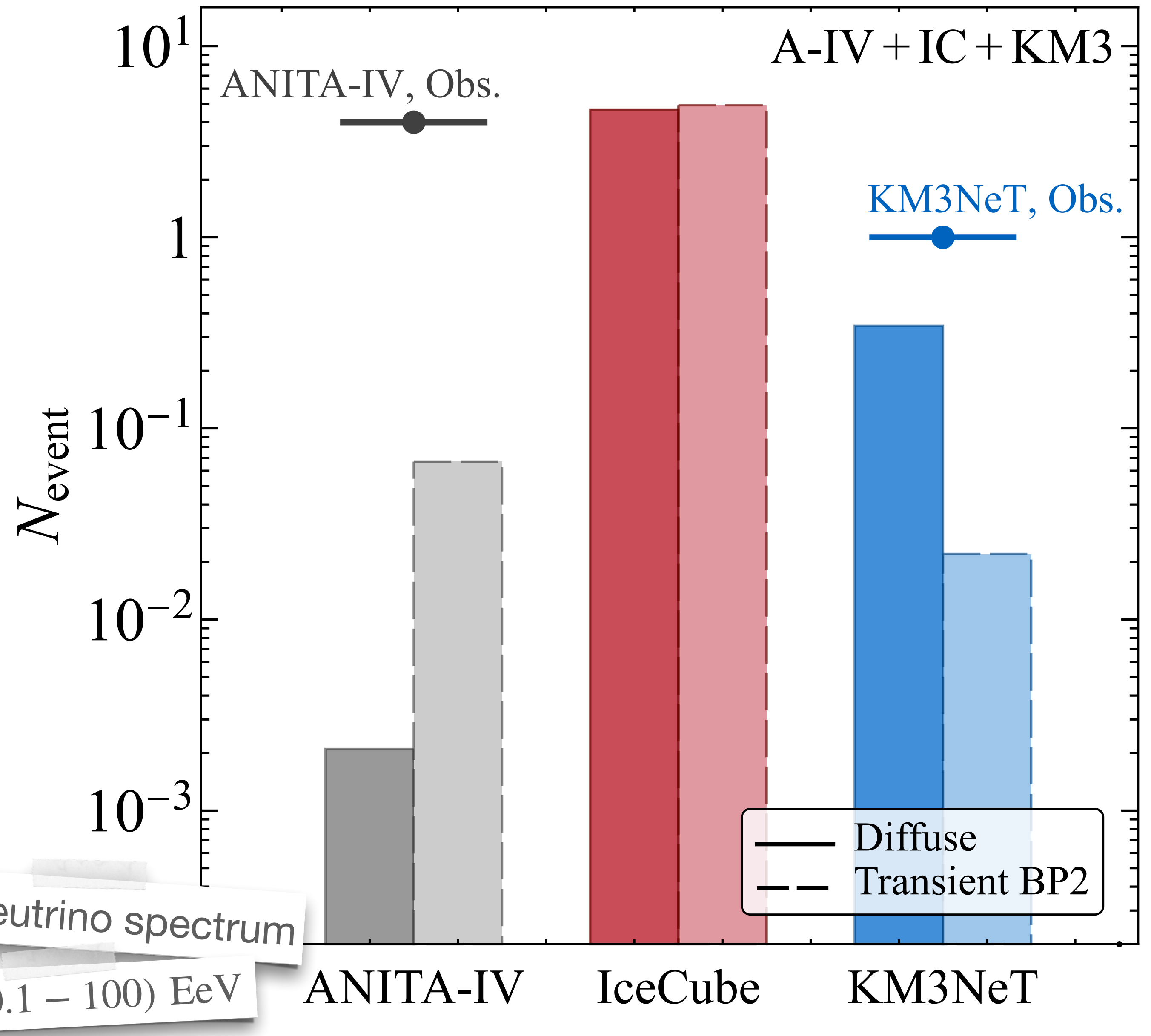
The anomaly

- ANITA-IV max. eff. area higher
- IceCube's max. effective area is ~3 times smaller
- KM3NeT (ARCA-21) has ~50 times smaller effective area...
- Larger angular exposure at IceCube + KM3NeT
- IC: ~15 years of exposure
A-IV: ~27 days of exposure
KM3: ~287 days, for ARCA-21



The anomaly

- Best-fit expected event numbers at ANITA-IV, IceCube, and KM3NeT (ARCA-21)
- Diffuse-flux: 7.9σ anomaly for a E_ν^{-2} neutrino spectrum...
- Transient (BP2), 185 sources +10-day duration: 5.9σ anomaly
- Randomly distributed over all-sky, and over 5400 days...
- Best-fit out of 10^5 MC runs



KM3-230213A



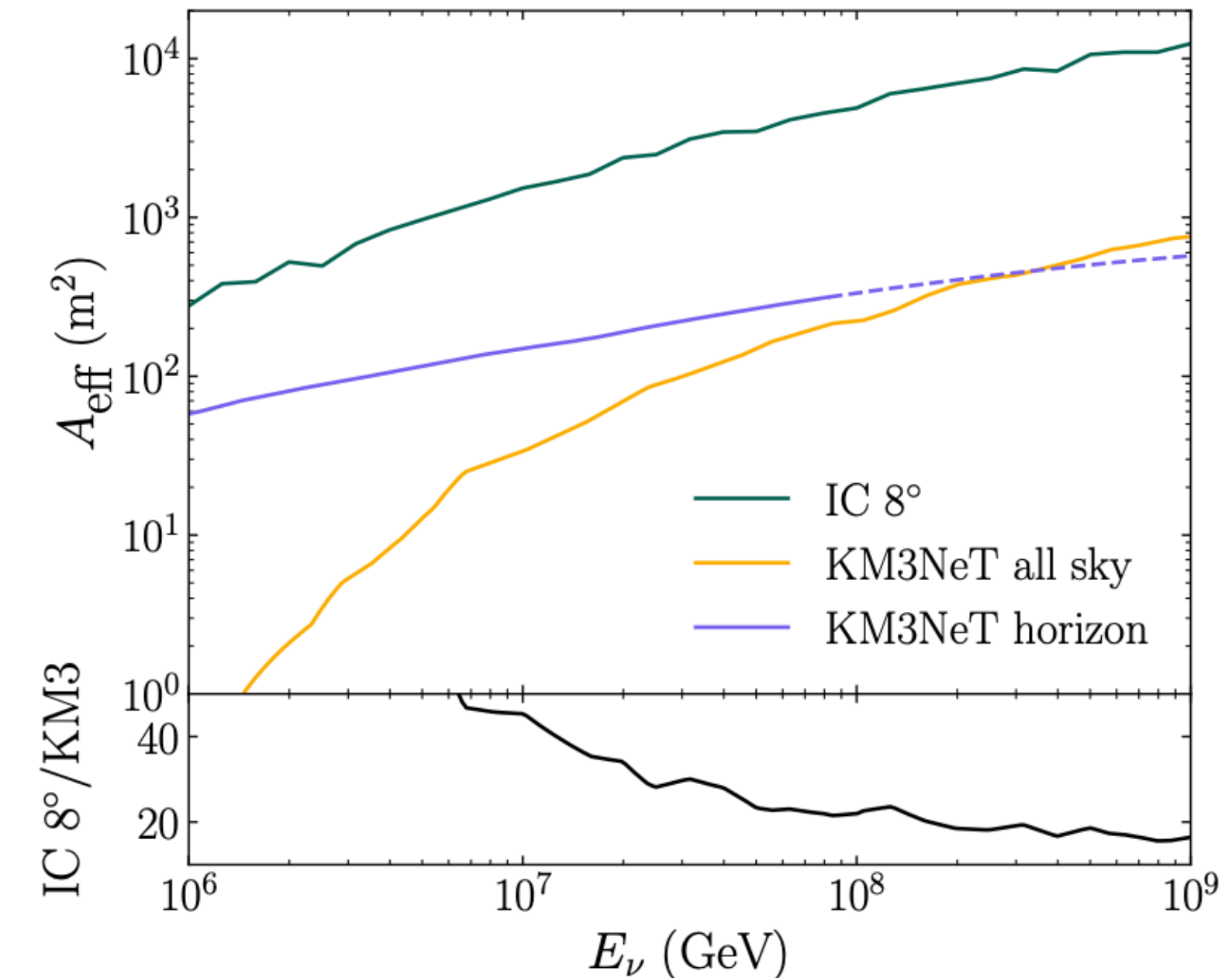
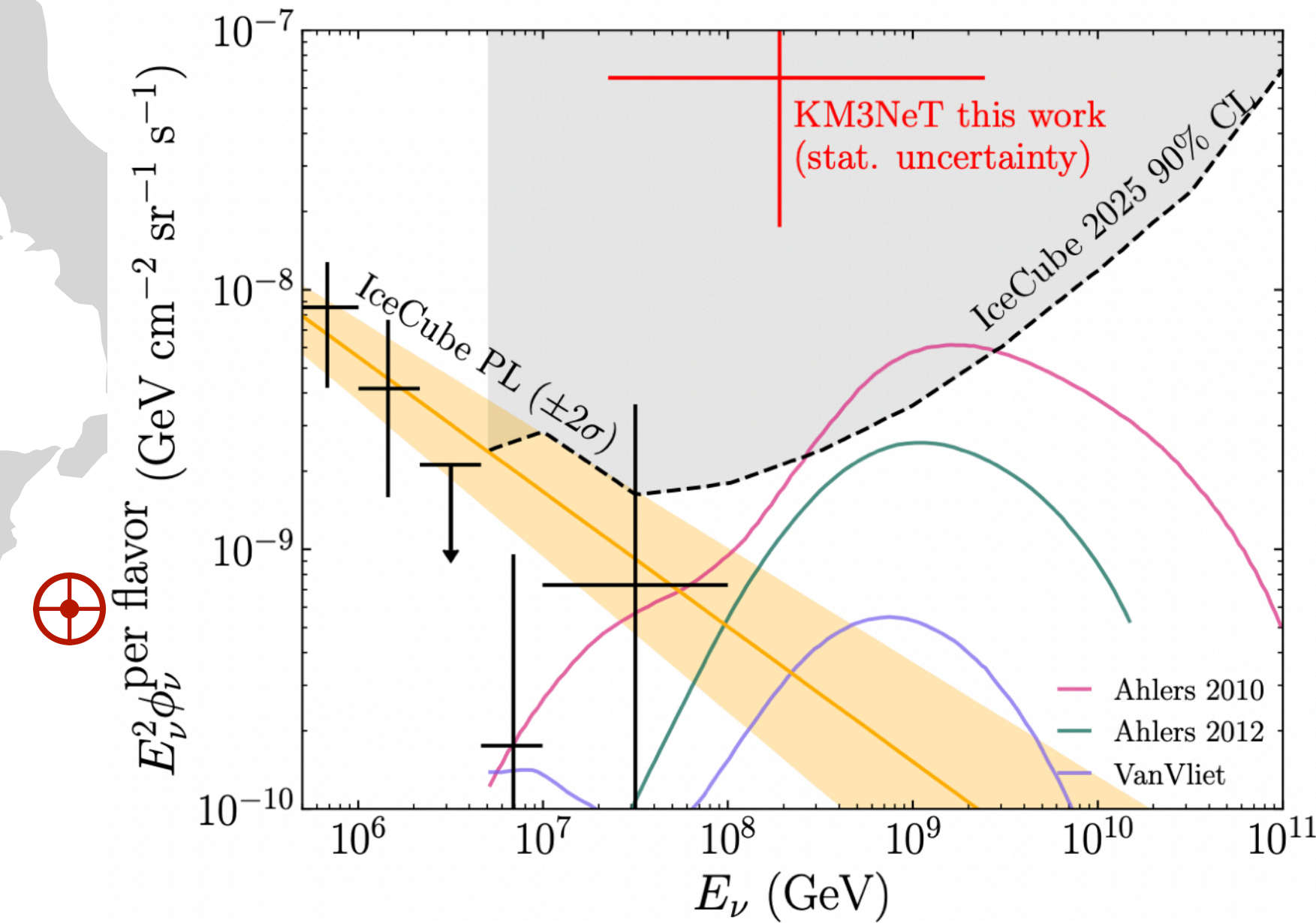
KM3NeT

Cubic Kilometre Neutrino
Telescope

KM3-230213A

- 13 February, 2023: a **220 PeV** neutrino, arriving from close to the horizon.
- $\mathcal{O}(10)$ more energetic than the highest energy IceCube counterpart.
- Unexpected: IceCube has larger effective area and longer run-time — Tension of $(2 - 3.5) \sigma$
- Even for a transient point-like source, for 1 event in KM3NeT, you would **expect** $\sim \mathcal{O}(30)$ **events** in **IceCube**...

[arXiv:2502.04508]
Li, Machado, Naredo-Tuero, Schwemberger



KM3-230213A: what about IceCube?



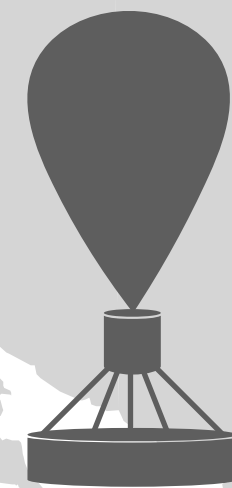
Observation of an ultra-high-energy
cosmic neutrino with KM3NeT
Nature volume 638, pages 376–382 (2025)

“A possible interpretation is that the KM3NeT event is an upward fluctuation
...event such as KM3-230213A would be expected in **70 years** of observation
...an upward fluctuation at the level of **2.2σ** ”

—KM3NeT Collaboration



ANITA



The ANITA anomaly: which one?

- ANITA-I & III events: anomalous upcoming extensive air showers
- ANITA-I & III: Steep angles, **too** anomalous?

arXiv:1803.05088

event, flight	3985267, ANITA-I	15717147, ANITA-III
date, time	2006-12-28,00:33:20UTC	2014-12-20,08:33:22.5UTC
Lat., Lon. ⁽¹⁾	-82.6559, 17.2842	-81.39856, 129.01626
Altitude	2.56 km	2.75 km
Ice depth	3.53 km	3.22 km
El., Az.	$-27.4 \pm 0.3^\circ, 159.62 \pm 0.7^\circ$	$-35.0 \pm 0.3^\circ, 61.41 \pm 0.7^\circ$
RA, Dec ⁽²⁾	282.14064, +20.33043	50.78203, +38.65498
$E_{shower}^{(3)}$	0.6 ± 0.4 EeV	$0.56^{+0.3}_{-0.2}$ EeV

¹ Latitude, Longitude of the estimated ground position of the event.

² Sky coordinates projected from event arrival angles at ANITA.

³ For upward shower initiation at or near ice surface.

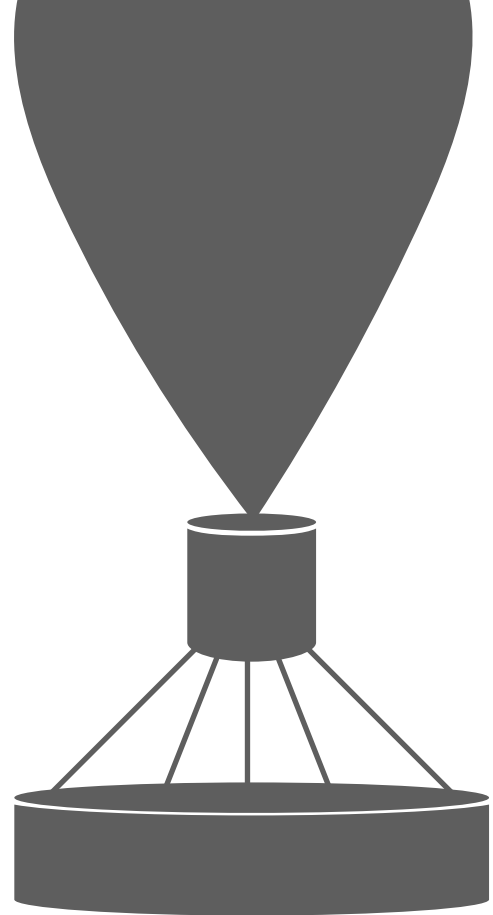
Chord length of
~5450 km, water
equivalent length
scale of ~20000 km
arXiv:1603.05218

Chord length of
~7000 km, water
equivalent length
scale of 30000 km
arXiv:1803.05088

arXiv:2502.04513

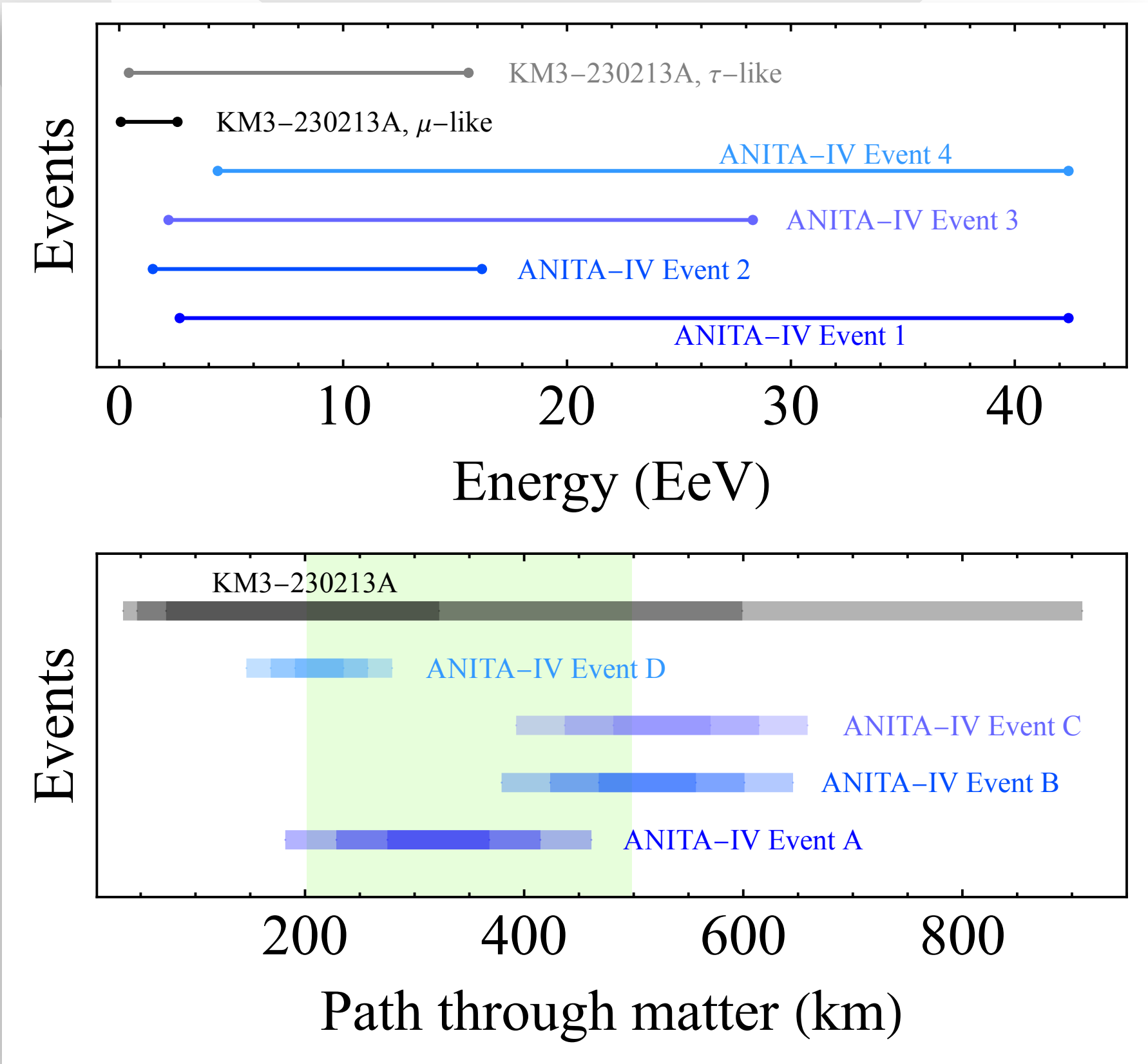
Strong disagreement with Pierre-Auger's search for upgoing shower-like events

- **ANITA-IV: 4 events consistent with up-going τ -induced extensive air showers, close to the horizon**



Details of the 5 events...

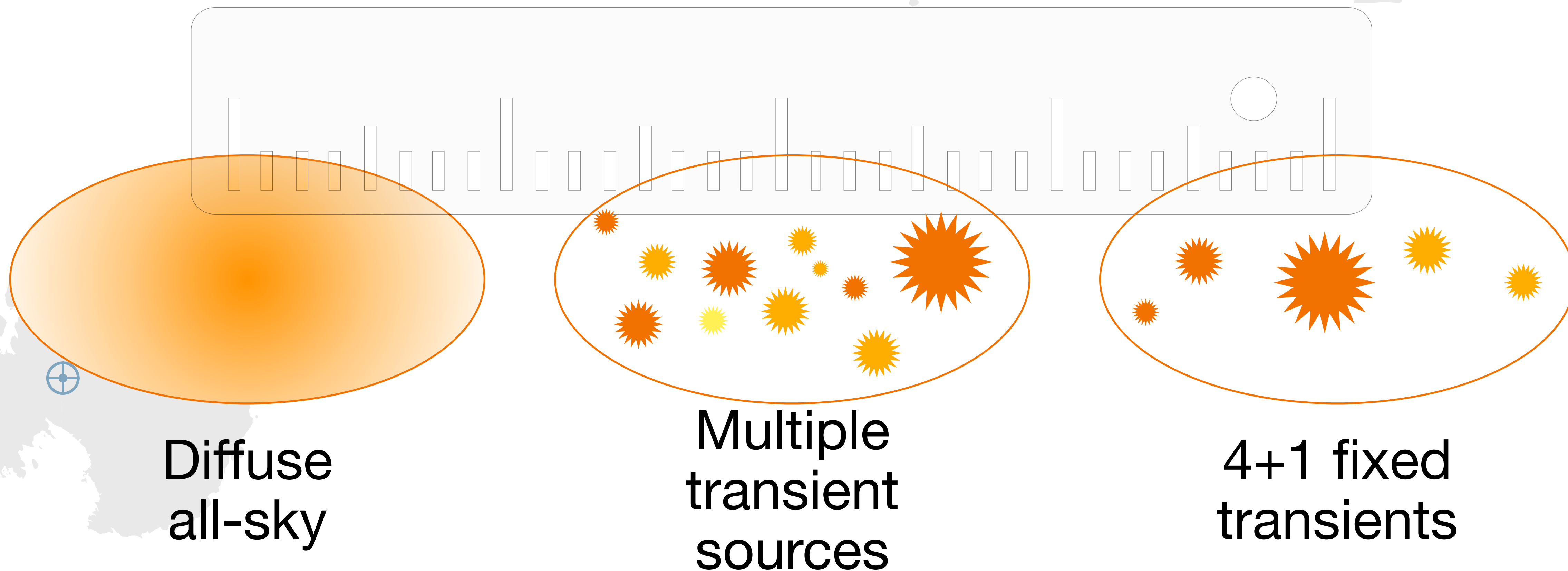
- **ANITA-IV**: 4 τ -induced extensive air showers, close to the horizon
- **KM3NeT**: 1 event close to the horizon
- KM3NeT: 72 PeV—2.6 EeV (90% C.L.) for muon neutrino event, or ν_τ of $\mathcal{O}(10)$ times more energy...



Detector	ANITA-IV				KM3NeT (ARCA-21)
Event ID	4098827	19848917	50549772	72164985	KM3-230213A
Event label	A	B	C	D	KM3-230213A
UTC date	2016 December 03	2016 December 08	2016 December 16	2016 December 22	2023 February 13
UTC time	10:03:27	11:44:54	15:03:19	06:28:14	01:16:47
Elevation angle (°)	-6.17 ± 0.21	-6.71 ± 0.20	-6.73 ± 0.20	-6.12 ± 0.10	0.60
Horizon angle (°)	-5.92 ± 0.02	-6.06 ± 0.02	-5.92 ± 0.02	-5.93 ± 0.02	—
Sky location RA (°)	331.52	15.14	232.18	224.00	94.3
Sky location dec. (°)	15.17	-6.31	2.03	3.83	-7.8

Quantifying the anomaly...

- The anomaly depends on whether we consider a diffuse, or a transient scenario, or something in between...

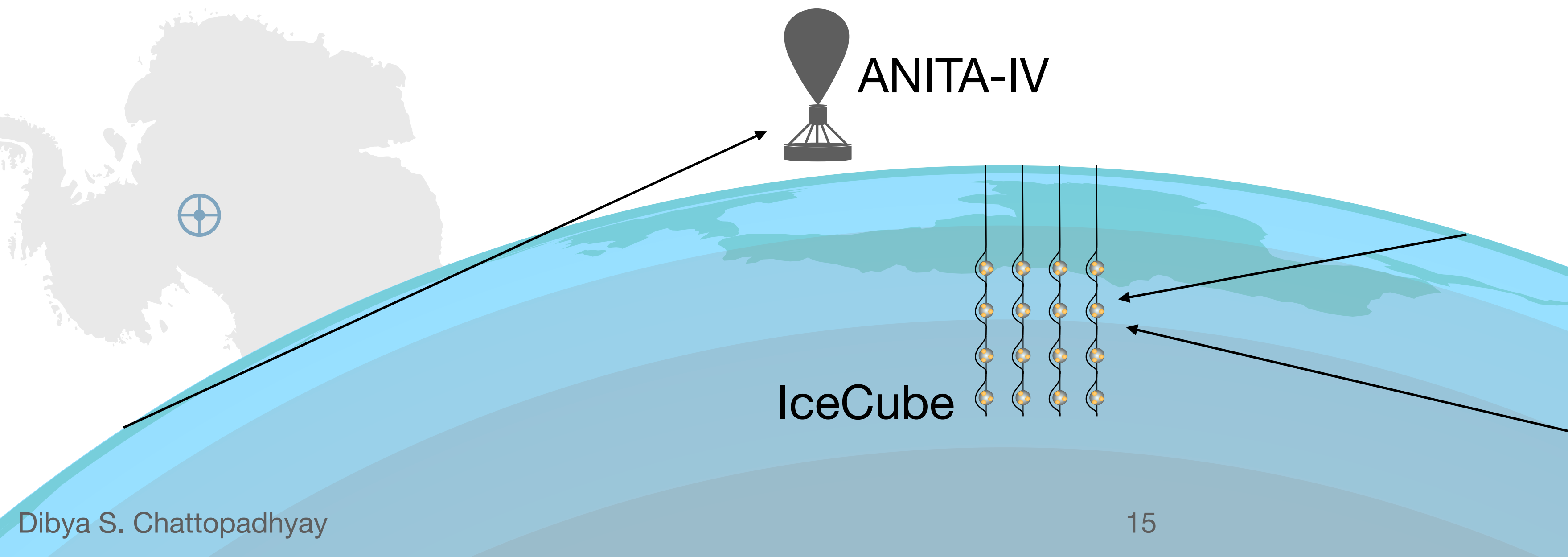
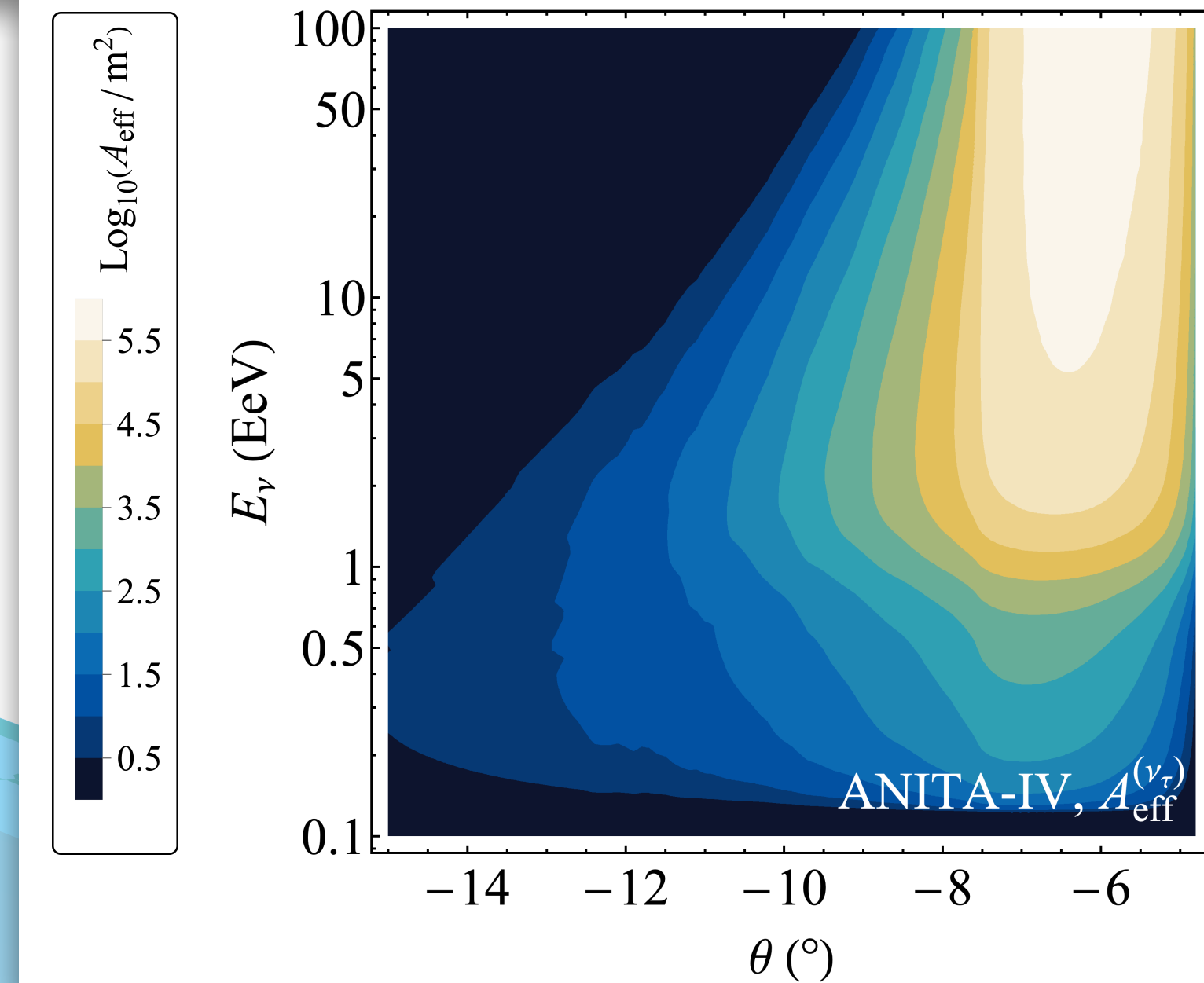
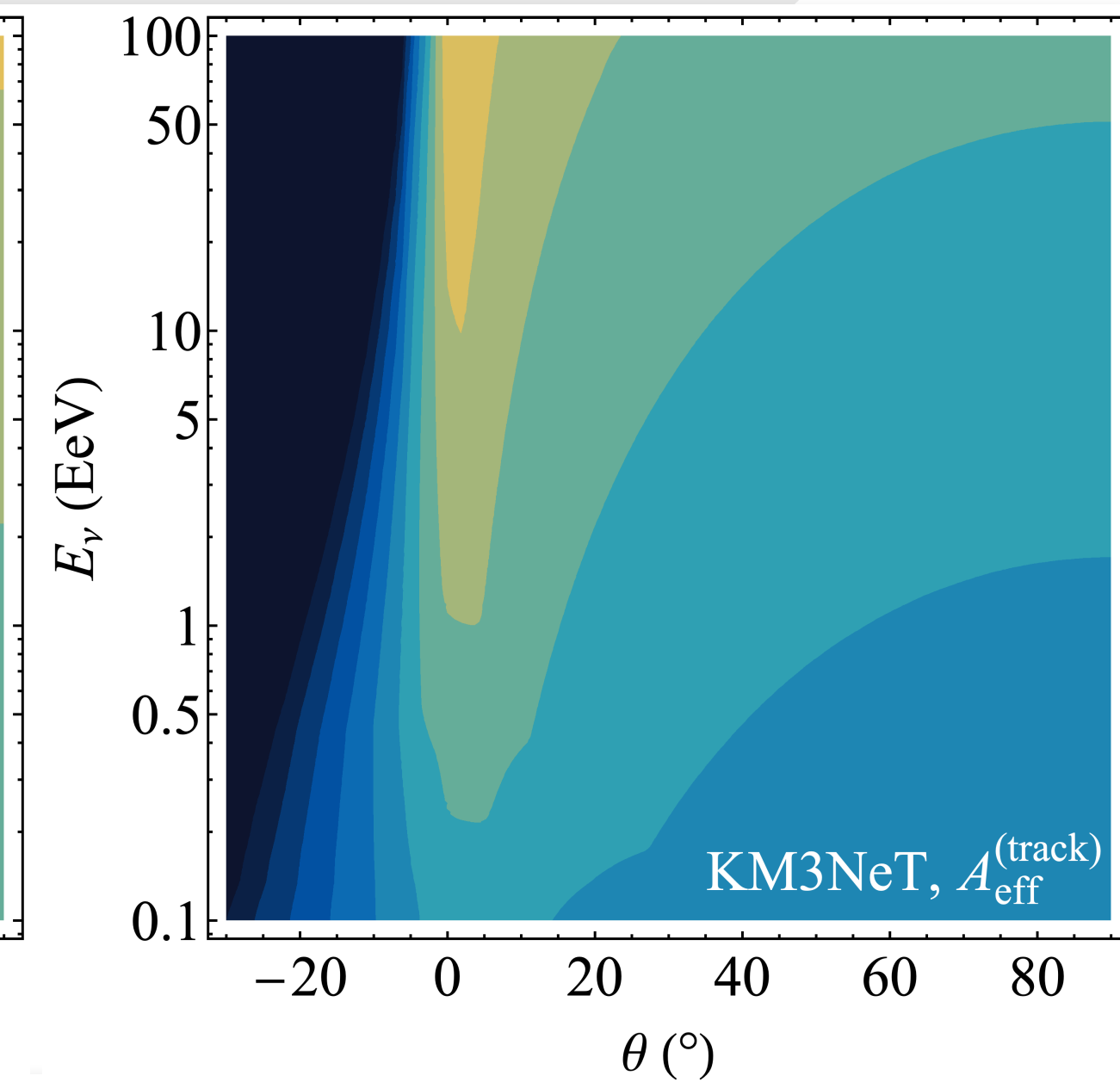
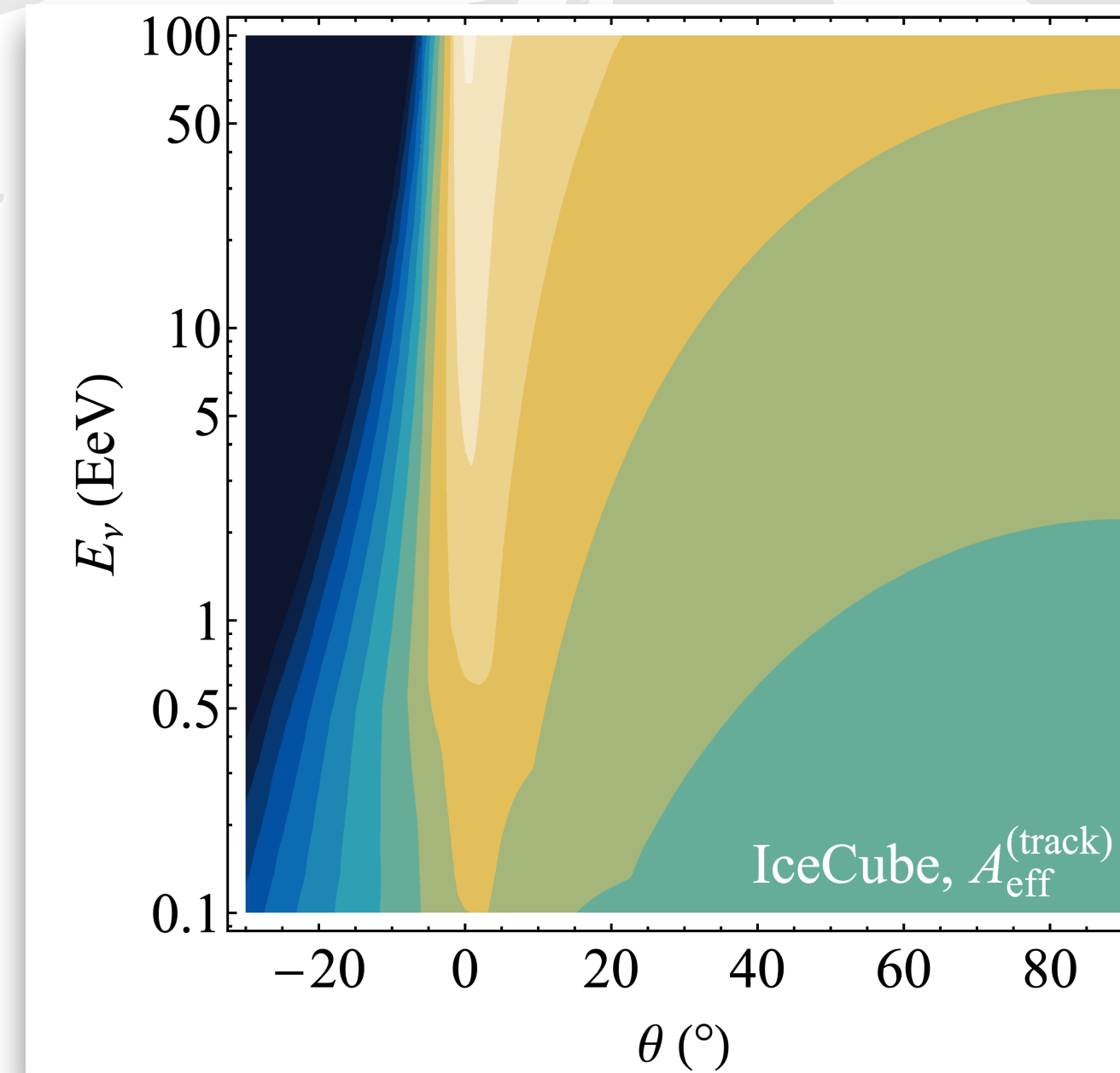


Details, details, details...



Effective area...

- Uniform flavor ratio for the ν flux
- ν_τ eff. area at ANITA-IV
- $\nu_\mu + \nu_\tau$ track-like eff. area at IceCube and KM3NeT (ARCA-21)

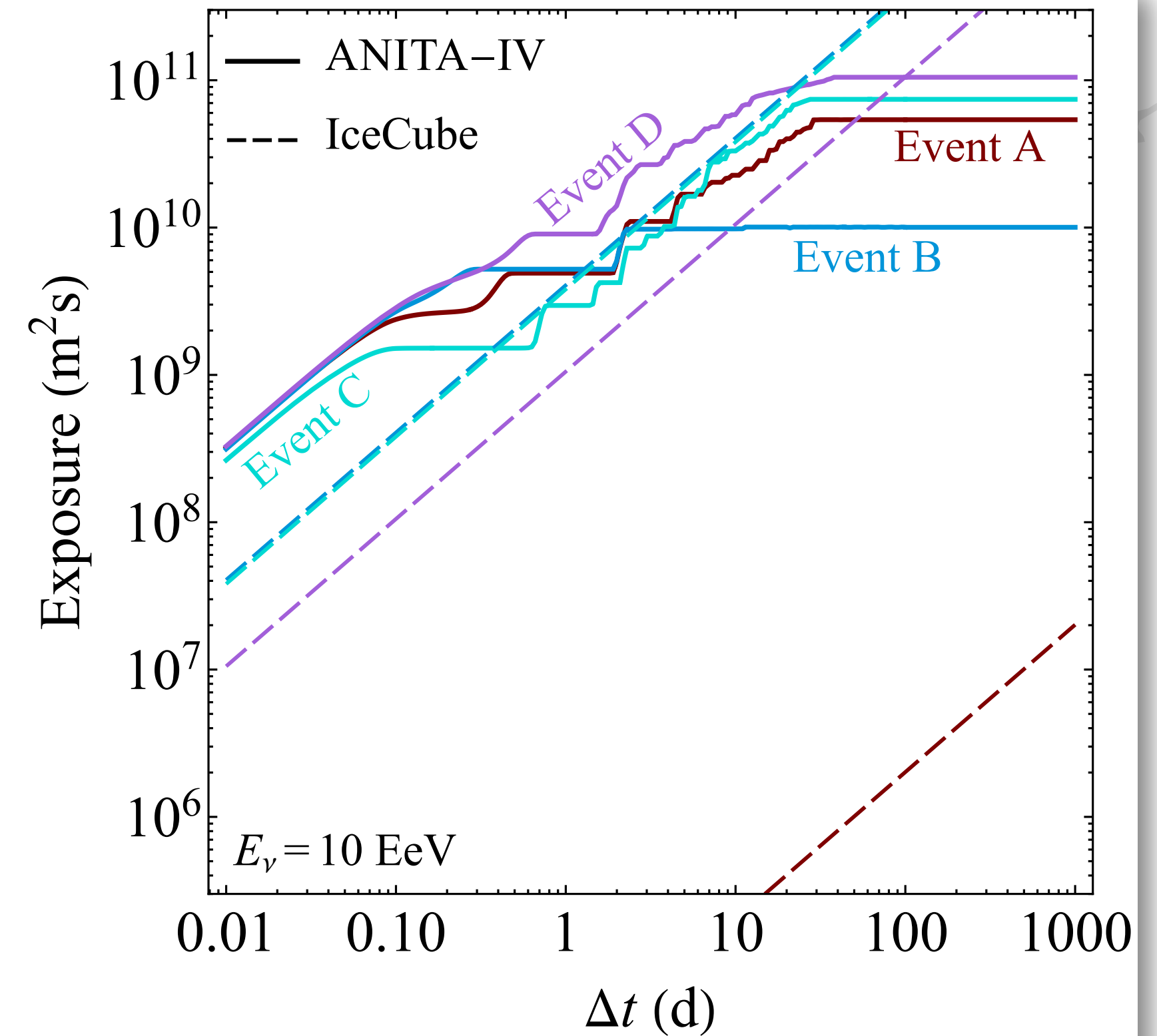


Directional effective areas and exposures

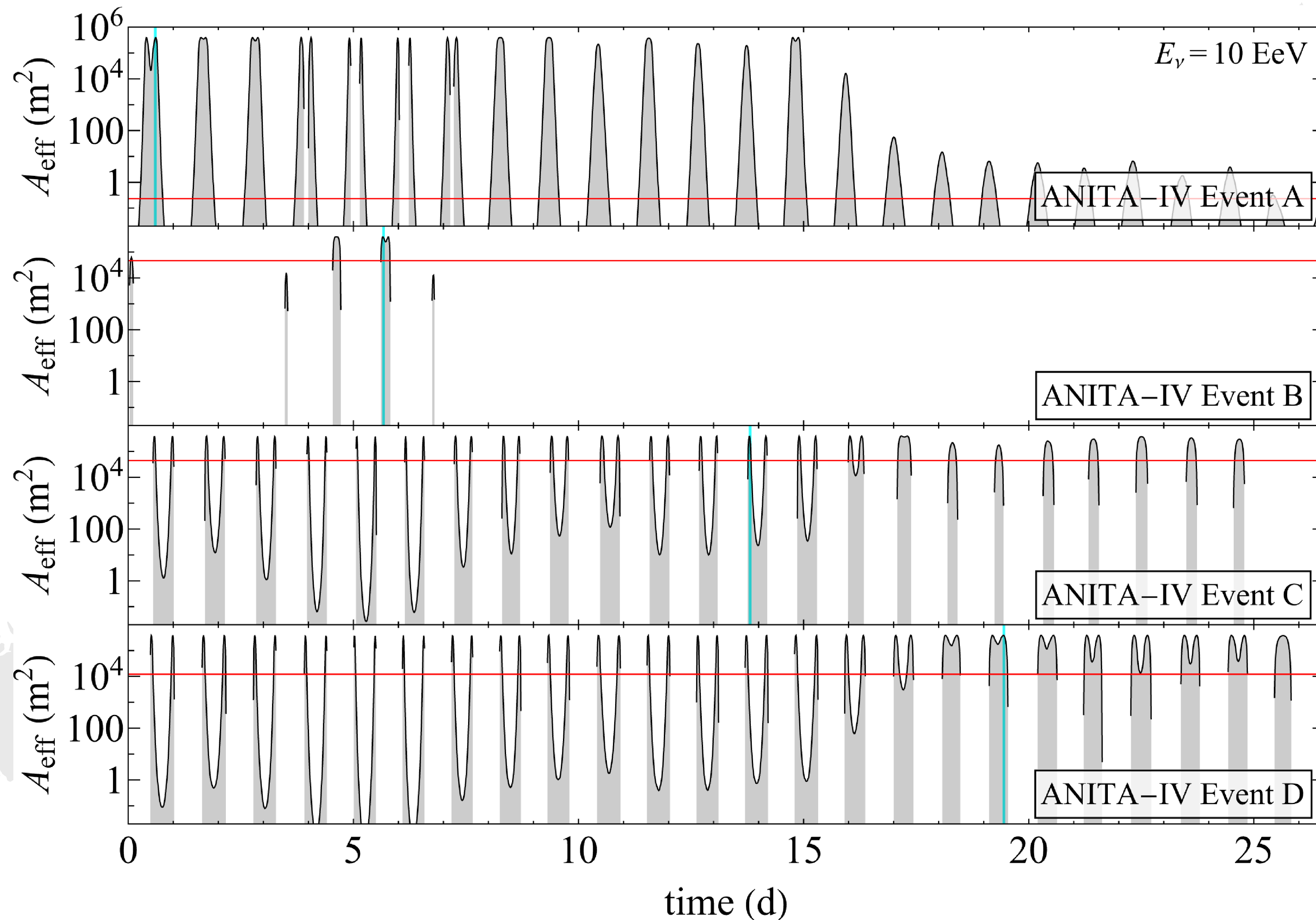
- Exposure towards a transient source

$$\mathcal{E}(E_\nu, \Omega; t_0, \Delta t) = \int_{t_0}^{t_0 + \Delta t} A_{\text{eff}}(E_\nu, \Omega; t) dt$$

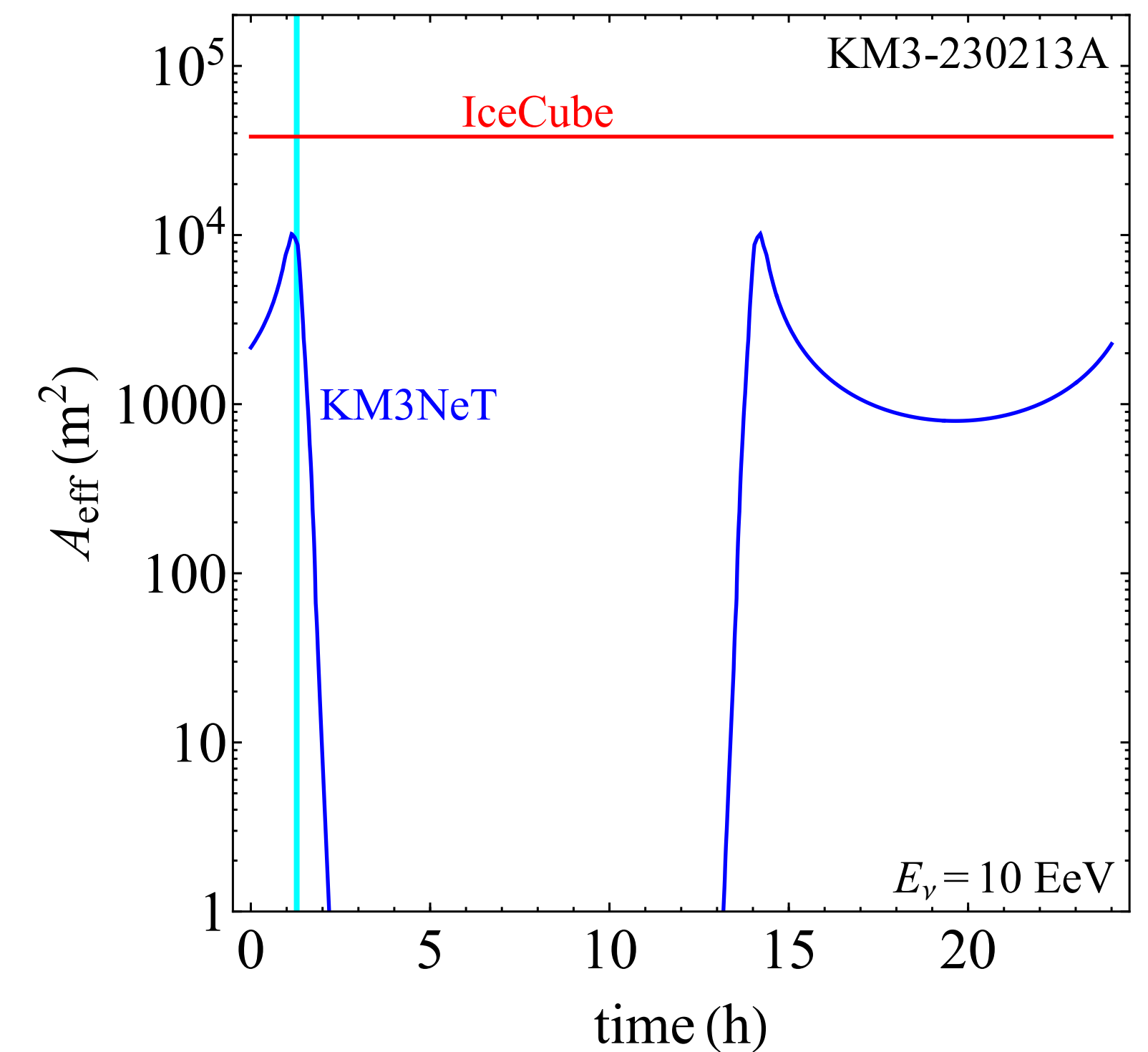
- ANITA-IV's changing location makes this a non-trivial issue...
- Earth's rotation also affects the exposure
- Ever-changing slice of the sky seen optimally at ANITA-IV and KM3NeT...



Directional effective areas and exposures



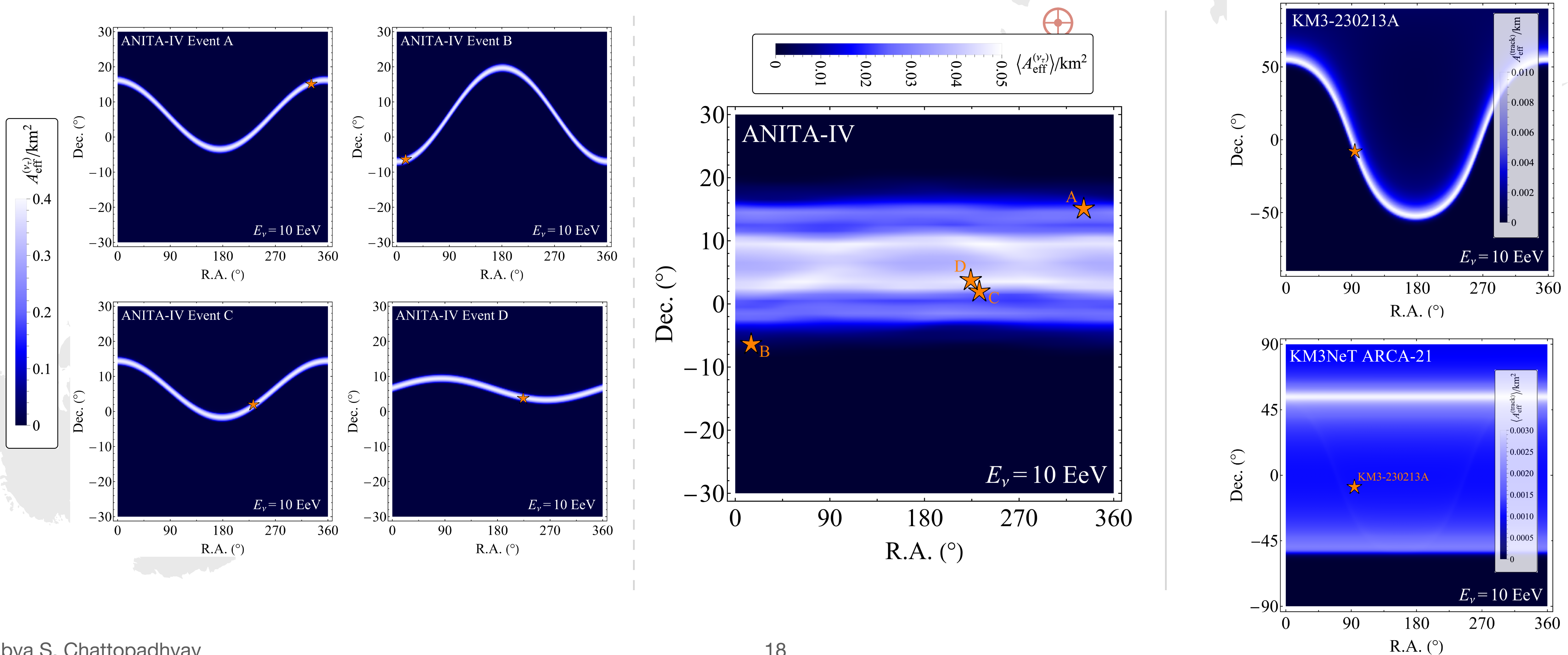
- All transients are equal, but some transients are more equal than others...



Directional effective areas and exposures

neutrinos

- The effective area in equatorial coordinates can shed further light



Diffuse all-sky flux



Diffuse flux interpretation

We consider the energy range of $E_\nu \in (0.1 - 100) \text{ EeV}$

- A common, isotropic diffuse flux, parametrized as

Flux normalization $\frac{d\Phi_\nu}{dE_\nu} = \phi_0 \left(\frac{E_\nu}{E_0} \right)^{-\gamma}$ Spectral index $E_0 = 1 \text{ EeV}$

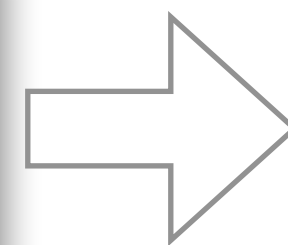
- We consider a uniform flavor ratio of $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$
- Expected number of events at a detector

$$\mu_{\mathcal{D}}(\phi_0, \gamma) = \int dt dE_\nu d\Omega \frac{d\Phi_\nu}{dE_\nu d\Omega} A_{\text{eff}}^{\mathcal{D}}(E_\nu, \Omega, t)$$

- Joint likelihood for the observed event counts calculated as

$(n_{\text{A-IV}}, n_{\text{IC}}, n_{\text{KM3}}) = (4, 0, 1)$

$$\mathcal{L}(\phi_0, \gamma) = \prod_{\mathcal{D}} \frac{\mu_{\mathcal{D}}^{n_{\mathcal{D}}} \exp(-\mu_{\mathcal{D}})}{n_{\mathcal{D}}!}$$

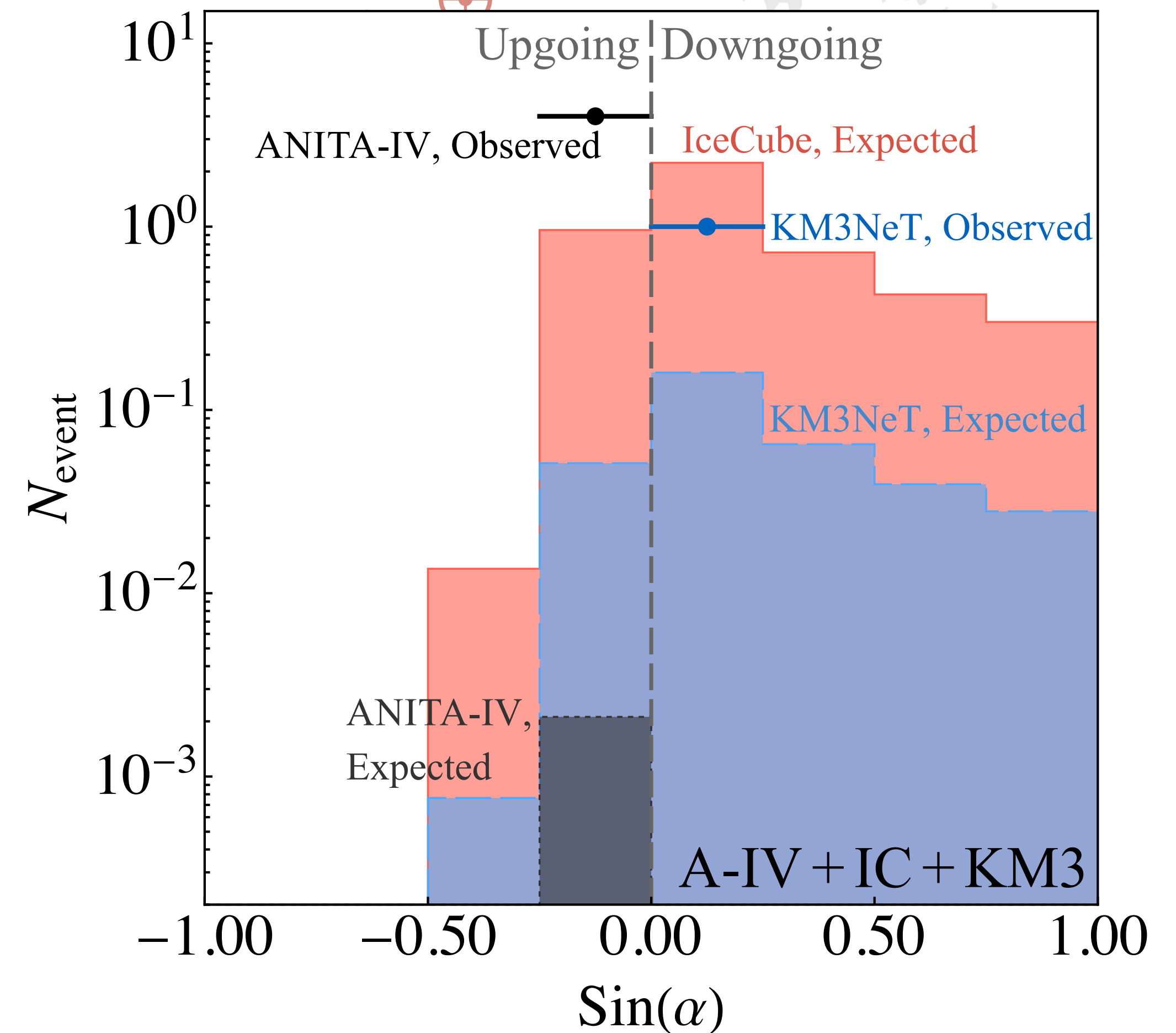
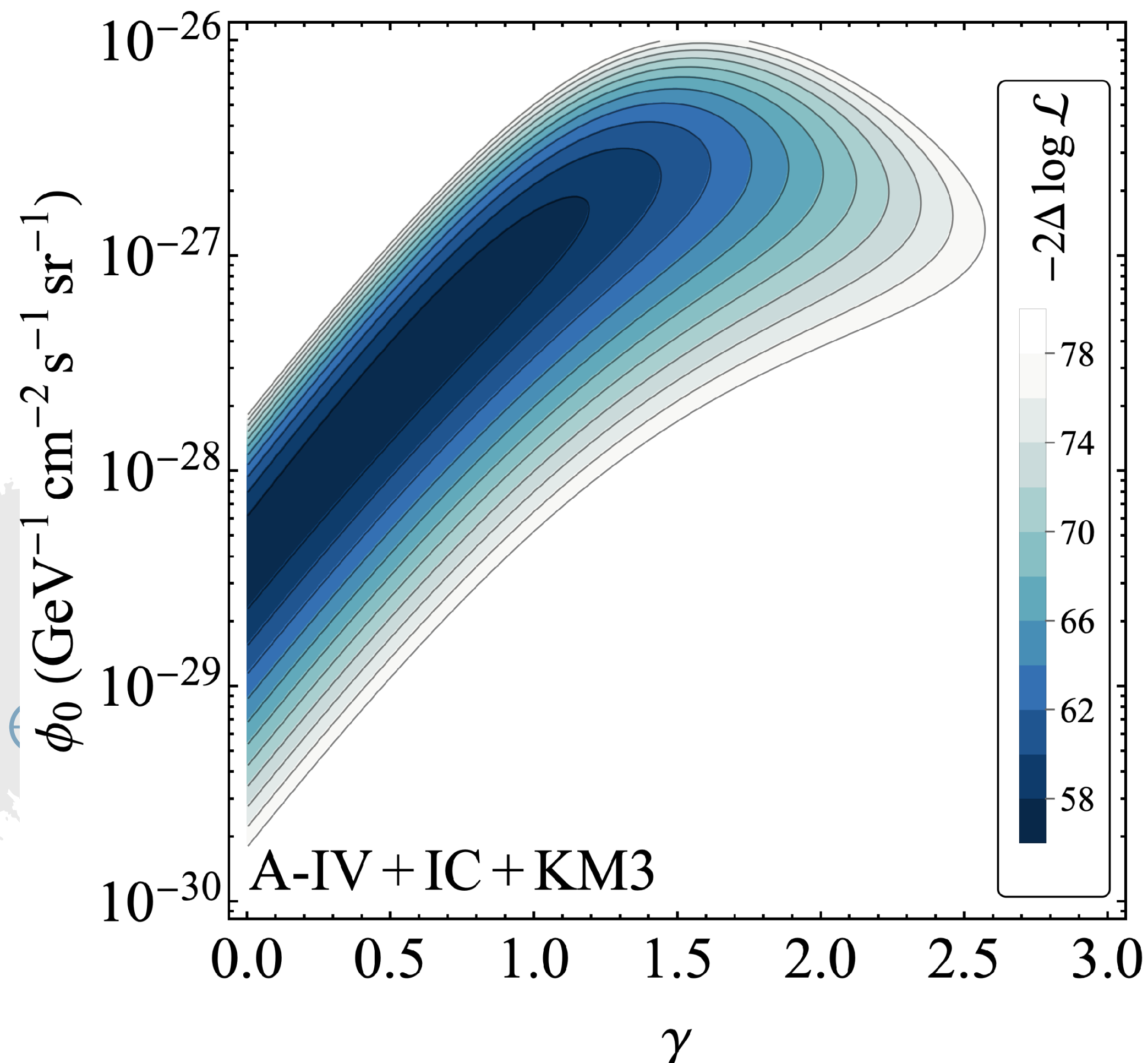


$$-2\Delta \log \mathcal{L} = -2 \log \left(\frac{L}{L_{\text{sat}}} \right)$$



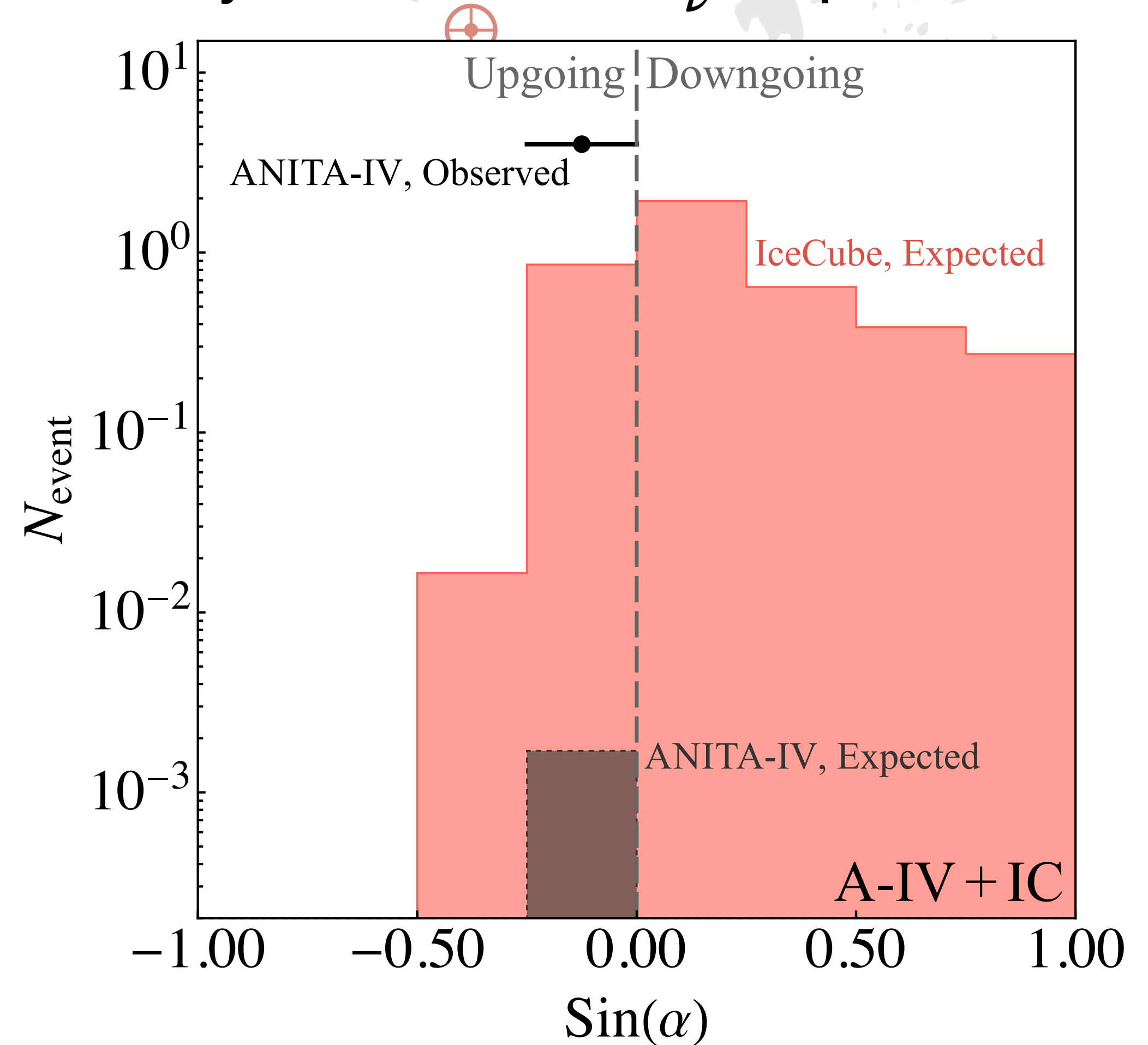
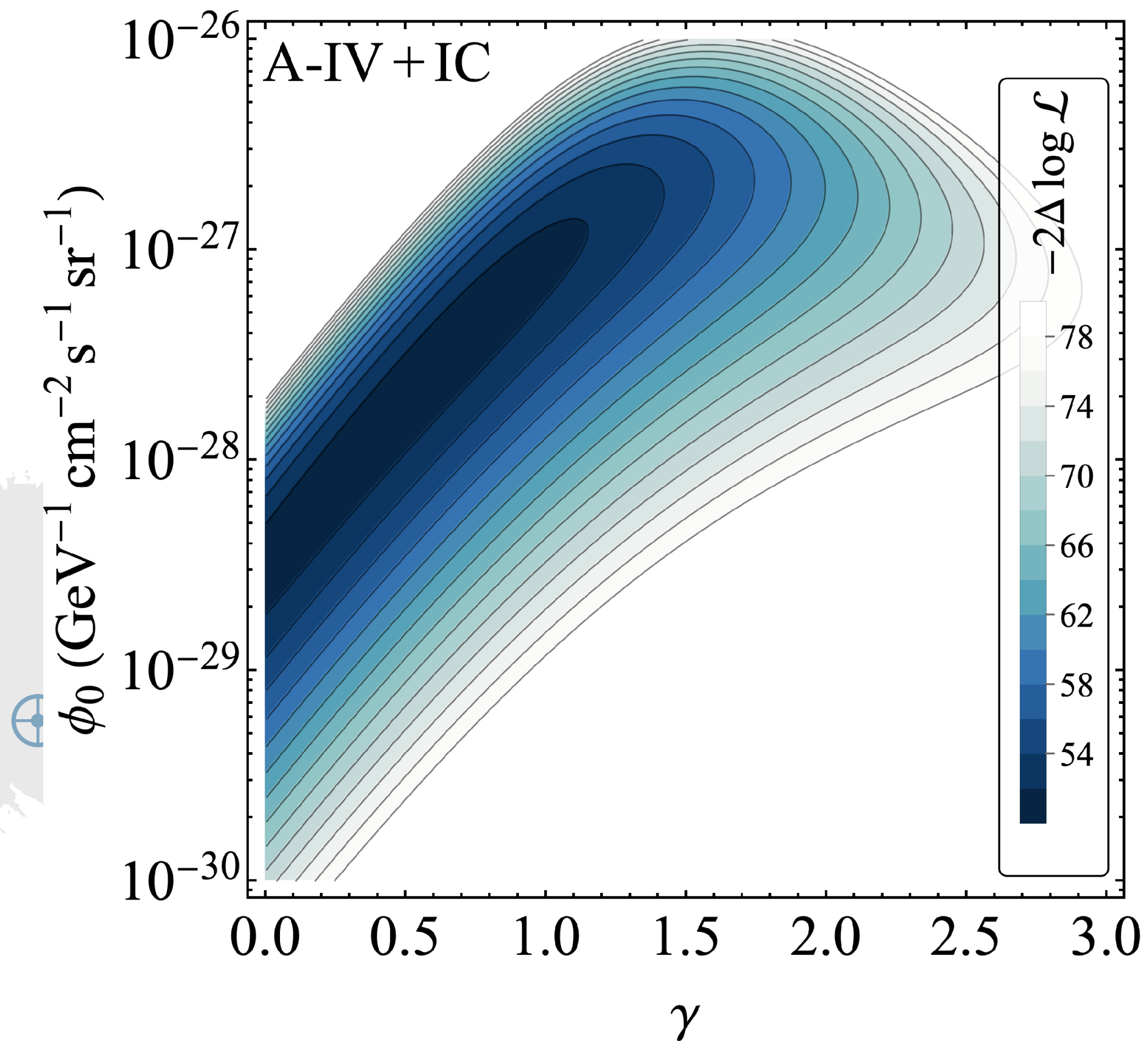
Diffuse flux interpretation

- All 3 detectors considered: best-fit 7.5σ anomaly, 7.9σ for E_ν^{-2} spectrum...



Diffuse flux interpretation

- For the 2-detector (A-IV+IC) scenario, anomaly of 7.8σ for E_ν^{-2} spectrum...

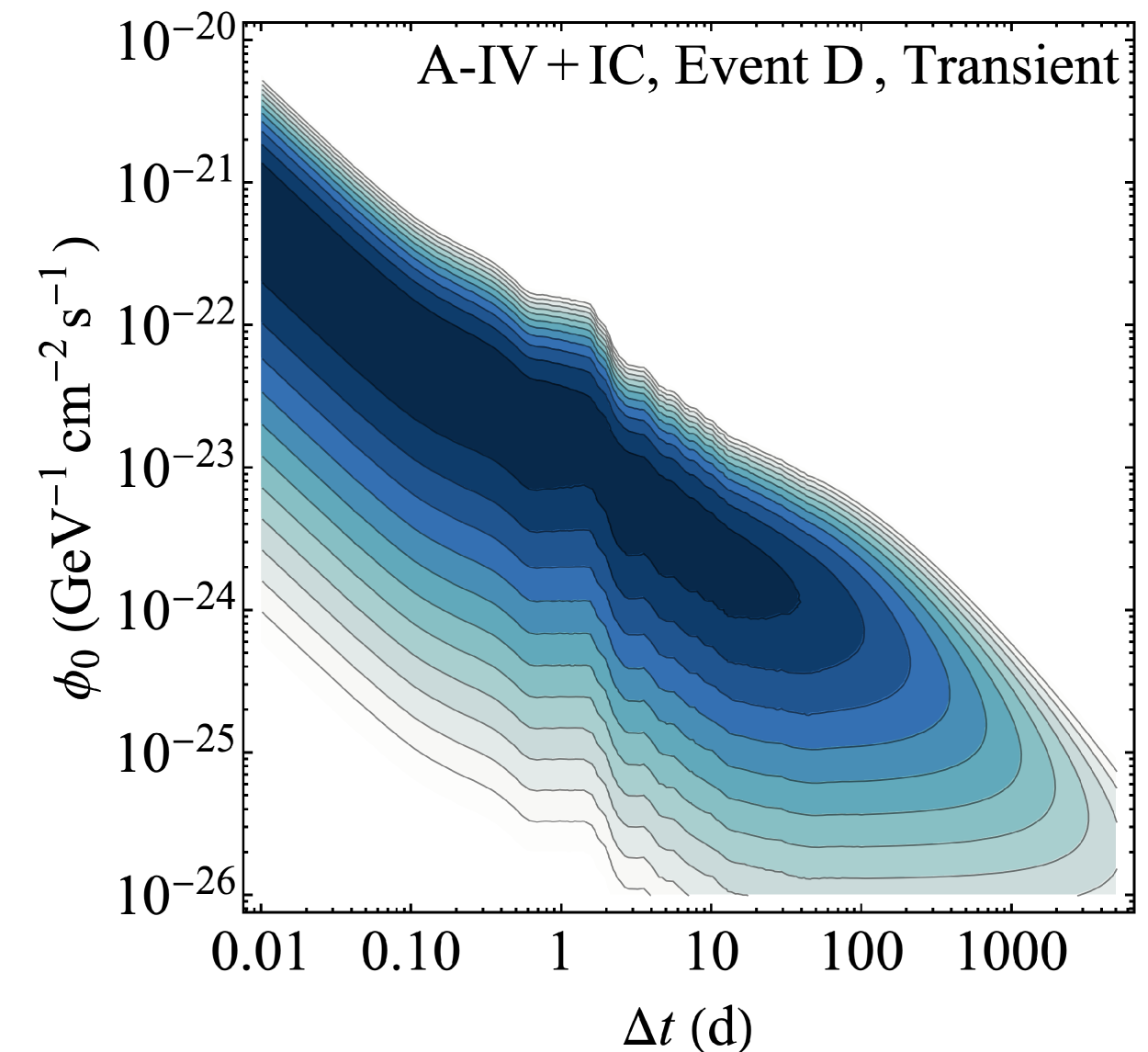
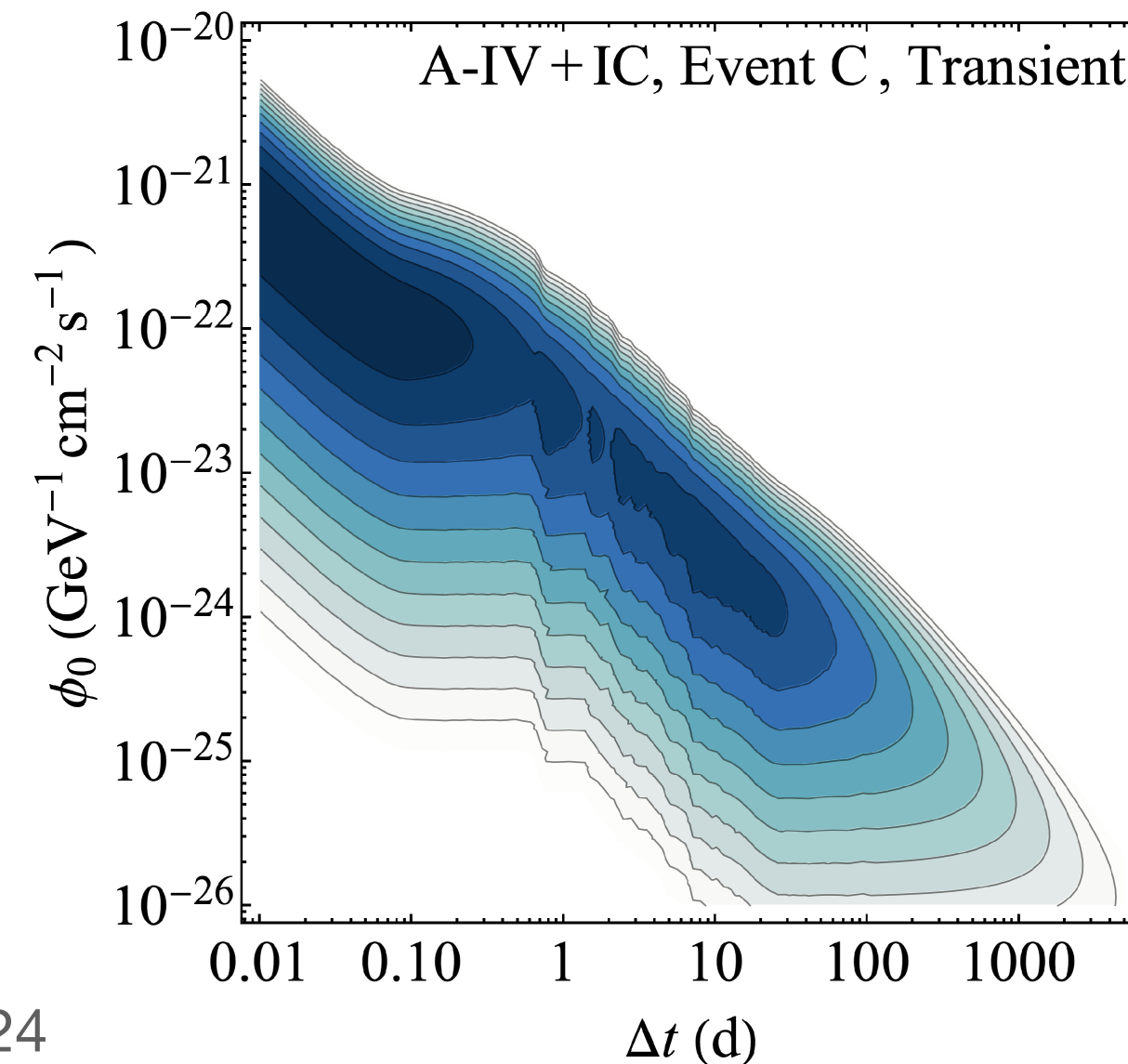
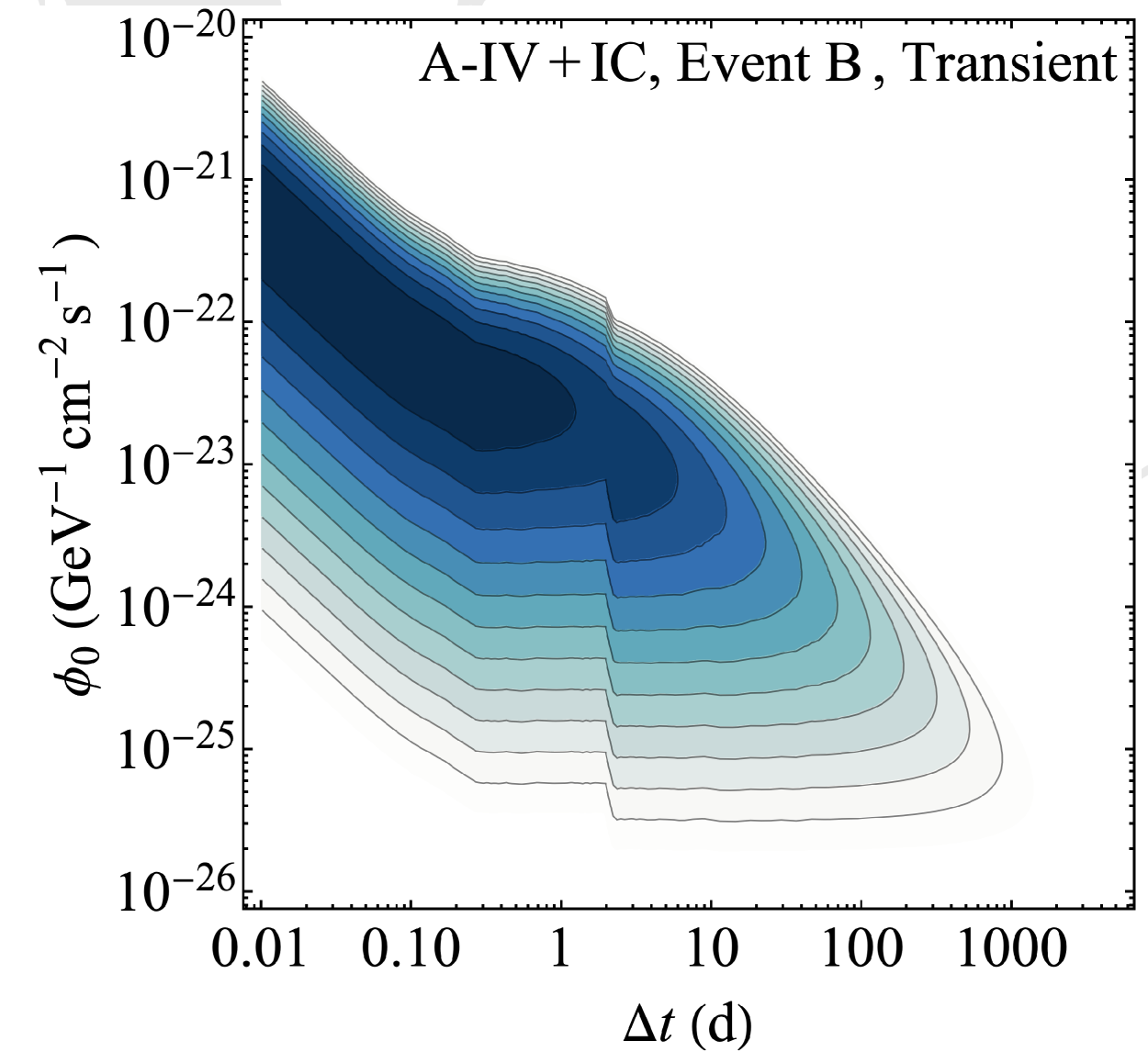
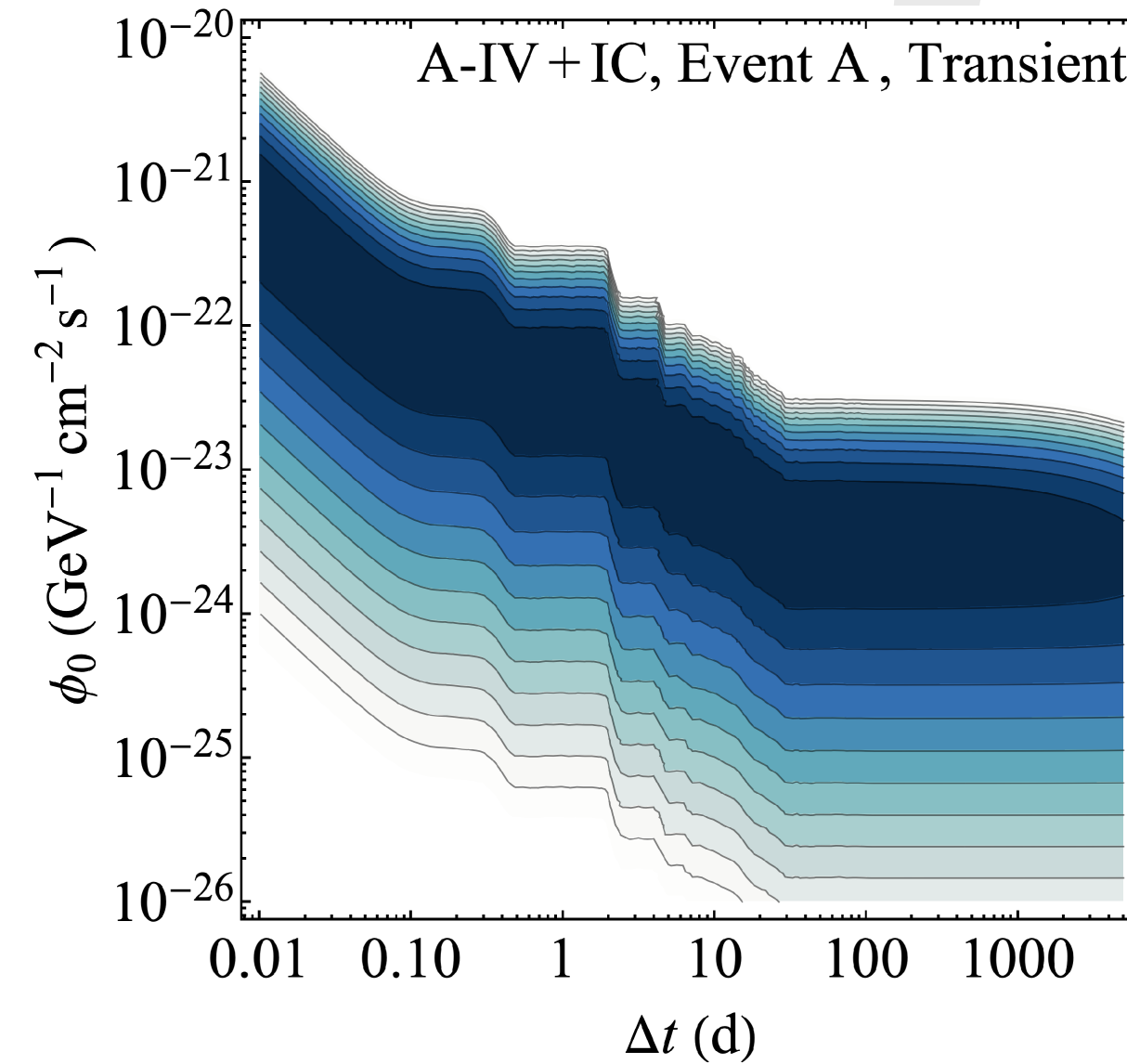
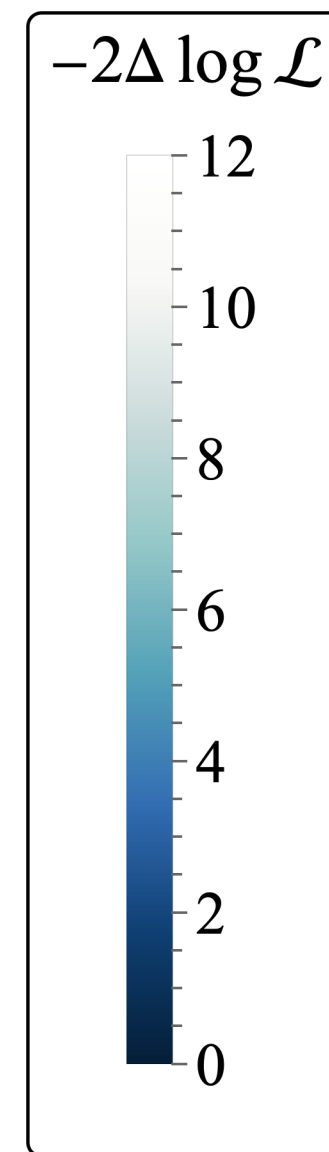


Transient rare sources



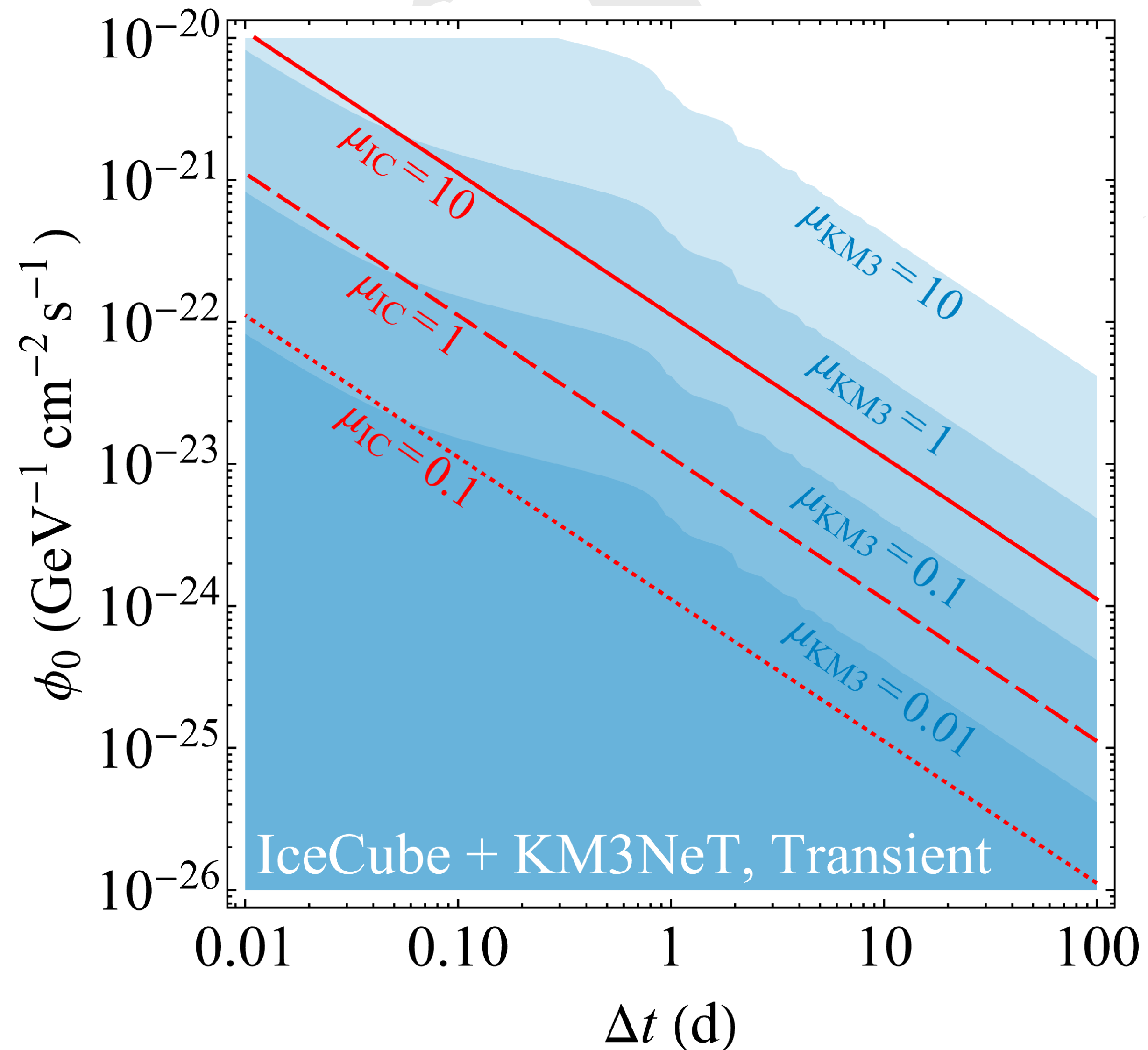
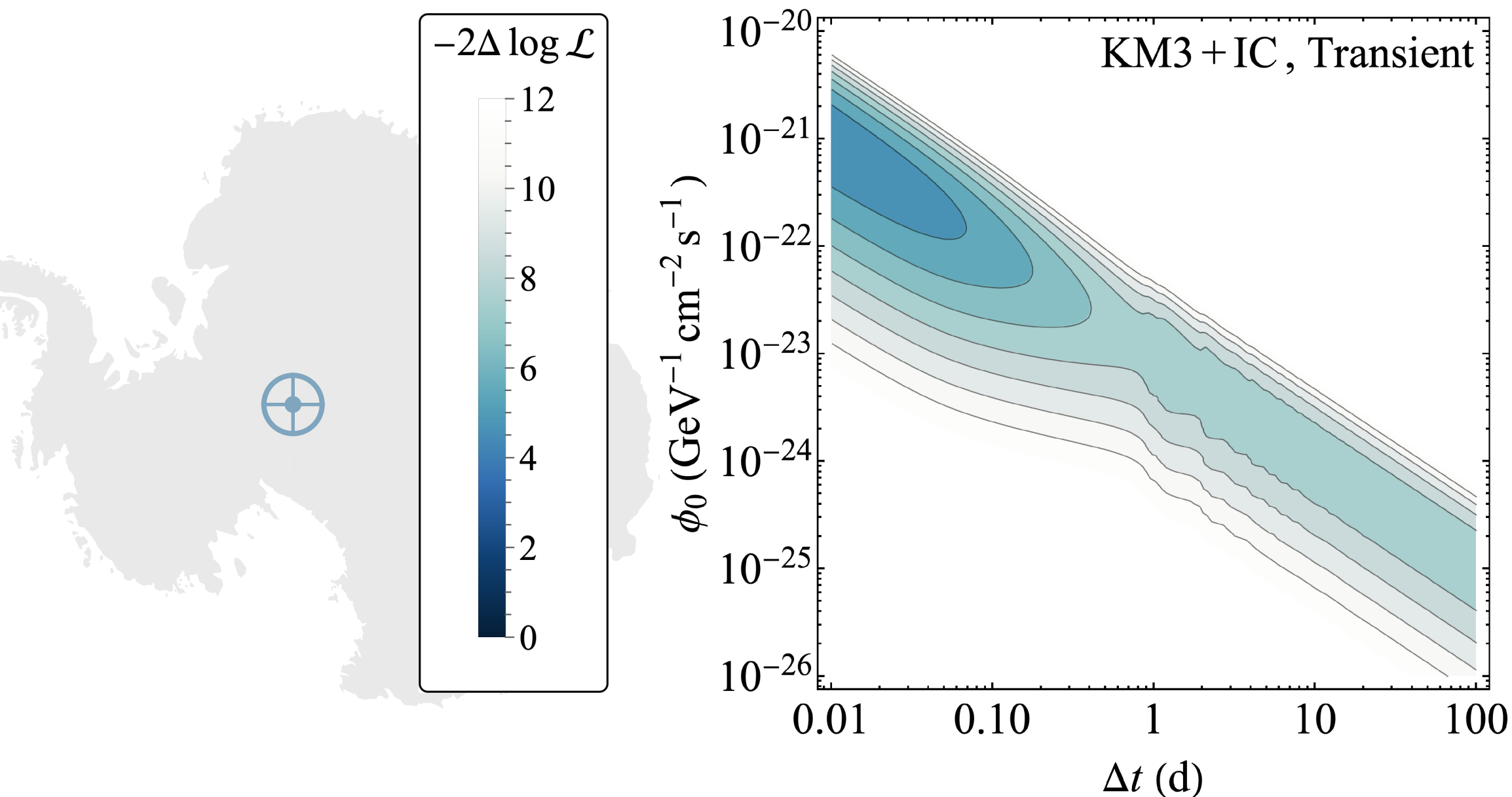
Fixed transient sources

- We consider a fixed E_ν^{-2} spectra
- ANITA-IV events:
 - Event A in unfavorable location for IceCube...
 - Event B and C prefer short-duration transients
 - Event D prefers $\mathcal{O}(100)$ day duration



The KM3-230213A anomaly

- Even for extremely short-duration transients, tension remains...
- Short duration transients: 1.8σ tension
- Longer durations: $\sim 2.5 \sigma$ tension

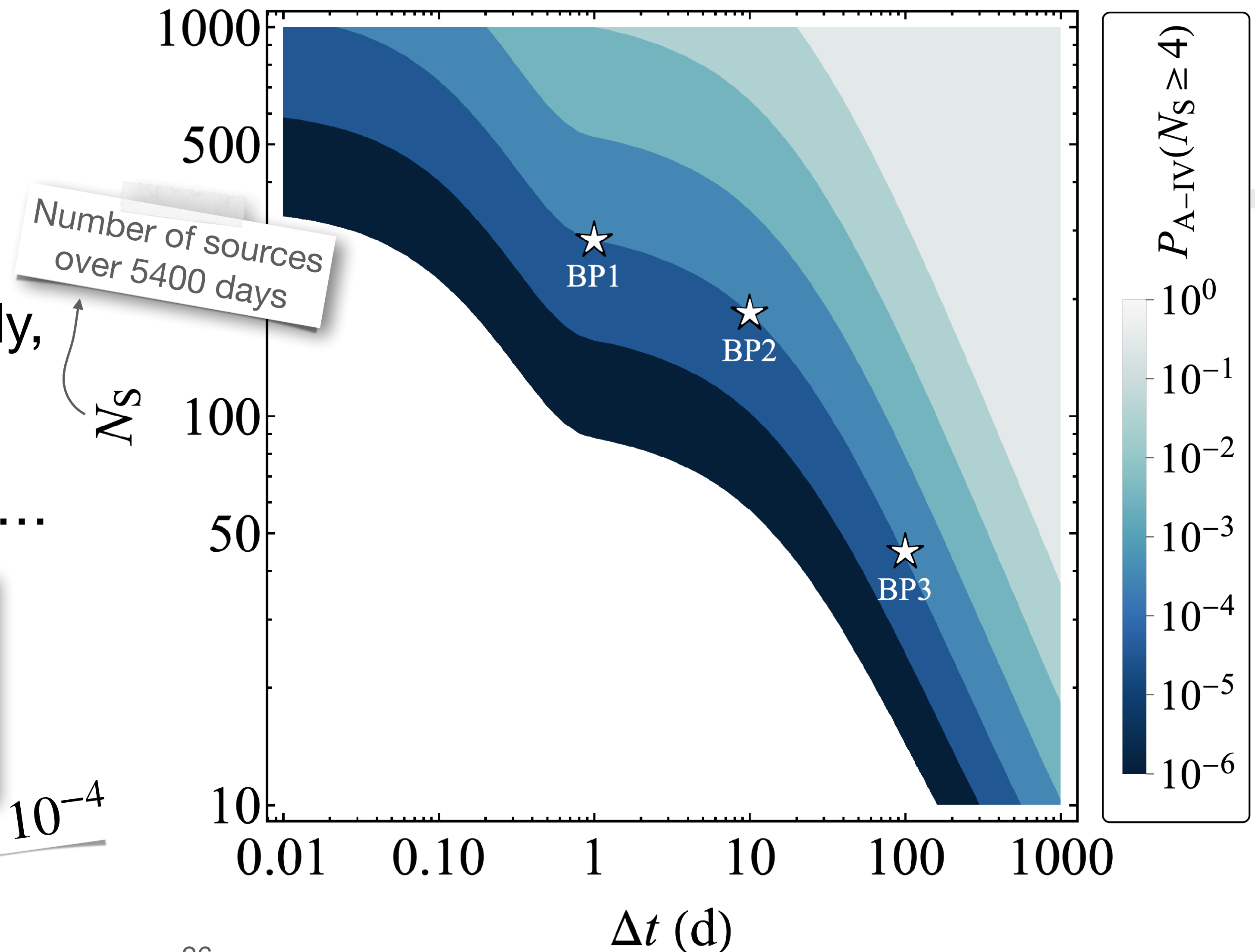


How rare is too rare?

- Highly fine tuned: Fixing 5 transients at 5 specific directions & detection times
- Probability that ANITA-IV observed 4 transients optimally, $\theta \in (-10^\circ, -5^\circ)$
- We take 3 benchmarks points...

BP1 : $(\Delta t, N_S) = (1 \text{ d}, 285)$
BP2 : $(\Delta t, N_S) = (10 \text{ d}, 185)$
BP3 : $(\Delta t, N_S) = (100 \text{ d}, 45)$

$$P_{\text{A-IV}}(N_S \geq 4) \approx 10^{-4}$$



A statistical treatment of rare transients

- Expected event count at ANITA-IV, IceCube, & KM3NeT
- Best-fit BP2 still leads to an anomaly of 5.9σ ...

Scenario	ϕ_0 ($\text{GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$)	$\mu_{\text{A-IV}}$	μ_{IC}	μ_{KM3}	$-2\Delta \log \mathcal{L}$
BP1	5.48×10^{-25}	0.035	4.945	0.020	45.80
	4.55×10^{-25}	0.032	4.955	0.013	47.37
	5.48×10^{-25}	0.025	4.948	0.027	47.90
BP2	8.39×10^{-26}	0.067	4.911	0.022	40.38
	7.16×10^{-26}	0.054	4.928	0.018	42.42
	8.57×10^{-26}	0.041	4.917	0.042	42.96
BP3	3.02×10^{-26}	0.048	4.914	0.038	41.93
	4.49×10^{-26}	0.046	4.943	0.011	44.78
	4.33×10^{-26}	0.032	4.931	0.038	45.26

BP1 : $(\Delta t, N_S) = (1 \text{ d}, 285)$

BP2 : $(\Delta t, N_S) = (10 \text{ d}, 185)$

BP3 : $(\Delta t, N_S) = (100 \text{ d}, 45)$

Choose the BP, fix the number of sources and duration



Run 10^5 MC realizations, uniform across 5400 days and over all-sky



Require 4 or more optimally observed sources at ANITA-IV, overlapping over ~ 26.6 days of flight



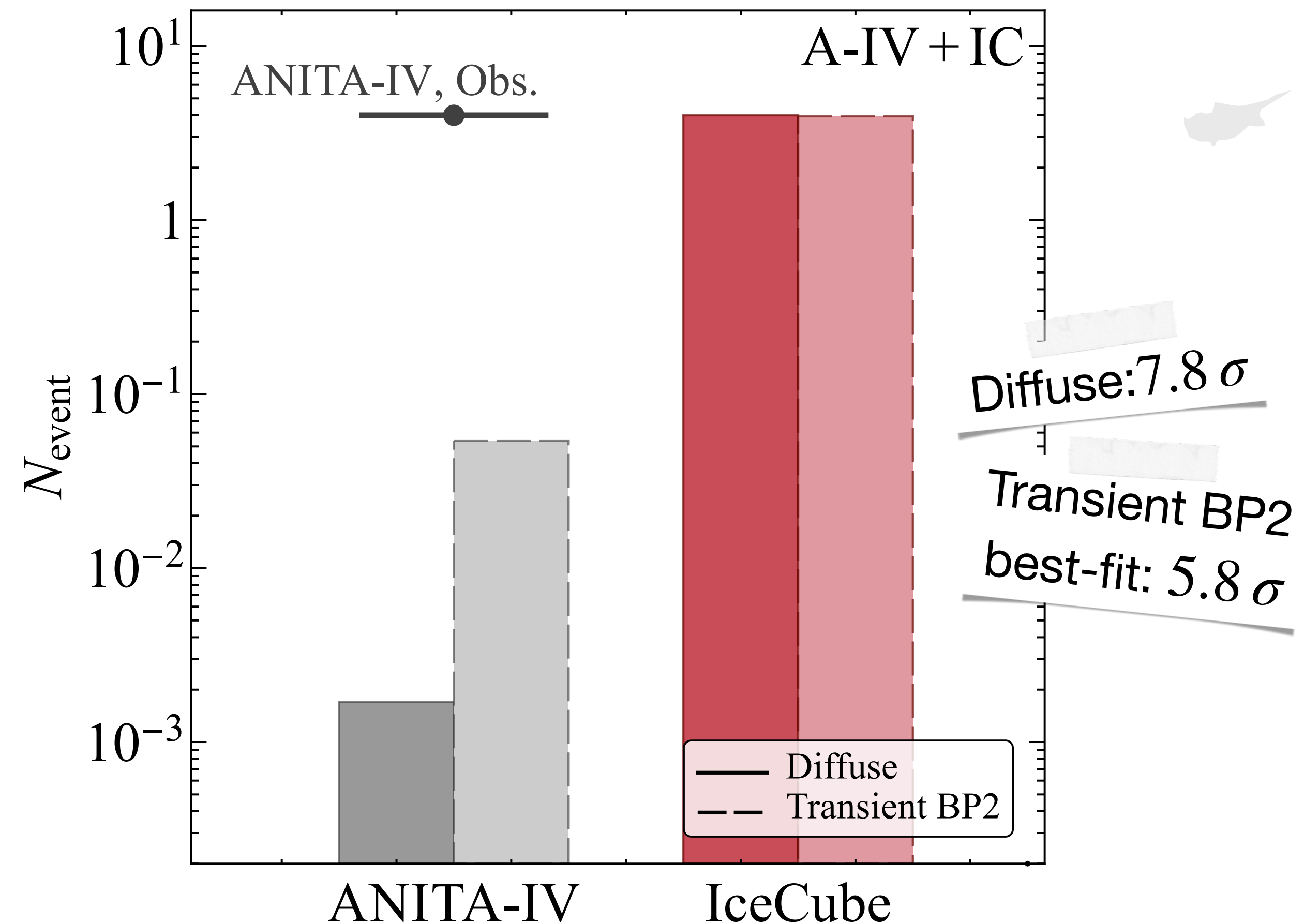
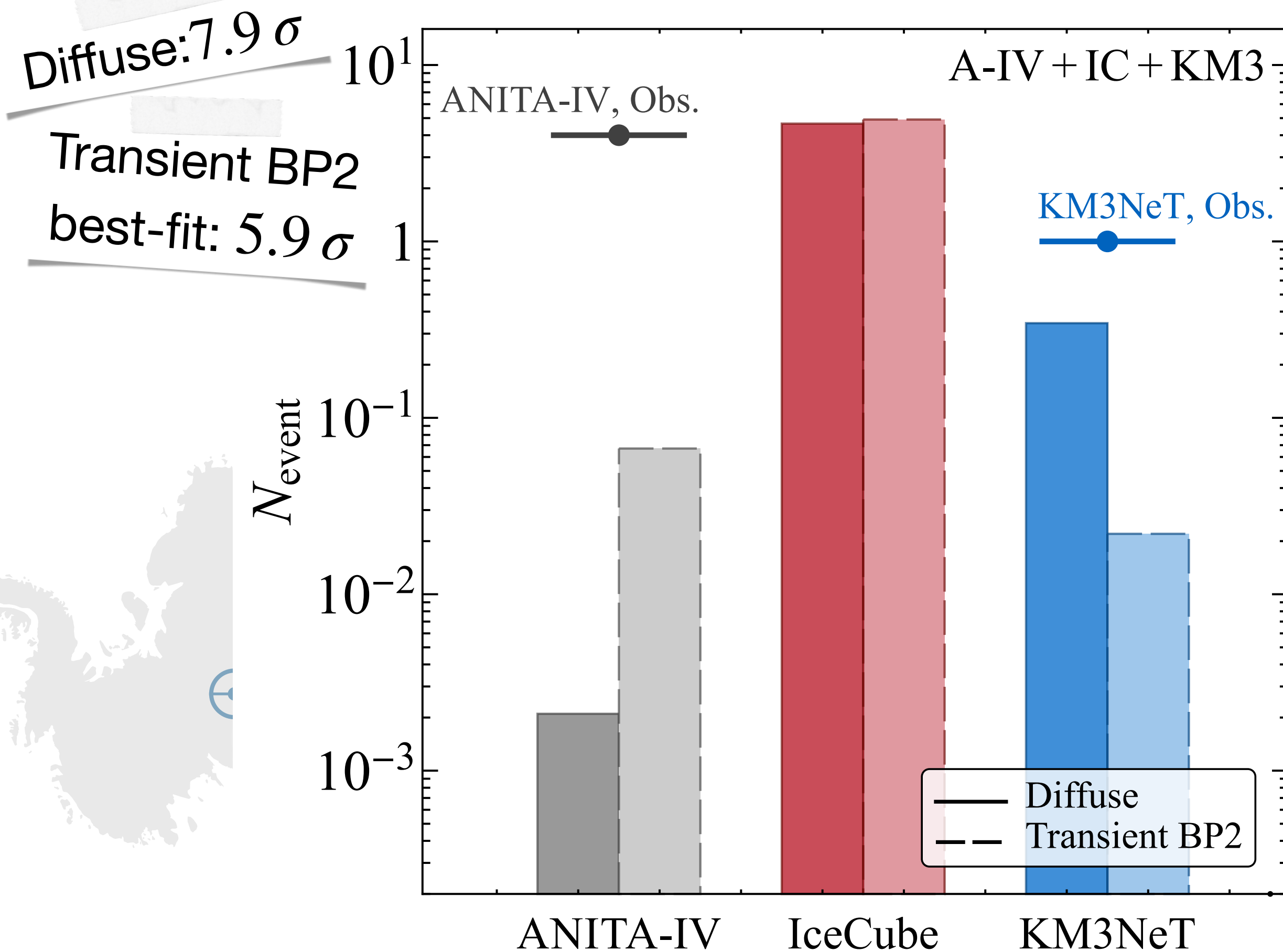
Select realizations with non-zero expected events at all 3 detectors



Present the top 3 realizations for each benchmark point, quantify the anomaly

Rare transients vs. all-sky diffuse...

- We run the analysis for both 3 detector and 2 detector combinations



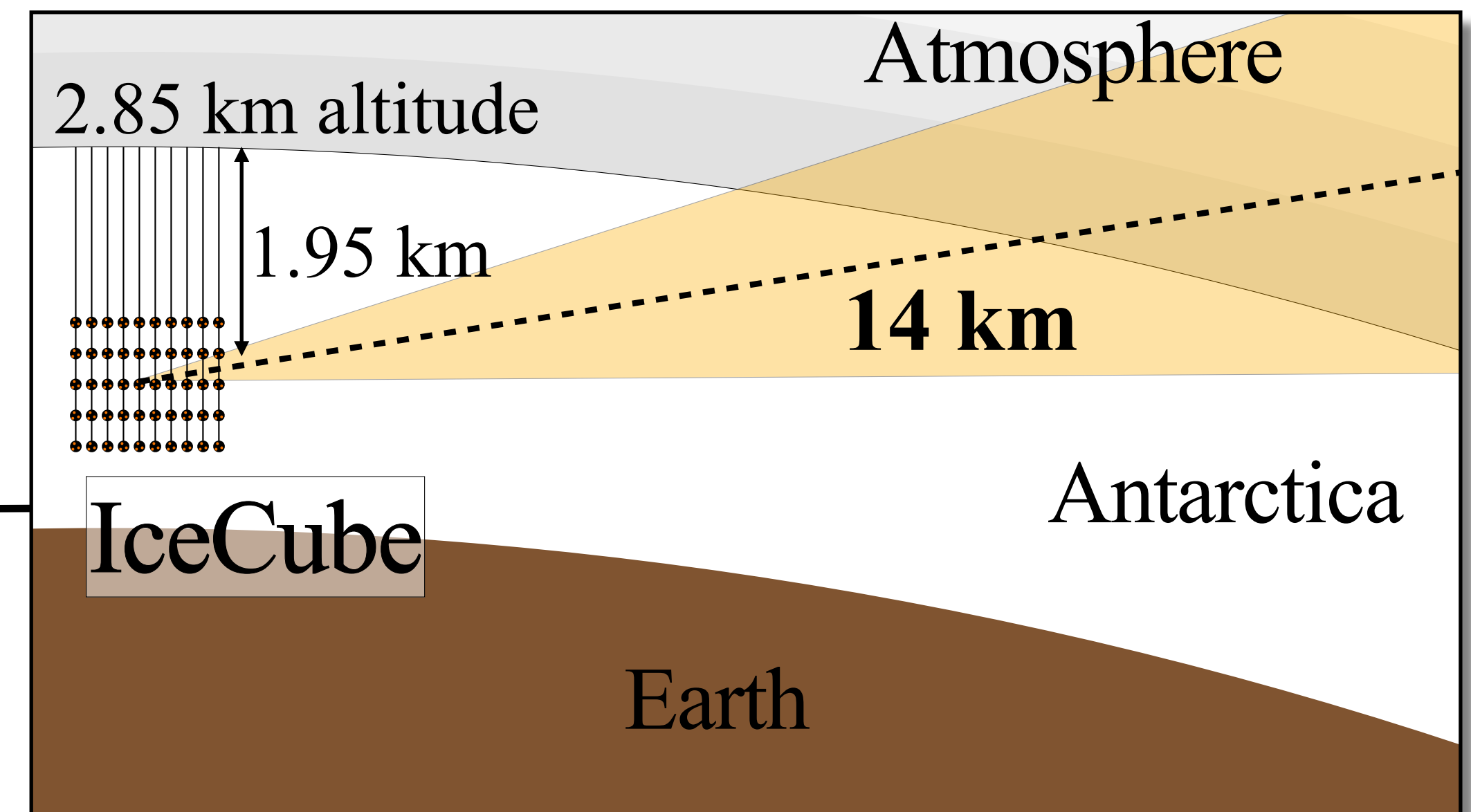
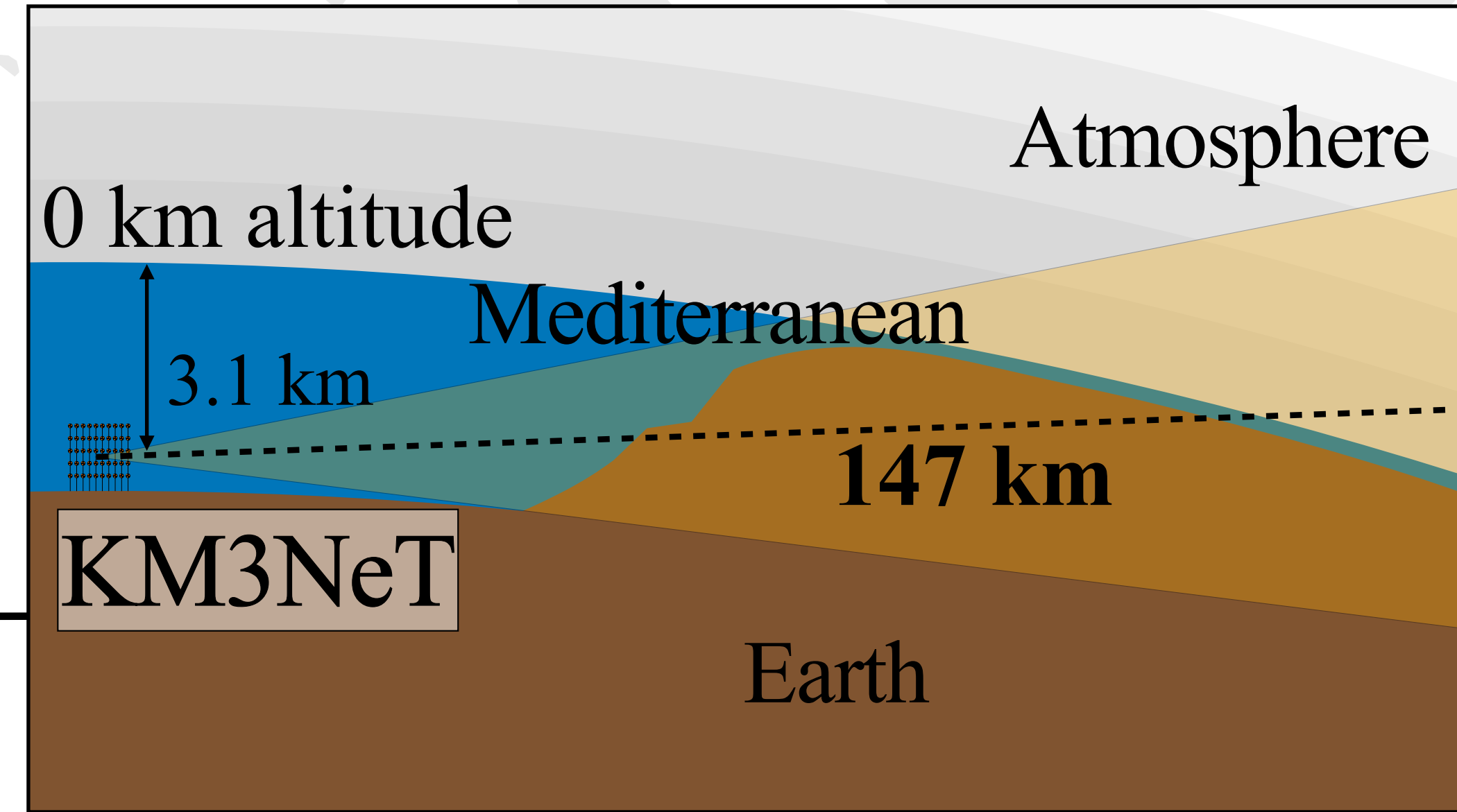
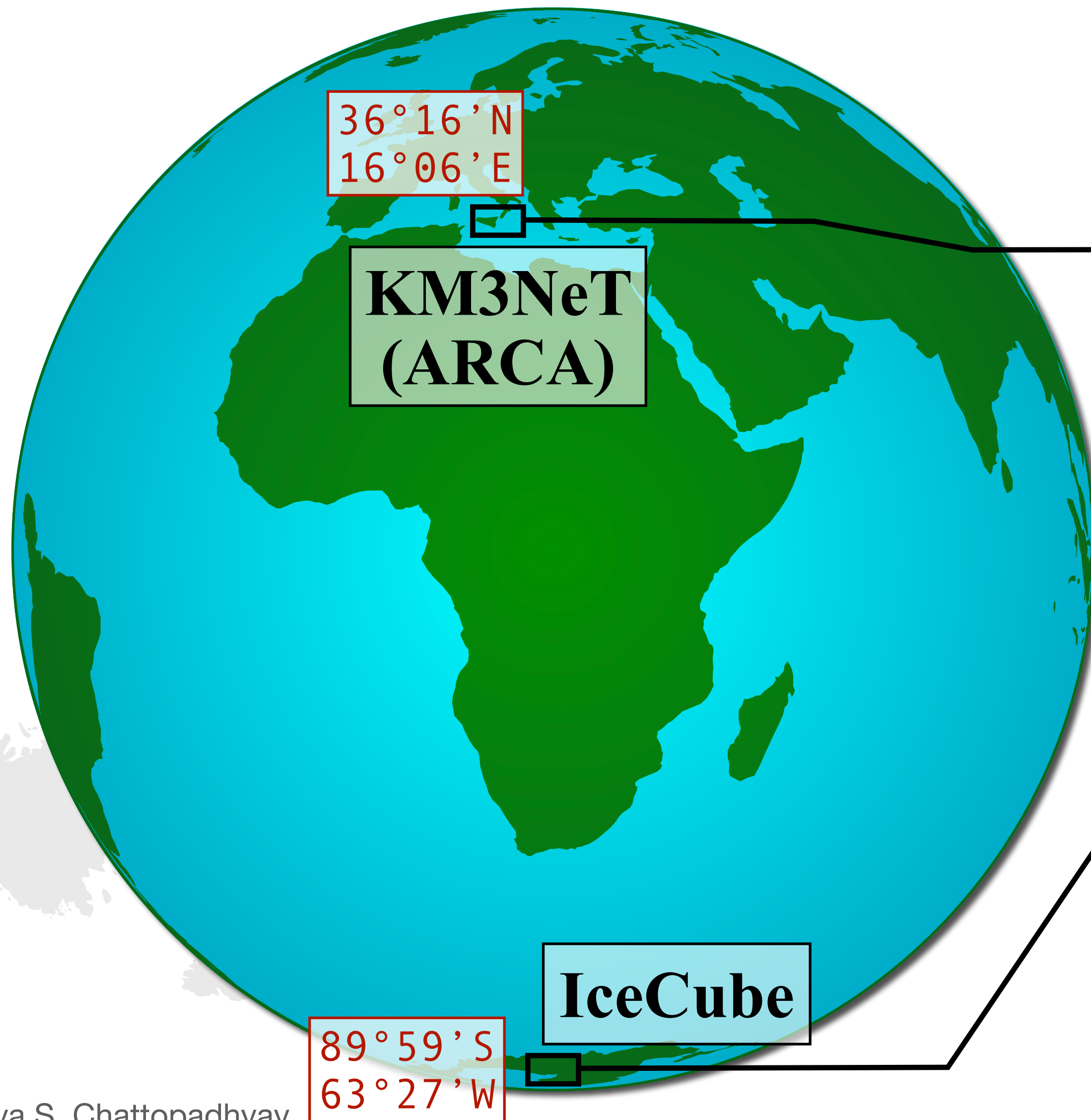


Trying to **resolve the anomaly**

If I had an hour to solve a problem I'd spend 55 minutes thinking about the problem and **5 minutes thinking about solutions.**

— Albert Einstein

KM3NeT vs. IceCube



Resonant sterile neutrinos

- We can fix the resonance as a function of sterile neutrino mass and the sterile potential
- Baryonic sterile neutrinos, resonance at UHE...

$$\mathcal{L} \supset g'_b \bar{\nu}_s \not{V} \nu_s + (g_b/3) \sum_q \bar{q} \not{V} q + \text{h.c.}$$

Maxim Pospelov,
arXiv:1103.3261 [hep-ph]

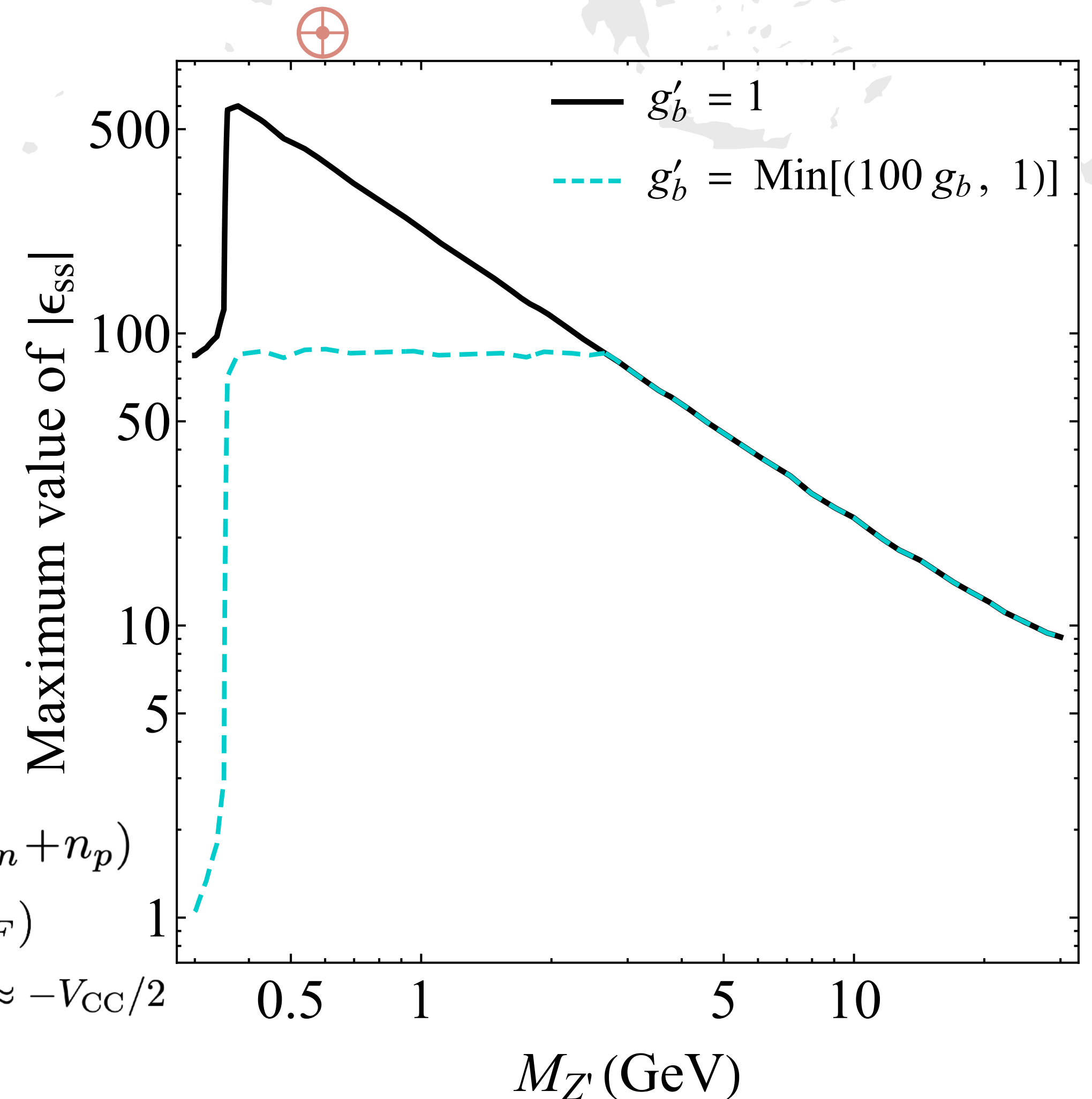
$$\mathcal{L}_{\text{eff}} \supset \frac{G_B}{2} [\bar{\nu}_s \gamma_\mu (1 - \gamma_5) \nu_s] [\bar{p} \gamma^\mu p + \bar{n} \gamma^\mu n]$$

$$H = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & \frac{m_s^2}{2E_\nu} \end{pmatrix} \begin{pmatrix} c_\theta & -s_\theta \\ s_\theta & c_\theta \end{pmatrix} + \begin{pmatrix} V_{\text{NC}} & 0 \\ 0 & V_s \end{pmatrix}$$

$$V_s = \sqrt{2} G_F \epsilon_{ss} (n_n + n_p)$$

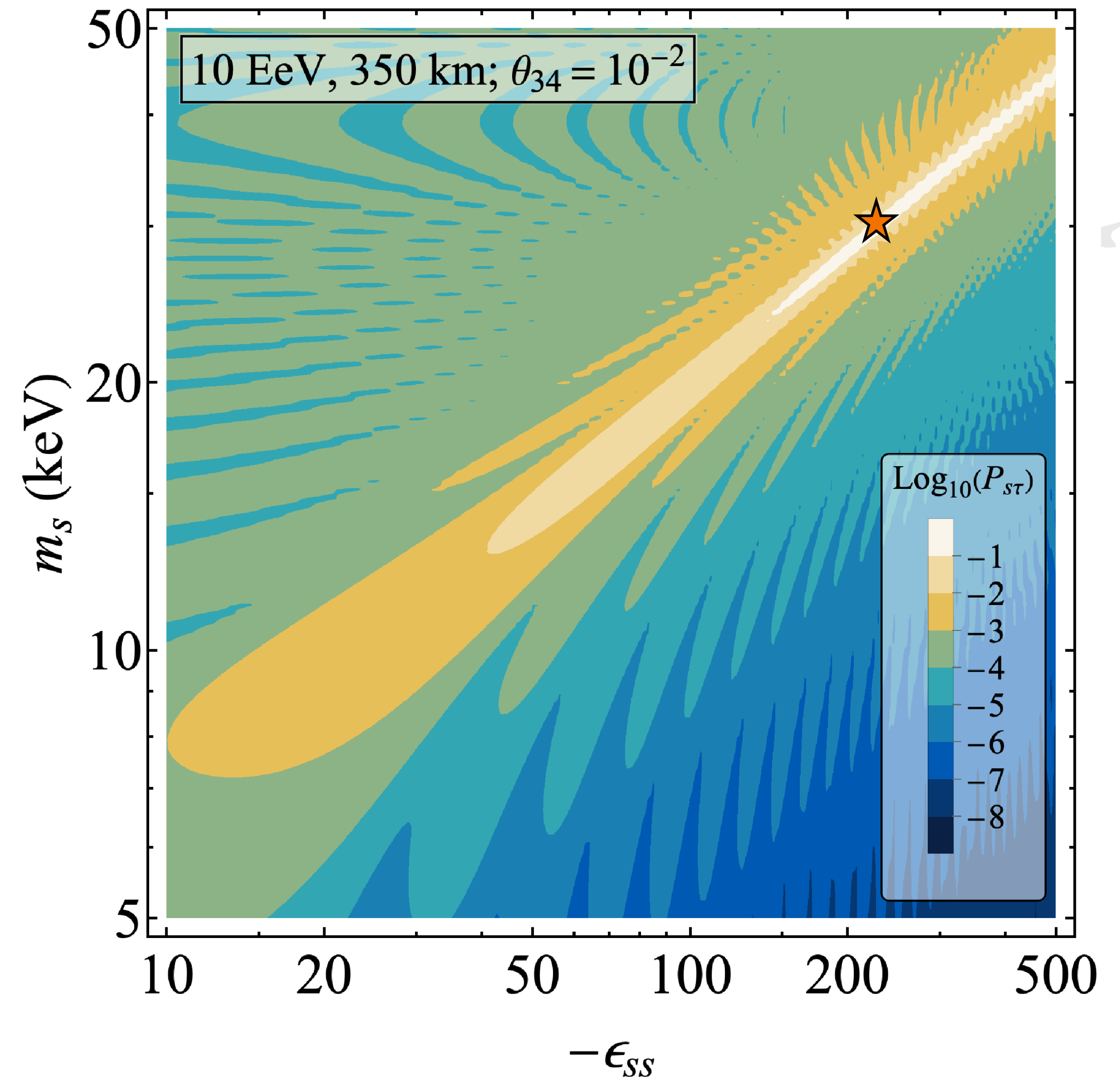
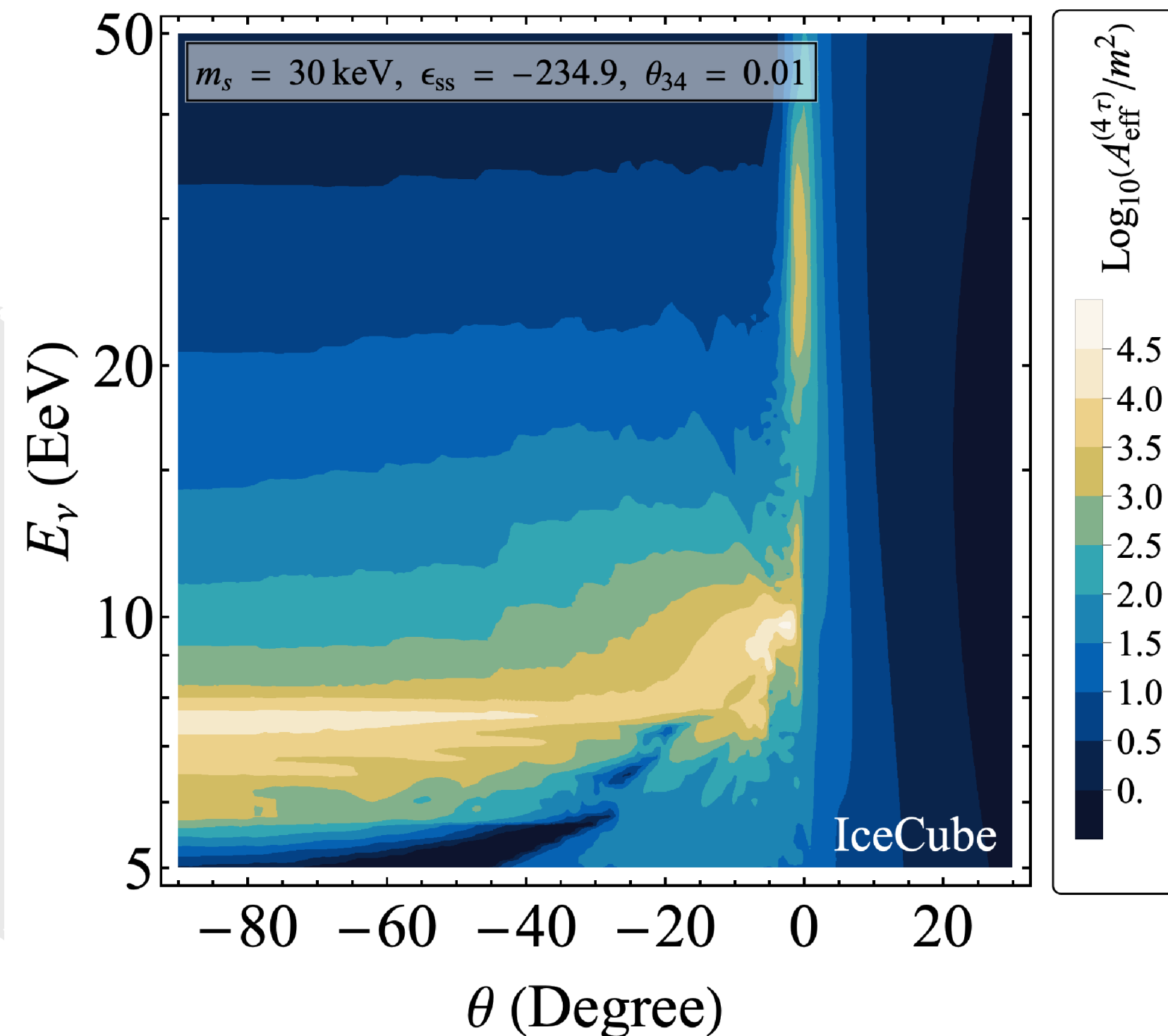
$$\epsilon_{ss} = G_B / (\sqrt{2} G_F)$$

$$V_{\text{NC}} = -G_F n_n / \sqrt{2} \approx -V_{\text{CC}}/2$$



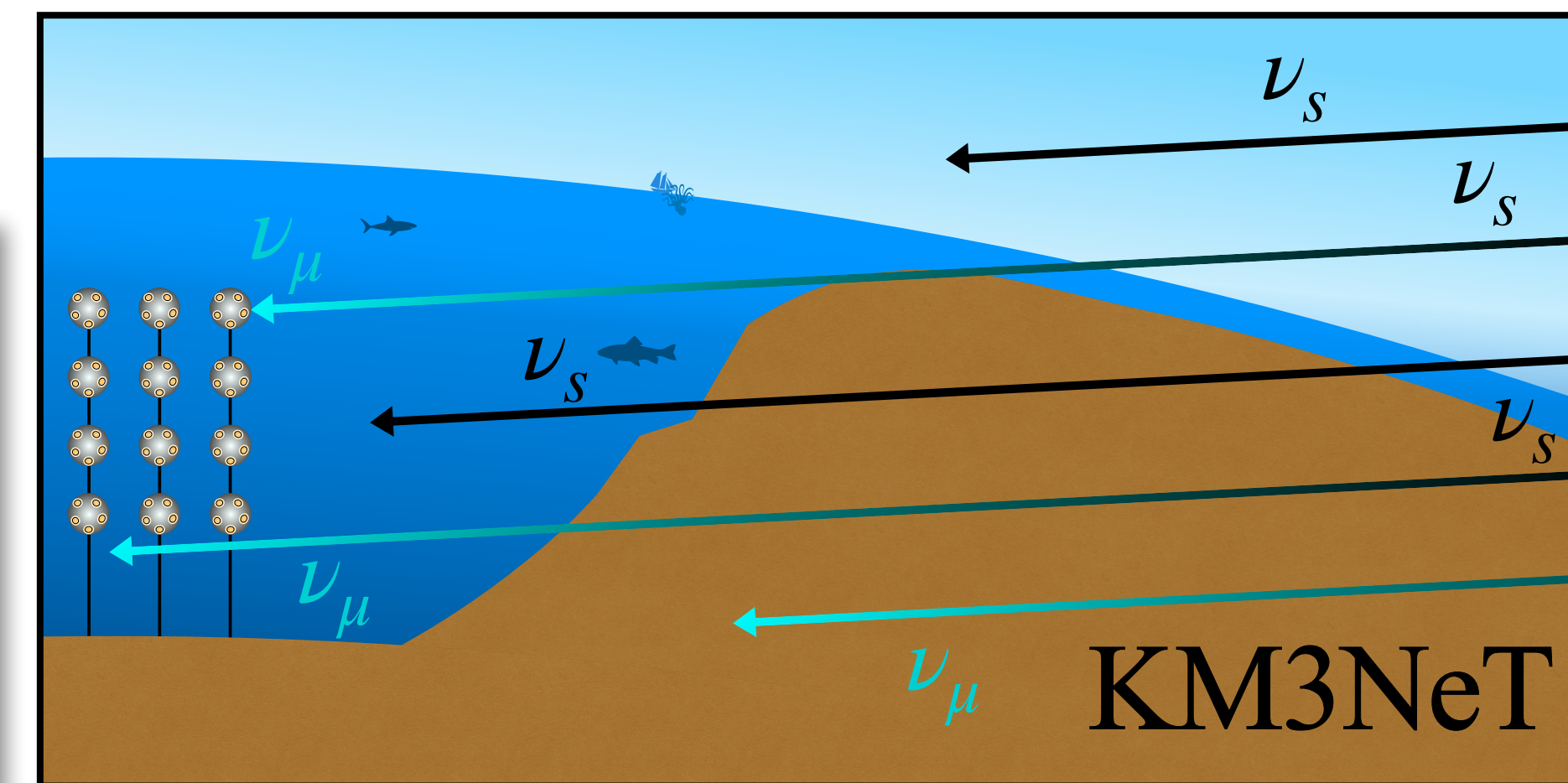
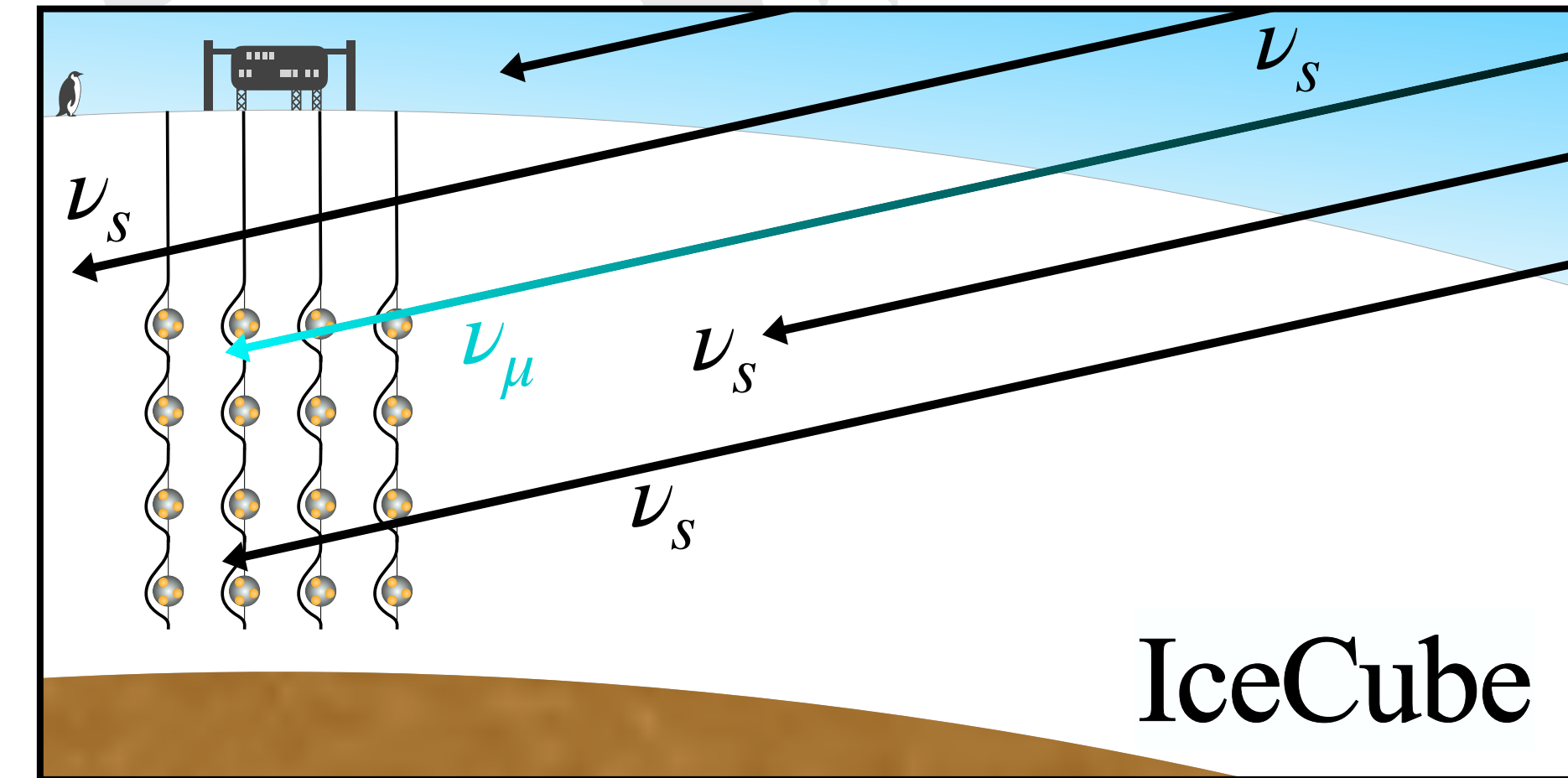
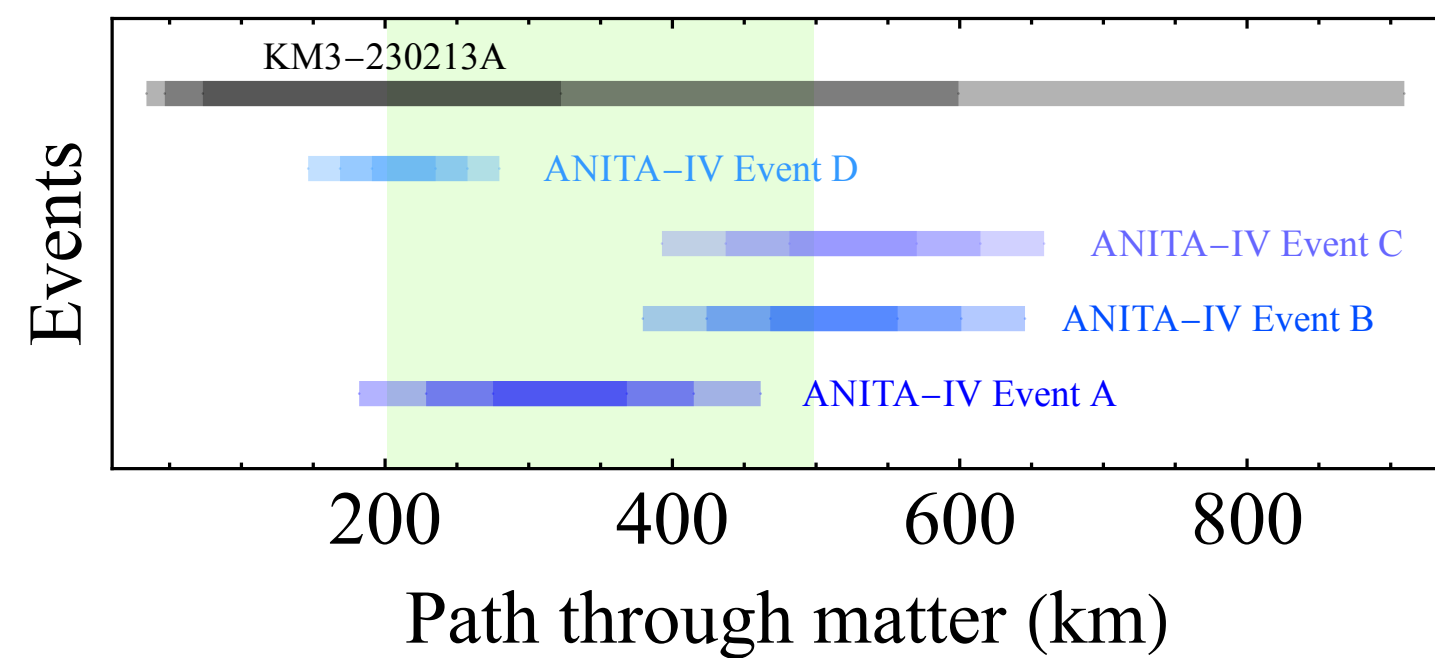
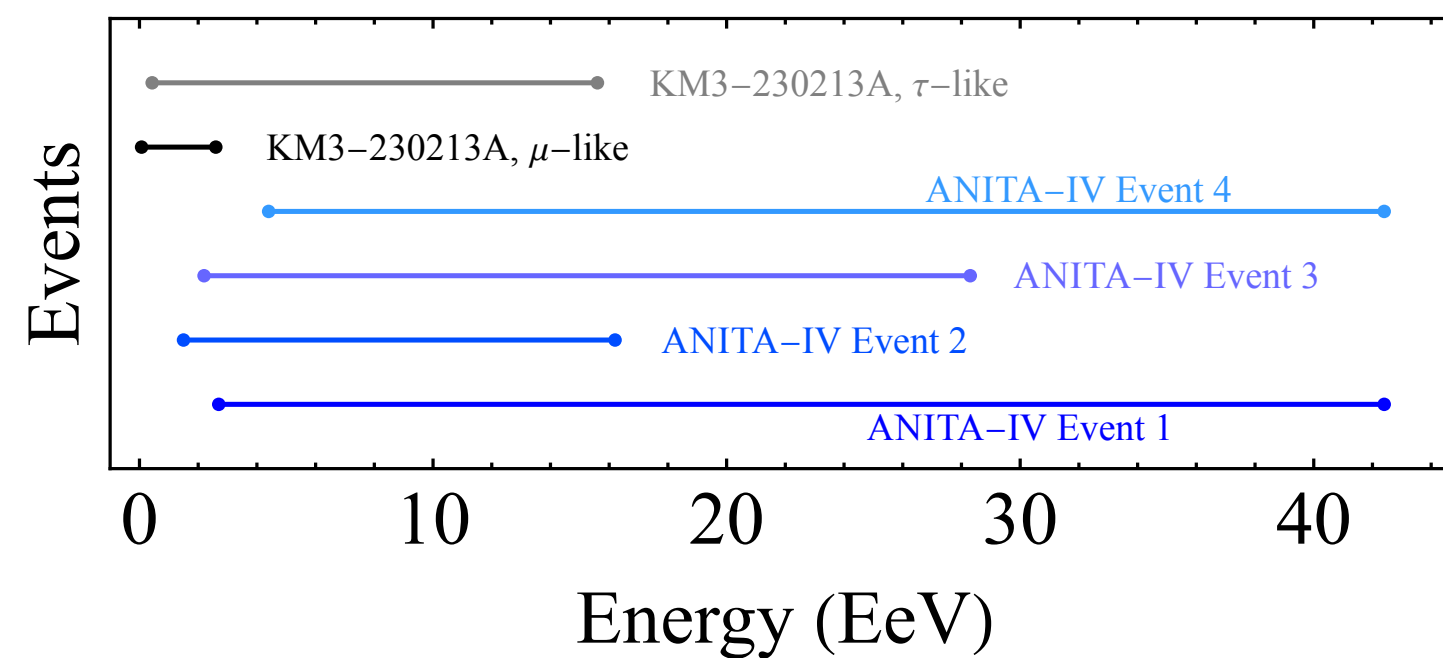
Through matter-induced resonance...

- Vacuum mixing angle at $\theta = 10^{-2}$
- Large sterile-to-active neutrino flux at KM3NeT, small flux at IceCube.



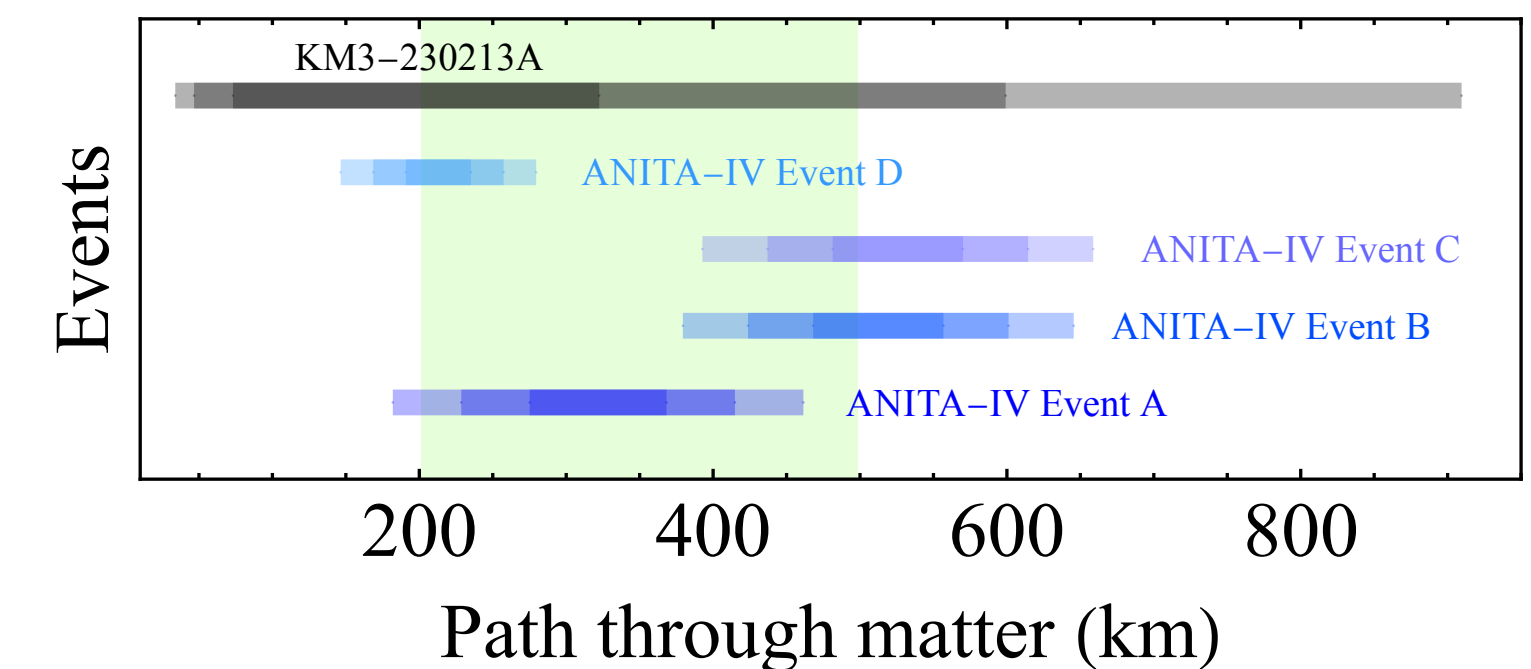
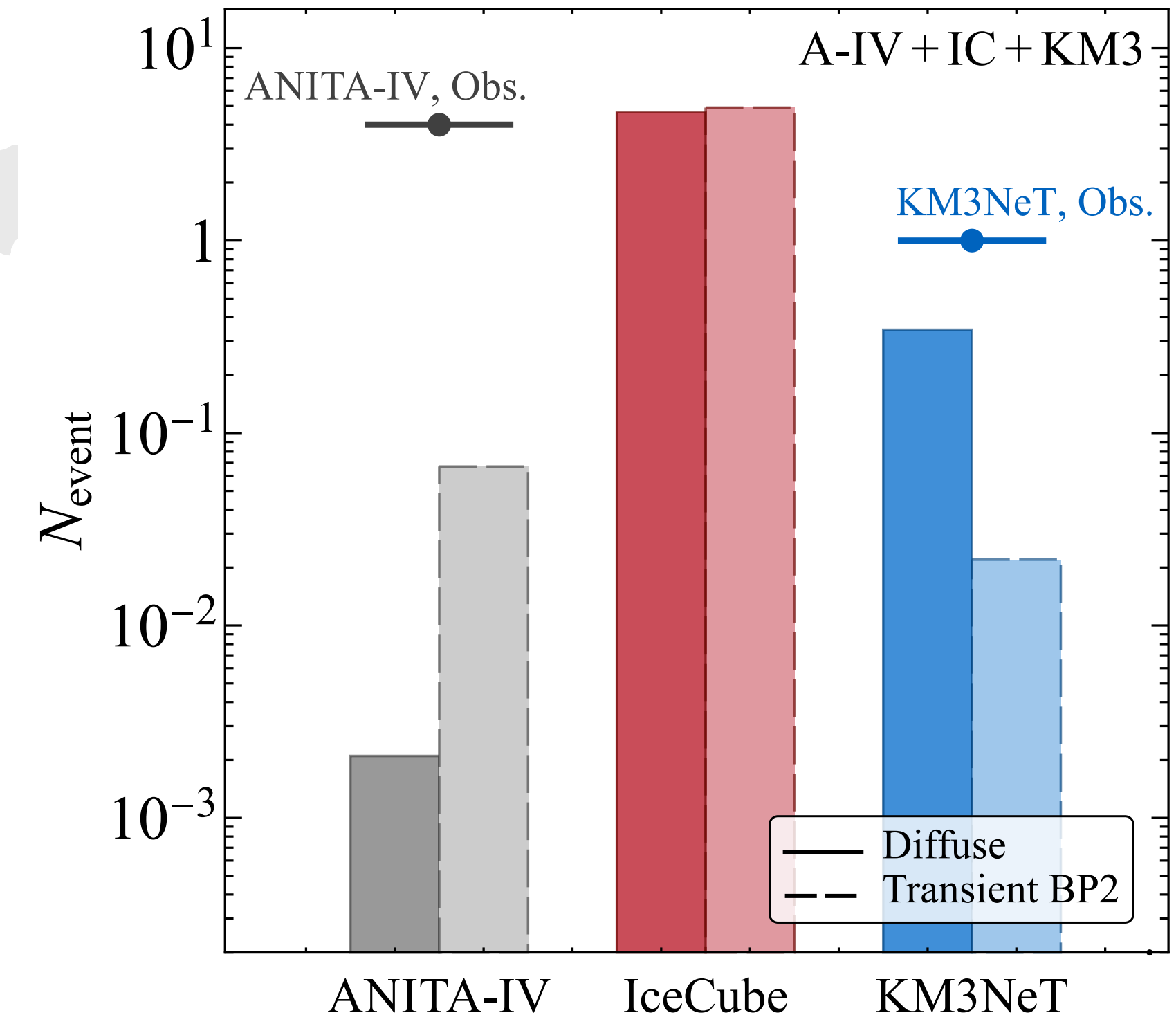
Matter enhanced BSM sector...

- A matter effect enhanced $\nu_s \rightarrow \nu_\tau/\nu_\mu$ scenario can alleviate the KM3NeT vs. IceCube tension
- For ANITA-IV, many transients over all-sky, ~ 15 years, makes IceCube non-observation difficult.
- BSM scenarios need to prefer $\mathcal{O}(100 - 1000)$ km, and $\mathcal{O}(1 - 10)$ EeV energies...



Conclusion

- UHEs: favourable regime for new physics
- Anomalous non-observation at IceCube: anomaly upwards of 7.5σ for a diffuse flux
- Even for transient sources, $\sim 6 \sigma$ anomaly
- For KM3-230213A, 1.8σ anomaly for short-duration transients, reaching up-to 2.5σ for longer-duration transients...
- Hint for BSM? Prefers a baseline of (300-1000) km; energy around $\sim (1-10)$ EeV
- Hard to escape detection of similar events at IceCube





Backup slides

Transient sources...

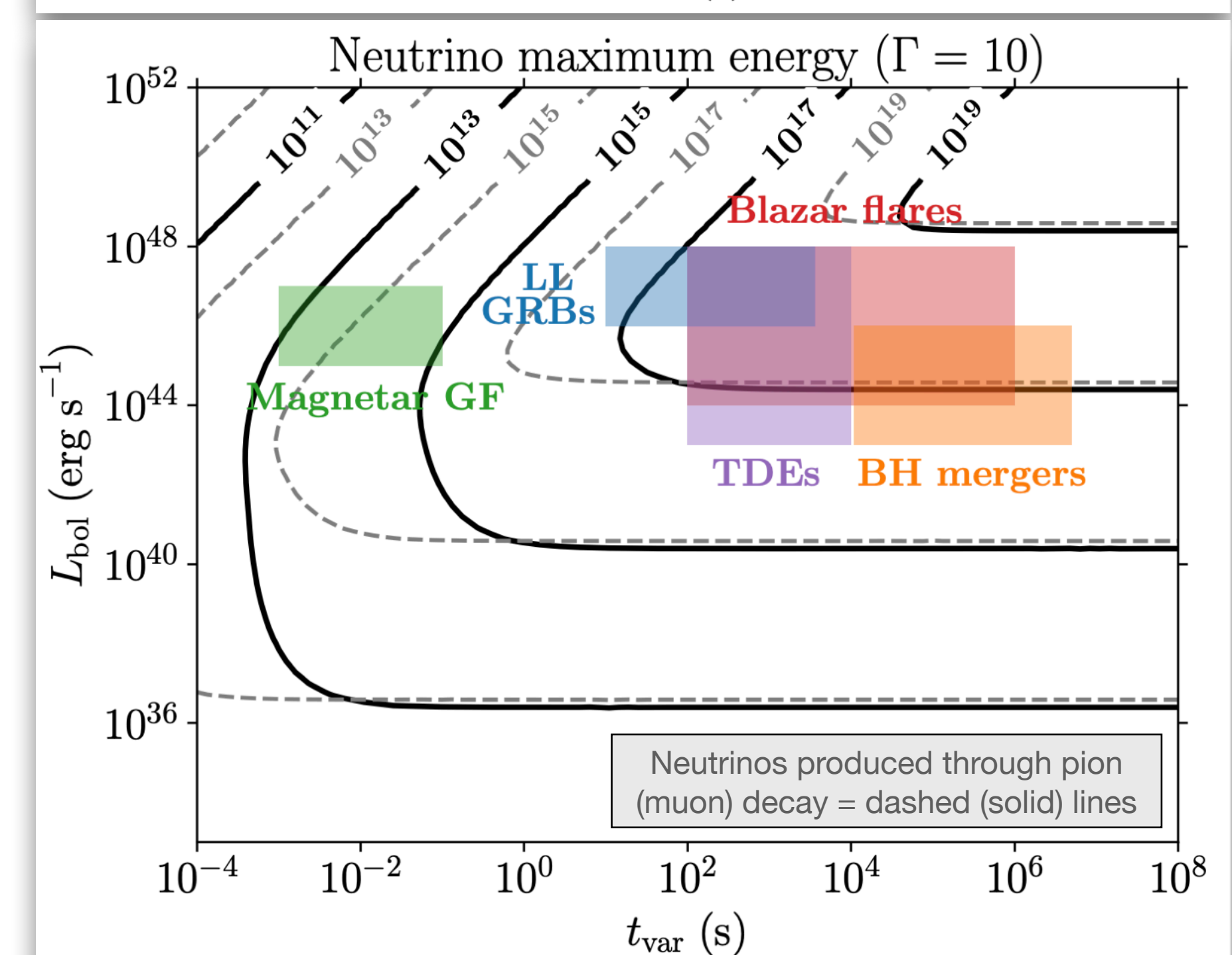
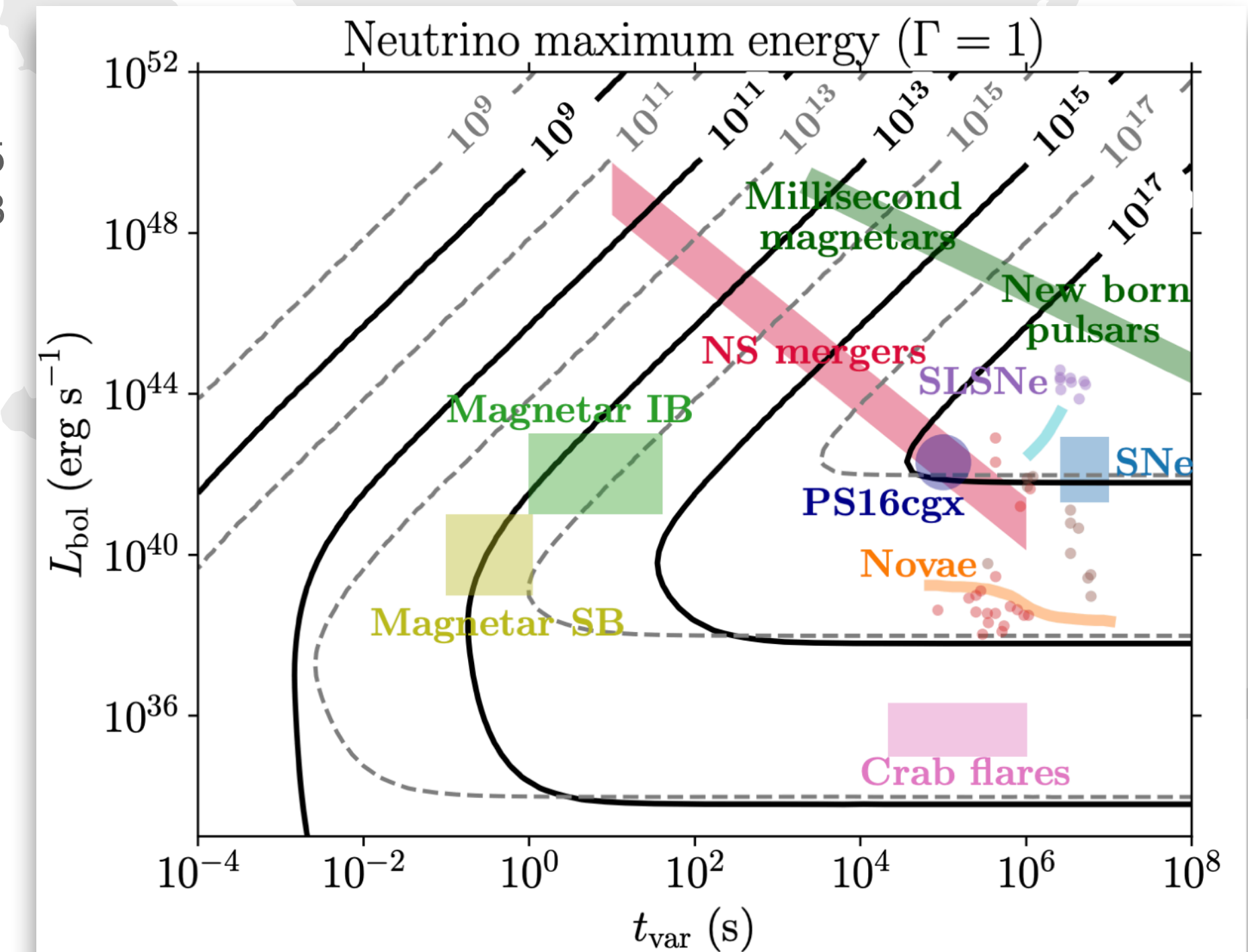
arXiv: 2207.12205
arXiv: 1701.07038

- UHE neutrino flux: Blazar flares, TDEs, Long-lived GRBs, SNe, New born pulsars...
- UHE usually requires a somewhat longer-lived transient source
- The bolometric luminosity requires the short-lived (~ 1000 s) sources to be within xyz Mpc distance

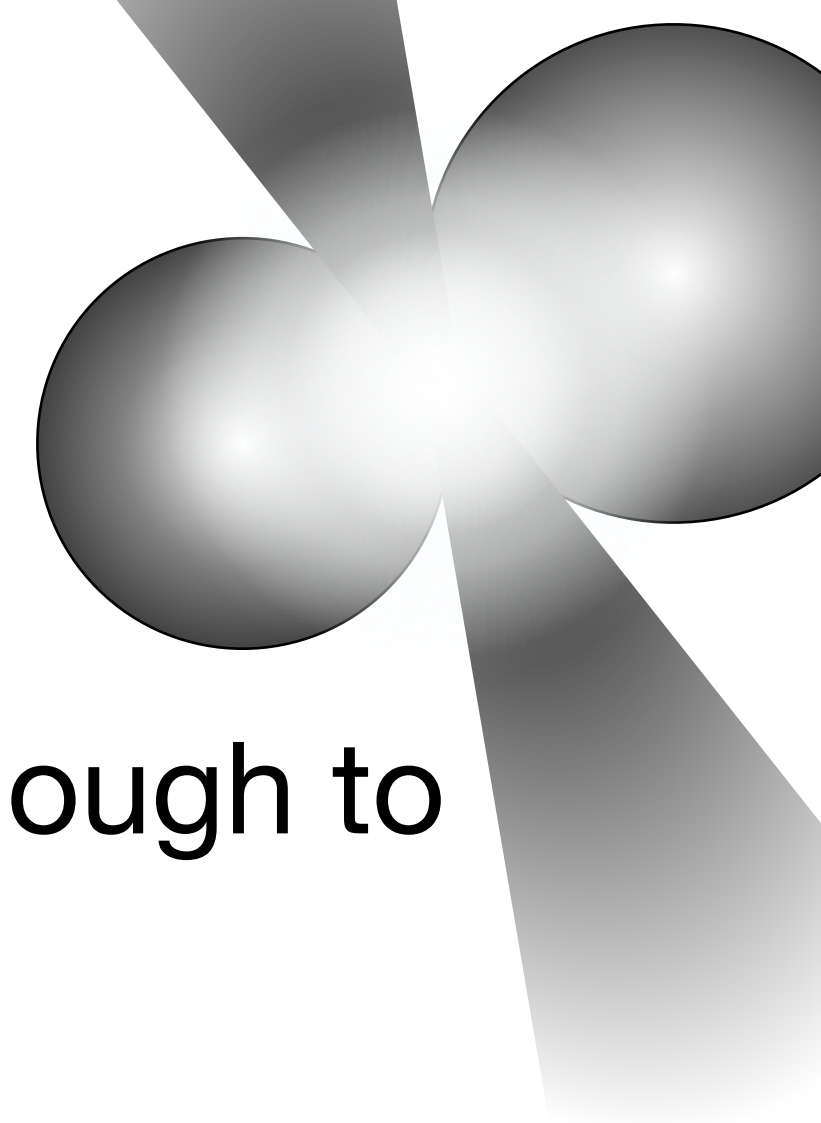
$$\phi_{E_\nu} \approx 10^{-6} \text{ erg cm}^{-2} \text{ s}^{-1}$$

$$\oplus 10^{50} \text{ erg s}^{-1} / (1 \text{ Gpc})^2 \approx 10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1}$$

- No SM counterpart observed from the directions of the 4 ANITA-IV events and KM3-230213A...



Transient sources, BSM edition

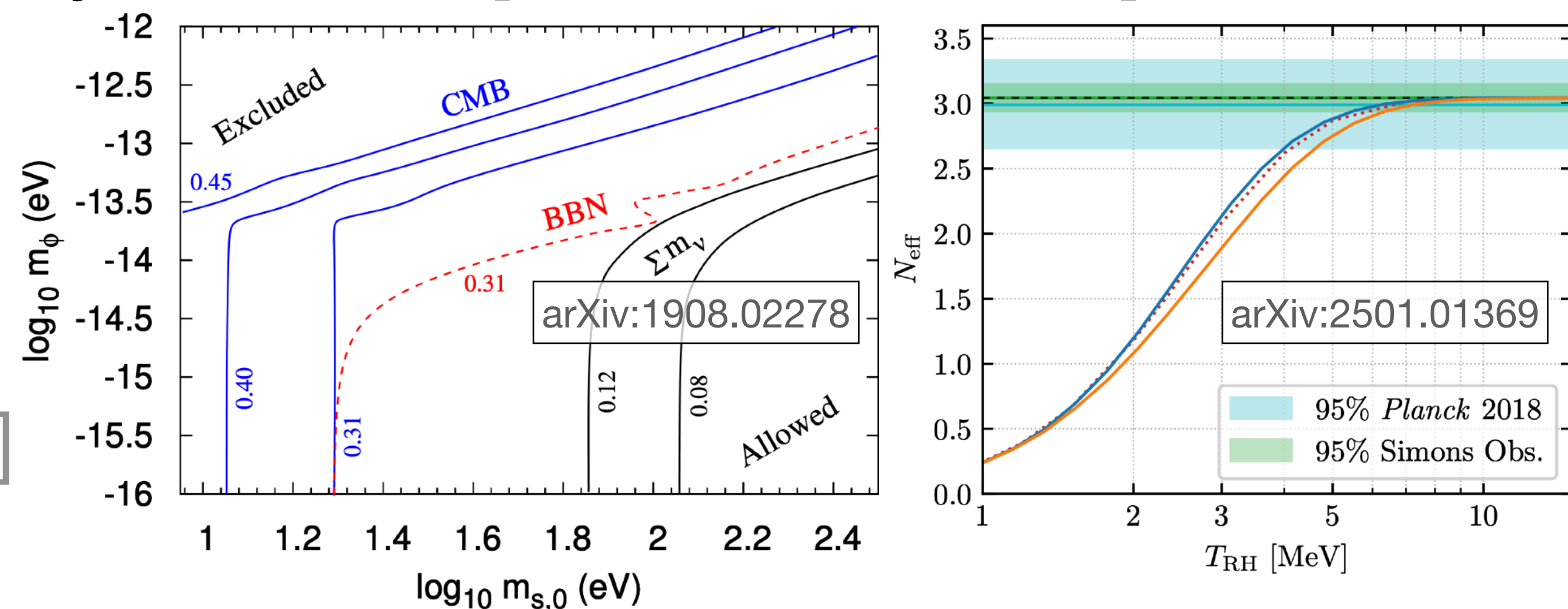


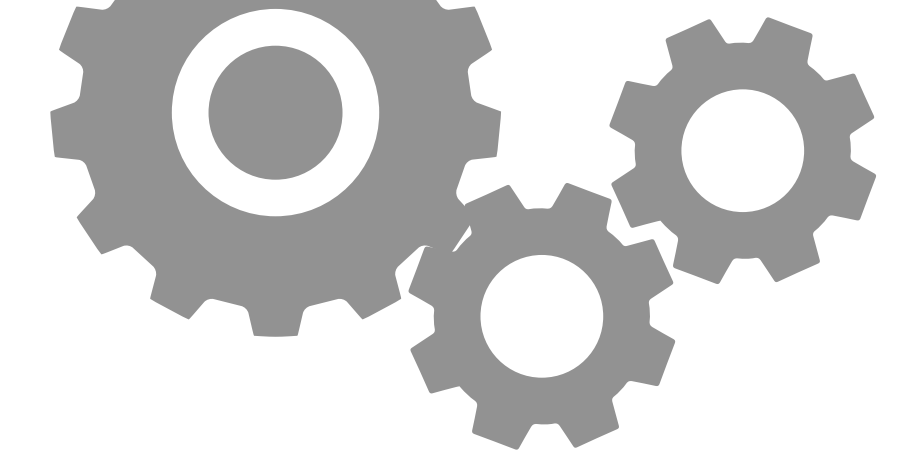
- Choked GRBs have column densities upto $(10^{11} - 10^{12}) \text{ g/cm}^2$, enough to stop PeV and higher energy active neutrinos.
- Mirror Dark Sector Stars
 - possible, but with constraints from microlensing, what process would create so many UHE sterile neutrinos?
- Dark sector interaction that stop active neutrinos
 - good idea, with caveats, neutrinos at lower energies should not be stopped upto $\sim \text{Gpc}$ distances.
- A mirror sector, with dark baryons giving us sterile neutrinos around Blazars?
 - Any sterile neutrino regulated story will be located where the blazars are

Large active-sterile mixing and cosmology

- Yukawa coupling of the sterile neutrinos to ultra-light scalar particles which contribute to the DM $\rightarrow$ larger masses in early universe [arXiv:1907.04271, arXiv:1908.02278]
- Sterile neutrinos + secret self interactions [arXiv:1310.6337]
- Sterile neutrinos with initially a very large mass generated by the vev of a new scalar field $\rightarrow$ production is kinematically forbidden [arXiv:1806.10629]
- Delayed Thermalization: low reheating temperature [arXiv:2501.01369]
- Non-standard cosmology (e.g. generalized gravity) [arXiv:1909.04168]

** This is a very incomplete list...*





Model building 101

- A light vector boson, associated with a spontaneously broken $U(1)_B$ symmetry, interacting with ν_s and quarks... [arXiv:1103.3261, M. Pospelov]
 - Introduce a new gauge group $U(1)_B$
 - Give all quark fields of the SM, the same charge ($g_b/3$) under $U(1)_B$
 - Introduce a new left-handed neutrino species that has a charge g_l under $U(1)_B$ + no charge under any of the SM gauge groups.
 - Assume that $U(1)_B$ is spontaneously broken by the $U(1)_B$ -Higgs vacuum expectation value

$$\mathcal{L} \supset g'_b \bar{\nu}_s \not{V} \nu_s + (g_b/3) \sum_q \bar{q} \not{V} q + \text{h.c.}$$

Maxim Pospelov, arXiv:1103.3261 [hep-ph]

$$\mathcal{L}_{\text{eff}} \supset \frac{G_B}{2} [\bar{\nu}_s \gamma_\mu (1 - \gamma_5) \nu_s] [\bar{p} \gamma^\mu p + \bar{n} \gamma^\mu n]$$

Joachim Kopp, Johannes Welter,
arXiv:1408.0289 [hep-ph]

Effective area...

- Effective area of a neutrino detector is given by:

$$A_{\text{eff}} \approx \rho N_A V \sigma(E_\nu) e^{-\tau(E_\nu, \cos \theta)} \epsilon(E_\nu, \cos \theta)$$

Avogadro's number N_A

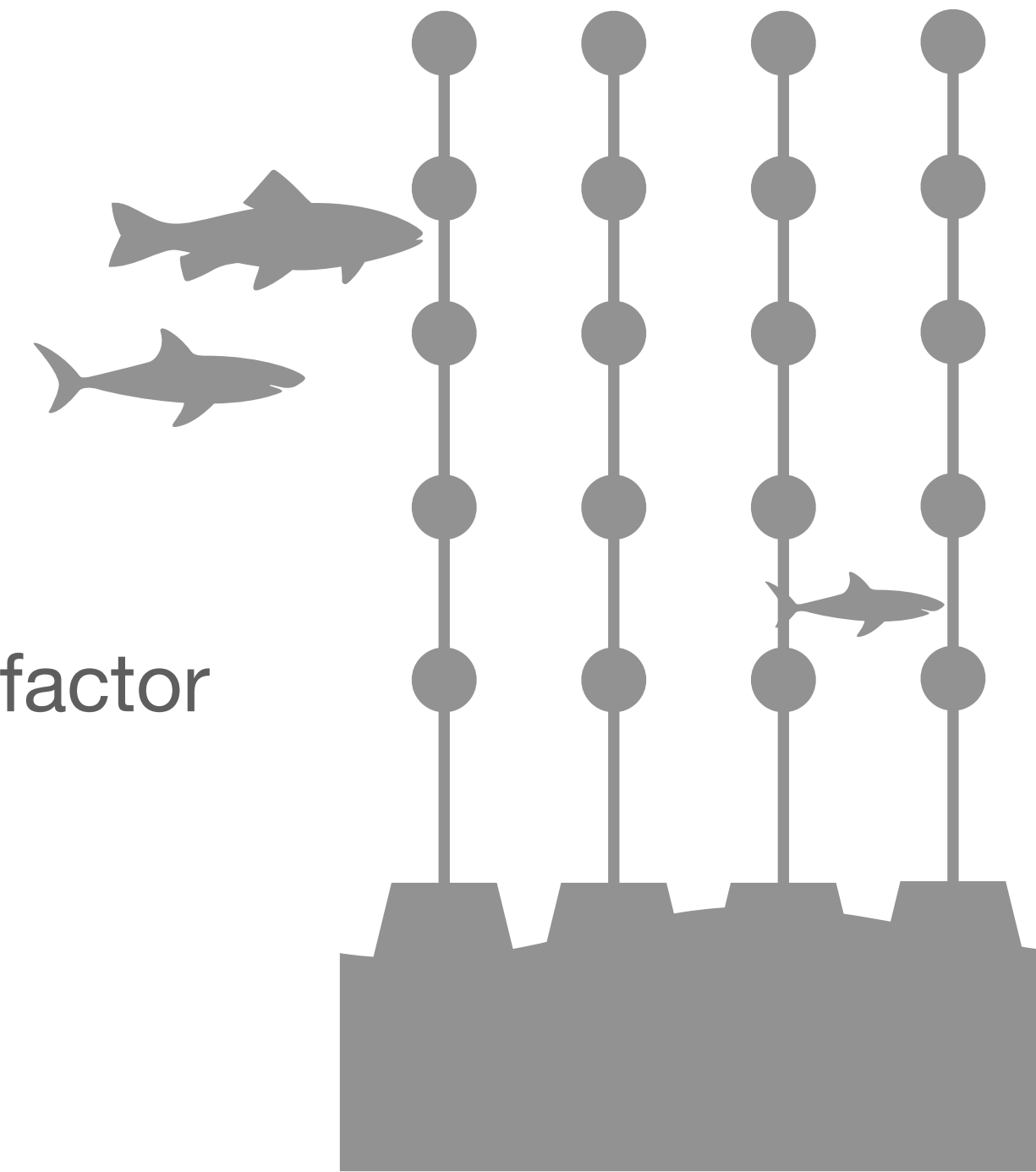
density ρ

volume V

cross-section $\sigma(E_\nu)$

attenuation factor $e^{-\tau(E_\nu, \cos \theta)}$

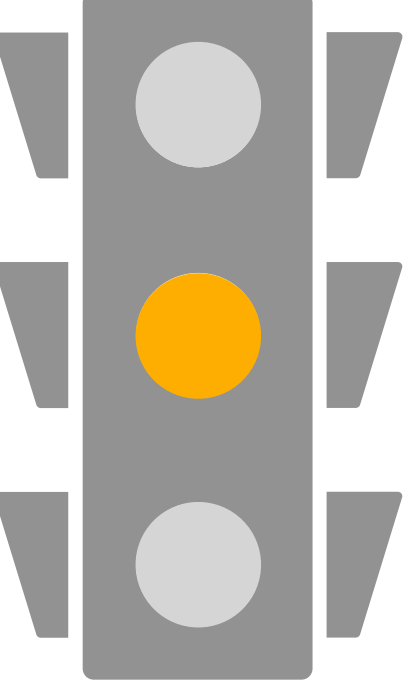
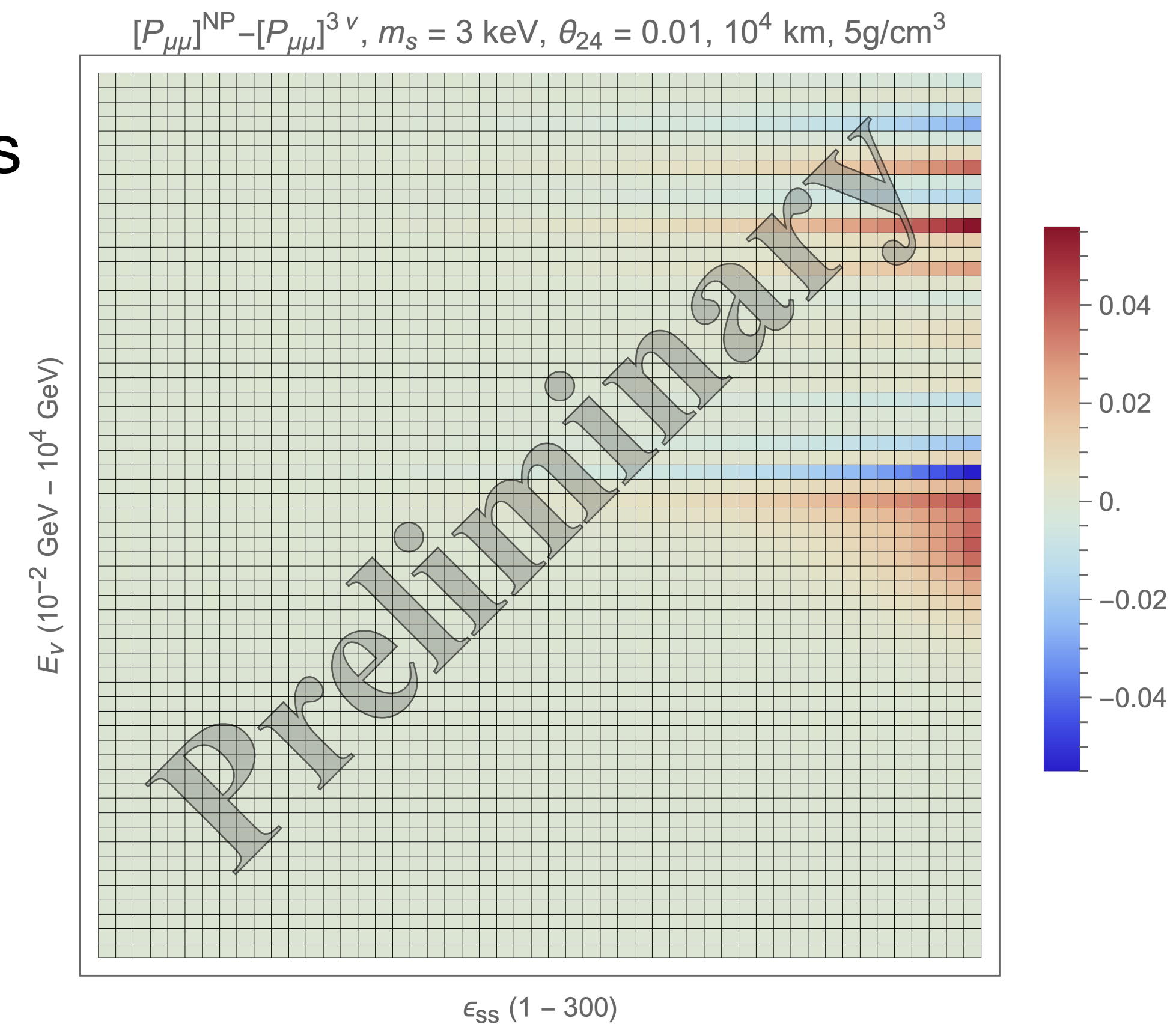
efficiency $\epsilon(E_\nu, \cos \theta)$
 $\epsilon \approx 1$



- On February 13, 2023, ARCA (KM3NeT) had 21 detection lines installed...
- Final tally of ~230, i.e., ~10% installed at the time of the 220 PeV event.
- Vertical strings, ~700 m tall, spaced ~100 meters apart

Constraints I

- Solar, reactor, atmospheric, long-baseline probabilities
- Constant density approximation
- Solar (full 3+1 flavor simulation): no noticeable effects in P_{ee} for either scenarios
- Reactor: Maximum change $\lesssim 0.5\%$ for $\epsilon_{ss} \approx 10^4$, negligible for $\epsilon_{\mu s}$
- LBL: negligible effects for $\epsilon_{\mu s}$, favours $\epsilon_{ss} \lesssim 10^3$
- Atmospheric: negligible effects for $\epsilon_{\mu s}$, favours $\epsilon_{ss} \lesssim \text{few} \times 10^2$



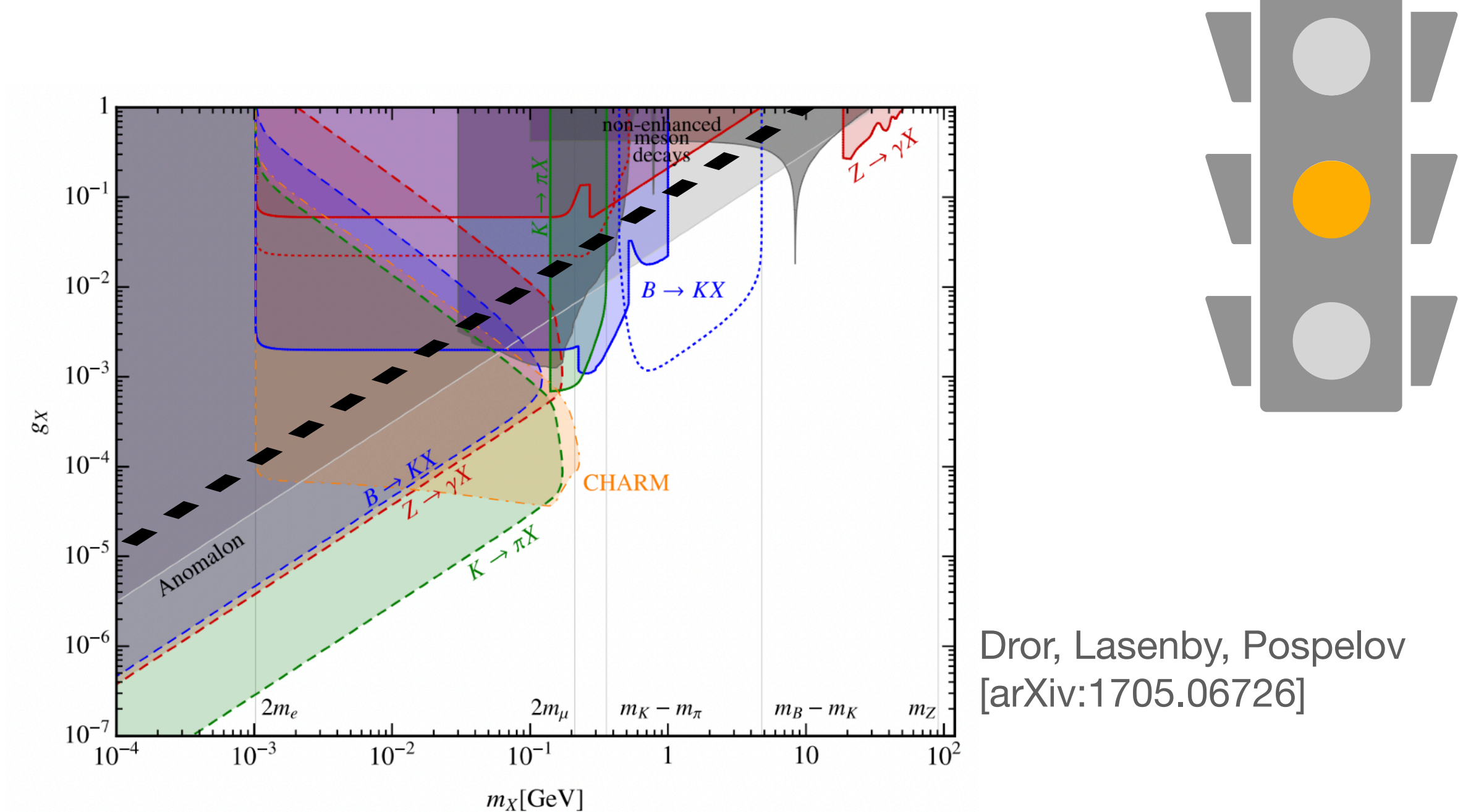
Constraints II

- For $\epsilon_{ss} \approx 150 \Rightarrow G_B \approx 200 G_F$, i.e.,

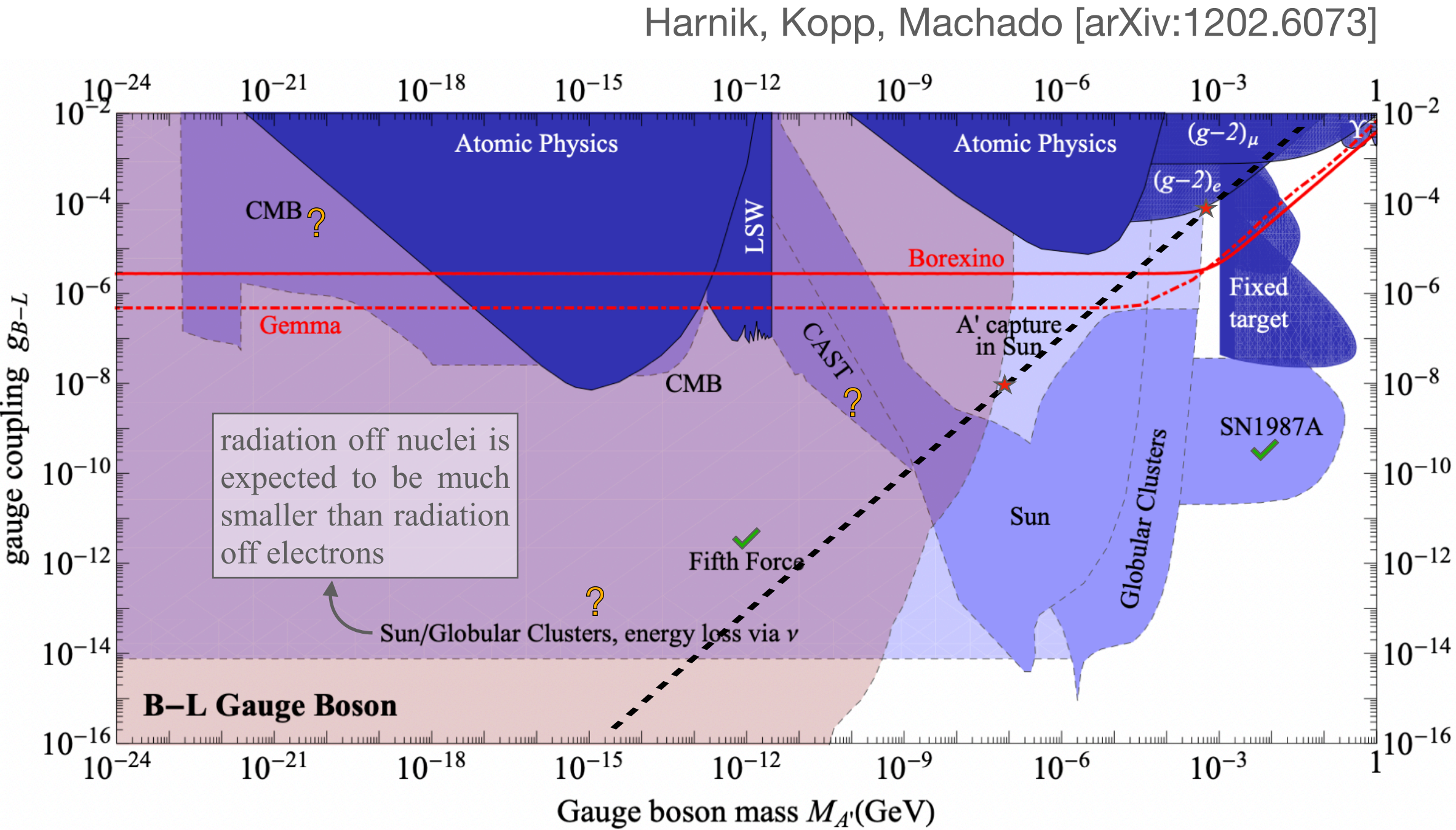
$$\epsilon_{ss} = G_B/(\sqrt{2}G_F) \qquad \left(\frac{g'}{g}\right)^2 \left(\frac{M_Z}{M_{Z'}}\right)^2 \approx 200$$

- For $M_{Z'} = 10^{-3} \text{ GeV}$, $g' \approx 10^{-4}$
- $M_{Z'} = \text{few} \times 10^{-8} \text{ GeV}$, $g' \approx 10^{-8}$

	$U(1)_{B-L}$ (vector couplings) (Model A)	Kinetically mixed (Model B)	$U(1)_B$ (vector couplings) (Model C)
$g-2$	✓	✓	✗
Fixed Target	✓	✓	✗ ^a
Υ	✓	✓	✗ ^b
Atomic physics	✓	✓	✗
Sun/Clusters/CAST	✓	✓	?
SN1987A	✓	✓	✓
LSW	✓	✓	✗
CMB	✓	✓	?
Borexino	✓	only if ν_s exist	✗
GEMMA	✓	✗	✗
Fifth force	✓	✗	✓



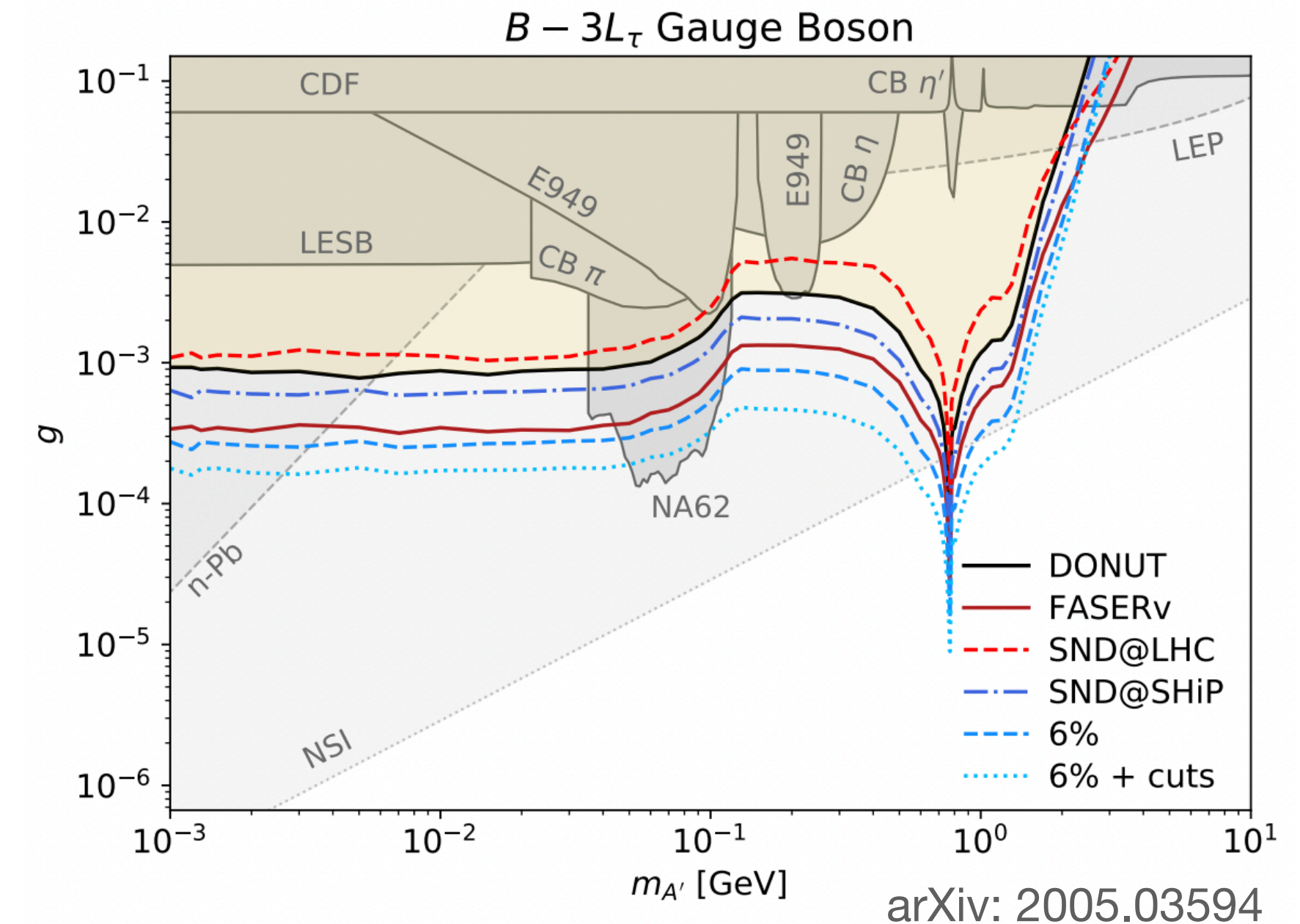
Dror, Lasenby, Pospelov
[arXiv:1705.06726]



Harnik, Kopp, Machado [arXiv:1202.6073]

Constraints III

- Maybe a $U(1)_{B-3L_\tau}$ could work...
- Anomaly free, easy to UV complete.
- Work in progress.
- More exotic mechanisms like leptophobic bosons arising from a theory with higher symmetries...
- For lower values of ϵ_{SS} our solution remains valid.



Model	$(\Delta\chi^2_{\text{LIGHT,NSI}})_{\min}$	$g' \leq \text{bound} \left(\frac{M_{Z'}}{100 \text{ MeV}} \right)$
$B - 3L_e$	-1.4	2.0×10^{-4}
$B - 3L_\mu$	0	4.6×10^{-5}
$B - 3L_\tau$	-0.6	4.7×10^{-5}
$B - \frac{3}{2}(L_\mu + L_\tau)$	-1.1	2.2×10^{-4}
$L_e - L_\mu$	-1.3	1.2×10^{-4}
$L_e - L_\tau$	-1.0	1.2×10^{-4}
$L_e - \frac{1}{2}(L_\mu + L_\tau)$	-1.3	3.0×10^{-4}
$B_y + L_\mu + L_\tau$ Ref. [22]	0	1.5×10^{-4}
$L_e + 2L_\mu + 2L_\tau$	-0.1	1.8×10^{-4}

arXiv: 2009.14220

