# Search for rare interactions of Dark Matter with high-energy neutrinos from distant point sources in the IceCube Neutrino Telescope

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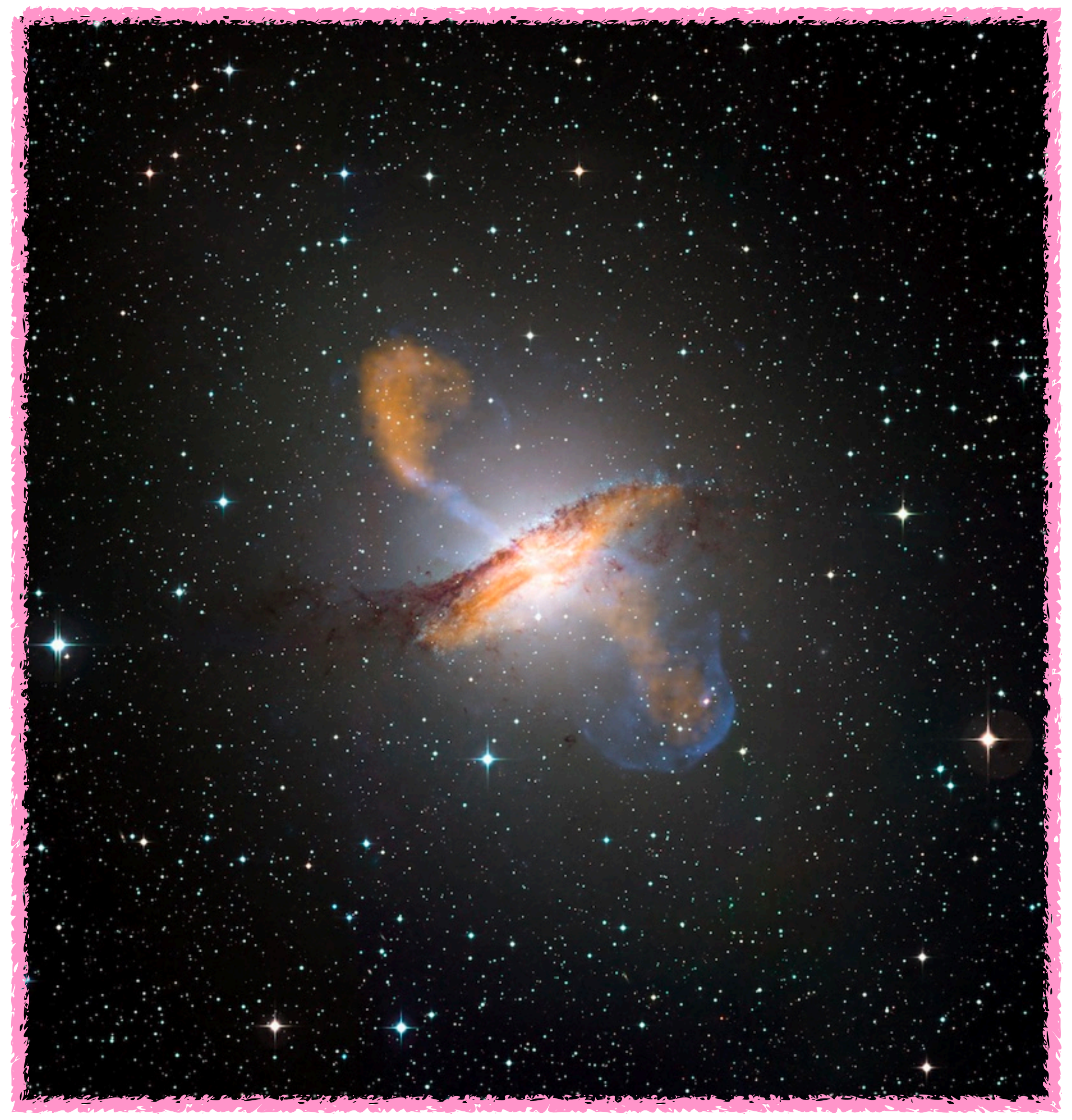
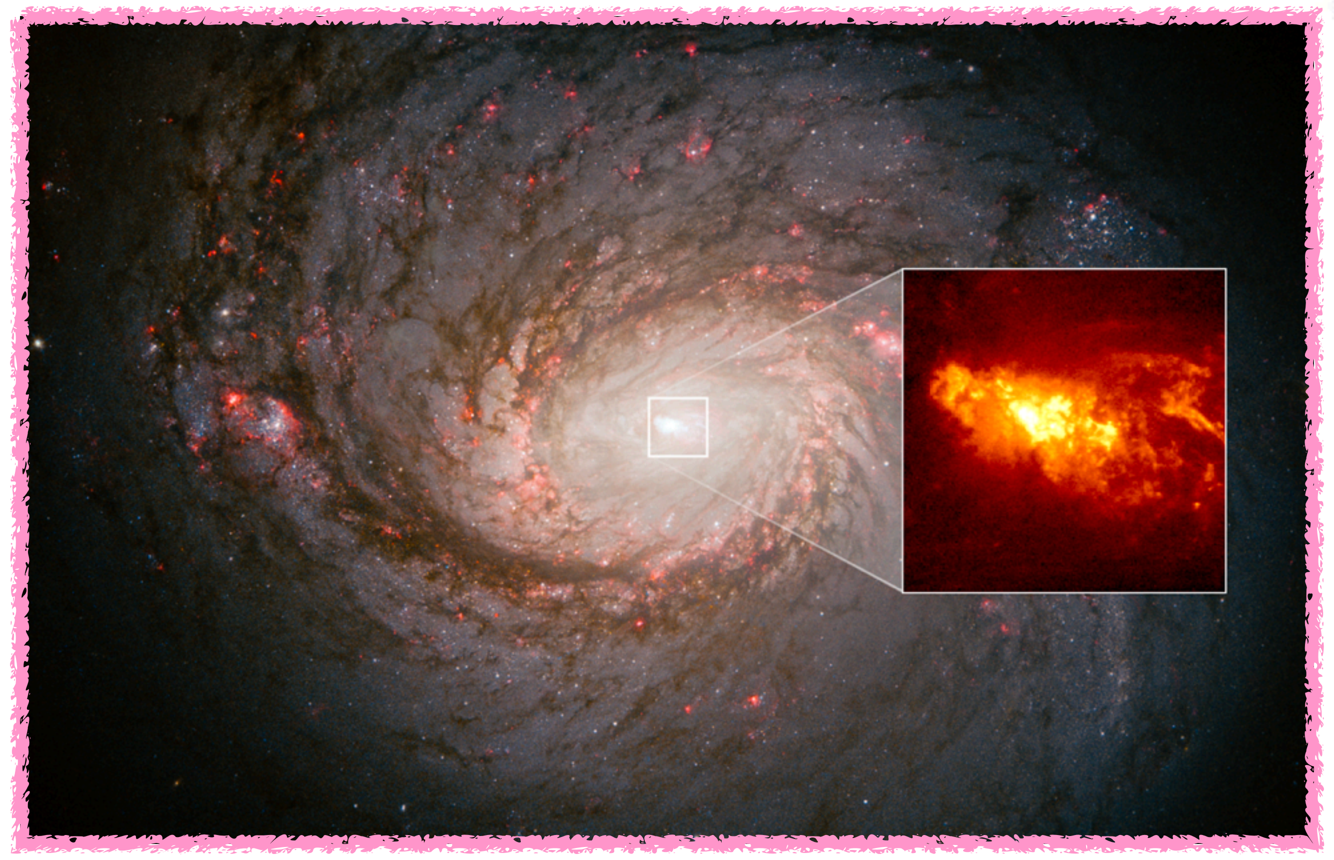
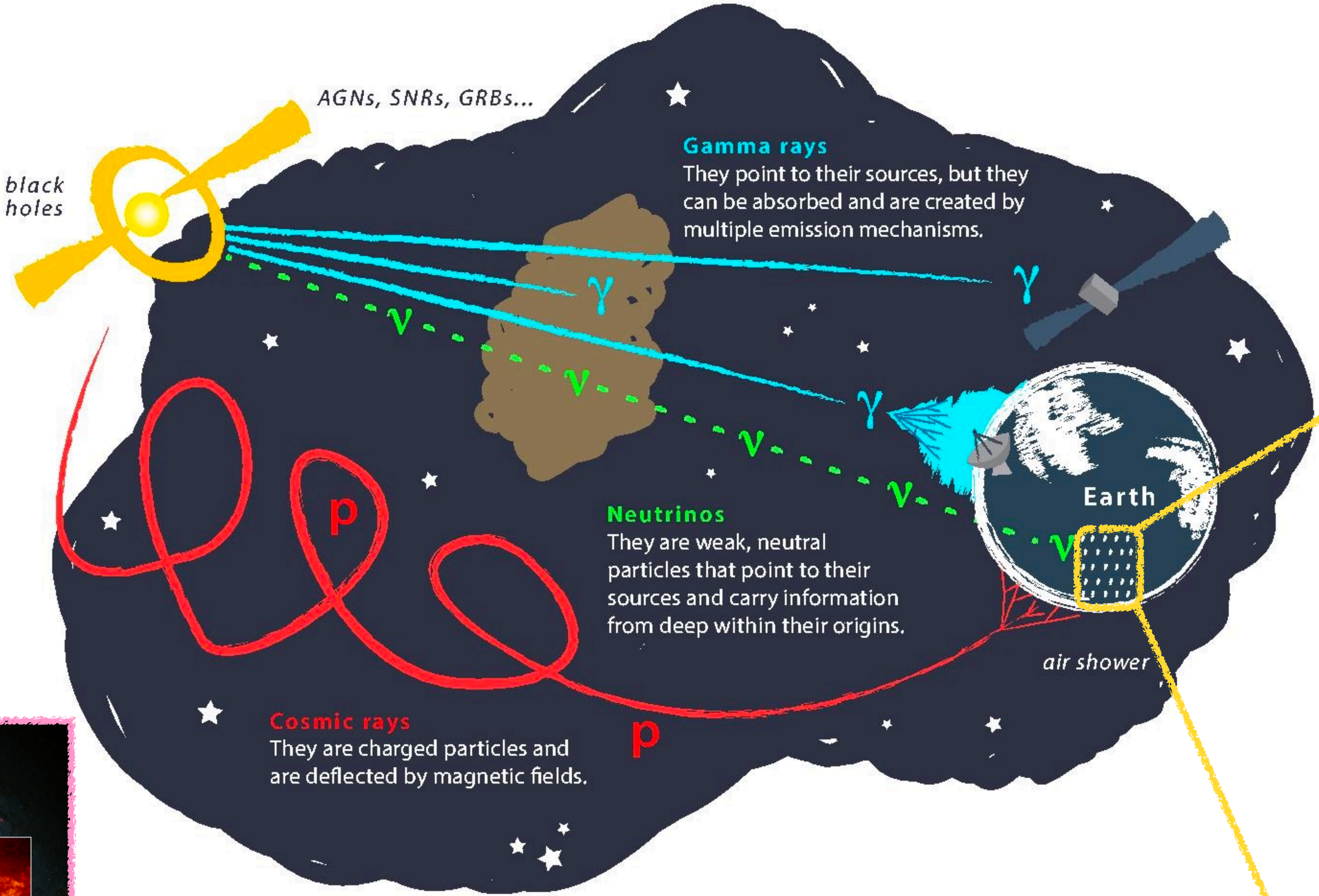
70th APCTP GWNR Workshop
Oct 4th, 2023

# High-energy neutrinos from Cosmos



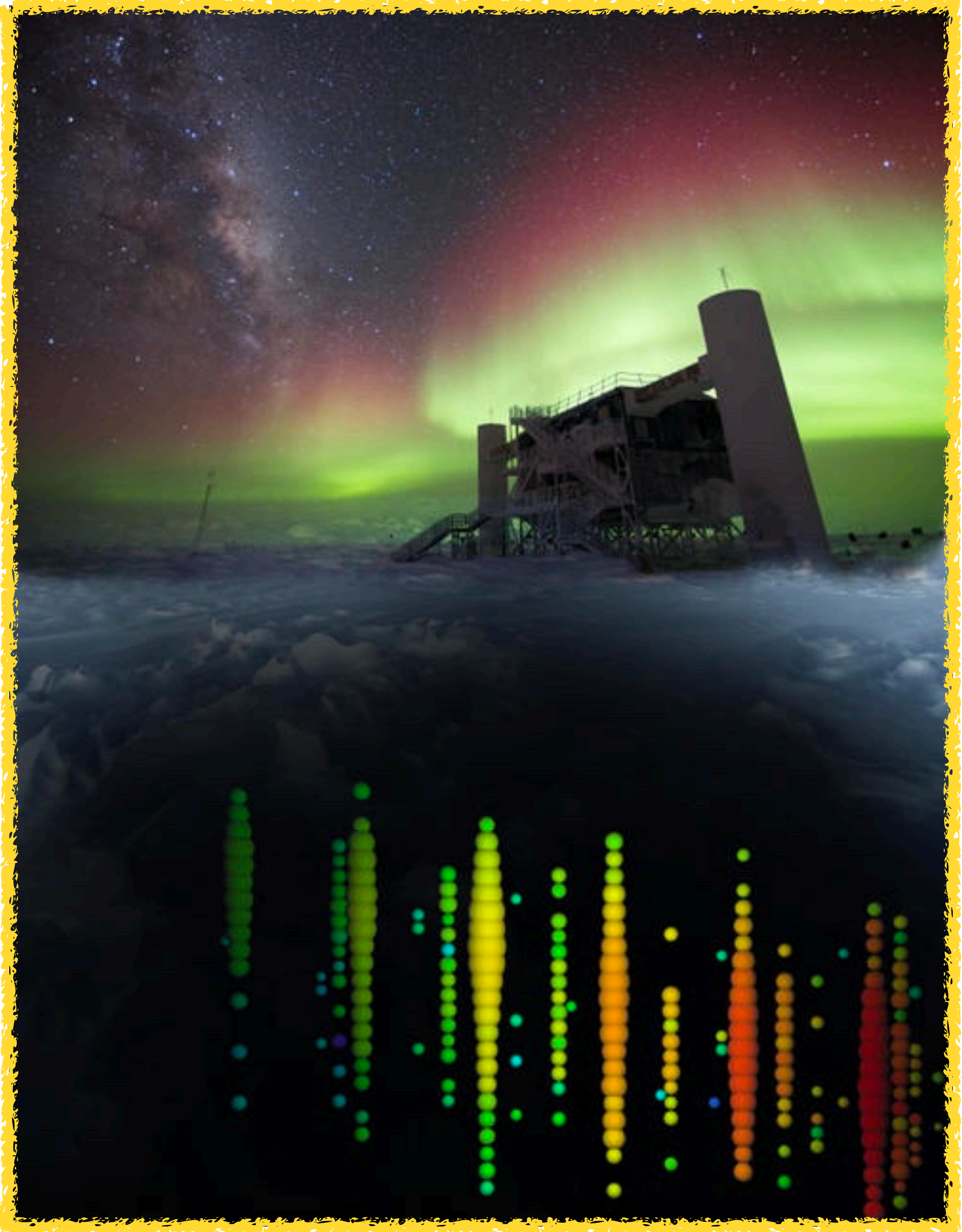


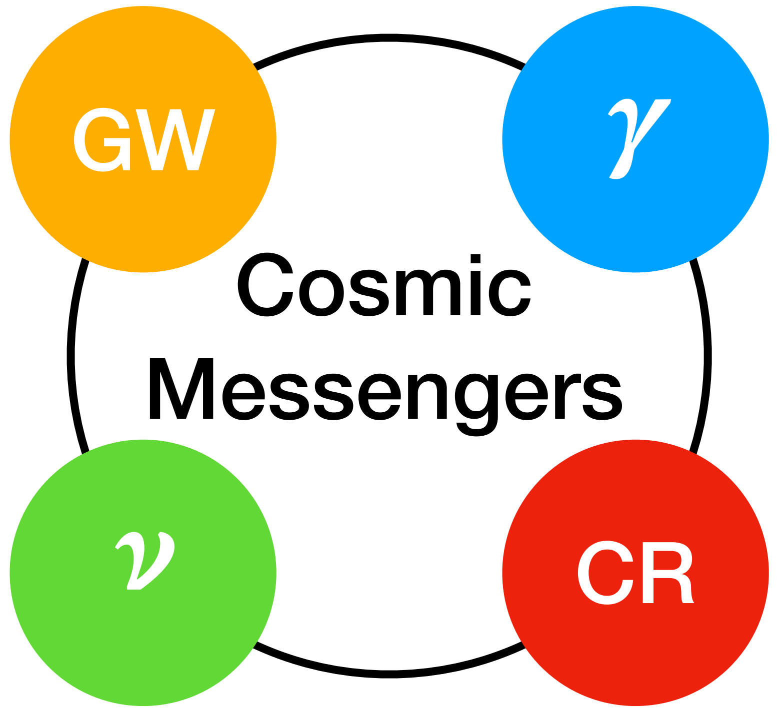


**Gamma rays**
They point to their sources, but they can be absorbed and are created by multiple emission mechanisms.

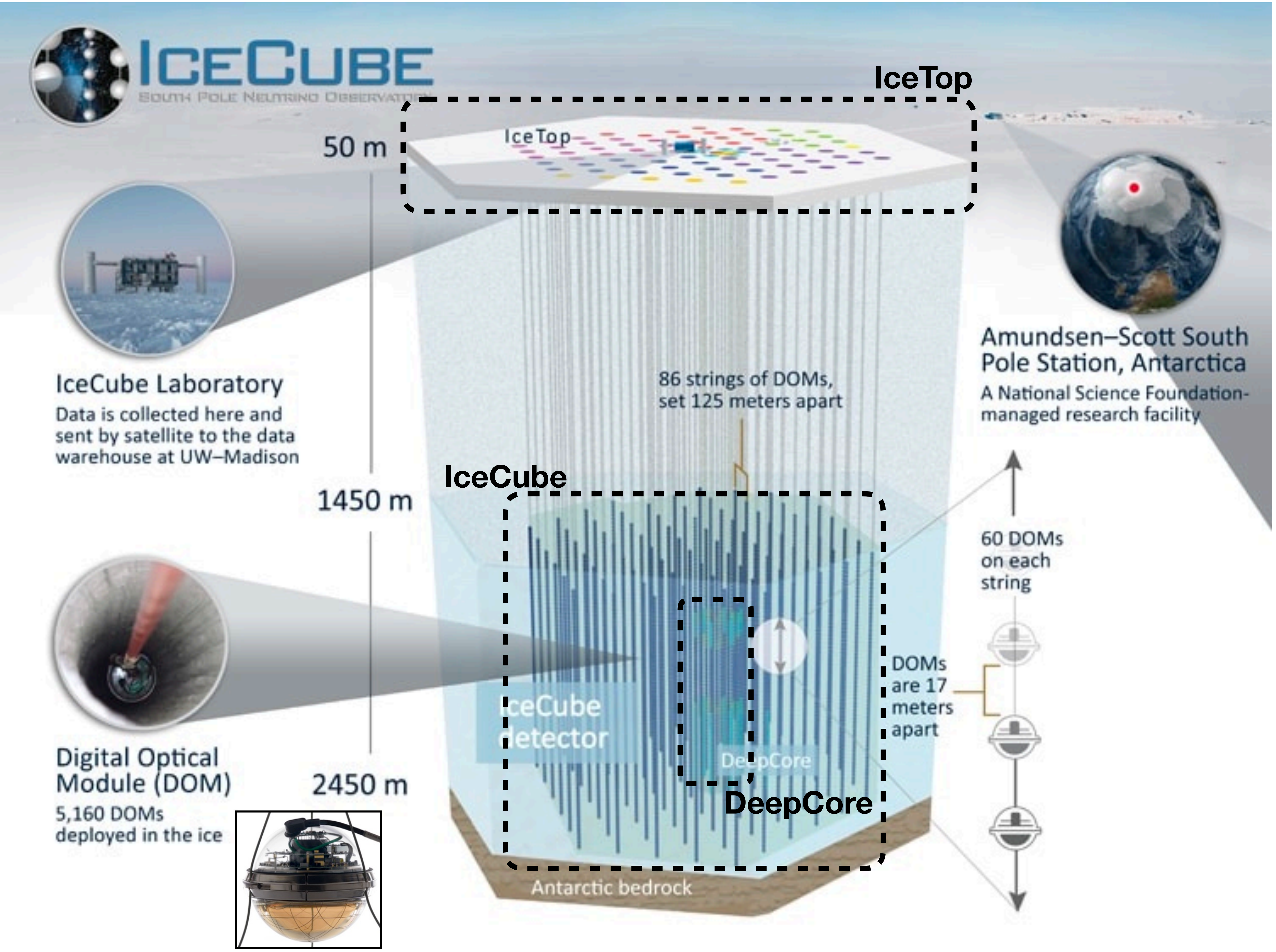
**Neutrinos**
They are weak, neutral particles that point to their sources and carry information from deep within their origins.

**Cosmic rays**
They are charged particles and are deflected by magnetic fields.





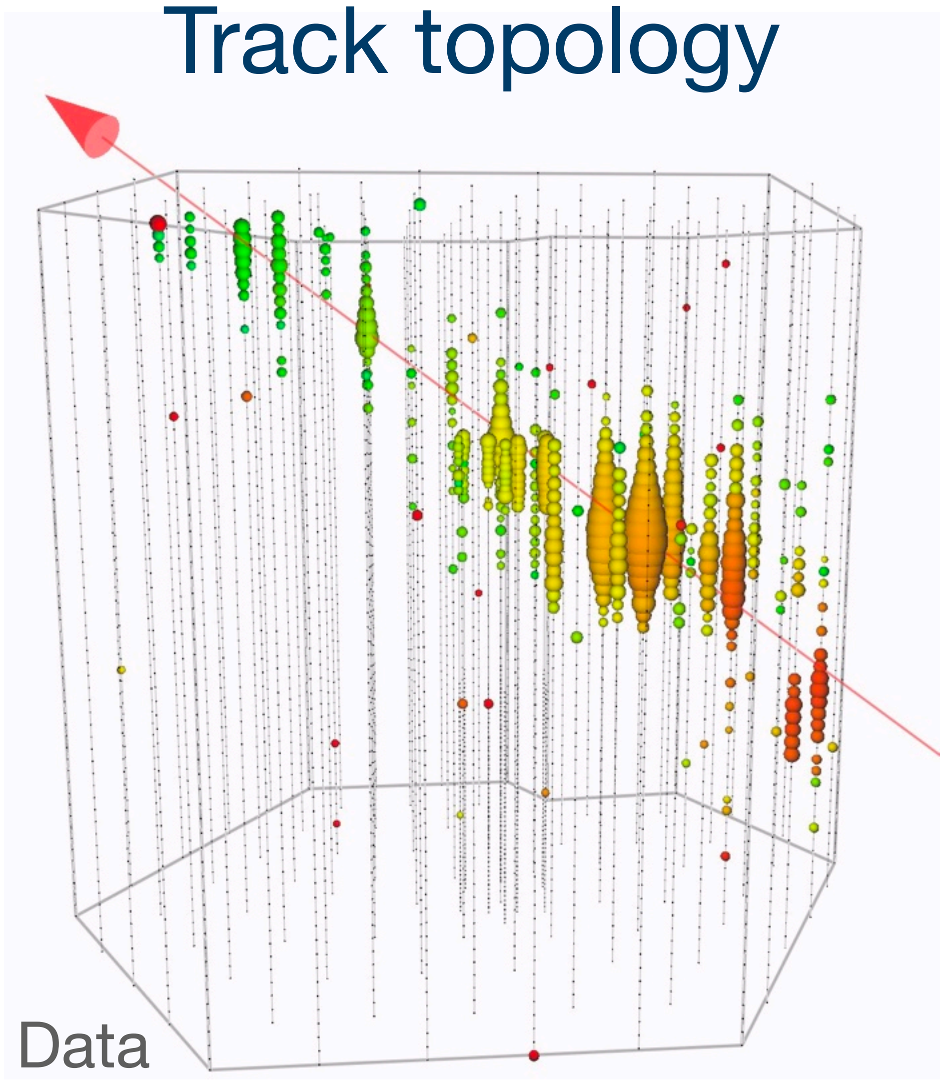
# IceCube Neutrino Observatory

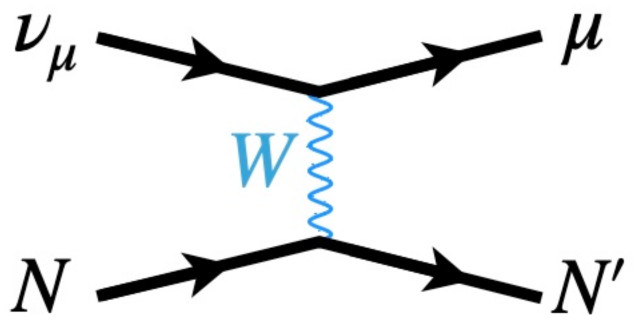


- The largest neutrino telescope in the world
- Located at the geographical South Pole
- 86 Strings with 60 DOMs each
- Volume ~ 1km$^3$
- $E_{\text{Threshold}}$ ~ 10 GeV (DeepCore)
- Trigger rate > 2 kHz, mainly from atmospheric muons
- The observatory consists of three sub-detectors: IceTop, IceCube, DeepCore

# How IceCube detects neutrinos?

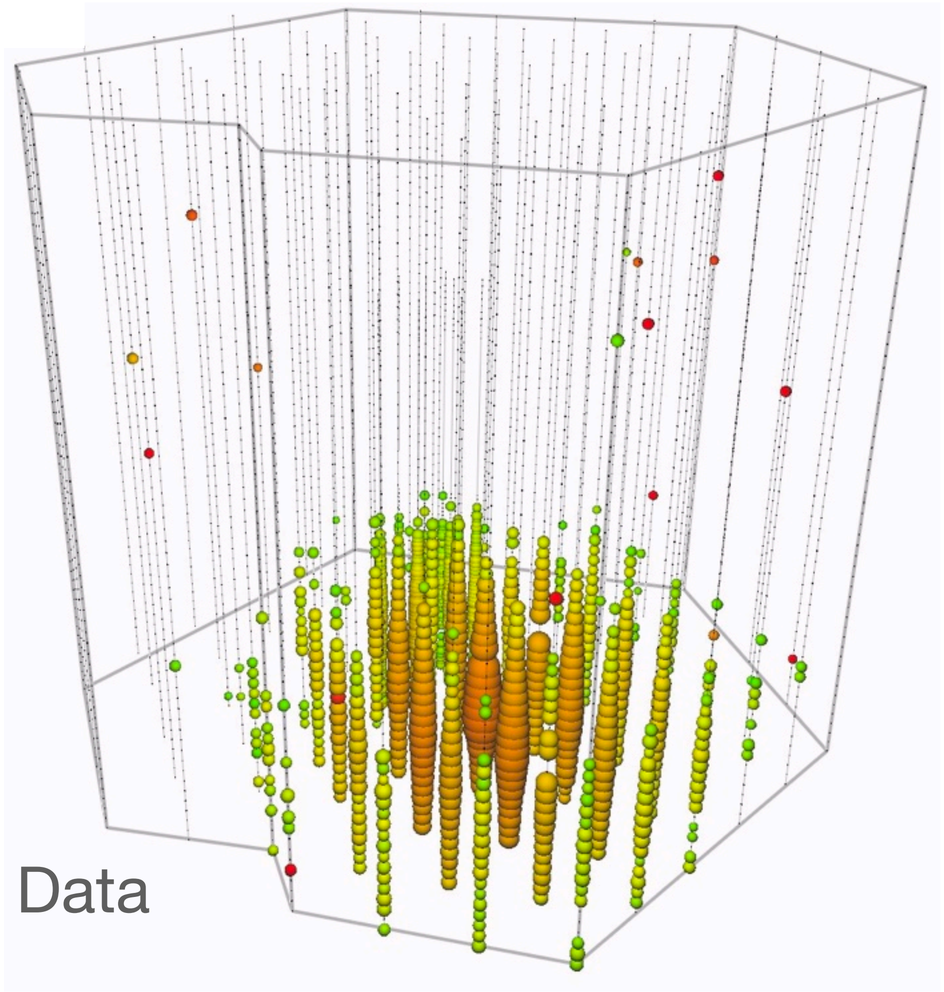
Track topology

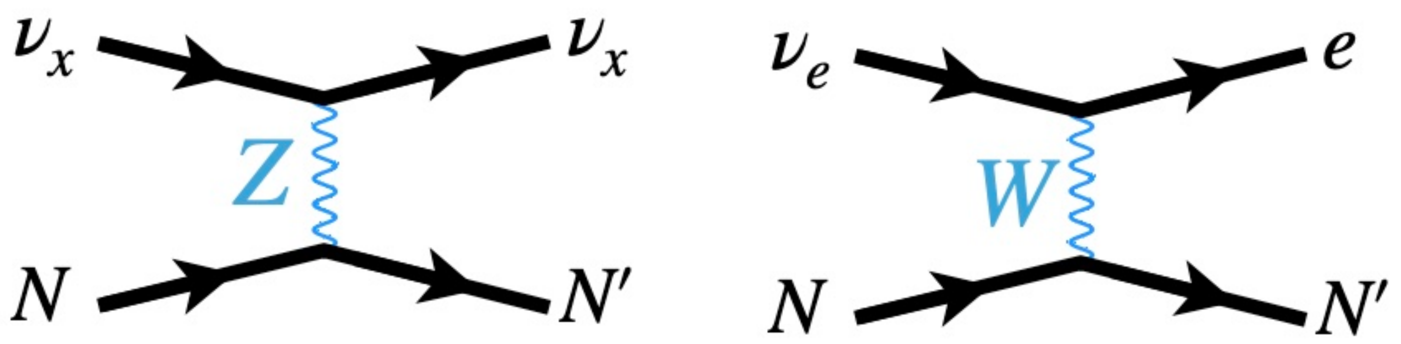




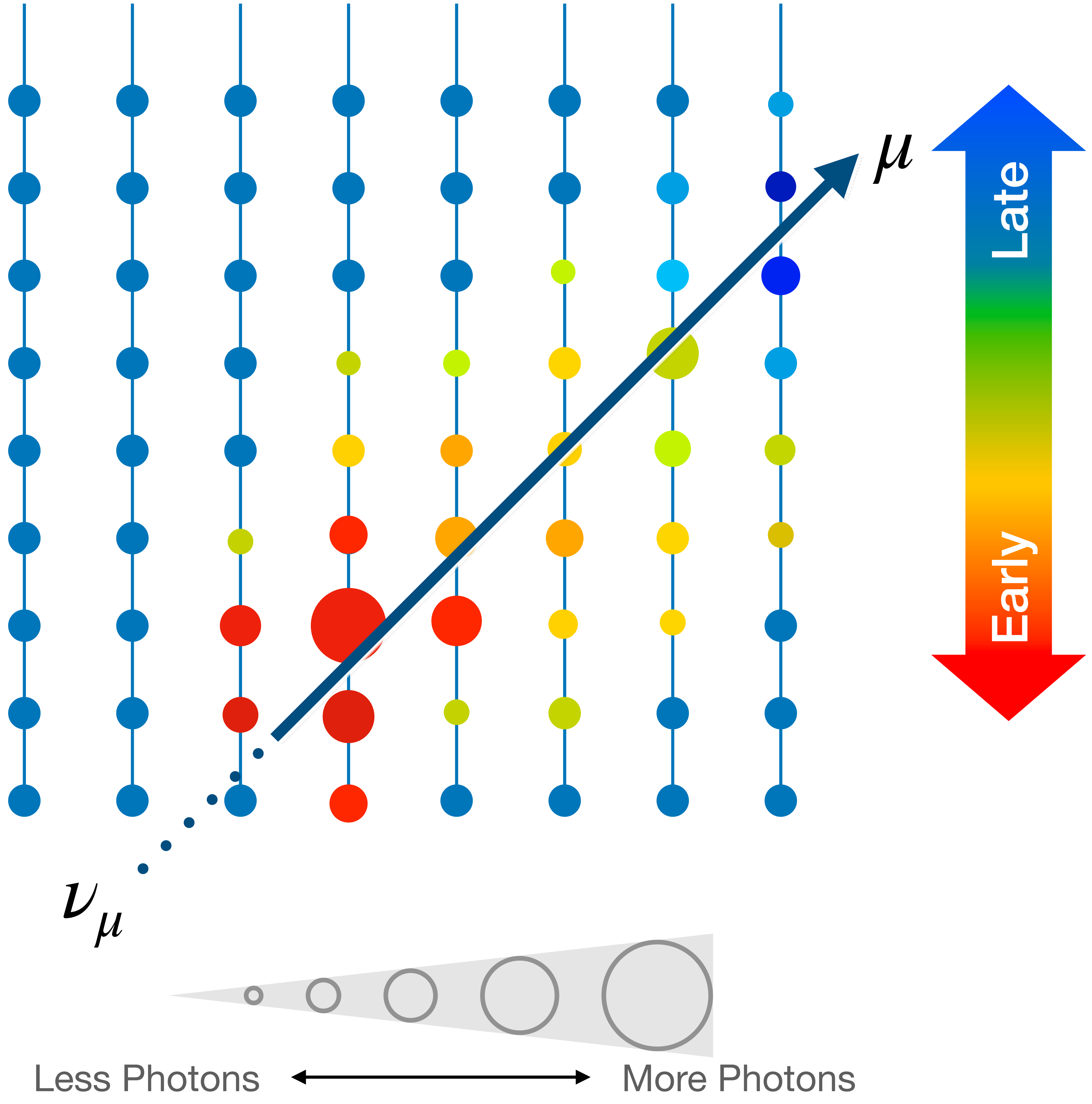
- Good angular resolution (~0.5°)
- Vertex can be outside the detector
- Stochastic energy loss
- More atmospheric background signal

Cascade topology

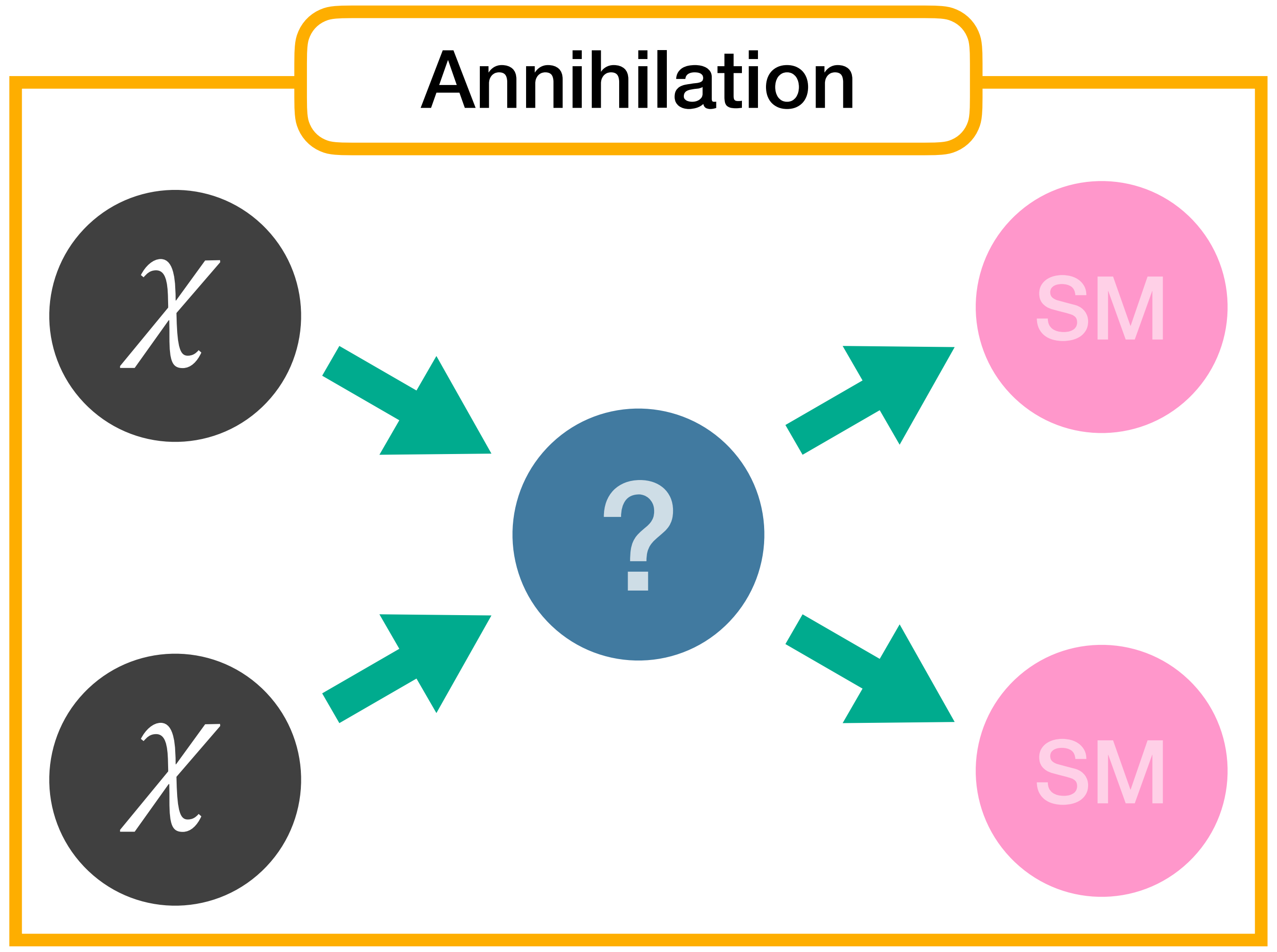


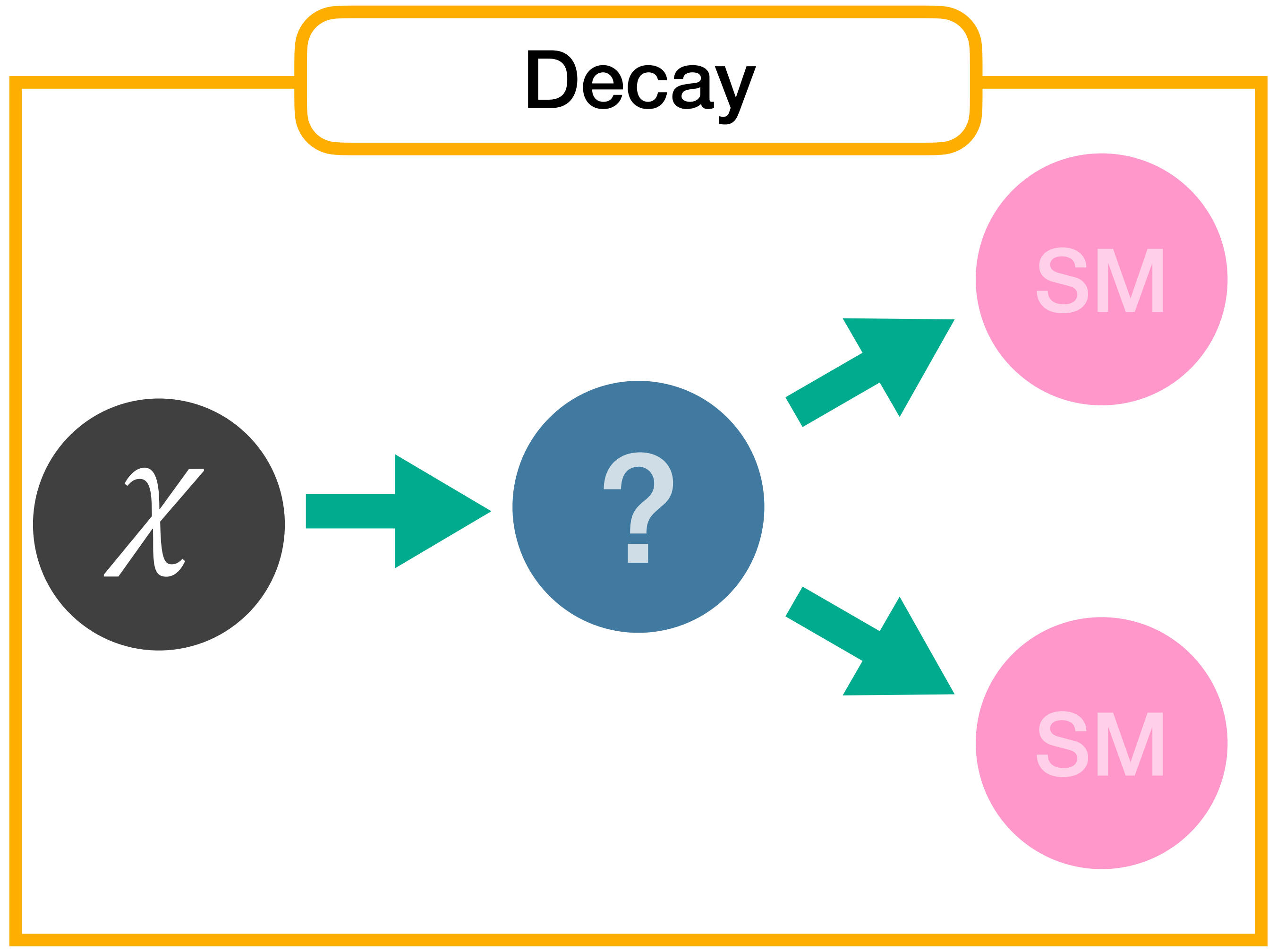


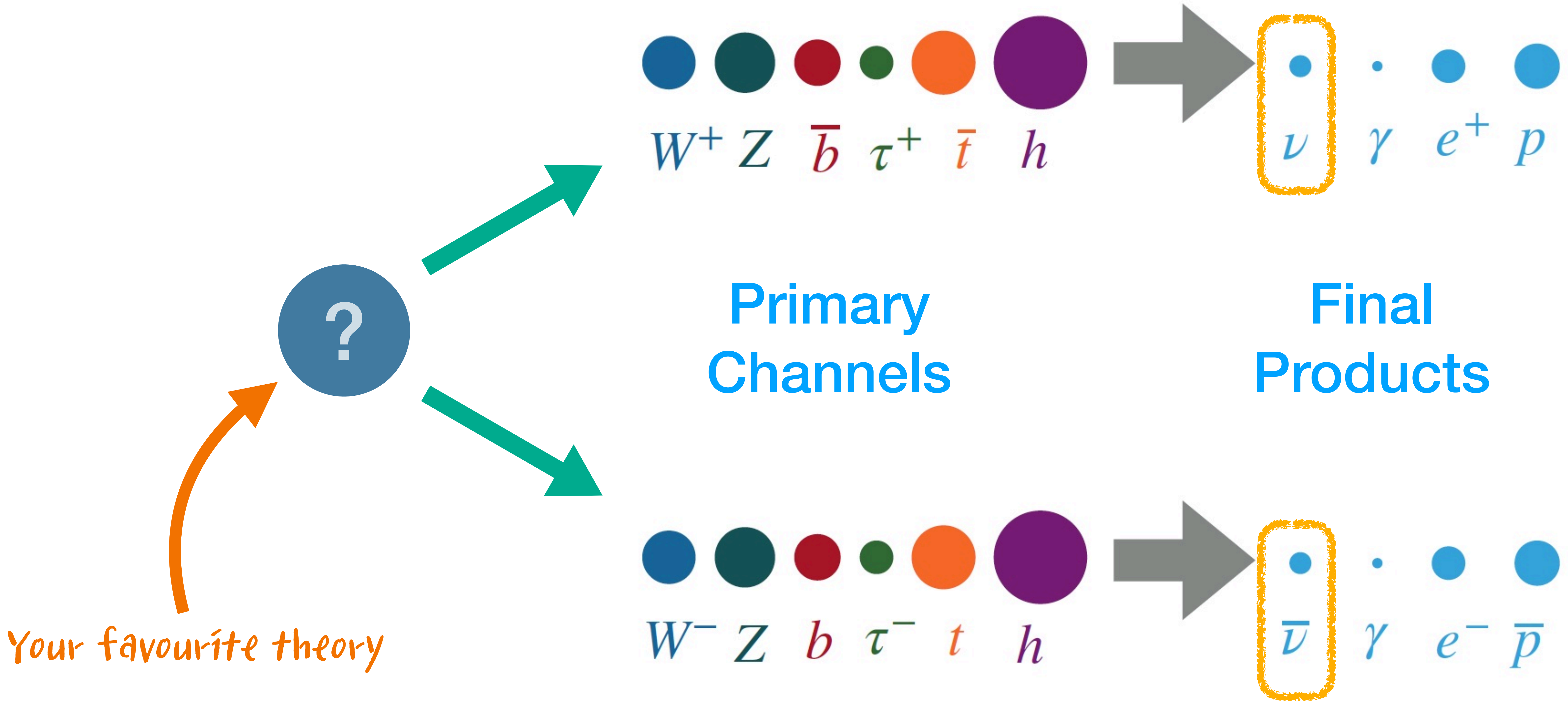
- All flavours
- Fully active calorimetre
- Suppressed atmospheric backgrounds
- Poor angular reconstruction (~20-30°)



# Dark Matter searches with high-energy neutrinos

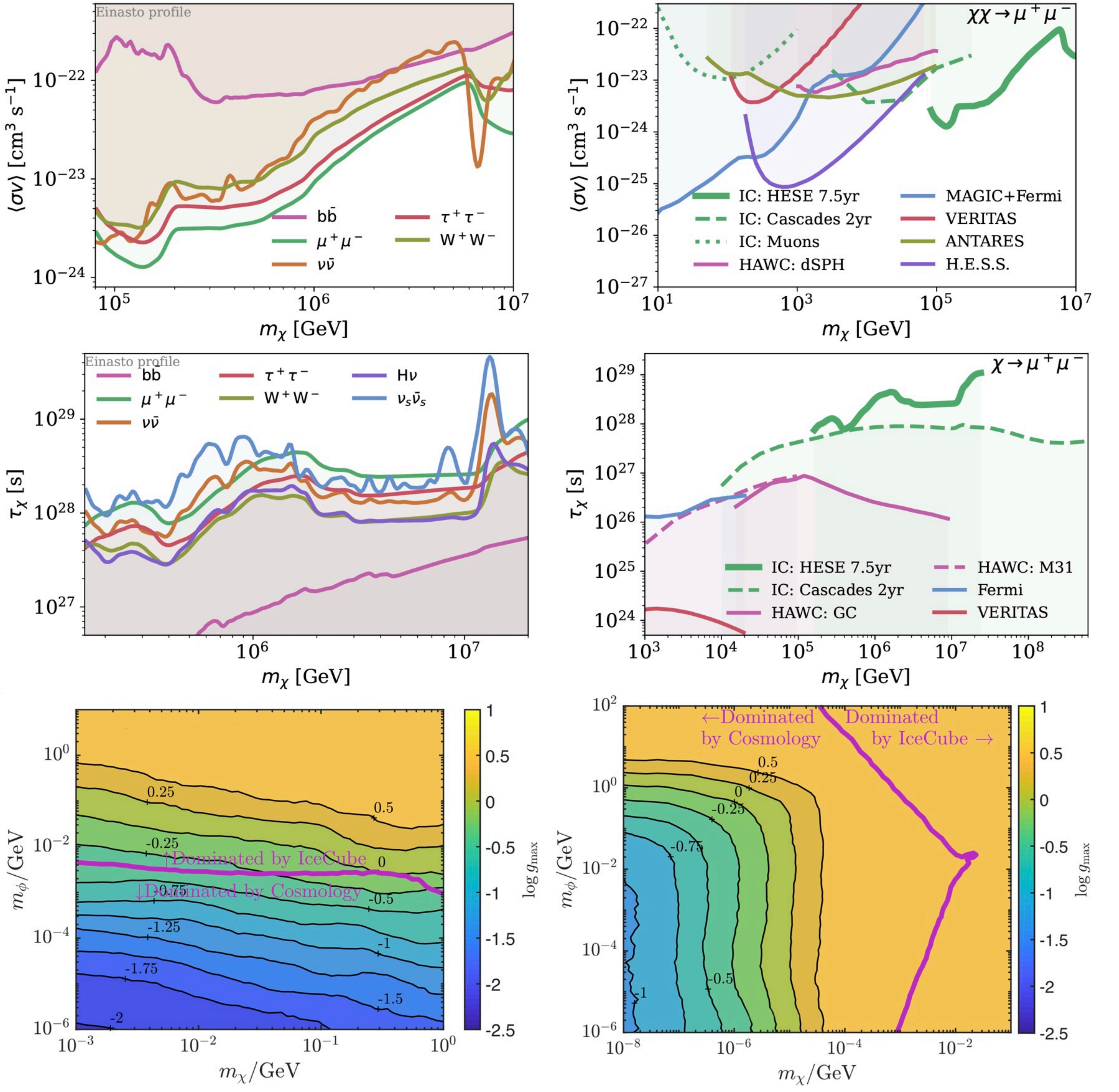




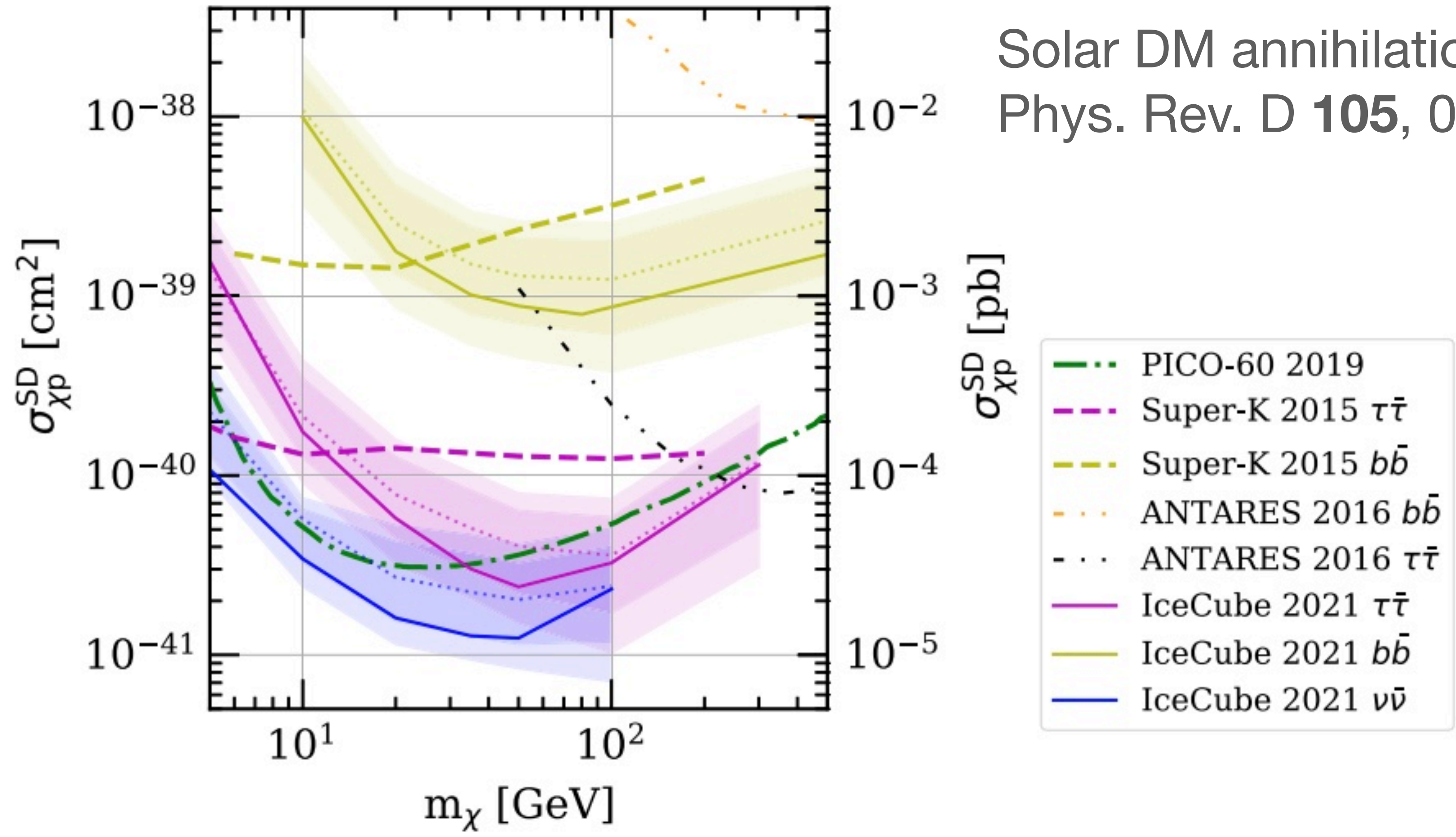


- No need of specialised detectors: Gamma-ray telescopes, **Neutrino detectors**, CR-experiments
  IceCube!!
- Search for products of dark matter annihilation / decay processes: **Focus on large reservoirs of dark matter**

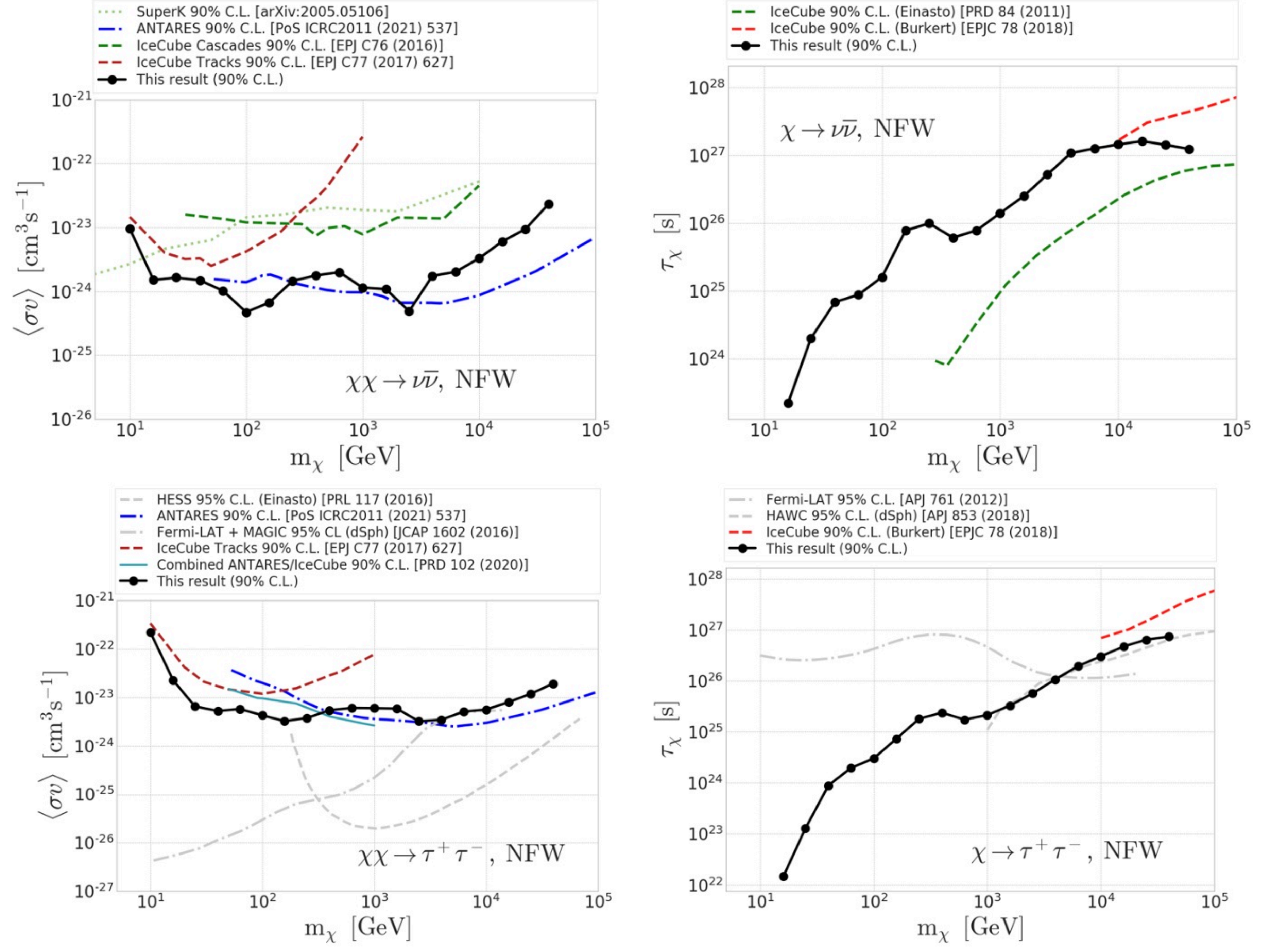
# Highlights on recent DM searches in IceCube



DM annihilation, decay & scattering with High-Energy Starting Events(HESE) 7.5 yrs: JCAP **10** 003 (2023)



Solar DM annihilation:
Phys. Rev. D **105**, 062004 (2022)

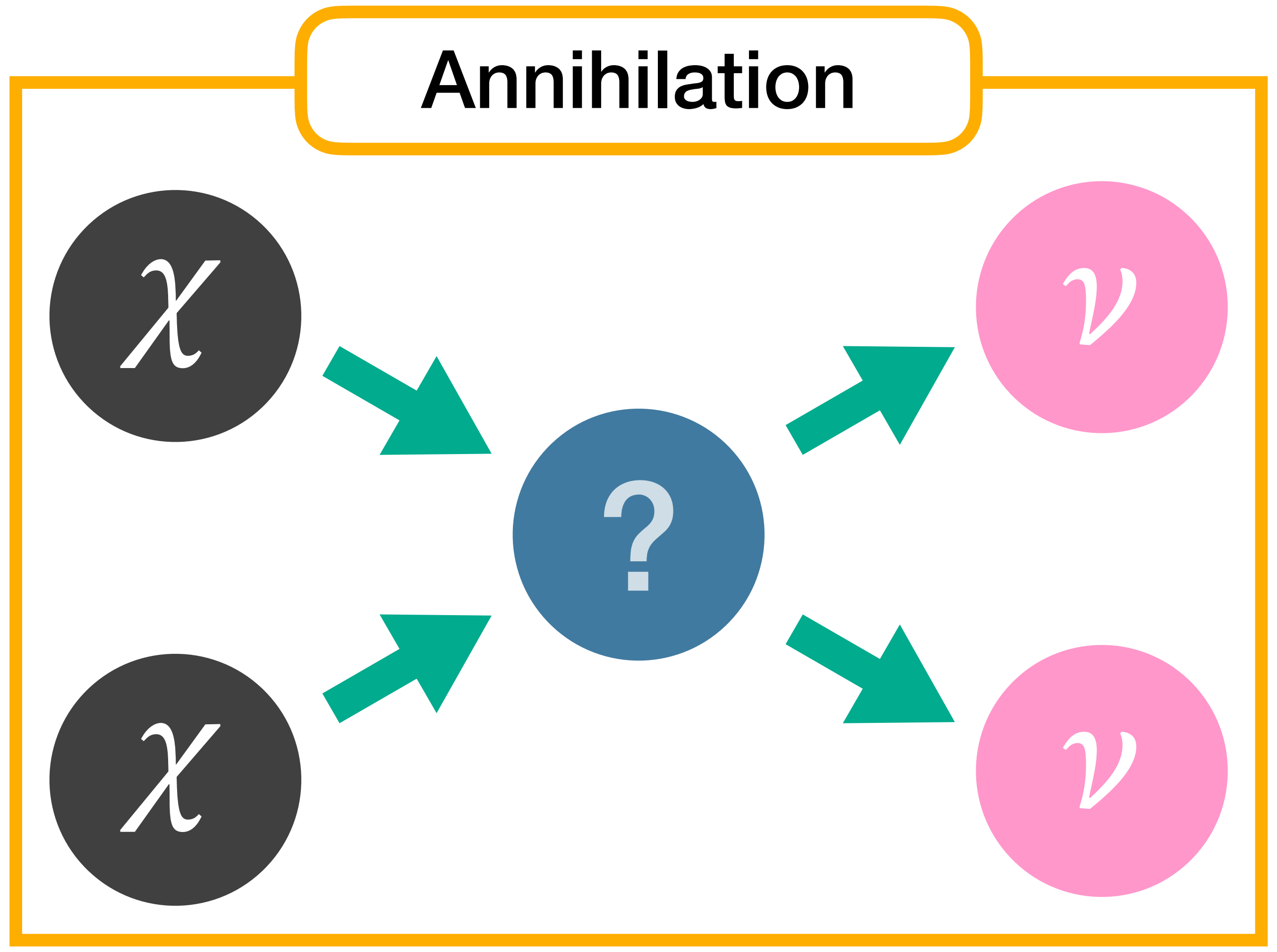


Monochromatic lines from DM annihilation & decay: arXiv: 2303.13663

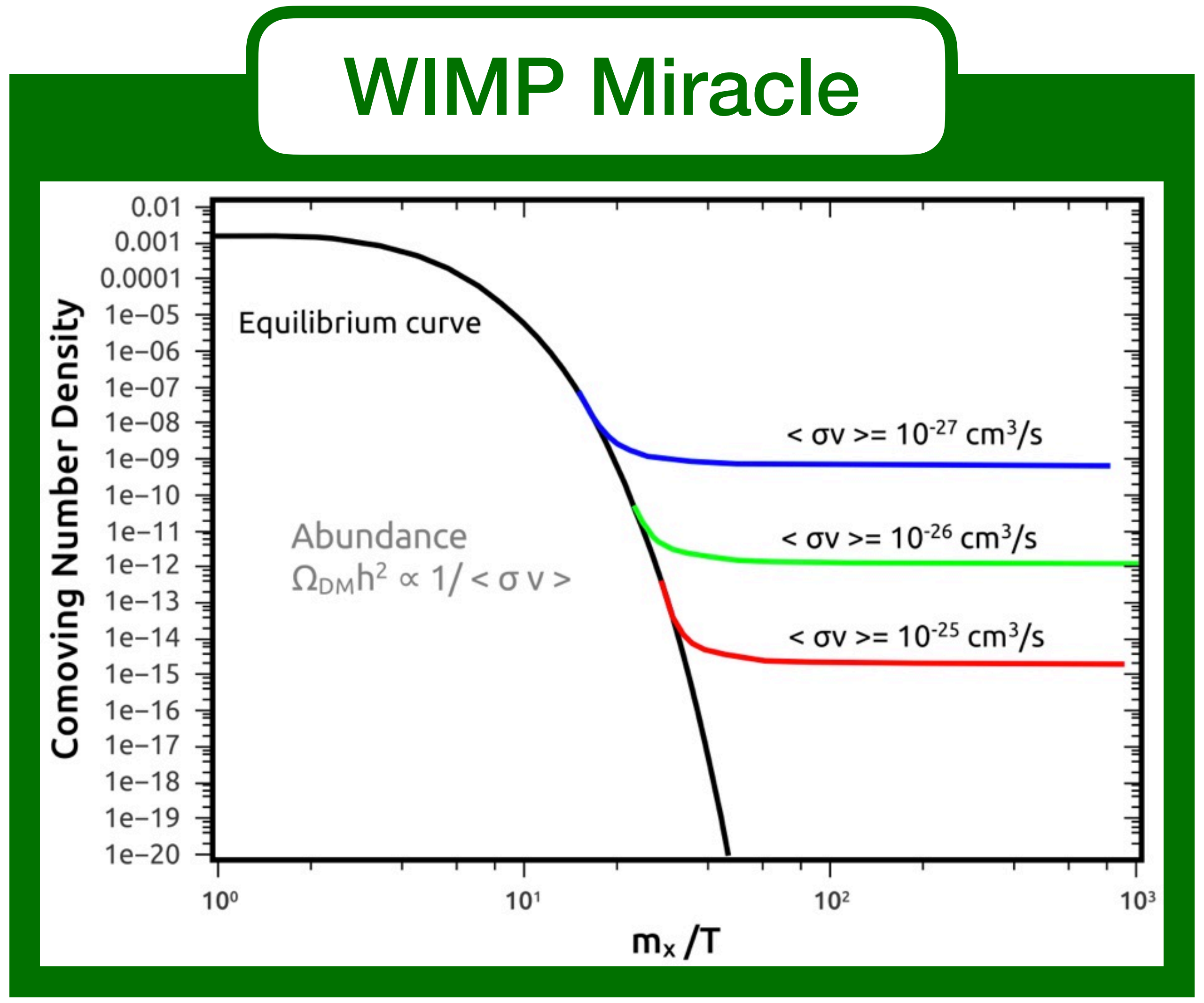
# Neutrino - Dark Matter interaction

- The interactions of neutrinos with DM are considered in cosmology
  - For WIMPs as an example,

**Annihilation**



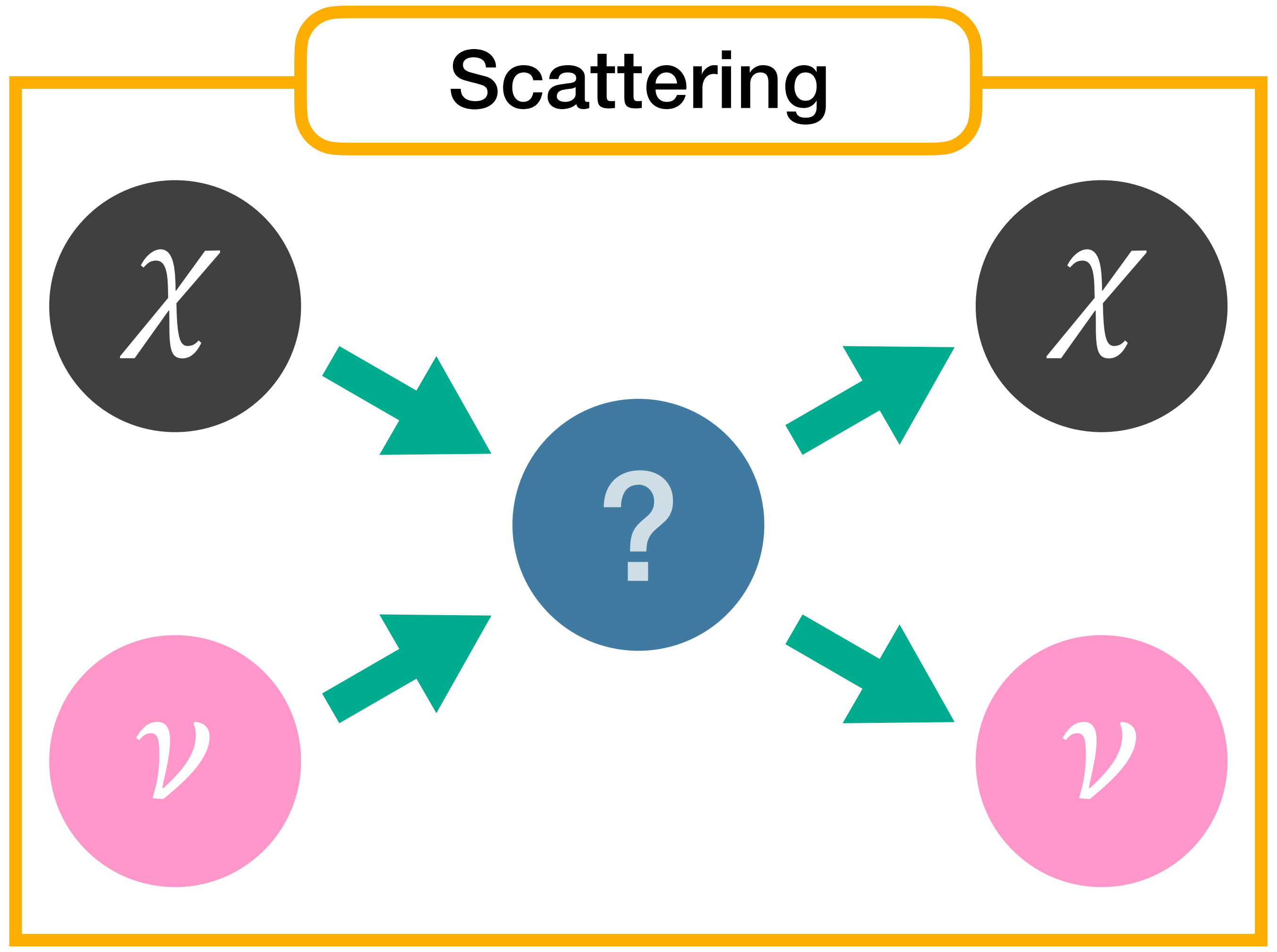
**WIMP Miracle**



G. Arcadi et al. *Eur. Phys. J. C* **78**, 203 (2018)

**Allowed**

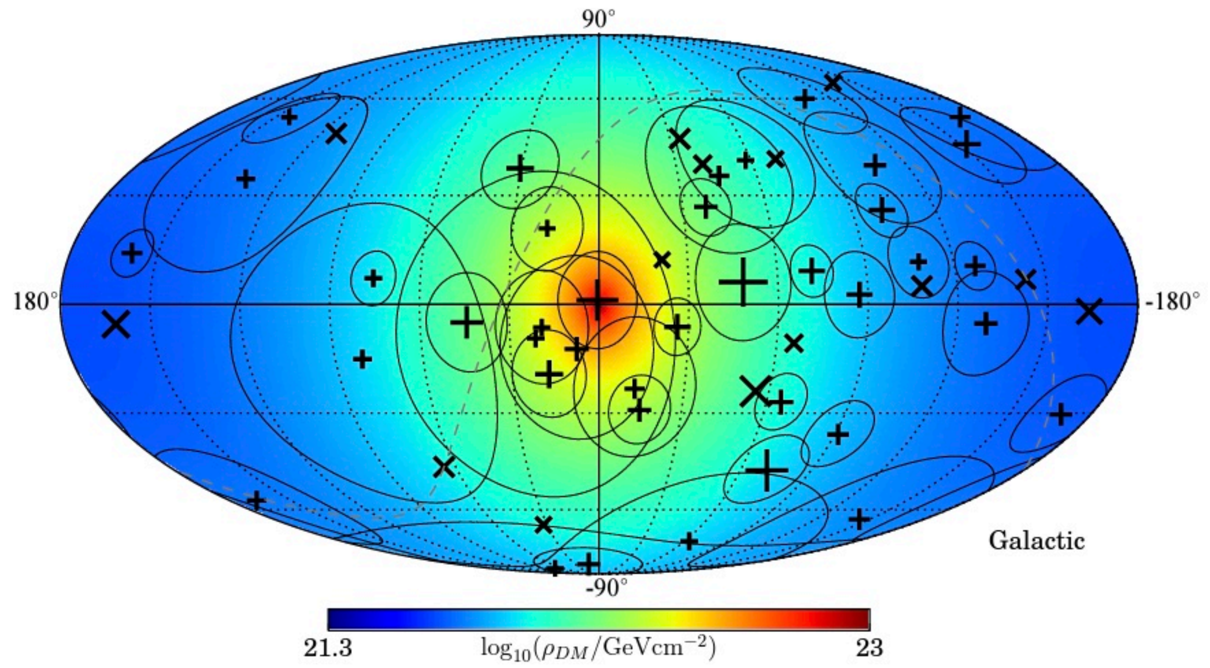
**Scattering**



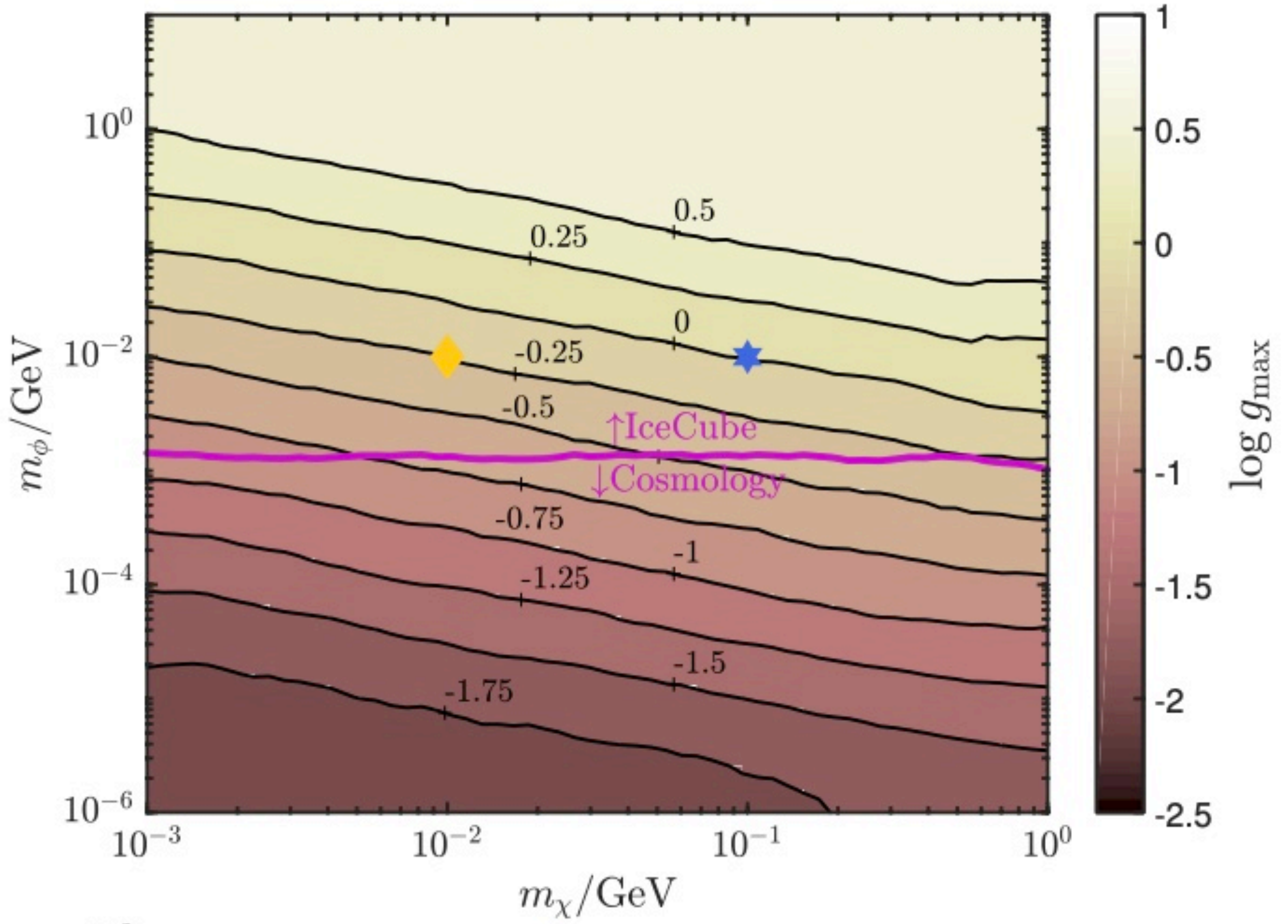
- In the present Universe, this interaction can dissipate neutrinos and hence suppress the neutrino flux at Earth which can be observed by large neutrino telescopes
  - Diffused astrophysical neutrinos
  - Astrophysical neutrinos from distant sources

# Studies with isotropic neutrino flux

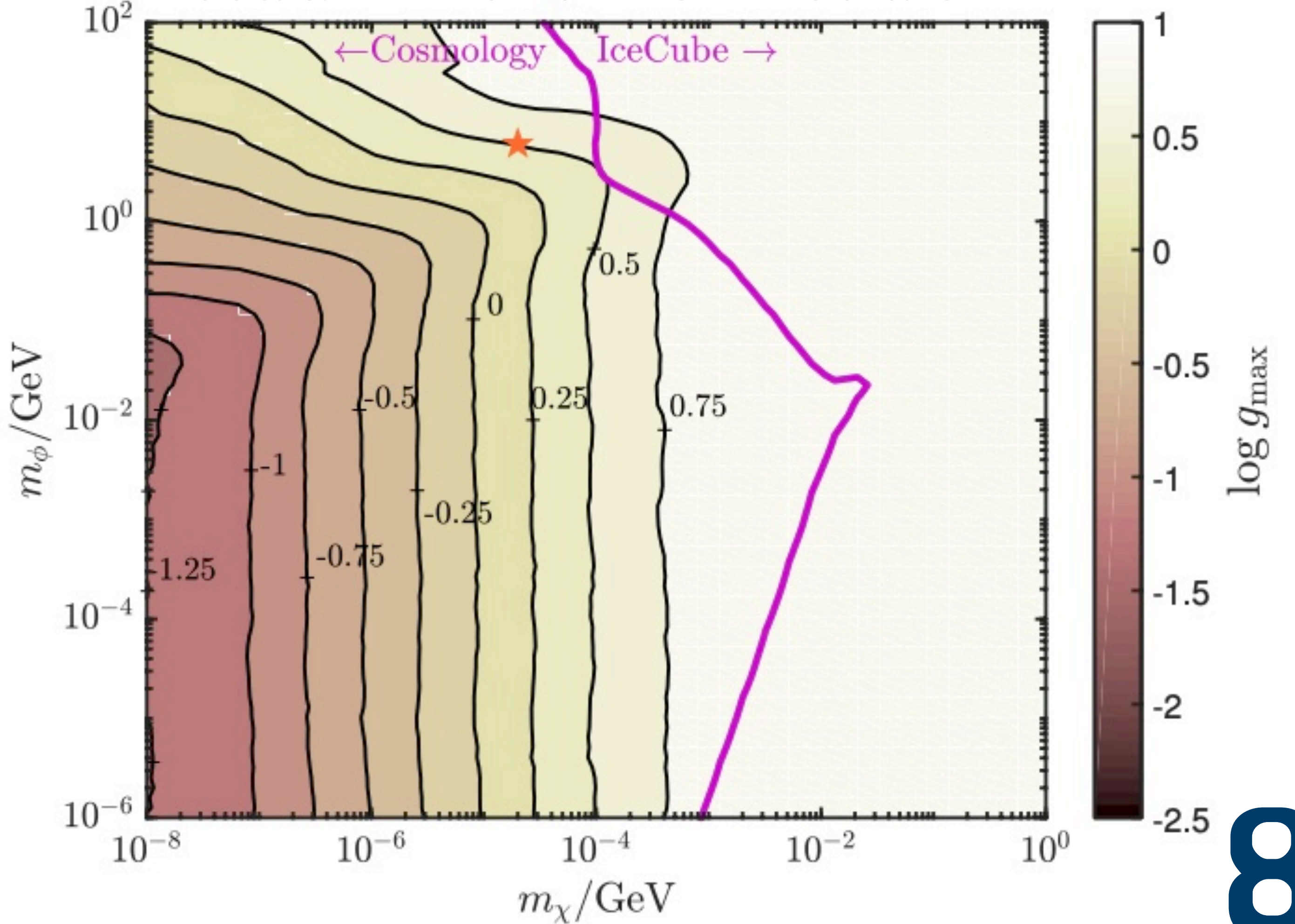
- Using the diffused high-energy astrophysical neutrino fluxes observed by IceCube to study the scattering of neutrinos with the Milky Way DM halo along their propagation to the Earth
- More flux attenuation to GC
- Constraints on interaction models

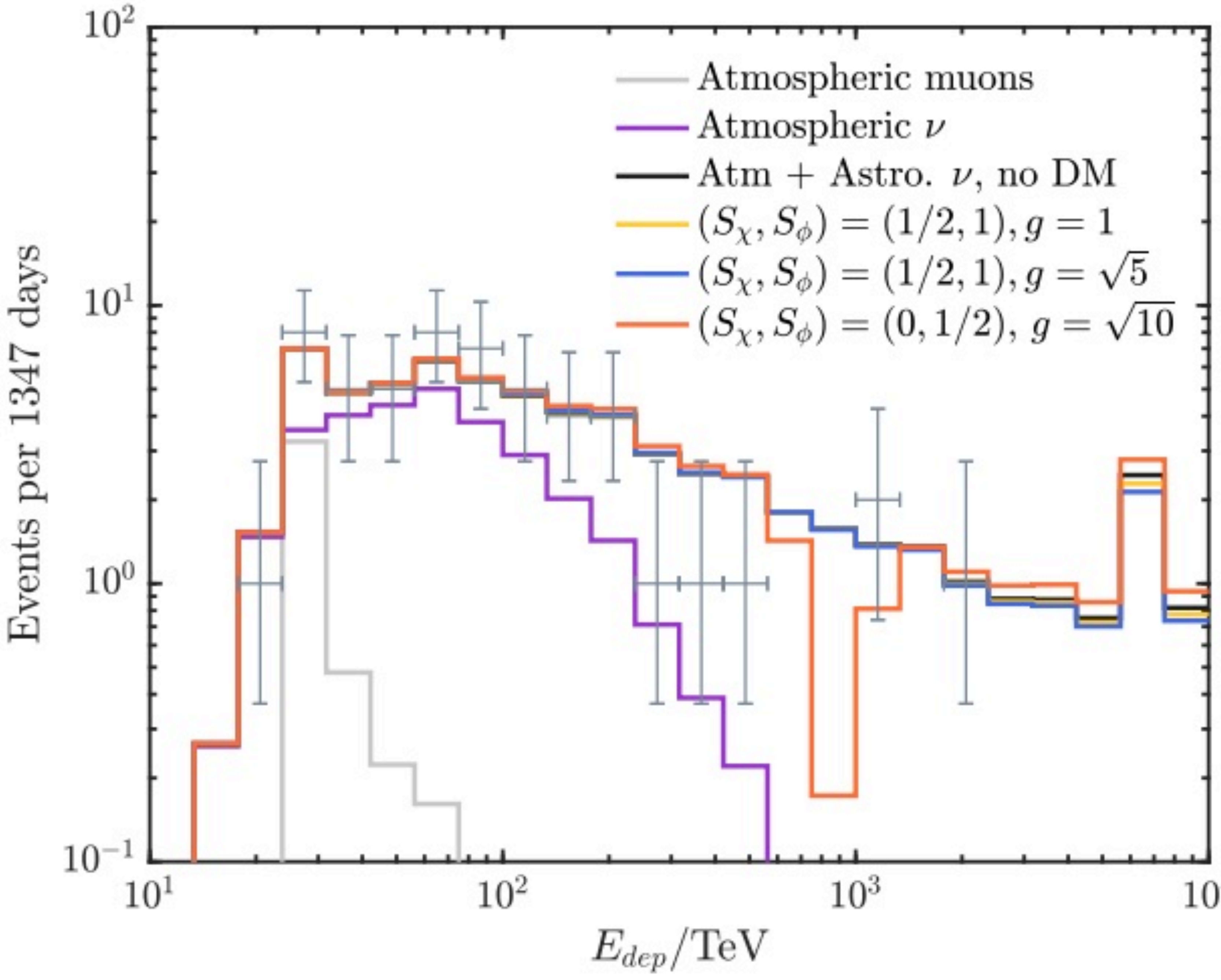


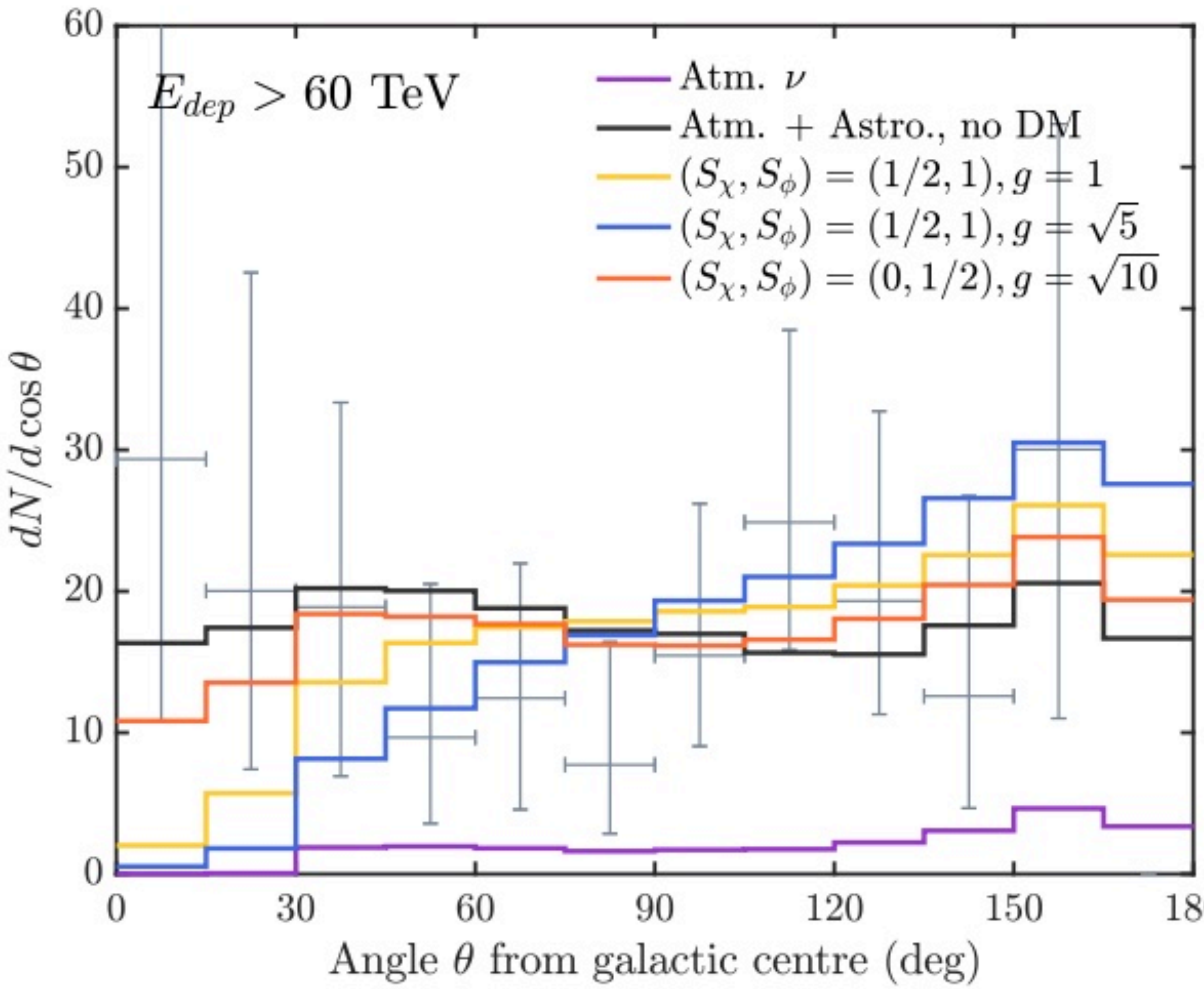
fermion DM & vector mediator



scalar DM & fermion mediator







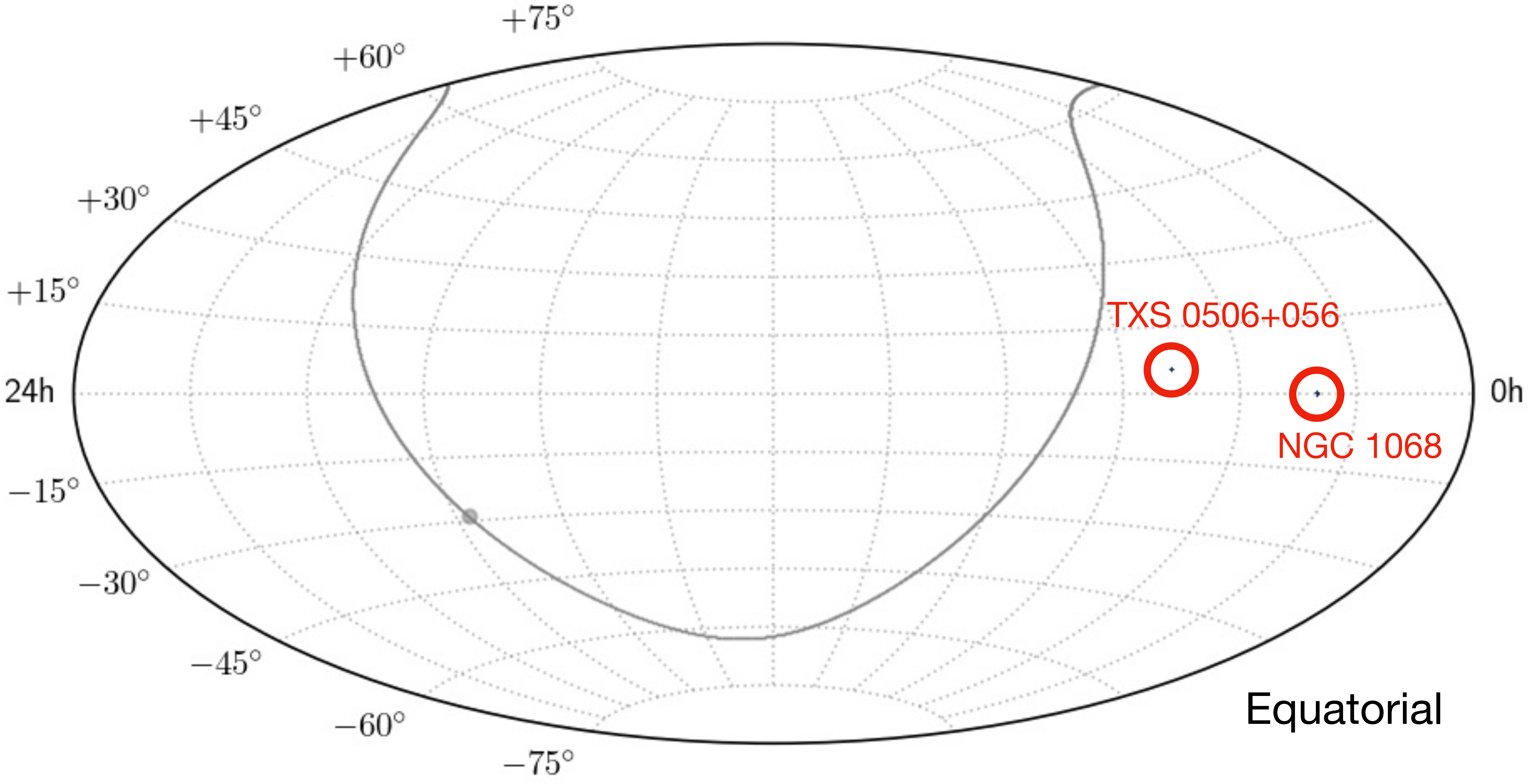
C. A. Argüelles, A. Kheirandish and A. C. Vincent, *Phys. Rev. Lett.* **119** (2017) no.20, 201801

$\nu$ initial neutrino flux
from a distant source

$\chi$

$\nu$
attenuated neutrino
flux at Earth

# IceCube-identified astrophysical neutrino point sources



- All in the northern sky
- Both are the target sources of this analysis
  - Treat each source independently (not stacking analysis)

- TXS 0506+056
  - First transient source: *IceCube-170922A* by 290 TeV neutrino → first multi-messenger astronomy with neutrinos *Science* **361**, eaat1378 *Science* **361**, 147-151
  - BL Lac-type blazar
  - (77.36°, 5.69°) in the equatorial coordinates
  - (195.41°, -19.64°) in the galactic coordinates
  - z = 0.3365 (1421 Mpc)

- NGC 1068
  - First steady source *Science* **378**, 538-543
  - Seyfert II galaxy - nearby active galaxy
  - (40.67°, -0.01°) in the equatorial coordinates
  - (172.10°, -51.93°) in the galactic coordinates
  - z =0.0038 (14.4 Mpc)

# Flux changes as a result of the interactions

- Estimate the change of high-energy astrophysical neutrino flux from a source

$$\frac{d\Phi}{d\tau}(E_\nu) = \underbrace{\boxed{-\,\sigma_{\nu\chi}(E_\nu)\Phi(E_\nu)}}_{\text{Attenuation}} + \underbrace{\boxed{\int_{E_\nu}^{\infty} dE'_\nu \frac{d\sigma_{\nu\chi}}{dE_\nu}(E'_\nu \to E_\nu)\Phi(E'_\nu)}}_{\text{Re-distribution}} \qquad (\tau = \Sigma_{DM}(r)/m_{DM})$$

- DM column density along the line of sight (l.o.s)

$$\Sigma_{DM} = \int_{path} dr\,\rho(r)$$

- Considering the contributions from the extragalactic DM and the Milky Way DM

$$\int_{path} \sigma n(\mathrm{x})\,dl = \frac{\sigma}{m_{DM}}\left(\overset{\text{Milky Way}}{\boxed{\int_{l.o.s.} \rho_{gal}(\mathrm{x})\,dl}} + \overset{\text{Cosmological}}{\boxed{\int_{l.o.s.} \rho_{cosmo}(z)\,dl}} + \overset{\text{Source Galaxy}}{\boxed{\int_{l.o.s.} \rho_{source}(r)\,dl}}\right)$$

# Galactic/extragalactic DM

- Considering both galactic and extragalactic dark matter contributions
  - Neutrino trajectory may not pass through the galactic centre but just the galactic halo
  - The large distance to a source compensates small cosmological DM density in intergalactic medium
  - The dense DM spike surrounding an extragalactic source would give much stronger effects

For TXS 0506+056 (1421 Mpc):

$$\int_{los} \rho(\mathrm{x})dl \backsimeq 1.12 \times 10^{22}\ \mathrm{GeV/cm^2}$$

Milky Way

$$\int_{los} \rho(z)dl \backsimeq 7.25 \times 10^{21}\ \mathrm{GeV/cm^2}$$

Cosmological

$$\int_{los} \rho(r)dl \simeq 8.73 \times 10^{28}\ \mathrm{GeV/cm^2}$$

Source Galaxy

Galactic DM density profiles

$\rho(\mathbf{x})$: **NFW profile**, Einasto profile, Burkert profile …

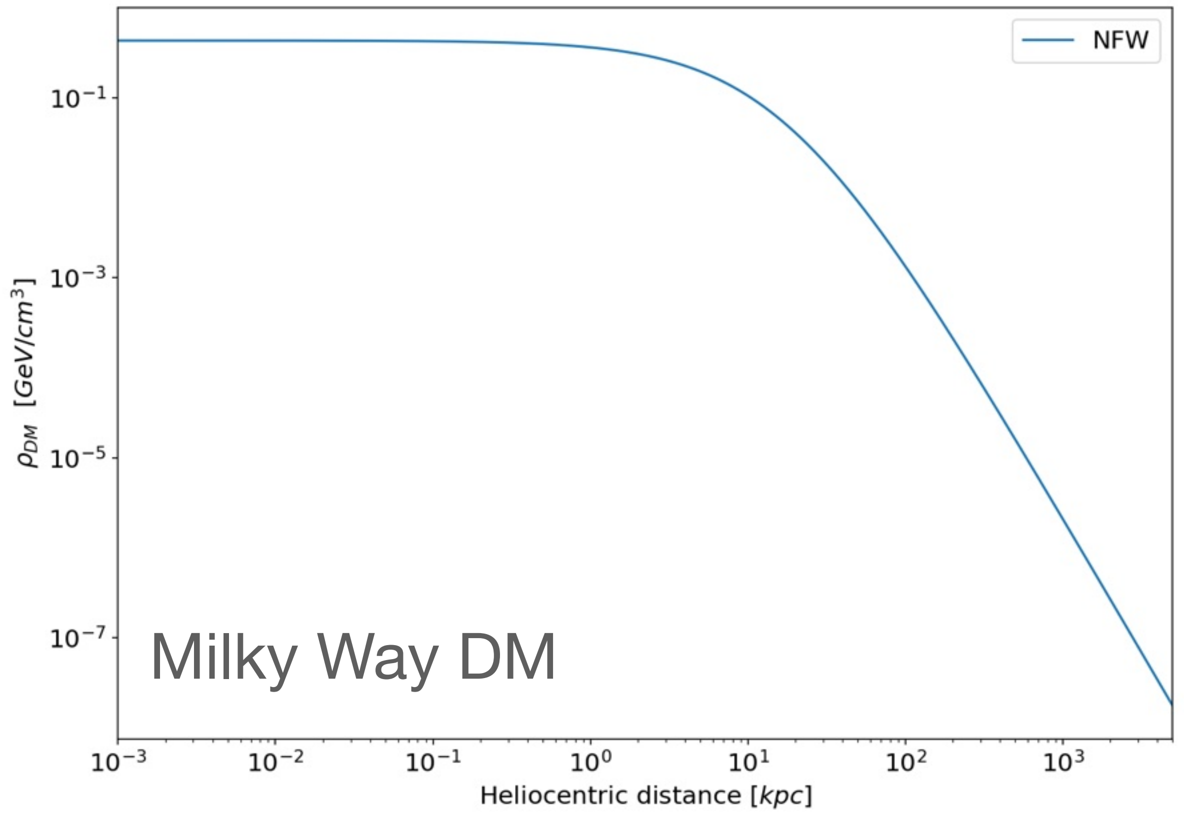
Intergalactic free space DM density (Planck 2018)

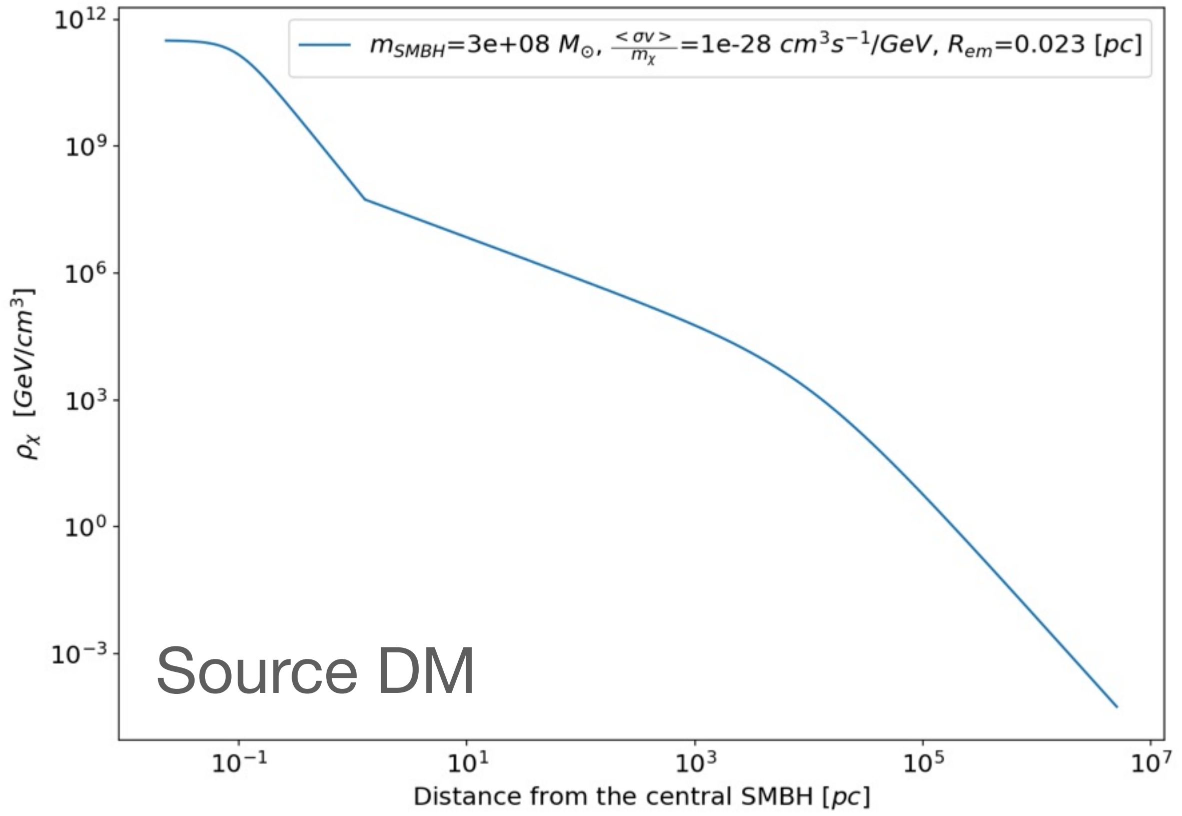
$$\rho(z) = \rho_c \Omega_{\chi,0}(1+z)^3\ \mathrm{GeV/cm^3}$$

Extragalactic source's DM spike density profiles

$$\rho(r) = \begin{cases} 0 & r \leq 4R_S \\ \frac{\rho_{\mathrm{sp}}(r)\rho_{\mathrm{sat}}}{\rho_{\mathrm{sp}}(r)+\rho_{\mathrm{sat}}} & 4R_S \leq r \leq R_{sp} \\ \rho_0 \left(\frac{r}{r_0}\right)^{-\gamma} \left(1+\frac{r}{r_0}\right)^{-2} & r \geq R_{sp}. \end{cases}$$

F. Ferrer, G. Herrera, and A. Ibarra;
arXiv:2209.06339 & JCAP 05 057 (2023)



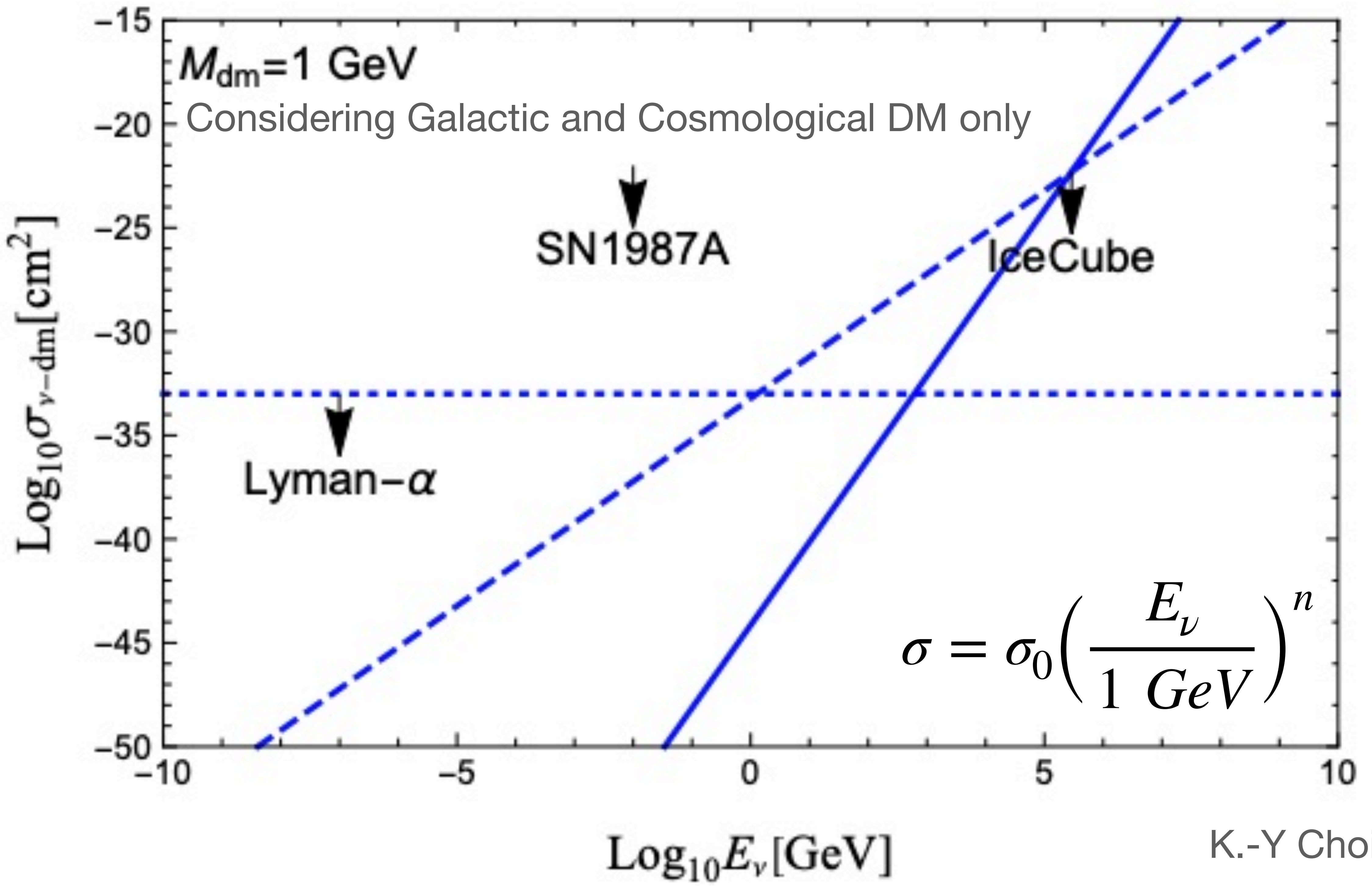


# Phenomenological study with a known source

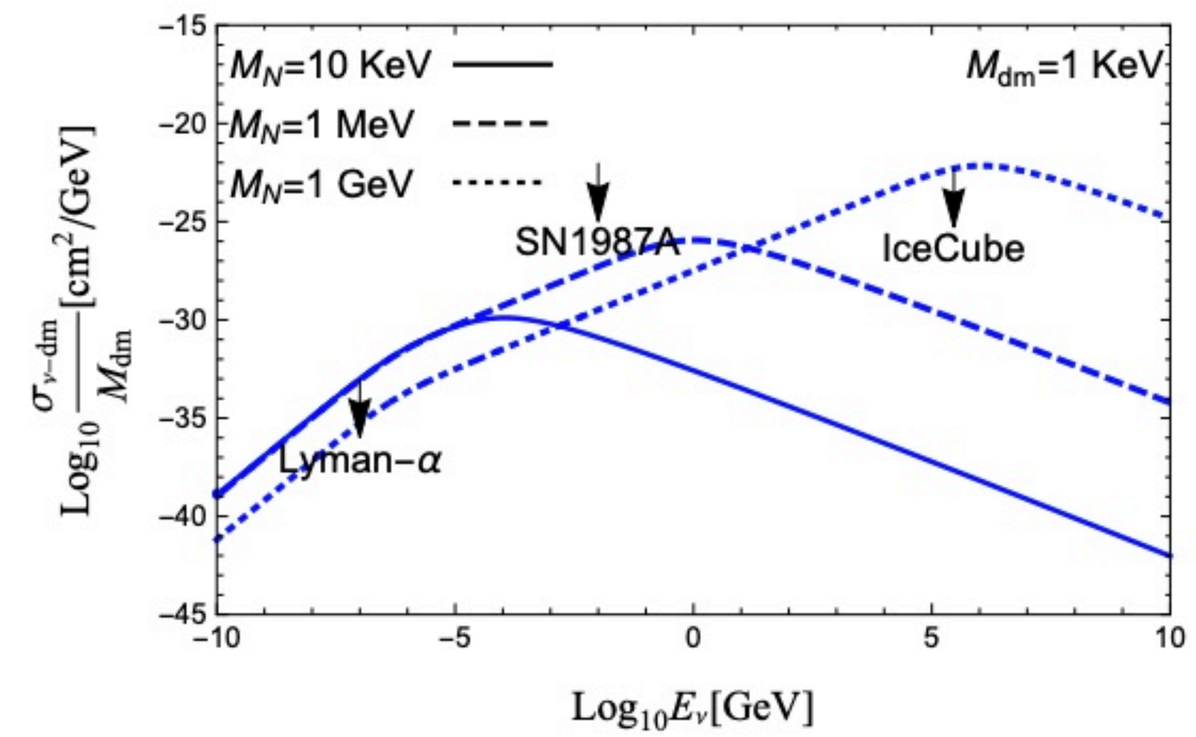
- A new approach has been proposed to use distant neutrino sources to search for rare interactions
- This theoretical work used public IceCube data and derived first bounds based on overall attenuation of the signal

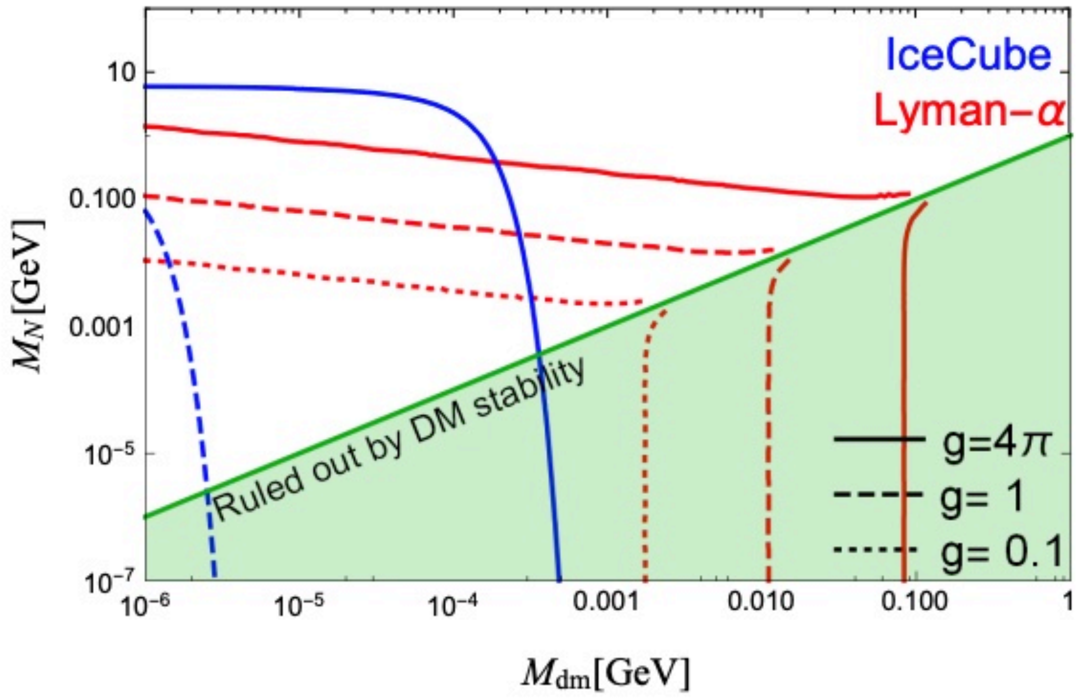
$$\exp\left(-\int n\sigma\, dl\right) = 0.1 \rightarrow \int_{l.o.s} \sigma_{DM} n_{DM}\, dl \lesssim 2.3$$

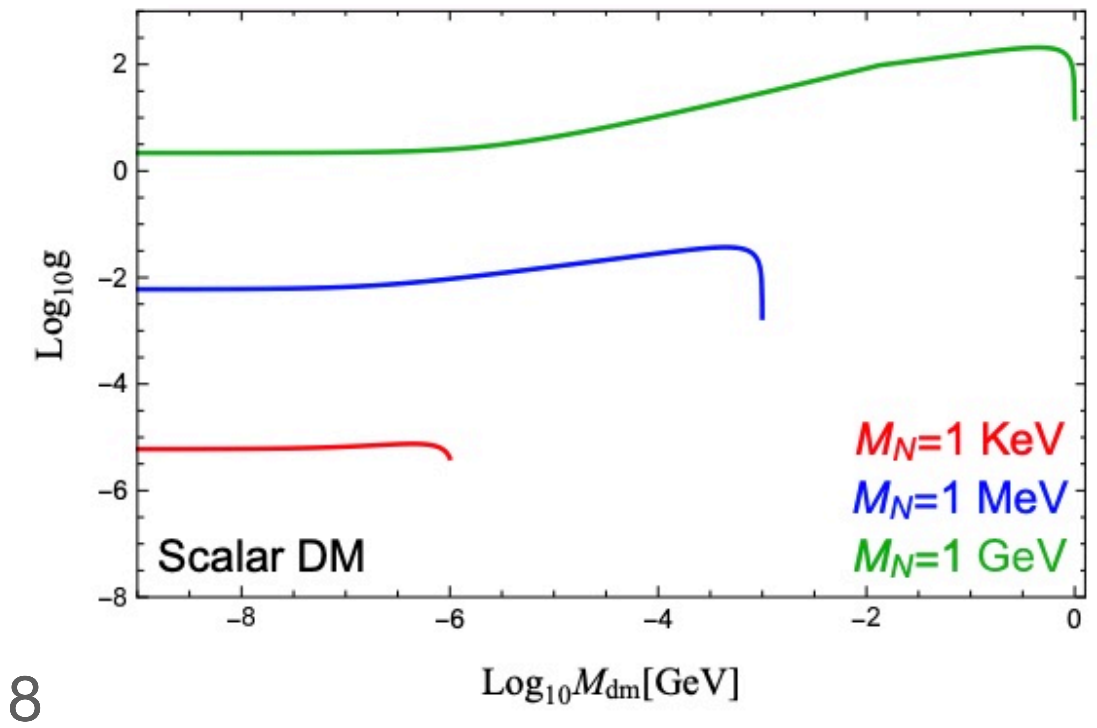
- 90% flux suppression gives sensitivity regions like:



Complex scalar DM + fermion mediator



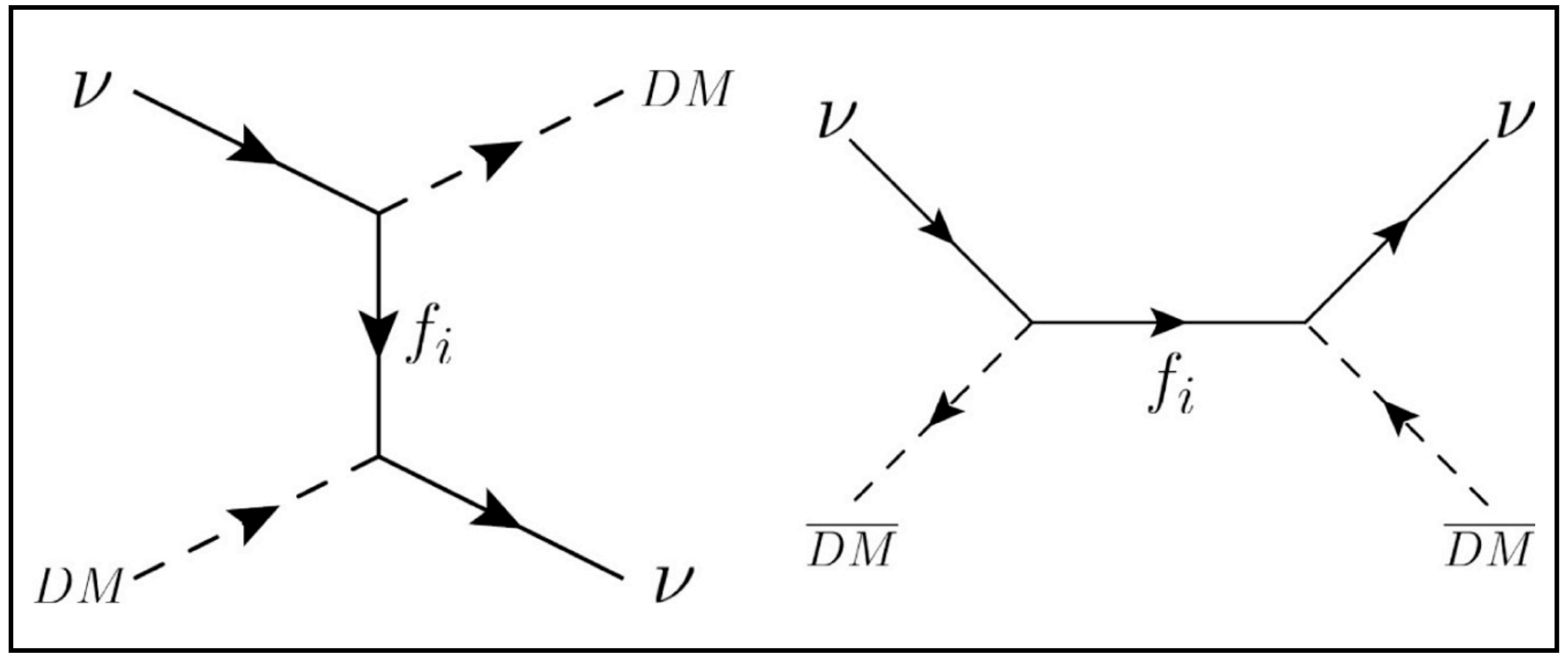




K.-Y Choi, J. Kim and C. Rott, Phys. Rev. D 99 (2019) 083018

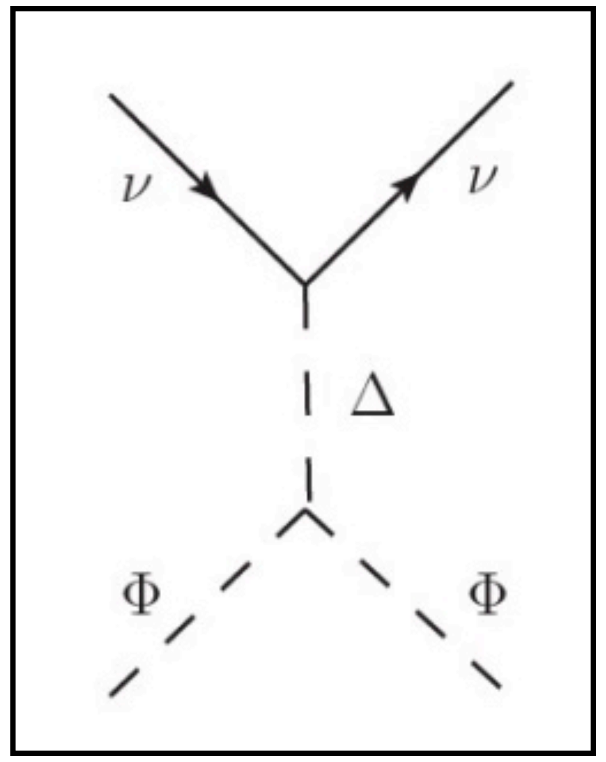
# Benchmark models

- Light mass DM $(m_{DM} \leq \mathrm{GeV})$
  - With fermion mediator



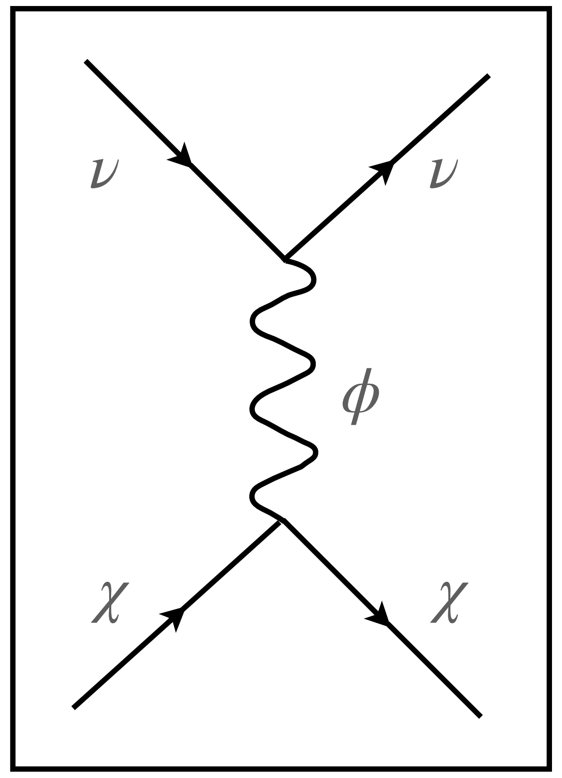
K.-Y. Choi, E. J. Chun and J. Kim, *Phys.Dark Univ.* **30** (2020) 100606

  - With scalar mediator

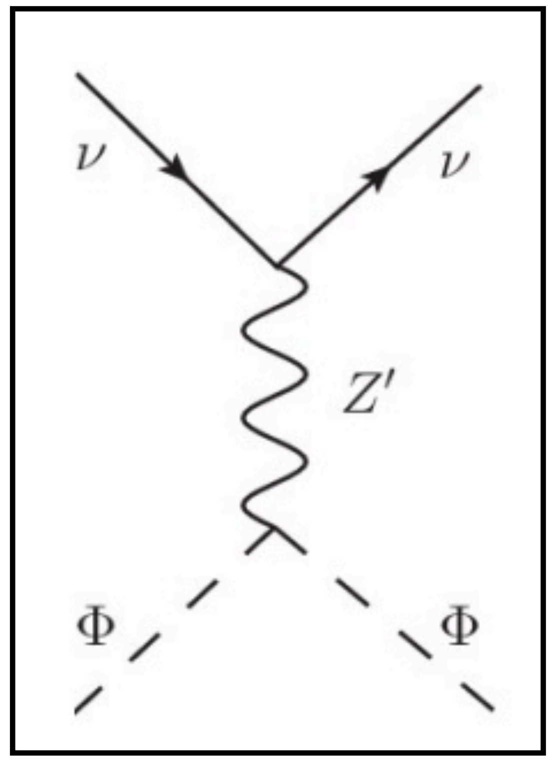


S. Pandey, S. Karmakar
and S. Rakshit, *JHEP* **01** (2019) 095

  - With vector mediator



C. Argüelles, A. Kheirandish and A. Vincent,
*Phys. Rev. Lett.* **119** (2017) no.20, 201801



S. Pandey, S. Karmakar
and S. Rakshit, *JHEP* **01** (2019) 095

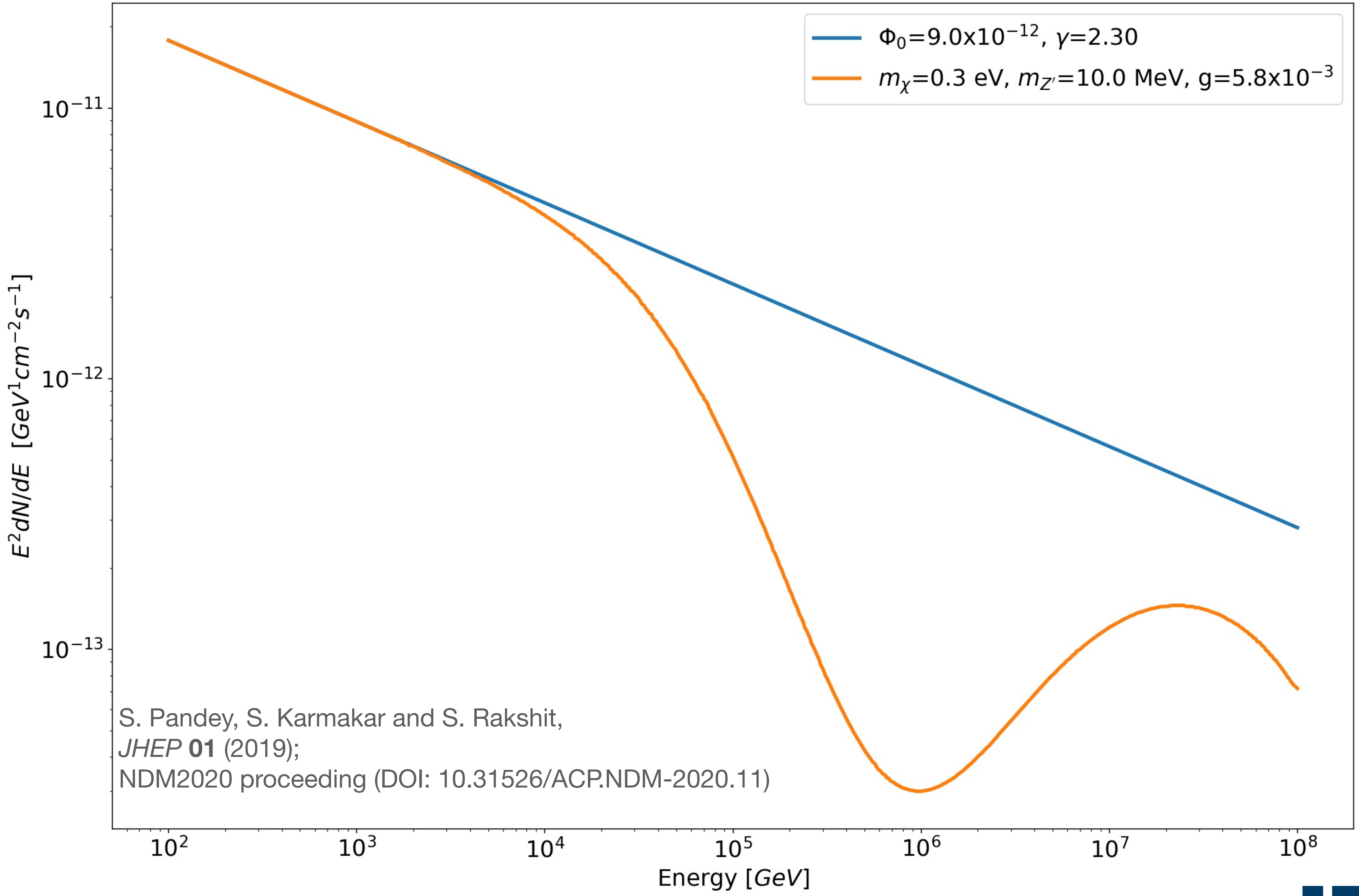
'Mediating via light $Z'$ boson'

- Selected as our benchmark scenario
- Strongly coupled with both $\chi$ and $\nu_\tau$ (assuming same coupling)
- Weak coupling with $\nu_e$ or $\nu_\mu$
- Oscillation over cosmological propagation baseline
  → Flavour-universal results in the end

$$\mathcal{L} \supset f_l' \bar{L}\gamma^\mu P_L L Z'_\mu + ig'(\Phi^*\partial^\mu\Phi - \Phi\partial^\mu\Phi^*)Z'_\mu$$

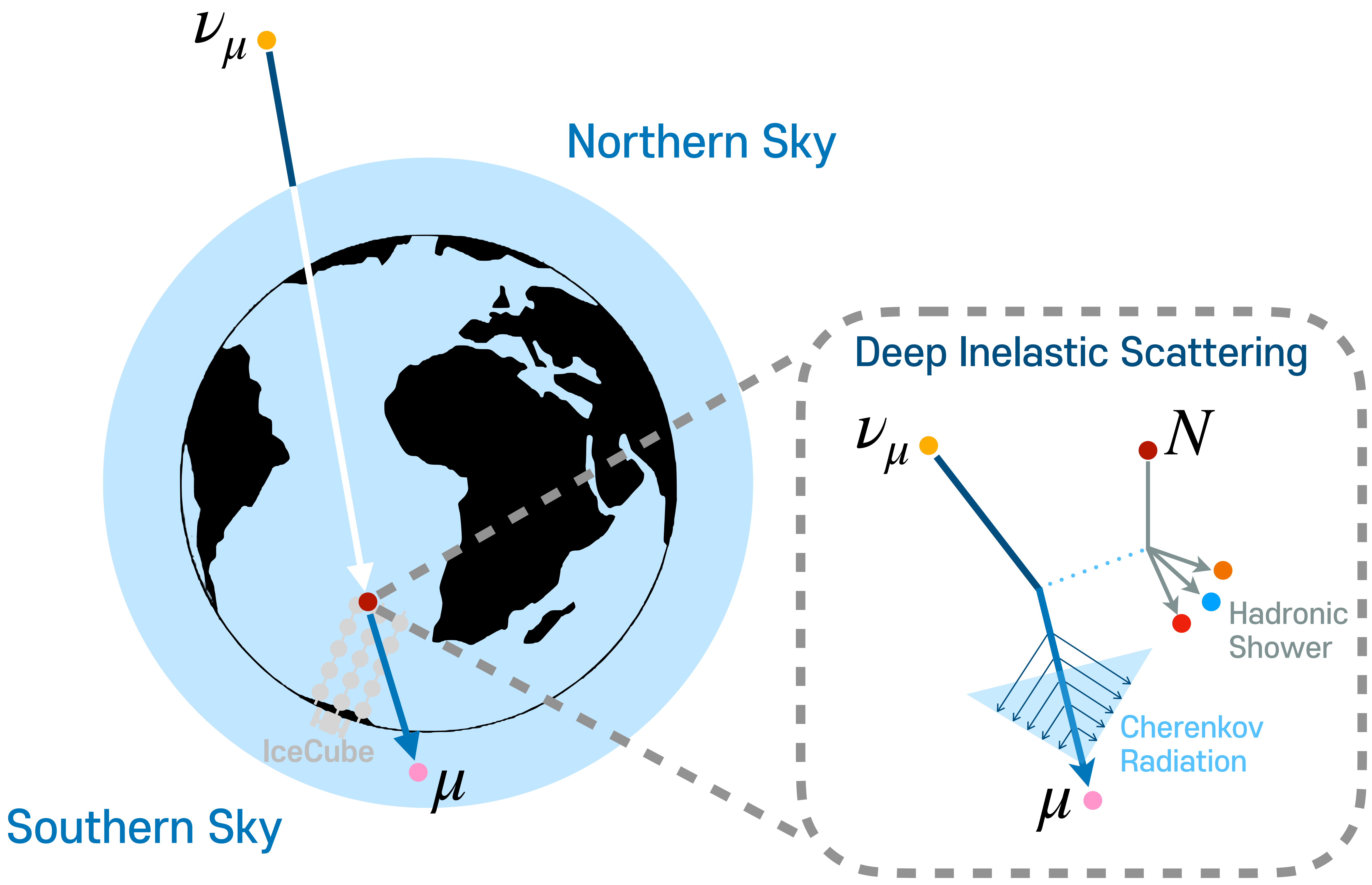
# Benchmark spectrum

- Mediating via $Z'$ vector boson
- Single Power Law + 'dip'
- Account for the dark matter contributions from the Milky Way halo and the cosmological (intergalactic) distribution
- To be optimised for each source (with the source properties; eg. distance, direction, flux, spectral index, …)



S. Pandey, S. Karmakar and S. Rakshit,
*JHEP* **01** (2019);
NDM2020 proceeding (DOI: 10.31526/ACP.NDM-2020.11)

# Neutrinos from Northern sky



- Through-going tracks from Northern sky ($-5^\circ < \delta < 90^\circ$)
- Good angular reconstruction and improved energy reconstruction
- For ~10.4 years of livetime in IC86 configuration

- Expected backgrounds
  - Atmospheric backgrounds
    - Conventional neutrinos
    - Prompt neutrinos
  - Astrophysical backgrounds
    - Diffused astrophysical neutrinos

# Analysis method

- Hypothesis tests - search for the astrophysical neutrino signal over the backgrounds
  - Null hypothesis: there exists a point source with a single power law spectrum $E^{-\gamma}$ resulting in $n_s$ signal events in the observed data in our detector
  - BSM alternative: the flux from the point source consists of the power law assumption as well as a signal of interaction with Dark Matter
- Unbinned Maximum Likelihood analysis with the modified PS likelihood

$$\mathscr{L}(n_s) = \prod_{i=0}^{N} \left[ \frac{n_s}{N} \mathcal{S}(\alpha_i, \delta_i, E_i \,|\, \gamma, \phi_0, m_\chi, m_\phi, g_{\nu\chi}) + \left(1 - \frac{n_s}{N}\right) \mathscr{B}(\alpha_i, \delta_i, E_i \,|\, \gamma, \phi_0) \right]$$

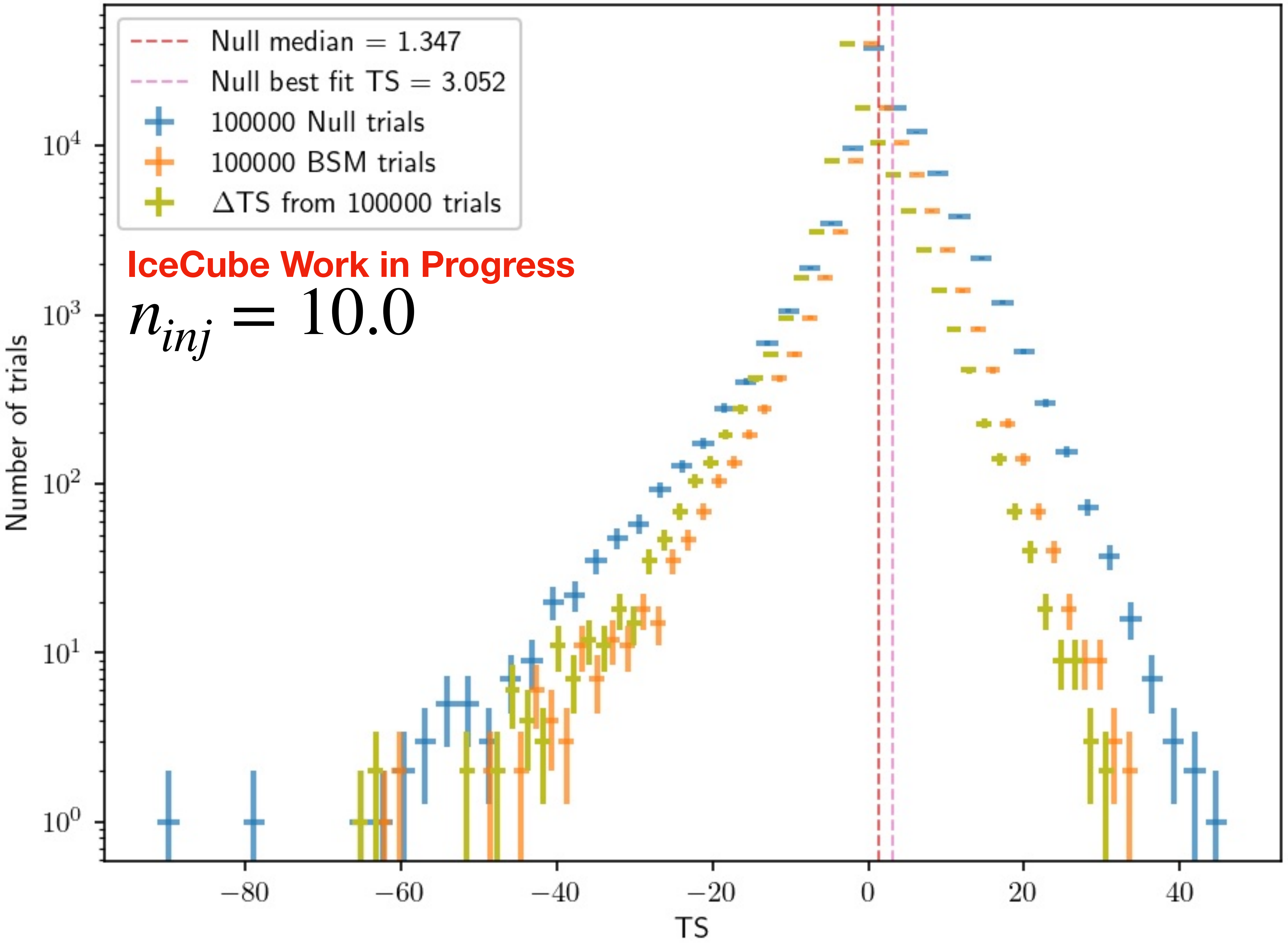
$$TS = -2 \cdot sign(n_s) \cdot \ln\left[\frac{\mathscr{L}_{Null}}{\mathscr{L}_{BSM}}\right]$$

$$= -2 \cdot sign(n_s) \cdot \ln\left[\frac{\mathscr{L}(n_s = \hat{\hat{n}}_s,\ \gamma = \hat{\hat{\gamma}},\ \Phi_0 = \hat{\hat{\Phi}}_0,\ g = 0)}{\mathscr{L}(n_s = \hat{n}_s,\ \gamma = \hat{\gamma},\ \Phi_0 = \hat{\Phi}_0,\ m_\chi = \hat{m}_\chi,\ m_\phi = \hat{m}_\phi,\ g = \hat{g})}\right]$$

# TS distributions

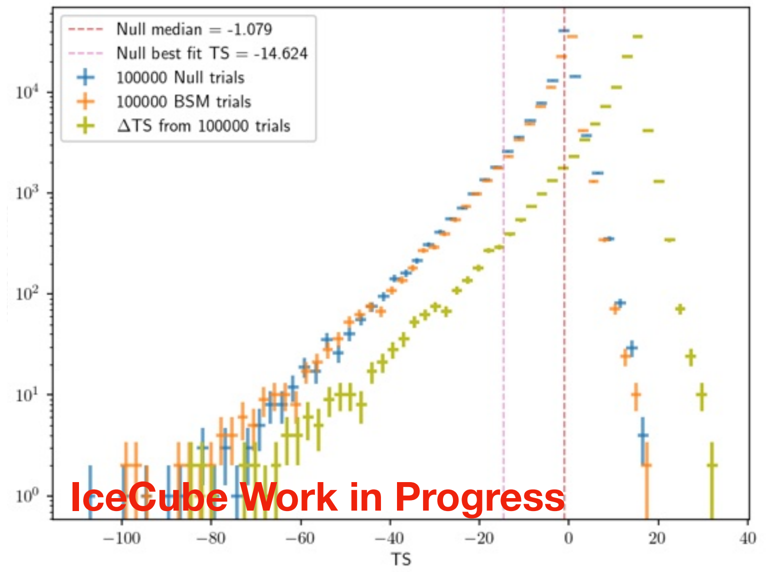
* From pseudo-experiments using Monte Carlo data

$\Delta TS = TS_{BSM} - TS_{Null;max}$

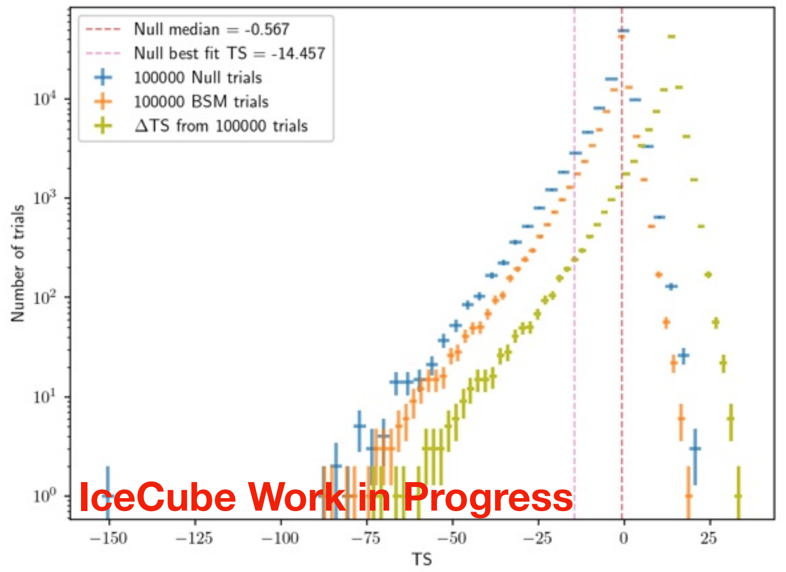


$n_{inj} = 10.0$

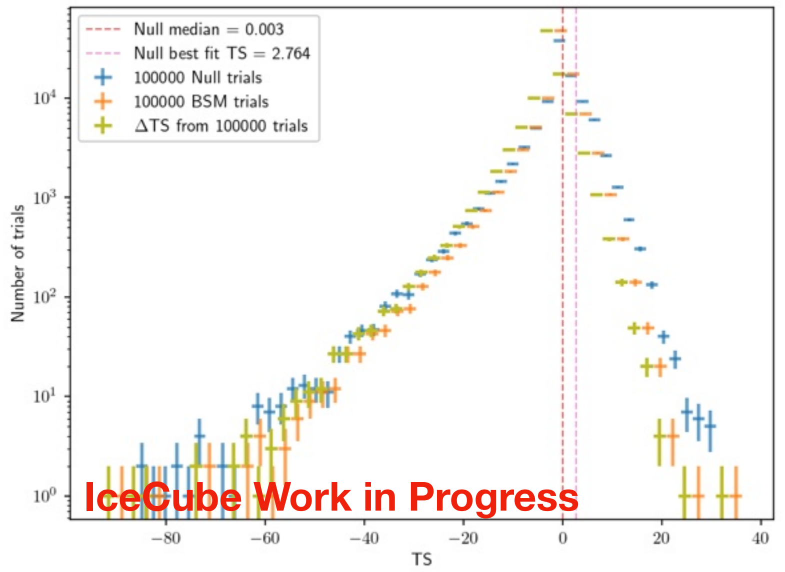
- From the comparison of $\Delta TS$ and $TS_{Null}$, the sensitivity of BSM models to the standard single power-law can be calculated.. to be updated soon!



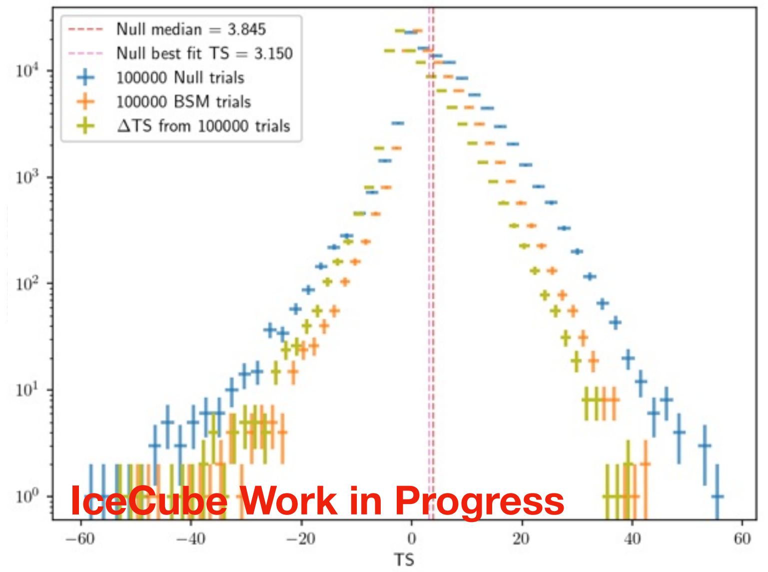
$n_{inj} = 1.0$



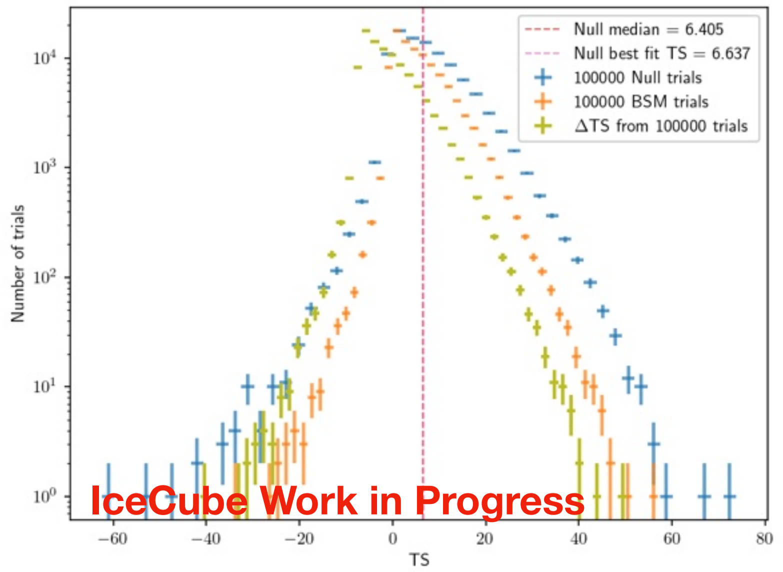
$n_{inj} = 2.0$



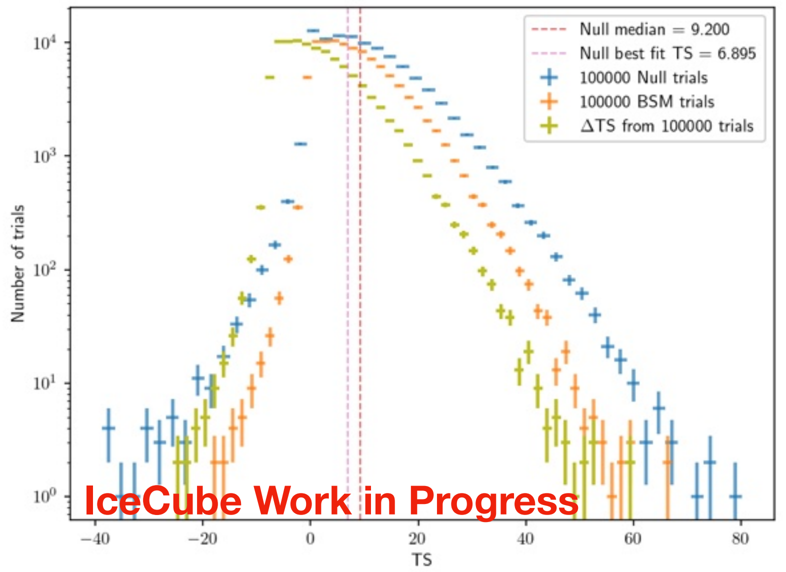
$n_{inj} = 5.0$



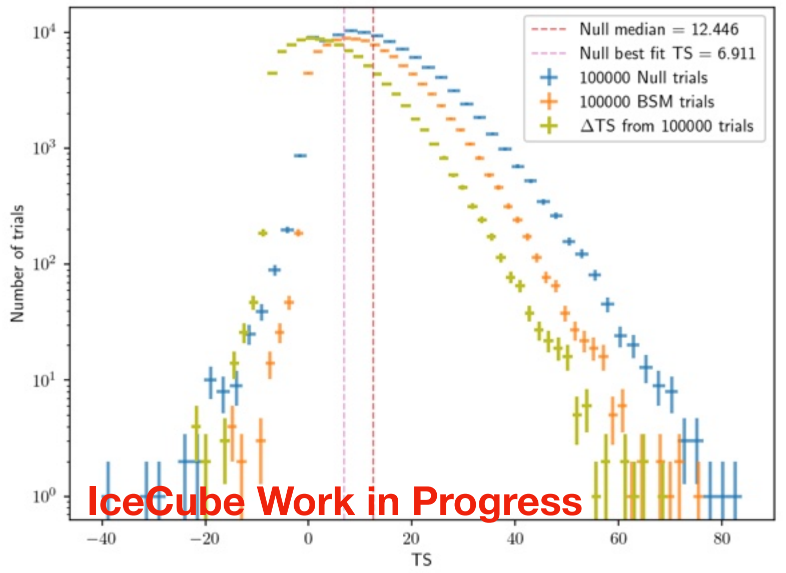
$n_{inj} = 15.0$



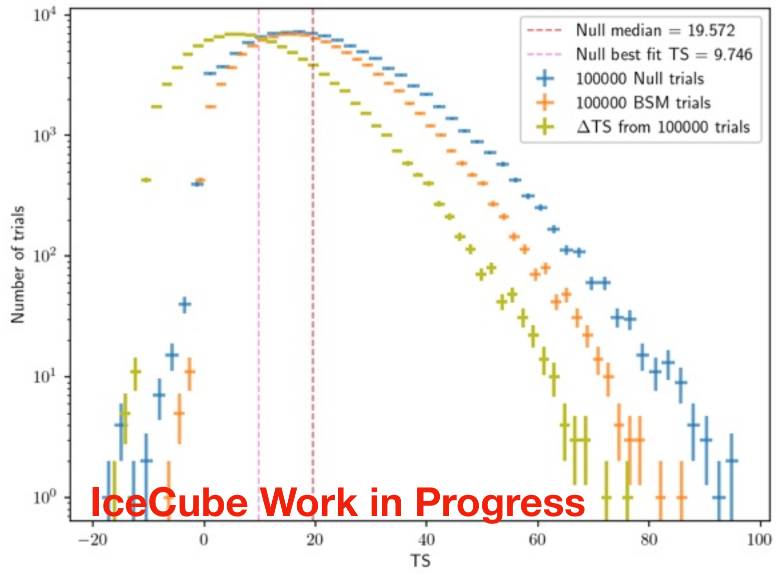
$n_{inj} = 20.0$



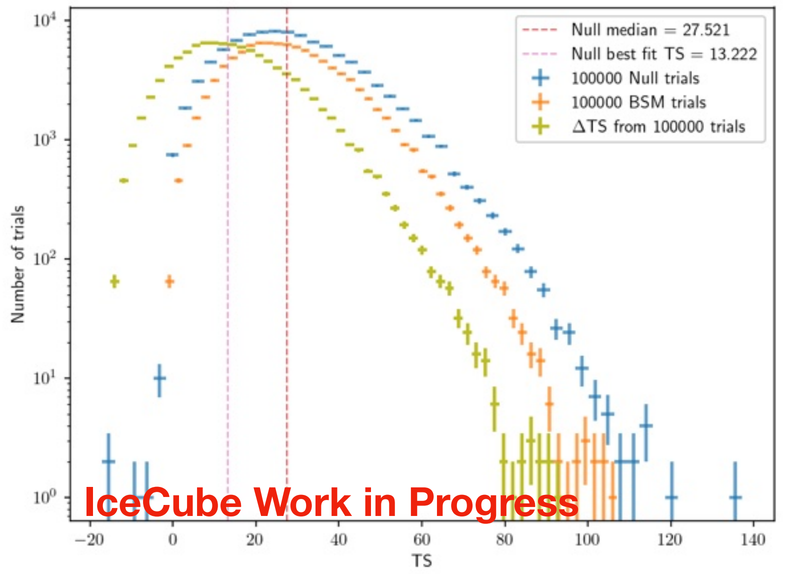
$n_{inj} = 25.0$



$n_{inj} = 30.0$



$n_{inj} = 40.0$



$n_{inj} = 50.0$

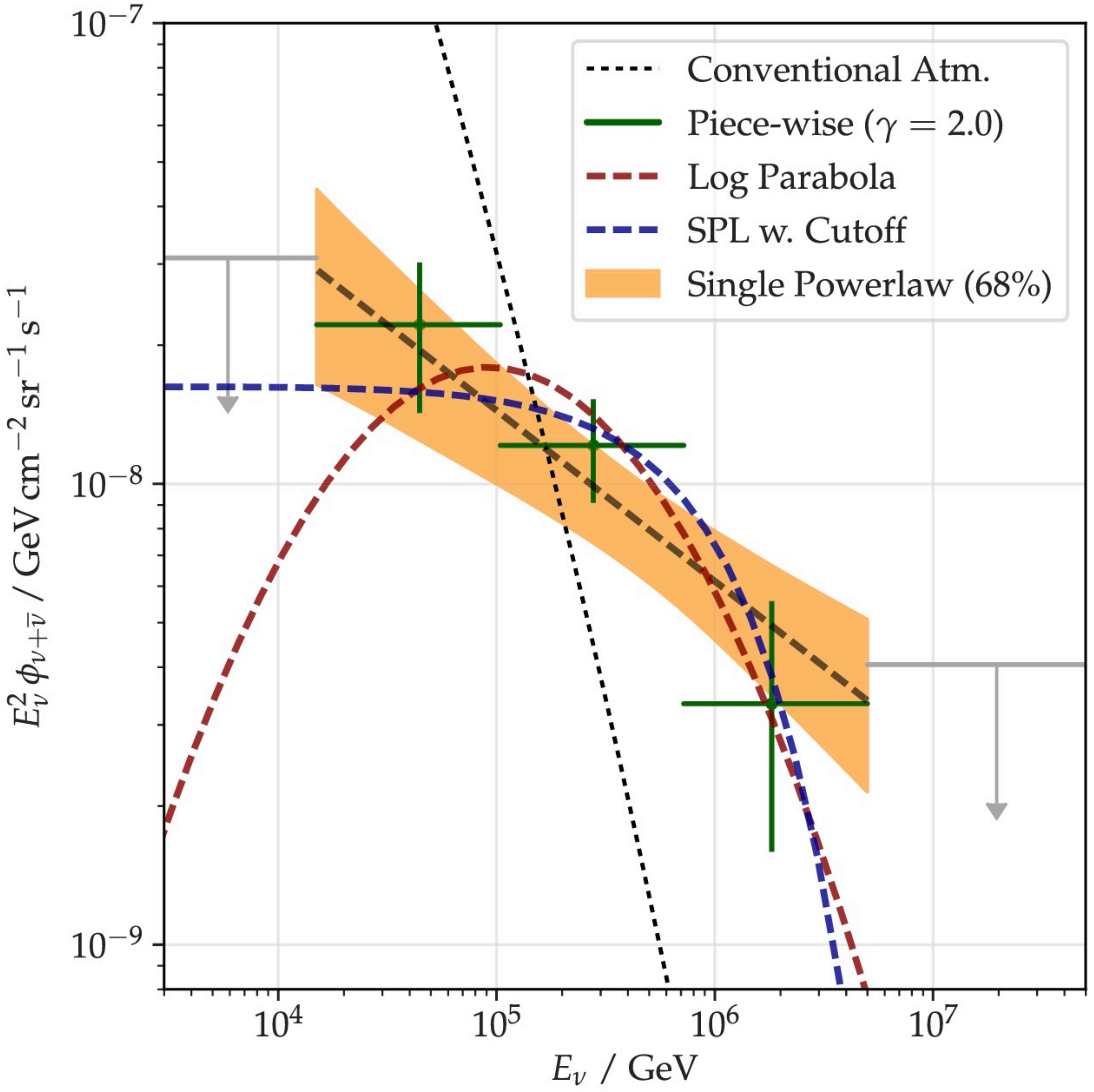
# What’s next?

- Sensitivity to the benchmark model (on $\sigma_{\nu\chi}, m_\chi, m_\phi, g_{\nu\chi}$)

- Testing different Neutrino - Dark matter interaction models

- In the current step, no systematics including models of astrophysical neutrino flux
  - Recent IceCube papers for the astrophysical neutrino flux testing various flux models
  - This analysis will test those models as well as the null hypothesis

IceCube Collaboration, *Astrophys. J.* **928** (2022) 1, 50



# Summary and Outlook

- IceCube opened the era of neutrino astronomy with the discoveries of distant astrophysical neutrino sources
  - As of now, two IceCube-identified point sources: TXS 0506+056 and NGC 1068
  - It allows novel approaches to study the BSM physics with the sources and neutrinos from them
- Searching for neutrino rare interaction signal with distant point sources
  - The vast distances to the sources make the neutrino flux susceptible to rare interactions that might occur on the long journeys of the neutrinos from source to Earth
  - Constraining the cross-section of neutrino - DM interaction with one IceCube neutrino event by a neutrino from TXS 0506+056 (IC170922A)
  - Developing analysis for generic point sources and various interaction models
    - $\nu$ - DM interaction with $Z'$ mediator as a benchmark case
    - Several contributions to signal from different DM distributions
    - Analysis sensitivity to the benchmark model will come out soon!

Thank you for your attention :)

© NSF/IceCube Collaboration

# Backup

$\nu$ initial neutrino flux
from a distant source

**Your Favourite BSM Theory**

$\nu$ attenuated neutrino
flux at Earth

# Objective

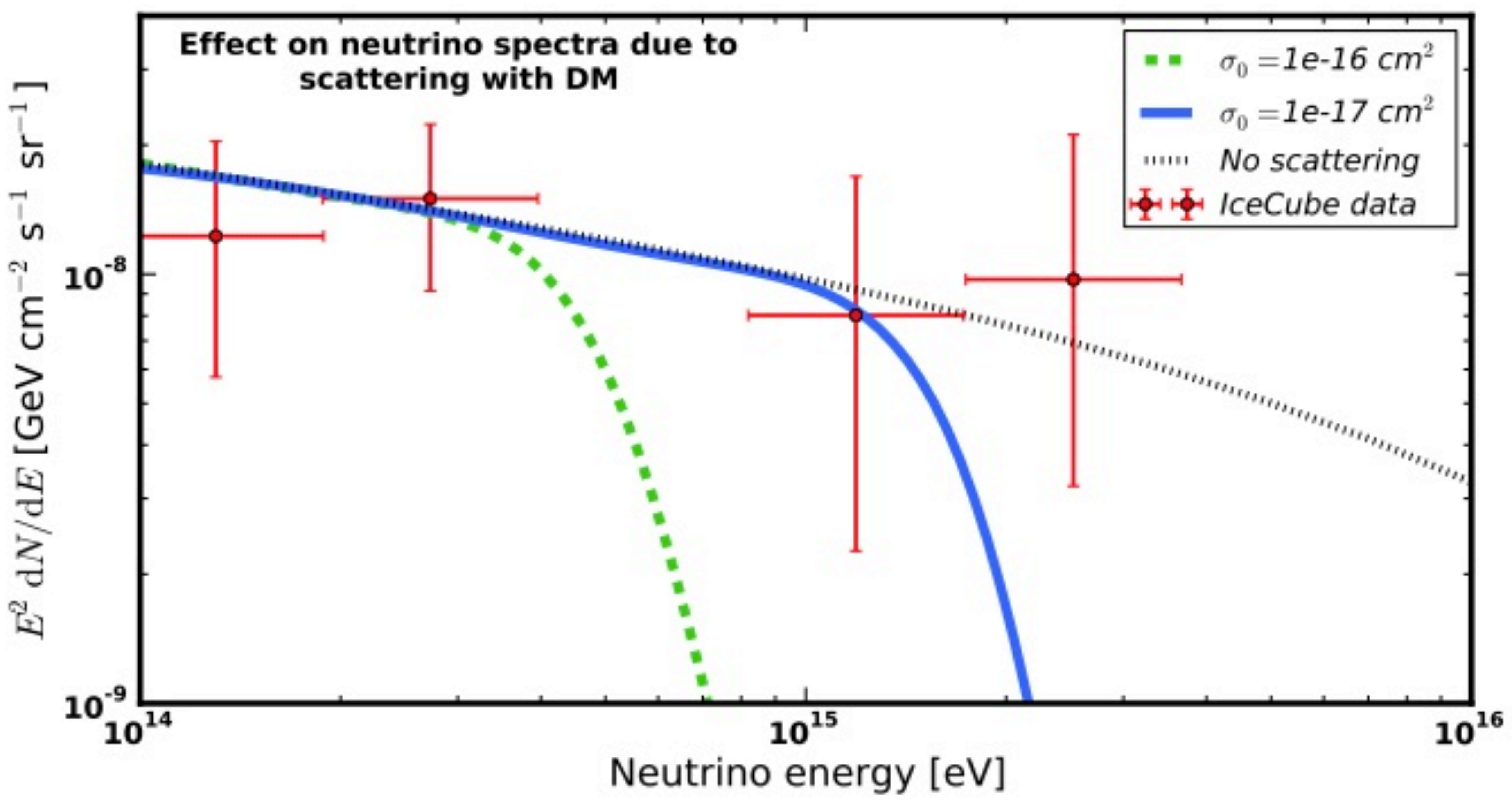
- The objective of the analysis is to search for the BSM interactions of neutrino from the IceCube high-energy astrophysical neutrino data and their source information

- This experimental DM study has never been done, and IceCube is the ideal detector so far

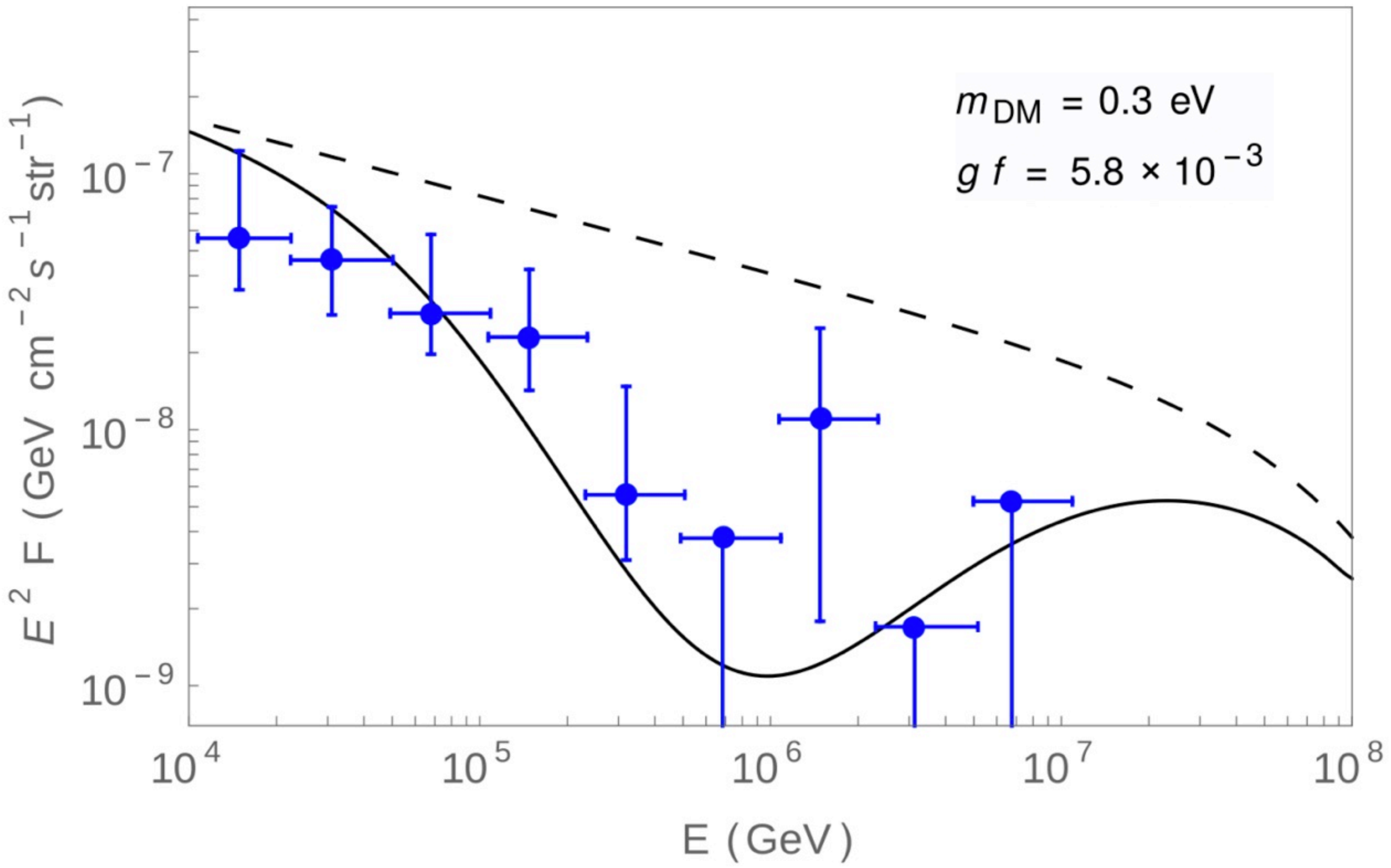
- Various interaction models can be applied and tested

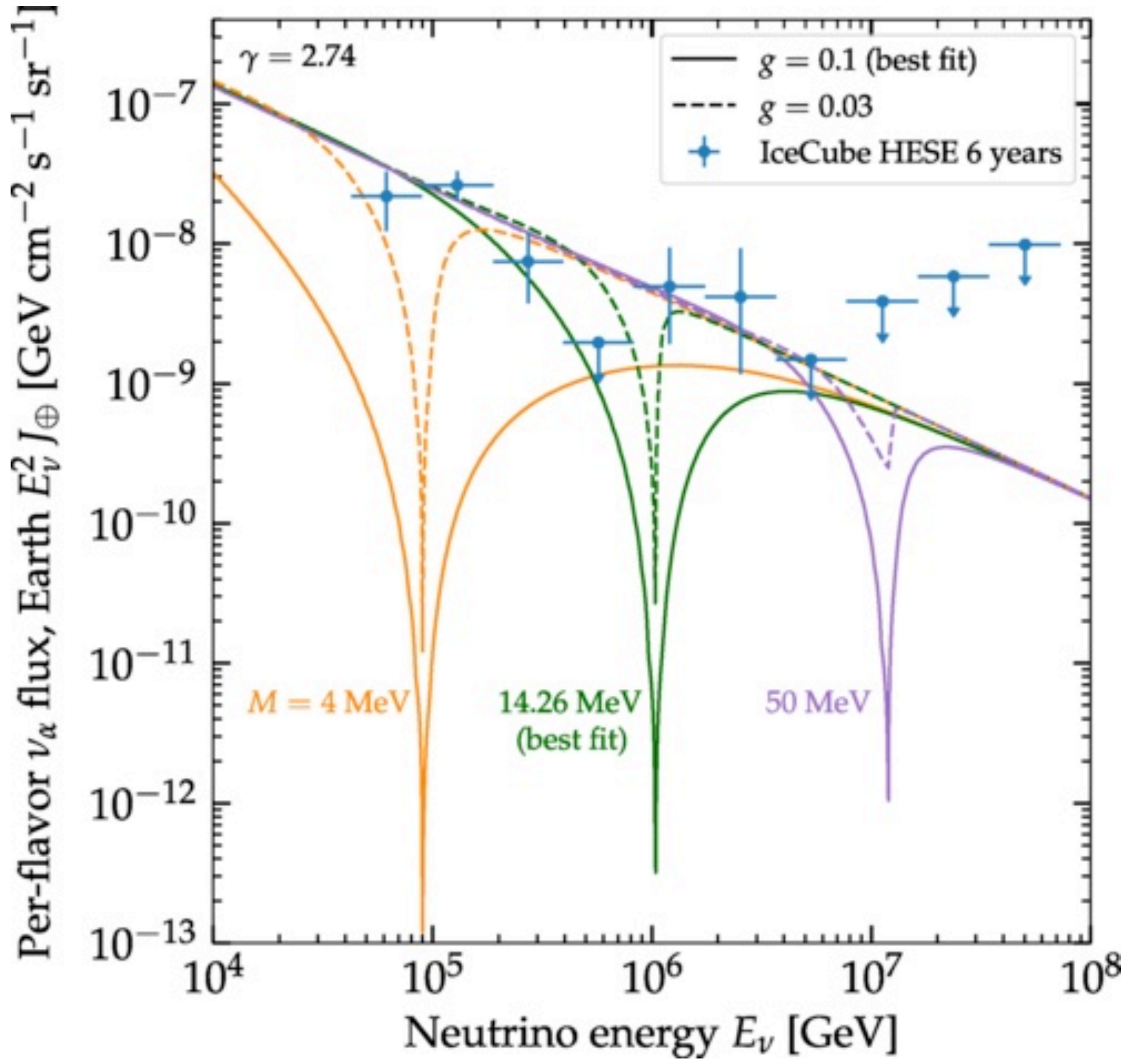
    - Resonant suppression (early cutoff or dip-shape) at a specific $E_\nu$ in the neutrino flux from the events on extended energy range following the given models are expected.

J. H. Davis and J, Silk, arXiv:1505.01843



S. Pandey *et al*, NDM2020 proceeding
(DOI: 10.31526/ACP.NDM-2020.11)





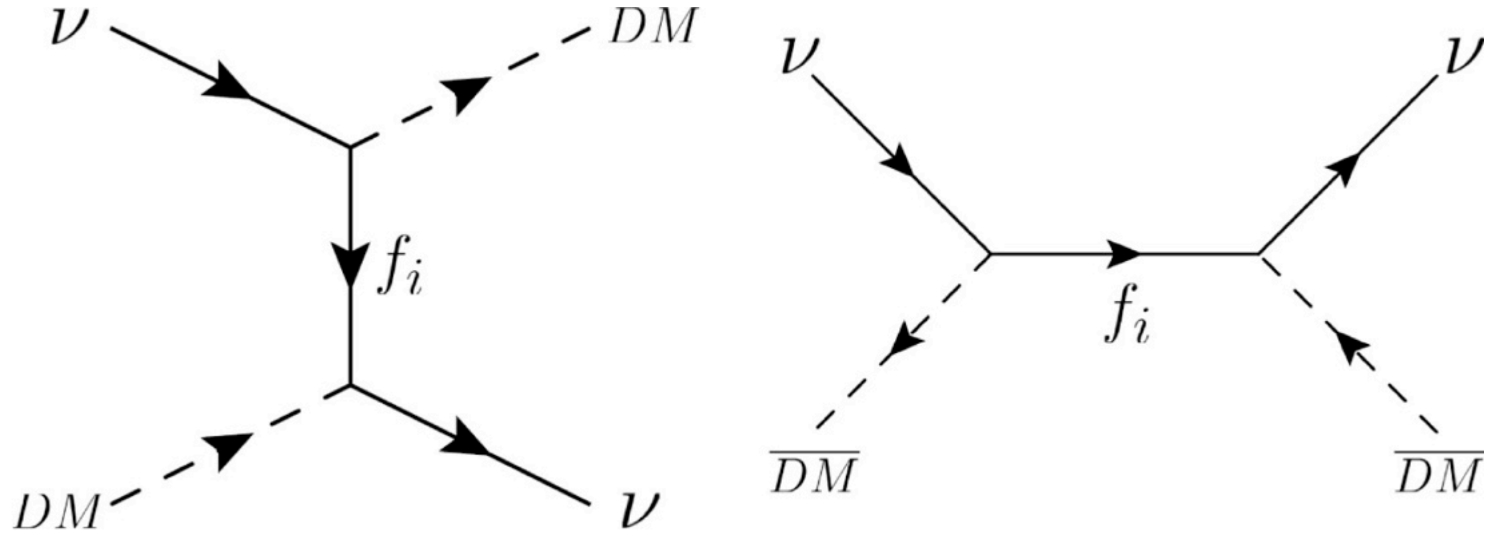
M. Bustamante *et al*,
*Phys. Rev. D* **101**, 123024 (2020);
for ‘secret’ neutrino interaction

# Study with a known source

- A new approach to study the propagation of the high-energy astrophysical neutrino through the cosmological DM as well as the DM in the Milky Way from the observation of IC170922A and the identification of its origin with a known path and distance.
- By assuming the attenuation-dominant case, 90% flux suppression gives bounds:

$$\exp\left(-\int n\sigma\, dl\right) = 0.1 \rightarrow \int_{l.o.s} \sigma_{DM} n_{DM}\, dl \lesssim 2.3$$

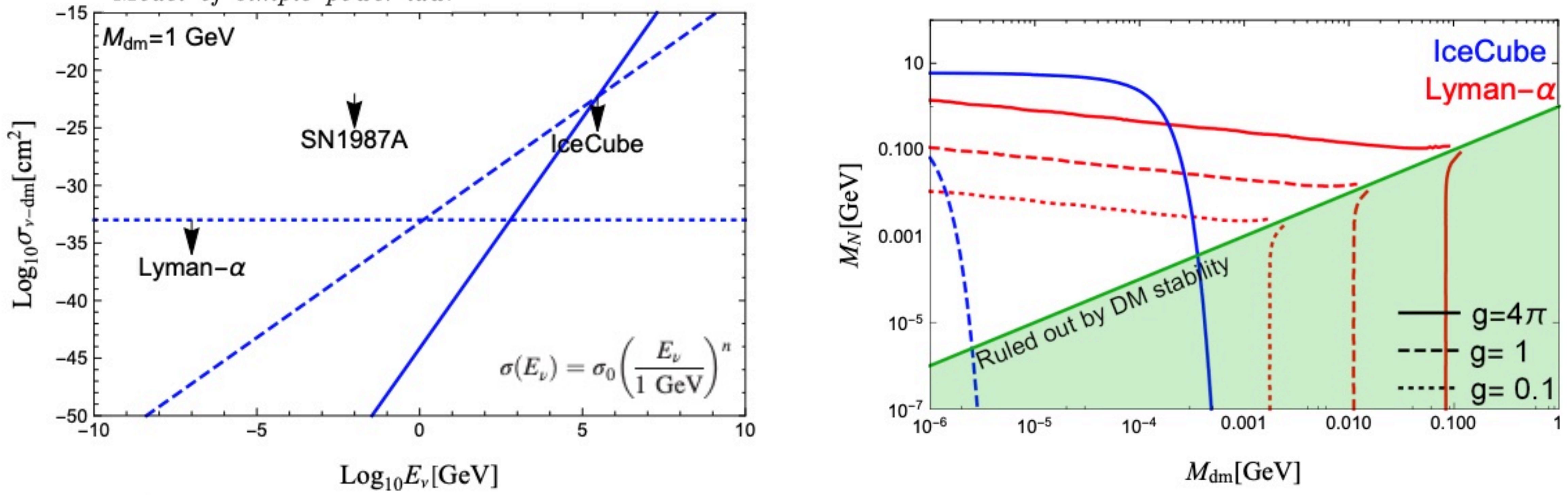
- Model of light scalar DM



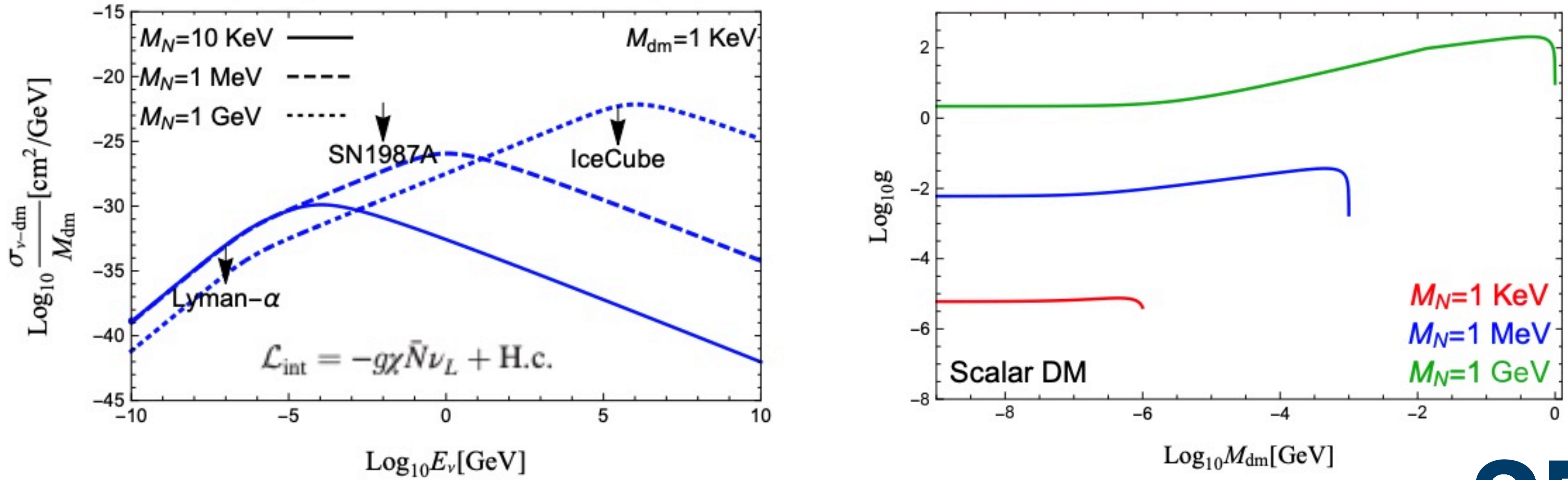
| Neutrino energy | $\sigma/M_{\rm dm}[\mathrm{cm}^2/\mathrm{GeV}]$ | Exp. [Ref.] |
|---|---|---|
| ~100 eV | $6\times10^{-31}$ | CMB [13–15] |
| ~100 eV | $10^{-33}$ | Lyman-α [11] |
| 10 MeV | $10^{-22}$ | SN1987A [9] |
| 290 TeV | $5.1\times10^{-23}$ | IceCube-170922A [1] |

K.-Y Choi, J. Kim and C. Rott, Phys. Rev. D 99 (2019) 083018

*Model of simple power-law.*



*Model of complex scalar DM mediated by a fermion.*



# Constraining $\nu$- DM interaction cross-section

- Assuming maximum suppression of initial flux to be 90% from attenuation-only:

$$\exp\left(-\int n\sigma\, dl\right) = 0.1 \rightarrow \int_{l.o.s} \sigma_{DM} n_{DM}\, dl \lesssim 2.3$$

$$\rightarrow \frac{\sigma_{\nu\chi}}{m_\chi} \lesssim \frac{2.3}{\Sigma_{DM;Gal} + \Sigma_{DM;Cos} + \Sigma_{DM;Sou}} \; [cm^2/GeV]$$

$$\Sigma_{DM;Galactic} \simeq 1.116 \times 10^{22} \; [GeV/cm^2]$$

$$\Sigma_{DM;Cosmological} \simeq 7.246 \times 10^{21} \; [GeV/cm^2]$$

$$\Sigma_{DM;Source} \simeq 8.728 \times 10^{28} \; [GeV/cm^2]$$

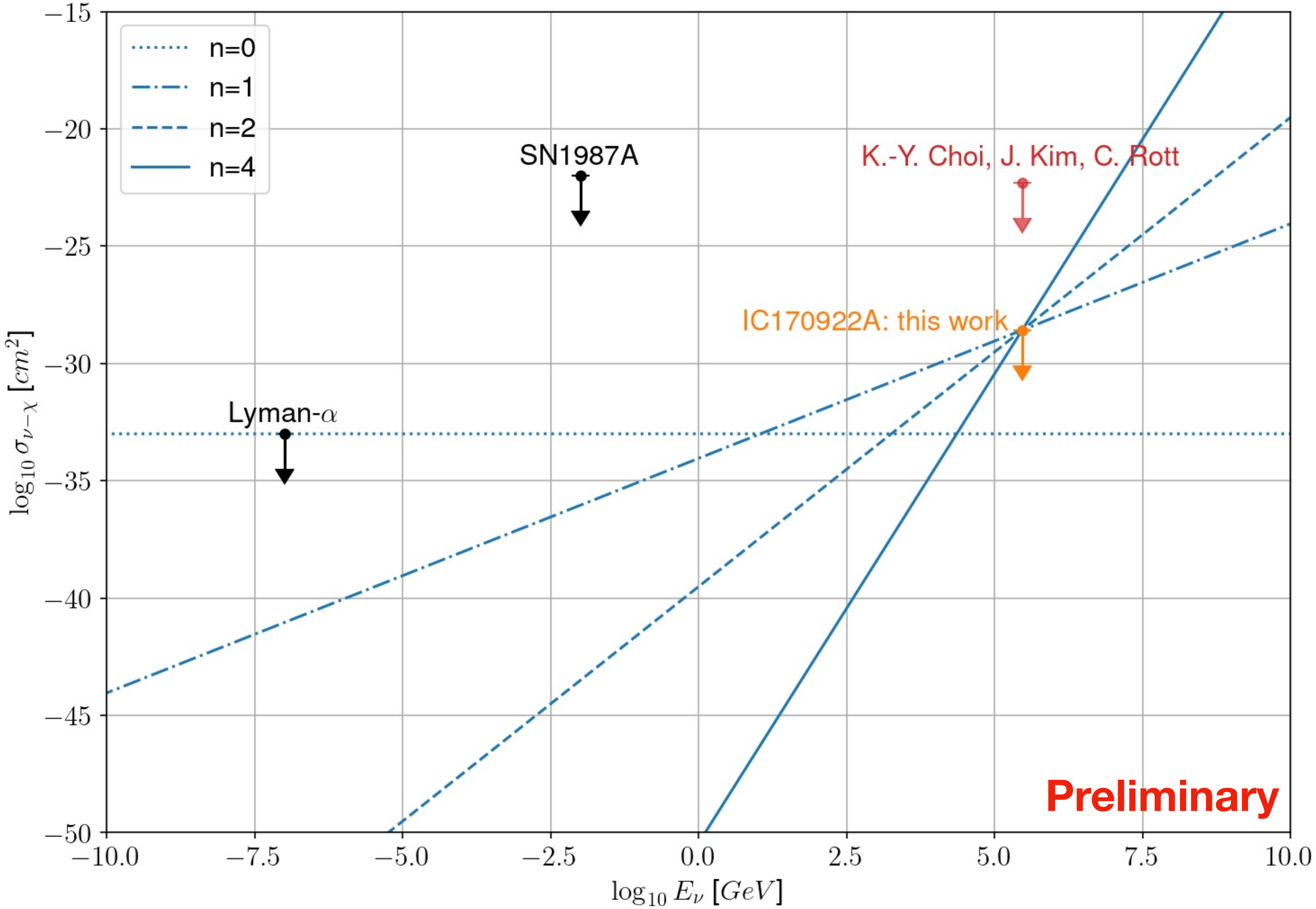
$$\frac{\sigma_{\nu\chi}}{m_\chi} \lesssim 2.6343 \times 10^{-29} \; cm^2/GeV \; (@ \; E_\nu = 290 \; TeV)$$ **Theory Estimations**

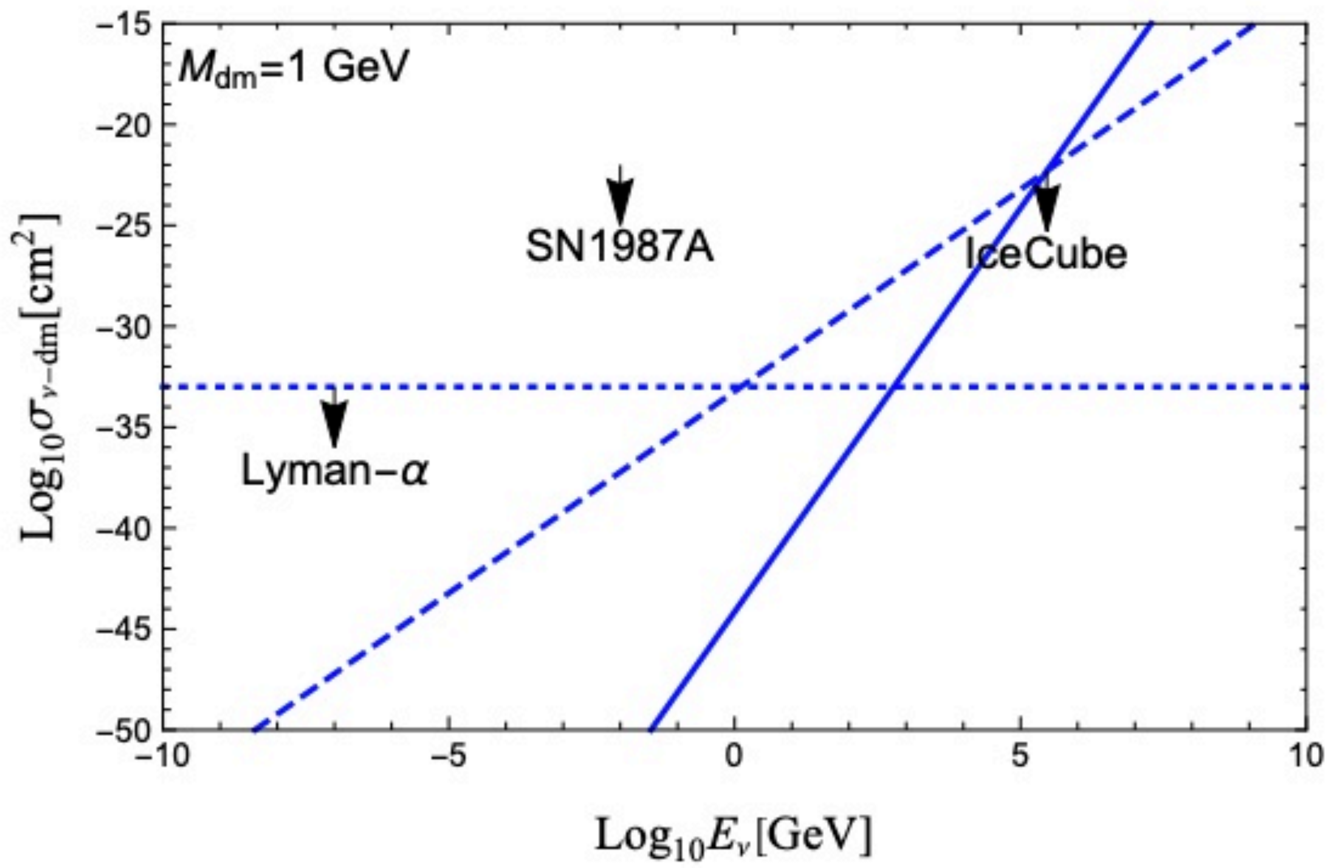
# Constraints with a single event (IC170922A)

- With a scattering cross-section depending on an energy in single power law

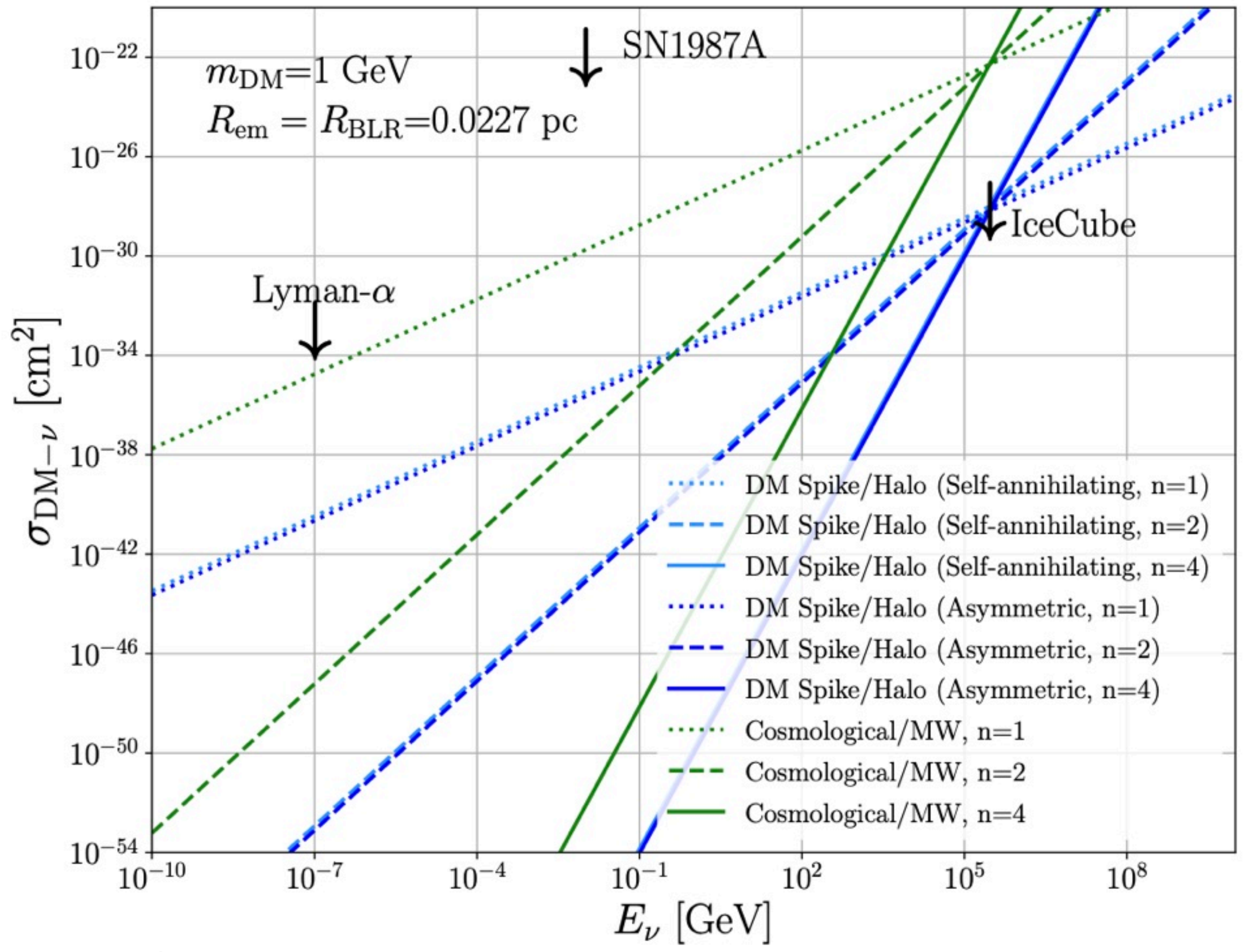
$$\sigma = \sigma_0 \left( \frac{E_\nu}{1\ GeV} \right)^n$$

**Theory Estimations**





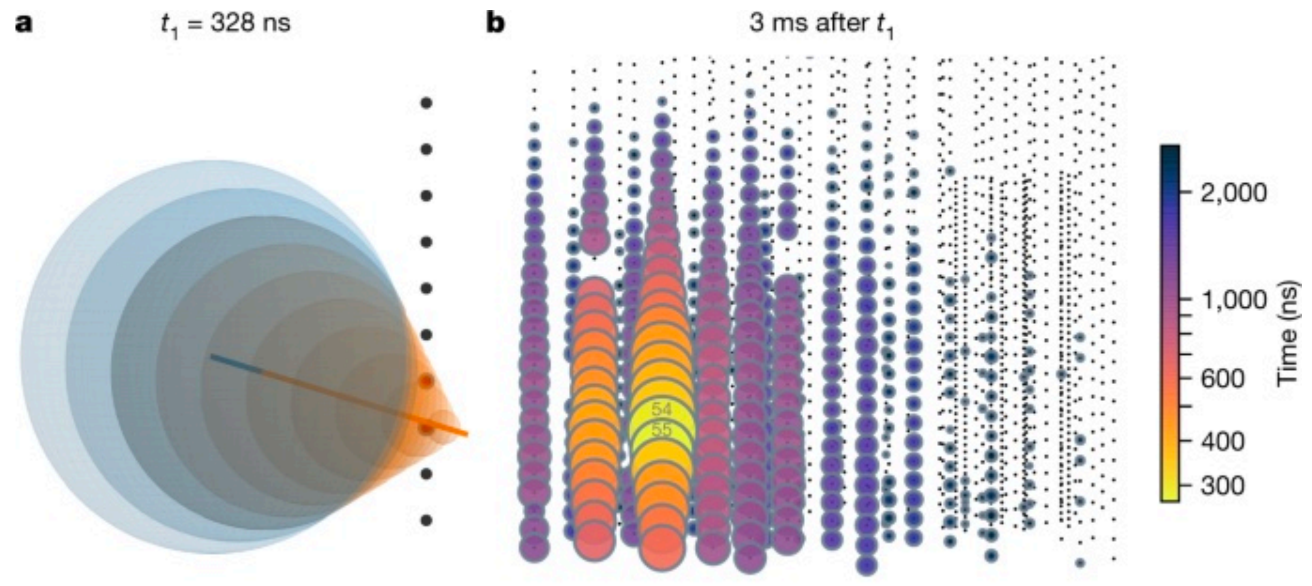
K.-Y Choi, J. Kim and C. Rott, Phys. Rev. D 99 (2019) 083018



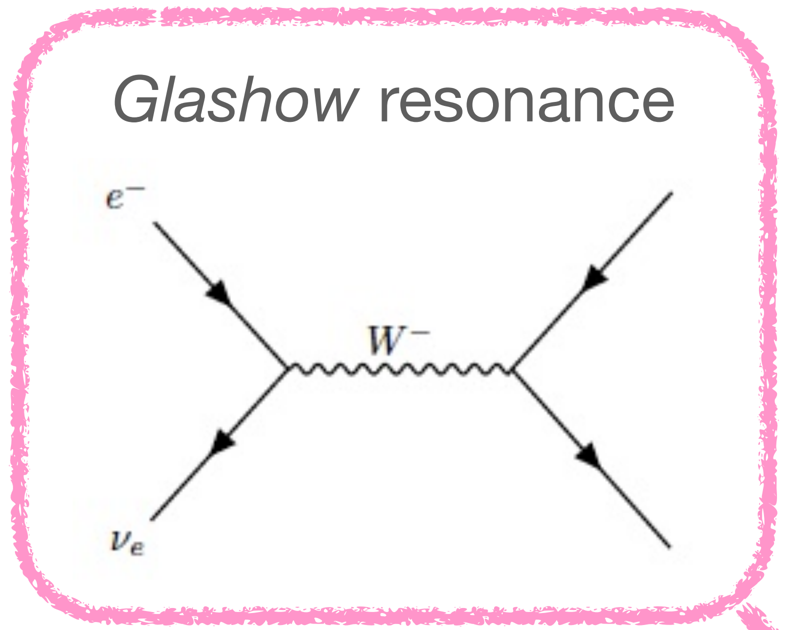
F. Ferrer, G. Herrera, and A. Ibarra; arXiv:2209.06339

# Neutrinos: here and there

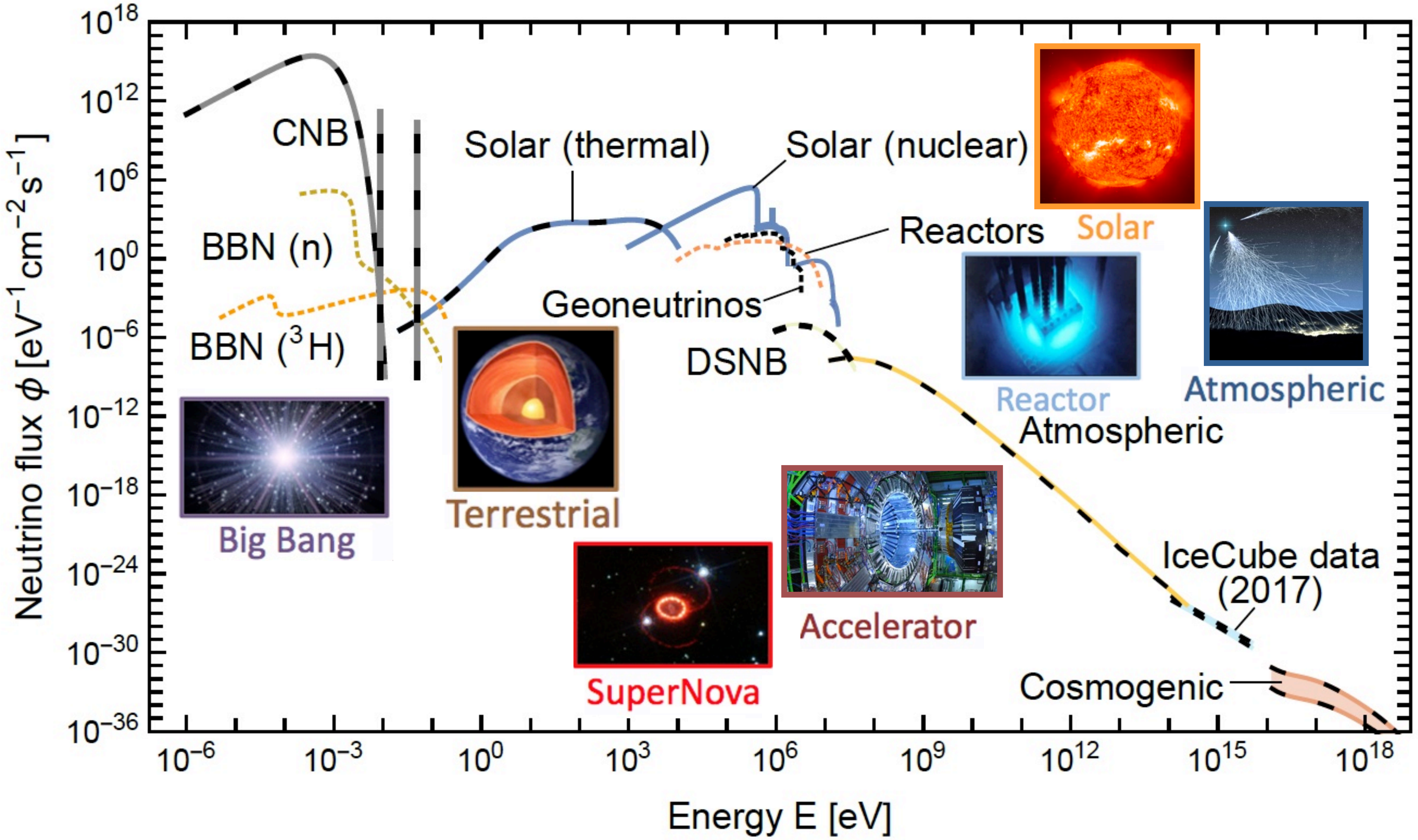
- Neutrinos are produced from a variety of sources across a wide energy range.
- With higher energies, much lower fluxes at the Earth but much bigger electroweak cross sections.



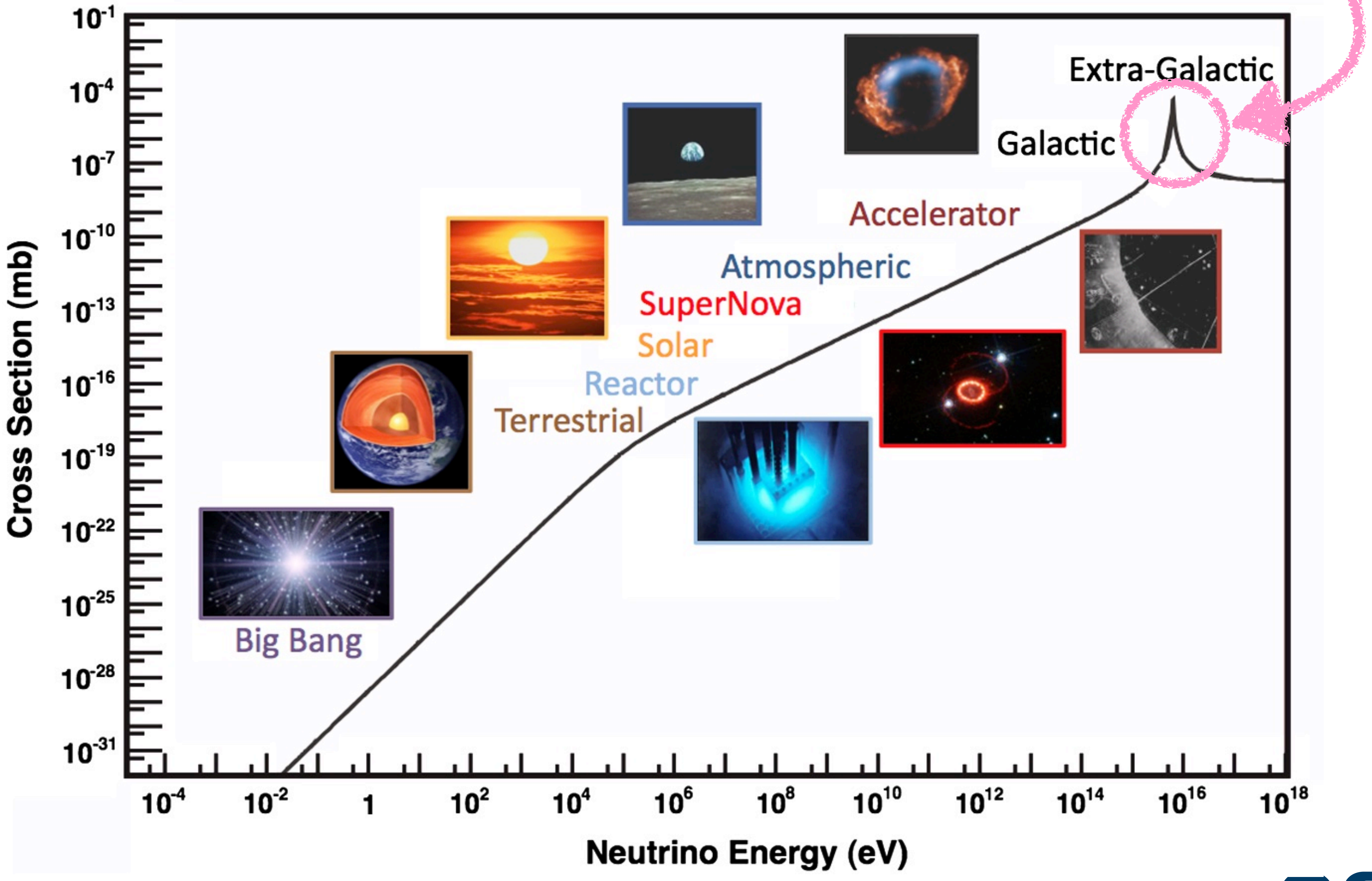
*Nature* **591**, 220–224 (2021)



E. Vitagliano, I. Tamborra and G. Raffelt, *Rev. Mod. Phys.* **92**, 45006 (2020)



J. A. Formaggio and G. P. Zeller, *Rev. Mod. Phys.* **84**, 1307 (2012)



# High-energy astrophysical neutrino

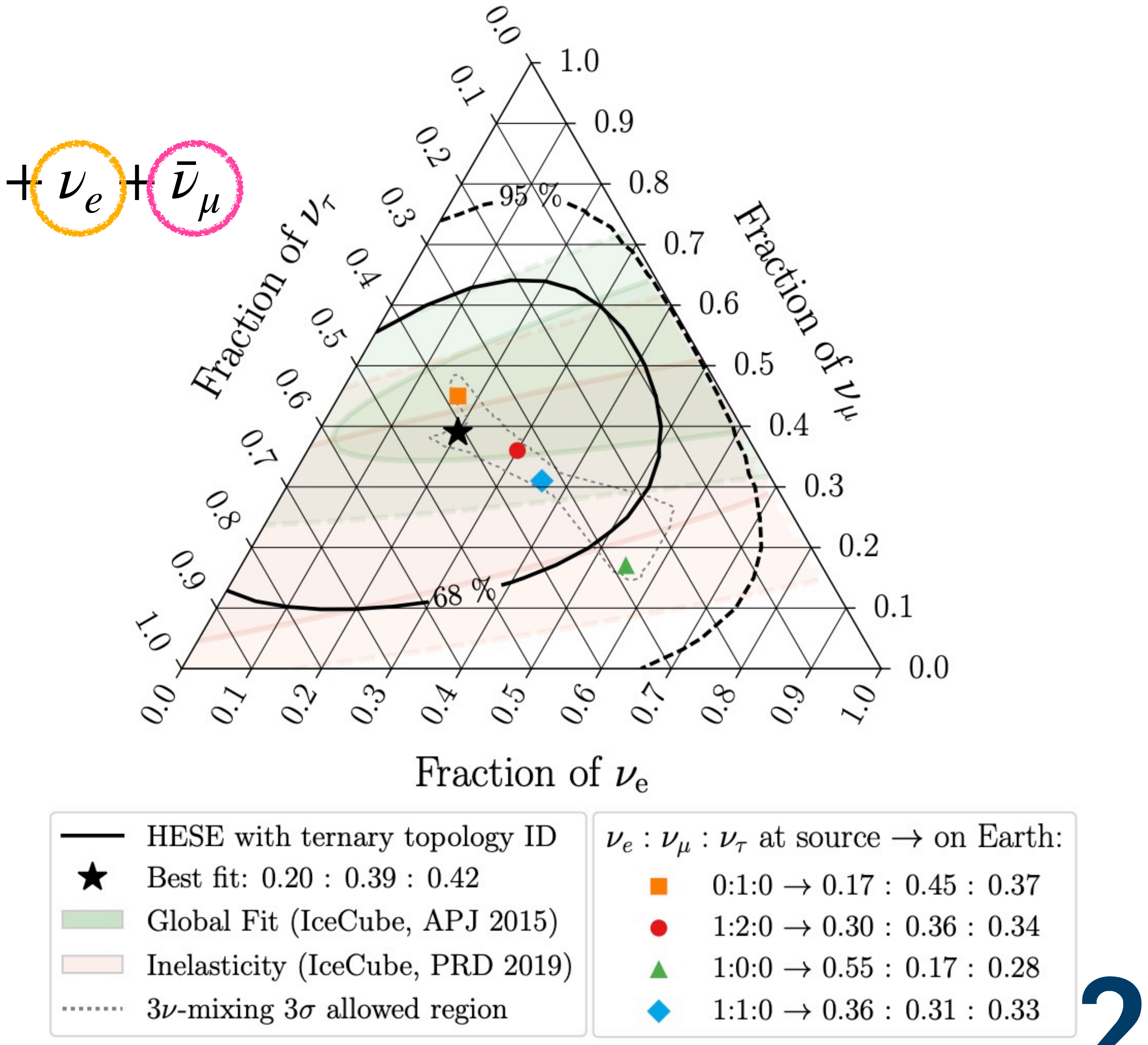
- A lot of models for astrophysical neutrinos production have neutrinos as the byproducts of cosmic ray interactions with gas and radiation via hadronic ($pp, pn$) and photohadronic ($\gamma p, \gamma n$) channels. (Fermi-acceleration)

- Dominant $pp, \gamma p$ interactions lead to producing the unstable mesons that subsequently decay into neutrinos

$$p + p \to \left| \begin{array}{l} \pi^+ \to \left| \begin{array}{l} \nu_\mu \\ \mu^+ \to e^- + \nu_e + \bar{\nu}_\mu \end{array} \right. \\ \pi^- \to \left| \begin{array}{l} \bar{\nu}_\mu \\ \mu^- \to e^- + \bar{\nu}_e + \nu_\mu \end{array} \right. \\ \pi^0 + X \to \gamma + \gamma + X \end{array} \right.$$

$$p + \gamma \to \Delta^+ \to \left| \begin{array}{l} \pi^+ + n \to \left| \begin{array}{l} \nu_\mu \\ \mu^+ \to e^- + \nu_e + \bar{\nu}_\mu \end{array} \right. \\ \pi^0 + p \to \gamma + \gamma \ + p \end{array} \right.$$

IceCube Collaboration, Eur. Phys. J. C **82**, 1031 (2022)

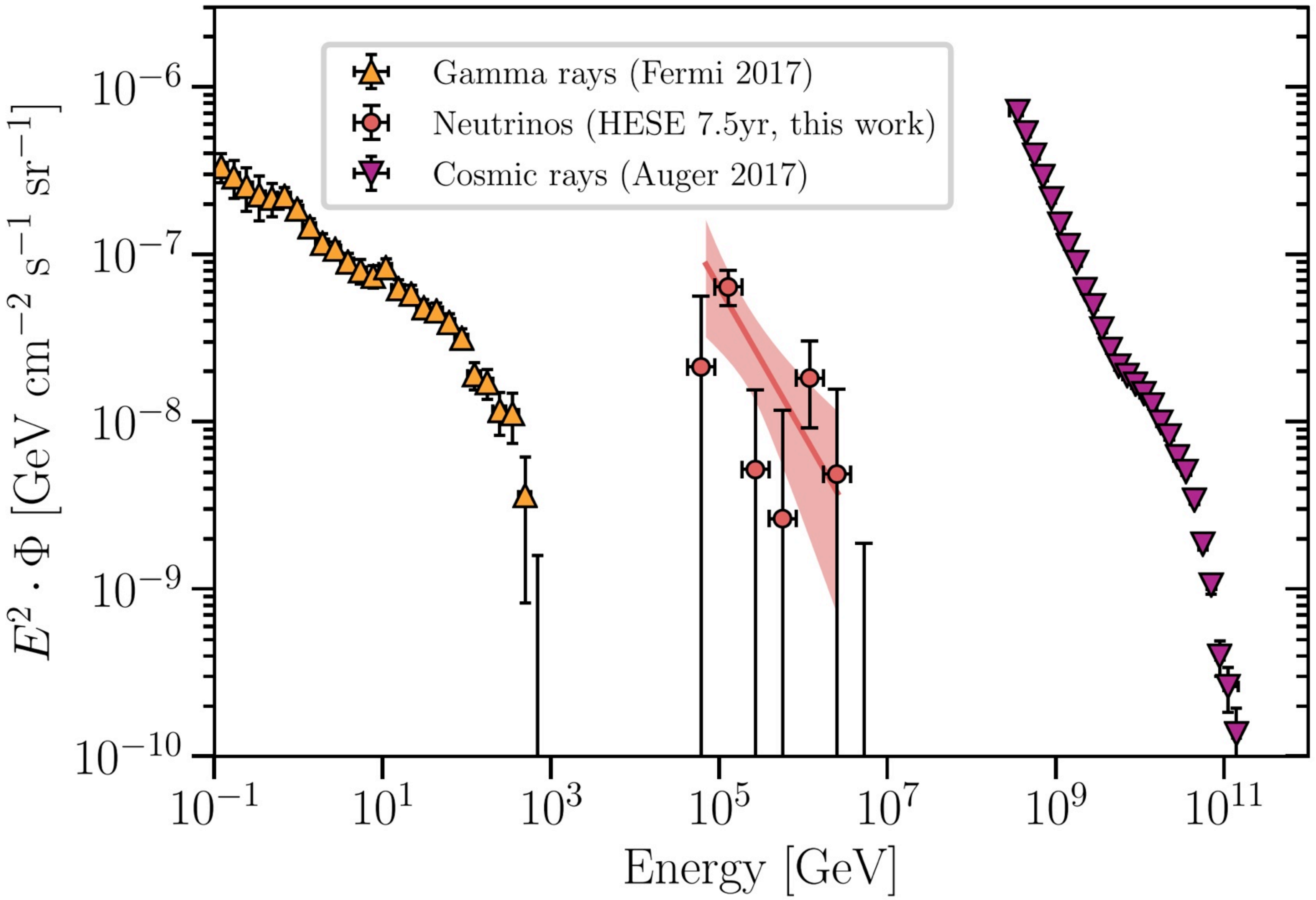


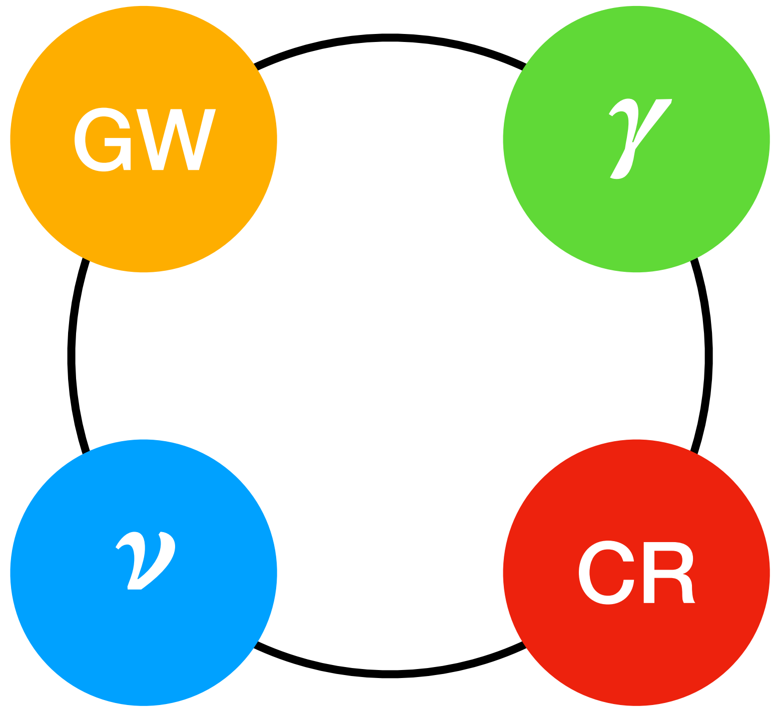
- Initial flavour ratio at a source is to be $(\nu_e : \nu_\mu : \nu_\tau)_{source} \simeq (1 : 2 : 0)$

- Flavour ratio among the astrophysical neutrinos at the Earth is average out to be $(\nu_e : \nu_\mu : \nu_\tau)_{Earth} \simeq (1 : 1 : 1)$ due to the neutrino oscillation during propagation to the Earth over the cosmological baseline.

# High-energy cosmic messengers

IceCube Collaboration, *Phys. Rev. D* **104**, 022002 (2021)



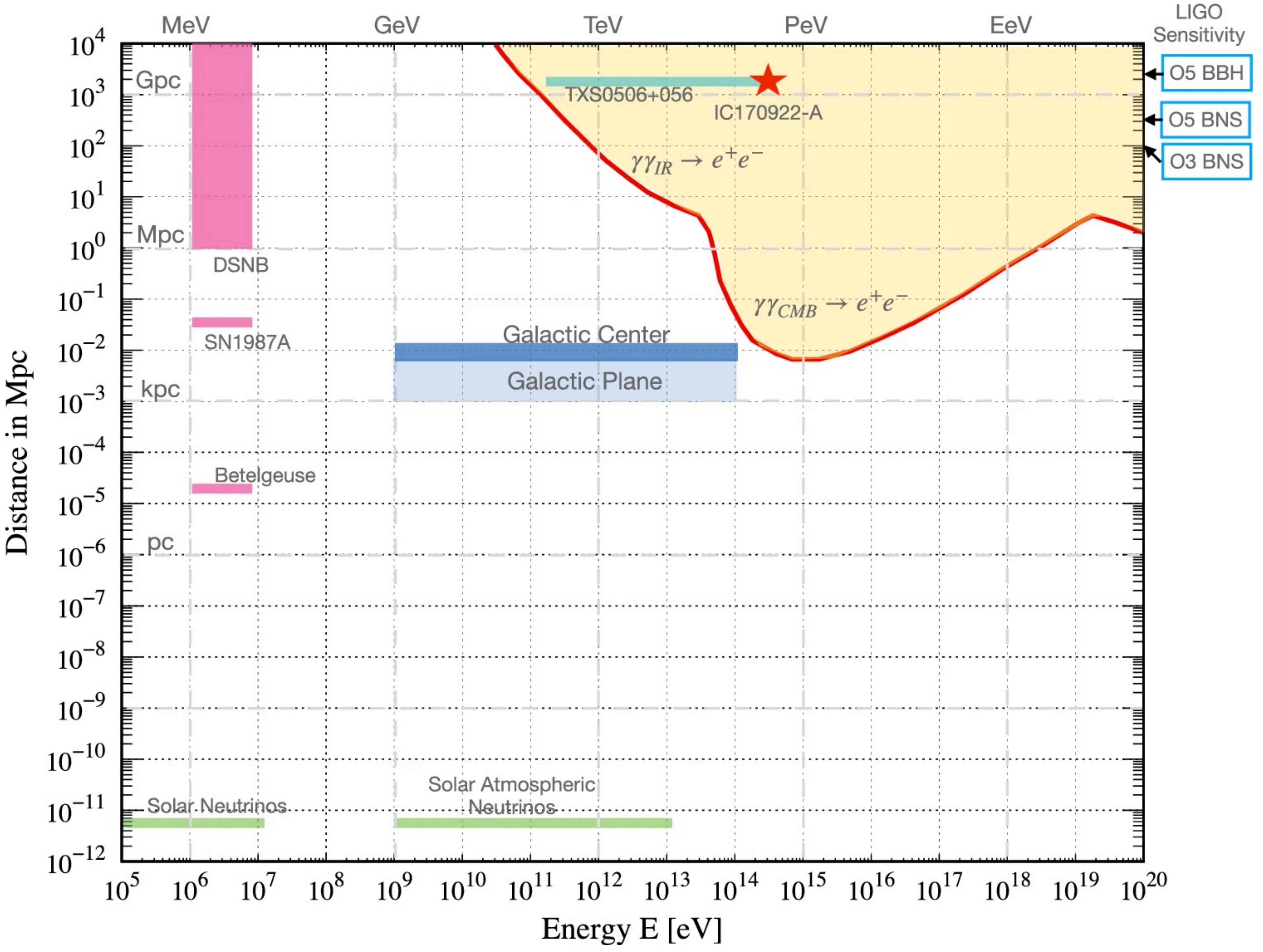


- Where do they came from?
  - Massive cosmic accelerator?
  - Catastrophic astrophysical event?
- How they are energised?
- How do they propagate?

- The cosmic messengers are connected at their source; each could be a clue to unveil the mystery of their origins and the production mechanisms

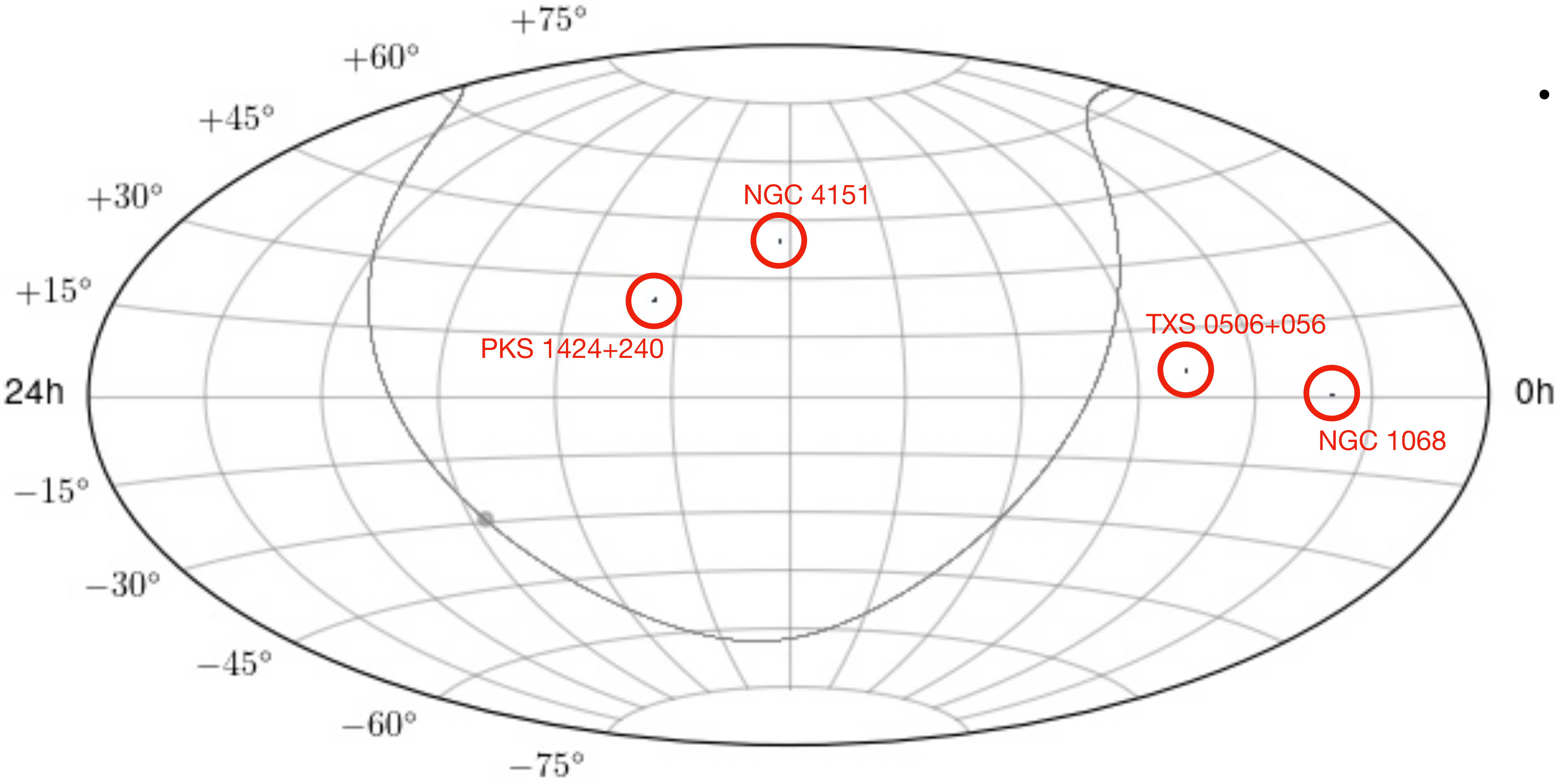
# Neutrinos, why?

- High-energy astrophysical neutrinos detected by the IceCube Neutrino Observatory provide the opportunity to explore the dense and energetic environment of the universe in the great distance



C. Rott, *J. Korean Phys. Soc.* **78**, 864–872 (2021)

# Sources (identified + high significance)

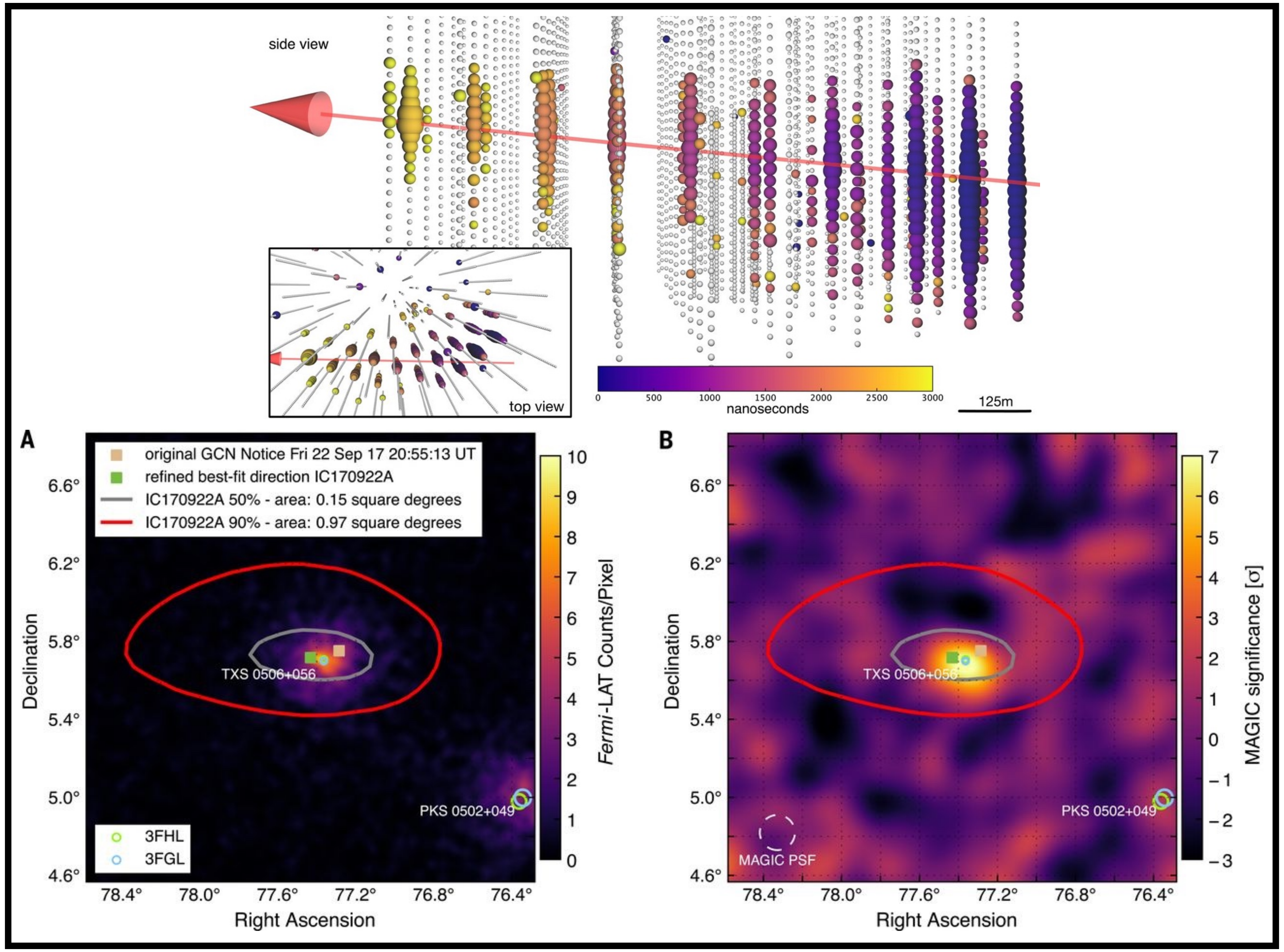


- Astrophysical neutrino sources
  - IceCube-identified
    - TXS 0506+056
    - NGC 1068
  - High significance from the recent IceCube searches
    - PKS 1424+240
    - NGC 4151

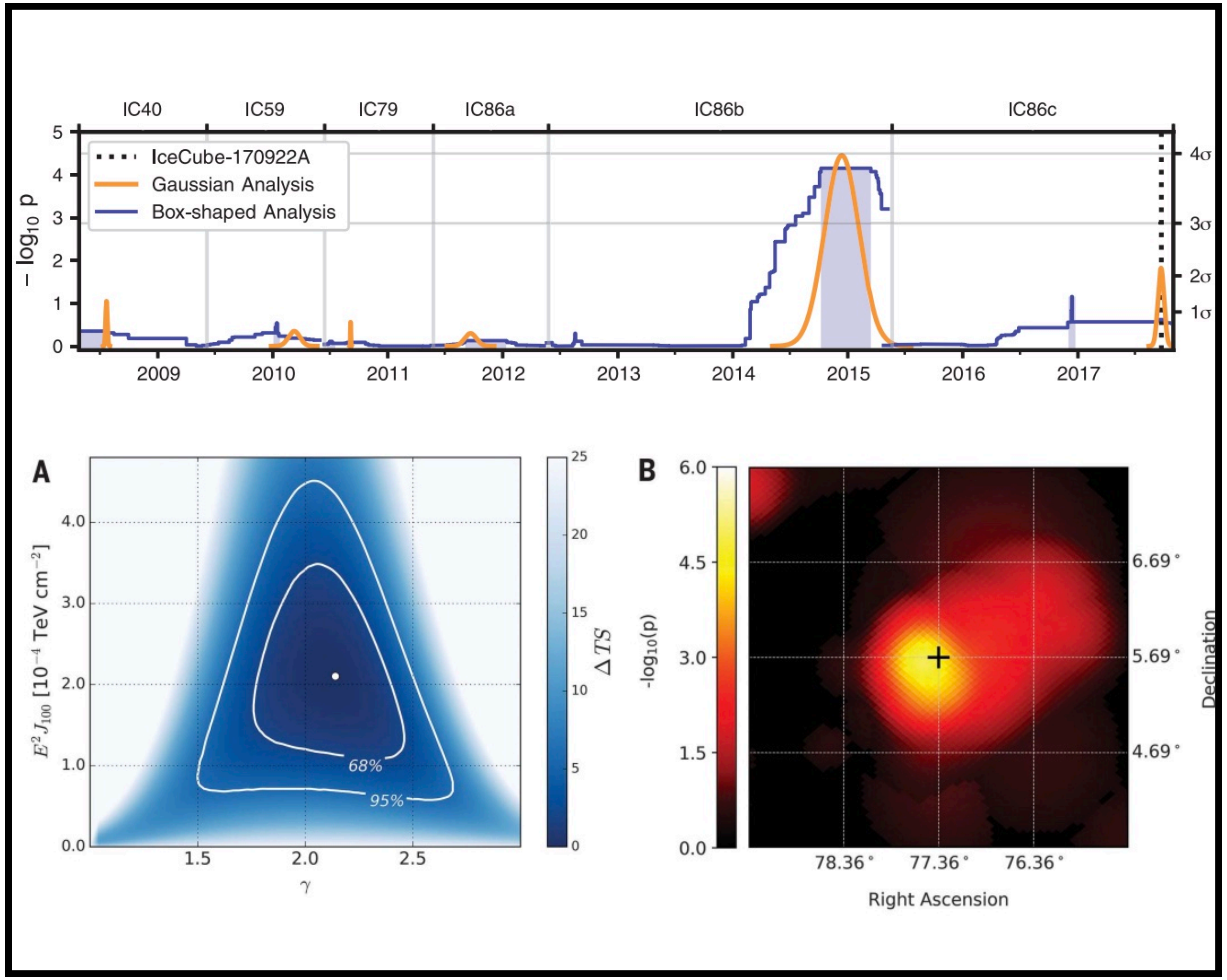
- All in the northern sky, yet

# TXS 0506+056

- BL-Lac blazar: multi-messenger observations for IC170922A + archival data



M. G. Aartsen et al. (IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, Swift NuSTAR, VERITAS, and VLA//17B-403 Collaborations); *Science* **361**, eaat1378 (2018).

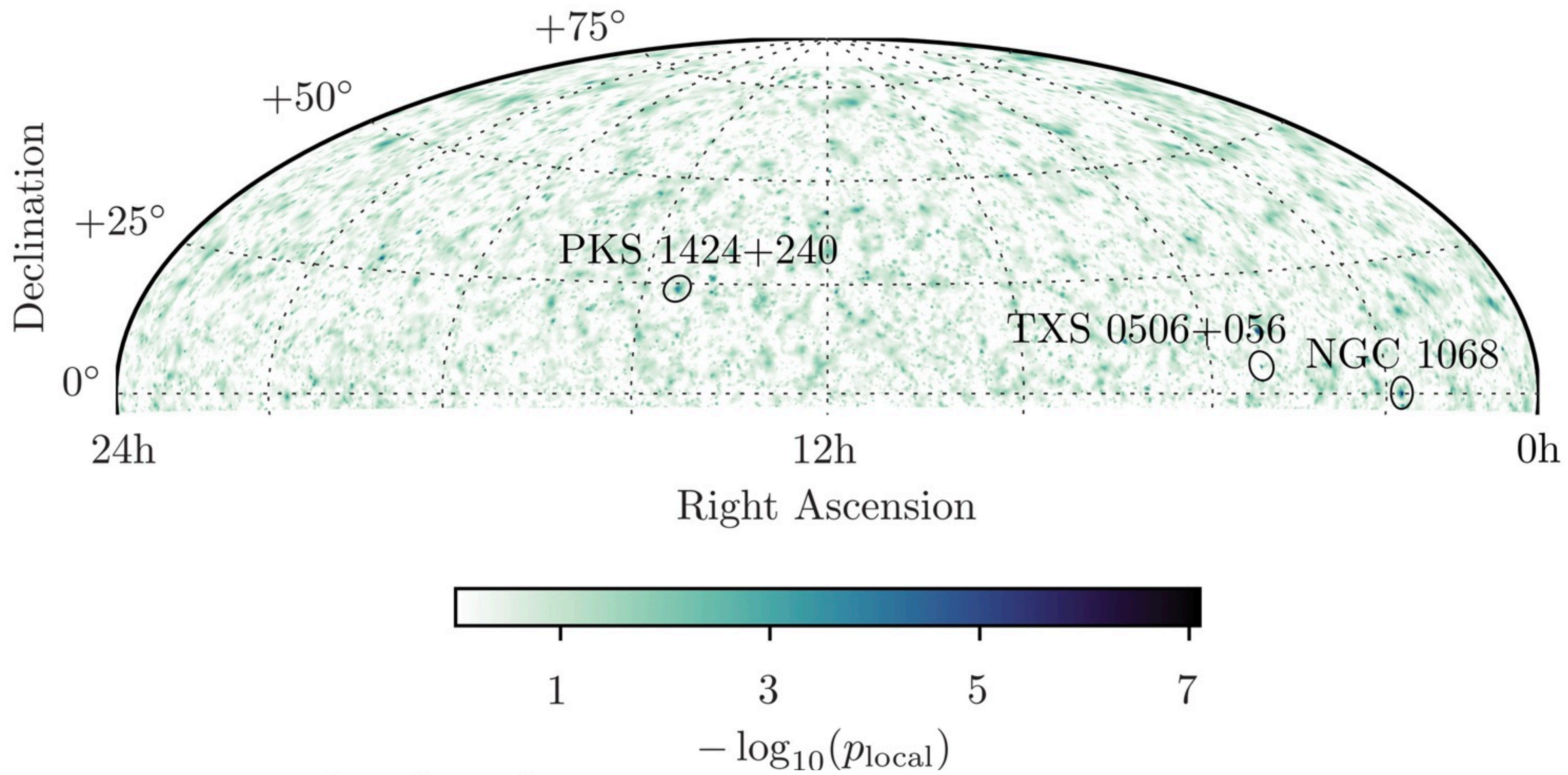


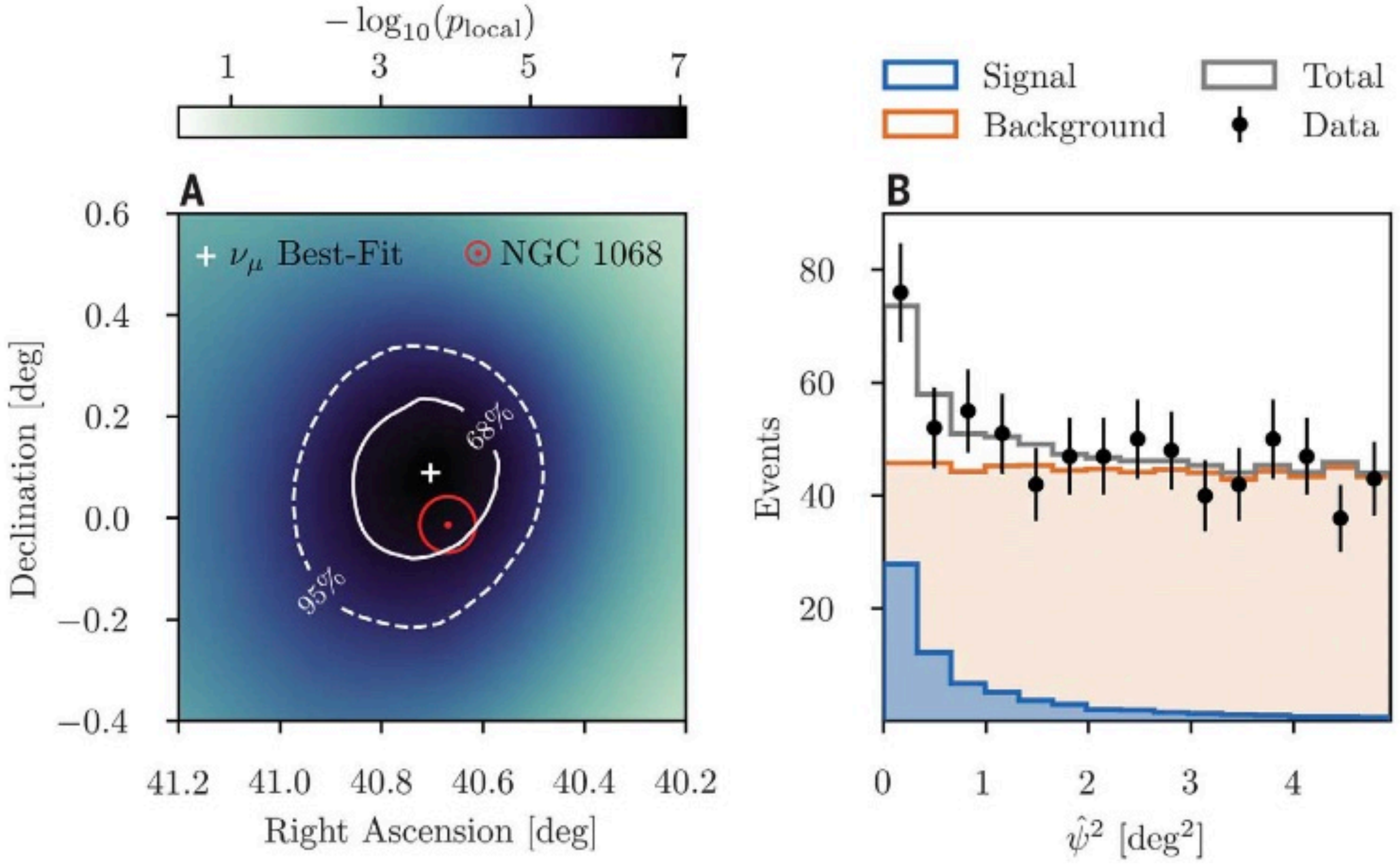
M. G. Aartsen et al.; *Science* **361**, 147-151 (2018).

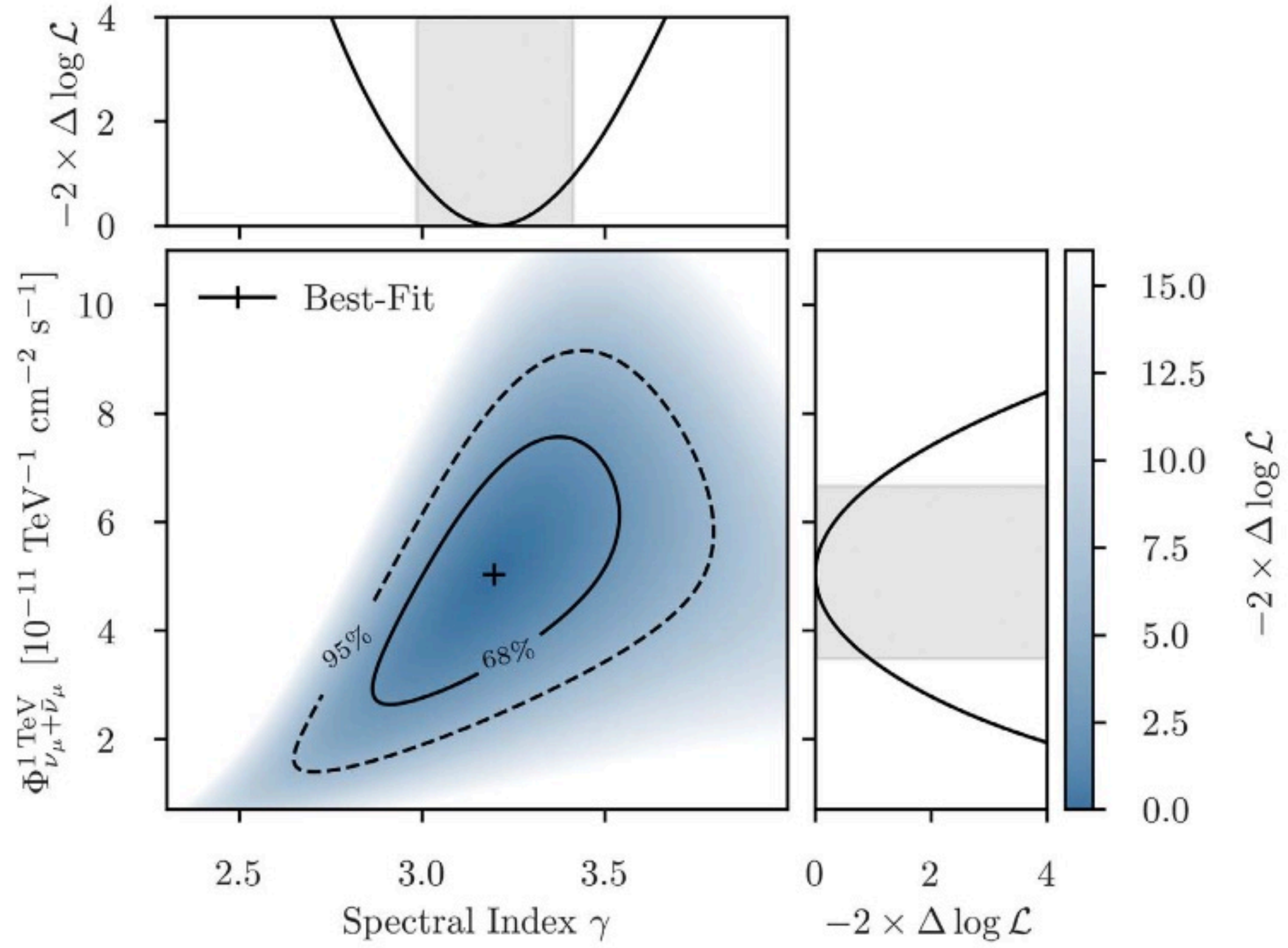
# NGC 1068

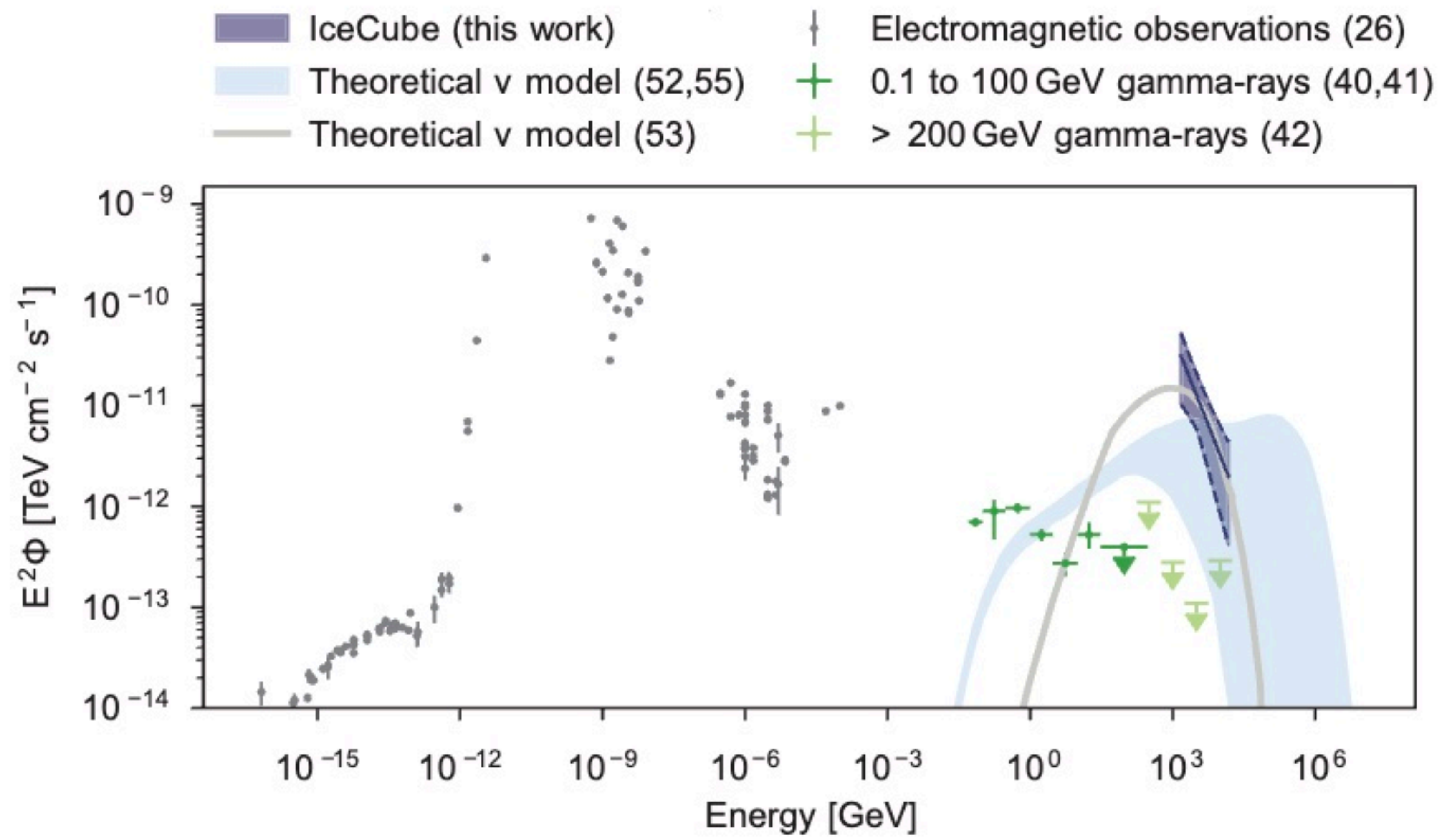
R. Abbasi et al.; *Science* **378**, 538-543 (2022).

- Seyfert II galaxy with AGN: highest significance among the candidate sources

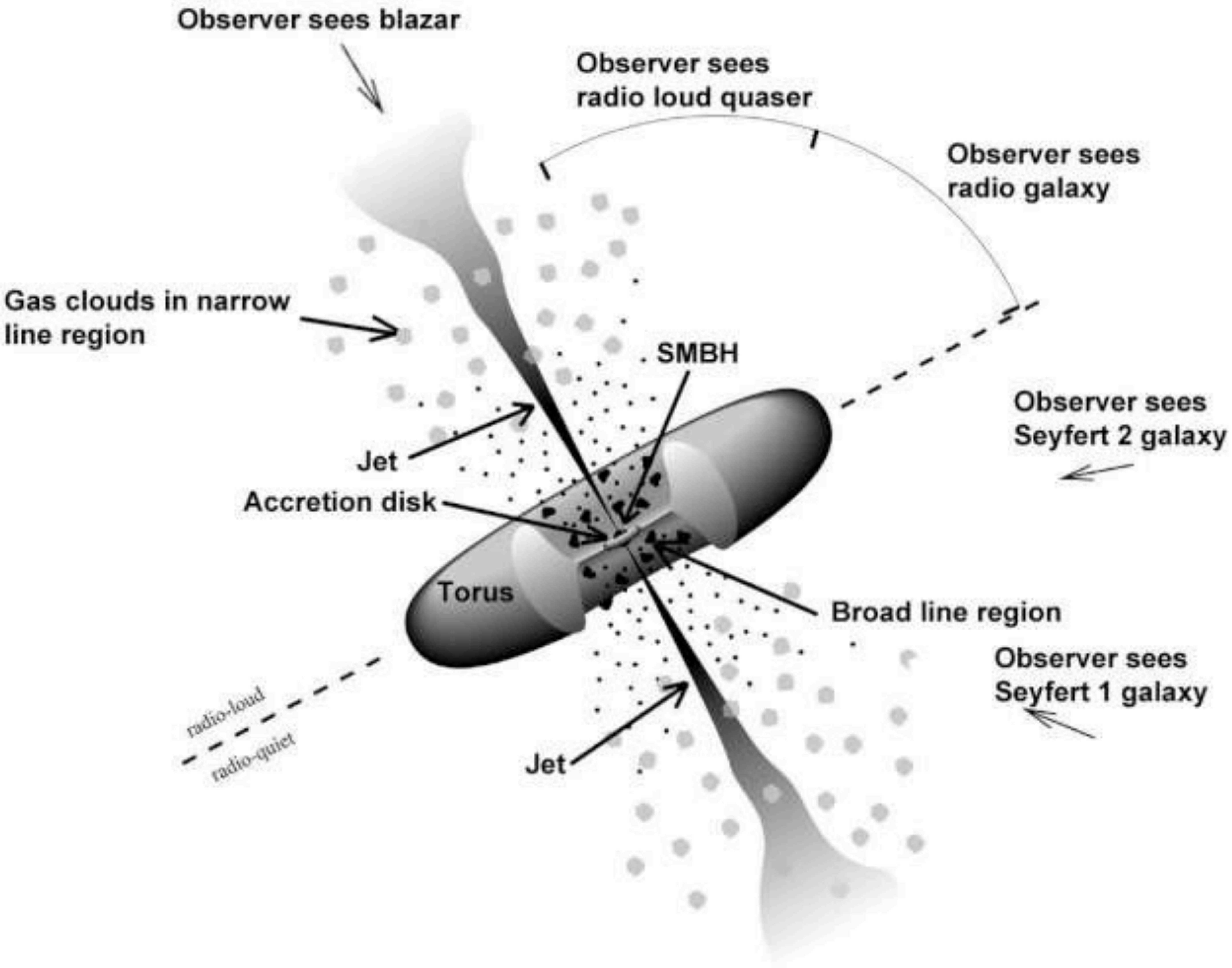








# Active Galactic Nuclei (AGN)



Credit: Fermi Gamma-ray Telescope, NASA

# Neutrino rare interactions

✓ benchmark case

## Neutrino - Dark Matter(DM)

- J. Barranco, O. G. Miranda, C. A. Moura, T. I. Rashba and F. Rossi-Torres, *JCAP* **10**, 007 (2011)
- M. M. Reynoso and O. A. Sampayo, *Astropart. Phys.* **82**, 10 (2016)
- K. J. Kelly and P. A. N. Machado, *JCAP* **10**, 048 (2018)
- S. Pandey, S. Karmakar and S. Rakshit, *JHEP* **01**, 095 (2019) [Erratum: *JHEP* **11**, 215 (2021)]
- J. B. G. Alvey and M. Fairbairn, *JCAP* **07** 041 (2019)
- K.-Y. Choi, E. J. Chun and J. Kim, *Phys.Dark Univ.* **30**, 100606 (2020)

…

- C. A. Argüelles, A. Kheirandish and A. C. Vincent, *Phys. Rev. Lett.* **119** no. 20, 201801 (2017)
- K.-Y Choi, J. Kim and C. Rott, *Phys. Rev. D* **99**, 083018 (2019)
- F. Ferrer, G. Herrera, and A. Ibarra, arXiv:2209.06339
- J. M. Cline and M. Puel, arXiv:2301.08756

…

## Neutrino - Neutrino($C\nu B$)

- K. C. Y. Ng and J. F. Beacom, *Phys. Rev. D* **90** no. 6, (2014) 065035 [Erratum: *Phys.Rev.D* **90**, 089904 (2014)]
- A. DiFranzo and D. Hooper, *Phys. Rev. D* **92** no. 9, 095007 (2015)
- T. Araki, F. Kaneko, T. Ota, J. Sato, and T. Shimomura, *Phys. Rev. D* **93** no. 1, 013014 (2016)
- K. J. Kelly and P. A. N. Machado, *JCAP* **10** 048 (2018)
- M. Bustamante, C. Rosenstrøm, S. Shalgar, and I. Tamborra, *Phys. Rev. D* **101** no. 12, 123024 (2020)
- I. Esteban, S. Pandey, V. Brdar, and J. F. Beacom, *Phys. Rev. D* **104** no. 12, 123014 (2021)
- D. Hooper, J. Iguaz Juan, and P. D. Serpico, arXiv:2302.03571

…

⋮

# Calculating TSs

$\mathscr{L}_{BG}$ : background-only $\mathscr{L}_{BSM}$ : BSM hyp. (SPL+attenuation)

$\mathscr{L}_{Null}$: null hyp. (single power-law)

$$
\begin{aligned}
\boxed{TS_{ana}} &= -2 \cdot sign(n_s) \cdot \ln\left[\frac{\mathscr{L}_{Null}}{\mathscr{L}_{BSM}}\right] \\
&= -2 \cdot sign(n_s) \cdot \left[\ln \mathscr{L}_{Null} - \ln \mathscr{L}_{BSM}\right] \\
&= -2 \cdot sign(n_s) \cdot \left[(\ln \mathscr{L}_{Null} - \ln \mathscr{L}_{BG}) - (\ln \mathscr{L}_{BSM} - \ln \mathscr{L}_{BG})\right] \\
&= -2 \cdot sign(n_s) \cdot \left[\ln\left[\frac{\mathscr{L}_{Null}}{\mathscr{L}_{BG}}\right] - \ln\left[\frac{\mathscr{L}_{BSM}}{\mathscr{L}_{BG}}\right]\right] \\
&= -2 \cdot sign(n_s) \cdot \left[-\ln\left[\frac{\mathscr{L}_{BG}}{\mathscr{L}_{Null}}\right] + \ln\left[\frac{\mathscr{L}_{BG}}{\mathscr{L}_{BSM}}\right]\right] \\
&= \left[-2 \cdot sign(n_s) \cdot \ln\left[\frac{\mathscr{L}_{BG}}{\mathscr{L}_{BSM}}\right]\right] - \left[-2 \cdot sign(n_s) \cdot \ln\left[\frac{\mathscr{L}_{BG}}{\mathscr{L}_{Null}}\right]\right] \\
&= \boxed{TS_{BSM} - TS_{Null} = \Delta TS}
\end{aligned}
$$

- How to get $TS_{ana}$ for a given $n_{inj}$:
  1. Setting two trials; one for Null hyp. and the other for BSM hyp. from multiple pseudo-experiments ($n_{exp}$>1000) with given $n_{inj}$ for each hypothesis
  2. Calculate the value of $TS_{Null}$ ($TS_{Null;max}$) from a scan of $n_s$ and $\gamma$ that maximise $\mathscr{L}_{Null}$
  3. Get $\Delta TS = TS_{BSM} - TS_{Null;max}$

# Modified Point Source Likelihood

$$\mathscr{L}(n_s, \gamma, \vec{\theta}) = \prod_i^N \left[\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i\right]$$

$$S_i = S_i(\vec{x}_s, \vec{x}_i, E_i \,|\, \gamma, \vec{\theta}) \cong \mathscr{S}_i(\vec{x}_i \,|\, \vec{x}_s) \boxed{\mathscr{E}_i(E_i \,|\, \gamma, \vec{\theta})} \qquad B_i \simeq \frac{\mathscr{E}_B(E_i \,|\, \phi_{atm} + \phi_{prompt} + \phi_{astro})}{\Omega_{band}}$$

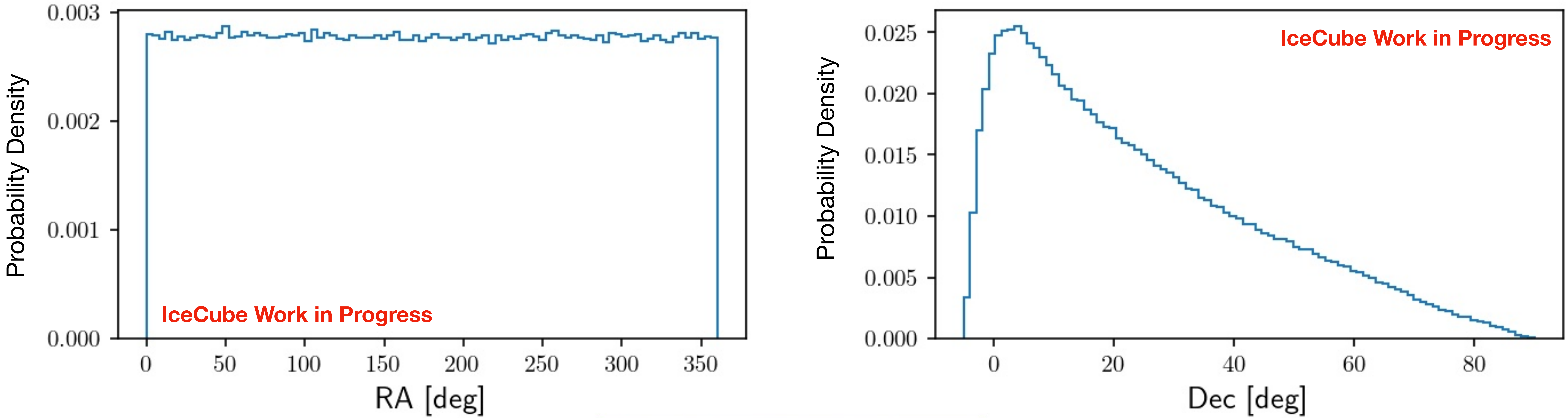
To include BSM hypothesis, only energy PDF needs to be modified
The modified energy PDF can be generated from the hypothetical fluxes

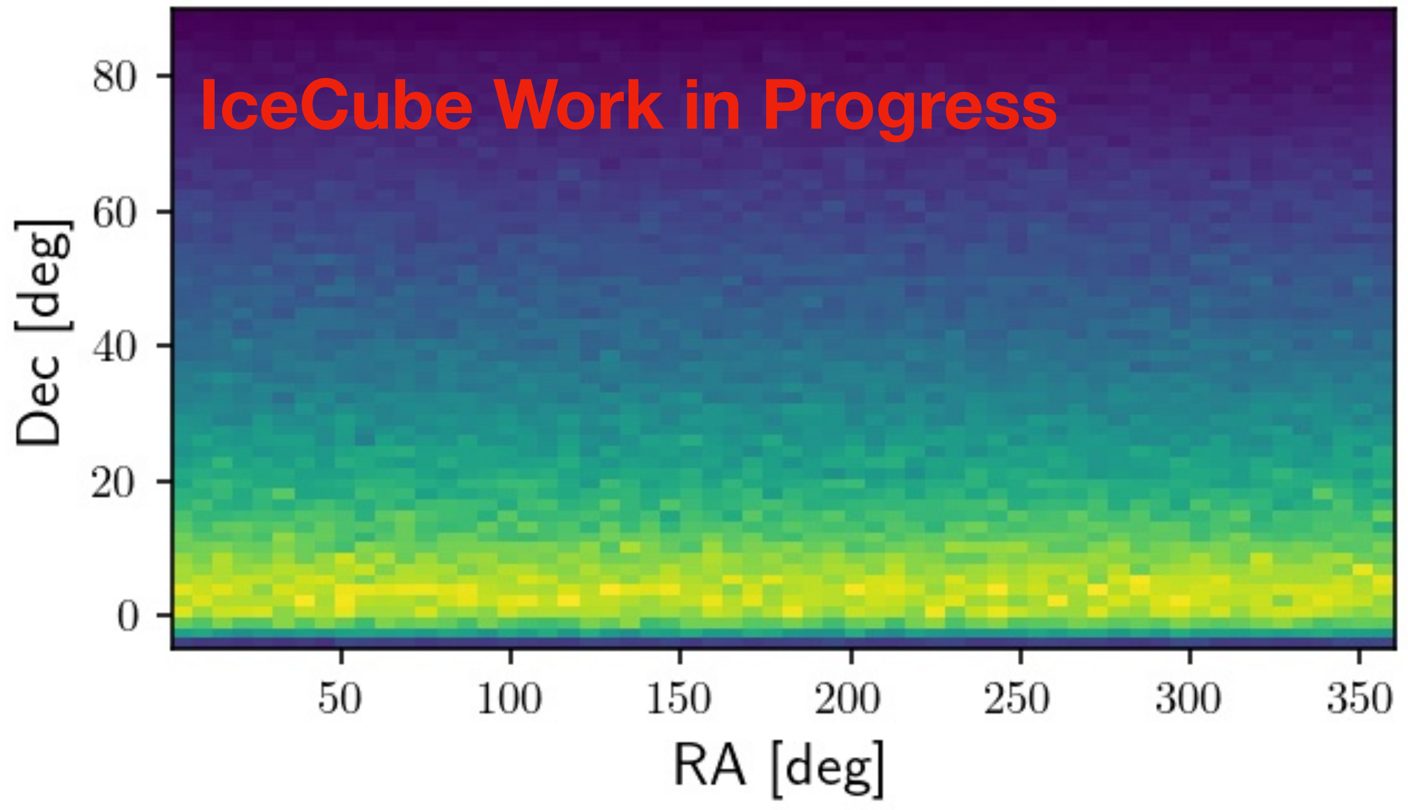
To this analysis, the parametres are $\boxed{\vec{\theta} = (m_\chi, m_\phi, g)}$

# Background PDFs

- Spatial background PDFs

Spatial background PDFs: TXS 0506+056

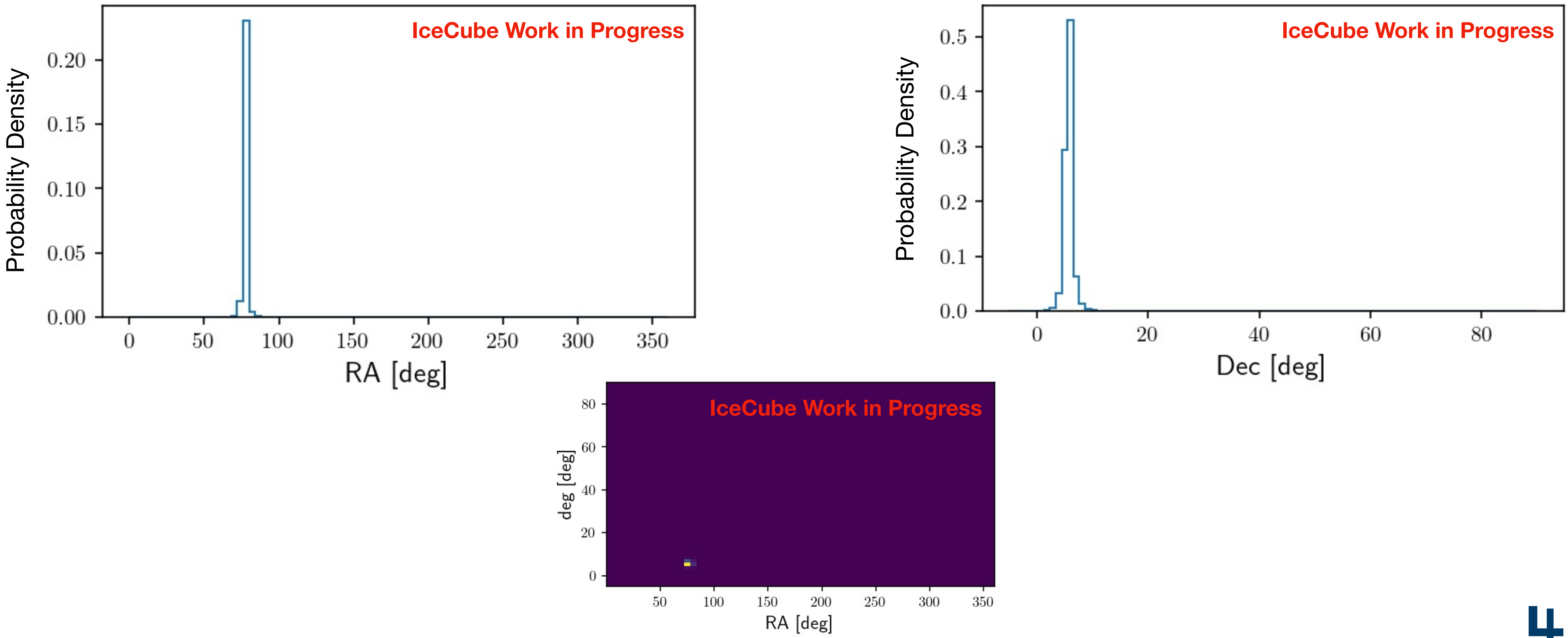




# Signal PDFs

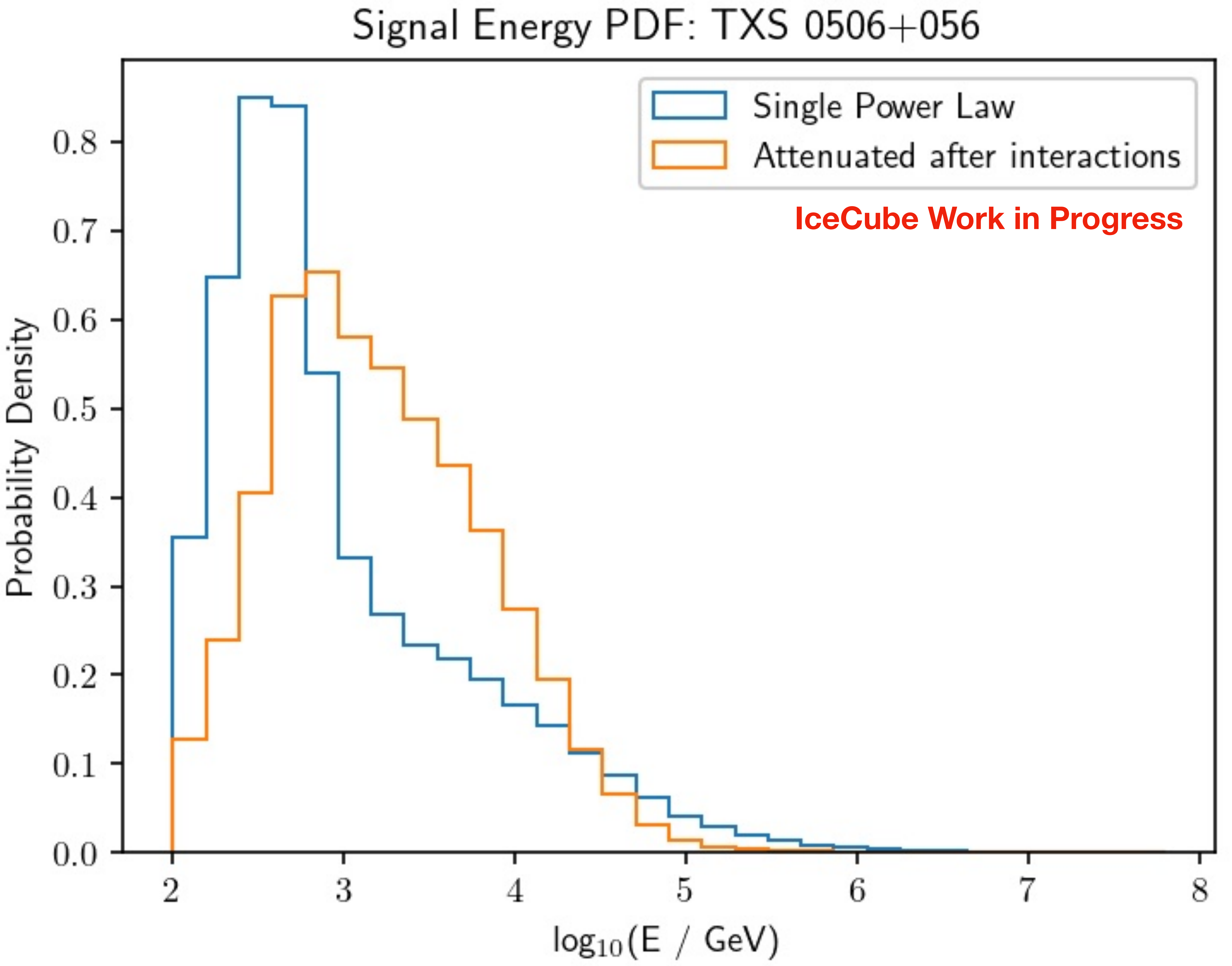
- Spatial signal PDFs

Spatial signal PDFs: TXS 0506+056

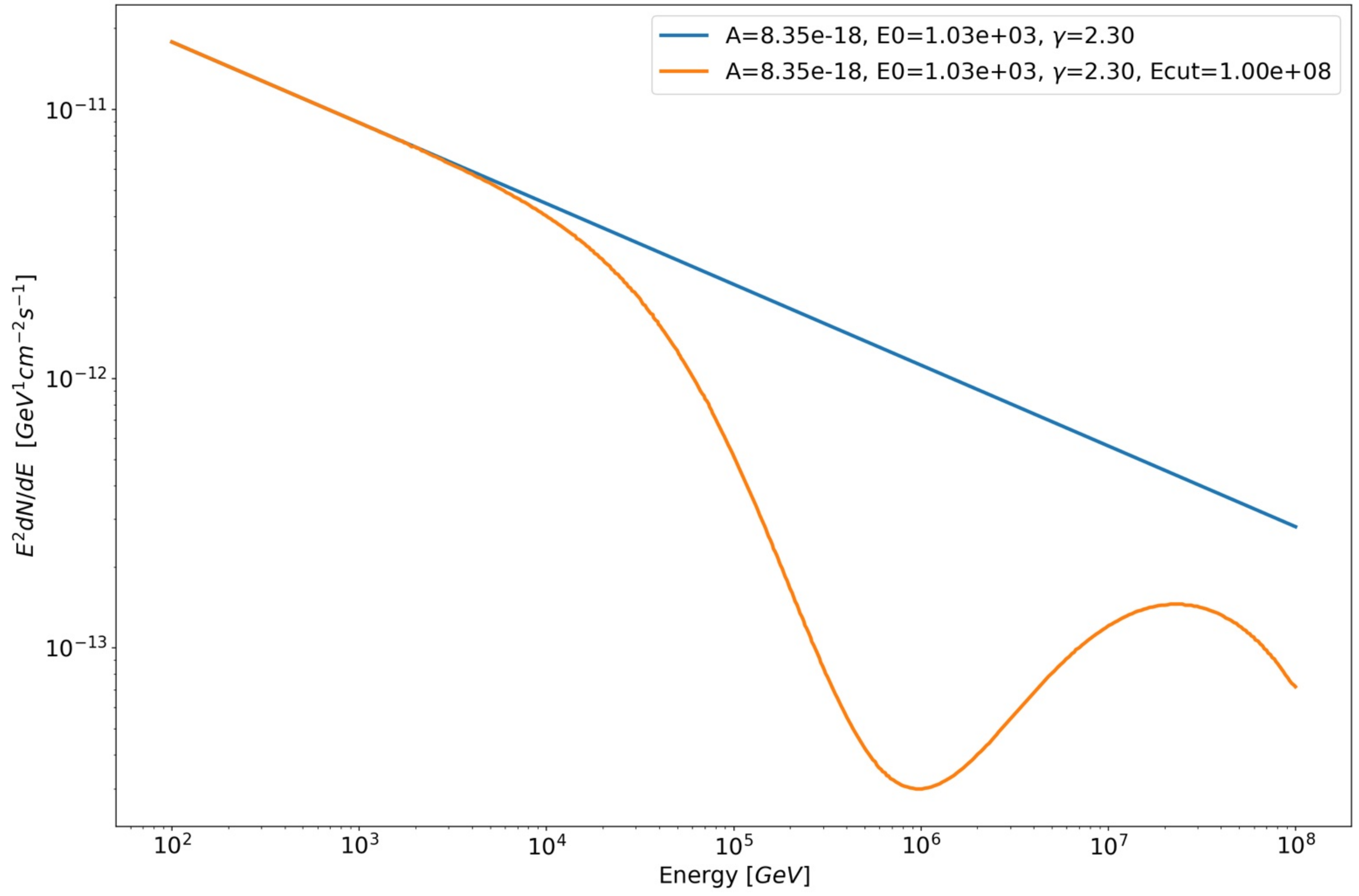


# Signal PDFs

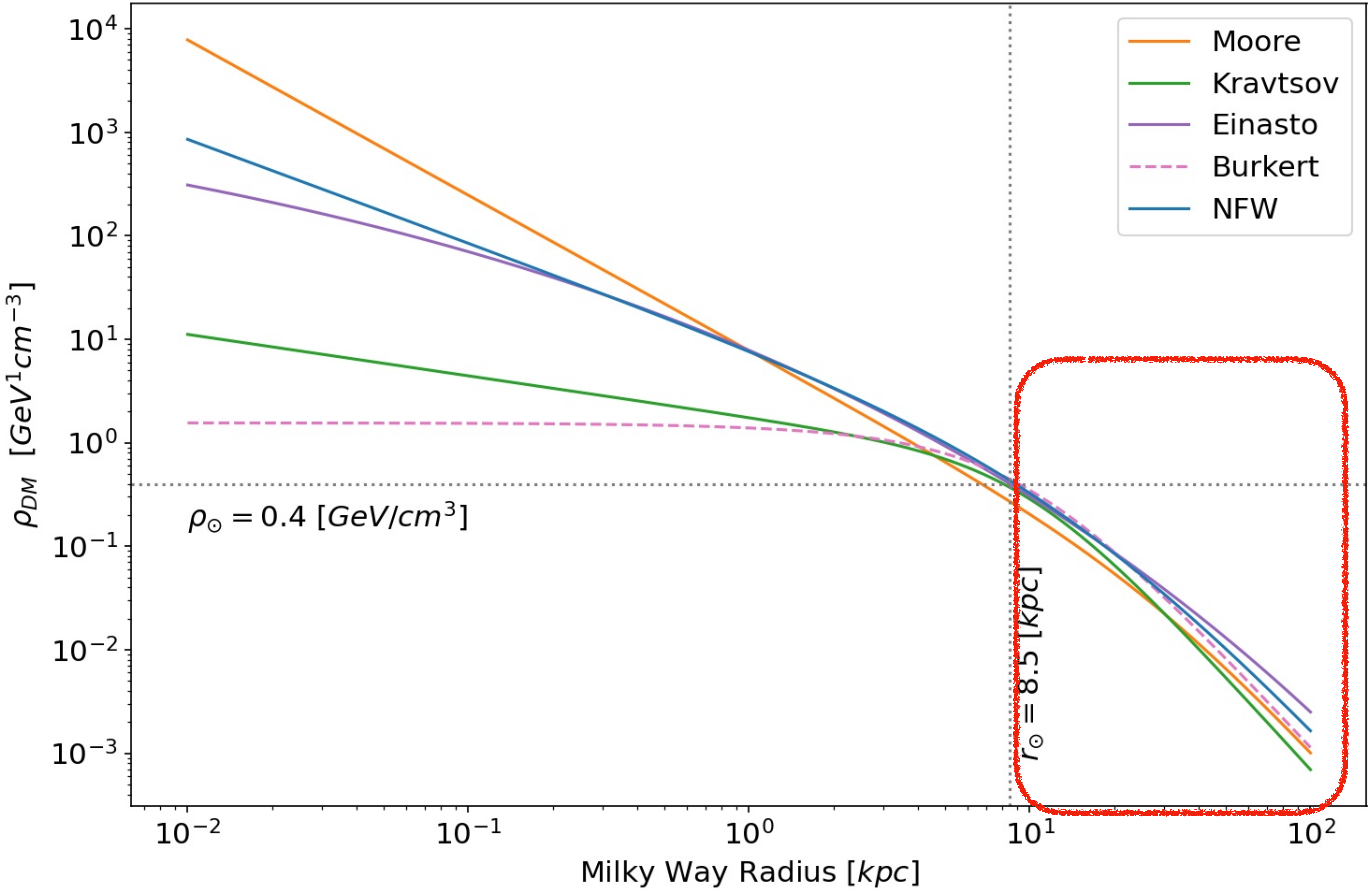
- Energy signal PDF (Normalised PDFs)



Signal Energy PDF: TXS 0506+056

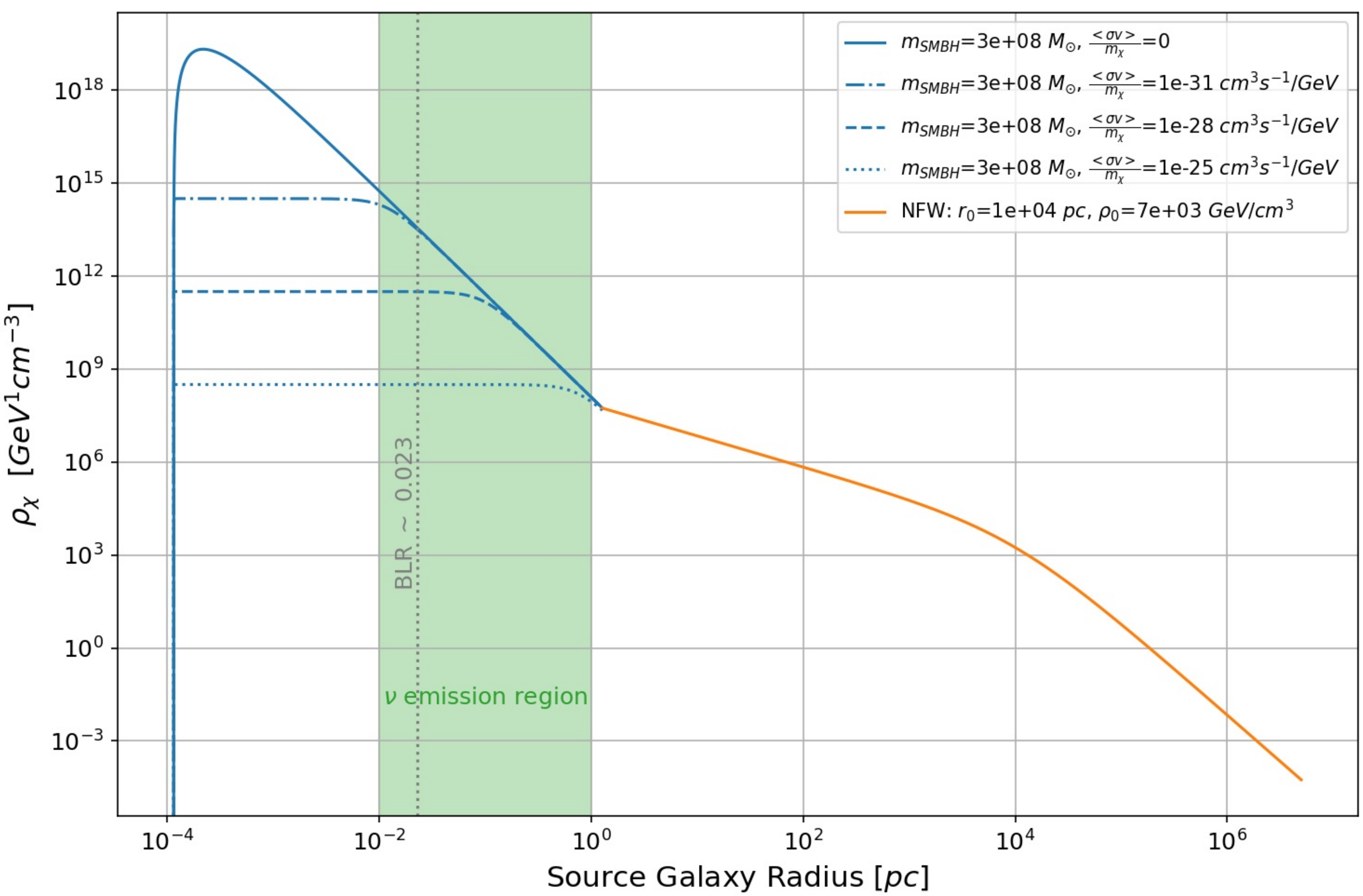


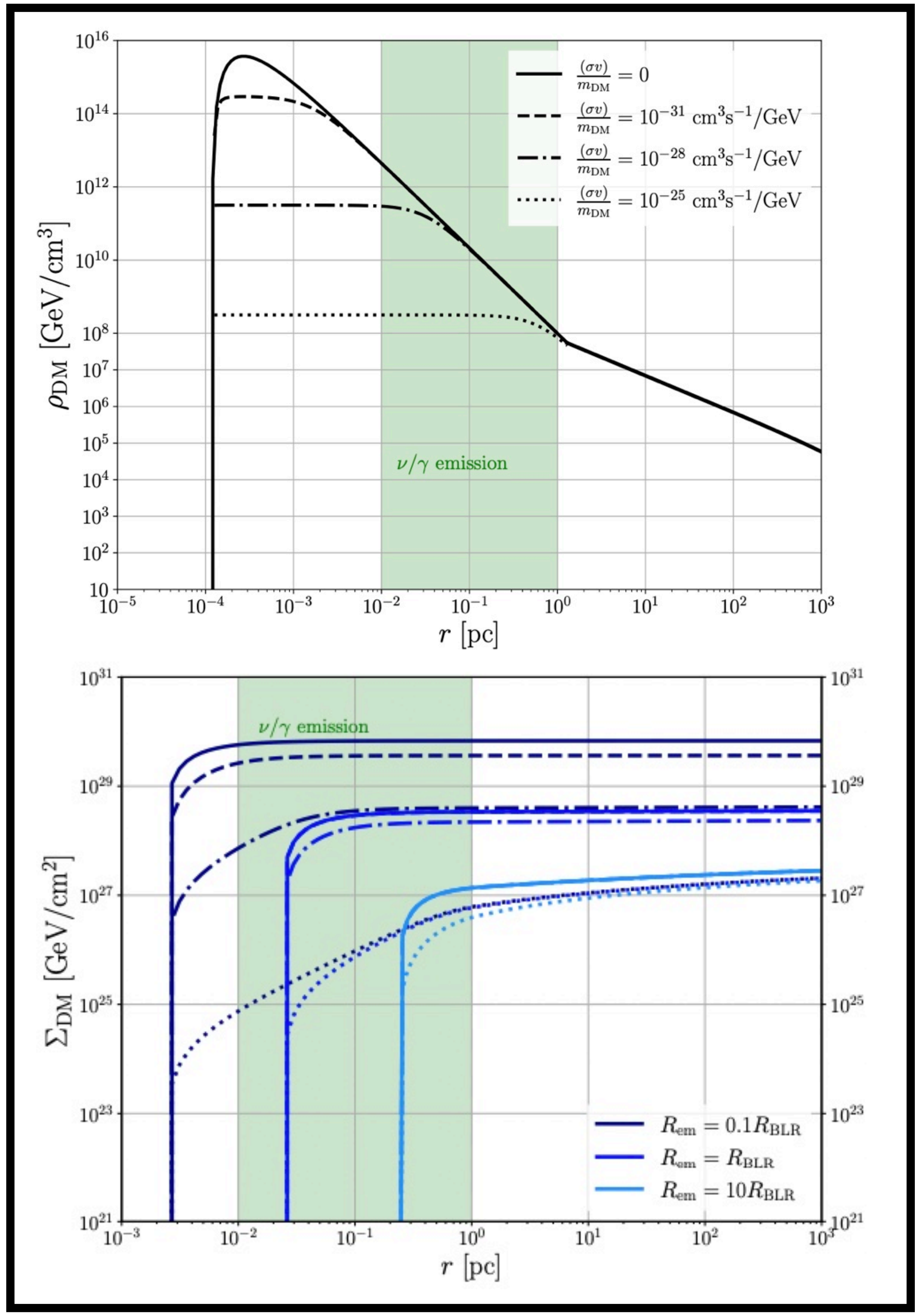
# Milky Way Dark Matter halo profiles



The outer region of the MW gives you small differences among DM halo models
→ using one representative model (NFW) for further study

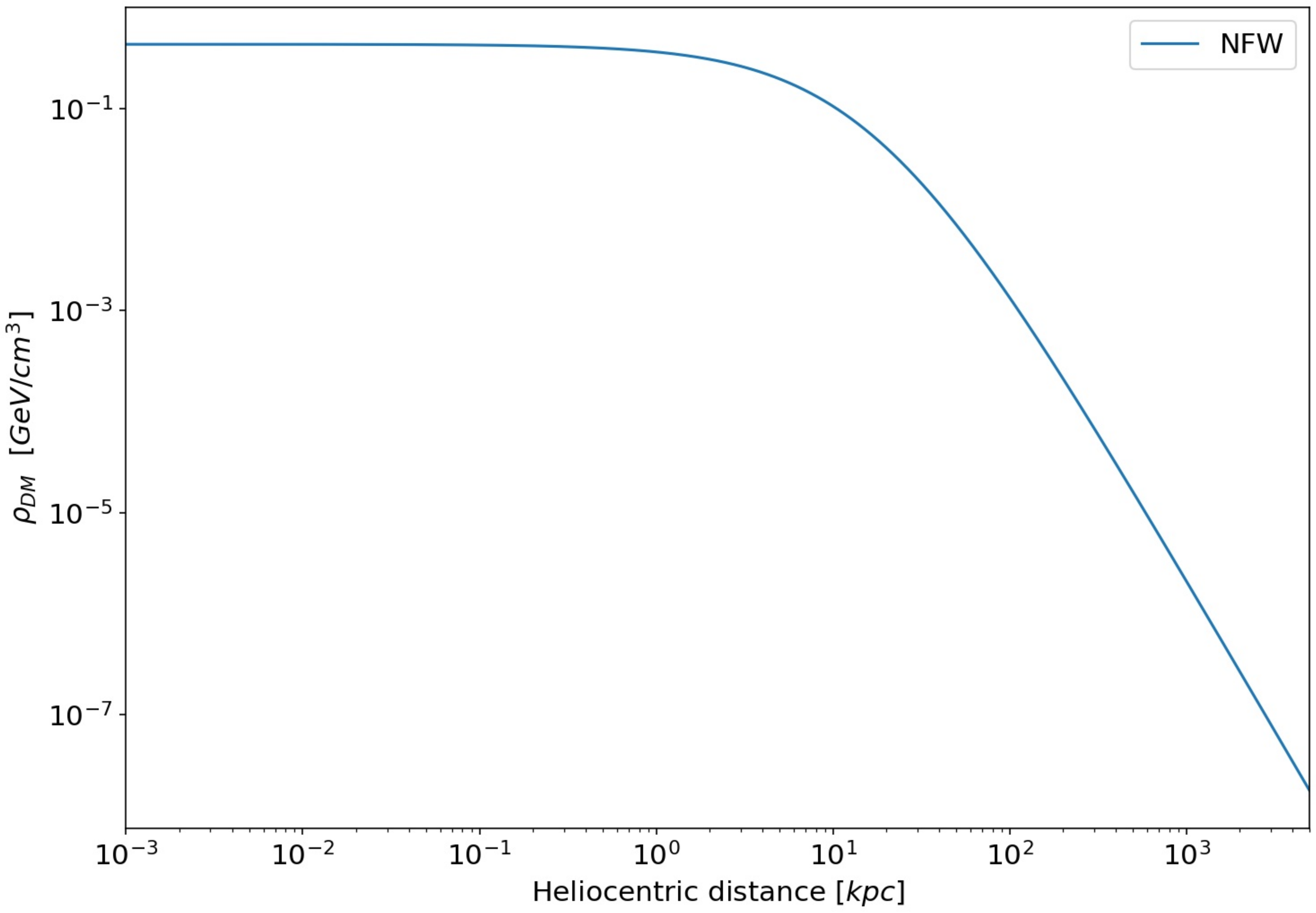
# Source Spike DM in the vicinity of TXS 0506+056



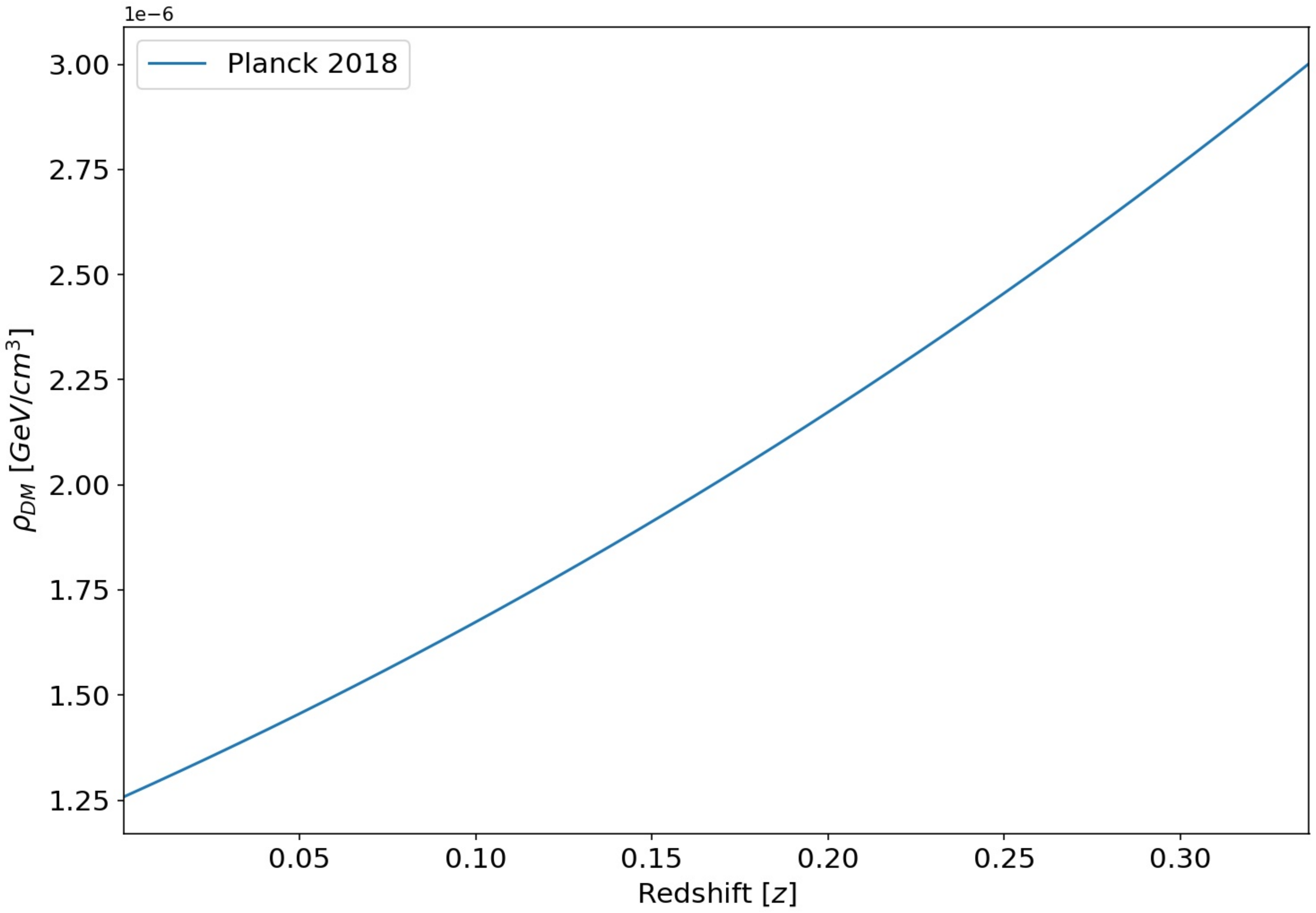


F. Ferrer, G. Herrera, and A. Ibarra; arXiv:2209.06339

# DM contributions to TXS 0506+056

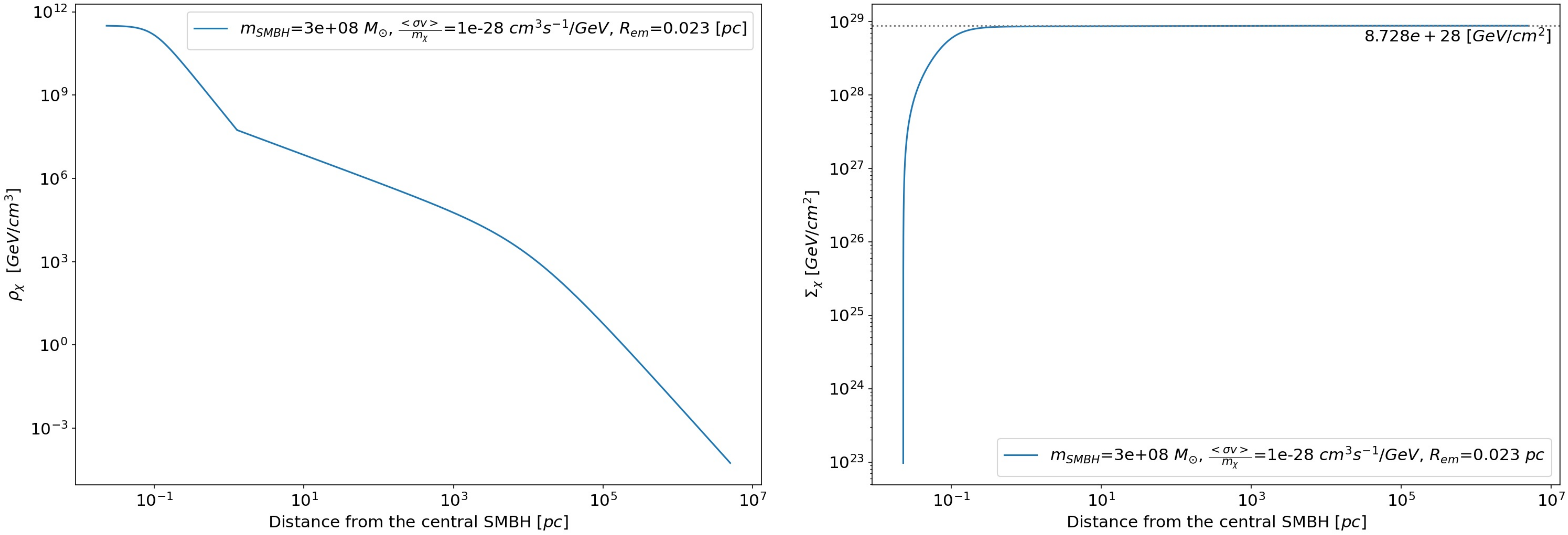


Milky Way galactic DM density along l.o.s to TXS 0506+056



Cosmological DM density along l.o.s to TXS 0506+056

# DM contributions near by TXS 0506+056



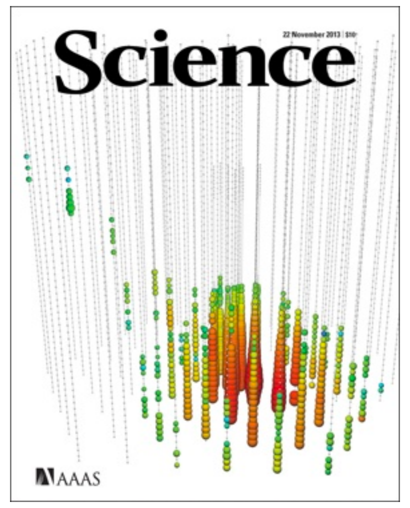
DM Density distribution

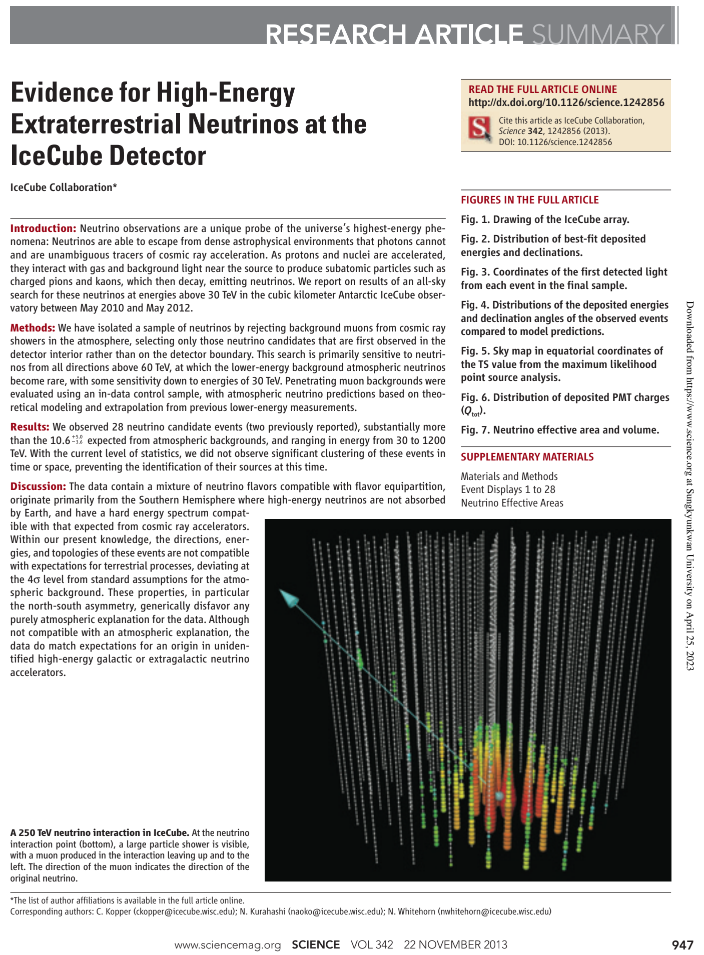
DM cumulative mass

# Primary goals of IceCube

- Observe extraterrestrial neutrinos ✅
  - 1st detection of astrophysical flux in 2013

    *Science* **342**, 1242856



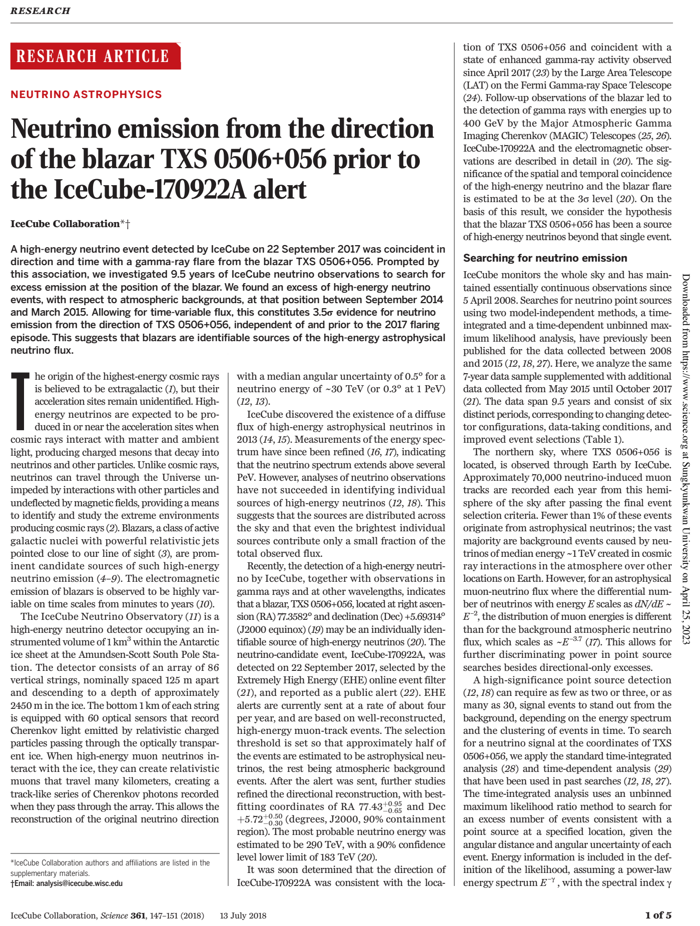

RESEARCH ARTICLE SUMMARY

Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

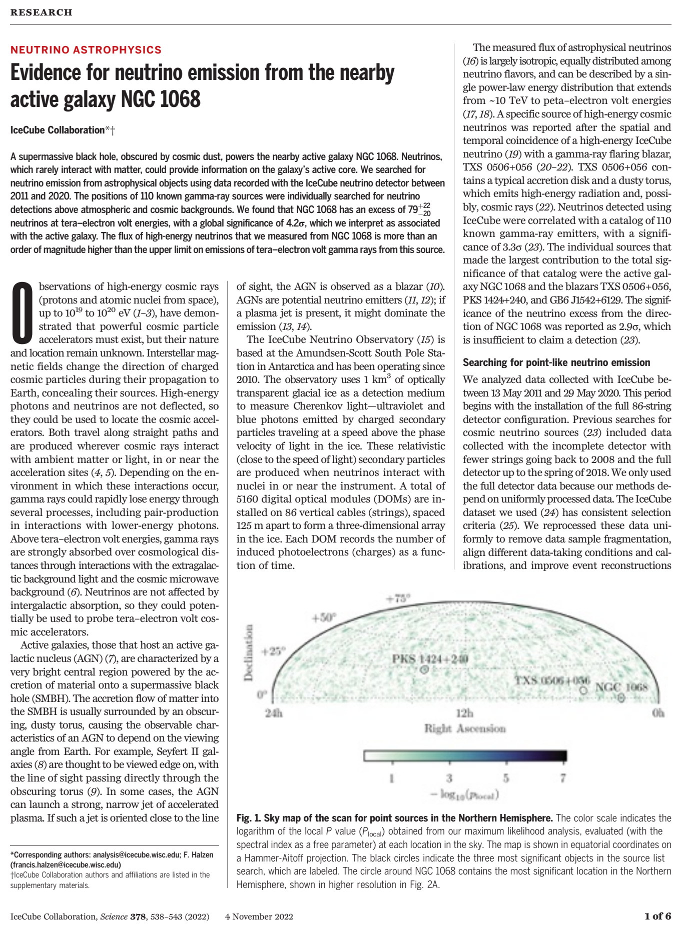
- Search for extraterrestrial neutrino sources ✅
  - 1st astrophysical source in 2018: *TXS 0506+056*

    *Science* **361**, 147-151
  - 2nd astrophysical source in 2022: *NGC 1068*

    *Science* **378**, 538-543


RESEARCH ARTICLE

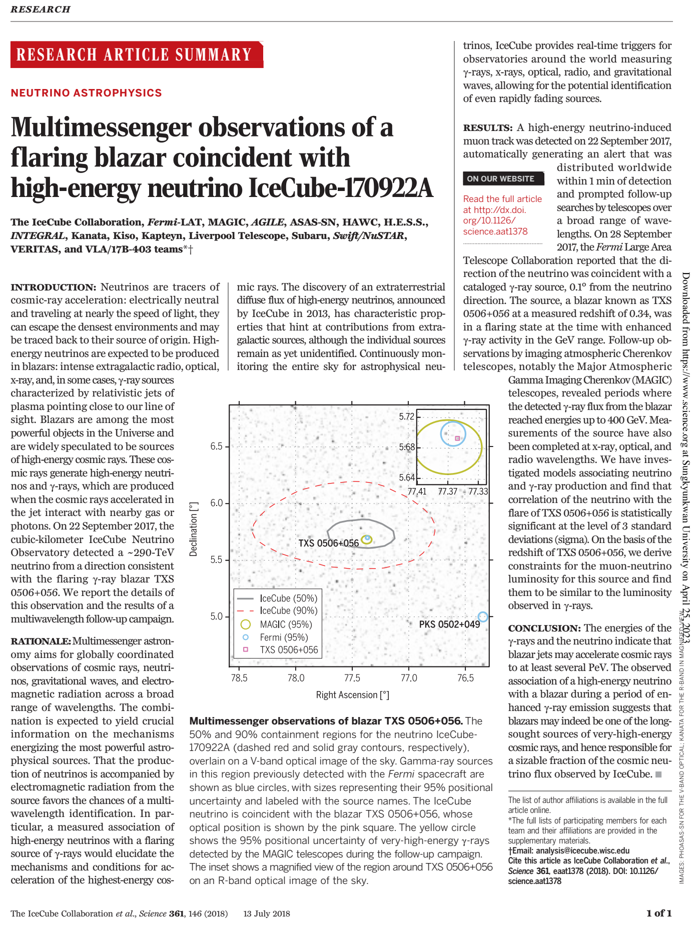
Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert


NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

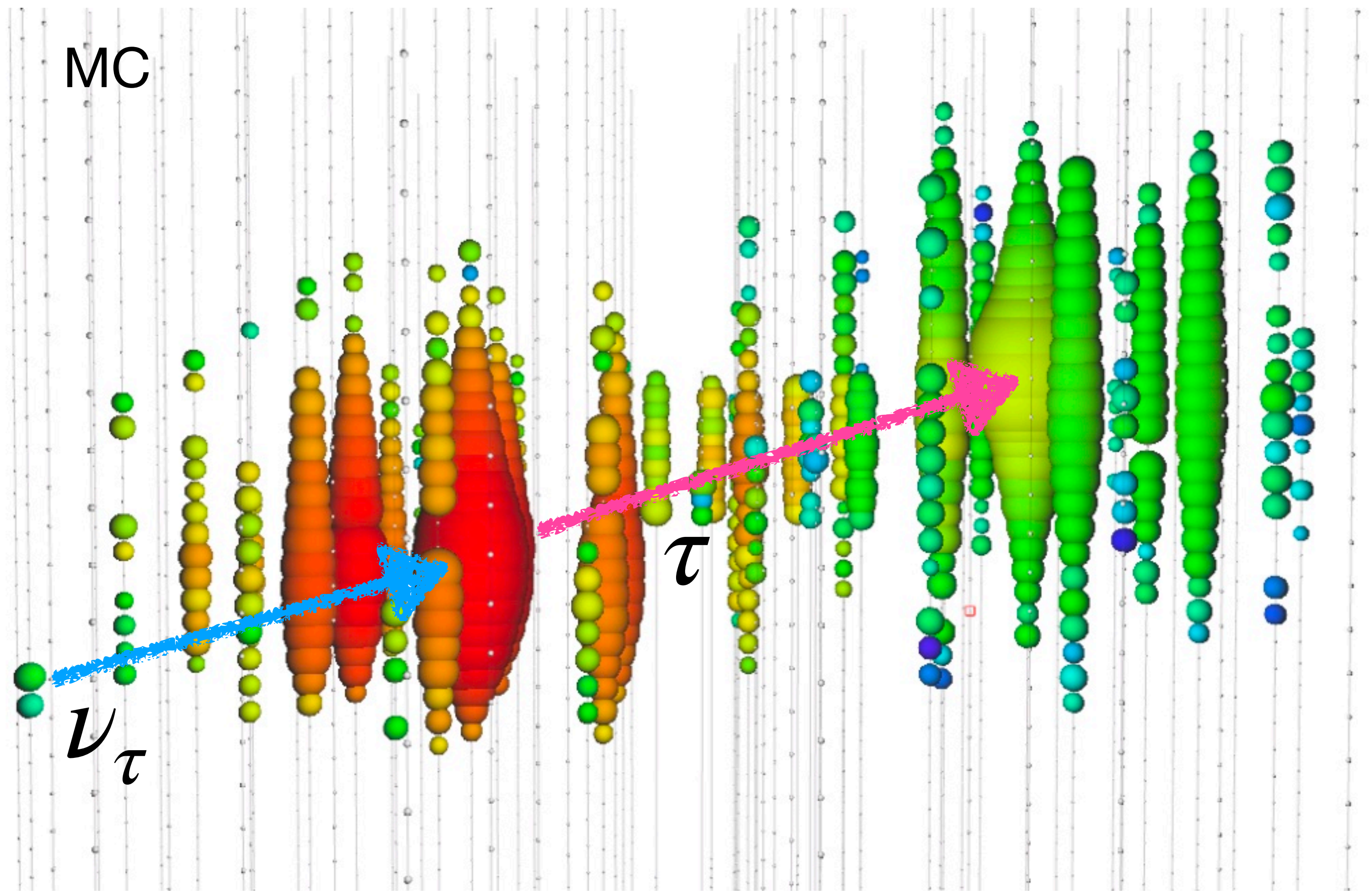
- Multi-messenger astronomy with neutrinos ✅
  - 1st multi-messenger observation in 2018: *TXS 0506+056*

    *Science* **361**, eaat1378

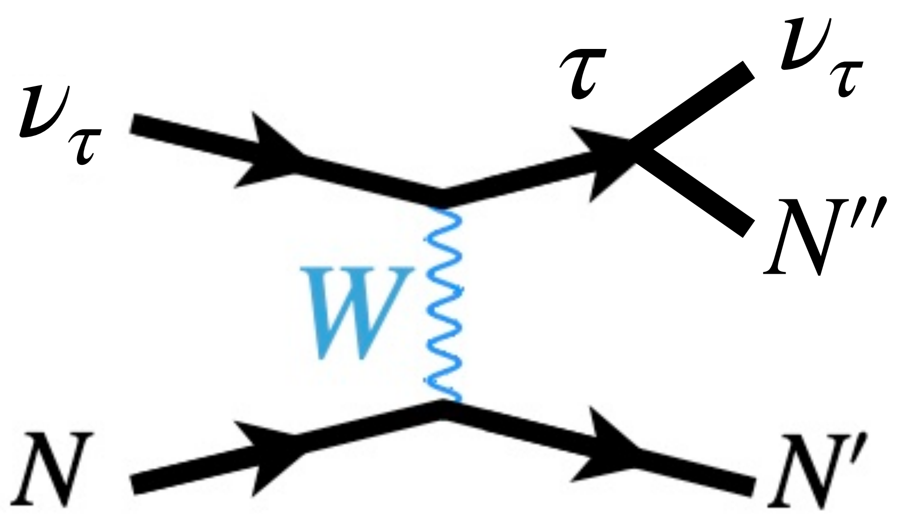

RESEARCH ARTICLE SUMMARY

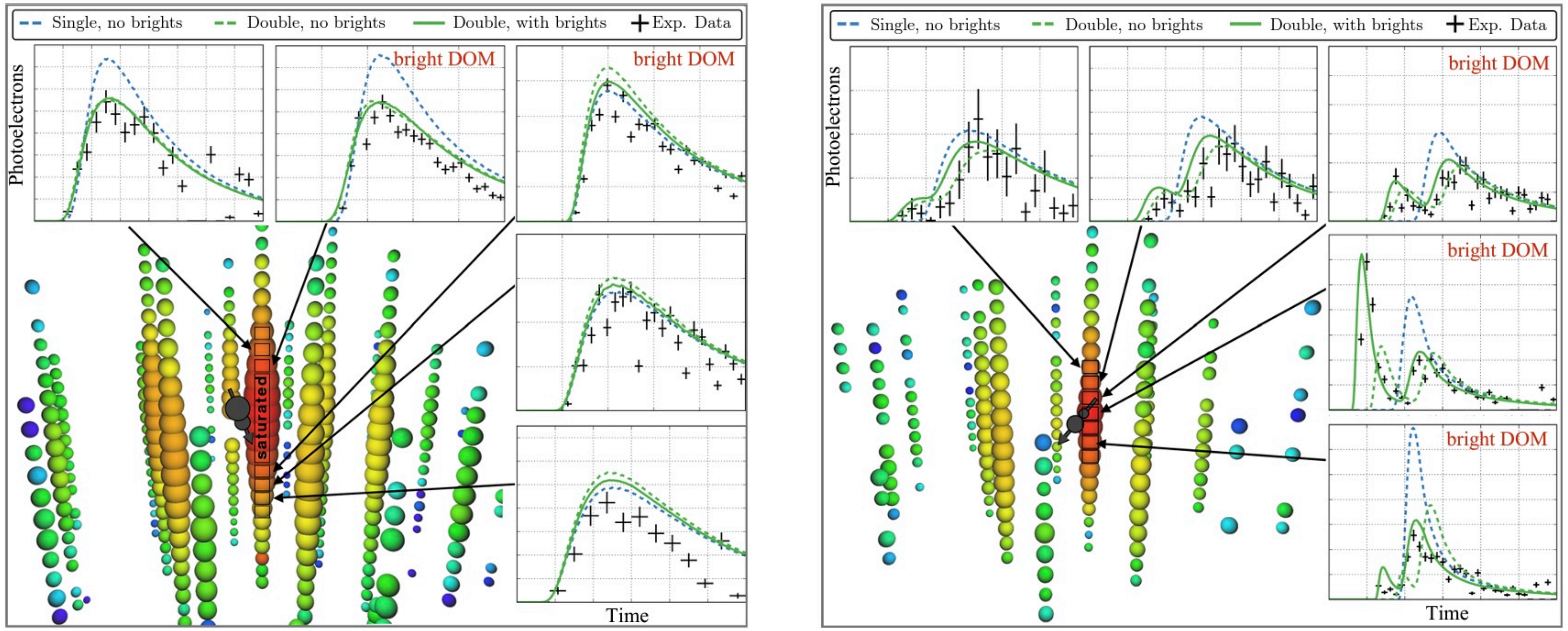
Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

# ‘Tau neutrino’-like events in IceCube



- Double-cascade
  - $\nu_\tau$ CC vertex
  - $\tau$ decay vertex





| Variable | Event #1 | Event #2 |
|---|---|---|
| Primary energy | > 1.5 PeV | > 65 TeV |
| Visible energy | 1–3 PeV | 60–300 TeV |
| Vertex, $r - r_{\mathrm{evt}}$ | 50 m | 50 m |
| Vertex, $z - z_{\mathrm{evt}}$ | ±25 m | ±25 m |
| Azimuth $\phi - \phi_{\mathrm{evt}}$ | ±110(40)° | ±110° |
| Zenith $\theta - \theta_{\mathrm{evt}}$ | ±35(17)° | ±35° |

IceCube Collaboration, Eur. Phys. J. C **82**, 1031 (2022)

# IceCube + : much precise, much energetic

**IceCube-Upgrade** | **IceCube** | **IceCube-Gen2**

0.1 TeV - 100 PeV

Higher energy

Better precision

(best) directional: < 1°, energy: 15%

- Lower energy threshold
- Better precision from the improved calibration

- Higher energy limit
- More neutrino events from the larger effective volume

**New goals**

“Identifying more astrophysical neutrino sources”

“Advanced understanding on cosmic accelerators”

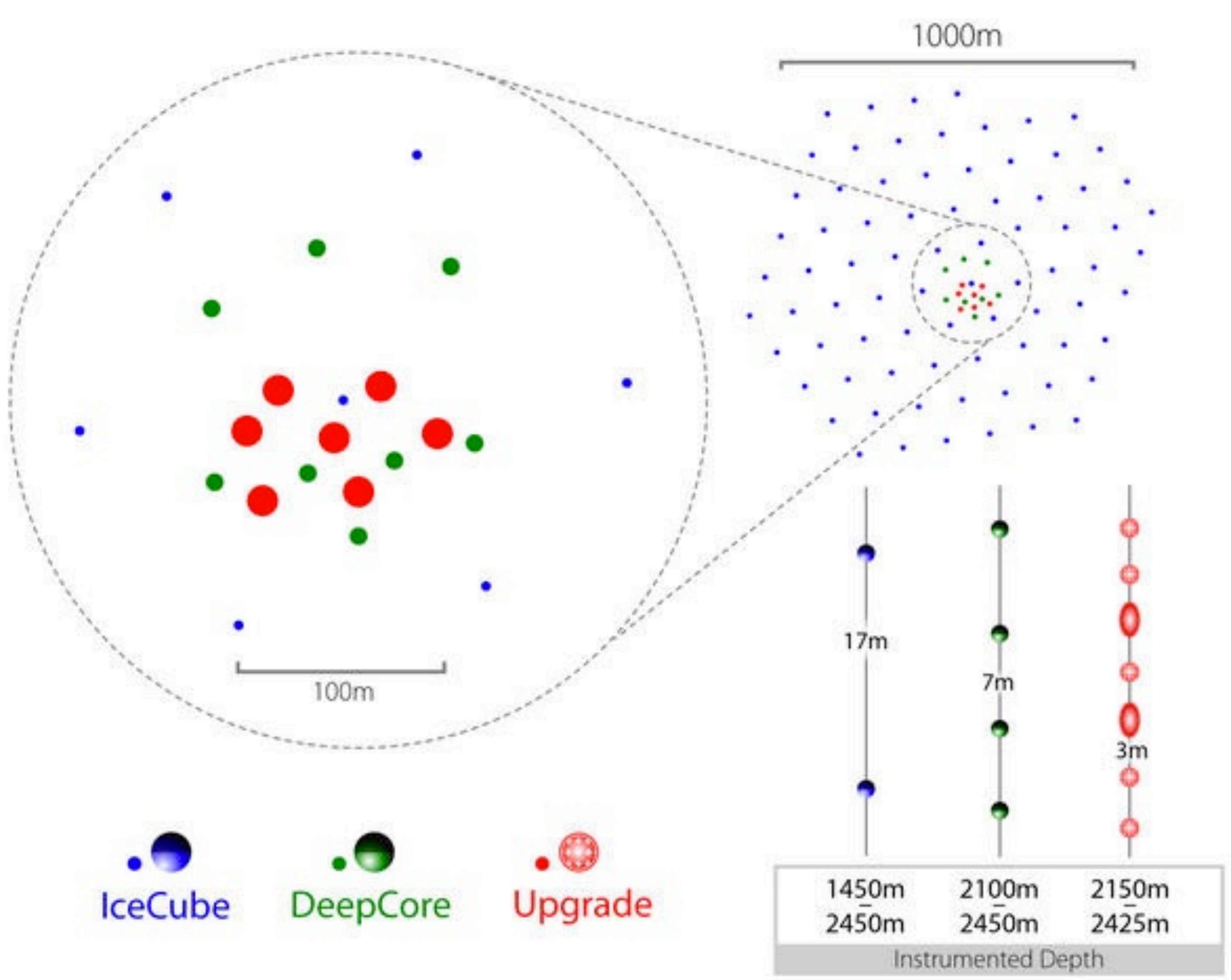
“Advanced understanding on Antarctic glacier”

“Progresses on scientific researches”

“More events from neutrino multi-messenger astronomy”

and more...

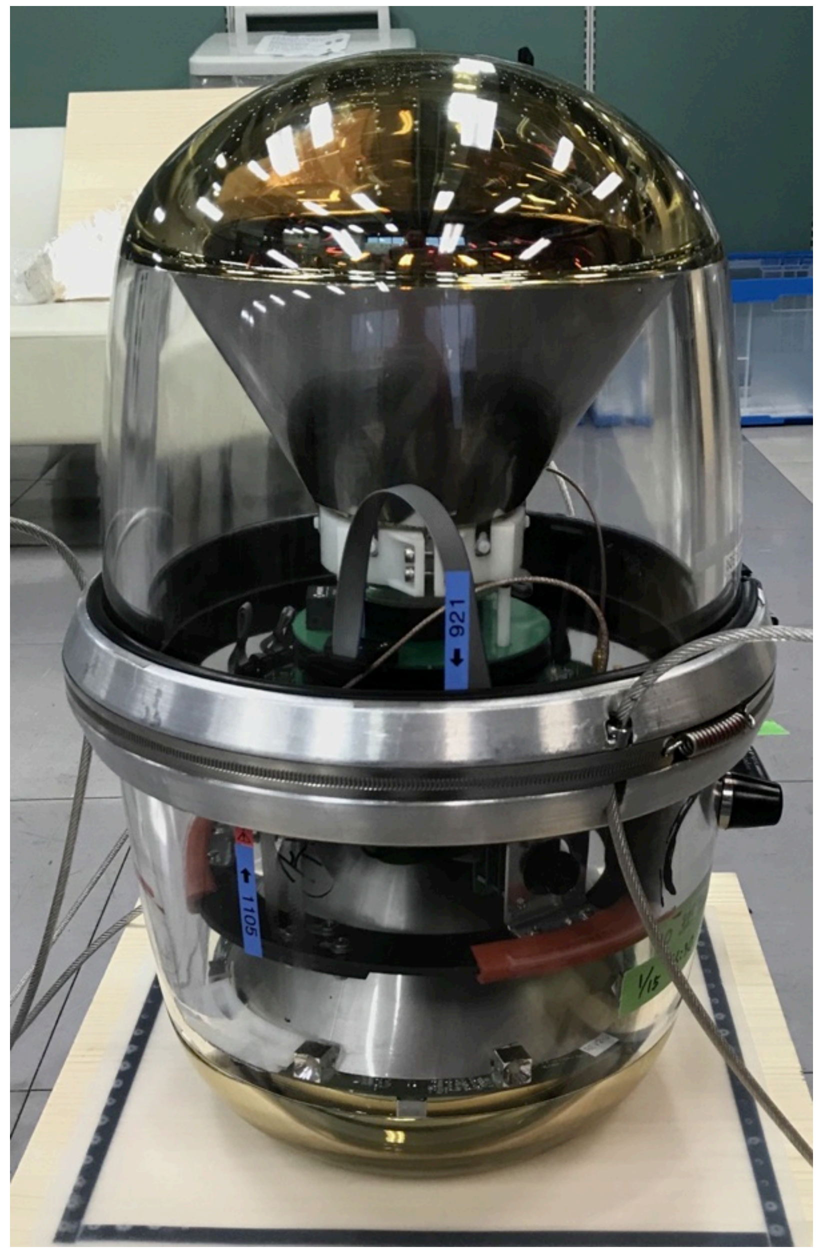
# IceCube-Upgrade



**IceCube-Upgrade**

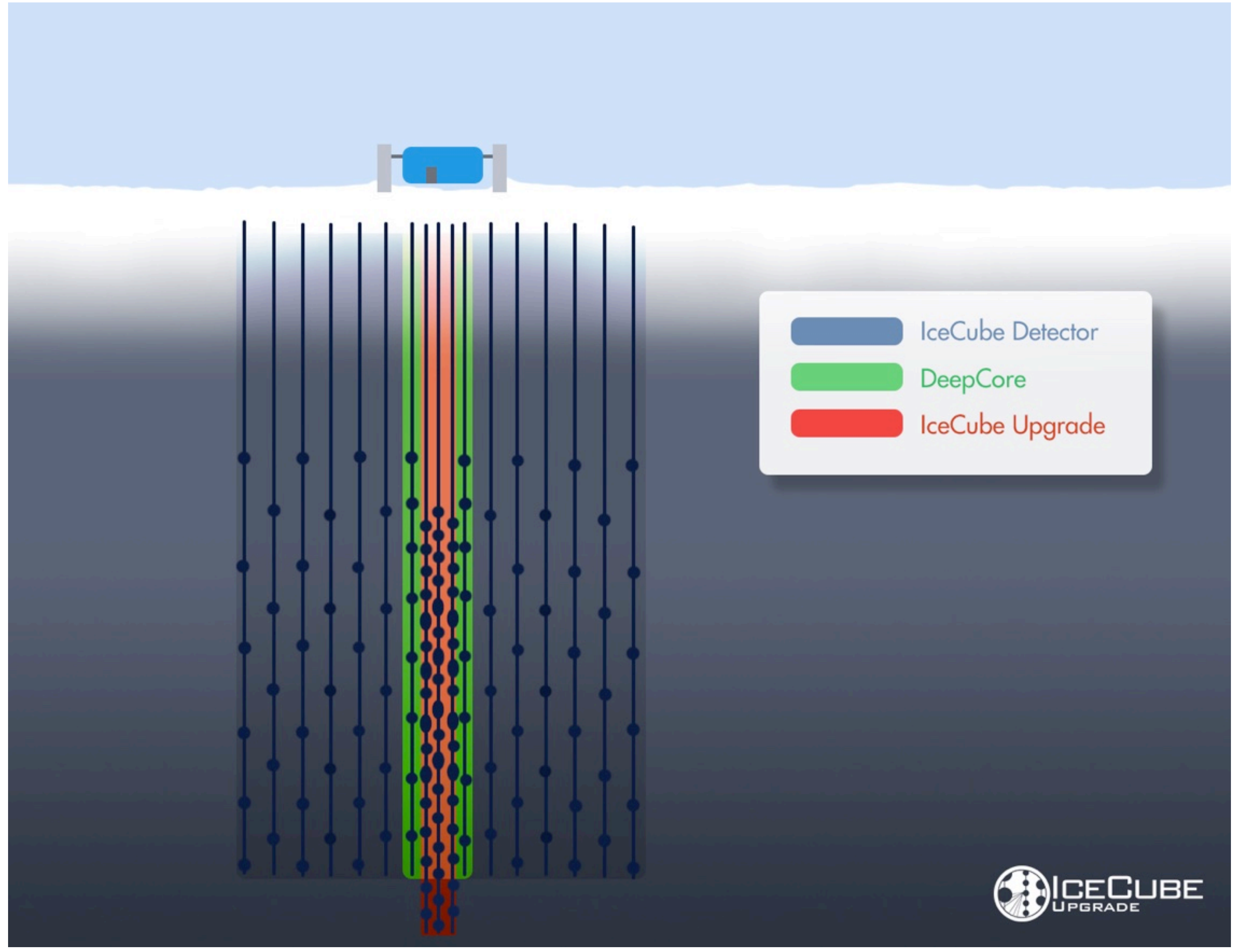
- 7 new strings
- 20 m inter-string distance
- 3 m inter-module distance
- Novel optical modules

mDOM



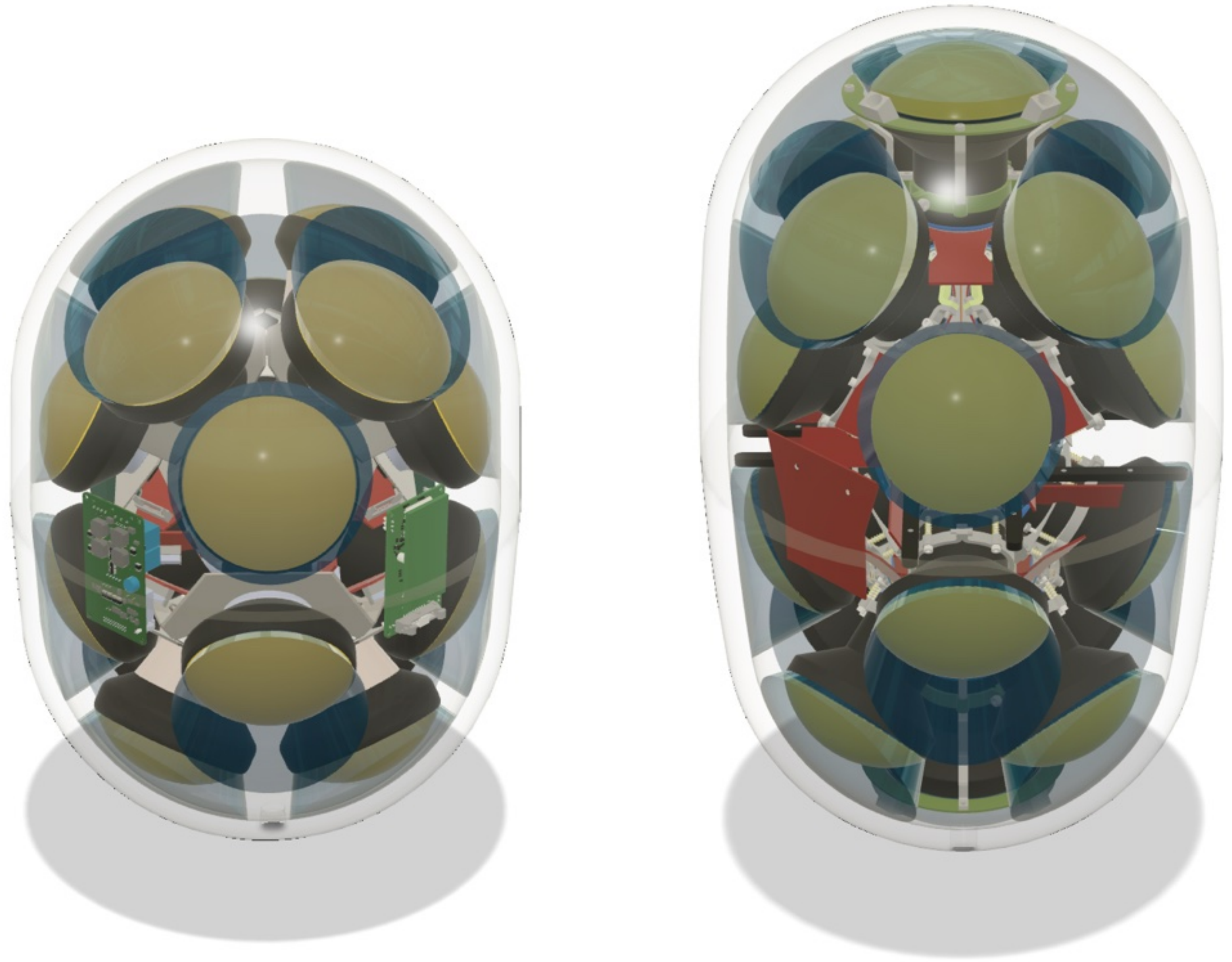
D-Egg

*PoS(ICRC2019)1031, PoS(ICRC2021)1042, PoS(ICRC2021)1070*

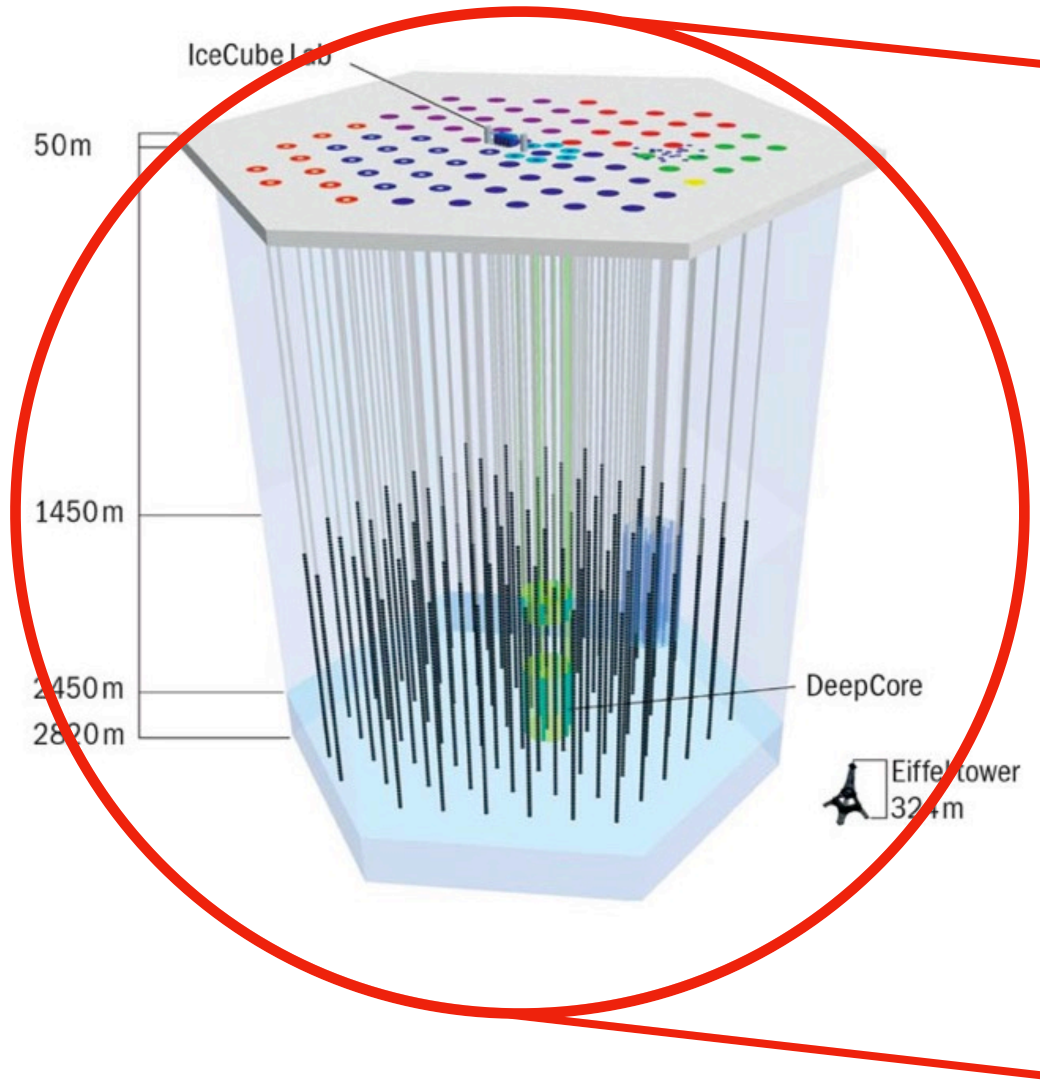


- Seven new strings: densely instrumented in the centre of active volume of the IceCube detector
- To enhance the capability to detect neutrinos in the GeV range for the measurement of the unitarity of the PMNS matrix
- To reduce ice properties related systematic uncertainties in the IceCube analyses by re-calibration of the IceCube detector
- Newly developed optical sensors with new calibration devices

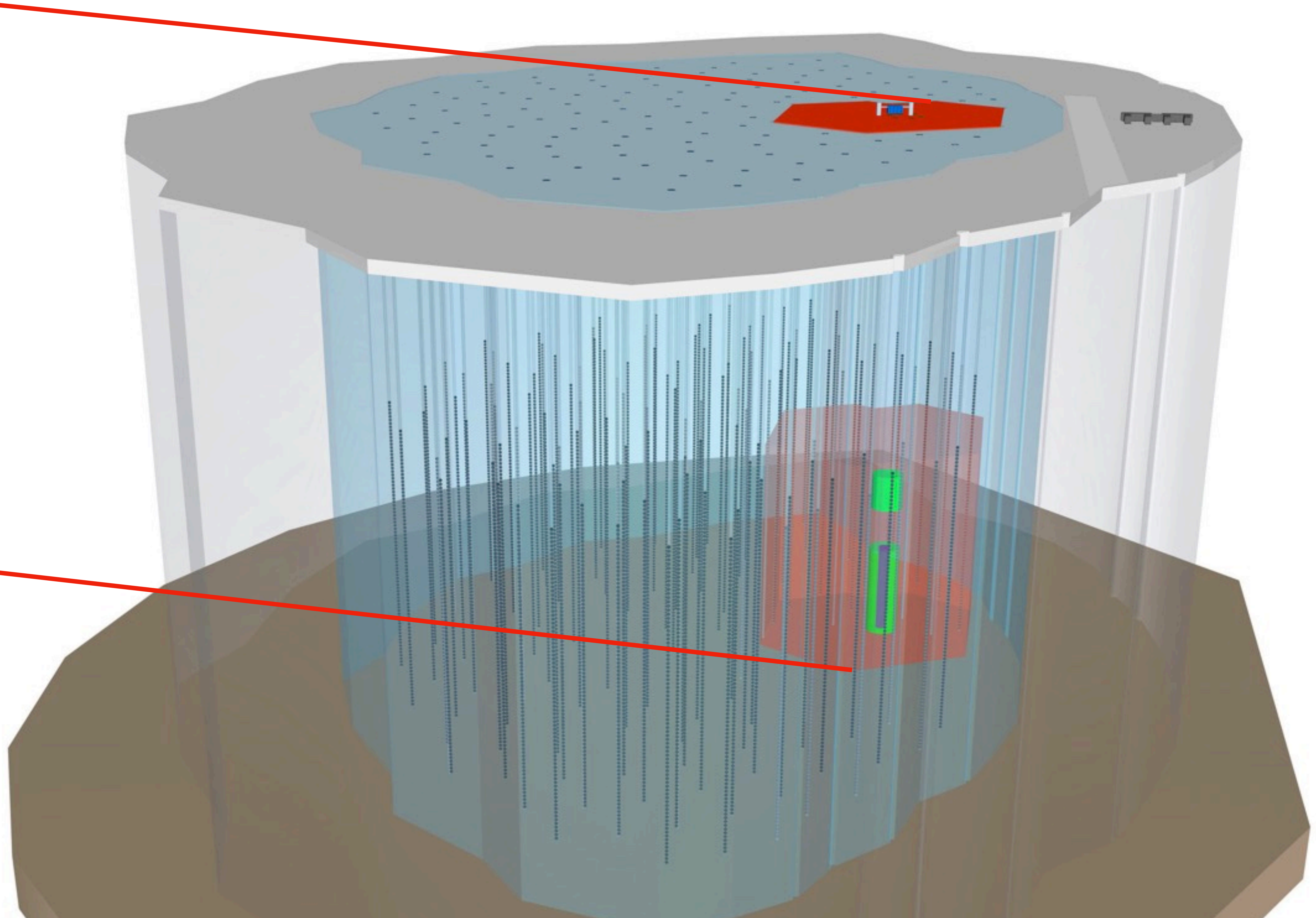
# IceCube-Gen2

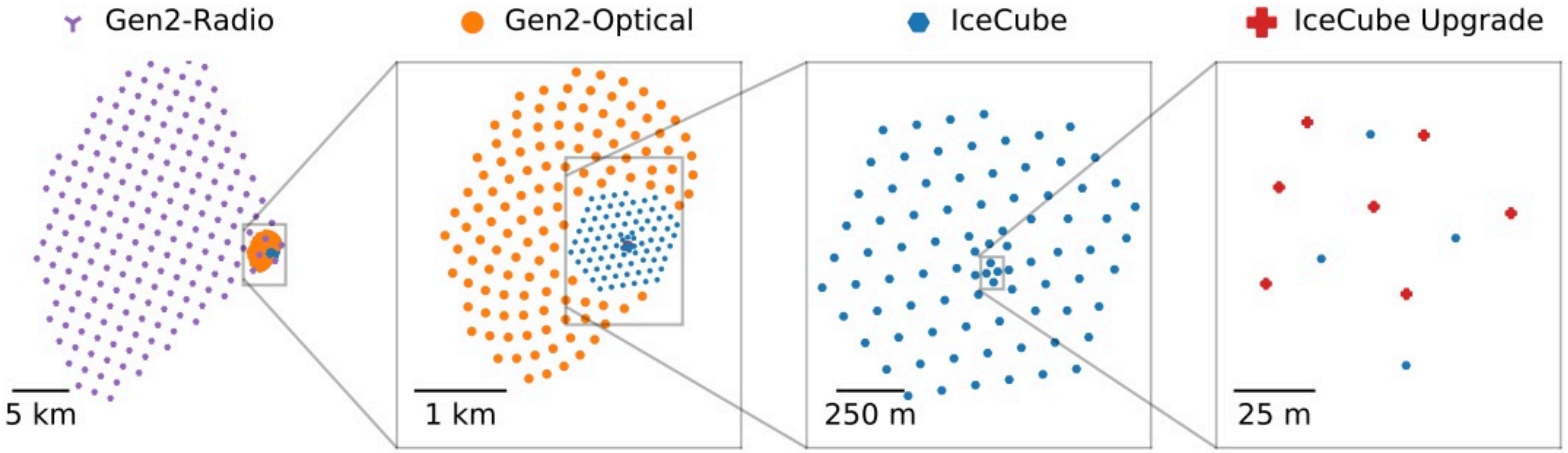


Gen2 Optical Module candidates
(left: 16 PMT option, right: 18 PMT option)



**IceCube**
- 86 strings
- 125 m inter-string distance
- 60 OMs per string
- 1 km³ volume





**Gen2**
- 120 new strings
- 240 m inter-string distance
- 80 OMs per string
- 8 km³ volume

J. Phys. G **48** 060501