

Dark Matter Searches with IceCube

Stephan Meighen-Berger on behalf of IceCube

Dark Ghosts - Workshop

Granada, March 31st, 2022

How to approach this topic?

- You'll hear a whole bunch of IceCube talks:

- “Neutrino lines in DM searches” - Juan
- “Dark Matter Decay and Annihilation to Neutrinos” - Diyaselis
- “DM Searches in the Galactic Centre with IceCube” - Nadege
- “Decaying Dark Matter at IceCube and its Signature in High-Energy Gamma-Ray Experiments” - Barbara
- “DM from the center of the Earth with IceCube” - Giovanni

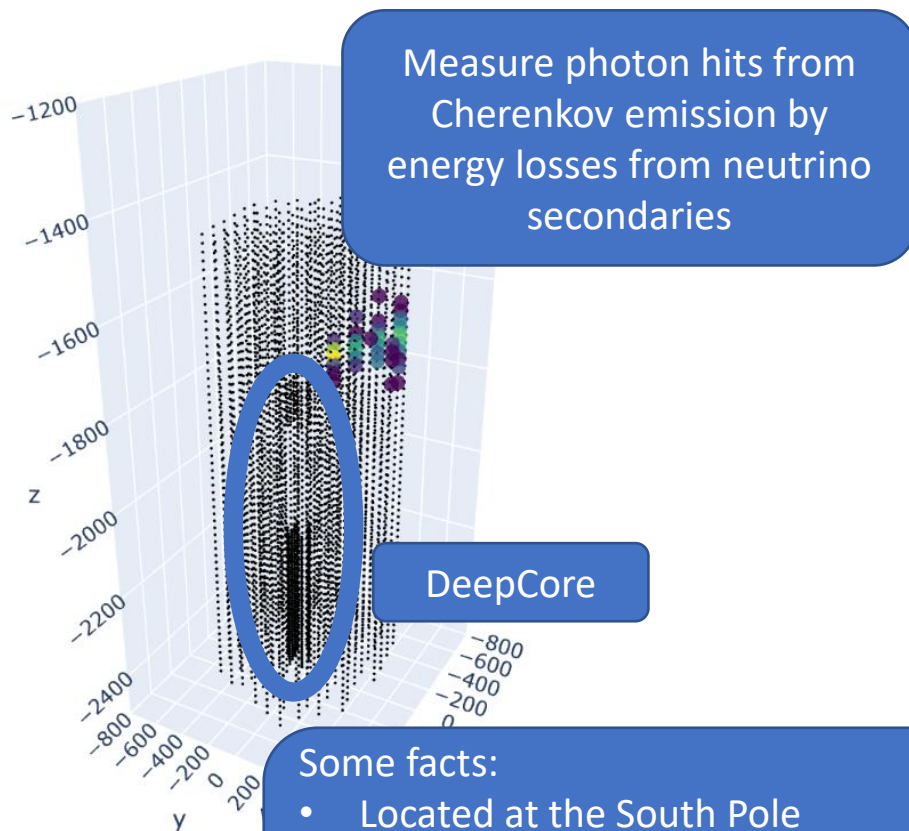
In addition, we have talks on DM searches using ANTARES, KM3NeT and GVD

- IceCube has published a few papers on the topic

- \approx 20 Published analyses
- \approx 24 PhD thesis on the topic

You'll be hearing a lot about neutrino detectors and probably be bored by the question:
„What is IceCube?“

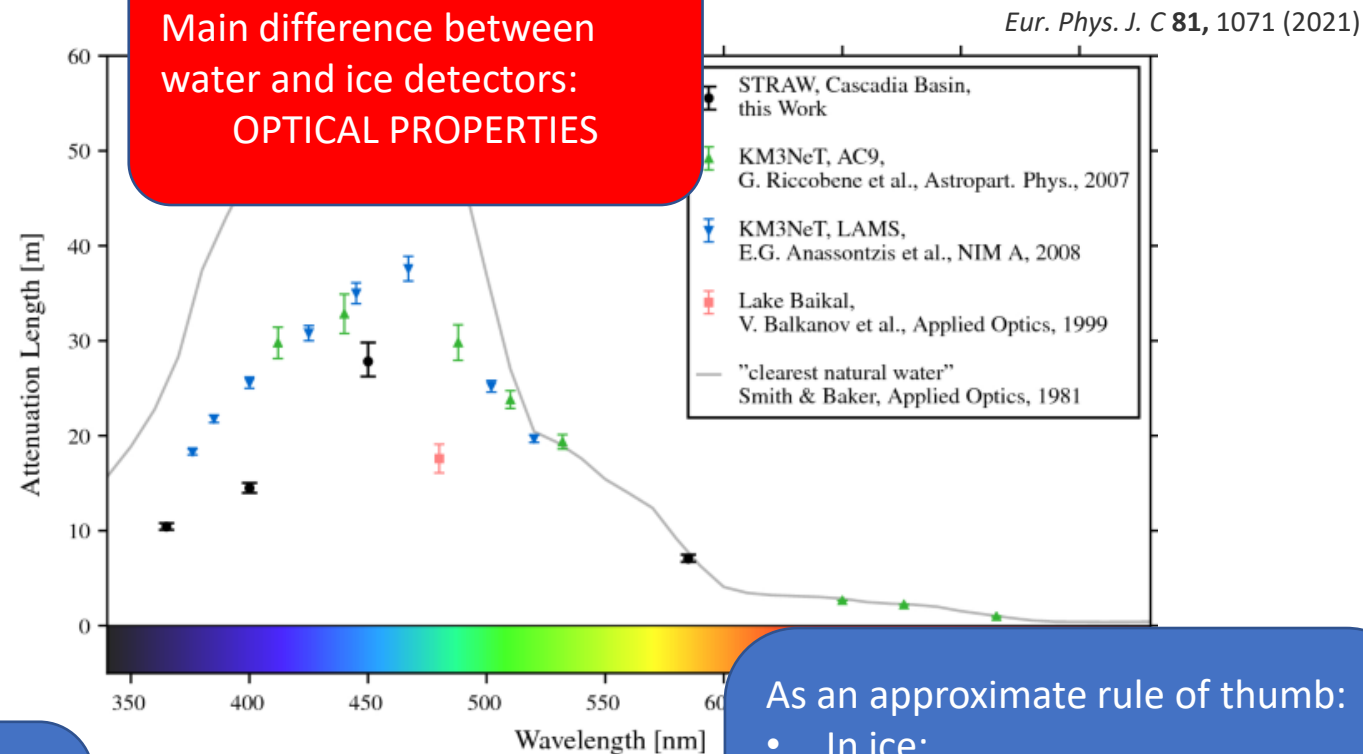
What is IceCube?



Some facts:

- Located at the South Pole
- 5160 Digital Optical Modules (DOMs)
- 86 Strings with 60 DOMs
- 6 denser strings called DeepCore
- Complete since 2010

Main difference between water and ice detectors:
OPTICAL PROPERTIES



As an approximate rule of thumb:

- In ice:
 - 150 m Attenuation length
 - 30 m Scattering length
- In water:
 - 30 m Attenuation length
 - 150 m Scattering length

IceCube does not have to contend with K40 decay or bioluminescence!

Performing a DM analysis using IceCube I

Is IceCube right for you?

DM



Theory stuff

You screwed up

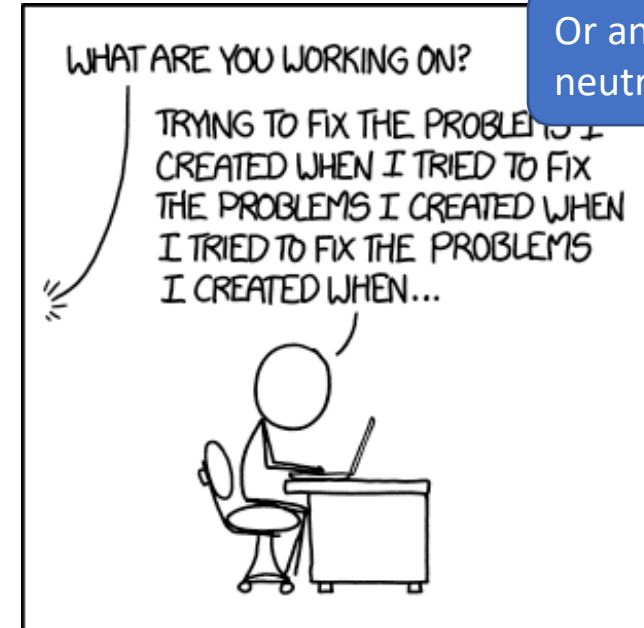
No?

Are you:

- Producing neutrinos?
- Scattering neutrinos?
- Removing neutrinos?

Yes?

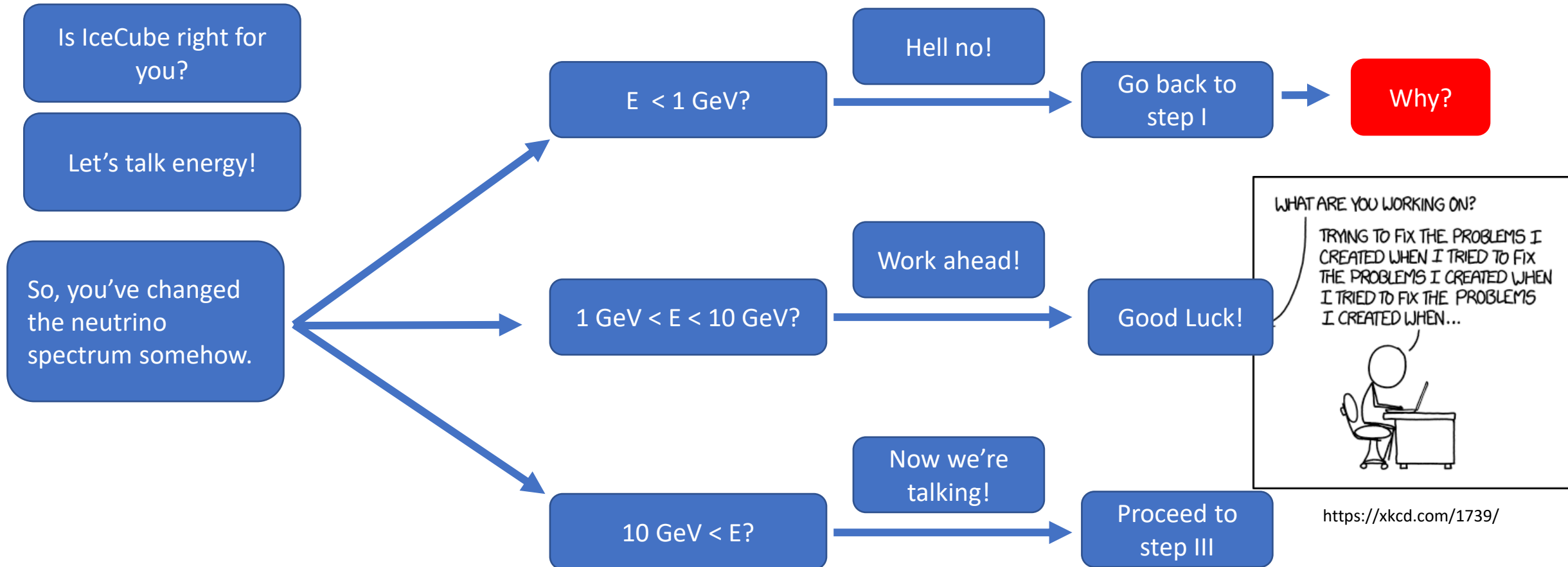
Good job!
Proceed to
step II.



Or any other
neutrino telescope...

<https://xkcd.com/1739/>

Performing a DM analysis using IceCube II

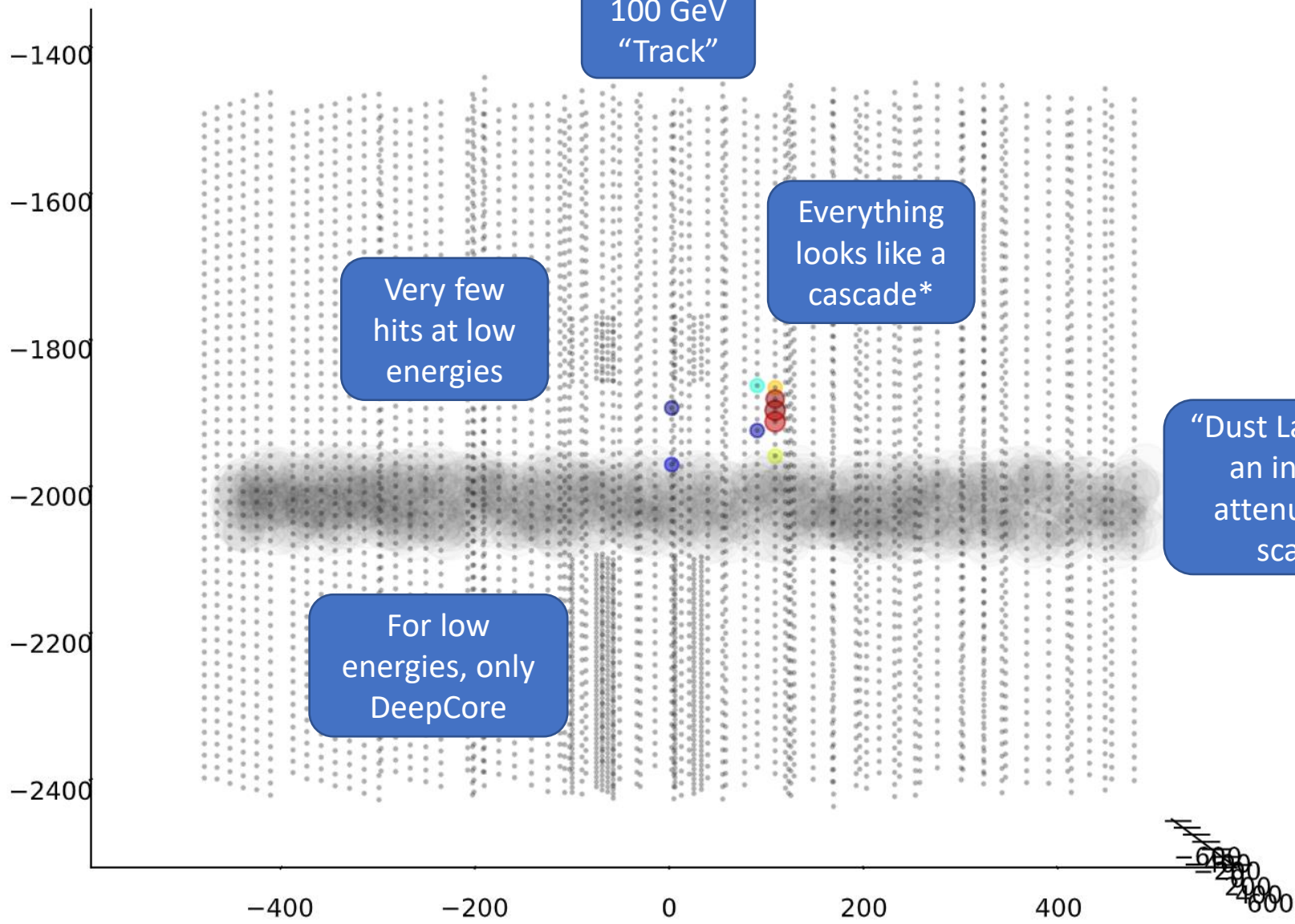


Perform

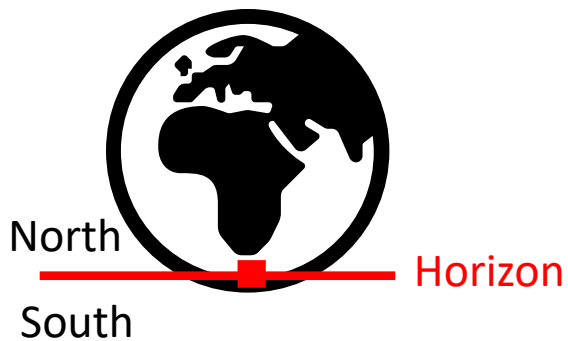
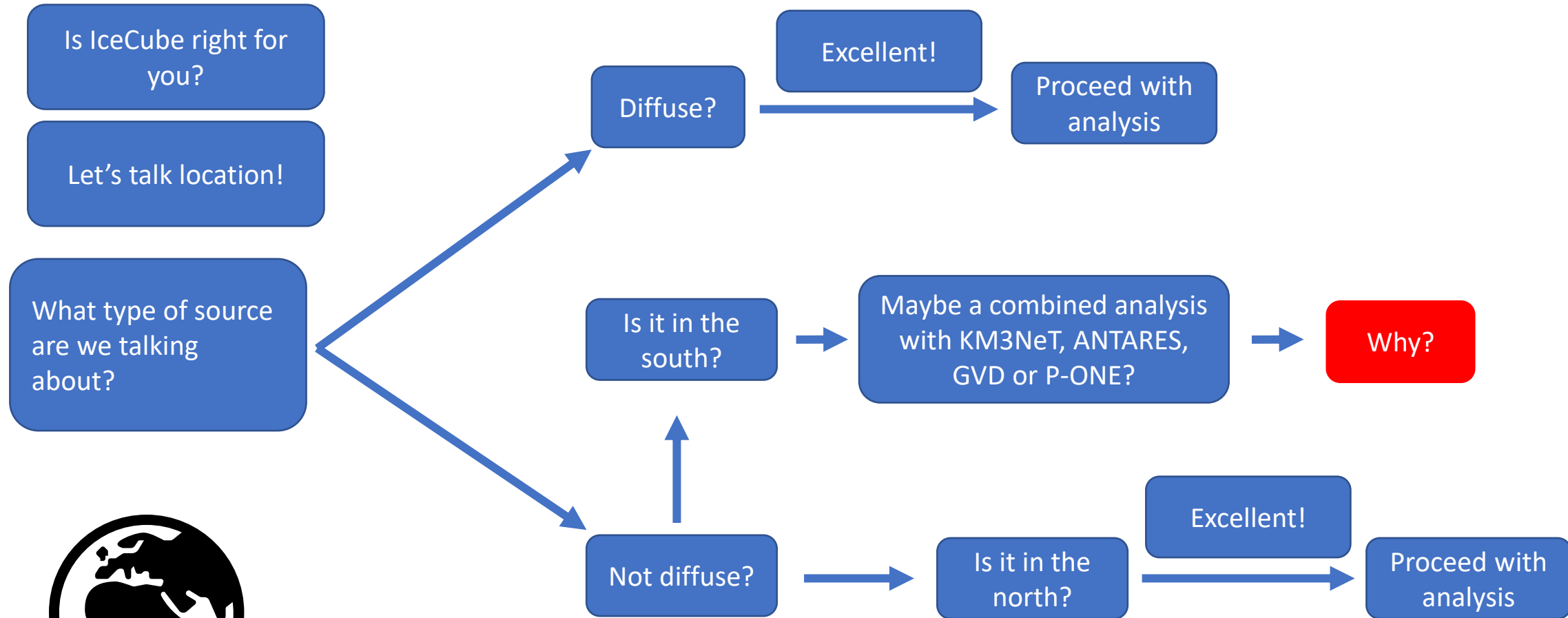
Is IceCube right for you?

Let's talk energy

So, you've changed the neutrino spectrum somehow



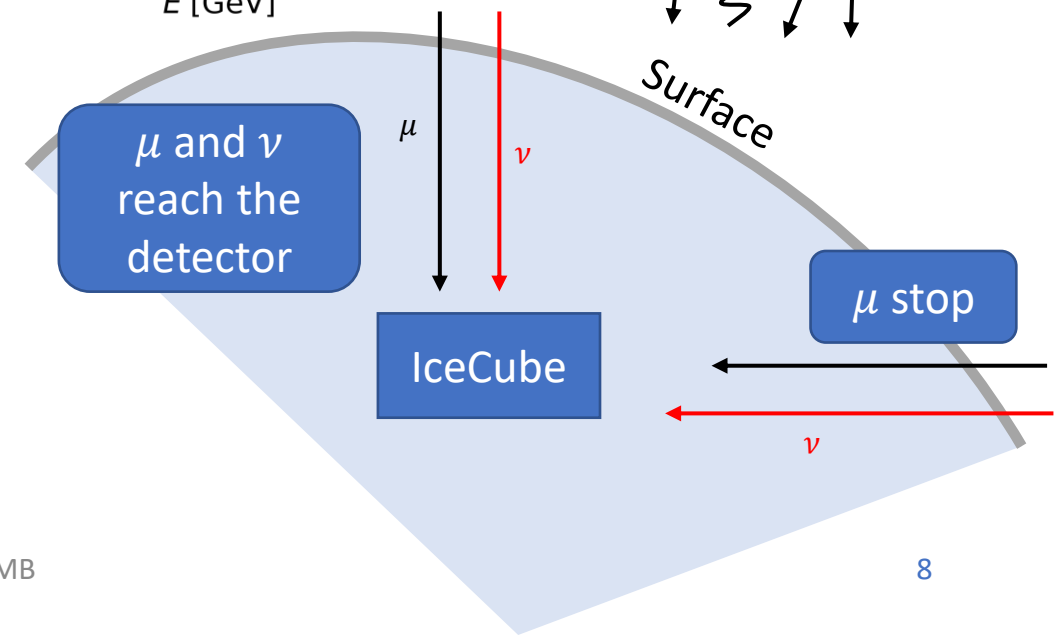
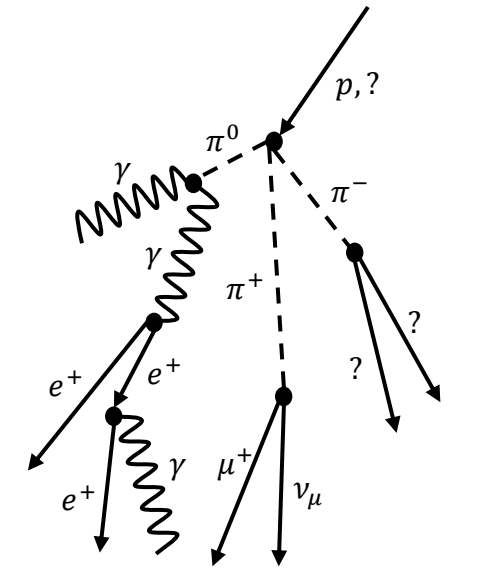
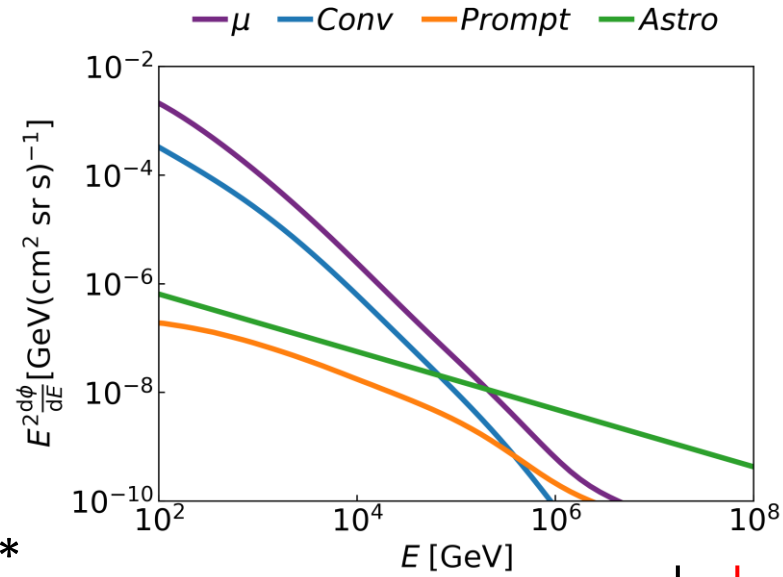
Performing a DM analysis using IceCube III



The main background(s) - Sources

- A DM analysis will have two main backgrounds*:
 - The atmospheric background
 - μ – For down-going searches*
 - ν – For any type of search below 100 TeV*
 - The diffuse astrophysical background
 - ν – For searches above 100 TeV*

*In General: There are specific searches where these rules of thumb don't apply



The main background(s) – Treatment I

This depends on the type of ν -Signal you expect:

- Diffuse?

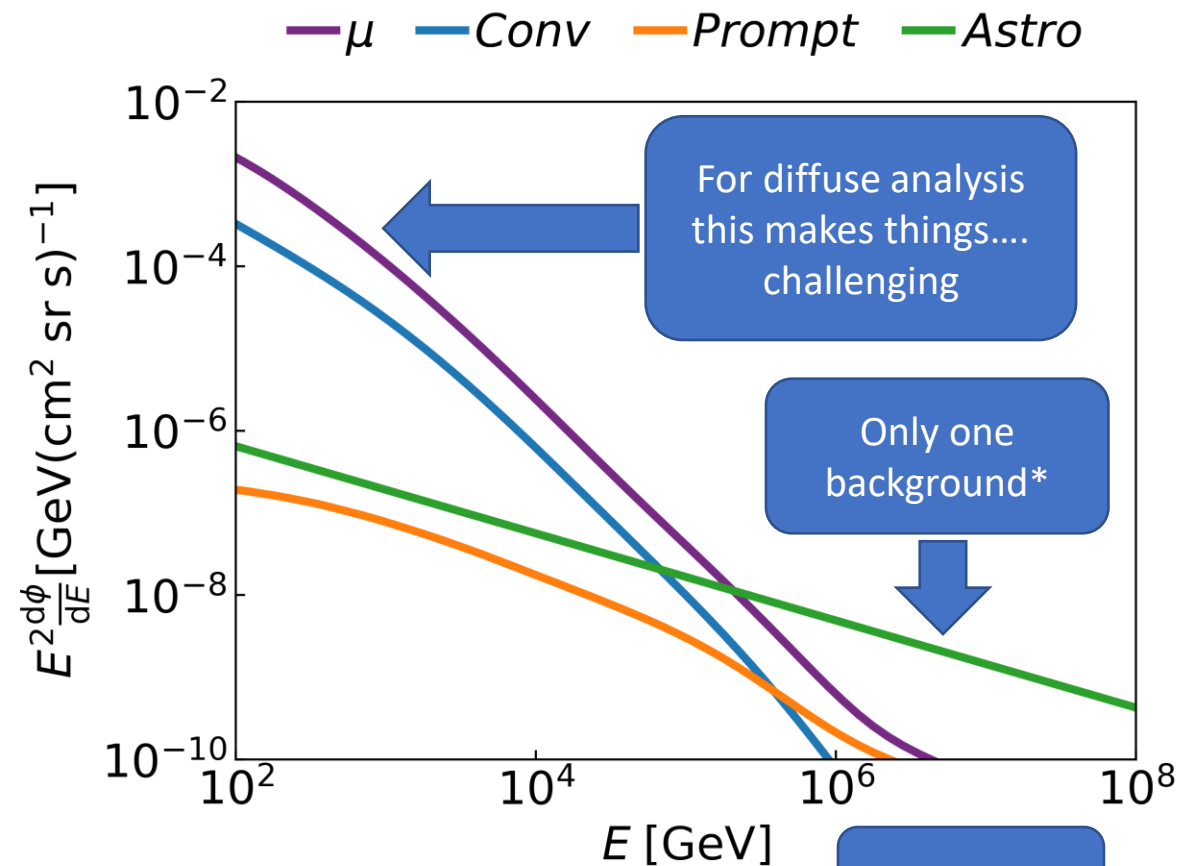
- Southern Sky?
 - > I think you're lost
- Northern Sky?

- What's the spectrum?

- Non-diffuse?

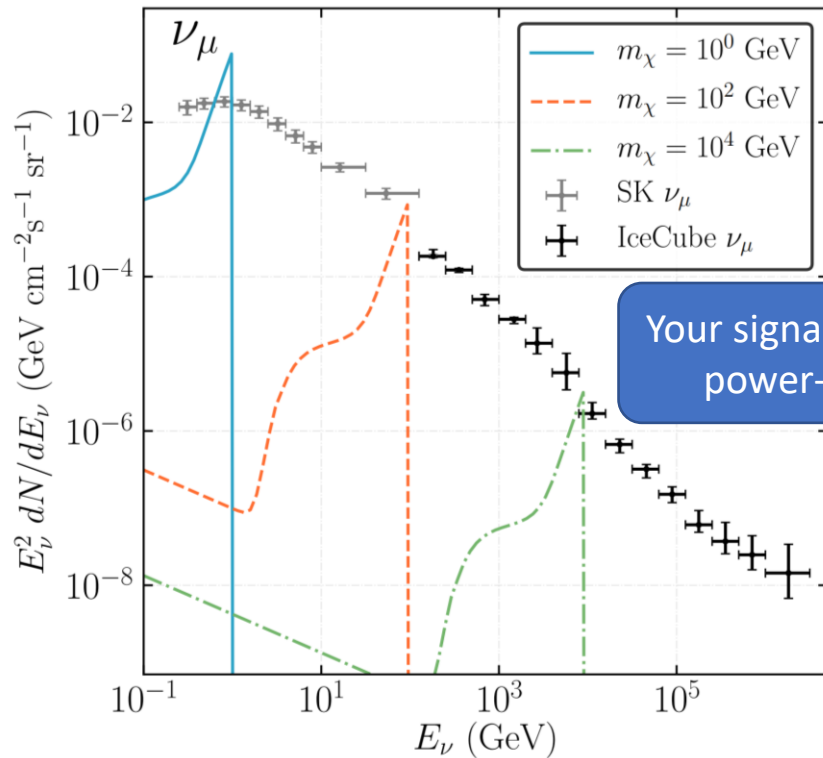
- Good choice!
 - What's the spectrum?

If it isn't a power-law, you're one of the lucky ones!



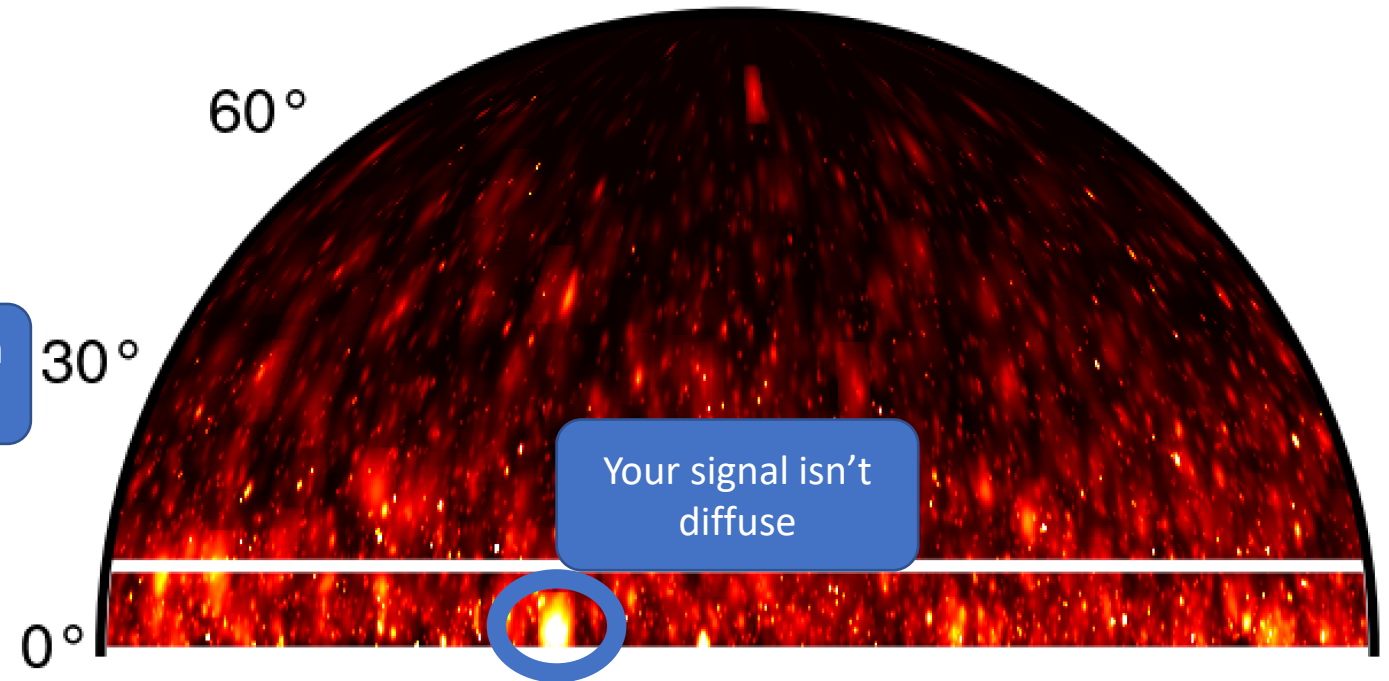
The main background(s) – Treatment II

Two Examples:



Rev. Mod. Phys. 93, 35007 (2021)

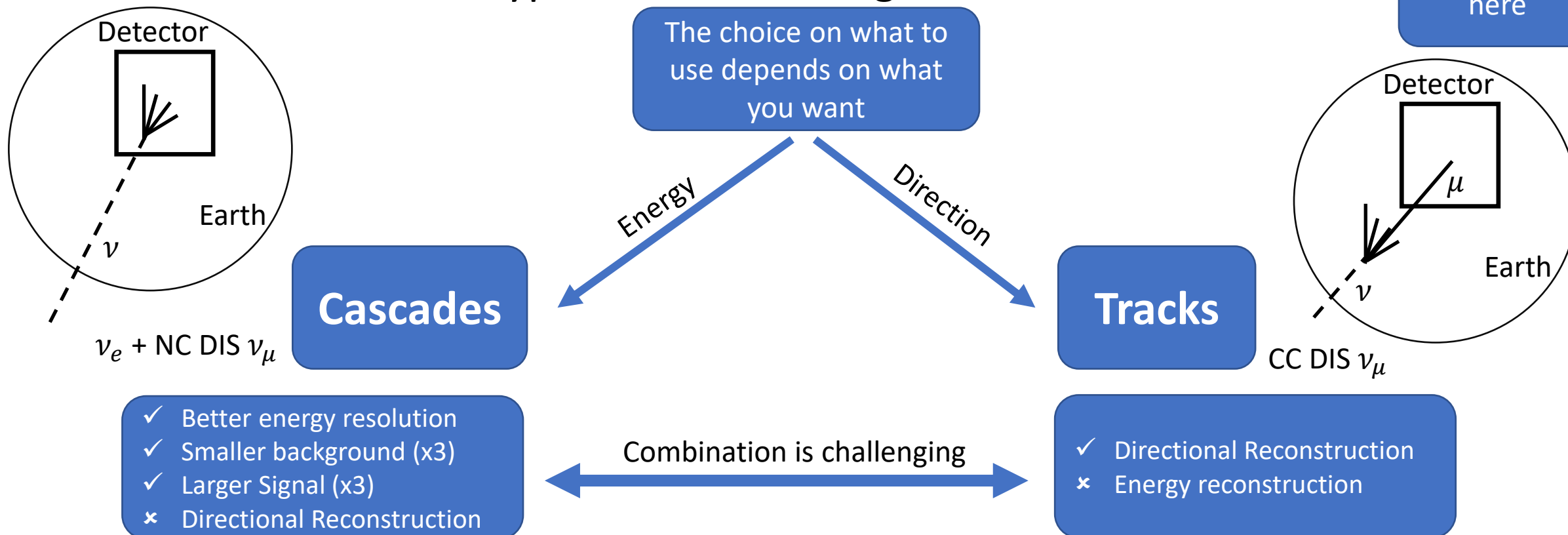
Your signal isn't a power-law



One Final Thing

There are two main* types of neutrino signals: **Tracks** or **Cascades**

*Ignoring τ
here



So, what type of analyses do we have?

Name	Diffuse?	Power-Law	Northern-Sky?	♥
Galactic Center	x	x	x	✓
DM-Nucleon Interaction	x	x	✓	✓
Sun	x	x	✓	✓
Galactic Halo	✓	x	x	✓
Earth	x	x	✓	✓

See the bibliography for examples

Annihilations /Decays

So what is currently in the works?

Current Analyses I

Last year's ICRC contributions:

<https://arxiv.org/html/2107.06966>

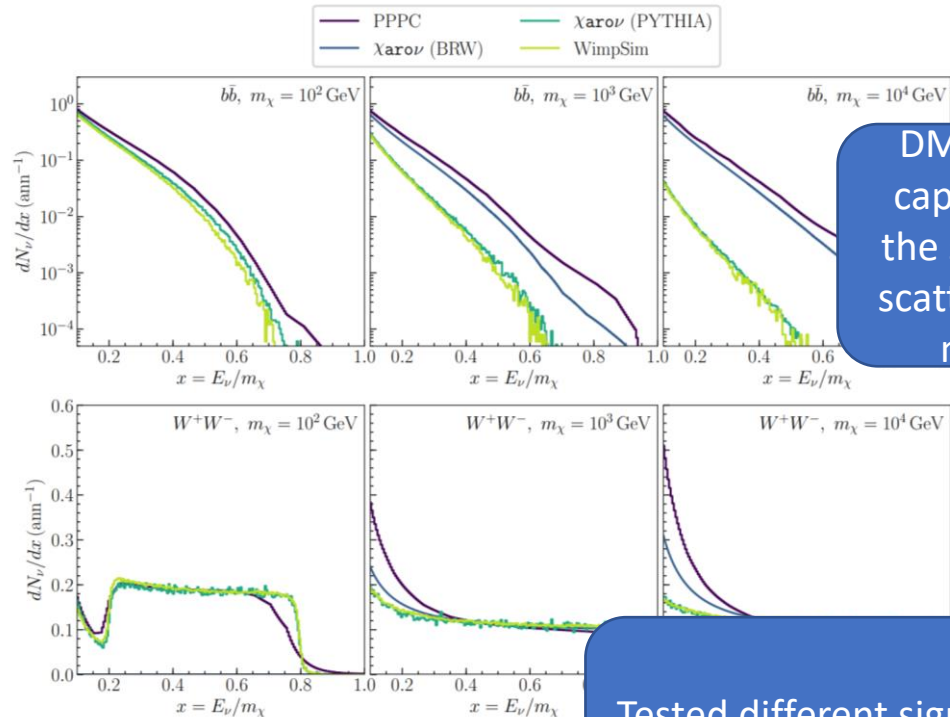
- “Search for Secluded Dark Matter with 6 years of IceCube Data” – Christoph Toennis, [arXiv:2107.10778](https://arxiv.org/abs/2107.10778)
- “A search for Neutrinos from Decaying Dark Matter in Galaxy Clusters and Galaxies with IceCube” – Minjin Jeong, [arXiv:2107.11527](https://arxiv.org/abs/2107.11527)
- “Search for Dark Matter from the Center of the Earth with 8 Years of IceCube Data” – Giovanni Renzi, [arXiv:2107.11244](https://arxiv.org/abs/2107.11244)
- “Indirect Searches for Dark Matter in the Galactic Center with IceCube” – Nadège Iovine, [arXiv:2107.11224](https://arxiv.org/abs/2107.11224)
- “Constraining Non-Standard Dark Matter-Nucleon Interactions with IceCube” – Lily Peters, [arXiv:2108.05203](https://arxiv.org/abs/2108.05203)
- “Dark Matter Neutrino Scattering in the Galactic Center with IceCube” – Adam McMullen, [arXiv:2107.11491](https://arxiv.org/abs/2107.11491)
- “Searching for Dark Matter from the Sun with the IceCube Detector” – Jeffrey Lazar, doi: [10.22323/1.395.0020](https://doi.org/10.22323/1.395.0020)

Contributions here:

- “Neutrino lines in DM searches” – Juan A.Aguilar
- “Dark Matter Decay and Annihilation to Neutrinos” – Diyaselis Delgado Lopez
- “Decaying Dark Matter at IceCube and its Signature in High-Energy Gamma-Ray Experiments” – Barbara Skrzpek

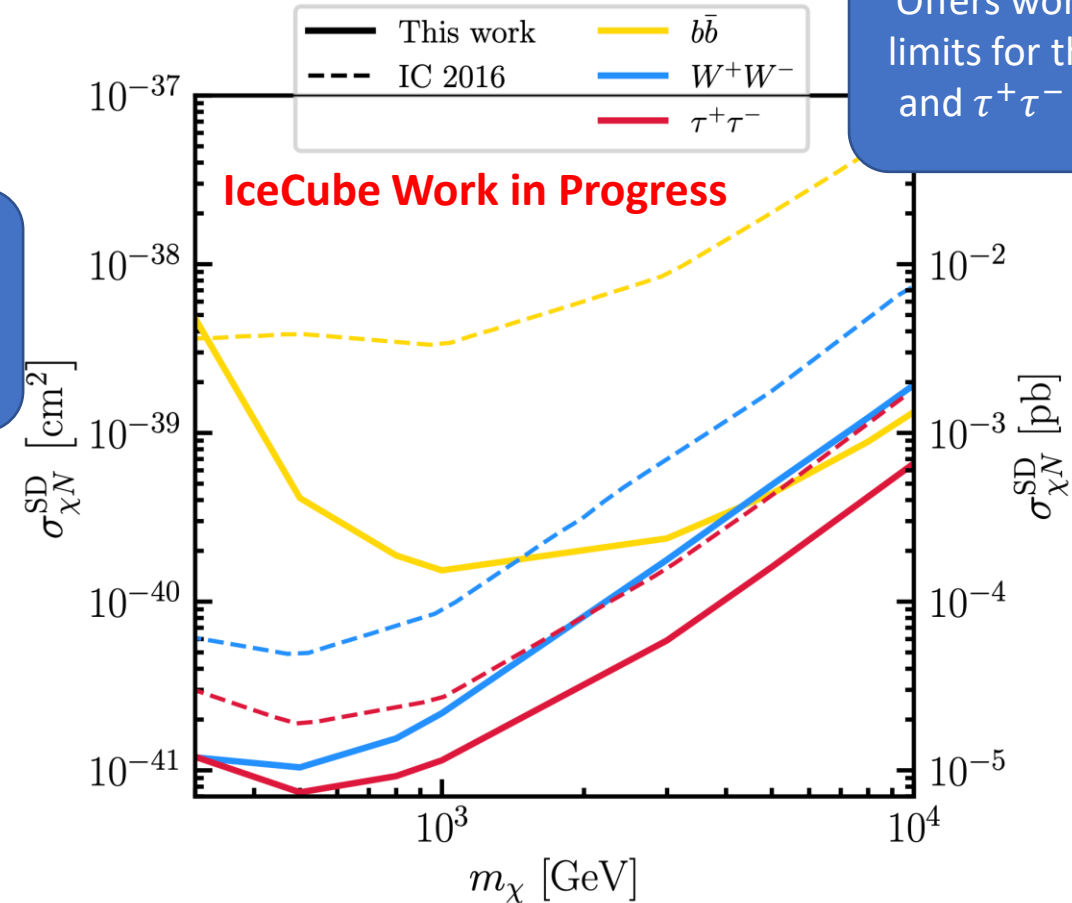
Current Analyses II

“Searching for Dark Matter from the Sun with the IceCube Detector” – Jeffrey Lazar, doi: [10.22323/1.395.0020](https://doi.org/10.22323/1.395.0020)



DM can be captured in the sun after scattering off nuclei

Tested different signal generators



Offers world leading limits for the W^+W^- and $\tau^+\tau^-$ channels!

Current Analyses III

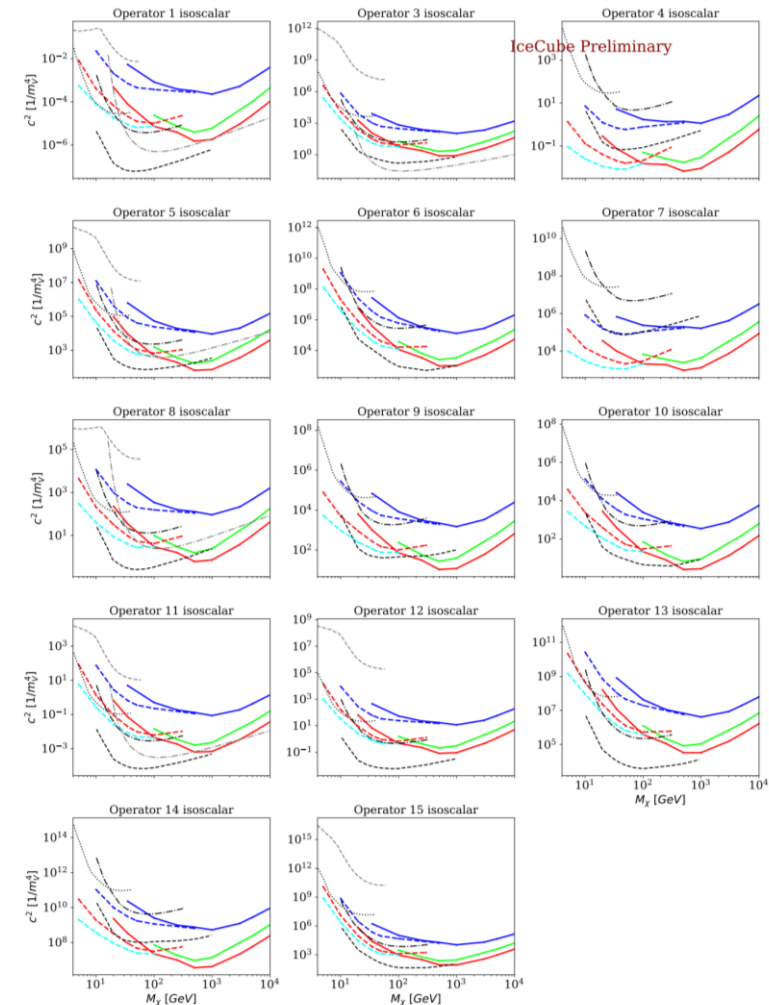
“Constraining Non-Standard Dark Matter-Nucleon Interactions with IceCube” – Lily Peters,
[arXiv:2108.05203](https://arxiv.org/abs/2108.05203)

$$\begin{aligned}
 O_1 &= \mathbb{1}_{\chi N} & O_{11} &= i\hat{\mathbf{S}}_{\chi} \cdot \frac{\hat{\mathbf{q}}}{m_N} \mathbb{1}_N \\
 O_3 &= i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^{\perp} \right) \mathbb{1}_{\chi} & O_{12} &= \hat{\mathbf{S}}_{\chi} \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^{\perp} \right) \\
 O_4 &= \hat{\mathbf{S}}_{\chi} \cdot \hat{\mathbf{S}}_N & O_{13} &= i \left(\hat{\mathbf{S}}_{\chi} \cdot \hat{\mathbf{v}}^{\perp} \right) \left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N} \right) \\
 O_5 &= i\hat{\mathbf{S}}_{\chi} \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^{\perp} \right) \mathbb{1}_N & O_{14} &= i \left(\hat{\mathbf{S}}_{\chi} \cdot \frac{\hat{\mathbf{q}}}{m_N} \right) \left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^{\perp} \right) \\
 O_6 &= \left(\hat{\mathbf{S}}_{\chi} \cdot \frac{\hat{\mathbf{q}}}{m_N} \right) \left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N} \right) & O_{15} &= - \left(\hat{\mathbf{S}}_{\chi} \cdot \frac{\hat{\mathbf{q}}}{m_N} \right) \left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^{\perp} \right) \cdot \frac{\hat{\mathbf{q}}}{m_N} \right] \\
 O_7 &= \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^{\perp} \mathbb{1}_{\chi} & O_{17} &= i \frac{\hat{\mathbf{q}}}{m_N} \cdot \mathbf{S} \cdot \hat{\mathbf{v}}^{\perp} \mathbb{1}_N \\
 O_8 &= \hat{\mathbf{S}}_{\chi} \cdot \hat{\mathbf{v}}^{\perp} \mathbb{1}_N & O_{18} &= i \frac{\hat{\mathbf{q}}}{m_N} \cdot \mathbf{S} \cdot \hat{\mathbf{S}}_N \\
 O_9 &= i\hat{\mathbf{S}}_{\chi} \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N} \right) & O_{19} &= \frac{\hat{\mathbf{q}}}{m_N} \cdot \mathbf{S} \cdot \frac{\hat{\mathbf{q}}}{m_N} \\
 O_{10} &= i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N} \mathbb{1}_{\chi} & O_{20} &= \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N} \right) \cdot \mathbf{S} \cdot \frac{\hat{\mathbf{q}}}{m_N}
 \end{aligned}$$

Assume effective non-relativistic DM-nucleon interactions

$$\frac{dN}{dt} = C_{cap} - C_{ann} N^2$$

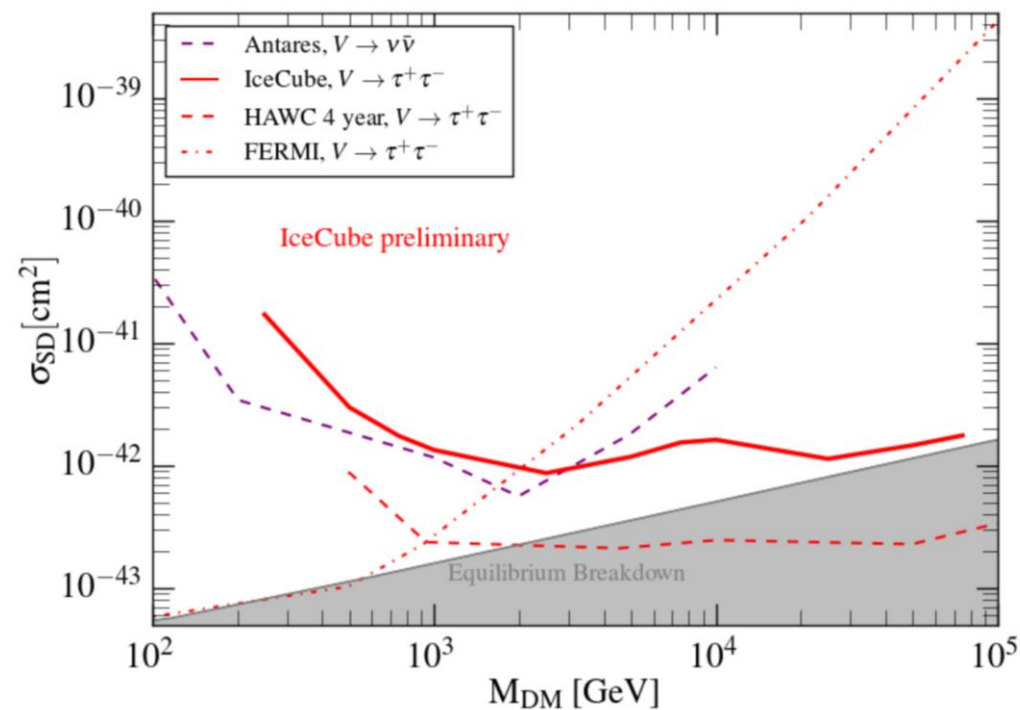
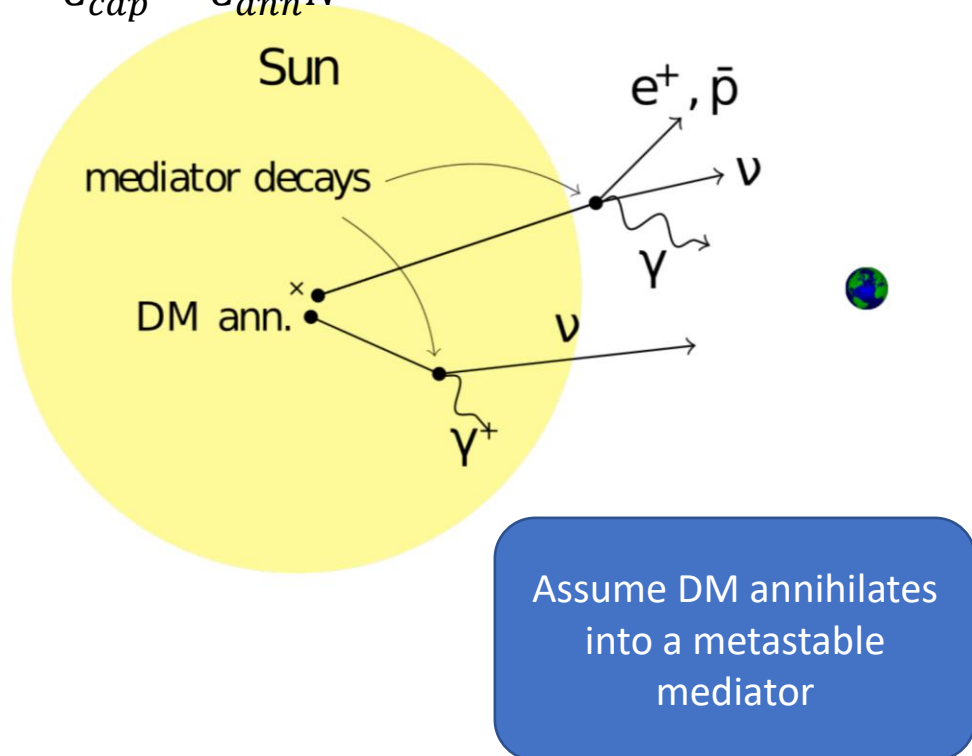
Captured DM then decays to observable neutrinos



Current Analyses IV

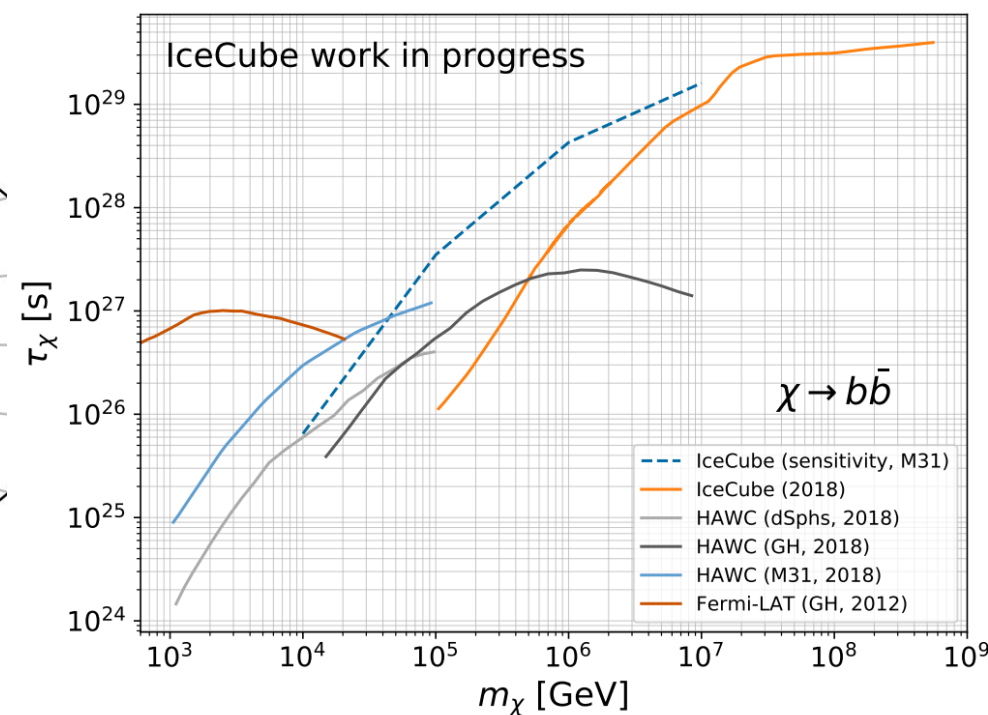
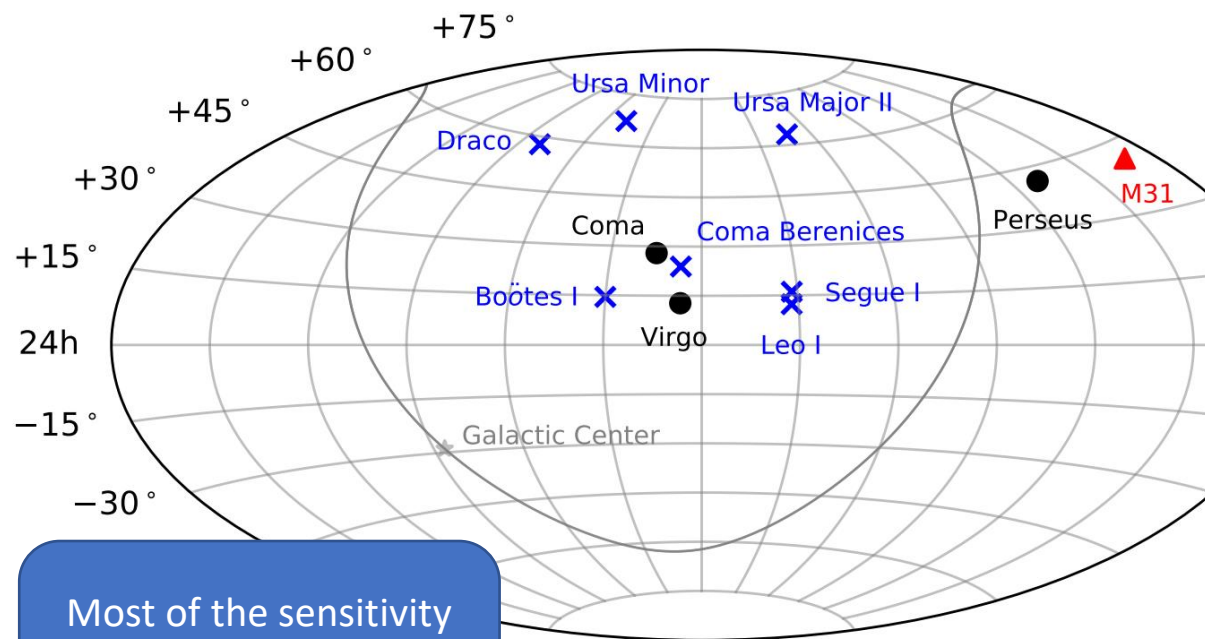
“Search for Secluded Dark Matter with 6 years of IceCube Data” – Christoph Toennis, [arXiv:2107.10778](https://arxiv.org/abs/2107.10778)

$$\frac{dN}{dt} = C_{cap} - C_{ann} N^2$$



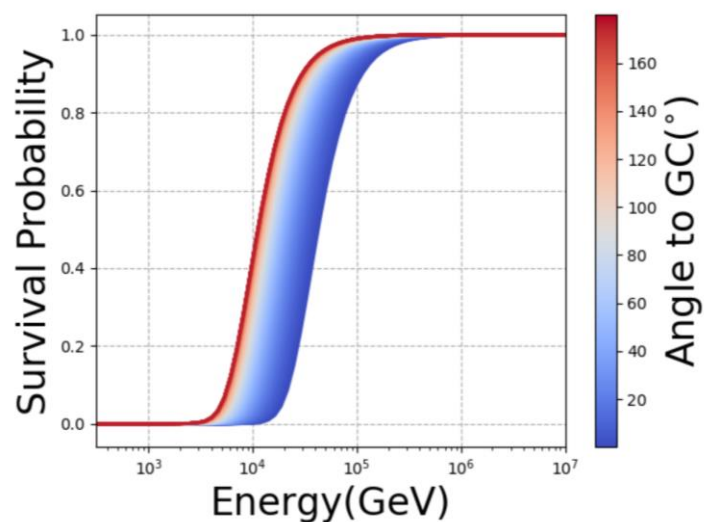
Current Analyses V

“A search for Neutrinos from Decaying Dark Matter in Galaxy Clusters and Galaxies with IceCube” – Minjin Jeong, [arXiv:2107.11527](https://arxiv.org/abs/2107.11527)

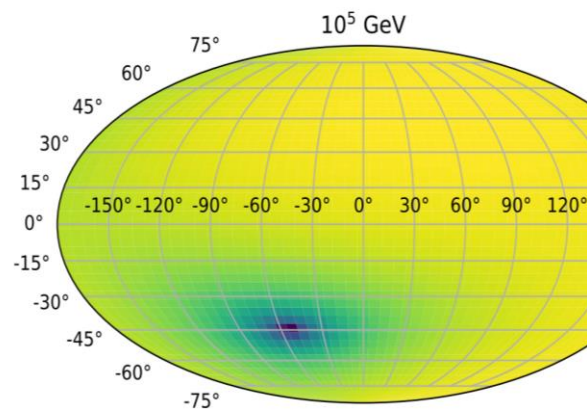


Current Analyses VI

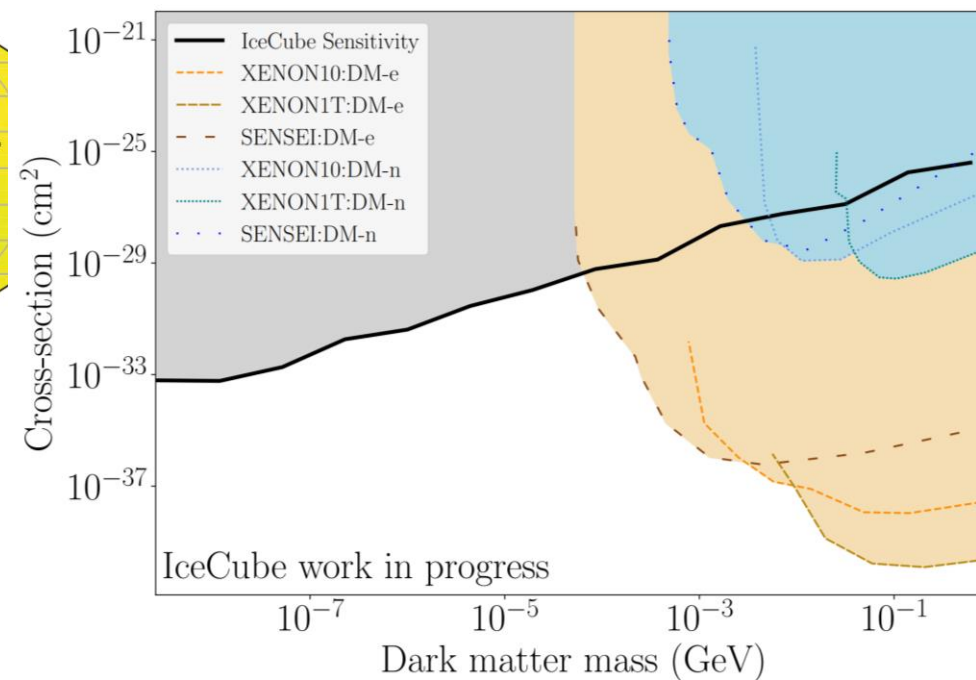
“Dark Matter Neutrino Scattering in the Galactic Center with IceCube” – Adam McMullen,
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Assume neutrinos and
DM couple
→ elastic scattering

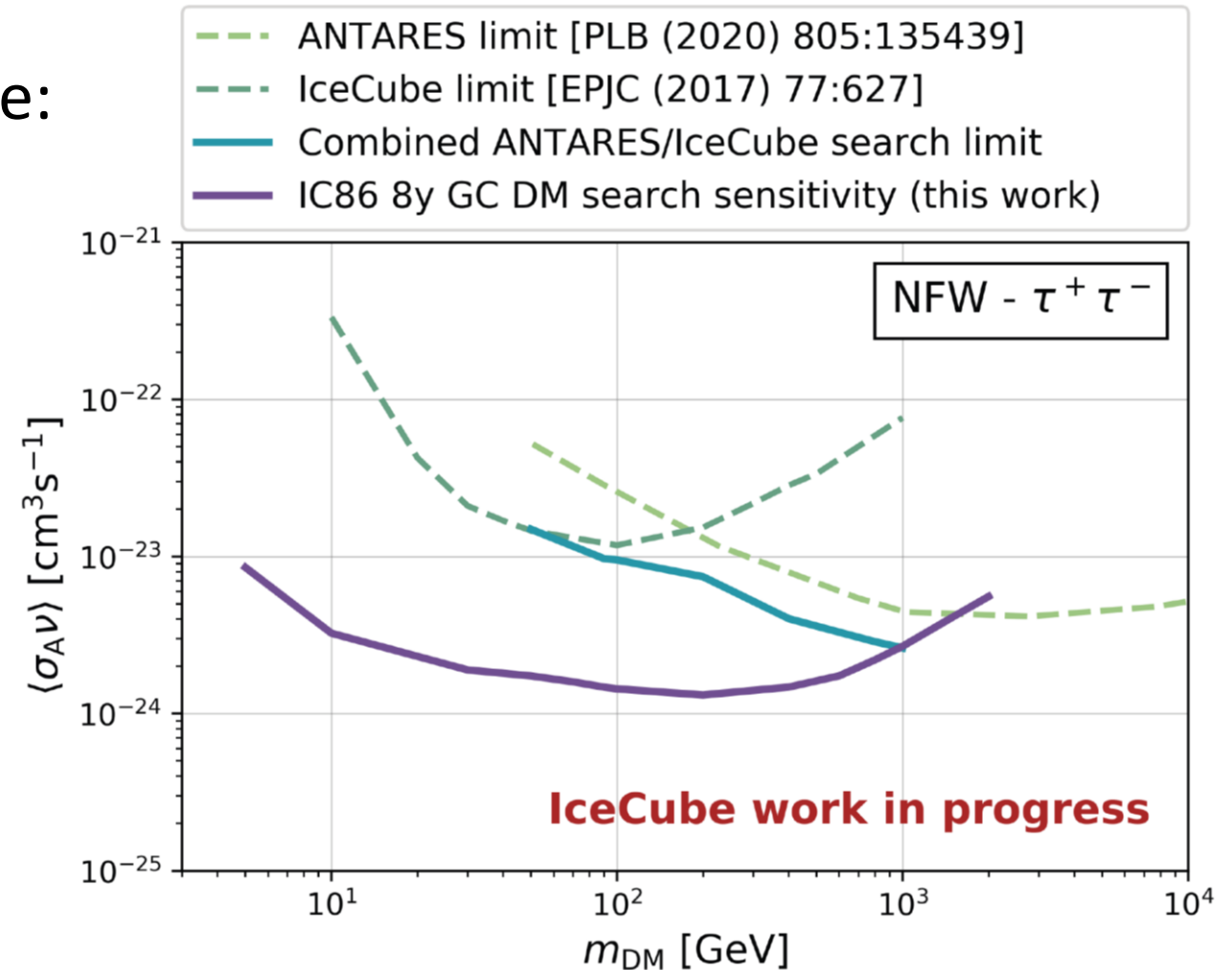
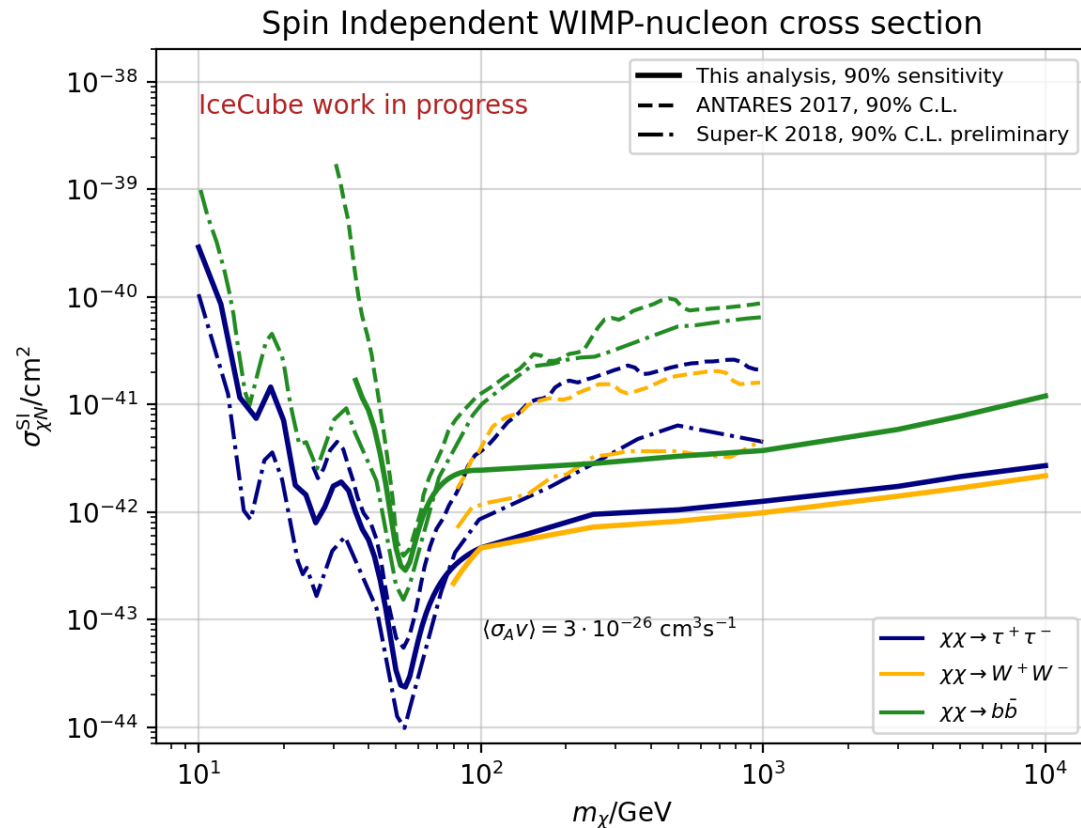


High energy neutrino
flux is attenuated and
observed as a deficit



Current Analyses VI

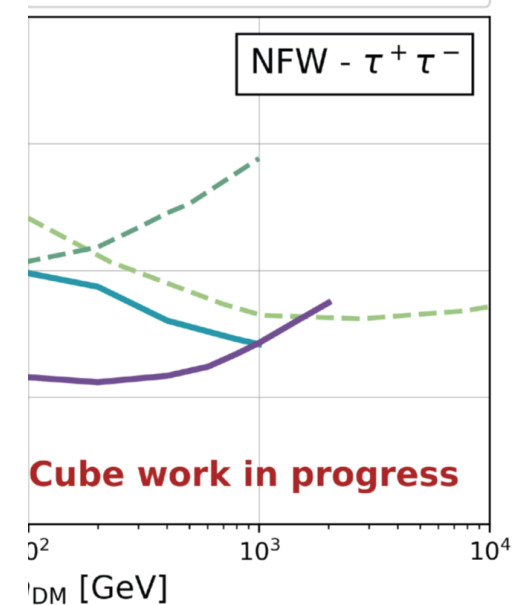
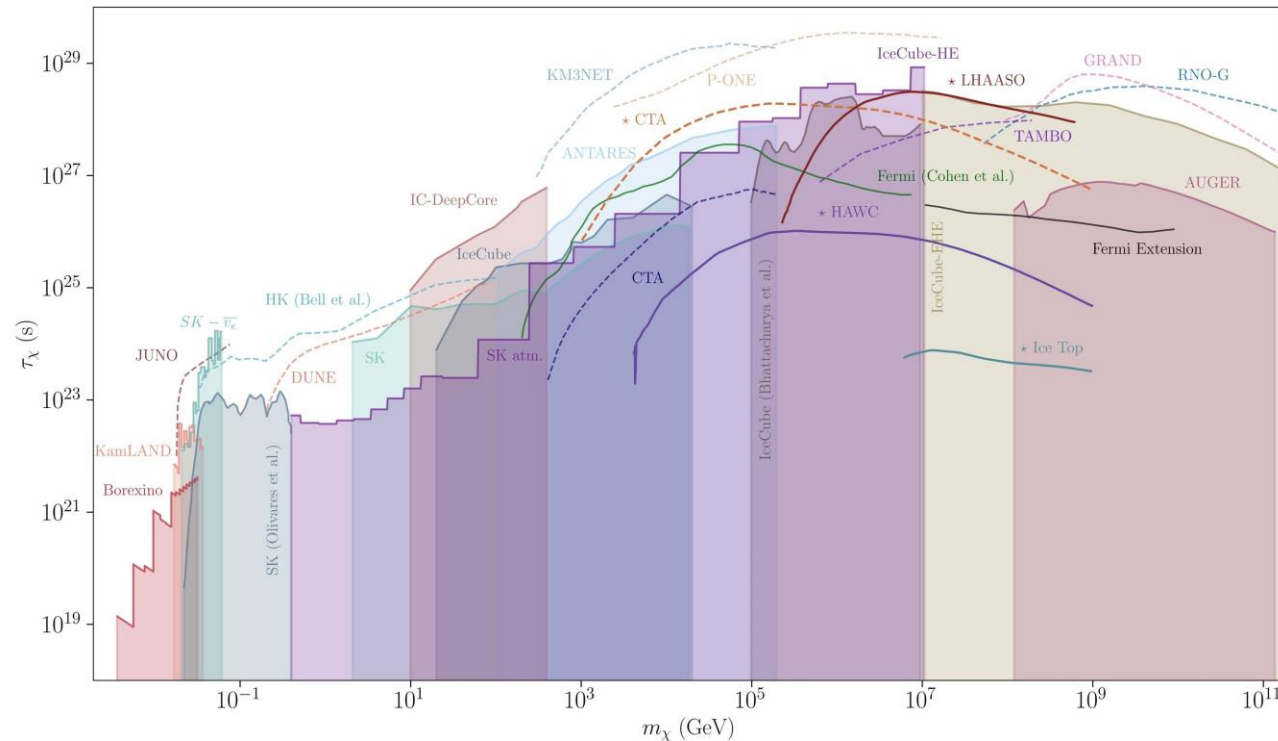
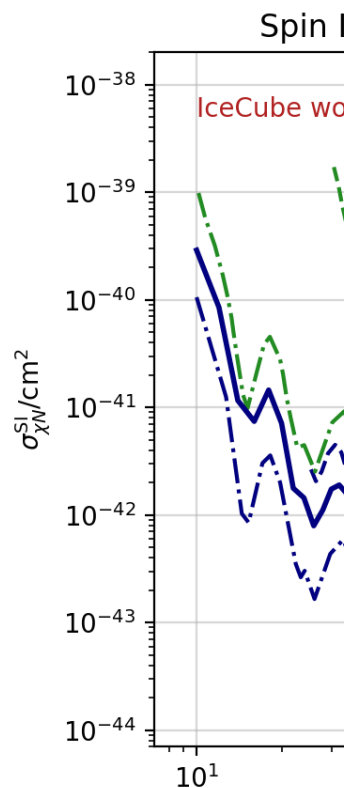
Example plots of what you'll see here:



Current Analyses VII

Example plots which you'll see here:

- ANTARES limit [PLB (2020) 805:135439]
- - - IceCube limit [EPJC (2017) 77:627]
- Combined ANTARES/IceCube search limit
- IC86 8v GC DM search sensitivity (this work)



Conclusions

IceCube offers a rich and diverse palette of Dark Matter and BSM studies

- DM annihilation and decay has very little background in IceCube
- Neutrino telescopes offer complimentary studies to Gamma-Ray, Cosmic Ray, and collider experiments
- Results will only improve with exposure time as well as the IceCube upgrade and Gen-2!
- Many exciting DM searches in the pipeline!

Bibliography

1. *Combined Search for neutrinos from Dark Matter Self-Annihilation in the Galactic Centre with ANTARES and IceCube* [Phys. Rev. D 102, 082002 \(2020\)](#)
2. *Velocity independent constraints on spin-dependent DM-nucleon interactions from IceCube and PICO.* [Eur. Phys. J. C 80 \(2020\) 819](#)
3. *Search for neutrinos from decaying dark matter with IceCube* [Eur.Phys.J. C78 \(2018\) no.10, 831](#)
4. *Search for Neutrinos from Dark Matter Self-Annihilations in the center of the Milky Way with 3 years of IceCube/DeepCore* [Eur. Phys. J. C \(2017\) 77: 627](#)
5. *First search for dark matter annihilations in the Earth with the IceCube Detector* [Eur. Phys. J. C \(2017\) 77: 82](#)
6. *Search for Secluded Dark Matter with 6 years of IceCube Data* – [arXiv:2107.10778](#)
7. *A search for Neutrinos from Decaying Dark Matter in Galaxy Clusters and Galaxies with IceCube* – [arXiv:2107.11527](#)
8. *Search for Dark Matter from the Center of the Earth with 8 Years of IceCube Data* – [arXiv:2107.11244](#)
9. *Indirect Searches for Dark Matter in the Galactic Center with IceCube* – [arXiv:2107.11224](#)
10. *Constraining Non-Standard Dark Matter-Nucleon Interactions with IceCube* – [arXiv:2108.05203](#)
11. *Dark Matter Neutrino Scattering in the Galactic Center with IceCube* – [arXiv:2107.11491](#)
12. *Searching for Dark Matter from the Sun with the IceCube Detector* – **doi:** [10.22323/1.395.0020](#)