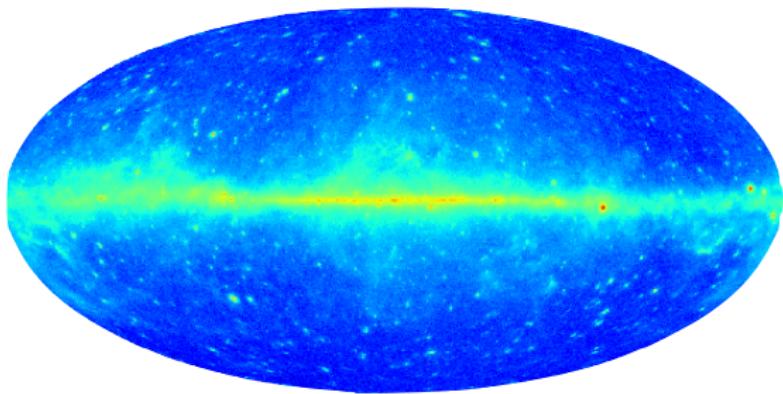


Gamma-ray Constraints on Decaying Dark Matter and Implications for IceCube

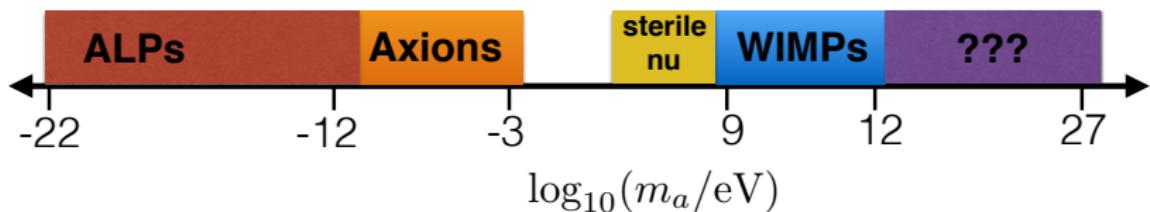


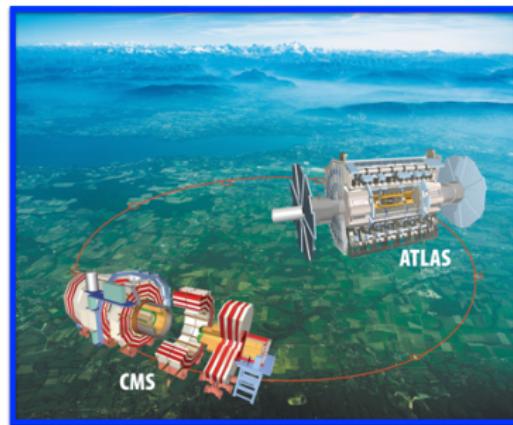
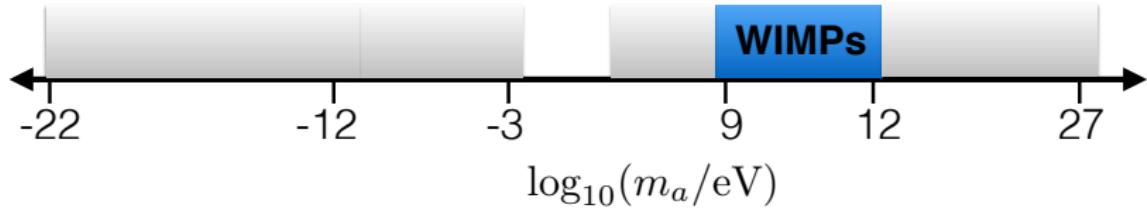
Ben Safdi

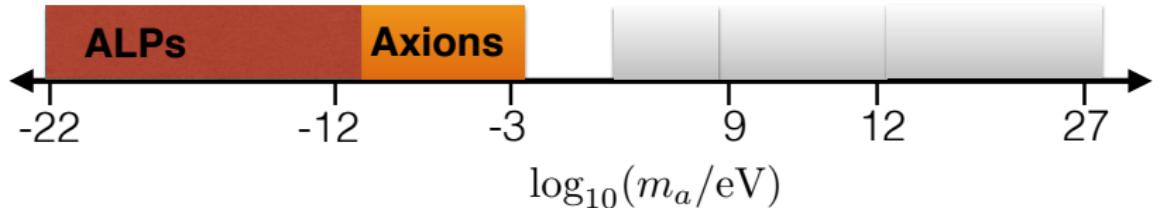
Massachusetts Institute of Technology

T. Cohen, K. Murase, N. Rodd, **B.S.**, Y. Soreq [1612.05638]

About 50 orders of magnitude in particle DM mass!







From Theory...

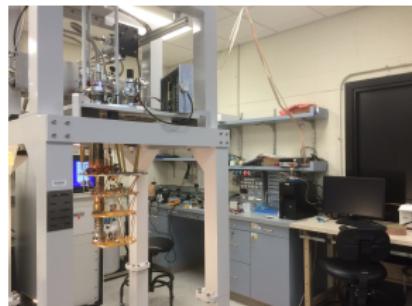
- ▶ **Phys. Rev. Lett.**, 117, 141801
(2016): Yoni Kahn, B.S., Jesse Thaler



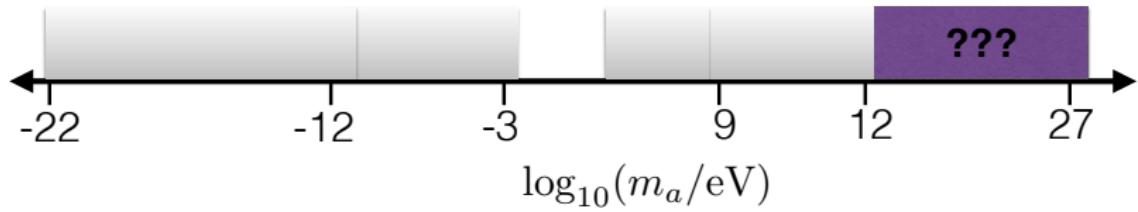
- ▶ Ultimate goal: Detect axion dark matter from GUT-scale solution to strong-CP problem

...to Experiment

- ▶ ABRACADABRA-10 cm



- ▶ The team: J. Conrad, J. Formaggio, S. Heine, J. Minervini, J. Ouellet, K. Perez, A. Radovinsky, D. Winklehner, L. Winslow, ...
- ▶ Funded by the NSF, data soon!



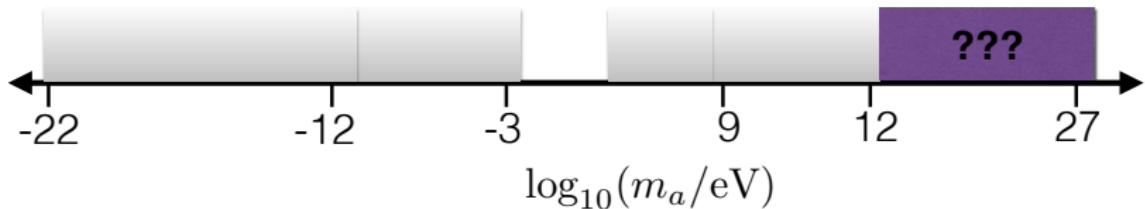
Fermi



IceCube



Heavy Dark-matter Example: Glueball

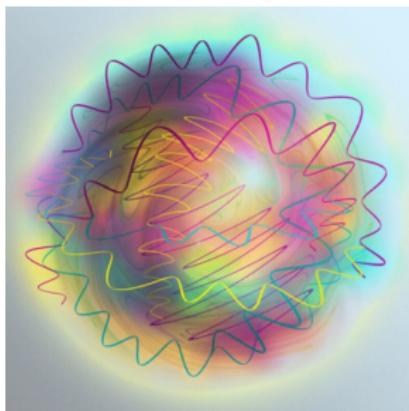


- ▶ Hidden $SU(N')$ coupled to SM: $\Lambda \sim 10^{16} - 10^{18}$ GeV
- ▶ Ex: $SU(3)$ and pure glue, $\Lambda_{\text{QCD}'} \sim 100$ TeV

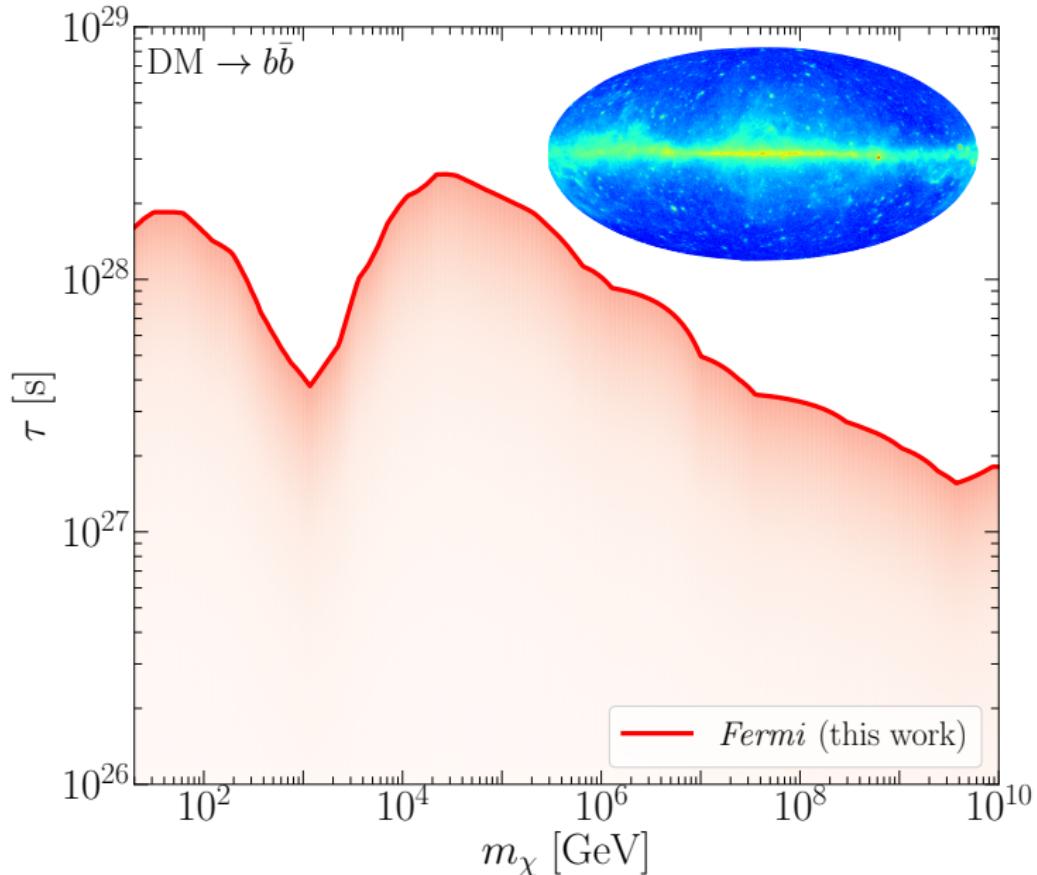
$$\begin{aligned}\mathcal{L} &\supset \frac{\lambda'}{\Lambda^2} G'_{\mu\nu} G'^{\mu\nu} |H|^2 \\ &\rightarrow \lambda' \frac{\Lambda_{\text{QCD}'}^3}{\Lambda^2} \phi_{G'} |H|^2\end{aligned}$$

- ▶ Slow decay to SM:

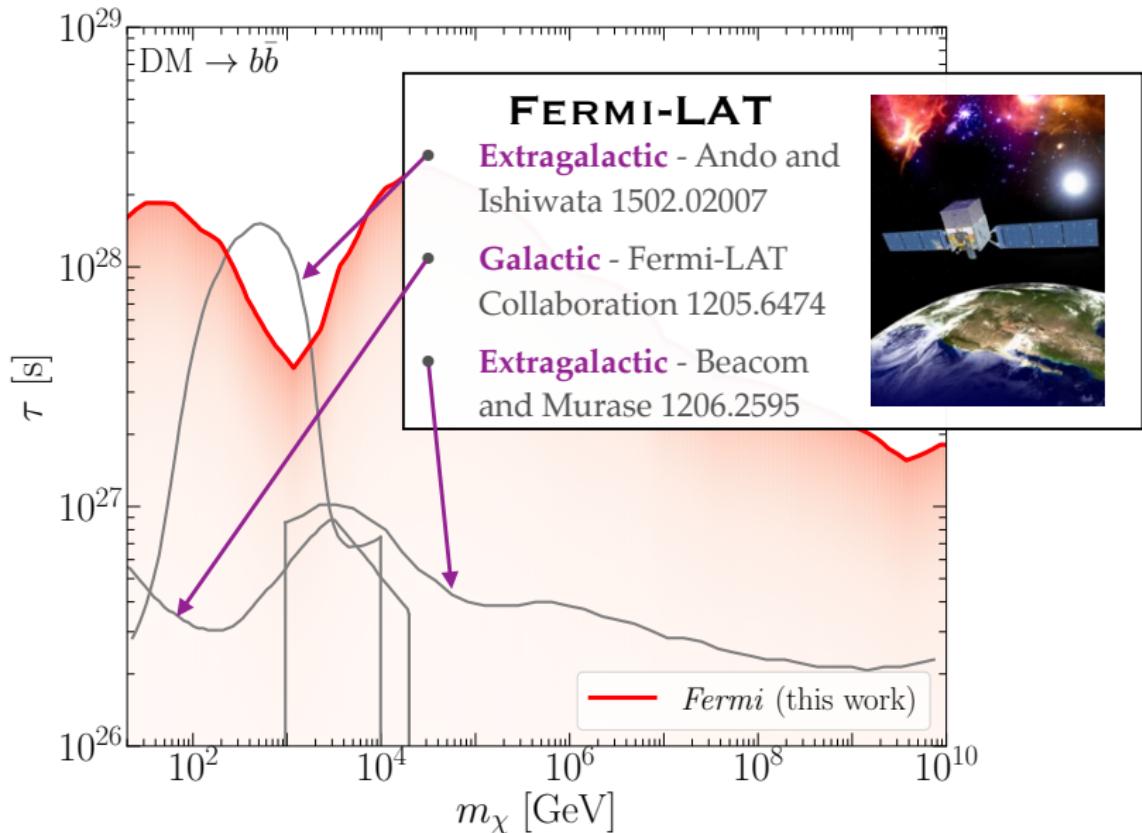
$$\tau \approx 5 \times 10^{27} \text{ s} \left(\frac{3}{N'} \frac{1}{4\pi\lambda'} \right)^2 \left(\frac{\Lambda}{m_{\text{pl}}} \right)^4 \left(\frac{100 \text{ TeV}}{\Lambda_{\text{QCD}'}} \right)^5$$



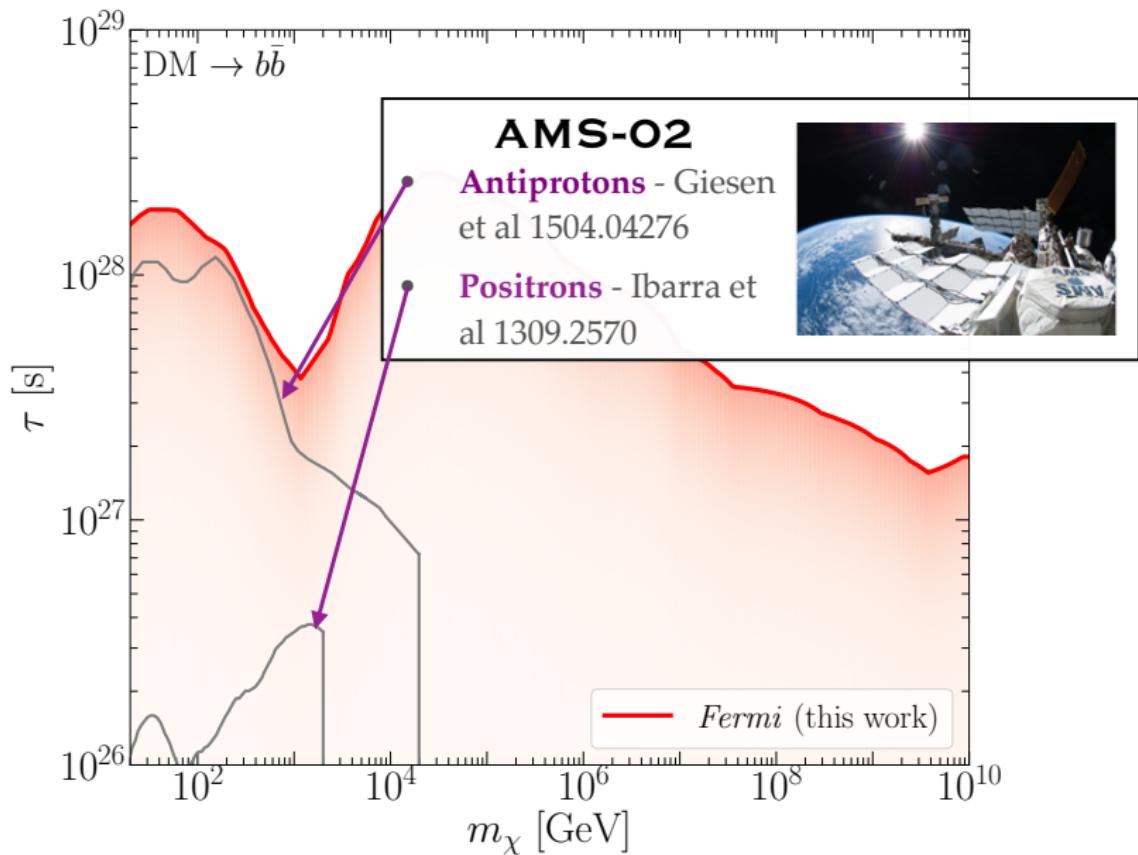
Looking ahead: our limit on the DM lifetime



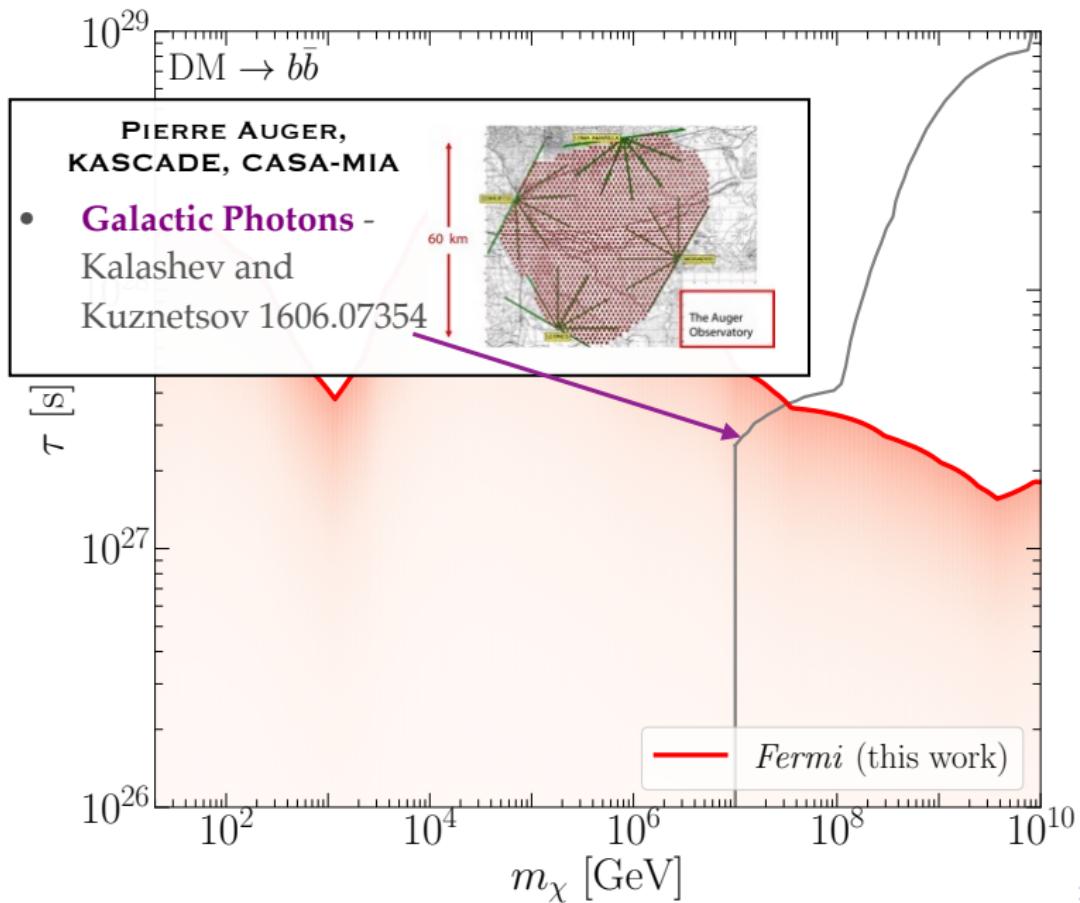
Comparison to previous limits



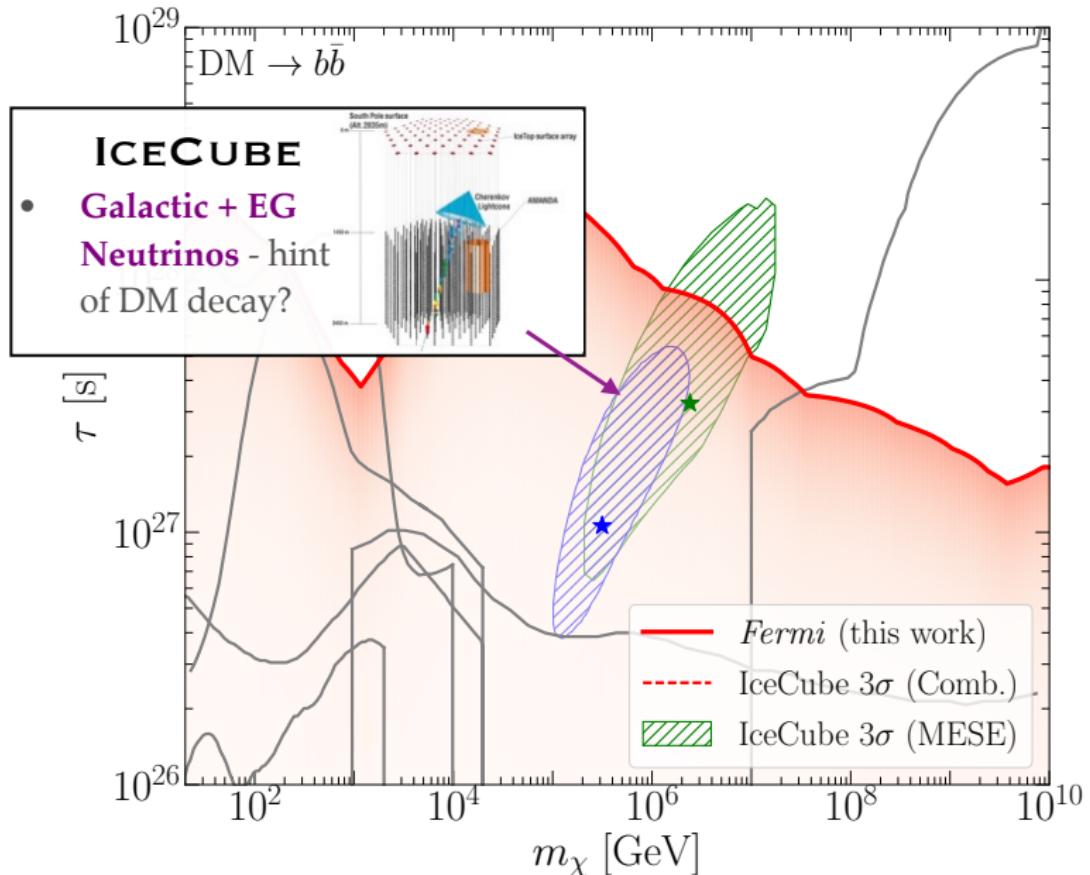
Comparison to previous limits



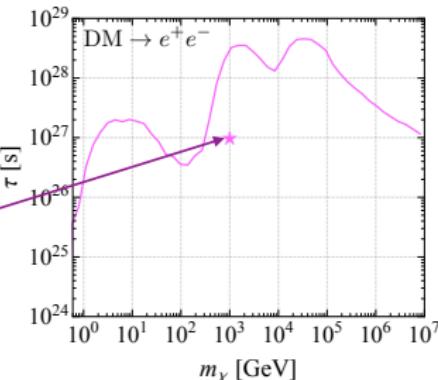
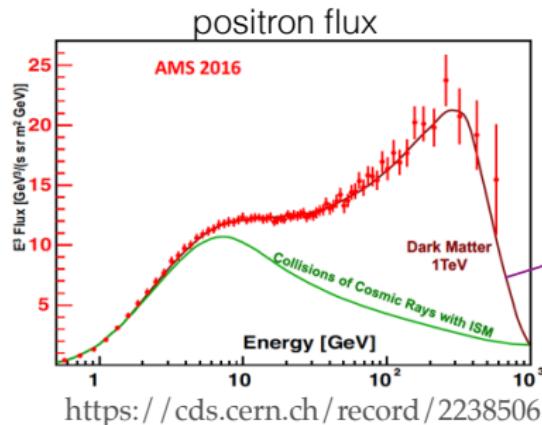
Comparison to previous limits



Has IceCube detected decaying DM?



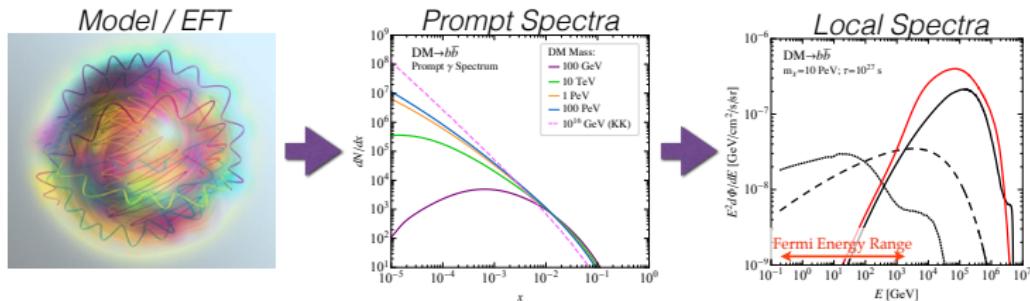
AMS-02 positron excess likely not from decaying DM



- ▶ **AMS-02 positron** flux appears to have excess and break
- ▶ Excess could arise from **pulsars, decaying DM**, ...
- ▶ Decaying DM appears in strong tension with *Fermi* data

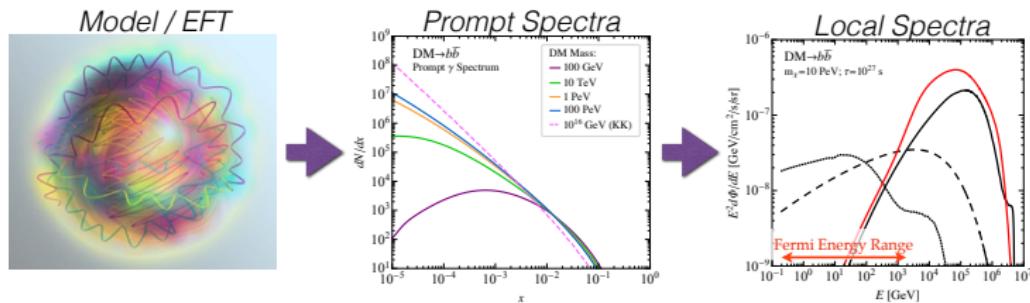
Decaying DM search proceeds in two steps:

- ▶ 1. Given a decaying DM model, how do we predict gamma-ray flux at Earth?

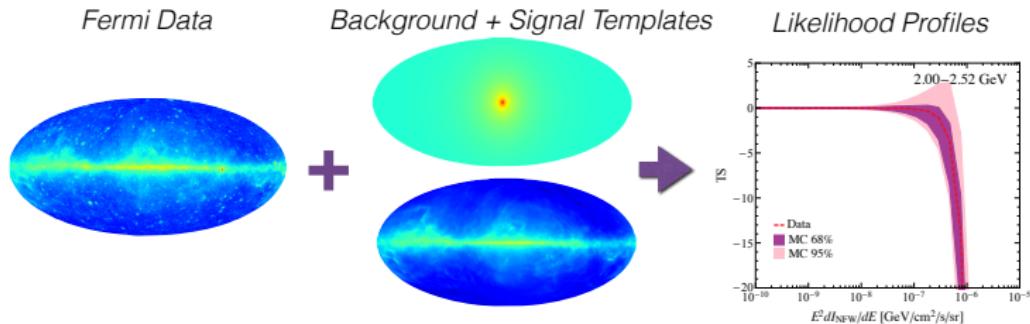


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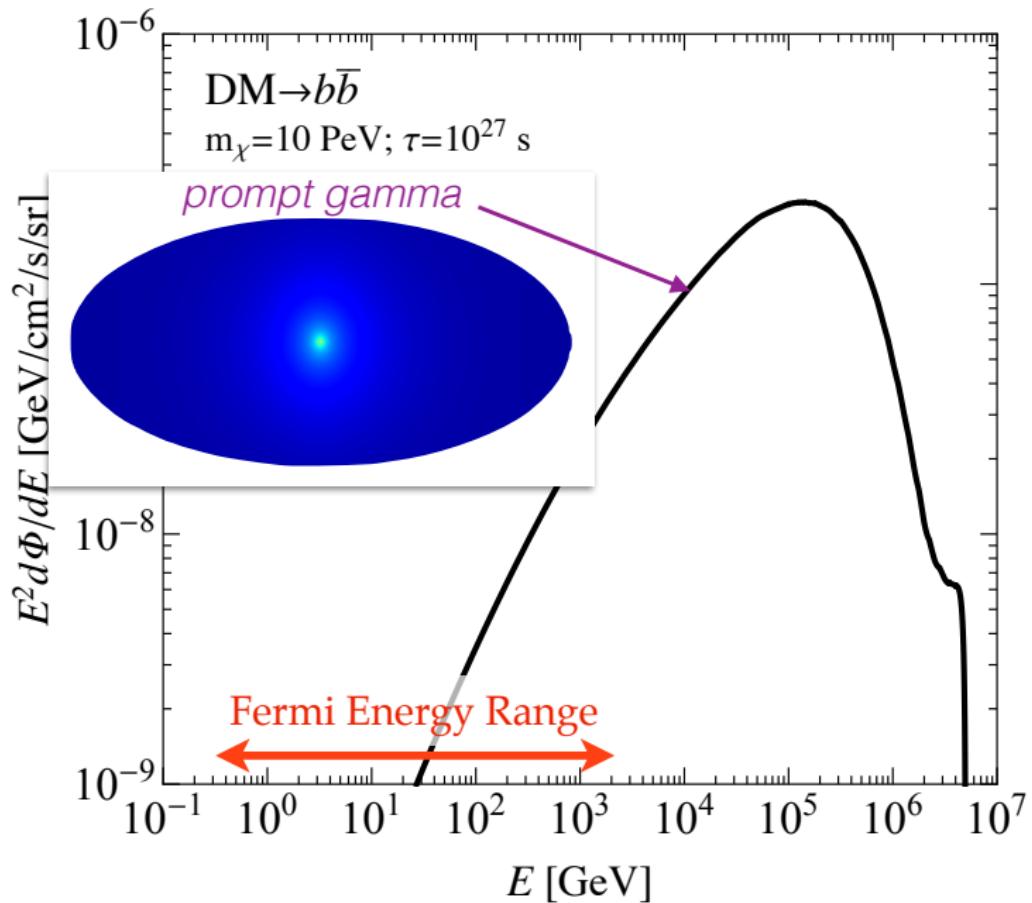
- ▶ 1. Given a decaying DM model, how do we predict gamma-ray flux at Earth?



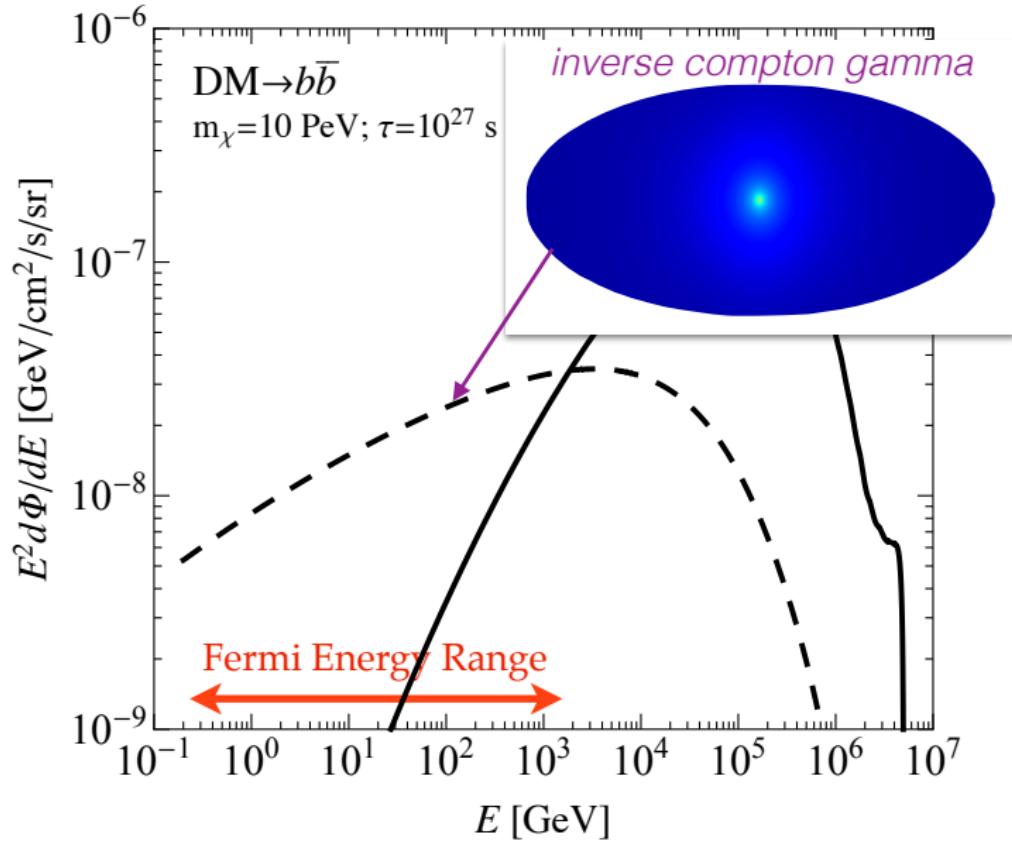
- ▶ 2. How do we search for that flux in *Fermi* data?



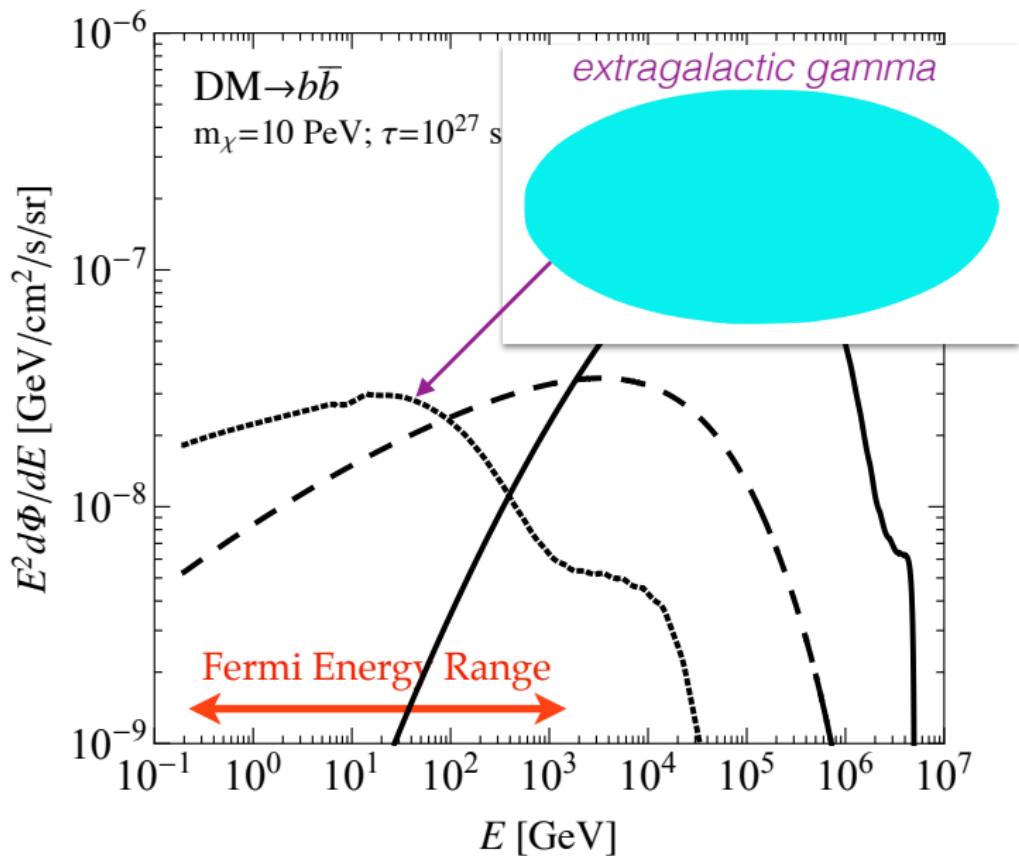
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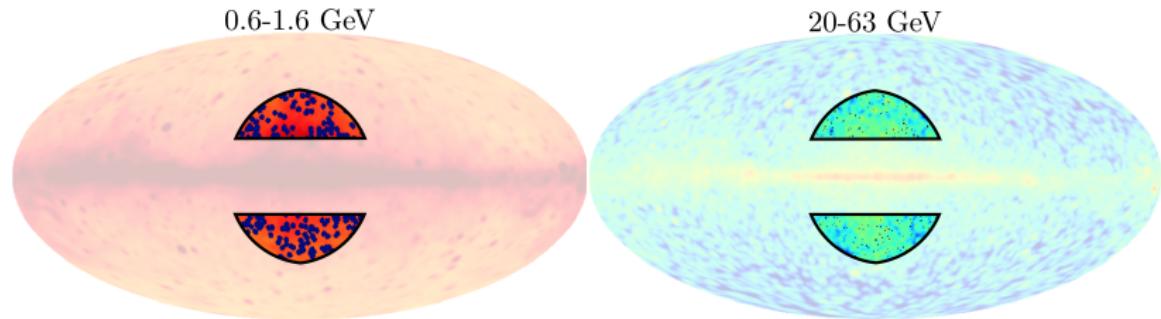
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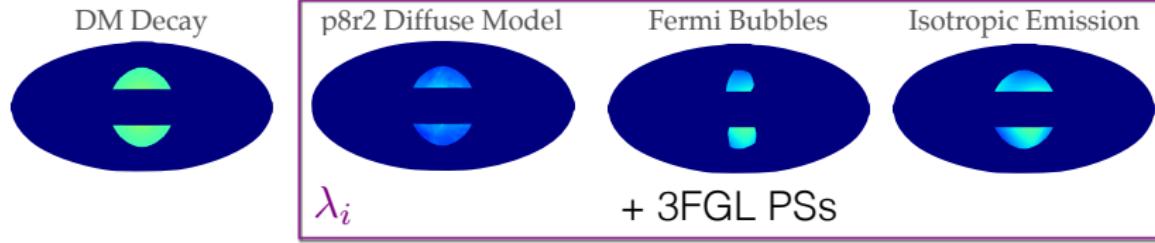
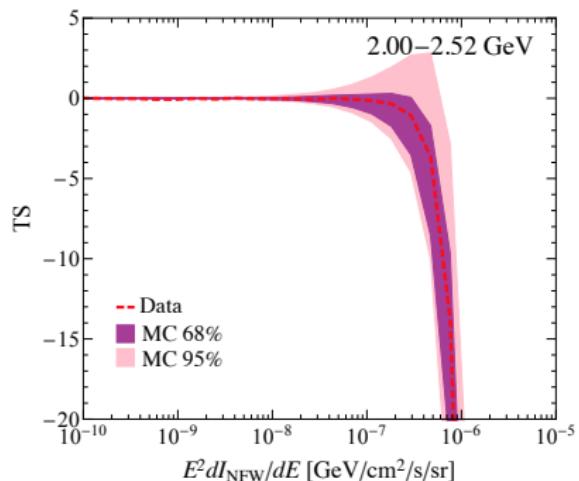
Step 2: *Fermi* data selection



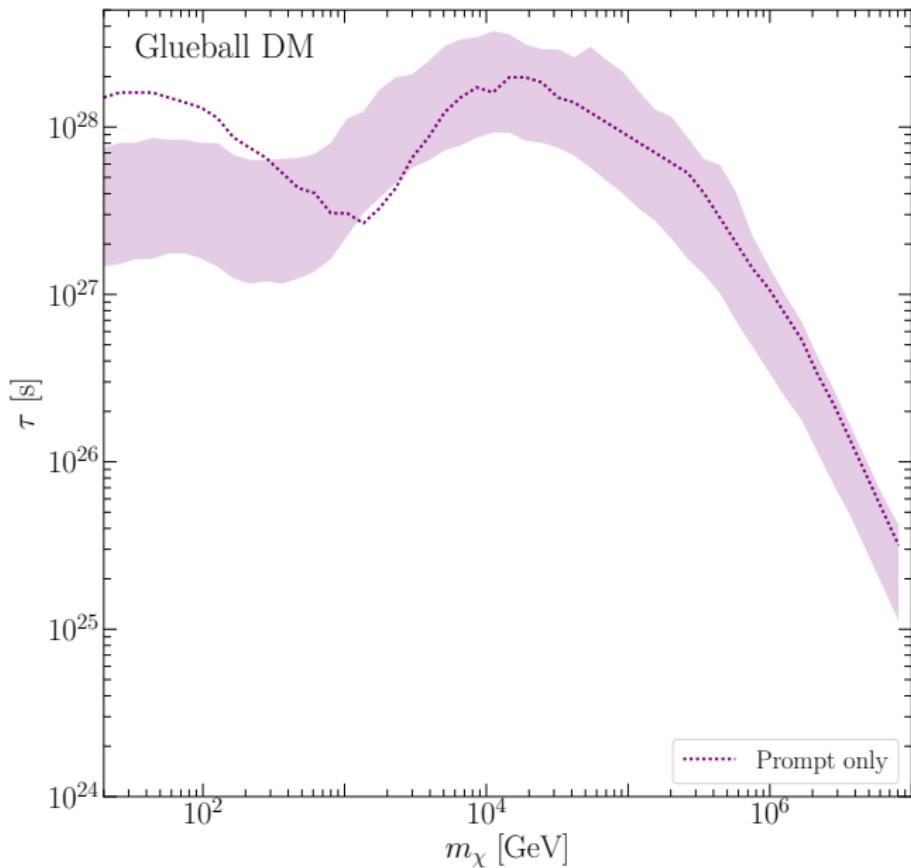
- ▶ 40 log-spaced bins between **200 MeV - 2 TeV**
- ▶ **423 weeks** Pass 8 UltracleanVeto BestPSF events
- ▶ mask: top 300 3FGL PSs, $|b| \leq 20^\circ$, $r > 45^\circ$

Step 2: Pre-compute likelihood profiles

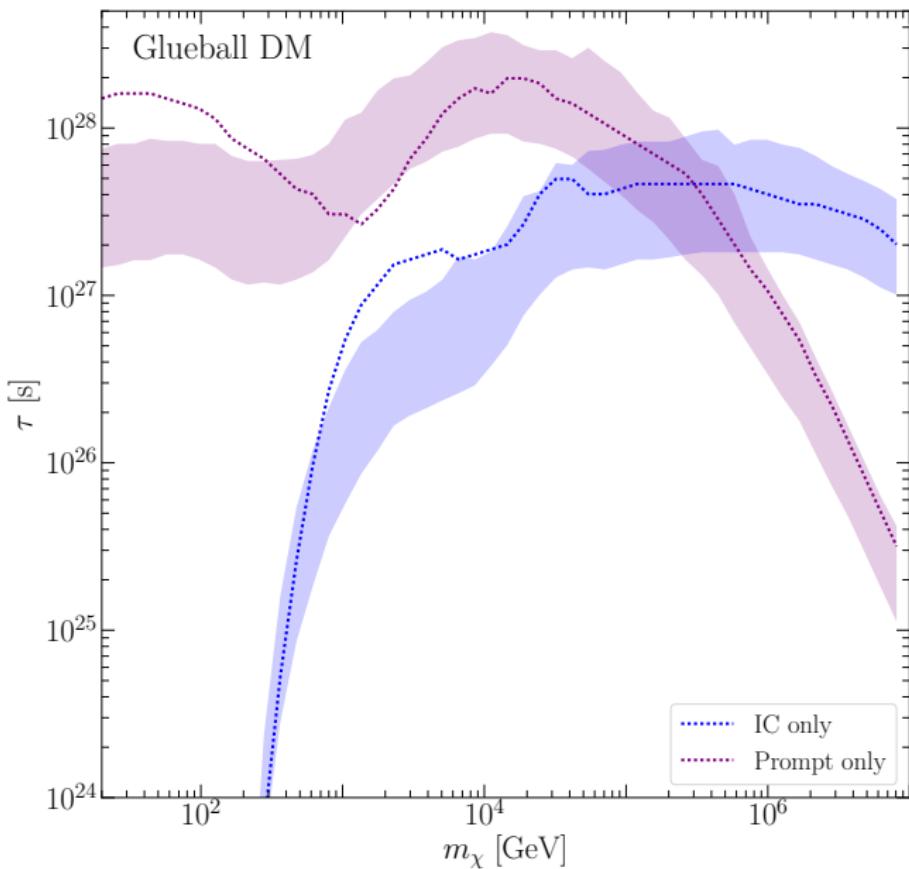
- ▶ 2-d intensity $\{I_{\text{EG-DM}}, I_{\text{Gal-DM}}\}$ profiles in 40 energy bins



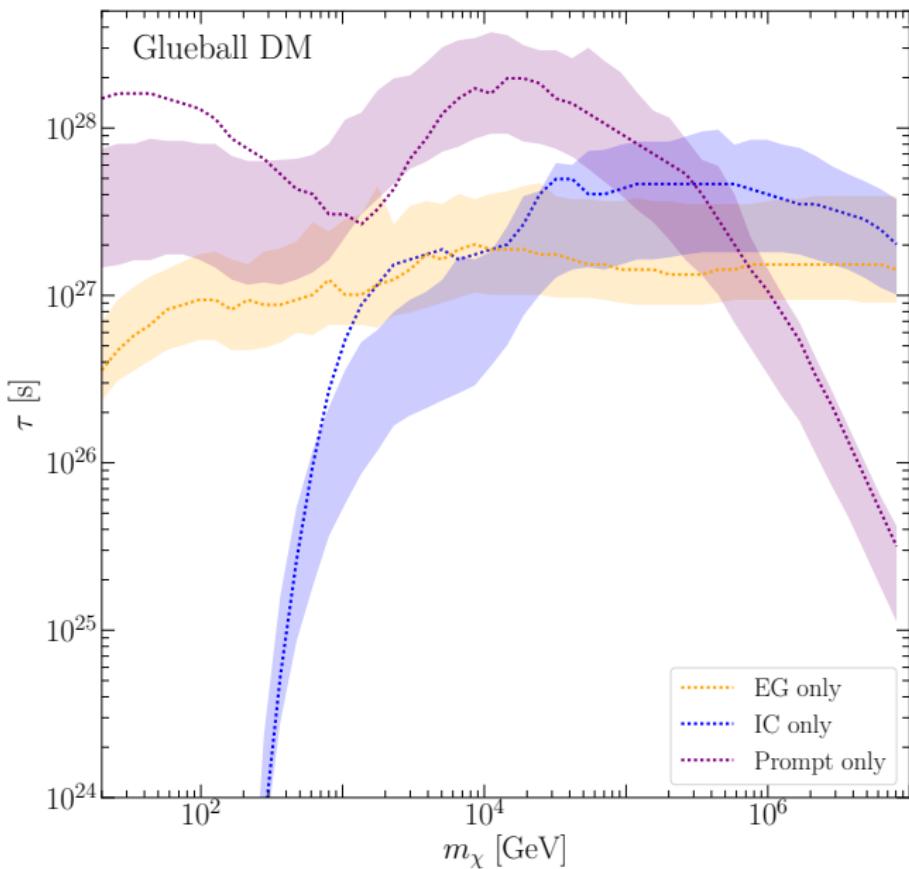
Limit: prompt only



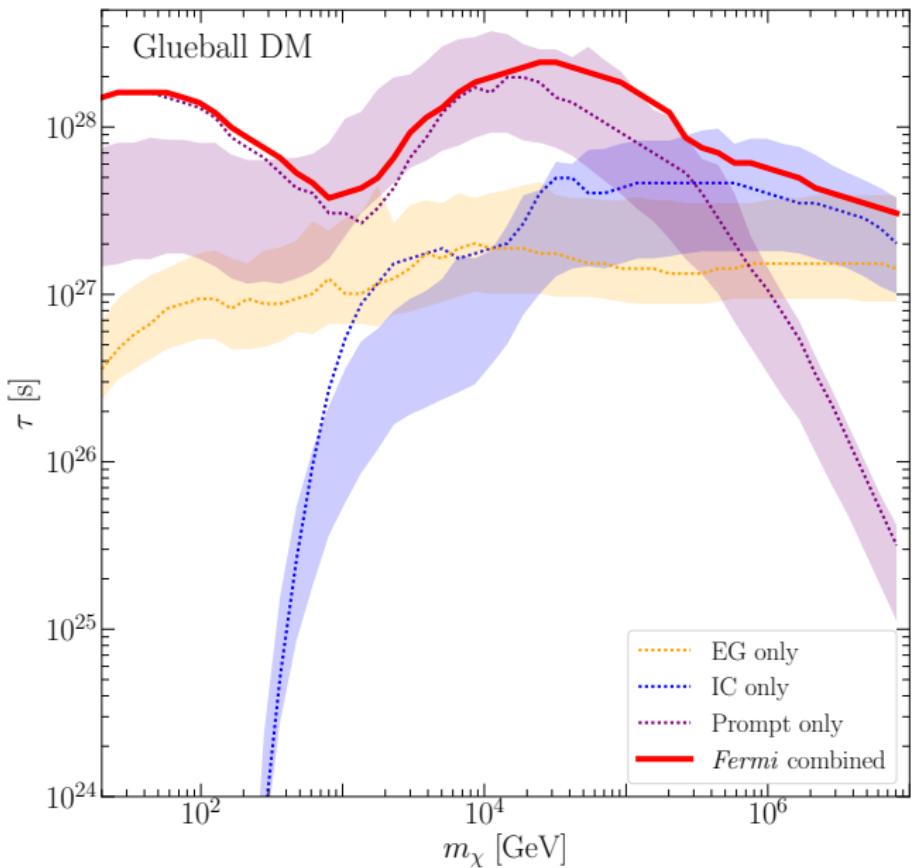
Limit: inverse compton only



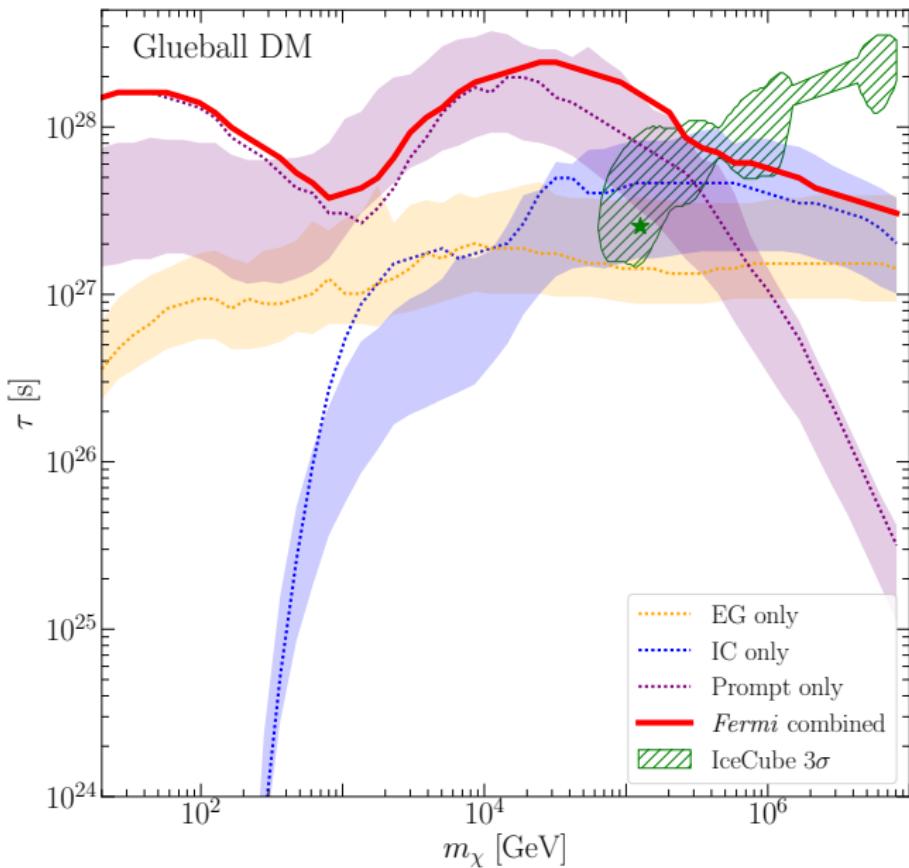
Limit: extragalactic only



Limit: combined



Limit: comparison to IceCube region



Data and code available

- ▶ <http://hdl.handle.net/1721.1/105550>: 2-d likelihood profiles in all energy bins + limits on final states

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- ▶ <https://github.com/bsafdi/NPTFit>: S. M.-Sharma, N. Rodd, **B.S.**, 1612.03173. Open-source code for performing template analysis

The screenshot shows the NPTFit Documentation page on the Read the Docs platform. The top navigation bar includes links for 'Docs' (highlighted), 'NPTFit Documentation', and 'Edit on GitHub'. The main content area is titled 'NPTFit Documentation' and describes the package as a specialized Python/Cython package for Non-Poissonian Template Fitting (NPTF). It highlights features like fast evaluation of likelihoods, an easy-to-use interface, and the ability to include arbitrary numbers of point source templates. Below the main text is a bulleted list of features. Further down, it mentions the latest version (v. latest) and provides a link to the GitHub repository. The sidebar on the left lists various examples and tutorials such as 'Initializing a scan', 'Loading data and exposure', 'Adding templates', etc. At the bottom, there's a 'Read the Docs' footer with a 'v. latest' dropdown and a terminal-like input field containing the command '\$ python setup.py install'.

NPTFit Documentation

NPTFit is a specialized Python/Cython package that implements Non-Poissonian Template Fitting (NPTF), originally developed for characterizing populations of unresolved point sources. The main features of the package are

- Fast evaluation of likelihoods for NPTF analyses
- Easy-to-use interface for performing non-Poissonian (as well as standard Poissonian) template fits using MultiNest or other inference tools
- Ability to include an arbitrary number of point source templates, with an arbitrary number of degrees of freedom in the modeled flux distribution
- Modules for analyzing and plotting the results of an NPTF

The most up-to-date version of the code can be found at <https://github.com/bsafdi/NPTFit>.

Installation

Out of the box, NPTFit relies on [MultiNest](#) for Bayesian inference, which must be installed and linked prior to use.

NPTFit supports both Python 2 and 3, specifically 2.7 and 3.5. It may work with earlier 3.* versions, although this has not been tested.

Make sure Cython is installed (e.g. `pip install Cython`). NPTFit along with its dependent Python packages can then be installed with

```
$ python setup.py install
```

Summary

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- ▶ Many systematic tests performed.
- ▶ DM decay may be only probe of decoupled hidden sectors
- ▶ Sensitivity is improvable (CTA, HAWC, KM3NeT, ...)

Questions?

Backup

Step 2: Poissonian template fit

- ▶ Model parameters: $\theta = \{\psi_{\text{DM}}, \lambda_{nuisance}\}$ ($\psi_{\text{DM}} = \{m_{\text{DM}}, \tau\}$)

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$$p_i(d_i|\theta) = \prod_p \frac{\mu_i^p(\theta)^{n_i^p} e^{-\mu_i^p(\theta)}}{n_i^p!}$$

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$$\log p(d|\psi_{\text{DM}}) = \sum_{i=0}^{39} \max_{\lambda_i} \log p_i(d_i|\theta)$$

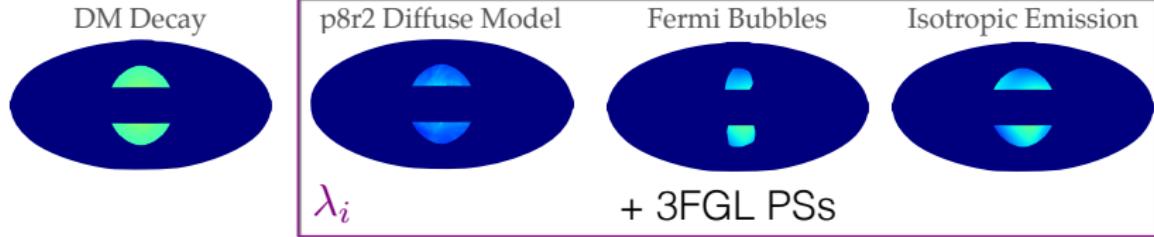
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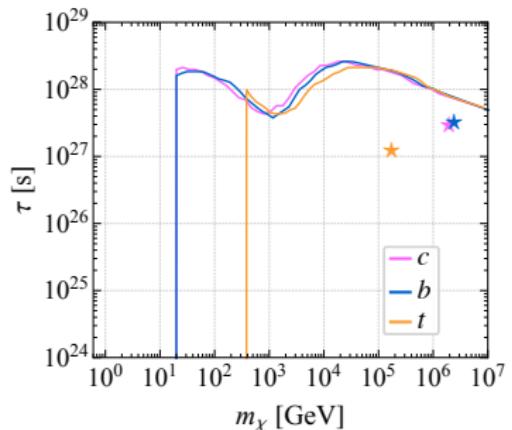
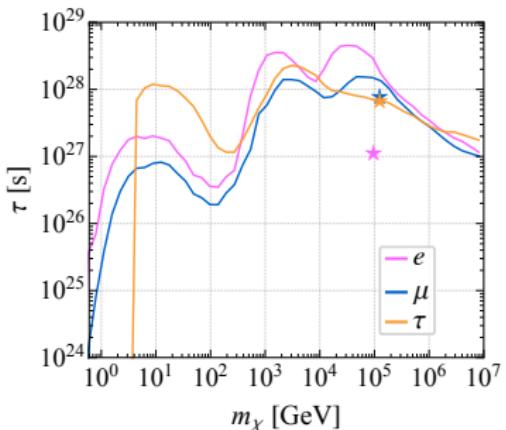
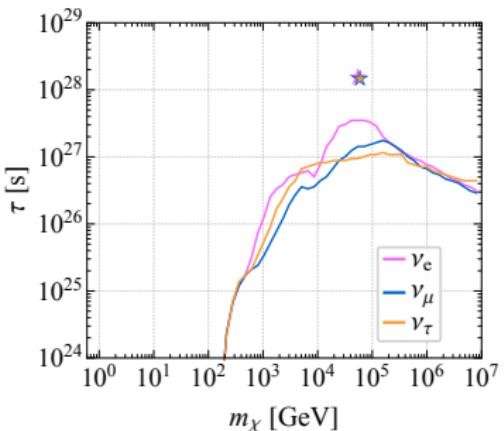
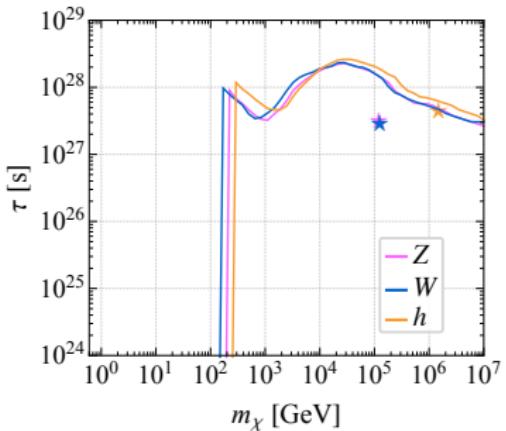
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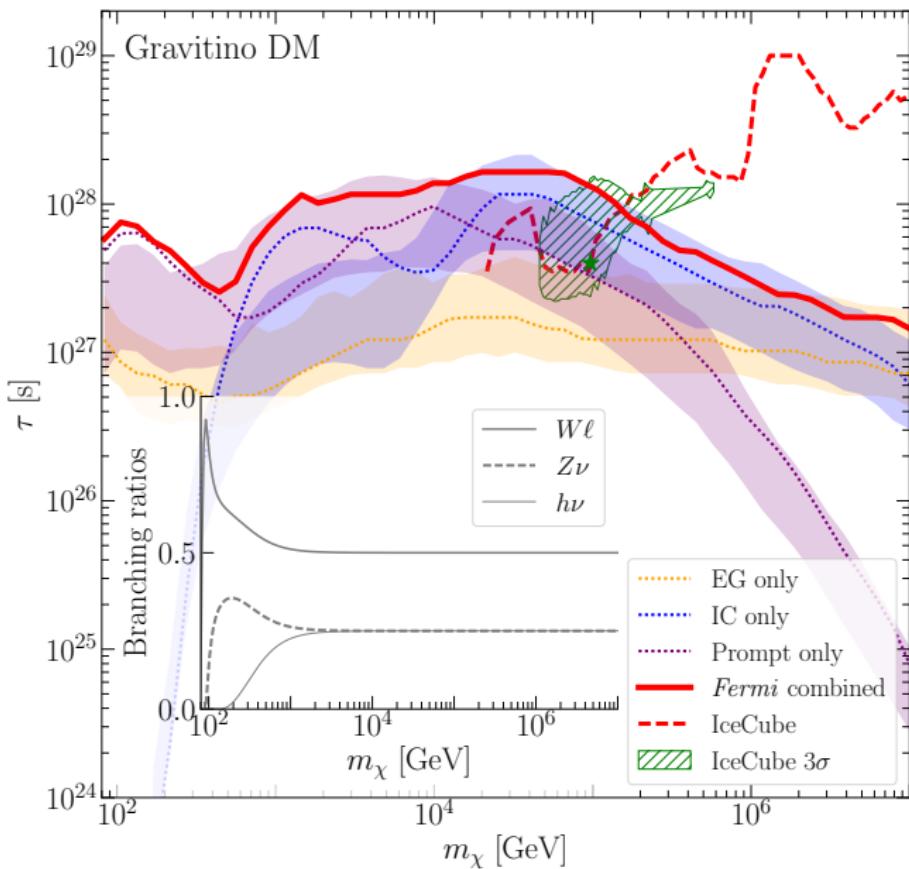
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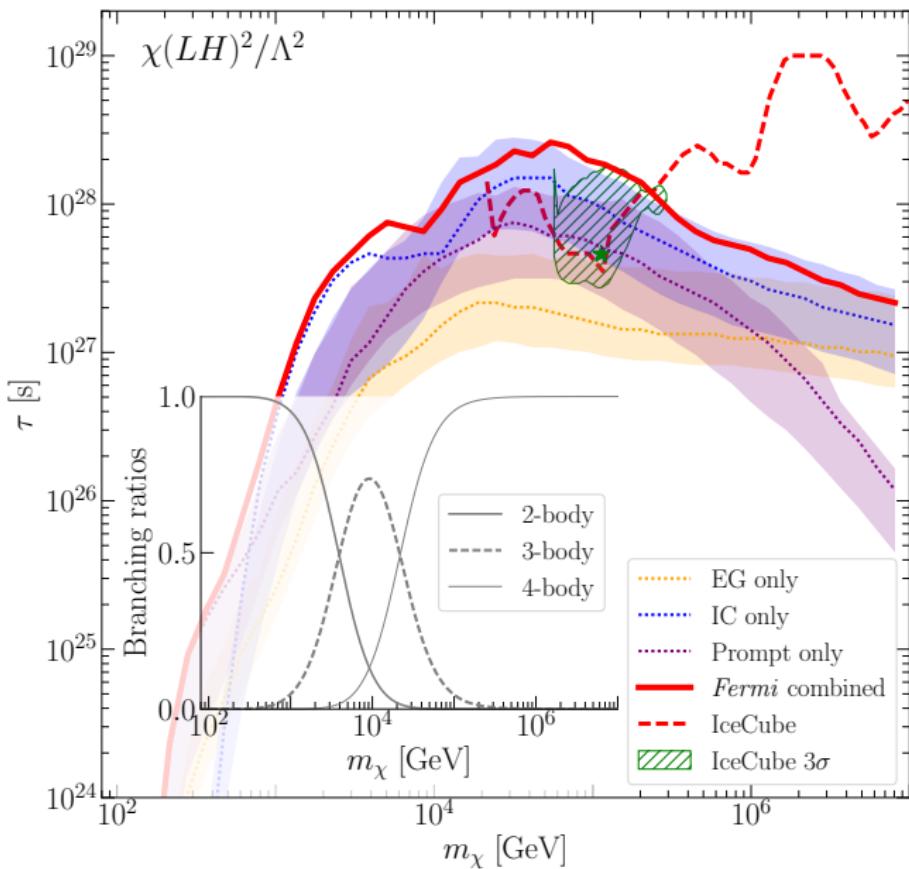
Limit: multiple channels



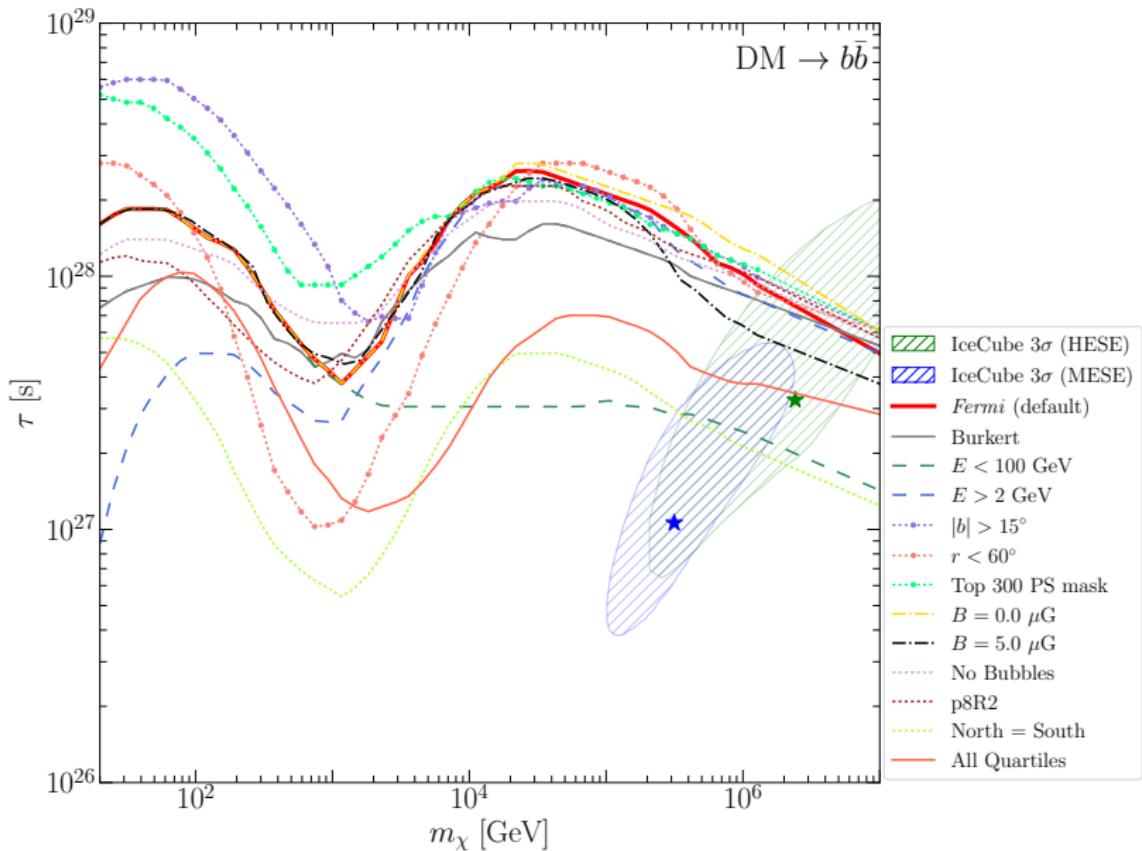
Limit: gravitino DM



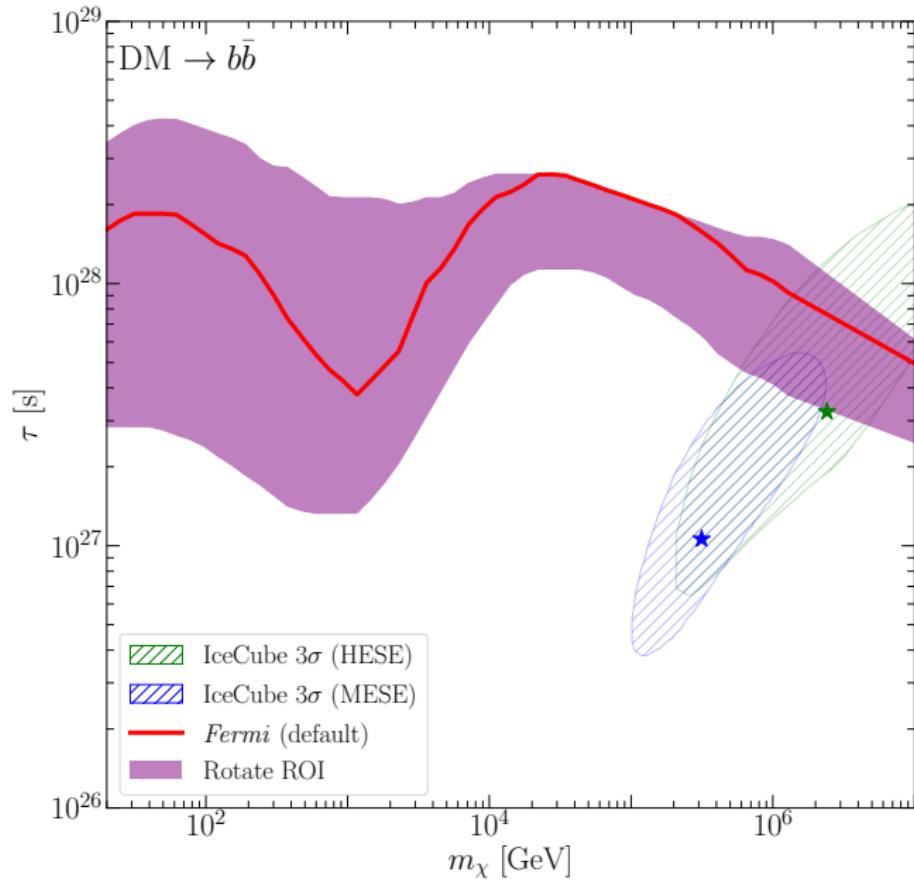
Limit: LHLH



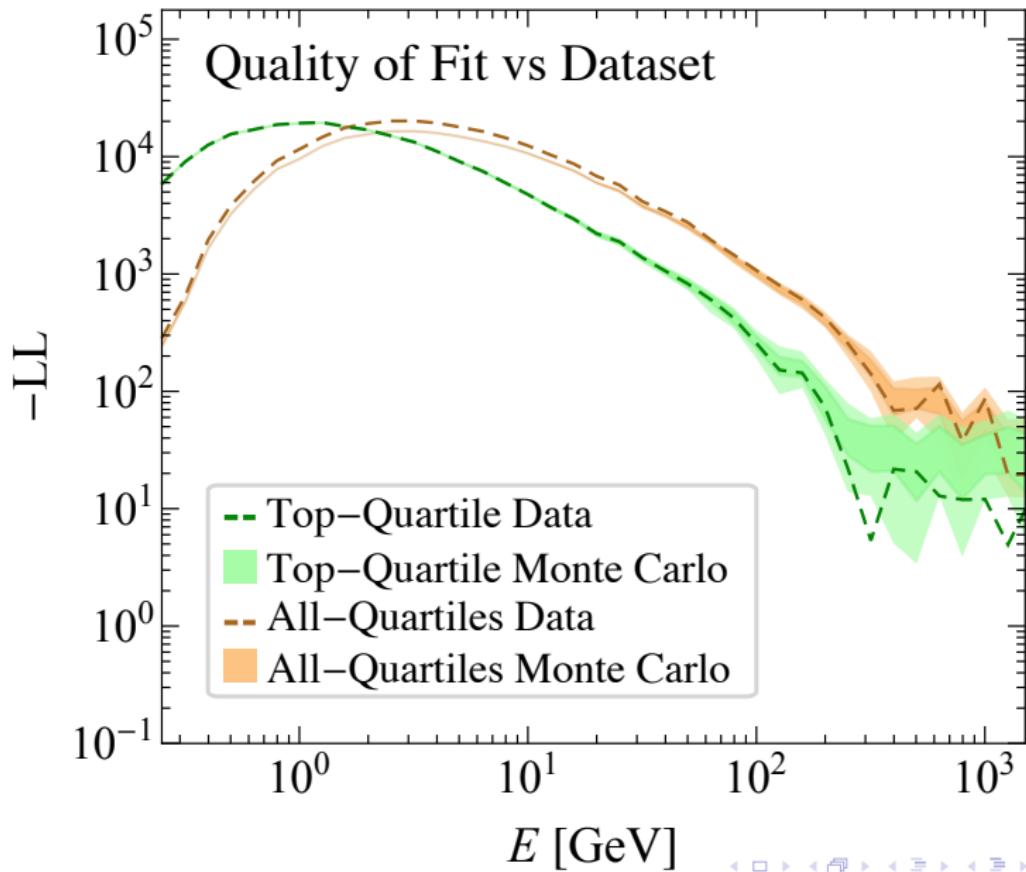
Systematics Summary



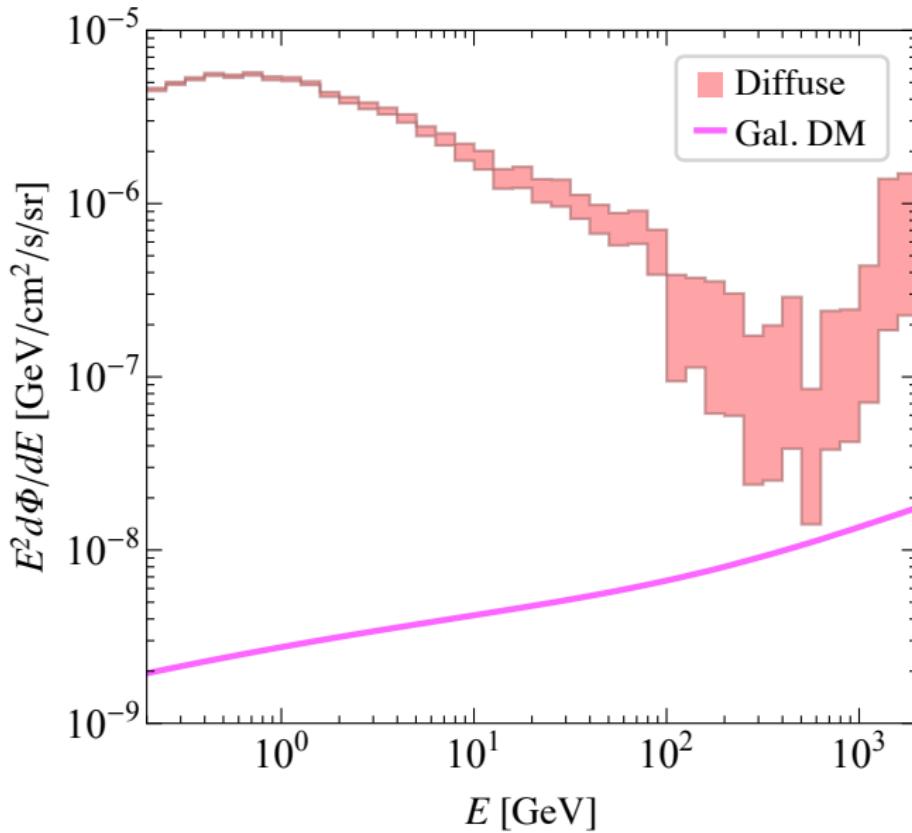
Rotate the region of interest about plane



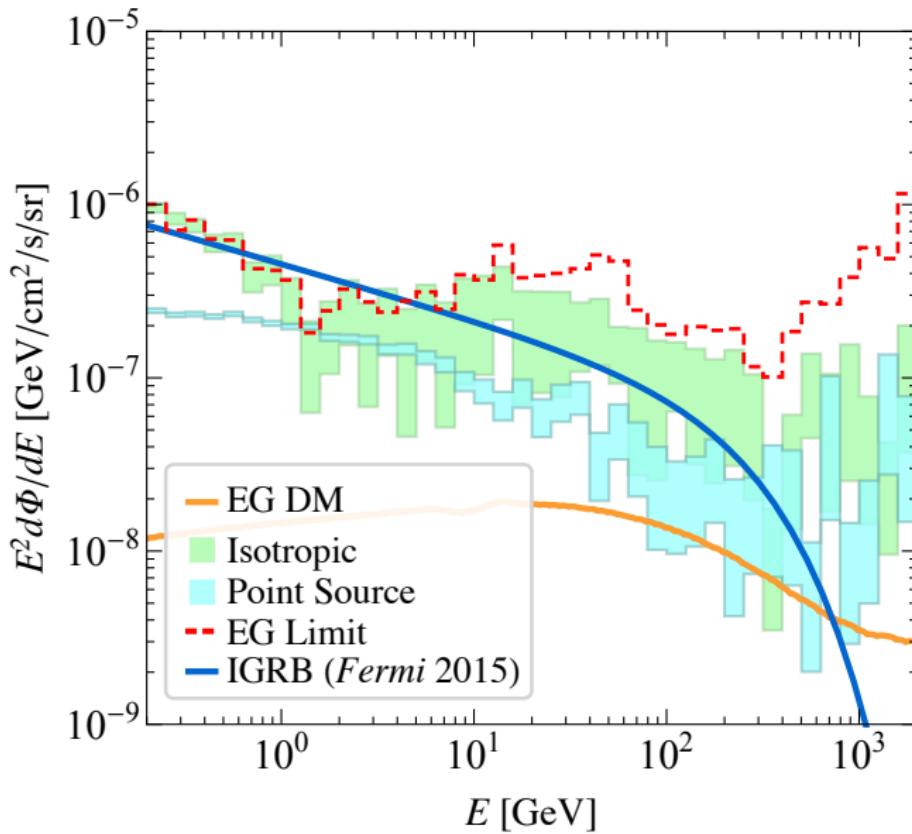
Overall quality of fit



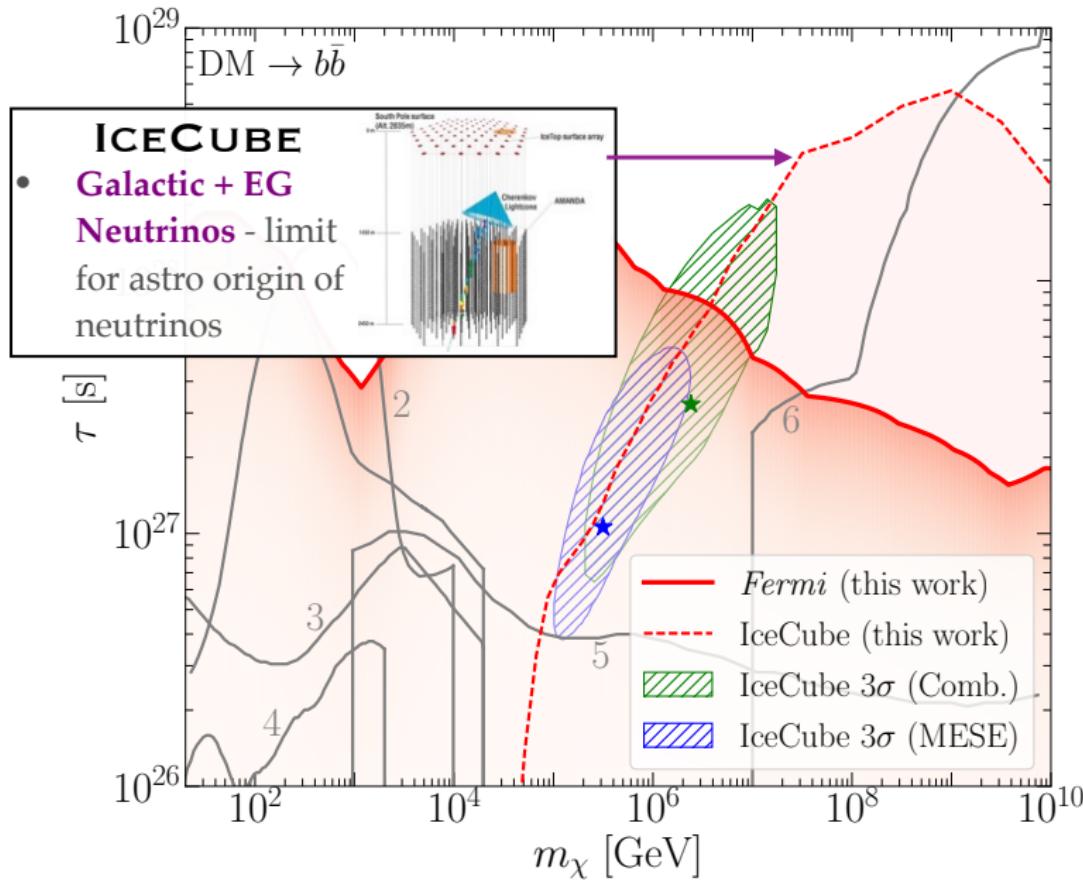
Signal vs background (1 PeV $b\bar{b}$)



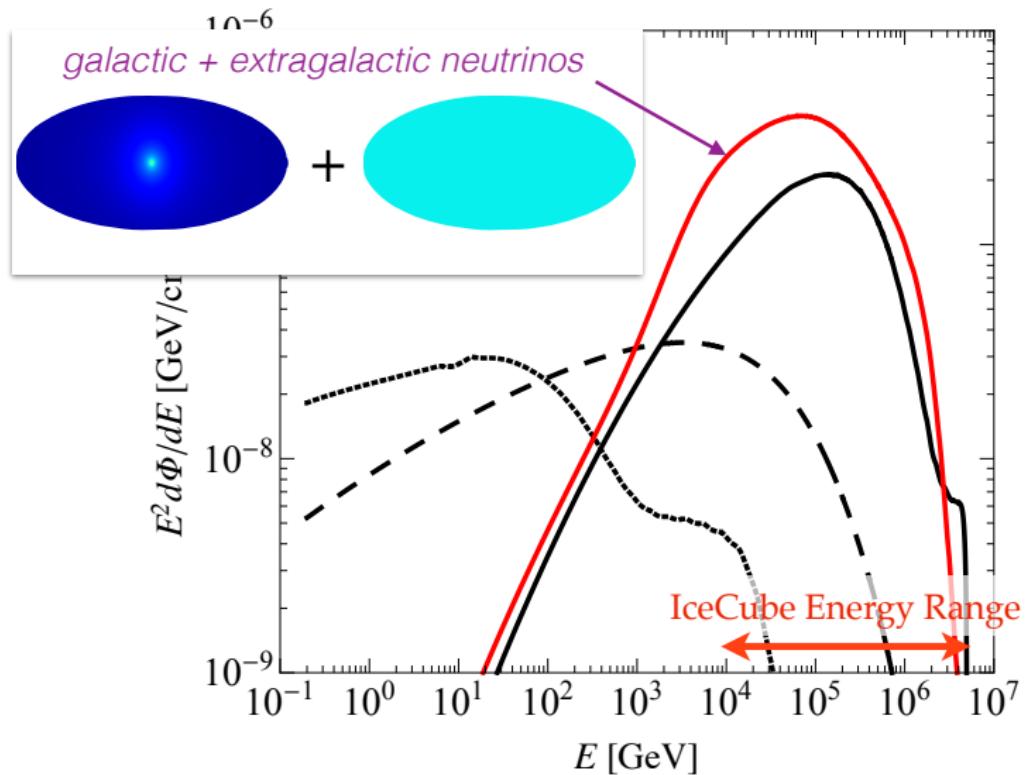
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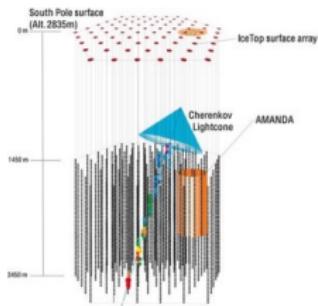
If not, what constraint does IceCube set?



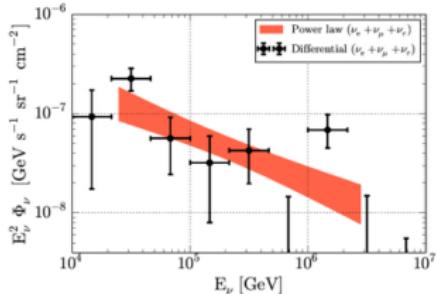
Step 1: computing the local spectra (ν 's)



IceCube has detected astrophysical neutrinos



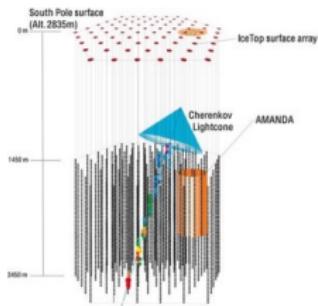
Spectrum from The IceCube Collaboration 1507.03991
Determined via a combined maximum-likelihood
analysis of six different IceCube analyses
See: <http://icecube.wisc.edu/science/data/combined-fit>



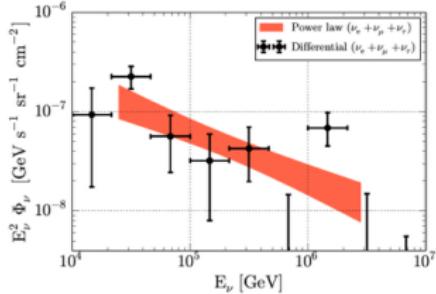
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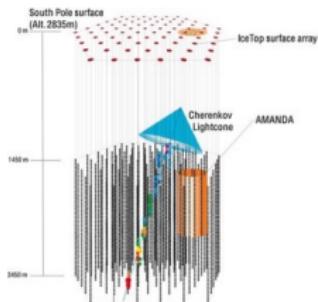
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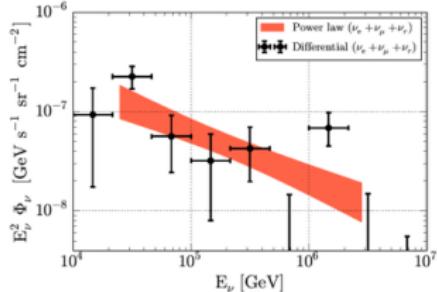
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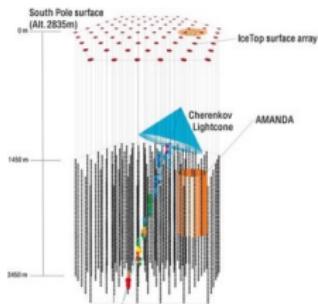
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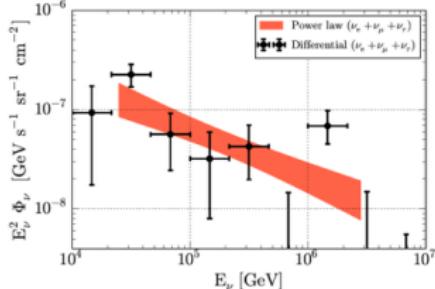
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 - ▶ pp in radio galaxies: promising, but gamma-ray variability may suggest $p\gamma$? (in progress)

Limit: what goes into glueball model?

