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

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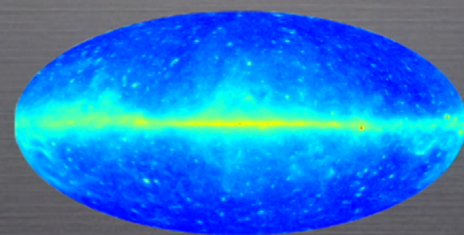
Abstract: <p>Utilizing the Fermi measurement of the gamma-ray spectrum toward the Galactic Center, we derive some of the strongest constraints to date on the dark matter (DM) lifetime in the mass range from hundreds of MeV to above an EeV. Our profile-likelihood based analysis relies on 413 weeks of Fermi Pass 8 data from 200 MeV to 2 TeV, along with up-to-date models for diffuse gamma-ray emission within the Milky Way. We model Galactic and extragalactic DM decay and include contributions to the DM-induced gamma-ray flux resulting from both primary emission and inverse-Compton scattering of primary electrons and positrons. For the extragalactic flux, we also calculate the spectrum associated with cascades of high-energy gamma-rays scattering off of the cosmic background radiation. We argue that a decaying DM interpretation for the 10 TeV-1 PeV neutrino flux observed by IceCube is disfavored by our constraints. We interpret the results in terms of individual final states and in the context of simplified scenarios such as a hidden-sector glueball model.</p>

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

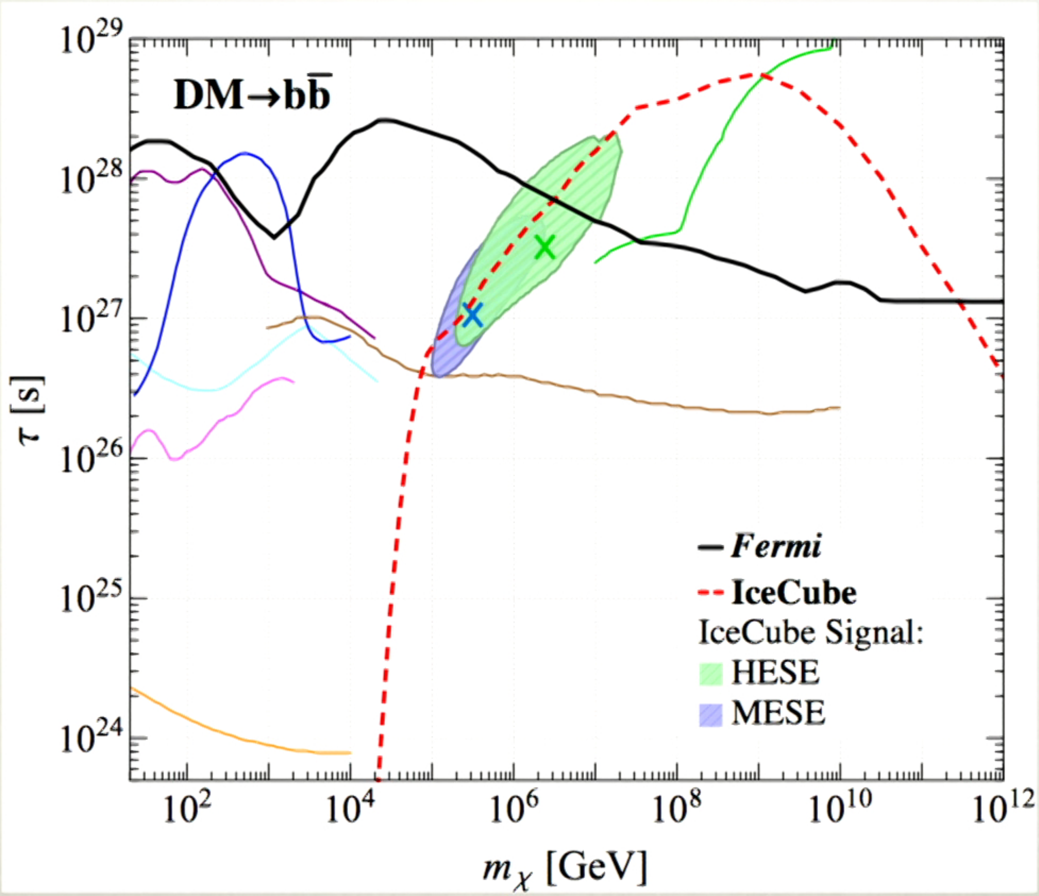


Nick Rodd

Based on 1612.05638 w/ Tim Cohen, Kohta Murase, Ben Safdi and Yotam Soreq

Perimeter Institute
28 March 2017

OUTLINE



Nick Rodd - Constraints on Dark Matter Decay

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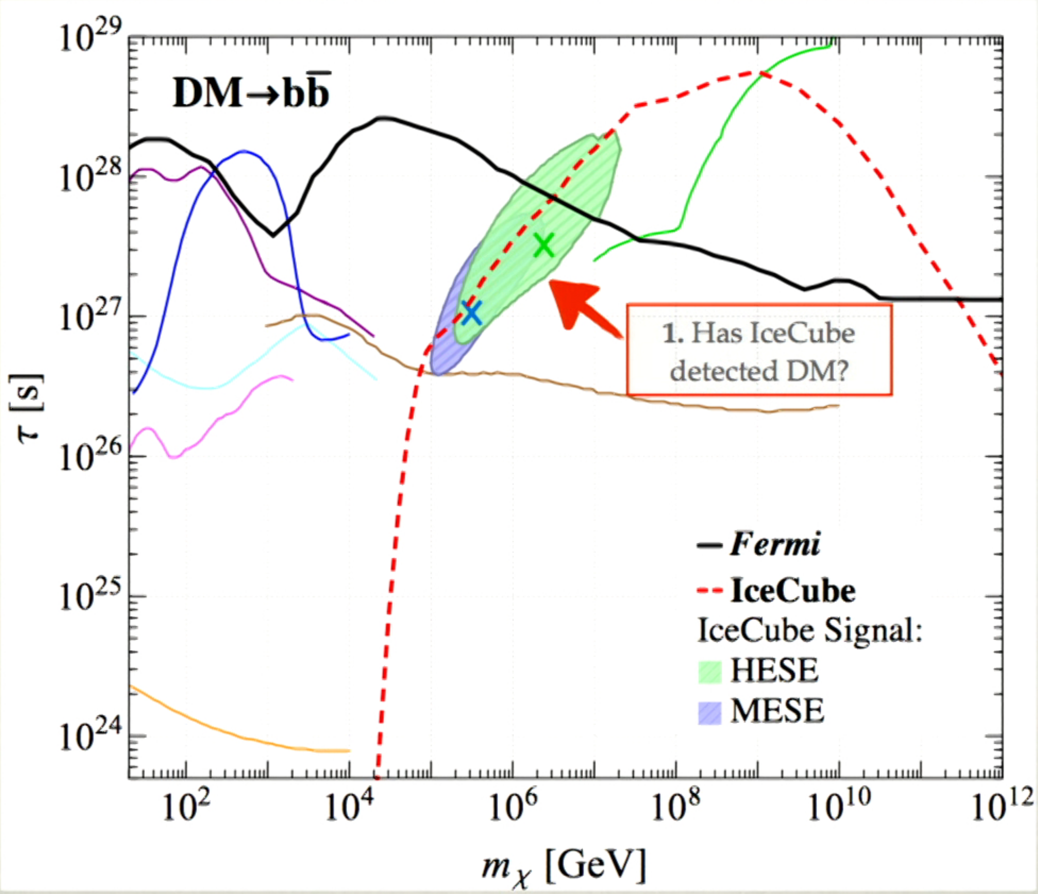
OUTLINE



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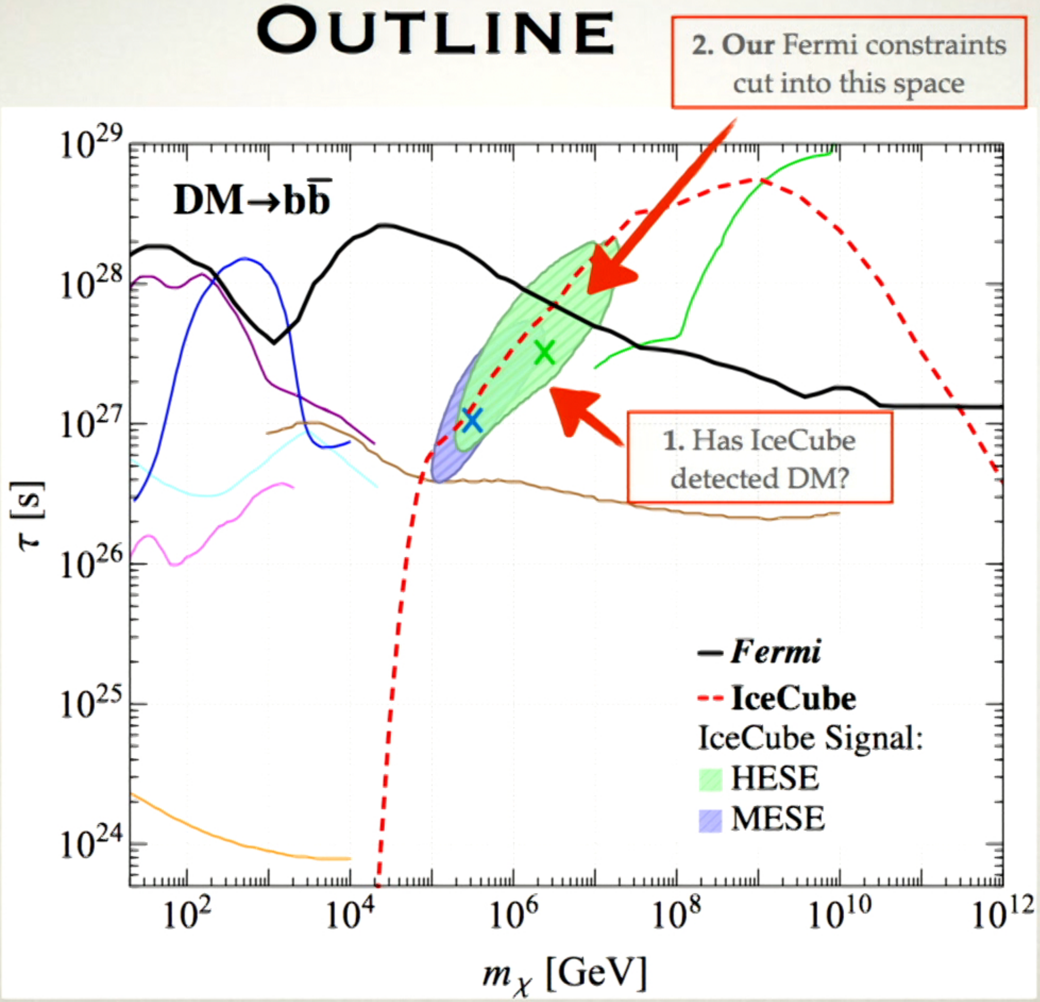

Nick Rodd - Constraints on Dark Matter Decay

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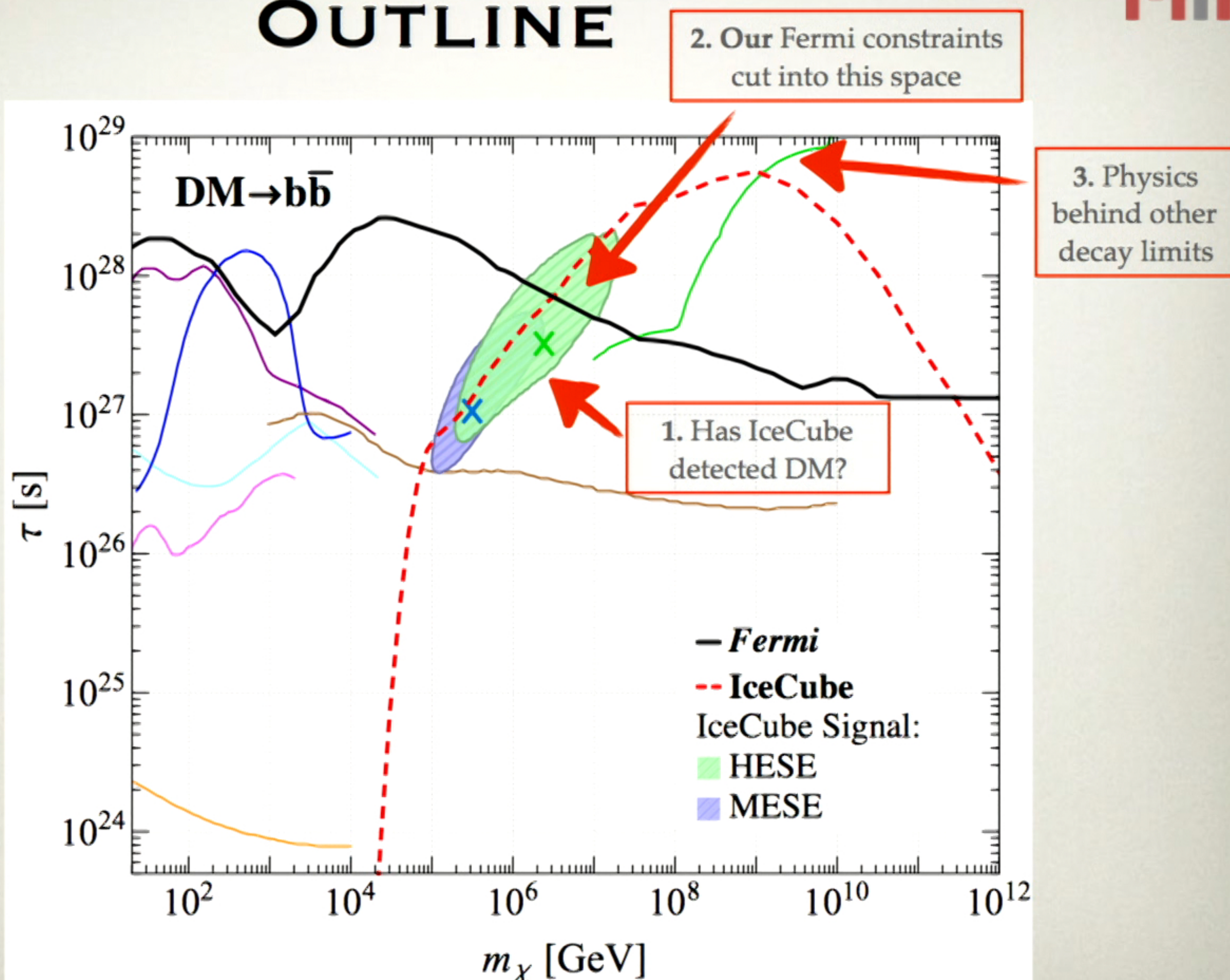

Nick Rodd - Constraints on Dark Matter Decay

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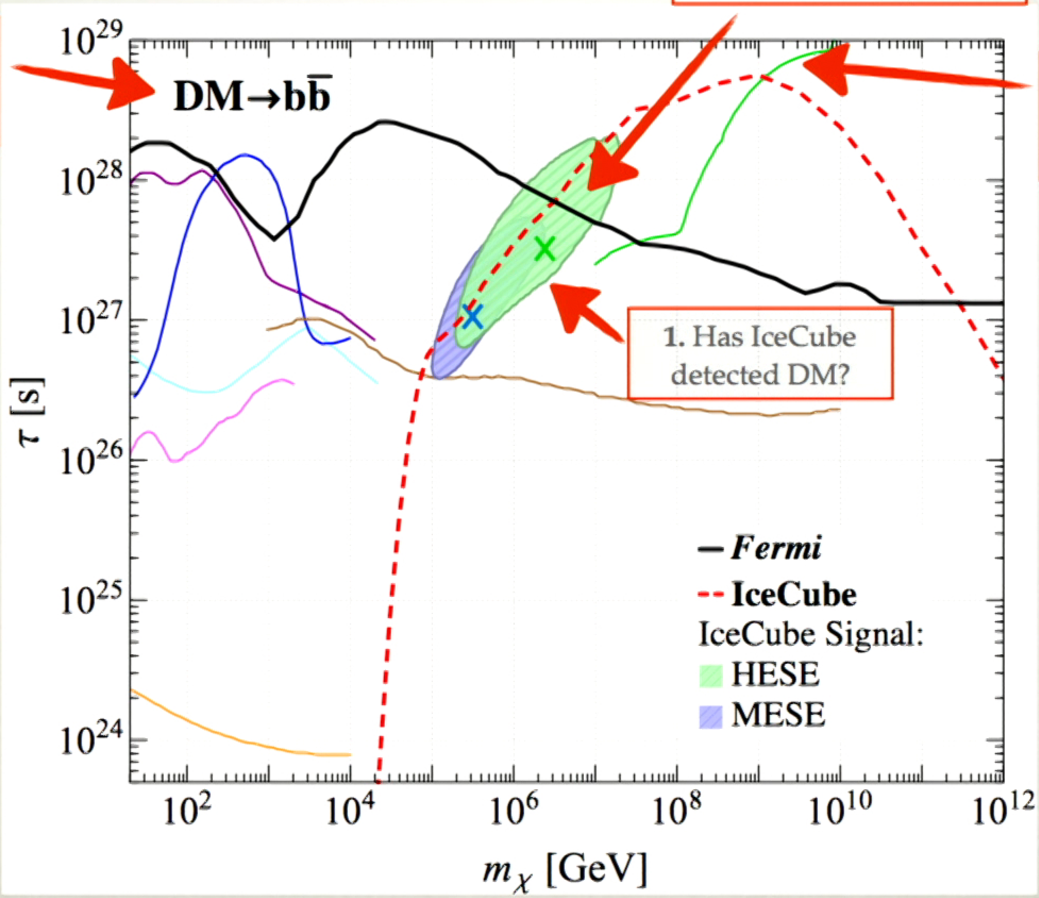

2. Our Fermi constraints cut into this space

4. From final states to models

3. Physics behind other decay limits

1. Has IceCube detected DM?

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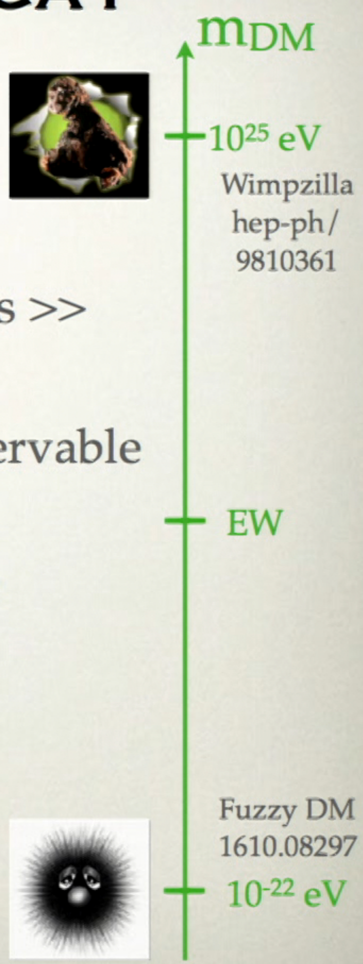
Heavy Dark Matter Decay

- **Fundamentally:** nothing forbids DM with a mass >> TeV
- **Key feature of these models:** might only be observable via indirect detection - IceCube and Fermi-LAT
  - Number density decreases could make nuclear scattering rates too low
  - Mass too high for colliders



Heavy Dark Matter Decay

m_{DM}

10^{25} eV
Wimpzilla
hep-ph/
9810361

- **Fundamentally:** nothing forbids DM with a mass >> TeV
- **Key feature of these models:** might only be observable via indirect detection - IceCube and Fermi-LAT
  - Number density decreases could make nuclear scattering rates too low
  - Mass too high for colliders

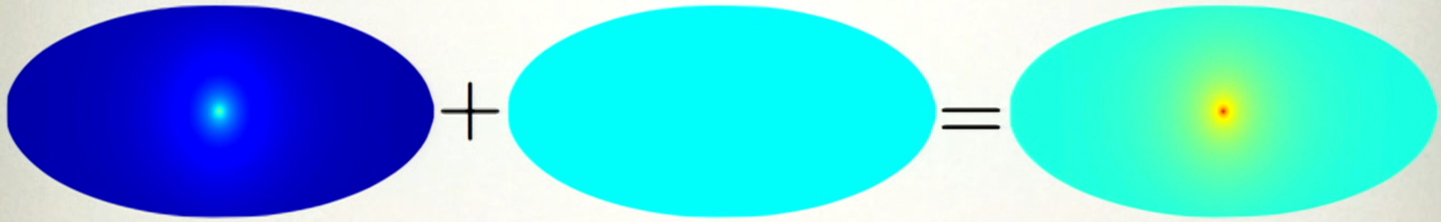
EW

Fuzzy DM
1610.08297
10^{-22} eV

Nick Rodd - Constraints on Dark Matter Decay

Heavy Dark Matter Decay

Decays in the Milky Way | **Extragalactic Decays** | **Total Flux**



$$\Phi_{\rm G} = \frac{1}{4\pi m_\chi \tau} \frac{dN}{dE} \int ds \; \rho_{\rm G}$$

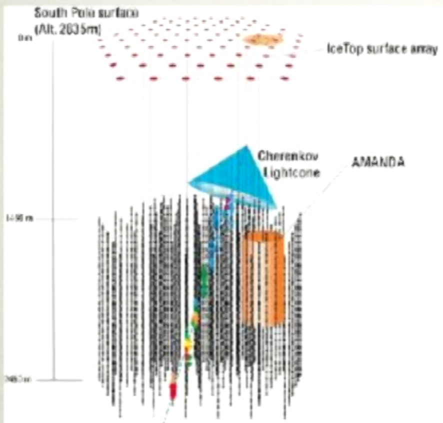
$$\Phi_{\rm EG} = \frac{\rho_{\rm EG}}{4\pi m_\chi \tau} \int \frac{c dz}{H(z)} \left. \frac{dN}{dE'} \right|_{E'=(1+z)E}$$

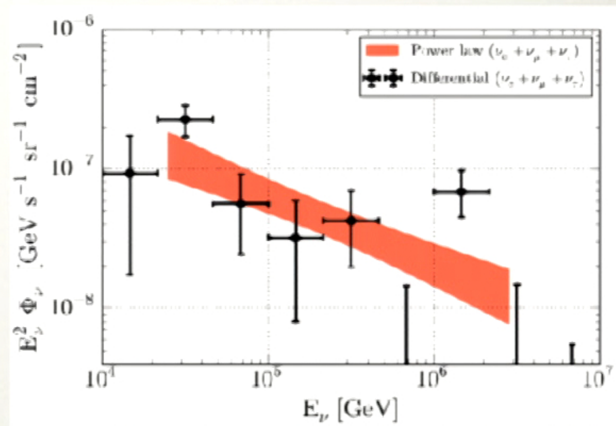
$$\Phi_{\rm total} = \Phi_{\rm G} + \Phi_{\rm EG}$$

- Neutrinos and photons travel straight from the source to us
- For DM decay galactic and extragalactic contributions important
- Total flux is less anisotropic than for DM annihilation

Dark Matter At IceCube

- IceCube has **conclusively measured** a flux of astrophysical neutrinos above 10 TeV



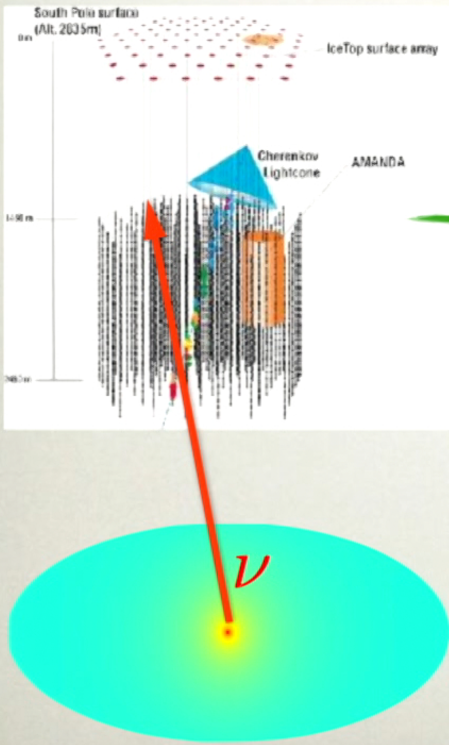


$$dN/dE \sim E^{-2.50 \pm 0.09}$$

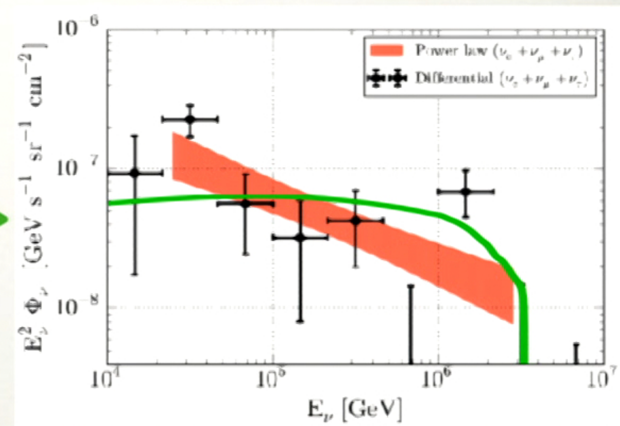
Spectrum from The IceCube Collaboration 1507.03991
Determined via a combined maximum-likelihood analysis of six different IceCube analyses
See: http://icecube.wisc.edu/science/data/combined-fit

Dark Matter At IceCube

- To **calibrate our expectation** for the interesting parameter space, what if this flux was due to **decaying Dark Matter**?



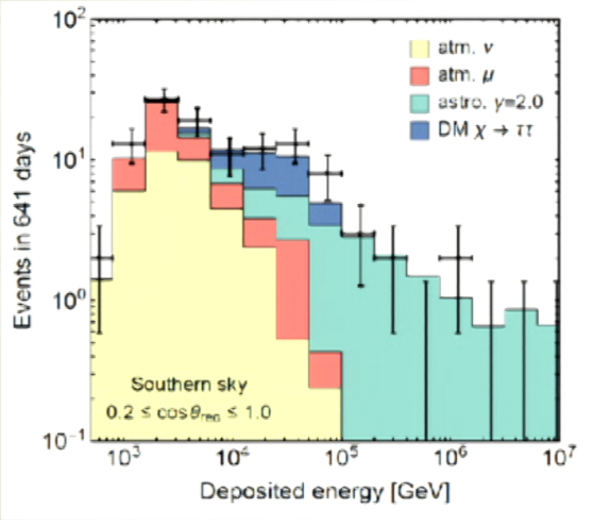
DM predicts a spectral shape, compare to the data

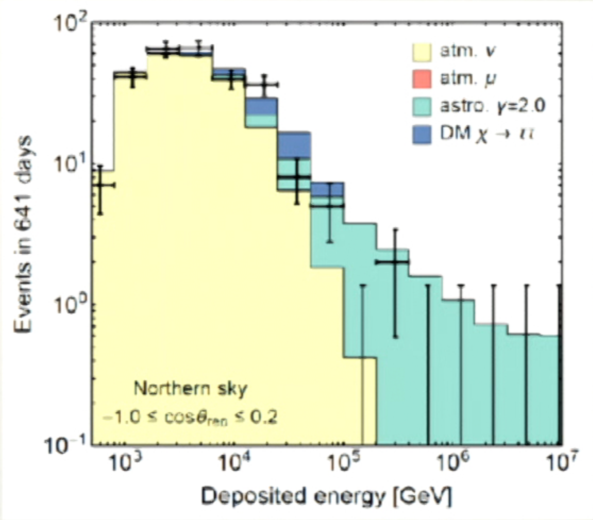


- Galactic and extragalactic DM decays can provide such neutrinos
- Expected DM anisotropy is consistent with the data, but also with an isotropic emission
  - e.g. Esmaili, Kang, and Serpico 1410.5979

Dark Matter At IceCube

- Another possible excess at lower energies, well fit by DM



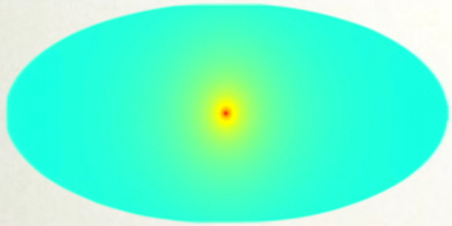


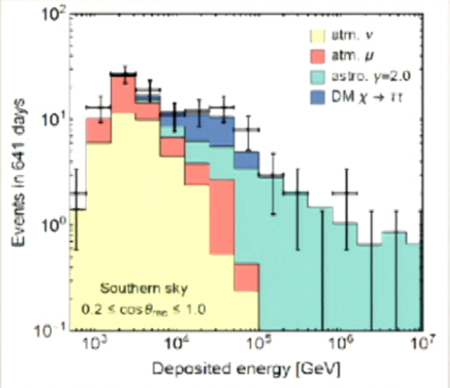
Chianese, Miele, and Morisi 1610.04612

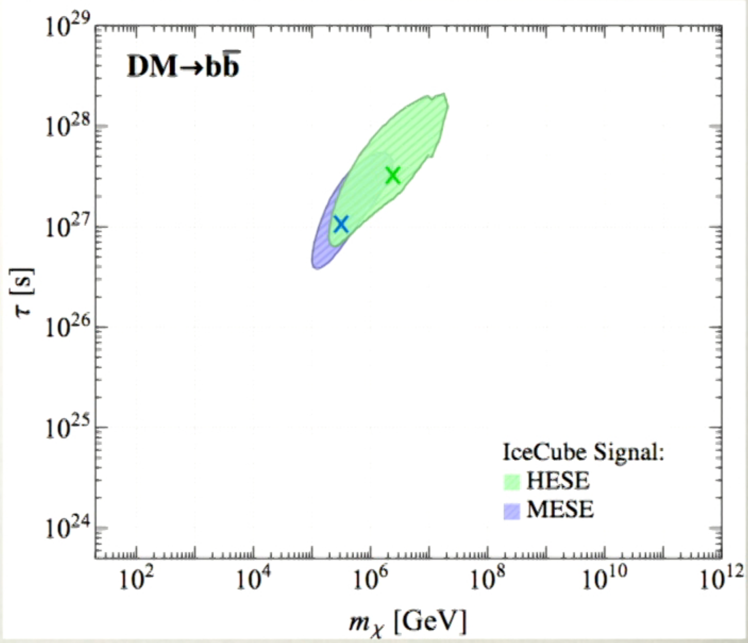
DARK MATTER AT ICECUBE

- To **calibrate our expectation** for the interesting parameter space, what if this flux was due to **decaying Dark Matter**?

DM Flux from Decay



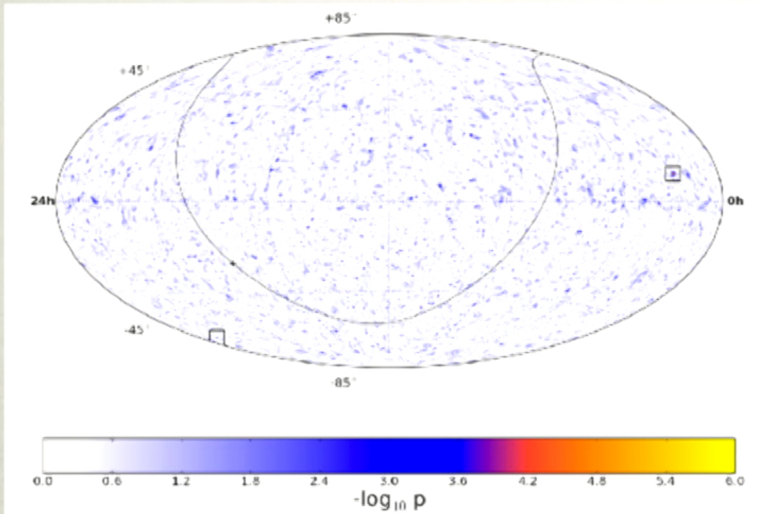




MESE: Medium Energy Starting Events

Astrophysics at IceCube

- Could the IceCube events be due to Active Galactic Nuclei?
- AGNs would appear as point sources in the data

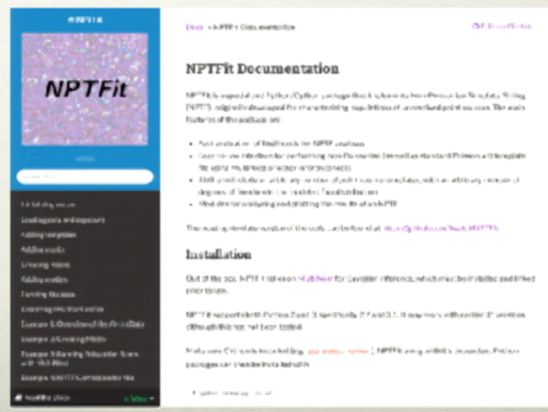


- IceCube collaboration has not detected any (1406.6757)
- Strong constraints on the fraction of events from AGNs
- Currently working with IceCube to improve this search using NPTF

Aside: NPTFit

- NPTF: rigorous way to test for presence of unresolved sources
- NPTFit: rapid NPTF
- Try it out yourself!
- Details: 1612.03173

github.com/bsafdi/NPTFit

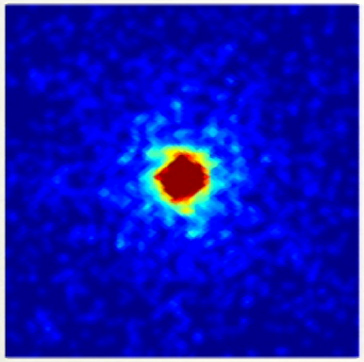


Nick Rodd - NPTFit (github.com/bsafdi/NPTFit)

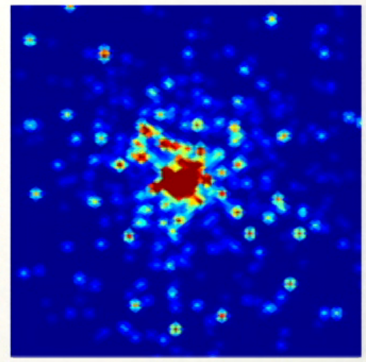
MOTIVATION: ORIGIN OF THE GCE

GCE: Dark Matter or Point Sources?

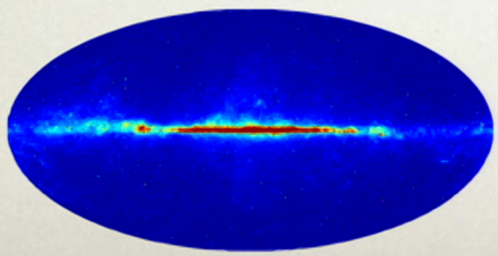
Dark Matter

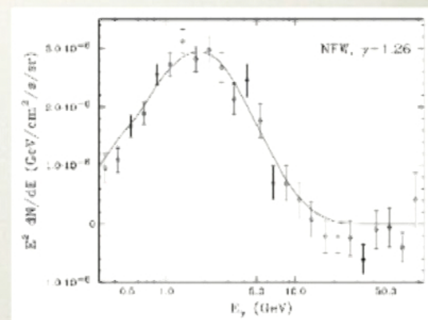


Point Sources



- Spectrum consistent with DM and MSPs
- Exploit spatial information to distinguish





NR et al (1402.6703)
See also **NR** et al (1604.01026)
and many more!

Statistics of Unresolved Sources

NPTFit

- Expect 10 photons per pixel, what is:

$$p(0),\ p(12),\ p(100)$$

- Poisson distribution, mean 10

$$p(12) = \frac{10^{12}e^{-10}}{12!} \sim 0.1$$

$$p(0) \sim 10^{-4},\ p(100) \sim 10^{-62}$$

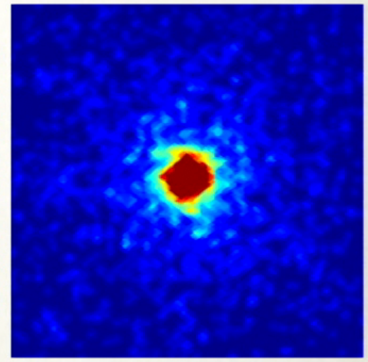
- Population of rare sources, mean 0.1 sources per pixel, 100 photons per source

$$p(12) = 0.1 \times \frac{100^{12}e^{-100}}{12!} \sim 10^{-29}$$

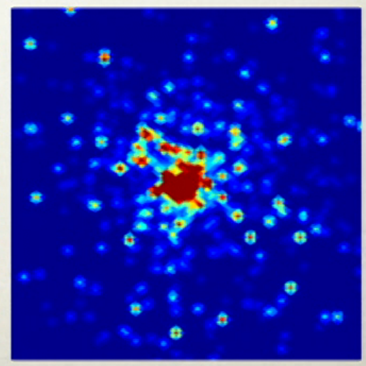
$$p(0) \sim 0.9,\ p(100) \sim 10^{-3}$$

- **Same mean, different statistics!**

Dark Matter



Point Sources



Nick Rodd - NPTFit (github.com/bsafdi/NPTFit)

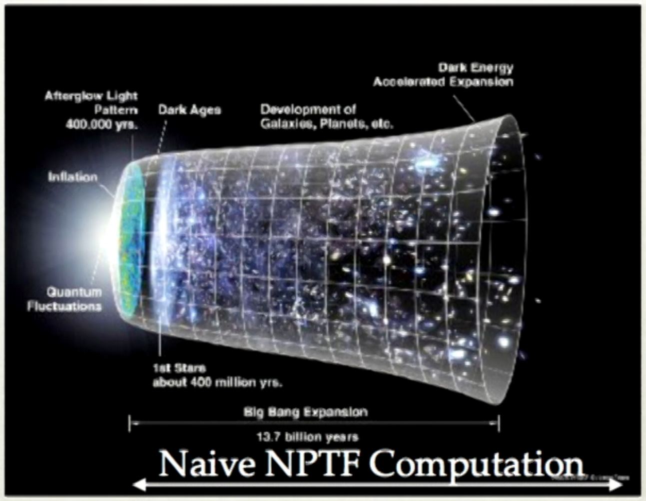
See also Malyshev and Hogg 2011

NPTFit: Rapid Evaluation of NPTF

- For the NPTF to be relevant, we must satisfy:

$$t_{\text{NPTF Computation}} < t_{\text{Hubble}}$$

- Approach on the previous slide fails this condition

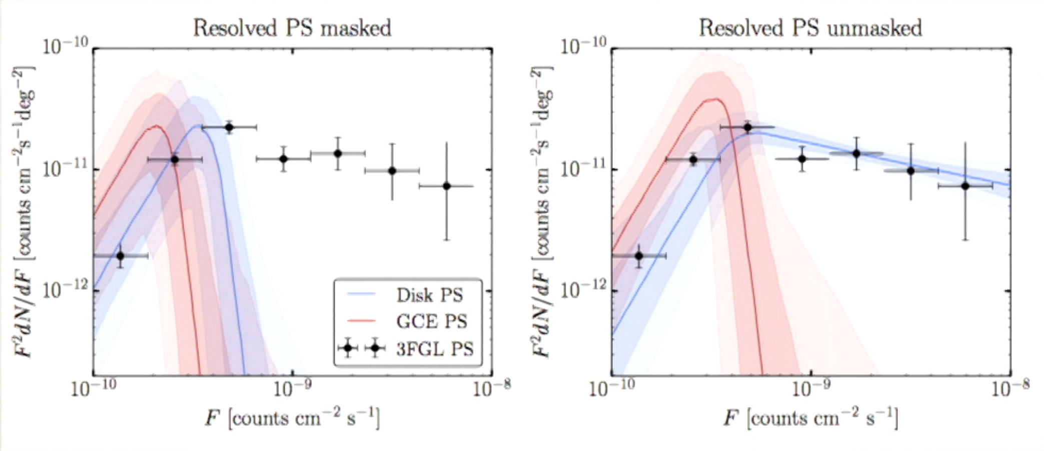


- **NPTFit:** a fast evaluation of the NPTF
- Also includes Poissonian Template Fitting

NPTFit: Looking for New Applications

NPTFit

- The method works on Fermi

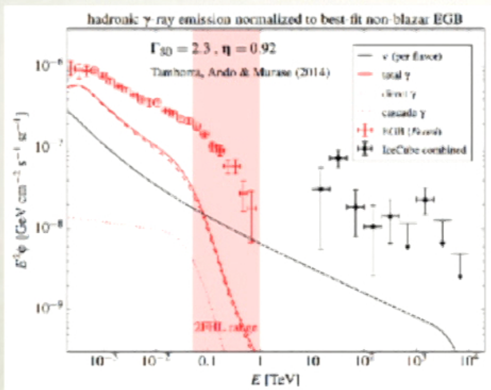


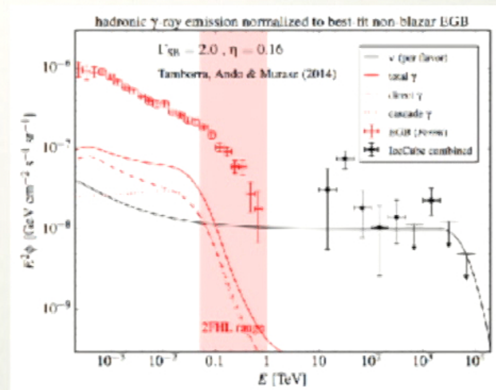
- Currently working to apply it to IceCube, potentially Chandra and NuStar, and extensions to time variability
- Looking for new applications!

Nick Rodd - NPTFit (github.com/bsafdi/NPTFit)

Astrophysics at IceCube

- Could the IceCube events be due to Starburst Galaxies?
- Inevitably also produce gamma rays Fermi should see

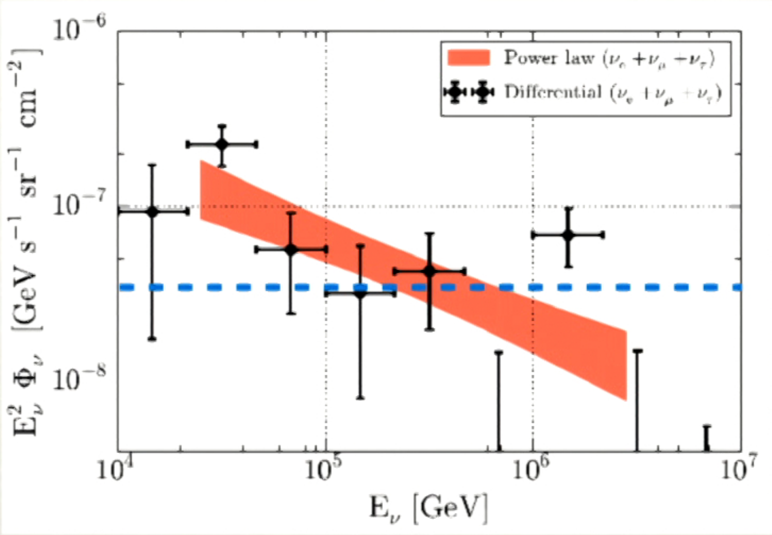




- There may be tension with gamma ray data
  - See e.g. Bechtol et al 1511.00688, but assumed blazar contribution is potentially controversial

ASTROPHYSICS AT ICECUBE

- Observed flux is roughly where it was expected (Waxman and Bahcall, hep-ph/9807282)



- Alternatives: radio galaxies (Hooper 1605.06504), new source or maybe Dark Matter?
- **Our work:** DM interpretation is in tension with the Fermi data

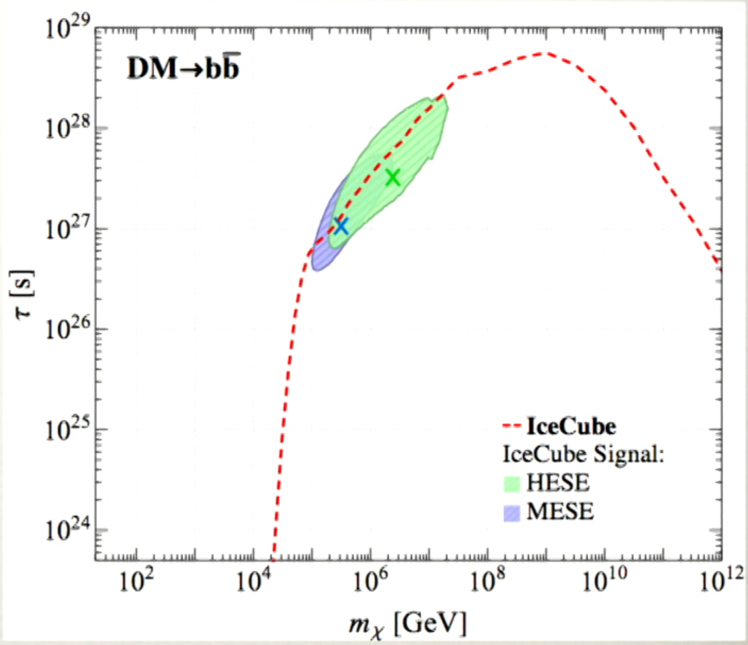
Astrophysics at IceCube

- To **calibrate our expectation** for the interesting parameter space, set limits assuming **astrophysics** contributes to the flux

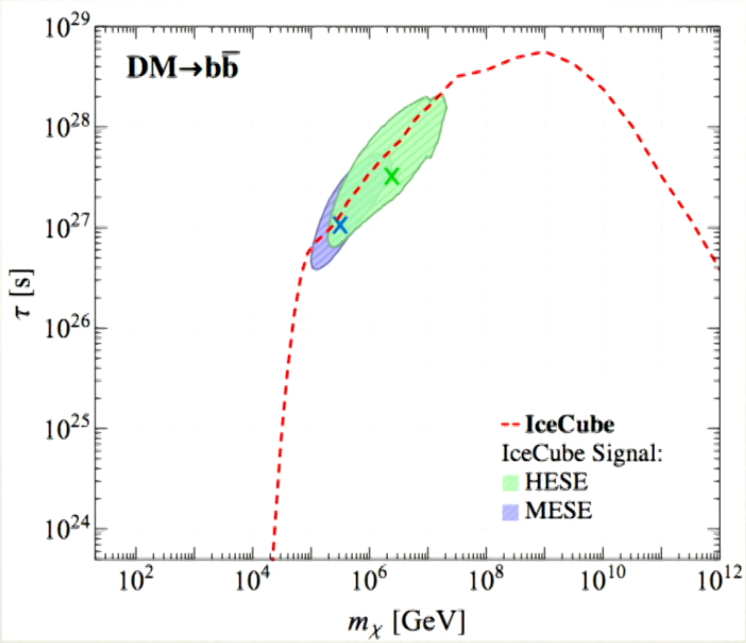
- Model the flux as astrophysical:

$$\Phi^{\nu}_{\rm astro} \propto E^{-\gamma} e^{-E/E_{\rm cut}}$$

- Marginalise over parameters
- Set 95% limits on a DM contribution on top of this, via profile likelihood



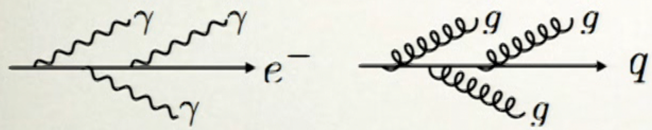
Dark Matter At IceCube



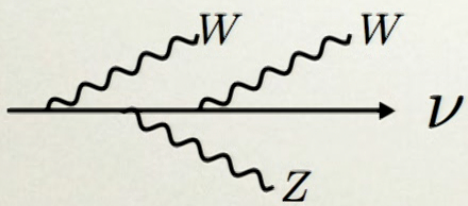
- **Suggestive** range of parameters relevant for IceCube
- Sets a benchmark for Fermi-LAT observations

Dark Matter at Fermi: Spectrum

- **Basic idea:** PeV DM decay will produce photons that can be seen by Fermi-LAT, so we can set limits
- True even for: $\mathrm{DM} \to \nu\bar{\nu}$
- Due to electroweak bremsstrahlung
- Photon/gluon radiation is familiar:

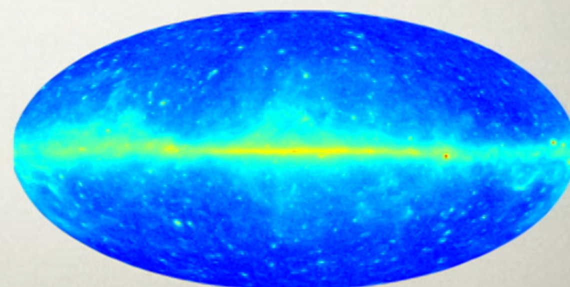


- Can also radiate W/Z bosons:



- Real effect, first measurements performed recently at ATLAS (1609.07045)

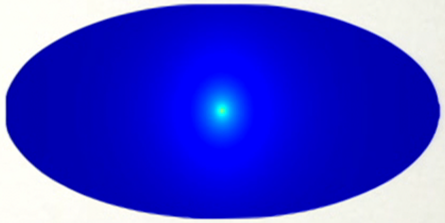
Fermi-LAT has collected more than 8 years of data from ~200 MeV - 2 TeV



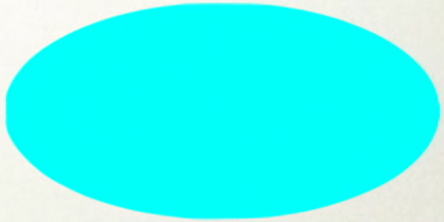
Dark Matter at Fermi: Spectrum

- **Prompt Galactic Spectrum:**
  - Photons ~ travel straight to us
- **Inverse Compton Galactic Spectrum:**
  - Prompt e^+/e^- also contribute
  - See e.g. Esmaili and Serpico 1505.06486
- **Extragalactic Spectrum:**
  - EG sky becomes opaque to photons above a few TeV (c.f. neutrinos & IceCube)
  - See e.g. Murase and Beacom 1206.2595
- **Total Flux:**
  - Combination of all three

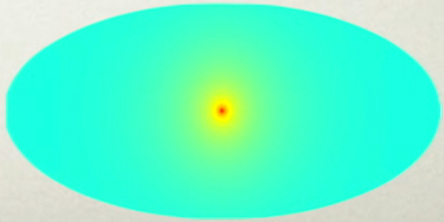
Decays in the Milky Way



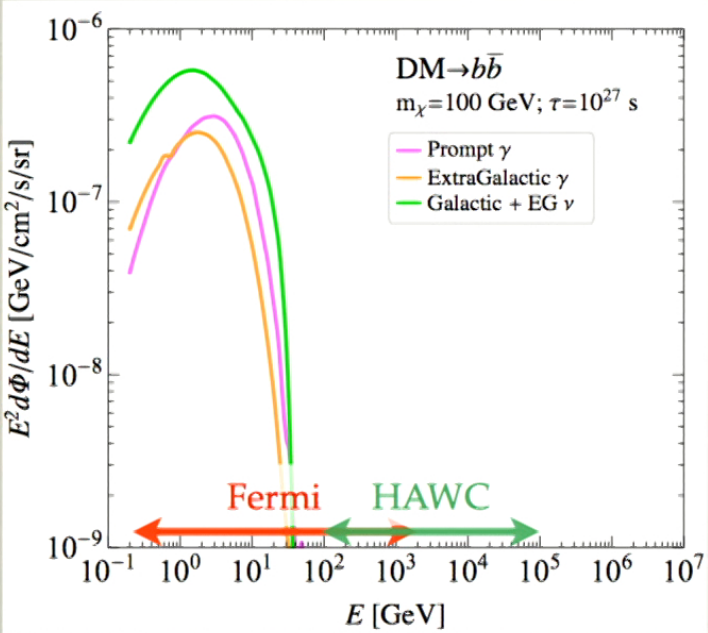
Extragalactic Decays

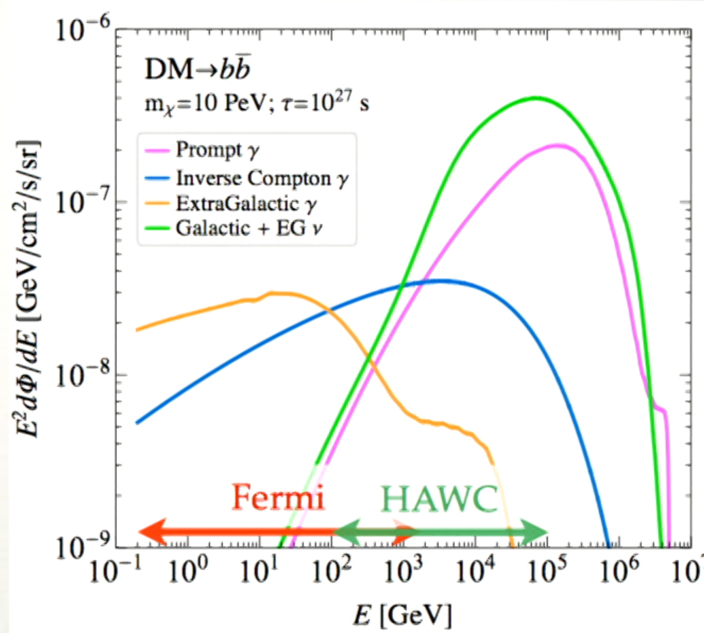


Total Flux

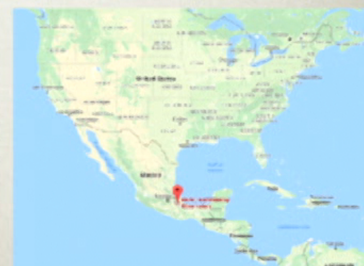


Dark Matter at Fermi: Spectrum





- HAWC data could be powerful in constraining high masses - working with the collaboration to realise this



DARK MATTER AT FERMI: PROFILE LIKELIHOOD

- Bin the data in energy (i) and spatial pixels (p): $\{l, b, E\} \Rightarrow n_i^p$
- Describe with model parameters: $\theta = \{\psi_{\rm DM}, \lambda_{\rm nuisance}\}$
- Construct the Poisson likelihood in each energy bin i

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

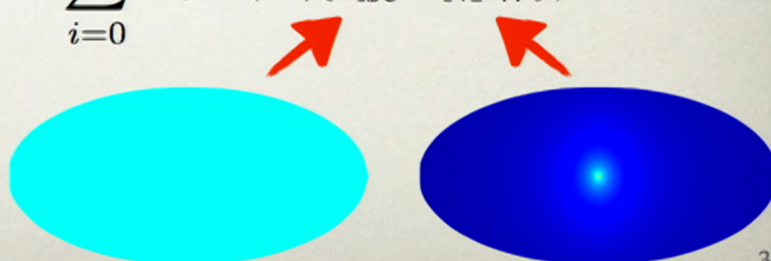
- Eliminate the nuisance parameters by profile likelihood

$$\log p_i(d_i|\psi_i) = \max_{\lambda_i} \log p_i(d_i|\theta_i)$$

- Likelihood of a model depends on the injected galactic and extragalactic flux

$$\log p(d|\mathcal{M}, \{\tau, m_{\rm DM}\}) = \sum_{i=0}^{39} \log p_i(d_i|\{I_{\rm iso}^i, I_{\rm NFW}^i\})$$

- From this define a TS, from which limits can be set
- Implement analysis using NPTFit (1612.03173)



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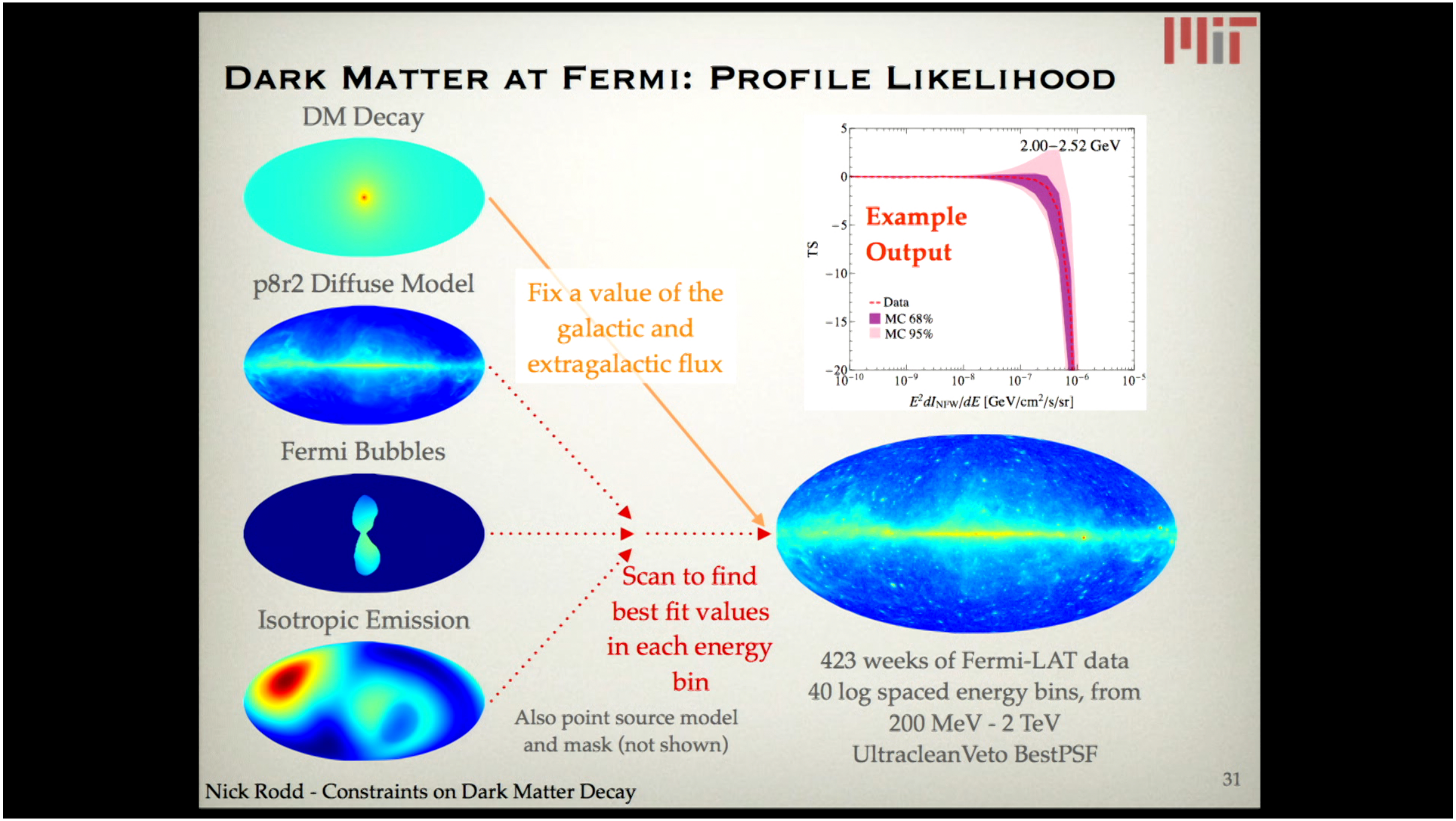

Dark Matter at Fermi: Profile Likelihood
DM Decay
p8r2 Diffuse Model
Fermi Bubbles
Isotropic Emission
Fix a value of the galactic and extragalactic flux
Scan to find best fit values in each energy bin
Also point source model and mask (not shown)
2.00–2.52 GeV
Example Output
TS
Data
MC 68%
MC 95%
$E^2 dI_{NFW}/dE$ [GeV/cm²/s/sr]
423 weeks of Fermi-LAT data
40 log spaced energy bins, from 200 MeV - 2 TeV
UltracleanVeto BestPSF
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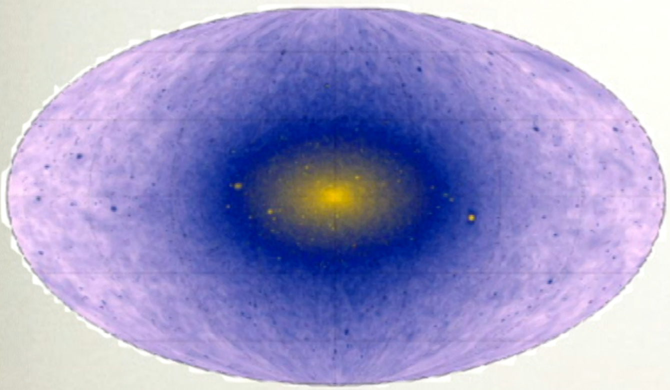
Dark Matter at Fermi: Profile Likelihood

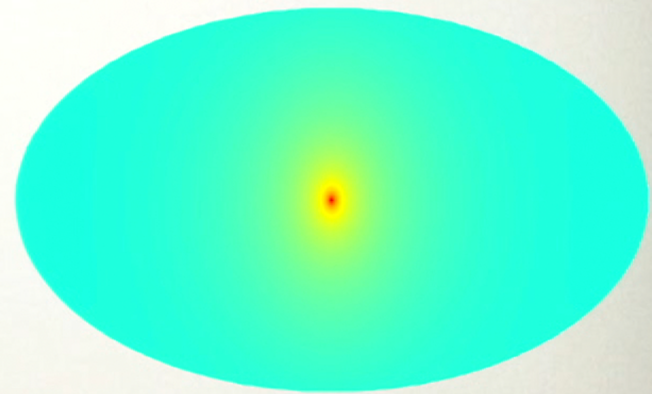
Expected Annihilation Flux



$$\Phi \propto \int ds \rho^2$$

Annihilation map from Kuhlen, Diemand, and Madau (0704.0944), determined using the Via Lactea simulation

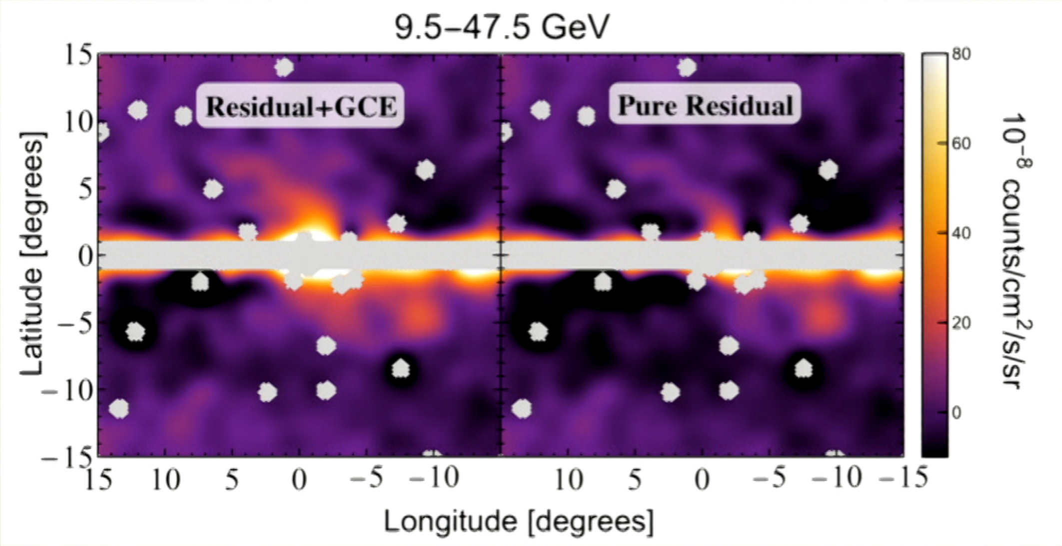
Expected Decay Flux



$$\Phi \propto \int ds \rho$$

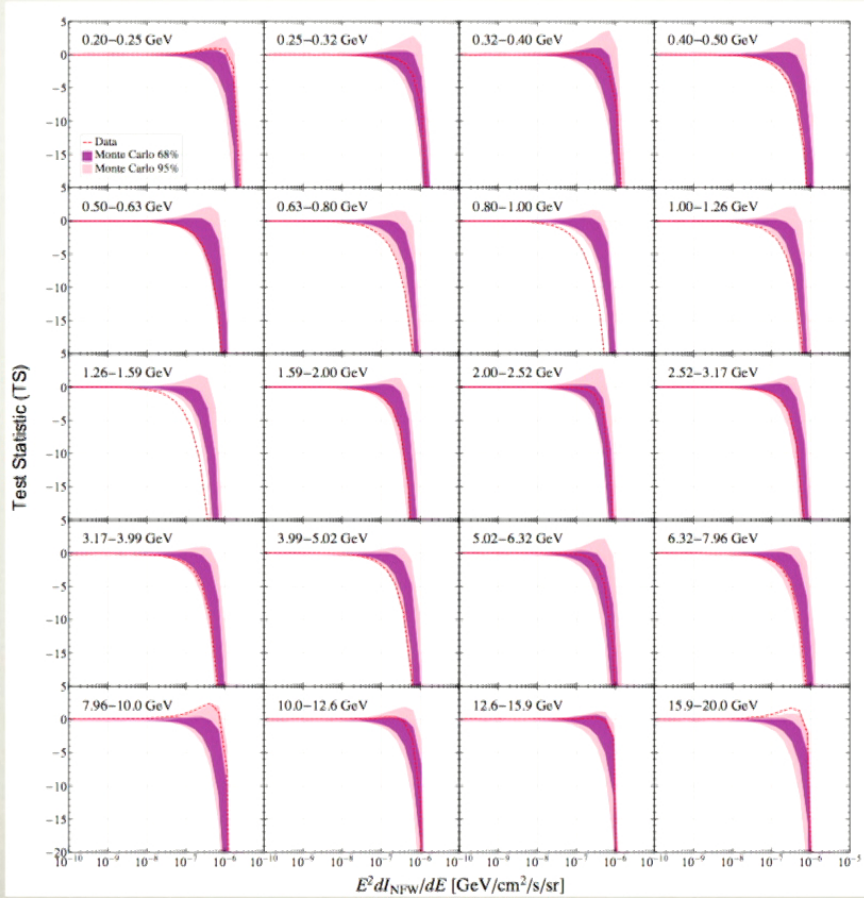
Dark Matter at Fermi: Profile Likelihood

- Models of the gamma ray sky do not explain the data to the level of Poisson noise, e.g. below for GCE from NR et al 1604.01026



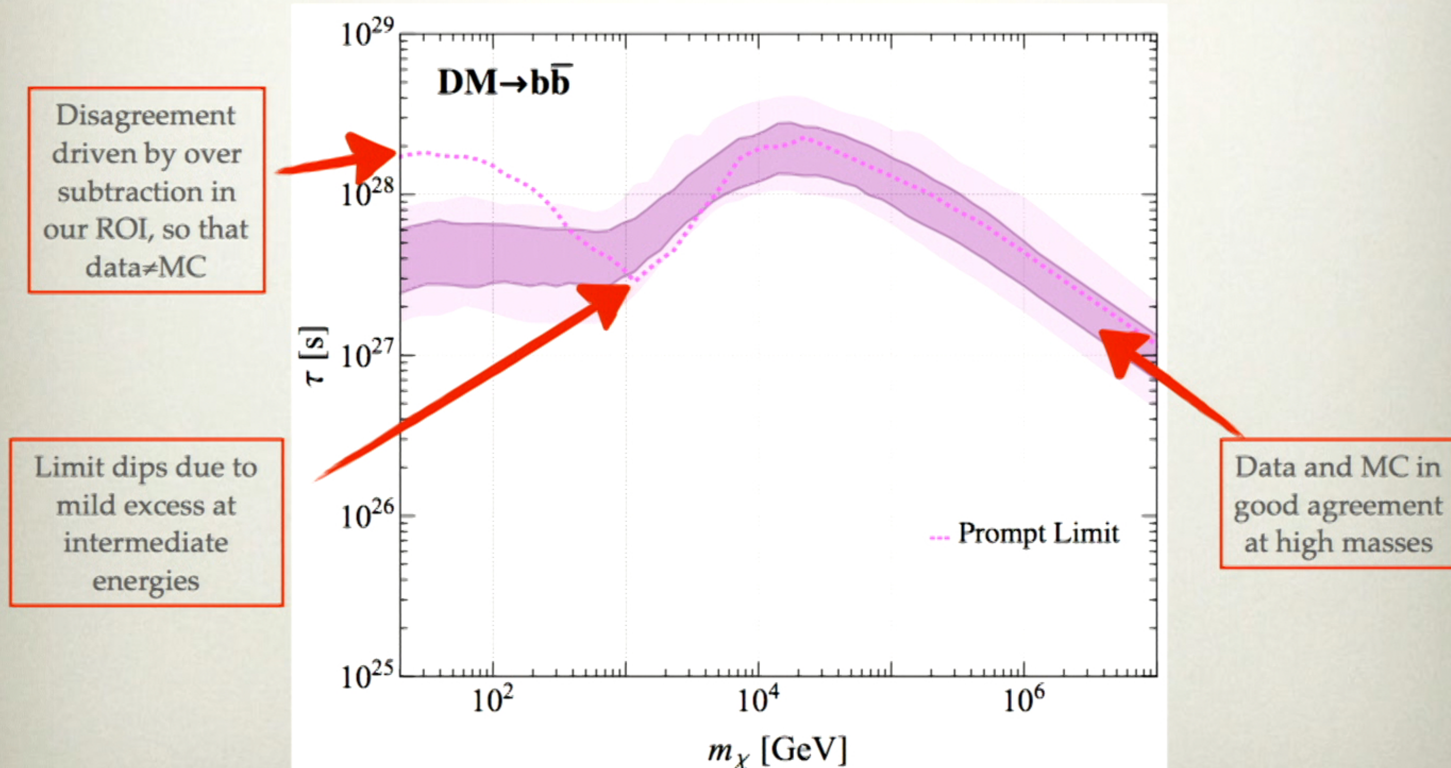
- These issues are much more pronounced for larger ROIs
- As modelling of the sky improves, will be able to safely use larger ROIs and thereby more data

Dark Matter at Fermi: Profile Likelihood



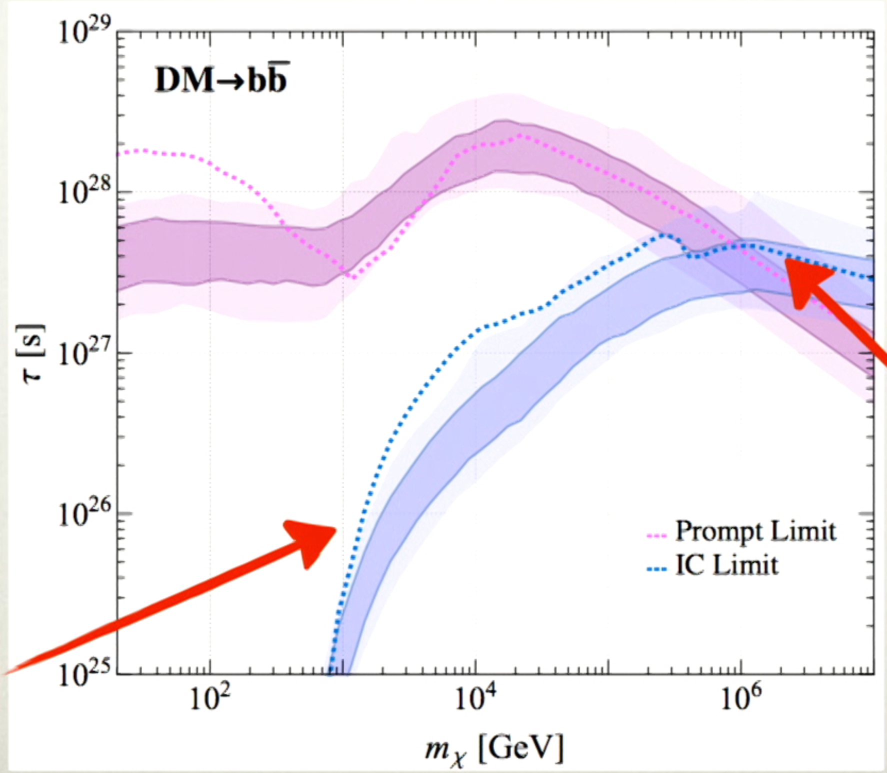
Dark Matter at Fermi: Building Limits

- Start with the **prompt** galactic contribution



Dark Matter at Fermi: Building Limits

- Add in the galactic **inverse Compton** contribution



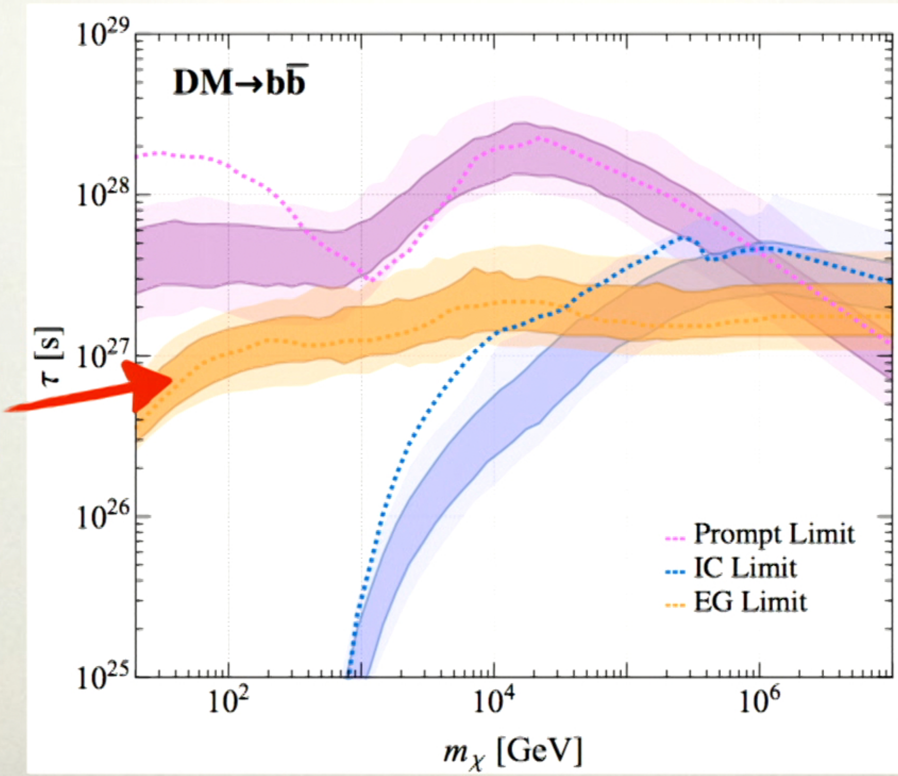
Over subtraction again at play

IC critical for PeV scale DM

DARK MATTER AT FERMI: BUILDING LIMITS

- Then add in the **extragalactic** contribution

Data and MC in good agreement



EG important at high masses

Nick Rodd - Constraints on Dark Matter Decay

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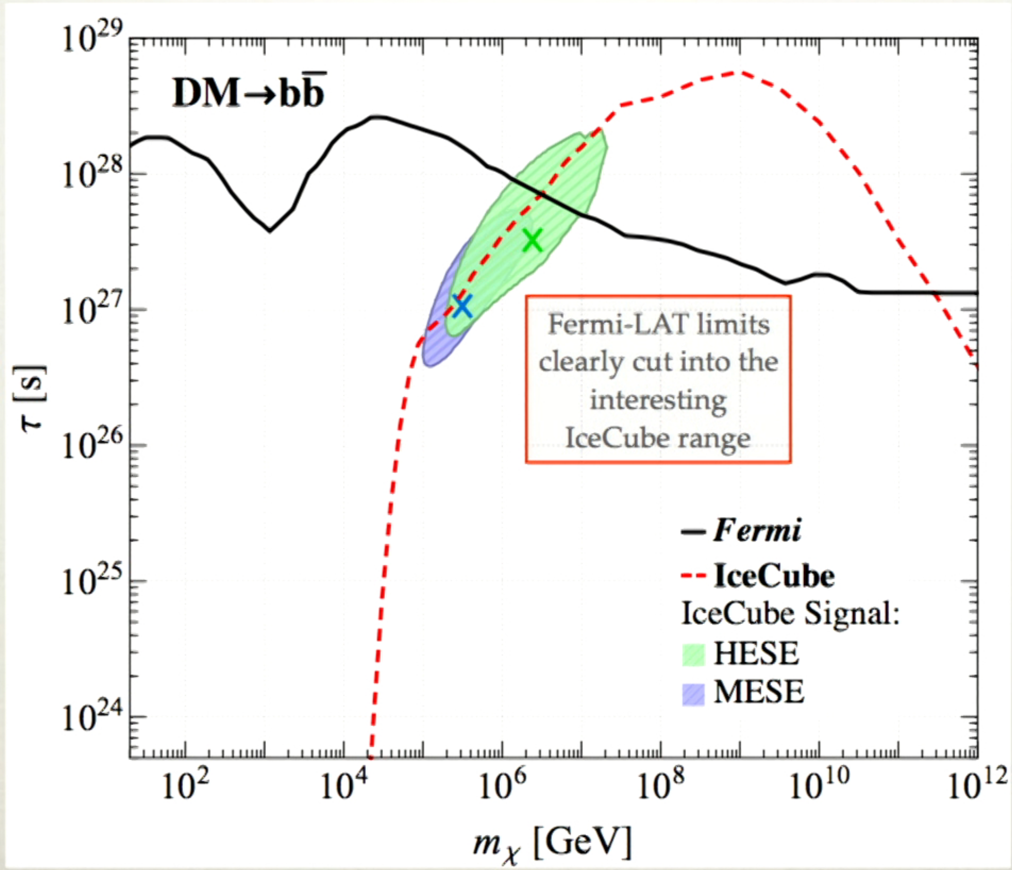
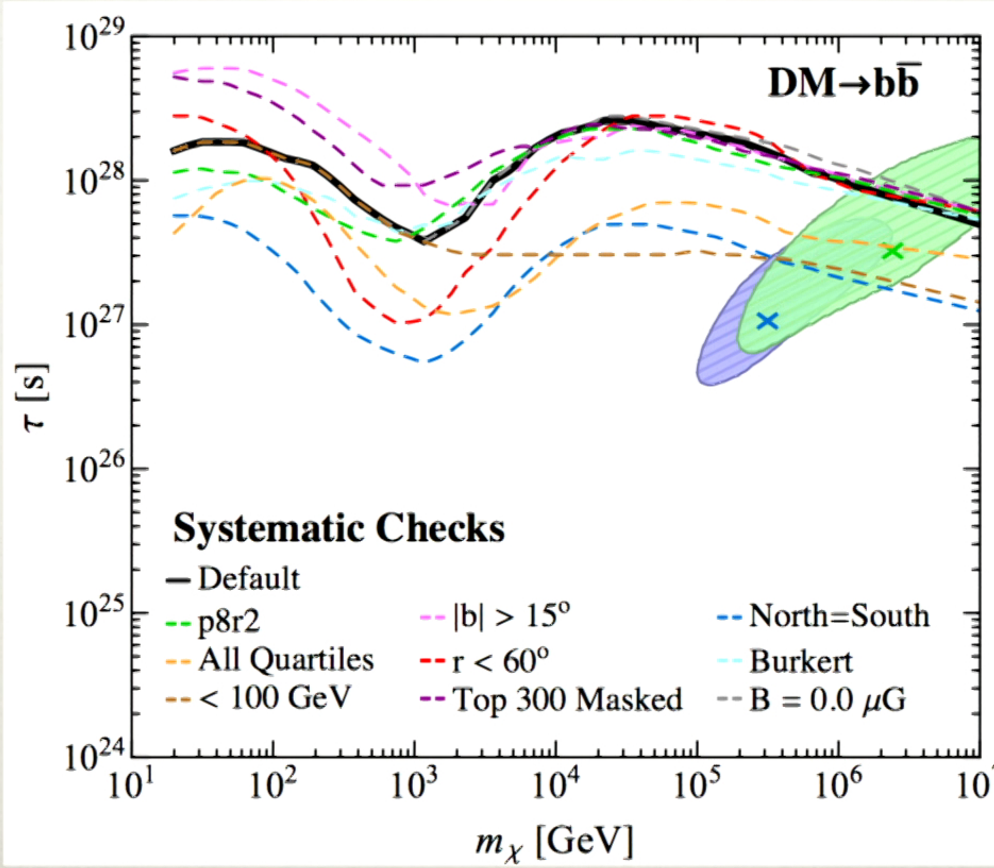
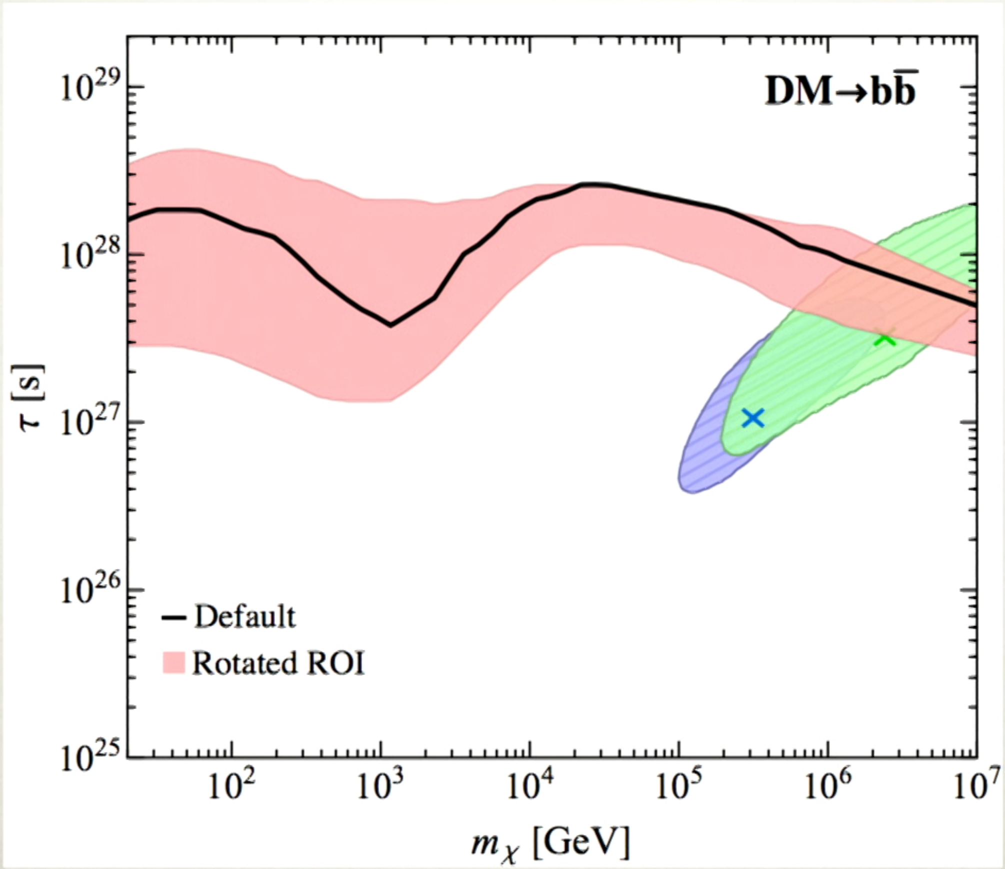
Dark Matter at Fermi: Final Limit



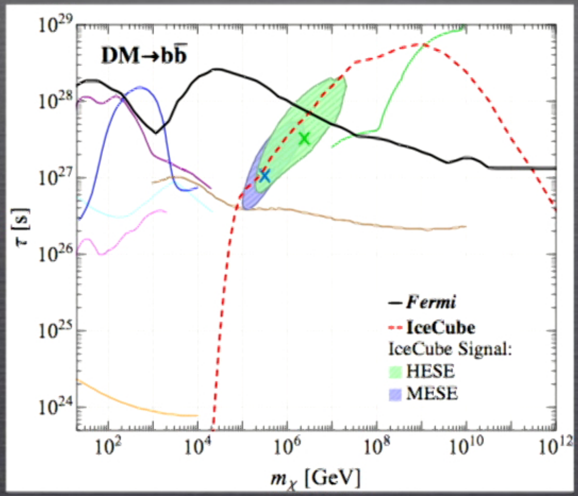
Dark Matter at Fermi: Systematics



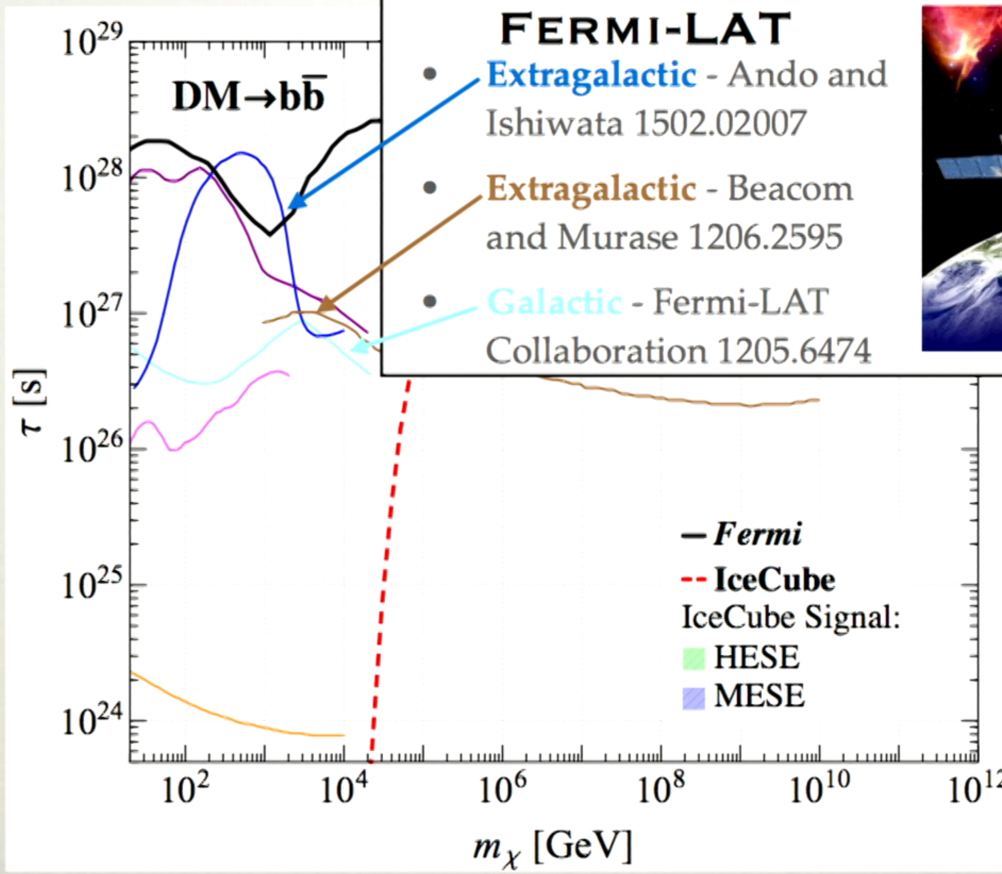
Dark Matter at Fermi: Systematics



Other Constraints



Dark Matter Constraints: Other Sources



Fermi-LAT

- **Extragalactic** - Ando and Ishiwata 1502.02007
- **Extragalactic** - Beacom and Murase 1206.2595
- **Galactic** - Fermi-LAT Collaboration 1205.6474

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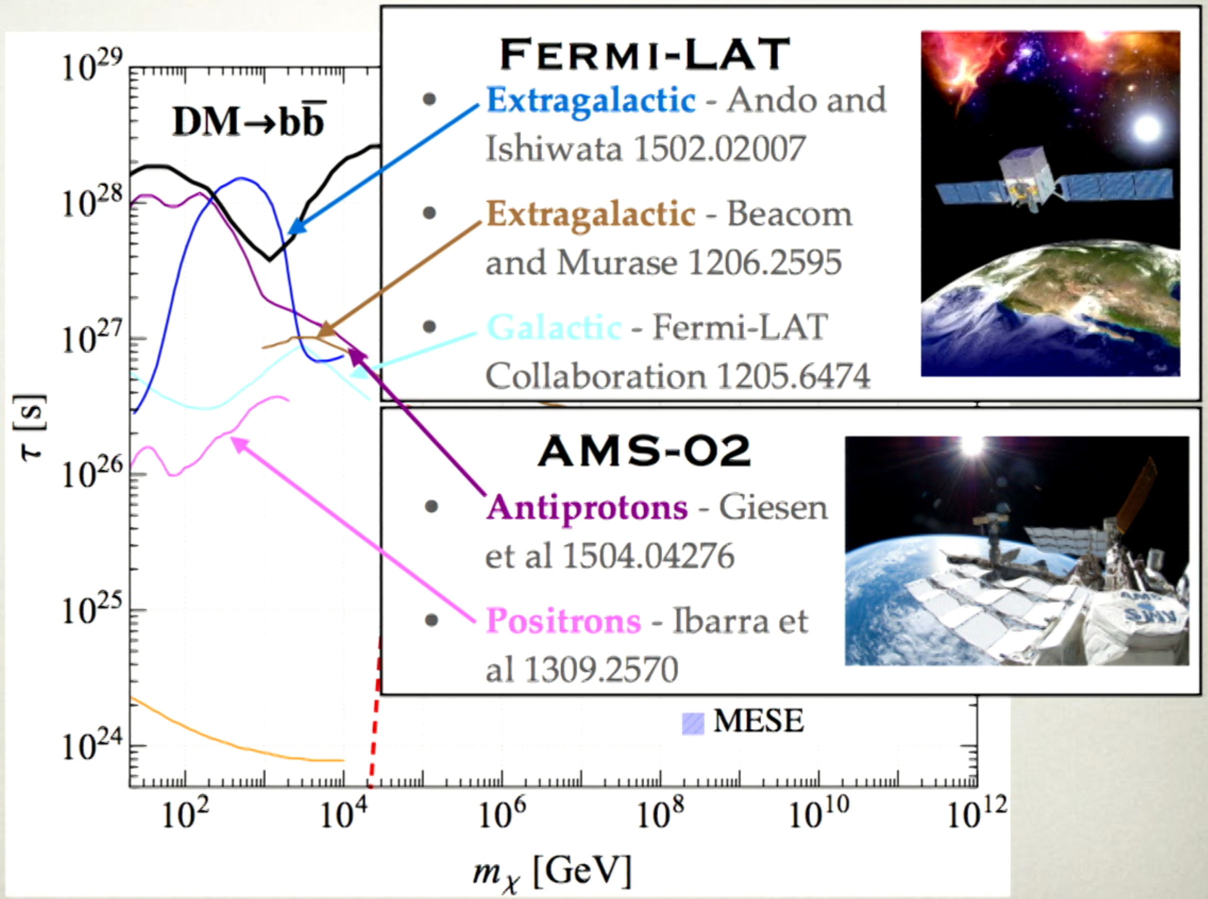
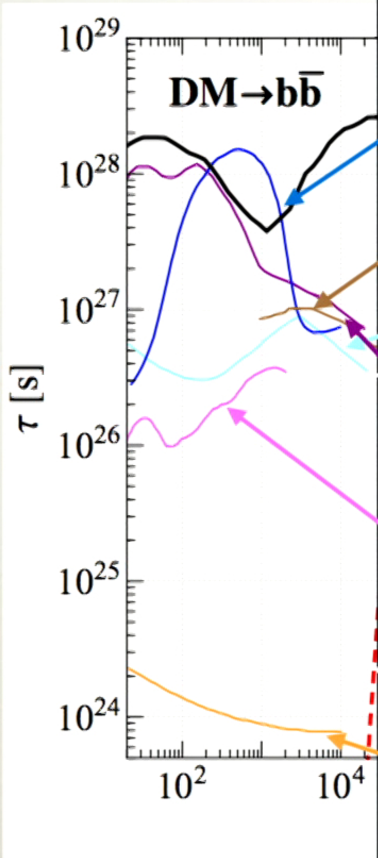
Dark Matter Constraints: Other Sources



Dark Matter Constraints: Other Sources



Fermi-LAT

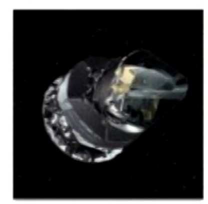
- **Extragalactic** - Ando and Ishiwata 1502.02007
- **Extragalactic** - Beacom and Murase 1206.2595
- **Galactic** - Fermi-LAT Collaboration 1205.6474

AMS-02

- **Antiprotons** - Giesen et al 1504.04276
- **Positrons** - Ibarra et al 1309.2570

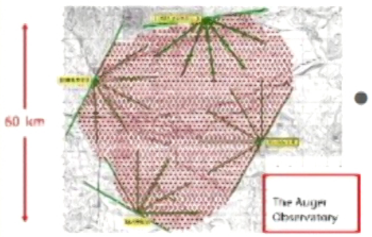
Planck

- **CMB** - Slatyer and Wu 1610.06933

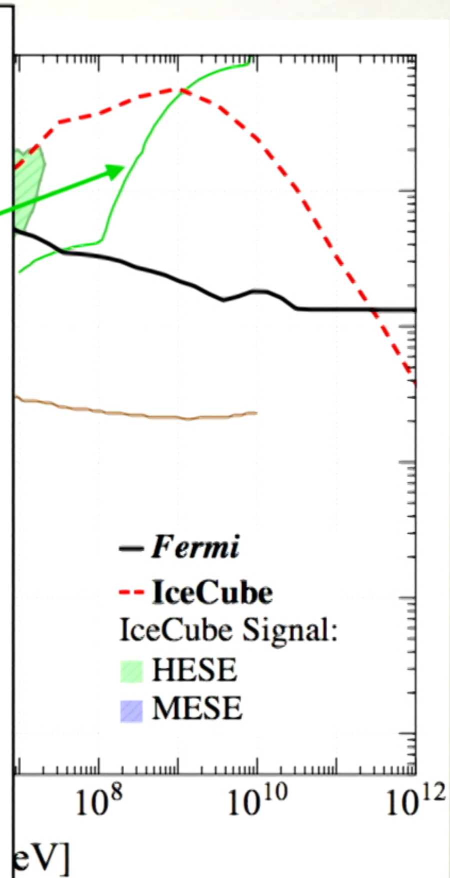


Dark Matter Constraints: Other Sources

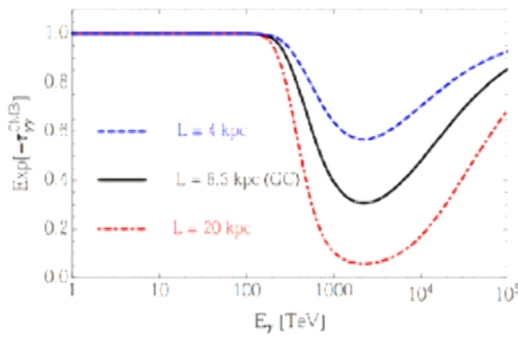
Pierre Auger Observatory, KASCADE, CASA-MIA



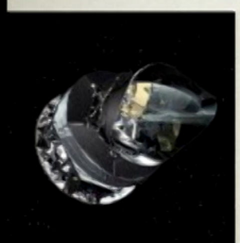
- **EAS** - Kalashev and Kuznetsov 1606.07354

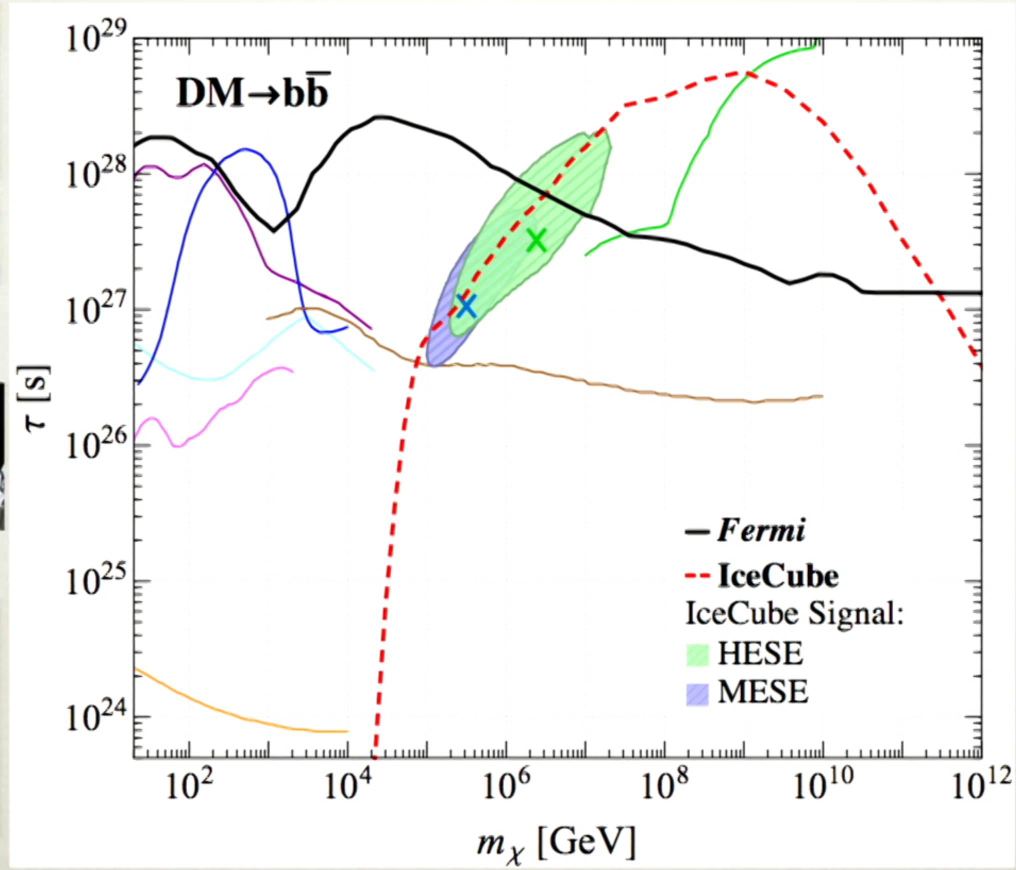


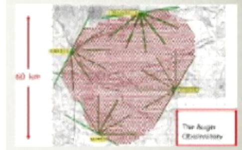
- Experiments have seen 0 photons
- At these energies galactic photons free stream to Earth, e.g. Esmaili and Serpico 1505.06486

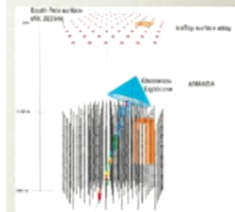


Dark Matter Constraints

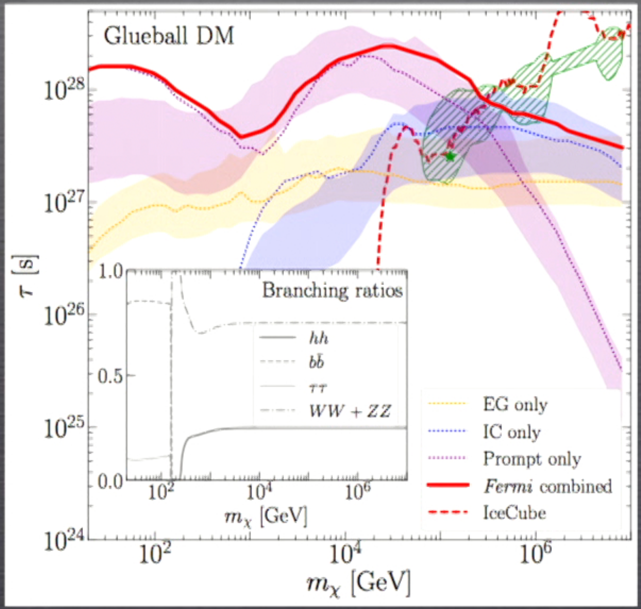




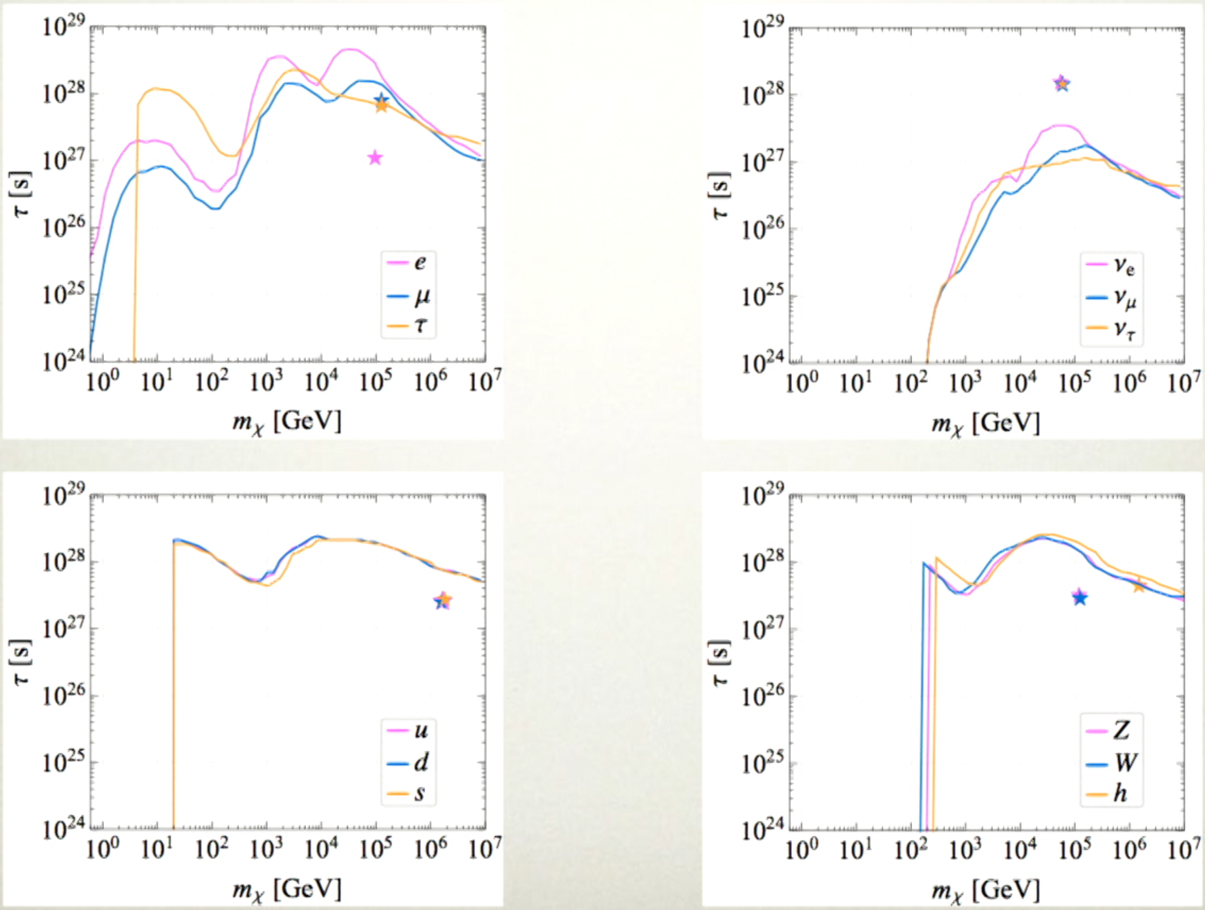




From Final States to Models

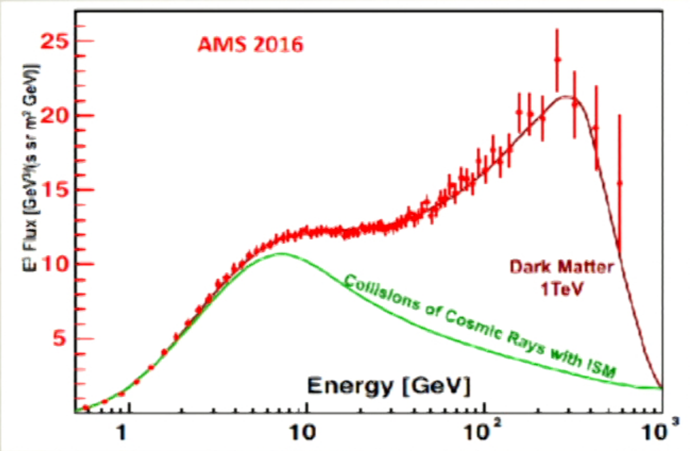


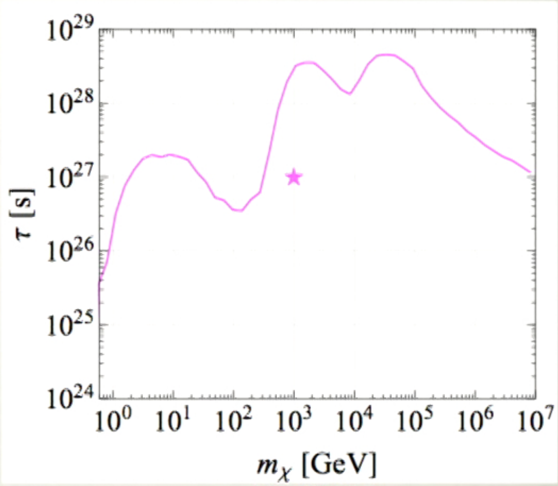
Dark Matter Constraints: Other Channels



Dark Matter Constraints: AMS-02 Positron Excess

- DM interpretations of the AMS-02 positron excess also appear to be in tension with our limits





https://cds.cern.ch/record/2238506

Towards a more realistic Model

- Converting a final state to a model: $\mathrm{DM} \to f\bar{f}$
- Potentially as a Z′ model:

$$\mathcal{L} \supset g Z'_\mu \bar{f} \gamma^\mu f$$

- For this model:

$$\Gamma \sim \frac{g^2 m_{Z'}}{16\pi}$$

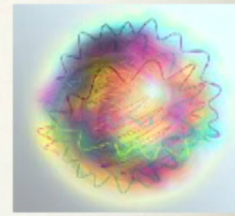
- For the interesting IceCube range:

$$m_Z \sim \mathrm{PeV}\ , \quad \tau \sim 10^{27}\ \mathrm{s} \quad \Rightarrow \quad g \sim 10^{-28}$$

- Not the most compelling model!
- What about more realistic models? Popular e.g. gravitino

Towards a more realistic Model: GlueBalls

- **Glueballs:** lowest lying state of a hidden sector containing only a confining SU(N) gauge theory (dark QCD)
  - Naturally long lived and thereby a DM candidate
  - Mass at the confinement scale - for SU(3) unifying with the SM can get $m \sim 100$ TeV



- Lowest order coupling to the standard model is dim-6

$$\mathcal{L} \supset \frac{\lambda'}{\Lambda^2} G'_{\mu\nu} G'^{\mu\nu} |H|^2 \;\rightarrow\; \lambda' \frac{\Lambda^3_{\mathrm{QCD}'}}{\Lambda^2} \phi_{G'} |H|^2$$

- The lifetime then comes out as:

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

Get a similar scaling for SUSY GUT models, see Arvanitaki et al 0812.2075 and 0904.2789

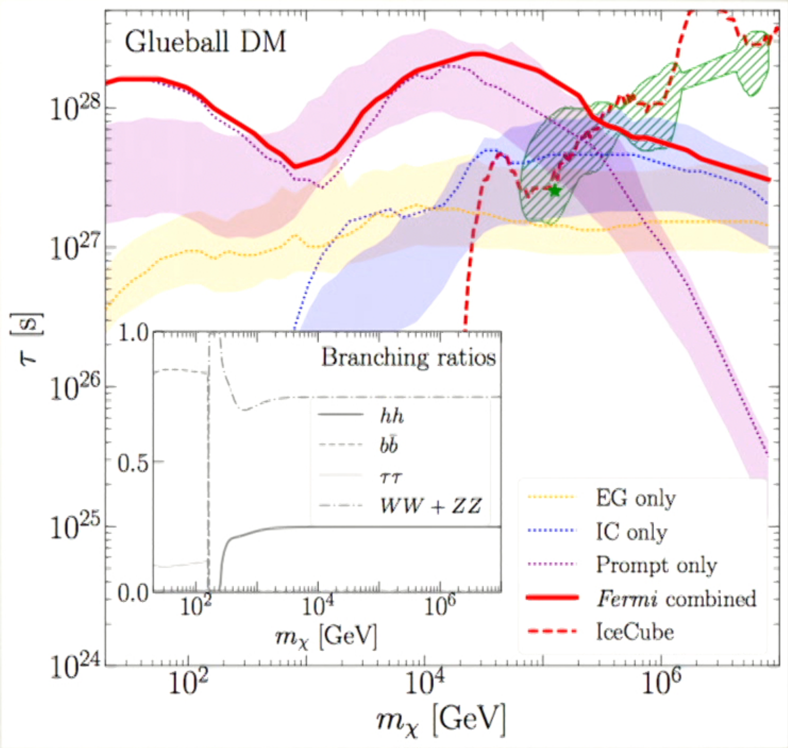
For Glueballs as a model of SIDM see e.g. hep-ph/0008223 or 1402.3629
For recent discussions see e.g. 1605.08048 or 1609.02151

Towards a more realistic Model: GlueBalls

- If assume minimal model:

$$\phi_{G'}|H|^2$$

- can set limits using Flux-TS tables
- Even in this more realistic scenario, a large part of the IceCube parameter region is excluded
- Flux-TS tables are publicly available along with all our limits: https://dspace.mit.edu/handle/1721.1/105550



CONCLUSION

- IceCube is already probing an interesting parameter space for PeV scale decaying dark matter
- These models also predict a photon flux at Fermi - the derived limits are an important input for DM interpretations of IceCube
- Our work improves these limits more than an order of magnitude and extends them to the PeV mass range