IceCube and Fermi-LAT: Complementary Limits on Heavy Dark Matter

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Based on soon to appear work w/ Tim Cohen, Kohta Murase, Ben Safdi and Yotam Soreq

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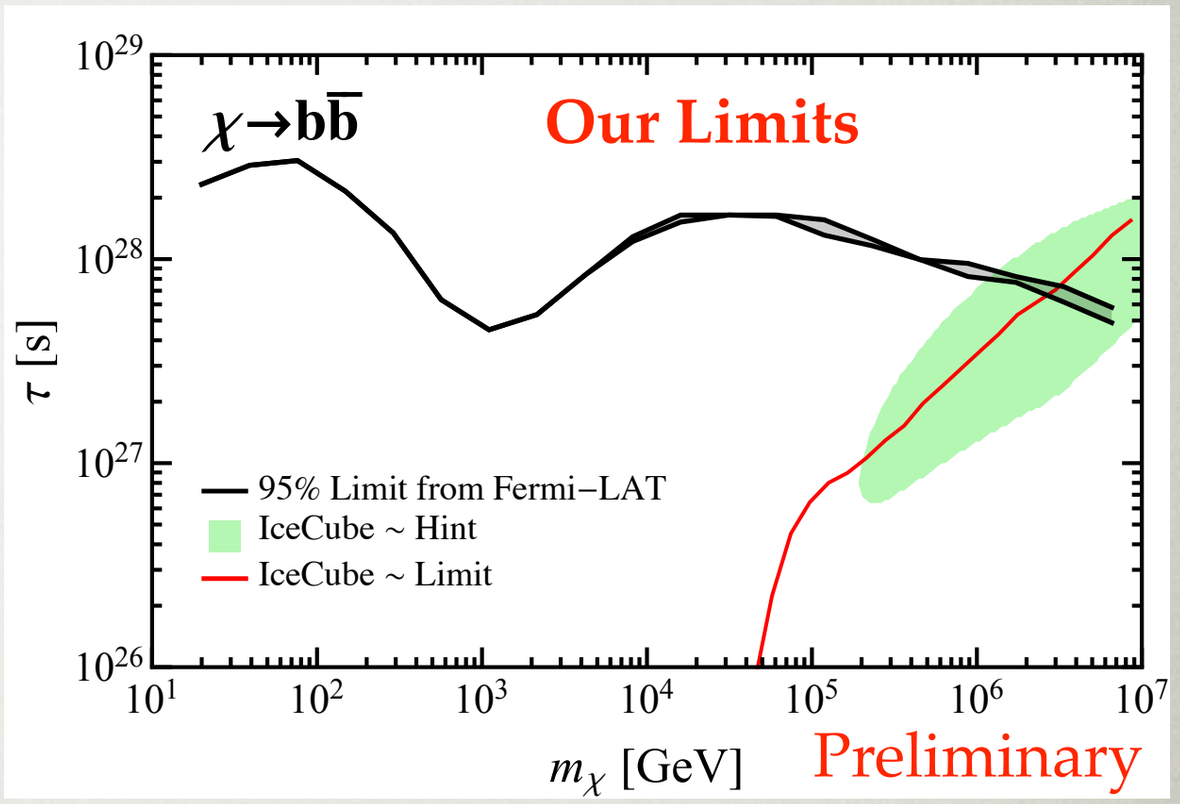
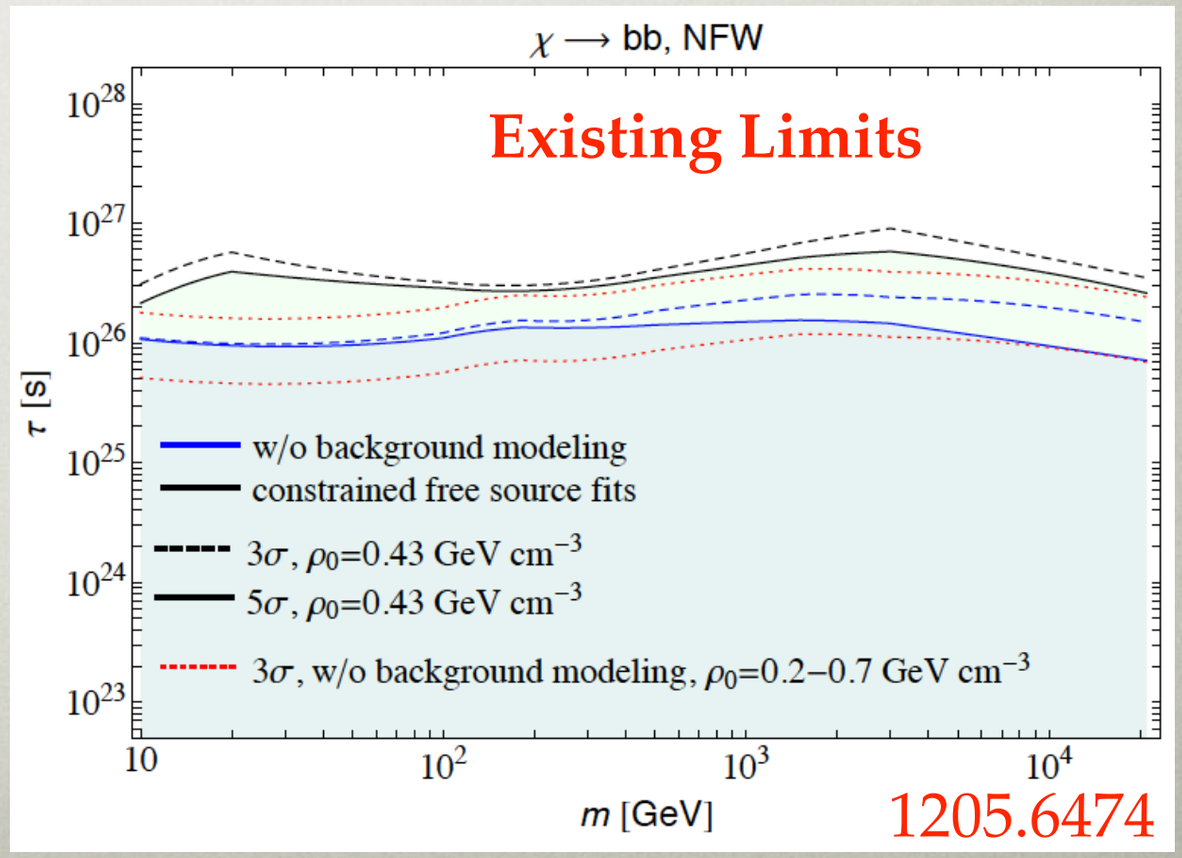
Outline

- Dark Matter decay = **neutrinos** + **photons**
- IceCube + Fermi-LAT
- We **improve** limits by over an order of magnitude
- Also extending them to **higher masses**



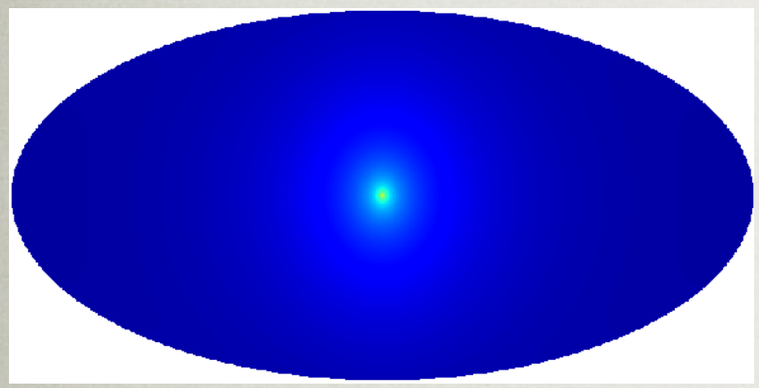


Heavy Dark Matter Decay

- **Fundamentally:** nothing forbids DM with a mass >> TeV
- Many dark matter decay models exist with masses in this range
- **Key feature of these models:** might only be testable via indirect detection - IceCube and Fermi-LAT
  - Number density too low for nuclear scattering
  - Mass too high for colliders

Heavy Dark Matter Decay

Decays in the Milky Way



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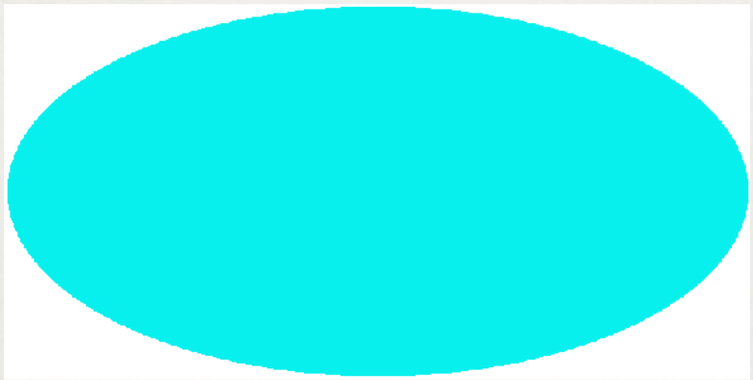
Extragalactic Decays



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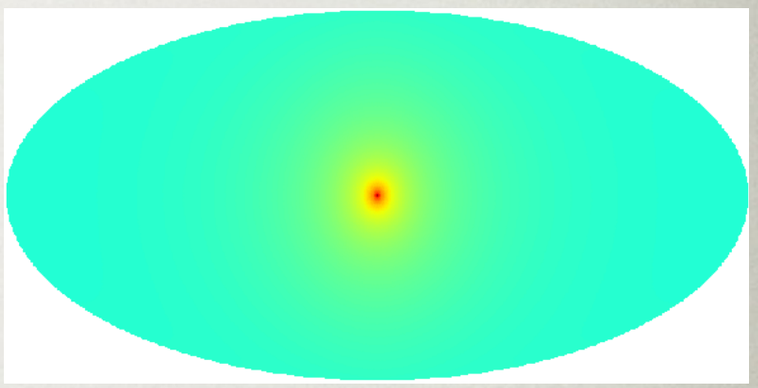
Total Flux



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

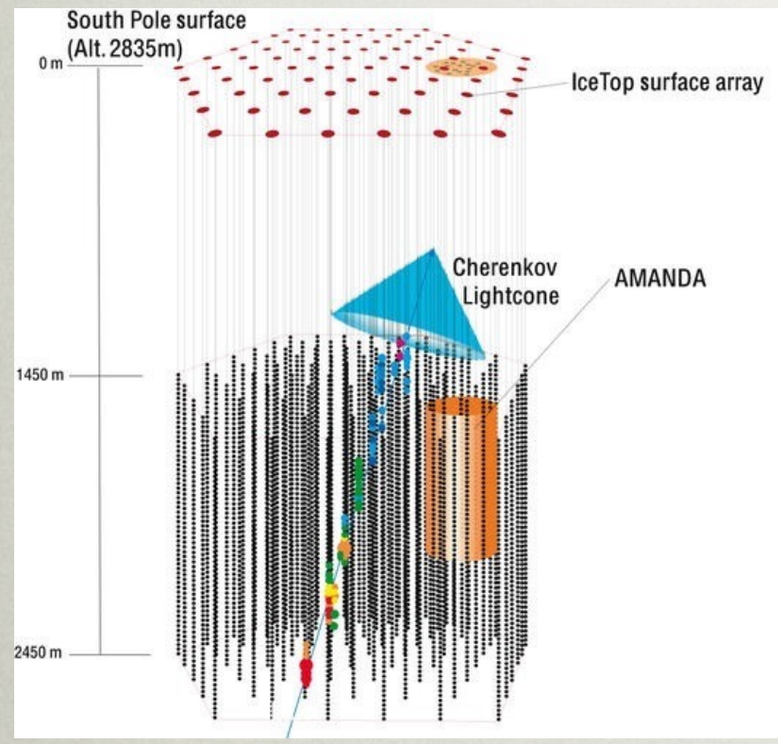
$$\Phi_{\rm EG} = \frac{\rho_{\rm EG}}{4\pi m_\chi \tau}\int \frac{cdz}{H(z)}\ \frac{dN}{dE'}\bigg|_{E'=(1+z)E}$$

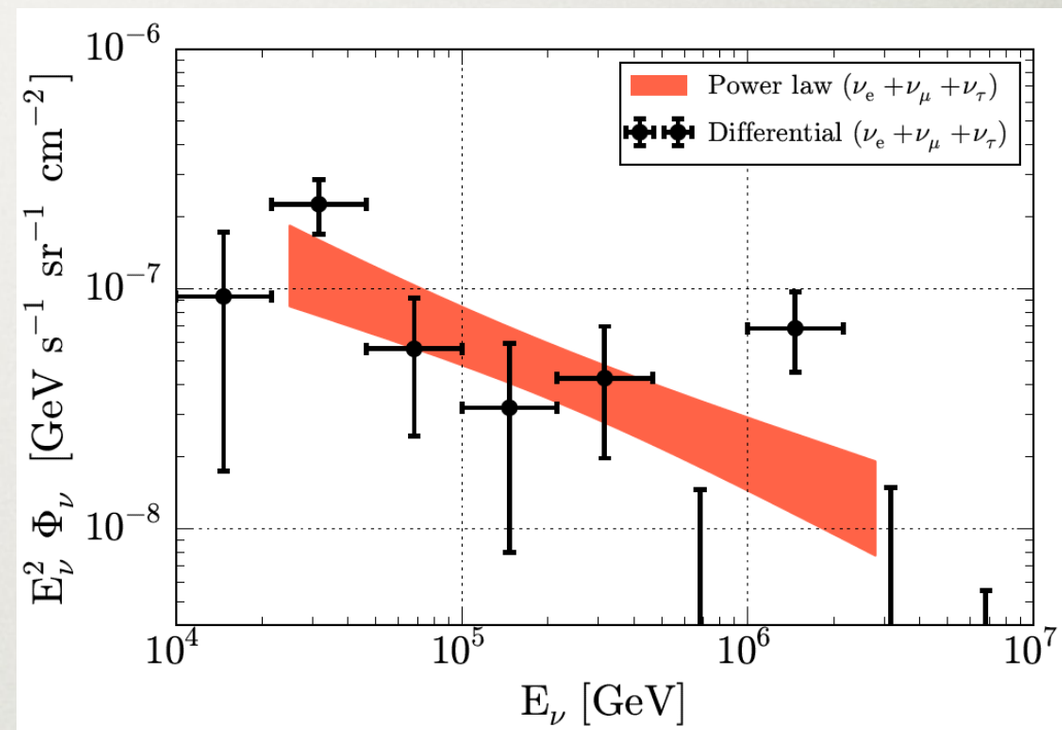
$$\Phi_{\rm total} = \Phi_{\rm G} + \Phi_{\rm EG}$$

- Neutrinos travel straight from the source to us (photons do not)
- 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

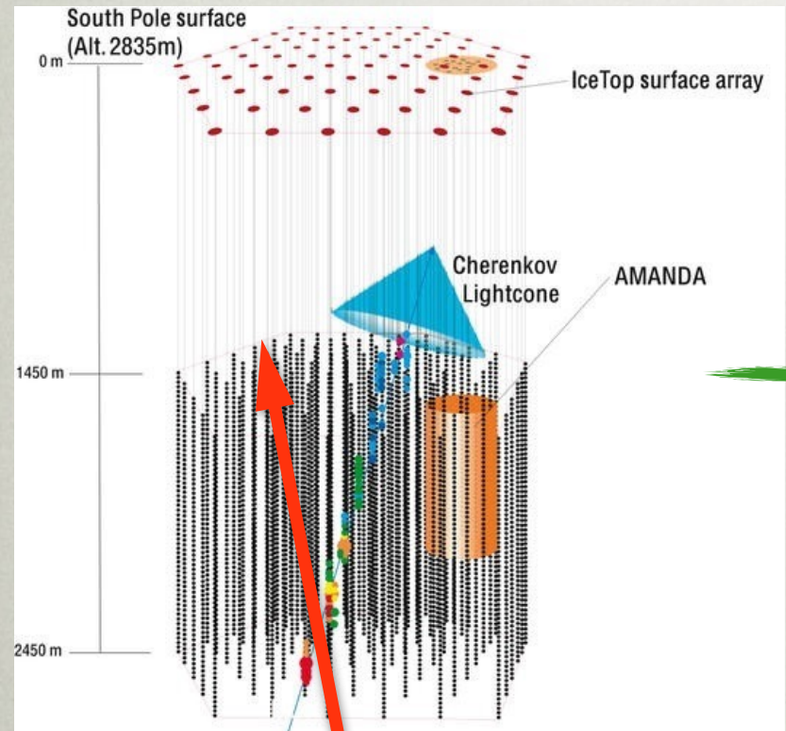


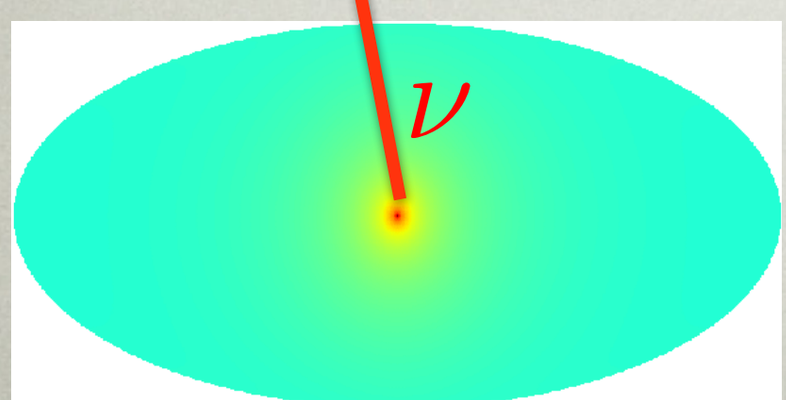


- Spectrum from Aartsen et al (The IceCube Collaboration) 1507.03991
- Determined via a combined maximum-likelihood analysis of six different IceCube analyses; fit shown is to a power law, $E^{-2.50\pm0.09}$

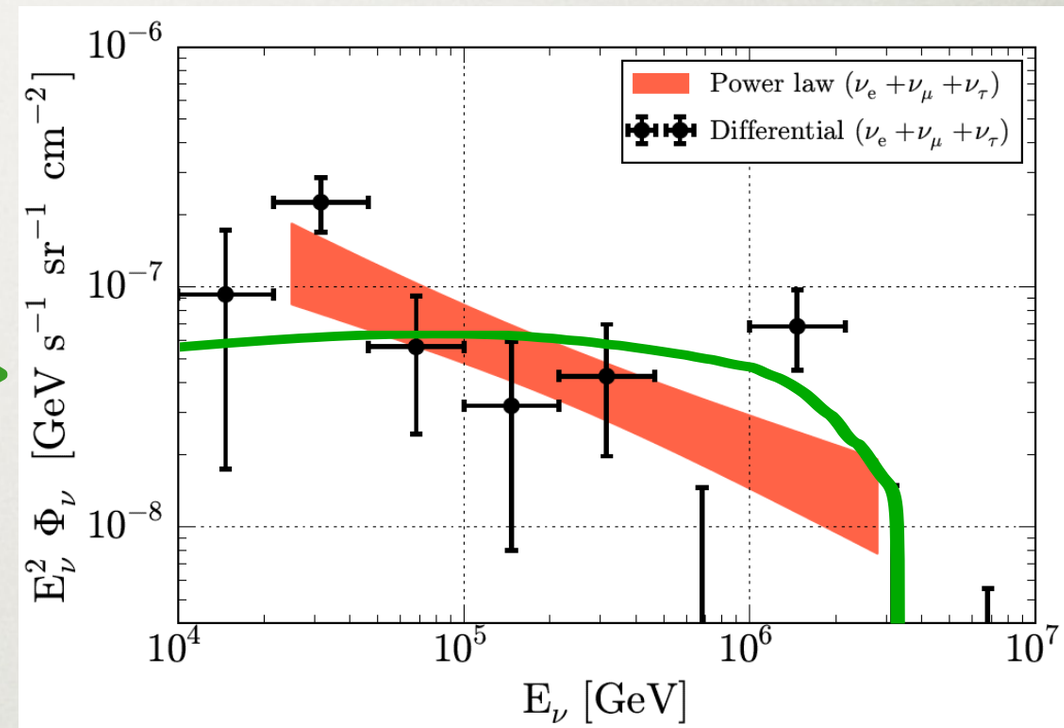
Dark Matter At IceCube

- 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

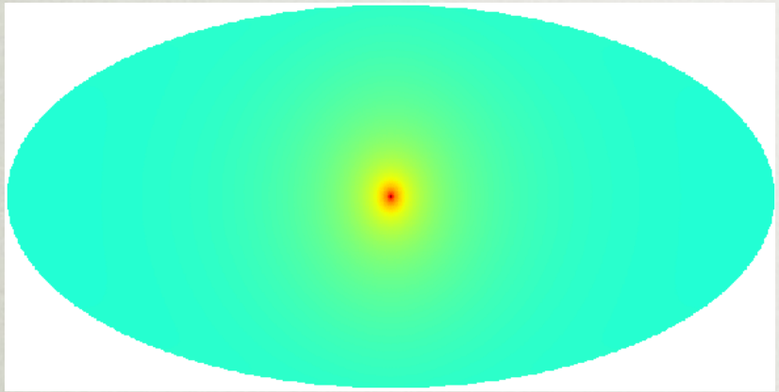


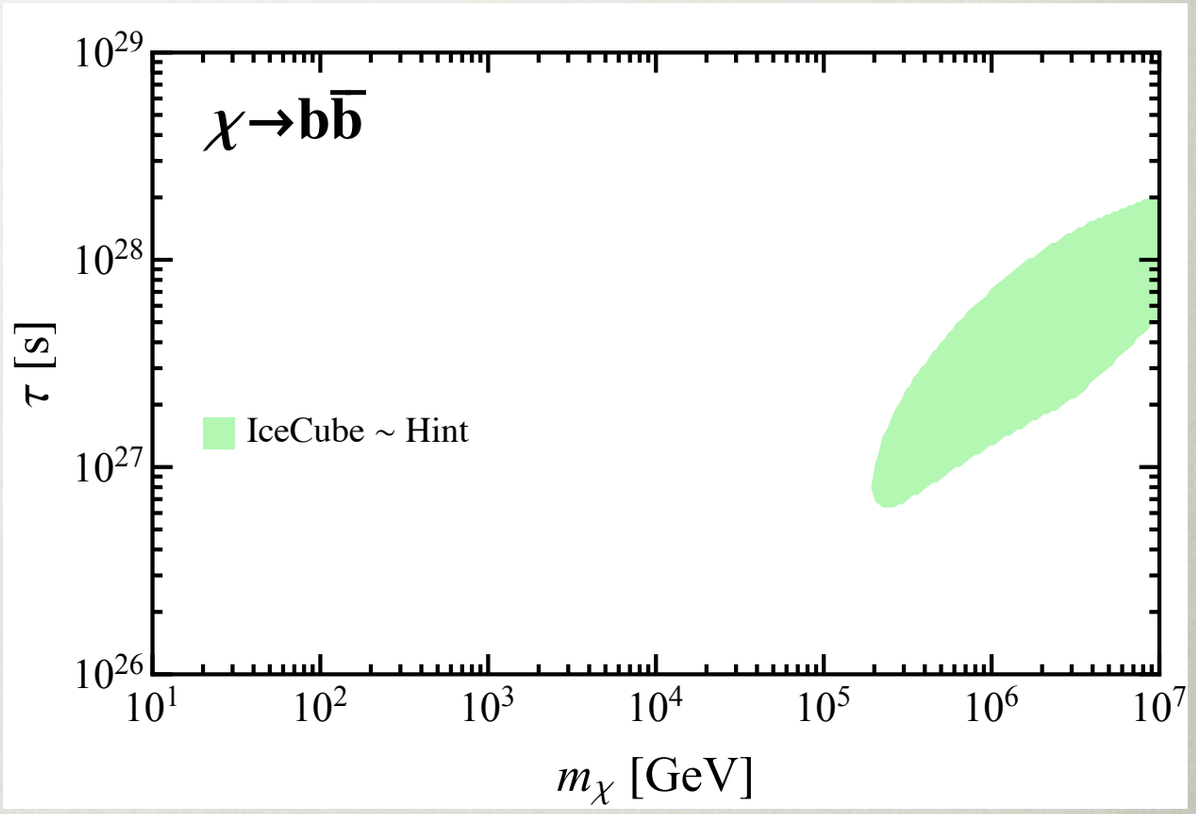
- Galactic and extragalactic DM decays can provide such neutrinos
- Expected DM anisotropy is consistent with the data, but also with an isotropic emission (see e.g. 1410.5979)

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

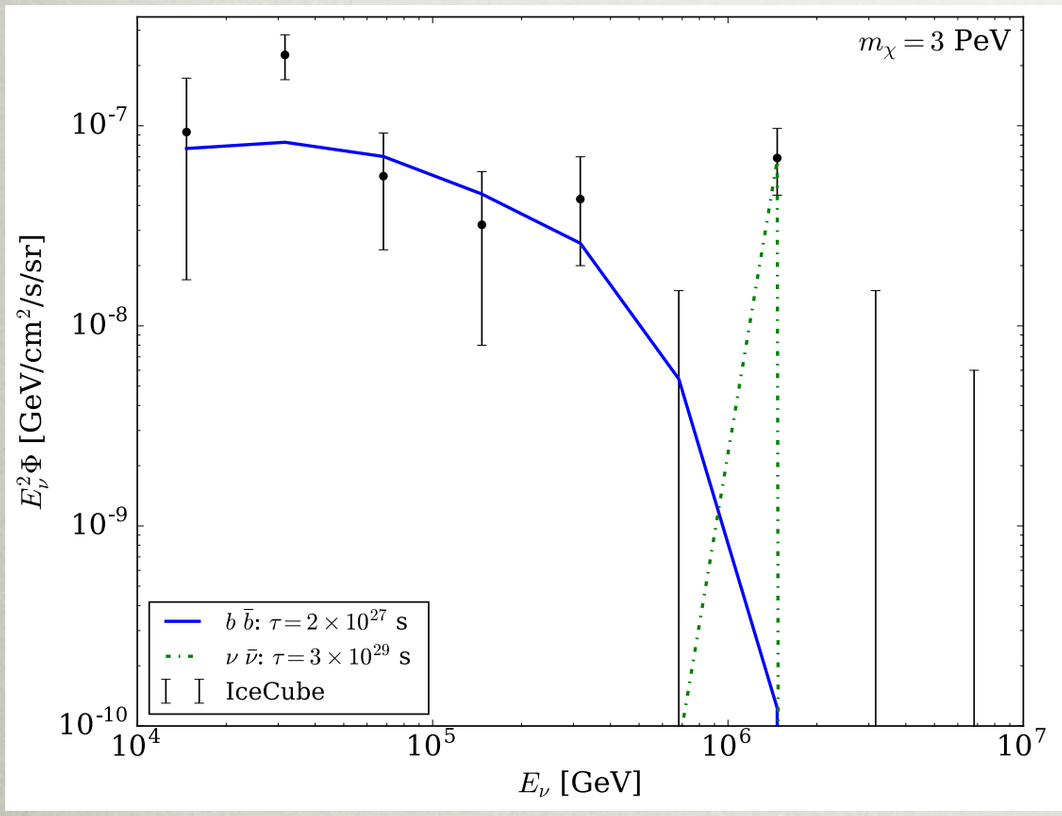


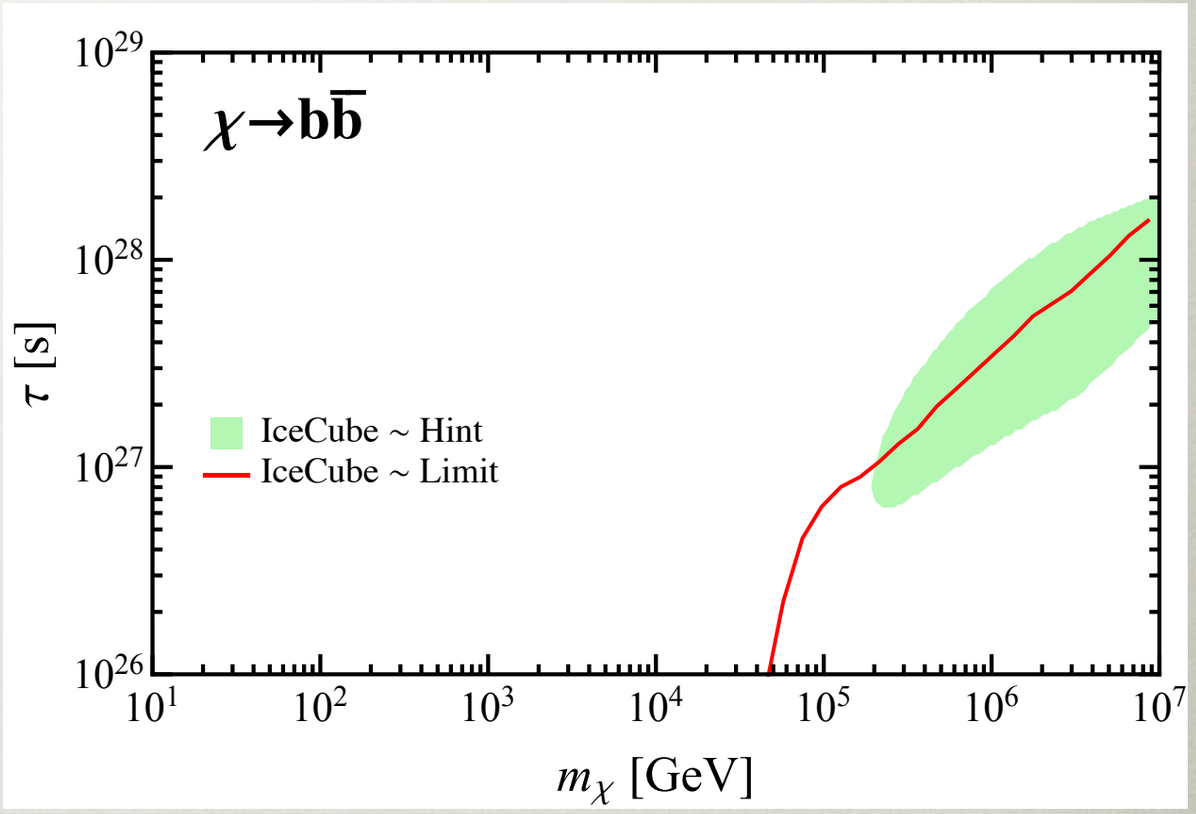


- Show the region in the m-τ plane where this channel can give a 3σ (relative to no DM) fit

Dark Matter At IceCube

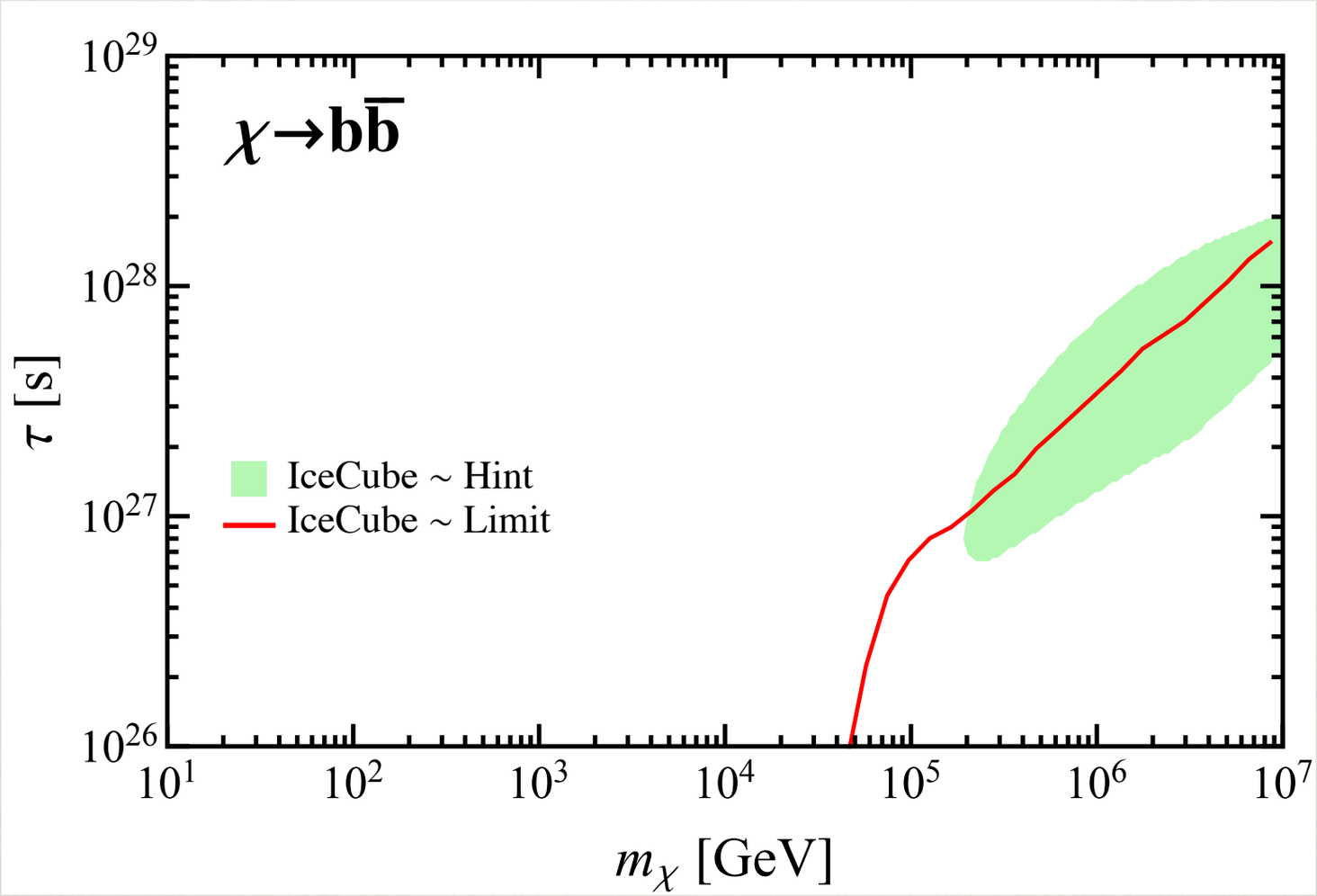
- To **calibrate our expectation** for the interesting parameter space, set limits assuming this flux was due to **astrophysics**





- Most channels more realistically only provide a feature of the spectrum
- As such model the flux as astrophysical: $\Phi^{\nu}_{\rm astro} \propto E^{-\gamma} e^{-E/E_{\rm cut}}$
- Set 95% limits on a DM contribution on top of this, via profile likelihood

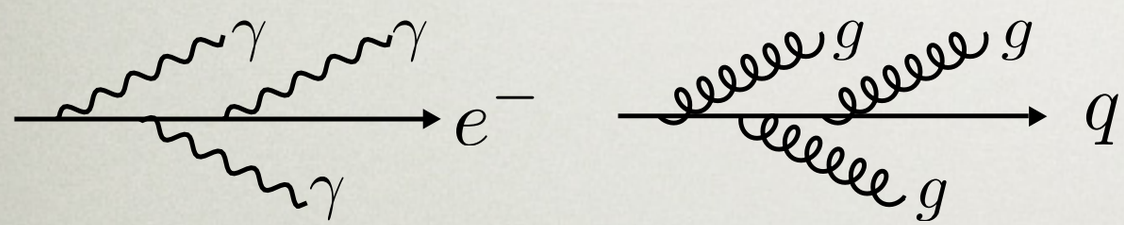
Dark Matter At IceCube



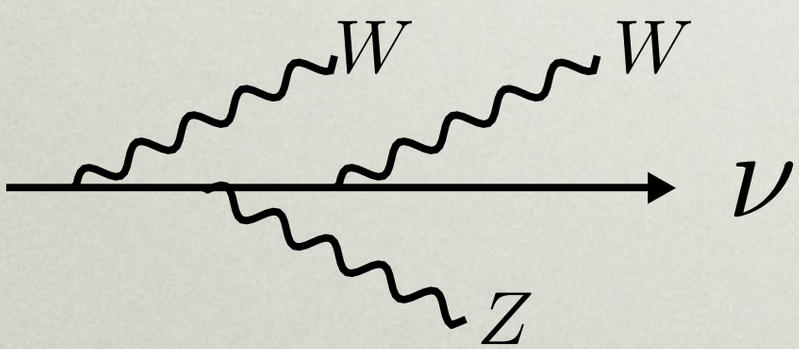
- This approach gives us a **suggestive** range of parameters that are relevant for IceCube
- This is the range we want to target using Fermi-LAT observations

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: $\chi \to \nu\bar{\nu}$
- Due to electroweak bremsstrahlung
- Photon/gluon radiation is familiar:

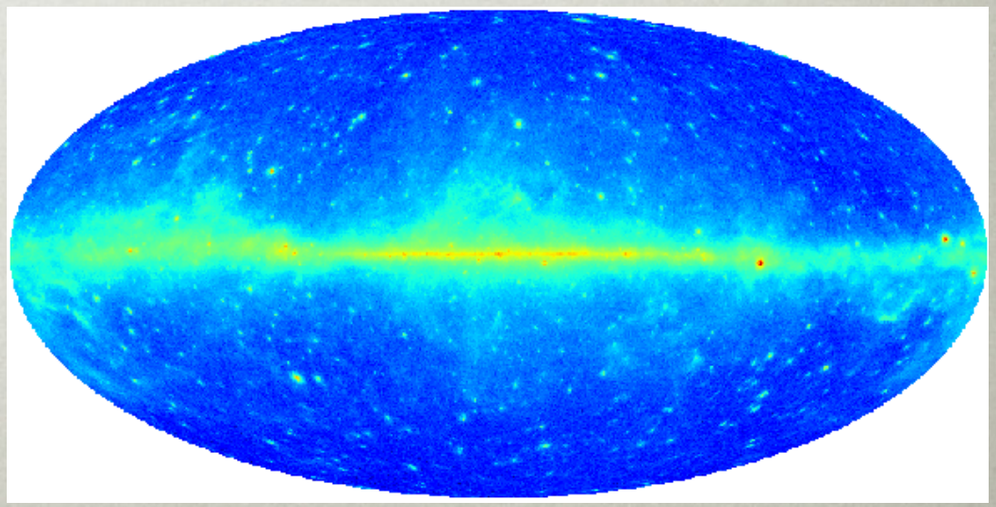


- Can also radiate W/Z bosons:



- Real effect, first measurements performed recently at ATLAS

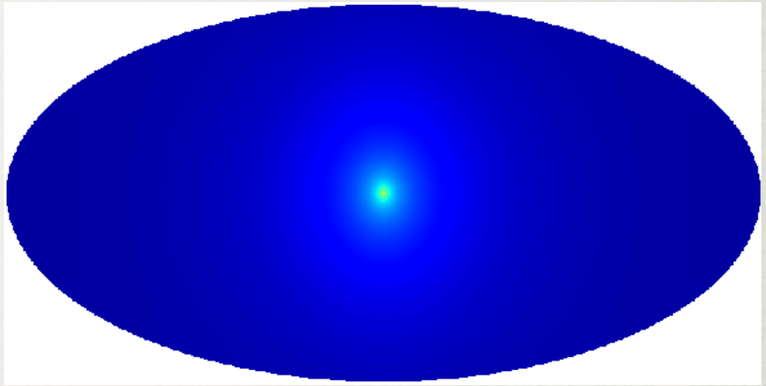
Fermi-LAT has collected more than 8 years of data from ~200 MeV - 2 TeV



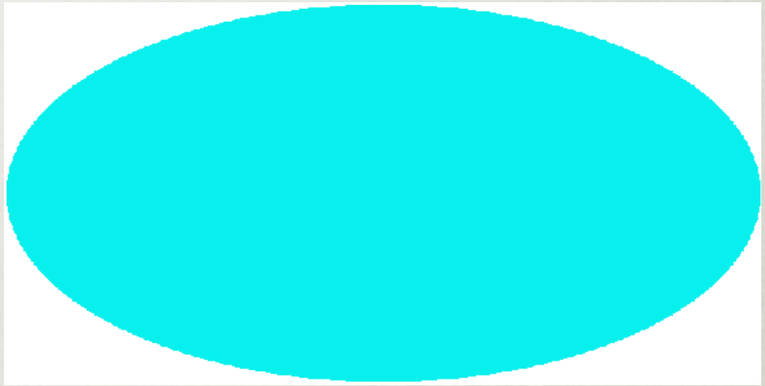
Dark Matter at Fermi: Spectrum

- **Prompt Galactic Spectrum:**
  - Photons ~ travel straight to us
- **Inverse Compton Galactic Spectrum:**
  - Prompt electrons 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

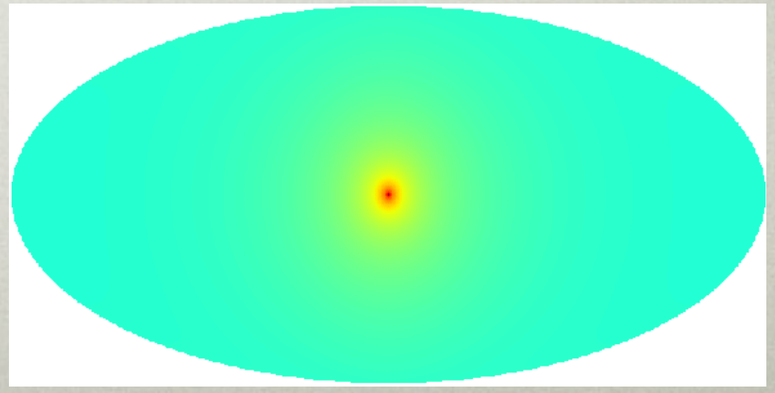
Decays in the Milky Way



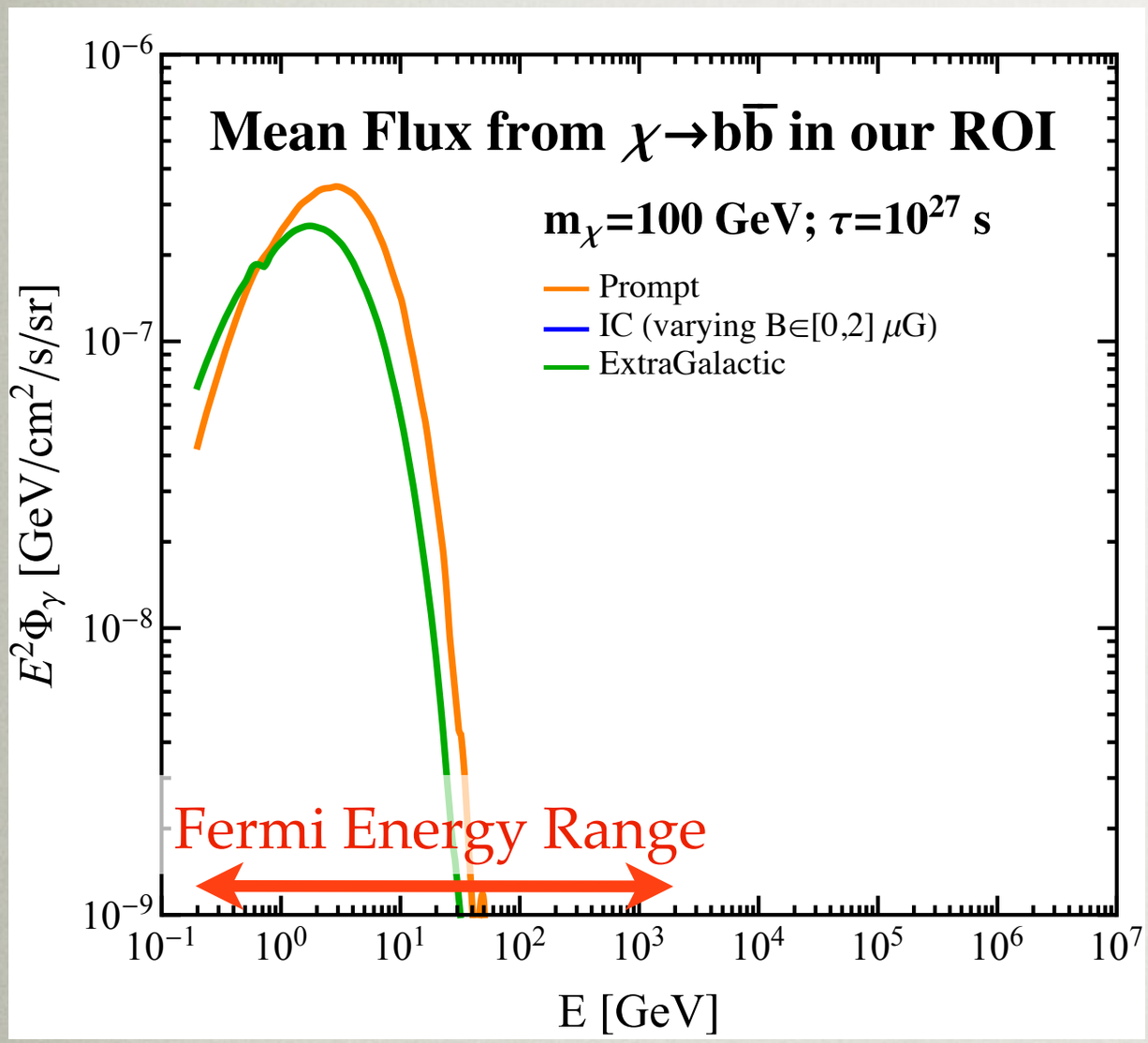
Extragalactic Decays

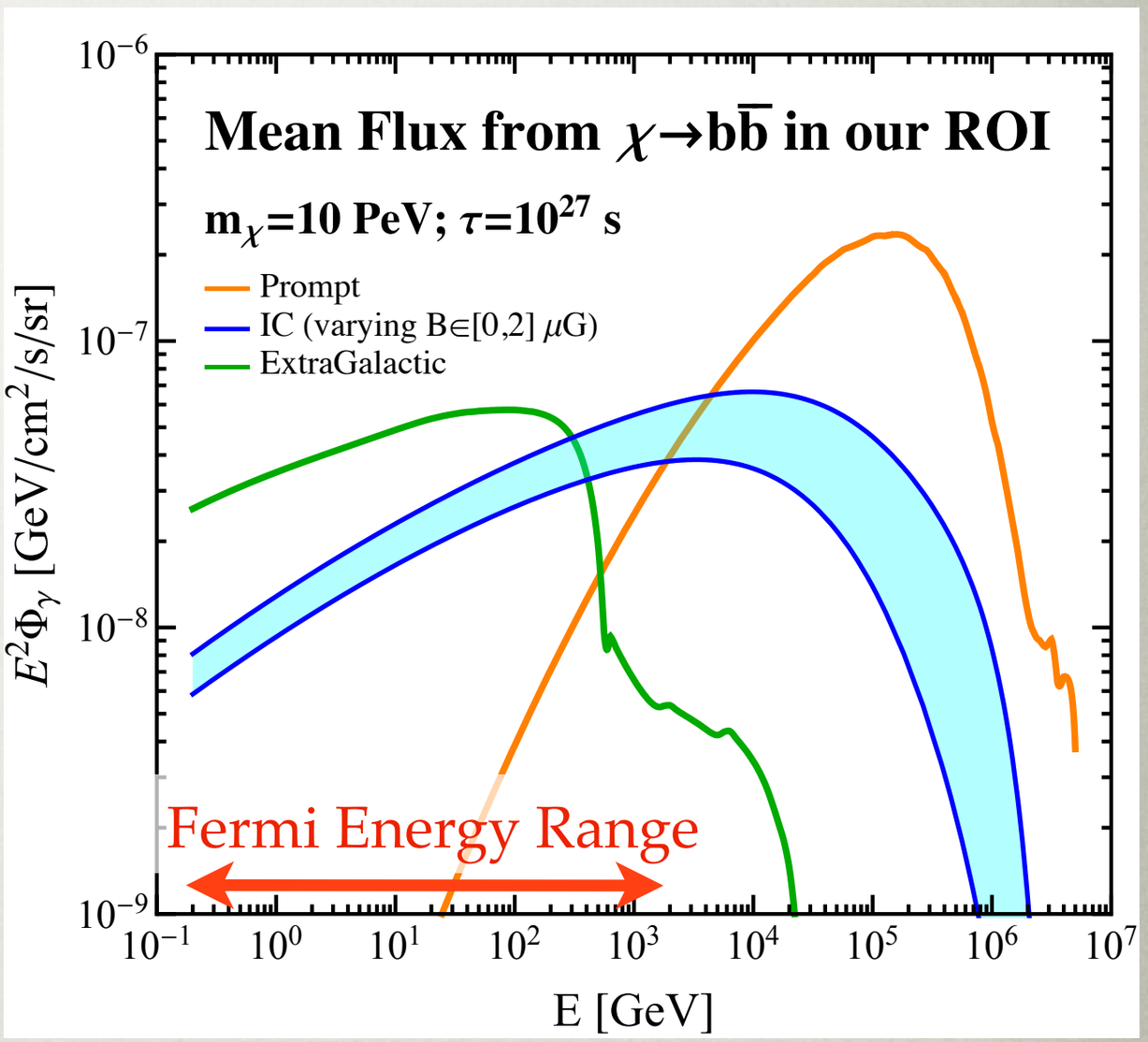


Total Flux



Dark Matter at Fermi: Spectrum

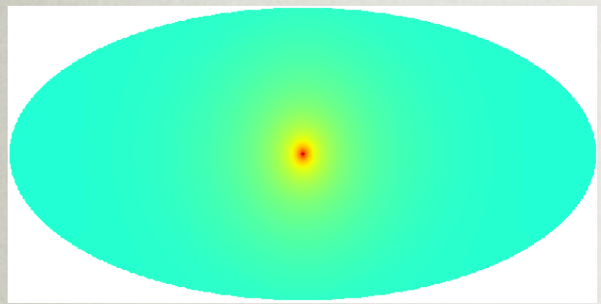




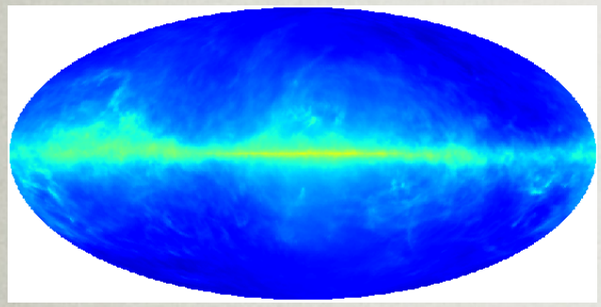
- At low masses the extragalactic contribution is subdominant, whereas Inverse Compton (IC) can be completely neglected
- At higher masses relevant for IceCube both effects are **crucial**

Dark Matter at Fermi: Profile Likelihood

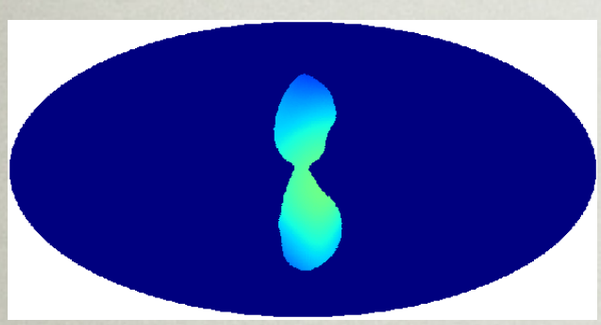
DM Decay



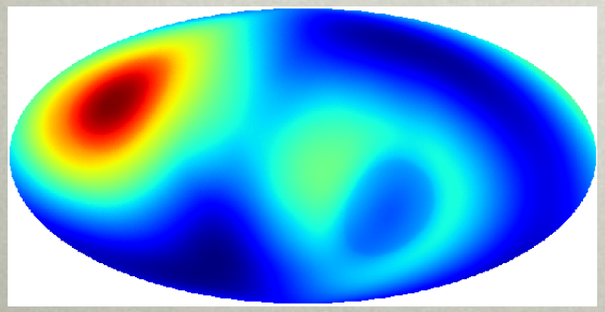
p8v6 Diffuse Model



Fermi Bubbles



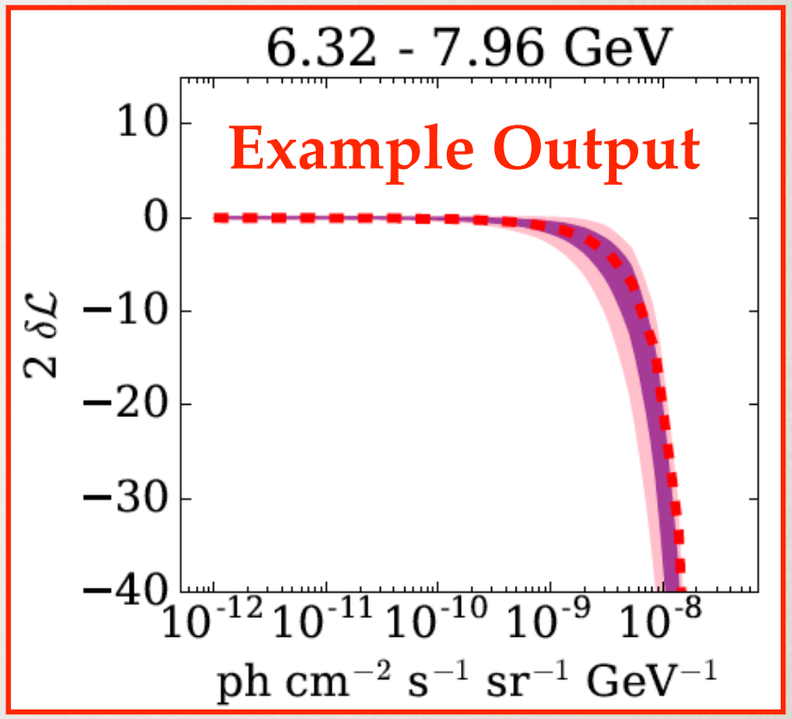
Isotropic Emission

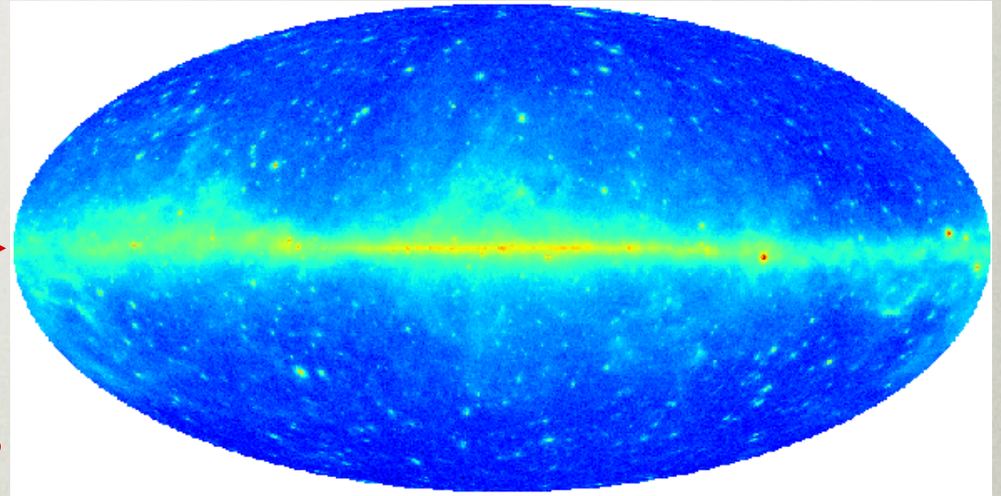


Fix a value of the galactic and extragalactic flux

Scan to find best fit values in each energy bin

Also point source model and mask (not shown)

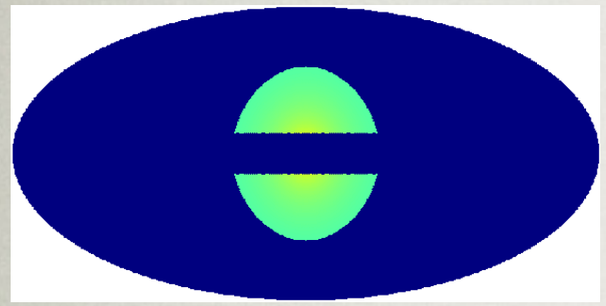




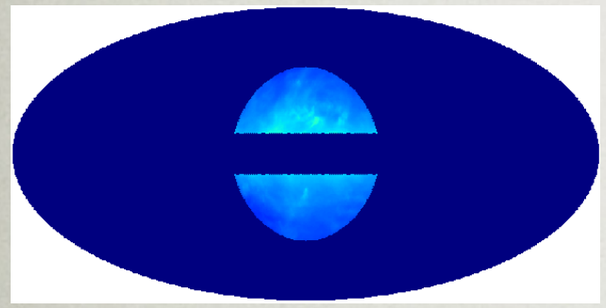
423 weeks of Fermi-LAT data
40 log spaced energy bins, from 200 MeV - 2 TeV
UltracleanVeto BestPSF

Dark Matter at Fermi: Profile Likelihood

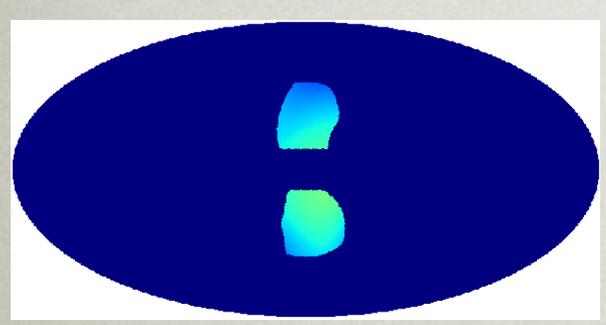
DM Decay



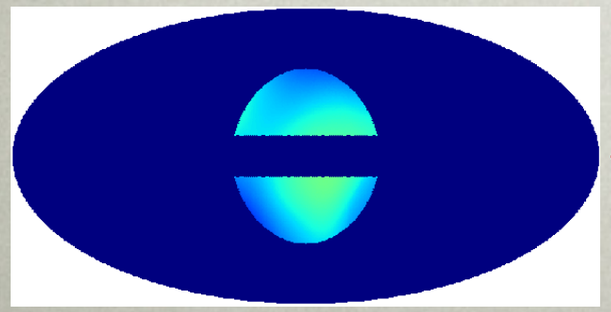
p8v6 Diffuse Model



Fermi Bubbles



Isotropic Emission

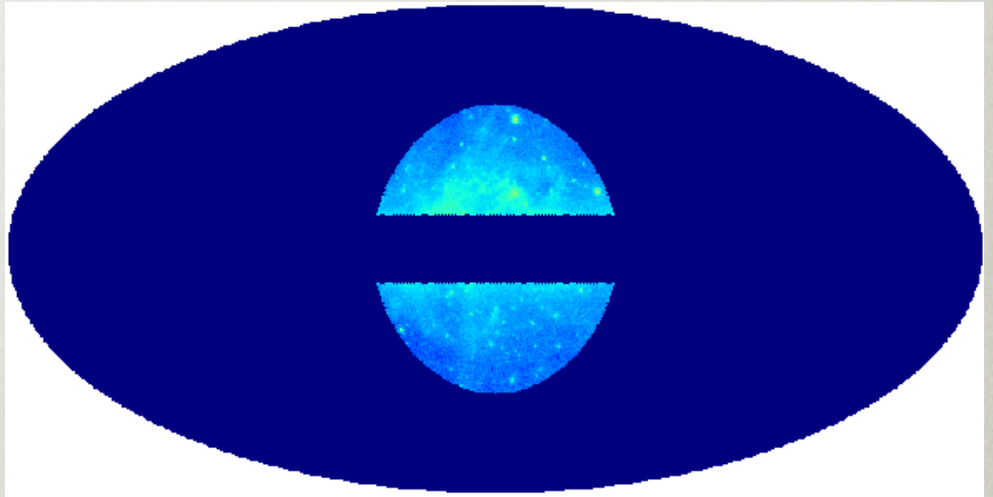


Fix a value of the galactic and extragalactic flux

Scan to find best fit values in each energy bin

Also point source model and mask (not shown)

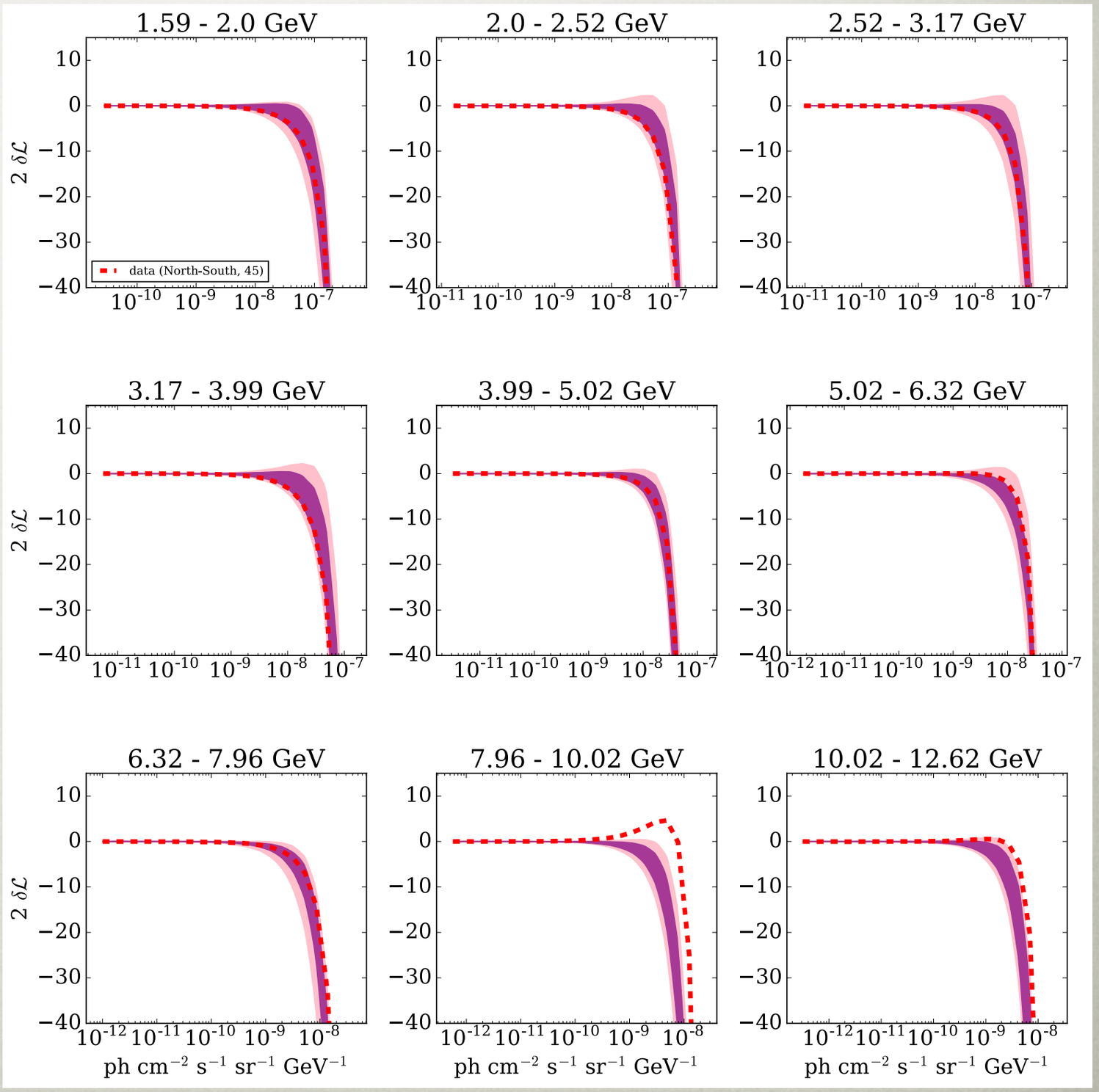
- Mask plane: $|b| < 10^\circ$
- Mask outside a ring: $r > 45^\circ$
- Still optimising spatial and energy ROI
- Choice of ROI is important for studying large scale structures in Fermi-LAT data
  - Galactic Center Excess, e.g. NR et al 1402.6703, NR et al 1604.01026
  - Fermi Bubbles, e.g. 1603.06582



423 weeks of Fermi-LAT data
40 log spaced energy bins, from 200 MeV - 2 TeV
UltracleanVeto BestPSF

Dark Matter at Fermi: Profile Likelihood

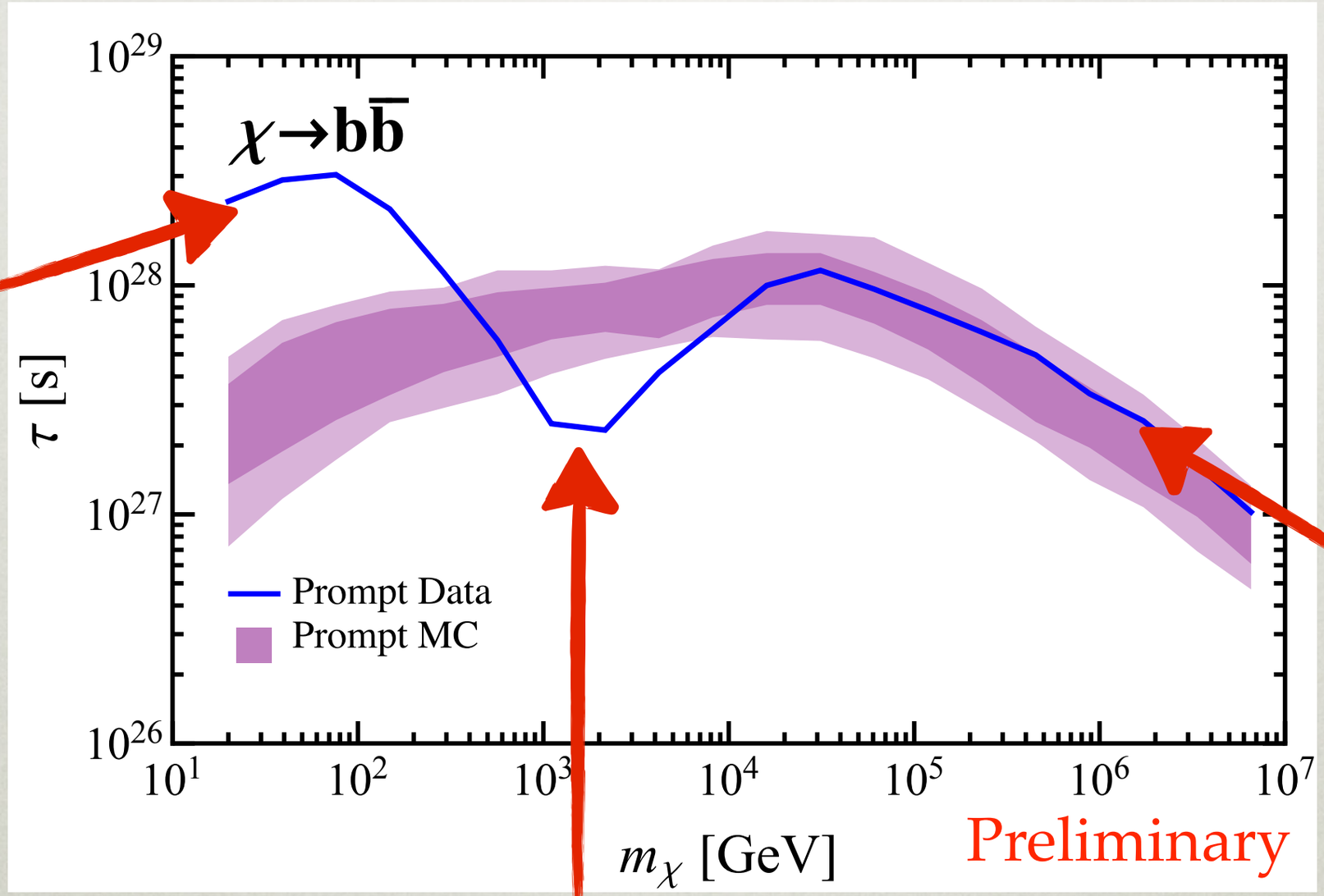
- Construct DM Flux versus Likelihood in all energy bins
  - 40 in total, 9 shown here
- Full scan is 2D: galactic and extragalactic flux
- Generally good agreement between data and MC
- For a given model can then derive 95% limits



Dark Matter at Fermi: Building Limits

- Start with the **prompt** galactic contribution

Limit stronger than expected due to over subtraction in lowest energy bins

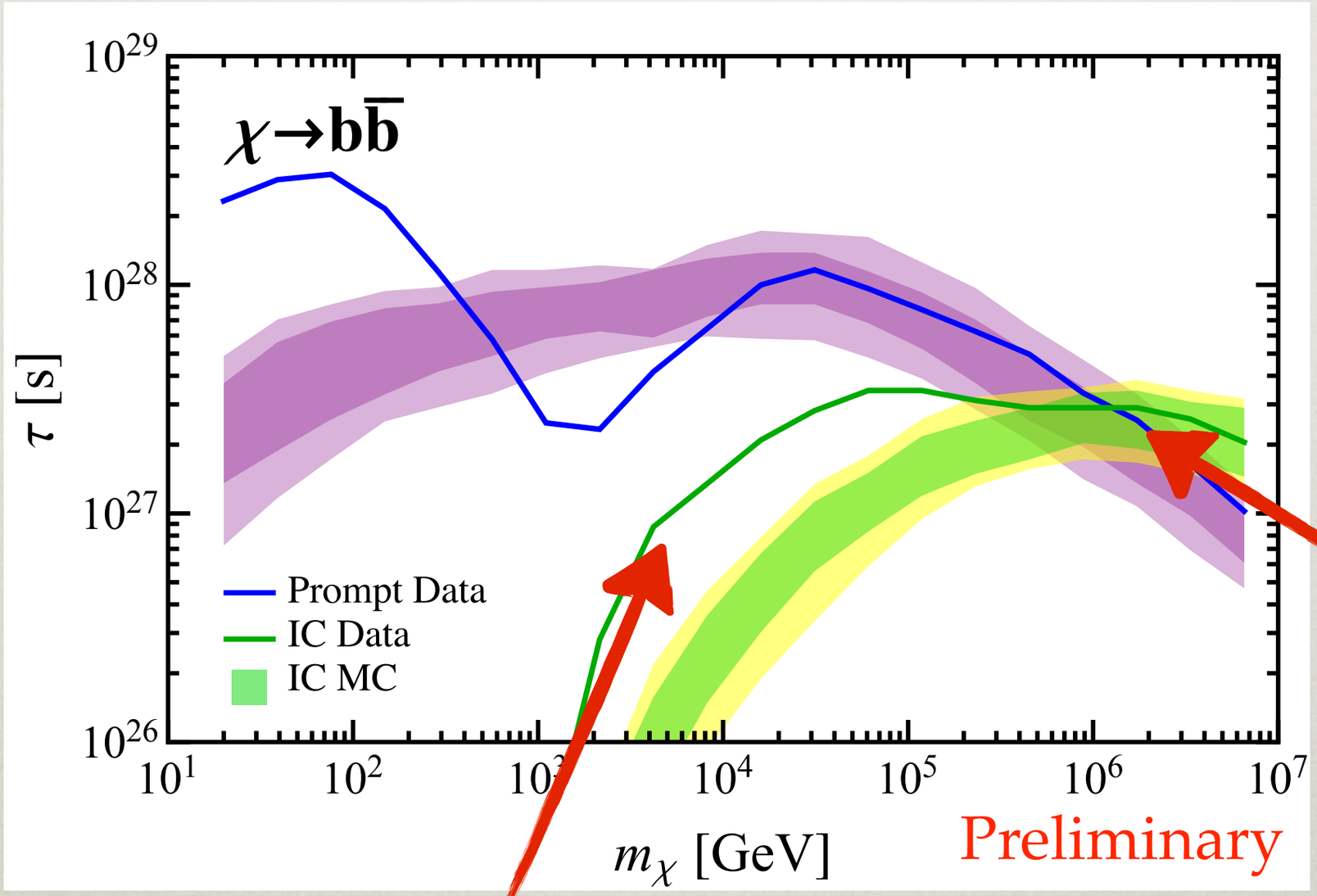


Data and MC in good agreement

Limit worse than expected due to mild excess at intermediate energies

Dark Matter at Fermi: Building Limits

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

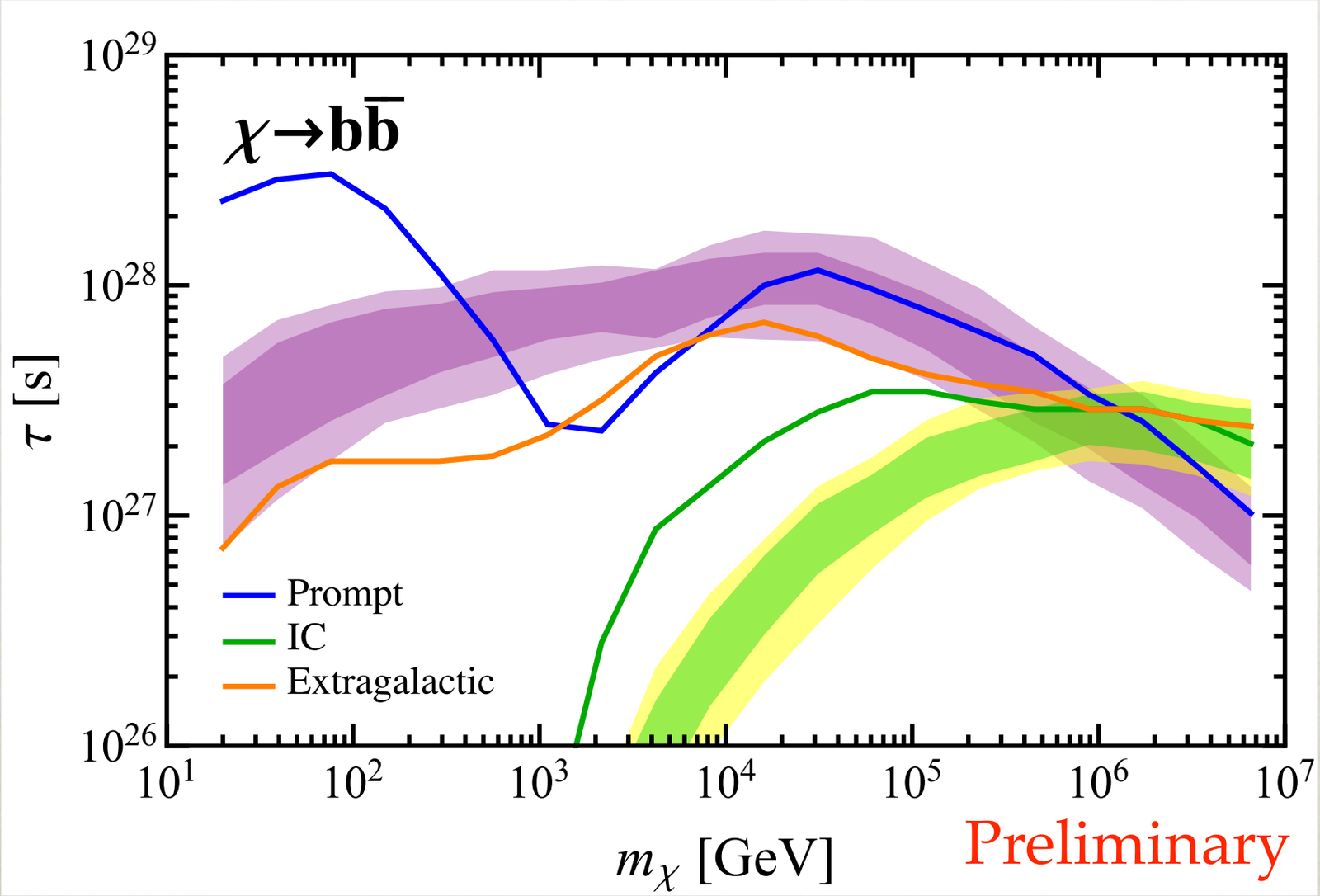


IC critical for PeV scale DM

Stronger limit again due to the lowest energy bins

Dark Matter at Fermi: Building Limits

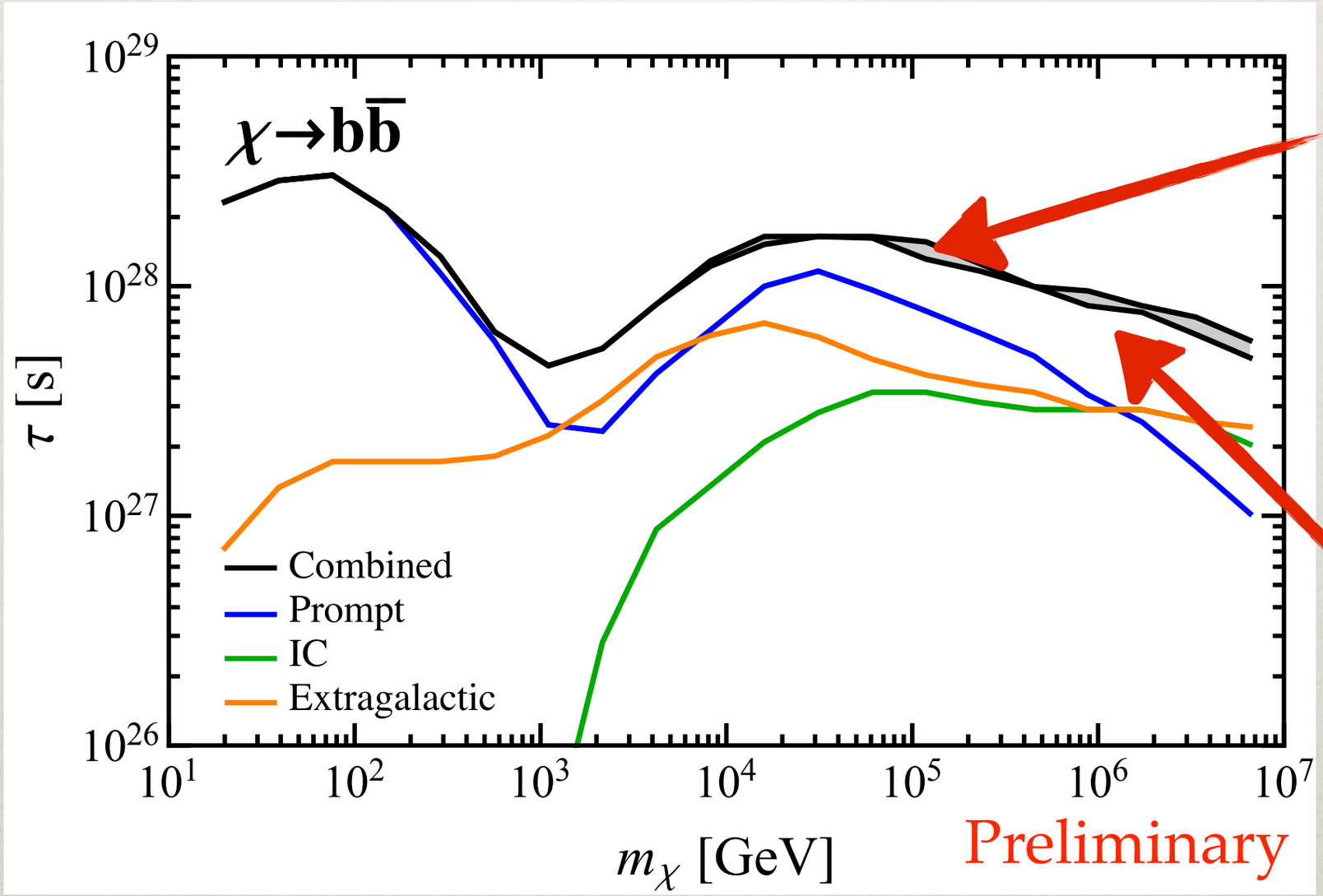
- Then add in the extragalactic contribution



EG important
above ~ 1 TeV

Dark Matter at Fermi: Building Limits

- Finally combine all three for the **full 95% limit**

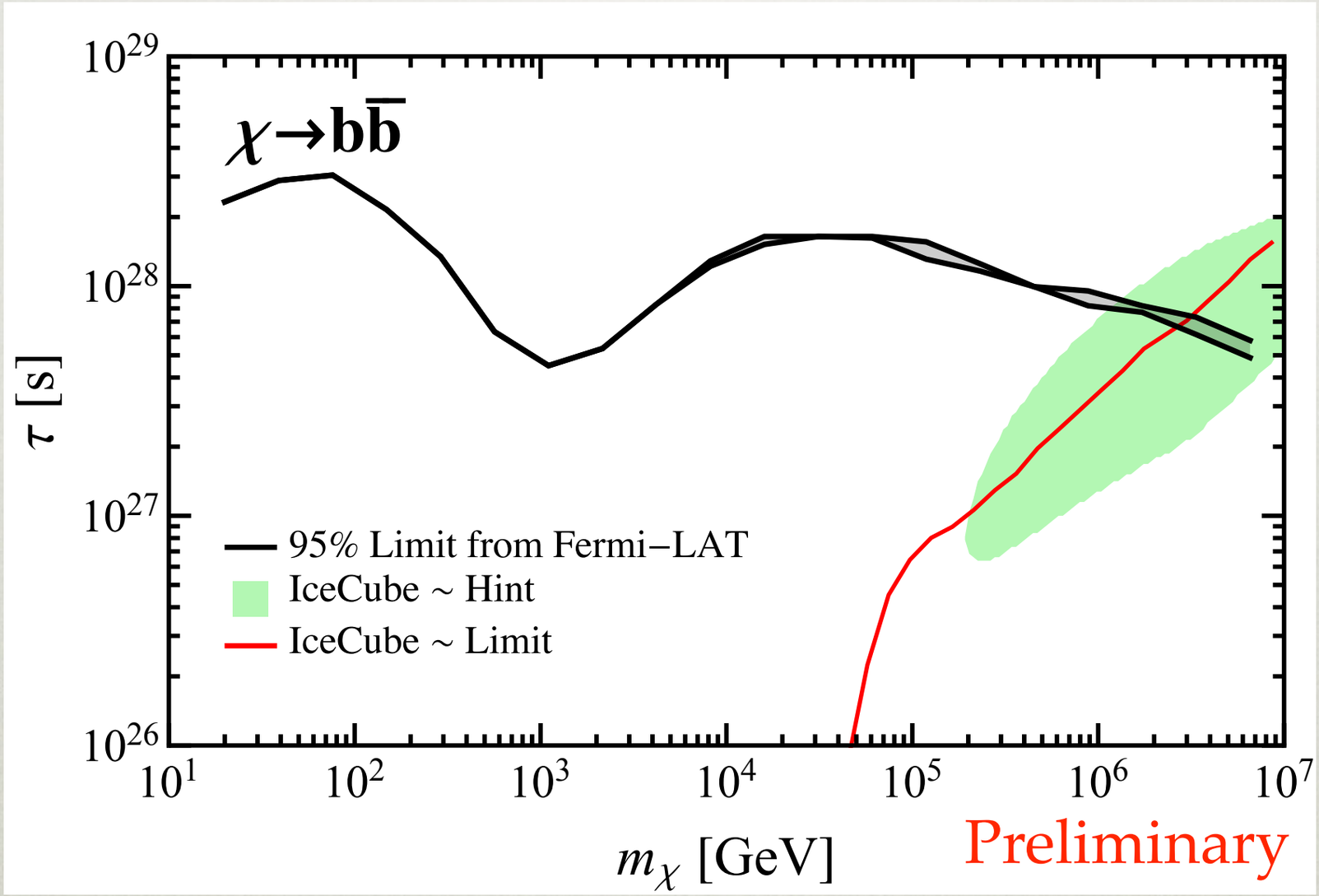


Band from varying magnetic field: $B \in [0, 2]\ \mu\mathrm{G}$

Limit in the IceCube range depends on all three contributions

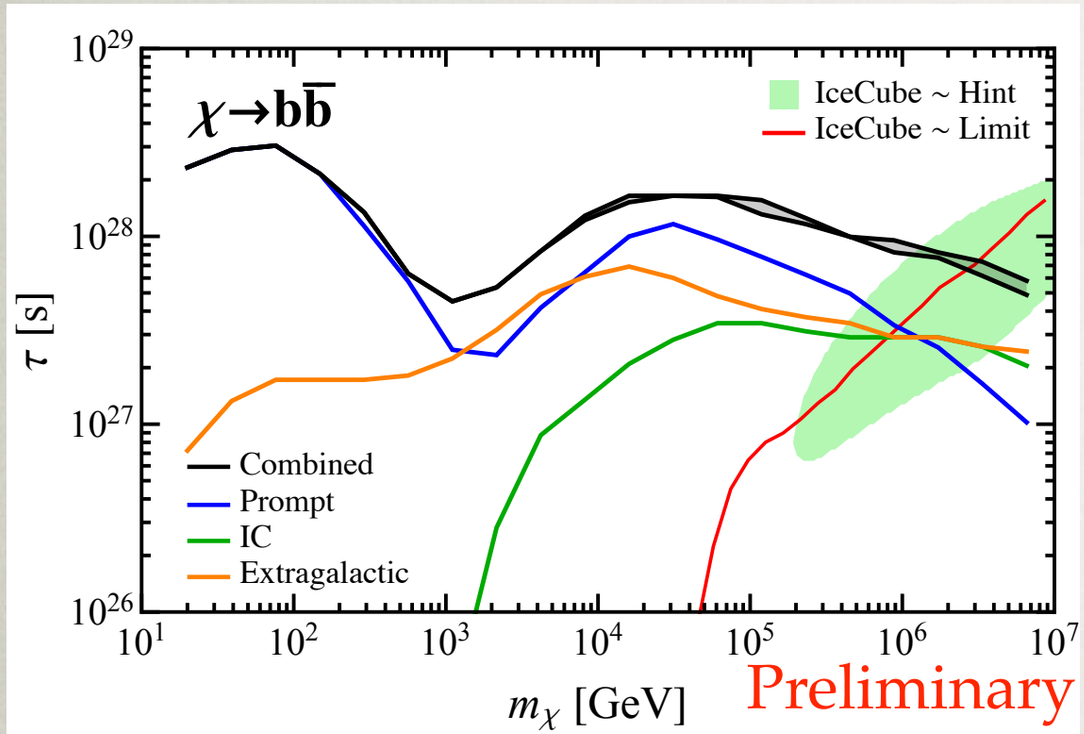
Dark Matter at Fermi: Building Limits

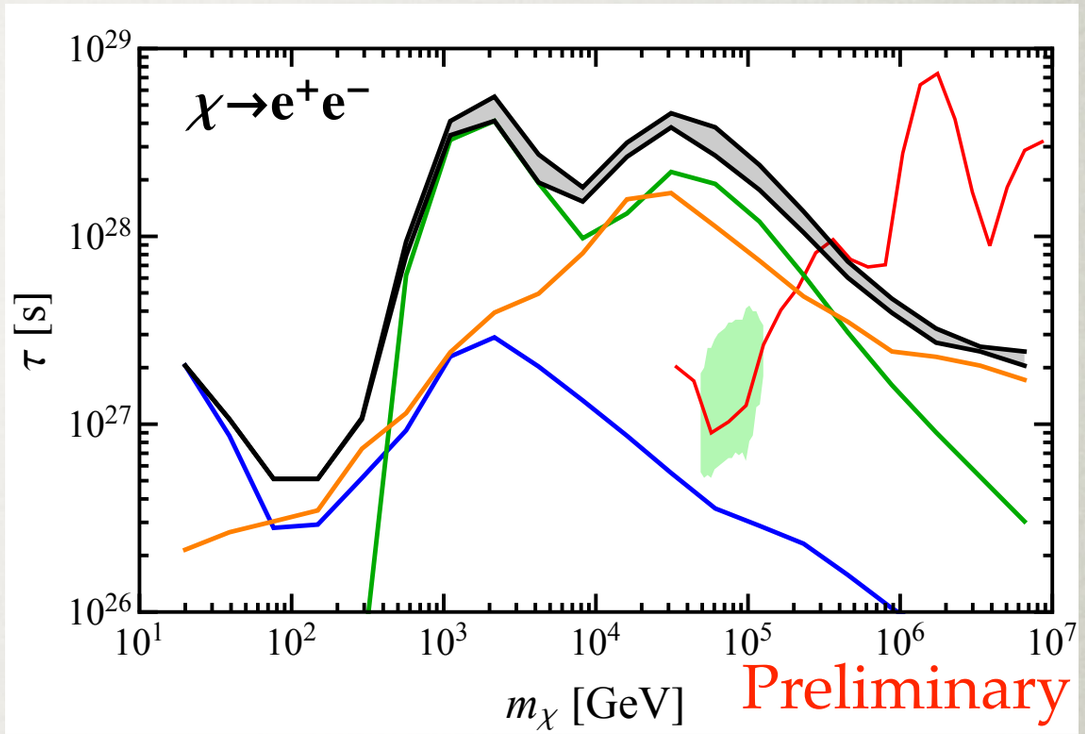
- Can now compare our result to the interesting IceCube region

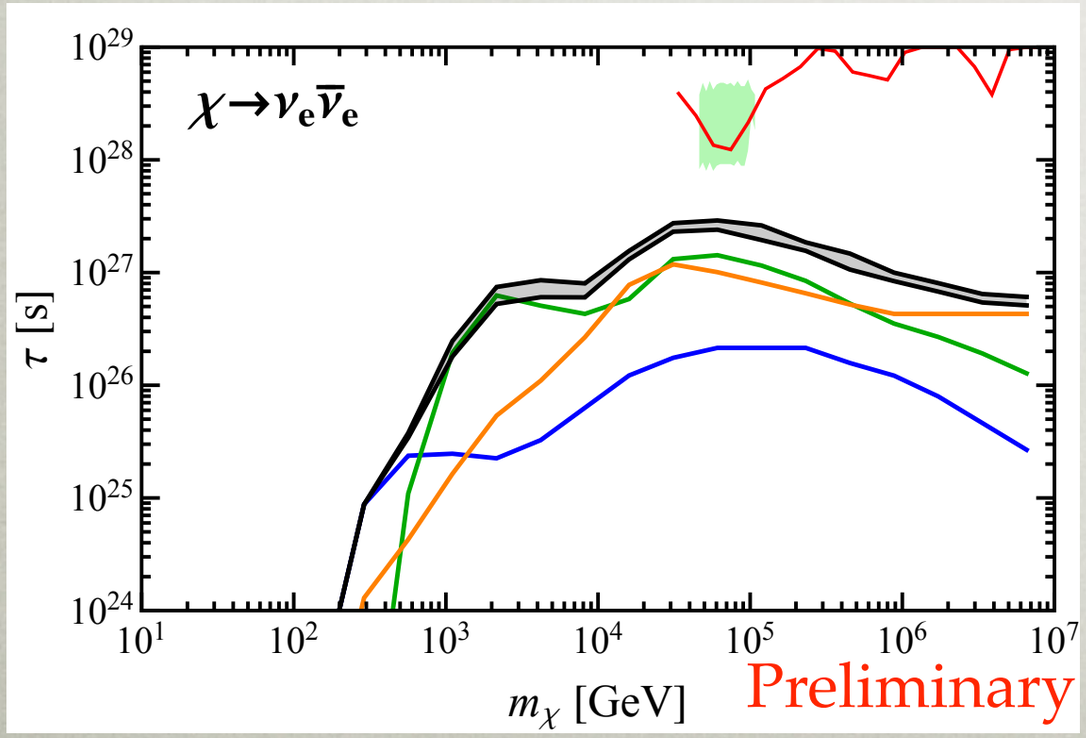


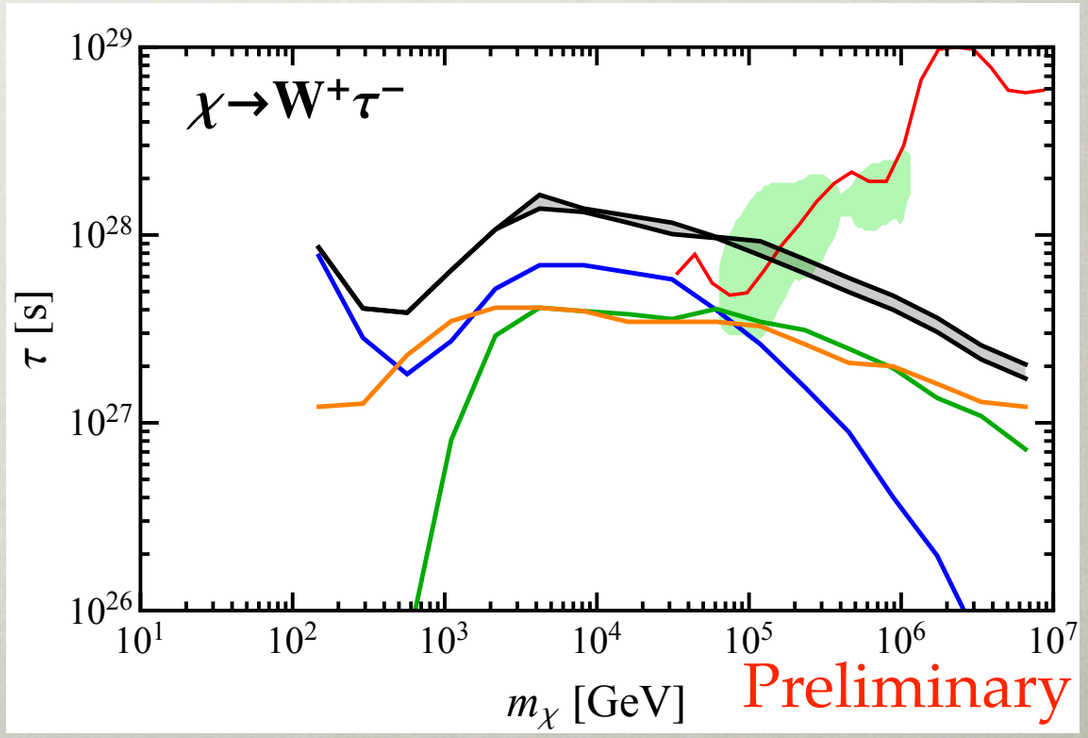
- Fermi-LAT limits clearly cut into the interesting IceCube range

Dark Matter at Fermi: Limits



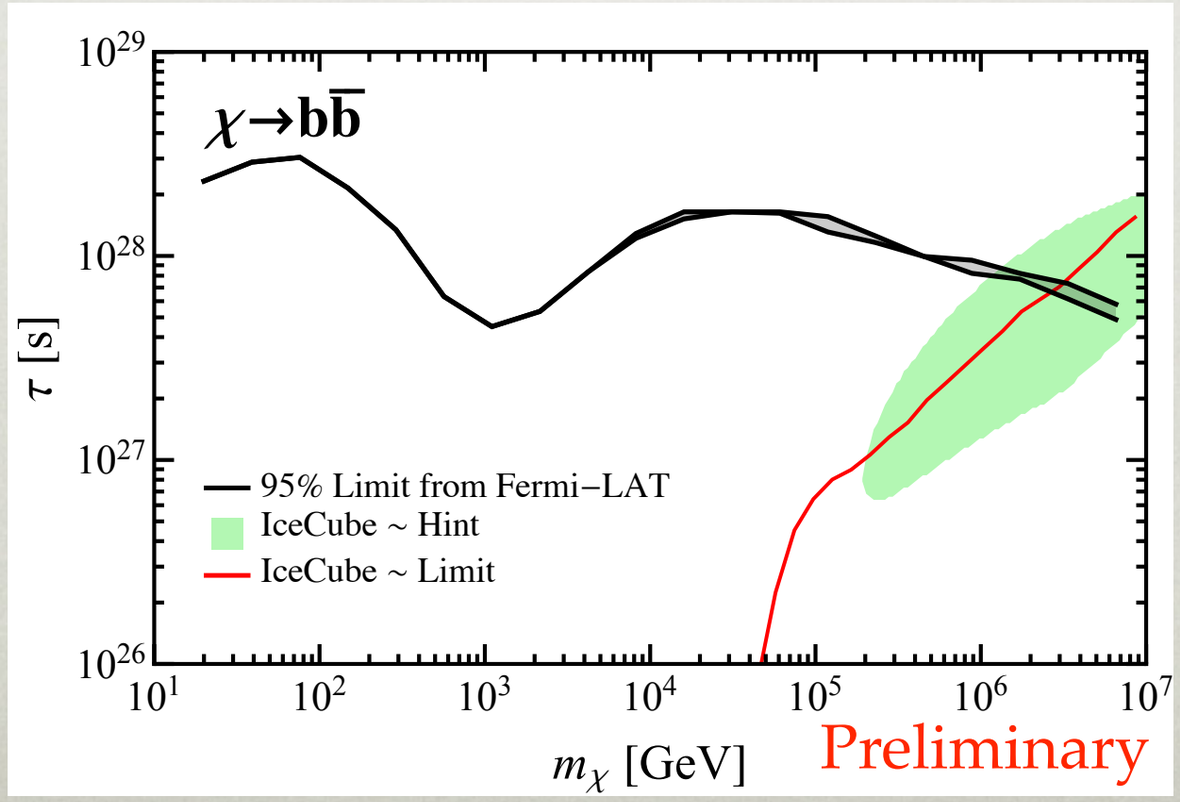






Conclusion

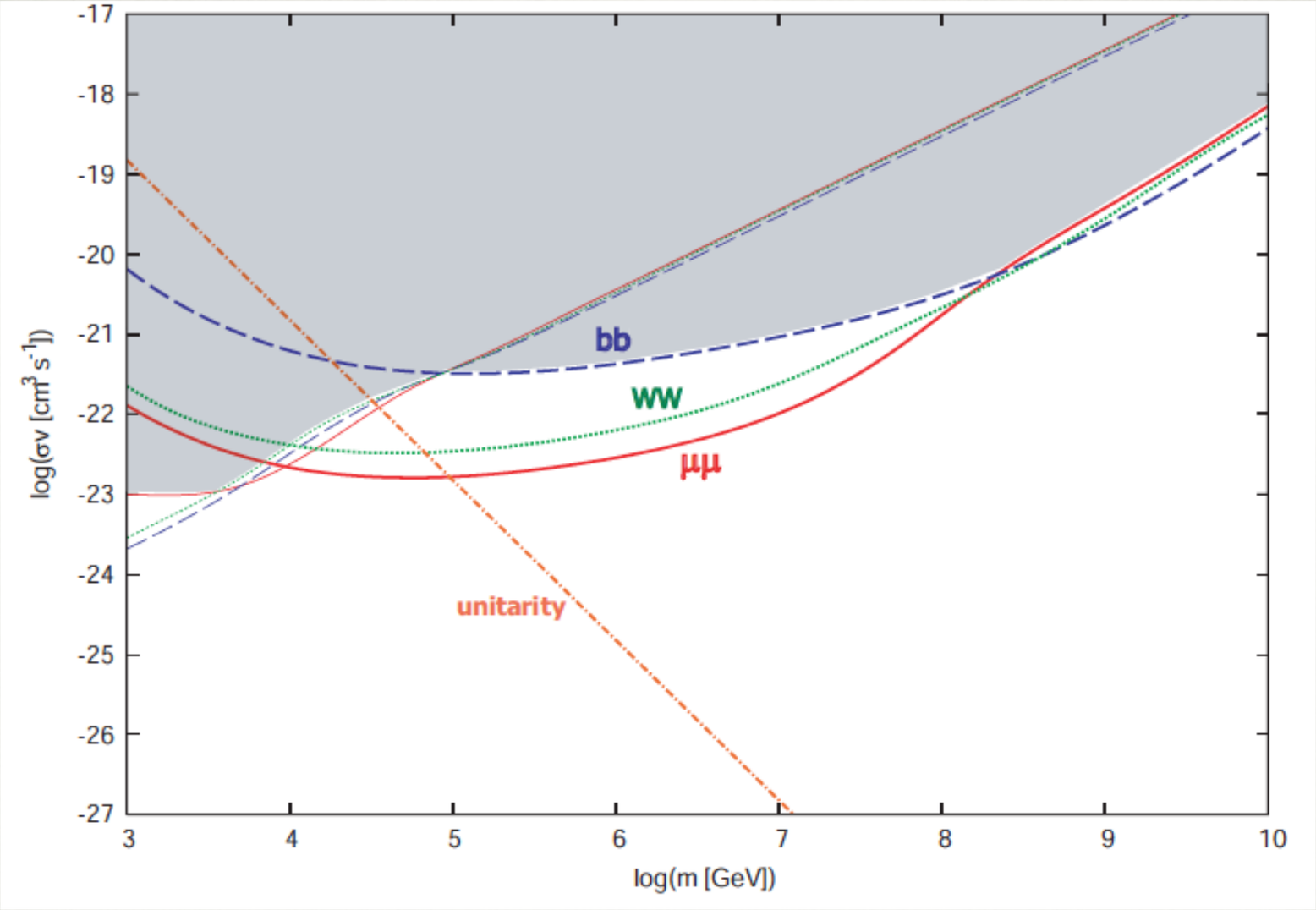
- IceCube is already probing an interesting parameter space for PeV scale decaying dark matter
- These models also predict a photon flux at Fermi - the derived limits are an important input for DM interpretations of IceCube
- Our work improves these limits more than an order of magnitude and extends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



Backup Slides

Dark Matter Annihilation

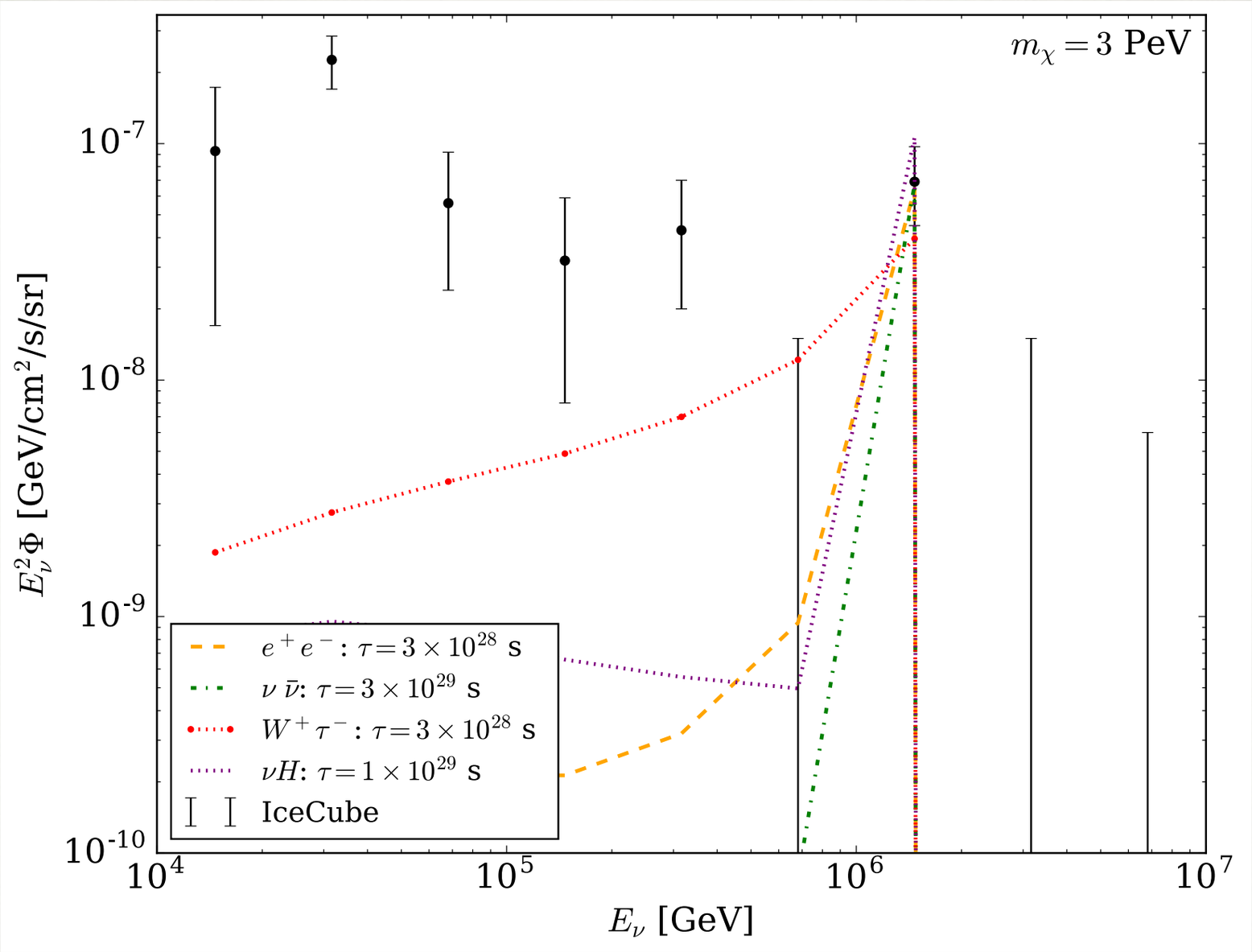
- At high masses, need to worry about the unitarity bound for dark matter annihilation, why we did not consider it



Plot from Murase and Beacom 1206.2595

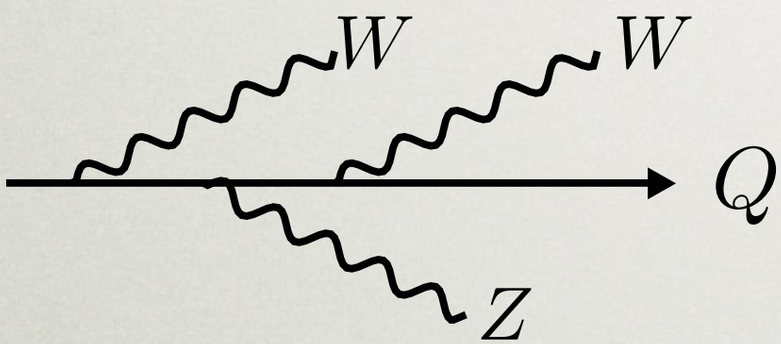
Prompt Neutrino Fits

- Here we show additional prompt spectra fits to the IceCube astrophysical spectra



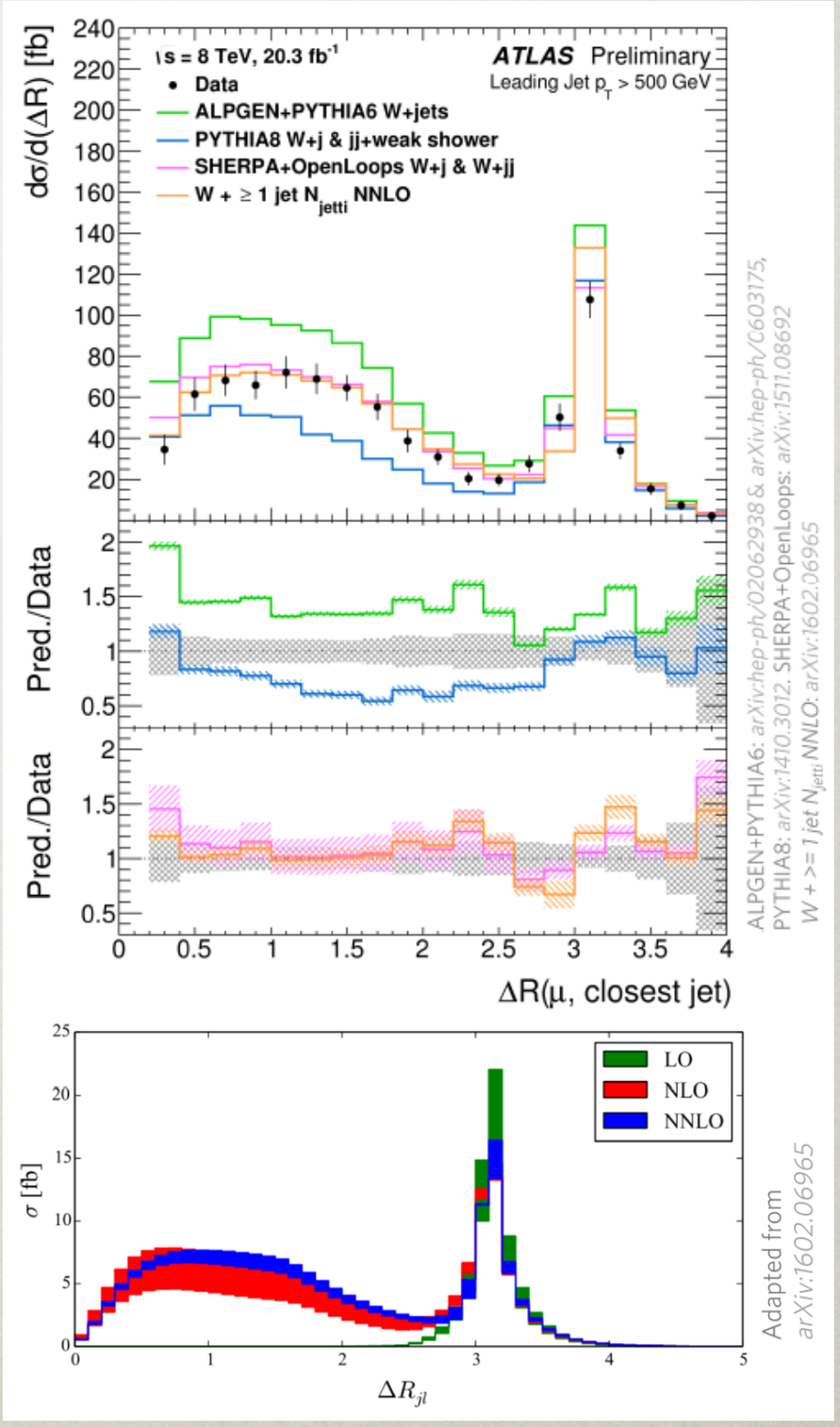
Electroweak Bremsstrahlung

- Electroweak bremsstrahlung is theoretically well known* and there if you believe in SU(2) as a gauge theory
- But it has only been tested experimentally very recently
- ATLAS searches for W emission from a jet:



- Study the angle between the jet and the W, ΔR
- Only MC with electroweak corrections can explain the data - it's a real effect!

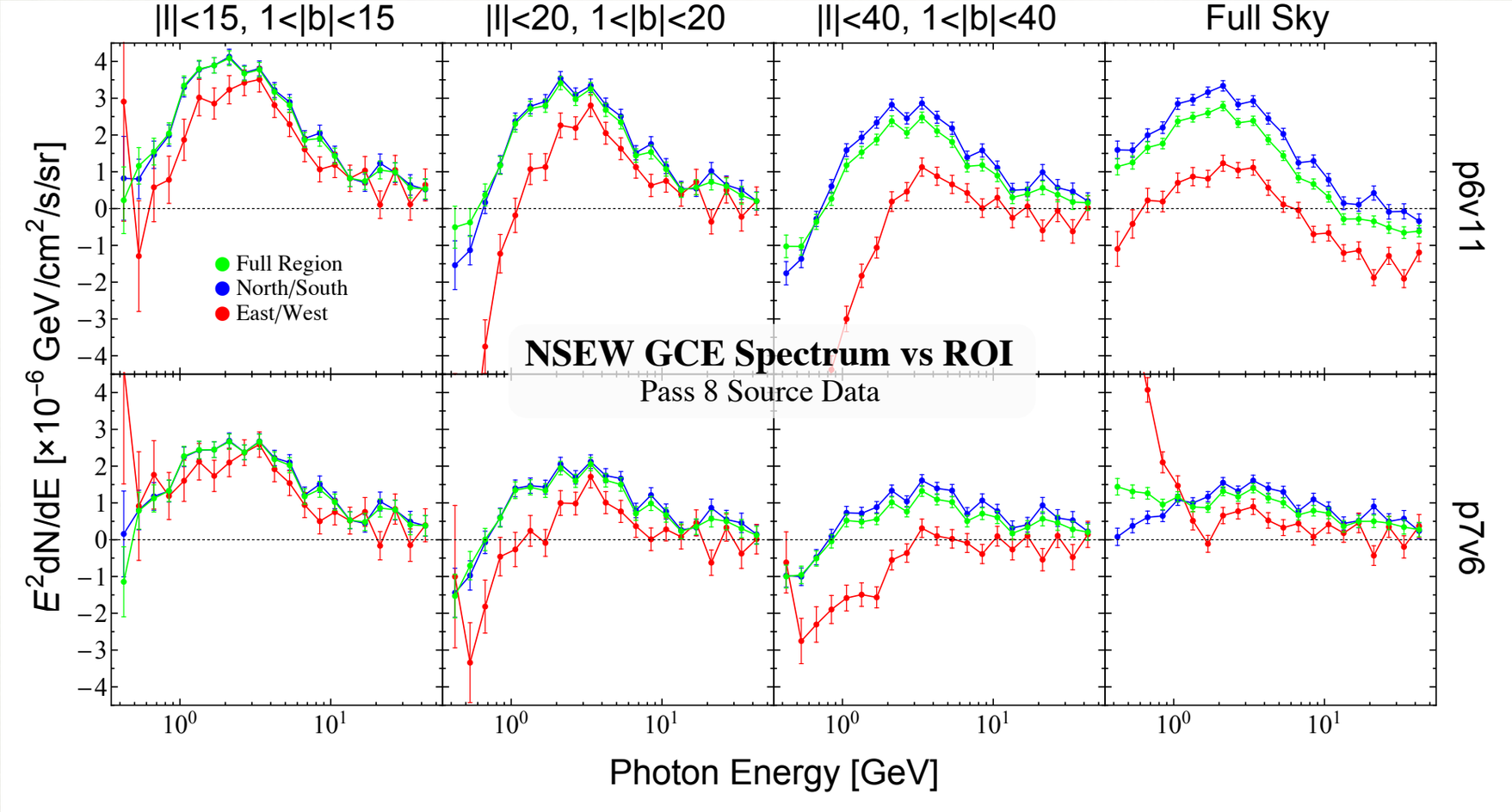
*See e.g. 0707.0209, 0802.0234, 0803.0157, 0805.3423, 0806.0370, 0809.2990, 0811.3744, 0904.3830, 0811.0821, 0911.0001, 1009.0224, and many more



Plots from Miles Wu's poster at ICHEP 2016

Oversubtraction in Template Fitting

- When using large regions, diffuse model normalisation can get fixed to its value away from where your signal is
- Can lead to overly optimistic limits unless accounted for



Plot from NR et al 1604.01026

Dark Matter at Fermi: Models Considered

- We repeat our analysis for a comprehensive set of models
  - Z′:

$$Z' \to \; q\bar{q},\; \nu\bar{\nu},\; \ell^-\ell^+,\; W^+W^-$$

  - RH neutrino/gravitino:

$$\psi_{3/2} \text{ or } N \to \; \gamma\nu,\; Z\nu,\; W\ell,\; h\nu$$

  - Scalar model: $\phi(LH)^2$

$$\phi \to \nu\nu,\; \nu\nu h,\; \nu\nu hh$$