

Search for secluded  
Dark Matter in the Sun  
with IceCube

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# Secluded Dark Matter



# Secluded Dark Matter

- Dark Matter,  $X$ , is secluded from 'normal' matter by a mediator,  $\Phi$ .
- Mediator could be some new gauge boson from the dark sector, or some other candidate.
- The dark sector may be simple or more complicated, in the simplest picture the dark matter annihilates into the mediator.

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{WIMP} + \mathcal{L}_{mediator} \quad \chi\chi \rightarrow \phi\phi$$



# Secluded DM: Properties

- If non-abelian symmetry exists in the dark sector.
- XX annihilation
- Sommerfeld enhancement  $\rightarrow$  large cross-section
- symmetry splitting possible, due to 'dark' Higgs (or small coupling to Higgs)
- Excited Dark Matter (XDM)  $\chi\chi \rightarrow \chi\chi' \rightarrow \chi\chi e^+e^-$
- Inelastic Dark Matter (iDM)  $\chi_1\chi_1 \rightarrow \chi_2\chi_3$
- Possible explanation of observations of new physics

Pamela/ATIC/Fermi INTEGRAL Direct Detection



# Sommerfeld Enhancement

- Light force carrier
- Could be scalar, pseudoscalar, or vector.
- Small mass splitting in X states (lightest is DM), two body state is attractive at short distances.
- Still requires existence of scalar, but scalar is not required to couple to X.
- On order of  $\sim 1$  GeV

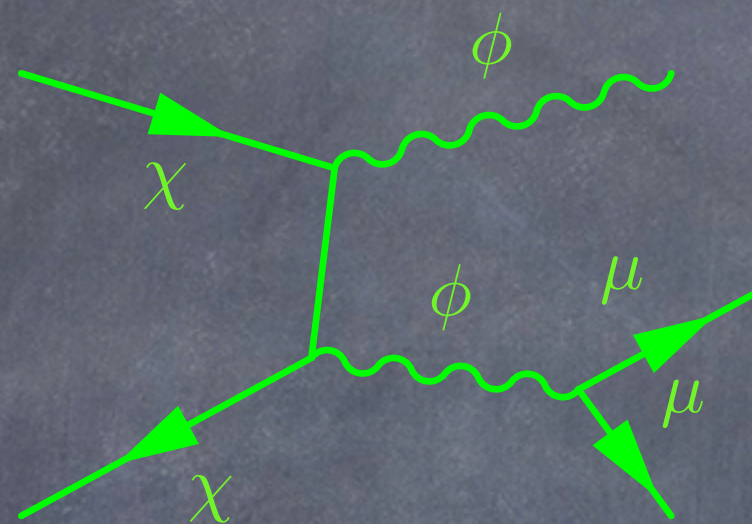


# Mediator Possibilities

- Hidden boson decays into pair of SM fermions.
- Hidden higgs decays to SM fermion at 1-loop.
- Hidden gaugino decays into gravitino and photon.
- Hidden gaugino decays into gravitino and hidden boson (and so fermions).



# Secluded DM: Signal



$$\epsilon_V F'_{\mu\nu} B^{\mu\nu}$$

$$m_\chi > m_\phi$$

'Typical'

$$\chi \sim 1\text{TeV}$$

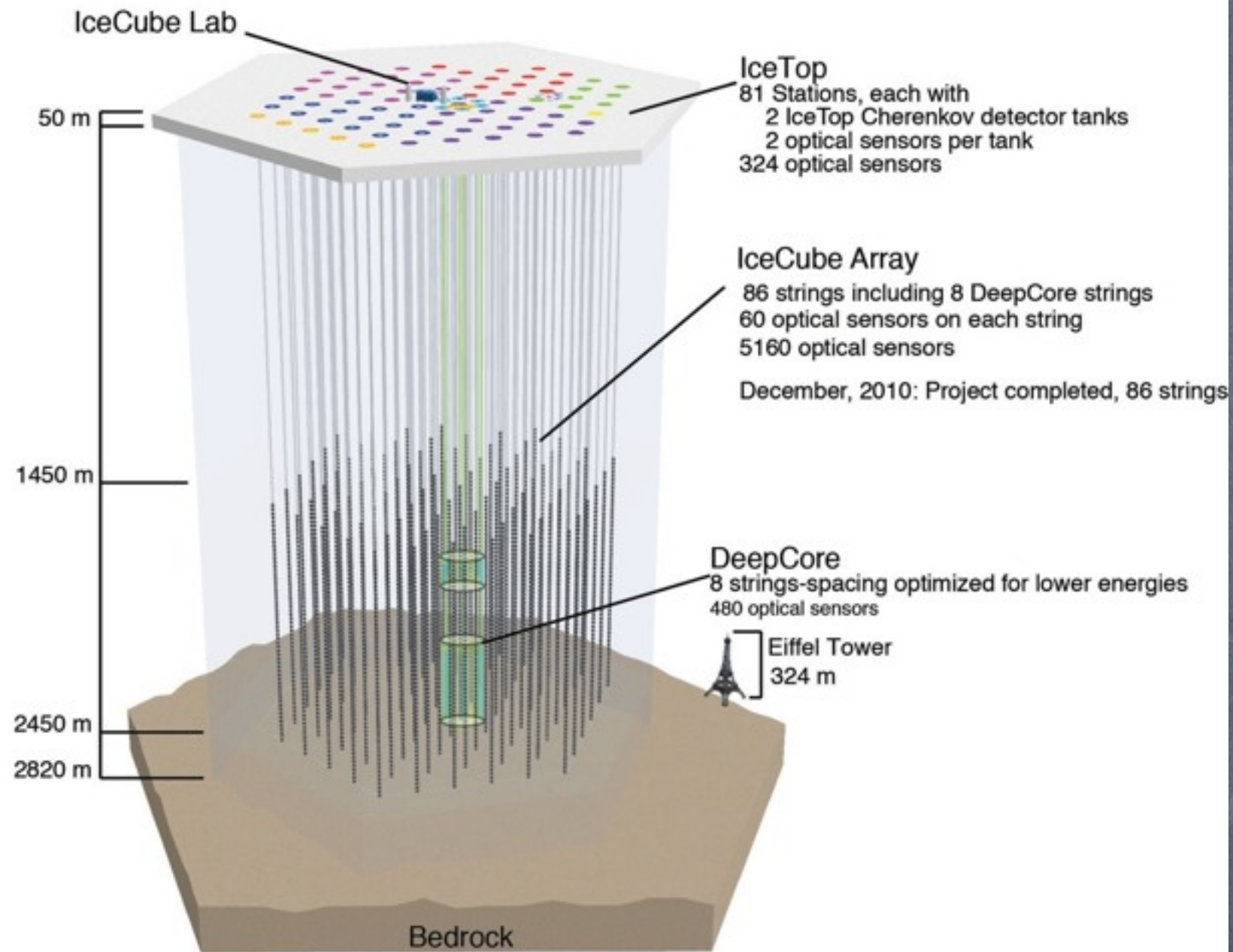
$$\phi \sim 1\text{GeV}$$

- Leptophilic DM due to interaction with the SM through the kinetic mixing portal
- 'Typical' mediator boosted due to DM mass being greater than mediator mass
- Lifetime of mediator could be long, could decay in the vicinity of the earth



# Signal in IceCube



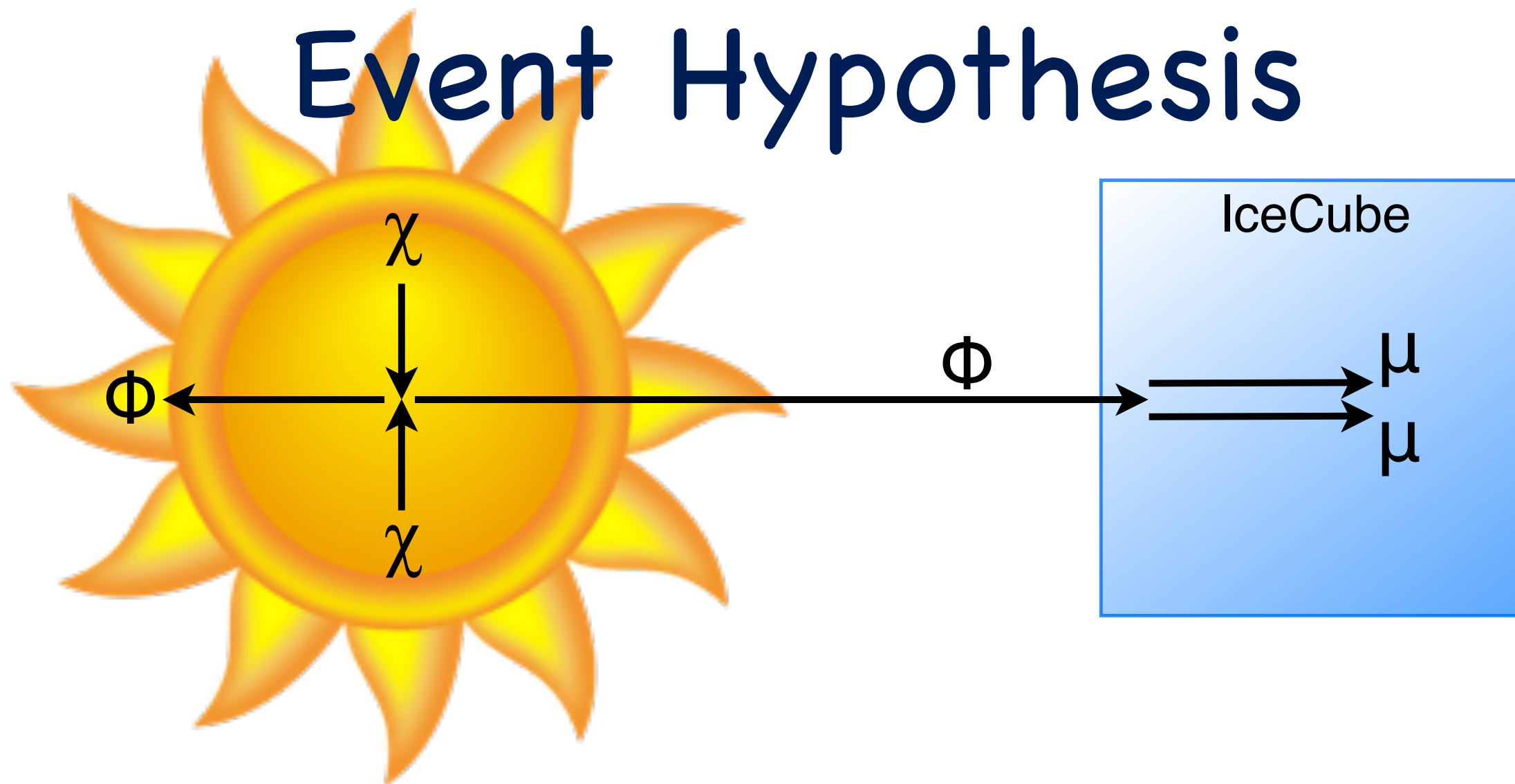


# IceCube Neutrino Detector

1 km cube instrumented array in the Antarctic ice. Secluded Dark Matter Analysis with 79 string configuration.



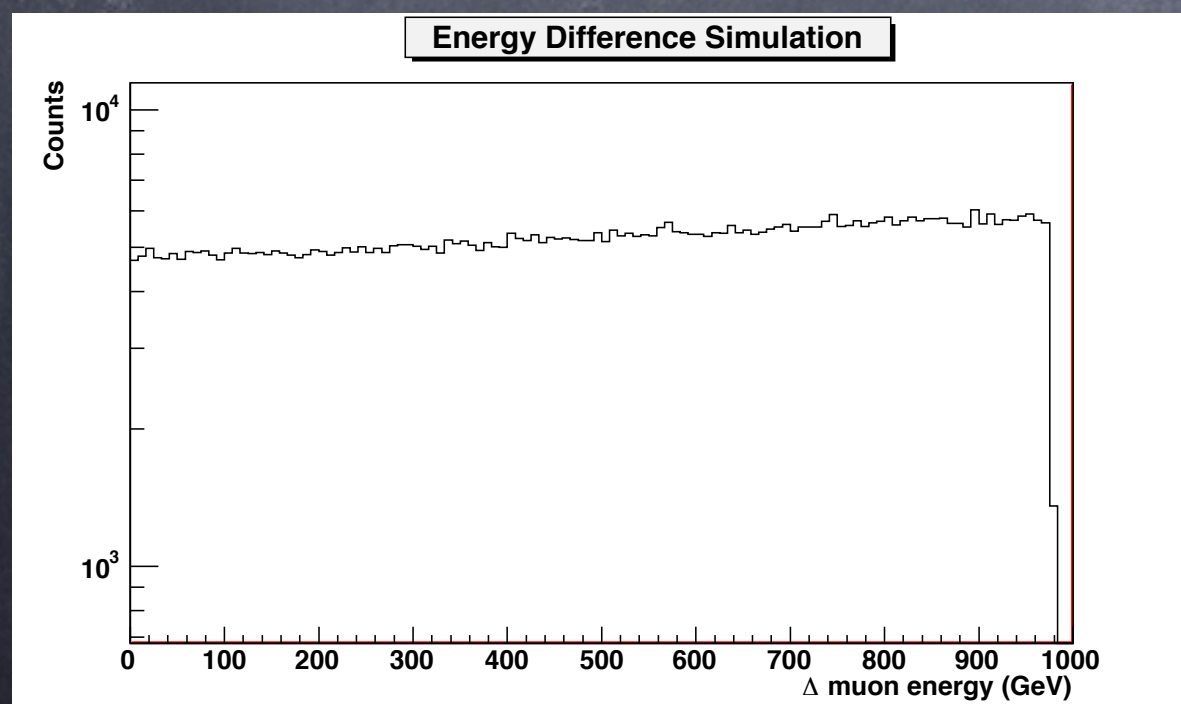
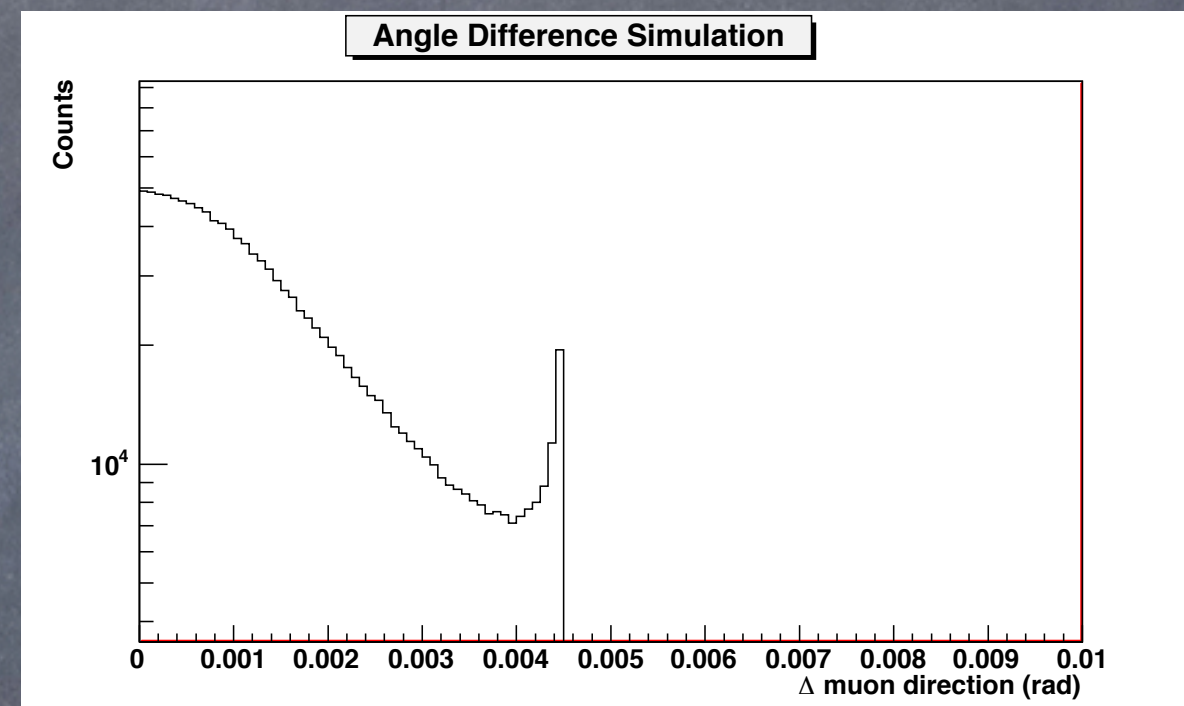
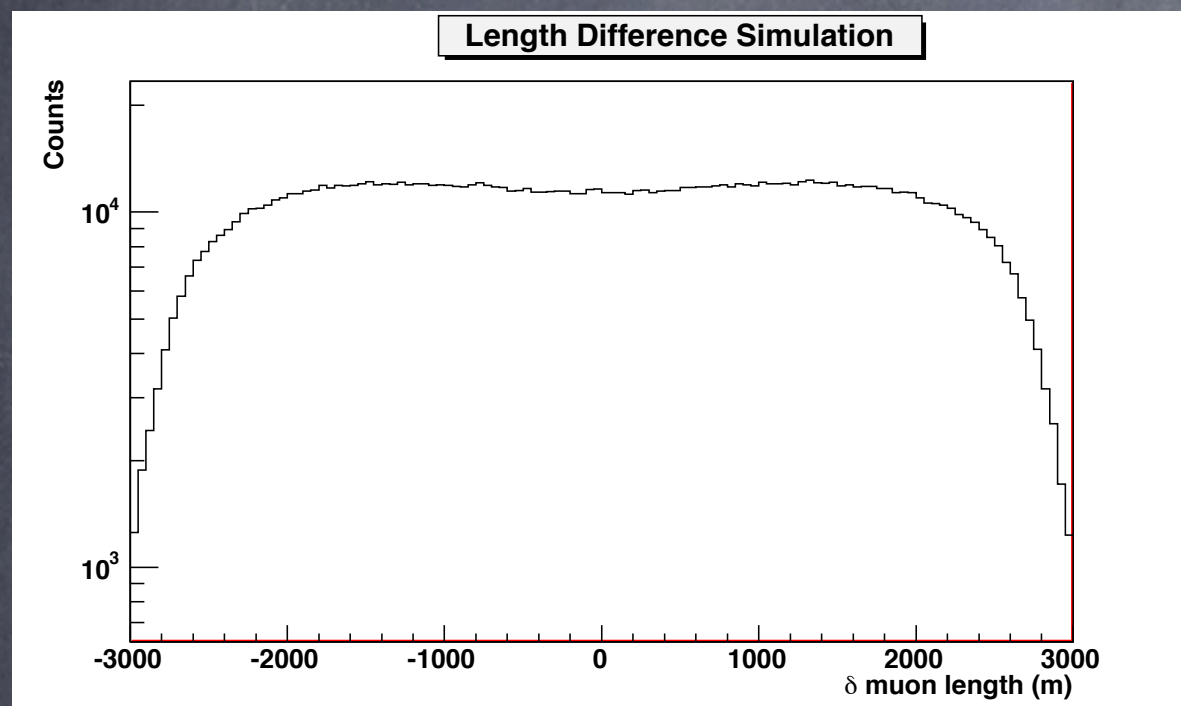
# Event Hypothesis



Dark Matter annihilates into mediator which decays within the vicinity of the detect to two boosted muons (isotropically in the mediator rest frame).



# Di-muon Simulation



Di-muons are created from isotropic decay in mediator rest frame. Shown are differences between muons in simulation at trigger level.



# Event Selection



# Analysis Scheme

Level 2 - Standard IceCube

Up-going and well-reconstructed events.

Level 3 - Standard WIMP

Up-going, well-reconstructed and horizontal events with number of DOM/string requirements.

Level 4 - High Energy

More stringent selection based on hit quality with included track length in selection process using SVM.

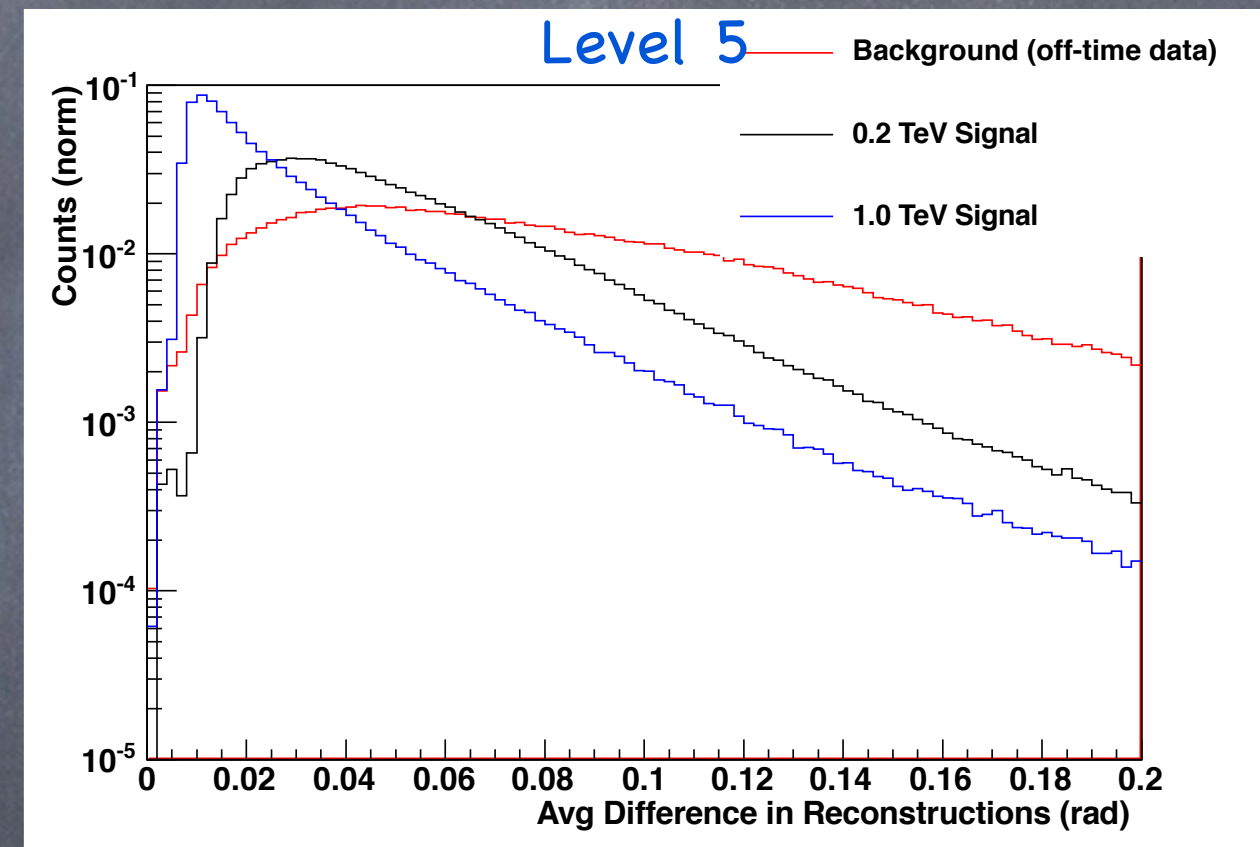
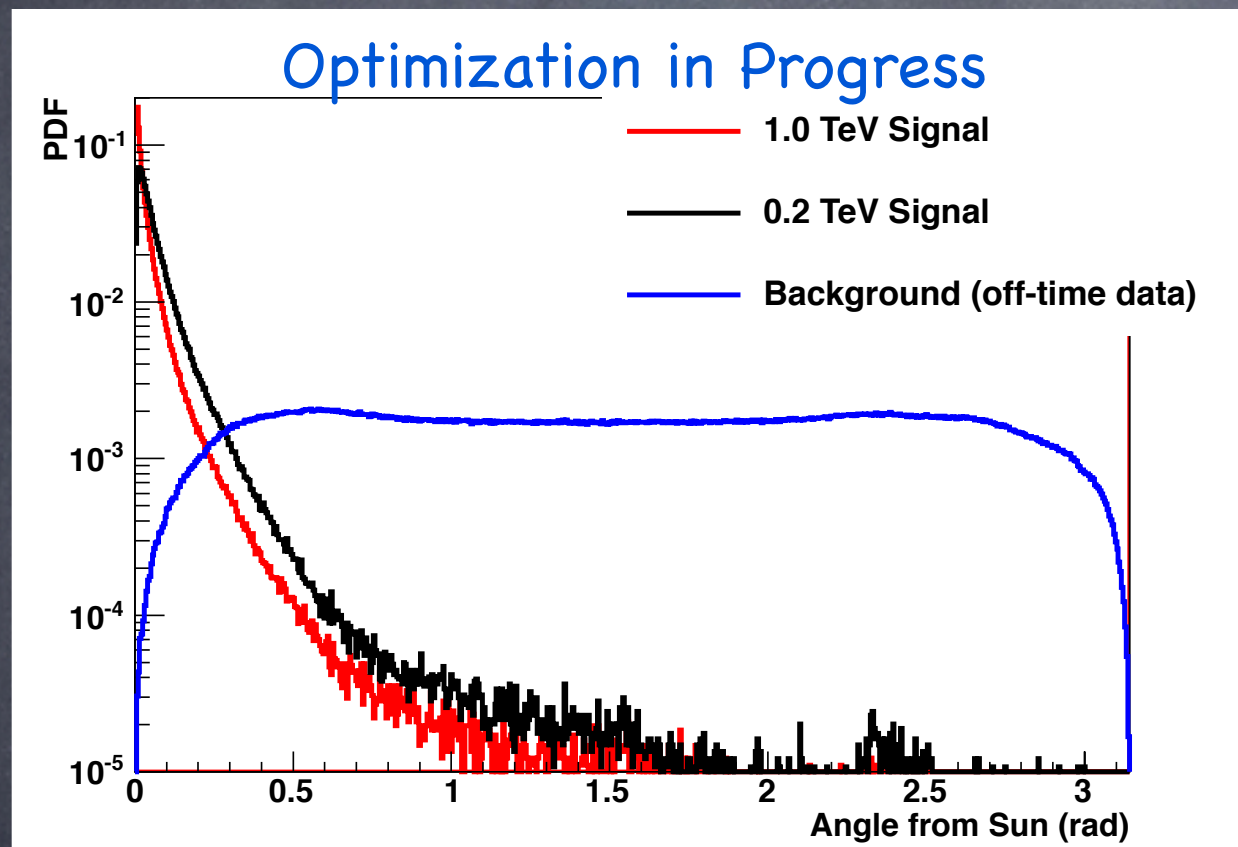
Level 5 - Energy Topology

Included energy variables in reconstruction. Placed cuts on quality of track length reconstruction.

2D Likelihood Analysis



# Solar Event Selection



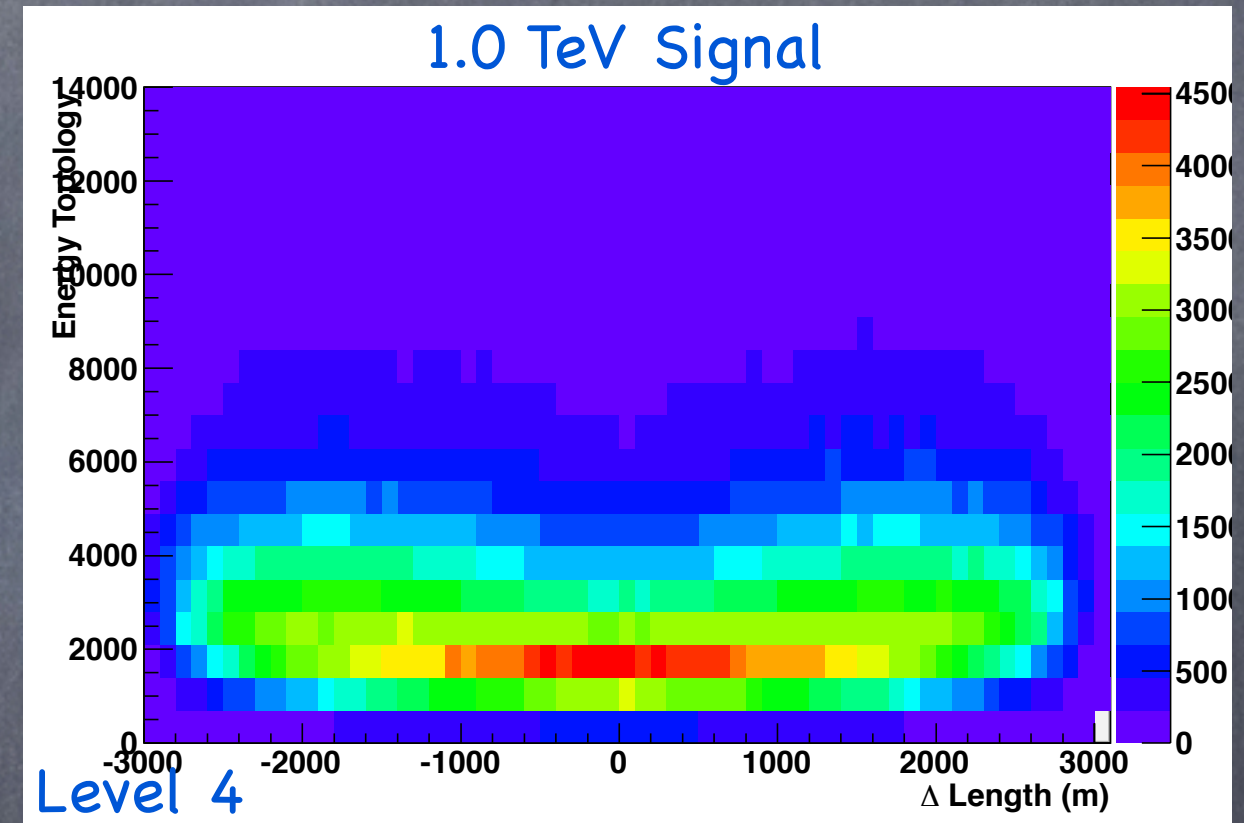
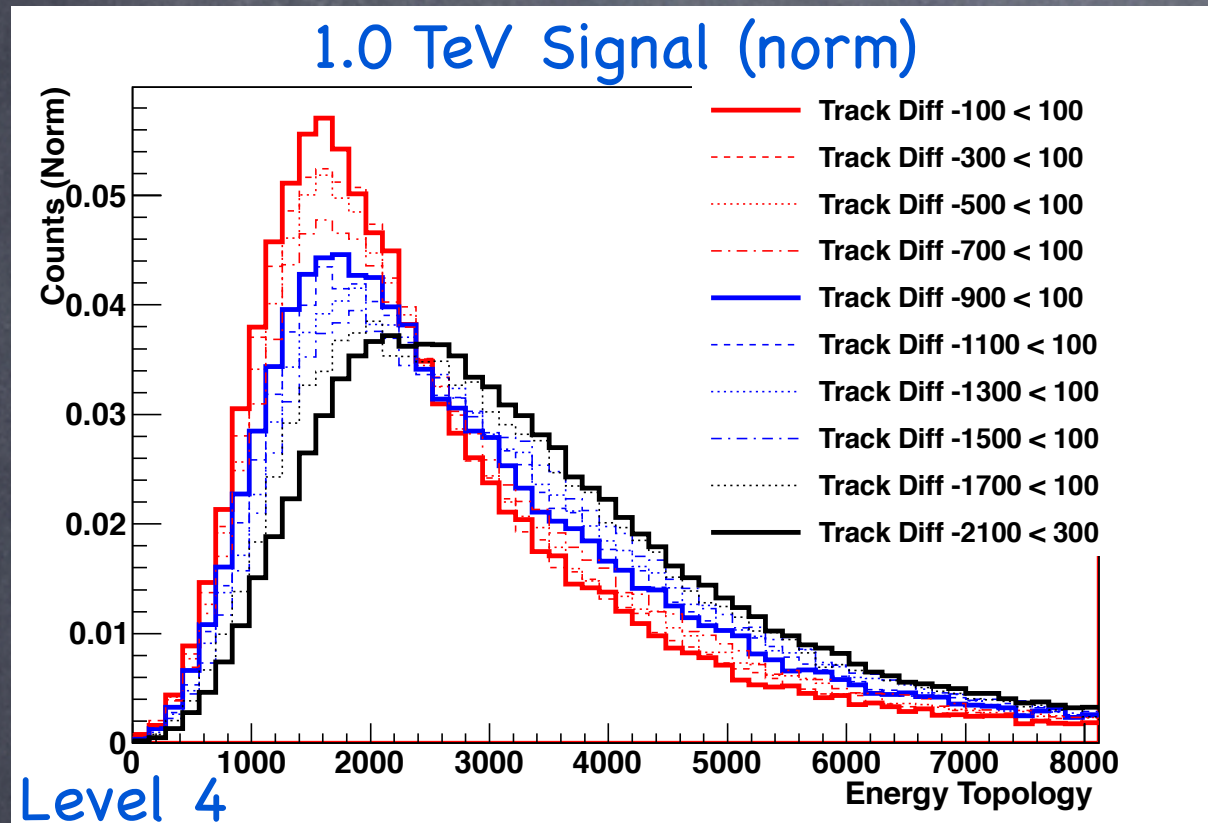
Initially we can use traditional variables like how horizontal the track is.

At the end of event selection, we have a strong set of data that is reconstructed as originating in the sun.

Interesting signal events are well reconstructed. This can be observed in the paraboloid reconstruction or in comparing multiple reconstructions.

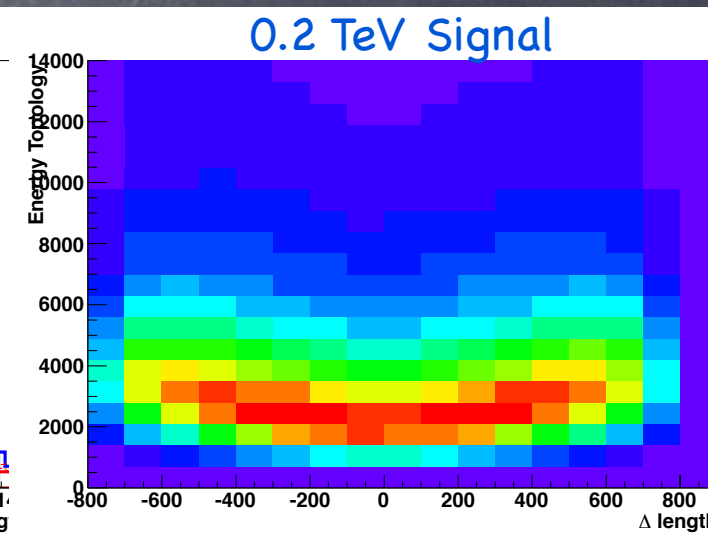
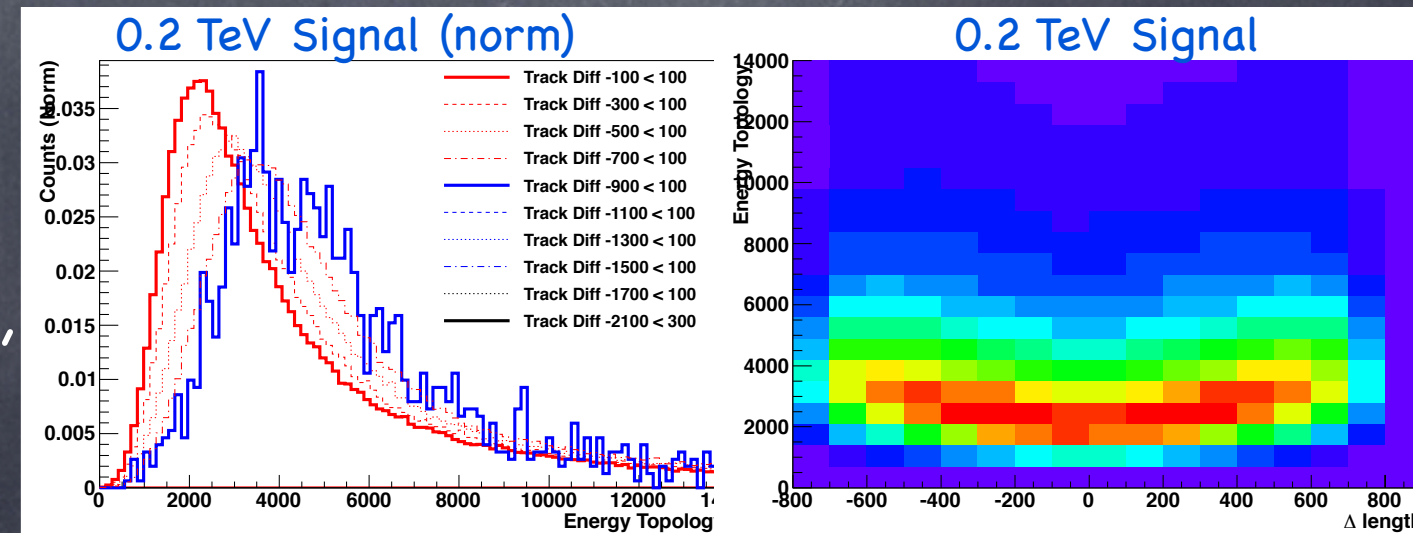


# Energy Topology



$$\text{Energy Topology} = \text{Length} / \text{dEdX}$$

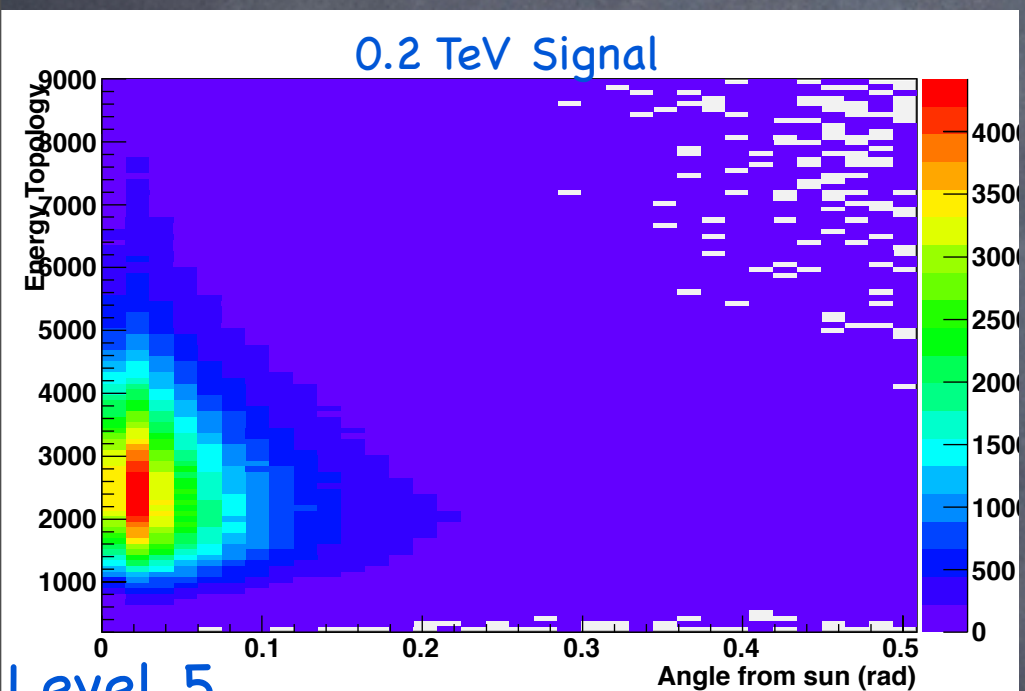
The signal di-muon type events is significantly different from a single track, even when the kinematics of the event give significant different muon tracks.



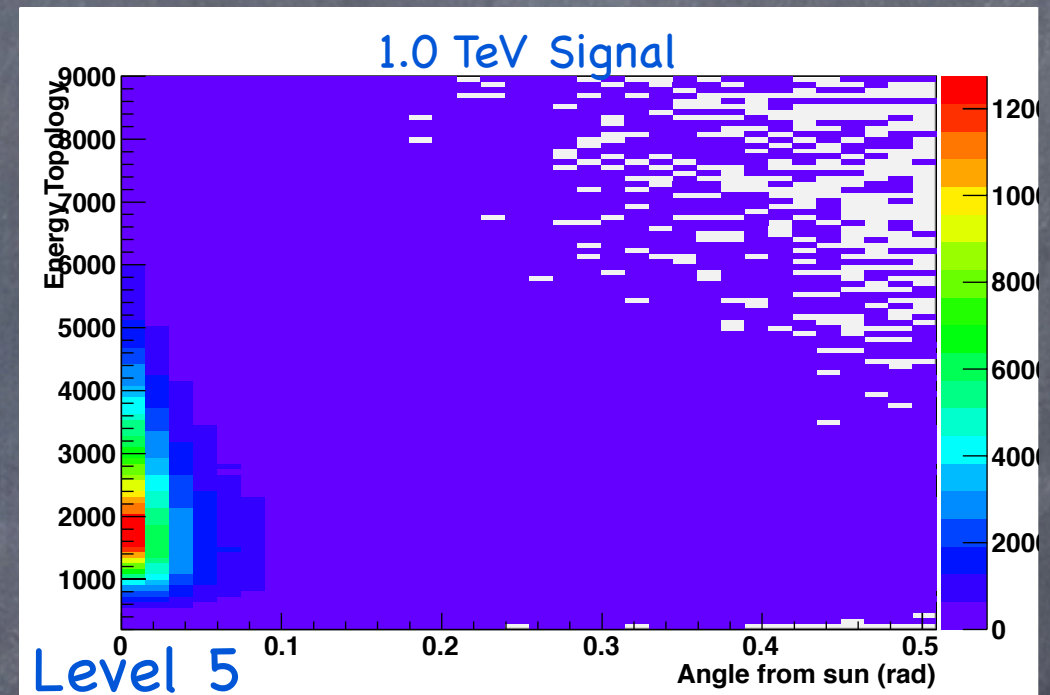
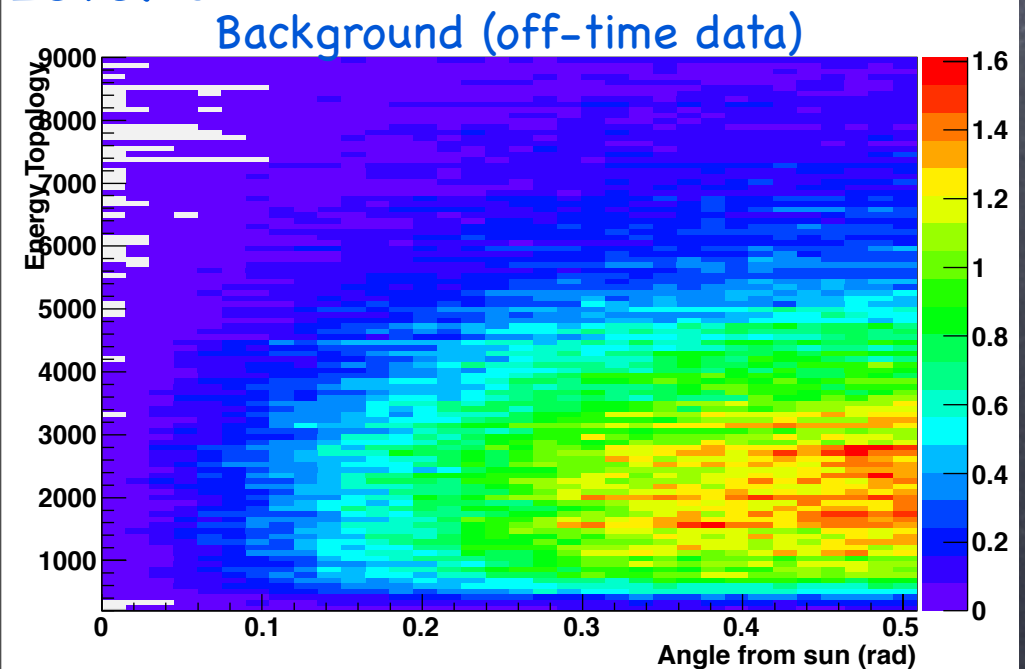


# Likelihood Analysis

Optimization in Progress



Level 5



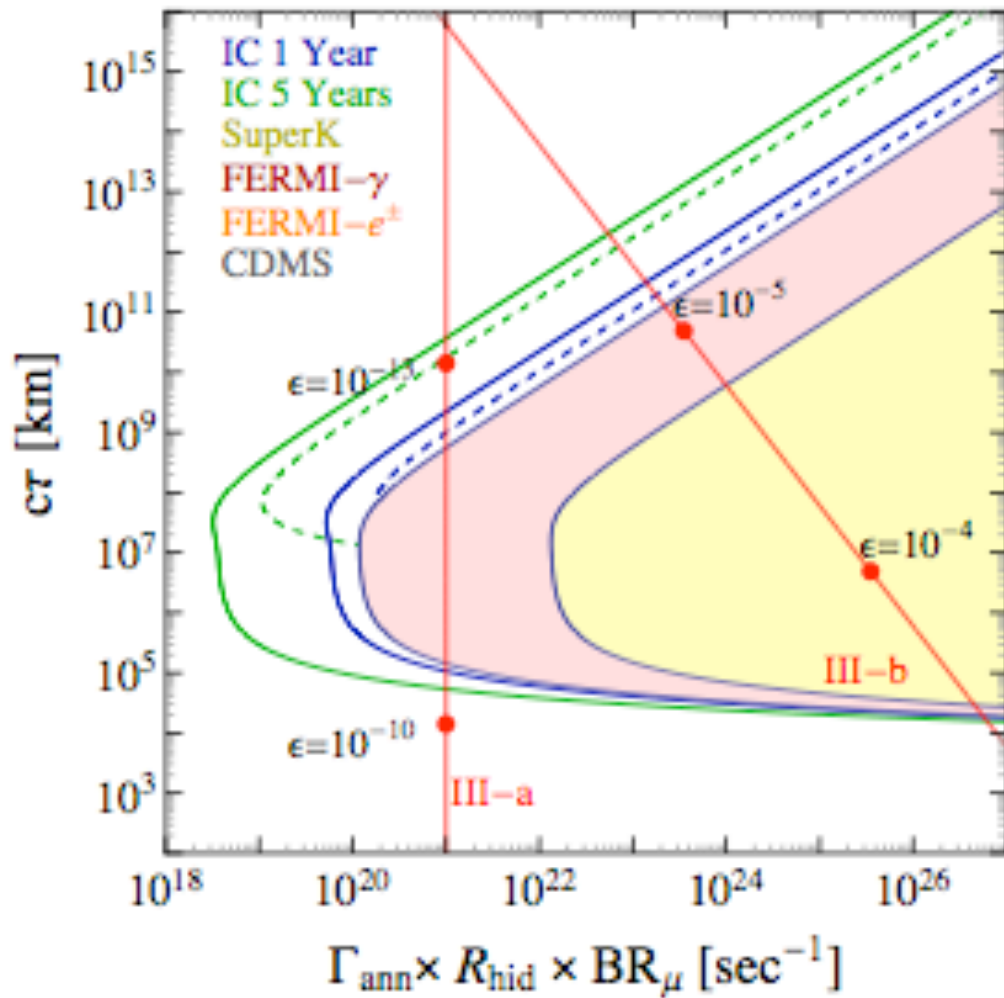
Level 5

Using both the Energy Topology variable and Space Angle allows the framework to be tested.



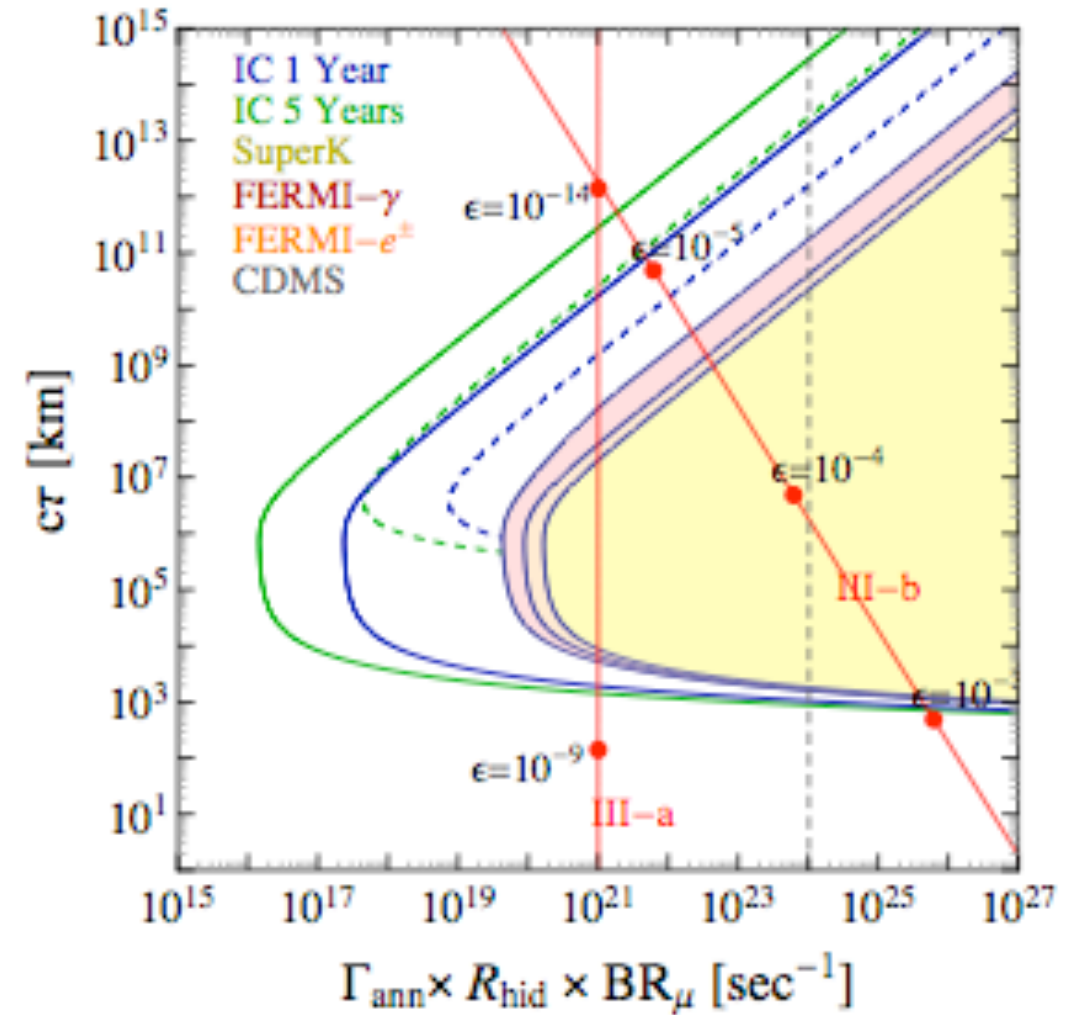
### Sun $\mu^\pm$ reach

$m_\chi = 100$  GeV,  $\delta = 200$  keV,  $m_{\text{LOLiP}} = 500$  MeV



### Sun $\mu^\pm$ reach

$m_\chi = 2$  TeV,  $\delta = 200$  keV,  $m_{\text{LOLiP}} = 500$  MeV



# Theoretical Limits

Theoretical calculation by Meade, Nussinov, Papucci, Volansky (2009).



# Conclusions

- IceCube is sensitive to signal in the Secluded Dark Matter framework.
- In IceCube, Secluded Dark Matter looks different than traditional Dark Matter.
- Look forward to results this summer!