Extending IceCube-DeepCore to Low Energies for a Dark Matter Search toward the Galactic Center

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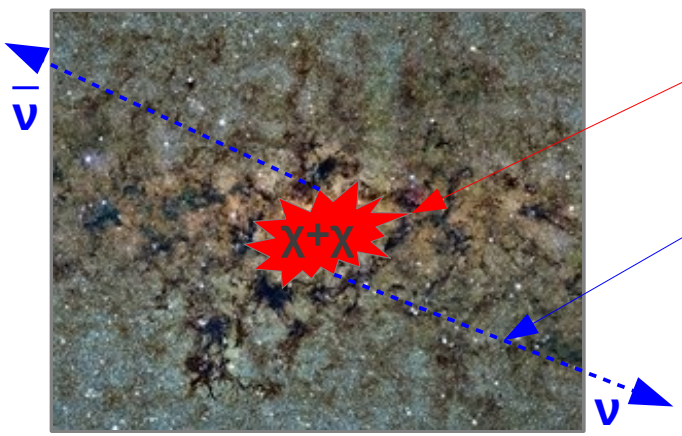
DM neutrino signals from the Galactic Center

- DM particles (WIMPs) annihilate with each other in the GC region and produce neutrinos through different annihilation channels

$$\chi + \chi \rightarrow \nu + \bar{\nu} \qquad \chi + \chi \rightarrow W^{+} + W^{-} \qquad \chi + \chi \rightarrow b + \bar{b} \qquad \ldots$$

- Neutrinos propagate + oscillate to the South Pole, convert into muons in CC interactions

Galactic Center (seen from South Pole at zenith angle 61º → down-going analysis)



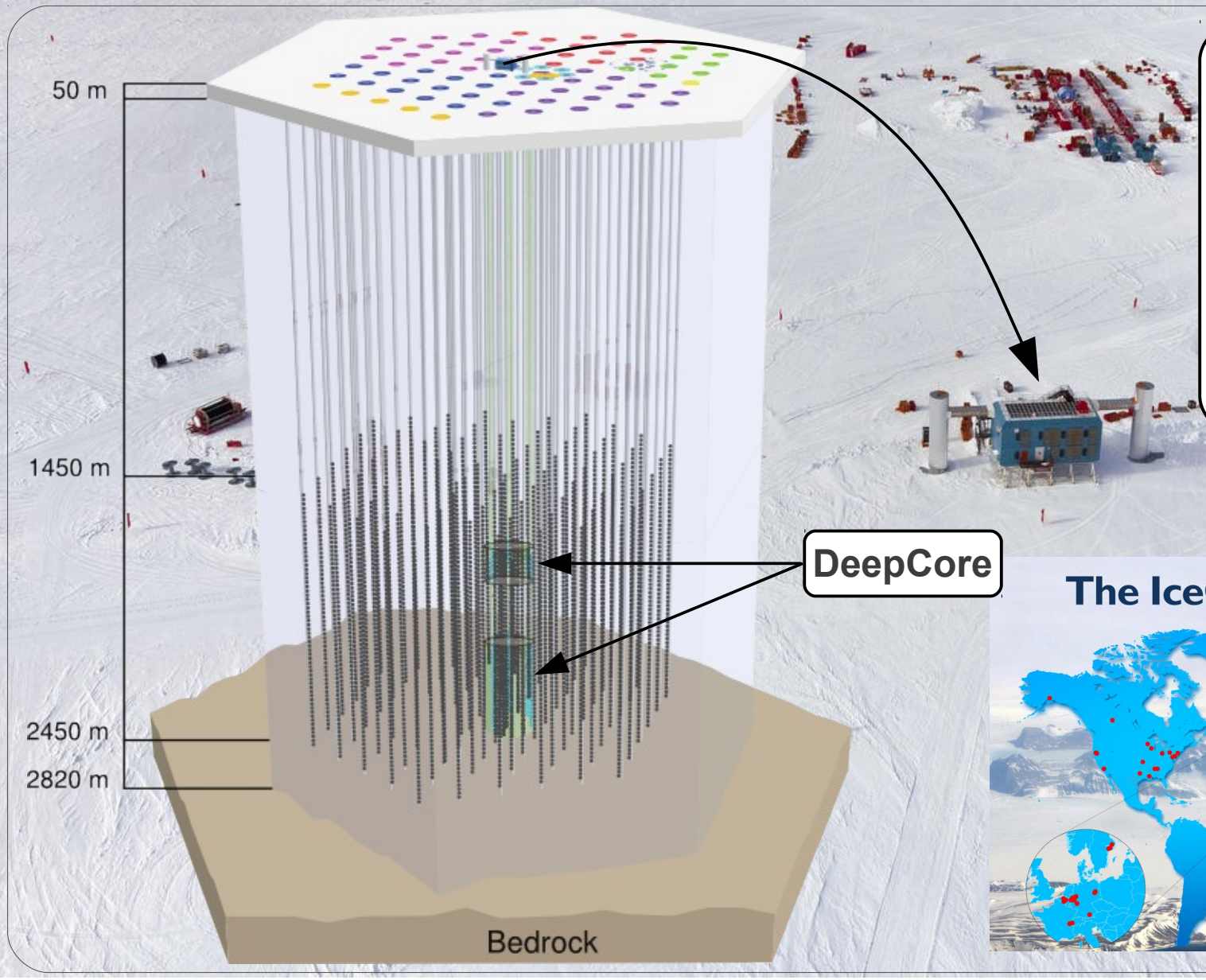
WIMP Annihilations
- Annihilation cross-section <σv>

Neutrinos
- Annihilation channel (branching ratios)

All processes depend on WIMP mass

Differential ν-flux: $$\frac{d\Phi_\nu}{dE} = \frac{\langle \sigma v \rangle}{2} J(\Psi) \frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2} \frac{dN_\nu}{dE}$$

The IceCube Neutrino Observatory at the South Pole



1.5 km – 2.5 km deep

typically 125 m spacing between strings (~70 m in DeepCore)

60 modules per string

1 km^3 | 1 Gton instr. volume

Analyses Description

- **Goal:** Searching for neutrinos from **self-annihilating WIMPs in the GC** with WIMP masses between **30 GeV and 10 TeV** with the 79 string configuration of IceCube-DeepCore (**320 live days of 2010 - 2011**)

two independent analyses

Low-Energy (m_χ < 300 GeV)

- Only DeepCore filter stream
- 5 linear cut levels
- 2 Boosted Decision Trees (BDTs)
  - DC-Contained (low-E) events
  - DC-Partially contained (higher-E) events
- BDT cut optimization & sensitivity determination via maximum likelihood analysis

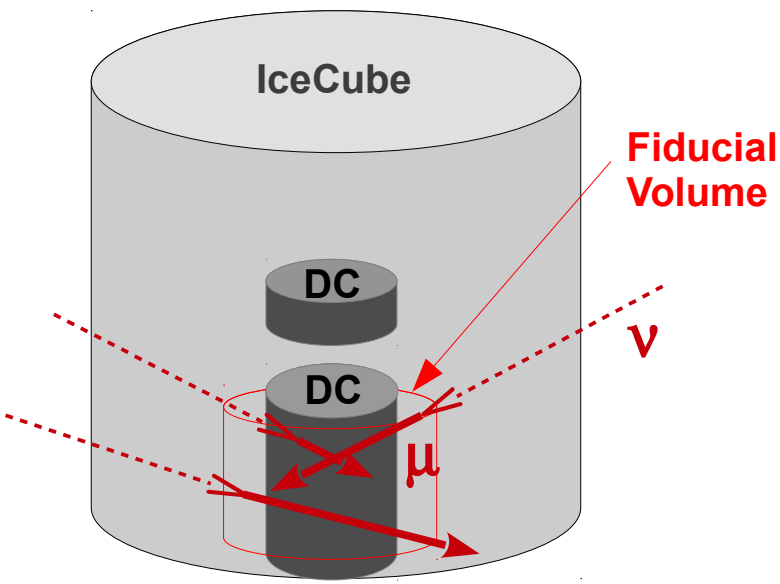
High-Energy (m_χ > 300 GeV)

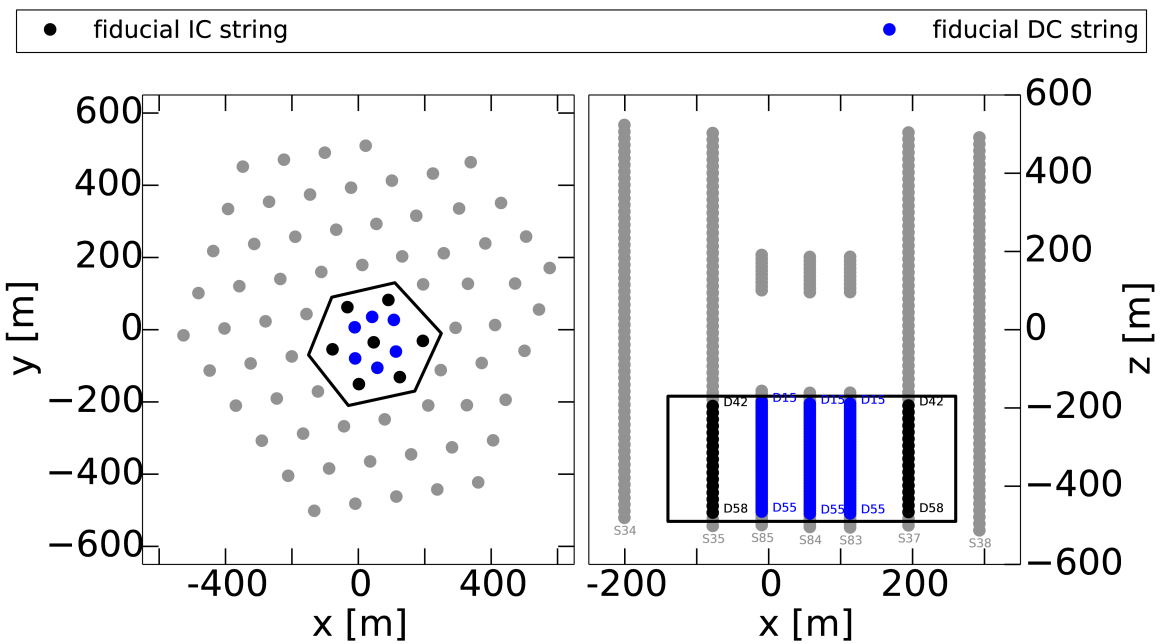
- GC & DeepCore filter stream
- Several vetoes against atm. muons
- Linear cut levels & BDT
- BDT cut optimized via Sig/sqrt(Bkg)
- Sensitivity via cut & count in search window (±15° RA, ±15° Dec) around GC or maximum likelihood analysis

90% CL calculated via Feldman & Cousins ordering principle

Low Energy Analysis

- **Low-Energy (< 300 GeV):** Events are partially or well contained within DeepCore
  - extends the methodology developed for the IC79 solar WIMP analysis [1]
  - Looking for downward going starting tracks within DC
  - Use IceCube as an active veto
  - Focus on contained events

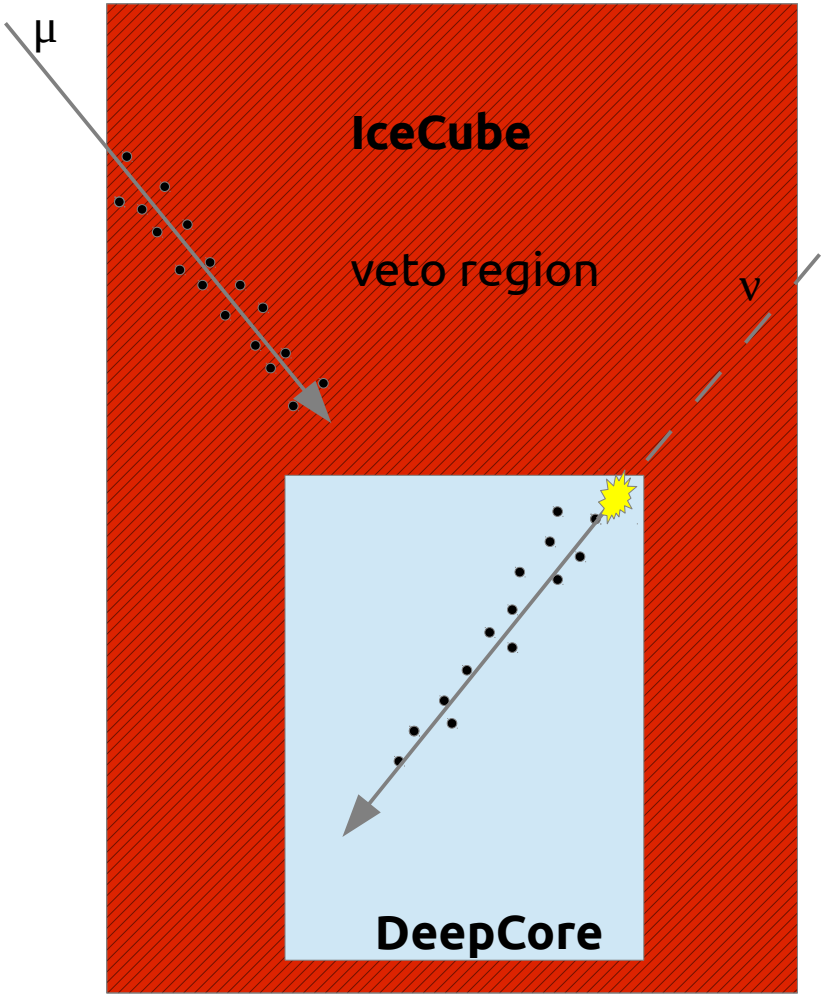




[1] M. G. Aartsen et al., Phys. Rev. Lett., 110(13) (2013) 131302.

Veto methods

- Identifying starting events opens up the Southern Sky for Icecube.
- Vetos needed to reject incoming tracks.
- Veto methods for this analysis focus on low energy events.
  - Using DeepCore as fiducial volume.
- Vetos need in general 'uncleaned hits'.
  - Reconstructions use cleaned hits.



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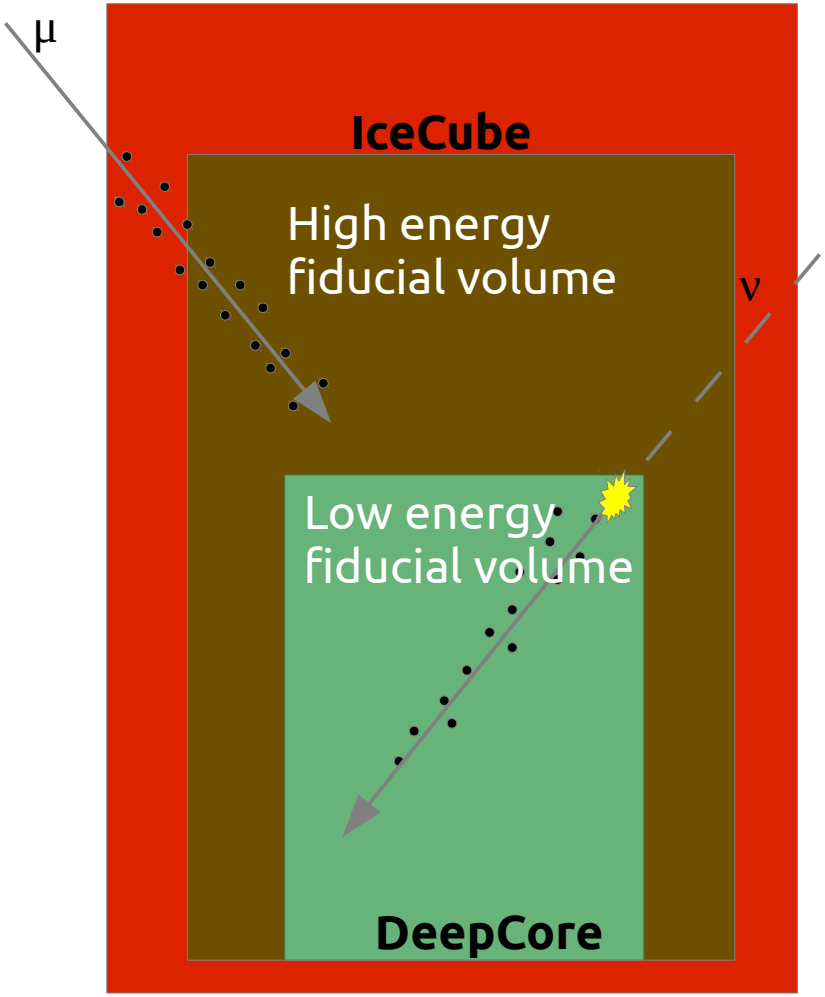

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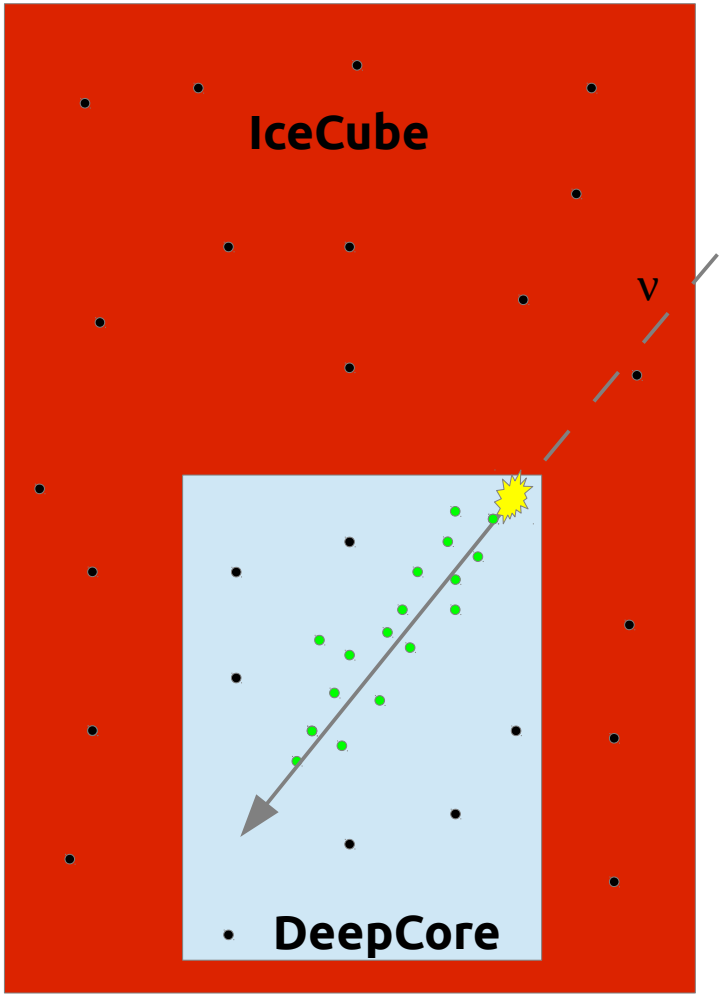

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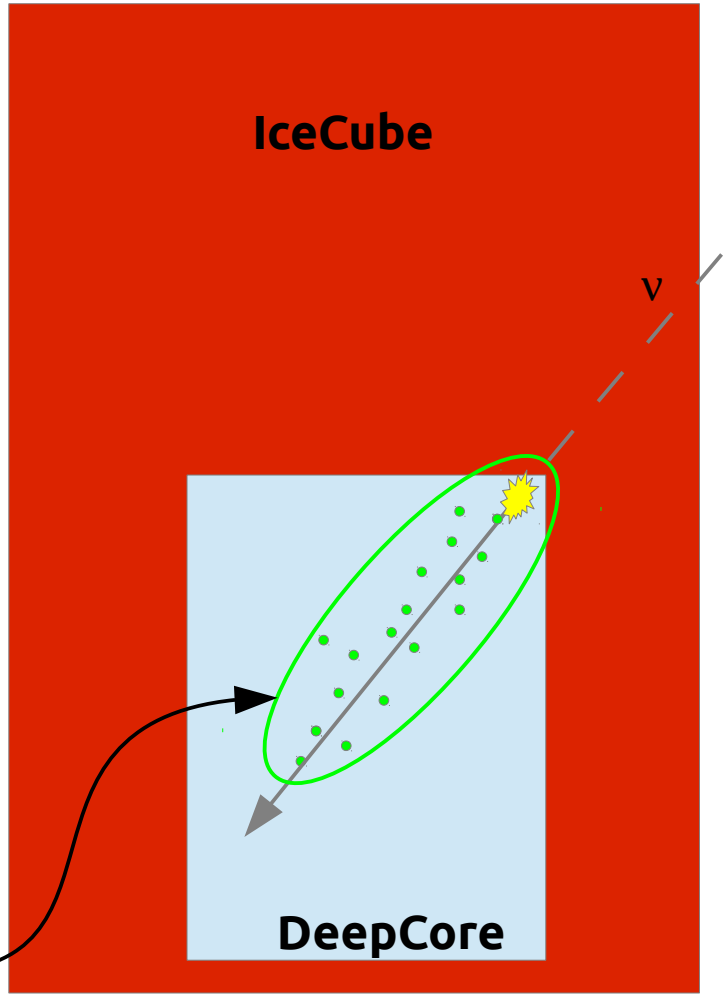
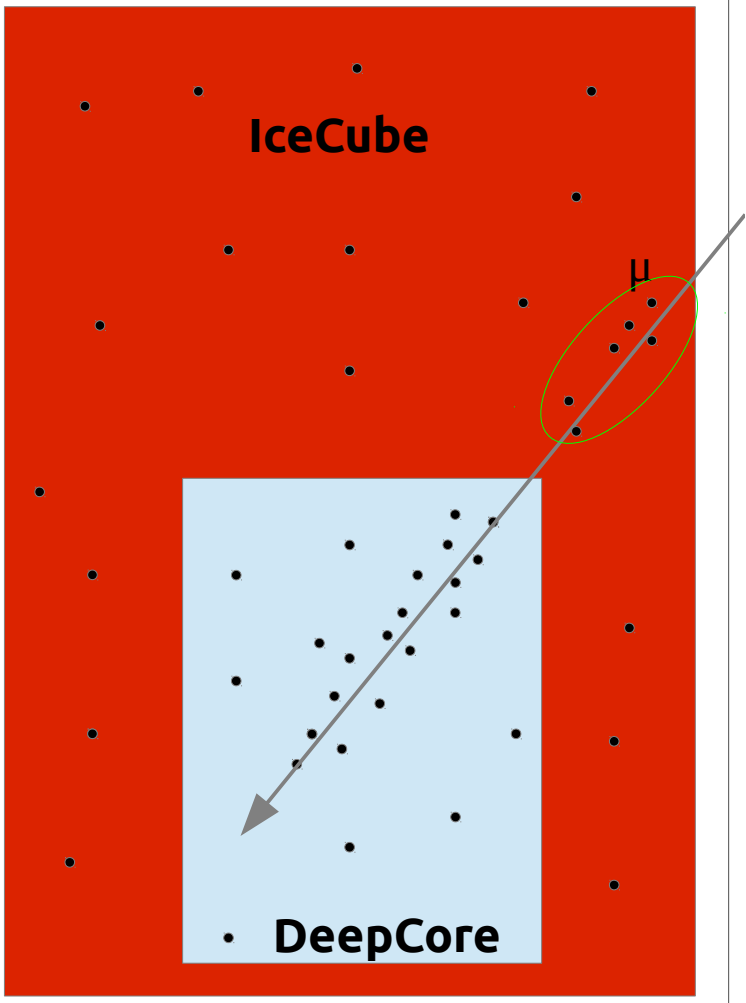
Cleaning algorithms collect hits that are causally connected into clusters.



Veto methods

- **Incoming atmospheric muon track might leave small clusters of hits in the veto region.**
  - These cluster are too distant and faint for the cleaning algorithms to connect them.
- **Consider hits in veto region before the event entered the fiducial volume.**
  - A modifed cleaning algorithm tries to find the largest cluster.

All hits:



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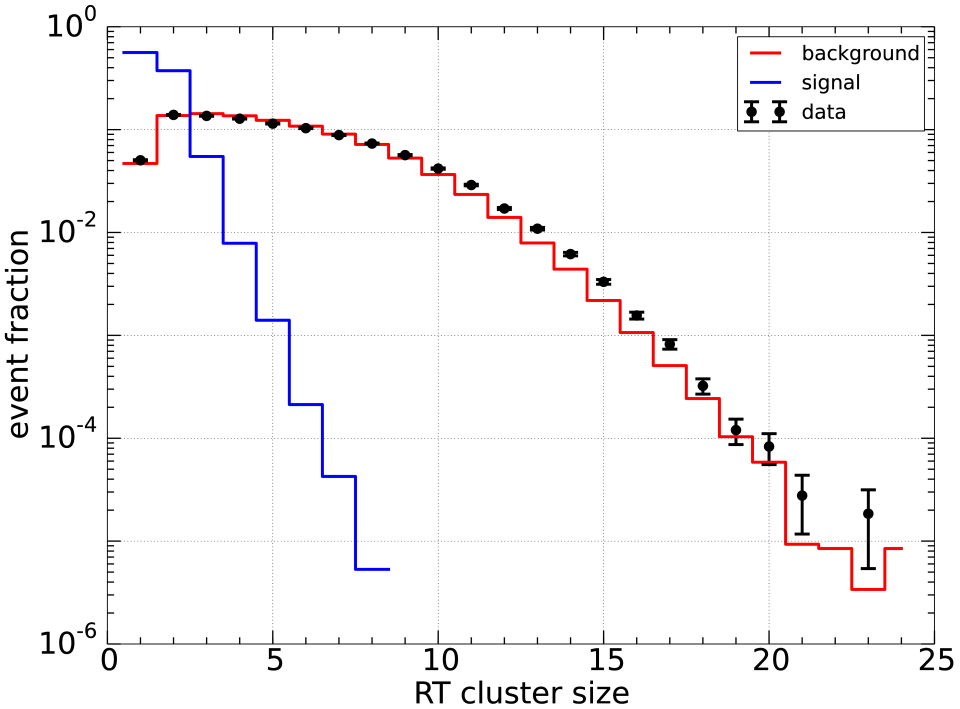
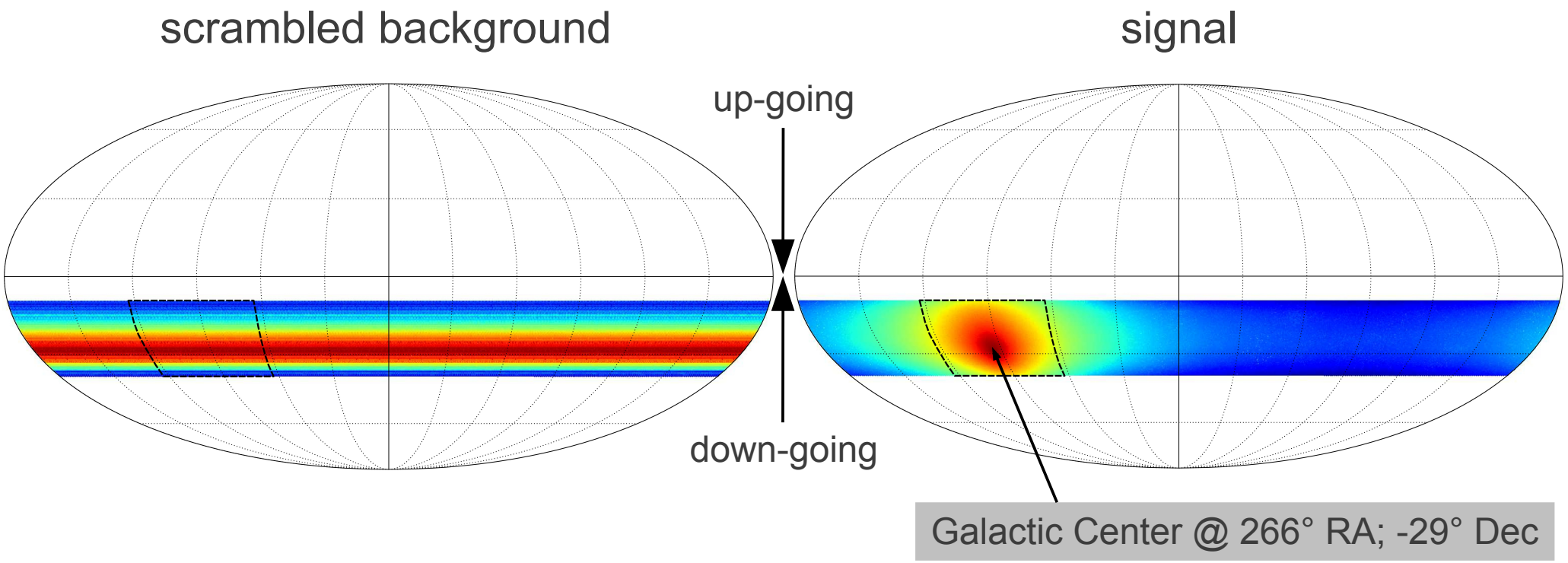
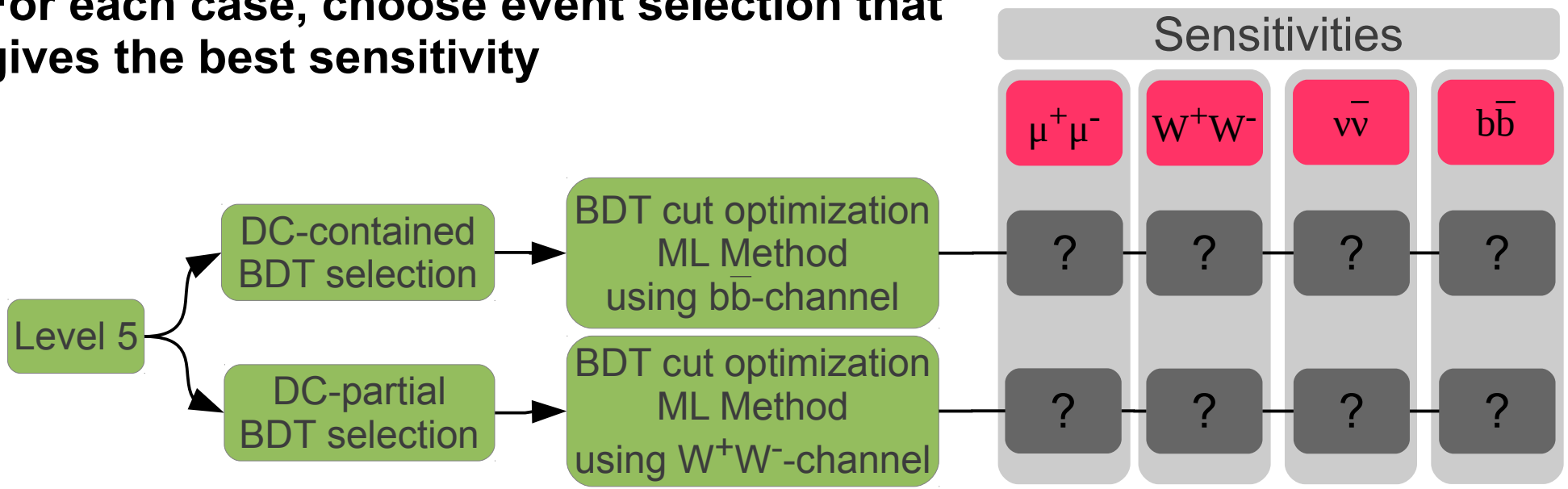


2D skymap PDFs generated with healpix
(equatorial coordinates)

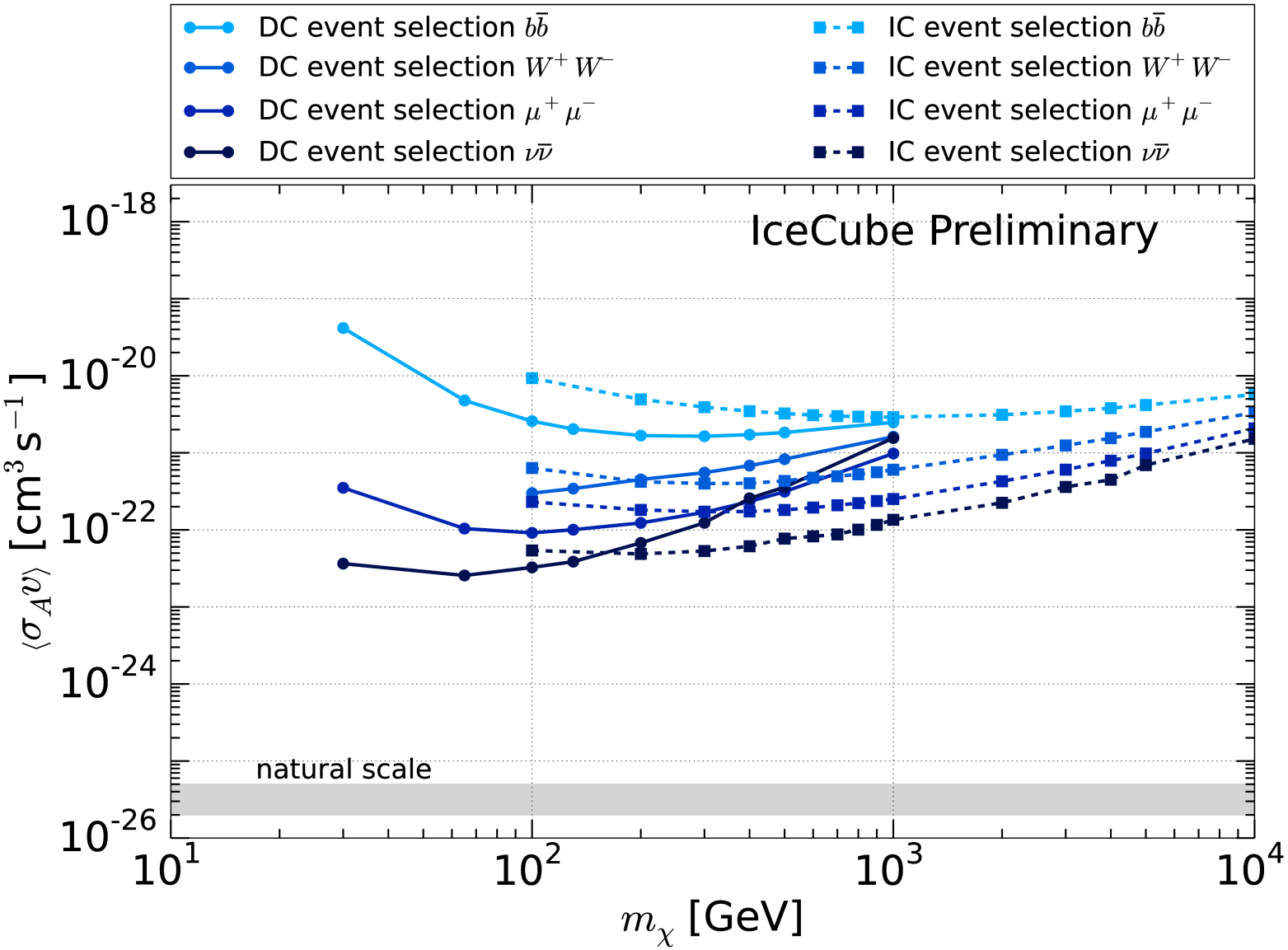


Low Energy Analysis
Sensitivity determination

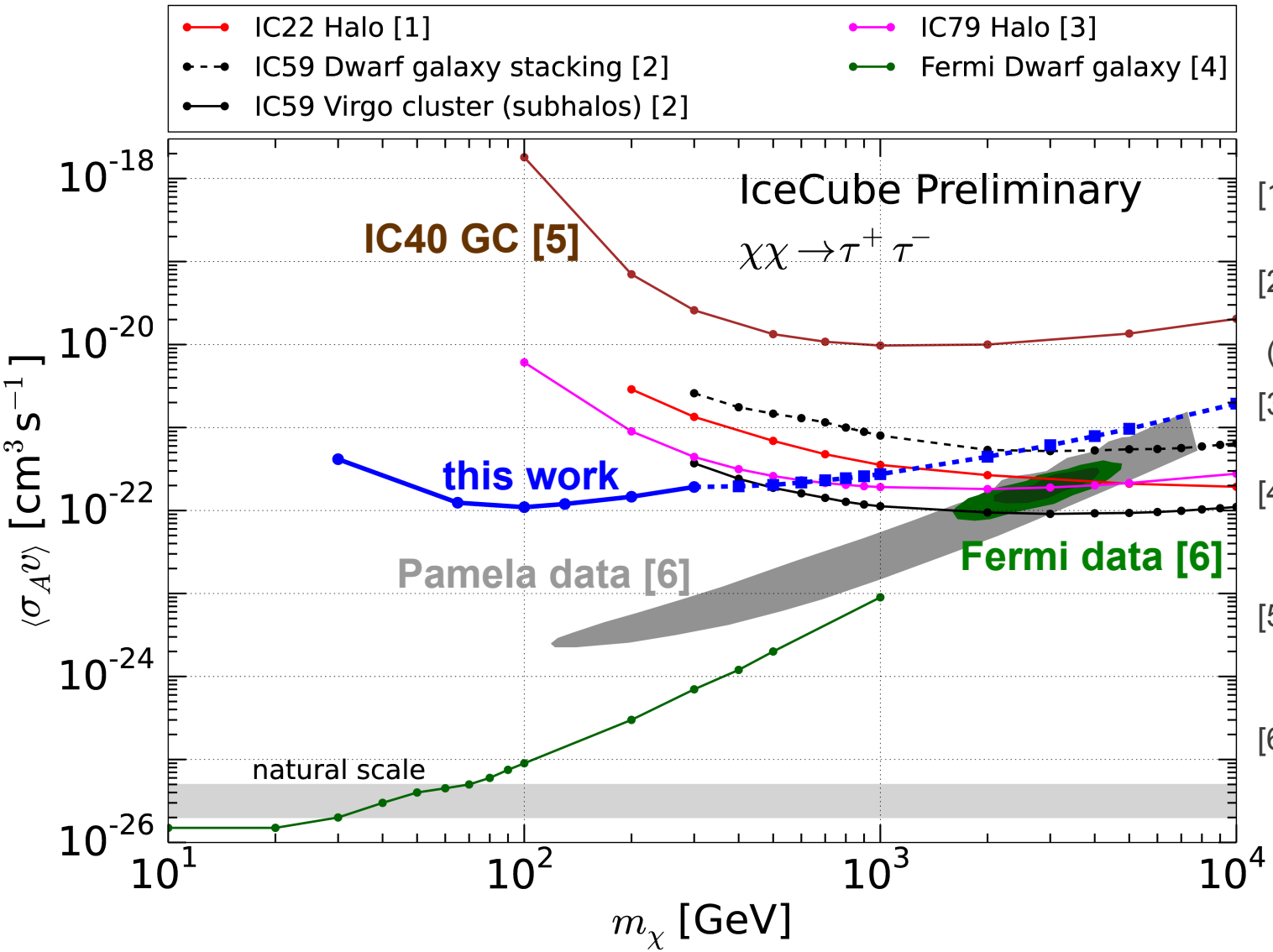
- **2 optimized event selections**
  - DC-contained optimized on $b\bar{b}$
  - DC-partial optimized on W^+W^-
- **Data rate:** $O(1)\,\mathrm{mHz}$
- **For each annihilation channel & WIMP mass, run the analysis with both event selections**
- **For each case, choose event selection that gives the best sensitivity**



Sensitivities



Sensitivity to other experiments



[1] R. Abbasi et al., Phys. Rev. D, 84 (2011) 022004.

[2] R. Abbasi et al., arXiv:1111.2738[hep-ex] (2011) (to be submitted to Phys. Rev. D).

[3] IceCube Coll., ICRC2013 contribution 0451.

[4] M. Ackermann et al., Phys. Rev. Lett., 107(24) (2011) 241302.

[5] R. Abbasi et al., arXiv:1210.3557[hep-ex] (2012).

[6] P. Meade, M. Papucci, A. Strumia and T. Volansky, Nucl. Phys. B, 831 (2010) 178.

Summary

- **First IceCube analysis looking at GC for low WIMP masses (< 100 GeV)**
- **4 orders of magnitude better sensitivity** @ 100 GeV $\tau^+\tau^-$ channel w.r.t. IC40 GC analysis
- **New veto methods to reject atmospheric muon background** using DeepCore as fiducial volume developed.
  - Improves IceCube WIMP searches in the Southern Hemisphere
- **Results Soon!**

Thank you!

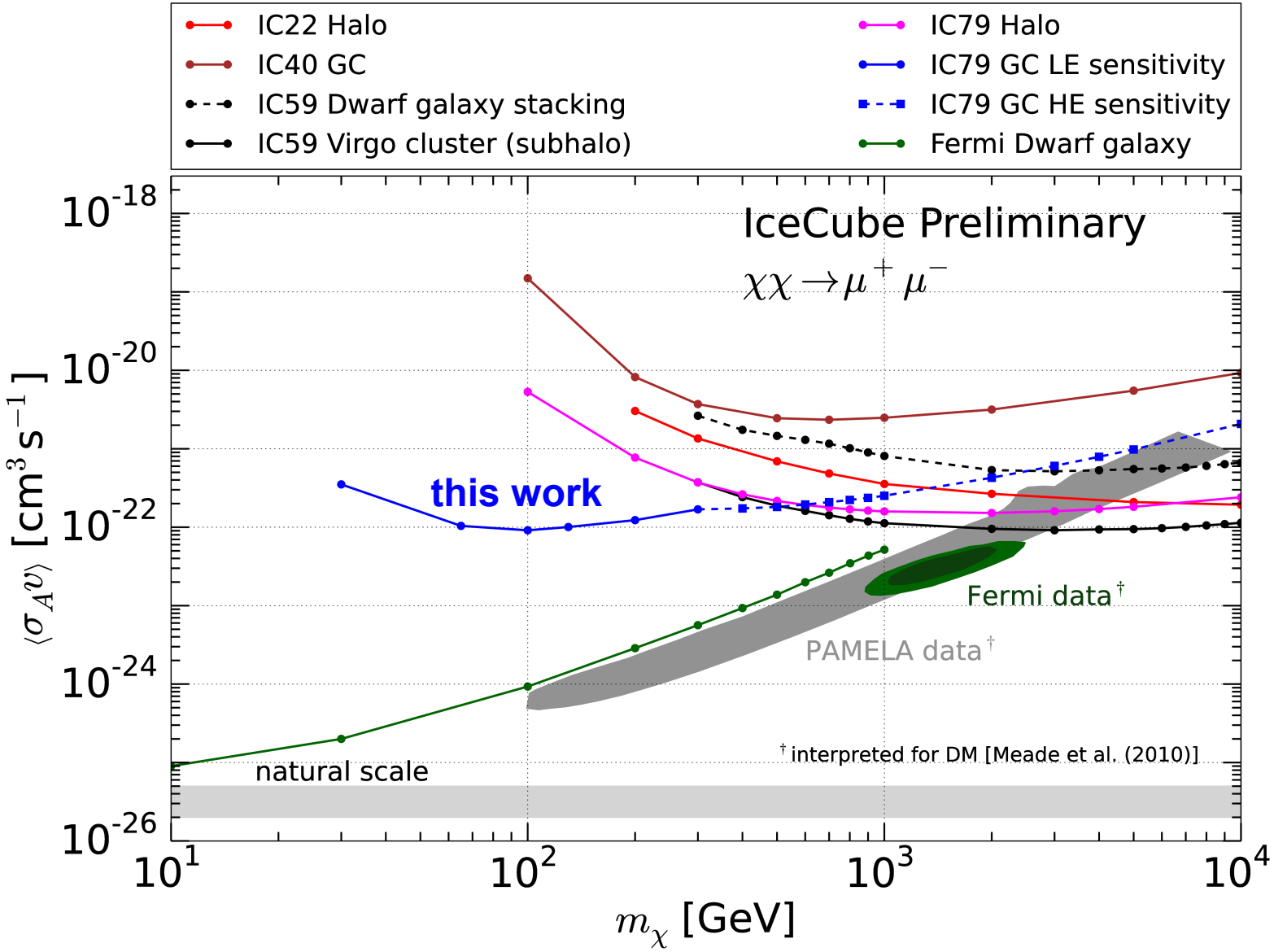
Additional slides

Procedure to weight signal events sampled from nugen MC

```
EventWeight =
OneWeight / nGeneratedEvents * J_psi * Constant * NeutrinoSpectrum
```

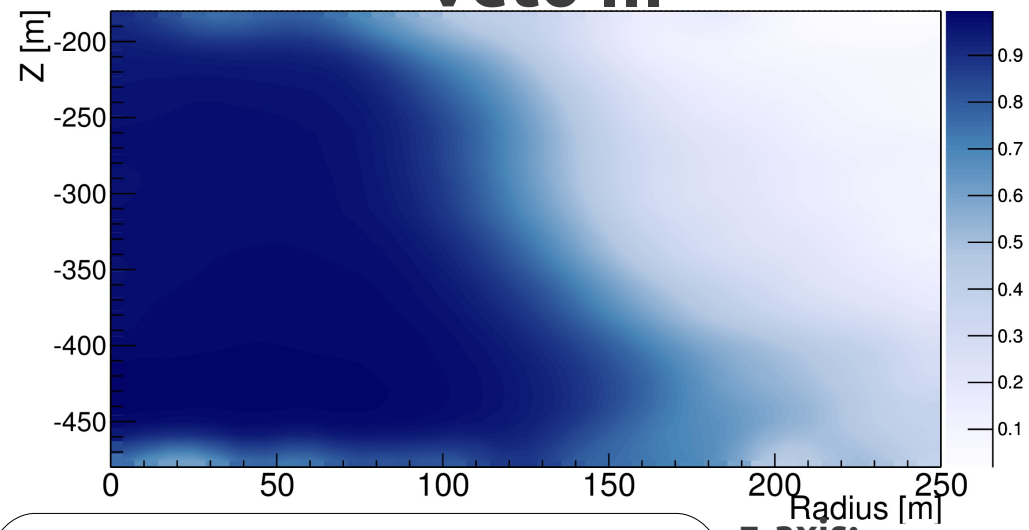
$$\frac{d\Phi_\nu}{dE} = \frac{\langle \sigma_A v \rangle}{2} J(\Psi) \frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2} \frac{dN_\nu}{dE}$$

Sensitivity to other experiments



Vetos
Radial-Z and Cone

Veto III



z-axis:
fraction of signal probability

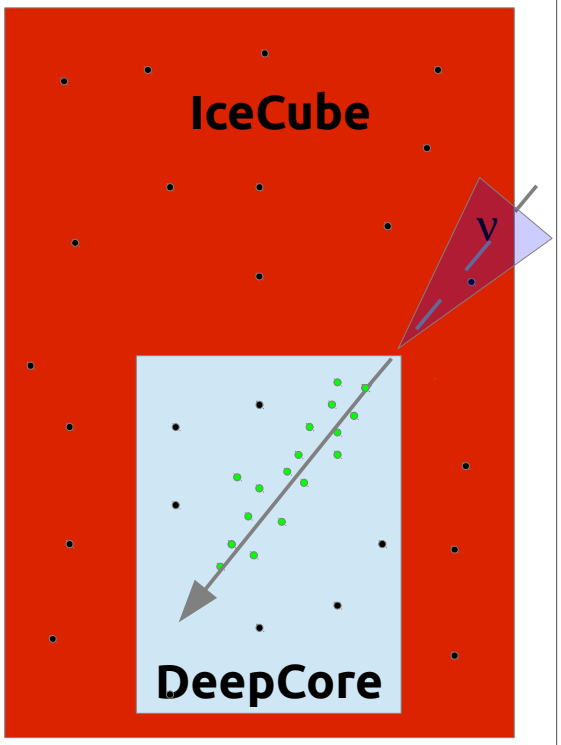
Incoming muon:
-High first hit in *Z*.
-Reconstructed vertex at the edge of fiducal volume

Starting event:
-Uniformly distributed first hit in *Z*.
-Reconstructed vertex within the fiducal volume

A maximum likelihood method is used to determine the starting point (vertex) and time of a track.

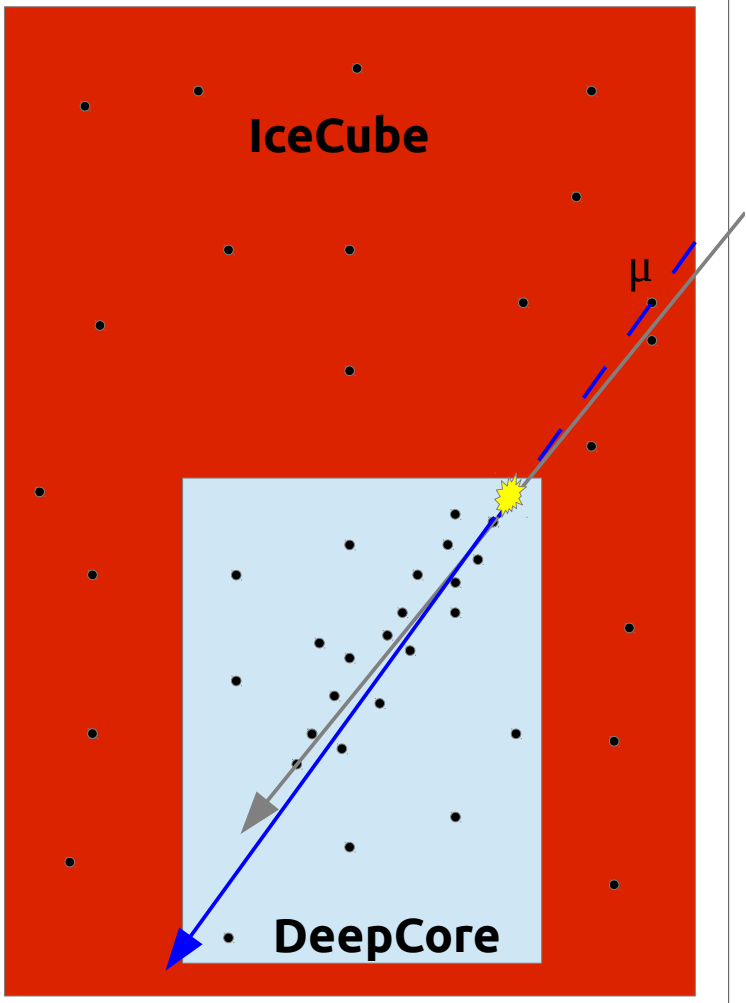
Veto IV

- Count hits in a cone
- Cone starts at reconstructed vertex
- Only consider hits before vertex time.



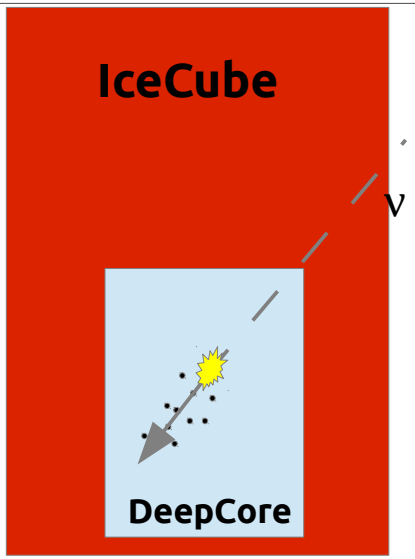
Track Likelihood Veto

- **Consider hits in veto region before the time of the reconstructed event vertex.**
  - Construct a cylinder in the veto region around the track reconstruction.
  - Compute the track likelihood using hits in the cylinder.
- **The likelihood value will reflect how likely the hits in the cylinder are associated with the track.**

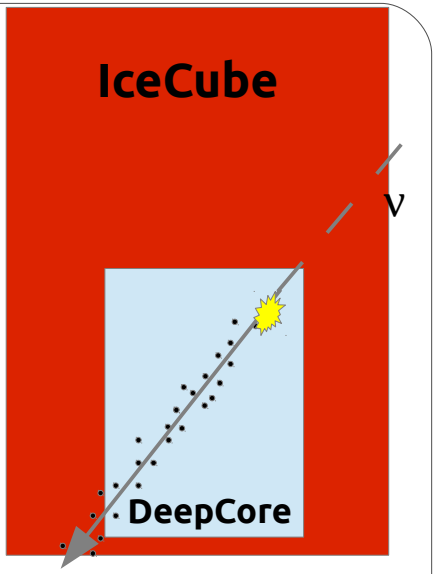


Event Selection

- **Split data into a high energy (HE) and low energy (LE) event selection.**
  - LE events are DeepCore dominated (more hits in DeepCore)
- **Apply cuts suited for each event selection independently.**



Case 1:
Contained low energy and quality events.



Case 2:
Outgoing high energy and quality events.