Latest Results on Searches for Dark Matter from IceCube

Matthias Danninger for the *IceCube Collaboration*
The Oskar Klein Centre for Cosmoparticle Physics, Stockholm University

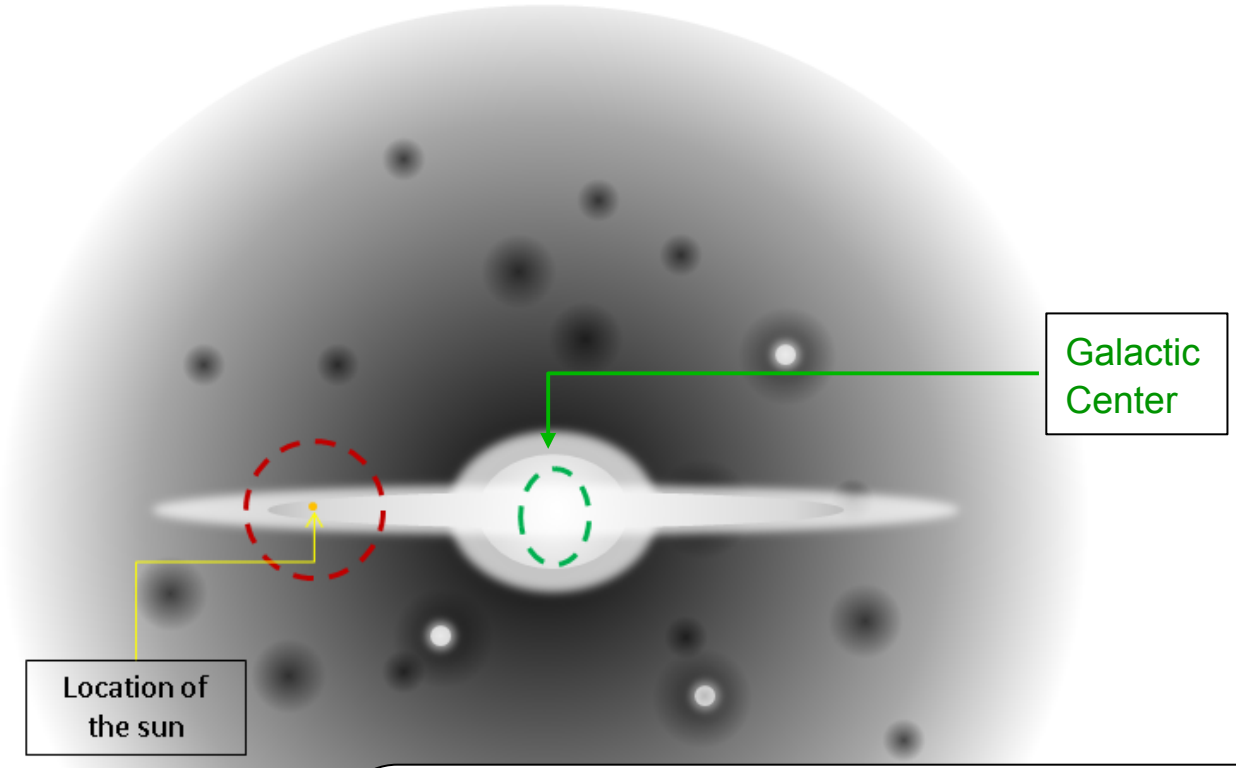
TAUP 2013 Topics in Astroparticle and Underground Physics
Asilomar, September 8-13, 2013

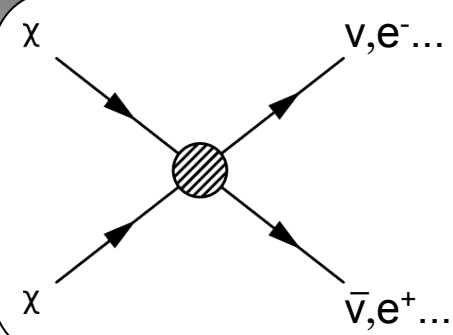
ICECUBE

Oskar Klein centre

Indirect Search with IceCube (Overview)

(Image: M.Strassler)





- Searching for DM-annihilations is in low energy regime for IceCube. (~10 GeV-TeV)
- Consider "extrema" to bracket possible neutrino spectrum. e.g. *hard* (W^+W^-) and *soft* (*bb*)

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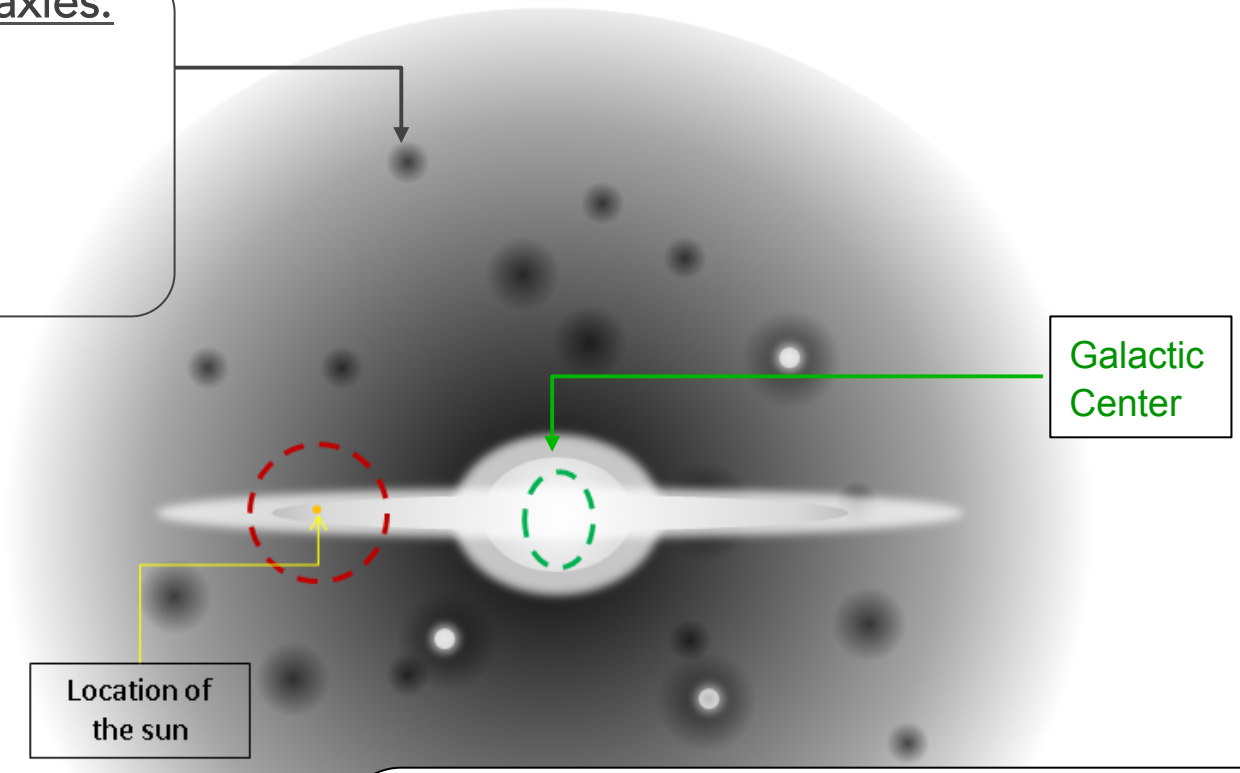
Dwarf spheroidal Galaxies:

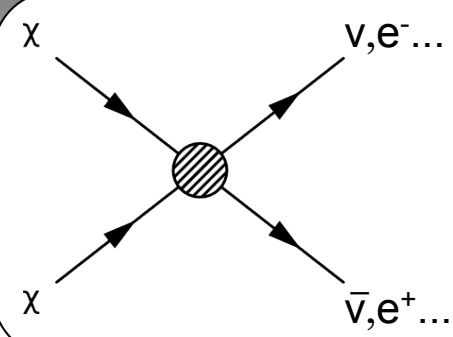
→ IceCube-59 limits

Clusters of Galaxies:

→ IceCube-59 limits

(arXiv:1210.3557 2012)





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→ IceCube-22 limits

(PRD 84 (2011) 022004)

→ IceCube-79 limits

Galactic Center:

→ IceCube-40 limits

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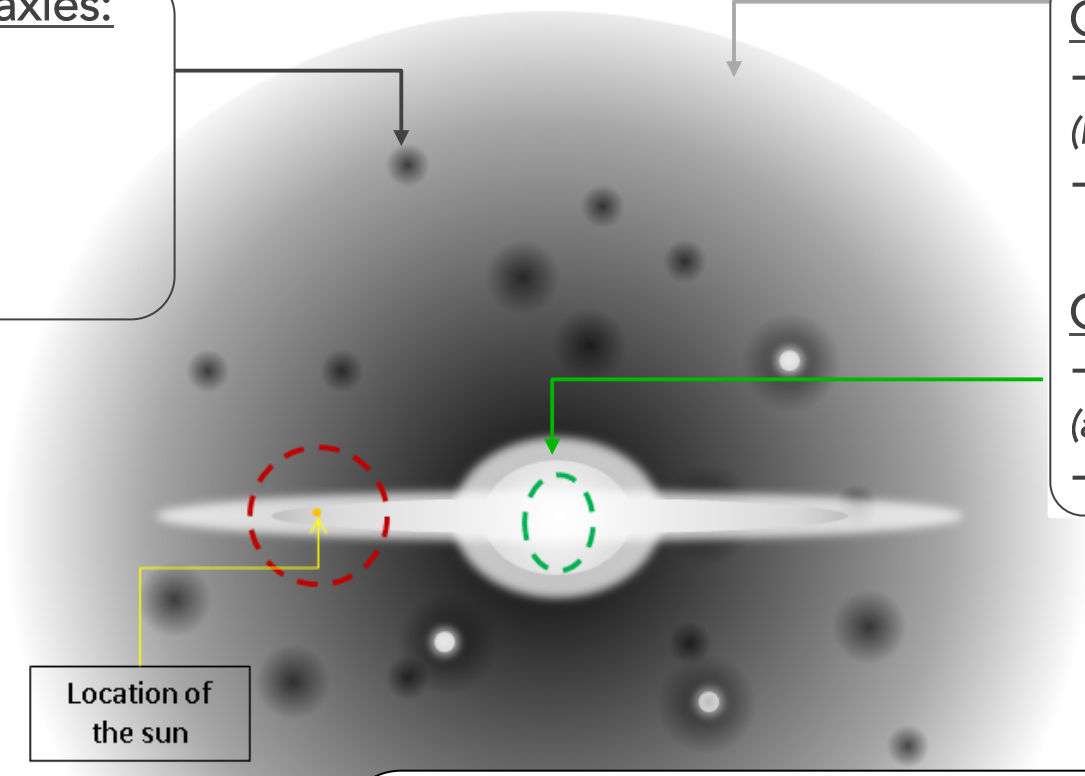
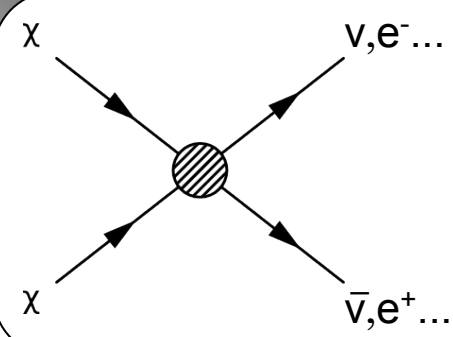
→ IceCube-79 sens





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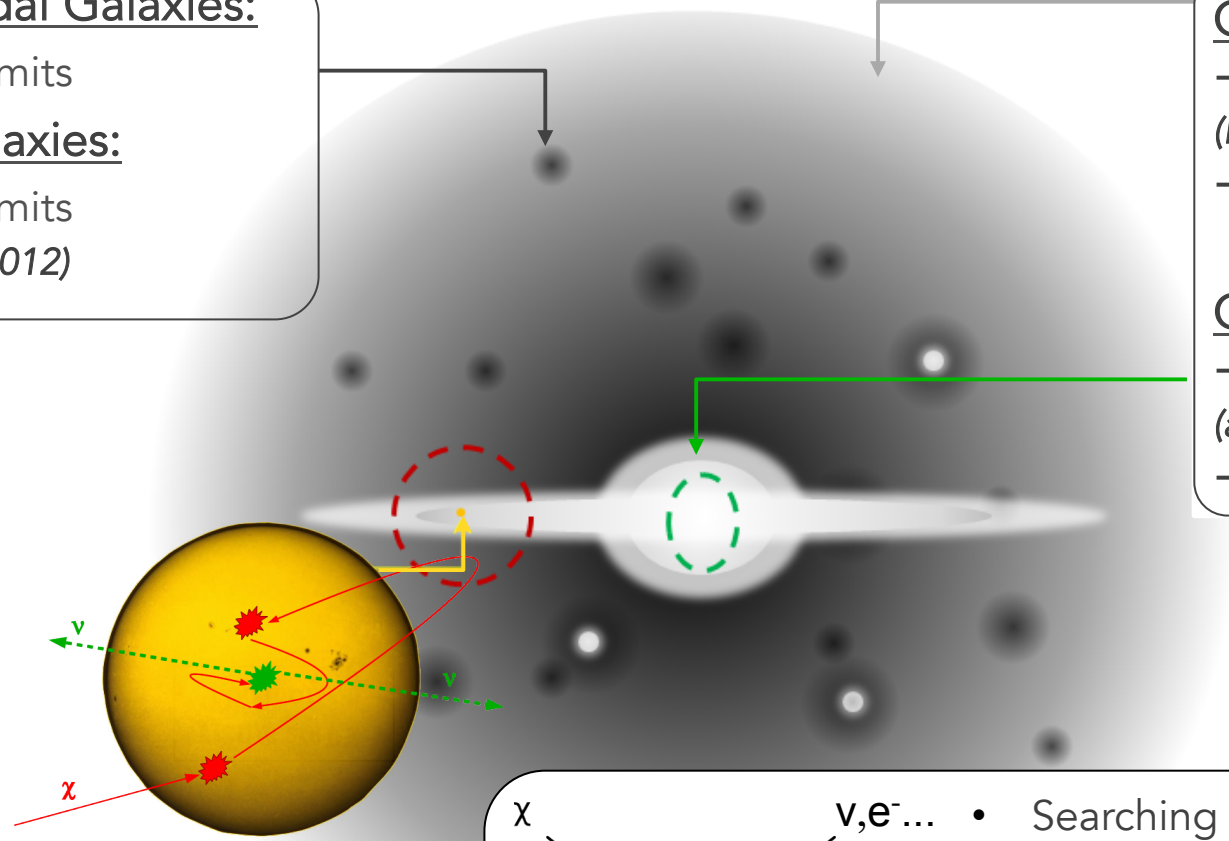
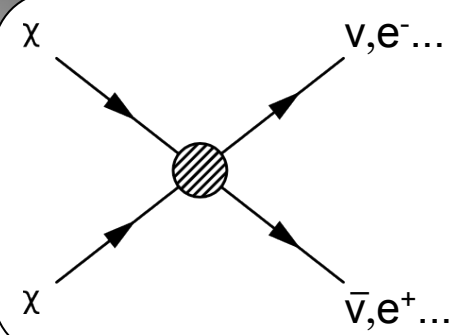


Local sources (Sun & Earth):
→ IceCube-79 limits
(PRL 110 (2013) 131302)
→ Specific models & Global fits
(JCAP 11 (2012) 057)



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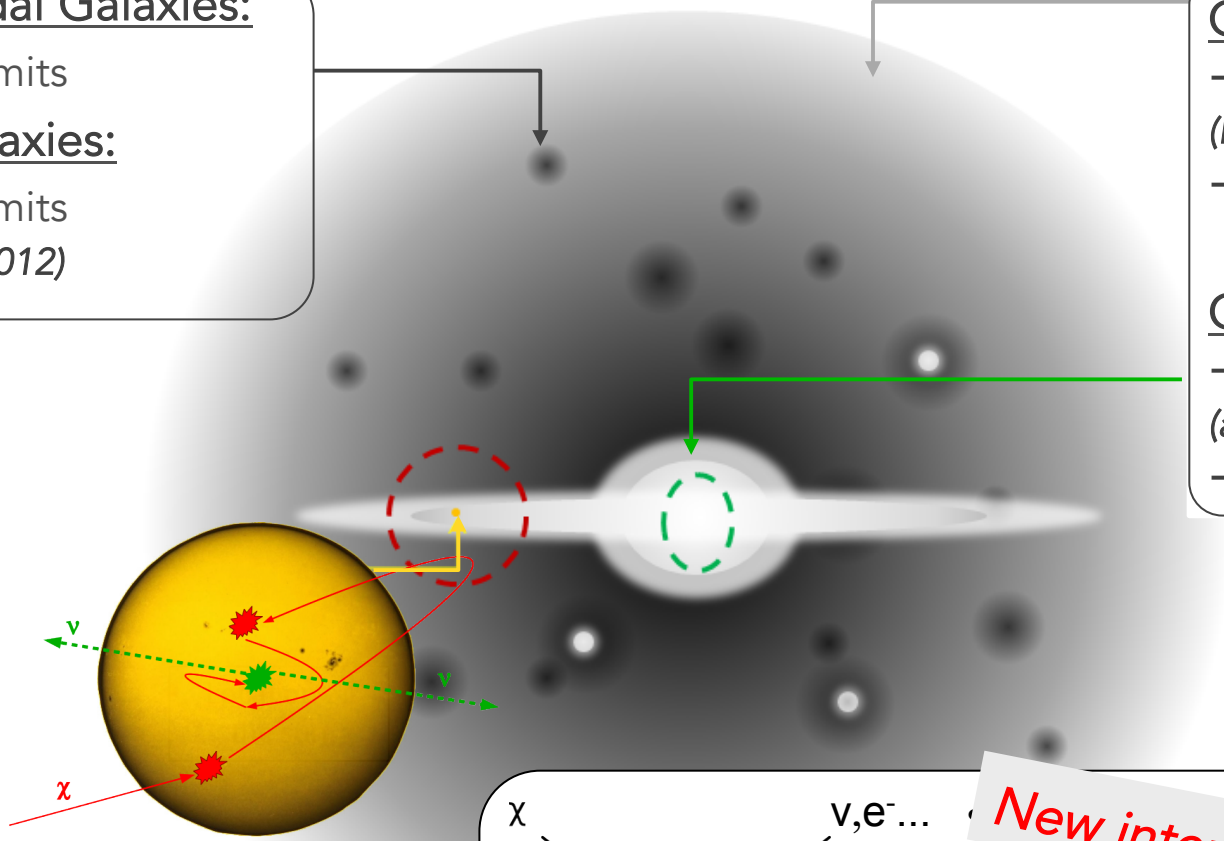

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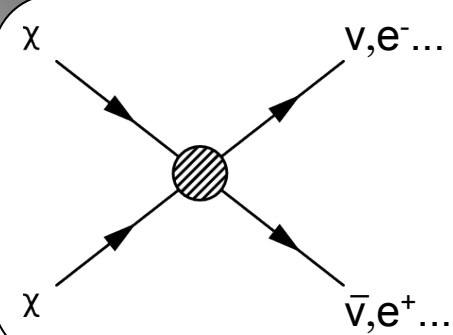
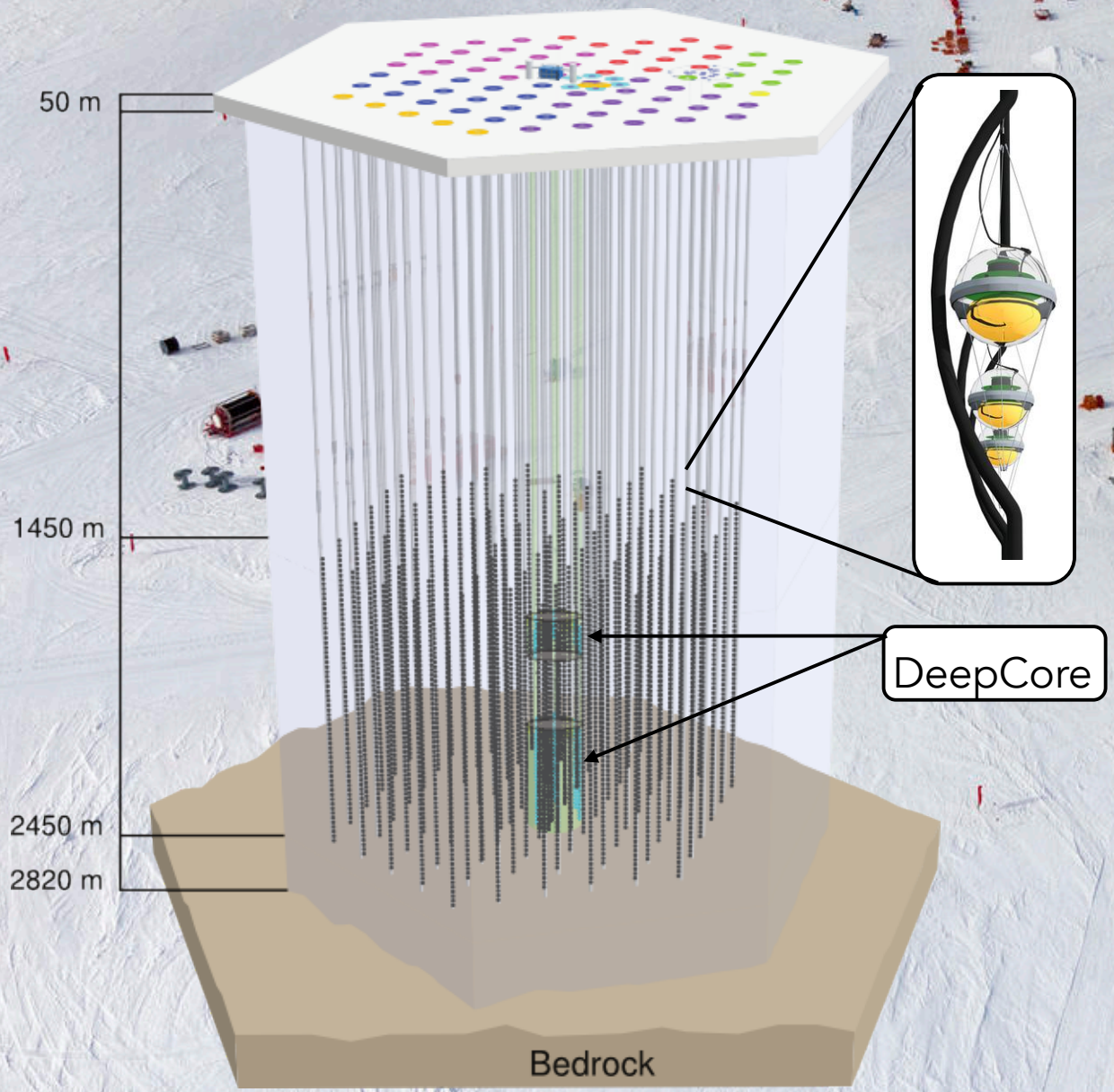


New interest in PeV range

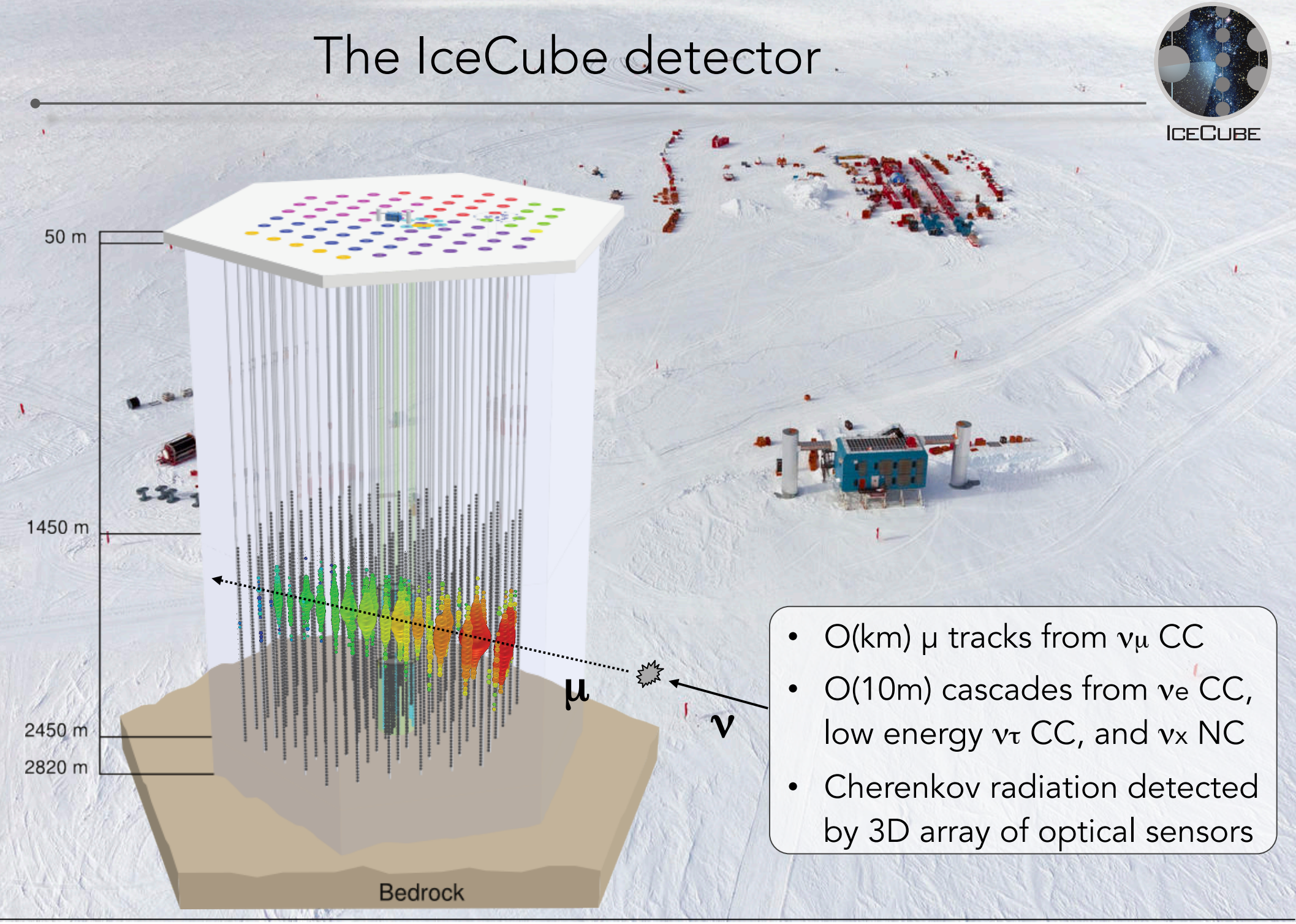
- DM-annihilations is in low energy (~10 GeV-TeV)
- Consider "extrema" to bracket possible neutrino spectrum. e.g. *hard* (W^+W^-) and *soft* (*bb*)

The IceCube detector



- 1.5 km - 2.5 km deep
- typically 125 m spacing between strings (~70 m in DeepCore)
- 60 Modules per string
- 1 km³ – 1 Gton instr. volume

The IceCube detector



- O(km) μ tracks from ν_μ CC
- O(10m) cascades from ν_e CC, low energy ν_τ CC, and ν_x NC
- Cherenkov radiation detected by 3D array of optical sensors

Solar Dark Matter Search with IceCube

- All processes depend on WIMP mass
- Annihilation channel (branching ratios)
- Annihilation cross-section
- Capture (scattering)
  → Scattering cross-sections (SI & SD)

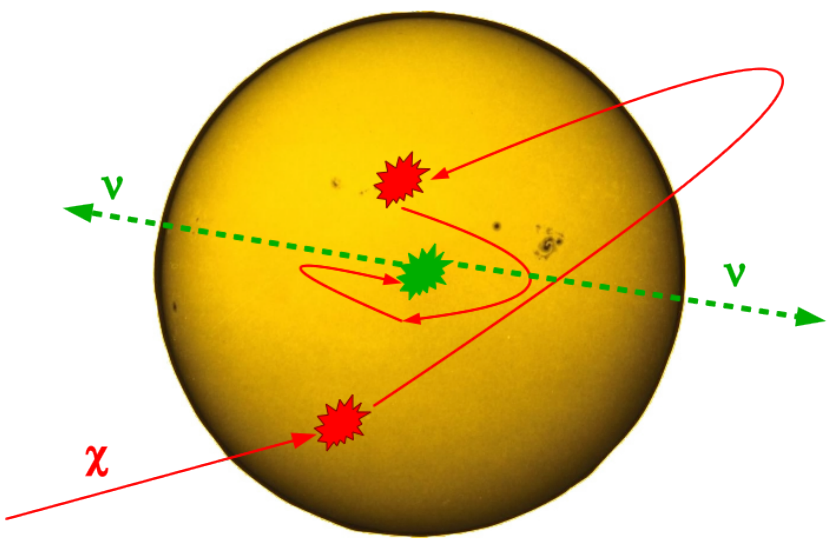
Details about Capture Process (e.g.):

Press & Spergel '85

Gould '88

Peter 2008

Sivertsson, Edsjö, PRD85 (2012) 123514



$$\frac{dN}{dt} = C_{capt.} - C_{ann.}$$

$$C_{ann.} = C_{capt.} \rightarrow \sigma_{total}$$

Proposed by:

Silk, Olive & Srednicki '85

Gaisser, Steigman & Tilav '86

Freese '86

Krauss, Srednicki & Wilzcek '86

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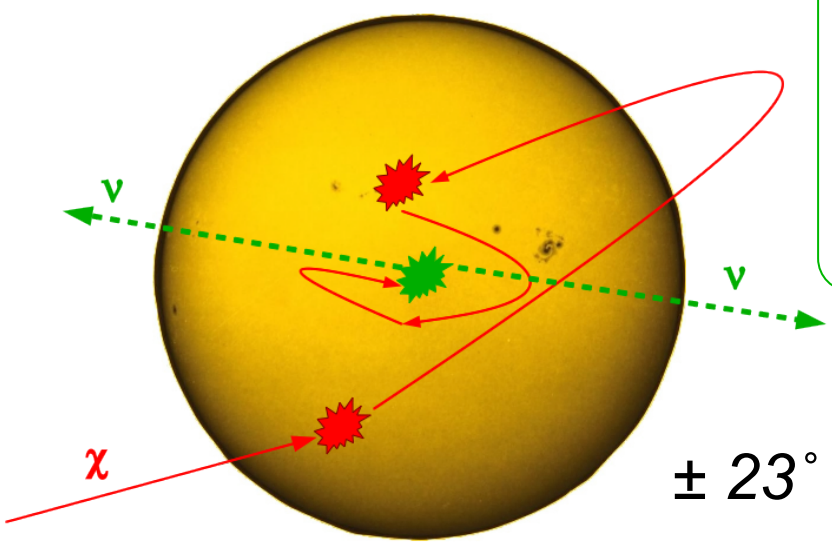
main analysis backgrounds:

atm.μ~O (10^8 triggering events/day)

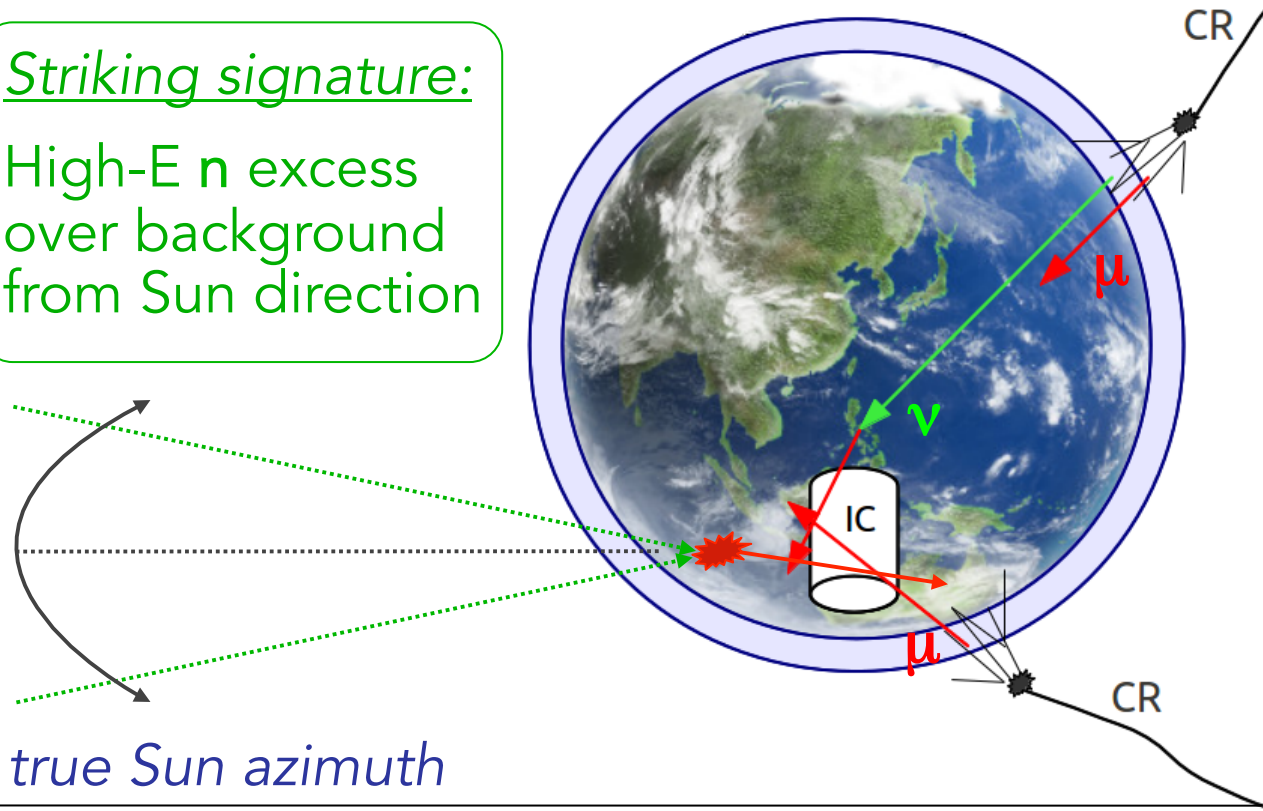
atm.ν~O (10^3 triggering events/day)

Striking signature:

High-E **n** excess over background from Sun direction



± 23°

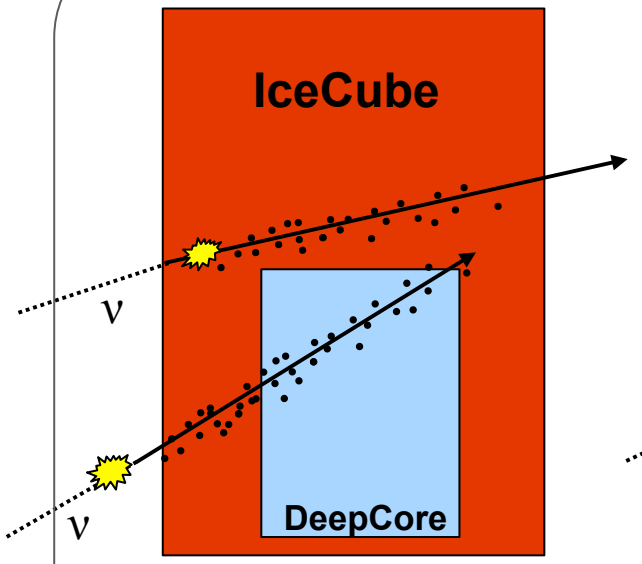


**Blind analysis with respect to true Sun azimuth*

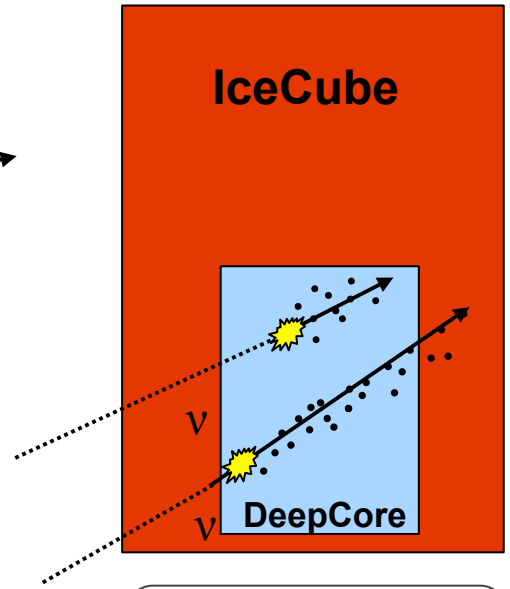
IceCube-79 string analysis details

- Analysis for the whole year! Used 317 days livetime
- With DeepCore, analysis reaches neutrino energies of *10-20GeV*

151 days austral winter

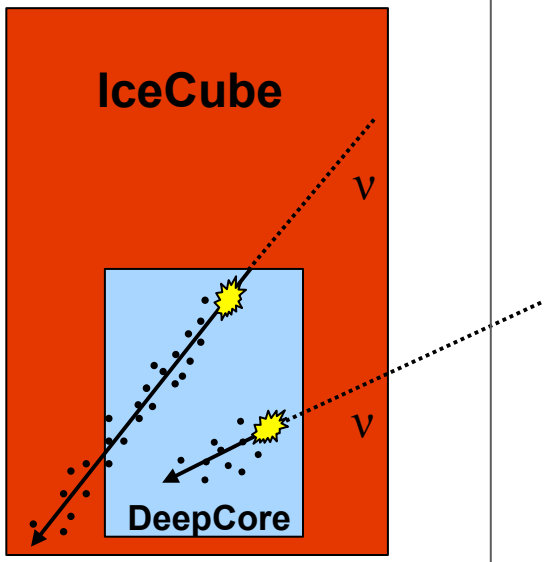


Case 1 (WH):
→ high energy
→ up-going
→ no contain-ment



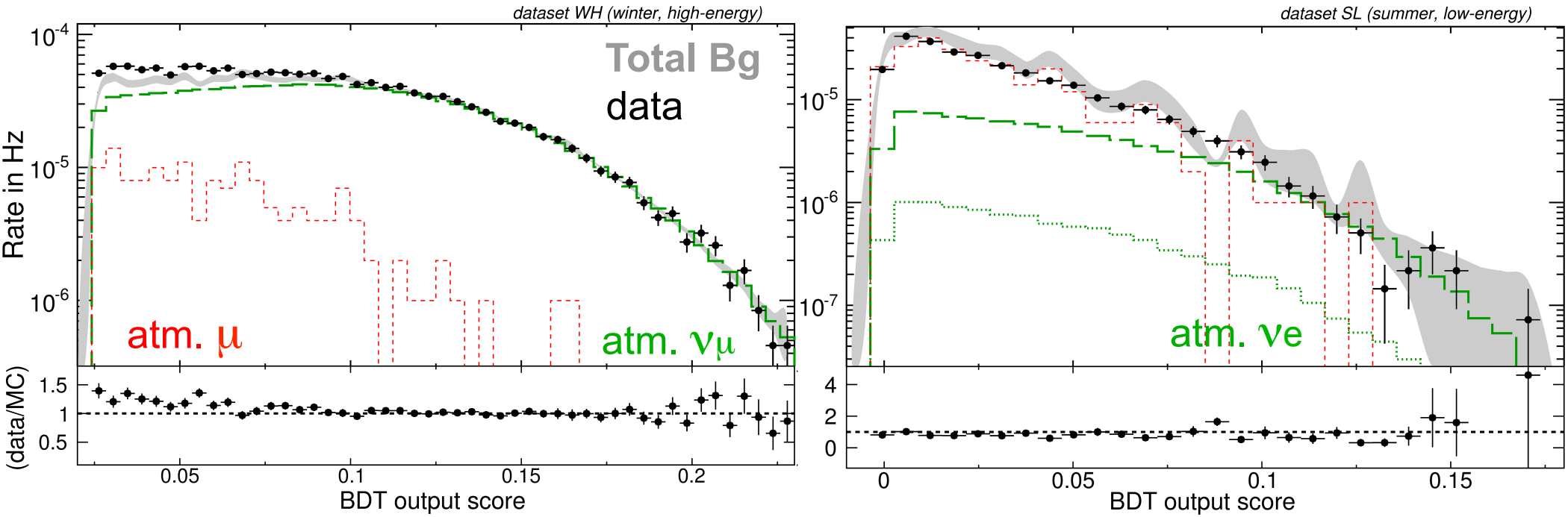
Case 2 (WL):
→ low energy
→ up-going
→ strong containment

166 days austral summer



Case 3 (SL):
→ low energy
→ down-going
→ strong containment

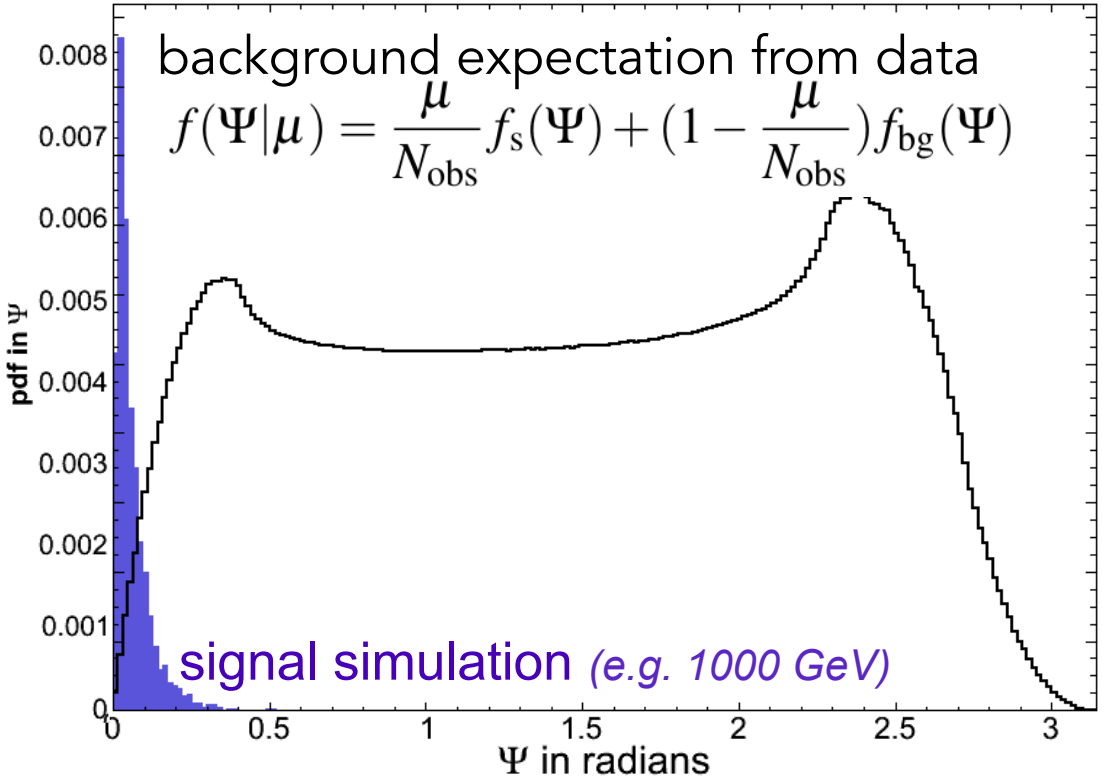
Multivariate analysis step (final cut applied)



- 1 separate BDT for each event selection
- Training on off-source exp. data + separate signal simulation
- Optimized final cut on BDT-output: run llh-analysis for various BDT cuts; determine cut value with best sensitivity

Maximum llh-analysis

The observed angle to the Sun is fitted with *signal* and *background* pdf:s



(Angle between event track & direction from the Sun)

Maximum llh-analysis

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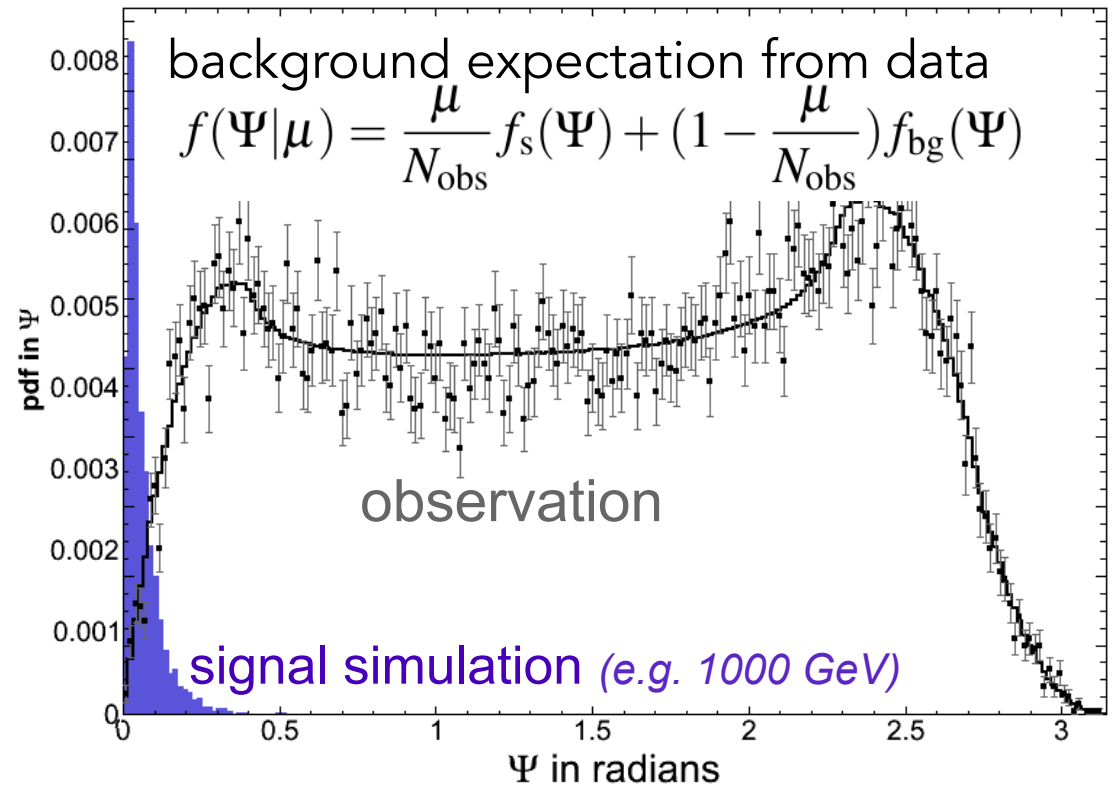


(Angle between event track & direction from the Sun)

Evaluate shape fit with log-likelihood rank (FC) to construct CI for the number of signal events μs

$$R(\mu) = \frac{\mathcal{L}(\mu)}{\mathcal{L}(\hat{\mu})}$$

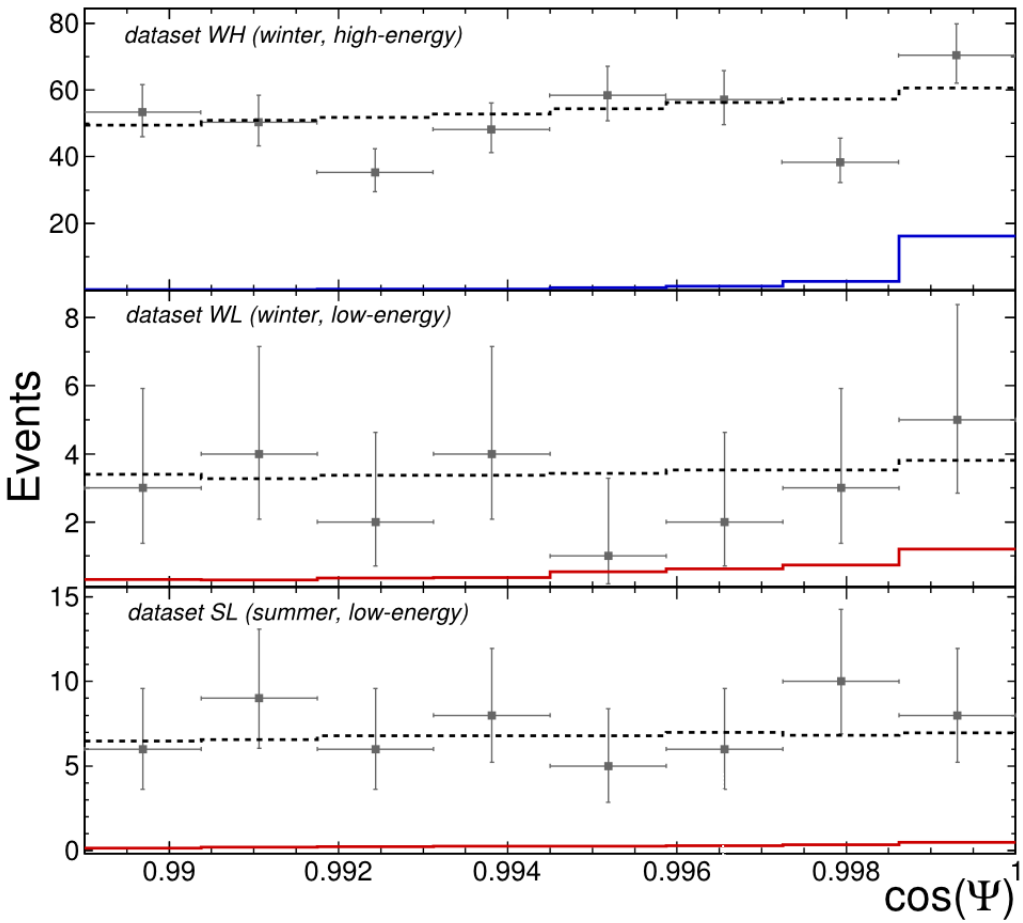
L(μ) is the pdf product over the final sample

$$\mu_j = \mu \frac{T^j_{\rm live} V^j_{\rm eff}}{T^1_{\rm live} V^1_{\rm eff} + T^2_{\rm live} V^2_{\rm eff}}$$

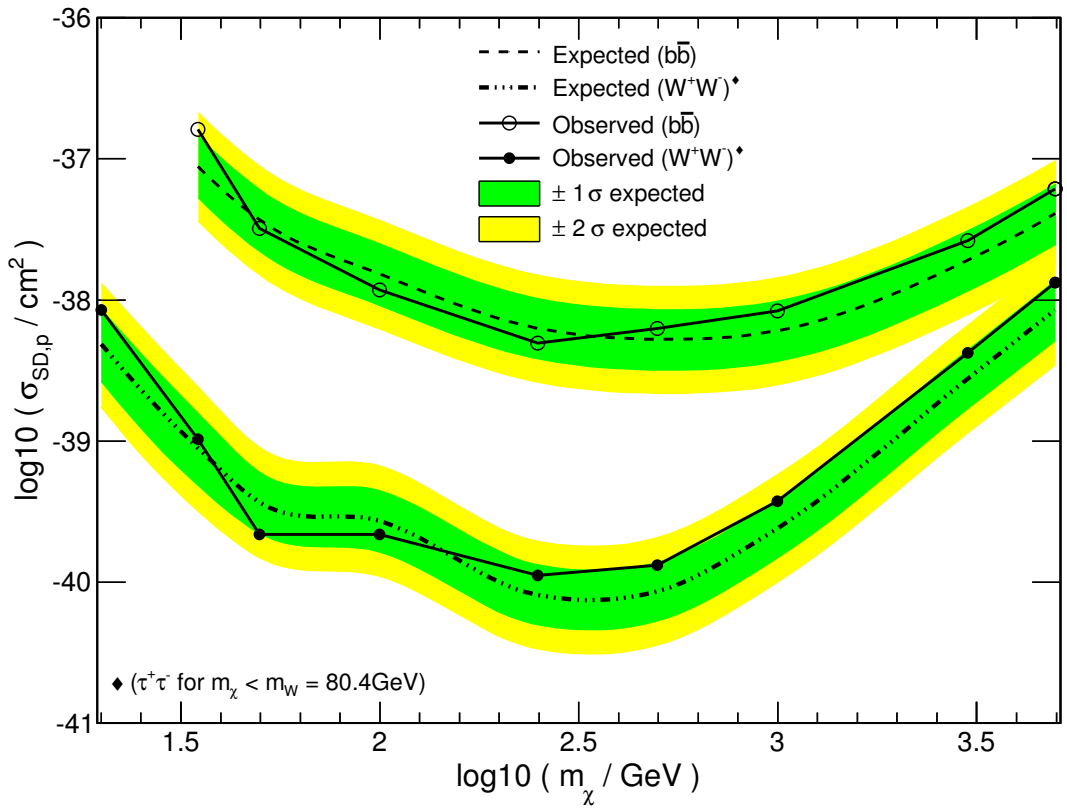
(scale to multiple datasets)

Unblinding results (observed results)

Unblinded events in different samples



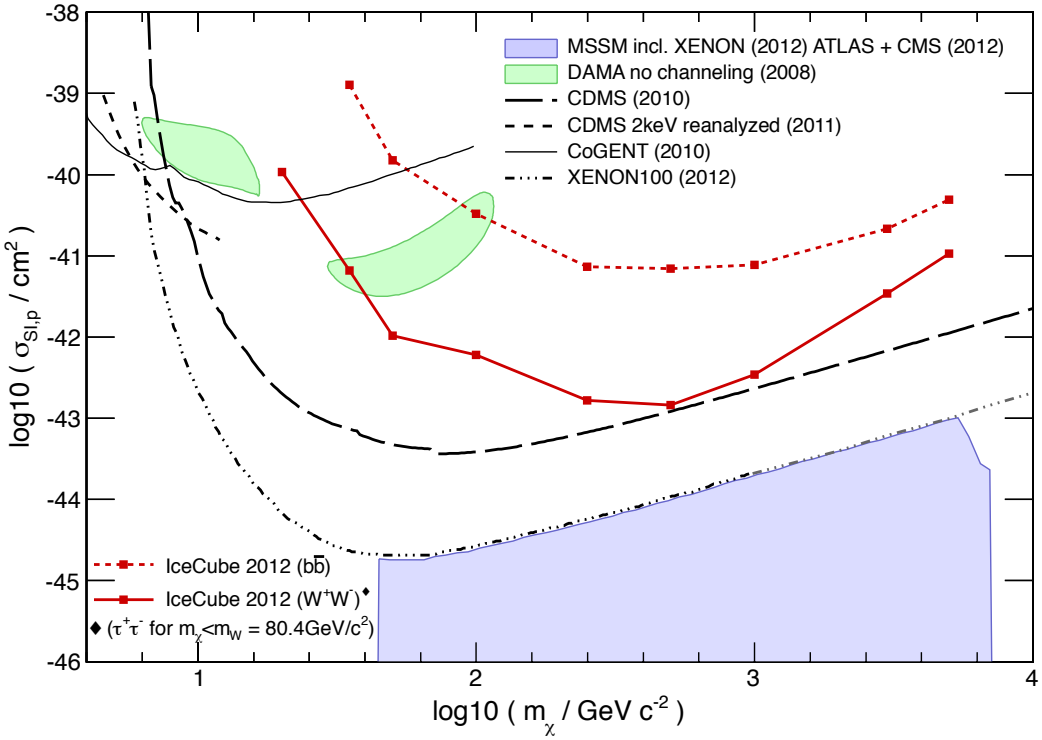
Expected sens. vs. observed result



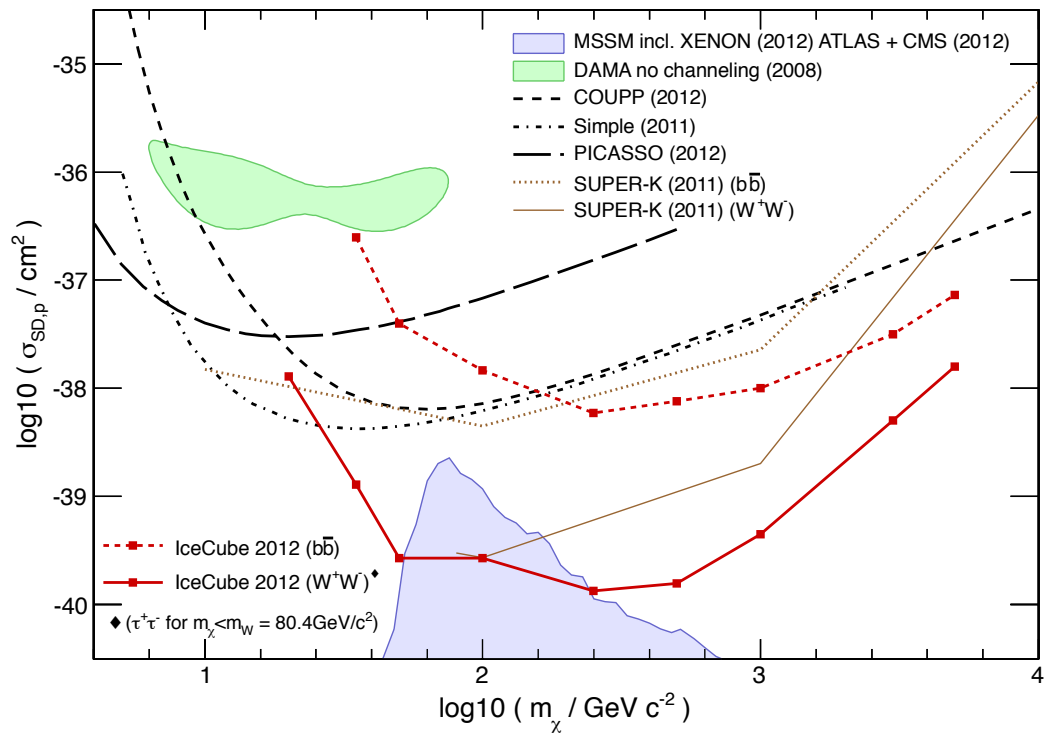
details on systematic uncertainties, see *PRL* ***110*** *(2013) 131302*

Solar WIMP search results (cross-section limit)

SI WIMP-proton cross-section limit



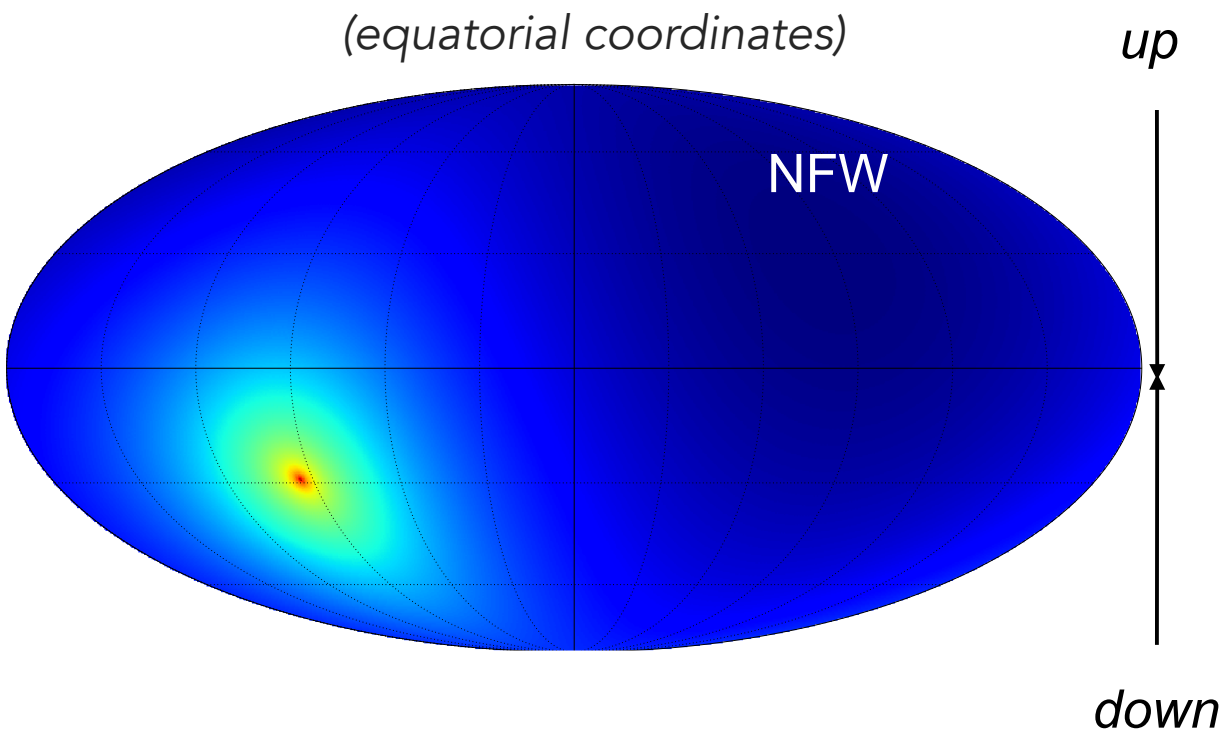
SD WIMP-proton cross-section limit



- most stringent SD cross-section limit for most models
- complementary to direct detection search efforts
- different astrophysical & nuclear form-factor uncertainties

Galactic Dark Matter searches (IceCube-79)

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



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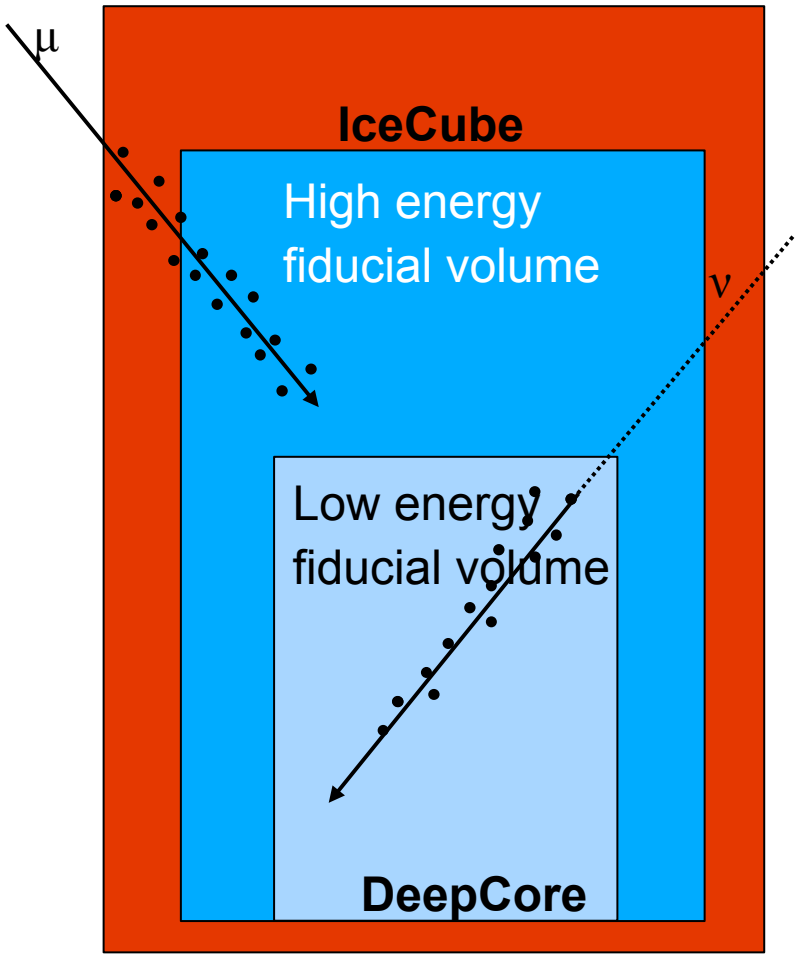
Low-Energy (m_χ < *300 GeV*)
High-Energy (m_χ > *300 GeV*)

- Identifying starting events opens up the Southern Sky for IceCube.



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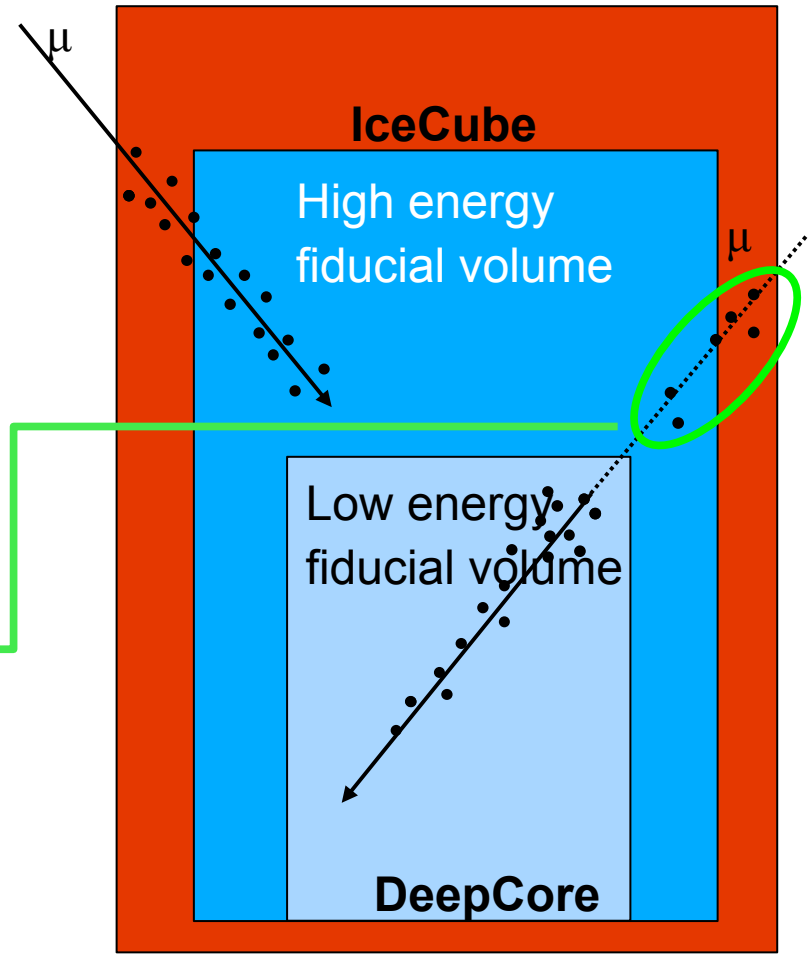
Low-Energy (m_χ < *300 GeV*)
High-Energy (m_χ > *300 GeV*)

- Identifying starting events opens up the Southern Sky for IceCube.
- Both analyses rely on veto methods to reject incoming tracks.



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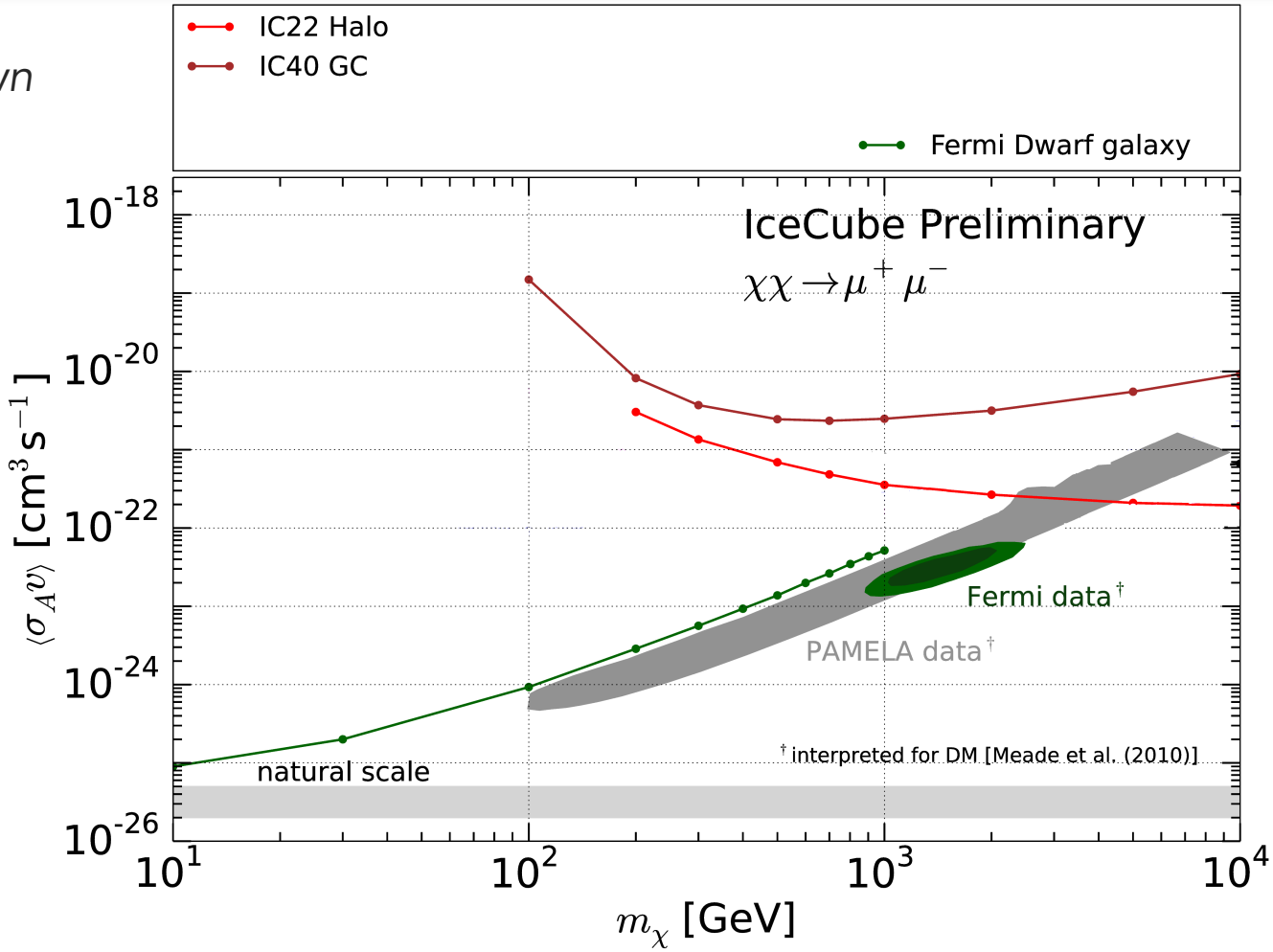
(IceCube results shown for NFW profile)



Search for many interesting potential annihilation channels:
(Various DM-Halo models tested)

$$\chi\chi \begin{cases} \nu\bar{\nu},\ \mu^+\mu^-,\ \tau^+\tau^-,\ W^+W^-,\ b\bar{b} \\ Z^0Z^0,\ Z^0\gamma \end{cases}$$

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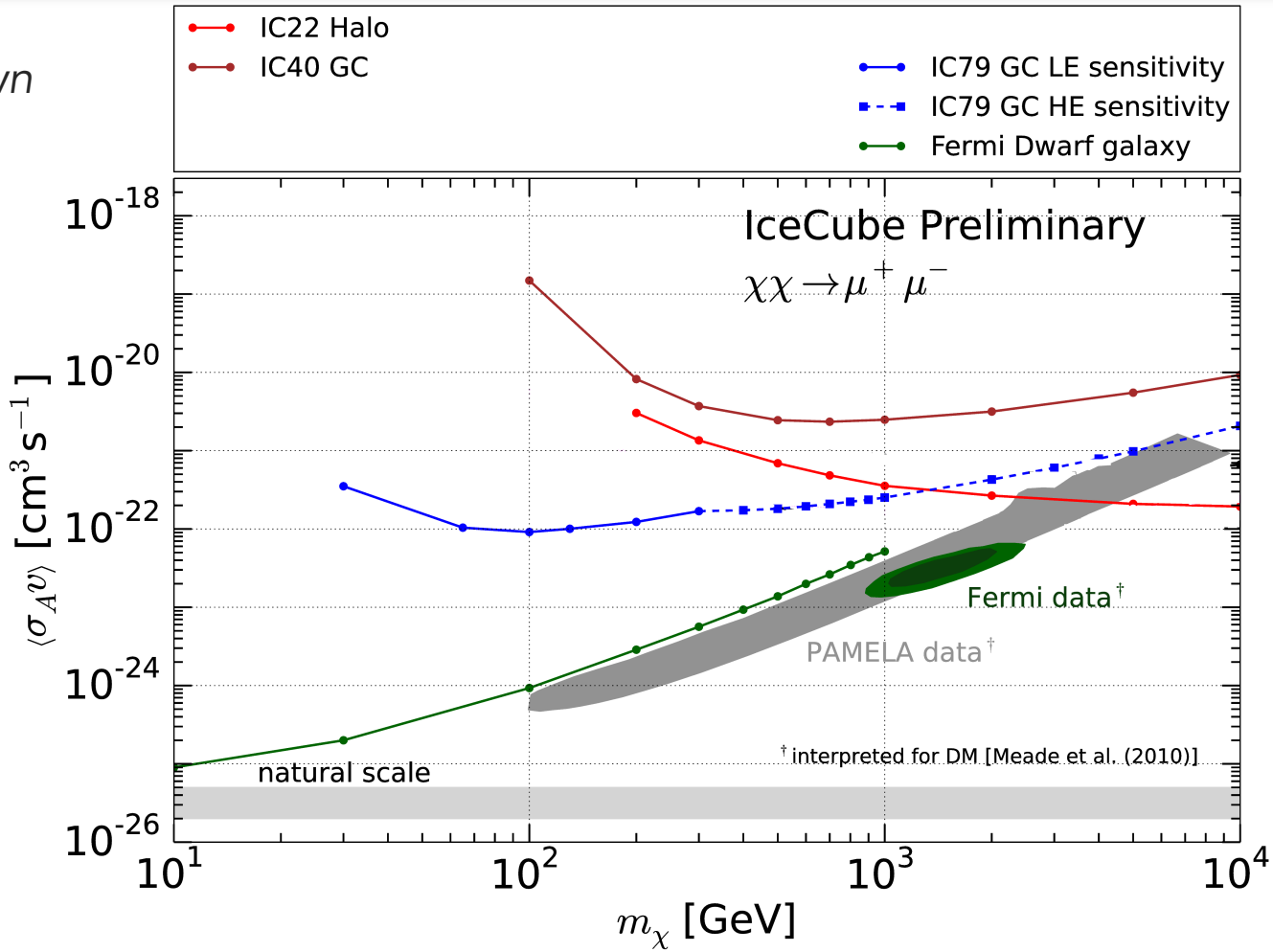
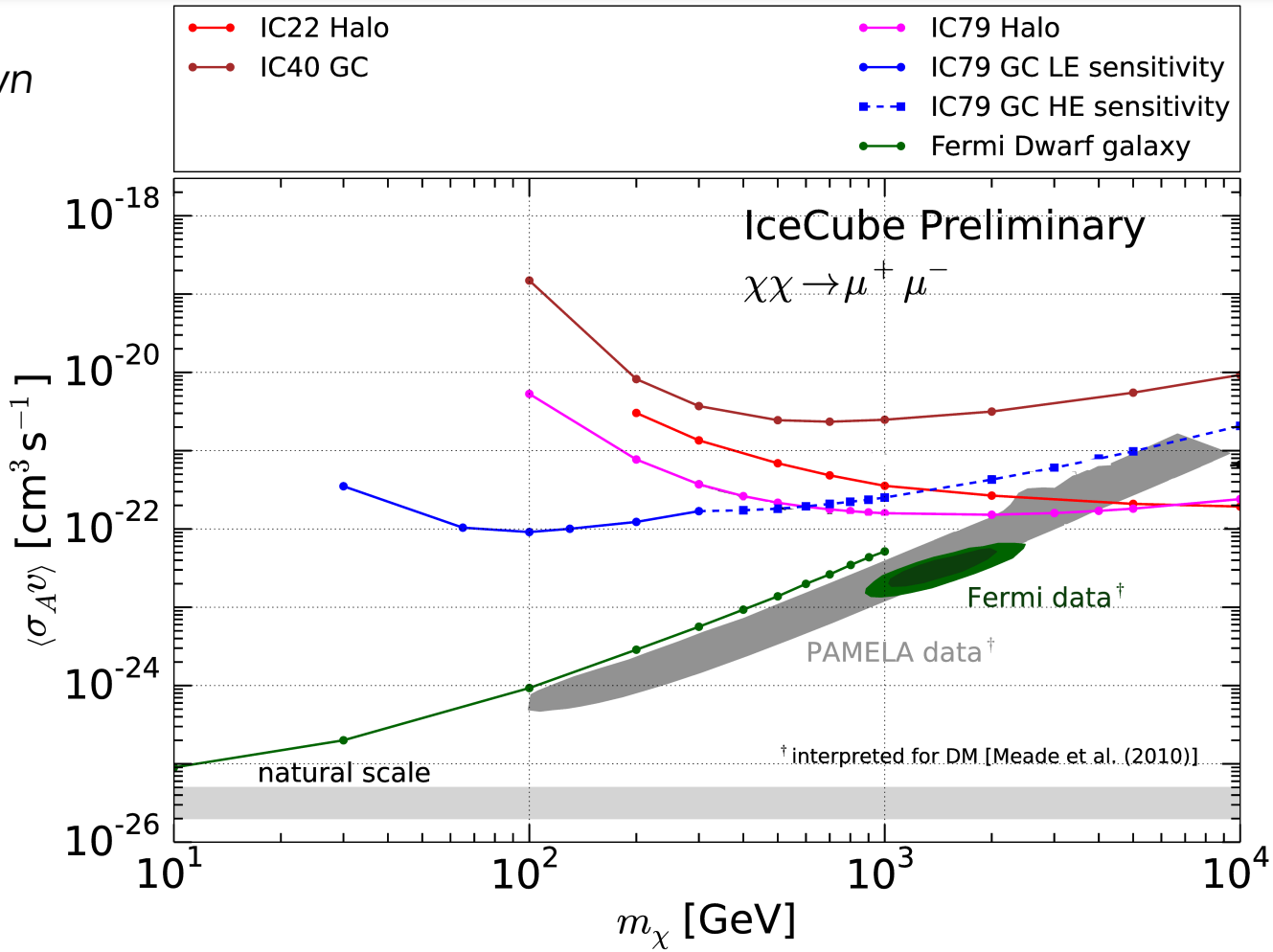


IceCube-79 Galactic Center analysis (sensitivity):

- First IceCube analysis looking at GC for low WIMP masses (< 100 GeV)
- Up to 4 orders of magnitude improved sensitivity @ 100 GeV
- Unblinding is going on within the collaboration

Galactic Dark Matter searches (IceCube-79)

(IceCube results shown for NFW profile)

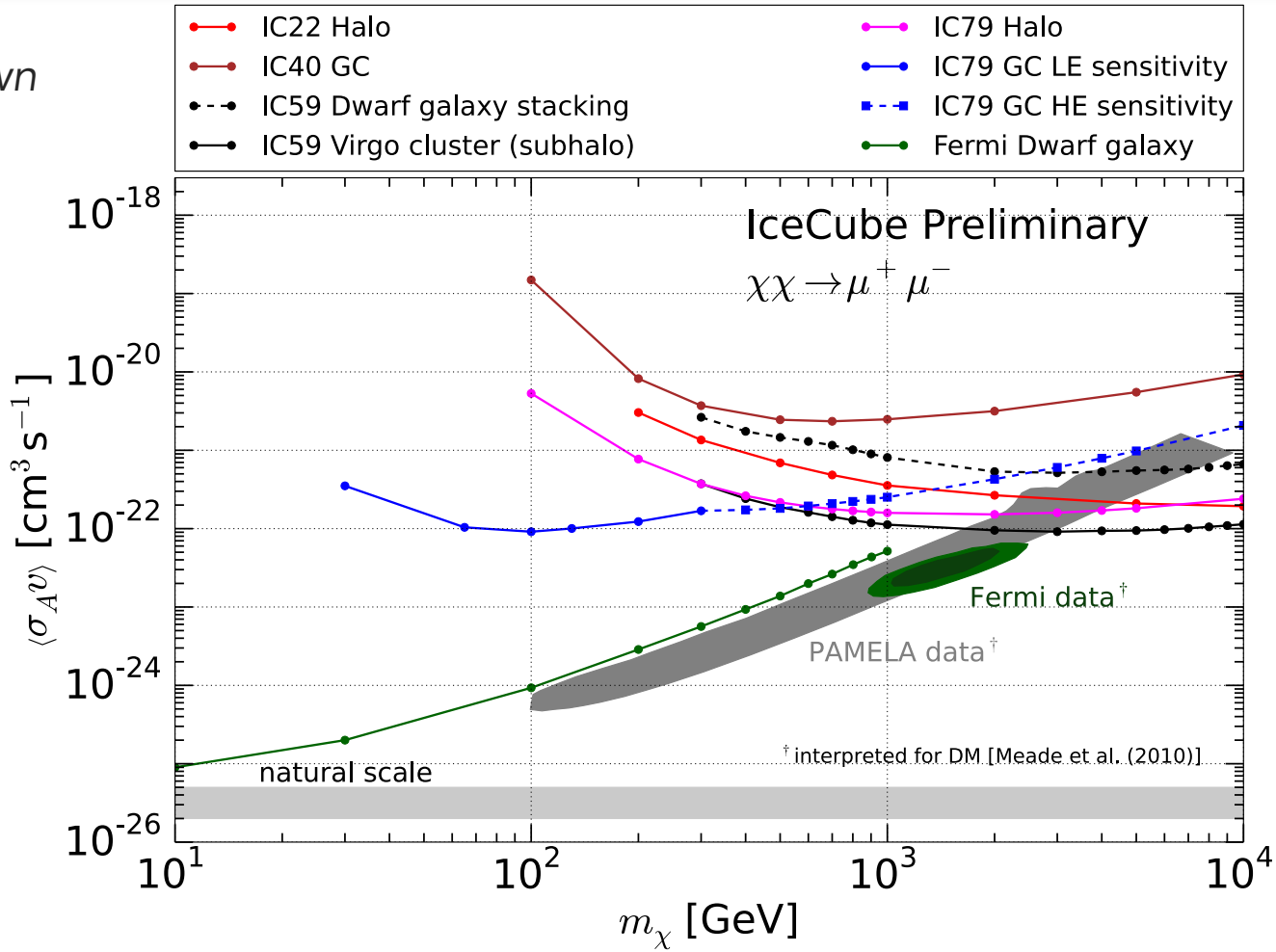


IceCube-79 Multipole analysis to search for Dark Matter in the Galactic Halo:

- focus on large scale anisotropies (l<100)
- small Halo-model dependency
- results are compatable with the background-only hypothesis

Galactic Dark Matter searches (IceCube-79)

(IceCube results shown for NFW profile)



<u>IceCube-59</u> Dwarf galaxy searches:

- Source stacking analysis
- Optimized size of search window

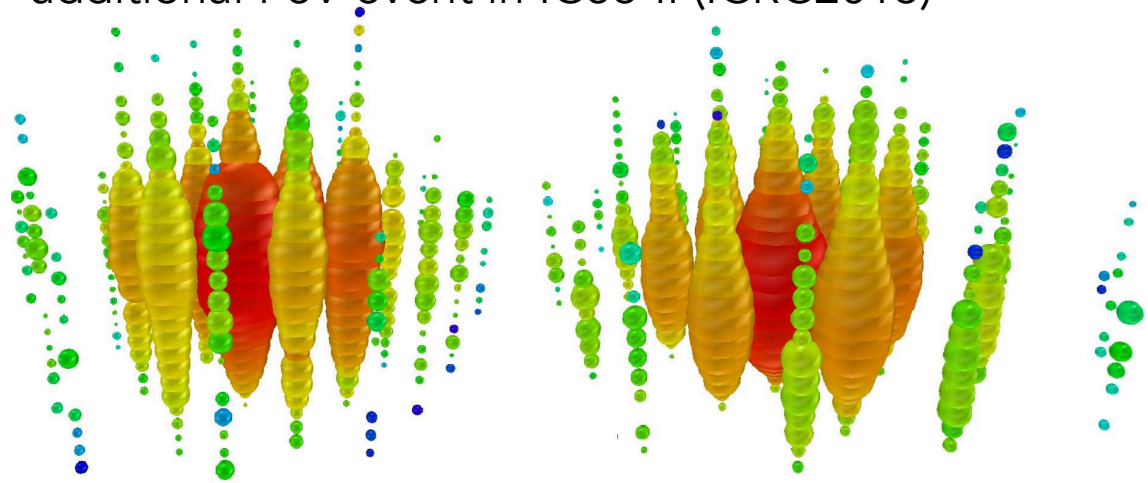
<u>IceCube-59</u> Galaxy cluster analysis:

- Extended point source search
- Optimized size of search window
- Substructures taken into account

Heavy Dark Matter

- IceCube has reported 2 high-energy cascade events in 2 years of IceCube 79 + 86-string data
- consistent with ν_e interactions at about 1PeV
- reported events are intriguingly close in energy

additional PeV event in IC86-II (ICRC2013)



PRL 111, 021103 (2013)

Could this be dark matter ?

- B. Feldstein, A. Kusenko, S. Matsumoto, and T. Yanagida PRD 88 (2013) 015004
- A. Arman and P.Serpico arXiv:1308.1105 (2013)

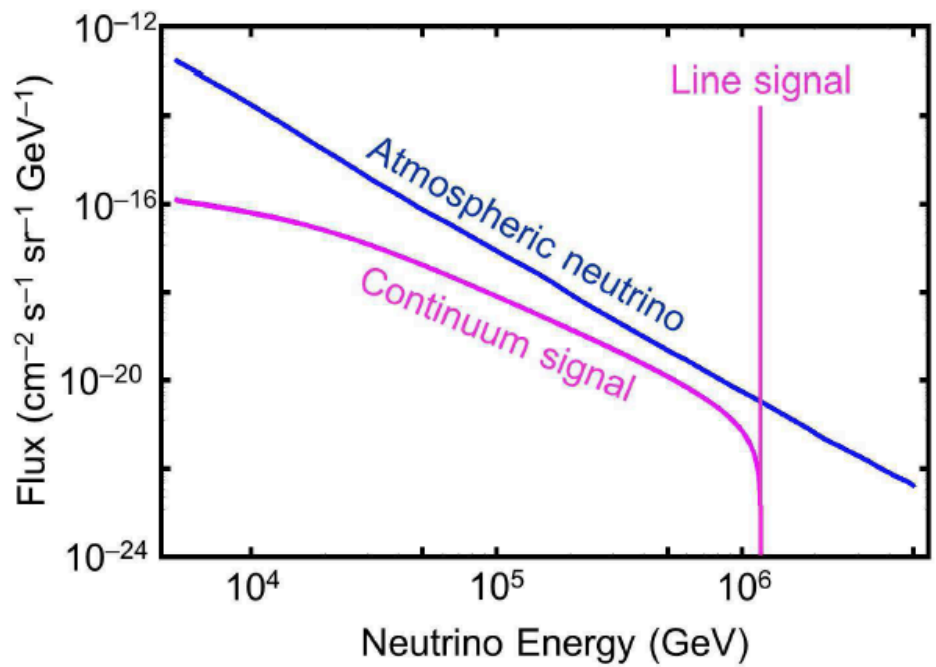
Possible evidence:

- 2.4PeV Dark Matter Particle mass
- Flux can be related to lifetime τ_{DM}

$$\tau_{\rm DM} \simeq 1.9 N_\nu \times 10^{28}\ {\rm s}$$

Models:

- Singlet fermion in extra dimension
- Hidden Sector Gauge Boson
- Gravitino Dark Matter



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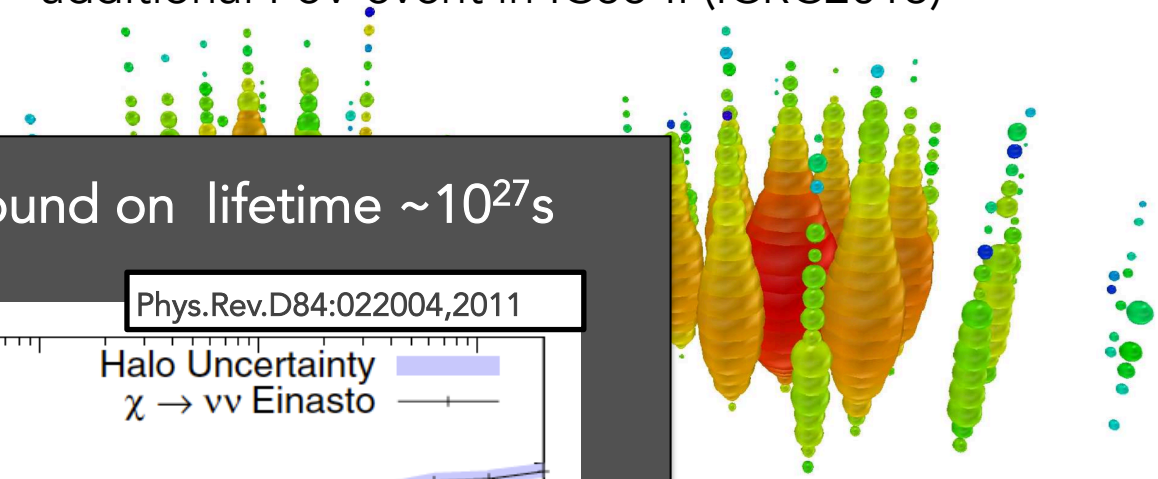

L 111, 021103 (2013)

Could this be dar

- B. Feldstein, A. Kusenko, S. Mat
Yanagida PRD 88 (2013) 01500
- A. Arman and P.Serpico arXiv:13

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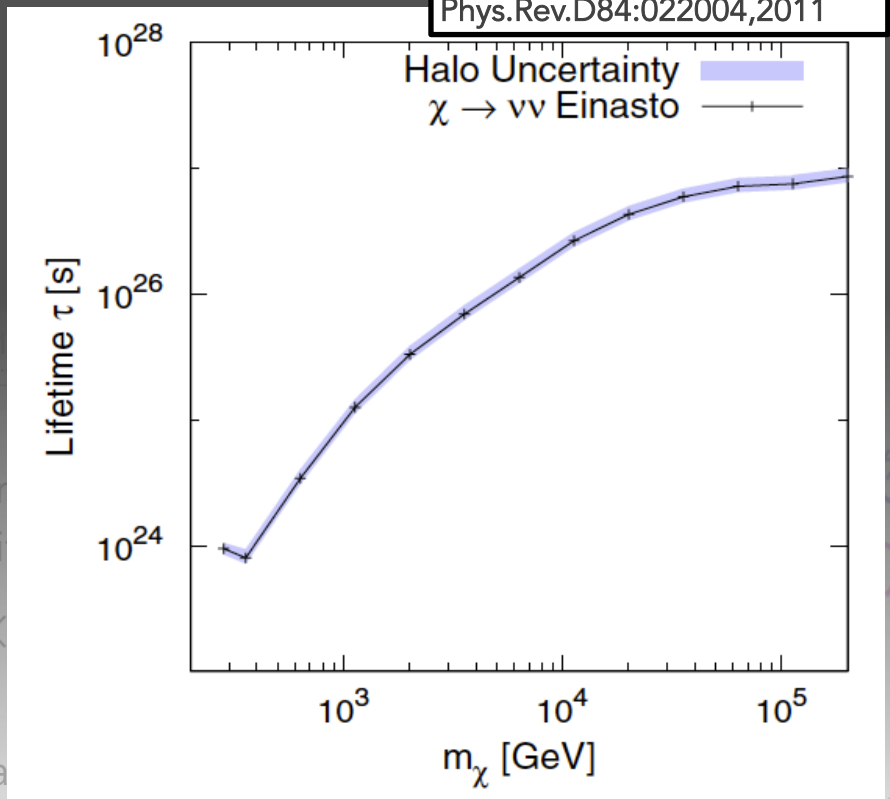
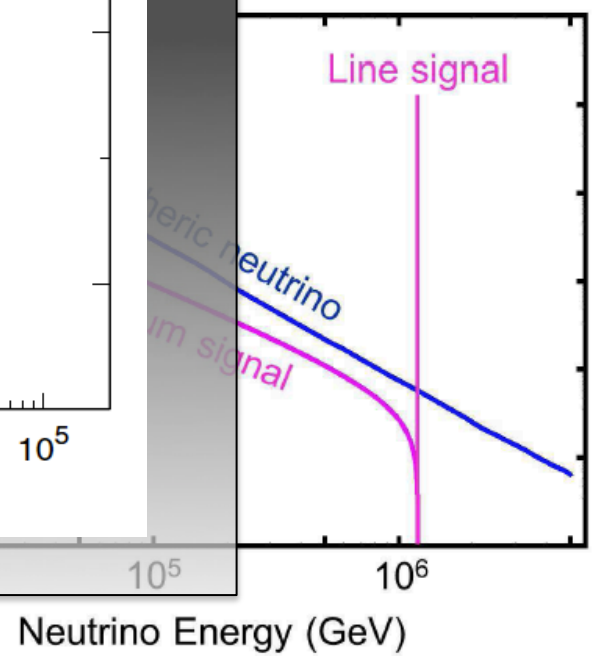
IceCube bound on lifetime ~10^{27}s

Phys.Rev.D84:022004,2011





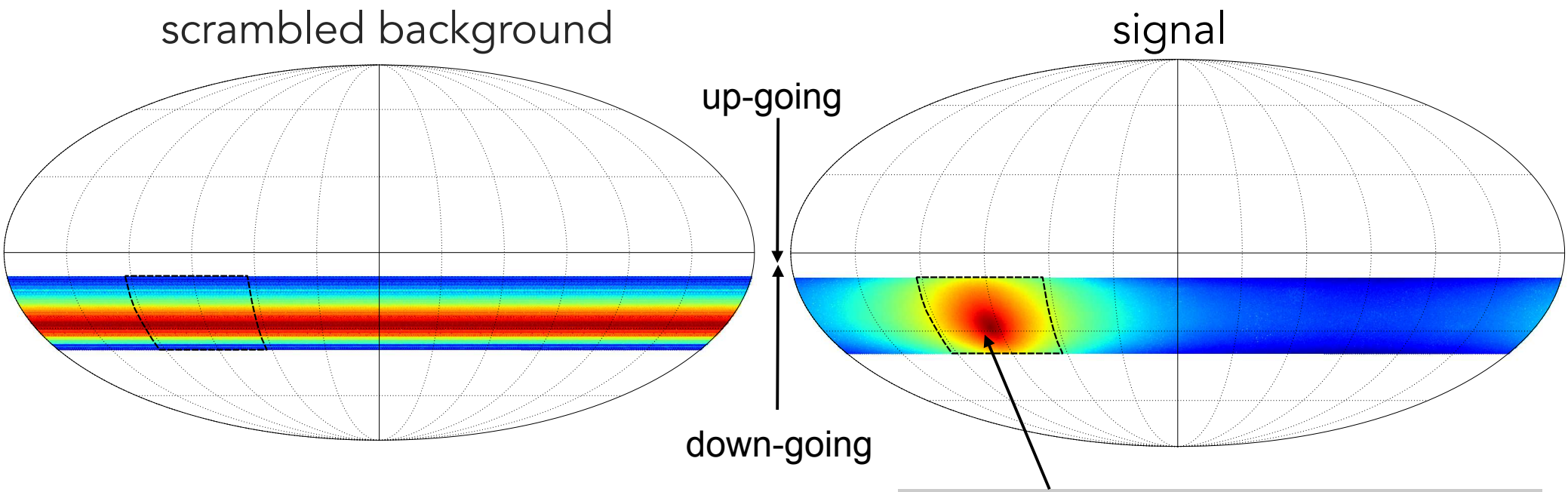
Summary

- Striking WIMP signatures provide high discovery potential for indirect searches with ν, complementary to searches using other astrophysical messengers & direct detection searches
- DeepCore plays crucial role in IceCube Dark Matter analyses
- IceCube provides most stringent limits on the SD-WIMP-proton scattering cross section for most WIMP models
- Clever new ideas for detection channels and sources spur new analyses → current detectors acquire fresh data
- Future detectors with lower energy thresholds will probe region of parameter space made interesting by direct detection experiments

Additional slides

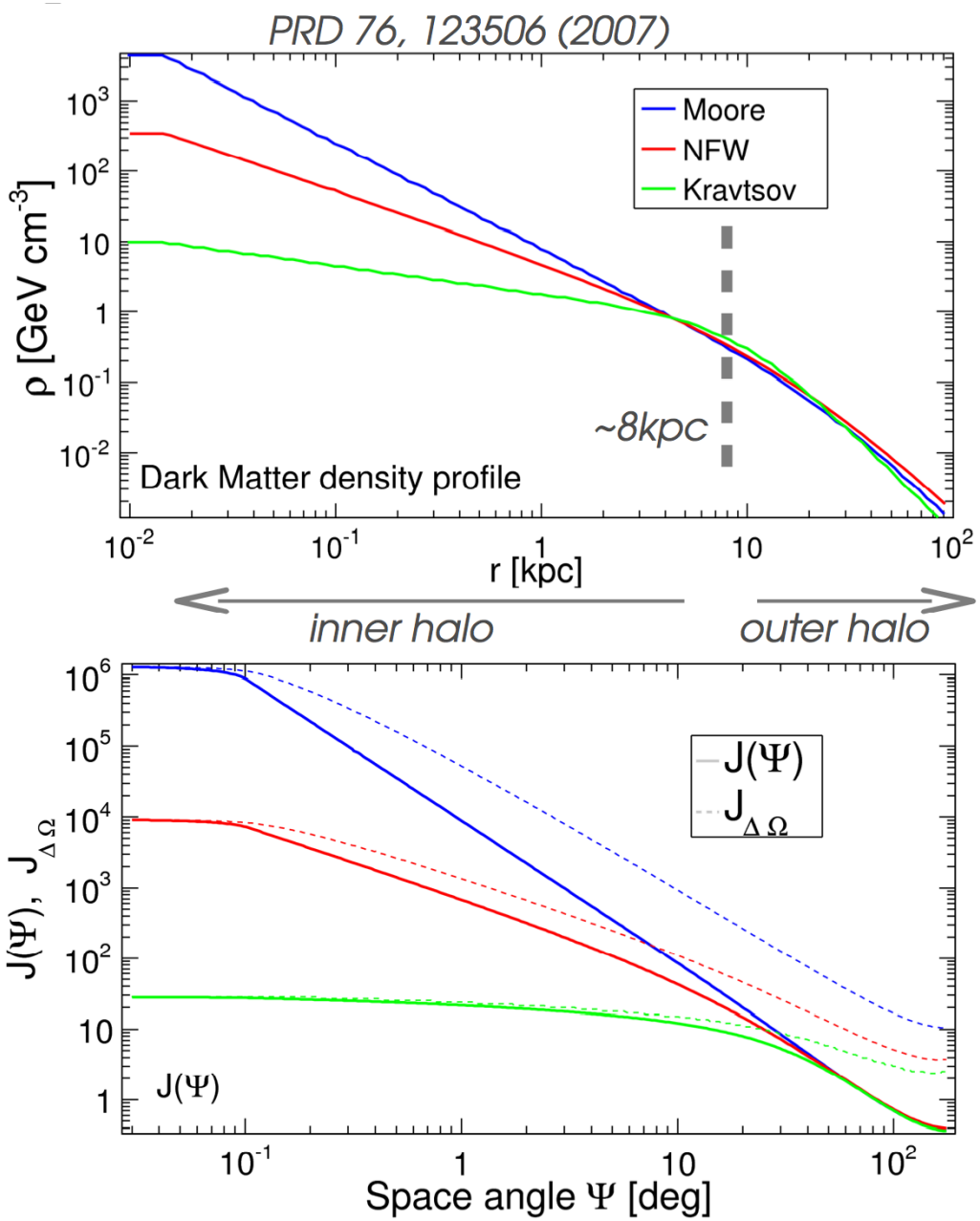
Galactic Dark Matter searches (IceCube-79)

2D skymap PDFs generated with healpix
(equatorial coordinates)



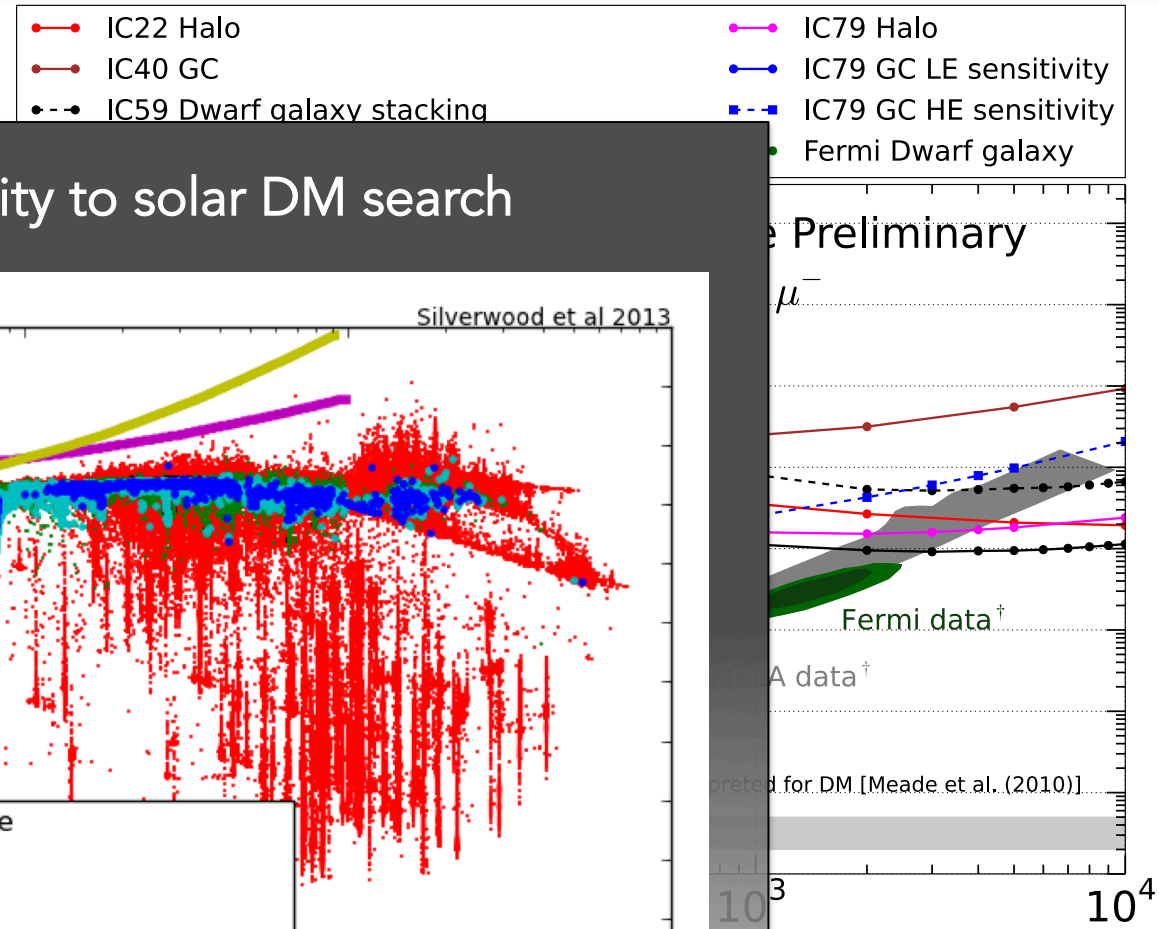
Galactic Center @ 266° RA; -29° Dec

Galactic Dark Matter searches (IceCube-79)

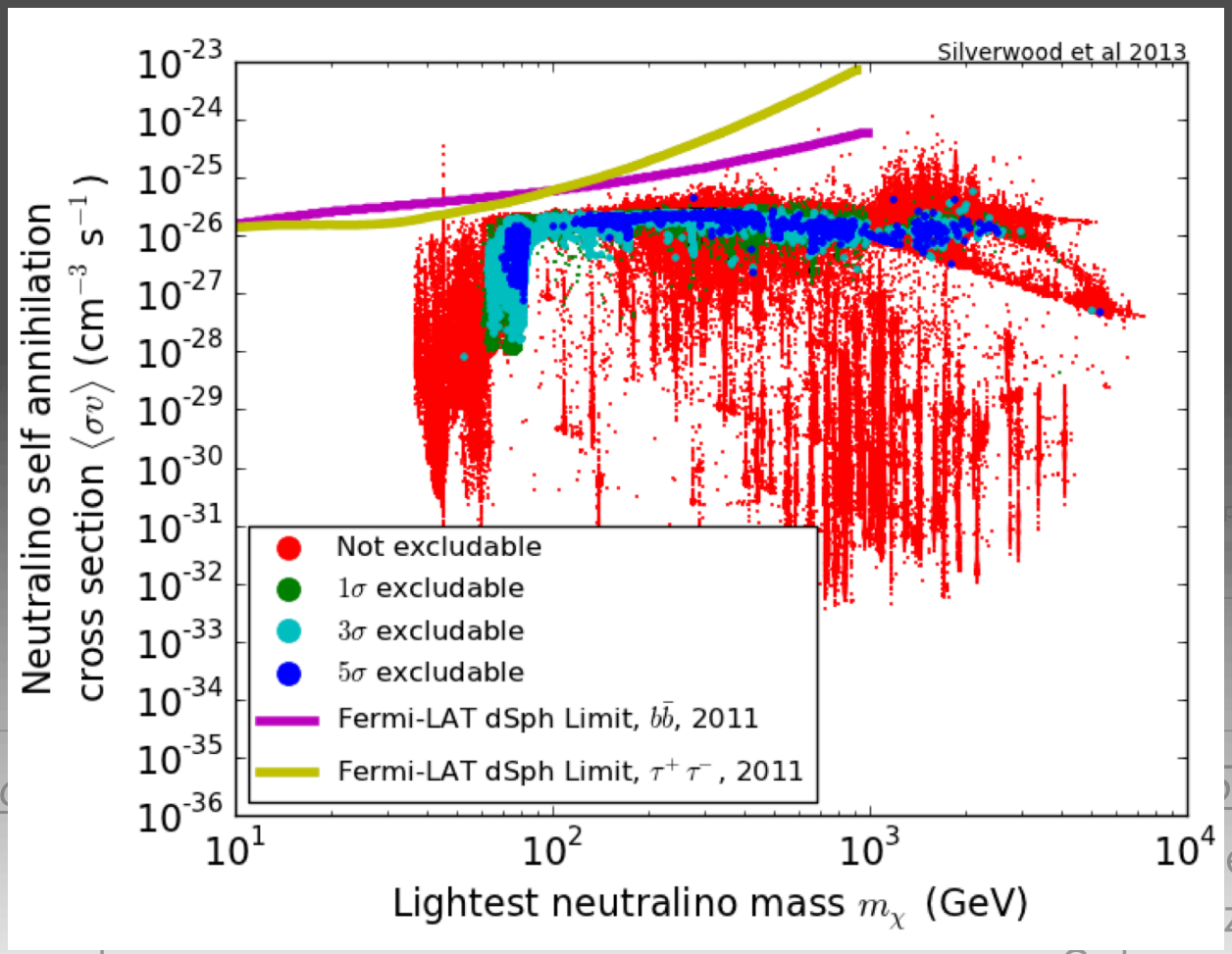


Galactic Dark Matter searches (IceCube-79)

(IceCube results shown fo



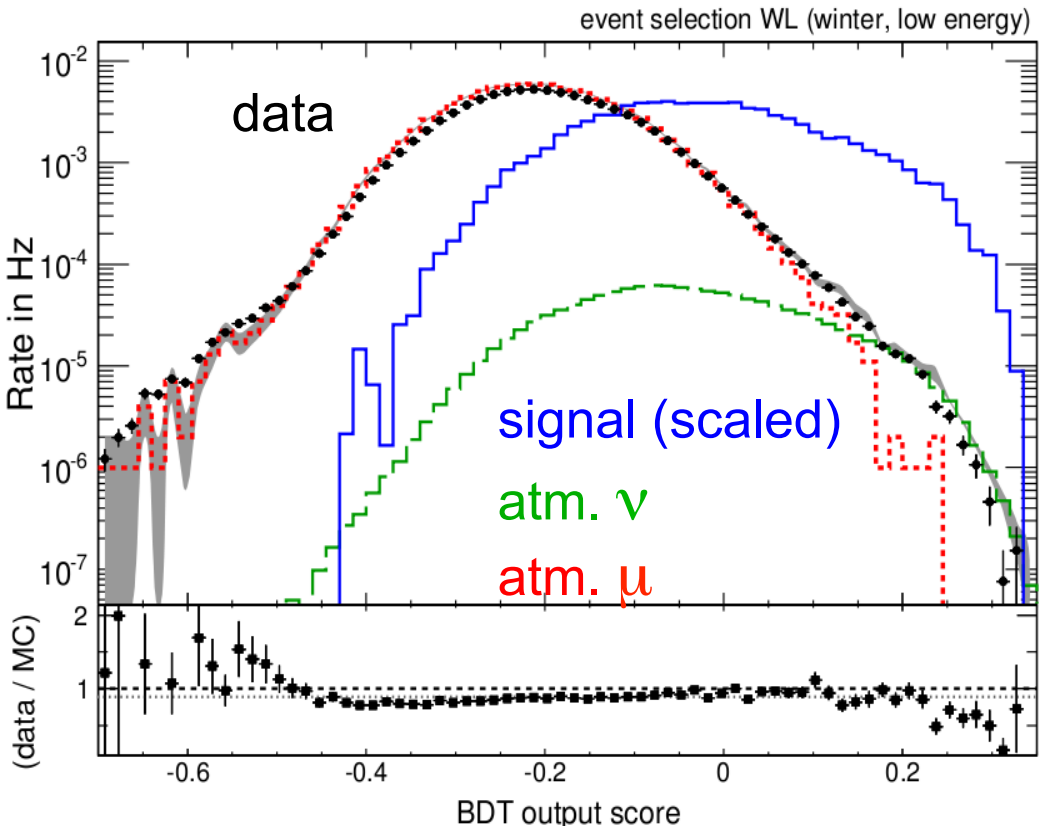
Complementarity to solar DM search

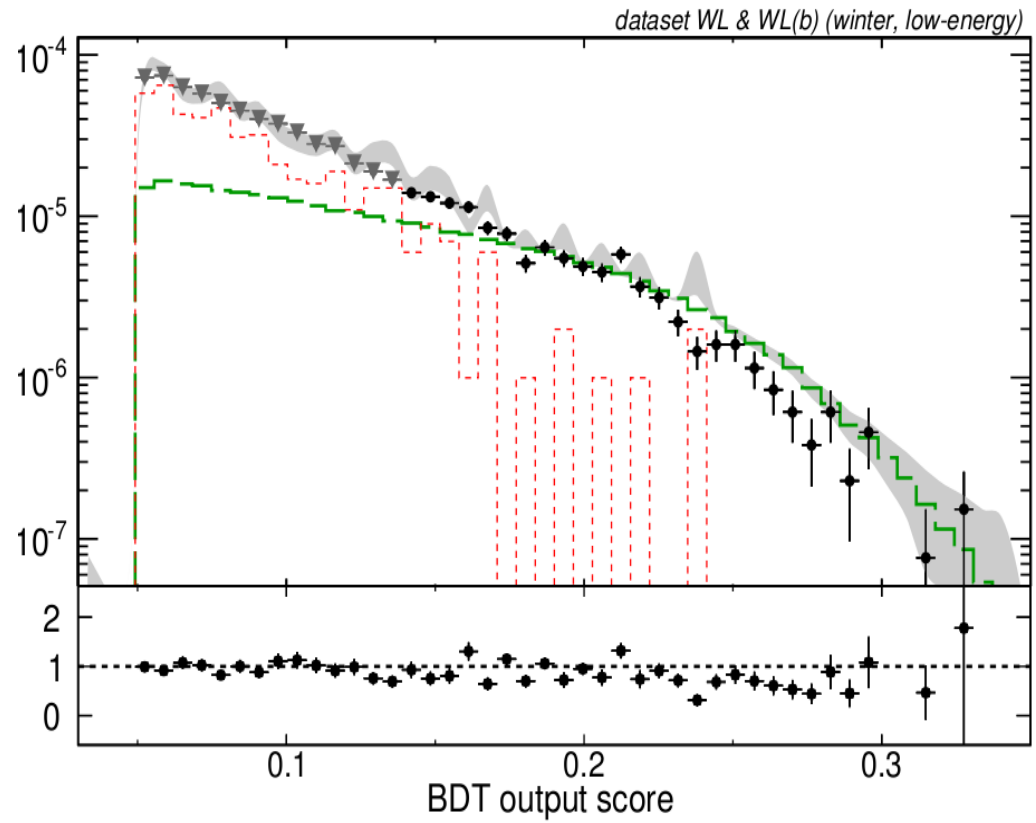


Galaxy cluster analysis:

- point source search
- d size of search window
- Substructures taken into account

Multivariate analysis step (BDT variable)





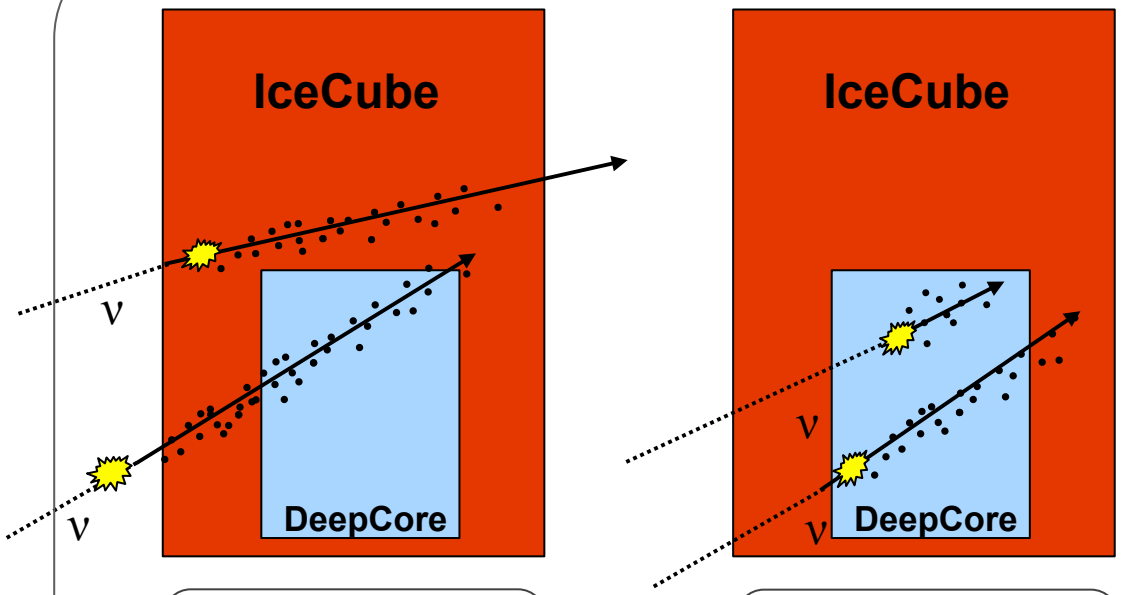
→ ***1*** separate BDT for each event selection

→ training on off-source exp. data + separate signal simulation

IceCube-79 string analysis details

→ Different event topologies require different selection criterias to be efficient.

151 days austral winter



Case 1 (WH):
→ high energy
→ up-going
→ no containment

Case 2 (WL):
→ low energy
→ up-going
→ strong containment

- Split data into a winter-high energy (WH) and winter-low energy (WL) event selection.
  - WL events are DeepCore dominated (more hits in DeepCore)
  - Split corrects for higher photocathode density in DeepCore

IceCube-79 string analysis details

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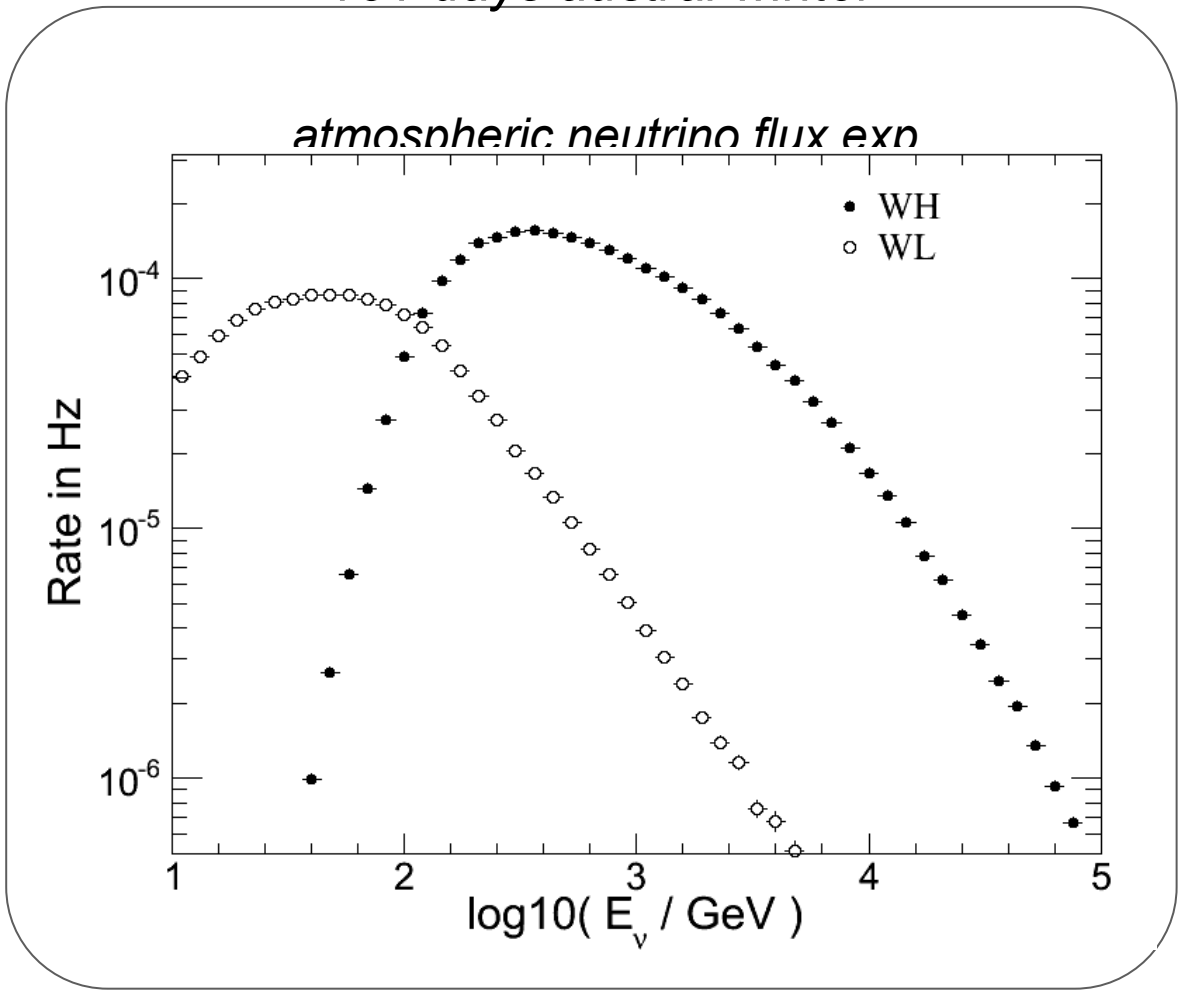
151 days austral winter



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