Indirect Searches for Dark Matter with Neutrinos

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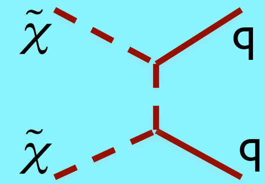
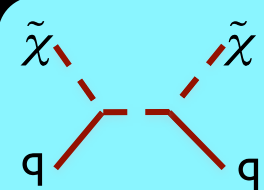
on behalf of the IceCube Collaboration
The Ohio State University
Center for Cosmology and AstroParticle Physics

Aspen 2013 - Closing in on Dark Matter
Monday 28 January 2013 - Sunday 03 February 2013

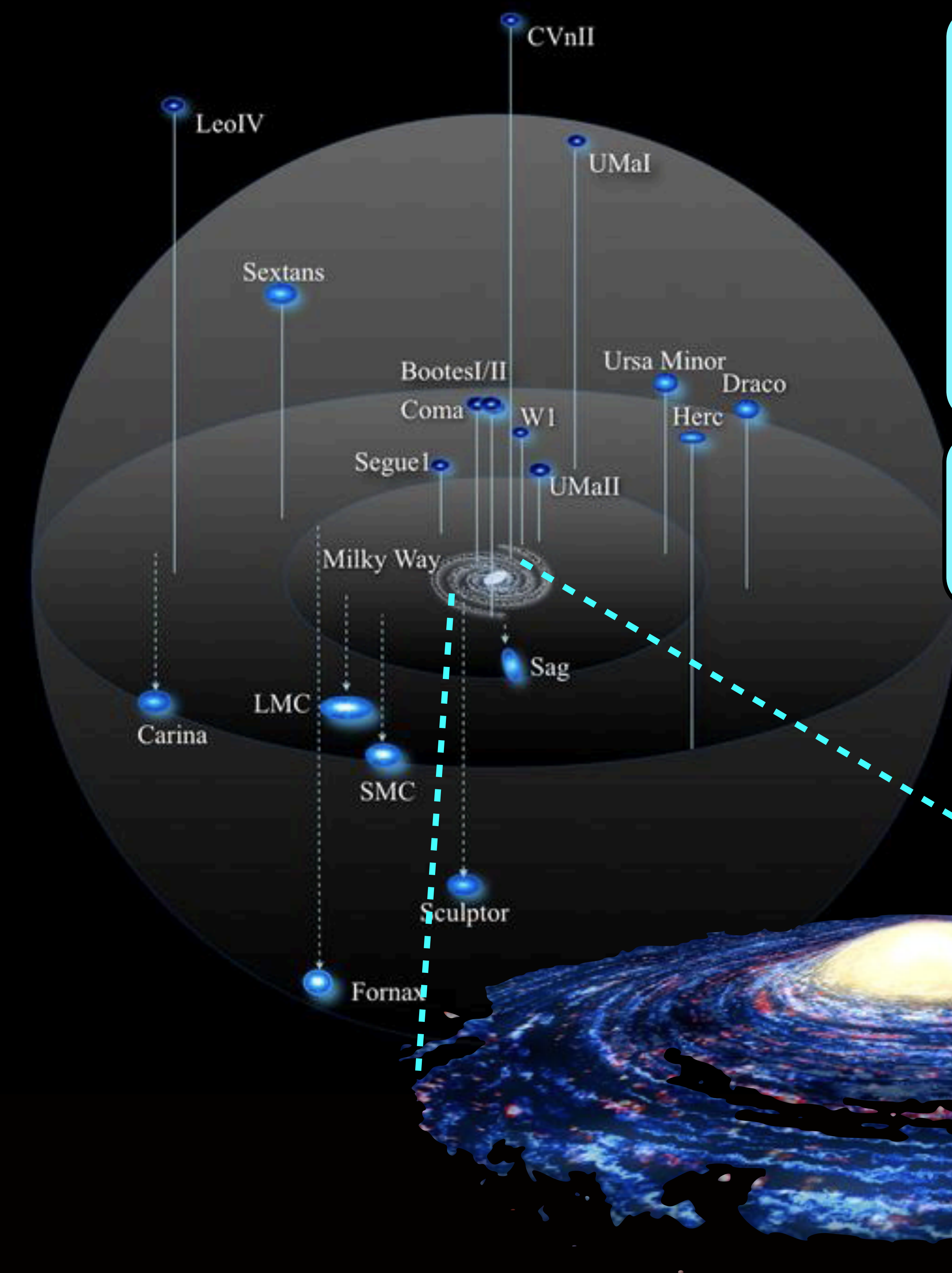
Overview

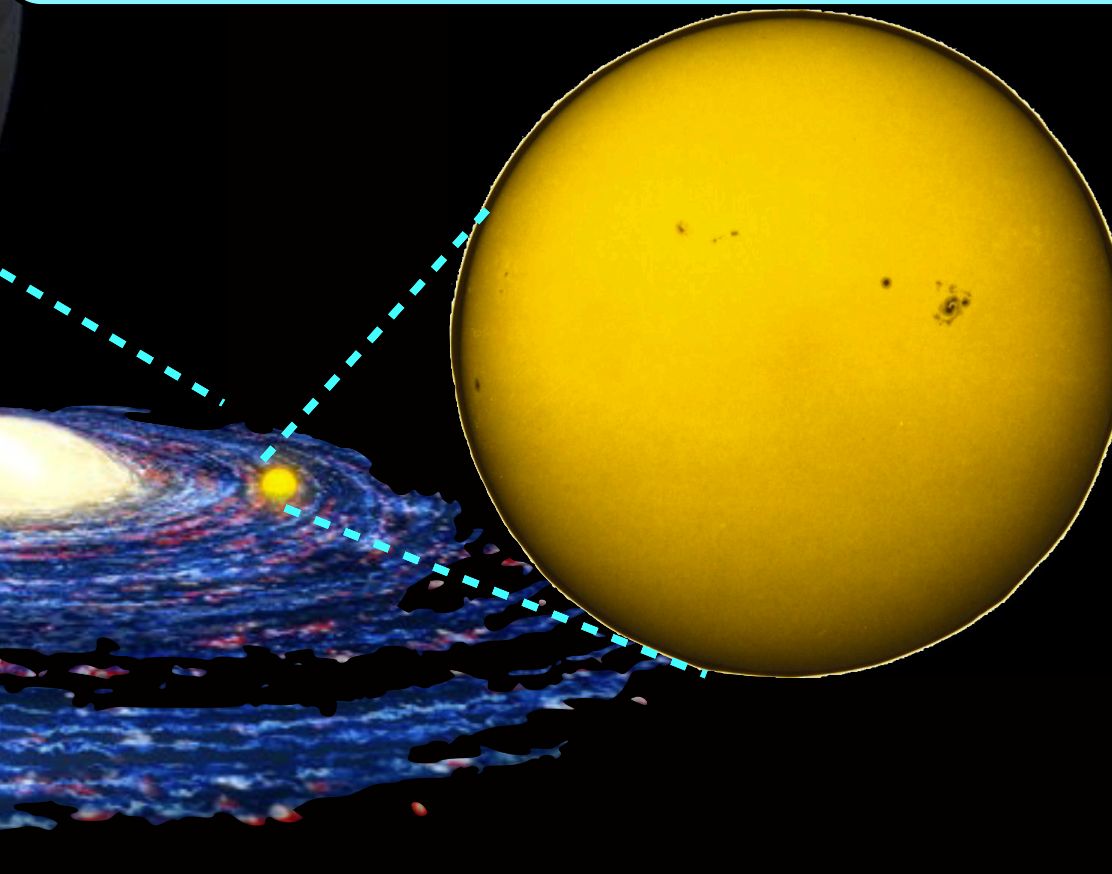


Extra galactic diffuse
Dwarf Spheriodals
Clusters of Galaxies
Milky Way Halo
Galactic Center



Sun
(Earth)





The IceCube Neutrino Telescope

Strings	Dataset
1	2005-2006
9	2006-2007
22	2007-2008
40	2008-2009
59	2009-2010
73 + 6	2010-2011
78 + 8	2011 - .....

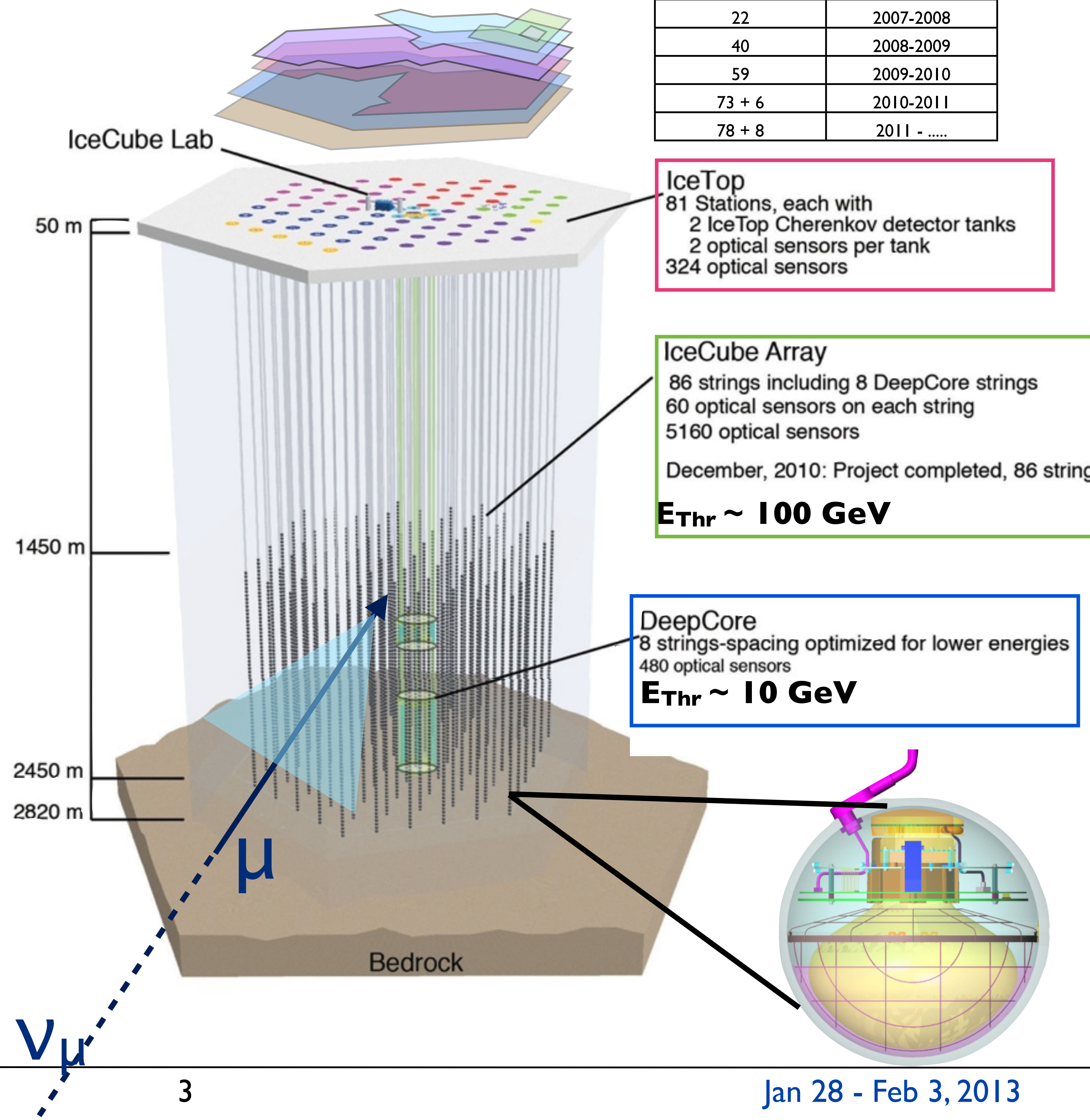
Gigaton Neutrino Detector at the Geographic South Pole

5160 Digital optical modules distributed over 86 strings

Completed in December 2010, start of data taking with full detector May 2011

Data acquired during the construction phase has been analyzed

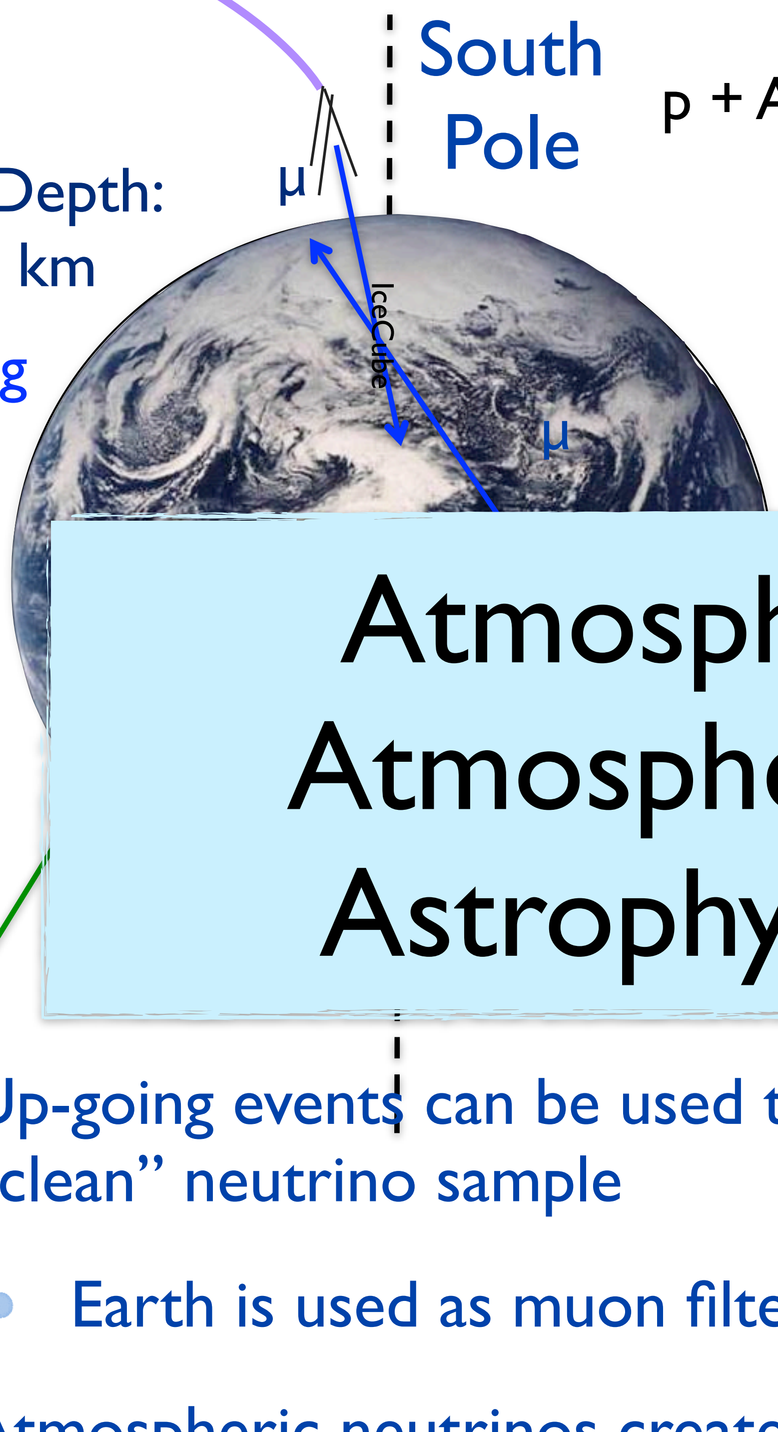
Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice



Signals in IceCube

IceCube Depth: 1.5-2.5 km

Downgoing Muons



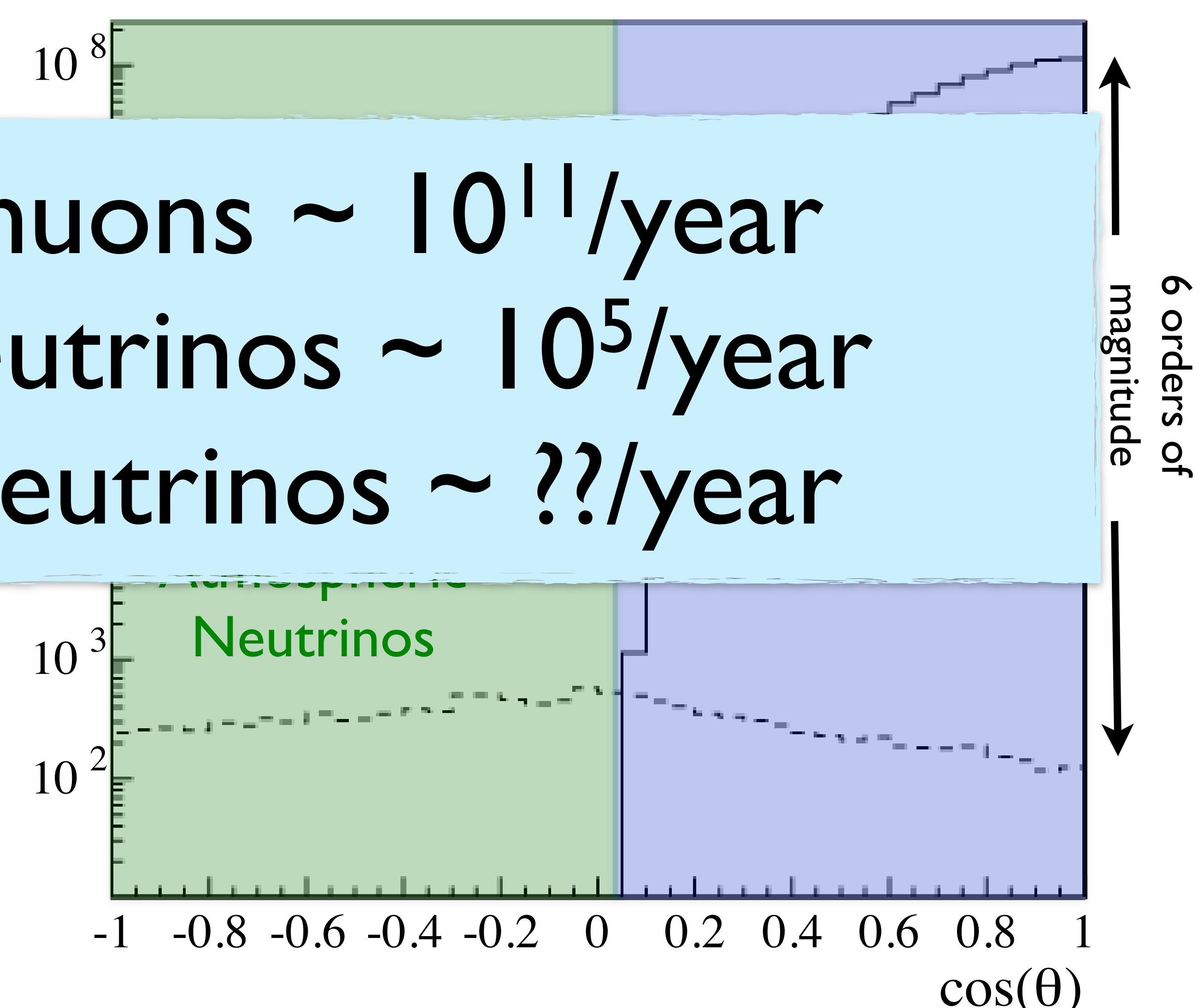
p + A → $\pi^{\pm}$ ($K^{\pm}$) + other hadrons ... $\pi^+ \to \mu^+ \nu_\mu \to e^+ \nu_e \nu_\mu \nu_\mu$

Atmospheric muons ~ 10^{11}/year

Atmospheric neutrinos ~ 10^5/year

Astrophysical neutrinos ~ ??/year

- Up-going events can be used to obtain "clean" neutrino sample
  - Earth is used as muon filter
- Atmospheric neutrinos create irreducible neutrino background to extra terrestrial neutrino fluxes



Atmospheric backgrounds for extra-terrestrial neutrino searches at the depth of IceCube

Galactic Center, Halo, Dwarfs, Clusters of Galaxies

Dark Matter Annihilation

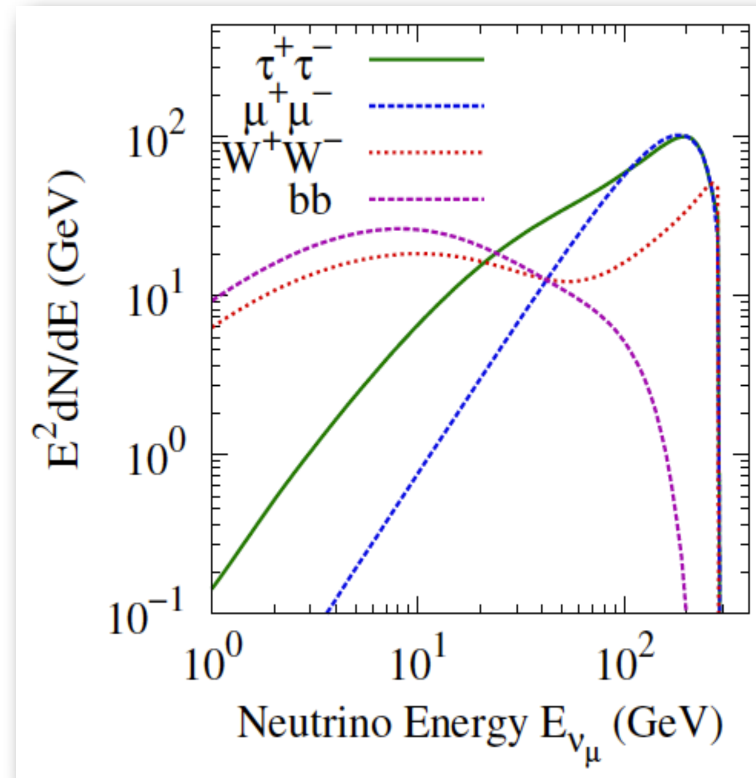
Measure Flux

$$\frac{d\Phi}{dE}(E,\phi,\theta)$$

=

Particle Physics

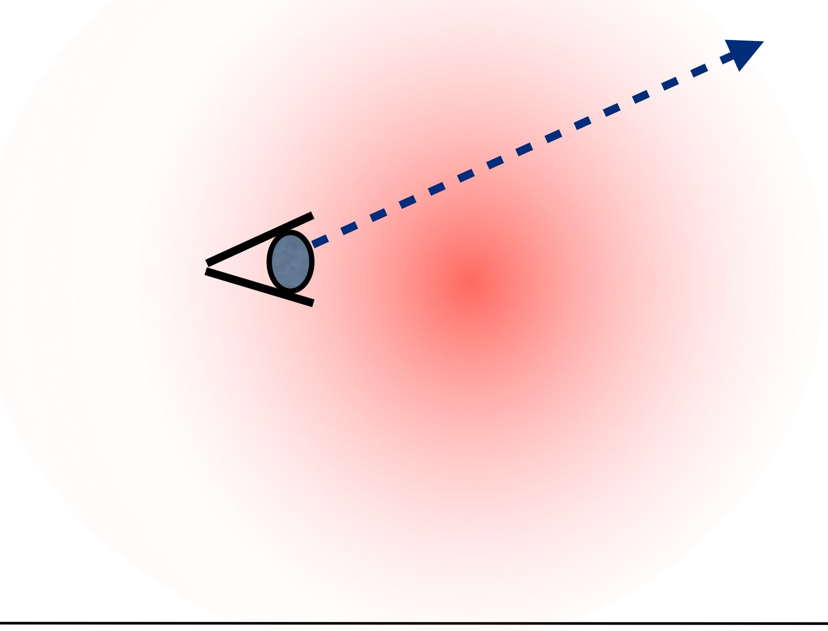
$$\frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\Sigma_f\frac{dN}{dE}B_f$$



x

Dark Matter Distribution

line of sight (los) integral

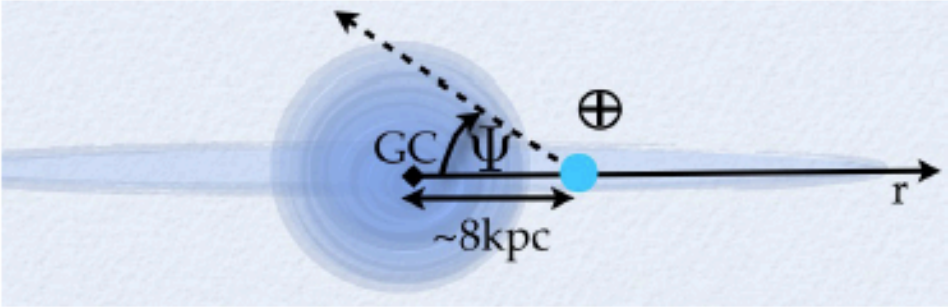


$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\text{los}} \rho^2(r(l,\phi'))dl(r,\phi')$$

Galactic Center / Halo

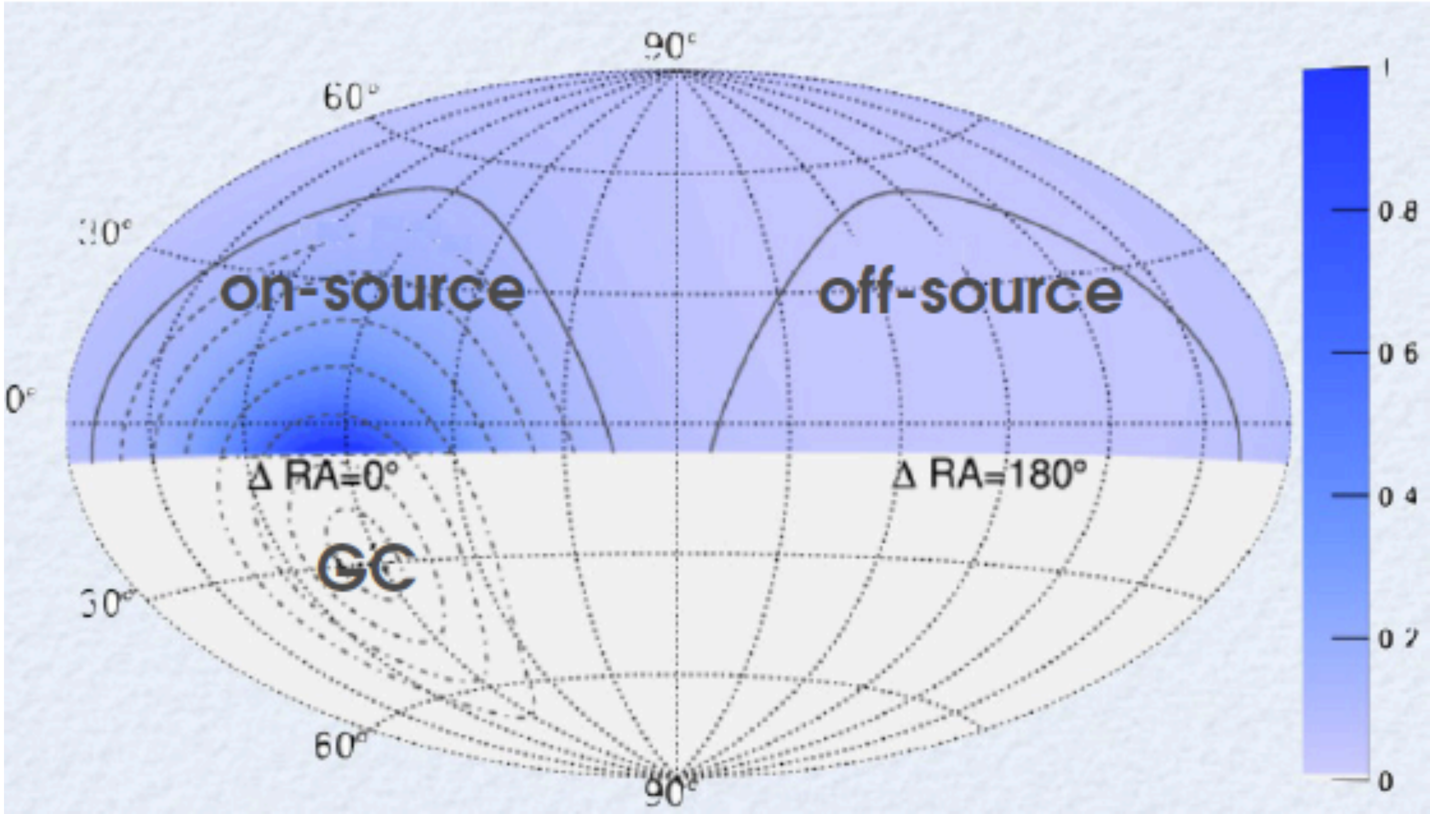
Analysis strategy:

Look for an excess of events in the on-source region w.r.t. the off-source



Galactic Center:

- ✗ on-source region above the horizon
- ✗ need to veto downgoing muons.
- ✗ Use central strings of detector as fiducial volume, surrounding layers as veto.



IC22 (Halo analysis – 275 days):
observed on-source: **1367** evts
observed off-source: **1389** evts
Event selection dominated by atm. ν

IC40 (G-Center analysis – 367 days):
observed on-source: **798842** evts
predicted from off-source: **798819** evts
Event selection dominated by atm. μ

Observations in both analyses were consistent with background-only expectations

Point/Extended Sources

- Dwarf spheriodal galaxies, clusters of galaxies, and large galaxies represent well defined sources of Dark Matter
  - Dark Matter distribution critical for optimization, assume conservative density profile

$$\frac{d\Phi_j(\Delta\Omega, E_j)}{dE_j} = \frac{\langle\sigma v\rangle}{2m_\chi^2}\frac{dN_j}{dE_j}J(\Delta\Omega)$$

Analysis performed with 340days of IceCube 59 string data

Event selection via Boosted Decision Tree

For robustness the search windows and cut values were **optimized for 5 TeV WIMPs** and used for all WIMP-masses.

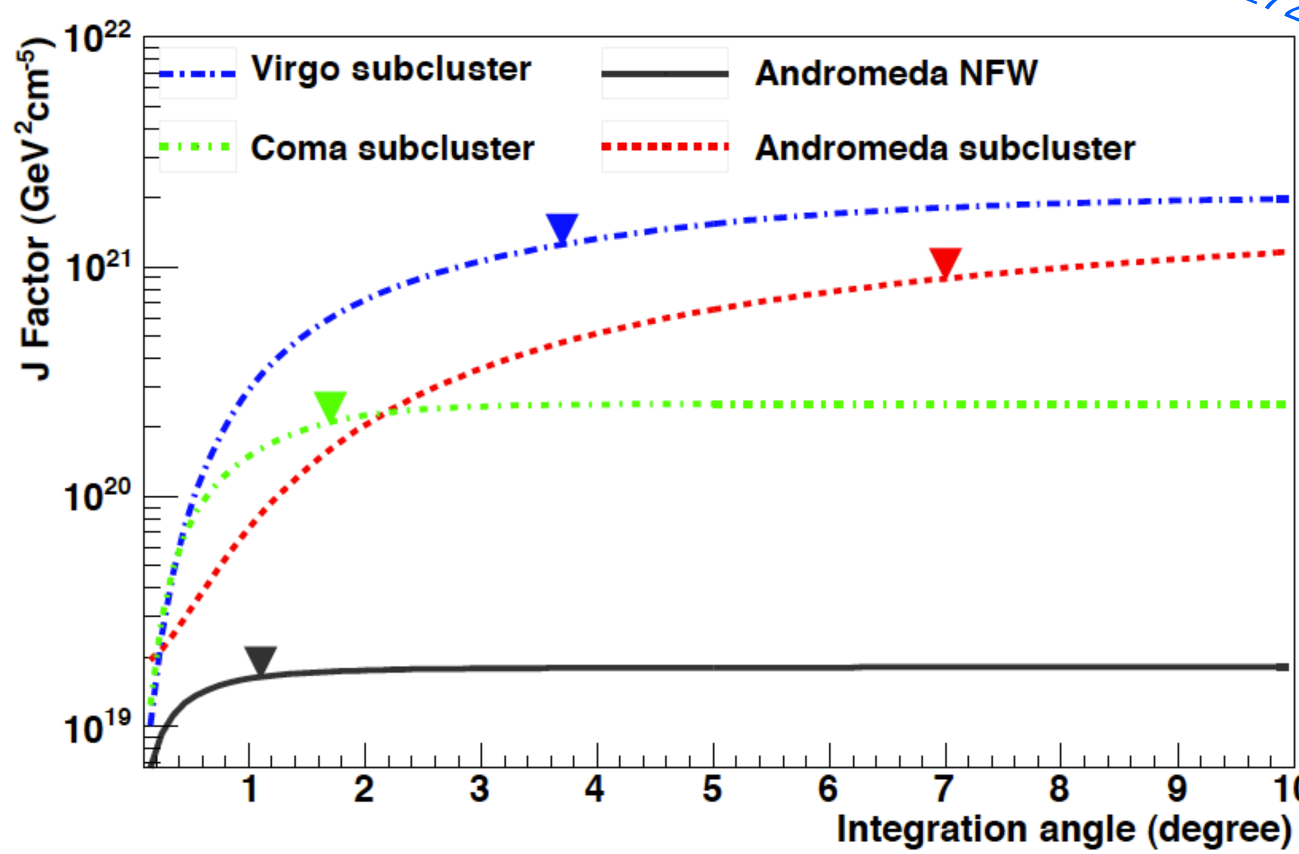
Source	declination	distance [kpc]	mass $[M_\odot]$	$\log_{10}J$ $[GeV^2 cm^{-5}]$
Segue 1	+16°04'55"	23	1.58×10^7	19.6 ± 0.53
Ursa Major II	+63°07'48"	30	1.09×10^7	19.6 ± 0.40
Coma Berenices	+23°55'09"	44	0.72×10^7	19.0 ± 0.37
Draco	+57°54'55"	80	1.87×10^7	18.8 ± 0.13
M31	+41°16'09"	778	6.9×10^{11}	19.2 *
Virgo	+12°20'13"	22300	6.9×10^{14}	18.2 *
Coma	+27°56'20"	95000	1.3×10^{15}	17.1 *

J-factor source

Phys. Rev. Lett. 107, 241302 (2011)

Temple et al. 0707.4374

Gao et al. Mon.Not.Roy.Astron.Soc. 419 (2012) 1721



J. Luenemann & C.Rott ICRC2011 arXiv:1111.2738 [astro-ph.HE]

Point + Extended Sources

Dwarf Spheriodal Galaxies

Large Galaxies

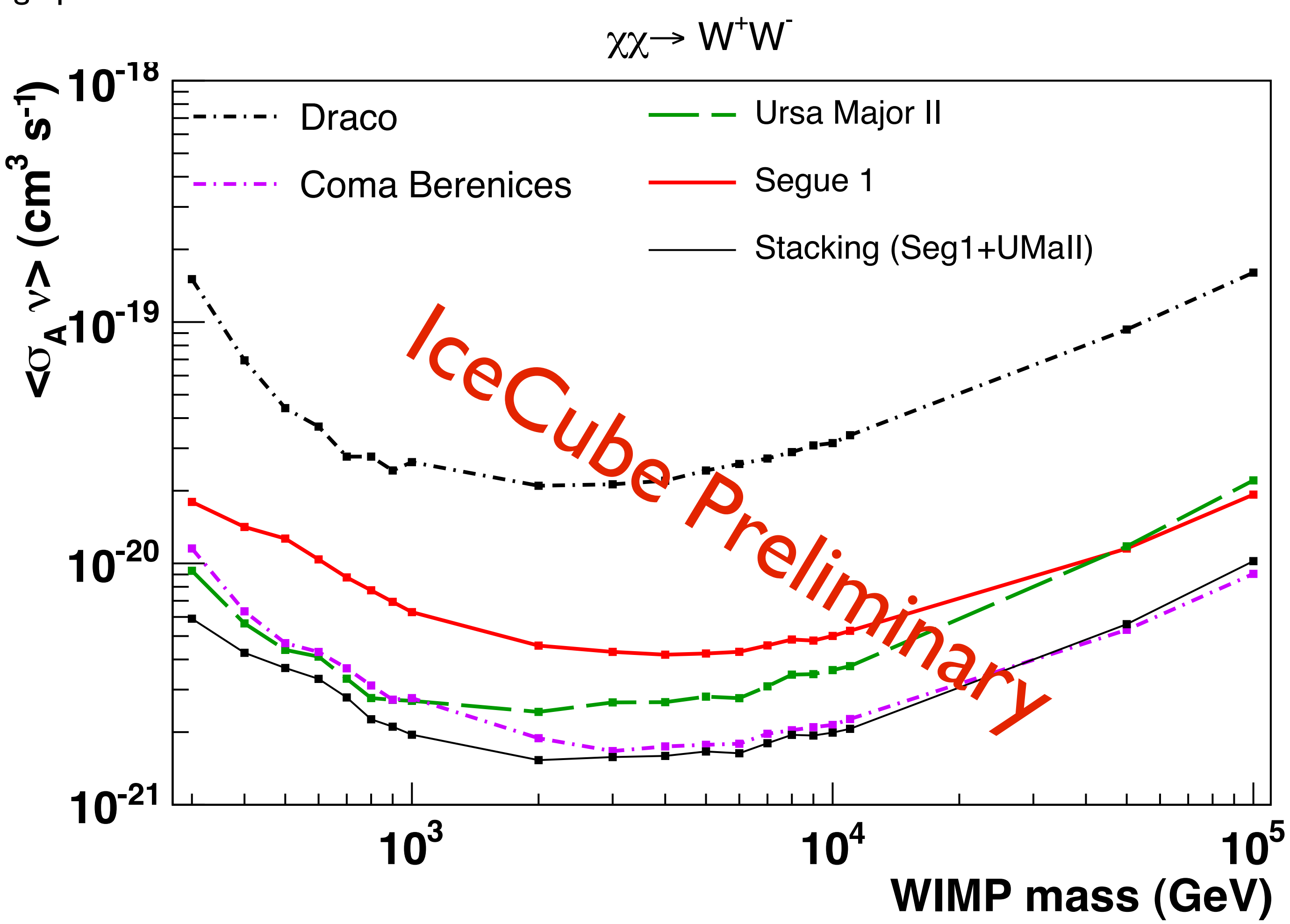
Source	$\tau^+\tau^-$ est. bg	$\tau^+\tau^-$ obs.	$b\bar{b}$ est. bg	$b\bar{b}$ obs.	W^+W^- est. bg	W^+W^- obs.	$\mu^+\mu^-$ est. bg	$\mu^+\mu^-$ obs.	$\nu\bar{\nu}$ est. bg	$\nu\bar{\nu}$ obs.
Segue 1	8.7	10	13.3	18	8.2	12	8.8	10	4.3	6
Ursa Major II	7.4	8	5.2	1	[illegible]	8	4.6	1	3.5	1
Coma Berenices	4.7	1	11.6	4	4.7	1	8.3	3	4.7	1
Draco	5.6	8	13.4	15	5.6	8	5.6	8	4.5	8
Stacking Seg1/UMaII	9.50	8	20.0	23	12.8	13	9.5	8	5.3	4
M31(subclusters)	200.7	194	413.0	418	200.7	194	200.7	194	200.7	194
M31 (NFW)	6.4	2	6.70	1	6.4	2	6.4	2	4.3	0

IceCube Preliminary

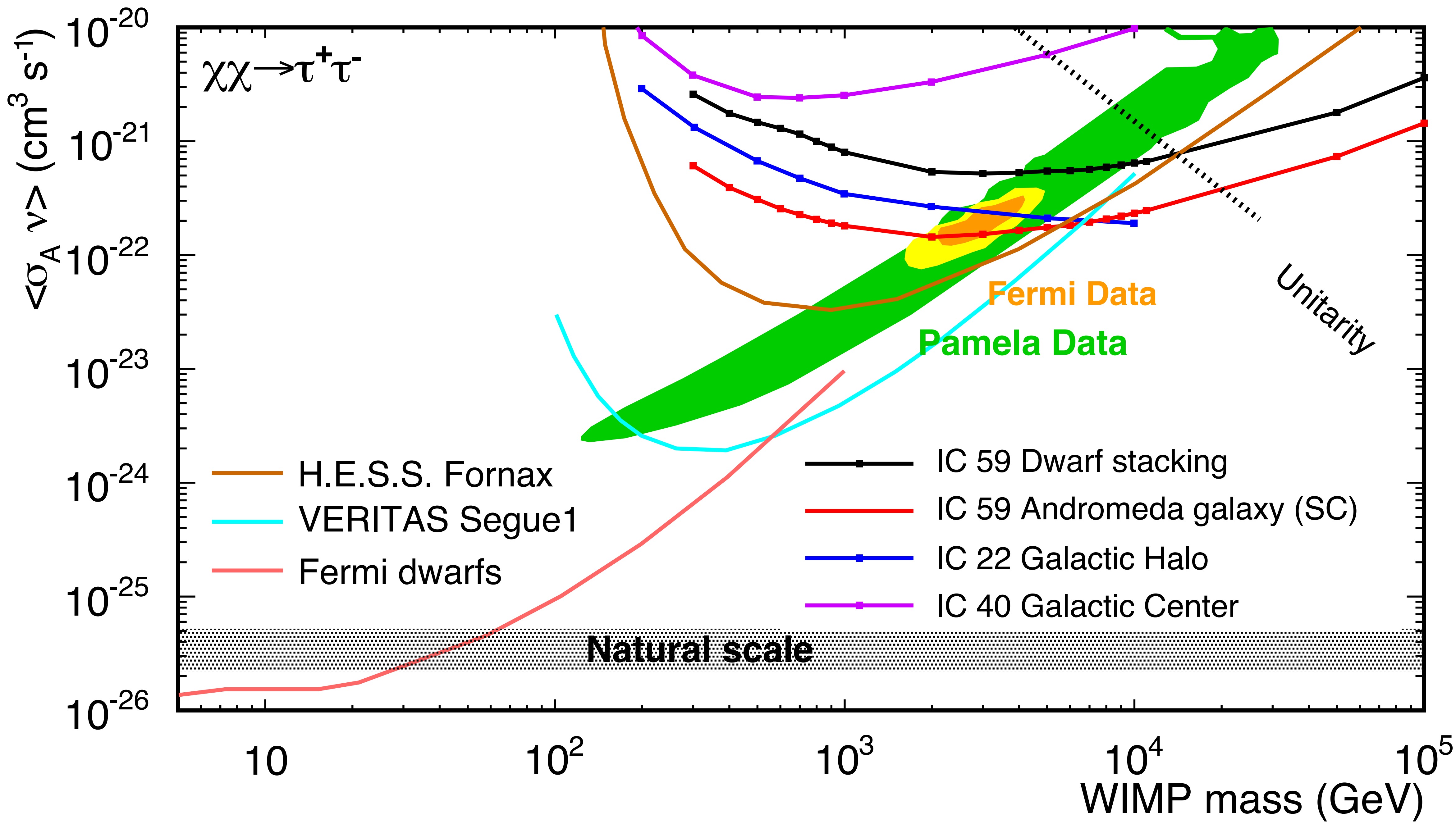
*Results for Cluster of Galaxies (Coma and Virgo) being updated

Observations consistent with background expectations

Limits computed at **90% C.L.** as function of WIMP mass assuming branching fraction of 100% WW and NFW profile

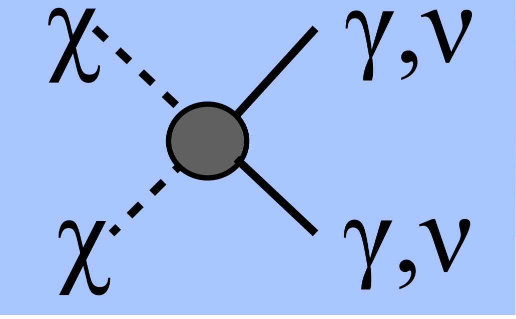


Results



IceCube can test dark matter models motivated by PAMELA and Fermi electron data (e.g. Meade et al. 2008)

Results extremely competitive for high-mass WIMPs



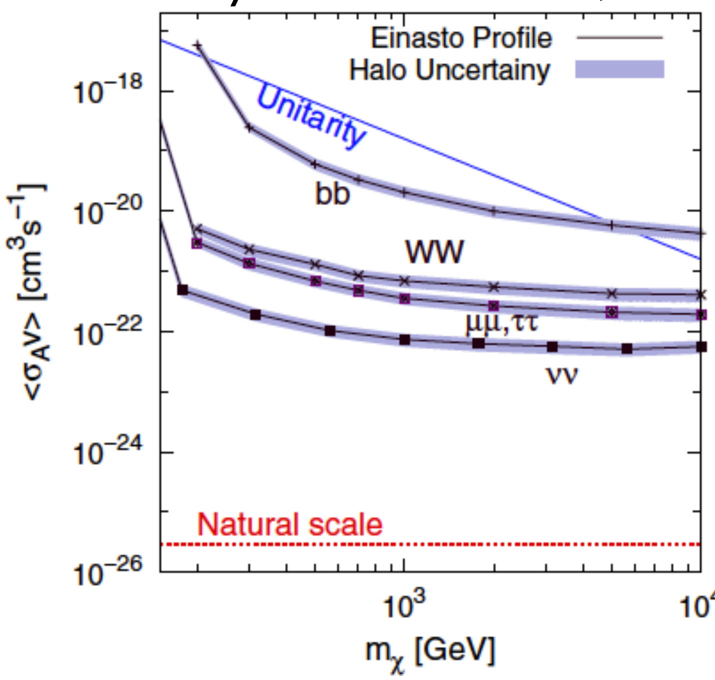
Neutrino Line Search

- Neutrinos set conservative upper limit on the total self-annihilation cross section using the line channel $\chi\chi\rightarrow\nu\nu$

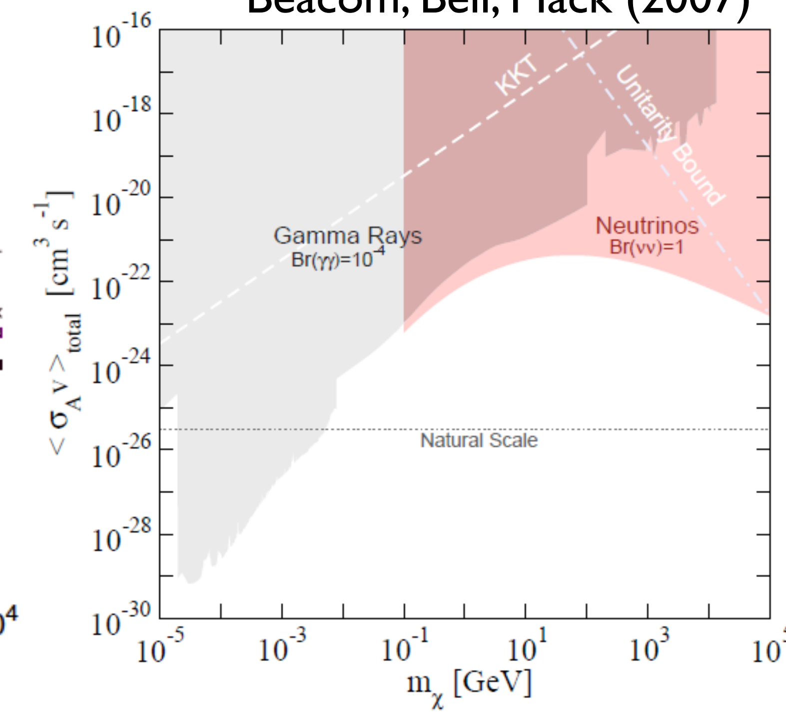
  Beacom, Bell, Mack (2007)

- IceCube has published limits for line channel for large WIMP masses m_χ
- $m_\chi \approx$100GeV match well contained events in DeepCore

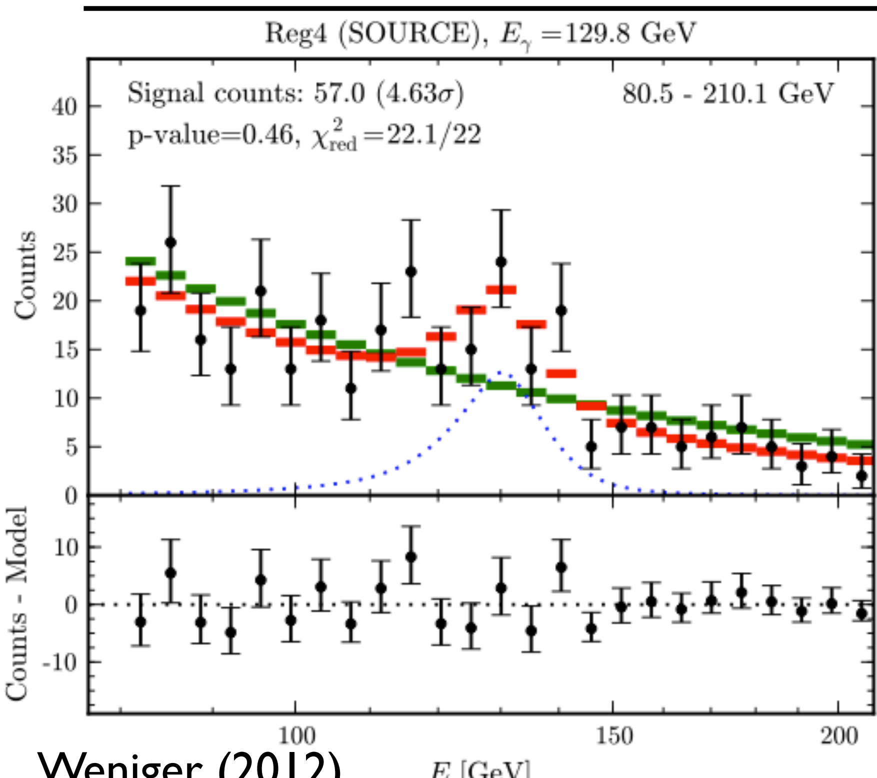
Phys.Rev.D84:022004,2011



Beacom, Bell, Mack (2007)

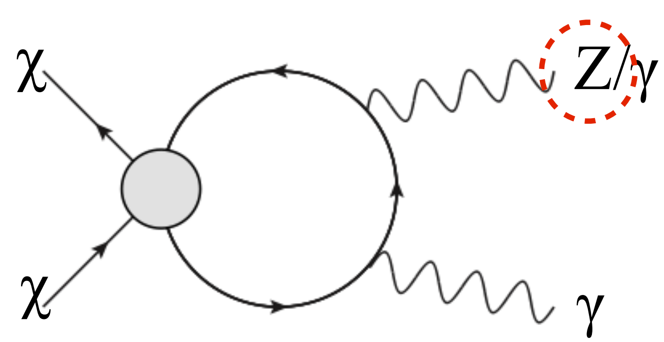


Neutrinos can also check predictions from gamma-ray lines:



Weniger (2012)

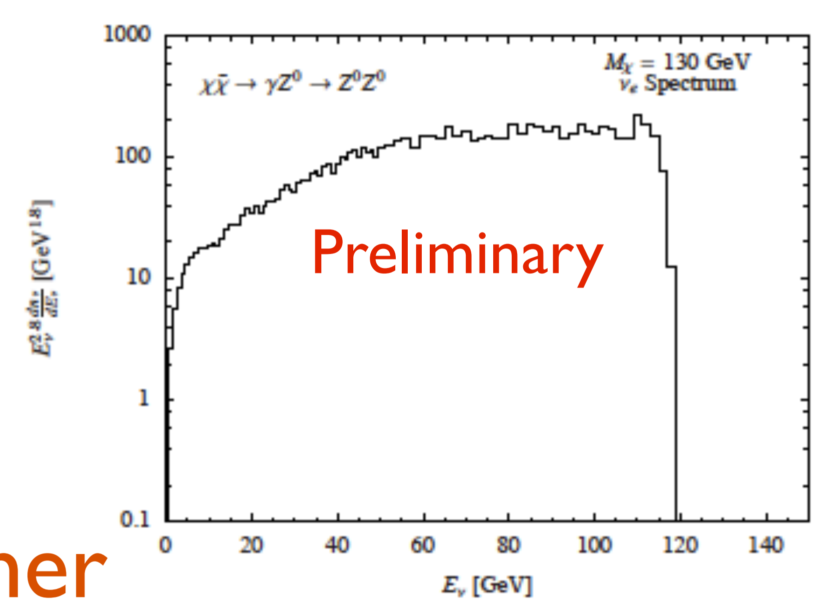
$$\langle\sigma v\rangle_{\gamma\gamma} \sim 10^{-27}\ \mathrm{cm}^3/\mathrm{s}$$



Cohen et al. arXiv:1207.0800v3

Dedicated analysis focuses on Neutrino lines in the energy range 20-200GeV

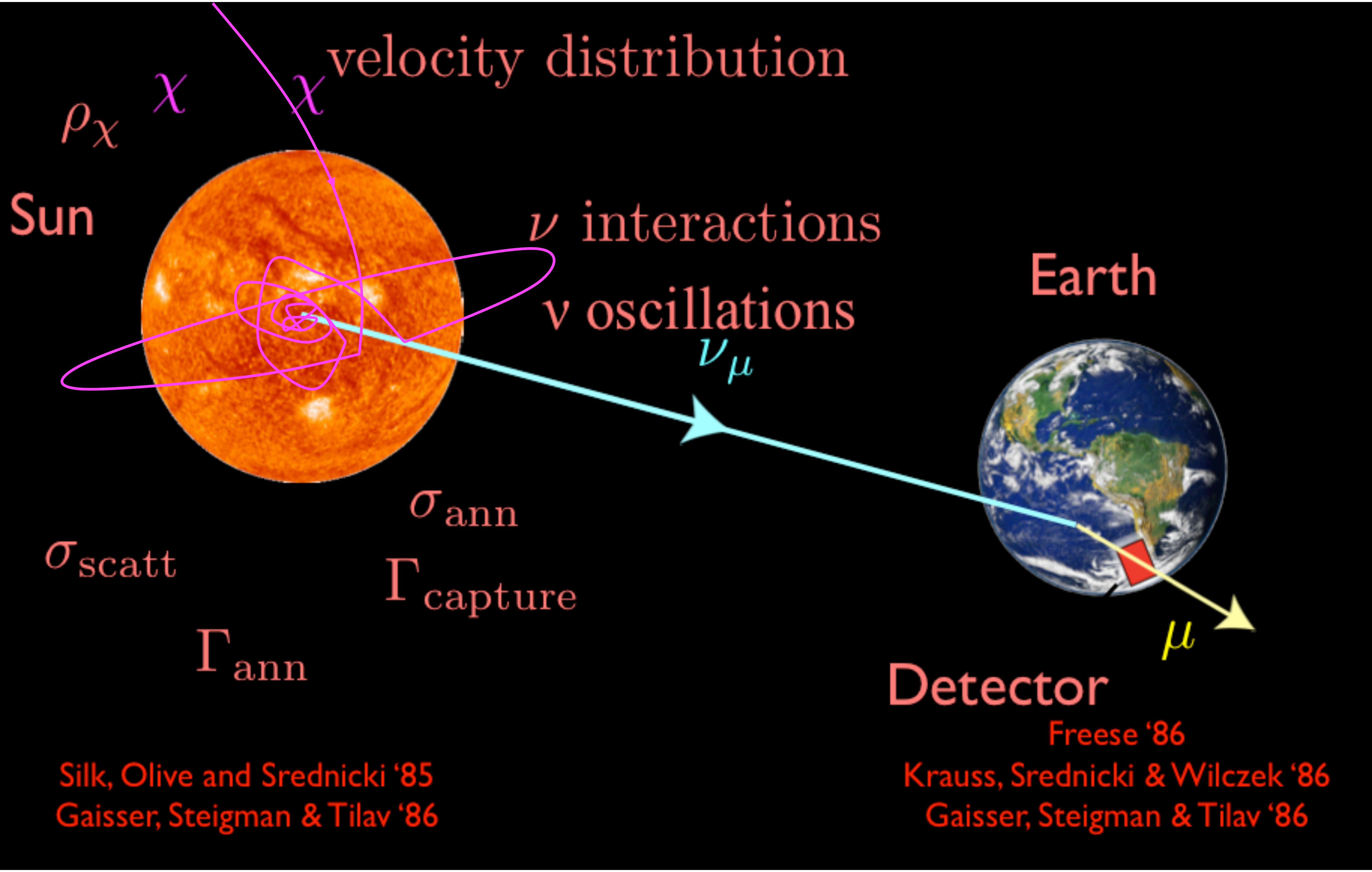
A. Z^0Z^0 Channel



Expect: Neutrino limit by the summer

Dark Matter in the Sun

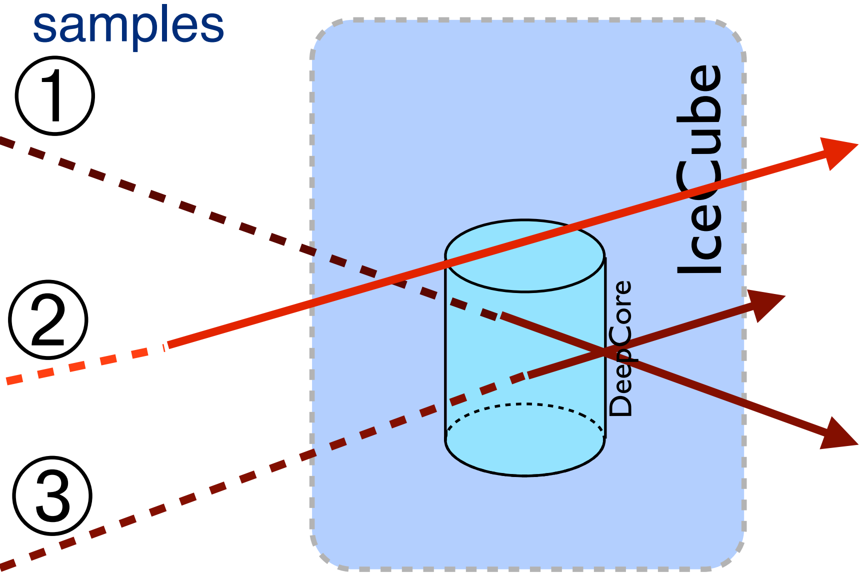
Solar WIMP Signal



DeepCore Solar WIMP Sensitivity

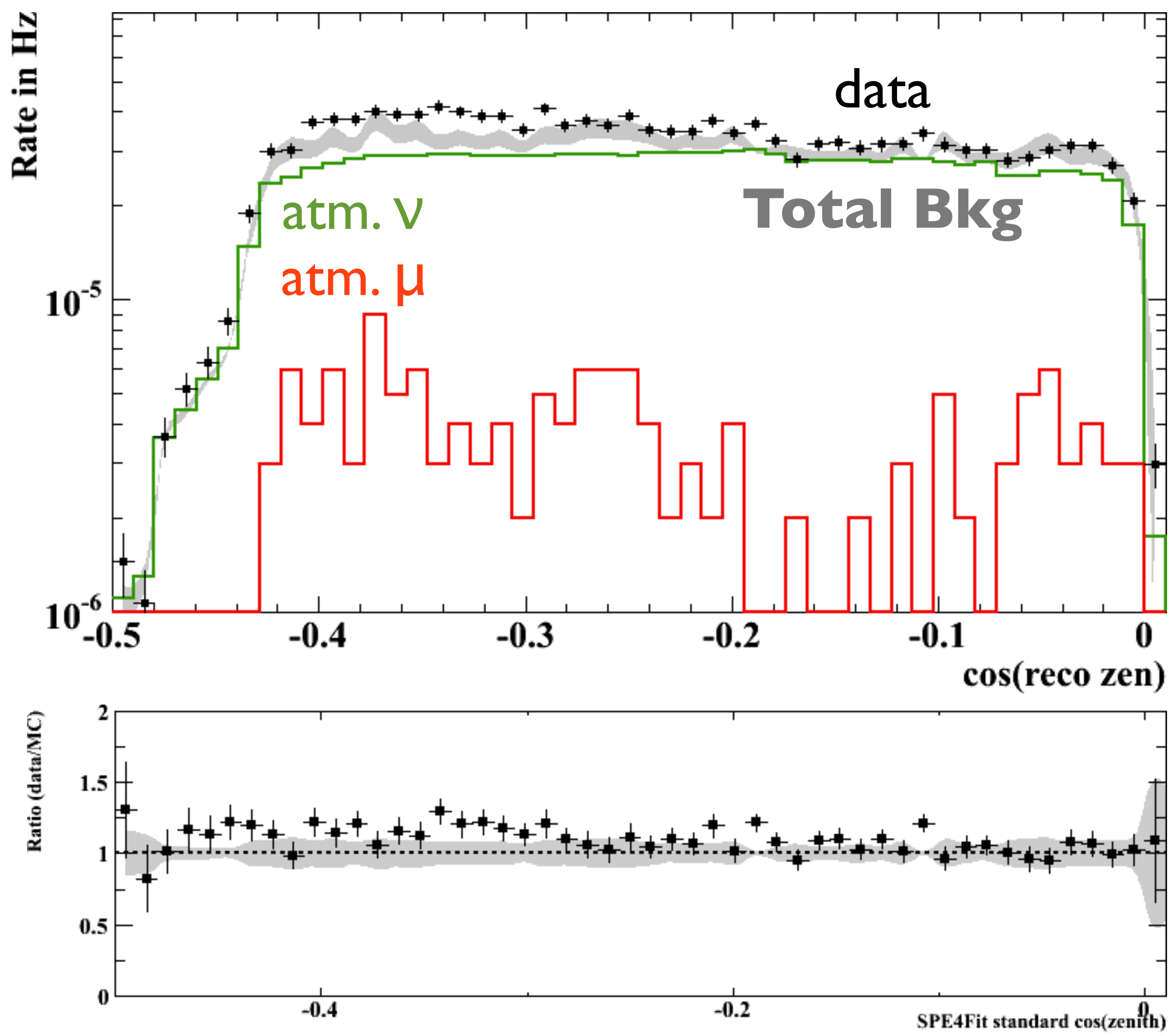
IceCube 79-string 318days (May 2010 - May 2011)

Analysis performed separately for austral summer (Sun above horizon) and austral winter (Sun below horizon) - 3 independent samples



Compare distribution of the final sample to these PDFs of background and signal to determine most likely signal content and combine likelihoods, weighted by relative livetime

② Event Selection (Winter, High energy, 151days)



- Event selection with separate BDT
- Training on off-source data + signal simulation
- Optimized final cut on BDT output- run llh-analysis for various selection criteria to determine best sensitivity

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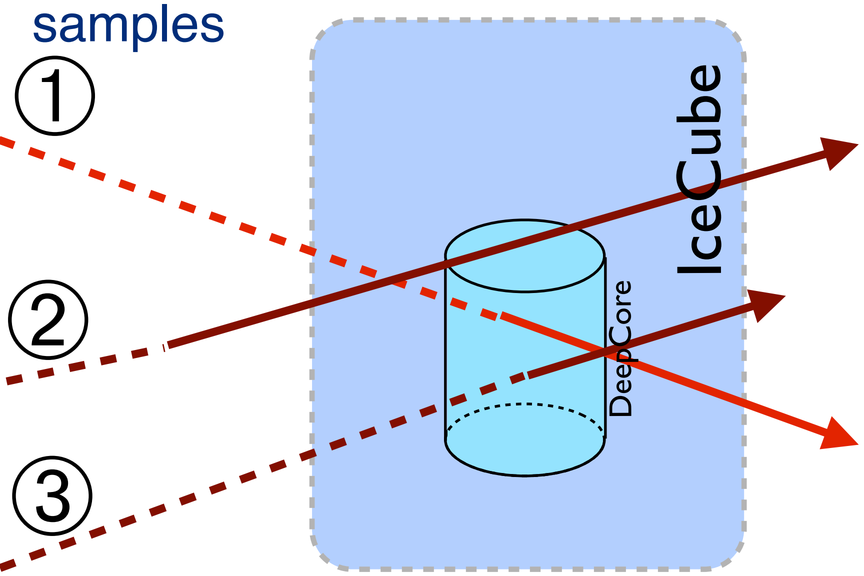
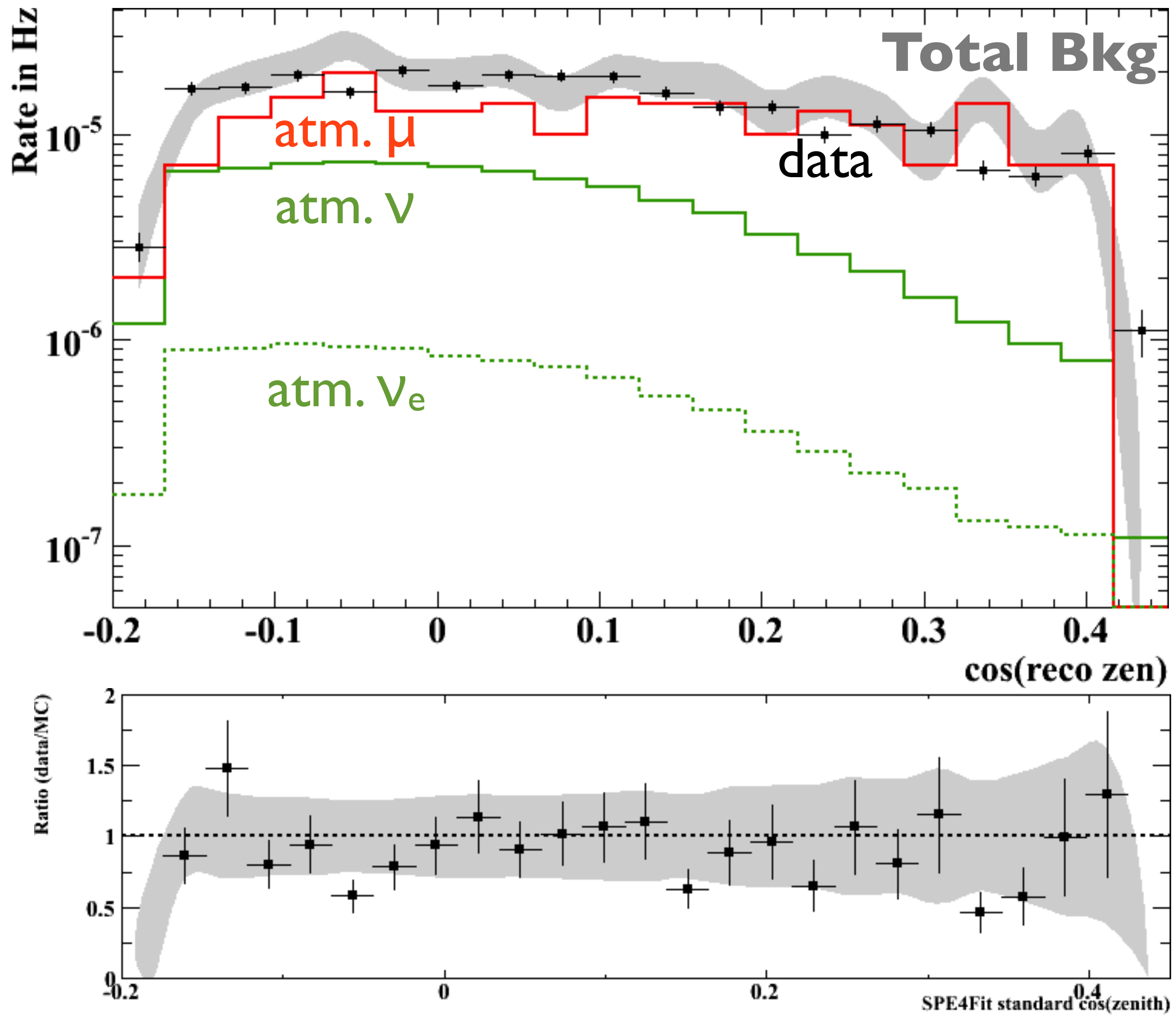


Compare distribution of the final sample to these PDFs of background and signal to determine most likely signal content and combine likelihoods, weighted by relative livetime

① Event Selection (Summer, Low energy, 166days)



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- Training on off-source data + signal simulation
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DeepCore Solar WIMP Sensitivity

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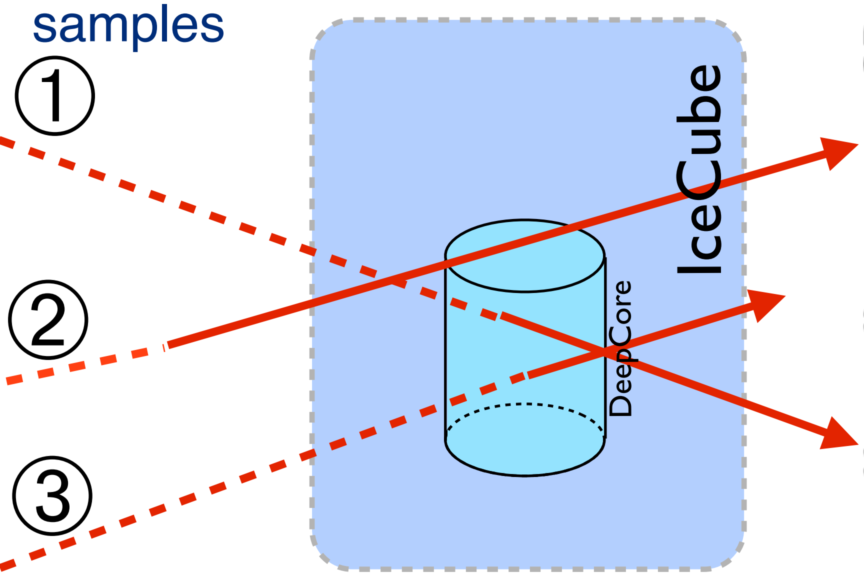
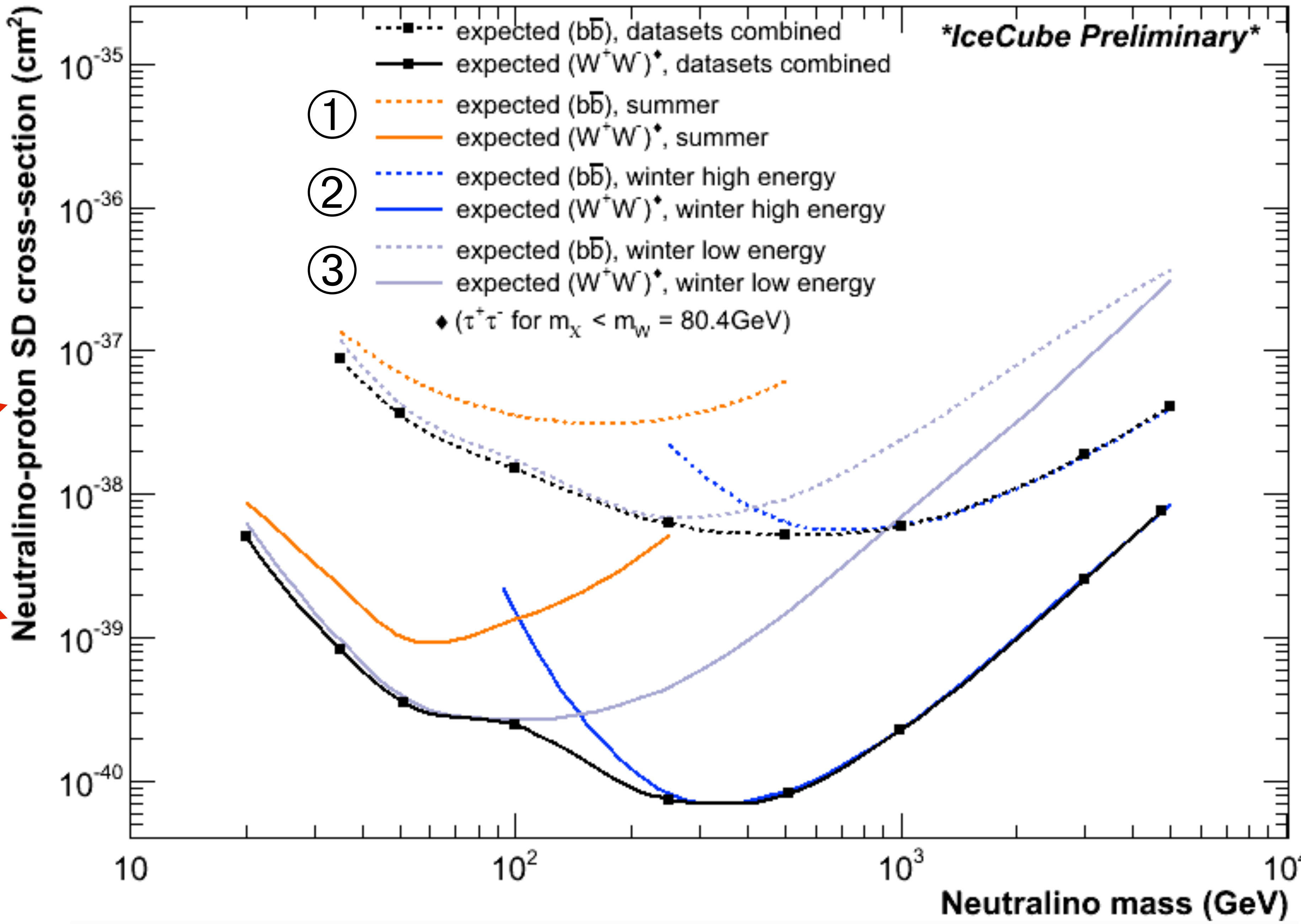
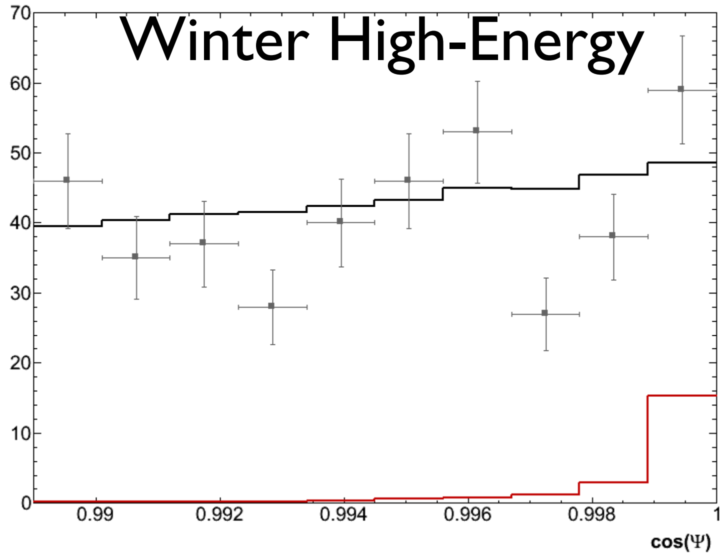


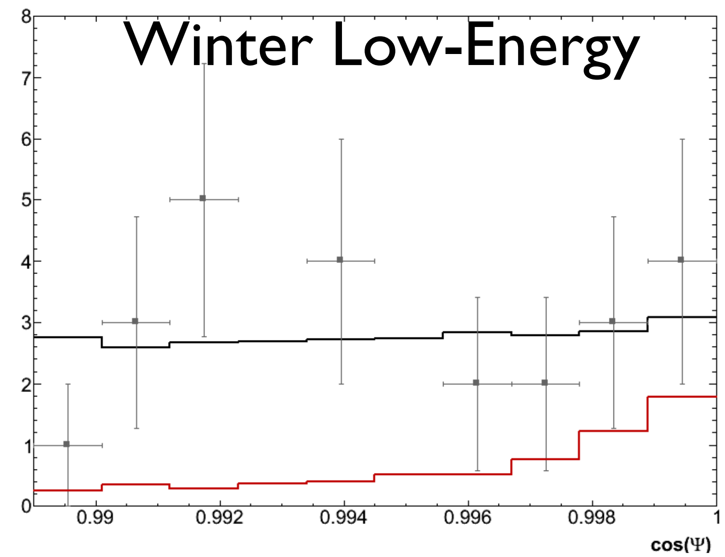


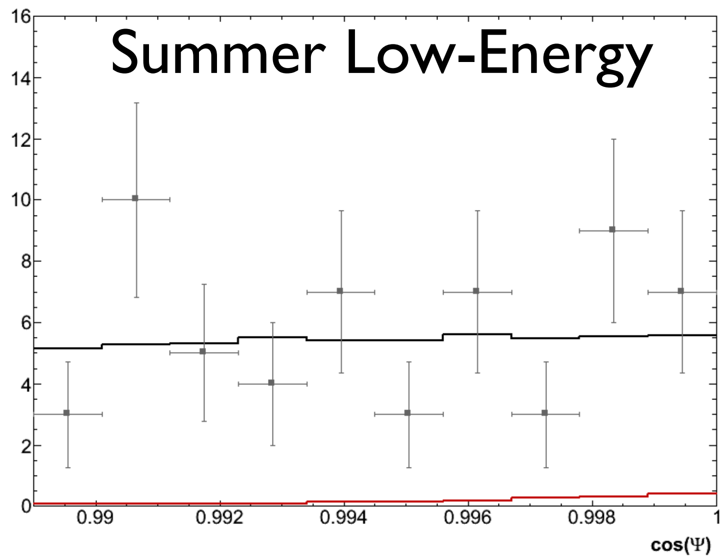
Compare distribution of the final sample to these PDFs of background and signal to determine most likely signal content and combine likelihoods, weighted by relative livetime

$$\mathcal{L}(\mu) = \prod_{i}^{n_{obs}} f(\Psi_i|\mu), \quad \text{where} \quad f(\Psi|\mu) = \frac{\mu}{n_{obs}} f_s(\Psi) + (1 - \frac{\mu}{n_{obs}}) f_{bg}(\Psi)$$

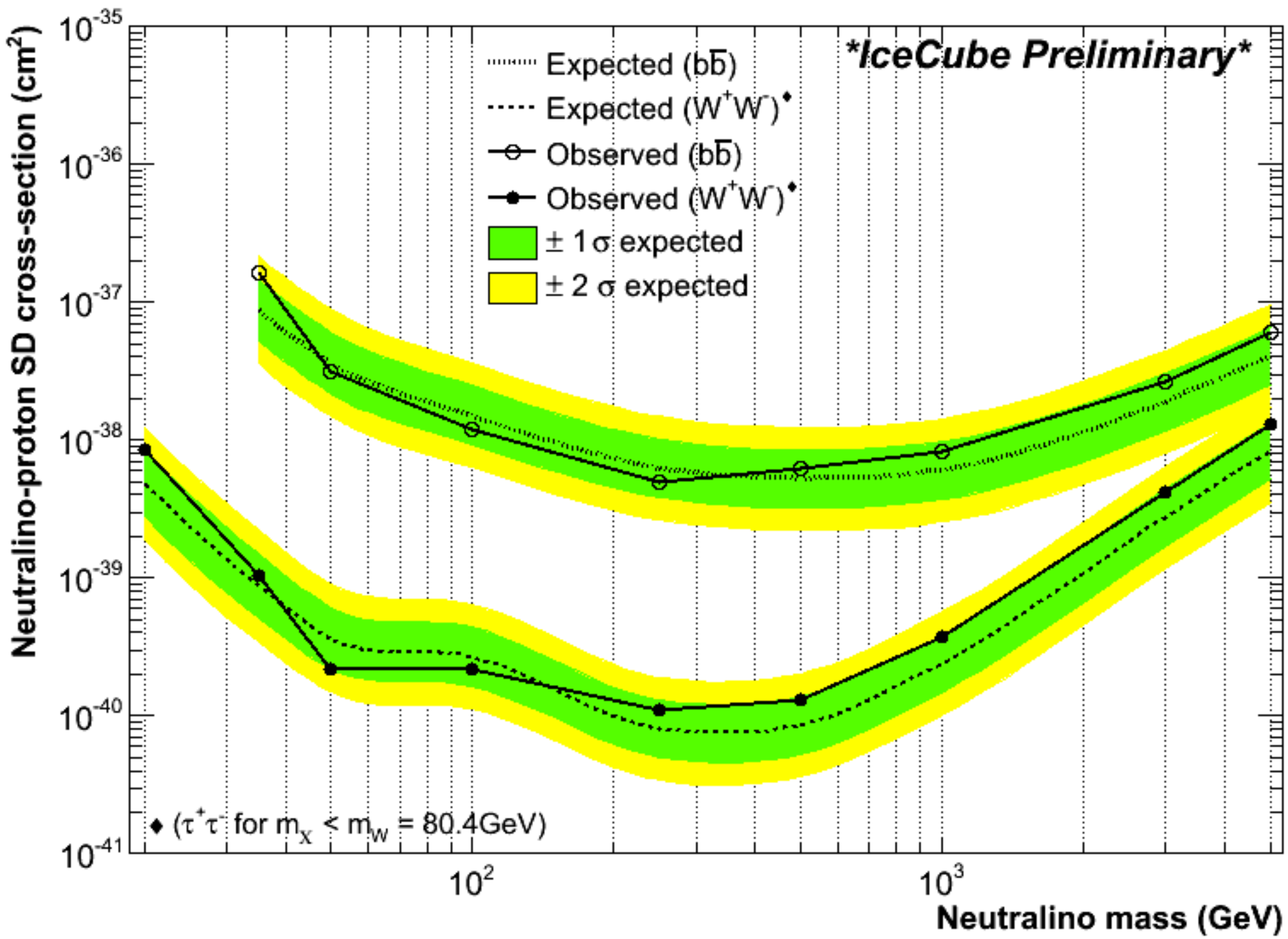
Results







All samples consistent with background expectations ... set limits



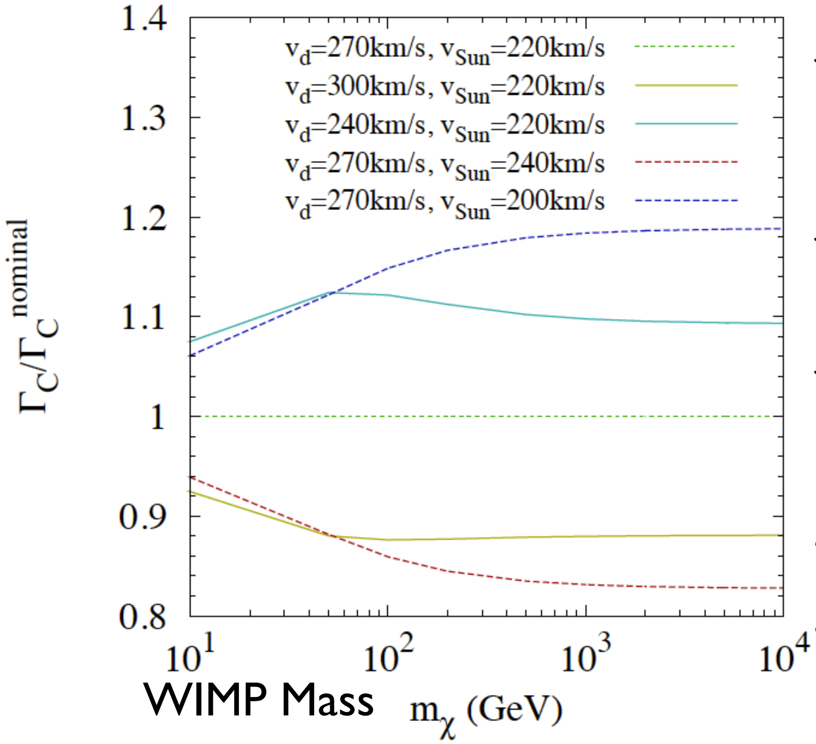
Systematic Uncertainties

Source	mass ranges (GeV) < 35	35-100	> 100
ν oscillations	6	6	6
ν-nucleon cross-section	7	5.5	3.5
μ-propagation in ice	<1	<1	<1
Time, position calibration	5	5	5
DOM sensitivity spread*	6	3	10
Photon propagation in ice*	15	10	5
Absolute DOM efficiency*	50	20	15
Total uncertainty	54	25	21

signal normalization — propagation

signal acceptance — detector

Velocity dependence

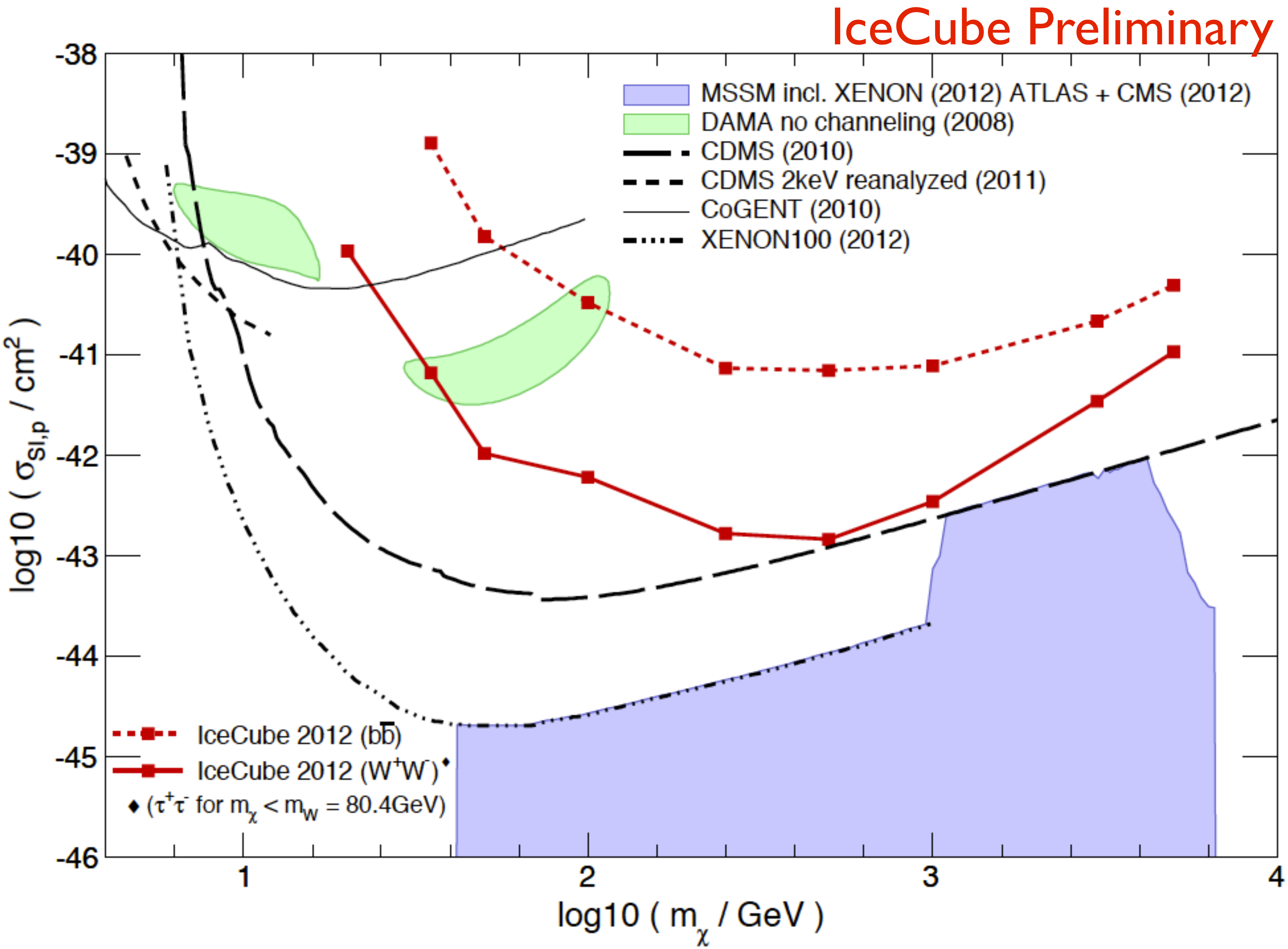


C.Rott, T. Tanaka, Y. Itow, JCAP09(2011)029

Astrophysical uncertainties well under control + use conservative local dark matter density ($0.3 GeV/cm^3$) used in analyses

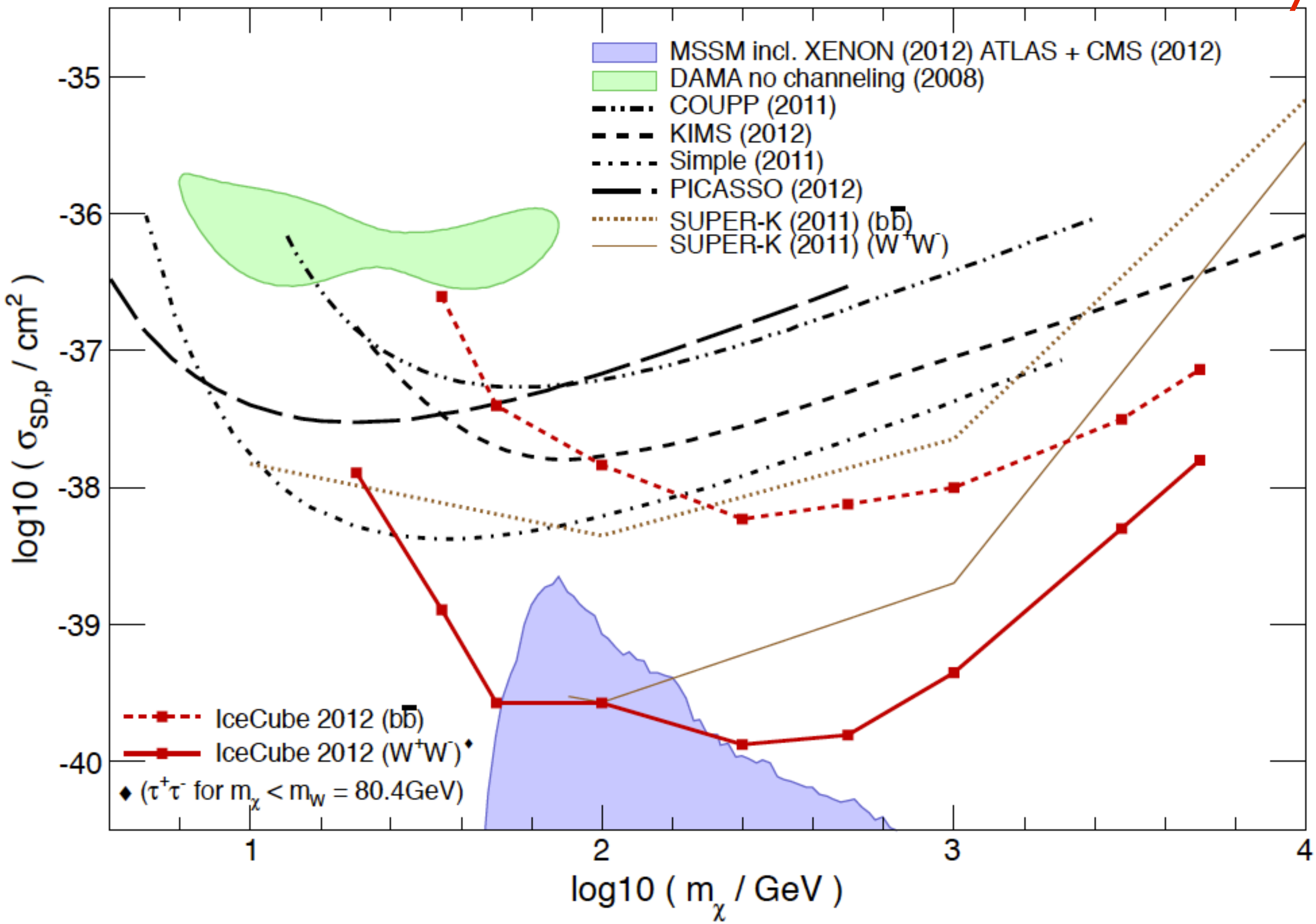
Capture Rate Γ_C — astrophysics

SI Solar WIMP Limit

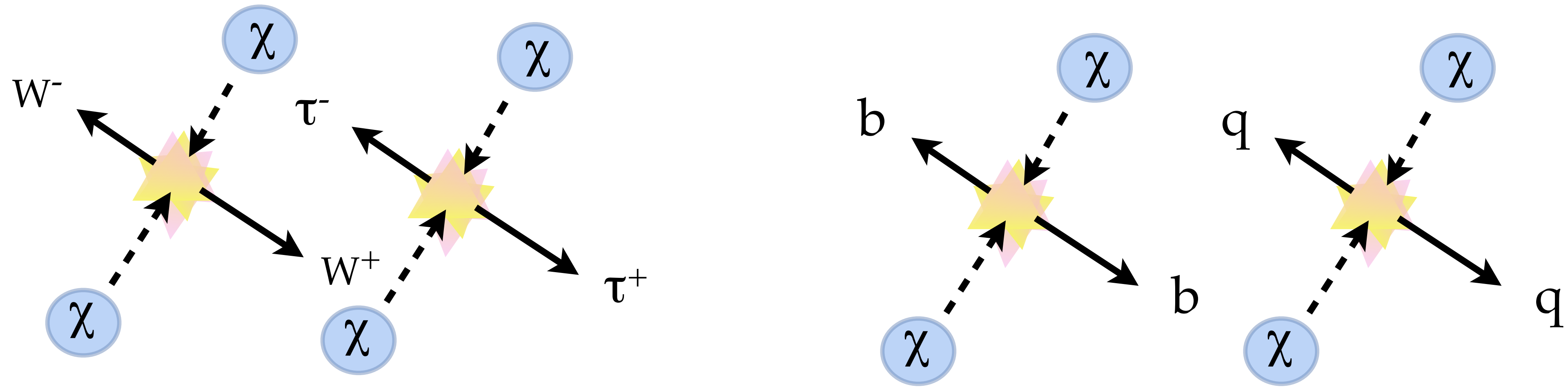


SD Solar WIMP Limit

IceCube Preliminary



Dark Matter Annihilation in the Sun



high energy neutrinos from annihilation / decay products

νν W⁻ W⁺ τ⁻ τ⁺ bb qq e⁺e⁻

highest energy neutrinos

fewest neutrinos

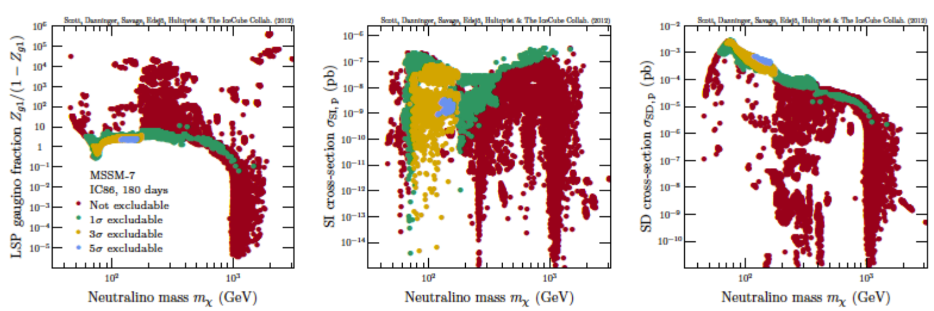
Benchmarks Br 100%

Hard channel

Soft channel

Specific Model

$$\mathcal{L}_{\text{total}}(n_{\text{tot}}, \Xi|\psi) = \mathcal{L}_{\text{num}}(n_{\text{tot}}|\psi) \prod^{n_{\text{tot}}} \mathcal{L}_{\text{ang},i}(\phi'_i|\psi)\, \mathcal{L}_{\text{spec},i}(N_i|\psi)$$



see: Scott, Savage, Edsjo and IceCube Collaboration "Use of event-level neutrino telescope data in global fits for theories of new physics" arXiv1207.0810

Relatively model independent

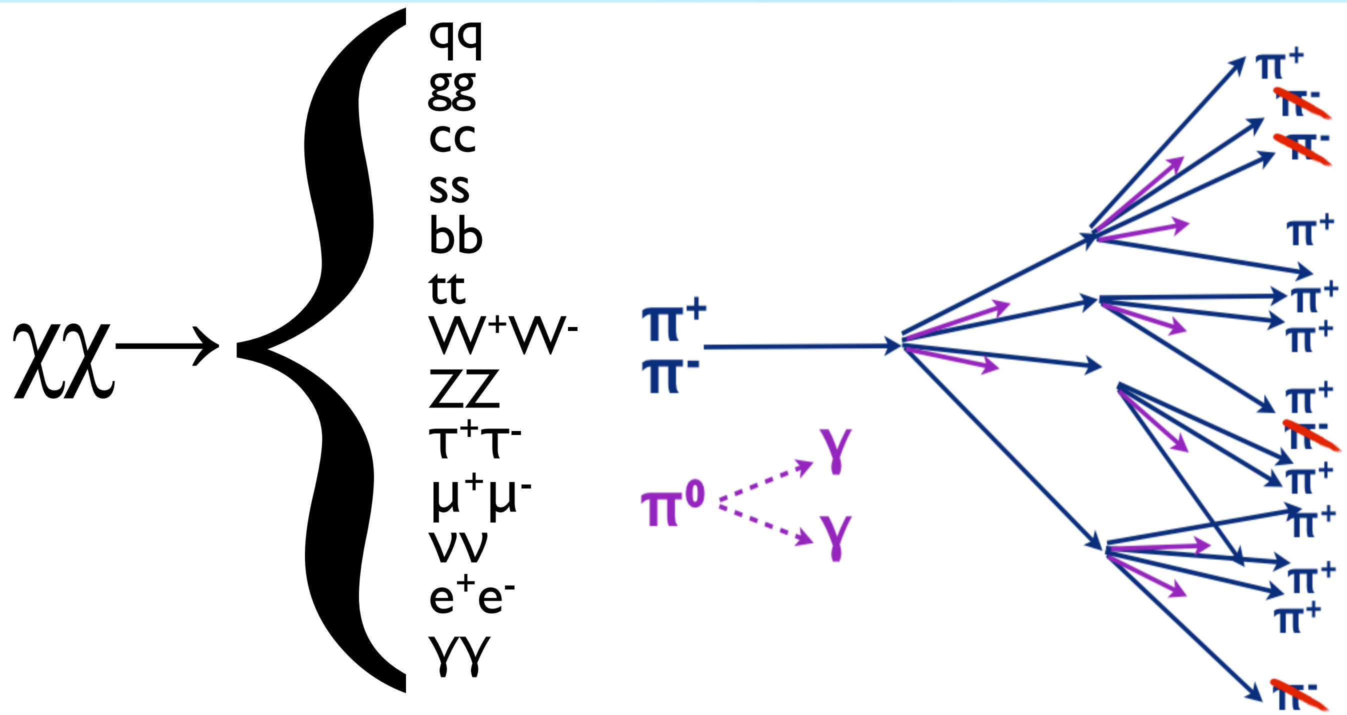
low energy neutrinos from hadronic shower

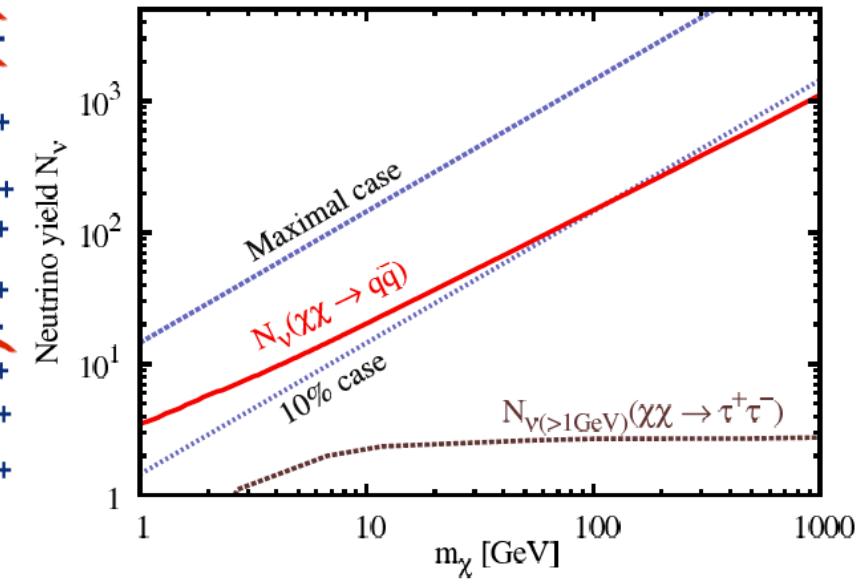
see: Rott, Siegal-Gaskins, Beacom arXiv1208.0827

Low-Energy Neutrinos - Solar WIMPs

Rott, Siegal-Gaskins, Beacom 2012

Previous searches relied on high energy neutrinos directly from the decays of annihilation products



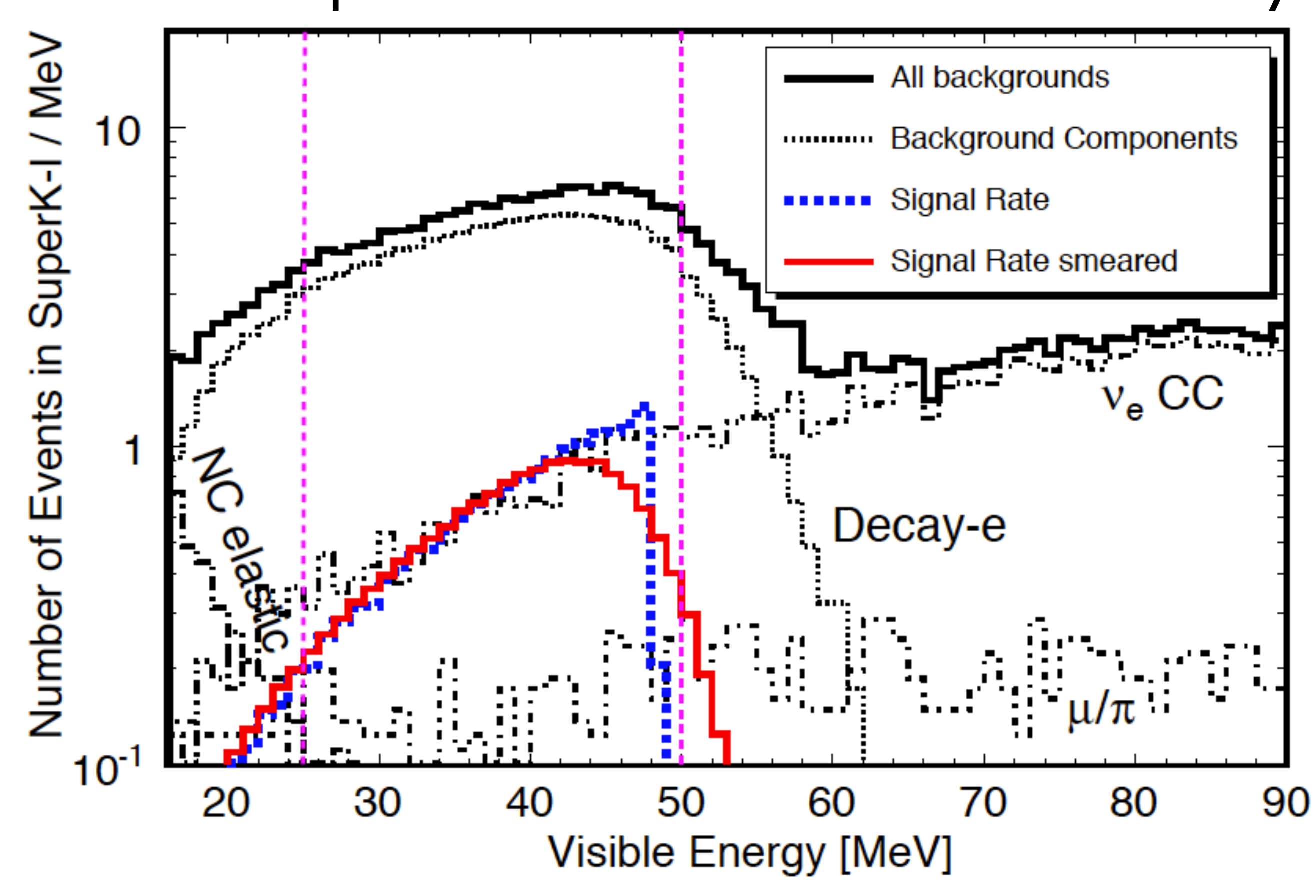


Model the full hadronic shower in the Sun

New key detection channel to compliment other searches; Super-K data can already be used to test DAMA

Interesting signatures for future neutrino detectors (Hyper-K, LBNE, ...), other nuclear final states could provide additional sensitivity

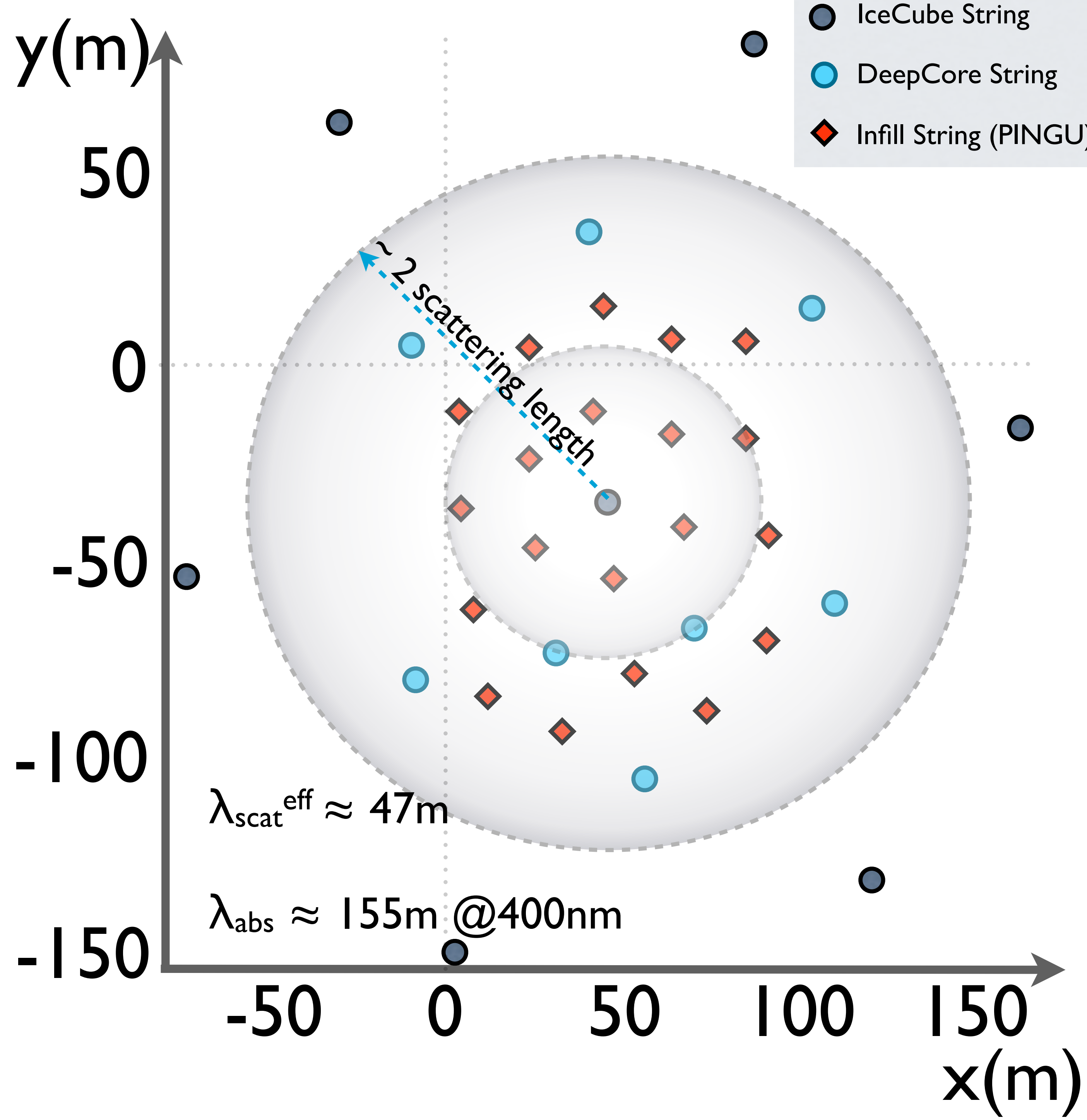
Example detection with inverse beta-decay



PINGU

- Test low mass WIMPs and precision measurements of neutrino oscillations
  - Needs energy threshold of few GeV
- Developing a proposal to further in-fill DeepCore, called PINGU
  - Instrument a volume of about 10MT with ~20 strings each containing 50-60 optical module
  - Rely on well established drilling technology and photo sensors
  - Create platform for calibration program and test technologies for future detectors

An example PINGU geometry

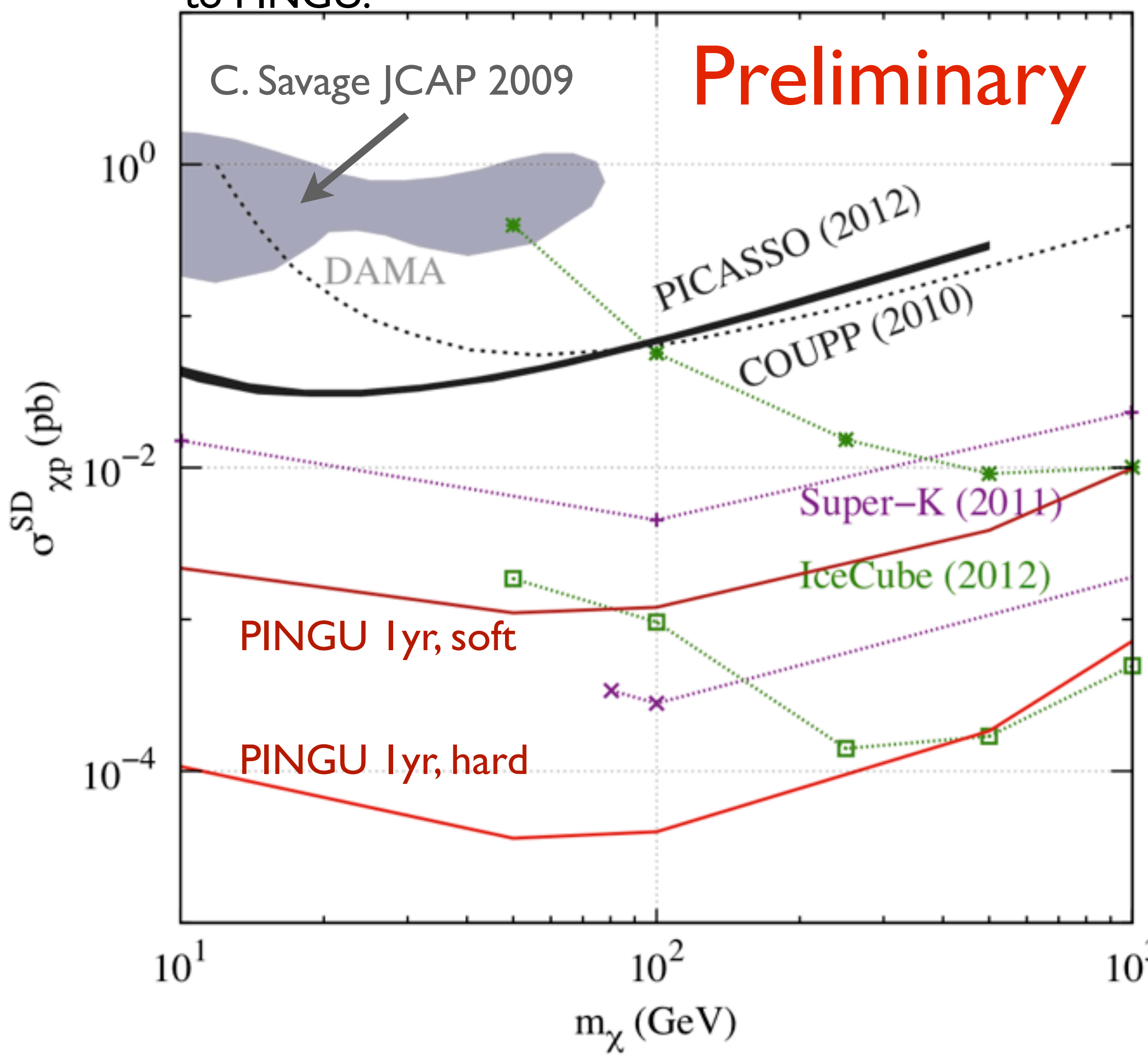


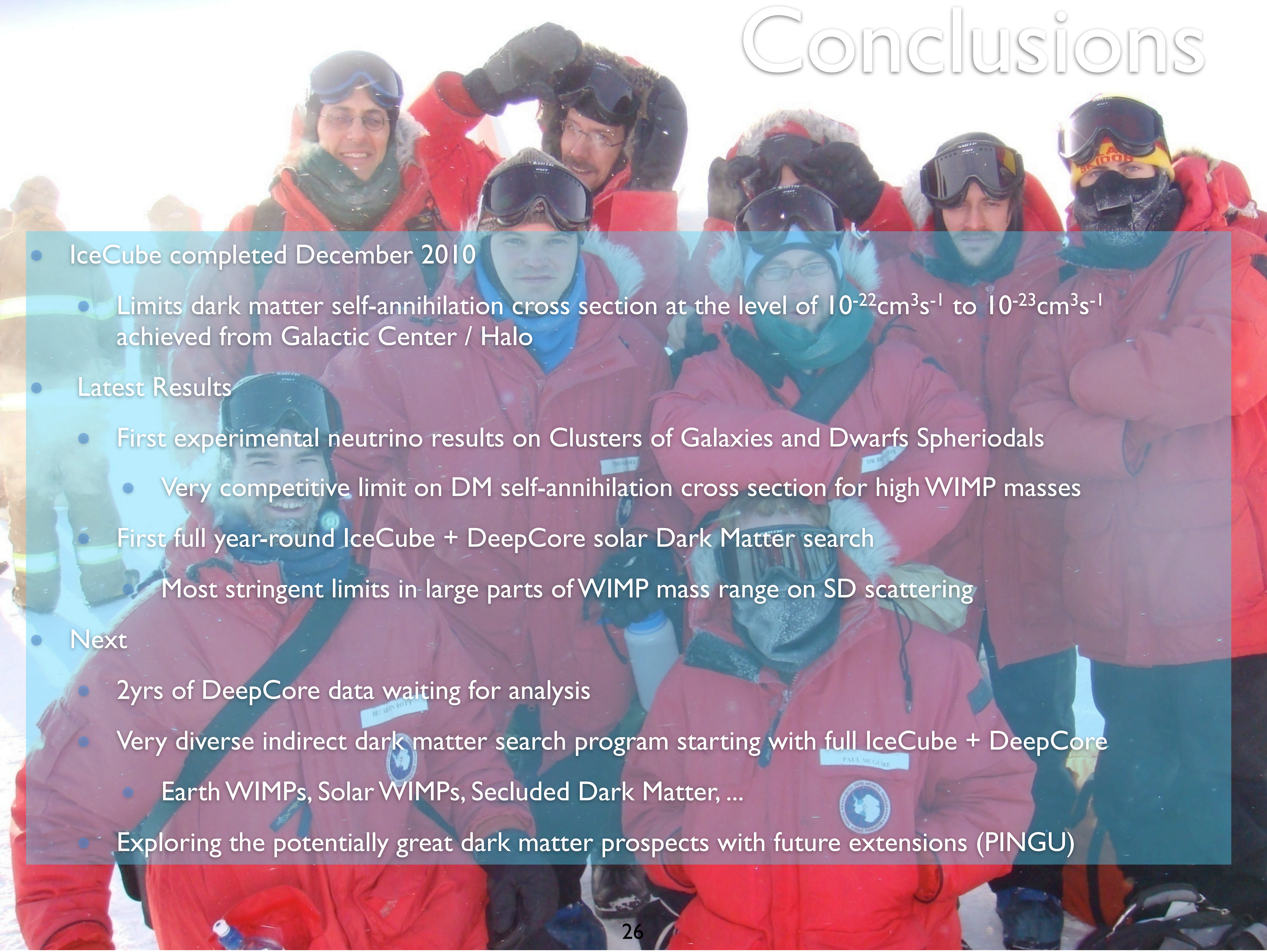
PINGU and Solar WIMPs

- Preliminary solar WIMP sensitivity based PINGUs effective volume
- Assume that atmospheric muon backgrounds can be effectively rejected (not included in the sensitivity)

- Low-mass WIMP scenarios well testable
- Next steps:
  - Detailed study with full PINGU simulation
  - More sophisticated event reconstruction
  - Check atmospheric muon background

Adapted **Rott, Tanaka, Itow JCAP09(2011)029** to PINGU.





Conclusions

- IceCube completed December 2010
  - Limits dark matter self-annihilation cross section at the level of $10^{-22}cm^3s^{-1}$ to $10^{-23}cm^3s^{-1}$ achieved from Galactic Center / Halo
- Latest Results
  - First experimental neutrino results on Clusters of Galaxies and Dwarfs Spheriodals
    - Very competitive limit on DM self-annihilation cross section for high WIMP masses
  - First full year-round IceCube + DeepCore solar Dark Matter search
    - Most stringent limits in large parts of WIMP mass range on SD scattering
- Next
  - 2yrs of DeepCore data waiting for analysis
  - Very diverse indirect dark matter search program starting with full IceCube + DeepCore
    - Earth WIMPs, Solar WIMPs, Secluded Dark Matter, ...
  - Exploring the potentially great dark matter prospects with future extensions (PINGU)