Searches for Dark Matter with the IceCube neutrino Telescope

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Outline

- Dark Matter Candidates
- IceCube and DeepCore detectors
- Searches for Solar WIMPs
- Searches for WIMPs from the Galactic Center and Halo

Dark Matter (WIMP)

- Srong evidence from astrophysical observations
- Interact only through weak and gravitational forces
- Models
  - SuperSymmetry, Universal Extra Dimension
- Detection
  - Direct – recoil of nuclei in ultra-low background detectors (Xenon, CDMS...)
  - Indirect – measure the decay products of dark matter annihilation (Fermi, IceCube, ...)
  - Collider – produce dark matter and measure missing energy (LEP, LHC, ...)

MSSM: Neutralino

- Lightest Supersymmetric Particle (Stable)
- Collected in Massive Object (Sun, Galatic Halo,...)
- Self-annihilation leads to SM particles and then neutrinos

$$\boxed{\chi\chi \rightarrow b\bar{b}, \tau^+\tau^-, W^+W^-, \ldots \rightarrow \nu}$$

- Event rate and energies depend on MSSM model parameters and astrophysics (relative velocities, galactic density profile)
  - few to 10^3 events per year
  - GeV to TeV energies (low energy!)

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soft hard

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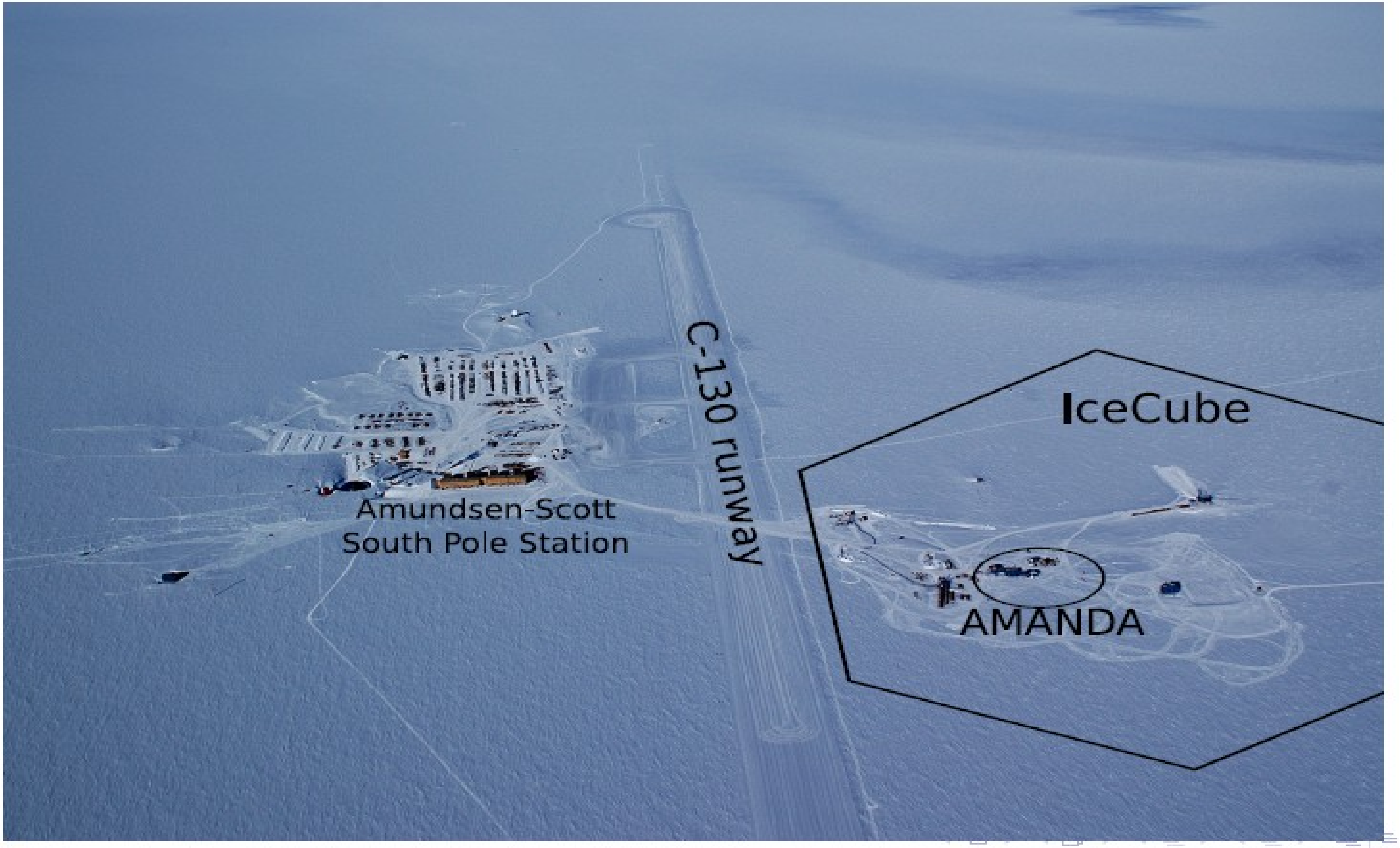
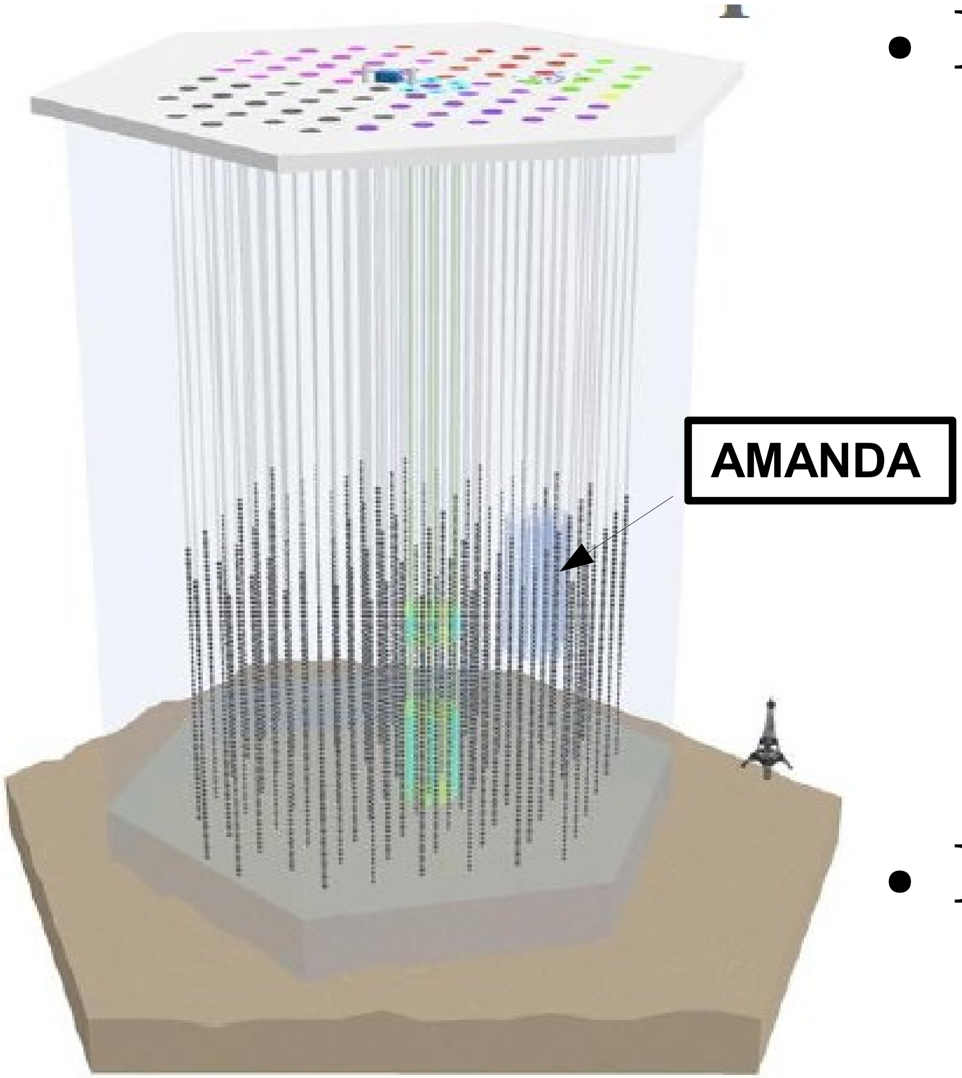
IceCube Collaboration

IceCube Observatory



IceCube Detector



- IceCube
  - Completion in 2011
  - 80 strings in total
  - Deployed 73 (+6) strings
  - 4800 Digital Optical Modules
  - Height ~ 1000 m
  - Diameter ~ 1000 m
- IceTop
  - 80 Stations, 320 DOMs
  - 2 Tanks x station

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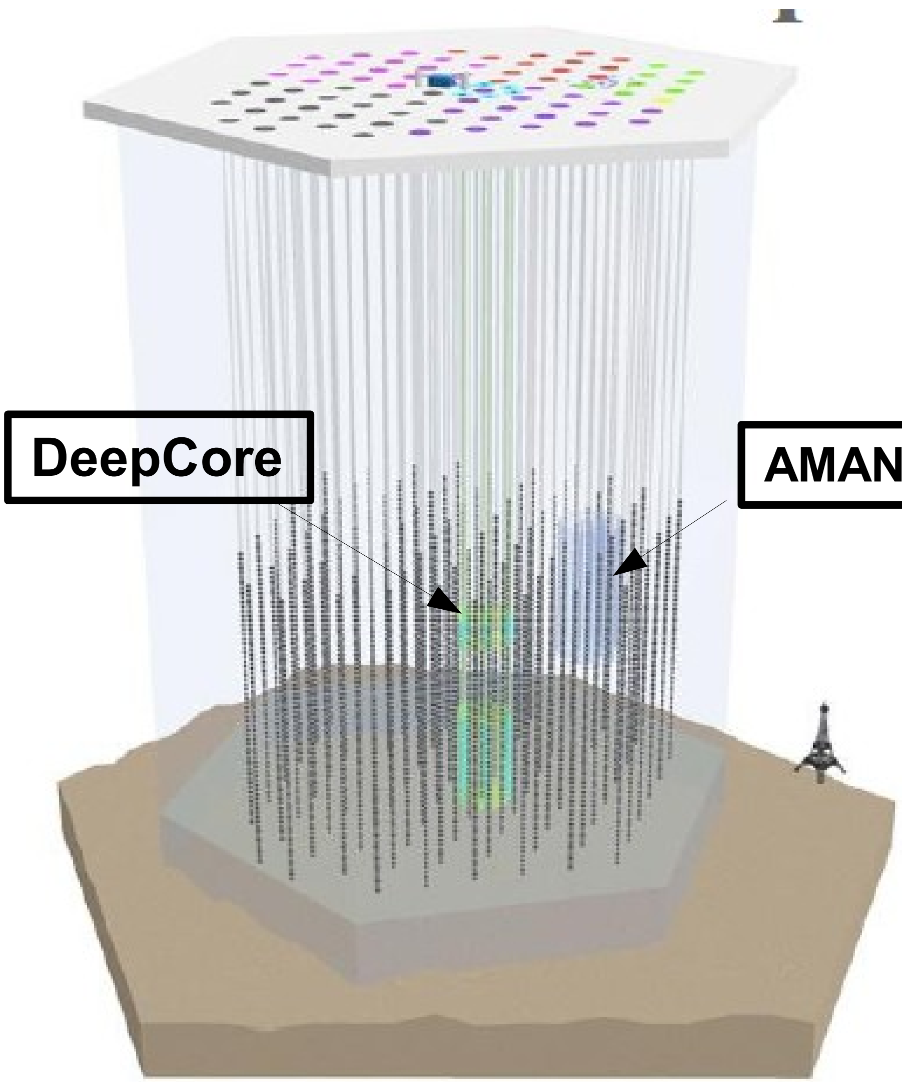
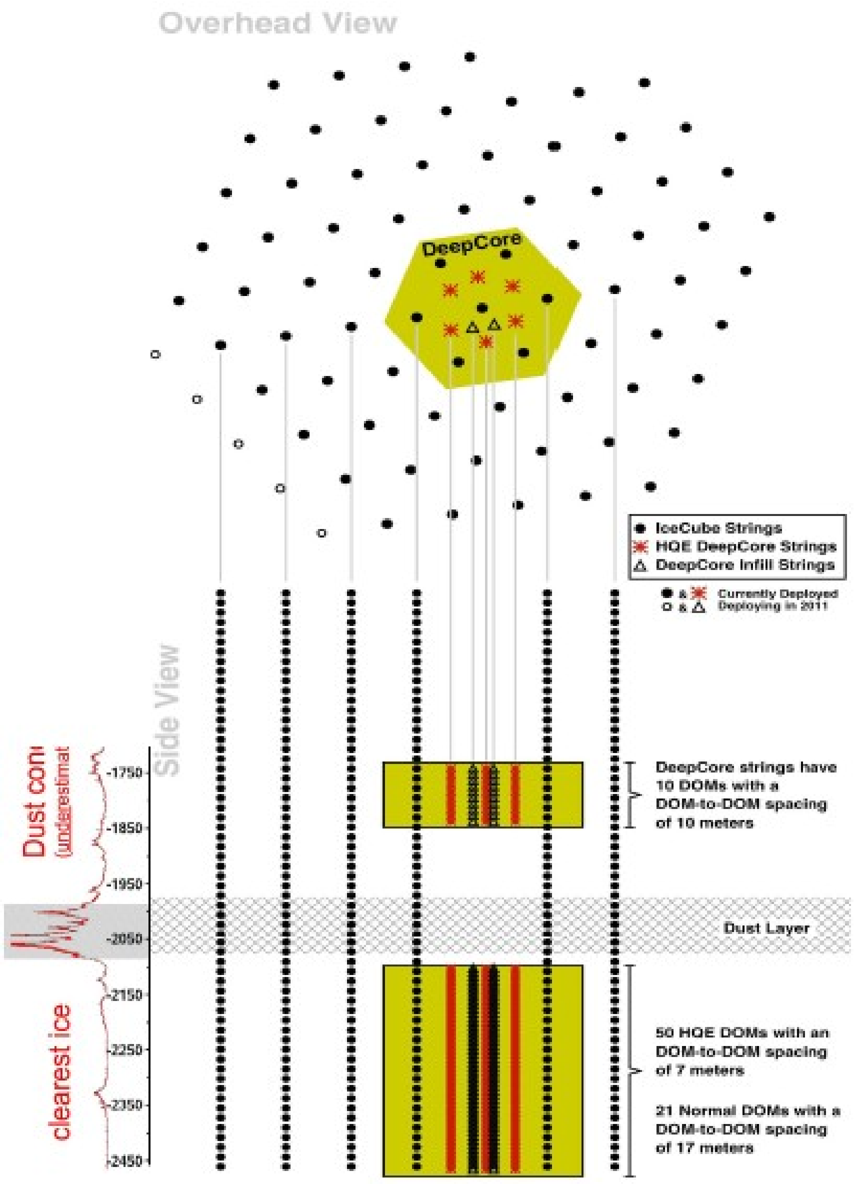
IceCube + DeepCore detector



- 6 string sub-array (completed!)
  - More densely instrumented
  - Closer string spacing
  - 60 x 6 high. Q.E. DOMs
  - Deployed in the deepest, clearest ice
- Extend sensitivity to $\sim$ 20 GeV
  - Dark Matter Searches
  - Neutrino Oscillation
- Use of IceCube as a veto extends searches to southern sky
  - Extended exposure
  - More sources including GC

IceCube + DeepCore detector



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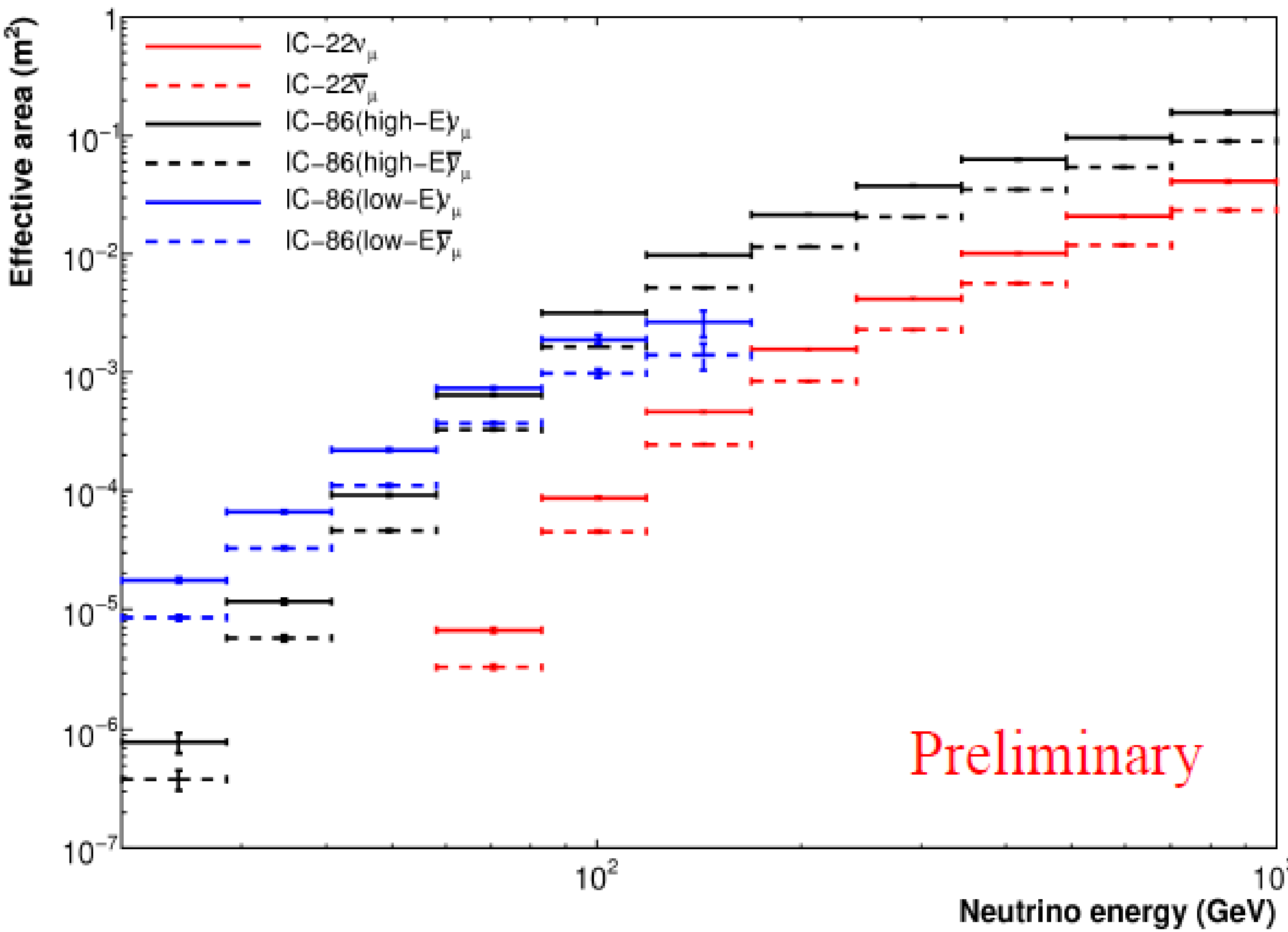
IceCube + DeepCore detector

Abbasi et al., *Physical Review* **D81** (2010) 057101. (IC22 result)



IC22: Systematic effects are in-cluded at the 1σ level, and statistical uncertainty of the same level are shown with error bars.

effective area for final event selection as function of E_ν in the range 20-1000 GeV, for ν_μ and anti-ν_μ from the direction of the Sun.

The result is an average over the austral winter.

Blue curve optimized for low WIMP masses

Black curve optimized for high WIMP masses

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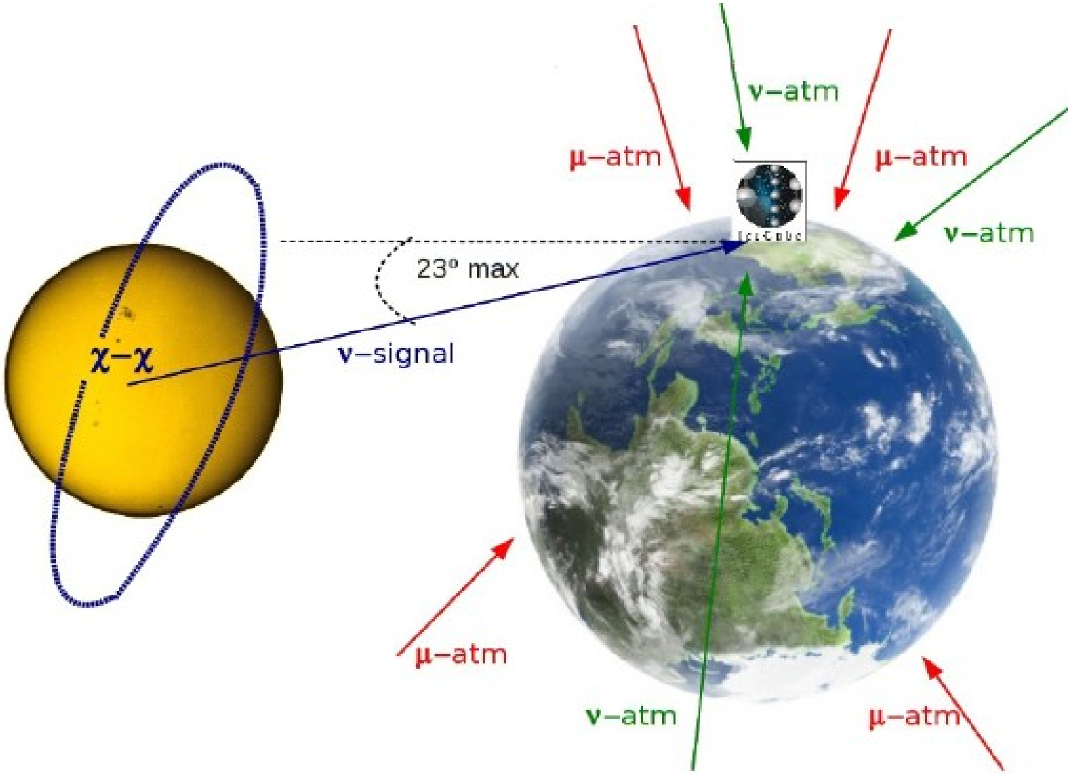
Neutralino induced neutrino from the Sun



$$C_{sun} \propto \frac{\rho_\chi \sigma_{\chi p}}{\bar{\nu}_\chi^3 m_\chi^2}$$

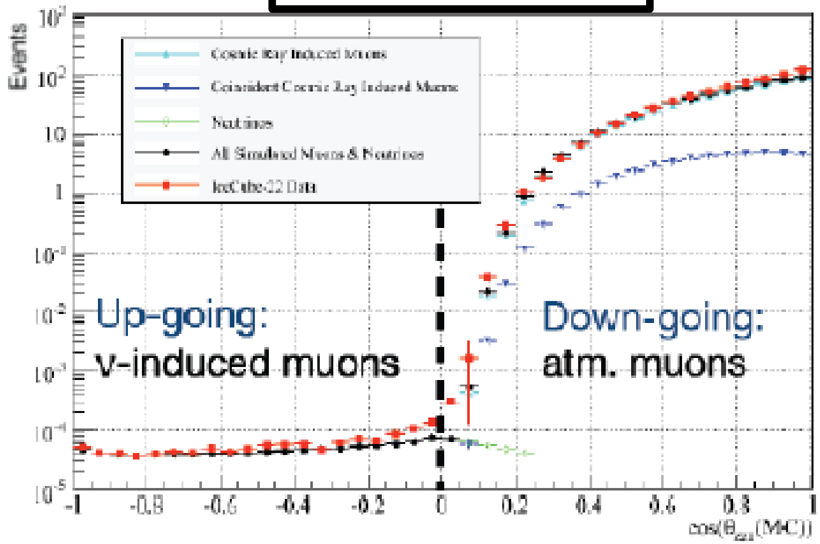
$$\Gamma_A = \frac{1}{2} C_{sun}$$

- Background:
  - Atm. μ ~ $O(10^9)$ events/year (downward)
  - Atm. ν ~ $O(10^3)$ events/year (all directions)

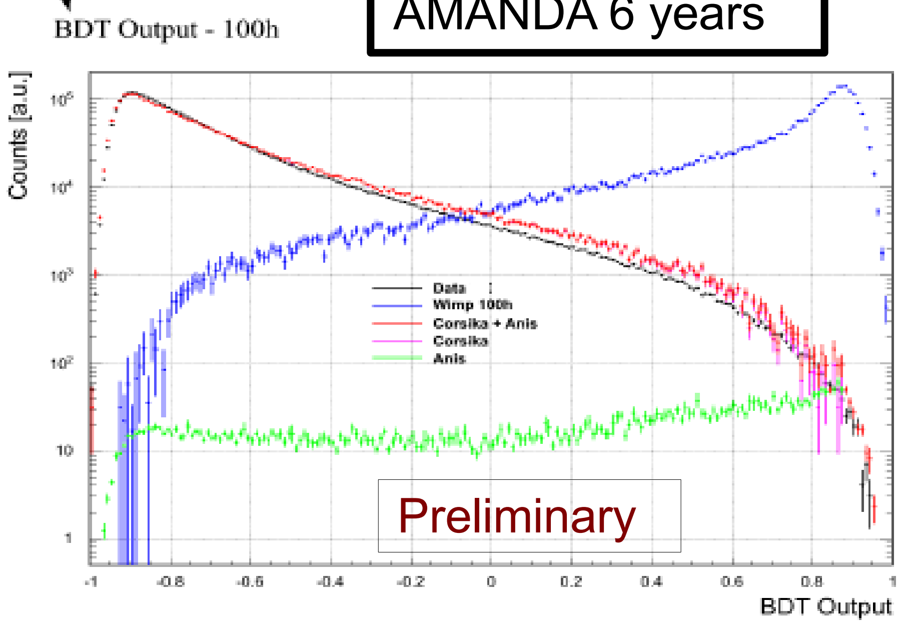
Analysis filtering strategy

- Multivariate methods (BDTs, SVM, NN,...) can be used to separate signal from background
- Variables should not be too much correlated (50%-65%)

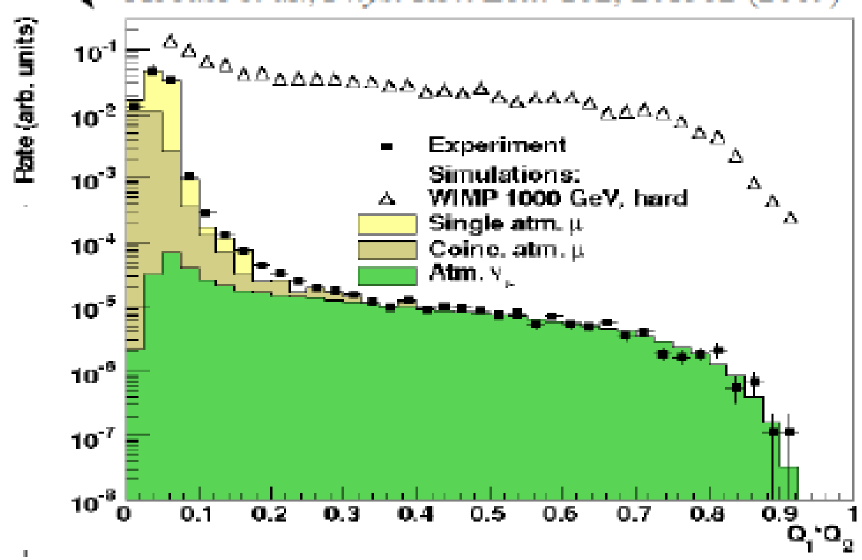
IceCube 22



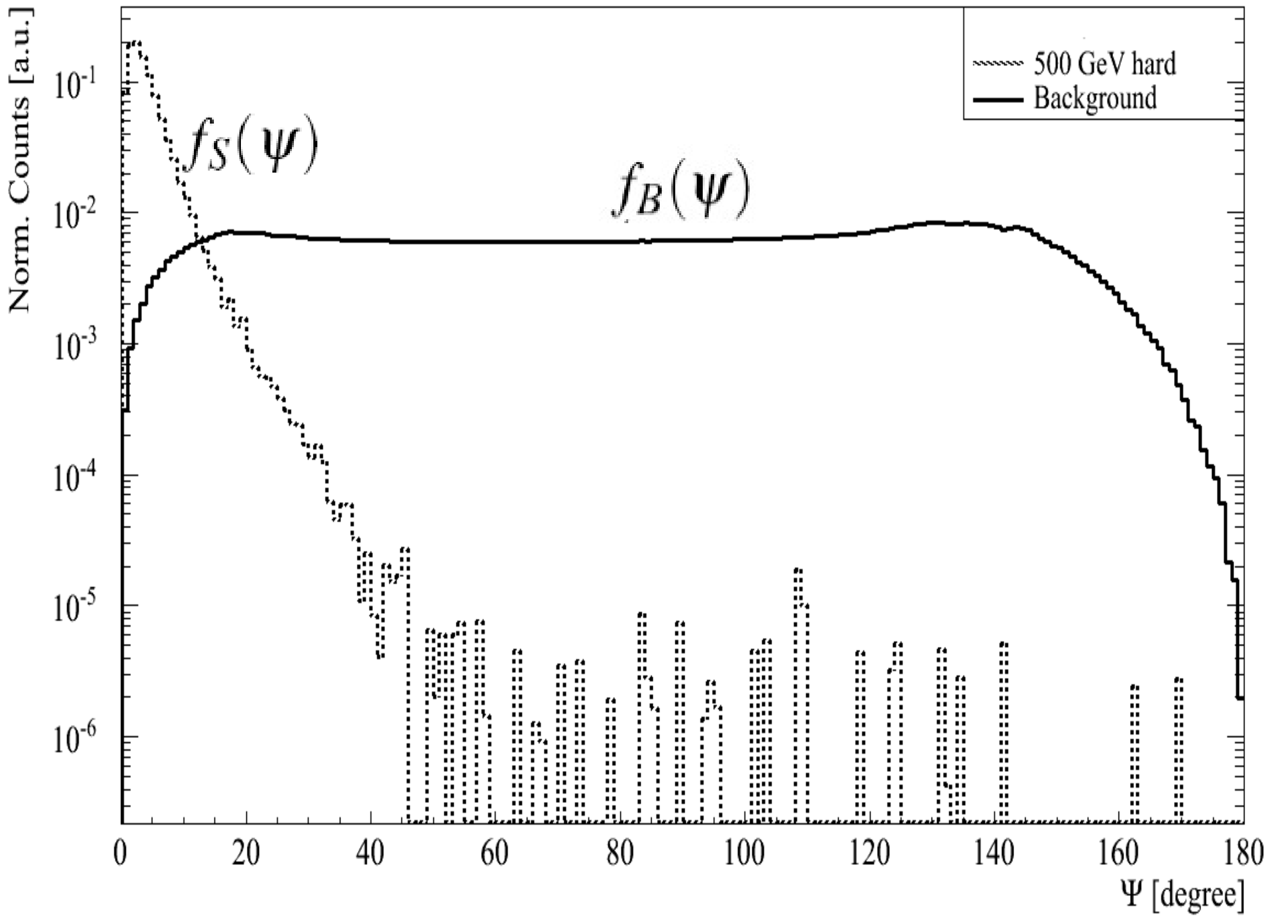
AMANDA 6 years

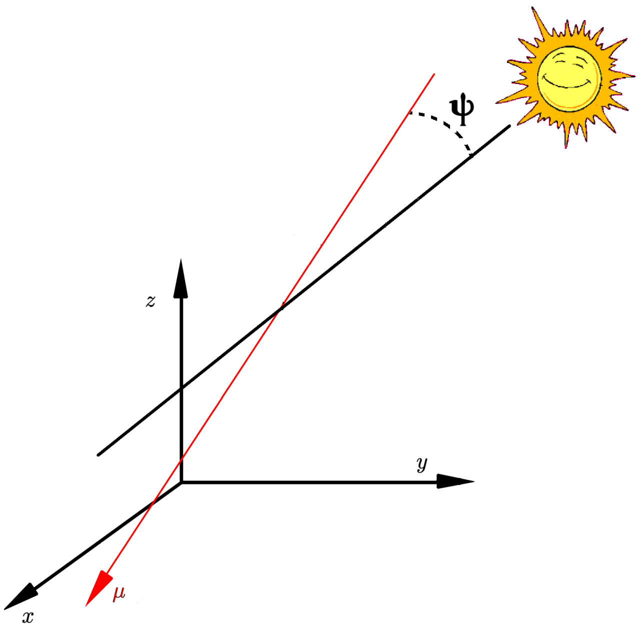


Abbasi et al., *Phys. Rev. Lett.* **102**, 201302 (2009)



Hypothesis testing
Correlation to the Sun: space angle





- Used the space-angle distributions (Ψ)
- Blindness: randomized Sun azimuth
- Defined combined p.d.f:

$$f(\psi|\mu) = \frac{\mu}{n_{obs}} f_S(\psi) + \left(1 - \frac{\mu}{n_{obs}}\right) f_B(\psi)$$

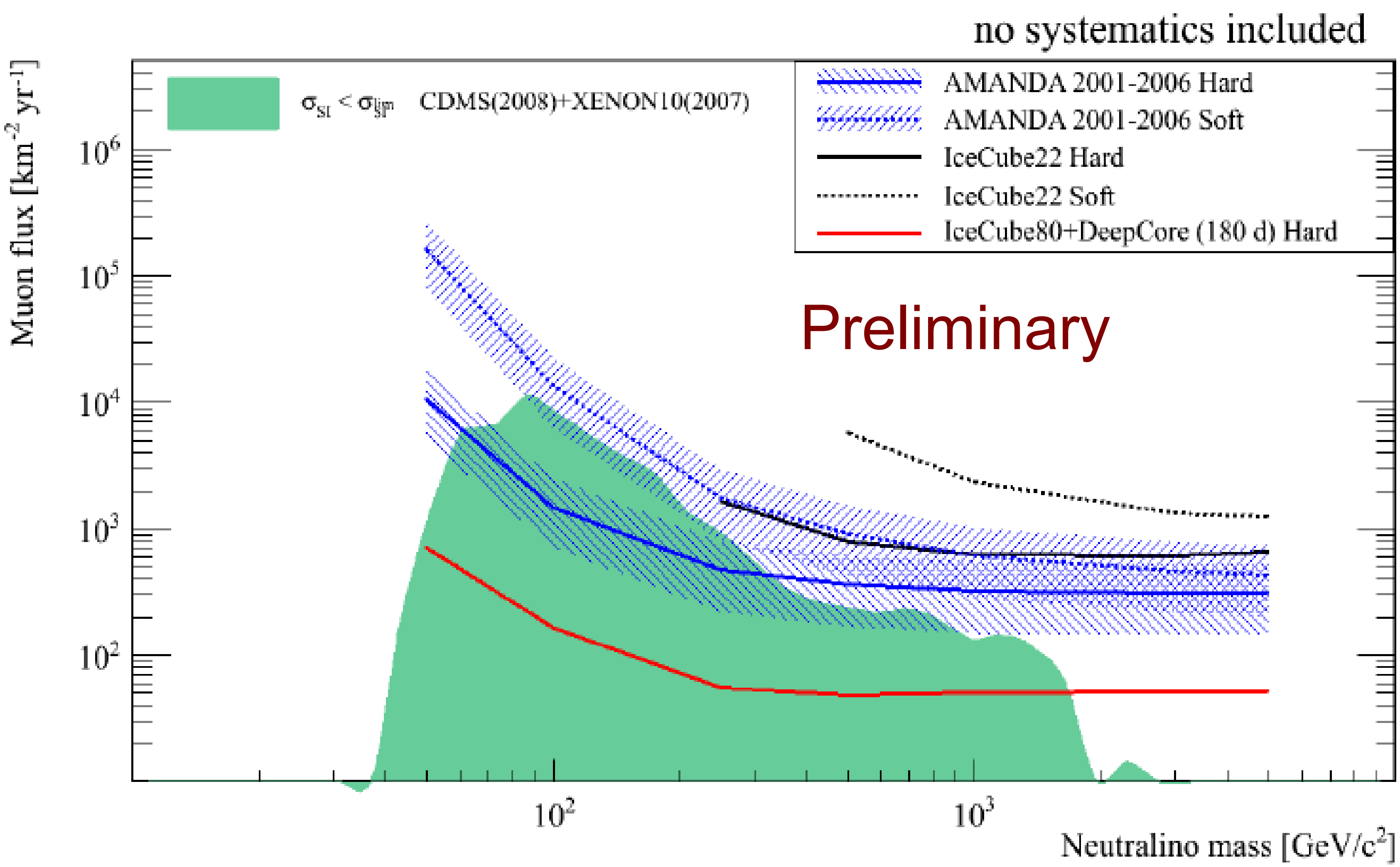
(From MC) (From off-source Data)

- Defined Log-LH ratio (FC approach , α=0.9)

$$R(\mu) = \frac{\mathcal{L}(\mu)}{\mathcal{L}(\hat{\mu})} \qquad \mathcal{L}(\mu) = \prod_{i=1}^{n_{obs}} f(\psi_i|\mu)$$

$$\Gamma^{90\%}_{\nu\to\mu} = \frac{\mu^{90\%}}{V_{eff} \cdot T_{live}} \qquad \phi^{90\%}_{\mu}(E_\mu \geq E_{thr}) = \frac{\Gamma^{90\%}_A}{4\pi r^2_\odot} \int_{E_{thr}}^{\infty} dE_\mu \frac{dN}{dE_\mu}$$

AMANDA 6 years Sensitivity



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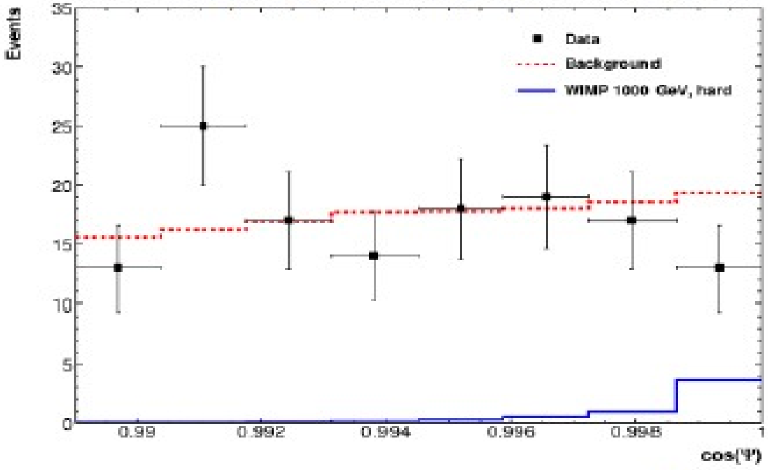
Limits IceCube 22

Abbasi et al., *Phys. Rev. Lett.* **102**, 201302 (2009)



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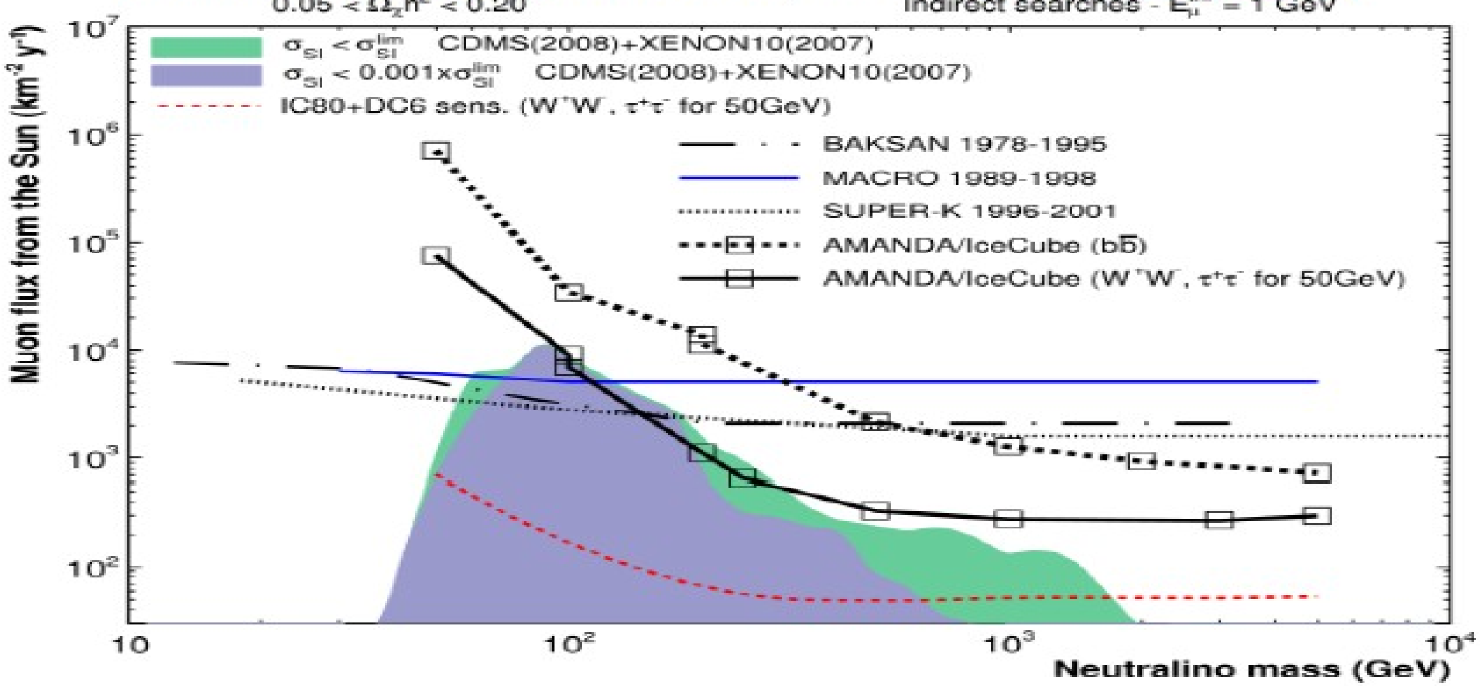
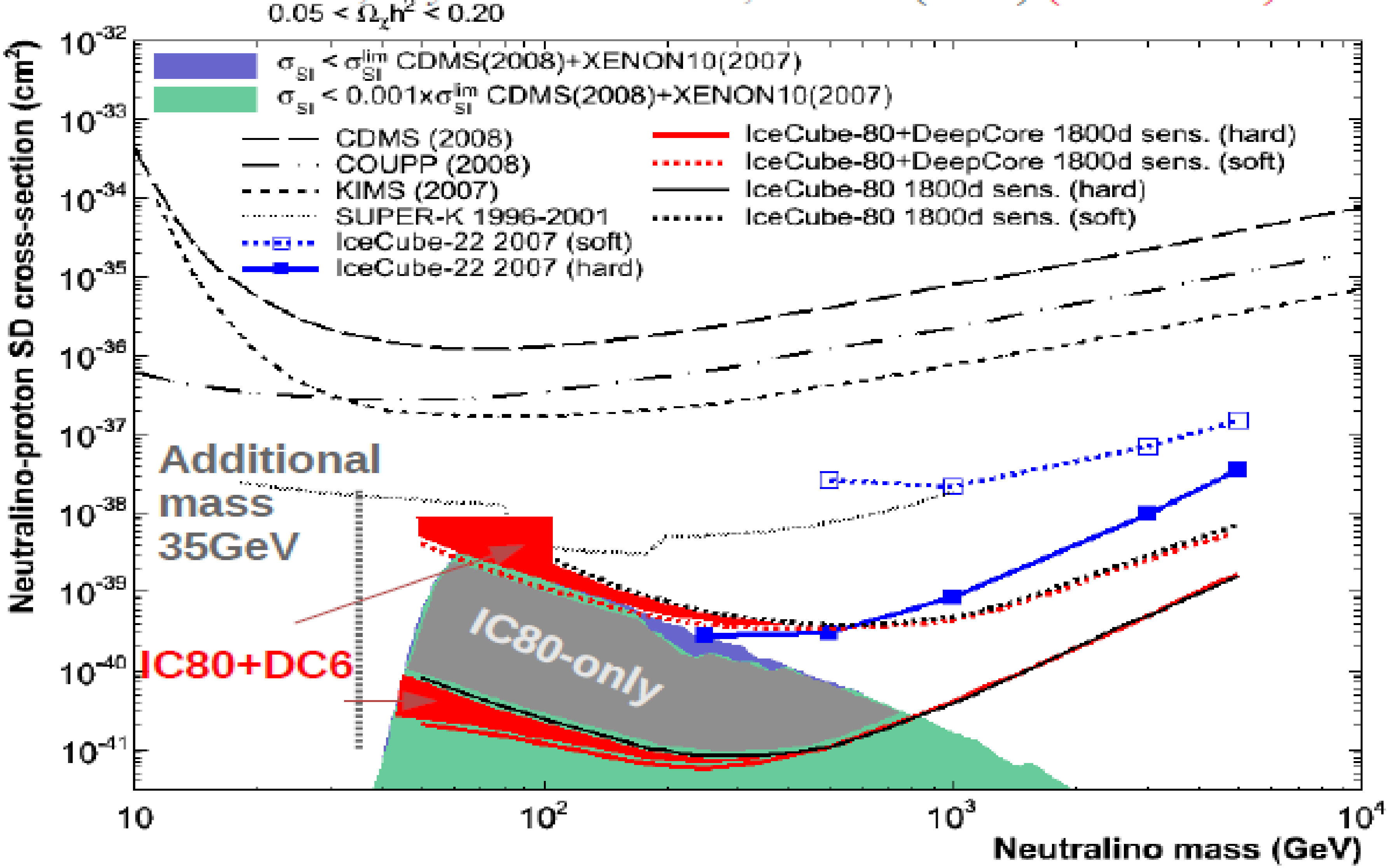
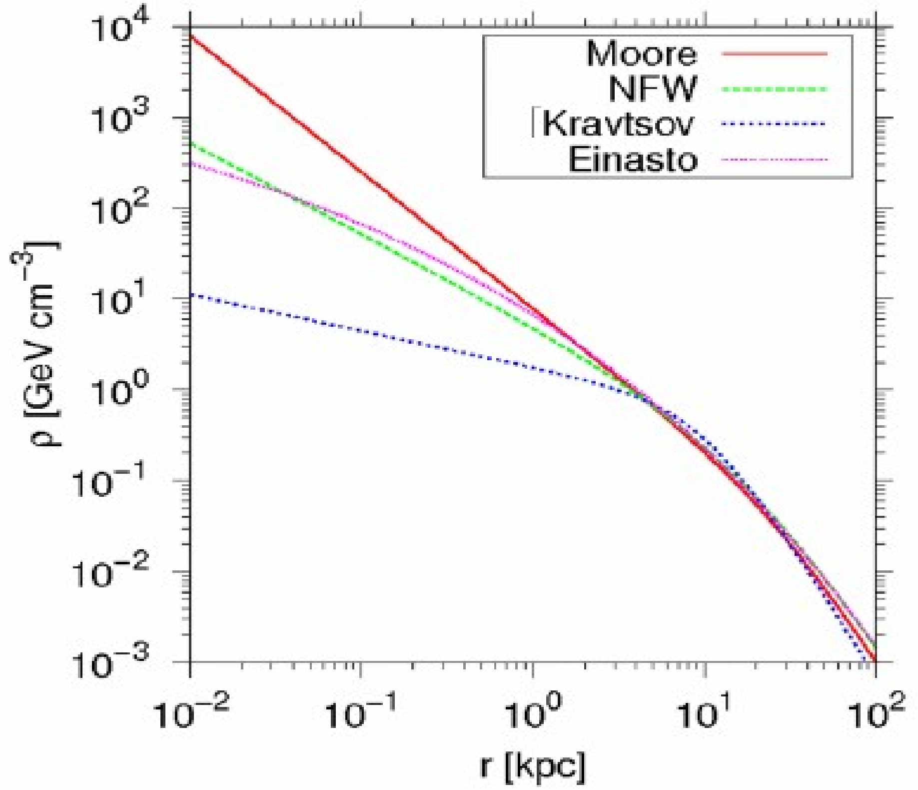


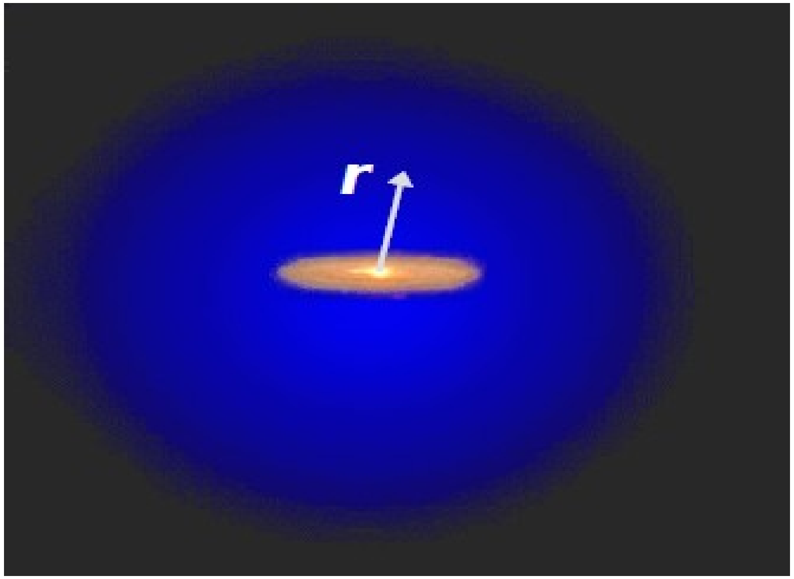
DeepCore Prospects

Abbasi et al., *Phys. Rev. Lett.* **102**, 201302 (2009) (IC22 result)



Dark Matter from the Galaxy





The remaining three profiles can be described by the following function:

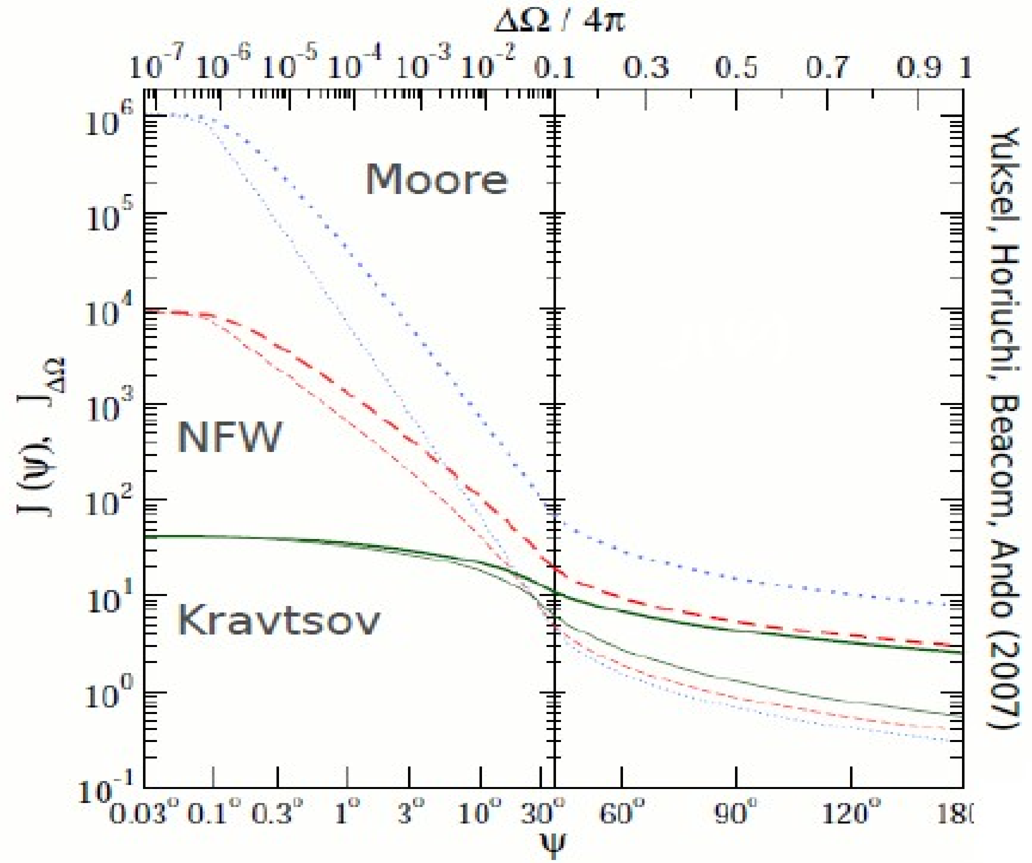
$$\rho(r) = \frac{\rho_0}{(\frac{r}{r_s})^\gamma \left[1 + (\frac{r}{r_s})^\alpha\right]^{(\beta-\gamma)/\alpha}}$$

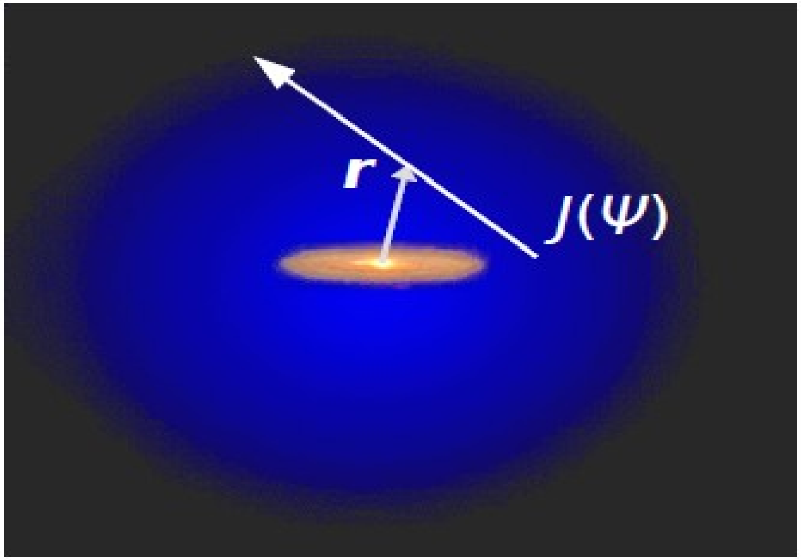
benchmark model

Einasto profile is given by:

$$\rho(r) = \rho_{-2} \times e^{(-\frac{2}{\alpha})\left[\left(\frac{r}{r_{-2}}\right)^\alpha - 1\right]}$$

with $\alpha = 0.16$ [17], $r_{-2} = 20$ kpc, and ρ_{-2} normalized to the dark matter density,





$$J(\psi) = \int_0^{l_{max}} \rho^2 \left(\sqrt{R_{sc}^2 - 2lR_{sc}\cos\psi + l^2}\right) \frac{}{R_{sc}\rho_{sc}^2} dl$$

Line of sight integral

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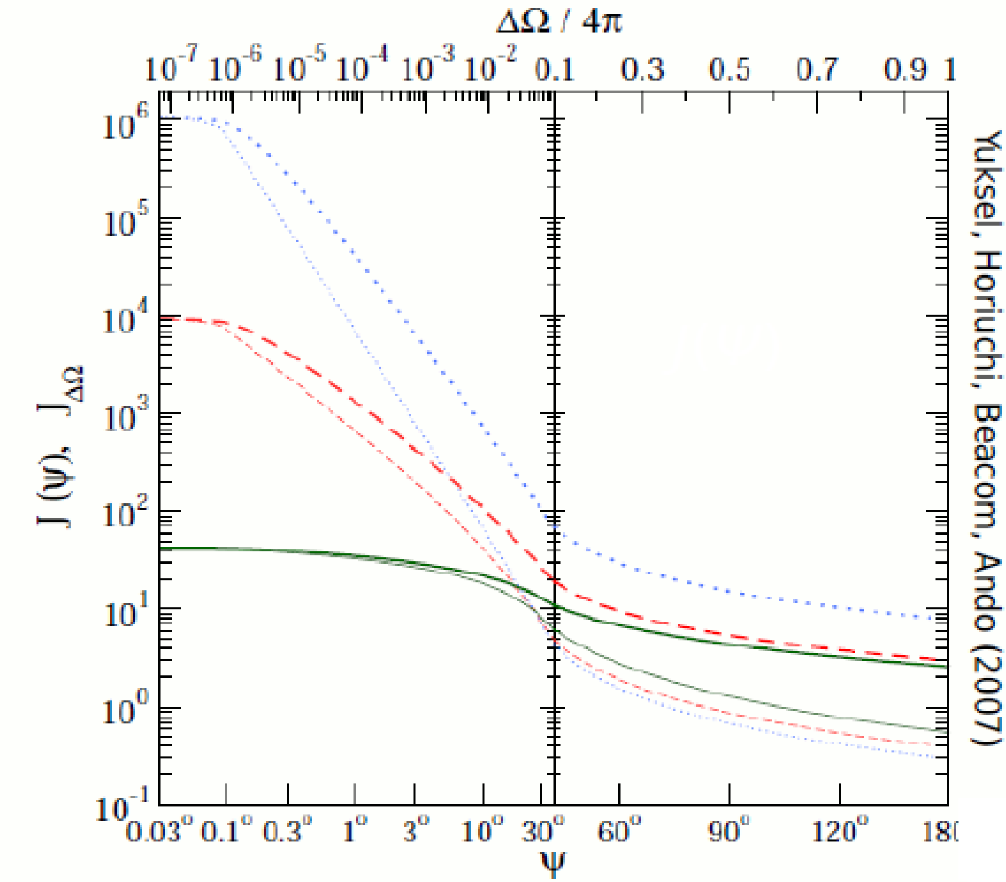


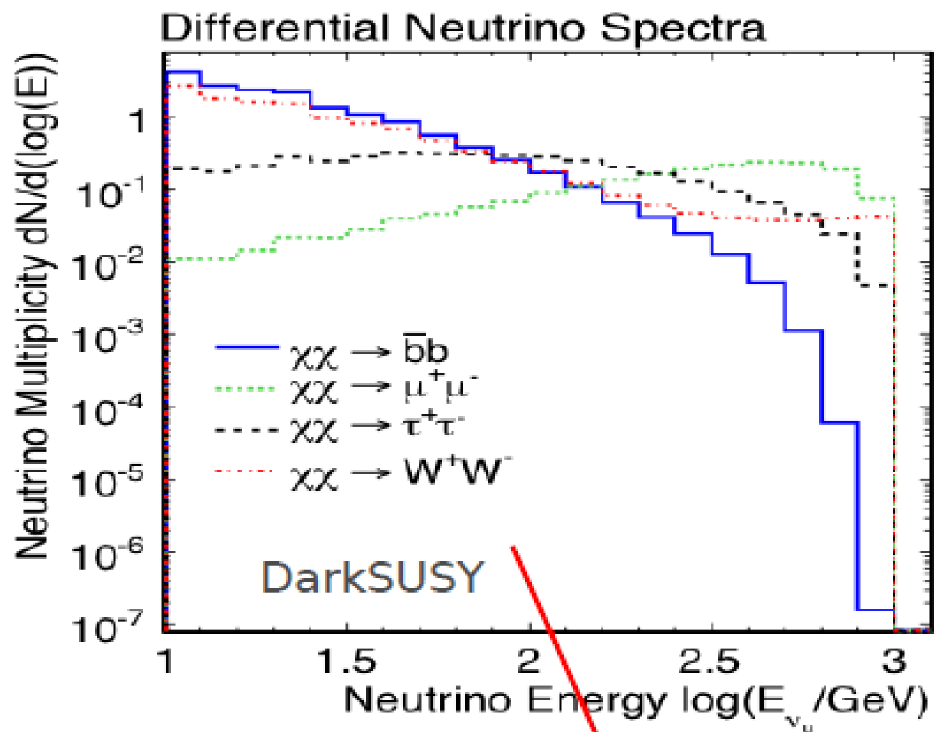


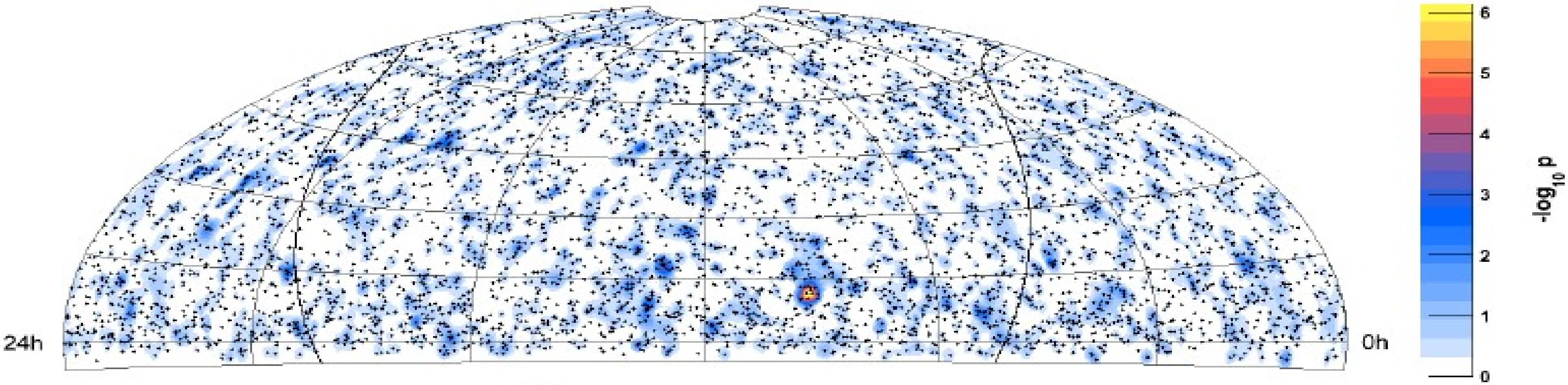
FIG. 2. Differential neutrino multiplicity per annihilation dN_ν/dE as an example for a WIMP mass of 988 GeV. The sum of all neutrino flavors at creation is plotted.

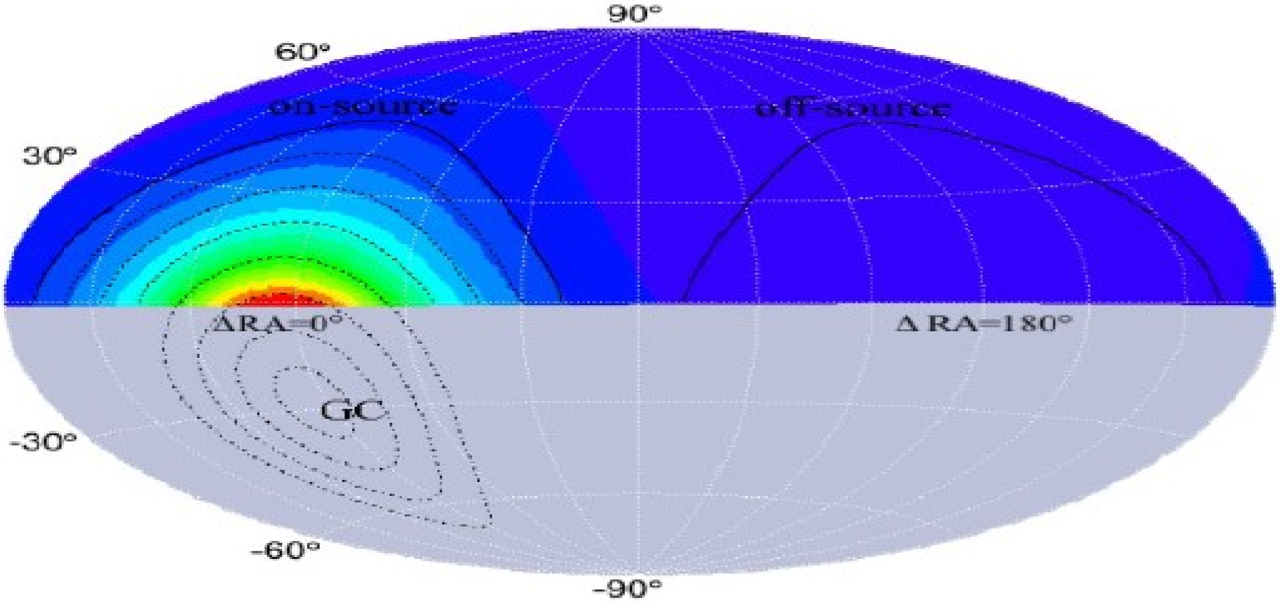
Line of sight integral

$$J(\psi) = \int_0^{l_{max}} \frac{\rho^2\left(\sqrt{R_{sc}^2 - 2lR_{sc}\cos\psi + l^2}\right)}{R_{sc}\rho_{sc}^2}\, dl$$

$$\frac{d\phi_\nu}{dE} = \frac{<\sigma_A v>}{2} J(\psi) \frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2} \frac{dN_\nu}{dE}.$$

IC-22 Point Source Search, ApJL 701, 47 (2009)

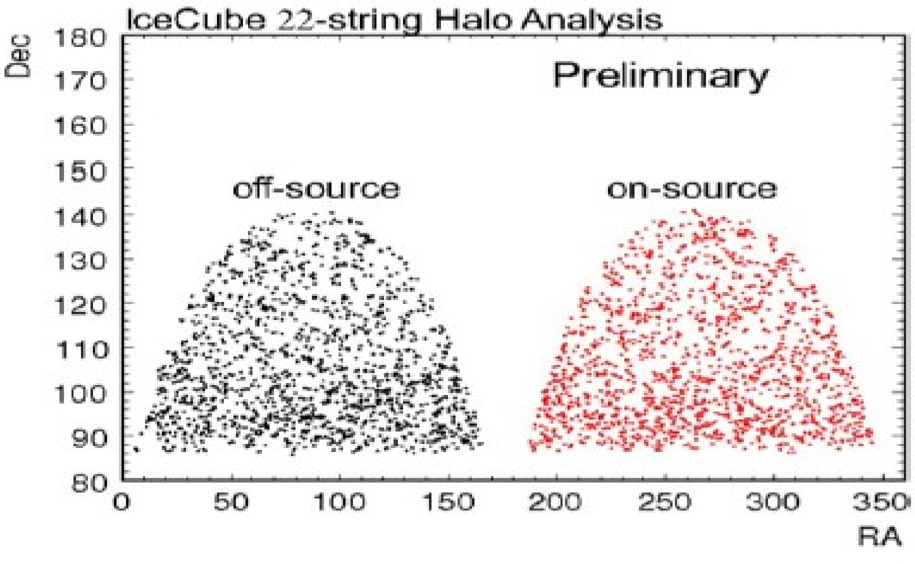




S / sqrt(B) no longer improves past **80° from Galactic Center** (zenith)

275.70 days livetime after selecting good runs.

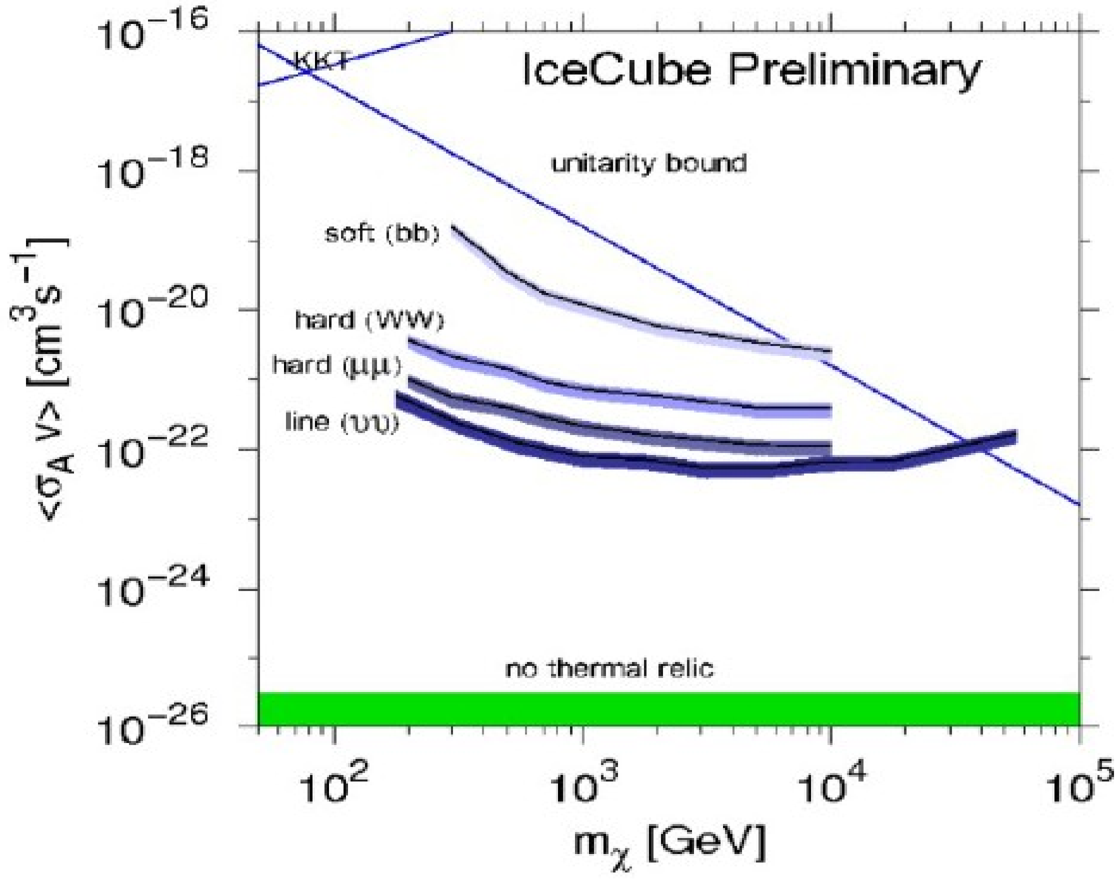
5114 selected events



Result: no excess in on-source region found, compared with off-source region.

Upper Limits: different curves represent dN/dE for different annihilation channels; thickness of curves is range due to different halo models

IC22-string result



crucial for GC analysis is effective veto for downgoing muon events and identify starting tracks within IceCube

Arxiv:0912.5183 See also J.Huelss, DPG

Result: no excess in on-source region found, compared with off-source region.

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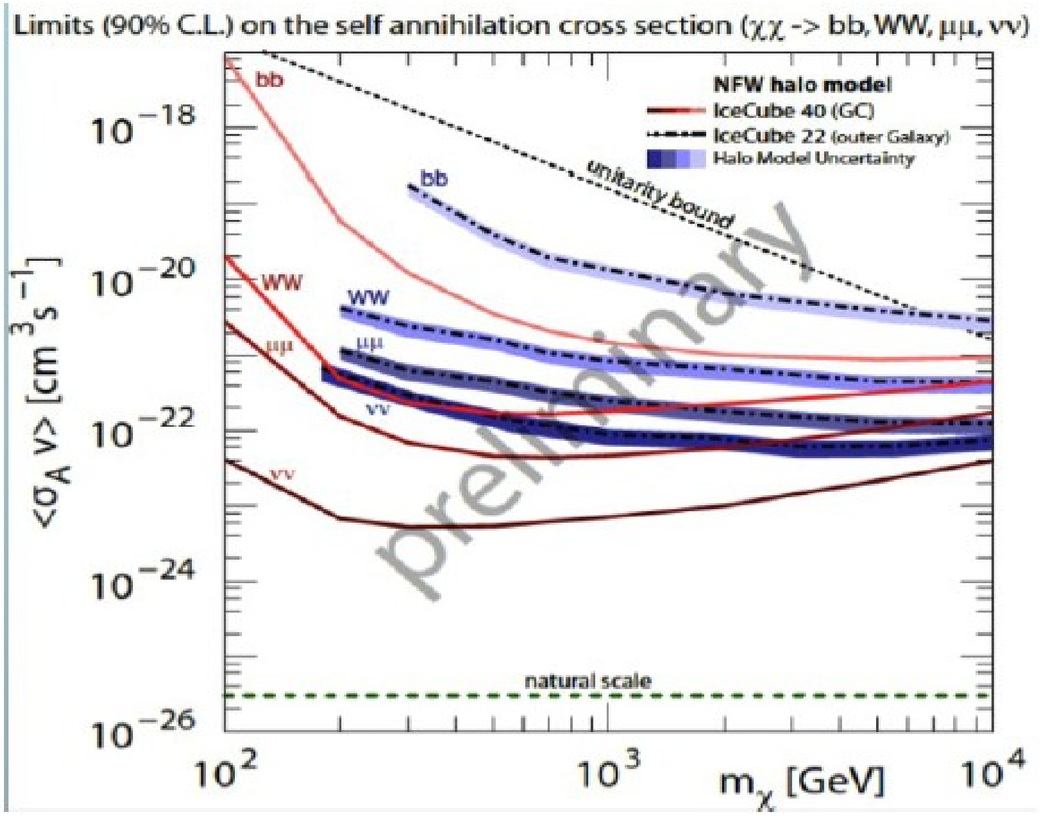
IC22-string result & IC40-string GC



Conclusion and Outlook

- Indirect searches with neutrinos can probe WIMP-nucleon scattering cross section (SUN) and the self-annihililation cross section (GC/GH)
- Final AMANDA 6 years analysis now finished
  - more sensitivite for low energies!
- First IceCube analyses completed (22, 40 strings)
- IceCube + DeepCore nearing completion
  - 79 string data taking and analysis have begun
  - New low energy triggers, filters, and reconstructions
  - Full year searches possible with active veto
  - Increased sensitivity to searches for low mass WIMPs (30-100 GeV)

Thanks!

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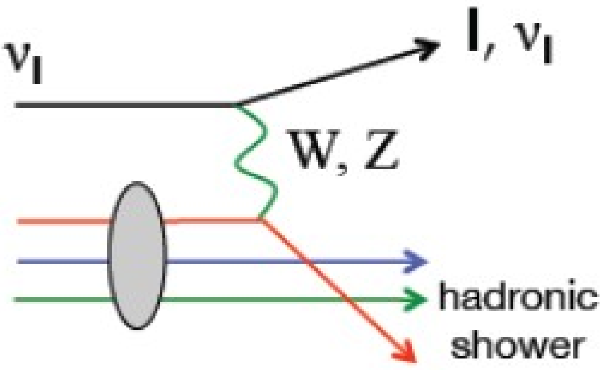
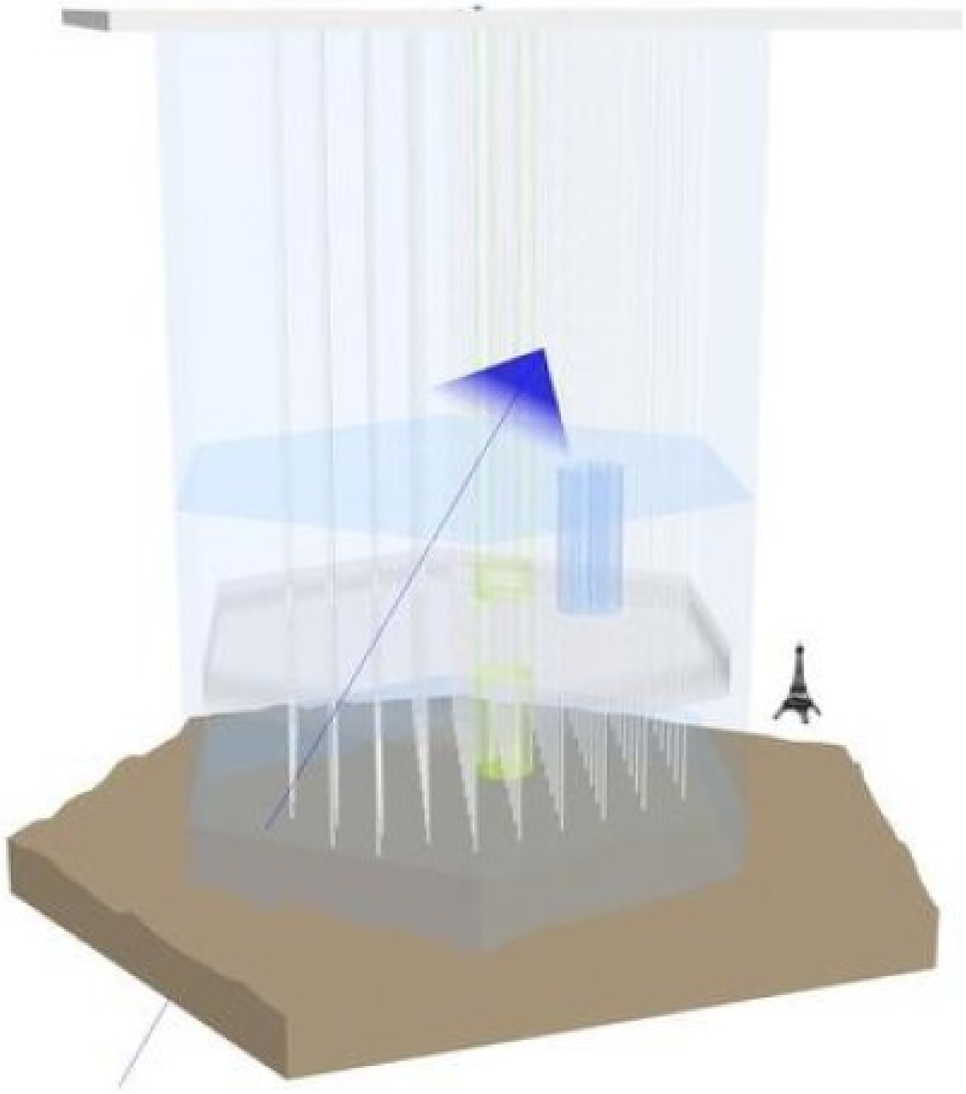
Backup slides

Neutrino detection



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



Uncertainties

- Statistics

$$\Gamma^{90\%}_{\nu\rightarrow\mu} = \frac{\mu^{90\%}}{V_{eff}\cdot T_{live}} \propto \Gamma_A, \Phi_\mu, \sigma$$

  - μ < 1 % (from statistical study)
  - V_{eff} 1-2 % (from MC, weight into account)
- Systematics
  - V_{eff}:

    1) Neutrino oscillation (from MC study)
    2) Neutrino-nucleon cross section (from literature)
    3) Tau neutrinos (from MC study)
    4) Muon propagation in ice (from literature)
    5) Ice + OM sensitvity (from MC study)
    6) Time and geometry calibration (from MC study)
    7) Possible Data-MC rate disagreement (from statistical study)

Total relative error on V_{eff}:

$$\frac{\Delta V}{V} = \sqrt{\sum_i \left(\frac{\Delta V}{V}\right)^2_i}$$

Total relative error on Γ:

$$\pm\frac{\Delta\Gamma}{\Gamma} = \sqrt{\left(\frac{\Delta\mu}{\mu}\right)^2 + \left(\frac{\Delta V}{V}\right)^2\left(\frac{1}{1\mp\frac{\Delta V}{V}}\right)^2}$$

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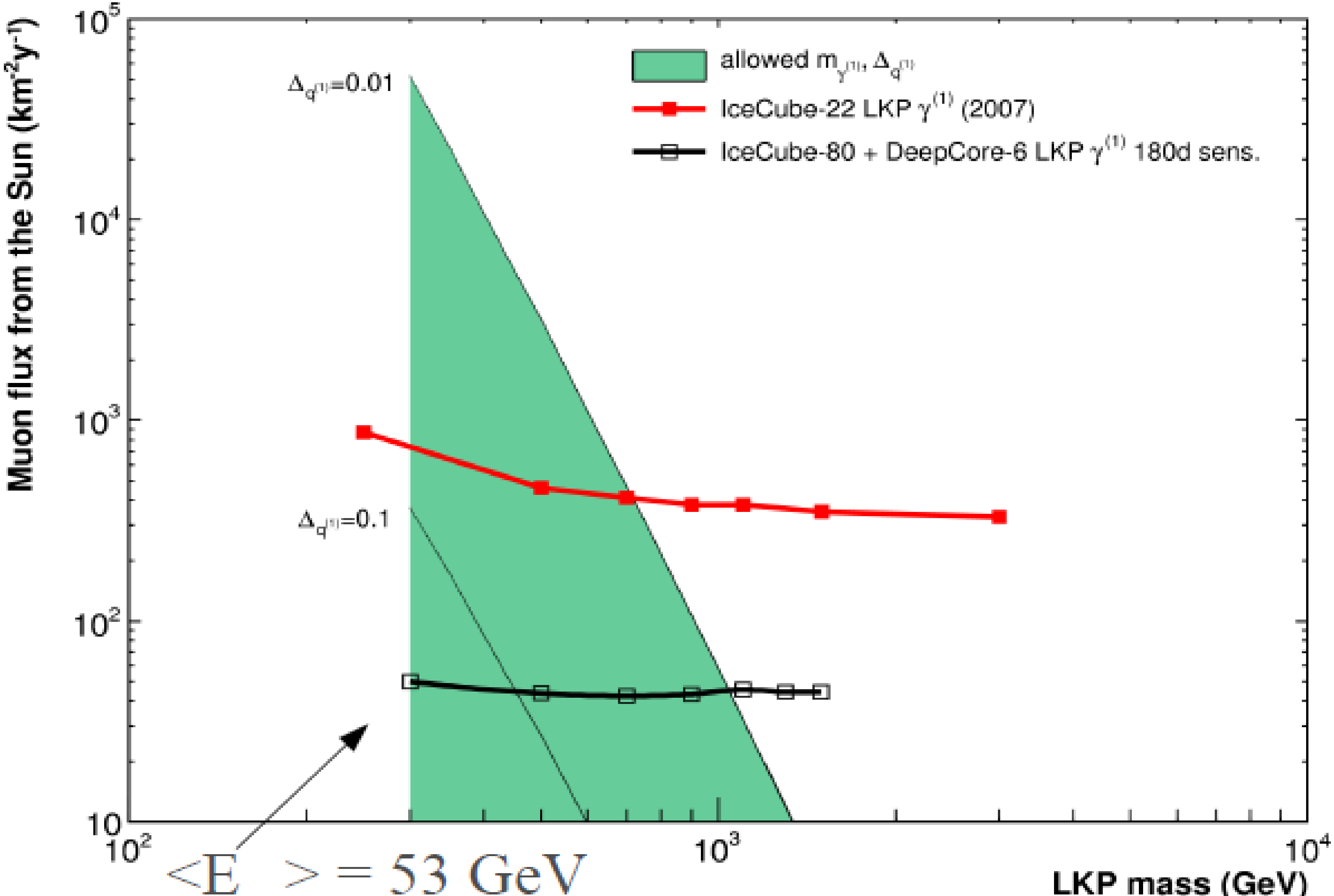
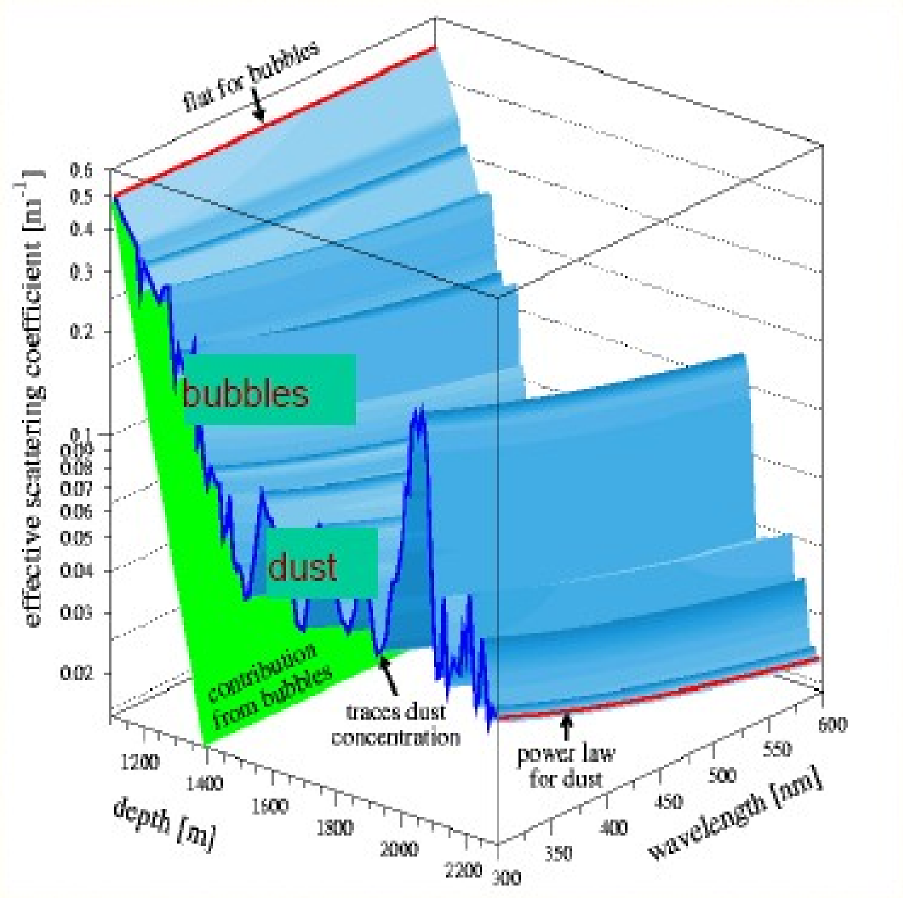


$<E_{\nu\mu}> = 53$ GeV

Ice Properties

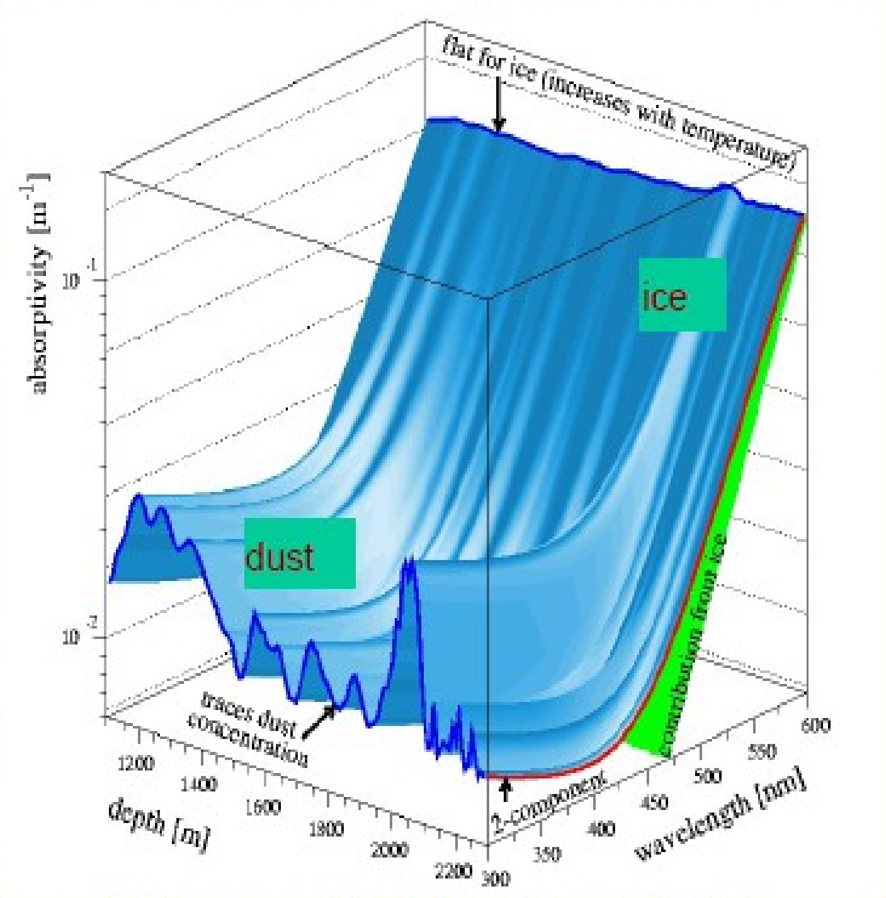
Scattering



Measurements:

- **in-situ light sources**
- **atmospheric muons**

Absorption



Average optical ice parameters:

λ_{abs} ~ 110 m @ 400 nm

λ_{sca_eff} ~ 20 m @ 400 nm