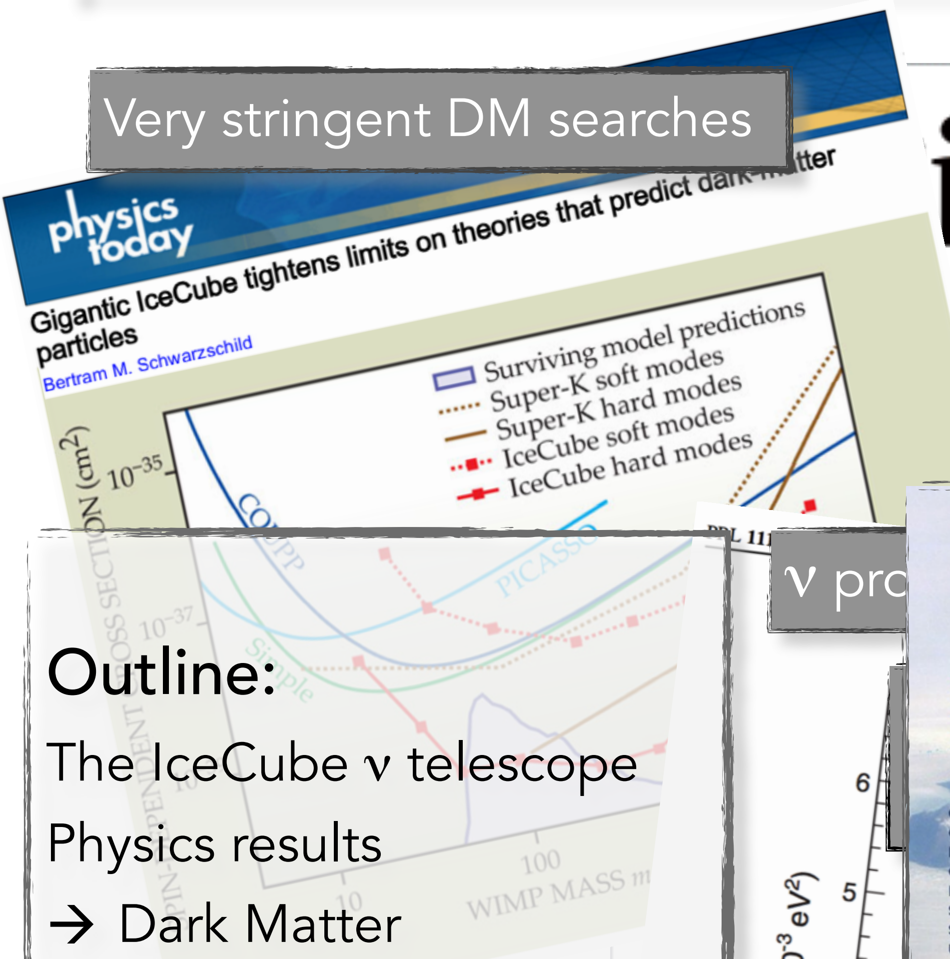
Recent Highlights from IceCube

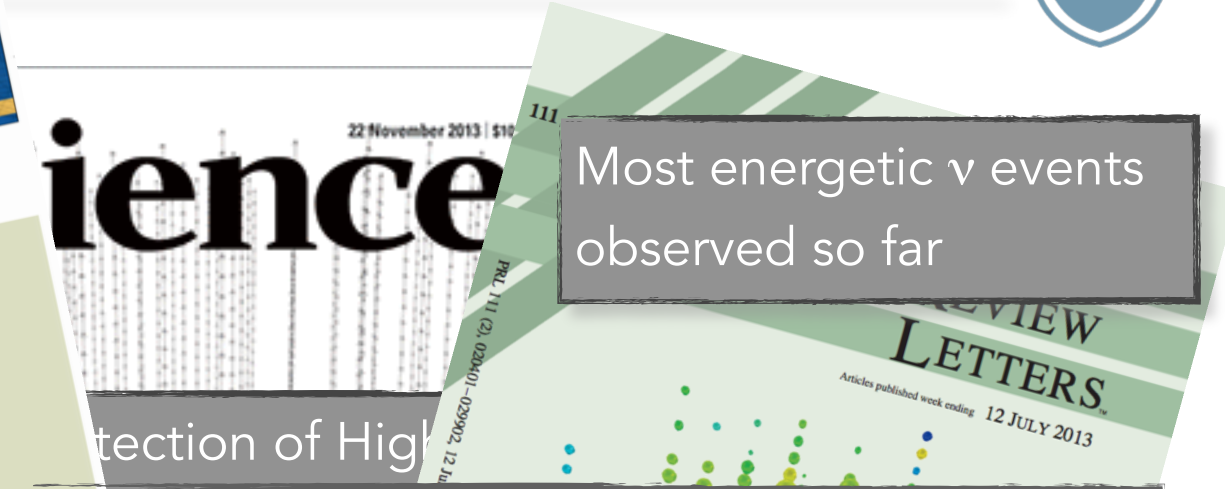
— with a focus of Dark Matter Searches —

Matthias Danninger, University of British Columbia

Overview

Very stringent DM searches

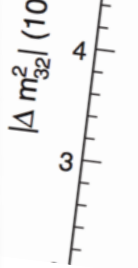




Most energetic ν events observed so far

tection of High

ν pro



Outline:

The IceCube ν telescope

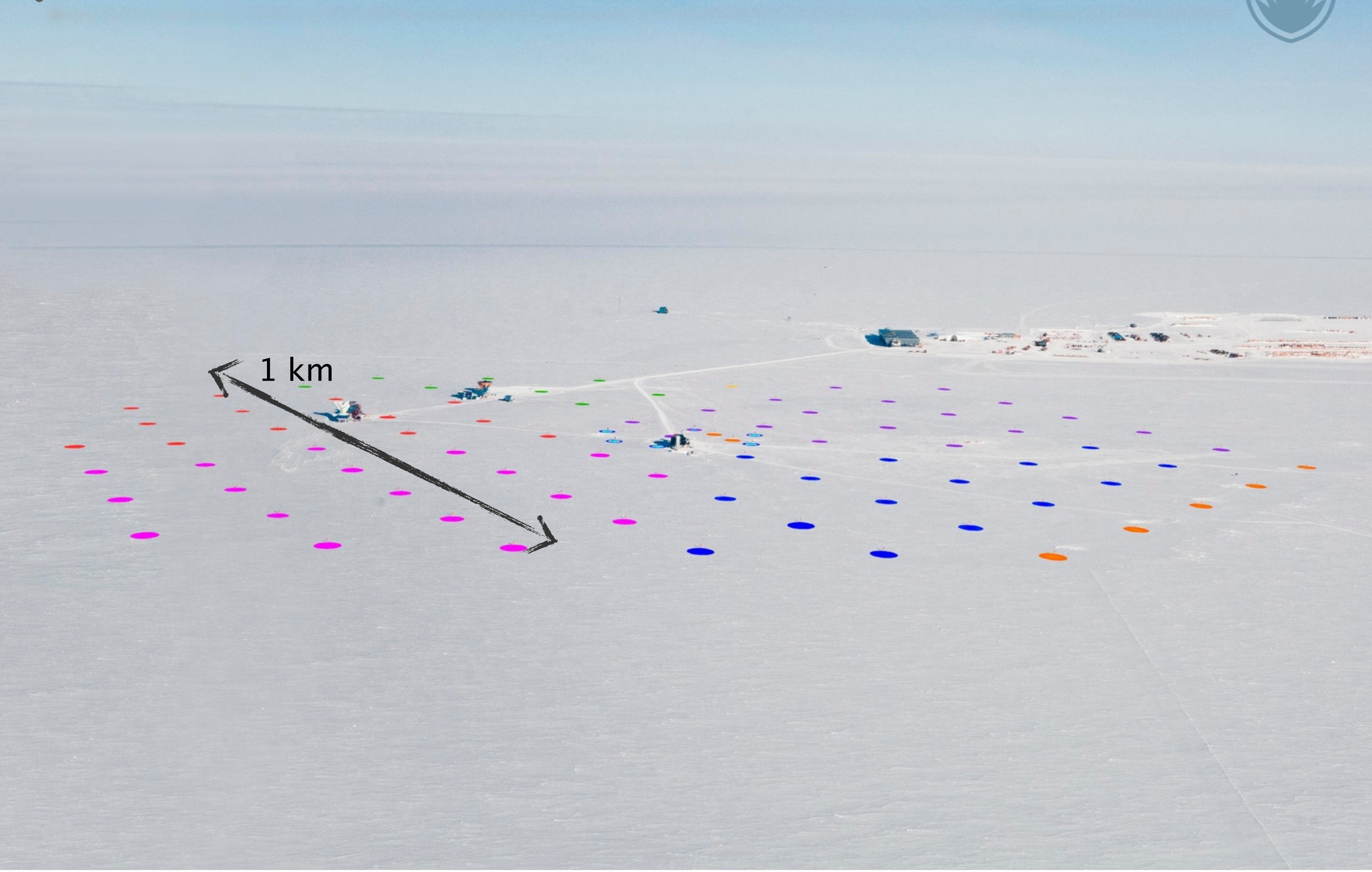
Physics results

→ Dark Matter

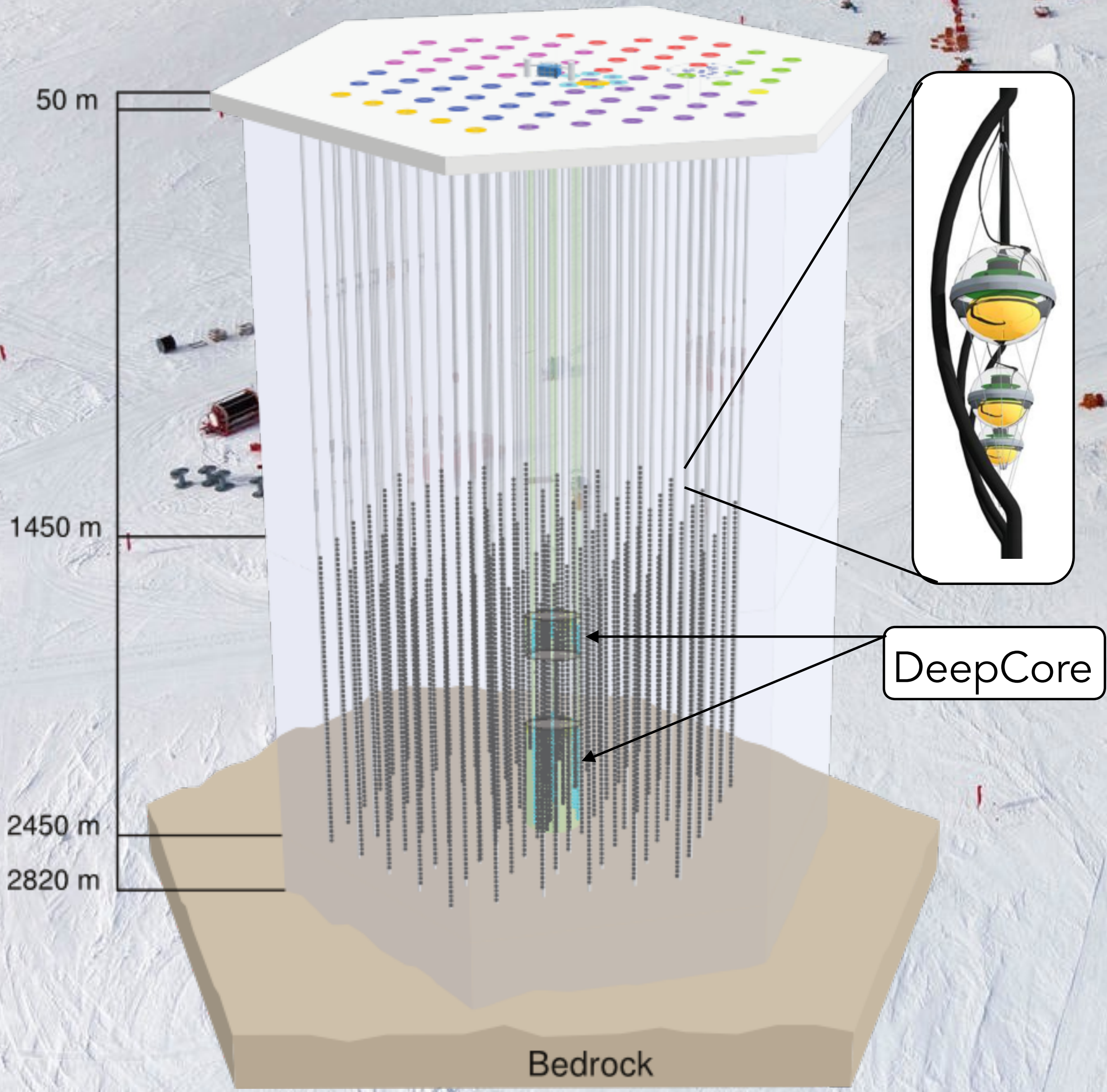
→ Observation of Astrophysical ν

→ ν oscillation & PINGU

IceCube at the South Pole

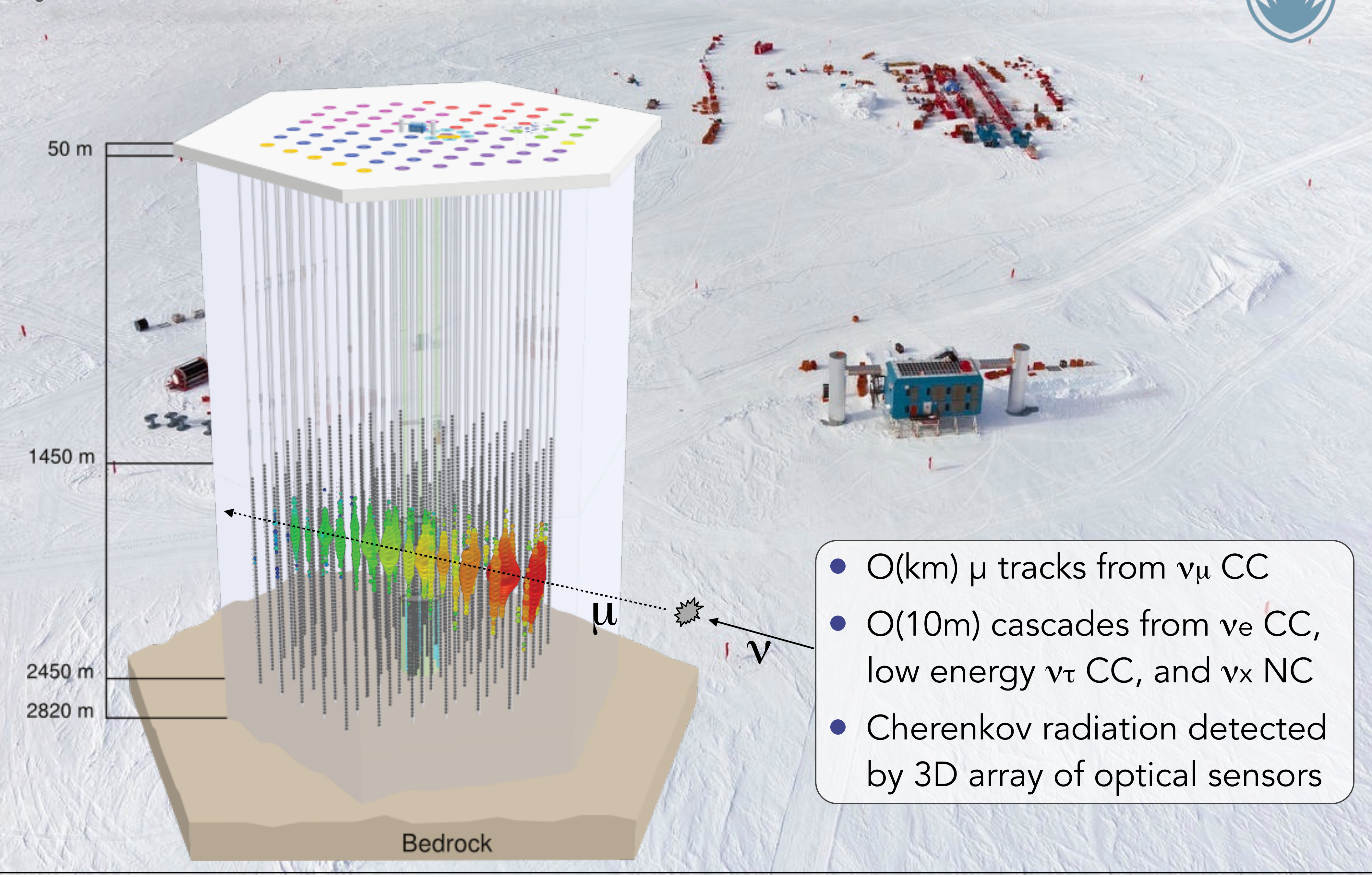


IceCube at the South Pole



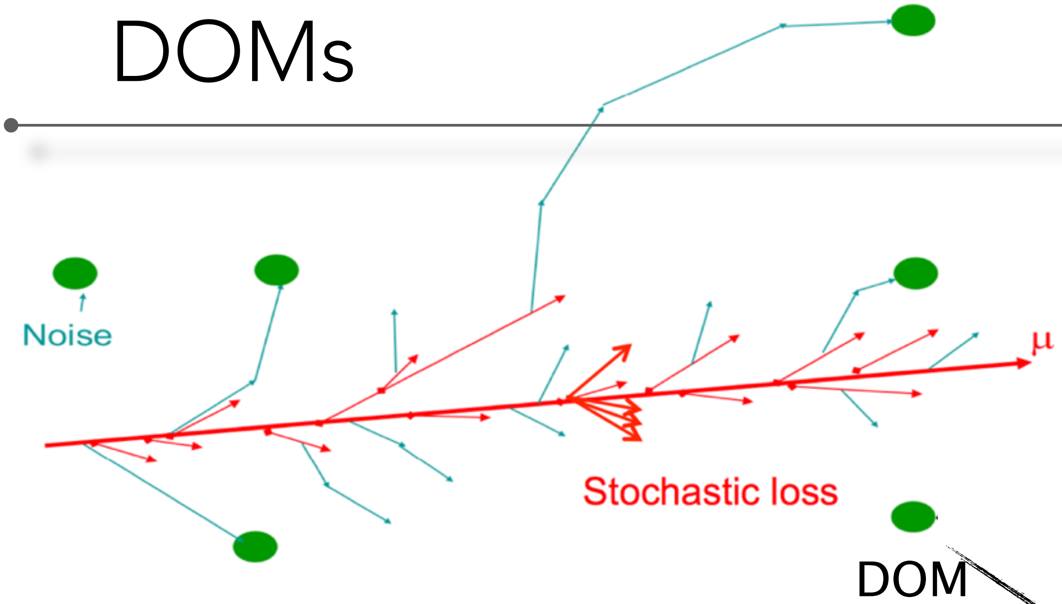
- 1.5 km – 2.5 km deep
- typically 125 m spacing between strings (~70 m in DeepCore)
- 60 Modules per string
- 1 km^3 – 1 Gton instr. volume

IceCube at the South Pole



- 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

DOMs



- Charged particles produce radiation from ionizations and stochastics in ice
- DOMs digitize the PMT waveforms of photoelectrons
- Arrival time and recorded charge information used to reconstruct events

PMT: Hamamatsu, 10"

Digitizers:

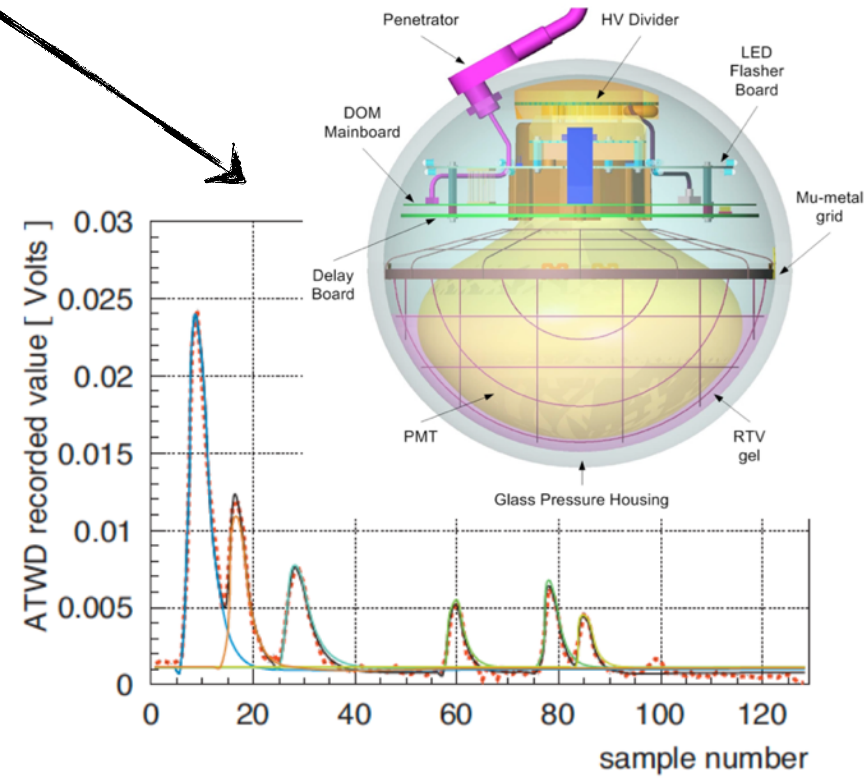
ATWD: 3 channels; sampling 300MHz, capture 400ns

FADC: sampling 40 MHz, capture 6.4 μs

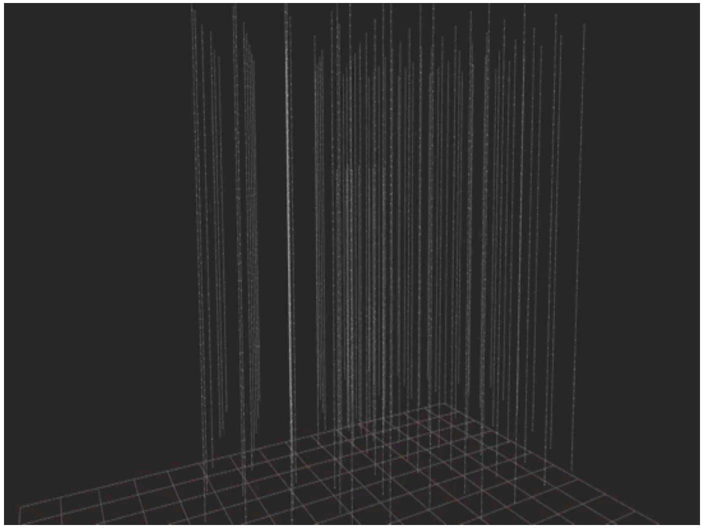
Flasher board:

12 controllable LEDs at 0 or 45 degrees

Dark Noise rate ~ 400 Hz
Local Coincidence rate ~ 15 Hz
Deadtime < 1%
Timing resolution ≤ 2-3 ns
Power consumption: 3W



Flavour identification (tracks & showers-cascades)



CC ν_μ interaction create μ

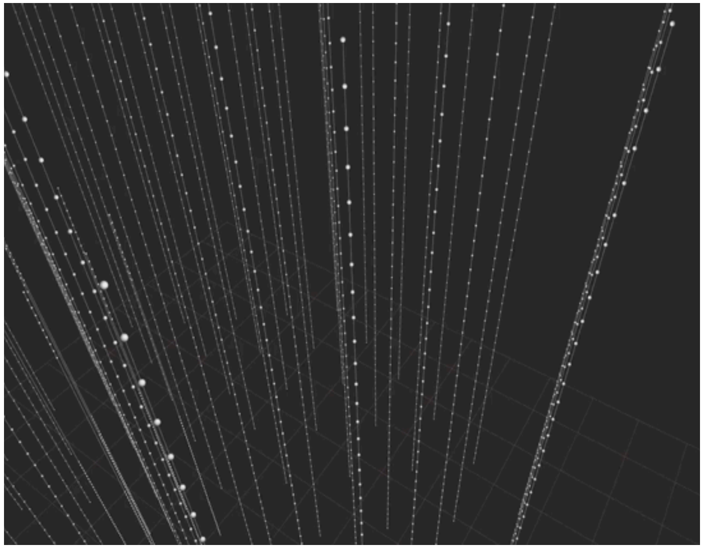
- can travel kilometres

Angular reconstruction

- can be as good as ~ 0.2°

Energy reconstruction

- only lower bound;
- most energy deposited outside the detector



CC $\nu_{\tau,e}$ interaction & NC ν_x interaction

- τ,e travel short distances
- NC: Hadron showers + ν

Angular reconstruction

- more difficult, more accurate with higher energy

Energy reconstruction

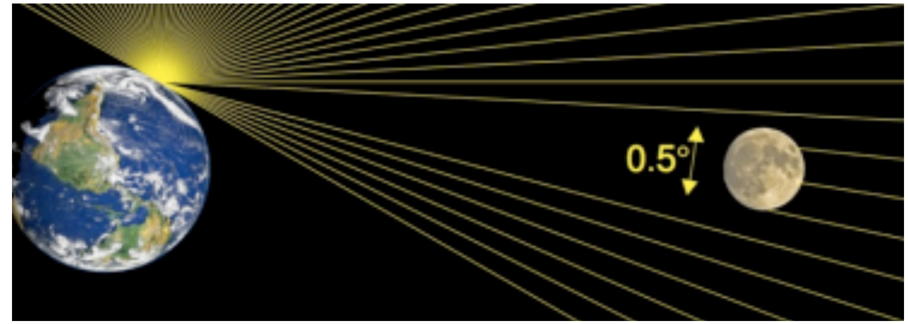
- ~10% for deposited E; less than E_ν if NC

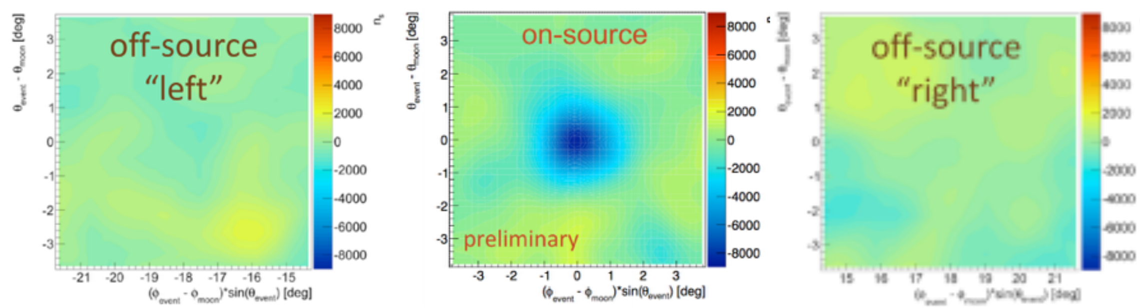
Calibration

Physical Review D89 (2014) 102004

Calibration Sources:

- LED Flasher on each DOM
- In-Ice Calibration Laser
- Cosmic Ray Energy Spectrum
- *Moon Shadow*
- Atmospheric Neutrino Energy Spectrum
- Minimum-Ionizing Muons

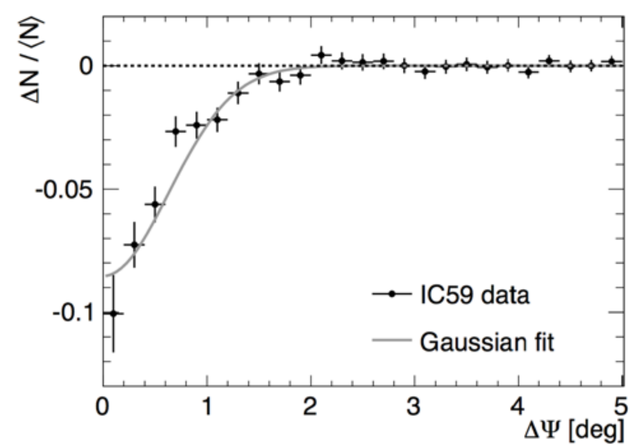




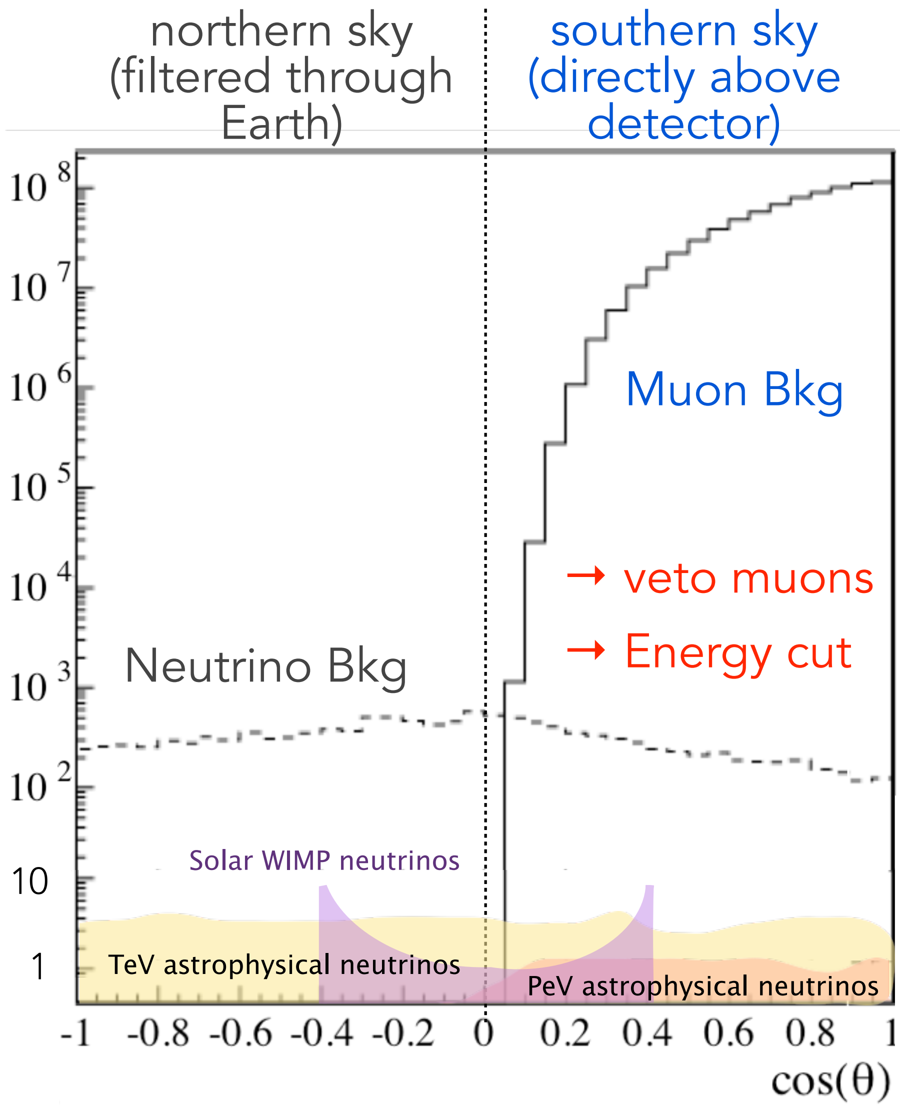
Moon Shadow in Cosmic Ray muons in IceCube (14σ)

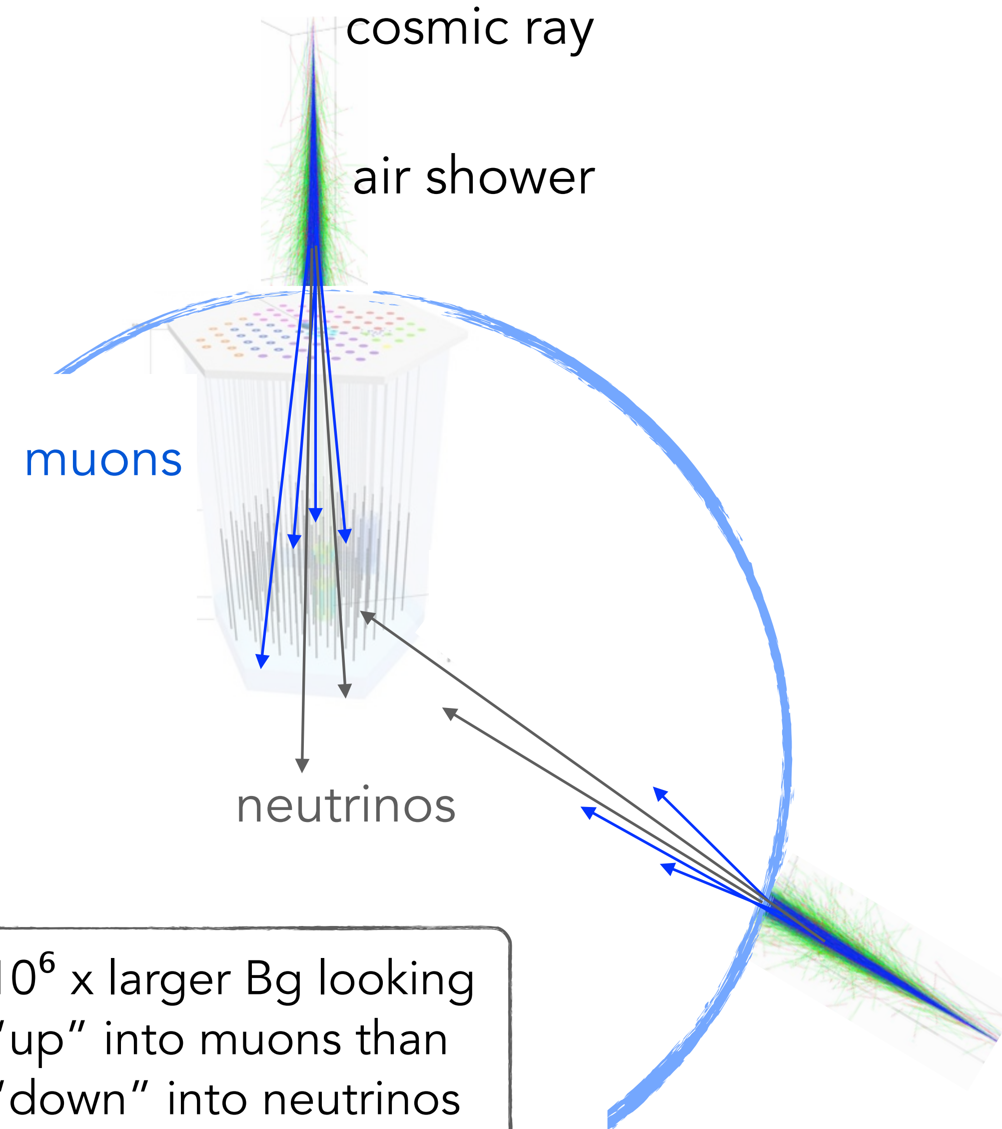
Resolution

Shadow profile vs. angular distance from the Moon



Cosmic Ray Background in IceCube





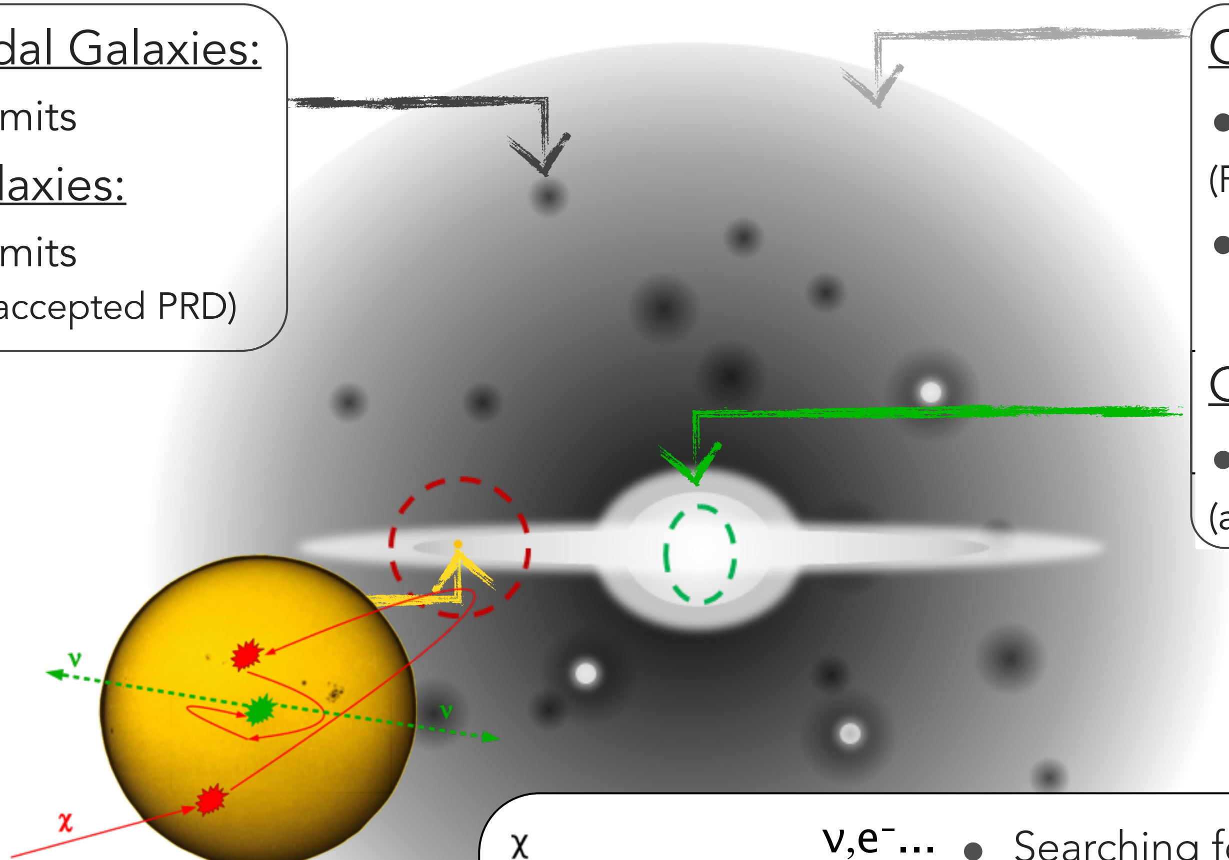
10^6 x larger Bg looking "up" into muons than "down" into neutrinos

(neutrino signal examples for illustration only)

Results from Dark Matter Searches with IceCube & DeepCore

Indirect Search with IceCube (Overview)

(Image: M.Strassler)



Dwarf spheroidal Galaxies:

- IceCube-59 limits

Clusters of Galaxies:

- IceCube-59 limits

(arXiv:1210.3557, accepted PRD)

Galactic Halo:

- IceCube-22 limits

(PRD 84 (2011) 022004)

- IceCube-79 limits

Galactic Center:

- IceCube-40 limits

(arXiv:1210.3557 2012)

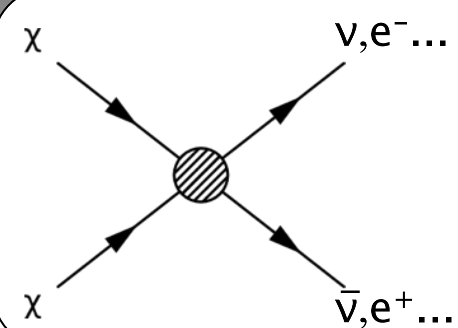
Local sources (Sun & Earth):

- IceCube-79 limits

(PRL 110 (2013) 131302)

- Specific models & Global fits

(JCAP 11 (2012) 057)



- 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 ($b\bar{b}$)

Solar Dark Matter Search with IceCube

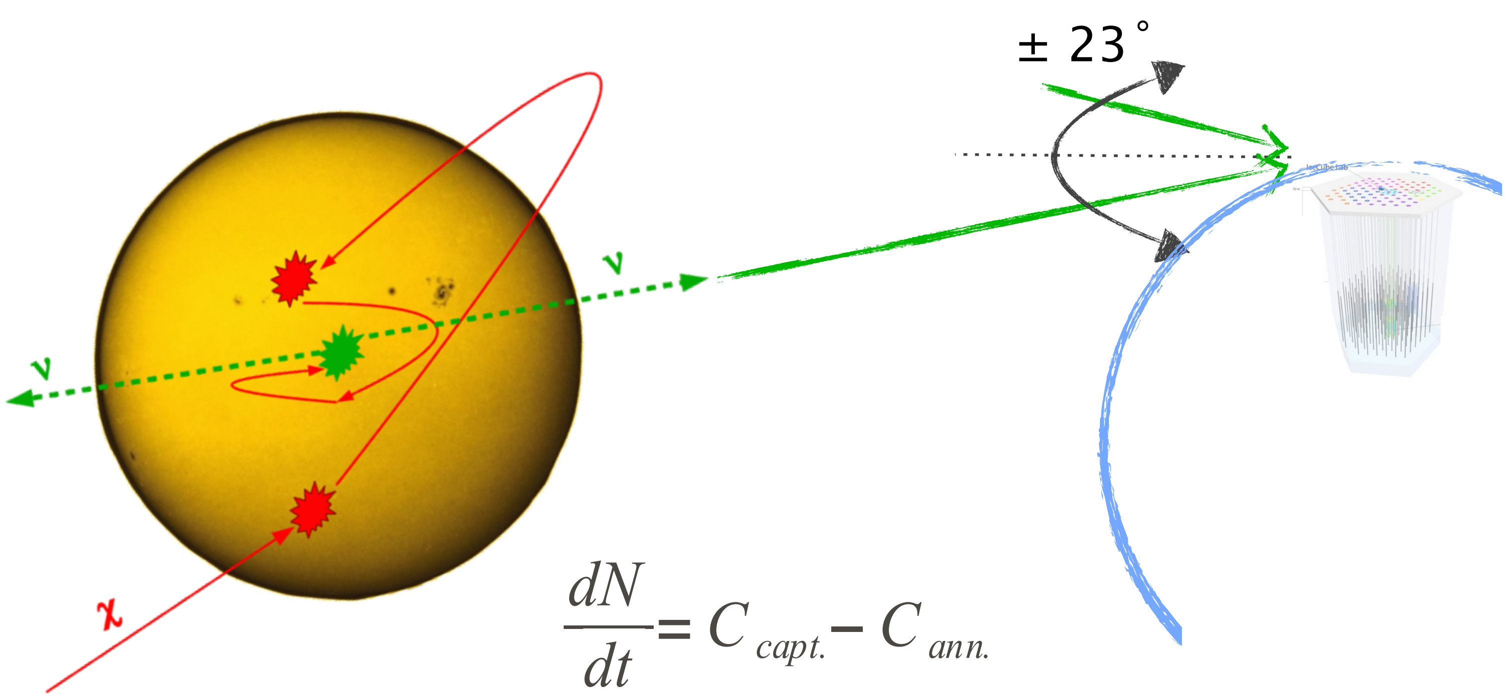
- All processes depend on WIMP mass
- Annihilation channel (branching ratios)
- Annihilation cross-section
- Capture (scattering)
  → Scattering cross-sections (SI & SD)

Proposed by:

Silk, Olive & Srednicki '85, Gaisser & Tilav 86, Freese '86, Krauss, Srednicki & Wilzcek '86

Details about Capture Process (e.g.):

Press & Spergel '85, Gould '88, Peter 2008
Sivertsson & Edsjö, PRD85 (2012) 123514

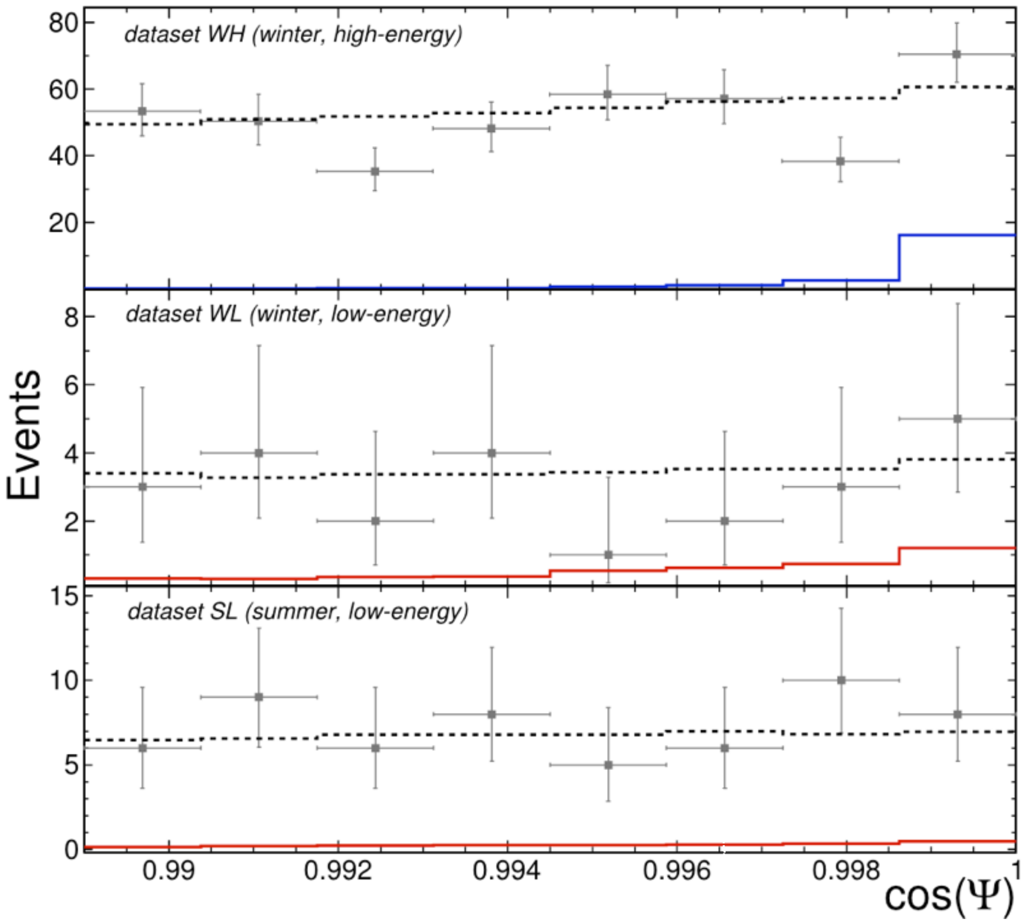


$$\frac{dN}{dt} = C_{capt.} - C_{ann.}$$

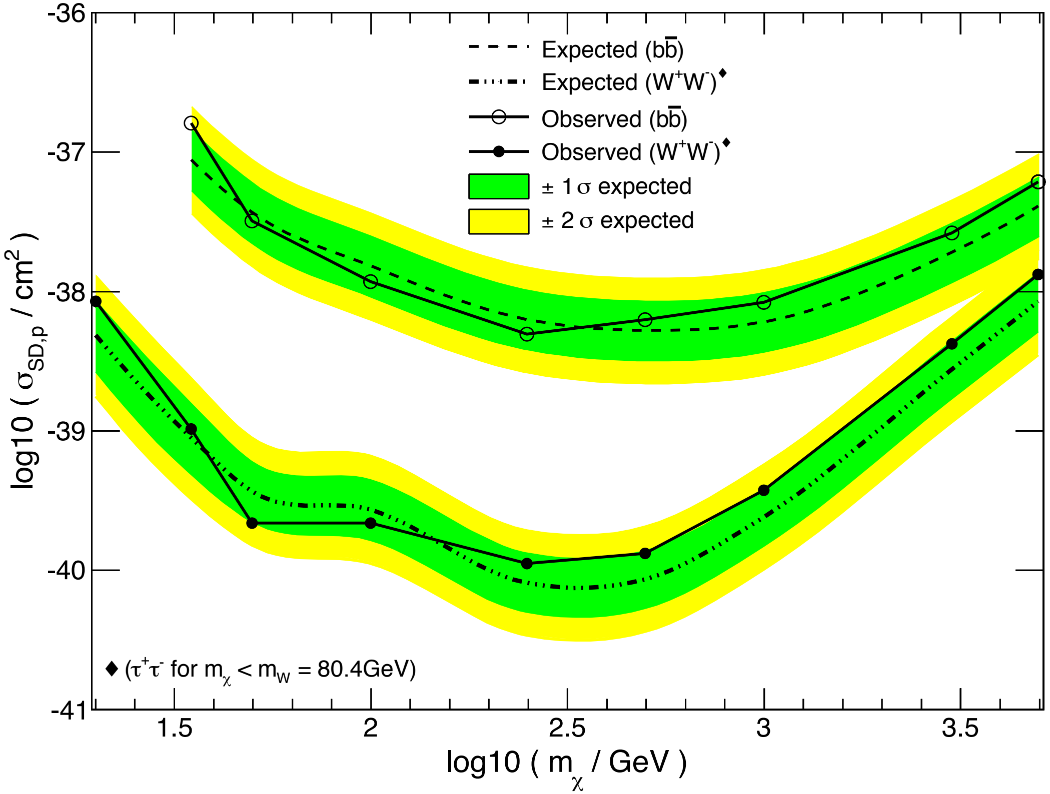
$$C_{ann.} = C_{capt.} \rightarrow \sigma_{total}$$

Solar Dark Matter Search - results

Unblinded events in different samples



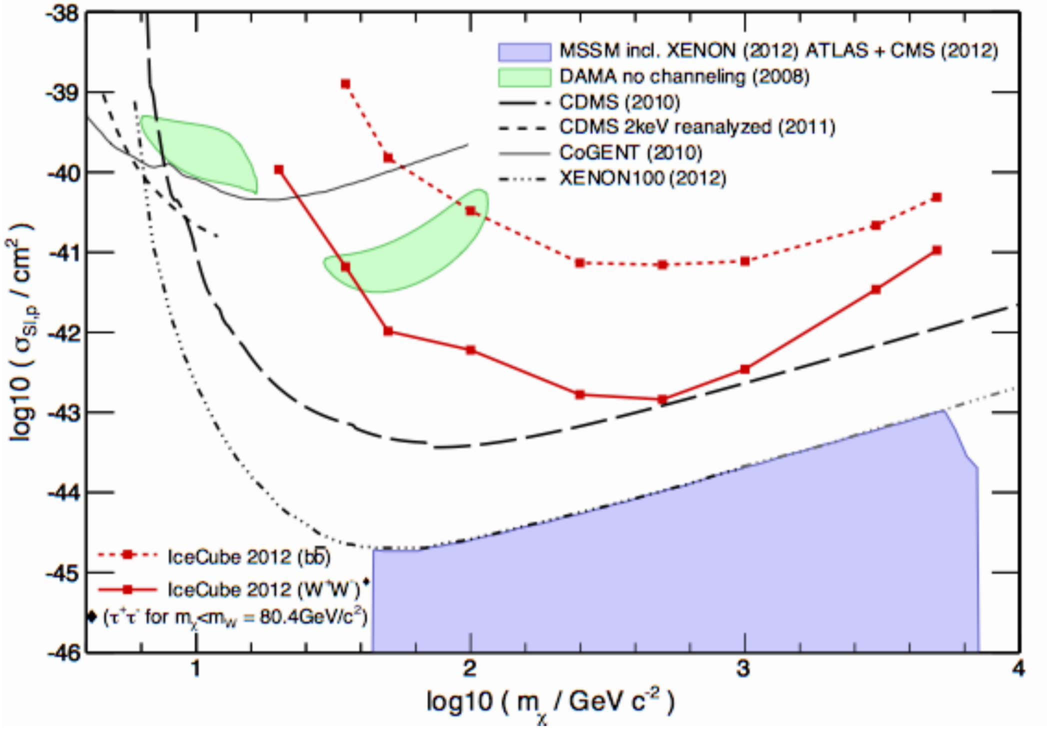
Expected sens. vs. observed result



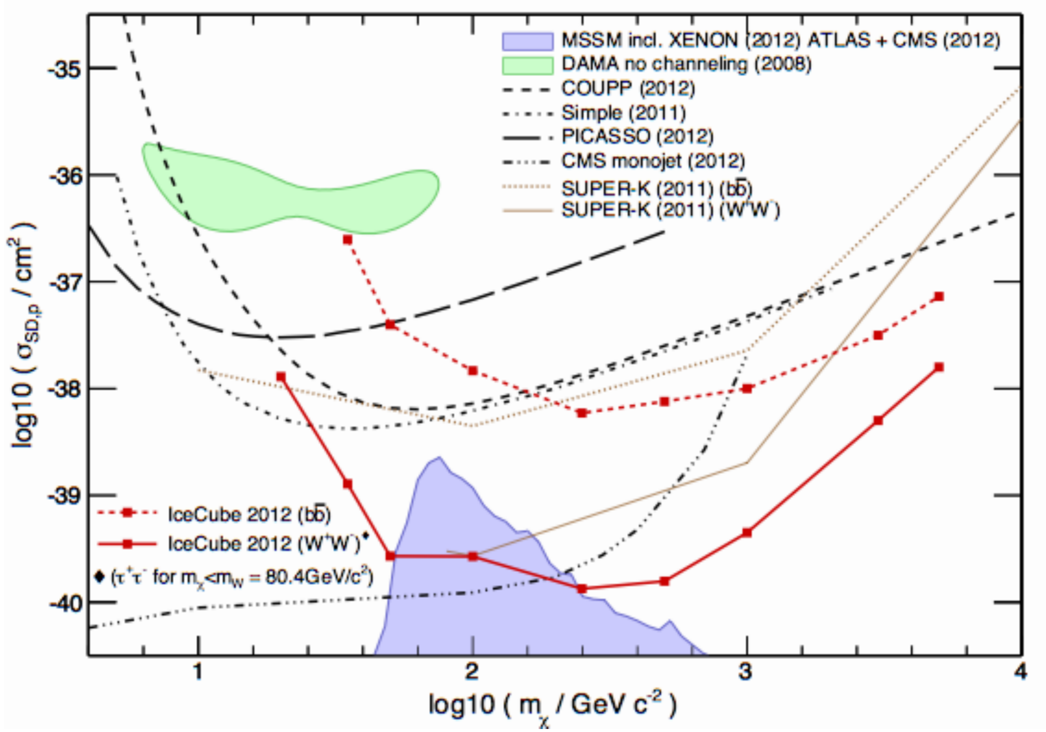
details on systematic uncertainties, see *PRL 110 (2013) 131302*

Solar Dark Matter Search - results

SI WIMP-proton cross-section limit



SD WIMP-proton cross-section limit



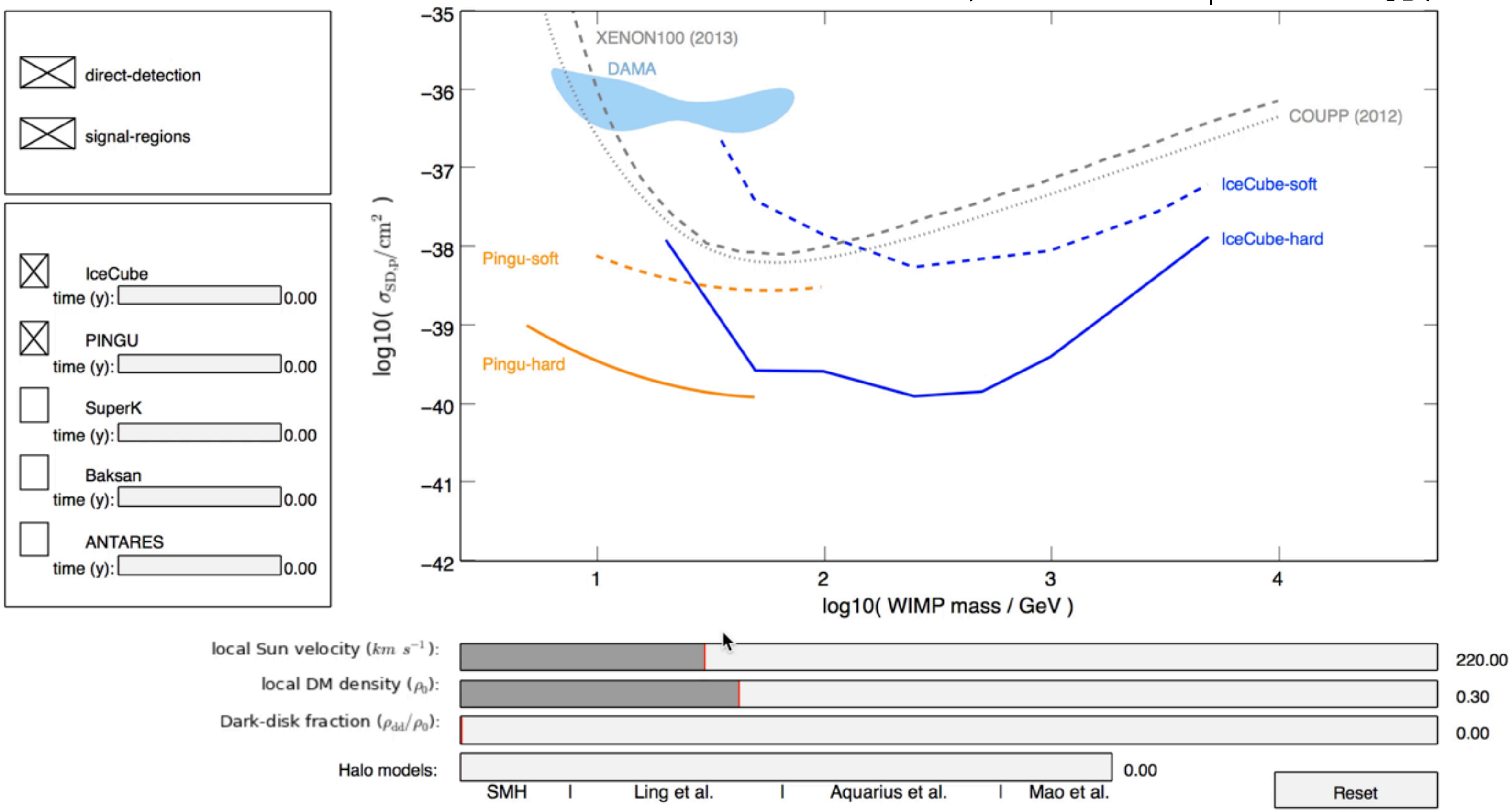
- most stringent SD cross-section limit for most models
- complementary to direct detection search efforts
- different astrophysical & nuclear form-factor uncertainties
- **Expect new results on Moriond time-scale**
- **Multi-year combined results later this summer**

Solar Dark Matter Search - astrophysical uncertainties

Interactive Tools to visualize astrophysical uncertainties in Solar WIMP searches

(C. Rott & M.D. doi:10.1016/j.dark.2014.10.002)

(Here: example for σ_{SD})

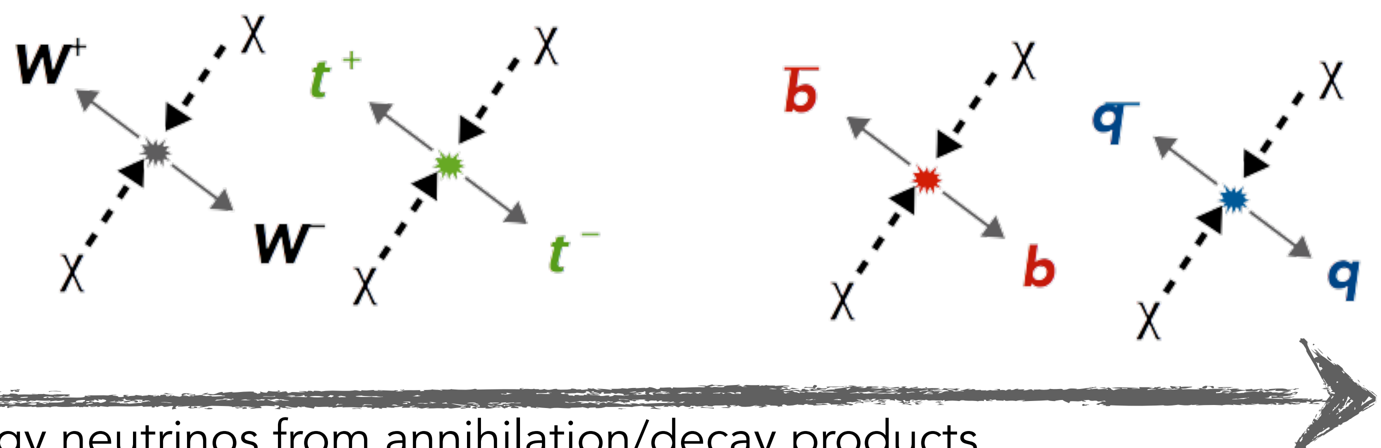


Included: local DM density, local Sun velocity, dark-disk fraction, and choice of Halo model

Not included: Solar composition & nuclear form-factor uncertainties

New SUSY analysis...

Benchmarks
100% Br.



high energy neutrinos from annihilation/decay products

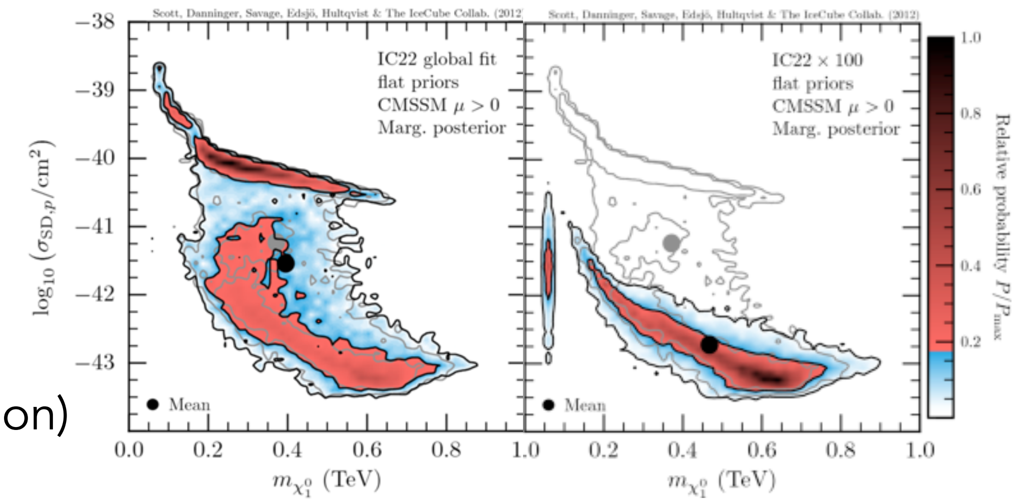
Scott, Savage, Edsjö & the IceCube Coll., JCAP **11**, 057 (2012)

Specific model (IceCube unbinned likelihood)

$$\mathcal{L} = \mathcal{L}_{\text{num}}(n|\theta_{\text{signal+BG}}) \prod_{i=1}^{n} \mathcal{L}_{\text{spec},i}\, \mathcal{L}_{\text{ang},i}$$

Include IceCube event level data in

- Model exclusion analysis
- Global statistical fit (parameter estimation)



Global SUSY fit analysis

$$\mathcal{L} = \mathcal{L}_{\text{num}}(n|\theta_{\text{signal+BG}}) \prod_{i=1}^{n} \mathcal{L}_{\text{spec},i}\, \mathcal{L}_{\text{ang},i}$$

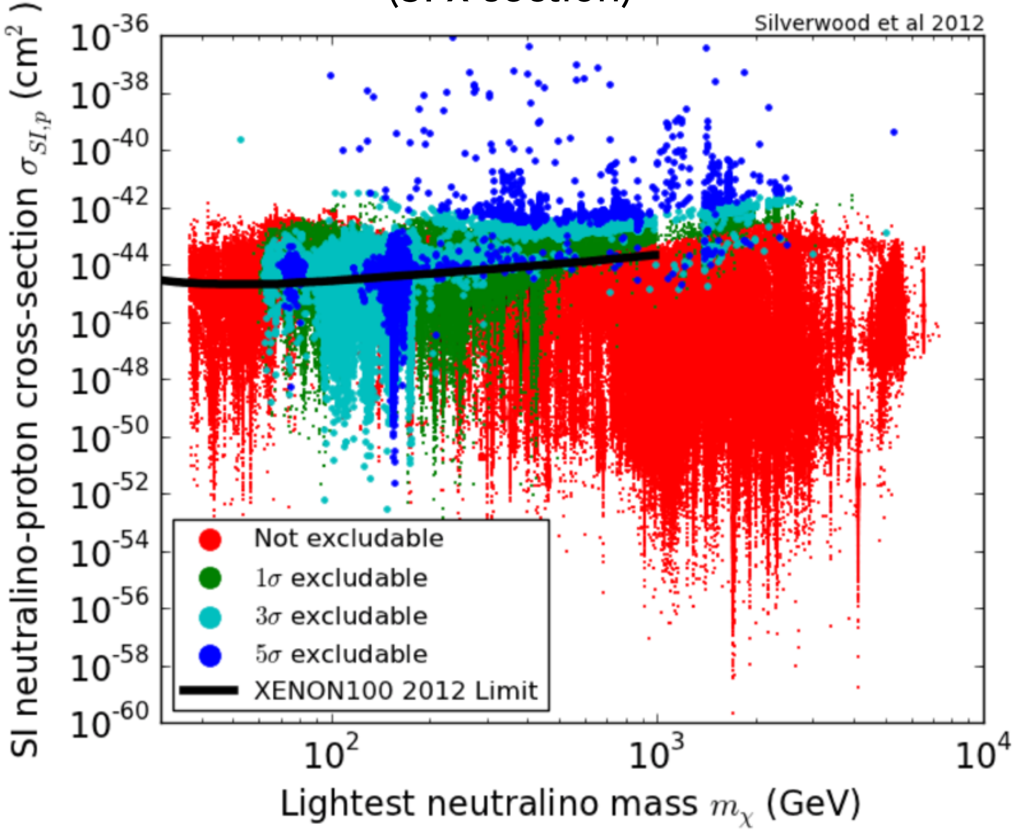
- Energy resolution (energy estimated by number of DOM hits)
- Angular resolution (incl. PSF of individual events)
- Systematic uncertainty included in effective area
- For initial publication, we calculated all quantities at neutrino level, as we looked at ν-energies above ~60 GeV.
- Good approximation that production angle (Φ_μ) between ν and μ is less than PSF
- DeepCore sensitive to ν-energies down to ~10 GeV.
- Data release in preparation for all IceCube-79 solar WIMP event selection —> including detector responses

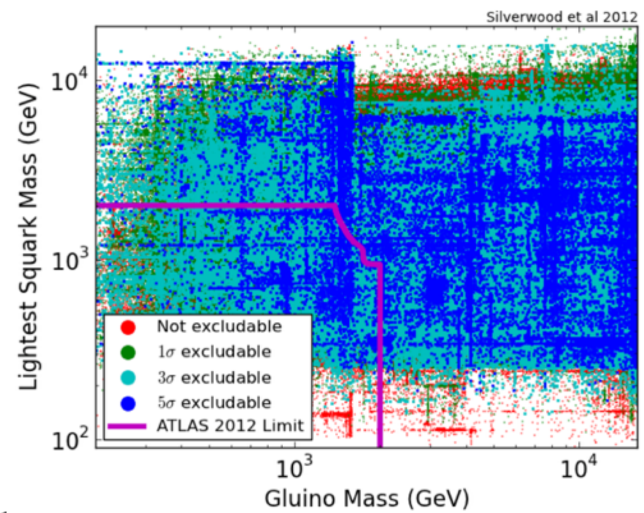
Model exclusion example (MSSM-25)

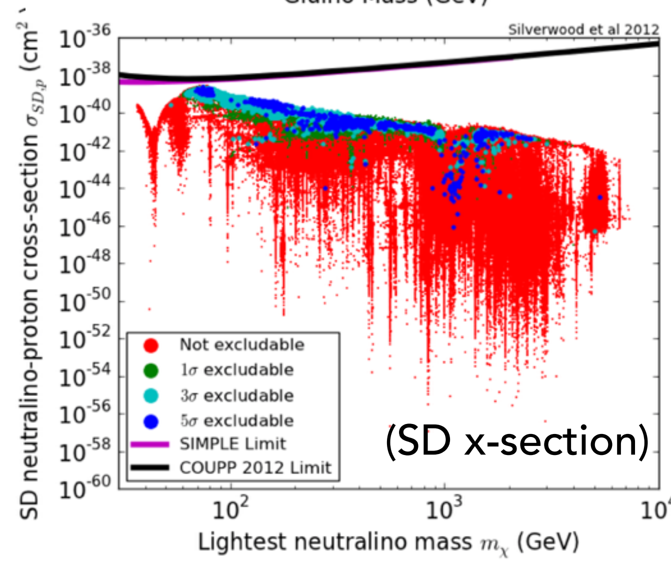
Ref: P.Scott, C.Savage, J. Edsjö & the IceCube Coll., JCAP11,057 (2012) & H.Silverwood et.al., arXiv:1210.0844

Details: 25-dim. parameter space (**MSSM-25**) using scanning based on importance sampling

(SI x-section)



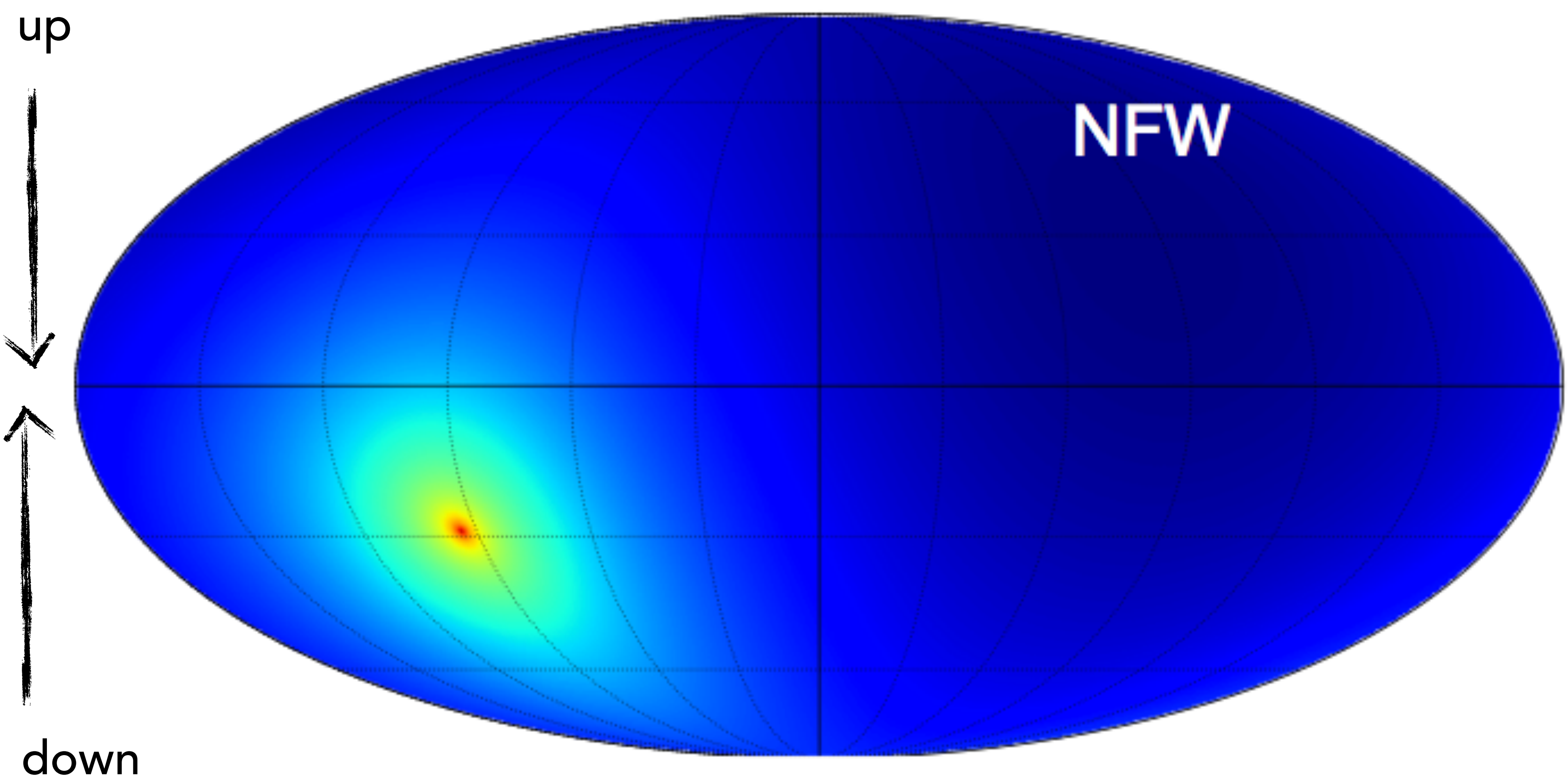




(SD x-section)

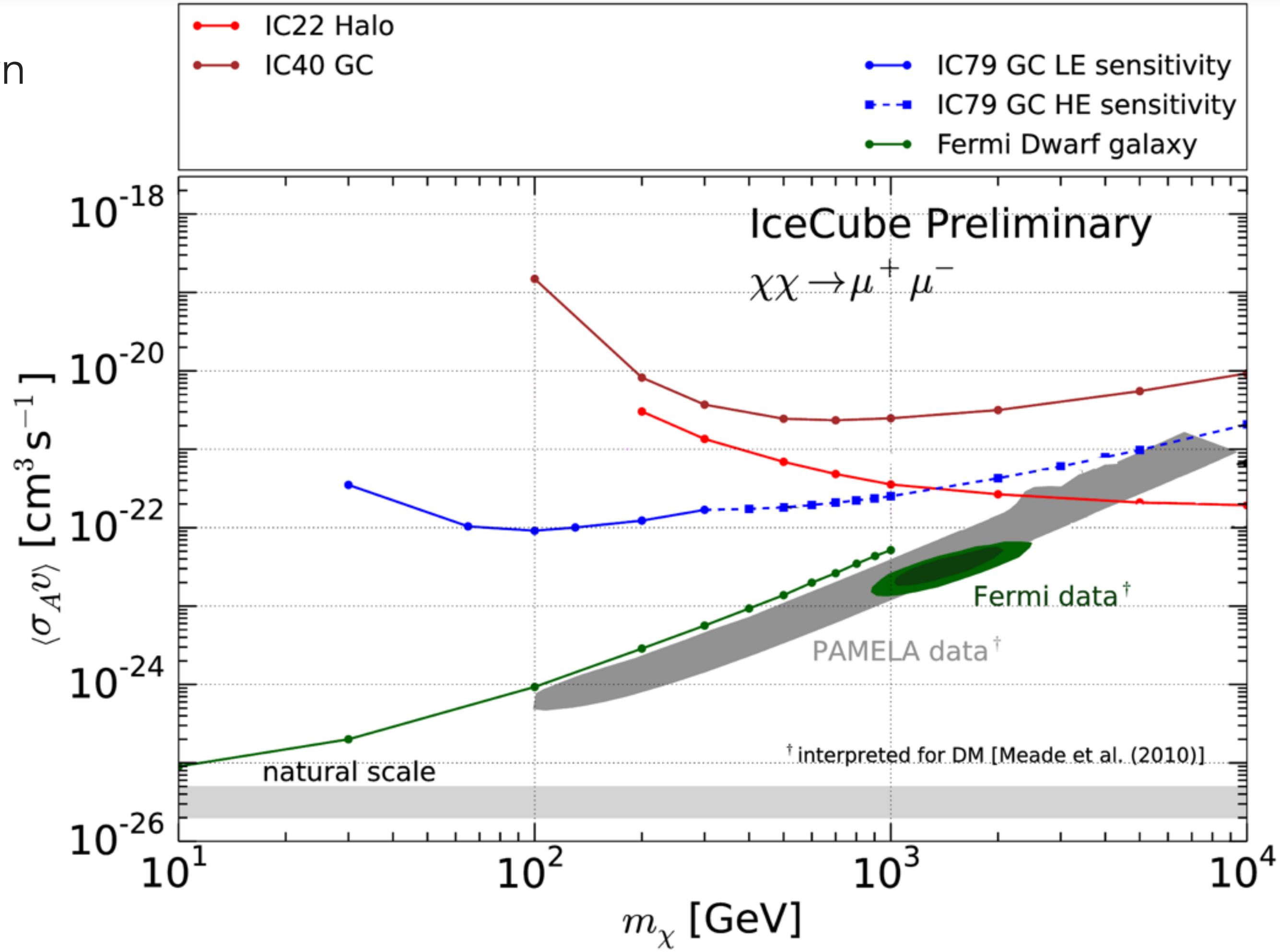
Galactic Dark Matter Searches

(equatorial coordinates)



Galactic Dark Matter Searches (IceCube-79)

(IceCube results shown for NFW profile)



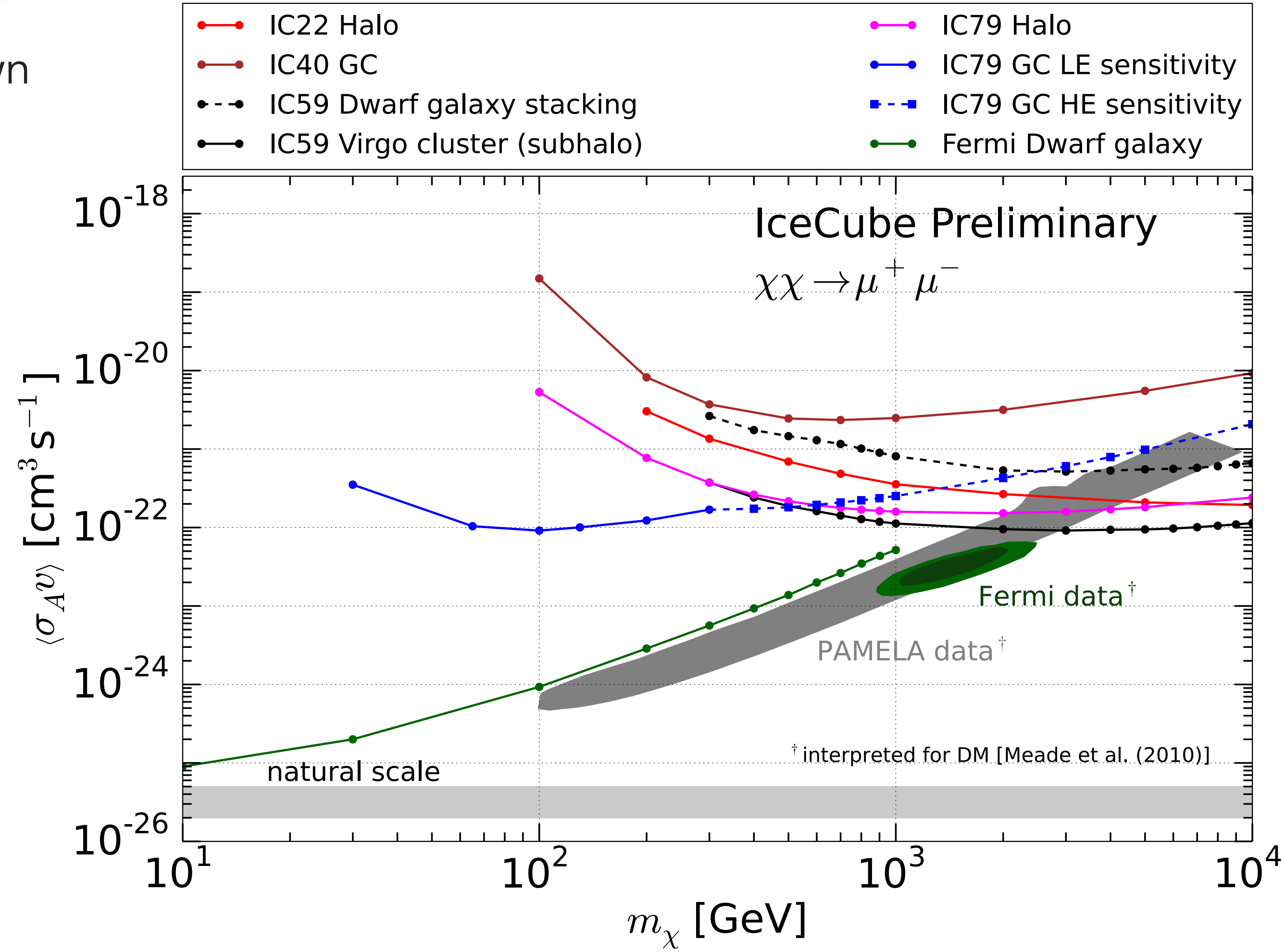
Search for many interesting potential annihilation channels:

(Various DM-Halo models tested)

$\chi\chi$ { νν, μμ, ττ, WW, bb
ZZ, Zγ

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:

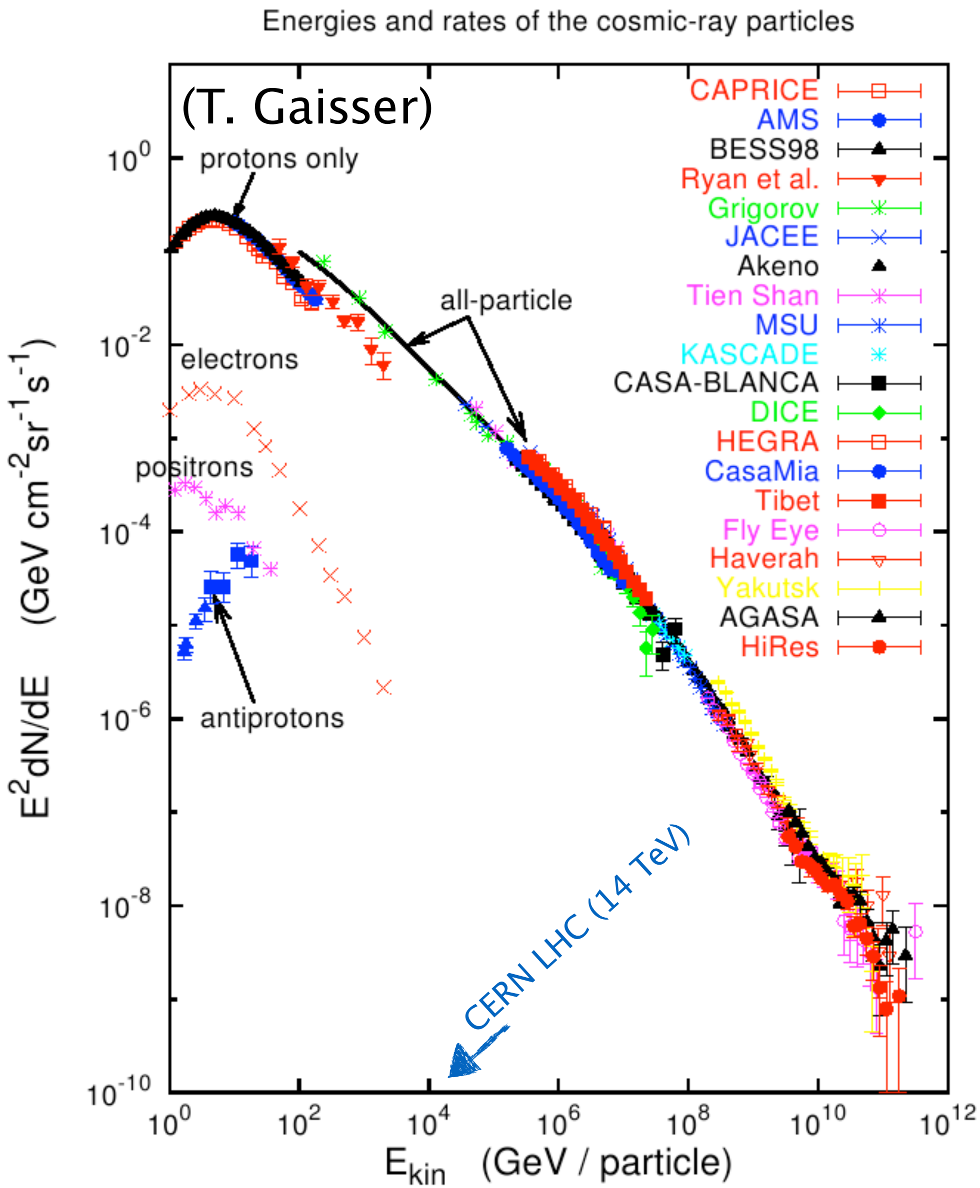
- Extended point source search
- Optimized size of search window
- Substructures taken into account

The High-Energy Tail

Searching for a signal above the atmospheric neutrino background

Cosmic rays - a 100 year old puzzle

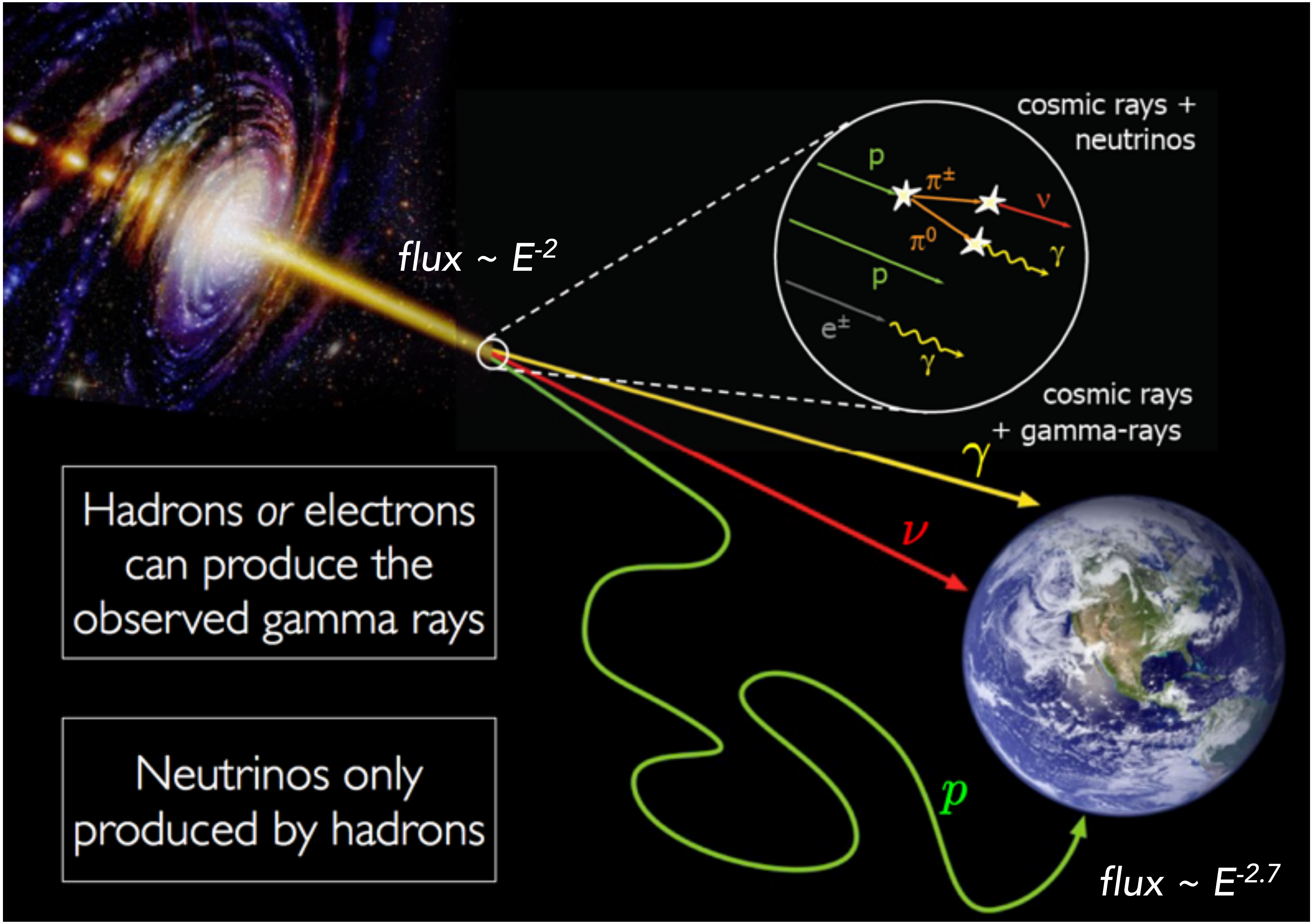
Discovered by Victor Hess



Extraordinary particle accelerators **somewhere**, but still **not identified** after 101 years:

- Supernova remnants?
- Active galactic nuclei?
- Gamma ray bursts?

Astrophysical messenger

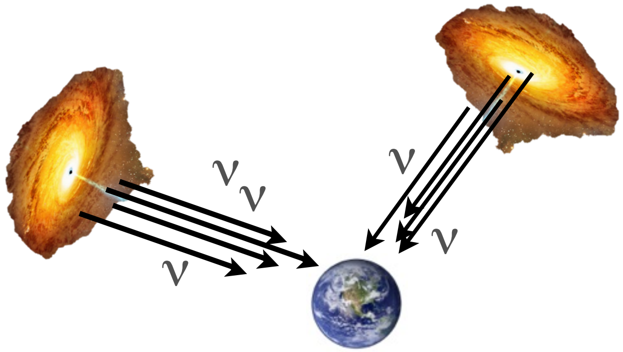


Hadrons *or* electrons can produce the observed gamma rays

Neutrinos only produced by hadrons

General search strategy

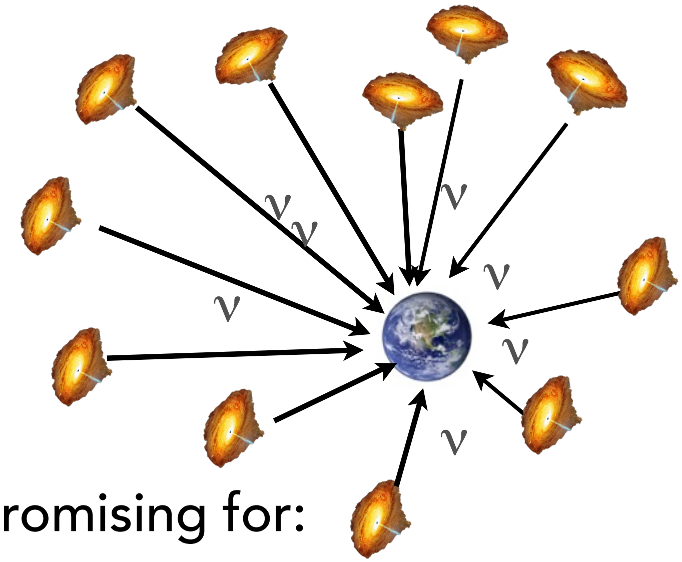
Point like ν sources



Promising for:

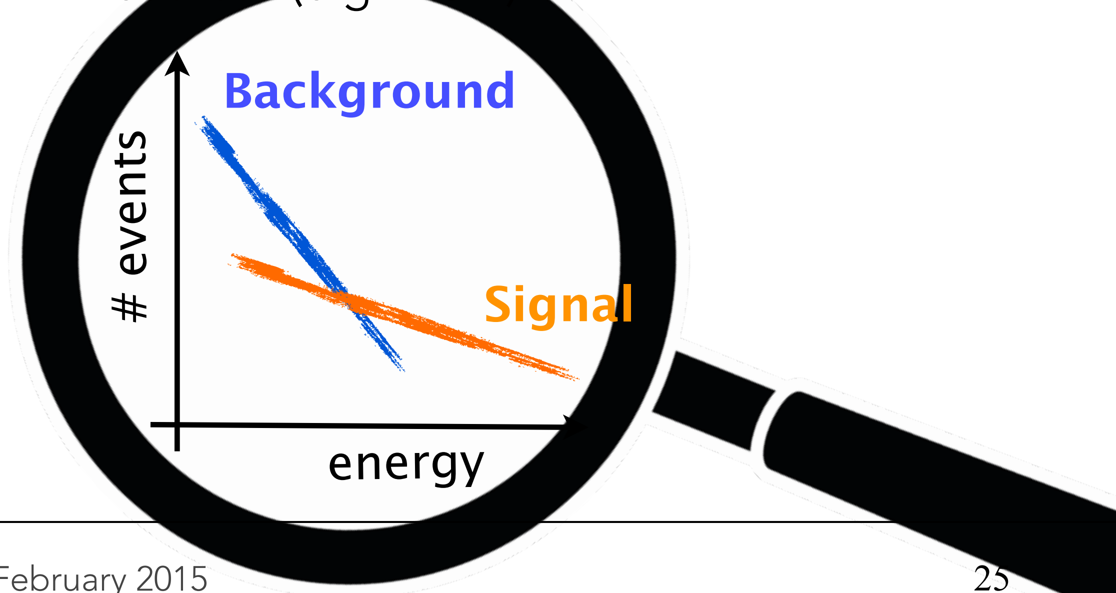
- rare bright sources (e.g. GRB)
- transient sources
- galactic sources

Diffuse ν fluxes



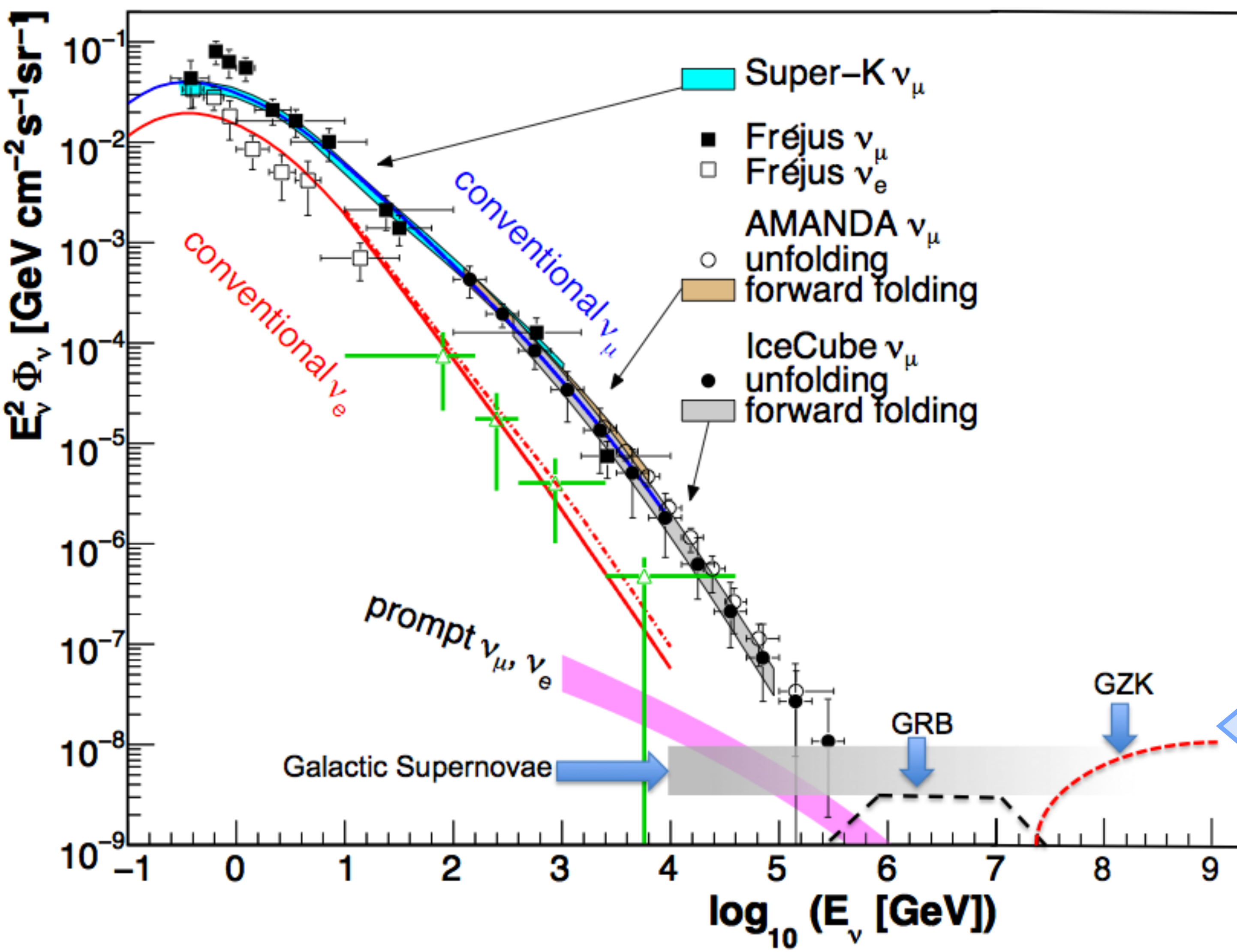
More promising for:

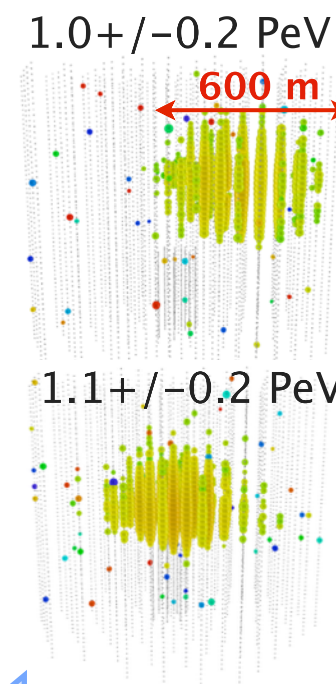
- more abundant extragalactic sources (e.g. AGN)



Summary of diffuse neutrino fluxes

- Precise measurement of atmospheric **ν_μ spectrum** (*arxiv:1409.4535*)
- First measurement of atmospheric **ν_e spectrum** at high energies (*PRL 110 (2013) 151105*)





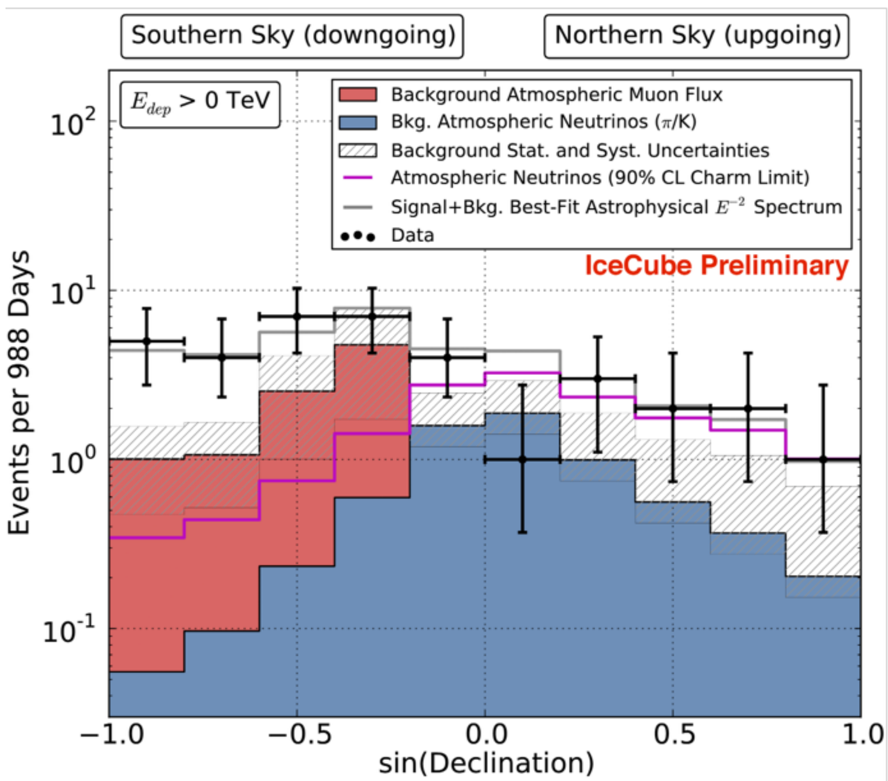
We look from UltraHighE to HighE

See also PRL 111, 021103 (2013)

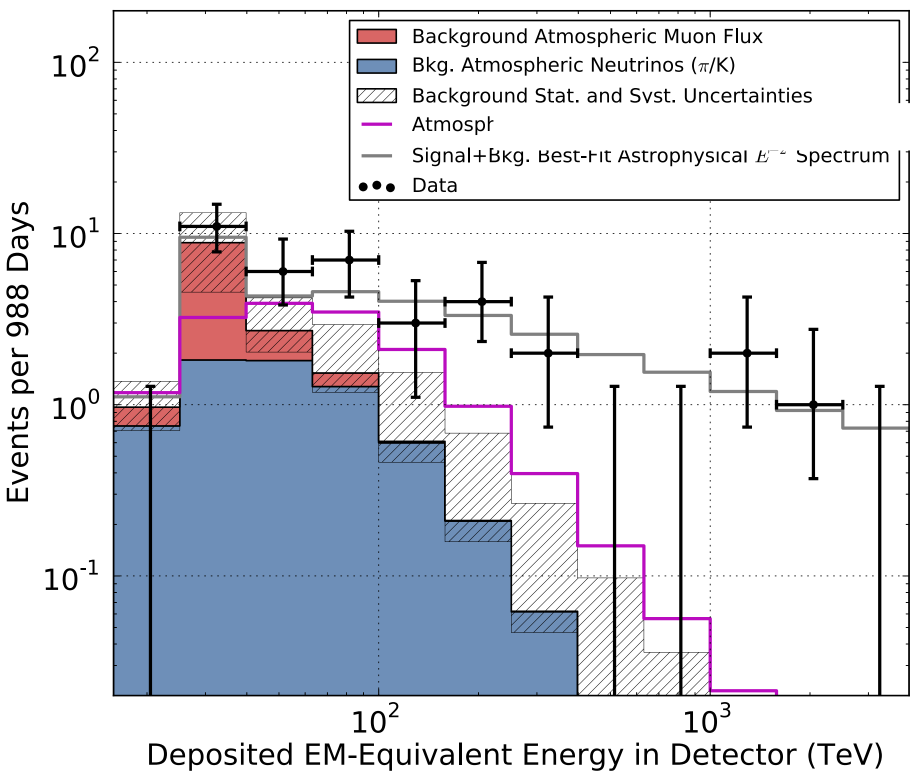
All flavour - all Sky - starting event analysis

IceCube discovers excess events at high energies using contained events

- Significant (**5.7 σ**) excess above the background-only expectation



- Compatible with isotropic flux
- Events from North absorbed in Earth
- Minor excess in South; not significant



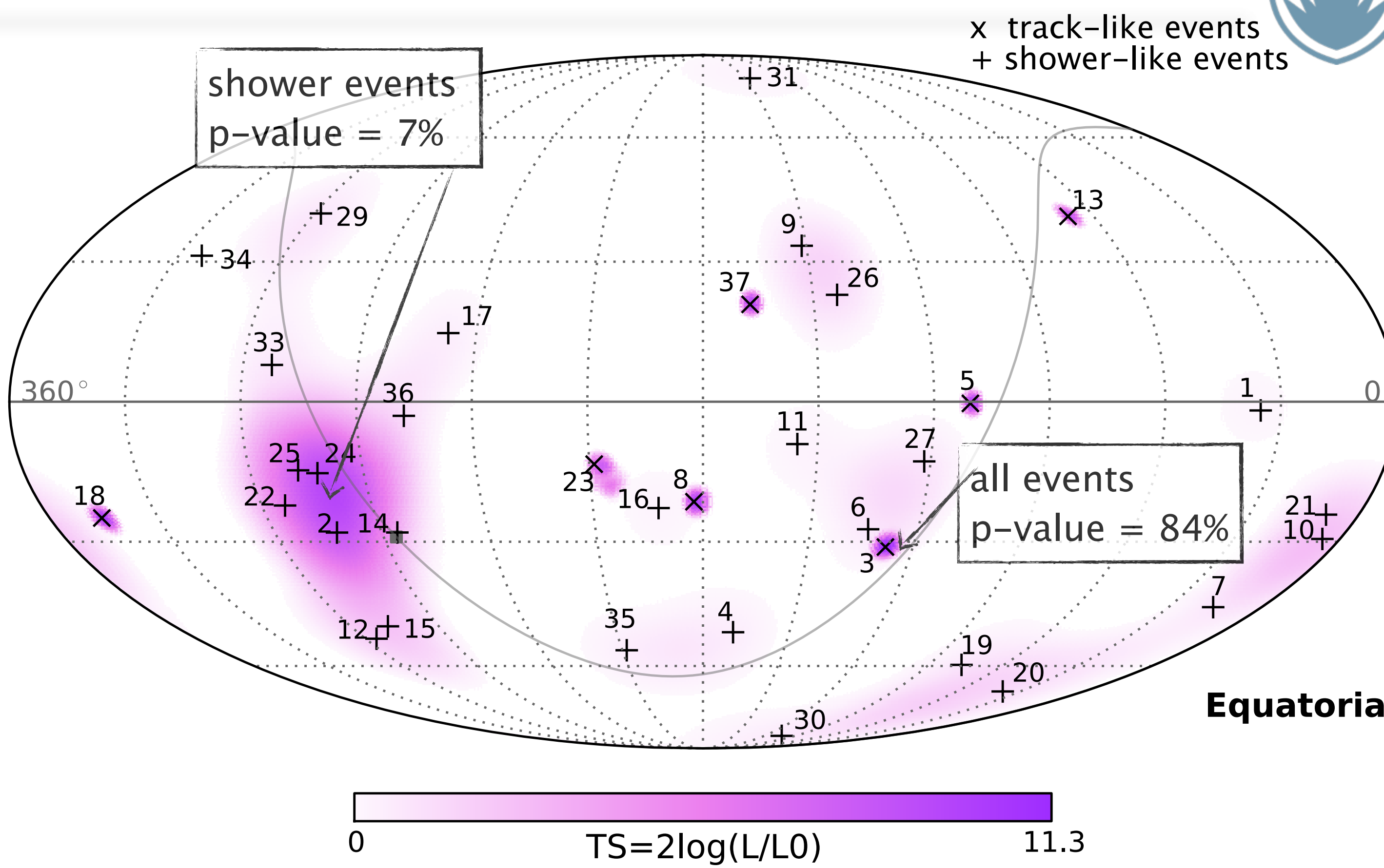
- Harder than expected atm Bg
- Merges well into expected Bg at low E
- Cut-off at PeV?

Skymap

Other searches:

- Galactic plane correlation (+-2.5 degrees, motivated by TeV γ observations)
- Time clustering / GRB

Not significant!

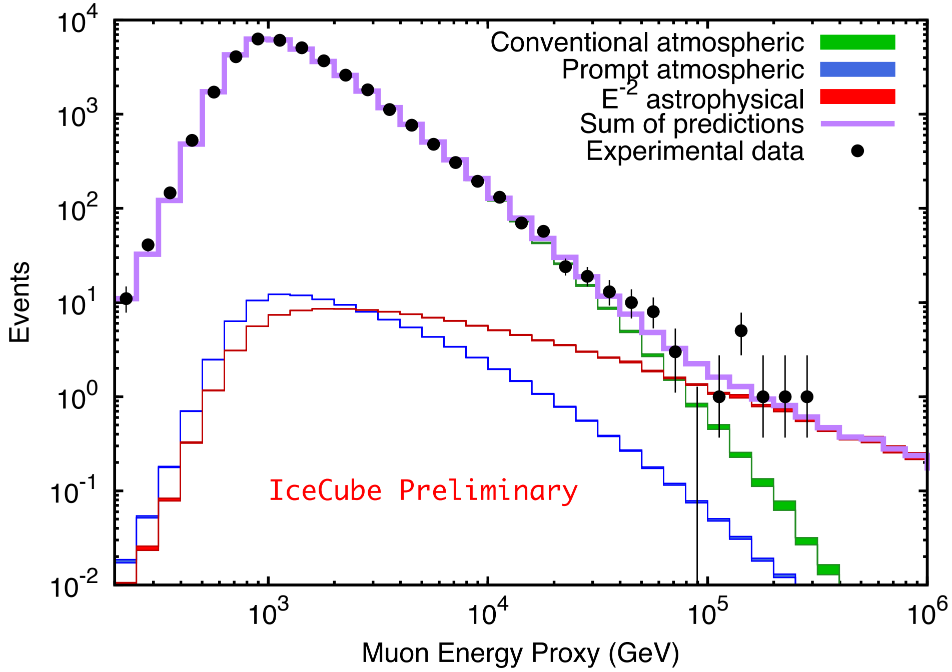


see also:
Science, 342 (2013) 1242856
Phys. Rev. Lett. 113, 101101

Quantifying the excess:

- Data is fit to a mixture of non-prompt atm., prompt atm. and astrophysical neutrinos
- In the range 60 TeV < E < 2 PeV, spectrum consistent with an E^{-2} spectrum
  → $E^2\varphi \sim 0.95 \pm 0.3 \cdot 10^{-8}$ GeV/cm²/s/sr per flavor
- E^{-2} spectrum predicts too may neutrinos above ~2 PeV
  → Cutoff or softer spectrum needed

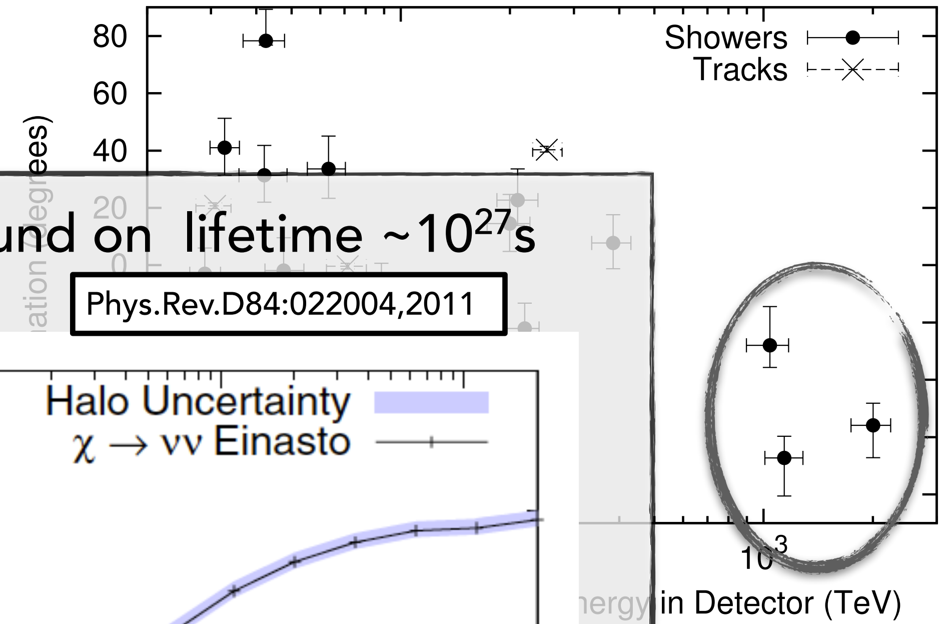
Northern Sky through going analysis



- Analysis of through-going events from the northern sky using 2 years of data—ν_μ charged current only, above ~1 TeV (publication in preparation)
- Excess over atmospheric background of 3.9σ
- Best fit astrophysical flux is compatible with 3yr HESE results
- Flavor Ratio of Astrophy. Neutrinos above 35 TeV in IceCube (arxiv:1502.03376)

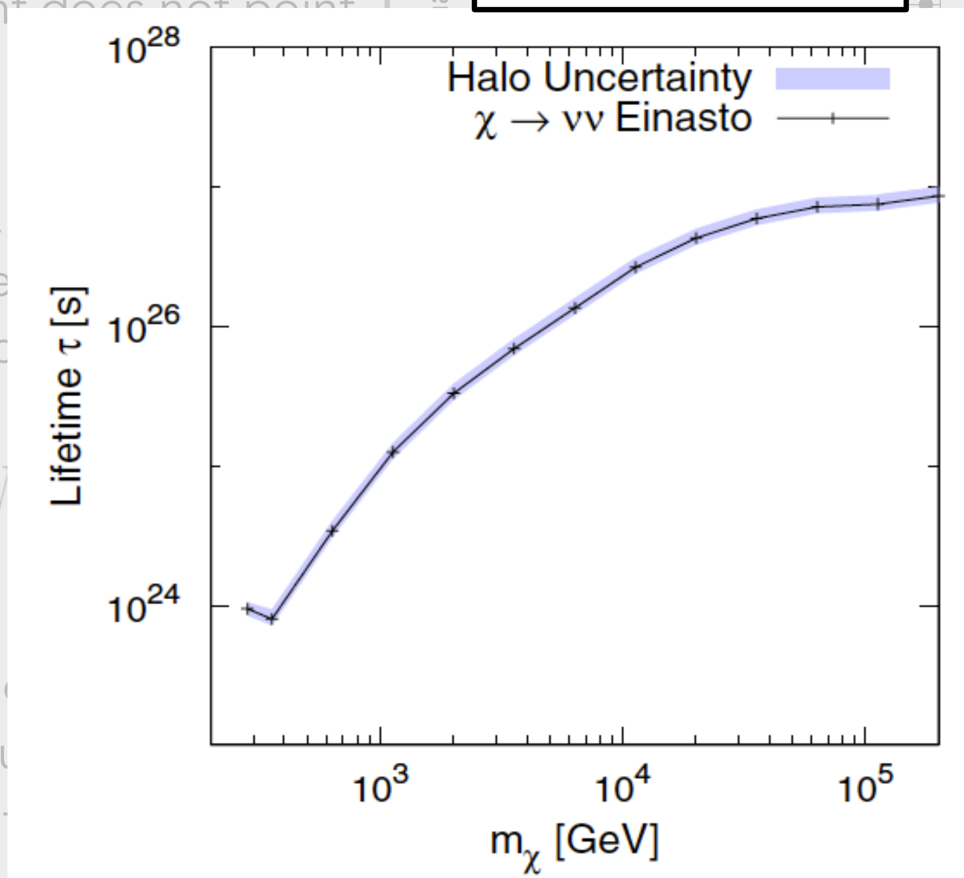
Could this be Heavy Dark Matter?

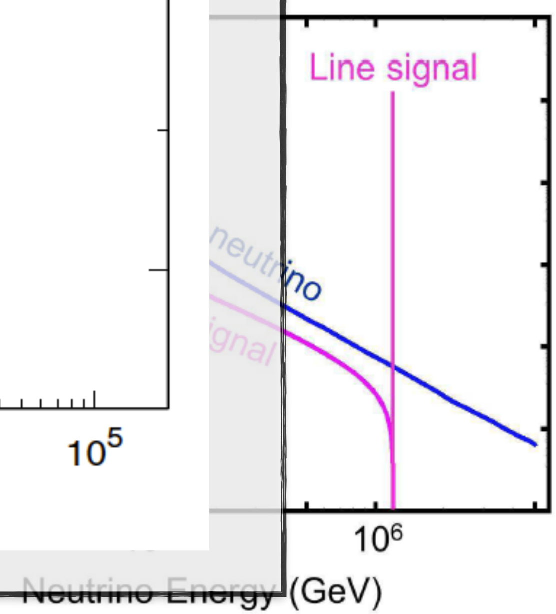
- reported PeV events are intriguingly close in energy
- consistent with ν_e interactions at about 1PeV
- latest ~2 PeV event does not point to a line signal



IceCube bound on lifetime ~10^{27}s

Phys.Rev.D84:022004,2011





Possible evidence:

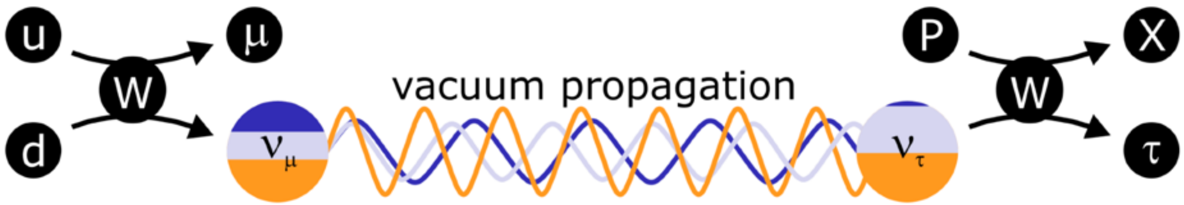
- 2.4PeV Dark Matte
- Flux can be related

$$\tau_{\rm DM} \simeq 1.9N$$

Models:

- Singlet fermion in
- Hidden Sector Gau
- Gravitino Dark Ma

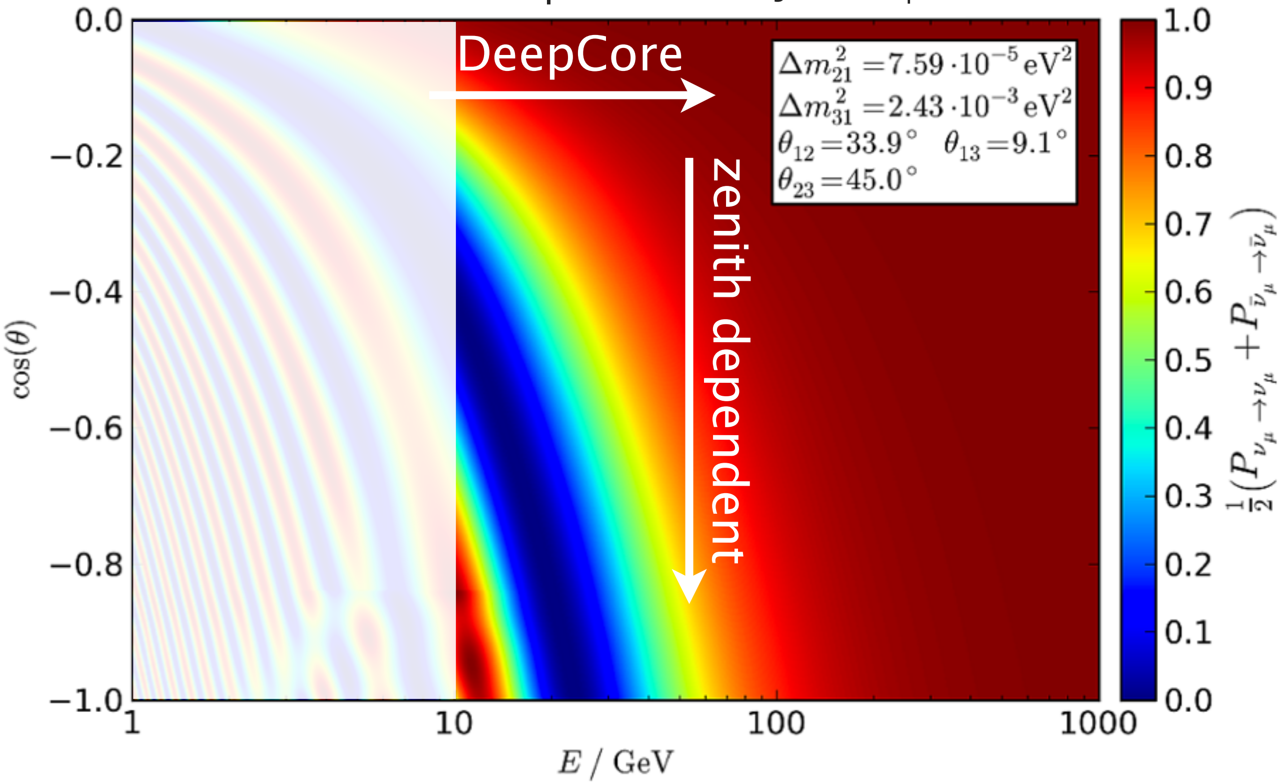
Atmospheric neutrino Oscillations analyses

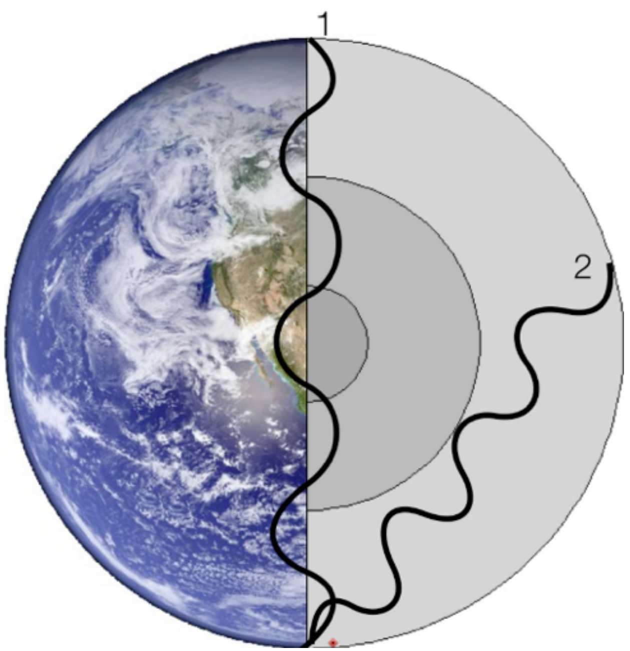


Neutrino oscillations

ν_μ – disappearance analysis:

Survival probability of ν_μ





$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

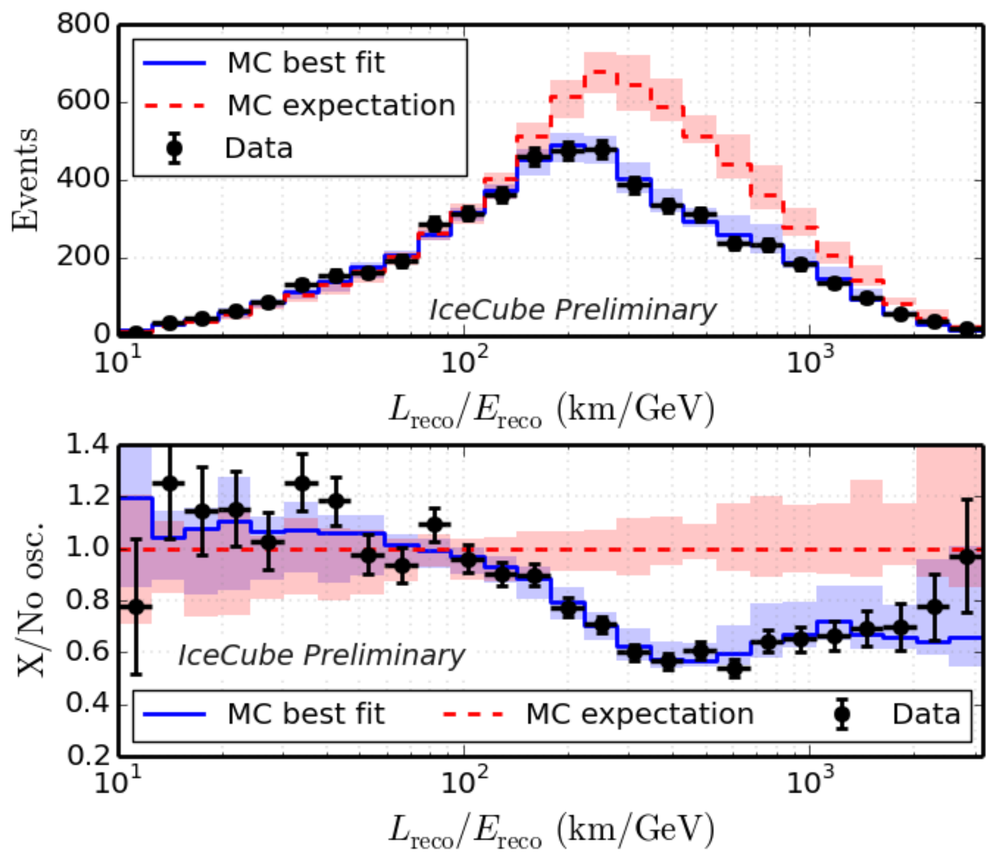
Oscillation parameters: θ and Δm^2 (in eV^2)

Variables: L (distance traveled in km) and E (neutrino energy in GeV)

Neutrino oscillations - results

ν_μ – disappearance analysis:

- current analysis: Fit for zenith angle and energy
- High statistics and low energy threshold (3 years of data)
- Reduced systematic uncertainties, compared to first analysis



Actual fit is simultaneously performed in 2 dimensions (energy+zenith)

Neutrino oscillations - results

ν_μ – disappearance analysis:

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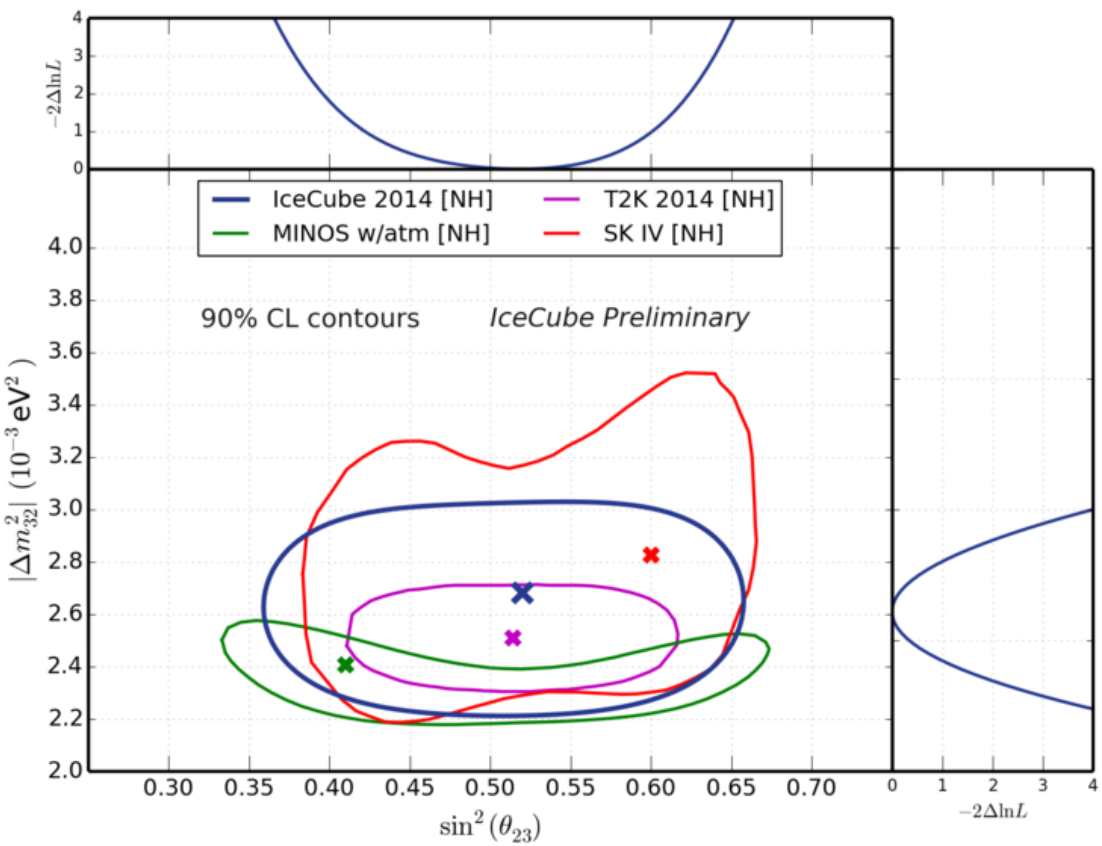
- High statistics and low energy threshold (3 years of data)
- Reduced systematic uncertainties, compared to first analysis



Results for normal hierarchy:

$$\sin^2(\theta_{23}) = 0.53^{+0.09}_{-0.12}$$

$$|\Delta m^2_{32}| = 2.72^{+0.19}_{-0.20} \times 10^{-3}\mathrm{eV}^2$$

Best fit values and 90% confidence interval

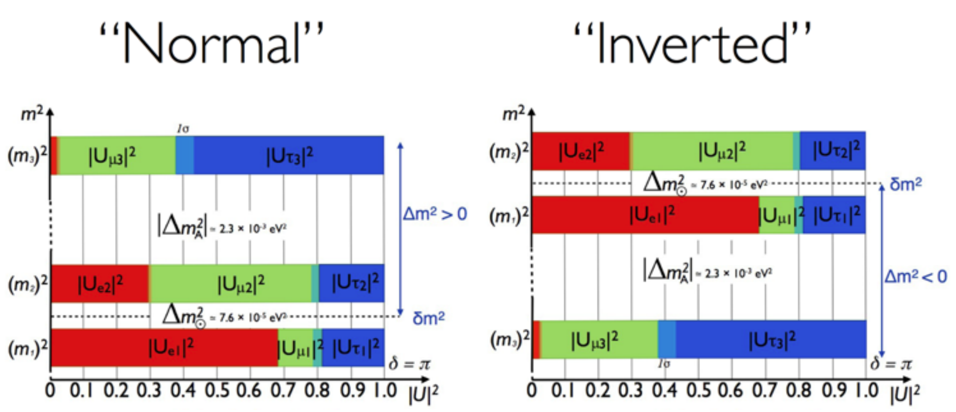
Looking ahead - PINGU (LOI: arXiv:1401.2046)

Precision IceCube Next Generation Upgrade:

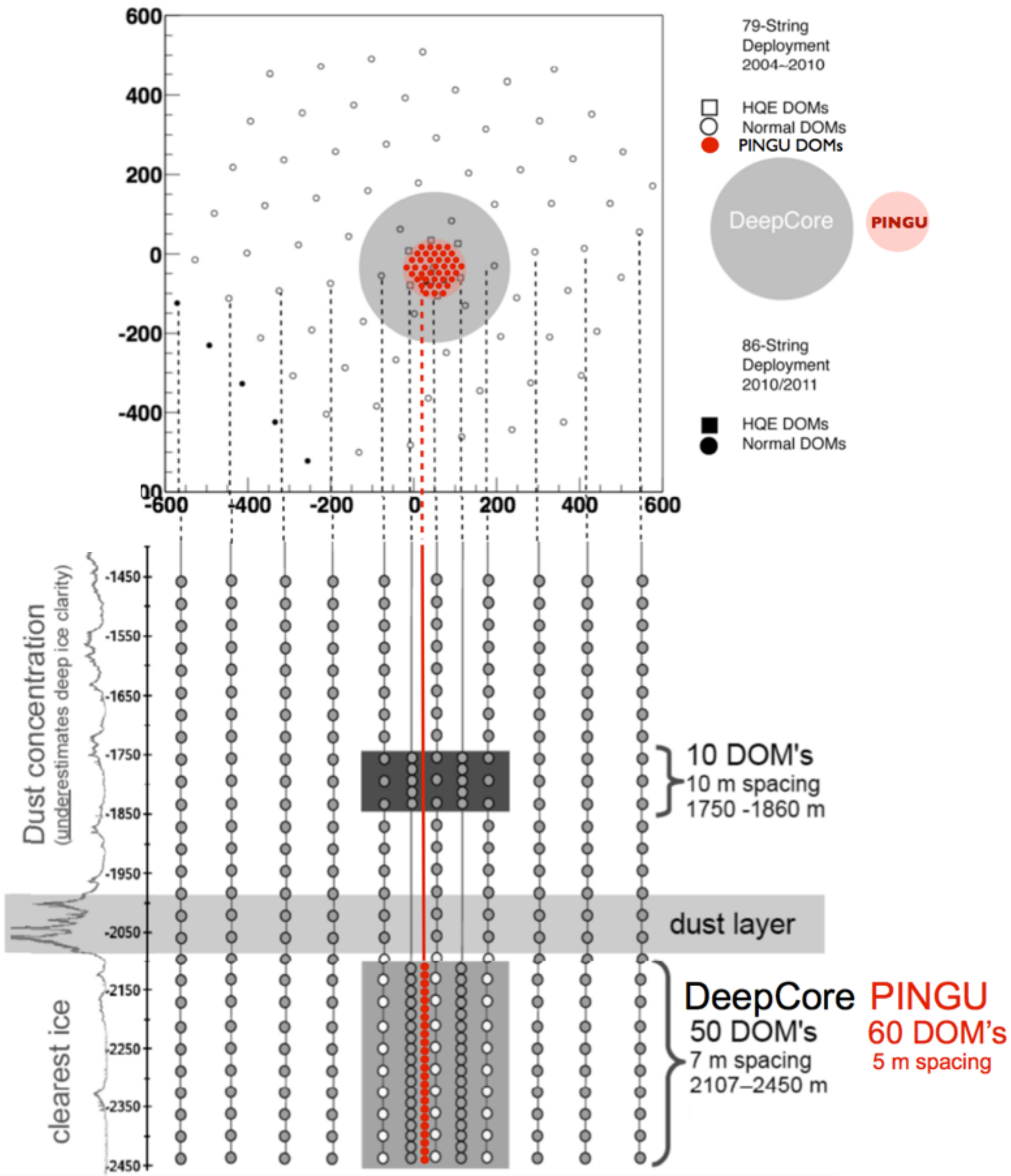
- Higher DOM density, lower energy threshold (few GeV)
- 20 – 40 (+) strings with ~ 20 m spacing
- 60 – 100 Optical Modules per string

Main Physics Topic:

neutrino mass hierarchy



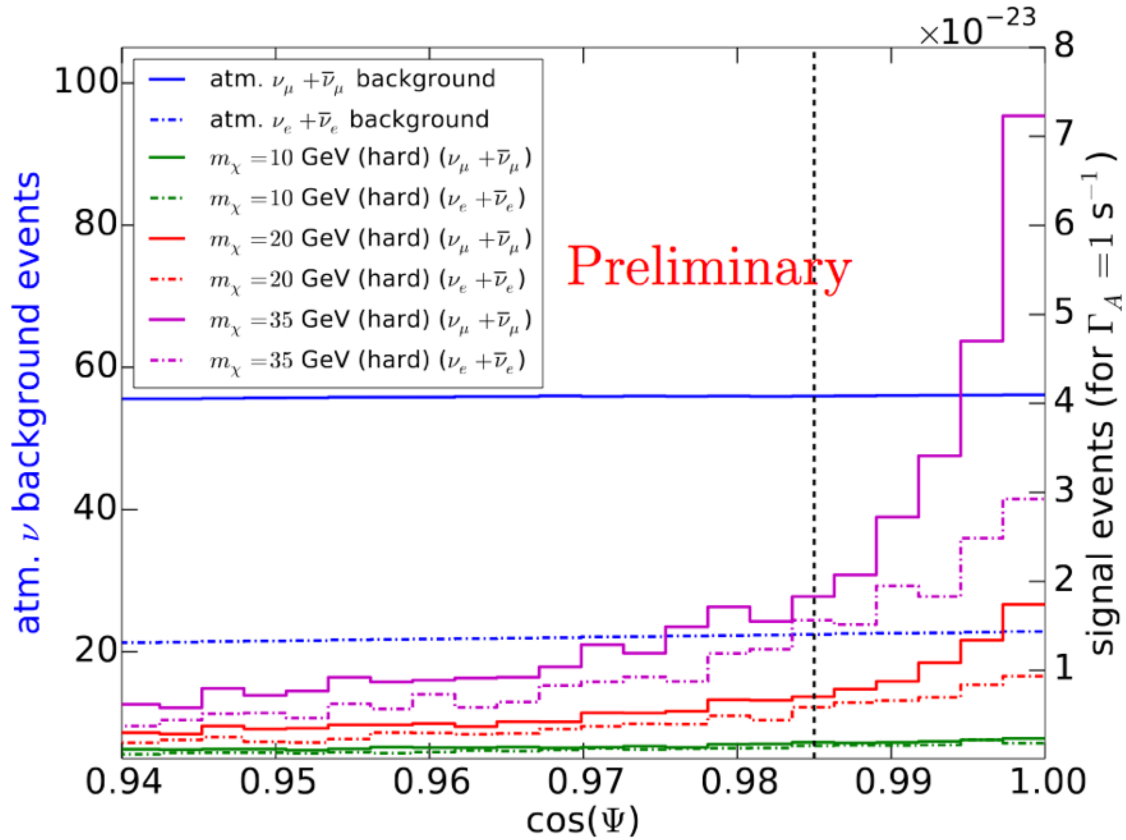
—> see LOI for details



PINGU — Dark Matter sensitivity

Sensitivity study based on current IceCube & DeepCore techniques:

- assume complete rejection of down going atm. muon Bg through veto techniques
- current reconstruction techniques used
- simplified analysis (On-source search window of 10 degrees)
- 1 year live time



PINGU's higher DOM density allows for inclusion of Cascade channel —> improved sensitivity

PINGU — Dark Matter sensitivity

Sensitivity study based on current IceCube & DeepCore techniques:

- assume complete rejection of down going atm. muon Bg through veto techniques
- current reconstruction techniques used
- simplified analysis (On-source search window of 10 degrees)
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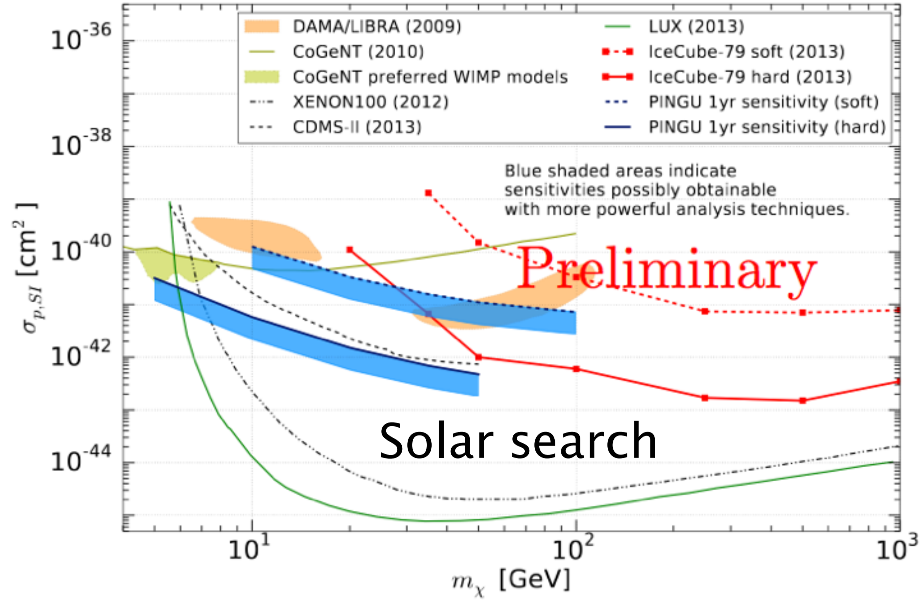
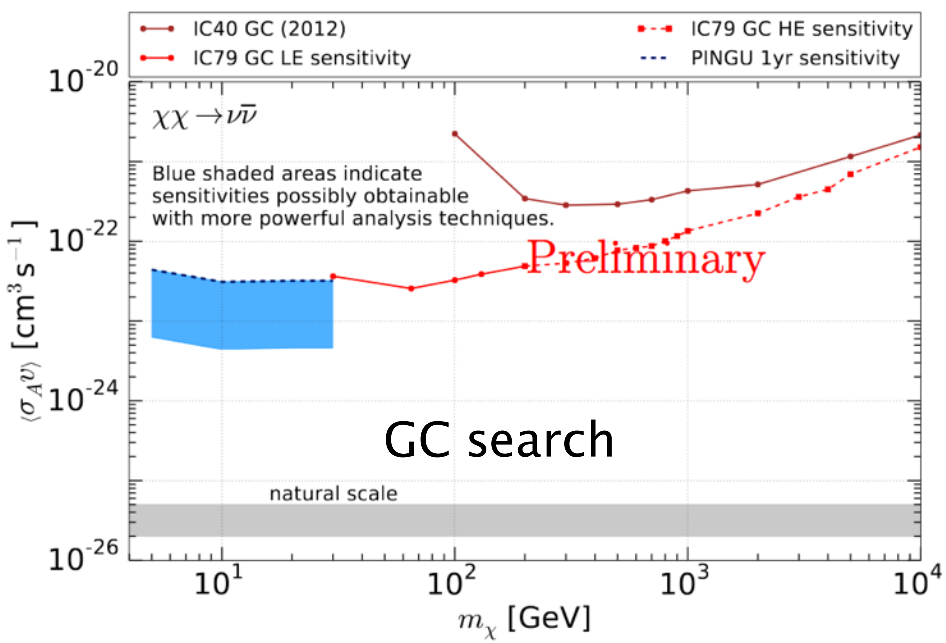
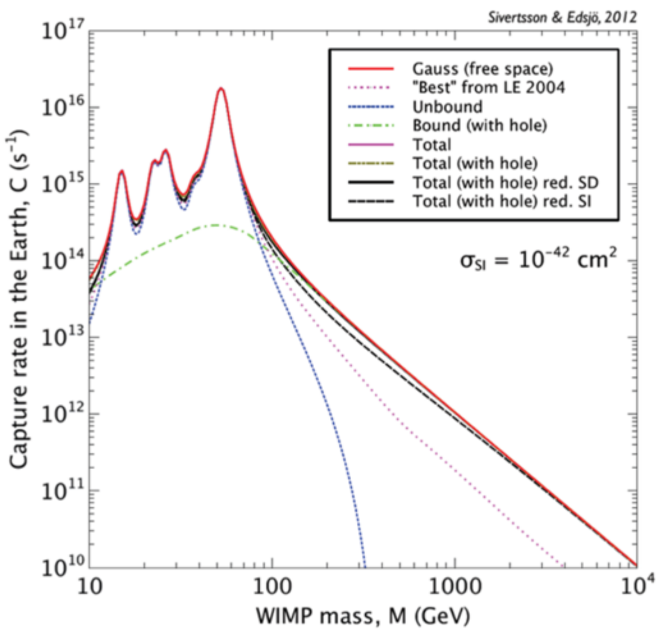




Conclusions — Dark Matter searches

- Competitive & Complementary searches for Dark Matter with IceCube (Sun & Galaxy)
- Searches for Kaluza Klein Dark Matter (*PRD 81 (2010) 057101*)
- Multiyear datasets from full detector being analyzed —> expect new results soon
- PINGU will allow to extend searches to very low WIMP masses (~few GeV)



Searches from the Earth (work in progress):

- Earth capture dominated by resonances with heavy elements
- interesting for WIMP masses below ~100GeV
- Background estimates from MC & extrapolations only (no On-Off-source search possible)

IceCube's physics program is very diverse:

Cosmic Rays. Atmospheric neutrinos, Particle Physics, Astronomy, Applied Science & Cosmology

Recent highlight:

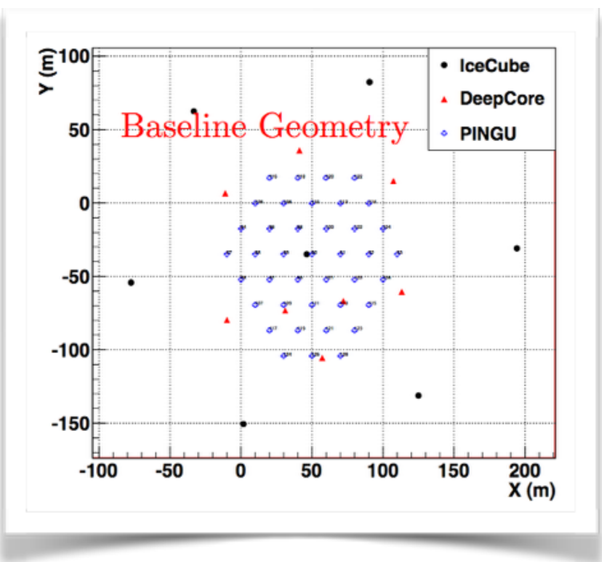
Observation of Astrophys. ν

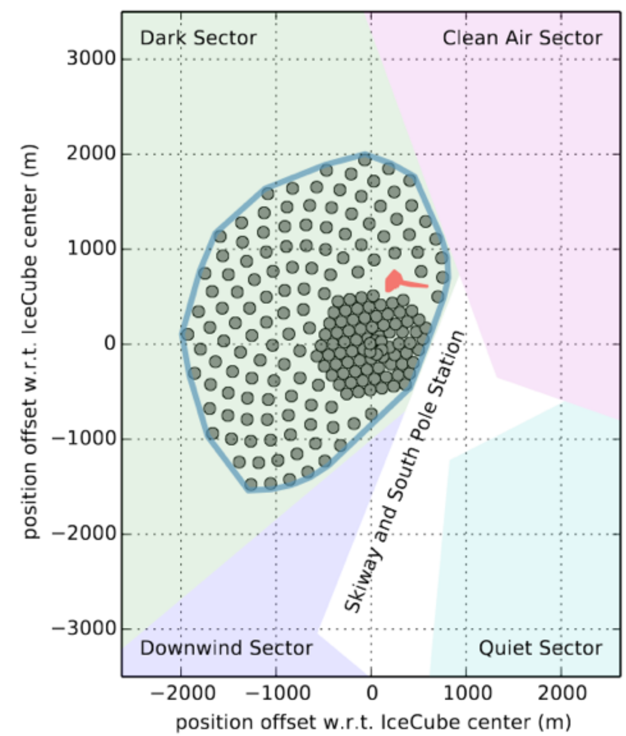
ν-Oscillation measurements

The Future

An upgraded IceCube detector for high energies - in addition to low energies (PINGU)

- PINGU
  - *O*(40) densely packed strings
  - Neutrino mass hierarchy, dark matter, neutrino physics
- High-Energy Upgrade (no name yet)
  - IceCube is optimized for ~1TeV -> focus on a threshold of ~30TeV
  - *O*(100) strings, ~10km^3
  - Identify astrophysical sources of neutrinos (and CR's), neutrino and particle physics



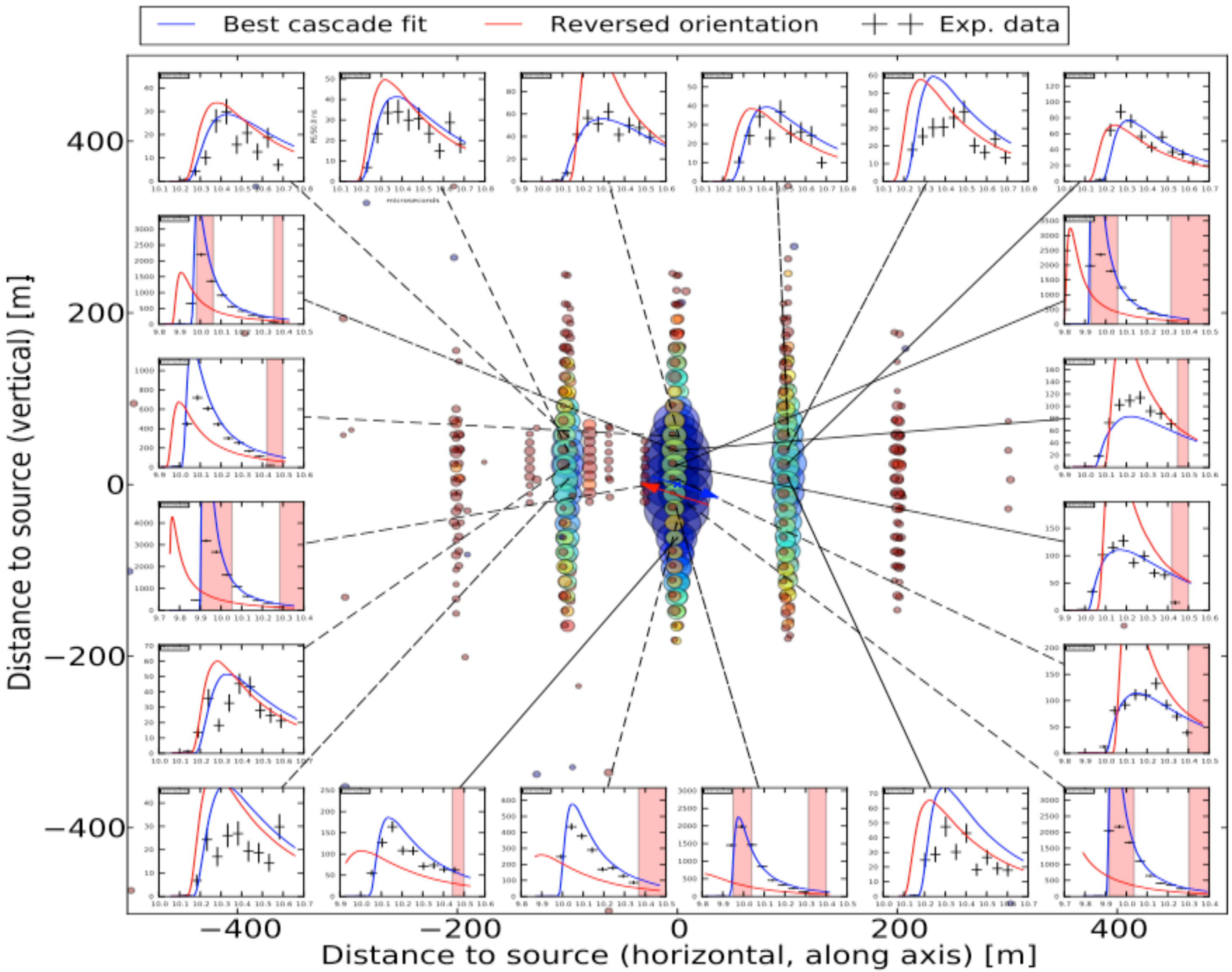


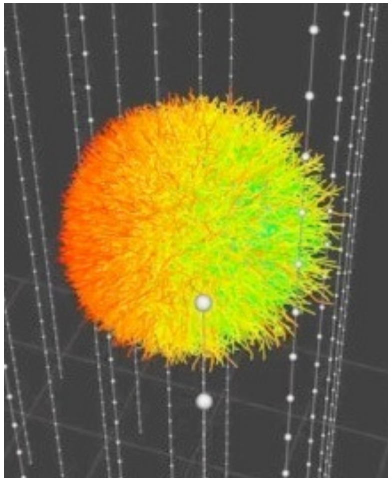

Geographic South Pole
Robert F. Scott
January 17, 1912
"The Pole. Yes, but
under very different
circumstances from
those expected."
elevation 9,301 feet
Thank you

Additional slides

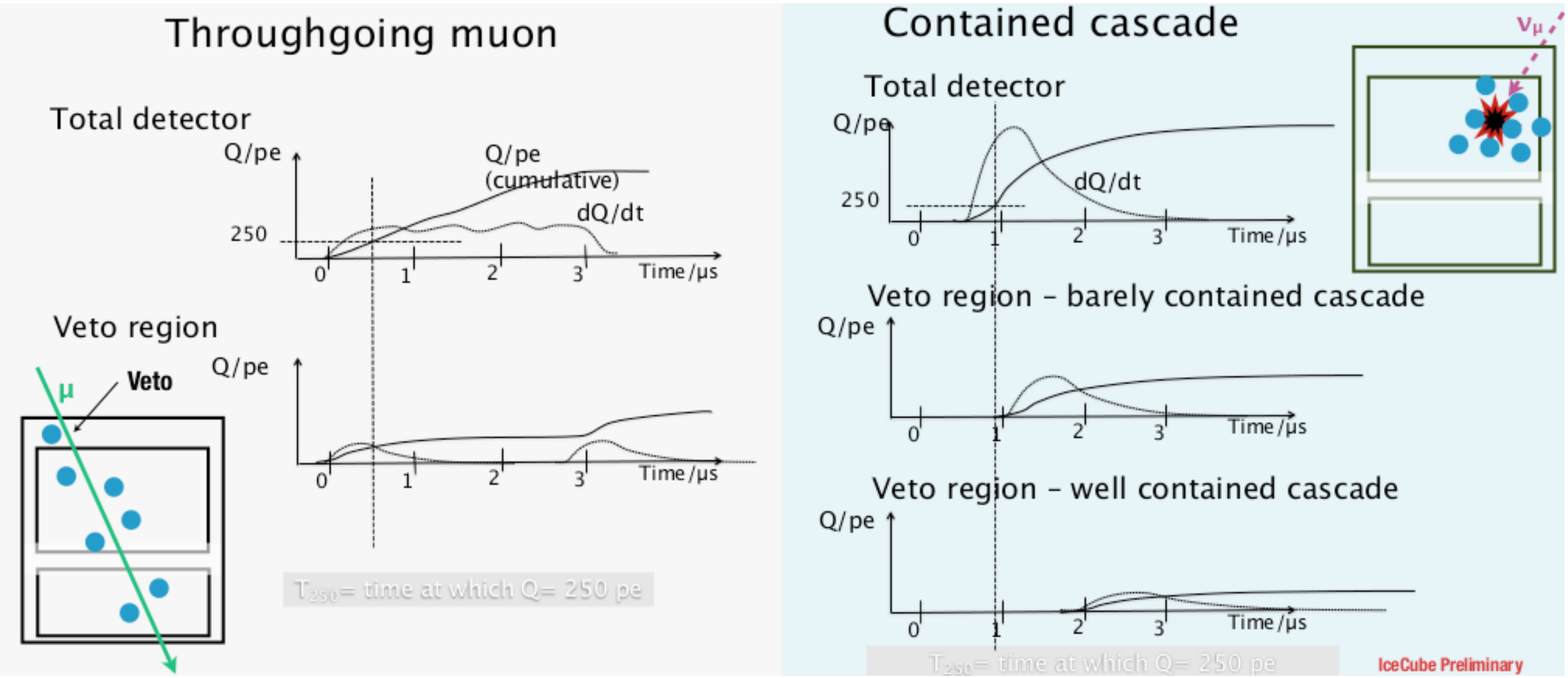
Flavor identification (showers-cascades)

Waveform examples from modules at various positions in the detector:



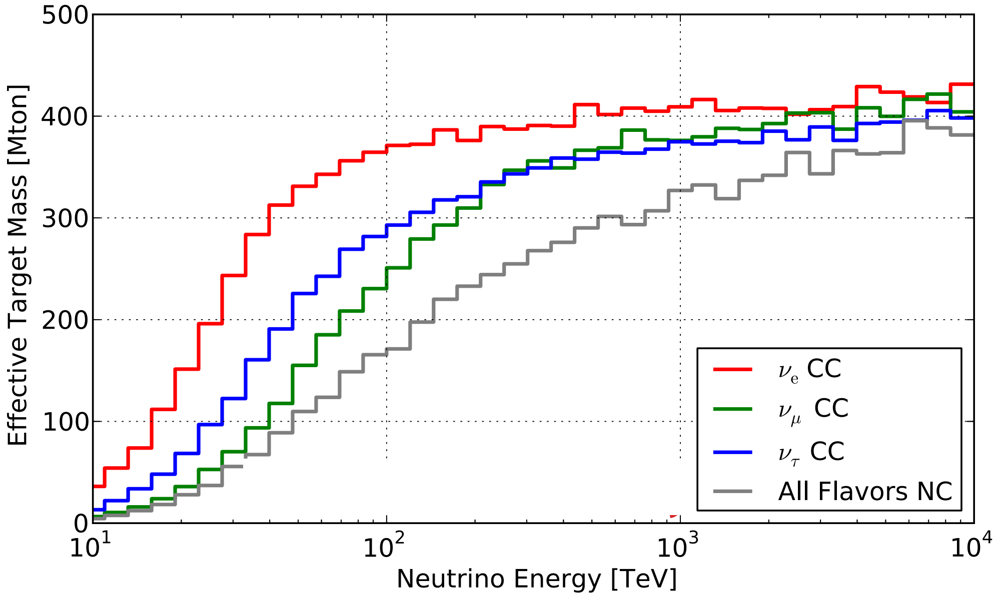


Starting event analysis - veto definition



(Image: A. Karle)

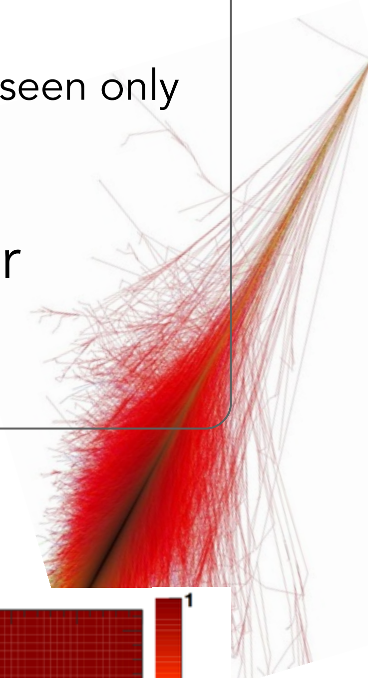
Starting event analysis



Look both up and down

PeV neutrinos **absorbed** in Earth; seen only horizontally or from above

Atmospheric self veto for down-going events



Largest sensitivity to ν_e CC:

All energy deposited inside the detector

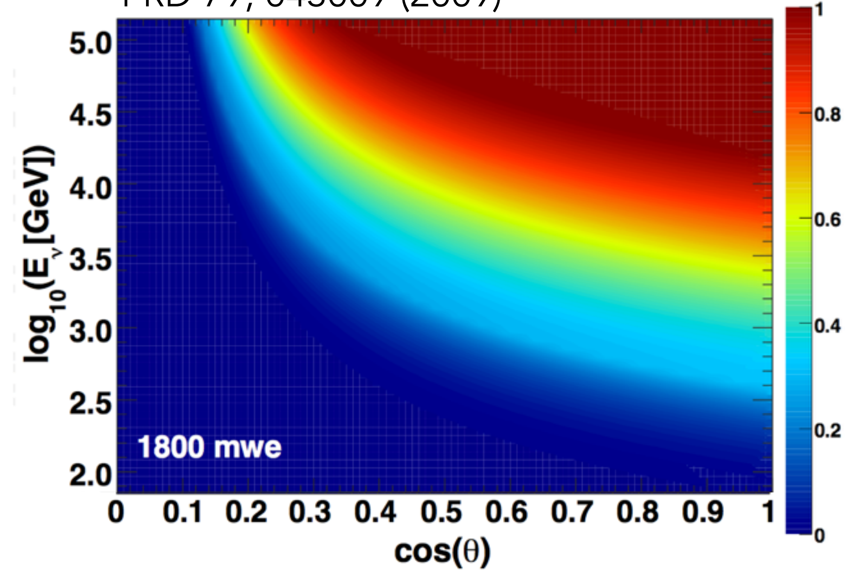
Smaller sensitivity for ν_τ and ν_μ CC:

muon and tau decay products carry out part of the initial neutrino energy

Smallest sensitivity to NC interactions:

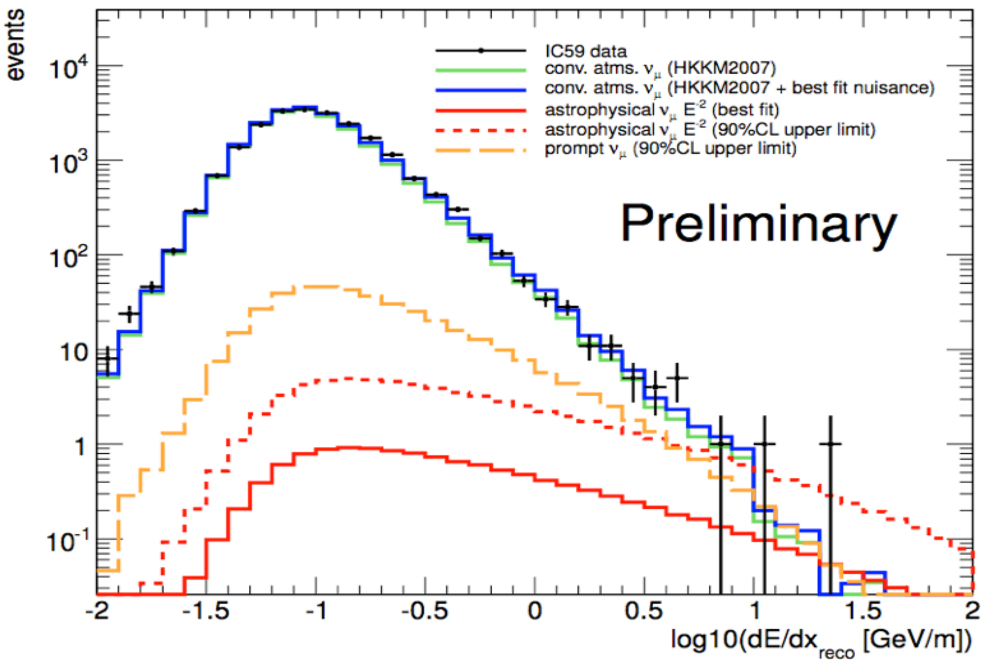
Significant fraction of the total energy disappears with the neutrino

PRD 79, 043009 (2009)



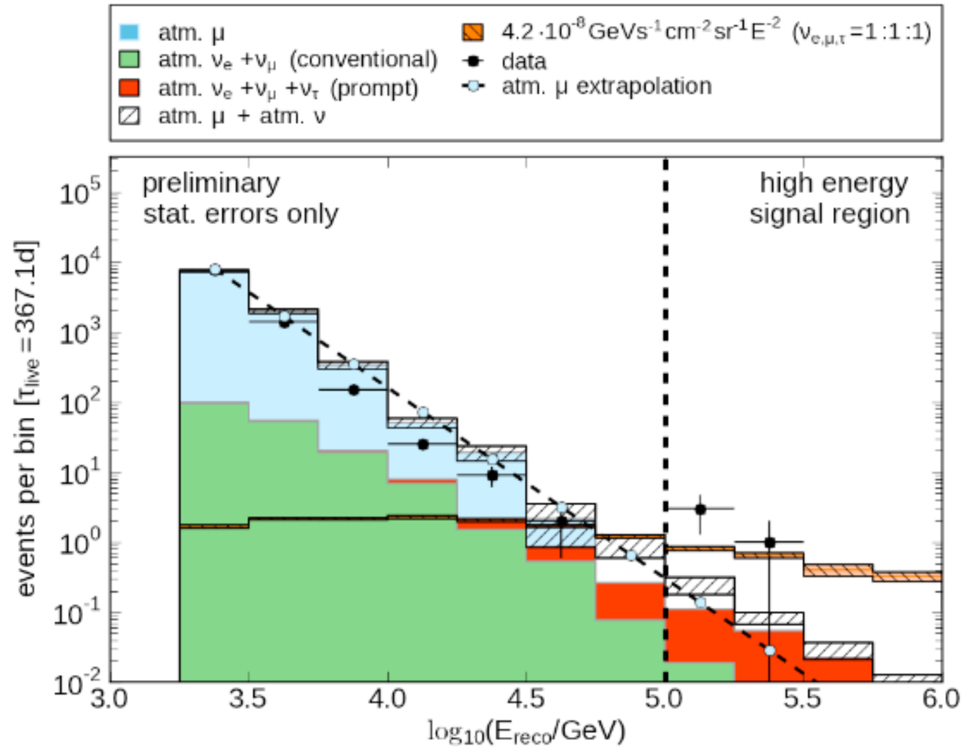
First hints in IceCube analyses (partial detector)

Diffuse muon neutrino search IC59



- Diffuse searches sum up muon neutrino flux from all directions
- Excess in high energy tail: 1.8 σ

Diffuse cascade search IC40



- Excess in high energy tail: 2.1σ

Cosmogenic (GZK) search

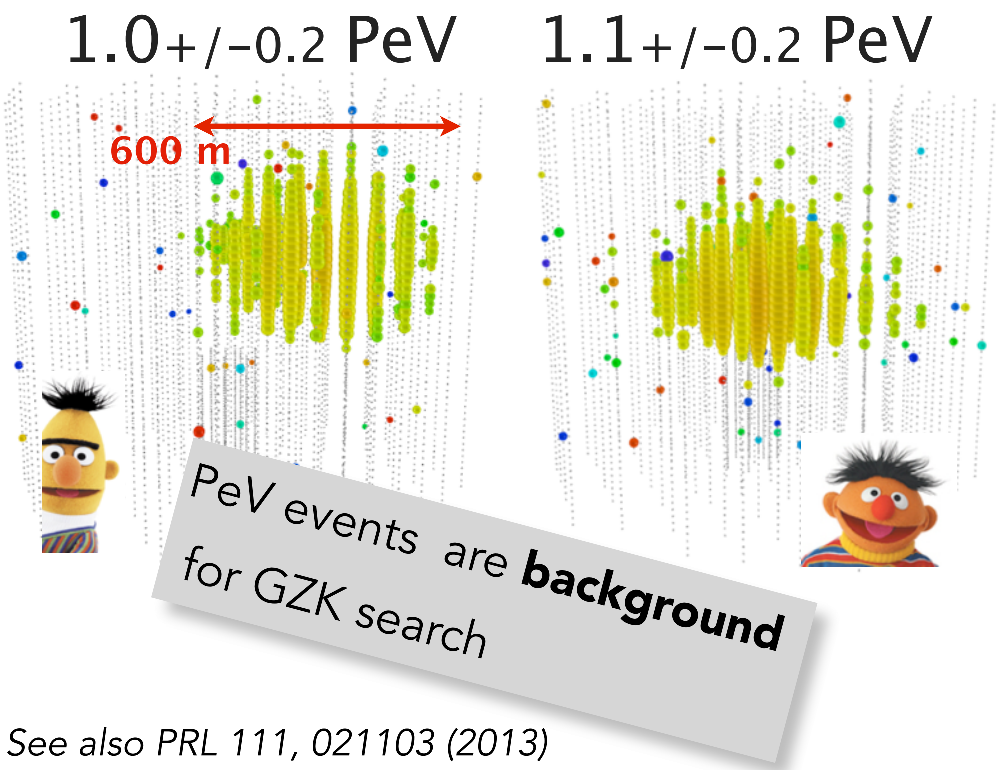
Analysis strategy:

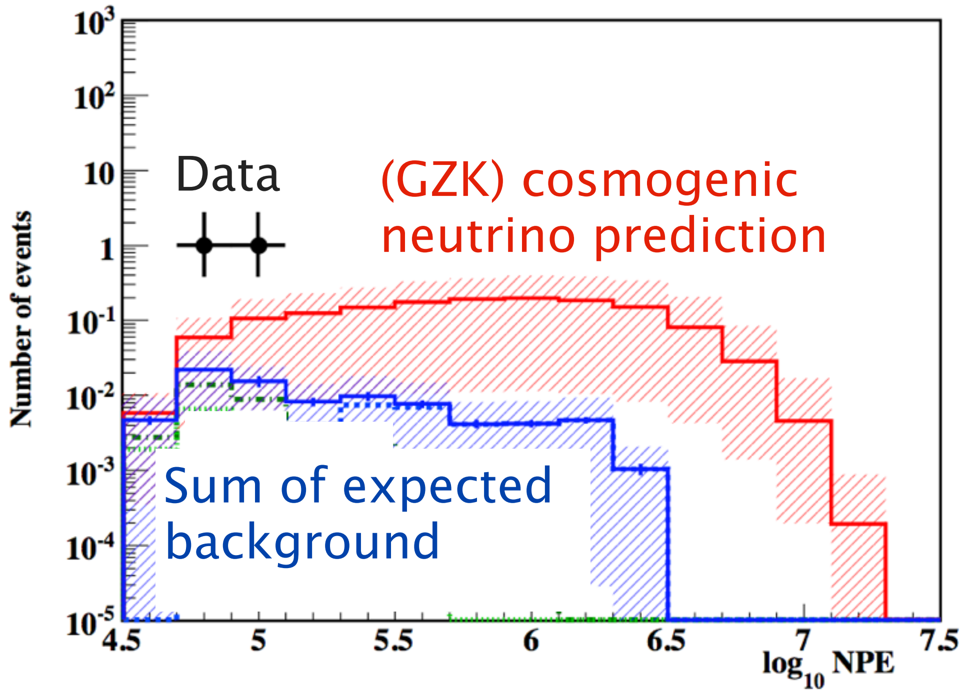
Select starting events with a high number of PE in the detector (>60000 PE, depending on zenith)
Makes analysis sensitive to E_ν> PeV

We found:

2 events in 616 days of livetime between May 2010- May 2012

Expected background: 0.08 ± 0.05 events → 2.8σ excess (Bg-only hypothesis)





See also PRL 111, 021103 (2013)

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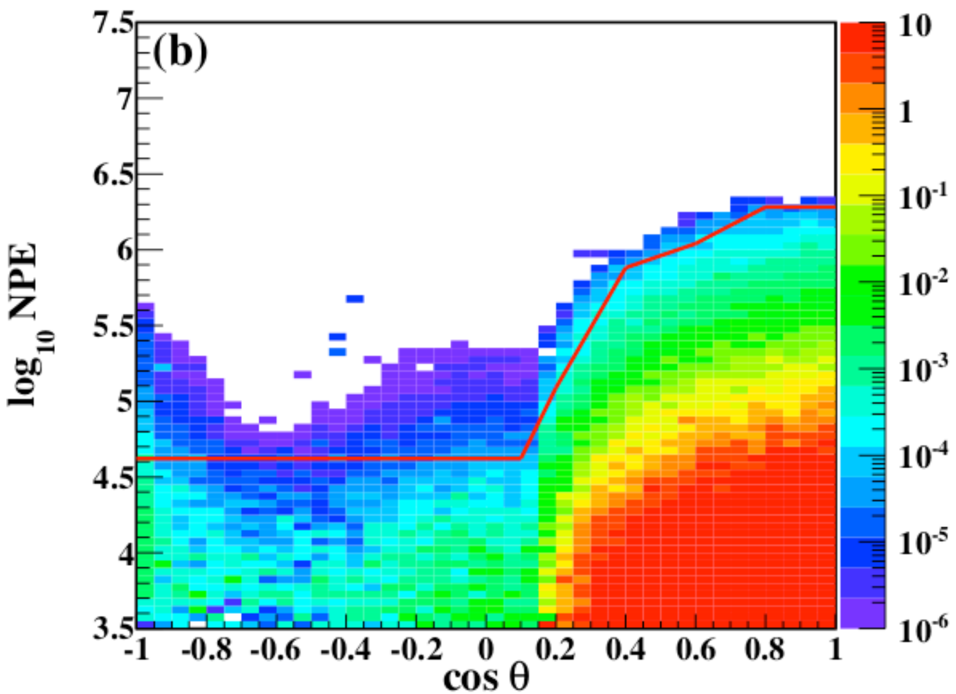
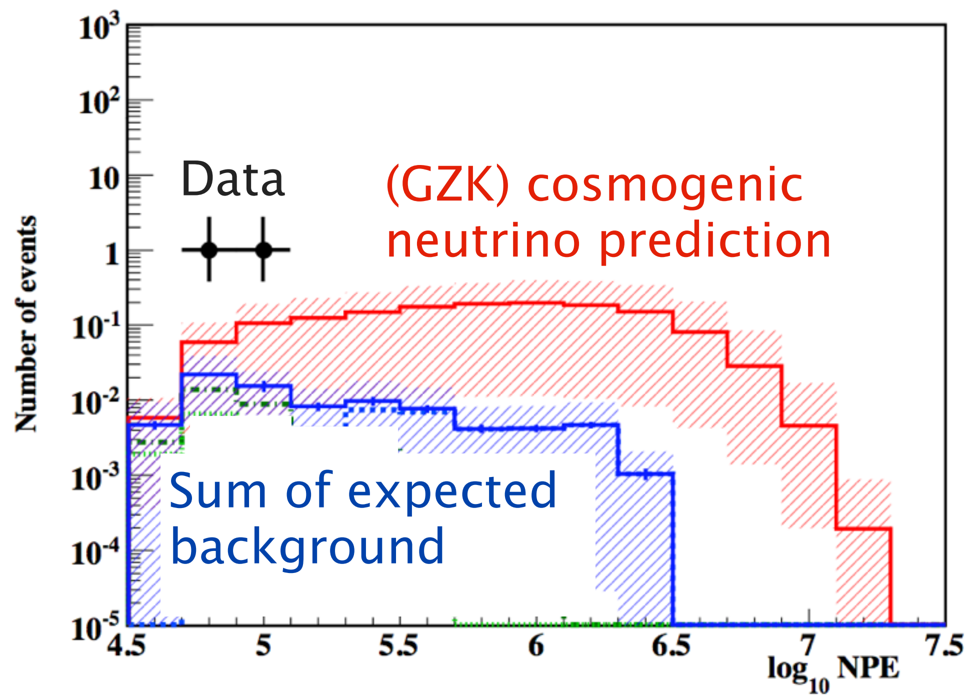
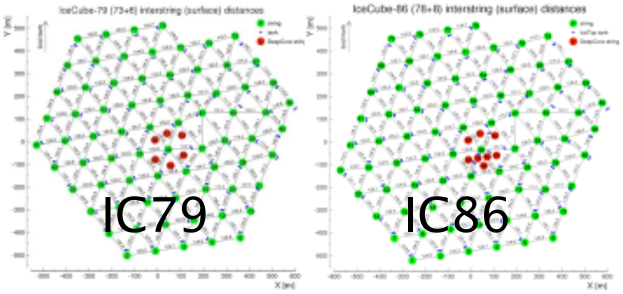




See also PRL 111, 021103 (2013)

Starting event analysis

May 2010 – June 2012



Atmospheric μ bg

Determined from data:

Define a second veto layer and tag events, which pass the first layer

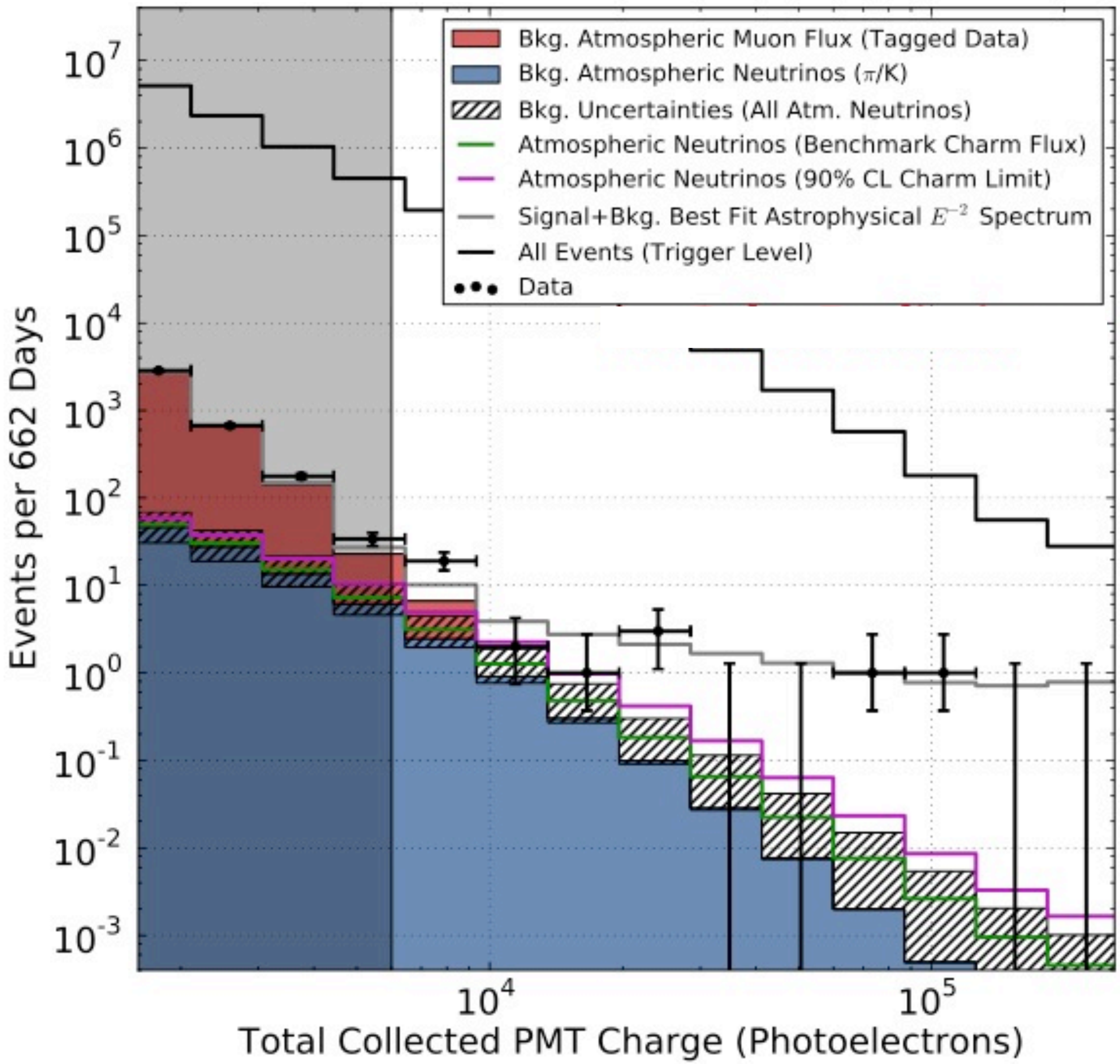
6 +/- 3.4

Atmospheric ν bg

Based on MC & previous IceCube measurements (including prompt flux measurement = 0 + σ)

4.6 +3.7-1.2

Charge threshold 6000 p.e.



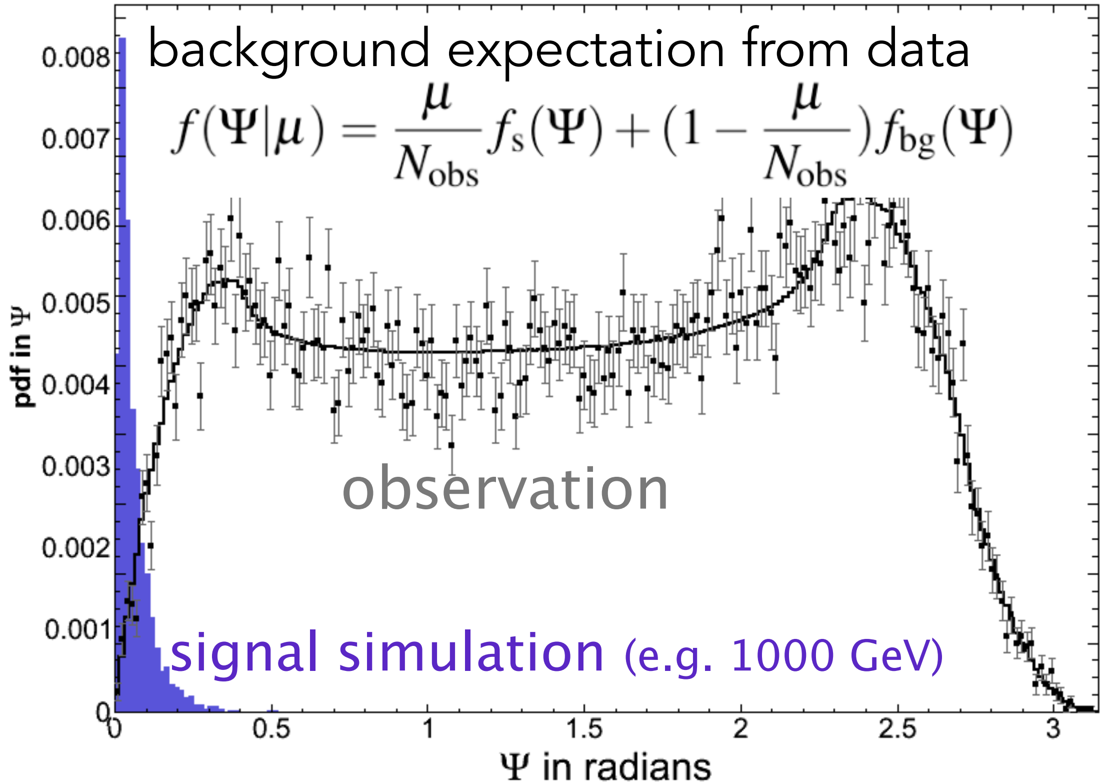
Maximum likelihood analysis

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

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

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

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



(Angle between event track & direction from the Sun)

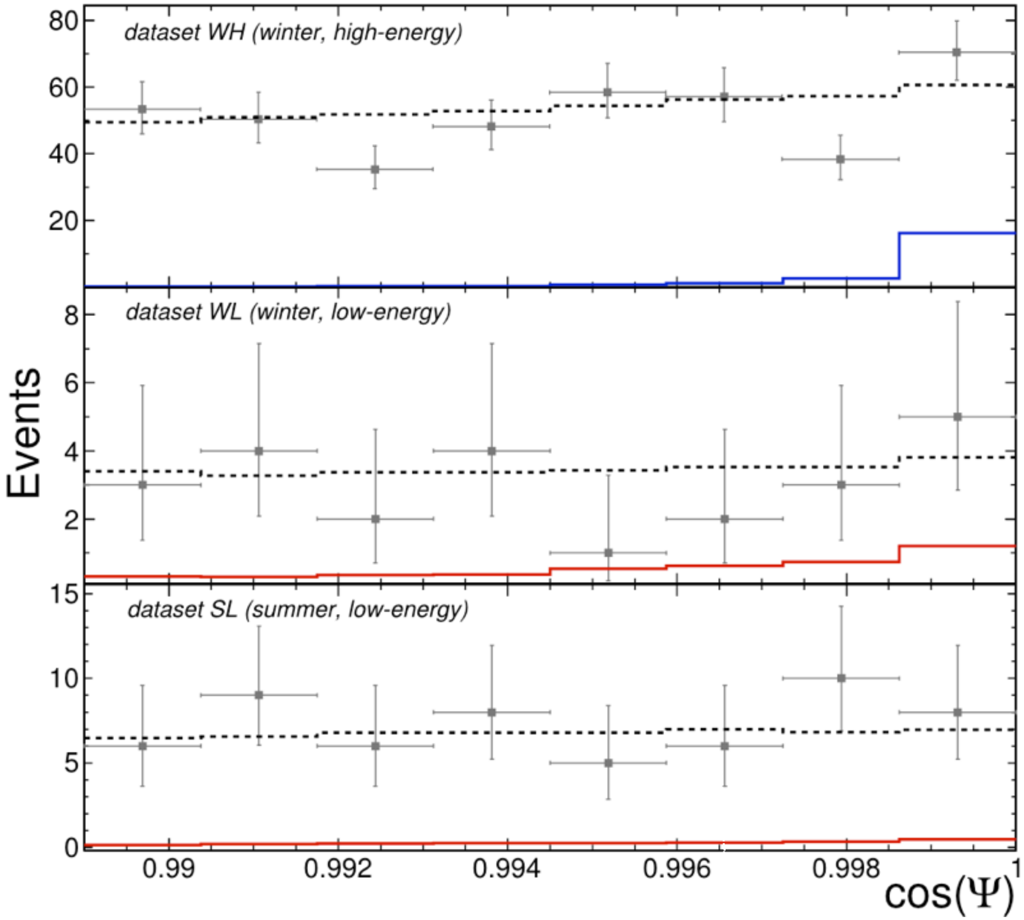
$$\mu_j = \mu \frac{T^j_{live} V^j_{eff}}{T^1_{live} V^1_{eff} + T^2_{live} V^2_{eff}}$$

(scale to multiple datasets)

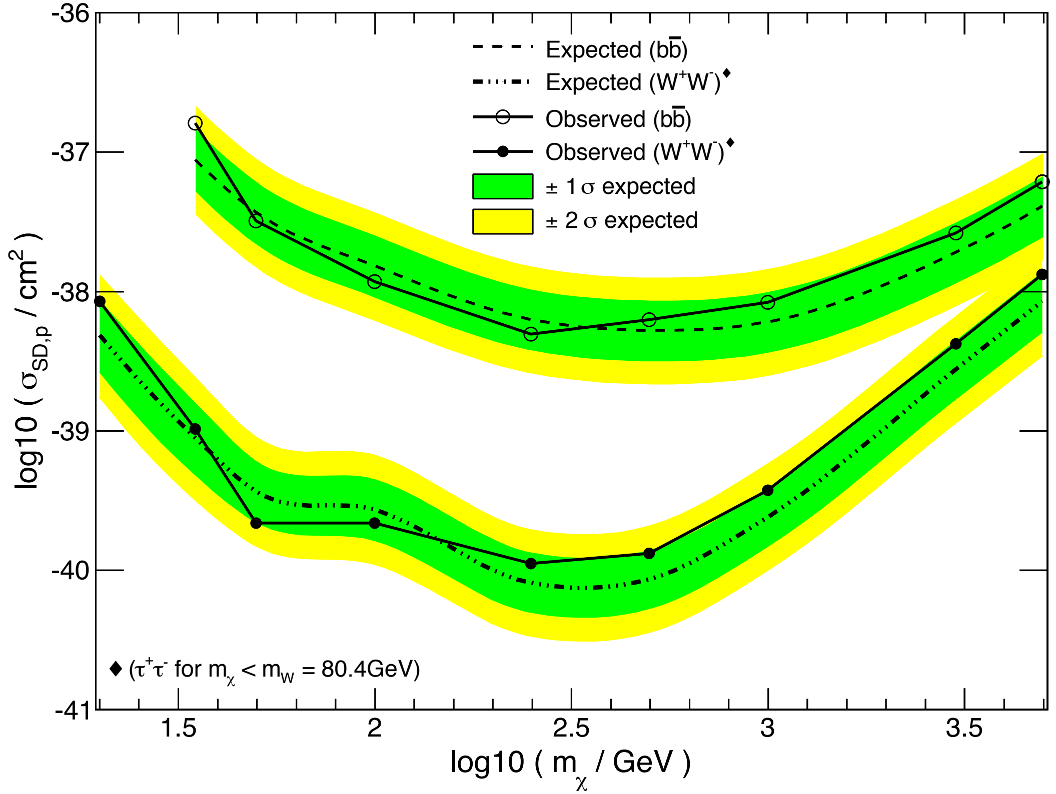
Solar Dark Matter Search - results

ICECUBE

Unblinded events in different samples



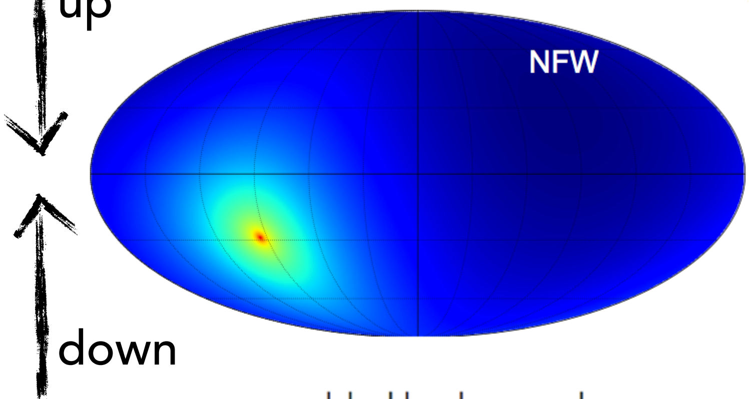
Expected sens. vs. observed result



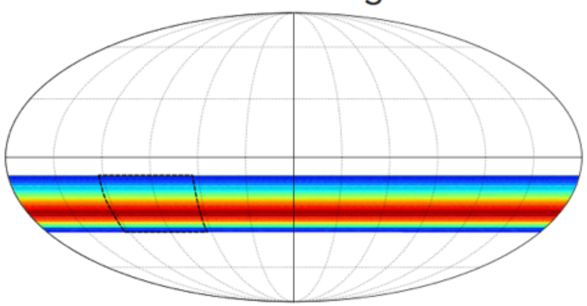
details on systematic uncertainties, see *PRL 110 (2013) 131302*

Galactic Dark Matter Searches

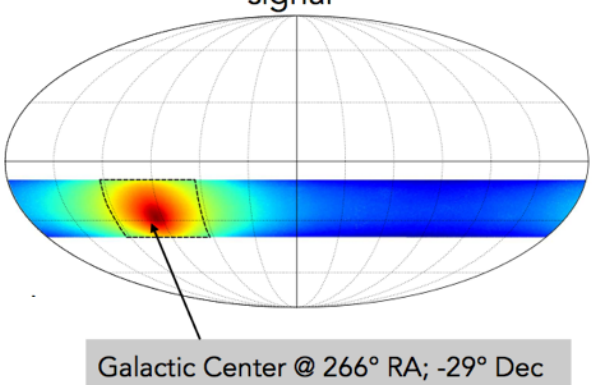
(equatorial coordinates)

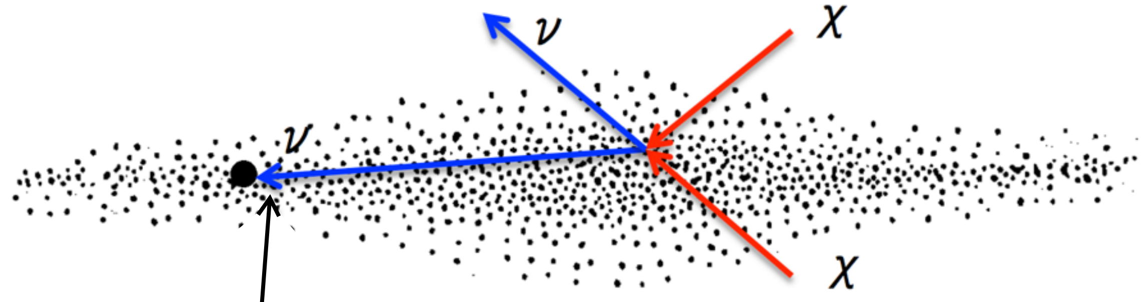


scrambled background



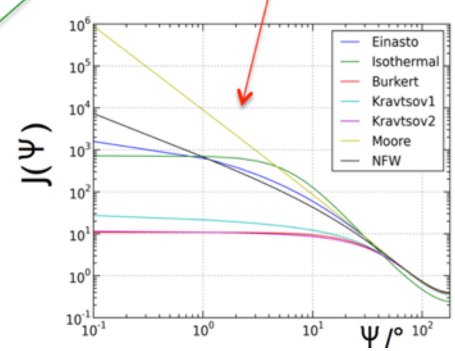
signal

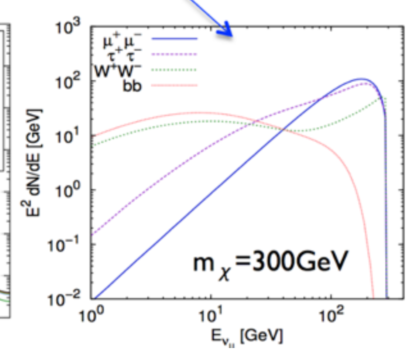




$$\frac{d\phi}{dE} = \frac{1}{2}\frac{1}{4\pi} < \sigma v > J(\Psi) R_{SC} \frac{\rho_{SC}^2}{m_\chi^2} \frac{dN_\nu}{dE}$$

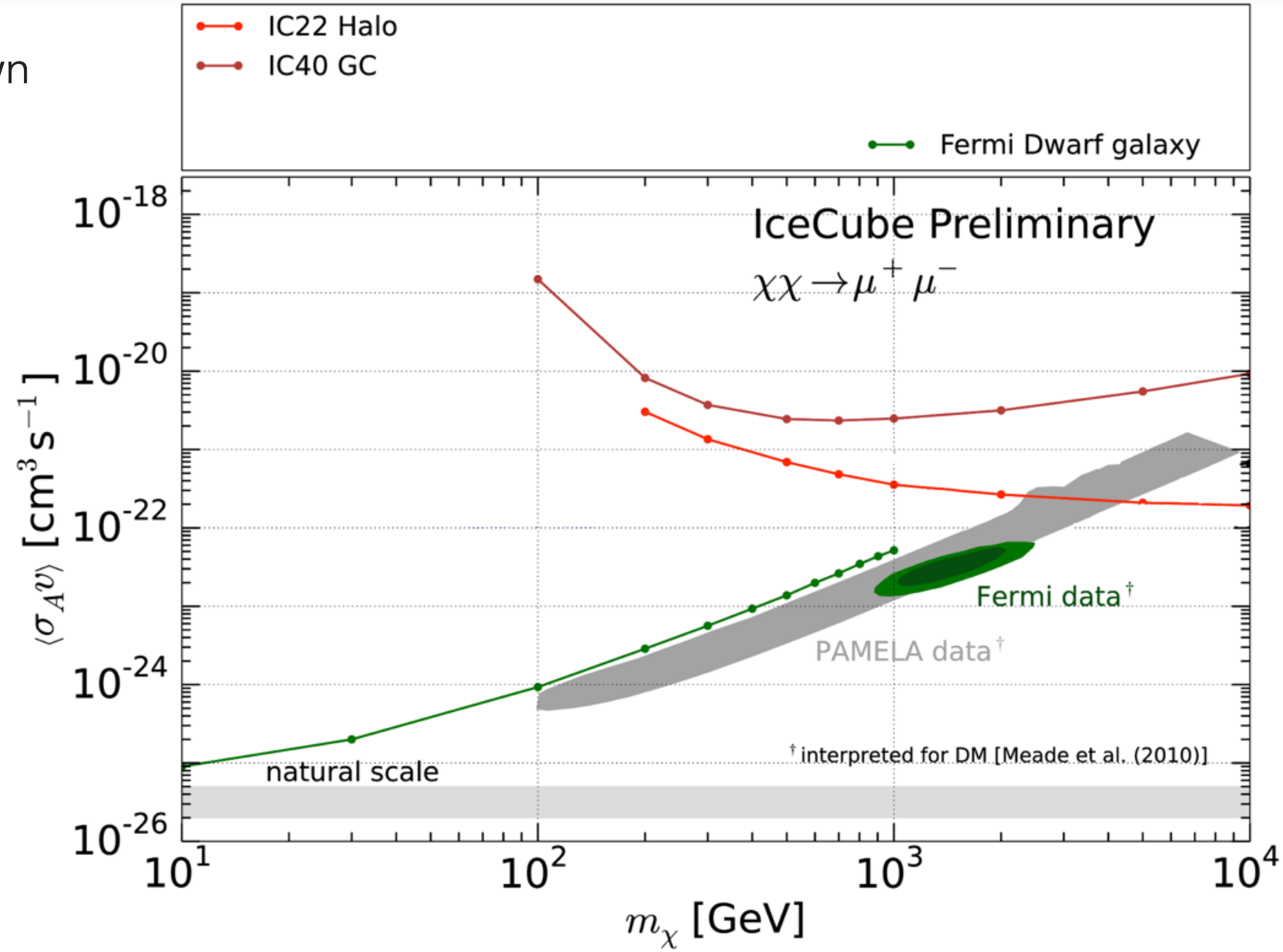
Physics quantity,
to be extracted





Galactic Dark Matter Searches (IceCube-79)

(IceCube results shown for NFW profile)

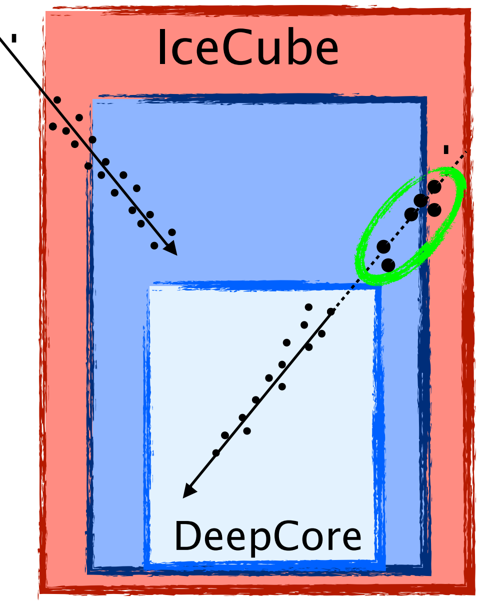


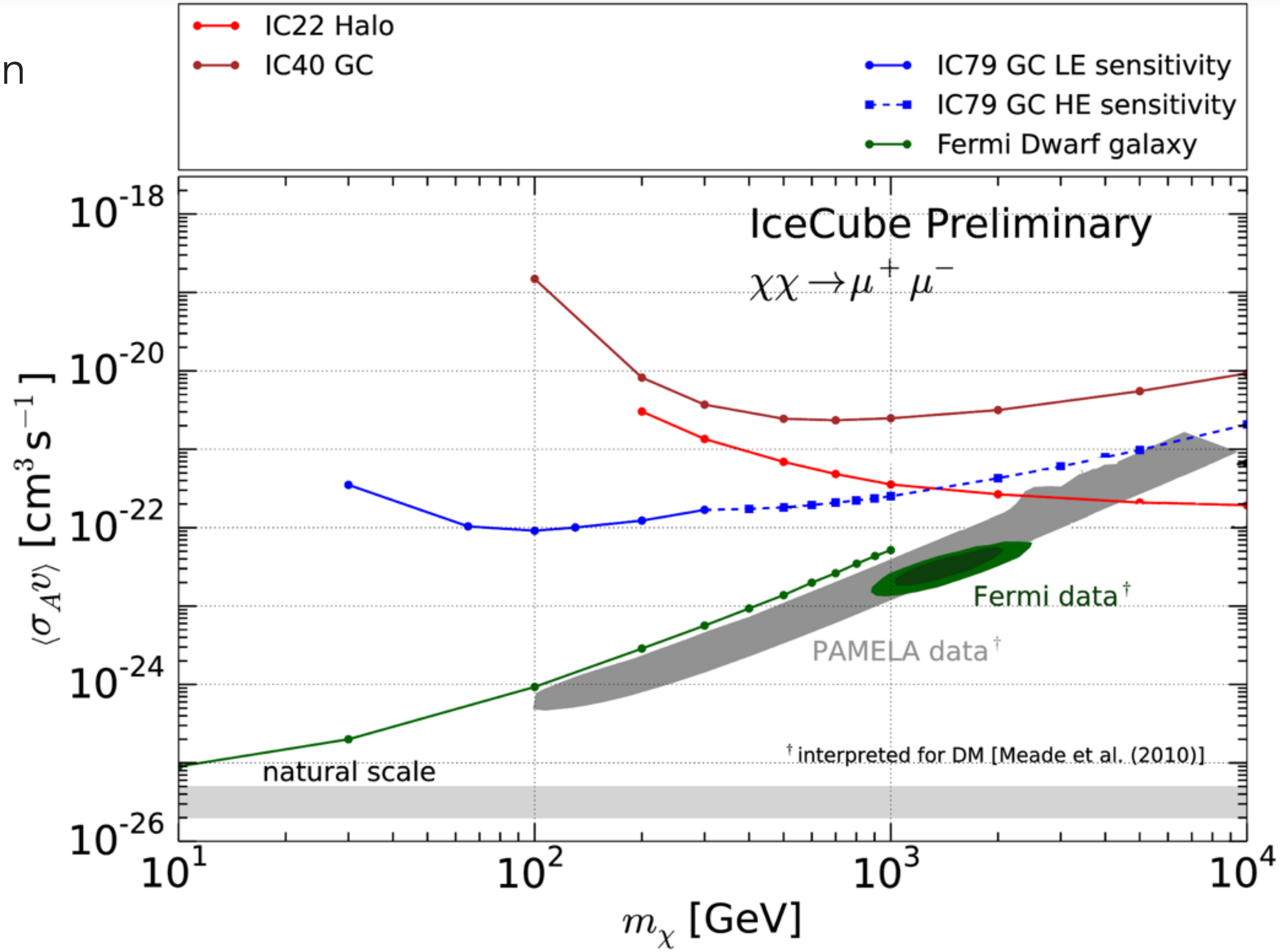
Search for many interesting potential annihilation channels:
(Various DM-Halo models tested)

$\chi\chi$ { νν, μμ, ττ, WW, bb
ZZ, Zγ }

Galactic Dark Matter Searches (IceCube-79)

(IceCube results shown for NFW profile)



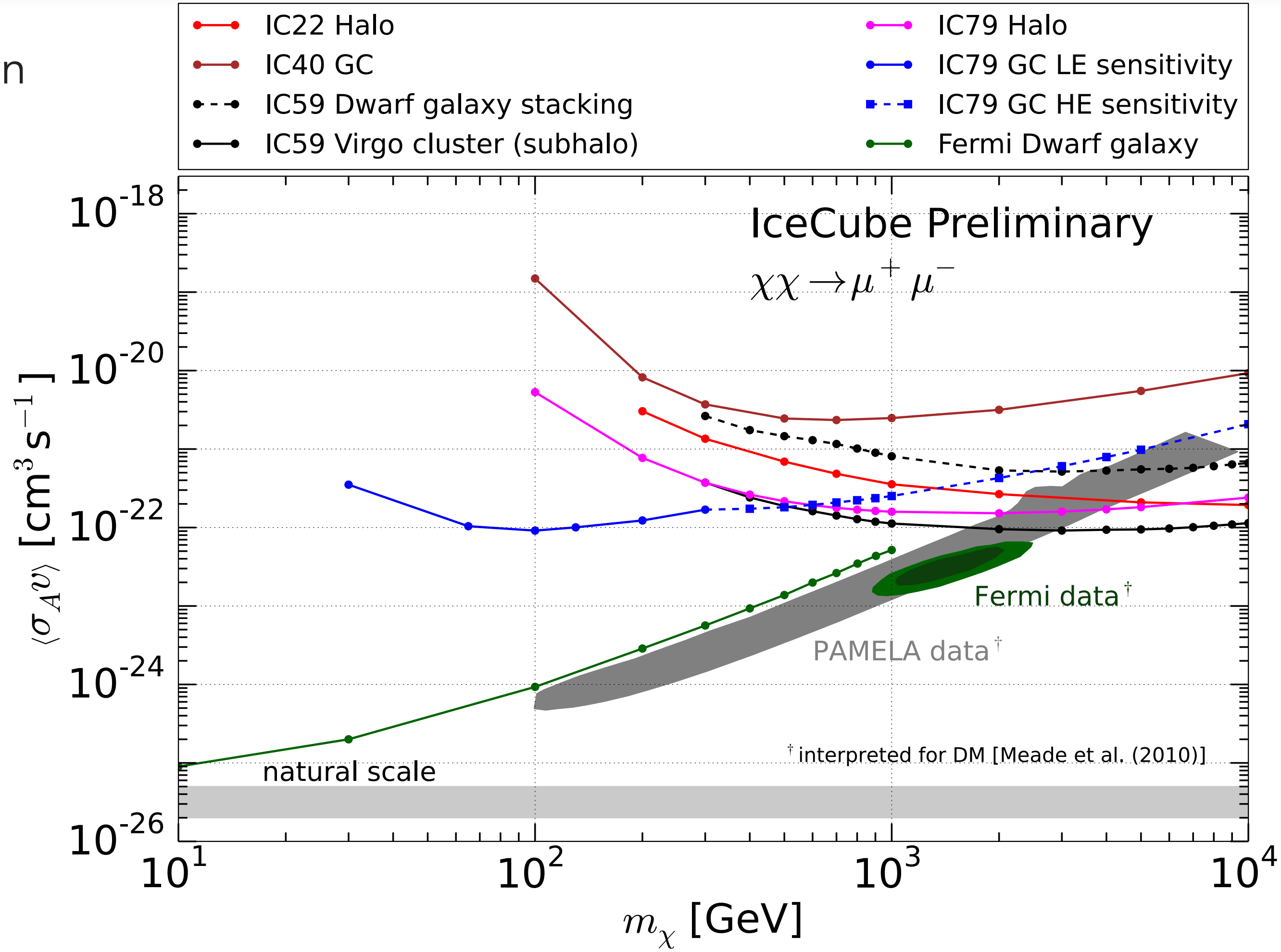


IceCube-79 Galactic Center analysis:

- First IceCube analysis looking at GC for low WIMP masses (< 100 GeV)
- Up to 4 orders of magnitude improved sensitivity @ 100 GeV
- Results are compatible with background only

Galactic Dark Matter Searches (IceCube-79)

(IceCube results shown for NFW profile)



IceCube-59 Dwarf galaxy searches:

- Source stacking analysis
- Optimized size of search window

IceCube-59 Galaxy cluster analysis:

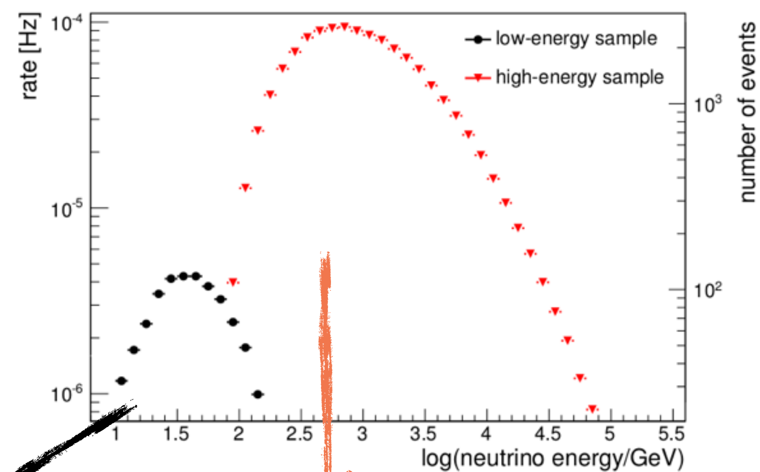
- Extended point source search
- Optimized size of search window
- Substructures taken into account

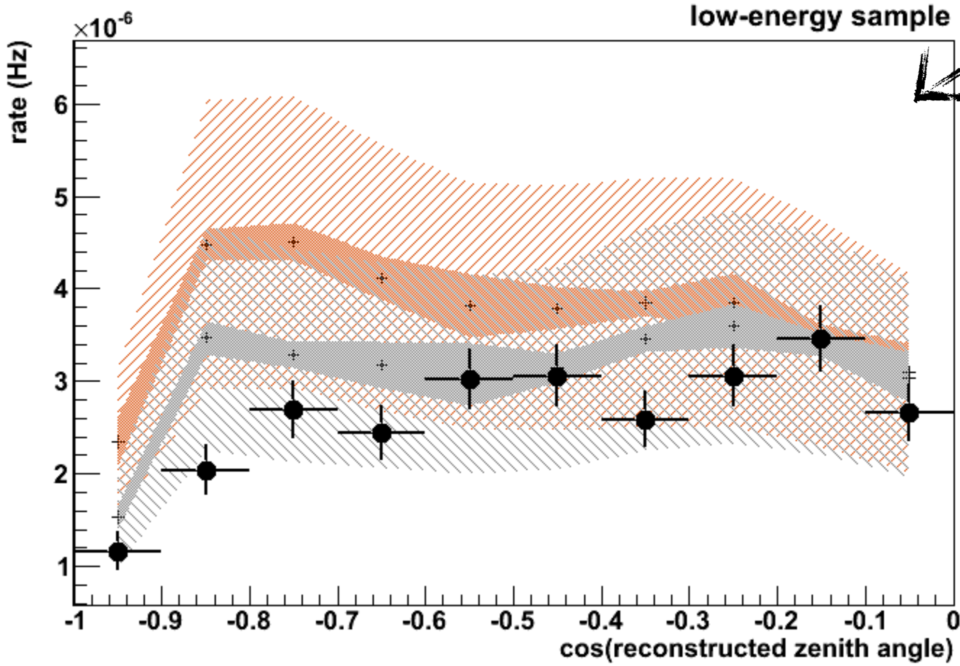
Neutrino oscillations - first analysis

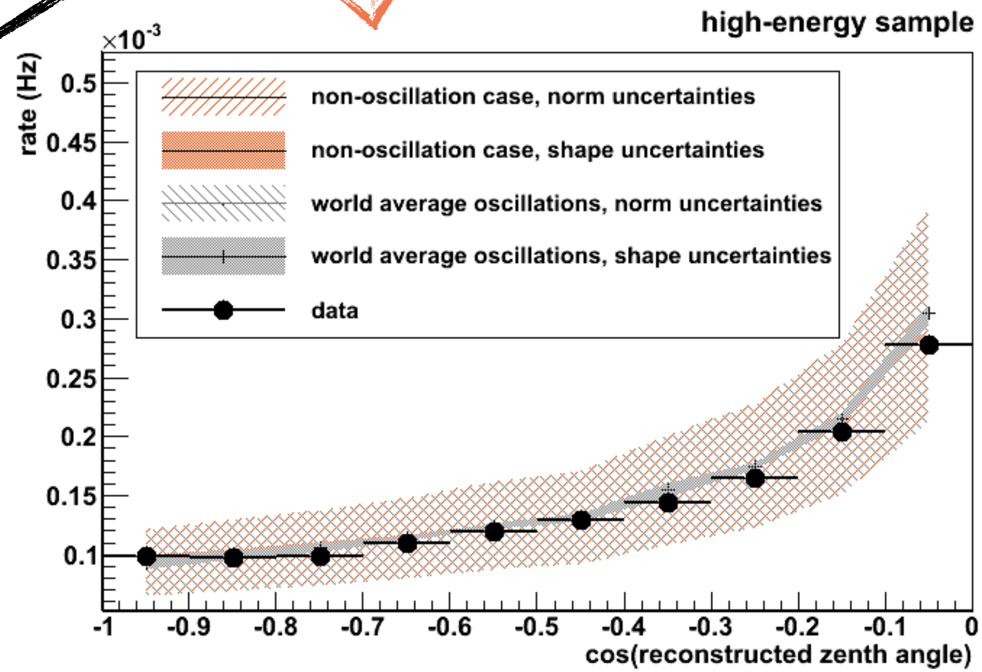
νμ – disappearance analysis:
- first analysis: Zenith angle only

(PRL accepted, arXiv:1305.3909)

- Significant zenith angle deviation in Low-energy sample







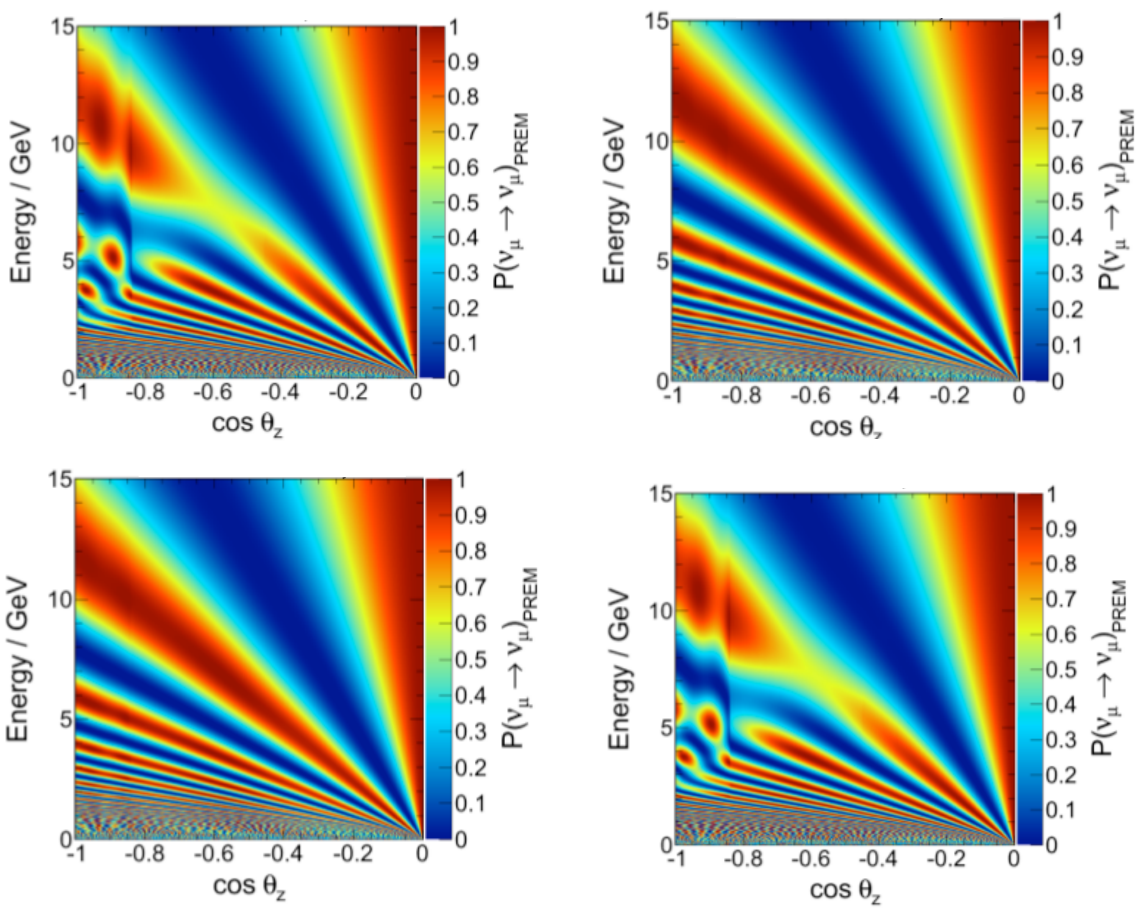
Analysis strategy - mass hierarchy

- Atm. neutrinos oscillations with resonant ν_e conversion in high electron densities in the Earths core
- Measurement looks for difference between patterns A & B

ν_μ | anti-ν_μ

Normal Hierarchy = [pattern A]

Inverted Hierarchy = [pattern B]



Without ability to distinguish ν_μ from anti-ν_μ, A=B...

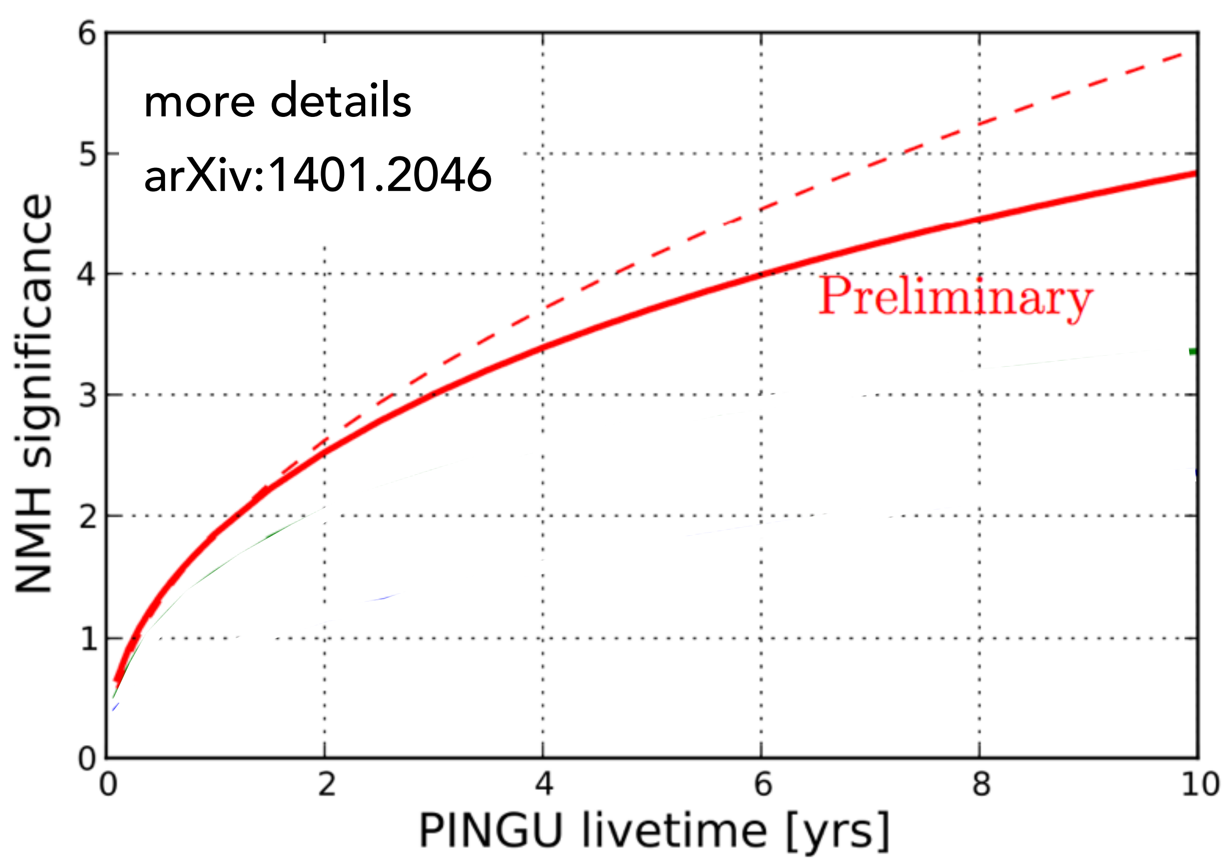
Analysis strategy - mass hierarchy

- Atm. neutrinos oscillations with resonant νe conver... ...igh electron densities in the Earths core
- Measurement looks for difference between patt...

But:

$\sigma(\nu) \sim 2\sigma(\text{anti-}\nu)$

$\varphi(\nu_{atm}) > \varphi(\text{anti-}\nu_{atm})$



= [pattern A]

...hout ability to ... from anti-... ...

Now A≠B!

= [pattern B]