10th Rencontres du Vietnam Aug 3 – 9

Very High Energy Phenomena in the Universe 2014

ICECUBE

Pingu and IceCube Dark Matter Results

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August 3 - 9, 2014

The IceCube–PINGU Collaboration

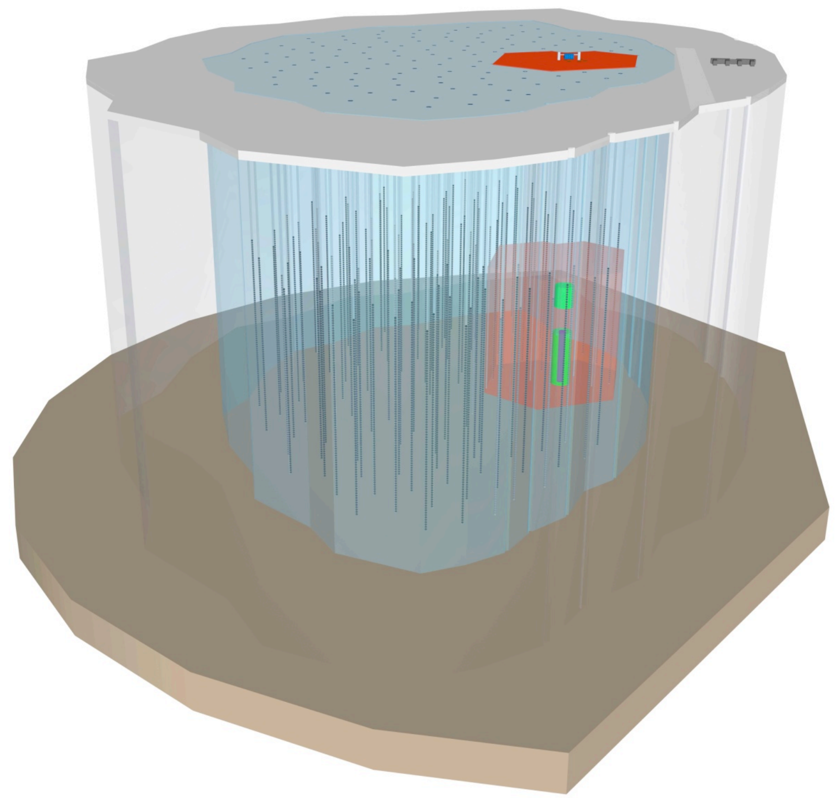
International Funding Agencies

Fonds de la Recherche Scientifique (FRS–FNRS)
Fonds Wetenschappelijk Onderzoek–Vlaanderen (FWO–Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen–Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
NSF–Office of Polar Programs
NSF–Physics Division
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

About 40 institutions and 300 members.

Overview

- Motivation
- PINGU Design
- PINGU Sensitivity
- PINGU Physics Potential
- Dark Matter Searches with IceCube
- Conclusions



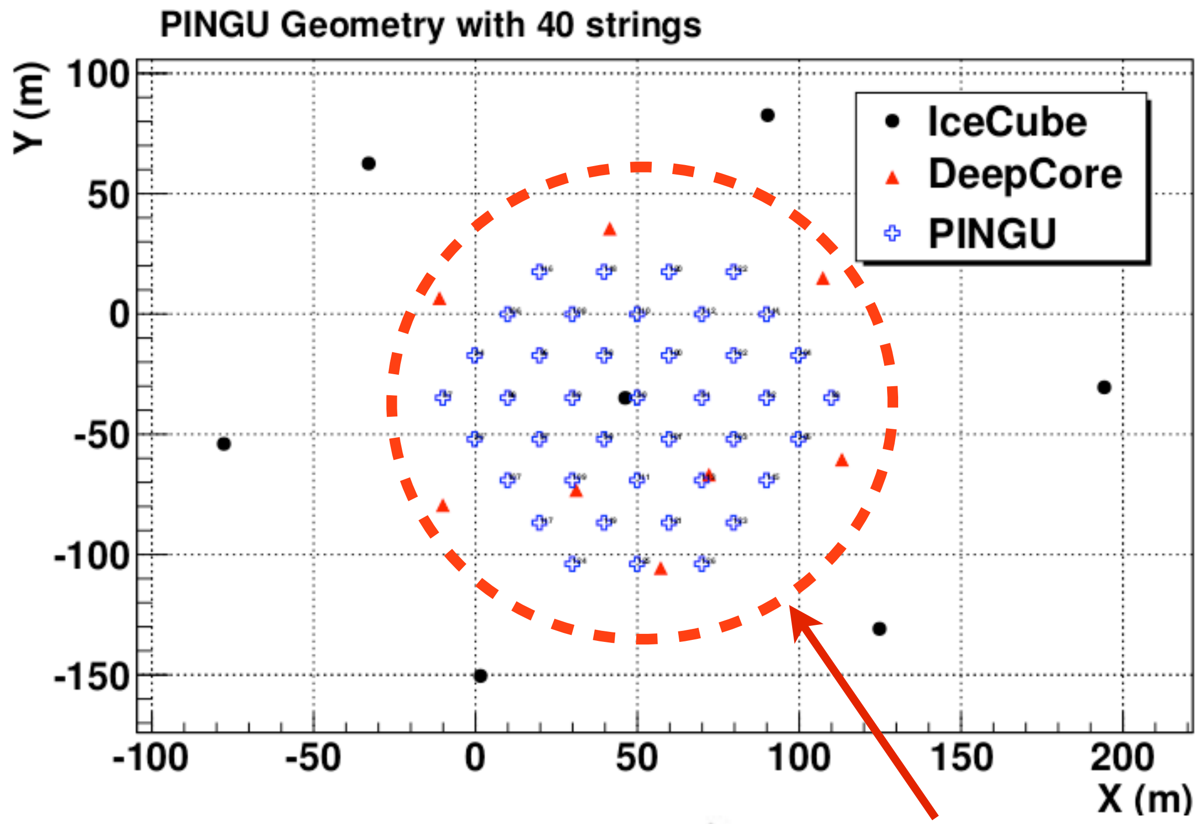
Future Plans @ South Pole

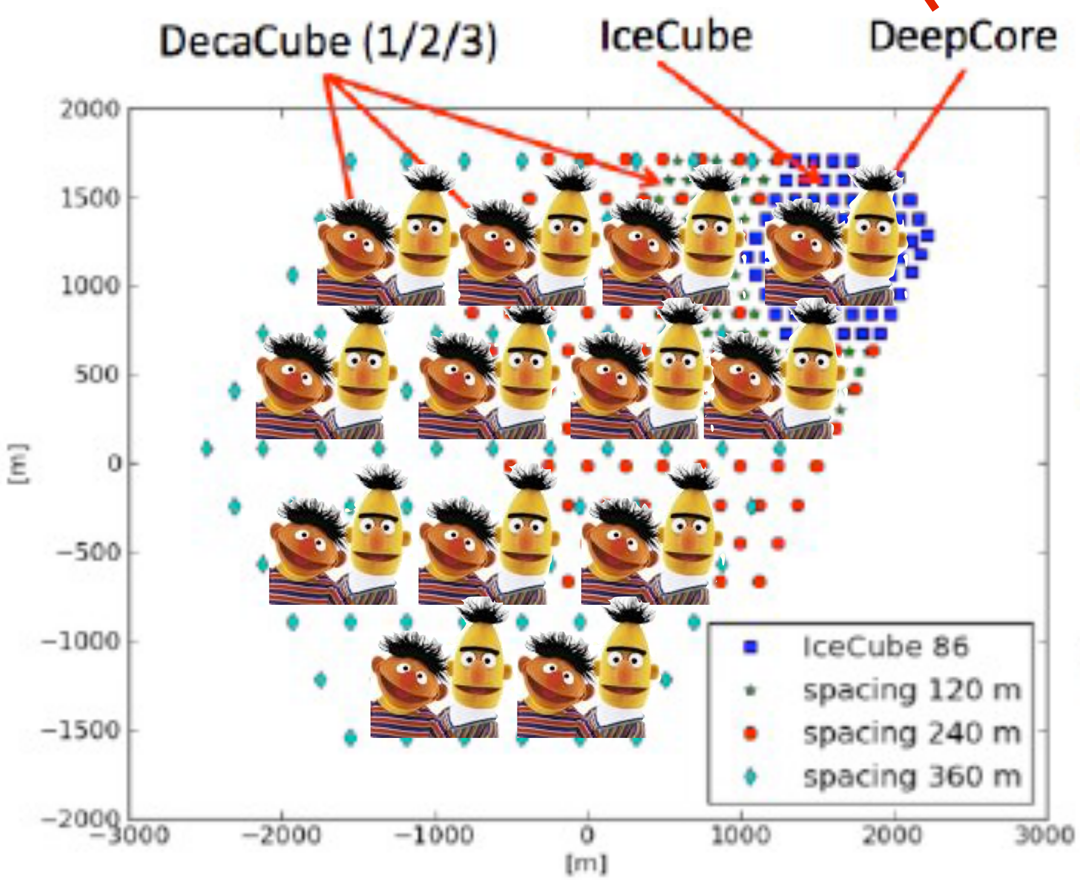
Future of IceCube

- Make it better
  - Precision detector with ~GeV threshold

- Make it bigger

see talk by Aya Ishihara





Spacing 1 (120m):
IceCube (1 km³)
+ 98 strings (1,3 km³)
= 2,3 km³

Spacing 2 (240m):
IceCube (1 km³)
+ 99 strings (5,3 km³)
= 6,3 km³

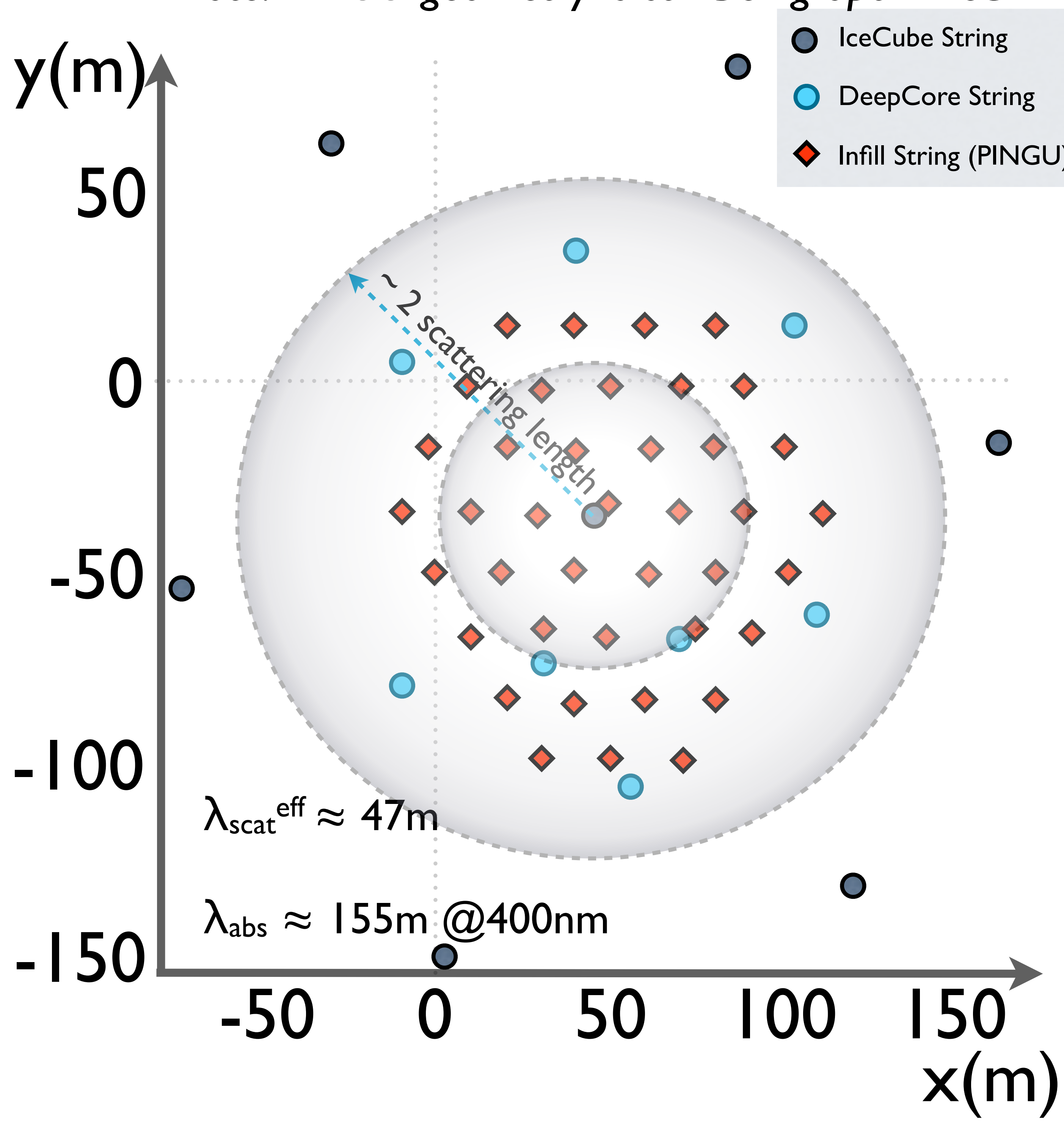
Spacing 3 (360m):
IceCube (1 km³)
+ 95 strings (11,6 km³)
= 12,6 km³

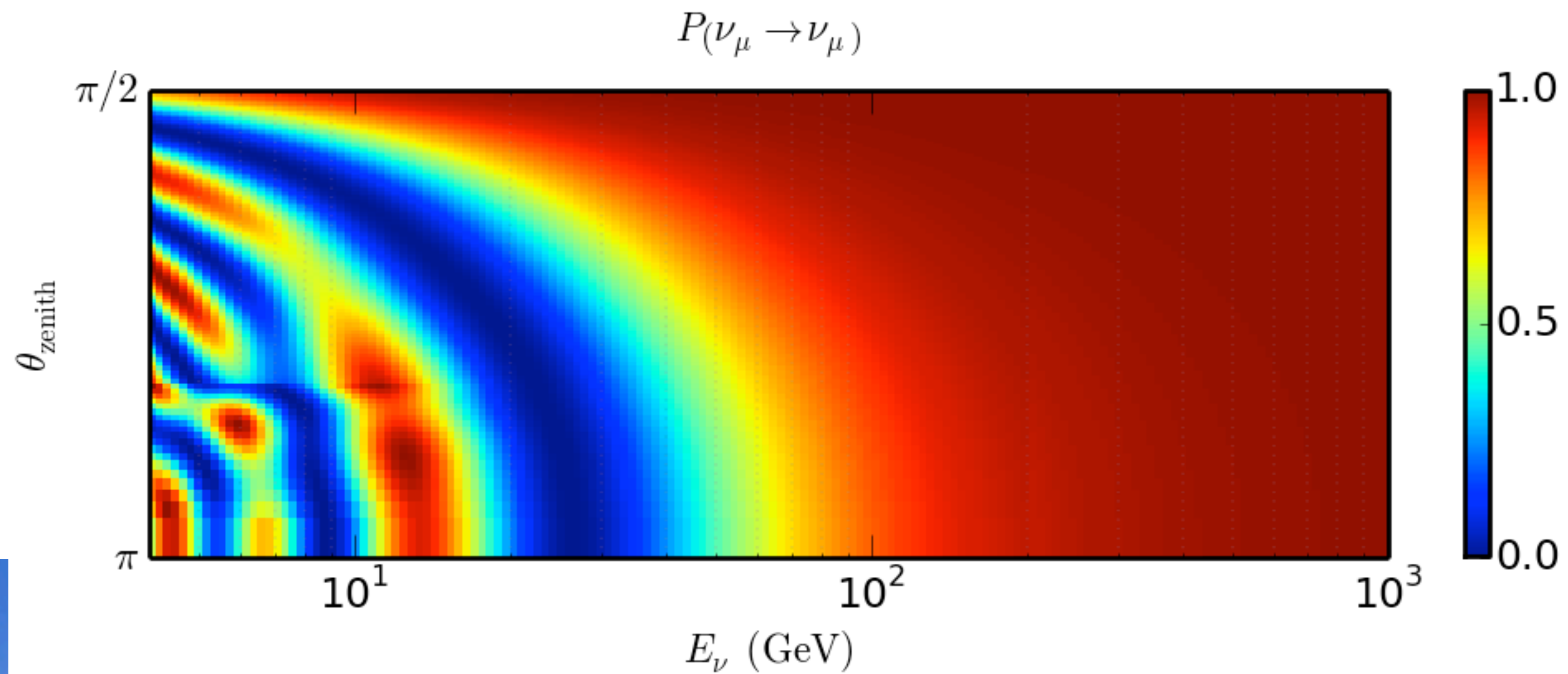
PINGU - Precision IceCube Next Generation Upgrade

- PINGU upgrade plan
  - Instrument a volume of about 5MT with ~40 strings each containing 60-100 optical modules
  - Rely on well established drilling technology and photo sensors
  - Create platform for calibration program and test technologies for future detectors
- Physics Goals:
  - Precision measurements of neutrino oscillations (mass hierarchy, ...)
  - Test low mass dark matter models

An example PINGU geometry (40 strings)

Note: PINGU geometry is still being optimized



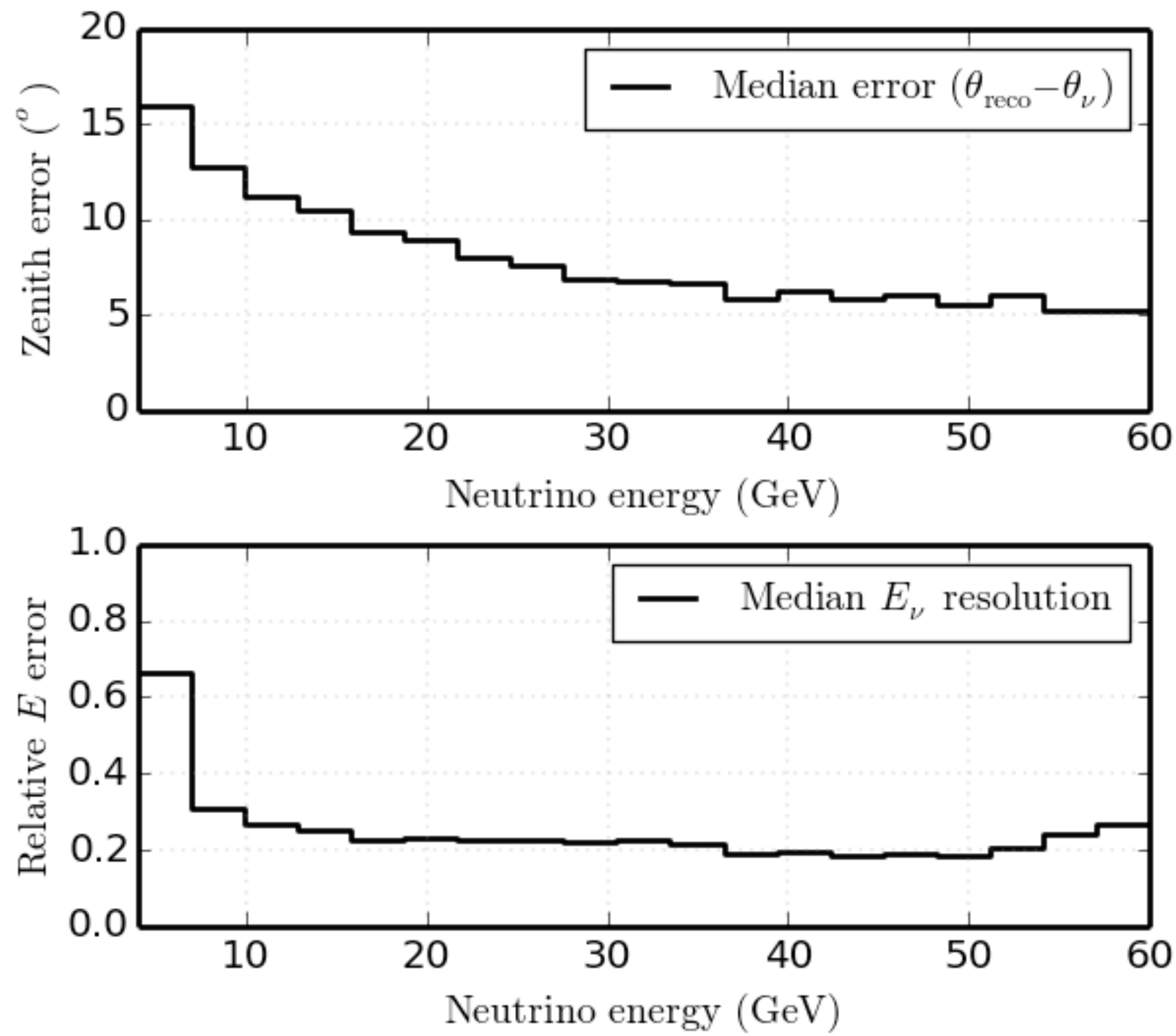


Neutrino Oscillations in IceCube

Event Sample (Final Selection Cut level)

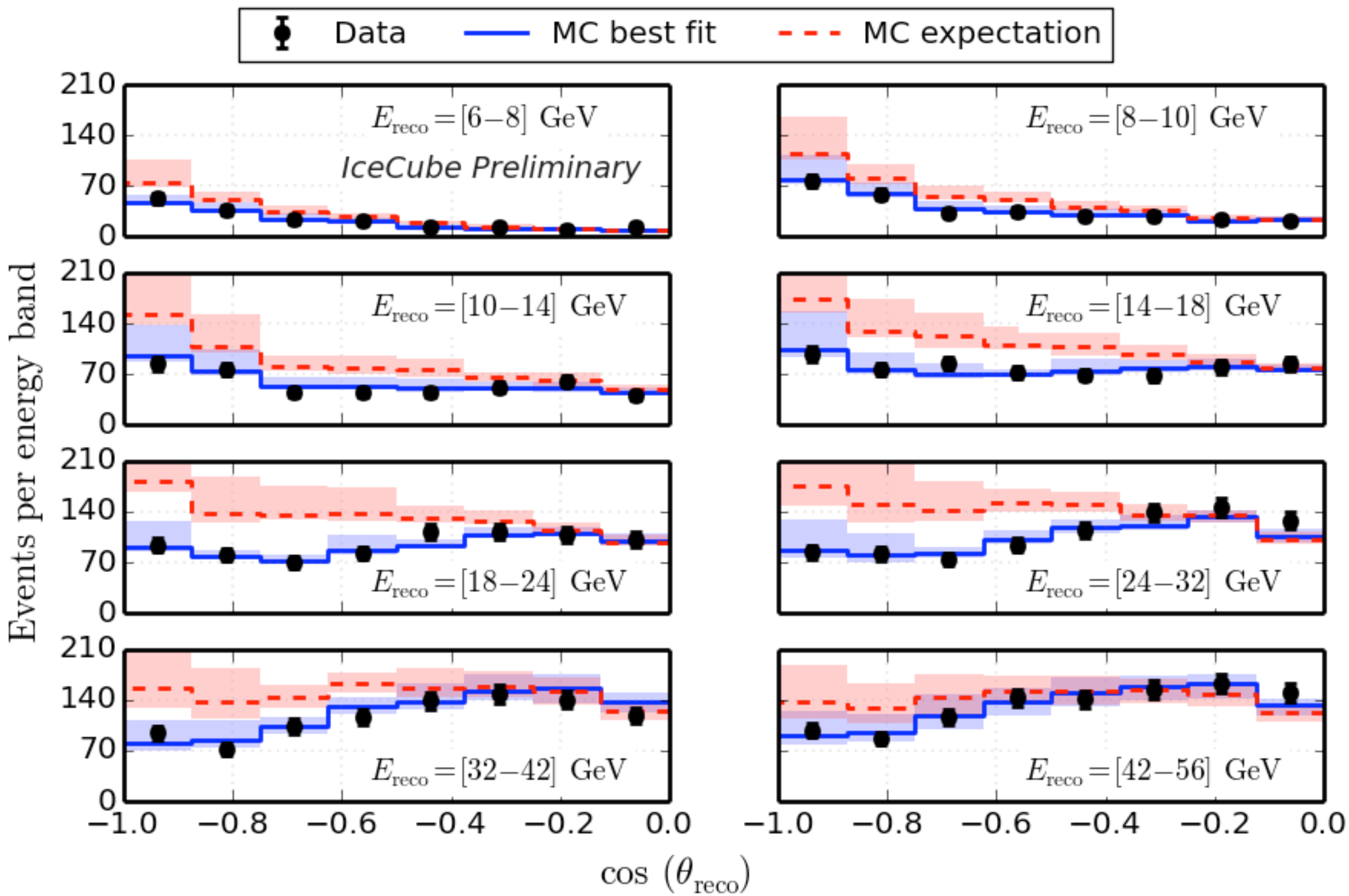
- 3 years of full detector configuration (IC86)
    - 2011-2014
        - 953 days of detector livetime
- MC expectation: ~ 7,000 events
    - Disappearance of ~ 1,900
- Energy threshold ~ 10 GeV
- Zenith angle: 12 deg. res. at 10 GeV
    - Low energy side: 15 deg. res.
    - High energy: 5 deg. res.
- Energy: 30% res. at 10 GeV
    - Reliable above 10 GeV
    - Above 50 GeV muons leave the detector

Resolutions of the final sample

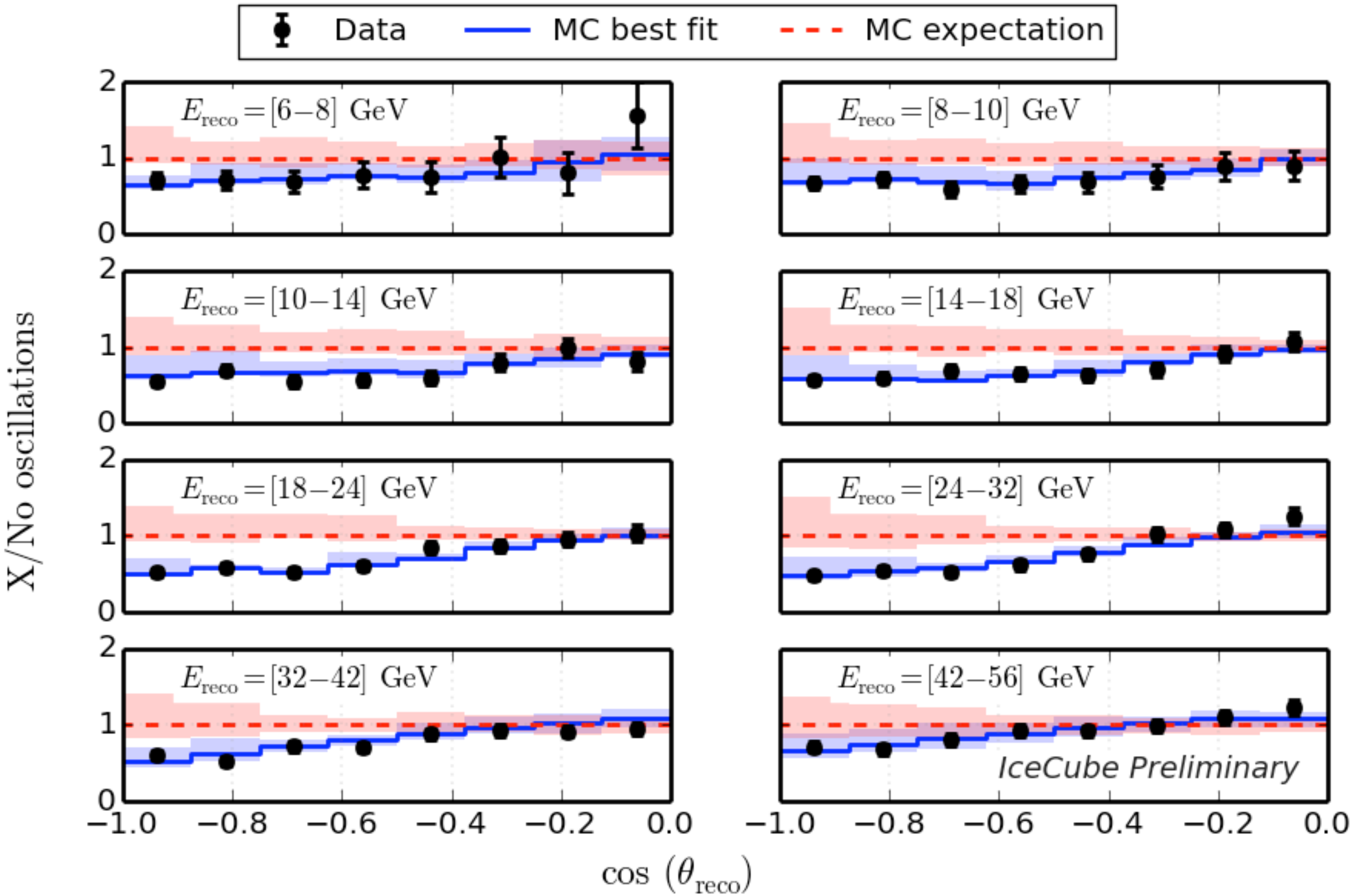


Data/MC Agreement

- Solid lines: Best fit (with osc.) and MC expectation (no osc.)
- Bands: variations allowed by the systematic uncertainties assumed



Ratio to MC expectation (2D histogram analyzed)

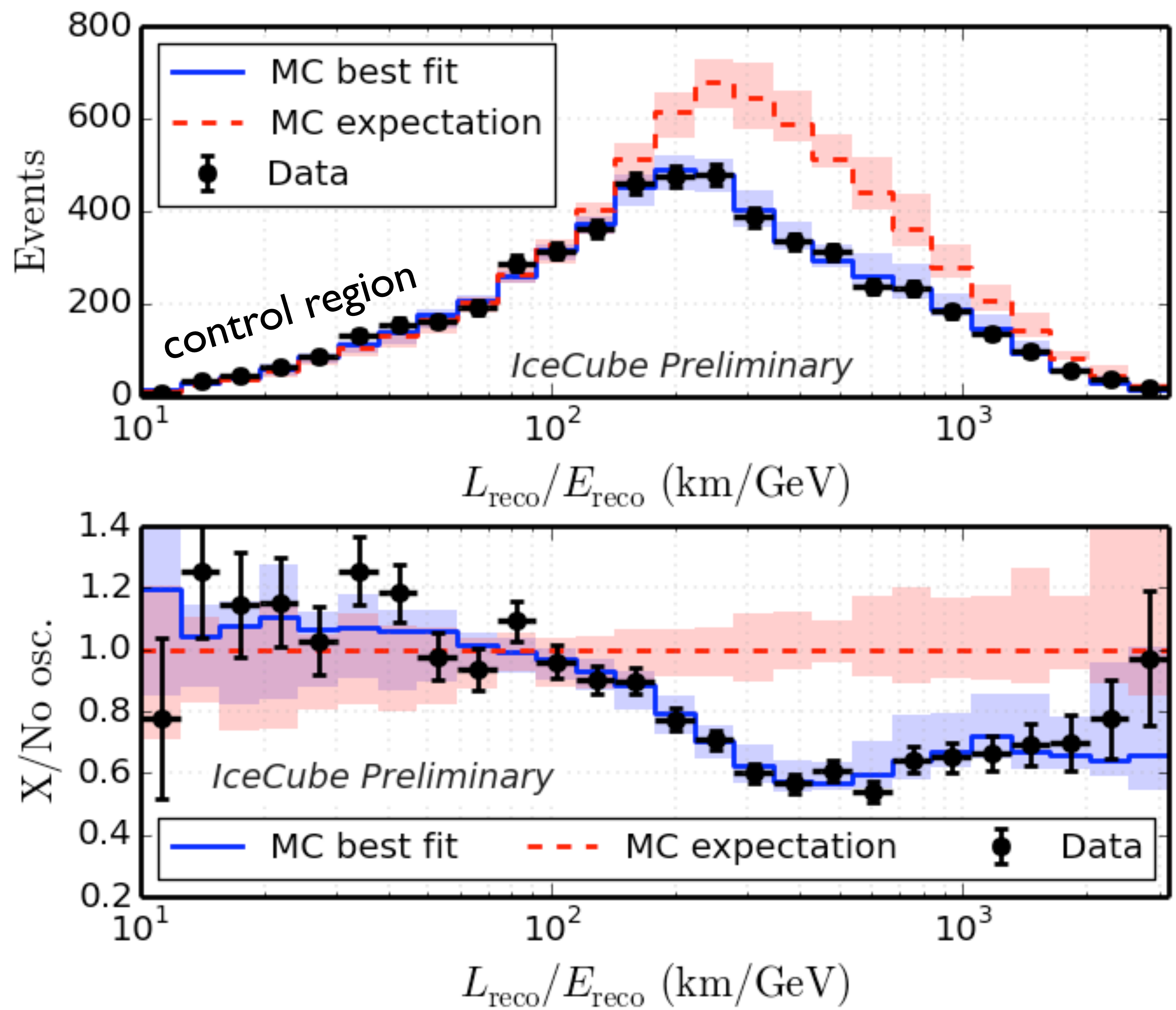


L/E (for display)

Data as function of reconstructed L/E

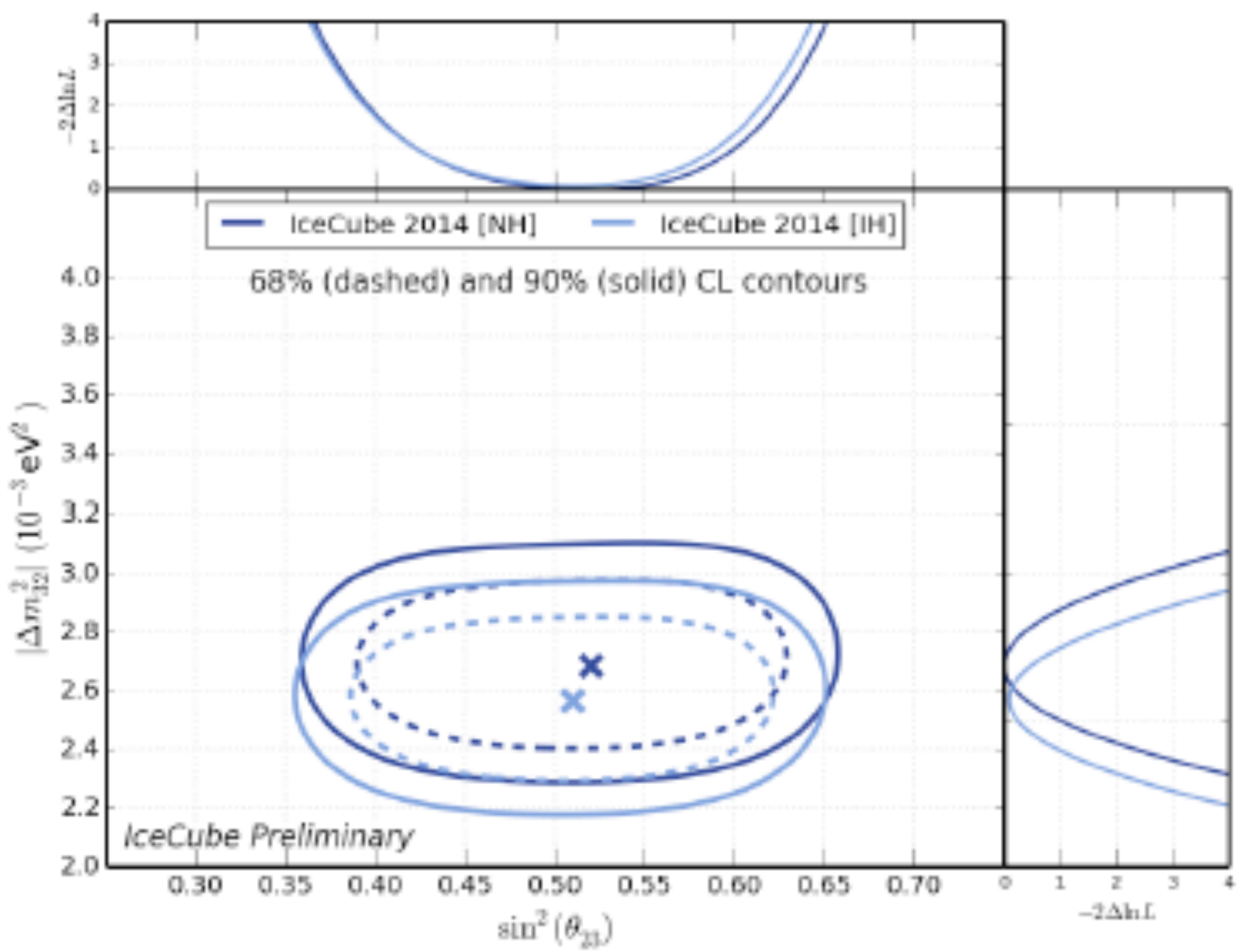
Highest statistics for disappearance maximum

Oscillation maximum is observed as well as rise



Results

Parameter	Normal hierarchy		Inverted hierarchy	
	Best fit	68% CI	Best fit	68% CI
$\sin^2(\theta_{23})$	0.512	0.422 – 0.600	0.509	0.417 – 0.594
Δm^2_{32} $(10^3\ \mathrm{eV}^2)$	2.684	2.503 - 2.877	2.563	2.385 - 2.754

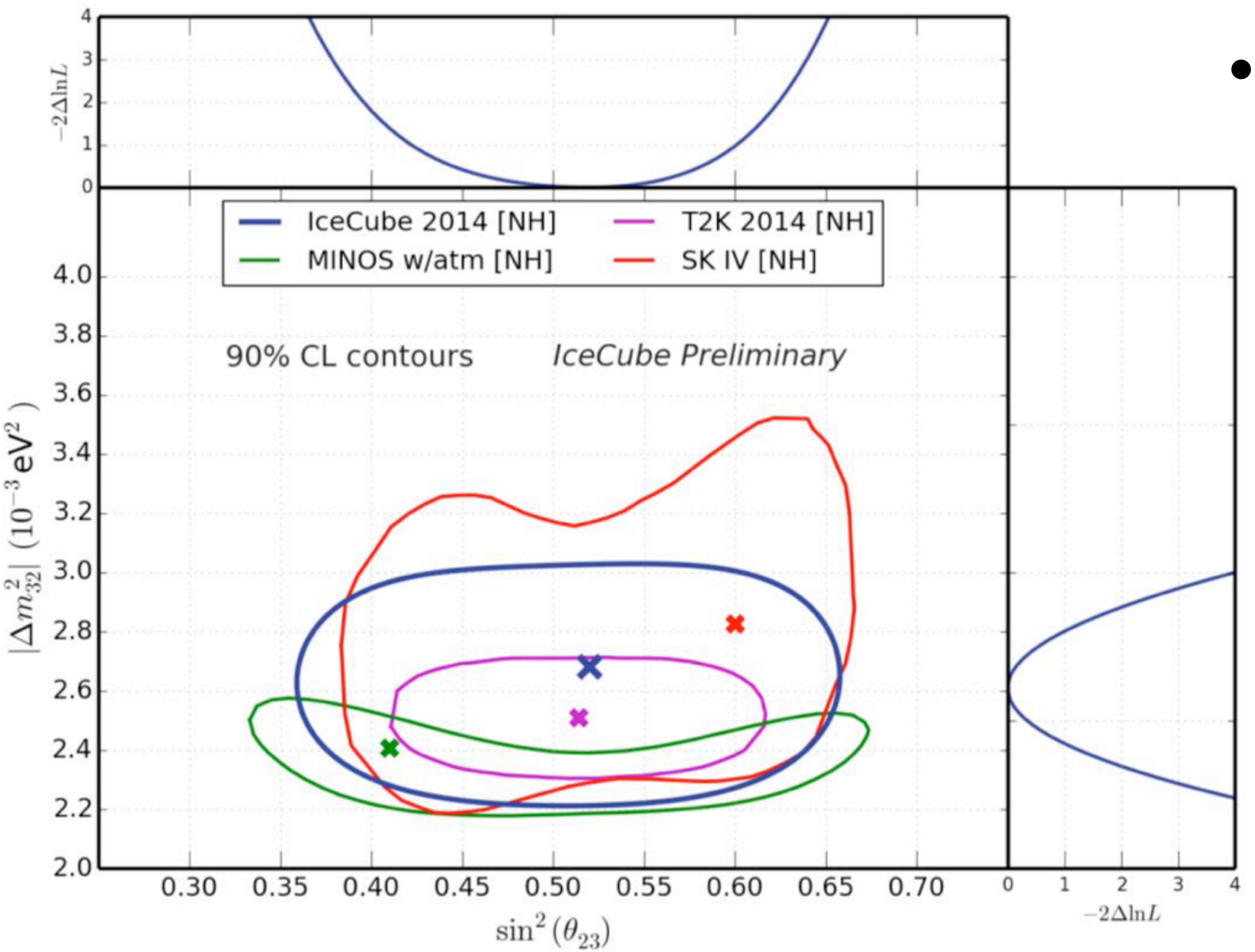


5293 events selected (2011-2014)
$\chi^2 = 45.5 / 56$ dof
No preference for NH vs IH
1σ preference matter/vacuum

Parameter	Deviation at best fit
Flux at horizon	- 1 σ
Spectral index	+ 0.48 σ
ν_e deviation	- 0.62 σ
DOM eff.	+ 0.02 σ
Scattering in ice columns	+ 0.63 σ

Juan-Pablo Yáñez | IceCube results on atmospheric neutrino oscillations | June 2014 | Page 19

Oscillation Analysis Fit

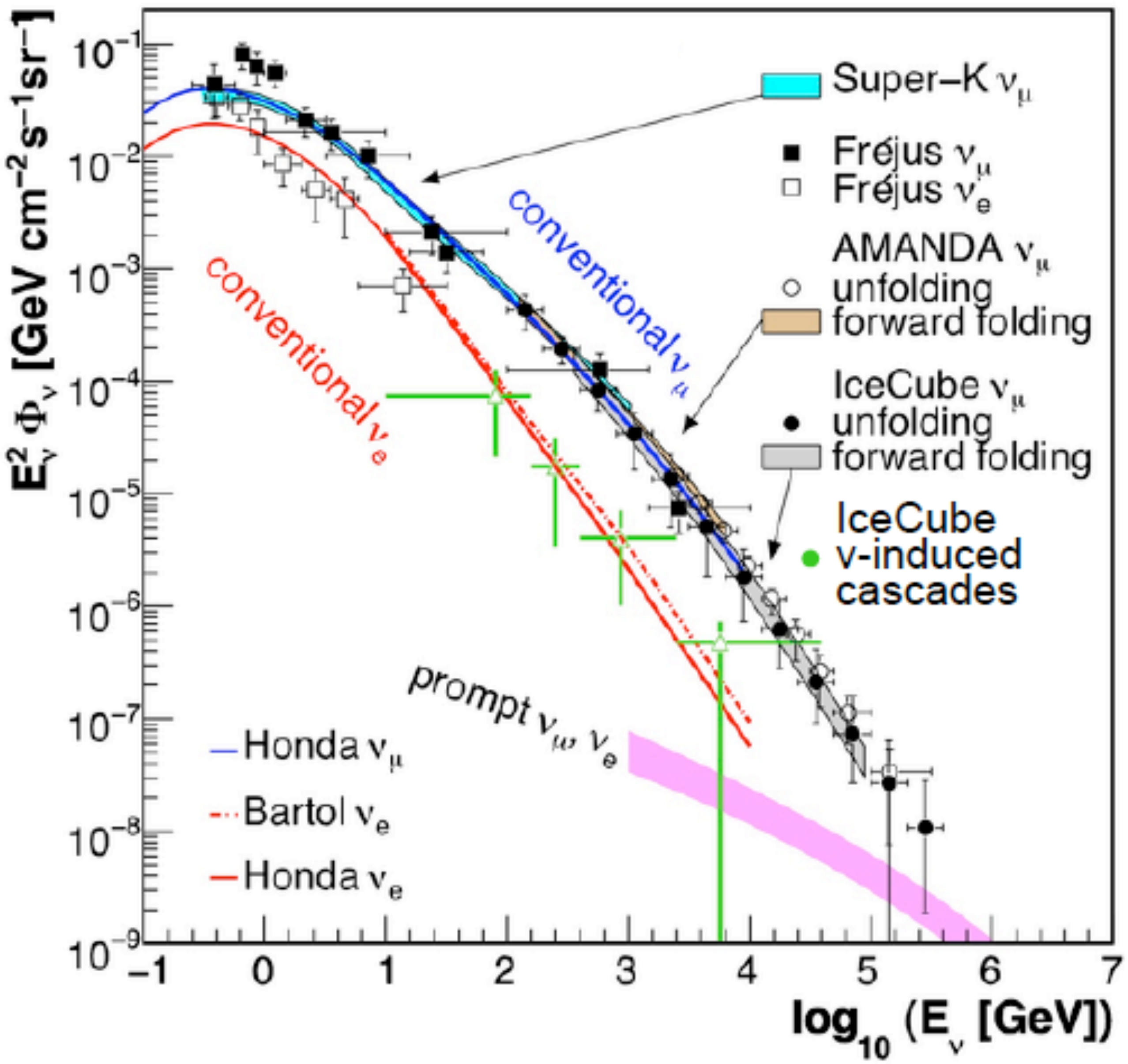


- Precision measurement of neutrino oscillations with IceCube/DeepCore
  - At the highest energies observed, test of 3-flavor paradigm
  - Results compatible with world's average (maximal mixing)
  - Systematic uncertainties under control, data/MC agreement
  - Further improvements expected in the future ... not just more statistics

PINGU

Atmospheric Neutrino Sample expected with PINGU

N(Events) Expected in PINGU per Year		
	Trigger Detector	Pass Baseline Analysis
ν_e CC	52k	26k
ν_μ CC	86k	35k
ν_τ CC	6.4k	2.7k
ν_x NC	17k	7.9k



ν_μ oscillation result, PRL 111, 081801 (2013)
Atm. ν_e detection result, PRL 110, 151105 (2013).

Neutrino Mass Hierarchy Signature

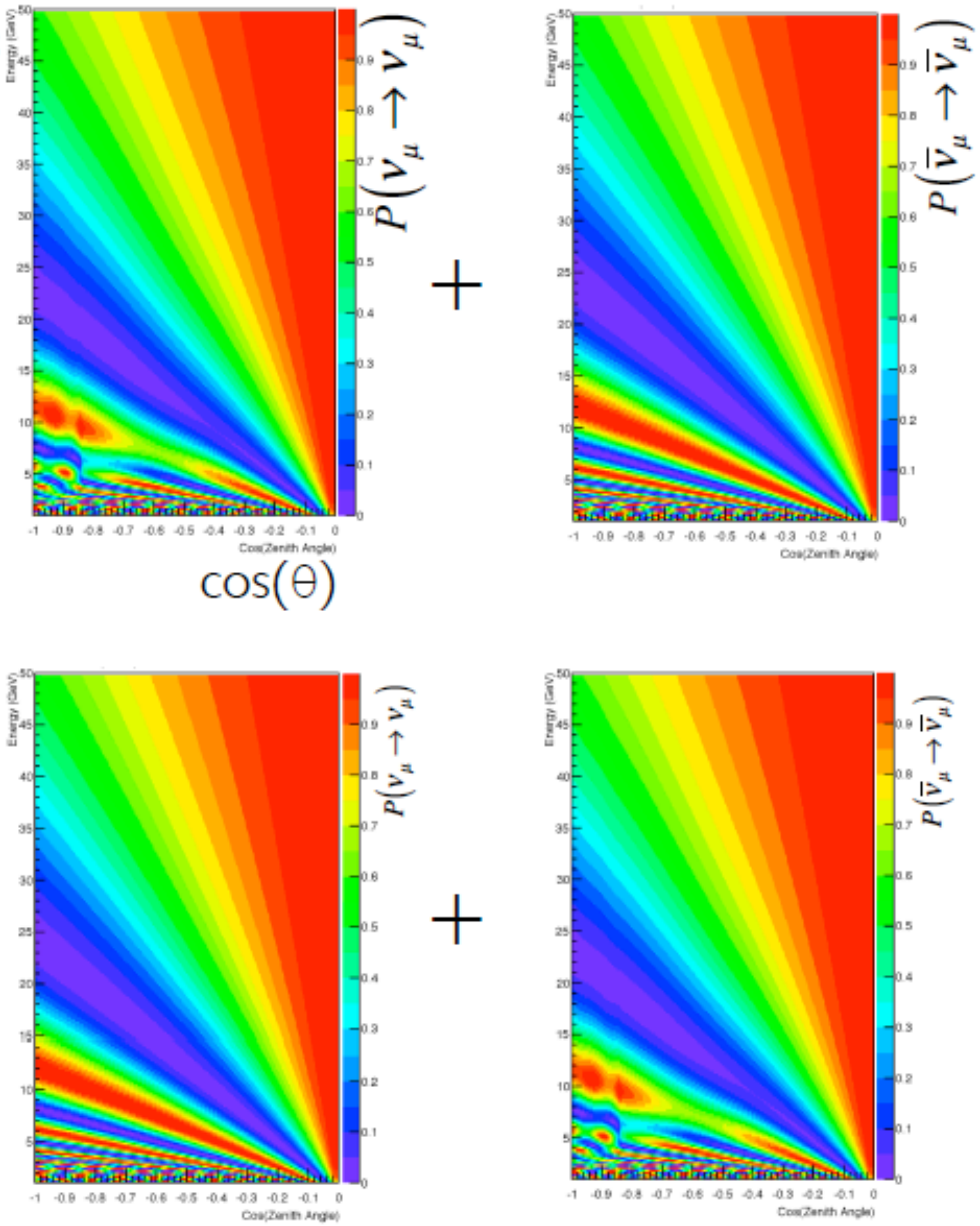
ν_μ anti-ν_μ

Energy

NH + = [pattern A]

cos(θ)

IH + = [pattern B]



MSW and Parametric Oscillations:
- L. Wolfenstein Phys.Rev. D17 (1978)
- S. Mikheyev and A.Y. Smirnov Prog.Part.Nucl.Phys. 23 (1989)
- E. K. Akhmedov, et al., Nucl.Phys. B542 (1999)

Feasible?
Pattern A =
Pattern B!

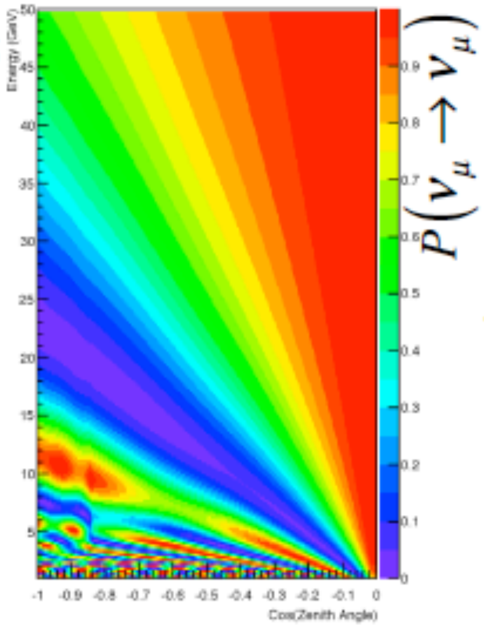
PINGU Signature:
- O. Mena, I. Mocioiu, and S. Razzaque, Phys. Rev. D 78 (2008)
- E. K. Akhmedov, S. Razzaque, and A.Y. Smirnov, JHEP 1302 (2013)
- PINGU LoI arXiv:1401.2046

Neutrino Mass Hierarchy Signature

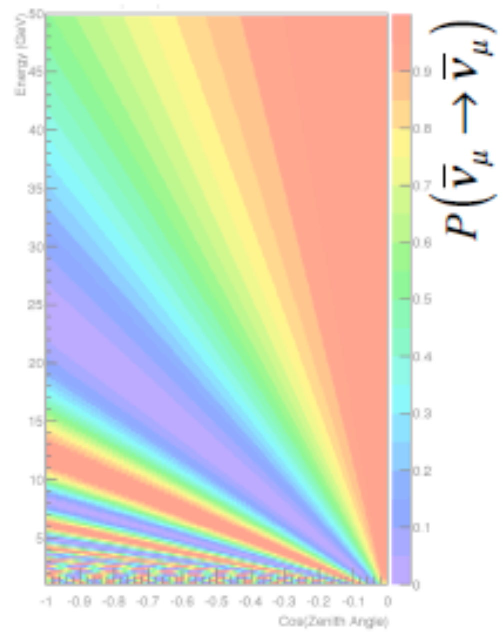
ν_μ anti-ν_μ

Energy

NH



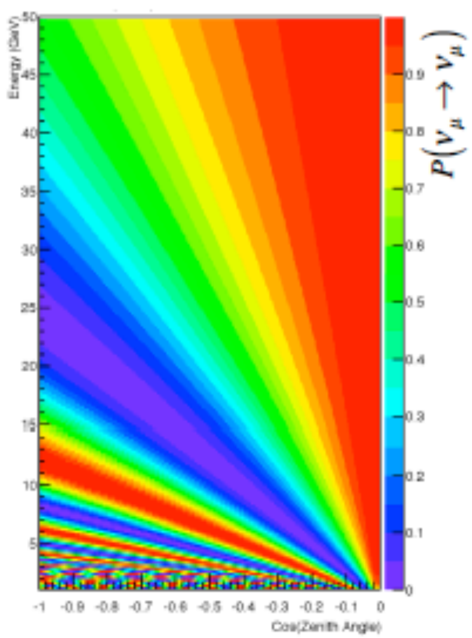
+



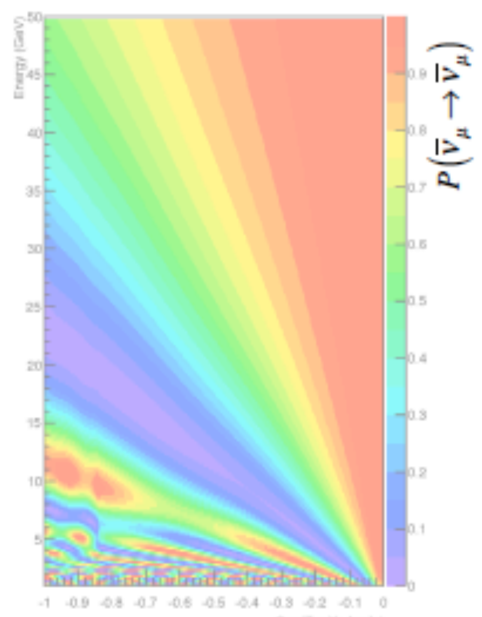
= [pattern A]

cos(θ)

IH



+



= [pattern B]

MSW and Parametric Oscillations:

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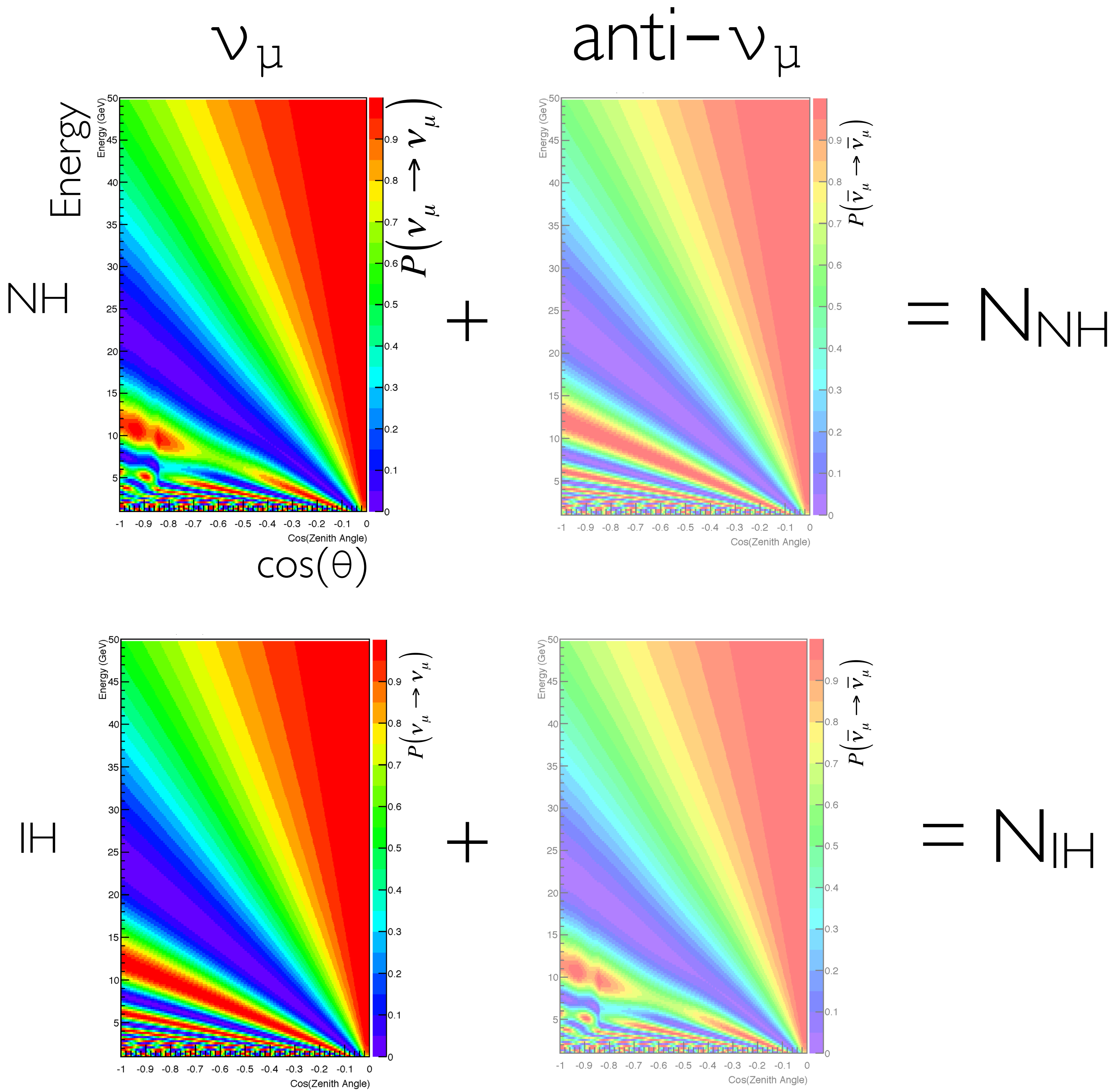
$\sigma(\nu)$~2σ(anti-ν),
$\varphi(\nu_{atm})>\varphi(\bar{\nu}_{atm})$
∴ A≠B!
(True for ν_e, too)

PINGU Signature:

- O. Mena, I. Mocioiu, and S. Razzaque, Phys. Rev. D 78 (2008)
- E. K. Akhmedov, S. Razzaque, and A.Y. Smirnov, JHEP 1302 (2013)
- PINGU LoI arXiv:1401.2046

Oscillation Probability x Cross-section x Flux = Event Rate

$\sigma(\nu) \sim 2\sigma(\text{anti-}\nu)$,
$\varphi(\nu_{atm}) > \varphi(\text{anti-}\nu_{atm})$
$\therefore N_{NH} \neq N_{IH}$!
(True for ν_e, too)



Distinguishability Plot

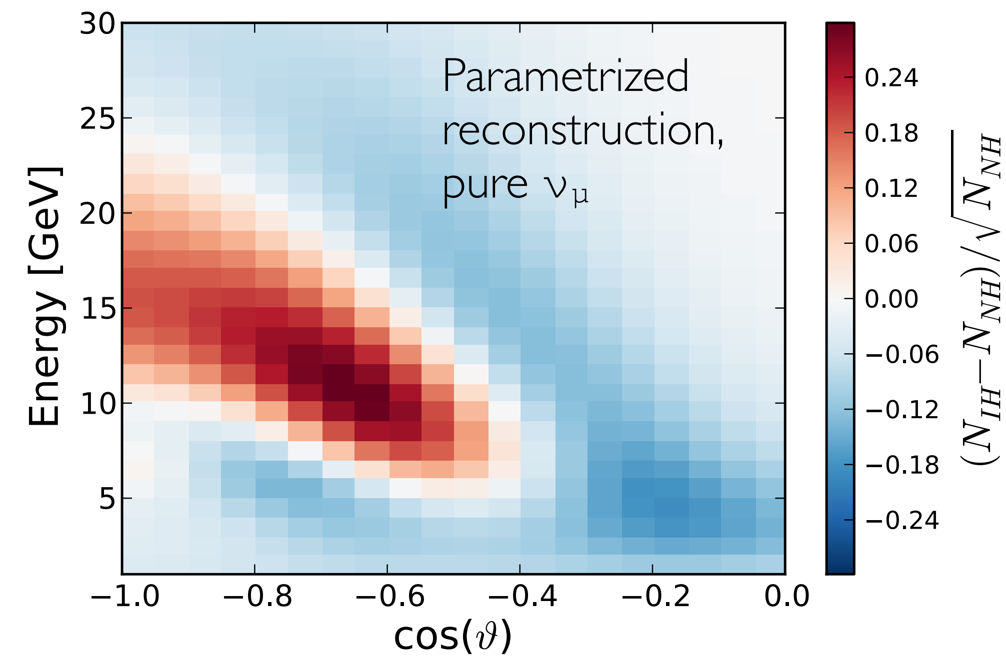
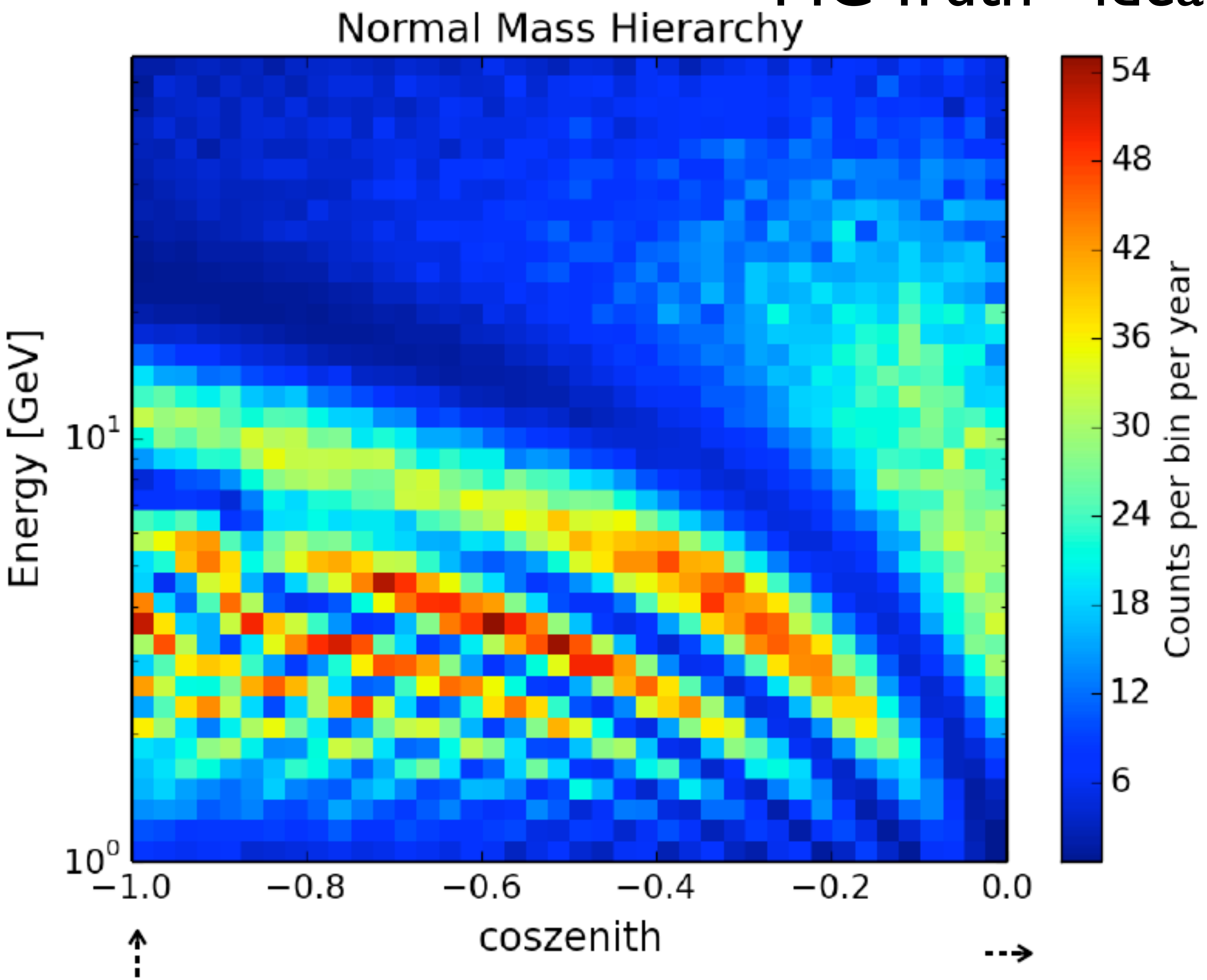


Illustration only

Mass Hierarchy by Eye

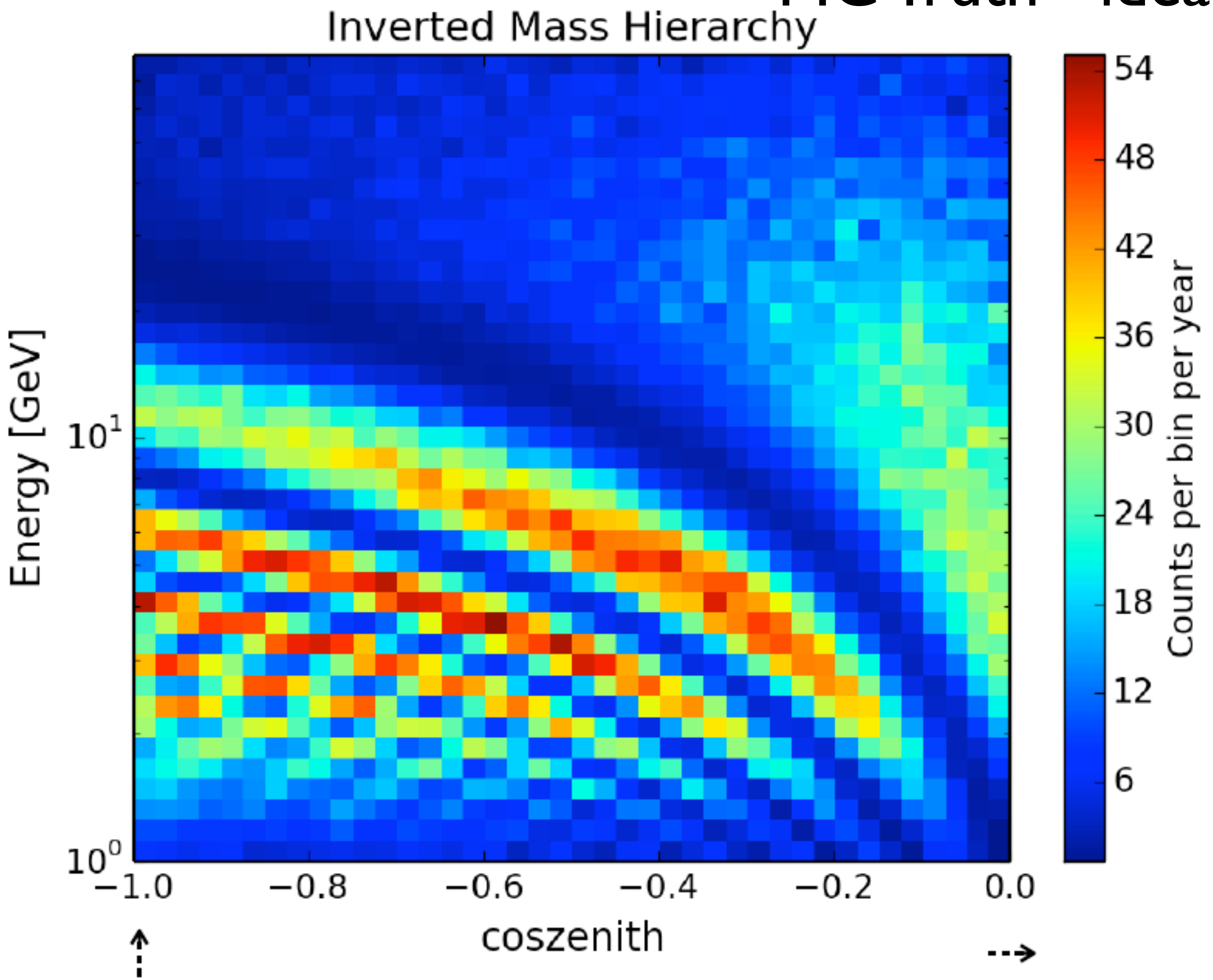
MC Truth - ideal detector



One year of data

Mass Hierarchy by Eye

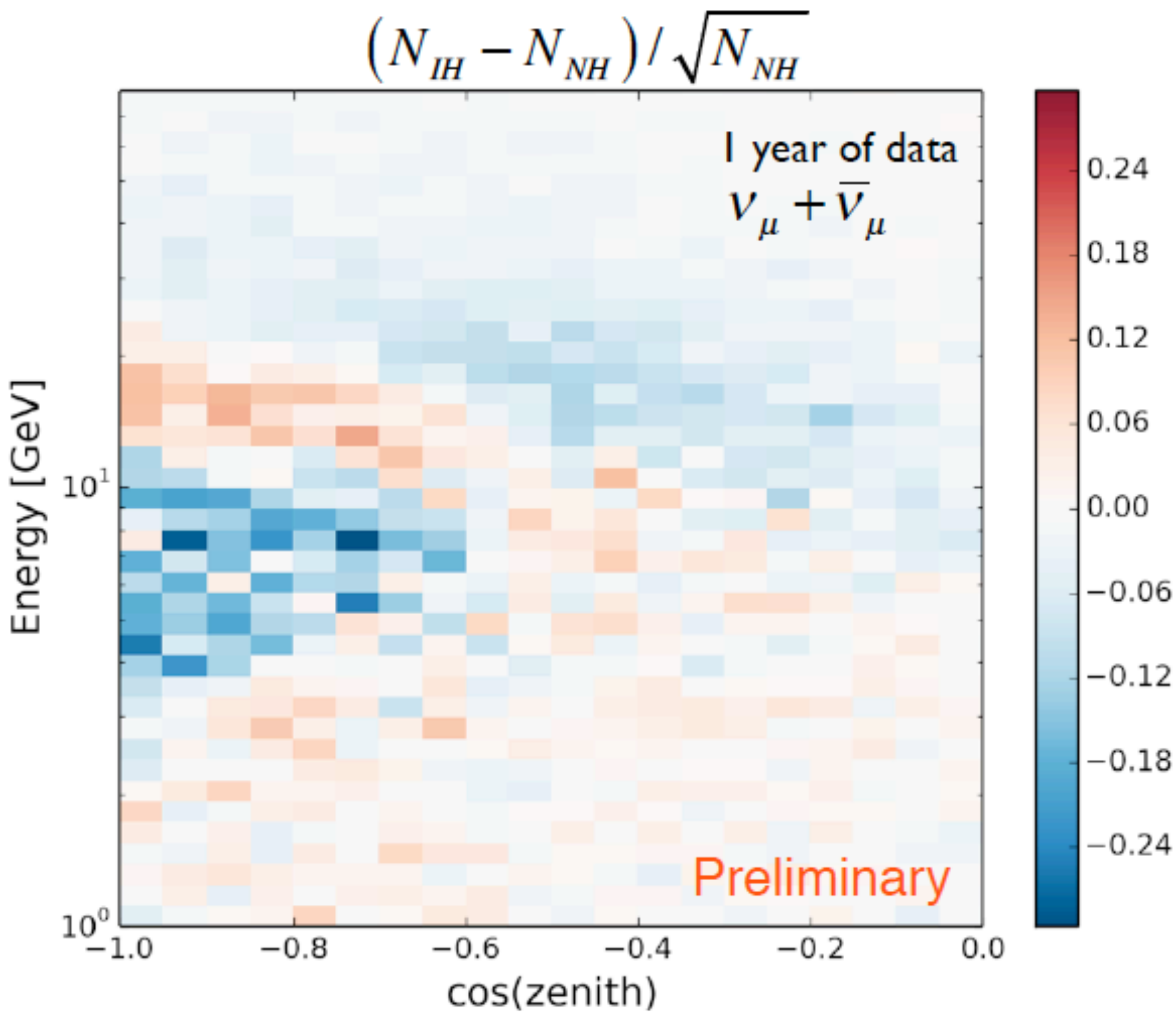
MC Truth - ideal detector



One year of data

Mass Hierarchy Signature

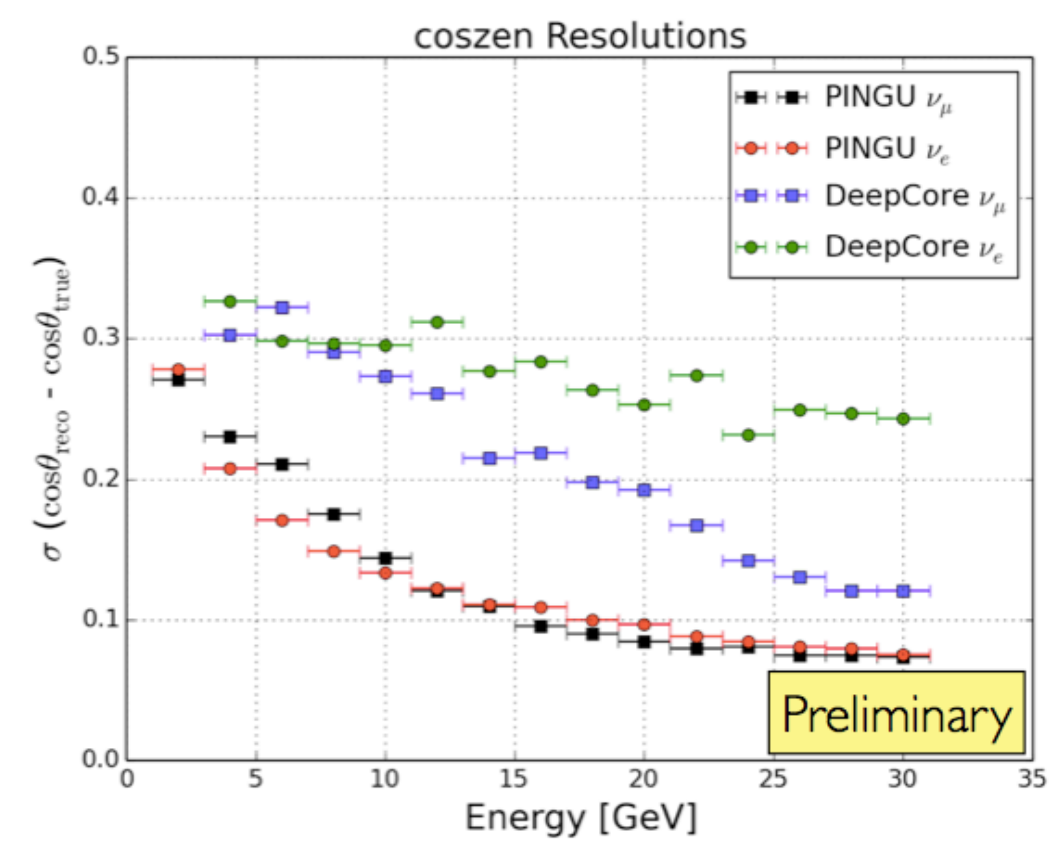
- Distinguishability as function of reconstructed energy and zenith angle
- Complex pattern in 2D helps to reduce systematics
- Plot includes reconstruction, but particle ID is not applied, yet.

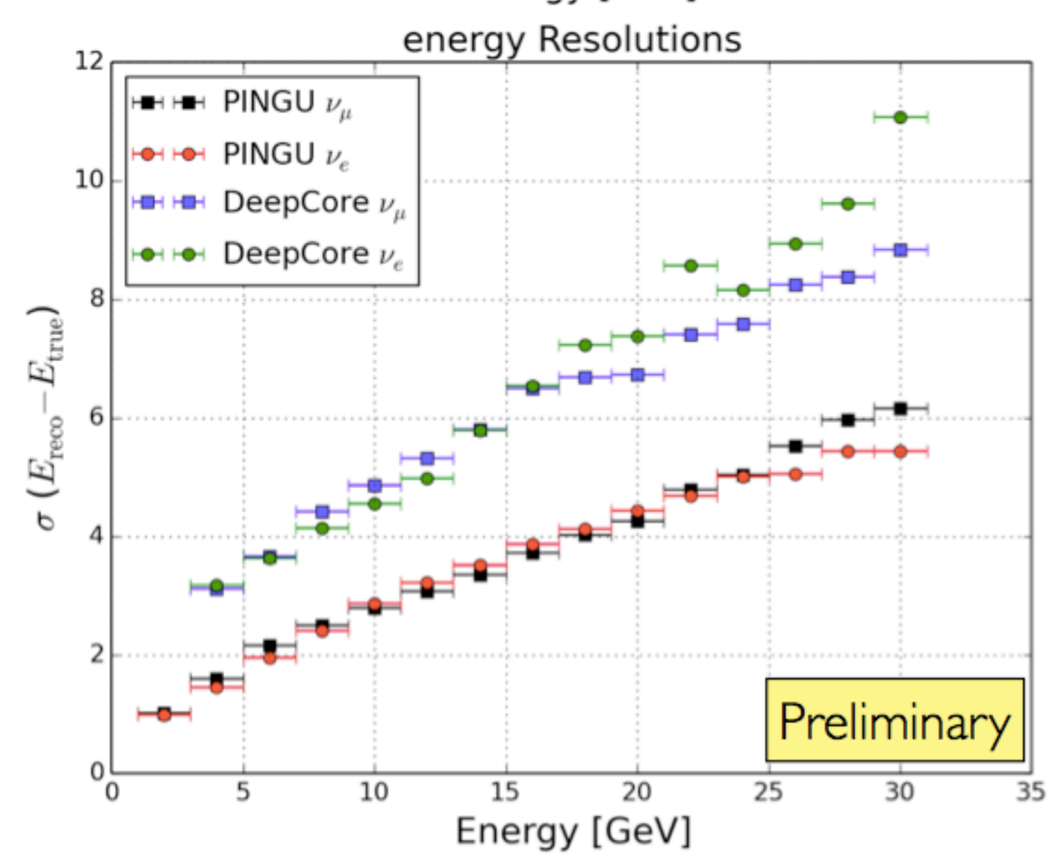


Distinguishability metric follows:
Akhmedov et al. JHEP 2013(02) pp. 1-39

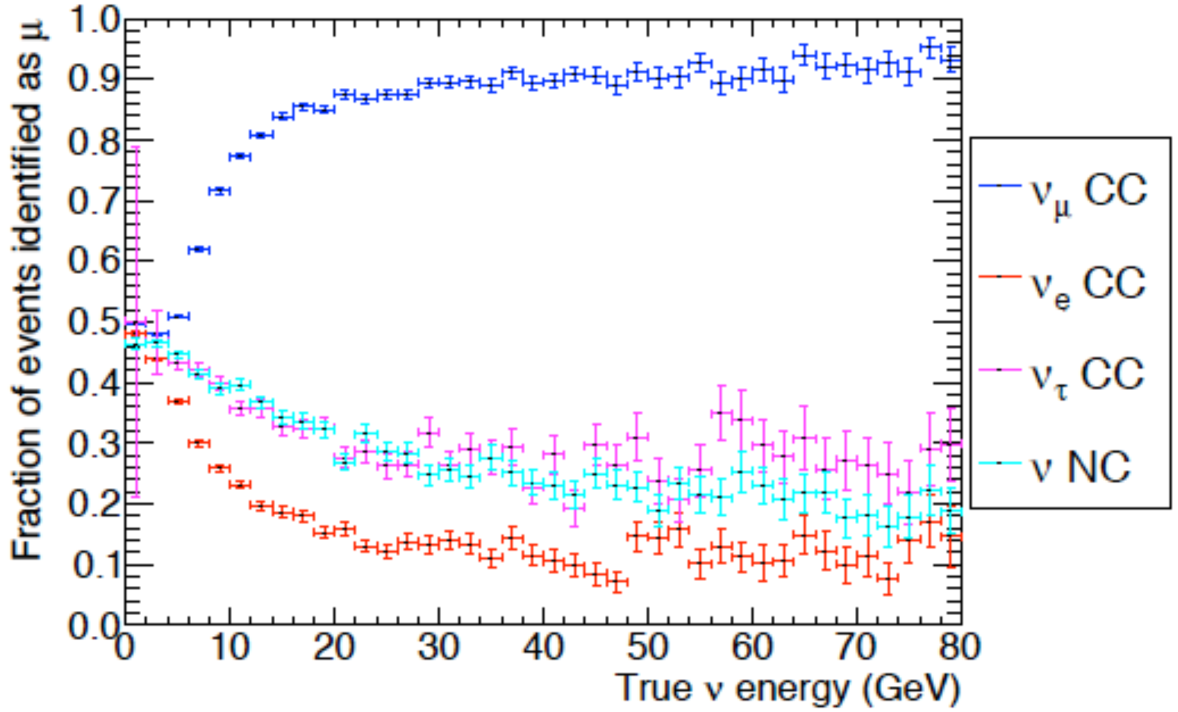
Reconstruction Performance and Mass Hierarchy

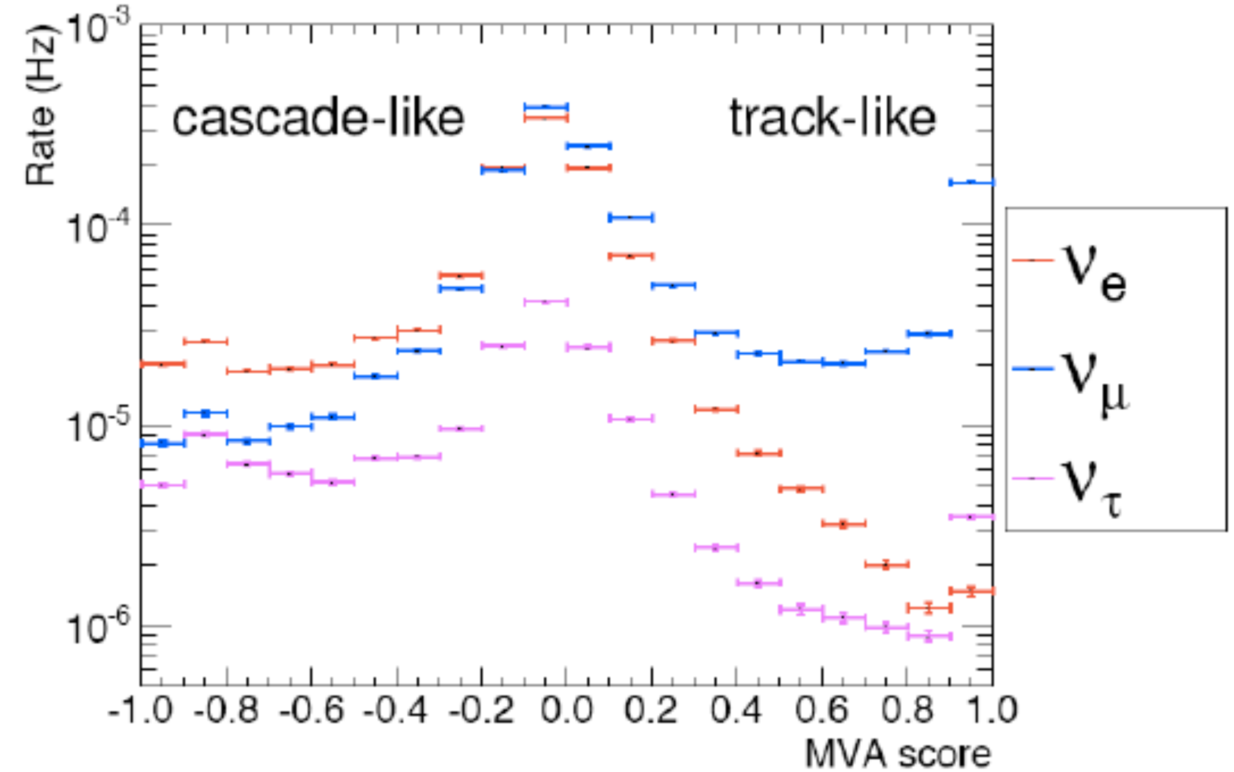
- Event selection and background rejection require
  - Reconstructed event vertex well-contained
  - Reconstructed event direction upward
- Reconstruction
  - Full likelihood minimization in 8-d parameter space (uses "MultiNest")
  - Interaction vertex (x,y,z,t,E), outgoing muon θ, φ, track length
  - Resolutions (improve with energy; given here at $E_{\nu,true}$ ~ 5 GeV):
    - $\Delta E/E \sim 0.27$, $\sigma_\theta \sim 13^\circ$ (θ: zenith angle; track & cascade resolutions ~same)
- Three independent analyses: Fisher/Parametric, Asimov, LLR
  - Very good agreement



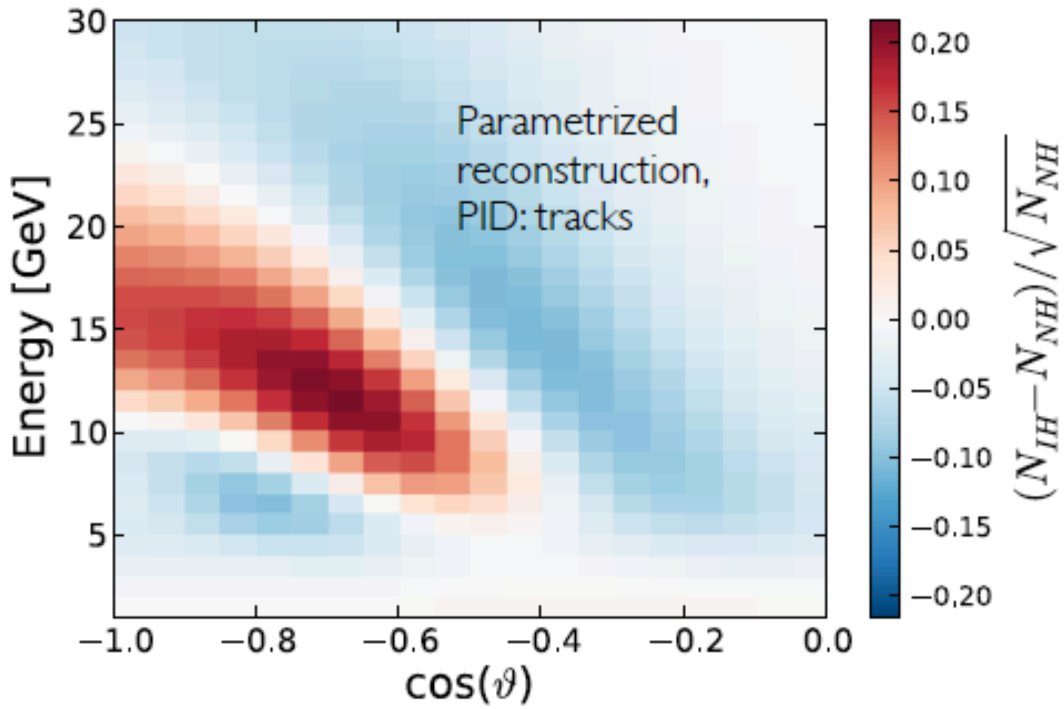


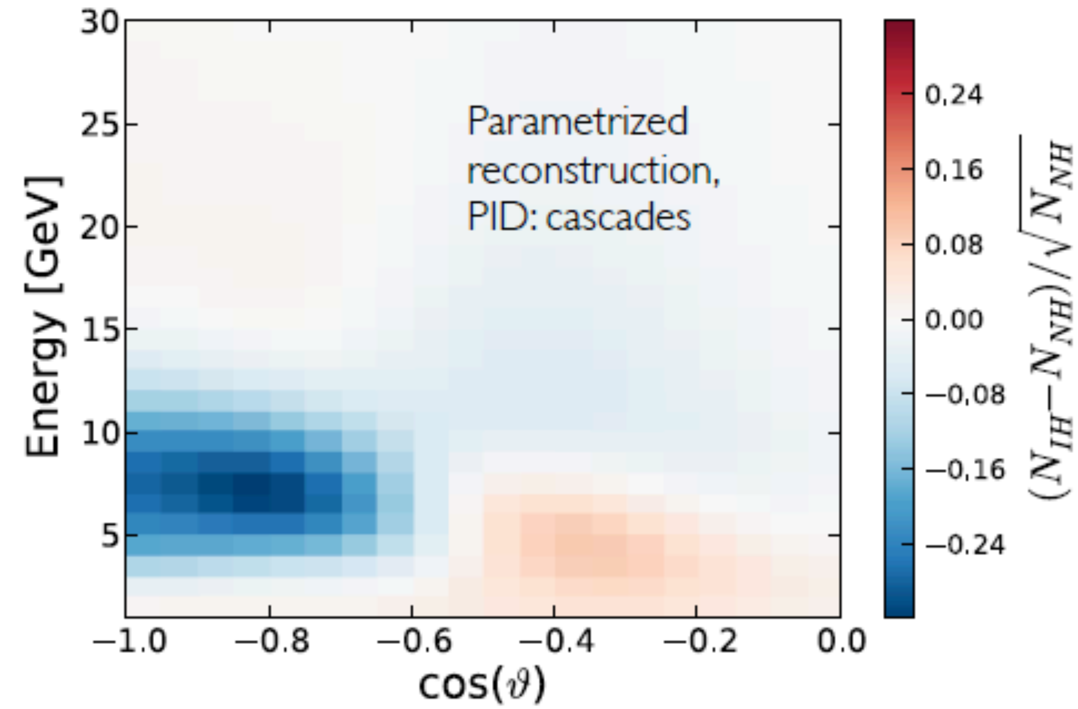
Particle ID





- ν_μ CC events distinguishable by presence of muon track

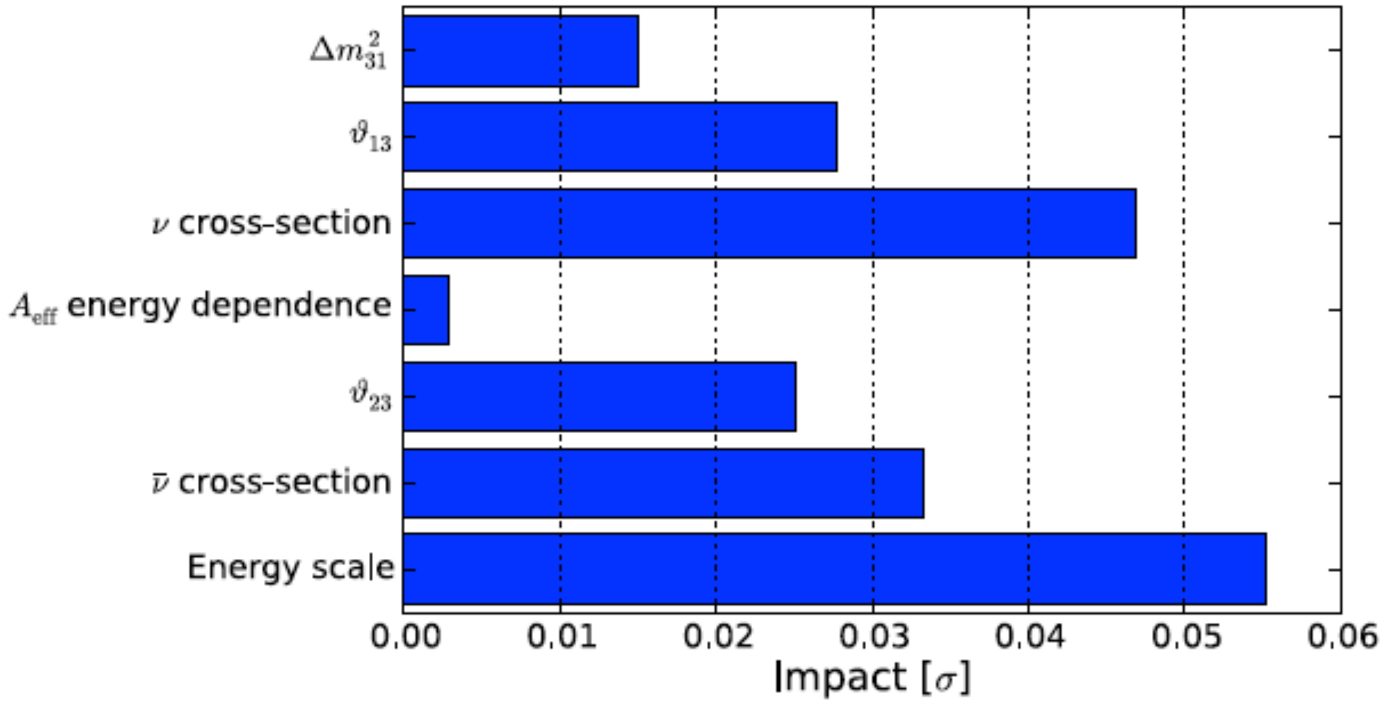




Systematics: Incorporated via Parametric Approach

- Physics-related
  - $\Delta(m_{31})^2$ (prior: $\pm 1\sigma$)*
  - θ_{13} ($\pm 1\sigma$)
  - θ_{23} ($\pm 1\sigma$)
  - cross sections ($\pm$15%)
    - ν, anti-ν independently
- Detector-related
  - Aeff(E, $\sigma(\nu)$, σ(anti-ν))
  - Energy scale ($\pm$5%)
  - [ice properties]

- Apply all systematics
- Un-apply one, "impact" is the observed increase in significance

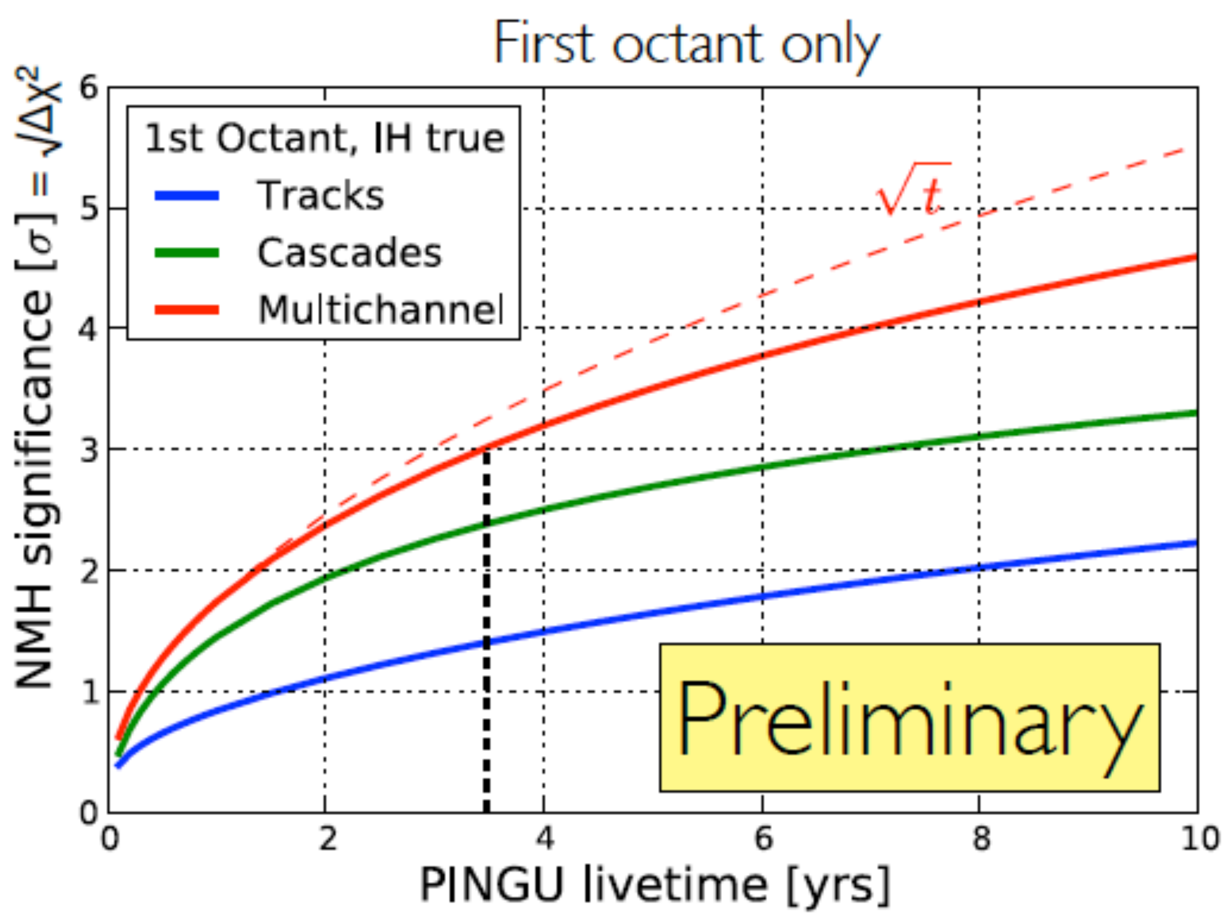


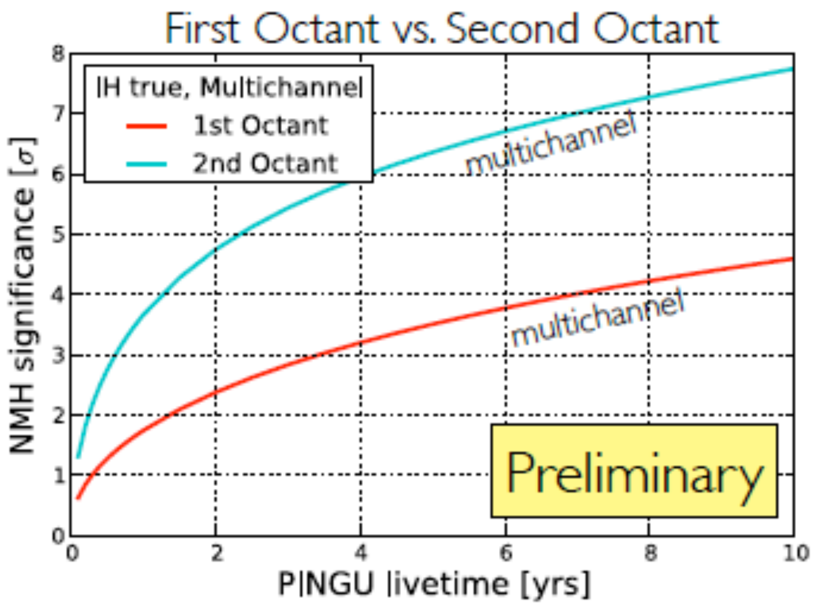
- Other (smaller) errors:
  - $\Delta(m_{21})^2$, θ_{12}, δ_{CP}
  - Scale factors for mis-ID, overall flux normalization

*Prior = $\pm 1\sigma$ error of world ave. msmt.

Result

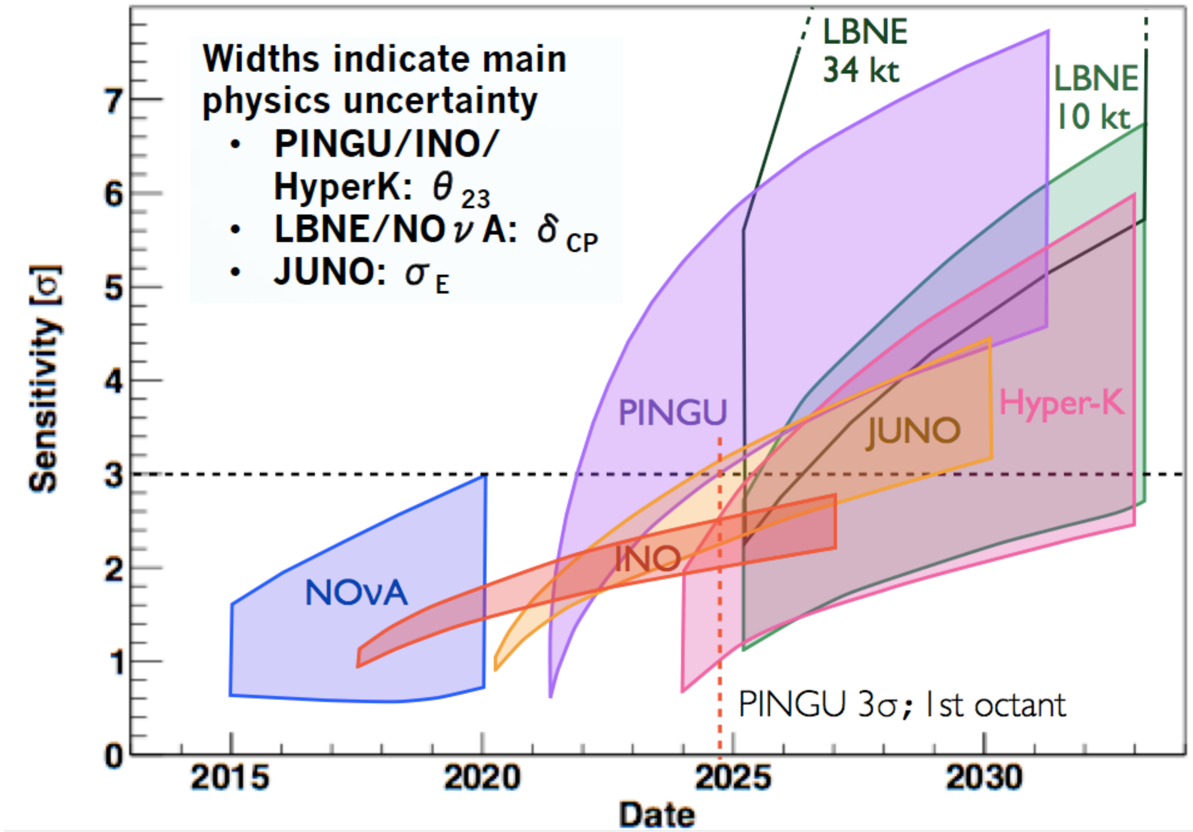
- Final significance from parametric analysis
  - Includes systematics from previous slide & basic PID
- Growth in significance as shown (for IH true)
  - Reach 3σ in roughly 3.5 yrs
    - NH true: faster
  - Livetime from partially built detector not included
    - would speed up result by about 0.5 yr





Advantages of PINGU

- Well-established detector and construction technology (low risk)
- Relatively low cost: ~$10M design/ startup plus ~$1.5M per string
- Rapid schedule
- Provides a platform for more detailed calibration systems to reduce detector systematics
- Multipurpose detector: Neutrino Properties, Dark Matter, Supernovae, Galactic Neutrino Sources, Neutrino Tomography, ...
- Opportunity for R&D toward other future ice/water Cherenkov detectors
- PINGU LOI released *arXiv:1401.2046*



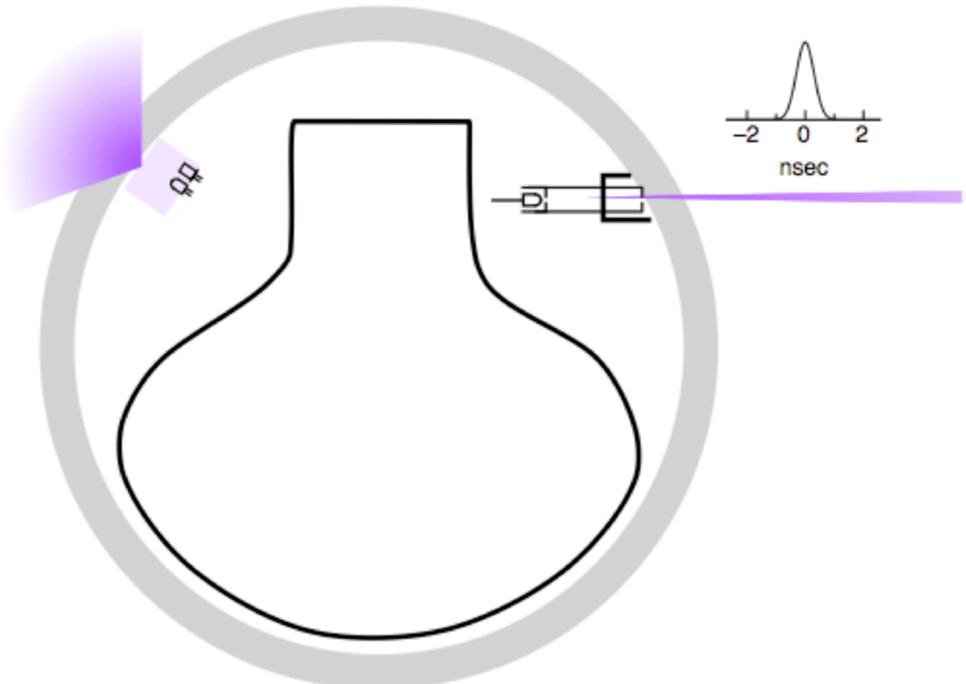
Blennow et al., arxiv:1311.1822, LBNE-doc-8087-v10, Hyper-K from arXiv:1109.3262 (2011) Hyper-K start date is 2025 (ICHEP14)

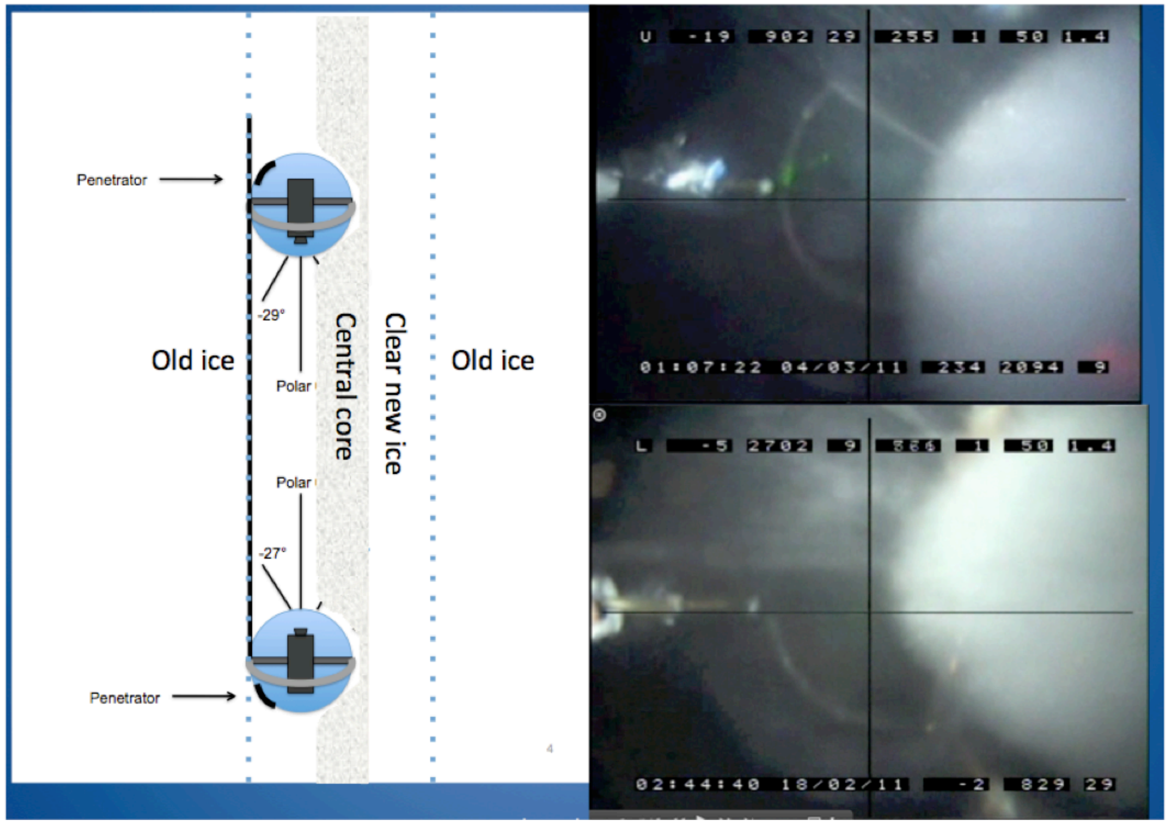
Additional Project Concepts

- Concepts to address various aspects of neutrino oscillation physics via alternative approaches were considered, including
  - RADAR
  - CHIPS
  - DAEdALUS and IsoDAR
  - LAr1
  - PINGU
  - NuSTORM
- These cannot go forward as major projects at this time, due to concept maturity and/or program cost considerations. However, further development of PINGU is recommended, and IsoDAR (precursor to DAEdALUS) should be considered in the context of a short-baseline oscillation program.

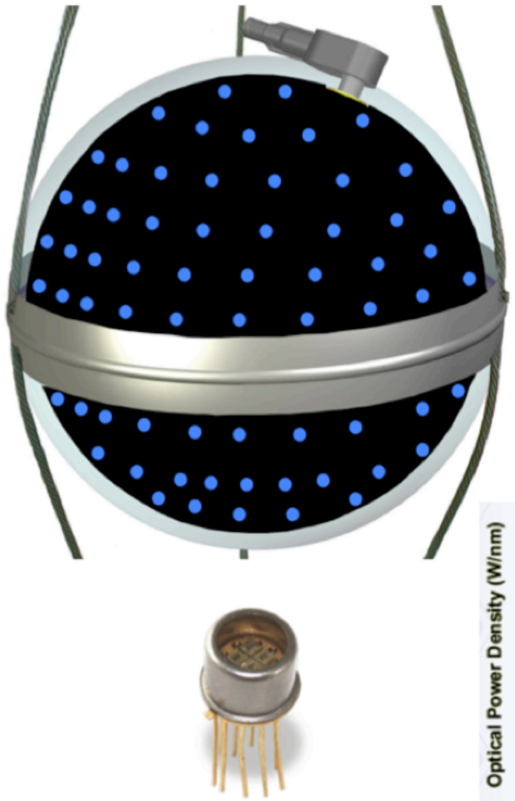
P5 Report May 2014

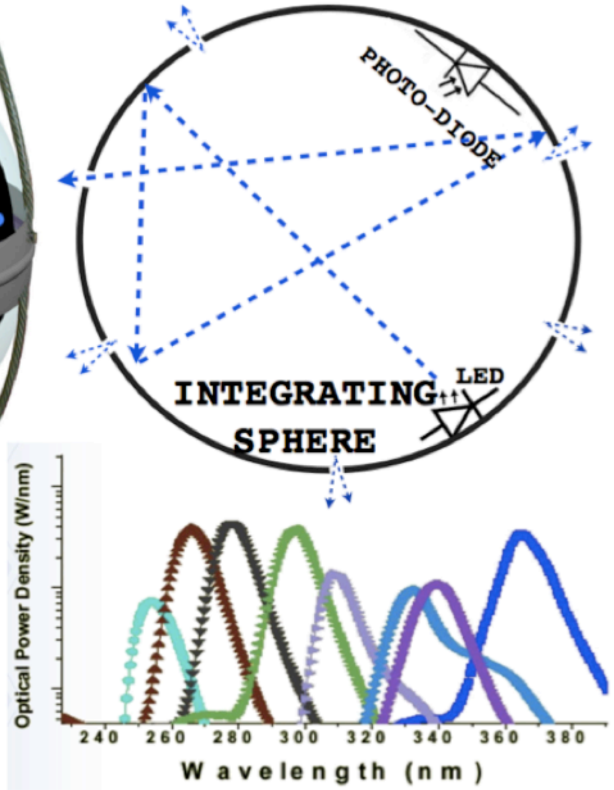
Calibration Devices





Flasher LEDs to be deployed with every pDOM: already used in IceCube to measure ice properties





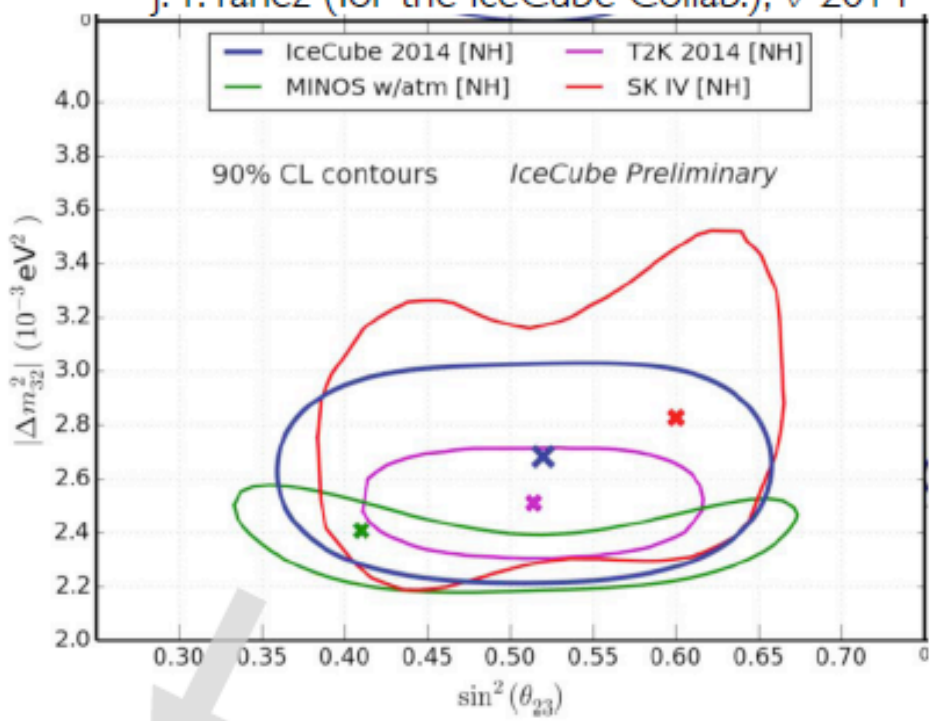
Cameras to investigate refrozen ice in the hole, verify degassing, check orientation of pDOM

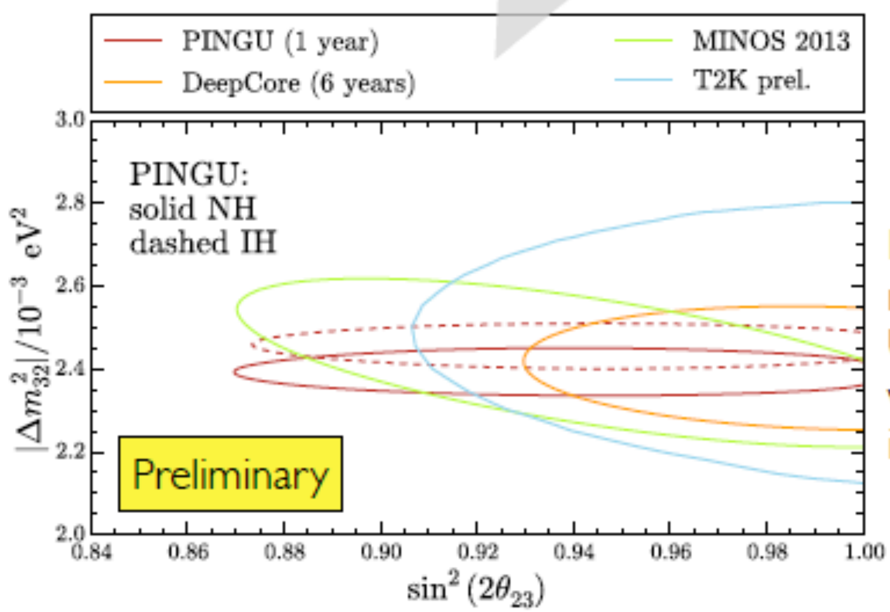
Under development: Precision Optical Calibration Module: diffuse multiwavelength source

PINGU Muon neutrino disappearance

Recent IceCube DeepCore ν_μ disapp. result

J.-P.Yanez (for the IceCube Collab.), ν 2014

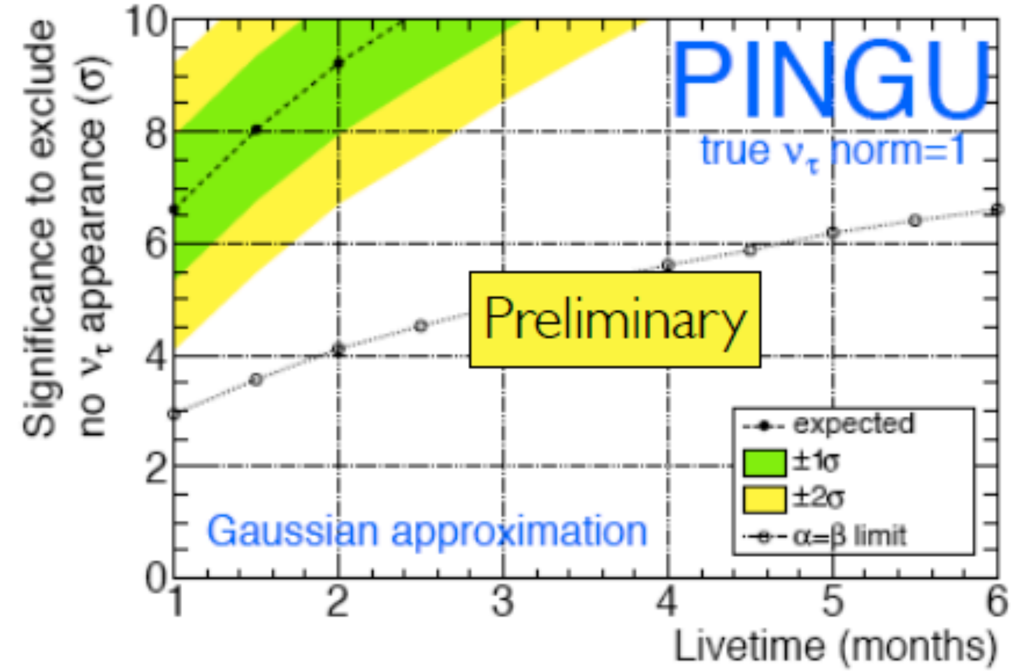




Based on old reconstruction. Updated result will be much improved.

ν_μ disappearance: Highly competitive after 1 yr

Also: See IceCube result, PRL 111, 081801 (2013)

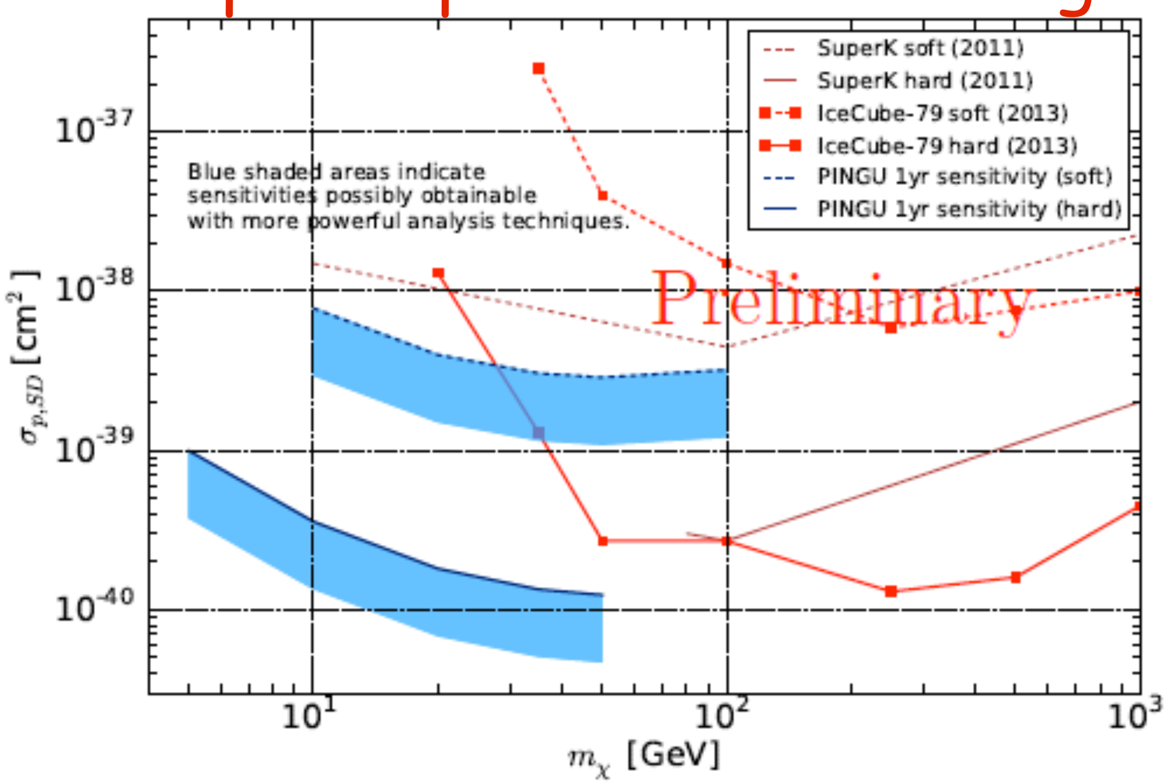


ν_τ appearance: Exclude null hypothesis at 5σ with ~1 month of data

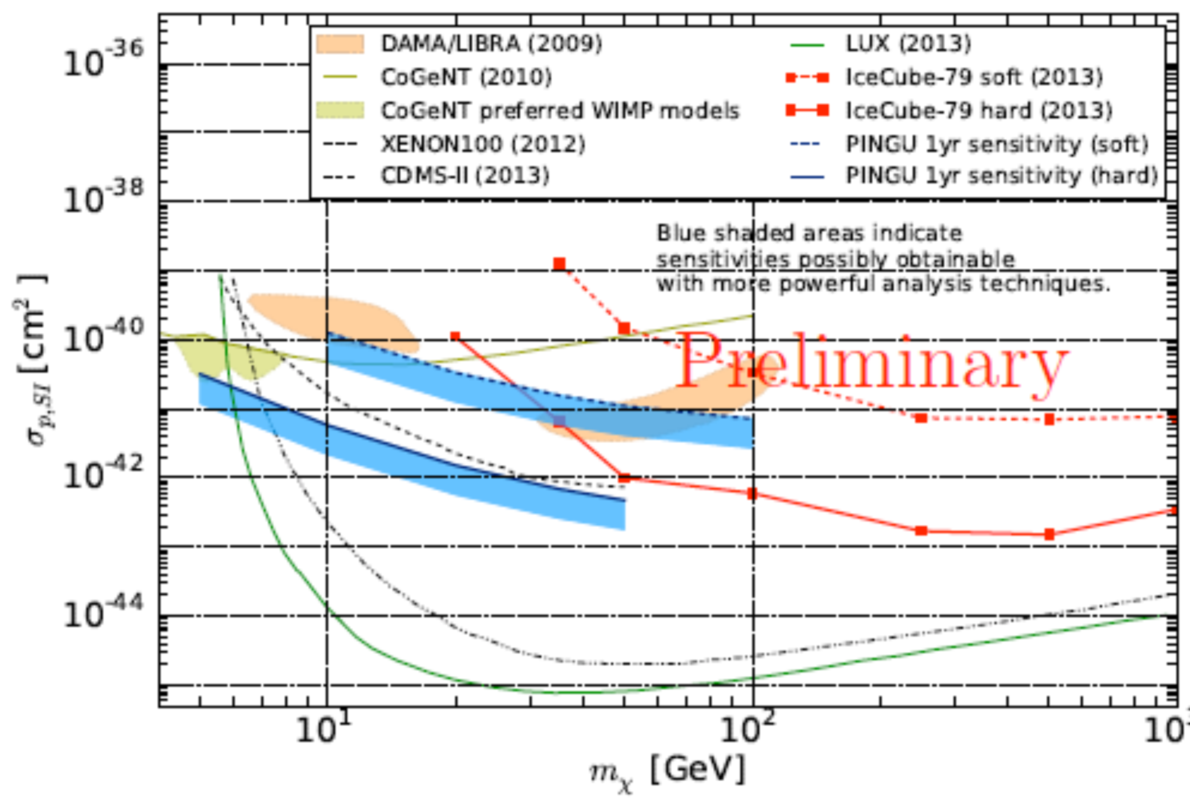
PINGU Dark Matter Sensitivity

- Solar WIMP dark matter
  - Sensitivity reaches to WIMP masses of ~5 GeV
  - World-leading limits for SD WIMPs with one year of data
- Low mass WIMP region testable

Spin-dependent scattering



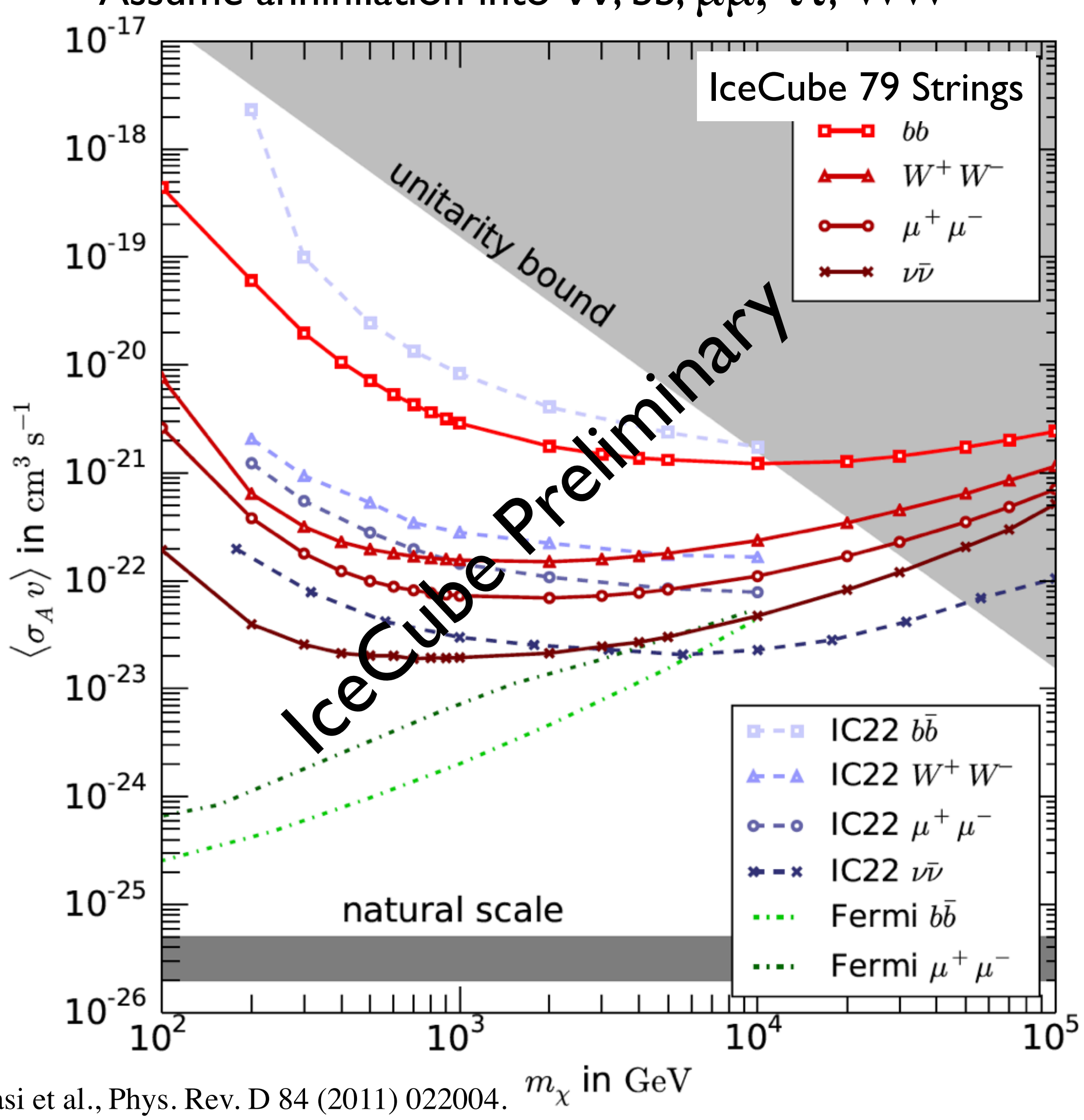
Spin-independent scattering



Dark Matter Searches with IceCube

IceCube Anisotropies in the Galactic Halo

- Galactic Center (GC) on the southern hemisphere
  - large backgrounds from down-going muons
- Search for anisotropy on Northern hemisphere
  - high-purity neutrino sample (up-going muon events)
- Assume annihilation into νν, bb, μμ, ττ, WW

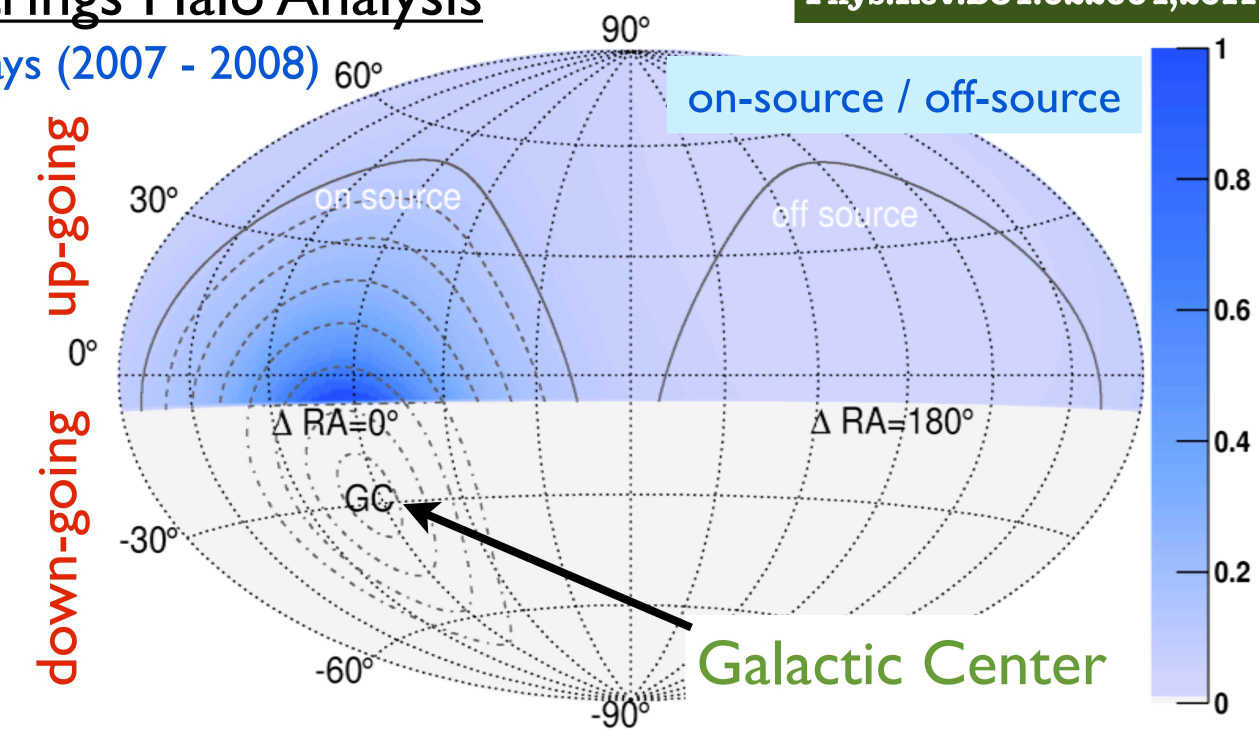


R. Abbasi et al., Phys. Rev. D 84 (2011) 022004.
M. Ackermann et al., Astrophys. J. 761 (2012) 91.

22-strings Halo Analysis

276 days (2007 - 2008)

Phys.Rev.D84:022004,2011

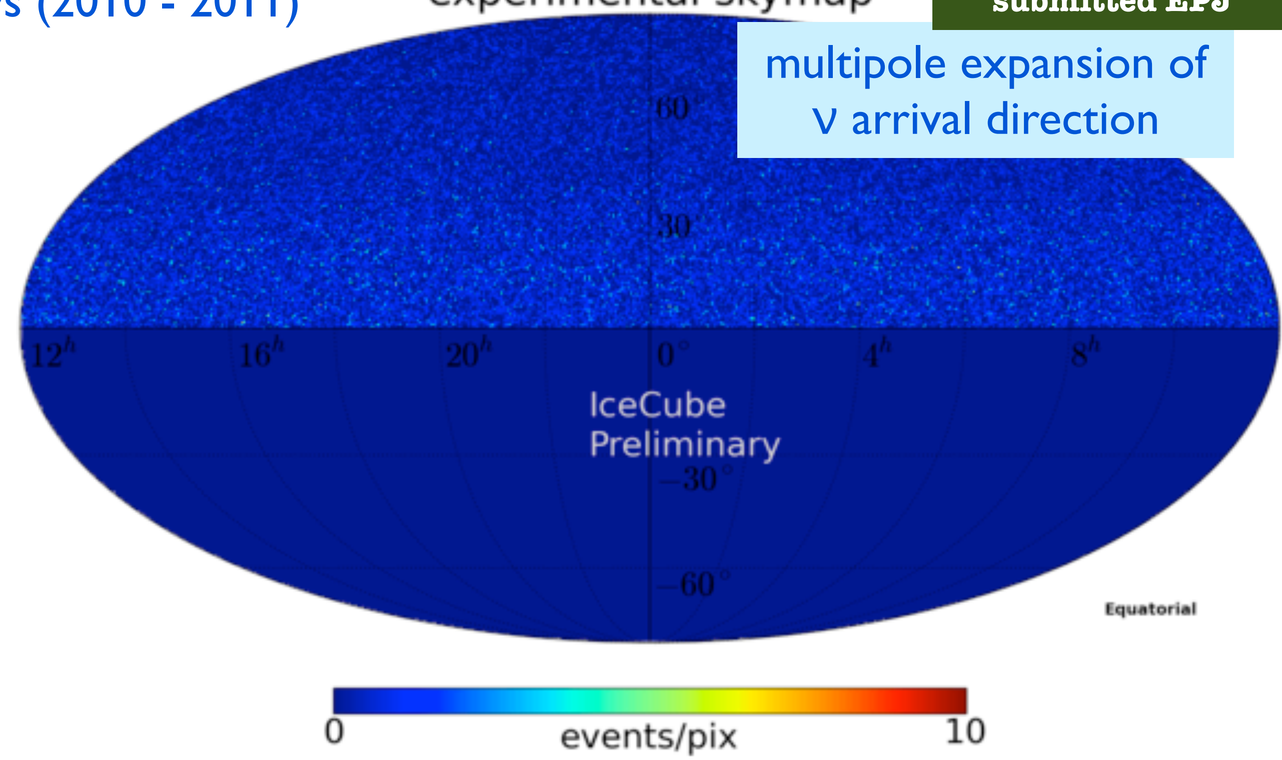


79-strings multipole WIMP analysis

316 days (2010 - 2011)

ICRC 2013
submitted EPJ

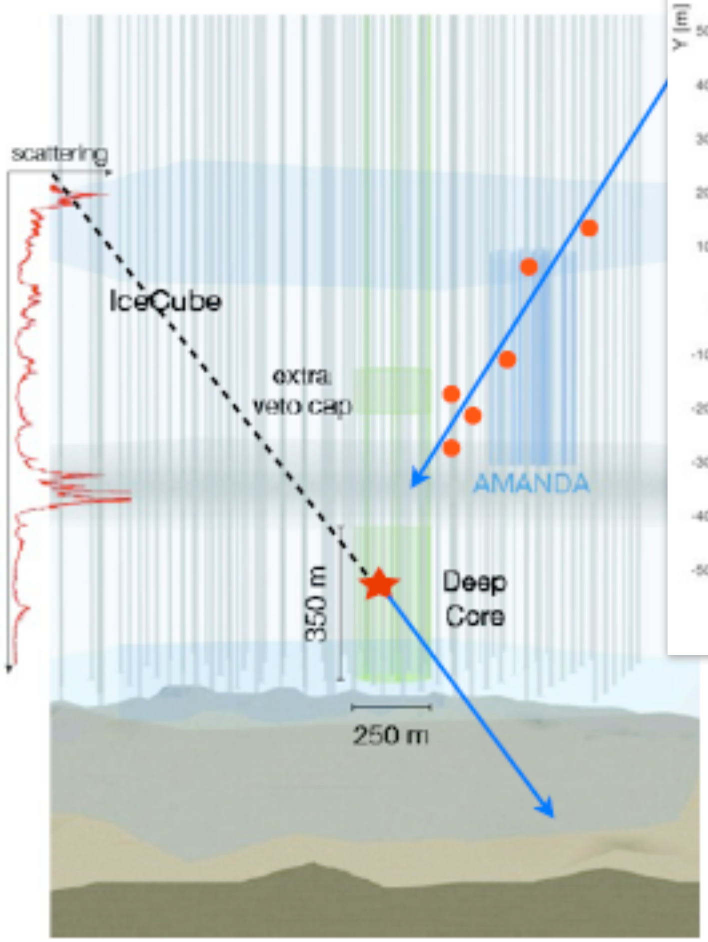
experimental skymap

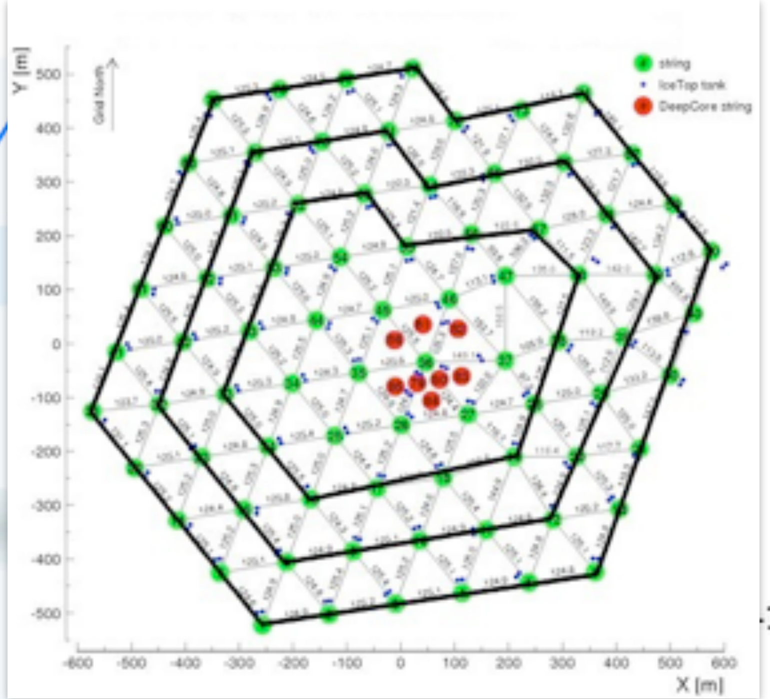


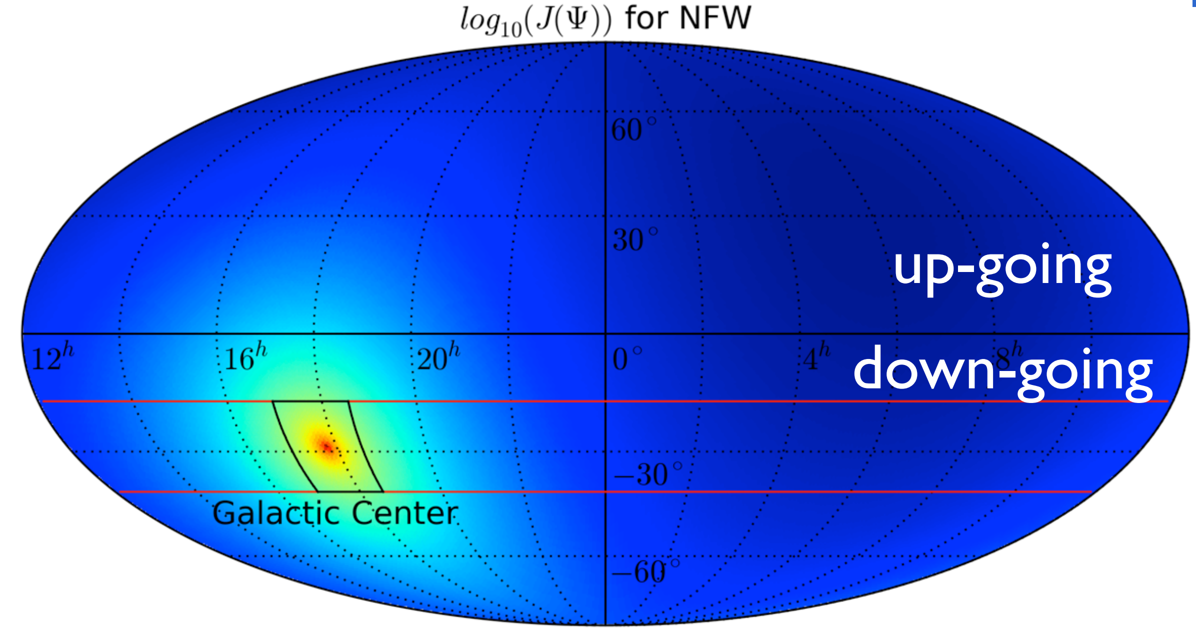
Galactic Center Search

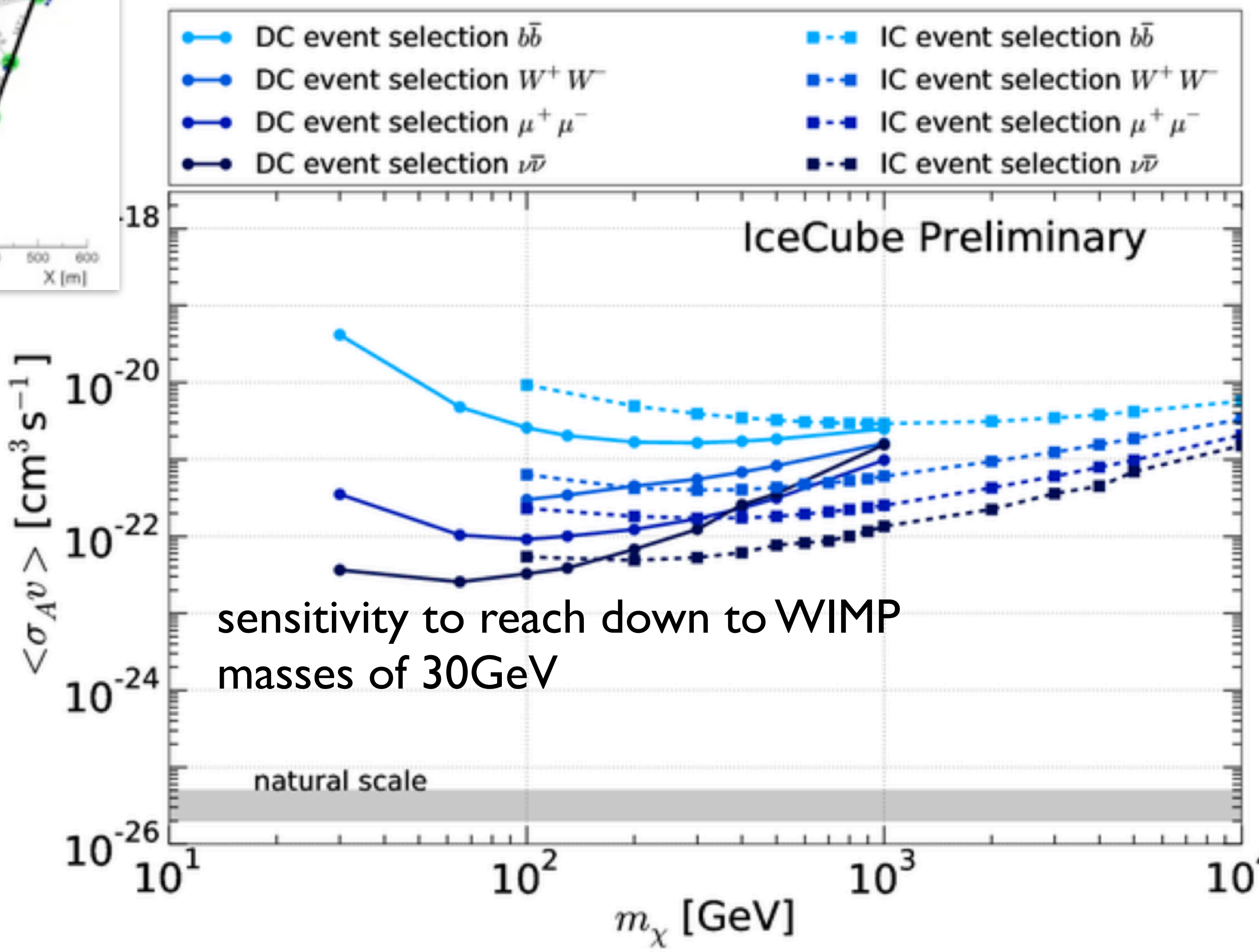
Use IceCube external strings as a veto:

- 3 complete layers around DeepCore (~ 375m)
- Full sky sensitivity: access to southern hemisphere



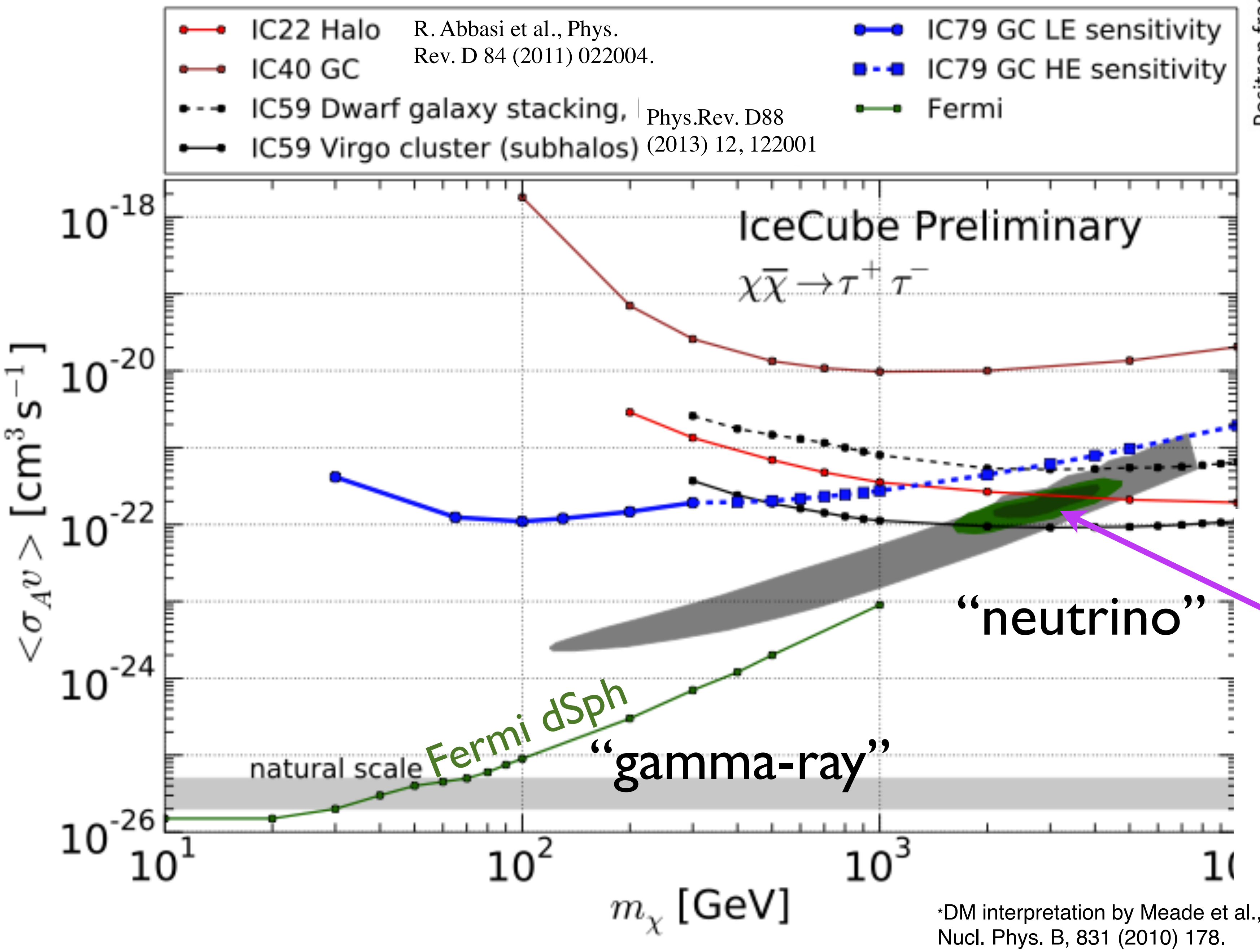




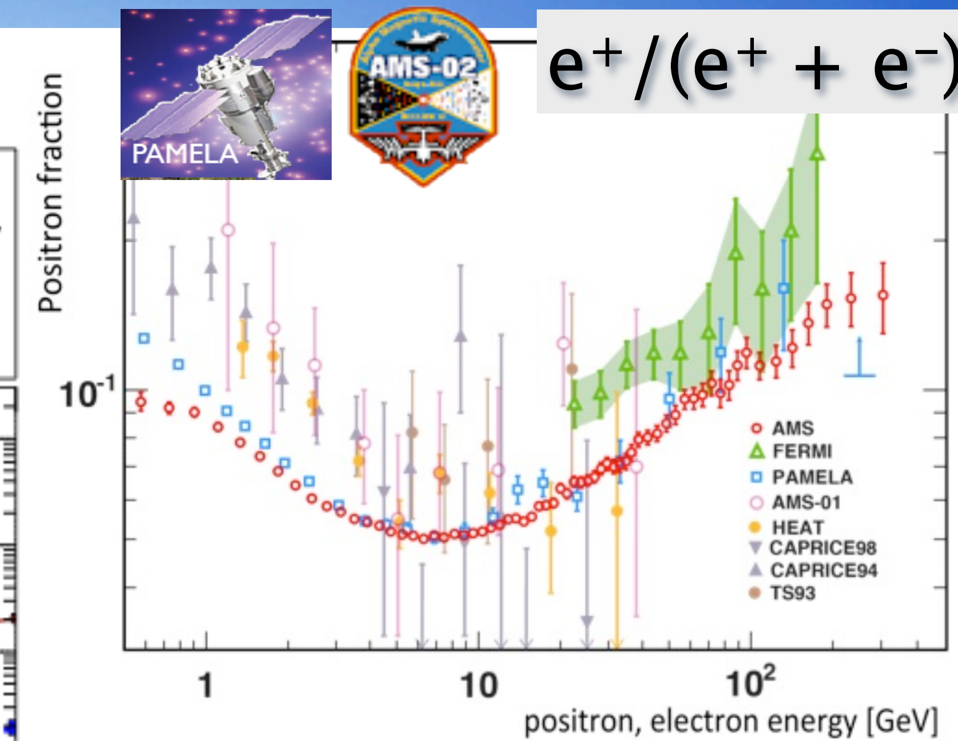


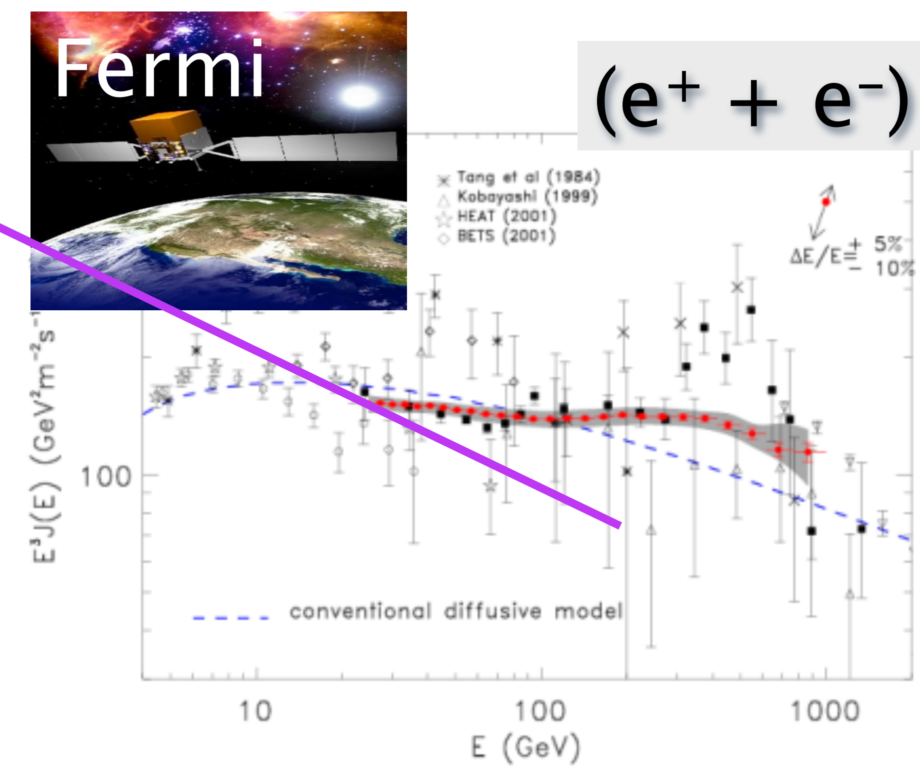
Separate Low energy and High energy optimizations:
GC is above the horizon
→ Fiducial volume in central strings
→ refined muon veto from surrounding layers
Use scrambled data for background estimation

Neutrinos test lepton anomalies



*DM interpretation by Meade et al., Nucl. Phys. B, 831 (2010) 178.





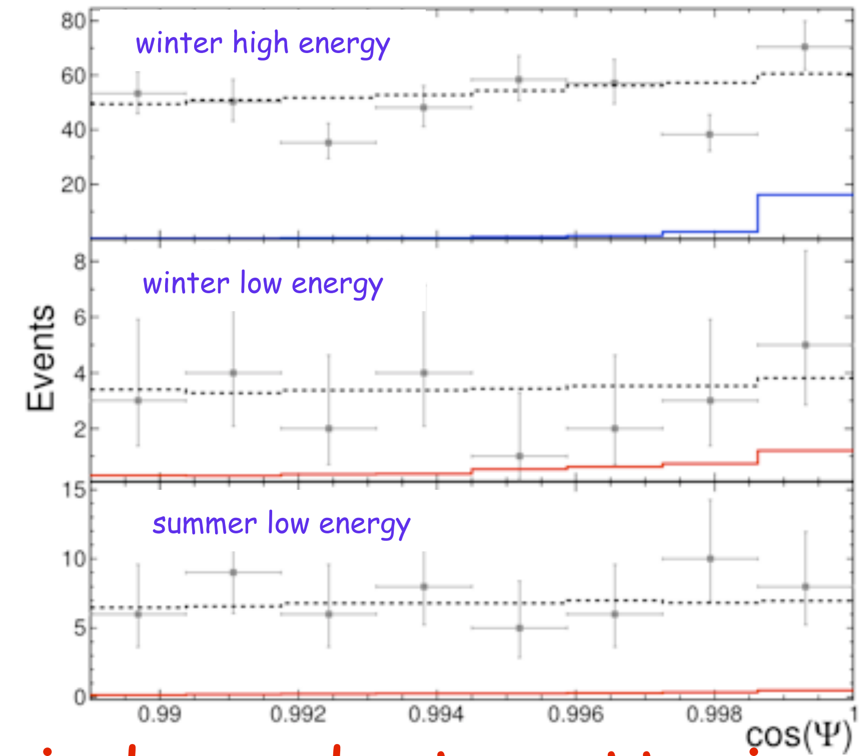
IceCube can probe models motivated by the observed lepton anomalies

IceCube Solar WIMP Limits

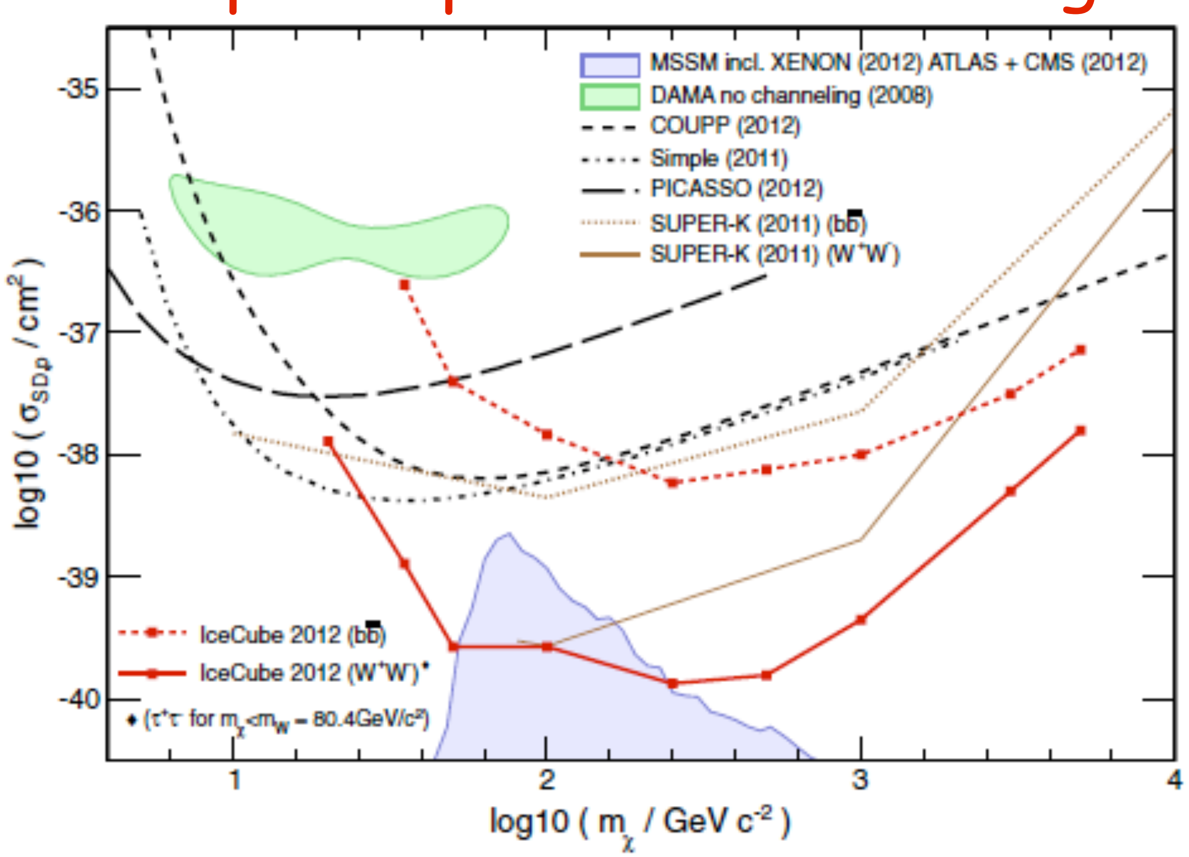
PRL 110, 131302 (2013)

- IceCube 79-strings configuration (partially completed DeepCore)
  - 318 days (May 2010 - May 2011)
- Search for an excess of events from the direction of the Sun
  - use track events for better pointing
- Separate summer and winter analysis
  - use outer detector to veto down-going muons for summer analysis

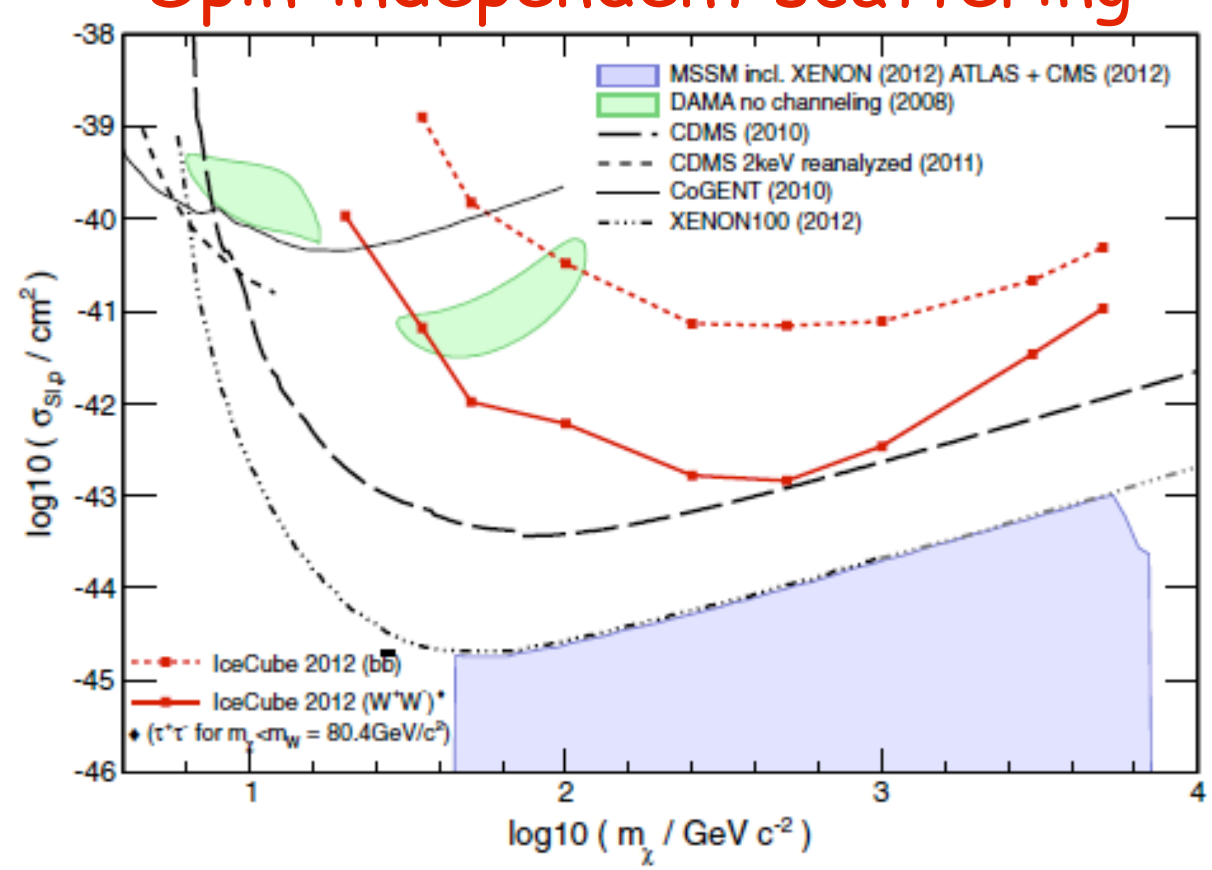
Observed events



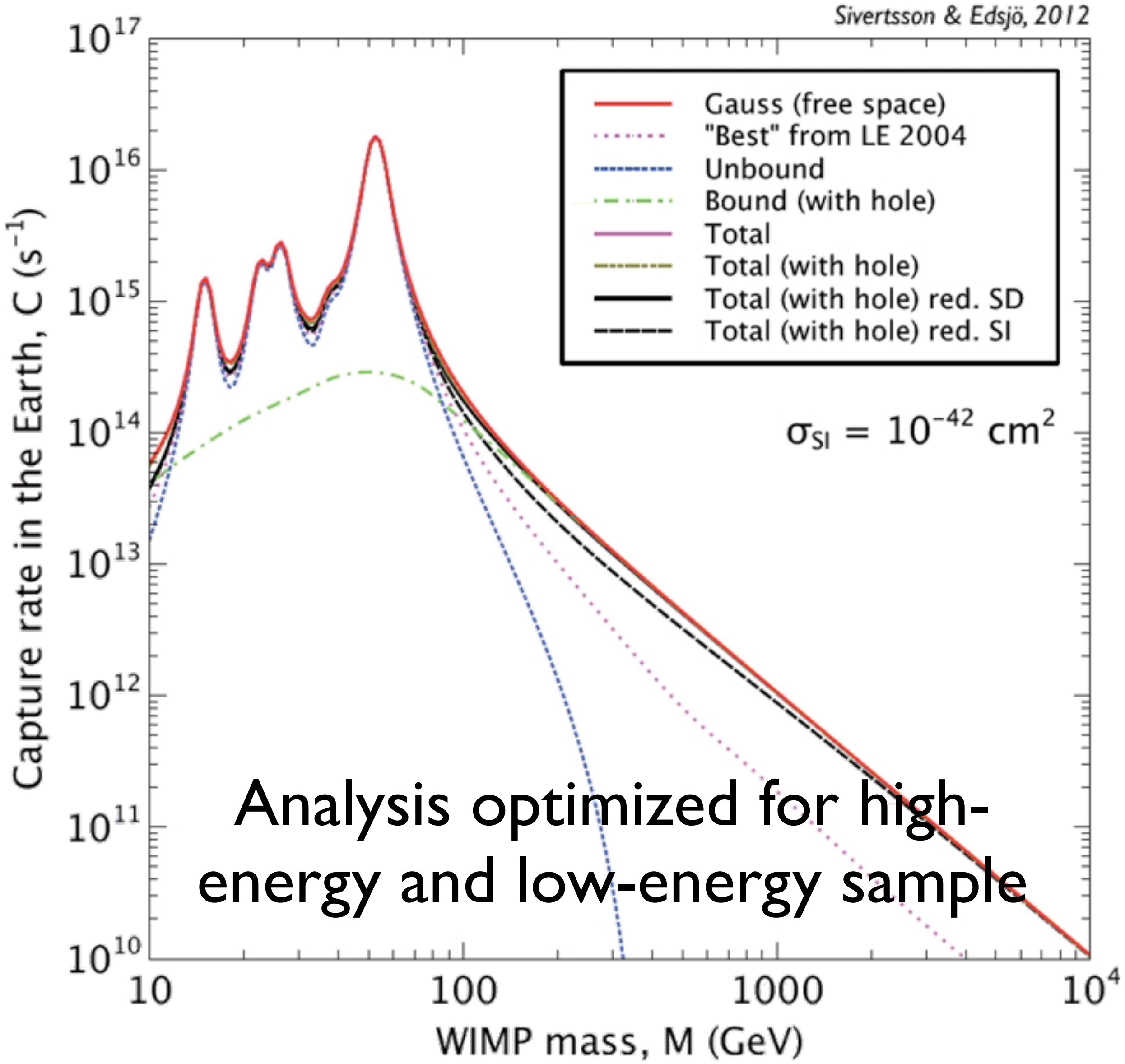
Spin-dependent scattering



Spin-independent scattering

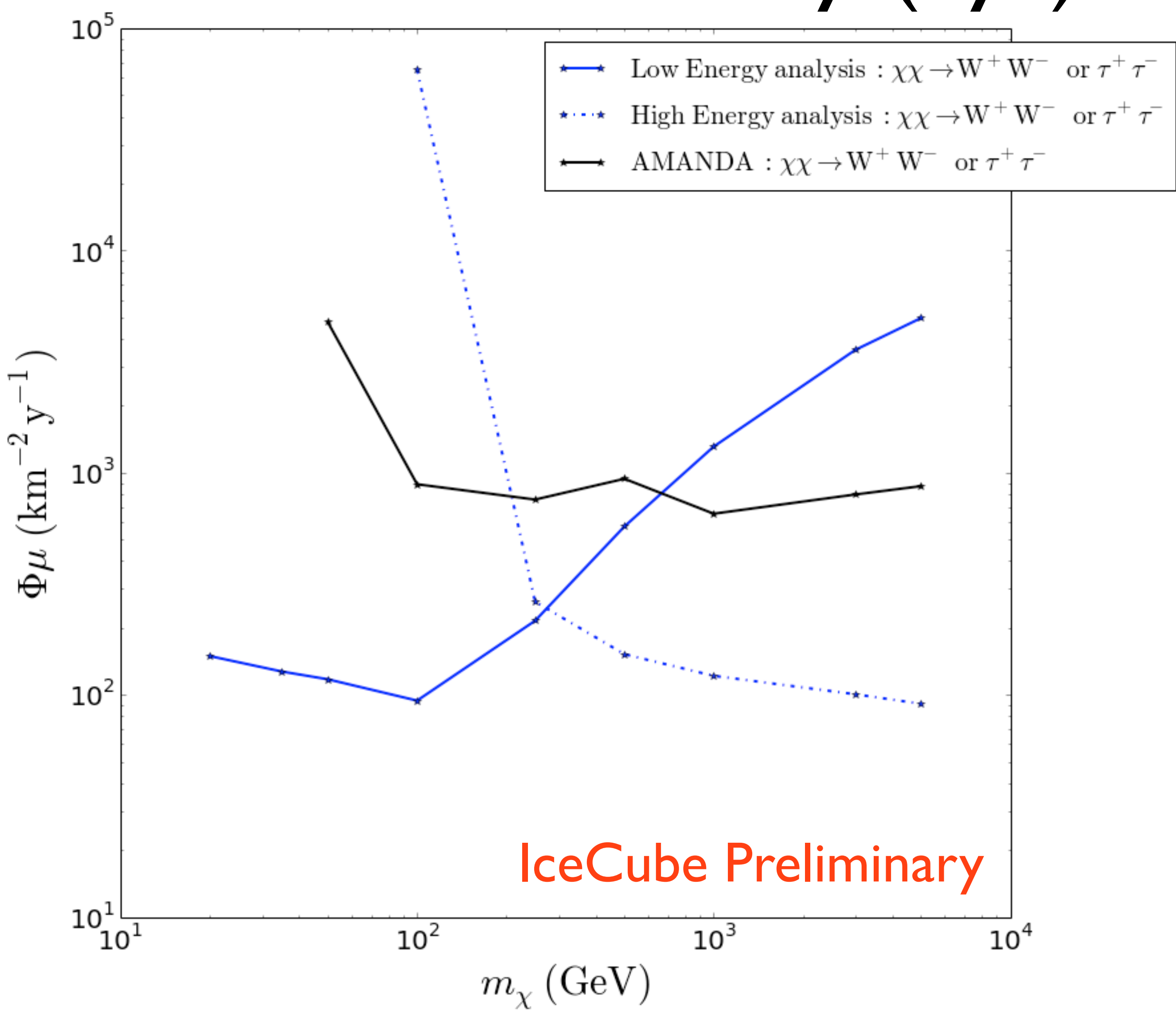


Dark Matter Captured in the Earth -- Look for vertical up-going events from self-annihilating dark matter in the Earth's Core



Analysis optimized for high-energy and low-energy sample

IceCube Sensitivity (1yr)



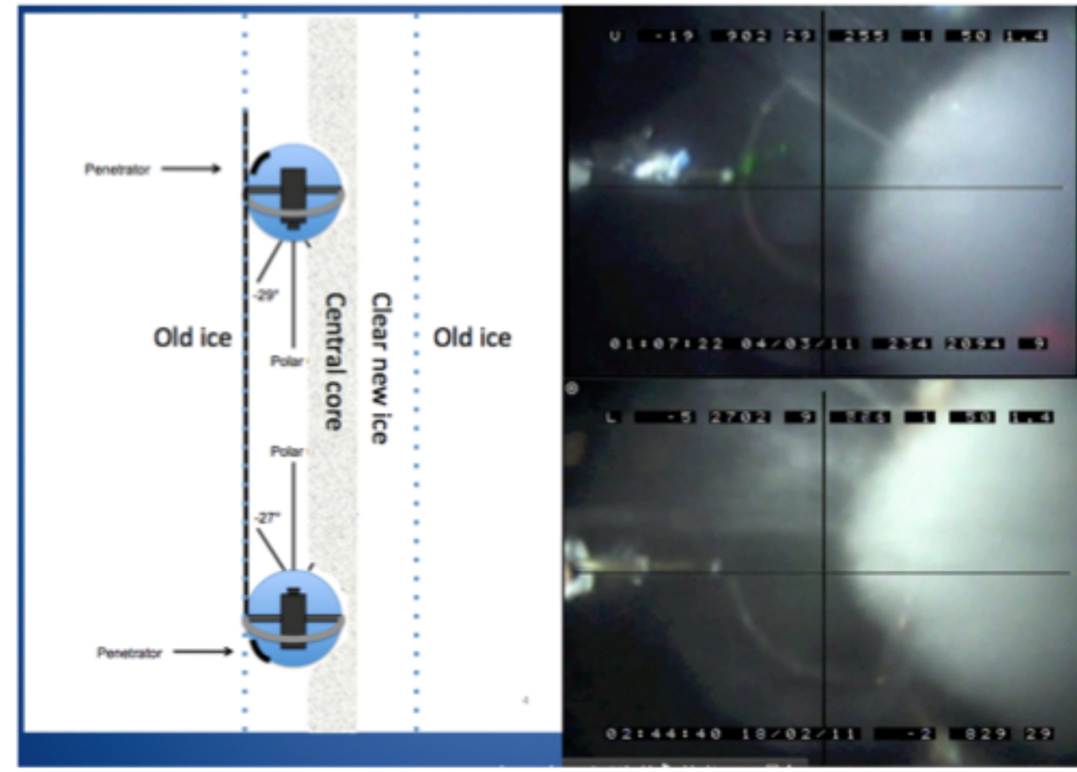
Conclusions

- IceCube with DeepCore has demonstrated sensitivity to atmospheric neutrino physics
- PINGU infill extension could measure NMH at 3σ in 3.5years
  - Technology has been proven with IceCube, relatively low cost
  - Analysis method are still being improved
  - PINGU is complementary to long baseline accelerator experiments
  - PINGU provides diverse physics potential , including indirect dark matter searches and tau appearance
- IceCube provides world best limit on SD WIMP-Proton scattering cross section and PINGU will allow to cover WIMP masses down to 5GeV

Thanks !

Camera System

- Refrozen ice (hole ice) is a major source uncertainty
- There is good reason to expect that the situation for each sensor module can be rather different
    - Understand the ice conditions in the vicinity of every sensor
        - Where is the sensor with respect to the hole ice ?
        - Are there any impurities, cracks, bubbles, etc ...
        - Where is the cable located ?



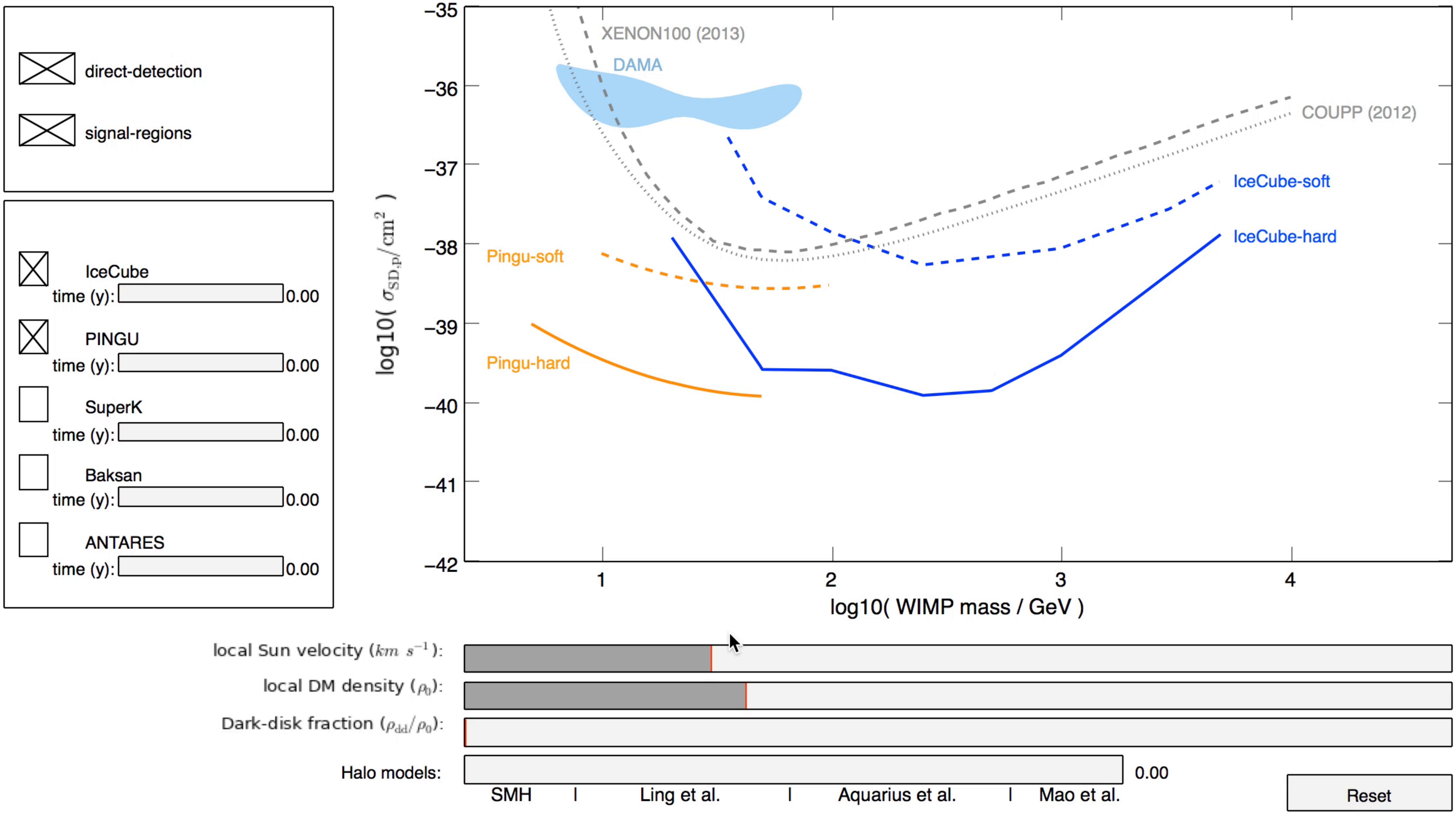
PINGU Costs

- Standalone PINGU
  - US cost $60m: $21m startup, $1.61m per string
  - Assume $25m non-US contribution
- PINGU as part of a facility at Pole
  - US cost $40m: $7m startup, $1.44m per string
  - Assume $25m non-US contribution
- Additional detectors (increasing from 60 to 96 modules per string) improves the resolution at low energies significantly moving the 3 year significance from 2.8σ to nearly 3.3σ for a 10% increase in project cost

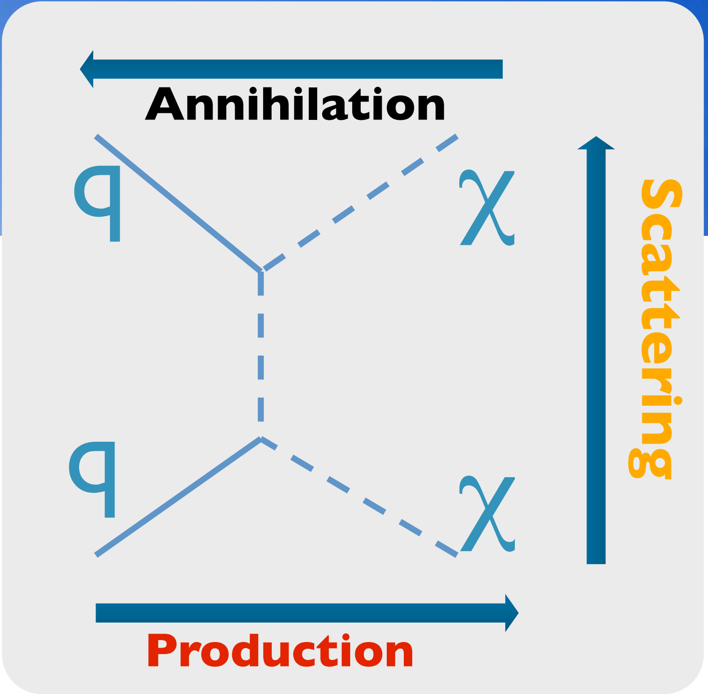
Impact of astrophysical uncertainties

M. Danninger & C. Rott "Solar WIMPs Unraveled" -- Invited Review for Physics of the Dark Universe (submitted)

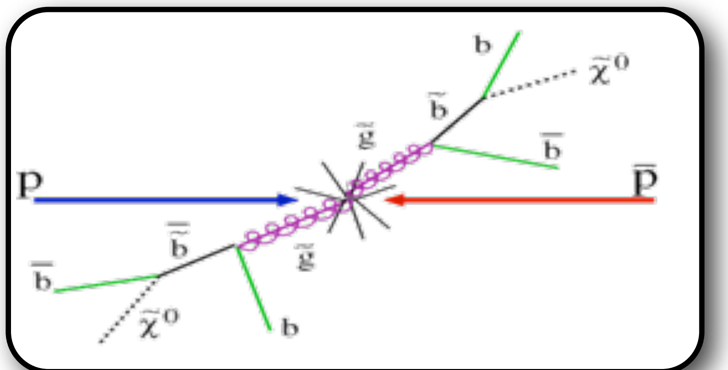
interactive tool to study impact of astrophysical parameters



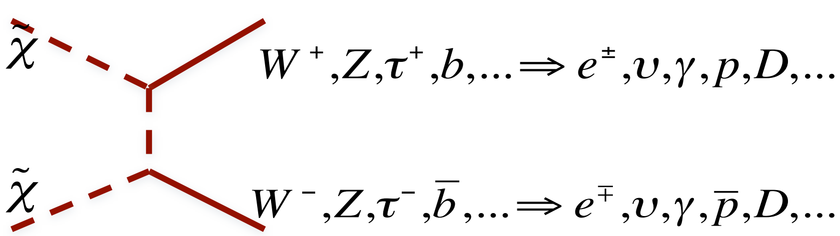
Role of Neutrinos

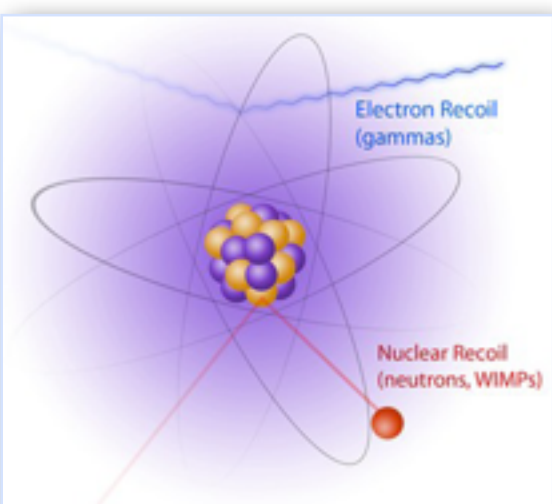


WIMP - Weakly Interacting Massive Particle



- **Production**
  - Colliders
- **Indirect Searches**
  - Annihilation of Dark Matter in Galactic Halo, ...
    - Gamma-rays, electrons, neutrinos, anti-matter, ...
  - Annihilation signals from WIMPs captured in the Sun (or Earth)
    - Neutrinos
- **Direct Searches**
  - WIMP scattering of nucleons → Nuclear recoils





WIMP Self-annihilation cross section

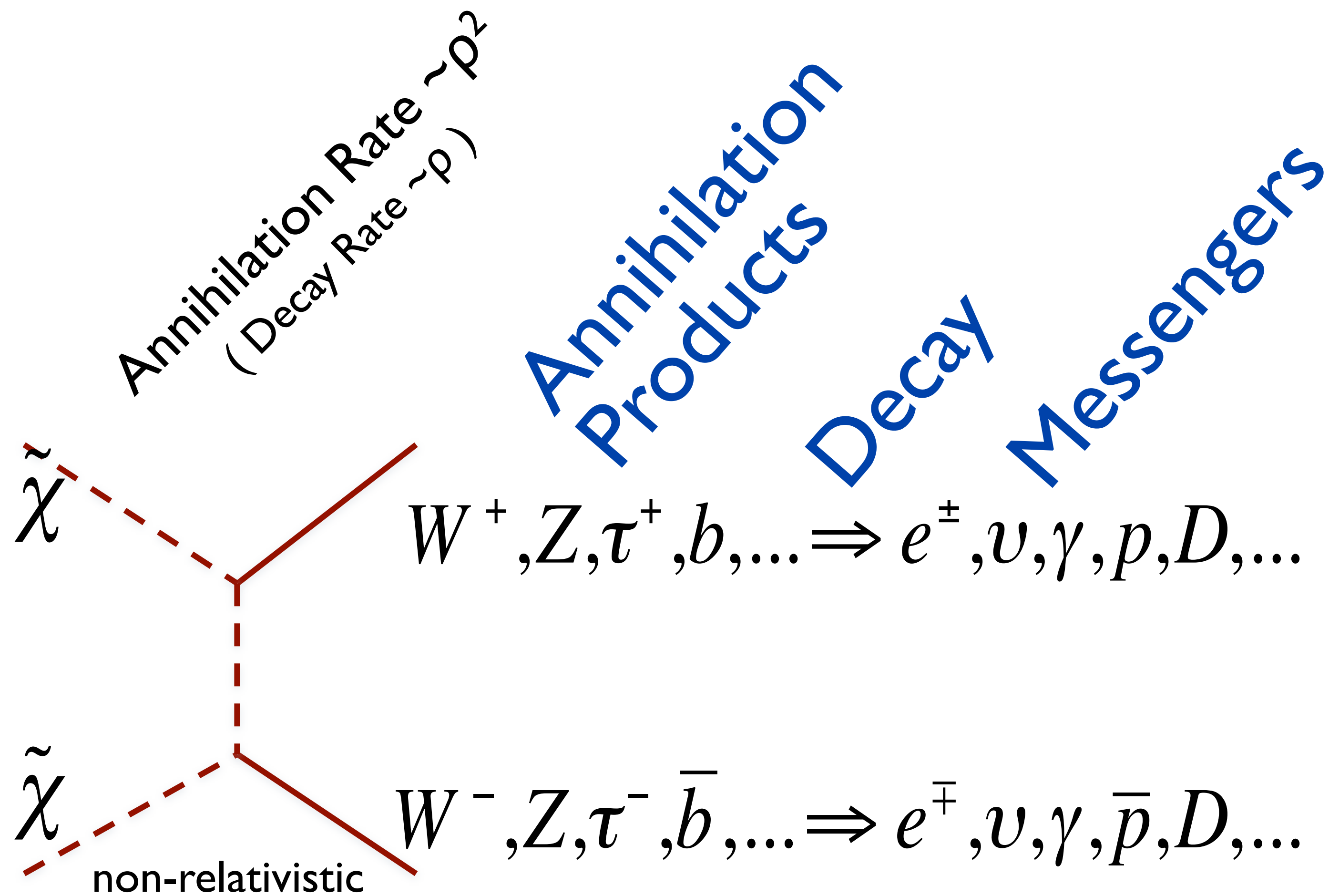
WIMP-Nucleon Scattering cross section

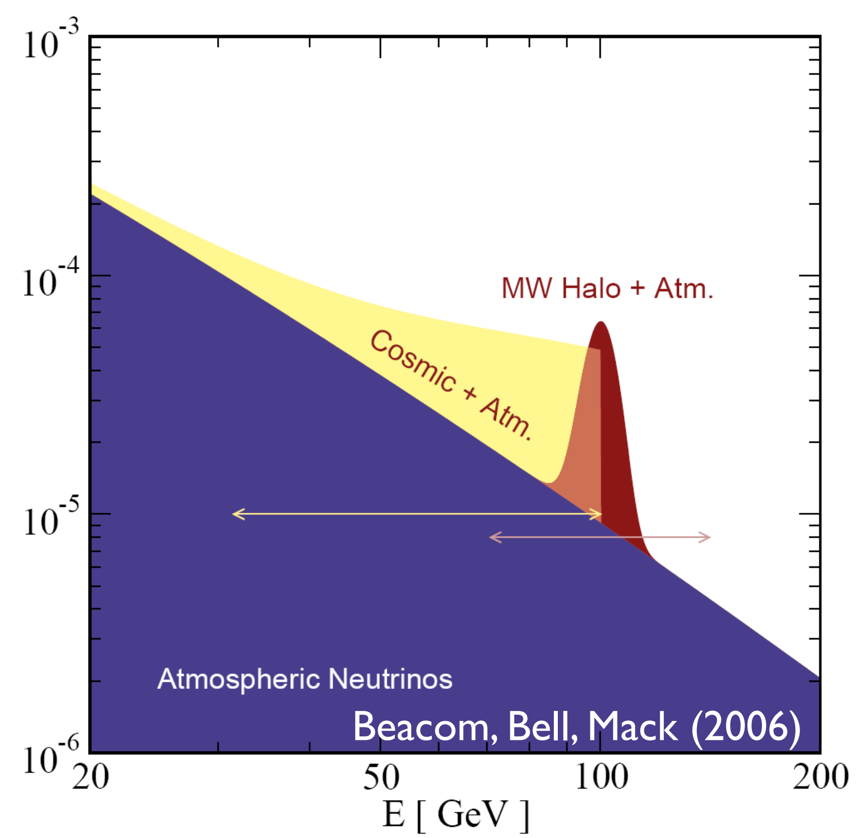
Dark Matter Annihilation Signals

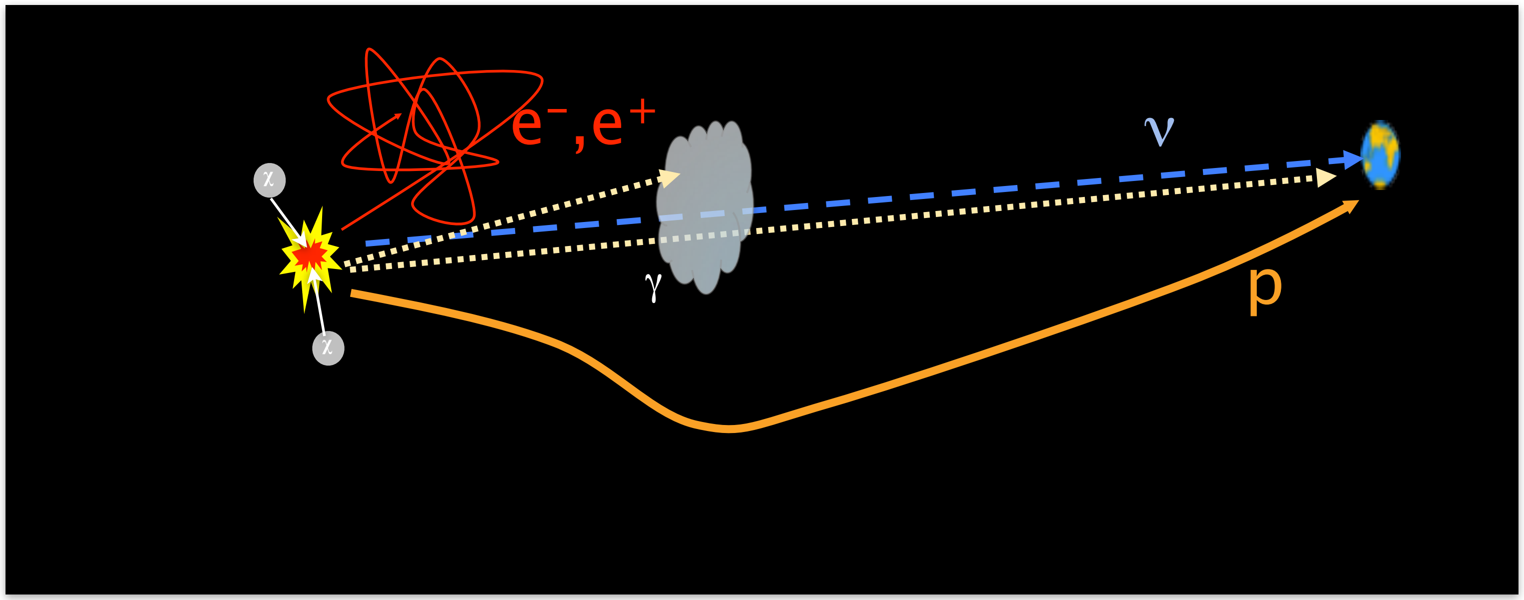
- Identify overdense regions of matter

  ⇒self-annihilation can occur at

  significant rates
- Pick prominent Dark Matter target
- Understand / predict backgrounds
- Exploit features in the signal to better distinguish against backgrounds







The IceCube Neutrino Telescope

see talk by Aya Ishihara

Gigaton Neutrino Detector at the Geographic South Pole

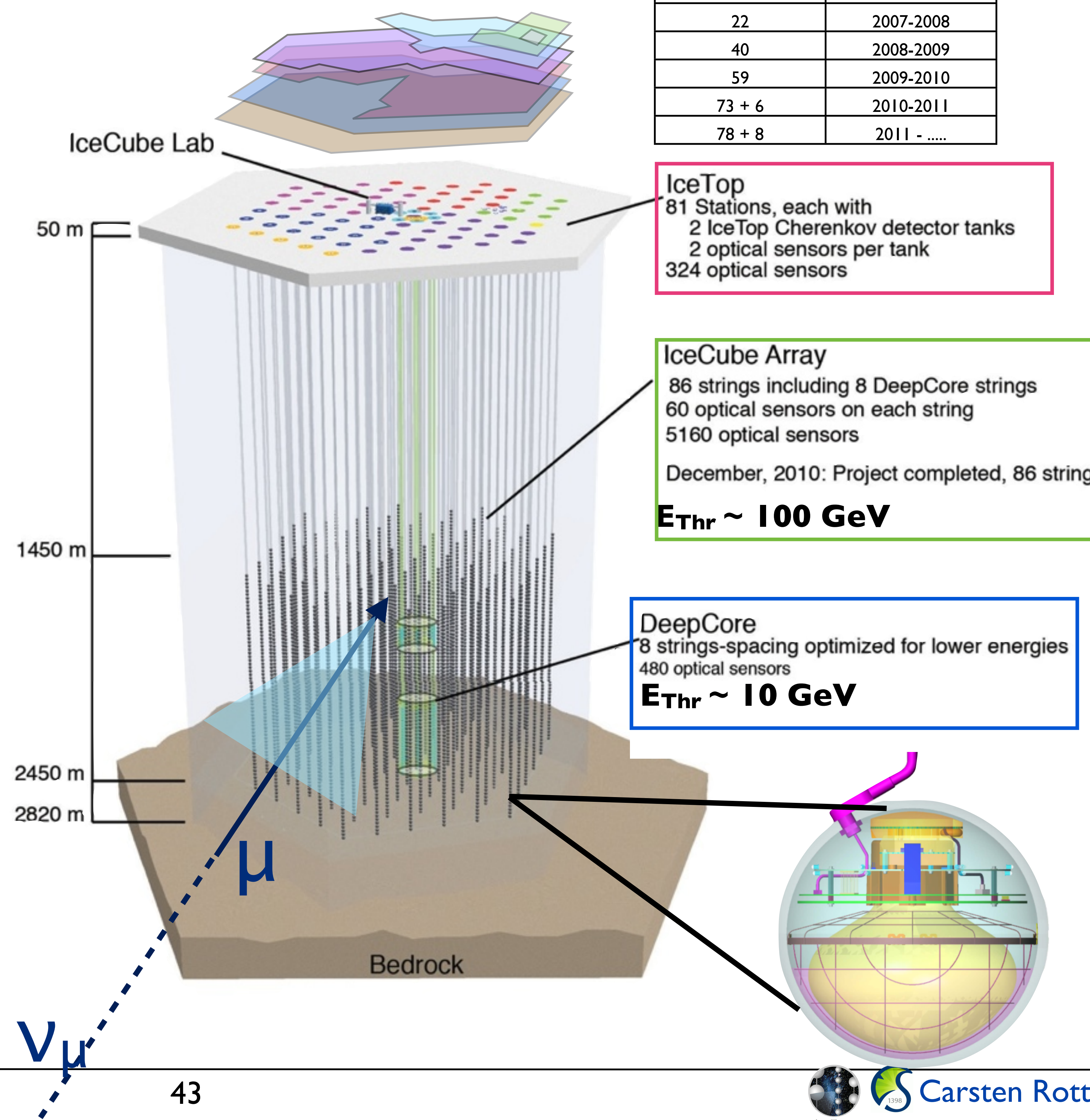
5160 Digital optical modules distributed over 86 strings

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

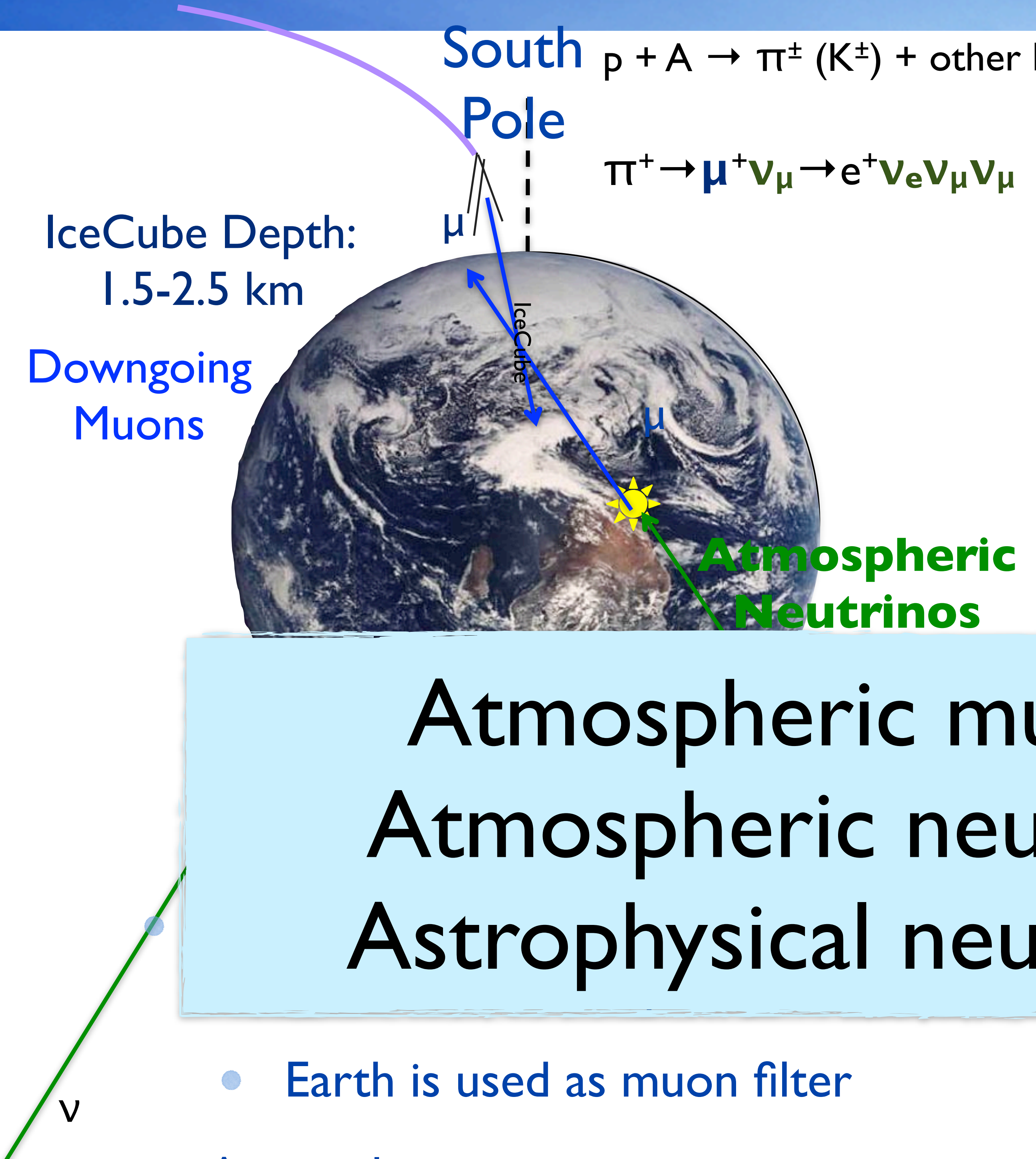
Data acquired during the construction phase has been analyzed

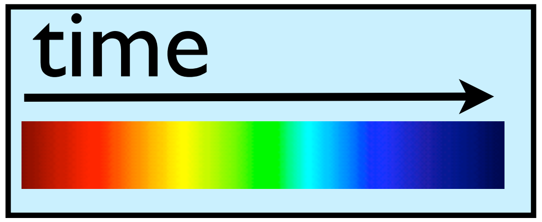
Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice

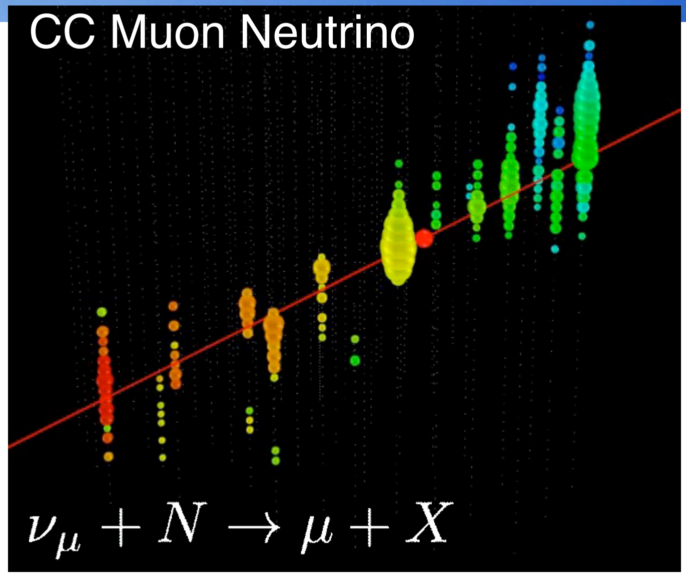
Strings	Dataset
1	2005-2006
9	2006-2007
22	2007-2008
40	2008-2009
59	2009-2010
73 + 6	2010-2011
78 + 8	2011 - .....

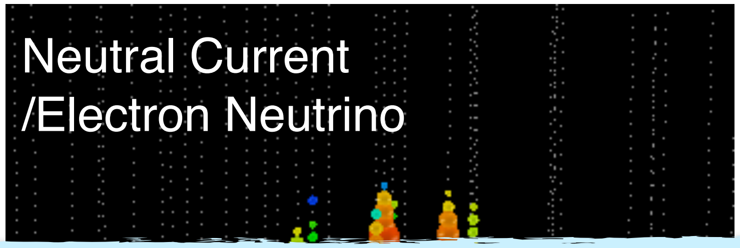


Signals in IceCube

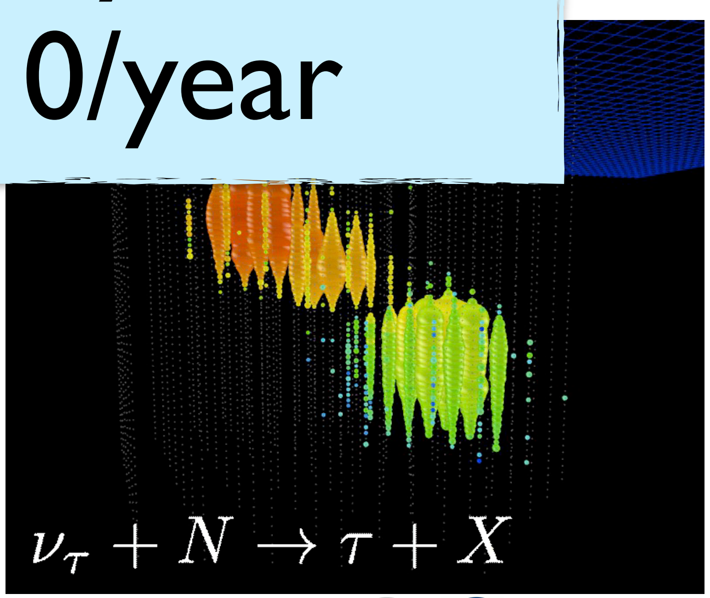








Atmospheric muons ~ 10^{11}/year
Atmospheric neutrinos ~ 10^5/year
Astrophysical neutrinos ~ >10/year



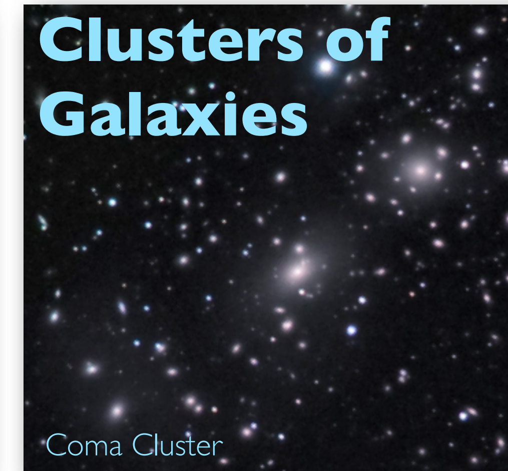
- Earth is used as muon filter
- Atmospheric neutrinos create irreducible neutrino background to extra terrestrial neutrino fluxes

Dark Matter Self-annihilations

$<\sigma_A v>$

Dark Matter in the Milky Way

Sources



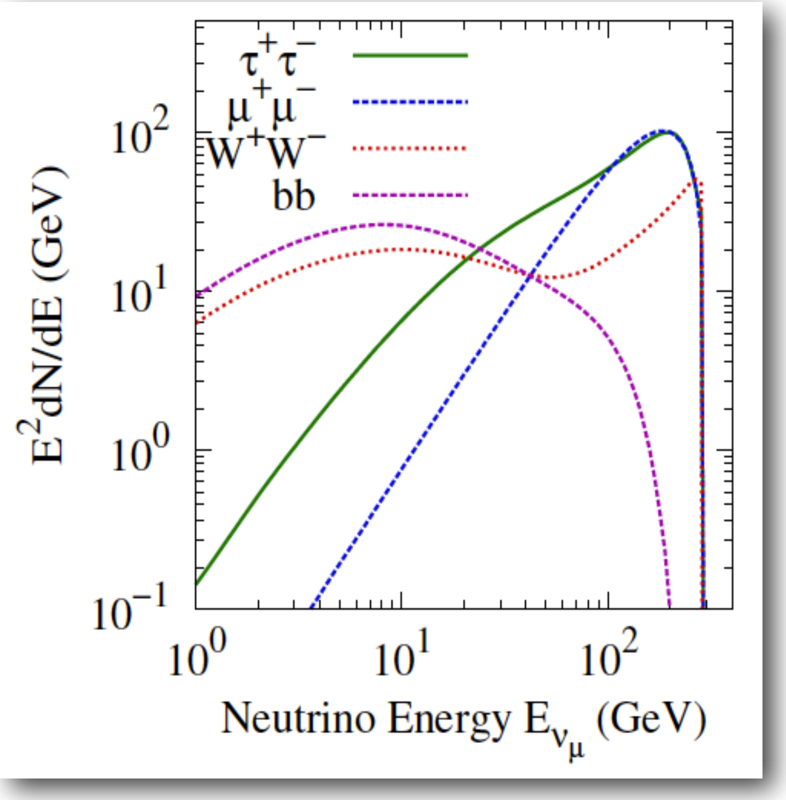
Extra-galactic	Milky Way Halo	Galactic Center	Dwarf Spheroidal	Clusters of Galaxies
small halo model dependence, boost factors	Large DM content, nearby source, O(10) larger flux than extra-galactic	Very dense DM accumulation, nearby source	no astrophysical backgrounds	large DM content, high boost factors from sub structure
Diffuse flux, spectral feature	Anisotropy	Extended Source	Point source	Extended source
signal weak compared to Galactic signal	relatively independent from DM halo profile	very strong dependence on DM density profile	cored profiles favored, less flux	understanding of boost factors

Dark Matter Annihilation

Measure Flux

Particle Physics

$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\Sigma_f\frac{dN}{dE}B_f$$

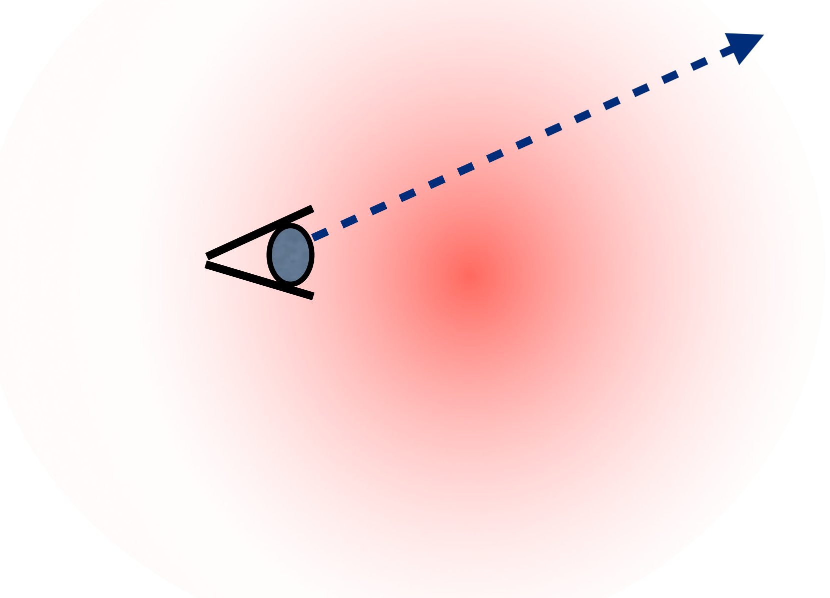


x

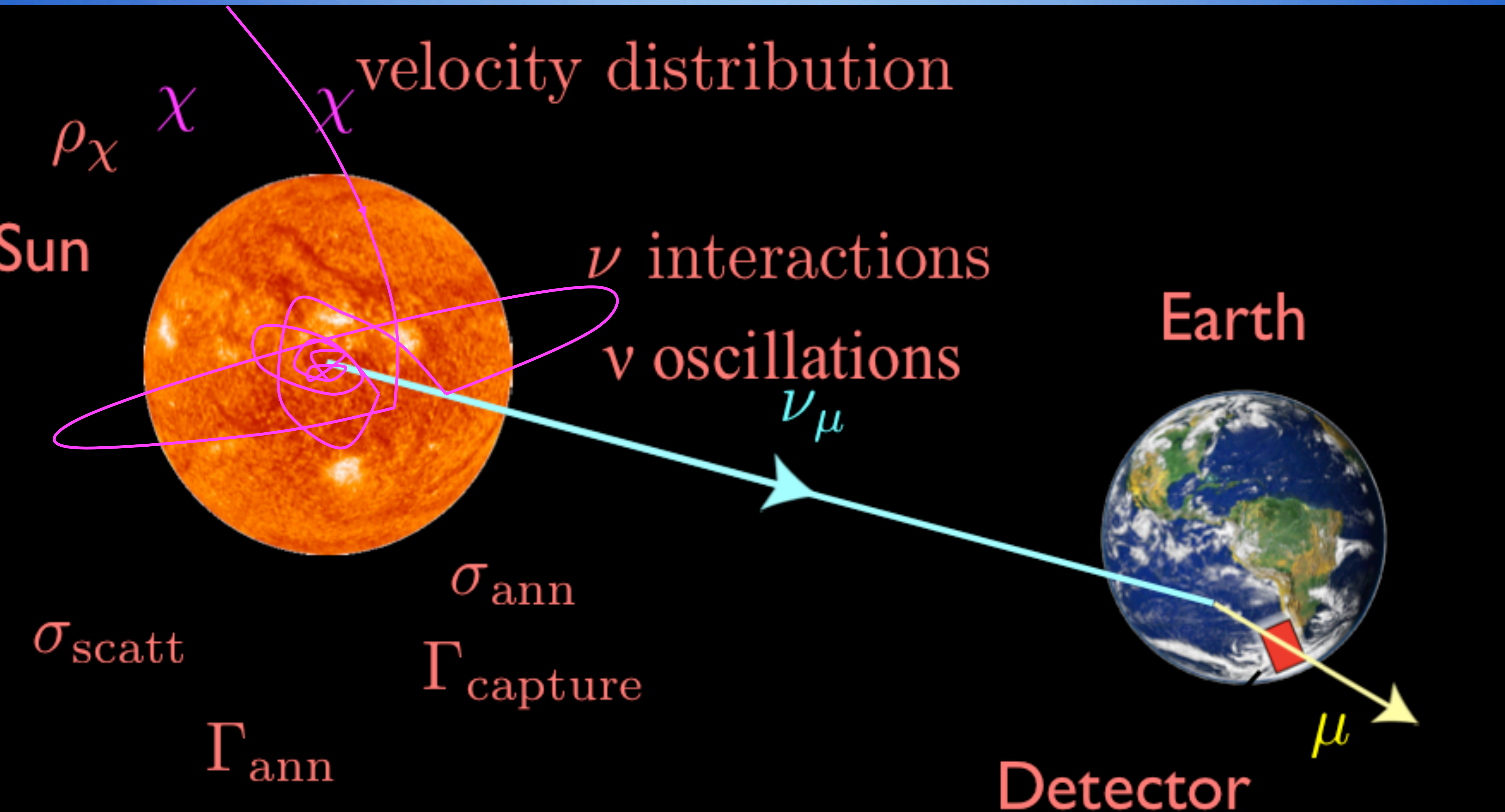
Dark Matter Distribution

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

line of sight (los) integral



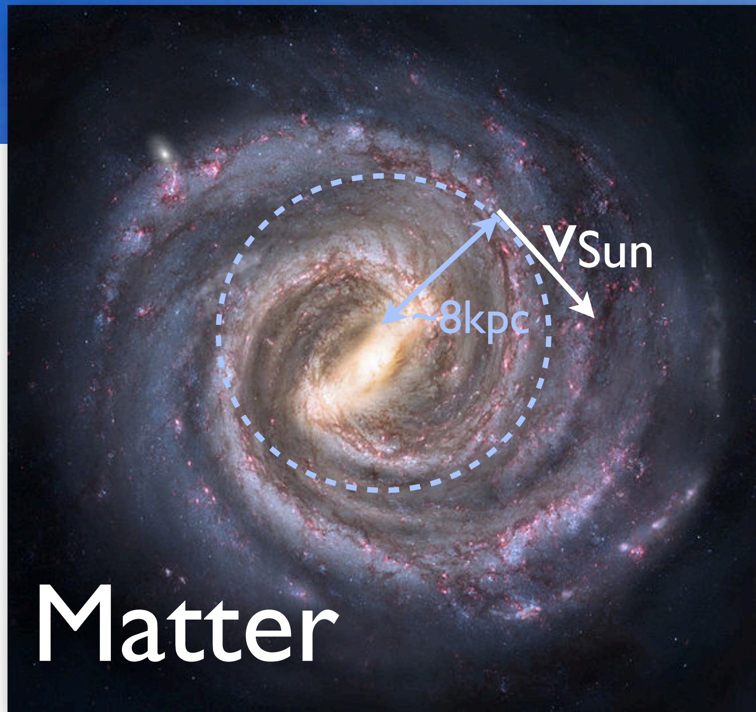
Solar WIMPs



Freese '86
Krauss, Srednicki & Wilczek '86
Gaisser, Steigman & Tilav '86

Silk, Olive and Srednicki '85
Gaisser, Steigman & Tilav '86

Solar WIMP Capture



+

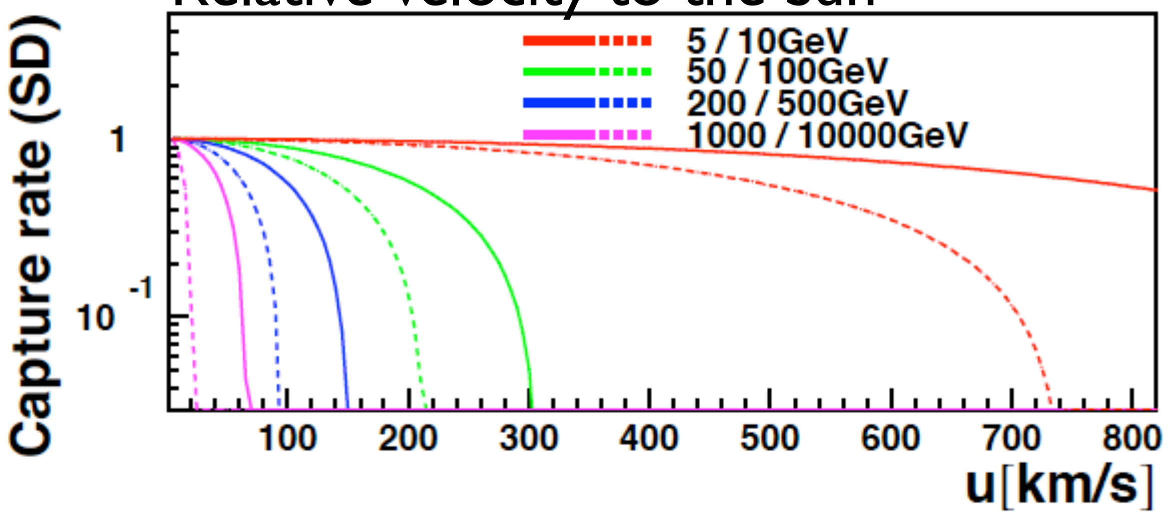
Standard assumption

DM isotropic with Maxwellian velocity distribution

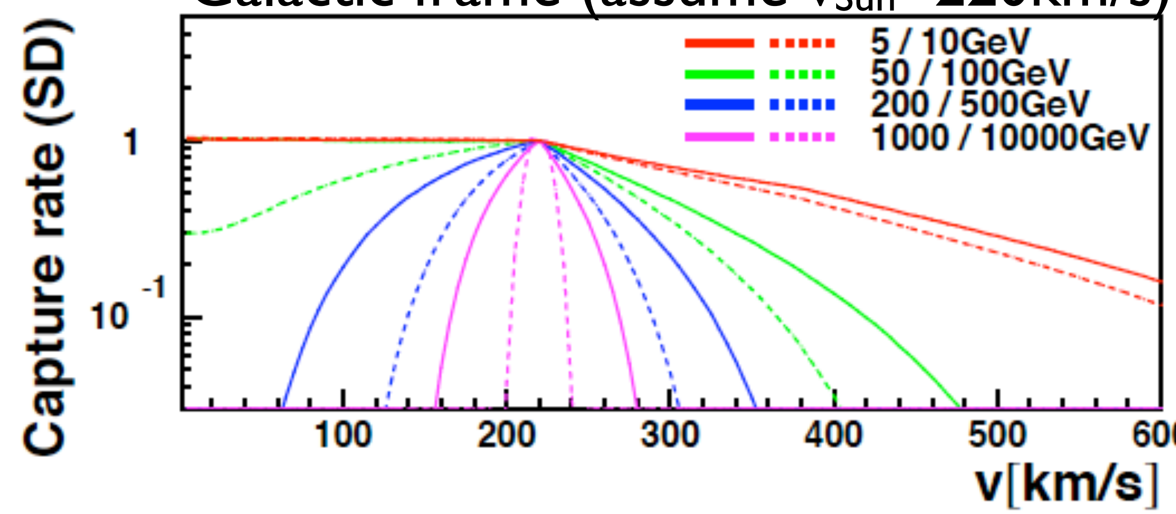
... consequence of a density profile $\rho(r) \propto r^{-2}$ of collisionless particles

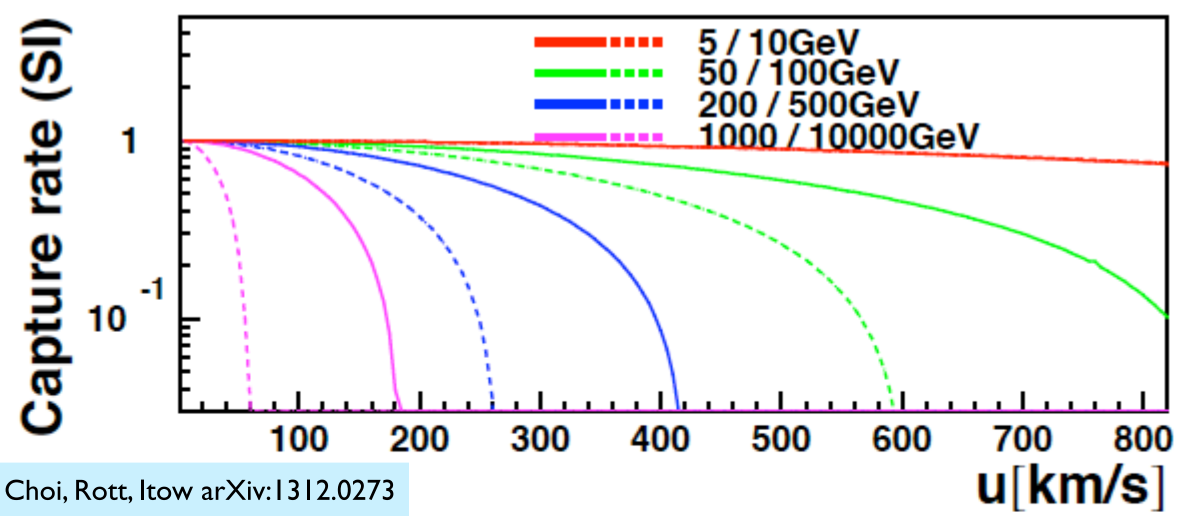
$$f(u) = \sqrt{\frac{3}{2\pi}}\frac{u}{v_\odot v_{\rm rms}}\left(\exp\left(-\frac{3(u-v_\odot)^2}{2v_{\rm rms}^2}\right) - \exp\left(-\frac{3(u+v_\odot)^2}{2v_{\rm rms}^2}\right)\right).$$

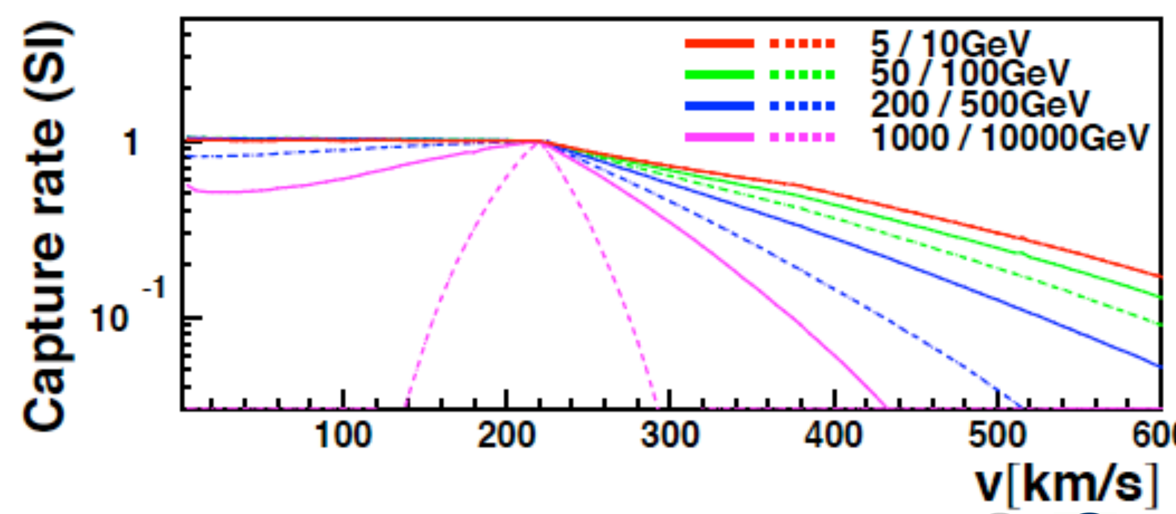
Relative velocity to the Sun



Galactic frame (assume v_{Sun}=220km/s)





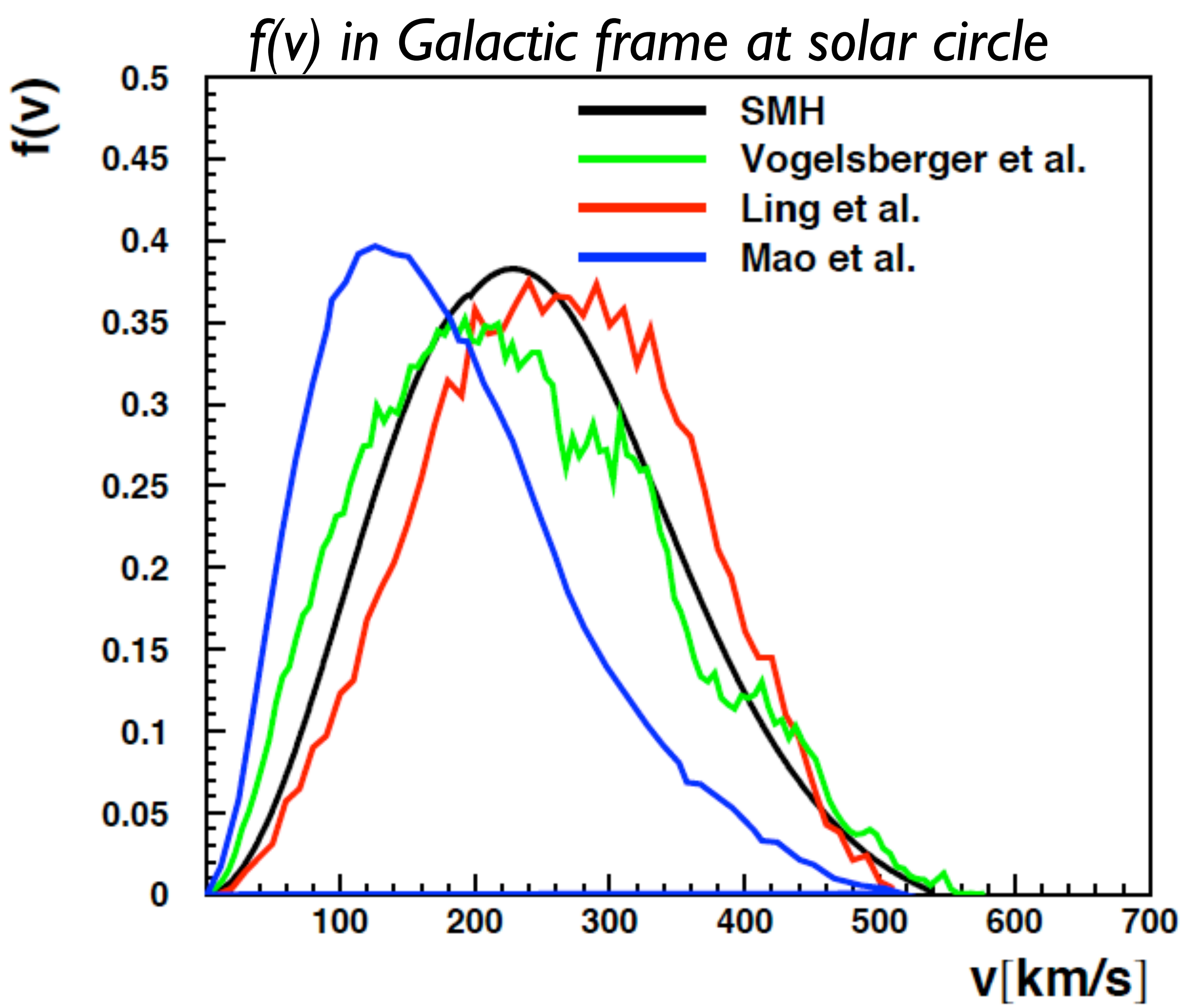


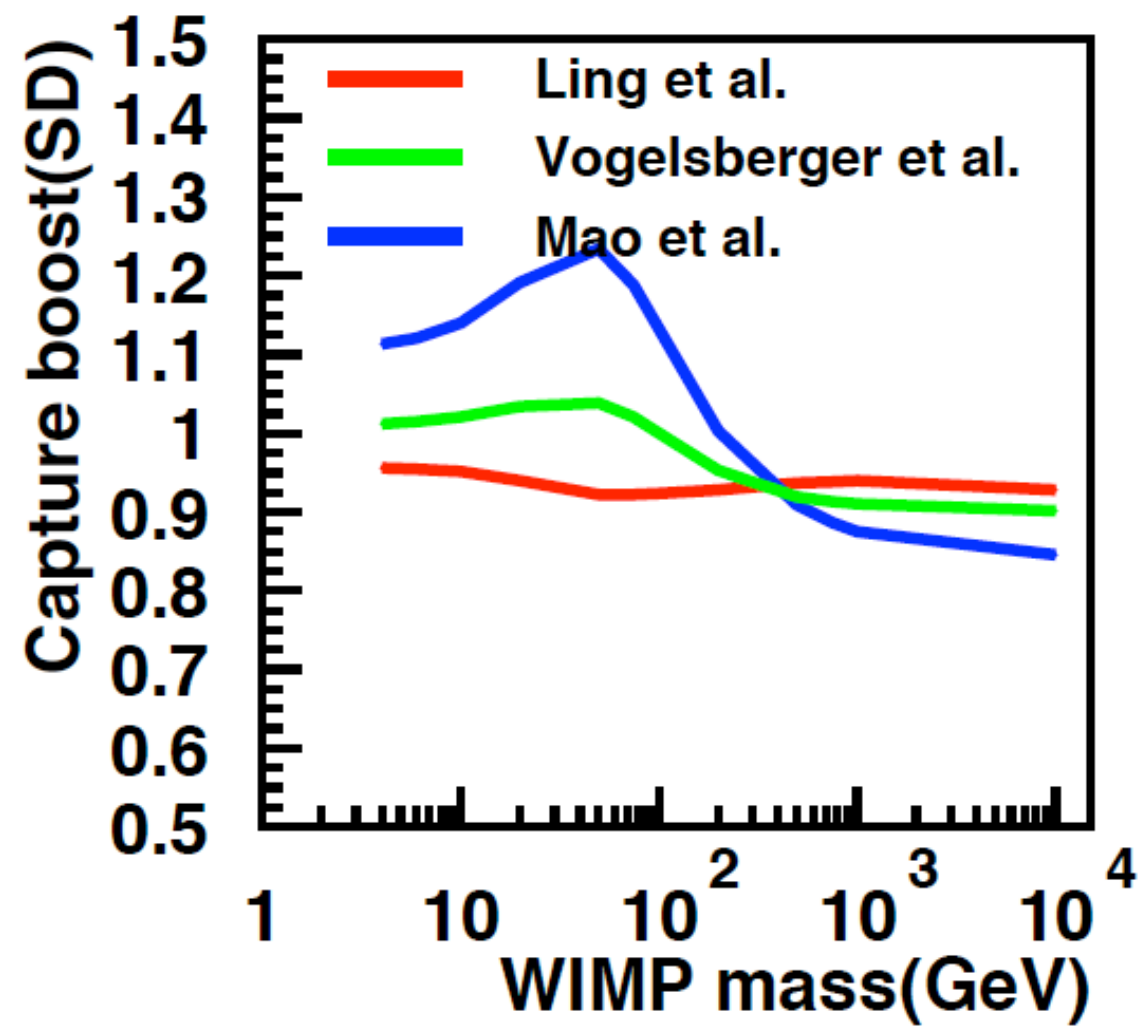
Choi, Rott, Itow arXiv:1312.0273

Impact of velocity distribution

- Explore the change in capture rate using different velocity distributions obtained from dark matter simulations

Choi, Rott, Itow JCAP 1405 (2014) 049



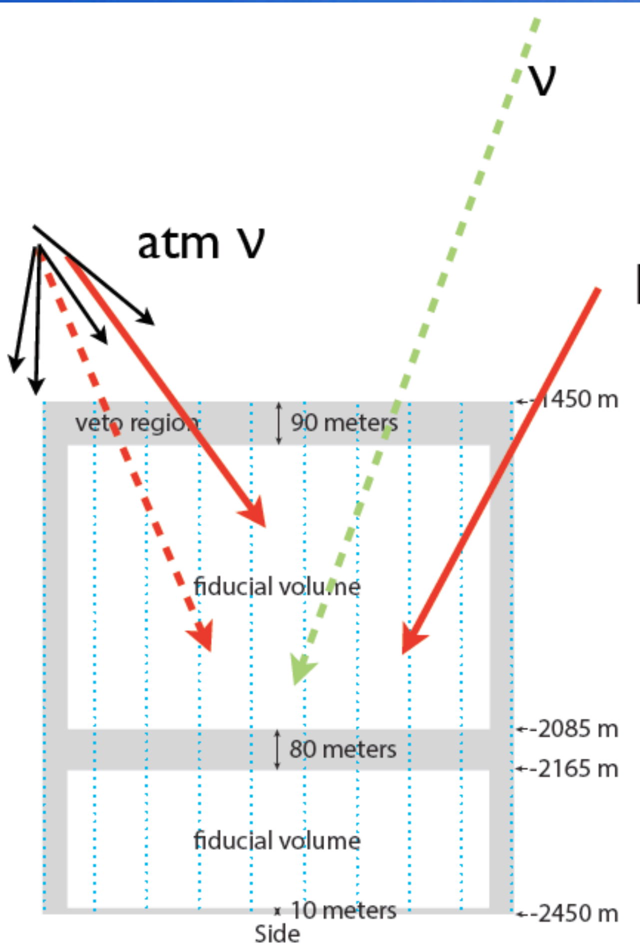


- A comparison of captures rates for different WIMP velocity distributions show that overall changes in the capture rate are smaller than 20%

Dark Matter Decay - High Mass Dark Matter

IceCube: High-energy neutrino events

IceCube Collaboration
arXiv:1405.5303v1



- 37 events observed (2010-2013)
  - 2 years analysis found 28 events Science 342, 1242856 (2013)
- energy spectrum >60TeV harder than background
- atmospheric origin rejected at 5.7σ