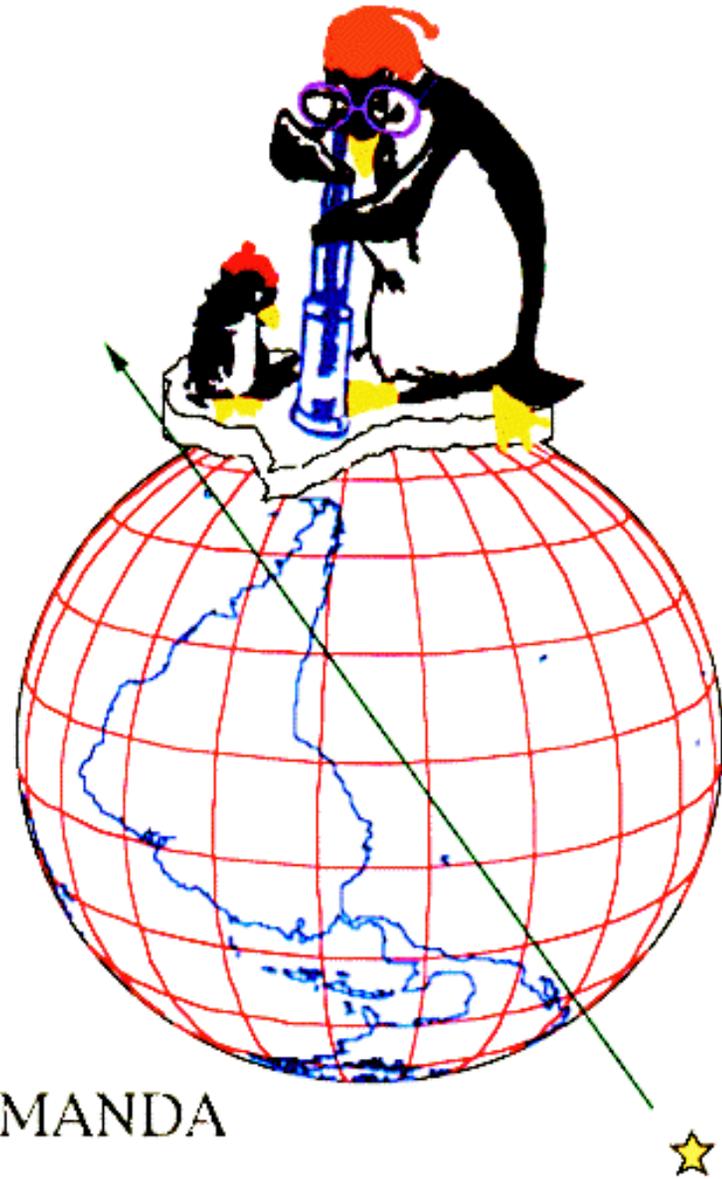


Cline meeting 2016

- IceCube
- atmospheric and cosmic neutrinos
- the search for dark matter

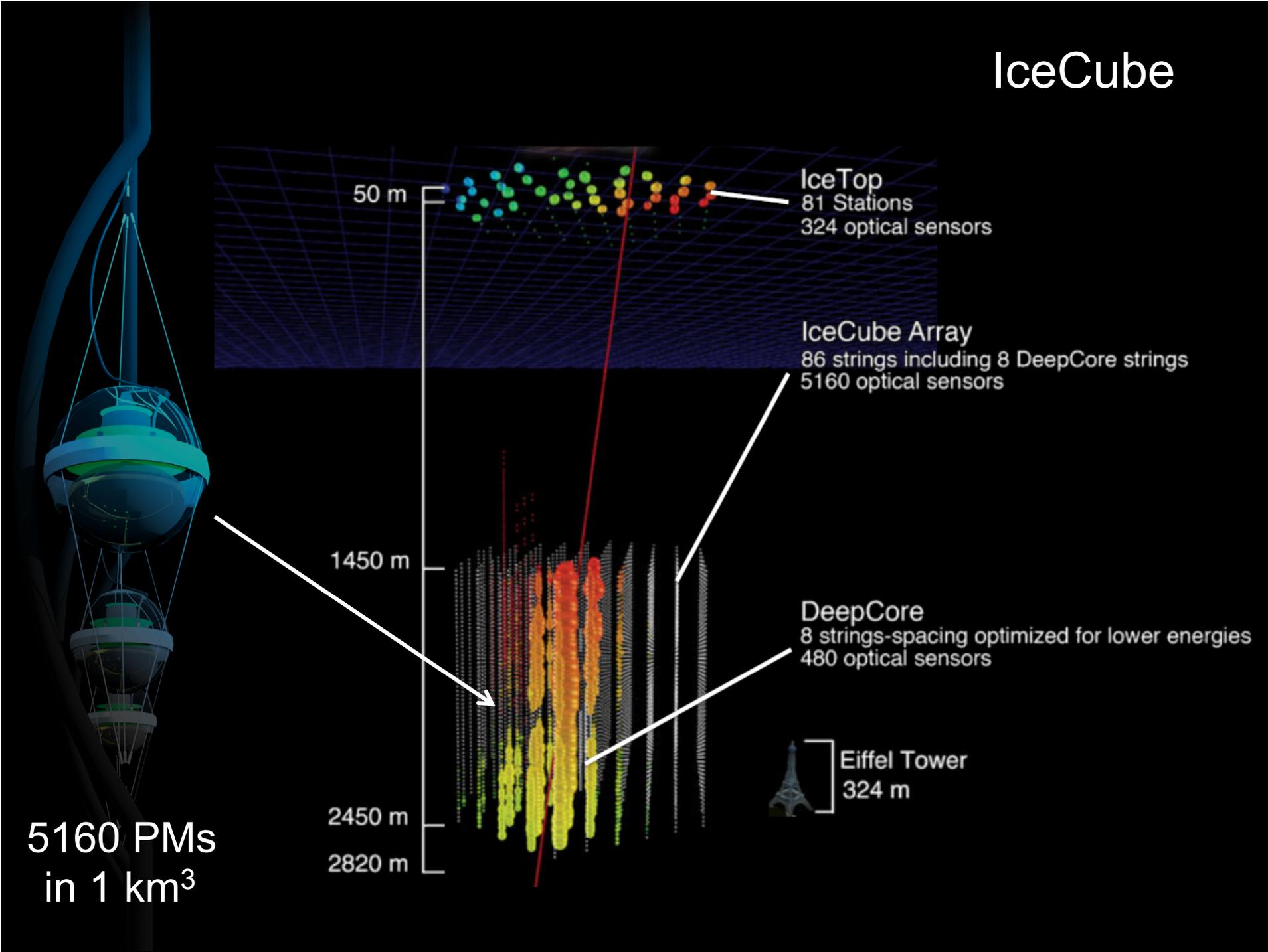
1992 Cline meeting at UCLA

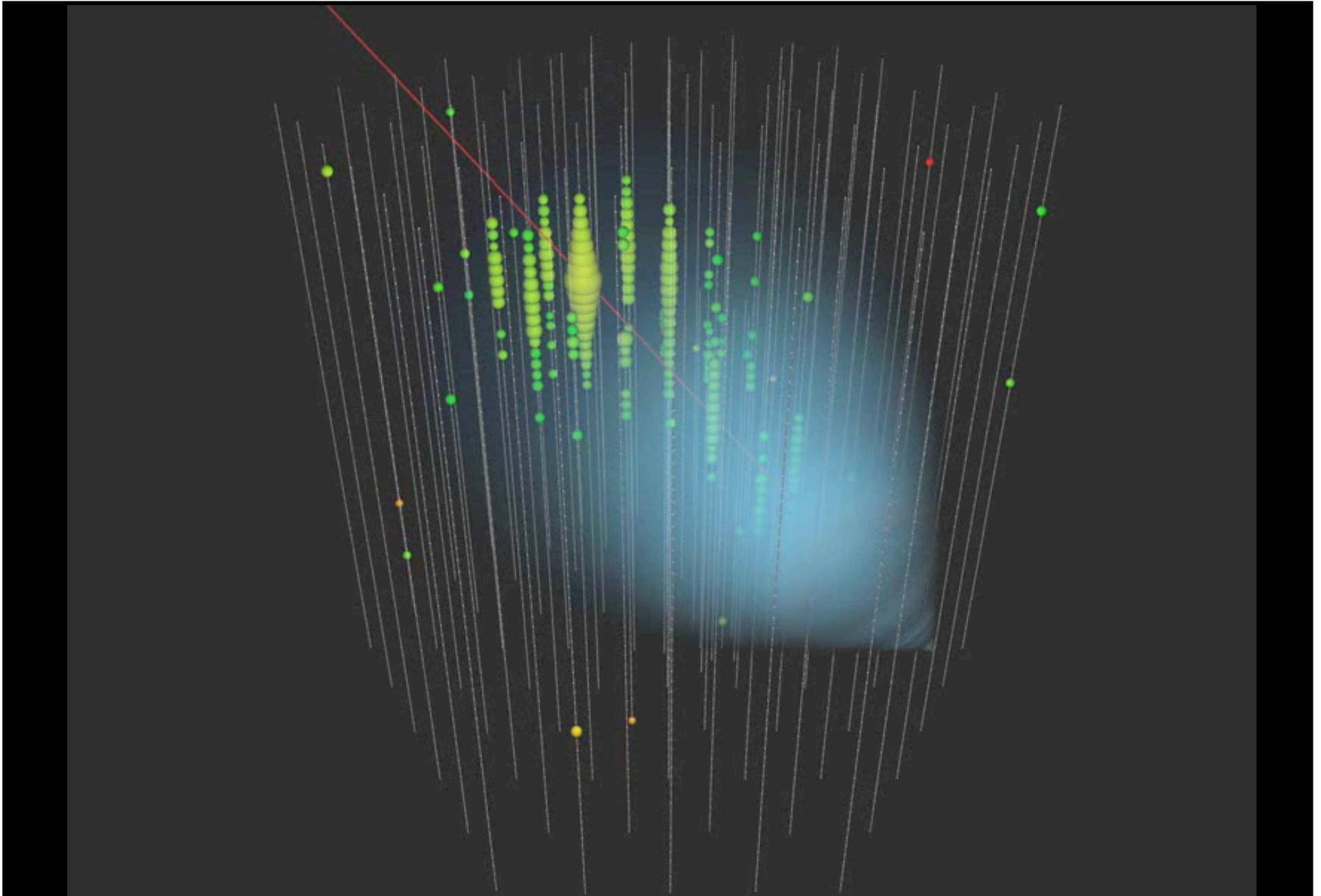
The Economist FEBRUARY 29TH-MARCH 6TH 1992	FLAWED SUPERFUND	pages 18 and 80
	CALIFORNIA'S WOMEN	page 32
	MULTI-MEDIA MADNESS	pages 17 and 73
	ANTARCTIC SCIENCE	pages 91-93



AMANDA

IceCube





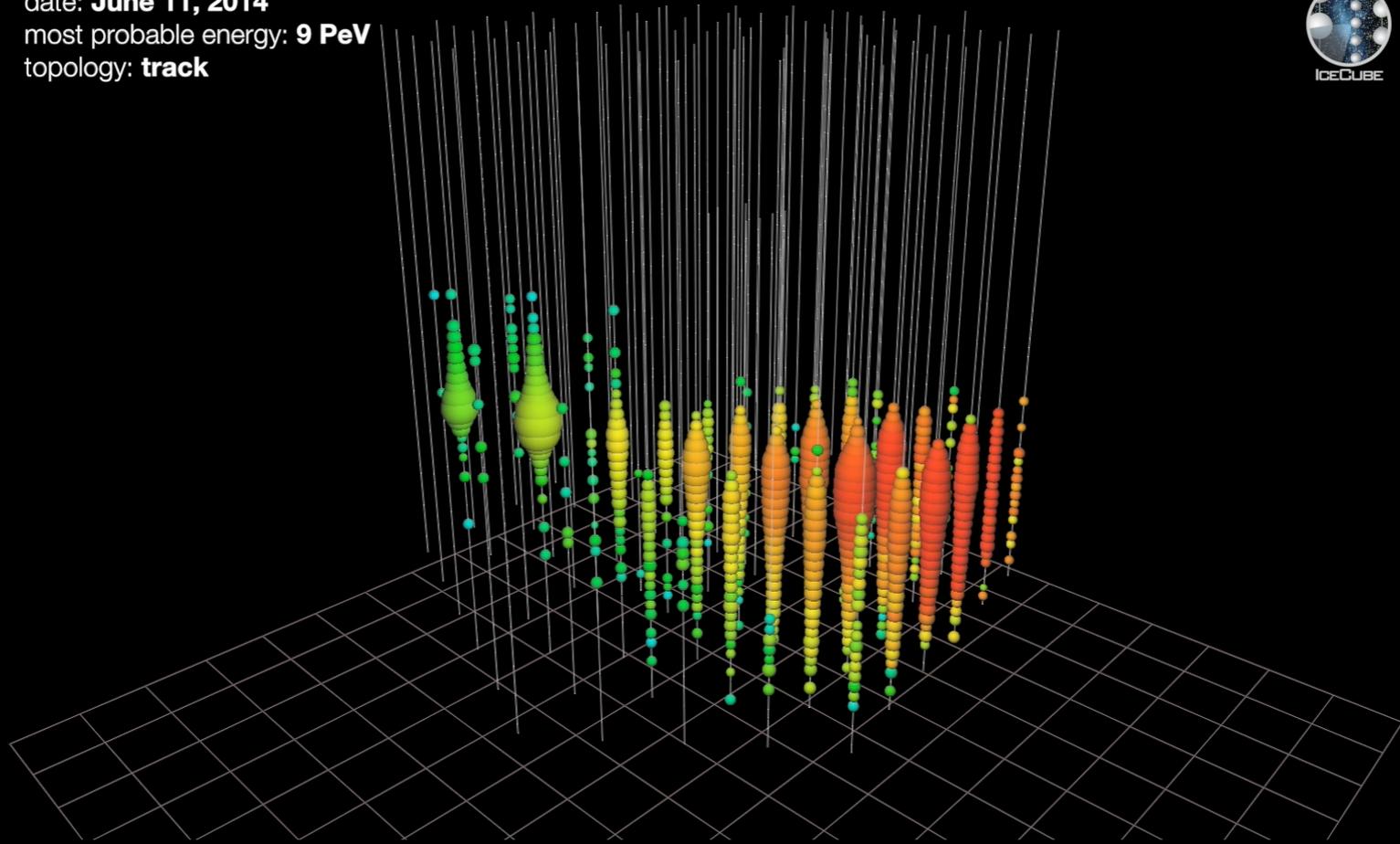
muon track: time is color; number of photons is energy

up-going muon track from muon neutrino (9 PeV)

date: **June 11, 2014**

most probable energy: **9 PeV**

topology: **track**



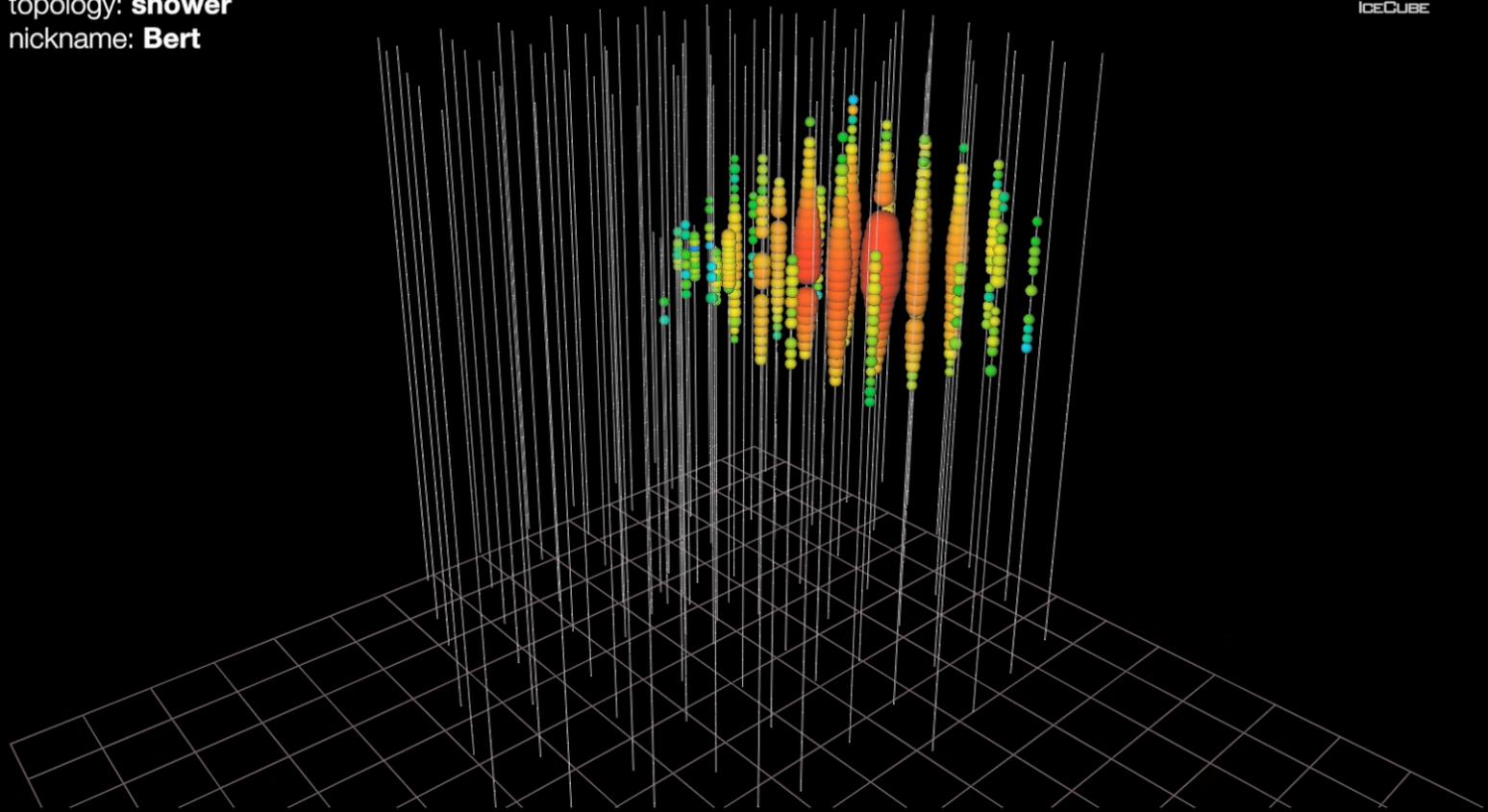
shower initiated inside the detector by electron neutrino (1 PeV)

date: **August 9, 2011**

energy: **1.04 PeV**

topology: **shower**

nickname: **Bert**



muons detected per year:

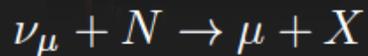
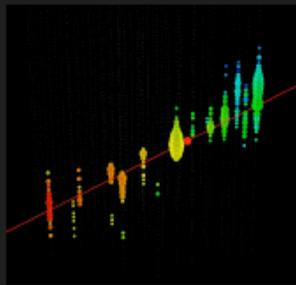
- atmospheric* μ $\sim 10^{11}$
- atmospheric** $\nu \rightarrow \mu$ $\sim 10^5$
- cosmic $\nu \rightarrow \mu$ ~ 10

* 3000 per second

** 1 every 6 minutes

neutrino flavors in IceCube

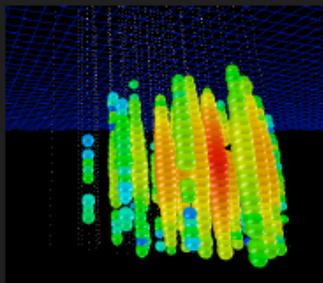
CC Muon Neutrino



track (data)

factor of ≈ 2 energy resolution
 $< 1^{\circ}$ angular resolution at high energies

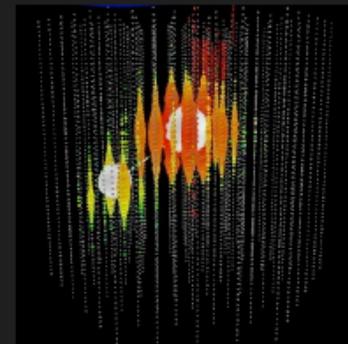
Neutral Current / Electron Neutrino



cascade (data)

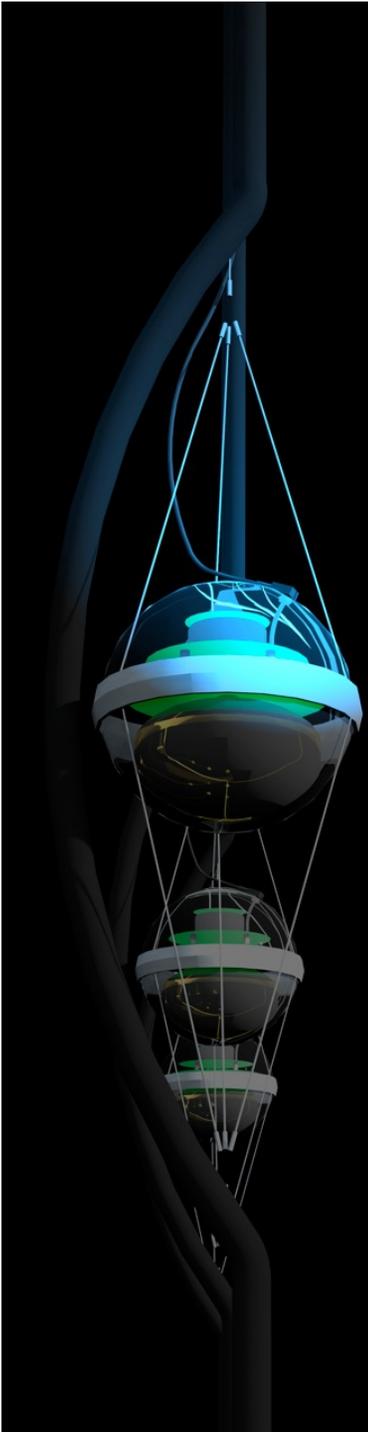
$\approx \pm 15\%$ deposited energy resolution
 $\approx 10^{\circ}$ angular resolution (in IceCube)
 (at energies $\gtrsim 100$ TeV)

CC Tau Neutrino



“double-bang” ($\gtrsim 10$ PeV) and other signatures (simulation)
 (not observed yet: τ decay length is 50 m/PeV)



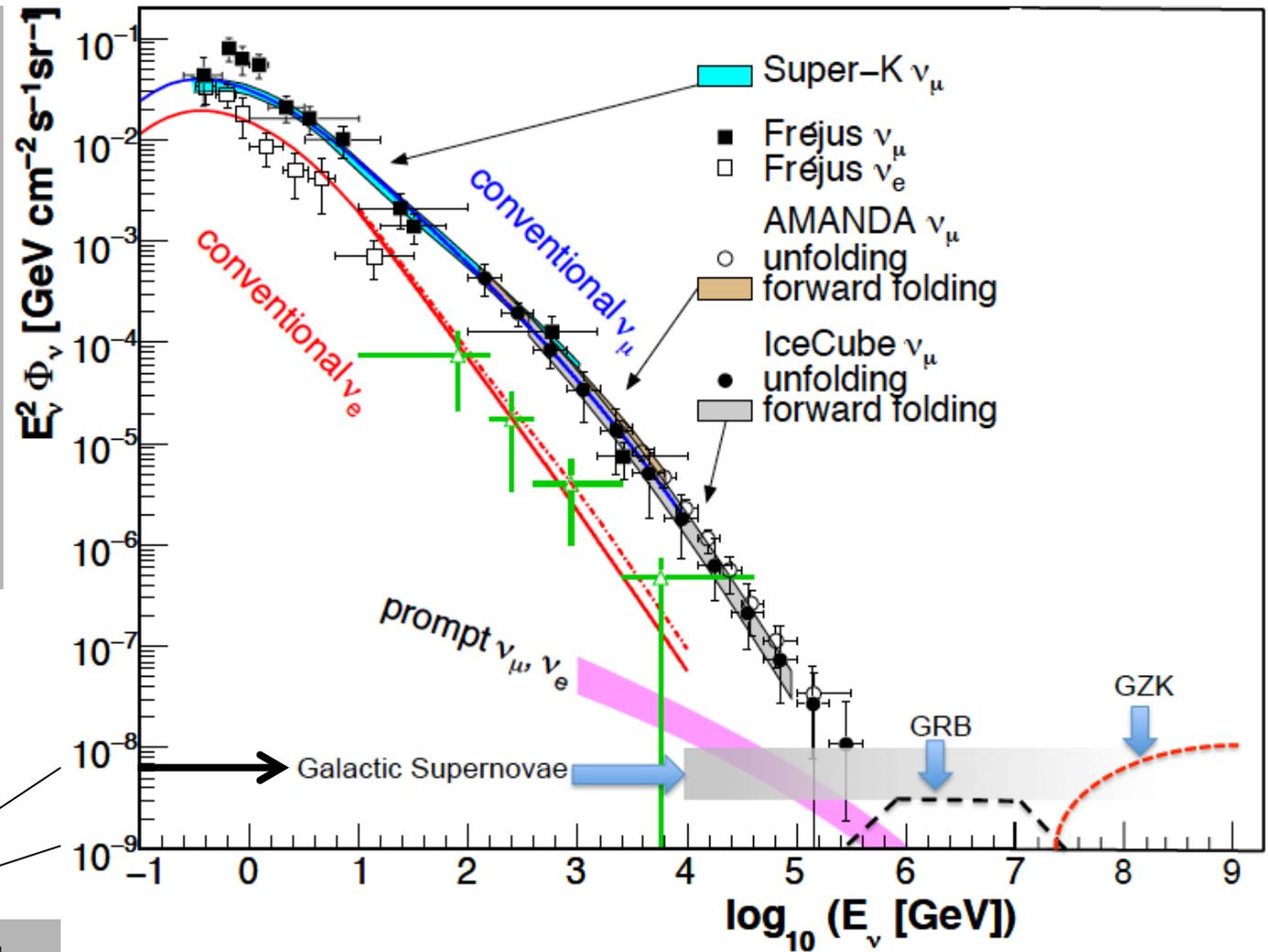
- 
- IceCube
 - atmospheric and cosmic neutrinos
 - the search for dark matter

above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

$$dN/dE \sim E^{-2}$$

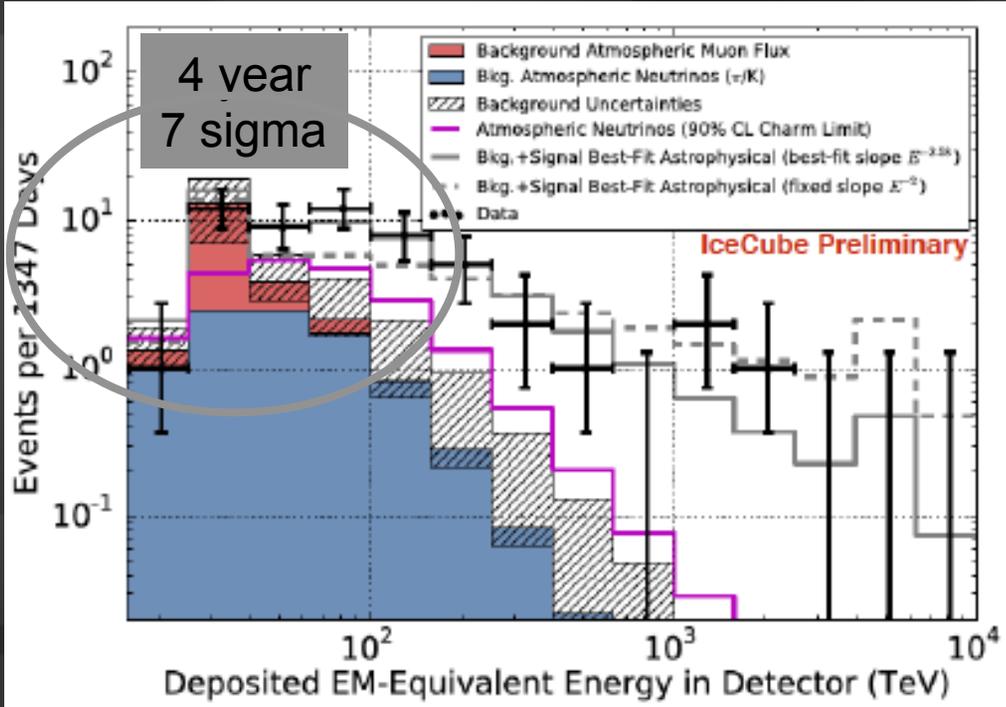
10—100 events per year for fully efficient 1 km³ detector



atmospheric

cosmic

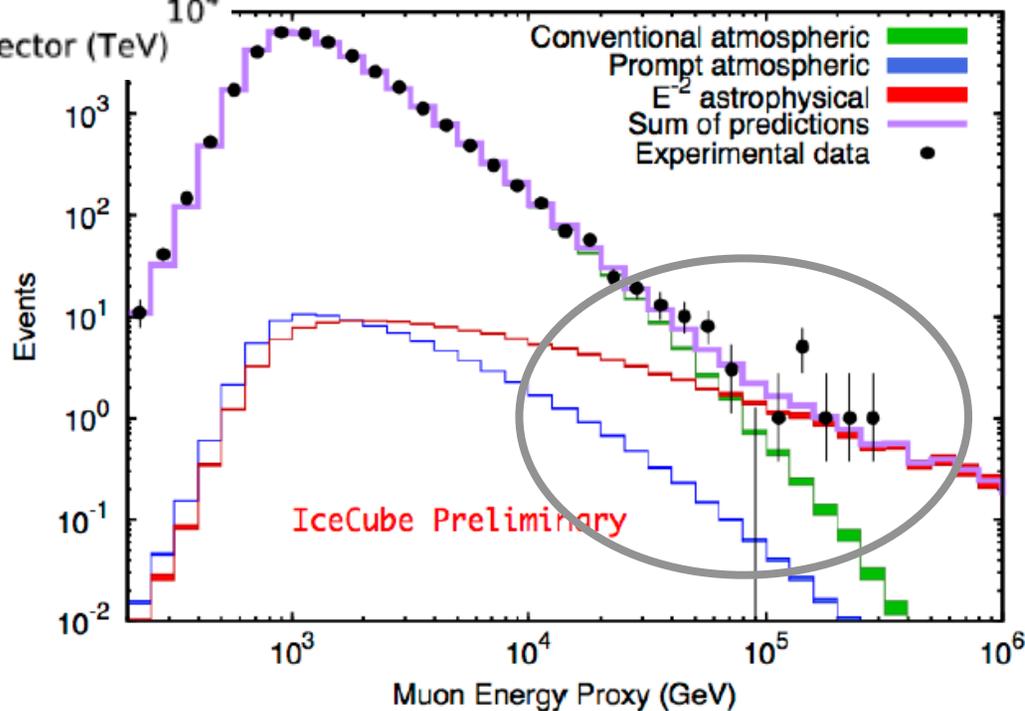
100 TeV



confirmation!
flux of muon neutrinos
through the Earth



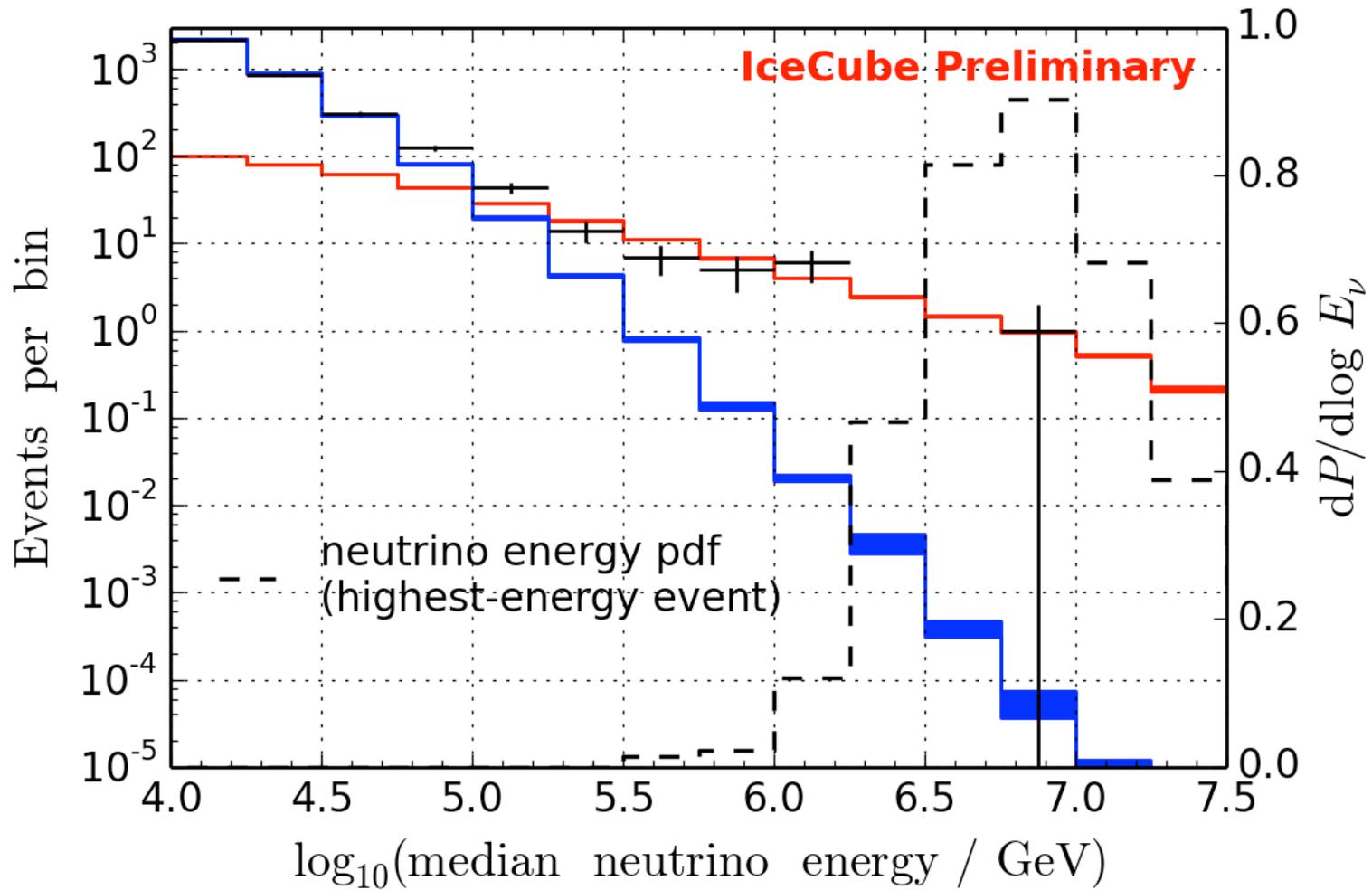
neutrinos of all flavors
interacting inside
IceCube



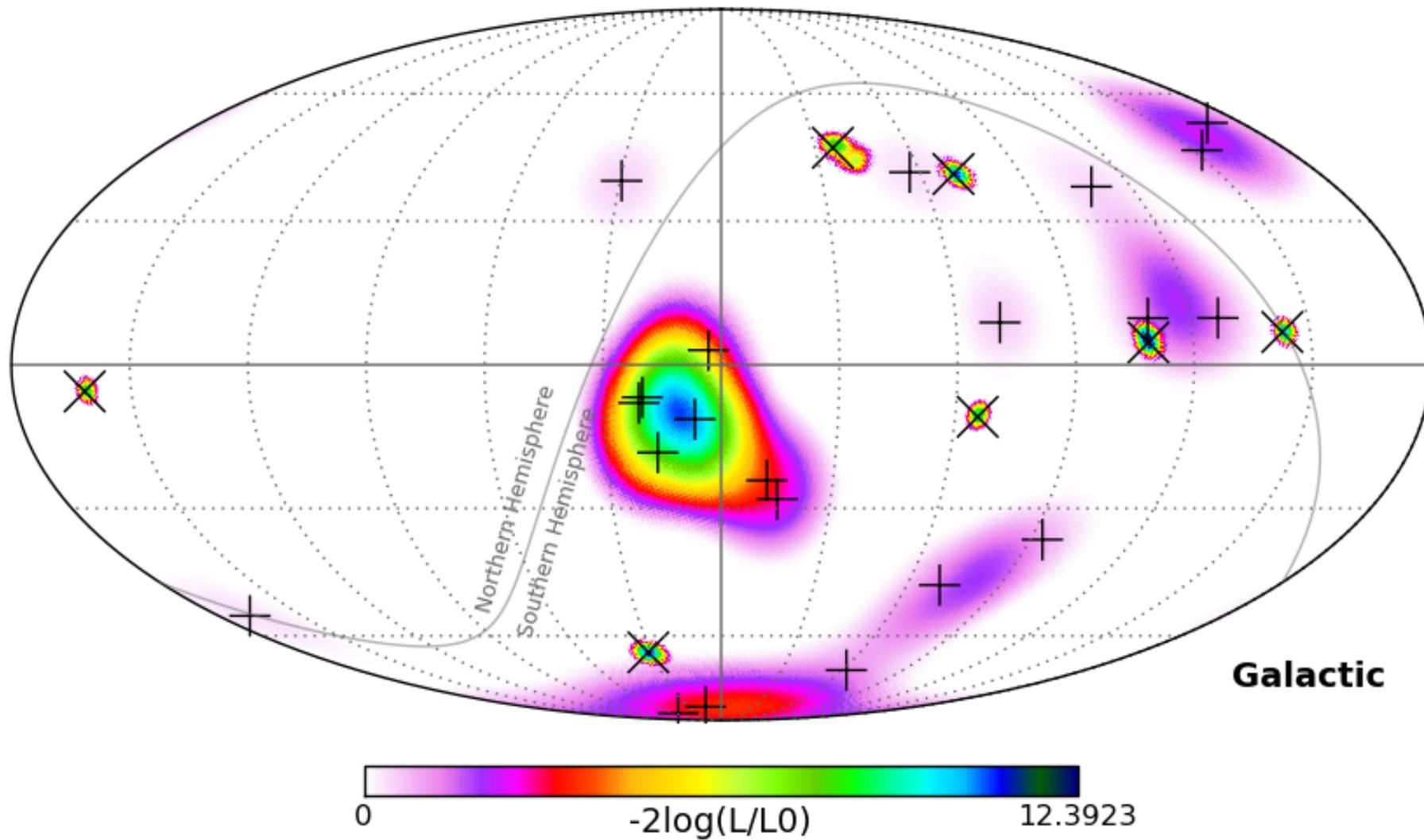
muon neutrinos through the Earth \rightarrow 6 sigma

Assuming best-fit power law:

- +++ Unfolding
- Conv. atmospheric $\nu_\mu + \bar{\nu}_\mu$
- Astrophysical $\nu_\mu + \bar{\nu}_\mu$

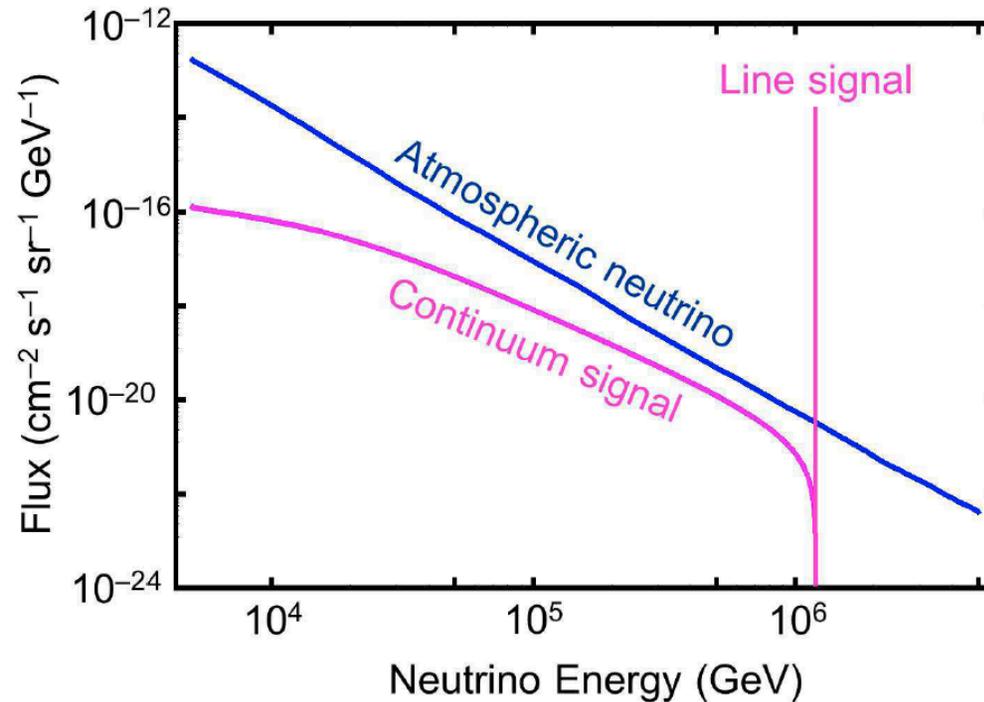


2 year HESE

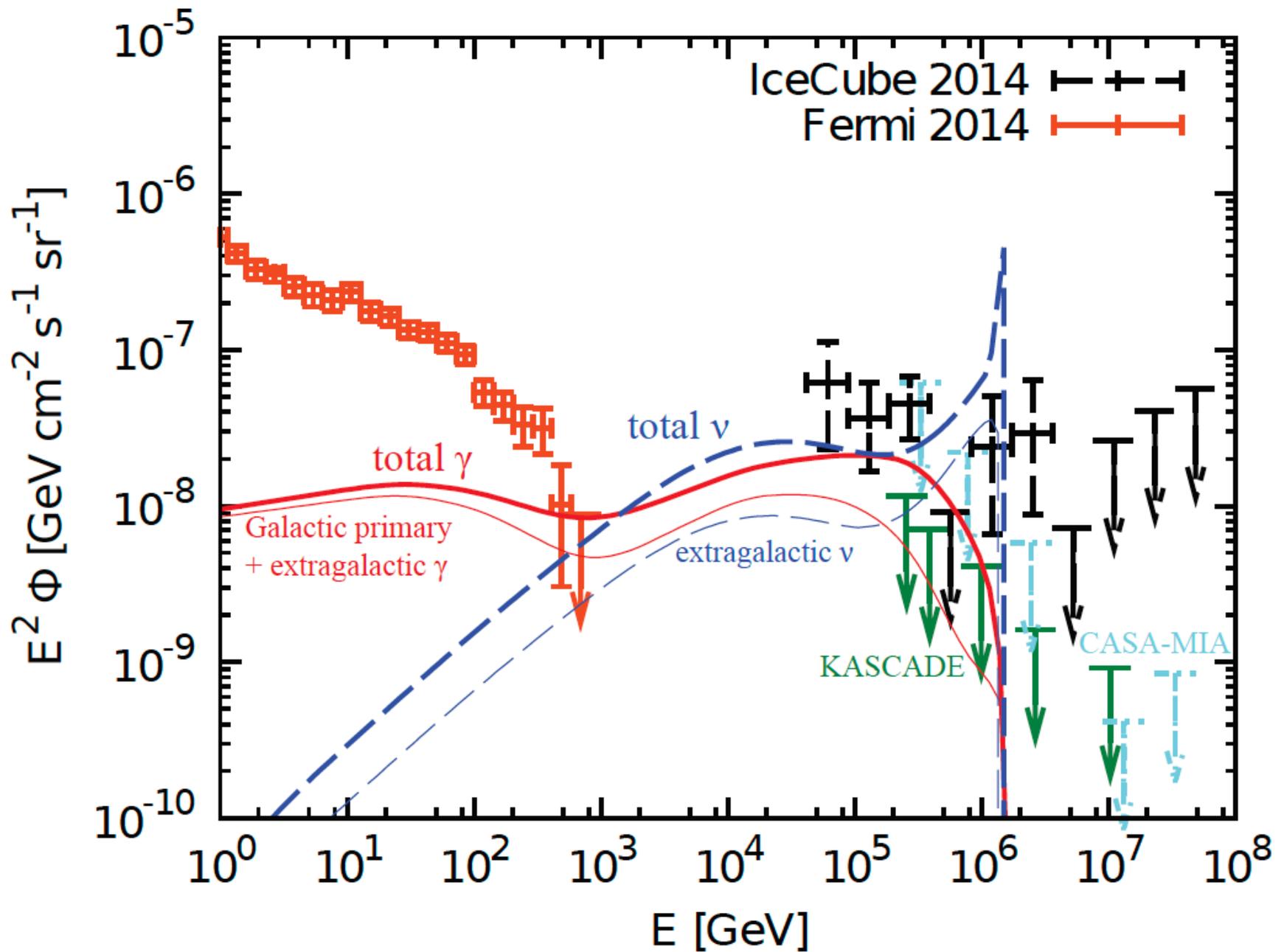


- we observe a diffuse and isotropic flux of neutrinos from extragalactic sources or the Galactic halo!
- where do they come from? Dark matter!

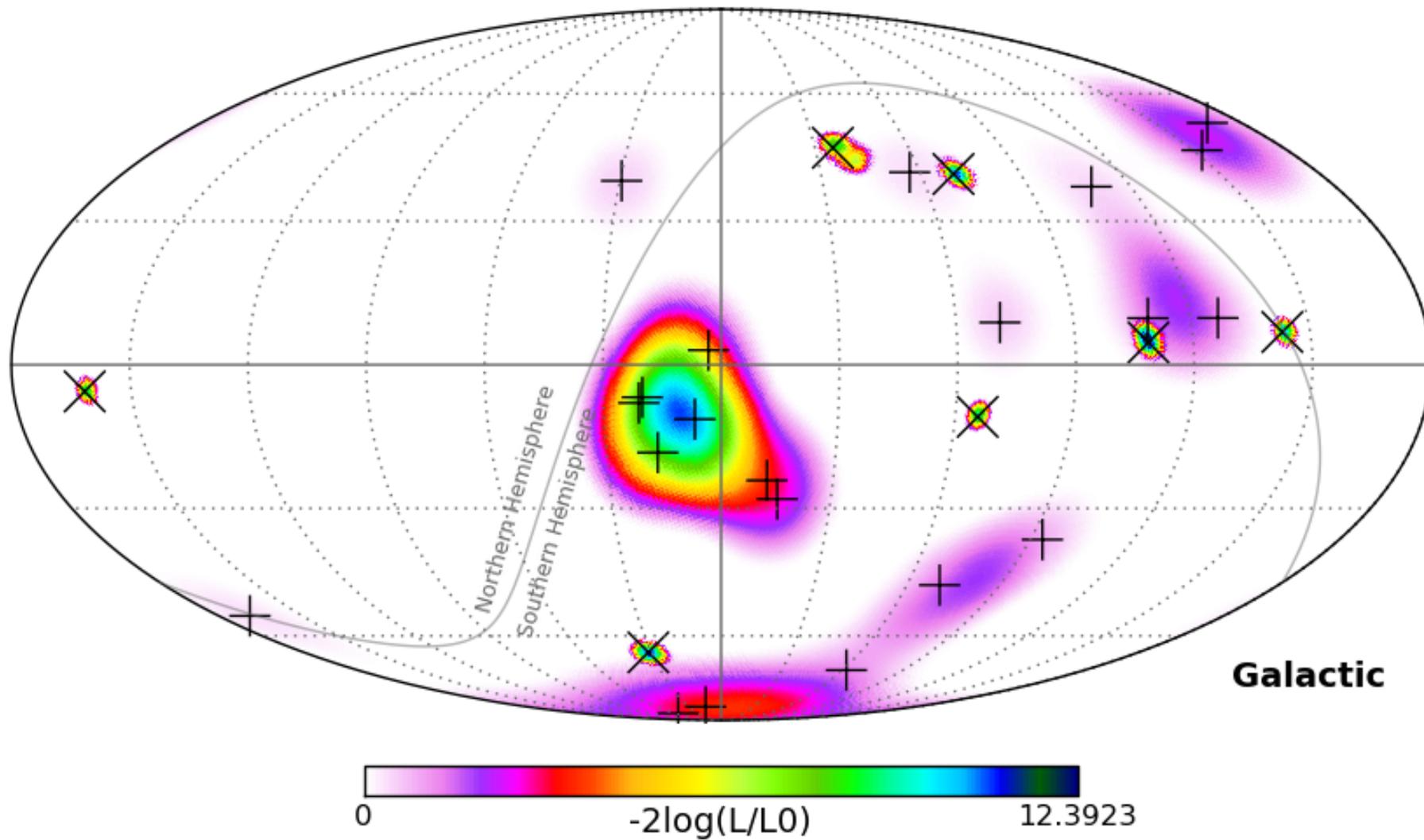
late decay of PeV-mass dark matter



Brian Feldstein^(a), Alexander Kusenko^(a,b),
Shigeki Matsumoto^(a), and Tsutomu T. Yanagida^(a)

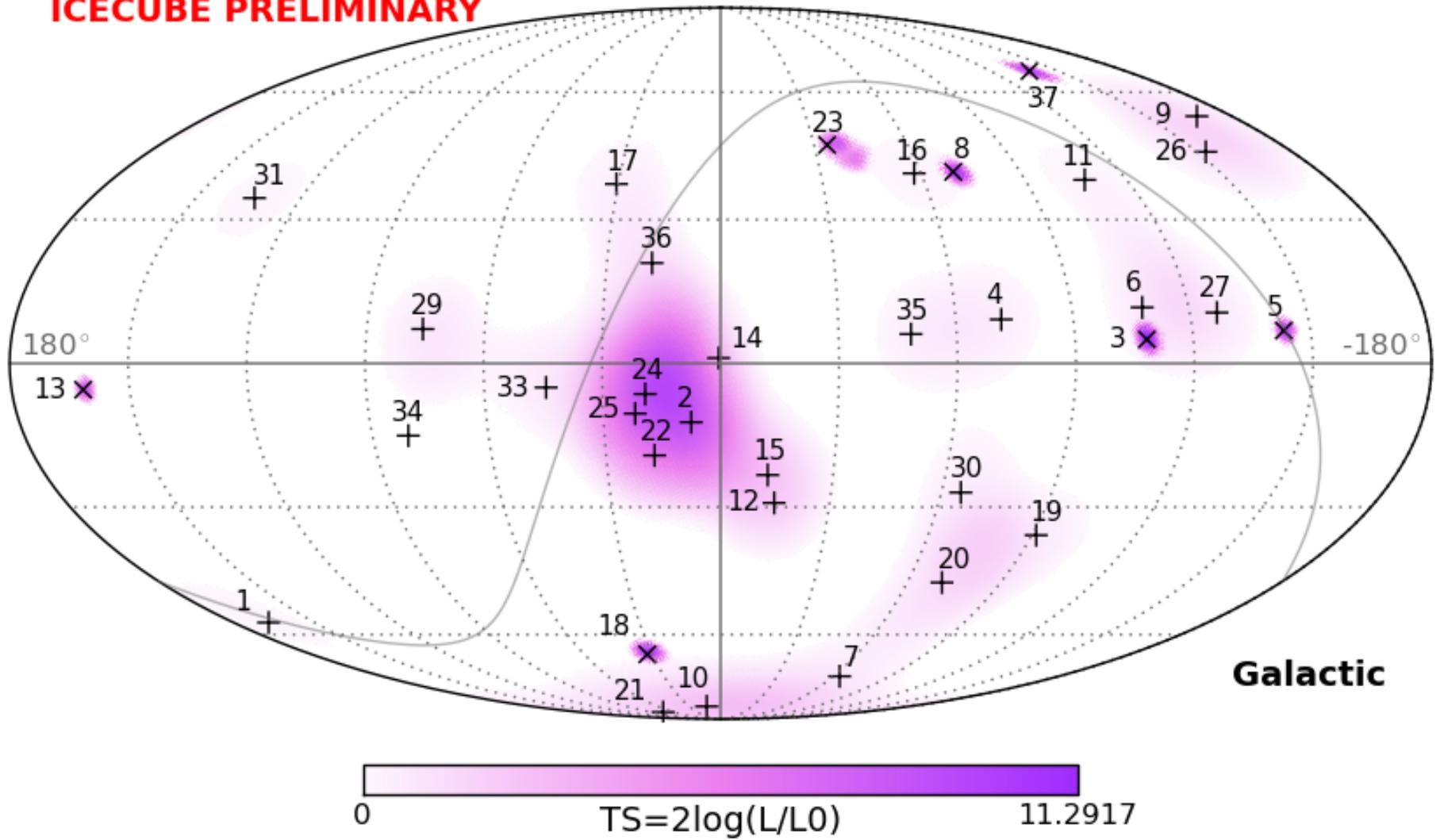


2 year HESE



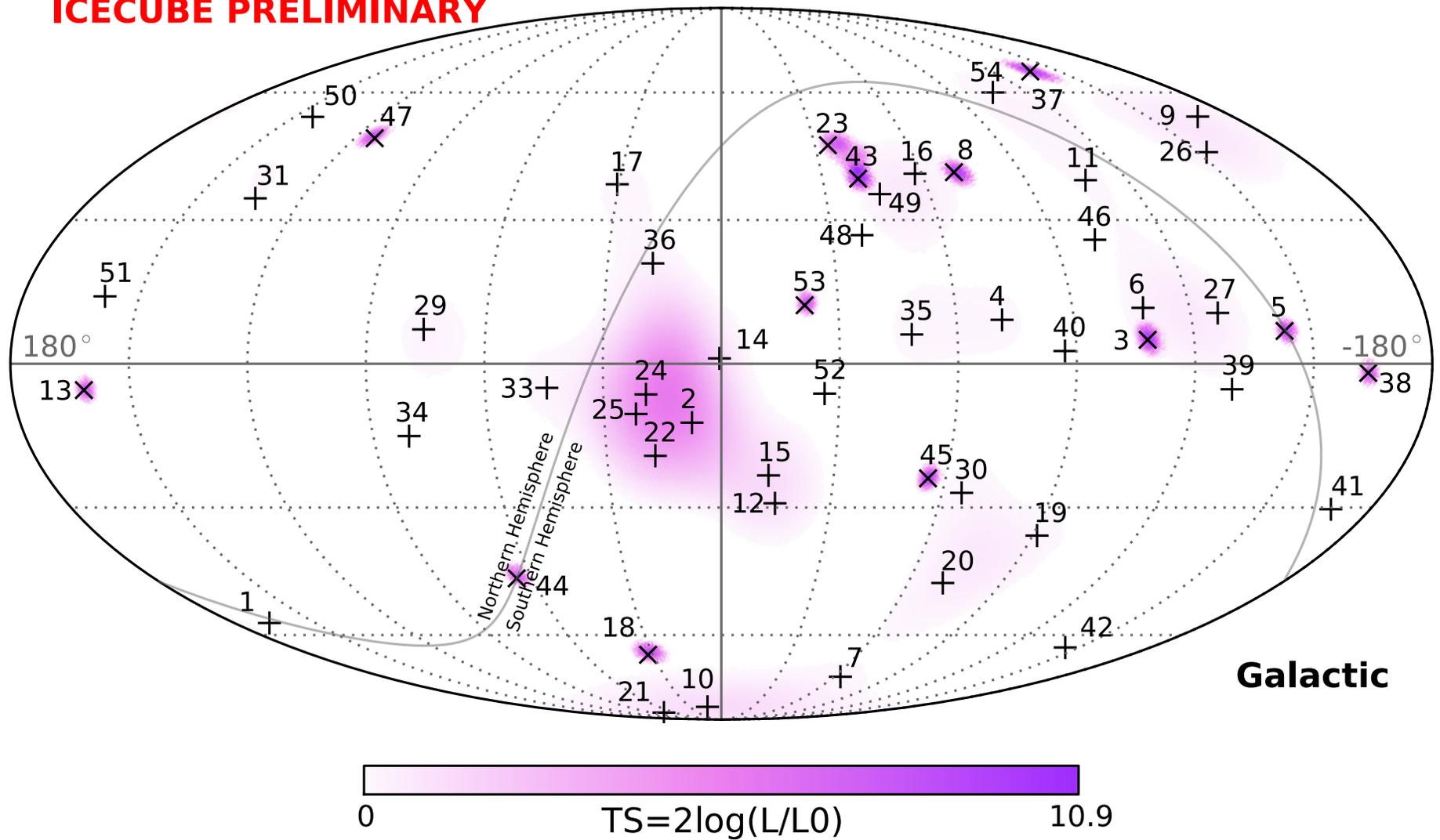
3 year HESE

ICECUBE PRELIMINARY

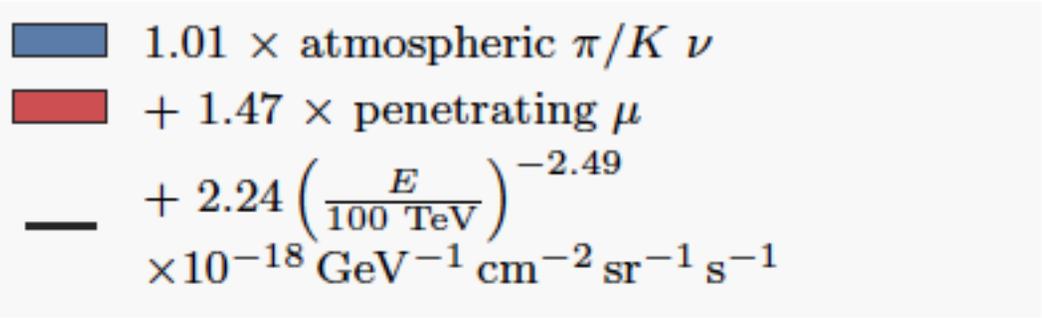


4 year HESE

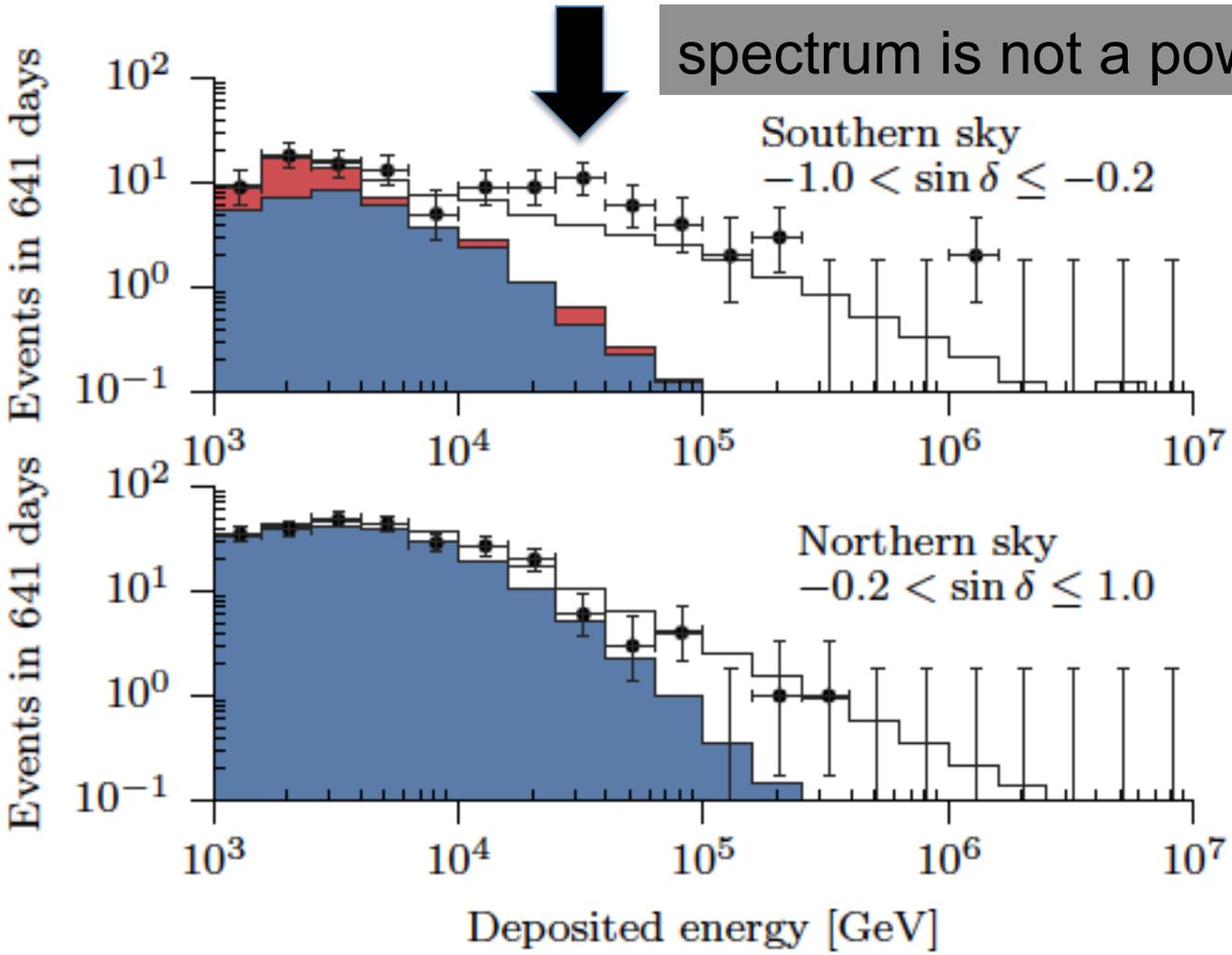
ICECUBE PRELIMINARY

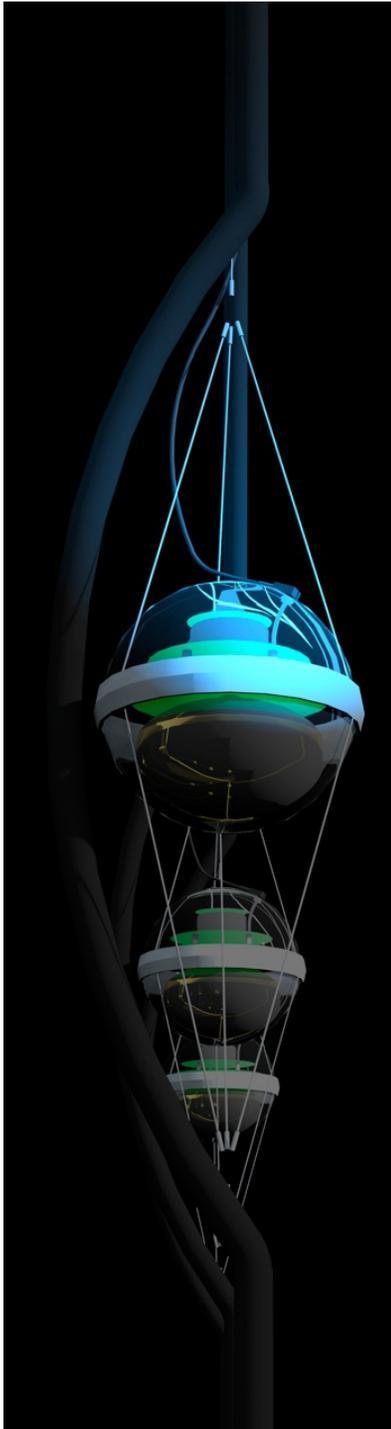


where do they come from?



spectrum is not a power

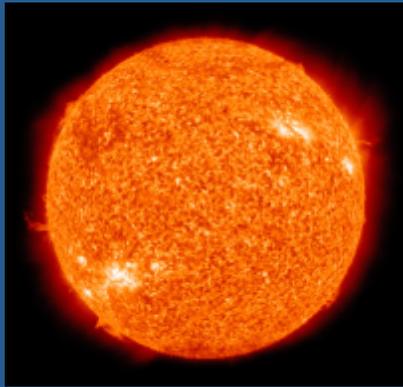




- IceCube
- atmospheric and cosmic neutrinos
- the search for dark matter

IceCube targets for dark matter annihilation

Sun



Galactic Centre



Dwarf galaxies



Earth

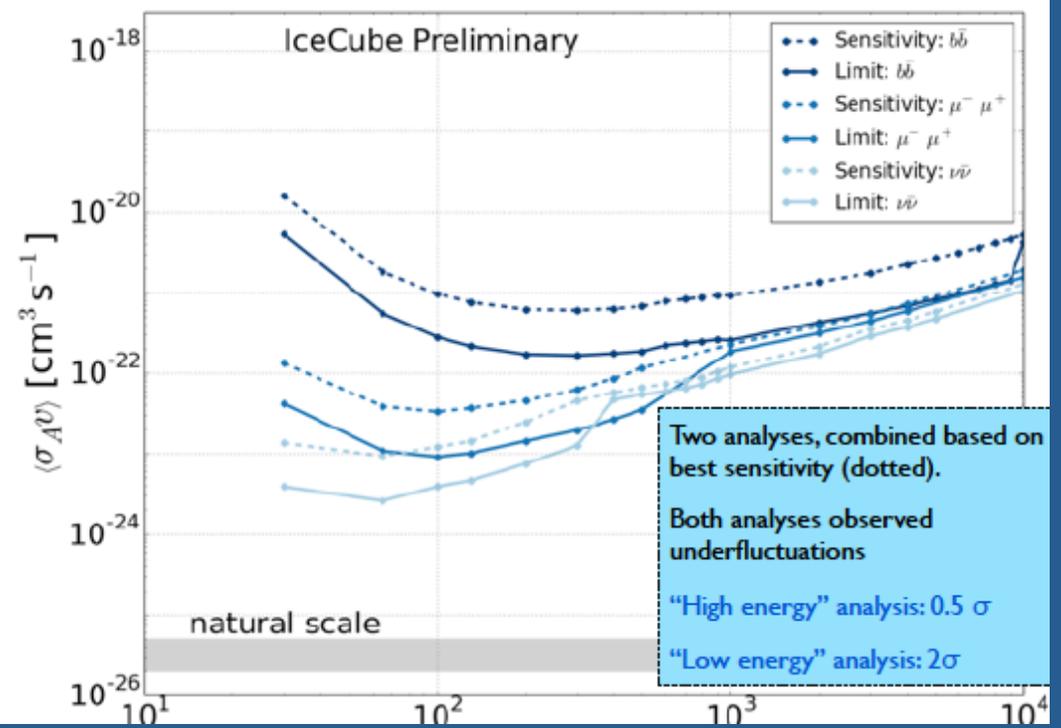
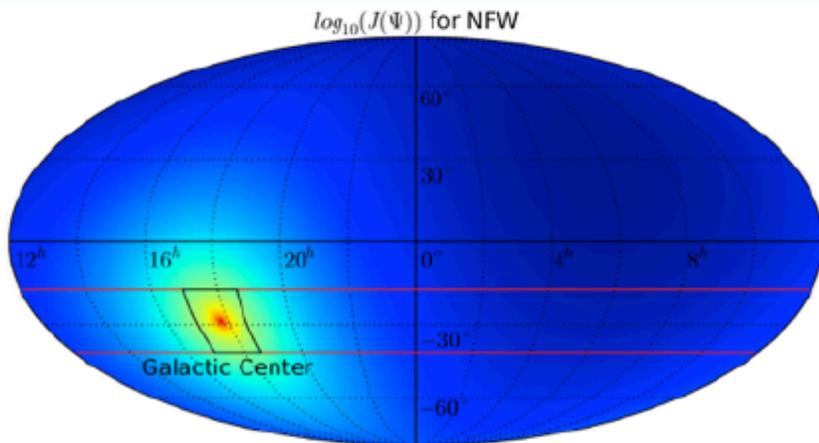


Galactic Halo

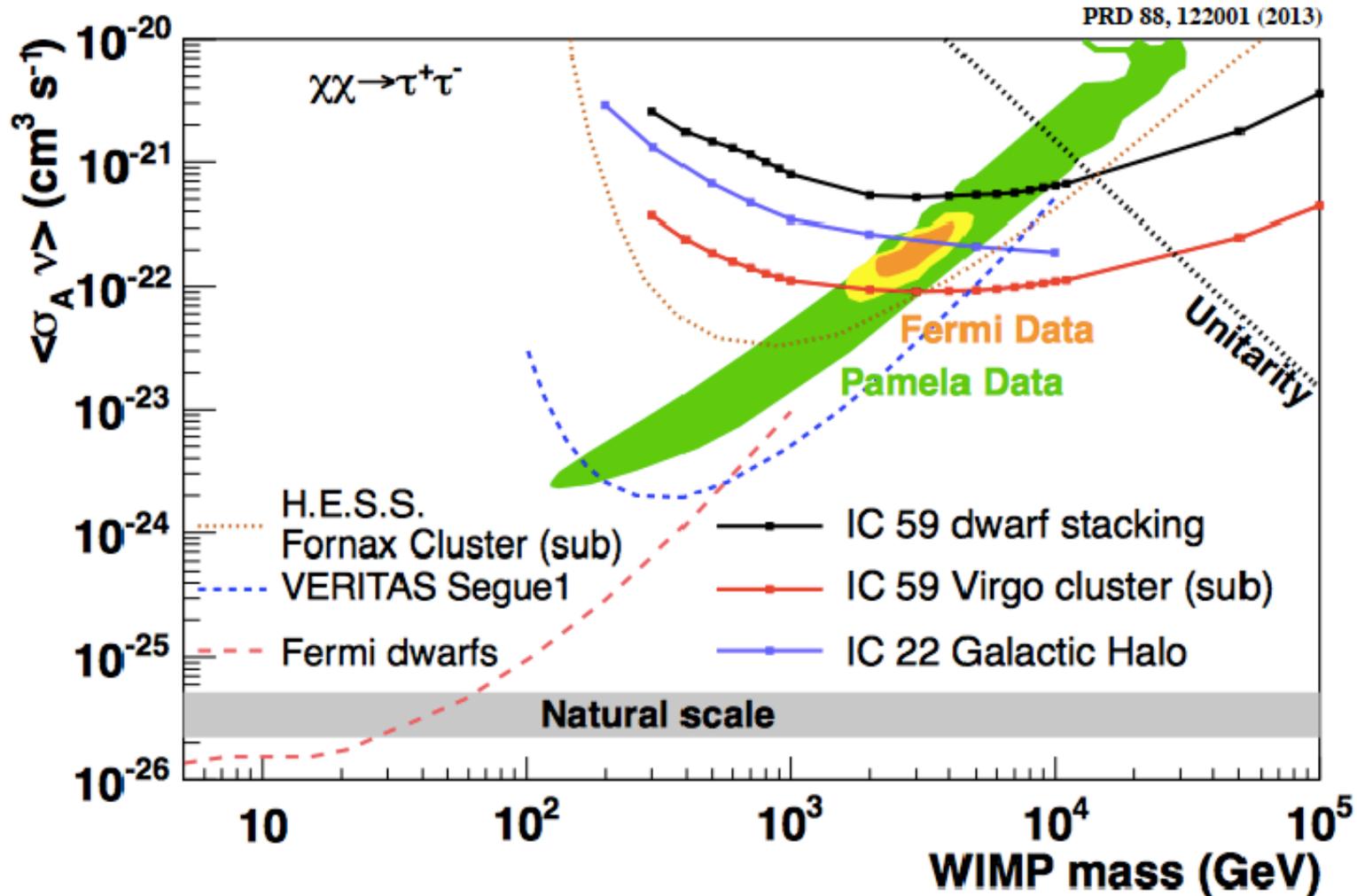


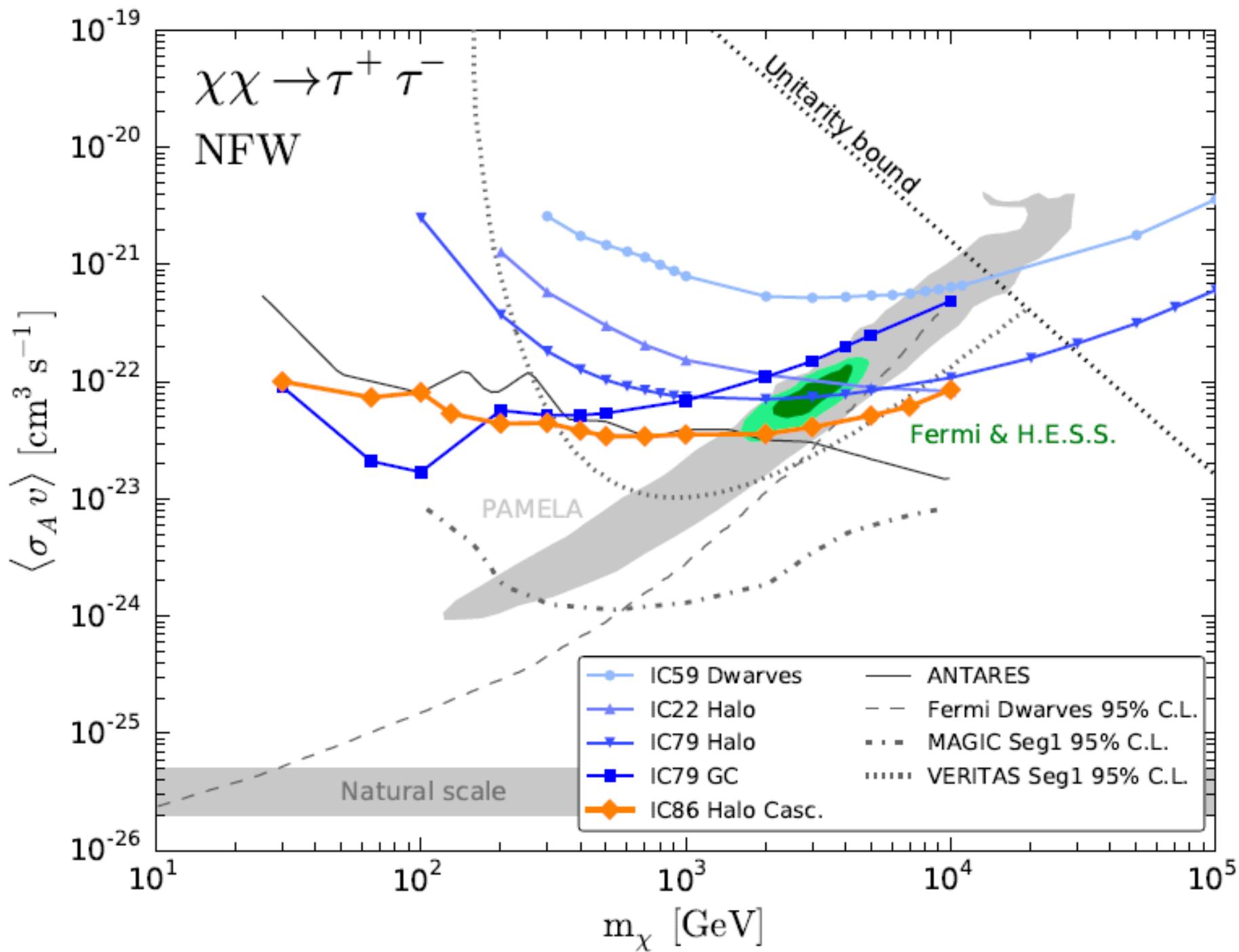
Galaxy clusters

Galactic center and halo



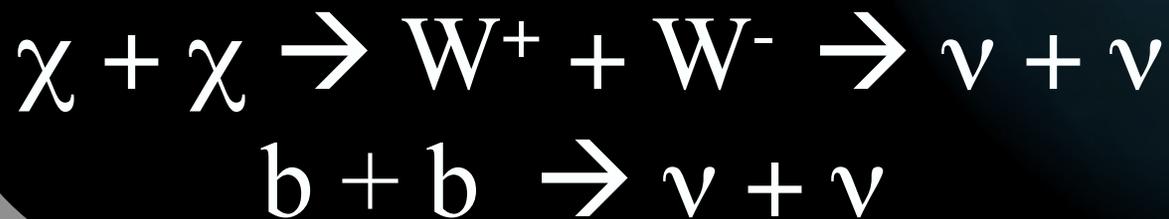
dwarfs and clusters of Galaxies





WIMP Capture and Annihilation

- 1 Halo WIMPs scatter on nuclei in the Sun
- 2 Some lose enough energy in the scatter to be gravitationally bound
- 3 Scatter some more, sink to the core
- 4 Annihilate with each other, producing neutrinos
- 5 Propagate+oscillate their way to the south pole, convert into muons in the ice



$$\frac{dN_{\chi}}{dt} = C_{sun} = \varphi_{\chi} \sigma_{sun}$$

- $\varphi_{\chi} = \left[\frac{\rho}{m_{\chi}} \right] v_{\chi}$

- $\sigma_{sun} = \frac{M_{sun}}{m_p} \sigma_{\chi p}$

- $C_{sun} = 2 C_{annihilation}$ (equilibrium)

given a cross section on protons and a branching ratio of the annihilation products into neutrinos (via τ , b or W for instance) the model is seen or ruled out

$$\frac{dN_{\chi}}{dt} = C_{sun} = \varphi_{\chi} \sigma_{sun}$$

- $\varphi_{\chi} = \left[\frac{\rho}{m_{\chi}} \right] v_{\chi}$

- $\sigma_{sun} = \left(\frac{M_{sun}}{m_p} \right) \sigma_{\chi p}$

- $C_{sun} = 2 C_{annihilation}$ (equilibrium)

astrophysical
assumptions !!!

number of protons
in the sun

given a cross section on protons and a branching ratio of the annihilation products into neutrinos (via τ , b or W for instance) the model is seen or ruled out

detection is a smoking gun

- indirect rates are dictated by the interaction cross section of WIMPS with hydrogen.
→ no unknown astrophysics
- in the neutrino case there is a direct connection between theory and observation and the background is understood.

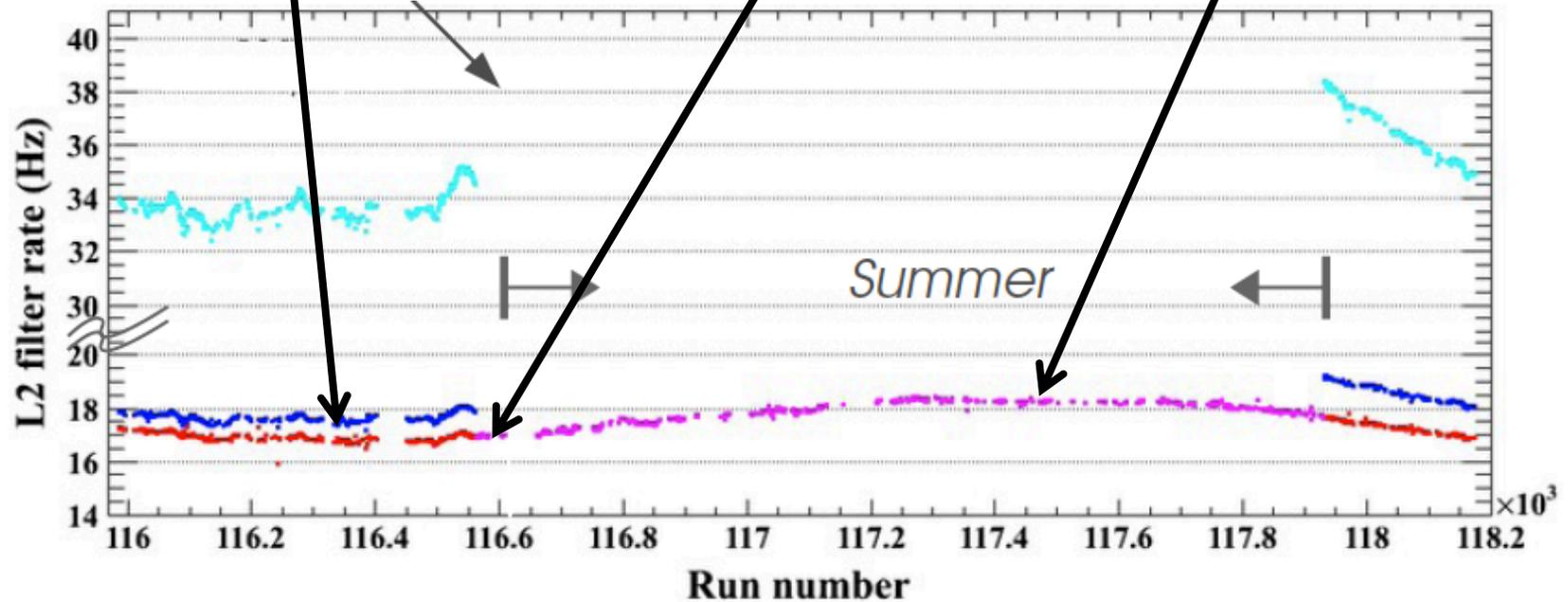
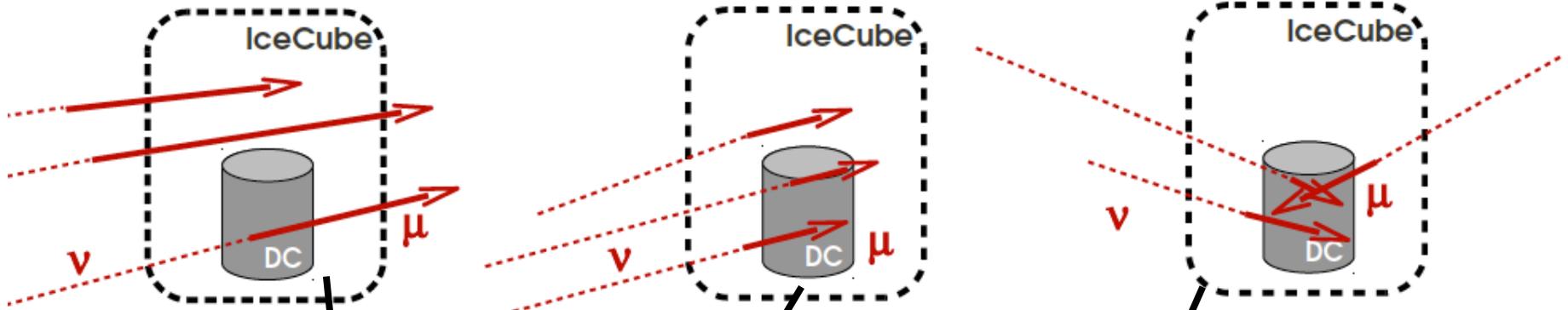
IceCube 79 data

starting events \rightarrow lower energy

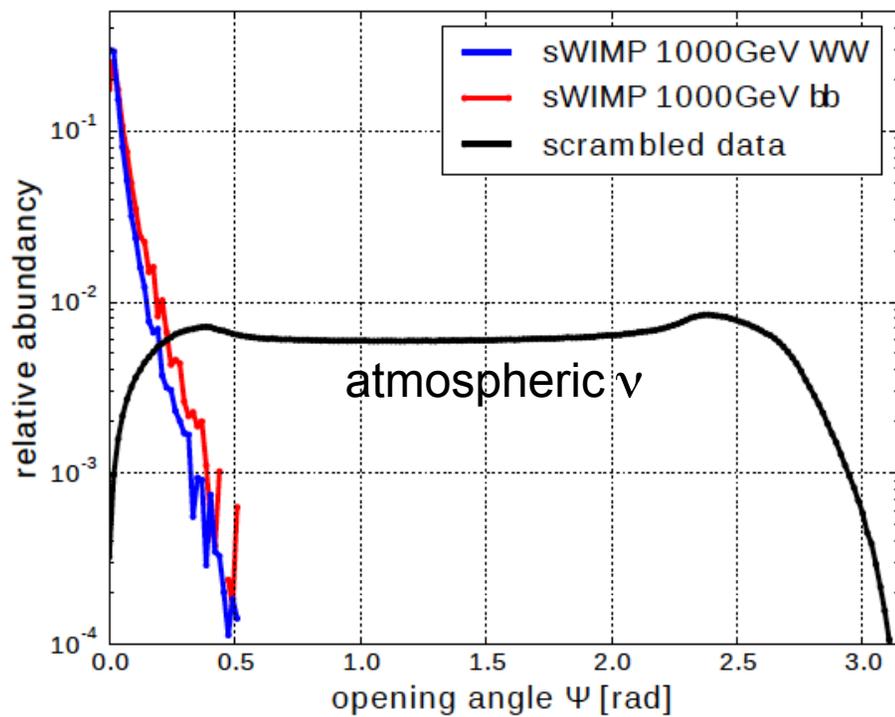
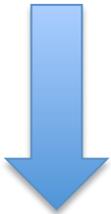
- Up-going ①
- No containment

- Up-going ②
- strong containment

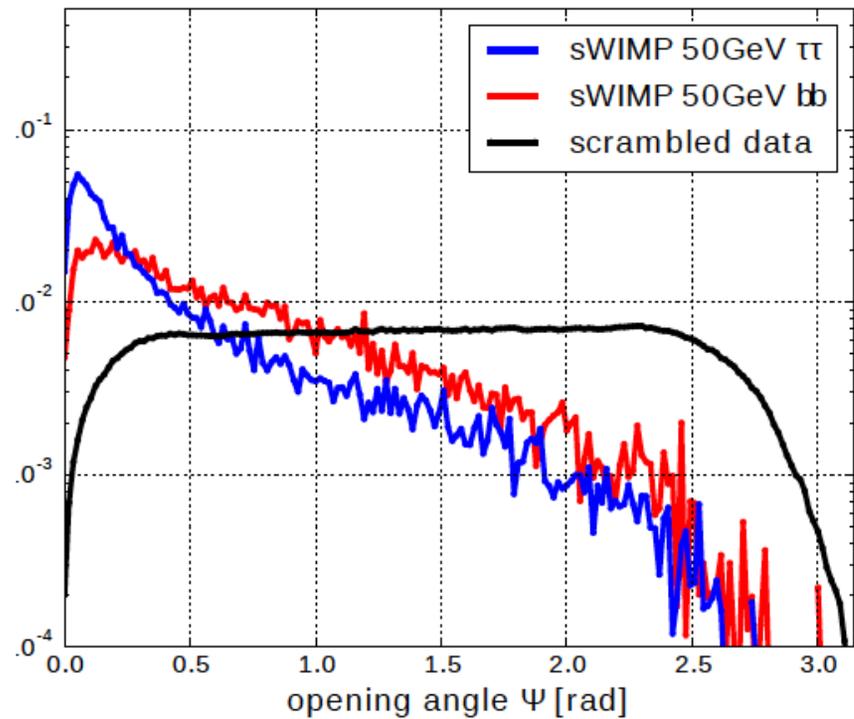
- Down-going ③
- strong containment



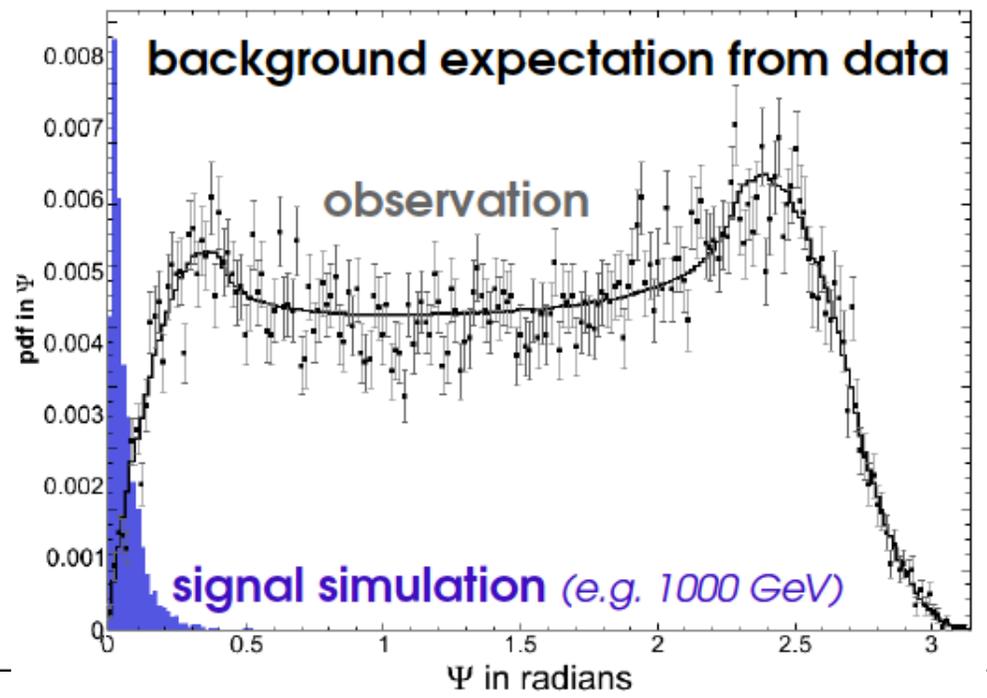
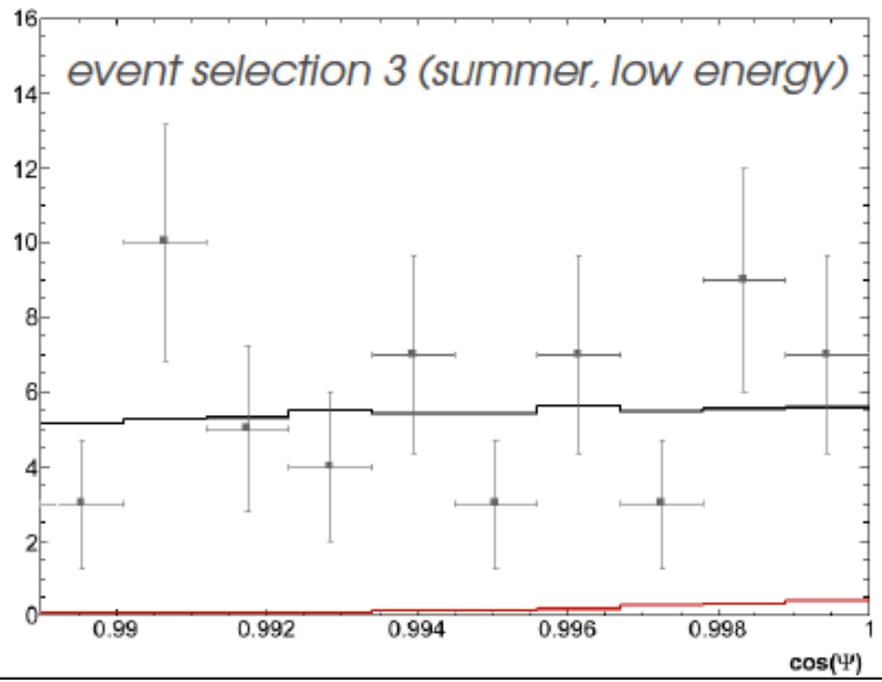
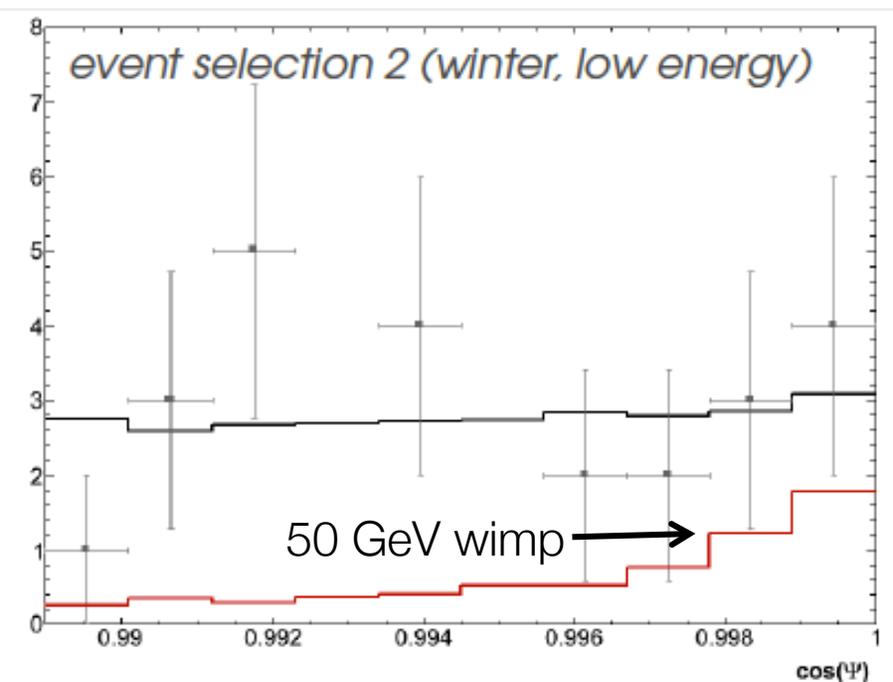
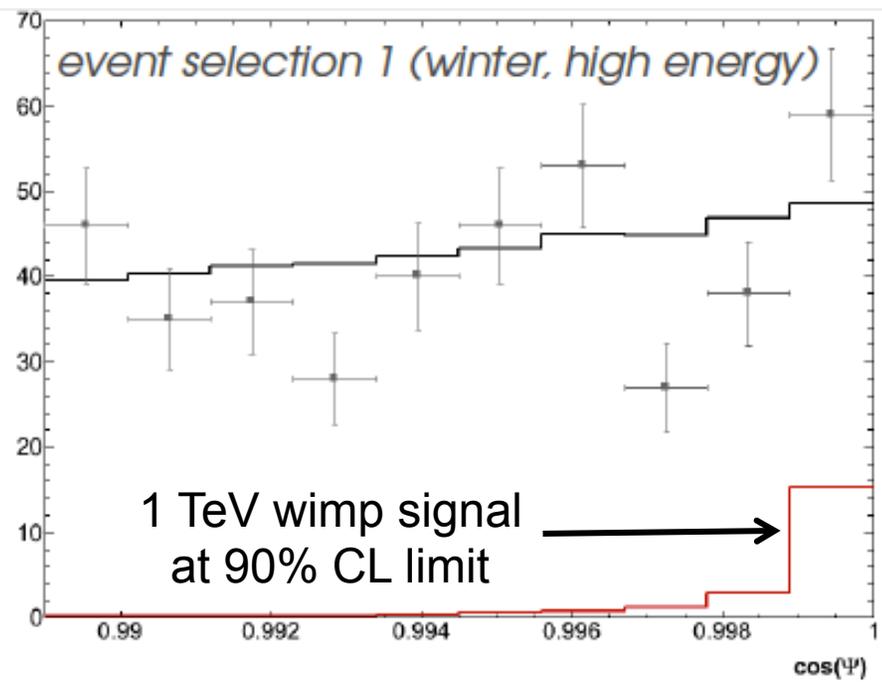
sun

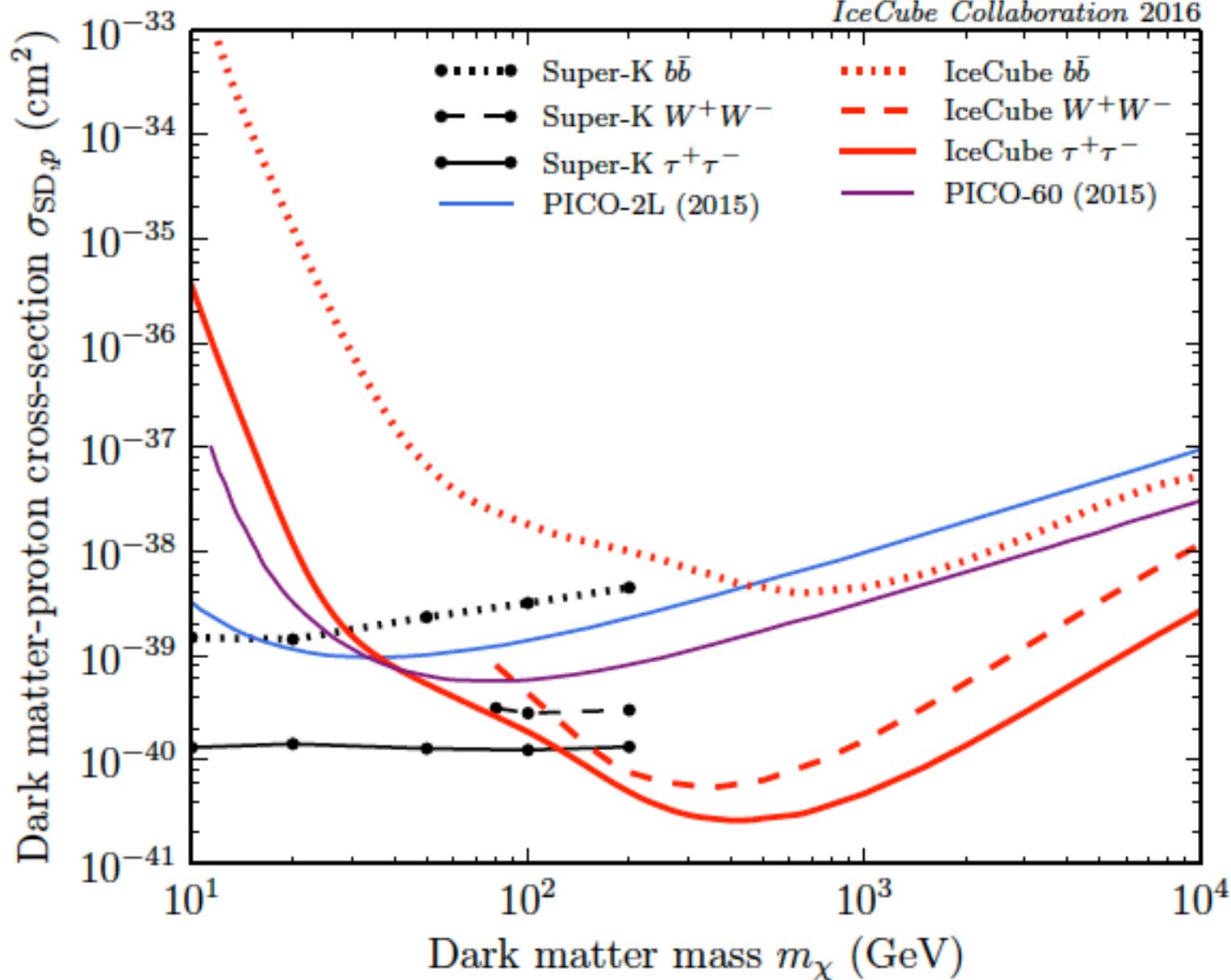


$$m_{\chi} = 1 \text{ TeV}$$

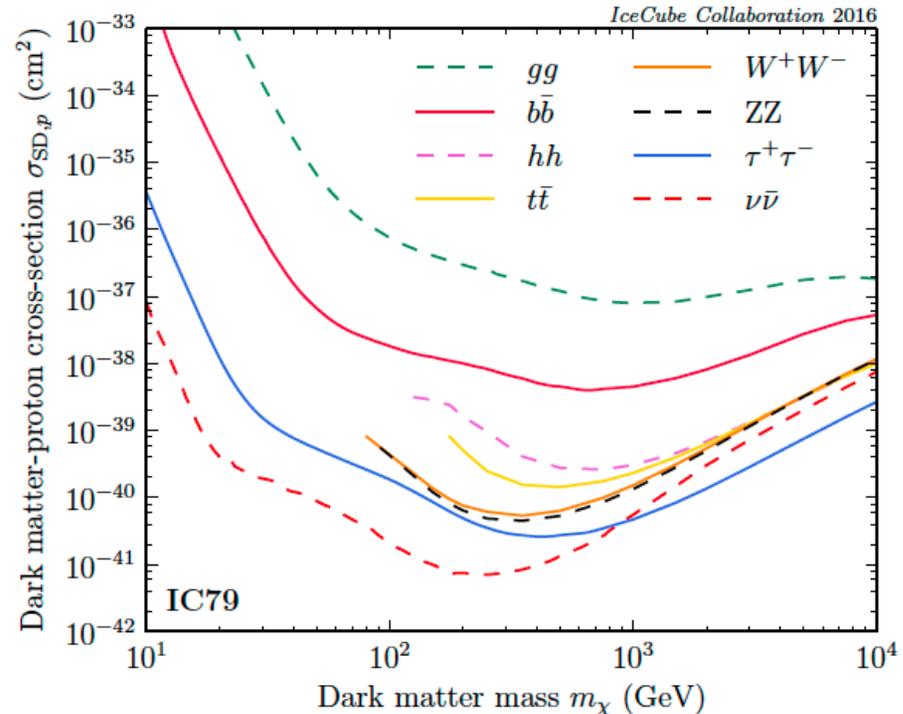


$$m_{\chi} = 50 \text{ GeV}$$



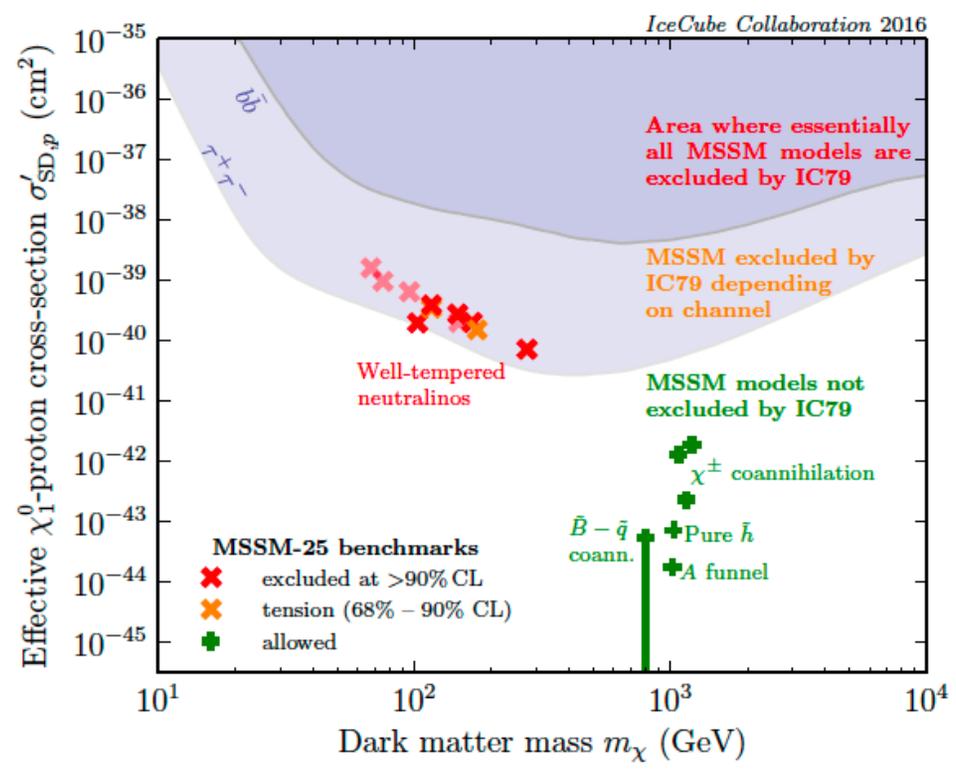


perform your own
IceCube dark matter search

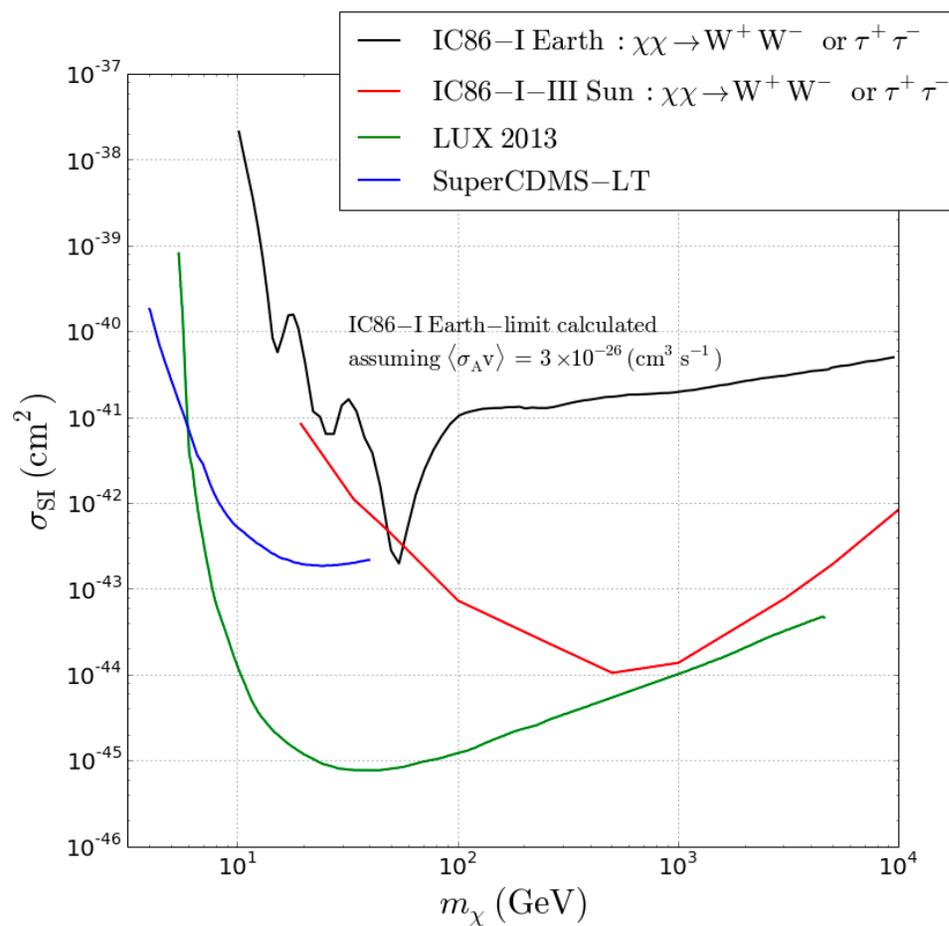
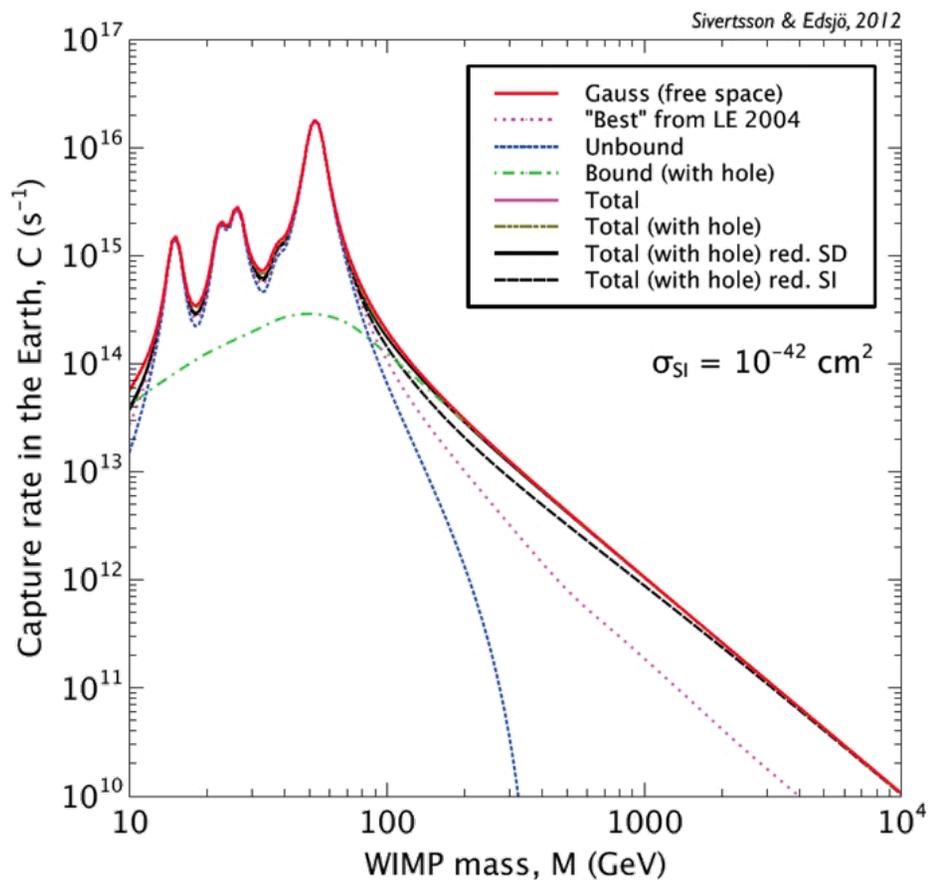


<http://arxiv.org/abs/1601.00653>

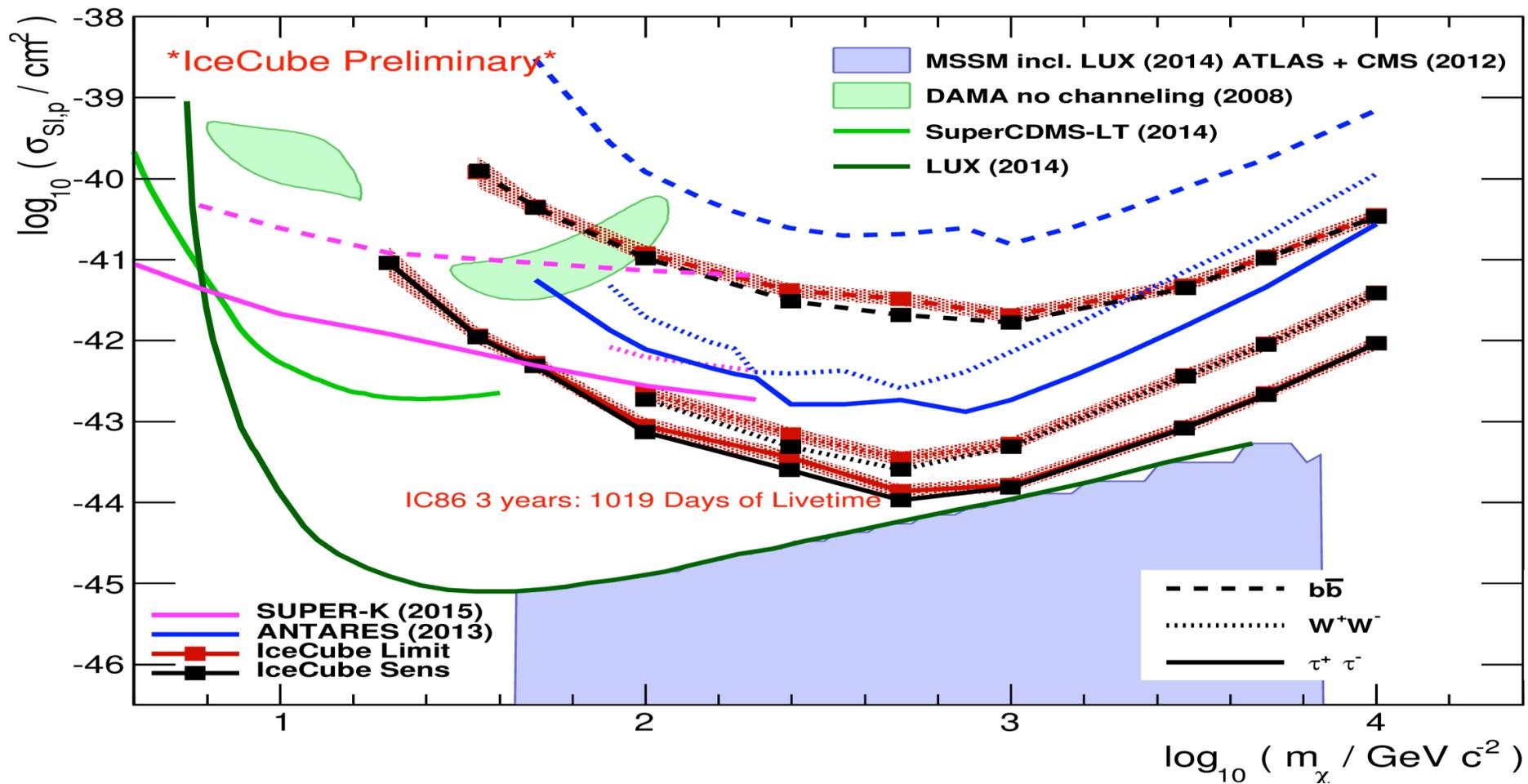
- software to test your own model (cross section/branching ratios)
- IceCube data available



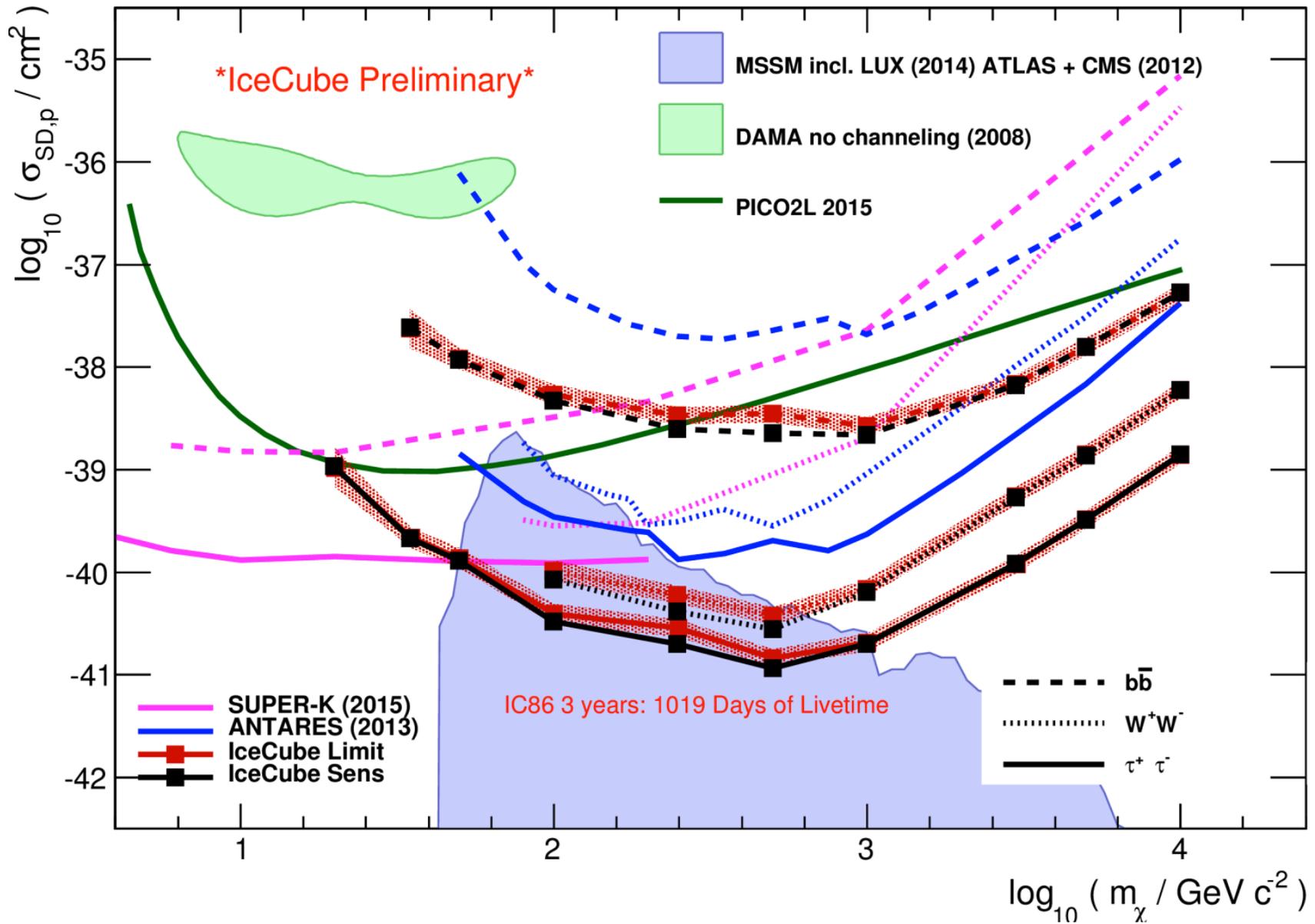
wimp annihilation in the center of the Earth



Limits after 3 years (6 soon)
 spin independent (A^2 handicap)



Limits after 3 years (6 soon)
spin dependent ($A^2=1$)



conclusions

- far from the square root regime
- we are designing a next-generation detector with a larger volume at higher energy and a lower threshold at low energy
- we want to deploy DMice at the South Pole (see talk by Reina Maruyama)

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)

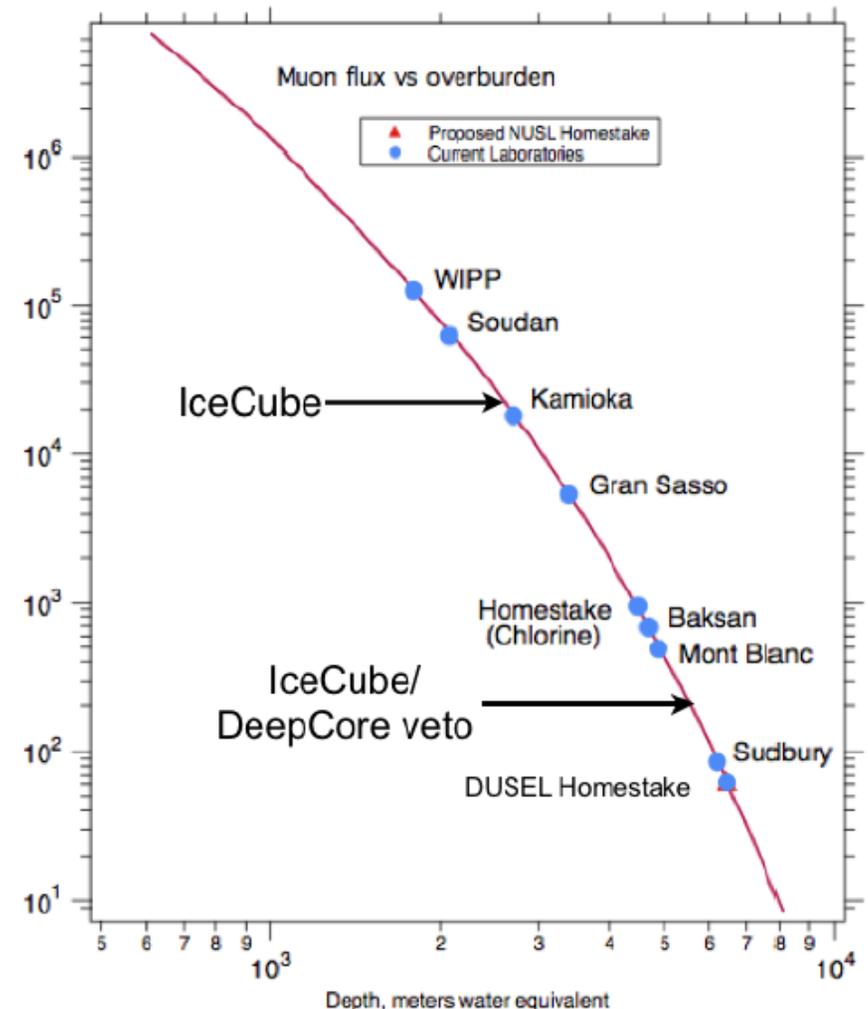
Deutsches Elektronen-Synchrotron (DESY)
 Inoue Foundation for Science, Japan
 Knut and Alice Wallenberg Foundation
 NSF-Office of Polar Programs
 NSF-Physics Division

Swedish Polar Research Secretariat
 The Swedish Research Council (VR)
 University of Wisconsin Alumni Research Foundation (WARF)
 US National Science Foundation (NSF)

IceCube drilling to best low background site on Earth:

- radio-pure ice
- no seasonal variations (temperature, humidity,...)
- shielded from cosmic rays by IceCube veto

- DM-ice, DeepCore upgrades
- \$1.25M per string of 60 ten inch PMTs (data to your pc, includes logistics)



DM-Ice Prototype Detector



DM-Ice Prototype Detector Deployment

