IceCube: Recent Results and Prospects

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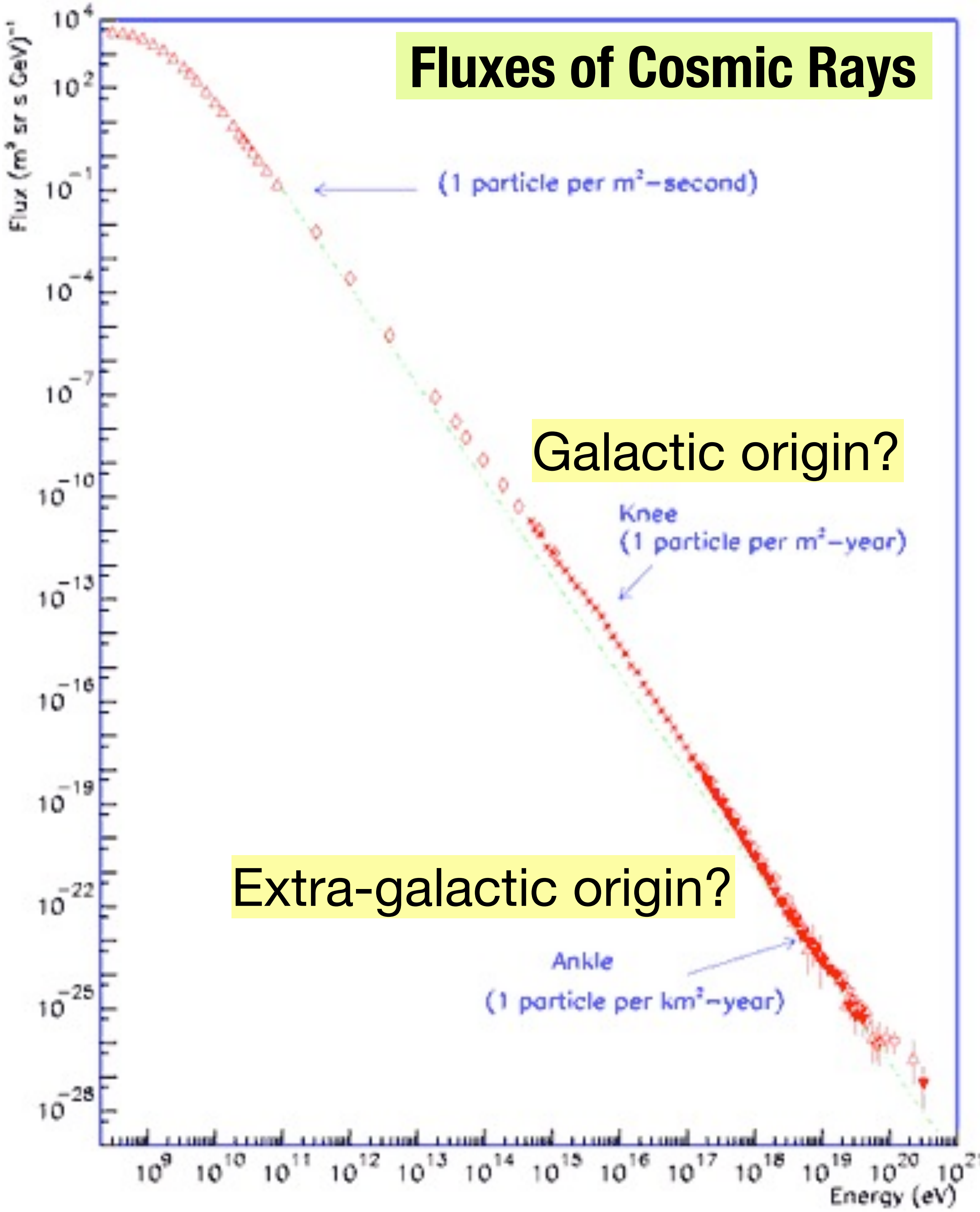
Photo by Patrick Cullis/NSF

Outline

- Why Neutrino Telescopes?
- IceCube Detector
- IceCube Results:
  - Detector performance: atm. ν, atm. μ
  - Astrophysical ν: point source, diffuse searches
  - Cosmic ray anisotropy
  - Dark Matter, magnetic monopole searches

✤ DeepCore, PINGU, & MICA

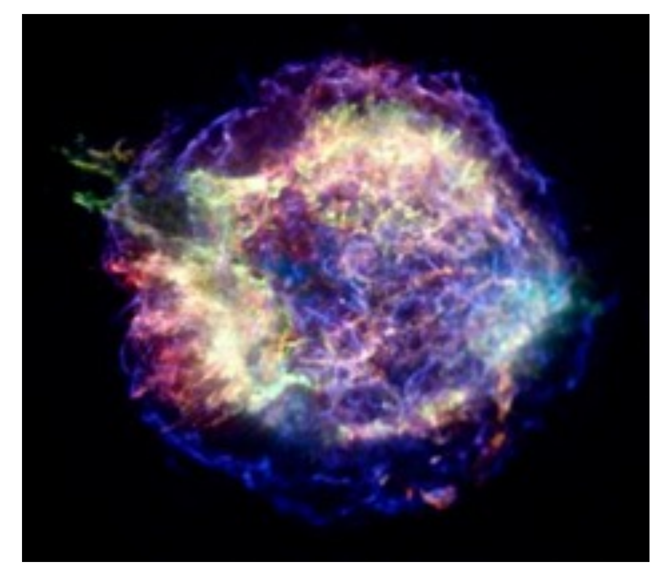
High Energy Particles from Cosmos



Astronomical messengers:

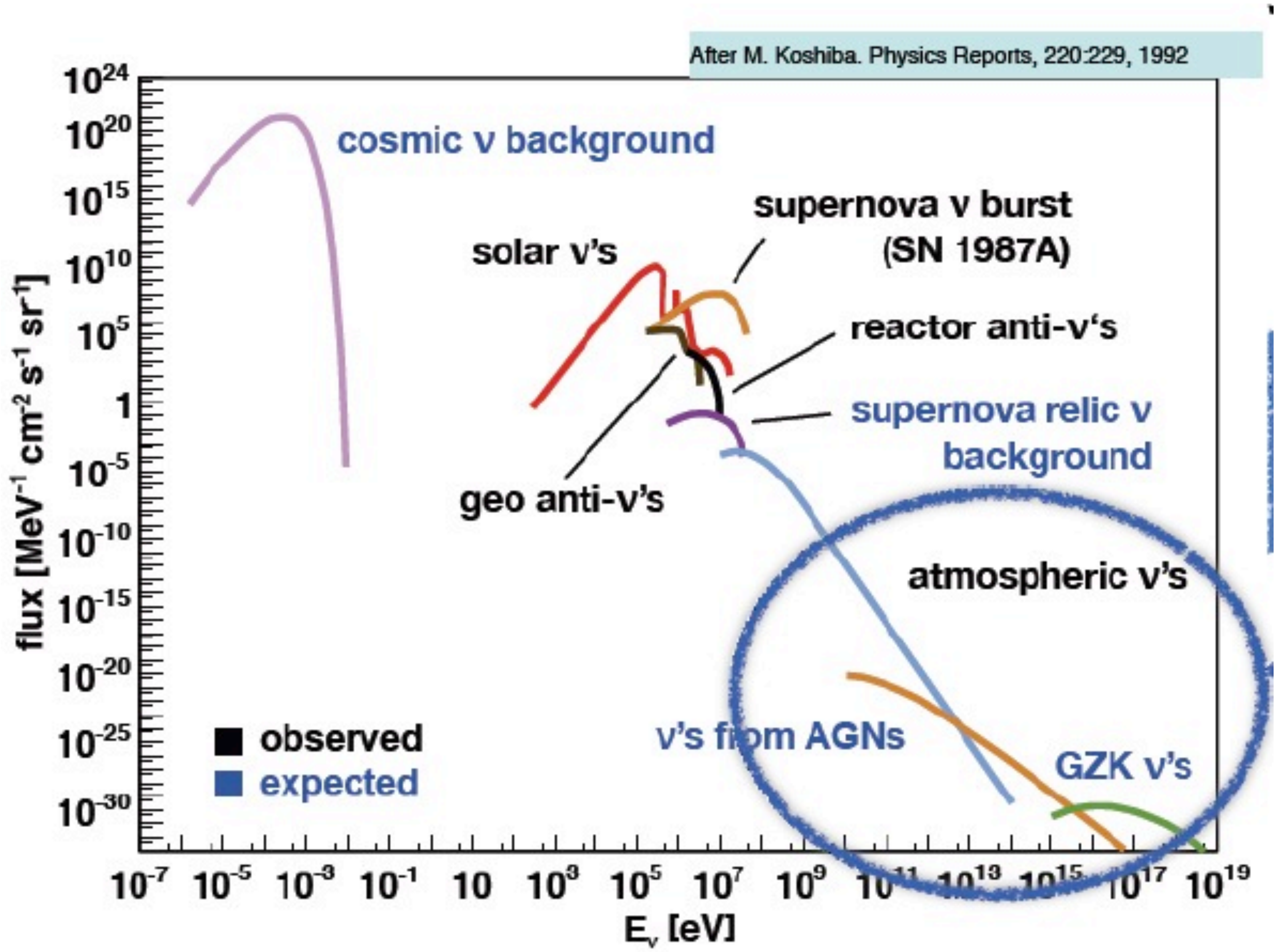
- cosmic rays (proton > ~80%)
- photon
- neutrinos (so far: Sun, SN1987A)

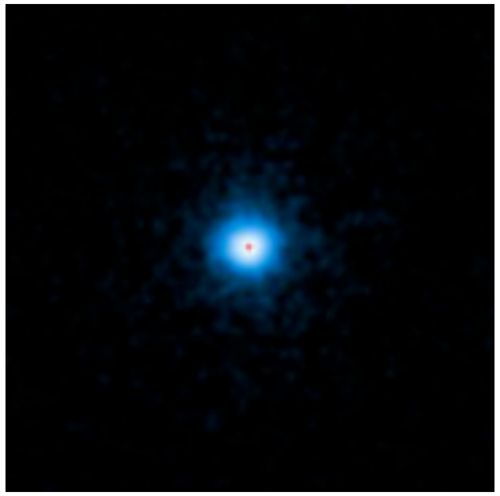
$$p + \gamma \rightarrow \Delta^+ \rightarrow (n)\,\pi^+ \rightarrow (e)\,\nu_e\,\nu_\mu\nu_\mu$$
$$p + p \rightarrow \pi^- / \pi^+ \rightarrow (e)\,\nu_e\,\nu_\mu\nu_\mu$$

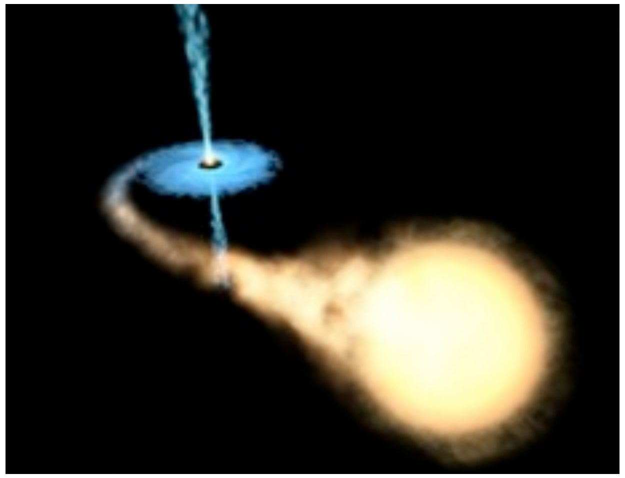


Credit: NASA

High Energy Neutrinos from Cosmos



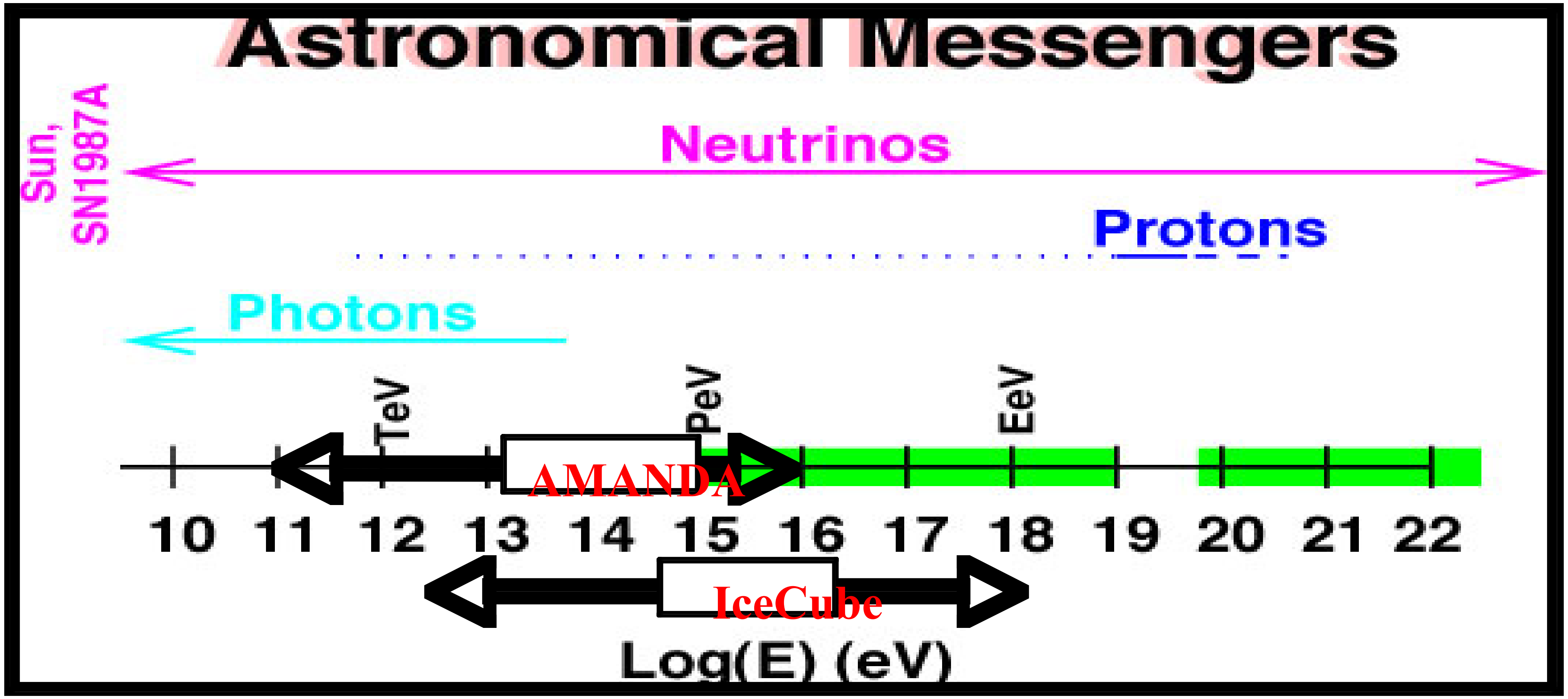




We'd like to answer:

1. What are the cosmic accelerators? GRB, AGN, SN remnants, etc..
2. What is the physics there?

Why Neutrino Telescope?



Pros and Cons:

- Protons get deflected below 10 EeV.
- Protons are strongly attenuated above 50 EeV (GZK cut-off).
- Photons are absorbed (or pair-production) above 50 TeV.
- Neutrinos cover all energy range, point back, but hard to detect.
  ---> thus, we need a big detector.

Neutrino Telescopes

Requirements:

- large detection volume
  to compensate
  small ν x-section
- optically transparent medium

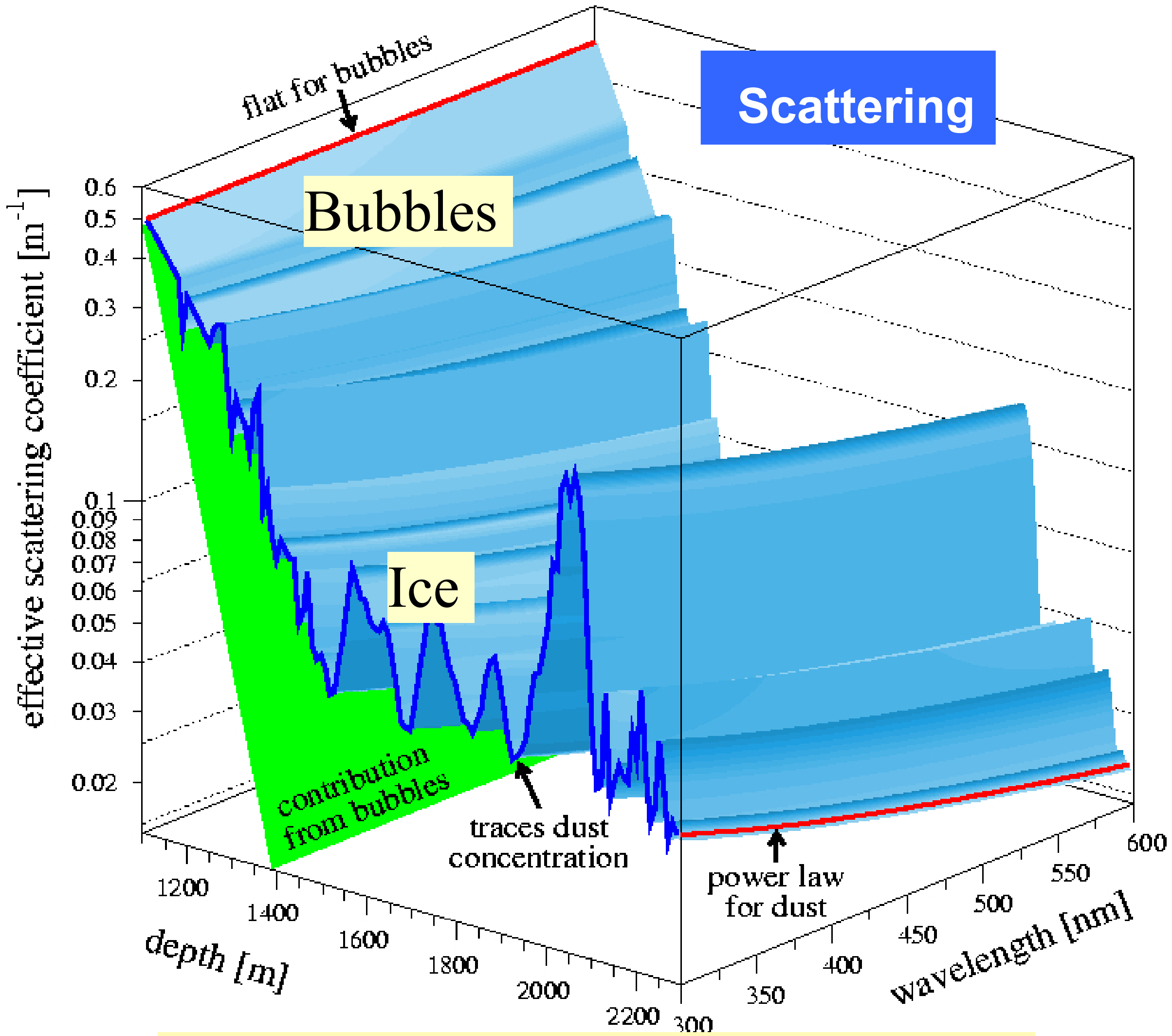
Experiments:

- in water: Baikal, ANTARES, NESTOR, NEMO, KM3NeT
- in ice: AMANDA, IceCube (successor of AMANDA)

Medium	Water	Ice
Location	Northern	Southern
Access	year-round	Austral summer
Noise rate	~40 kHz	~0.5 kHz
Scattering length	> 100 m @466 nm	~20 m @400 nm
Absorption length	~60 m @466 nm	~110 m @400 nm

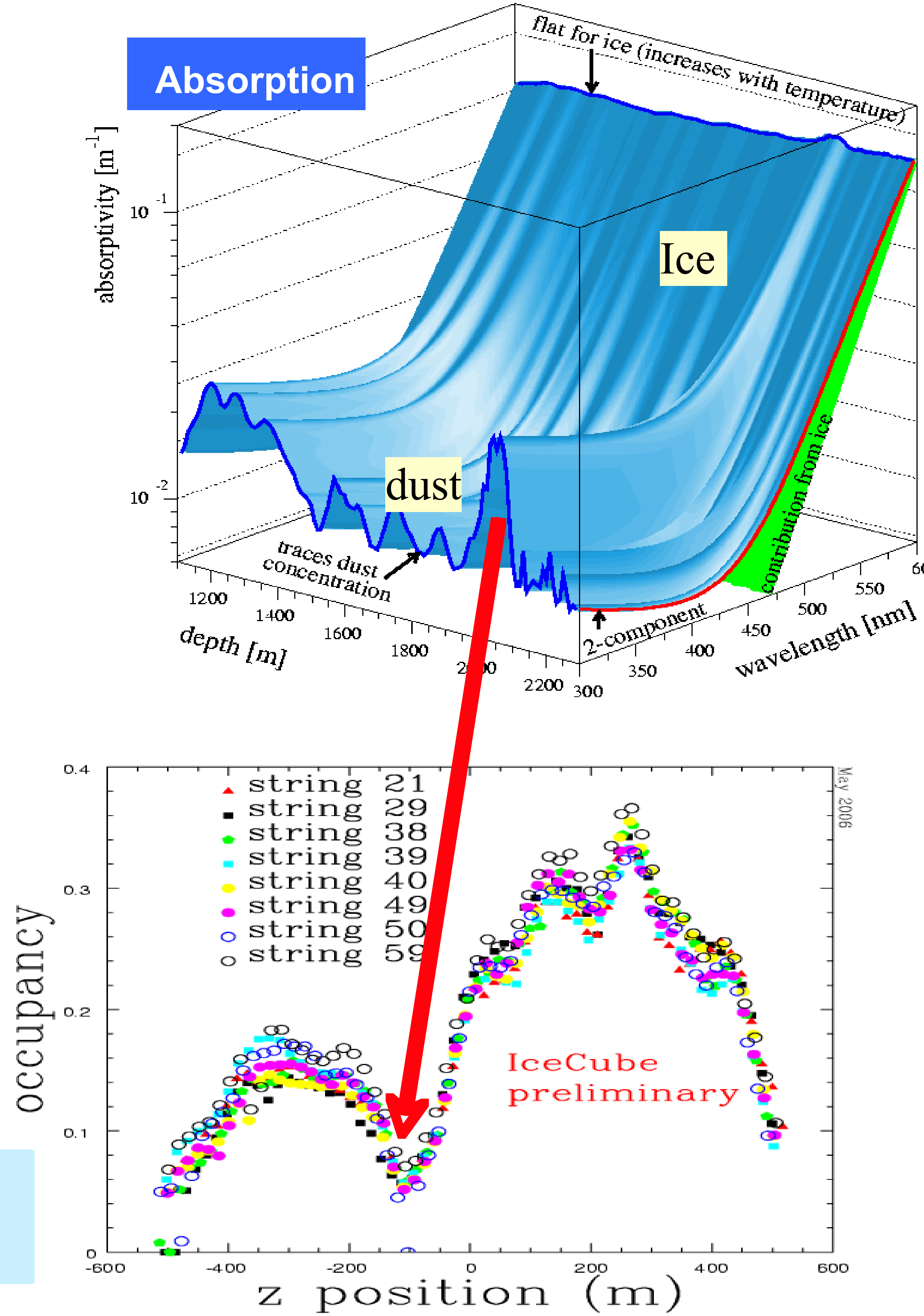

Antarctic ice is
the most transparent & clean ice
in the world.

Ice Properties



Average optical parameters:
λ_{abs} ~ 110 m @ 400 nm
λ_{sca} ~ 20 m @ 400 nm

Below 2100 m (very clear ice):
λ_{abs} ~155 m, λ_{sca} ~47 m @400 nm



The IceCube Collaboration

11 countries, 39 institutions, ~250 members

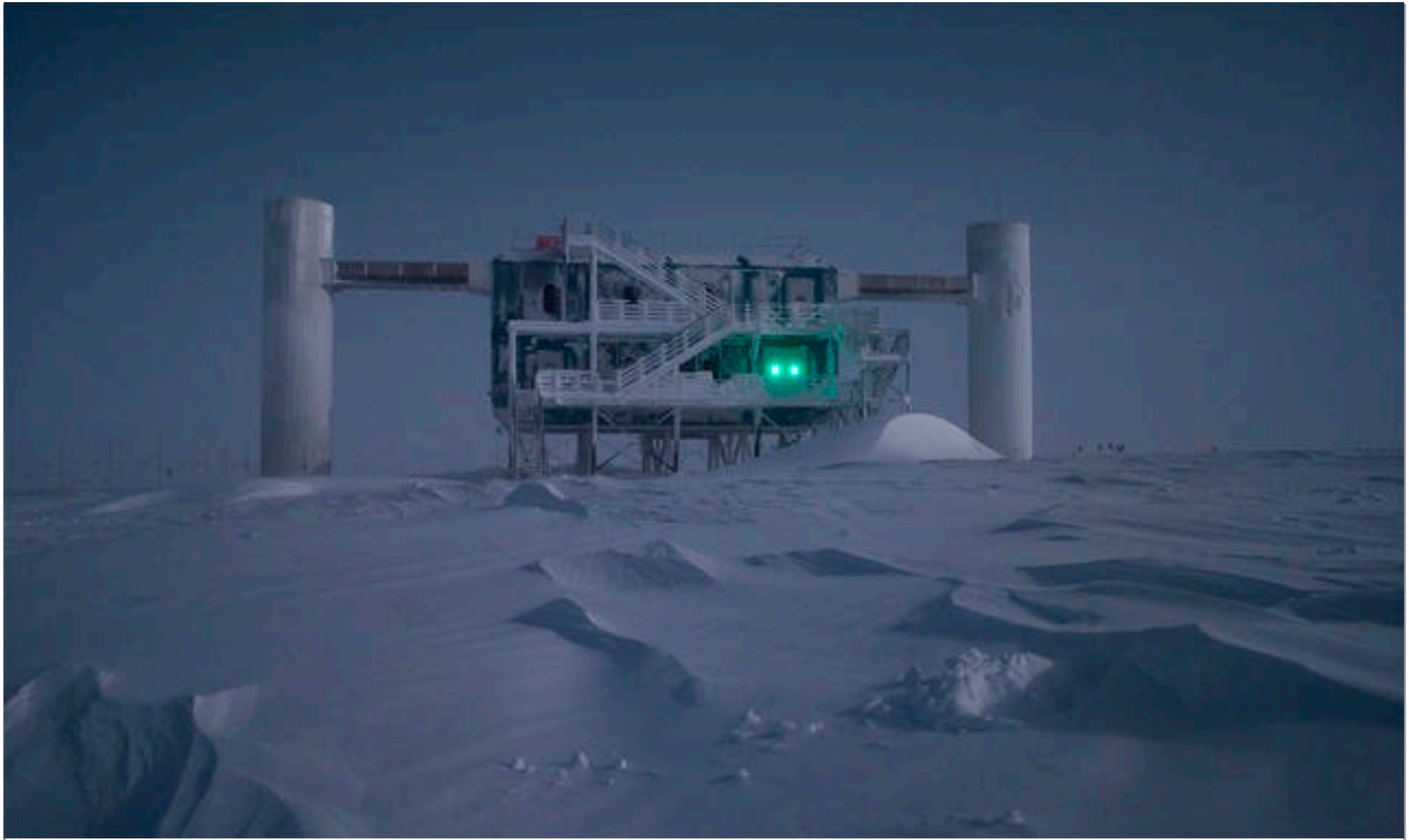
Internationl Funding Agencies

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

Let’s Go to the South Pole!

Arriving at the South Pole

Drill Camp



IceCube Lab (ICL)

Life at the S. Pole

Life at the S. Pole

Life at the S. Pole

Life at the S. Pole

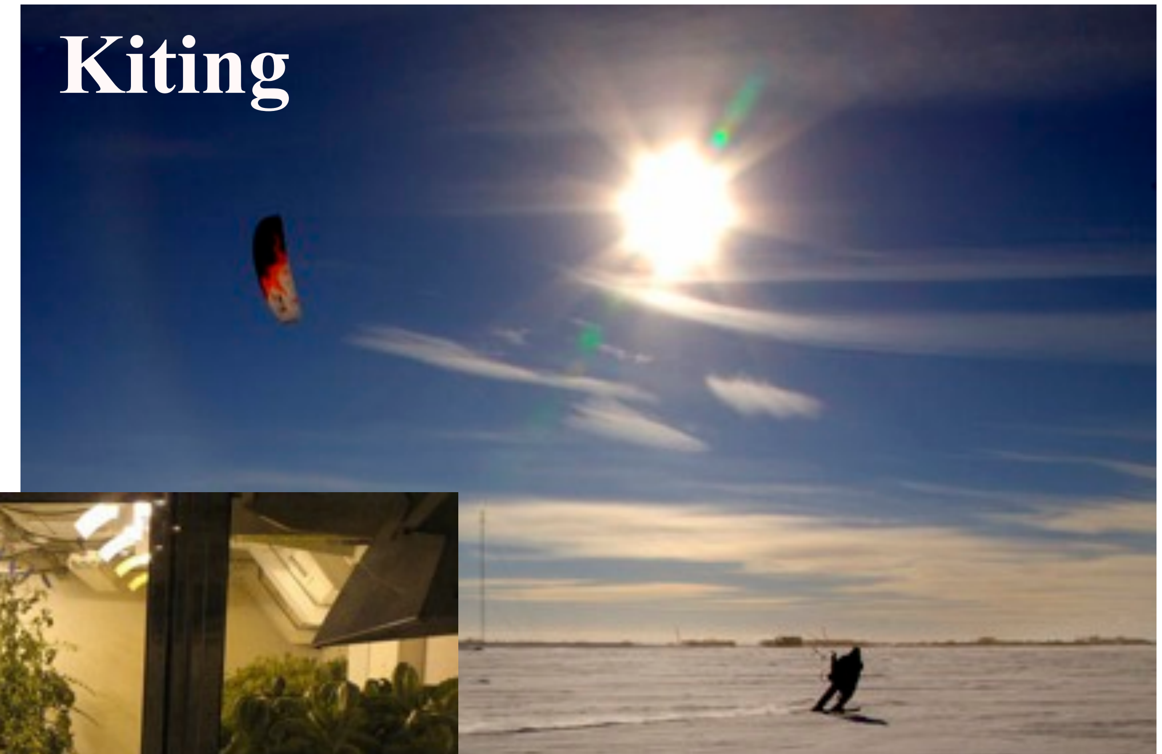

Golfing


Kiting


New Year’s race around the world

Life at the S. Pole

Golfing



Kiting

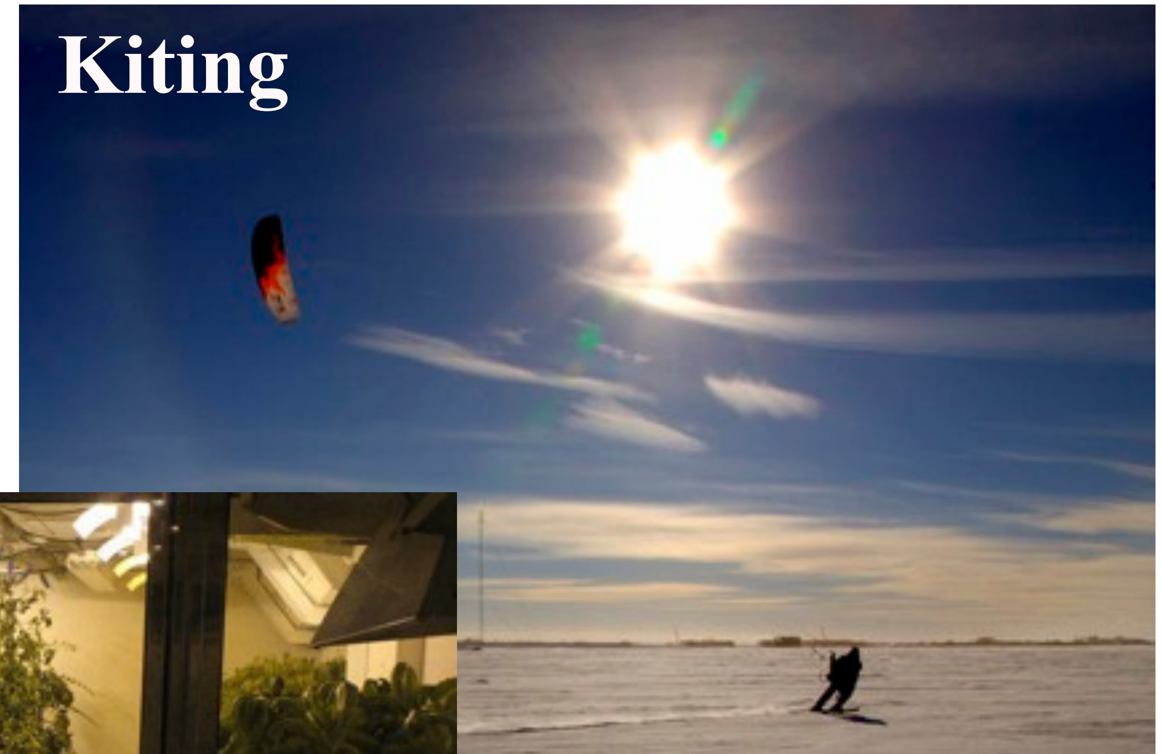
Green house

New Year's race around the world

Life at the S. Pole

Fun!


Golfing


Kiting


Green house

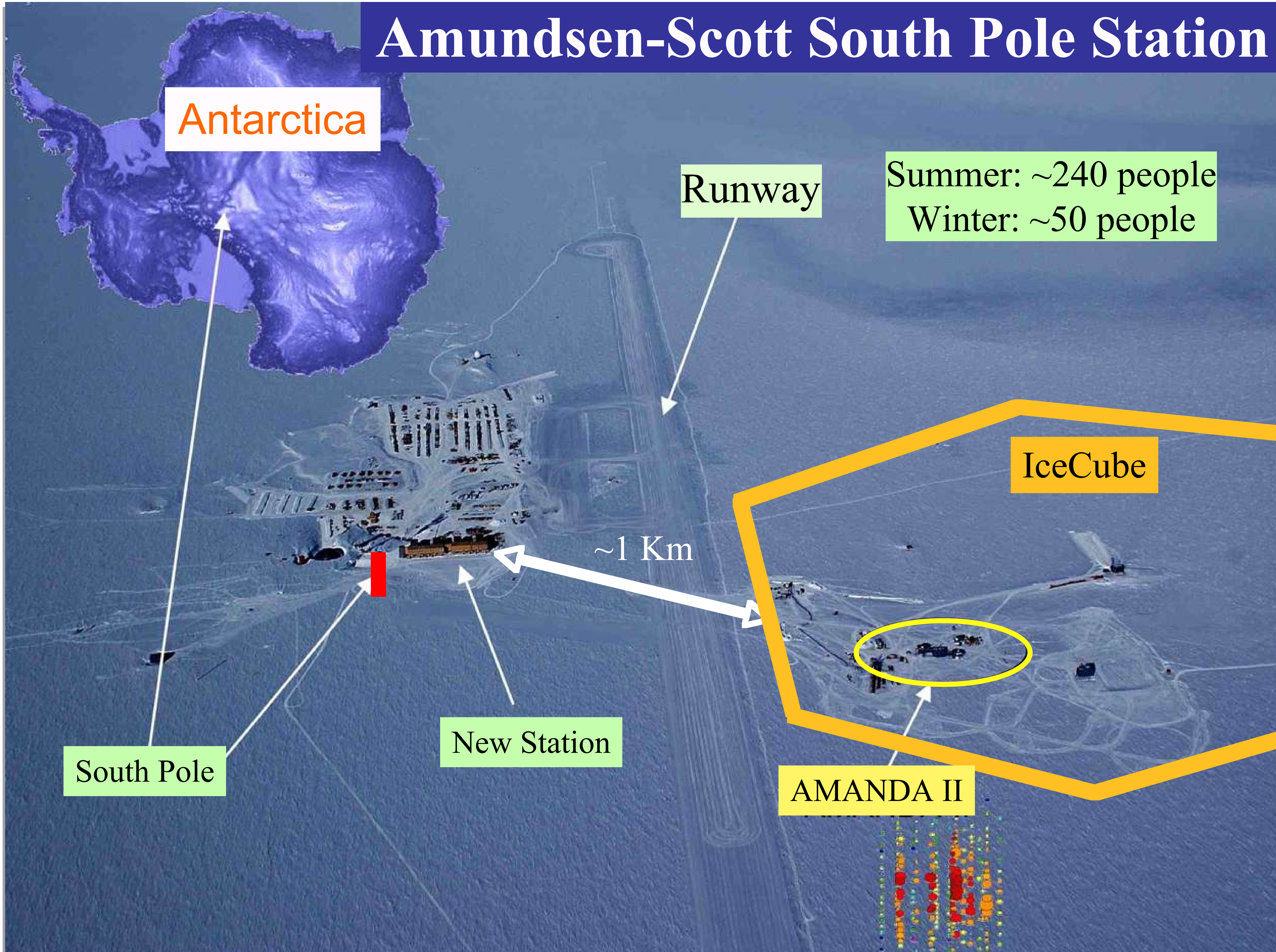

New Year's race around the world

The 300 Club

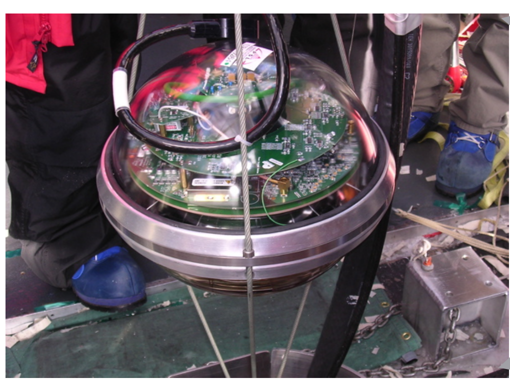
-100F (-73C) outside
+200F (+93C) sauna

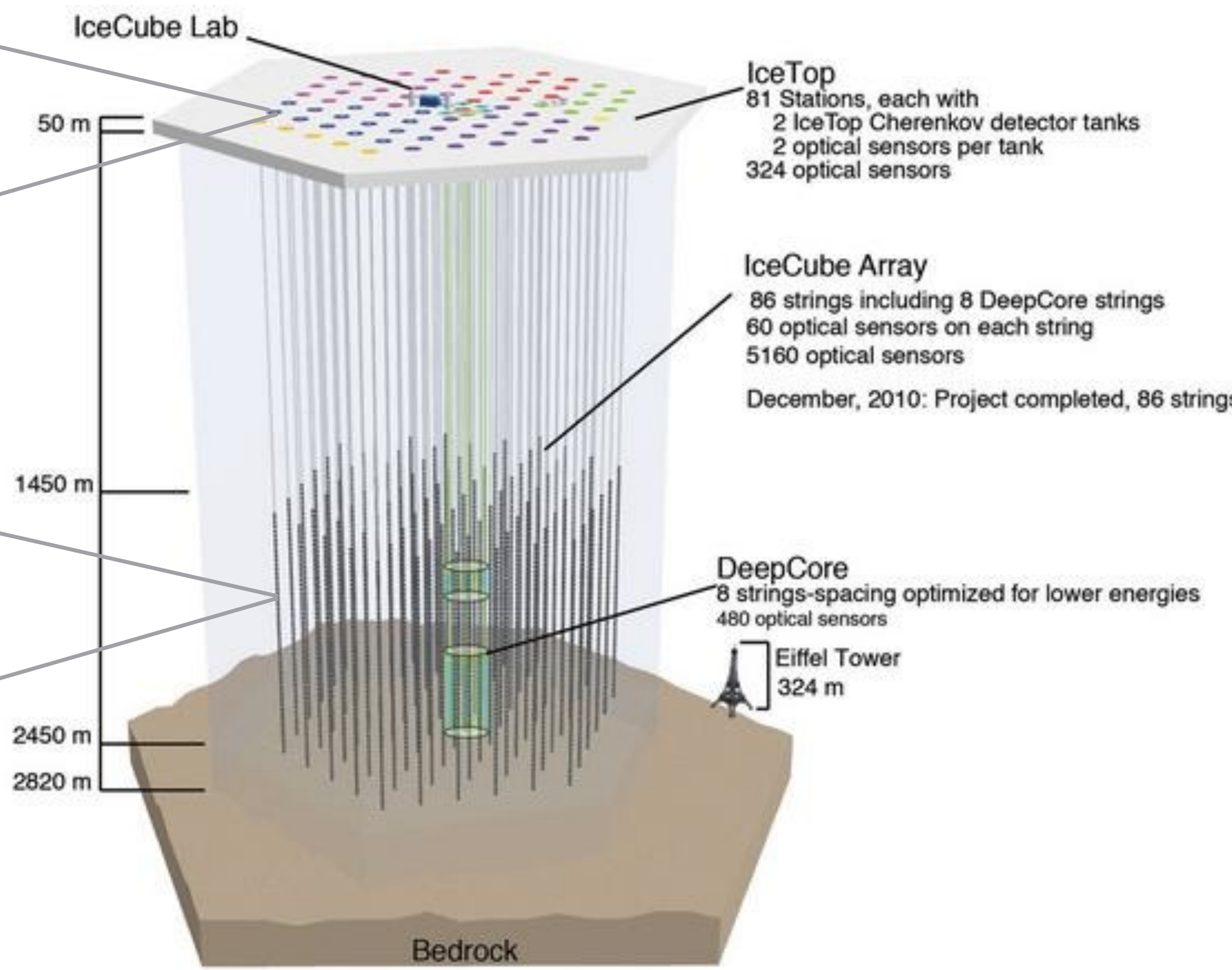
http://theglobalguy.com/world-travels/antarctica/the-300-club

Amundsen-Scott South Pole Station



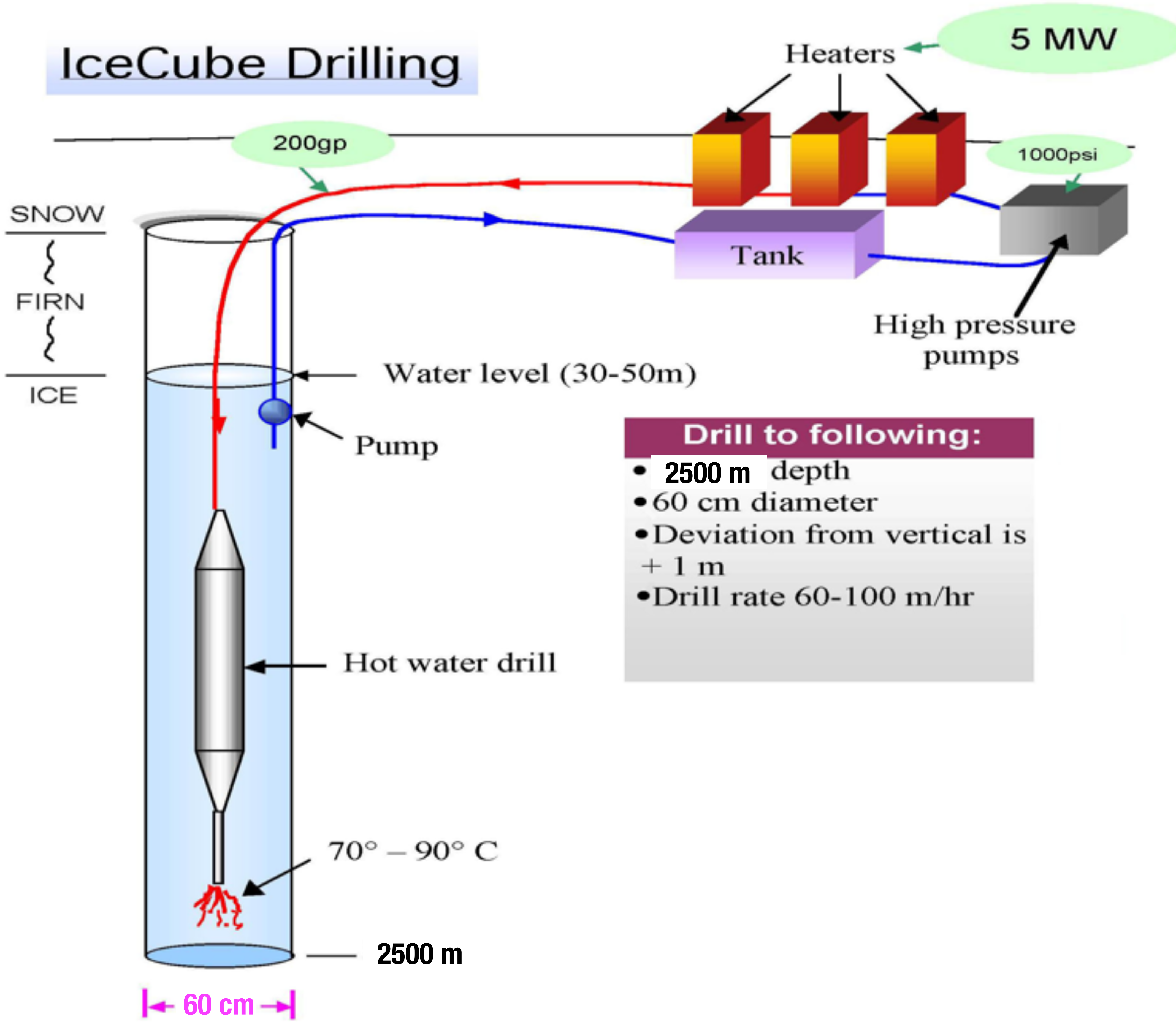
The IceCube Detector





String Deployment

IceCube Drilling



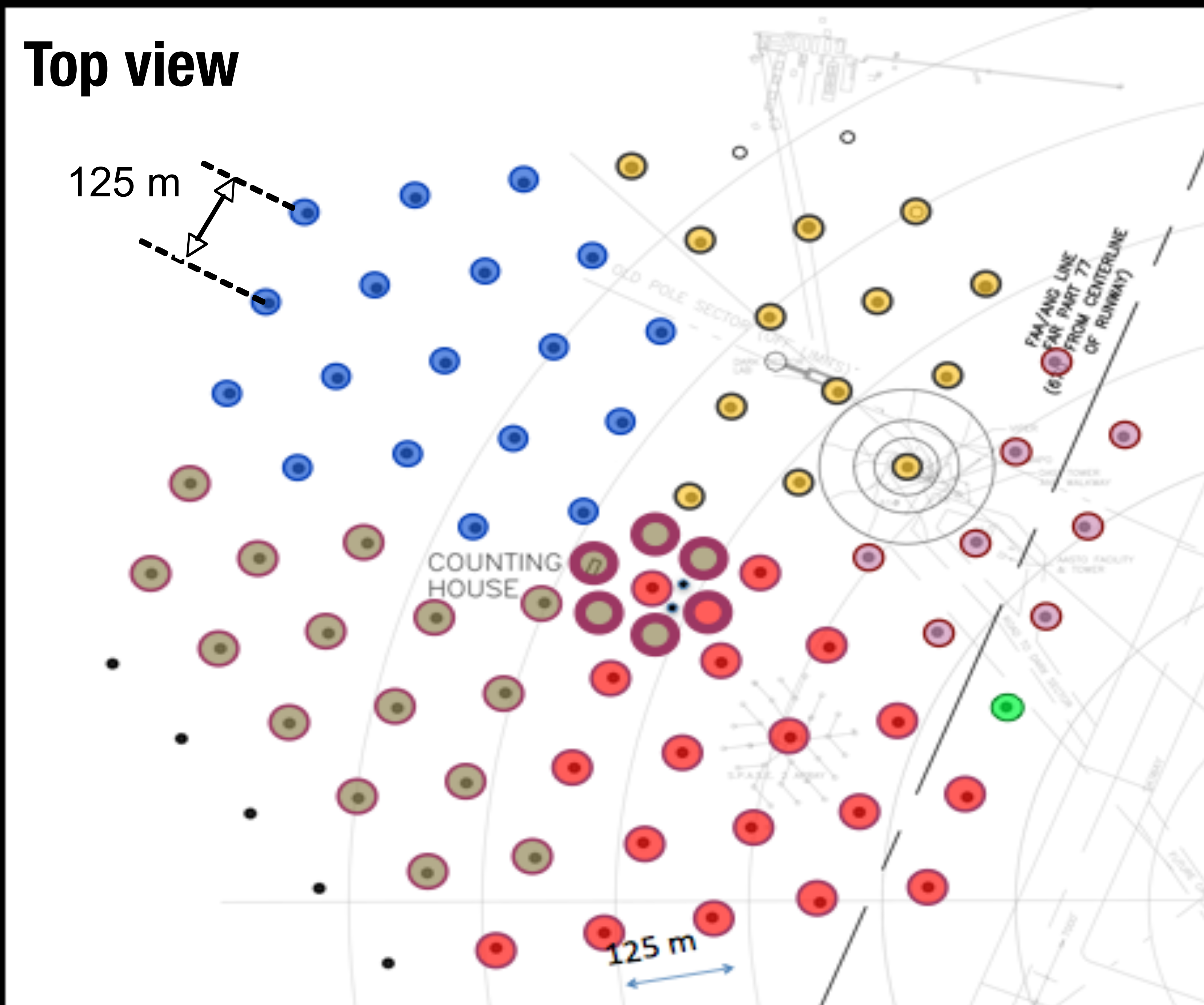
Drill to following:

- 2500 m depth
- 60 cm diameter
- Deviation from vertical is + 1 m
- Drill rate 60-100 m/hr

IceCube Construction Status

Finished…!!! 18th Dec. 2010

Total 86 strings now! (world's largest ν teles)



60 DOMs / string

125 m horizontal spacing
17 m vertical spacing

IC1	2004 - 2005
IC9	2005 - 2006
IC22	2006 - 2007
IC40	2007 - 2008
IC59	2008 - 2009
IC79	2009 - 2010
IC86	Dec. 2010

Digital Optical Module (DOM)

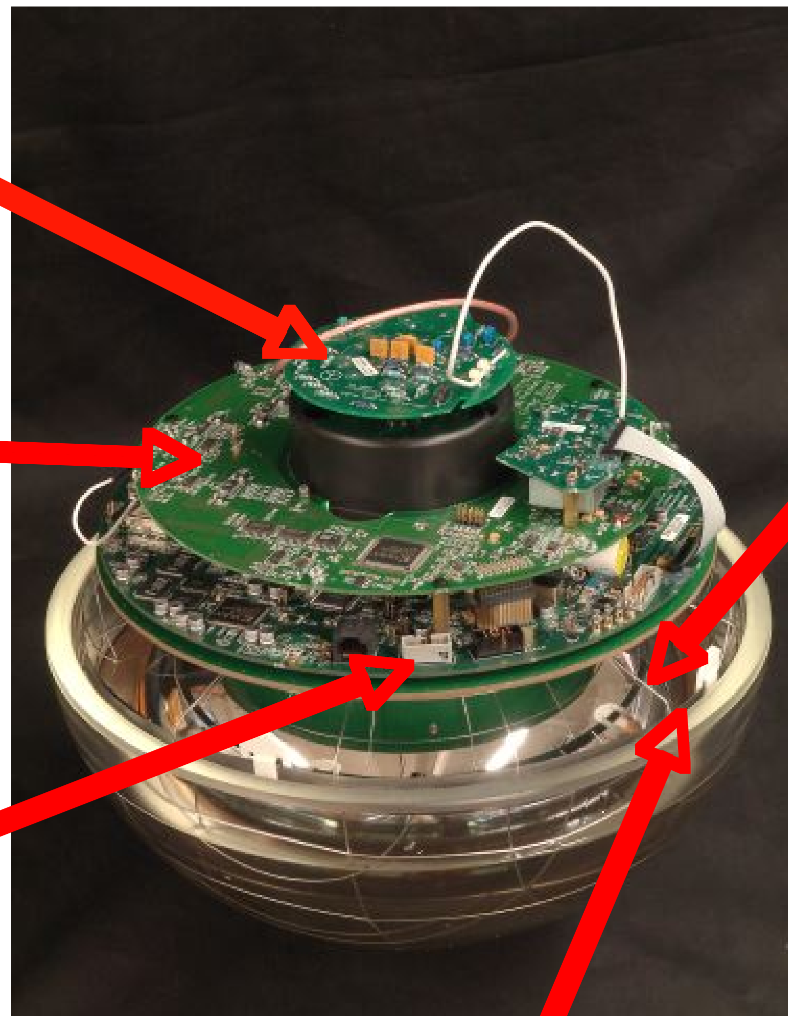
Hamamatsu R7081-02
(10”, 10-stage, 10^7 gain)

PMT base

LED flasher board

main board

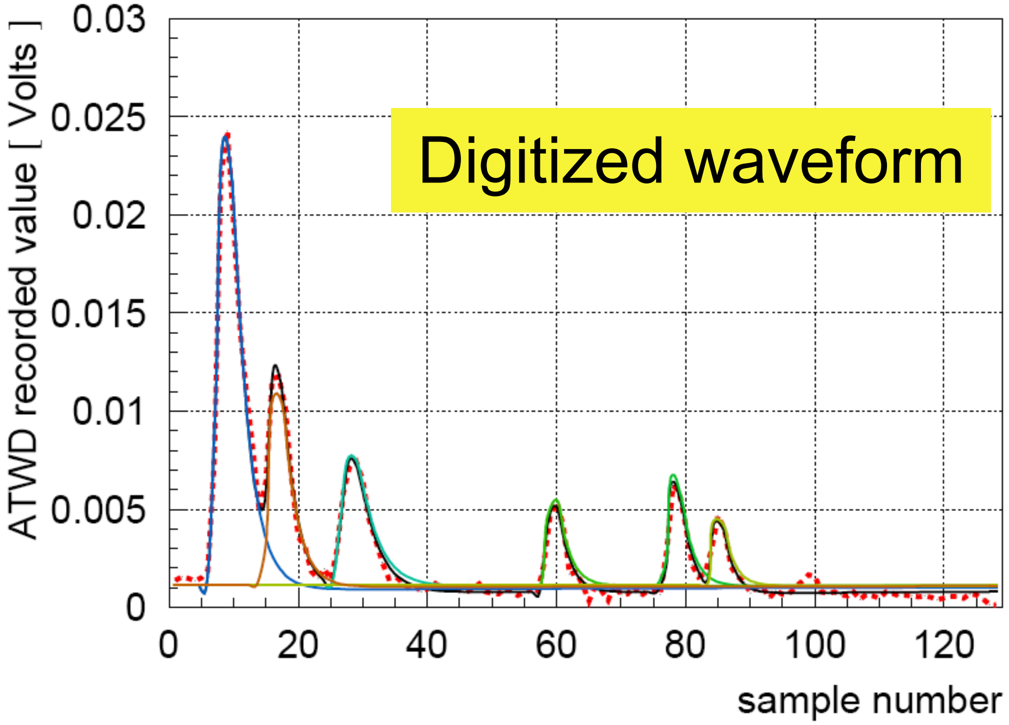
PMT



Housed in

33 cm Benthosphere

Power consumption: 3W
Dead time: < 1%
Dark noise rate: < 400 Hz
Local coincidence rate: ~15 Hz



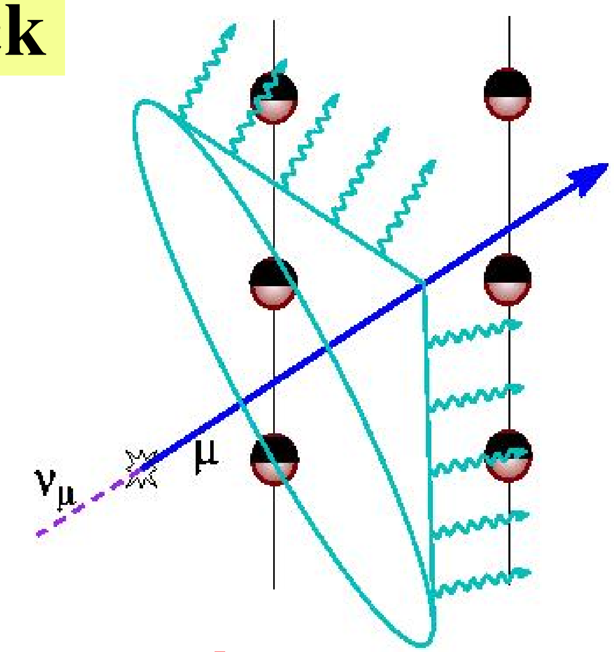
Digitize analog signal *in situ*!

Neutrino Detection

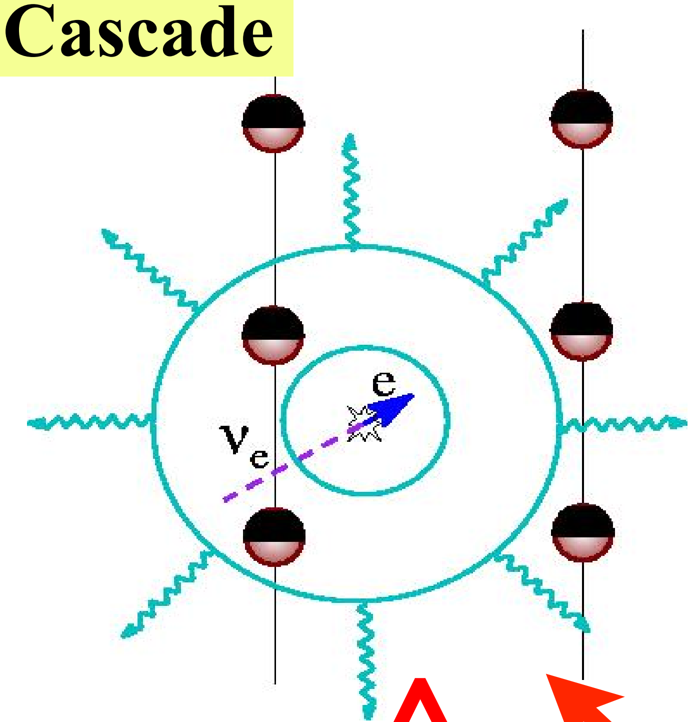
Detect 3 flavors: ν_e, ν_μ, ν_τ

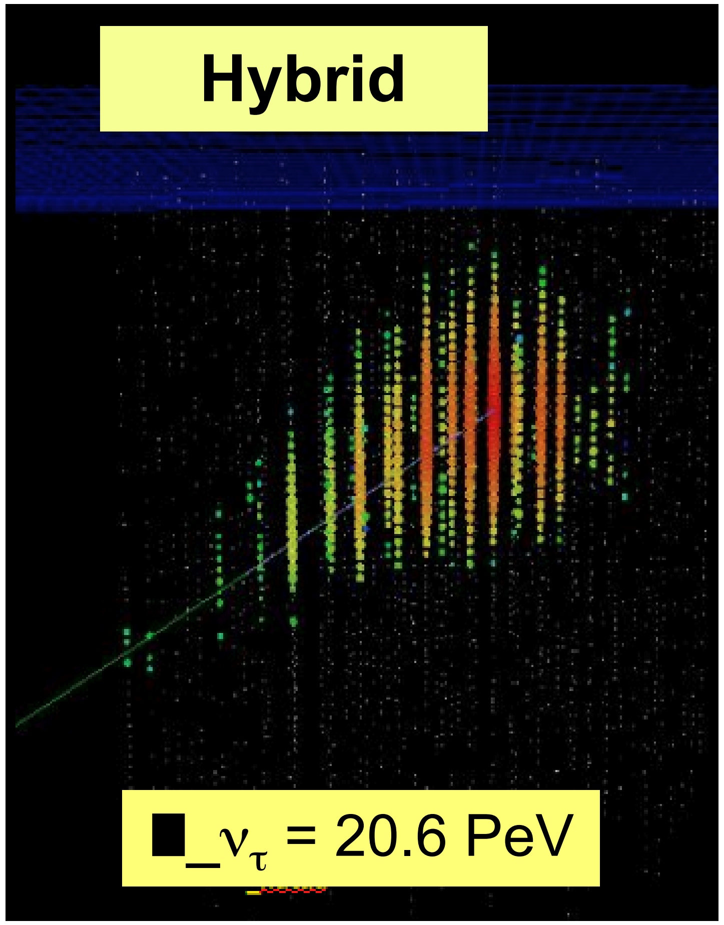
Method: detect Cherenkov light from secondary particles produced by neutrino interaction

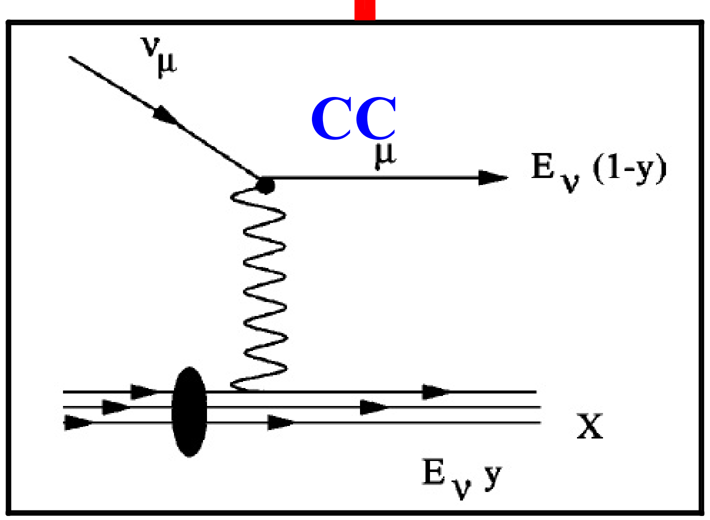
Track

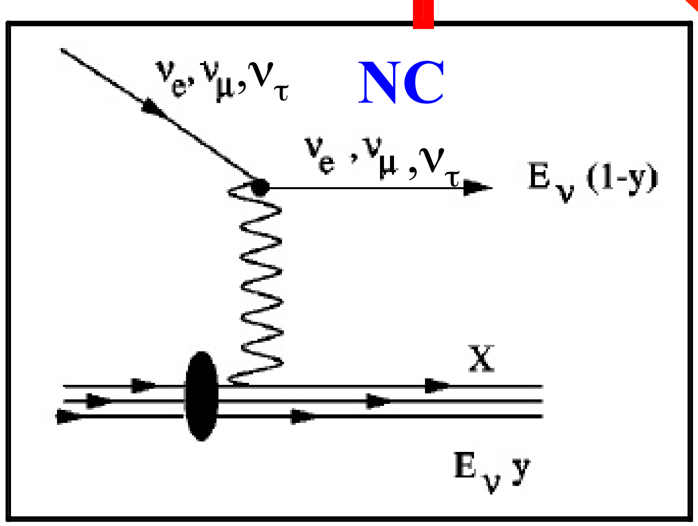


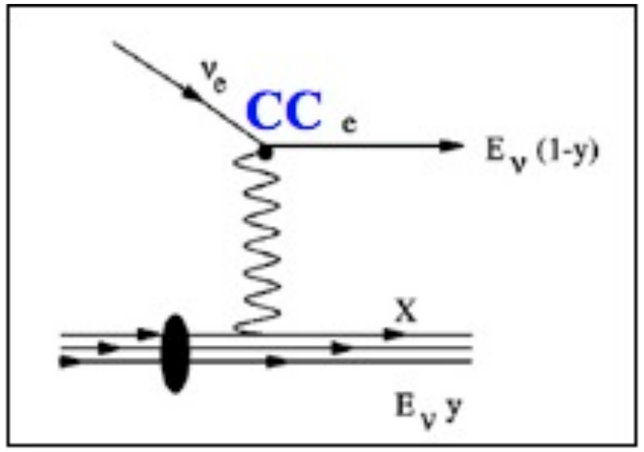
Cascade



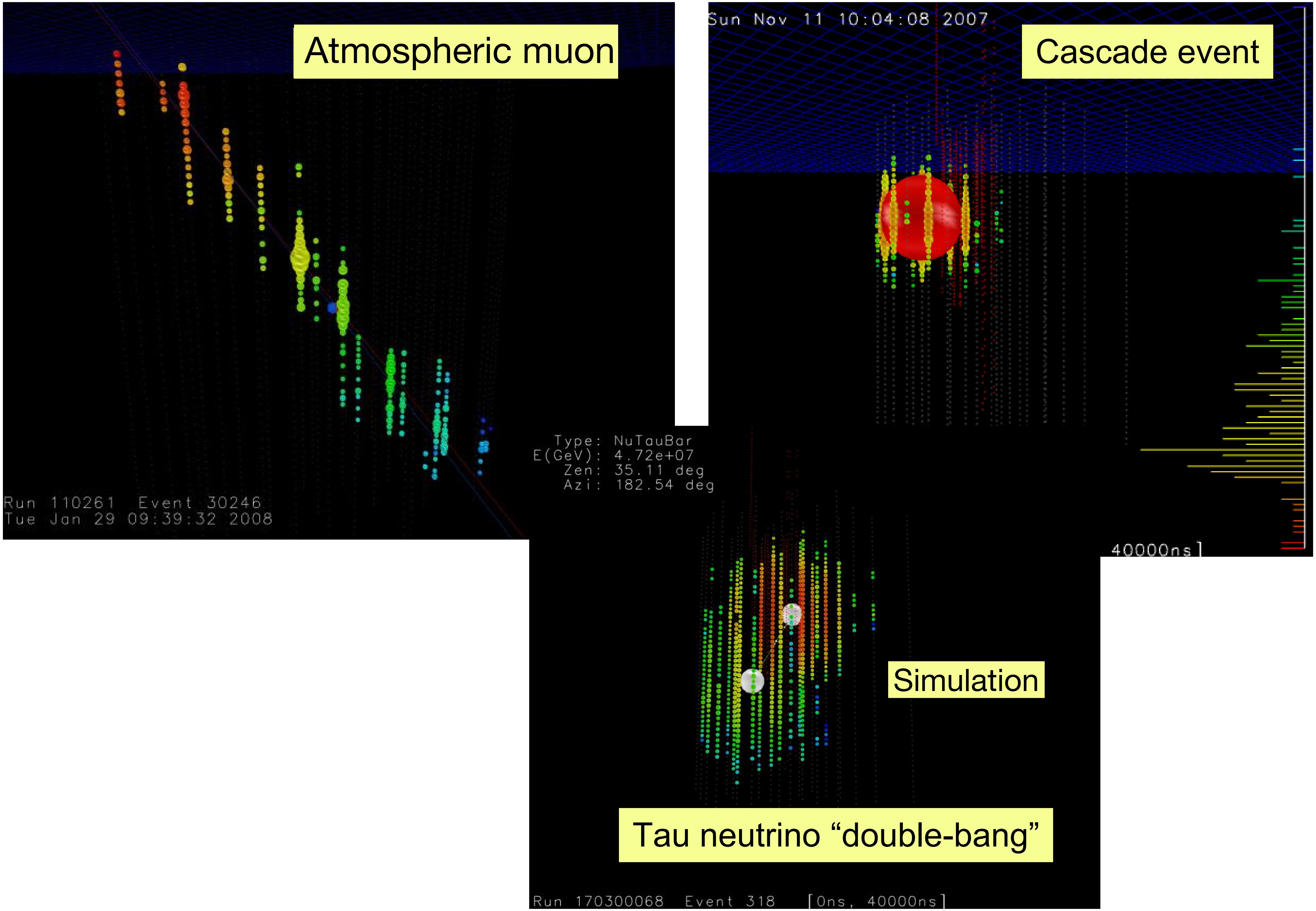






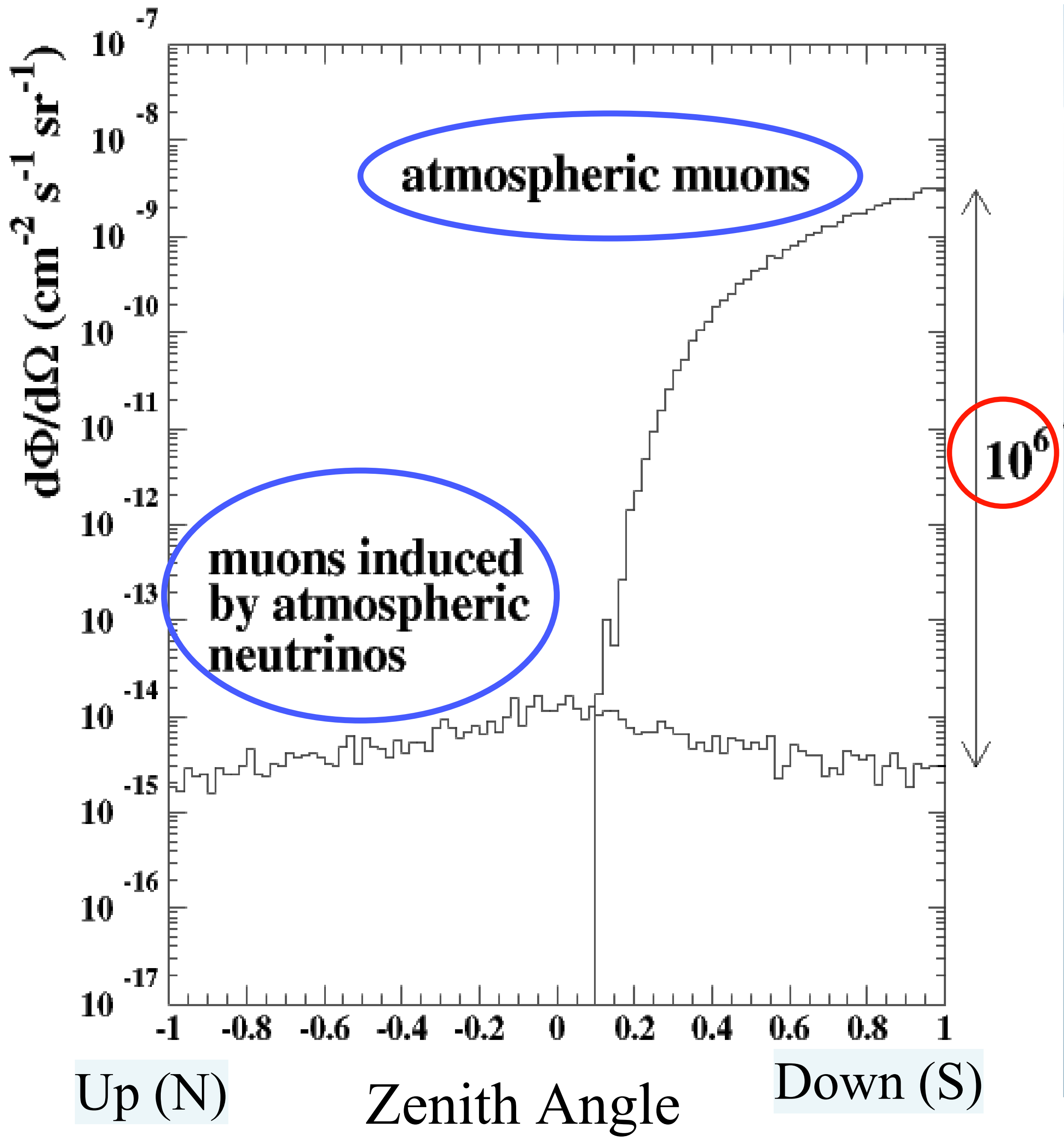


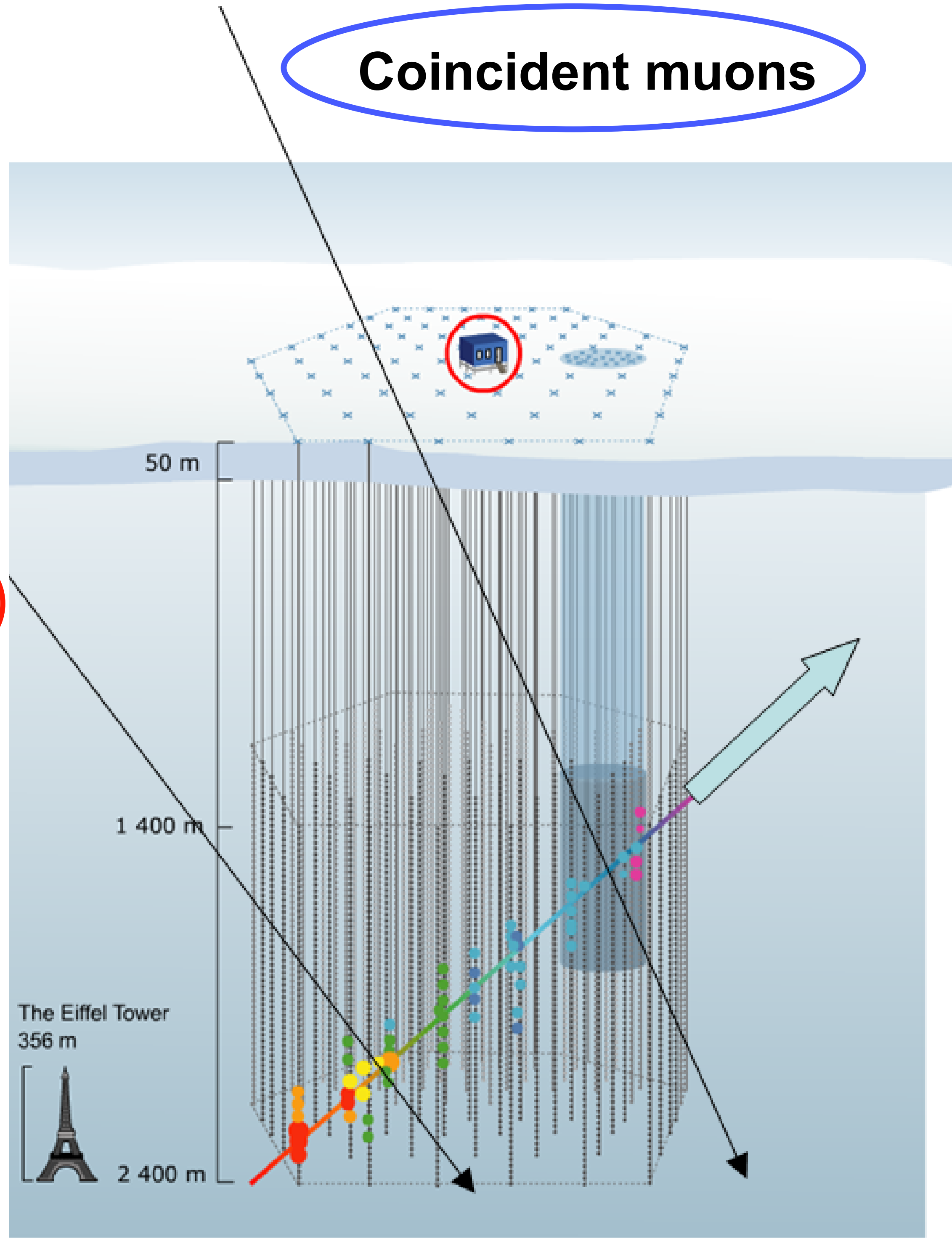
Event Views



Atmospheric muon
Run 110261 Event 30246
Tue Jan 29 09:39:32 2008
Sun Nov 11 10:04:08 2007
Cascade event
40000ns]
Type: NuTauBar
E(GeV): 4.72e+07
Zen: 35.11 deg
Azi: 182.54 deg
Simulation
Tau neutrino “double-bang”
Run 170300068 Event 318 [0ns, 40000ns]

Backgrounds



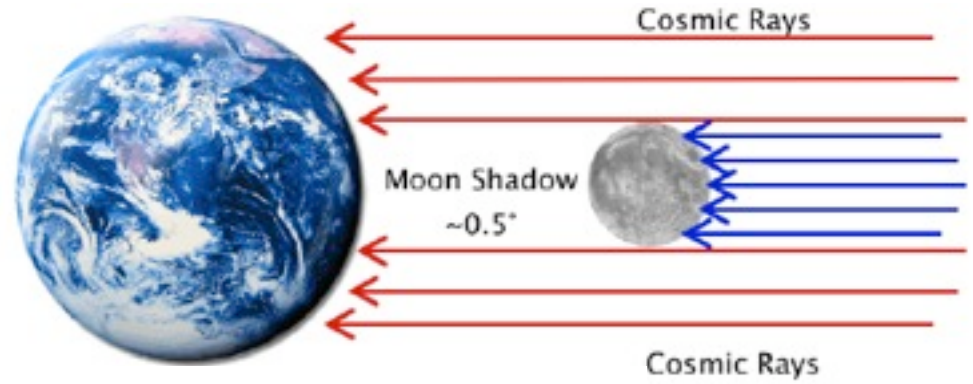


& performance.

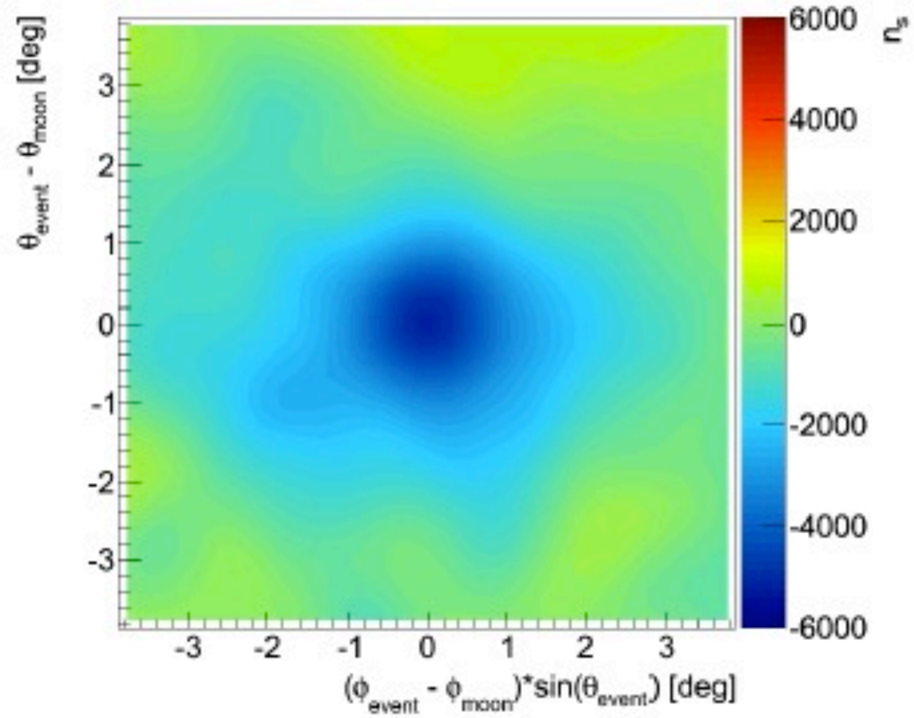
➡ These background particles can be used for detector calibration!

Moon Shadow

➡ **Deficit of muons in moon direction**

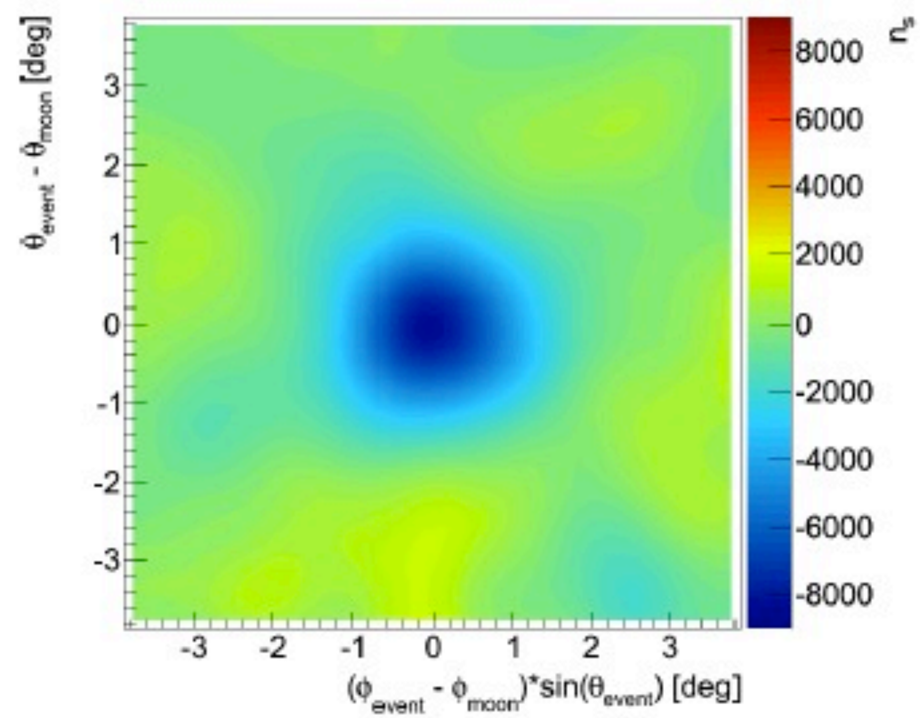


40 strings (2008-2009)



- $n_s^{obs} = -5326 \pm 544$
- $n_s^{exp} = -5734 \pm 76$
- No shift

59 strings (2009-2010)



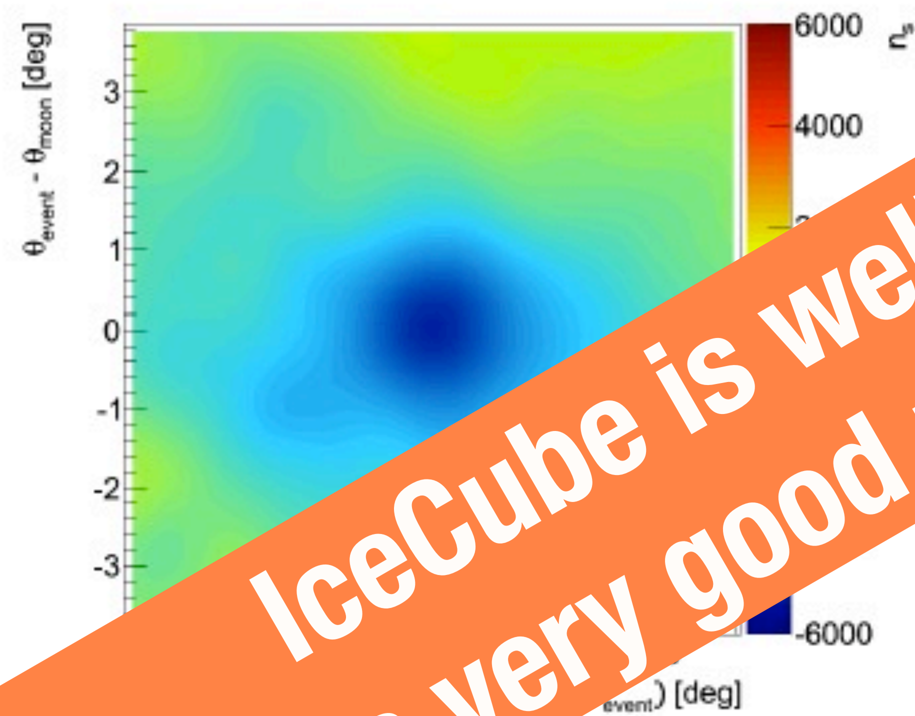
- $n_s^{obs} = -8660 \pm 565$
- $n_s^{exp} = -8192 \pm 91$
- $\vec{x}_s^{obs} = (-0.1° \pm 0.1°, 0.0° \pm 0.1°)$

IC59: More than 13σ deficiency (14 moon cycles)
systematic pointing error < 0.1° , *Boersma*, ICRC2011

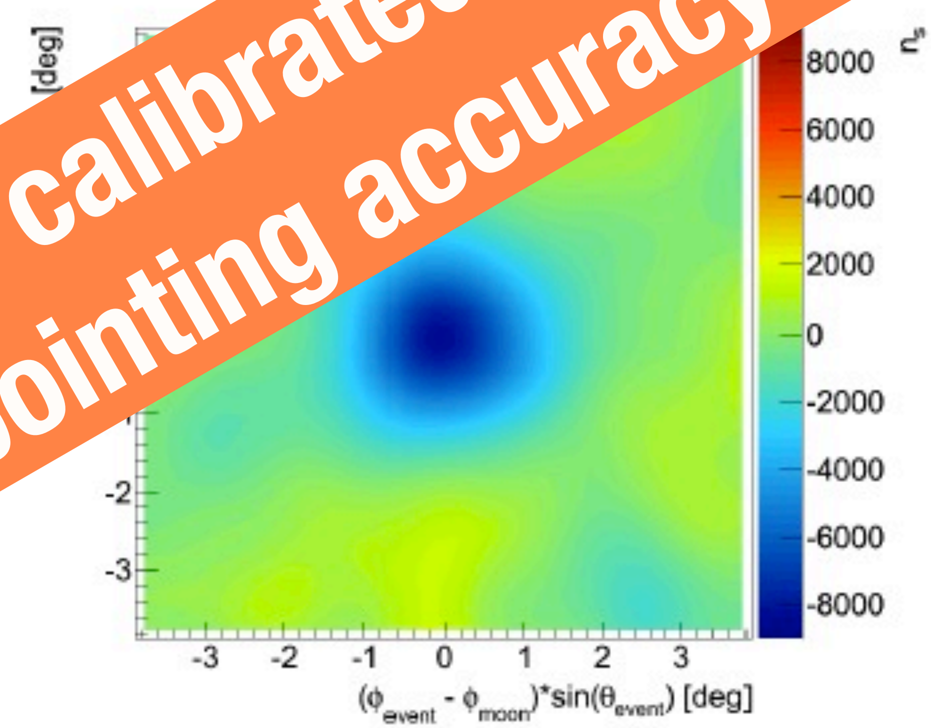
Moon Shadow

➡ **Deficit of muons in moon direction**

40 strings (2008-2009)



59 strings (20



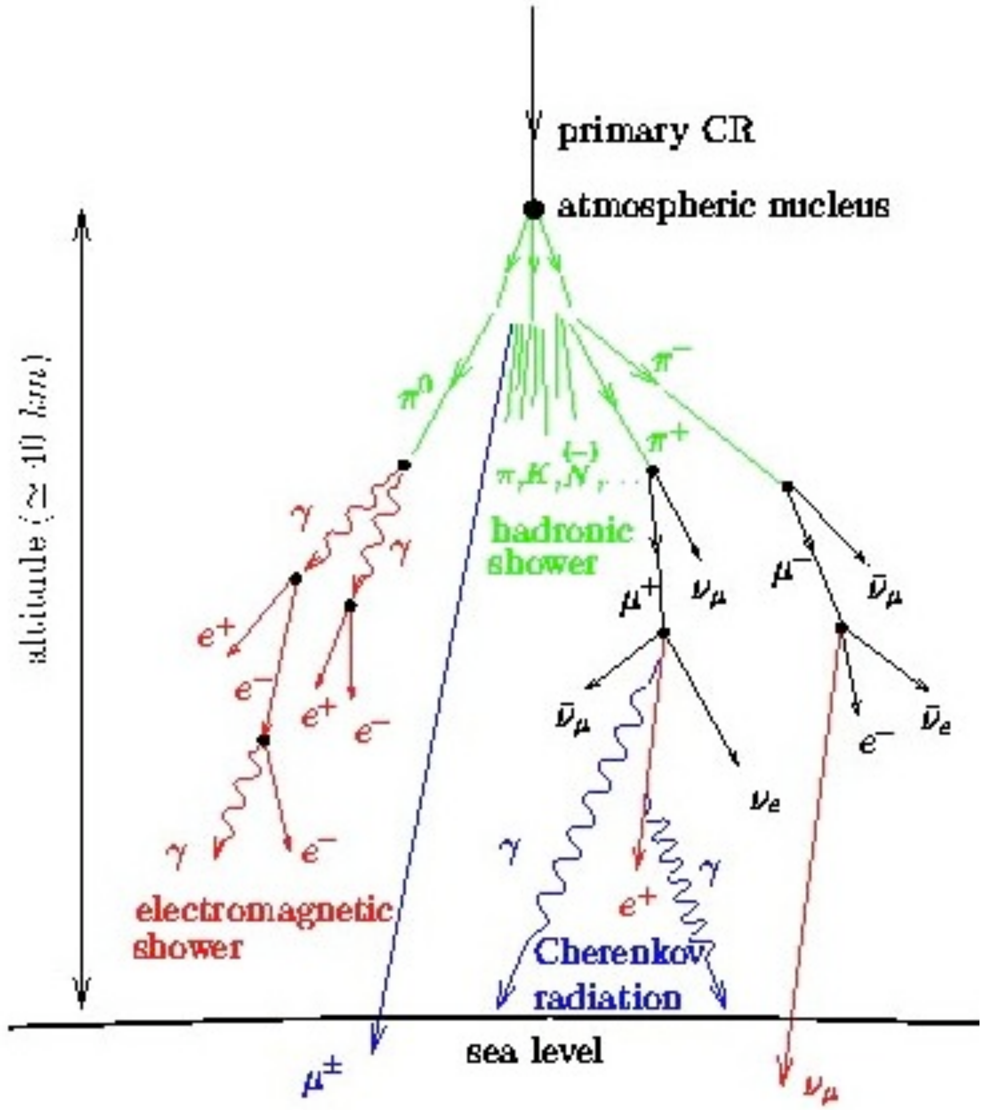
IceCube is well calibrated with a very good pointing accuracy!

- $\ldots 26 \pm 544$
- $\ldots -5734 \pm 76$
- No shift

- $n_s^{obs} = -8660 \pm 565$
- $n_s^{exp} = -8192 \pm 91$
- $\vec{x}_s^{obs} = (-0.1° \pm 0.1°, 0.0° \pm 0.1°)$

IC59: More than 13σ deficiency (14 moon cycles)
systematic pointing error < 0.1° , *Boersma*, ICRC2011

Atmospheric Neutrinos



Background for astrophysical neutrinos!

(E spectrum: softer in high energy region)

Conventional ν:

$$p + p \rightarrow \pi^- / \pi^+ \rightarrow \mu\, \nu_\mu \rightarrow (e)\, \nu_e\, \nu_\mu \nu_\mu$$

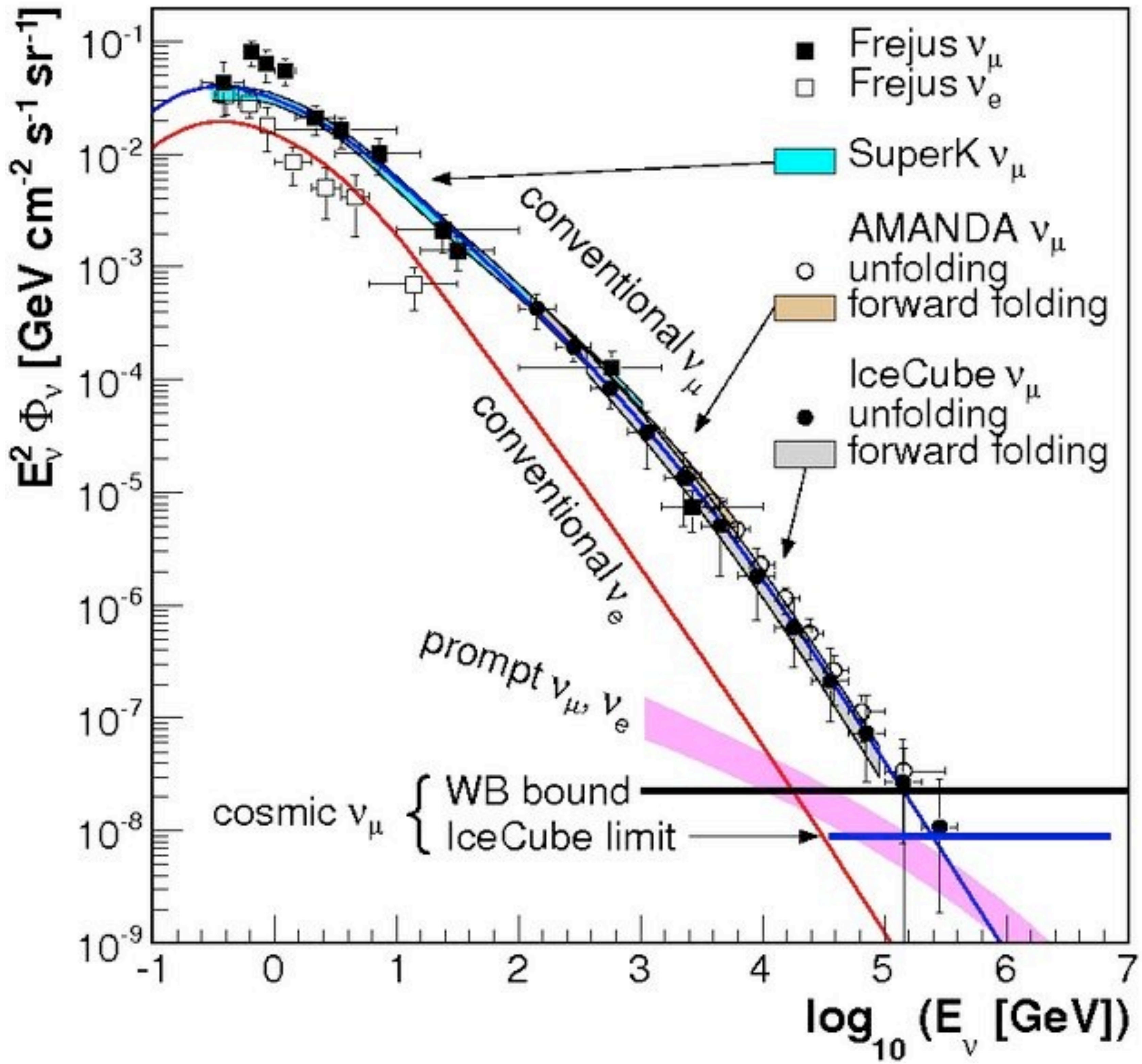
$$\nu_e : \nu_\mu : \nu_\tau \;=\; 1 : 2 : 0$$

Prompt ν:

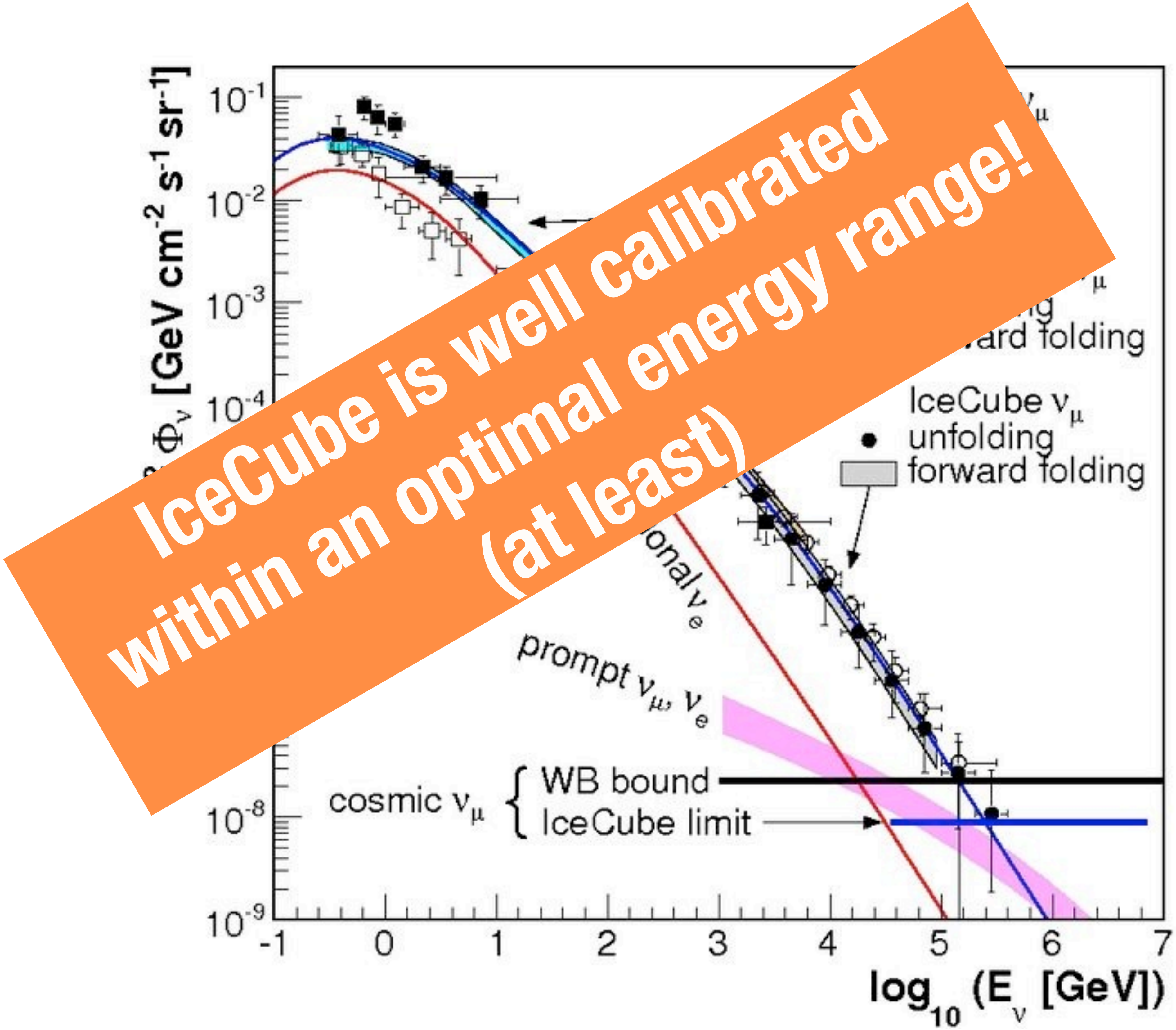
Prompt decay of charmed hadrons

$$\begin{aligned} D^+ &\rightarrow \overline{K^0} + l^+ + \nu_l \\ D^0 &\rightarrow K^- + l^+ + \nu_l \\ \Lambda_c &\rightarrow \Lambda_0 + l^+ + \nu_l . \end{aligned}$$

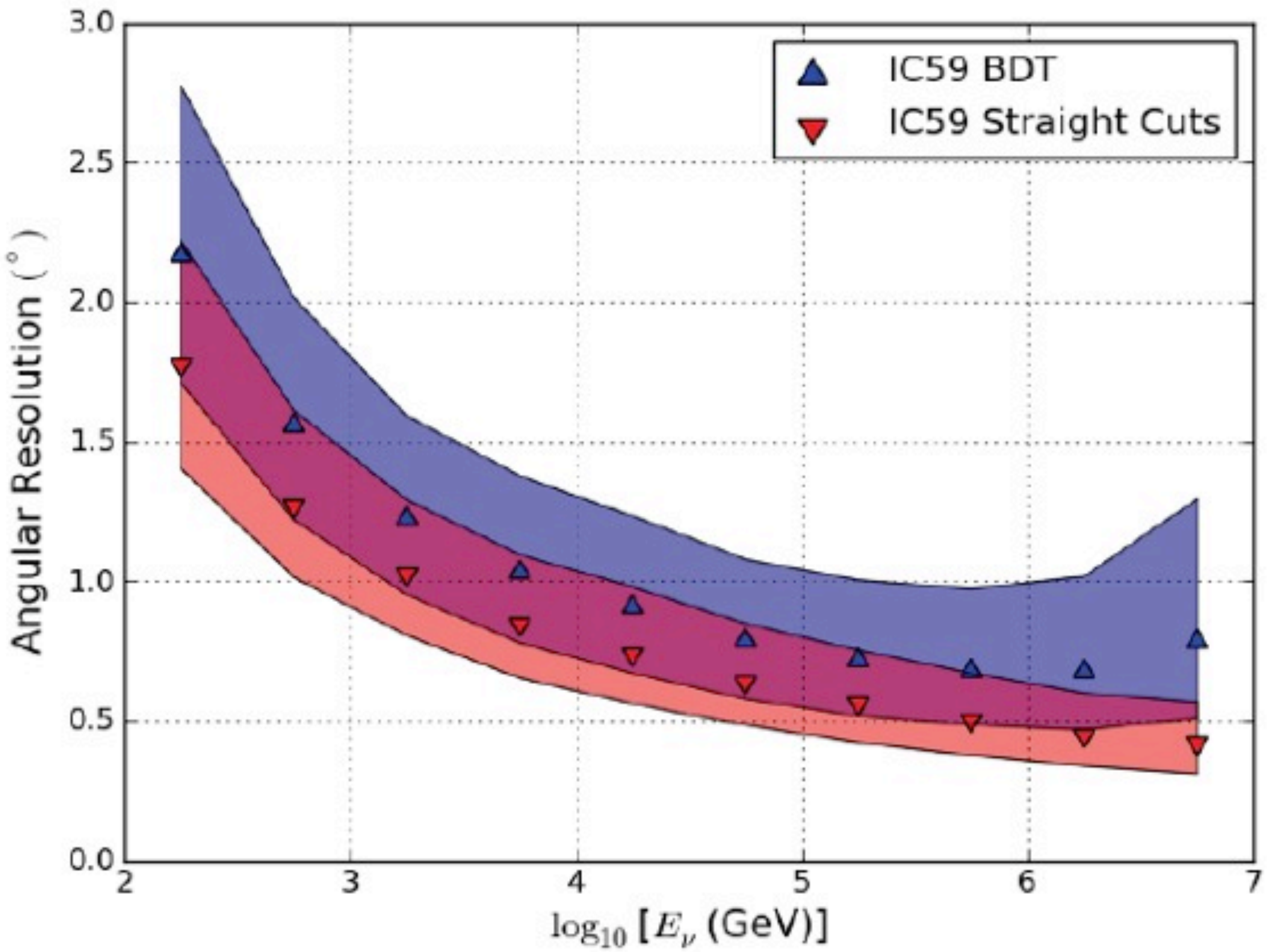
Atmospheric Neutrino Flux



Atmospheric Neutrino Flux



IceCube: Performance



Angular Resolution

- 1.0-1.5 deg at TeV
- 0.5-0.7 deg at PeV

Energy Resolution

- track: 0.25 $\log_{10}$(E/GeV)
- cascade:
  ~0.1-0.2 $\log_{10}$(E/GeV)

IceCube: Data Rates

Year	#. Strings	Run length	μ rate (kHz)	ν rate
2005/06	IC1	---	---	total 2
2006/07	IC9	137 d	0.08	1.7 / d
2007/08	IC22	275 d	0.6	28 / d
2008/09	IC40	375.5 d	1.1	37.6 / d
2009/10	IC59	348 d	1.9	124.5 / d
2010/11	IC79	~365 d	2.3	~170+500 / d
2011/-	IC86	since May	2.7	~190+500 / d

DeepCore

Data Transfer

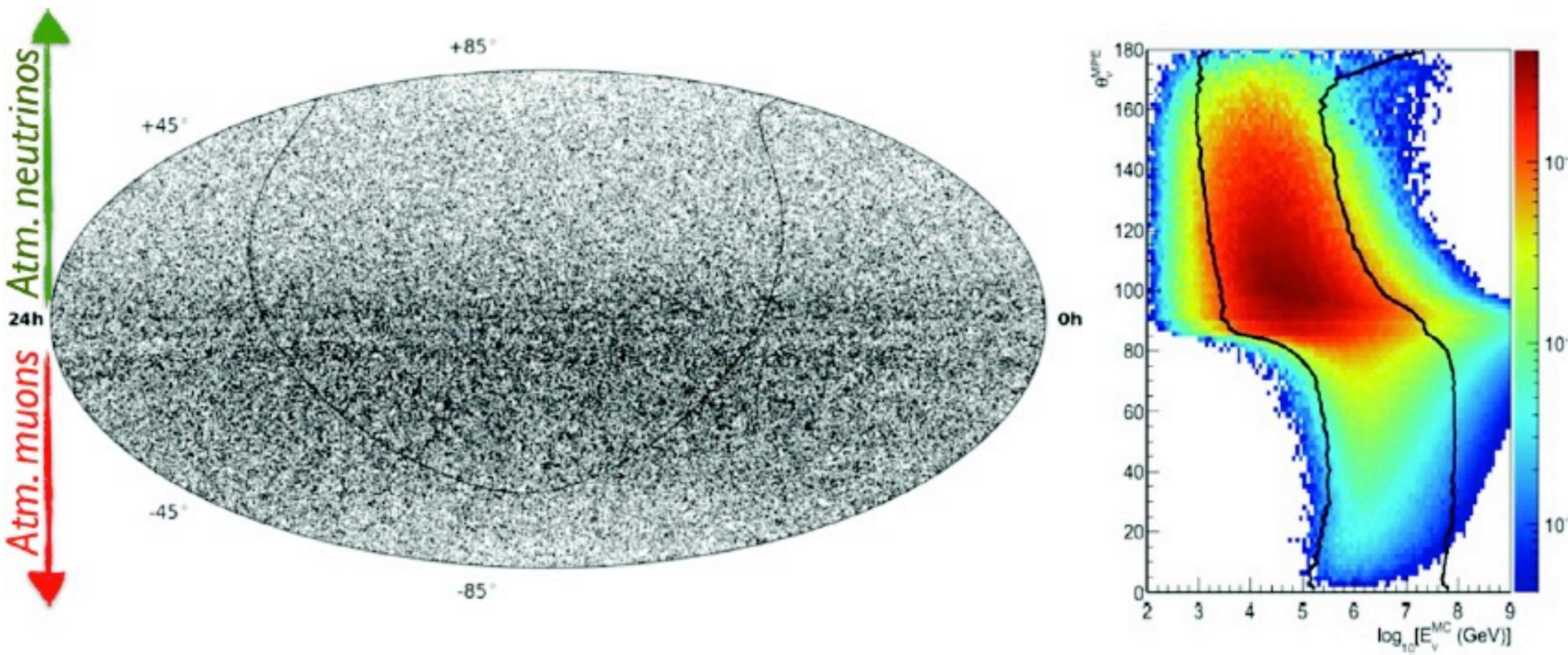
- Satellite: ~90 GB/day, (pre-scaled) filtered data
- Ship: for all filtered data, once a year to northern hemisphere

IceCube: Physics Menu

- **Astronomy/Astrophysics:**
  -- Point source search: GRB, AGN, SNR, SN, etc...
  -- Diffuse search: all sky search
- **Cosmic ray physics:**
  -- compositions, energy spectrum
- **Particle physics:**
  -- neutrino oscillation: atmospheric
  -- charm production process at high energy
  -- etc.
- **New physics:**
  -- Exotic Particle Search: WIMPs, magnetic monopoles
  -- Violation of Lorenz invariance
  -- sterile neutrinos ?

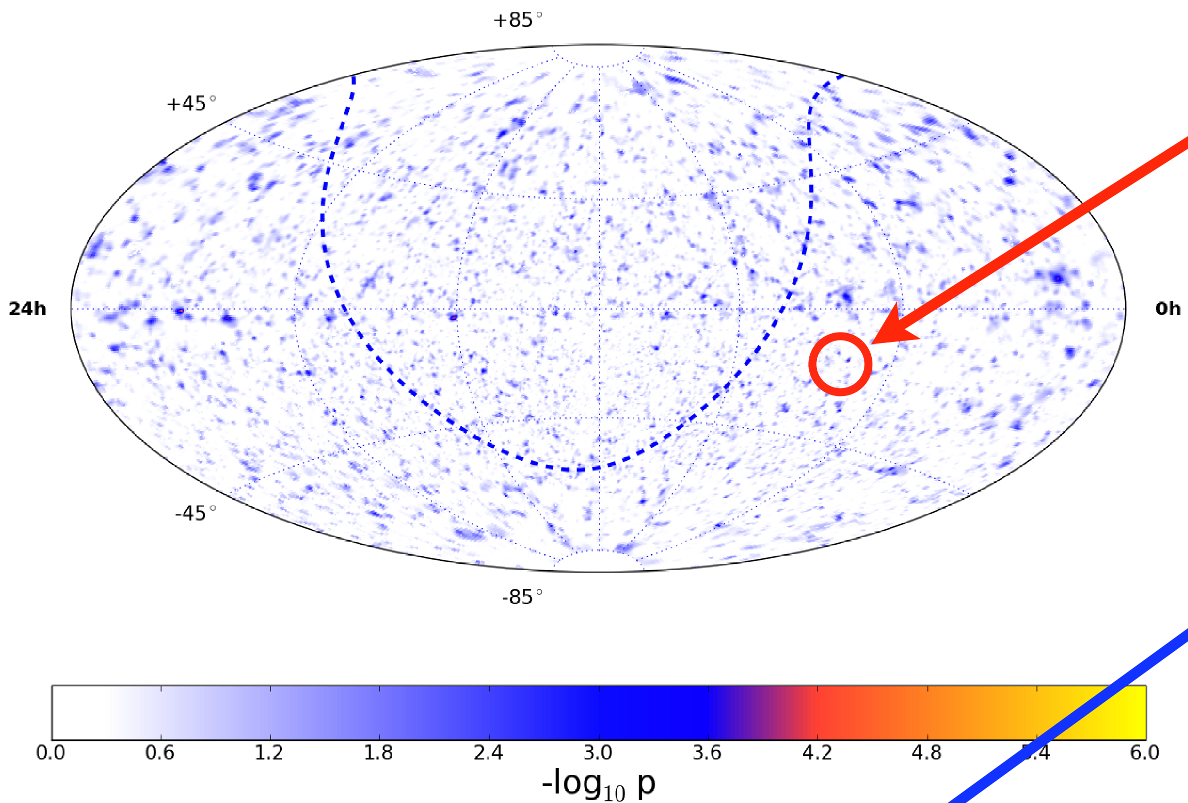
Sorry,… I can not cover all these topics here.

Point Source Search: IC40 + IC59

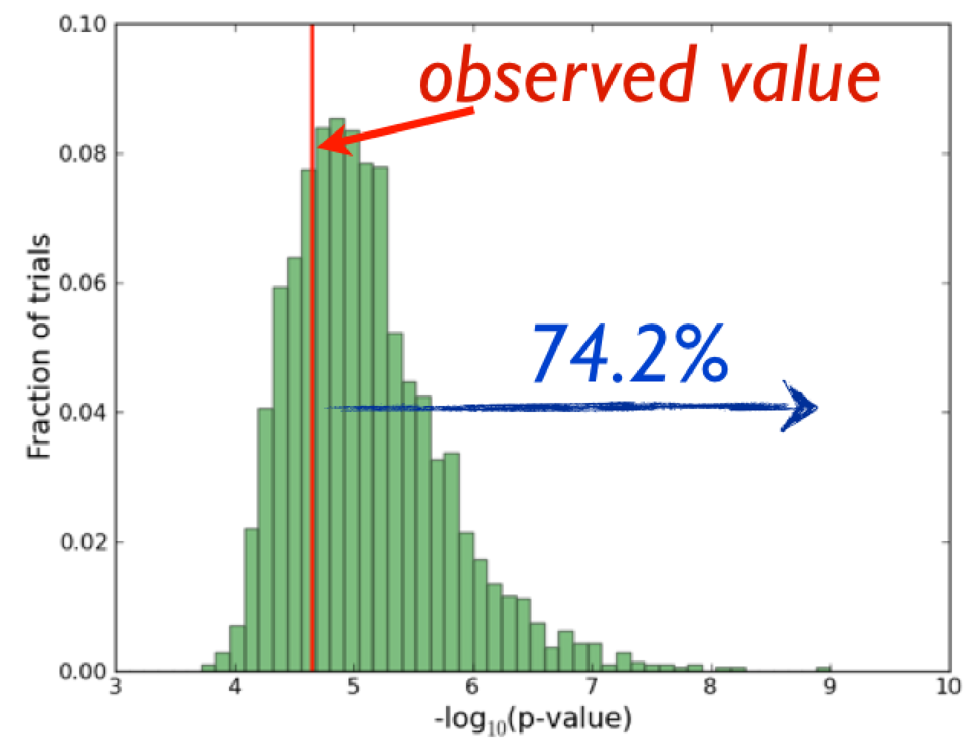


- **Livetime: 375 d (IC40) + 348 d (IC59)**
- **Total events: 43K (up-going) + 63K (down-going),**
  37K (IC40) + 70K (IC59)

Point Source Sky Map: IC40 + IC59



Most significant spot:
r.a. = 75.45°
dec = -18.15°
n_s = 18.3
γ = -3.9
-log$_{10}$p-value = 4.65



Signal pdf:

$$\mathcal{S}_i = \frac{1}{2\pi\sigma_i^2} e^{-r_i^2/2\sigma_i^2} \cdot P(E_i|\gamma)$$

Background pdf:

$$\mathcal{B}_i = B_{\text{zen}} \cdot P_{\text{atm}}(E_i)$$

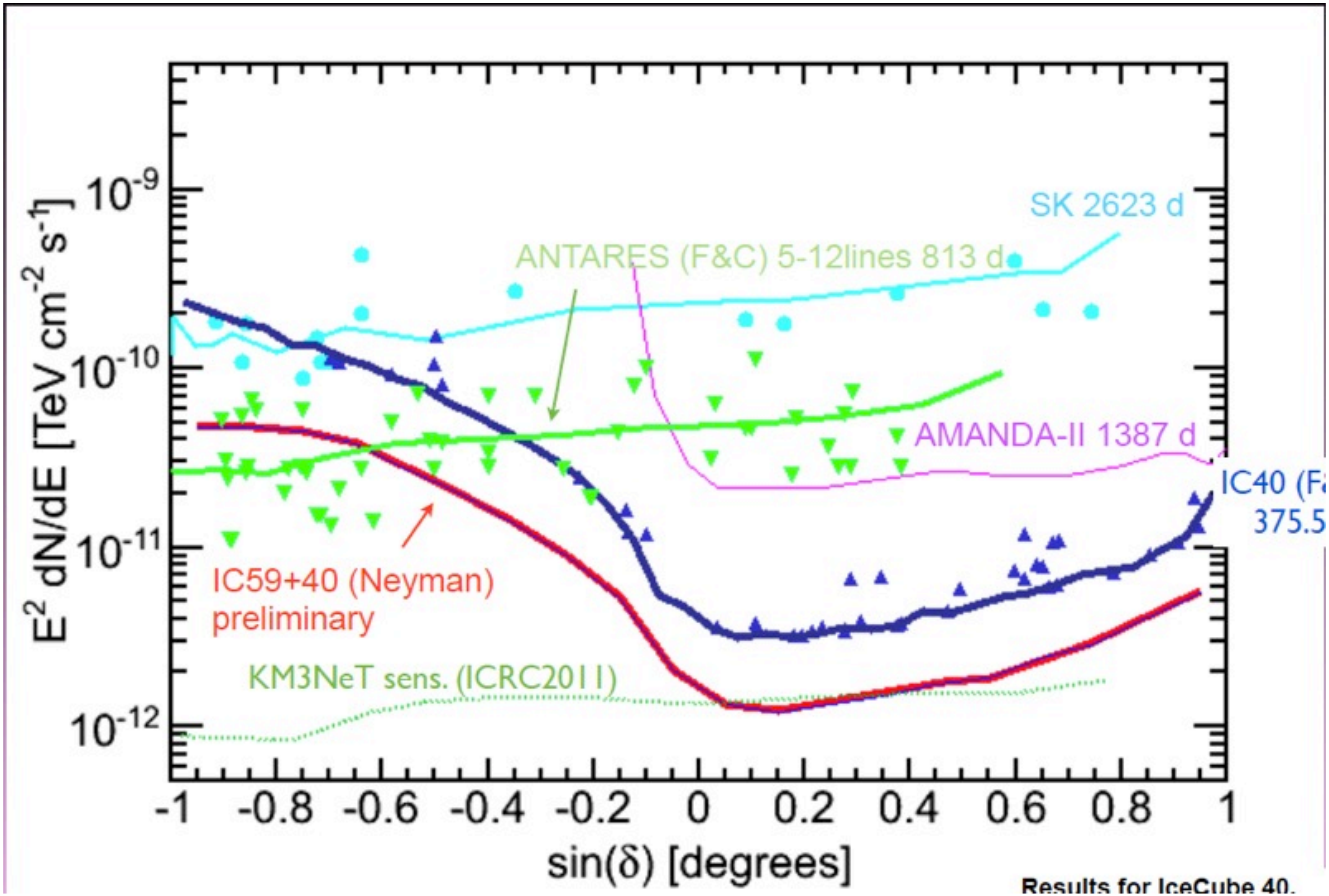
Likelihood:

$$\mathcal{L}(n_s, \gamma) = \prod_{i=1}^{N} \left(\frac{n_s}{N} \mathcal{S}_i(\gamma) + (1 - \frac{n_s}{N}) \mathcal{B}_i \right)$$

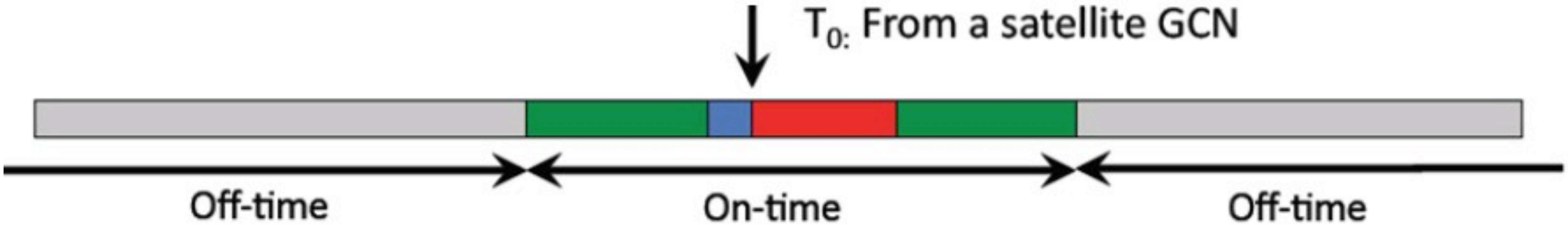
Maximize:

- γ, the neutrino spectral index
- $\mathbf{n_s}$, number of signal events

Point Source:
E^{-2} Median Sensitivities, Upper Limits (90%CL)



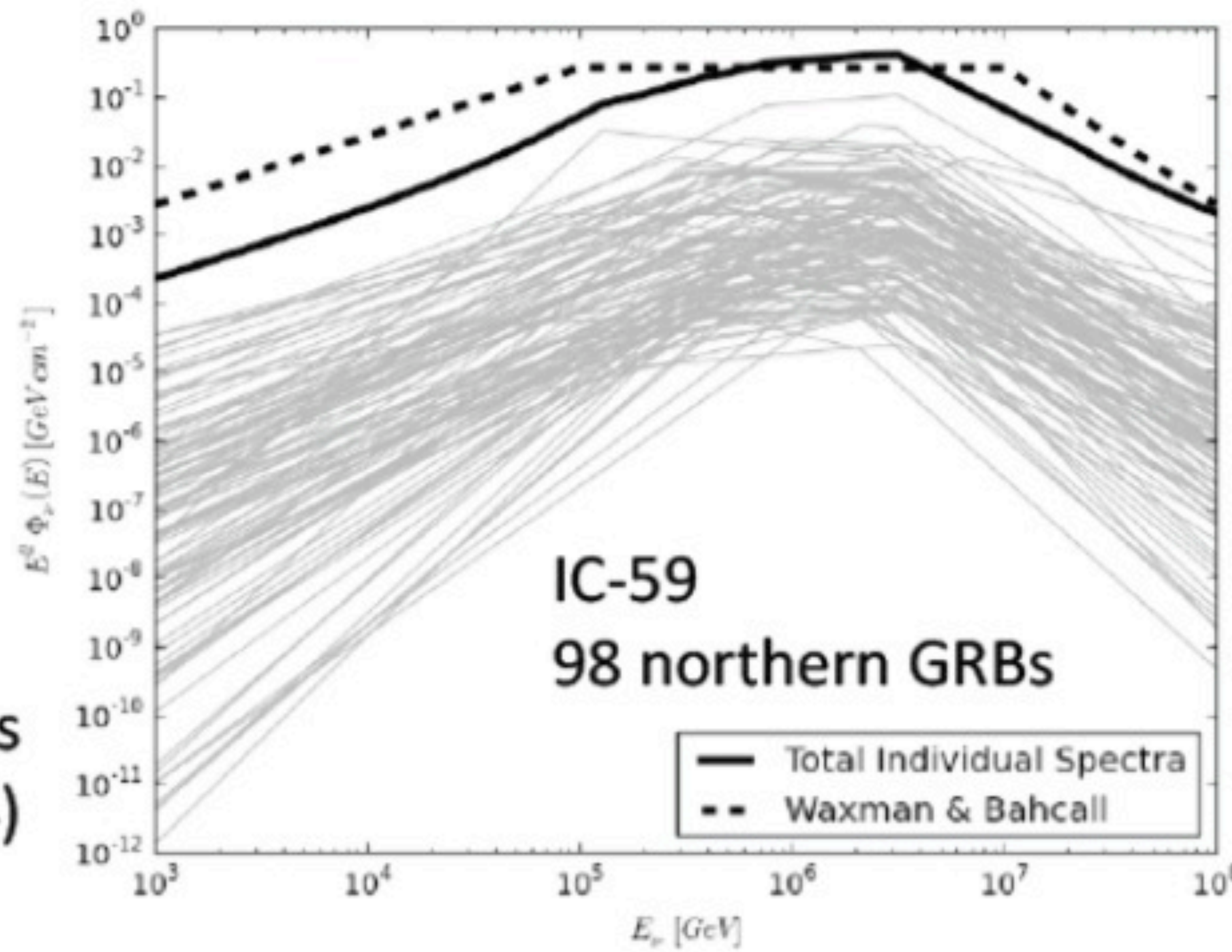
GRB Neutrinos



- Precursor (~100 s)
- Prompt
- Model Independent (24 h)
- Background (full year)

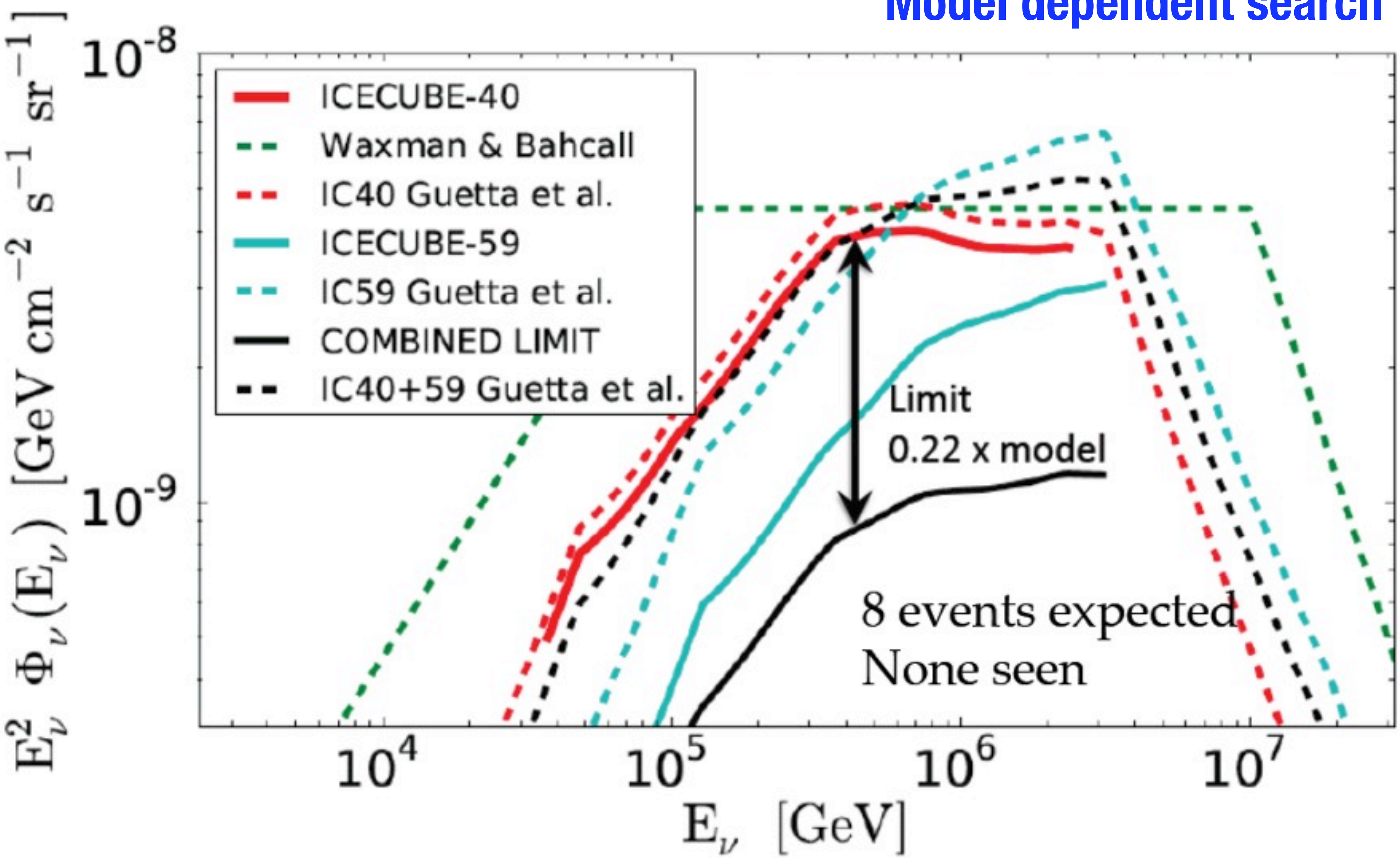
Very low background
One event can be significant

Individual modeling of GRBs
(Guetta et al. 2004)



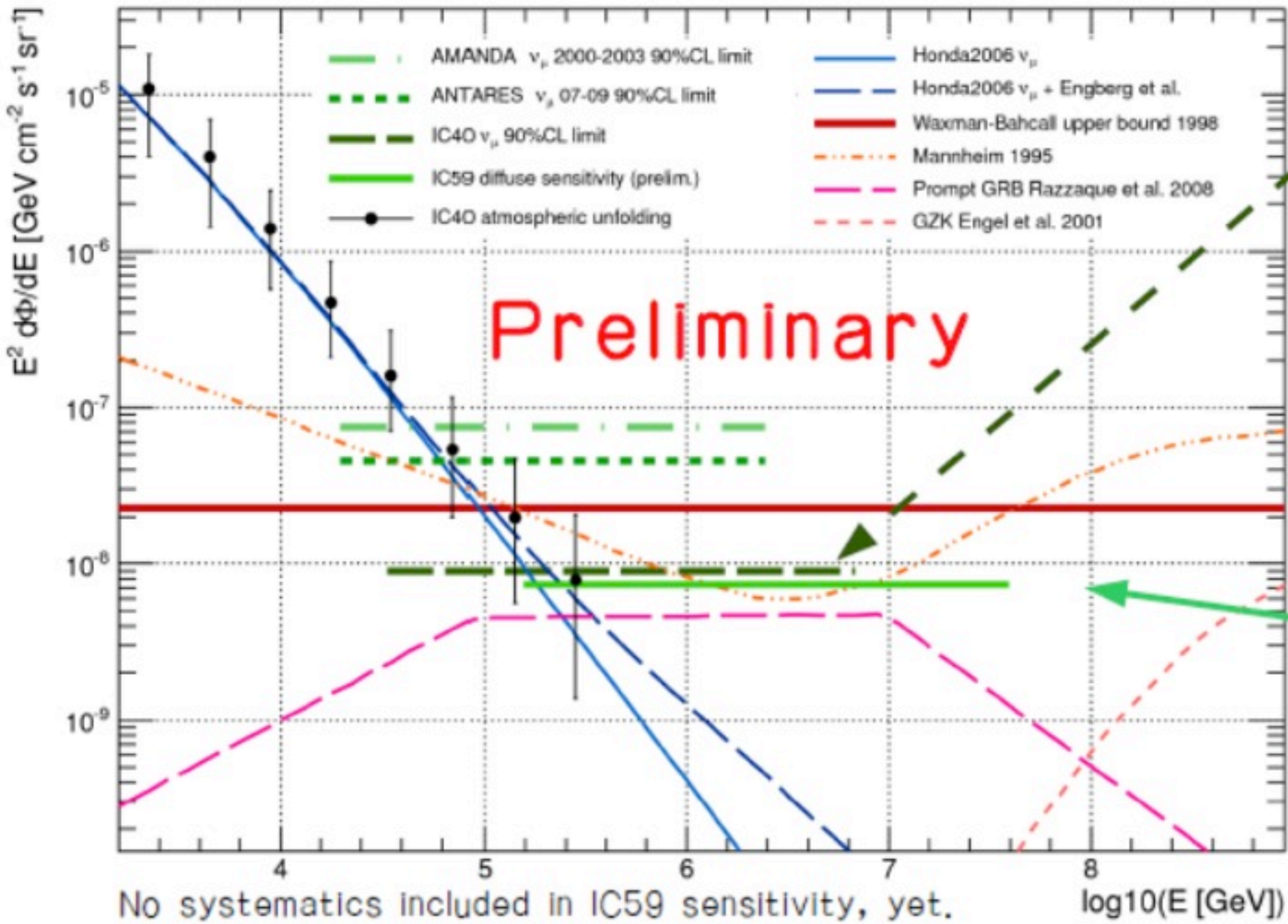
GRB: IC40, IC59 Results

Model dependent search



IC40 data started probing below WB flux.

Diffuse Astrophysical ν_μ Search



IC40
result

90%CL upper limit at

$8.9 * 10^{-9}$
GeV^{-1} cm^{-2} s^{-1} sr^{-1}

Factor 2.5 below the WB upper bound

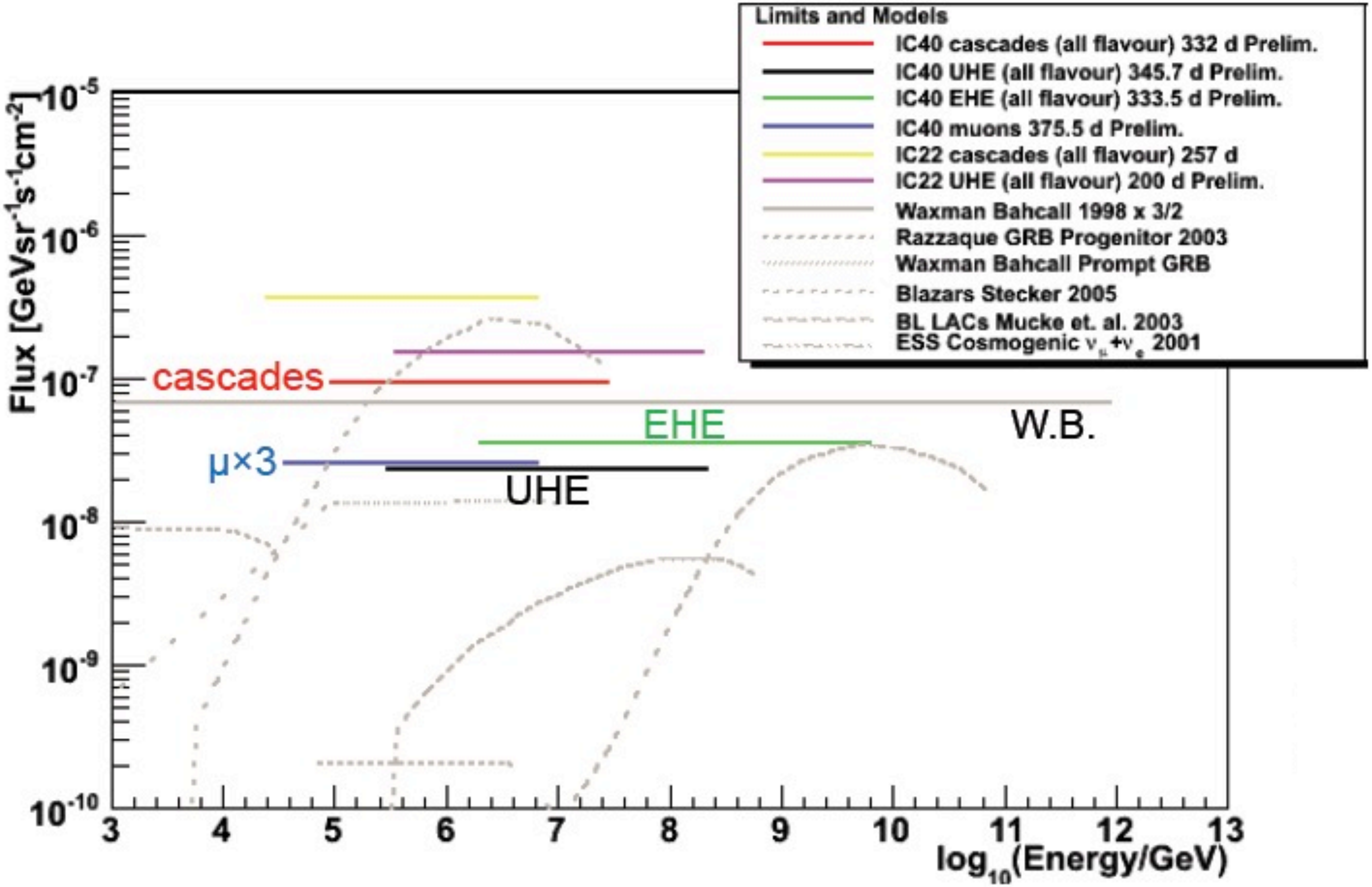
IC59
Prelim. sensitivity

$7.2 * 10^{-9}$
GeV^{-1} cm^{-2} s^{-1} sr^{-1}
(without neutrino knee)

~ factor 3 below the WB upper bound

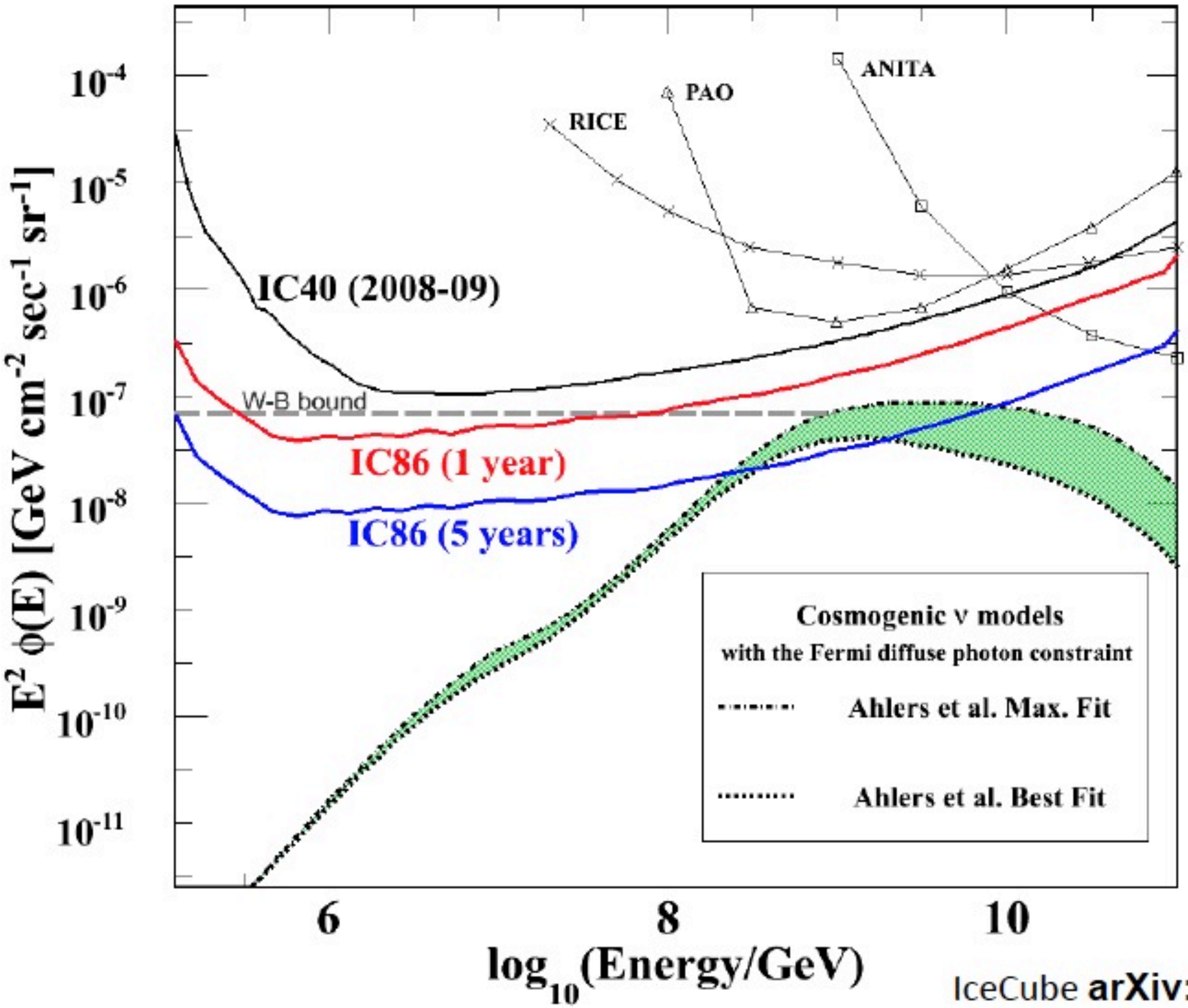
IC40 data started probing below WB bound.

Diffuse Astrophysical ν_{all} Search



IC40 data started probing below WB bound.

EHE Neutrino Flux



W&B with cosmological evolution: 24.5 events in IC86 3 yrs (4.5 in IC40)

GZK Max fit (M. Ahlers, et al., 2010): 4.8 events in IC86 3 yrs (w Fermi-LAT constrain)

IceCube **arXiv:1103.4250**

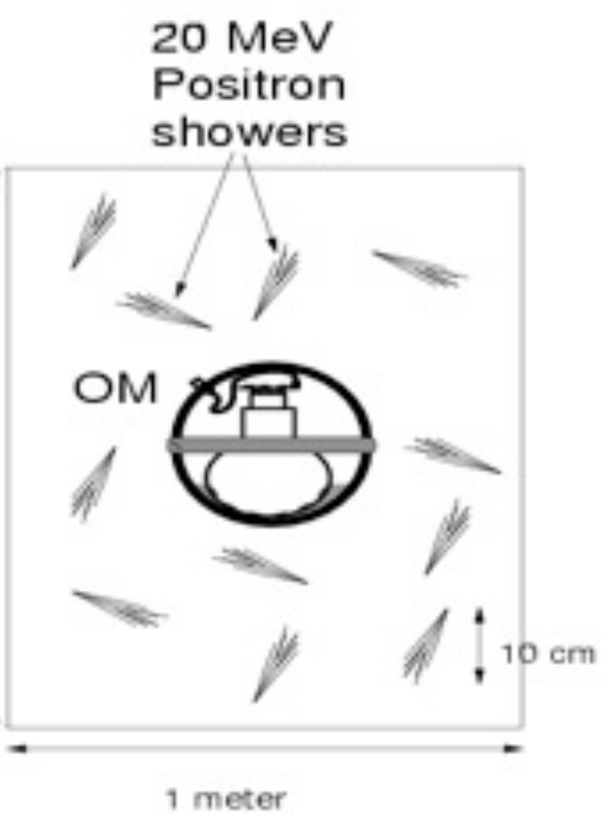
IC86 (5yr) will be sensitive to guaranteed neutrino flux from GZK.

SuperNova Neutrinos

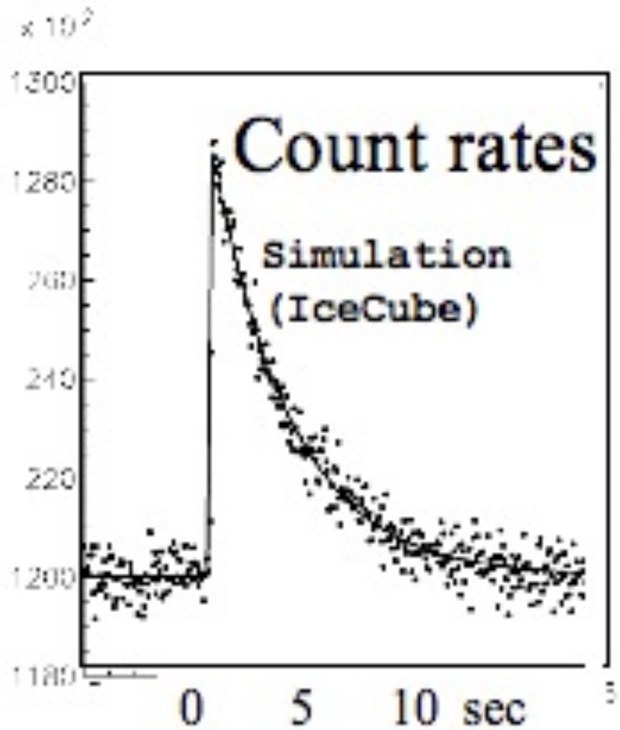
Bursts of low-energy (MeV) neutrinos from core collapse supernovae

$$\bar{\nu}_e + p \rightarrow n + e^+$$

The produced positron is emitted almost isotropically

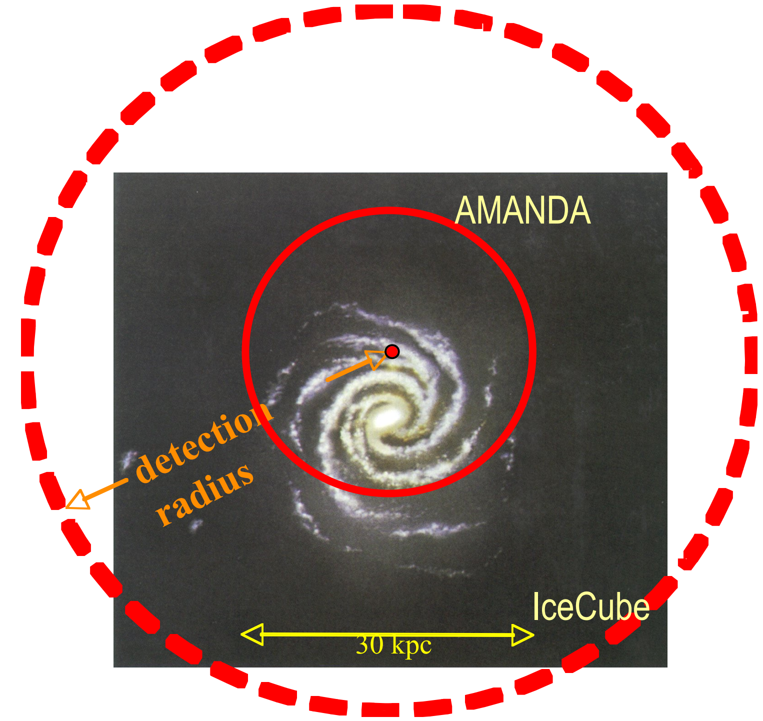


O(10cm) long tracks

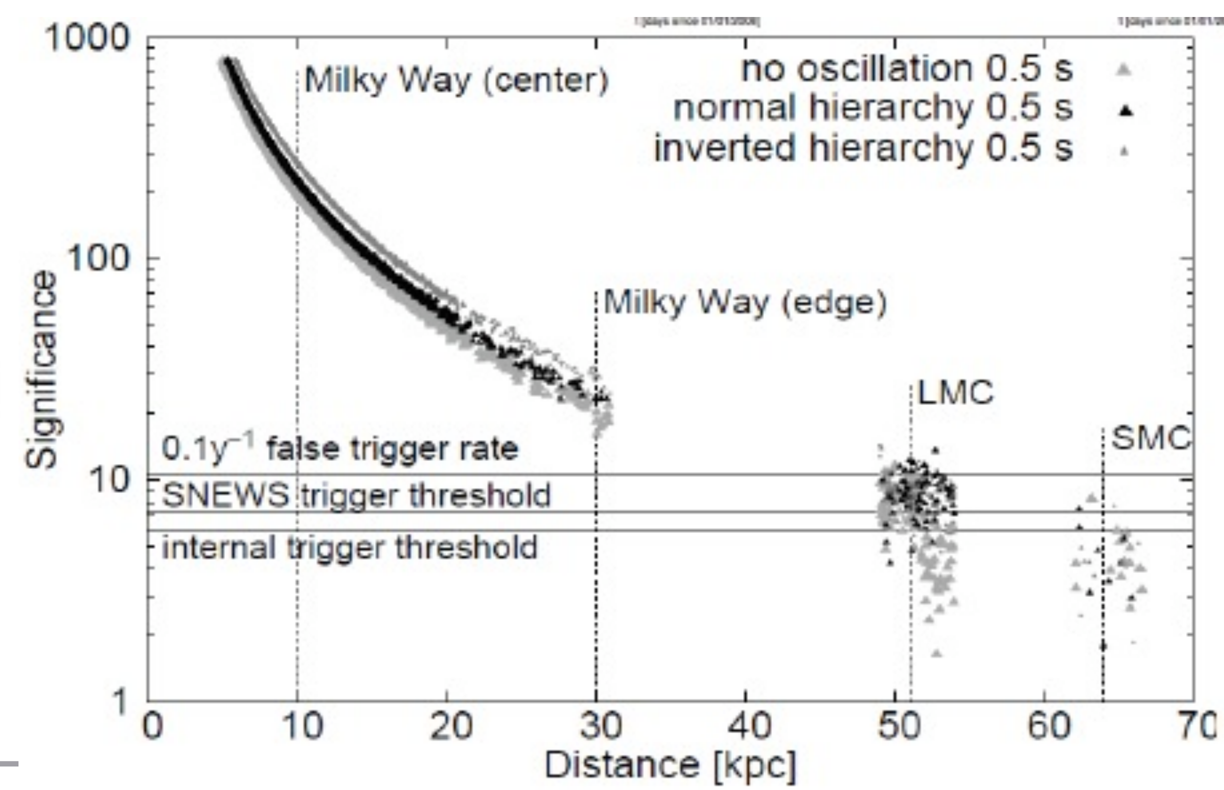


Rate increase on top of dark noise

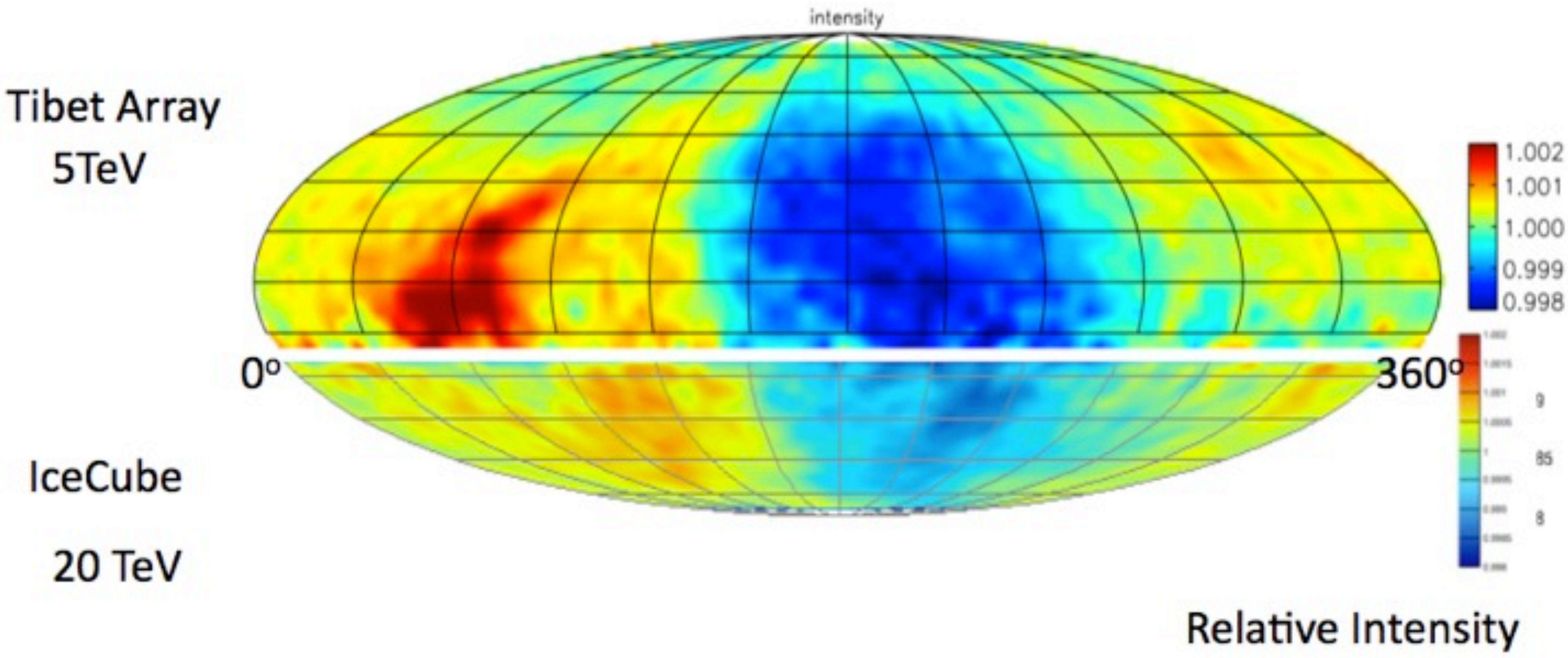
SNEWS (SuperNova Early Warning System) is a collaborative effort among Sper-K, SNO, LVD, KamLand, BooNE, and gravitational exp., etc.



- AMANDA sees 90% of the galaxy
- IceCube will see out to the LMC (Large Magellanic Cloud, ~50 kpc)



Cosmic Ray Anisotropy



*** Cause of anisotropy is not known. Some speculations are:**

-- Isolated nearby and recent SNR

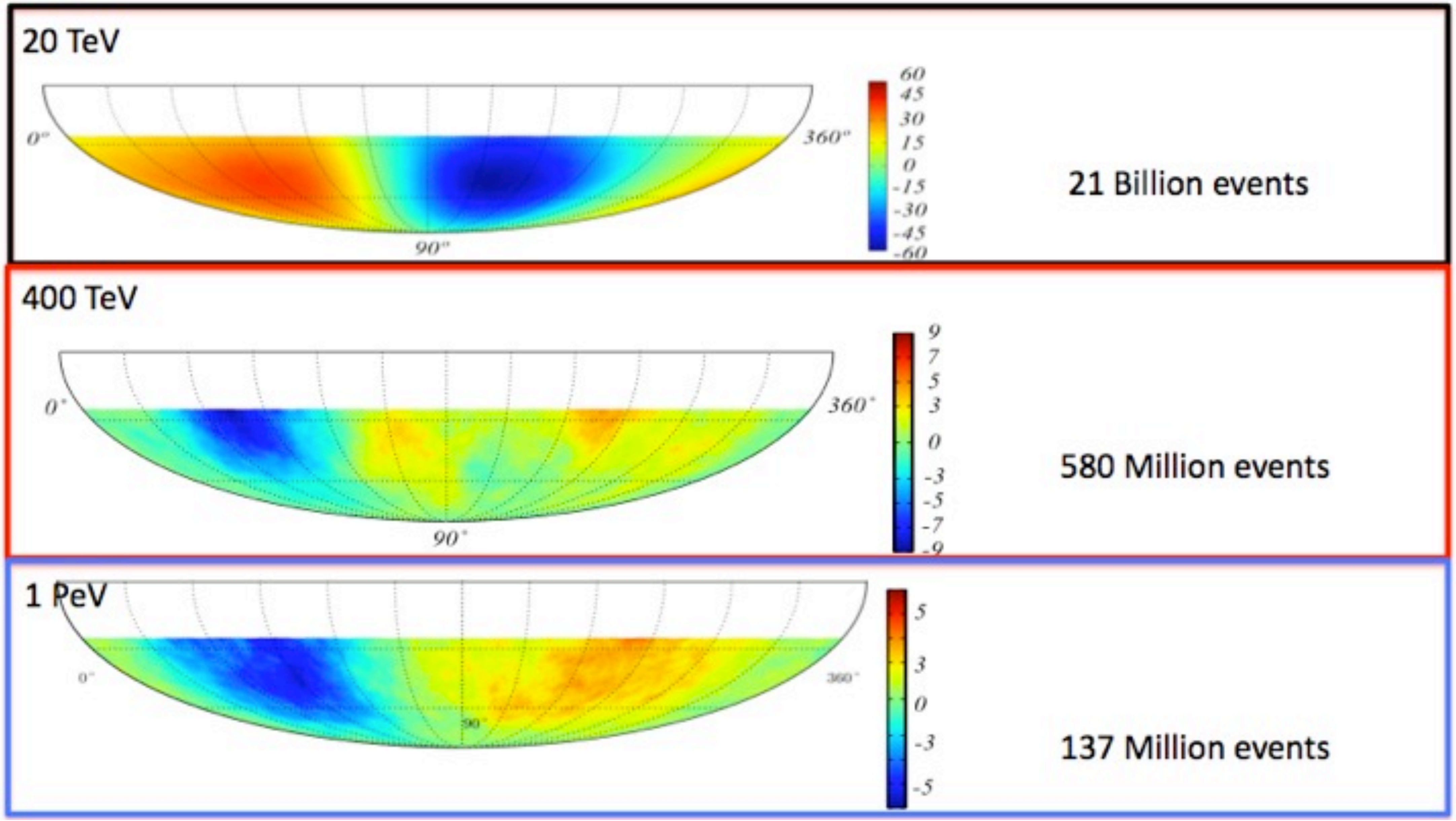
-- Configuration of magnetic field in or near solar system

*** Further studies of anisotropy are on-going.**

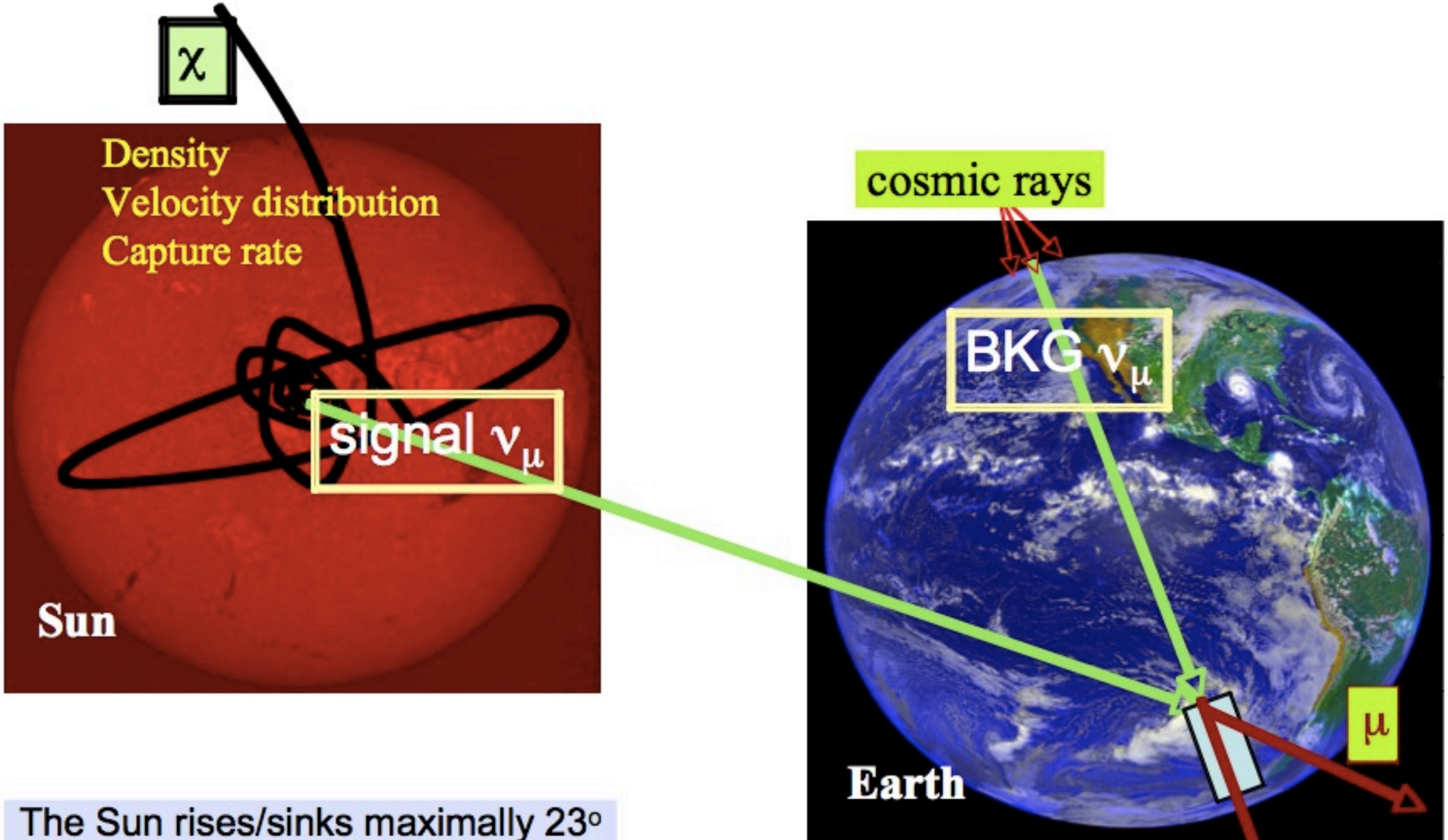
Cosmic Ray Anisotropy: Energy dependency

* This weird energy dependency has not been understood at all!

IC59 Data (2009-10)



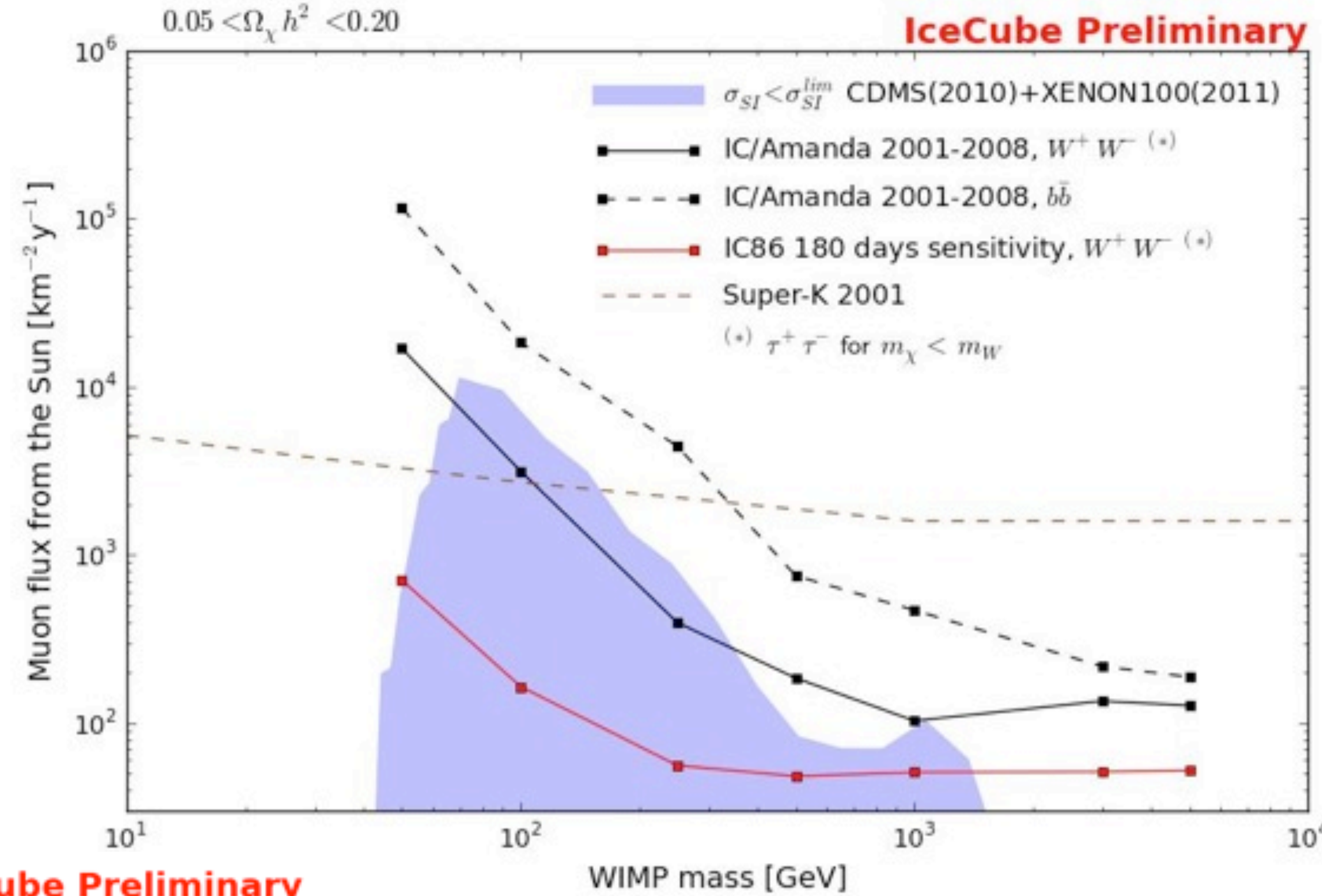
Indirect Dark Matter Search: Method



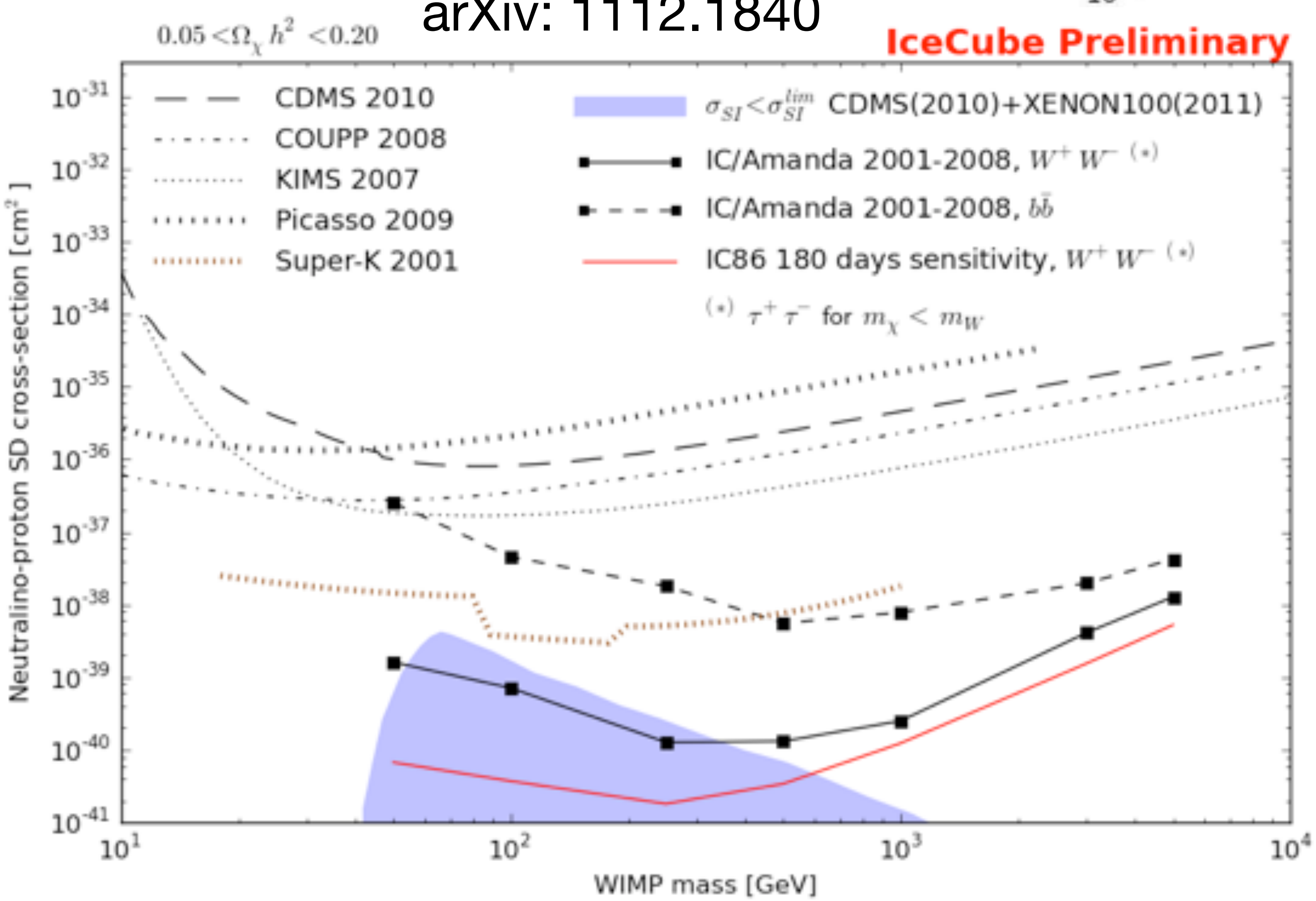
The Sun rises/sinks maximally 23° above/below the horizon at the south pole.

look for excess ν_μ
In the Sun direction

Indirect DM: Sun WIMP



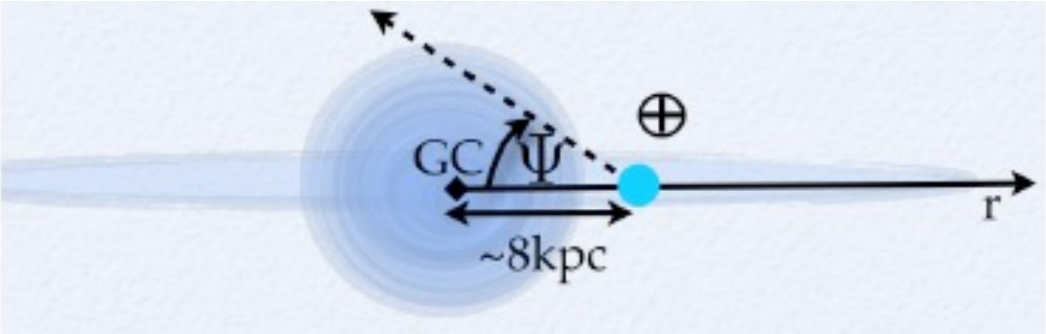
arXiv: 1112.1840



- Combined data of IceCube and AMANDA (2001-2008) started probing SUSY parameter space unexplored by direct DM experiments.

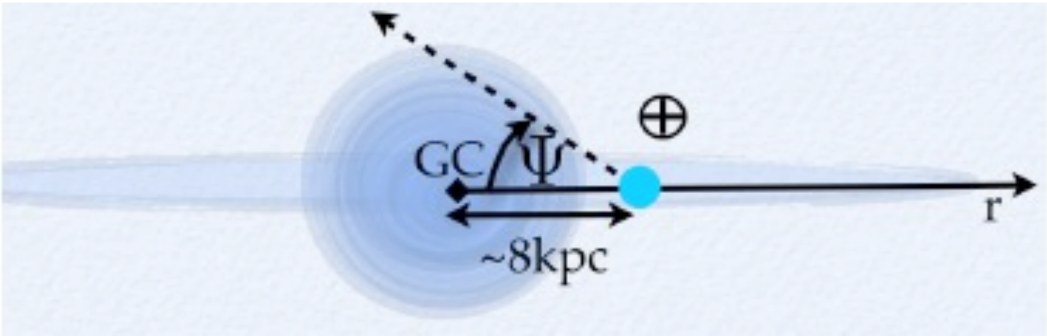
➡ IC86 alone will do much better job!

Indirect DM: Galactic Center/Halo



➡ **Look for excess of events in on-source region w.r.t. off-source region.**

Indirect DM: Galactic Center/Halo



➡ **Look for excess of events in on-source region w.r.t. off-source region.**

arXiv: 1101.3349

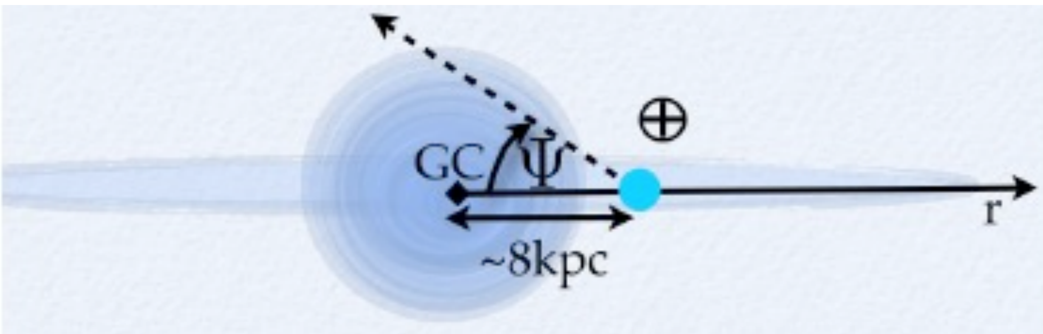
IC22 (Halo analysis: 275 days)

obs. on-source: 1367 events
obs. off-source: 1389 events
(atm. nu dominant)

IC40 (GC analysis: 367 days)

obs. on-source: 798842 events
obs. off-source: 798819 events
(atm. mu dominant)

Indirect DM: Galactic Center/Halo



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

arXiv: 1101.3349

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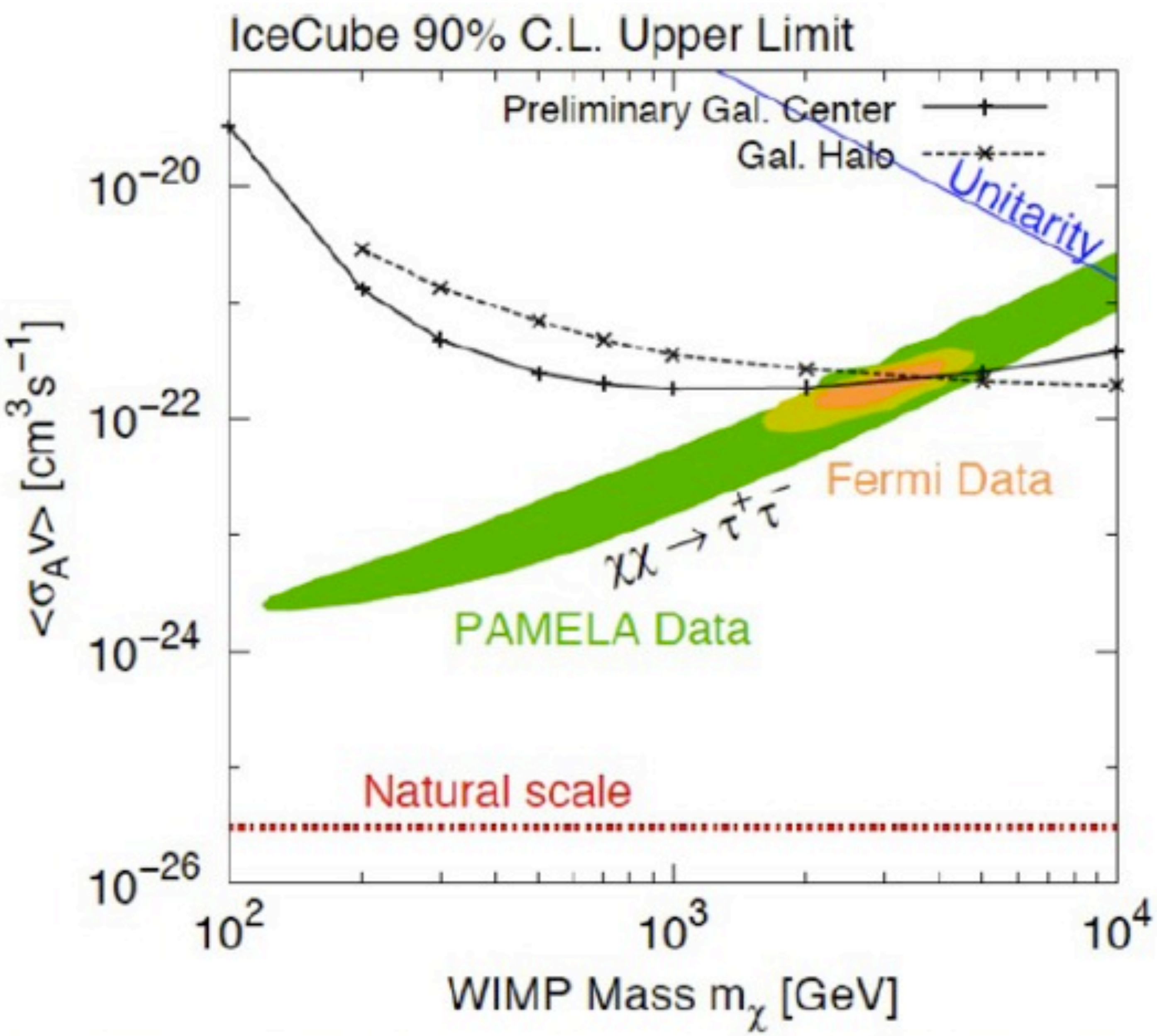


Magnetic Monopoles

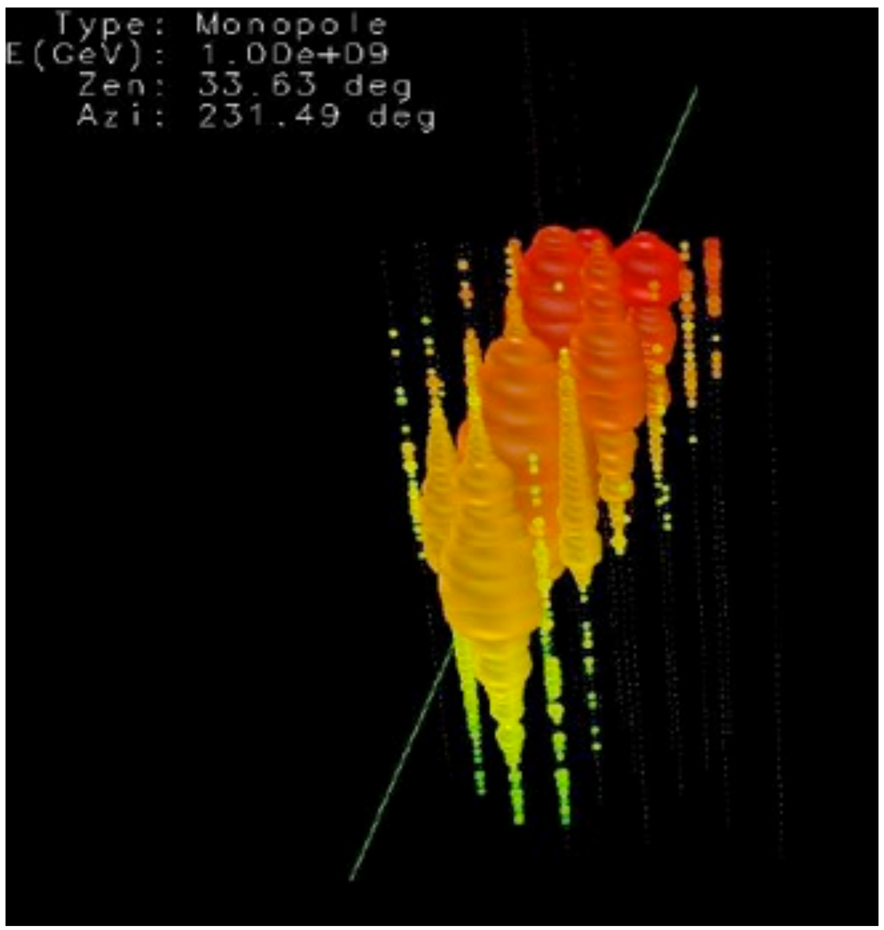
- **Hypothetical particle: Dirac postulated it in 1931 (symmetry in E&M).**
  -- If MP exists $\overset{\rightarrow}{\underset{?}{\leftarrow}}$ then electric charge is quantized.
  -- Charge: $g_D = (n/2)*(e/\alpha)$, where n = 1, 2, 3, …
- **GUT monopoles (non-relativistic MPs):**
  -- 10^{16} - 10^{17} GeV GeV
  -- produced during phase transition of early universe.
- **(Sub-)Relativistic monopoles:**
  -- 10^{5} - 10^{15} GeV
  -- produced in later stage of the phase transition

- $MP + p \rightarrow MP + e^{+} + \pi^{0}(2\gamma) \rightarrow$ *em shower*

➡ **Monopole catalysis of nucleon decay: $\sigma \sim 10^{-56}\mathrm{cm}^2$ (negligible) however, enhancement by RubaKov-Callan mechanism where σ ~ becomes strong interaction level**

Relativistic Monopole Limits

Relativistic monopole will leave very bright track: ~8300 x μ



Monopole simulation (IC22)

Relativistic Monopole Limits

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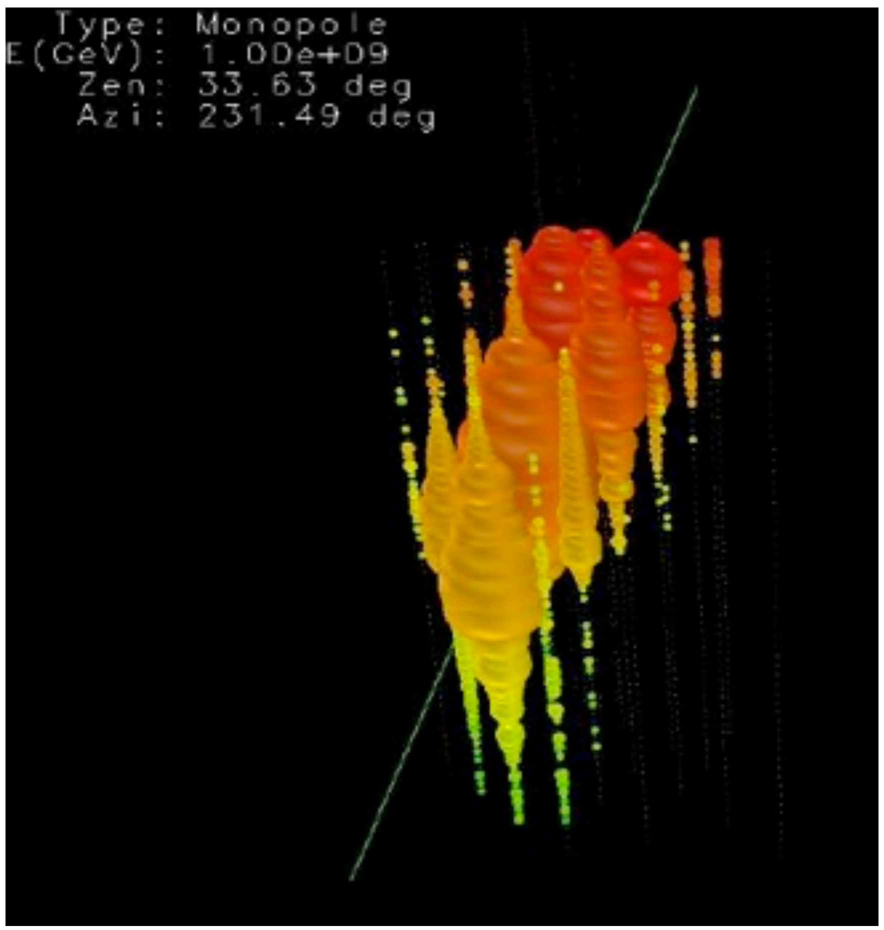
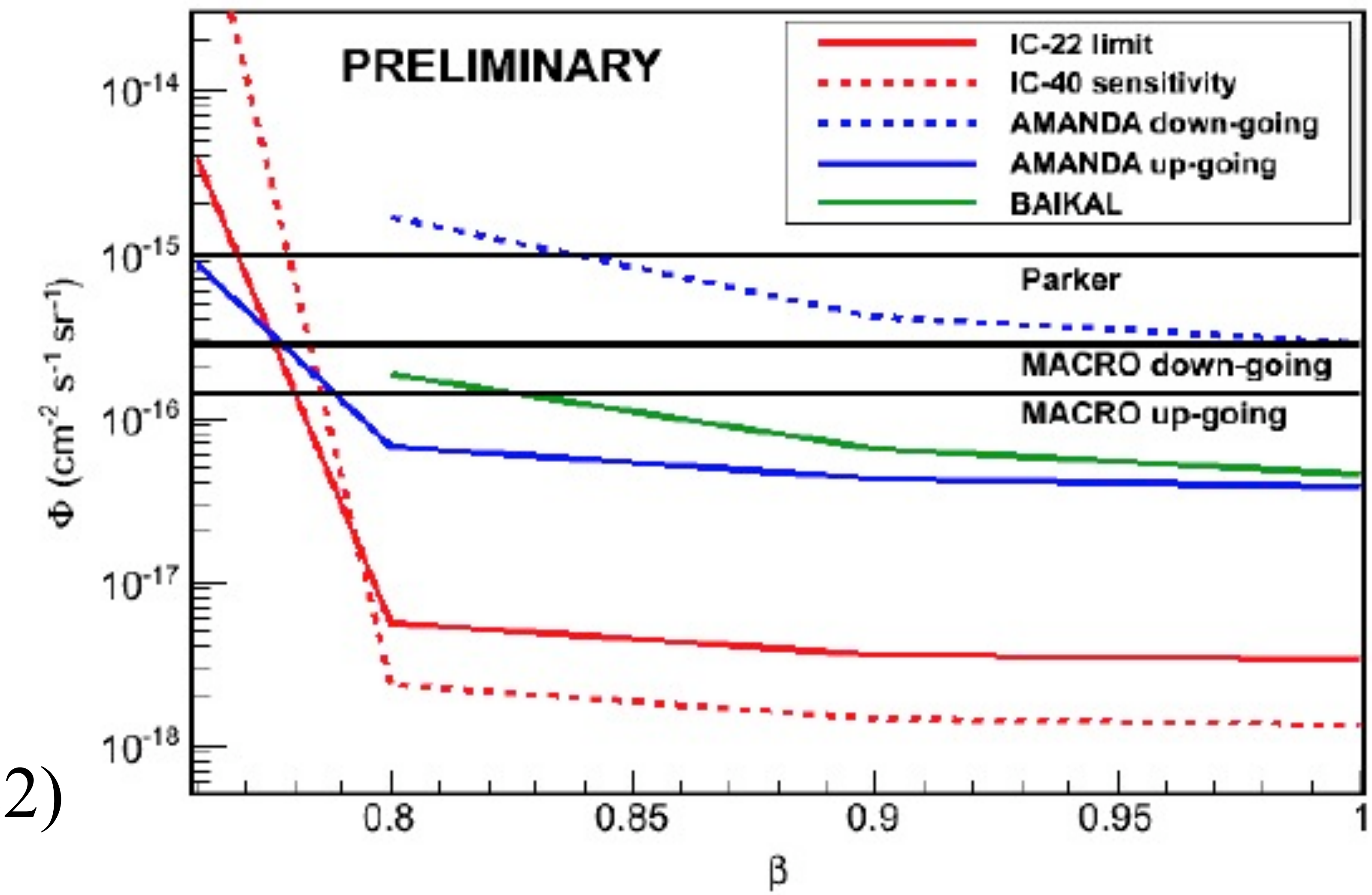


Monopole simulation (IC22)



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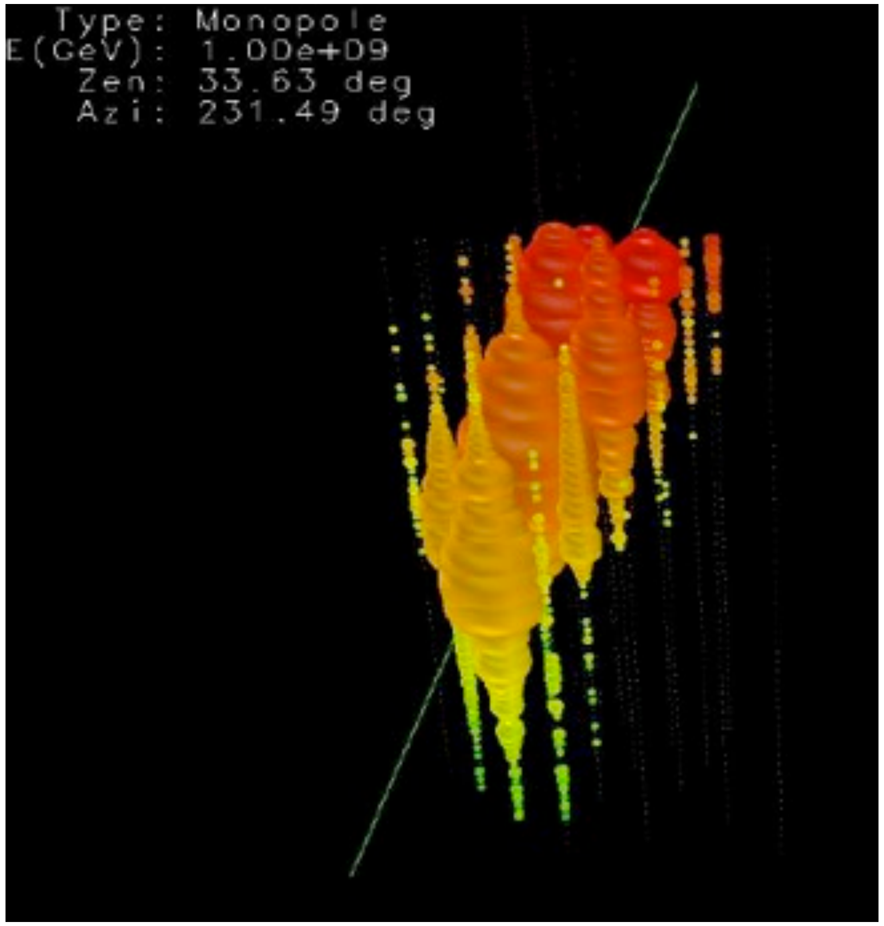
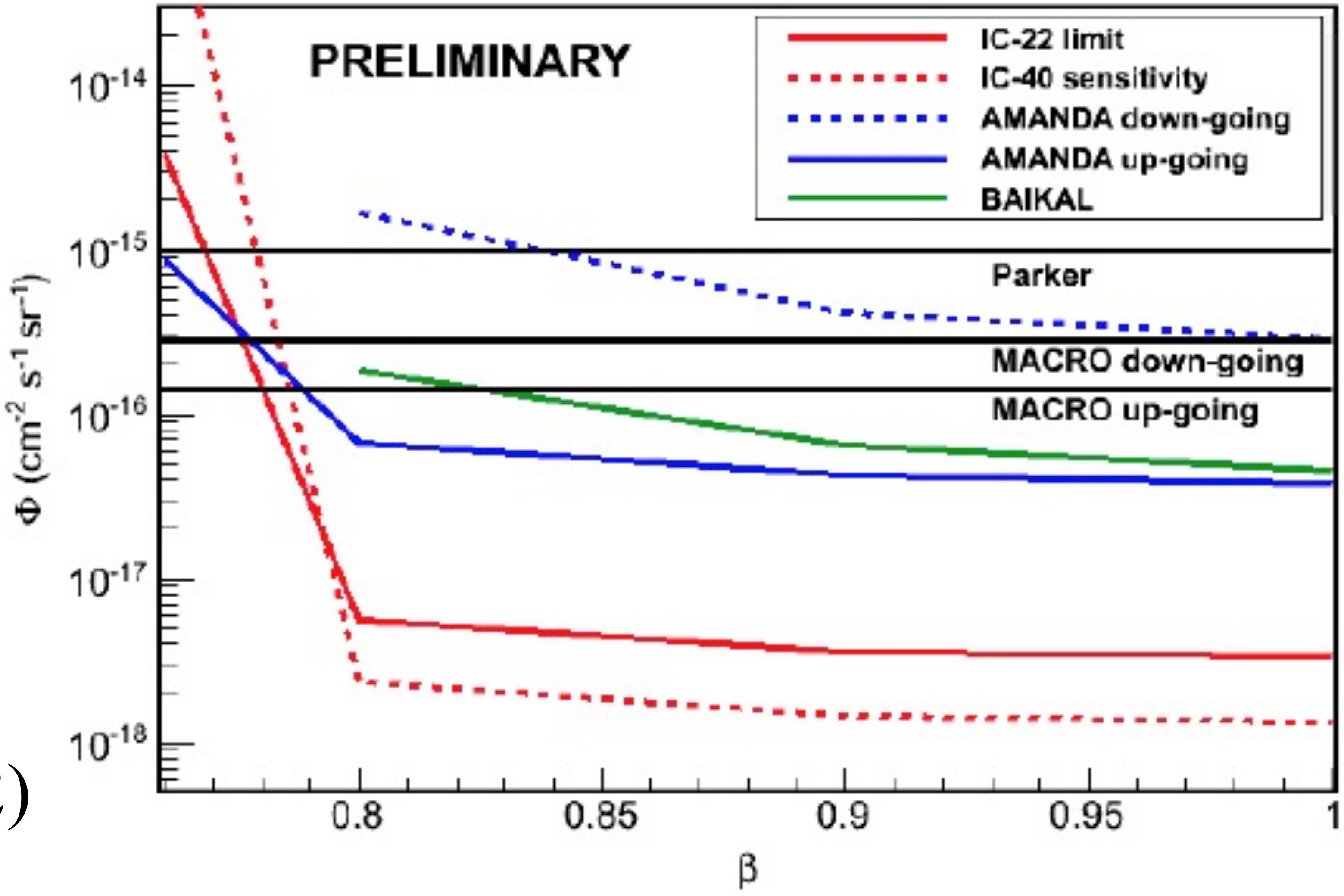


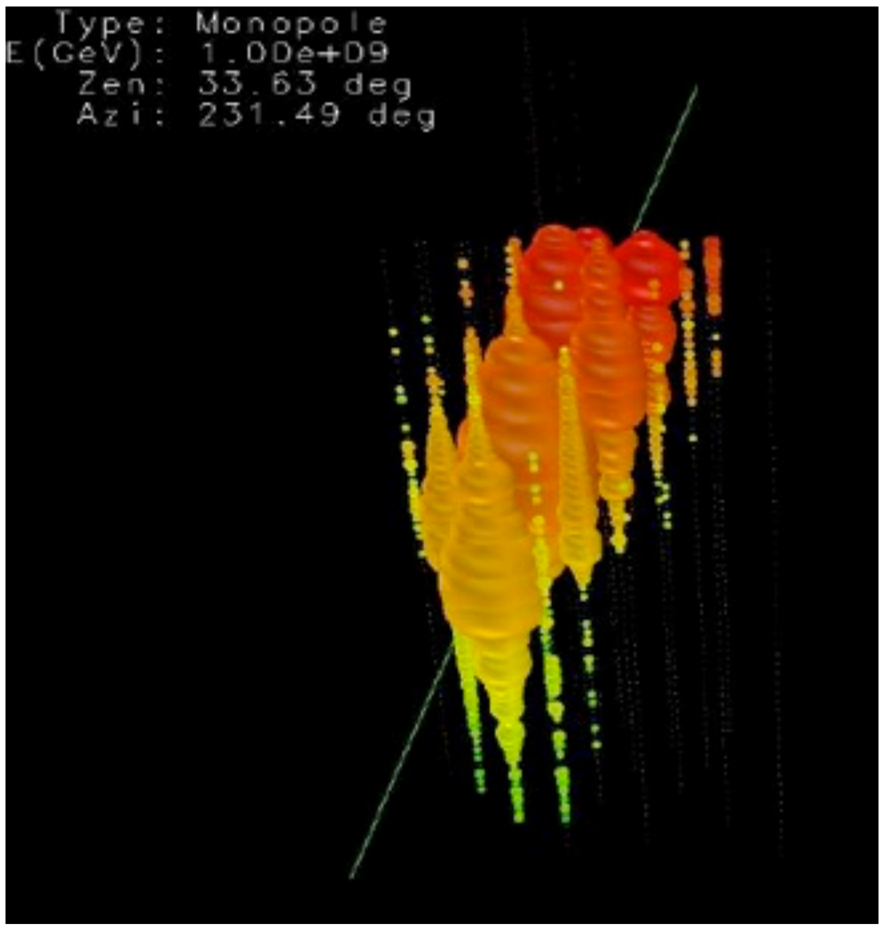
Monopole simulation (IC22)



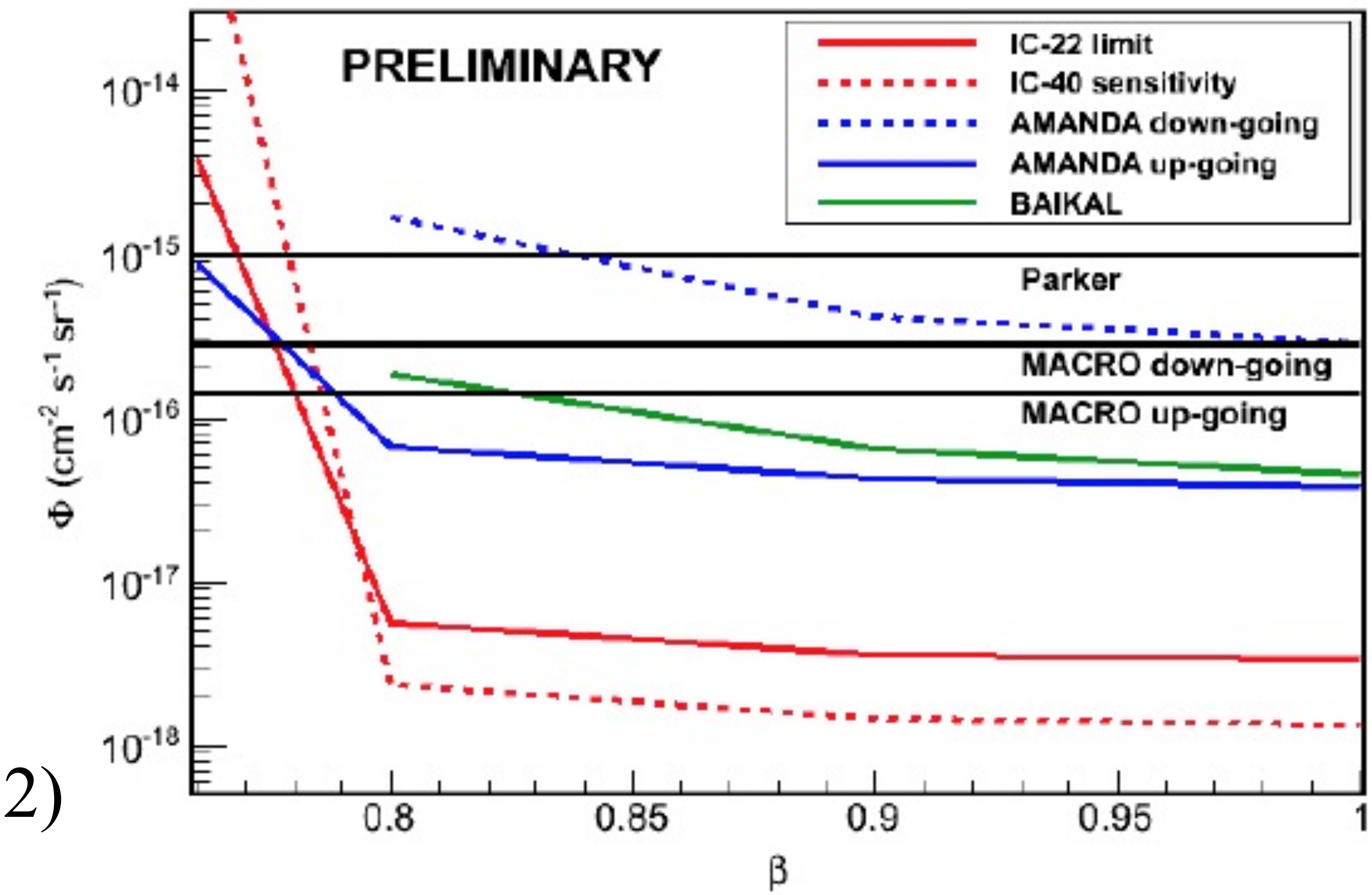
↪ IC86 data will push the flux limit down to ~10^{-19}cm^{-2}s^{-1}sr^{-1}.

Relativistic Monopole Limits

Relativistic monopole will leave very bright track: **~8300 x μ**



Monopole simulation (IC22)



** GUT monopole search is also on-going with IC59 data.

↳ IC86 data will push the flux limit down to $\sim 10^{-19} cm^{-2} s^{-1} sr^{-1}$.

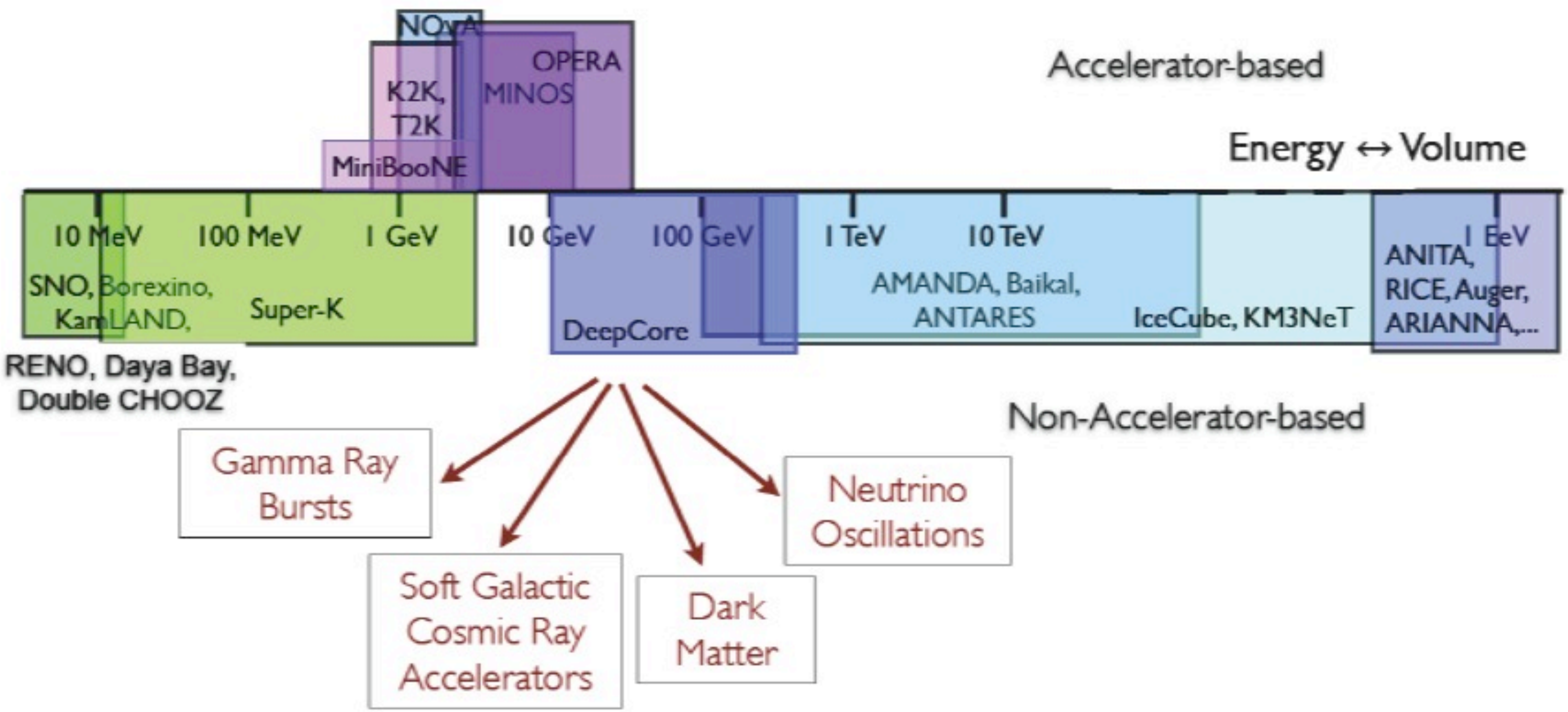
Towards Lower Energy Physics!

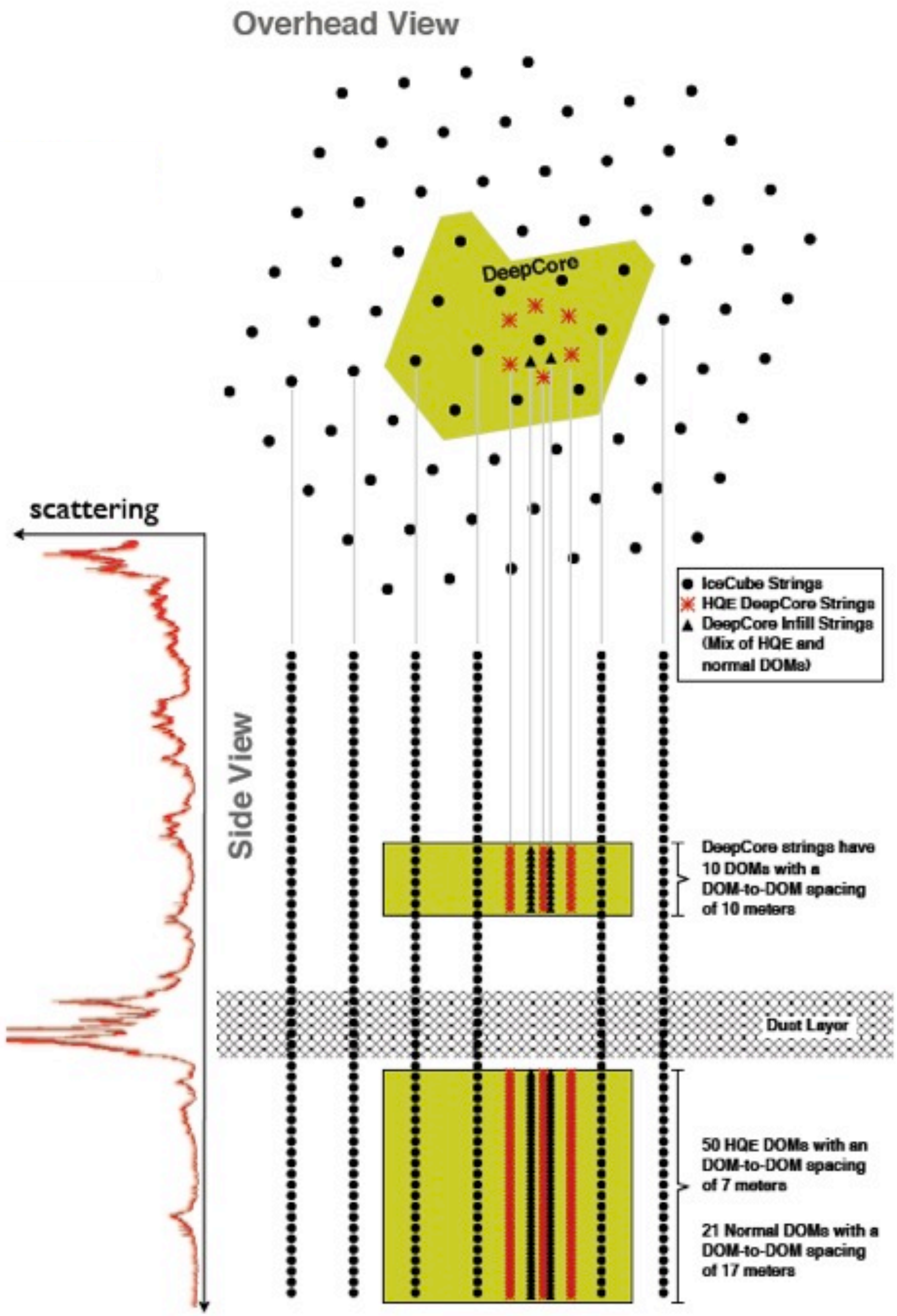
- **DeepCore:** already deployed & taking data
- **PINGU:** possible shorter term future project

  Precision **I**ceCube **N**ext **G**eneration **U**pgrade
- **MICA:** possible longer term future project

  Multi-megaton **I**ce **C**herenkov **A**rray

Neutrino Detectors & Energy Coverage





DeepCore

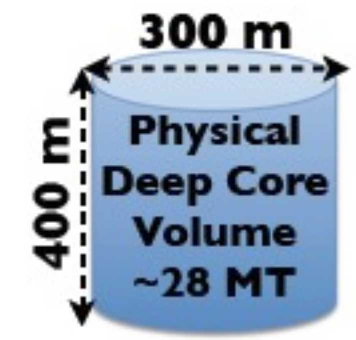
- **Spec:**
- ~30 Mton ice
- Energy: ~10 GeV threshold
- atm. ν: O(200 k) / year
- 4π detector:
  -- veto surrounding DeepCore,
  -- explore southern sky, GC

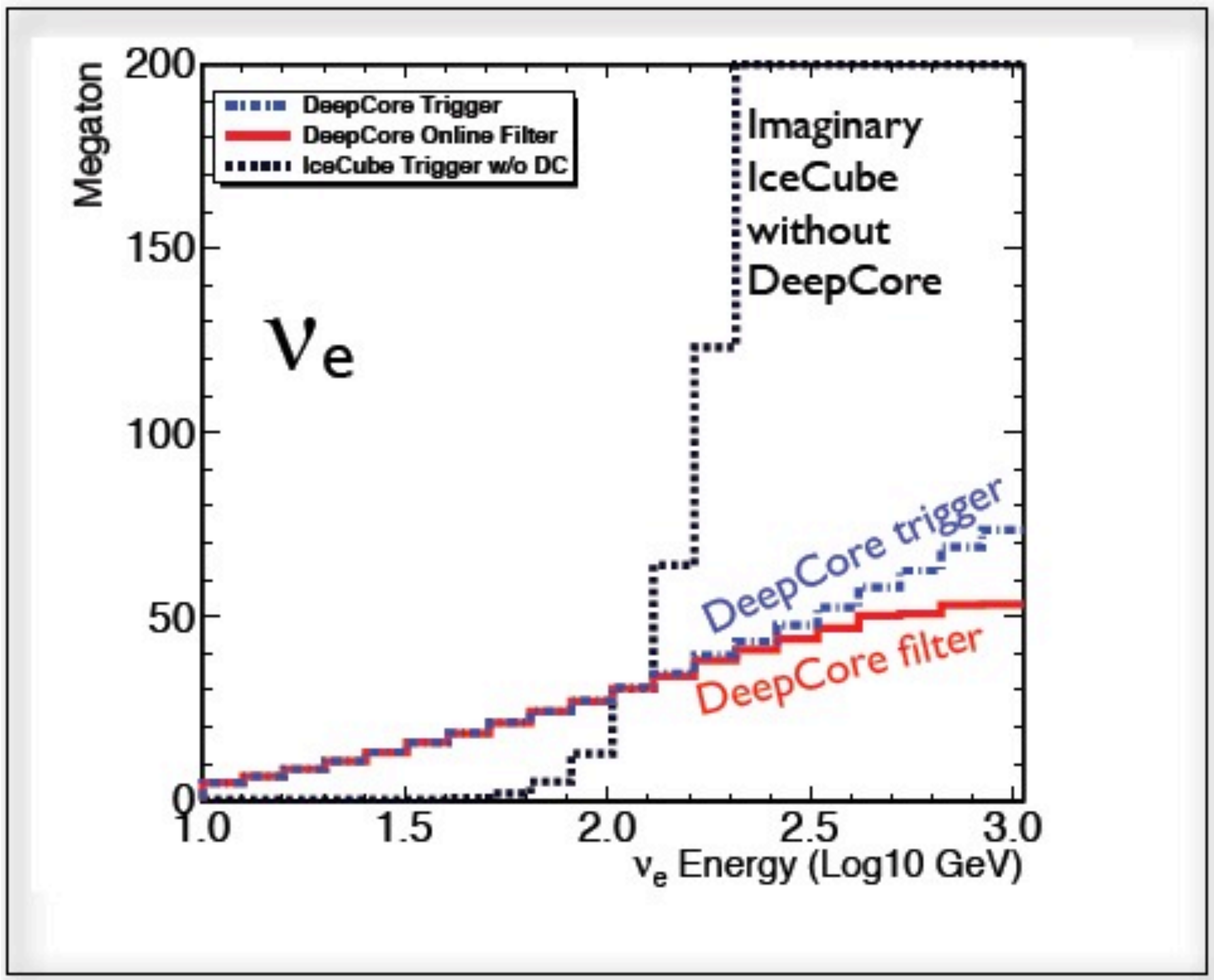
- **Geometry:**
- 8 (special) + 12 (IceCube) strings
- 72 m horizontal spacing
  (42 m spacing for 6 strings)
- 7 m vertical spacing

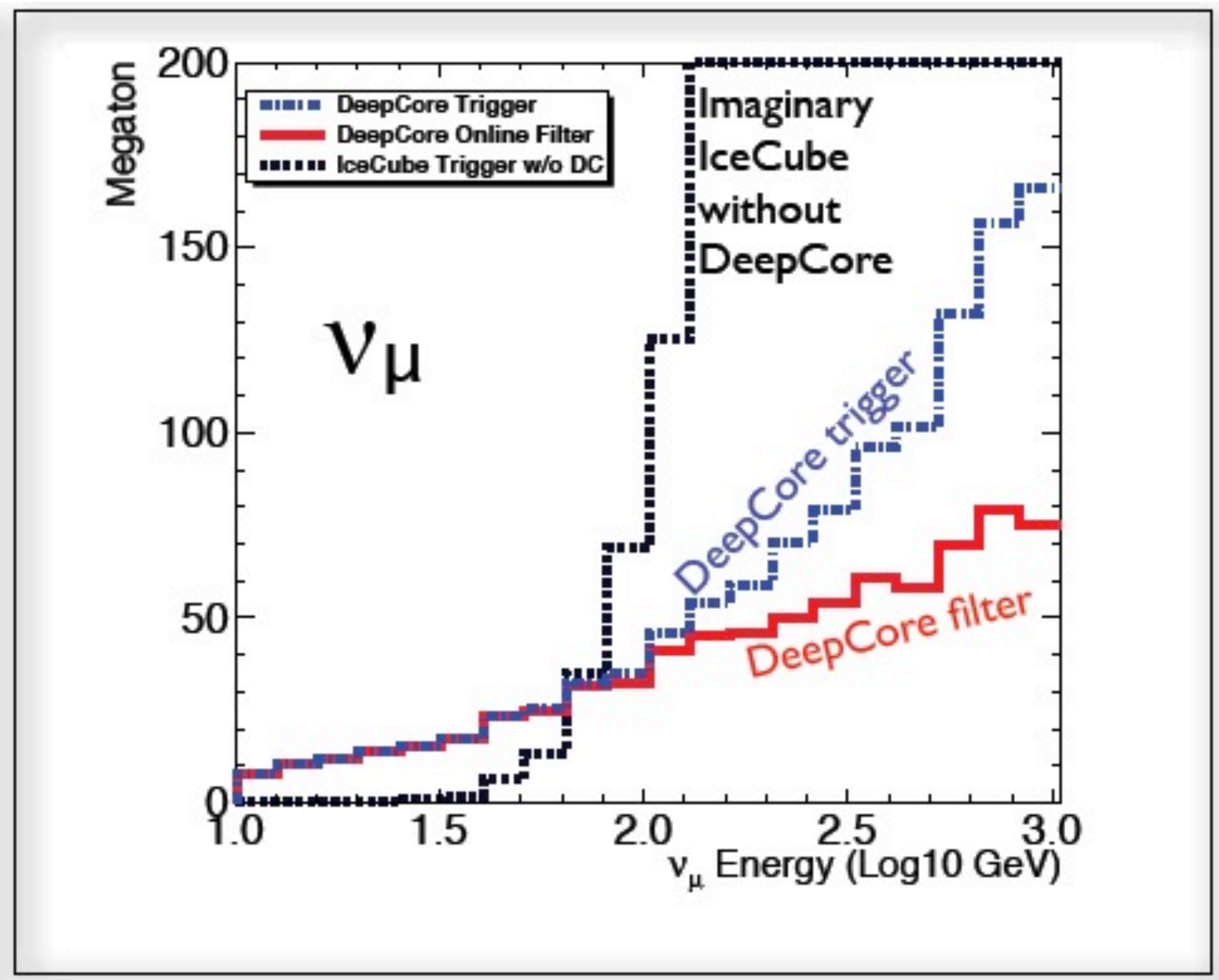
- **PMTs:**
- ~40% higher Q.E. PMTs
- ~5x higher effective photocathode density (but 0.1% coverage)

DeepCore: Effective Volume

$$V_{eff} = \frac{N_{acc}}{N_{gen}} V_{gen}$$

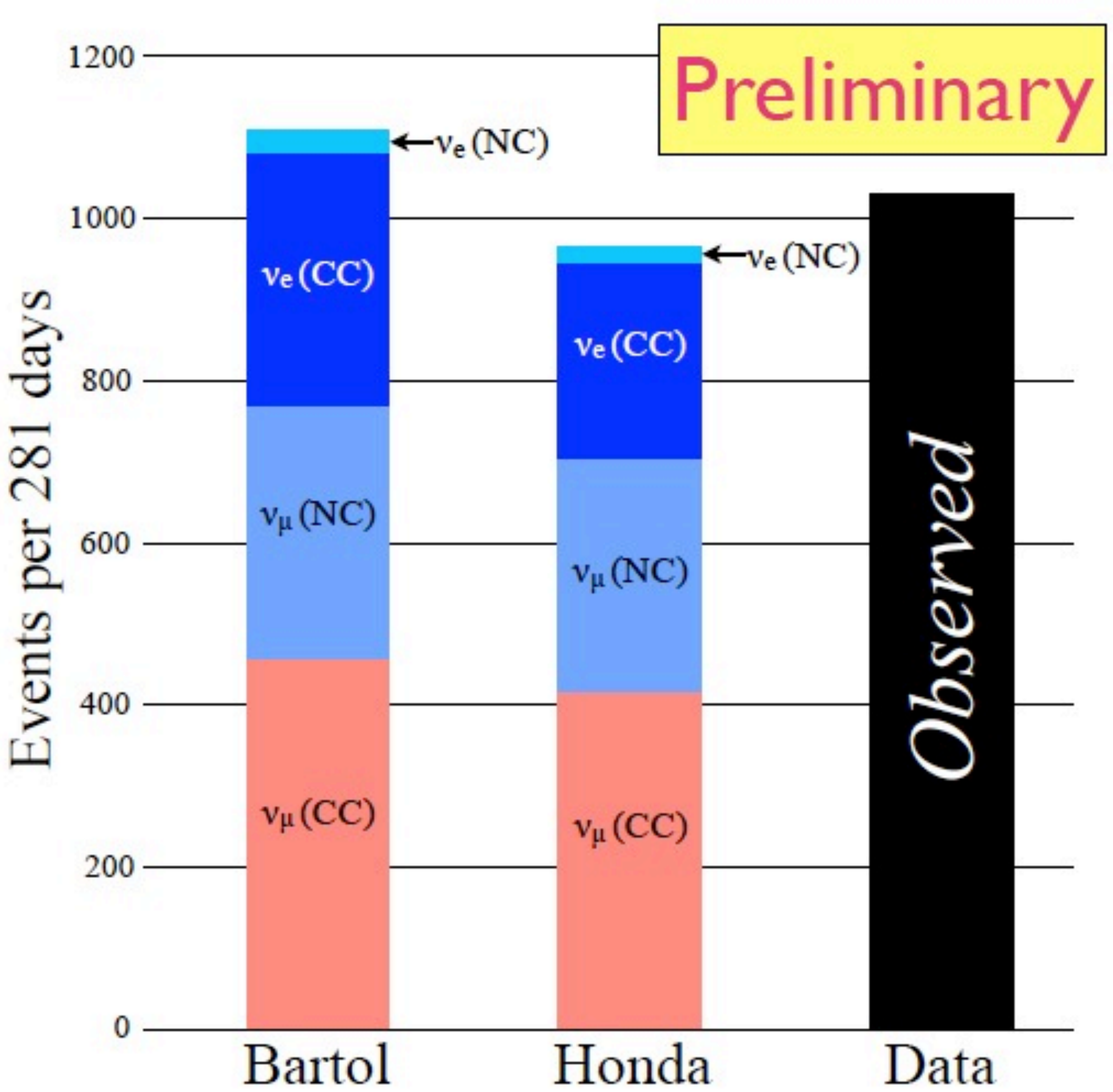






Below ~100 GeV, DeepCore improves V_{eff} significantly!

DeepCore: Cascade Search



- Search for atmospheric ν induced cascade events:
  ν_e CC + ν_x NC

- **Final sample:**

  -- 1029 events

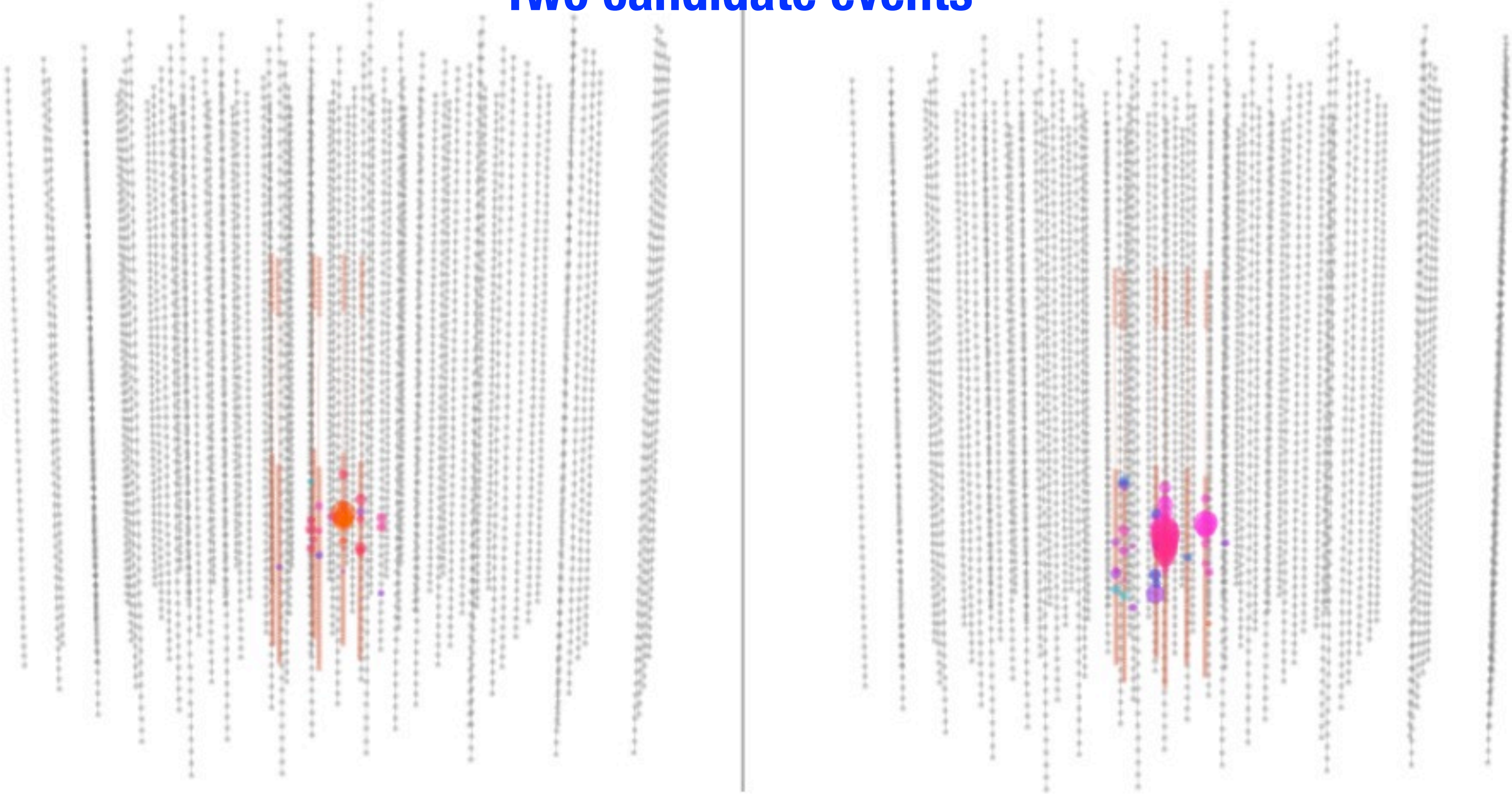
  -- 59% cascade + 41% ν_μ CC

  -- ~5x enrichment of cascade signal w/o reconstruction

  -- ~10^8x reduction of atm. muon background (Signal/Noise = 100/1)

DeepCore: Cascade Candidate Events

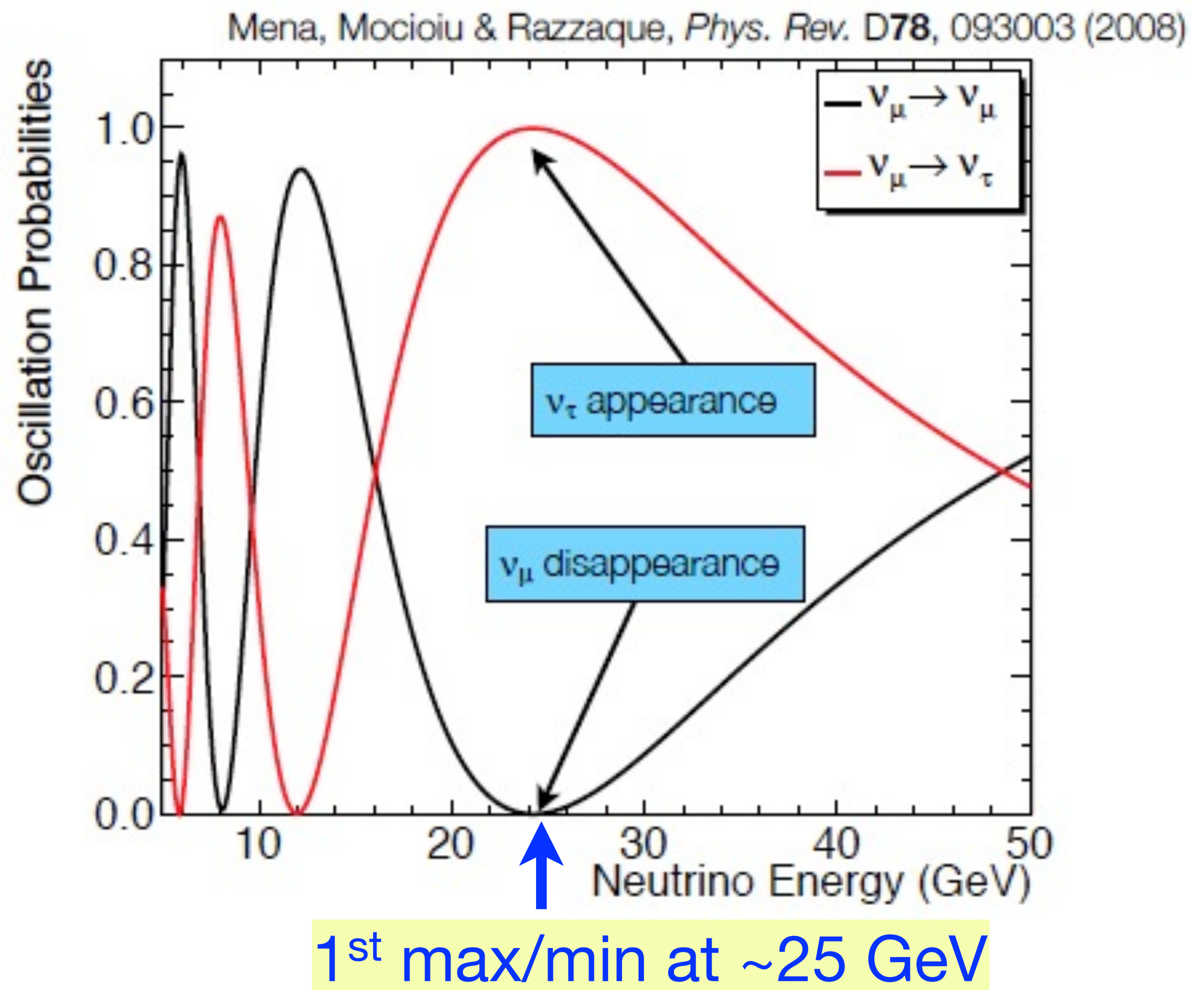
Two candidate events

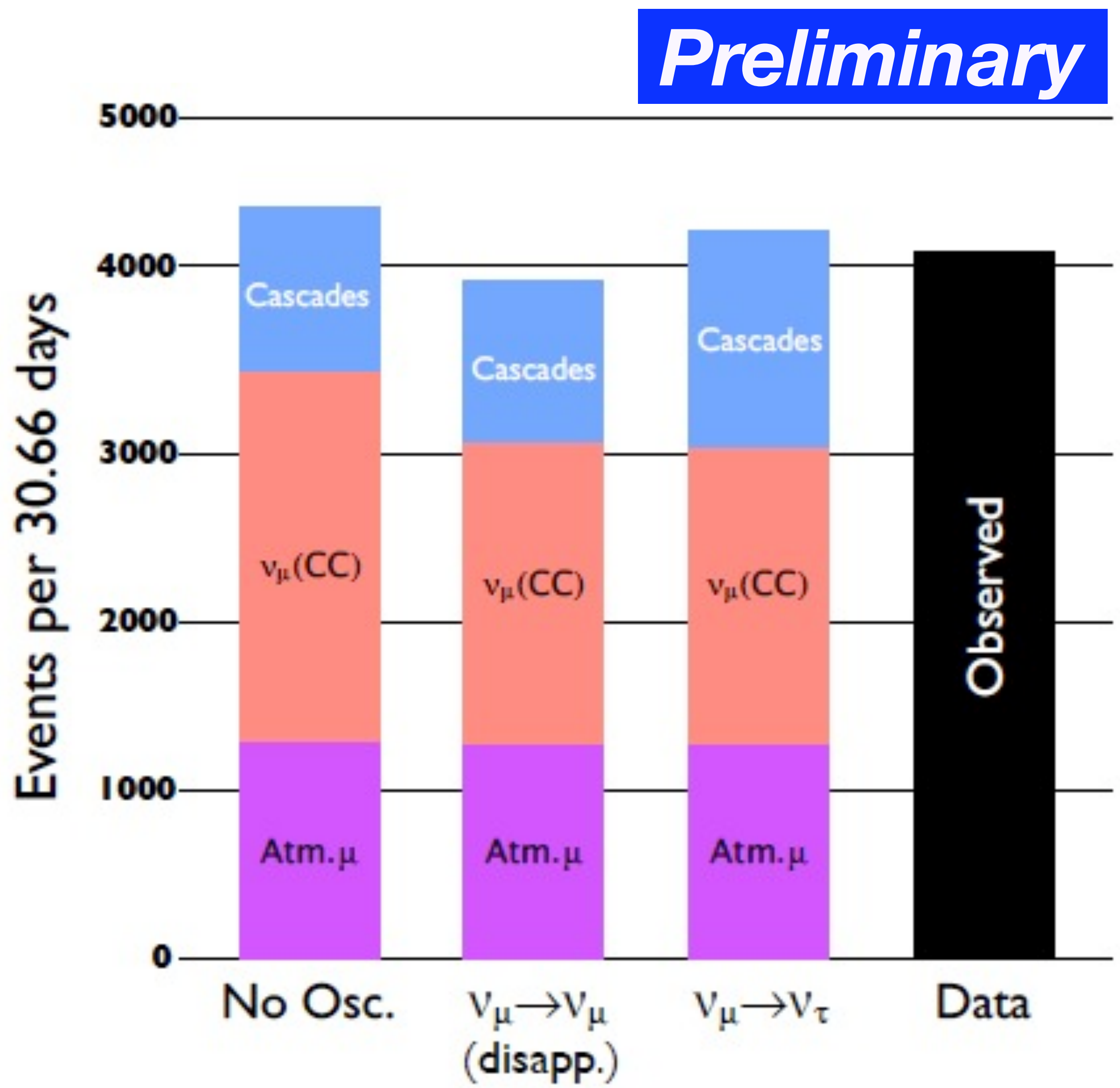


** Standard hit cleaning algorithm removed all noise hits in rest of detector.

DeepCore: ν Oscillation

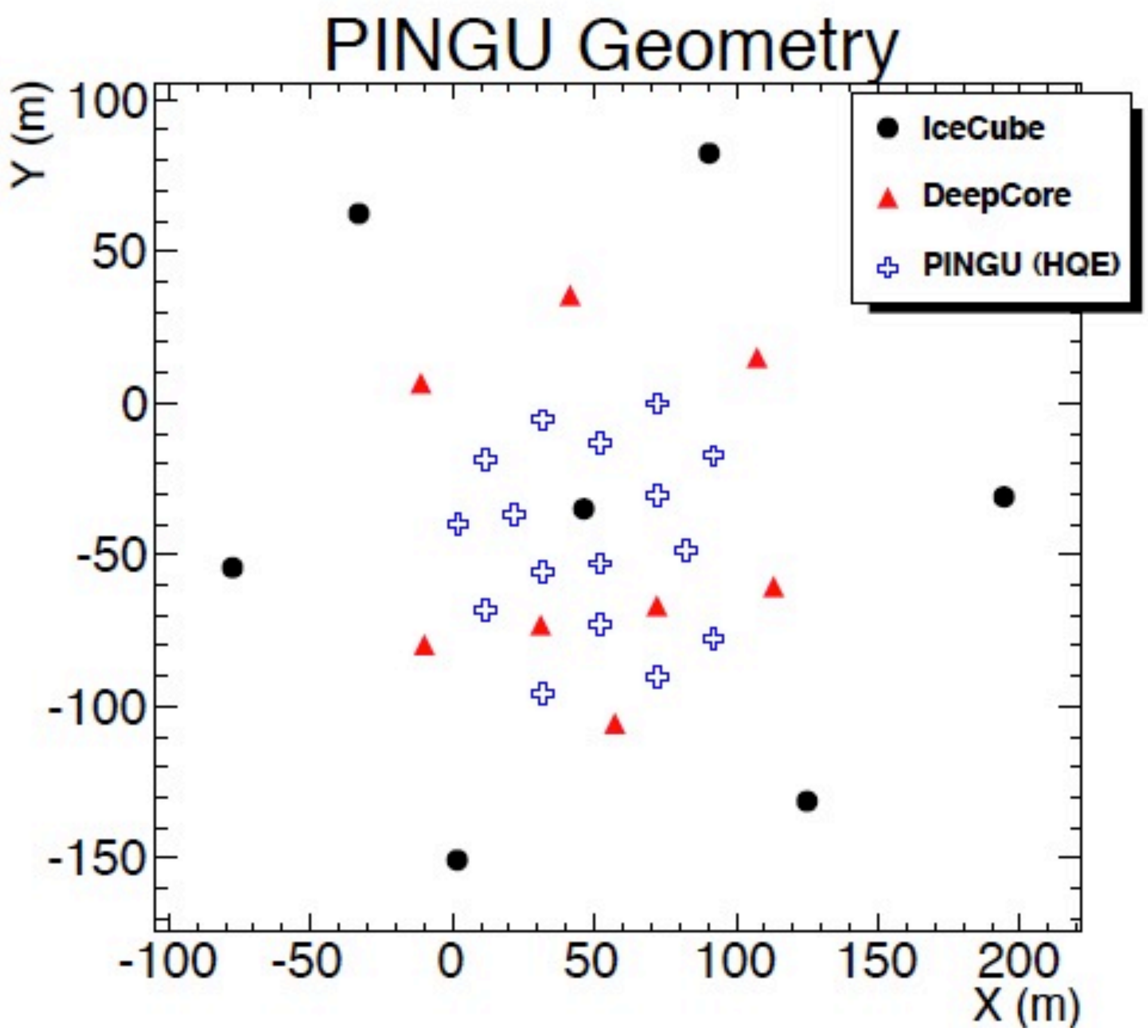
$P(\nu_\alpha \text{-->} \nu_\alpha) = 1 - \sin^2(2\theta)*\sin^2(1.27*\Delta m^2(eV^2)*L(km)/E(GeV))$





- Loosen cuts to see possible $\nu_\mu \rightarrow \nu_\tau$ oscillation.
- Lots of statistics: > 10x more data in hand,
  need a good control of systematics
- Similar to Super-K measurement

PINGU: Concept



Goals:

- Energy: ~ few GeV threshold
- Reconstruction: Cherenkov ring imaging (as R&D)
- Calibration: down to 1 GeV light level (include low-E calibration device)

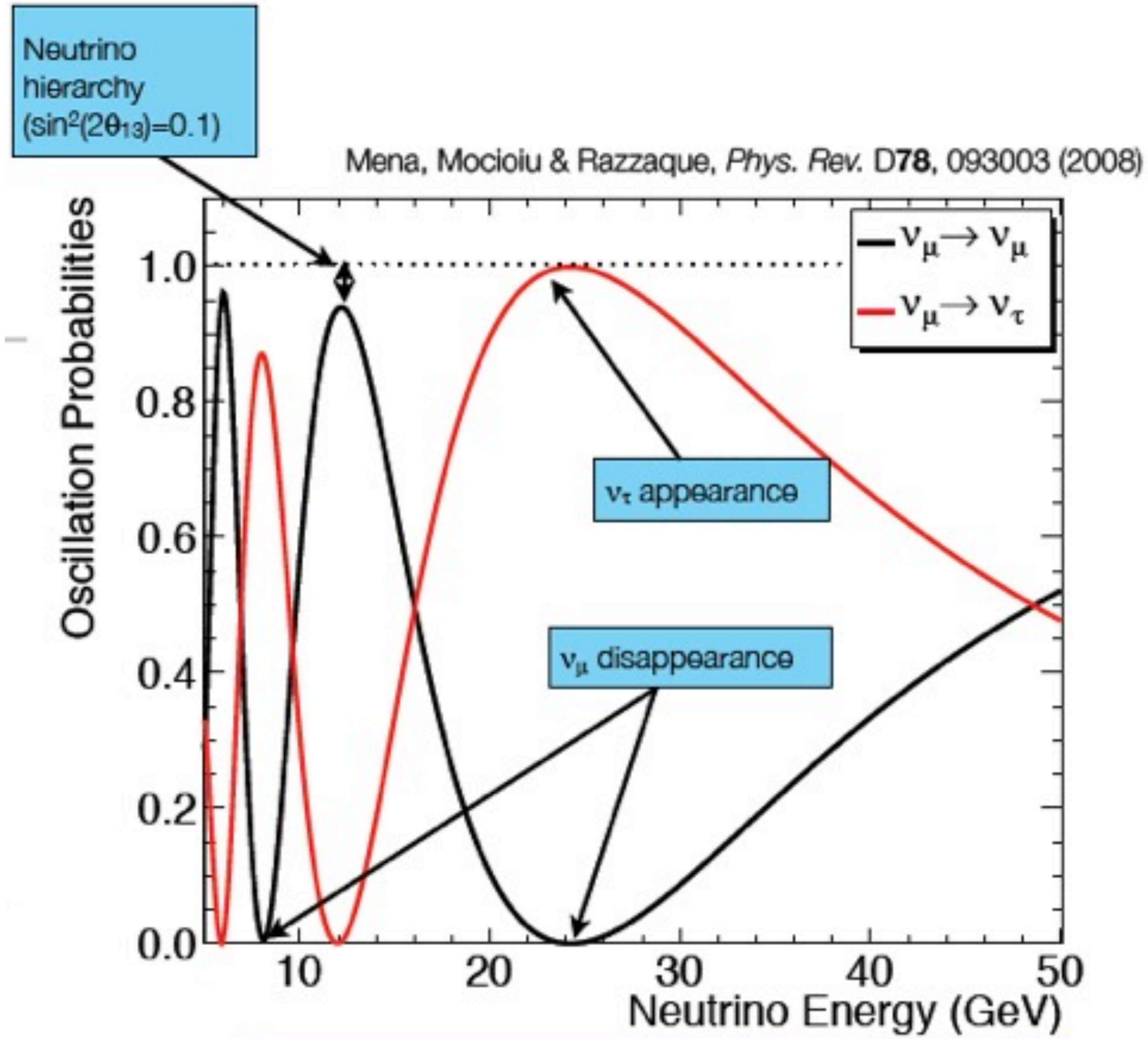
Geometry:

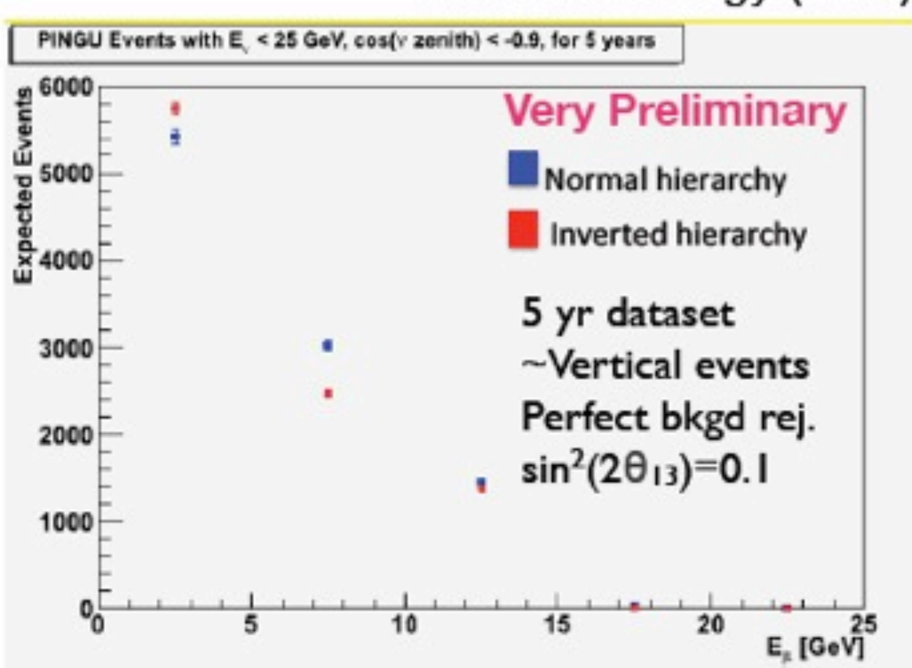
- ~20 additional strings: (DeepCore + R&D) strings

Collaboration:

- IceCube + UM-Duluth + U.Erlangen + NIKHEF + U.Wuerzburg + TUM
- Conference calls, wiki, listserv
- 2nd workshop in Jan. 2012 at Penn State Univ.

PINGU: Physics

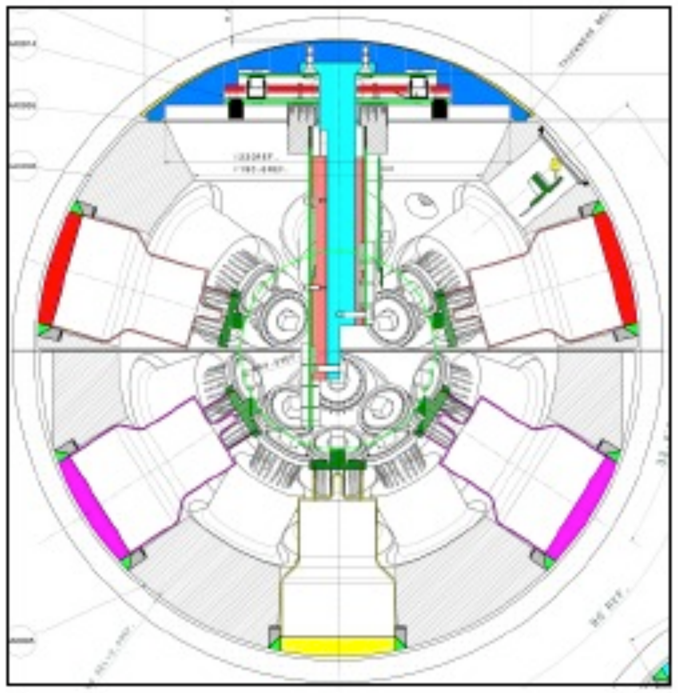




- Neutrino oscillation:
  + pin down $(\Delta m_{23})^2$
  + neutrino hierarchy:
    - exploit asymmetry in nu/anti-nu σ's
    - largest effect at $E(\nu)<5$GeV, $r = R_{Earth}$
    - need large θ_{13}
    - need good control of systematics
- Probe lower mass WIMPs
- Extensive calibration program
- Pathfinder technological R&D for MICA

➡ We need/expect to gain sensitivity to $E(\nu) <$ ~5GeV

PINGU: Detector R&D



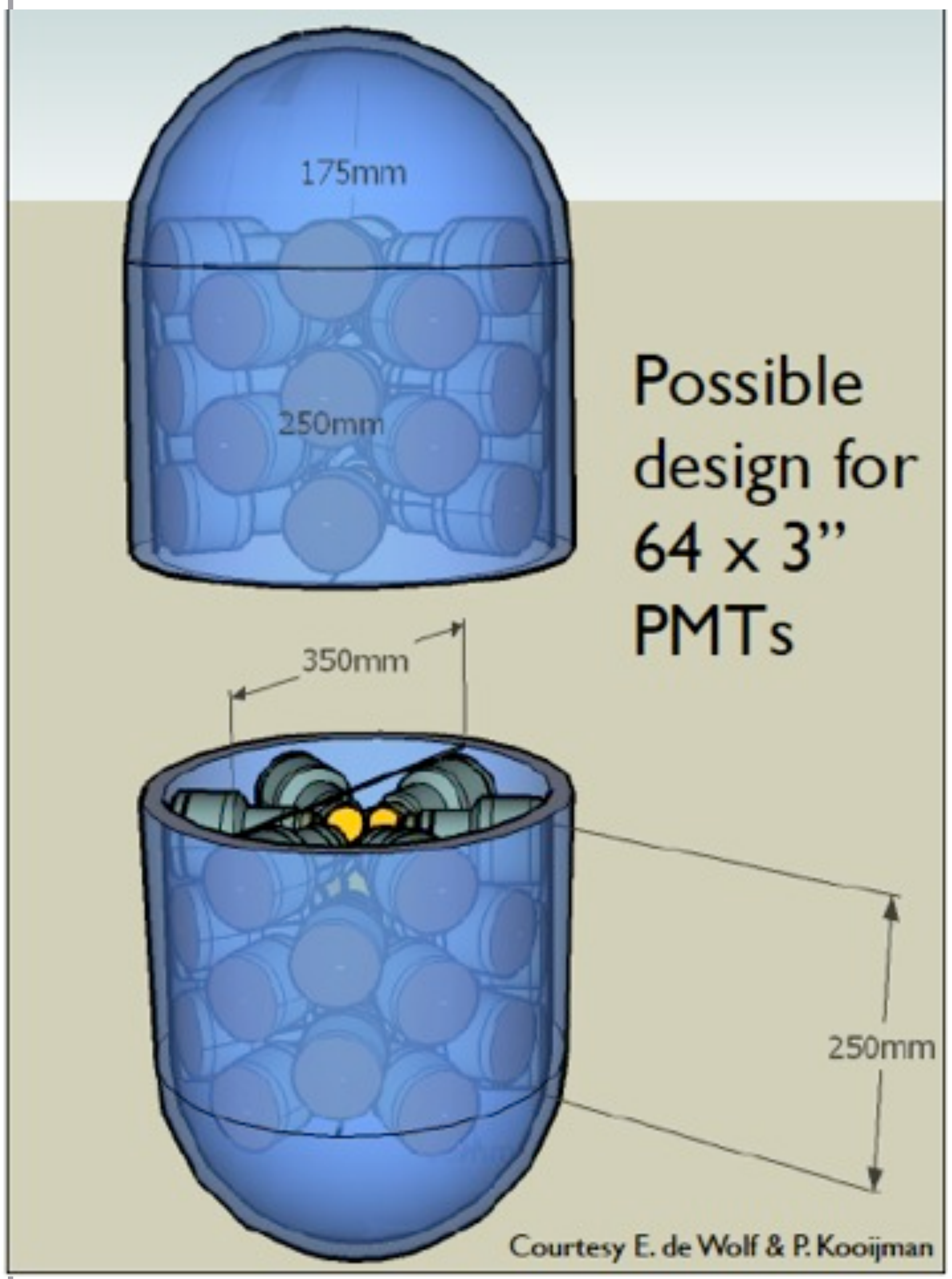
P. Kooijman, NIM A567 (2006), S. Kuch NIM A567 (2006), KM3NeT TDR

Composite Digital Optical Module

- ❖ Based on a KM3NeT proposed design (NIKHEF)
- ❖ Glass sphere (X cm diameter) contains
  -- total 31 of 3-inch-PMT:
  - 4x more effective photocathode area compared to that of 8-inch-PMT
  - better granularity
  - hopefully lower cost/area

  -- electronics
- ❖ Pro: single connector simplifies deployment

PINGU: Detector R&D



Compact Digital Optical Module

❖ Design/technology study underway (NIKHEF, Erlangen)

❖ Cylinder-type pressure vessel contains

-- total 64 of 3-inch-PMT:

- > 5x more effective photocathode area compared to that of 10-inch-PMT
- similar diameter to IceCube DOM → easy deployment

-- electronics

❖ Pro: single connector simplifies deployment

MICA

Multi-Mton (MeV-GeV) detector in the Ice

Physics goals:

-- Super Nova neutrino bursts with > ~10 MeV neutrinos

-- Proton decay: $p \rightarrow \pi^o e^+$; $p \rightarrow K^+ \bar{\nu}$;

Requirements:

-- adequate % photocathode area for attainable Cherenkov ring image

-- possible reconstruction of Cherenkov ring

Geometry: **not finalized yet!**

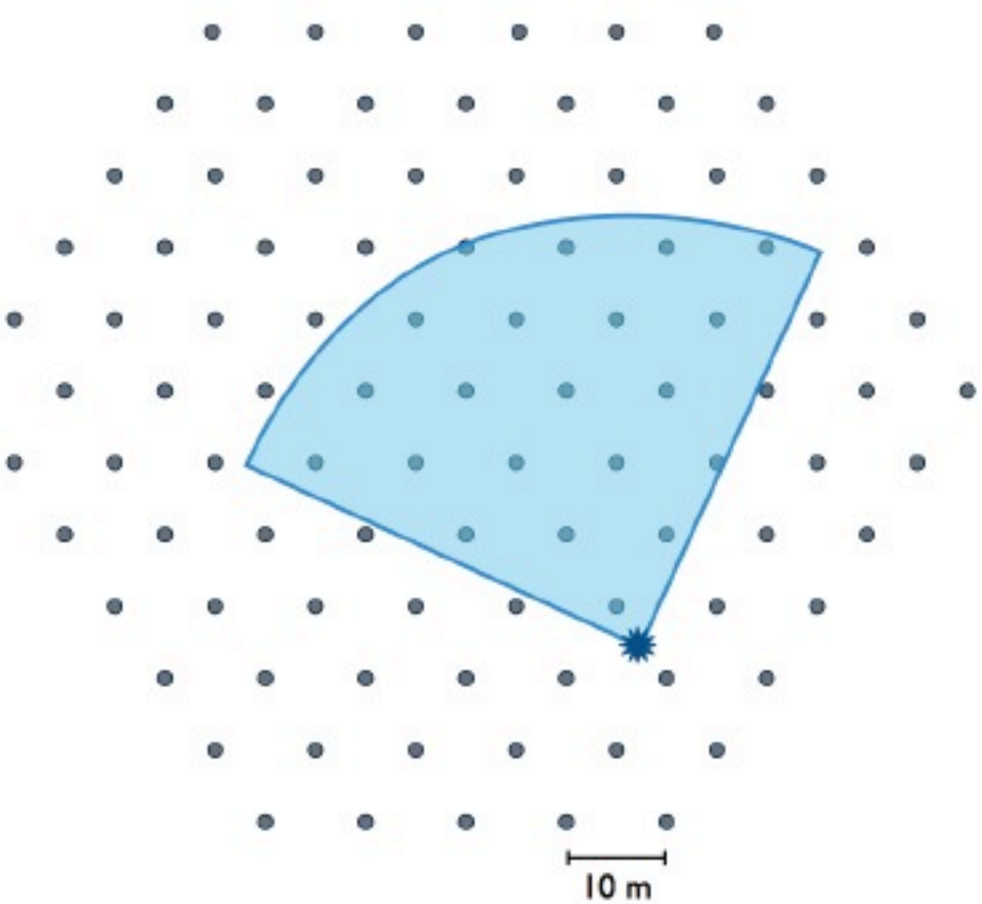
-- 100 m diameter nested cylinders or triangular grid (3 MTon ice)

-- O(m) vertical and O(5 m) horizontal spacing

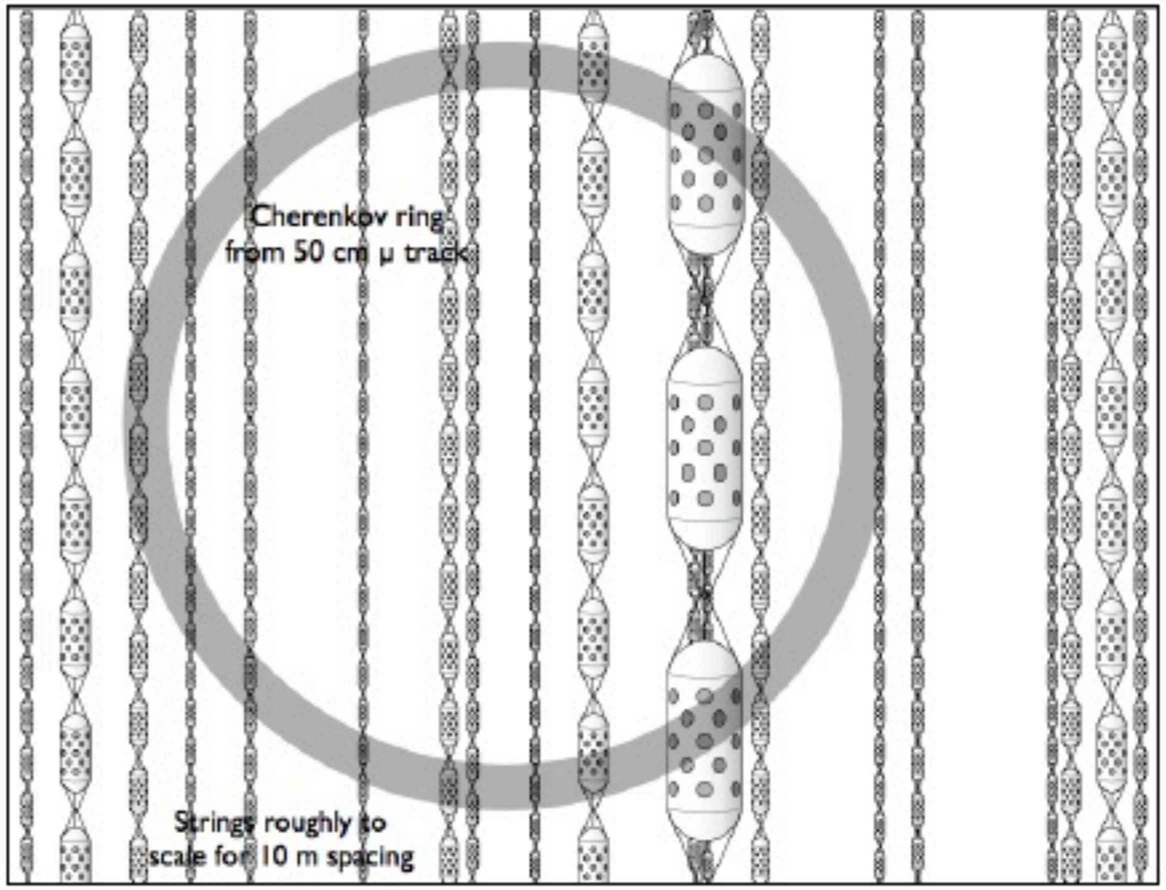
-- need optimization with PMTs

MICA: Toy Geometry

O(200) strings

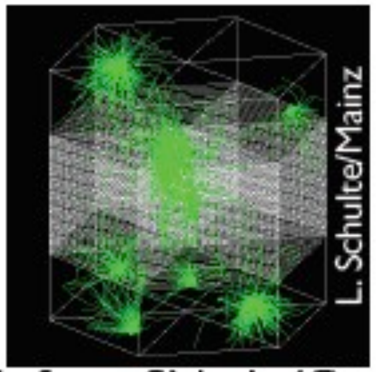


Top view



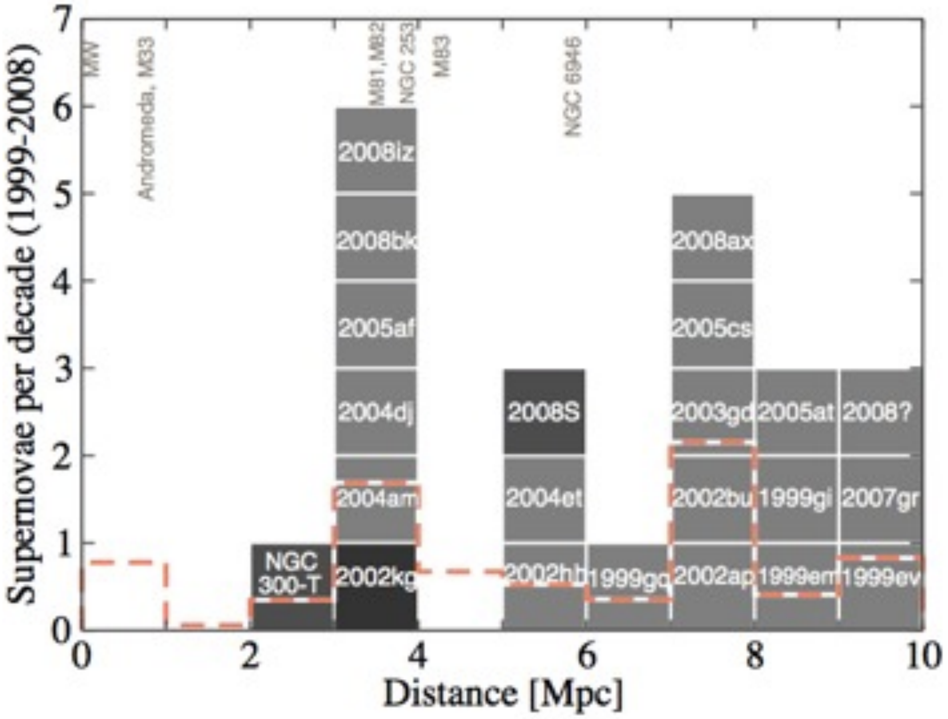
Side view

MICA: Super Nova ν



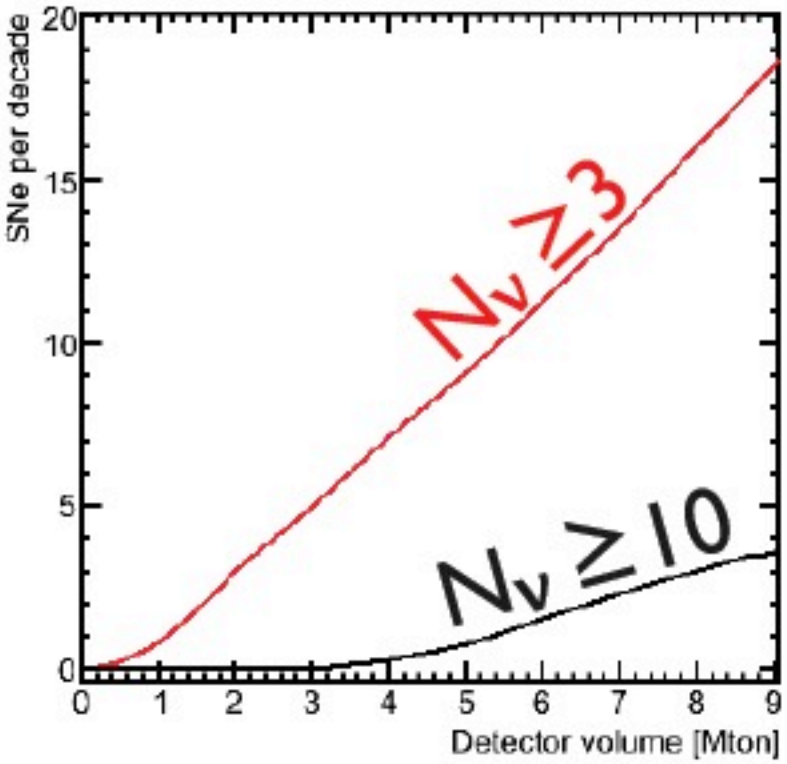
γ's from SN ν's (Geant4)

- A 5 M-Ton detector could see ~10Mpc.
- SN of 10-20 MeV produces 2k-4k Cherenkov photons
  -- need few % photocathode coverage
  -- a burst of >=3 neutrinos in 1-10s
  would be above atm. ν background



M.Kistler et al., PR D83, 123008

- Other benefits:
  -- early trigger for optical det.
  -- for gravitational detector:
  10^6x BG reduction,
  10^3x signal enhancement



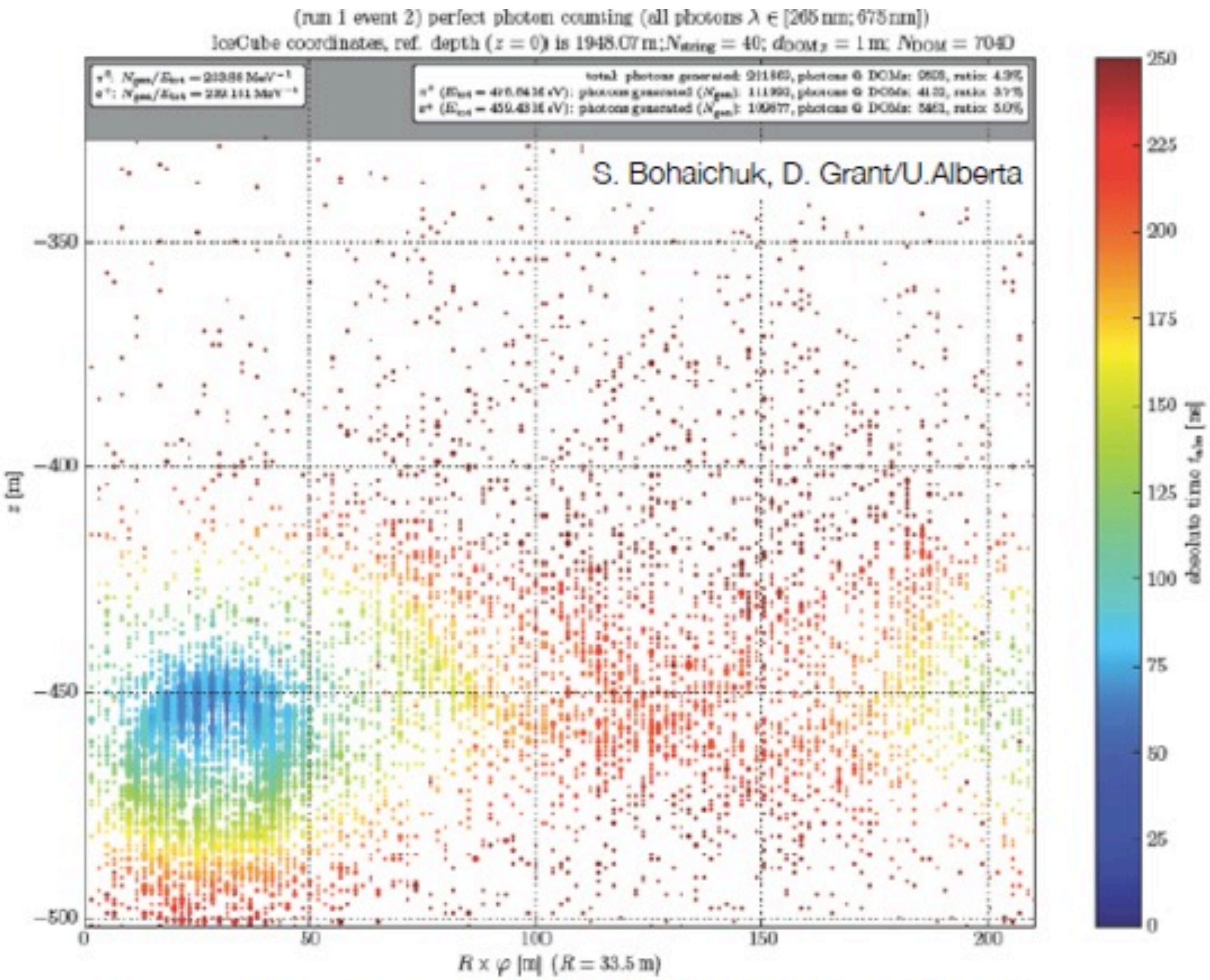
M. Kowalski/Bonn

- Caution: lots of uncertainties (reconstruction, particle ID, etc.)

MICA: Proton Decay

Challenging!

(but competitive to other proposed projects of this scale)



$p \rightarrow \pi^0 + e^+$

1.5 MTon (5x10^{35} protons),
10 MeV threshold,
240 photons/MeV,
5% photons detected

❖ BG: atm. ν,
muon spallation products

❖ Requirements:
-- good energy (momentum) resolution
-- particle ID by Cherenkov ring reconstruction
-- high photocathode area

❖ Simulation study is underway

Summary & Outlook

✓ IceCube is the world's largest neutrino telescope at the S. Pole.
(It has finished its 7 year construction in 2010.)

✓ IceCube has been producing very interesting results.:

-- probes below WB flux/bound: GRB/diffuse neutrinos with IC40
-- dark matter: probe SUSY models (8 yr. AMANDA+IceCube)
-- cosmic-ray anisotropy & its mysterious E dependence
-- etc…

✓ IceCube has strengthened low its energy capabilities with DeepCore.
-- First atm. cascade observation was made with IC79.
-- neutrino oscillation/hierarchy, lower mass WIMPs are under study.

✓ Possible future projects, PINGU and MICA in the DeepCore region will even further lower down the energy threshold.