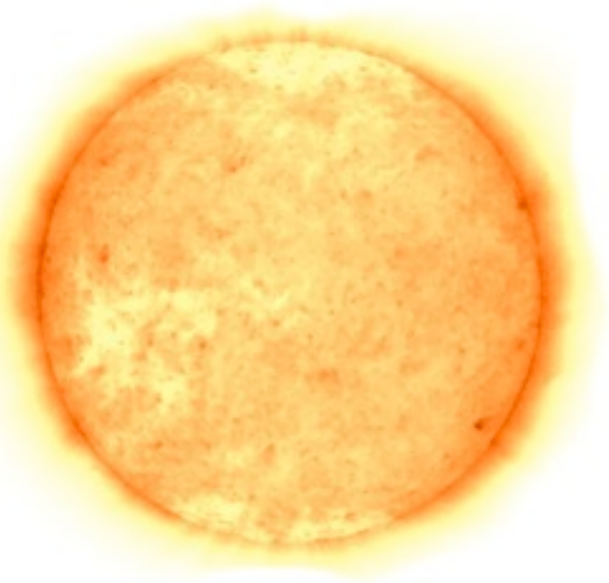
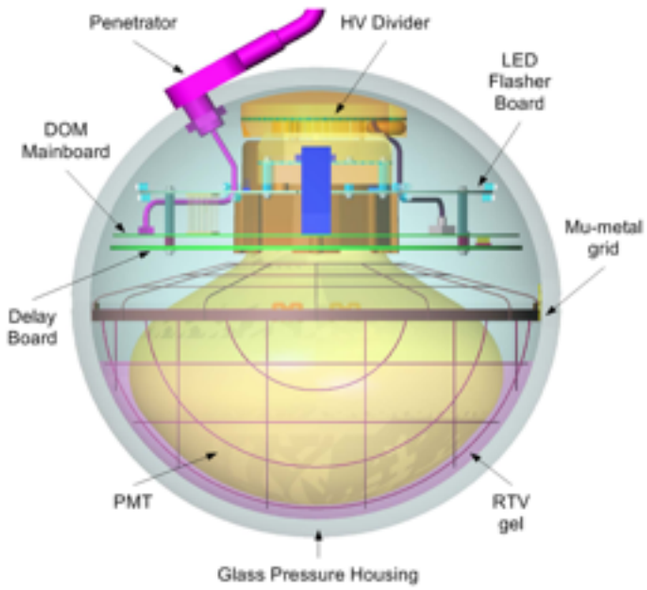
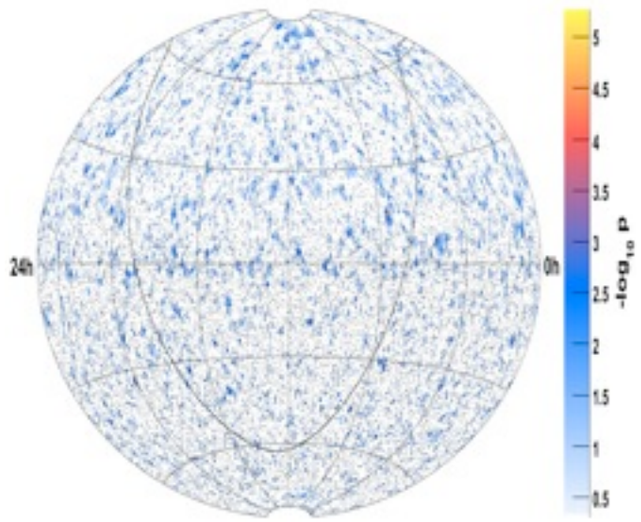




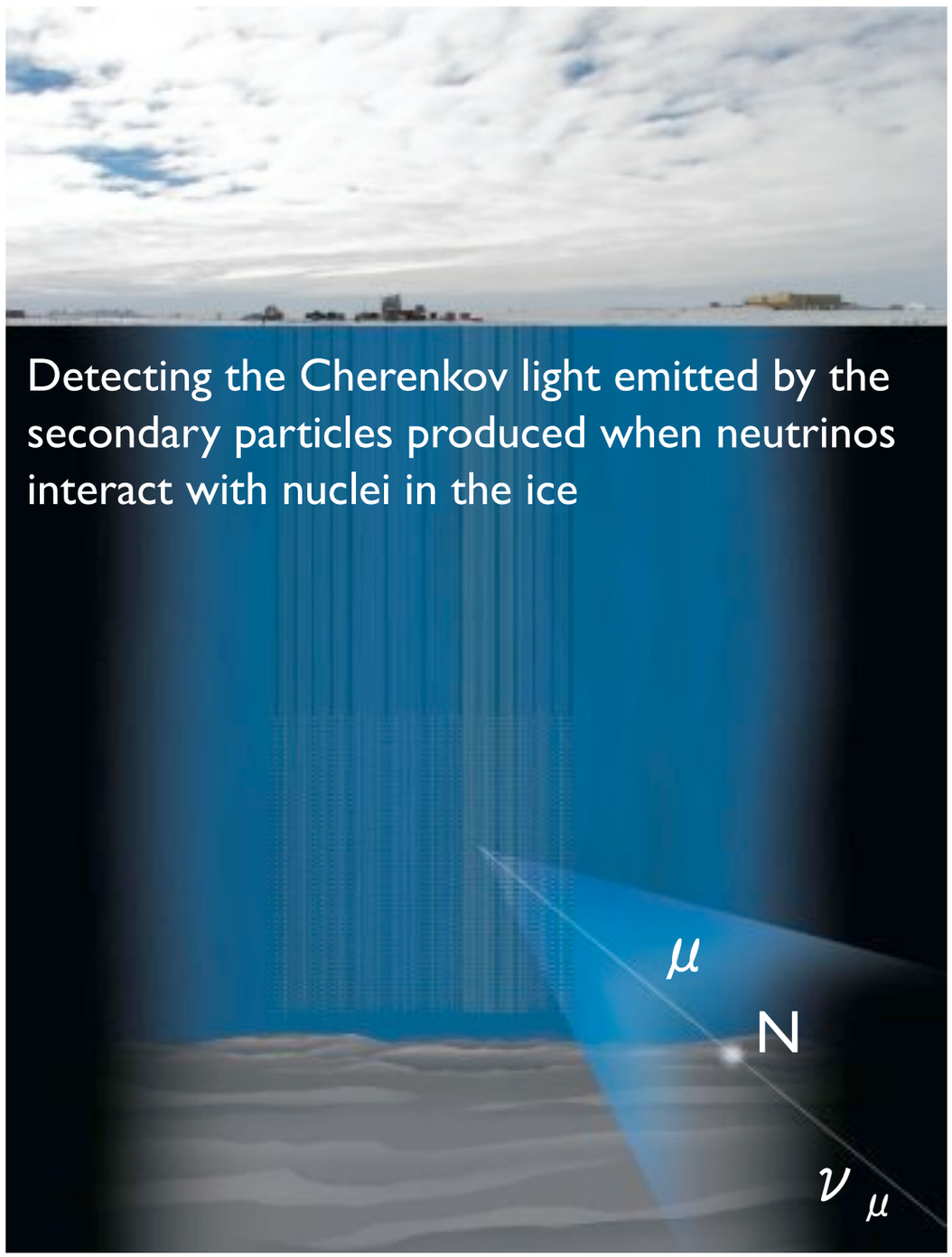


IceCube

Neutrino detection on the South Pole

Stijn Buitink (LBNL) Nov. 10 2010 UCSB HEP seminar

IceCube



Search for cosmic neutrinos in TeV-PeV range

Need km3 scale detector volume

Dense, dielectric, transparent medium: ice

IceCube collaboration

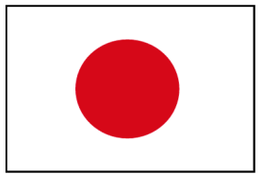
University of Alabama
University of Alaska, Anchorage
University of California, Berkeley
University of California, Irvine
Clark-Atlanta University
Bartol Research Institute, University of Delaware
Georgia Institute of Technology
University of Kansas
Lawrence Berkeley Natl. Laboratory
University of Maryland
Ohio State University
Pennsylvania State University
Southern University and A&M College
University of Wisconsin, Madison
University of Wisconsin, River Falls

RWTH Aachen
Ruhr-Universität Bochum
Universität Bonn
DESY, Zeuthen
Universität Dortmund
MPIfK Heidelberg
Humboldt Universität, Berlin
Universität Mainz
BUGH Wuppertal

Stockholms Universitet
Uppsala Universitet

Vrije Universiteit Brussel
Université Libre de Bruxelles
Universiteit Gent
Université de Mons

University of Alberta



Chiba University

University of Canterbury

EPF Lausanne

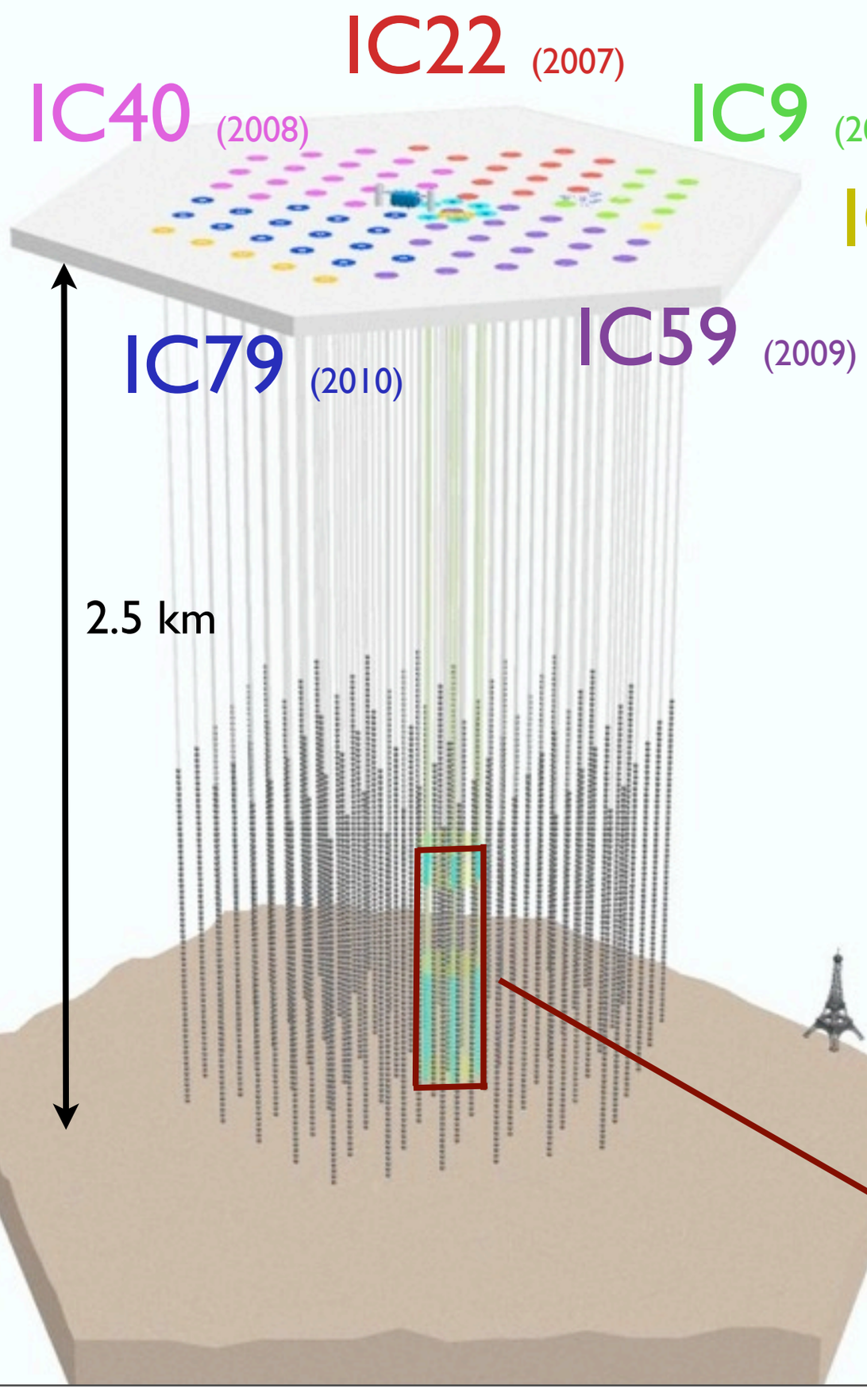
Oxford University

University of the West Indies

IceCube nearing completion: 86 strings

IceTop
80 station
2 tanks per station

IceCube
80 strings ~125 m spacing
60 DOMs per string
~17 m spacing



IceCube Lab (ICL)
central computing facility

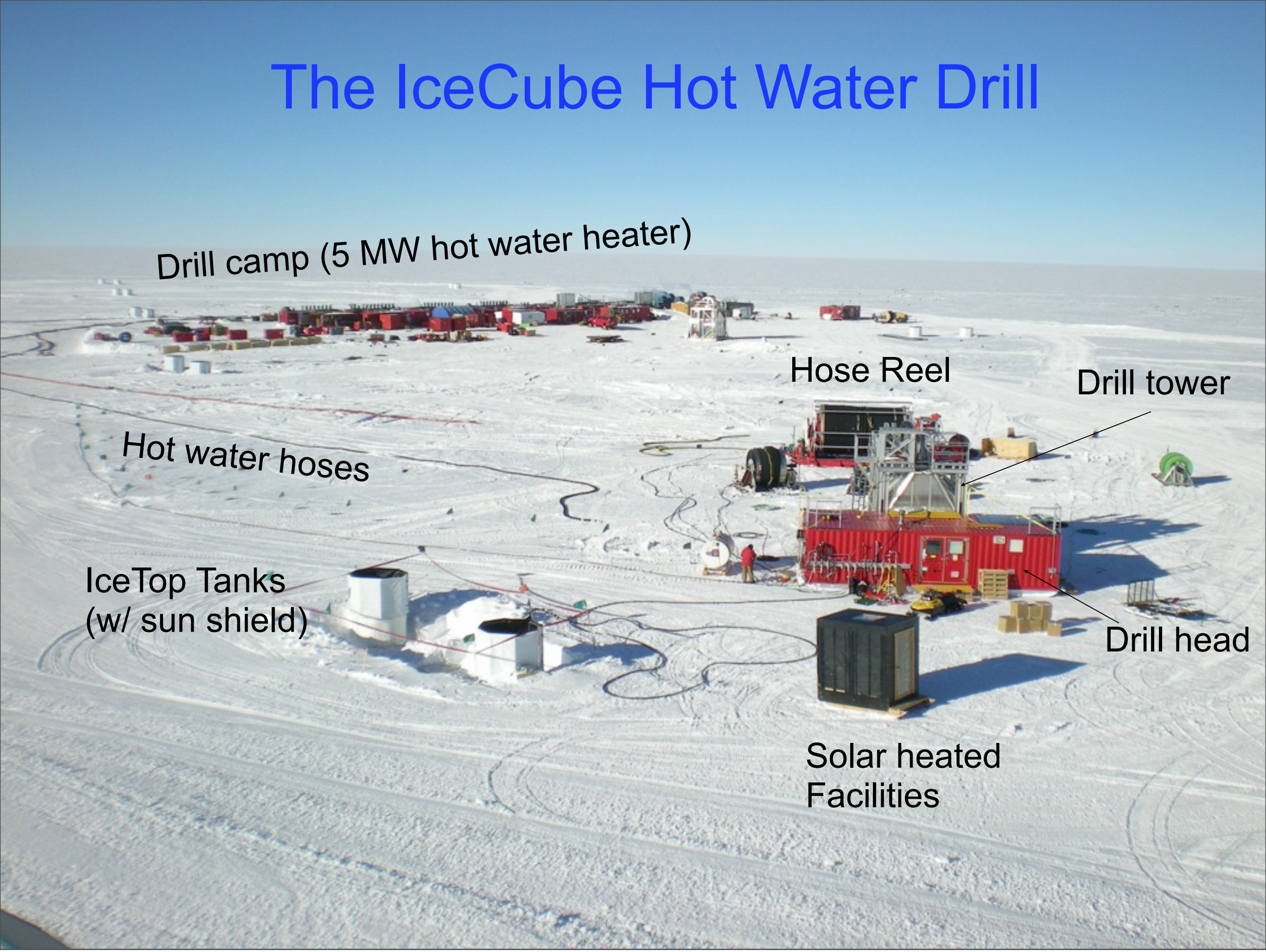
DeepCore infill array
6 strings
60 DOMs per string
~7 m spacing

Amundsen Scott Station

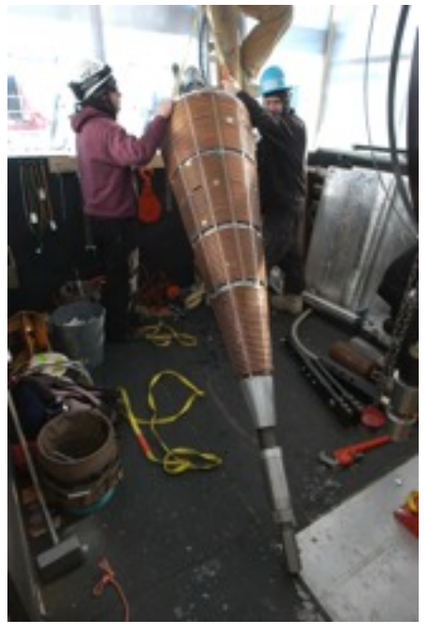
IceCube

South Pole

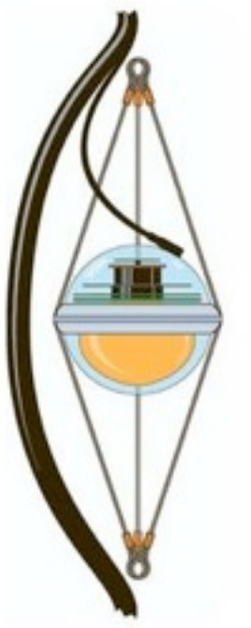
The IceCube Hot Water Drill



Drilling & deployment

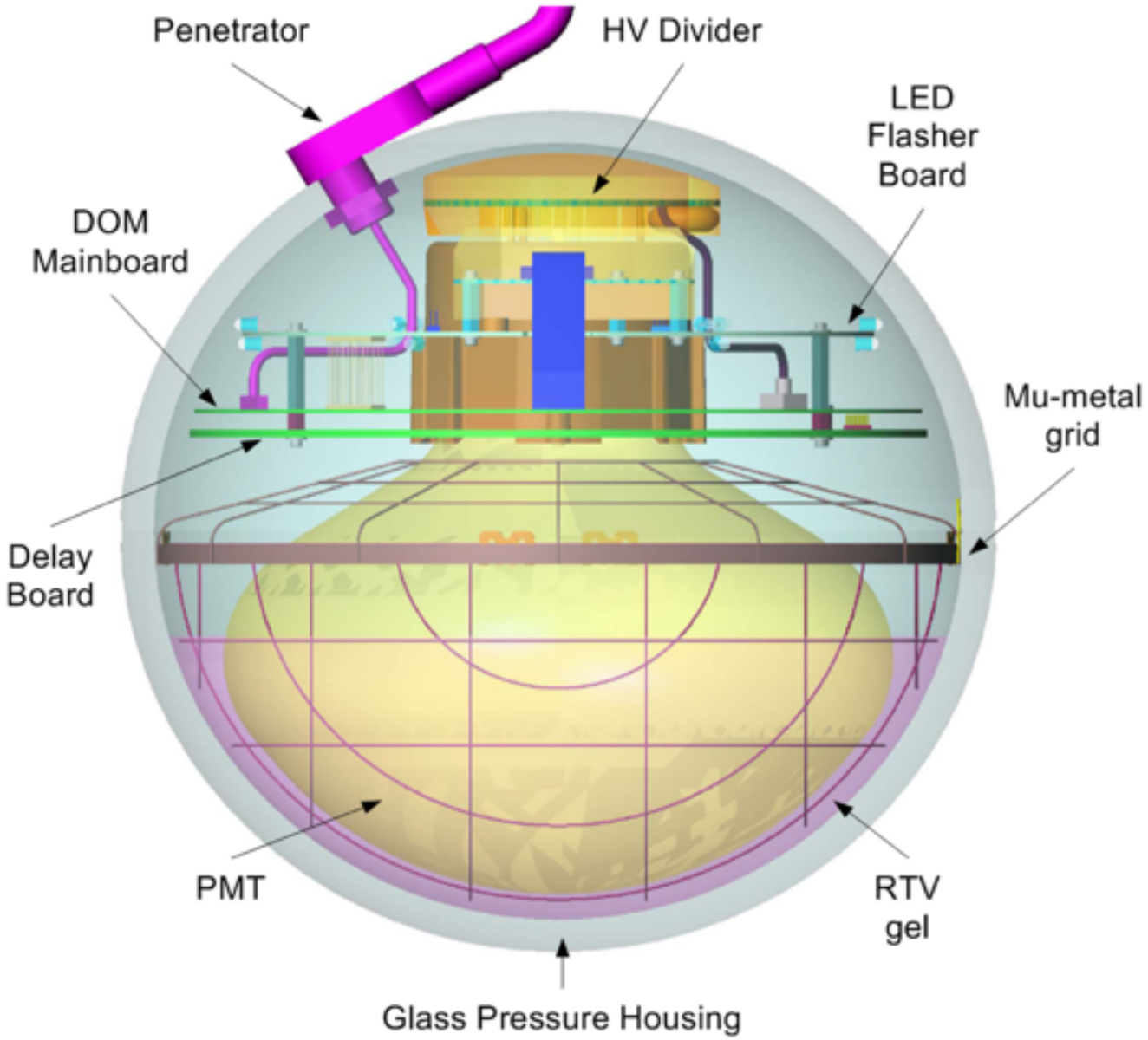


Drill speeds ~ 2 m/minute
~40 hours to drill a hole



~12 hours to deploy a string

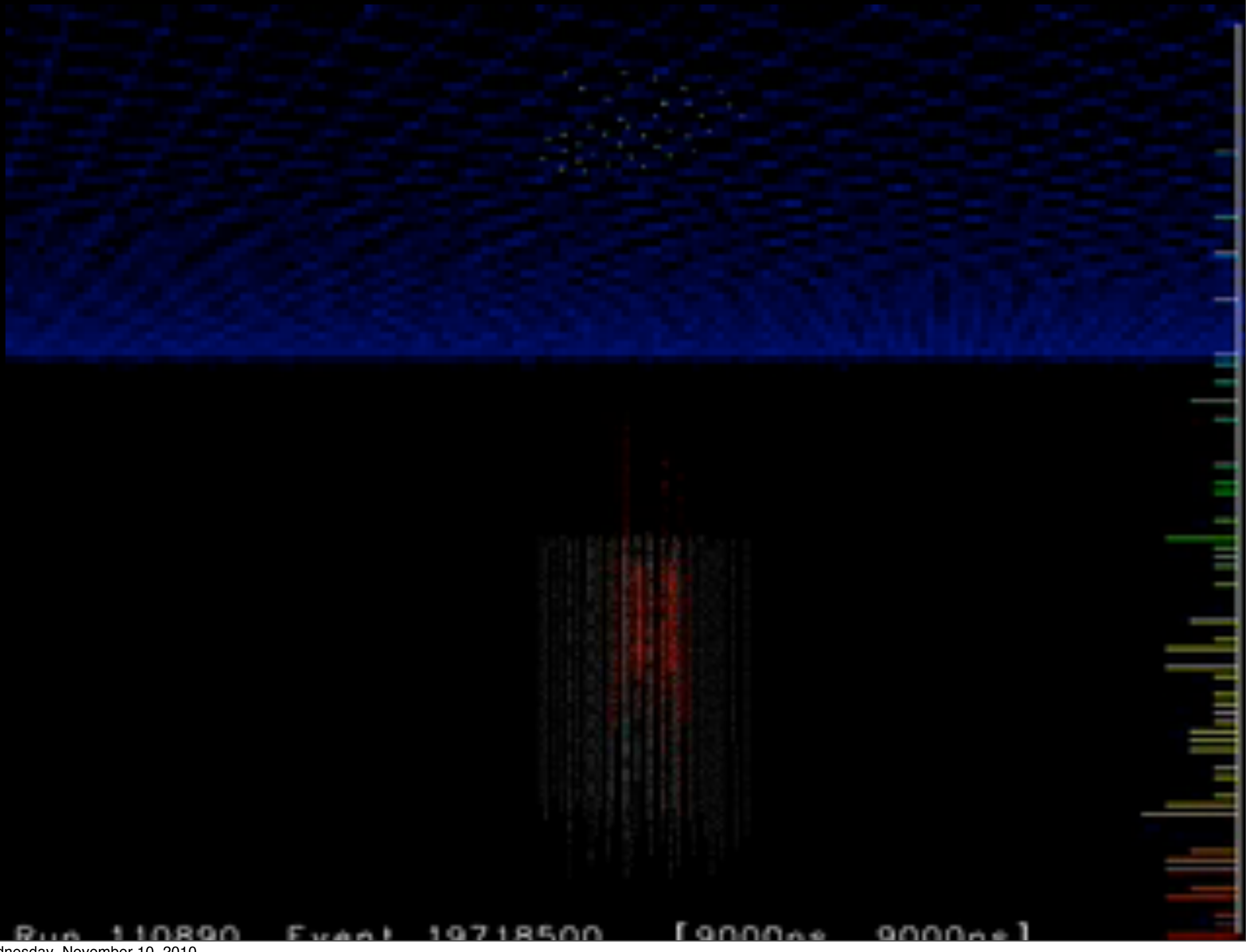
Digital Optical Modules



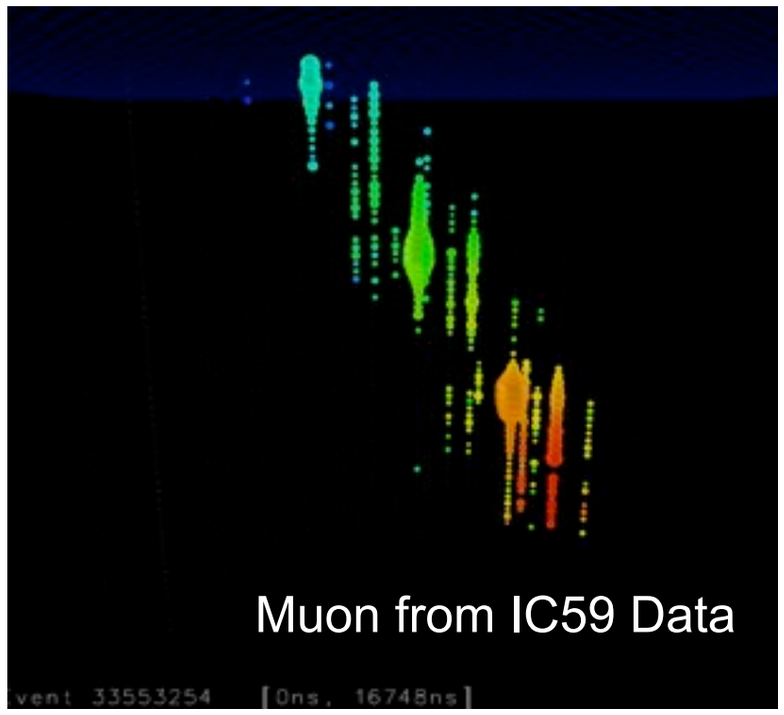
- 25 cm PMT
- 12 LED flashers for calibration
- full digitized waveforms:

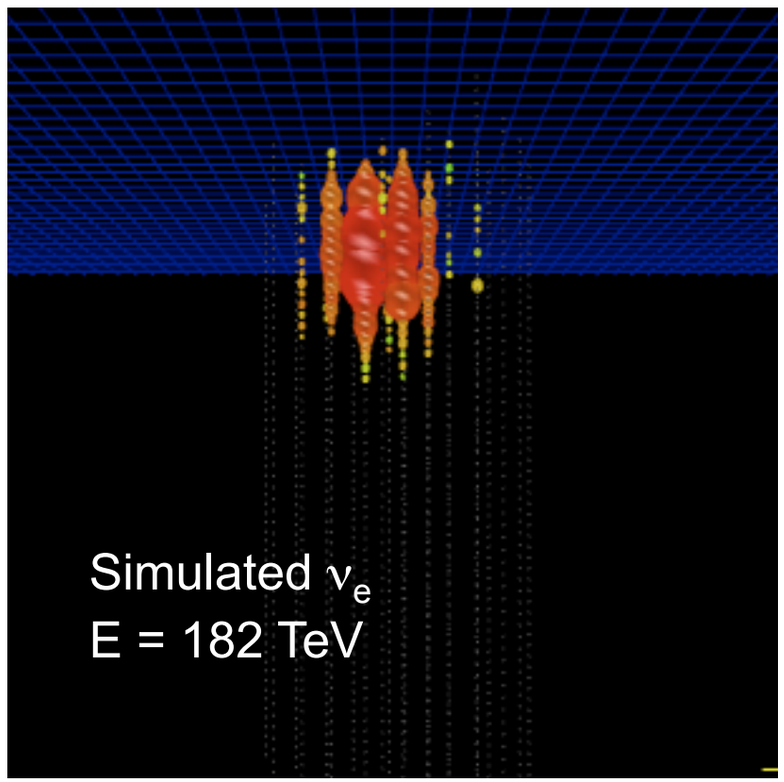
Analogue Transient Waveform Digitizer (ATWD)
400 ns / 320 MHz sampling
x 3 different gains

fast ADC
6.4 μs / 40 MHz sampling

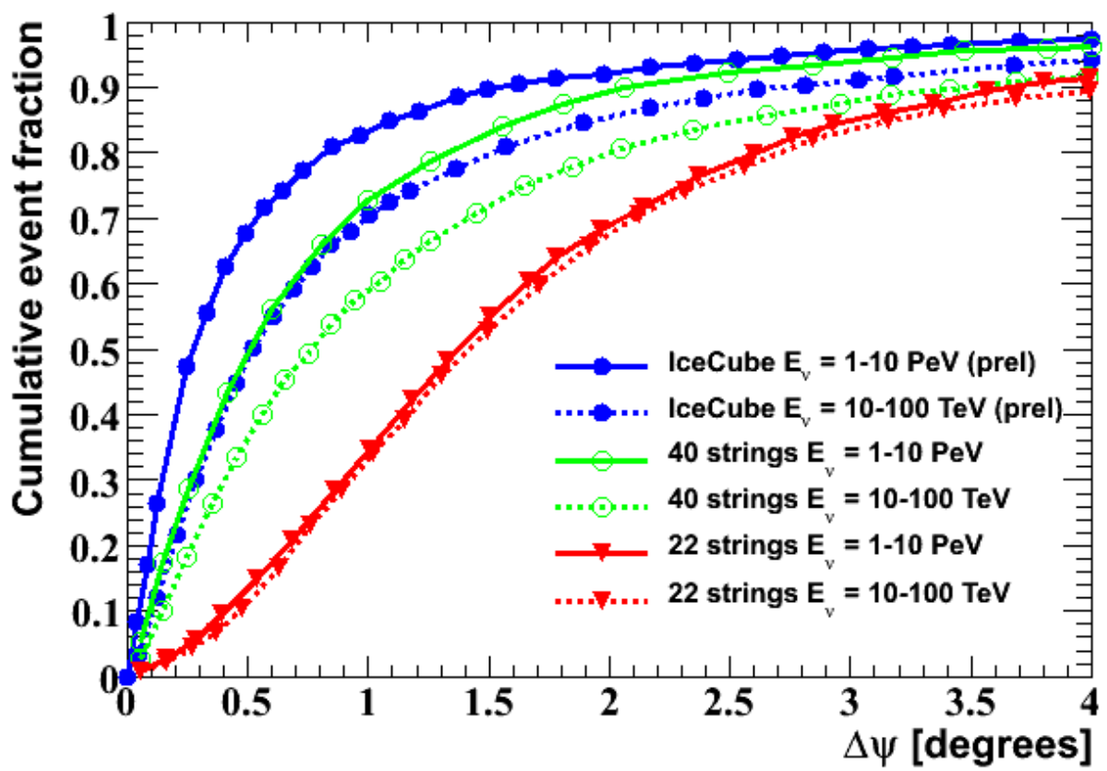


Topologies



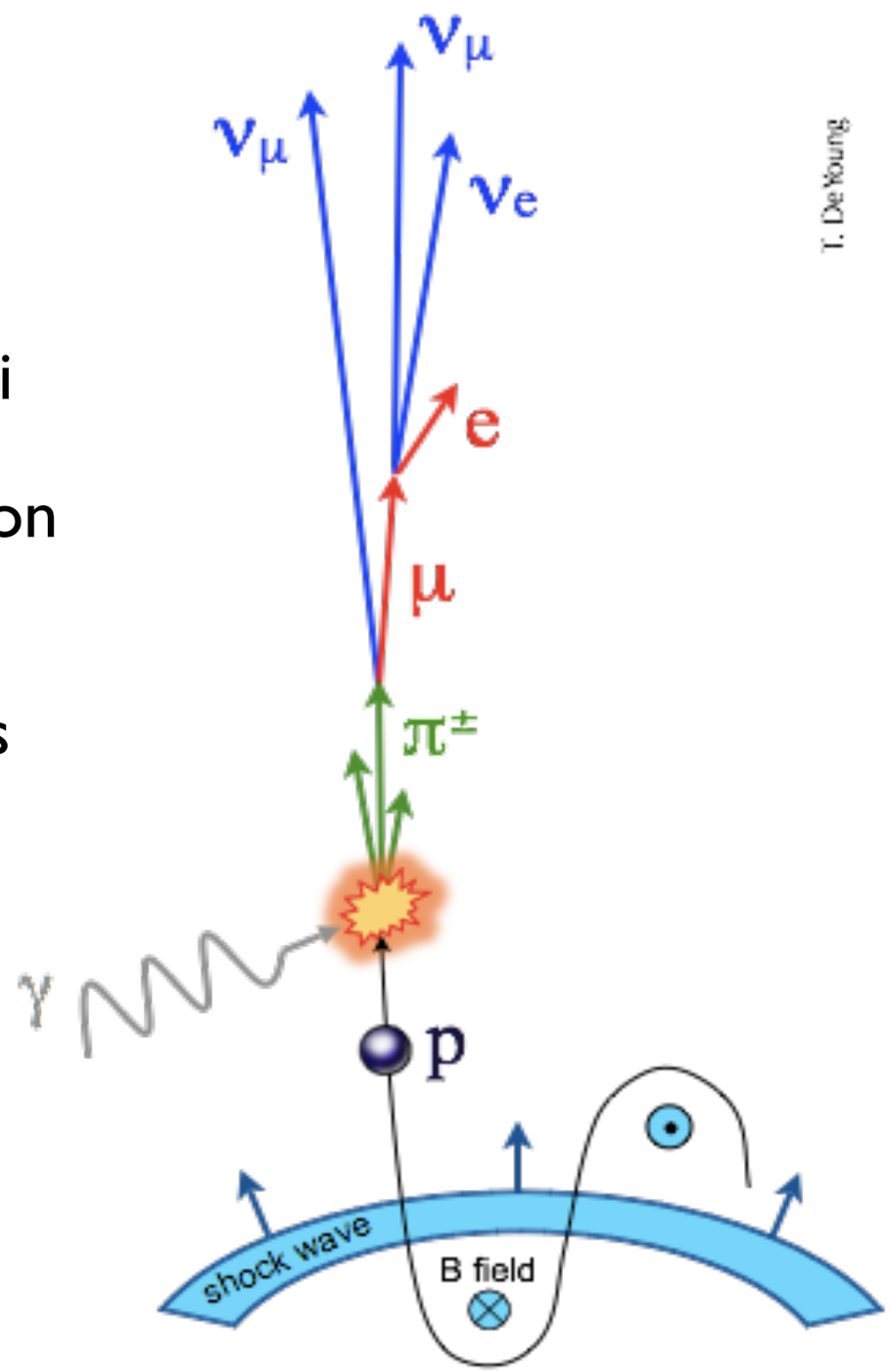


- Tracks ~1 km
  ν_μ & ν_τ
  angular res. <1°
  energy res. <0.3 log(E)
- Cascades ~10 m
  ν_e &ν_τ CC & ν_x NC
  angular res. 30°- 40°
  energy res. <0.1 log(E)



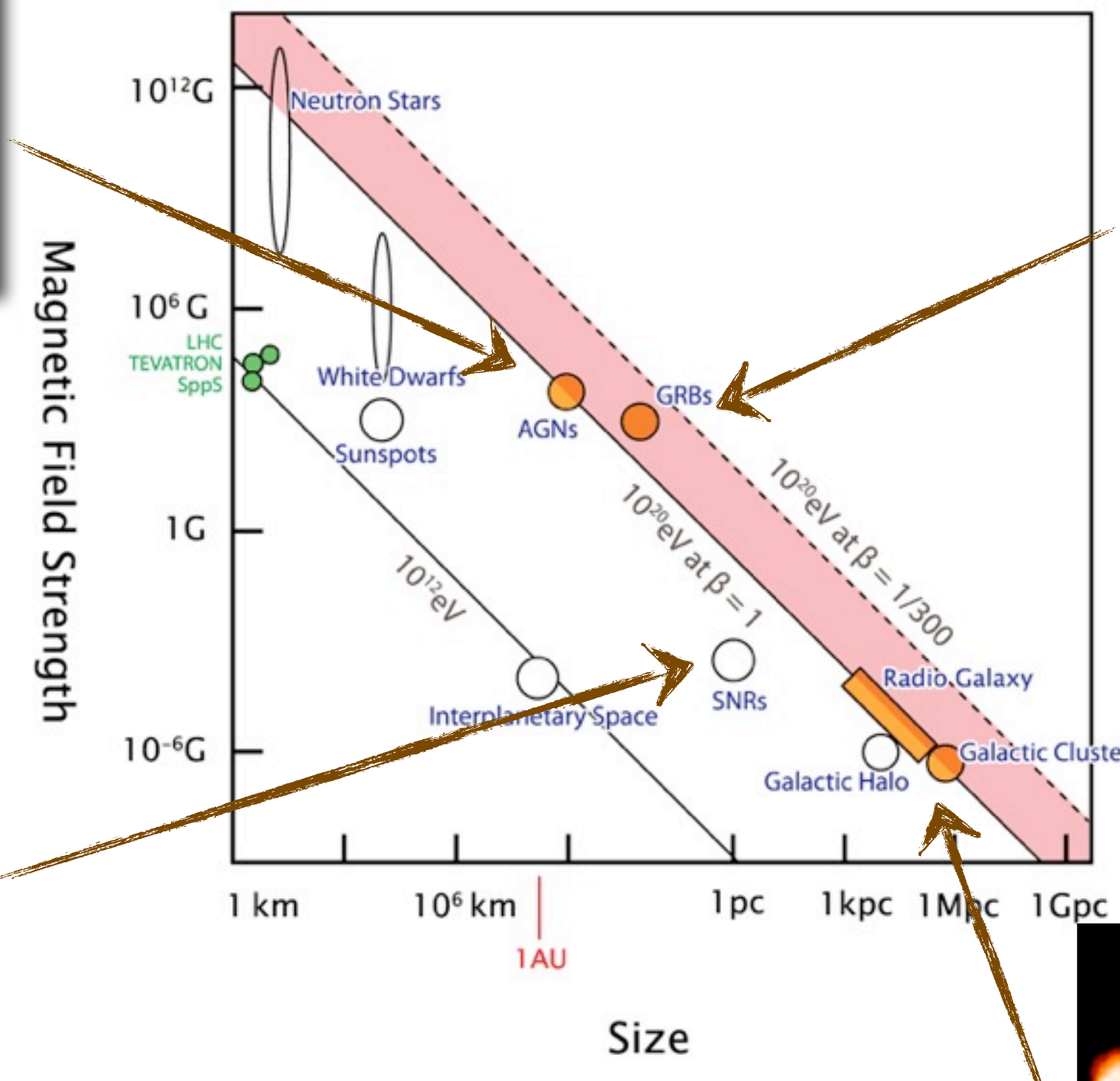
Cosmic Ray acceleration

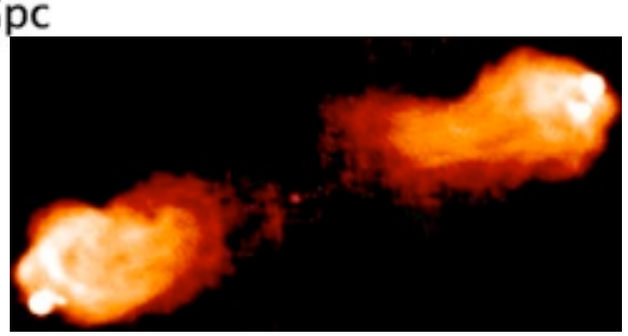
- Cosmic rays accelerated in shock waves: 1st order Fermi
- Interaction with photons: pion production
- pions decay into gamma rays and neutrinos



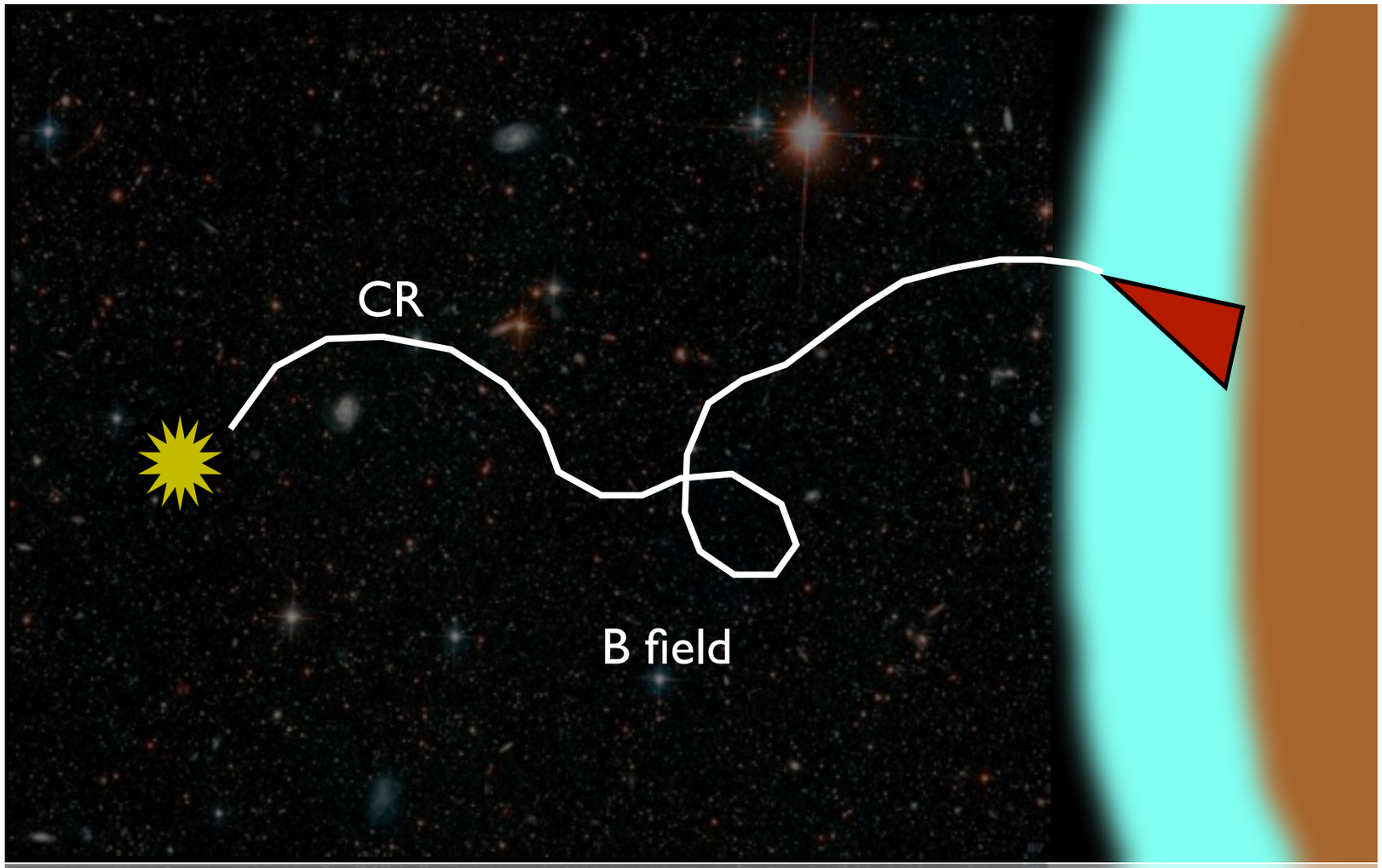
T. DeYoung

Acceleration sites



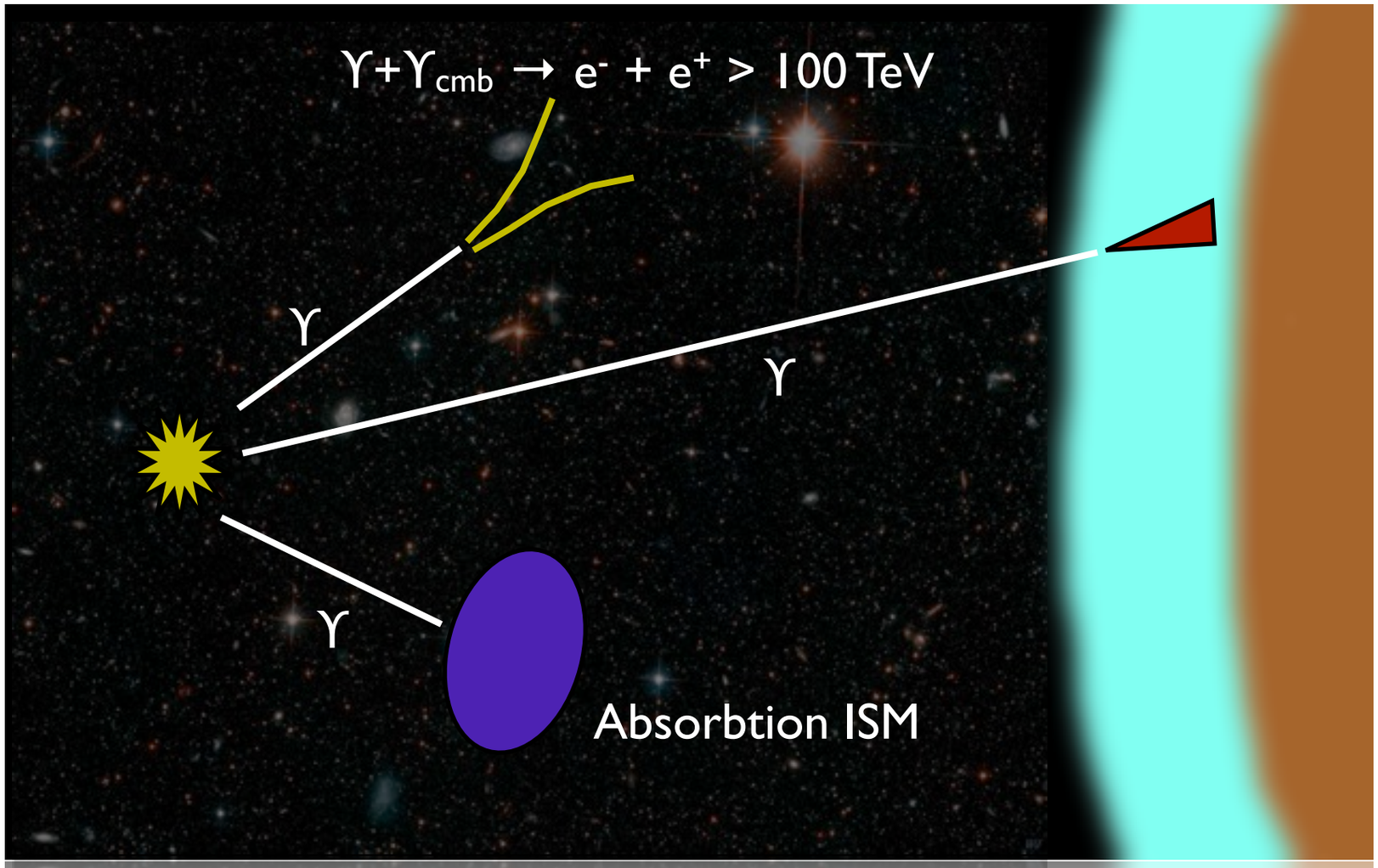


Propagation



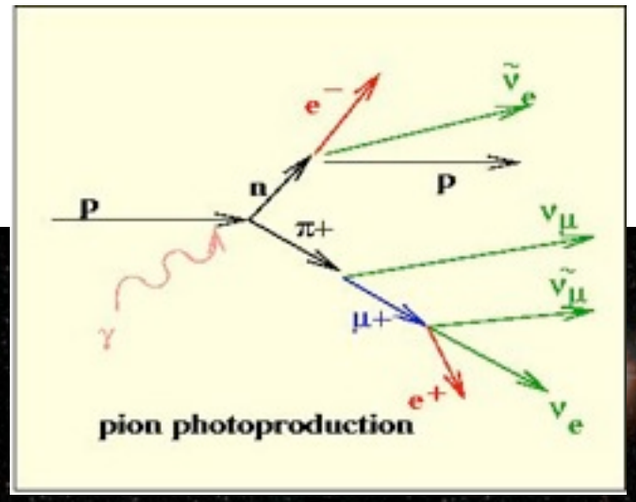
- Cosmic rays scrambled by (inter-) Galactic magnetic field
- Cosmic ray spectrum at Earth $E^{-2.7}$ / source spectra harder
- How to identify sources?

Propagation



- Photons produce showers with composition different from CR
- Pair production length at 1 PeV ≈ 100 kpc Only Galactic origin.
- Photons also produced in leptonic jets No proof of CR acceleration

Propagation



above $4 \cdot 10^{19}$ eV

CR

ν

ν

ν

CR

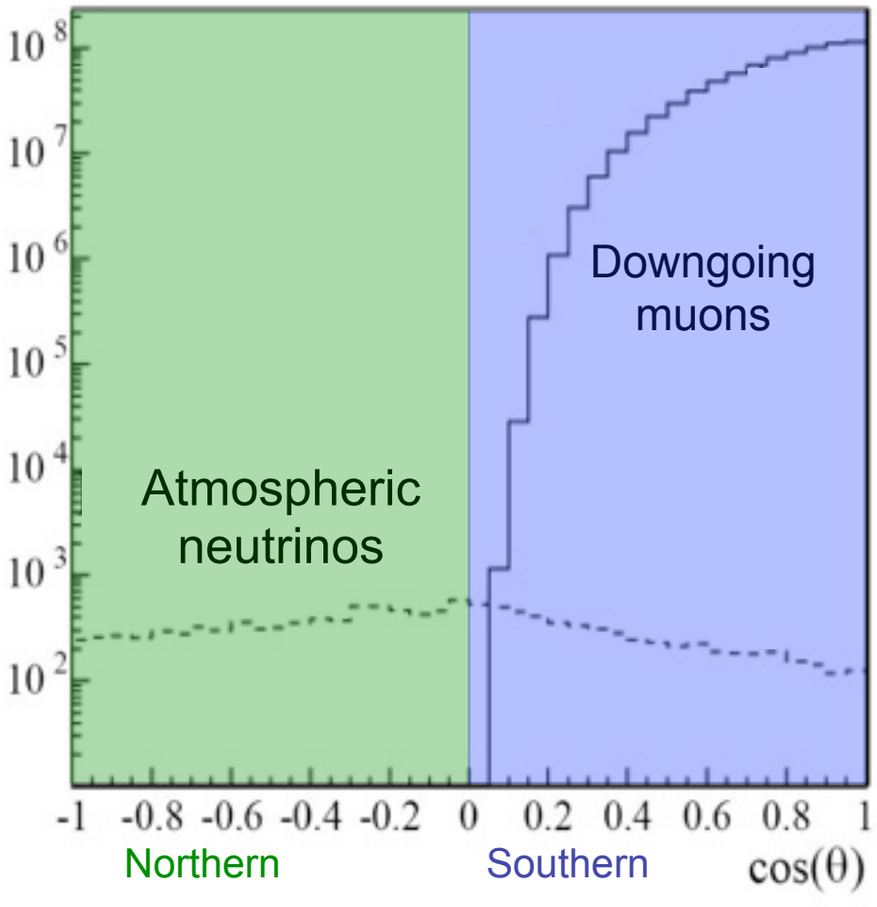
μ

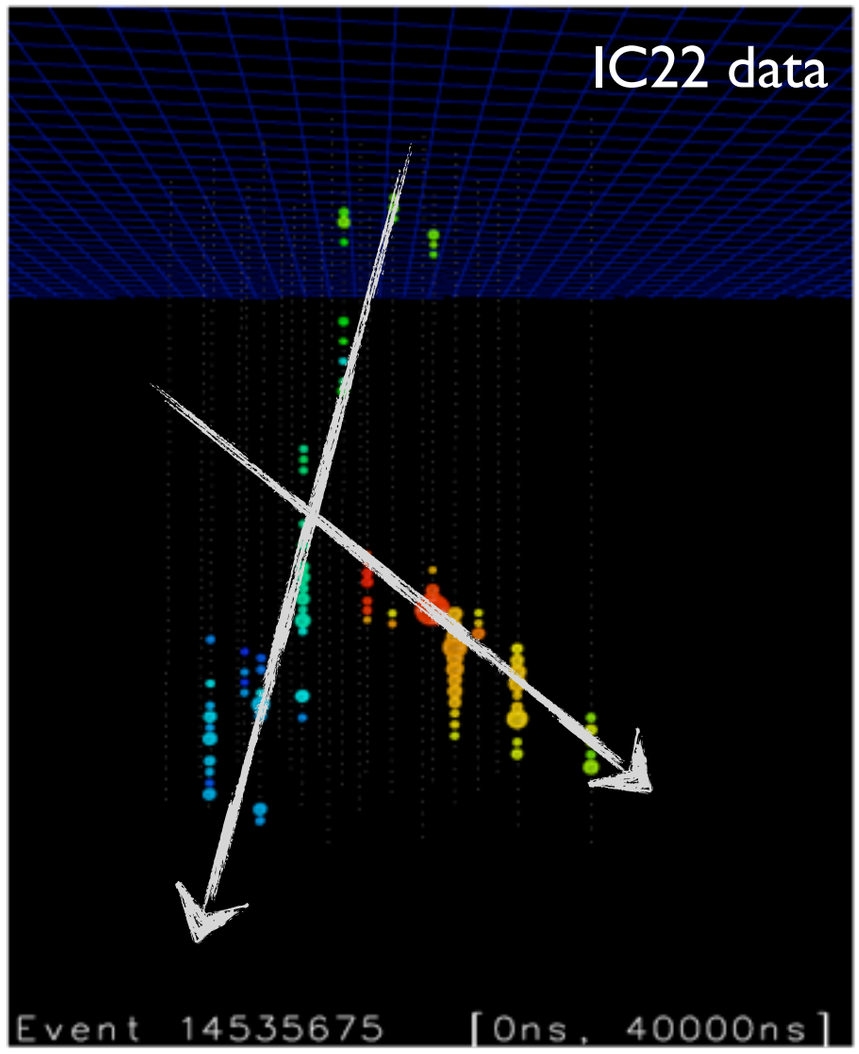
- Neutrinos from source propagate almost unattenuated in straight line
- Background: atmospheric ν and μ from CR shower
- Above GZK energy: extremely high energy ν from CRs

Atmospheric background: muons

- per year:
  60 billion downgoing muons
  74,000 upgoing muons

- strategies:
  search below horizon
  search at high energy
  use IceTop as veto





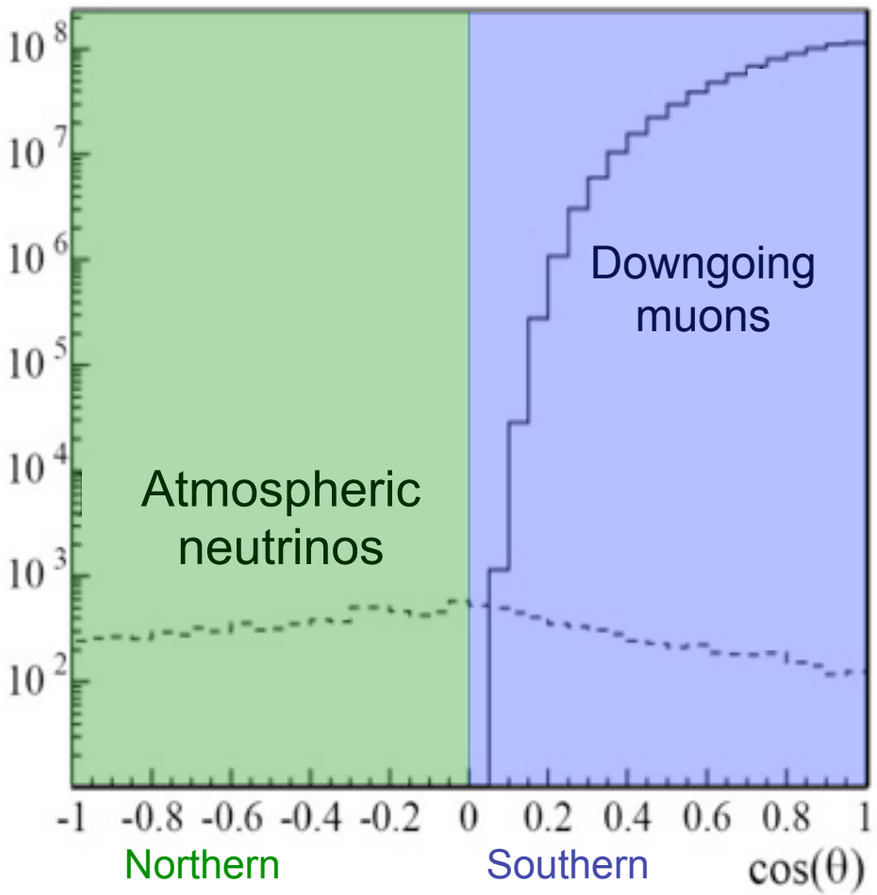
Coincident events can cause misreconstructions

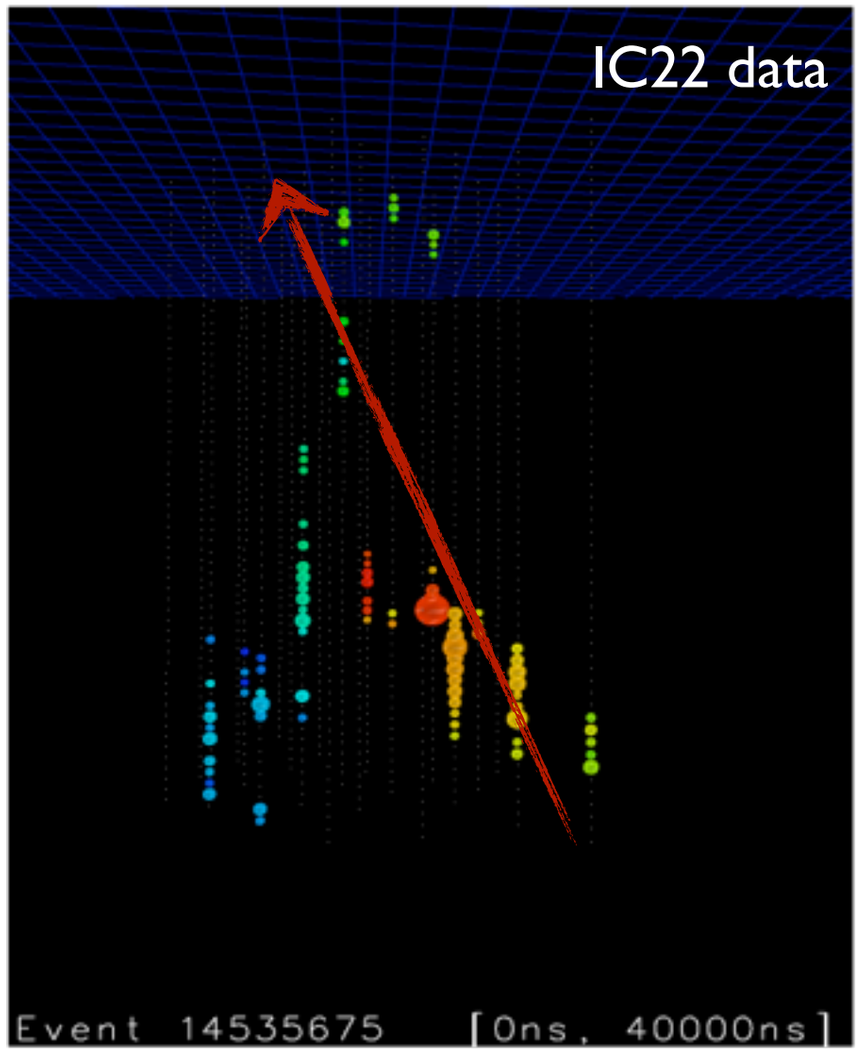
Significant backgroung of fake upgoing tracks

Atmospheric background: muons

- per year:
  60 billion downgoing muons
  74,000 upgoing muons

- strategies:
  search below horizon
  search at high energy
  use IceTop as veto





Coincident events can cause misreconstructions

Significant backgroung of fake upgoing tracks

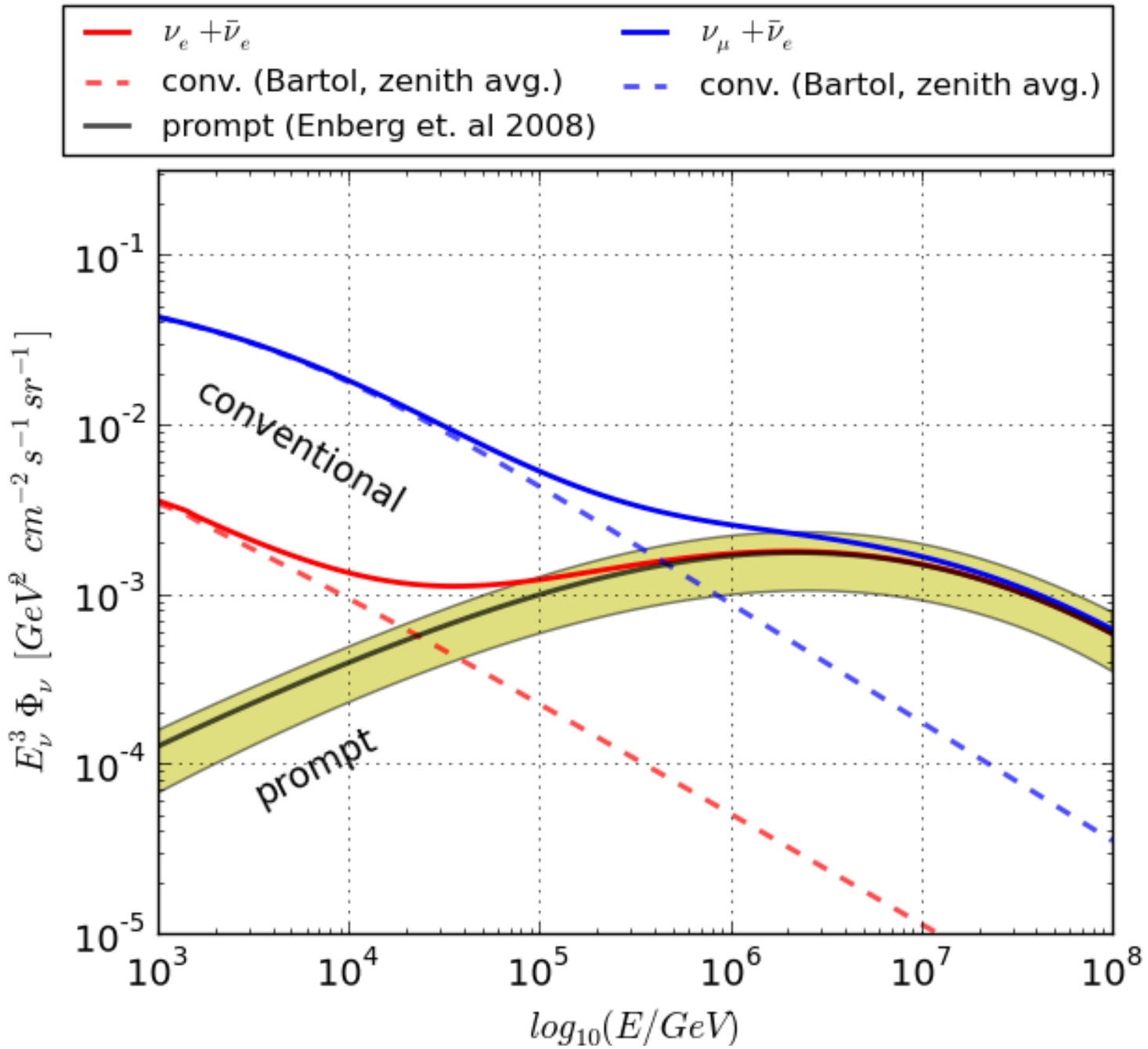
Atmospheric background: neutrinos

- Pion decay
  $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
  $\Upsilon \sim 2.7$ below 100 GeV
  $\Upsilon \sim 3.7$ above 100 GeV

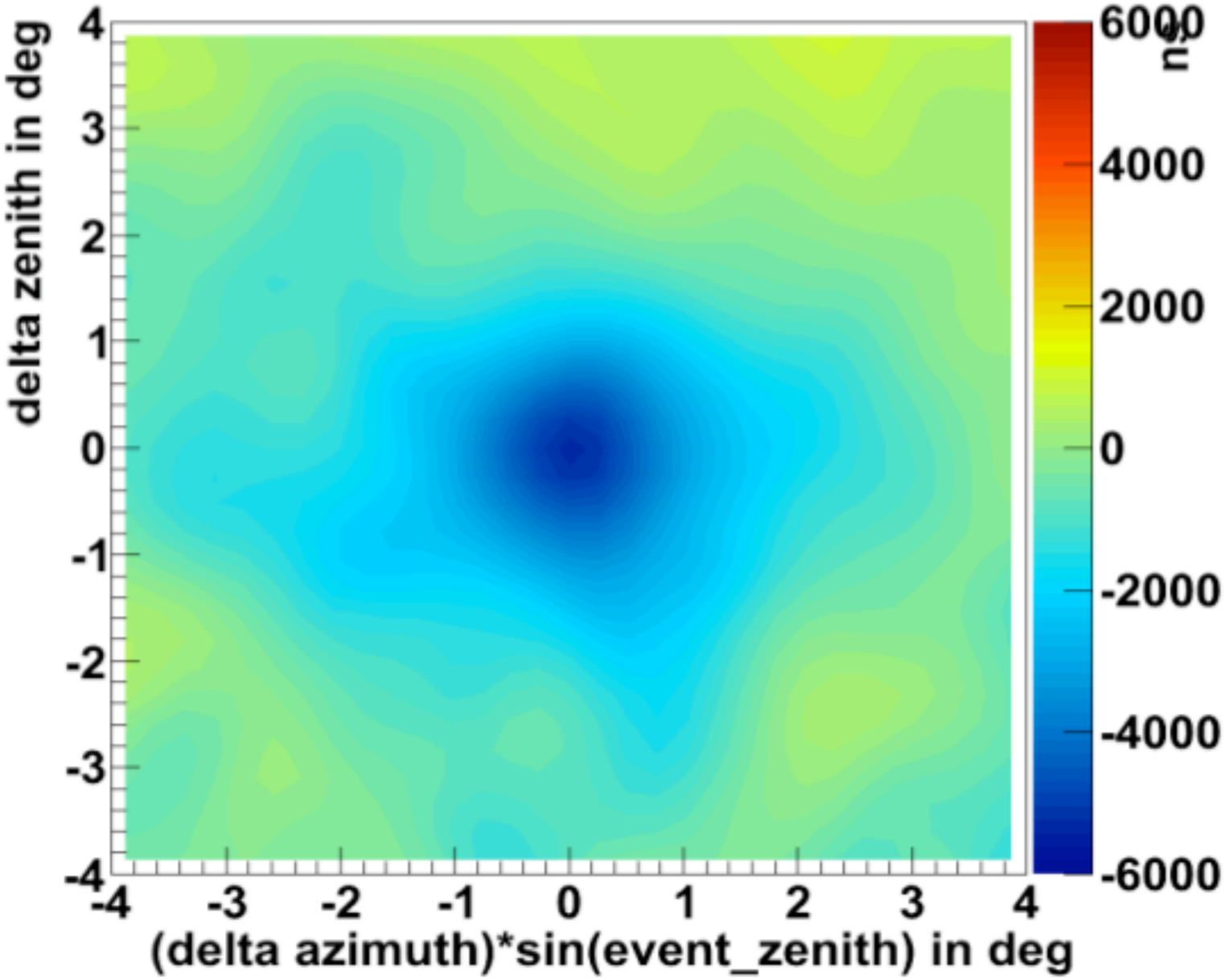
- Muon decay
  $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$
  $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$

- Prompt decay of charmed mesons
  $\Upsilon \sim 2.7$ up to 10^4 TeV
  ν_μ and ν_e

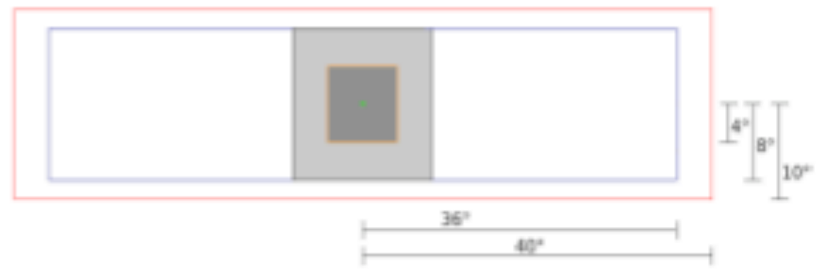
- No ν_τ



Moon shadow

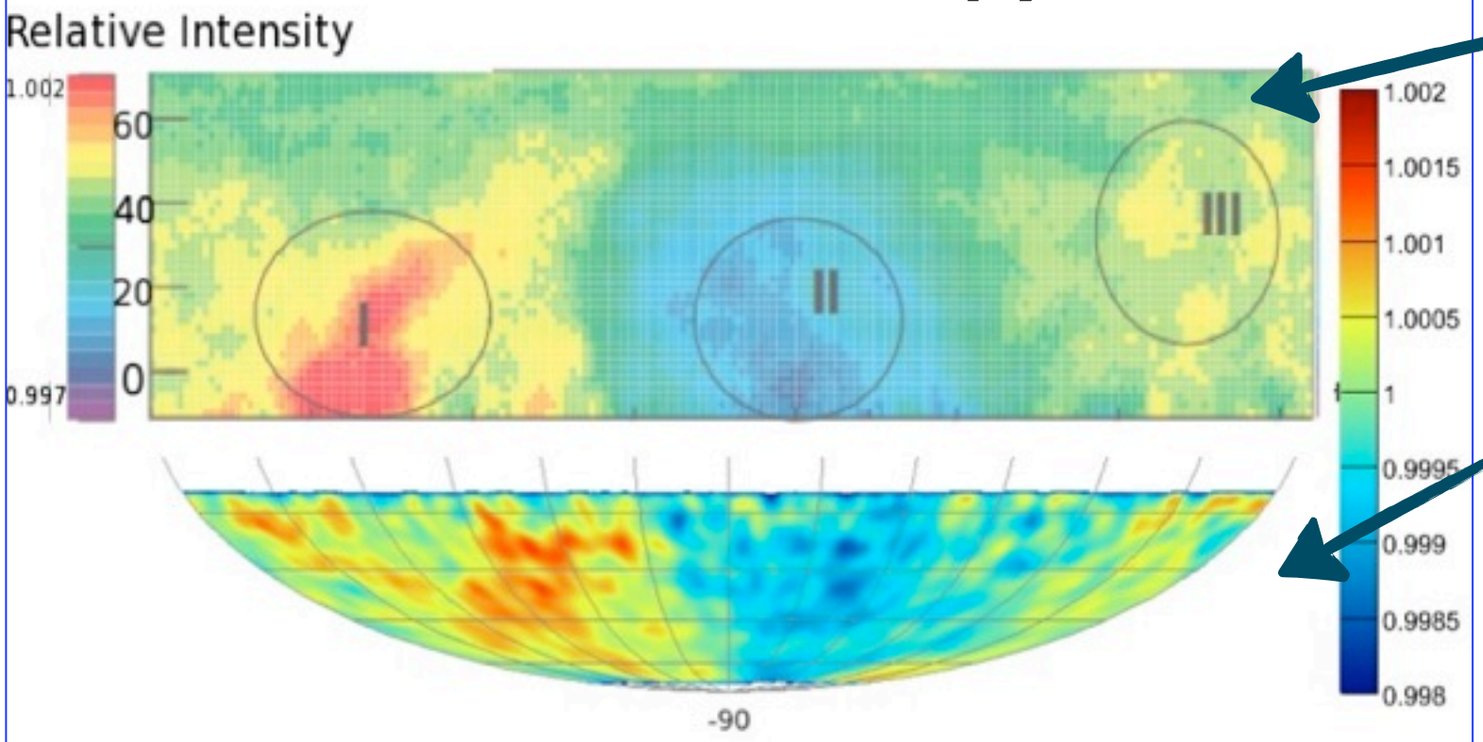


Size of the moon
(radius ~= 0.25°)



8380055 events are left considering cuts & window of 16.00 x 16.00 deg
expected number of shadowed events : 5732
observed shadowed events at moon position : -5378

CR anisotropy

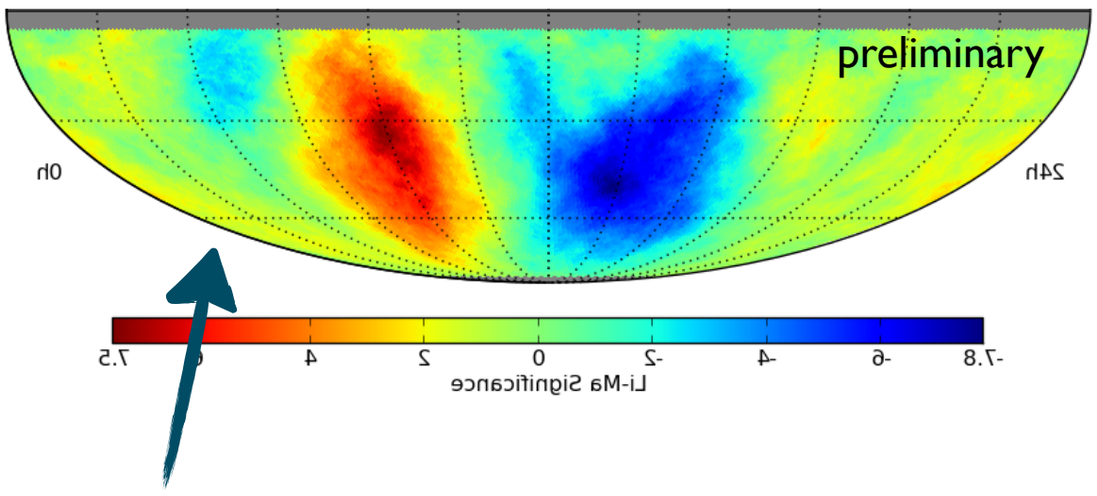


Tibet Array
northern hemisphere

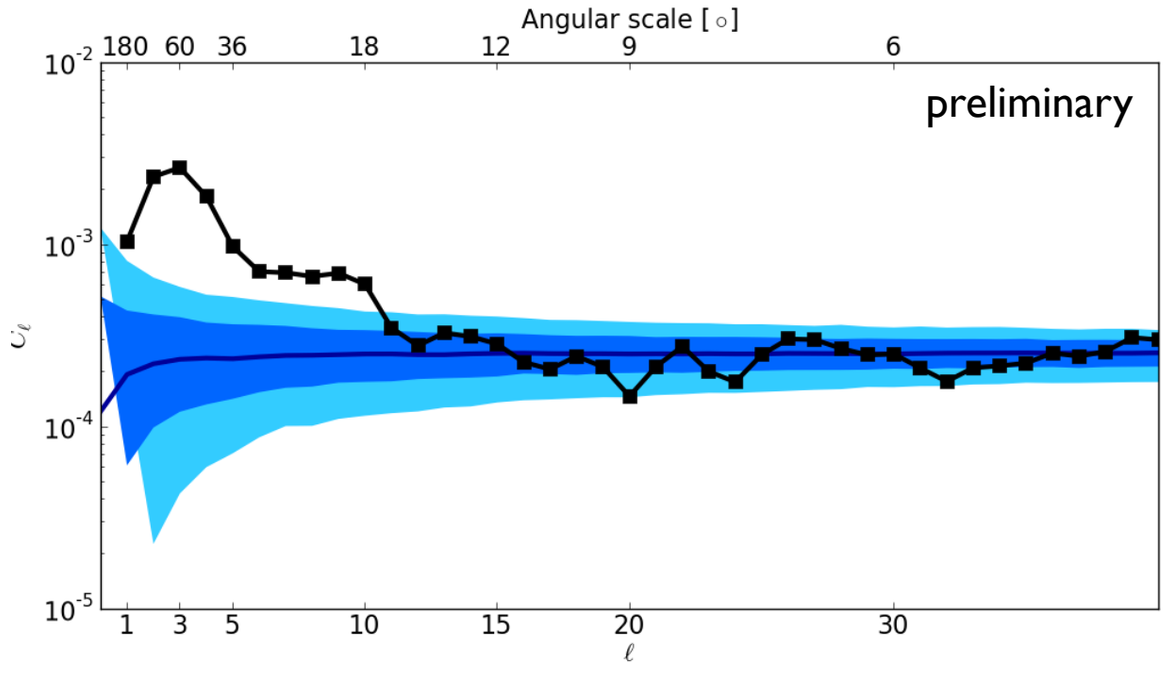
IC22
4.3G muon tracks
median energy 12 TeV
median angular resolution 3 degr

$A1 = 6.4 \pm 0.2 \text{ stat.} \pm 0.8 \text{ syst.} \cdot 10^{-4}$
$A2 = 2.1 \pm 0.3 \text{ stat.} \pm 0.5 \text{ syst.} \cdot 10^{-4}$

$$\sum_{i=1}^{n=2} A_i \cos(i(\alpha - \phi_i)) + B$$



IC40
20G muon tracks
medium scale structure 20 degrees
not just dipole + quadrupole



Why CR Anisotropy ?

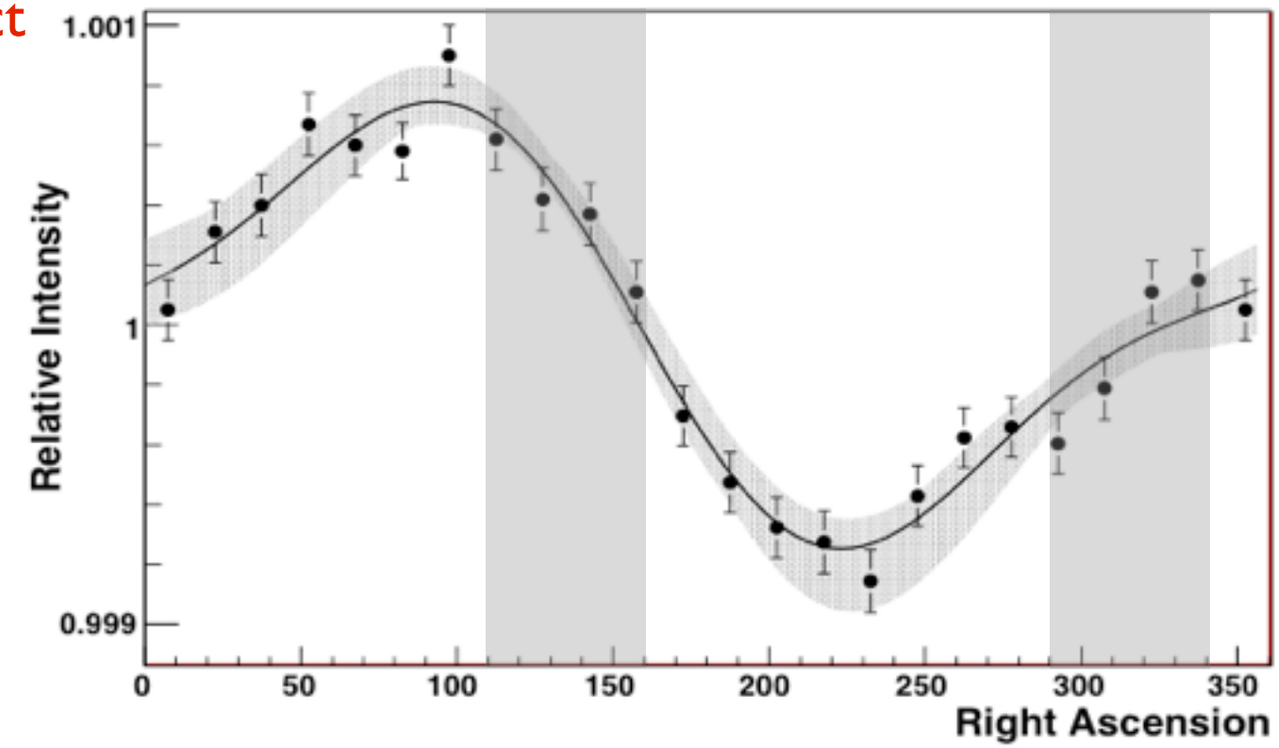
- Compton-Getting effect: CR dipole due to motion of solar system through Galaxy.

Structure more complicated

Dipole phase not correct

Expected Minimum

Expected Maximum



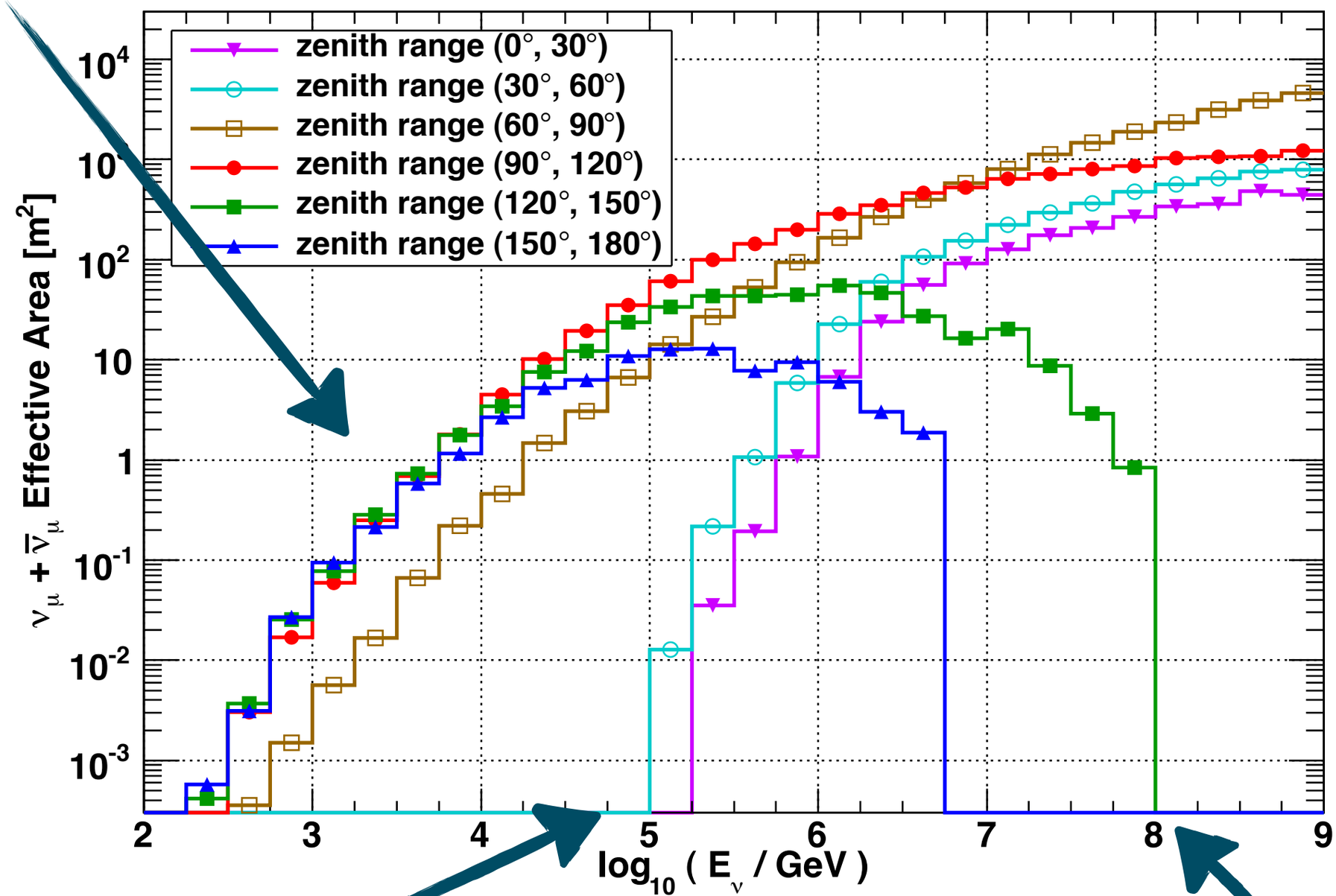
- Maybe local/Galactic B field structure?
  Study on energy dependence in progress...

Effective Area for muon neutrinos

4π sensitivity!

low E: below horizon

high E: most target when inclined

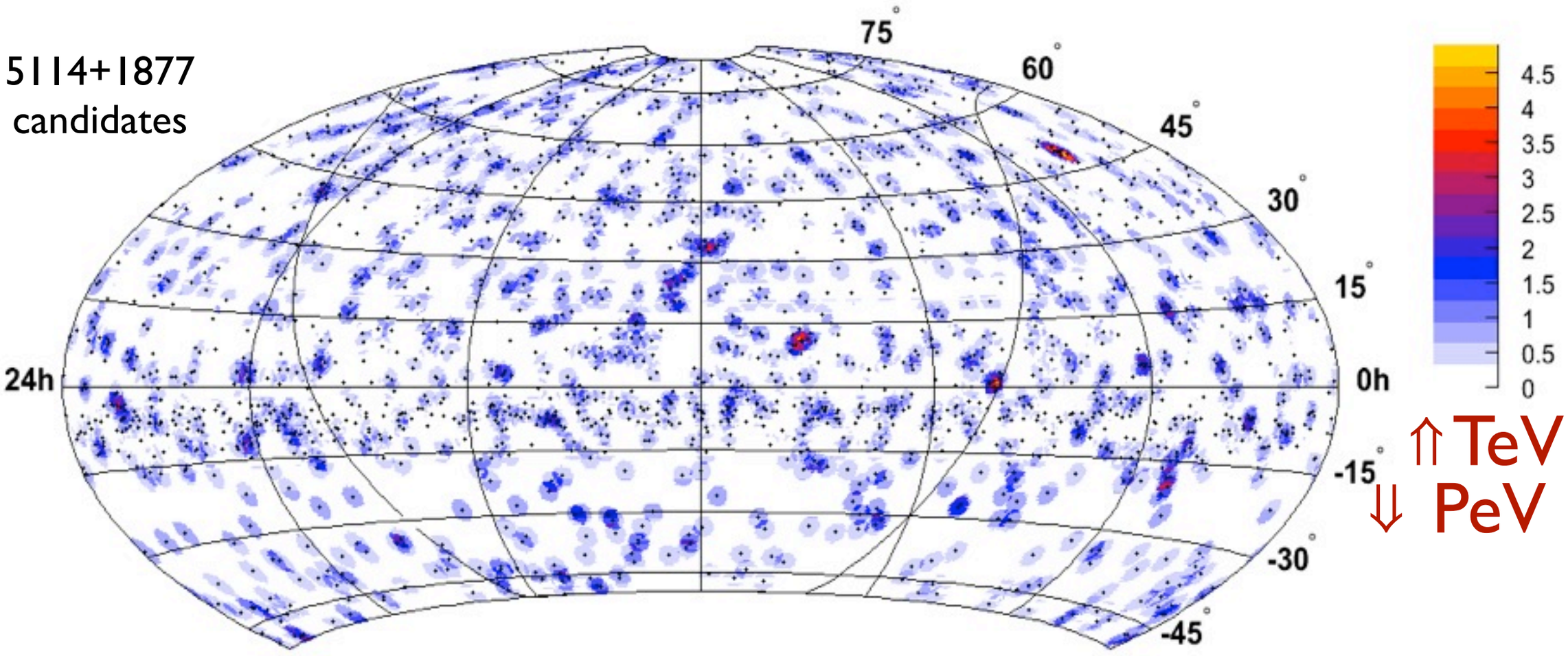


downgoing atm. μ bg: low E cut out

Earth opaque at high E

IC22 Point source search

5114+1877
candidates



Unbinned likelihood search

$$\mathcal{L} = \prod_{i=1}^{n_t} \left(\begin{matrix} n_s \\ n_t \end{matrix} S_i(x_i, x_s, E_i, \gamma) + \begin{matrix} n_{bg} \\ n_t \end{matrix} B_i(x_i, E_i) \right)$$

signal pdf
includes E^{-2}
spectrum

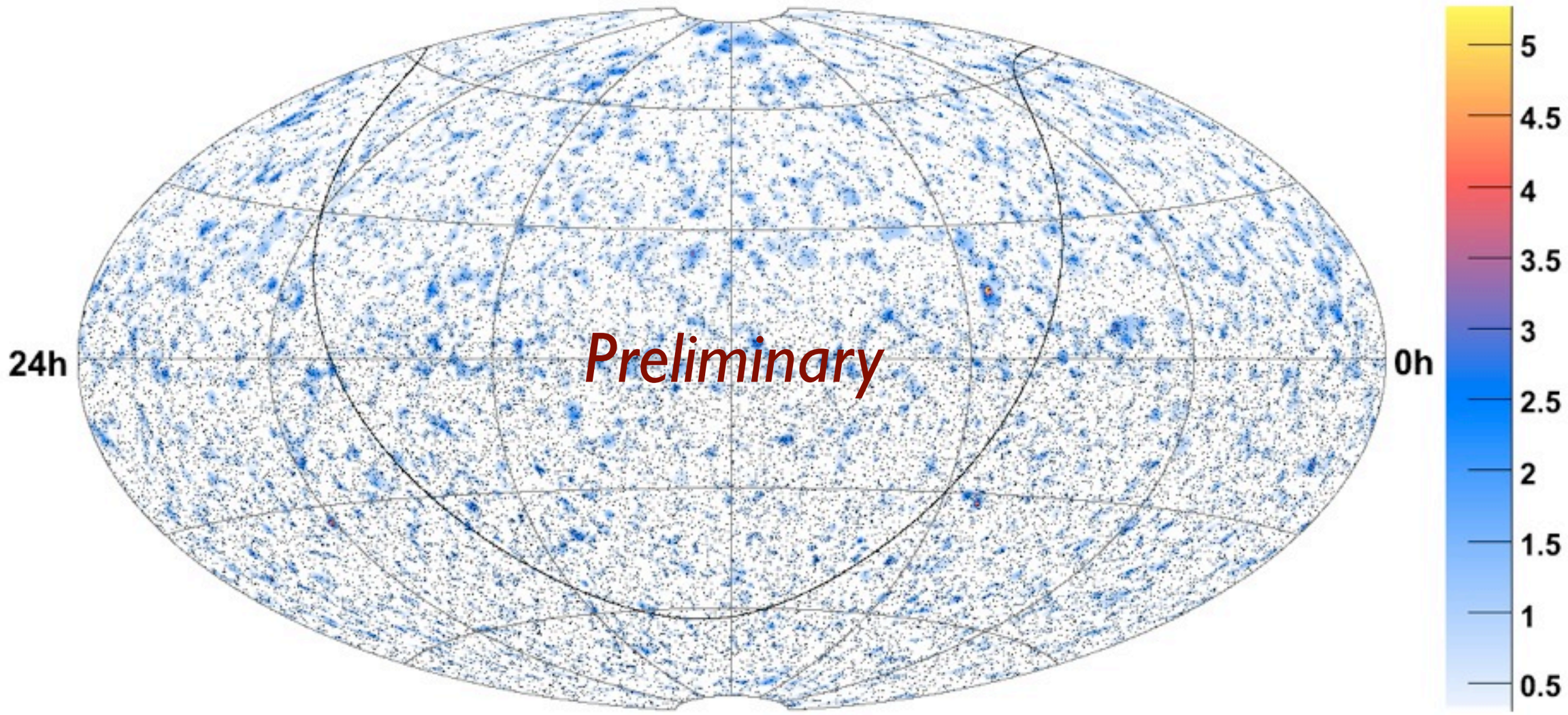
background pdf
from data

Hottest spot: RA 153.375°, decl 11.375°
post-trial p-value ~1%

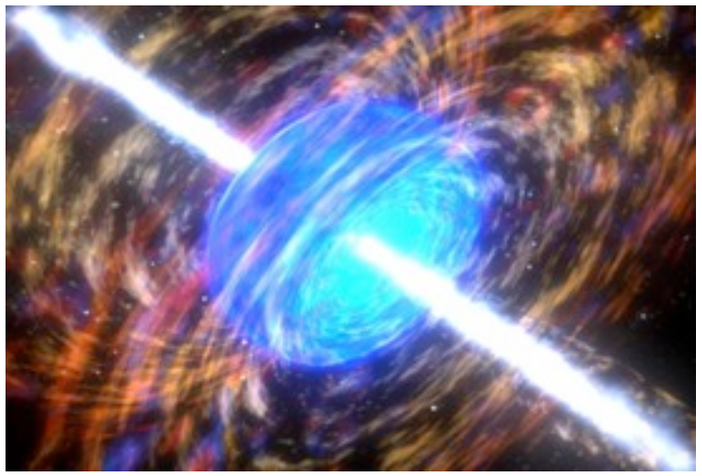
(67 out of 10,000 scrambled datasets show hotspot of similar or higher significance)

no significant result

IC40 Point source search



- IC22 hotspot disappeared
- No sign of a source: 96% of scrambled data sets have more significant spot
- No significant results for list of possible sources
- 4π sky coverage



Gamma Ray Bursts

Using SWIFT, BATSE and other satellite data

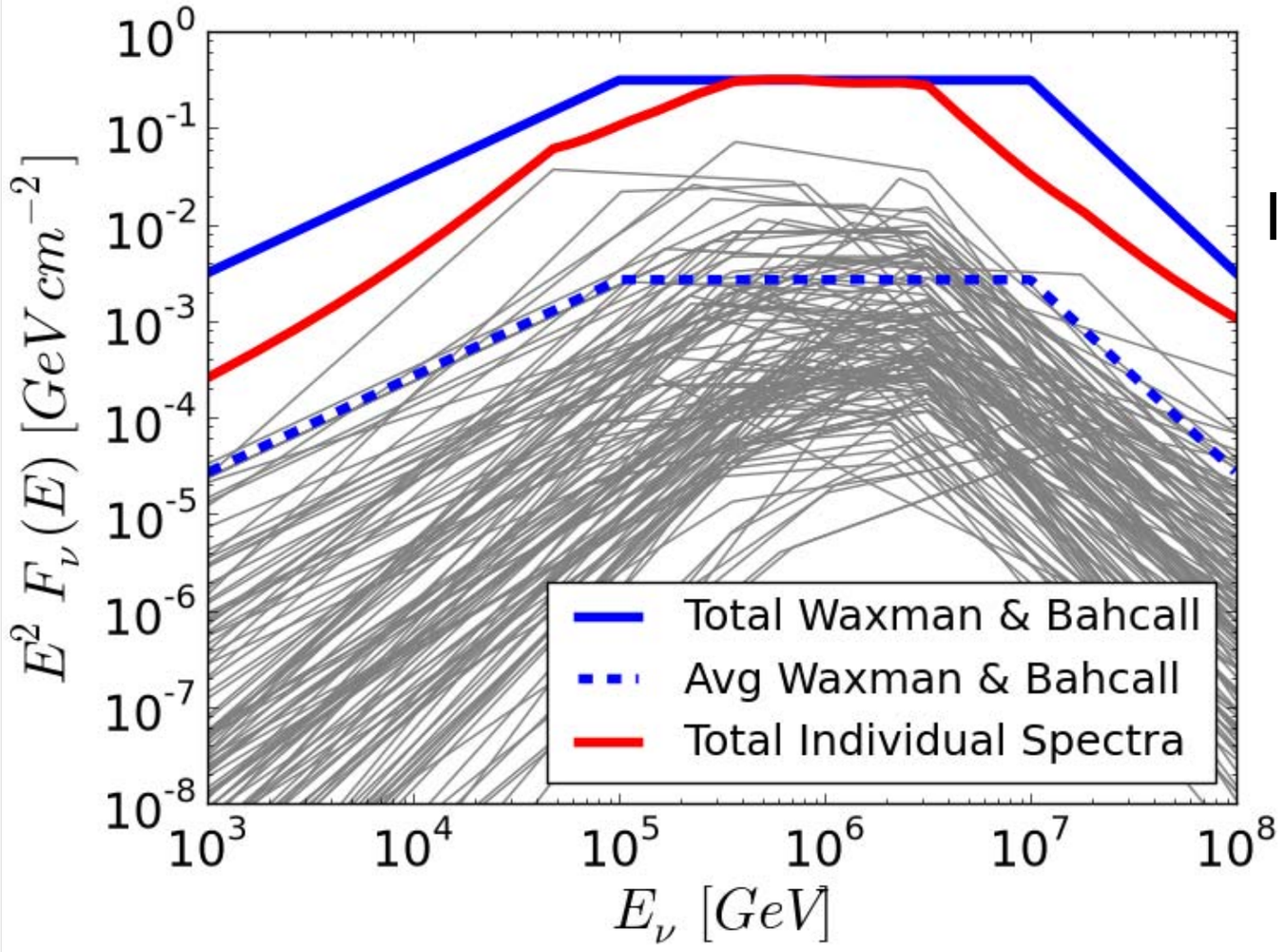
Individual neutrino spectra based on photon spectra (cf. Guetta et al 2004)

$p\gamma \rightarrow \Delta \rightarrow n\pi^+$

Neutrinos from pion and muon decay

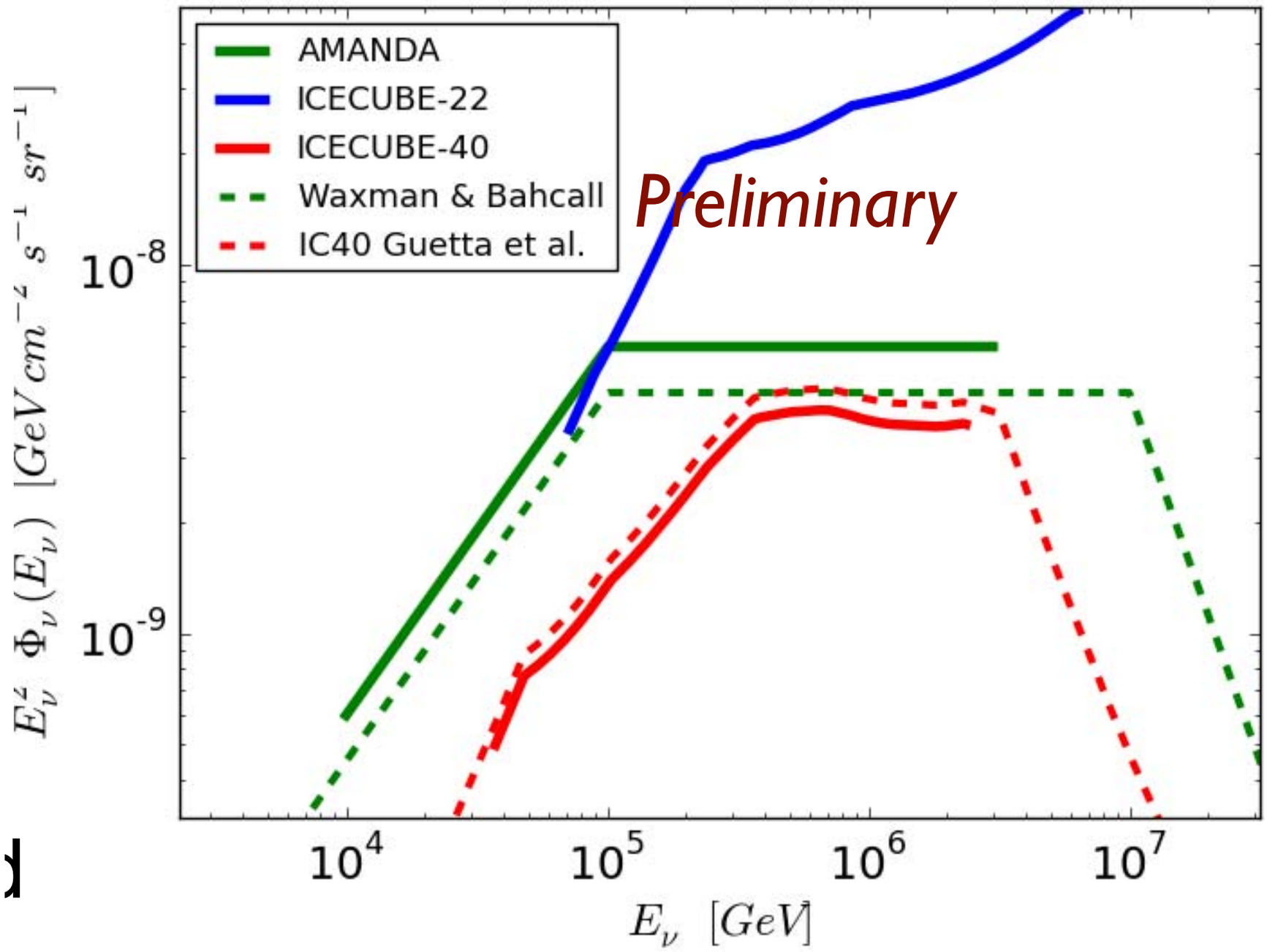
First breakpoint: inversely proportional to photon spectrum breakpoint

Second breakpoint: $\tau_\pi, \tau_\mu > \tau_{sync}$



IC40: 117 GRBs accumulated

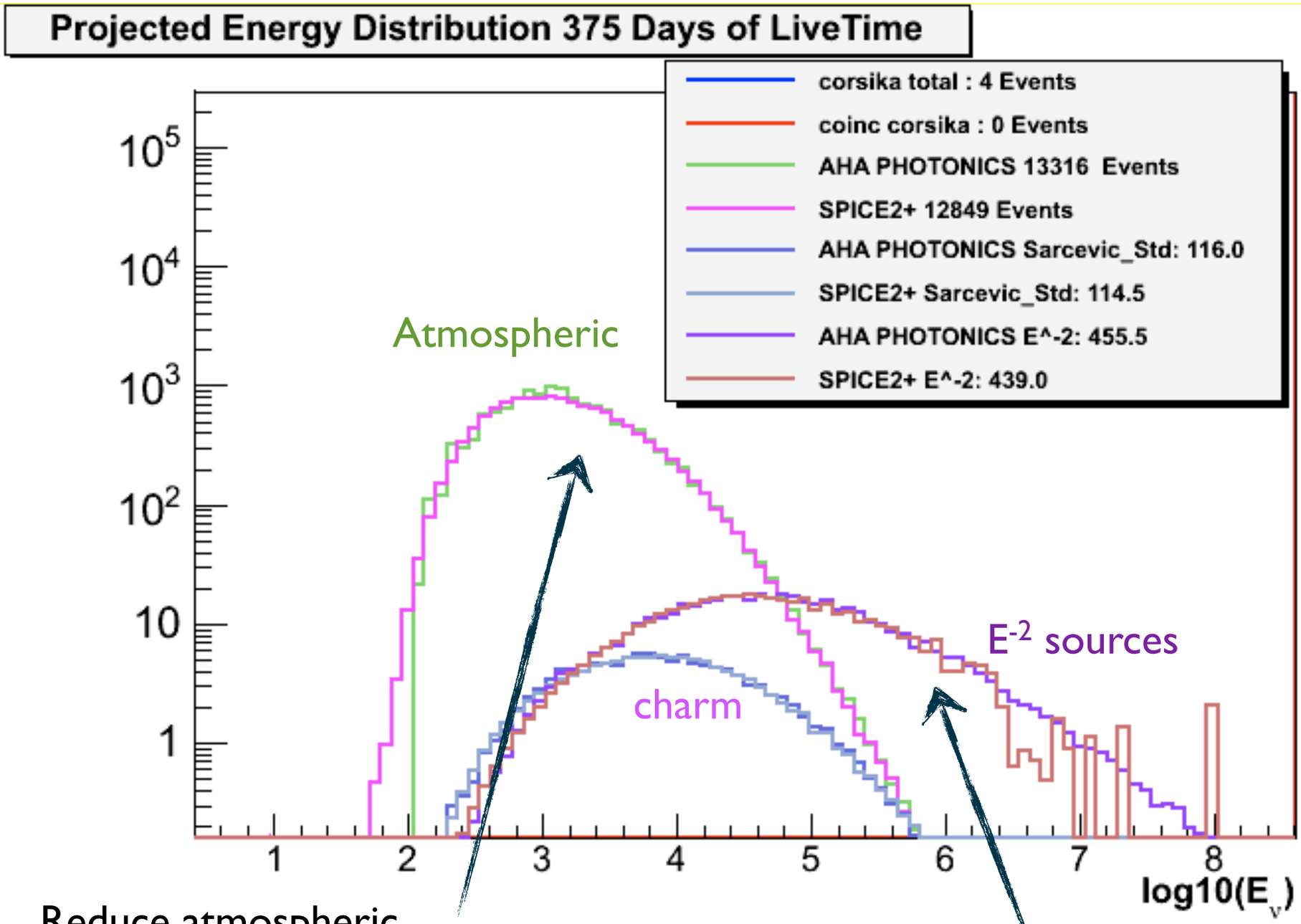
Gamma Ray Bursts



IC59 analysis in progress...

Diffuse analysis

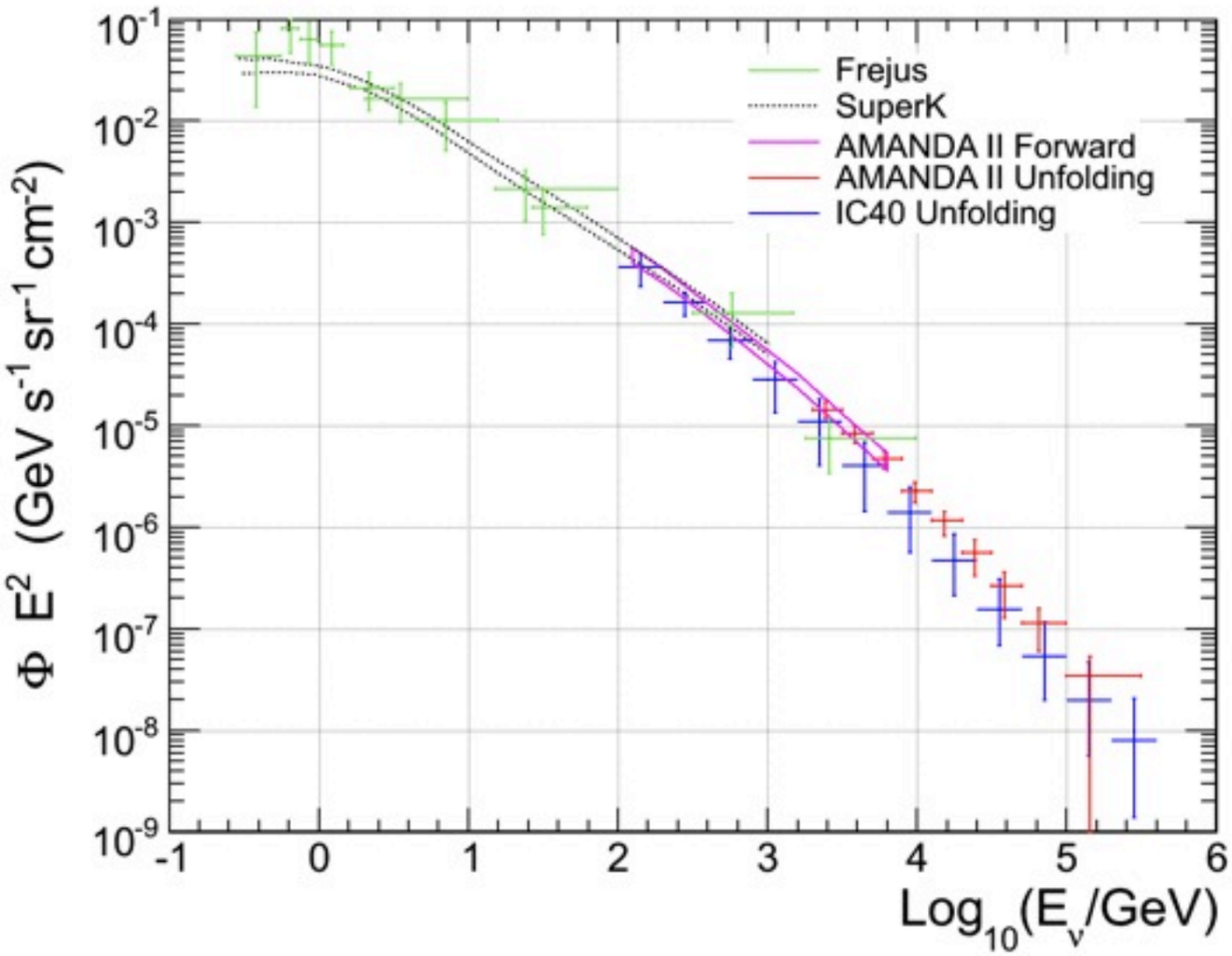
- look for combined flux of all neutrino sources (in northern hemisphere)



Reduce atmospheric background by searching for cascade events

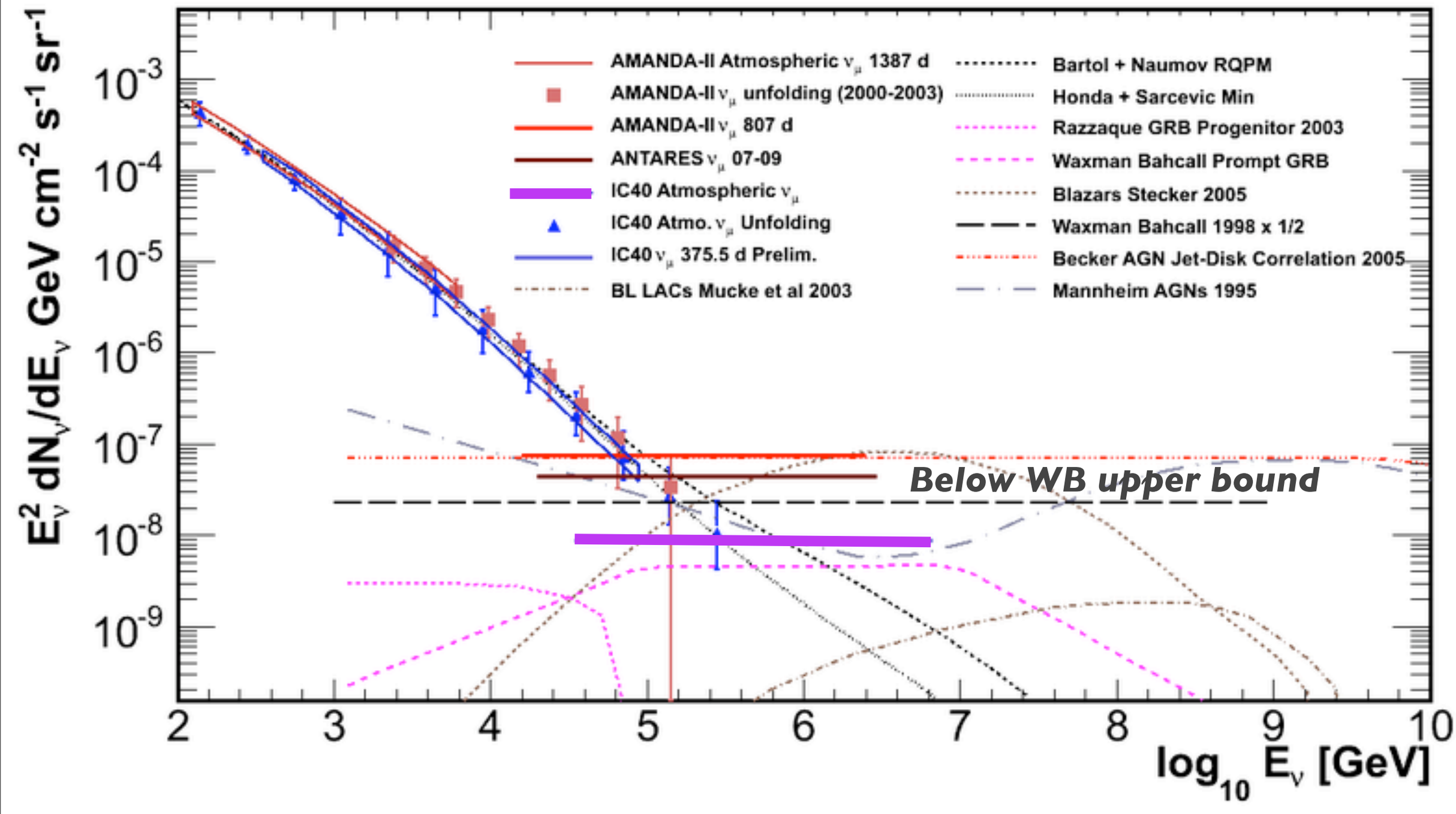
Look for hardening of spectrum at high energies

IC40 atmospheric

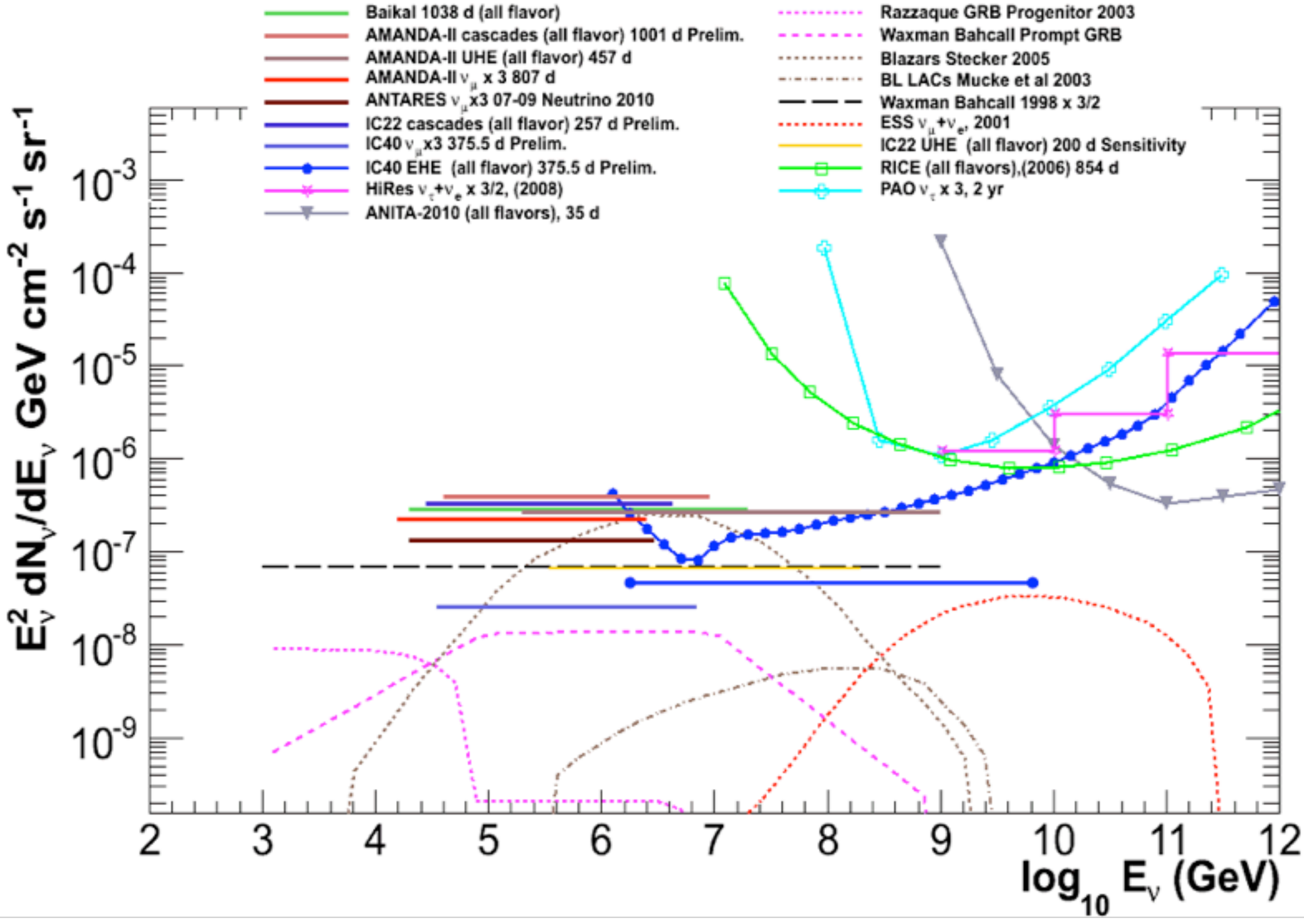


- Measured atmosperic flux consistent with theory and other experiments
- Multi-year full detector will extend range > PeV charm region

Diffuse IC40 ν_μ



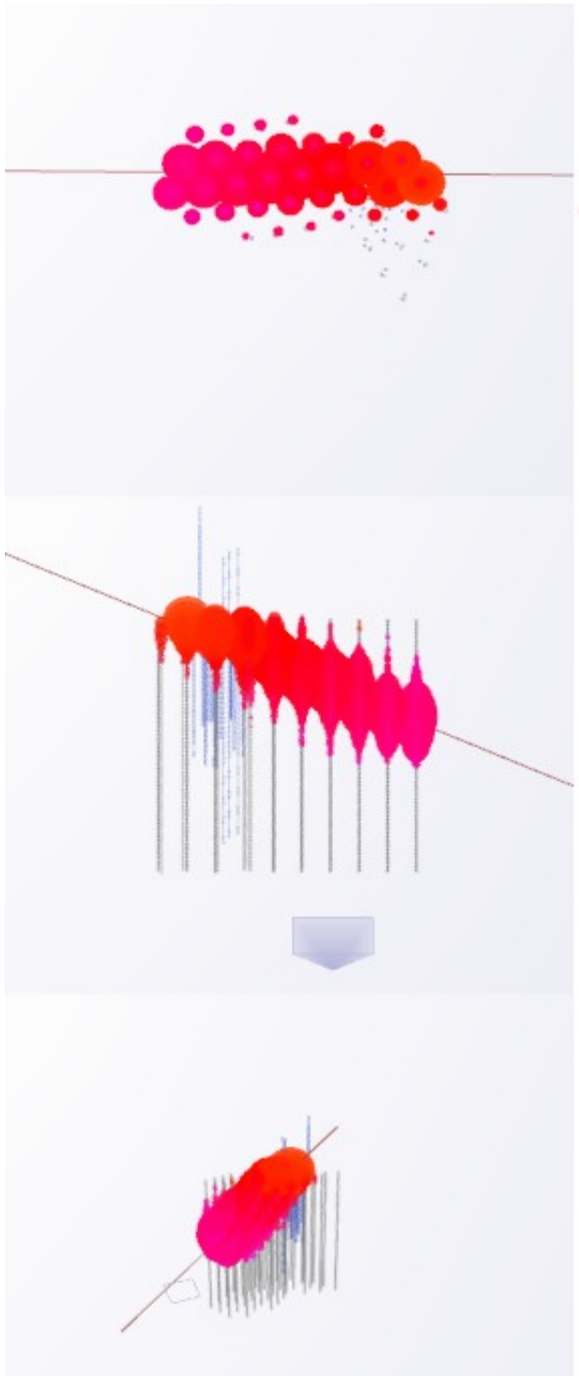
Extremely high energy

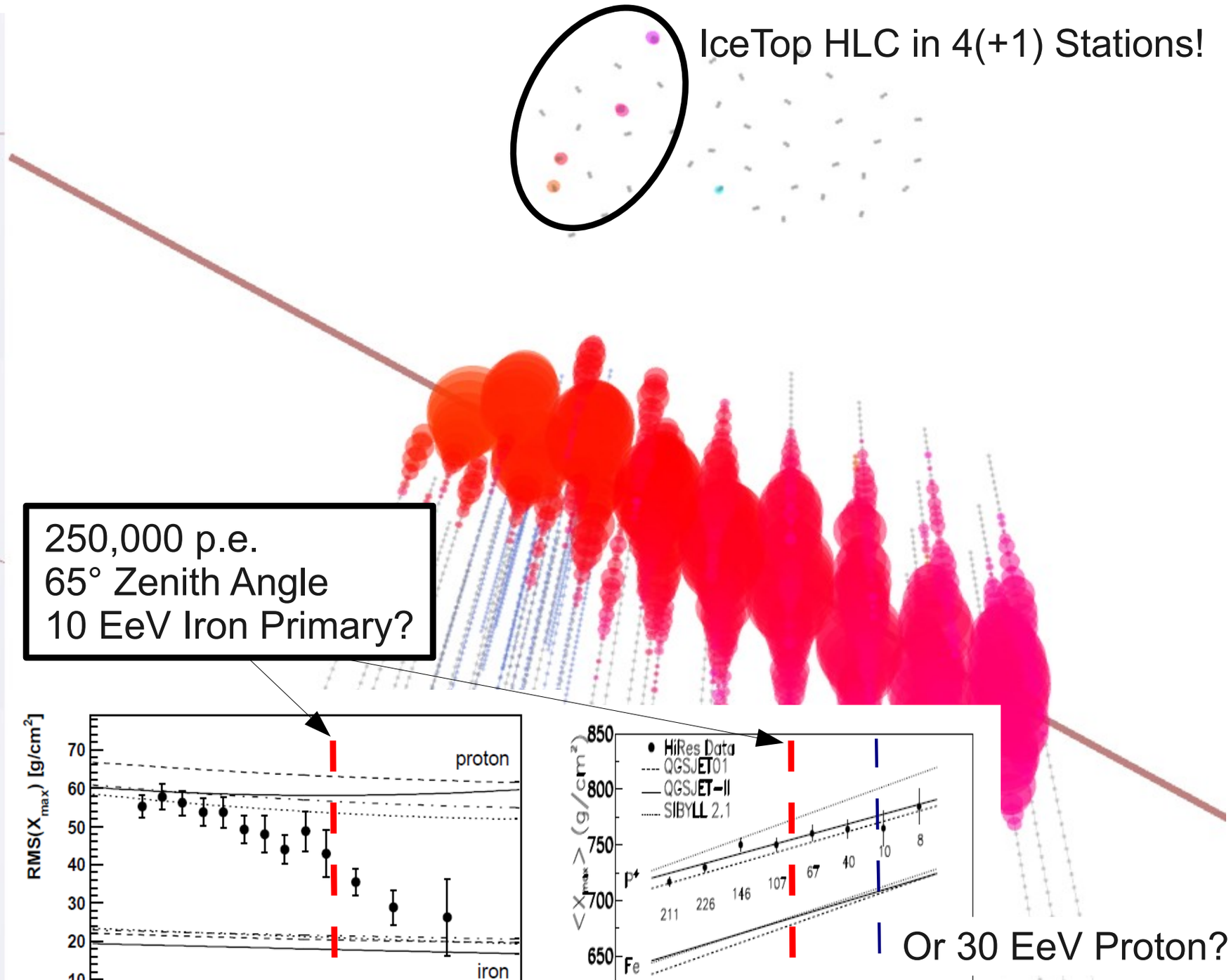


Look upward: Earth opaque to high energy neutrinos

Low background: heavy element CR showers

Biggest Shower in IC40 EHE Analysis





IceTop HLC in 4(+1) Stations!

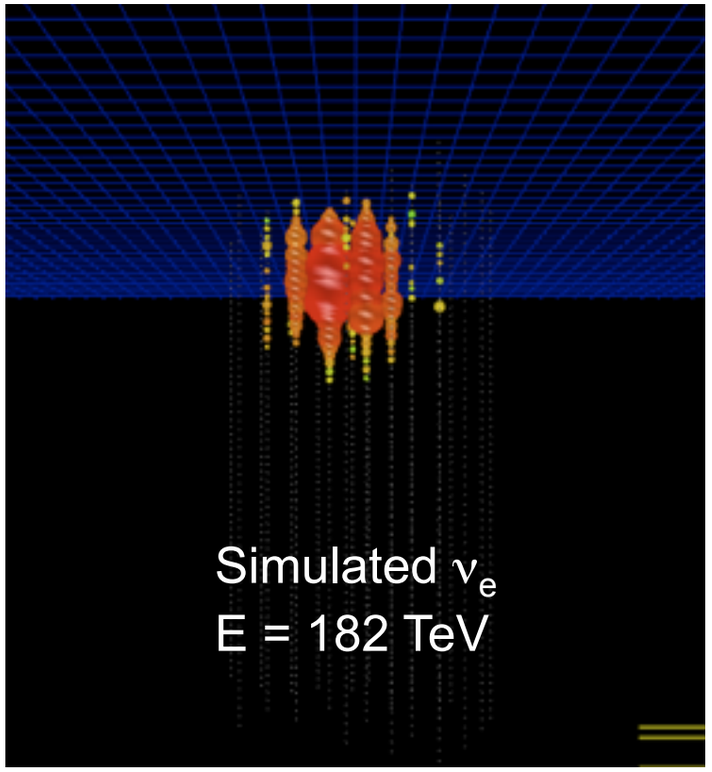
250,000 p.e.
65° Zenith Angle
10 EeV Iron Primary?

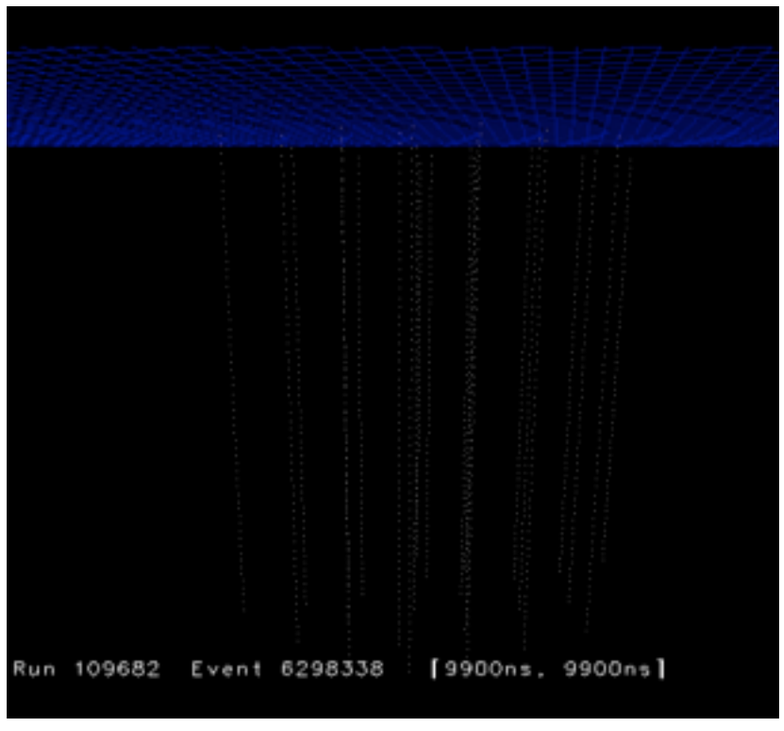
J. Abraham et al.: arxiv:1002-0699

R.U.Abbasi et al., arxiv:0910-4184

Or 30 EeV Proton?

Cascades





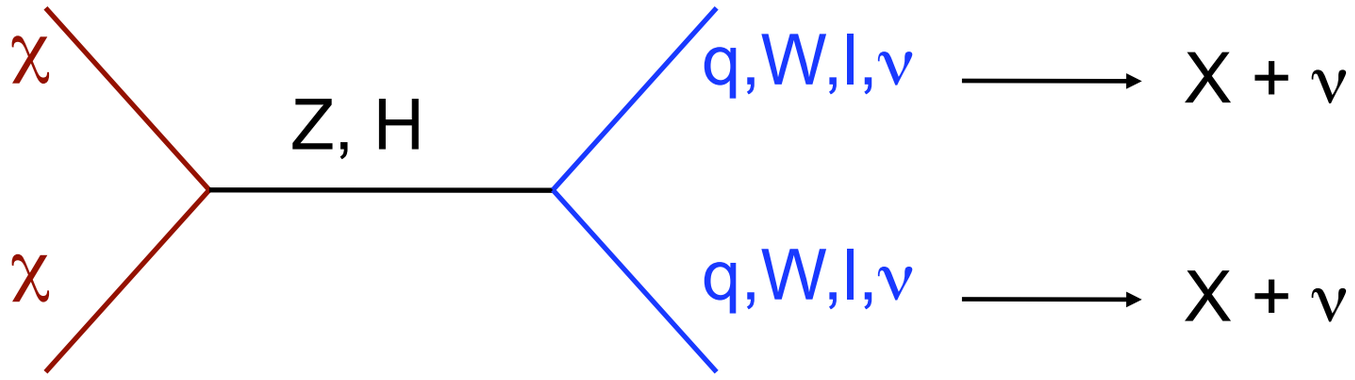
- From ν_e, ν_τ charged current and ν_x neutral current: atmospheric bg lower
- Use surrounding strings for veto
- IC22 (270 days):
  14 candidates
  8.3 ± 3.6 expected background

Surviving event with
highest energy: 134 TeV

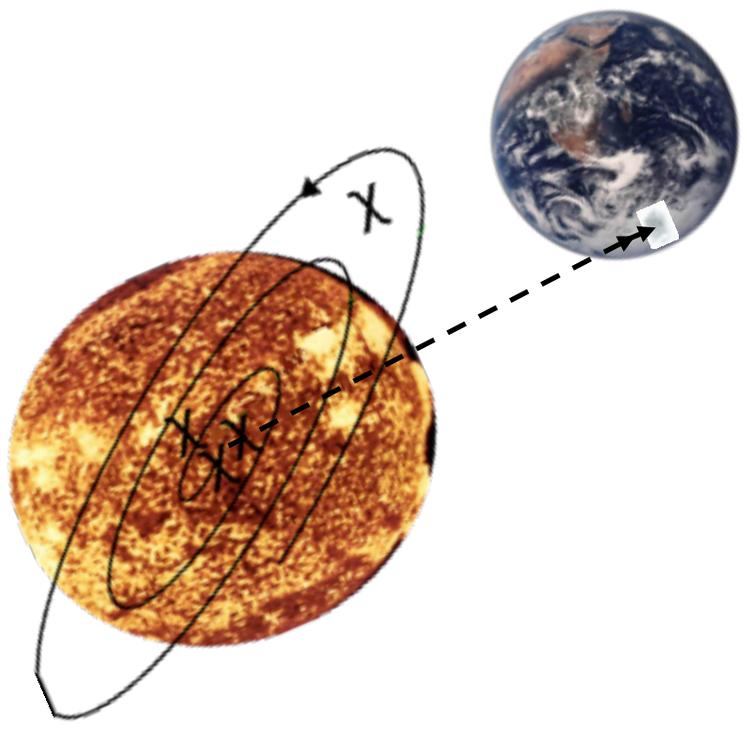
Brightest hit ~10,000 p.e.'s

Bigger detector:
- *more veto strings*
- *lower E threshold*

Search for Dark Matter

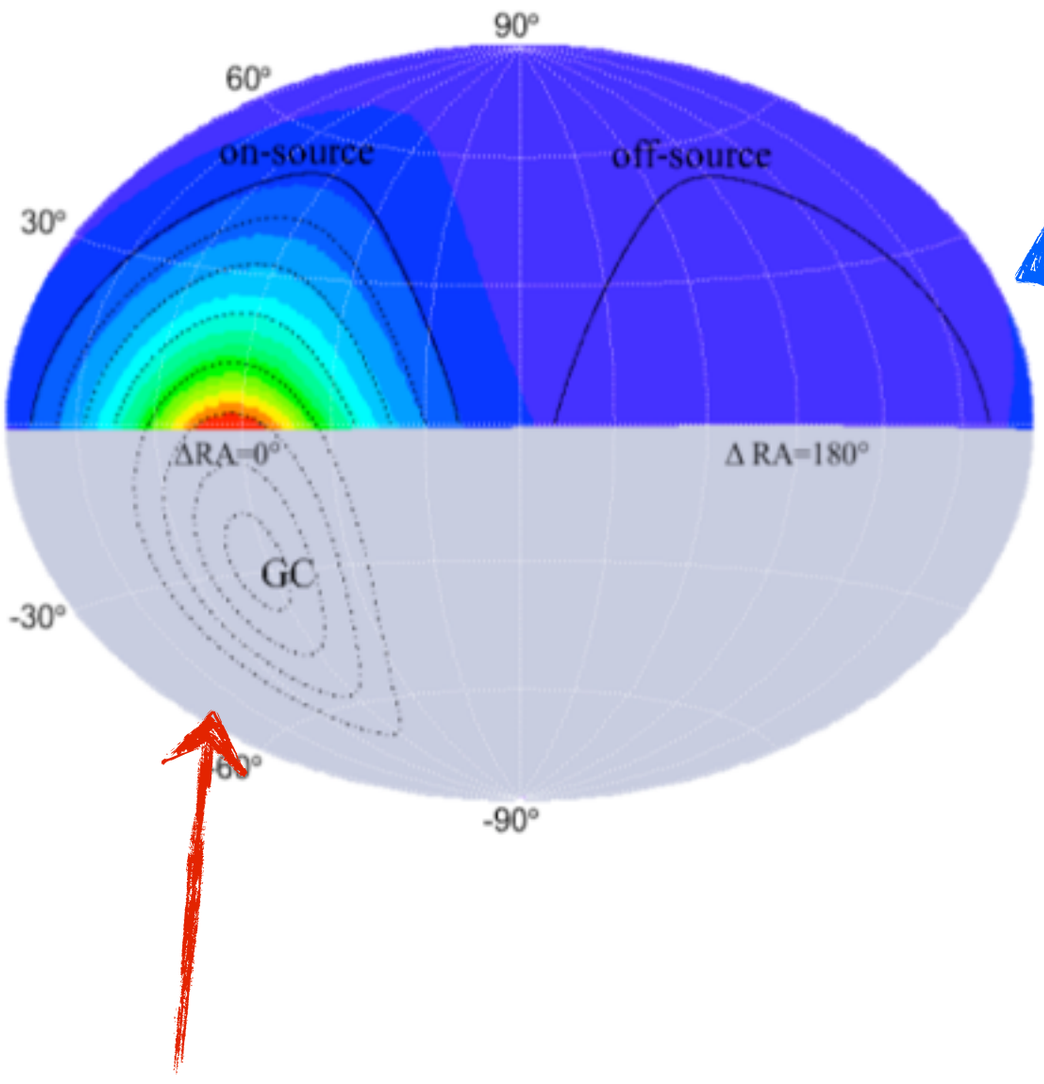


- Promising WIMP candidate:
  Neutralino χ (lightest susy particle, stable)
- weak interaction allows χ capture in dense objects:
  Earth, Sun, Galactic center
- χ is Majorana particle: self annihilation → neutrinos
  Search for excess from dense objects

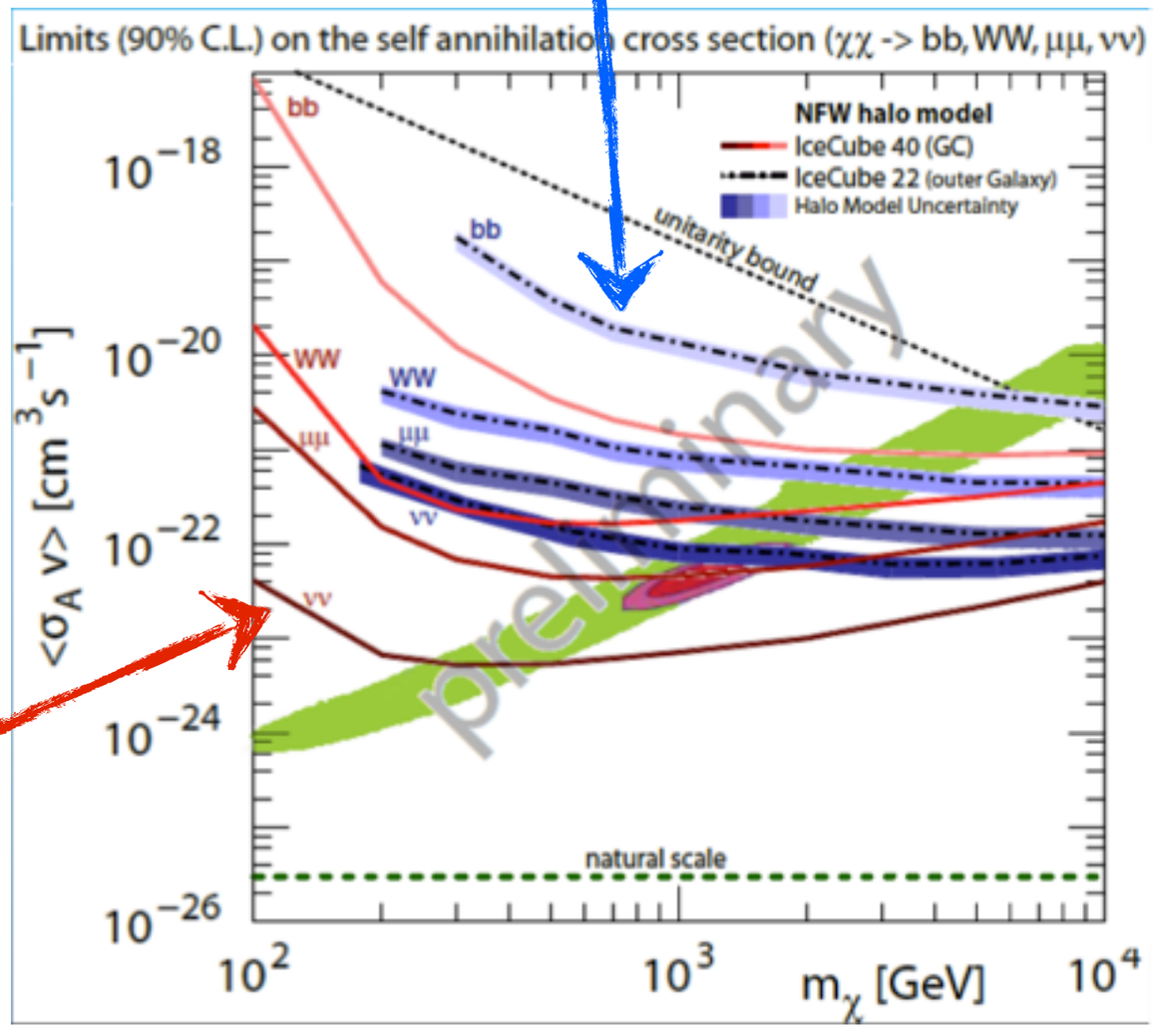


DM from Galactic center

Northern sky:
Compare on-source
and off-source region



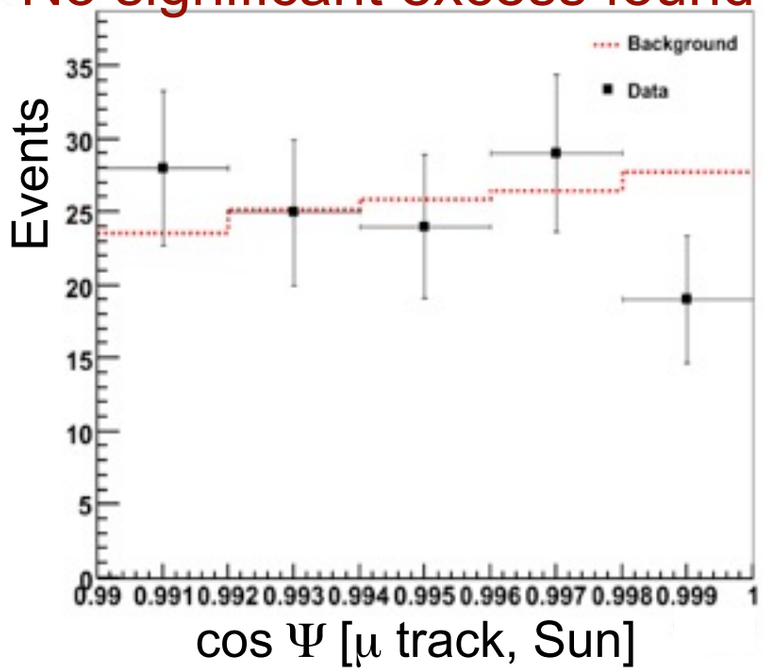
Southern sky:
View on Galactic Center
CR muon background
look for tracks starting in detector

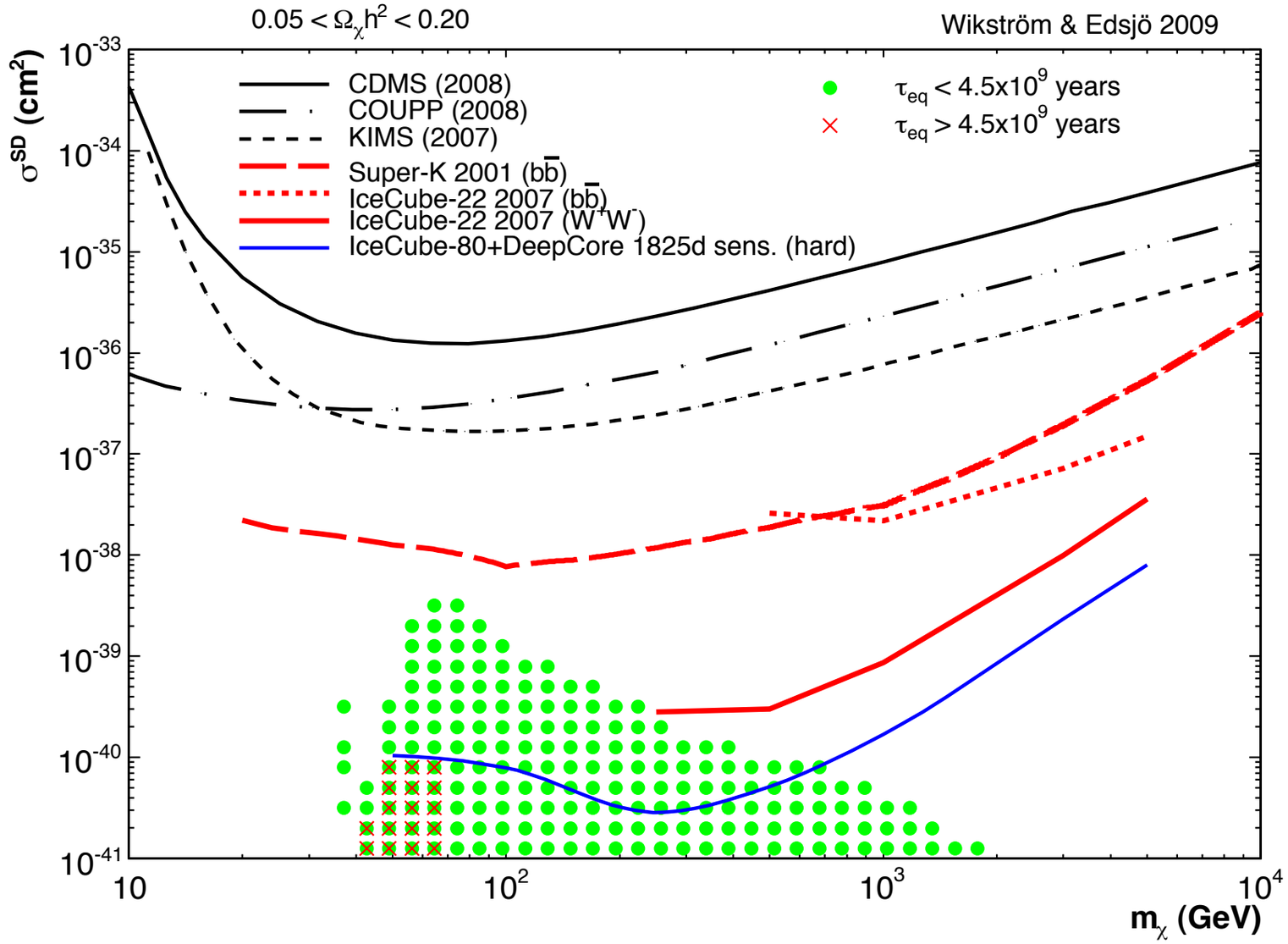


Solar neutralinos

- χ annihilation rate from Sun depends on capture rate
  (if equilibrium condition is satisfied)
- hydrogen:
  spin dependent cross section most relevant
- complementary to direct searches (mostly spin independent)

No significant excess found

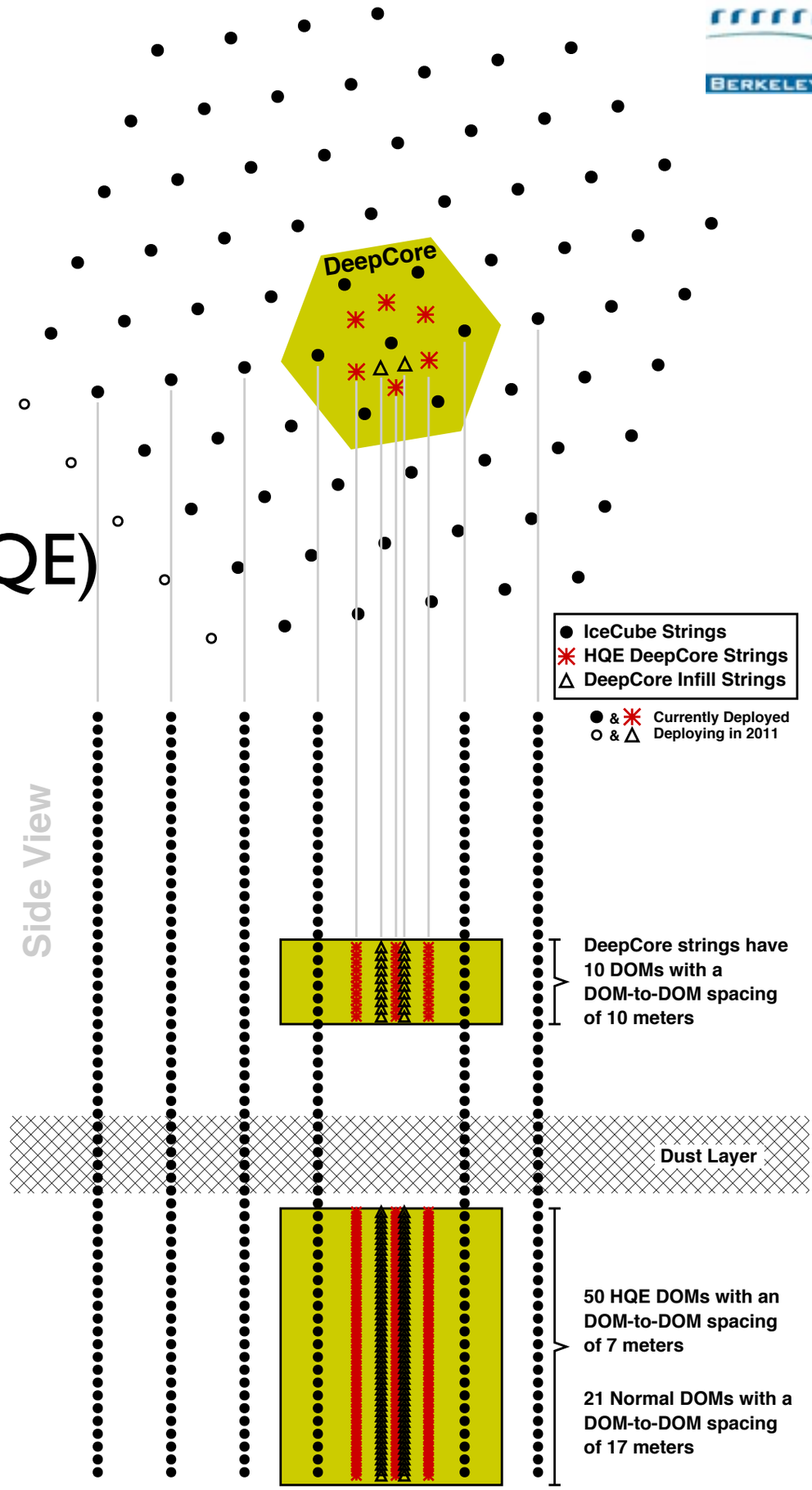




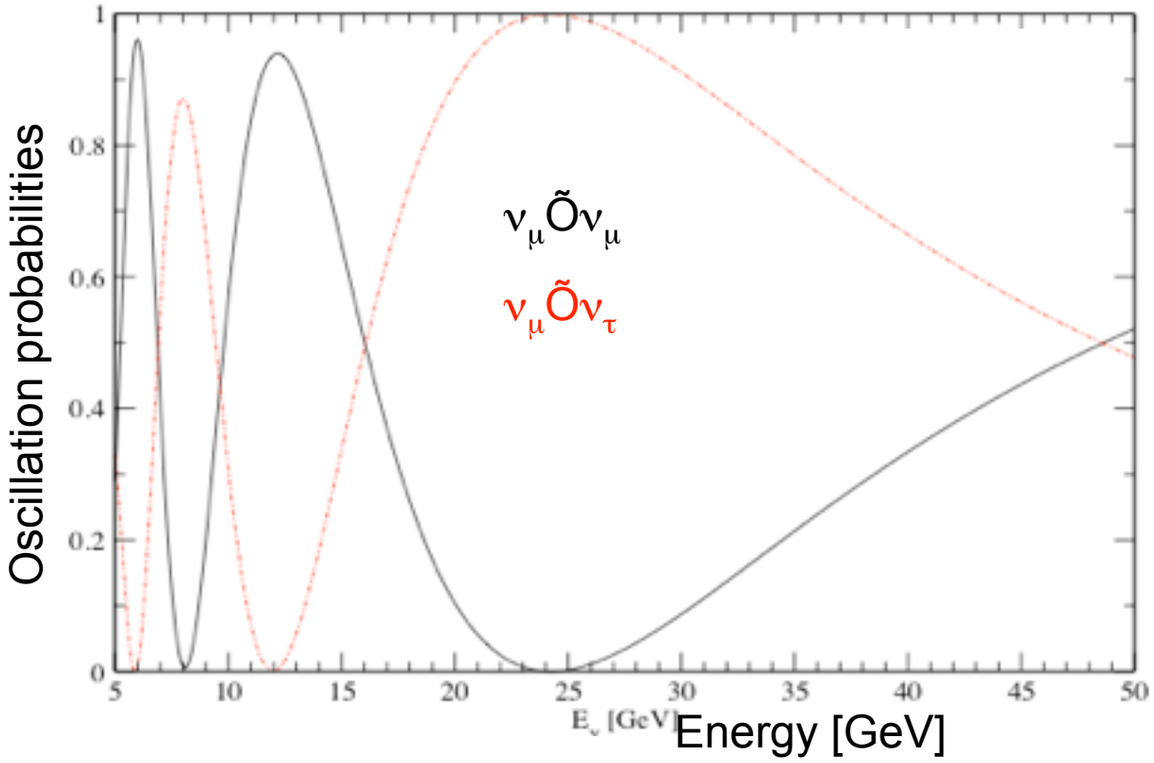
DeepCore

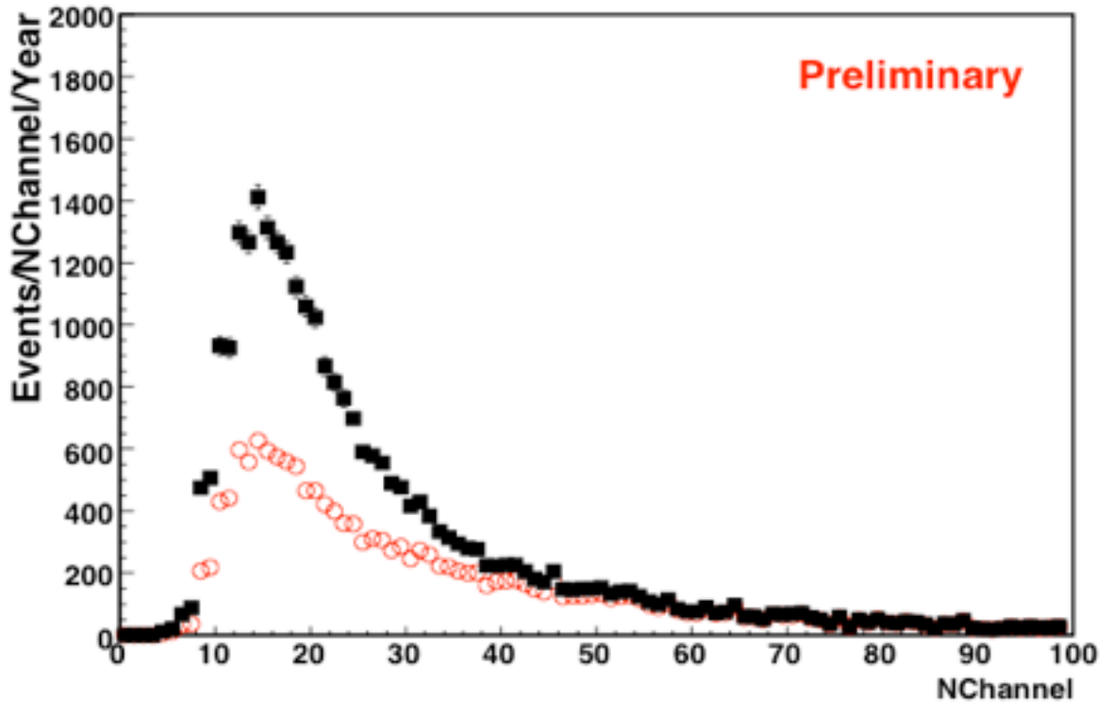
* dense infill array
* cleanest ice
* more sensitive DOMs (30% higher QE)

- dense volume + veto from other strings:
  open southern sky at lower energies
- lower energy threshold <10 GeV
  WIMP search
  atm. neutr ino spectrum
  ν_μ disappearance at 25 GeV



DeepCore: oscillations

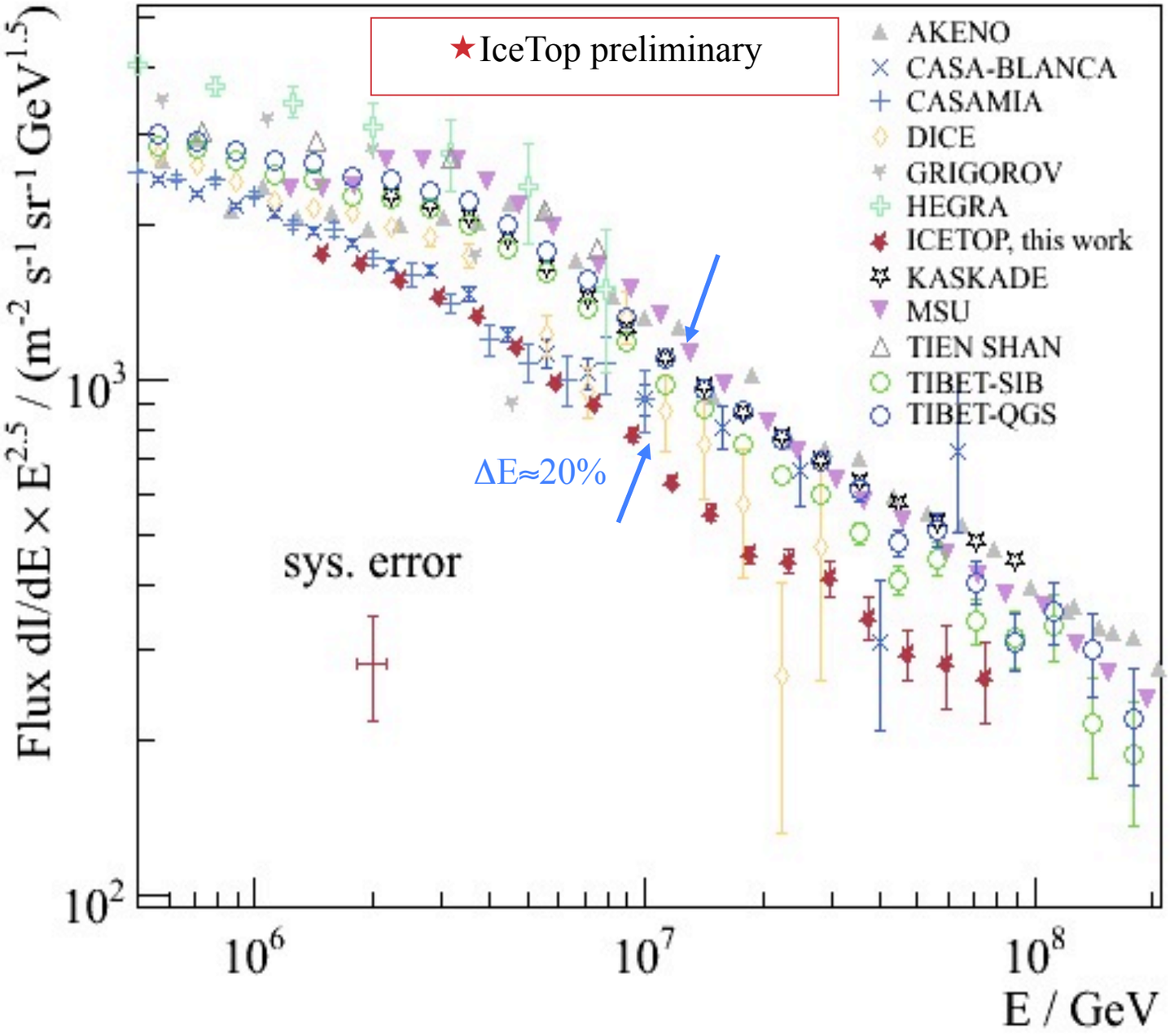




- ν_μ disappearance in 10-100 GeV region on Earth baseline
- ν_τ appearance? background of ν_μ C.C. with short muon track

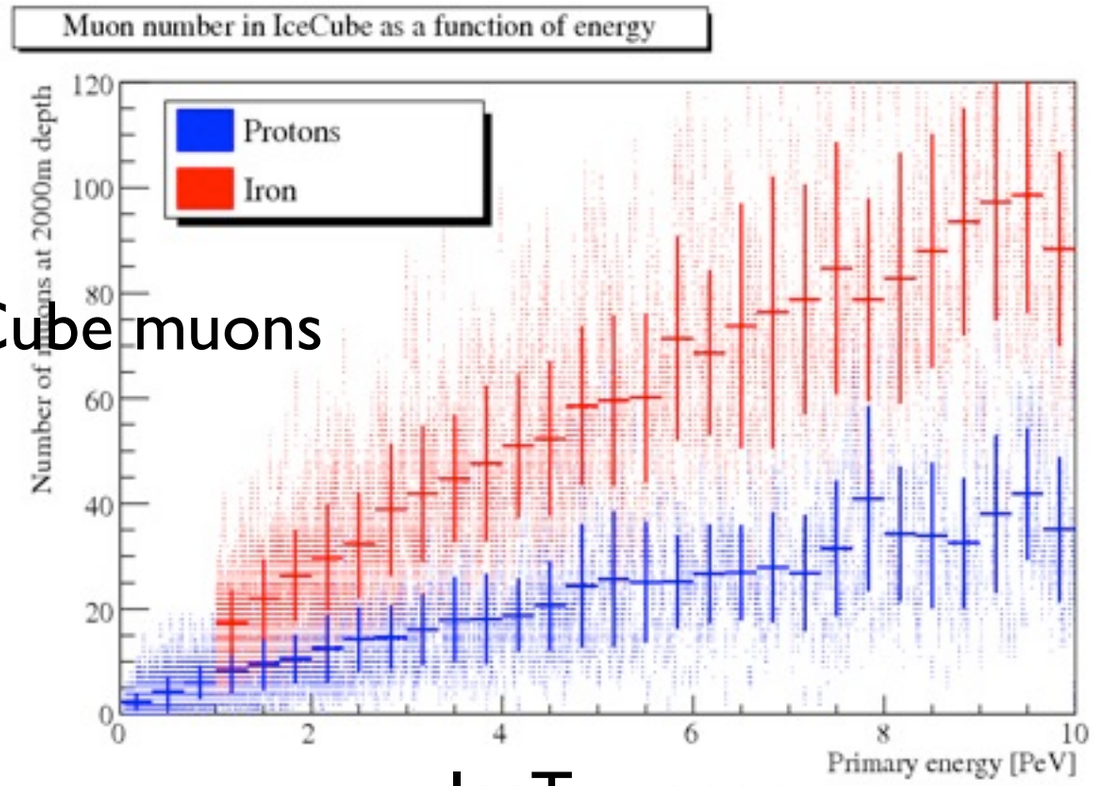
IceTop

- Sensitive to CRs at and above the knee
- IceCube provides measurement of muonic component
- Composition studies
- Veto for neutrino analyses

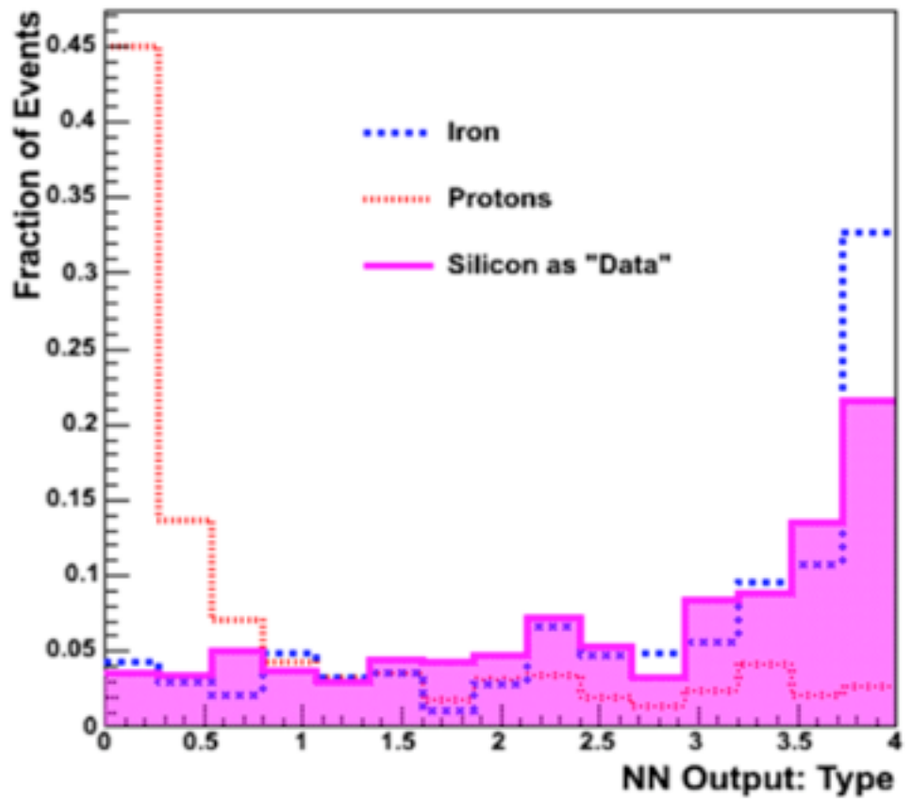


IC22 composition

IceCube muons

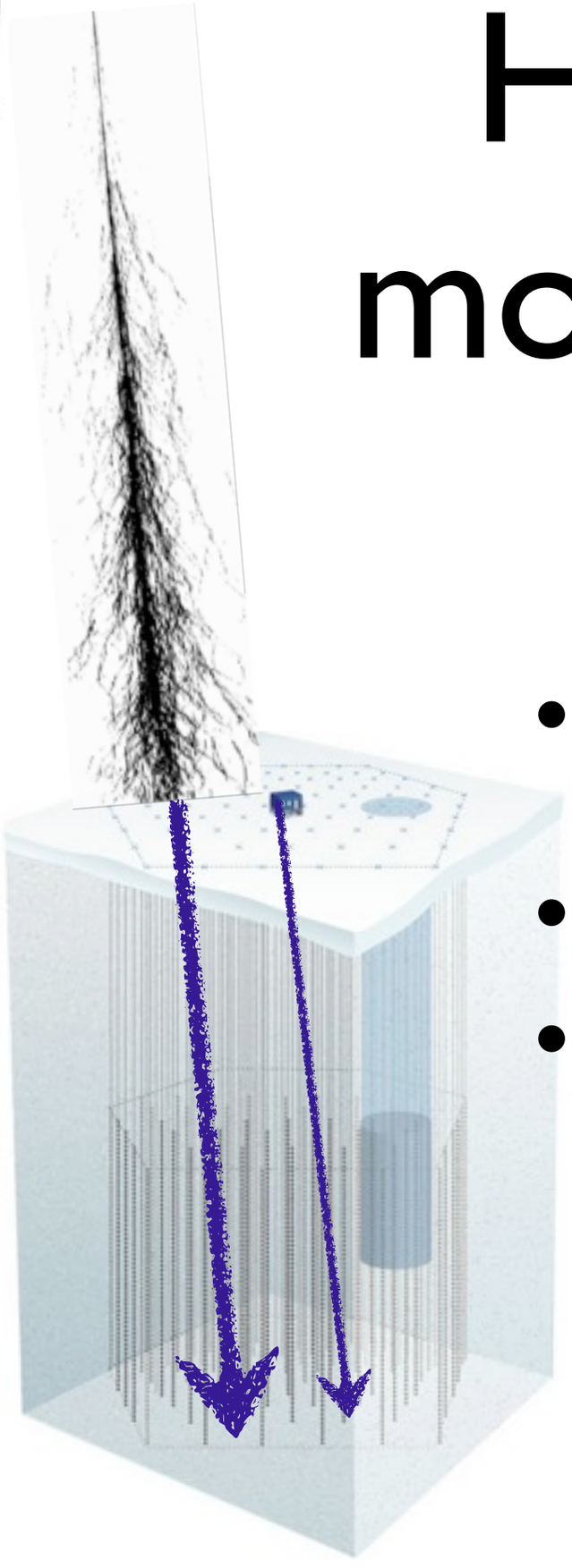


IceTop energy

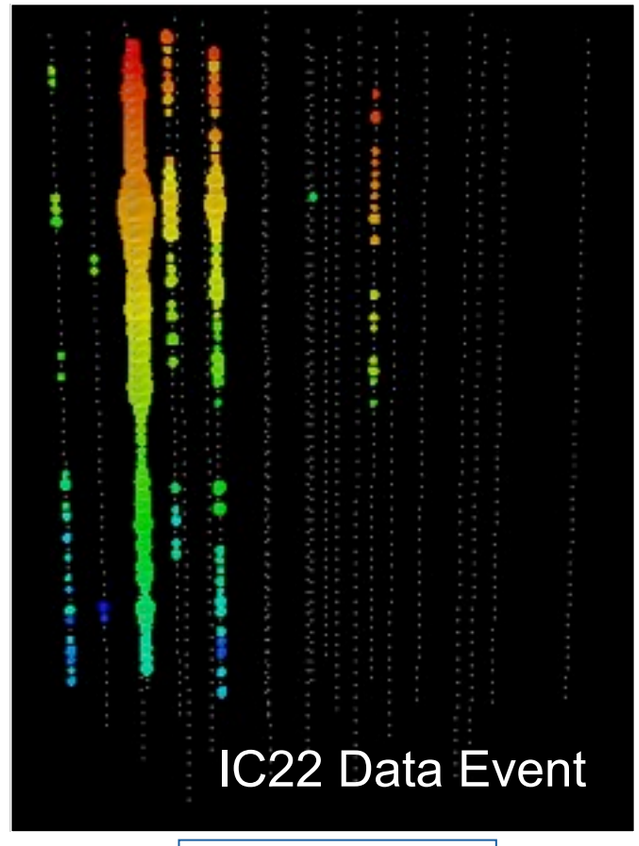


- Neural network training
- Likelihood fit of data to find composition

High transverse momentum muons

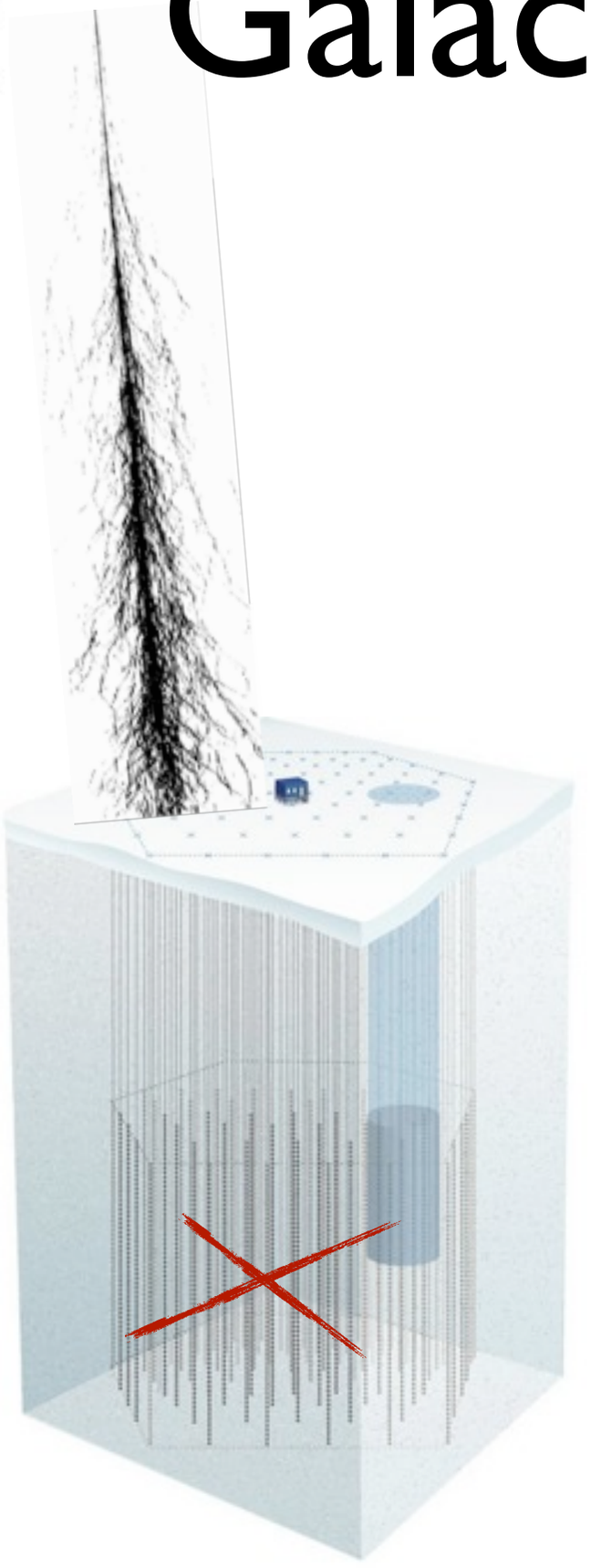


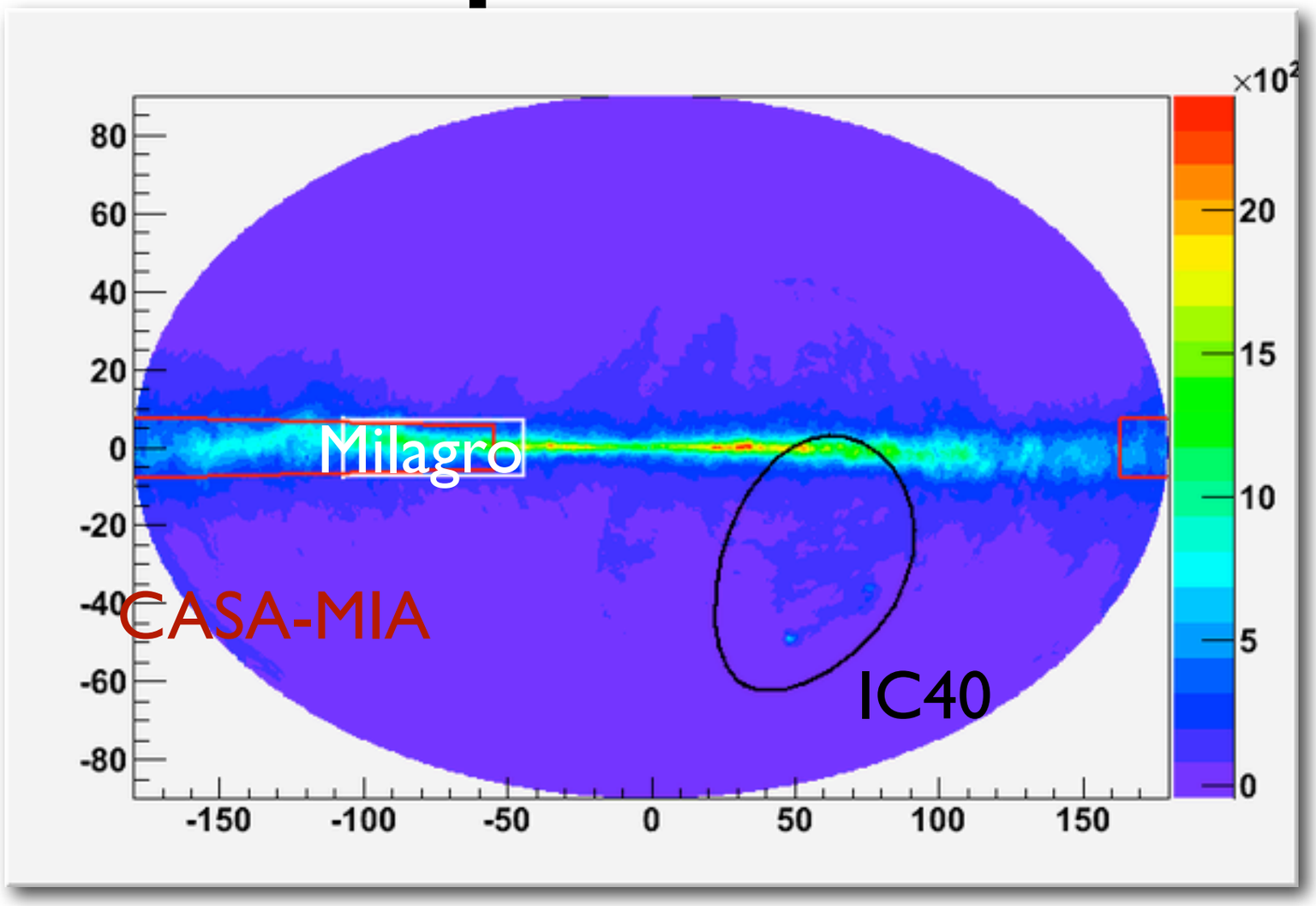
- Produced early in shower with >8 GeV/c P_T
- Separated, parallel track
- Independent method of studying composition



Dist 400 m
$\Delta\theta$ 1°
Δt 66 ns

Galactic PeV photons





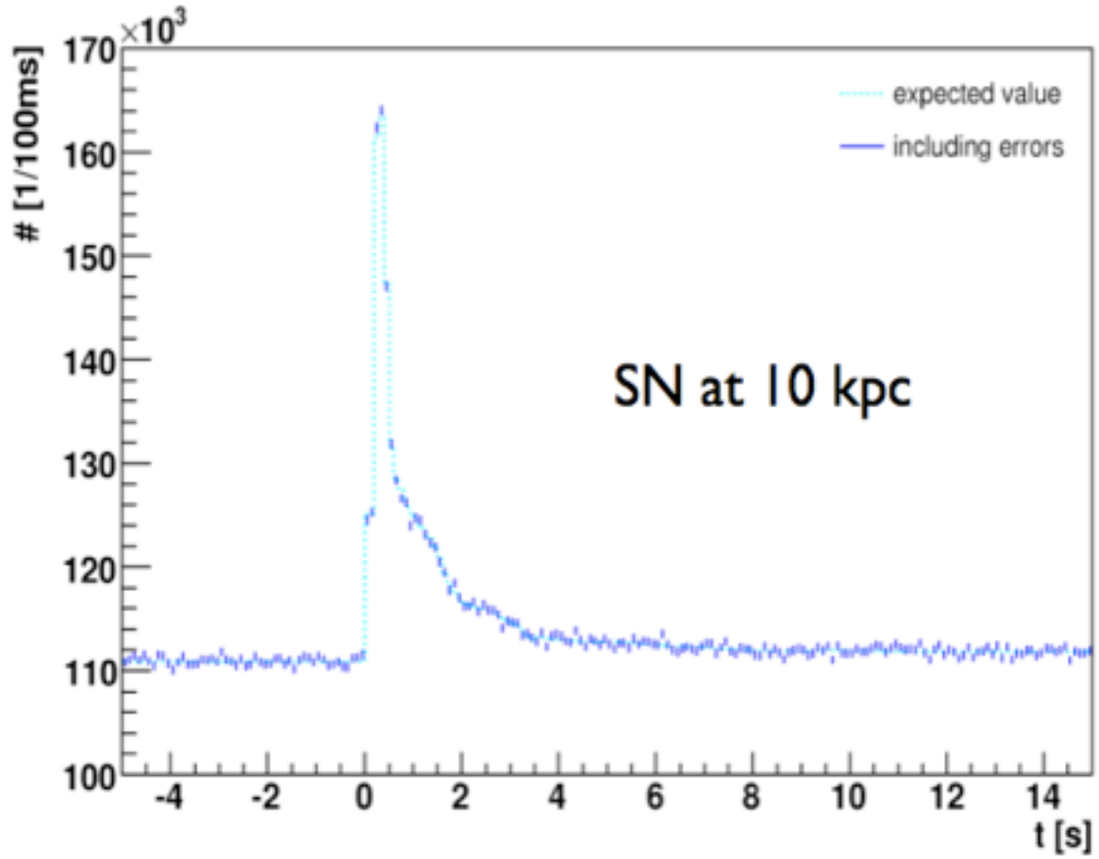
>80% of PeV gamma ray showers give no signal in IceCube
<0.1% of CR showers has no muons that reach IceCube

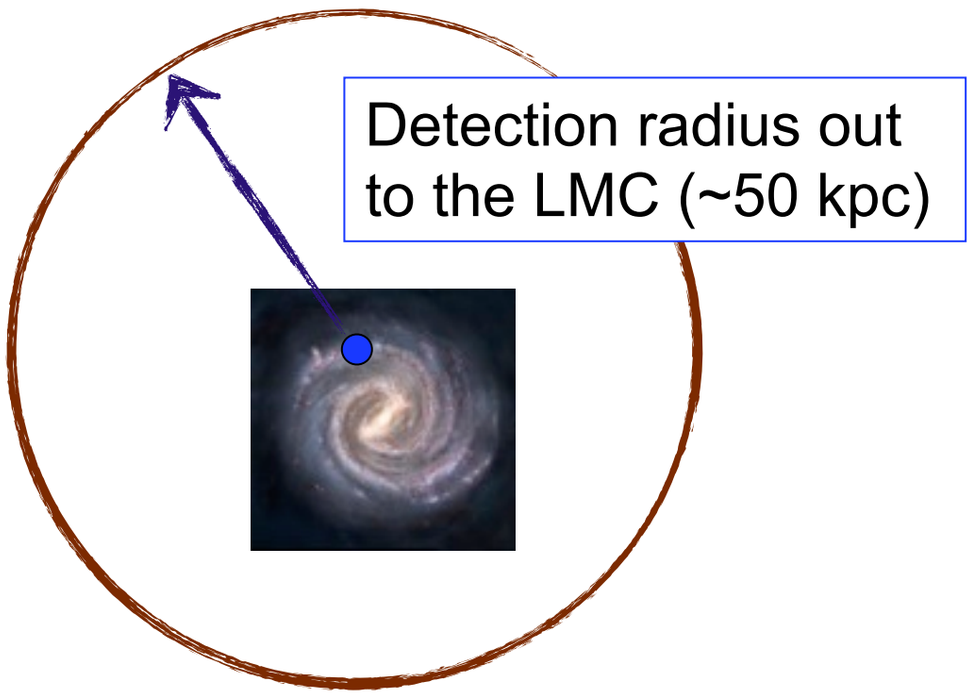
Coincident geometry confines Field Of View

IC40: 268 candidate events
no hot spot, no correlation with Gal Plane

Supernova Detection

- On average every 30 years a massive star (>8$M_\odot$) explodes, releases 99% of the energy in MeV neutrinos
- Show up as a spike in noise rates, monitored by dedicated DAQ
- No directionality, but excellent time resolution and high significance signal





SNEWS: Look for supernovae

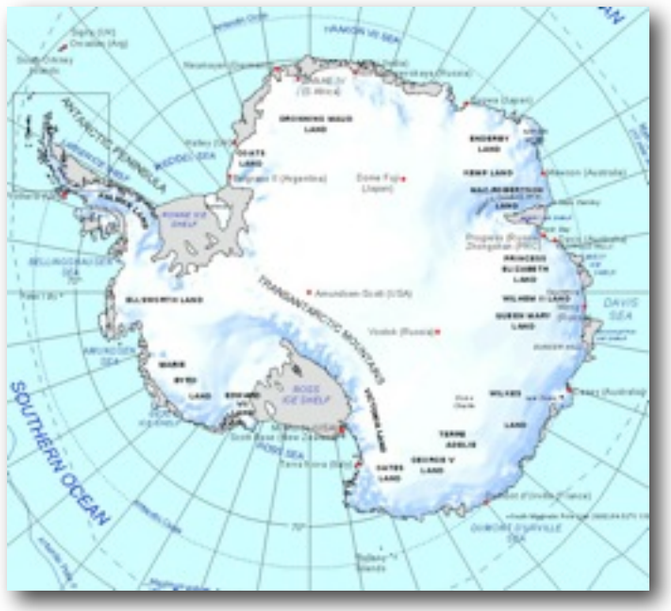
Future extensions

- IceCube deployment finished in 2011
  - Seven more strings bring the total to 86
  - Full km^3 volume, dense DeepCore
- Multi-messenger astronomy
  - Correlations with ROTSE, SWIFT, and LIGO
- New Technologies
  - 4 Hydrophones deployed above IceCube
  - 3 Prototype digital radio strings deployed with IceCube strings
  - DM-ice; direct Dark Matter experiment with NaI crystals

Conclusions

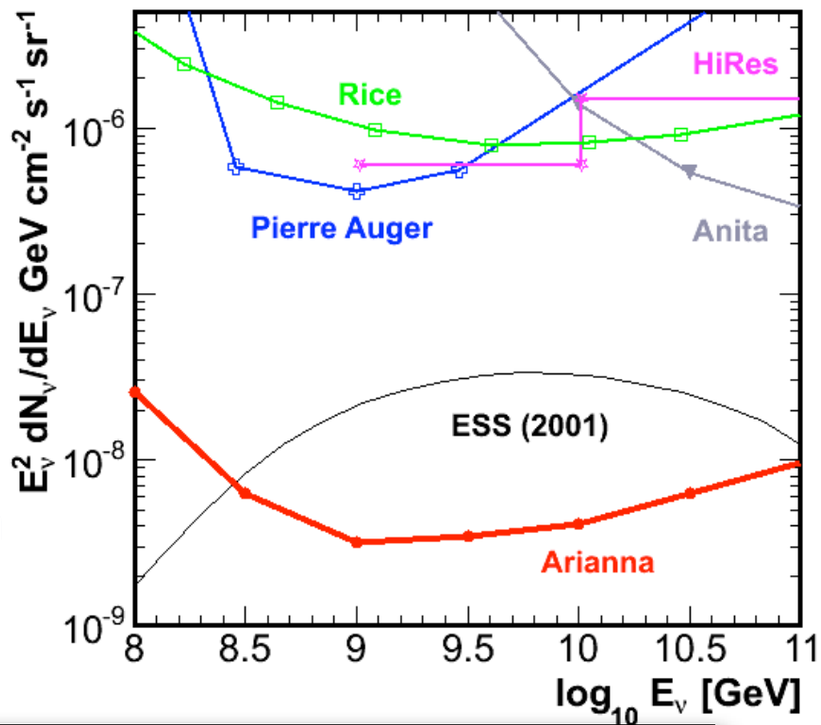
- IceCube will be finished in the coming months: official inauguration May 2011
- Analysis with growing detector is producing challenging limits in many areas
- Many exciting discoveries ahead
- Pilot projects for next generation experiments

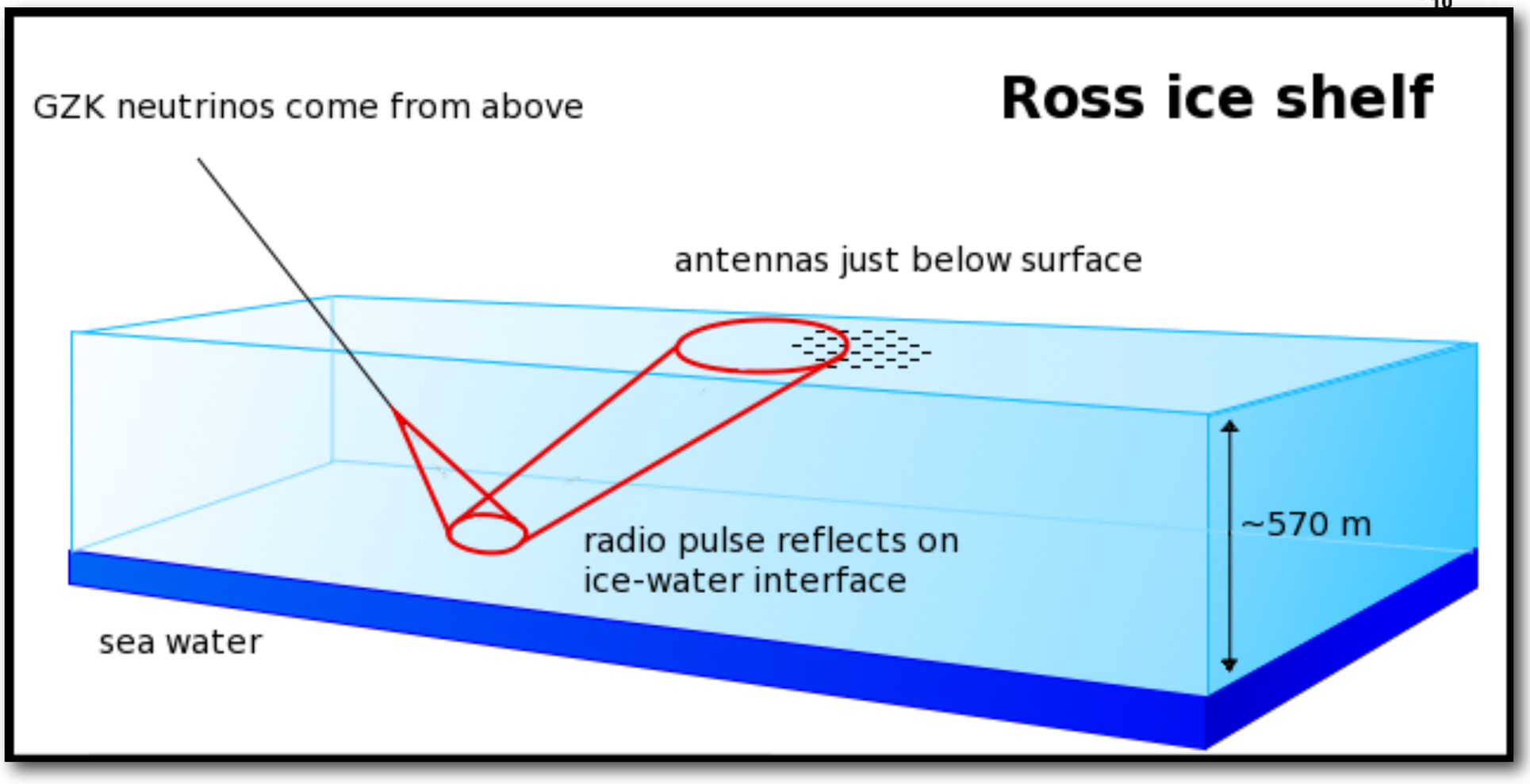
...beyond IceCube



Arianna

Detect Cherenkov radio pulse of hadronic cascade of EHE neutrino interaction (Askaryan effect)

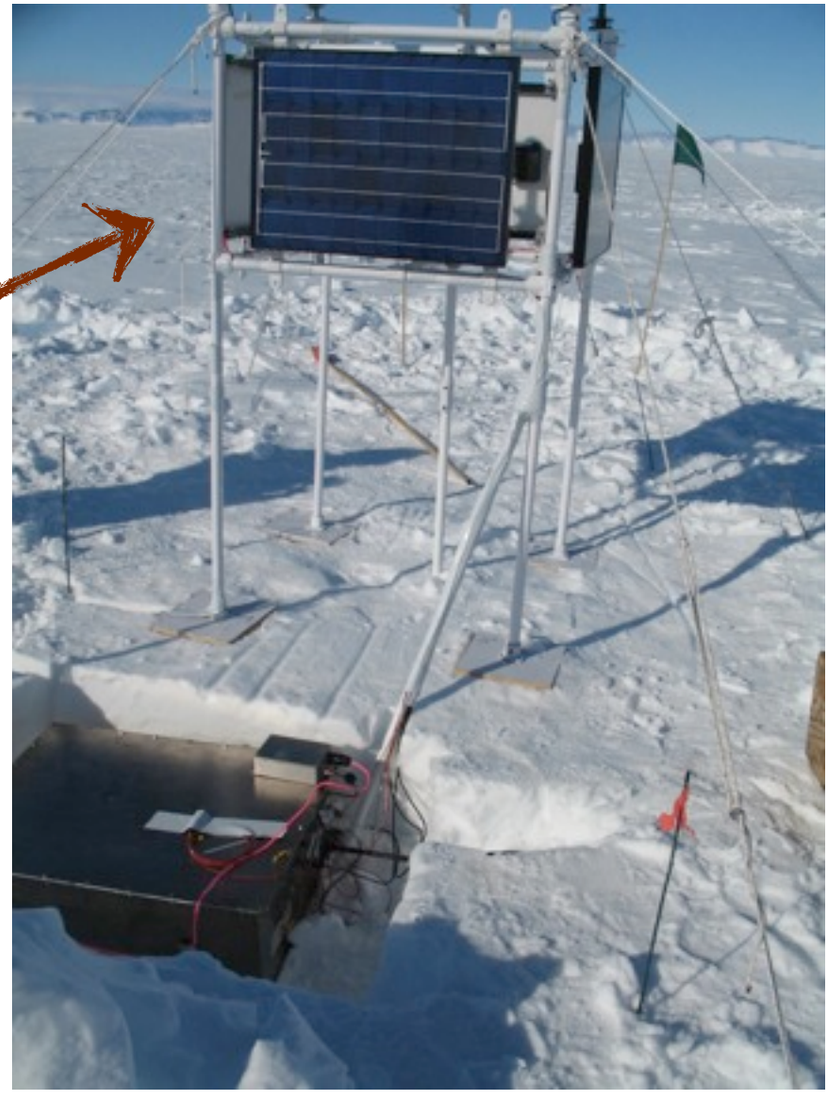




first station deployment

Periodic log dipole antenna (4 total)

Solar panels
+
wind mill

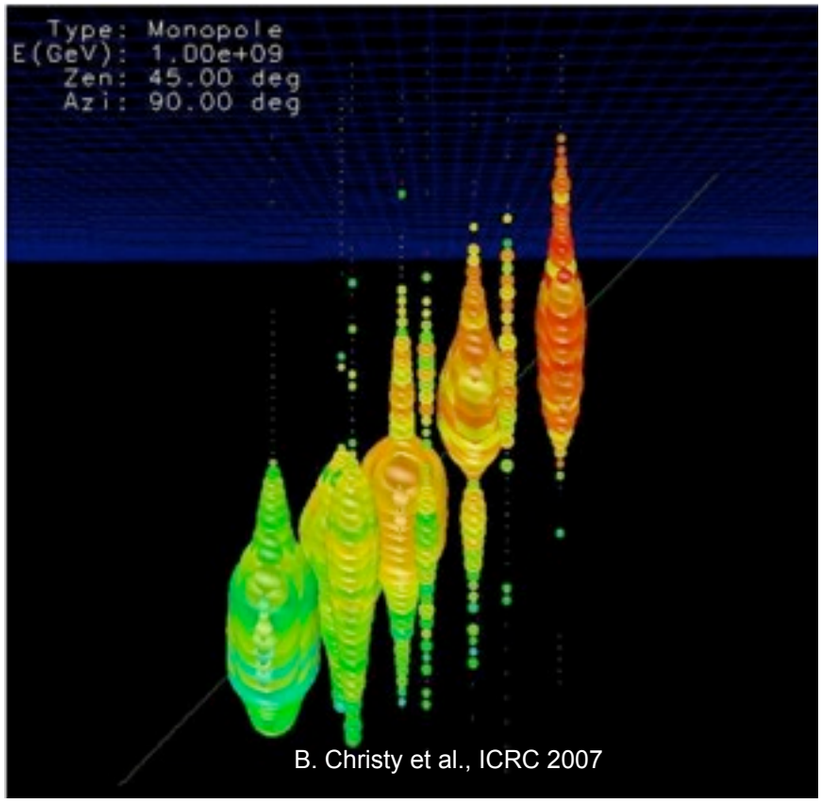


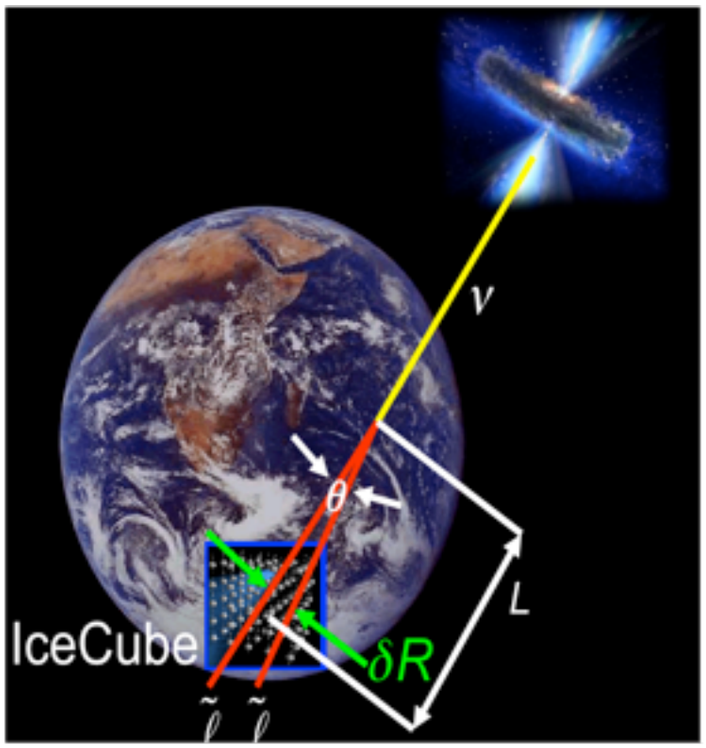
50-800 MHz
2.5 GS/s

2011: hexagonal array 7 stations
goal: order 100 km^3 effective volume

Exotic Physics

- Magnetic monopoles
  - Extremely bright events, Cherenkov radiation is 8300 times bare muon
  - Speed 0.76c - 0.99c
- TeV gravity
  - Extra dimensions allow creation of microscopic BHs - decay into massive cascades of particles



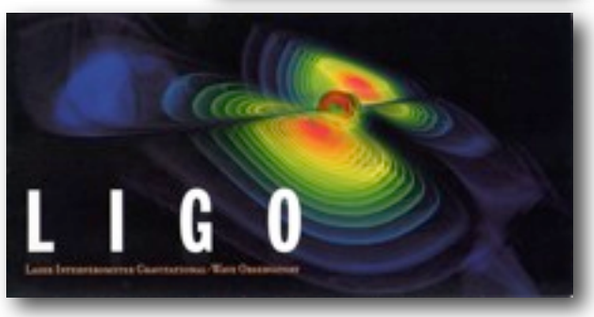


- Supersymmetric particles
  - High energy neutrinos can produce pairs of staus
  - Unique signature of two simultaneous, parallel tracks in detector
- Lorentz invariance violation
  - Look for unusual oscillation of atm ν's

Multi Wavelength

ROTSE: Robotic Optical Transient Search Experiment
IC40: 22 IceCube doublets observed by ROTSE
IC59: 39 observed

SWIFT: Look for choked (no γ's) GRBs



LIGO: Offline search for coincidences between the two datasets. Eventually mutual online triggering

SNEWS: Look for supernovae