IceCube: neutrino astronomy at the South Pole

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SACLAY
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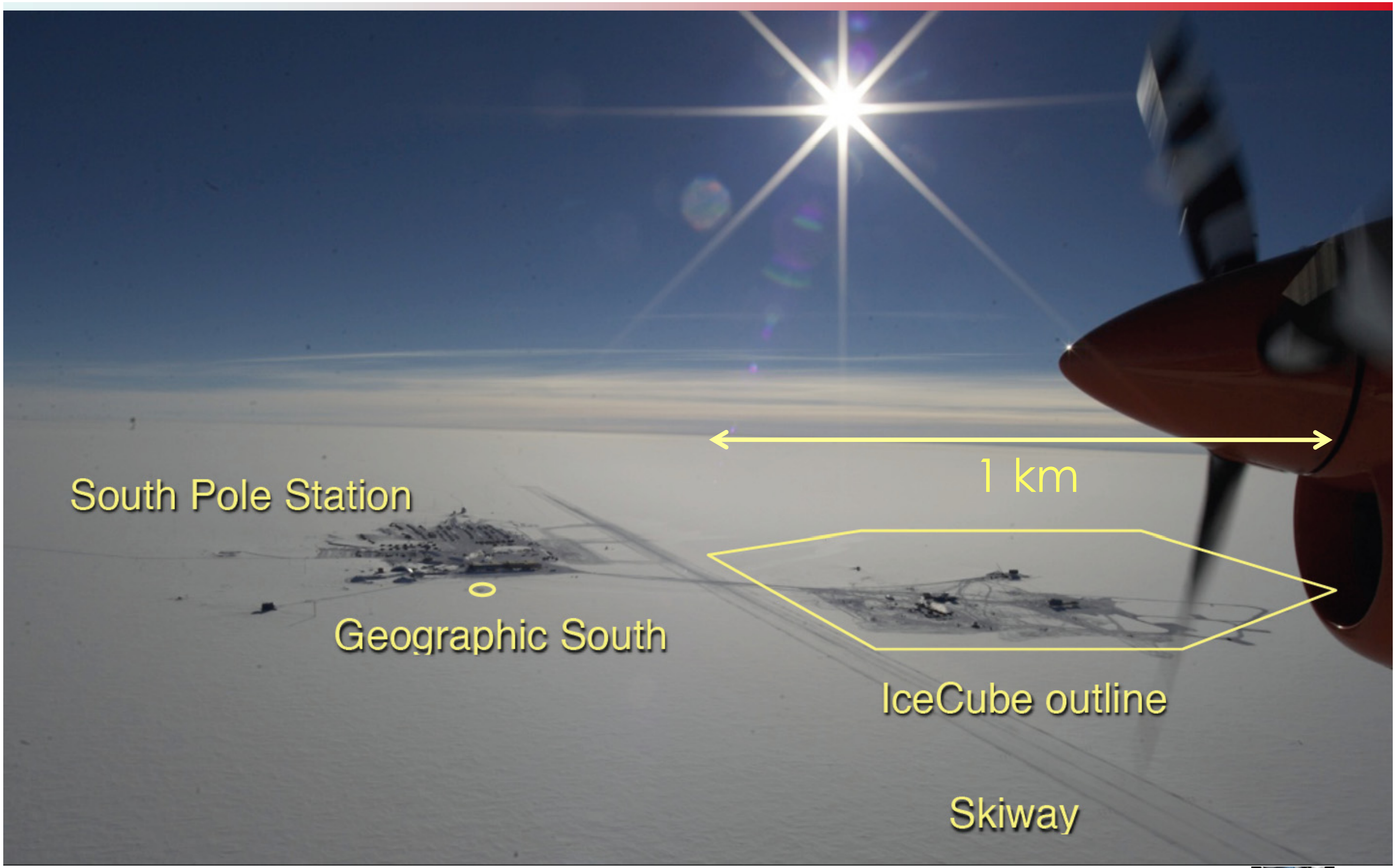
An adventure at the bottom of the world

A DETECTOR AT THE SOUTH POLE

IceCube

Amundsen Scott South Pole station



Outline

- Neutrino astronomy: why and how?
- The IceCube detector
- Event reconstruction
- Search for sources of high-energy neutrinos:
  - point sources
  - diffuse fluxes
- Indirect dark matter search
- Many other research activities
- Summary

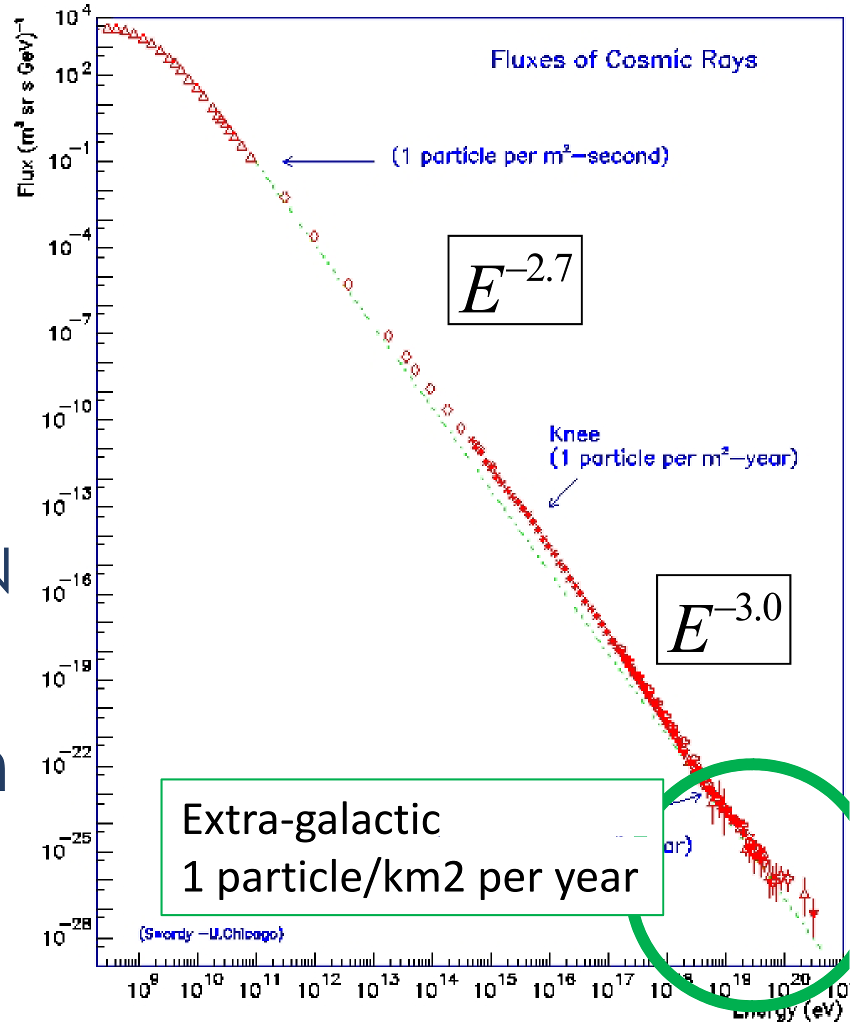
Neutrino astronomy: why and how?

IceCube

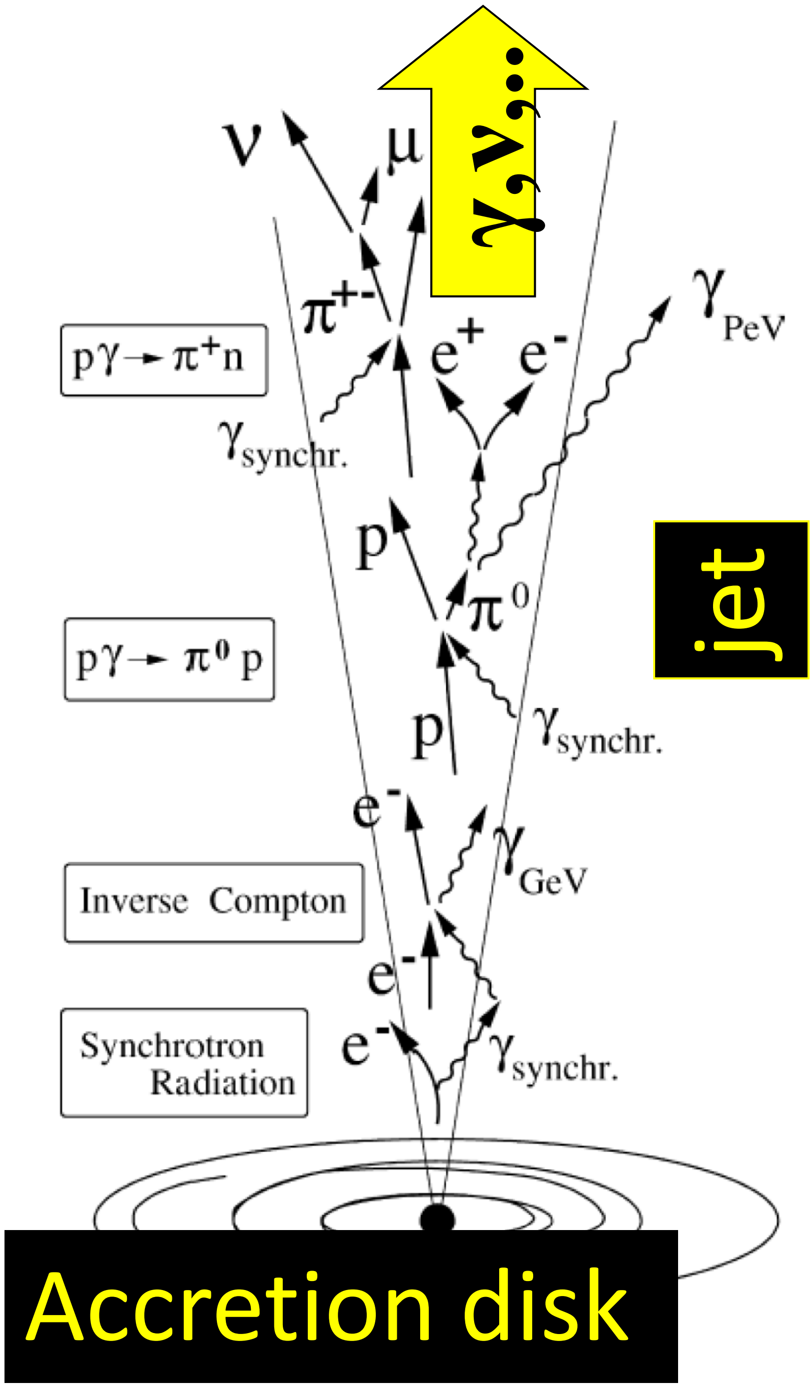
IceCube Mission

- search for extra-terrestrial neutrinos
- From natural accelerators where High Energy Cosmic Rays originate
- Such as
  - Active Galactic Nuclei - AGN
  - Gamma Ray Bursts - GRB
- Cosmic ray air showers with IceTop

+ Many other topics



Model for AGN jets



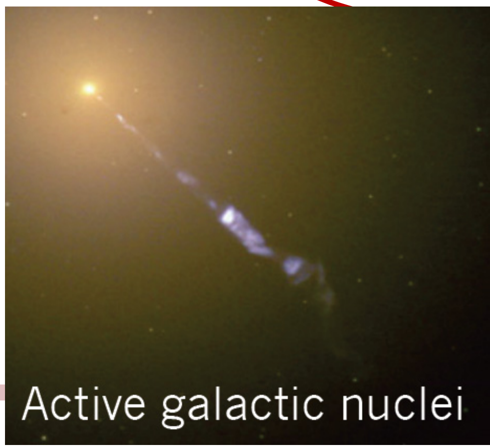
expect $\frac{dN}{dE_\nu} \sim E_\nu^{-2}$

$$e + \gamma \rightarrow \gamma'$$

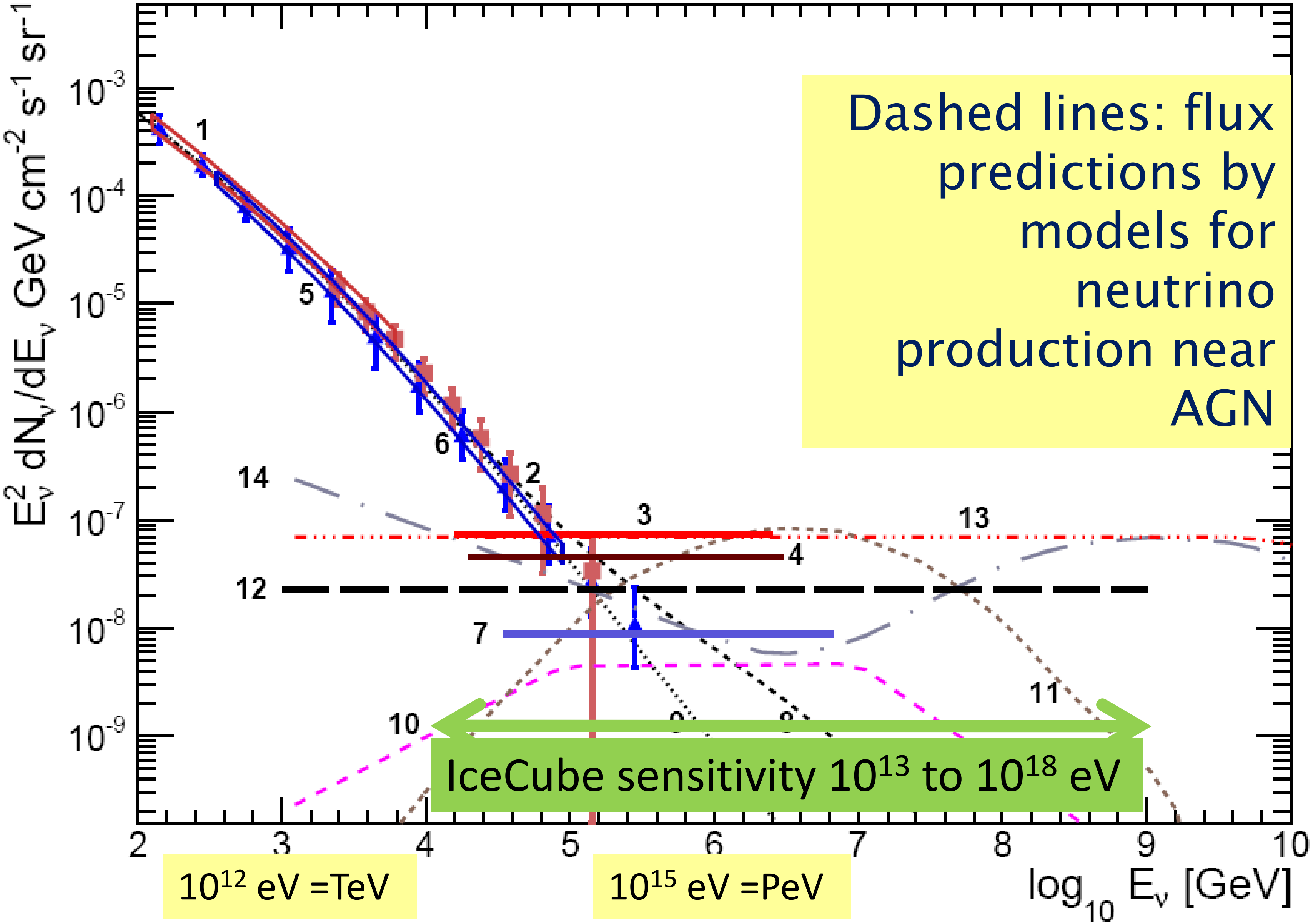
$$p + \gamma \rightarrow \pi^+, \pi^0, \ldots$$

$$\pi^0 \rightarrow \gamma + \gamma$$

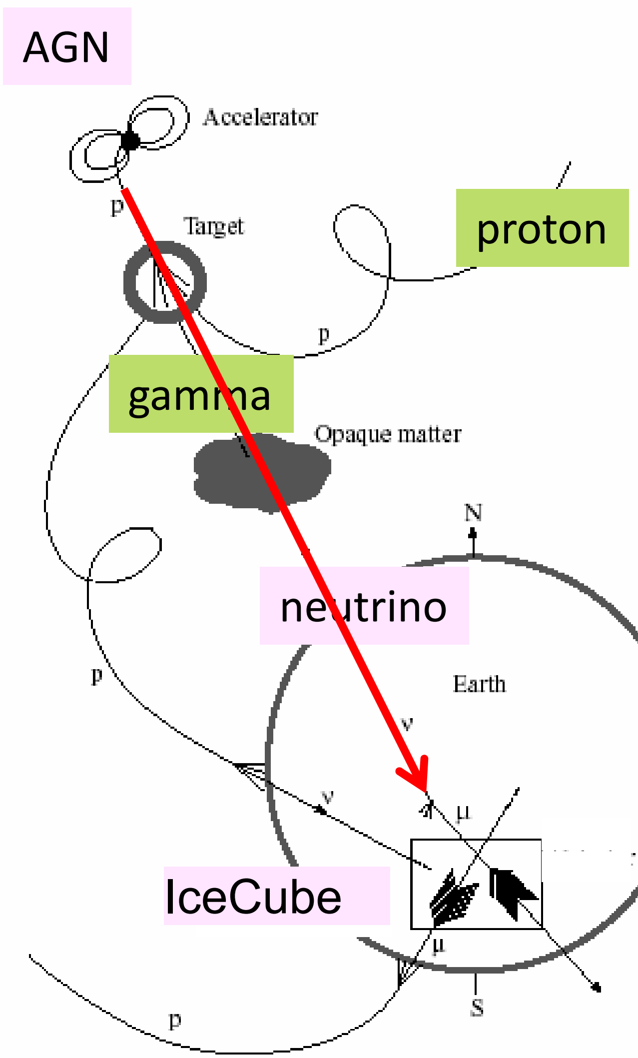
$$\pi^+ \rightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$$



Expected neutrino energies



Neutrino detection : pros



- Are not absorbed by interstellar matter
- Are not bent by magnetic fields

- Convey information from the interior of objects
- Reach us from far away sources
- Point straight back to the source

Neutrino detection : cons

- Observed rate = neutrino flux from source

  x absorption in Earth

  x neutrino cross section(weak interactions!)

  x size of detector

  x range of muon (4 to 15 km w.e. for E_{ν} ~ 10 – 1000 TeV)

⇒ Need large volume of cheap medium

natural water or ice

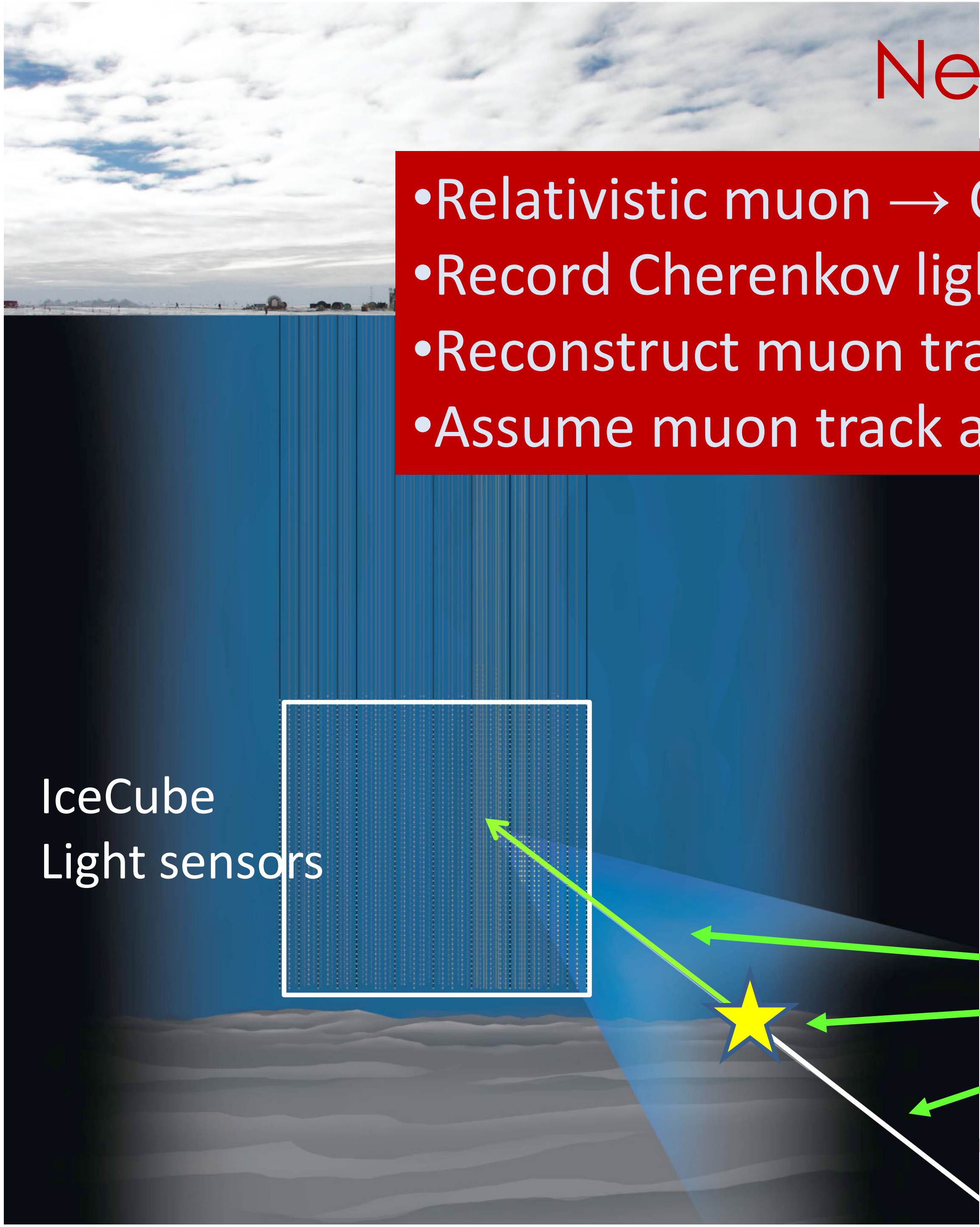
Neutrino detection

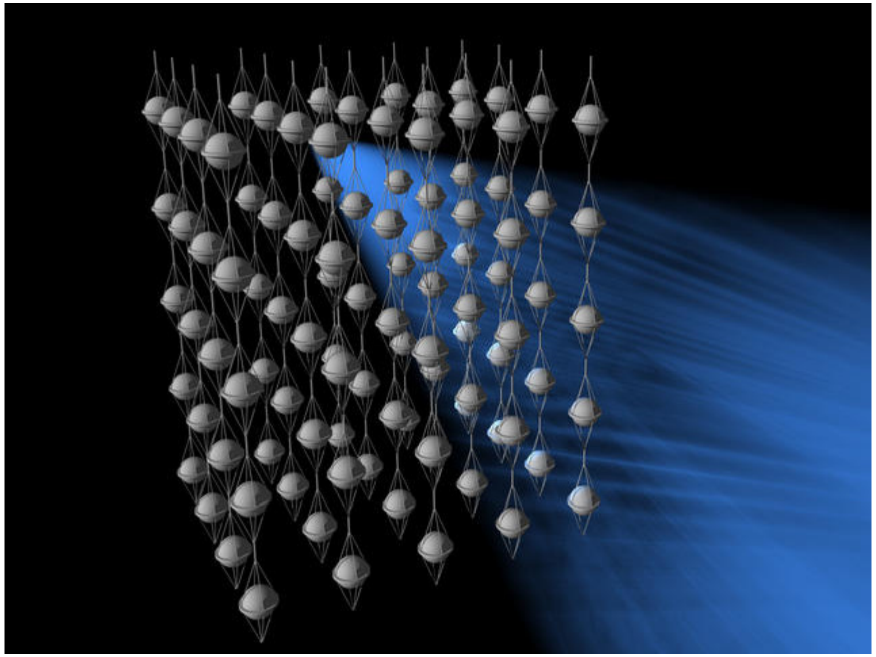
- Relativistic muon → Cherenkov light cone
- Record Cherenkov light pattern
- Reconstruct muon track
- Assume muon track aligned to neutrino path

$$\theta(\nu,\mu) \approx 30° \cdot \sqrt{1/E(GeV)}$$

$$1\,TeV \rightarrow 1°$$

$$\nu_\mu + N \rightarrow \mu + X$$

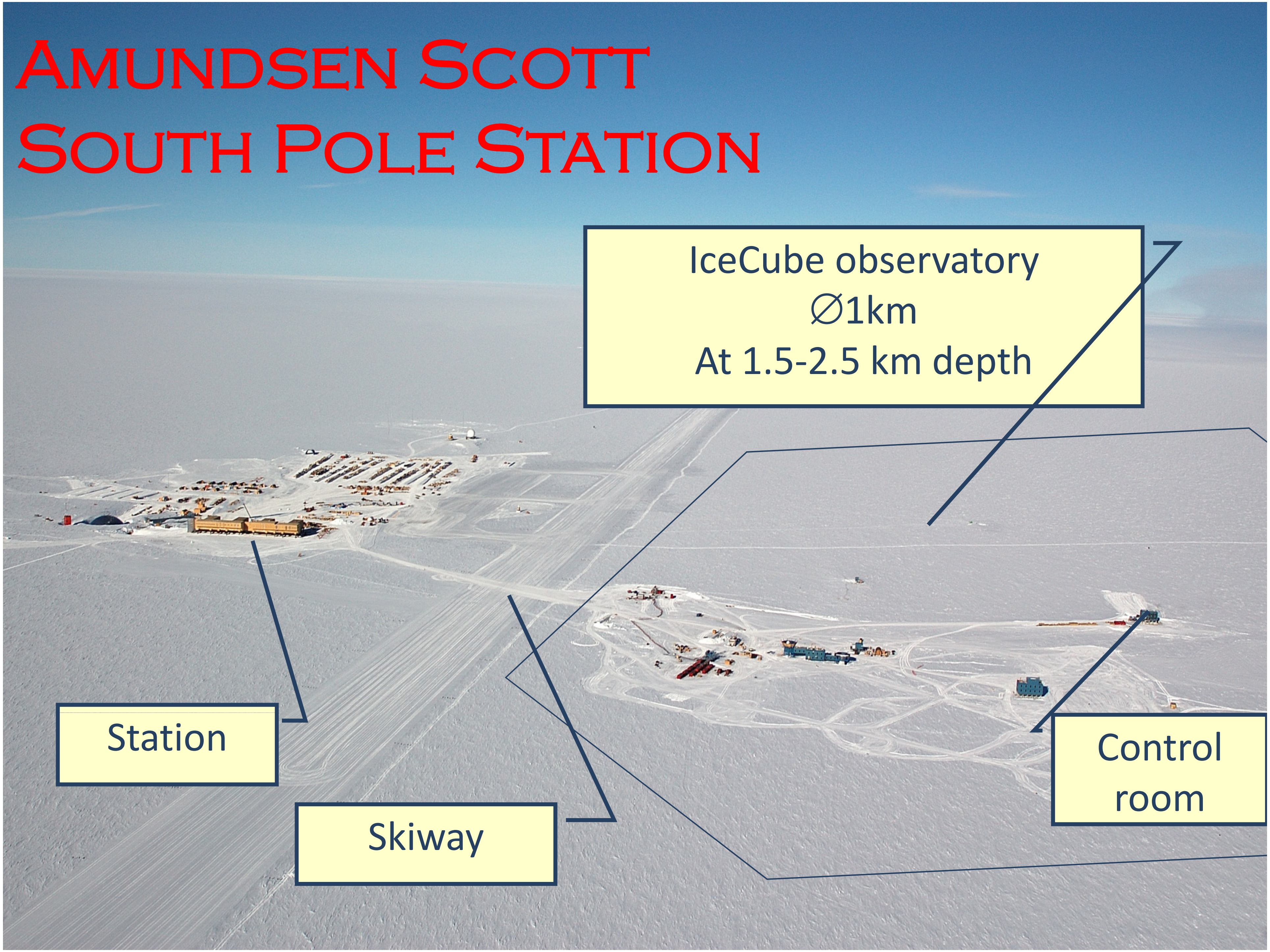




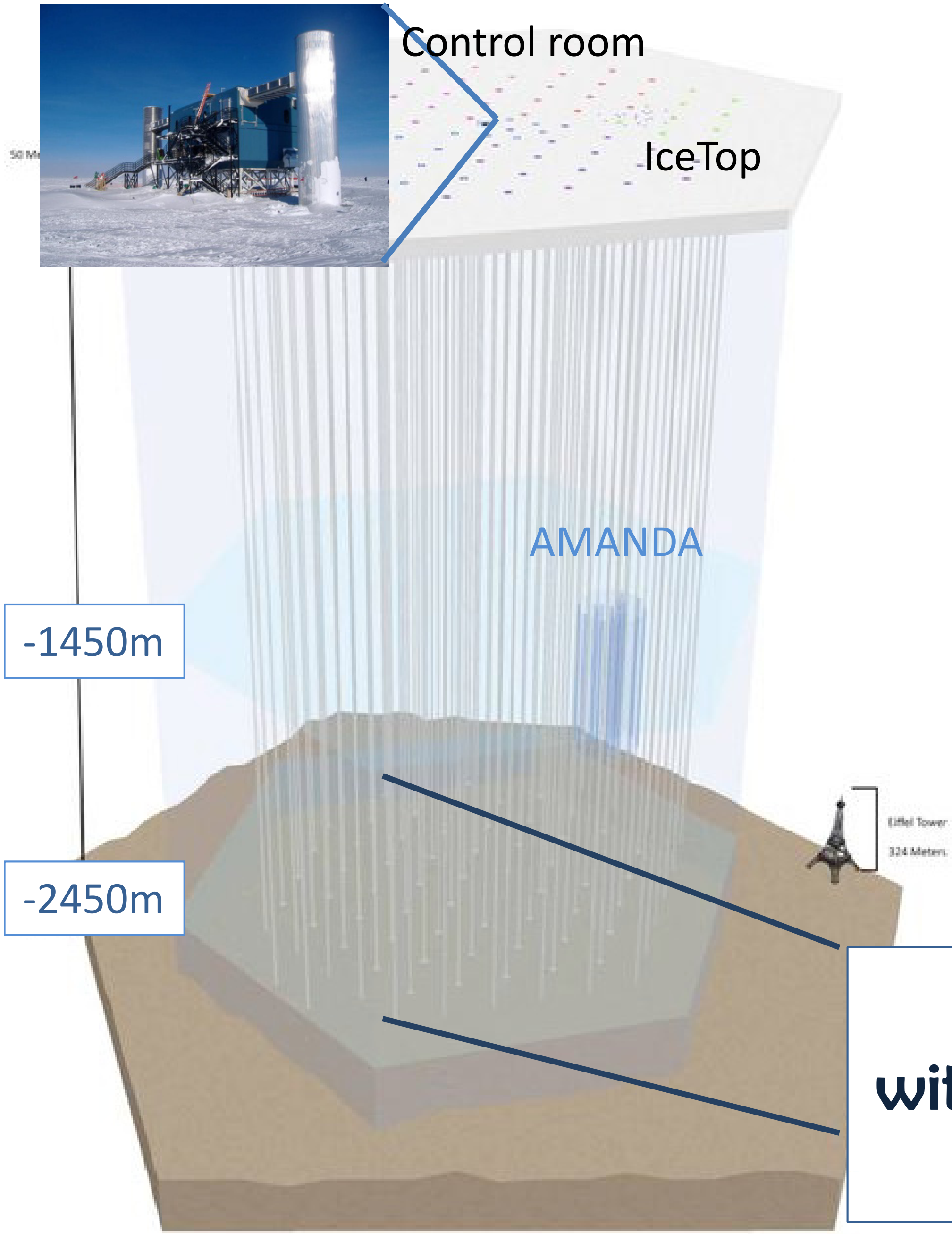
The IceCube detector

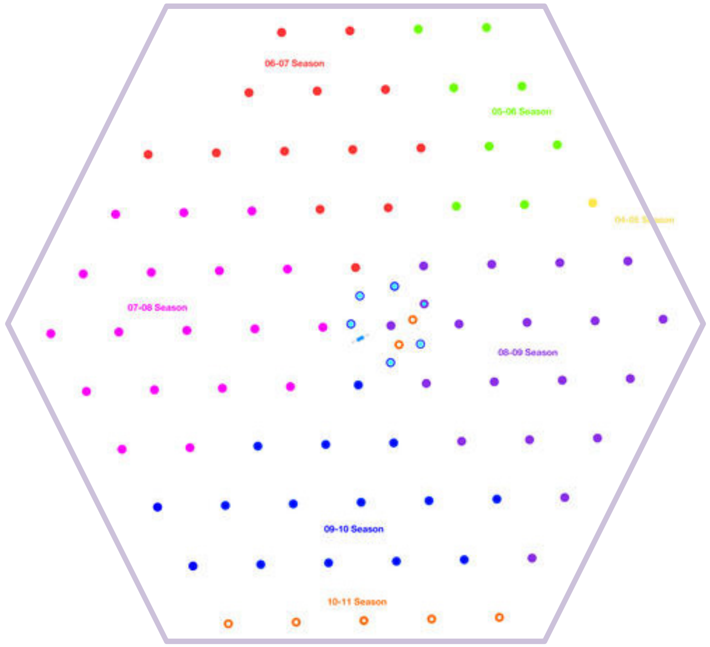
IceCube

Amundsen Scott South Pole Station



IceCube detector

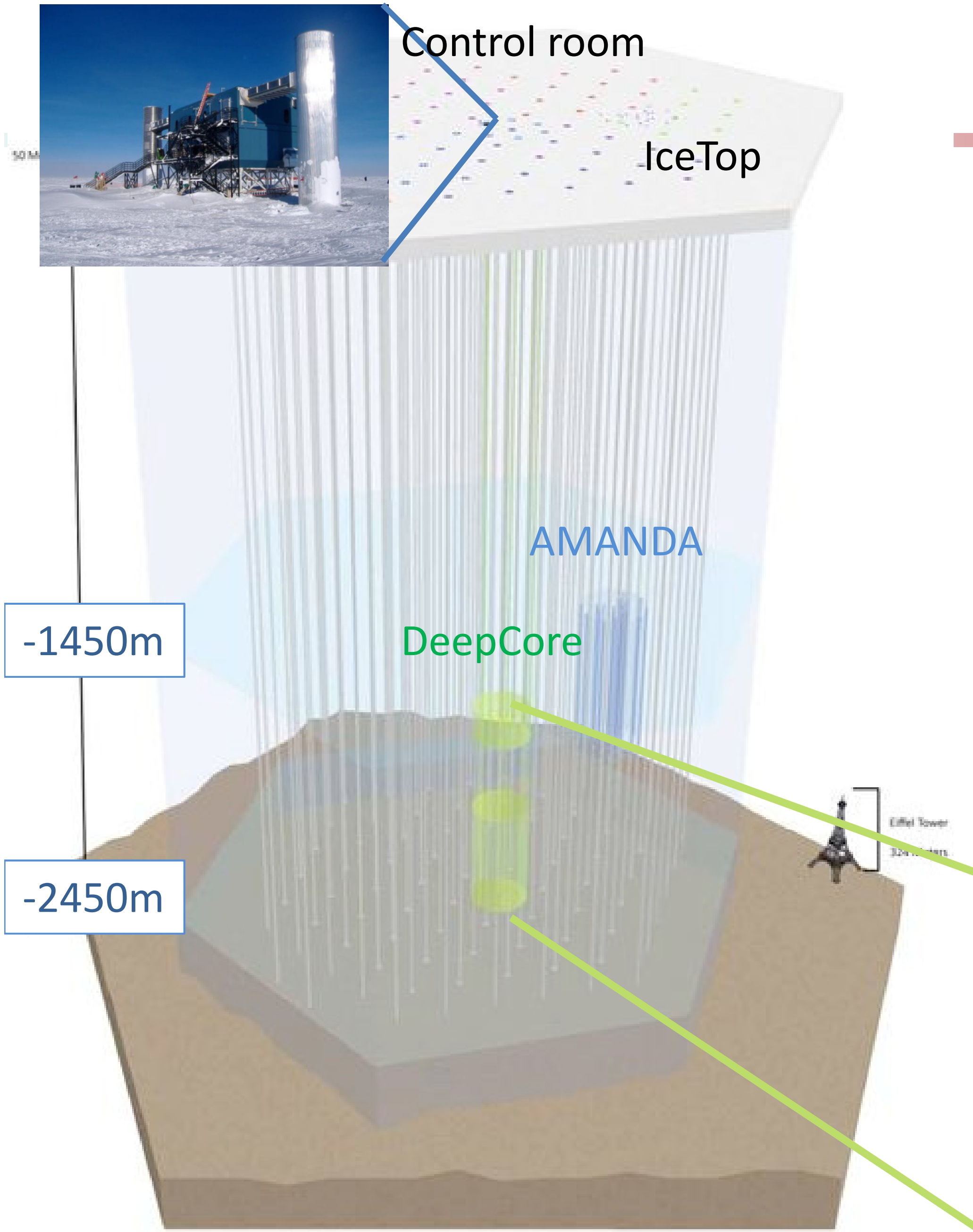


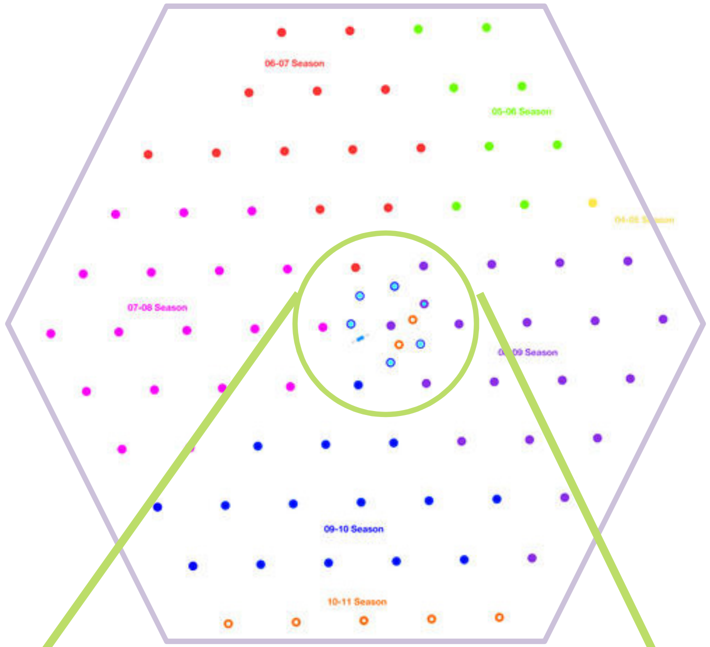


1 km

Array of 80 strings
with 60 Digital Optical Modules
125m spacing

IceCube detector



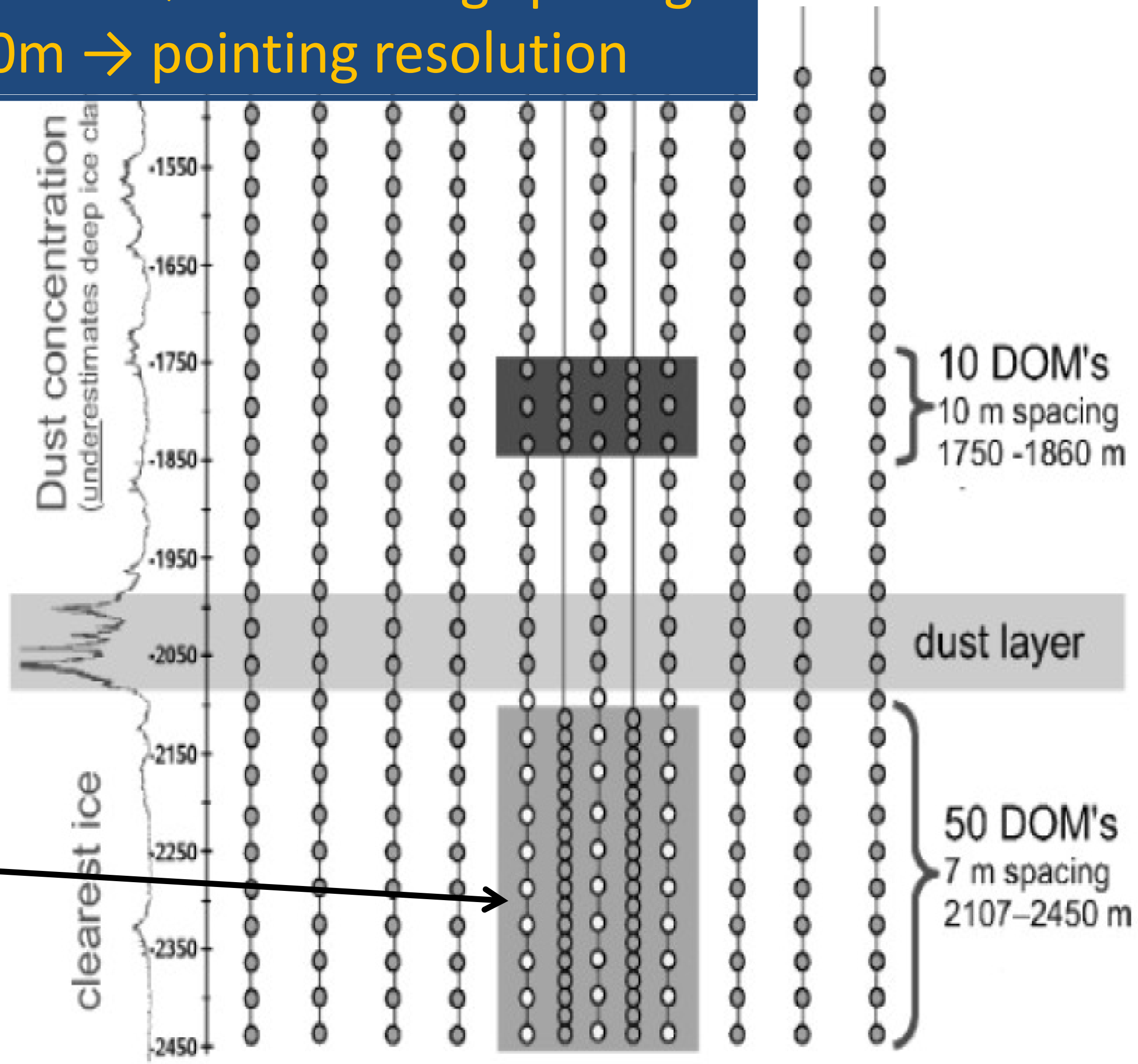


DeepCore

- Denser spacing
- Low energy GeV-TeV
- Southern hemisphere

Clear ice and dust layers

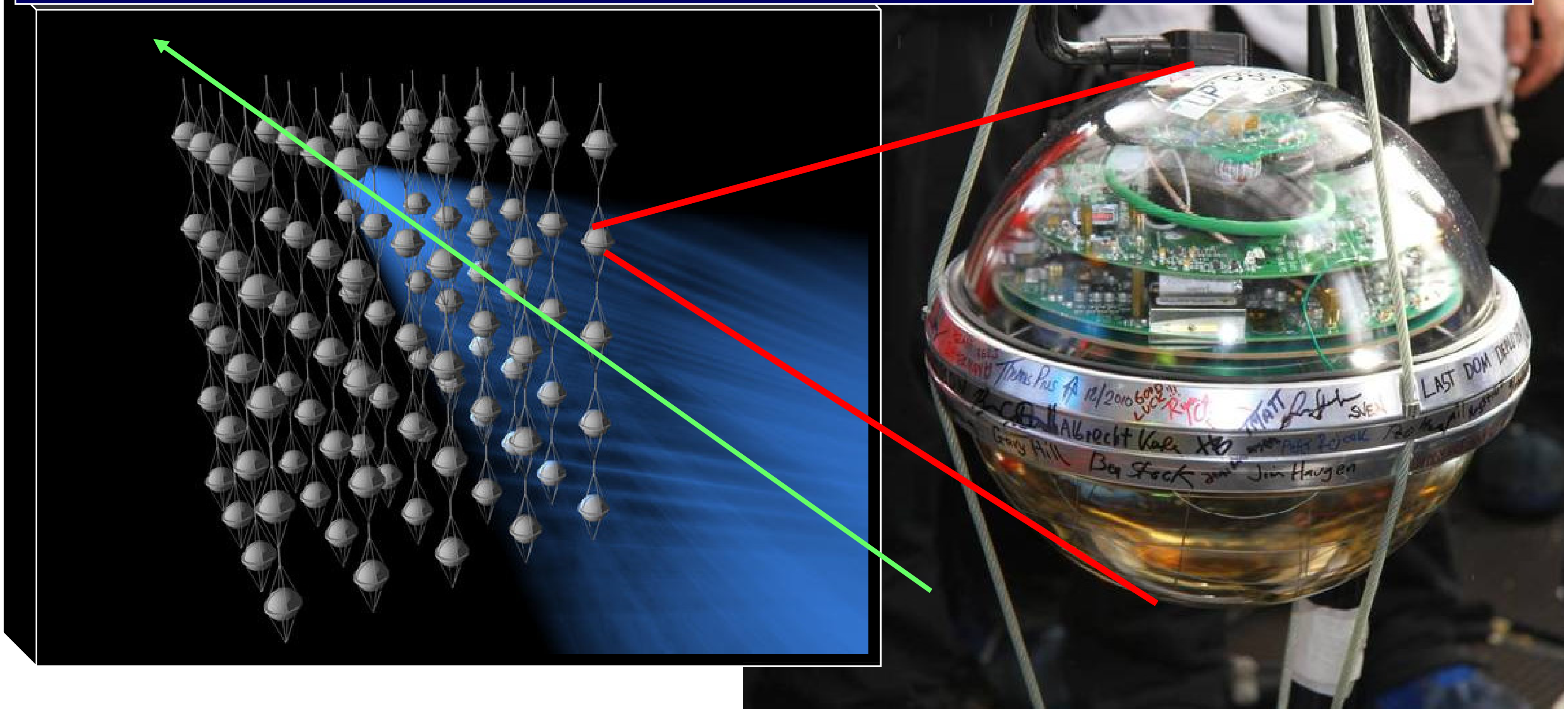
Absorption length about 100m → inter-string spacing
Scattering length about 20m → pointing resolution



Deep Core
low energy detector

5160 Digital Optical Modules

- ✓Photo Multipliers in pressure sphere
- ✓Record arrival time and pulse height
- ✓Oriented downwards



Access during summer
November-February

Inaccessible during
February-November

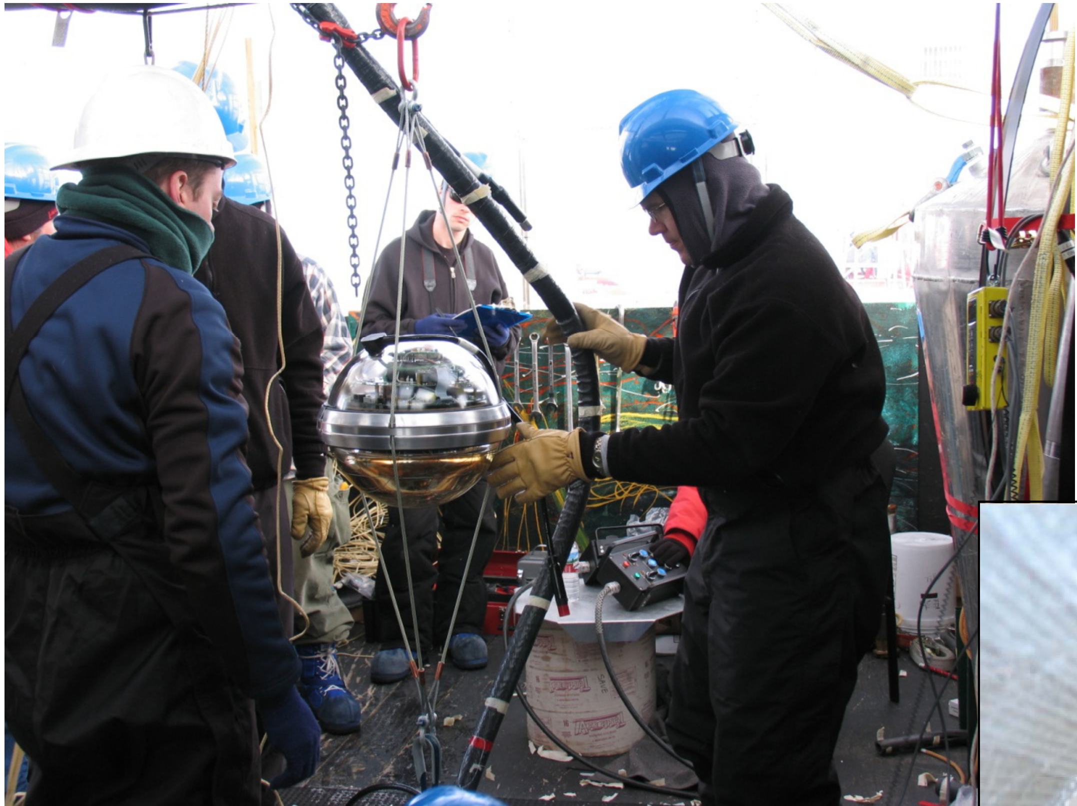
200 scientists
-30°C

About 20 winter-overs
-70°C

Drilling the holes

- 2450m deep - 60cm diameter
- hot-water-drill 80°C
- Drill a hole in 24h
- 16-20 holes per season
- South Pole accessible during November-February

Installing the sensors

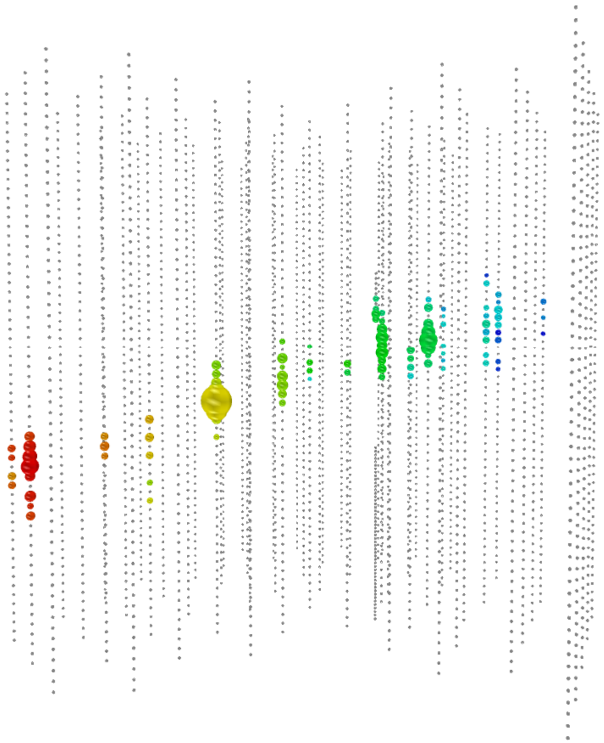


60 Digital Optical Modules on a string installed in 20 h

Completed on 18 December 2010!

(Nature.com) Giant, frozen neutrino telescope completed - December 18, 2010

ScienceDaily (Dec. 19, 2010) — Culminating a decade of planning, innovation and testing, construction of the world's largest neutrino observatory, installed in the ice of the Antarctic plateau at the geographic South Pole, was successfully completed December 18, 2010, New Zealand time.

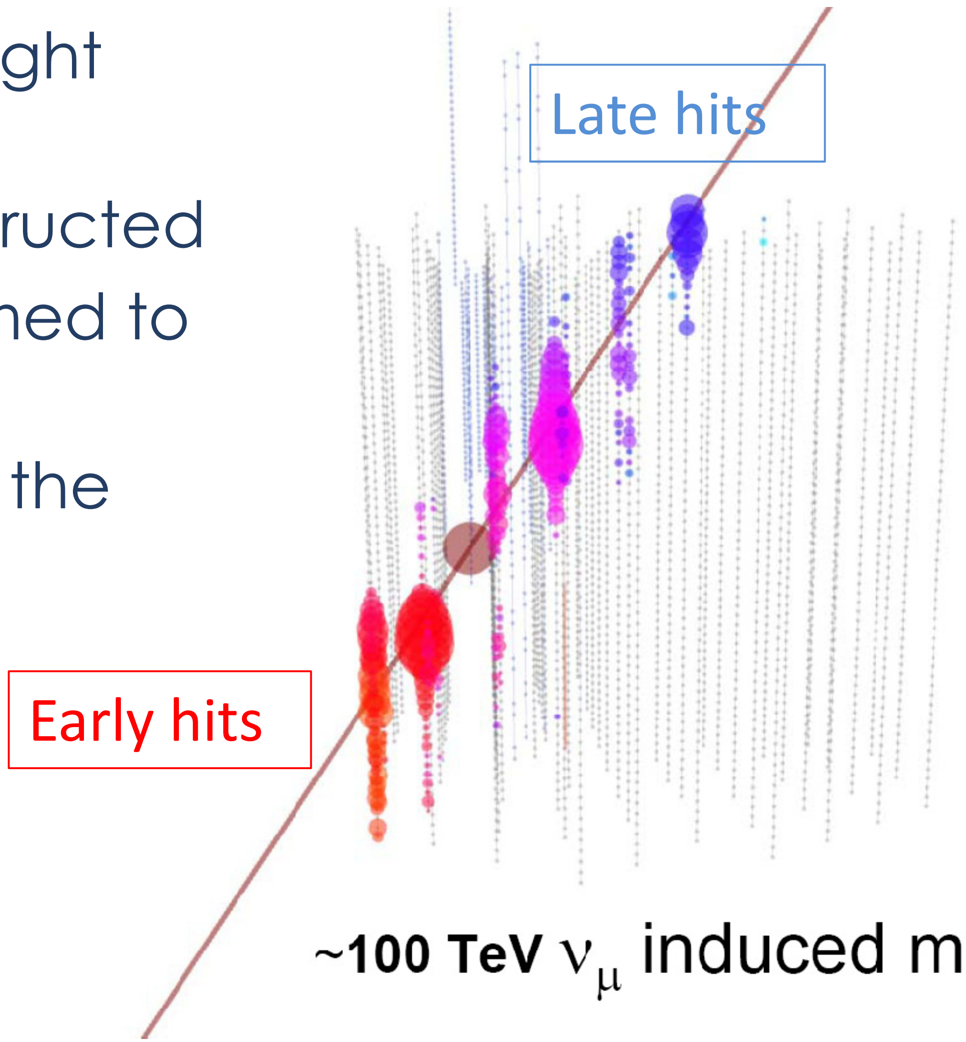


Event reconstruction

IceCube

ν_μ : track reconstruction

- Through the recorded light pattern
- A muon track is reconstructed
- The muon track is assumed to give the neutrino path
- the neutrino path gives the source direction



~100 TeV ν_μ induced muon

signal and background

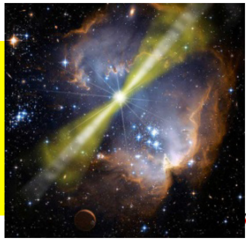
BG

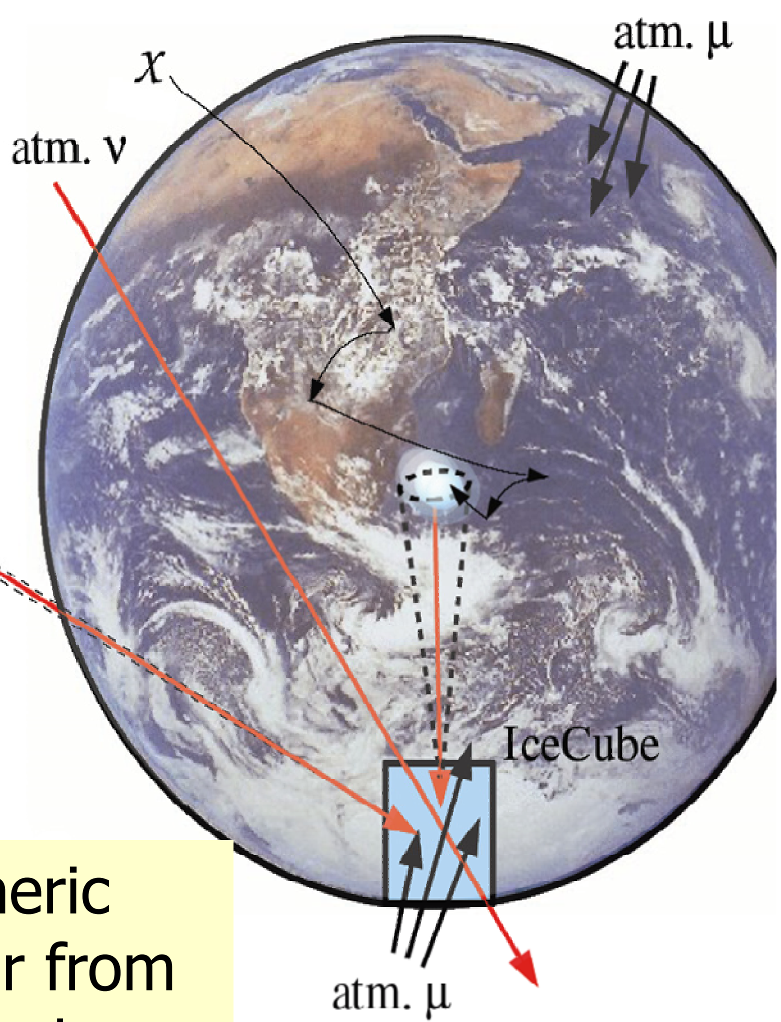
~10^5 atmospheric neutrinos per year from northern hemisphere

signal

Max. a few neutrinos per year

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



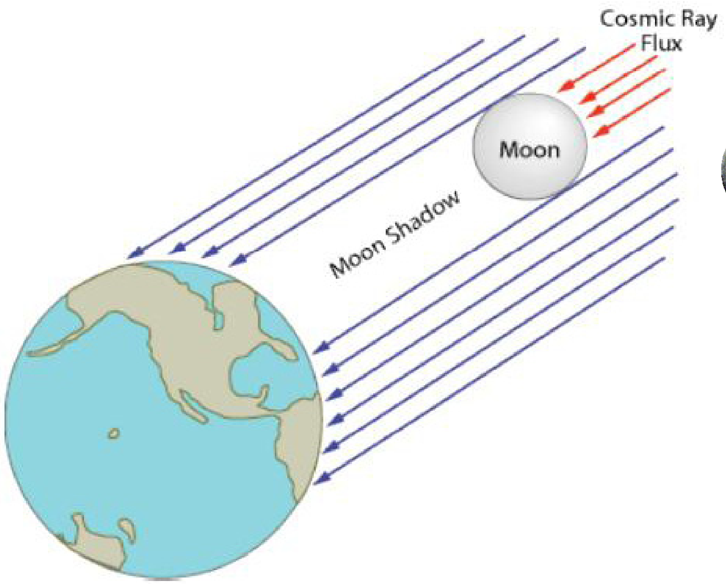


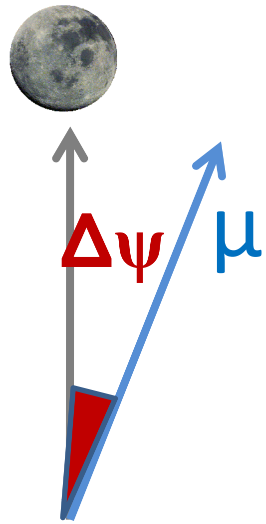
BG

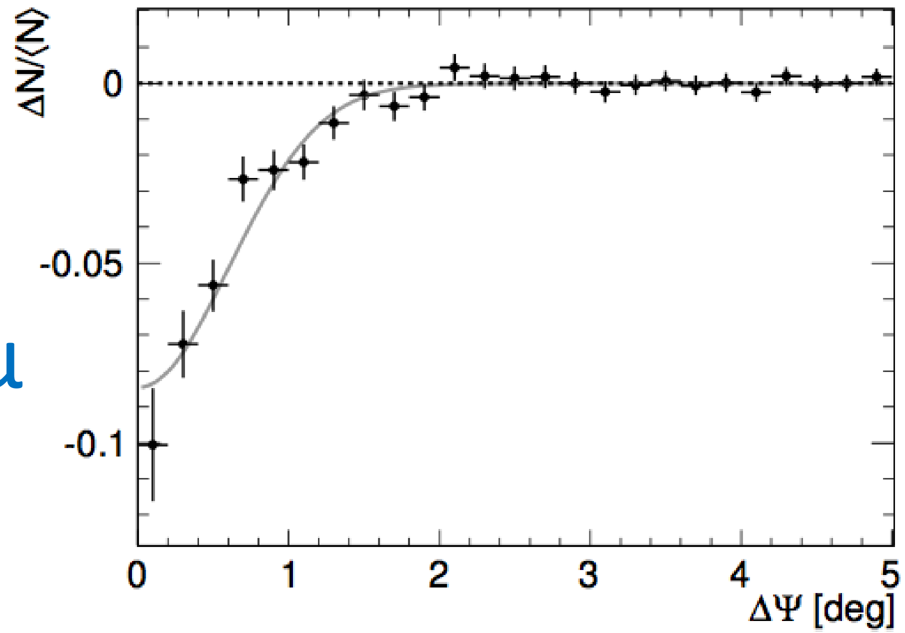
~10^{11} atmospheric muons per year from southern hemisphere

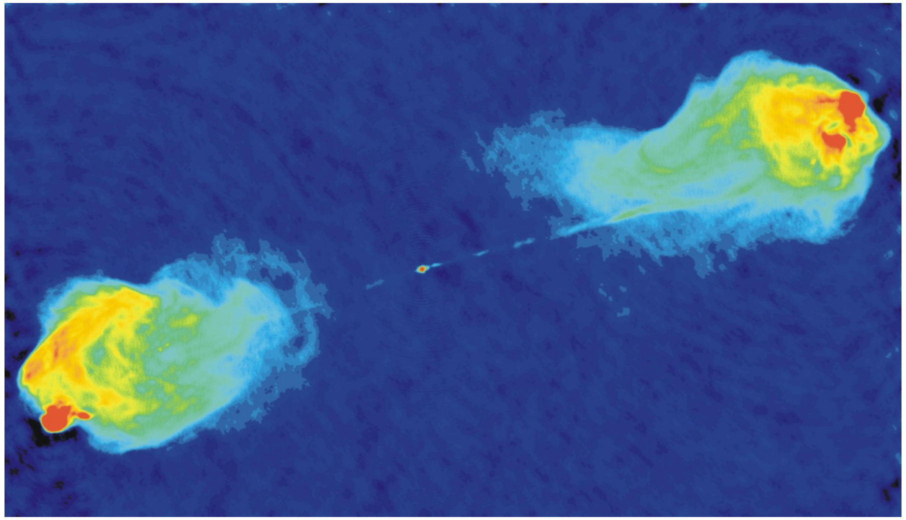
Pointing resolution: Moon shadow

- ***Downgoing atmospheric muons*** recorded by IC59
- deficit due to absorption of cosmic rays by the Moon
- Simulation 1 TeV muon : $\Delta\Psi \approx 1°$
- Moon shadow observed in IC59 with 12σ









Search for sources of high-energy neutrinos

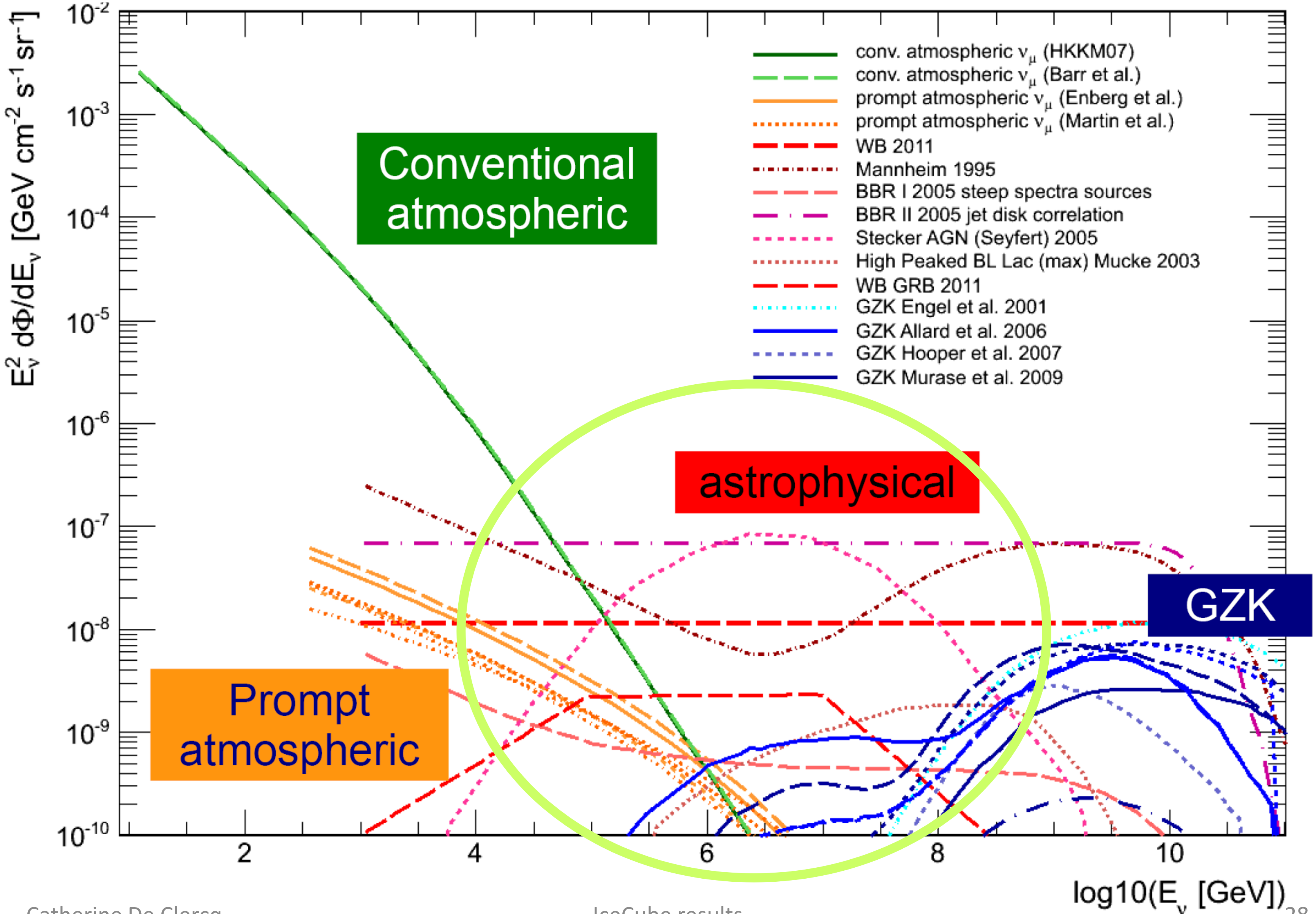
IceCube

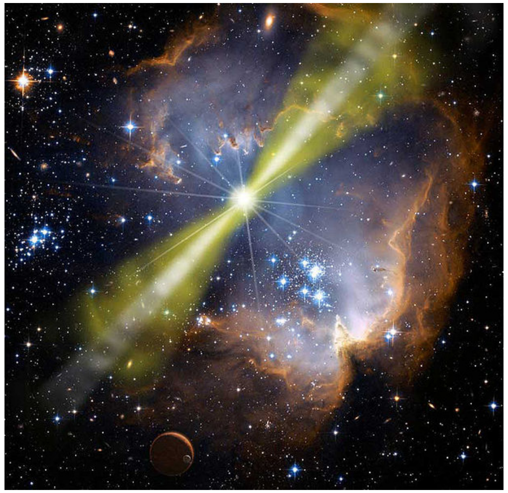
strategies

- Search for a **clustering** of high-energy neutrinos in certain directions
  - Full sky search for point sources
  - look into directions of catalogued active galaxies
  - Look for neutrinos from catalogued Gamma Ray Bursts
  - Look for neutrinos from temporarily active (flaring) objects

- search for a **diffuse flux** of high energy muon neutrinos or cascade-like events
- Search for a diffuse flux of very high energy neutrinos

The diffuse neutrino energy spectrum





Hotspots in the neutrino skymap

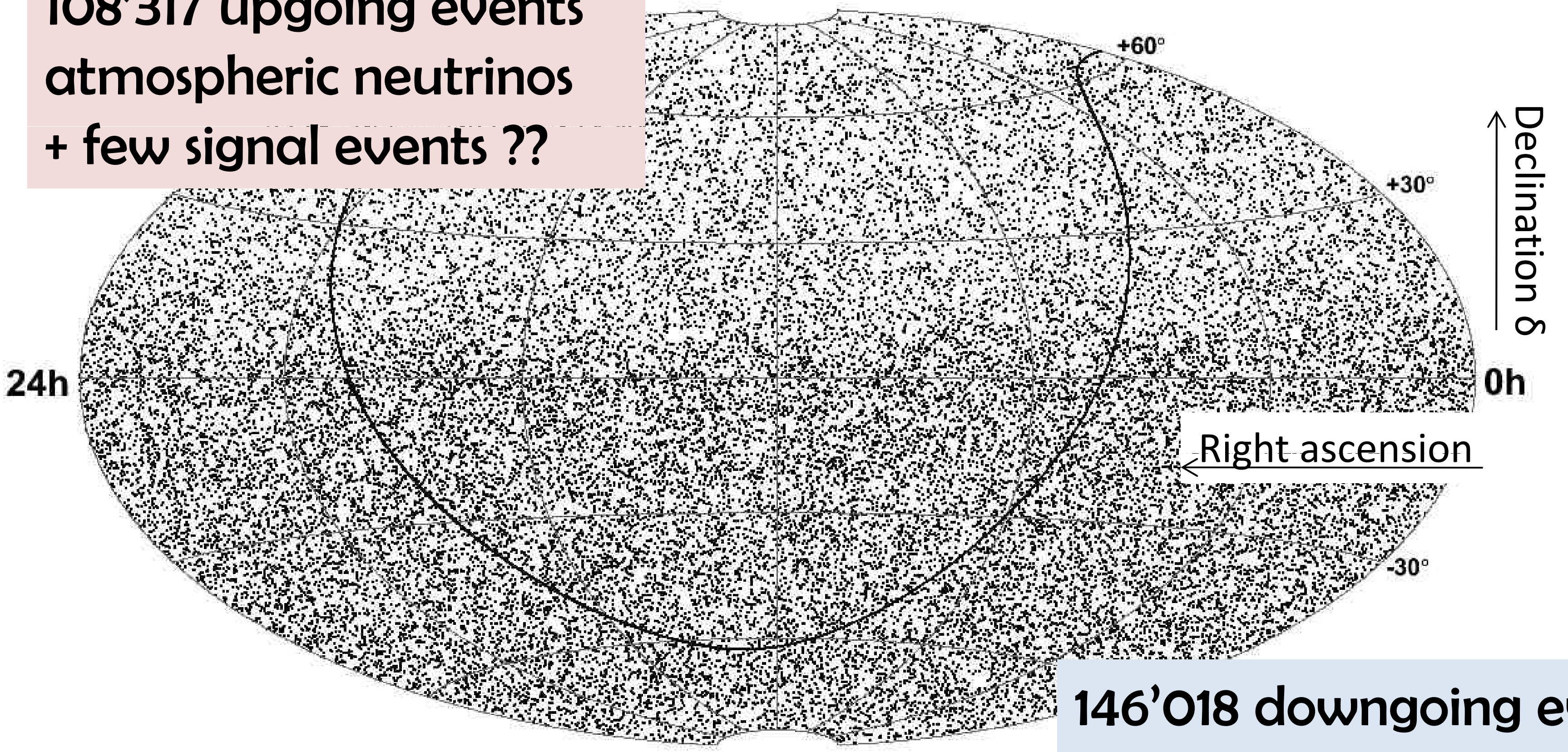
Neutrinos from Gamma Ray Bursts

Point sources

IceCube

IC40+IC59+IC79 neutrino skymap

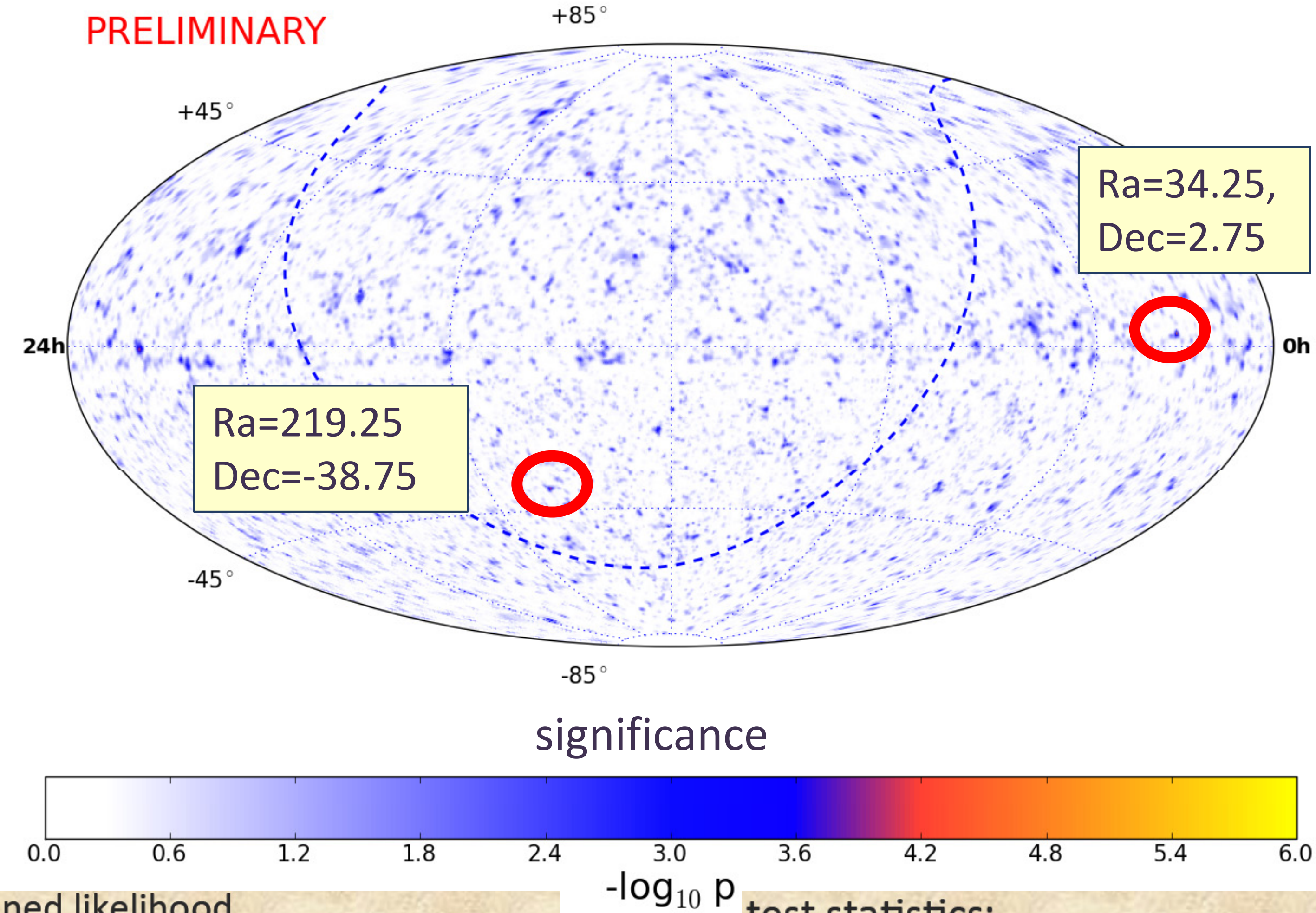
108'317 upgoing events
atmospheric neutrinos
+ few signal events ??



146'018 downgoing events
atmospheric μ + ν
+ few signal events ??

- IC 40 to 79 strings - data from 2008-11
- 375 days (IC40) + 348 days (IC59) + 316 days (IC79)

Hotspots? Use pointing & energy



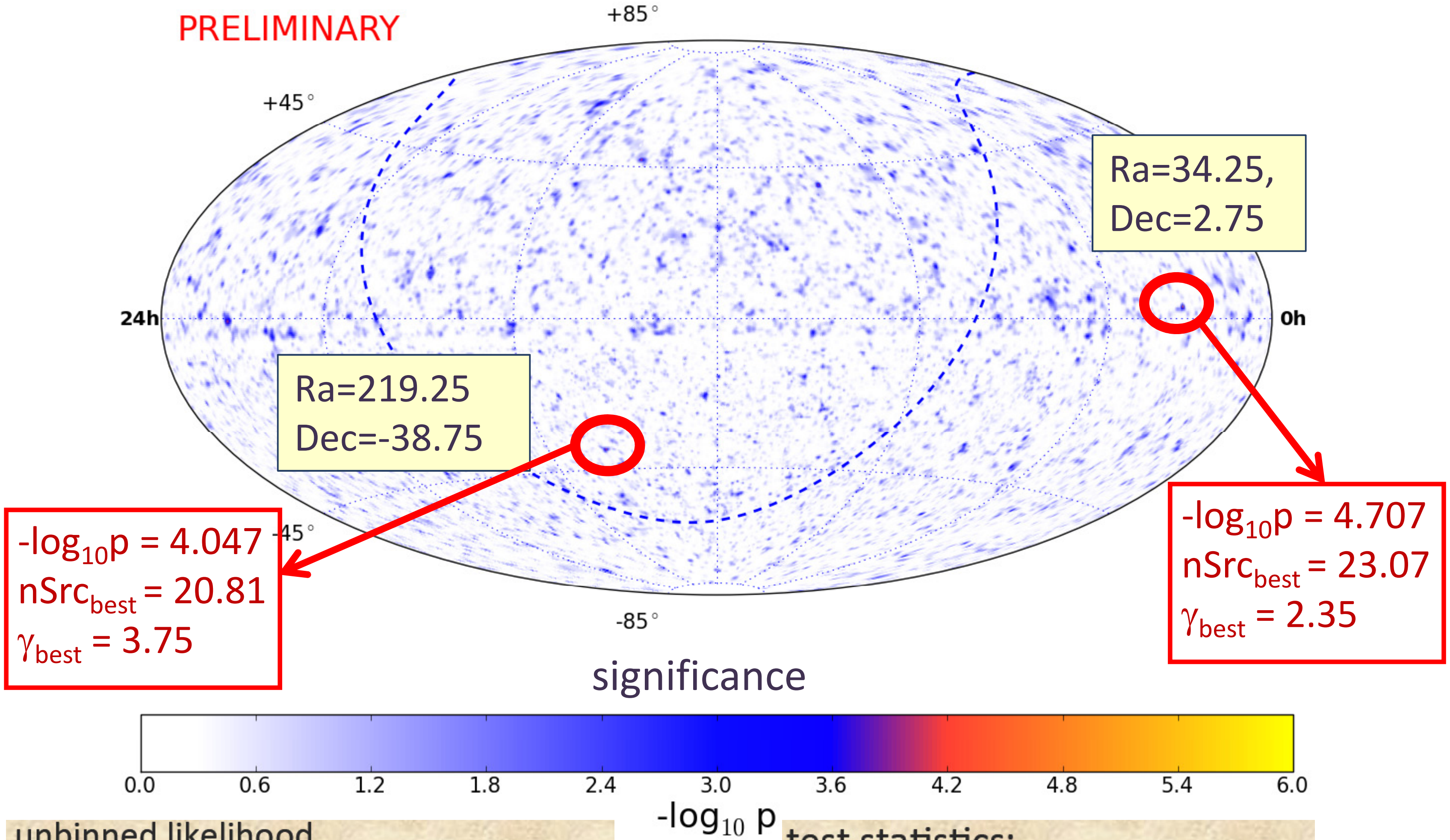
unbinned likelihood

$$L(n_s, \gamma) = \prod_{i=1}^{N} \left(\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i \right)$$

test statistics:

$$\lambda = \frac{L(\hat{n}_s, \hat{\gamma})}{L(n_s = 0)} \Rightarrow \text{p} - \text{value}$$

Hotspots? Significance map



unbinned likelihood

$$L(n_s, \gamma) = \prod_{i=1}^{N} \left(\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i \right)$$

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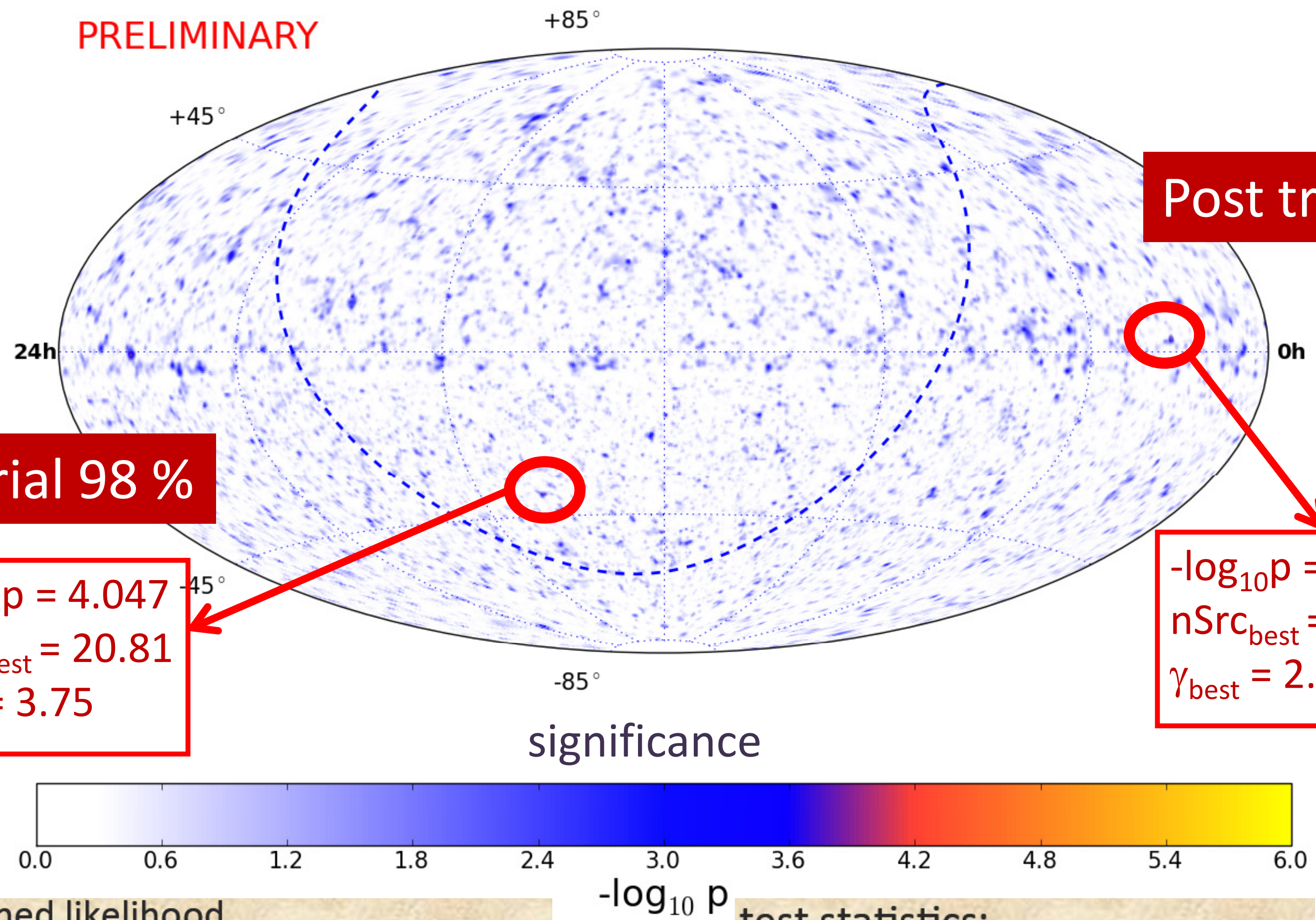
Hotspots? Significance map



Post trial 98 %

$-\log_{10}p = 4.047$
$nSrc_{best} = 20.81$
$\gamma_{best} = 3.75$

Post trial 57 %

$-\log_{10}p = 4.707$
$nSrc_{best} = 23.07$
$\gamma_{best} = 2.35$

unbinned likelihood

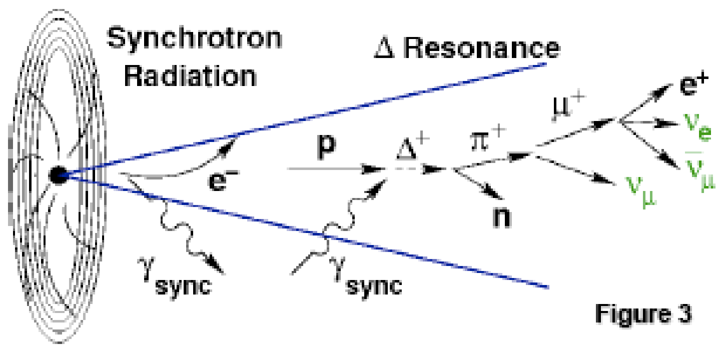
$$L(n_s, \gamma) = \prod_{i=1}^{N} \left(\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i \right)$$

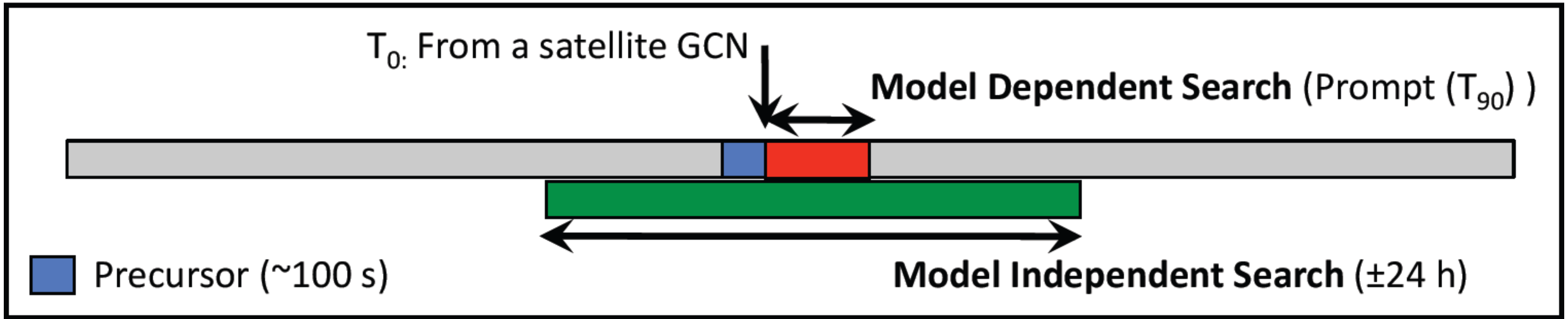
test statistics:

$$\lambda = \frac{L(\hat{n}_s, \hat{\gamma})}{L(n_s = 0)} \Rightarrow \mathrm{p-value}$$

Gamma ray bursts

- Search for neutrinos emitted in time Δt around observed GRB
- Position & time given – background from off-source data

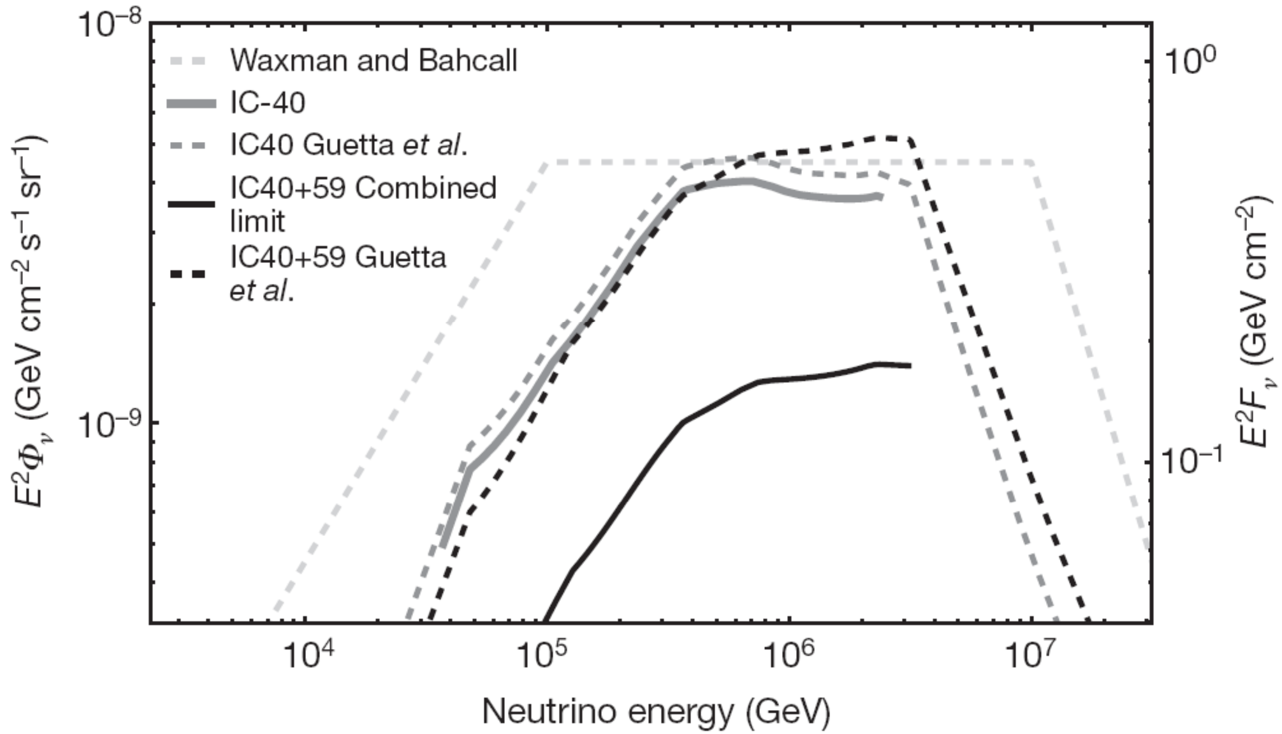




IC40 + IC59 GRB results

- 215 GRBs in Northern sky
- 2 events found, compaticle with atmospheric background

Nature **84**, 351 (2012)



Atmospheric neutrinos

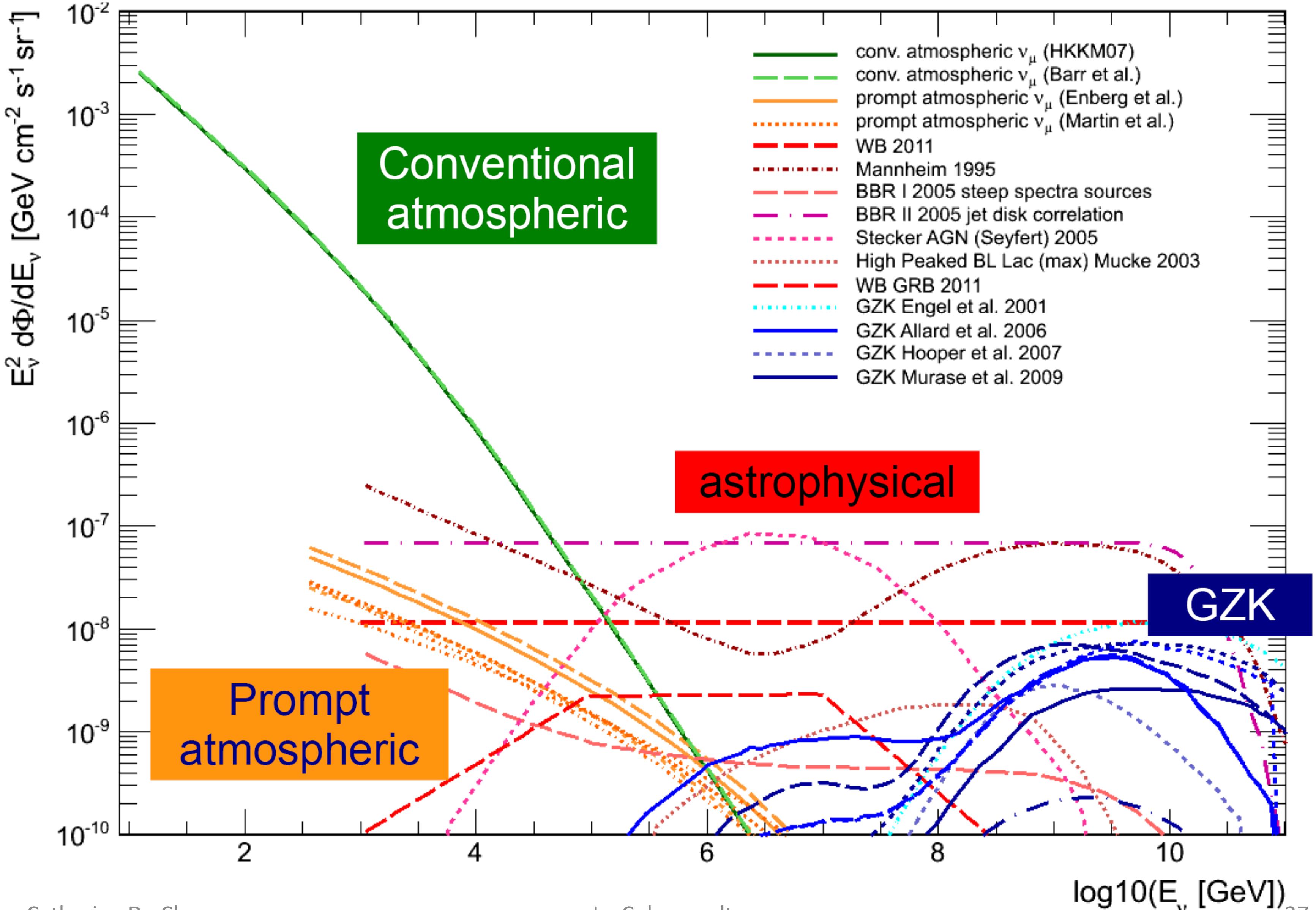
Astrophysical muon neutrinos

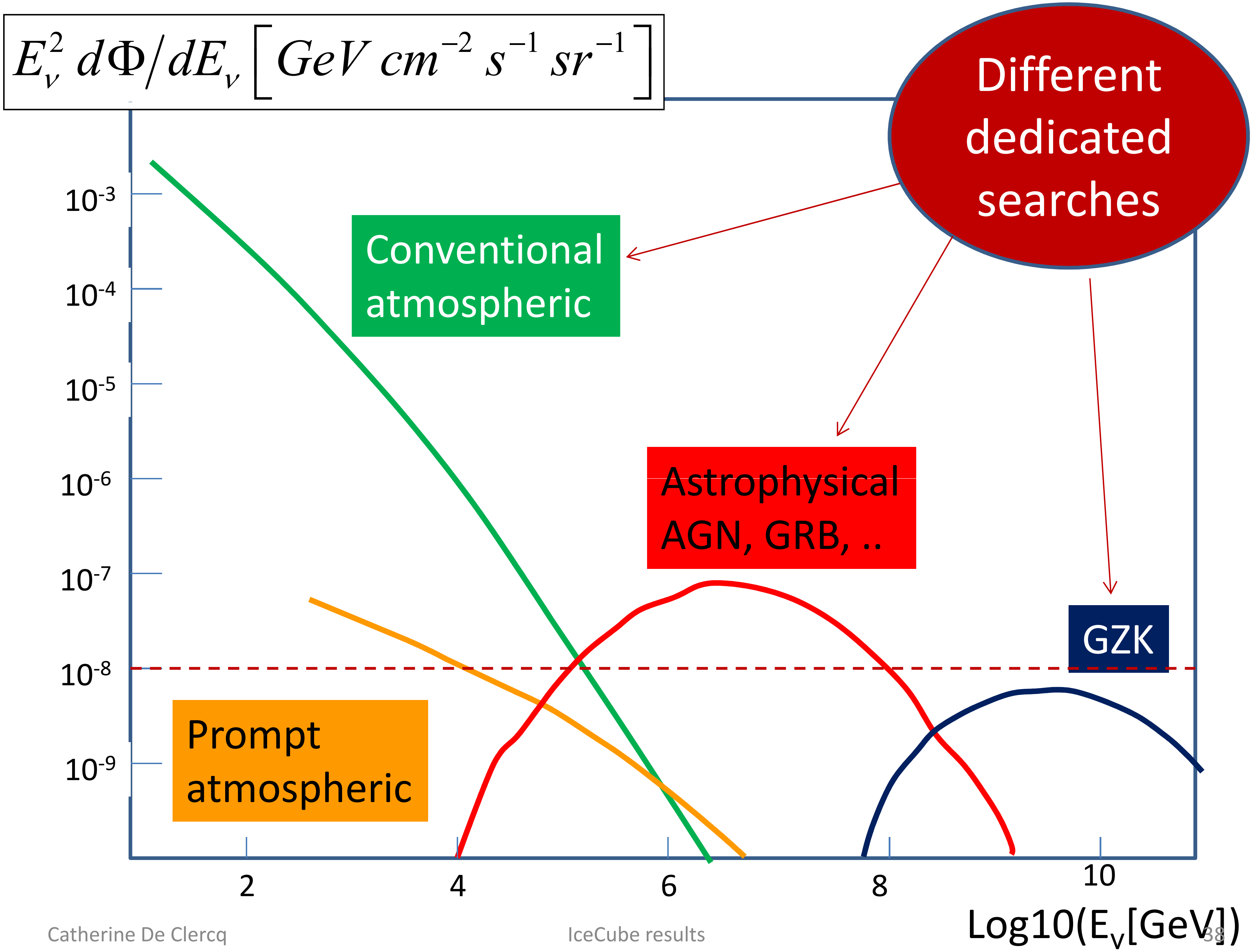
Extremely High Energy neutrinos

DIFFUSE NEUTRINO FLUXES

IceCube

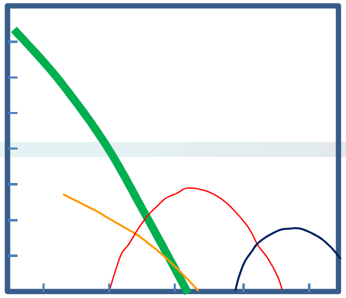
The diffuse neutrino energy spectrum

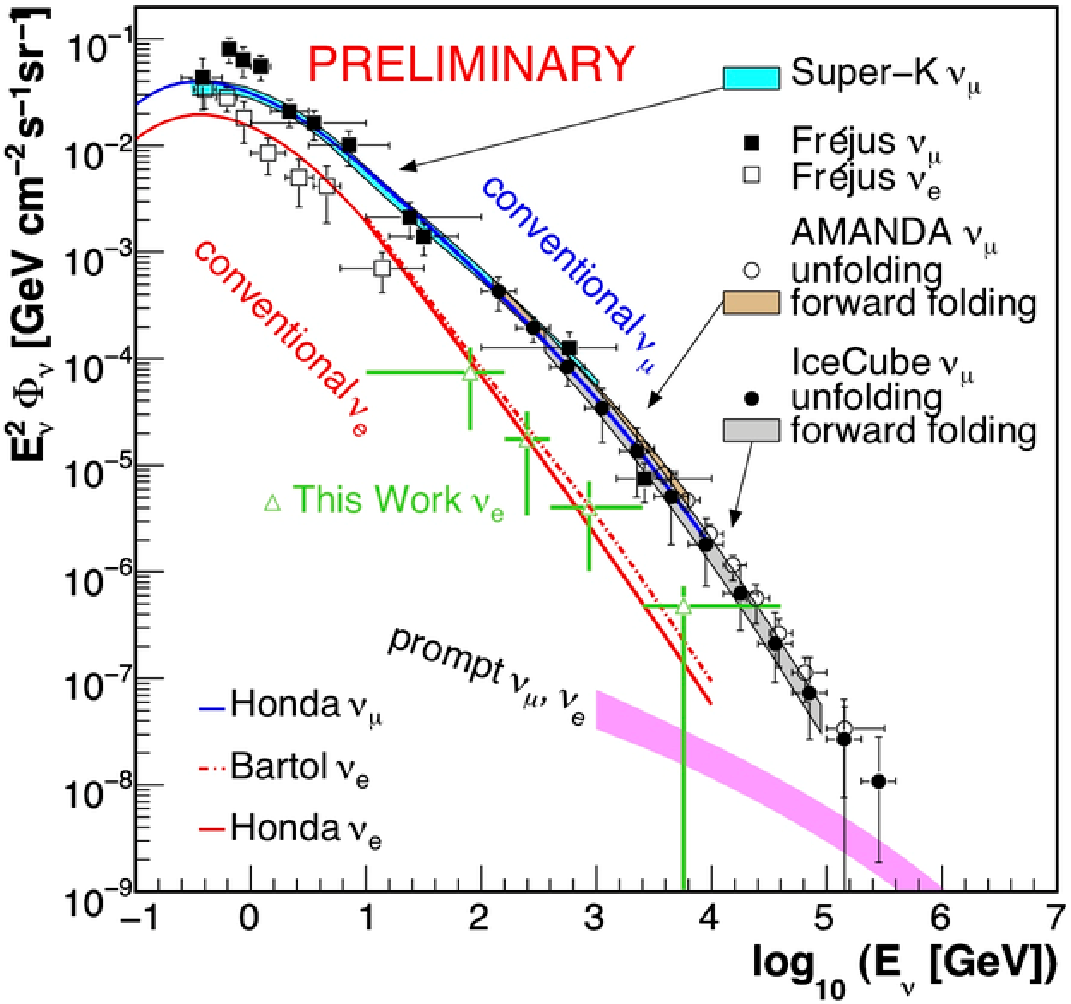




$E_\nu^2\, d\Phi/dE_\nu \left[GeV\, cm^{-2}\, s^{-1}\, sr^{-1} \right]$
Different dedicated searches
Conventional atmospheric
Astrophysical AGN, GRB, ..
GZK
Prompt atmospheric
10-3
10-4
10-5
10-6
10-7
10-8
10-9
2
4
6
8
10
Log10(Eν[GeV])

Atmospheric neutrinos





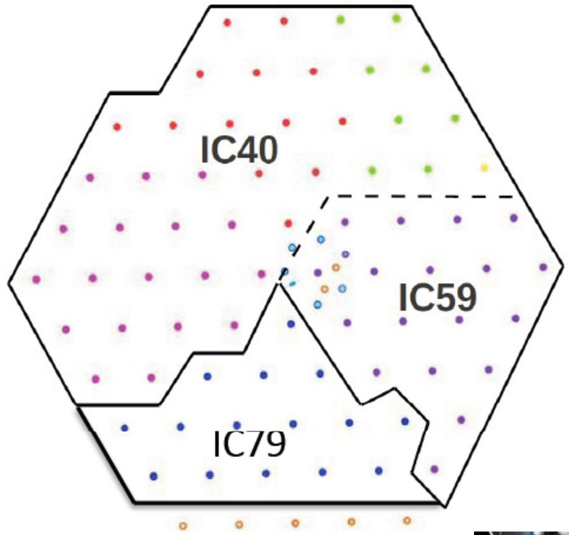
ν_μ IC40

Phys.Rev.D83:012001(2011)

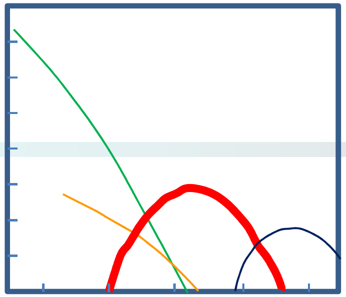
Phys.Rev.D84:082001(2011)

ν_e IC79

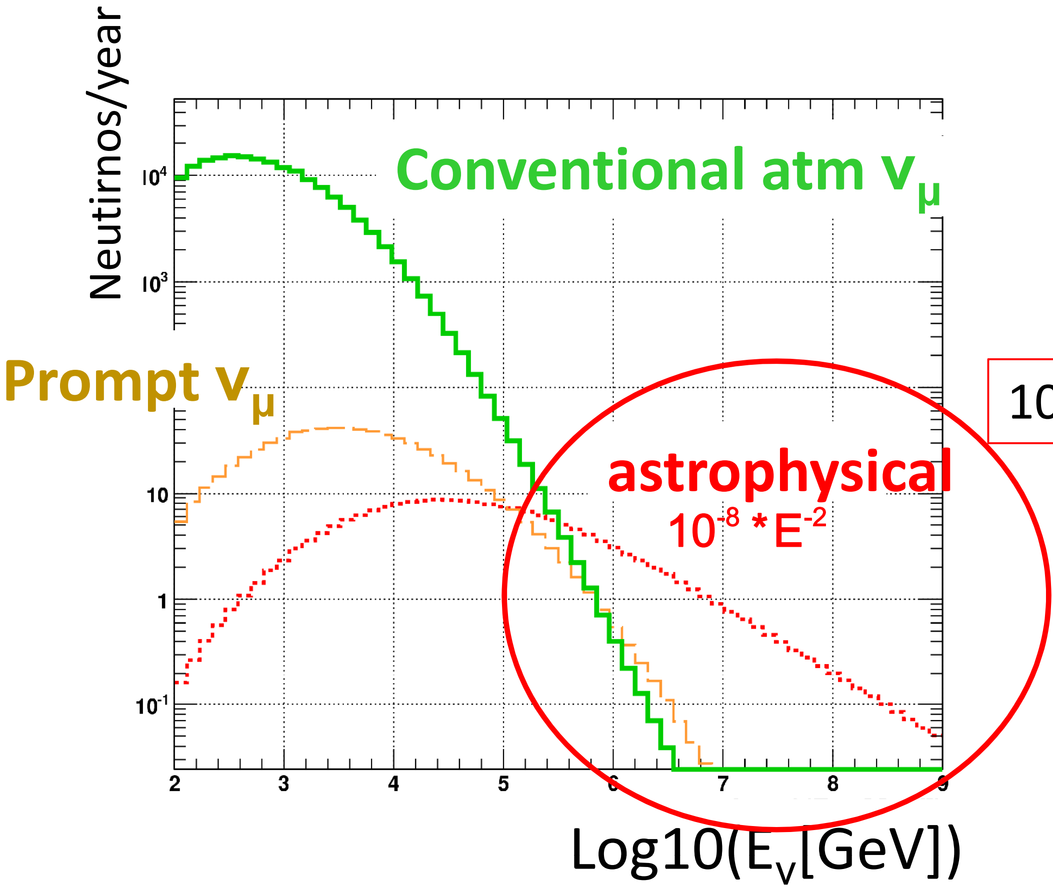
arxiv.org/1212.4760

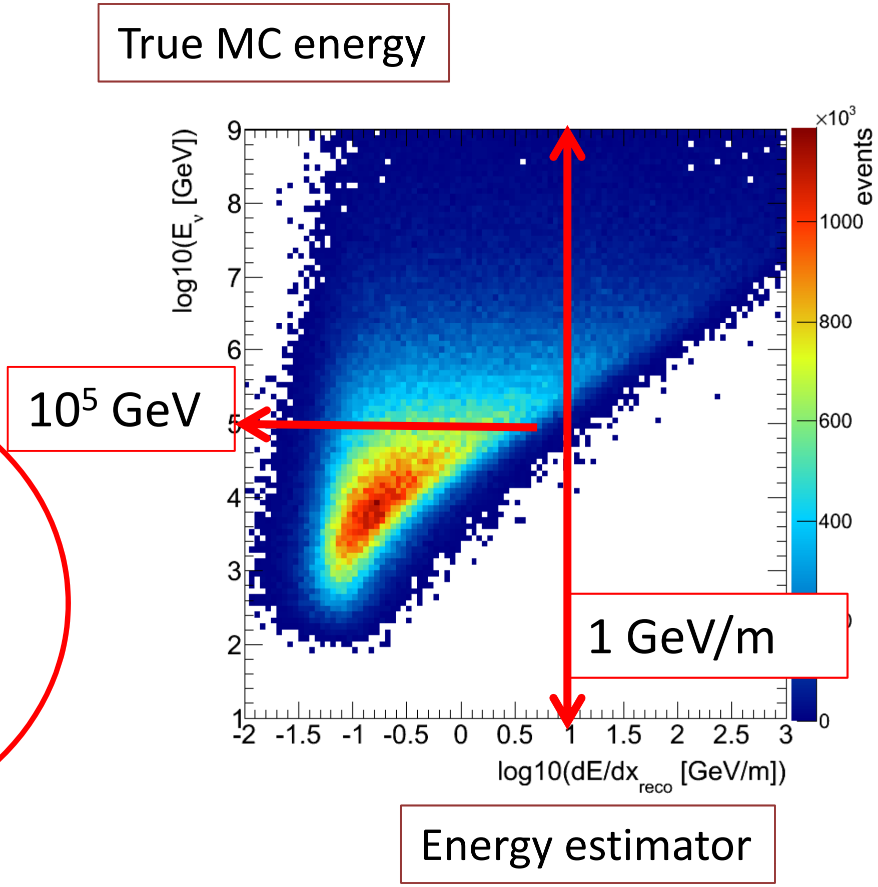


diffuse ν_μ flux



relies on energy reconstruction
upgoing neutrinos from Northern sky

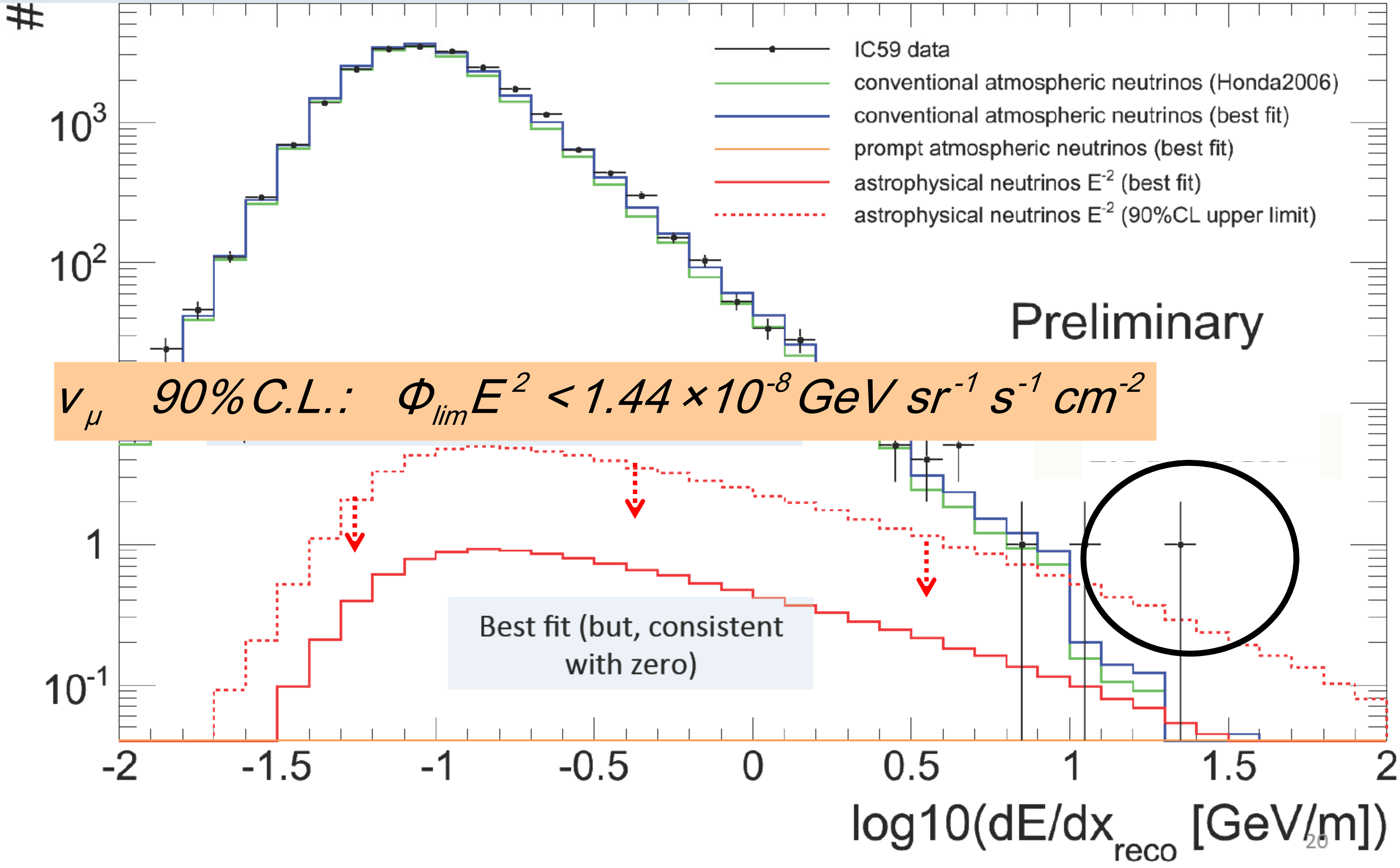




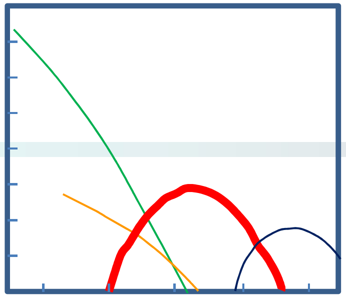
IC59 Diffuse ν_μ Search fit to data

Atm. Muon contamination <0.2%!

Livetime: 348 days   Events: 21943



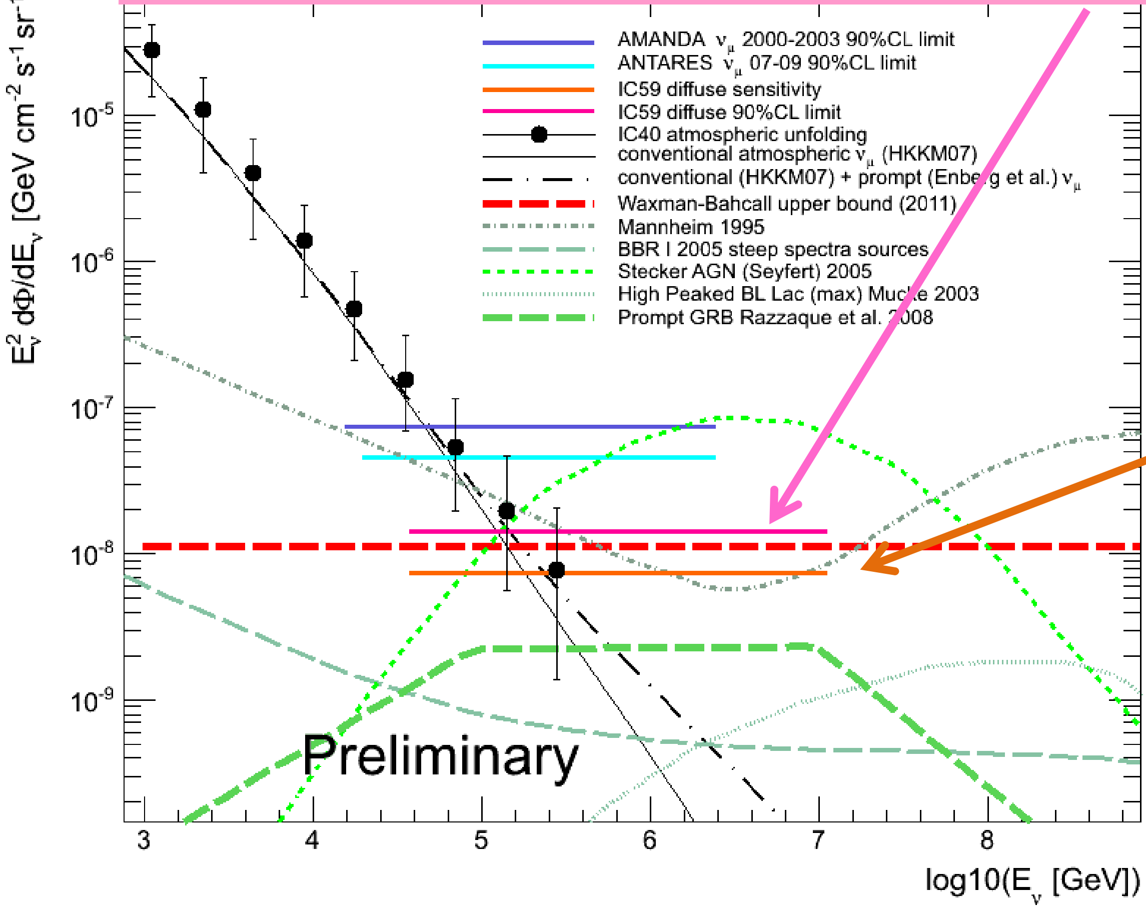
ν_μ 90% C.L.: $\Phi_{lim} E^2 < 1.44 \times 10^{-8}$ GeV sr^{-1} s^{-1} cm^{-2}



IC59 diffuse ν_μ flux upper limit

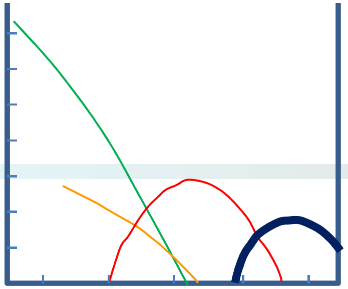
for neutrino flux with E^{-2} energy spectrum

90% C.L. upper limit $\Phi_{lim} E^2 < 1.44 \times 10^{-8}\ GeV\ sr^{-1}\ s^{-1}\ cm^{-2}$



sensitivity

Factor 1.5 above the Waxman-Bahcall upper bound



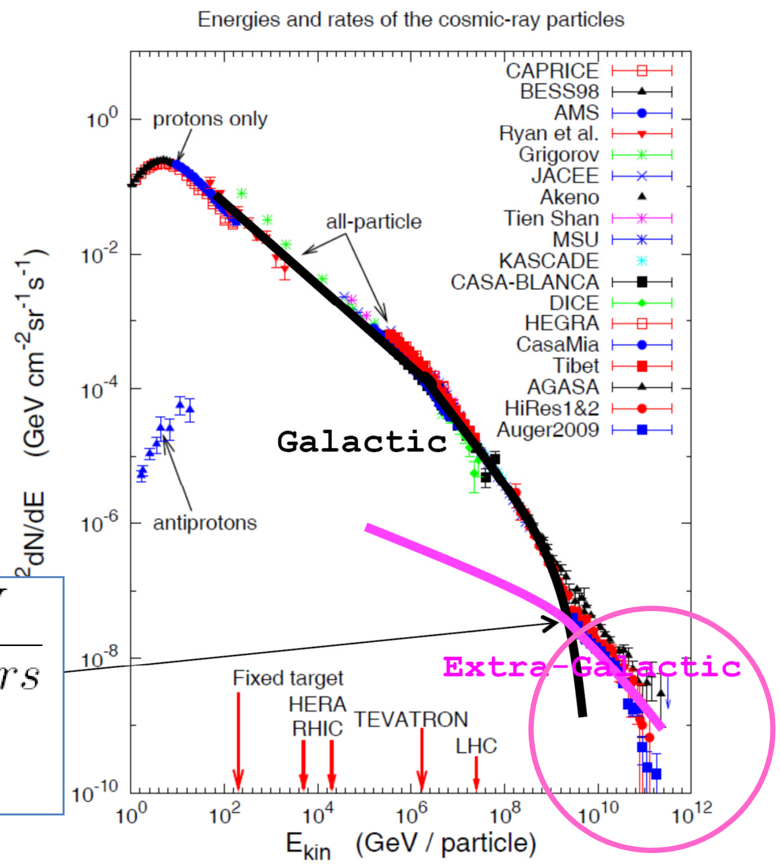
Extremely High Energy neutrinos

- Cosmic Ray connection: **GZK(*) effect** observed in charged CR

  –> expect neutrino flux

- Near accelerator of CR

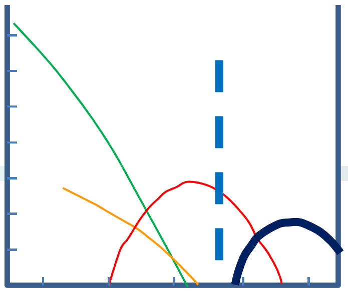
$$p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow \pi^{+} n \rightarrow \nu$$



$$E\frac{dN}{d\ln E} \approx 3\times10^{-8}\ \frac{\mathrm{GeV}}{cm^2 srs}$$

at 10^{10} GeV (10^{19} eV)

(*)Greisen Zatsepin Kuzmin



Two ν_e like events

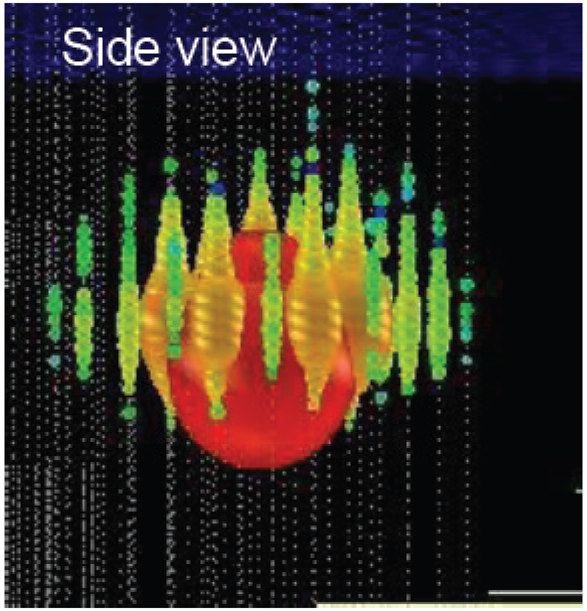
- IC79+IC86 – May 2010 - May 2012 – 672 days
- Remove background with an energy cut
- Earth becomes opaque at PeV -> search for downgoing neutrinos

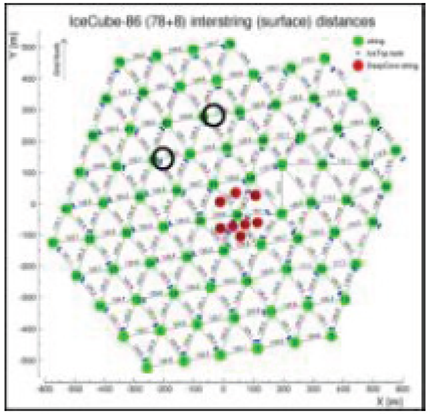
- First PeV events observed in IceCube
- Find 2 events, expect ~0.14 background (atm. μ & conventional & prompt atm. ν_μ)

After unblind - Observation of 2 events

Run119316-Event36556705
NPE 9.628x10[4]
GMT time: 2012/1/3 9:34:01

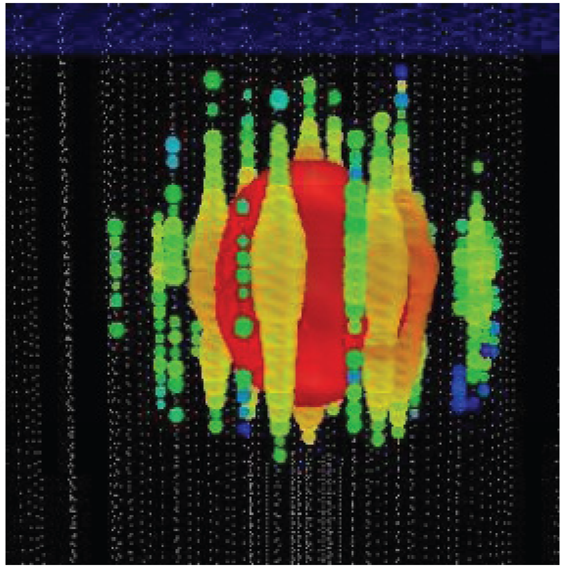
"Ernie"





Run118545-Event6373366
NPE 6.9928x10[4]
GMT time: 2012/8/8 12:23:18

"Bert"



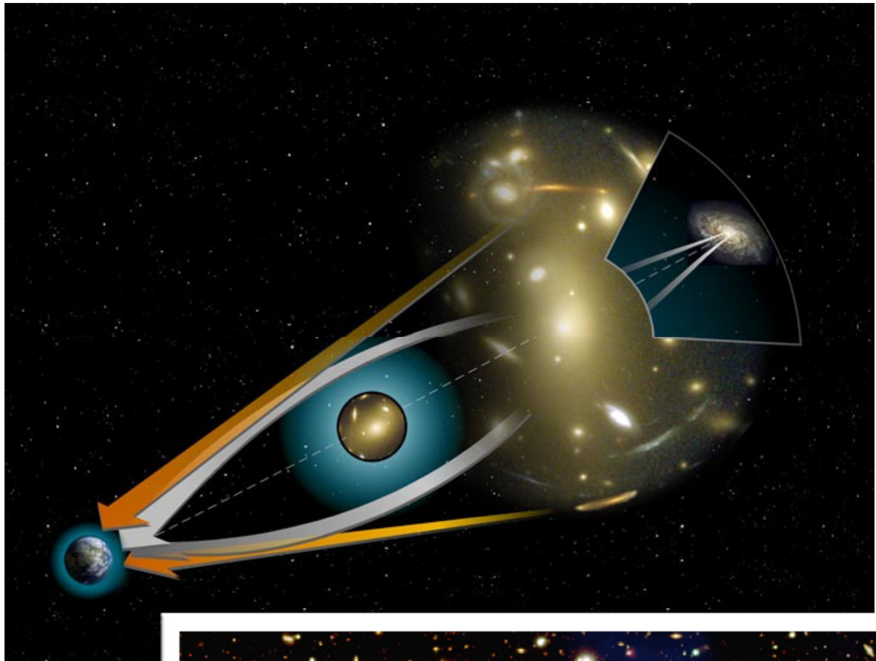
No counter arguments to the hypothesis of neutrino induced cascades so far

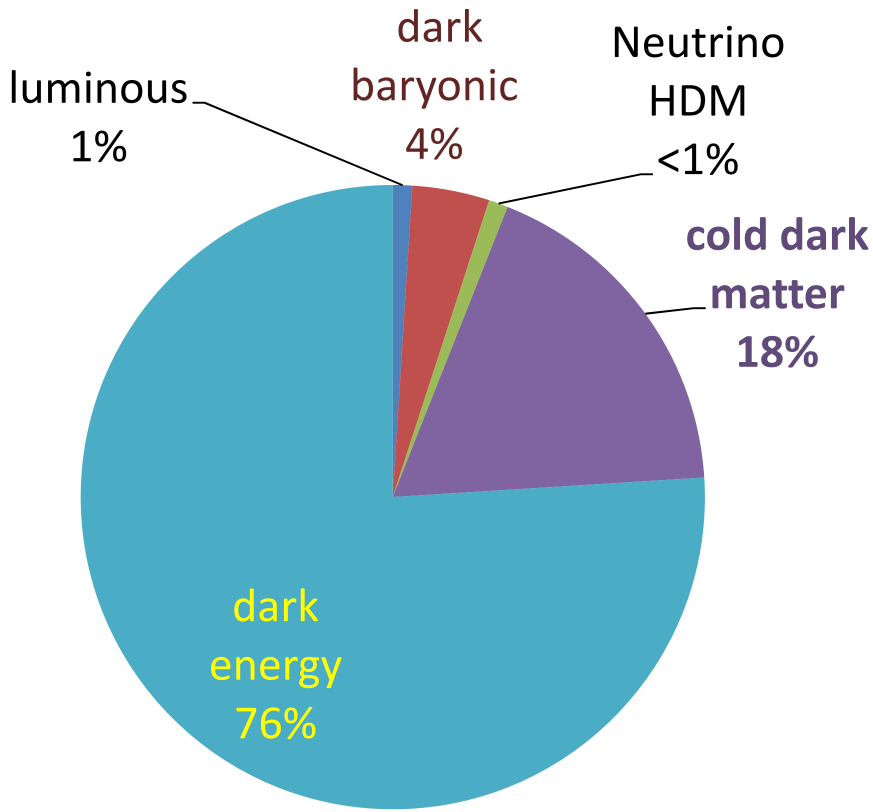
2 events / 671 days
background (atm. μ + conventional atm. ν) expectation 0.06 events

p-value 1.9×10^{-3} (2.9σ) beyond conventional background

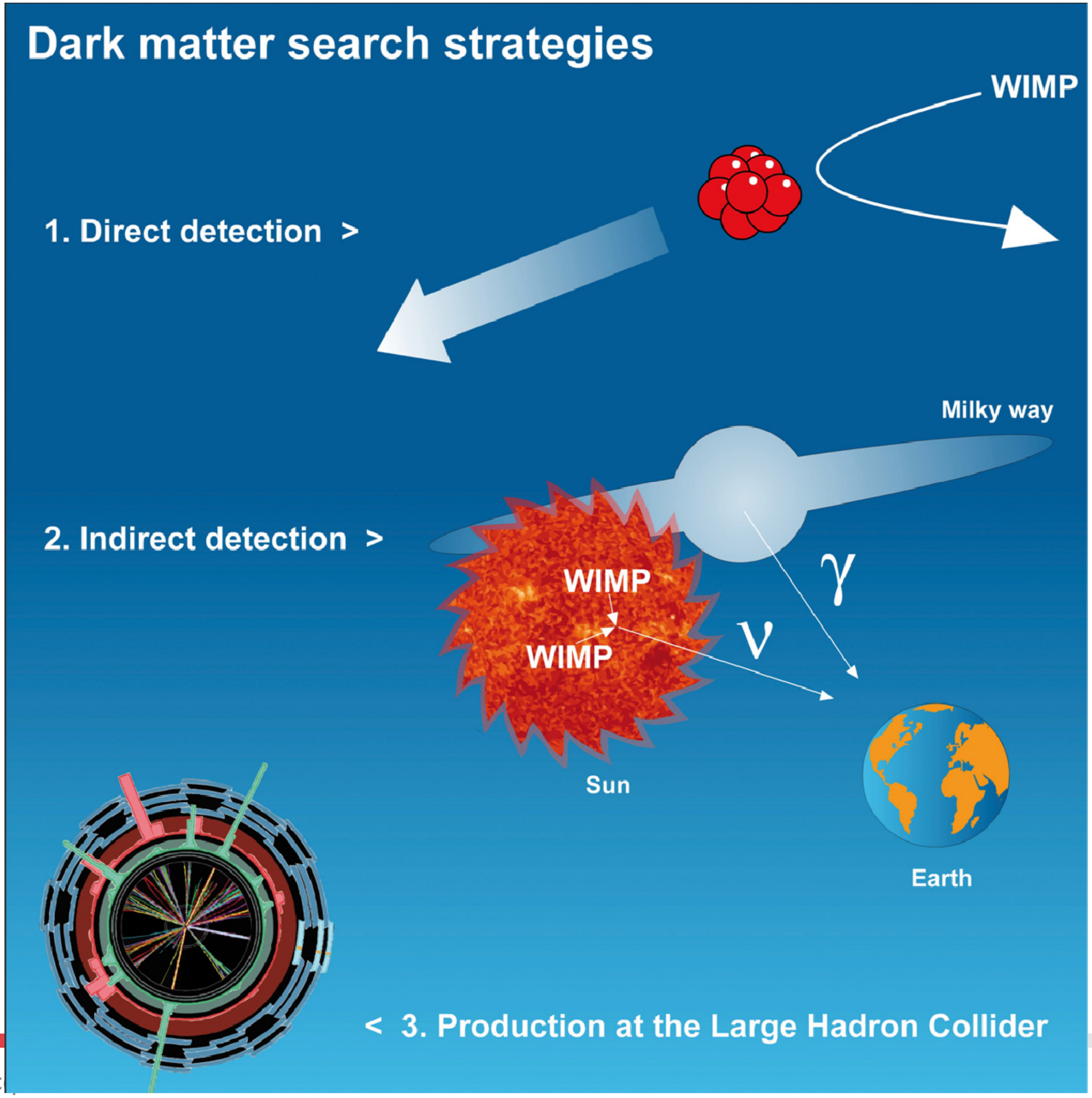
Indirect dark matter search

Gravitational evidence for missing mass



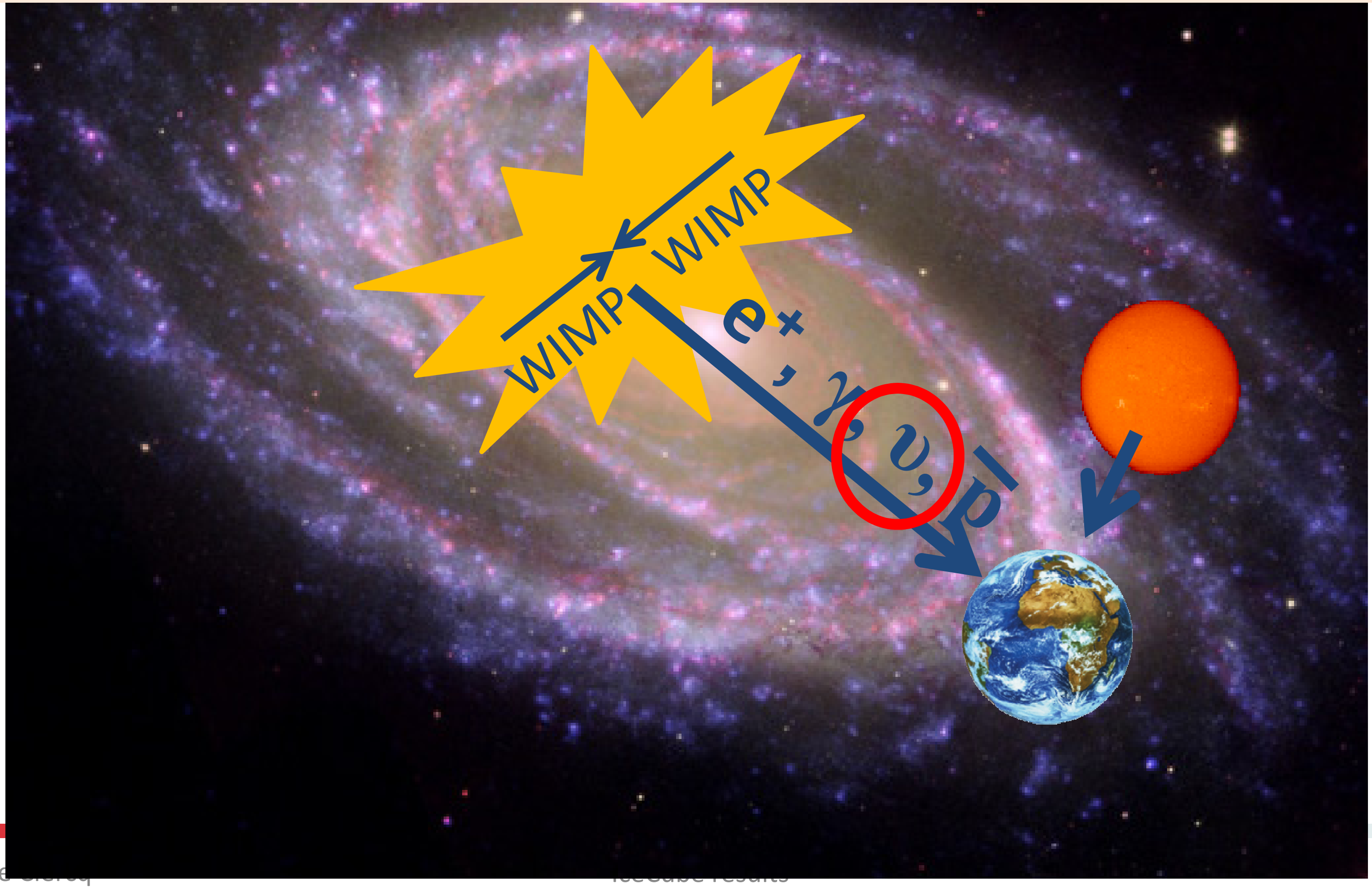


three complementary strategies

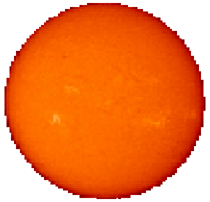


Indirect detection

dark matter particles are attracted by heavy objects through gravitation
They are massive, stable and weakly interacting ***WIMPs***
They can annihilate with each other and produce known particles



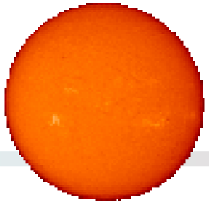
iceCube searches



- Neutrinos from WIMP annihilations in the Sun

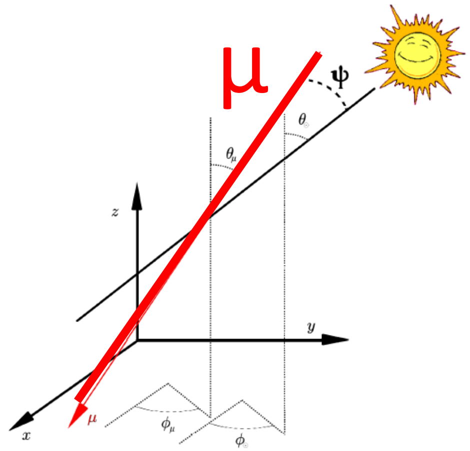
- Neutrinos from WIMP annihilations in galactic halo, galactic centre, dwarf spheroidal galaxies

- Neutrinos from WIMP annihilations in the centre of the Earth

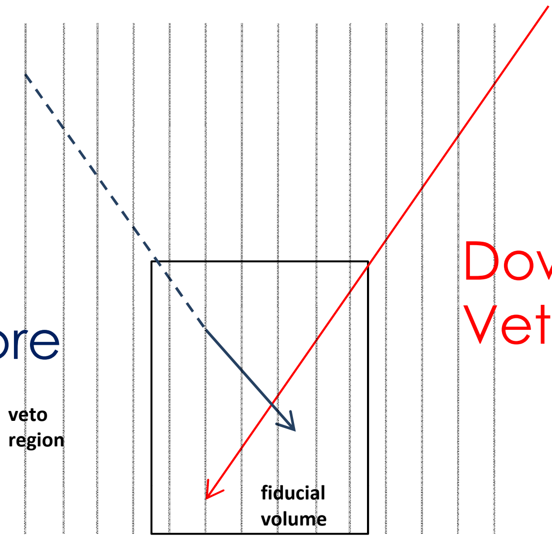


IC79 Solar WIMP search

- Any excess above atmospheric background in the direction of the Sun?
- New: **DeepCore + IceCube veto**
- Extend down to $E_\nu \sim 20$ GeV and to austral summer
- No evidence for excess

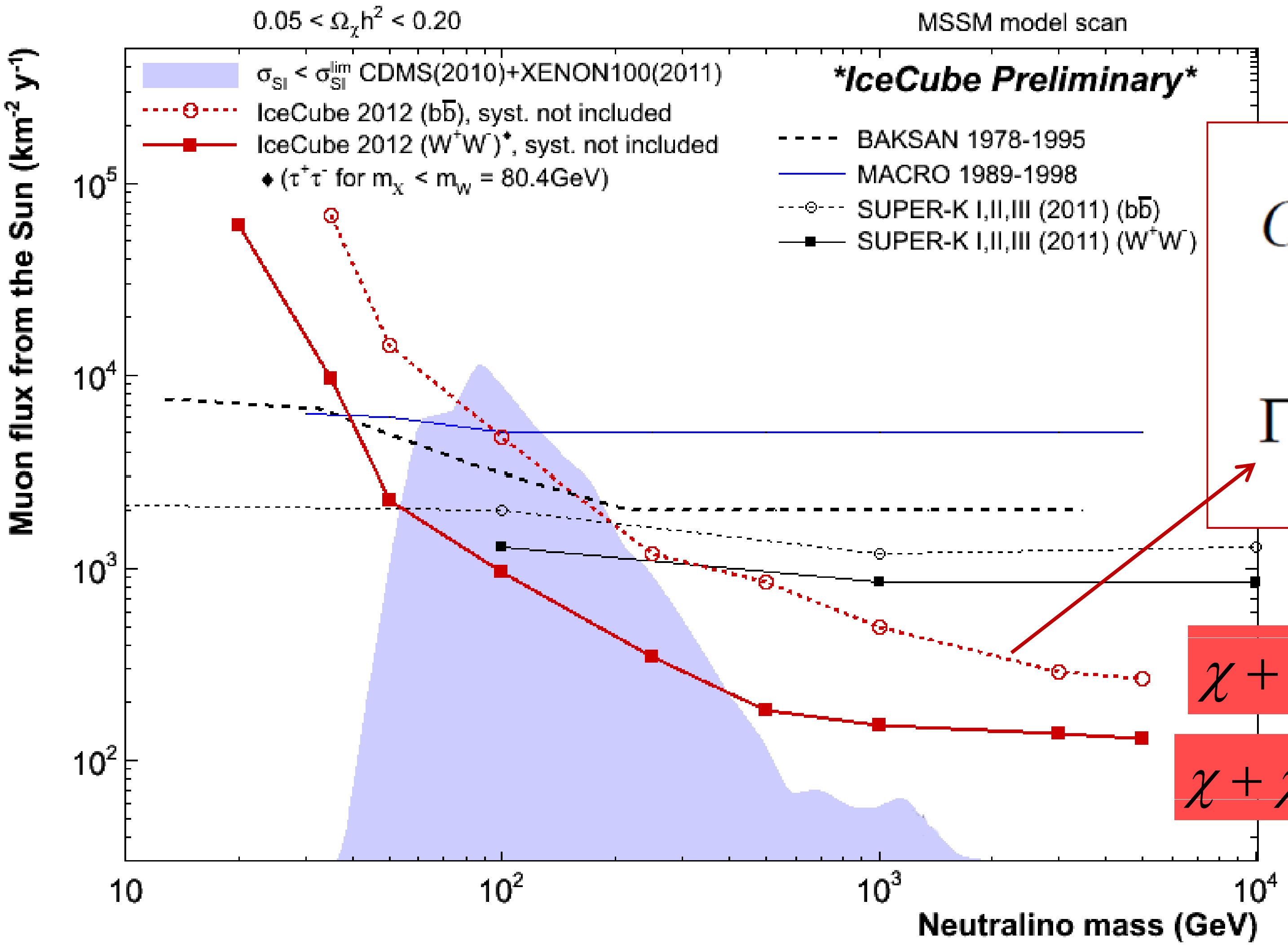


Downgoing ν
Interacting in DeepCore



Downgoing μ
Vetoed by IceCube strings

Upper limits on the muon flux



$$C_{sun} \propto \frac{\rho_\chi \sigma_{\chi p}}{\bar{v}_\chi^3 m_\chi^2}$$

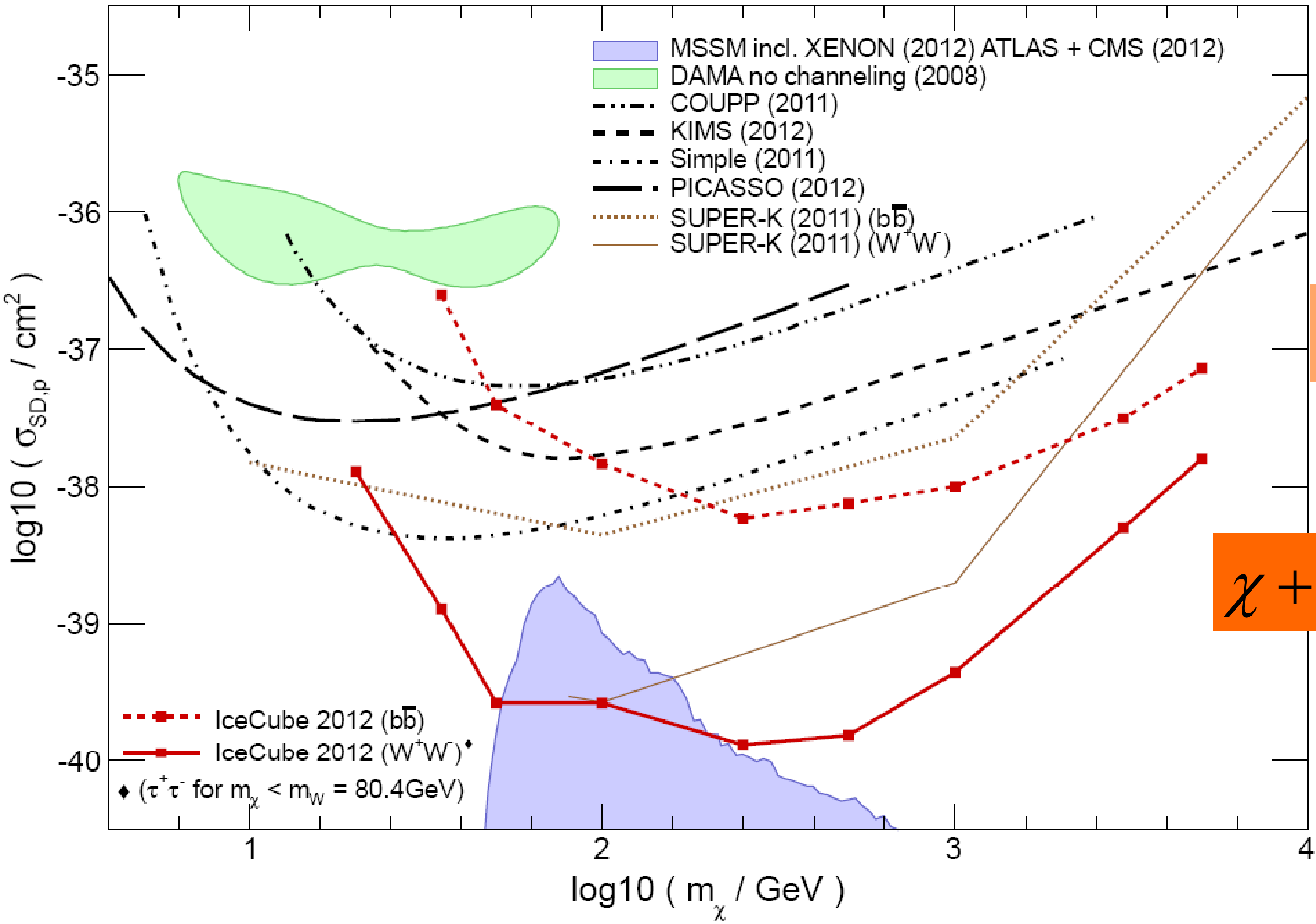
$$\Gamma_A = \frac{1}{2} C_{sun}$$

$$\chi + \chi \rightarrow b + \bar{b}$$

$$\chi + \chi \rightarrow W^+ + W^-$$

WIMP-nucleon cross section uper limits

arXiv:1212.4097v1

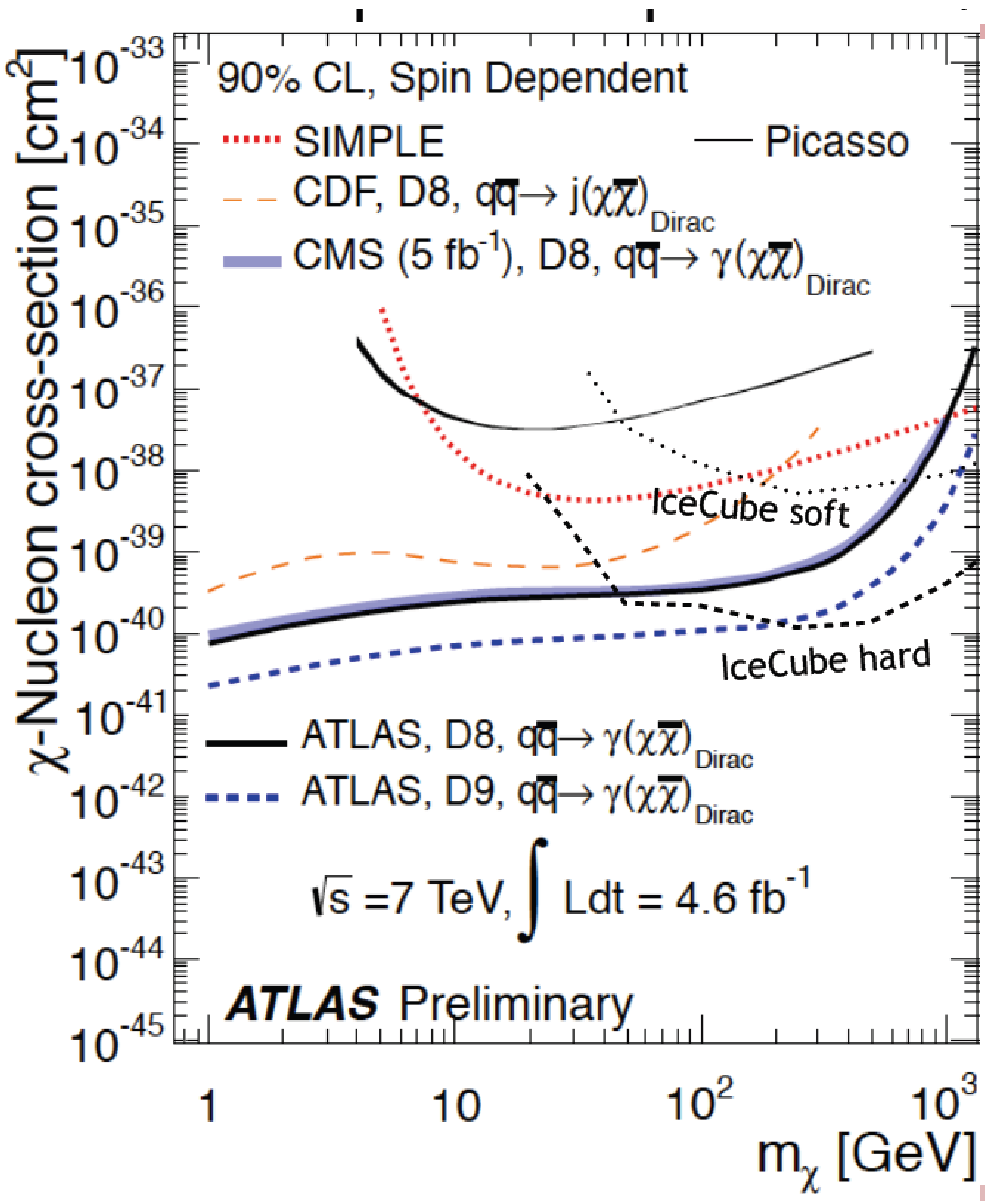


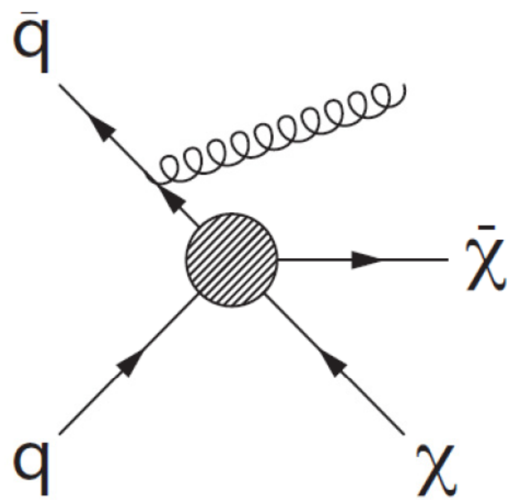
$$\chi + \chi \rightarrow b + \bar{b}$$

$$\chi + \chi \rightarrow W^+ + W^-$$

complementarities

- Direct searches
- Indirect neutrino search
- Tevatron and LHC monophoton





Summary

To conclude

- IceCube is largest operating neutrino detector
- Data taking with full detector since 2011
- Search for point sources of HE neutrinos: no evidence yet
- Search for neutrinos from GRBs: tension with fireball model
- Search for diffuse flux of HE and EHE neutrinos: upward fluctuations show up?
- Many exciting topics in (astro-)particle physics
- And hopefully unexpected surprises soon …

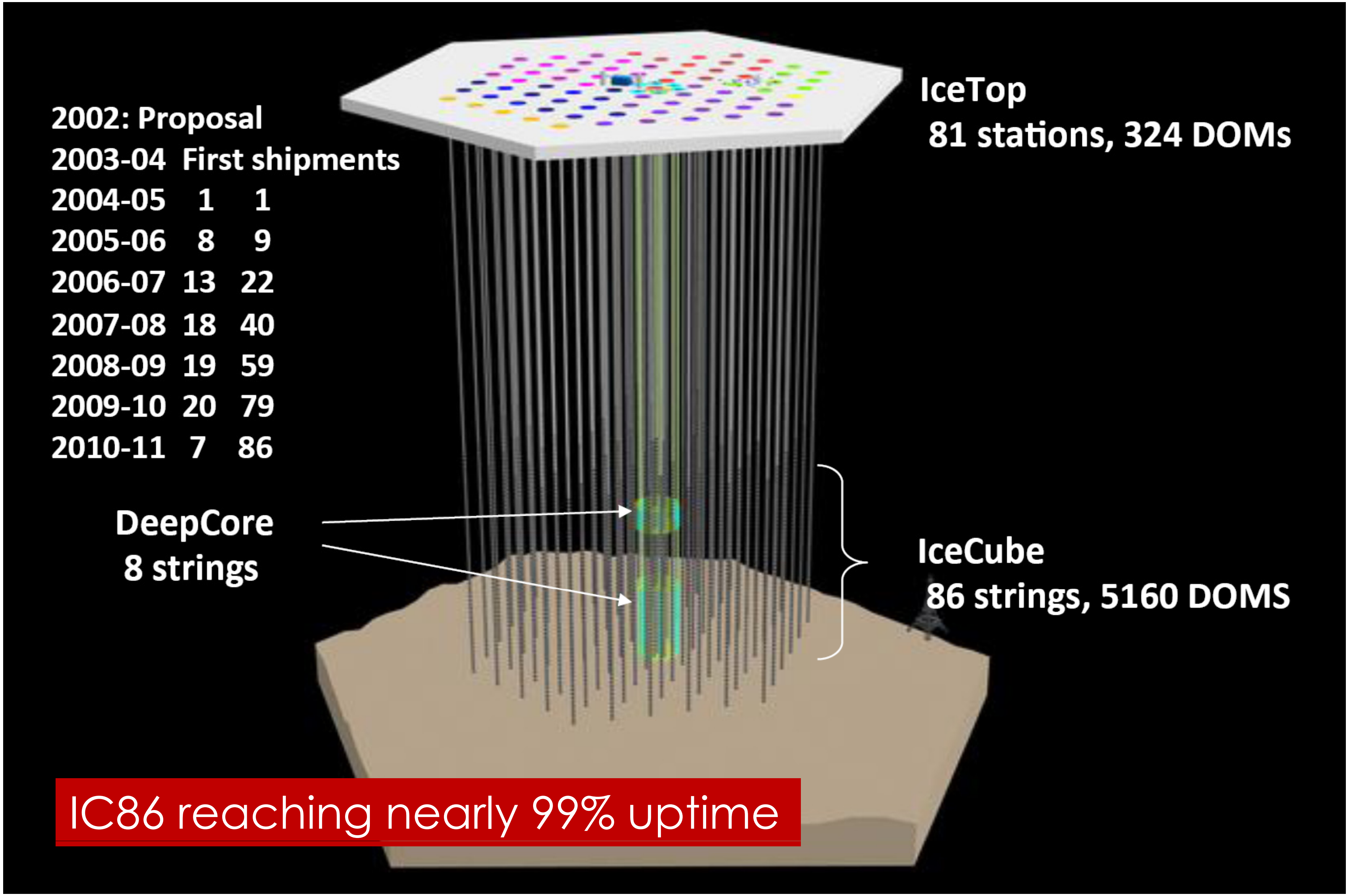
The IceCube Collaboration

More information: icecube.wisc.edu

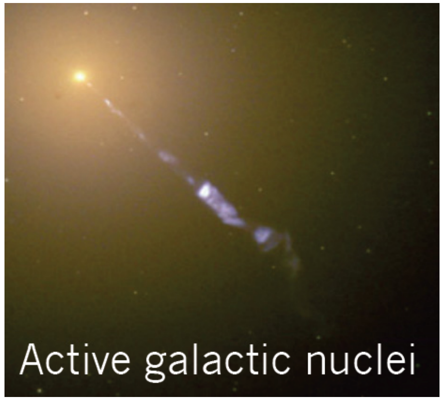
International Funding Agencies

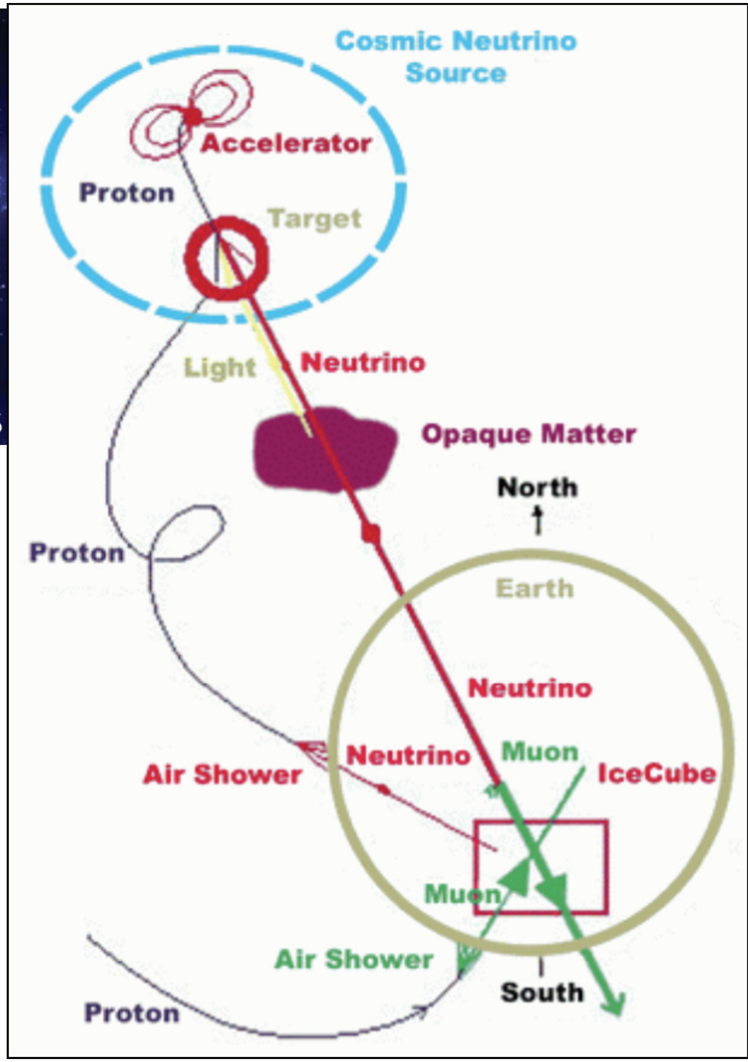
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The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

Backup material


2002: Proposal
2003-04 First shipments
2004-05 1 1
2005-06 8 9
2006-07 13 22
2007-08 18 40
2008-09 19 59
2009-10 20 79
2010-11 7 86
IceTop
81 stations, 324 DOMs
DeepCore
8 strings
IceCube
86 strings, 5160 DOMS
IC86 reaching nearly 99% uptime

Sources of high-energy neutrinos





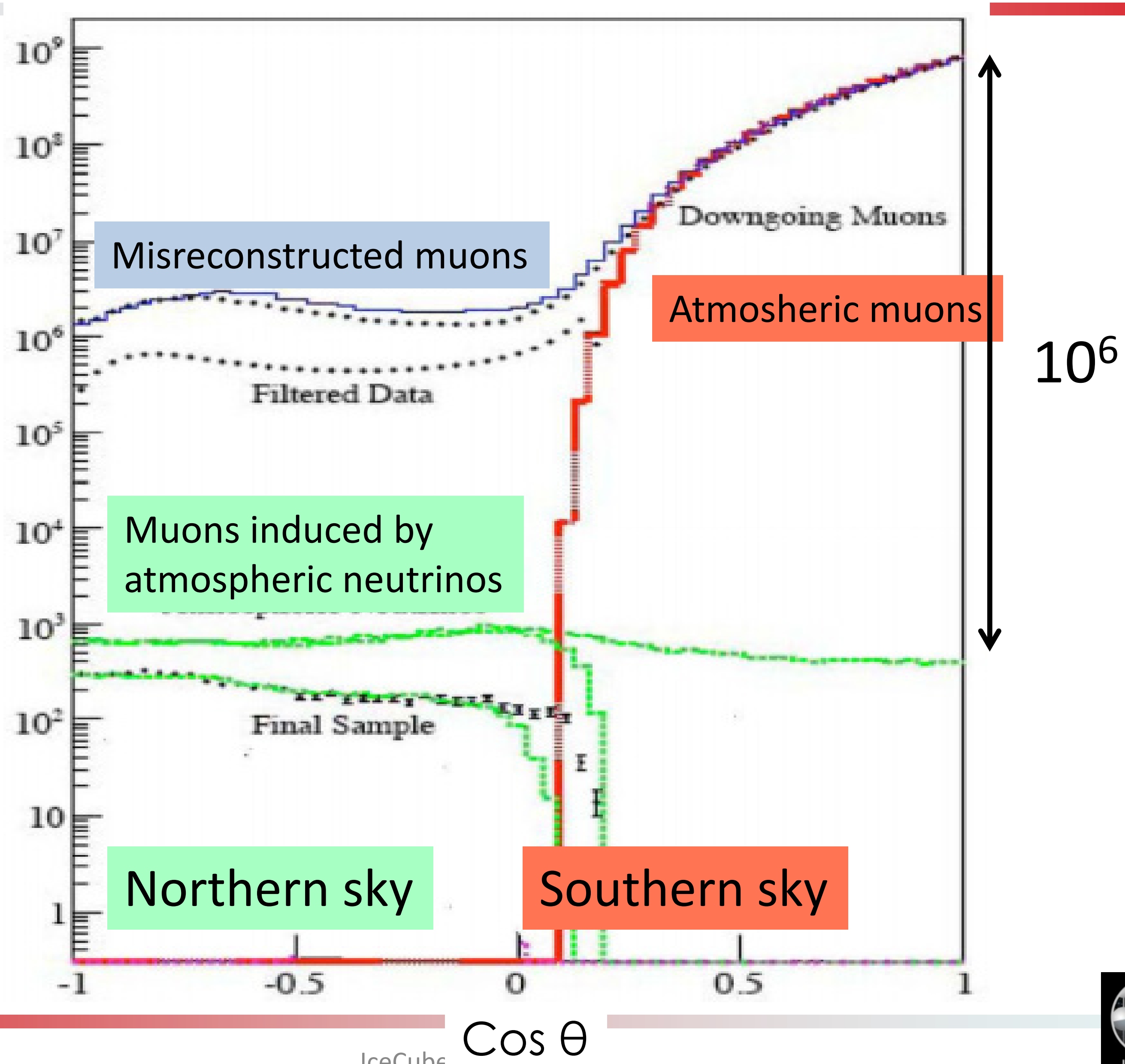
Sources of highest energy cosmic rays are also potential neutrino sources

Upgoing and downgoing muons

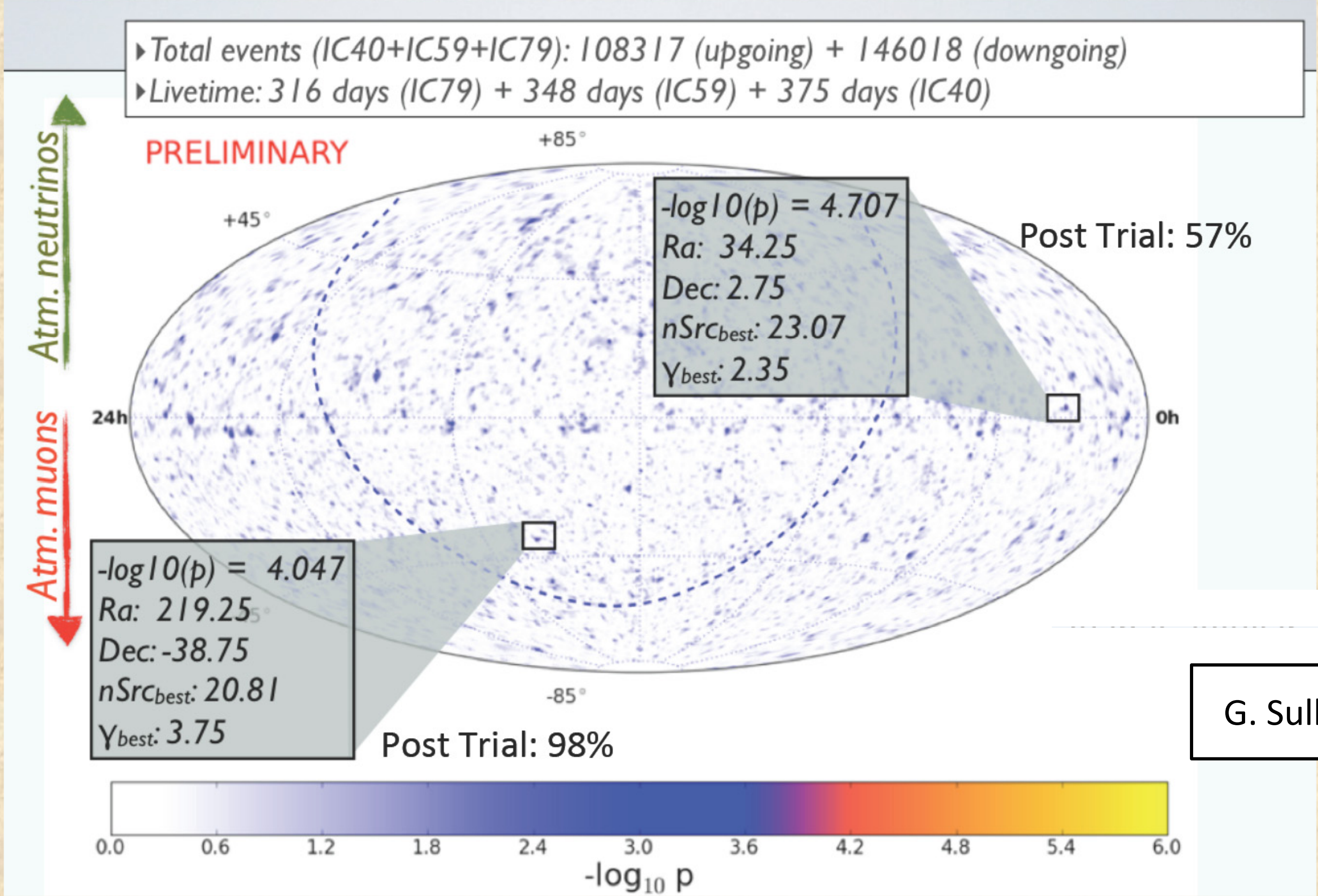
Trigger: kHz

Filter 100 Hz

Final cut level



Point Source Search in Skymap (IC40+59+IC79)



G. Sullivan

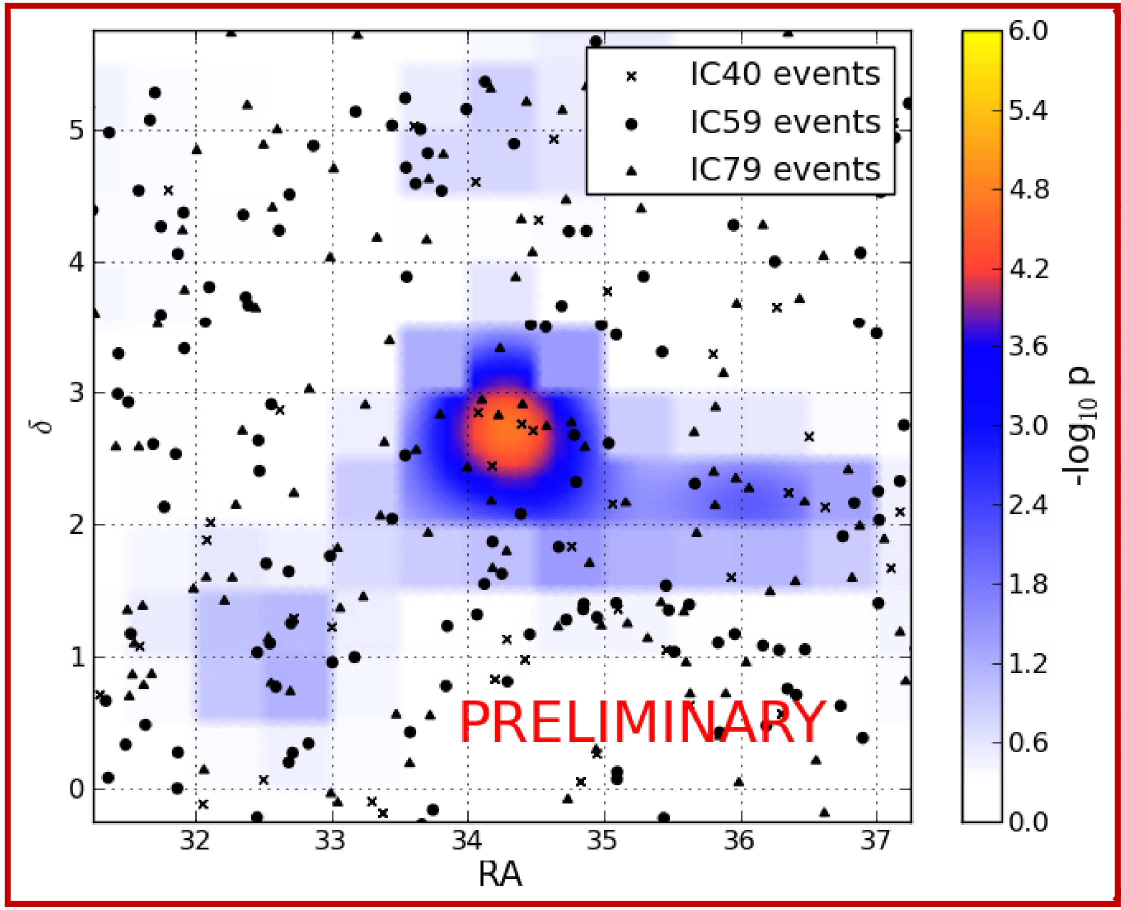
unbinned likelihood

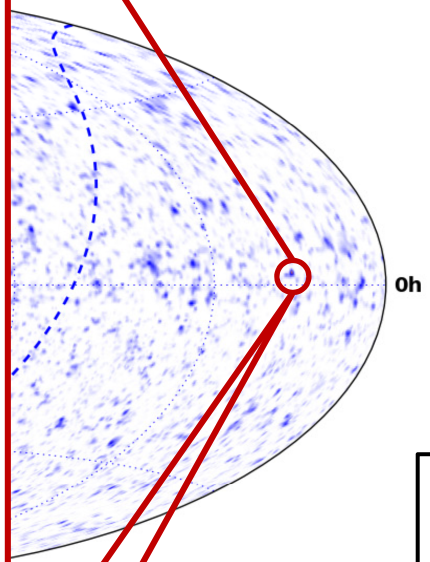
$$L(n_s, \gamma) = \prod^{N} \left(\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i \right)$$

test statistics:

$$\lambda = \frac{L(\hat{n}_s, \hat{\gamma})}{L(n_s = 0)} \Rightarrow \mathrm{p-value}$$

IC40+IC59+IC79





K. Woschnagg

$-\log_{10}p = 4.707$
$nSrc_{best} = 23.07$
$\gamma_{best} = 2.35$

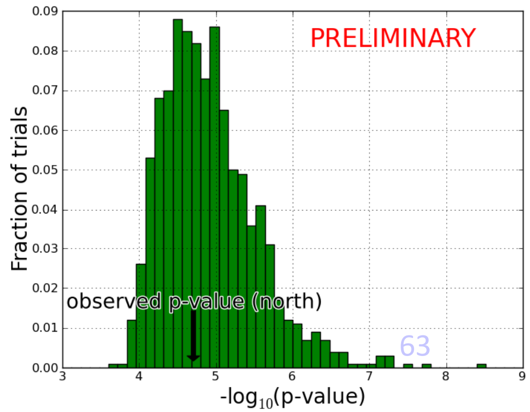
Hottest spot in Northern sky

(Ra=34.25, Dec=2.75)

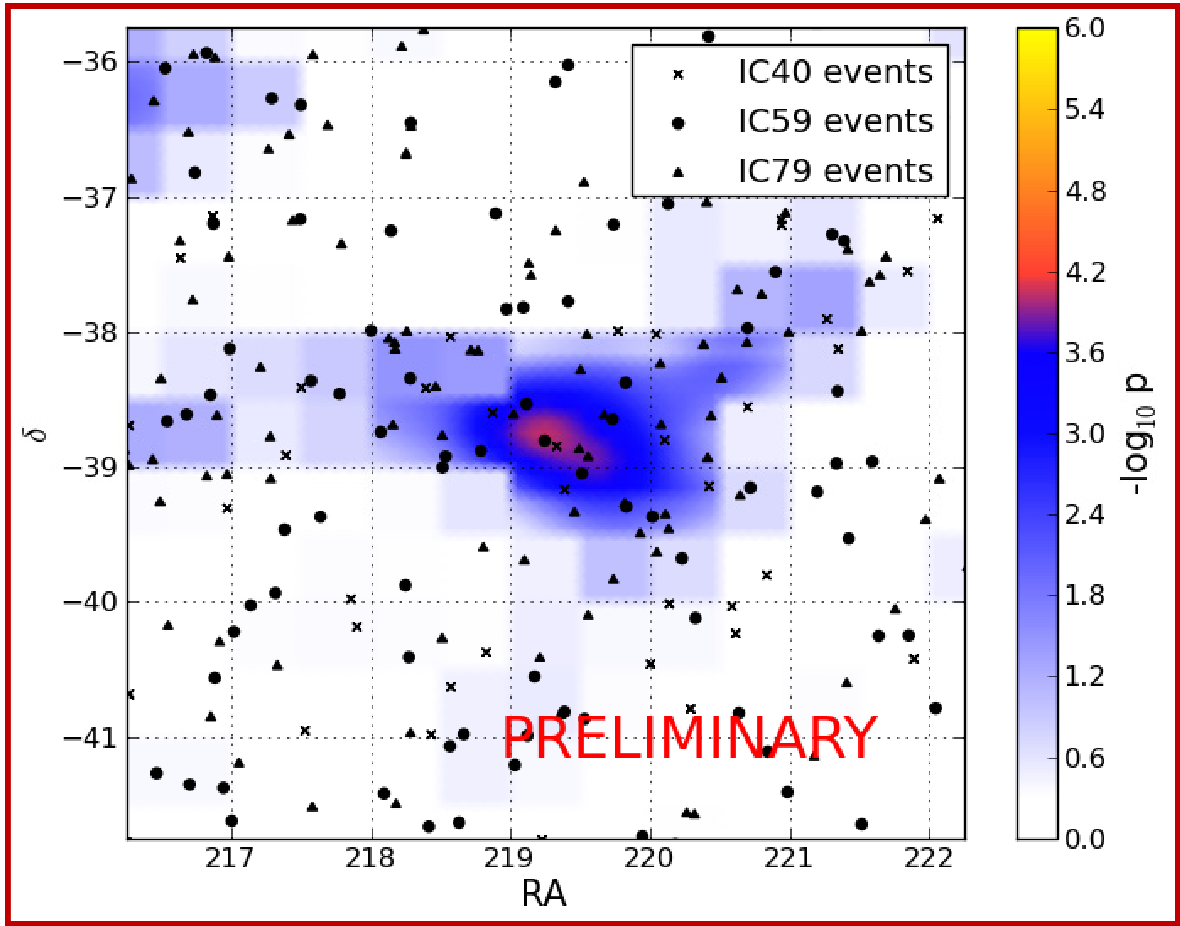
Not significant:

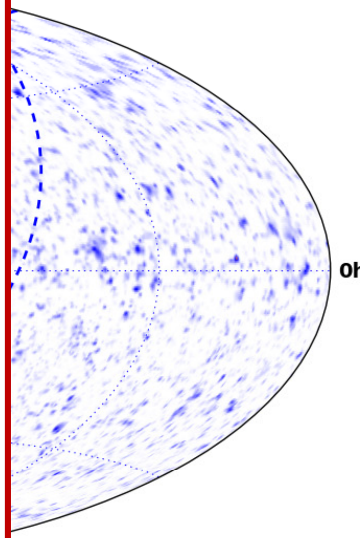
57% of trials have significance ≥ hottest spot

Highest significance in azimuthally scrambled skymaps (2000 trials)



IC40+IC59+IC79





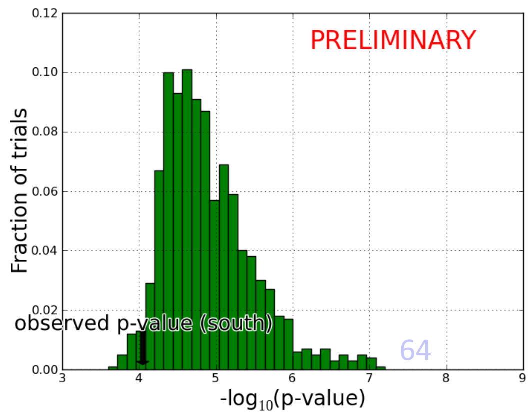
K. Woschnagg

$-\log_{10}p = 4.047$
$nSrc_{best} = 20.81$
$\gamma_{best} = 3.75$

Hottest spot in Southern sky

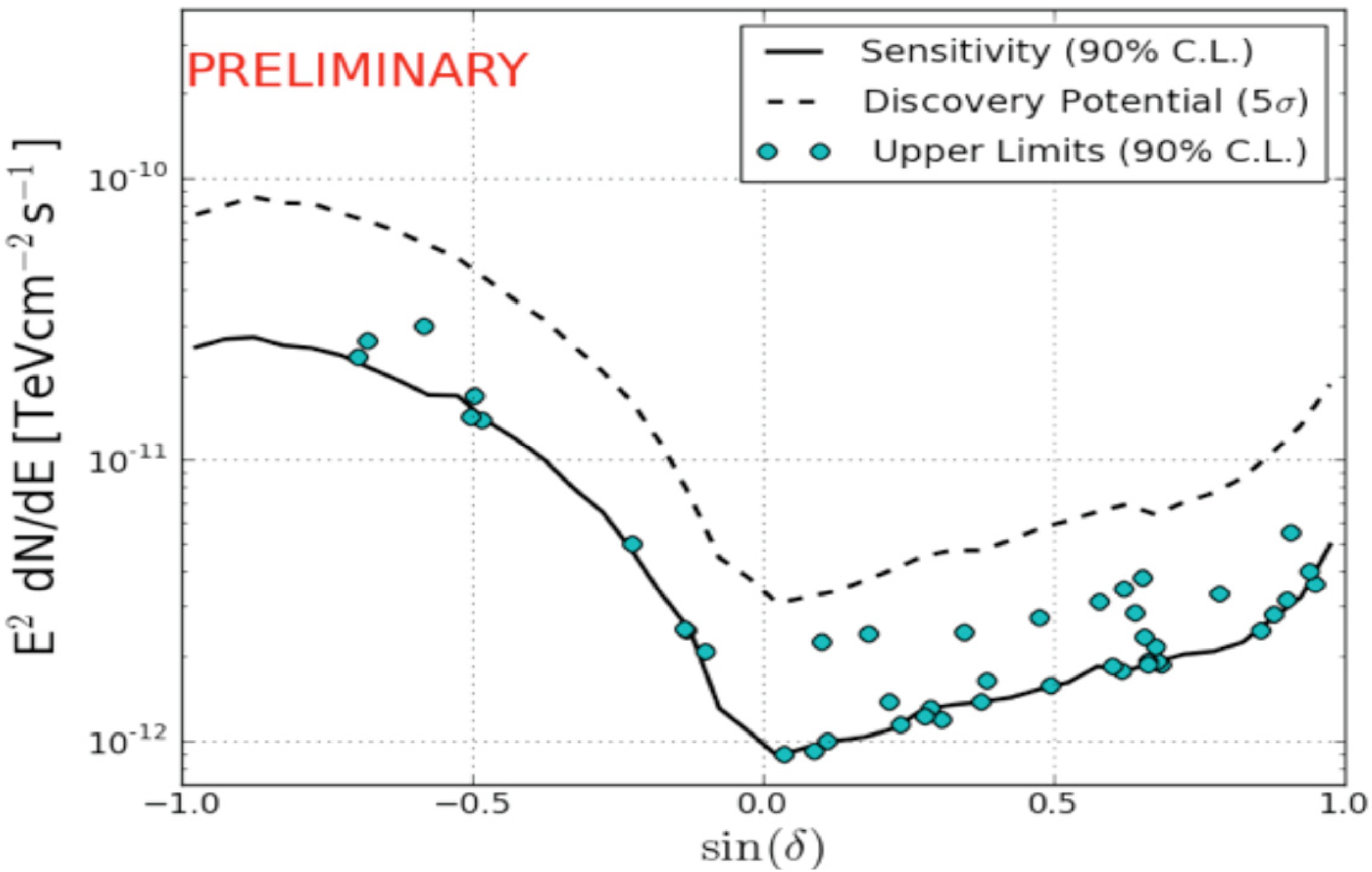
(Ra=219.25, Dec=-38.75)

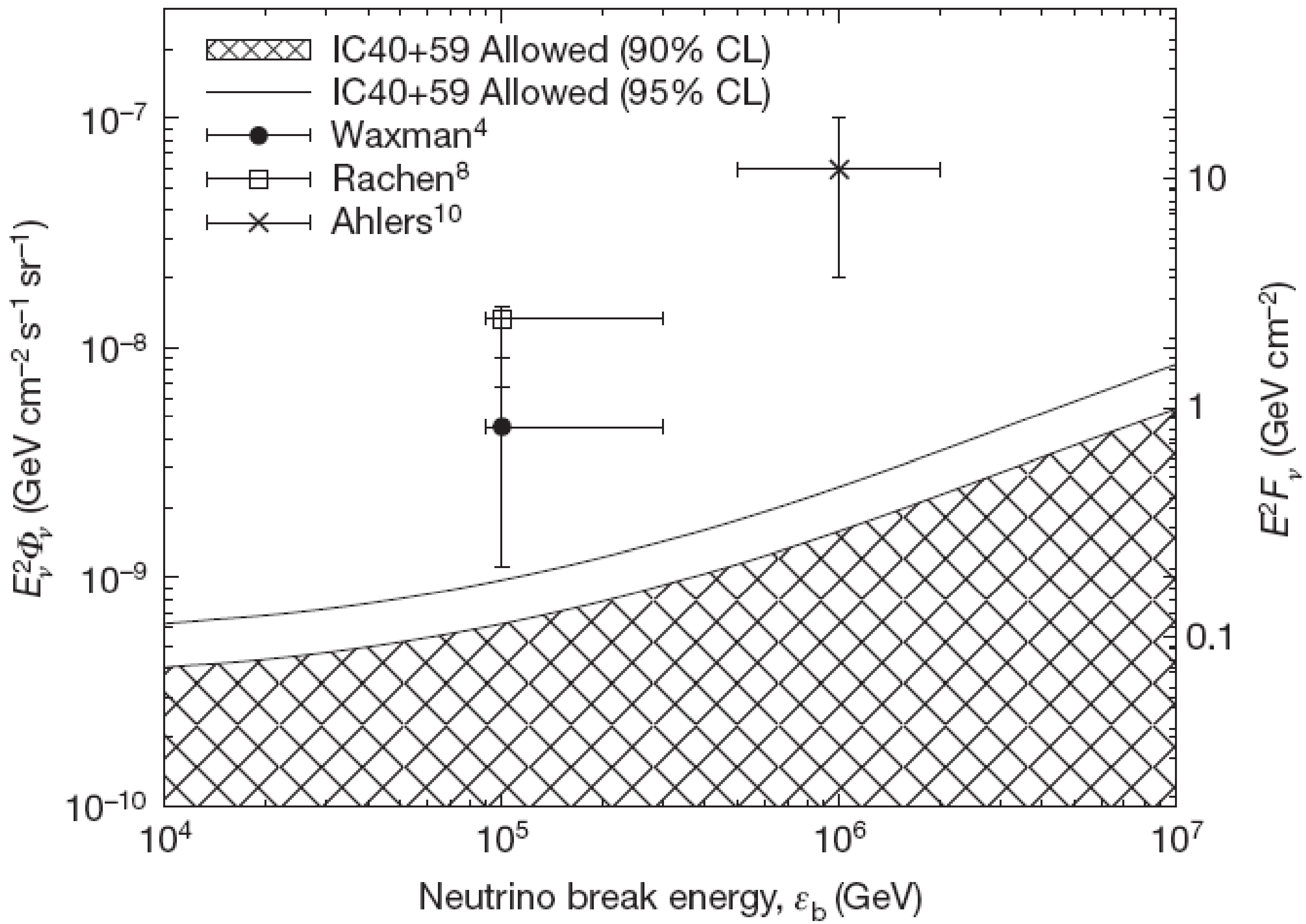
Highest significance in azimuthally scrambled skymaps (2000 trials)



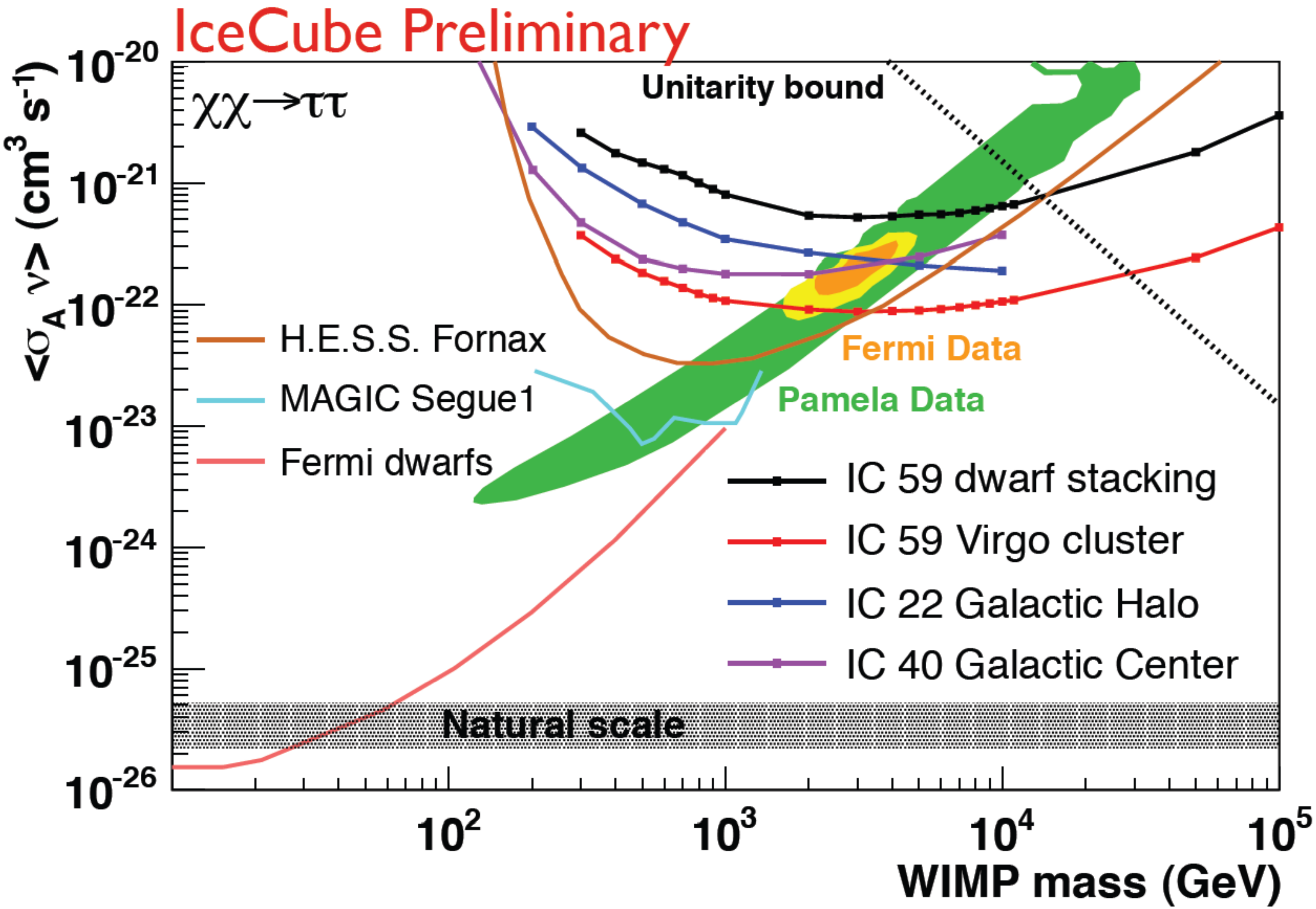
Not significant:

98% of trials have significance ≥ hottest spot


PRELIMINARY
Sensitivity (90% C.L.)
Discovery Potential (5σ)
Upper Limits (90% C.L.)
E^2 dN/dE [TeVcm^{-2}s^{-1}]
10^{-10}
10^{-11}
10^{-12}
−1.0
−0.5
0.0
0.5
1.0
sin(δ)



IC40+59 Allowed (90% CL)
IC40+59 Allowed (95% CL)
Waxman[4]
Rachen[8]
Ahlers[10]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
$E_\nu^2\Phi_\nu$ (GeV cm^{-2} s^{-1} sr^{-1})
10
1
0.1
E^2F_ν (GeV cm^{-2})
10^4
10^5
10^6
10^7
Neutrino break energy, ε_b (GeV)


IceCube Preliminary
χχ→ττ
Unitarity bound
H.E.S.S. Fornax
MAGIC Segue1
Fermi dwarfs
Fermi Data
Pamela Data
IC 59 dwarf stacking
IC 59 Virgo cluster
IC 22 Galactic Halo
IC 40 Galactic Center
Natural scale
$<\sigma_A v>$ ($cm^3 s^{-1}$)
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^2
10^3
10^4
10^5
WIMP mass (GeV)