Status and Results from IceCube

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Cosmic Rays · 1949

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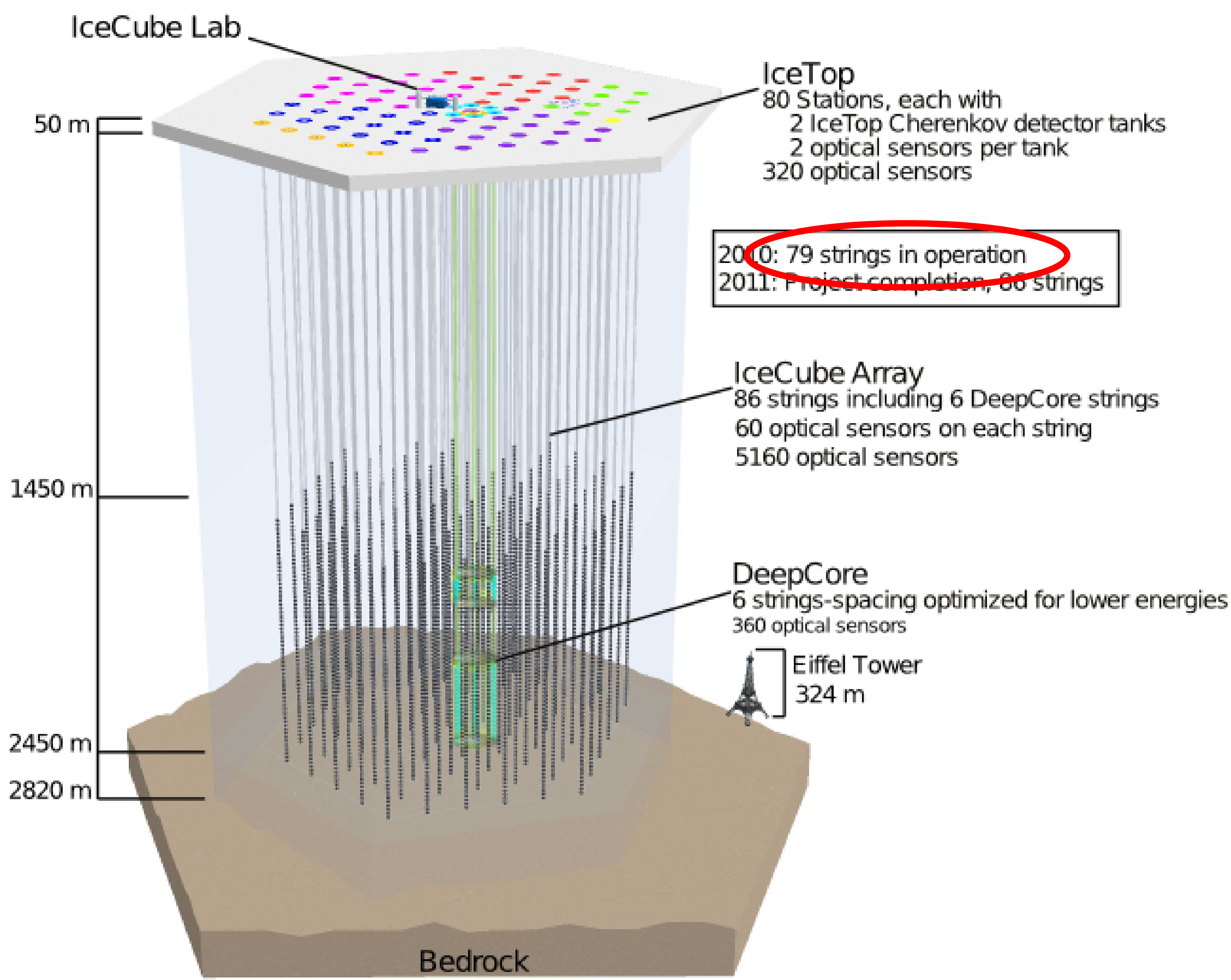
The IceCube Observatory: Status

Since April this year:

- IC79 in operation
- IceTop: 79 stations
- includes 6 DeepCore strings

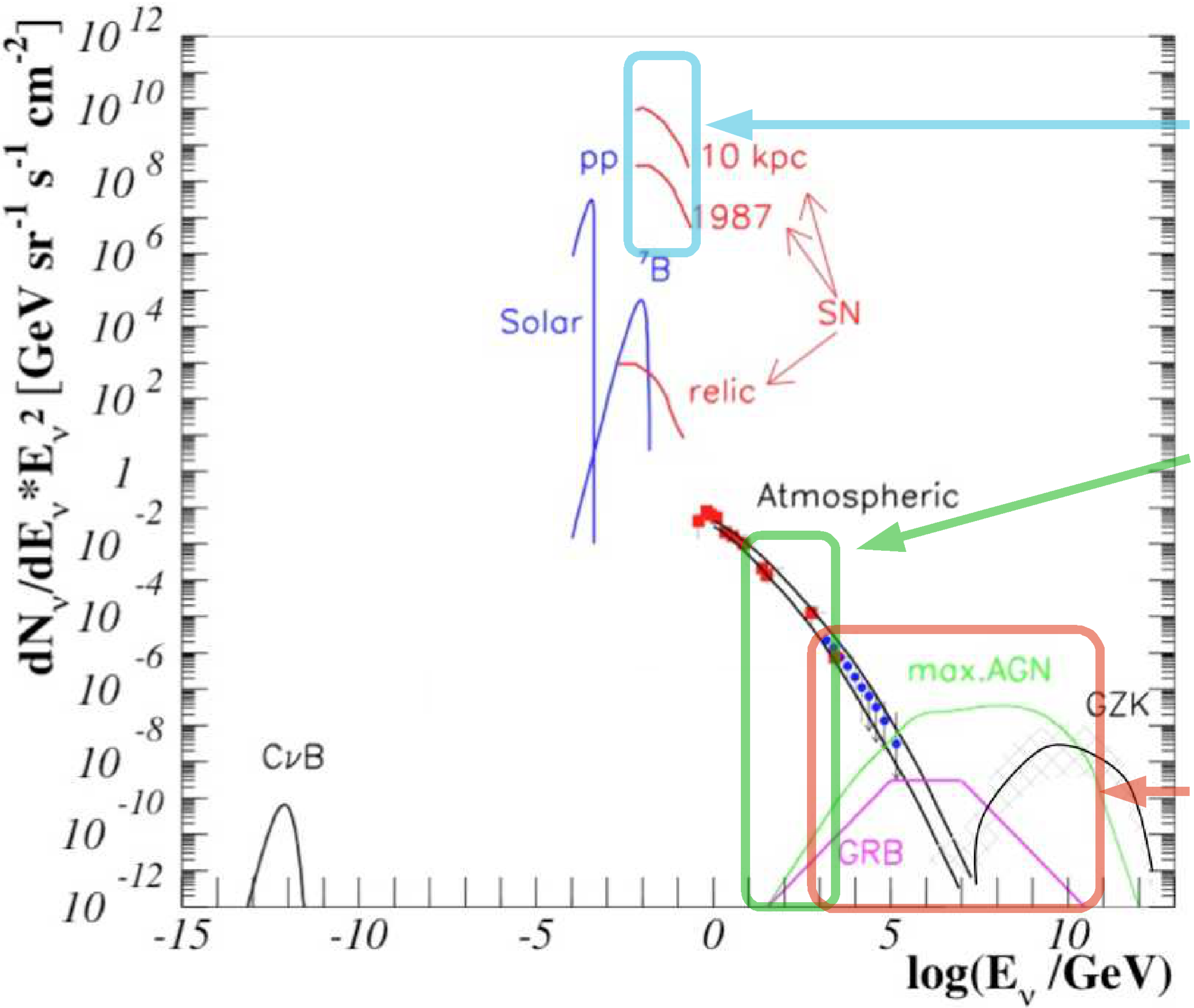
- missing seven strings will be deployed next season $\rightarrow$ complete IceCube!



Evolution of the DAQ:

	Rate	Livetime
IC-22	800Hz	95.9%
IC-40	1400Hz	97.0%
IC-59	1800Hz	98.2%
IC-79	2200Hz	t.b.d.

Neutrino Energy Ranges in IceCube



MeV:
Galactic Supernovae

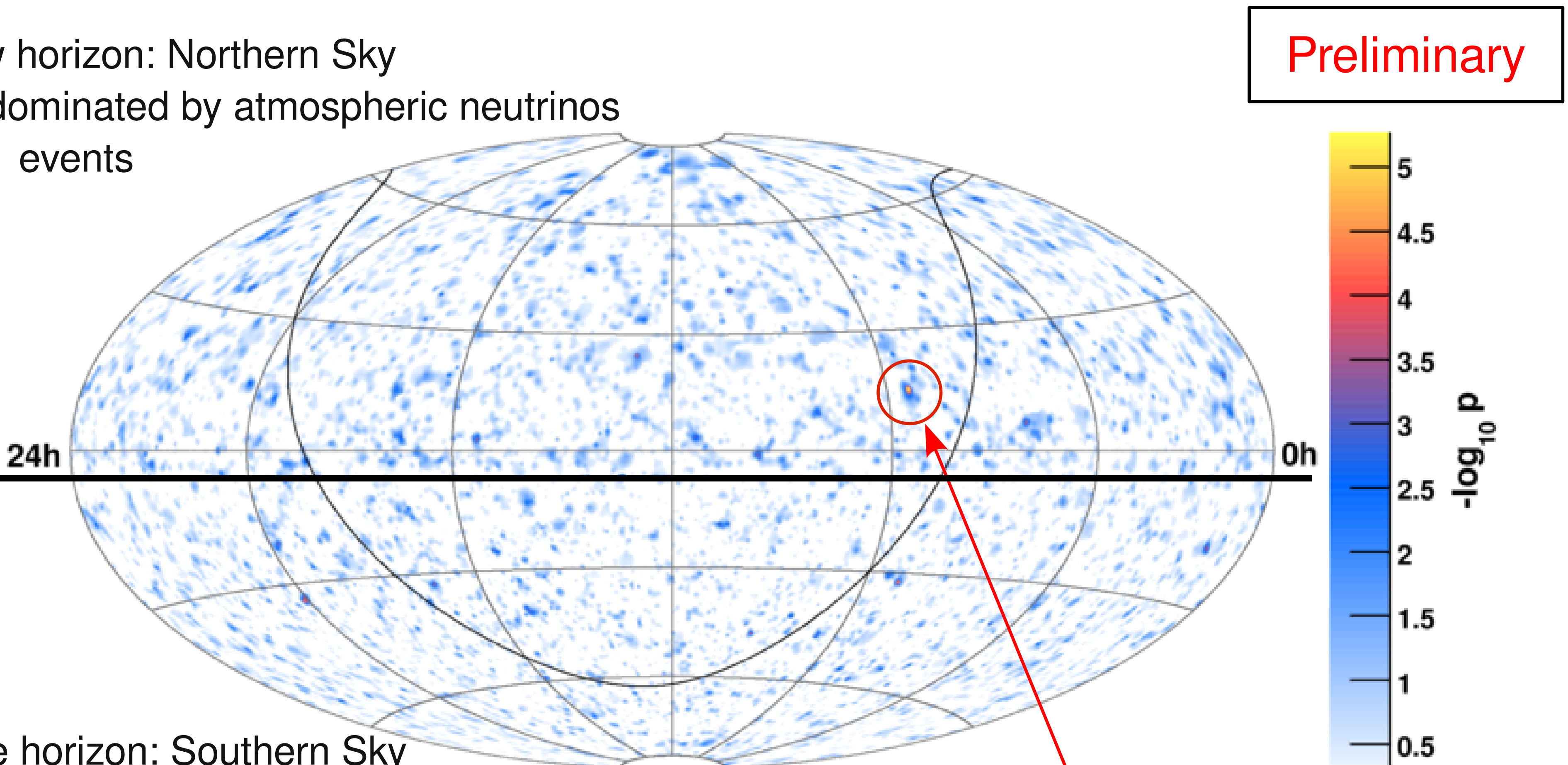
GeV/TeV:
DM searches
ν oscillations

>TeV enegies:
Astrophysical ν
Cosmogenic ν

Searches for Neutrino Flux from Astrophysical Sources

Time Averaged All-Sky Point Source Search

Below horizon: Northern Sky
data dominated by atmospheric neutrinos
14121 events



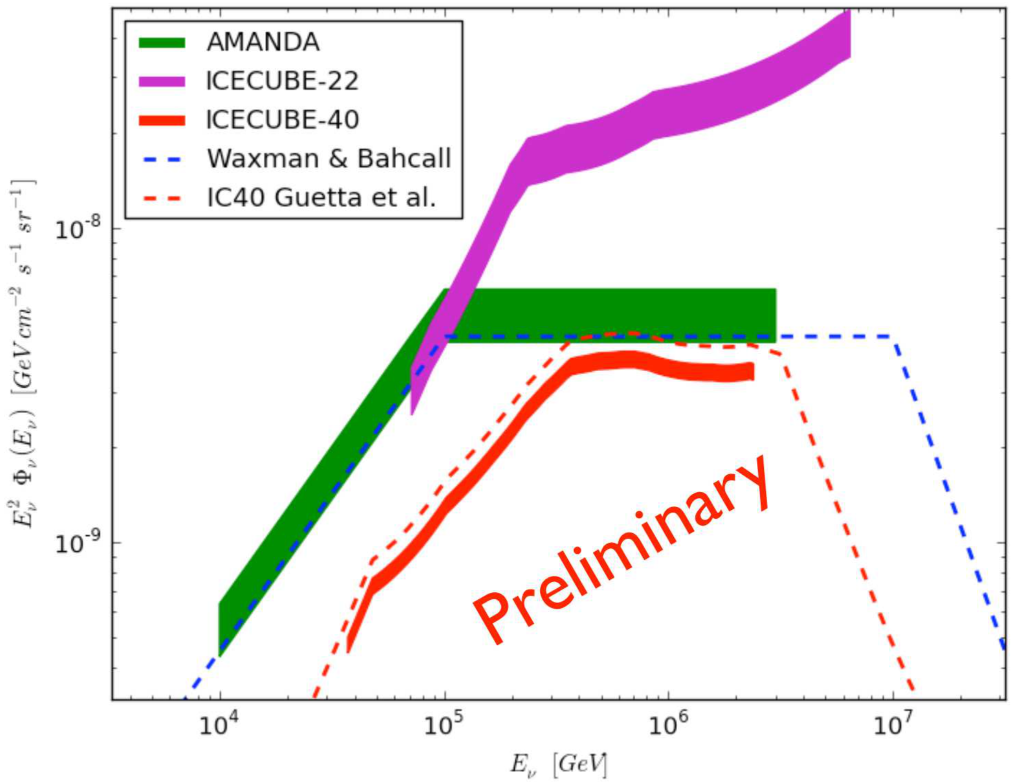
Above horizon: Southern Sky
data dominated by atmospheric muons
22779 events

IceCube-40: 375.7d livetime
36900 events

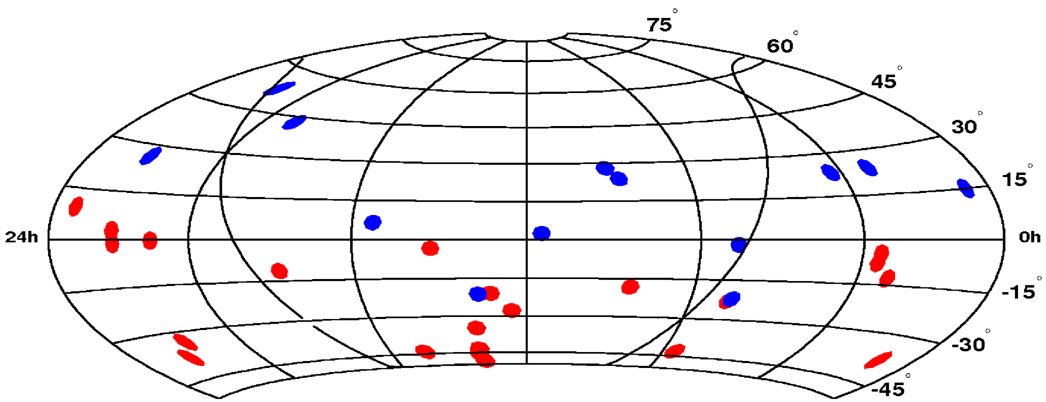
α = 115deg, δ = +15deg
pre-trial -log p = 5.28
scrambled skies with equal or larger excess:
18% → not significant

Search for Neutrinos from GRBs

- Based on 117 satellite detected GRB in the Northern Hemisphere
- Model Independent Search by looking for high energy events at various times around emission point
- Model Dependent Search by modeling expected neutrino spectra according to
  Guetta *et al*, Astropart. Phys., 20, 429 (2004).
- Both searches used the IceCube 40 data set, found no event candidates
  $\rightarrow$ Waxman-Bahcall flux excluded at better than 90% confidence level.



UHECR Correlation Study



13 HiRes and 22 Auger events
> 57 EeV
in IceCube-22 UHE field of view

3° search bin selected a priori
(allow mag. deflection offset
between UHECR and source)

IceCube 22 string result:

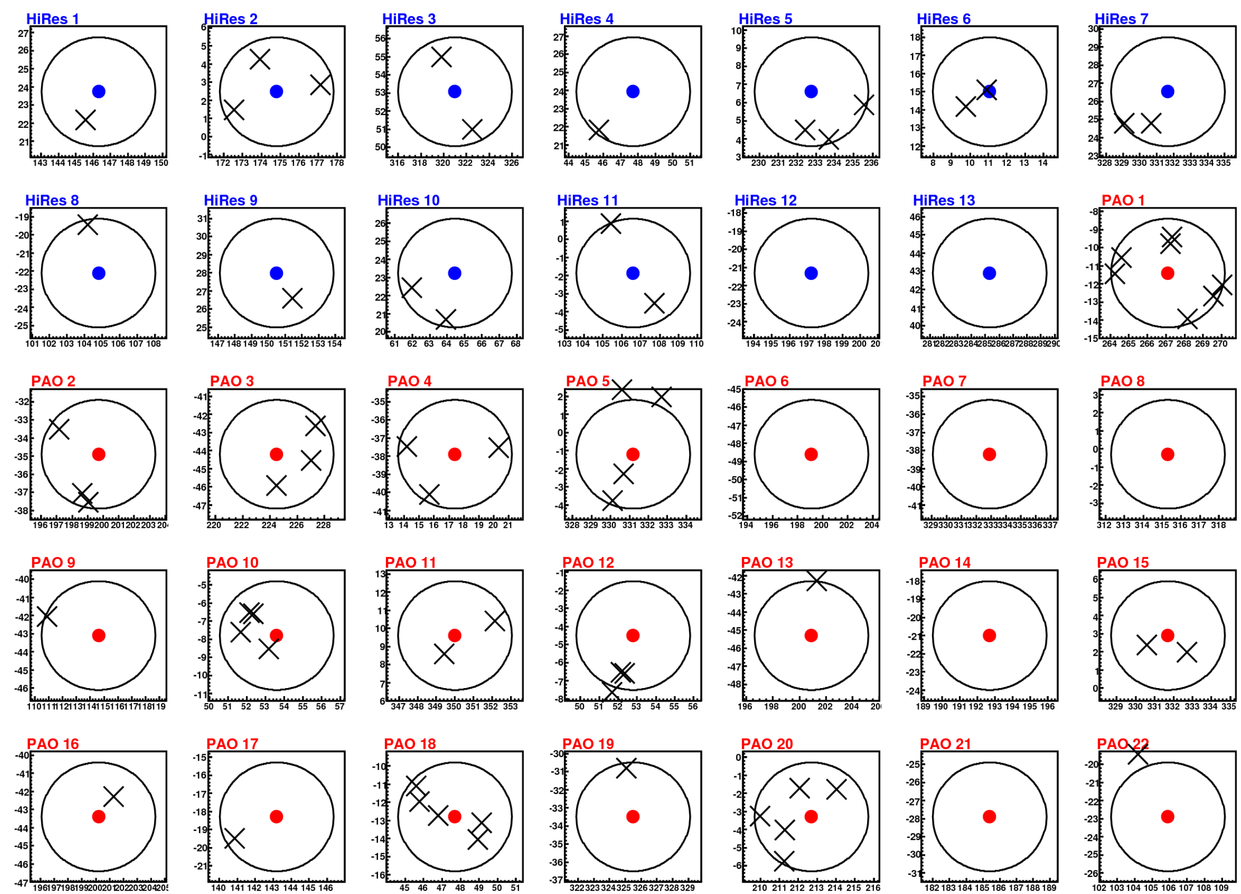
- 60 events observed
- 43.7 events bkg. expected

→ p-value ~ 1% (2.3σ)
not significant!

Follow-up:

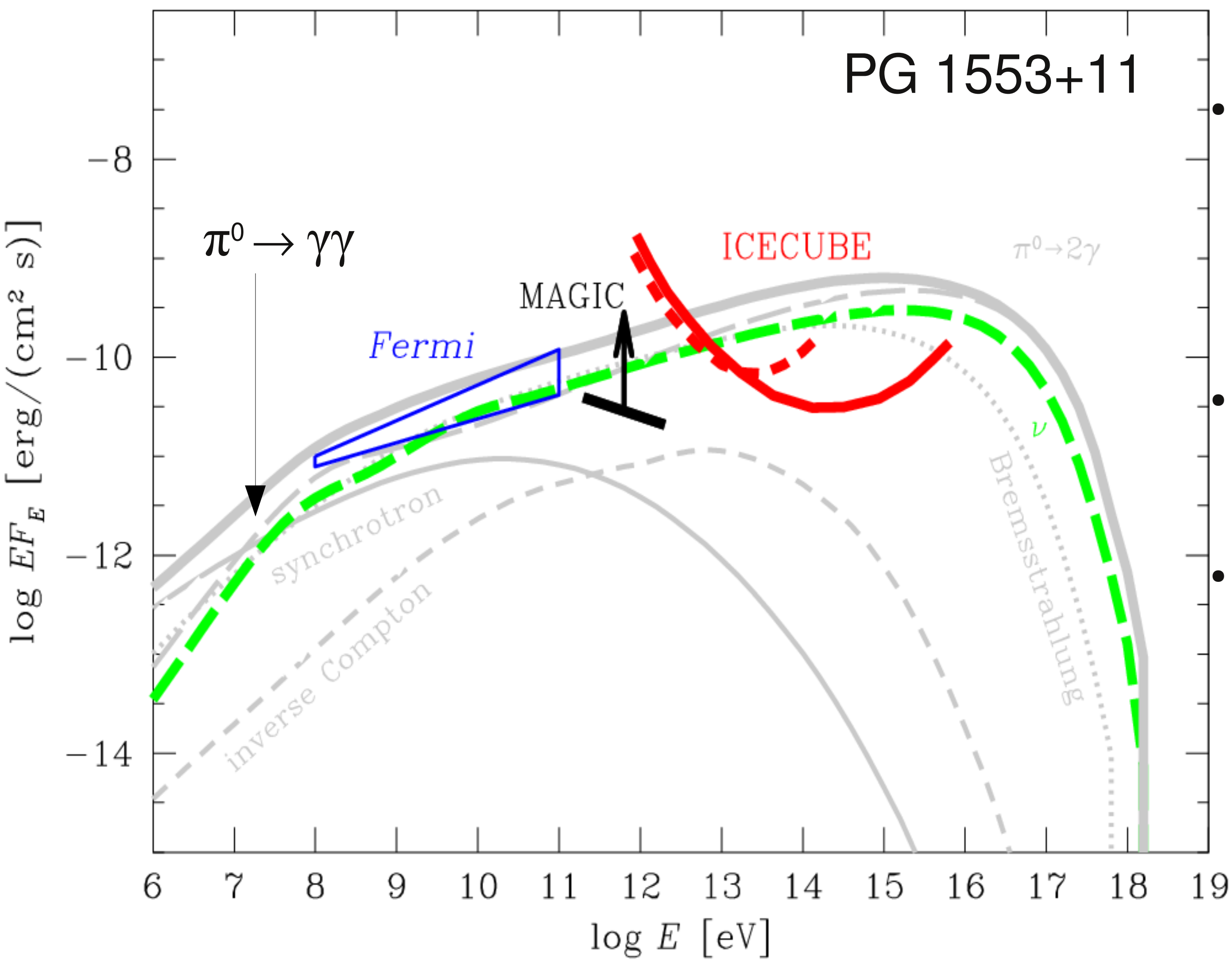
- updated Auger data set
- IceCube-40 data set

Each has ~ 2x more events



Neutrino Flux from AGNs

Neutrino emission model from Neronov and Ribordy, Phys. Rev. D80, 083008 (2009)



- Neutrino spectrum is modelled by using γ spectrum from Fermi "Bright AGN Source List" Abdo et al, Astrophys. J. 700, 597 (2009)
- Exclusive hadronic model: broadband emission dominated by $\pi^0 \rightarrow \gamma\gamma$
- In Red: IceCube 80 discovery potential at different declination:
  15deg (solid)
  75deg (dashed)

Neutrino Flux from AGNs

Preliminary

detectability in 3yr of IceCube 80	Name	1yr of IceCube 22	
		n (5σ)	n expected
above 5σ	B3 0133+388	11	4
above 5σ	1ES 1011+496	12	3
above 5σ	Mrk 421	11	8
above 5σ	PKS 1424+240	11	4
above 5σ	PG 1553+11	12	28
above 5σ	Mrk 501	11	4
above 5σ	PKS 1717+177	12	3
above 5σ	3C 66A	14	1
close to 5σ	AO 235+164	13	<1
close to 5σ	1ES 0502+675	12	2
close to 5σ	B 1218+30	12	1
close to 5σ	W Com	11	<1
close to 5σ	1ES 1959+650	15	<1

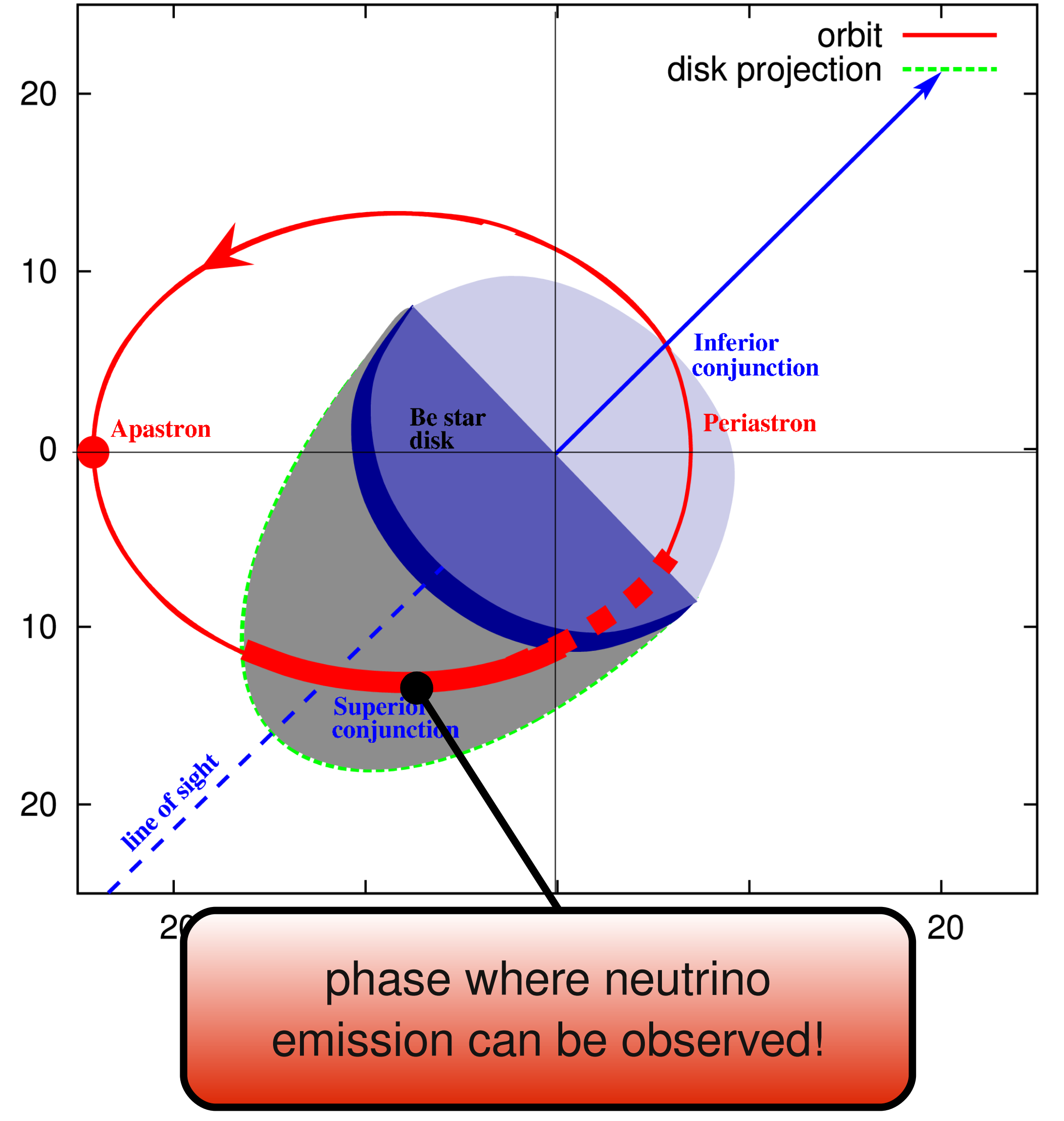
- Model was tested with IceCube 22 data
- A binned search with optimal search bin radius and low energy cutoff was setup
- Number of needed and expected events were calculated according to neutrino spectrum prediction
- One source was expected to easily detectable while IC22 sky showed no excess

Neutrino Flux from LS I +61 303

Neutrino emission model from Neronov and Ribordy, Phys. Rev. D79, 043013 (2008)

- First IceCube search based on model predictions of time-dependent, periodic neutrino emission !

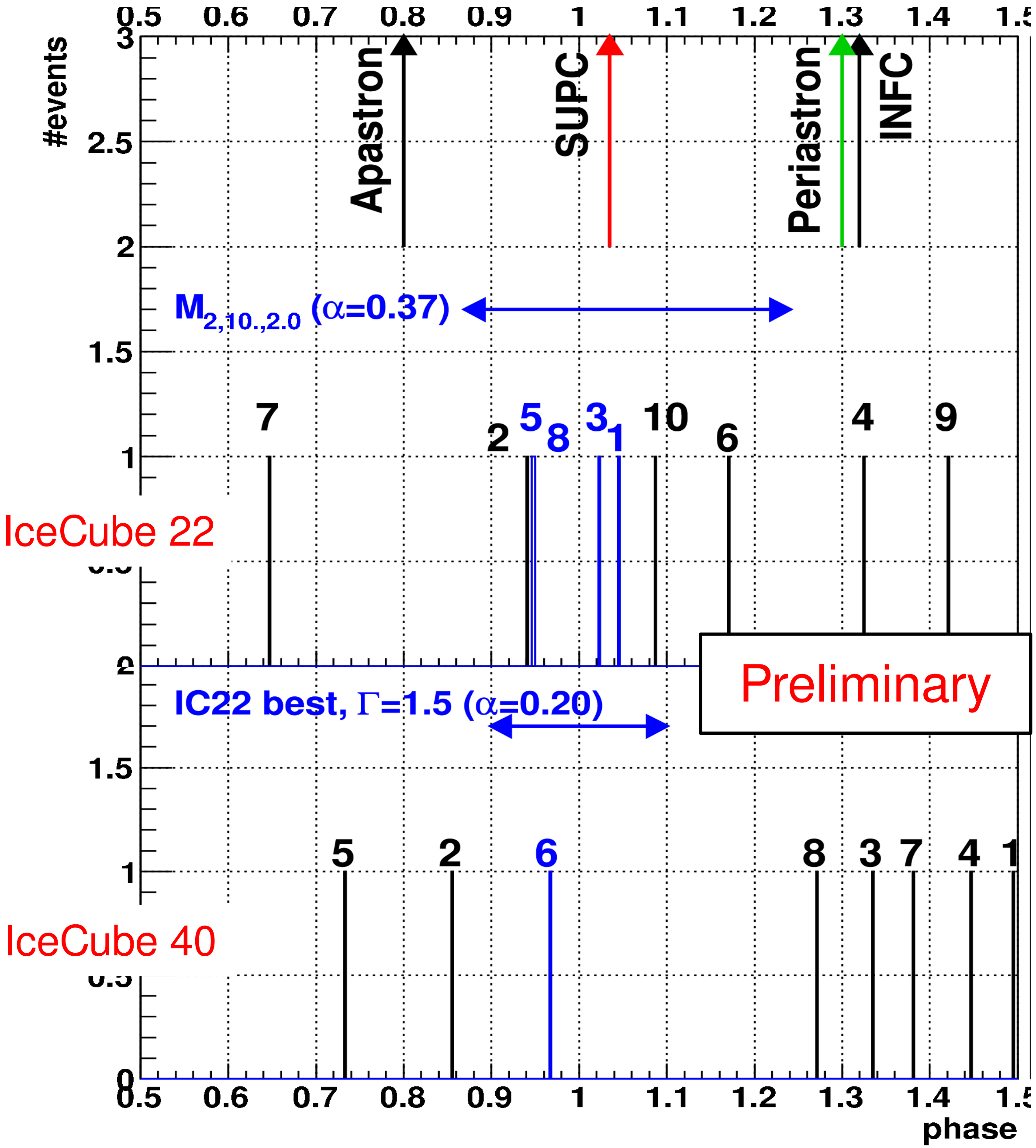
- Model based on system's geometry
- HE protons from the companion interact with the dense stellar disk
- HE protons are only weakly deflected
  $\rightarrow$ neutrinos are produced into a cone with its axis aligned between the companion – star.
  $\rightarrow$ observable neutrino signal when companion is behind stellar disk w.r.t. line of sight.
- stellar disk assumed to be perpendicular w.r.t. line of sight

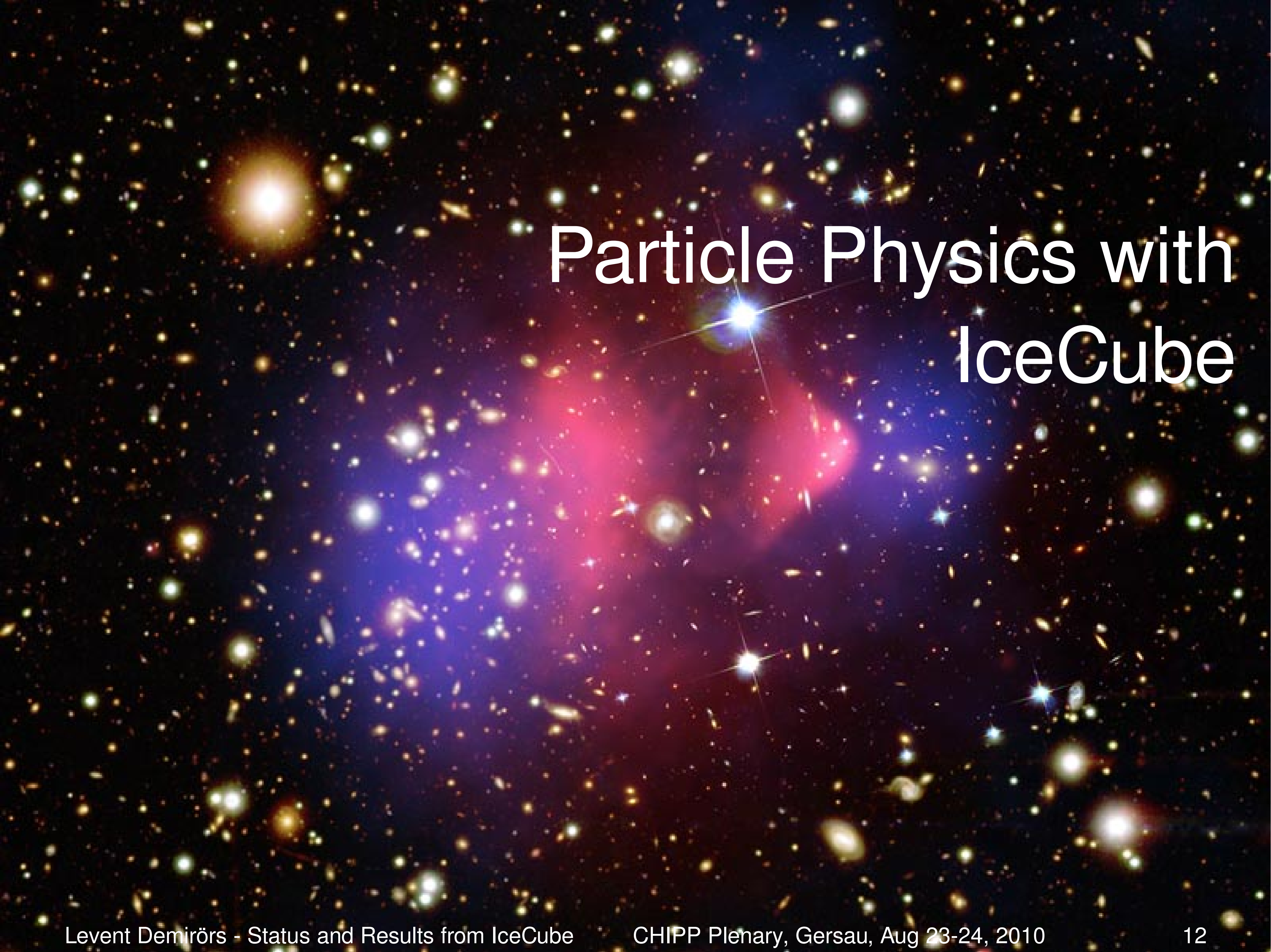


Neutrino Flux from LS I +61 303

- Search was done with IceCube 22 and 40 string data
- Black: event candidates within a search bin ~2x the PSF
- Blue: event candidates selected by the model with the largest pre-trial significance
- Search results (post-trial p-values):
  - IC22: ~6%
  - IC40: ~65%

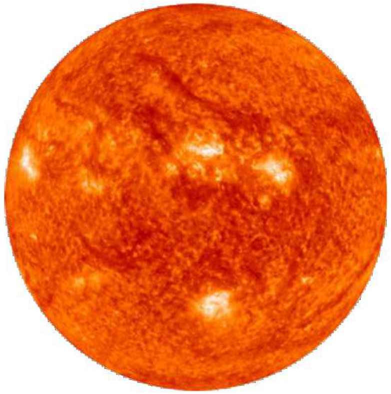
  → not significant!
- Possible positive/negative correlation with radio modulation phase?

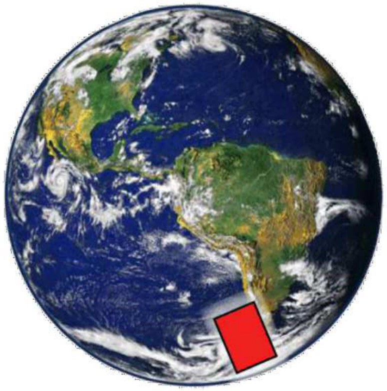


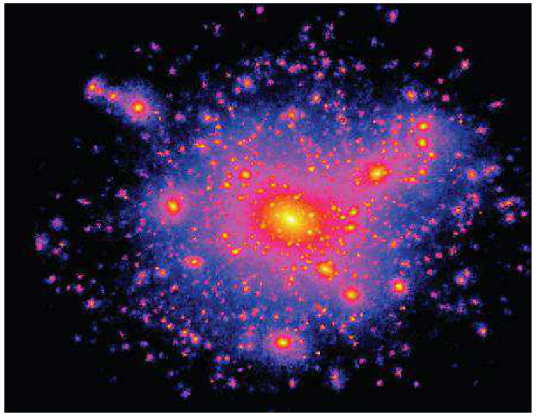


Particle Physics with IceCube

IceCube Searches for Dark Matter

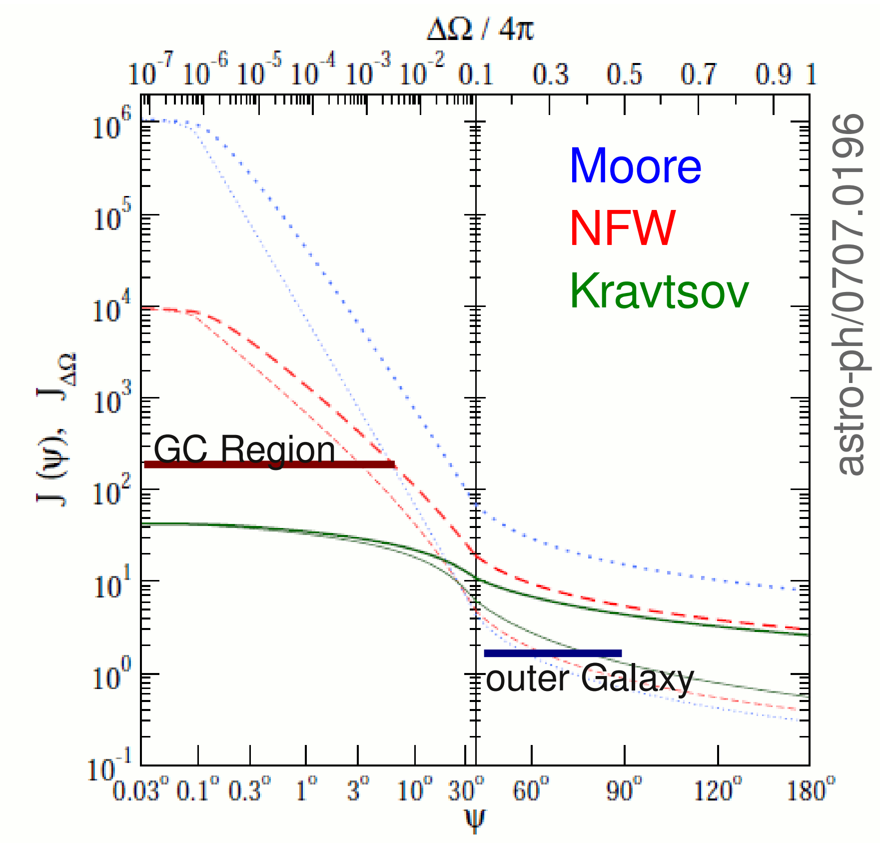


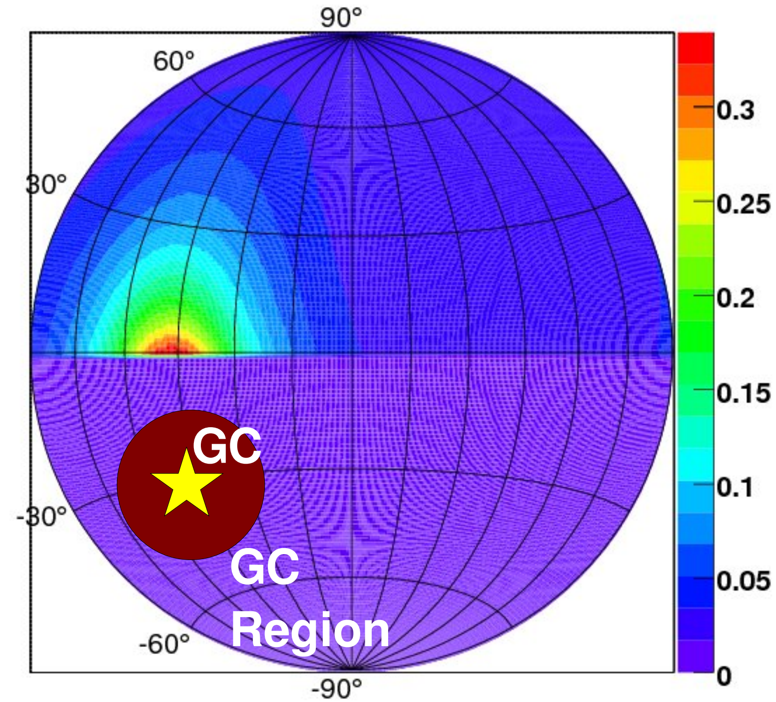




Solar	Earth	Halo
Neutrino Flux, Scattering cross section	Neutrino Flux, ?	Neutrino Flux, Self annihilation cross section
Muon neutrinos	Muon neutrinos	Muon neutrinos, Cascades
Background off source on source	Background simulations	Background off source on source
Excess	Excess	Anisotropy, Spectrum
IceCube (+Deep Core)	IceCube (+Deep Core)	DeepCore (+IceCube)

IceCube Galactic DM Halo limit





Two search regions for DM from the Galactic Halo:

Outer Galactic region:

- DM density less model dependent
- weak neutrino flux, less atm. background

→ IceCube 22 Search

Galactic Center:

- DM density depends on halo model
- stronger neutrino flux, huge atm. background

→ IceCube 40 Search

IceCube Galactic Halo DM limit

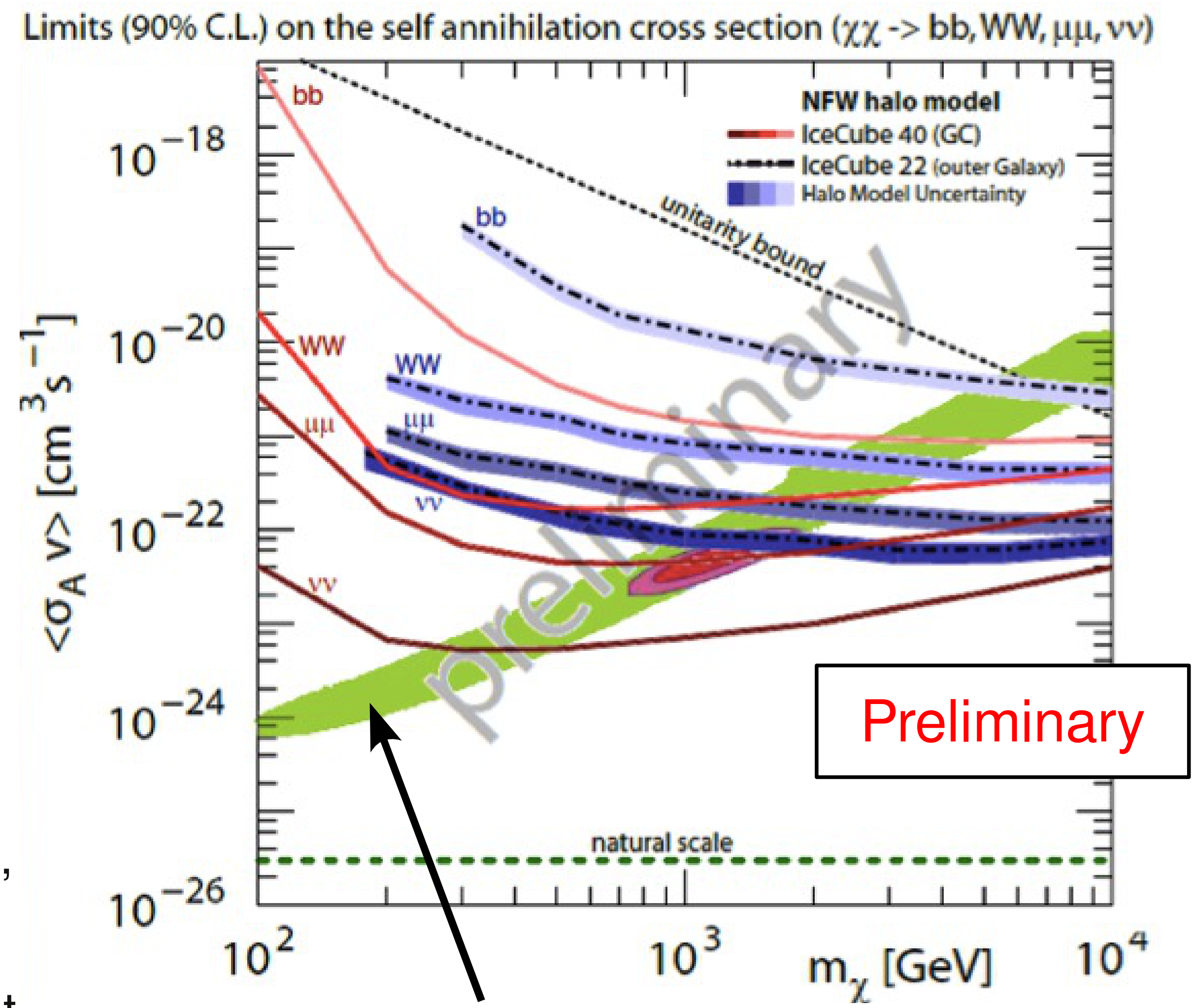
- No excess of events in the on source region in both analyses
- limit WIMP self annihilation x-section

  from Icecube 40:

  - Limits by GC analysis more restrictive, but

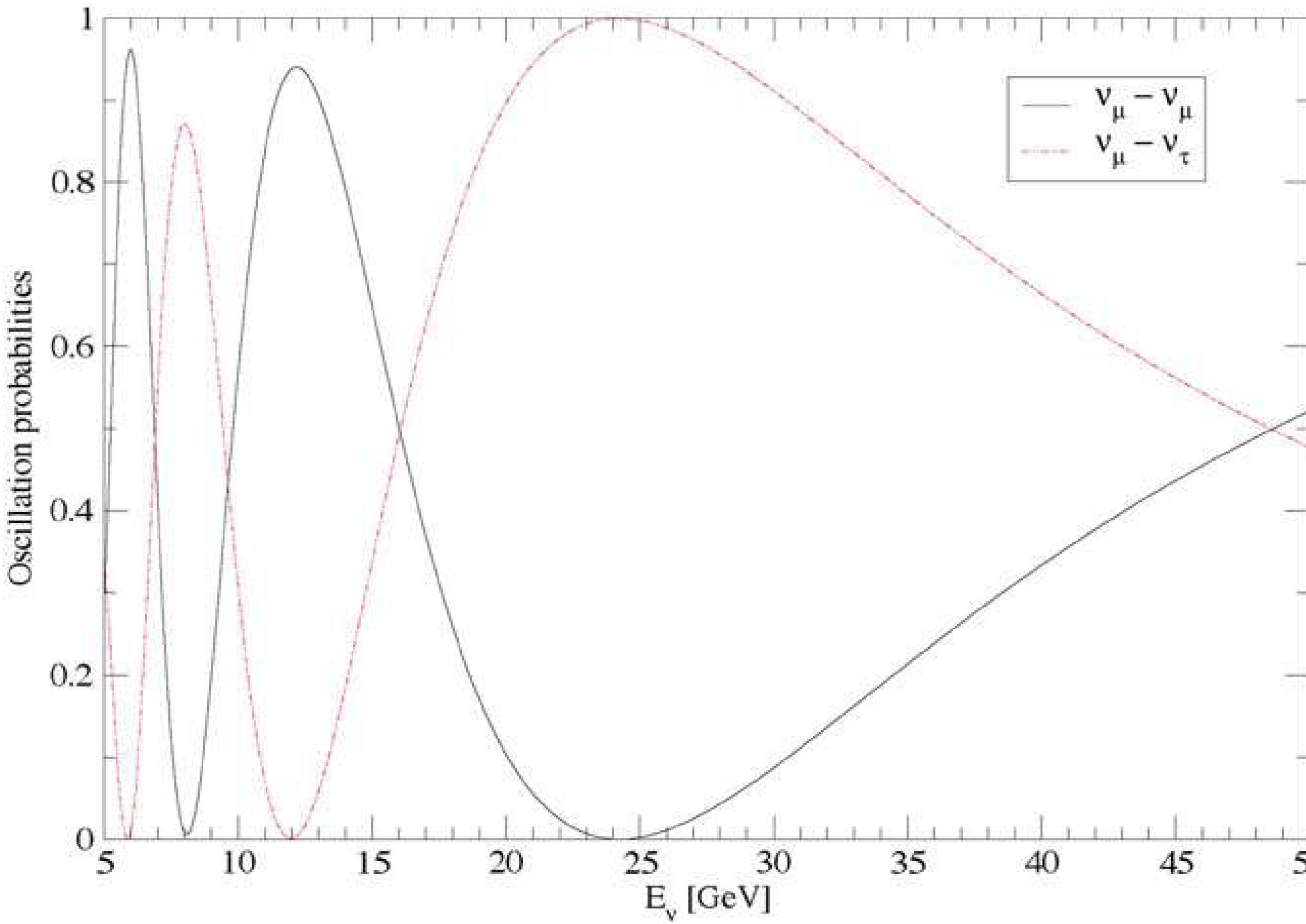
    halo model dependent
- from Icecube 22:
  - Outer Galaxy analysis more sensitive for large WIMP masses, and

    is mostly halo model independent



Region allowed by Pamela / HESS / Fermi
P. Meade, M. Papucci, A. Strumia, T. Volansky, [0905.0480]

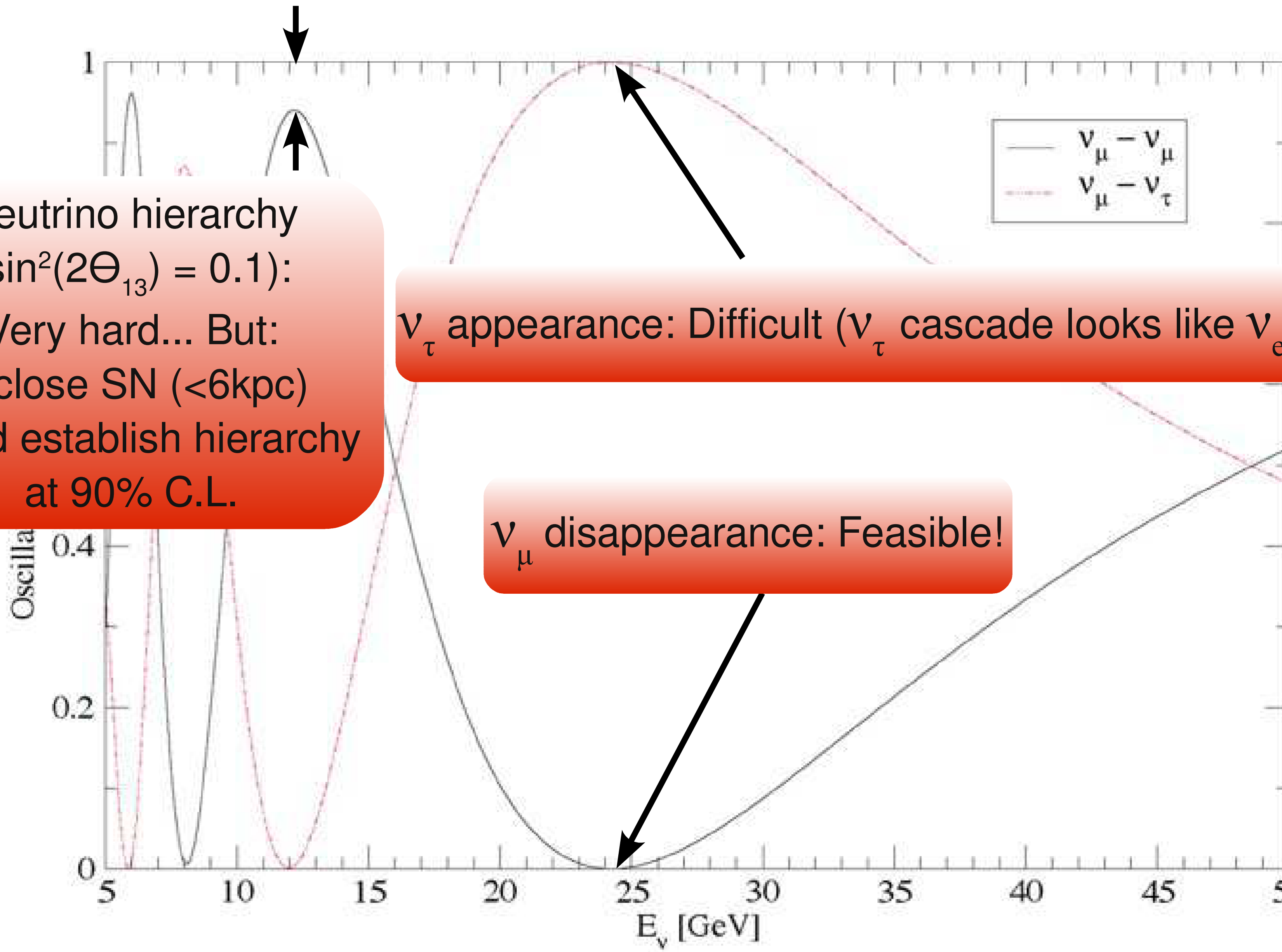
Neutrino Oscillations



Mena, Mocioiu, and Razzaque, Phys. Rev. D78, 093003 (2008)

For vertically upgoing neutrinos (L = Earth diameter)

Neutrino Oscillations



Neutrino hierarchy ($\sin^2(2\Theta_{13}) = 0.1$):
Very hard... But:
A close SN (<6kpc) would establish hierarchy at 90% C.L.

ν_τ appearance: Difficult (ν_τ cascade looks like ν_e)

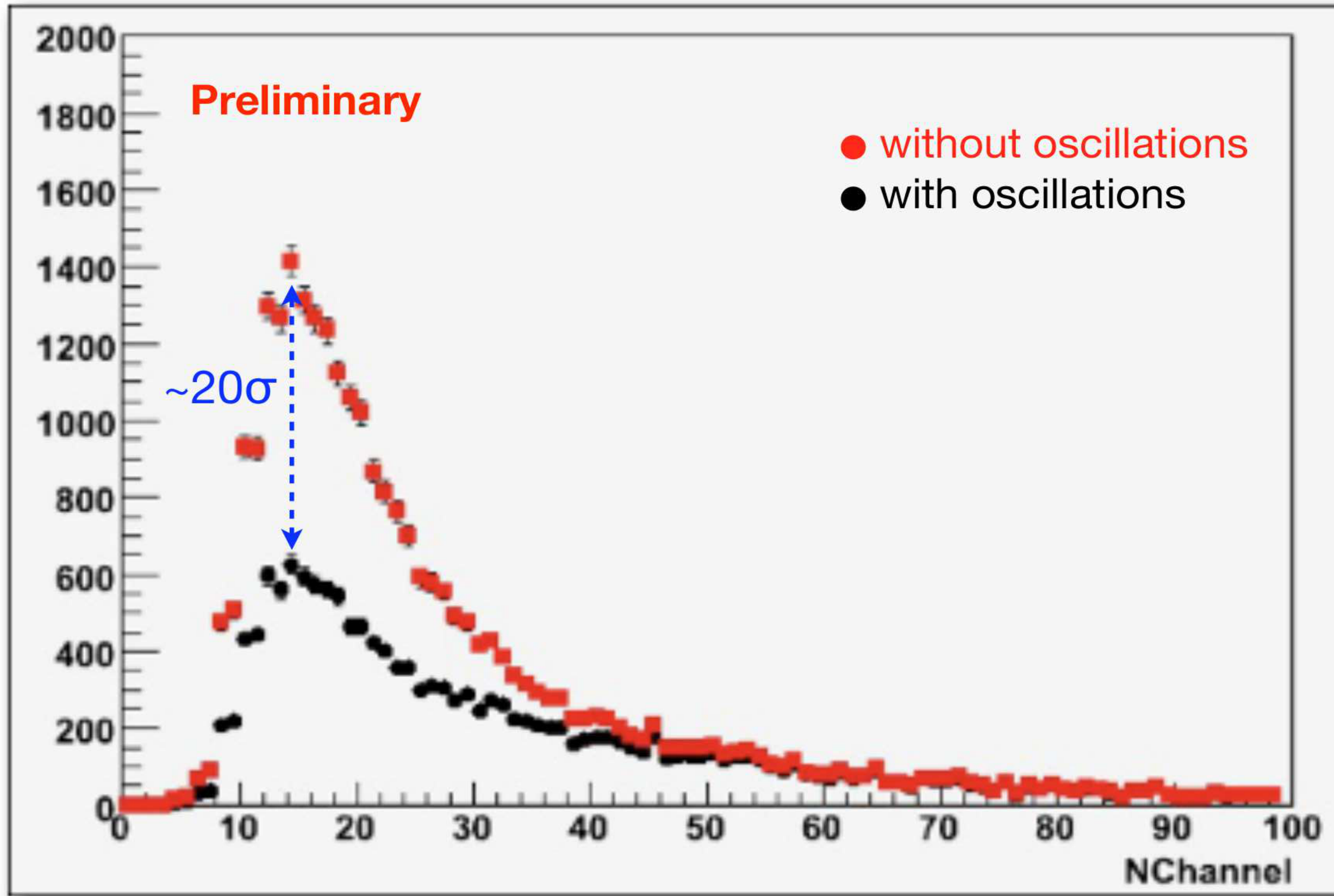
ν_μ disappearance: Feasible!

Mena, Mocioiu, and Razzaque, Phys. Rev. D78, 093003 (2008)

For vertically upgoing neutrinos (L = Earth diameter)

Muon Neutrino Disappearance

- Full detector simulation of signal
  - 3-flavor oscillations, PREM
  - 1 year DC
  - No BG
  - cos(Θ)<-0.6 (up-going)

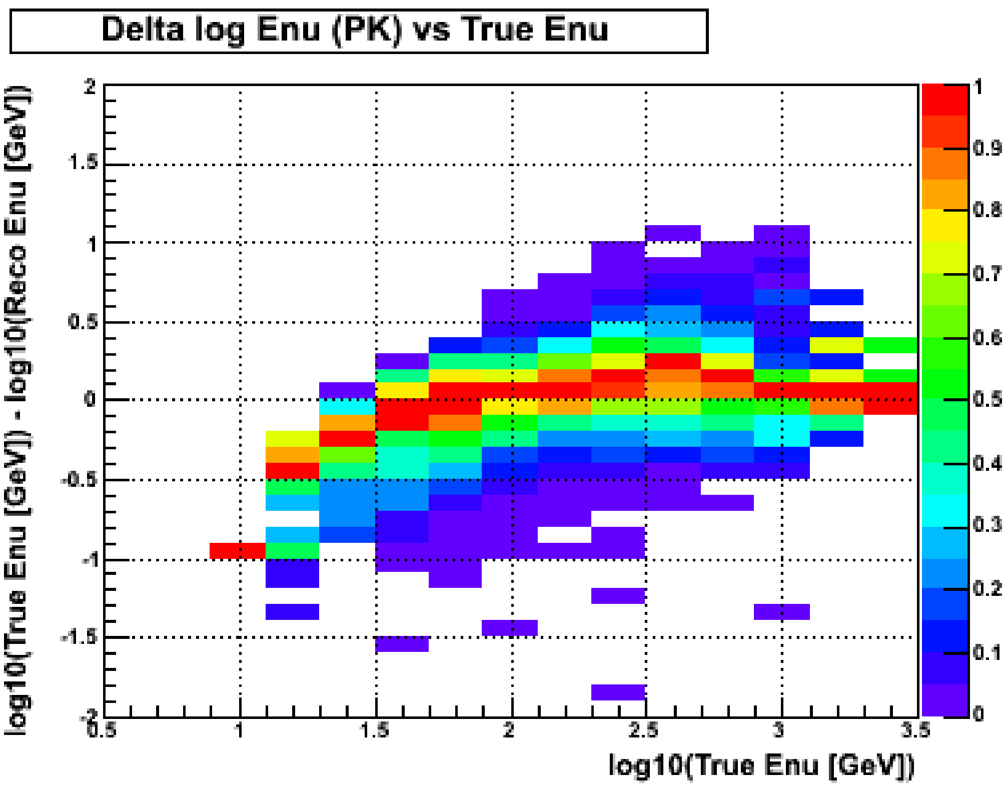


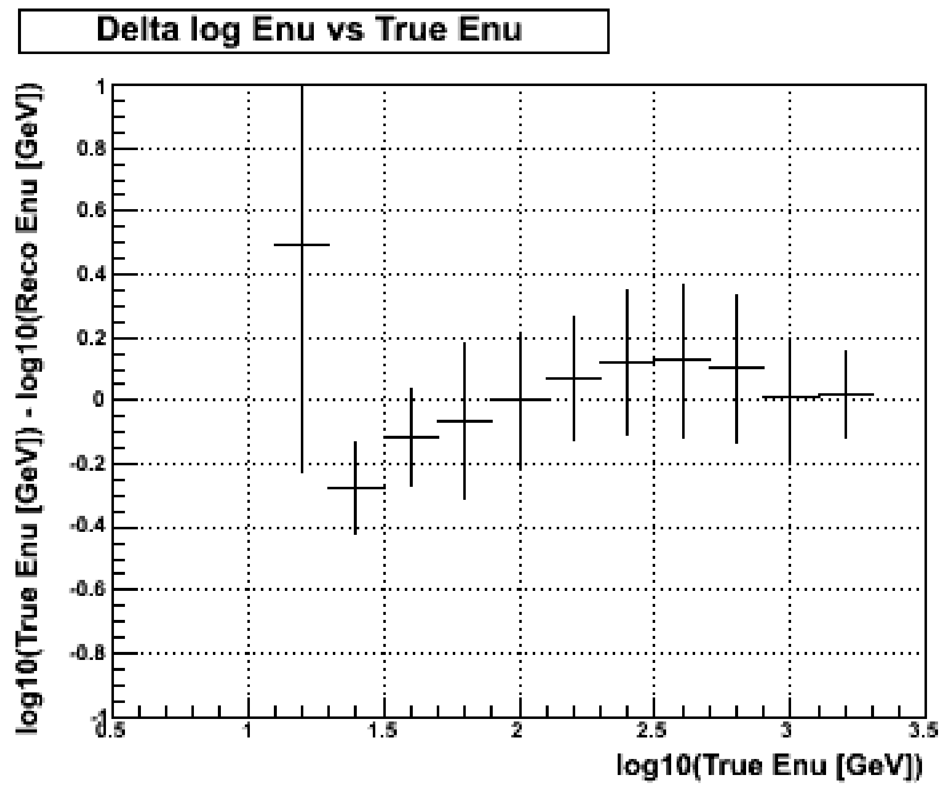
- Number of hit channels used as simple energy estimator

Neutrino energy reconstruction

- Full likelihood reconstruction of contained tracks (< 300GeV) in IceCube
- Parameterize track as initial cascade plus muon track

→ Direct access to neutrino type through energy and inelasticity!
→ Event by event with some tagging probability!



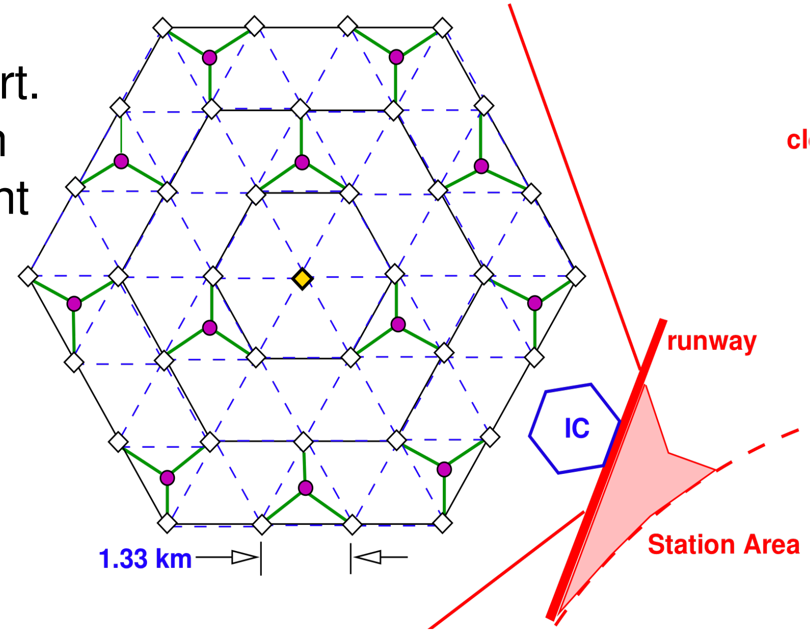


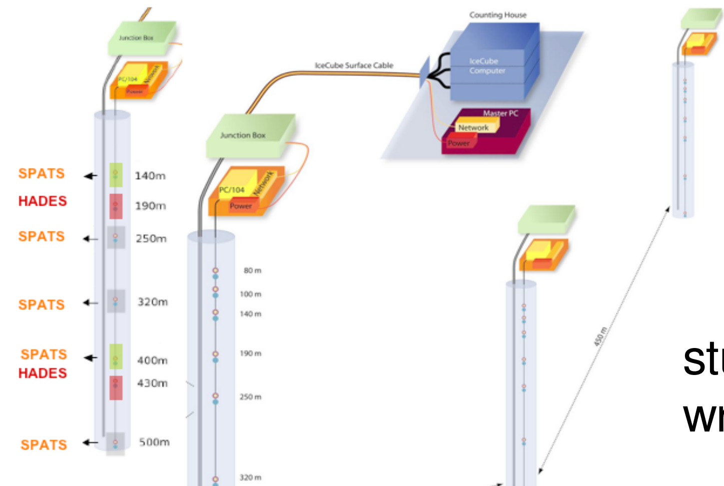
R&D Projects: Radio and Acoustic

NARC

study of ice radio properties wrt. feasibility of neutrino detection

→ ARA prototype deployment recently funded



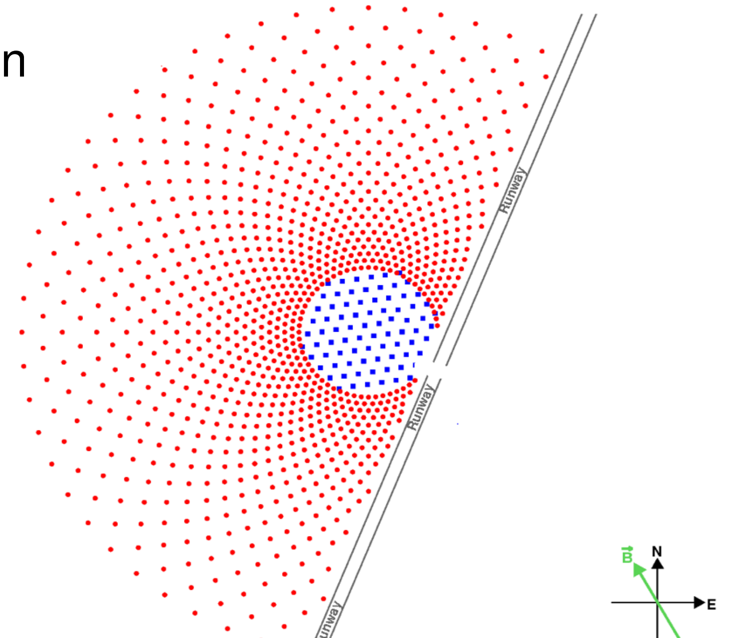


SPATS

study of ice acoustic properties wrt. feasibility of neutrino detection

RASTA

radio air shower detector to augment IceTop and IceCube (CR composition, UHE photon searches, CR veto for UHE neutrino searches)



Next Austral Season: Deployment of EPFL acoustic module! Characterization of South Pole noise

Summary/Outlook

- The IceCube Observatory is here!
- 22 string data analyzed, 40 string almost done, 59 string in preparation

- Search methods are maturing, lots of new topics:
  - UHECR correlation, CR anisotropy, low energy neutrinos

- Neutrino Astronomy is increasingly becoming part of the MWL family!
  - Either MWL observation (ToO, SN/GRB alert), or
  - MWL motivated model-based searches (Fermi Blazars, LS I +61 303)

- Detector R&D: Radio and Acoustic are now moving into the spotlight
  - EPFL acoustic detector is going on ice (and then below...)
  - Open the sky at Extreme High Energies (cosmogenic neutrinos)

USA:
Bartol Research Institute, Delaware
University of California, Berkeley
University of California, Irvine
Pennsylvania State University
Clark-Atlanta University
Ohio State University
Georgia Institute of Technology
University of Maryland
University of Alabama, Tuscaloosa
University of Wisconsin-Madison
University of Wisconsin-River Falls
Lawrence Berkeley National Lab.
University of Kansas
Southern University and A&M College, Baton Rouge
University of Alaska, Anchorage

Sweden:
Uppsala Universitet
Stockholm Universitet

UK:
Oxford University

Belgium:
Université Libre de Bruxelles
Vrije Universiteit Brussel
Universiteit Gent
Université de Mons-Hainaut

Germany:
DESY-Zeuthen
Universität Bonn
Universität Mainz
Universität Dortmund
Universität Wuppertal
Humboldt Universität
MPI Heidelberg
RWTH Aachen
Universität Bochum

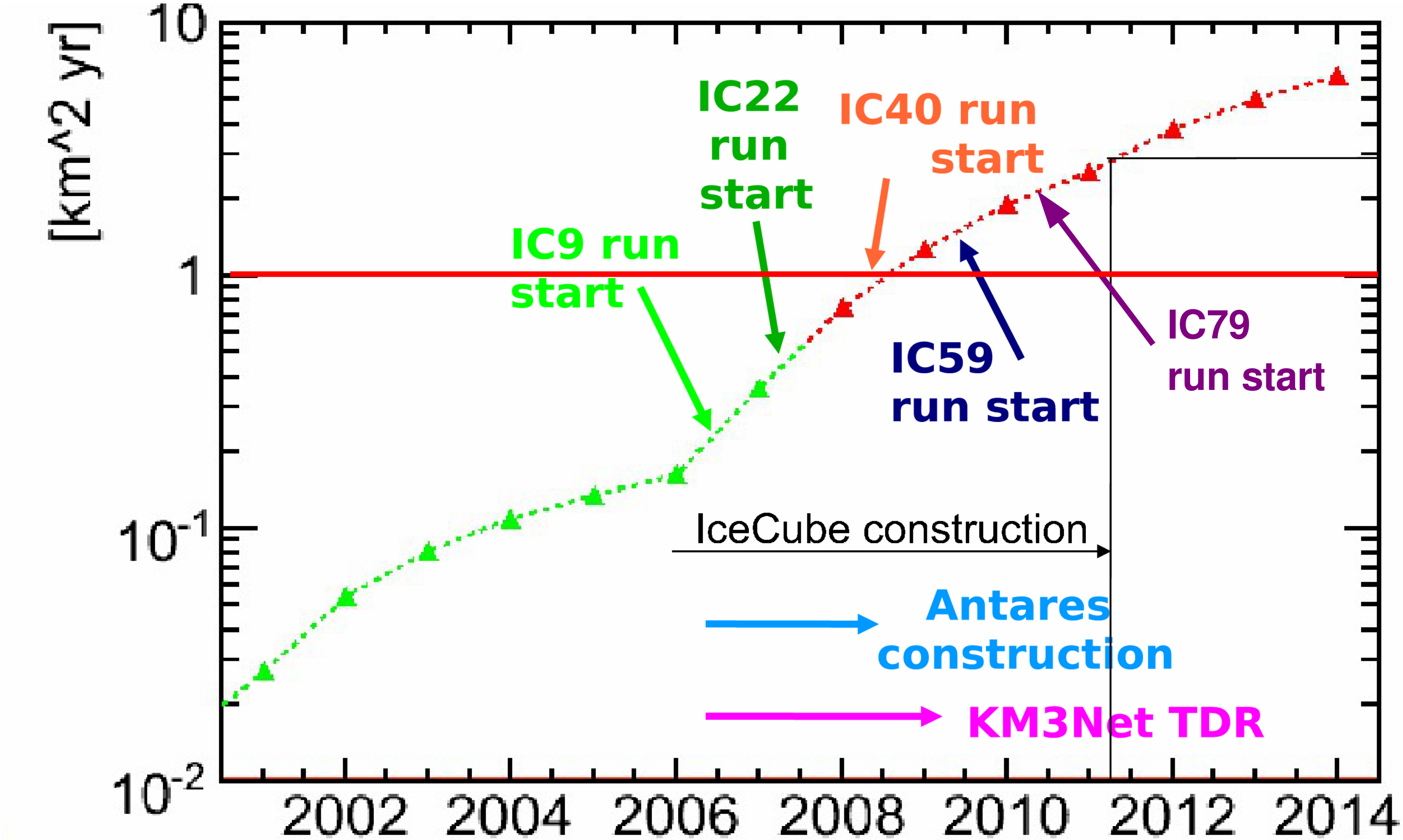
Switzerland:
EPF Lausanne

Japan:
Chiba University

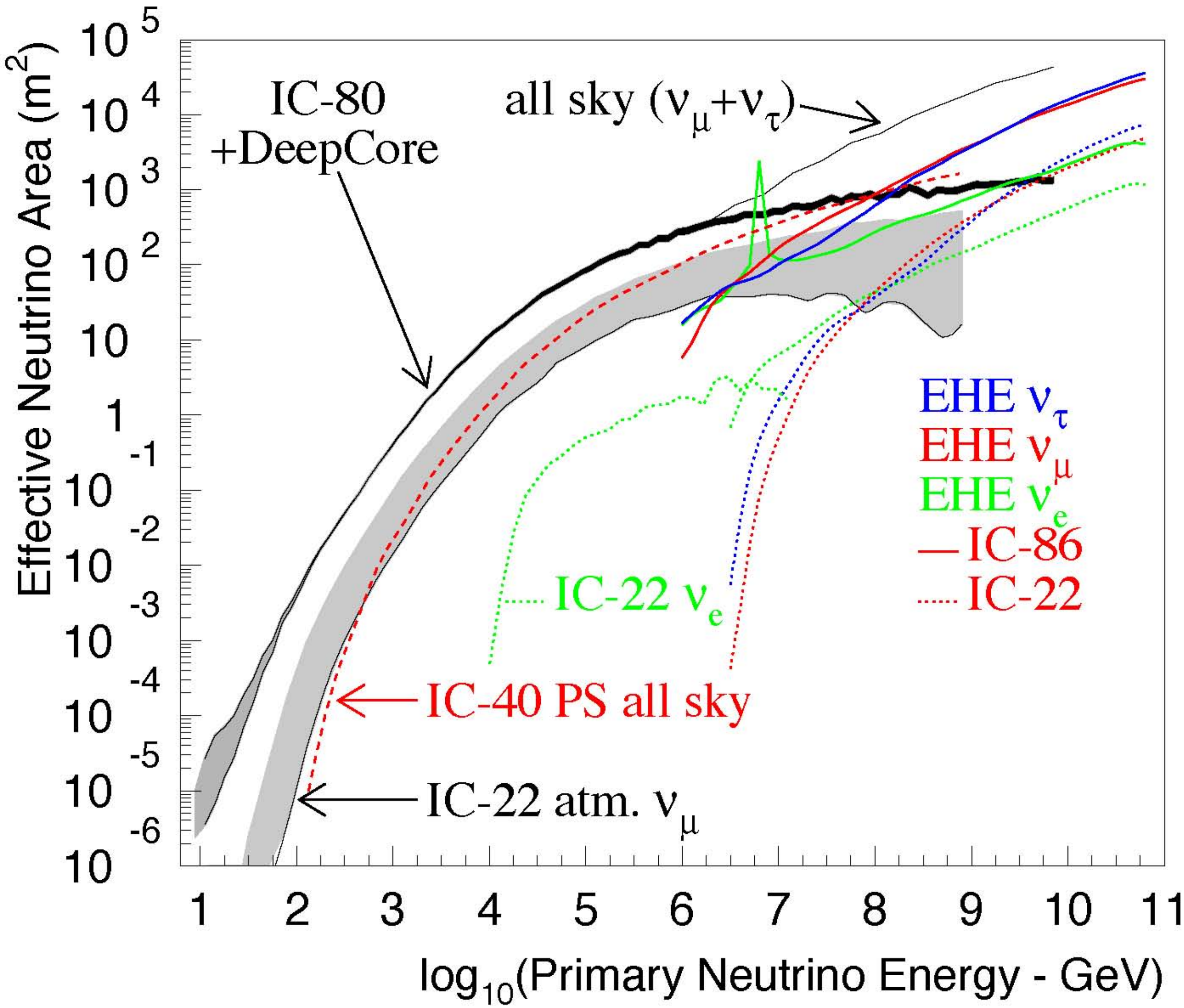
New Zealand:
University of Canterbury

34 institutions, approx. 250 members
http://icecube.wisc.edu/

IceCube Integral Exposure to Muons @ 100 TeV



IceCube Effective Areas for Neutrinos



Effective Areas:

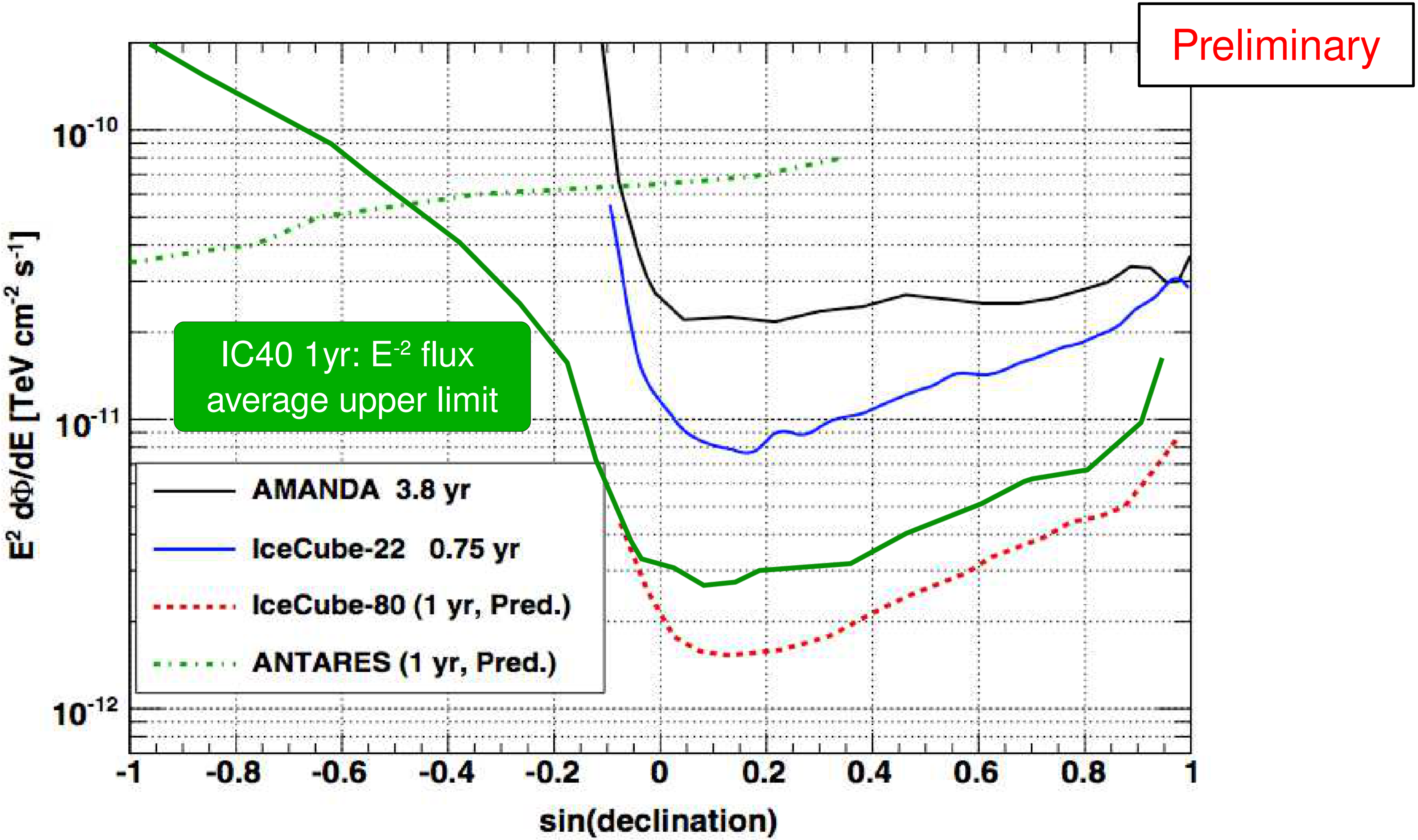
@ 1TeV:

AMANDA-II:	$0.005m^2$
IceCube-86:	$0.3m^2$

@ 100TeV:

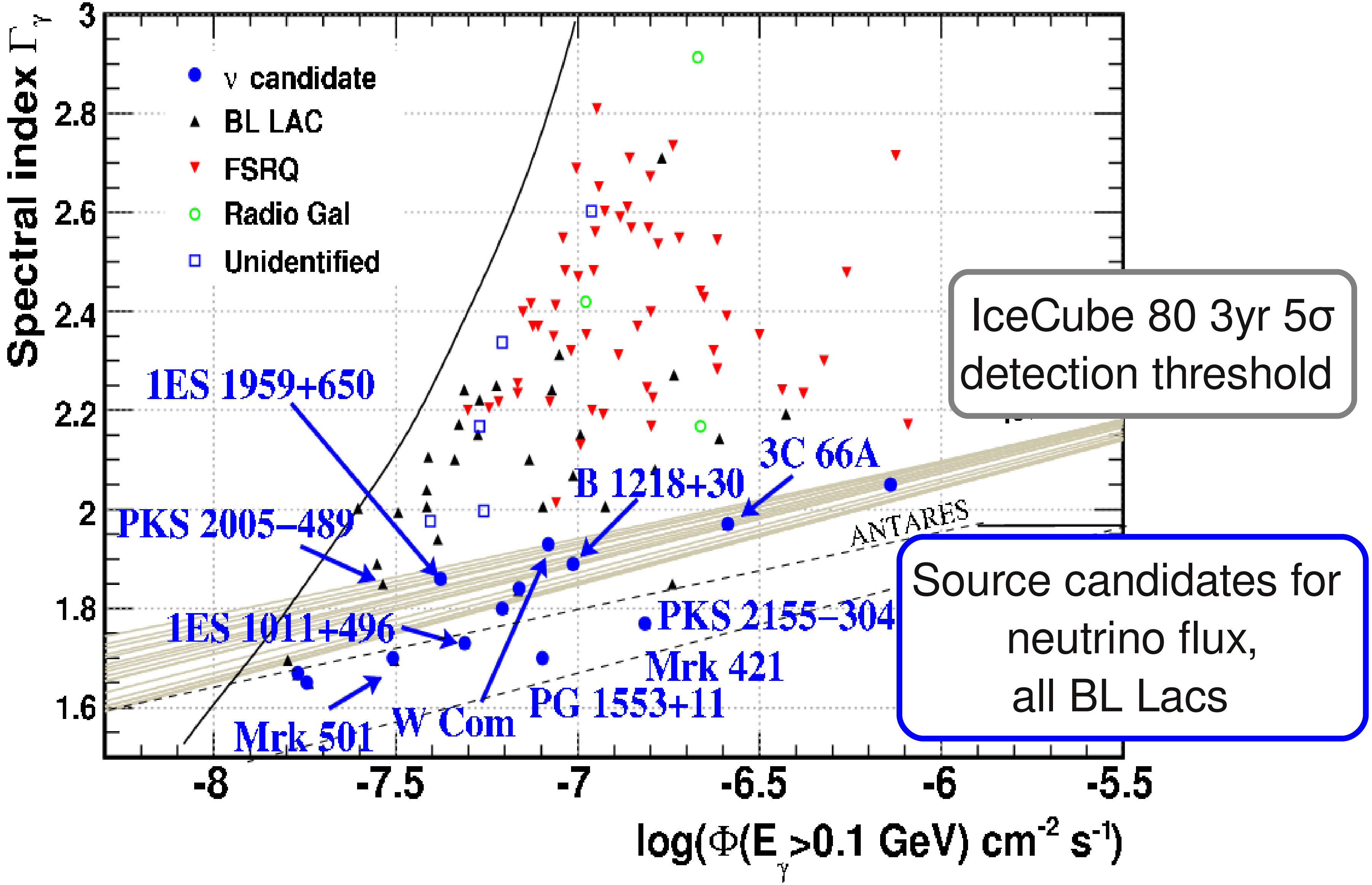
AMANDA-II:	$3m^2$
IceCube-86:	$100m^2$

Time Averaged All-Sky Point Source Search: Limits



Neutrino Flux from AGNs

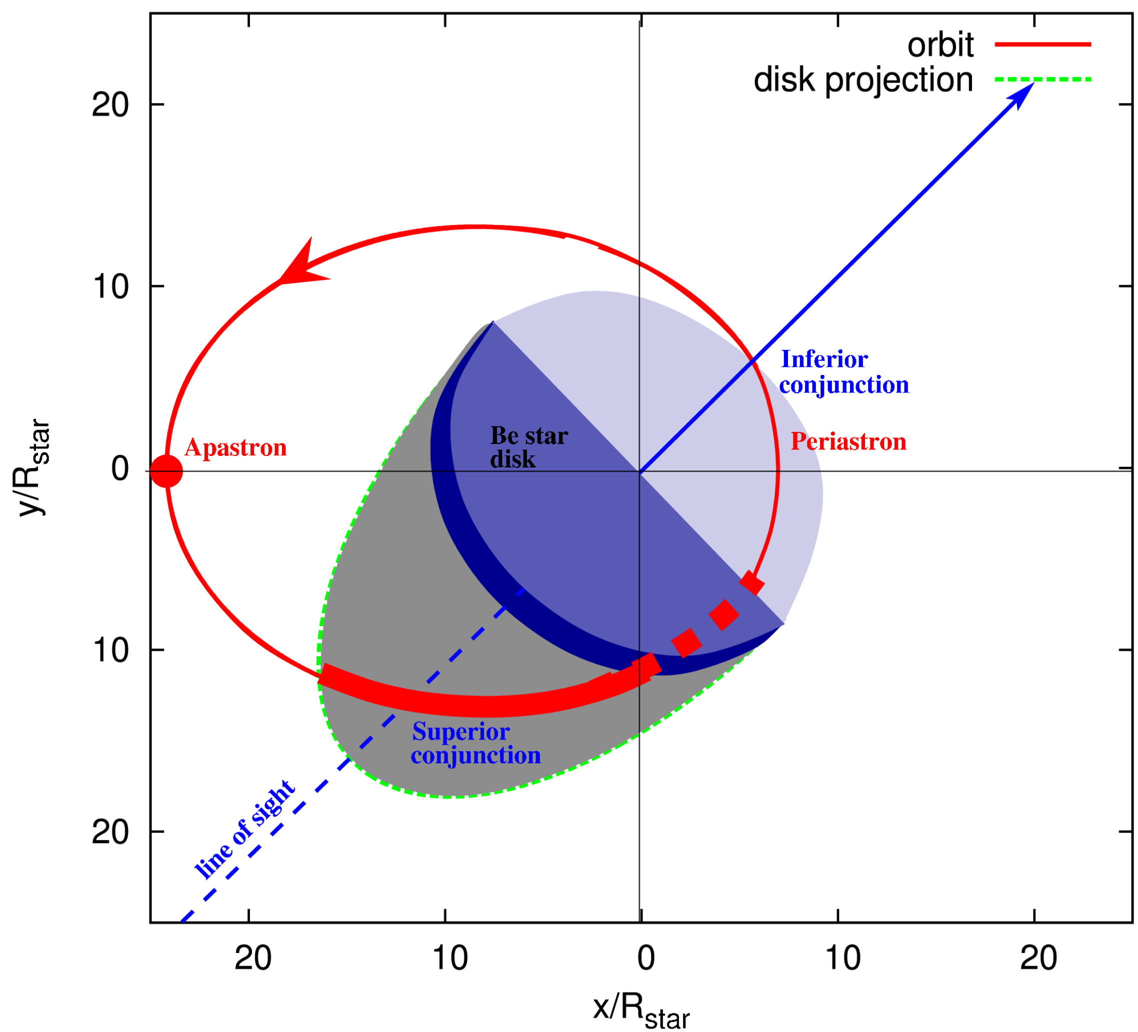
Fermi AGN in "flux vs. spectral index" parameter space, Abdo et al., Astrophys. J. 700, 597 (2009)



Neutrino Flux from LS I +61 303

- central Be star
- outflow from central star forms dense stellar disk
- compact object of unknown origin: neutron star? black hole?
- broadband observations from radio to X—ray
- together with LS 5039 the only two X—ray binaries seen in γ-rays
- However: origin of VHE emission still unknown

- ν emission $\rightarrow$ hadronic interactions!
- HE protons from the companion interacting with the dense stellar disk?
- combining MWL observations $\rightarrow$ time variable emission models!

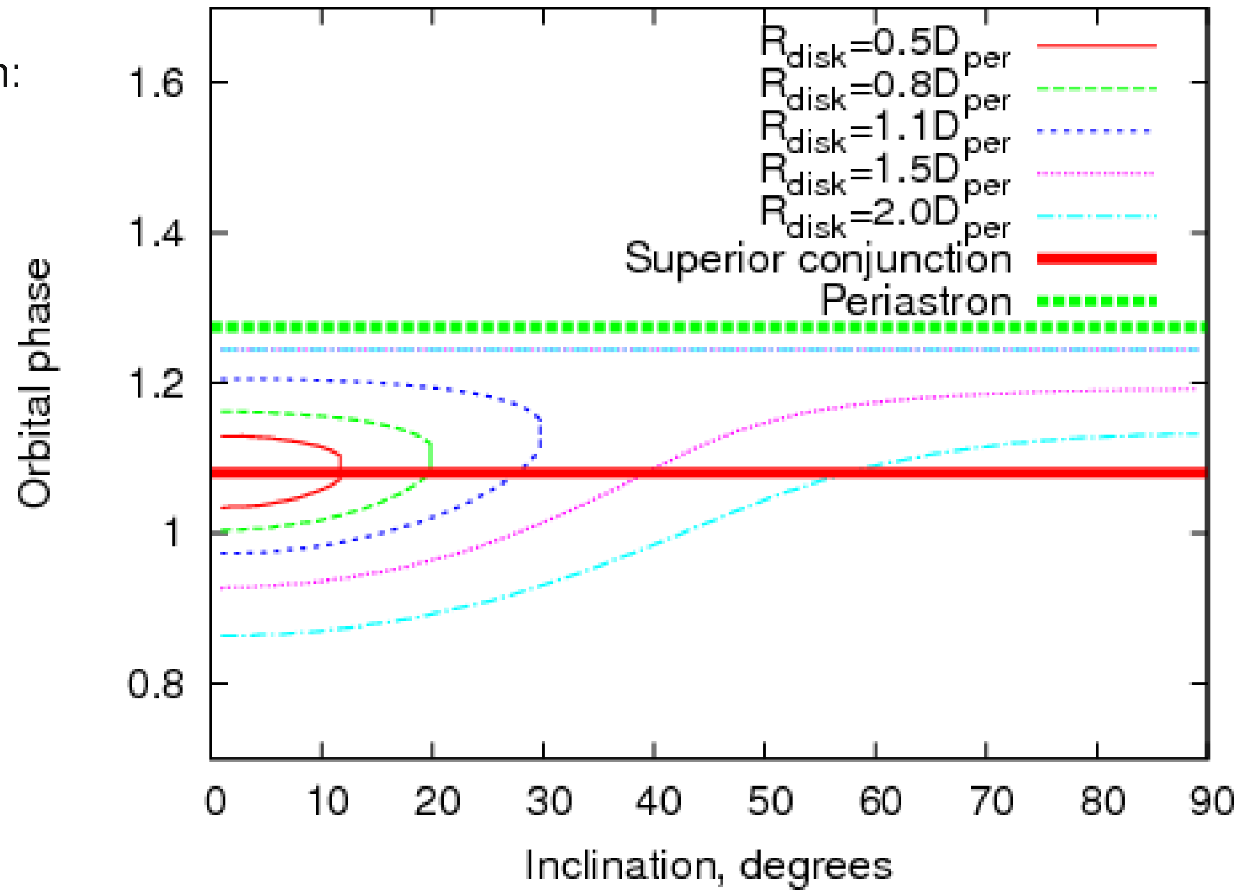


Neutrino Flux from LS I +61 303

- ν emission observable only during certain orbital phases depending on:
  - system's inclination
  - radius of stellar disk

- To cover a wide range of the parameter space we chose
  3 disk sizes at 10° (neutron star)
  1 disk size at 30° (black hole)
- No spectrum prediction available
  $\rightarrow$ assume simple power law with spectral index Γ=2, 1.5

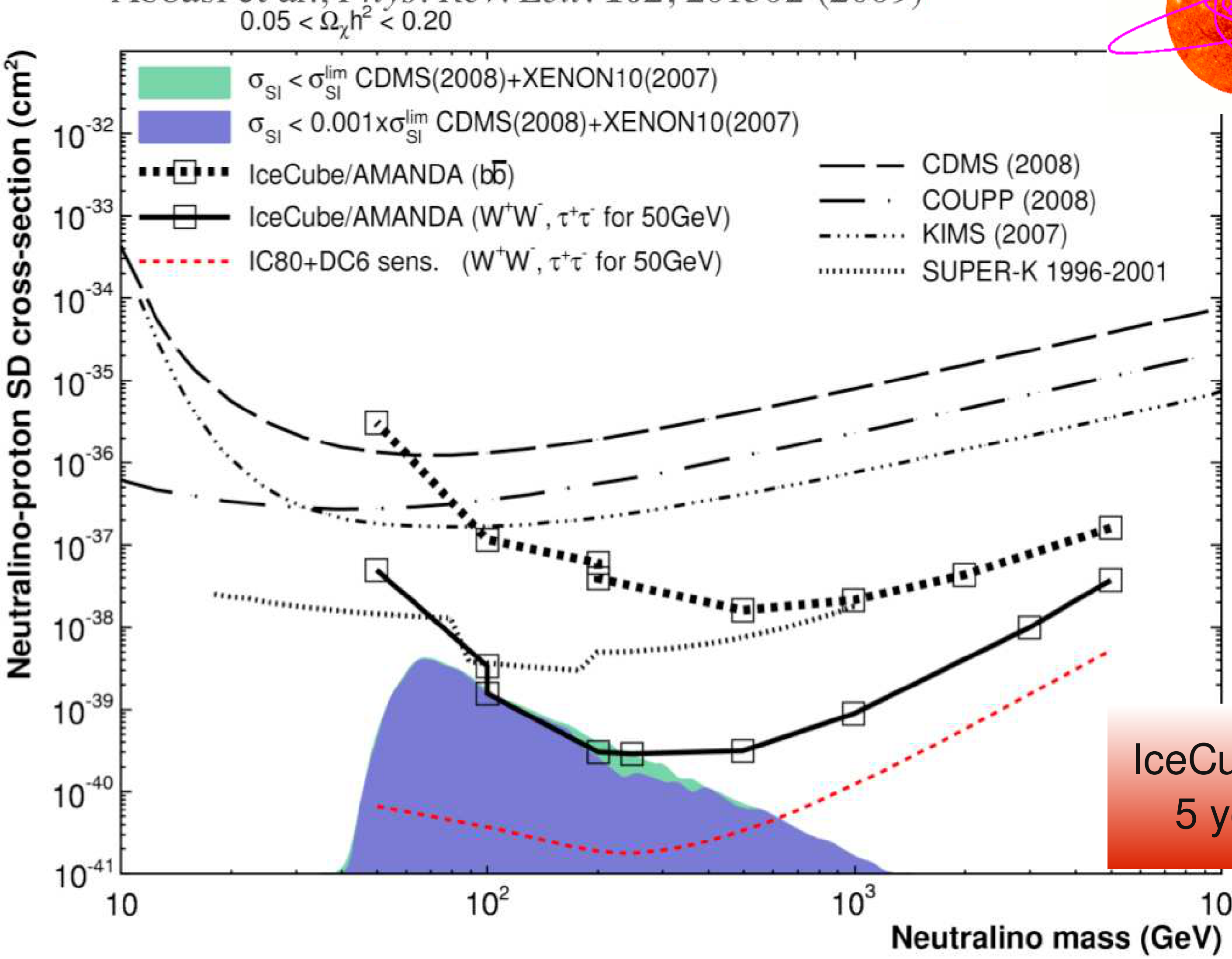
  $\rightarrow$ 8 models to test

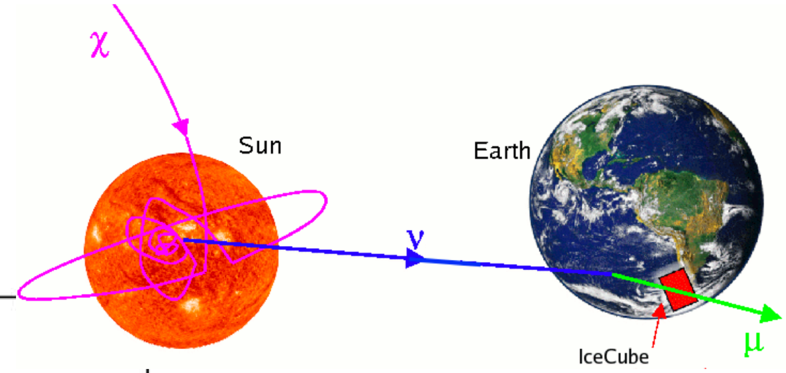


- Binned search with energy esimator based likelihood
- Emission window prediction is used to scale background expectation.
- Search parameters:
  - search bin radius and low energy cutoff
  - determined by optimizing the 5σ discovery potential in 90% of trials

IceCube-22/AMANDA Solar DM limits

Abbasi et al., *Phys. Rev. Lett.* **102**, 201302 (2009)





IceCube/DeepCore 86
5 years sensitivity

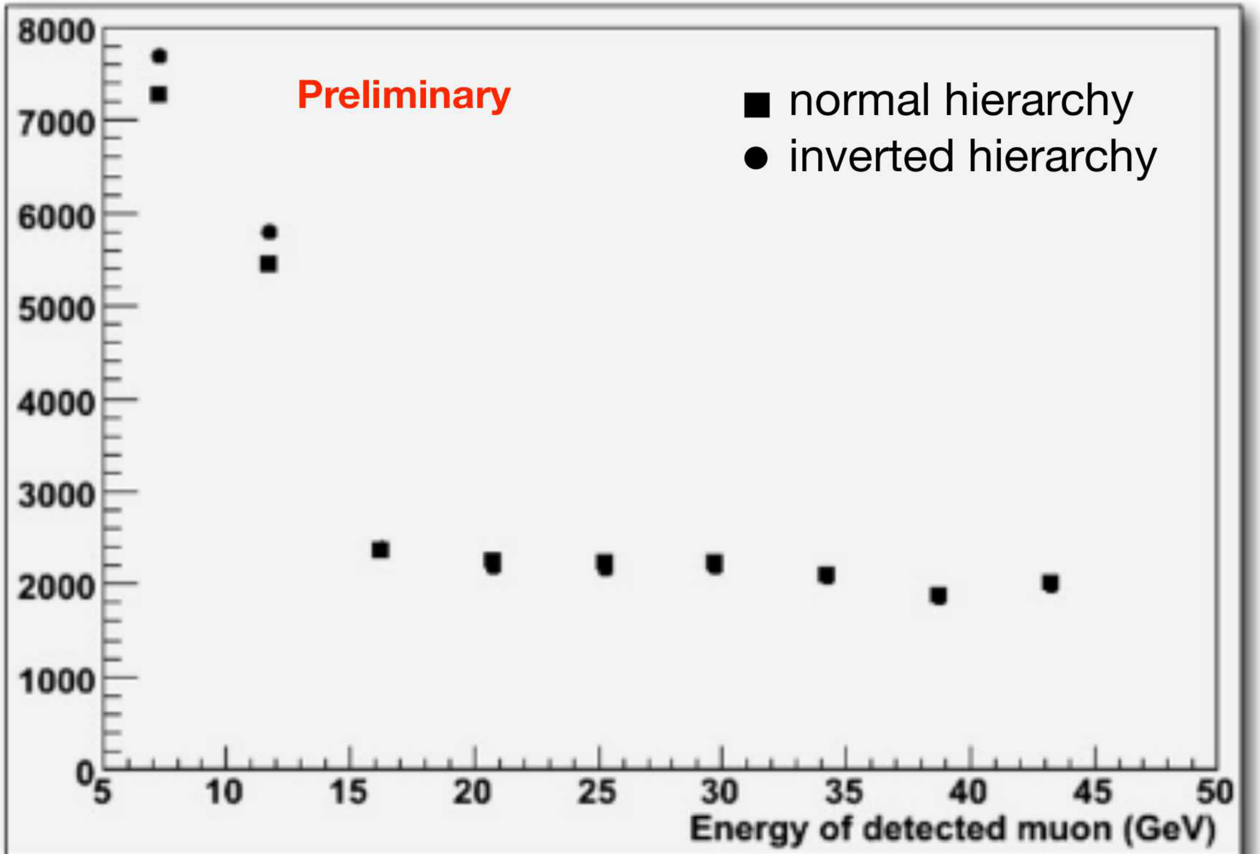
Neutrino Physics with DeepCore

- Caveat: preliminary studies
  - Full detector simulation of signal (only)
  - Assume high suppression of atmospheric muons by veto techniques
    $\rightarrow$ #signal is shown at trigger level (unrealistic)
  - Specialized reconstruction algorithms for low energy events needed, now under development

- Three possible measurements
  - Muon neutrino disappearance: Feasible
  - Tau neutrino appearance: Reasonable
  - Neutrino mass hierarchy? Very hard

Neutrino Mass Hierarchy

- Exploit asymmetries between neutrinos and antineutrinos (Mena, Mocioiu, Razzaque arXiv:0803.3044)
  - Resonance in effective Θ_{13} angle in Earth at 10 GeV for Earth diameter
  - $P_{\mu\mu}$: max at 12 GeV, min at 8 GeV
  - Asymmetries in $P_{\mu\mu}$, $\sigma_{\nu N}$, <y>
- Requires large Θ_{13}

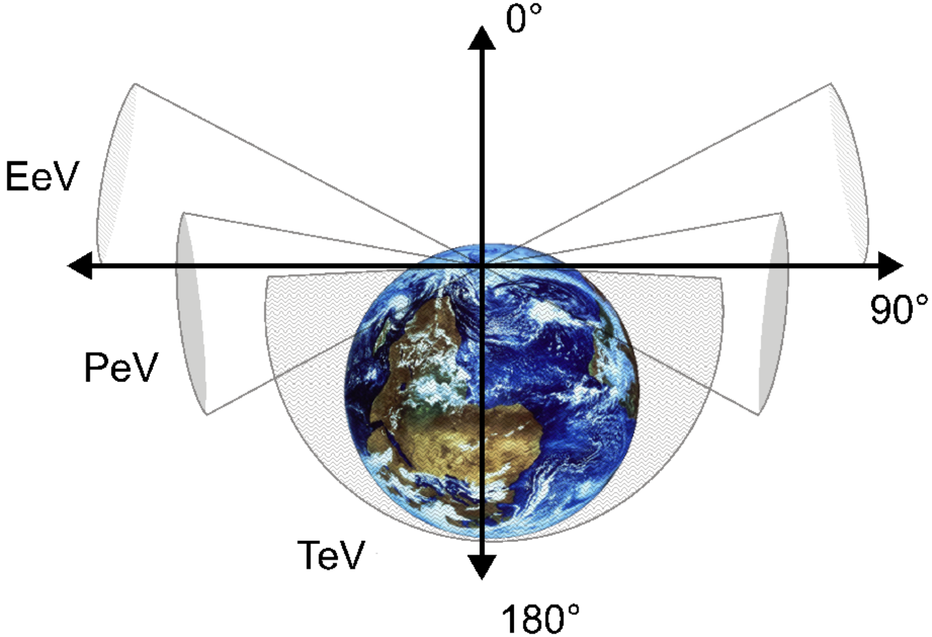


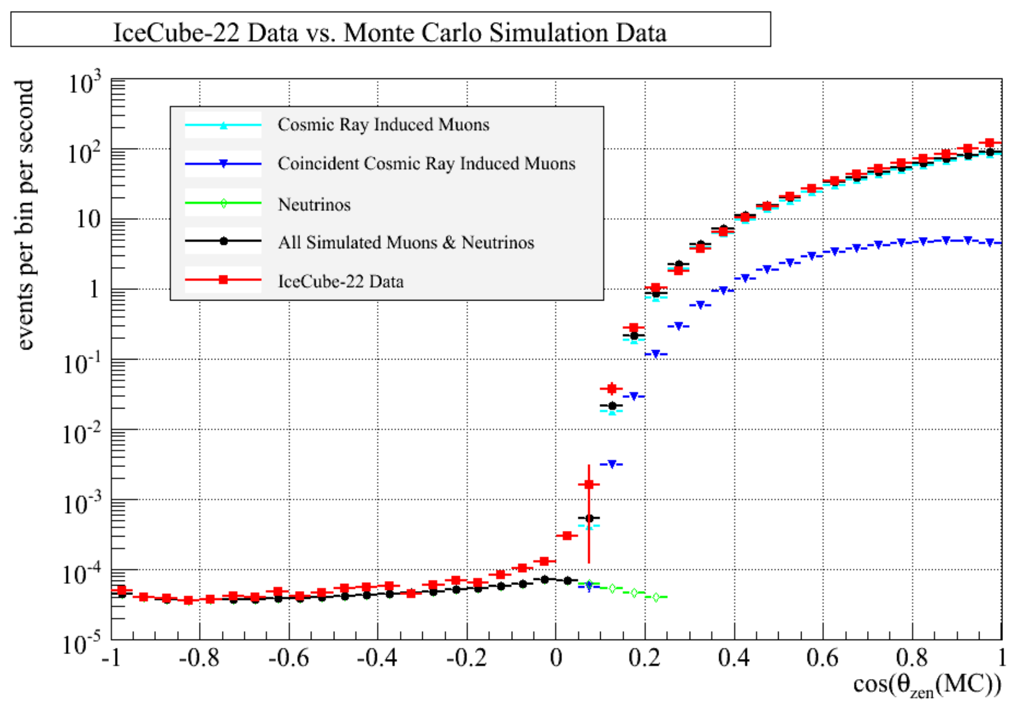
- 5 year prediction for IceCube + Deep Core, cos(Θ) < -0.7 (up-going), muon threshold 5 GeV (~25 m), similar assumptions as previous studies

GZK neutrino search in IceCube

- Low flux
- Cross section increasing with energy, Earth shadowing effect
- Signal is in the same zenith region as the background
- Large uncertainty on muon bundle background

Neutrino signal zenith dependence



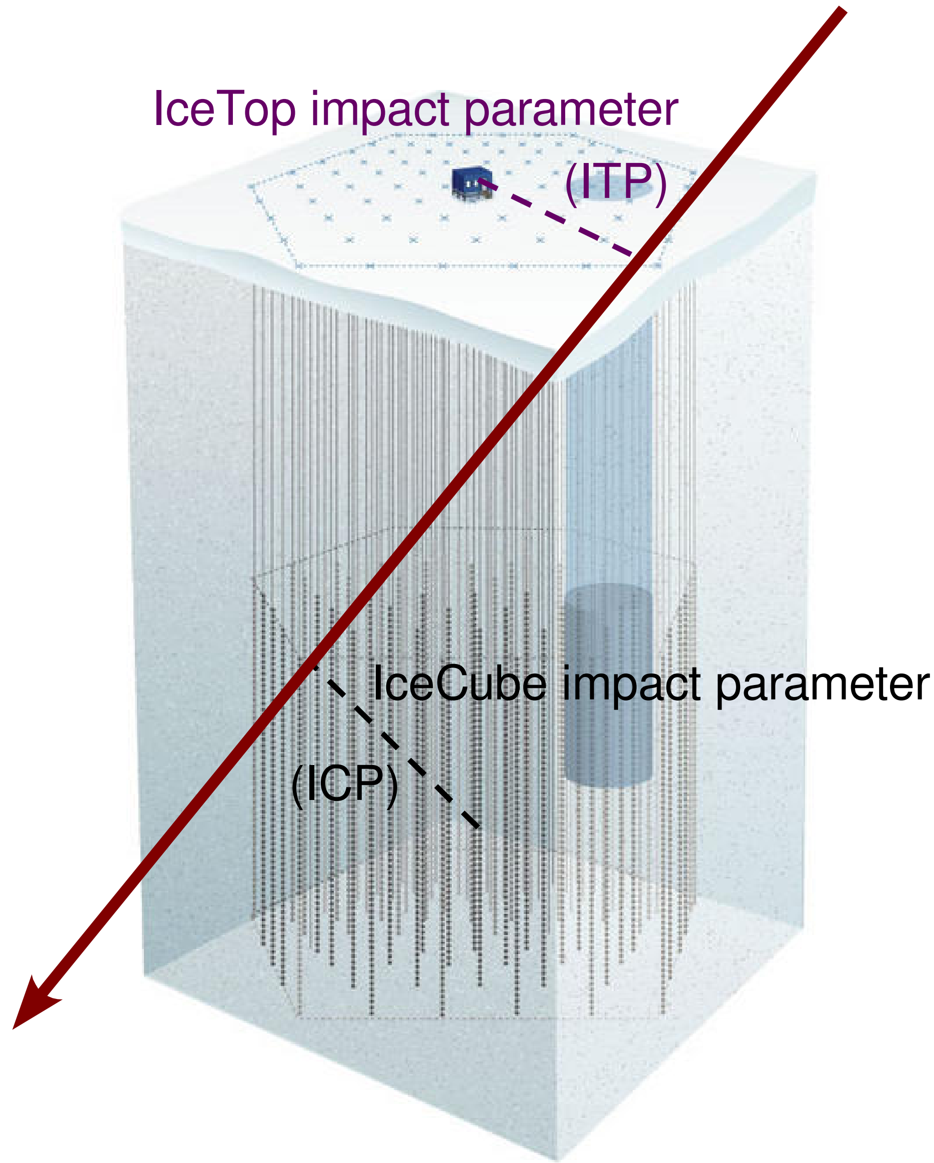


upgoing

downgoing

Vetoing HE muon bundles with IceTop

- In IC40 an event can pass through IceTop and InIce with zenith angle < 36°
- One event is expected in signal region zenith < 36° (cos(z)>0.8)
- Does an UHE InIce events have IceTop hits associated with it? Veto it
- Study shows high efficiency for small angles and bright events
- Can do even better for contained events (shower position dependency)
- Another advantage: vetoing tracks that are mis-reconstructed as horizontal to upgoing



IceTop Veto Impact

- Veto efficiency depends on Impact Parameters, CR angle and energy
- Not CR primary dependent!
- Nearly background free regions after veto?