High-Energy Neutrino Astronomy (2)

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Summer School
UNDERSTANDING NEUTRINOS
Prague, Sept 2012

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  - What can one do with neutrino telescopes?
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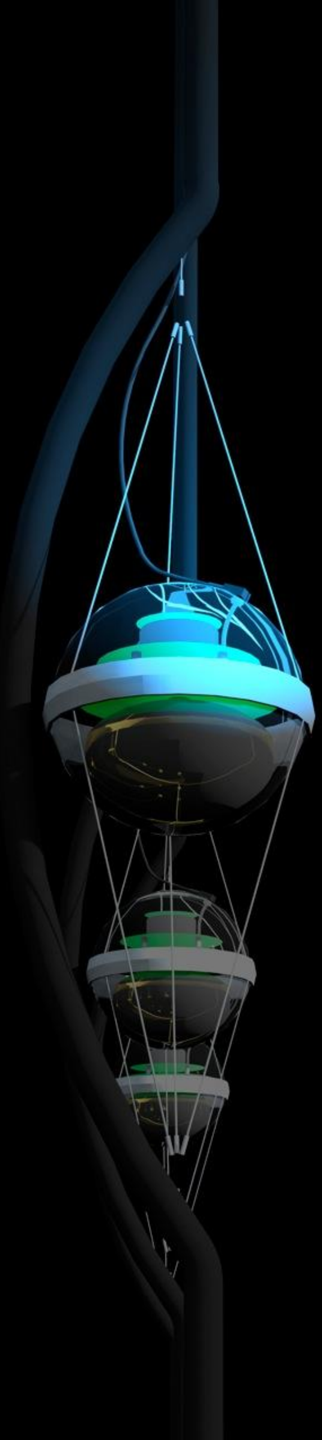
  - Search for high-energy extraterrestrial neutrinos
  - Nu-Telescopes as supernova monitors
  - Cosmic ray physics with nu-telescopes
  - Particle physics with nu-telescopes
  - Summary



Why can one do with Neutrino Telescopes ?

Physics with neutrino telescopes

Cosmic accelerators

- Point-like sources (SNRs, binaries ...)
- Extended sources (SNRs, molecular clouds ...)
- Transients (GRBs, AGN flares ...)

Diffuse fluxes

- All-sky fluxes (e.g. cosmogenic)
- Galactic plane
- Extended structures

Dark Matter & Exotic Physics

- Indirect DM search (Sun, Galactic halo)
- Magnetic monopoles, Q-balls, . . .
- Lorentz invariance violation
- ν faster than light?

Cosmic rays

- Anisotropy
- Galactic CR: spectrum and composition

Supernova explosions

- Galactic/LMC SNe
- Phases
- Neutrino hierarchy

Neutrino Properties & Particle Physics

- Neutrino oscillations
- Heavy flavors in showers
- K/π ratio in showers
- Cross sections at very high energies

Physics with neutrino telescopes

Cosmic accelerators

- Point-like sources (SNRs, binaries ...)
-
- Transients (GRBs

Diffuse fluxes

- All-sky fluxes (e.g. cosmogenic)
-
-

Dark Matter & Exotic Physics

- Indirect DM search (Sun, Galactic halo)
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- Lorentz invariance violation
- ν faster than light?

Cosmic rays

- Anisotropy
-

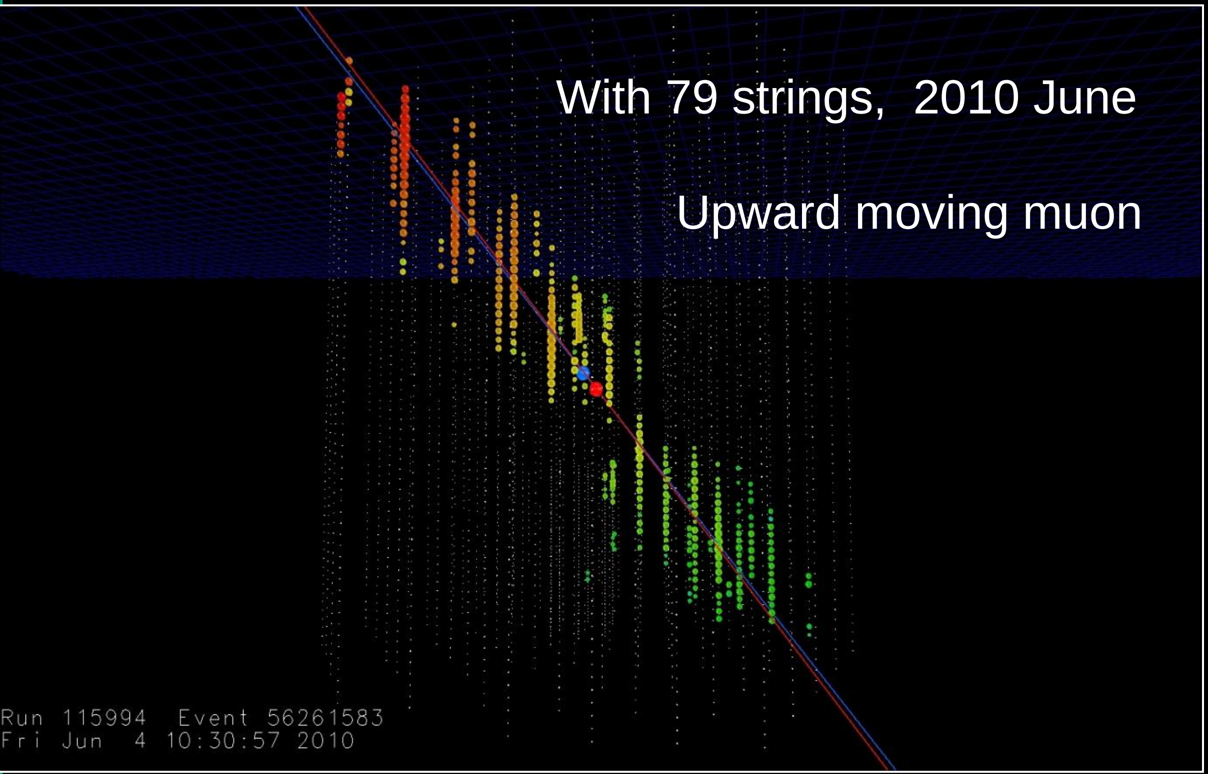
Supernova explosions

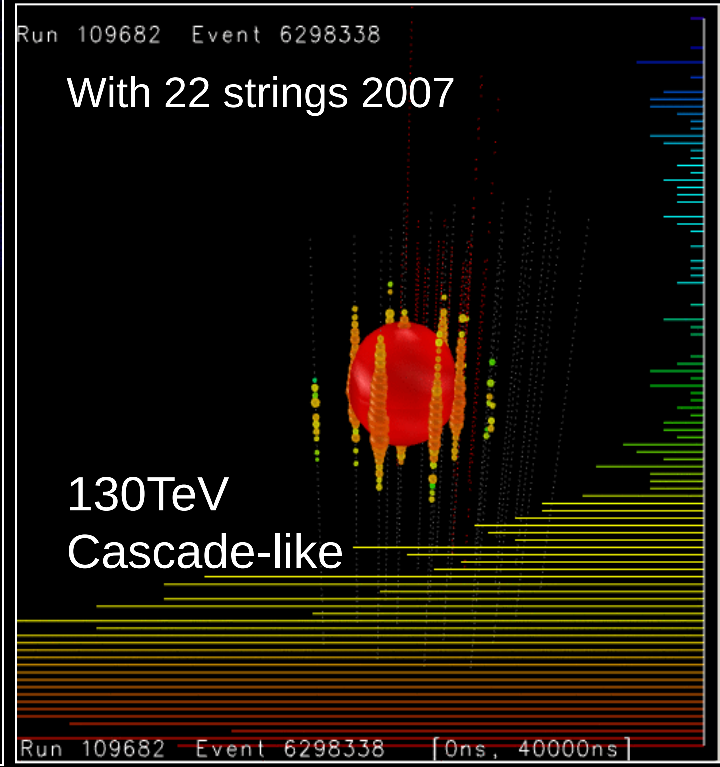
- Galactic/LMC SNe
-
-

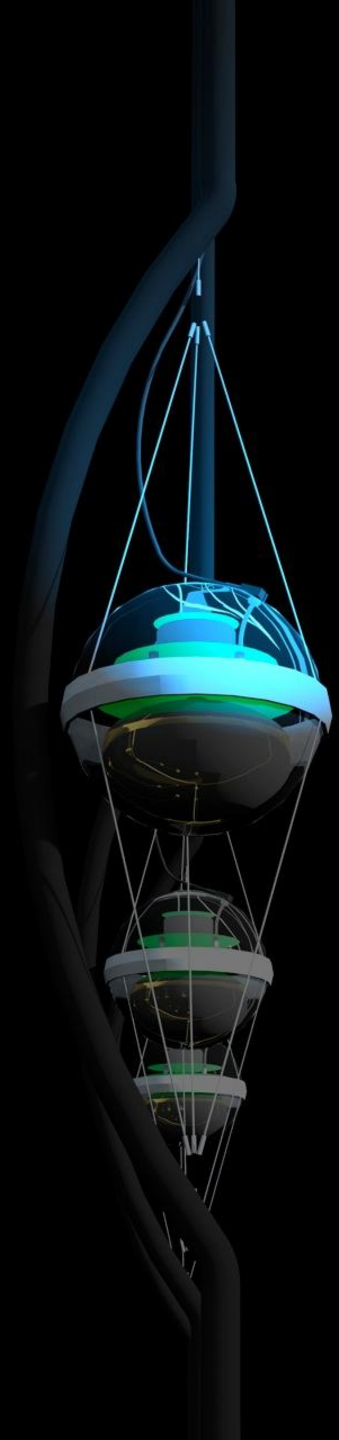
Neutrino Properties & Particle Physics

- Neutrino oscillations
- Heavy flavors in showers
-
-

Neutrino events in IceCube

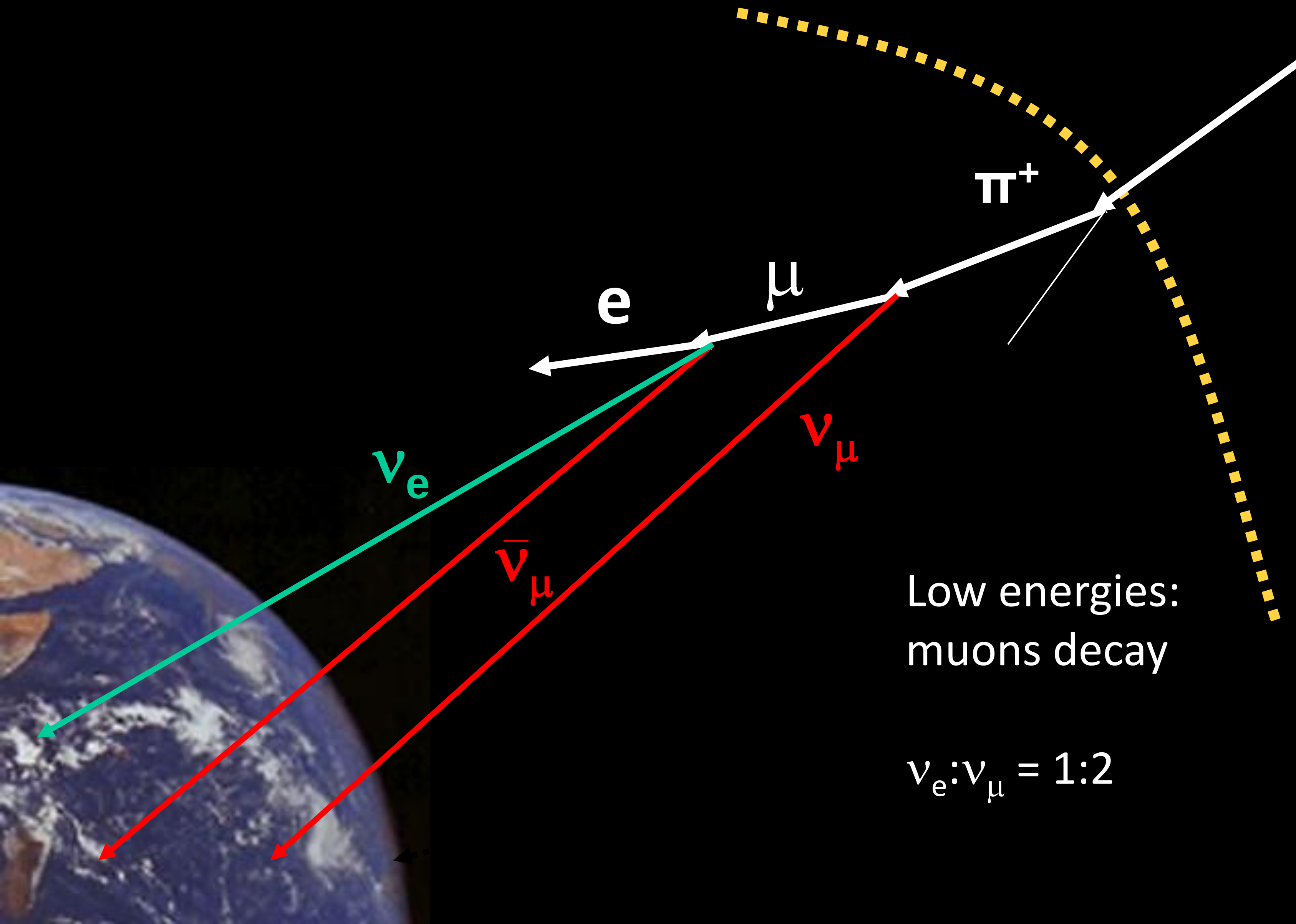






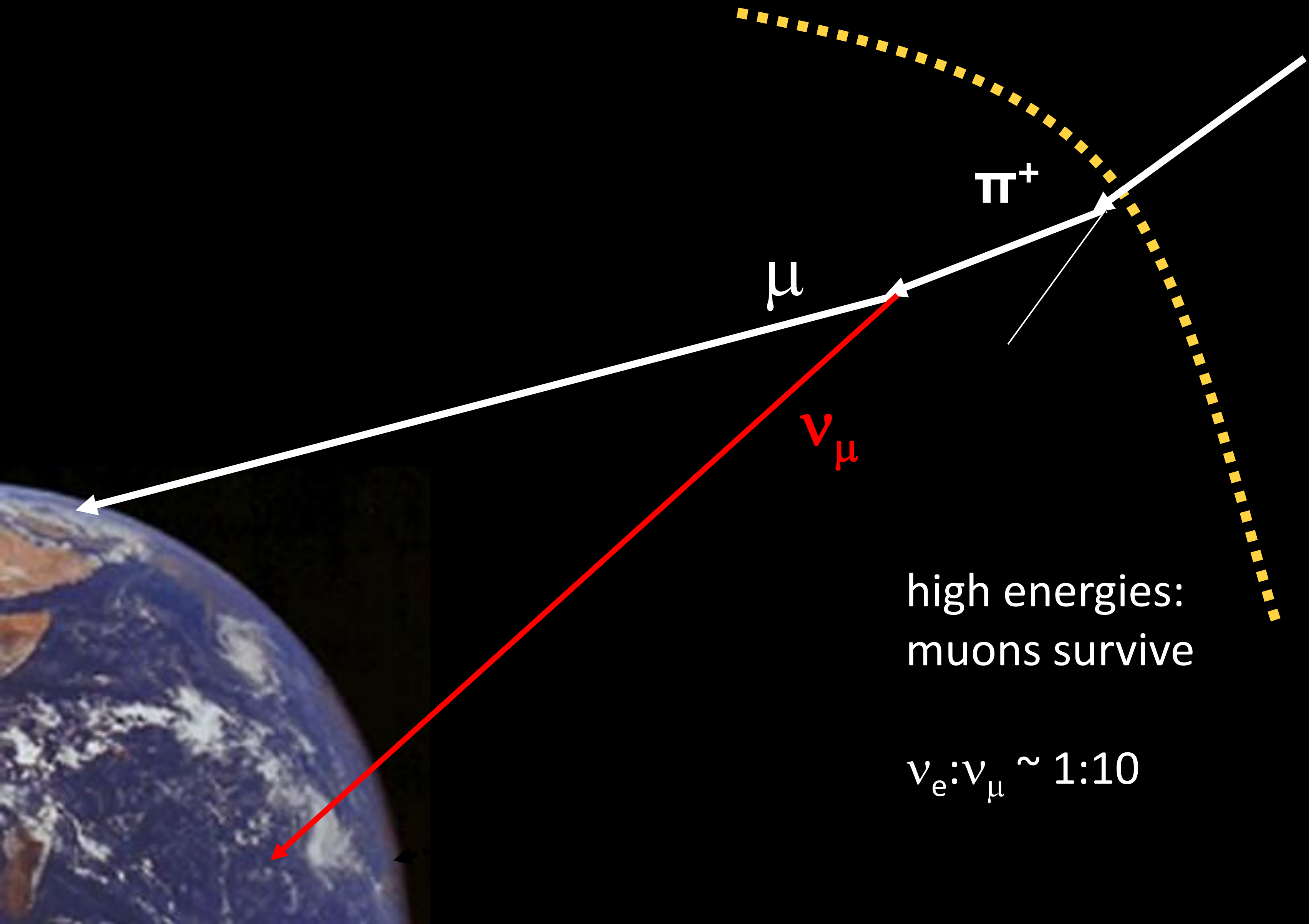
Performance checks

- atmospheric muons
- atmospheric neutrinos
- shadow of the moon



Low energies:
muons decay

$\nu_e:\nu_\mu$ = 1:2

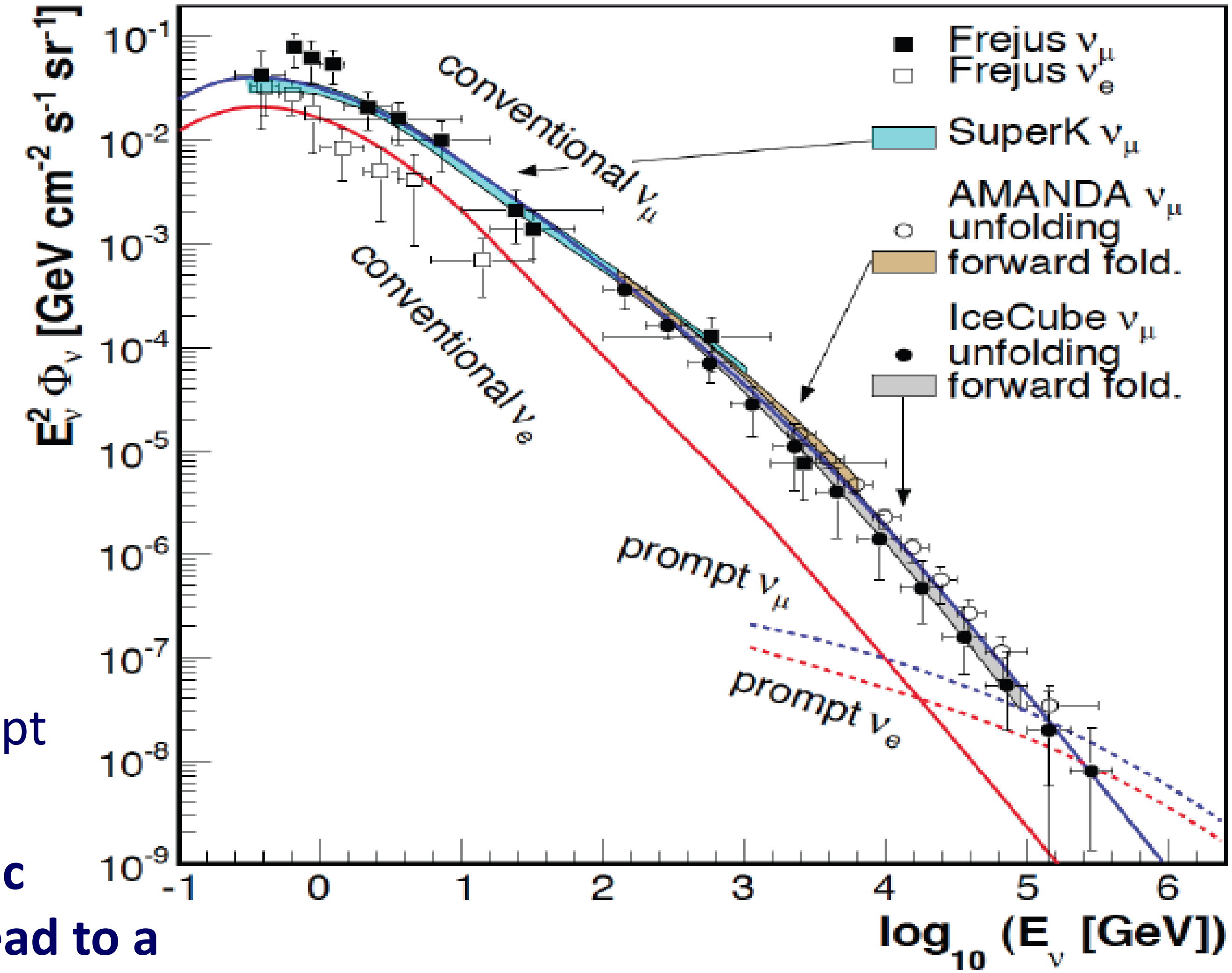


high energies:
muons survive

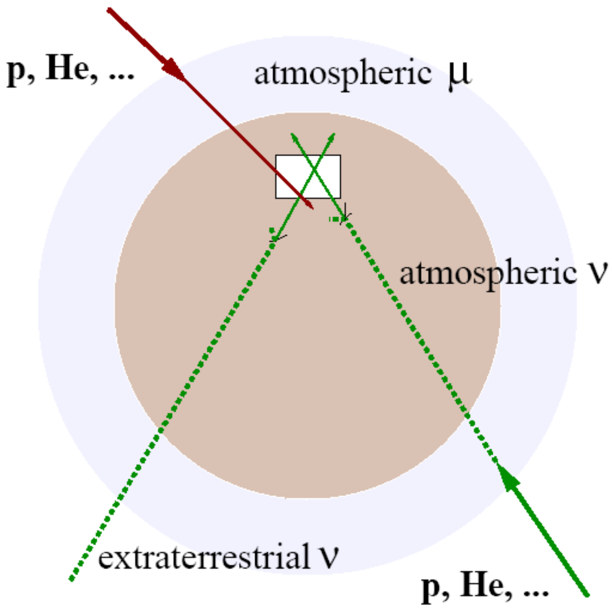
$\nu_e : \nu_\mu \sim 1:10$

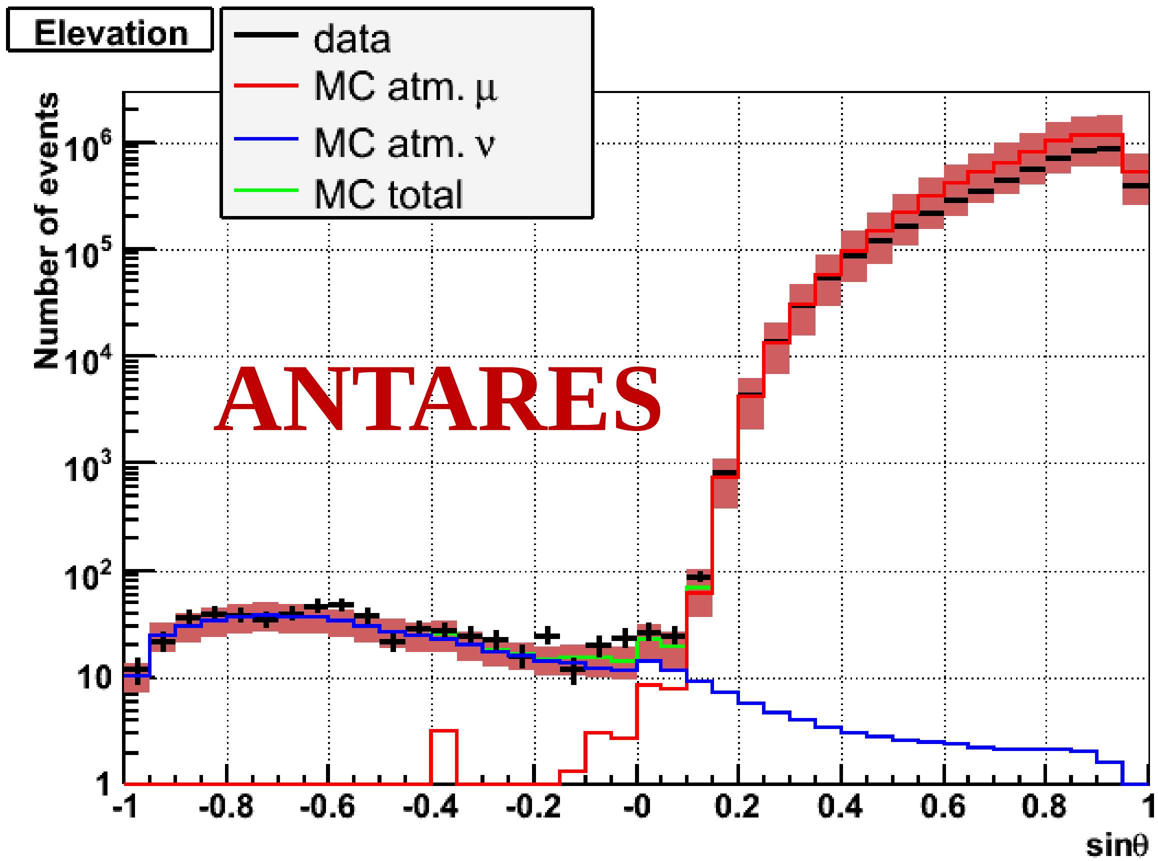
Energy spectrum of atm. muon neutrinos

- Frejus, Super-K, Amanda, IceCube
- IC-40: ~18,000 ν_μ CC events
- θ= 180°-97°
- Compatible with Bartol/Honda predictions
- Close to constrain estimates for prompt neutrinos
- Glashow: **tachyonic neutrinos would lead to a depletion at high energies !**



Downgoing and upgoing muons

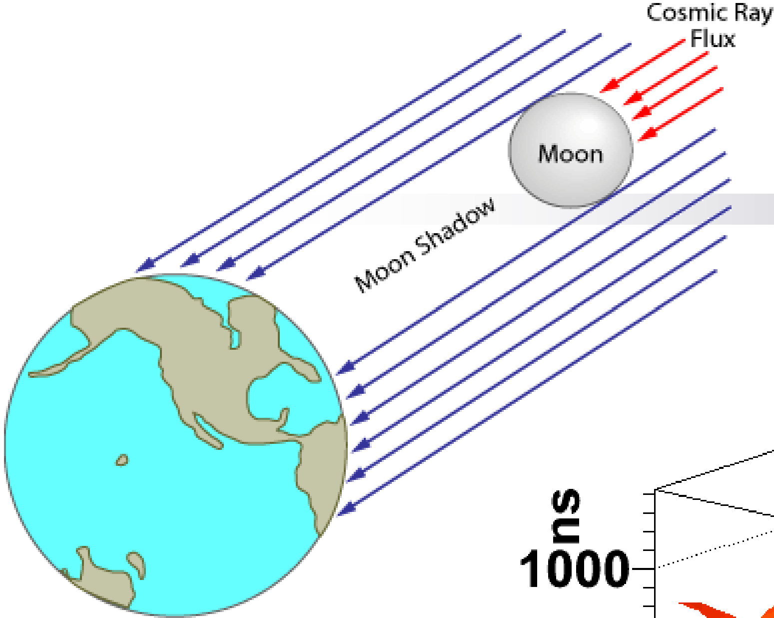


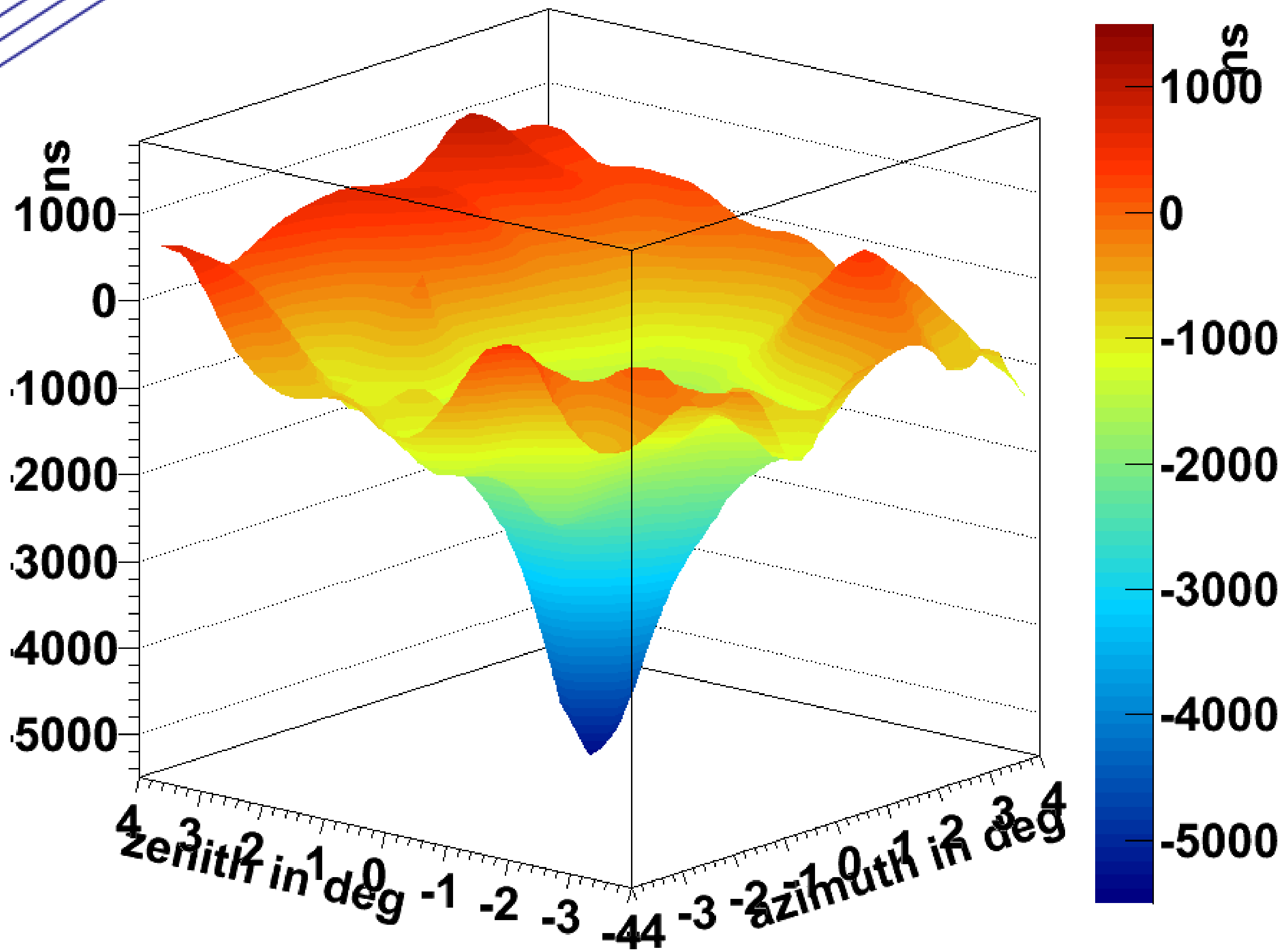


Muons detected per year (IceCube/Antares)

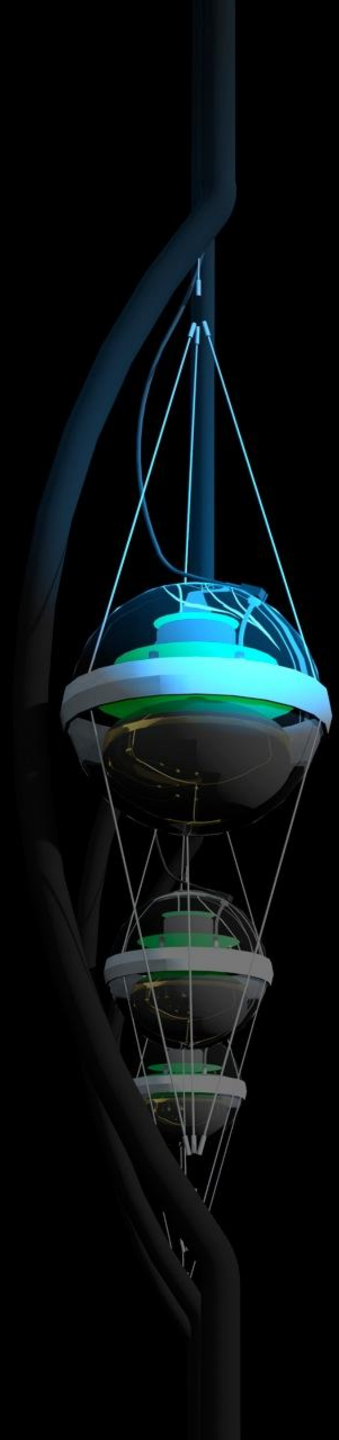
- Atmospheric μ 7×10^{10} / 7×10^{8} or 2000/20 per second
- Atmospheric ν→μ 8×10^{4} / 2×10^{3} or 1 every 6 min/5h
- Cosmic ν→μ ~10

Moon Shadow





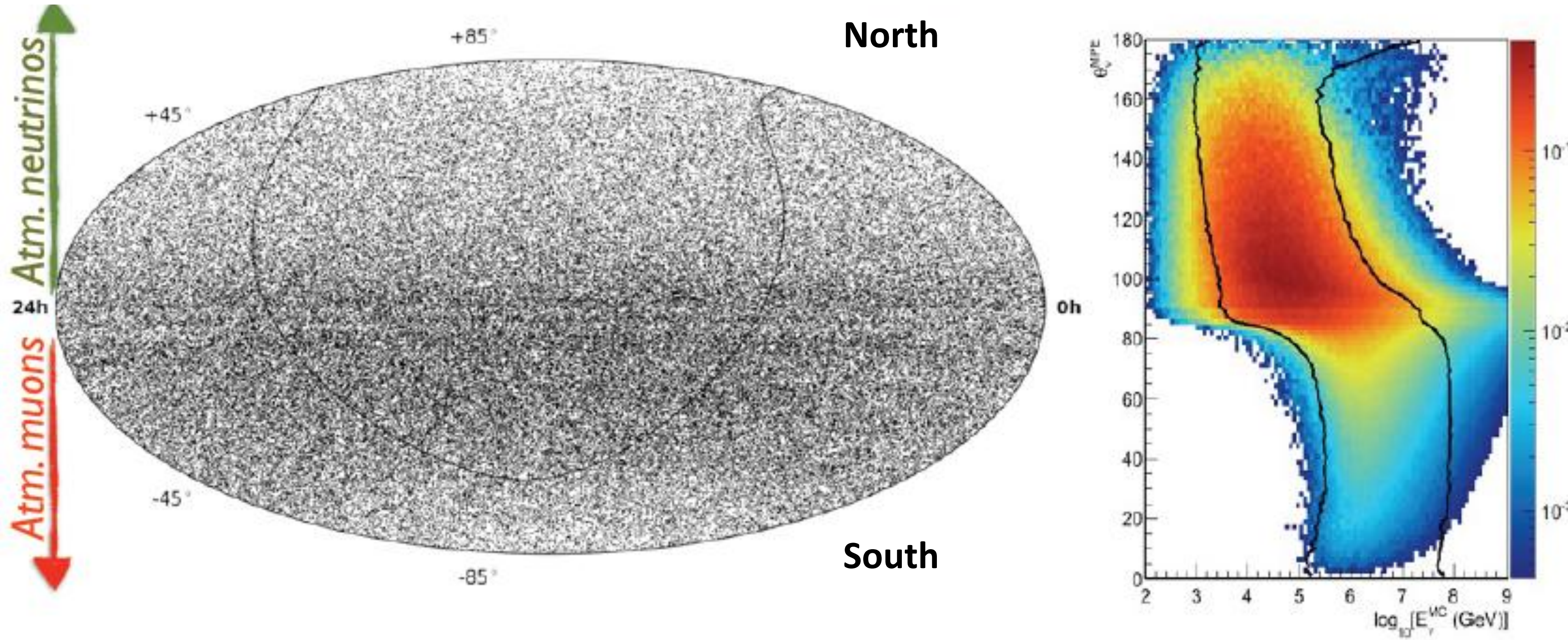
- IC59 ~ 12σ
- Gaussian fit 0.61°± 0.05°
- systematic pointing < 0.1°



Search for
extraterrestrial neutrinos

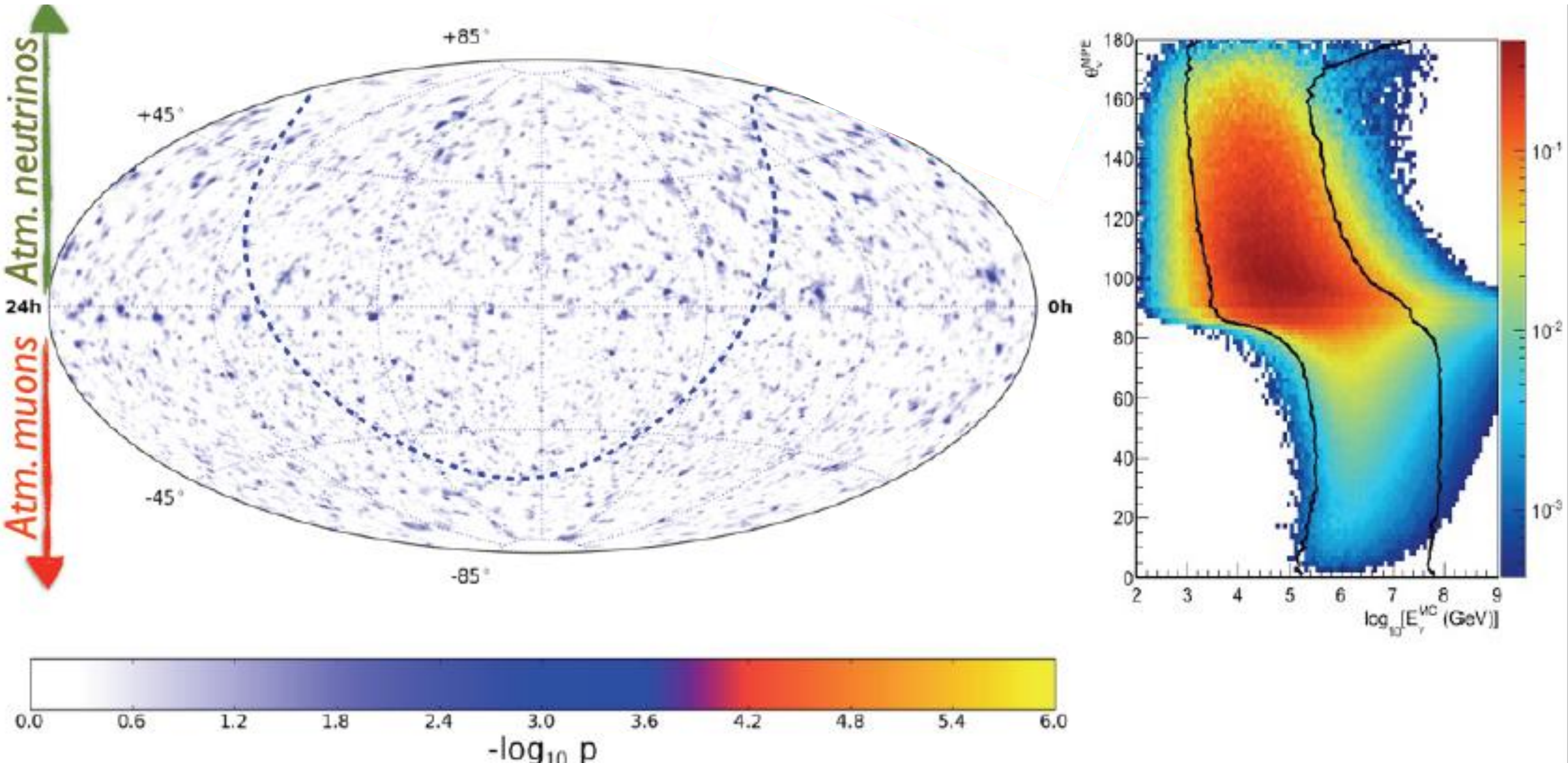
- Point sources

Point Source Search IceCube 40 strings

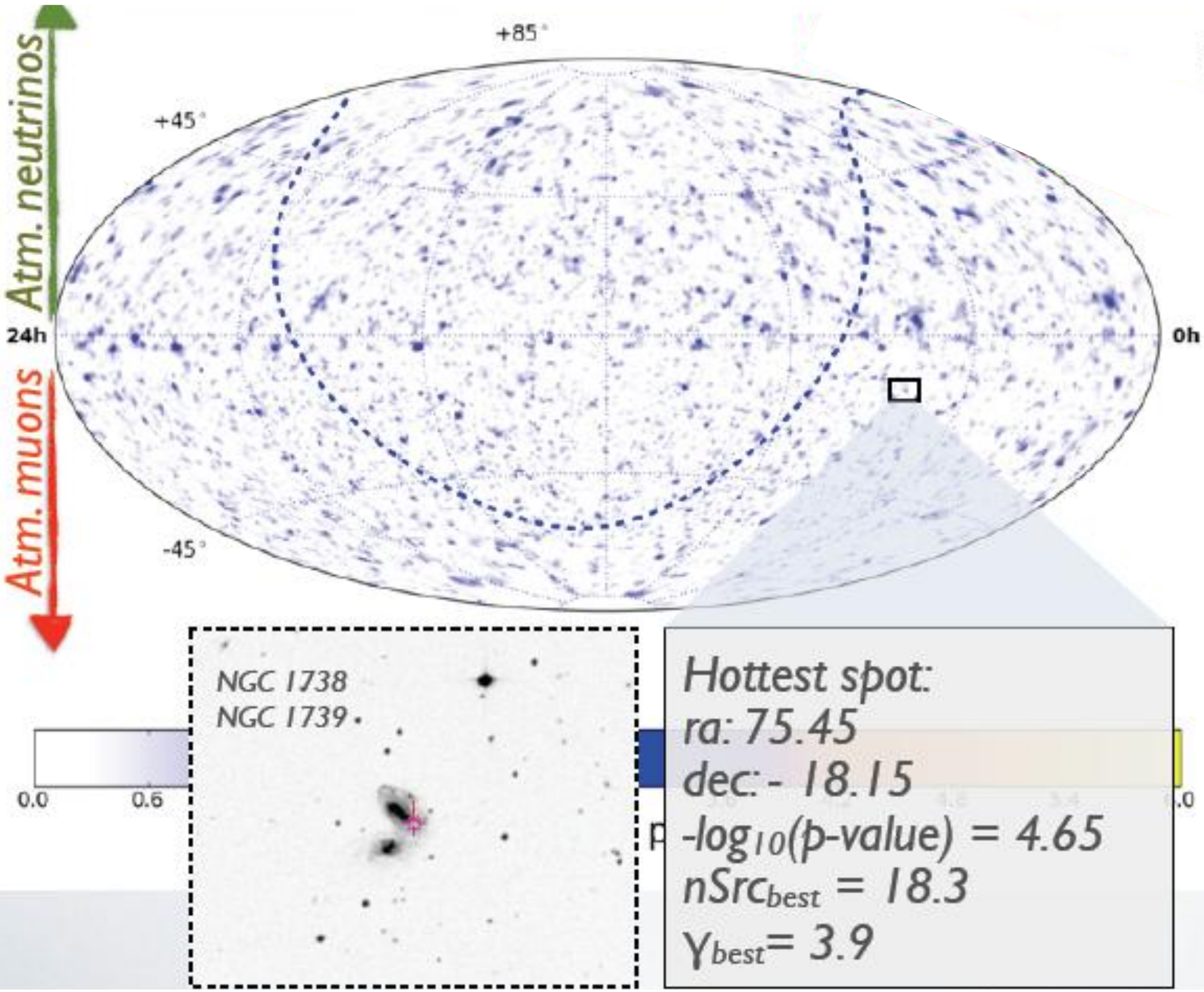


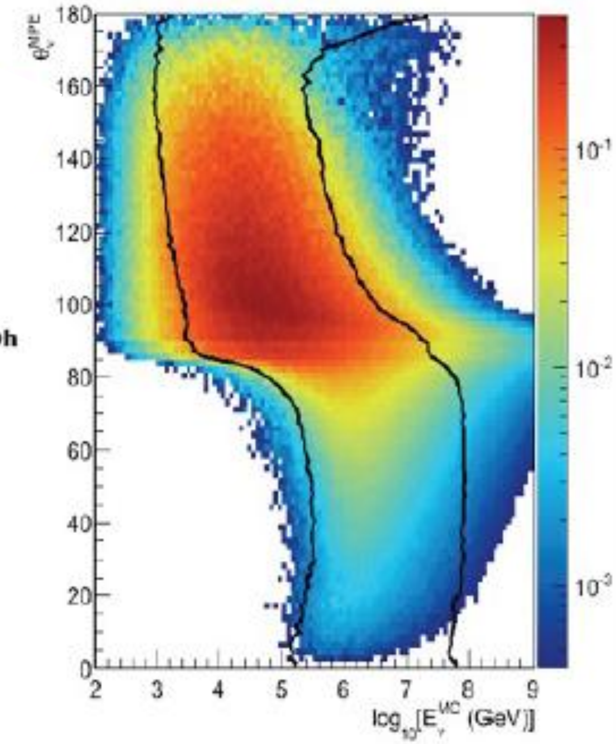
- Total events: 43339 (upgoing) + 64230 (downgoing)
- Livetime: 348 days (IC59) + 375 days (IC40)

Point Source Search IceCube 40 strings



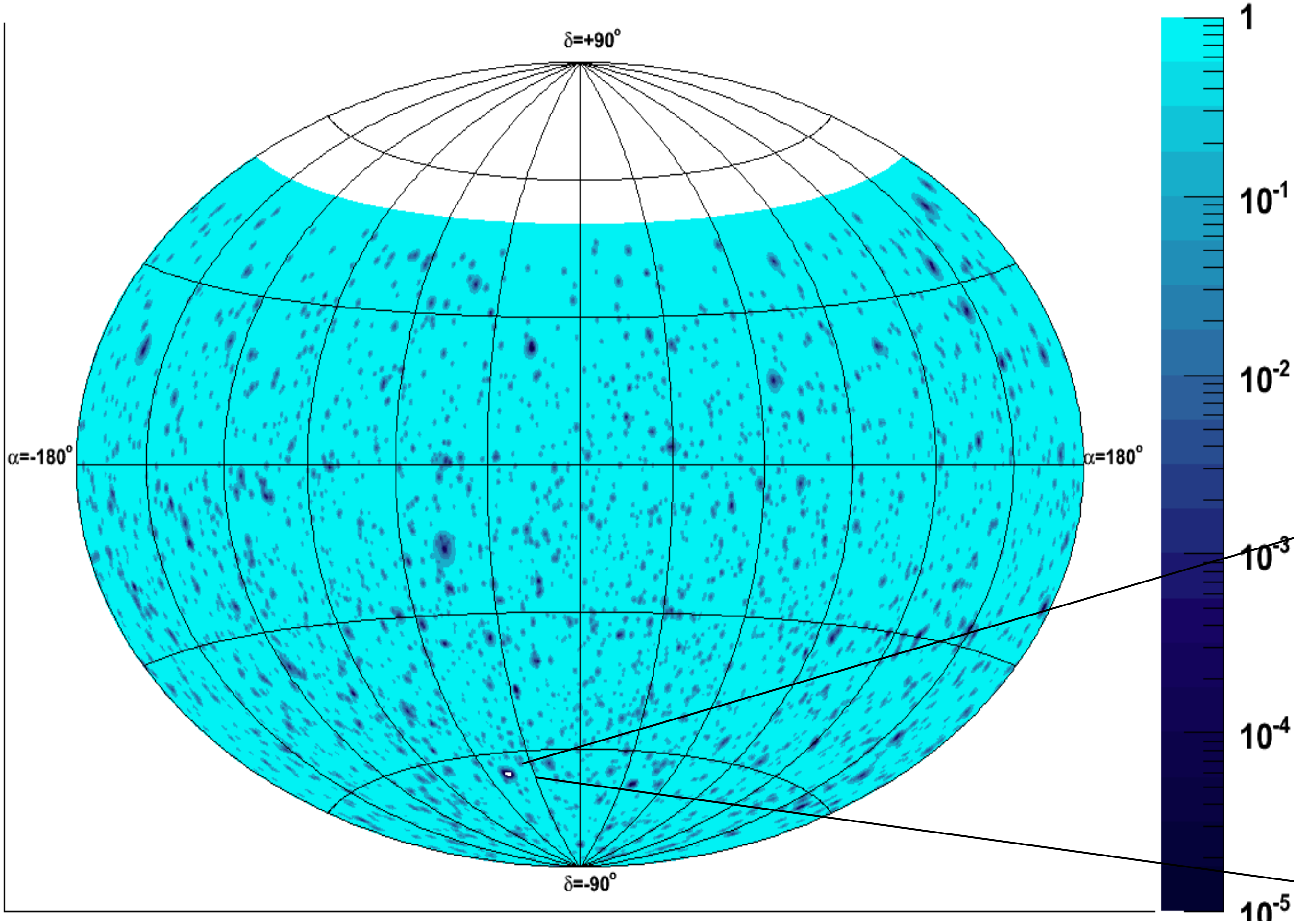
Point Source Search IceCube 40 strings





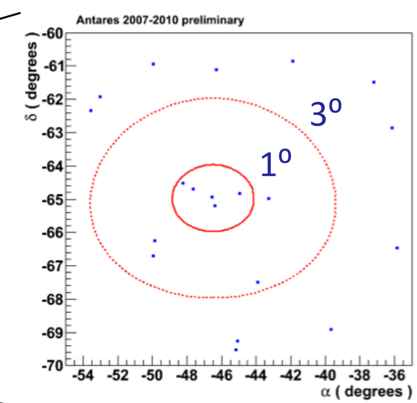
Point source Search ANTARES (2007-2010)

Sky map in equatorial coordinates



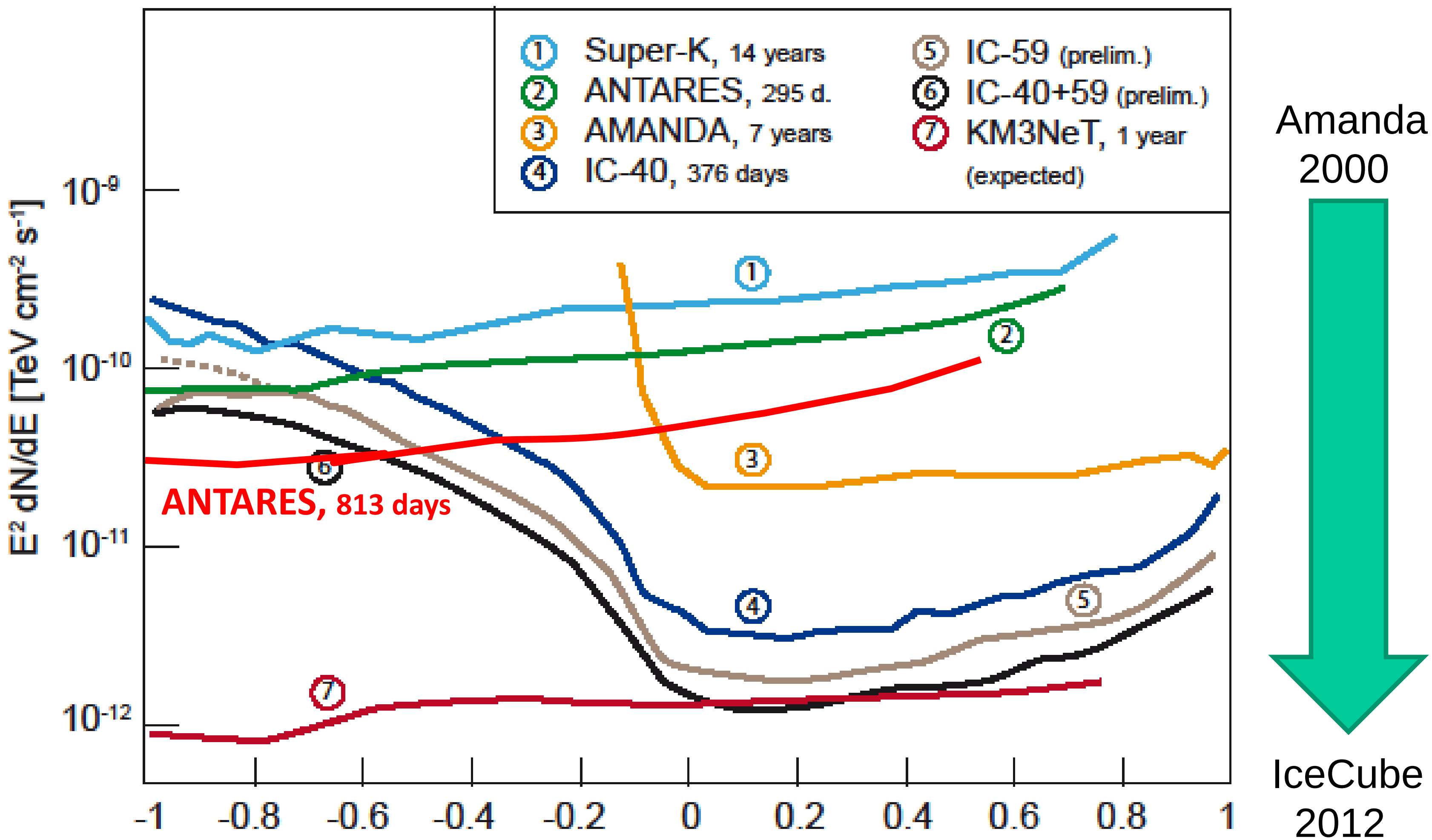
Most significant cluster at:
RA= −46.5°,
δ= −65.0°

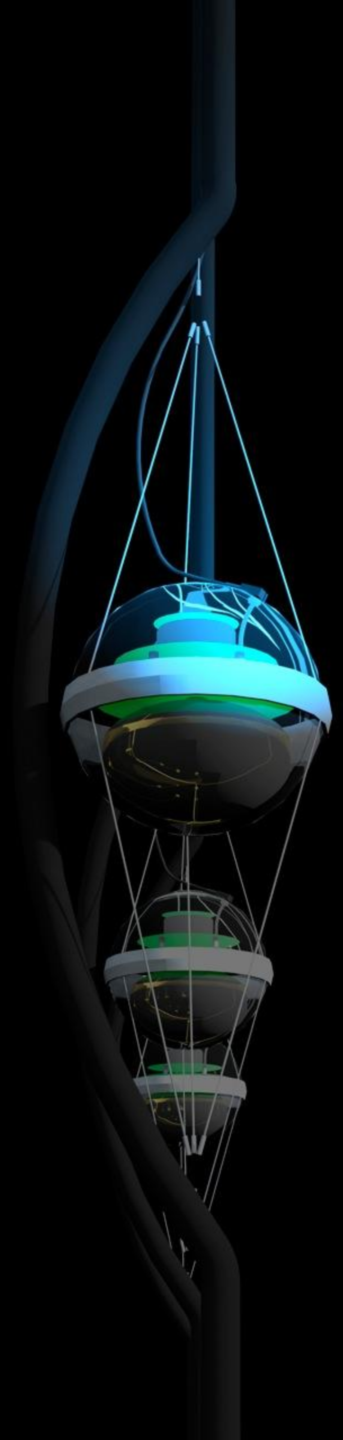
N_{sig} = 5
p-value = 0.026
Significance = 2.2 σ



Result compatible with the background hypothesis

Point sources: factor 1000 in 12 years

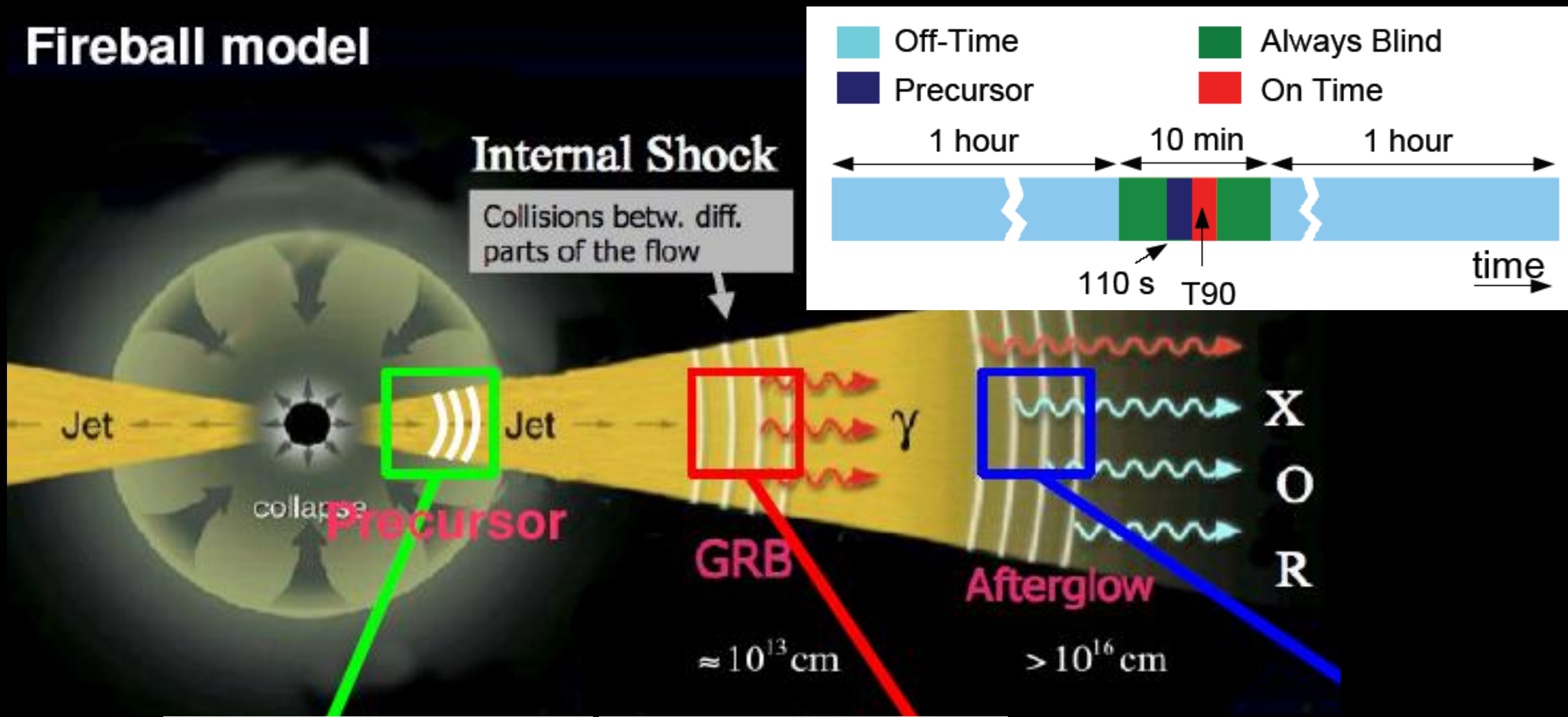


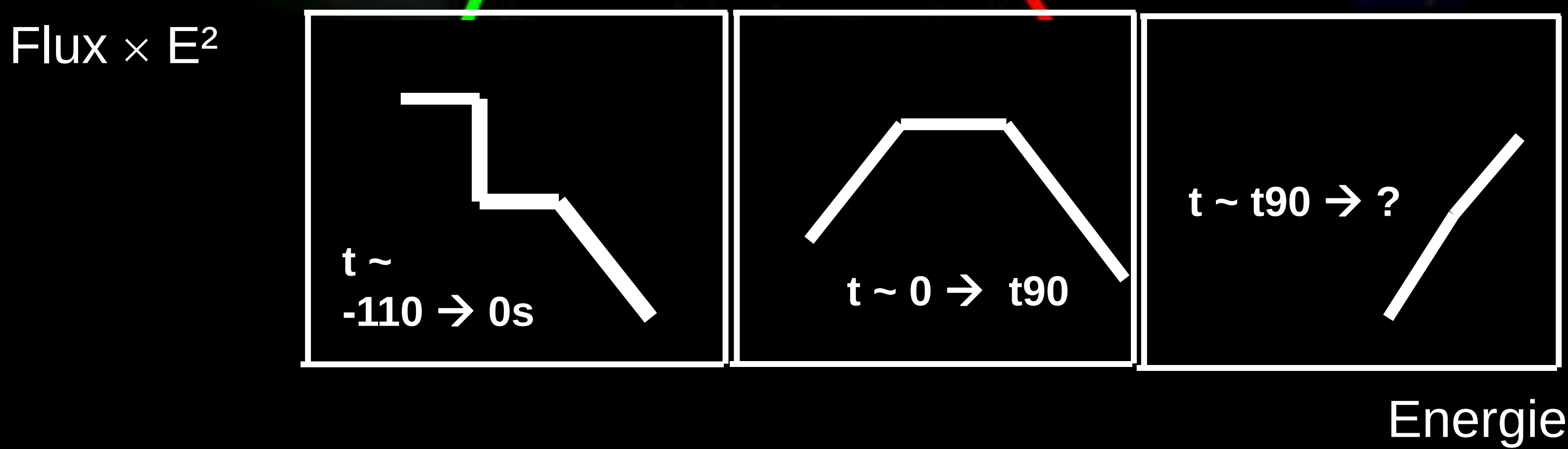


Search for extraterrestrial neutrinos

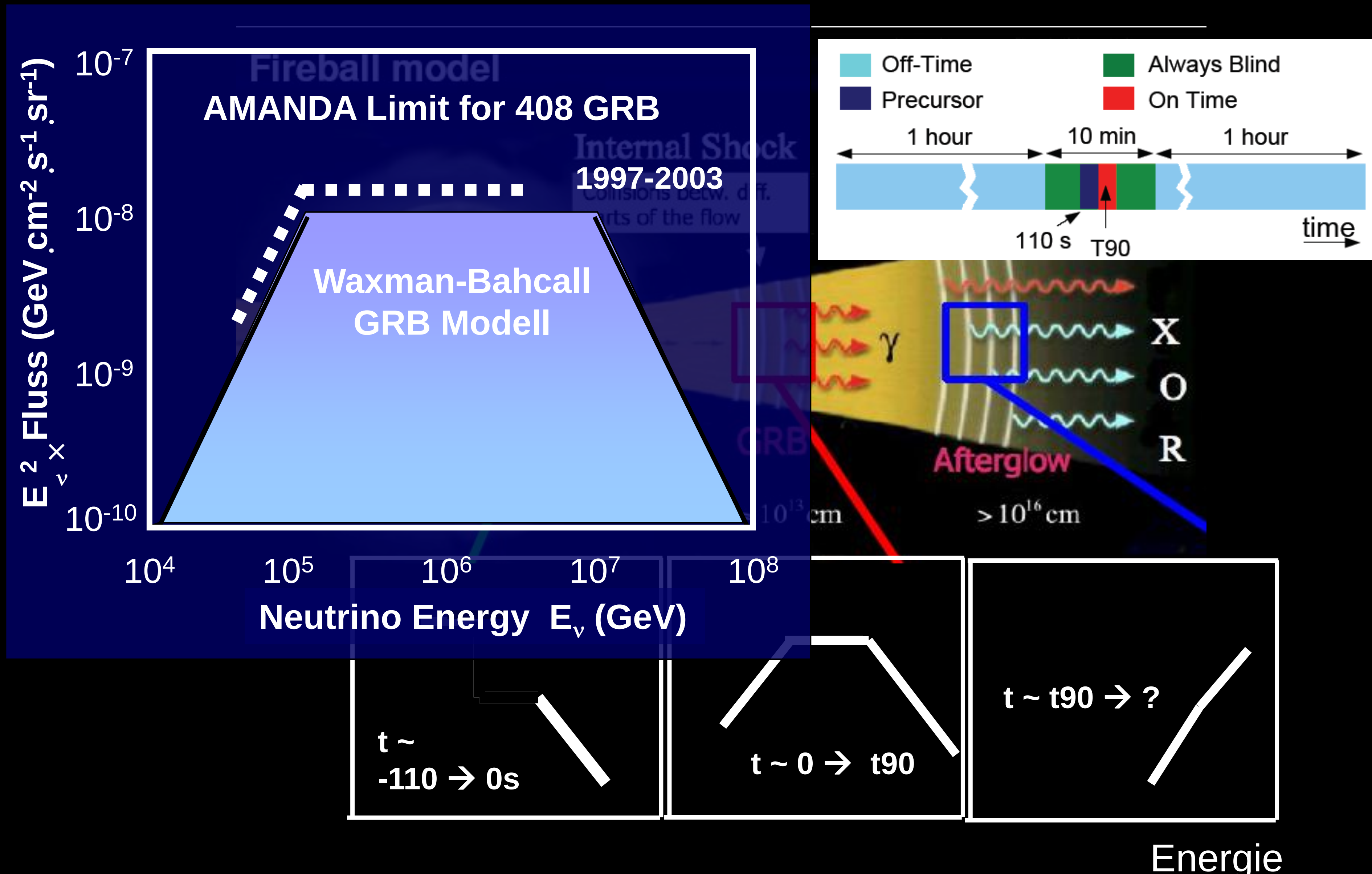
- Gamma Ray Bursts

Neutrinos from GRB

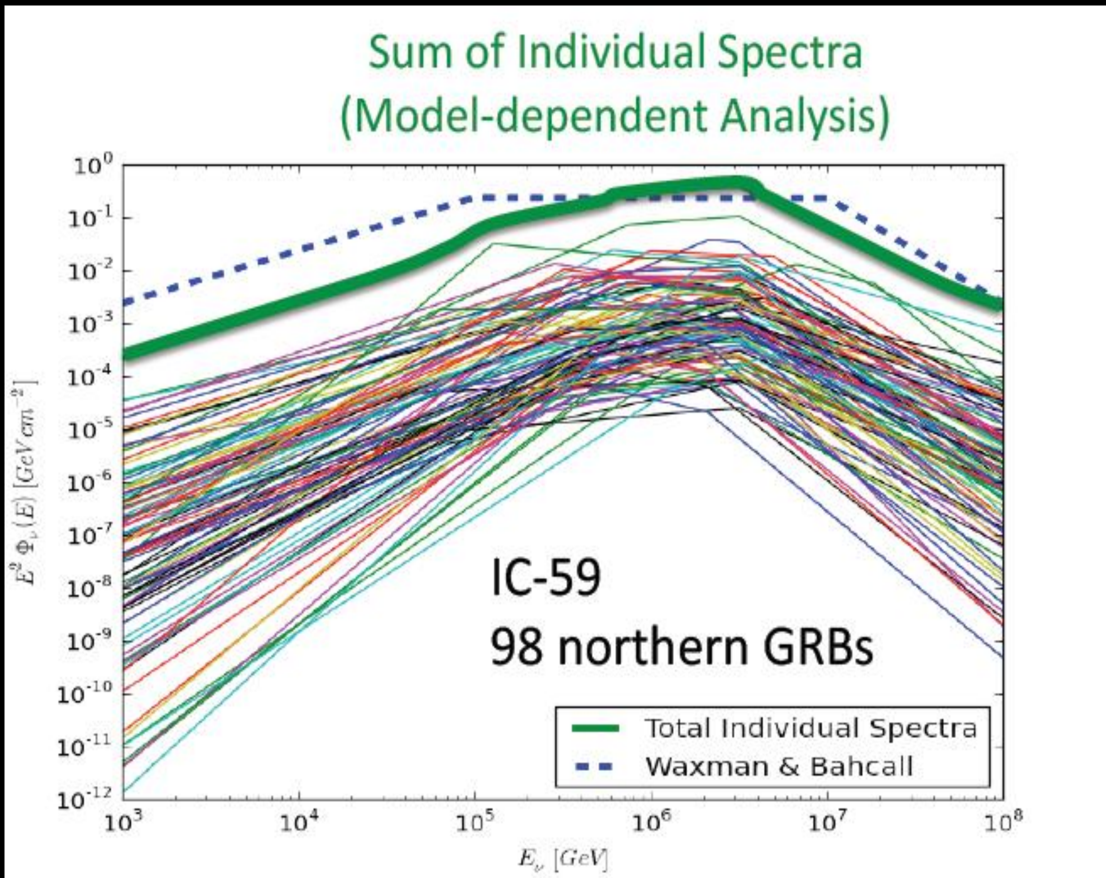


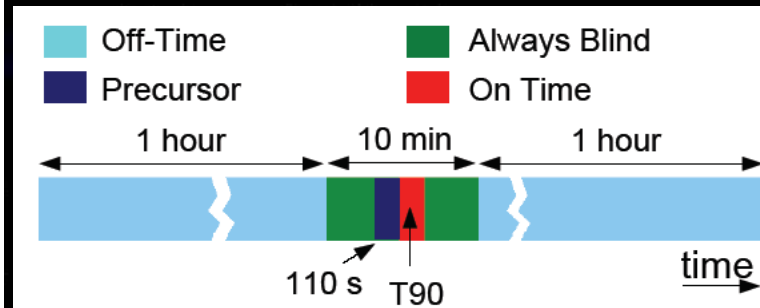


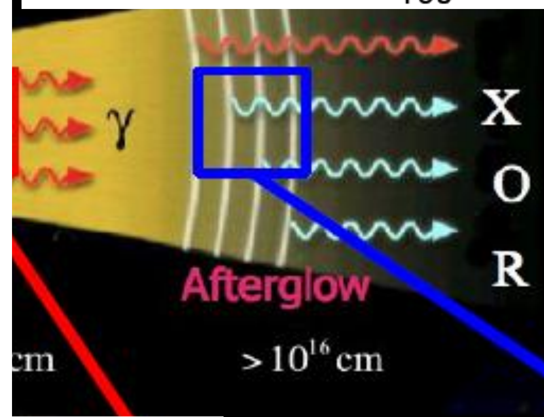
Neutrinos from GRB

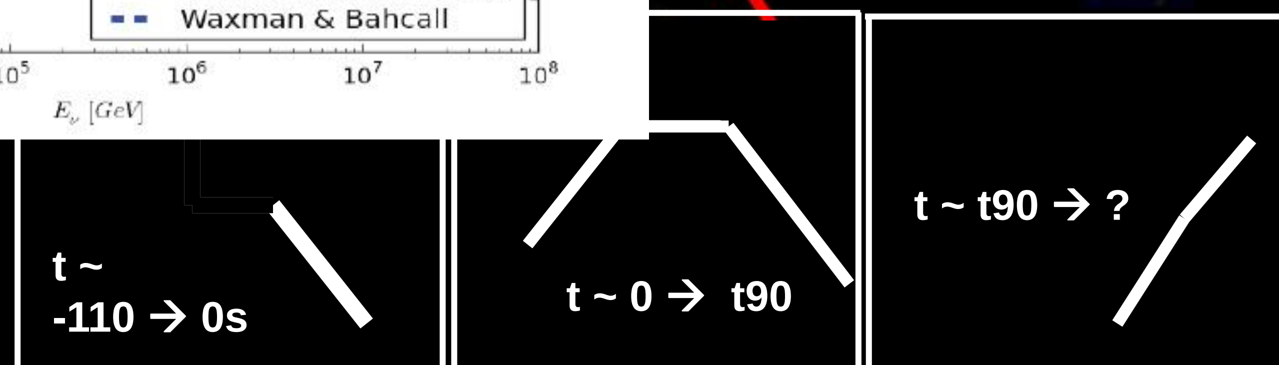


Neutrinos from GRB





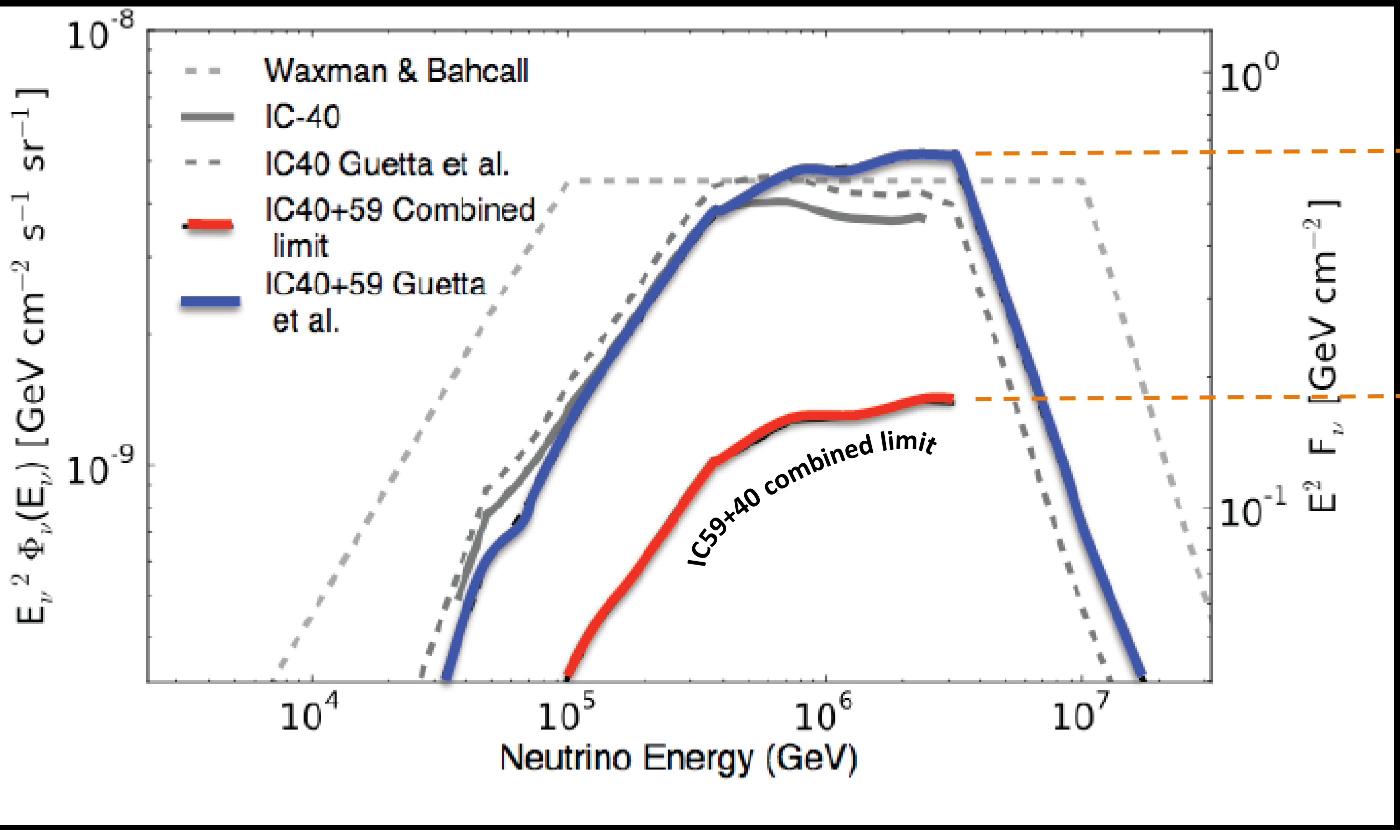




Energie

Neutrinos from GRB

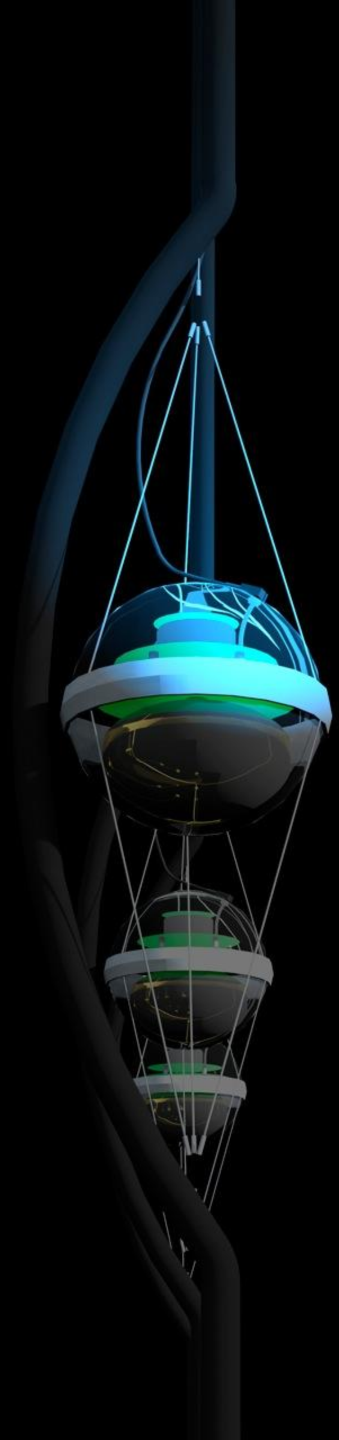
IceCube-40, 59: challenging the GRB fireball model



90% c.l.
= 0.27 model

8.4 events expected
0 events observed

Nature **Vol. 484**, 351 (2012)

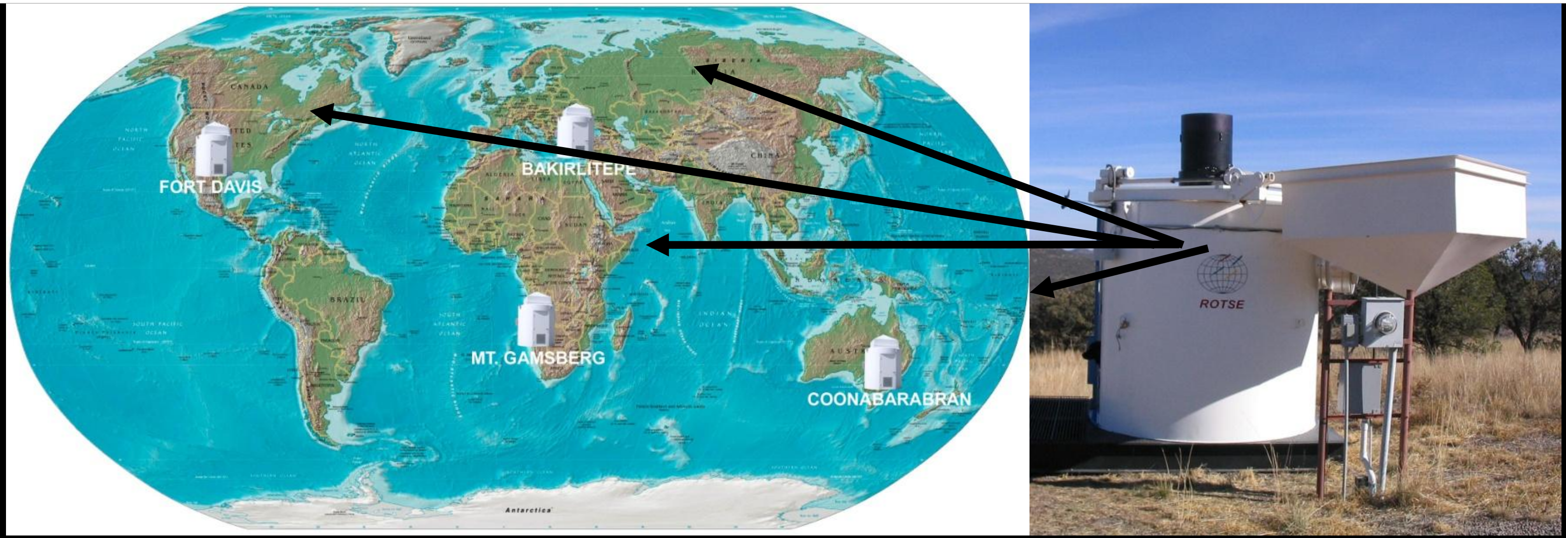


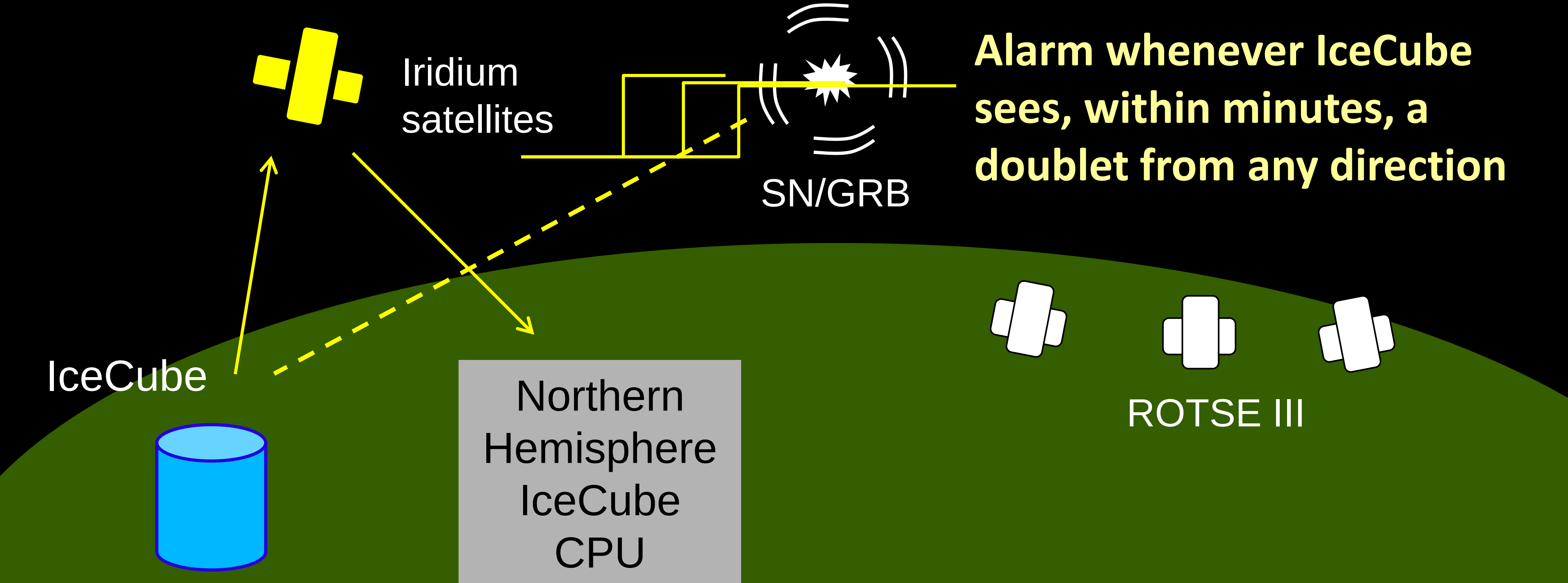
Search for extraterrestrial neutrinos

- Multi-Messenger Programs

Optical Follow-Up with ROTSE

Similar Antares with TAROT





Optical Follow-Up with ROTSE

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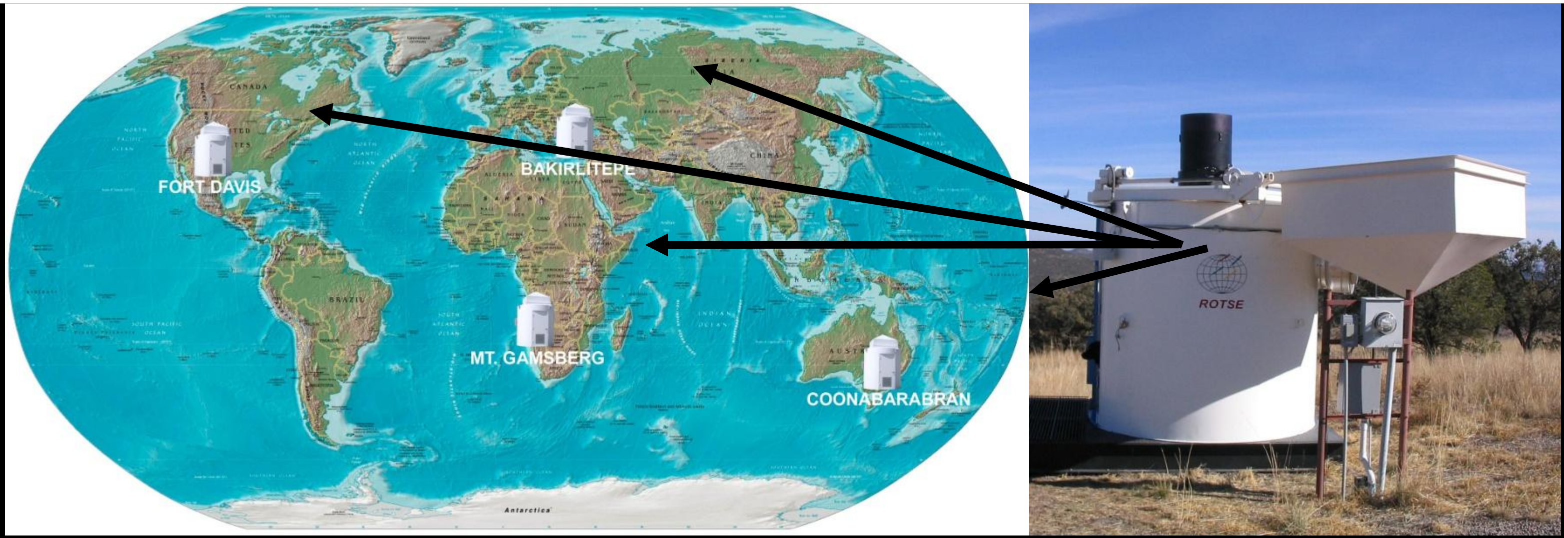
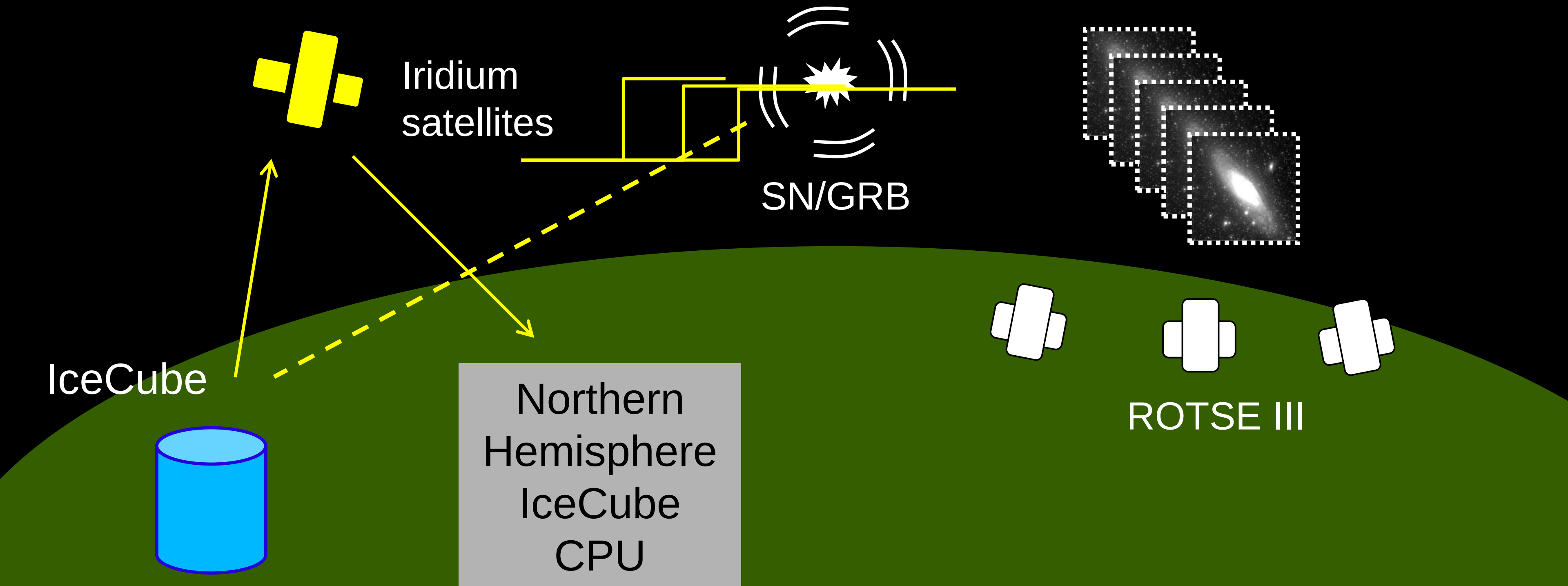
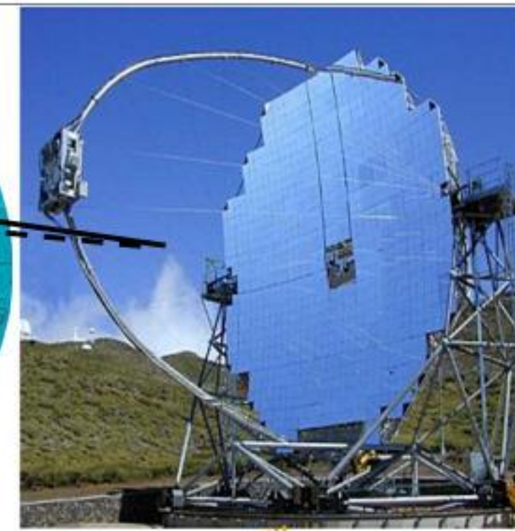
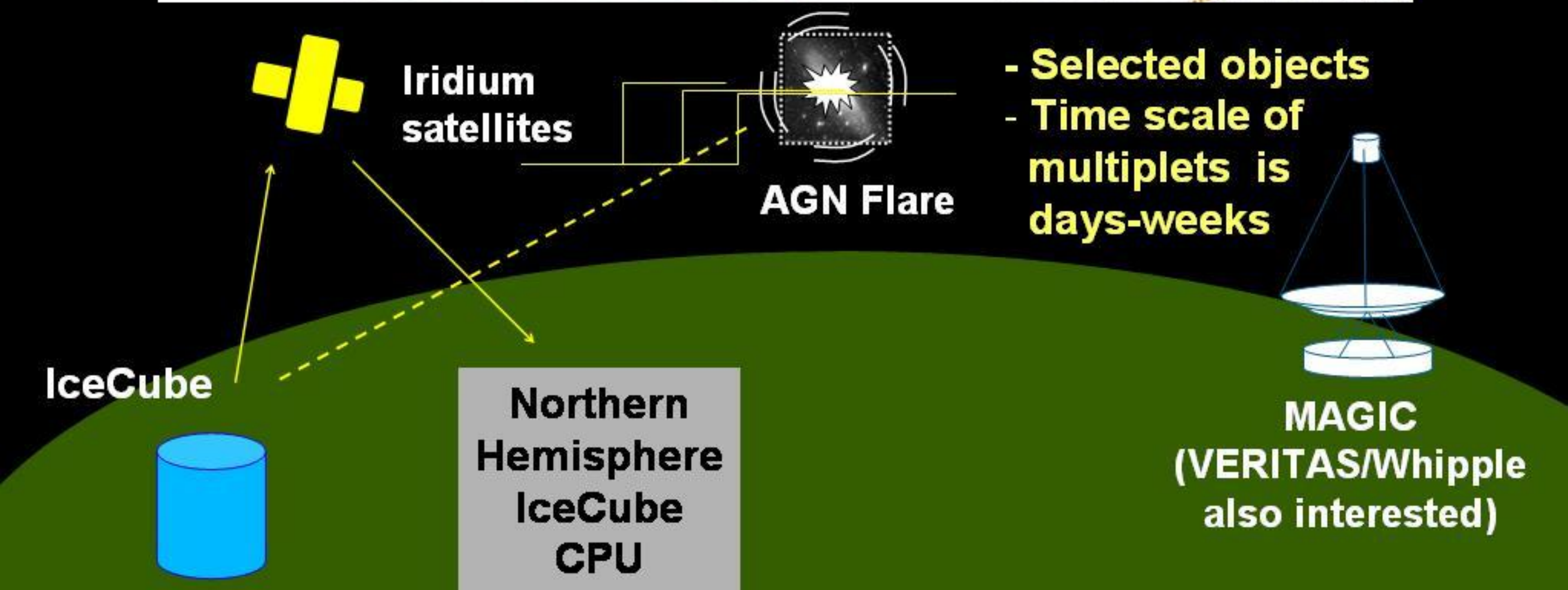
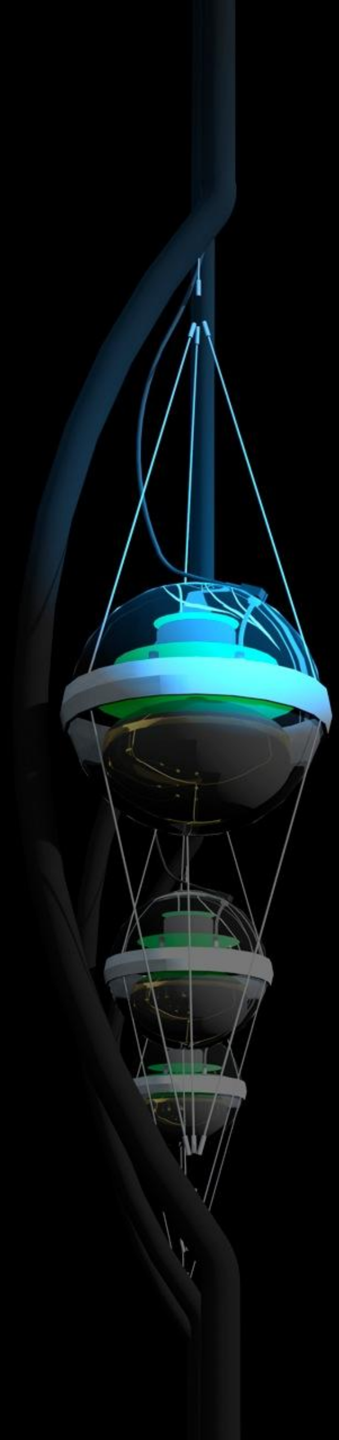




Neutrino Target of Opportunity with MAGIC



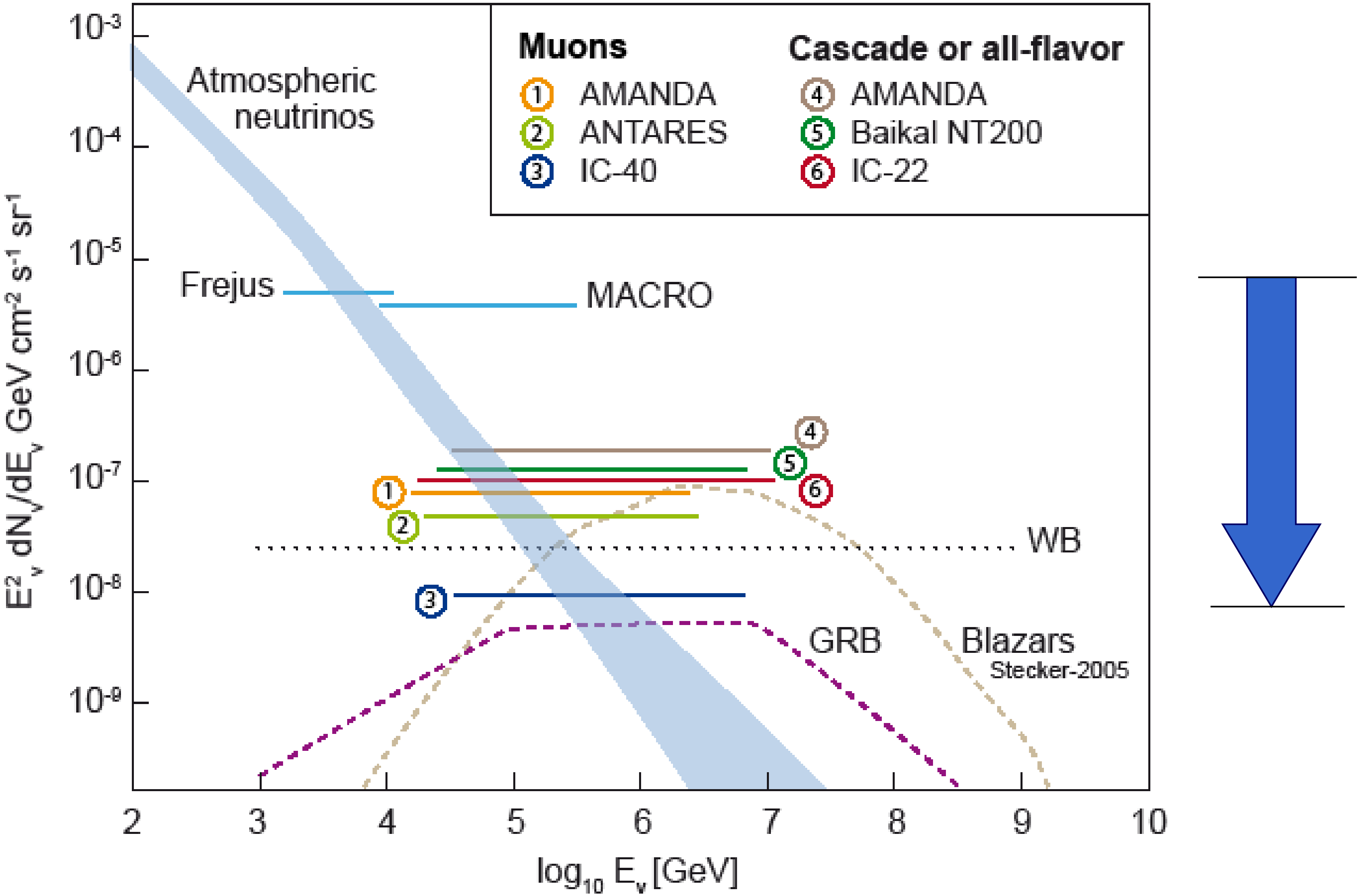




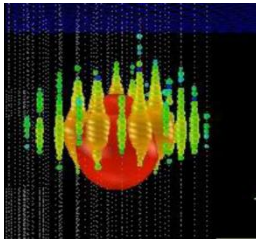
Search for
extraterrestrial neutrinos

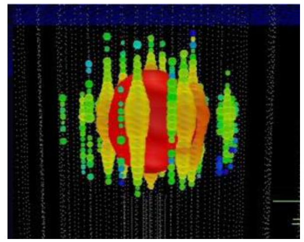
- Diffuse Fluxes

Diffuse Fluxes: a factor 1000 w.r.t. underground detectors

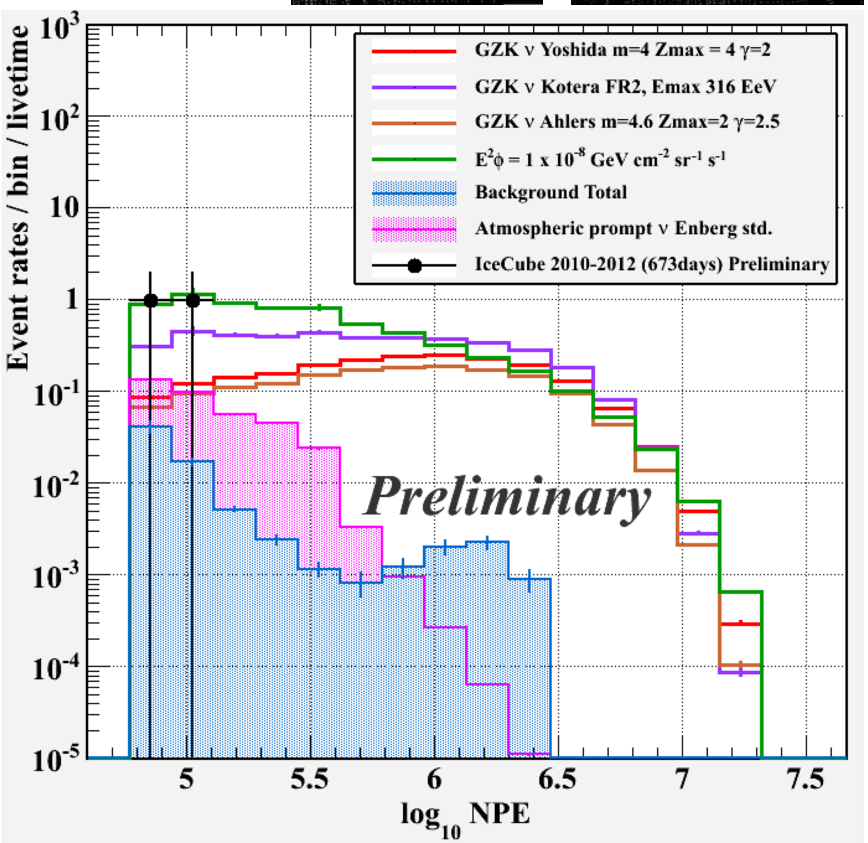


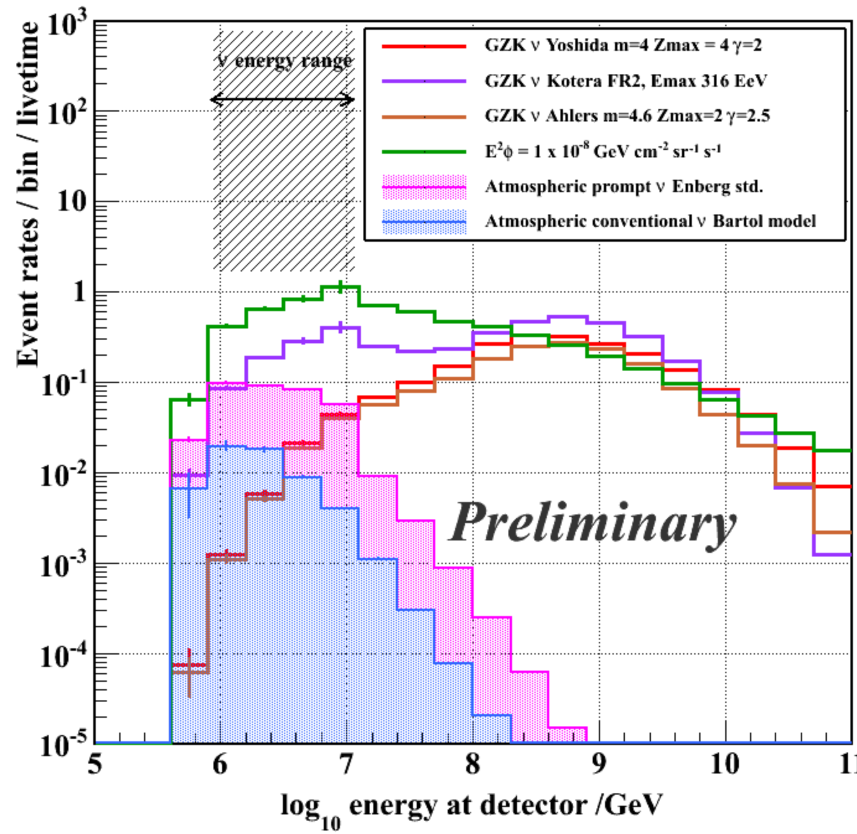
Search for extremely high energy events



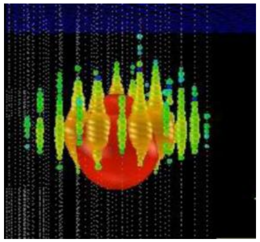


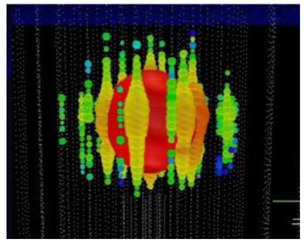
IceCube May 31, 2010 - May 14, 2012





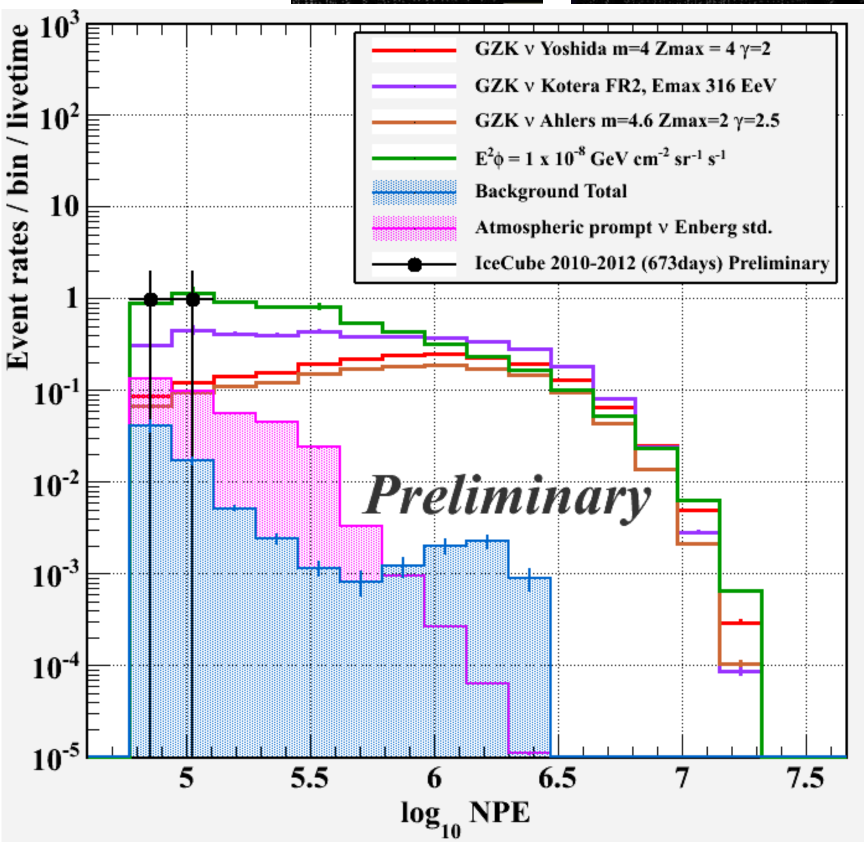
Search for extremely high energy events

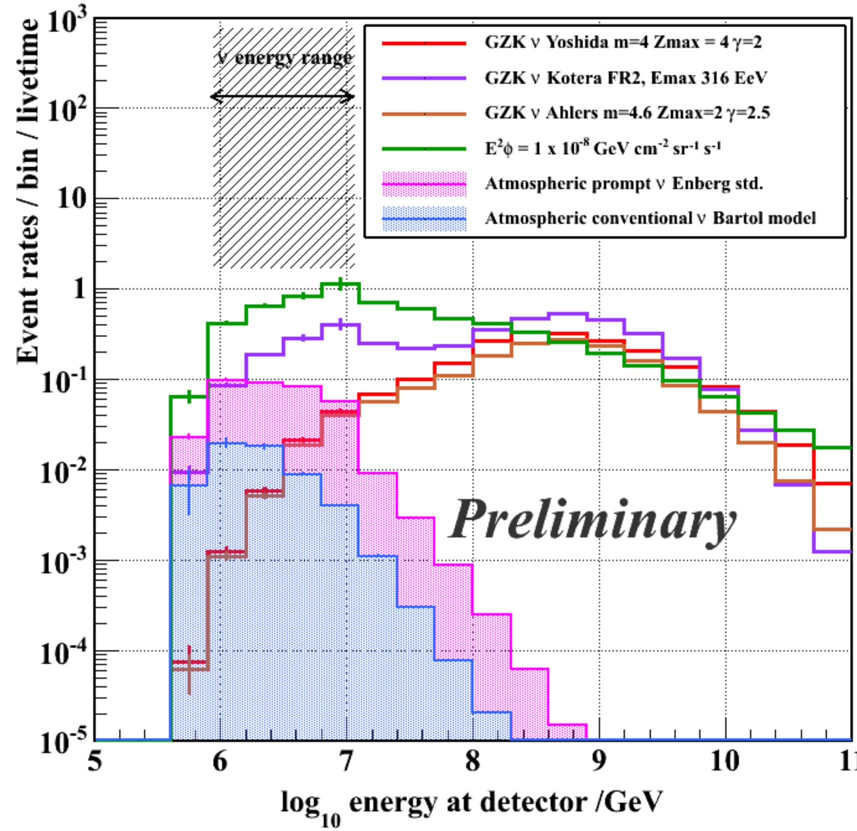




IceCube May 31, 2010 - May 14, 2012

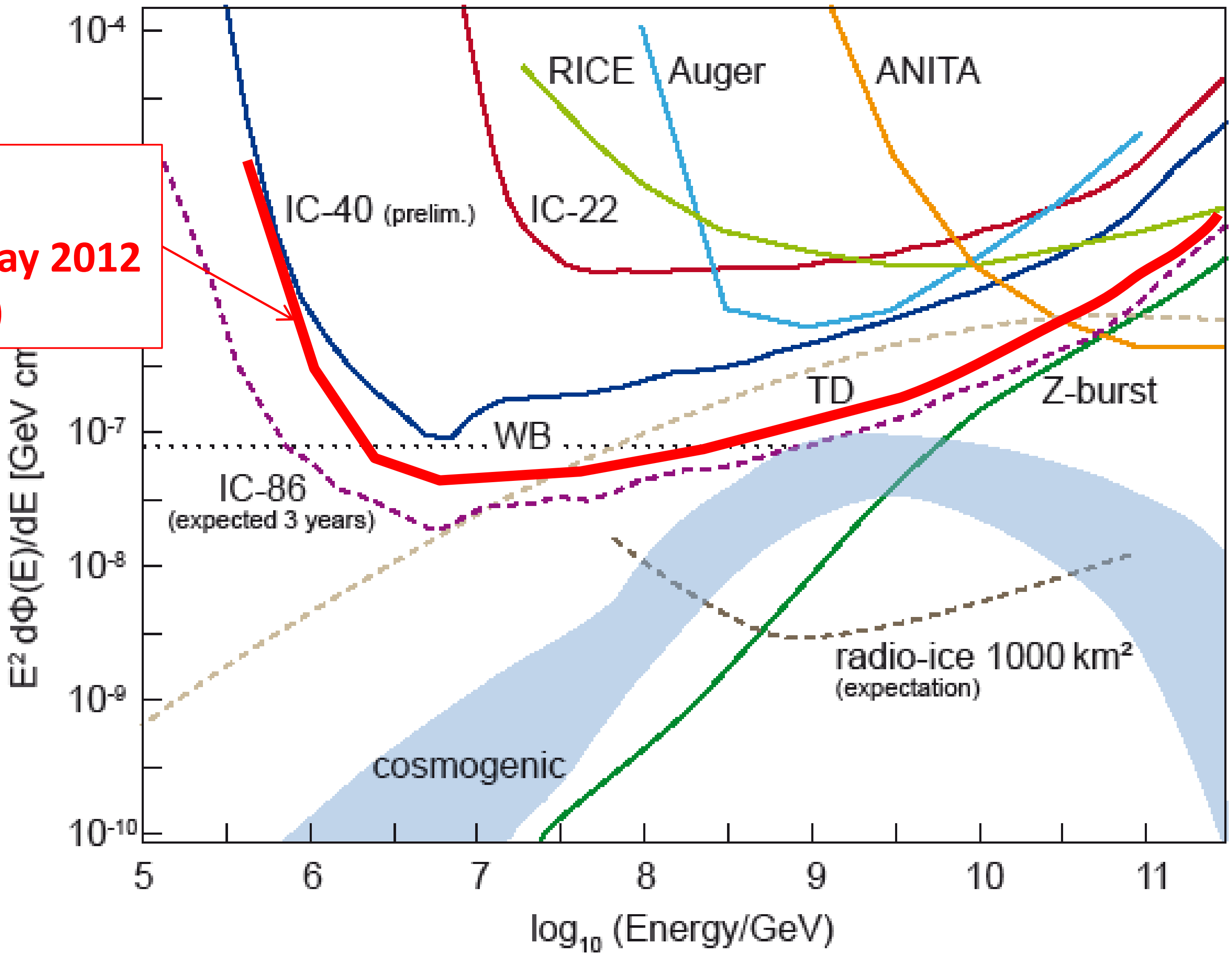
Meanwhile the estimate is 1-2 PeV
(not 6.3 PeV which would be the Glashow resonance!)

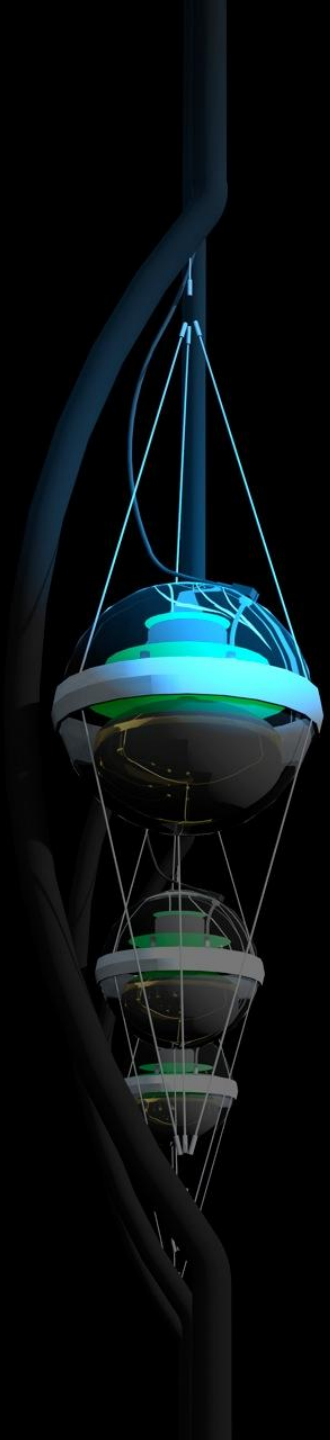




Peering into the EeV region

IceCube
May 2010-May 2012
(preliminary)





Neutrino Telescopes as Supernova Monitors

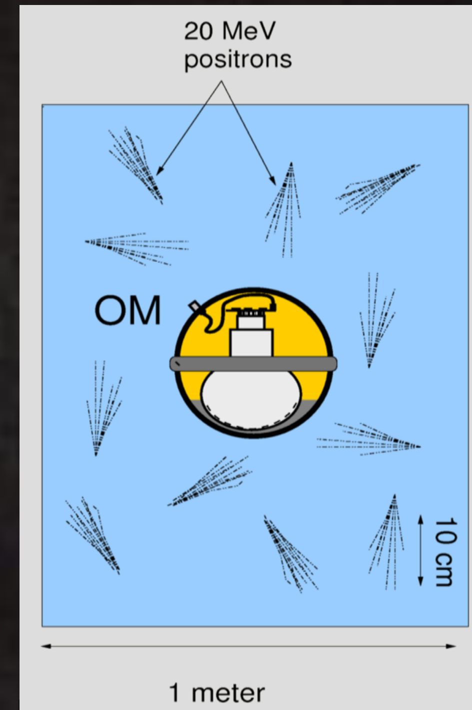
Supernova in IceCube

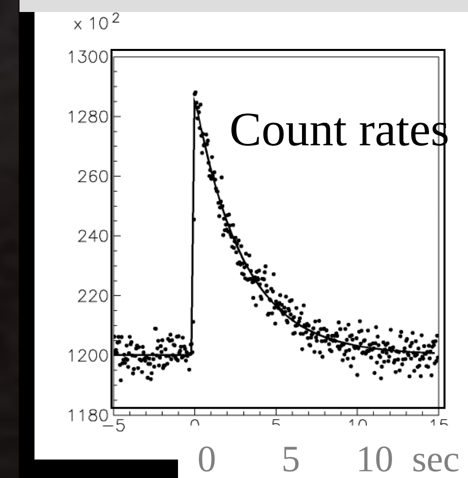
Detection via enhanced PMT noise rates

Dark noise (1PE) in IceCube photomultipliers only ~ 320 Hz !

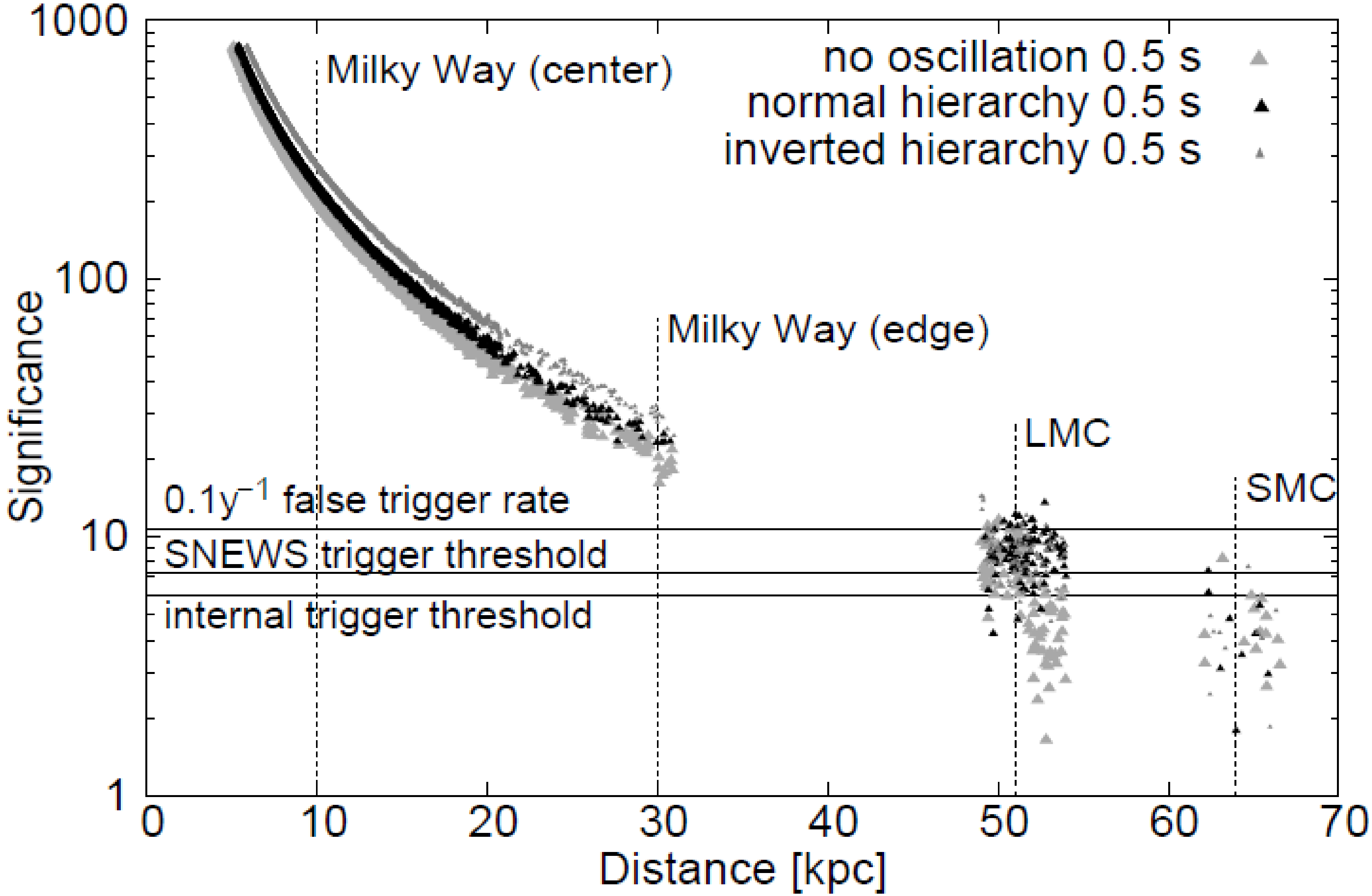
Magellanic

Clouds

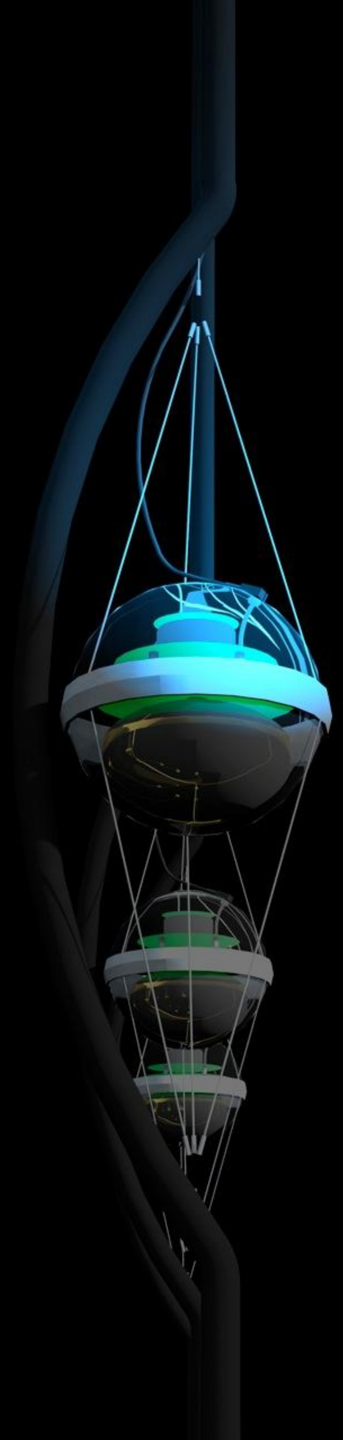




Signal for SN in GC, 10^6 counts

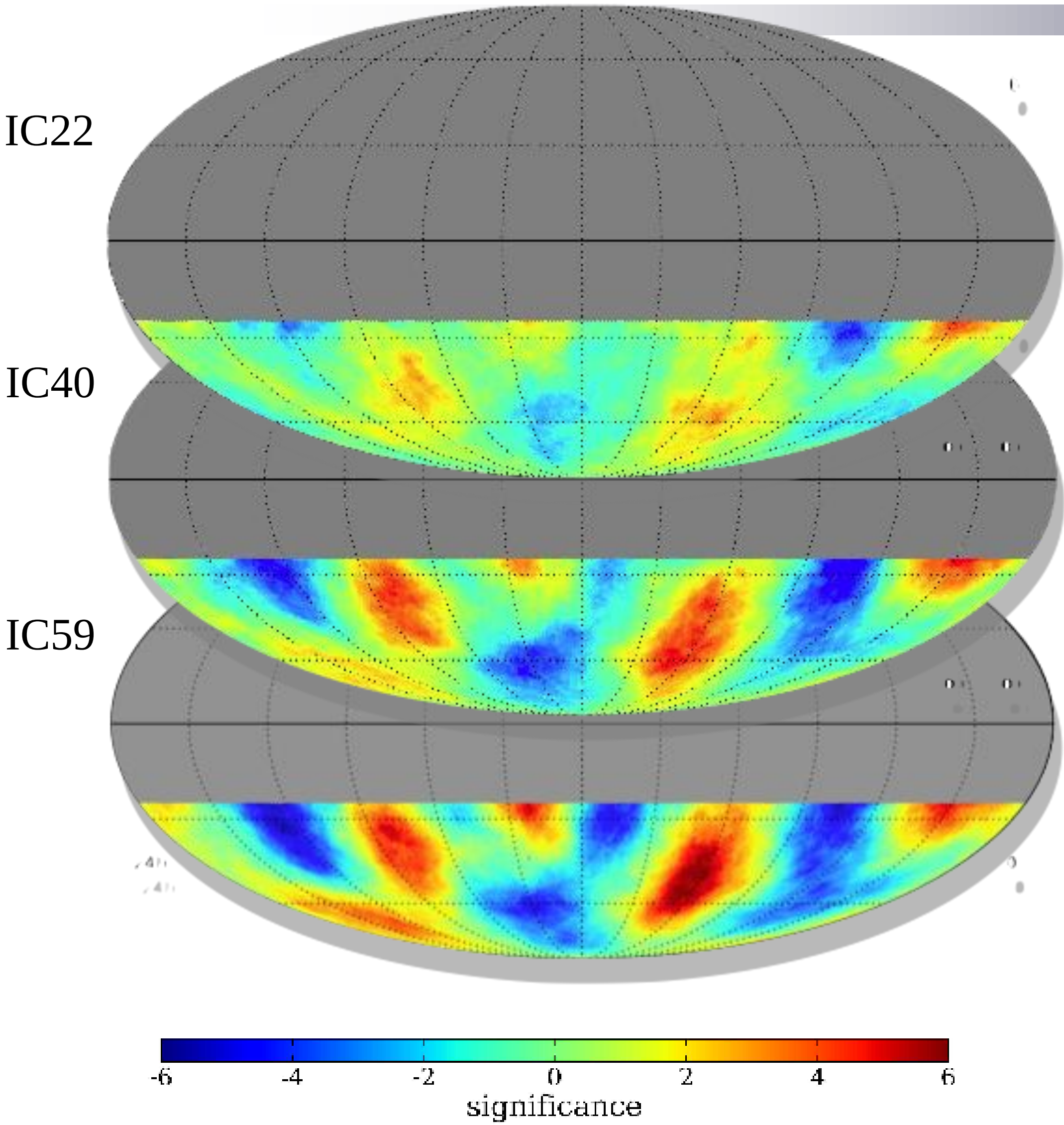


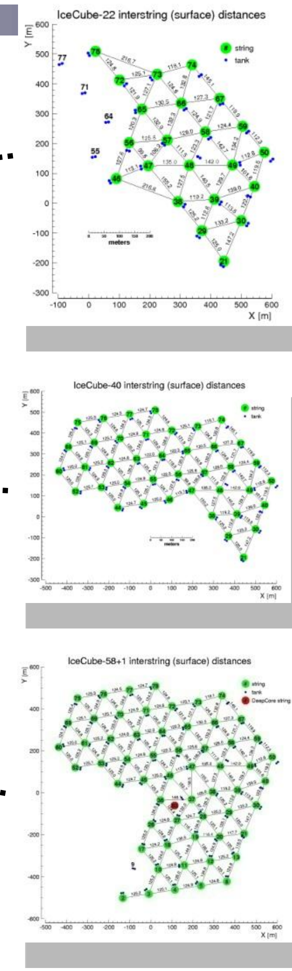
1000
100
10
1
Significance
0
10
20
30
40
50
60
70
Distance [kpc]
Milky Way (center)
Milky Way (edge)
LMC
SMC
no oscillation 0.5 s
normal hierarchy 0.5 s
inverted hierarchy 0.5 s
0.1y^{-1} false trigger rate
SNEWS trigger threshold
internal trigger threshold



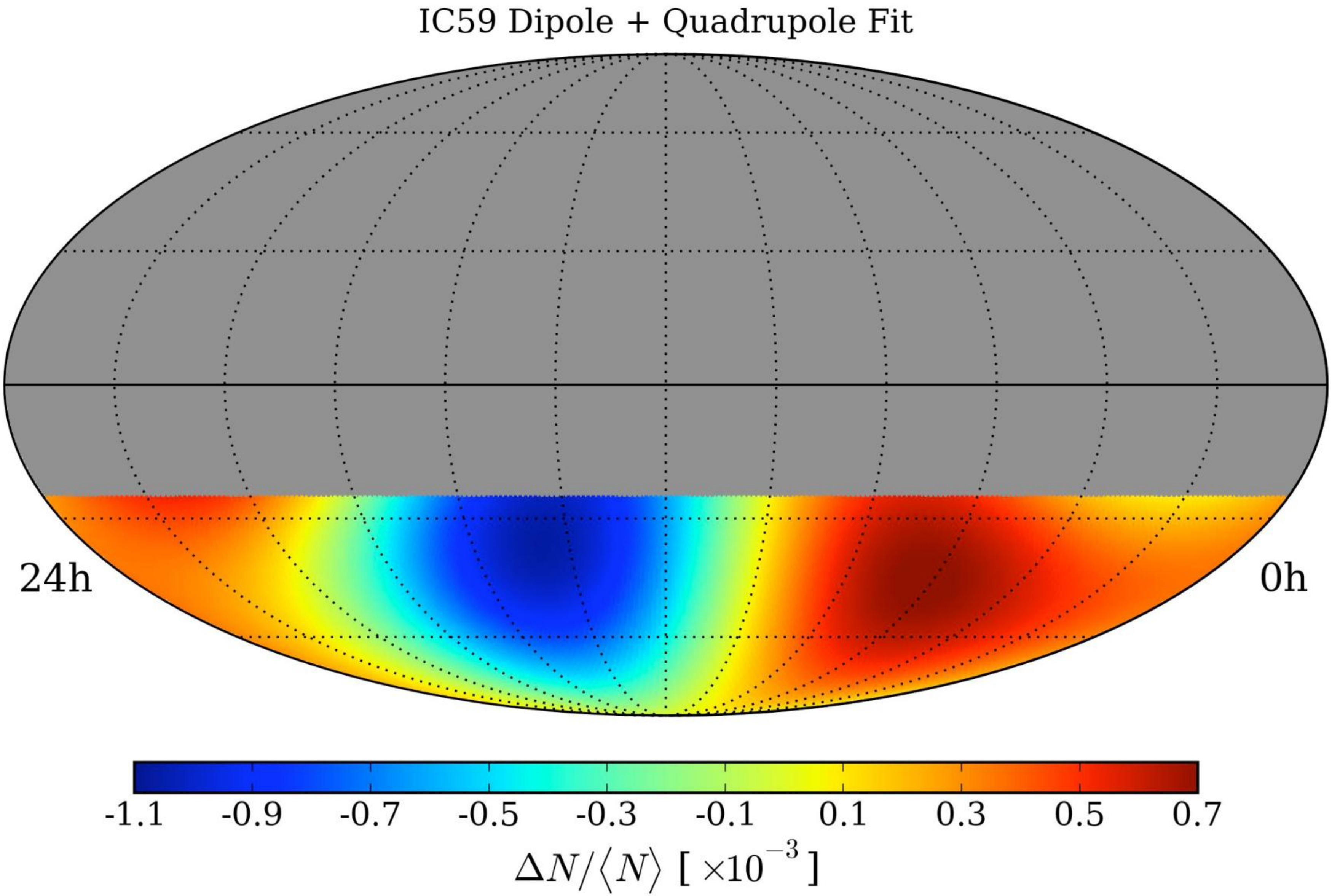
Muon Astronomy with Neutrino Telescopes?

Muon Astronomy

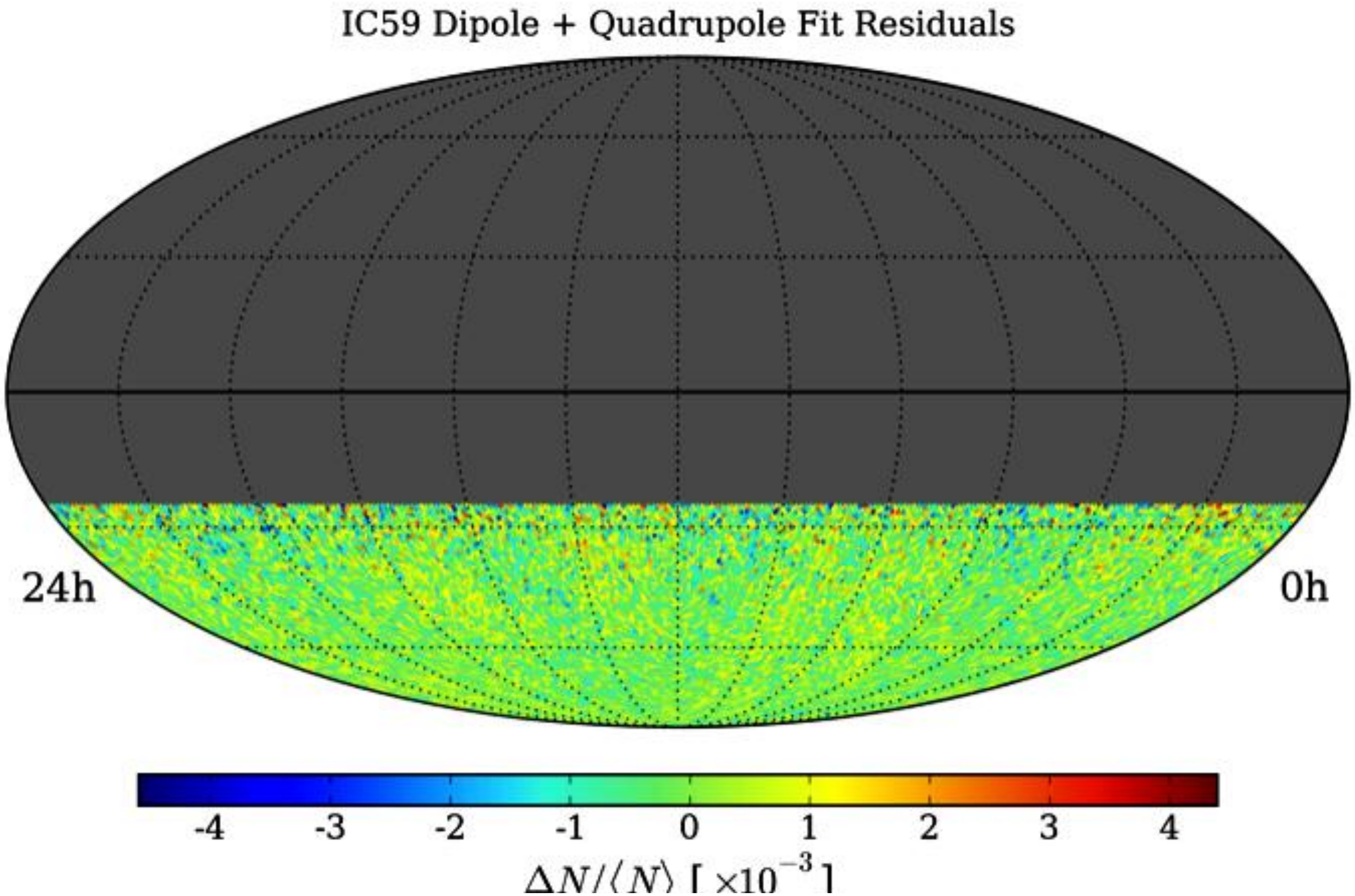




Different geometries, same structure

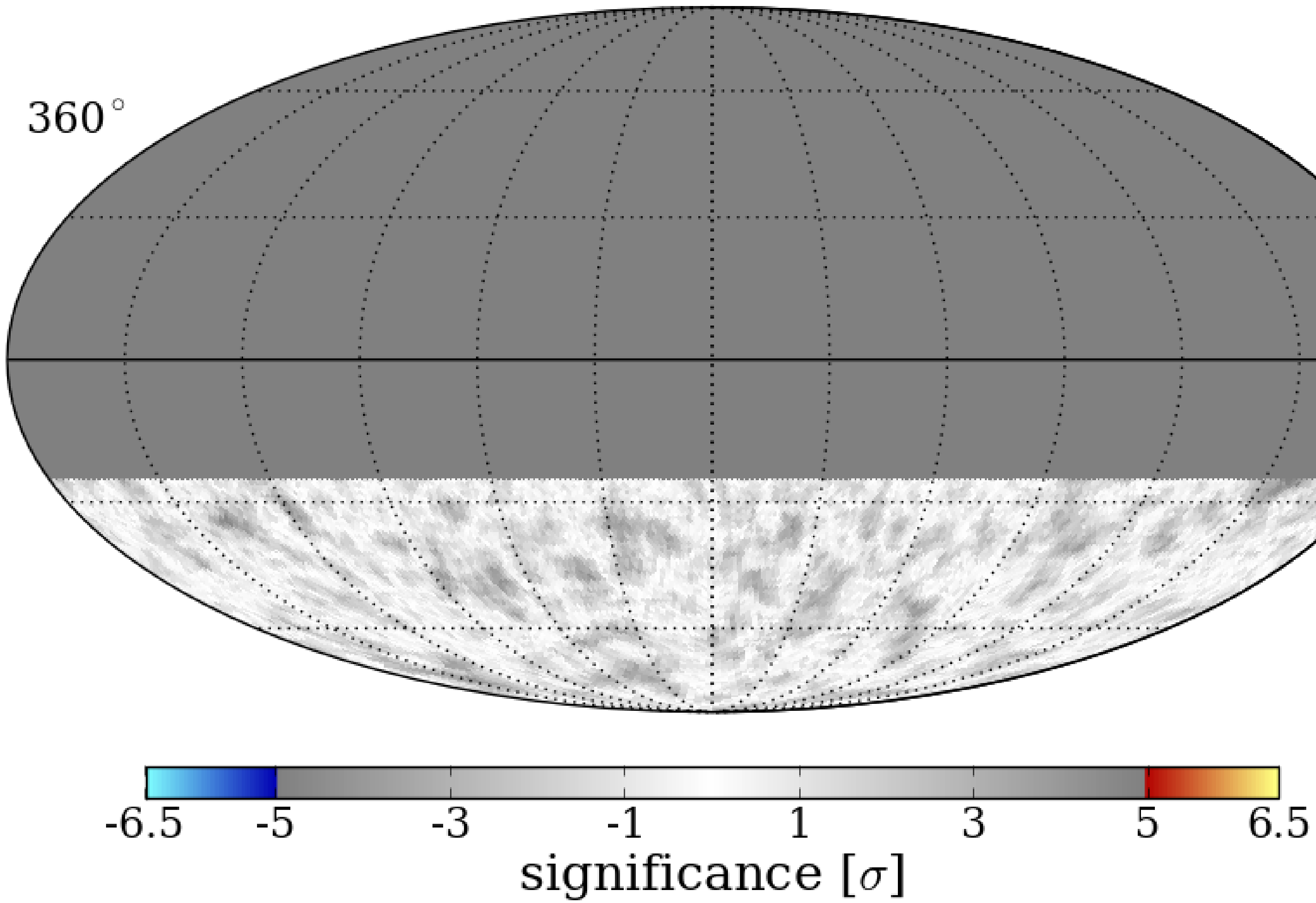

IC59 Dipole + Quadrupole Fit
24h
0h
-1.1
-0.9
-0.7
-0.5
-0.3
-0.1
0.1
0.3
0.5
0.7
$\Delta N/\langle N \rangle$ [$\times 10^{-3}$]

Fit residuals map



> Anisotropy not immediately visible (smoothing needed)

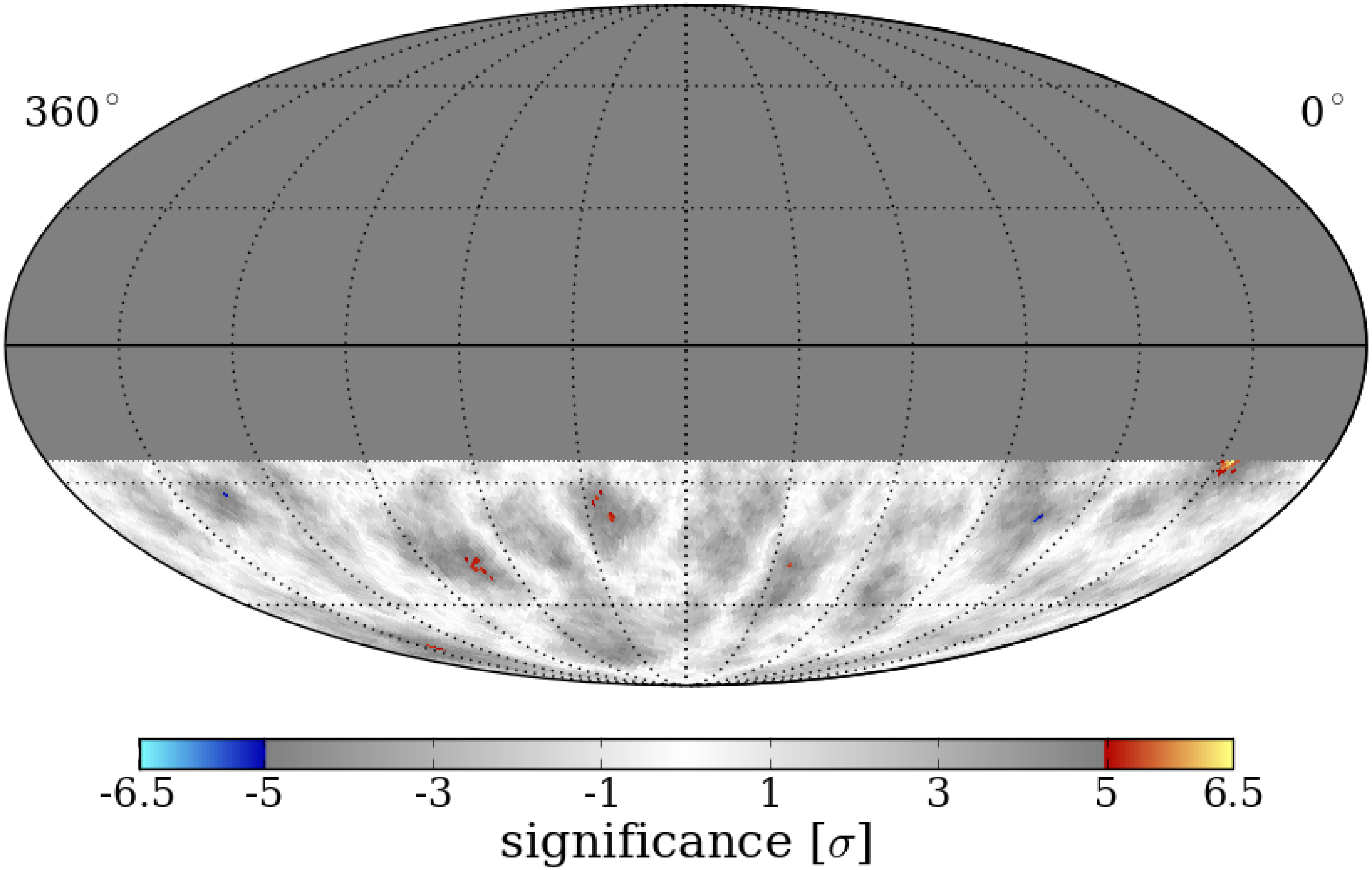
Map smoothing scan



Scan from 1 - 30° in smoothing
Different regions have different optimal smoothings
Significances are pre-trial

3° smoothing

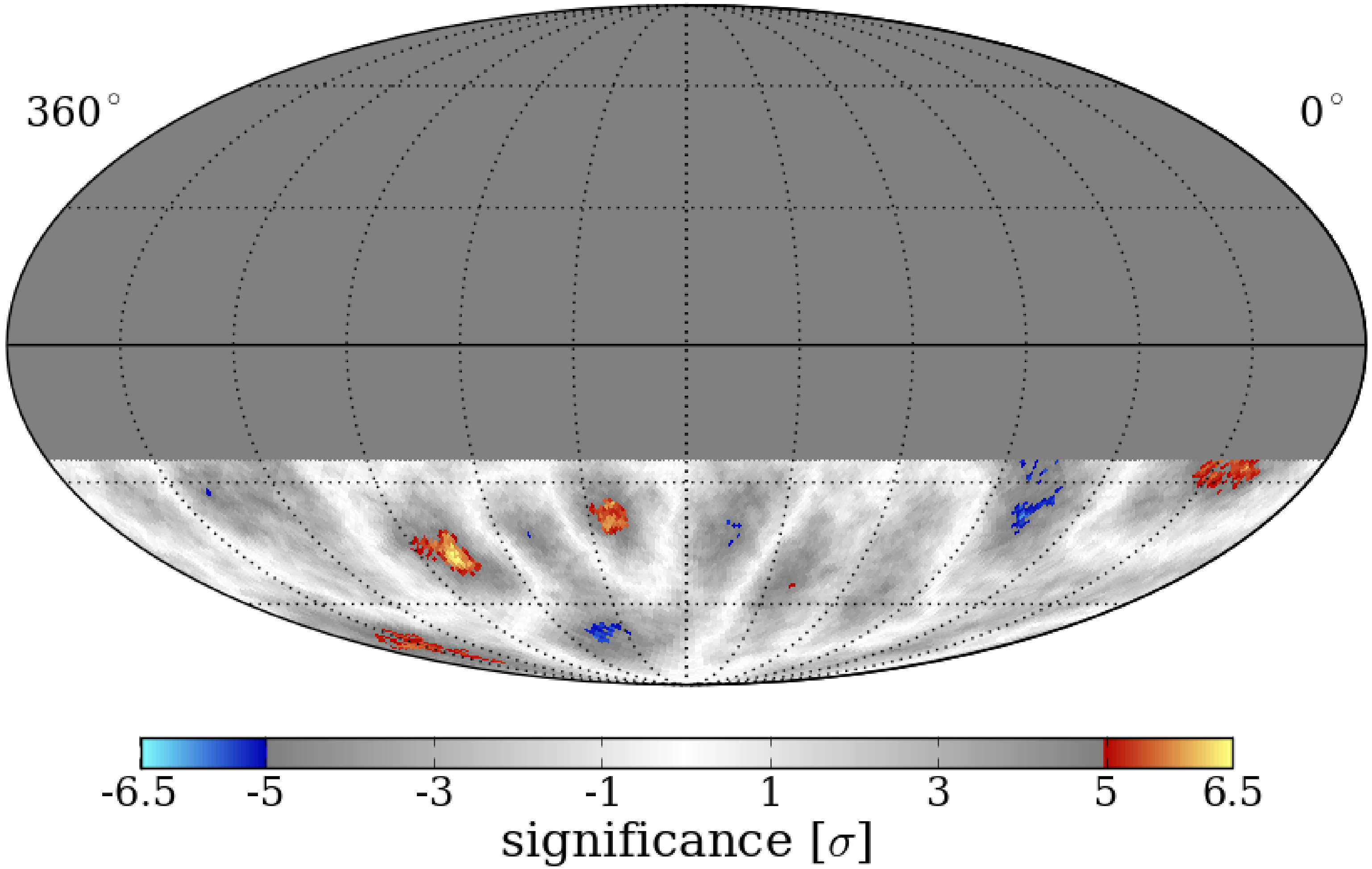
Map smoothing scan



Scan from 1 - 30° in smoothing
Different regions have different optimal smoothings
Significances are pre-trial

6° smoothing

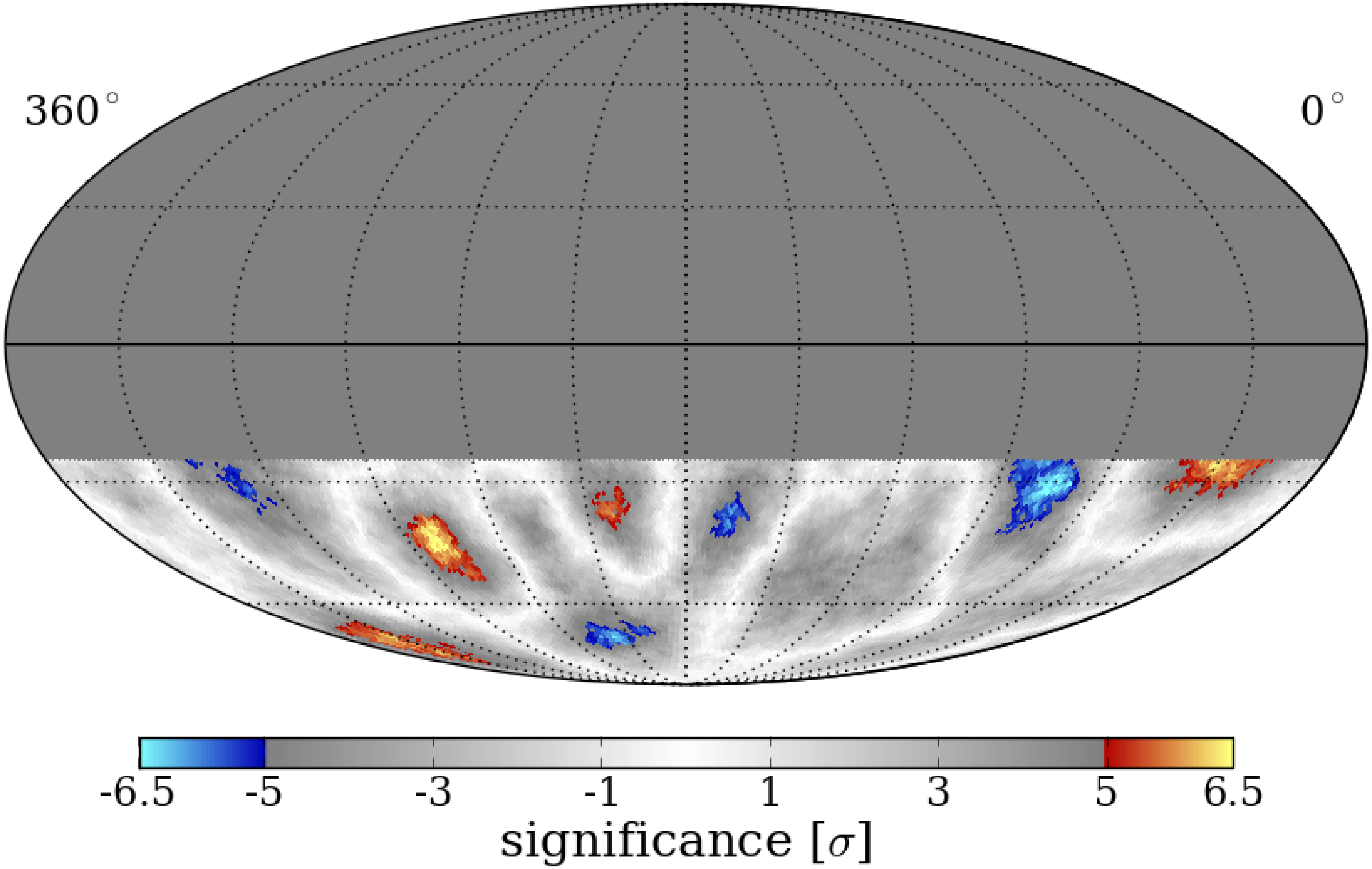
Map smoothing scan



Scan from 1 - 30° in smoothing
Different regions have different optimal smoothings
Significances are pre-trial

9° smoothing

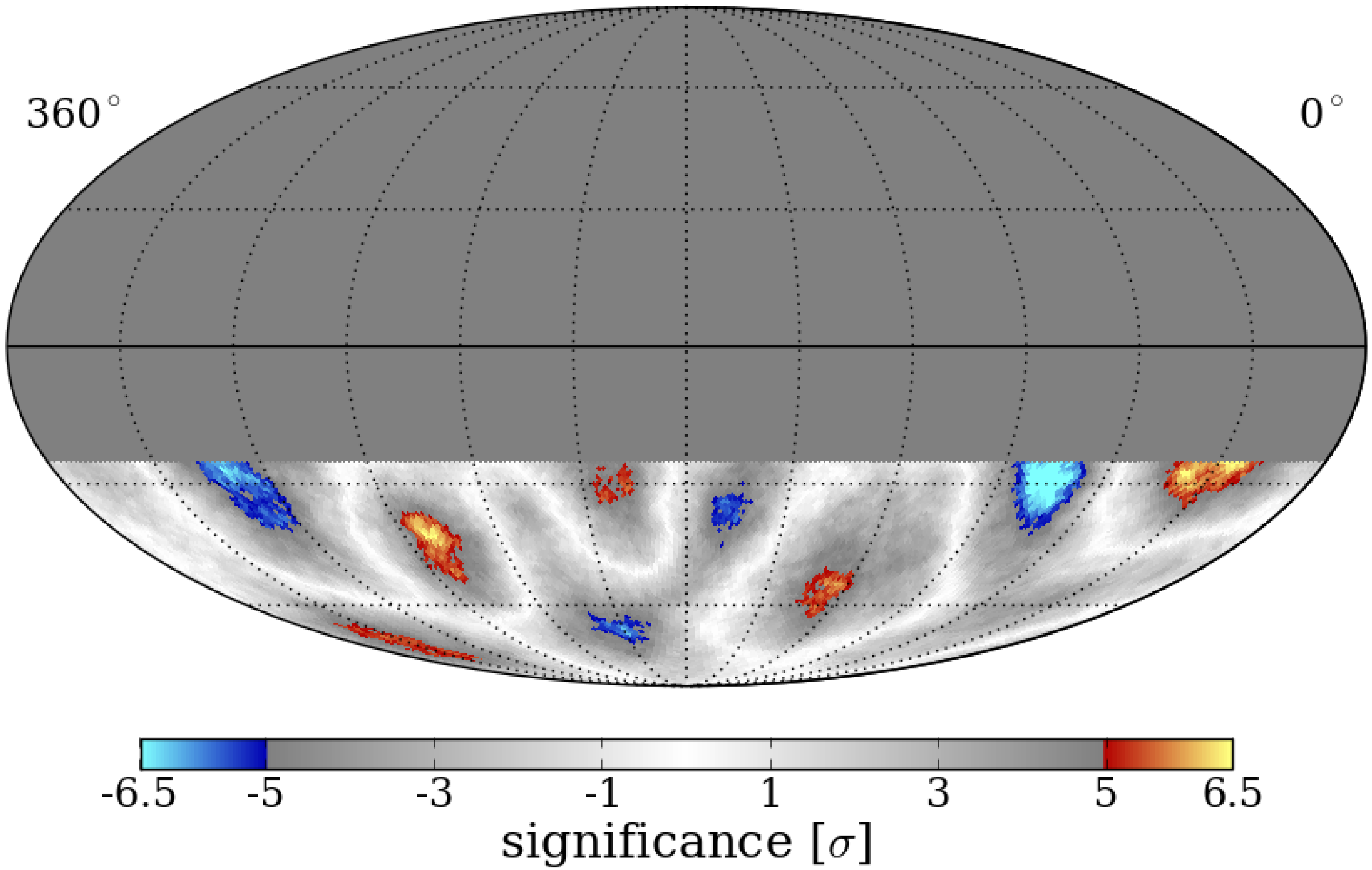
Map smoothing scan



Scan from 1 - 30° in smoothing
Different regions have different optimal smoothings
Significances are pre-trial

12° smoothing

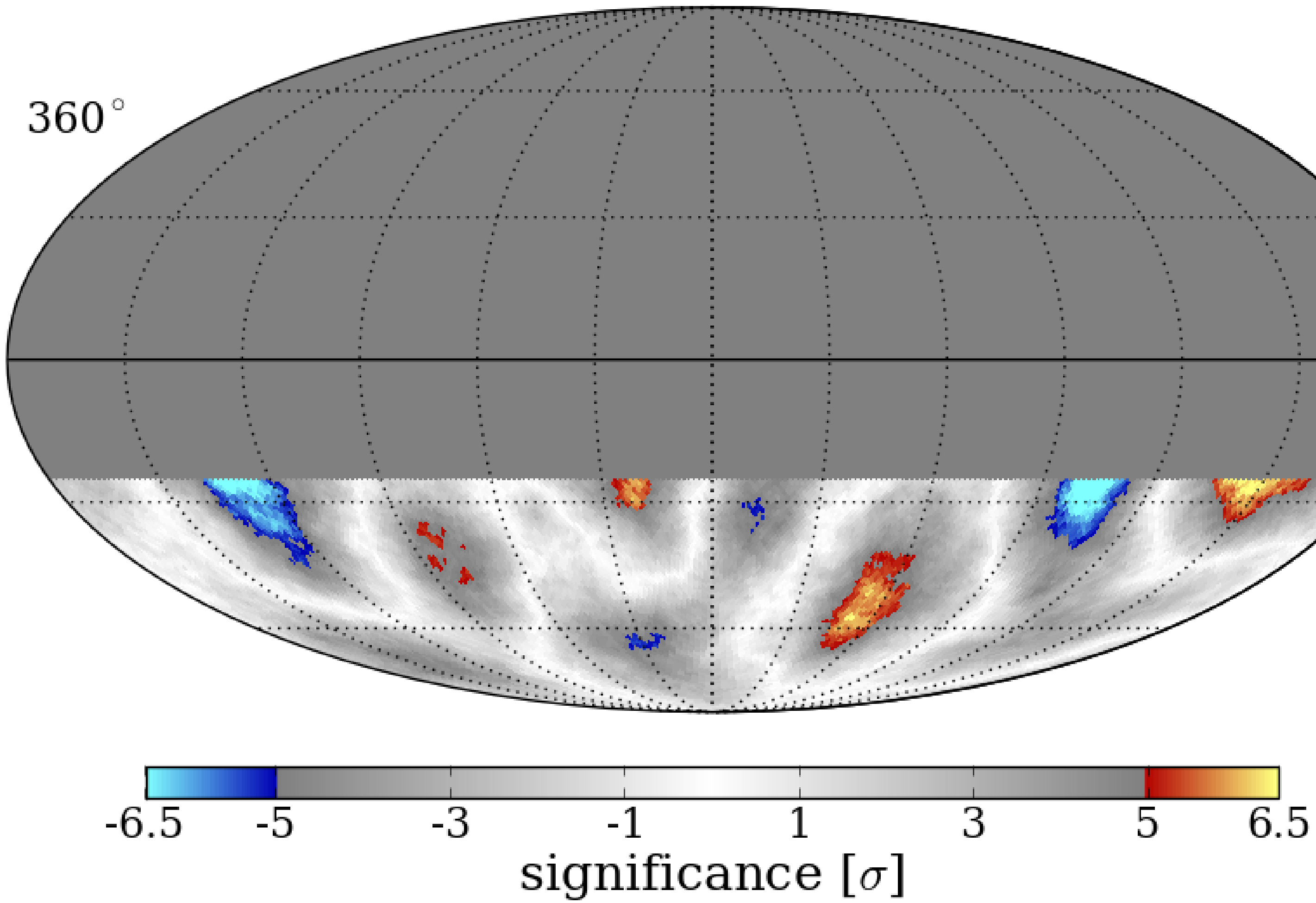
Map smoothing scan



Scan from 1 - 30° in smoothing
Different regions have different optimal smoothings
Significances are pre-trial

15° smoothing

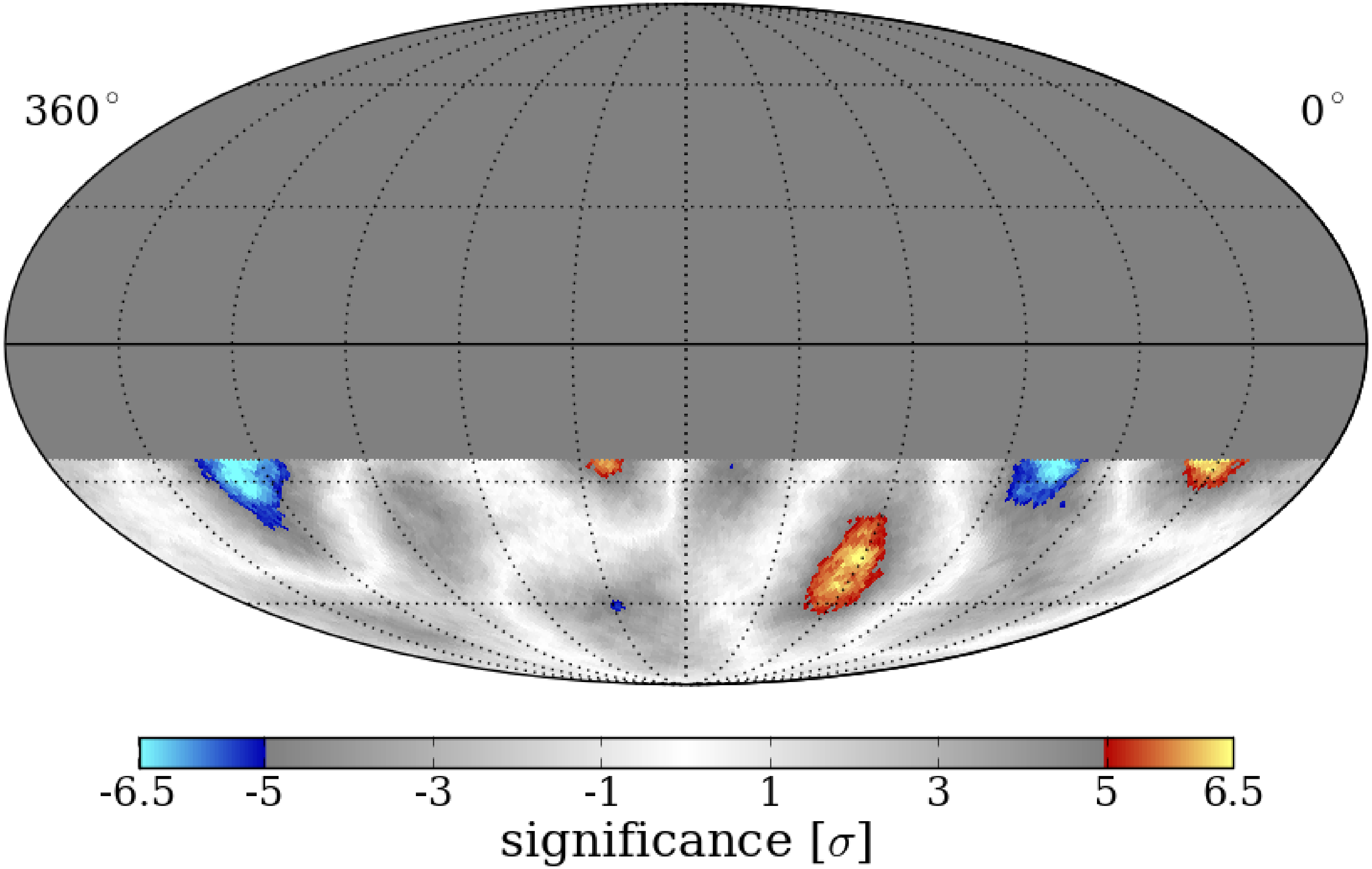
Map smoothing scan



Scan from 1 - 30° in smoothing
Different regions have different optimal smoothings
Significances are pre-trial

18° smoothing

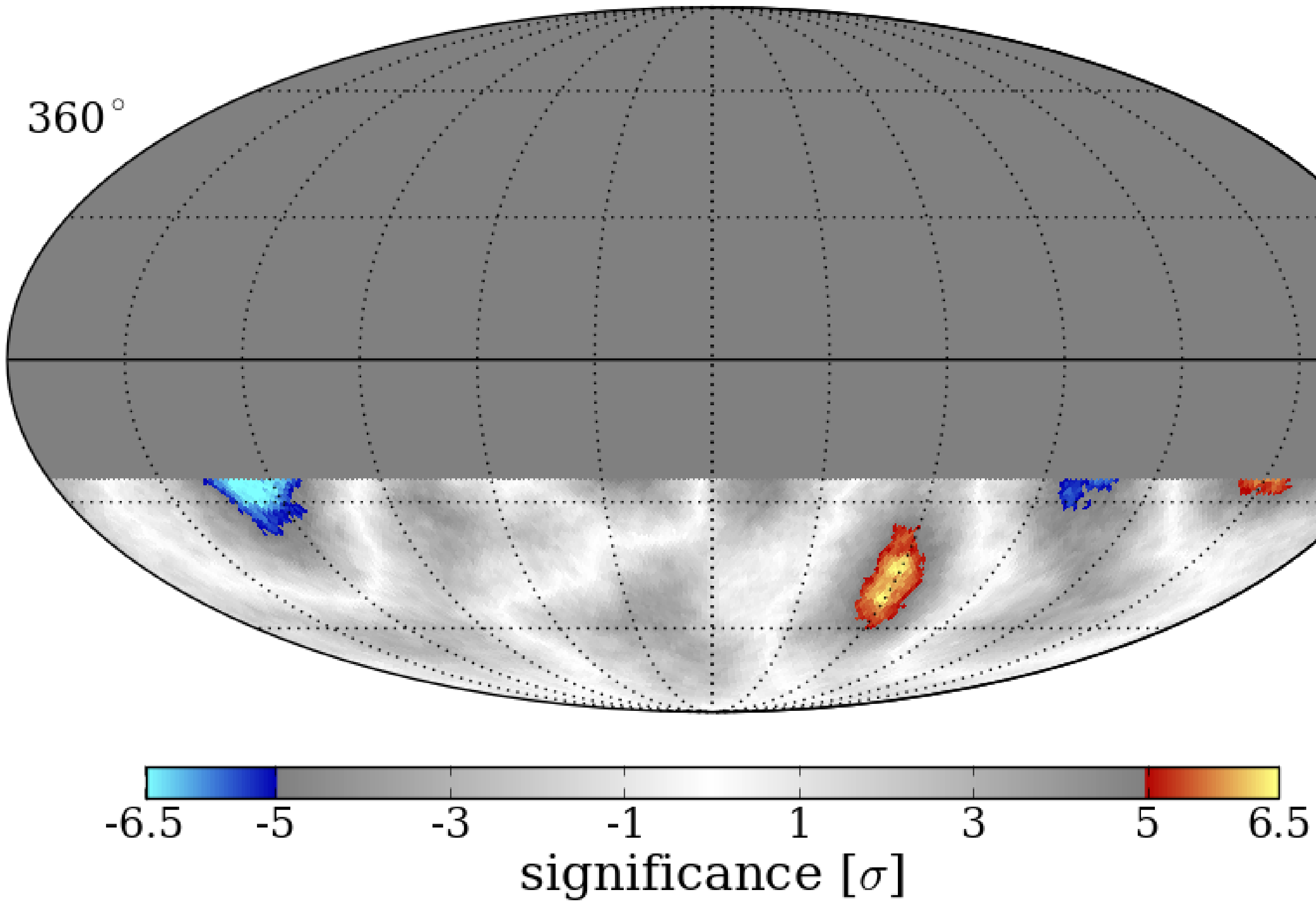
Map smoothing scan



Scan from 1 - 30° in smoothing
Different regions have different optimal smoothings
Significances are pre-trial

21° smoothing

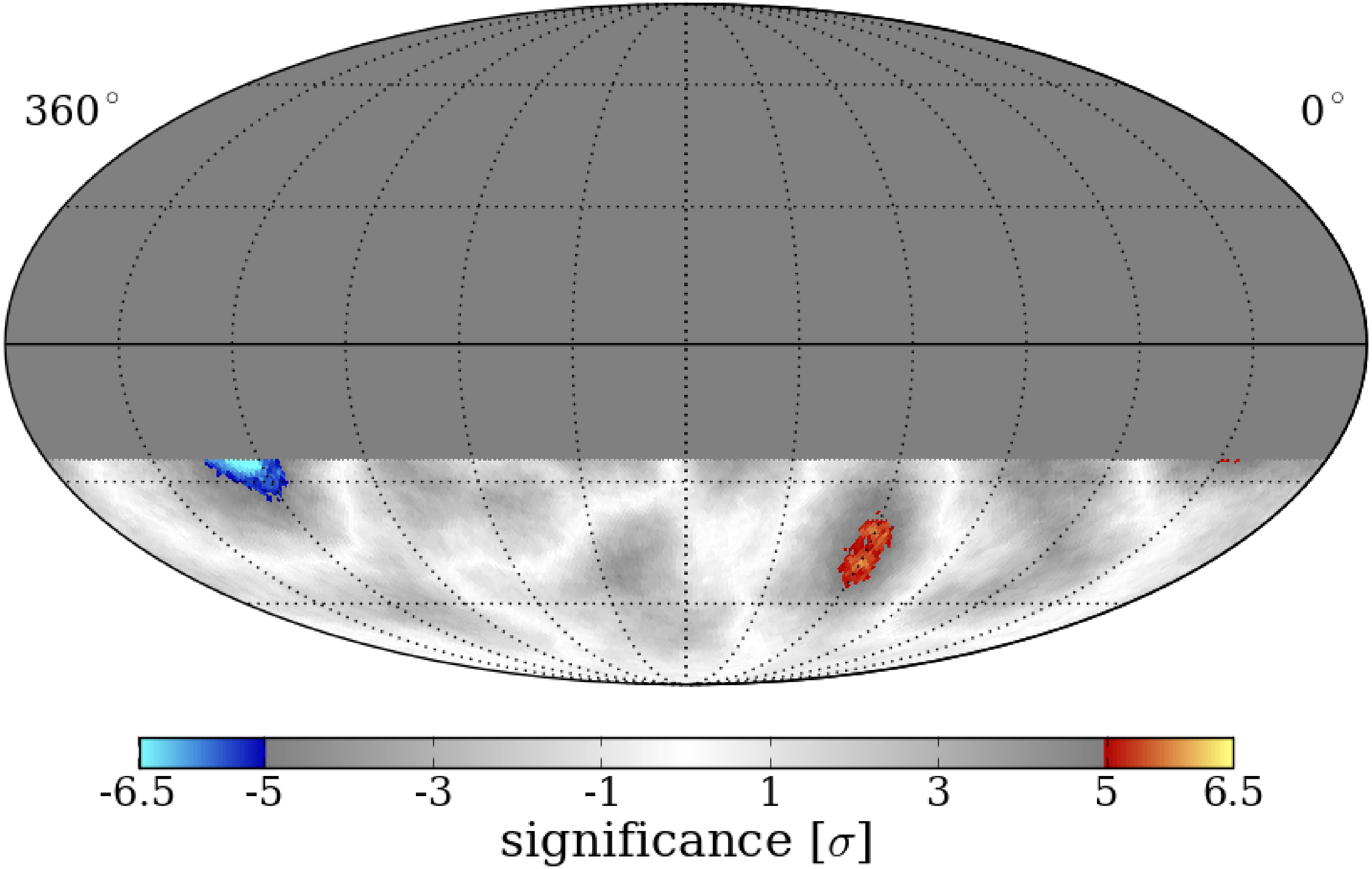
Map smoothing scan



Scan from 1 - 30° in smoothing
Different regions have different optimal smoothings
Significances are pre-trial

24° smoothing

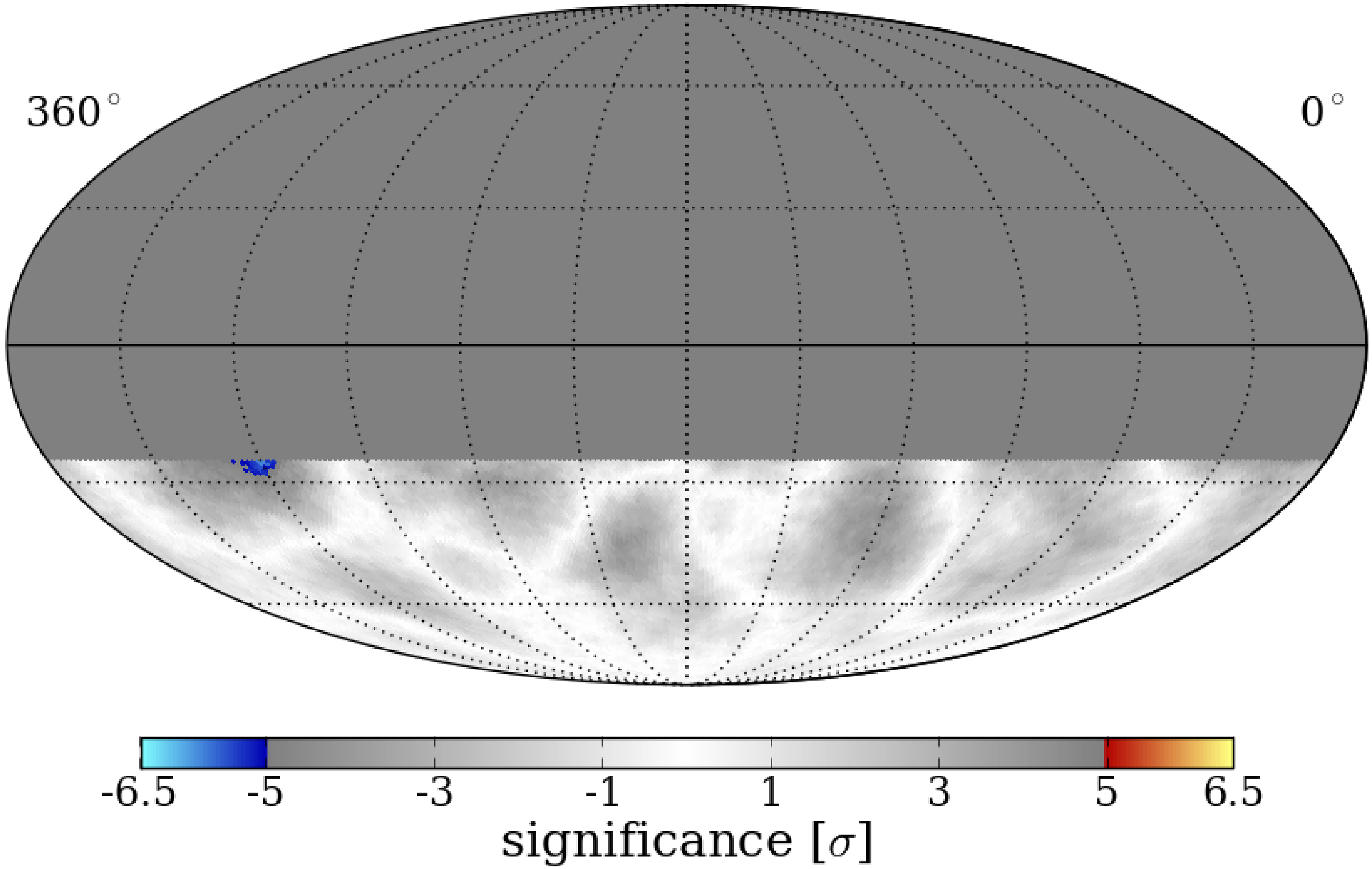
Map smoothing scan



Scan from 1 - 30° in smoothing
Different regions have different optimal smoothings
Significances are pre-trial

27° smoothing

Map smoothing scan

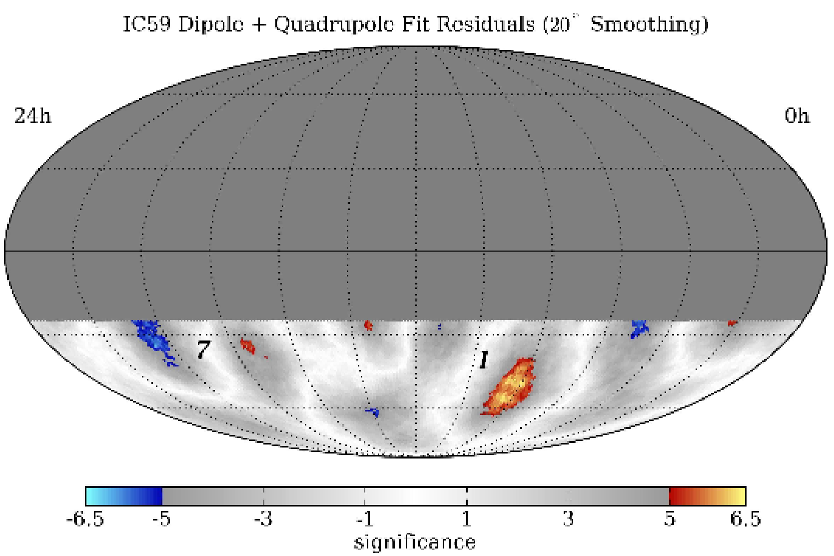


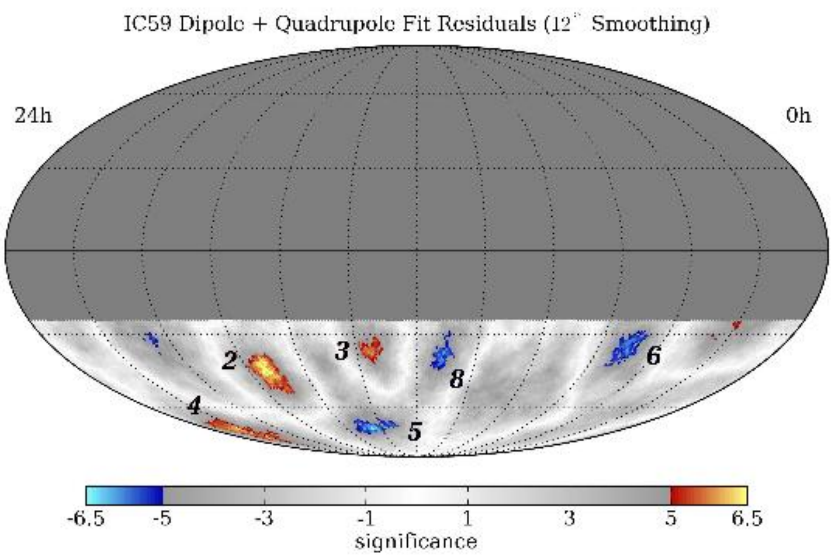
Scan from 1 - 30° in smoothing
Different regions have different optimal smoothings
Significances are pre-trial

30° smoothing

Smoothing scan results

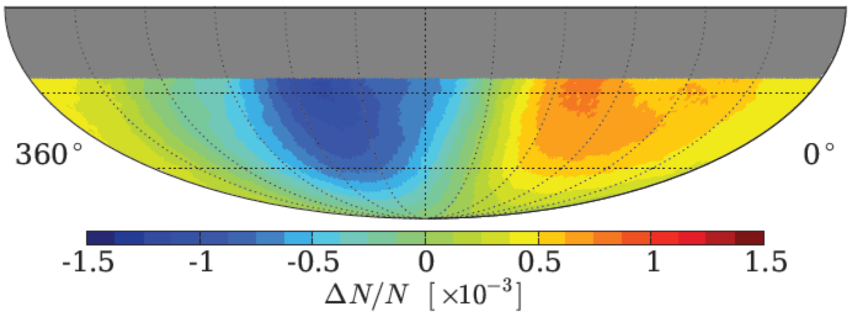
region	right ascension	declination	optimal scale	peak significance	post-trials
1	$(122.4^{+4.1}_{-4.7})^\circ$	$(-47.4^{+7.5}_{-3.2})^\circ$	22°	7.0σ	5.3σ
2	$(263.0^{+3.7}_{-3.8})^\circ$	$(-44.1^{+5.3}_{-5.1})^\circ$	13°	6.7σ	4.9σ
3	$(201.6^{+6.0}_{-1.1})^\circ$	$(-37.0^{+2.2}_{-1.9})^\circ$	11°	6.3σ	4.4σ
4	$(332.4^{+9.5}_{-7.1})^\circ$	$(-70.0^{+4.2}_{-7.6})^\circ$	12°	6.2σ	4.2σ
5	$(217.7^{+10.2}_{-7.8})^\circ$	$(-70.0^{+3.6}_{-2.3})^\circ$	12°	-6.4σ	-4.5σ
6	$(77.6^{+3.9}_{-8.4})^\circ$	$(-31.9^{+3.2}_{-8.6})^\circ$	13°	-6.1σ	-4.1σ
7	$(308.2^{+4.8}_{-7.7})^\circ$	$(-34.5^{+9.6}_{-6.9})^\circ$	20°	-6.1σ	-4.1σ
8	$(166.5^{+4.5}_{-5.7})^\circ$	$(-37.2^{+5.0}_{-5.7})^\circ$	12°	-6.0σ	-4.0σ





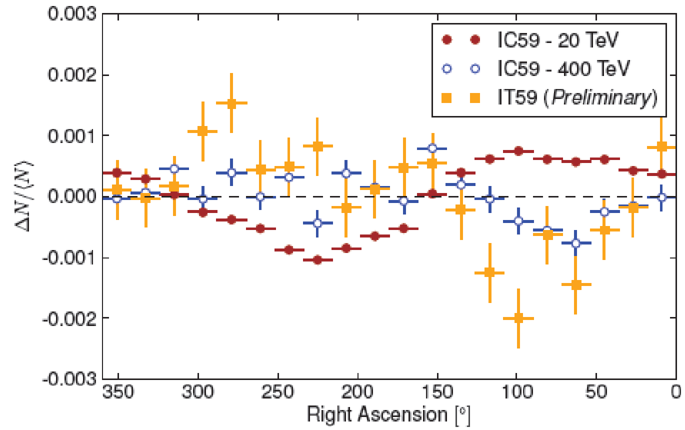
Abbasi et al., ApJ, 740, 16, 2011 arxiv/1105.2326

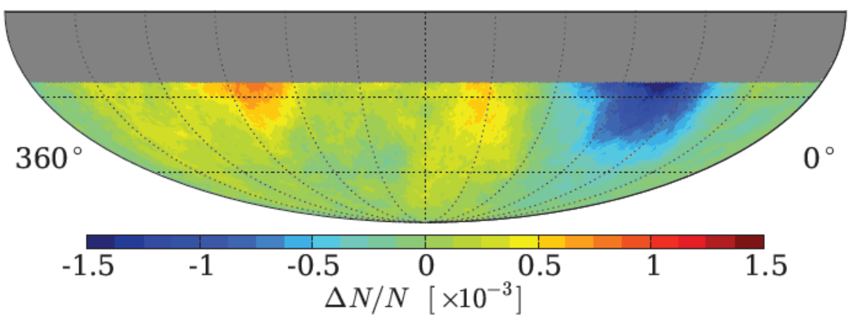
Energy dependence



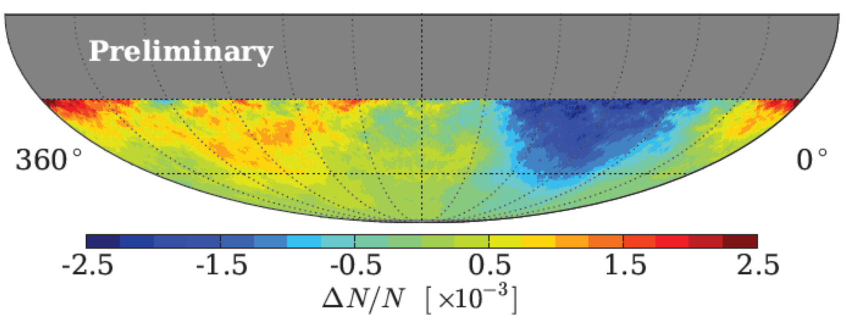
- IceCube-59: 20 TeV

Change of polarity





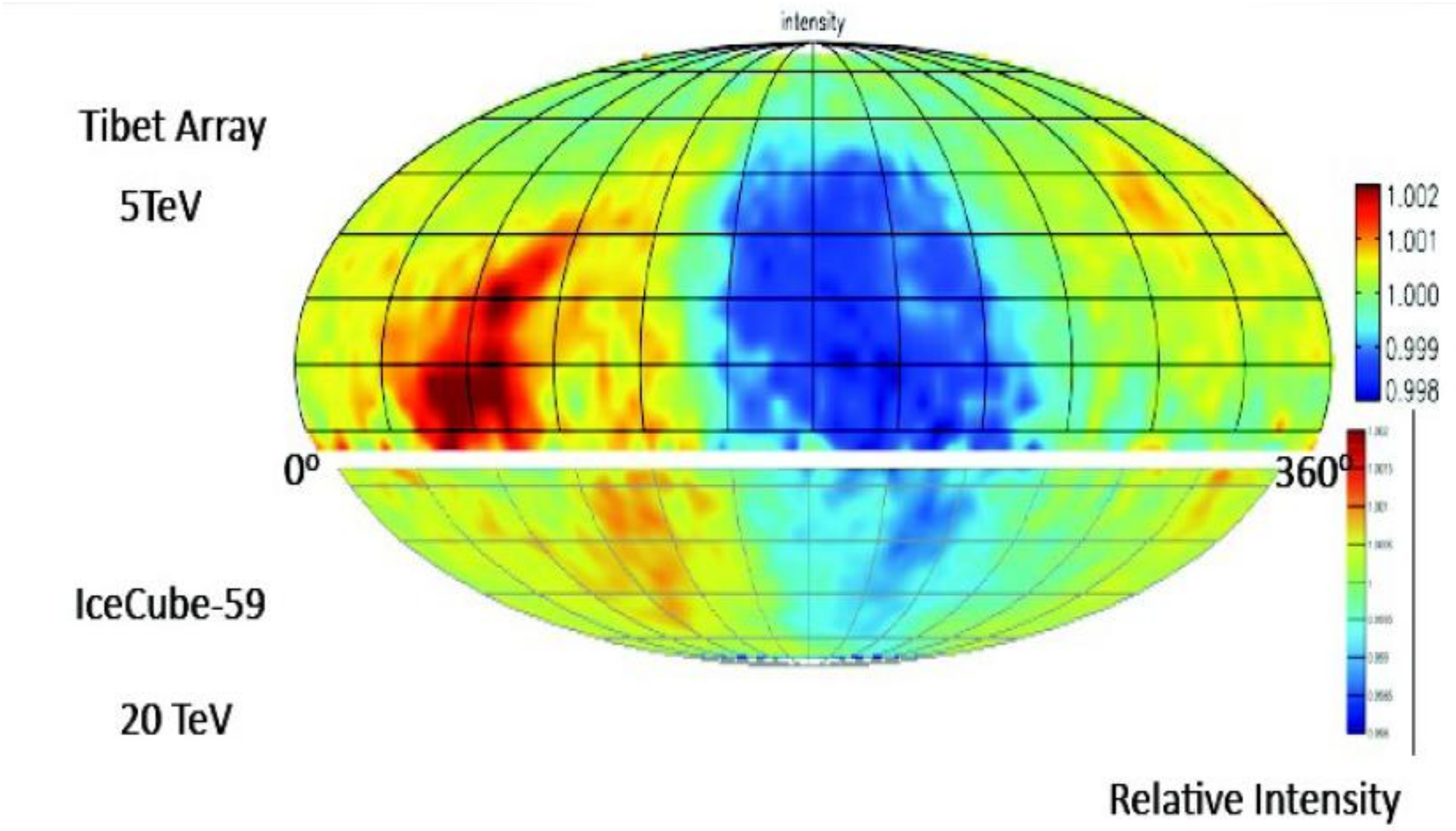
- IceCube-59: 400 TeV



- IceTop-59: PeV-range

North and South

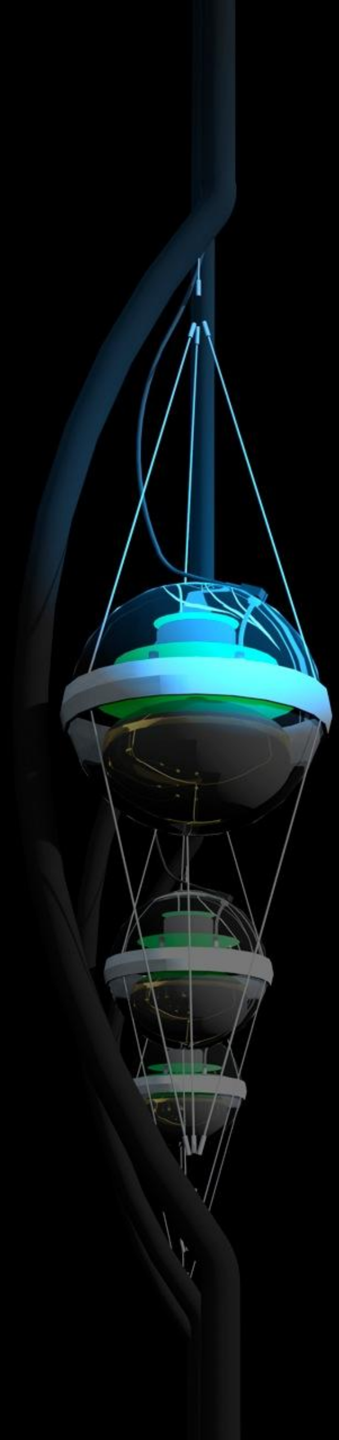
Anisotropies of cosmic rays/muons seen on the Northern hemisphere (Tibet, Milagro/Super-K) are also seen via IceCube muons from the Southern hemisphere.



Possible reasons for anisotropies

- Dipole:
  - Discrete spatial distribution of PeV cosmic ray sources?
  - Compton-Getting effect (movement of solar system against the plasma of cosmic rays)?

- Smaller structures:
  - Special magnetic field configurations (channeling)?
  - Turbulent propagation of cosmic rays in galactic magnetic fields?
  - Heliospheric effects ???? (not at >> TeV)
  - Nearby sources??



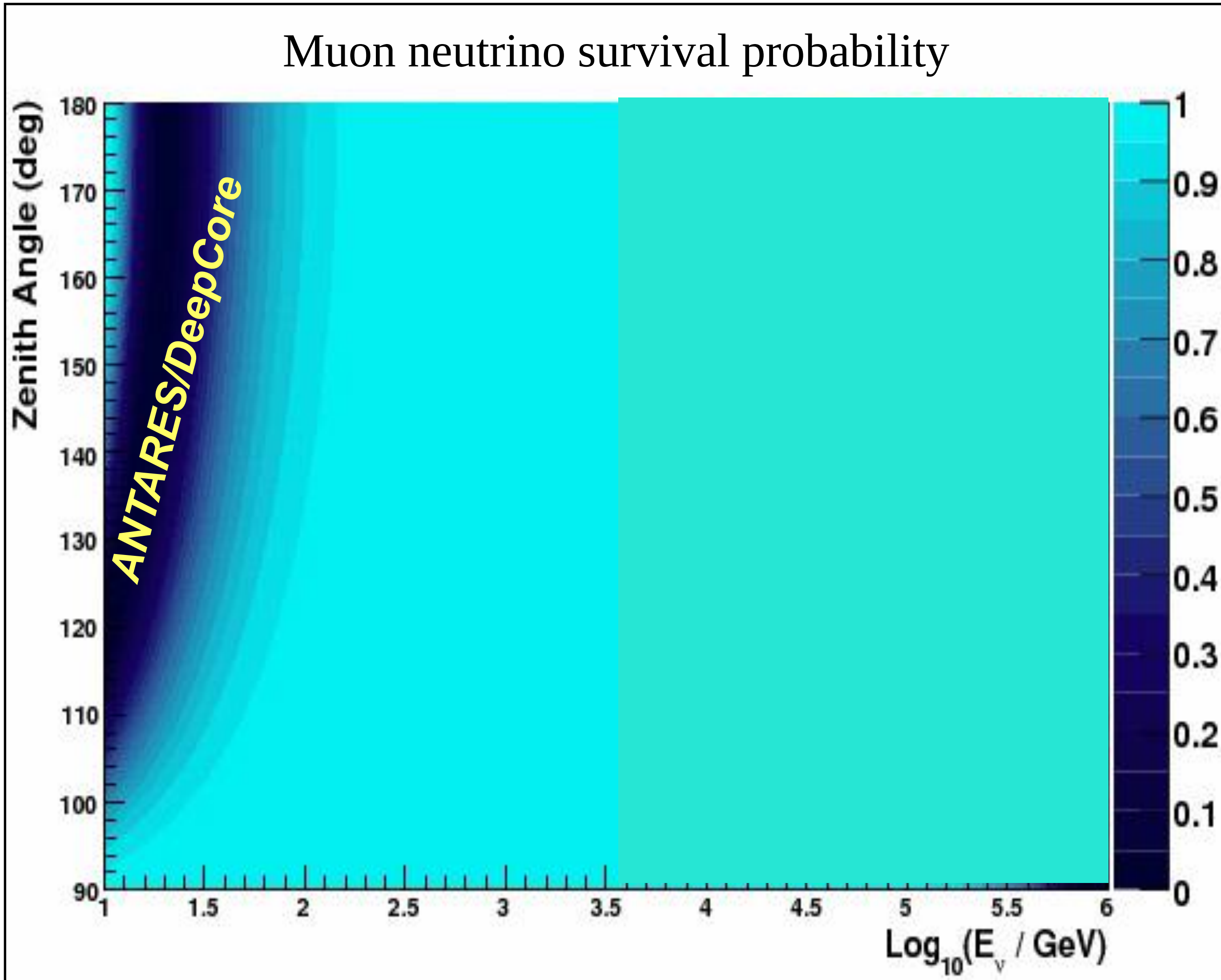
Neutrino Oscillations:

a) Standard Oscillations

Oscillations of atmospheric neutrinos

Vertically upward

Horizontal



ANTARES 2007-2010

2008-2010 data (863 days):

No oscillation: χ^2/NDF = 40/24 (2.1%)

Best fit: χ^2/NDF = 17.1/21

$\Delta m^2 = 3.1 \cdot 10^{-3}$ eV^2

$\sin^2 2\theta$ =1.00

Systematics:

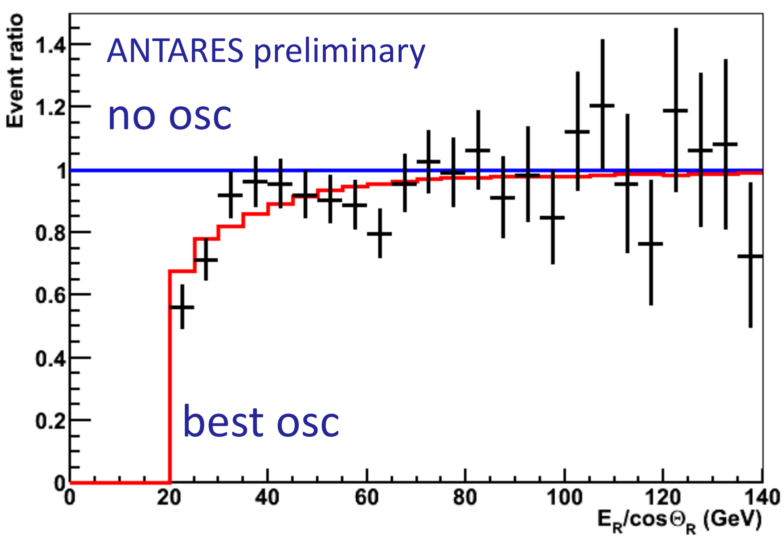
(Absolute normalisation free)

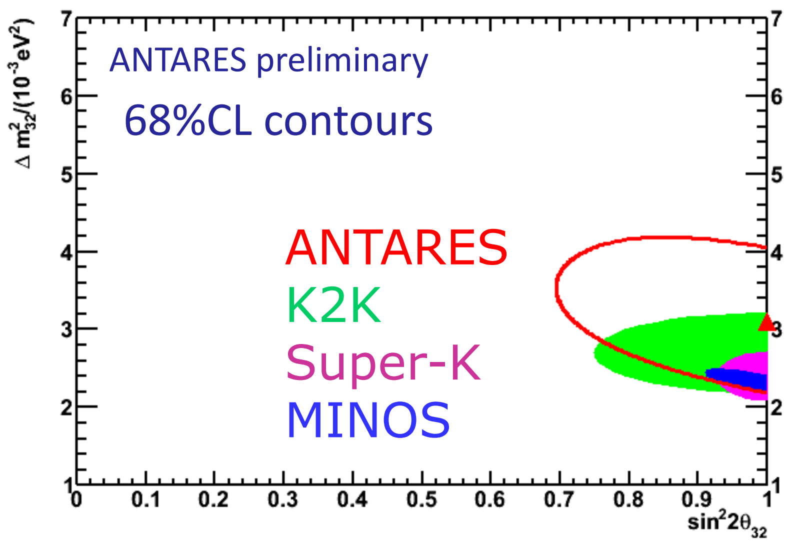
Absorption length: ±10%

Detector efficiency: ±10%

Spectral index of ν flux: ±0.03

OM angular acceptance

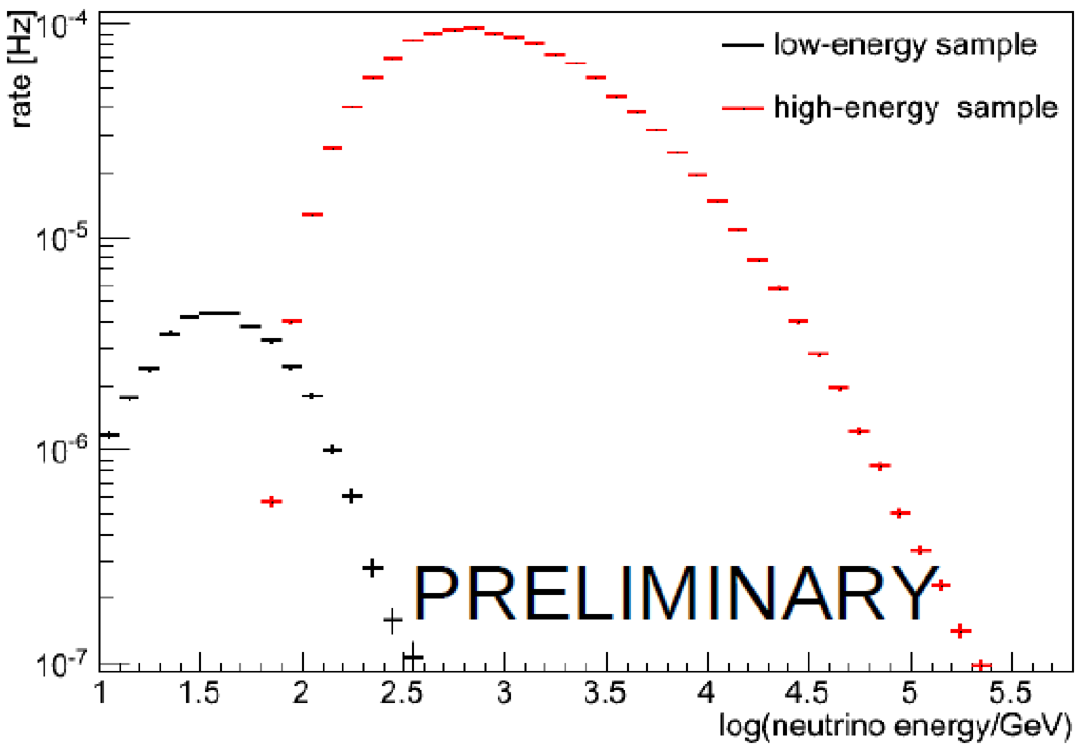




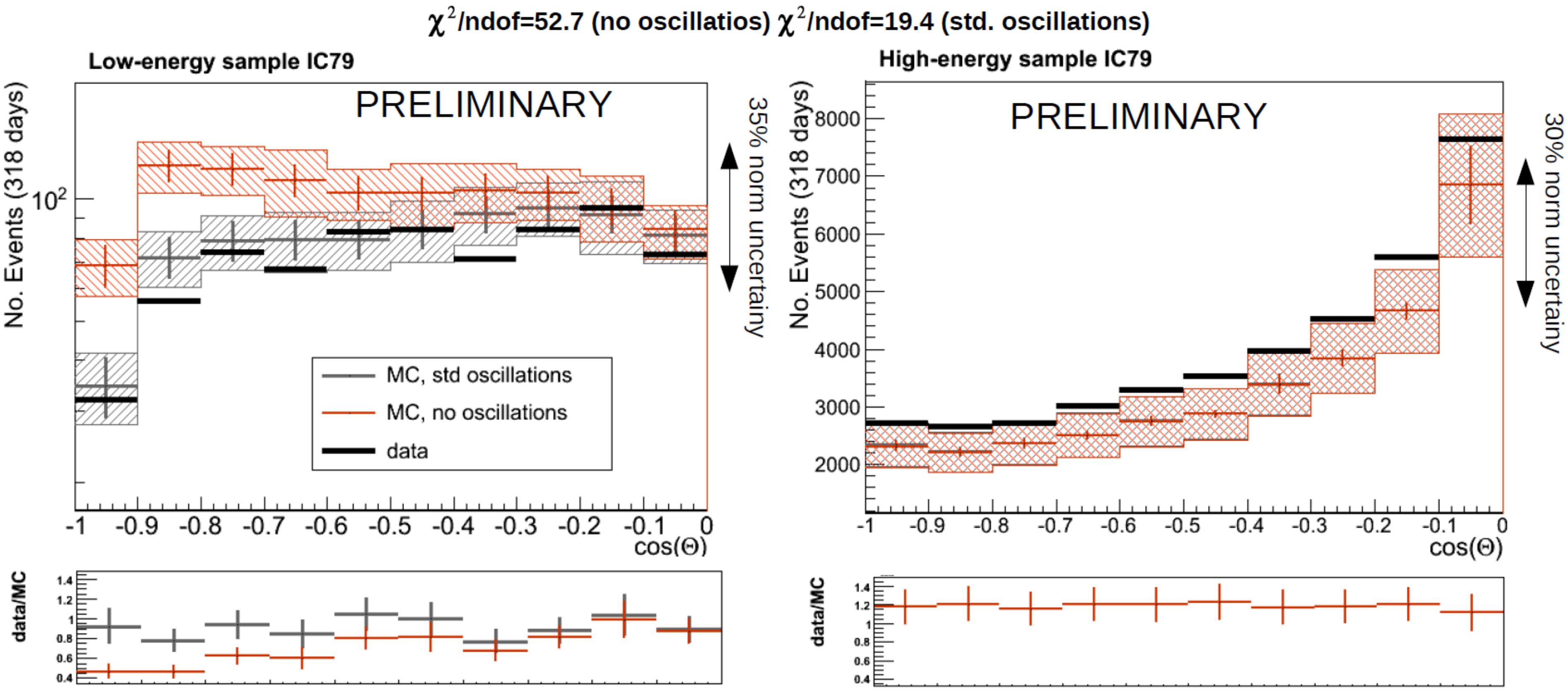
Assuming maximal mixing: Δm^2=(3.1±0.9) 10^{-3} eV^2

IceCube/DeepCore (79 strings)

- PRELIMINARY
- **Simple** cuts and reconstruction in Deep Core to extend sample to low energies and look for consistency with standard neutrino oscillations.
- Is not optimized for DeepCore efficiency, angular resolution,…
- Ongoing Work: more “sophisticated” analysis for measurement of oscillation parameters



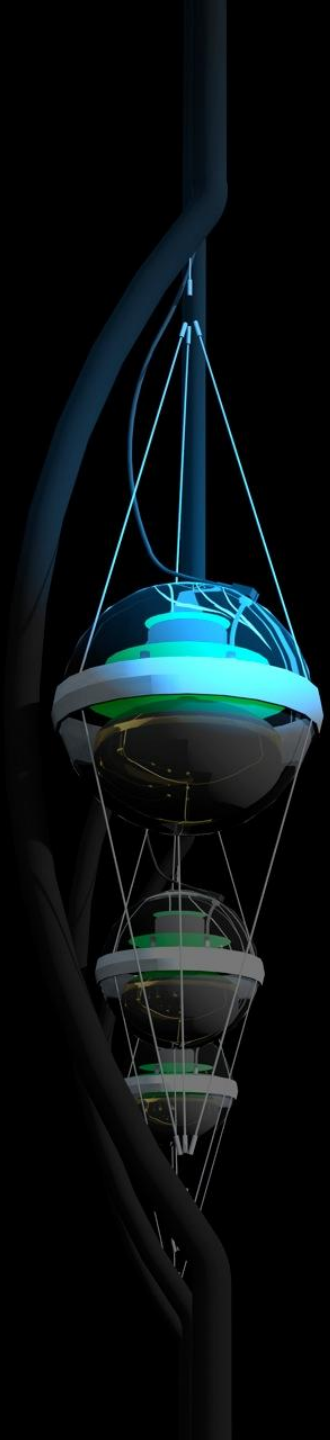
IceCube/DeepCore (79 strings)



delta chi-square = 33.3, p-value = 1 x 10^{-8}

More sophisticated analyses are under work.

Expect determination of osc. parameters in some months



Neutrino Oscillations:

b) Oscillations due to Violation of Lorentz Invariance (VLI)

Exotic Oscillations

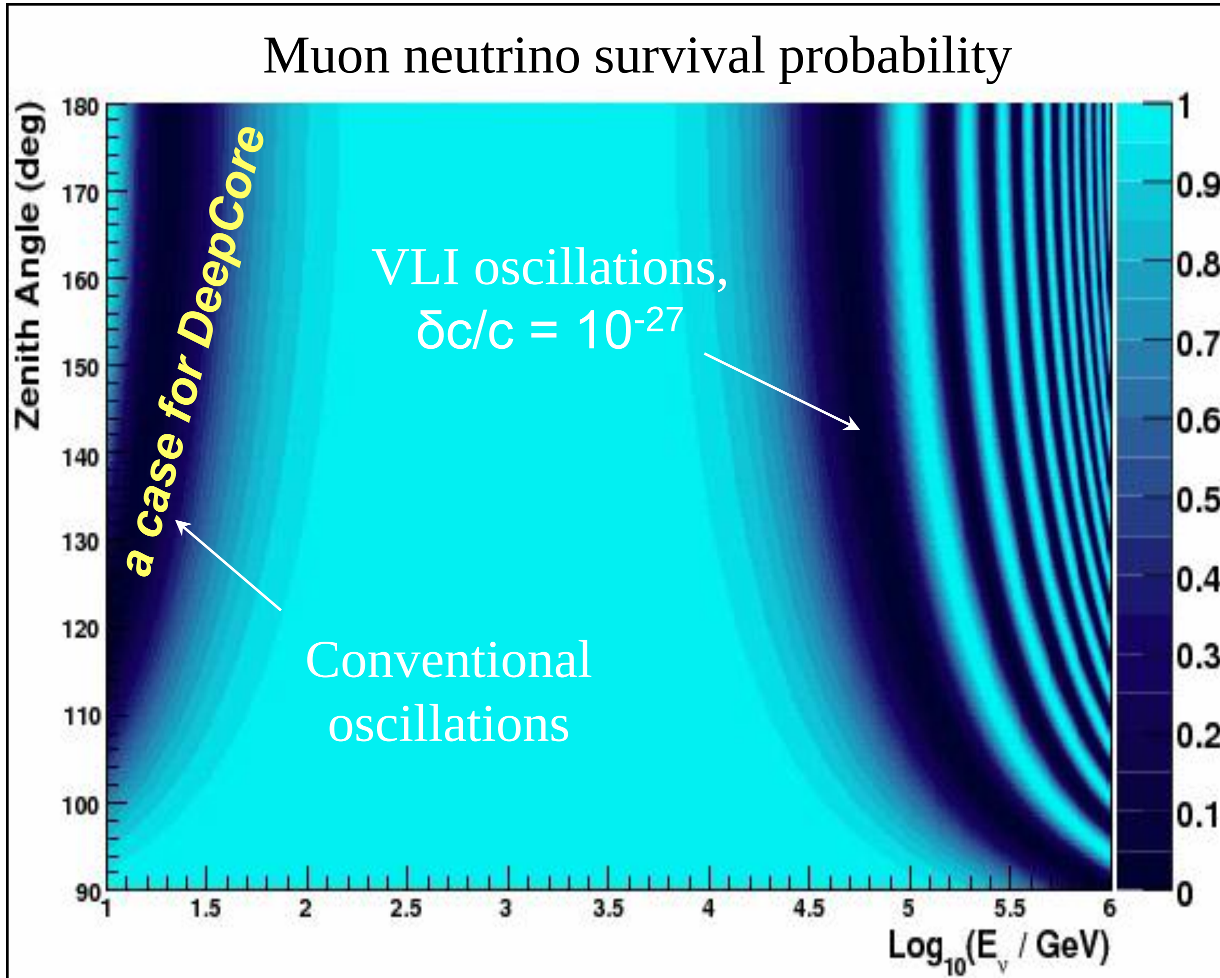
"ν_μ disappearance" in atmospheric neutrinos

- Violation of Lorentz Invariance
- Quantum Decoherence

(both effects in Quantum Gravity)

Parameters:
VLI: $\delta c/c$, sin 2ξ, Phase η
QD: D_3 und D_8, D_6 und D_7

Different to standard oscillations (~ 1/E), QG Oscillations go like ~ E (or even E²)



Exotic Oscillations

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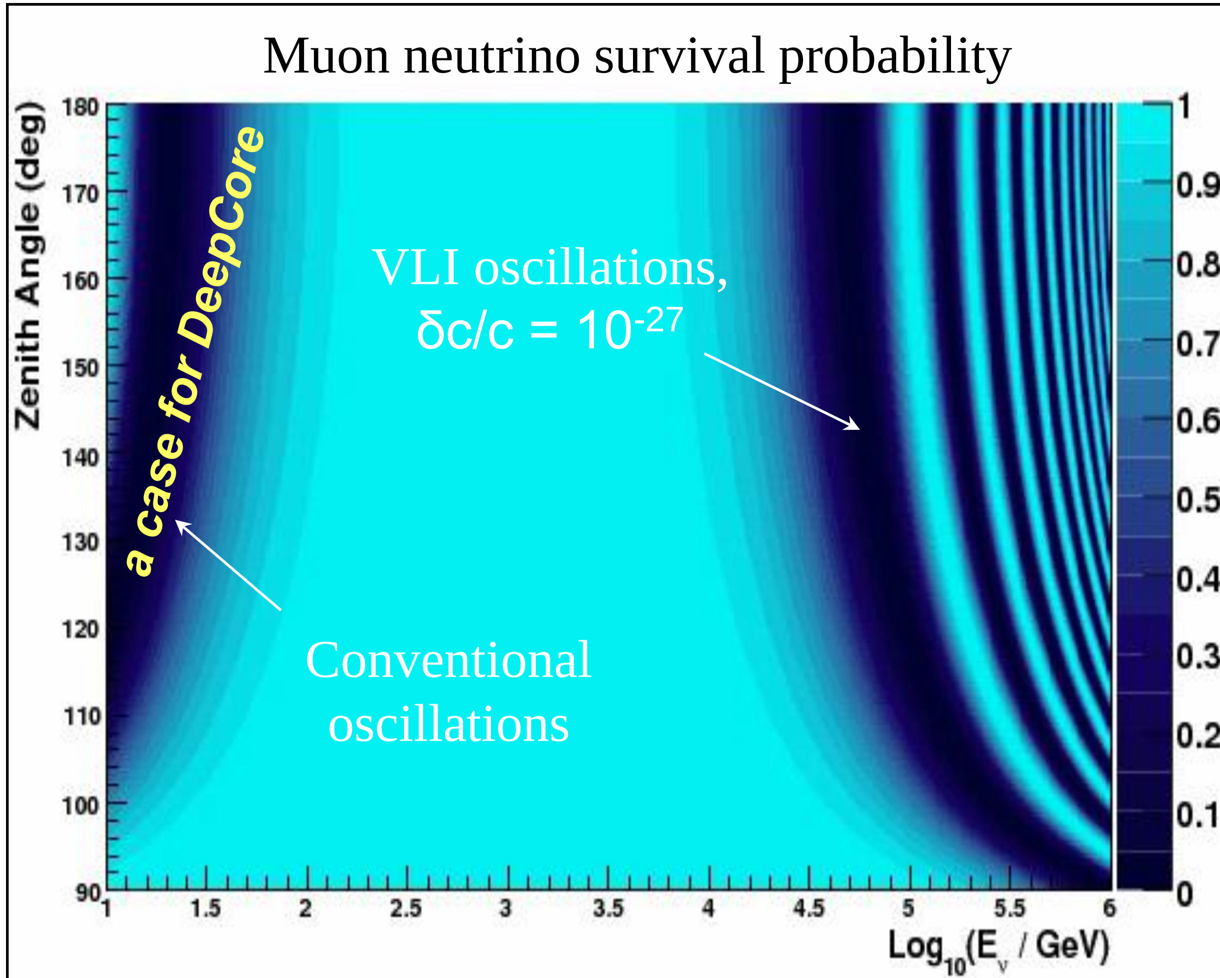
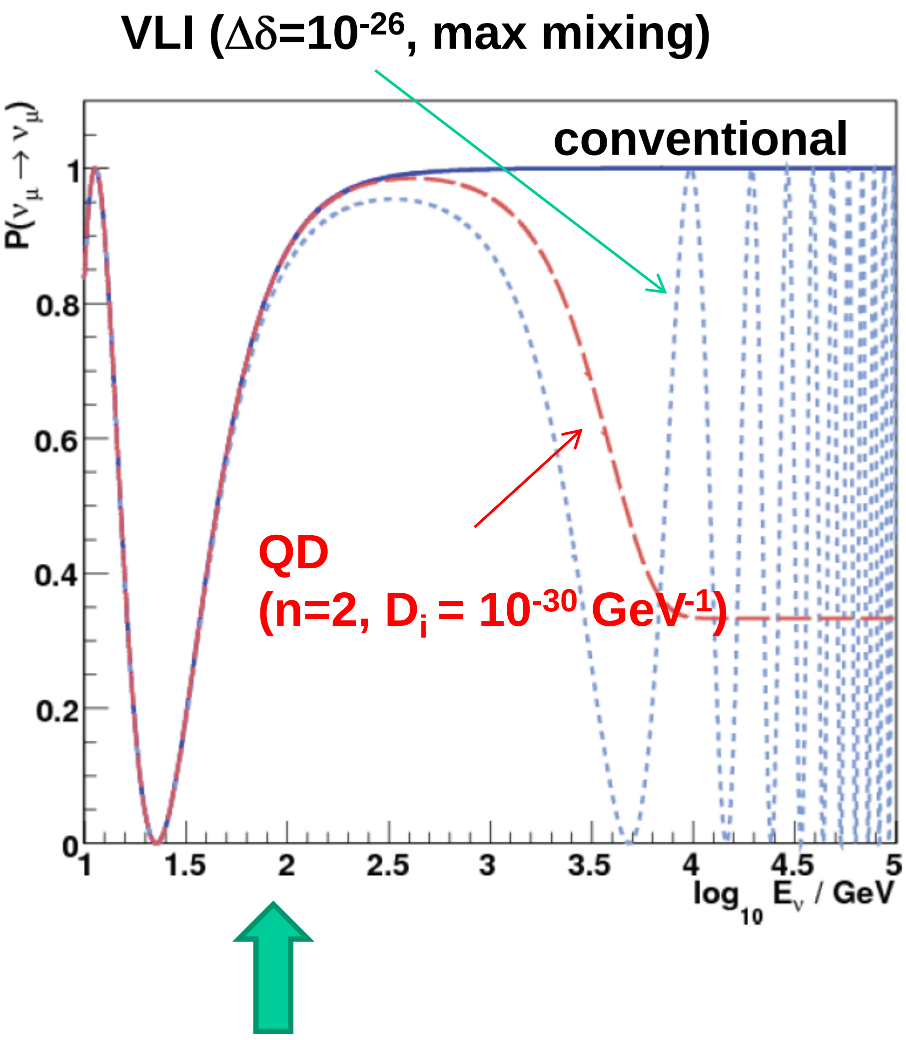
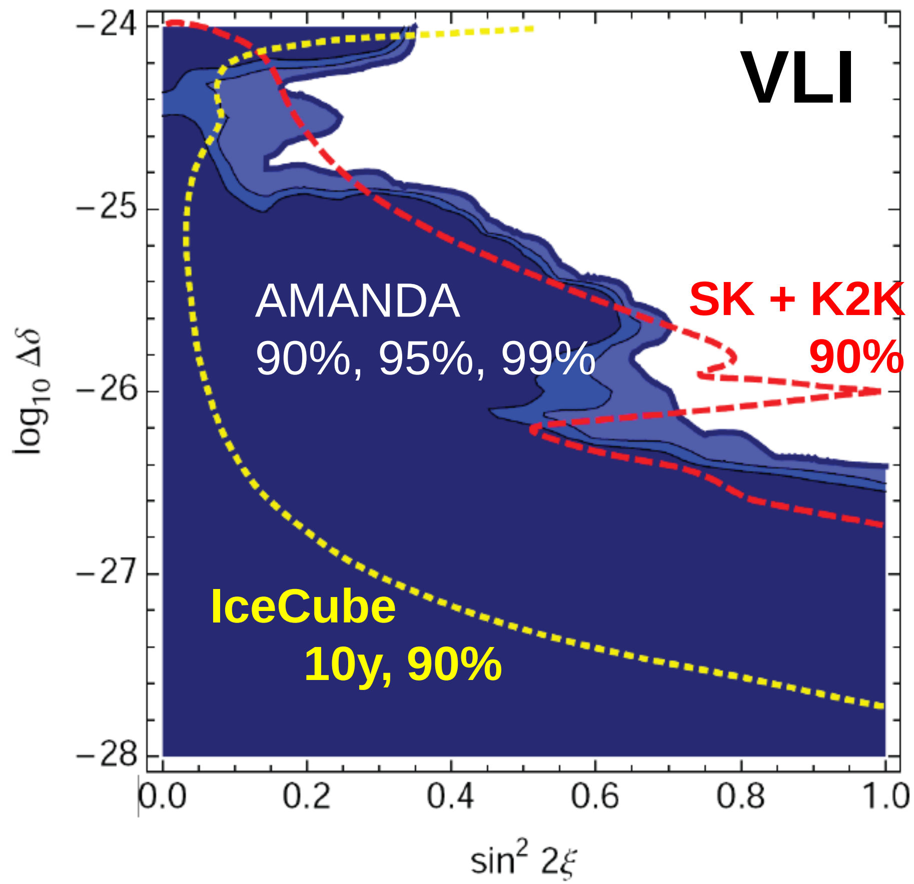


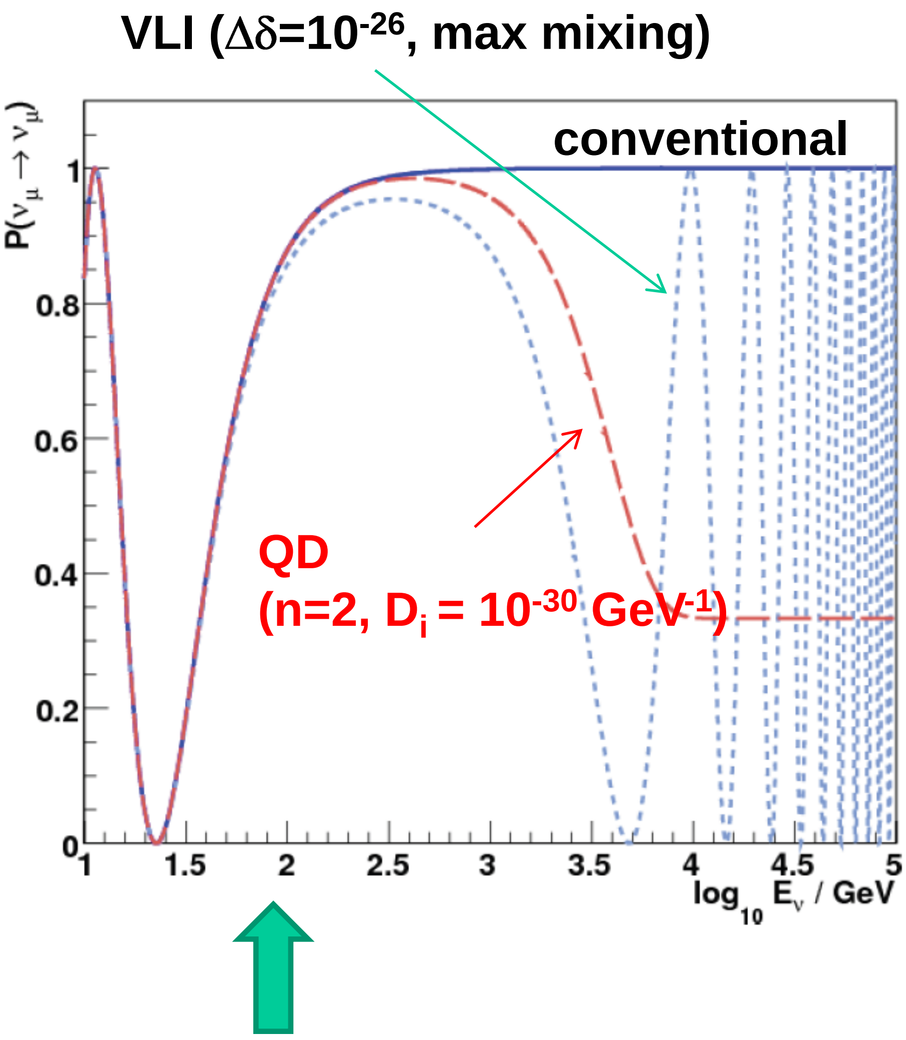
Exotic Oscillations

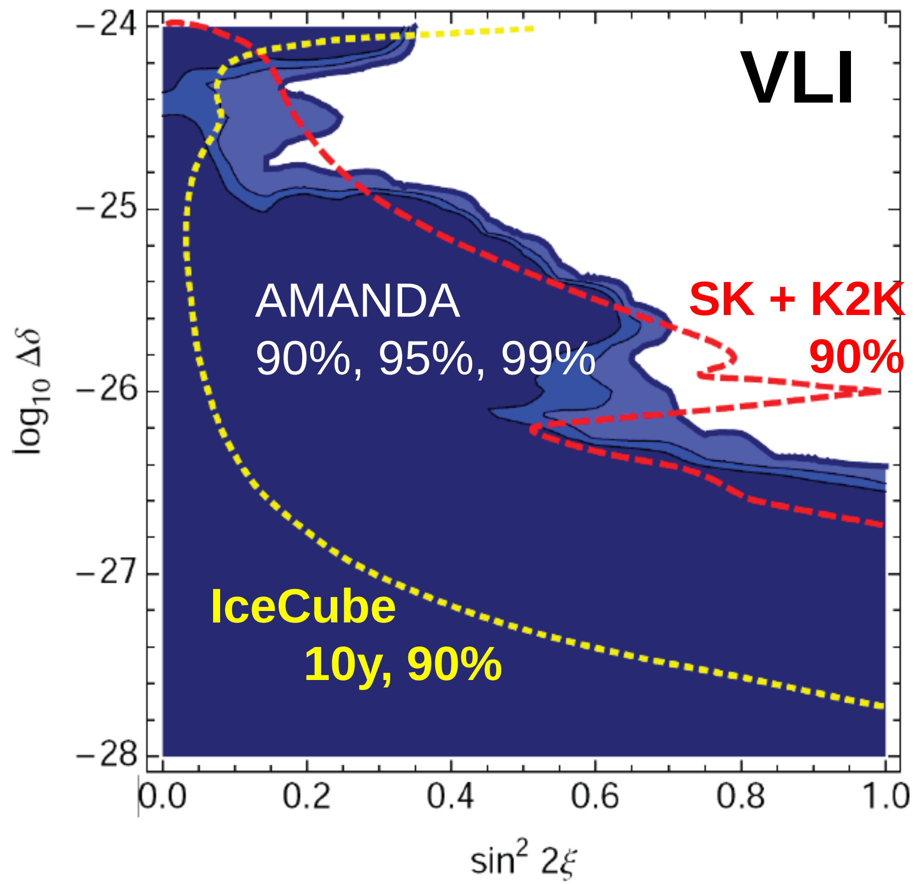




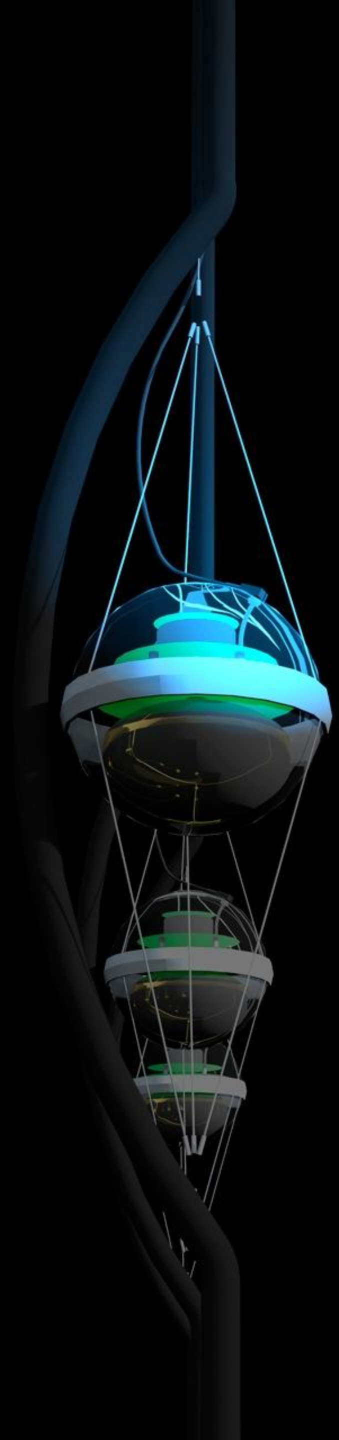
ν_μ survival probability as a function of energy for a baseline of the Earth diameter

Exotic Oscillations





ν_μ survival probability as a function of energy for a baseline of the Earth diameter



Neutrino Oscillations:

c) Sterile Neutrinos

Searches for sterile neutrinos with IceCube DeepCore

arXiv:1203.5406v2

Soebur Razzaque[1,2,*] and A. Yu. Smirnov[3,†]

- Visible as distortion of standard pattern with DeepCore
- Visible as distortion of angular spectrum in the standard Icecube energy range

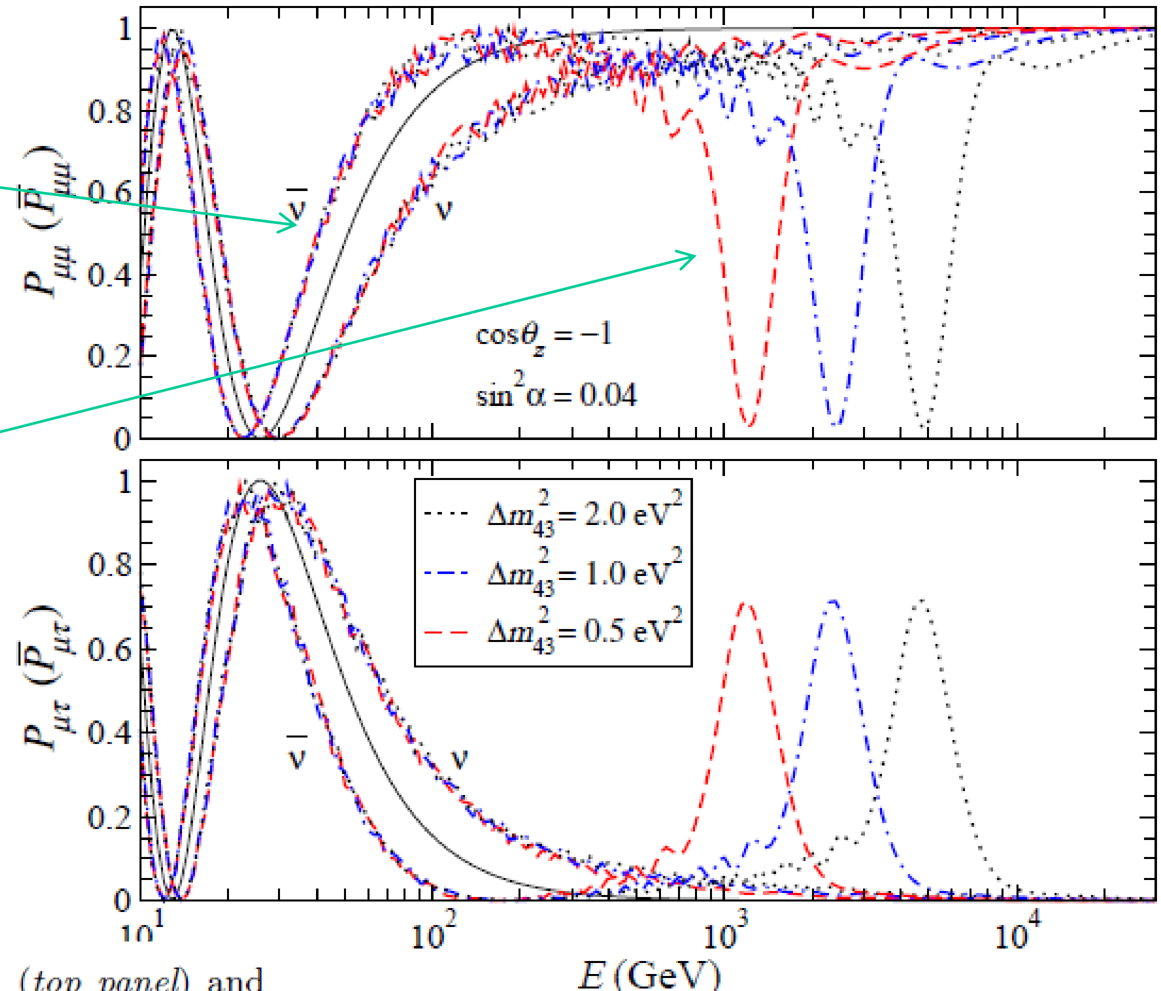
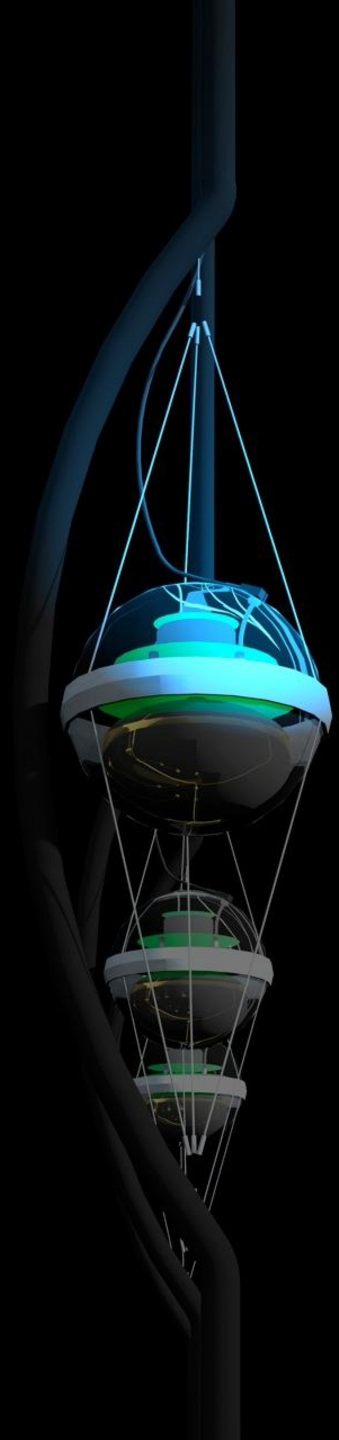


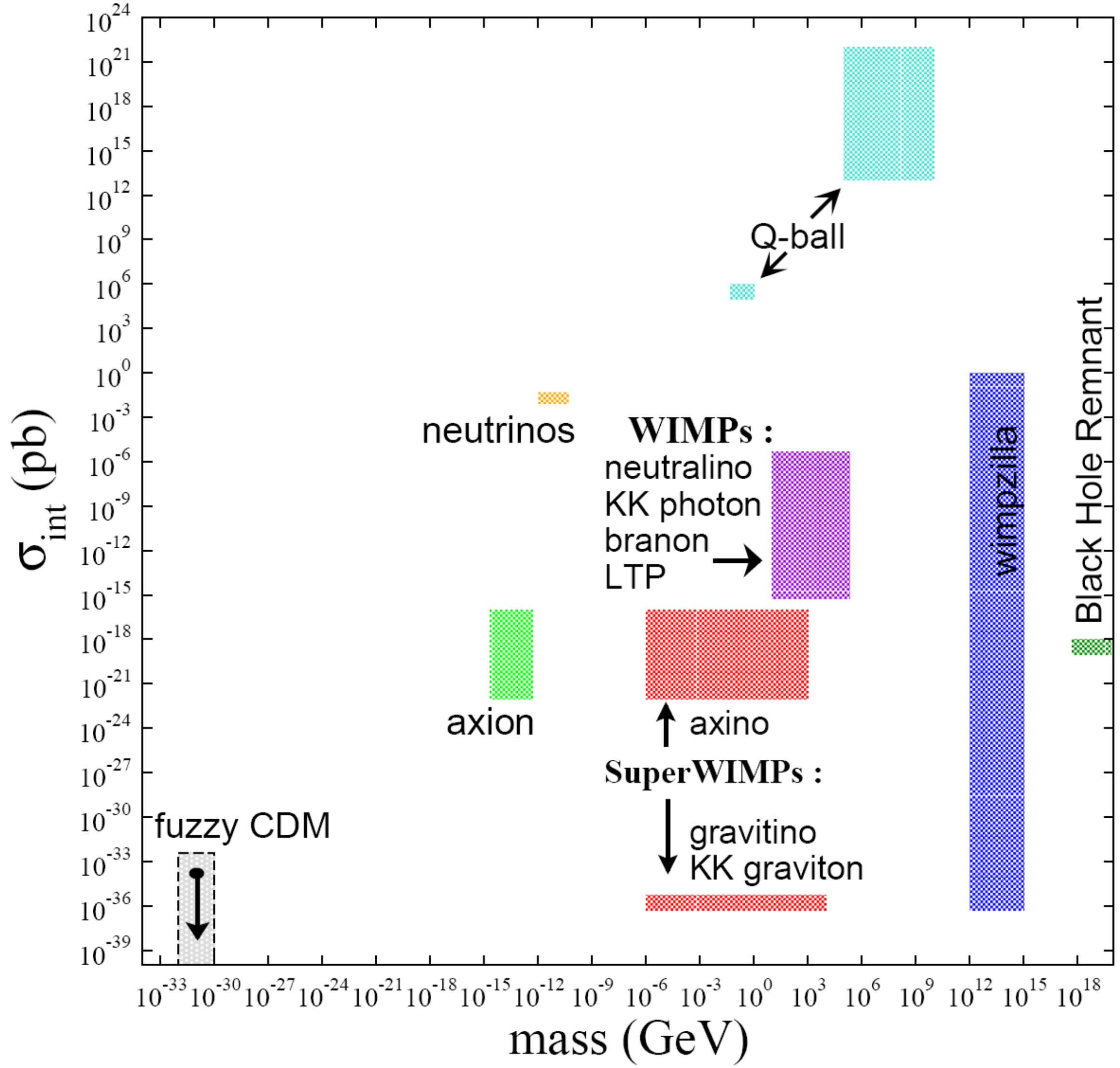
FIG. 1: Oscillation probabilities $\nu_\mu \to \nu_\mu$ (*top panel*) and $\nu_\mu \to \nu_\tau$ (*bottom panel*) for different values of Δm^2_{43}. The solid (broken) lines correspond to the probabilities without (with) ν_s mixing. The normal mass hierarchy is assumed.



Indirect Dark Matter Search

Indirect Dark Matter Search

- **WIMPs**
  - Neutralinos
  - Kaluza-Klein particles
  - …
- **Axions**
- **Super-WIMPs**
- **Axinos**
- **Sterile neutrinos**
- **Q-balls**
- **WIMPzillas**
- **Elementary BHs**
- …



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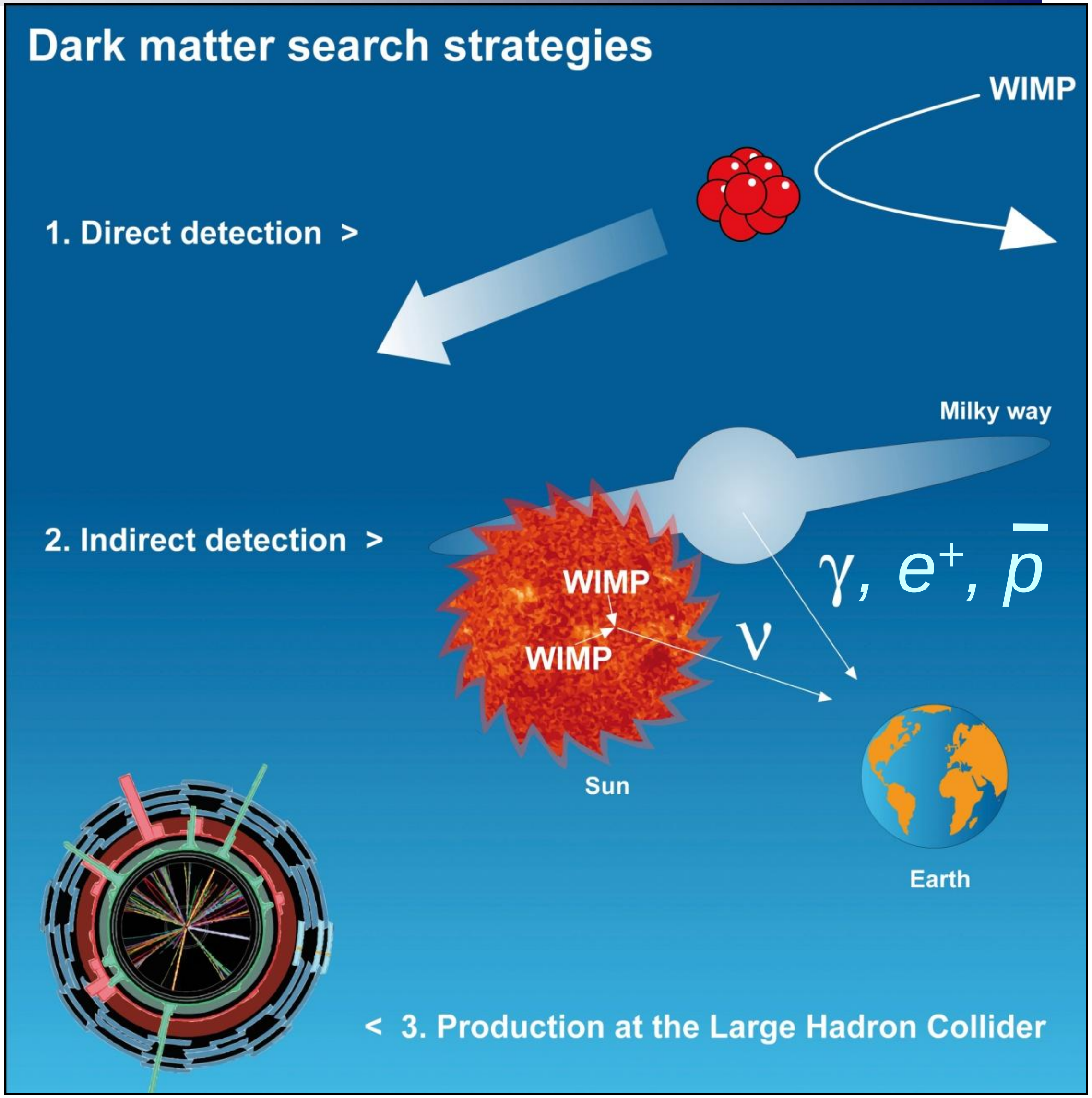

Indirect Dark Matter Search

- **WIMPs**
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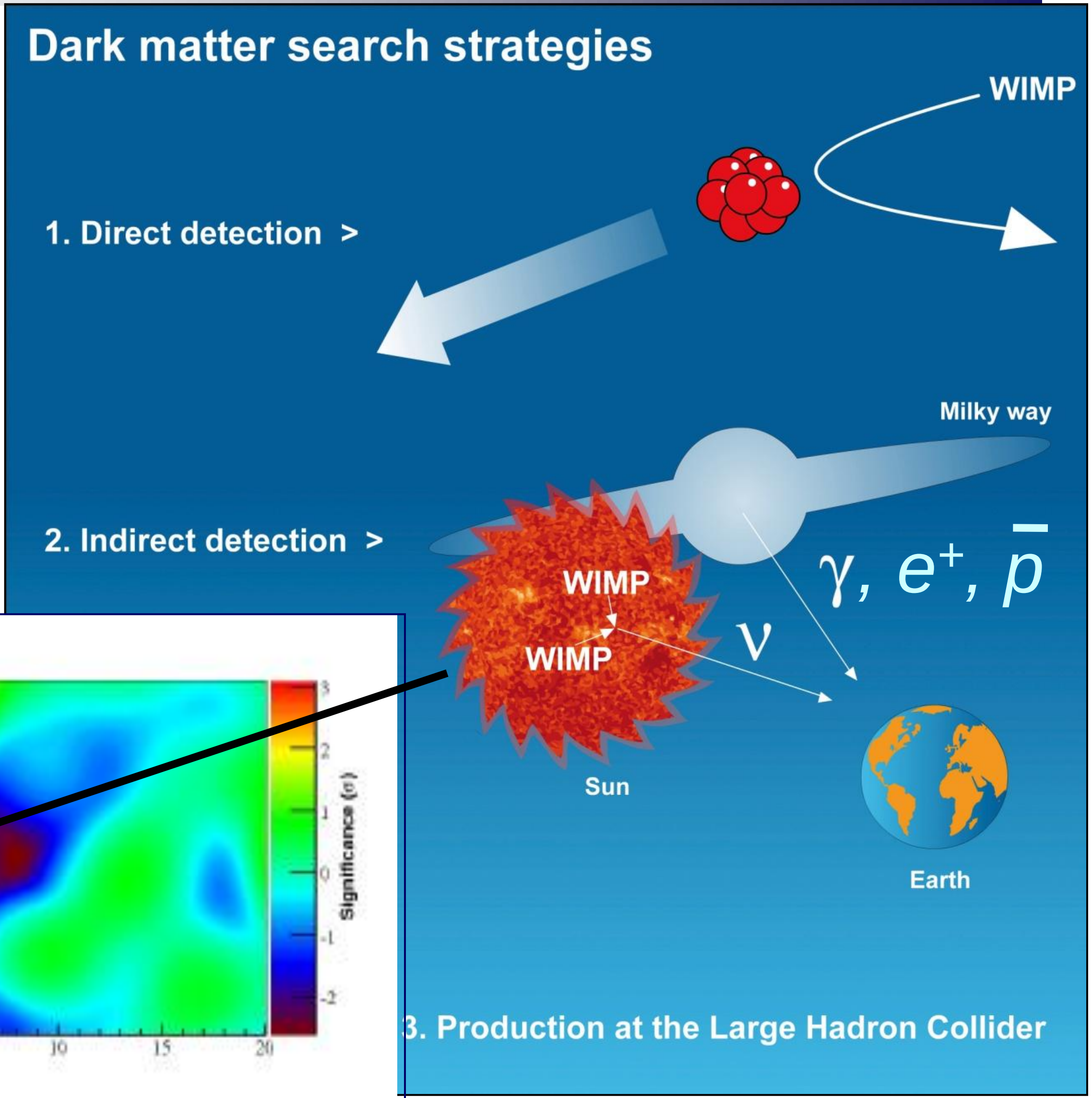
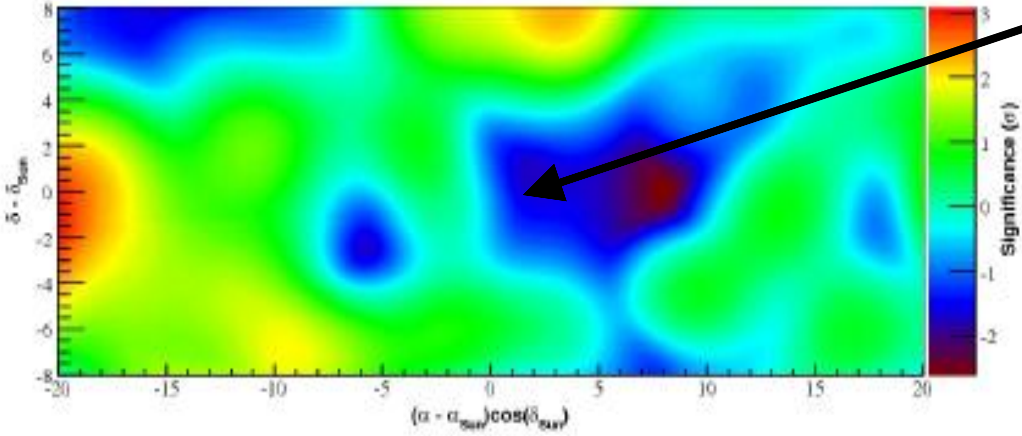
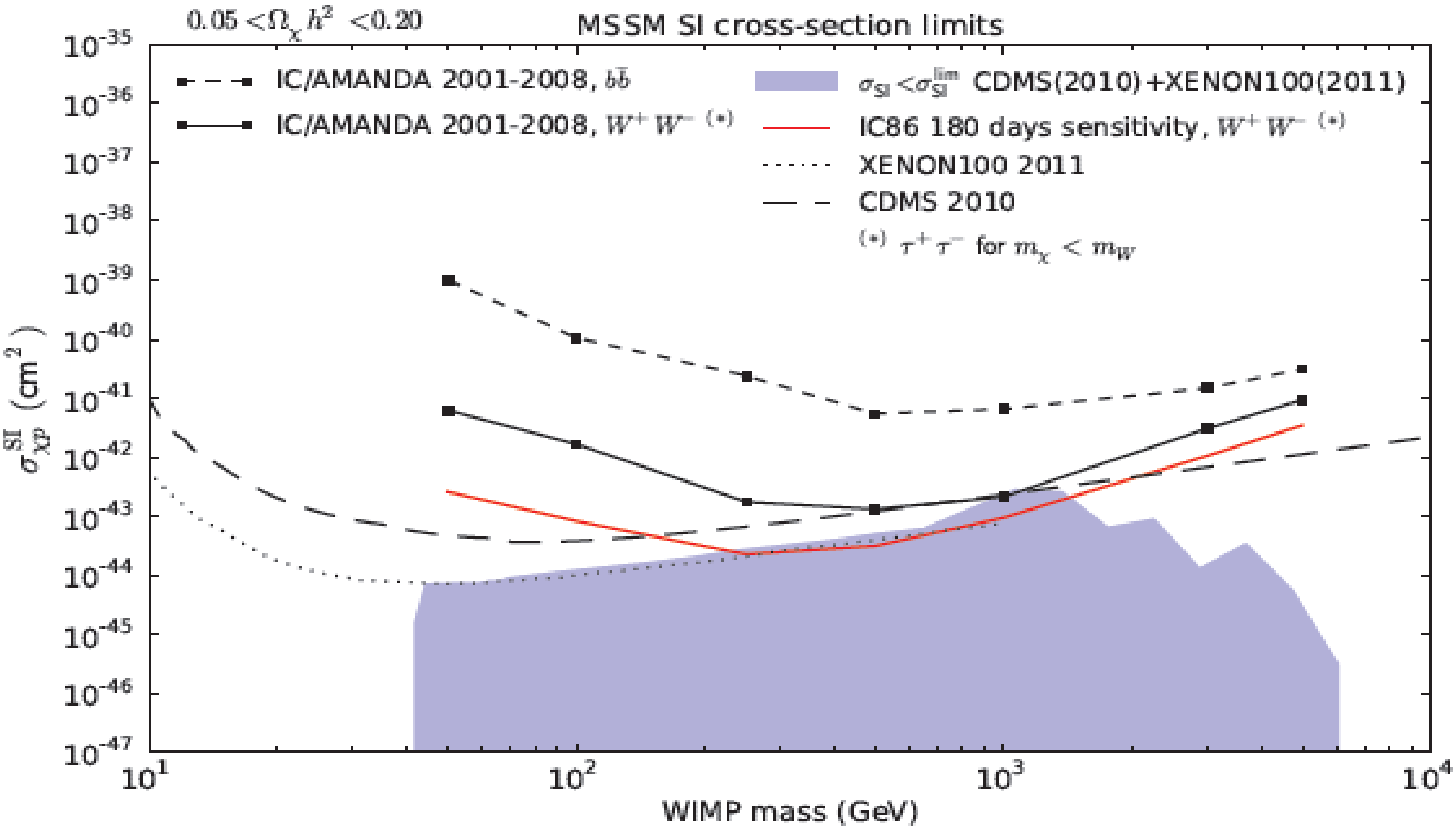


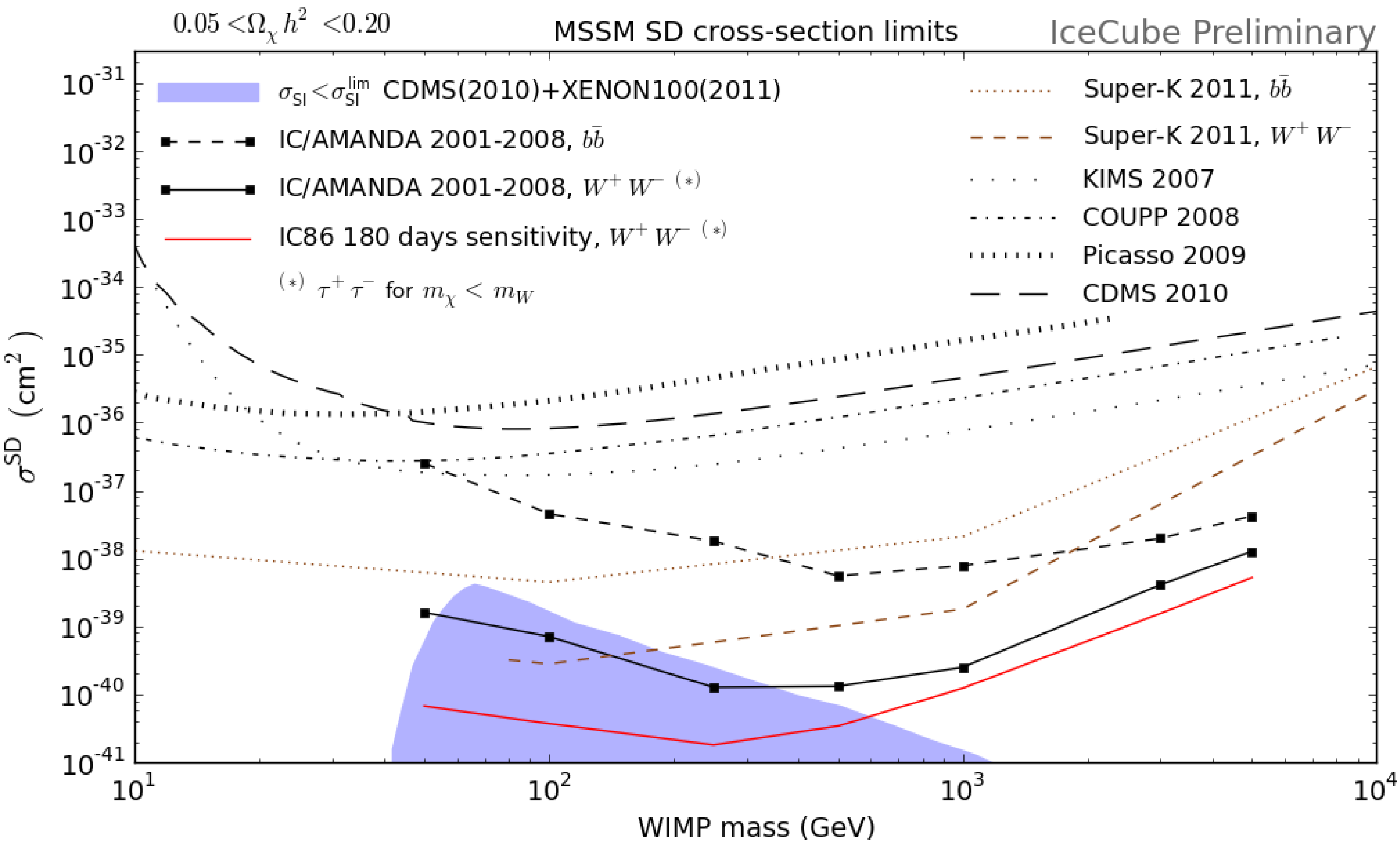
AMANDA skymap around Sun

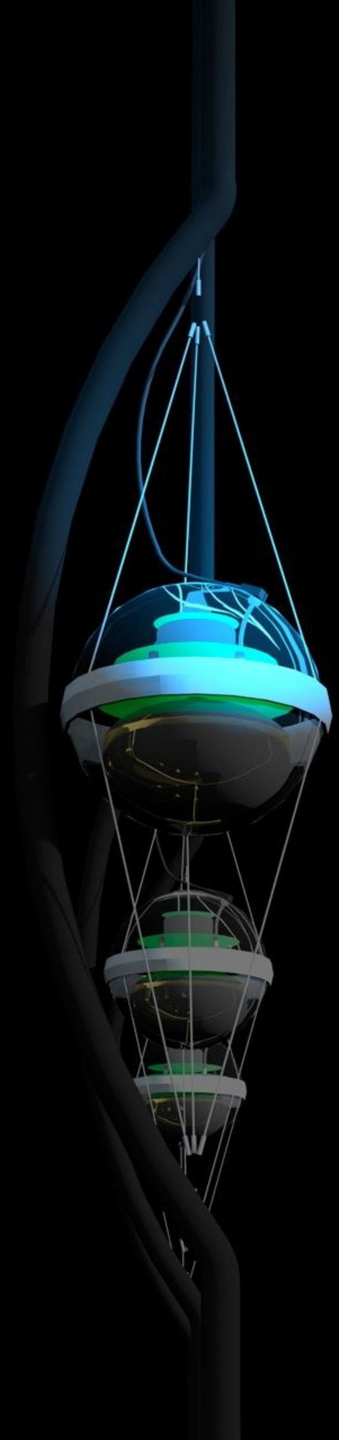


Indirect Dark Matter Search



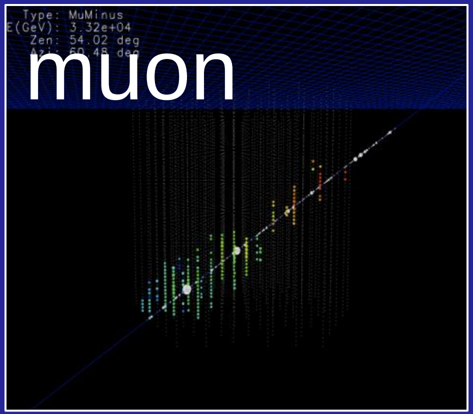
Indirect Dark Matter Search

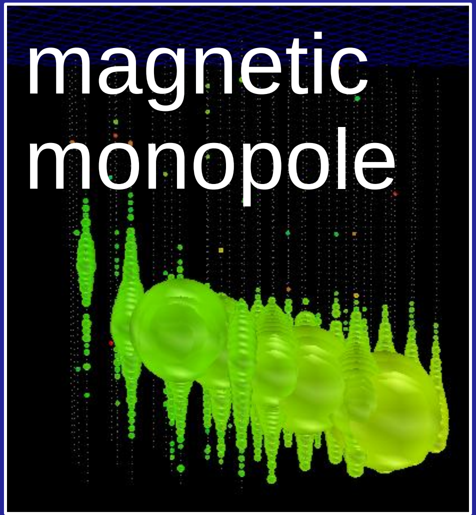


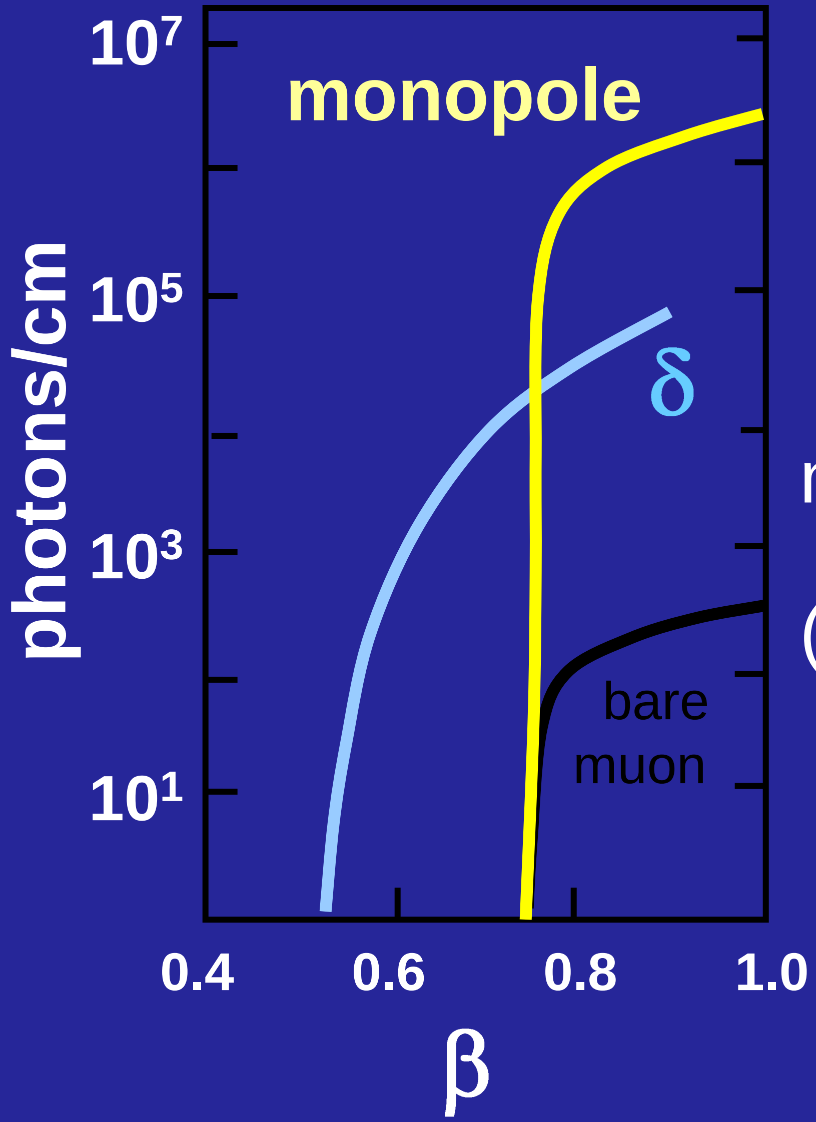


Search for relativistic magnetic monopoles

Relativistic Magnetic Monopoles







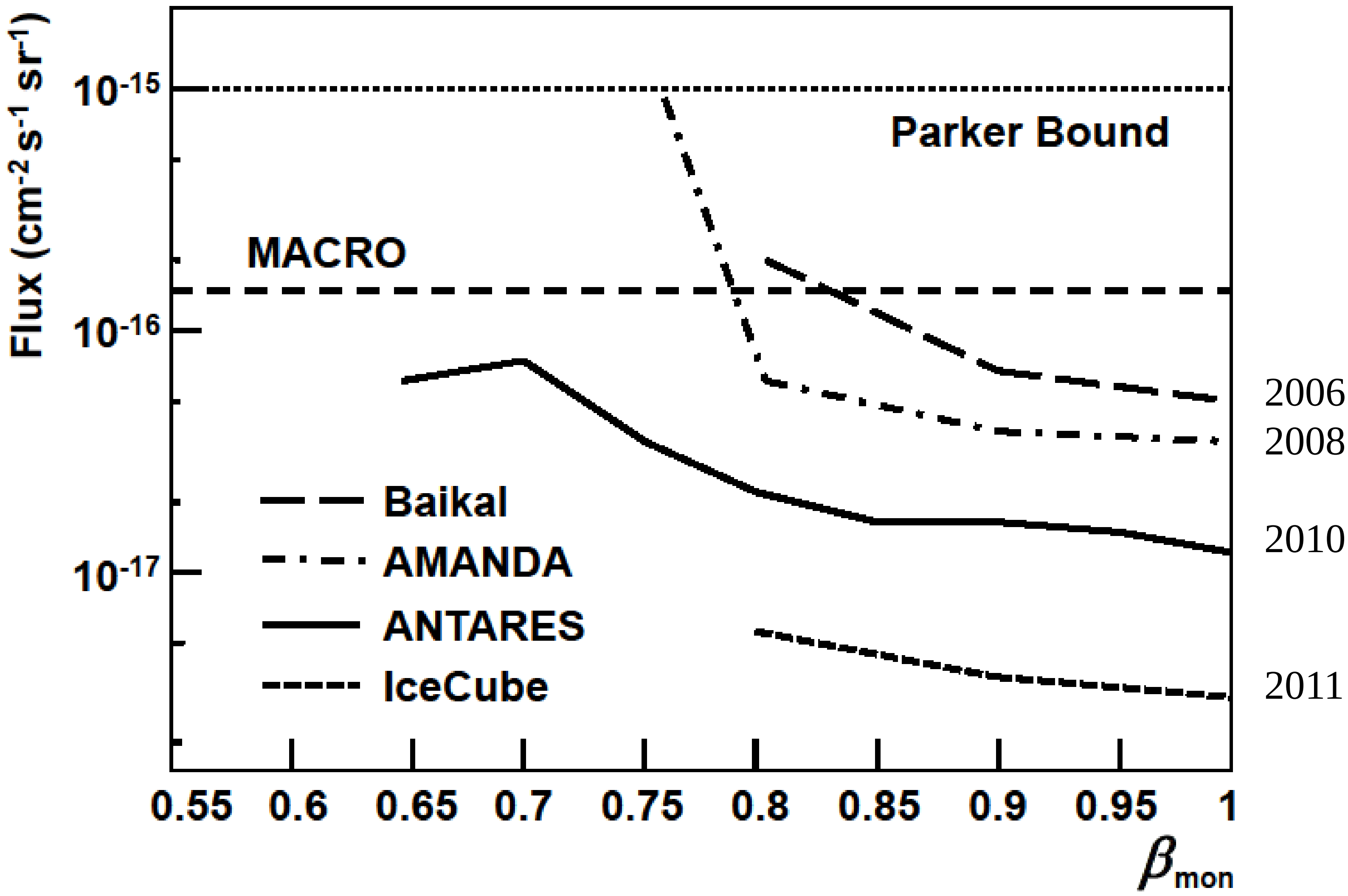
Cherenkov Light $\propto$ $n^2 \cdot (g/e)^2$

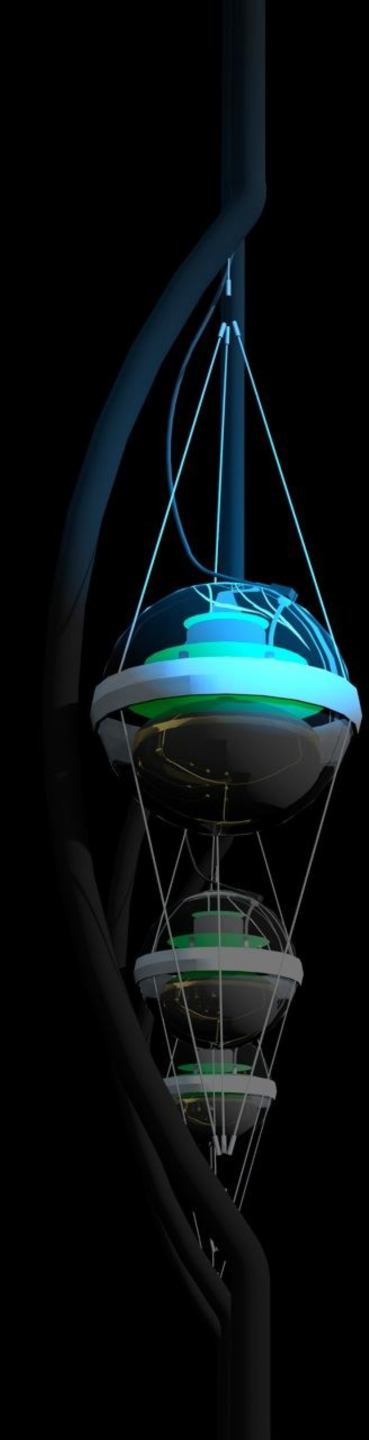
$n = 1.33$

$(g/e) = {}^{137}/_{2}$

≈ 8300

Relativistic Magnetic Monopoles





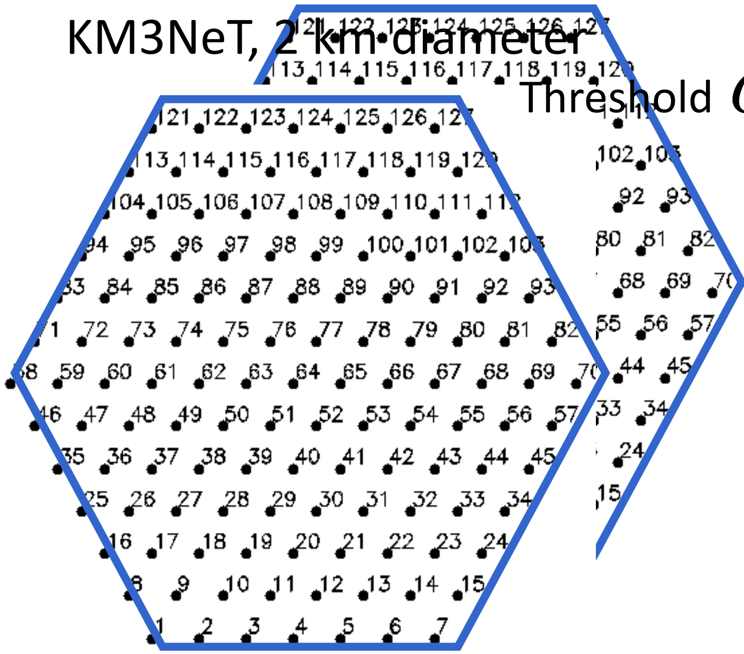
Status

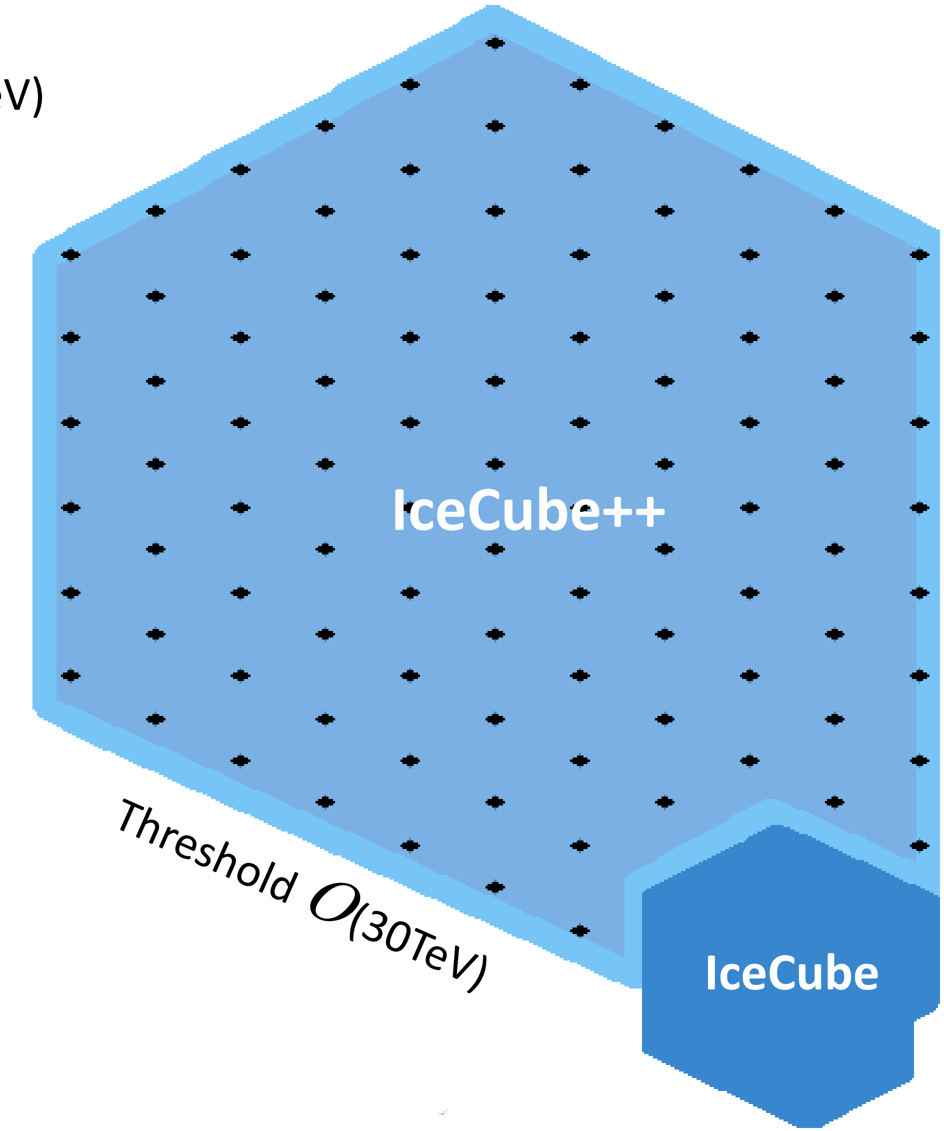
- High-energy neutrino astronomy:
  We may be close to first discoveries. Two events which tantalizingly look like extraterrestric.
- Have started muon astronomy?
- Record limits on LVI effects, dark matter cross sections and monopole fluxes
- Neutrino telescopes demonstrate their capability to measure „standard oscillations“.
- Neutrino telescopes are sensitive to certain sterile-neutrino scenarios.
- Neutrino telescope may be capable to determine the neutrino mass hierarchy (see talk of D. Wark).

... and the future?

KM3NeT, 2 km diameter

Threshold $\mathcal{O}$(1TeV)

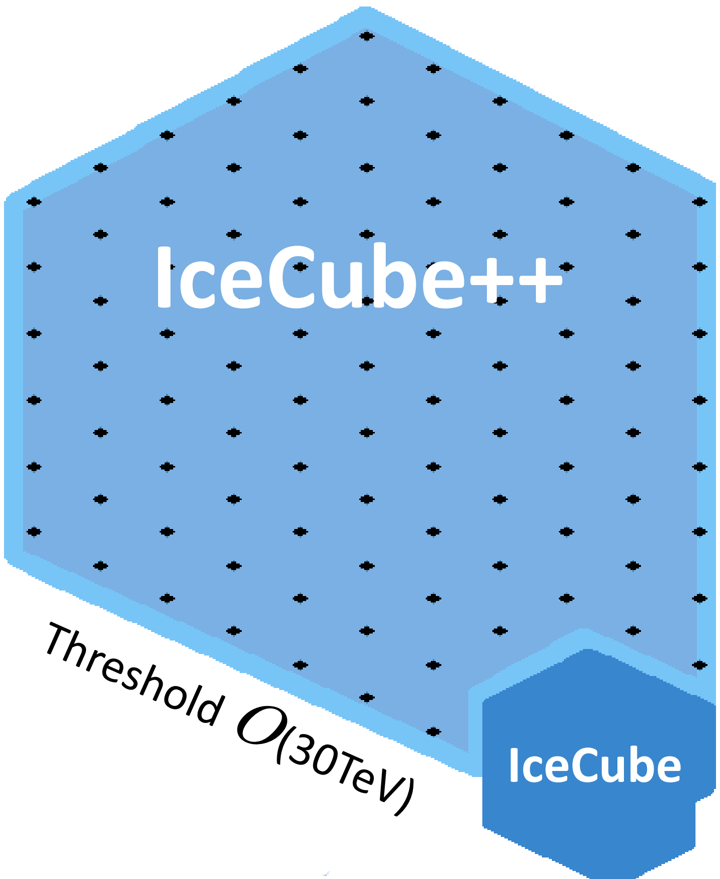




Threshold $\mathcal{O}$(30TeV)

Threshold $\mathcal{O}$(10TeV)

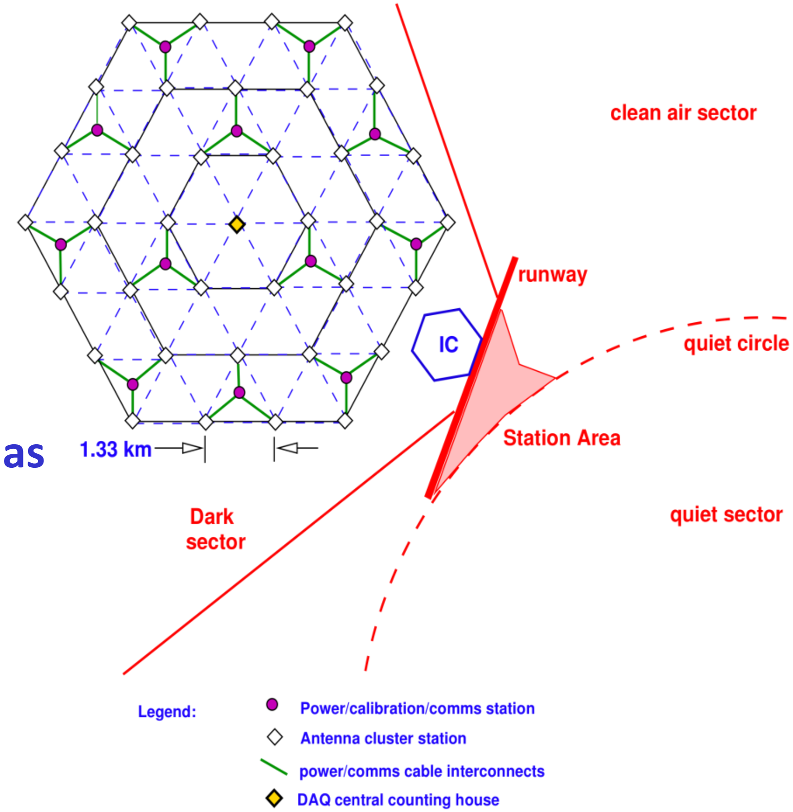
TeV-PeV vs. PeV-EeV vs. GeV

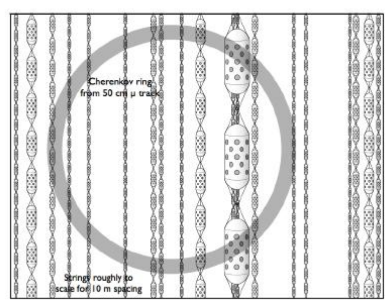


30 TeV – 30 PeV
continuation of
IceCube core program

ARA

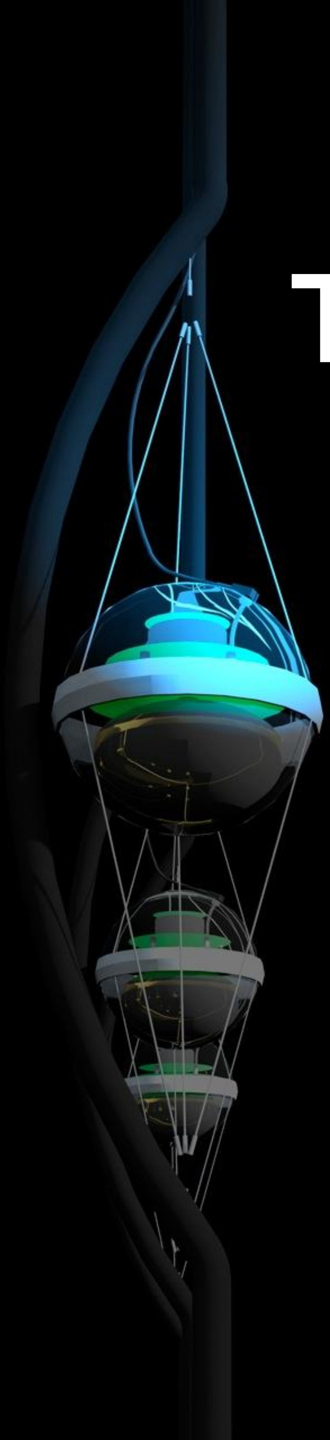
> 30 PeV:
Cosmogenic
Neutrinos
(> 50 PeV)
160 km²
radio antennas





PINGU

< 10 GeV: neutrino oscillations
SN collapses beyond our Galaxy
proton decay (??).



The next 2 years will be the moment of truth.

Keep your fingers crossed!