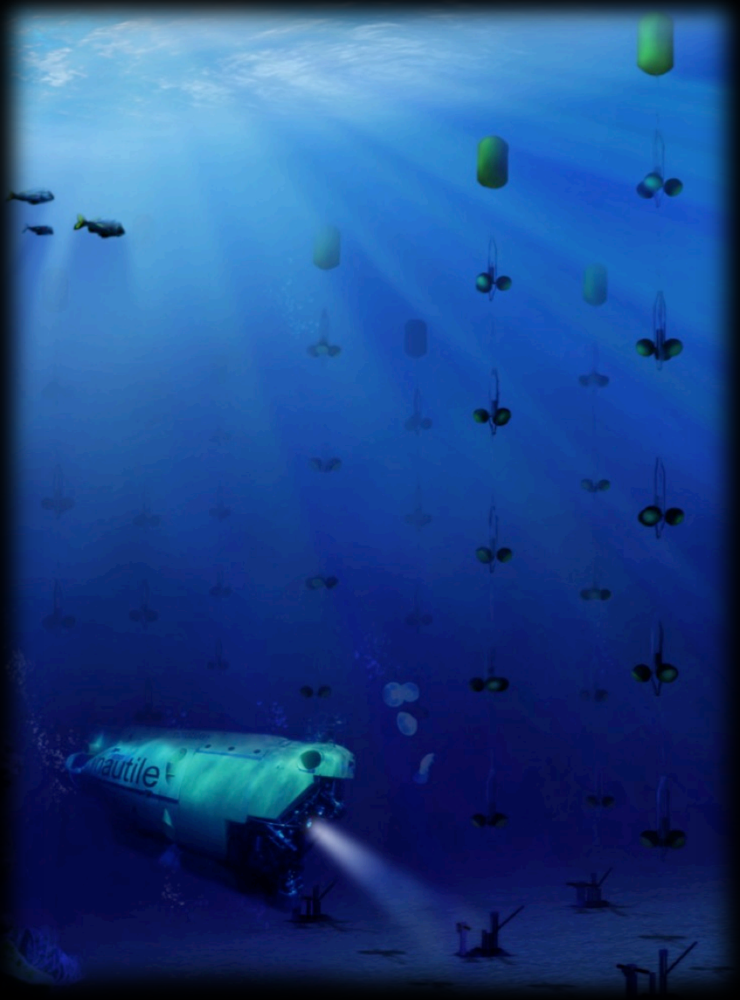
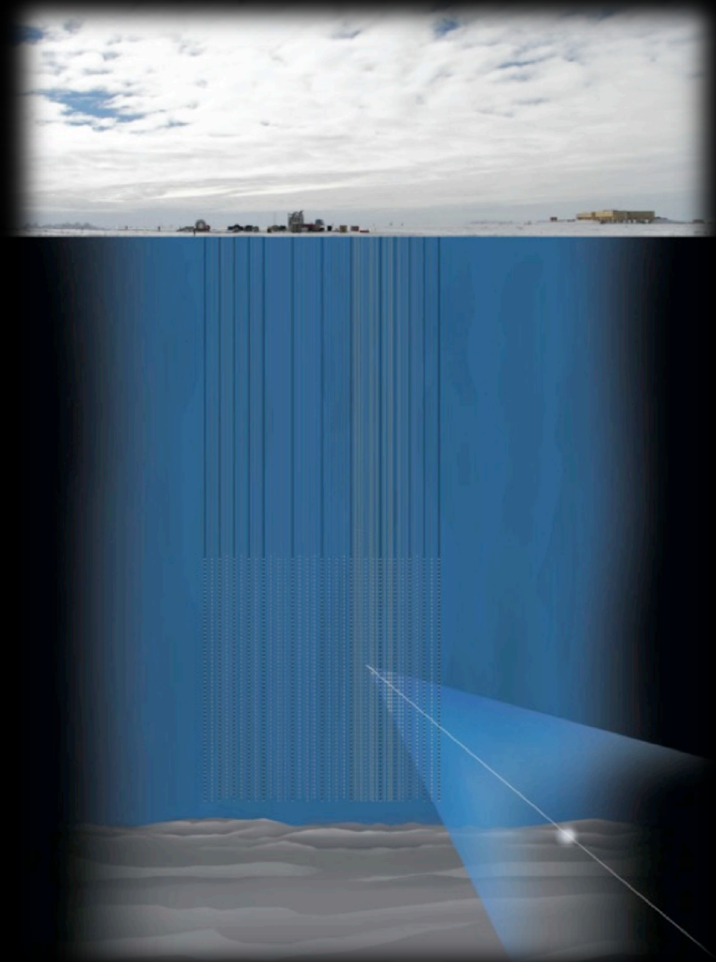
Neutrino Telescopes: Opening a New Window on the Universe

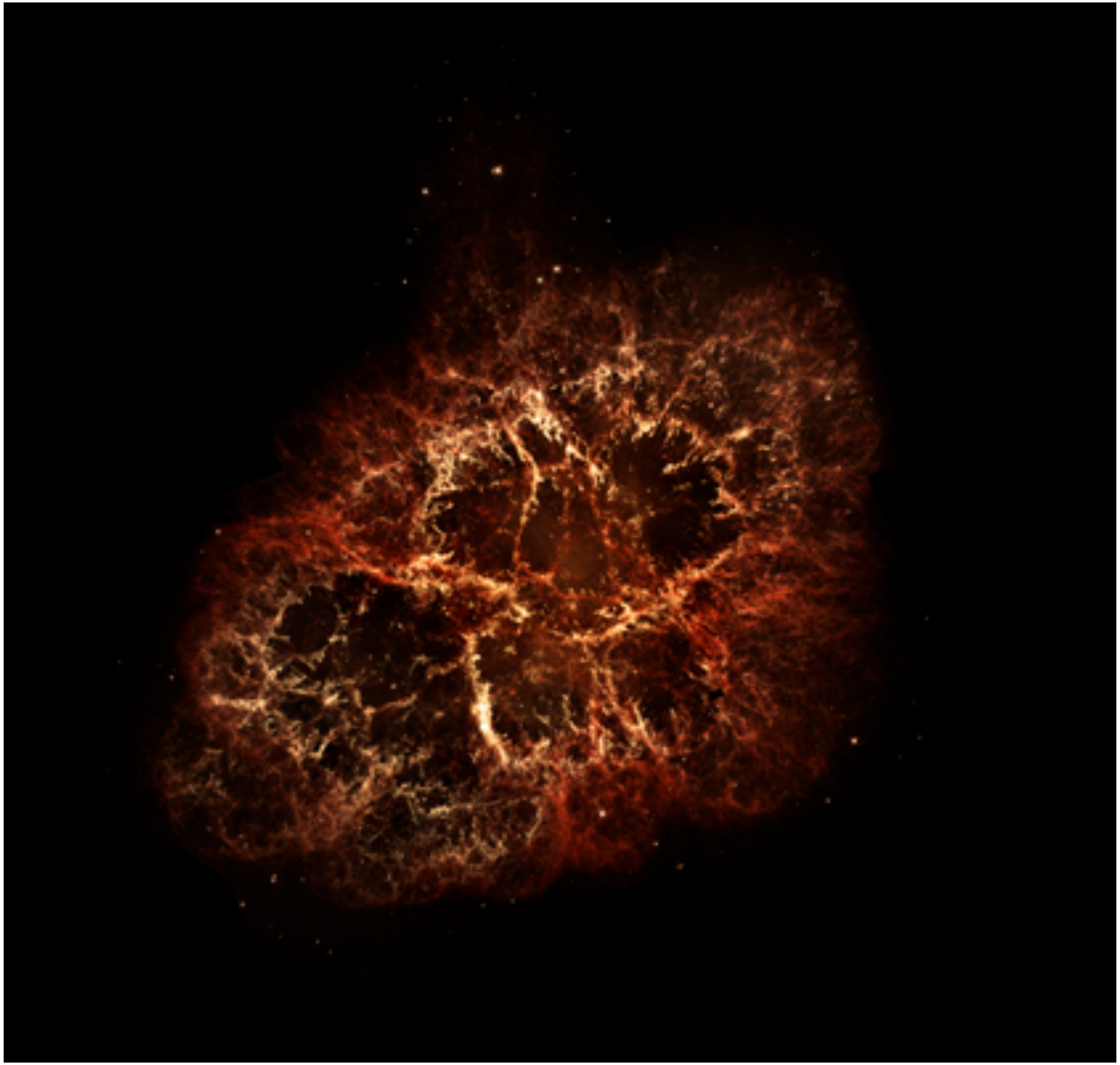




Chad Finley Oskar Klein Centre Stockholm University

XL IMFP - Benasque, Spain 2012 May 29

Crab Nebula – Optical (Hubble)



Crab Nebula – X-Ray (Chandra)

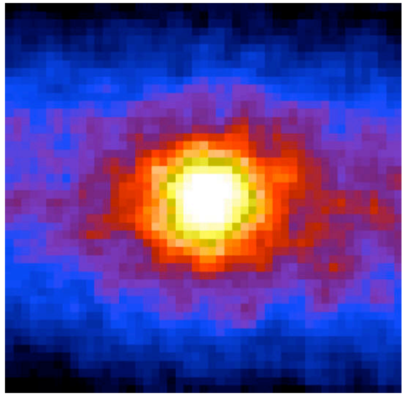
Crab Nebula - Composite

A New Window

Every band of the electromagnetic spectrum is a unique window

If we can detect high energy neutrinos from space, a new and complimentary window onto astronomy will be opened

The sun, “seen” in MeV neutrinos by Super-Kamiokande



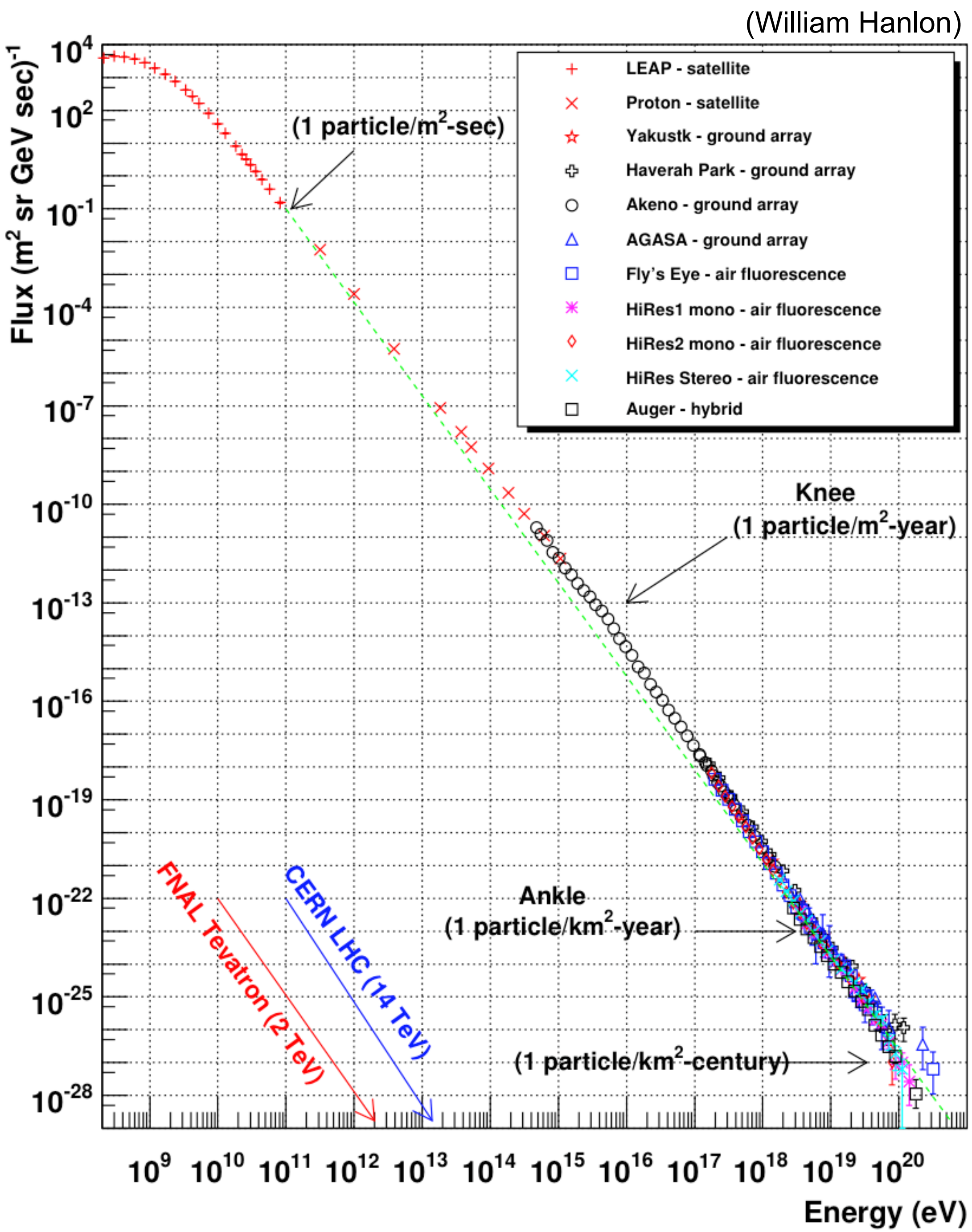
Why Neutrinos?

Cosmic ray spectrum of protons and nuclei extends above **10^8 TeV**

Extraordinary particle accelerators **exist**, but still **not identified** after 100 years (this year!)

- Supernova remnants?
- Microquasars?
- Active galactic nuclei?
- Gamma ray bursts?

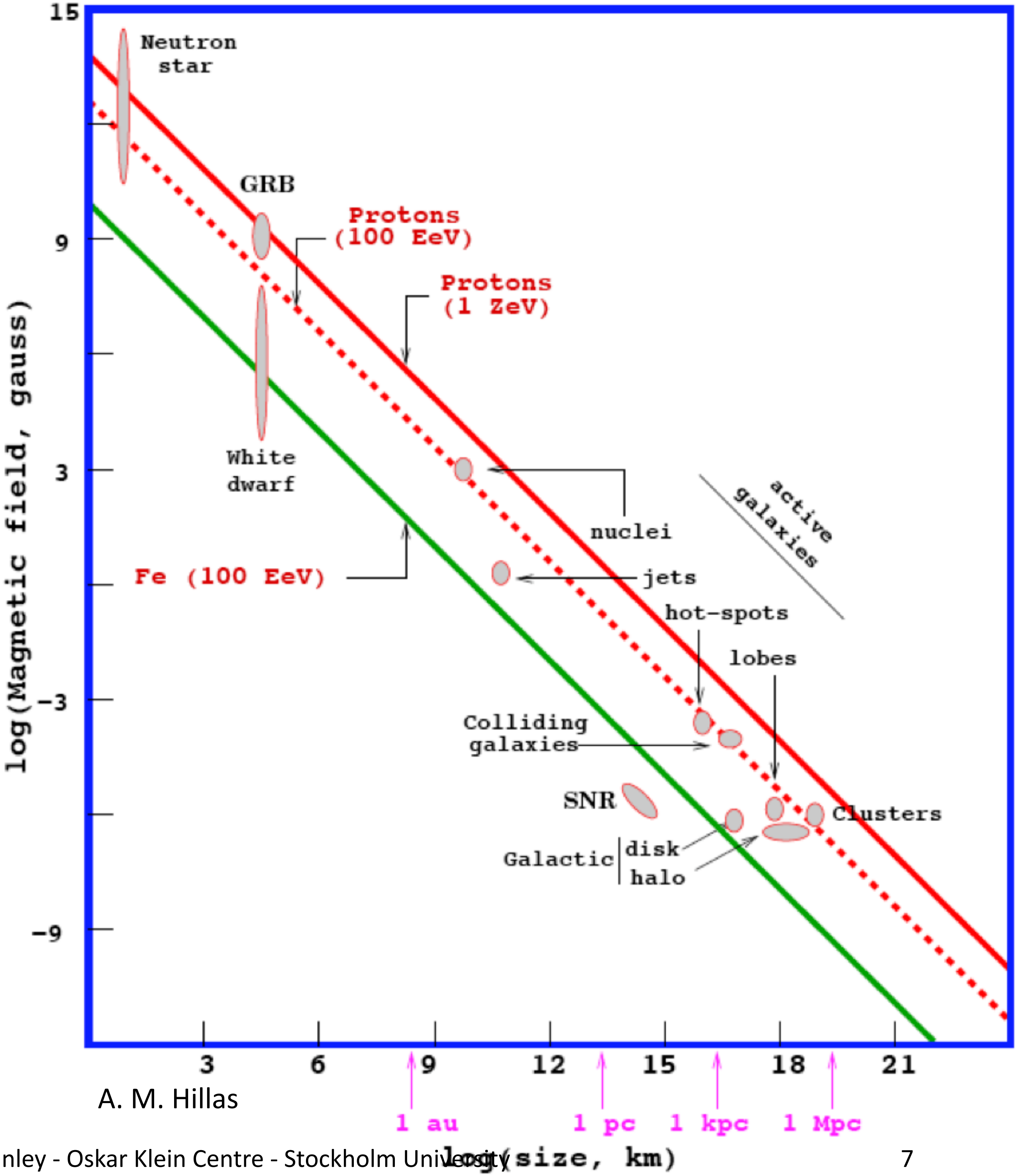
Cosmic ray interactions with matter and photons near source produce:
pions ➔ decay to **neutrinos**



Cosmic Ray Challenge: "Hillas Plot"

Size of accelerator and **magnetic field** within accelerator must be large enough to keep particles confined during acceleration

Biggest challenge:
Ultrahigh energy cosmic rays –
UHECR:
accelerating protons, nuclei up to 10^{20} eV



A. M. Hillas

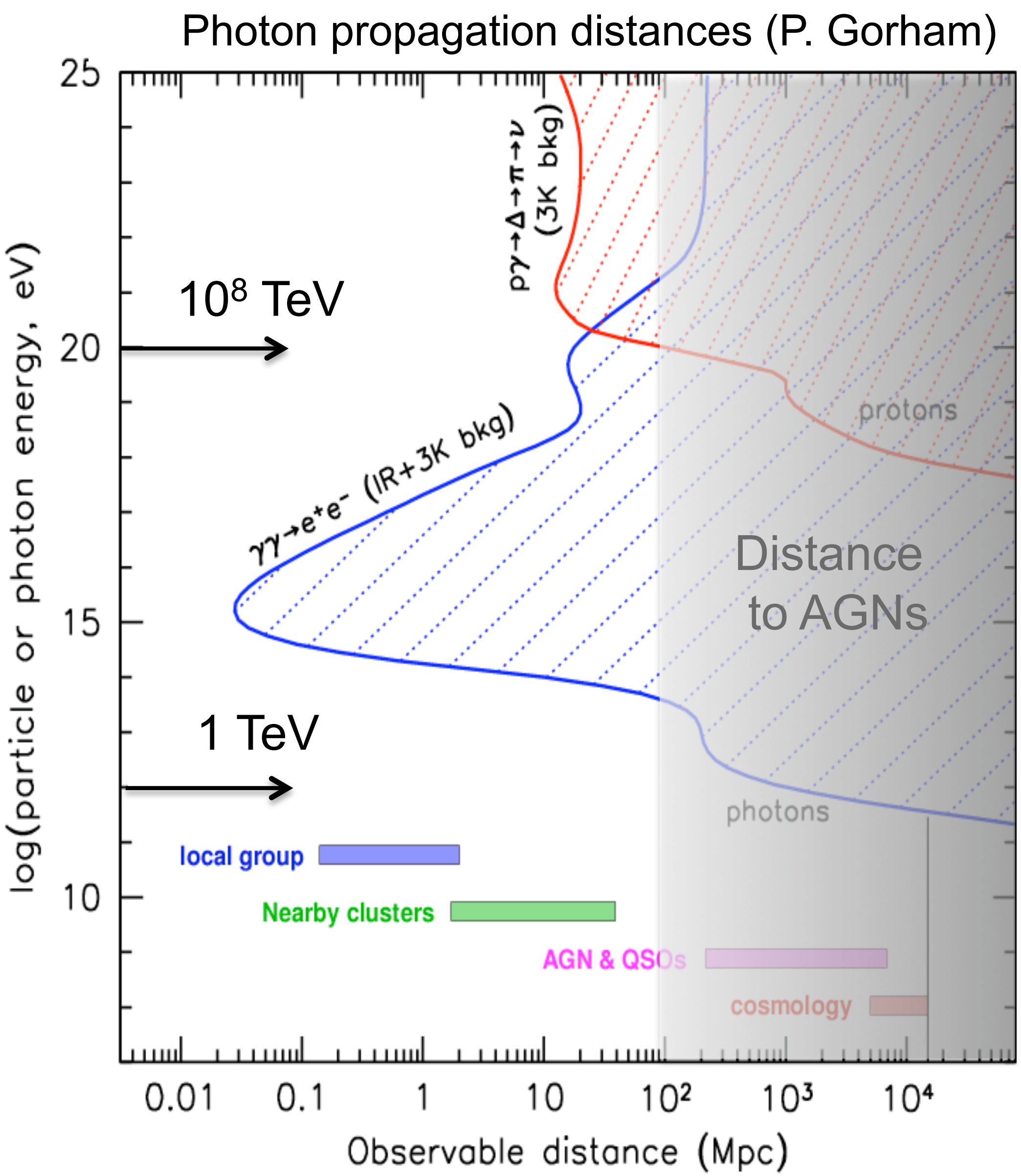
Why Neutrinos?

Cosmic ray sources may be optically thick; neutrinos can reveal **“hidden”** sources

Above 100 TeV, universe is **opaque for photons**, due to pair-production off background radiation fields (CMB, IR)

$$\gamma + \gamma_{IR,CMB,radio} \rightarrow e^{+} + e^{-}$$

Neutrinos are unique probe above these energies

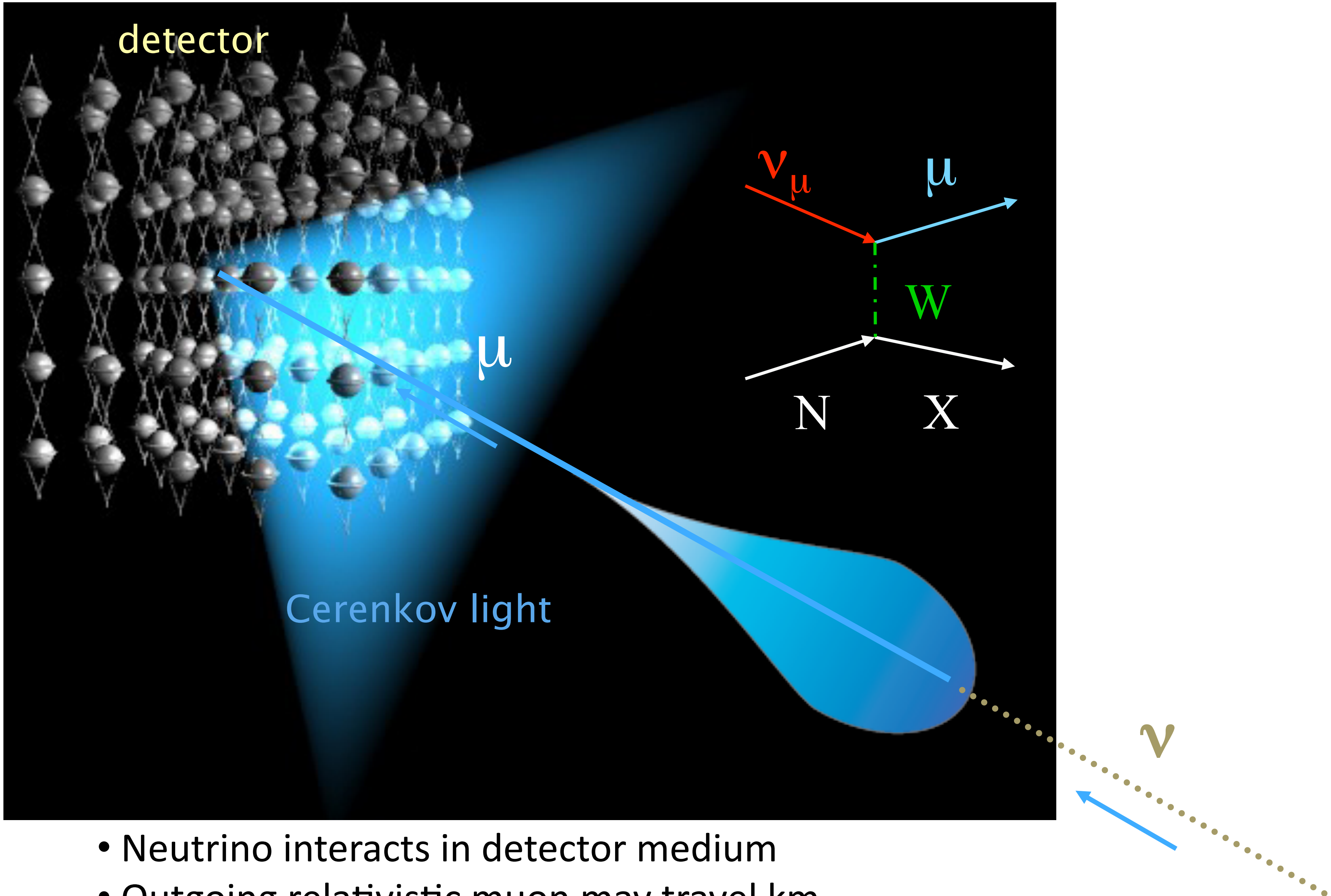


	favorite sources	possible science
*****	Atmospheric (~100,000 per year, up to 1000 TeV, charm ?)	Oscillations New neutrino interactions Tests of relativity and equivalence principle
***	GRB (successful and failed)	Sources of cosmic rays Test of Lorenz invariance Planck scale physics, quantum decoherence
**	AGN	Sources of cosmic rays
*	Starburst Galaxies	
****	Supernova remnants also, microquasars, magnetars, PWNe, binaries, unidentified EGRET sources, plane of the galaxy	Sources of galactic cosmic rays
****	Cosmic rays interacting with microwave photons	Identify sources of cosmic rays Neutrino cross section at EeV energy
	Dark Matter	Annihilation in the sun, mostly spin-dependent
*****	Cosmic rays interacting with the sun	Background to WIMP search
*****	Supernova explosion	Deleptonization, TeV emission, hierarchy, $\sin\theta_{13}$

	favorite sources	possible science
*****	Atmospheric (~100,000 per year, up to 1000 TeV, charm ?)	Oscillations New neutrino interactions Tests of relativity and equivalence principle
***	GRB (successful and failed)	Sources of cosmic rays Test of Lorenz invariance Planck scale physics, quantum decoherence
**	AGN	Sources of cosmic rays
*	Starburst Galaxies	
****	Supernova remnants also, microquasars, magnetars, PWNe, binaries, unidentified EGRET sources, plane of the galaxy	Sources of galactic cosmic rays
****	Cosmic rays interacting with microwave photons	Identify sources of cosmic rays Neutrino cross section at EeV energy
	Dark Matter	Annihilation in the sun, mostly spin-dependent
*****	Cosmic rays interacting with the sun	Background to WIMP search
*****	Supernova explosion	Deleptonization, TeV emission, hierarchy, $\sin\theta_{13}$

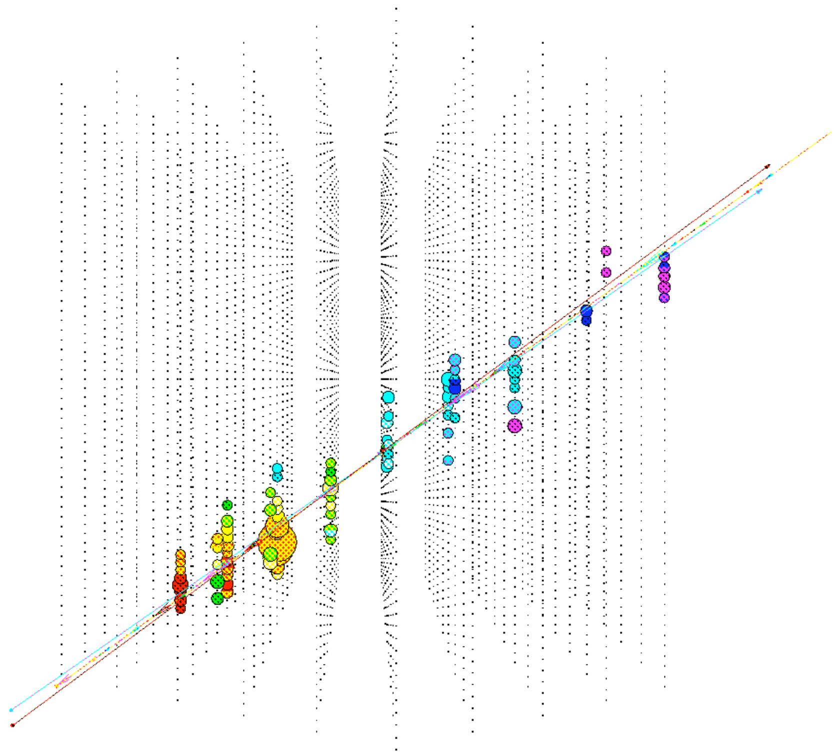
	favorite sources	possible science
*****	Atmospheric (~100,000 per year, up to 1000 TeV, charm ?)	Oscillations New neutrino interactions Tests of relativity and equivalence principle
***	GRB (successful and failed)	Sources of cosmic rays Test of Lorenz invariance Planck scale physics, quantum decoherence
**	AGN	Sources of cosmic rays
*	Starburst Galaxies	
****	Supernova remnants also, microquasars, magnetars, PWNe, binaries, unidentified EGRET sources, plane of the galaxy	Sources of galactic cosmic rays
****	Cosmic rays interacting with microwave photons	Identify sources of cosmic rays Neutrino cross section at EeV energy
	Dark Matter	Annihilation in the sun, mostly spin-dependent
*****	Cosmic rays interacting with the sun	Background to WIMP search
*****	Supernova explosion	Deleptonization, TeV emission, hierarchy, $\sin\theta_{13}$

Neutrino Detection Principles

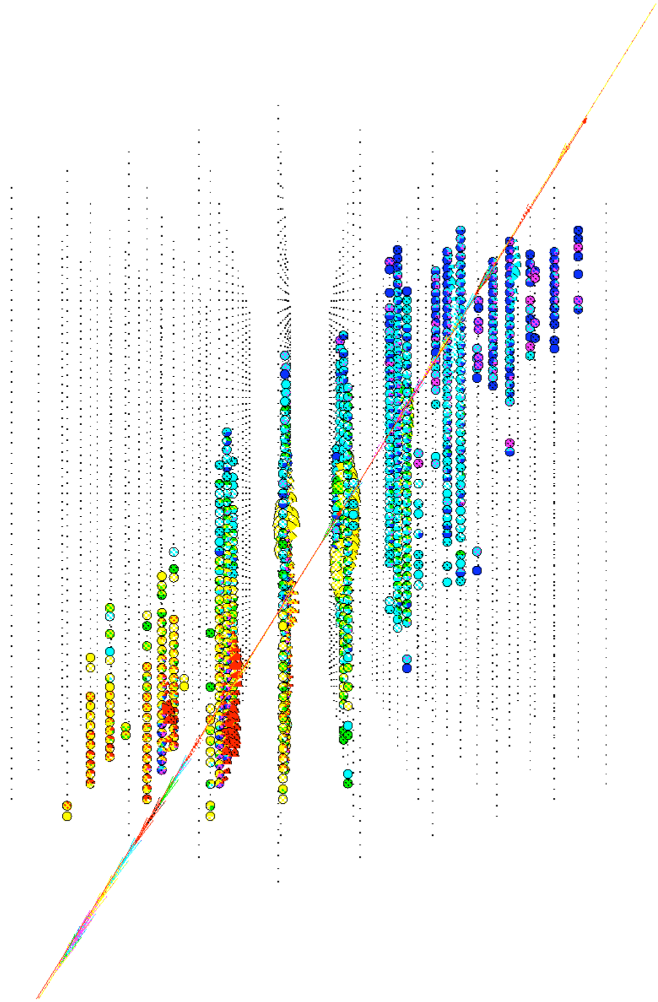


- Neutrino interacts in detector medium
- Outgoing relativistic muon may travel km
- Detector records times and locations of Cerenkov photon hits

Muon Neutrinos



E = 6 TeV



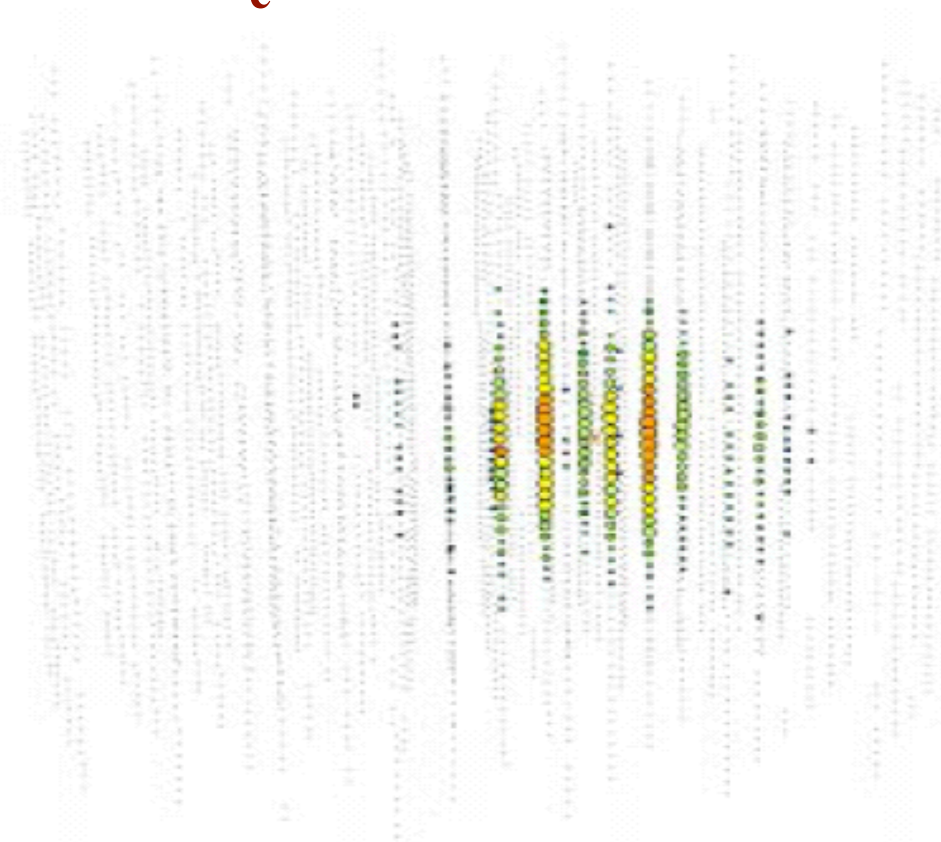
E = 6400 TeV

Long muon track ➔ good pointing

Neutrino interaction outside detector ➔ energy (light) measured is lower bound

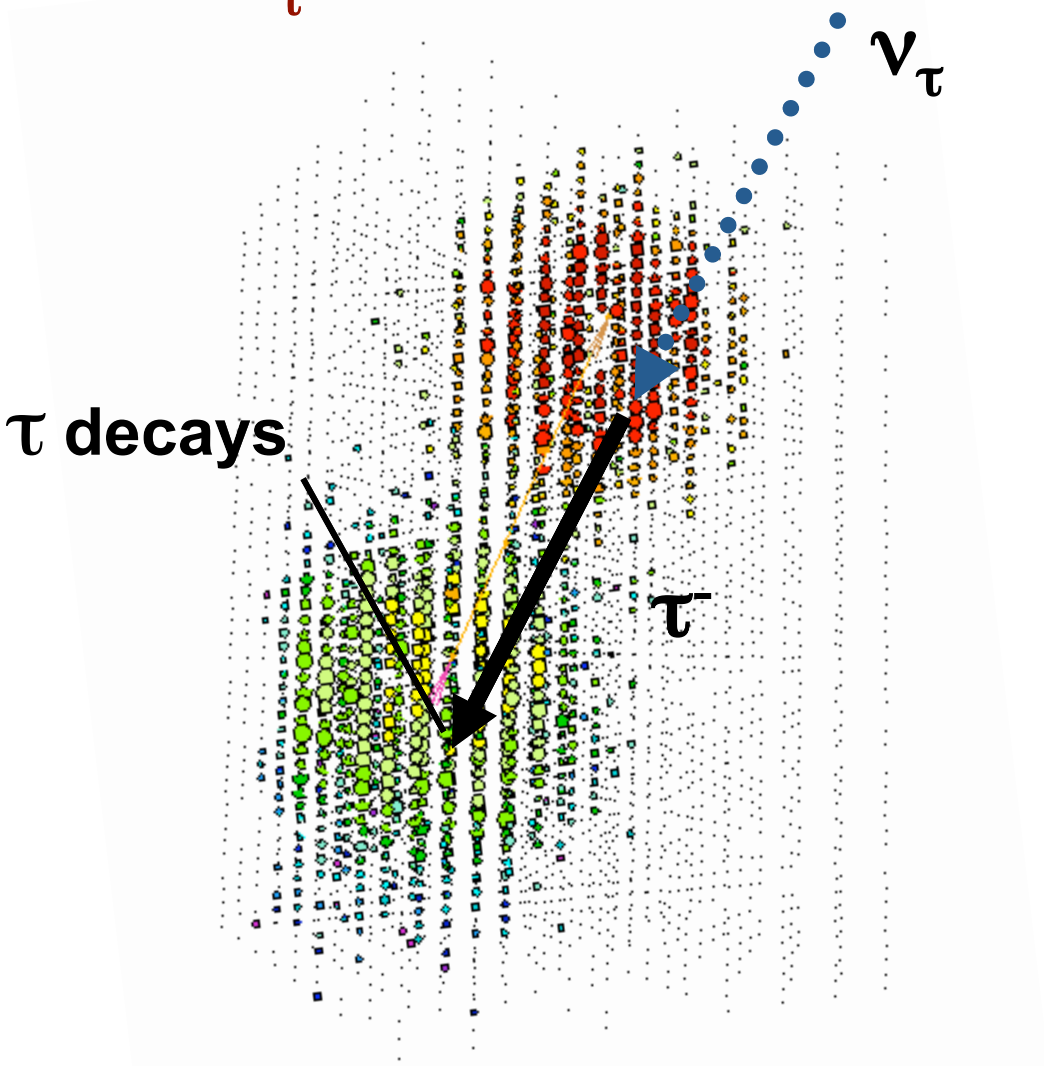
ν_e and ν_τ cascade events

$\nu_e + N \rightarrow e^- + X$

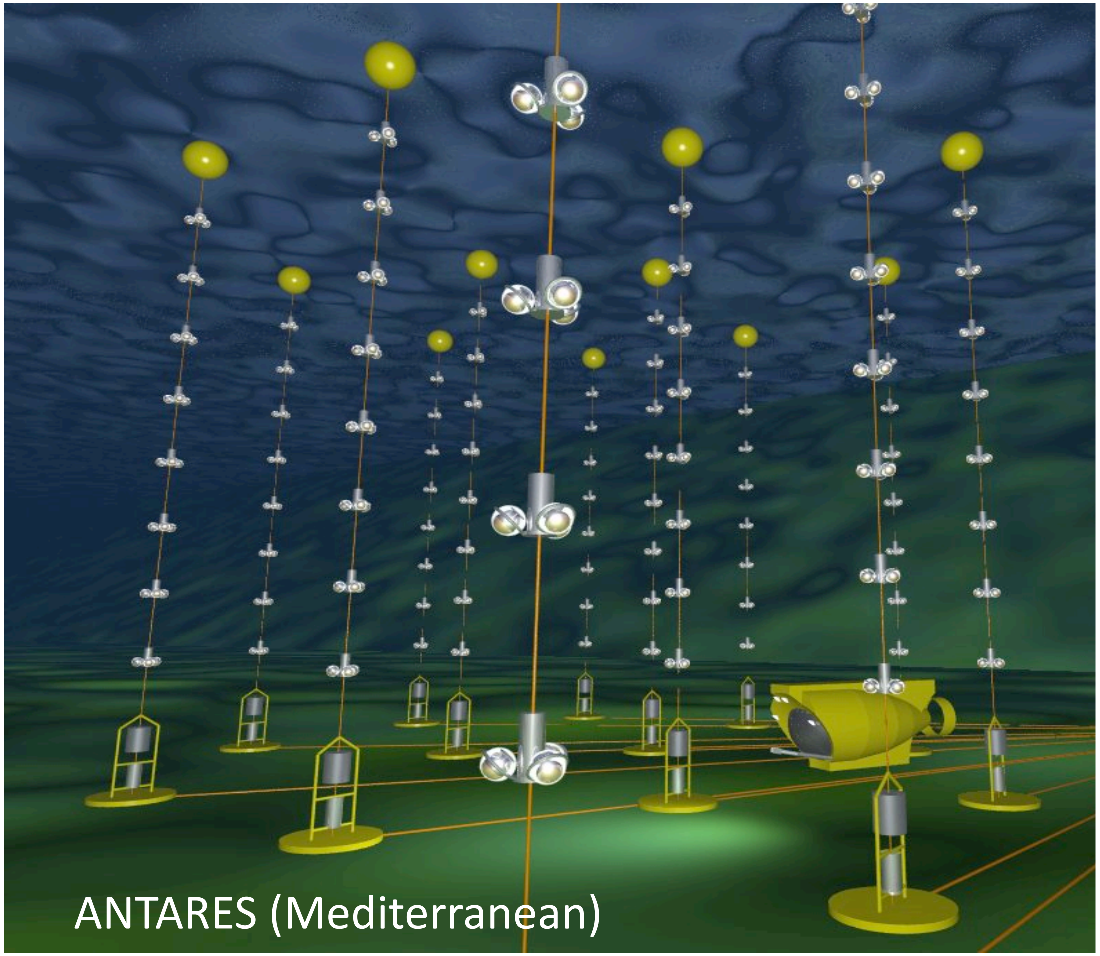


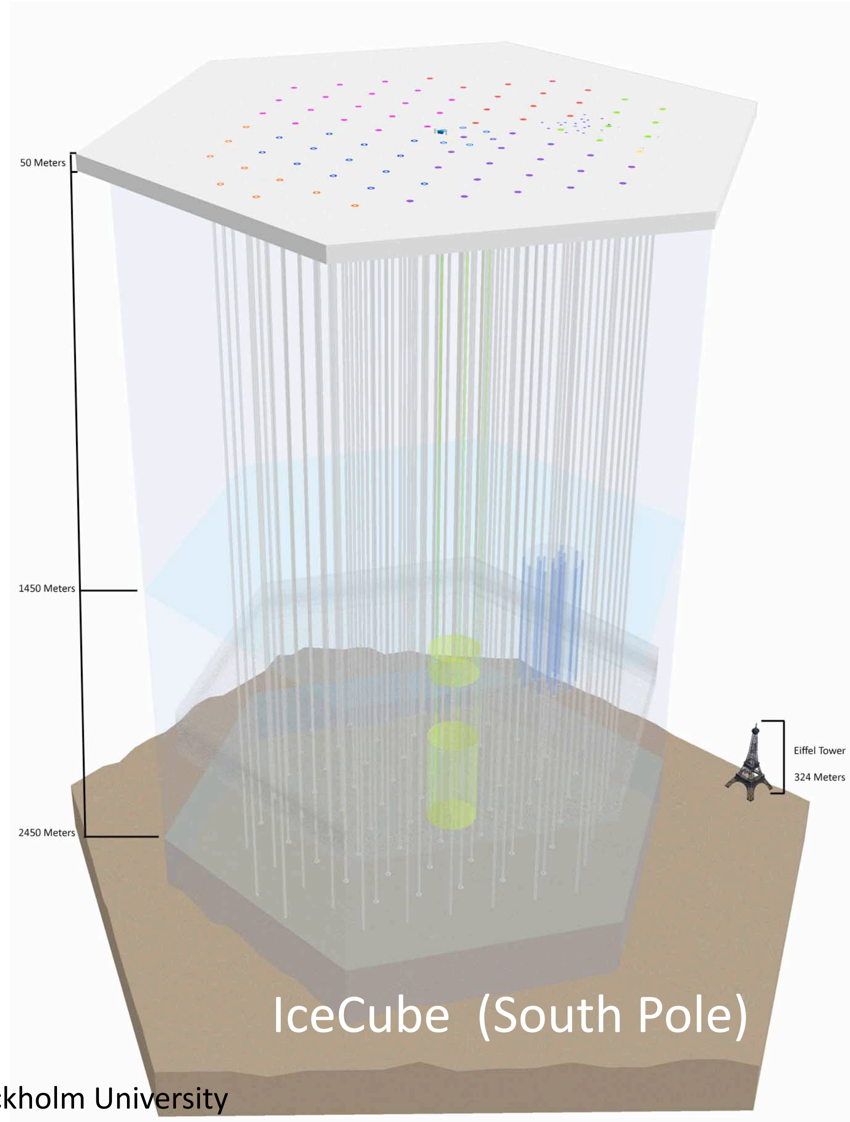
E = 375 TeV

$\nu_\tau + N \rightarrow \tau^- + X$



E = 6000 TeV





Water and **Ice** are both excellent media, with different advantages

Detector Media

	Fresh Water	Sea Water	Glacial Ice
	Baikal	ANTARES / KM3NeT	IceCube
Scattering Length:	30 – 50 m	> 250 m	~ 20 m
Absorption Length:	22 – 24 m	55 – 60 m	~ 100 m
Background:	Moderately low	~ 45 kHz (^{40}K)	~ 300 Hz

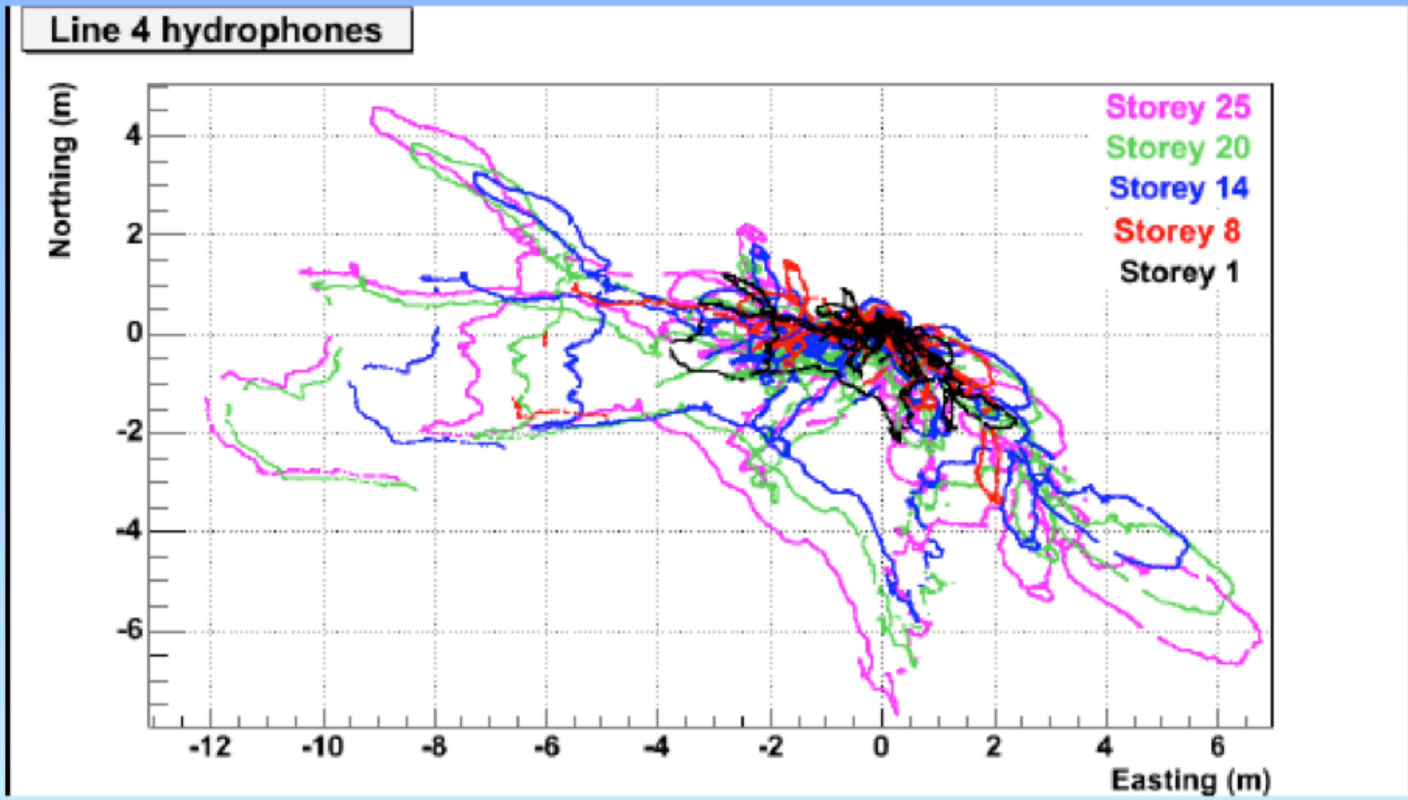
Glacial ice is not as clear as water
(though much clearer than ice from your freezer)

Glacial ice extremely dark / low background environment

Operating detector in ocean or glacier present different technical challenges as well…

Sea Water is Moving:

- Examples of radial displacement on Line 4 hydrophones given by triangulation



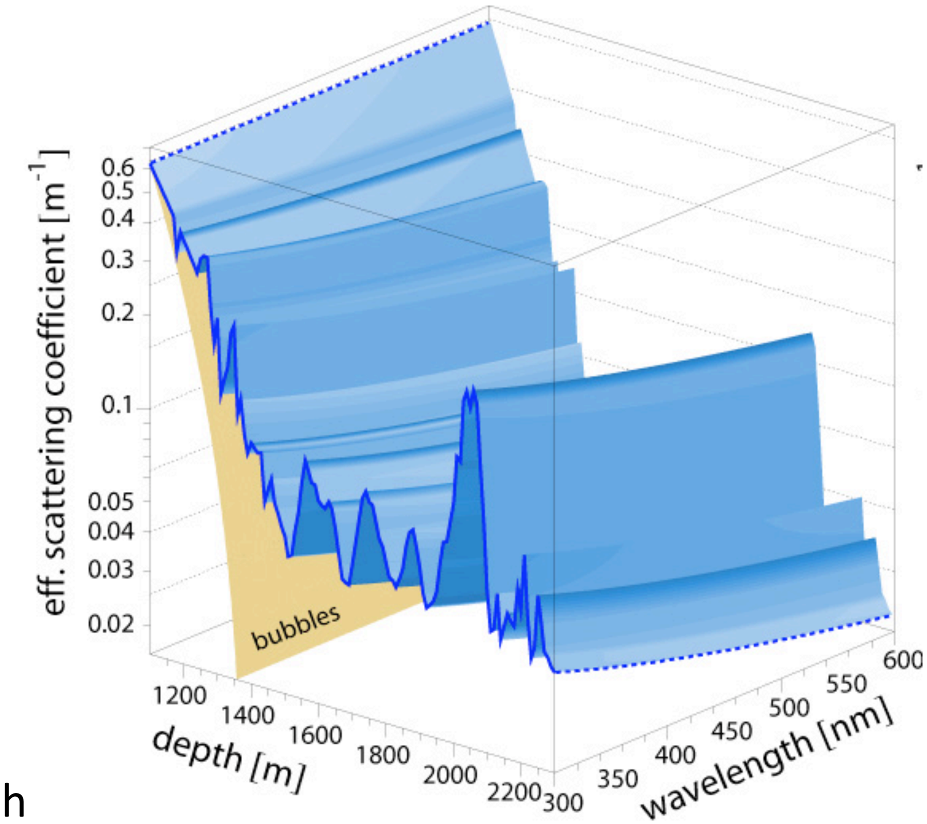
- Hydrophone displacements followed with few cm accuracy
- Larger displacements are observed for the top storeys
- Line movement dominated by East-West heading of the Ligurian current.

VLVNT'08 - Toulon M. Ardid – Positioning System of the ANTARES Neutrino Telescope

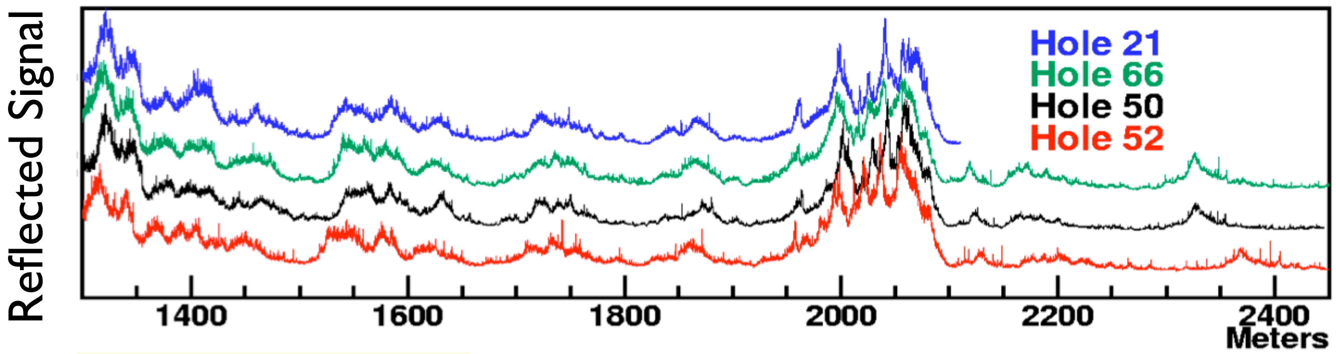
Ice Properties are Inhomogeneous

Small dust in ice varies with depth

Traces climate changes over past 90 000 years

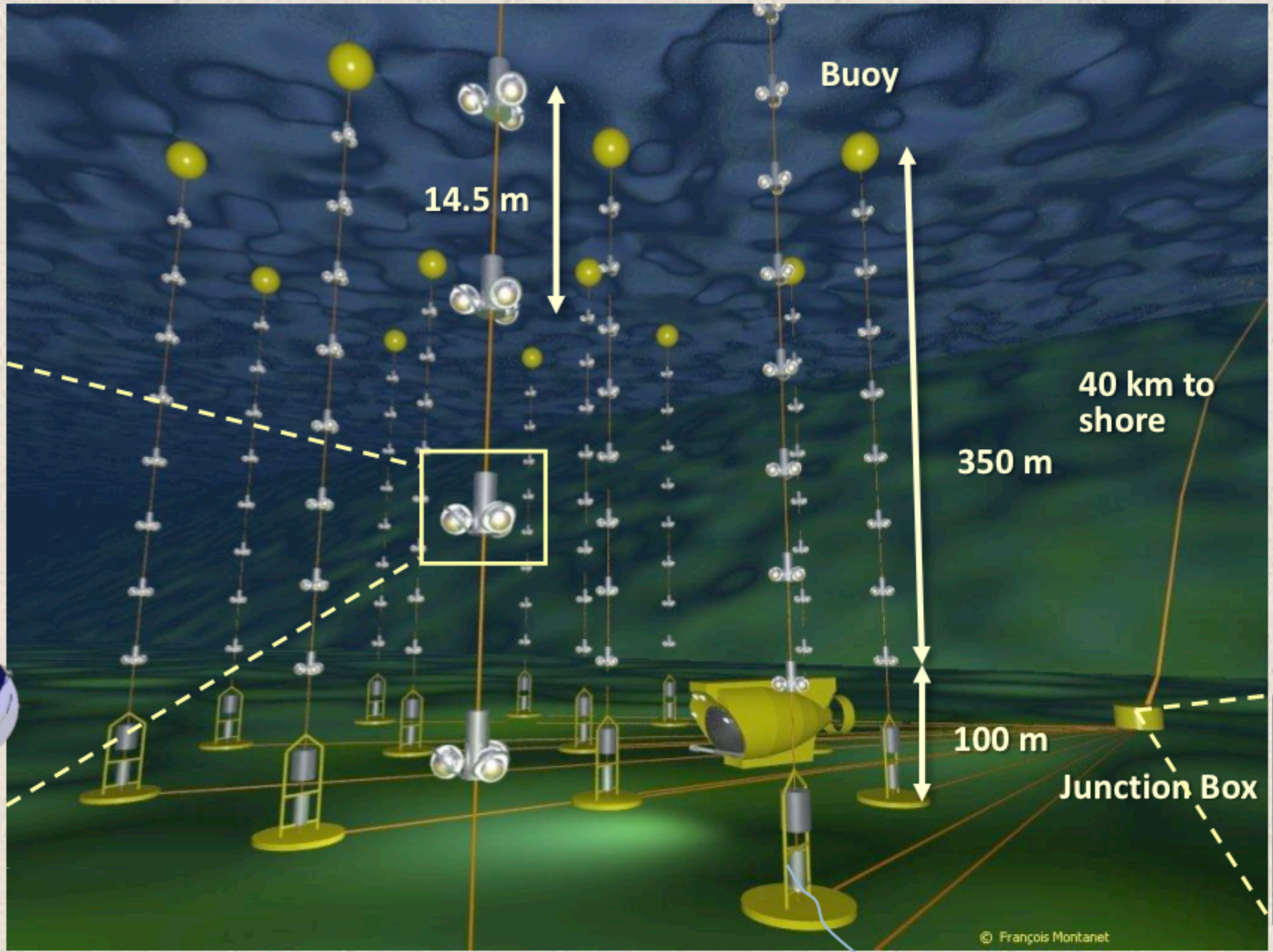


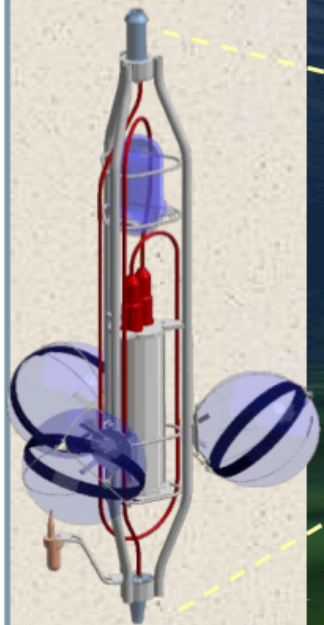
Ice Properties measured with specialized device



J. J. Hernandez-Rey (VLVnT11)

ANTARES





12 lines (885 PMTs)
25 storeys / line
3 PMTs / storey

5-line setup in 2007
Completed in 2008

λ_{abs}
55-60 m

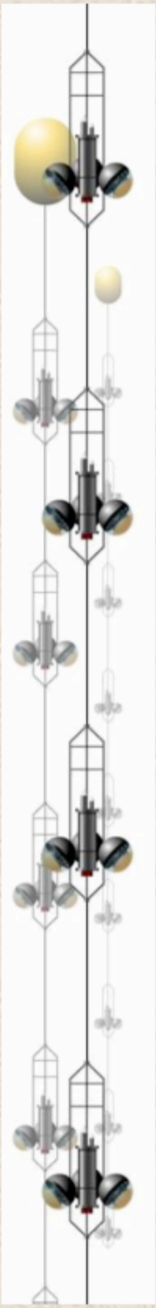
$\lambda_{scatt}/(1-\langle\cos\theta\rangle)$
> 250 m

In the Mediterranean Sea
(near Toulon) at 2475 m depth
Latitude N 42º

Astrop. Phys. **26** (2006) 314
NIM **A581** (2007) 695
Astrop. Phys. **31** (2009) 277
NIM **A656** (2011) 11

J. J. Hernandez-Rey (VLVnT11)

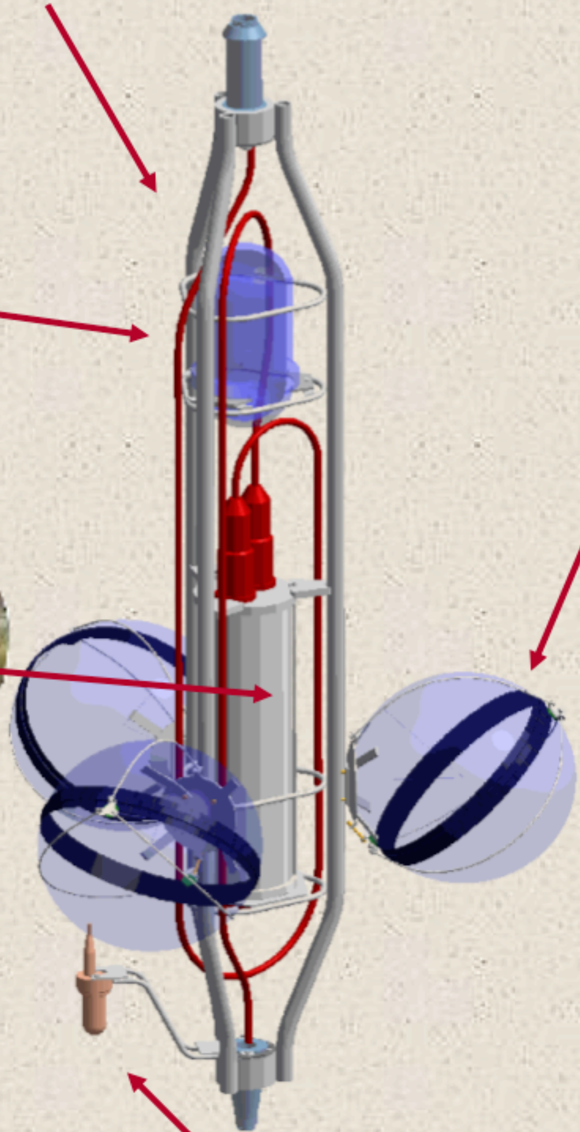
Basic detector element: storey

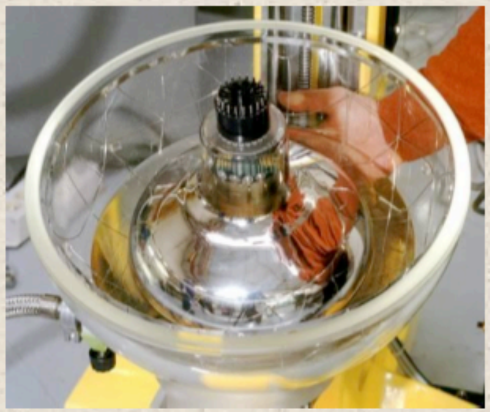


Titanium frame: *support structure*

Optical Beacon
with blue LEDs:
timing calibration

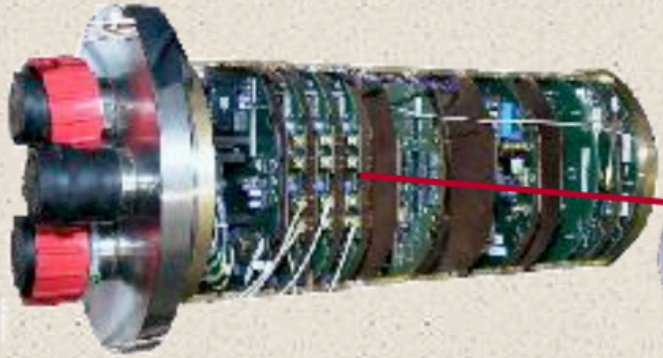
NIM **A578** (2007) 498
Astrop. Phys **34** (2011) 539





Optical Module:
10″ Hamamatsu PMT in
17″ glass sphere
photon detection

NIM **A484** (2002) 369
NIM **A555** (2005) 132



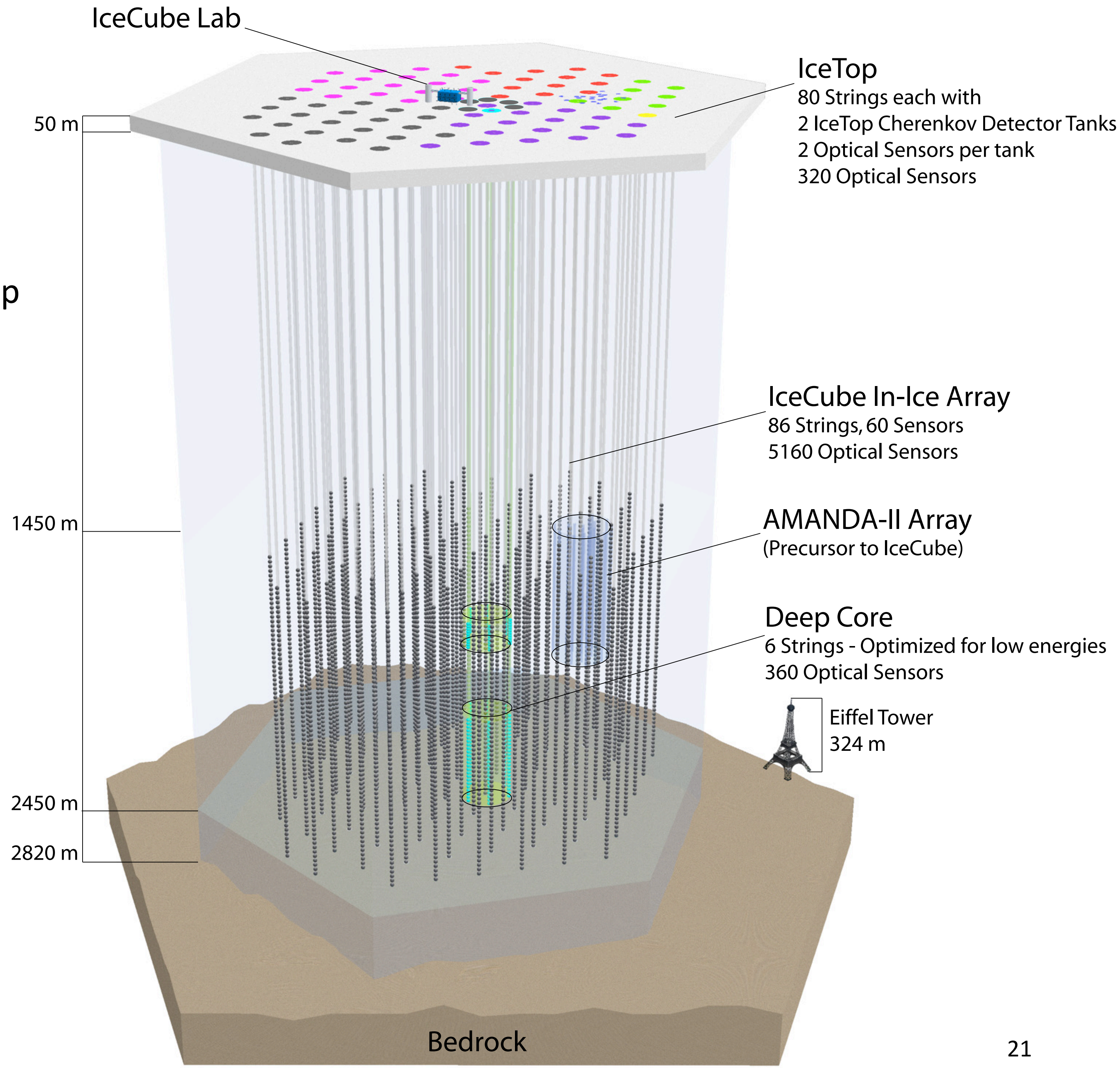
Local Control Module (Ti):
Front-end ASIC, DAQ/SC, DWDM,
Clock, tilt/compass, power distribution…

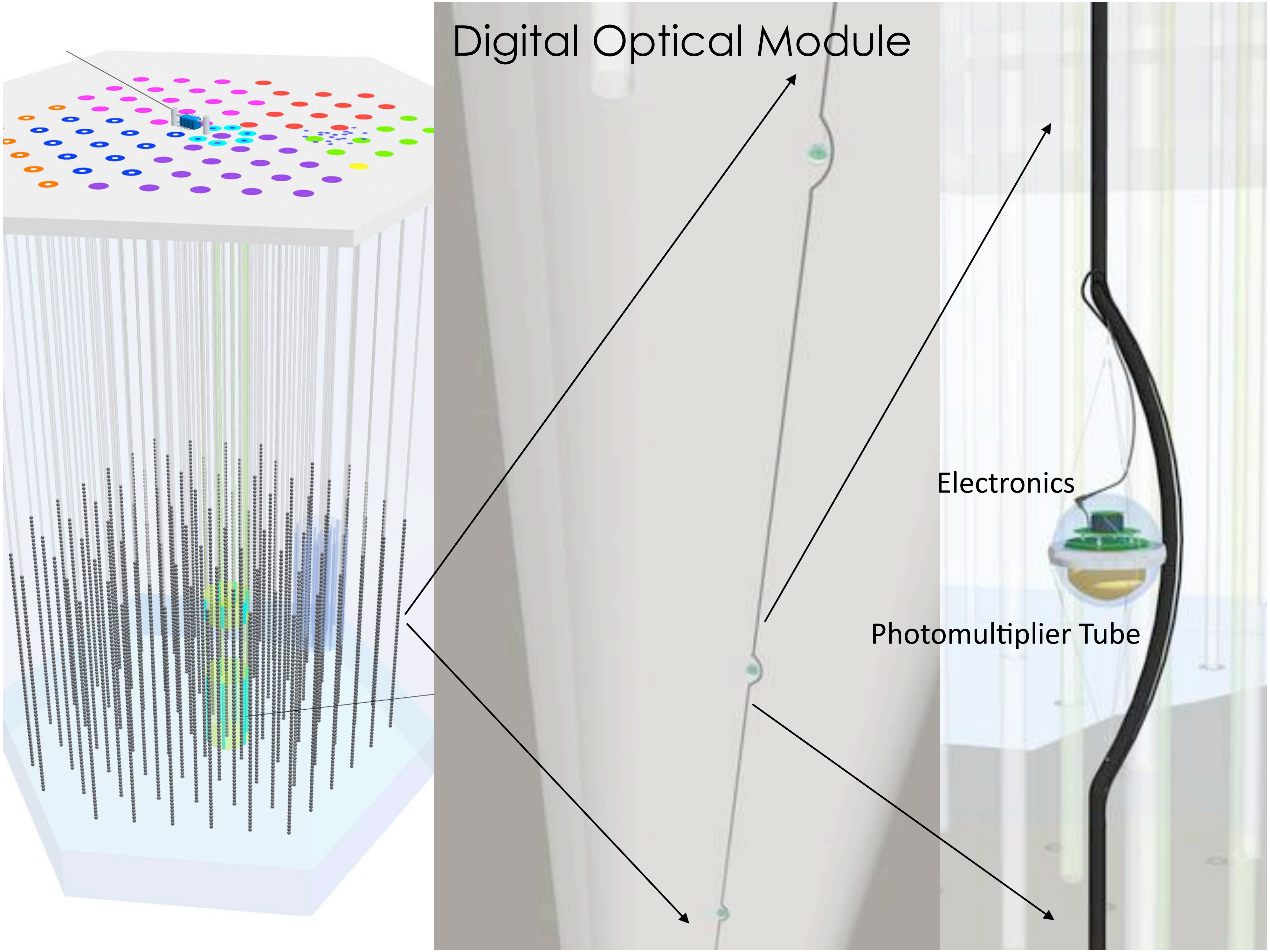
NIM **A570** (2007) 107
NIM **A622** (2010) 59

Hydrophone:
acoustic positioning

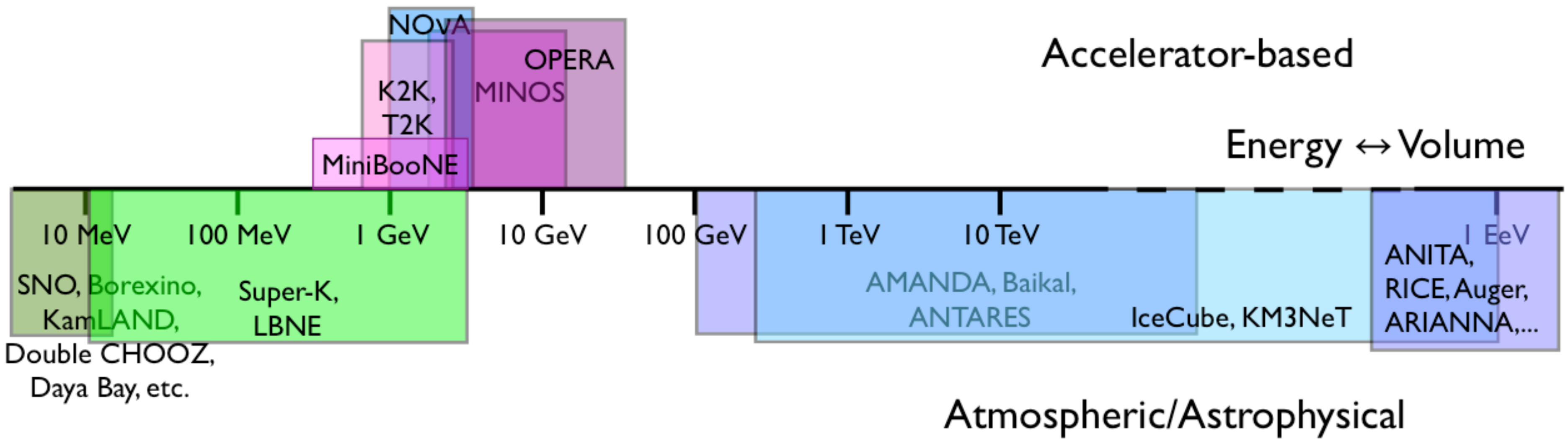
IceCube

- 86 strings
- 1.5 km - 2.5 km deep
- typically 125 m spacing between strings
- 60 Modules per string
- 1 km^3 -- 1 Gton instrumented volume

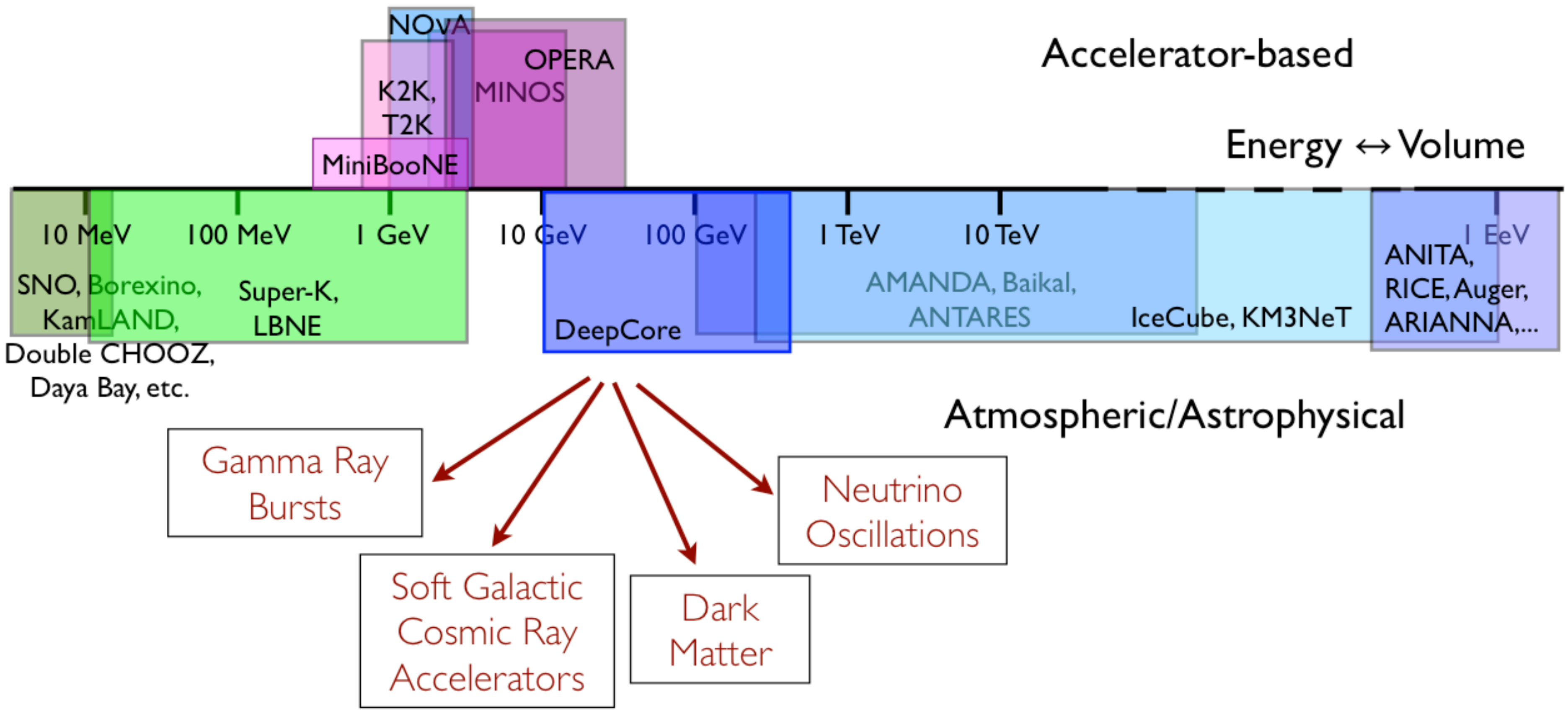



Digital Optical Module
Electronics
Photomultiplier Tube

The Neutrino Detector Spectrum

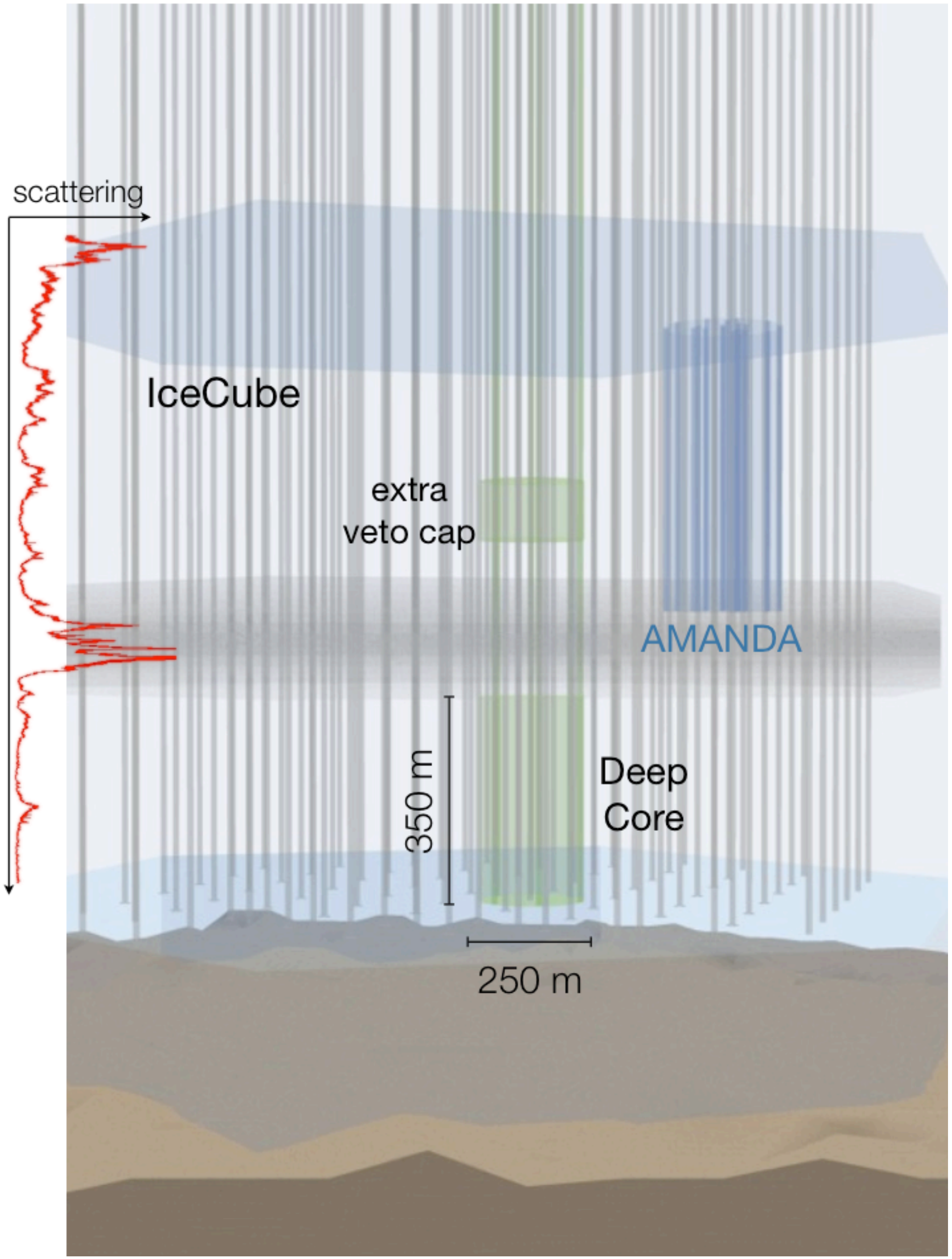


The Neutrino Detector Spectrum



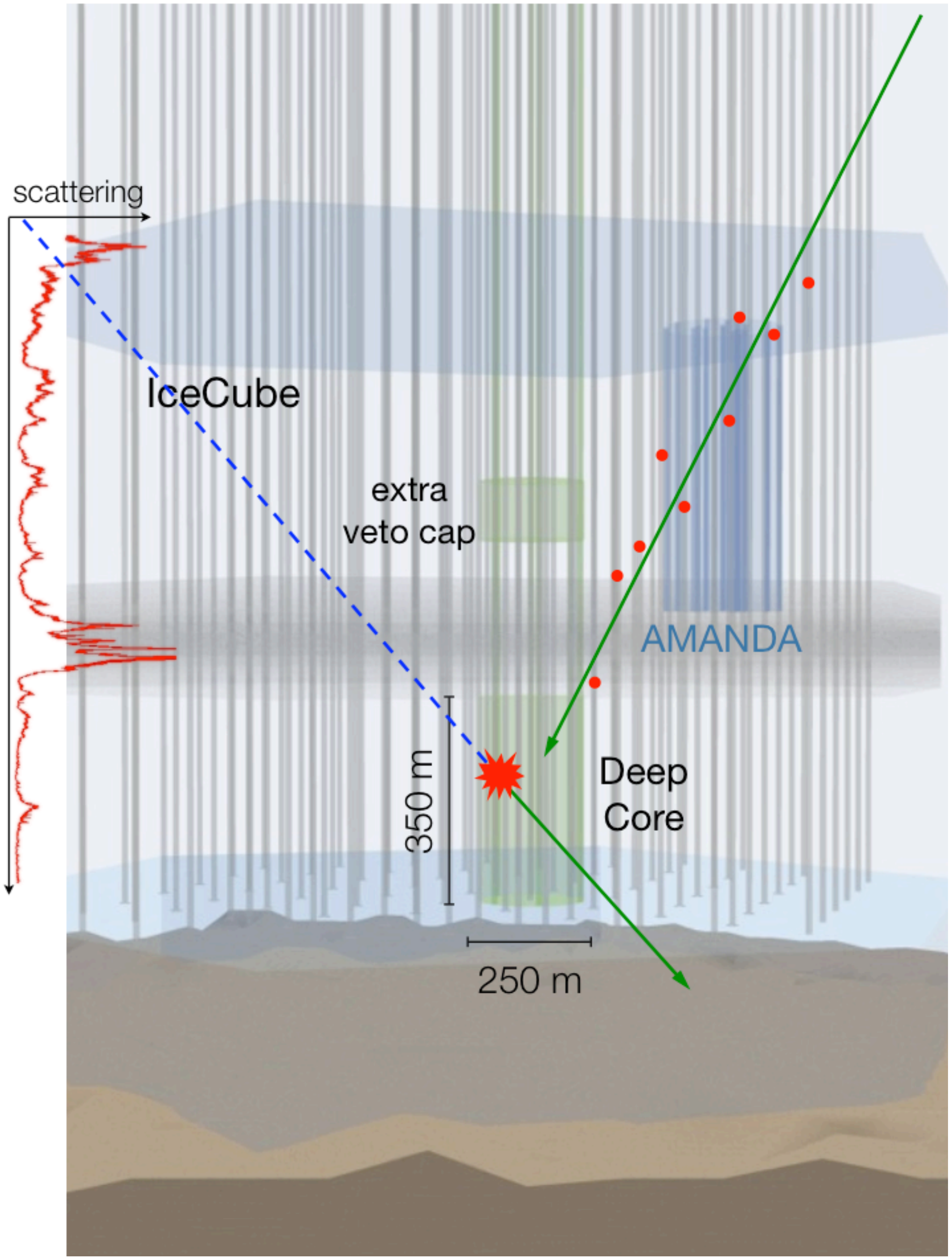
IceCube DeepCore

- Eight special strings plus 12 nearest standard IceCube strings
  - 72 m interstring spacing
  - 7 m DOM spacing
  - High Q.E. PMTs
  - ~5x higher effective photocathode density
- In the clearest ice, below 2100 m
  - $\lambda_{atten} \approx$ 40-45 m
- 30 MTon detector with ~10 GeV threshold, $\mathcal{O}(10^5)$ atm. ν / year
- IceCube is an active veto against cosmic ray muon background

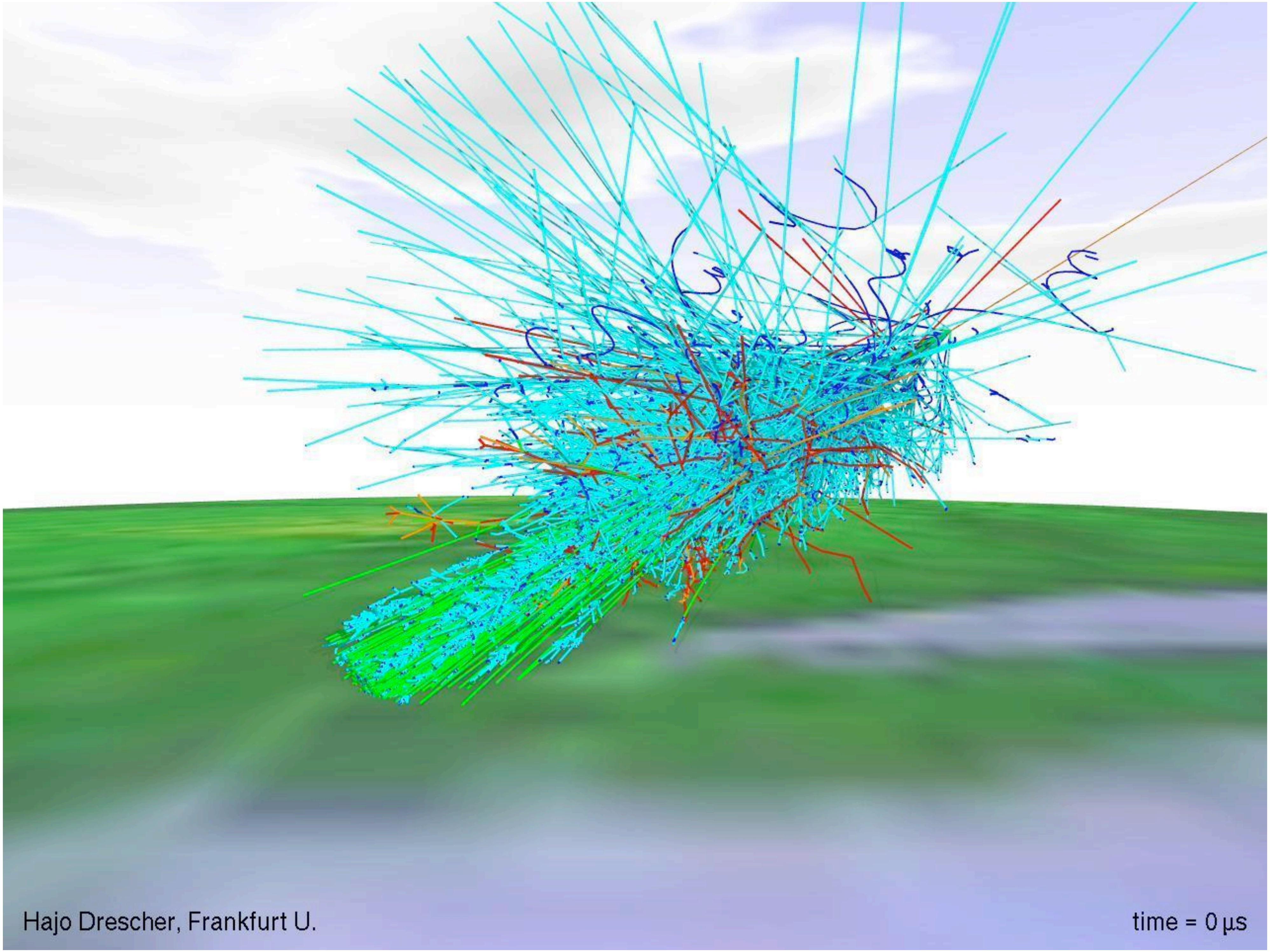


IceCube DeepCore

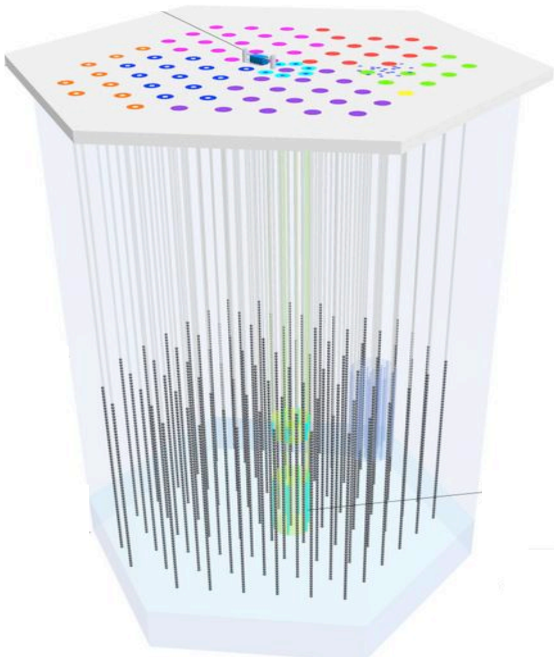
- Eight special strings plus 12 nearest standard IceCube strings
  - 72 m interstring spacing
  - 7 m DOM spacing
  - High Q.E. PMTs
  - ~5x higher effective photocathode density
- In the clearest ice, below 2100 m
  - $\lambda_{atten} \approx$ 40-45 m
- 30 MTon detector with ~10 GeV threshold, $\mathcal{O}(10^5)$ atm. ν / year
- IceCube is an active veto against cosmic ray muon background

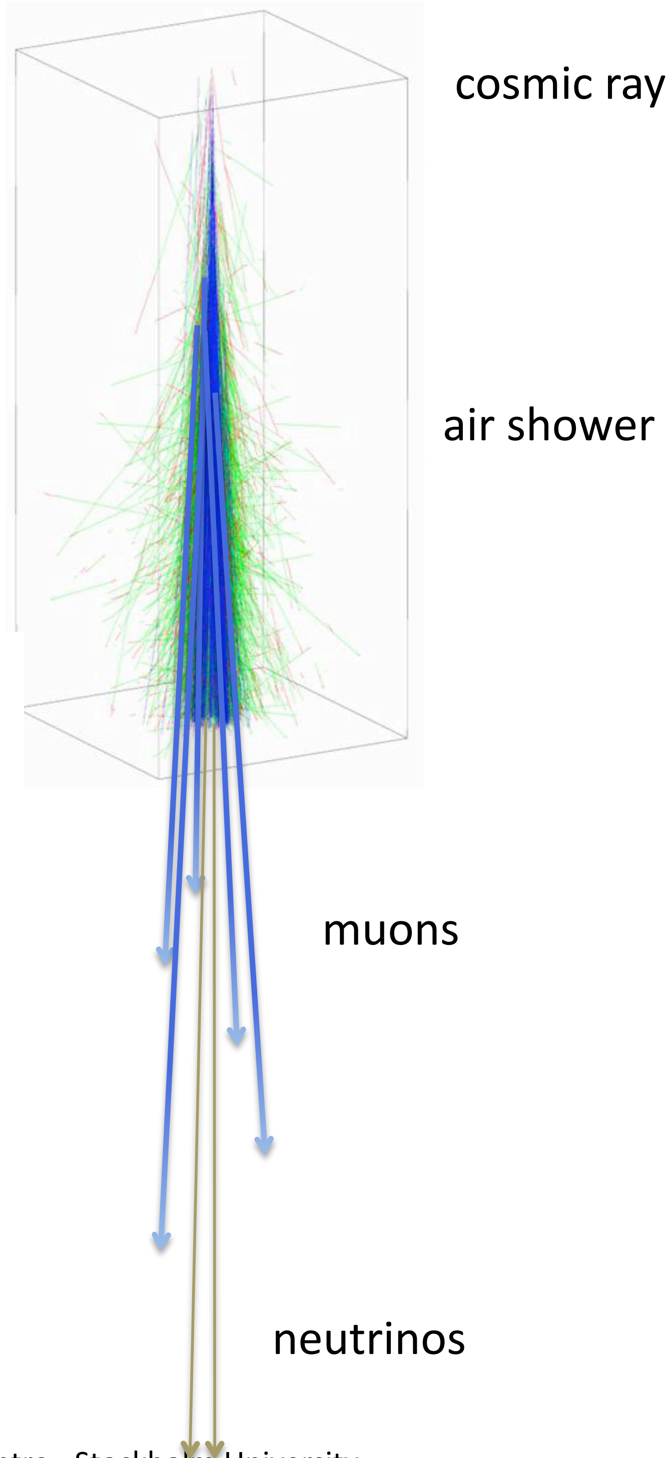



Hajo Drescher, Frankfurt U.
time = -300 µs

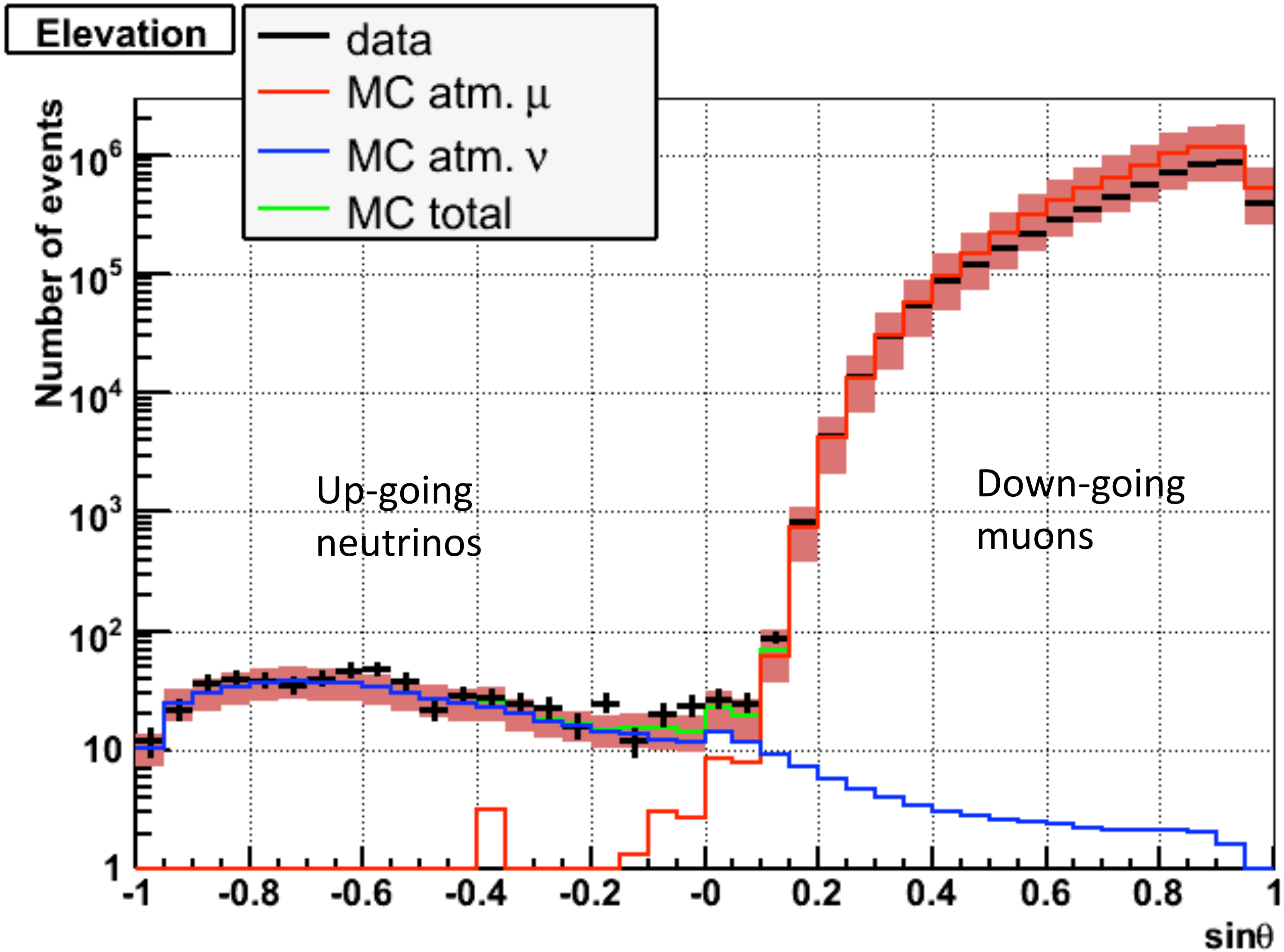

Hajo Drescher, Frankfurt U.
time = 0 μs

Cosmic Ray Background



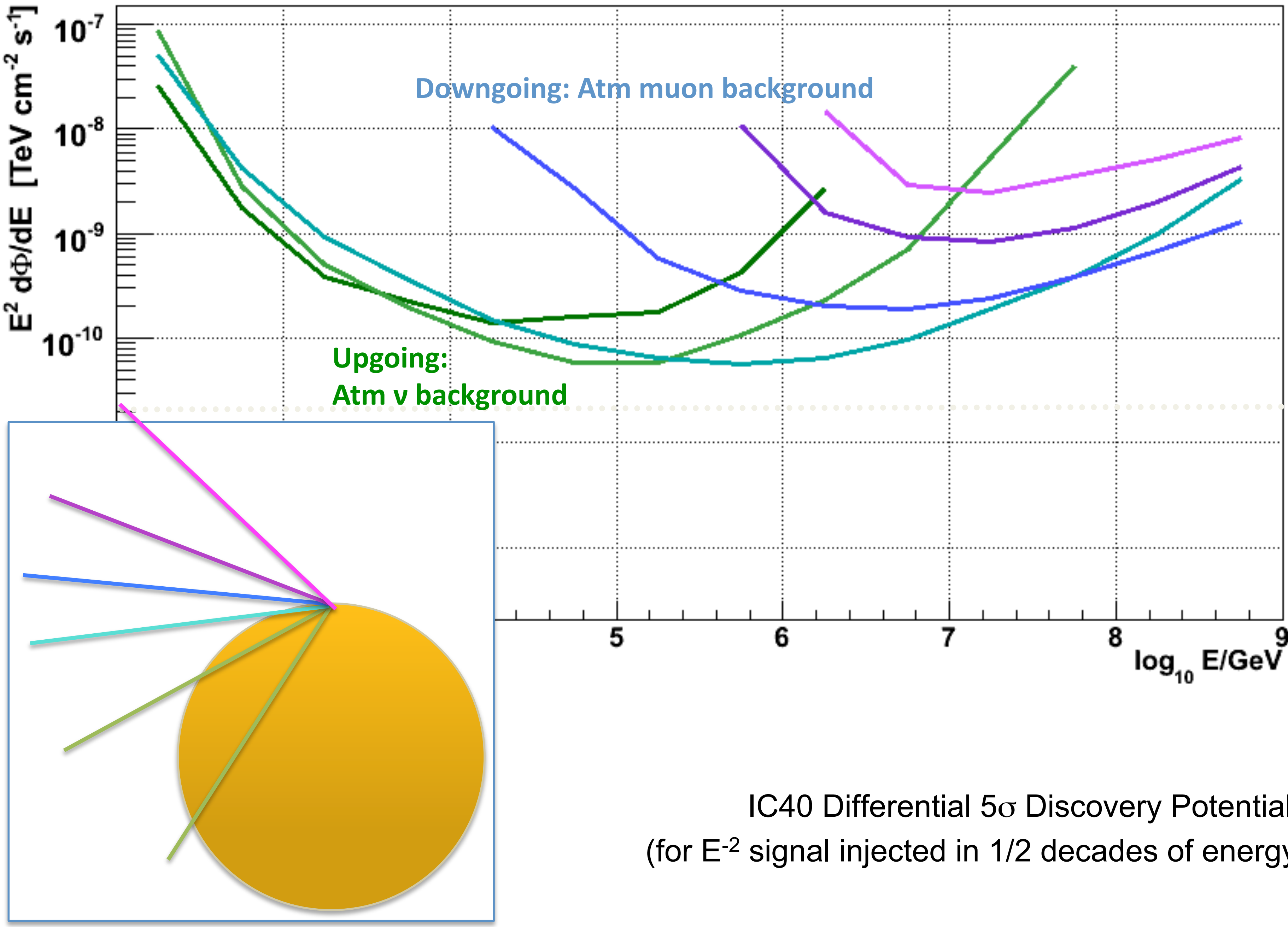


Atm **nu** Bkg vs. Atm **muon** Bkg



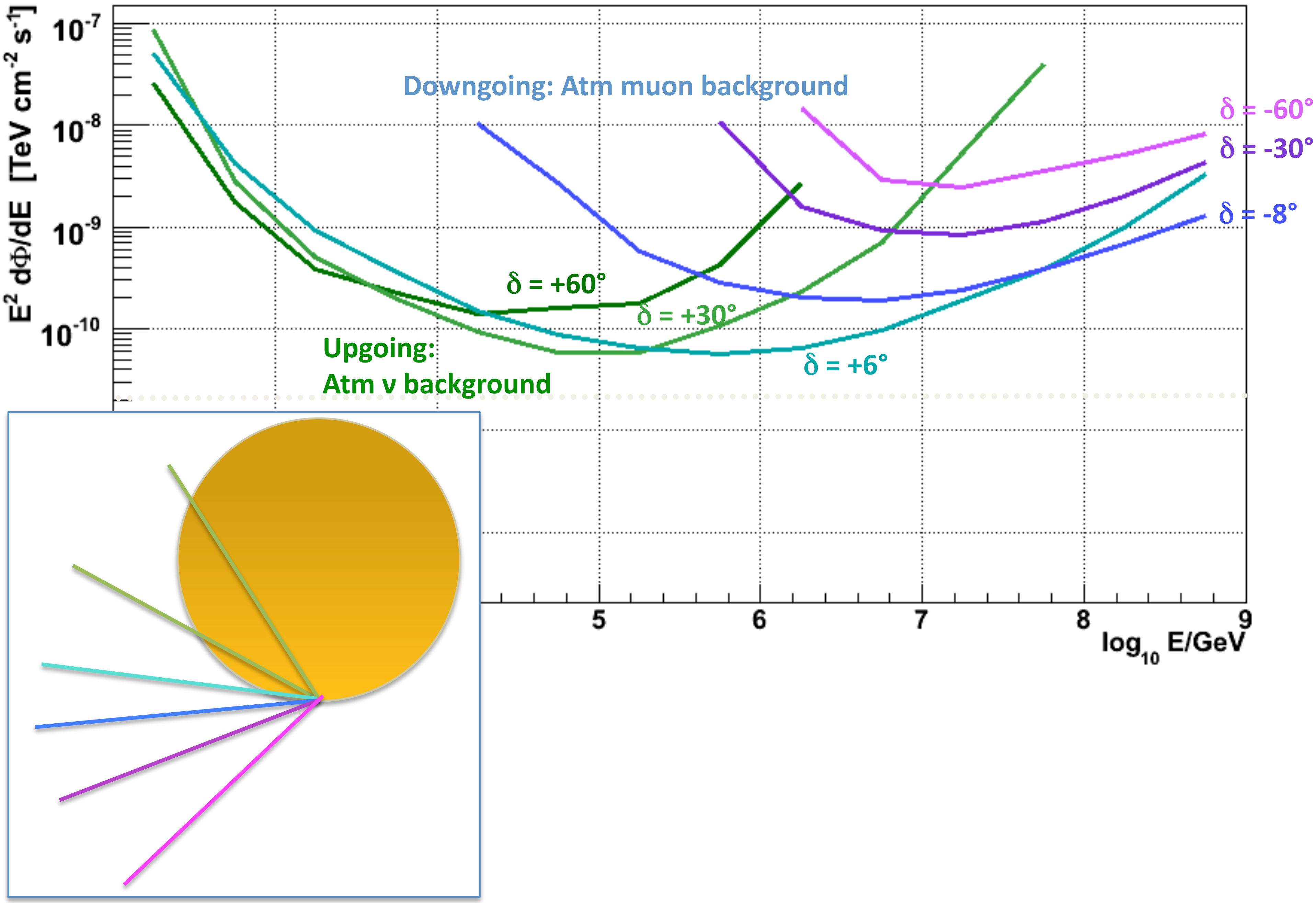
ANTARES 2008 data (173 active days)
D. Dornic Moriond 2009

Differential Sensitivity Dependence on Direction

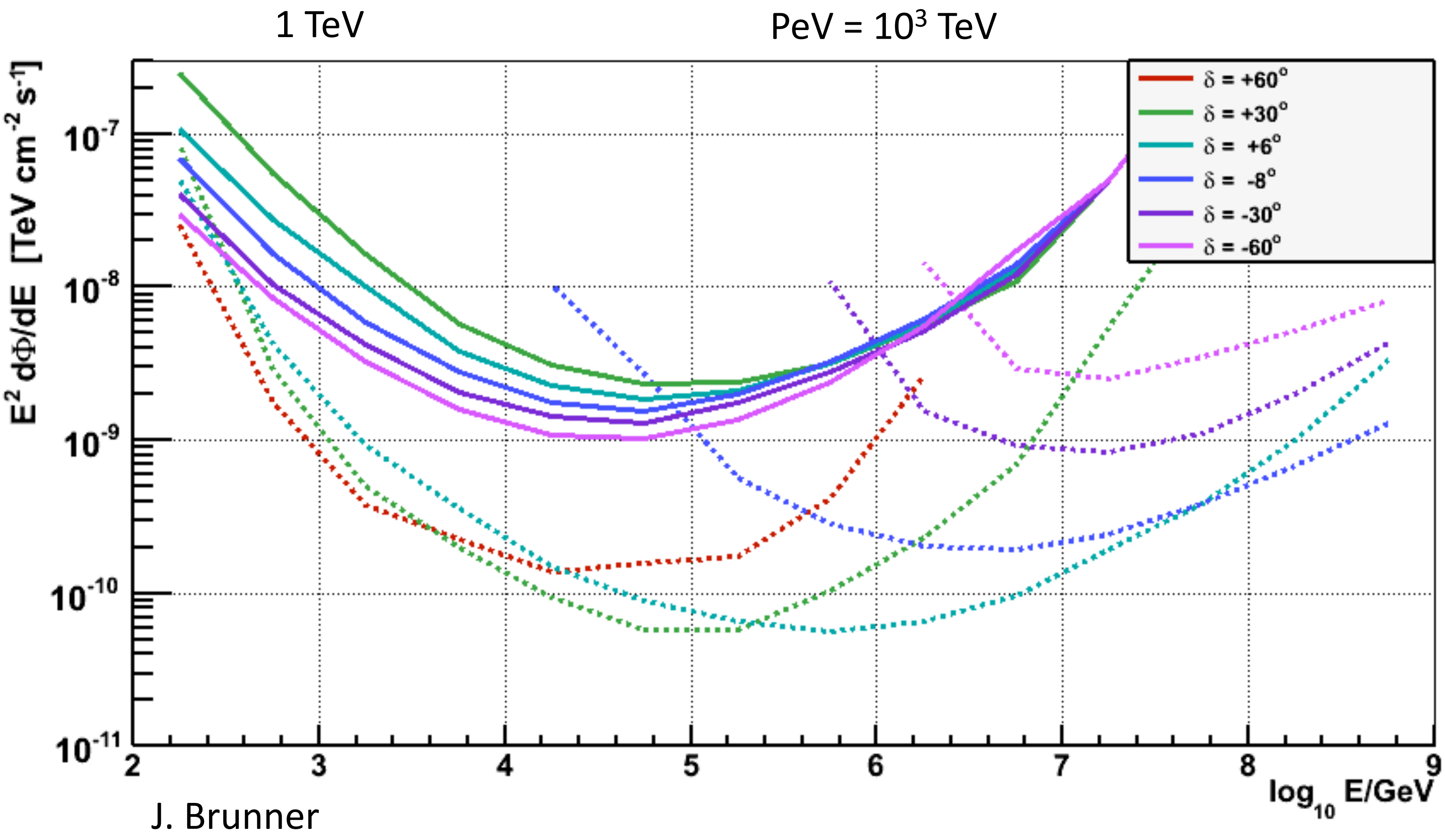


IC40 Differential 5σ Discovery Potentials
(for E^{-2} signal injected in 1/2 decades of energy)

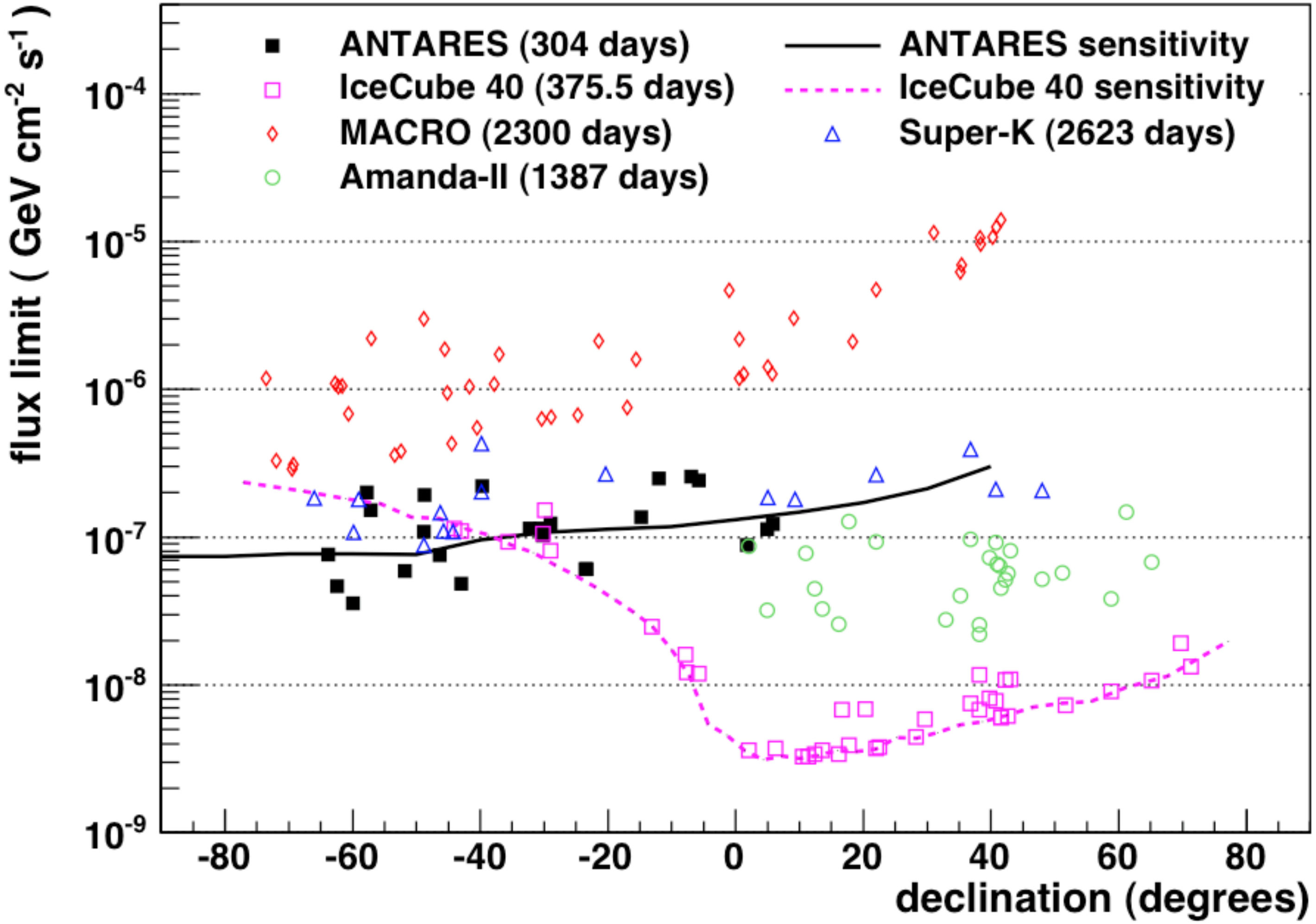
Differential Sensitivity Dependence on Direction



ANTARES and IceCube-40 differential sensitivities



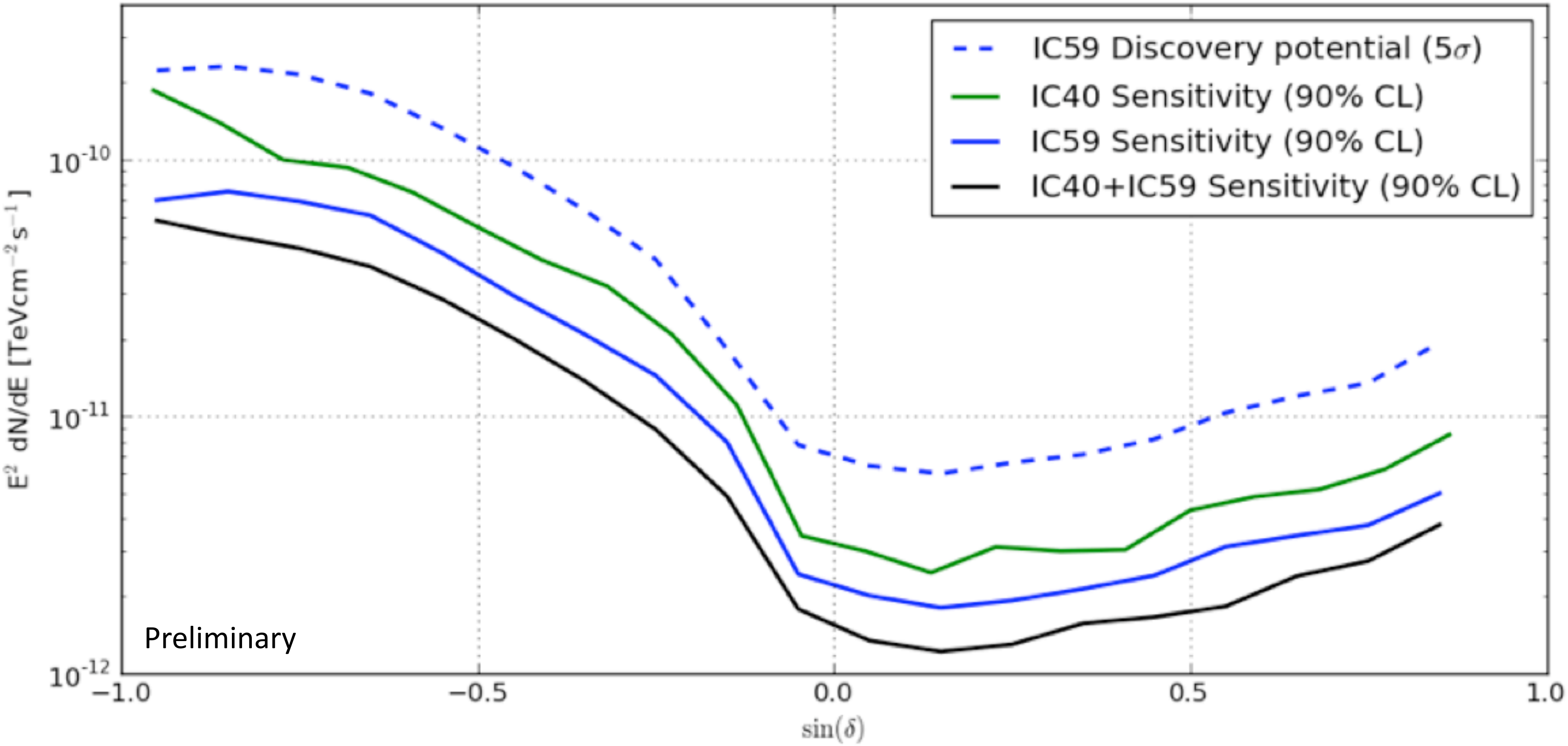
Dashed: IceCube , Full: ANTARES



ANTARES 2007-08 (5 & 12 lines) 304 days livetime arXiv:1108.0292 ApJL in press

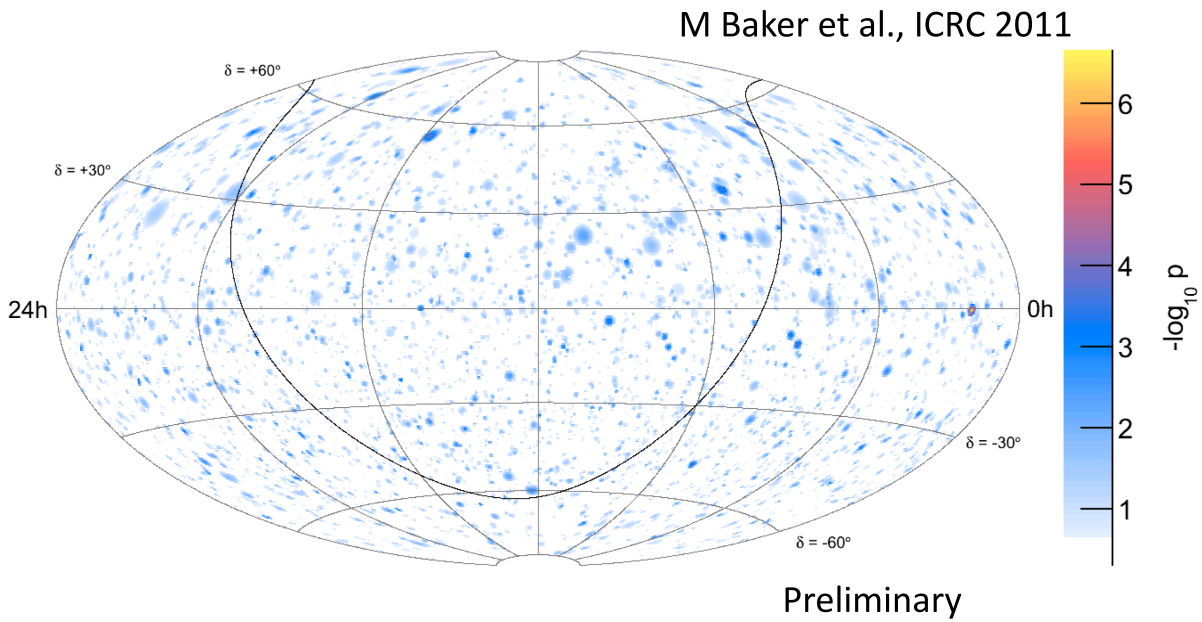
IceCube 2008-09 (40 strings) 375 days livetime

IceCube 40 + IceCube 59 E^{-2} Sensitivity



J. A. Aguilar et al., ICRC 2011

Time-Dependent All-Sky Search (IceCube-59)



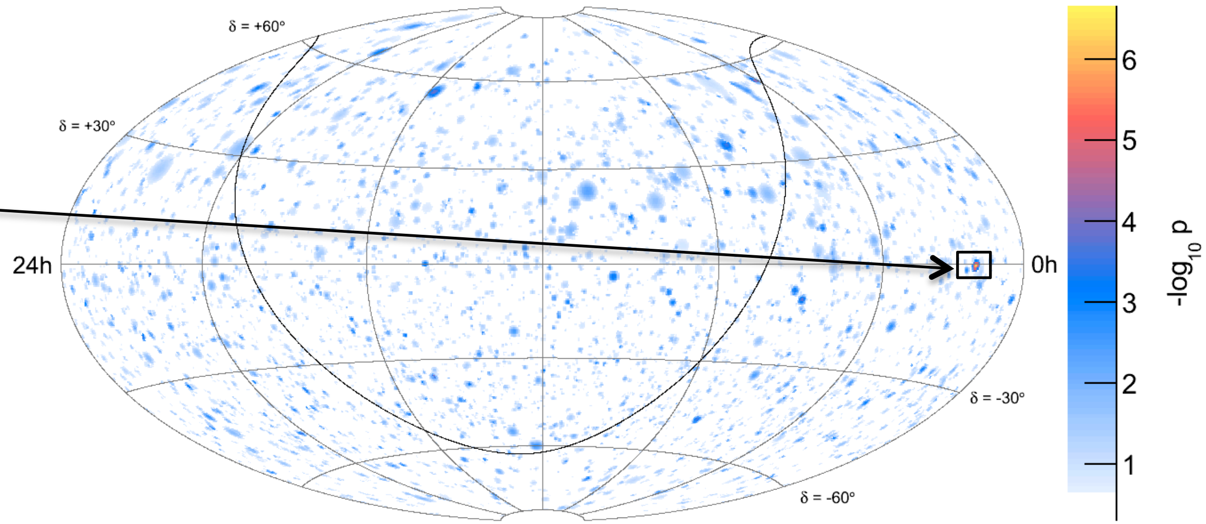
$$\mathcal{S}_i = \frac{1}{2\pi\sigma_i^2} e^{-|\vec{x}_i - \vec{x}_\mathrm{s}|^2/2\sigma_i^2} \cdot P(E_i|\gamma) \cdot \boxed{\frac{1}{\sqrt{2\pi}\sigma_\mathrm{T}} e^{-(t_i - T_0)^2/2\sigma_\mathrm{T}^2}}$$

$$\mathcal{L}(n_s, \gamma, \underline{\sigma_\mathrm{T}, T_0}) = \prod_{i=1}^{N} \left(\frac{n_s}{N} \mathcal{S}_i(\gamma, \underline{\sigma_\mathrm{T}, T_0}) + (1 - \frac{n_s}{N}) \mathcal{B}_i \right)$$

Time-Dependent All-Sky Search (IceCube-59)

M Baker et al., ICRC 2011

Most significant spot:
r.a. = 21.35°
dec. = -0.25°
n_s = 14.5
γ = -3.9
σ_T = 5.5 days (FWHM 13 days)
T_0 = 55259 MJD (2010 Mar. 4)
$-\log_{10}$ p-value = 6.69



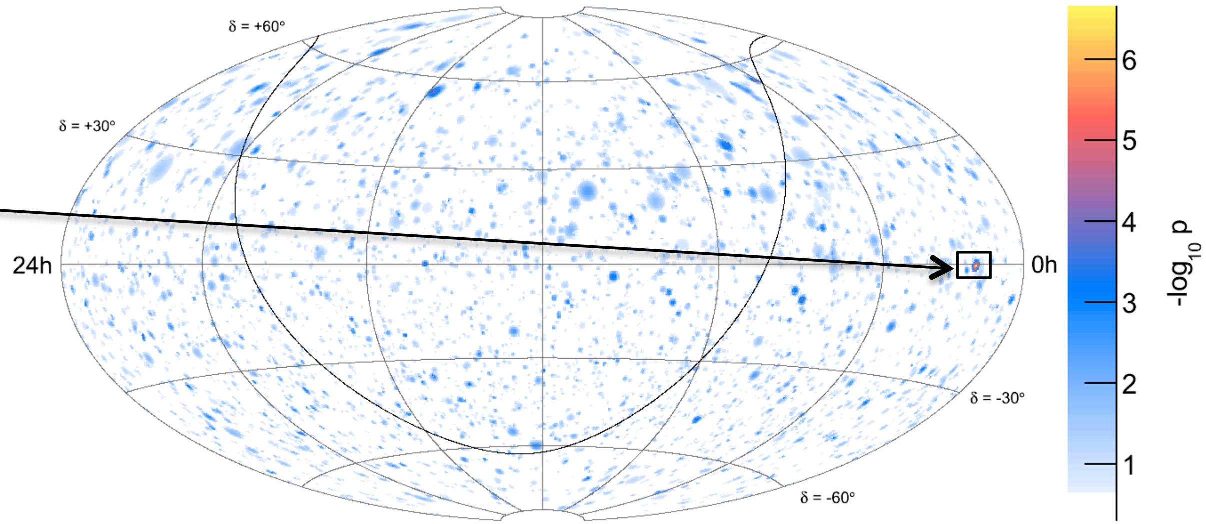
Preliminary

$$\mathcal{S}_i = \frac{1}{2\pi\sigma_i^2} e^{-|\vec{x}_i - \vec{x}_s|^2/2\sigma_i^2} \cdot P(E_i|\gamma) \cdot \boxed{\frac{1}{\sqrt{2\pi}\sigma_T} e^{-(t_i - T_0)^2/2\sigma_T^2}}$$

$$\mathcal{L}(n_s, \gamma, \underline{\sigma_T, T_0}) = \prod_{i=1}^{N} \left(\frac{n_s}{N} \mathcal{S}_i(\gamma, \underline{\sigma_T, T_0}) + (1 - \frac{n_s}{N}) \mathcal{B}_i \right)$$

Time-Dependent All-Sky Search (IceCube-59)

M Baker et al., ICRC 2011



Most significant spot:

r.a. = 21.35°

dec. = -0.25°

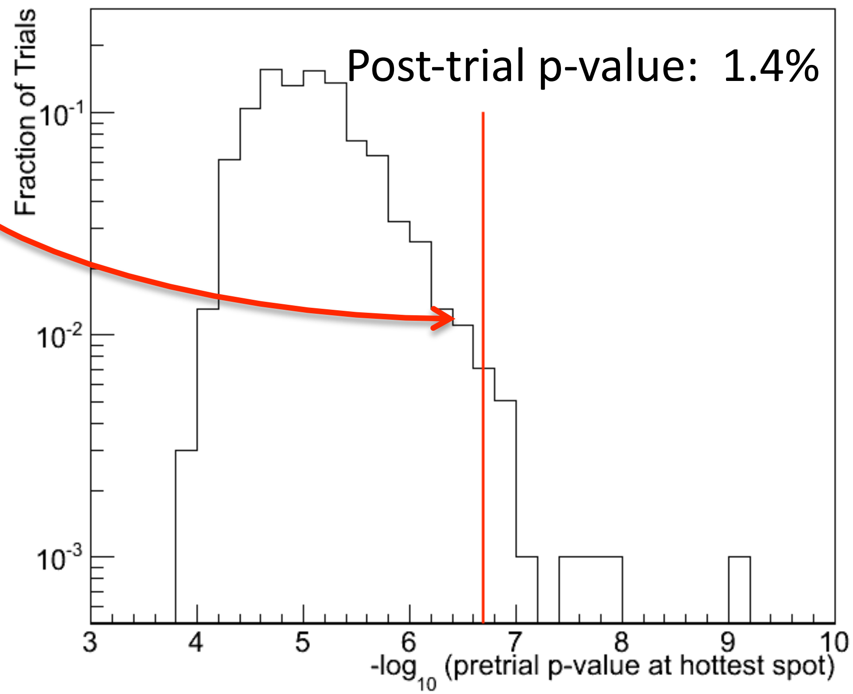
n_s = 14.5

γ = -3.9

σ_T = 5.5 days (FWHM 13 days)

T_0 = 55259 MJD (2010 Mar. 4)

$-\log_{10}$ p-value = 6.69



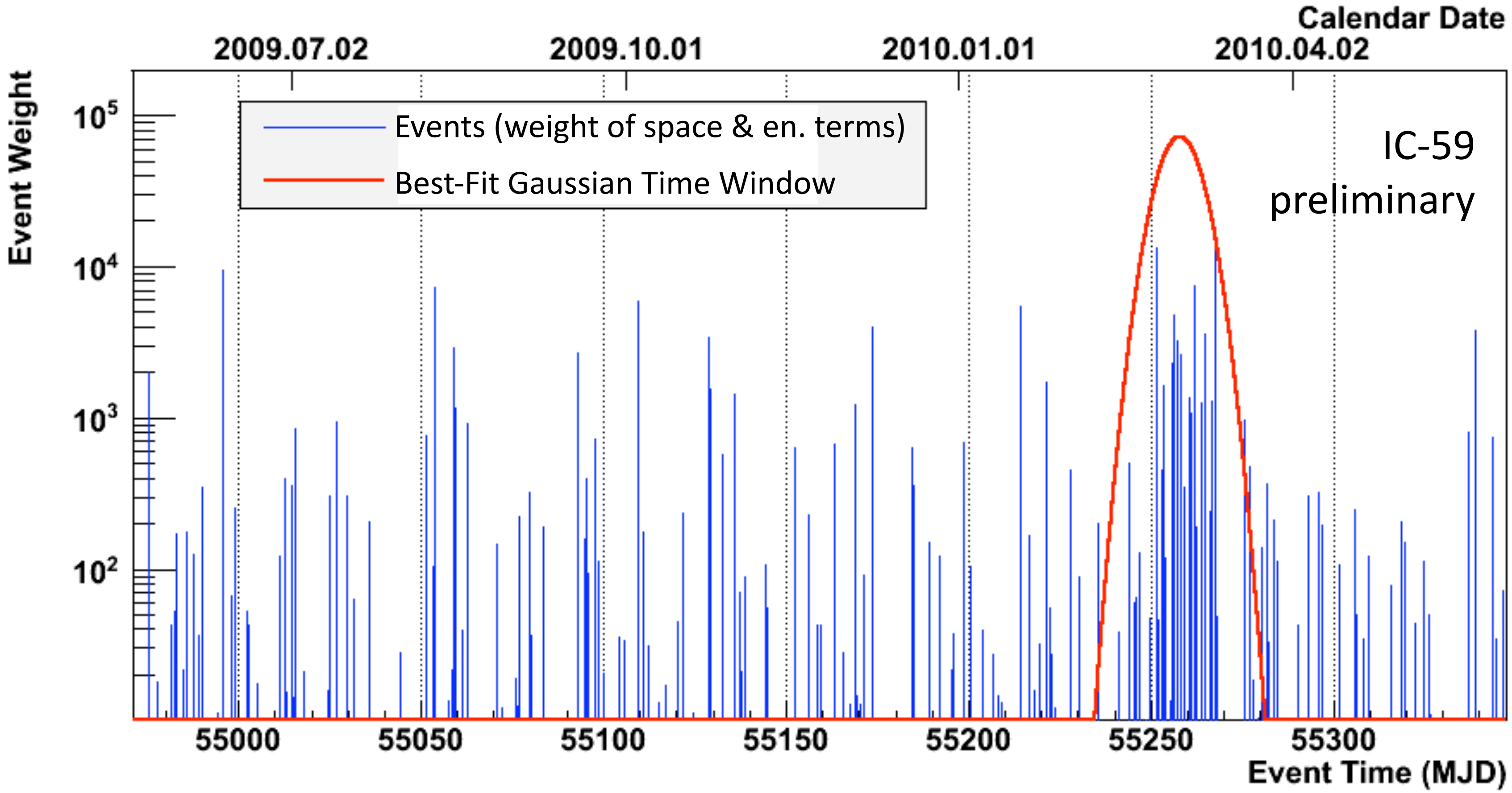
Preliminary

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

$$\mathcal{L}(n_s, \gamma, \underline{\sigma_T, T_0}) = \prod_{i=1}^{N} \left(\frac{n_s}{N} \mathcal{S}_i(\gamma, \sigma\right.$$

Time-Dependent All-Sky Search (IceCube-59)

M Baker et al., ICRC 2011



Most significant spot: r.a. = 21.35° dec. = -0.25°

n_s = 14.5

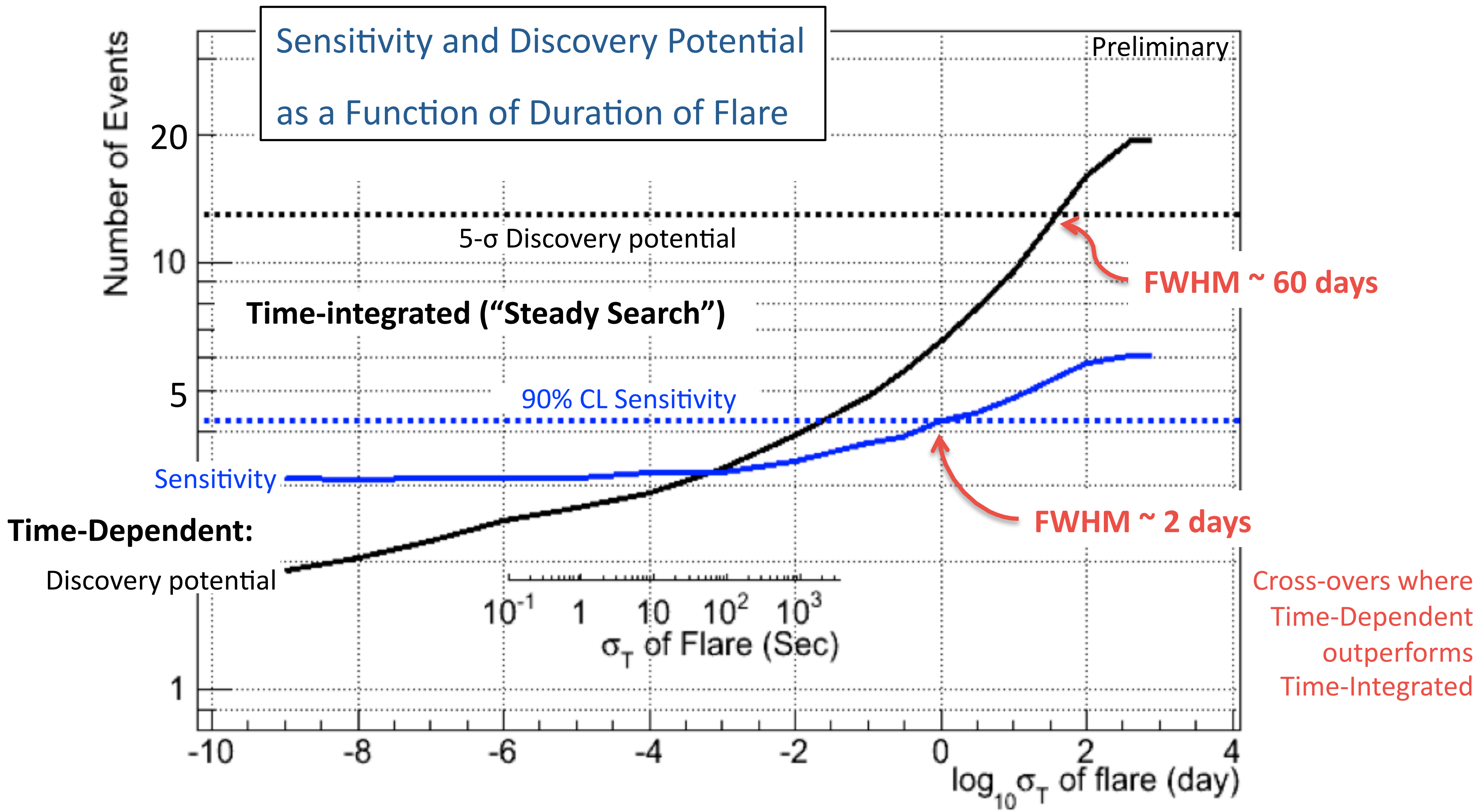
γ = -3.9

σ_T = 5.5 days (FWHM 13 days)

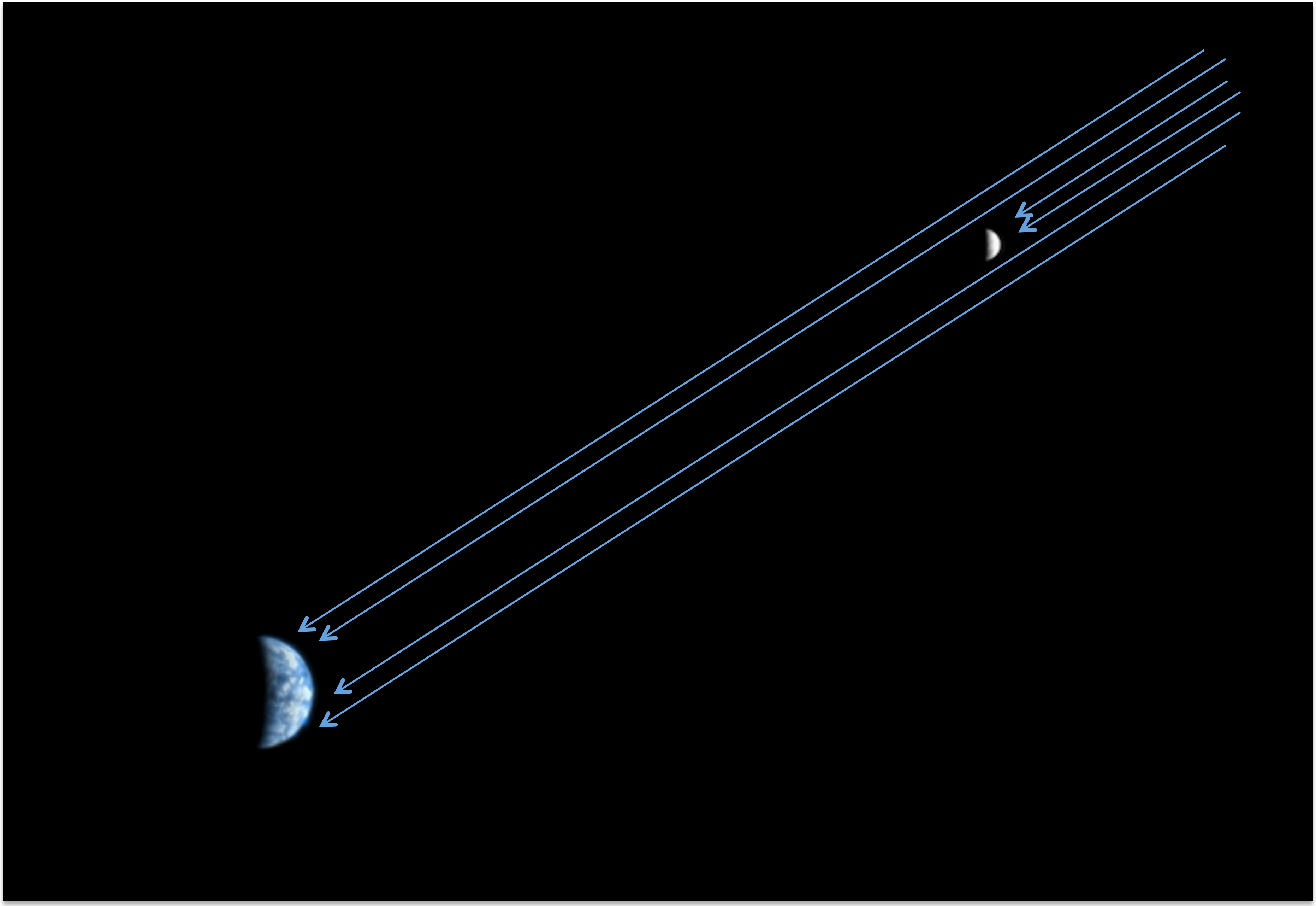
T_0 = 55259 MJD (2010 Mar. 4)

Time-Dependent Search (IceCube-59)

M Baker et al., ICRC 2011



Cosmic Ray Moon Shadow

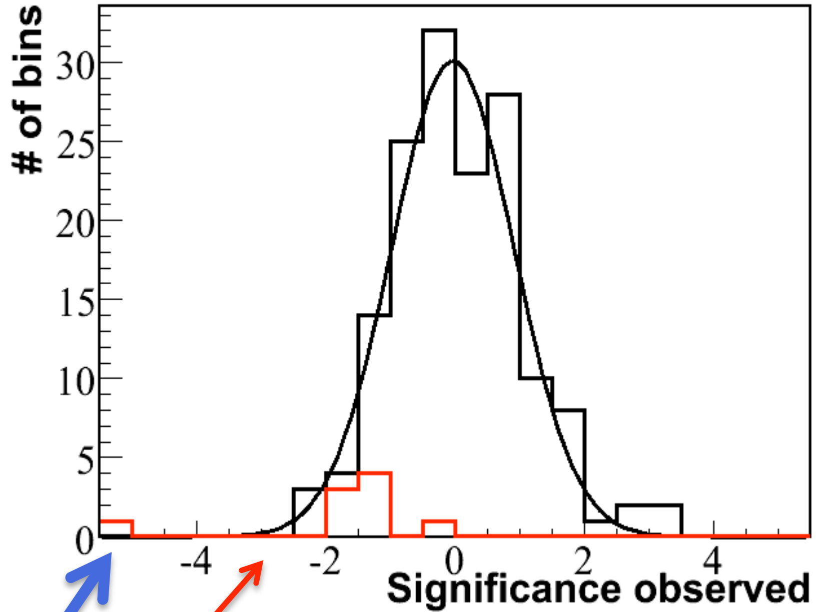


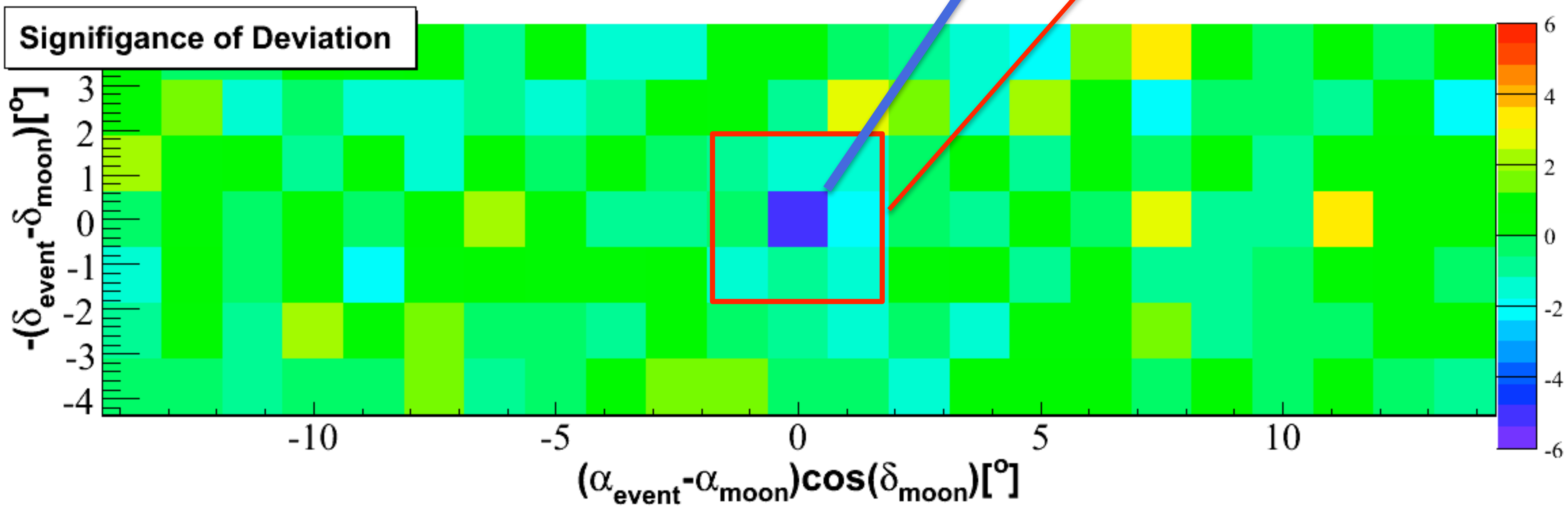
Moon Shadow Seen in Cosmic Ray Muons by IC-40

Moon bin contains 30% of point-spread function.

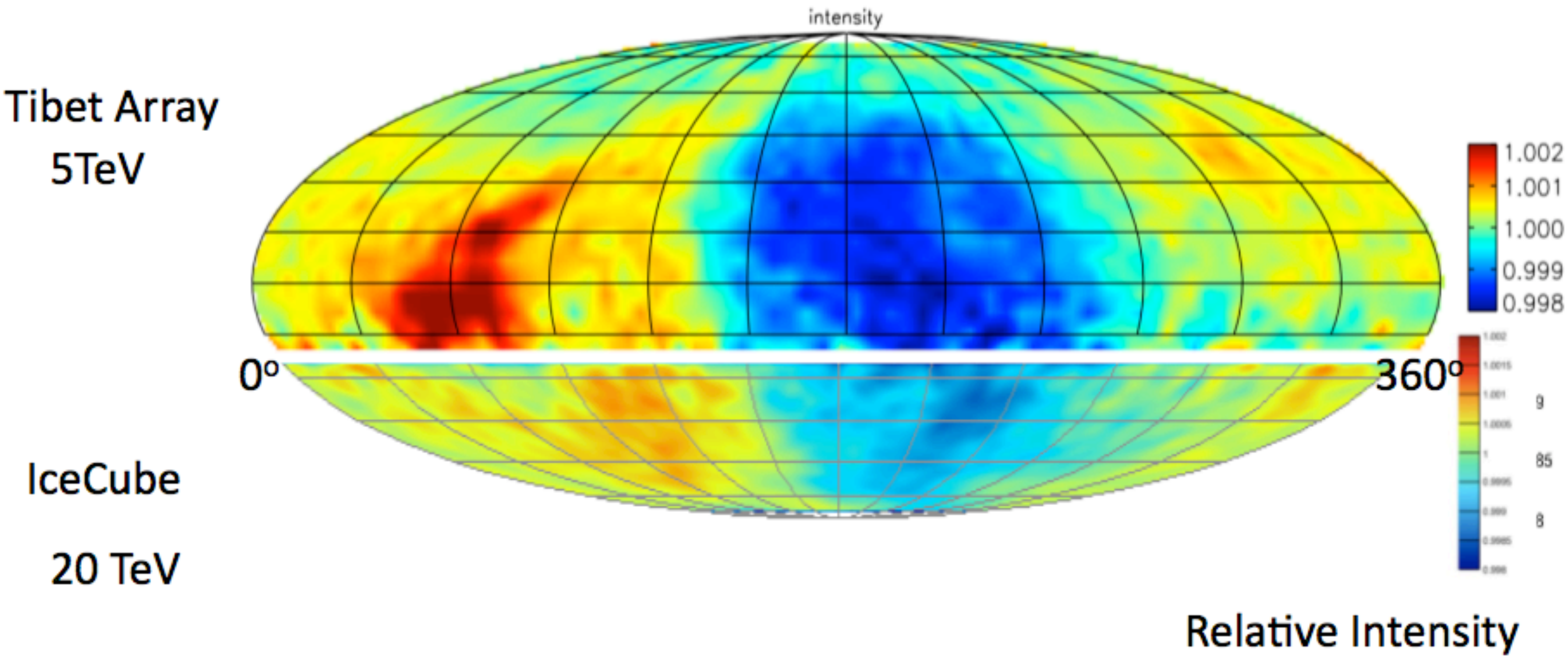
In bin, **expect** deficit of 3400×0.3 = **1000**

Observe deficit of **900** out of 27 000.
➔ 5 σ.





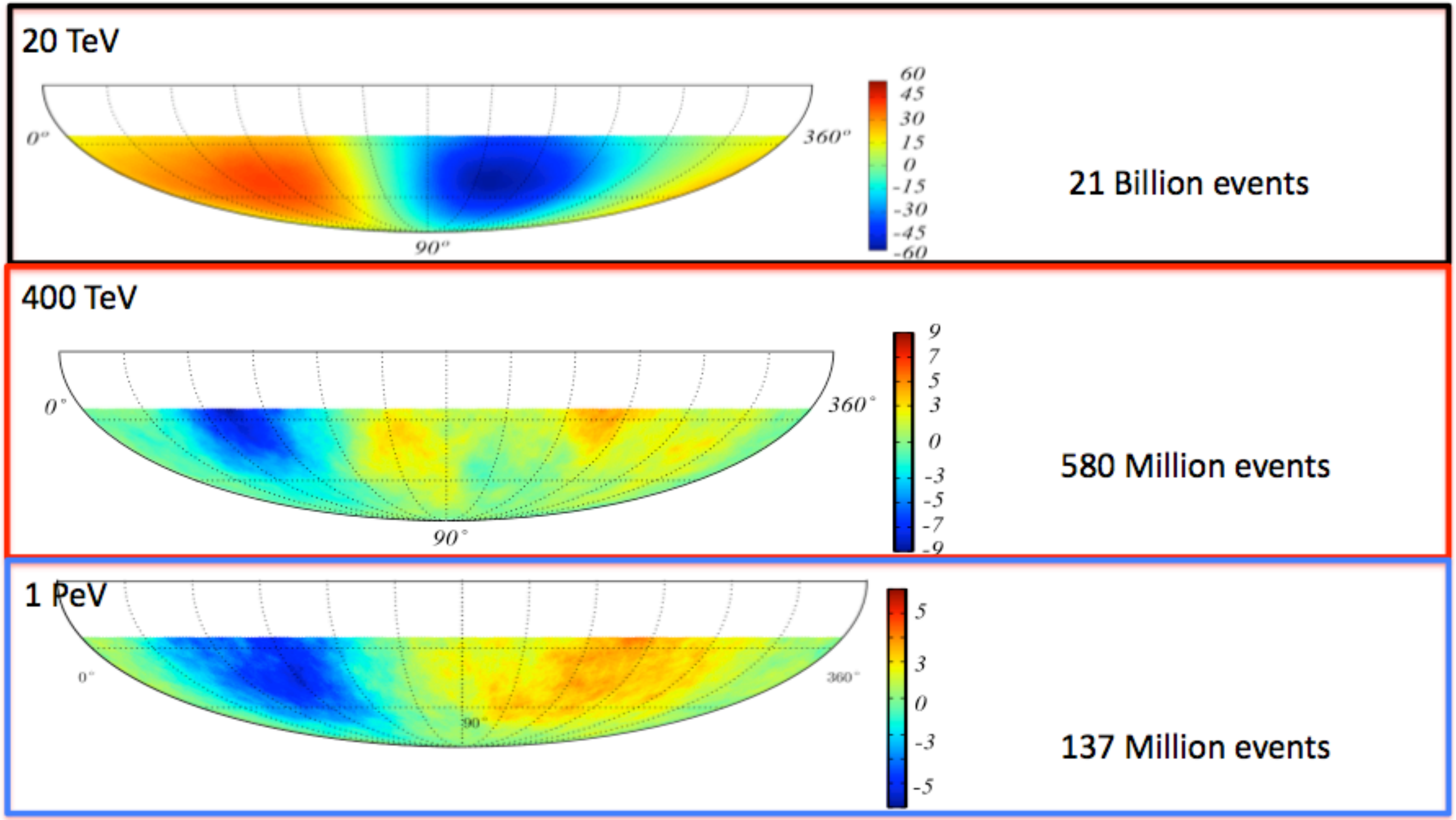
Cosmic Ray Anisotropy



Features seen by IceCube in Southern sky match features in North seen by Tibet Array

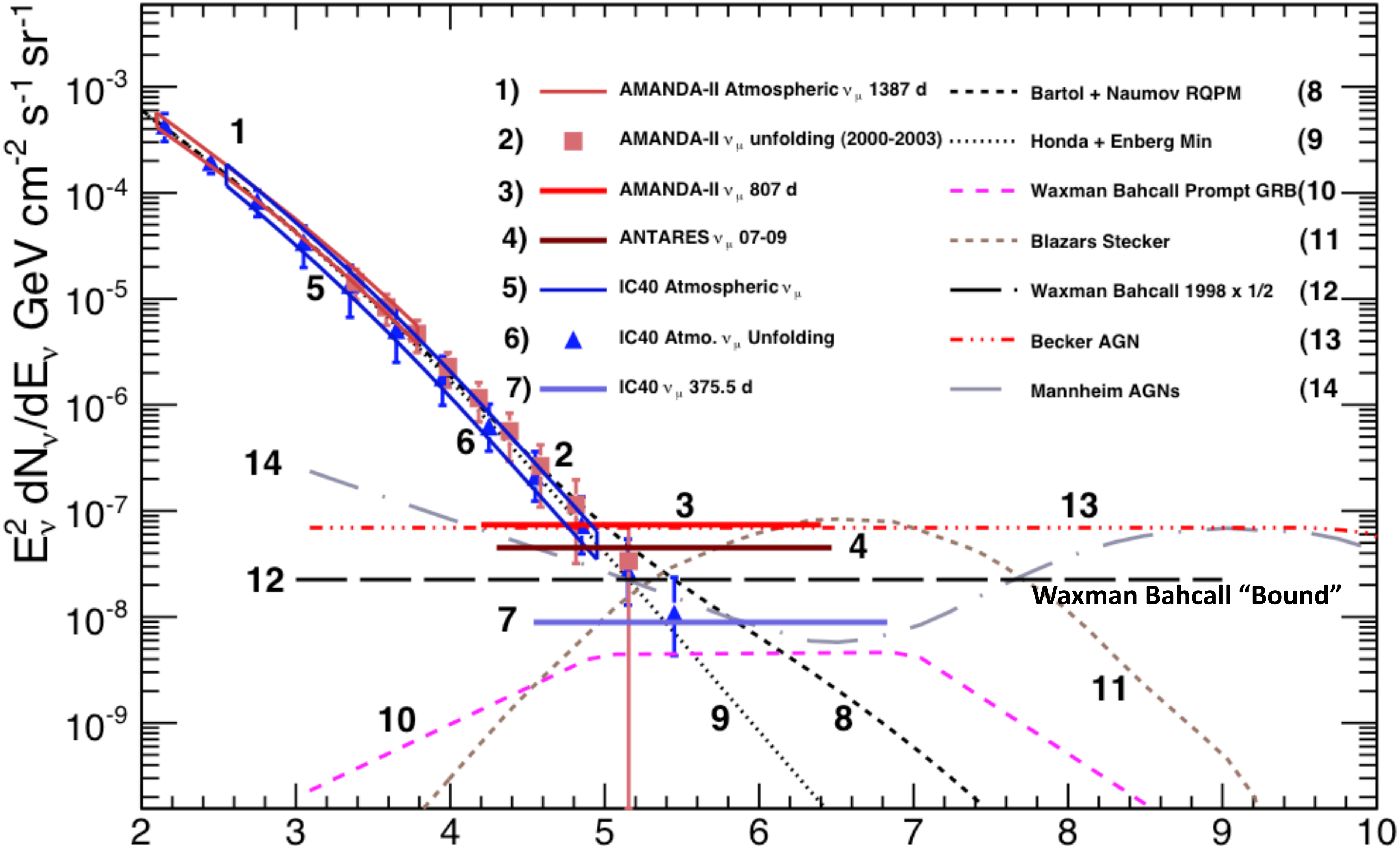
Cosmic Ray Anisotropy – Energy Dependence

IceCube 59-string data (2009-10)



2012 ApJ 746 33

Diffuse Astrophysical Neutrino Fluxes



ANTARES -- Phys. Lett. B 696 (2011) 1622
IceCube -- Phys. Rev. D 84, 082001 (2011)

Indirect Dark Matter Searches

$$\chi + \chi \rightarrow W + W \rightarrow \nu + \nu$$

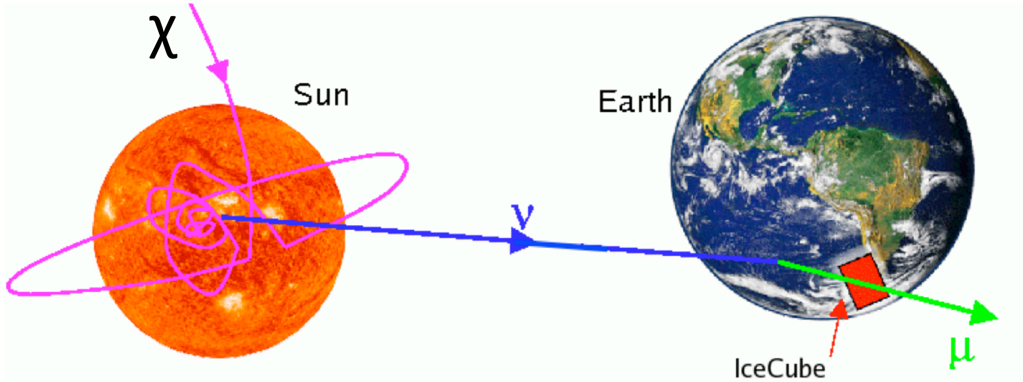
Neutrinos are typical end products of dark matter annihilation

Solar Searches:

Dark matter particles scatter and get trapped in sun.

As trapped density grows, annihilation rate reaches equilibrium with capture rate.

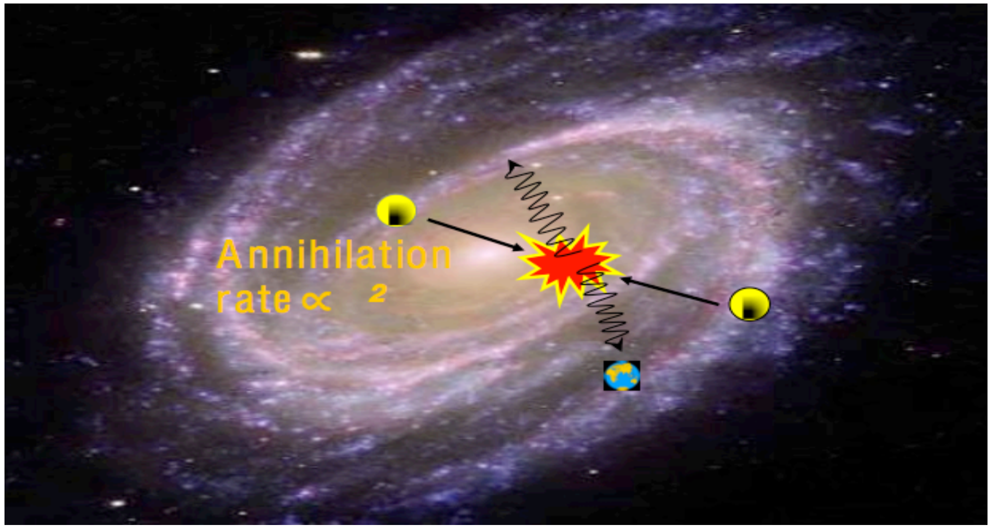
Search sensitive to **scattering cross section**



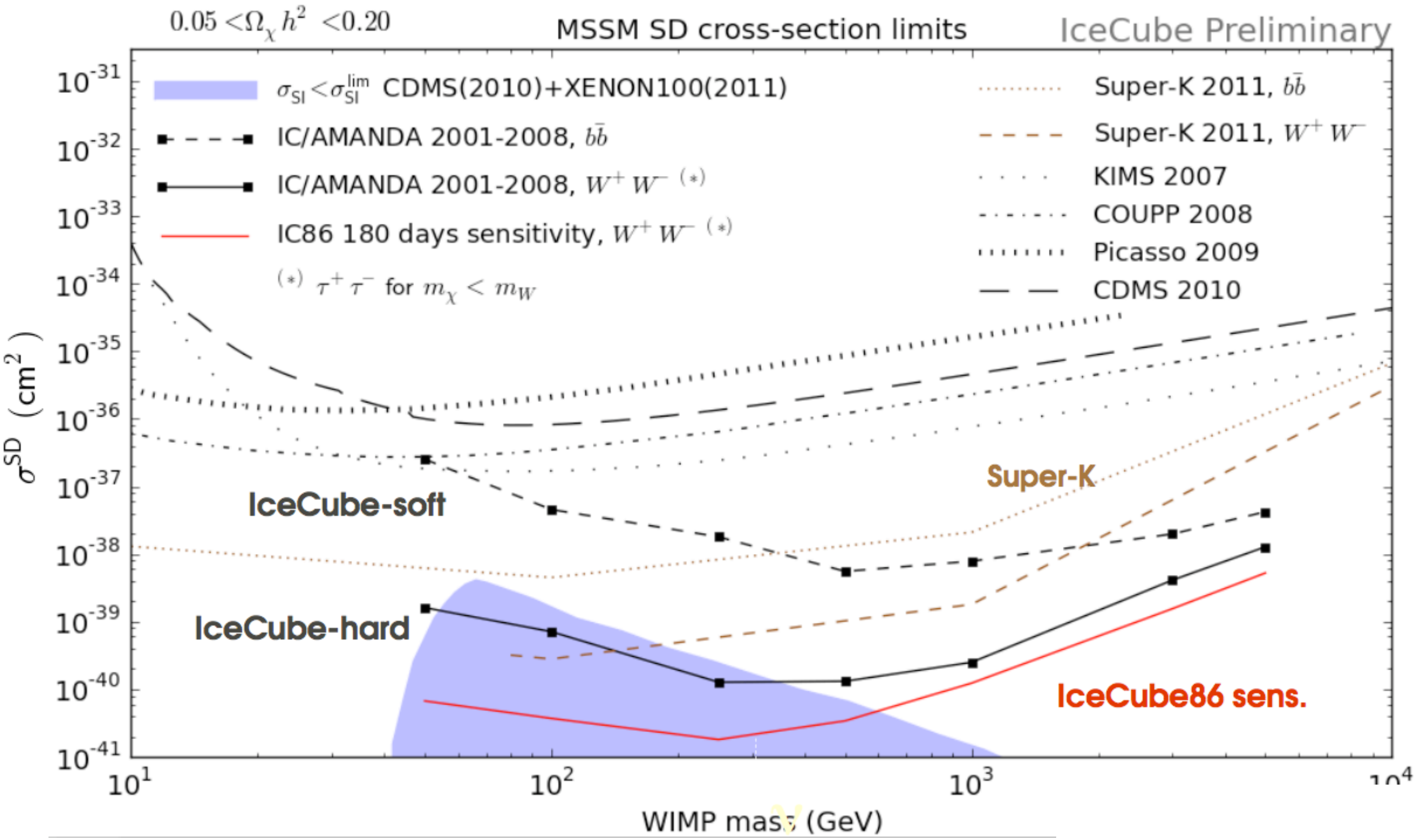
Galactic Halo Searches:

Annihilation occurs in densest region of dark matter halo in galactic center

Search sensitive to **annihilation cross section**



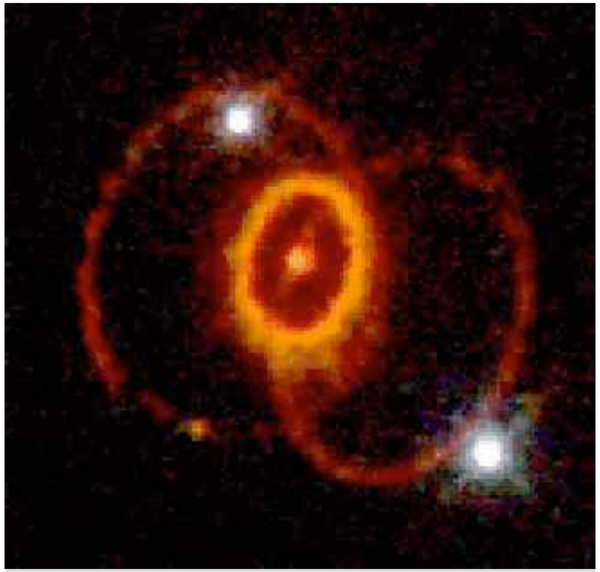
Spin-Dependent Scattering Cross Section Limits

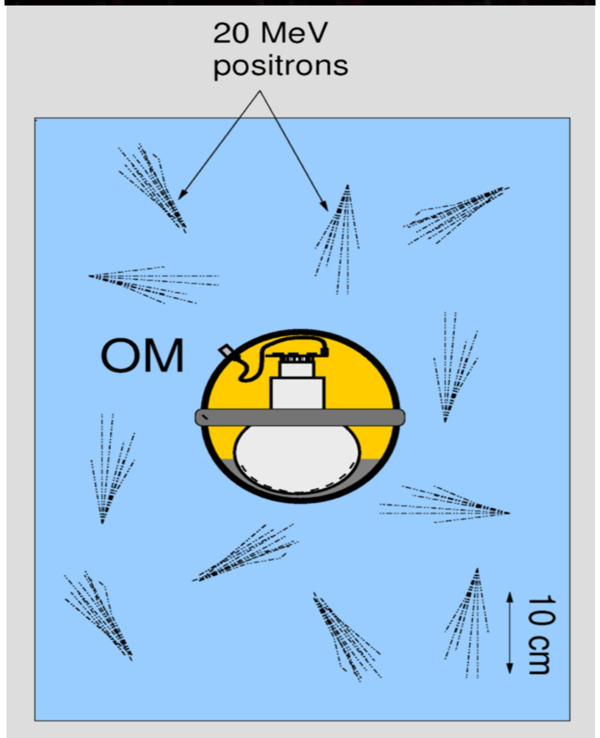


M. Danninger, Schleching 2012

IceCube = AMANDA + IceCube-22 + IceCube-40

Supernova MeV Neutrino Detection in IceCube



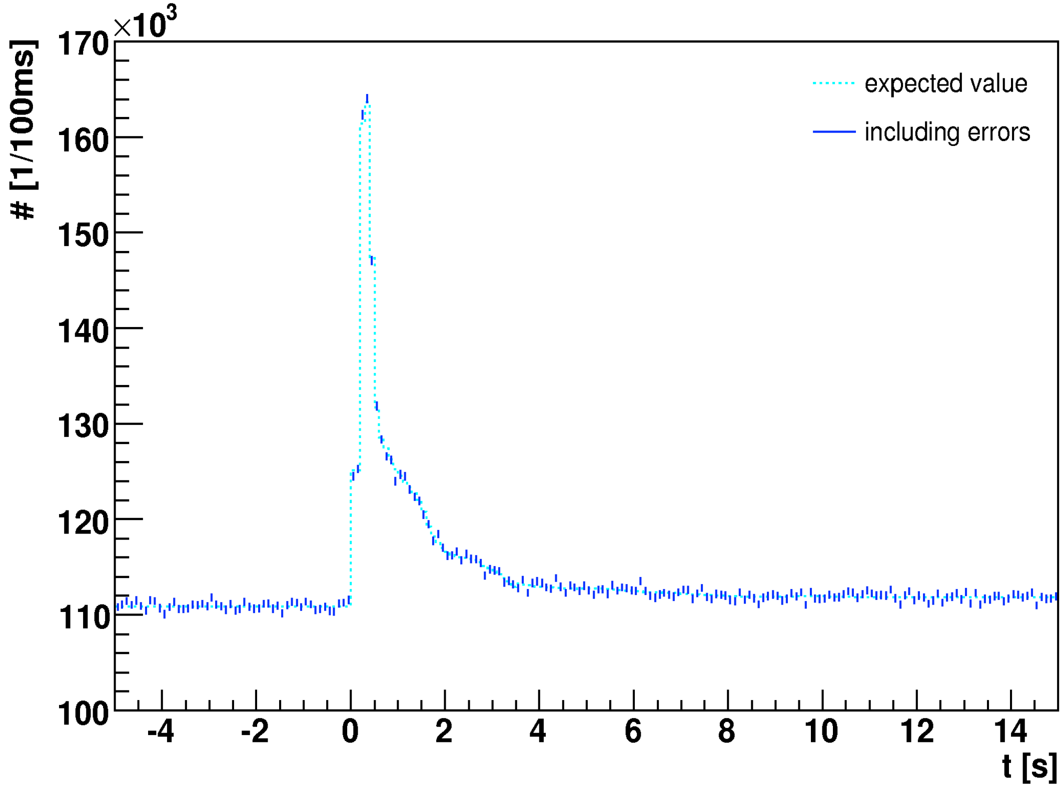


Bursts of low-energy (MeV) neutrinos
from core collapse supernovae
Neutrinos interact in the ice:

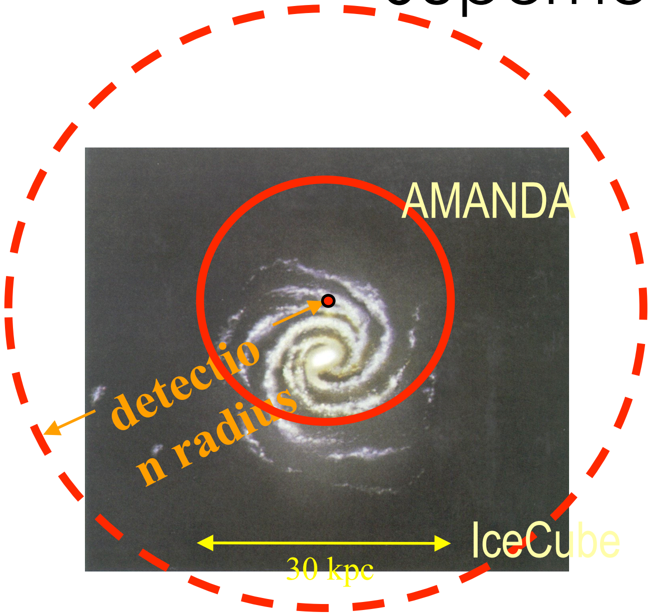
$$\nu_e + p \rightarrow n + e^+$$

The produced positron is emitted almost isotropically

Short paths of MeV positrons do not create detectable "tracks." But they increase the **noise rate**.



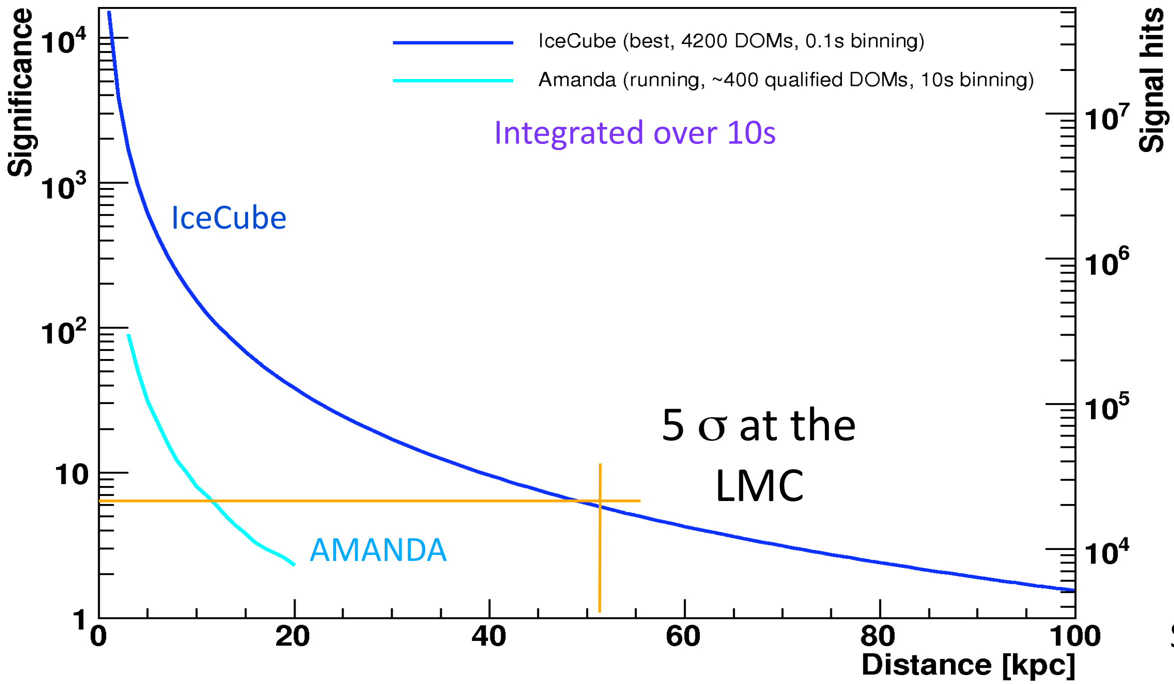
Supernova Neutrino Search

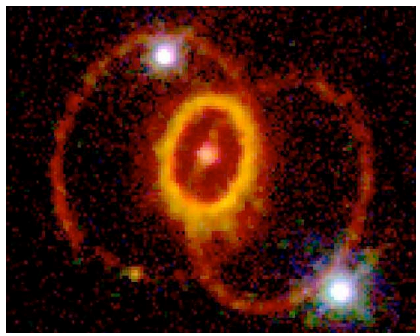


Participate in SNEWS (SuperNova Early Warning System): a collaborative effort among Super-K, SNO, LVD, KamLAND, IceCube, BooNE and gravitational wave experiments

IceCube sees out to the LMC (~50 kpc)

~ few per century => long wait!





SN 1987A in Large Magellanic Cloud

LETTER

doi:10.1038/nature11068

An absence of neutrinos associated with cosmic-ray acceleration in γ-ray bursts

IceCube Collaboration*

Very energetic astrophysical events are required to accelerate cosmic rays to above 10^{18} electronvolts. GRBs (γ-ray bursts) have been proposed as possible candidate sources[1–3]. In the GRB 'fireball' model, cosmic-ray acceleration should be accompanied by neutrinos produced in the decay of charged pions created in interactions between the high-energy cosmic-ray protons and γ-rays[4]. Previous searches for such neutrinos found none, but the constraints were weak because the sensitivity was at best approximately equal to the predicted flux[5–7]. Here we report an upper limit on the flux of energetic neutrinos associated with GRBs that is at least a factor of 3.7 below the predictions[4,8–10]. This implies either that GRBs are not the only sources of cosmic rays with energies exceeding 10^{18} electronvolts or that the efficiency of neutrino production is much lower than has been predicted.

Neutrinos from GRBs are produced in the decay of charged pions produced in interactions between high-energy protons and the intense γ-ray background within the GRB fireball, for example in the Δ-resonance process $p+\gamma \rightarrow \Delta^{+} \rightarrow n+\pi^{+}$ (p, proton; γ, photon (here γ-ray); Δ^{+}, delta baryon; n, neutron; π^{+}, pion). When these pions decay via $\pi^{+} \rightarrow \mu^{+}\nu_{\mu}$ and $\mu^{+} \rightarrow e^{+}\nu_{e}\bar{\nu}_{\mu}$, they produce a flux of high-energy muon neutrinos (ν_{μ}) and electron neutrinos (ν_{e}), coincident with the γ-rays, and peaking at energies of several hundred tera-electronvolts (TeV)[4,11] (μ^{+}, antimuon; e^{+}, positron). Such a flux should be detectable using km^3-scale instruments like the IceCube

As in our previous study[7], we conducted two analyses of the IceCube data. In a model-dependent search, we examine data during the period of γ-ray emission reported by any satellite for neutrinos with the energy spectrum predicted from the γ-ray spectra of individual GRBs[6,9]. The model-independent analysis searches more generically for neutrinos on wider timescales, up to the limit of sensitivity to small numbers of events at ±1 day, or with different spectra. Both analyses follow the methods used in our previous work[7], with the exception of slightly changed event selection and the addition of the Southern Hemisphere to the model-independent search. Owing to the large background of downgoing muons from the southern sky, the Southern Hemisphere analysis is sensitive mainly to higher-energy events (Supplementary Fig. 3). Systematic uncertainties from detector effects have been included in the reported limits from both analyses, and were estimated by varying the simulated detector response and recomputing the limit, with the dominant factor being the efficiency of the detector's optical sensors.

In the 59-string portion of the model-dependent analysis, no events were found to be both on-source and on time (within 10° of a GRB and between T_{start} and T_{stop}). From the individual burst spectra[6,9] with an assumed ratio of energy in protons to energy in electrons $\varepsilon_p/\varepsilon_e = 10$ (ref. 6), 8.4 signal events were predicted from the combined 2-year data set and a final upper limit (90% confidence) of 0.27 times the predicted flux can be set (Fig. 1). This corresponds to a 90% upper limit on $\varepsilon_p/\varepsilon_e$

GRBs best candidate for UHE CR

• Internal shocks as fireball expands, accelerate particles via Fermi mechanism

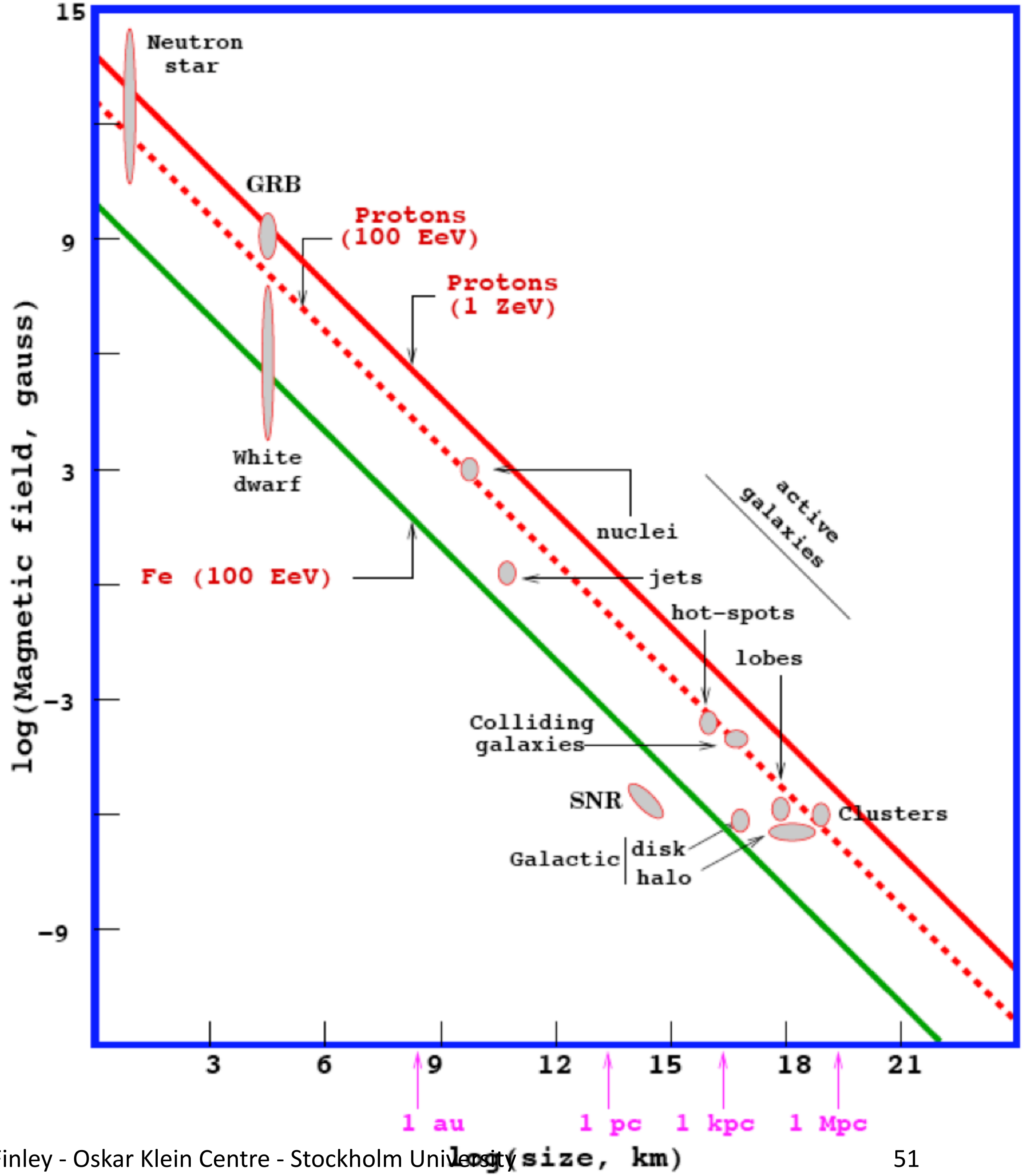
• Aggregate energy output of GRBs good match to cosmic ray energy density

Prediction:

HE protons coexist in the expanding fireball with the photons which we later observe as the GRB

p + γ interactions => pions
=> neutrinos

Predicted neutrino fluxes well within reach of km3 detector

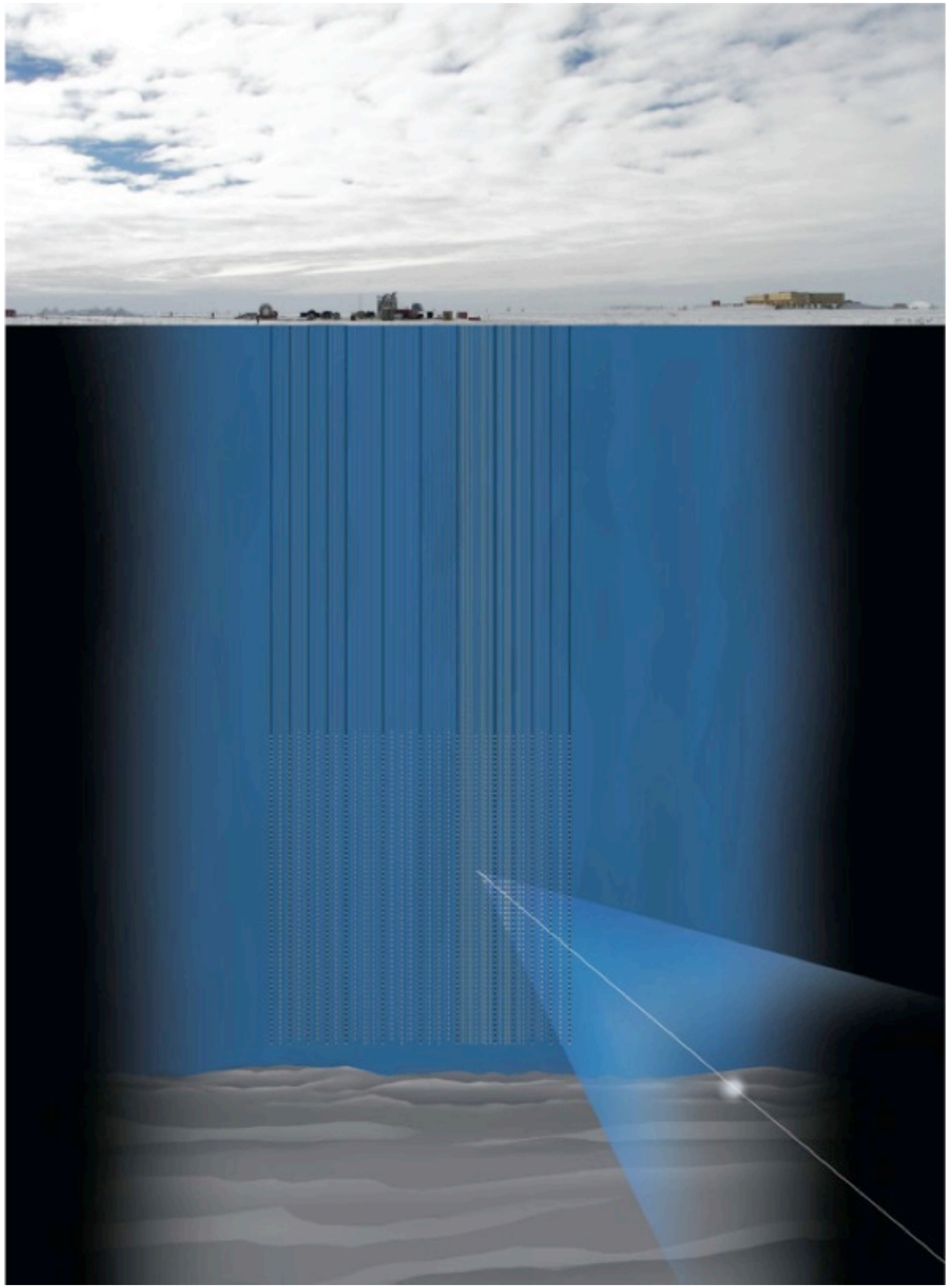


Analysis: two-years of data used from the partially-constructed IceCube detector (2008-10)

Stack 215 GRBs (mostly from Fermi GBM)

Typical gamma emission duration:
~ 30 seconds

=> Low background search

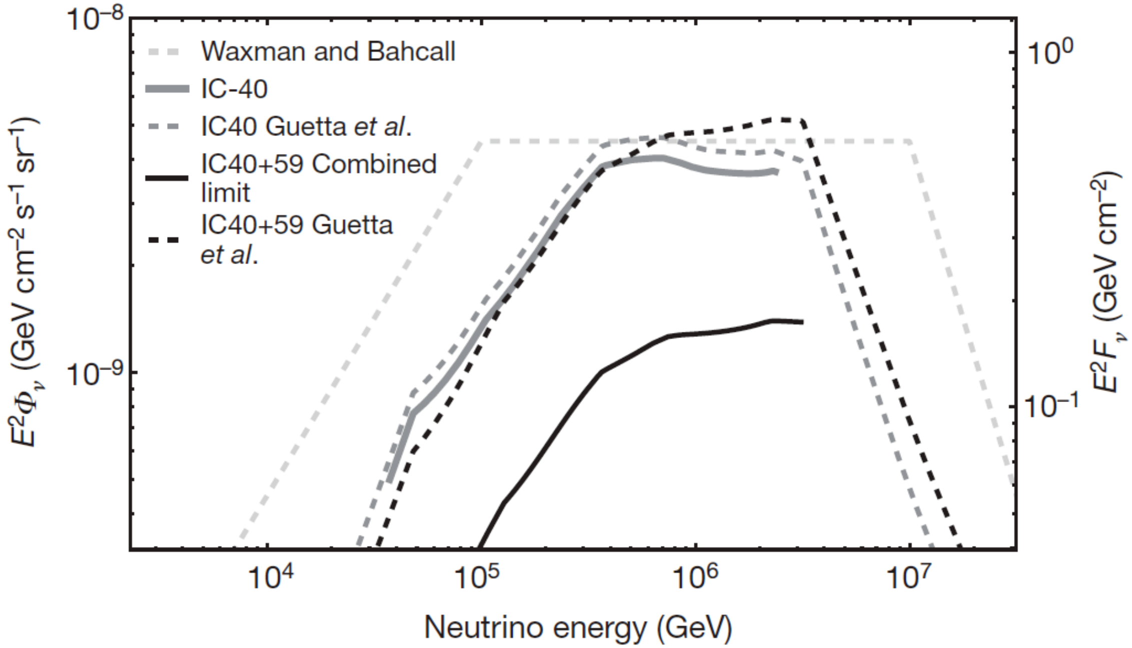


Two Searches performed in parallel:

“Model-Dependent” search:

- Use search window defined by start and end of observed gamma emission
- Use model prediction of neutrino flux and energy spectrum to weight the search

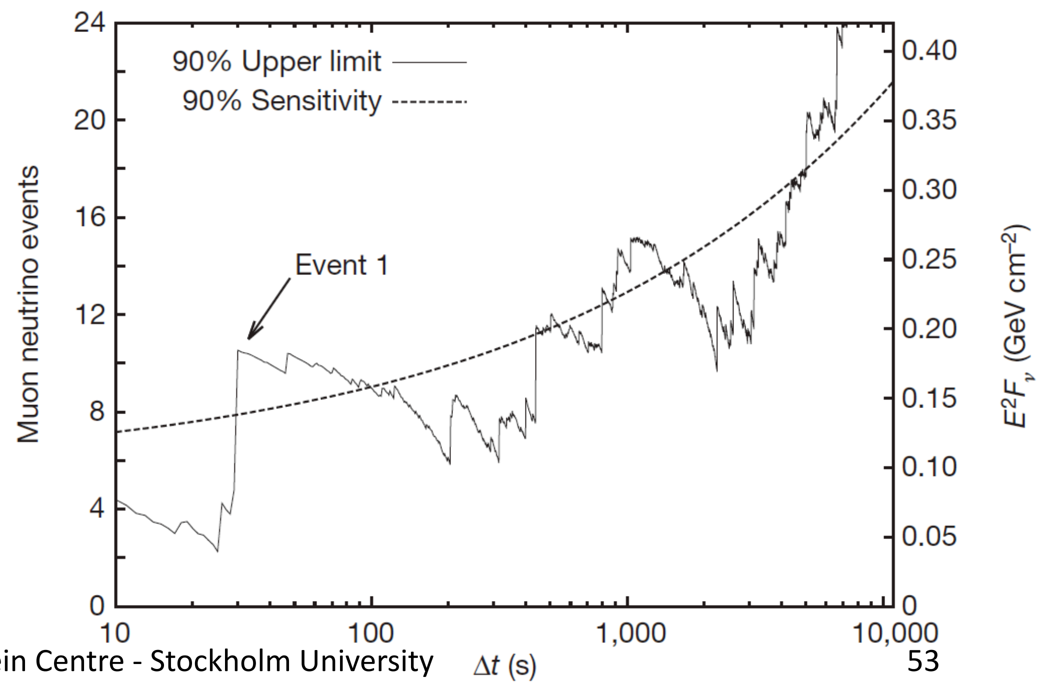
⇒Most sensitive if models are right



“Model-Independent” search:

- coincident search time window expandable up to ± 1 day (NB: neutrinos closer to GRB time given more significance)
- No specific weighting to model predictions

⇒“Catch-all” analysis

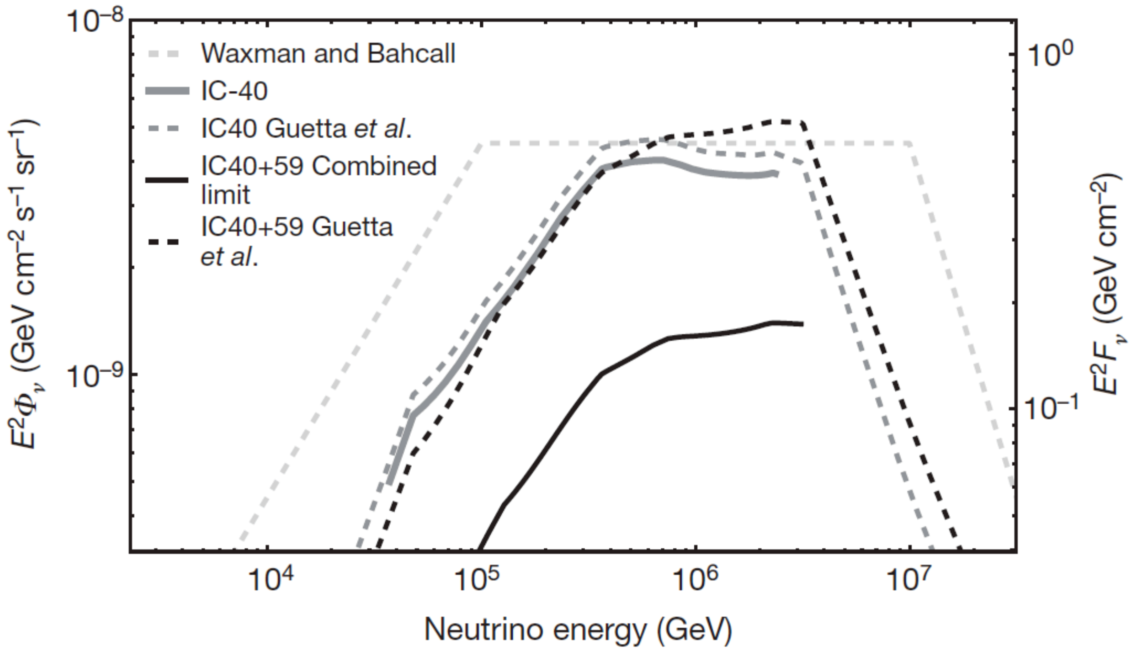


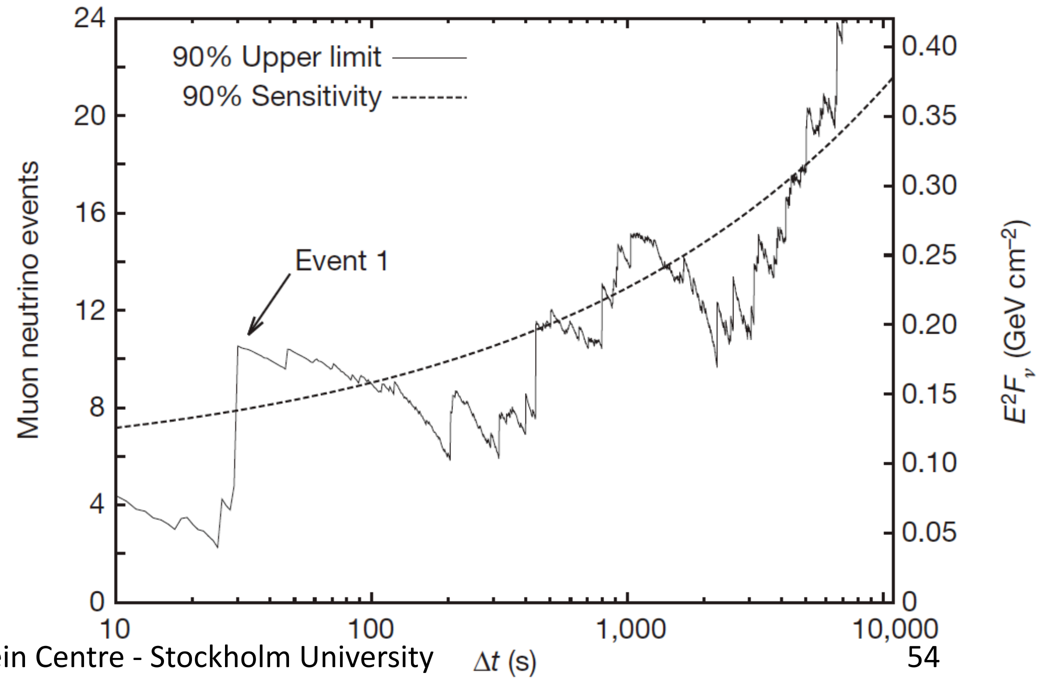
Results:

both searches consistent with background-only hypothesis.

No single neutrino candidate event from GRB detected.

Upper limits 4x or more below predictions





Results: both searches consistent with background-only hypothesis. No single neutrino candidate event from GRB detected.

What's ruled out?

Model	Normalization	Predicted neutrinos
Ahlers et al. (2011)	Cosmic rays (via neutrons)	113
Rachen et al. (1998)	Cosmic rays (via neutrons)	84
Waxman (2003)	Cosmic rays	27
Guetta et al. (2004)	Gamma spectrum	14

Recent detailed numerical calculations (e.g. http://arxiv.org/abs/1112.1076) with the same astrophysical assumptions as analytical models claim flux could be 10x lower.

⇒Still detectable or excludable by full IceCube detector

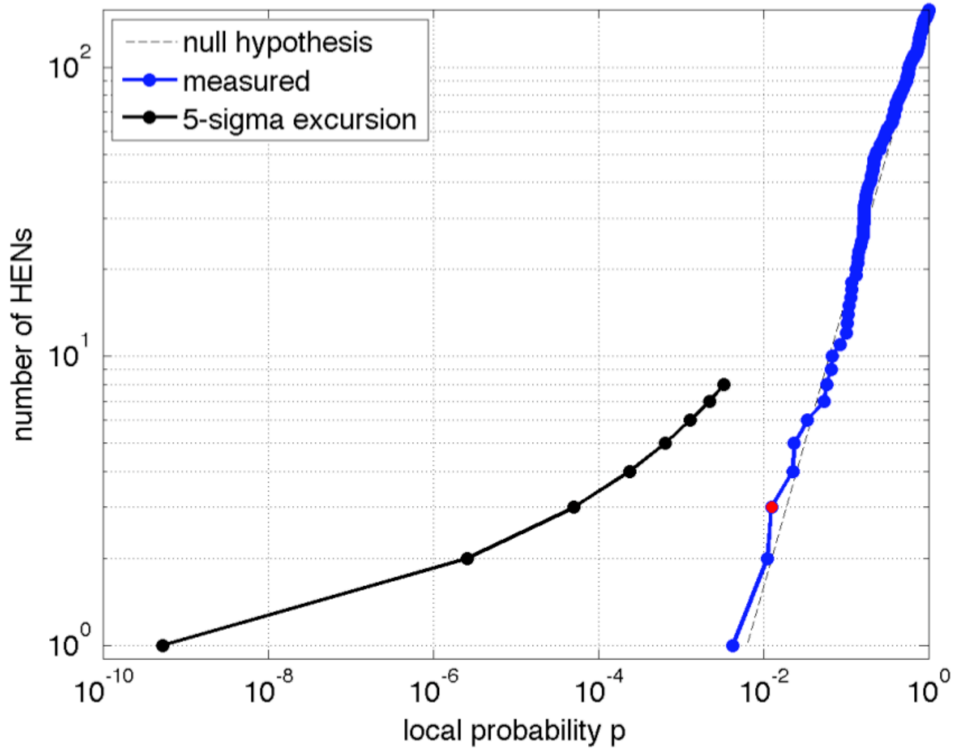
Otherwise, challenge intensifies how to explain the origin of UHECR

A First Search for coincident Gravitational Waves and High Energy Neutrinos using LIGO, VIRGO and ANTARES data from 2007

The ANTARES Collaboration, the LIGO Scientific Collaboration and the VIRGO Collaboration

ANTARES in its 5 line configuration during the period January - September 2007, which coincided with the fifth and first science runs of LIGO and Virgo, respectively.

The LIGO-Virgo data were analysed for candidate gravitational-wave signals coincident in time and direction with the neutrino events.
144 2-line events and 14 3-line events were coincident with on-time of at least 2 GW sites.



Distribution of observed p values for the loudest GW event associated with each neutrino analysed in the low frequency analysis. The red dot indicates the largest deviation of the low p tail from the uniform distribution null hypothesis; this occurs due to having the three loudest events below p_3 ~ 0.013. Deviations this large or larger occur in approximately 64% of experiments under the null hypothesis. The black line shows the threshold for a 5-sigma deviation from the null hypothesis.

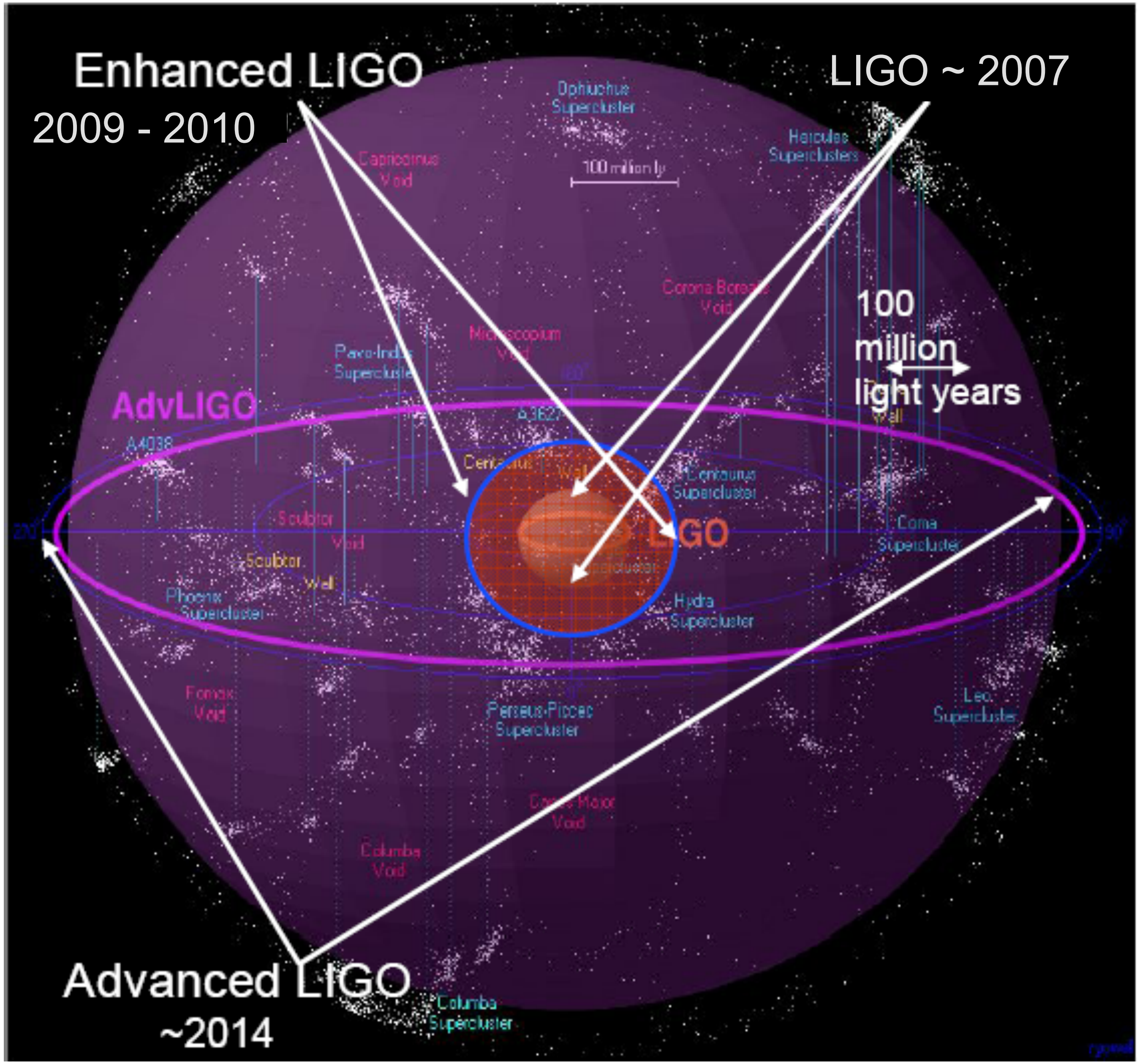
GW + ν Astronomical Reach

Advanced LIGO:

x10 better amplitude sensitivity

⇒ **x1000**
rate=(reach)^3

⇒ 1 year of Initial LIGO < 1 day of Advanced LIGO!



- Neutrino Telescopes: proven technology, in sea and in ice
- Limits beginning to challenge conventional wisdom on origins of extra-galactic cosmic rays
- If discovery made by either ANTARES or IceCube, need for KM3NeT will become essential
- IceCube is planned to operate for ~ 20 years. But detection in next ~ few years most important (e.g. galactic sources)
- Transient and Multimessenger approaches will be indispensable
- Still not one full year of complete IceCube analyzed. Stay tuned!