Astrophysical Neutrinos

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IDPASC Summer School

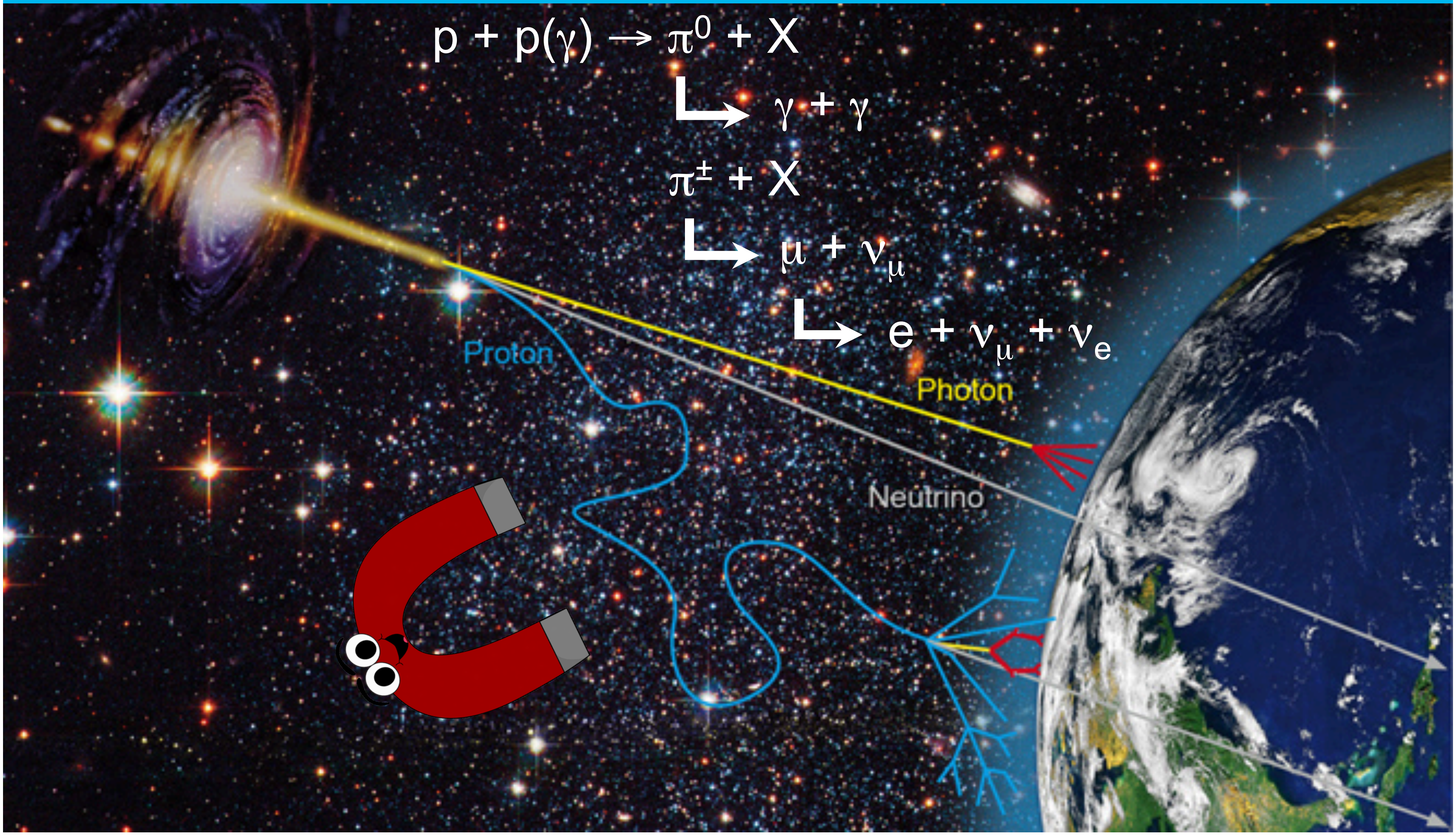
Content

- Prediction of the neutrino
- First detection of neutrinos
- Neutrinos from the sun
- Neutrinos from supernova 1987A

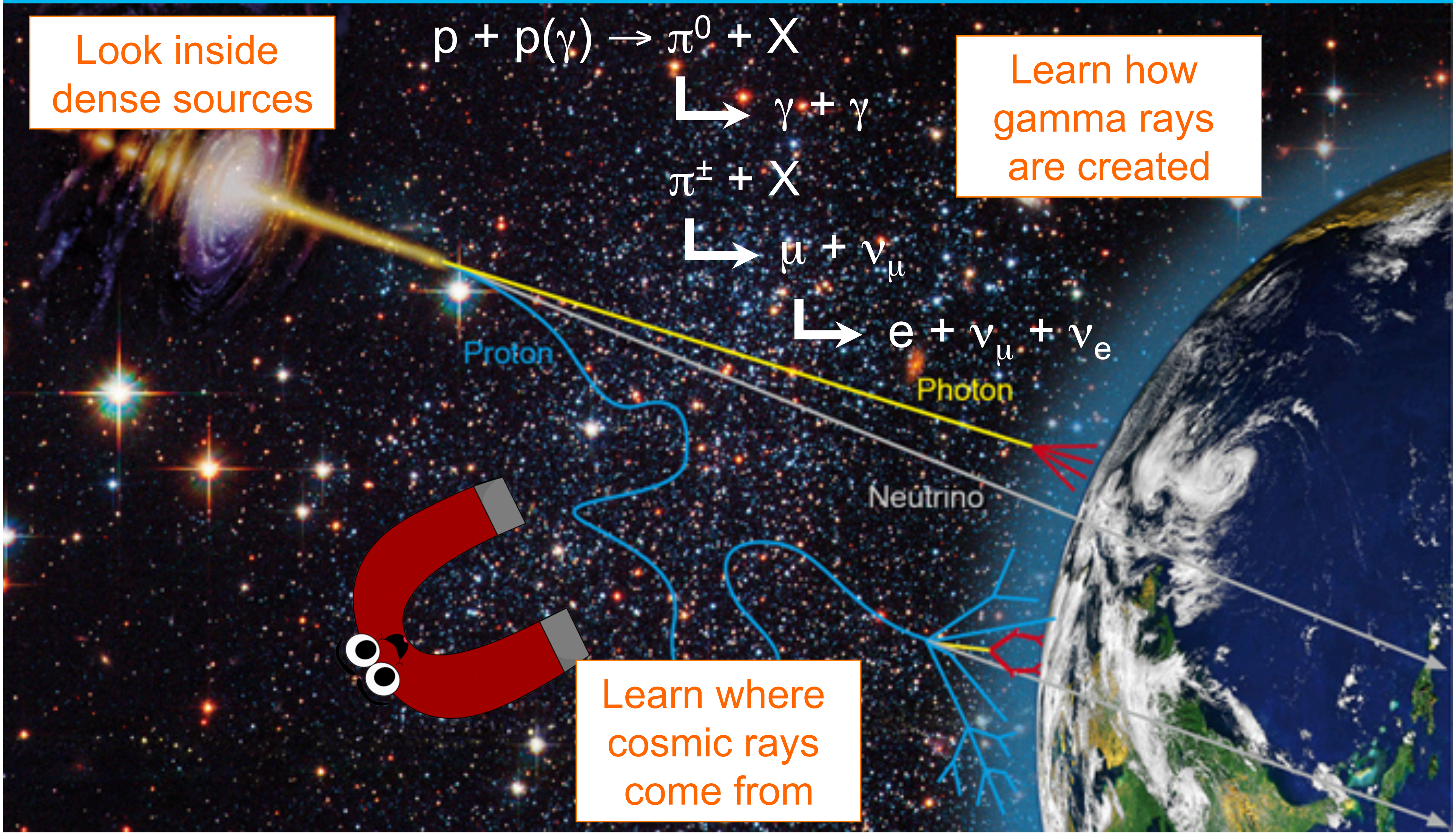
- Neutrino cosmic-ray connection
- High-energy neutrino astronomy
- Multi-messenger astronomy with neutrinos

High-Energy Astrophysical Neutrinos

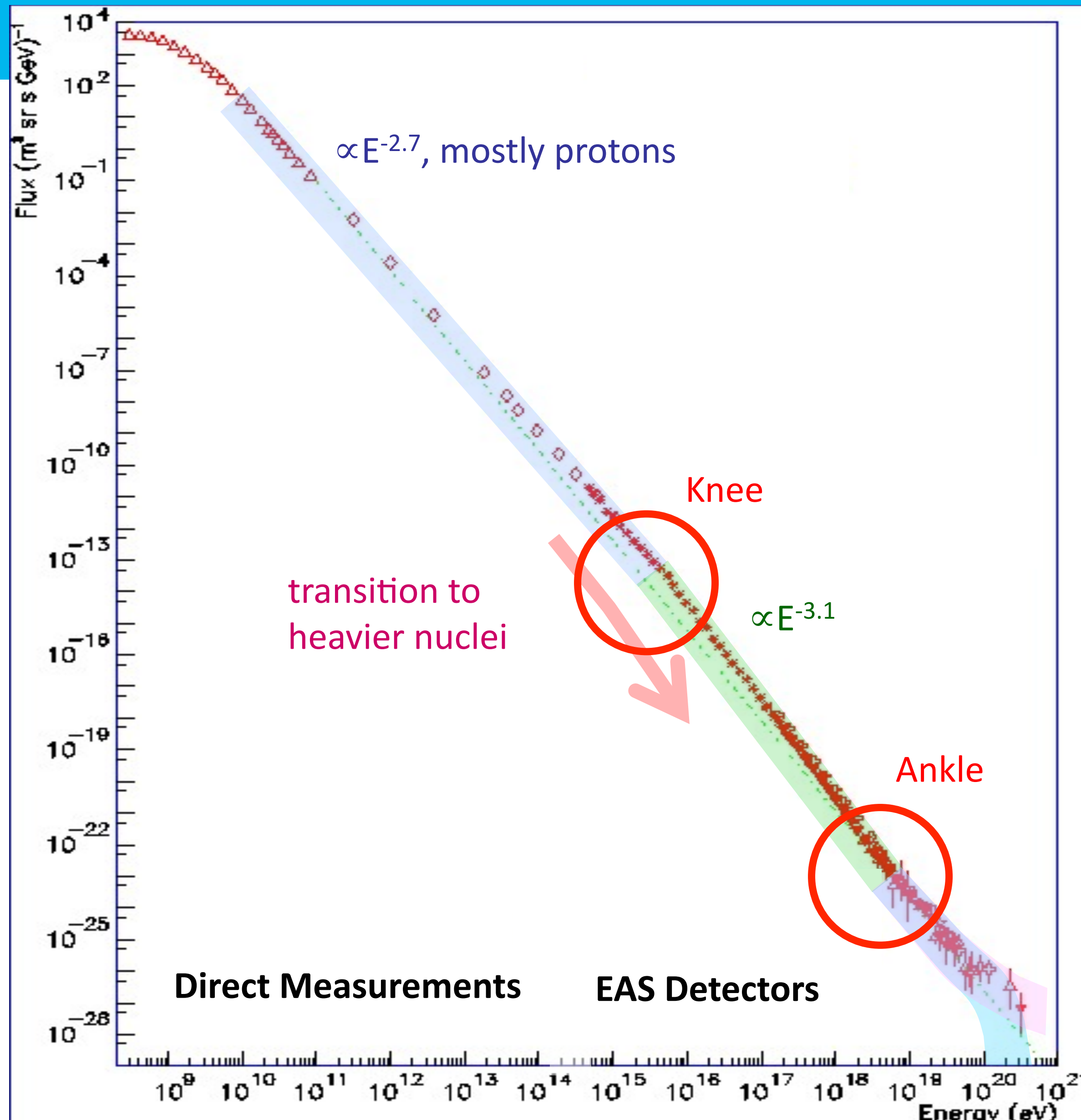
High-energy Neutrino CR connection



High-energy Neutrino CR connection



Cosmic Rays (CR)



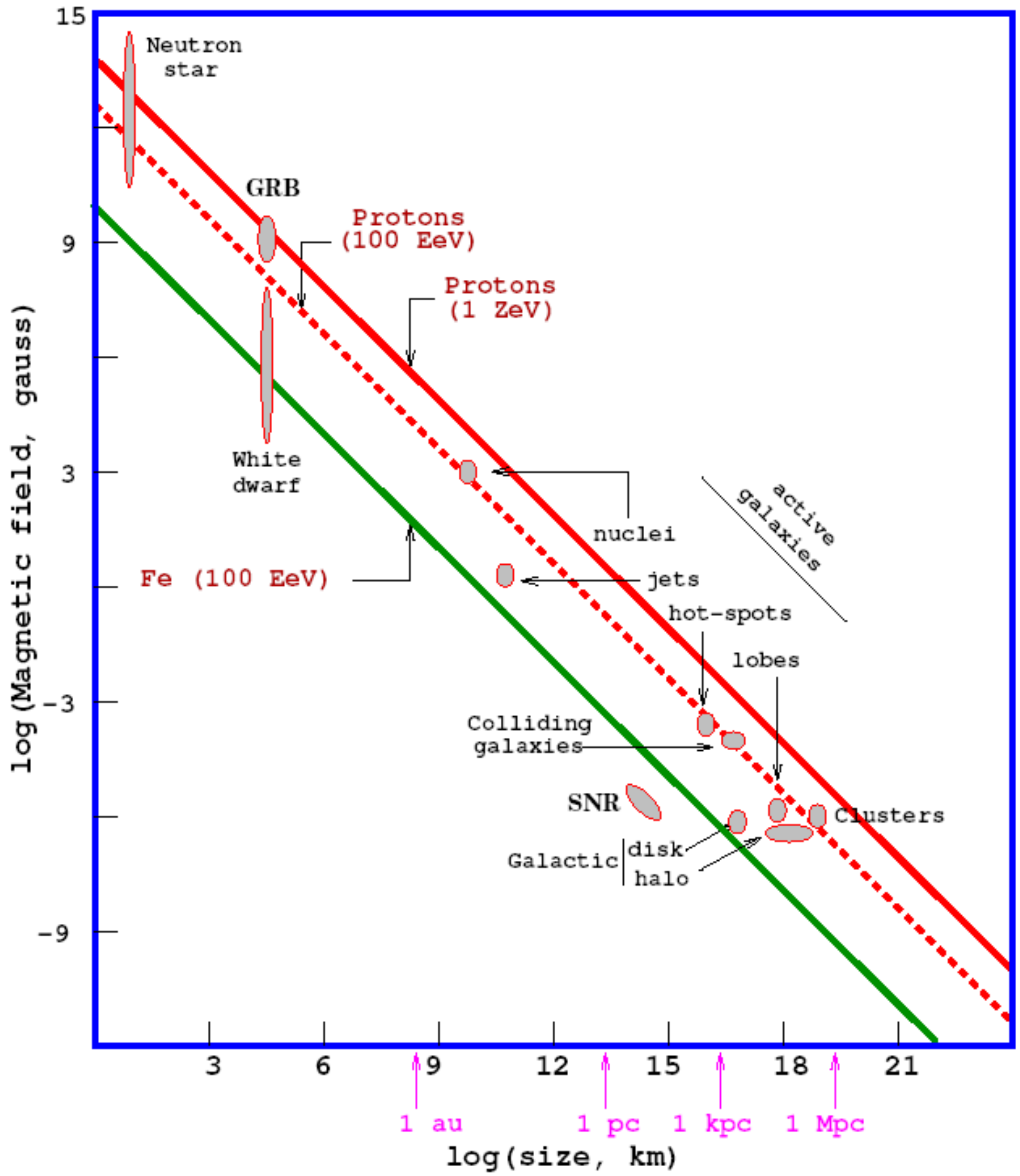
Hillas' Plot

- Which sources are capable of producing high-energy CR
- Sources need to confine CR

$$\varepsilon_{\max} = qBR$$

max. CR particle energy; charge of CR particle; magnetic field; radius of accelerator

- Galactic sources (e.g. supernova remnants too small for highest energy CR



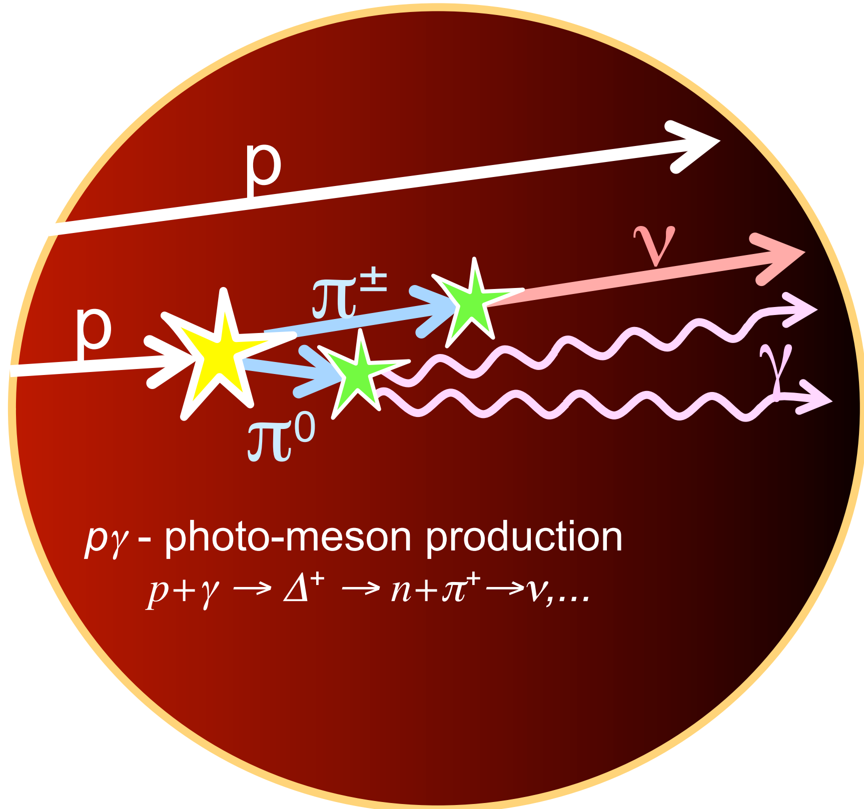
CR and neutrino energy budget

$$\int E_\nu \frac{dN_\nu}{dE_\nu} dE = Z_{p\rightarrow\nu}\varepsilon_\nu \int E_p \frac{dN_p}{dE_p} dE_p$$

$Z_{p\rightarrow\nu}$ = kinematic scale factor

$\varepsilon \quad \Leftrightarrow$ source environment

$$\varepsilon = \begin{cases} \ll 1 \text{ optically thin to } p\text{-}\gamma \\ > 1 \text{ optically thick to } p\text{-}\gamma \end{cases}$$

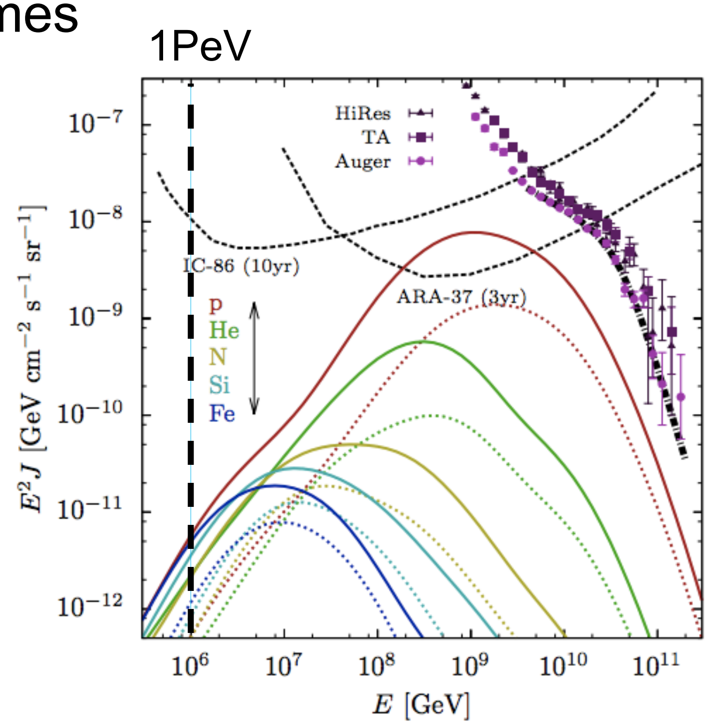


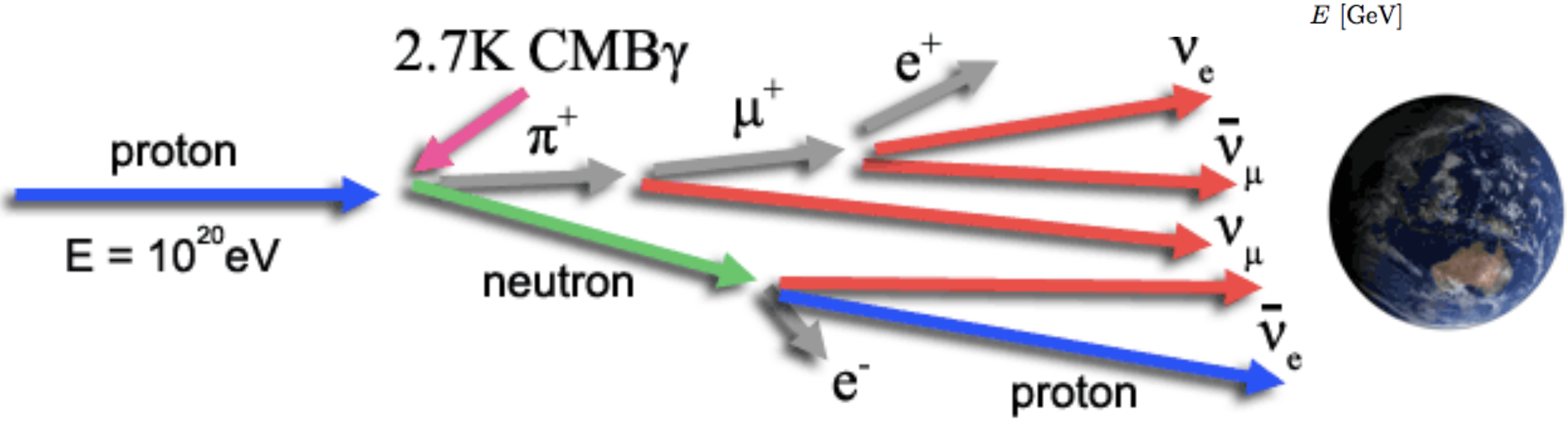
GZK Cutoff

- Above 10^{19}-10^{20} GeV, the Universe becomes opaque for protons: $\varepsilon_{CMB} \approx 1$
- Protons interact with CMB photons

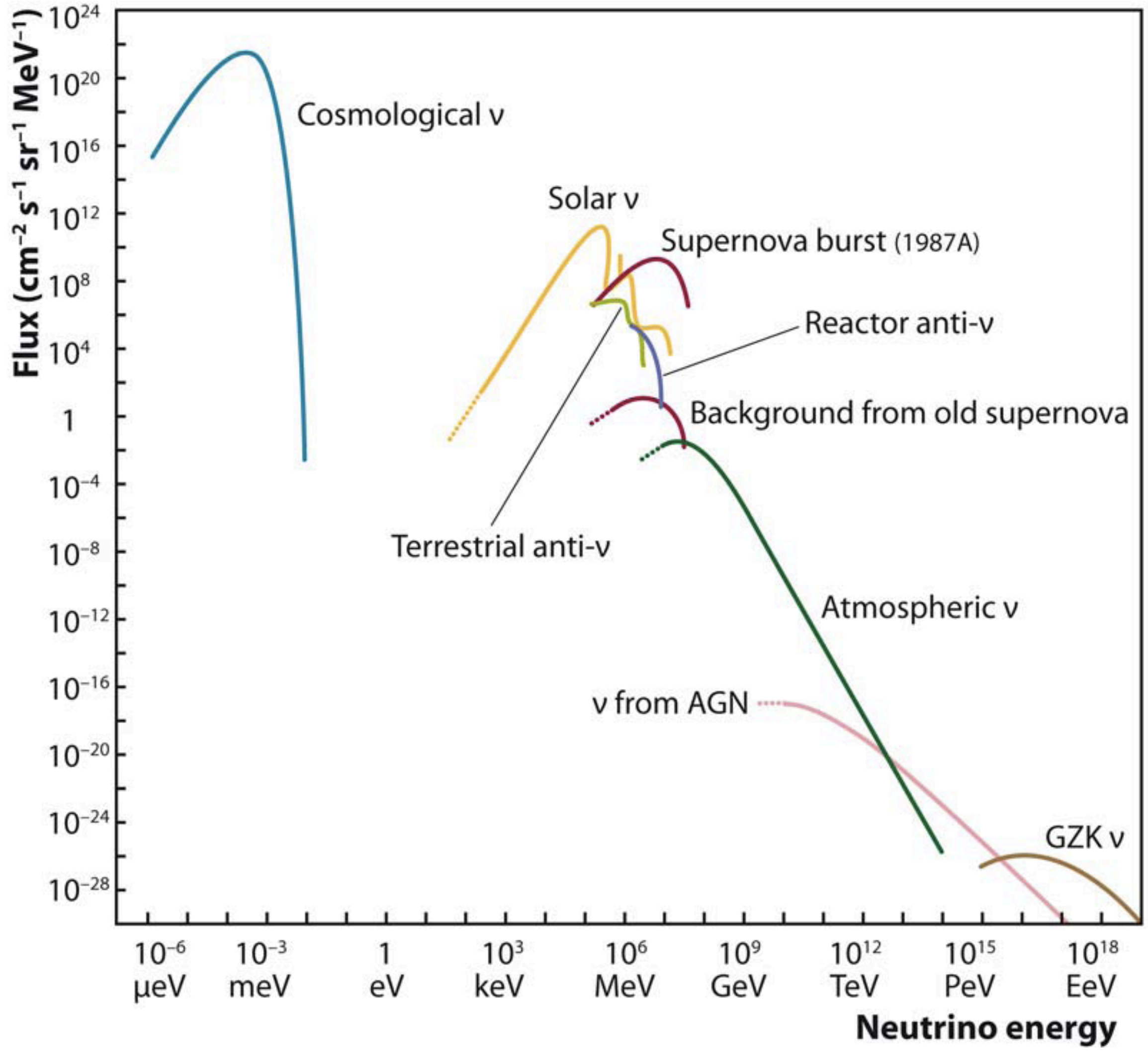
$$\gamma_{\rm CMB} + p \rightarrow \Delta^+ \rightarrow p + \pi^0,$$
$$\gamma_{\rm CMB} + p \rightarrow \Delta^+ \rightarrow n + \pi^+.$$

- Guarantied neutrino flux, but composition dependent





Neutrino Energy Scale



Waxman Bahcall Bound

Energy density of extragalactic CR

ρ_{CR} (>10EeV) ~ 10^{44} ergs/yr/Mpc^3

Waxman & Bahcall upper bound

$\varepsilon \leq 1 \Rightarrow \rho_{\nu} \geq Z_{p\rightarrow\nu}\, \rho_{CR}$

- assume that CRs lose some fraction ε of their energy through pion photoproduction before escaping the source
- fraction of proton energy carried by neutrino produced in this way is about 5% independent of proton energy, so neutrino energy spectrum follows scaled-down version of proton spectrum
- resulting bound is $E_{\nu}^{2}\varphi_{\nu} < 2\times10{-}8$ GeV cm−2 s^{-1} sr^{-1}
- 1 km^3 volume is needed to probe this flux

Waxman Bahcall Bound

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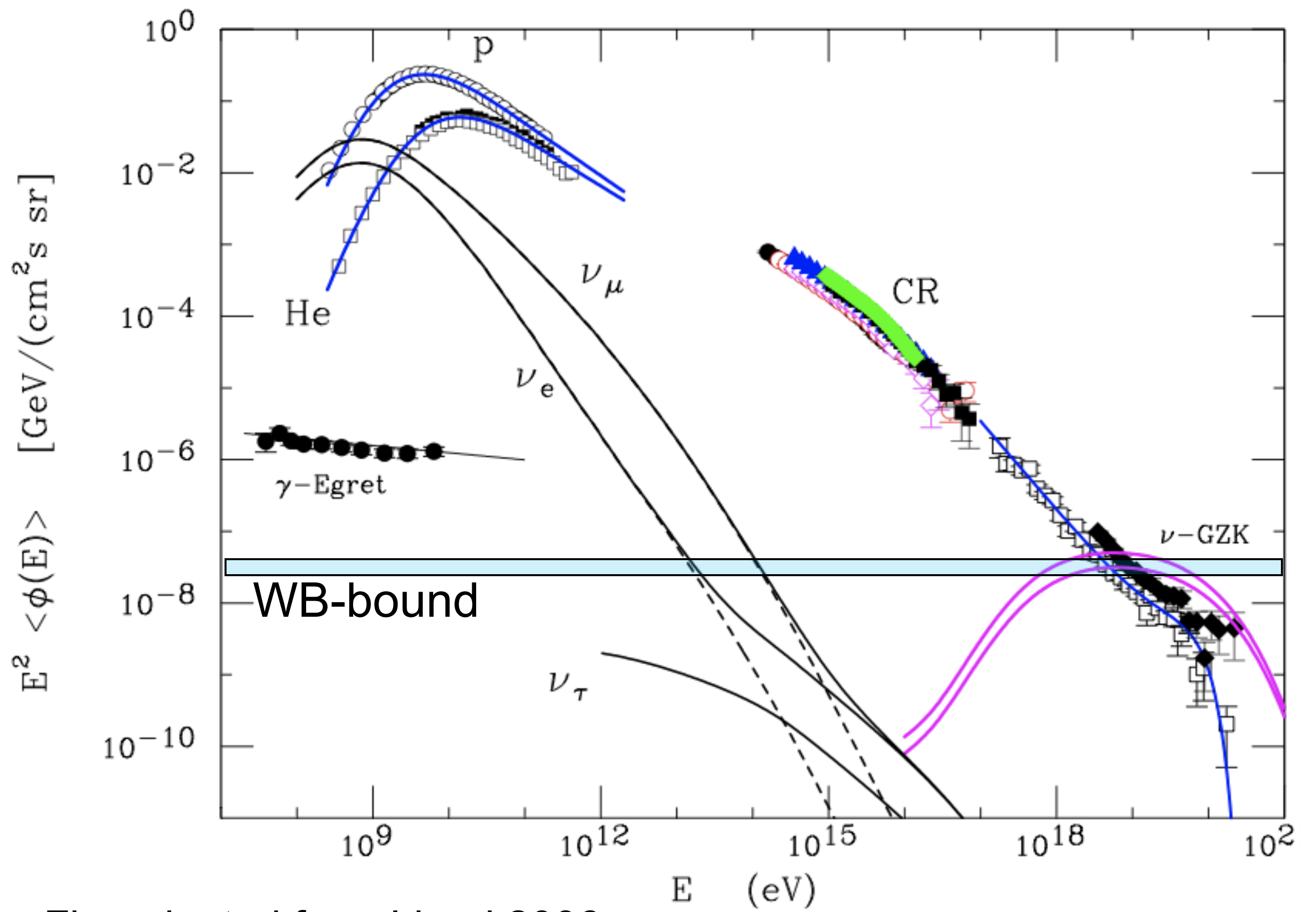
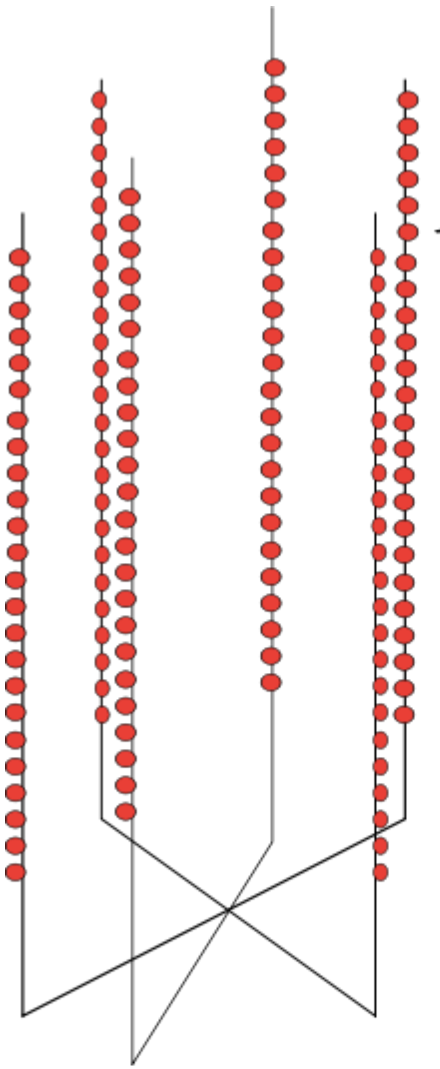
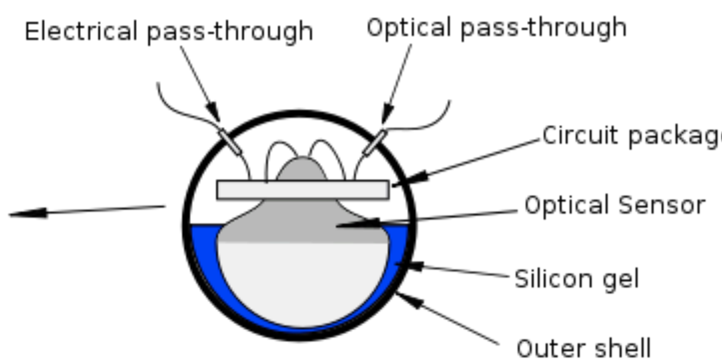


1 km3 size detectors needed to reach WB bound

Fig. adapted from Lipari 2006

DUMAND (Deep Underwater Muon And Neutrino Detector)

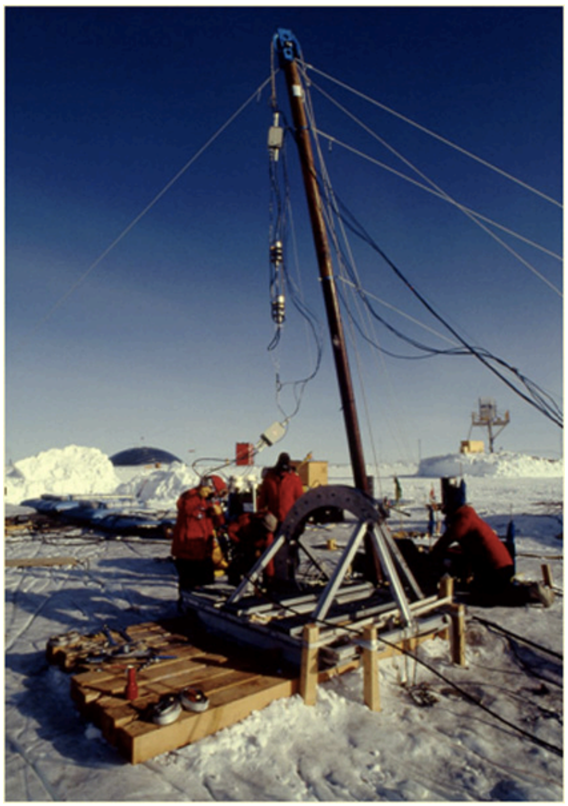


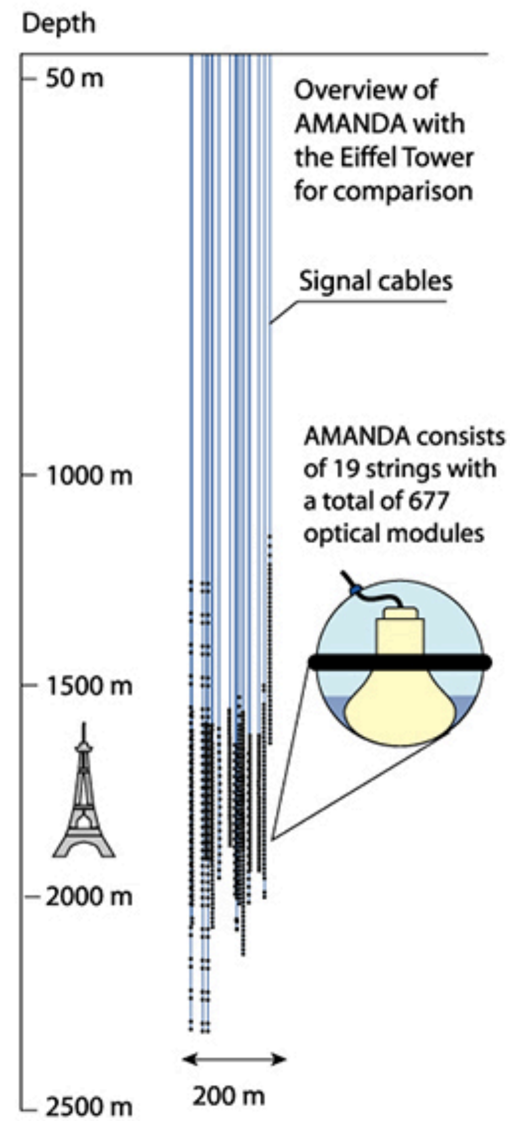


1995 cancelled due to technical problems

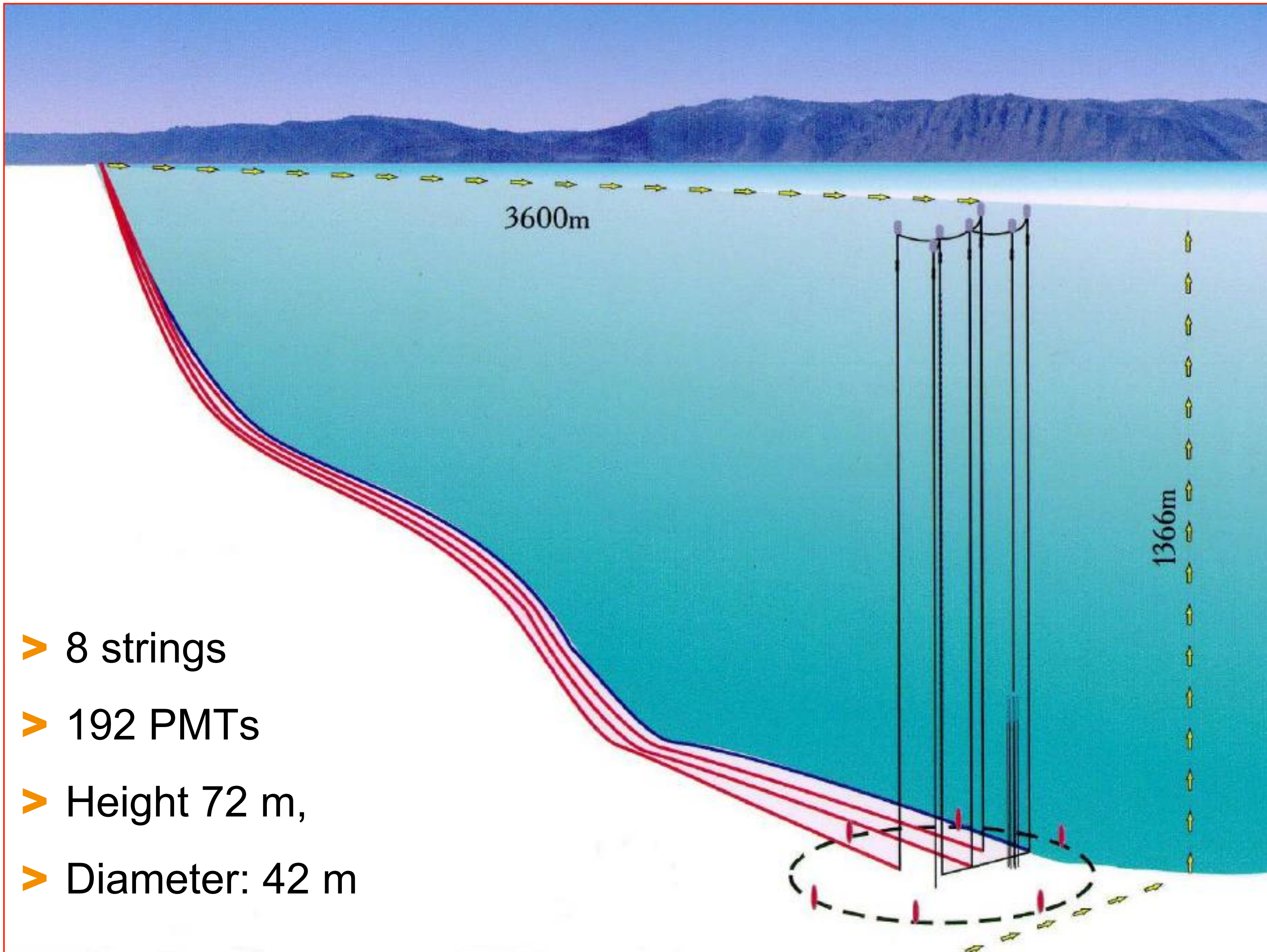
AMANDA

- 677 optical modules
- 19 strings
- Diameter 200 m, height 500 m
- 1997 - 2009



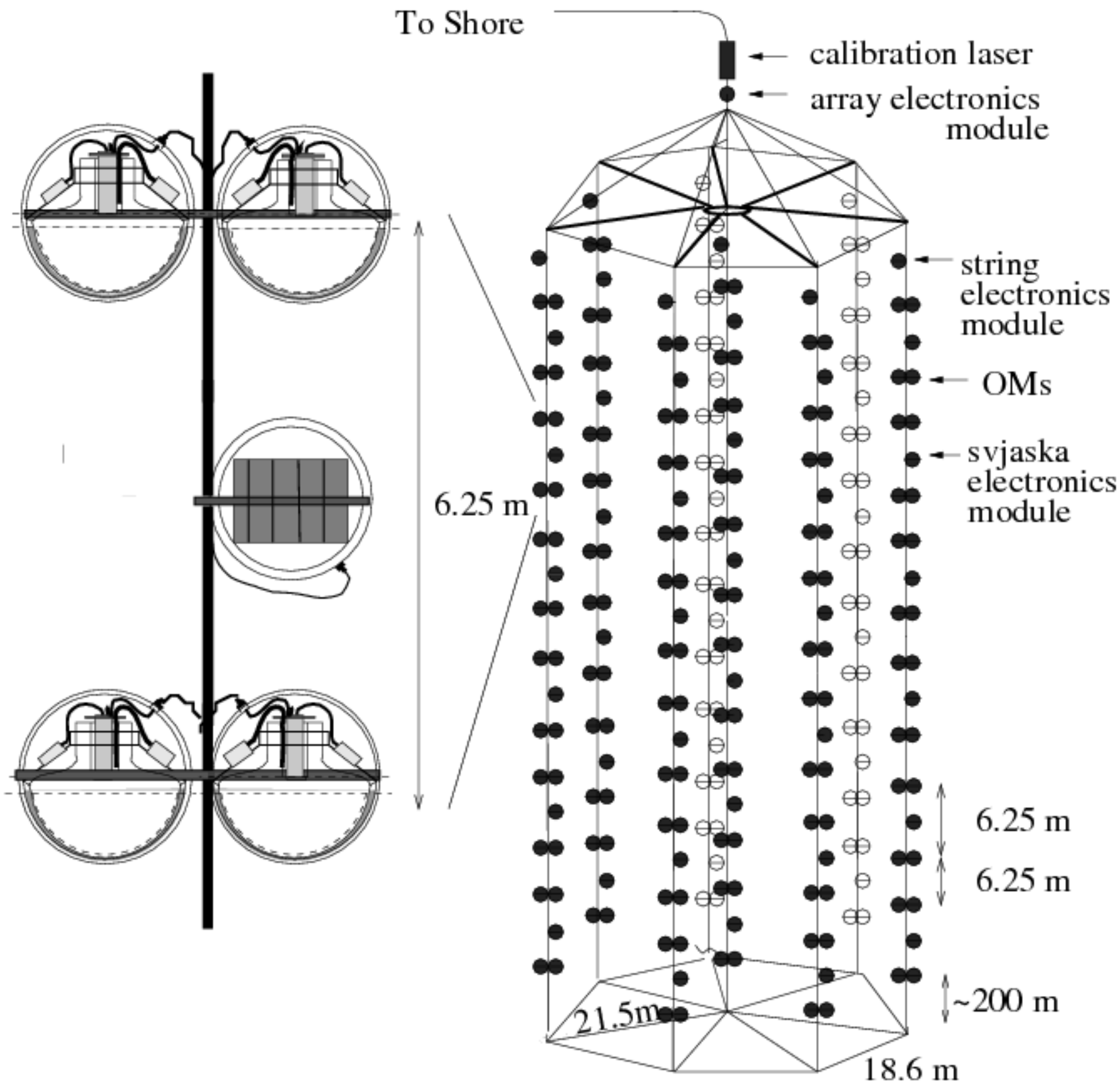


NT200, Lake Baikal

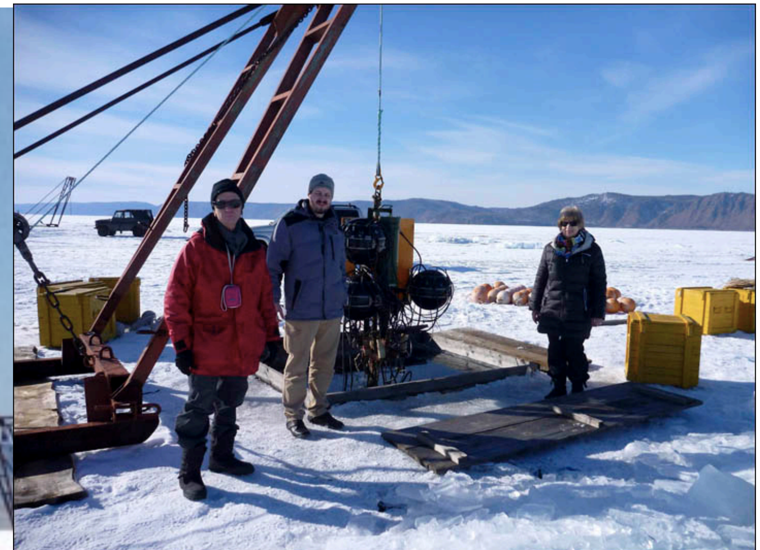


- 8 strings
- 192 PMTs
- Height 72 m,
- Diameter: 42 m

NT200, Lake Baikal

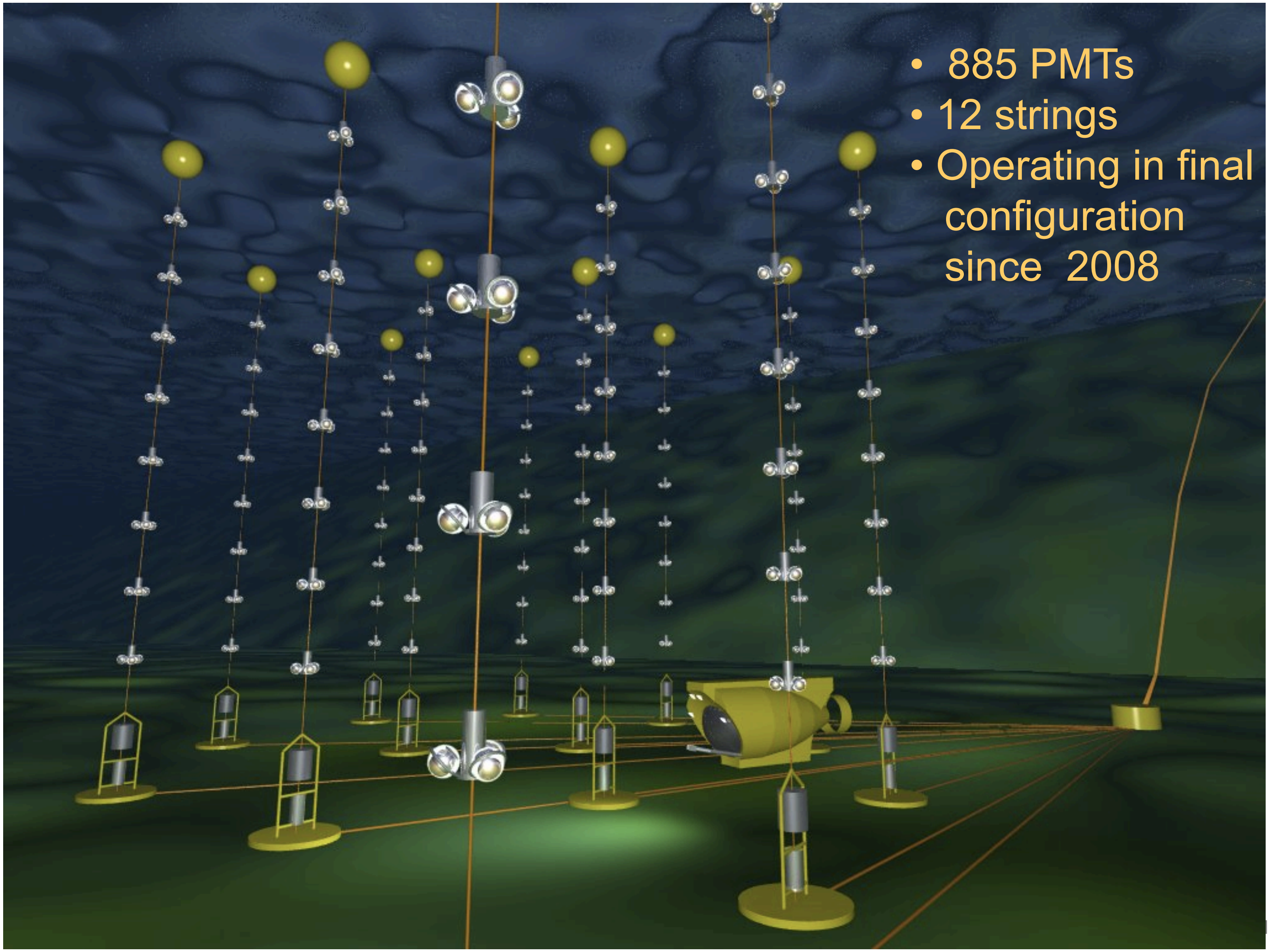


Deployment at Lake Baikal



Deployment during the winter month, when lake Baikal is frozen

ANTARES, Mediterranean Neutrino Detector



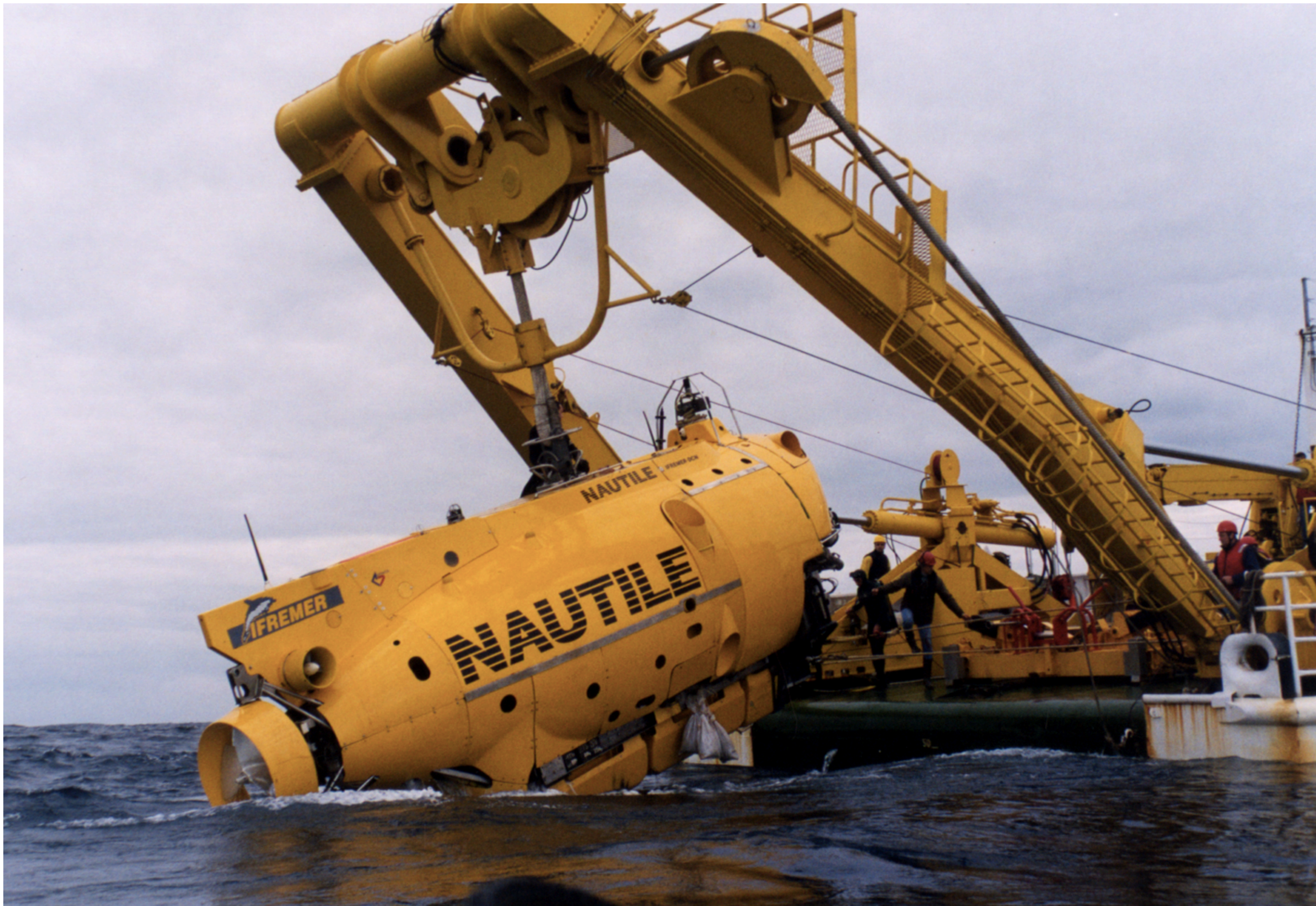
- 885 PMTs
- 12 strings
- Operating in final configuration since 2008

ANTARES

Deployment by boat

ANTARES

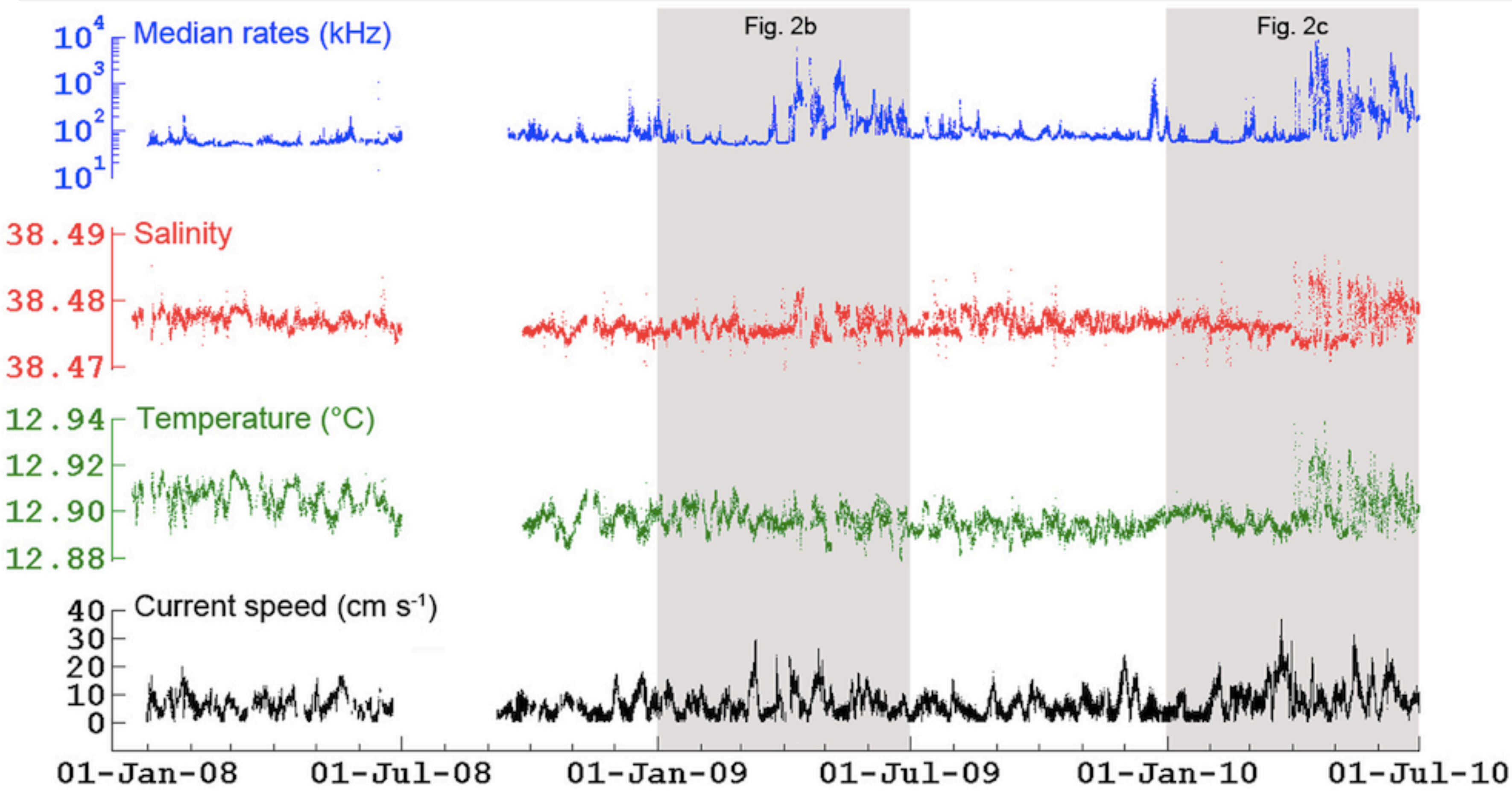
Manned submarine plugs in cable to junction box on the ground



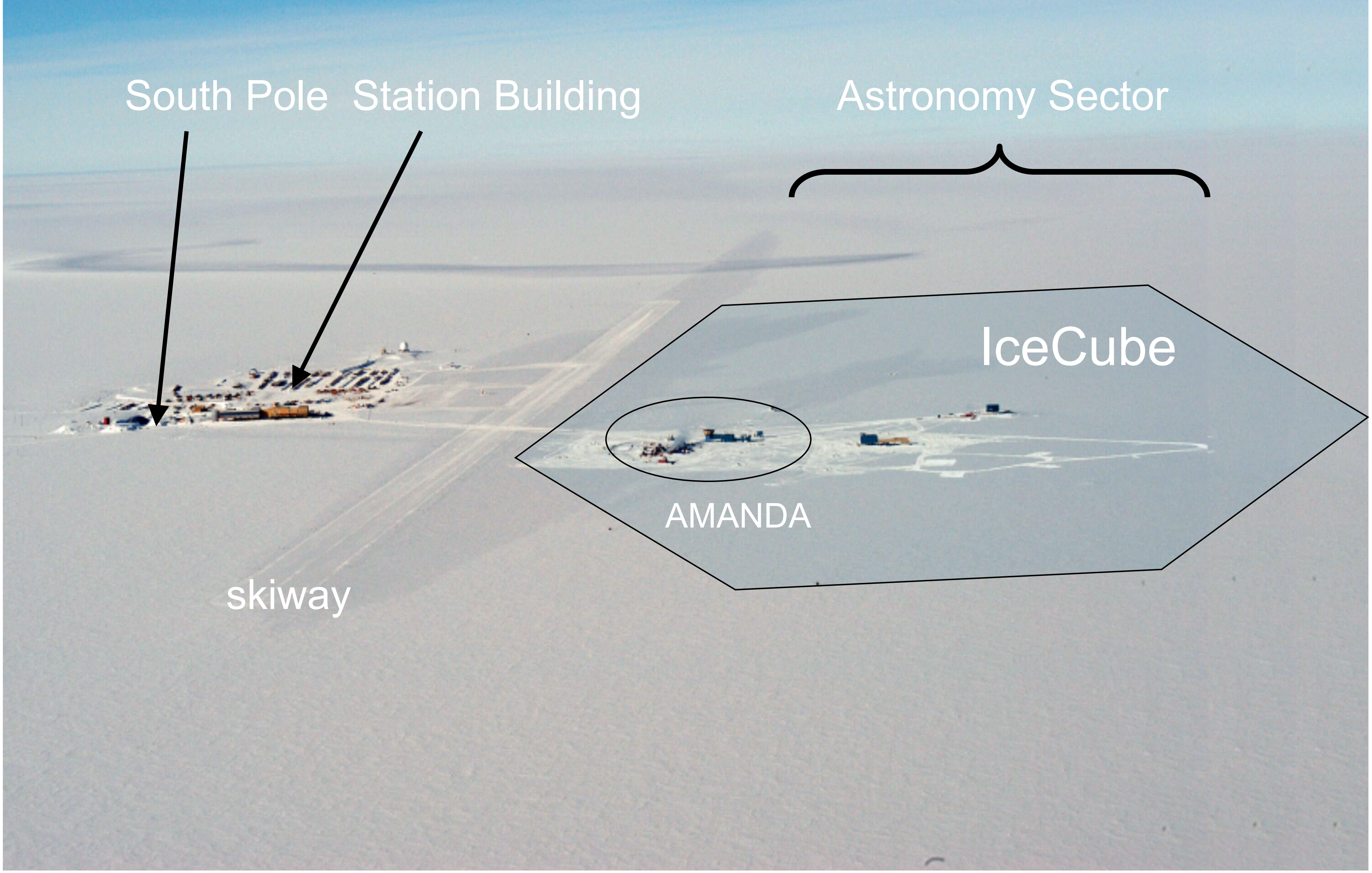
Bioluminescence in Water

Bioluminescence in Water

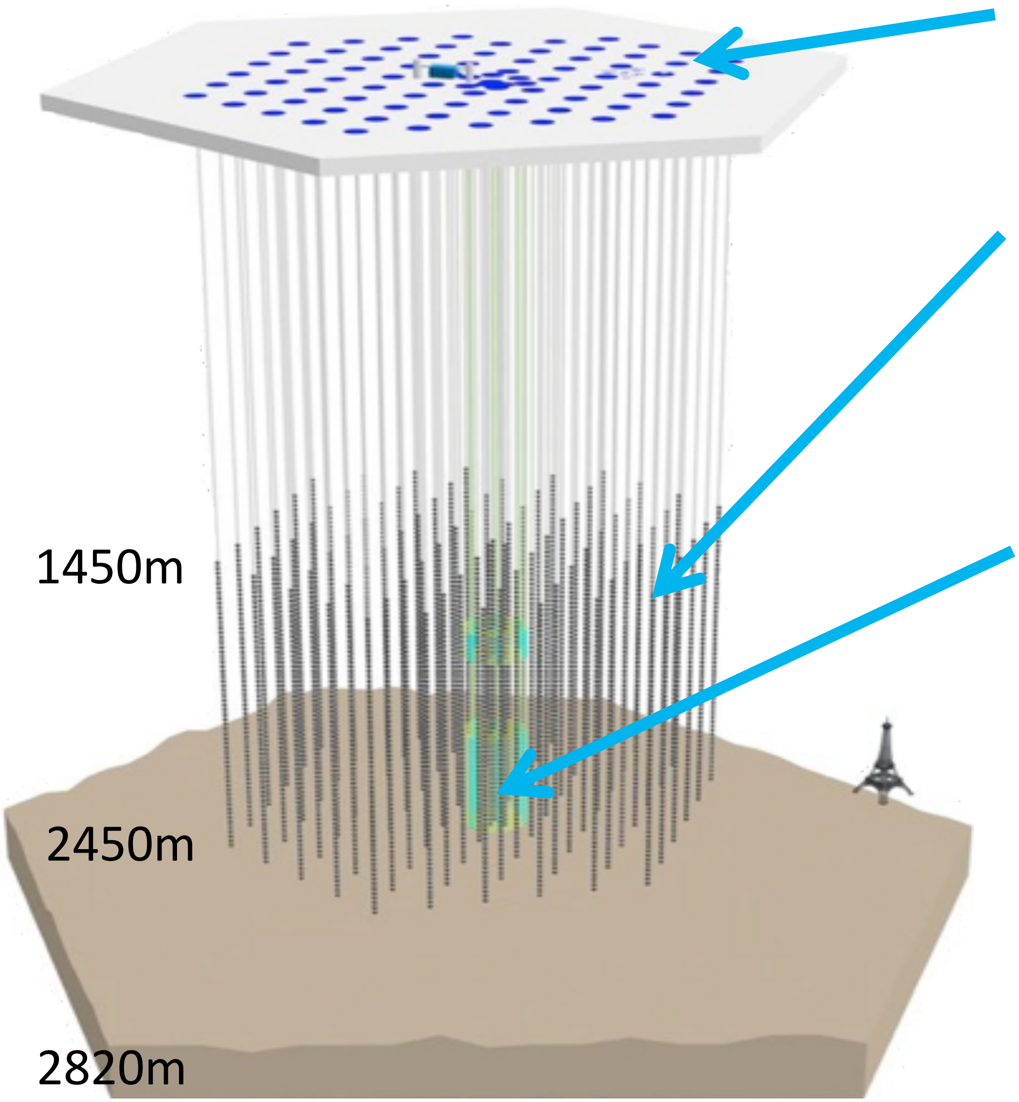
Mainly bioluminescent plankton and bacteria



The Amundsen-Scott Station



IceCube



IceTop air shower detector
81 pairs of water Cherenkov tanks

IceCube
86 strings including 8 Deep Core strings
60 PMT per string

DeepCore
8 closely spaced strings

- ~220 ν/day
- Volume: 1km^3
- Threshold
  - IceCube ~ 100 GeV
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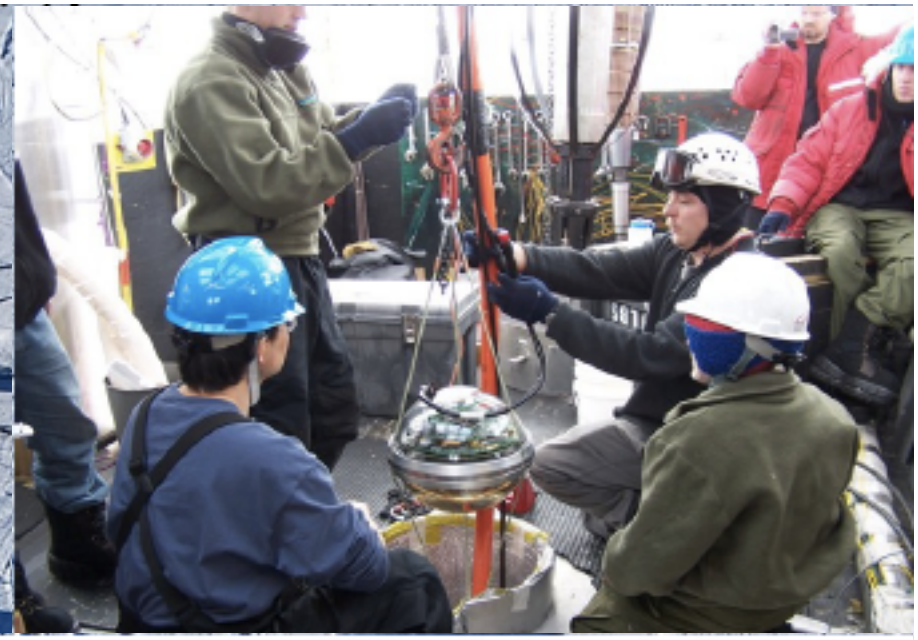
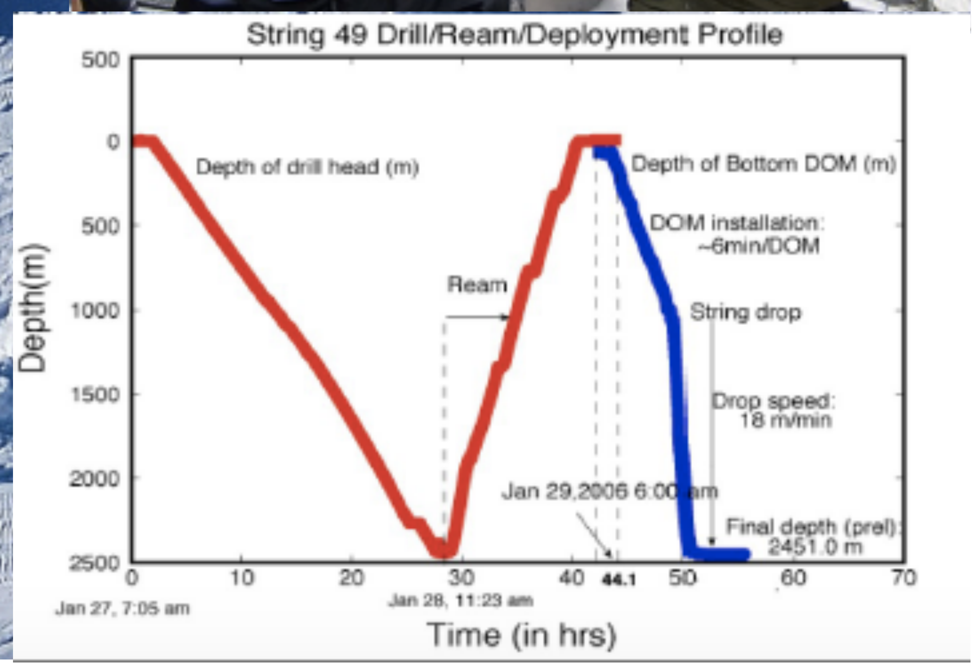
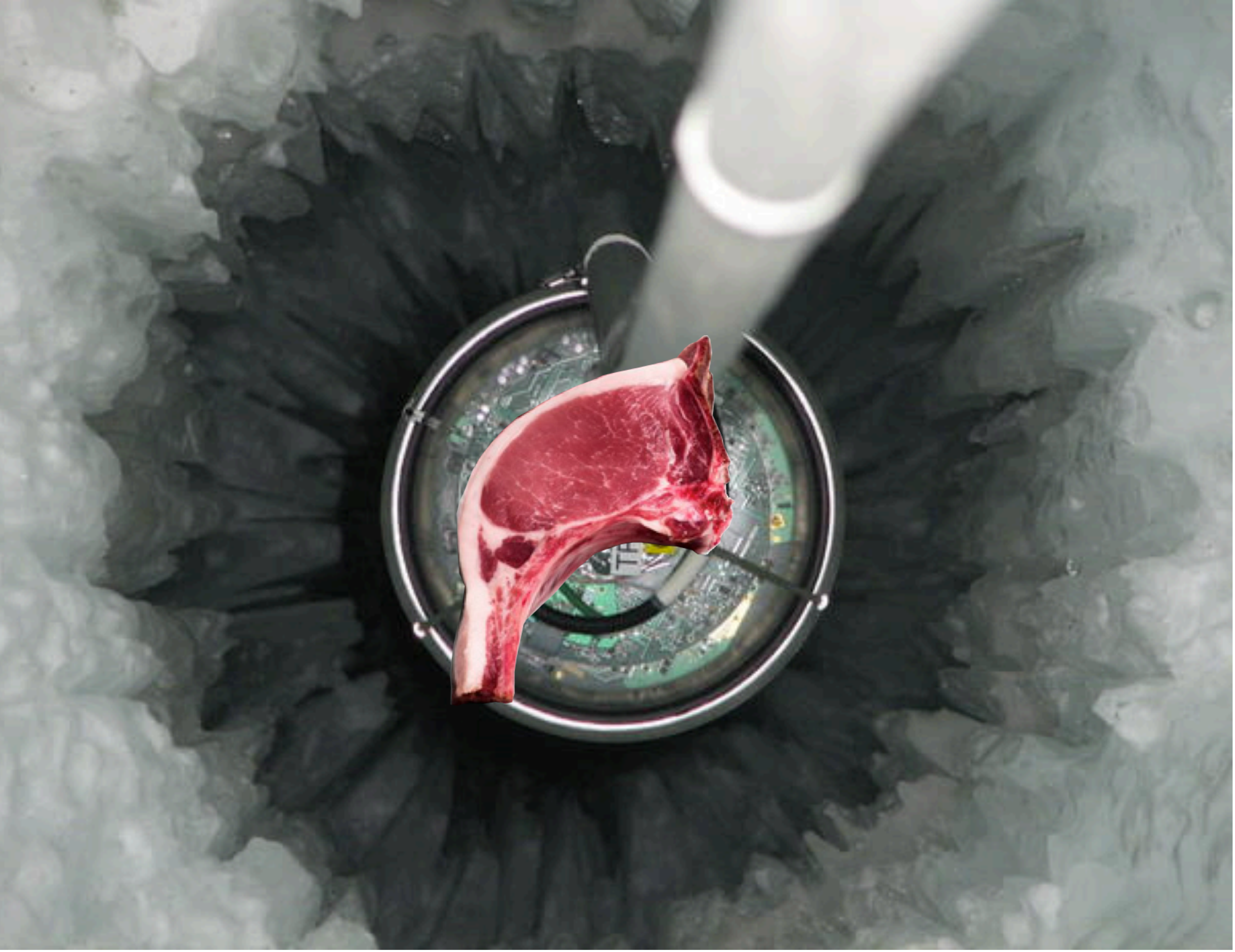
IceCube - Deployment





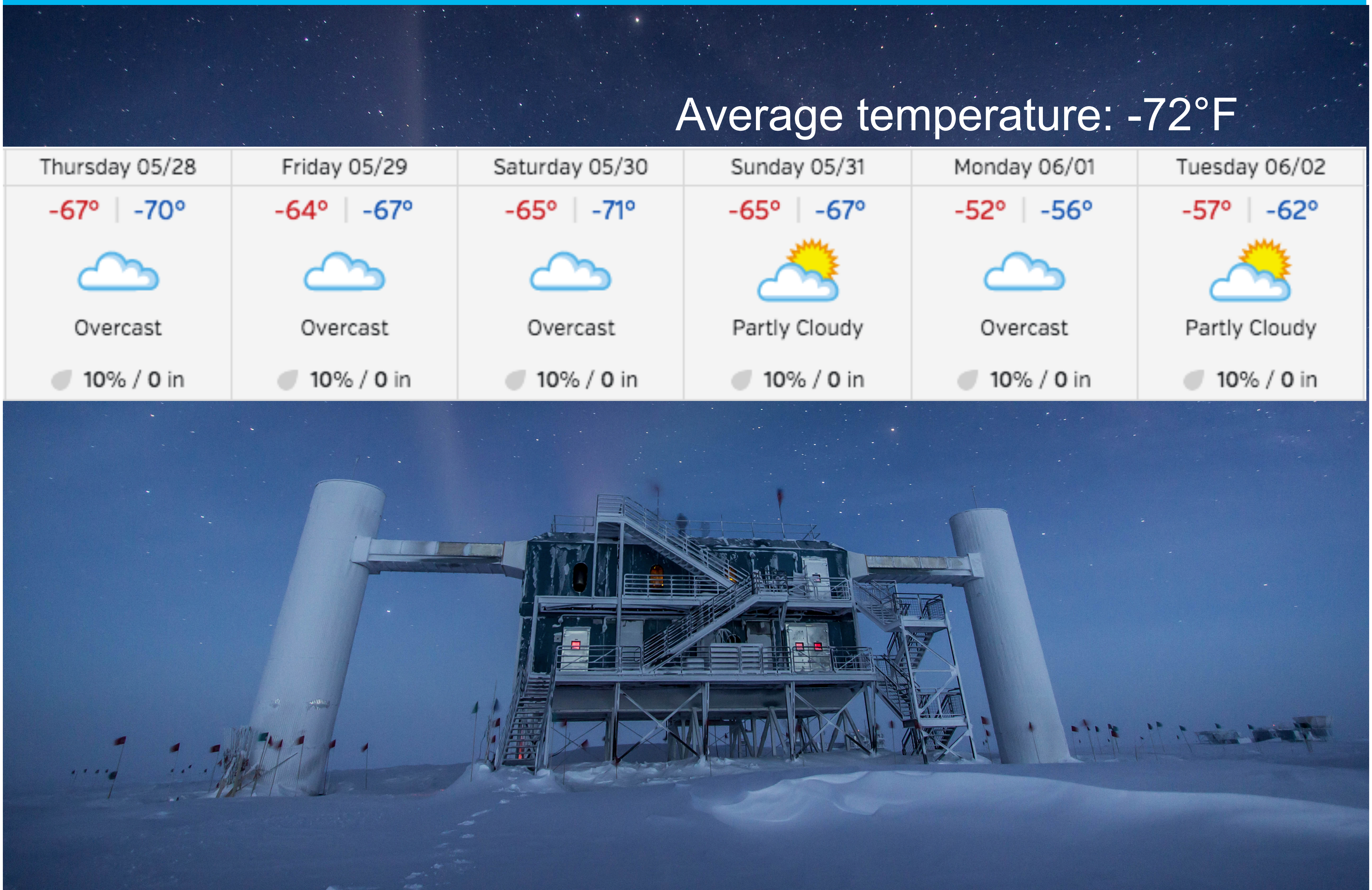


South Pole in Summer

February 2015

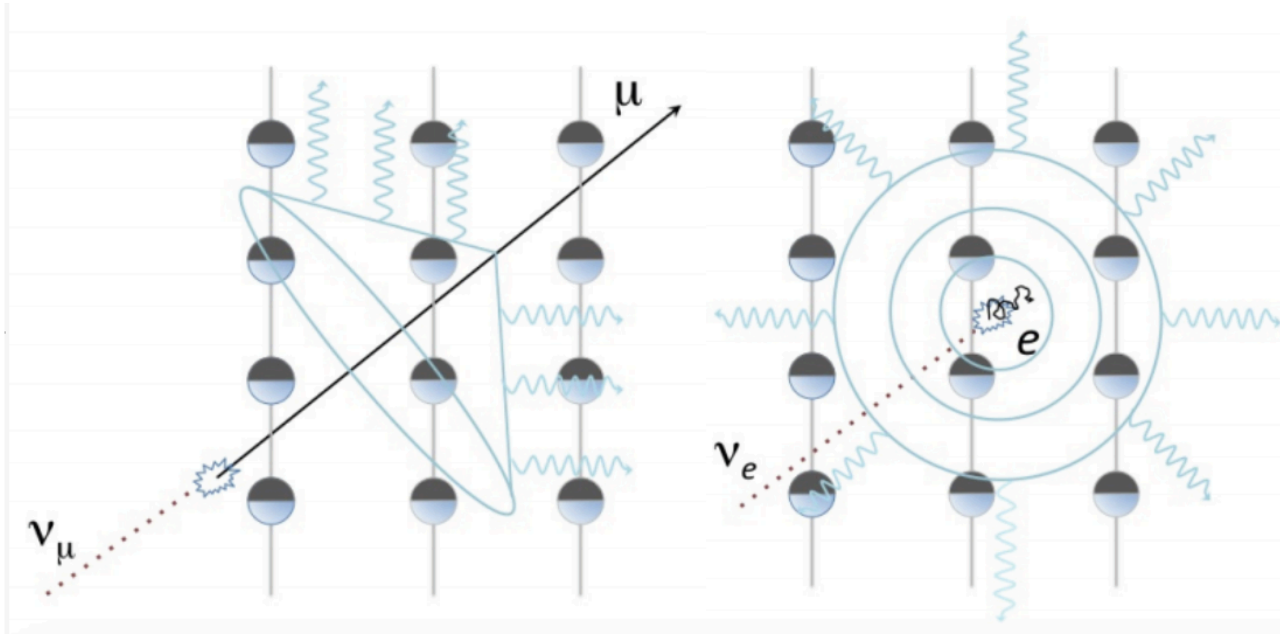
Sun	Mon	Tue	Wed	Thu	Fri	Sat
1	2	3	4 View historic weather ▸	5 -32 / -29 °F	6 -31 / -24 °F	7 -32 / -25 °F
8 -30 / -23 °F	9 -25 / -18 °F	10 -23 / -17 °F	11 -22 / -20 °F	12 -24 / -21 °F	13 -34 / -22 °F	14 -39 / -29 °F
15 -45 / -36 °F	16 -47 / -44 °F	17 -46 / -43 °F	18 -45 / -40 °F	19 -42 / -39 °F	20	21

South Pole in Winter



Thursday 05/28	Friday 05/29	Saturday 05/30	Sunday 05/31	Monday 06/01	Tuesday 06/02
-67° | -70°	-64° | -67°	-65° | -71°	-65° | -67°	-52° | -56°	-57° | -62°
Overcast	Overcast	Overcast	Partly Cloudy	Overcast	Partly Cloudy
10% / 0 in	10% / 0 in	10% / 0 in	10% / 0 in	10% / 0 in	10% / 0 in

IceCube neutrino event signatures



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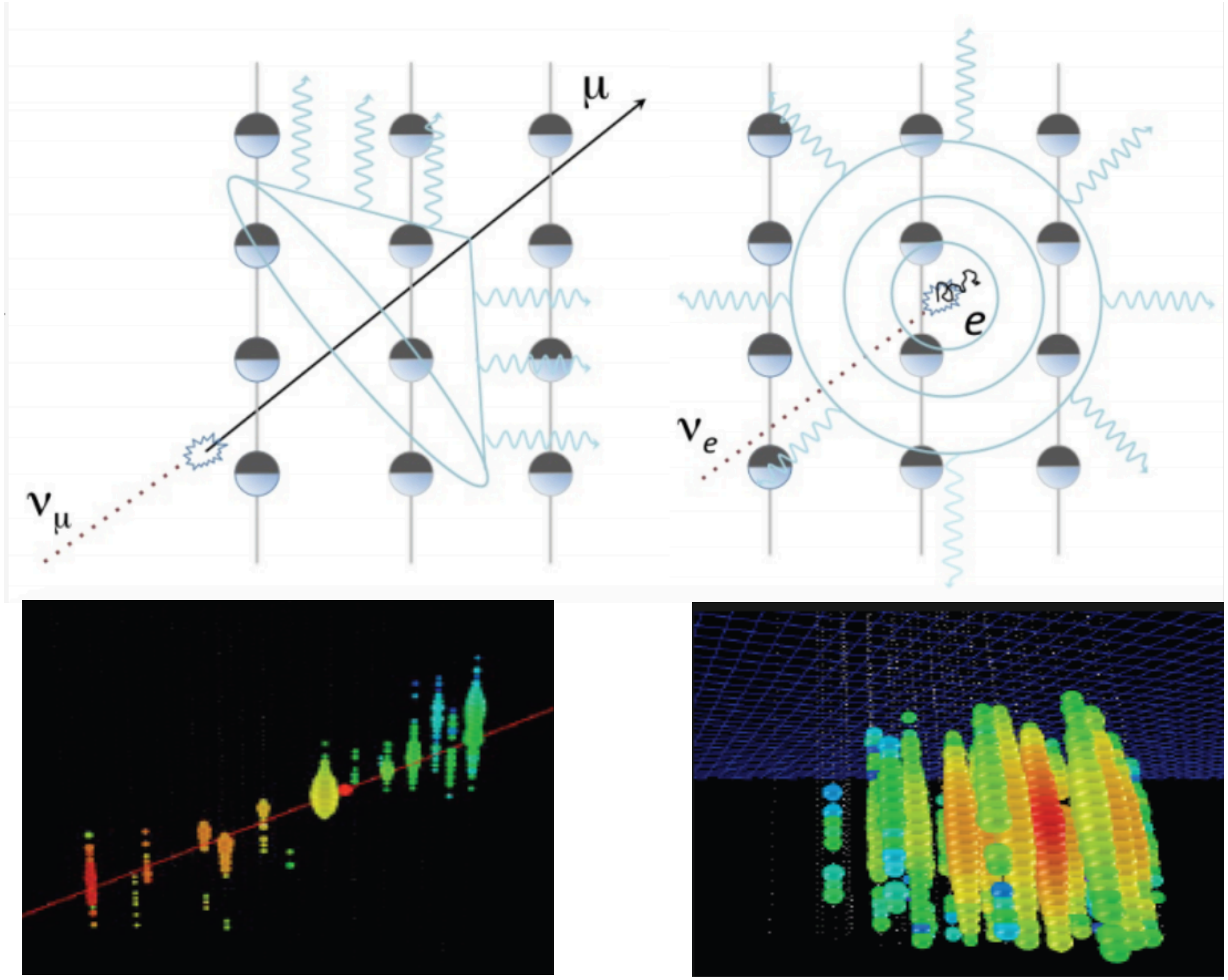
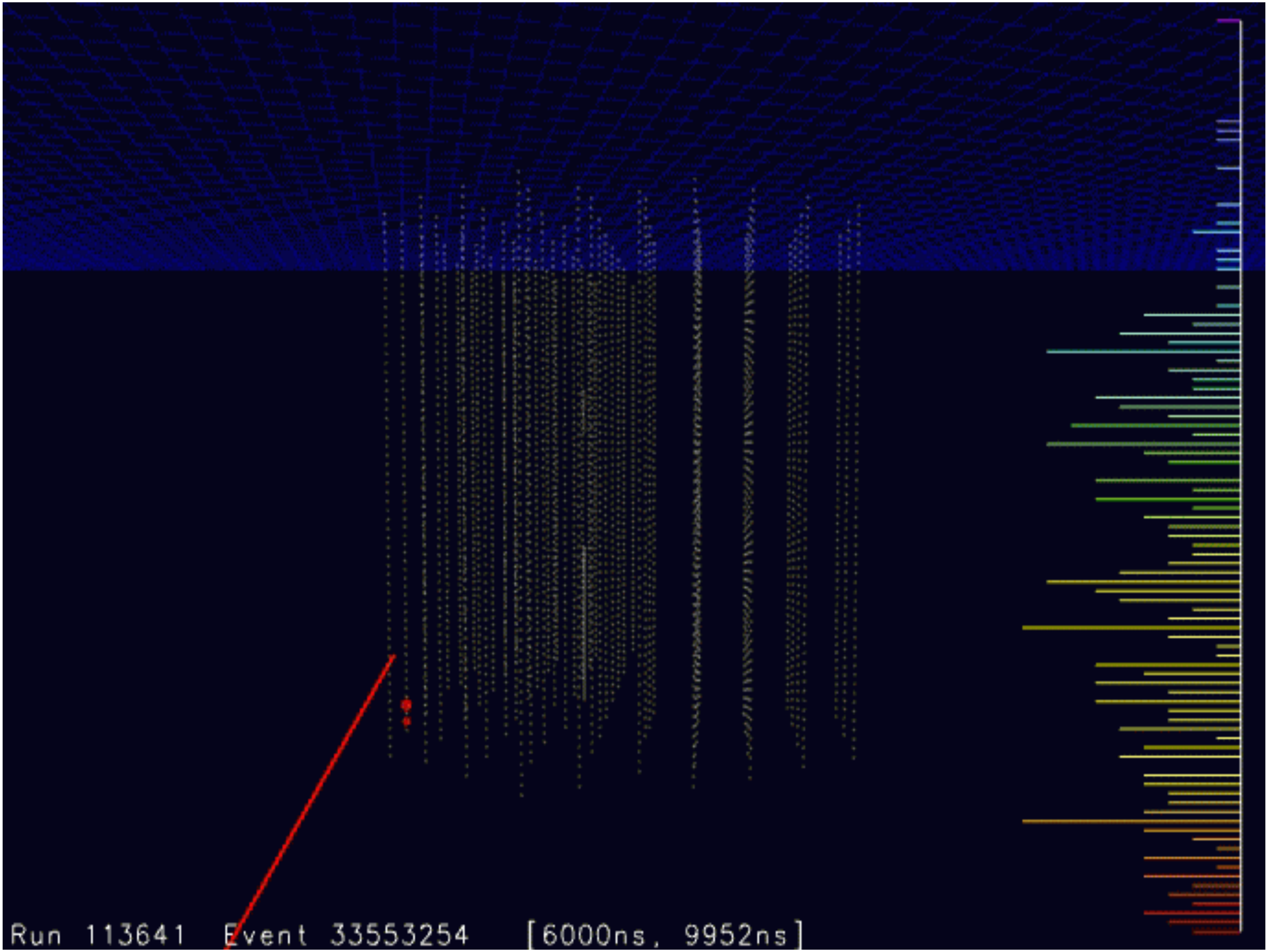
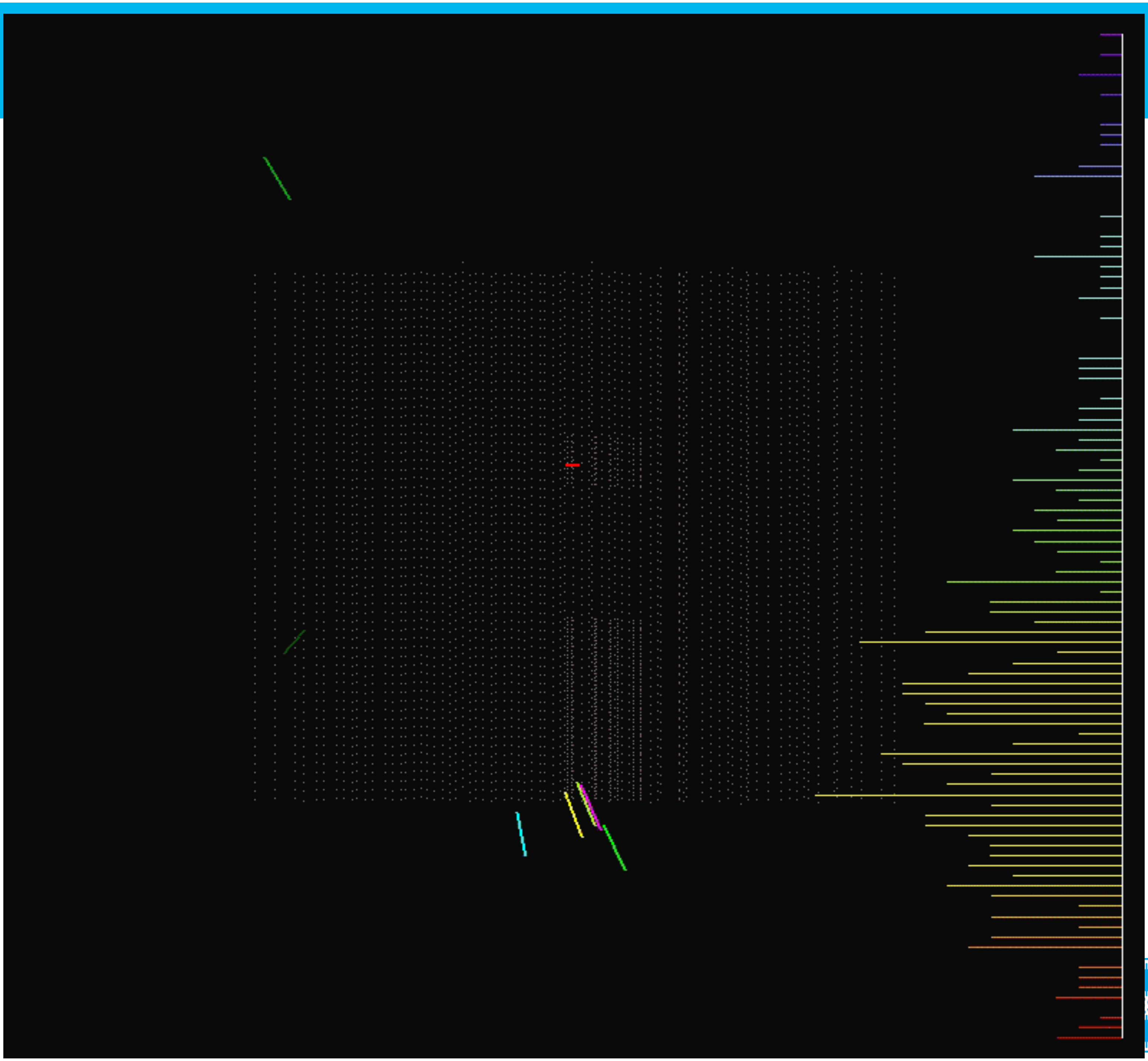
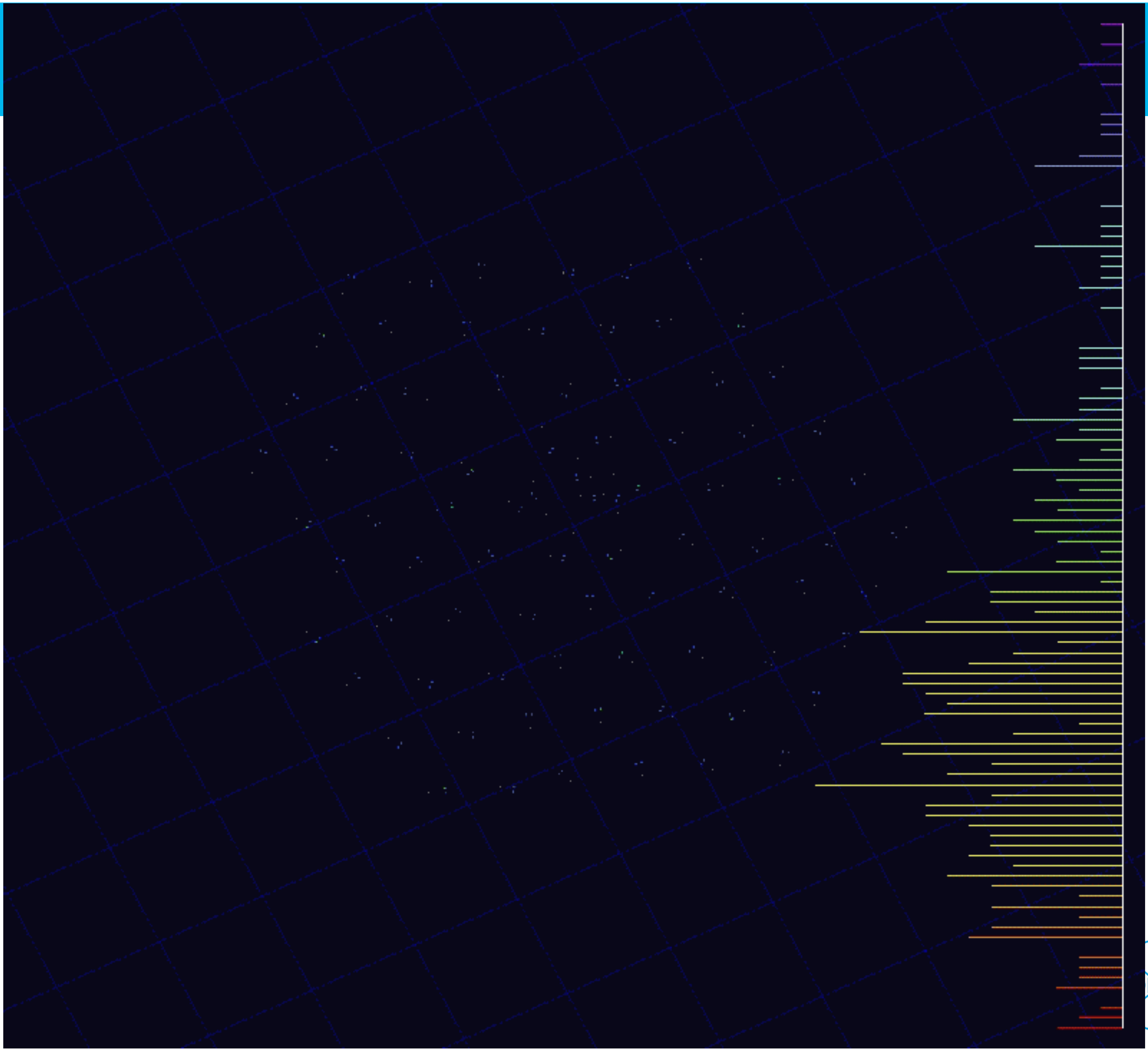



Run 113641 Event 33553254 [6000ns, 9952ns]





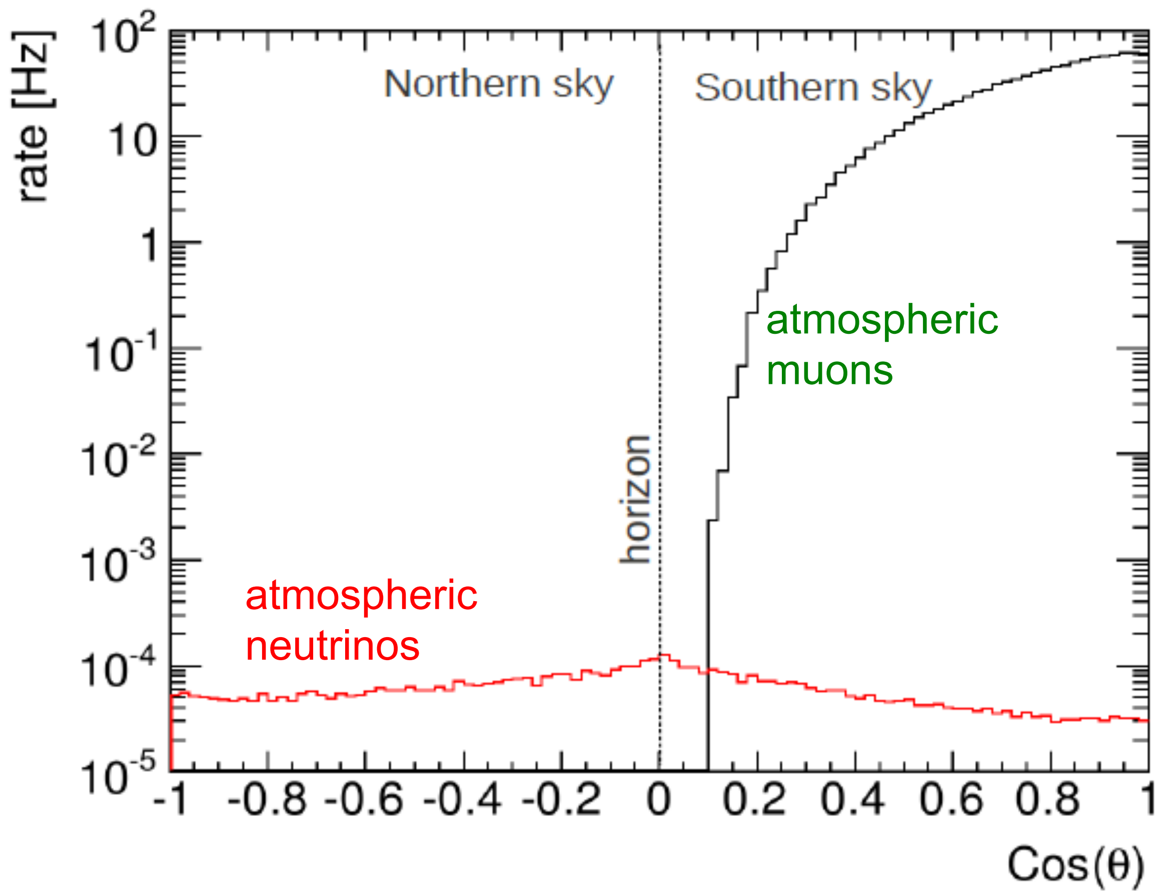
Comparison of different detector media

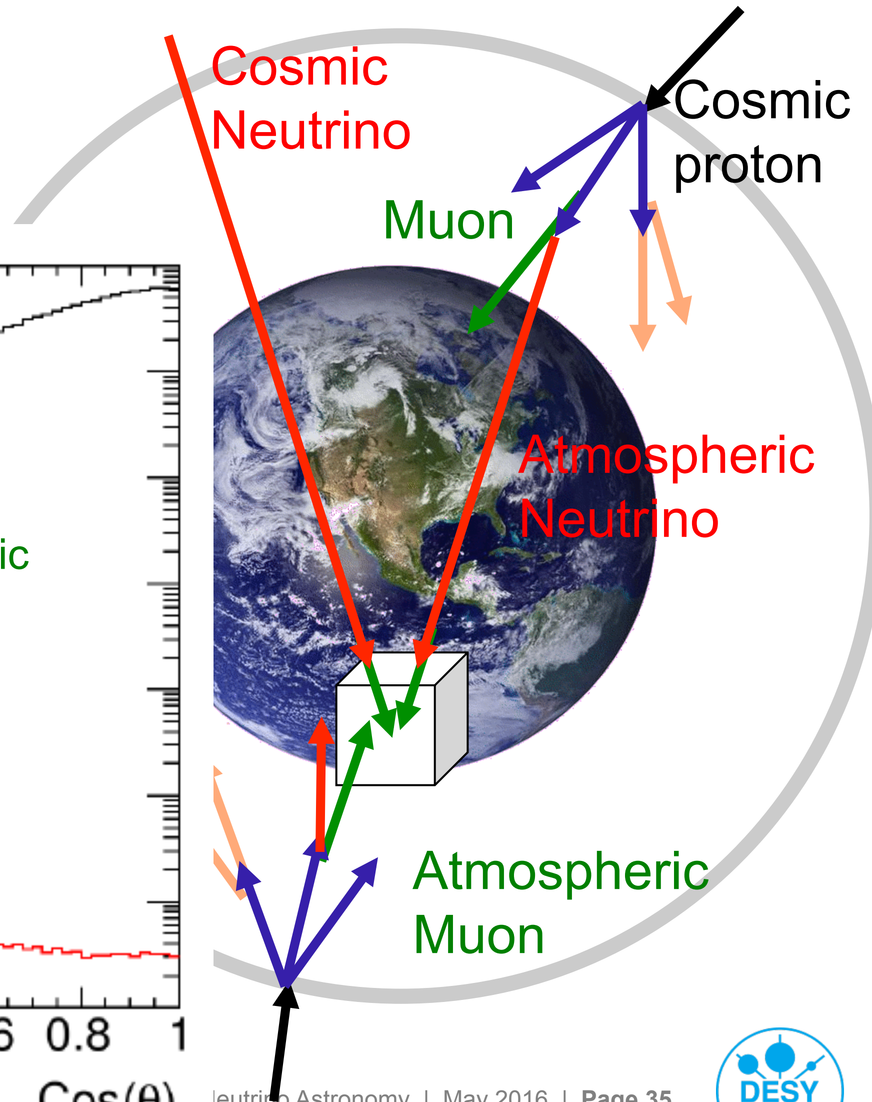
Property	Lake Baikal	Mediterranean (ANTARES)	Antarctic ice
Absorption length (m)	20–24	50–70 (blue)	~100
Scattering length (m)	30–70	230–300 (blue)	~20
Depth	1370	2475	2450
Noise	Quiet	^{40}K, bioluminescence	Quiet
Retrieve/ redeploy	Yes	Yes	No

Long scattering length for ANTARES implies better angular resolution; long absorption length for IceCube implies sparser instrumentation. Smaller depth implies larger atmospheric muon background.

Atmospheric Neutrinos

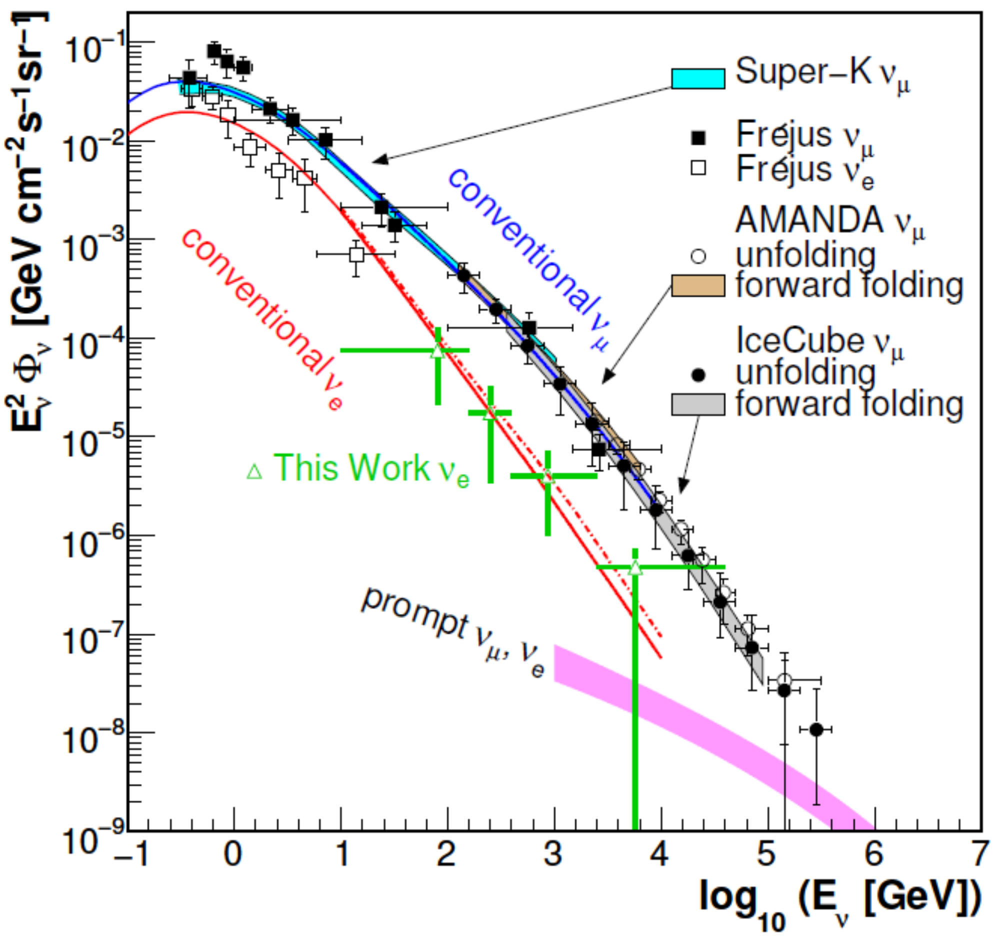
- Are a background for astrophysical neutrino searches

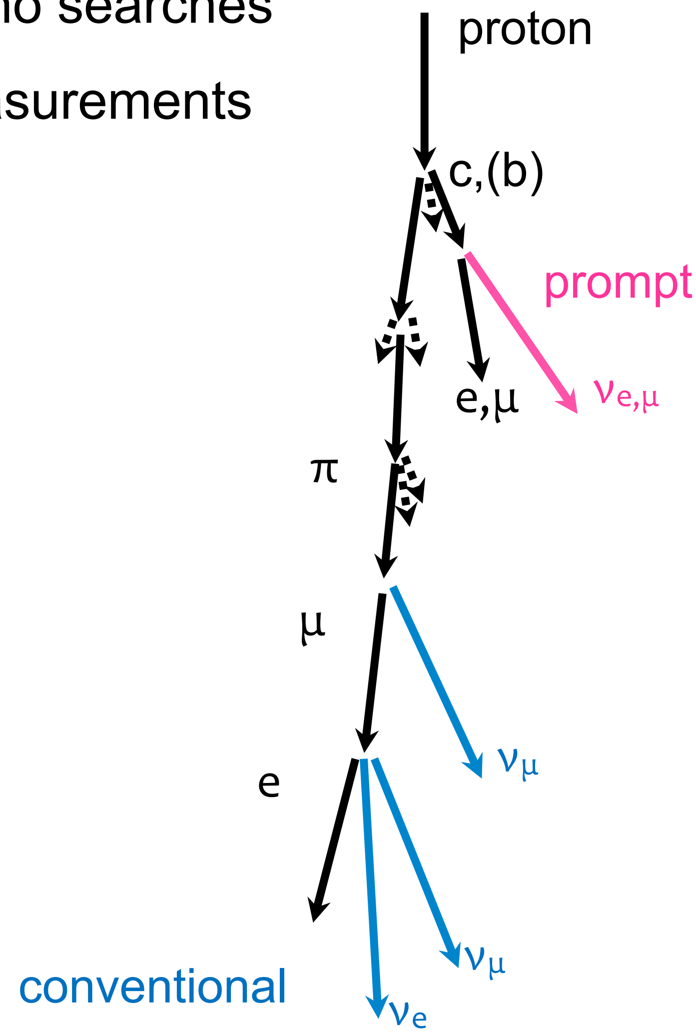




Atmospheric Neutrinos

- Are a background for astrophysical neutrino searches
- But interesting for neutrino oscillation measurements





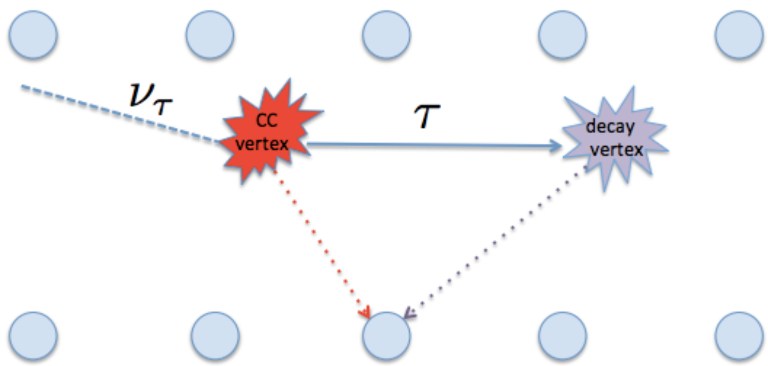
Start of second lecture

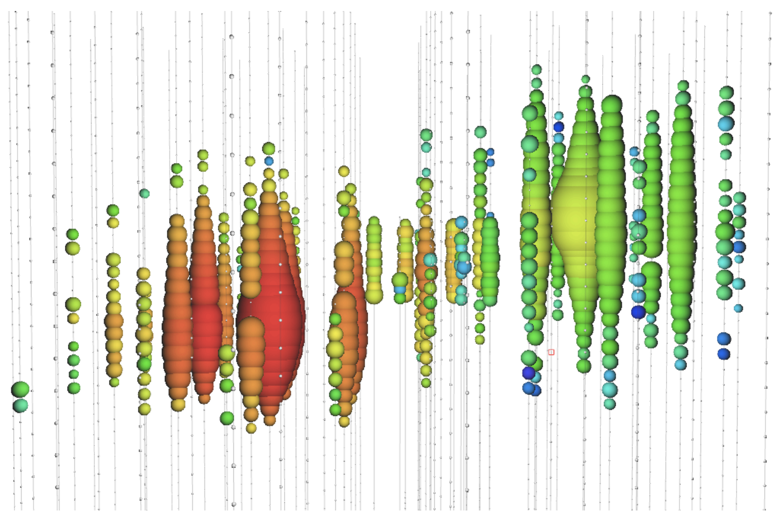
Questions from yesterday

- Tau neutrinos in IceCube
- Movement of glacier
- Neutrinos from GZK cutoff

Tau neutrinos in IceCube

- "double bang signature"
- No atmospheric background





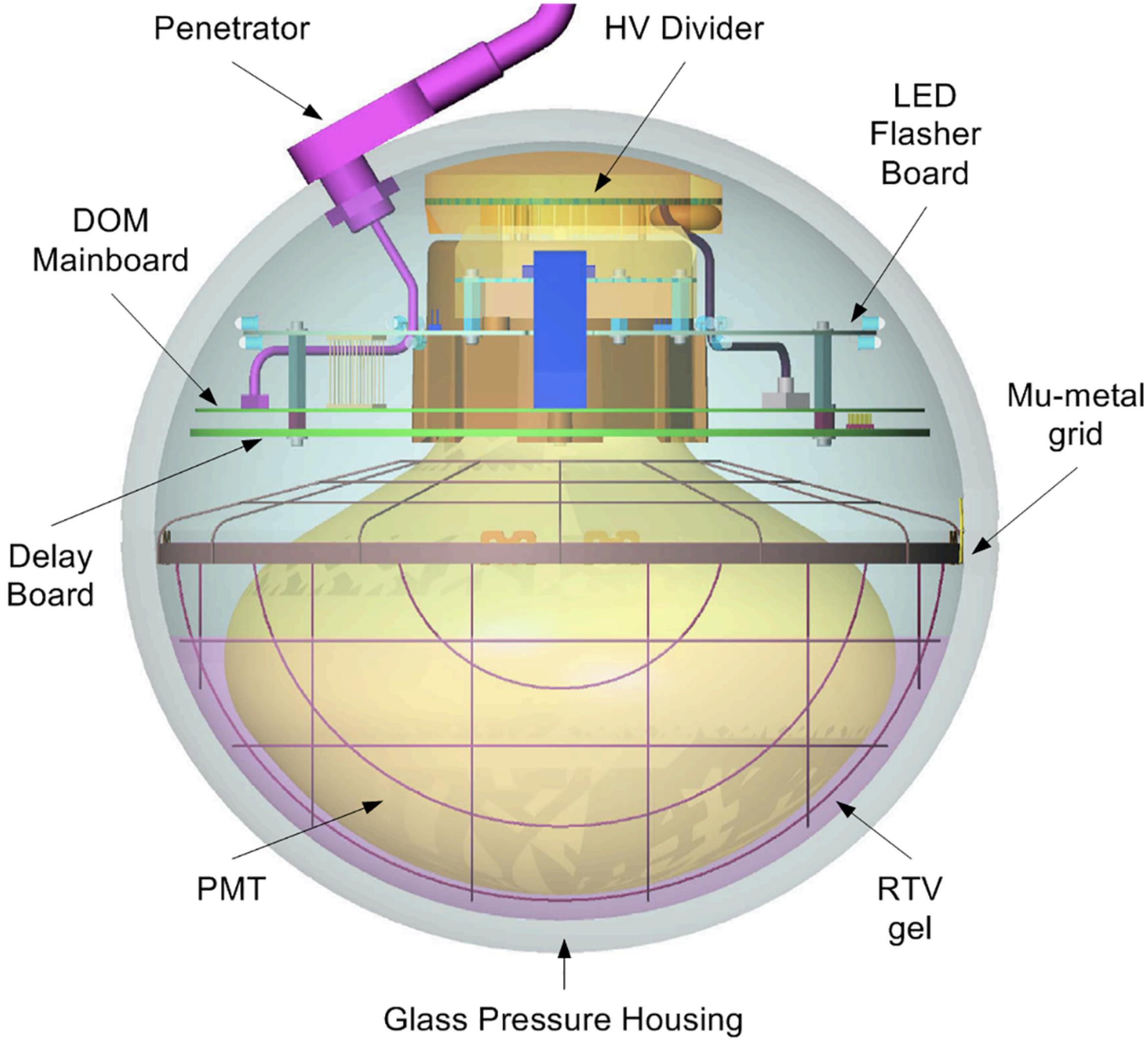
Tau neutrinos in IceCube

- average tau decay length roughly scales as 5 cm/TeV
- E > few hundred TeV needed to produce tau with sufficient decay length to find both "bangs"
- IceCube spacing: 17m between modules on each string, 125m between strings

Data samples	Events in 914.1 days (final cut)
Astrophysical ν_τ CC	$(5.4 \pm 0.1) \cdot 10^{-1}$
Astrophysical ν_μ CC	$(1.8 \pm 0.1) \cdot 10^{-1}$
Astrophysical ν_e	$(6.0 \pm 1.7) \cdot 10^{-2}$
Atmospheric ν	$(3.2 \pm 1.4) \cdot 10^{-2}$
Atmospheric muons	$(7.5 \pm 5.8) \cdot 10^{-2}$

Movement of Glacier

> Accurate measurement of the detector geometry by “flasher” runs



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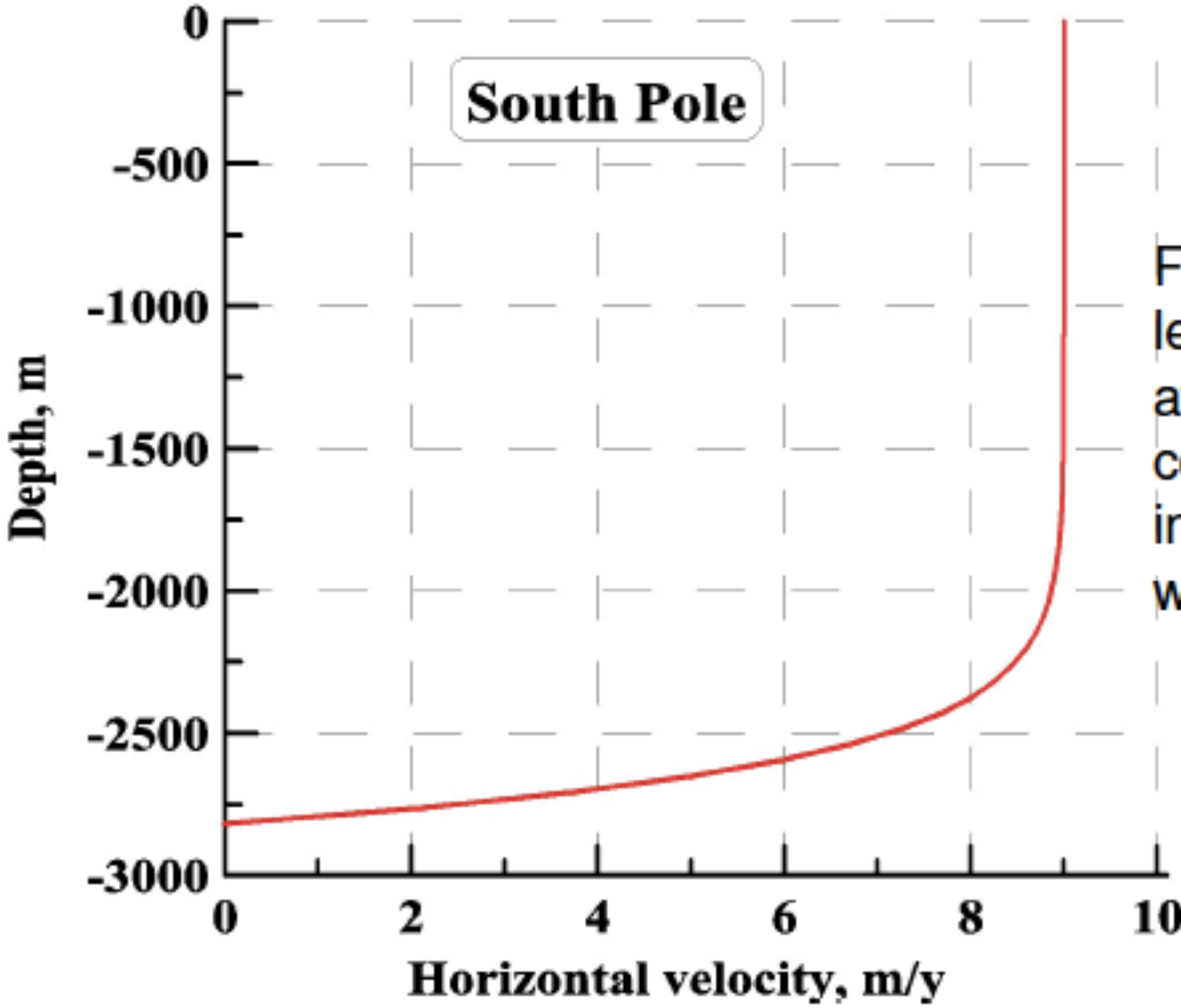
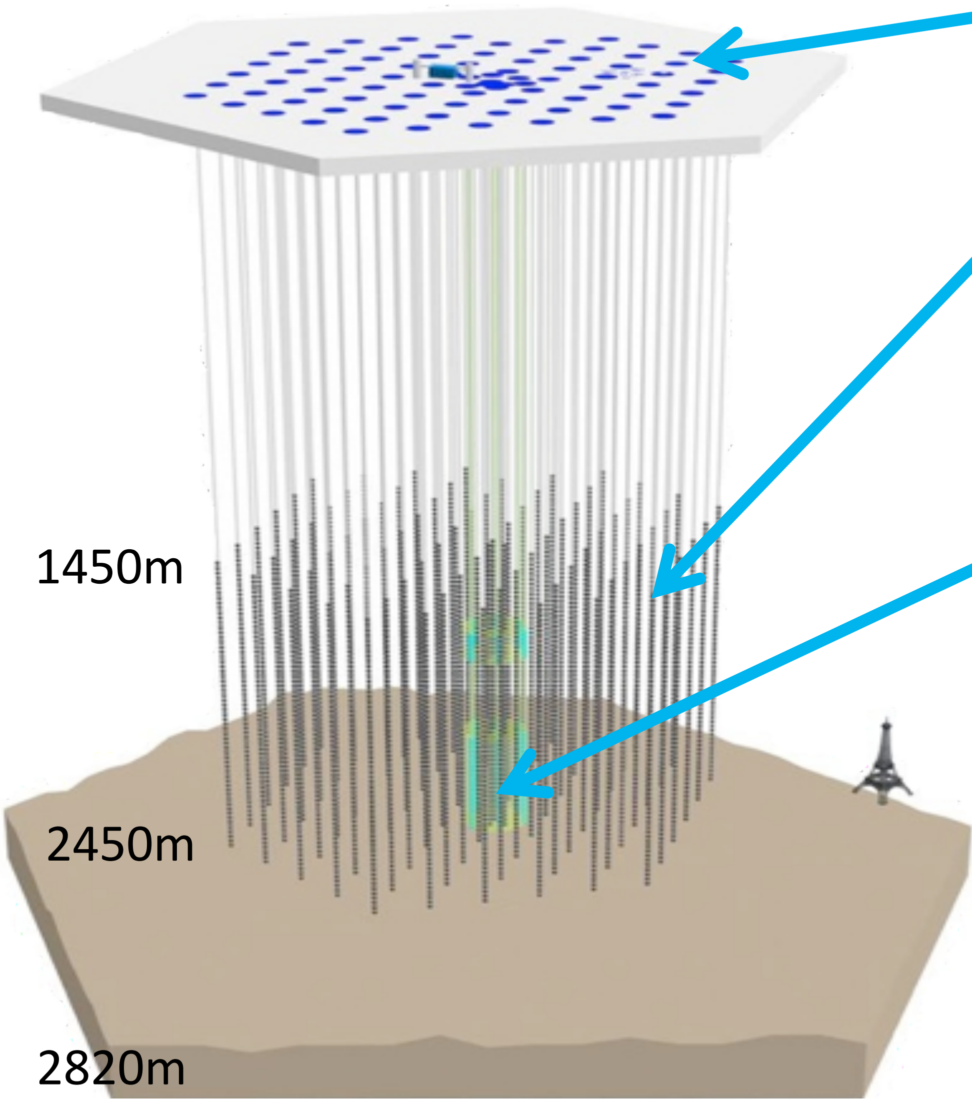


Fractional increase in cable lenght expected to be ~0.1% after 20 yrs
copper wire and plastic insulation can easily withstand without breaking

GZK Protons

- 4-vector momentum

IceCube



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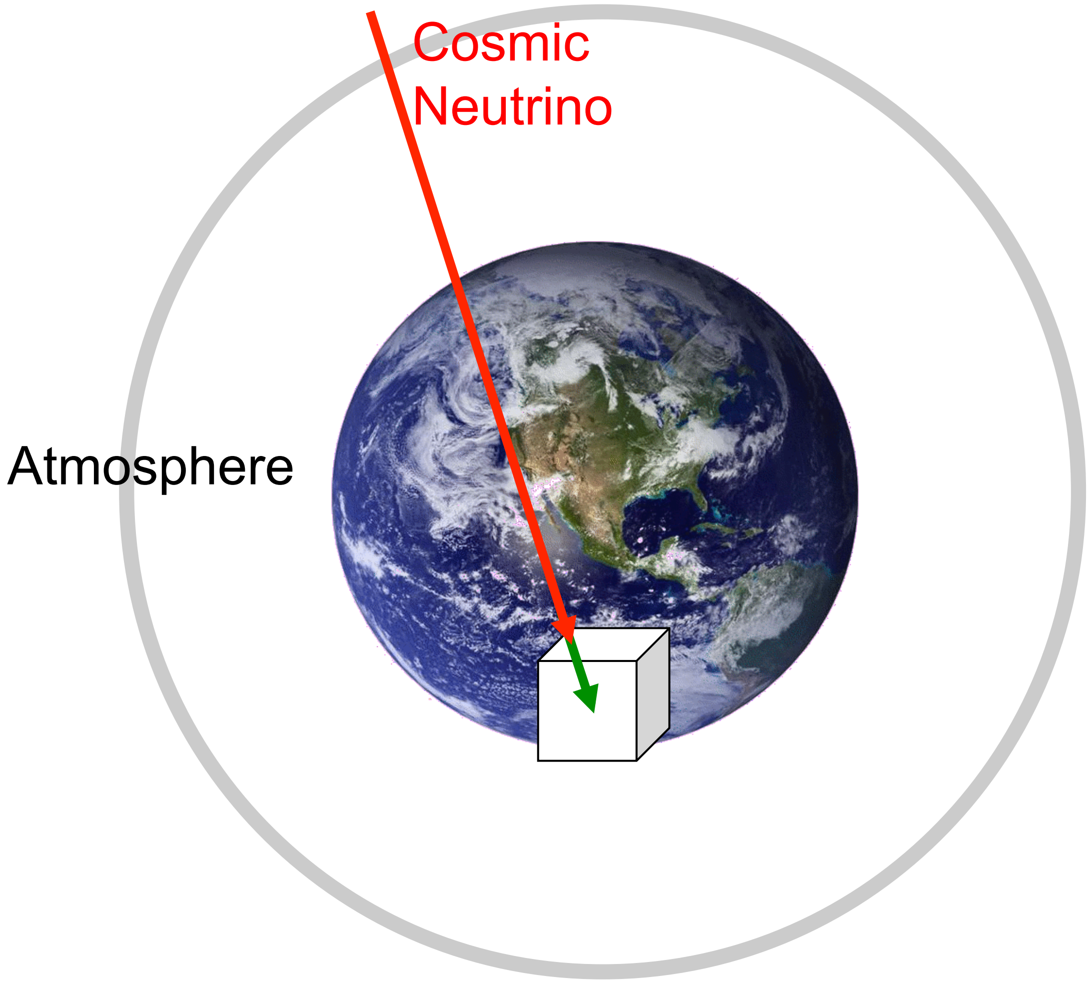
Background in Search for Cosmic Neutrinos



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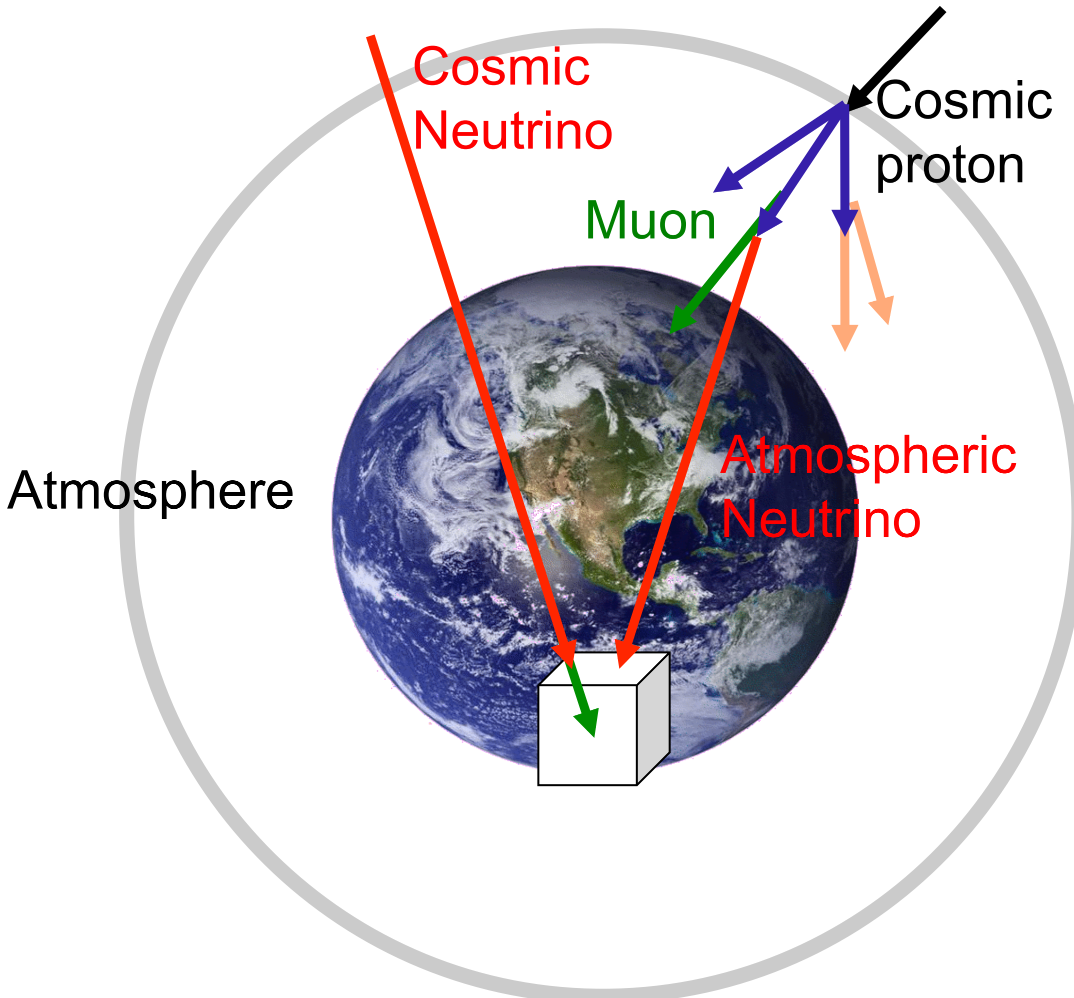

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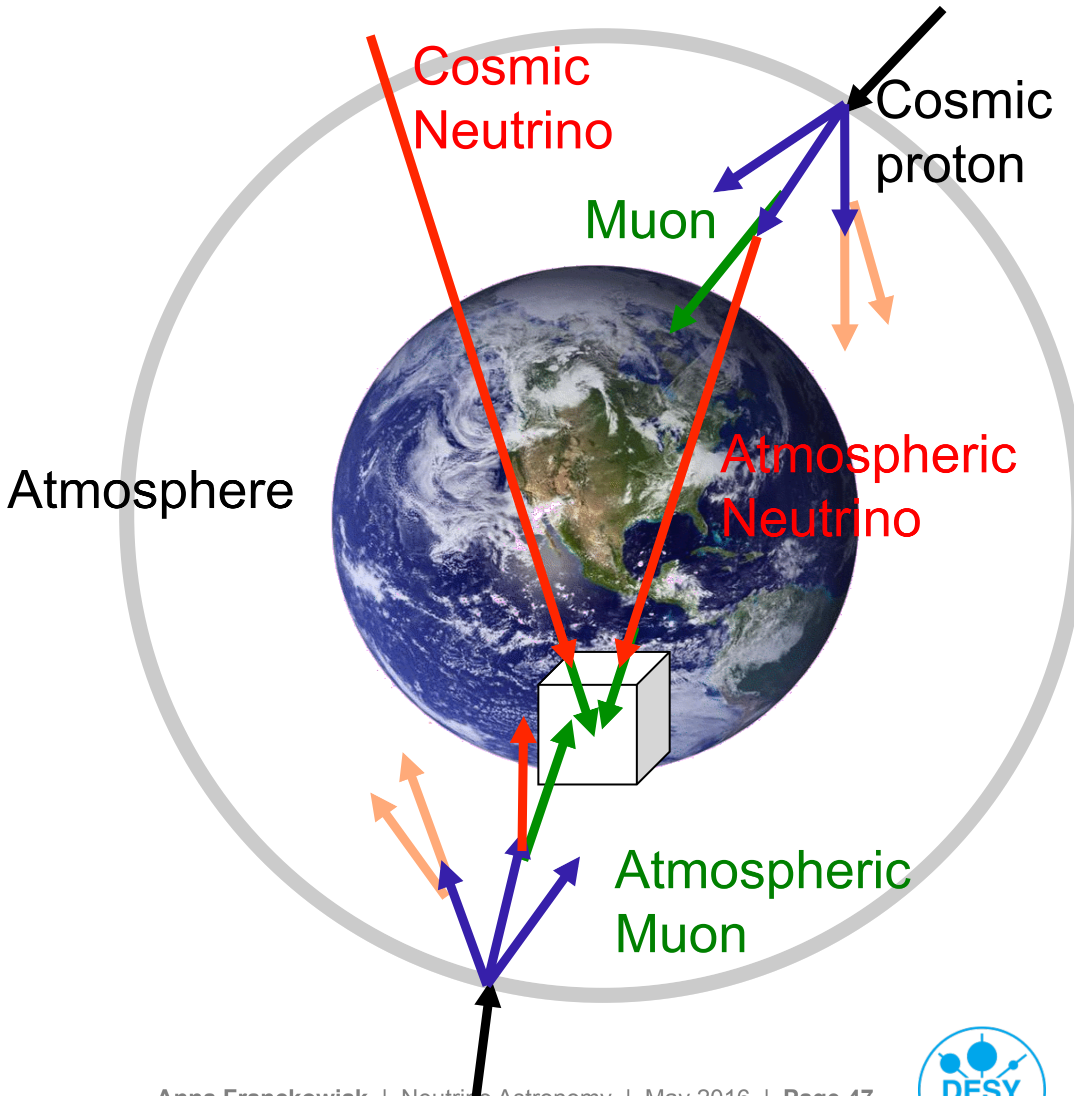

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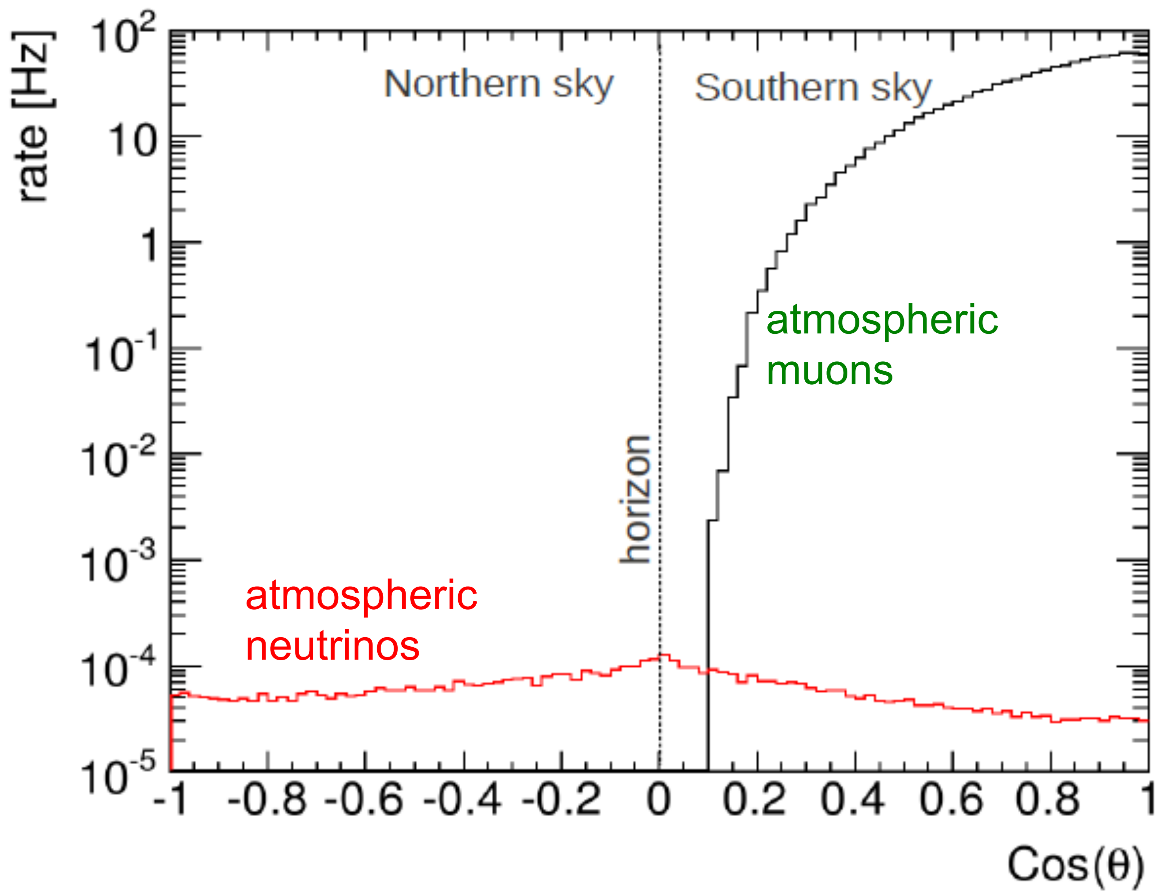
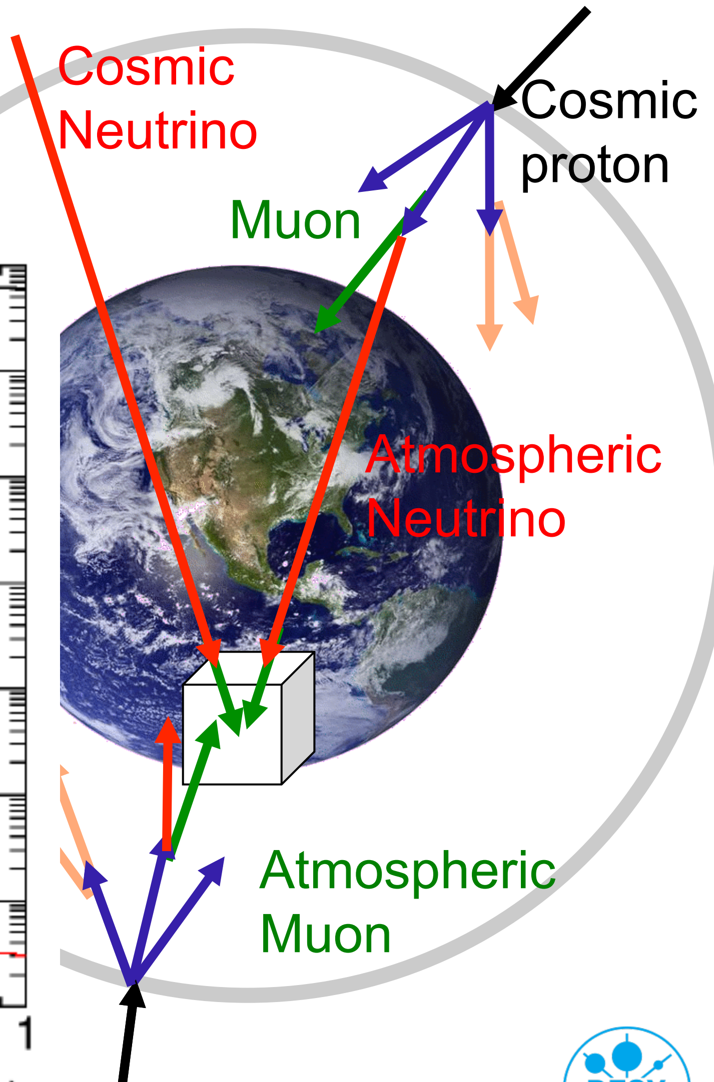
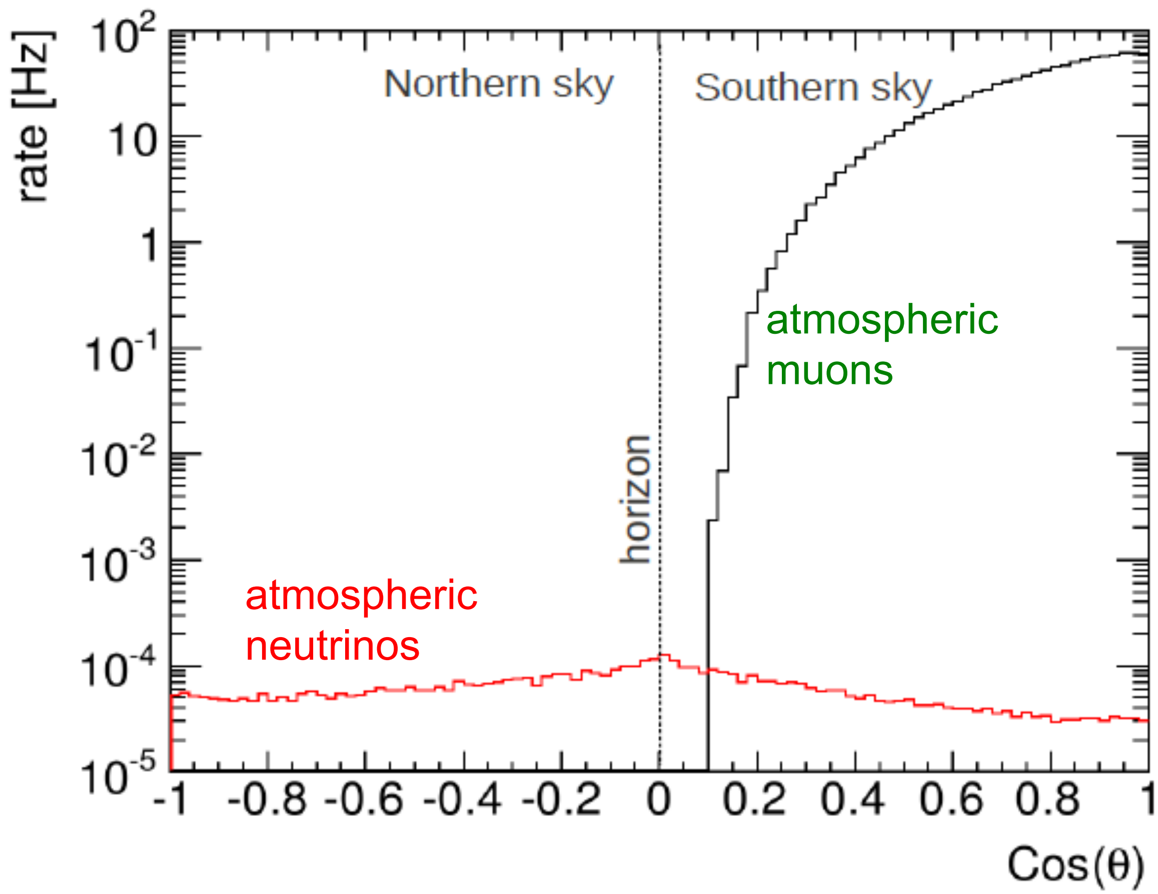
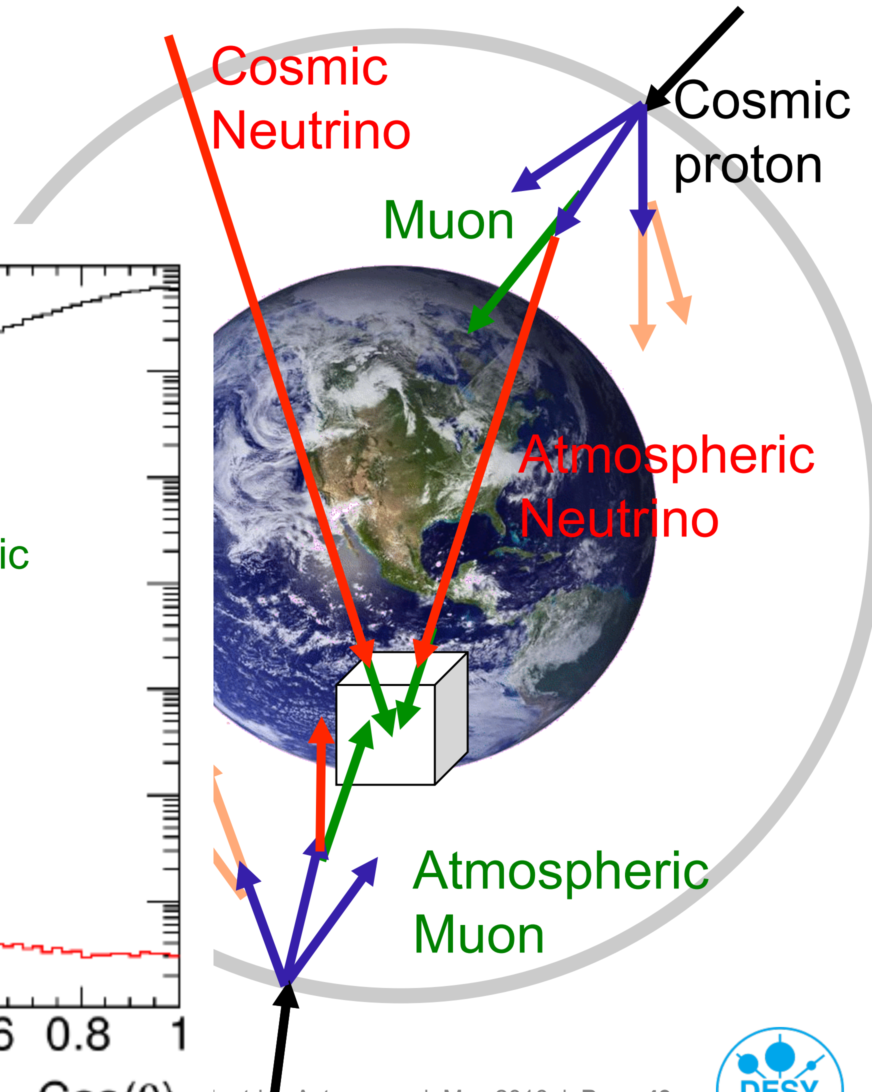




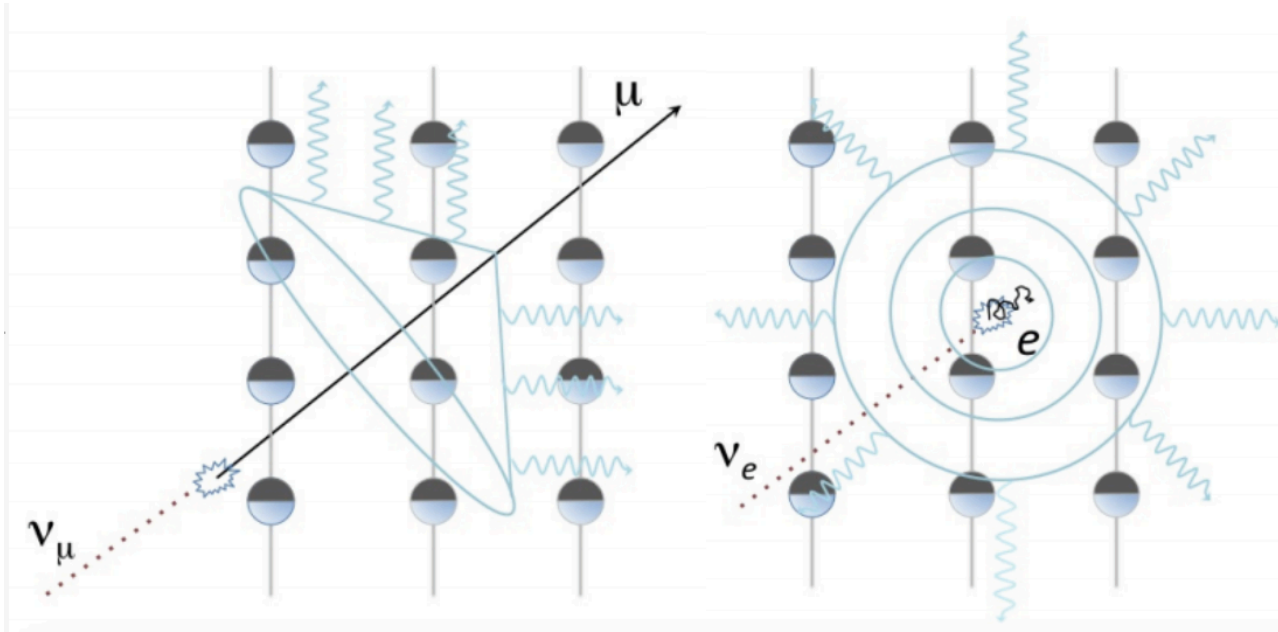
Background in Search for Cosmic Neutrinos

- Use only Northern sky neutrinos
- Use very high-energy Southern sky neutrinos





IceCube neutrino event signatures



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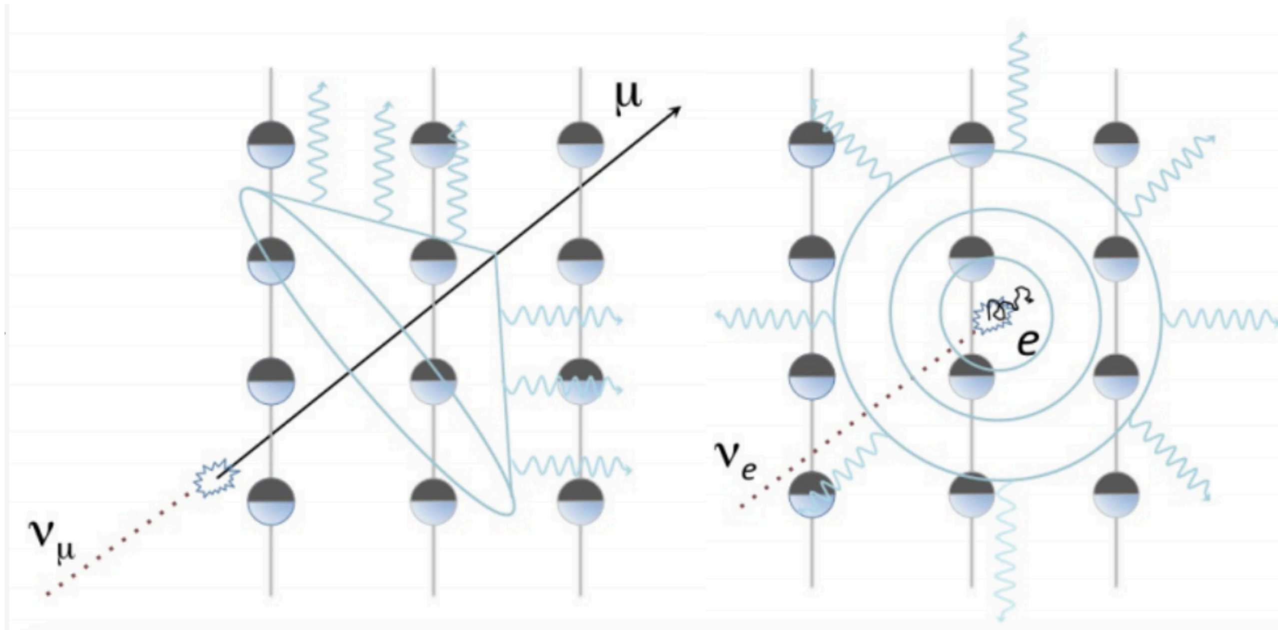

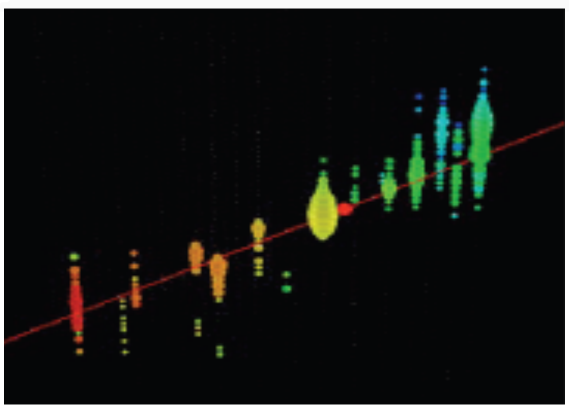

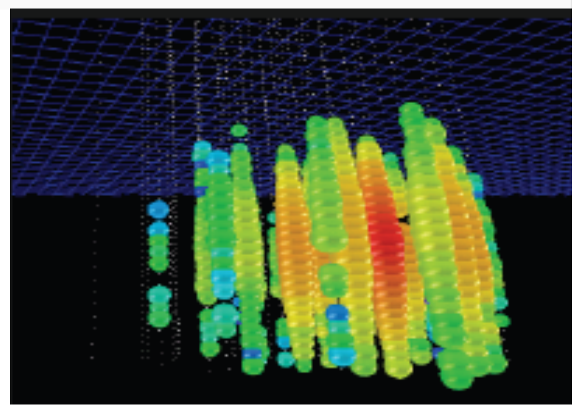

Detection of the first PeV neutrino events

Dedicated analysis looking for extremly high-energy events from GZK proton interactions

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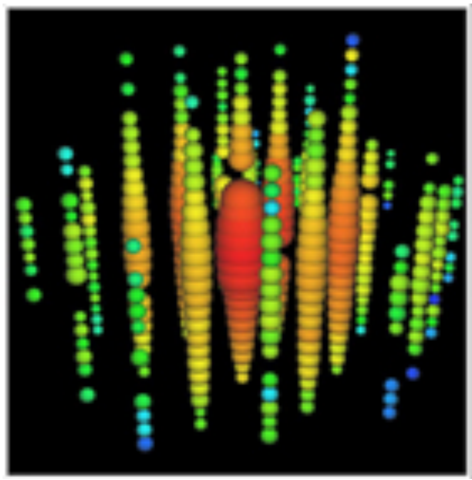
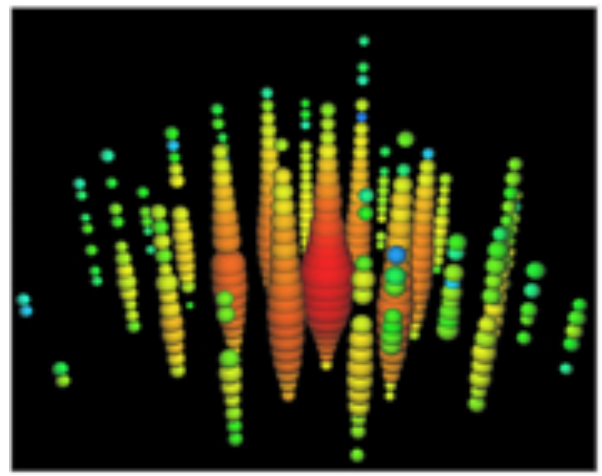
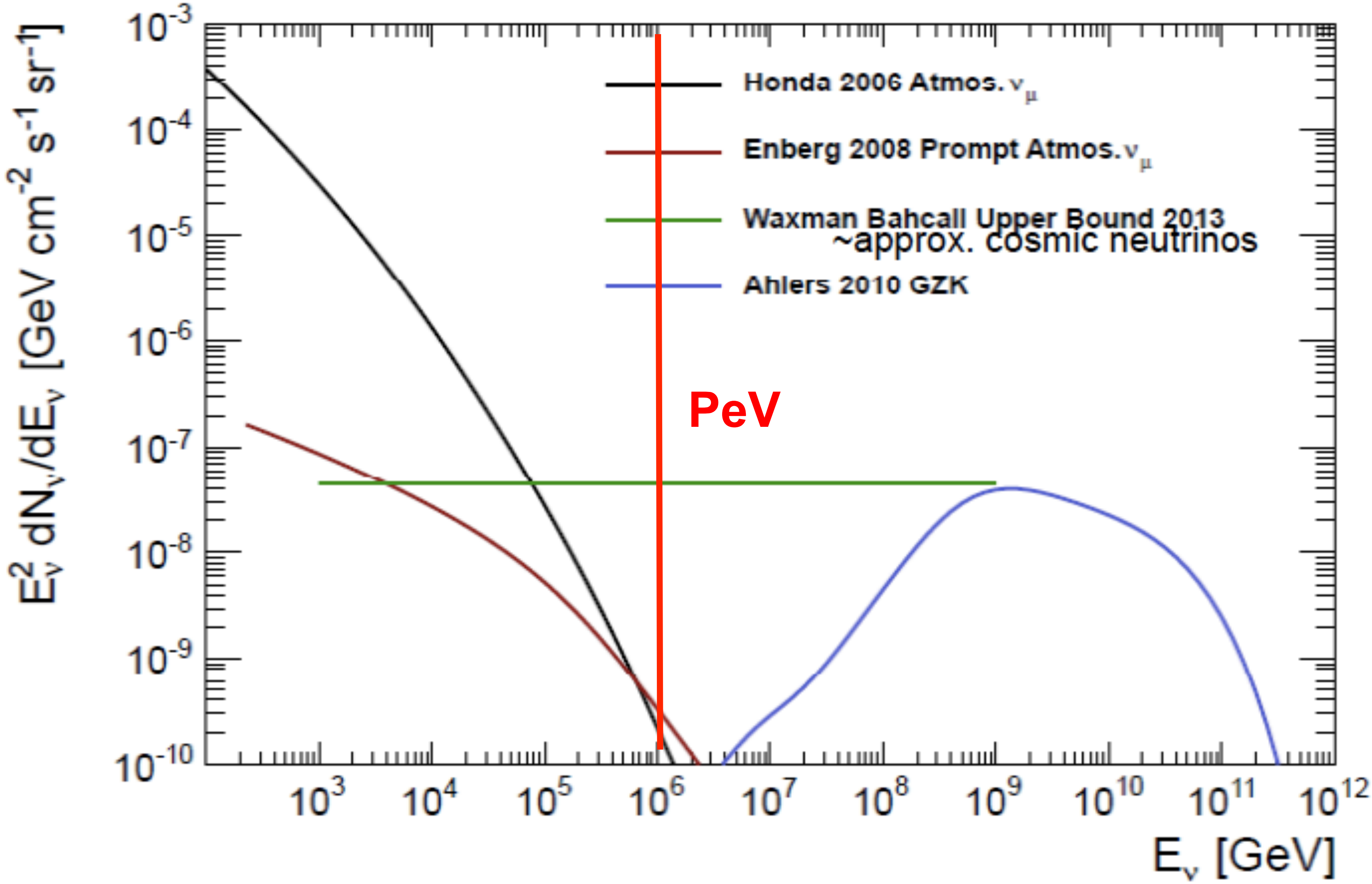
"Ernie"
1.14 PeV
Jan. 2012





"Bert"
1.04 PeV
Aug. 2011

Reminder: Expected Neutrino Spectra



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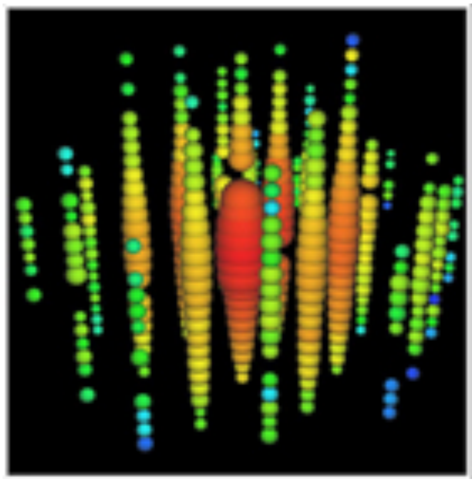
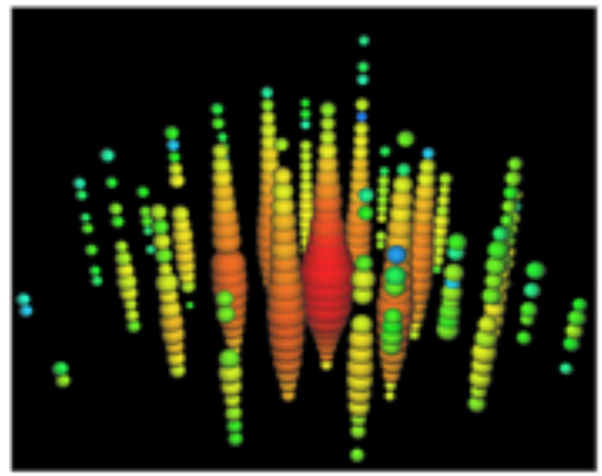




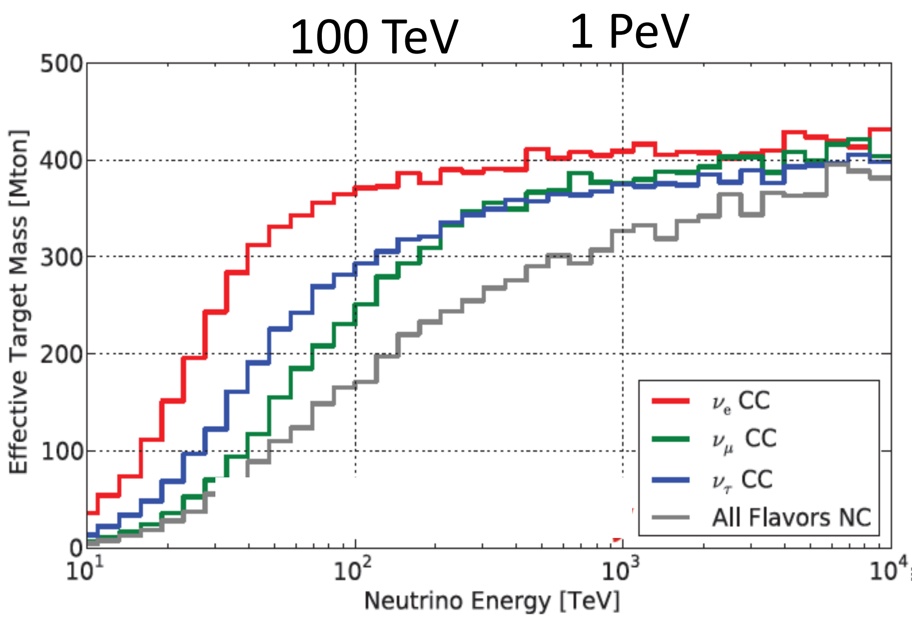
"Bert"
1.04 PeV
Aug. 2011

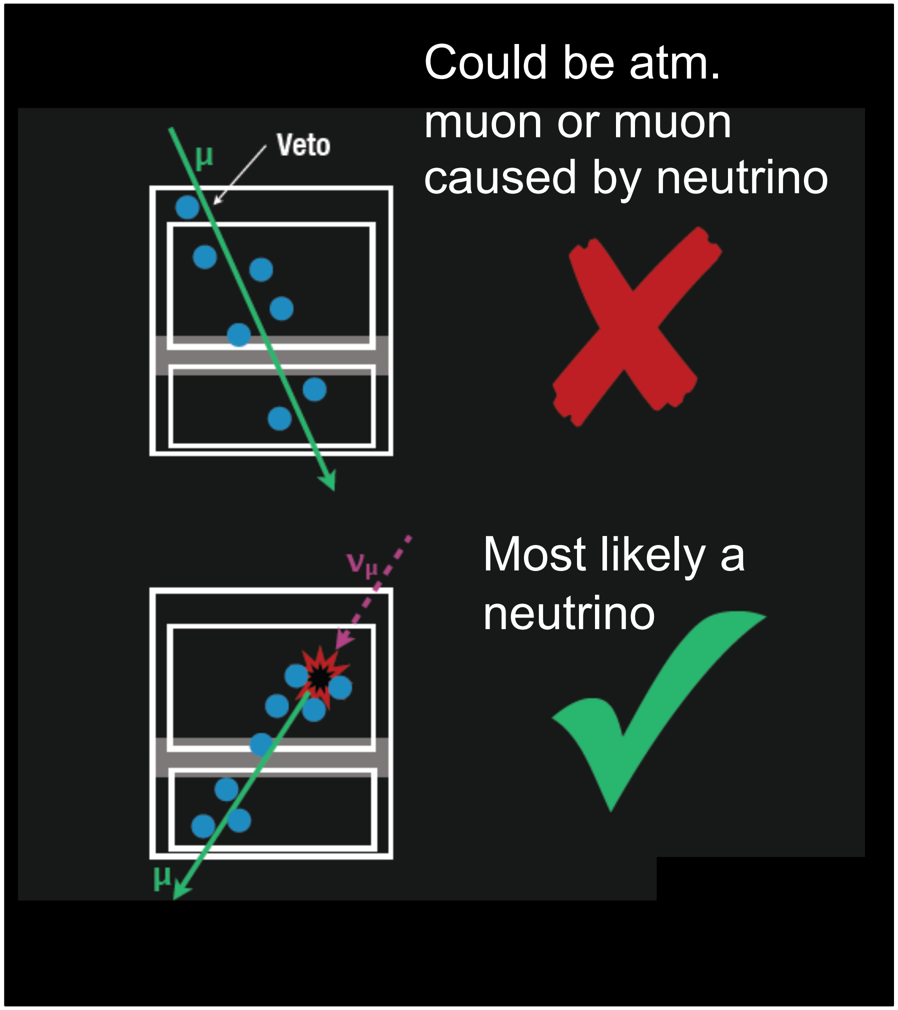
Significance: 2.8σ

- Both downgoing
- Unbroken E^{-2} spectrum would have made 8-9 events at higher energy → cut-off

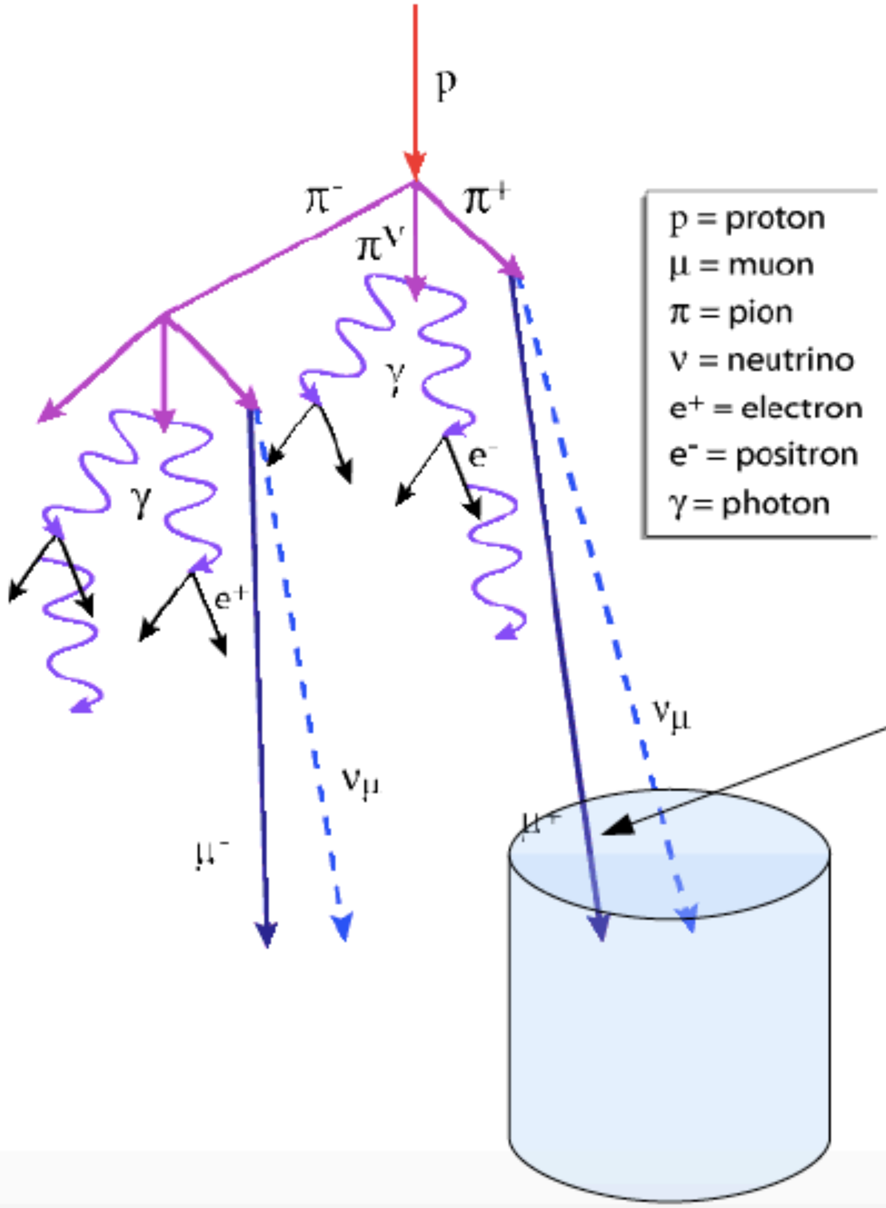
Refined Analysis

- High-energy starting events (HESE)
- Outer detector layer used a veto for incoming muon tracks
- 400 Mt effective volume
- Total charge > 6000 photoelectrons
- Sensitive to all flavors > 60 TeV





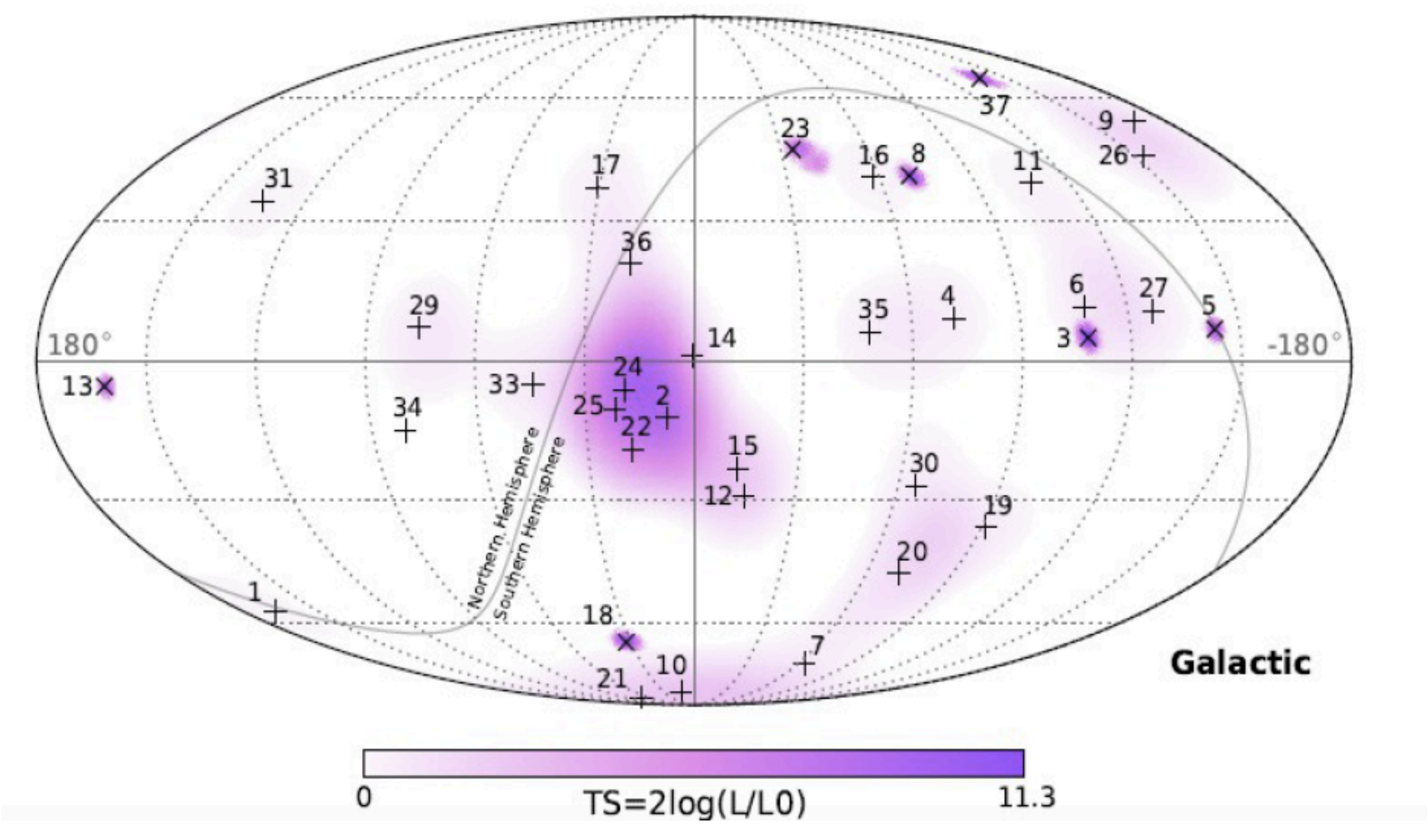
Self-Veto reduces background of atm. neutrinos



The accompanying muon trips the veto!
→ "Self-veto"

HESE Results

- First results: Ernie & Bert + 26 additional events (2 years of data)
- Significance: 4.1σ



Likelihood Analysis

Maximize the likelihood L assuming a source at point x with energy spectrum $E^{-\gamma}$

Total # of events

# of events from source
Varied to maximize L

$$L(x) = \prod_{i}^{n_{tot}} \left[\frac{n_s}{n_{tot}} \times S_i(x) + \frac{n_{tot} - n_s}{n_{tot}} \times B_i(x) \right]$$

Probability density that event i comes from a source at position x

×

Probability density that event i comes form a source with spectrum γ

Probability density that event i is from backgrounds expected at position x

×

Probability density that event i comes form a known background energy spectrum

TS is calculated for every point in the sky x

$$TS(x) = 2 \times \log\left(L(x) / L_0(x) \right)$$

where $L_0 = L(x, n_s = 0)$

DESY

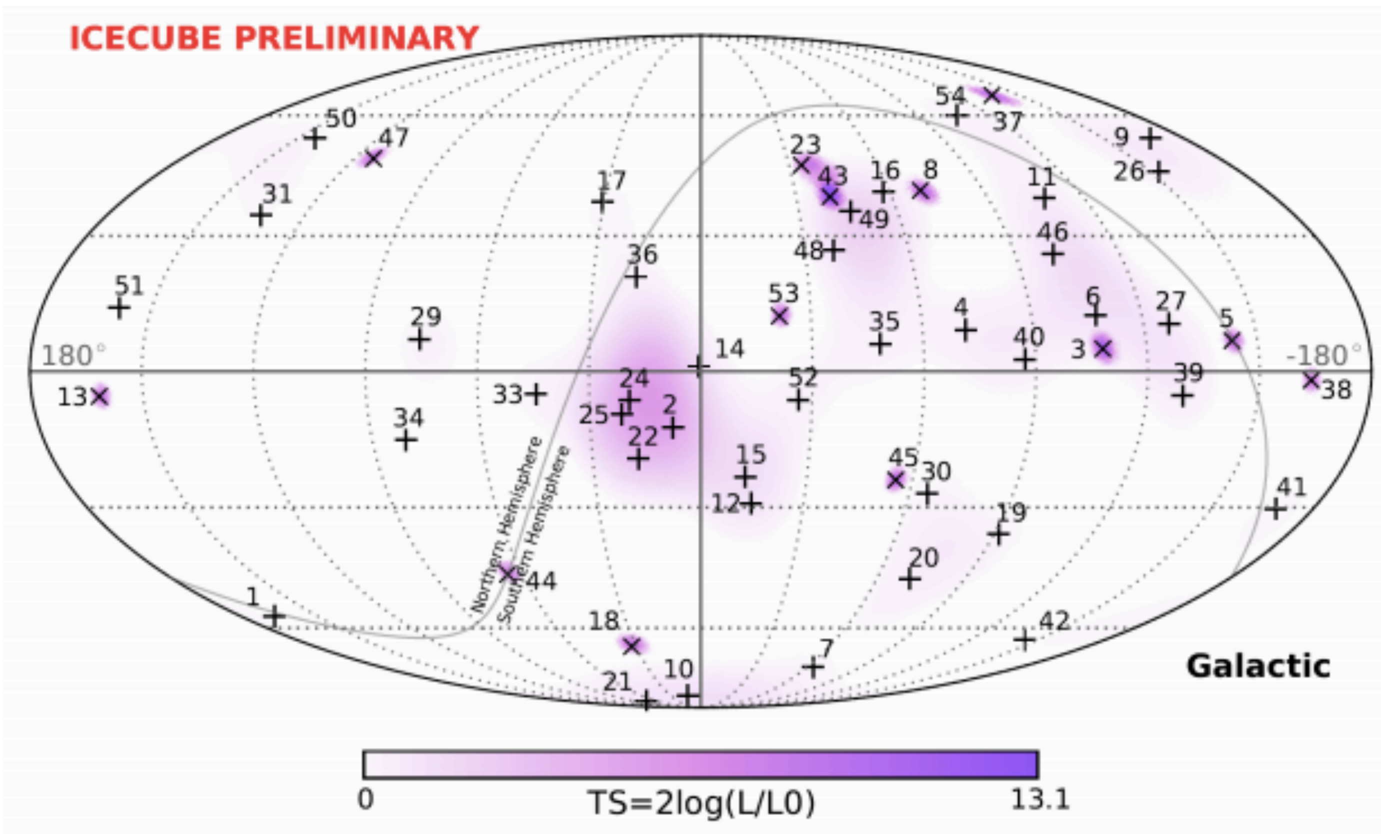
HESE Results

Science 342, 1242856 (2013)

HESE Results (Updated, 4 years)

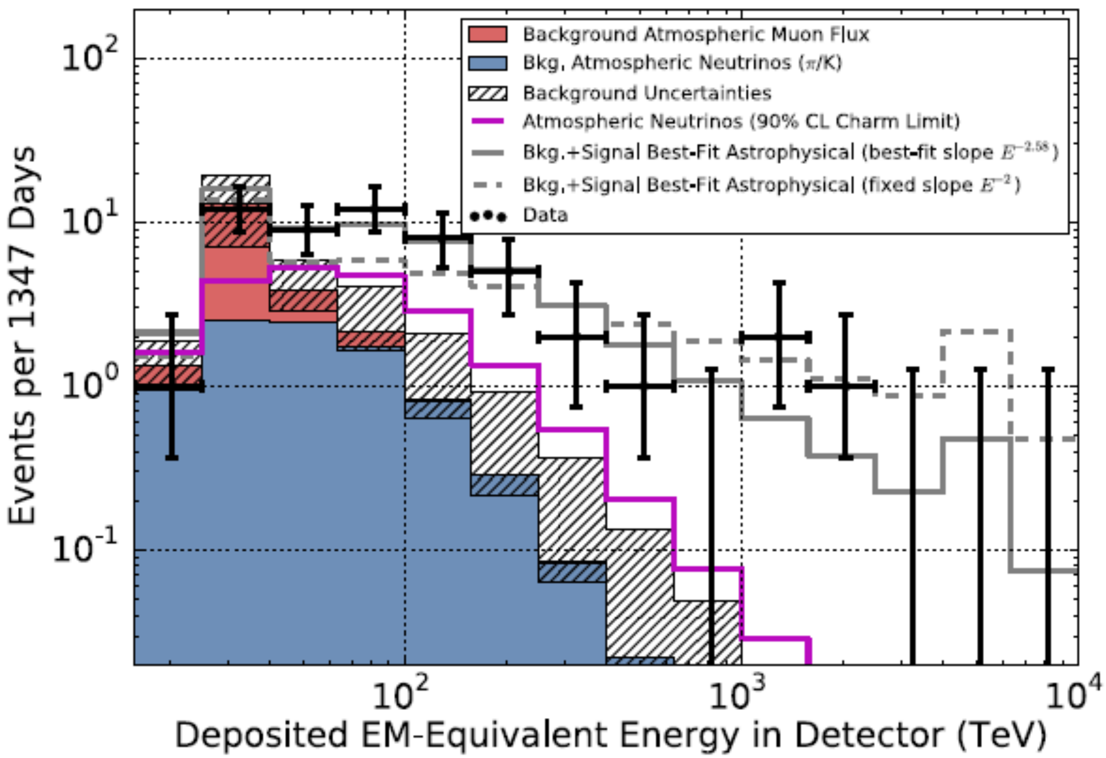
- 54 events (14 track events)
- Significance: >10 σ

No significant clustering → extragalactic component very likely



HESE Results (Updated)

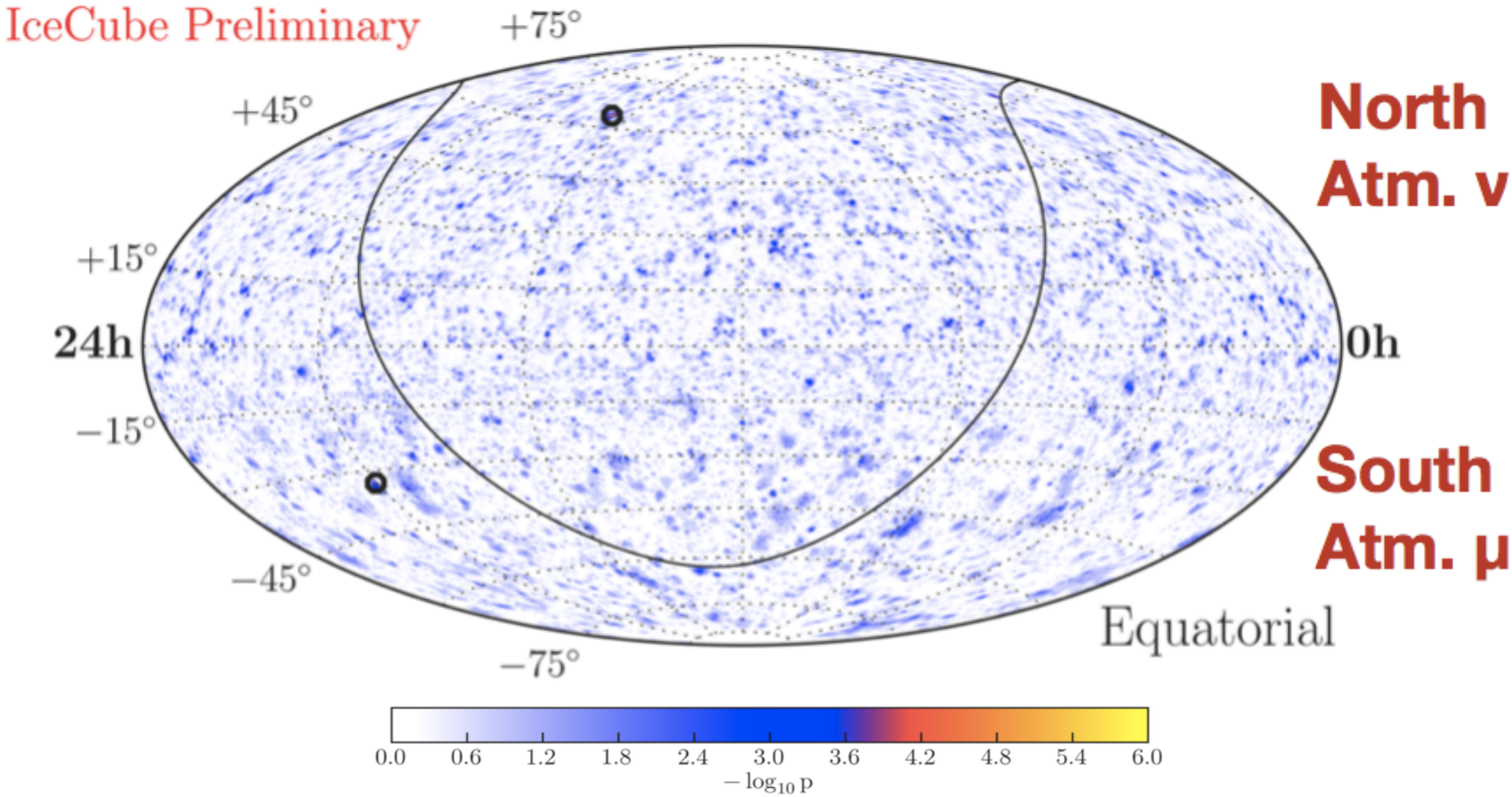
- Spectrum:
  - Flux Level: ~1 x 10^{-8} E^{-2} [/GeV/cm2/s/sr] per flavor
  - Spectral index: -2.6



Saturates Waxman-Bahcall bound!

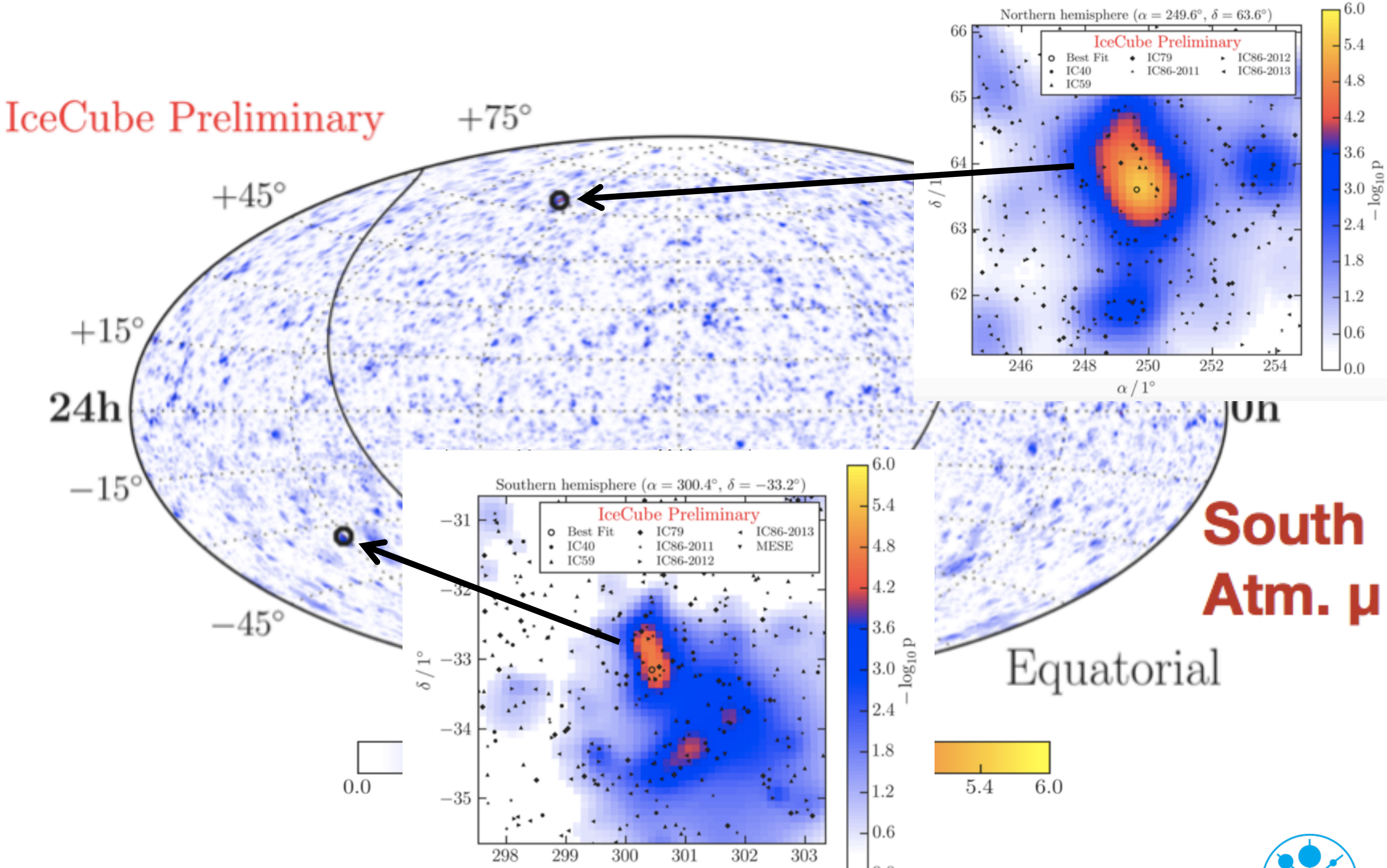
Indication of CR neutrino connection

Trying to find clustering including low E events

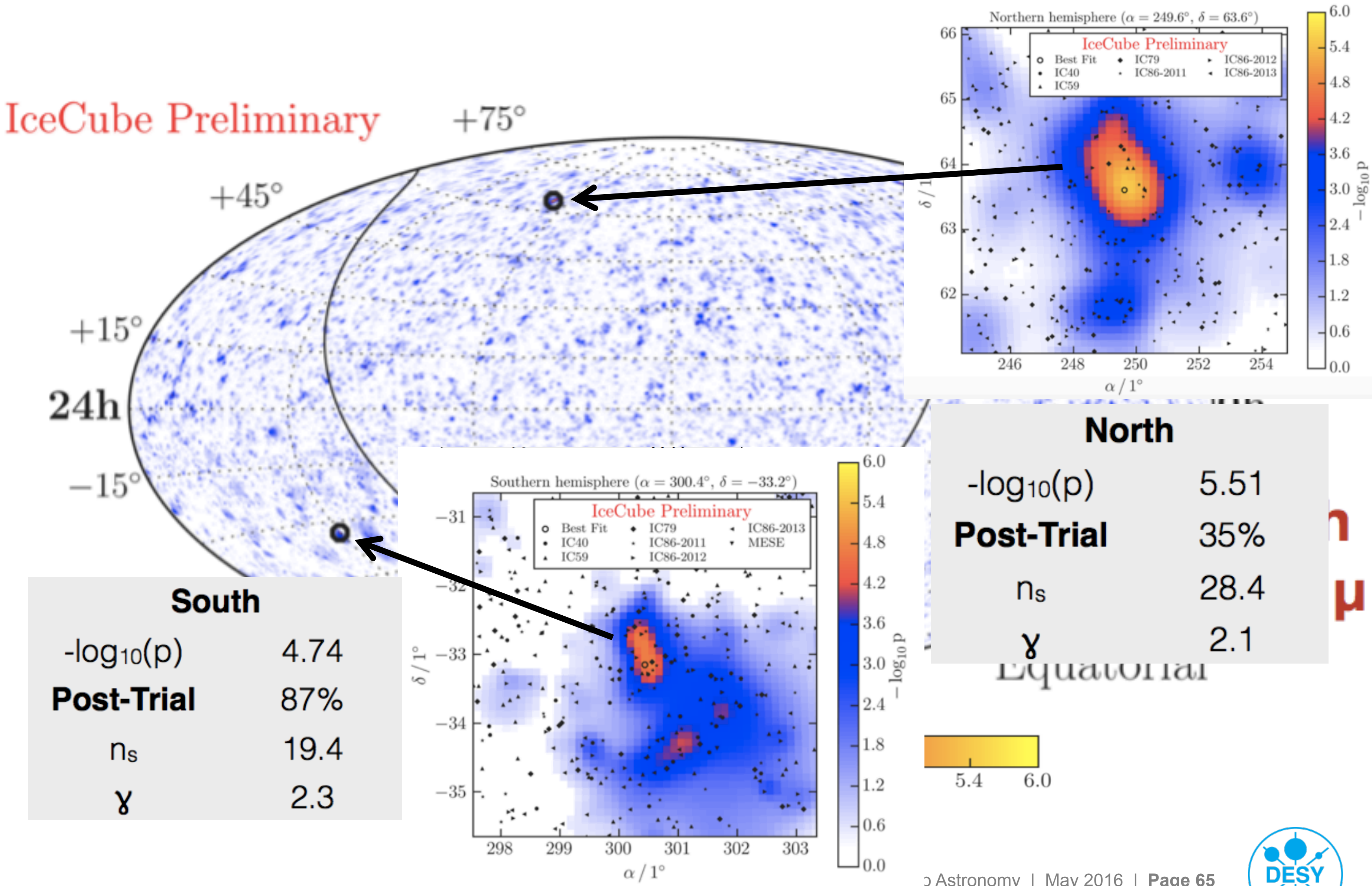


= TS (test statistic)

Trying to find clustering including low E events



Trying to find clustering including low E events



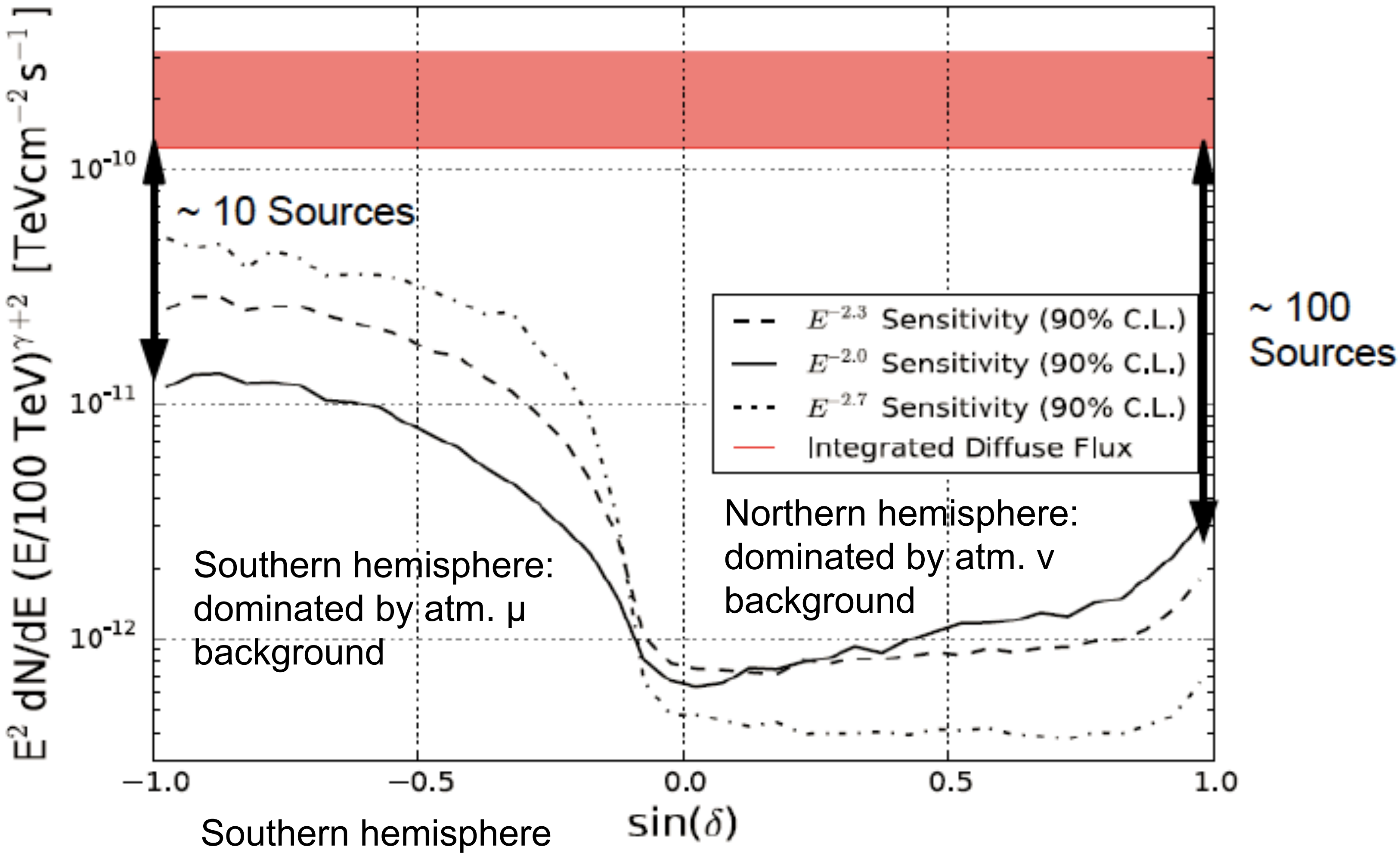
South

$-\log_{10}(p)$	4.74
Post-Trial	87%
n_s	19.4
γ	2.3

North

$-\log_{10}(p)$	5.51
Post-Trial	35%
n_s	28.4
γ	2.1

Point Source Flux Limit



Ways around:

- Extended sources?
- Transient sources?

Flavor composition: what do we expect?

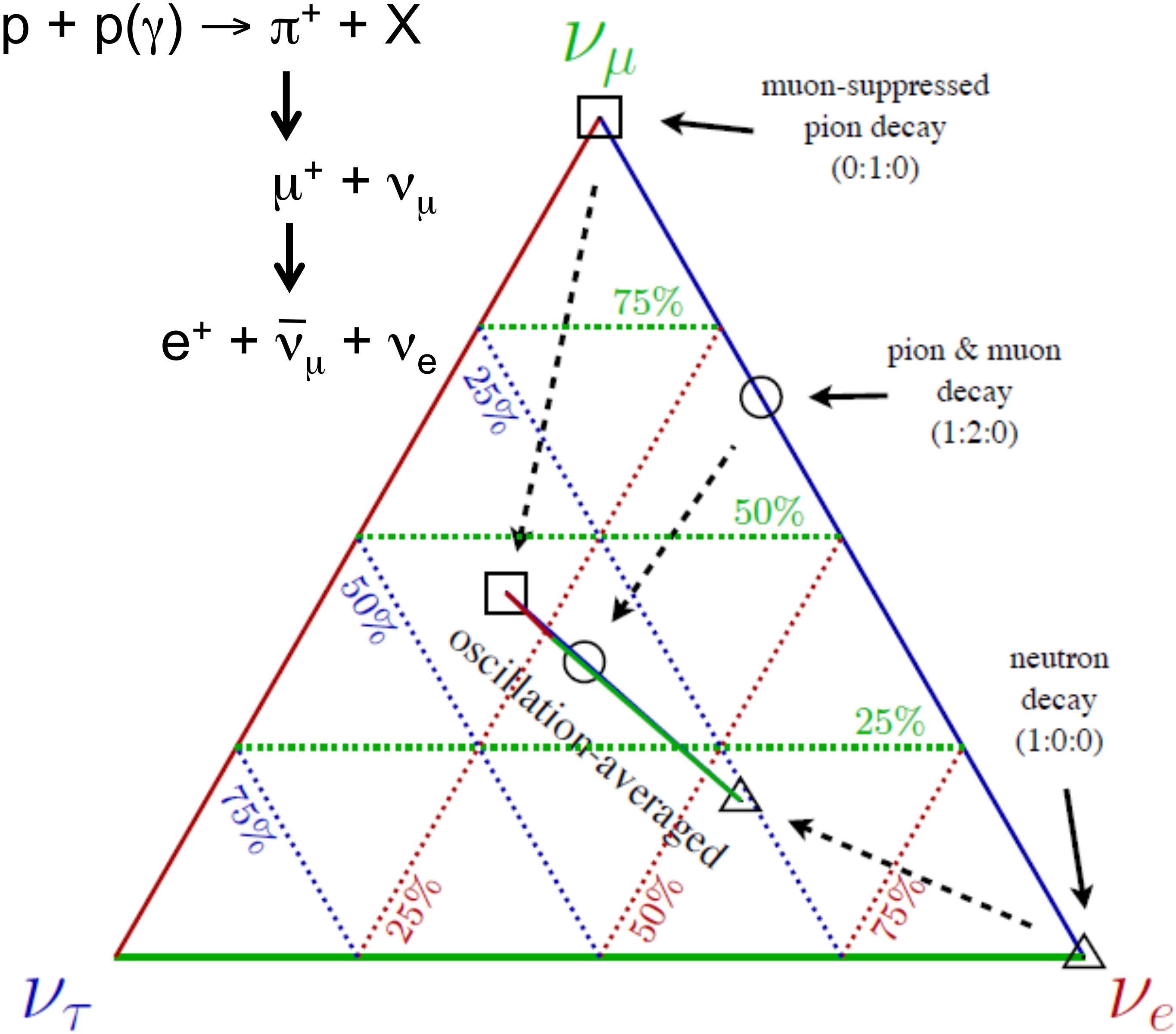
$p + p(\gamma) \rightarrow \pi^+ + X$

$\downarrow$

$\mu^+ + \nu_\mu$

$\downarrow$

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

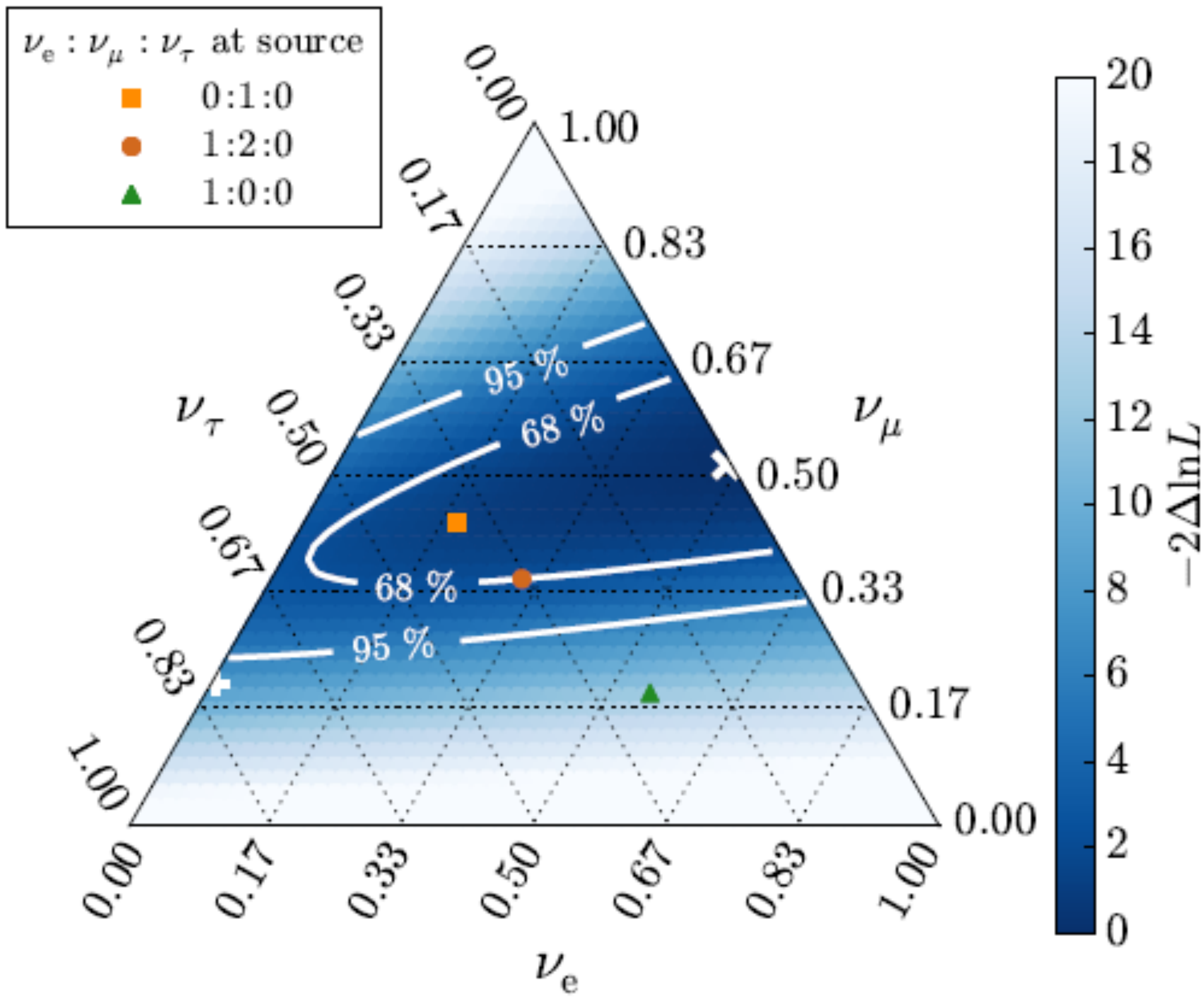


Muon loses energy before it decays due to large magnetic fields

"standard" scenario, pion decay

Dominant Fe CR component creation of free neutrons via nuclei photodisintegration on background photon fields

Flavor composition: what do we measure?



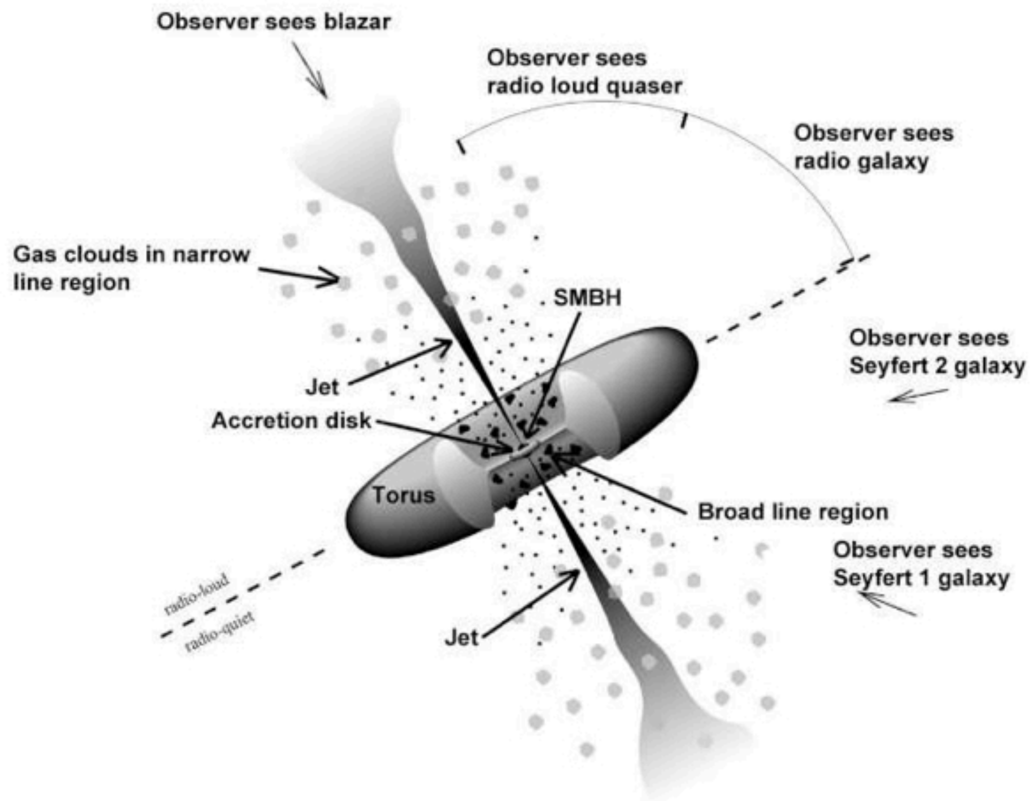
the best fit flavor composition disfavors 1:0:0 at source at 3.6 σ

Extragalactic Source Candidates

- Sources need to be powerful particle accelerator
- Sources need to provide a target
- Good candidates:
  - Active Galactic Nuclei
  - Gamma-ray Bursts
  - Supernovae

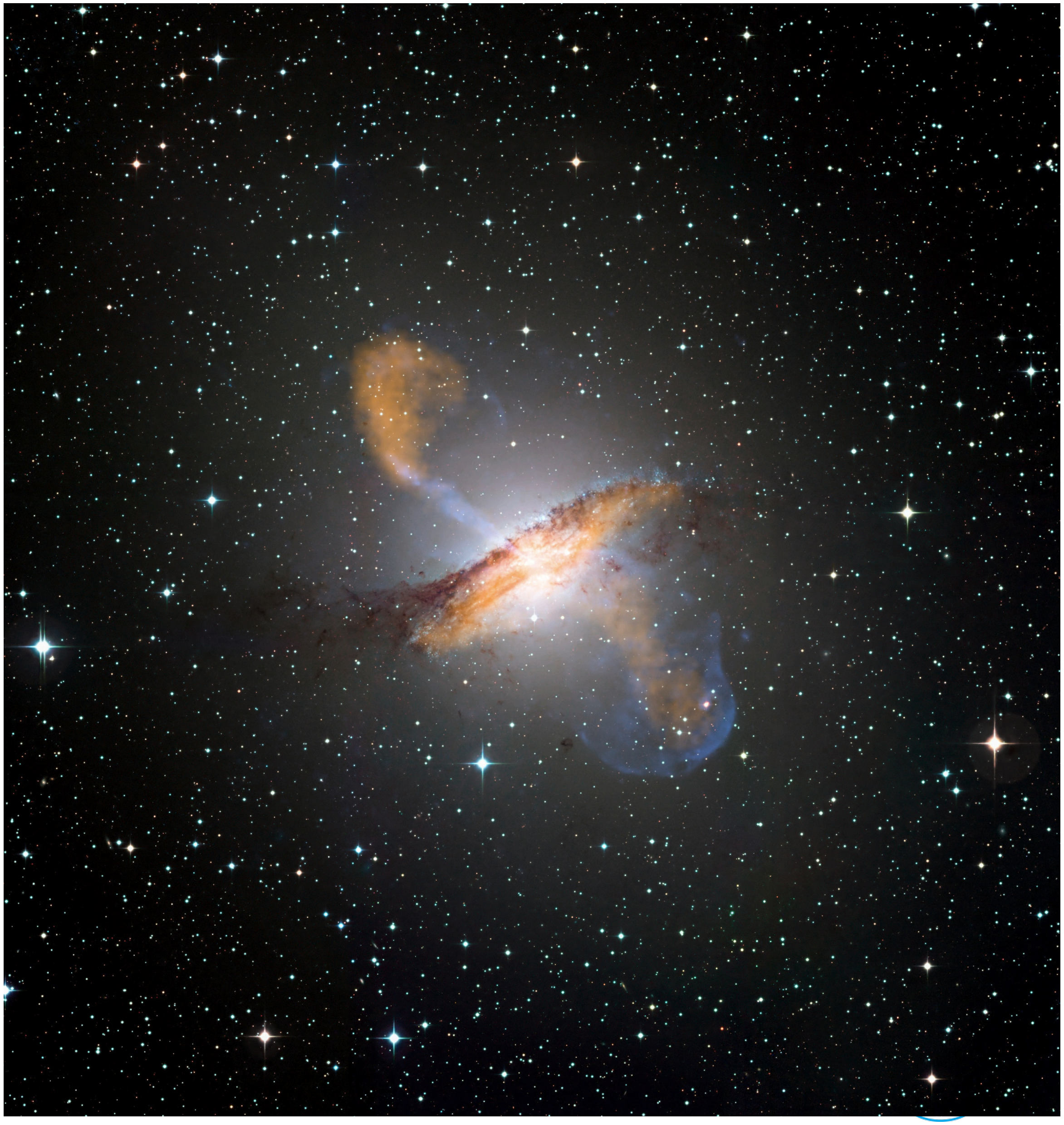
Active Galactic Nuclei

- extremely bright centers
- powered by accretion onto supermassive black hole
- Some accelerate relativistic bipolar jets of ejected material
  - speeds near the speed of light
  - stretch up to hundreds of kiloparsecs outside the host galaxy (milky way diameter ~30kpc)
- If jets point at us: blazars
  - extremely bright at all wavelengths, from radio to gamma rays



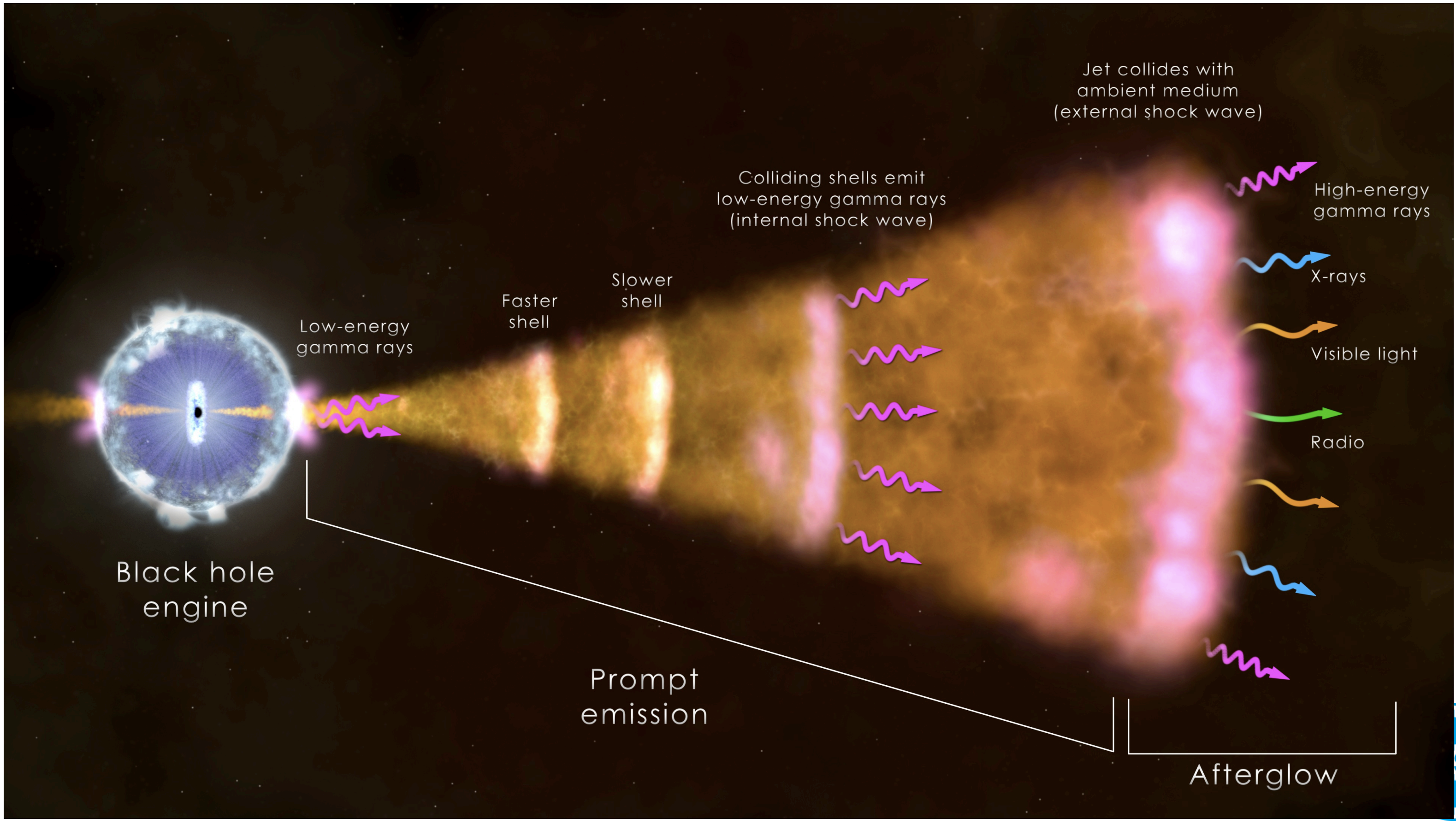
AGN - Example

- Centaurus A
- 3 Mpc distance (10 Mly)

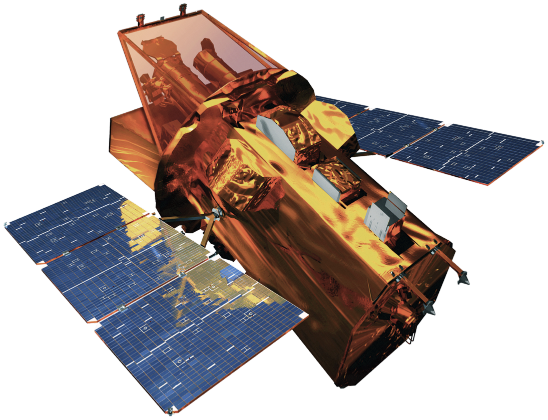


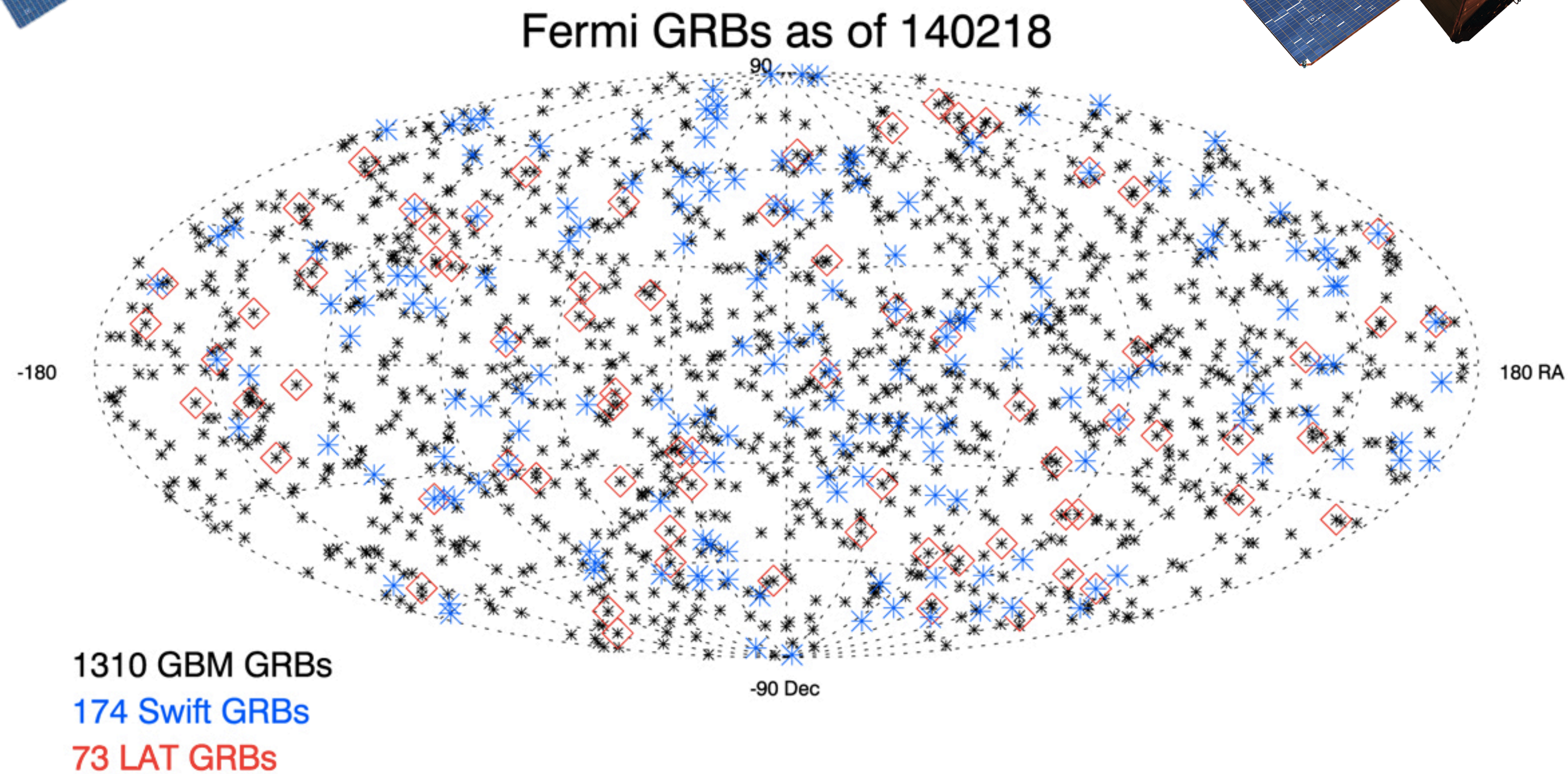
Gamma-Ray Bursts (GRBs)

- Collapse of massive, rapidly rotating star
- Short flashes of gamma rays (ca. 50s)
- Highly relativistic jets, extreme energy release up to 10^{54}erg (the sun's mass turned into energy

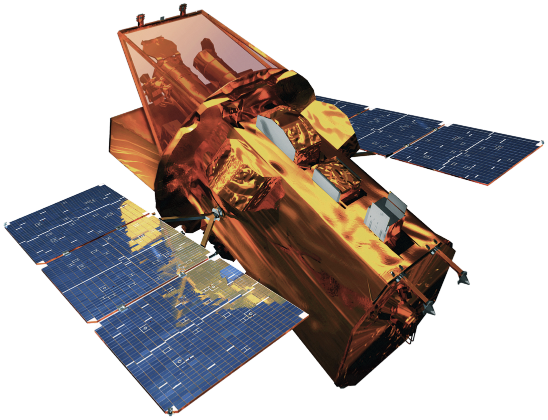


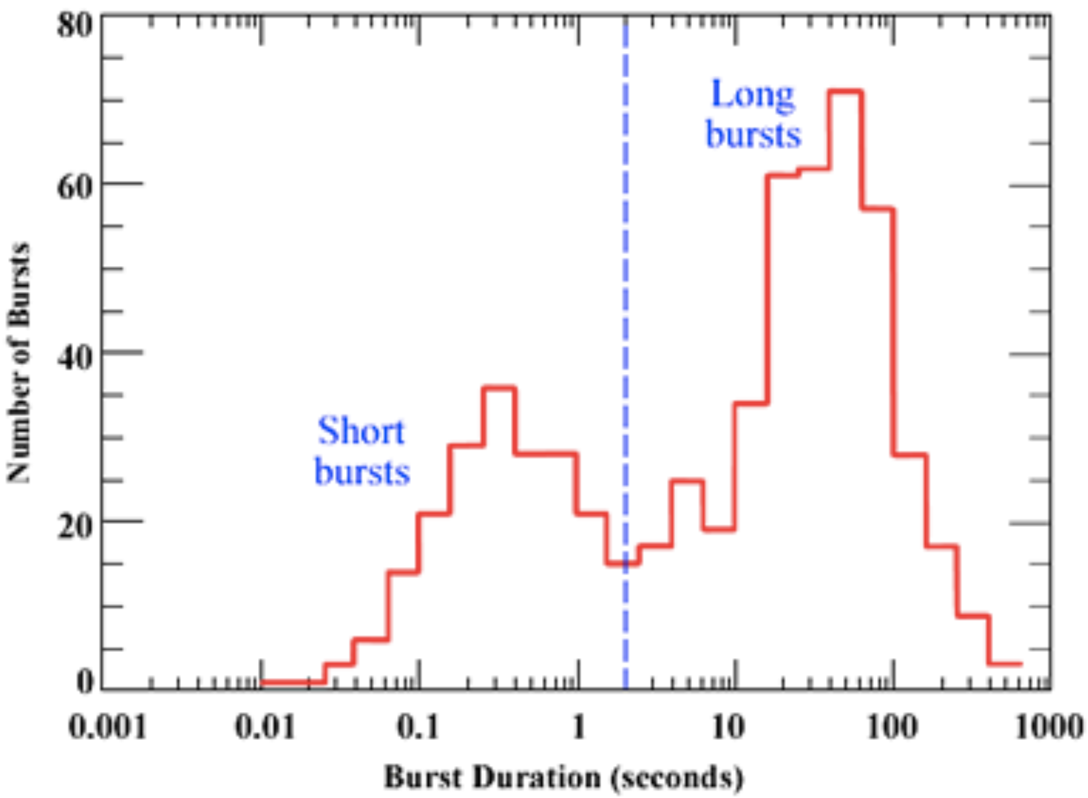
GRBs




Fermi GRBs as of 140218
90
-180
180 RA
-90 Dec
1310 GBM GRBs
174 Swift GRBs
73 LAT GRBs

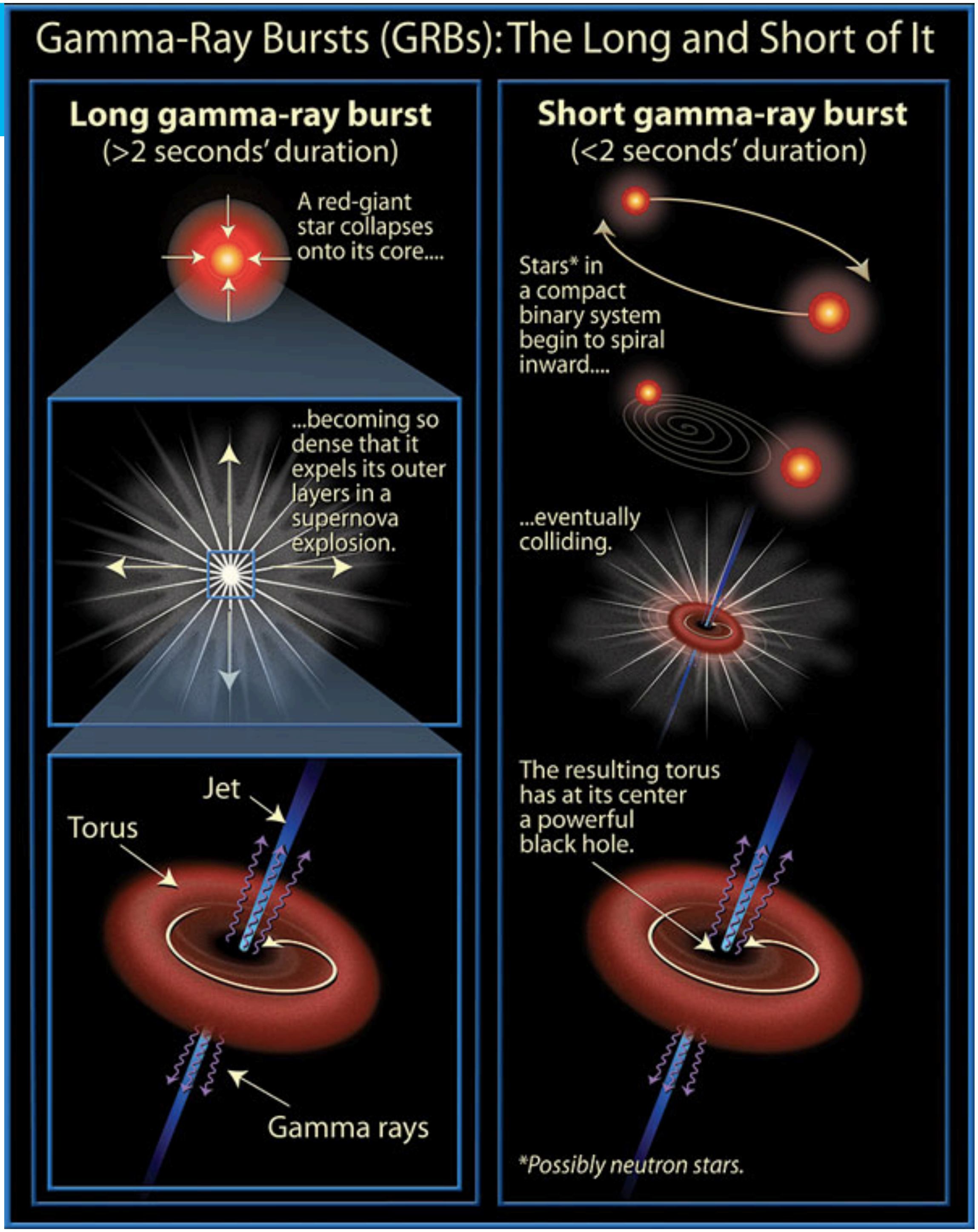
GRBs





Long
bursts
Short
bursts
Number of Bursts
Burst Duration (seconds)
0
20
40
60
80
0.001
0.01
0.1
1
10
100
1000

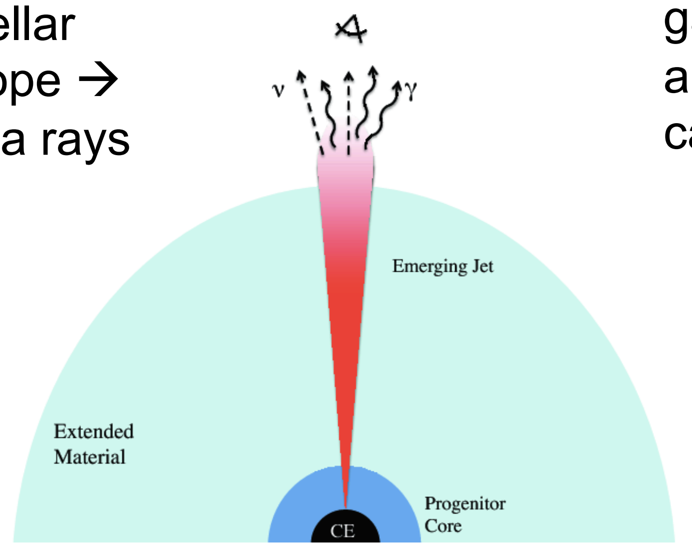
GRBs models



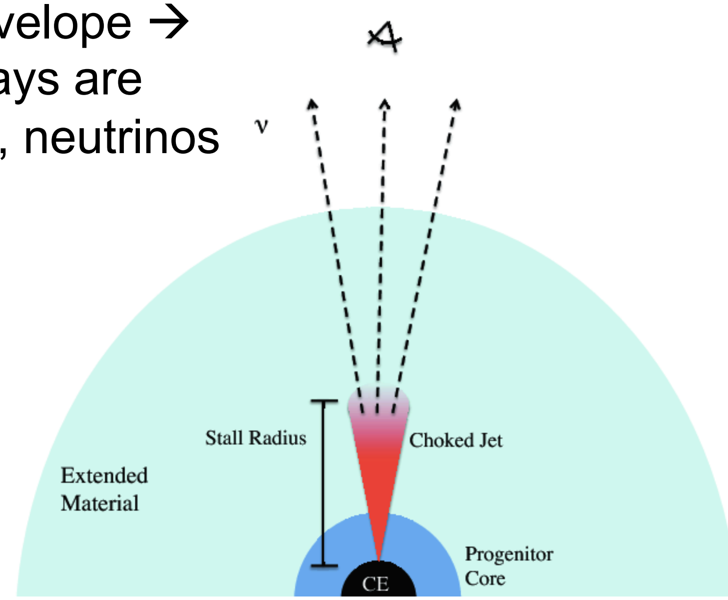
Gamma-Ray Bursts (GRBs): The Long and Short of It
Long gamma-ray burst
(>2 seconds' duration)
A red-giant star collapses onto its core....
...becoming so dense that it expels its outer layers in a supernova explosion.
Jet
Torus
Gamma rays
Short gamma-ray burst
(<2 seconds' duration)
Stars* in a compact binary system begin to spiral inward....
...eventually colliding.
The resulting torus has at its center a powerful black hole.
*Possibly neutron stars.

Failed GRB – chocked jet Supernovae

GRB – jet leaves the stellar envelope → gamma rays



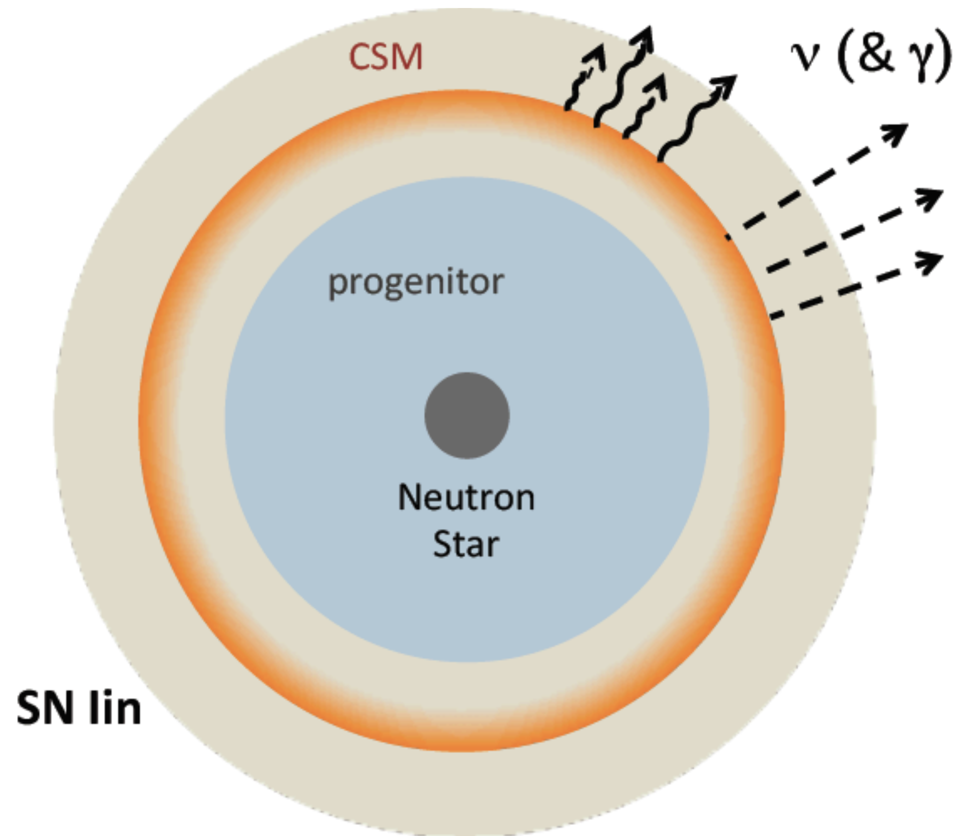
Jet gets stuck in stellar envelope → gamma rays are absorbed, neutrinos can leave



Supernova in dense circumstellar material (type IIn)

- Spherical supernova ejecta collides with dense circumstellar medium → efficient particle acceleration

- Dense medium from smaller pre-outbursts
- Typically long lasting optical light curve
- Characteristic spectral features



Murase et al., PRD 84 (2011)

The Multi-Messenger Ansatz

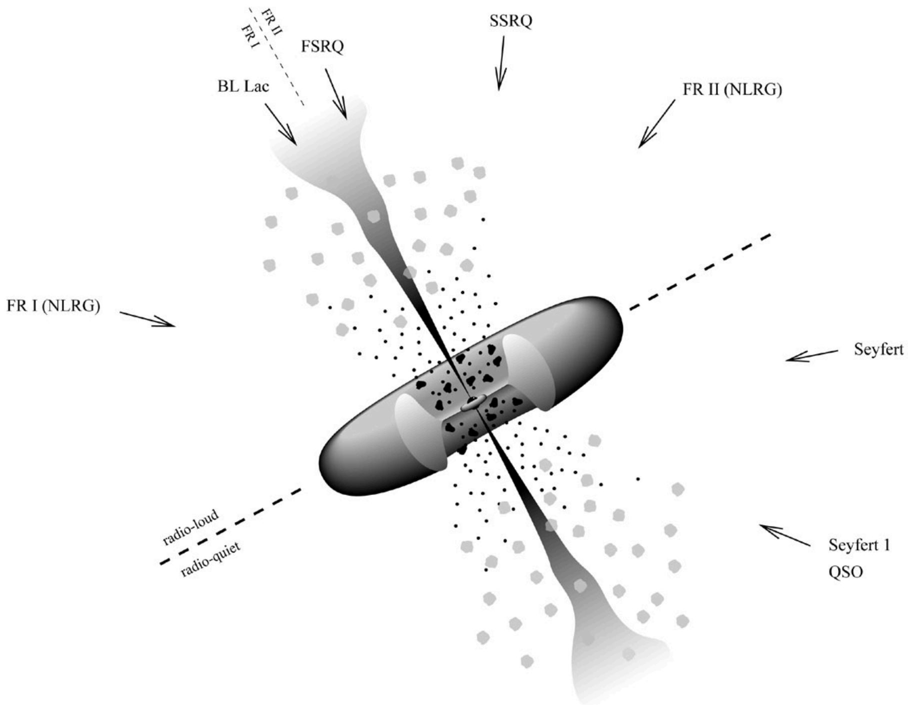
No significant cluster of neutrinos found: Neutrinos alone do not (yet) reveal a source

If we know **WHERE** and/or **WHEN** to look we can increase our sensitivity
(reduce trails factor!)

Electro-magnetic data can tell us **WHERE** and/or **WHEN**

Blazars

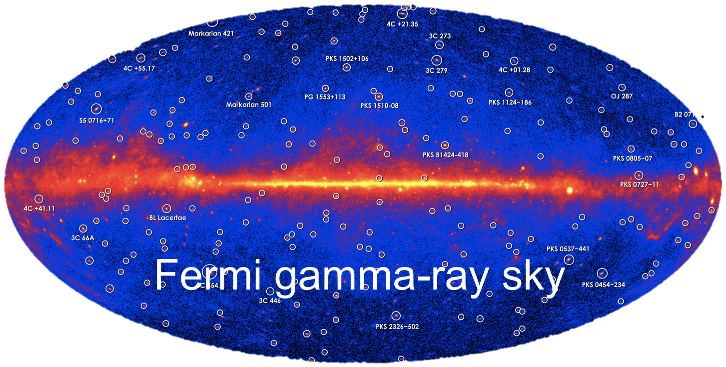
- Gamma rays tell us WHERE

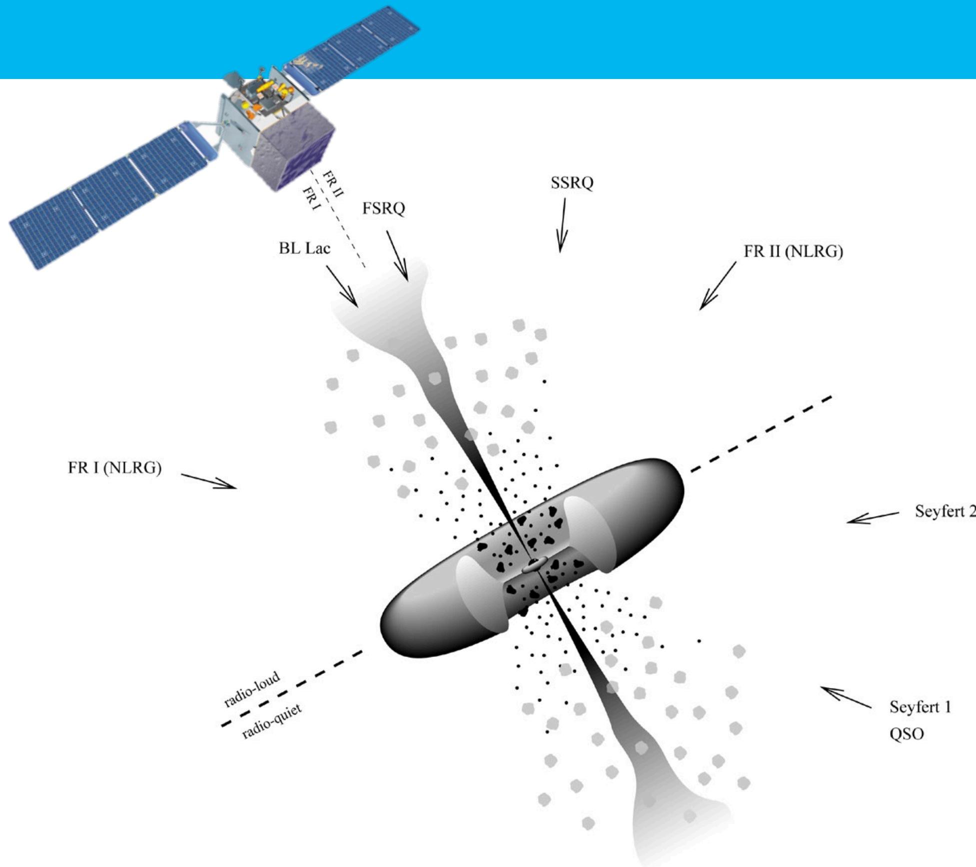


IceCube Coll., arXiv:1502.03104

Blazars

> Gamma rays tell us WHERE





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Blazars

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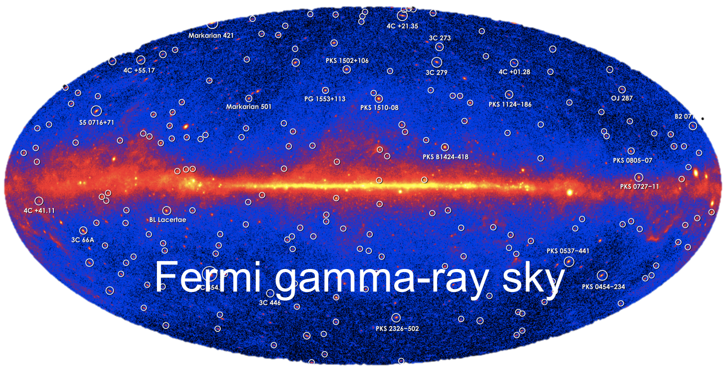
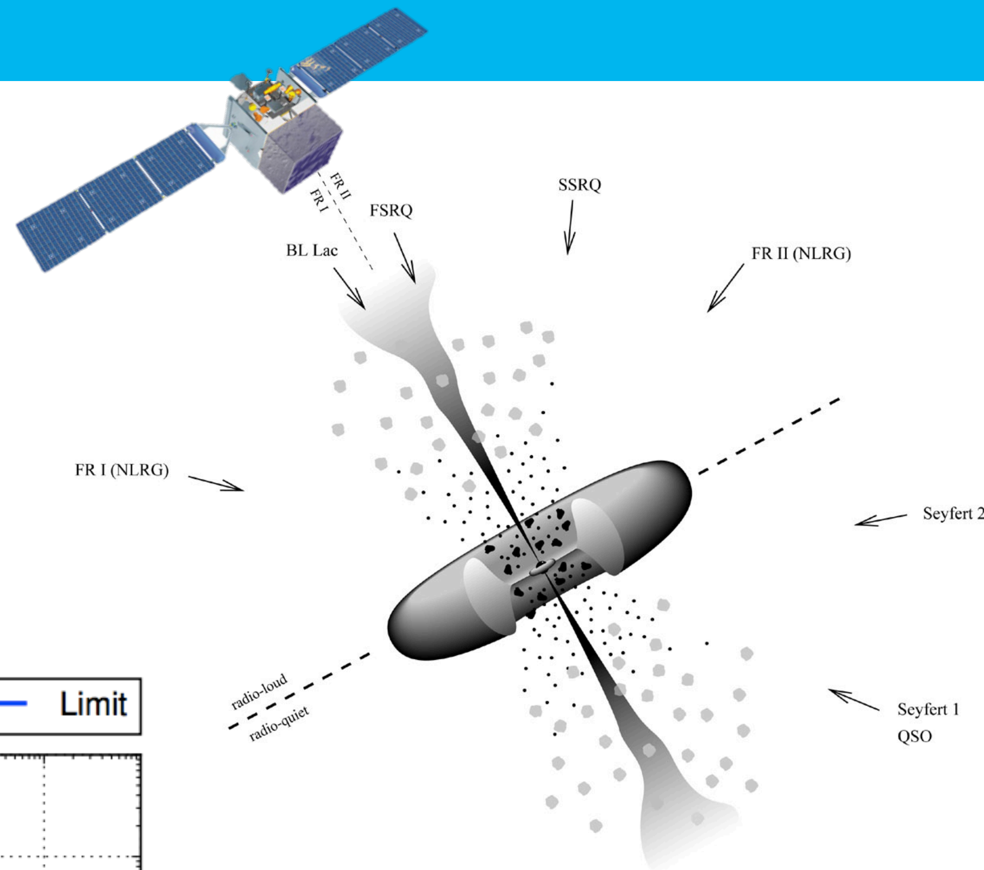
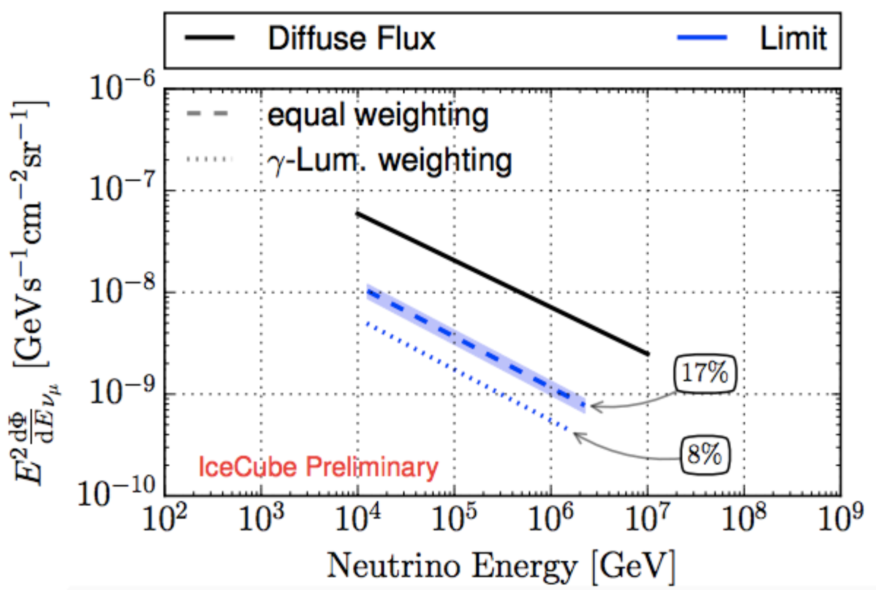




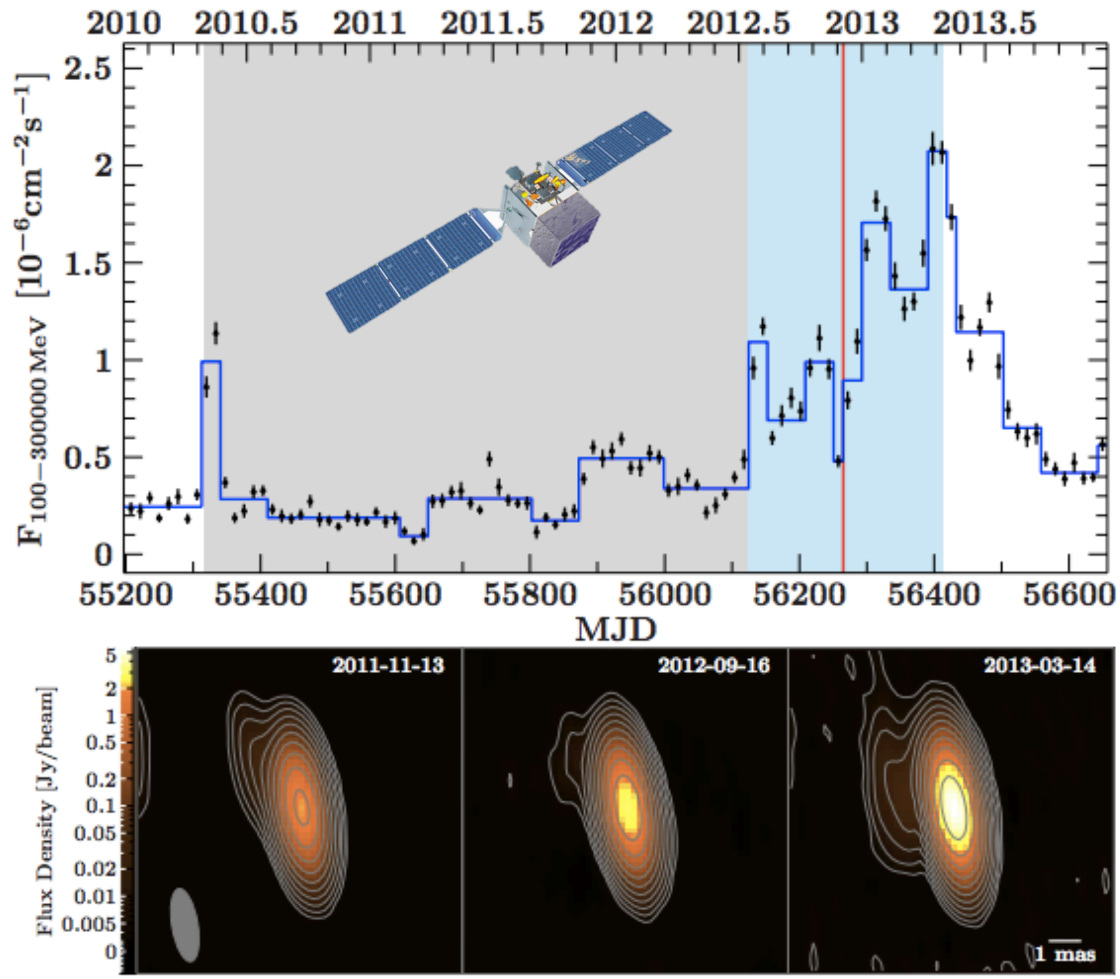


Correlation study of 3 years of IceCube data and 862 Fermi-LAT blazars

IceCube Coll., arXiv:1502.03104

Blazar Flares

- Gamma rays tell us WHERE and WHEN
- Major outburst of blazar PKS B1424−418 occurred in temporal and positional coincidence PeV neutrino
- single source has sufficiently high fluence to explain an observed coinciding PeV neutrino event
- 5% chance coincidence
- Distant source (z=1.5)

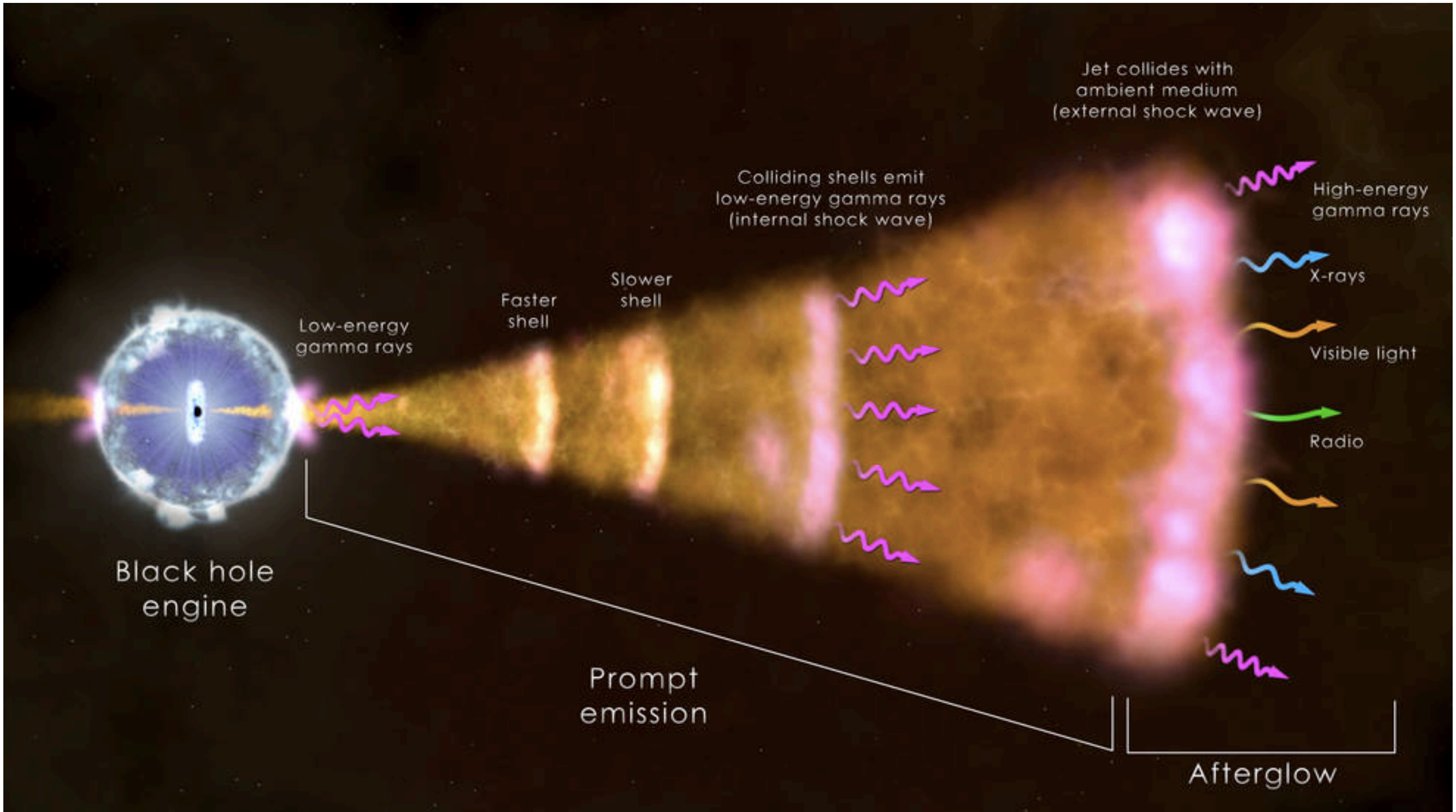


8.3pc

Kadler et al., Nature, 2016

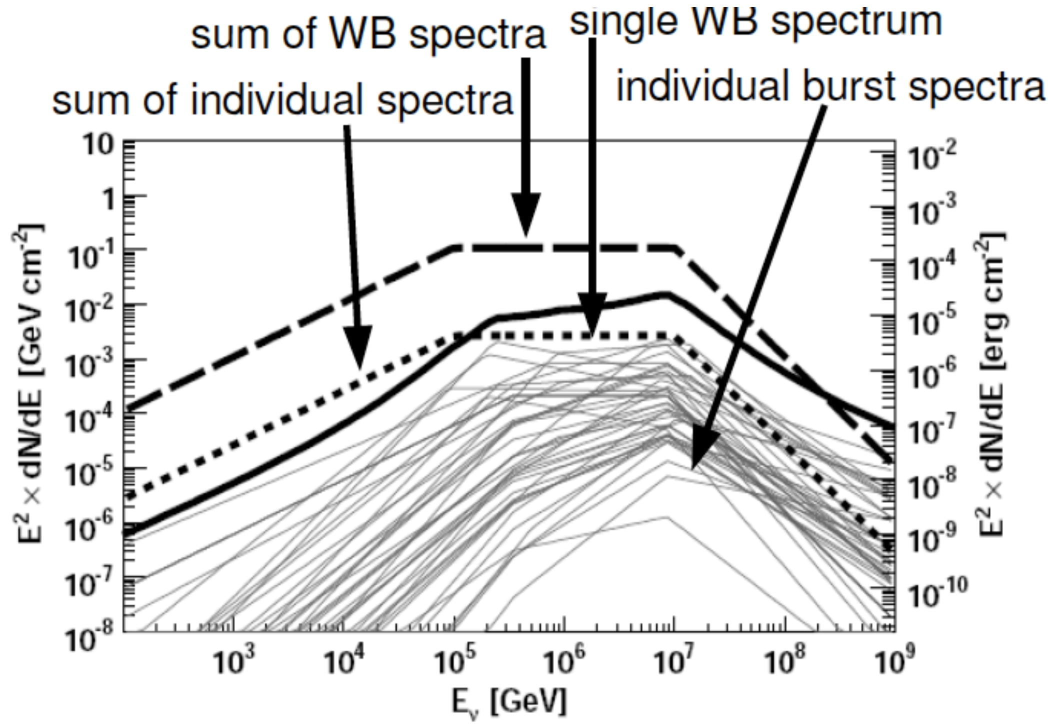
Gamma-Ray Bursts (GRBs)

- Gamma rays and X-rays tell us WHERE and WHEN



Gamma-Ray Bursts (GRBs)

- Extremely large energy release on the time-scale of 10^{-3}-10^{3} seconds
- Gamma rays and X-rays tell us WHERE and WHEN



4 years of IceCube Northern sky data correlated with 506 GRBs

IceCube Coll., ApJ 805, 2015

Gamma-Ray Bursts (GRBs)

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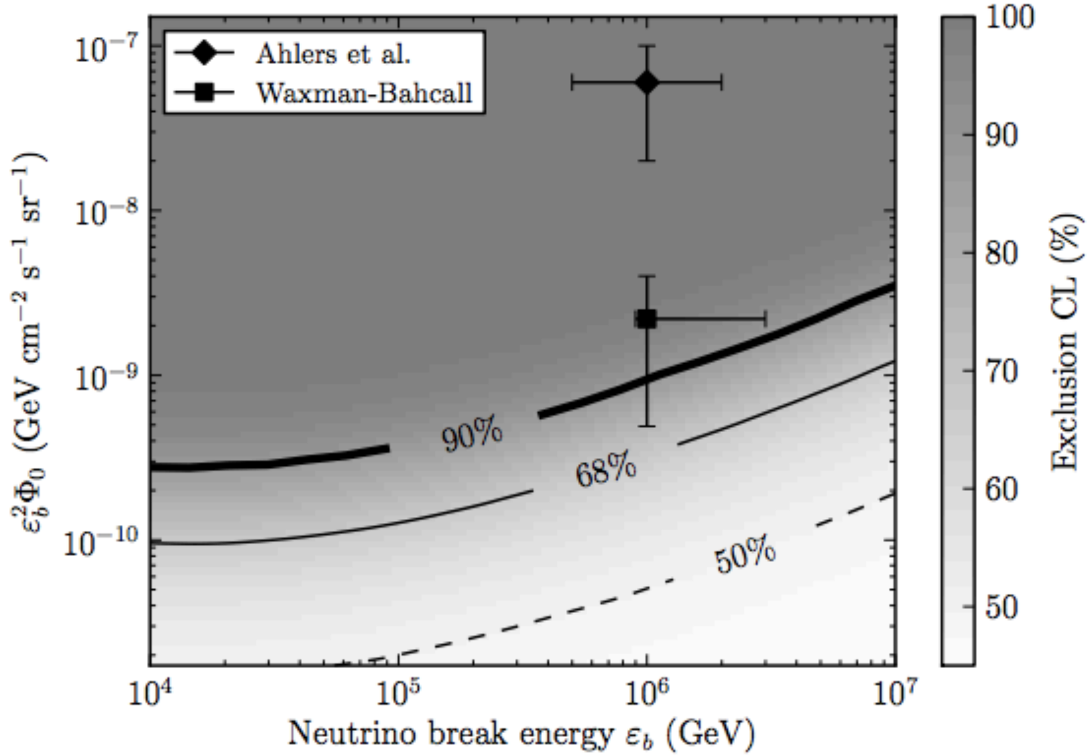
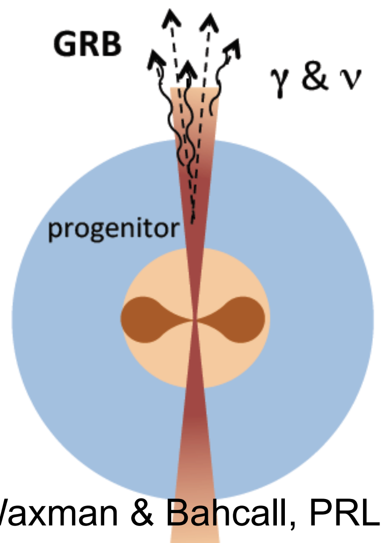


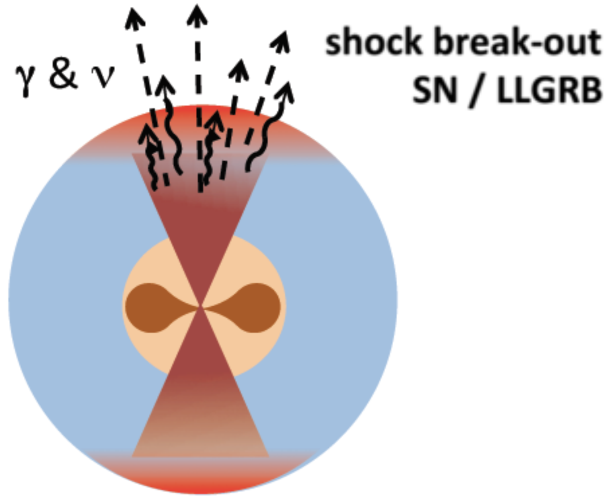
**GRBs contribute less than 1% to observed diffuse neutrino flux.
Potential large population of nearby low-luminosity GRBs not constrained.**

IceCube Coll., ApJ 805, 2015

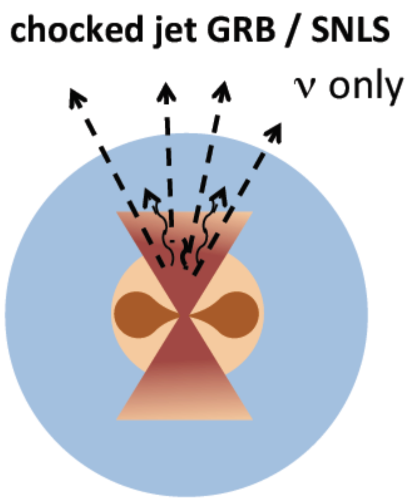
Supernovae (SNe)



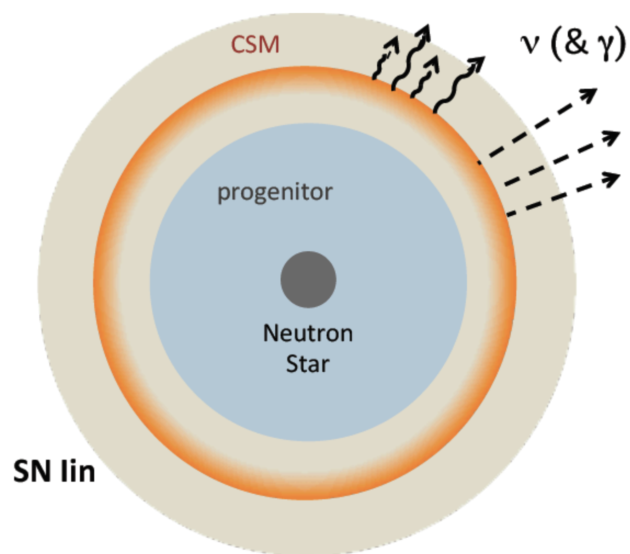
Waxman & Bahcall, PRL, 78 (1997)



Murase et al, ApJL,651 (2006)

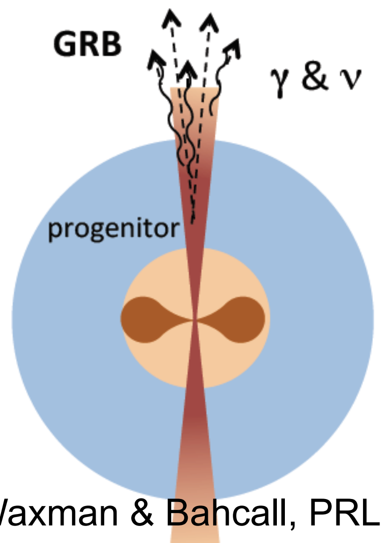


Ando & Beacom, PRL 95 (2005)



Murase et al., PRD 84 (2011)

Supernovae (SNe)



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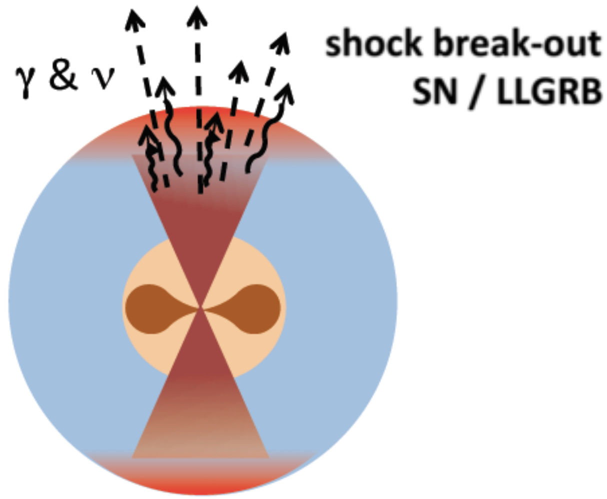
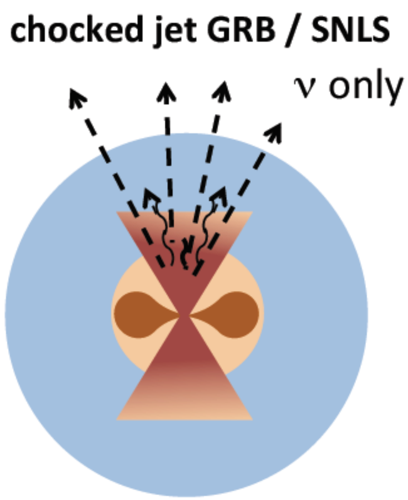
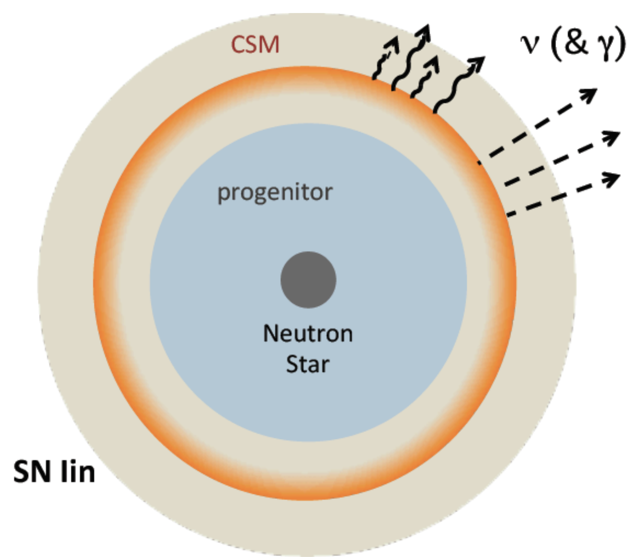


Murase et al, ApJL,651 (2006)



Ando & Beacom, PRL 95 (2005)



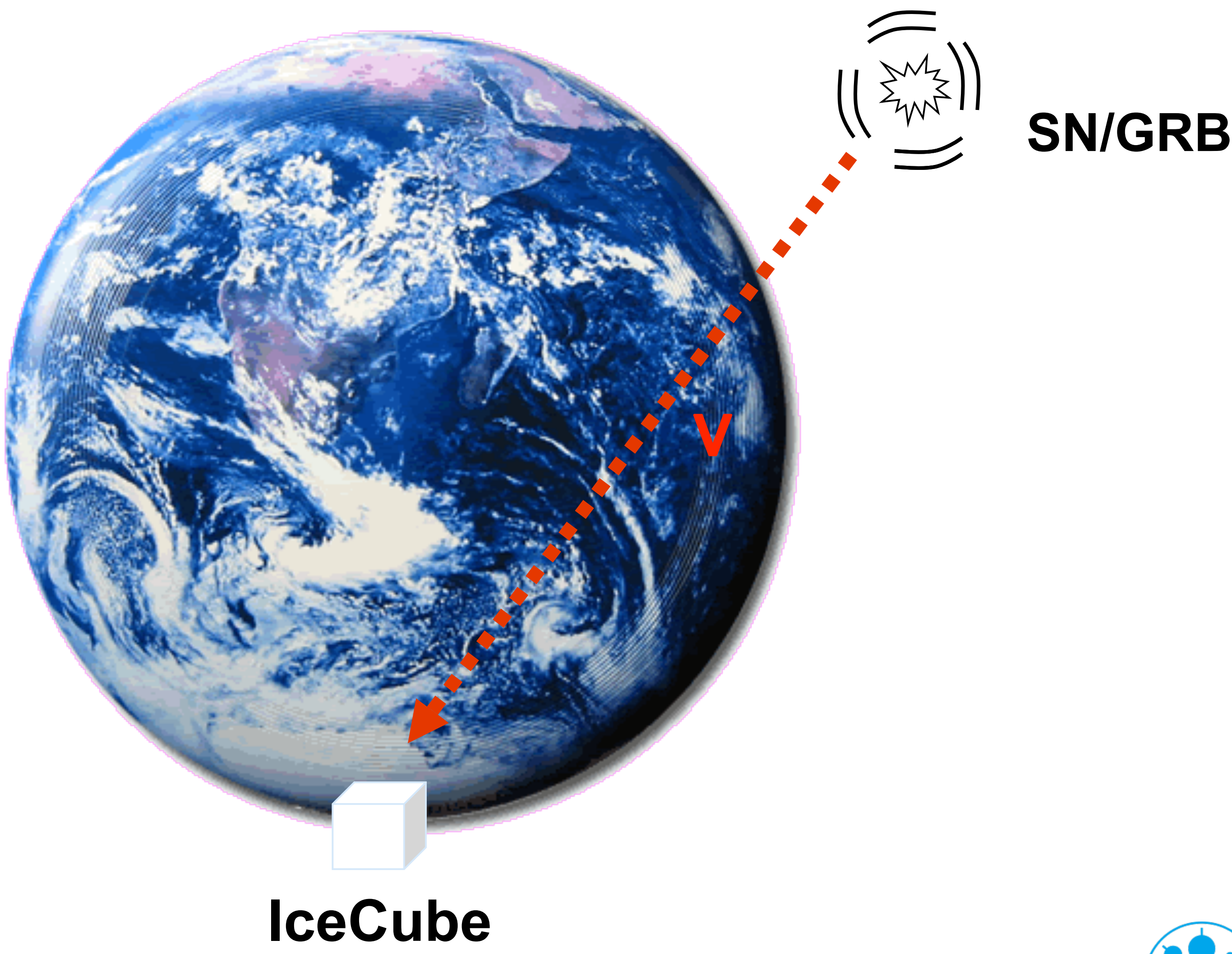
Murase et al., PRD 84 (2011)

SNe are best discovered in optical

optical surveys do not cover the whole sky

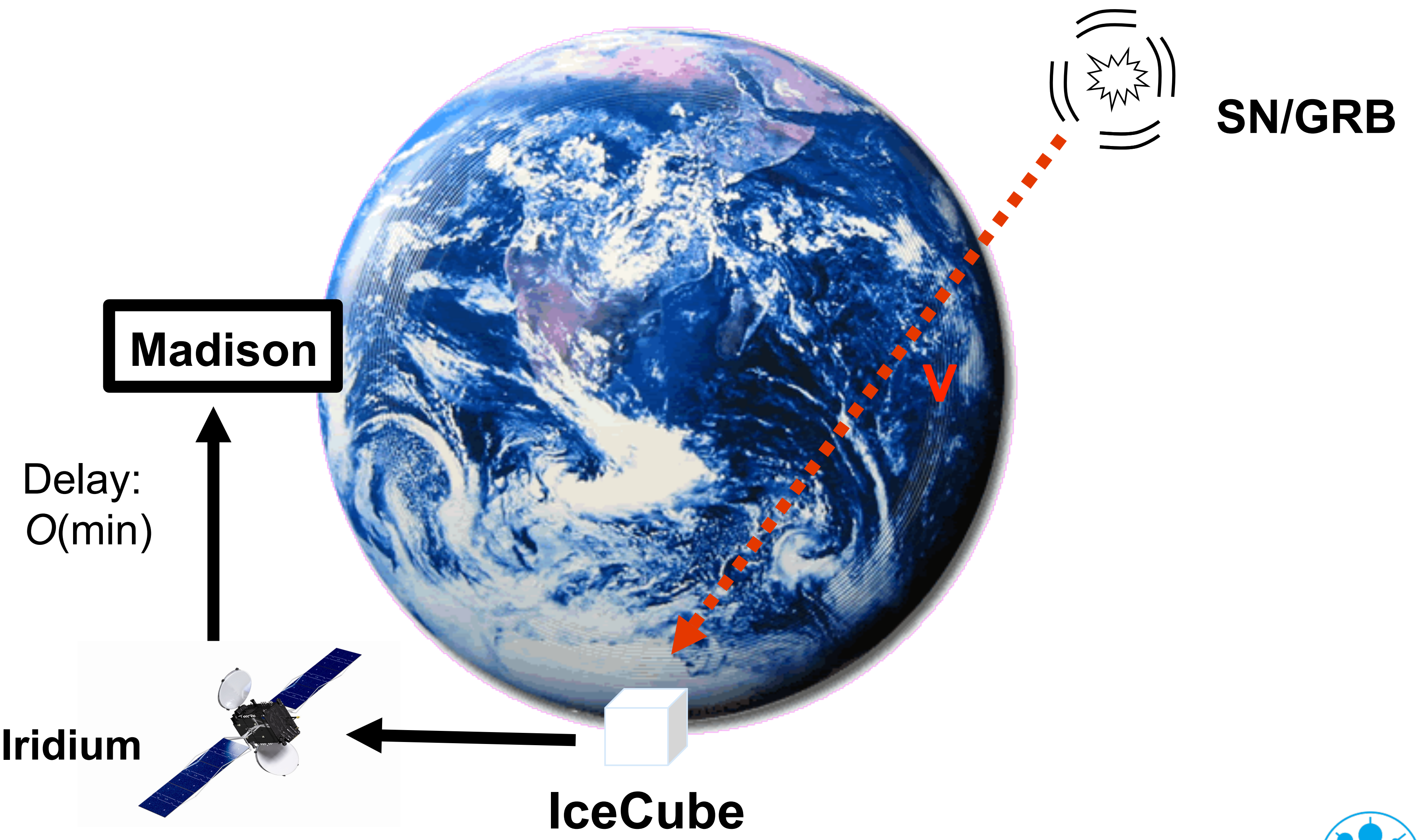
use IceCube to trigger EM follow-up

IceCube Optical, X-ray, and Gamma-Ray Follow-Up



IceCube A&A 539, A60 (2012)

IceCube Optical, X-ray, and Gamma-Ray Follow-Up



IceCube A&A 539, A60 (2012)

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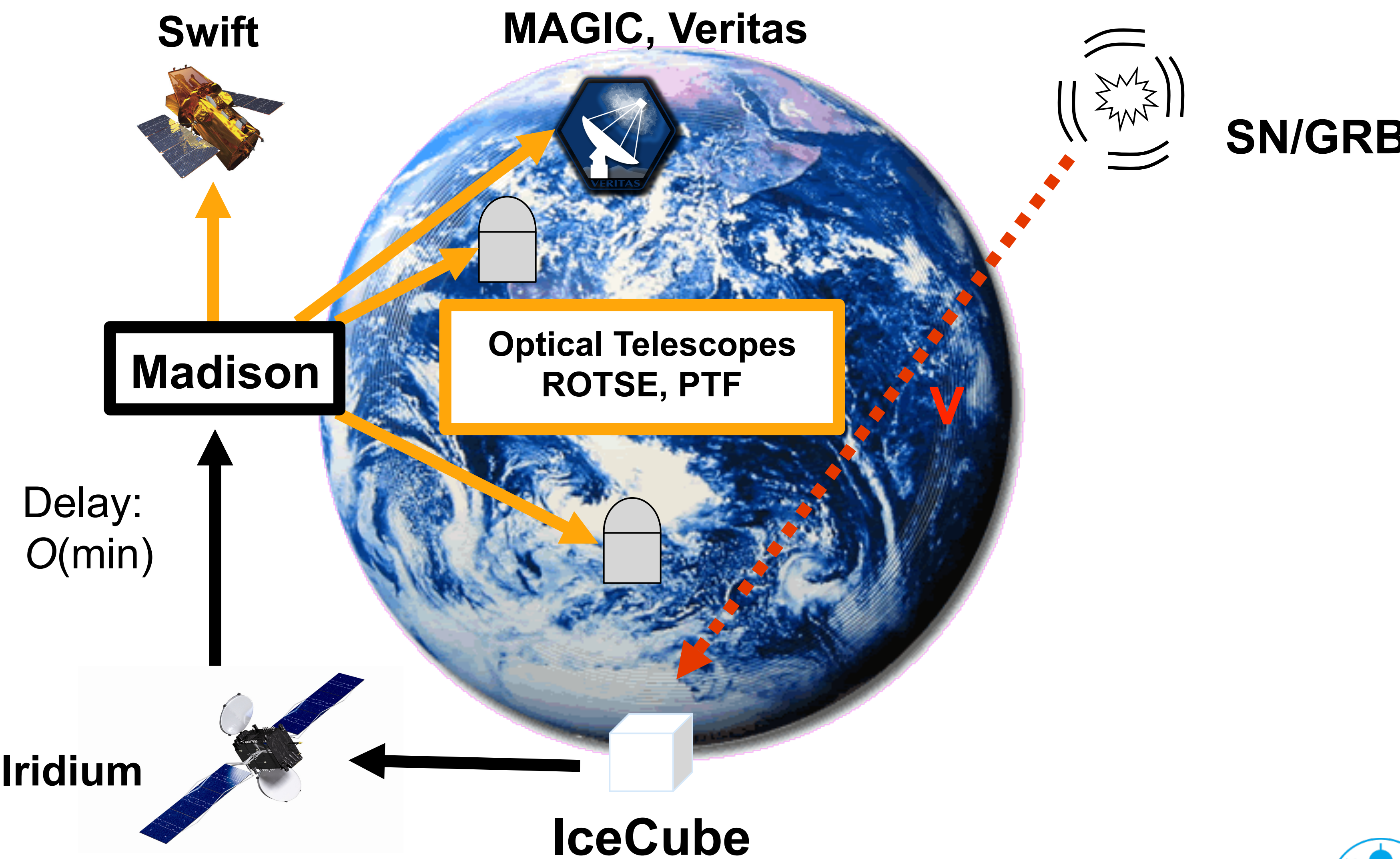
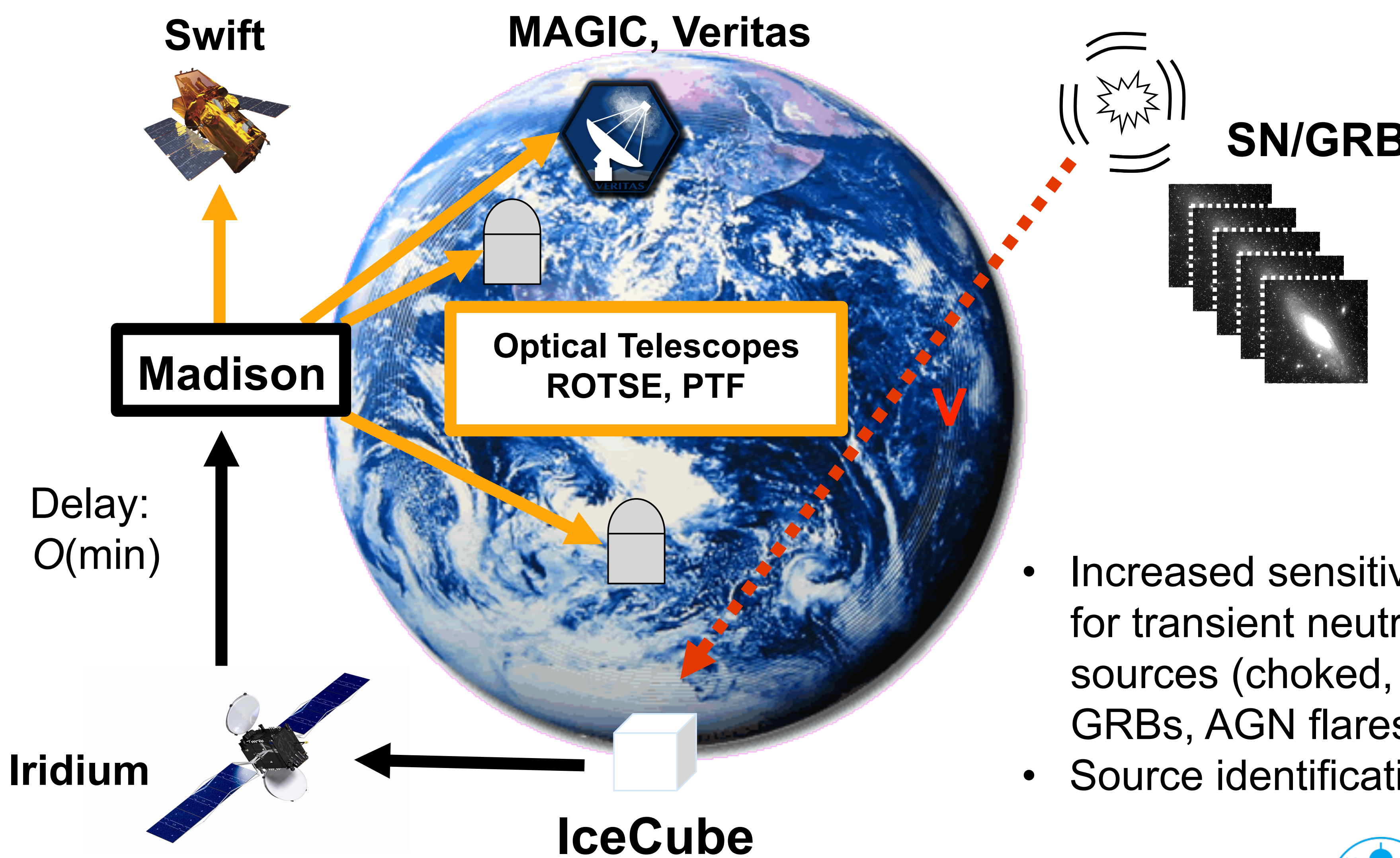


IceCube A&A 539, A60 (2012)

IceCube Optical, X-ray, and Gamma-Ray Follow-Up



- Increased sensitivity for transient neutrino sources (choked, dark GRBs, AGN flares)
- Source identification

IceCube A&A 539, A60 (2012)

Multiplicity Trigger for Optical and X-ray Follow-up

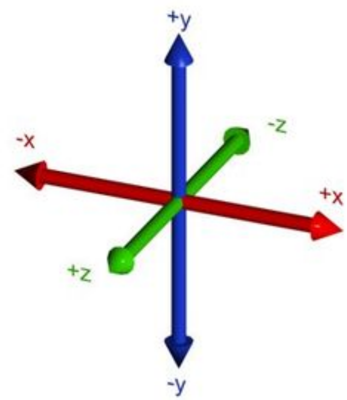
Require at least 2 neutrinos (doublet)
→ Reduce background of atmospheric ν-background
25 background doublets per year

Time

Time between events
ΔT<100 s

&

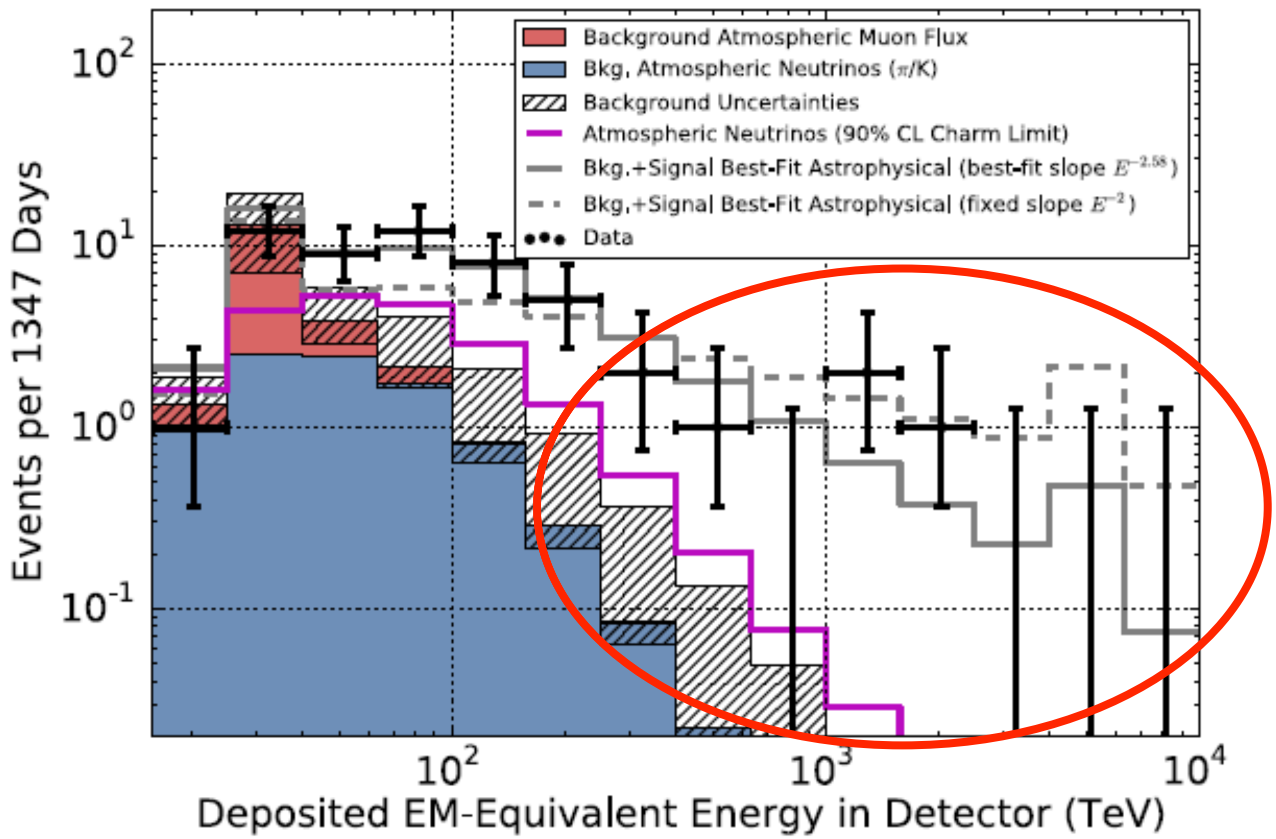
Direction



Angular distance between
reconstructed direction ΔΨ **< 3.5°**

Single high-energy neutrino event trigger

High-energy single event trigger
(signal spectrum is harder than atmospheric background)

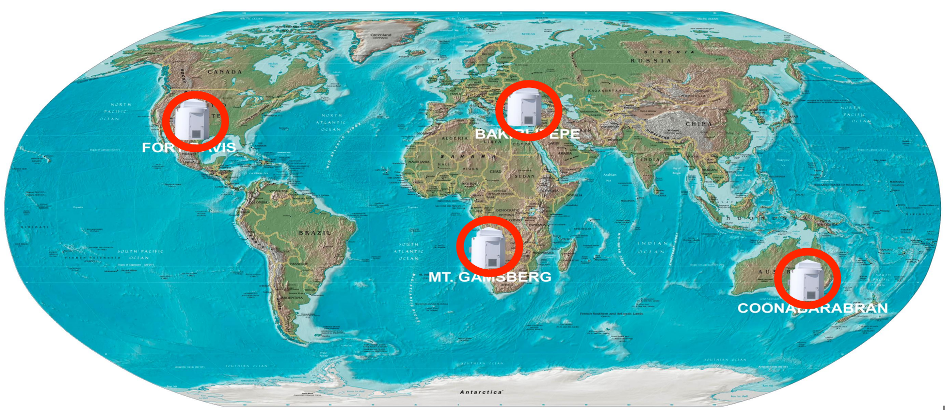


Optical Follow-Up Instruments: Need wide-field!

ROTSE
Robotic Optical Transient
Search Experiment

4 x 0.45m
FoV 1.85° x 1.85°
25 alerts per year

Now retired



PTF
Palomar Transient
Factory

1 x 1.2 m
FoV 3.5° x 2.3°

Spectroscopy of interesting
candidates possible
10 alerts per year

Optical Follow-Up Instruments (Soon)

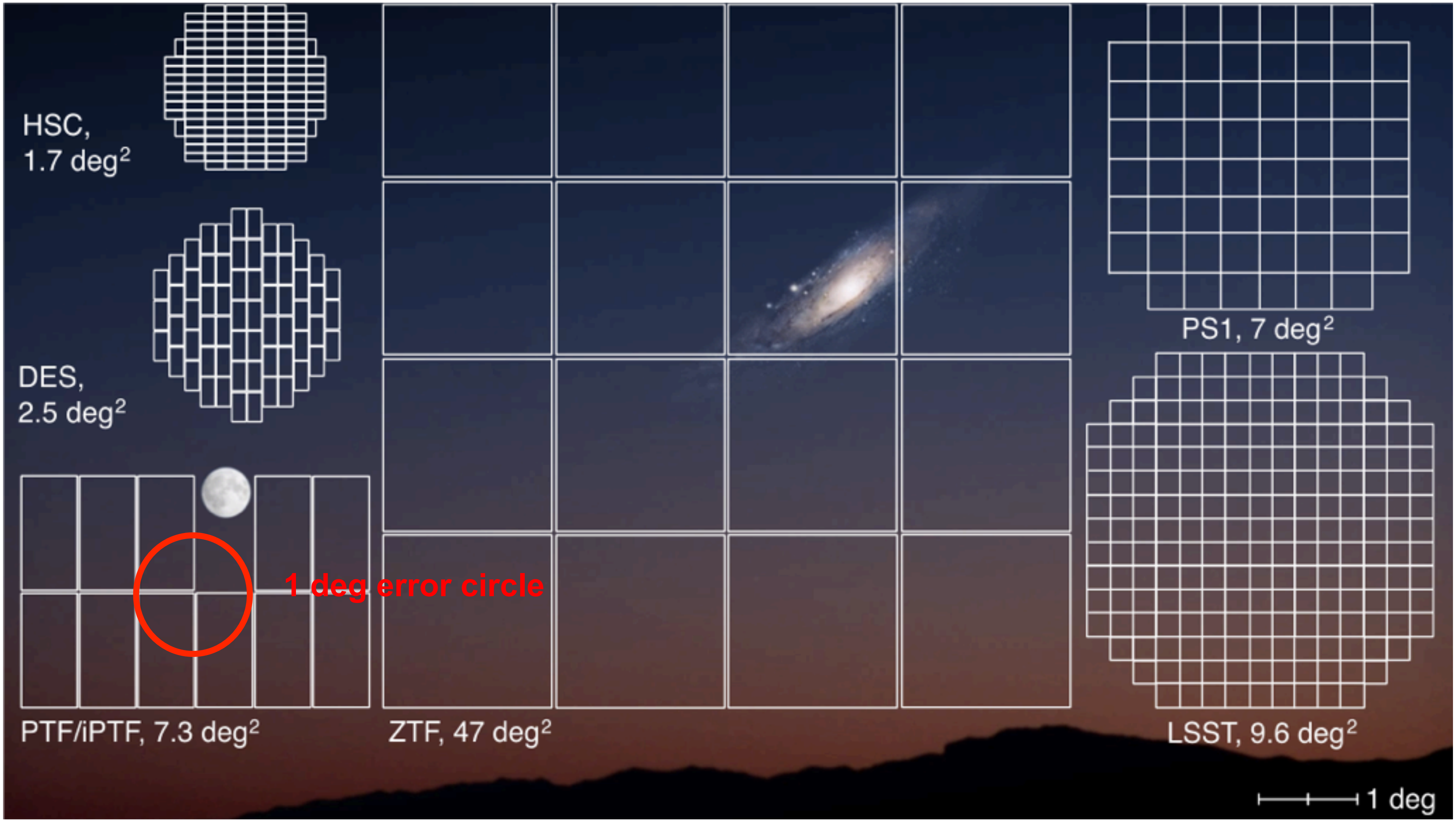
Zwicky Transient Facility (ZTF)

ASAS-SN

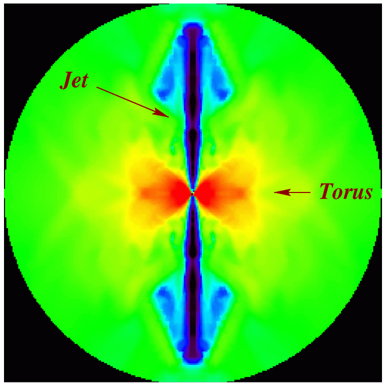
MASTER

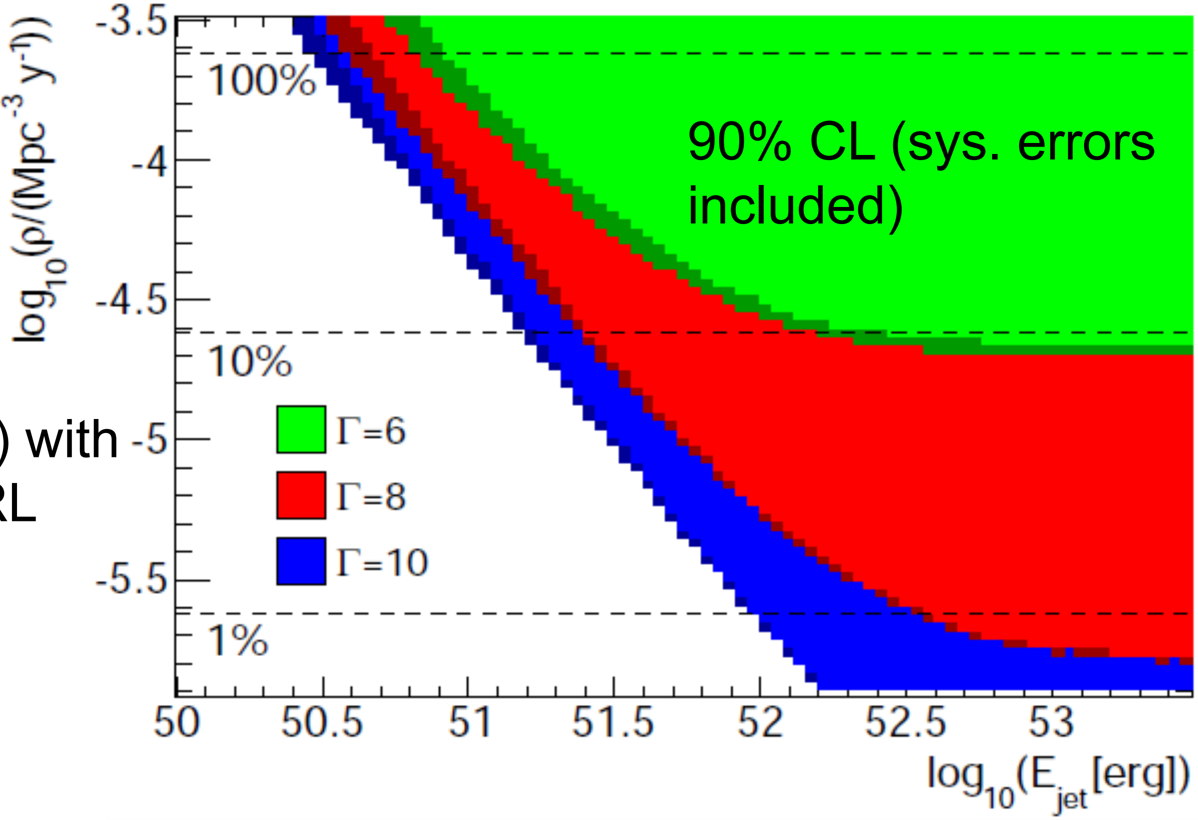
LCOGT

Optical field of view



Optical Follow-up Program: Results after first Year





Core-collapse SNe (CCSN) with Jets, Ando & Beacom PRL 95, 2005

Model parameters:

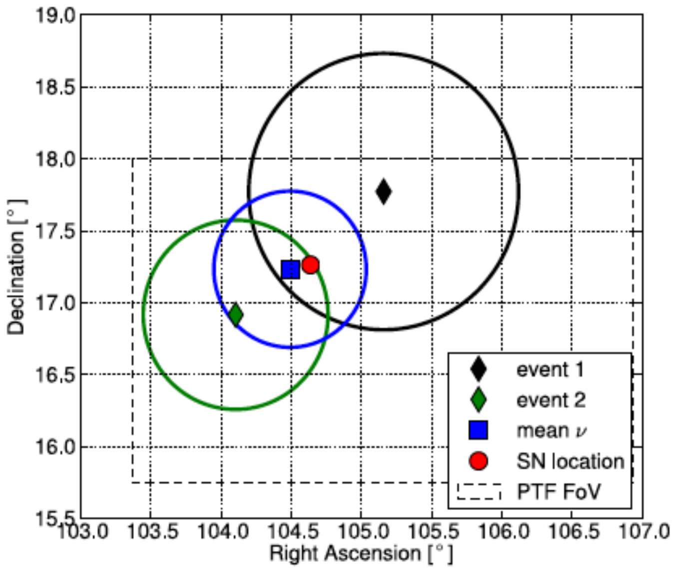
- Rate of CCSN with jets ρ
- Jet energy E_{jet}
- Lorentz boost factor Γ

Less than 4.2% of all CCSN host a jet with typical values of $\Gamma = 10$ and $E_{jet} = 3\times10^{51}$erg

IceCube A&A 539, A60 (2012)

Optical Follow-up Program: Supernova Detection

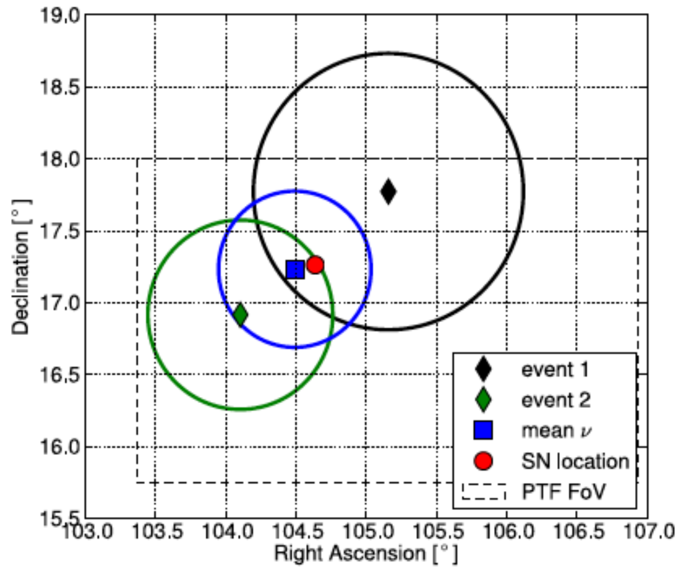
- PTF12csy, a very bright SNe IIn at 300 Mpc
- Coincident with the most significant neutrino alert (two neutrinos detected only 1.6 s apart)
- Chance probability 1.6%

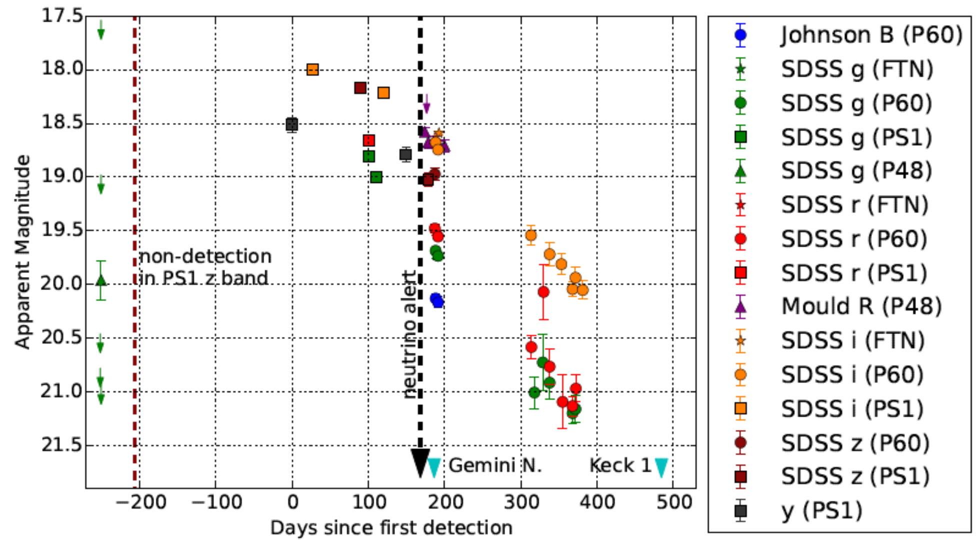


IceCube & PTF Coll. ApJ, 811, 52 (2015)

Optical Follow-up Program: Supernova Detection

- PTF12csy, a very bright SNe IIn at 300 Mpc
- Coincident with the most significant neutrino alert (two neutrinos detected only 1.6 s apart)
- Chance probability 1.6%
- SN 100 days old at time of neutrino detection





IceCube & PTF Coll. ApJ, 811, 52 (2015)

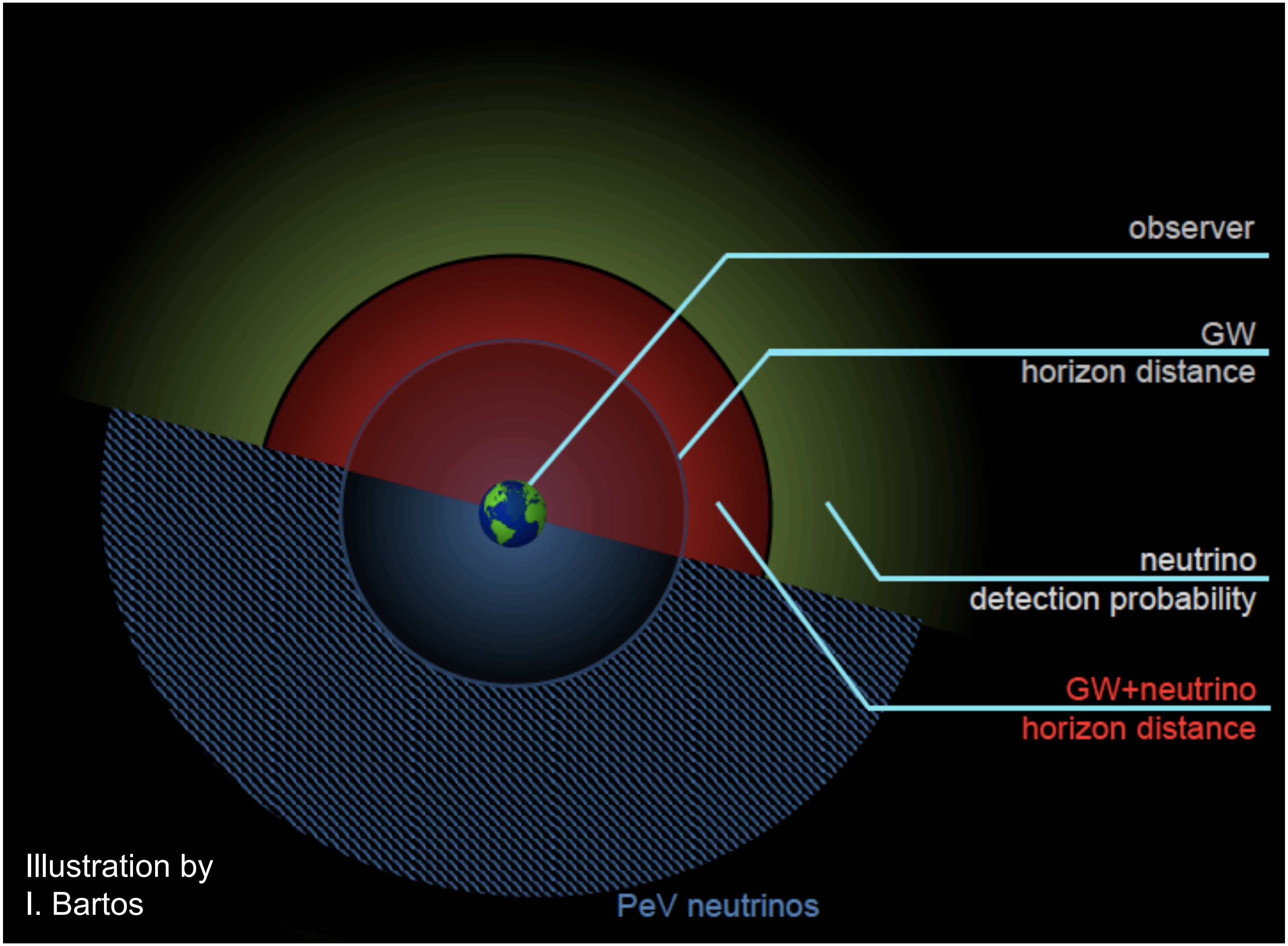
TeV Follow-up Program with MAGIC / Veritas

- Aiming for detection of flaring sources on time scales of up to 3 weeks
- Predefined source list in the Northern Sky
  - Bright, hard and variable GeV sources
  - 21 blazars
  - Time clustering algorithm

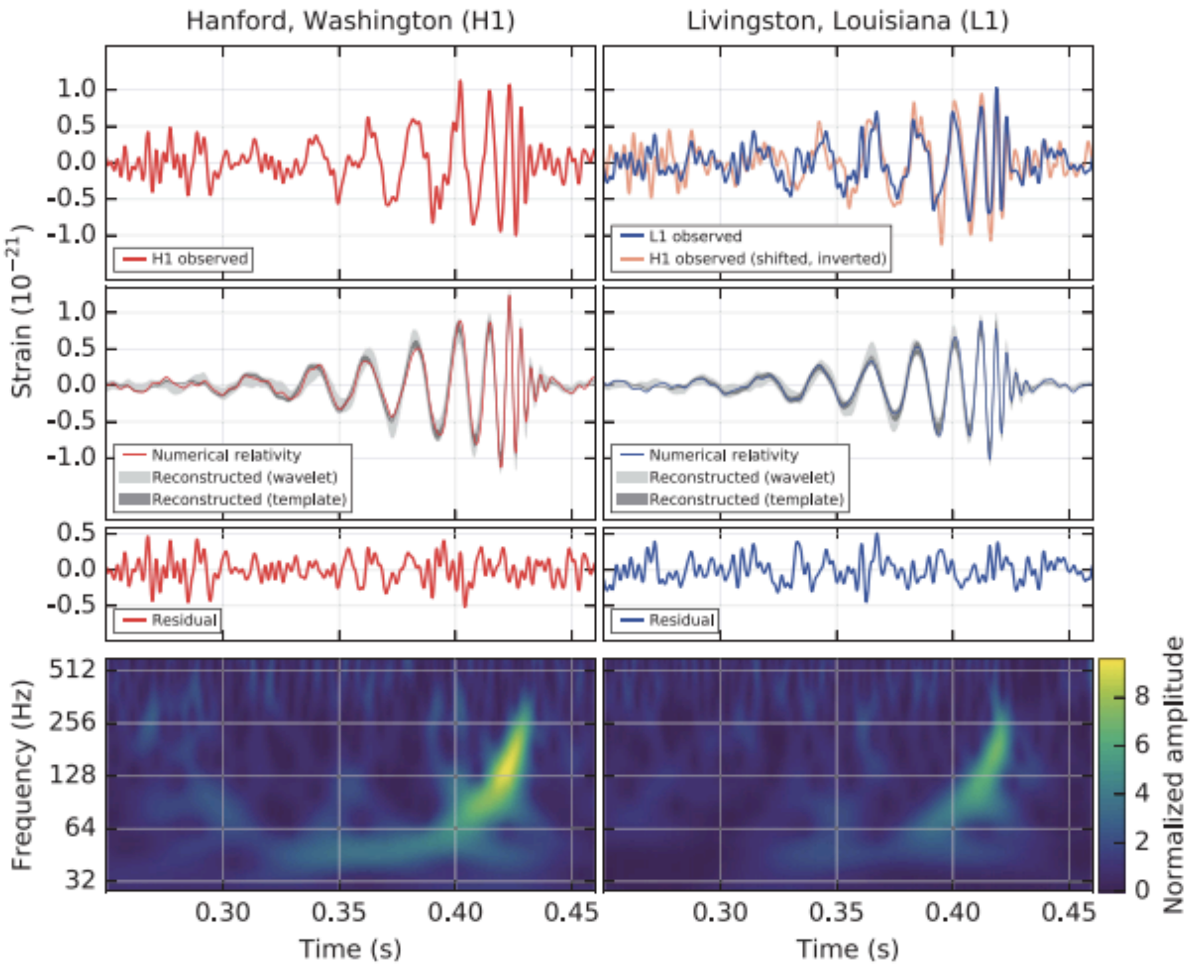
- Southern Sky analysis in preparation
- Real time analysis of high-energy single events in preparation
  - Also with HESS

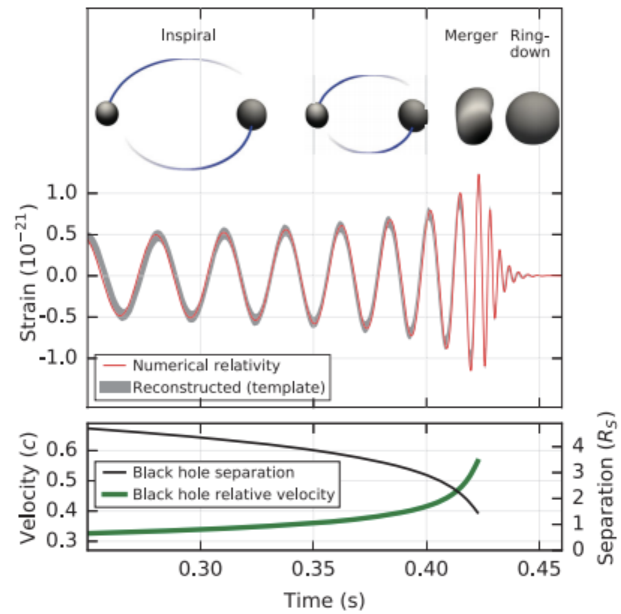
R. Franke et al, ICRC 2013

Gravitational Waves and Neutrinos



First Detection of Gravitational Waves

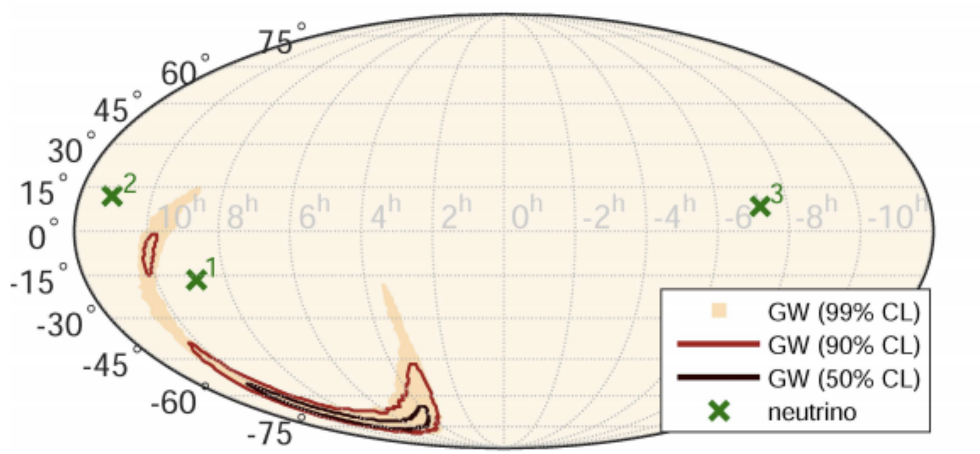




First observation of a binary black hole merger

LIGO / Virgo Gravitational Wave Follow-Up

> Search for Neutrinos:
  - +/- 500 sec around GW signal
  - No neutrinos in Antares
  - 3 neutrinos in IceCube, but none in spatial coincidence



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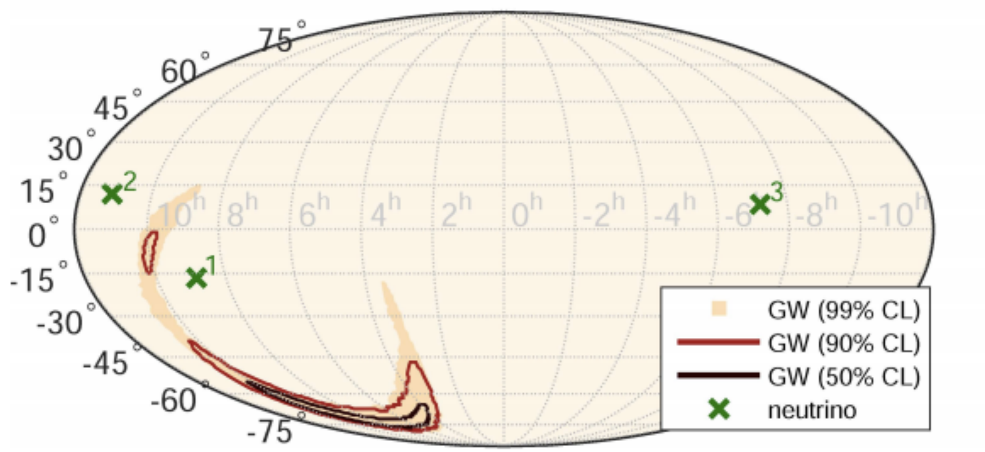
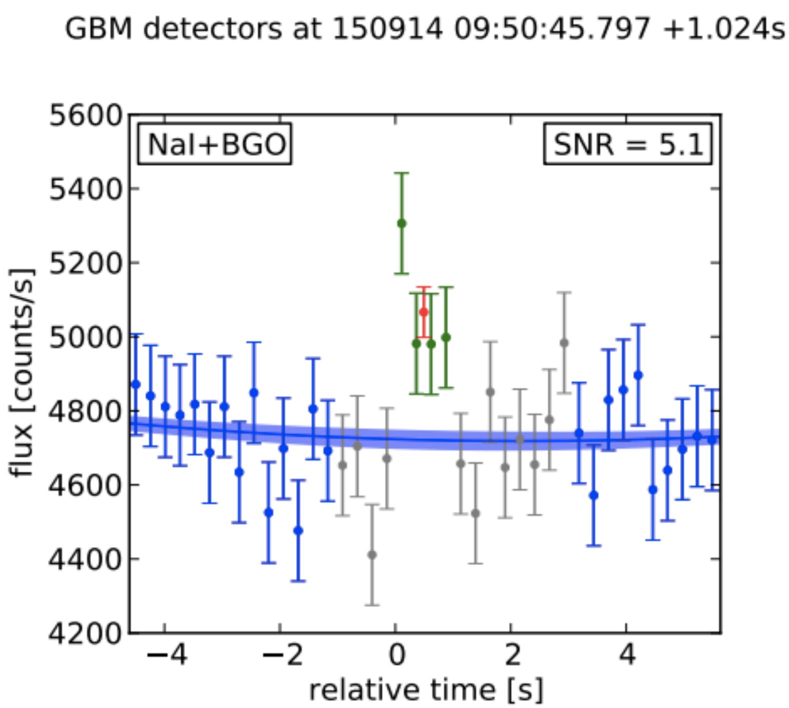


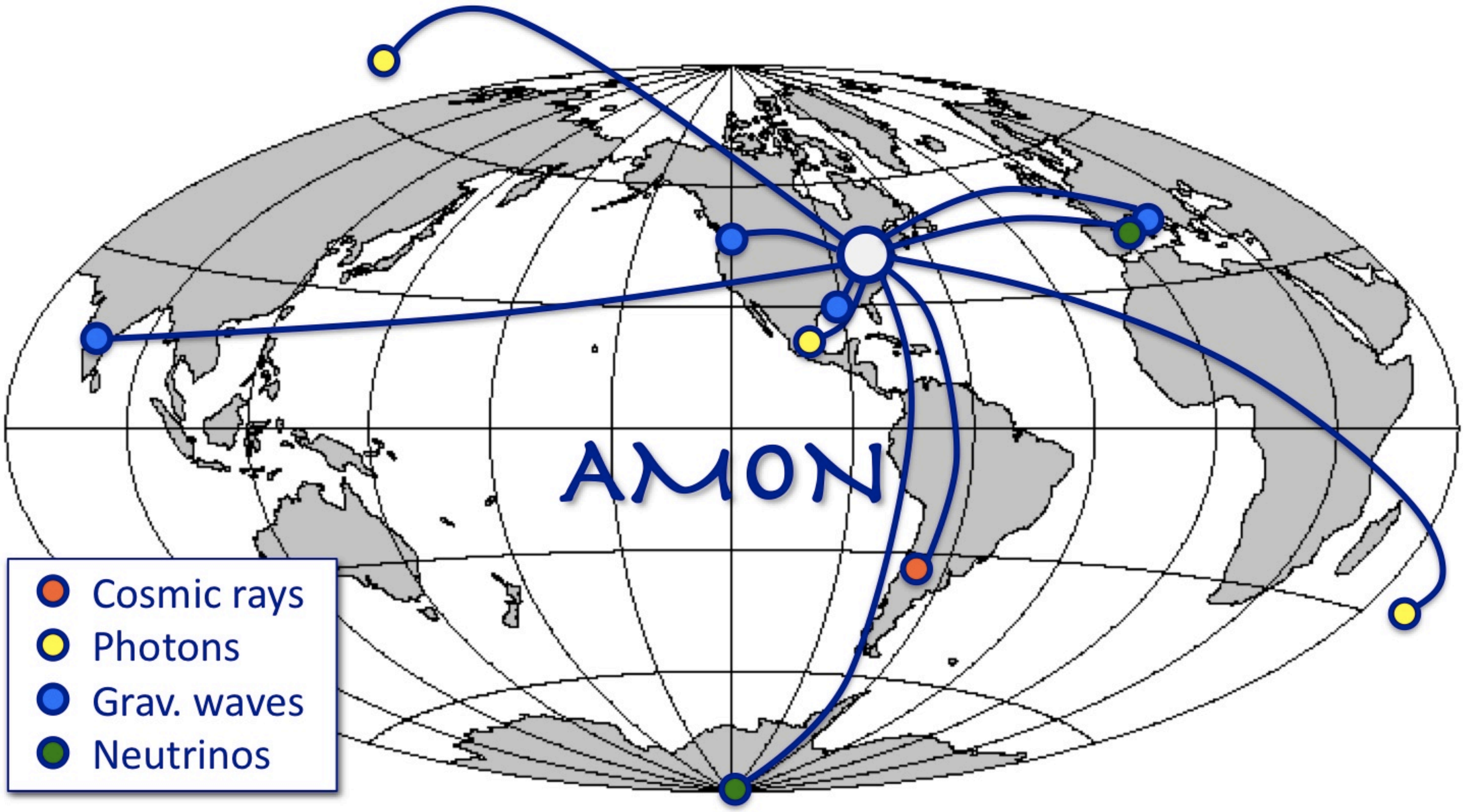


> Search for gamma-rays:

- GBM found excess 0.4s after GW signal
- False alarm probability 0.0022
- chance coincidence of 1.0×10^{-3} for a signal to accidentally match the signature of GW150914-GBM in a 60 s period

Connaughton, arXiv:1602.03920

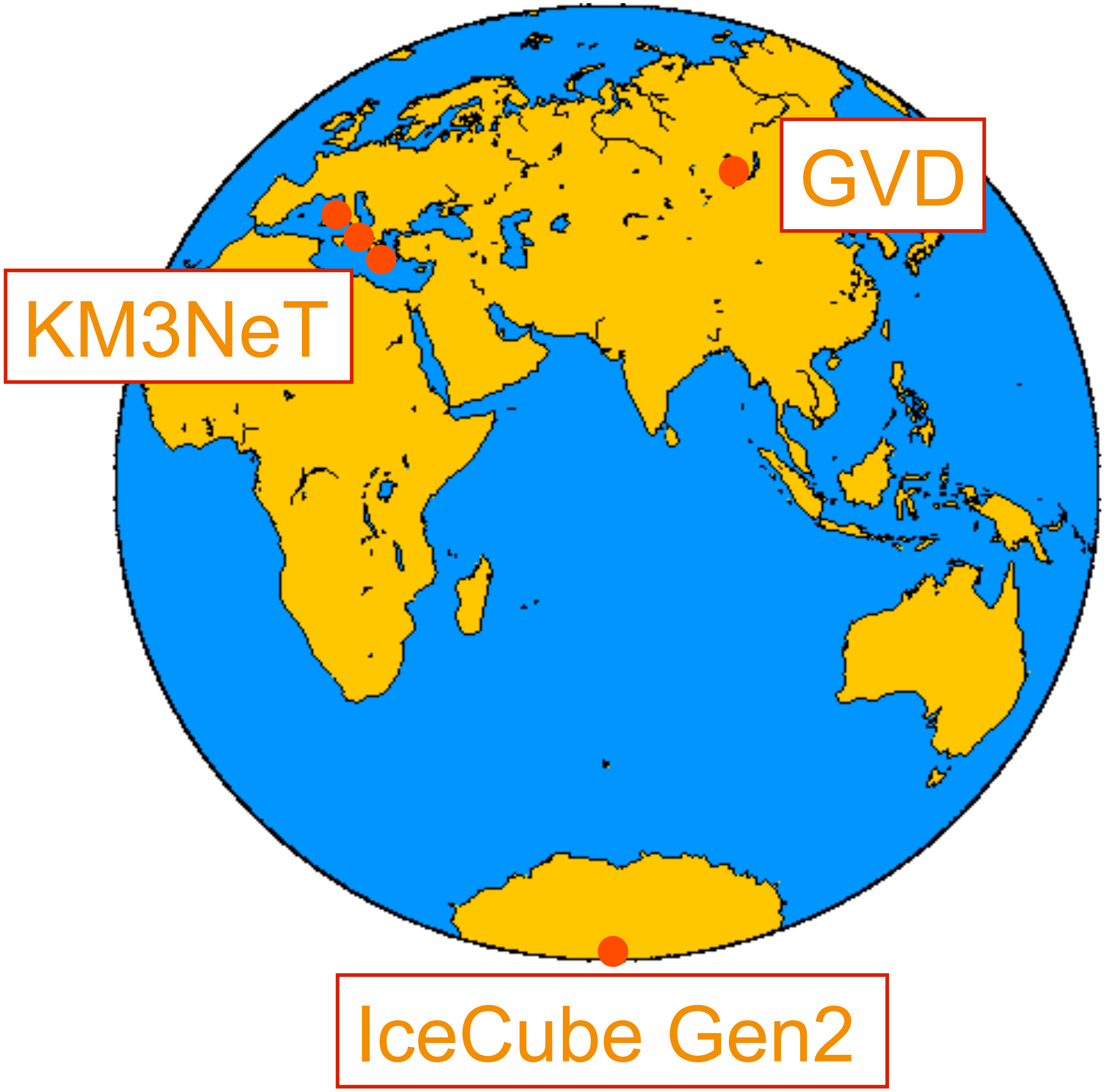
Astrophysical Multimessenger Observatory Network (AMON)



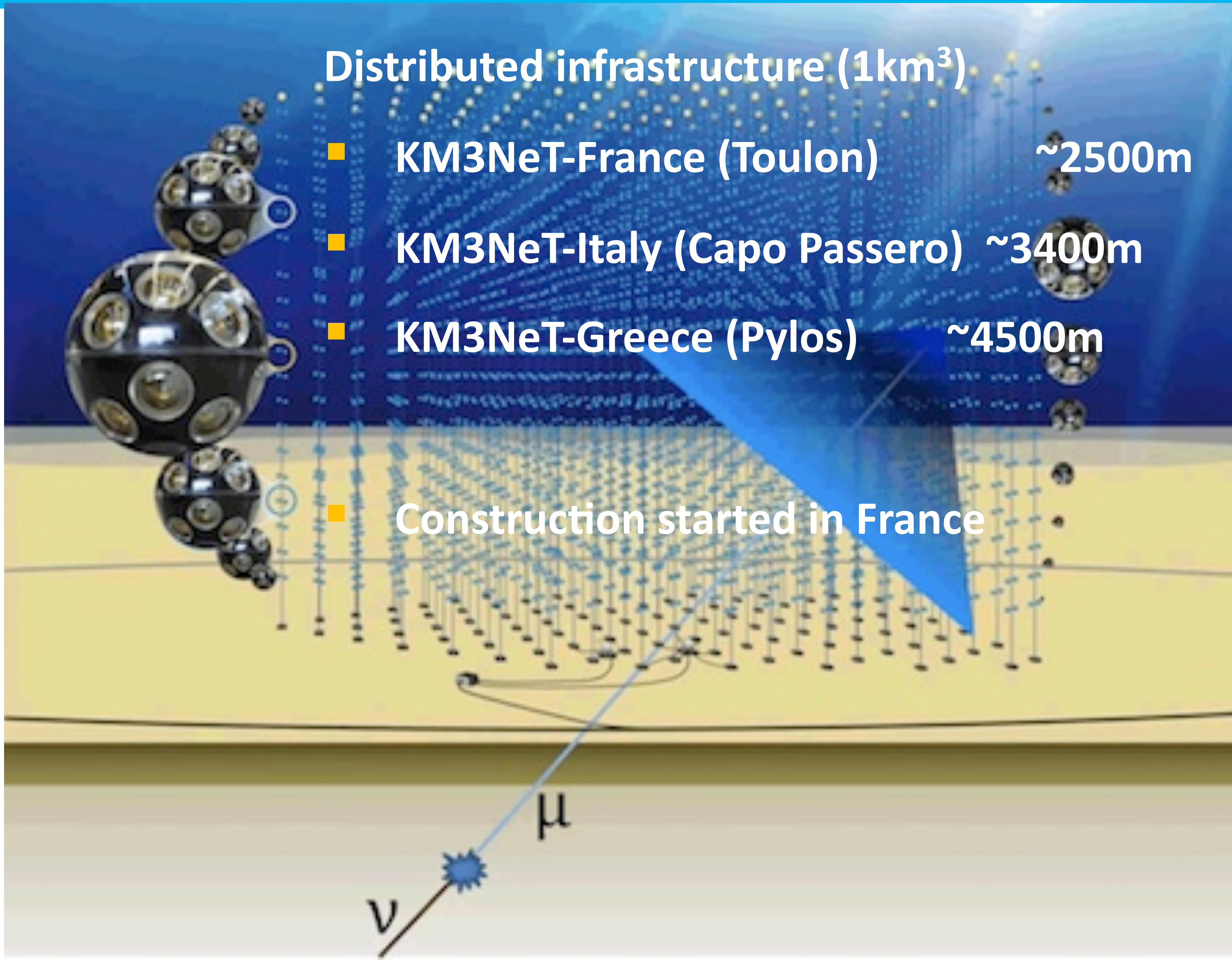
http://amon.gravity.psu.edu

Smith et al., Astropart. Phys., 45 (2013)

Future Projects



KM3NeT

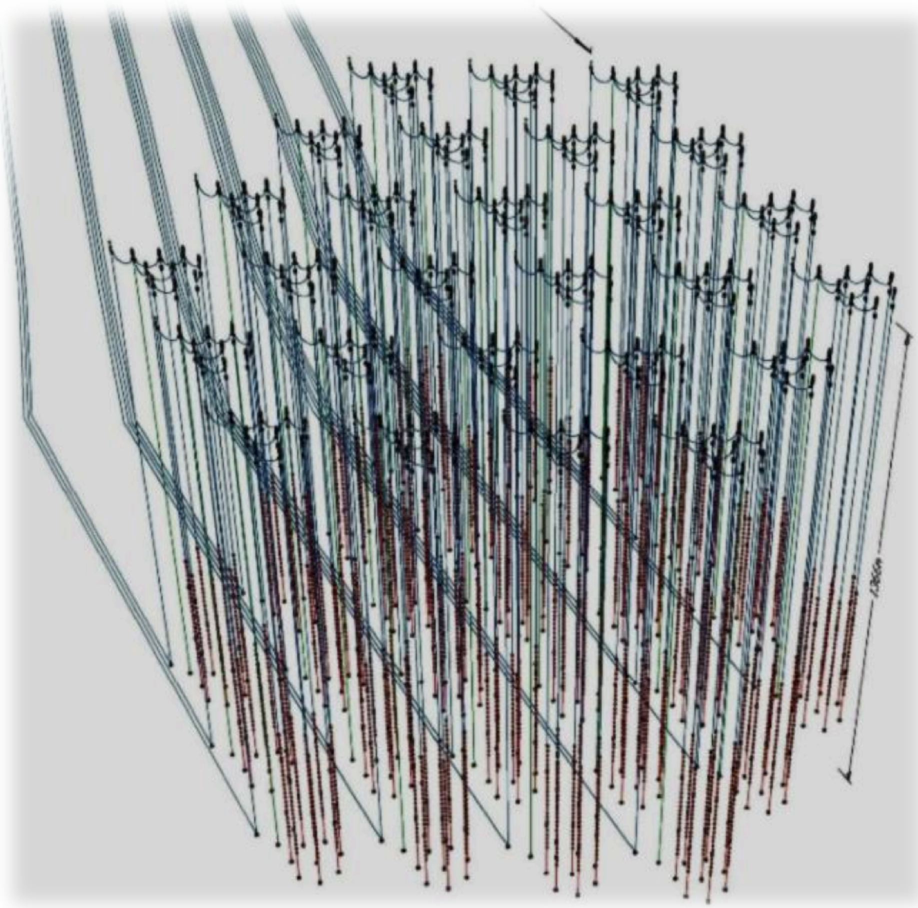


Distributed infrastructure (1km³)

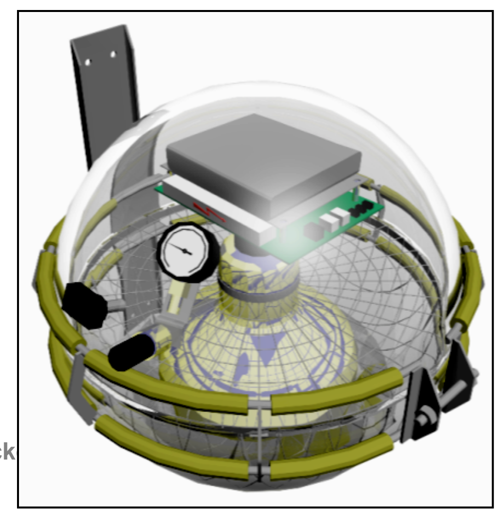
- KM3NeT-France (Toulon) ~2500m
- KM3NeT-Italy (Capo Passero) ~3400m
- KM3NeT-Greece (Pylos) ~4500m

- Construction started in France

Gigaton Volume Detector, Lake Baikal



- **Stage 1: volume ~0.5 km³**
- **Stage 2: volume ~ 1.5 km³**
  - Stage 1: ~0.5 km³ volume
  - Stage 2: ~1.5 km³ volume
  - 27 clusters with 8 strings each
  - Height 700 m (depth 600 m– 1300 m)
  - 48 OMs per string



PMT

Hamamatsu

R7081-HQE

∅ = 10”

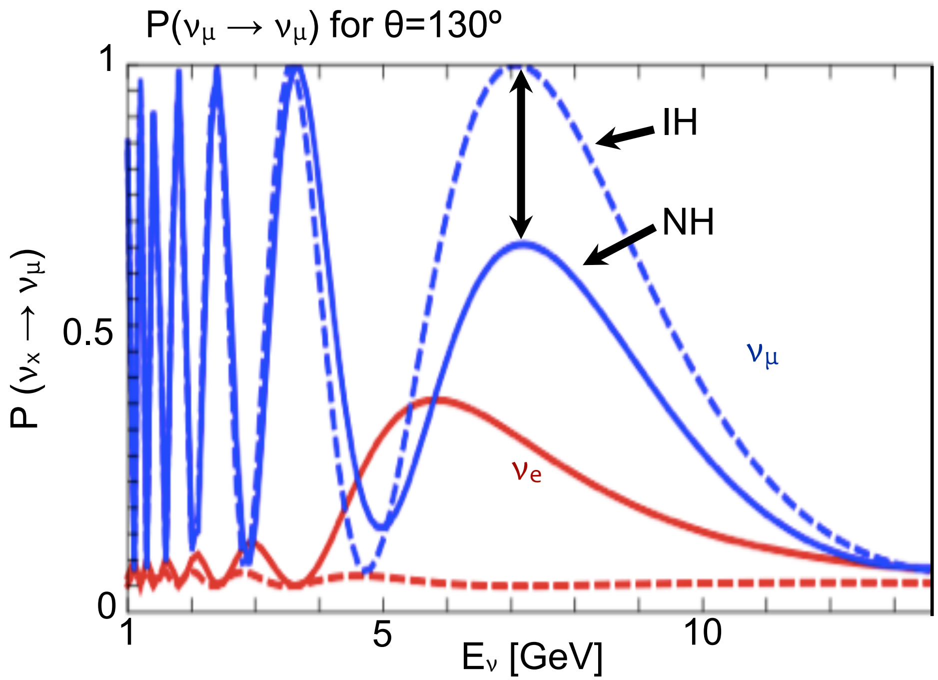
QE ~ 35%

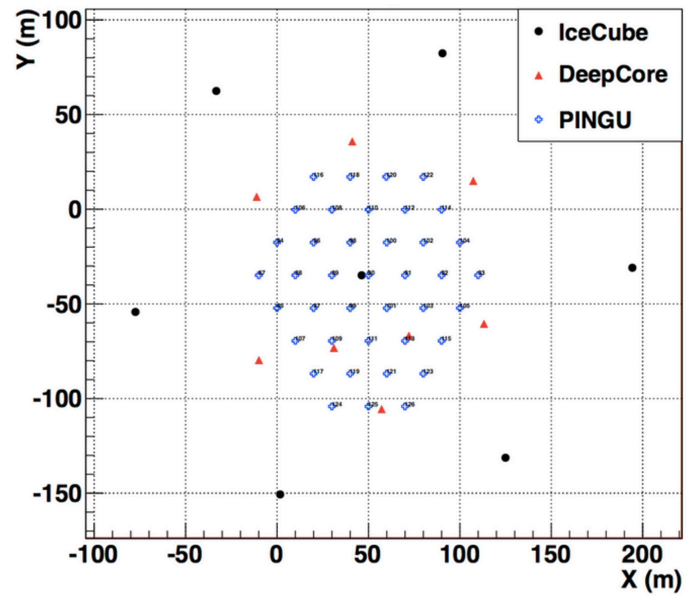
South Pole infrastructure

Device	Volume	Threshold	Primary Goal
> PINGU	few Mton	2-3 GeV	ν mass hierarchy
> DecaCube*	7-12 km³	~10 TeV	ν astronomy, GZK ν
> Surface veto	~120 km²		veto for IceCube, CR physics
> ARA	~120 km²	~50 PeV	GZK neutrinos

* including IceCube (1 km³ with 100 GeV threshold)

PINGU: determine ν mass hierarchy

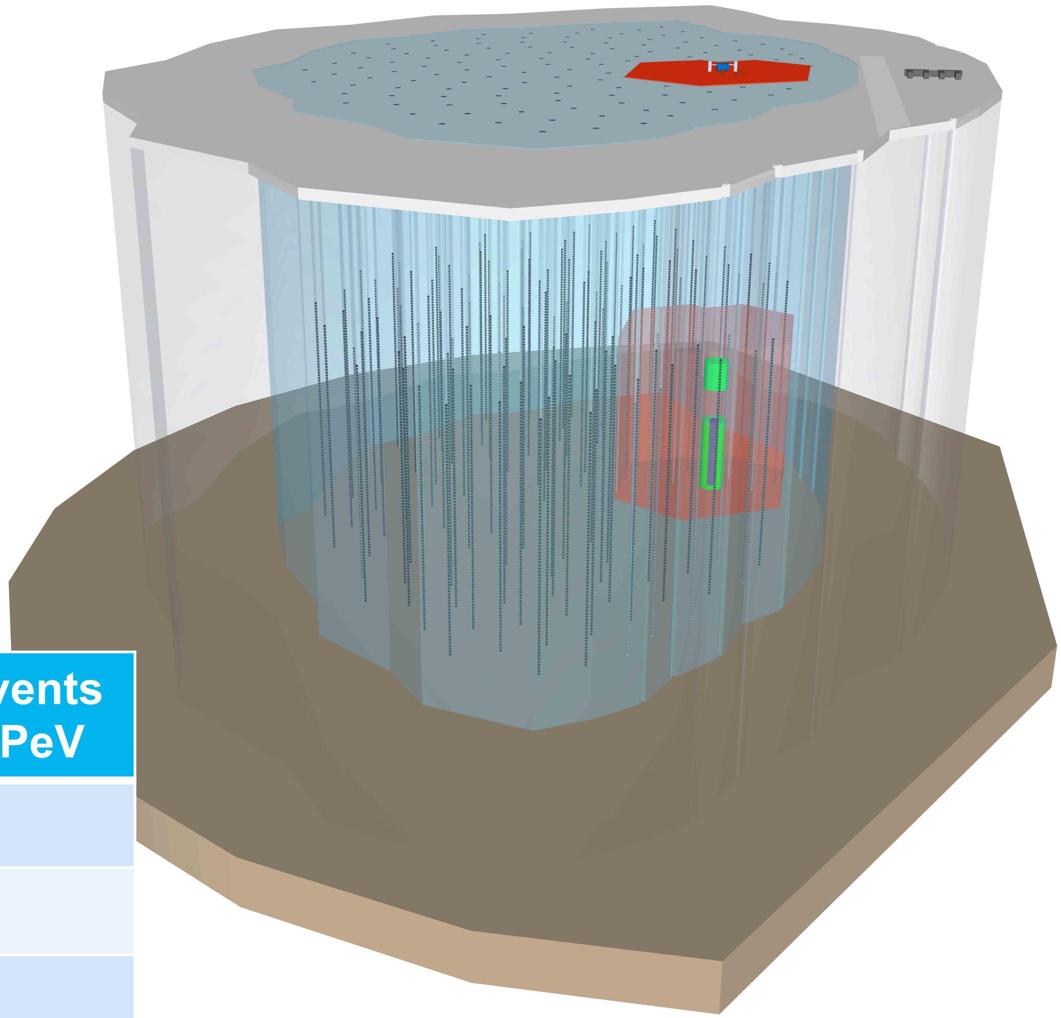




> ~40 additional strings

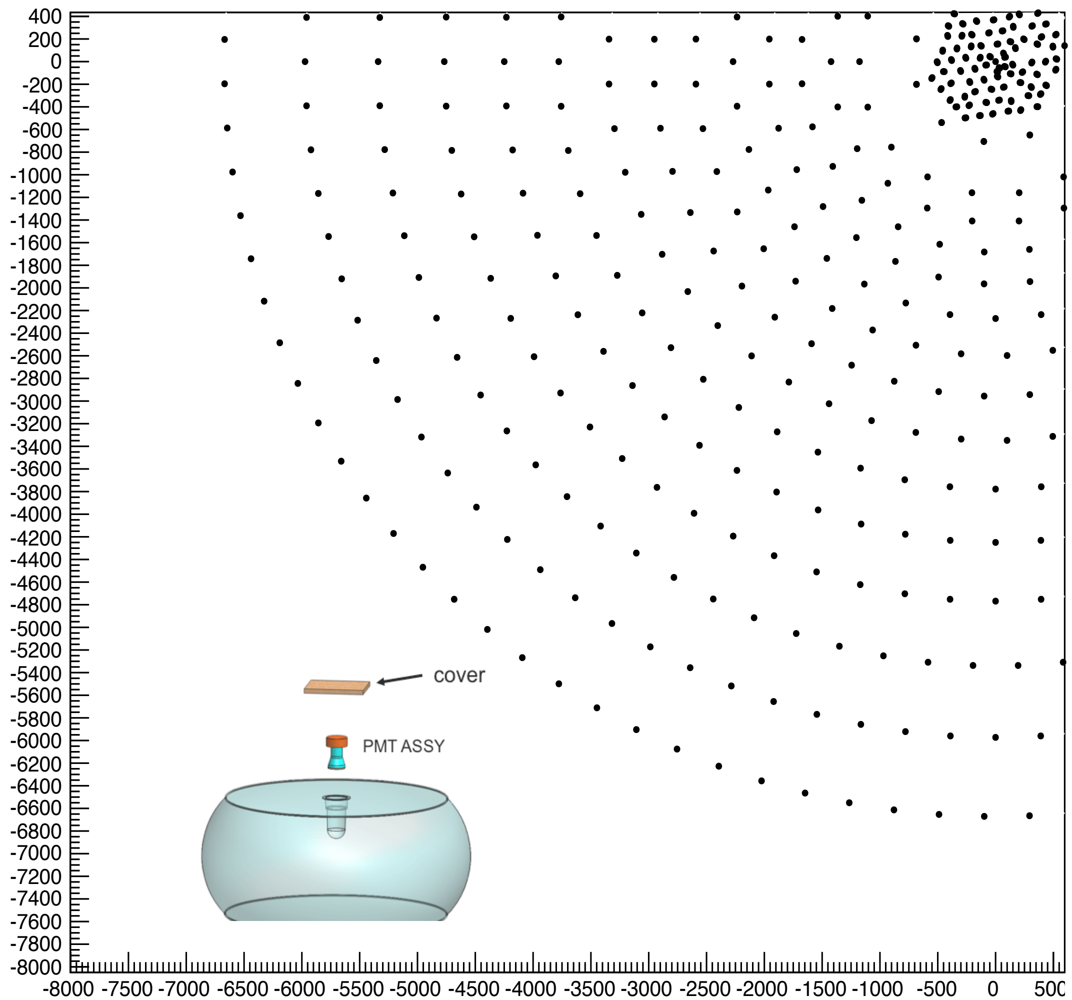
DecaCube Version with 240 m spacing

- 100 strings
- ~ 7 km³ volume
- Muons: 3 times IC
- Cascades: 7 times IC
- Threshold ~ 10 TeV



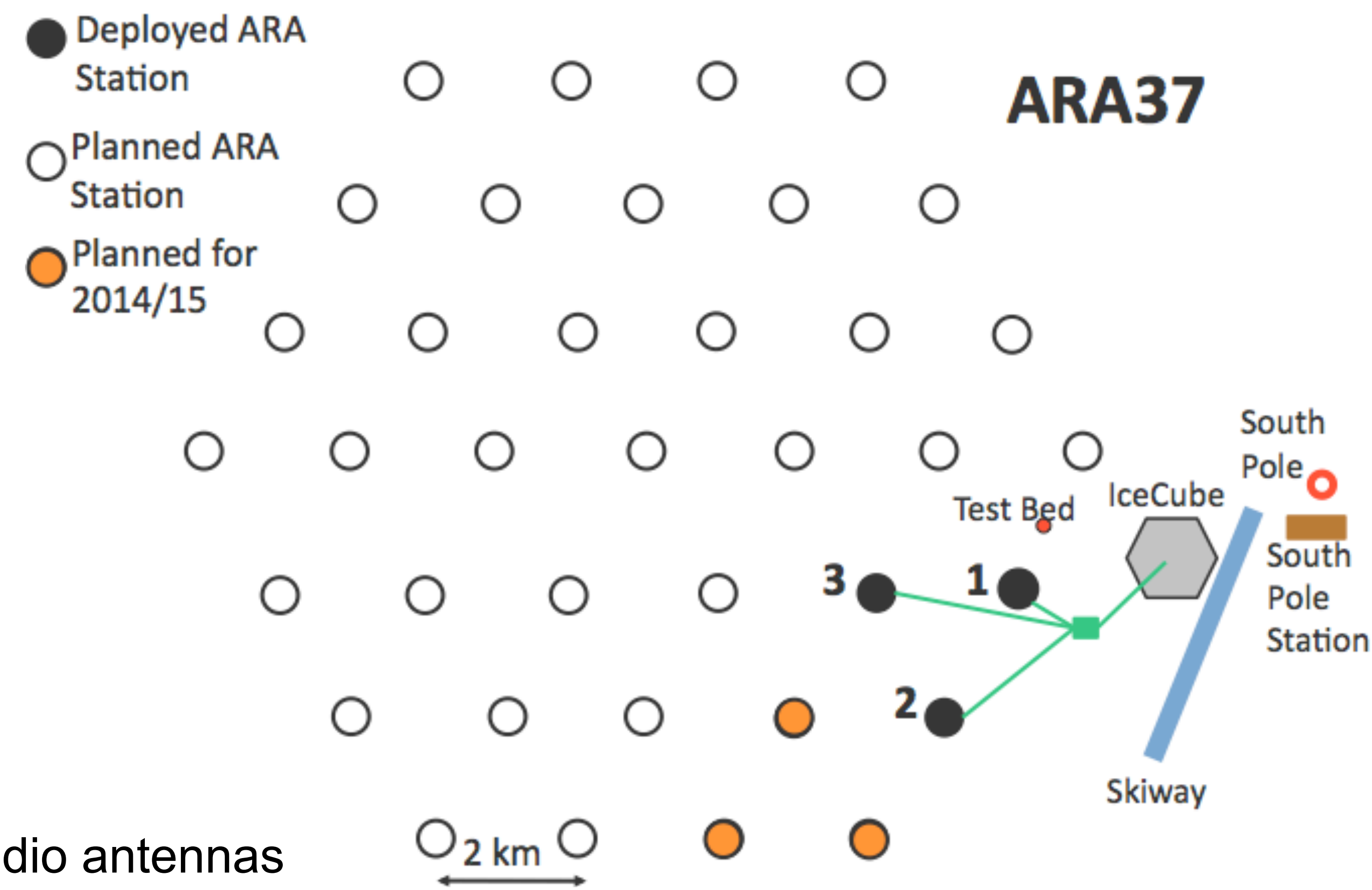
Fiducial region	Volume Gton	#events >60TeV	#events > 1PeV
HESE	0.4	8	1
IC+1ring	1.6	32	4
IC+3rings	4	**80**	**10**

A surface veto



- 943 stations on surface
- Radius 6.7 km
- Efficient down to 72°
- Efficiency > 99.99% for > 4000 PE in IceCube

ARA Askaryan Radio Array



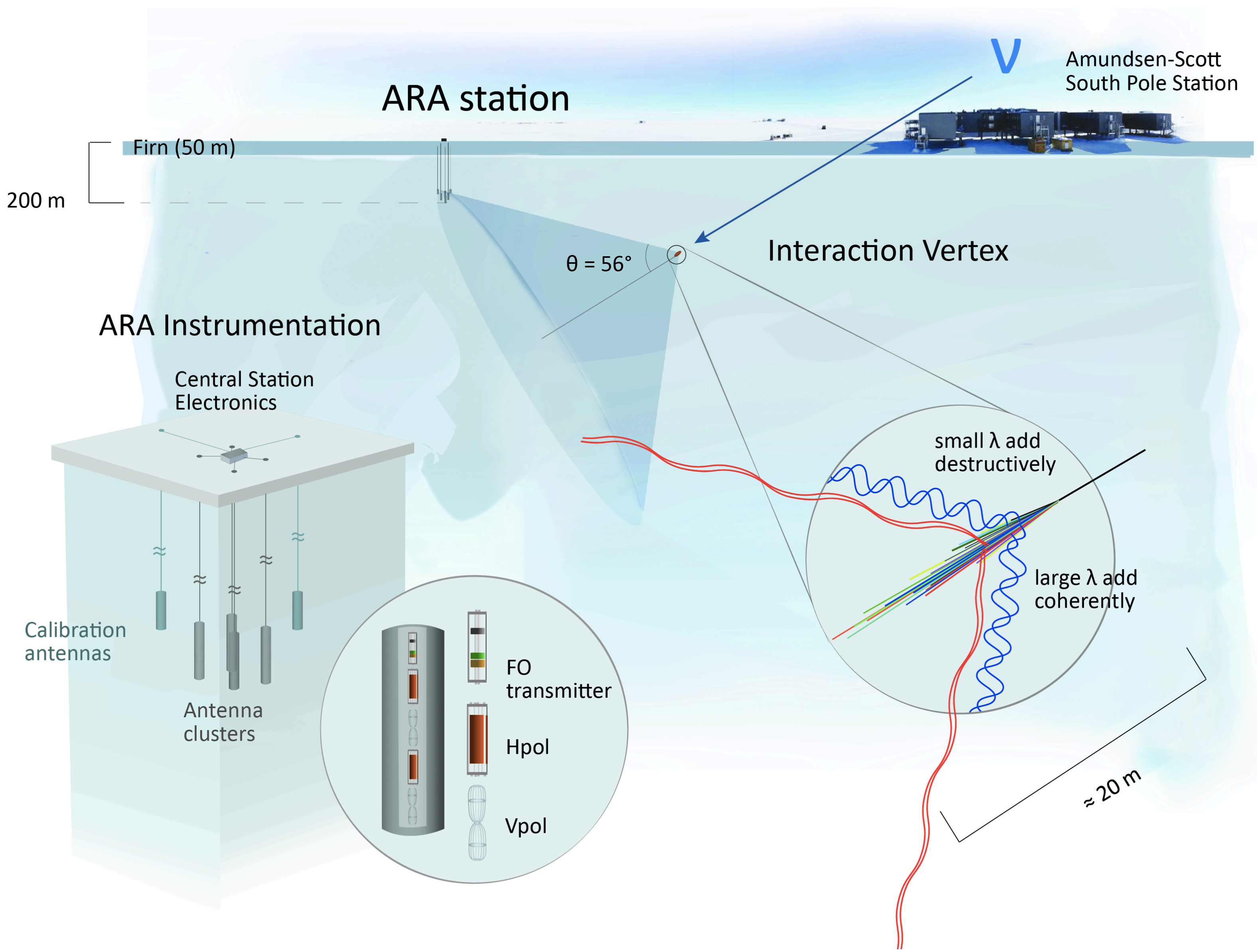
- Shallow radio antennas
- ~ 120 km²
- Threshold ~ 50 PeV

New Detection Techniques

- Radio
- Acoustic
- Air showers

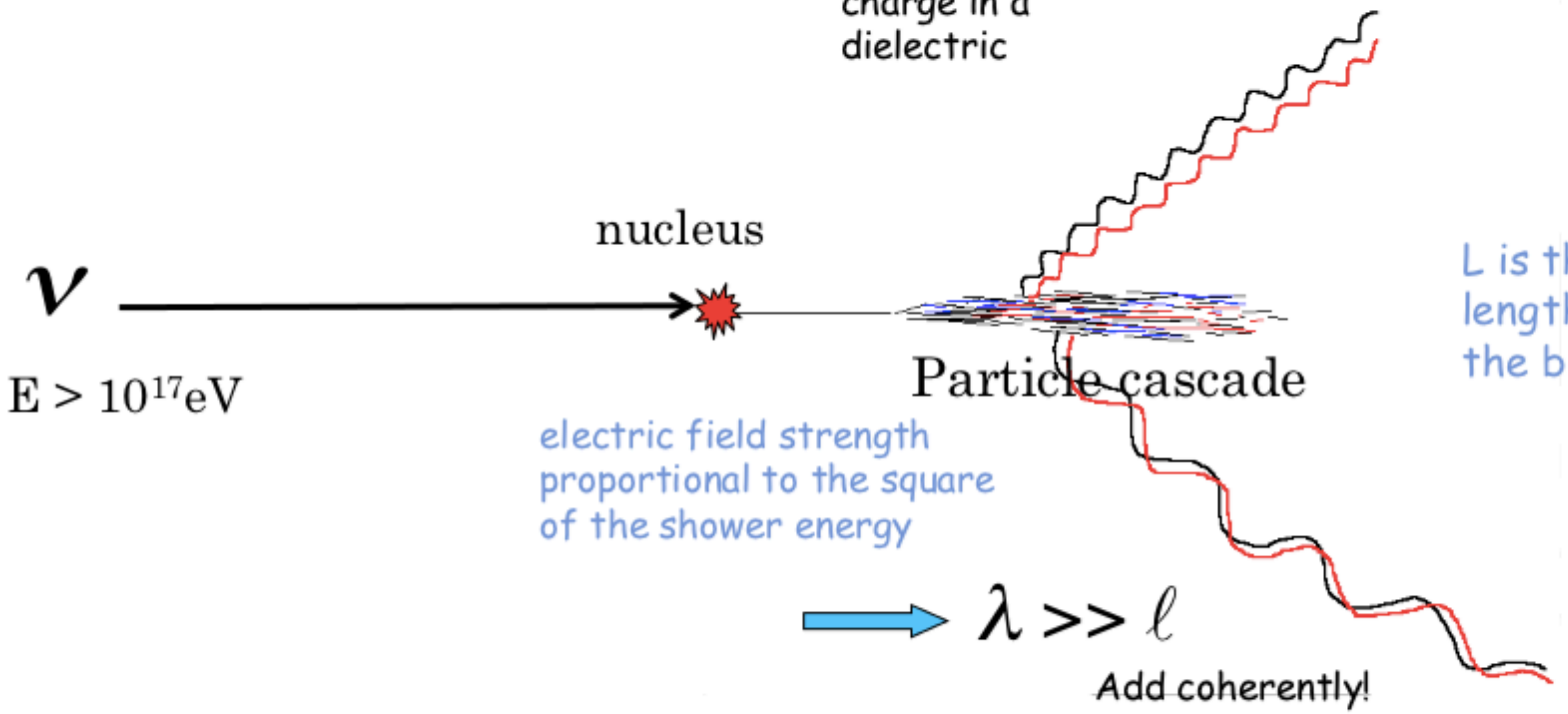
ARA

Detection of ultrahigh-energy neutrinos in ARA



Askaryan effect

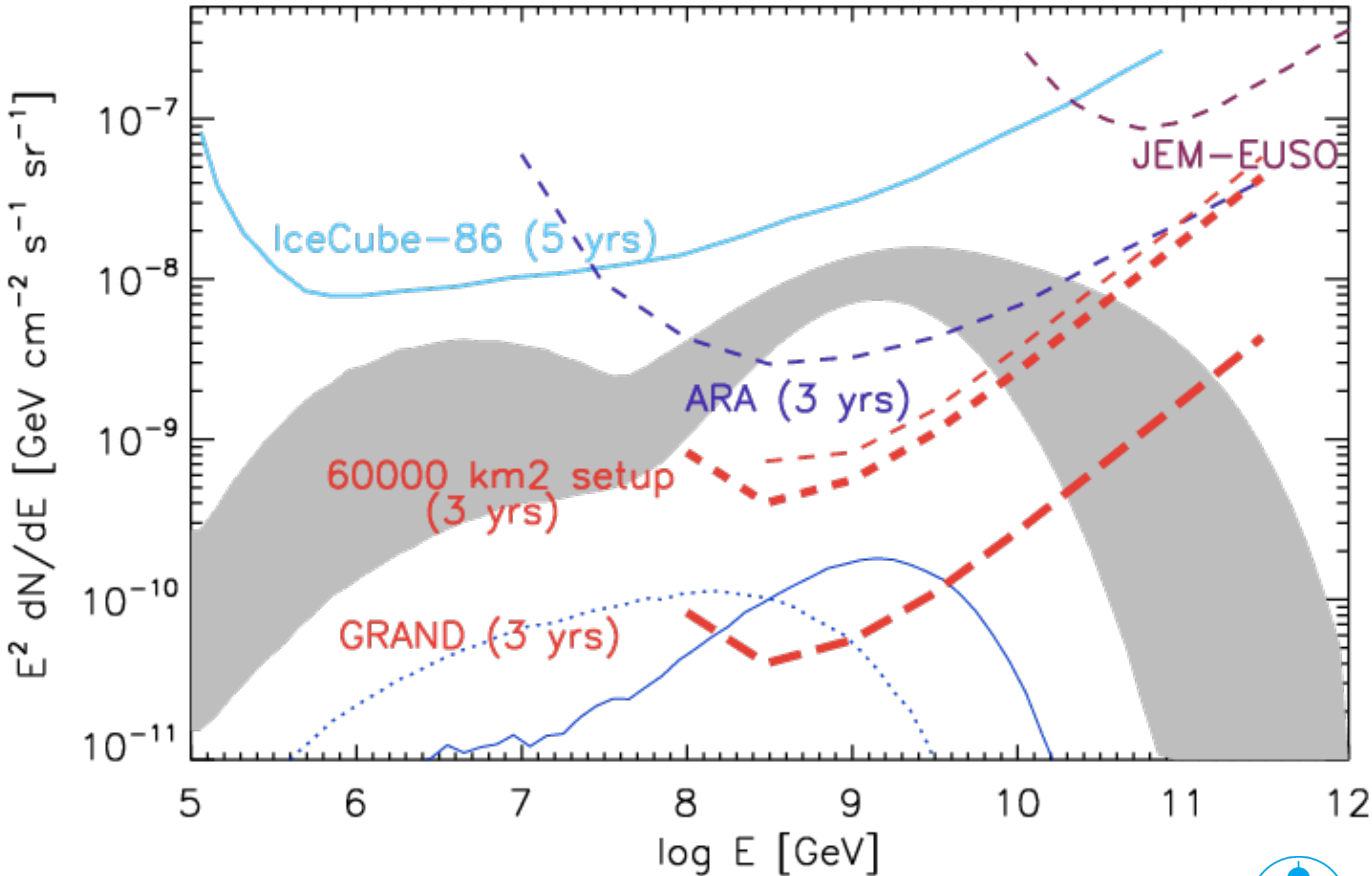
charge asymmetry in particle shower development results in a 20% excess of electrons over positrons in a particle shower → moves as a compact bunch, a few cm wide and ~1cm thick → Moving net charge in a dielectric → wavelengths shorter than the bunch length suffer from destructive interference



electric field strength proportional to the square of the shower energy

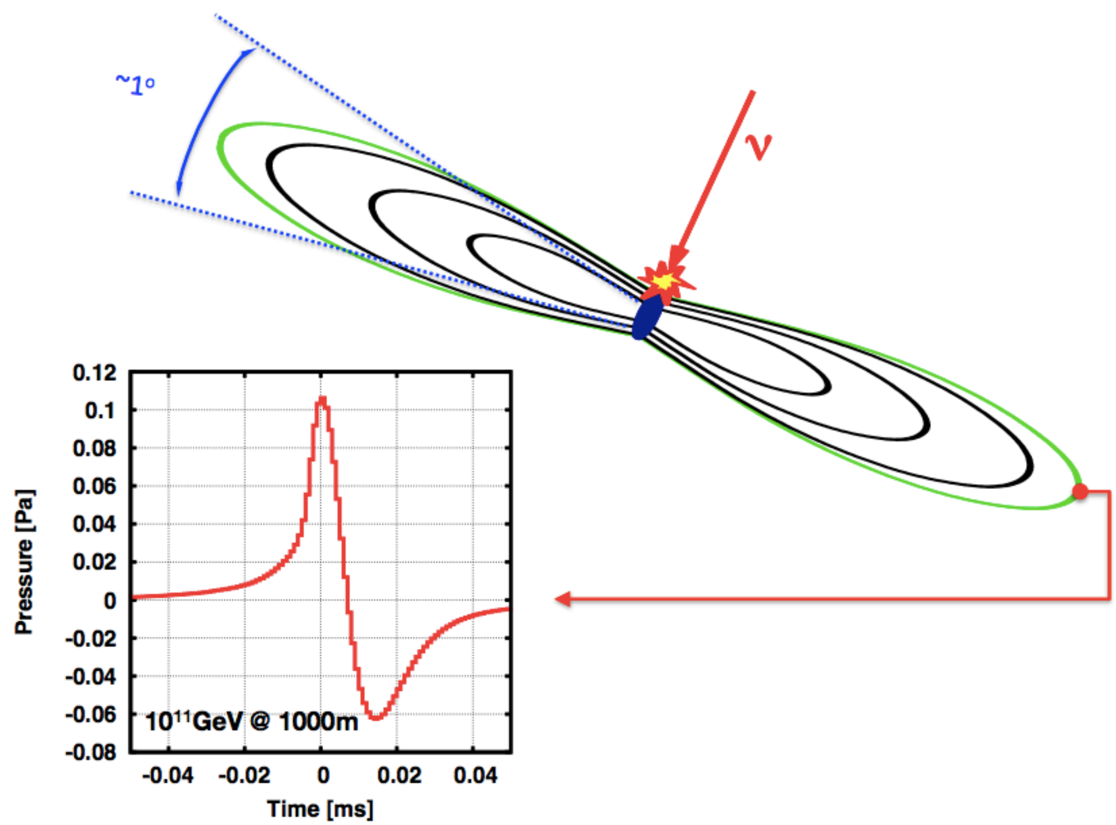
L is the length of the bunch

Radio is sensitive to high-energy neutrinos

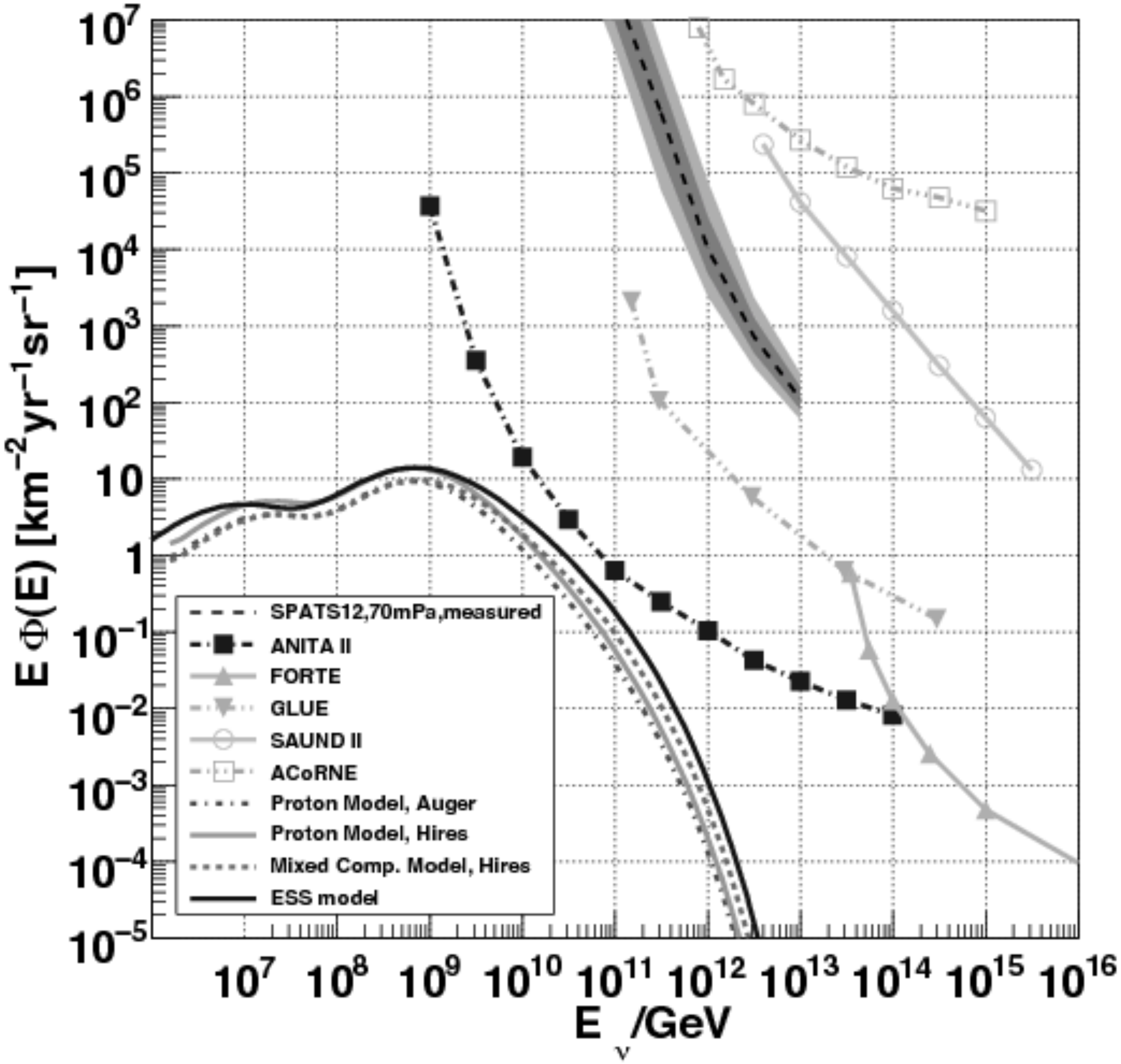


Acoustic neutrino detection

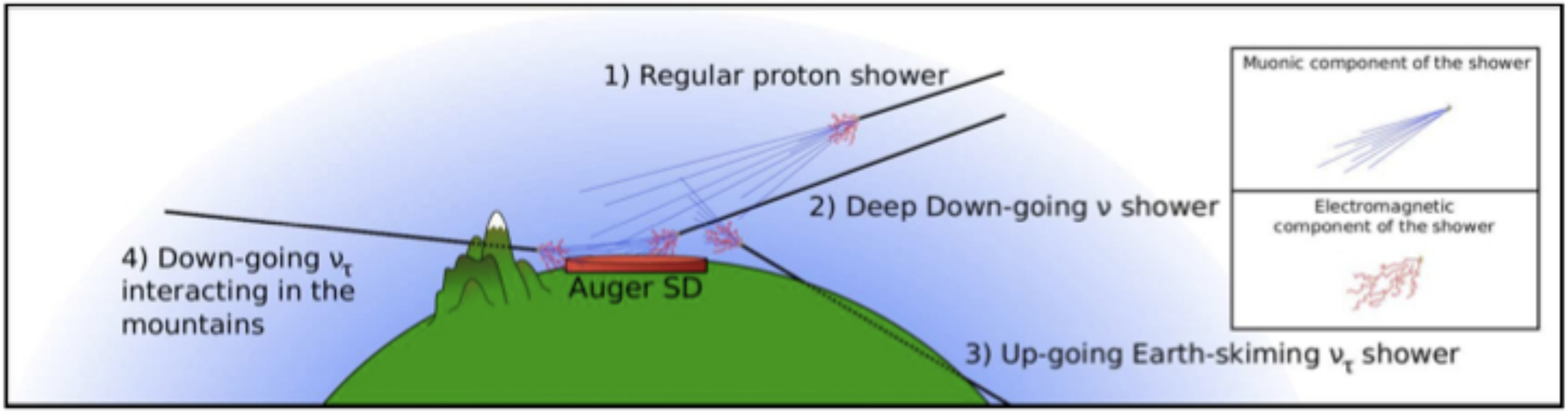
- The pressure signals produced by the particle cascades
- Local heating of the medium
- Temperature change induces expansion → pressure pulse of bipolar shape

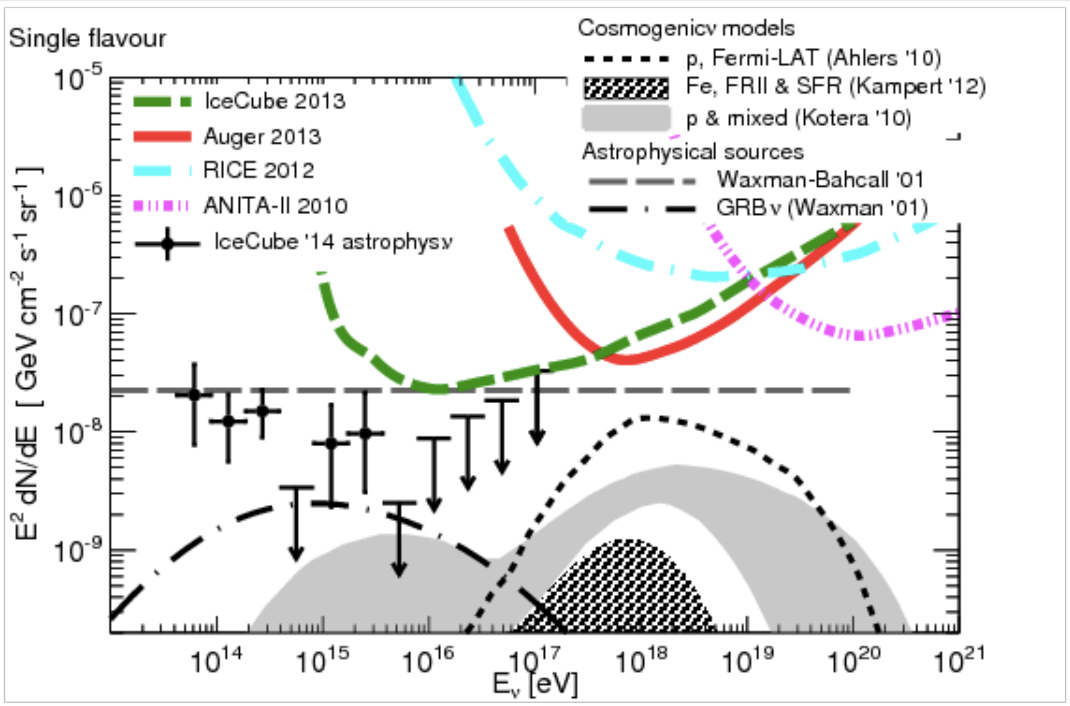


Acoustic detection sensitivity



Air showers


1) Regular proton shower
2) Deep Down-going ν shower
3) Up-going Earth-skiming ν_τ shower
4) Down-going ν_τ interacting in the mountains
Auger SD
Muonic component of the shower
Electromagnetic component of the shower

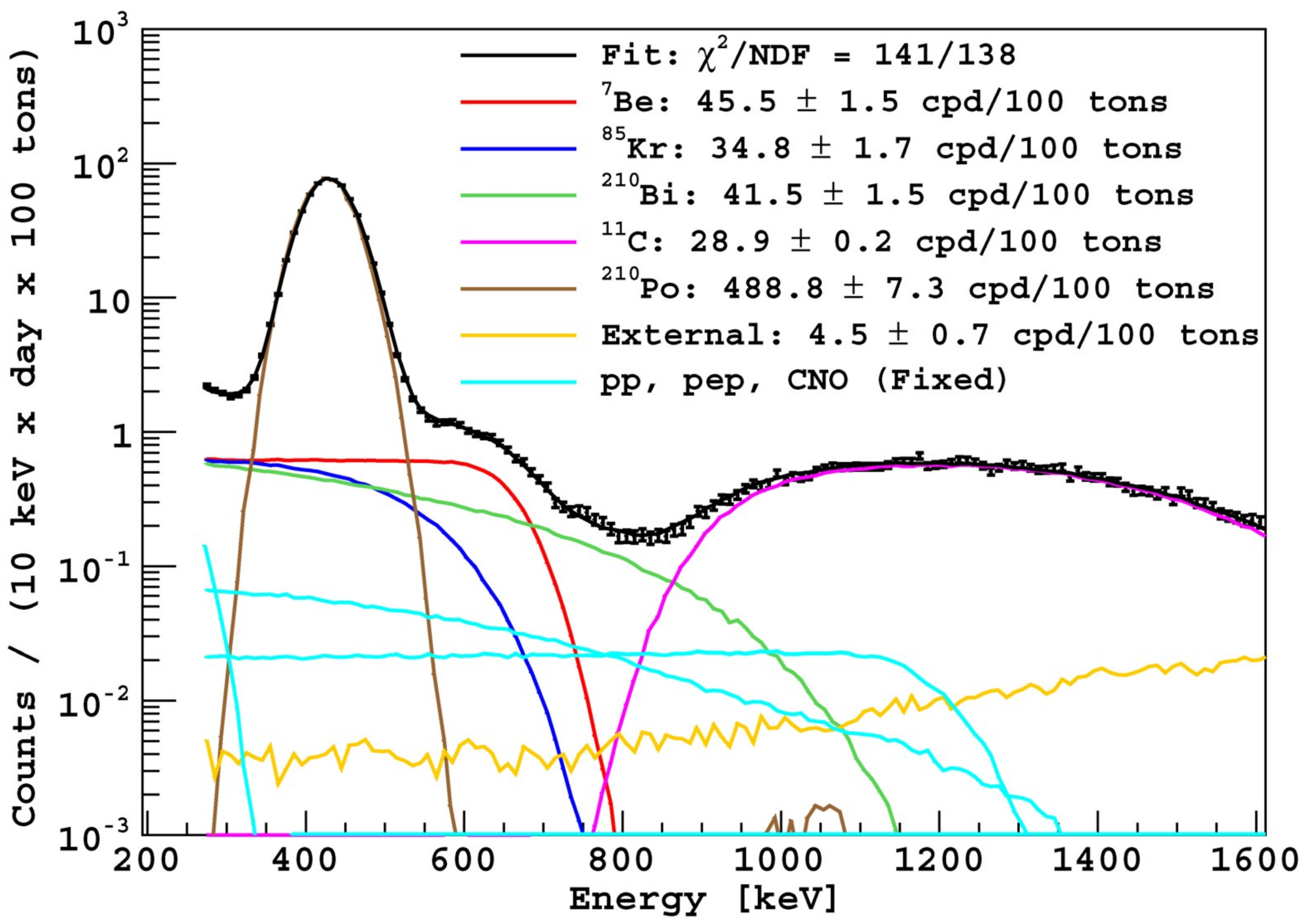

Single flavour
Cosmogenic ν models
p, Fermi-LAT (Ahlers '10)
Fe, FRII & SFR (Kampert '12)
p & mixed (Kotera '10)
Astrophysical sources
Waxman-Bahcall '01
GRB ν (Waxman '01)
IceCube 2013
Auger 2013
RICE 2012
ANITA-II 2010
IceCube '14 astrophys ν
E^2 dN/dE [GeV cm^{-2} s^{-1} sr^{-1}]
E_ν [eV]

Summary

- Pauli was right: Neutrinos exist!
- Two extraterrestrial neutrino sources found: Sun and SN1987A
- IceCube measured diffuse flux of astrophysical neutrinos
  - Sources still unknown
  - Multiwavelength analyses might help to identify sources
- New bigger better neutrino detectors planned

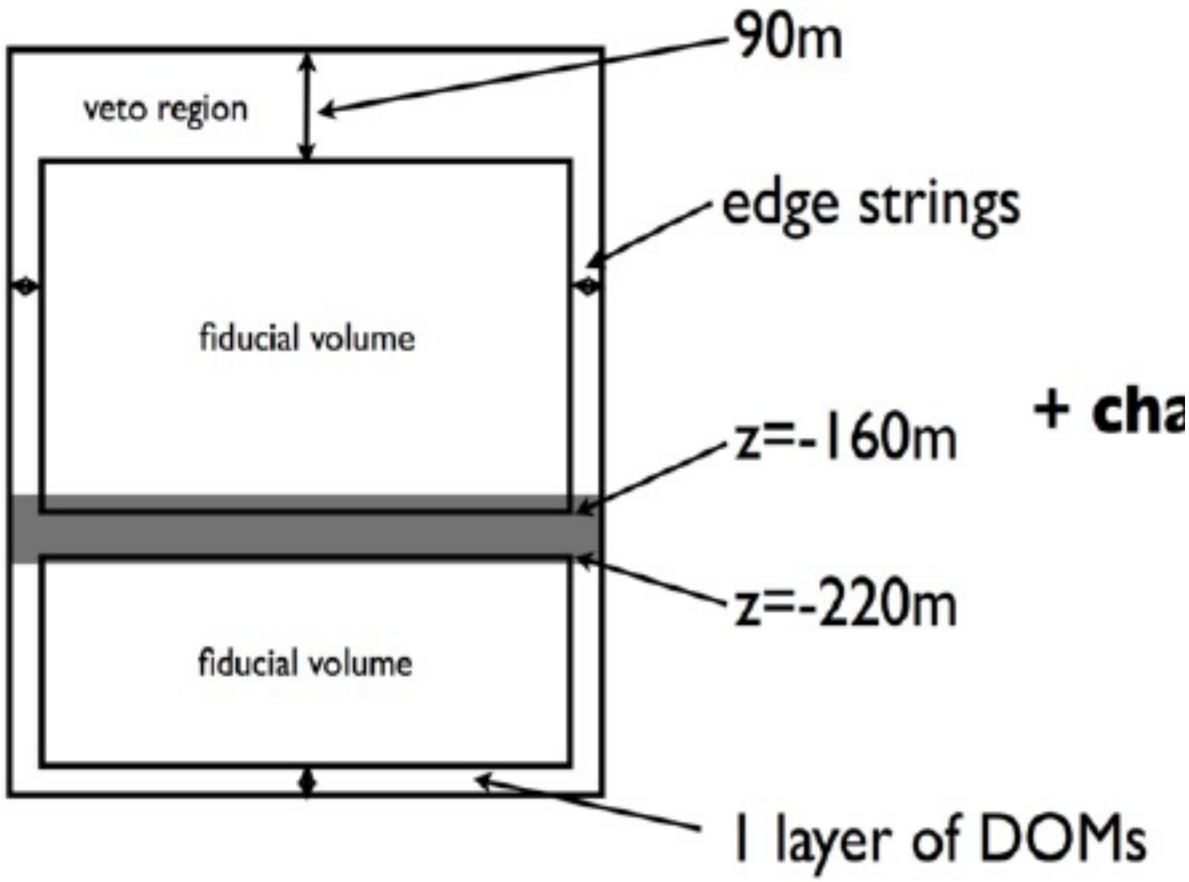
Back up

Solar Neutrinos with Borexino

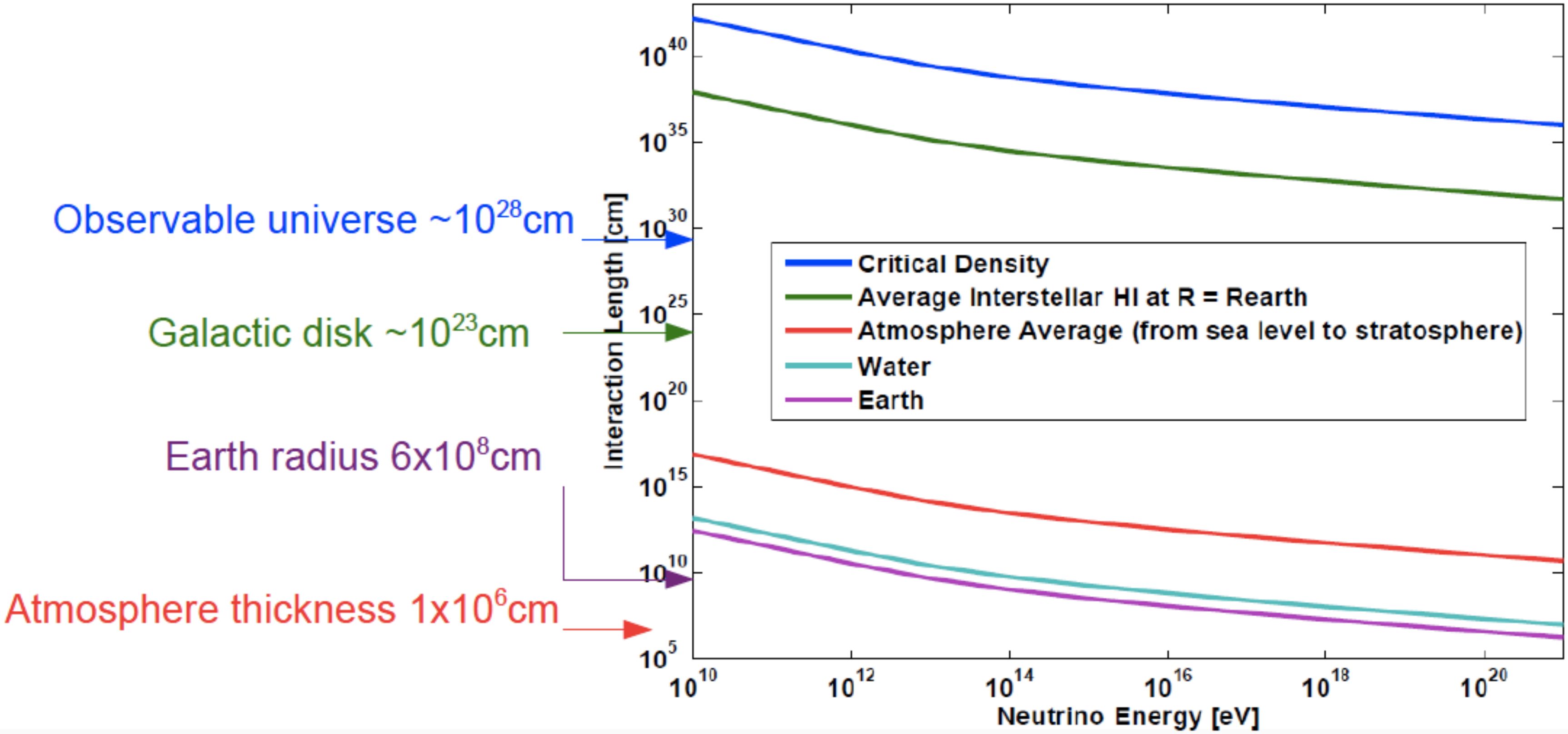


Borexino Collaboration, arXiv:1104.1816

IceCube Veto



Neutrino Interaction Length



Cross section from **Gandhi et al., Phys. Rev. D 58 (1998) 093009**