Neutrinoastrophysics with IceCube

Sebastian Böser
Colloquium | Grenoble | Sept. 8th 2015

PRISMA

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

A hundred year old puzzle...

1912 Victor Hess

- several balloon flights

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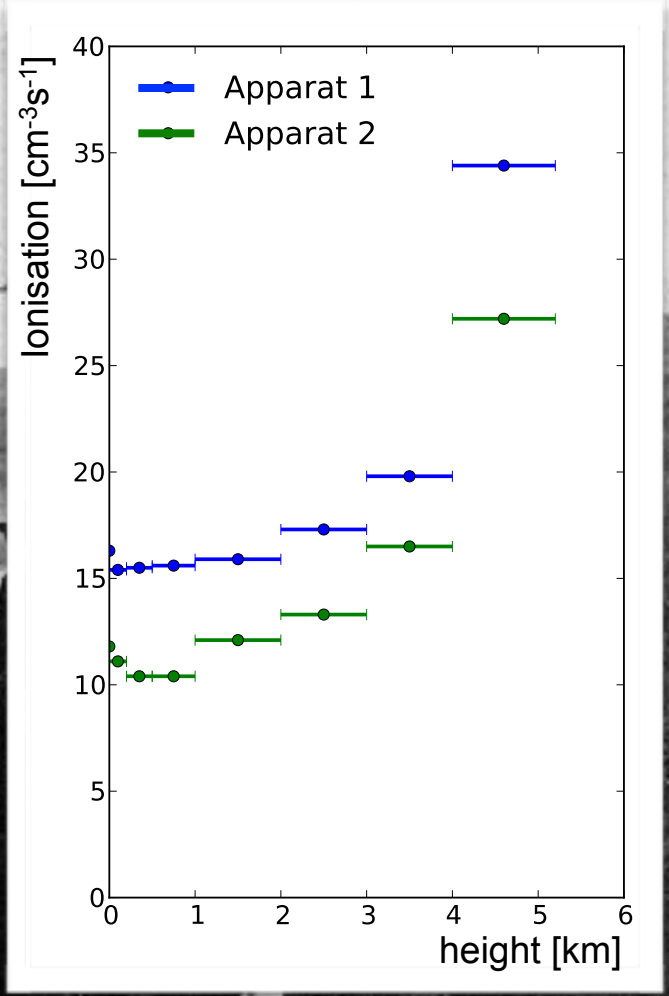
  - ionization increases with height!



A hundred year old puzzle…

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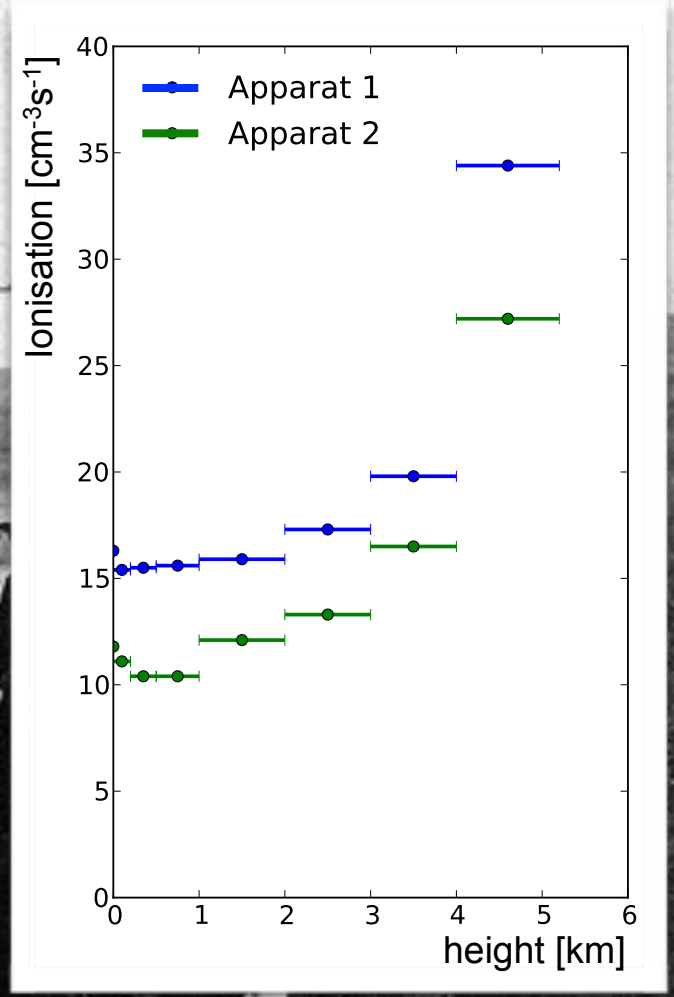


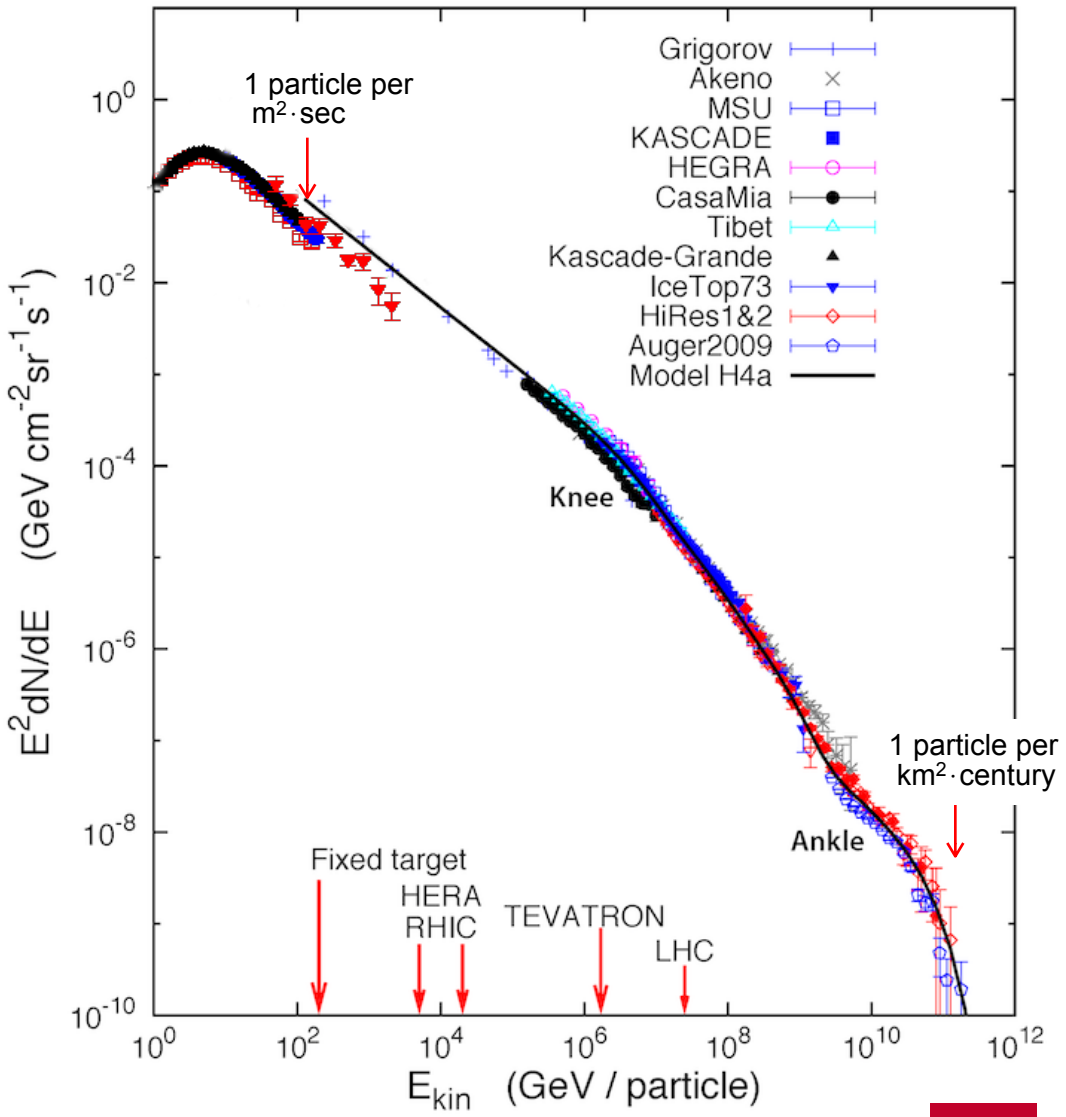
"The results are best explained … by the assumption that some radiation of high penetration power enters the atmosphere from above."

V.Hess, Phys. Z (1912)

Cosmic rays today

Cosmic ray spectrum

- mostly protons / hadrons
- power law spectrum F α $E^{-2.7}$



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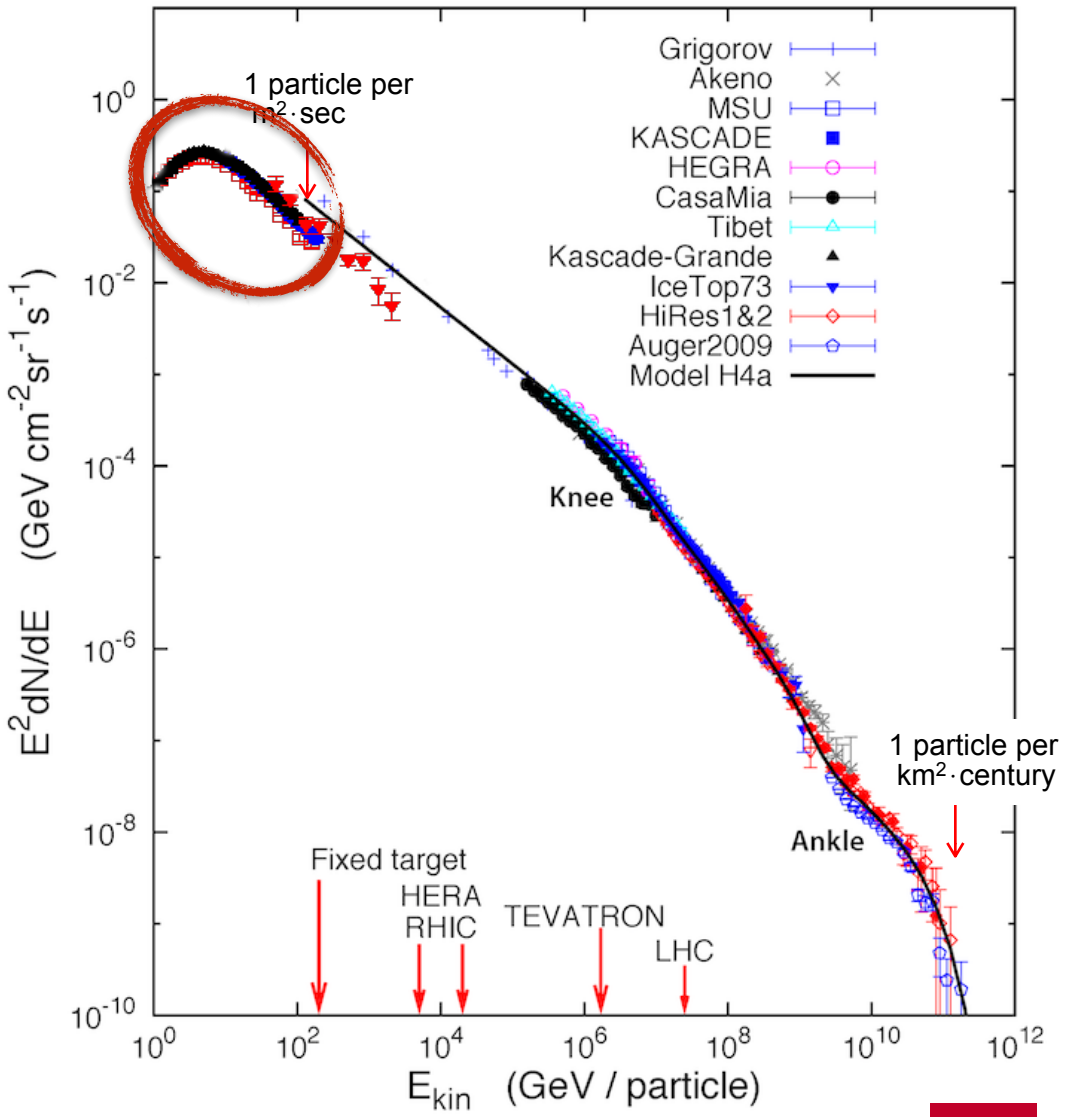
Normal energy (< GeV)

- the sun



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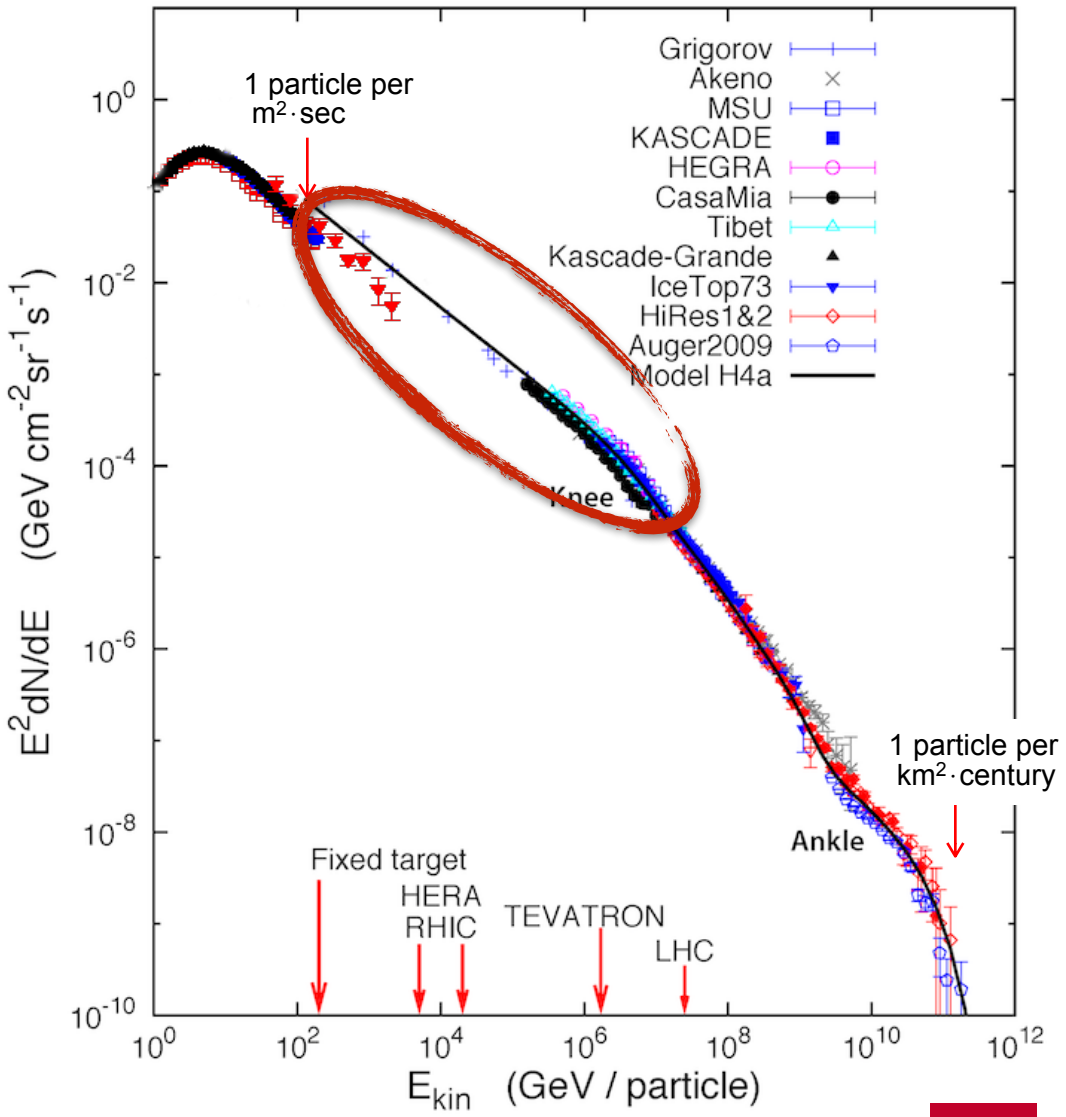
High energy (GeV-PeV): ?

- **plausible** scenario
  - supernova remnants



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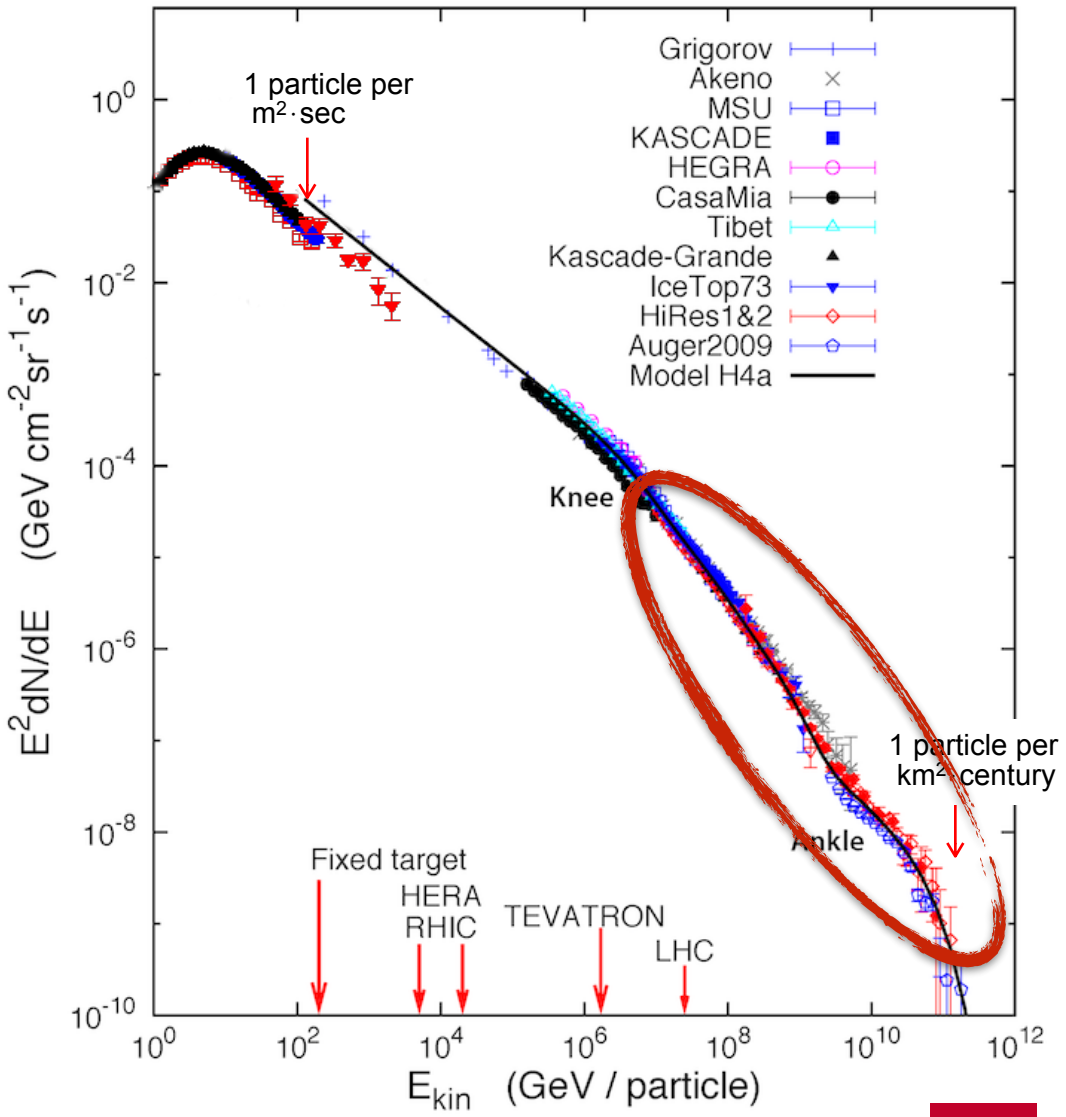
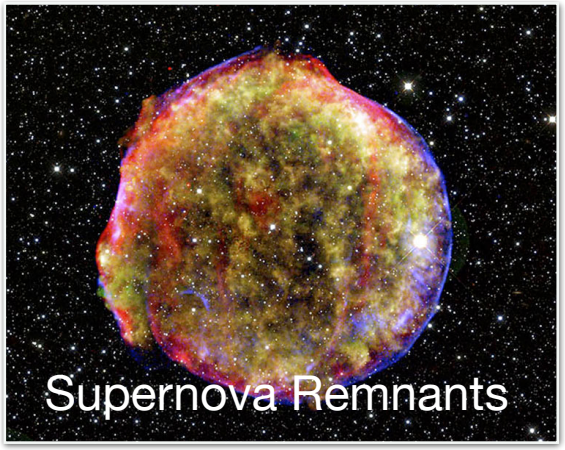
Ultra-high energy (> PeV): ???

- **possible** scenarios
  - Active Galactic Nuclei
  - Gamma-ray burst
  - ...



Neutrinos from the sky

Cosmic Neutrino Sources



Source power: up to 10^{45} Joule

Fermi Acceleration: Protons with energies up to 10^{19} eV

Particle interactions: in cosmic ray sources

$$p + p \to \pi, K, \ldots$$

$$\hookrightarrow \pi \to \mu + \nu_\mu$$

$$\hookrightarrow \mu \to e + \nu_e + \nu_\mu$$

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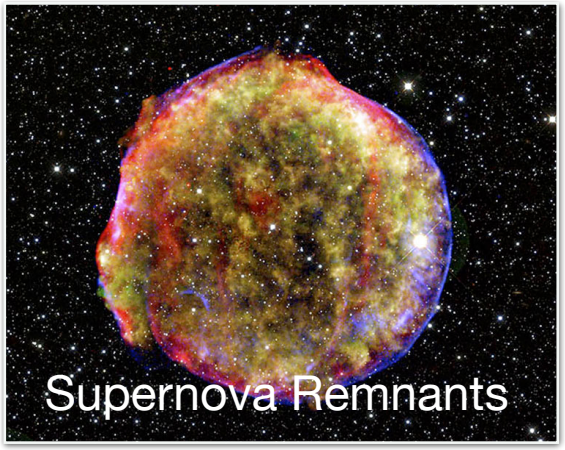

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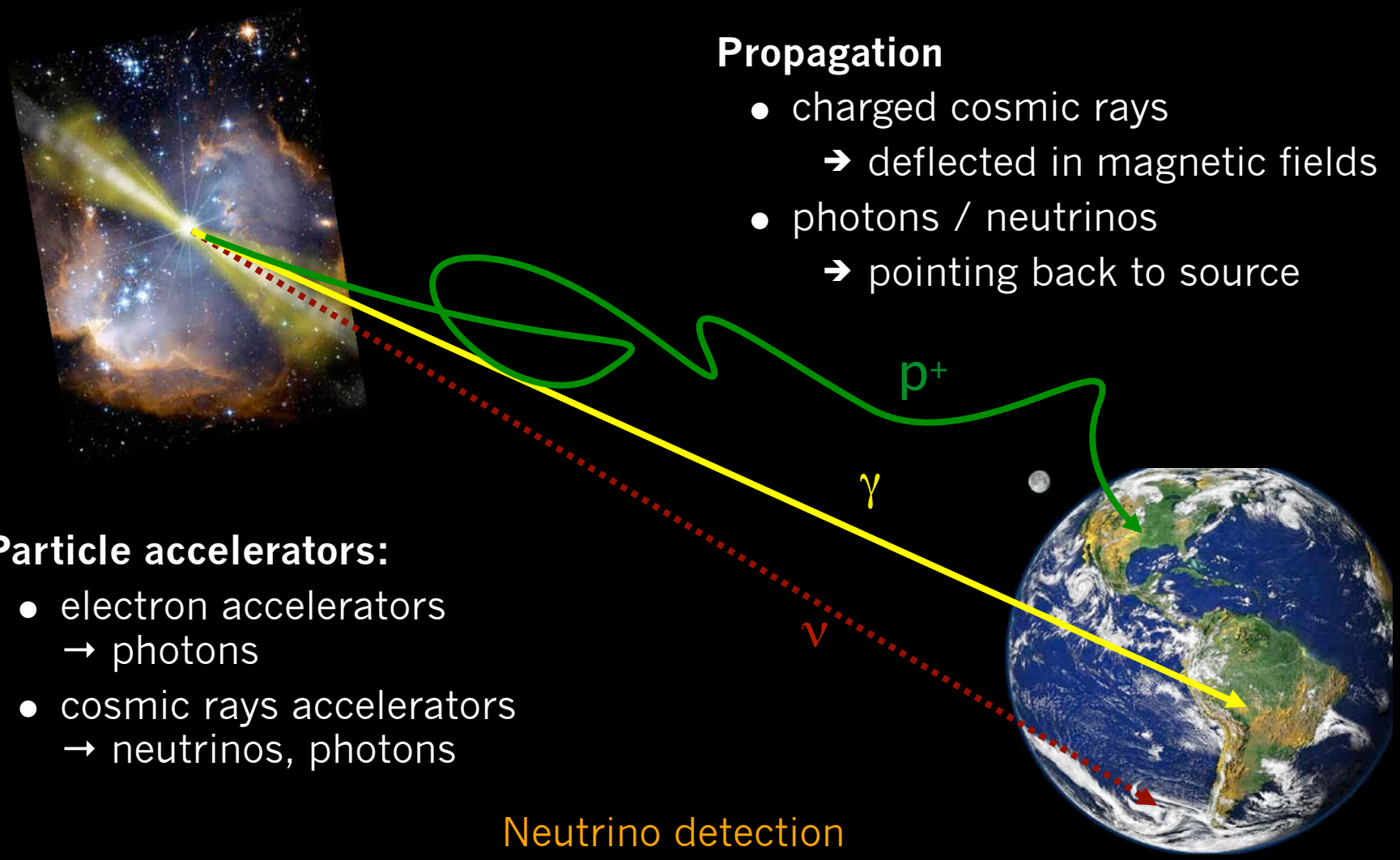
The cosmic ray – gamma – neutrino link



Propagation

- charged cosmic rays
  ➔ deflected in magnetic fields
- photons / neutrinos
  ➔ pointing back to source

Particle accelerators:

- electron accelerators
  → photons
- cosmic rays accelerators
  → neutrinos, photons

Neutrino detection

➔ "smoking gun" for CR acceleration

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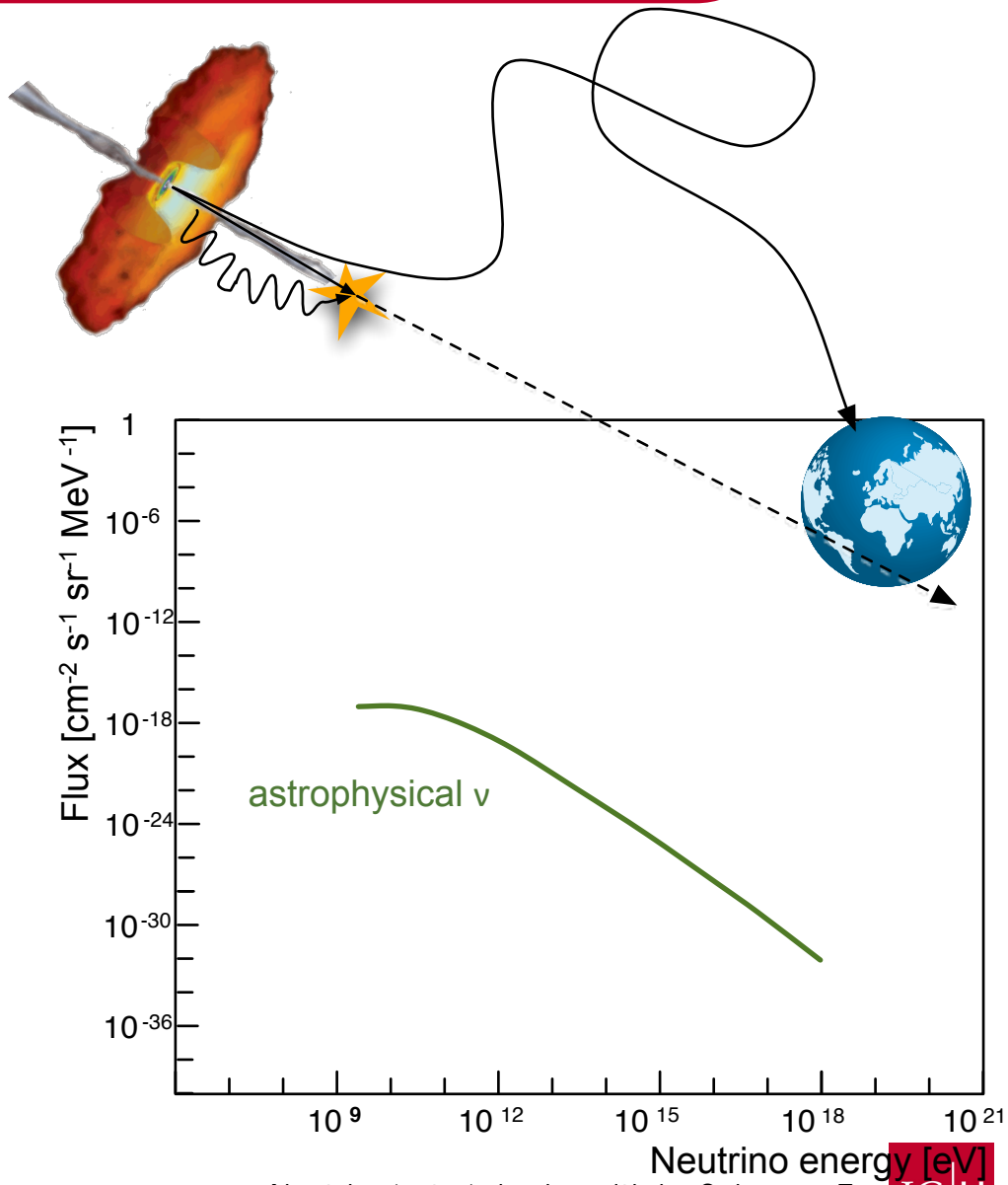
Neutrino sources

Astrophysical neutrinos

- p+γ/p interaction in the source
  - e.g. synchrotron radiation
  - generic spectrum ~ E^{-2}



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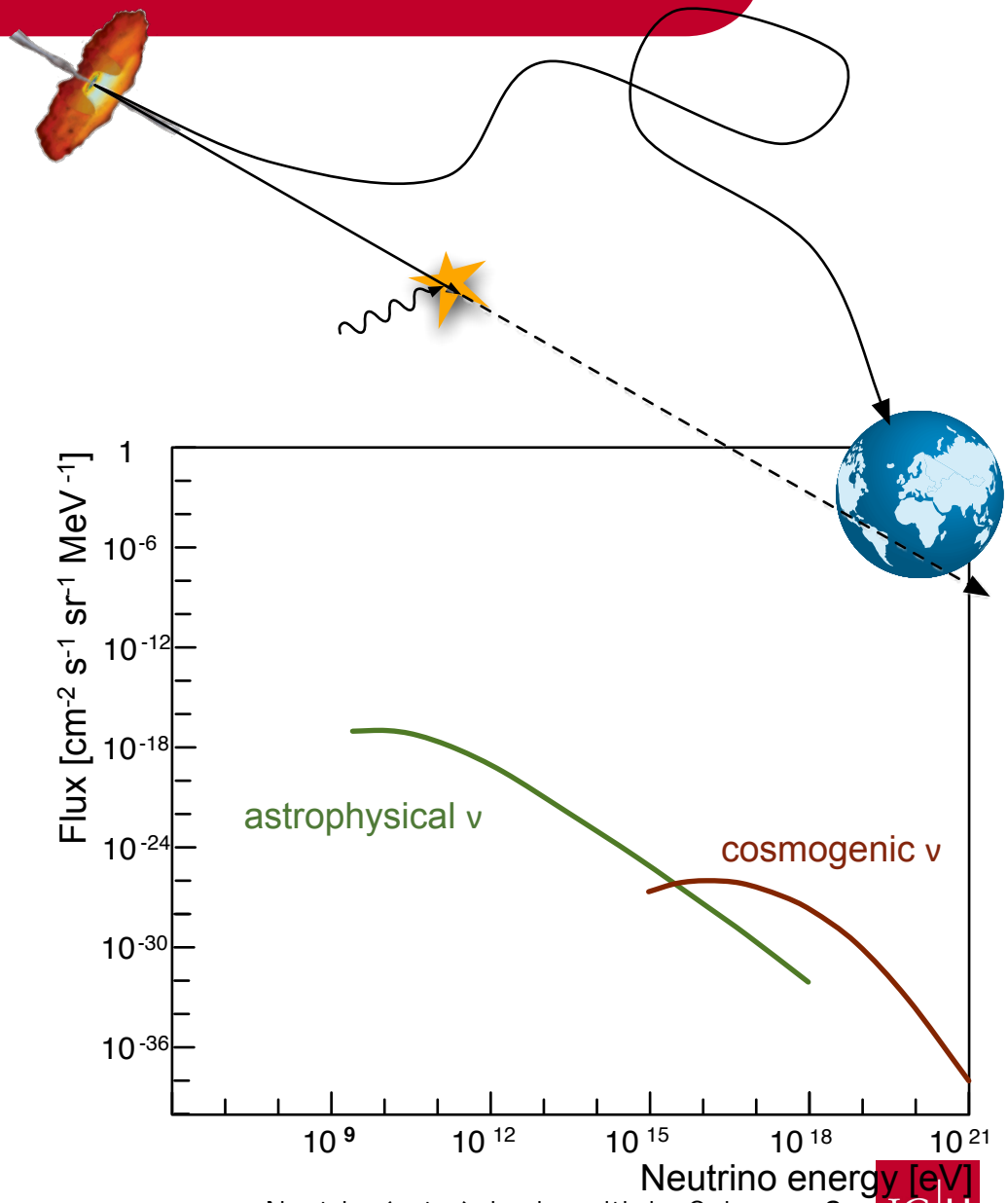
Cosmogenic neutrinos

- p+γ interaction with the CMB
  - *guaranteed* neutrino flux



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  - generic spectrum ~ E^{-2}

Cosmogenic neutrinos

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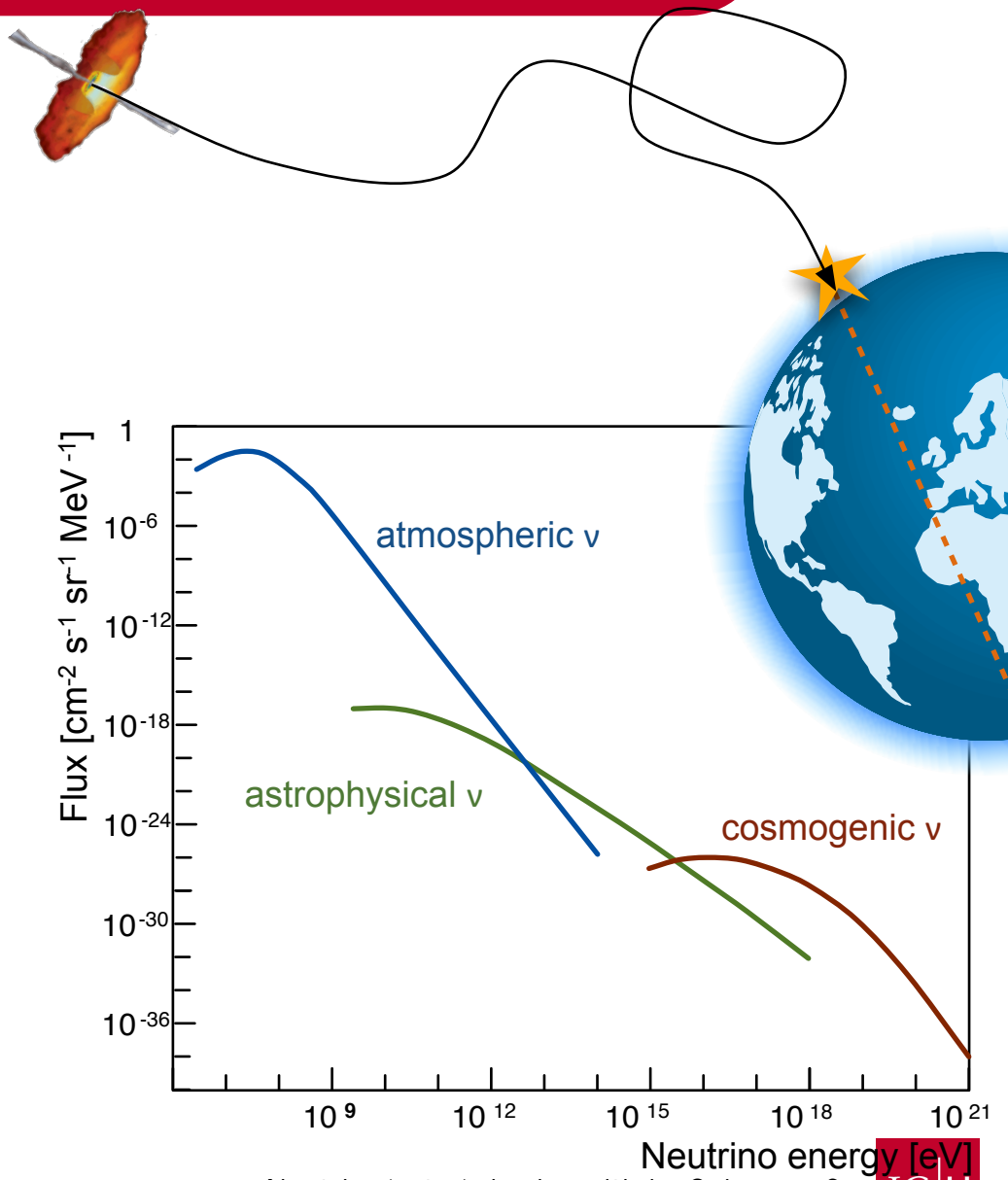
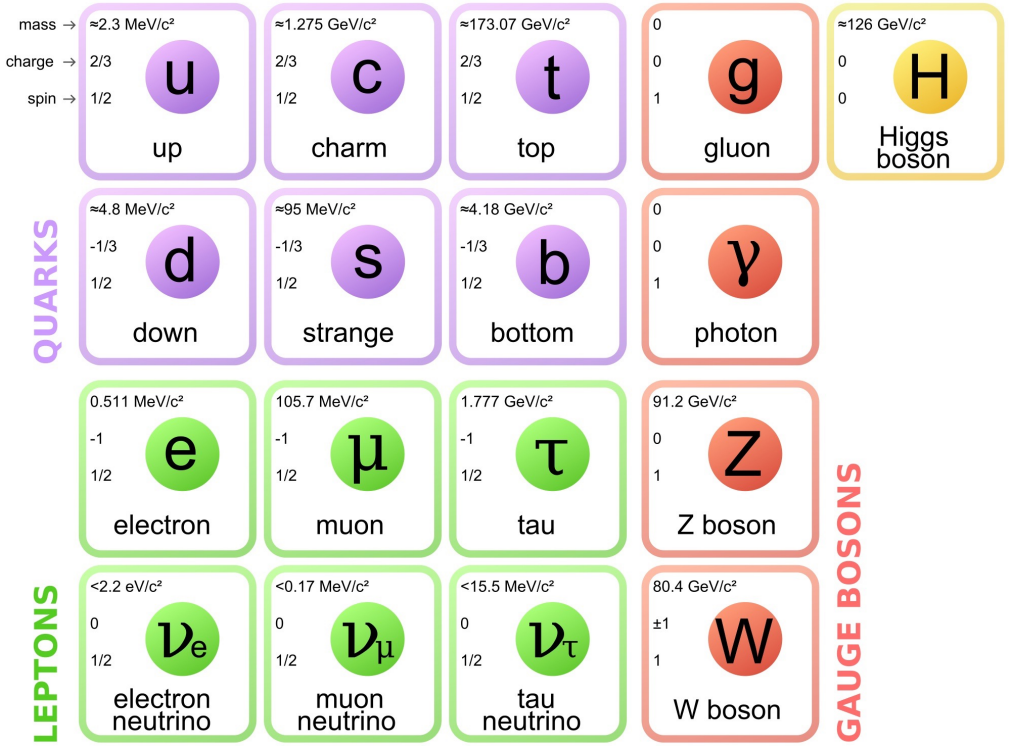
Atmospheric neutrinos

- p+p interaction in the atmosphere
  - but π/K interact
  - steeper spectrum ~ $E^{-3.7}$
- also *charmed mesons*
  - prompt flux ~ E^{-2}



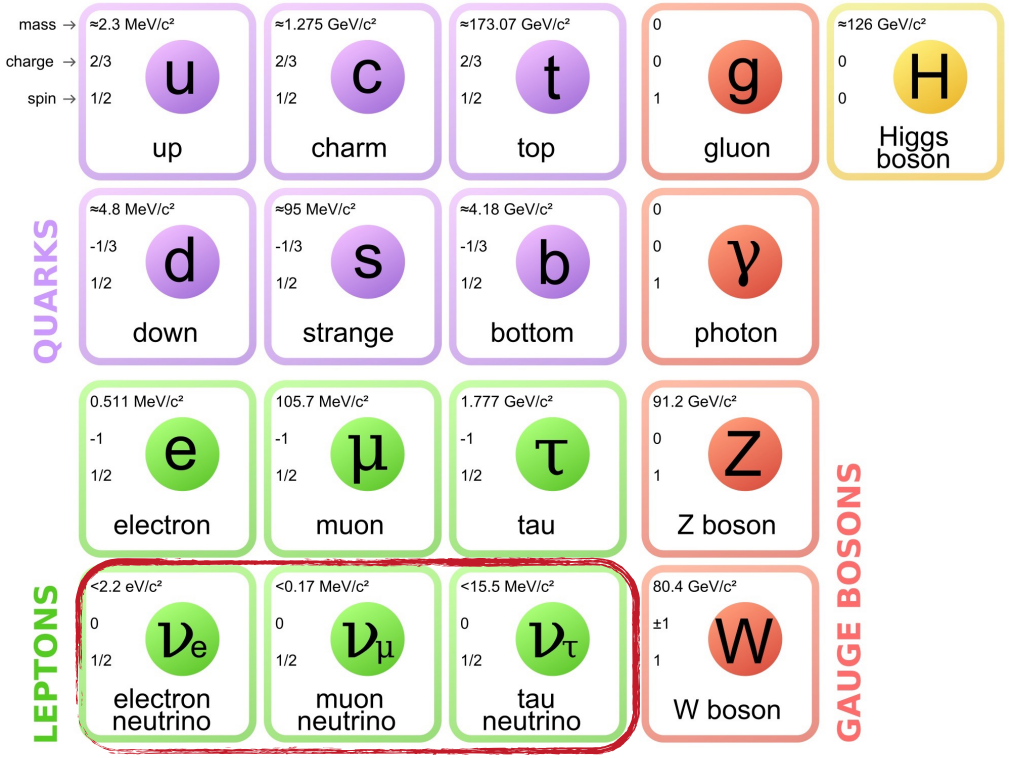
Neutrinos


mass →
charge →
spin →
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS

Neutrinos

Fact sheet

- three flavors (ν_e, ν_μ, ν_τ)
- no charge
- tiny mass (~ eV)
- only interact via **weak** force
  - extremely low interaction rate



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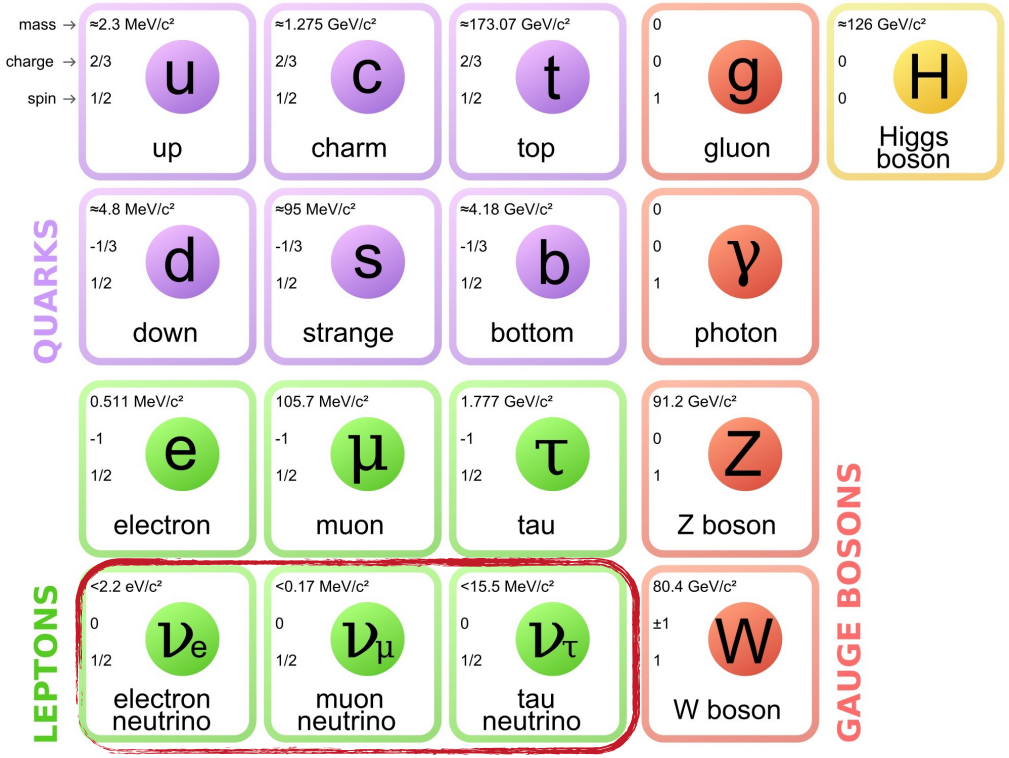
- can escape from extreme environments



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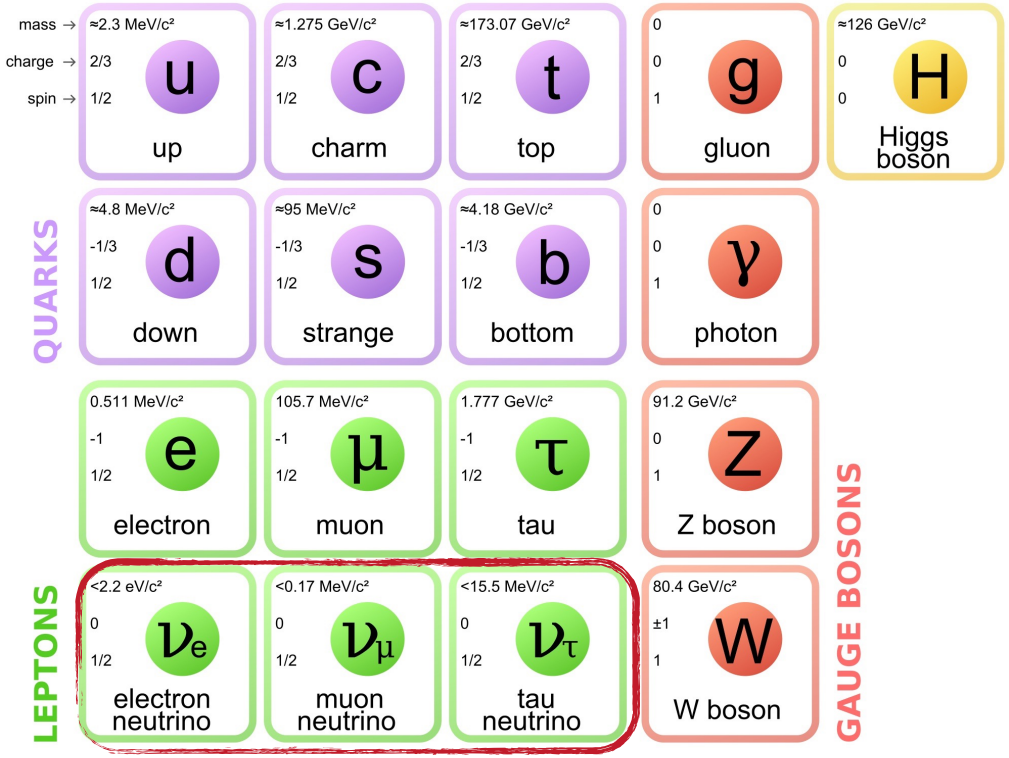
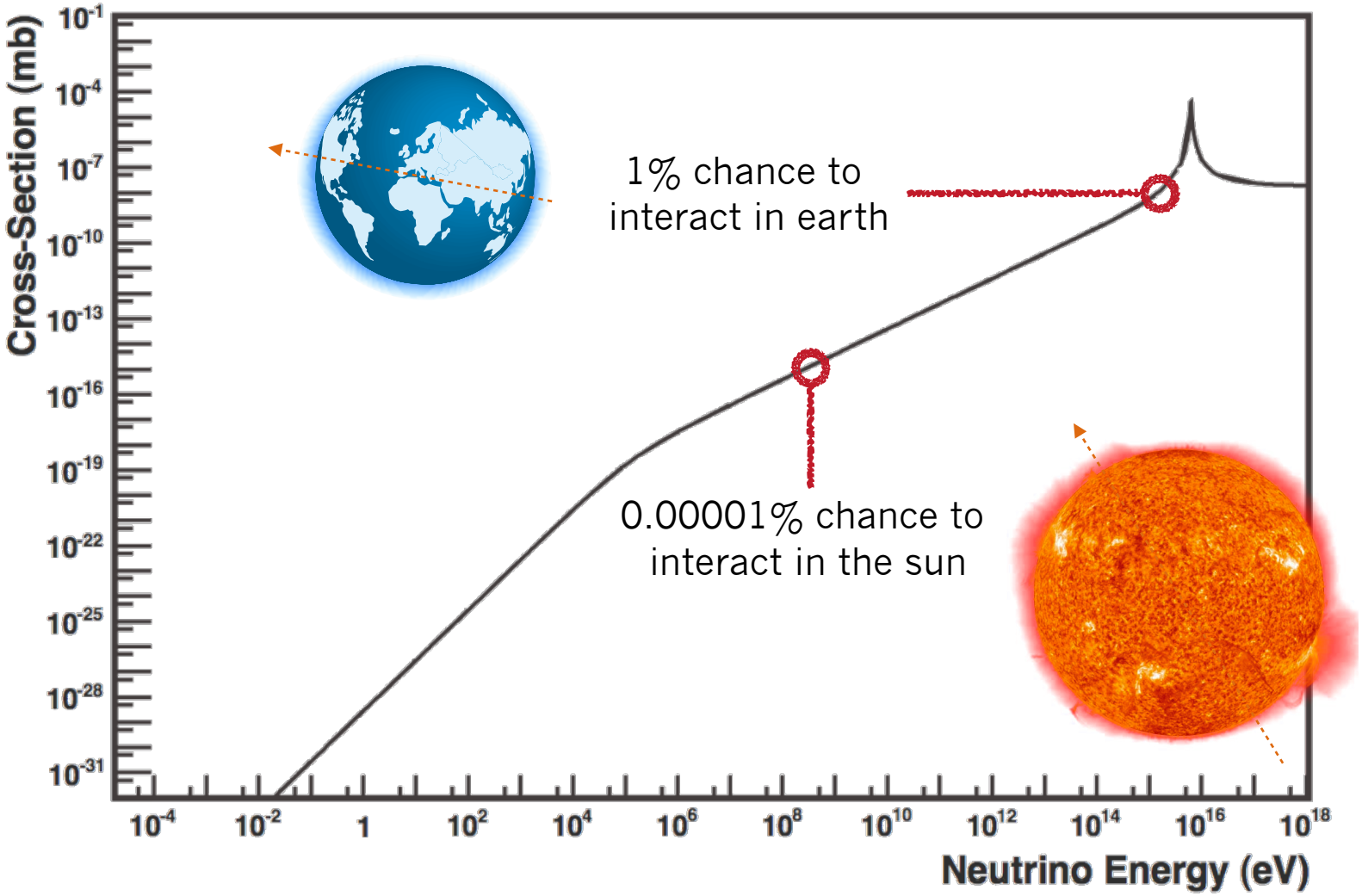
Disadvantage

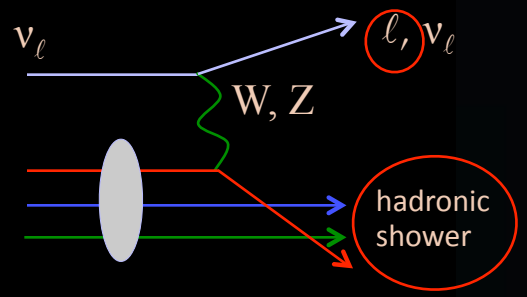
- extremely hard to detect



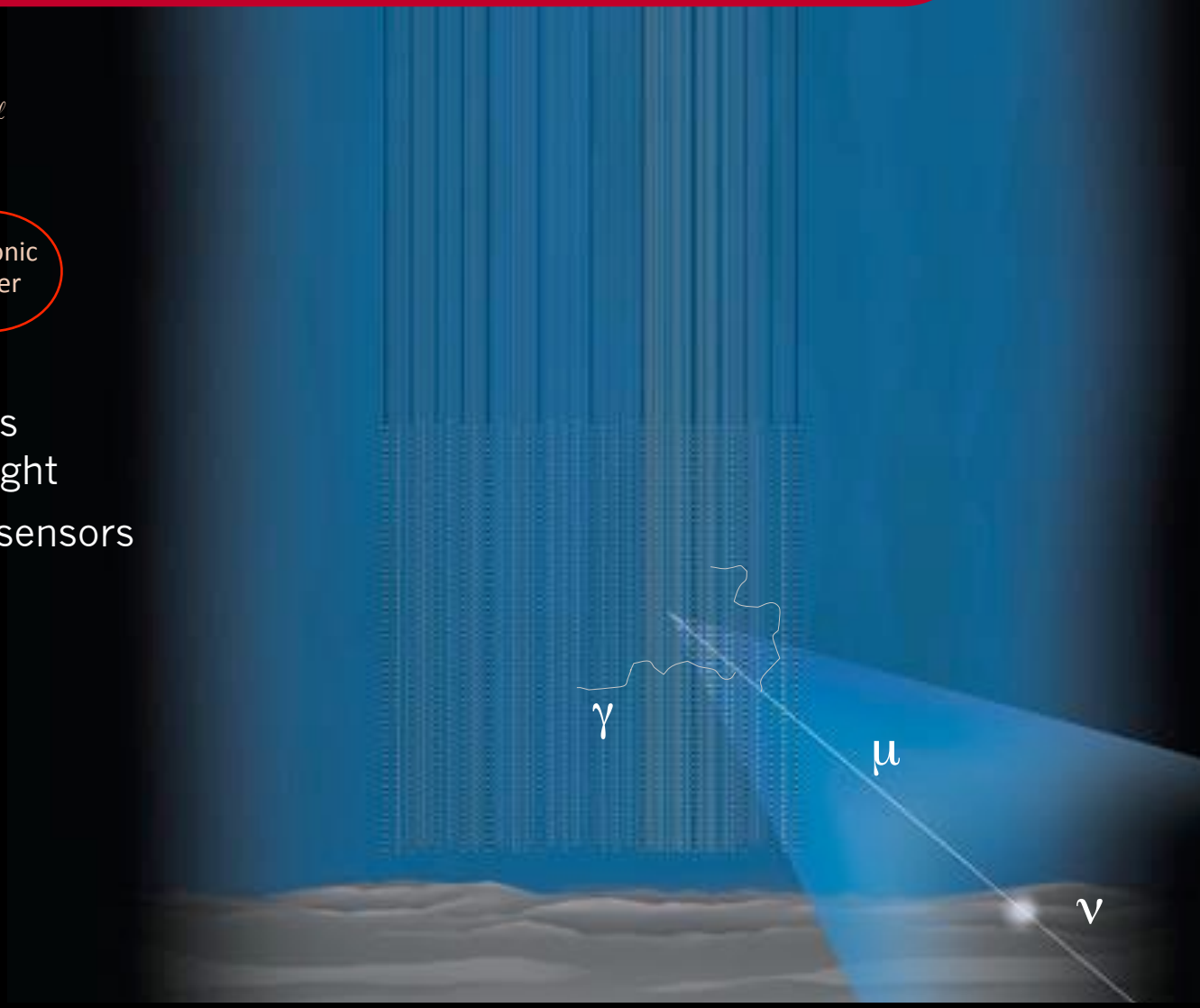
Neutrino interactions



Detection principle



- Charged secondaries emit Cherenkov light
  - array of optical sensors



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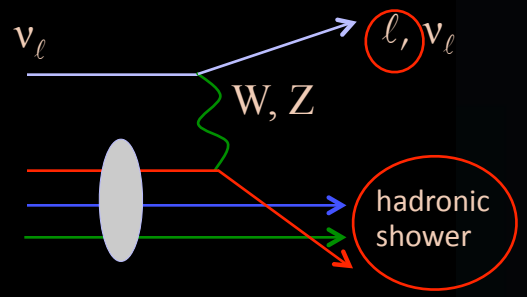

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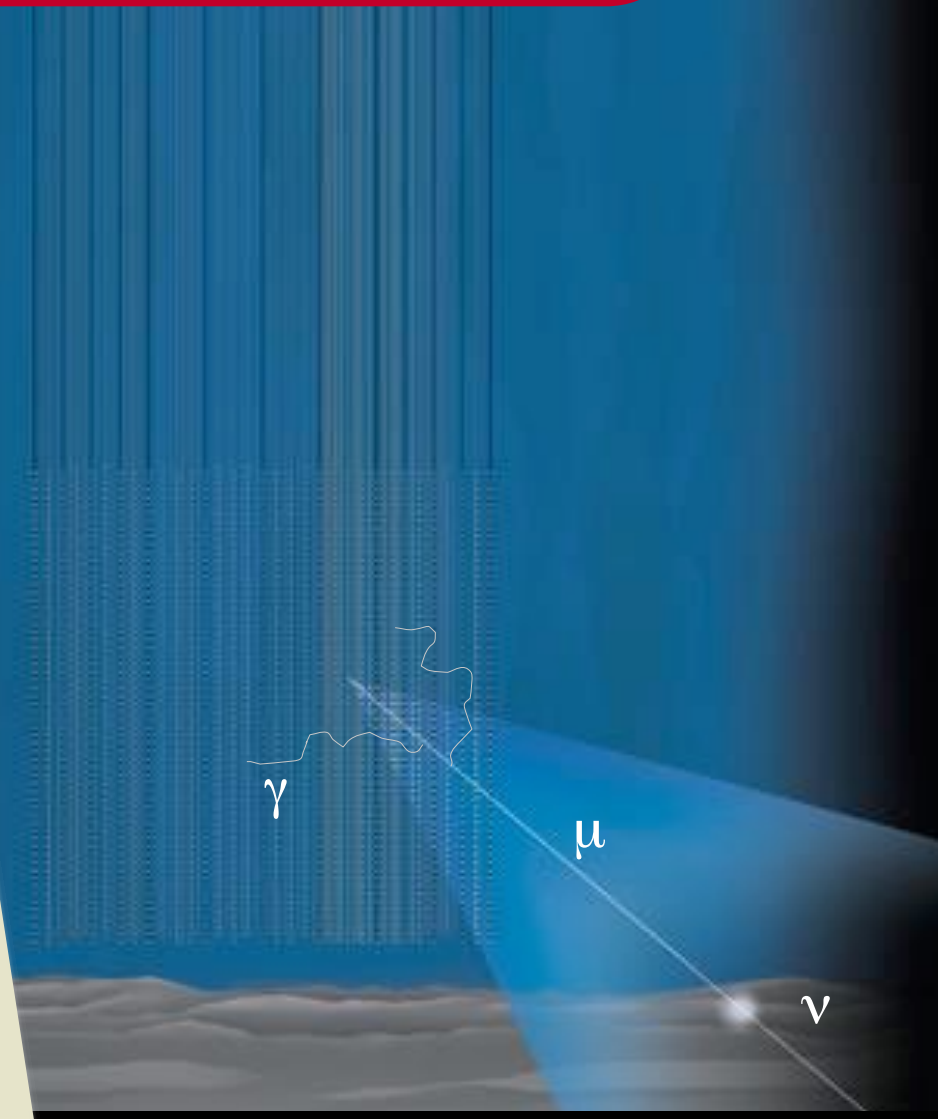
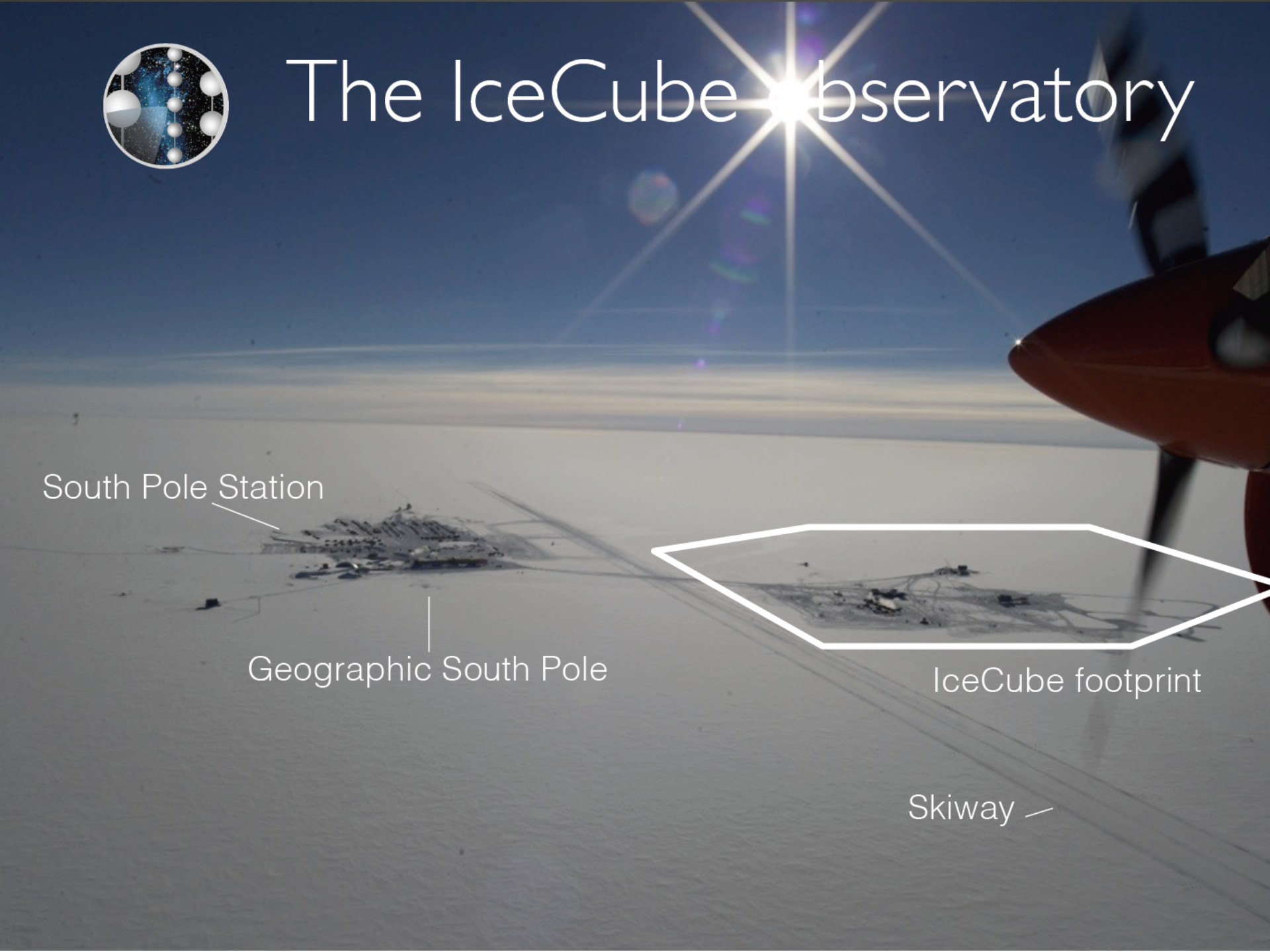


The IceCube Observatory



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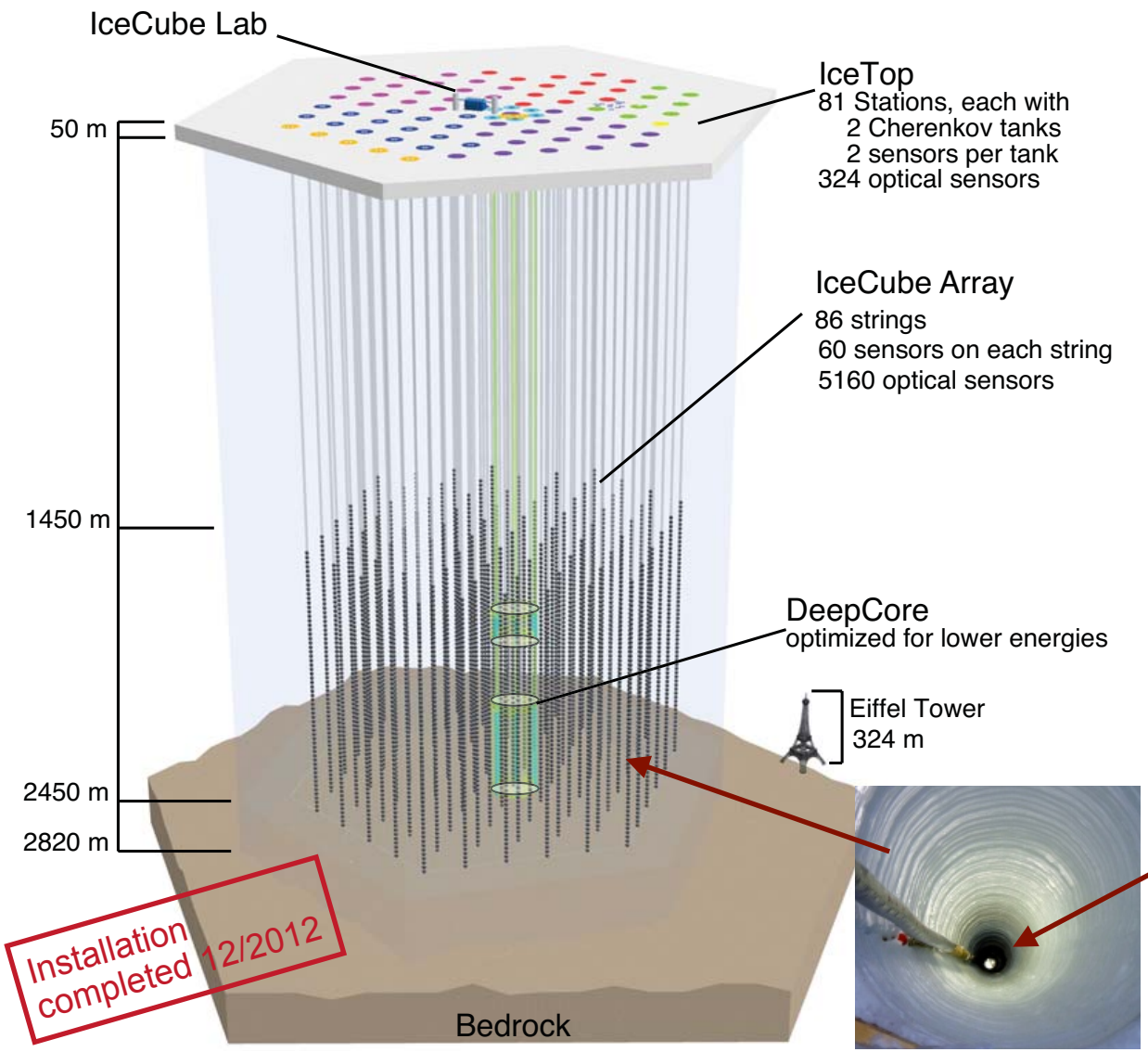
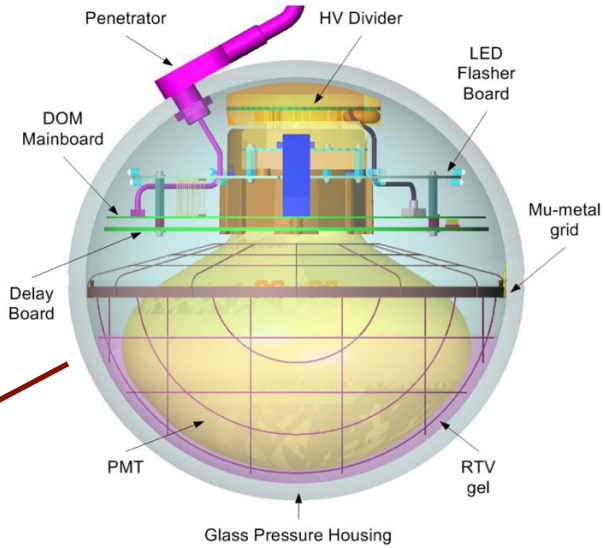


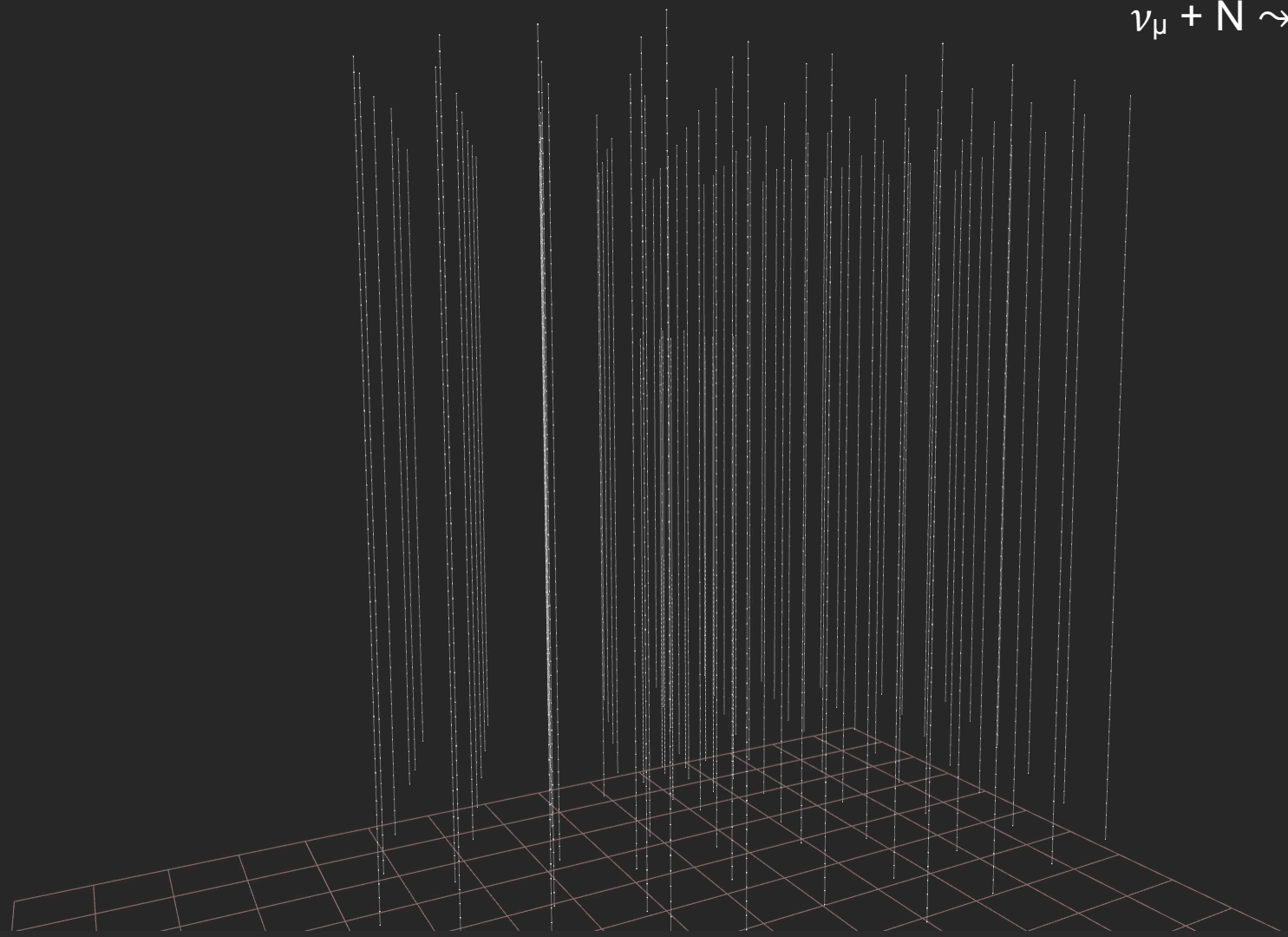
Digital optical module

- sensor 10'' PMT Hamamatsu
- digital waveform $\delta t = 40ns$
- ambient up to 200bar down to -55°C



Cherenkov light

$\nu_\mu + N \rightsquigarrow \mu$ (100 TeV)



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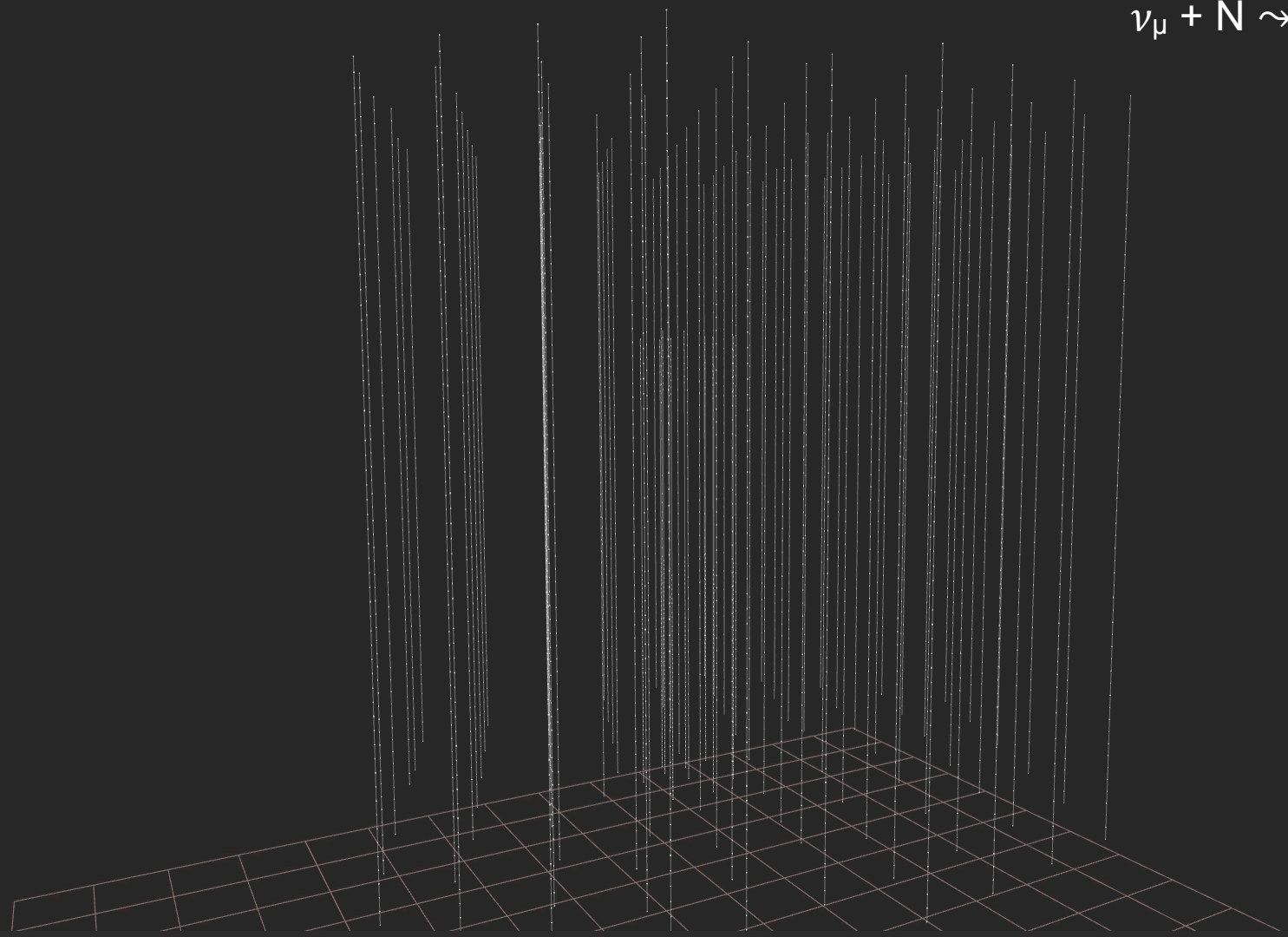
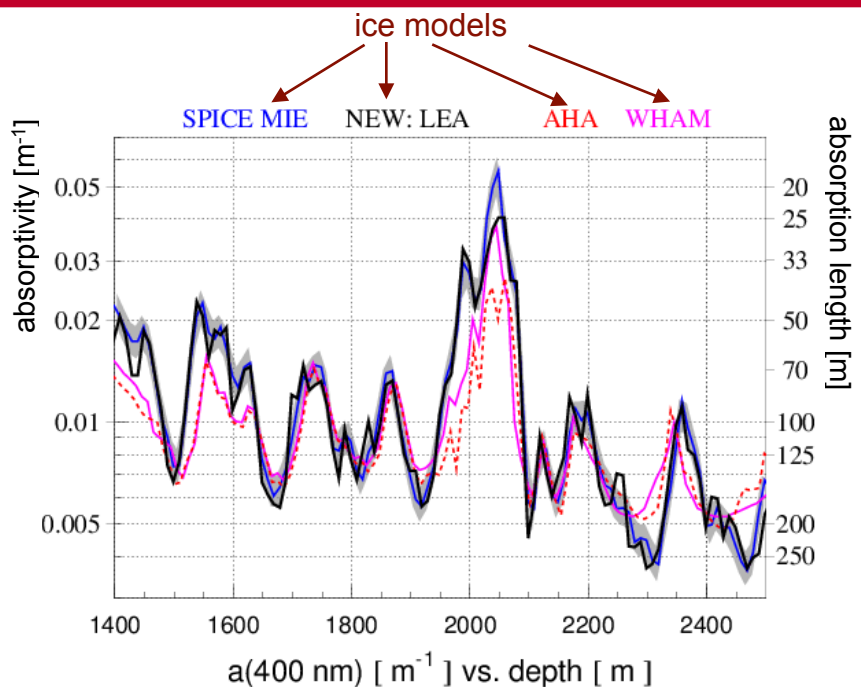
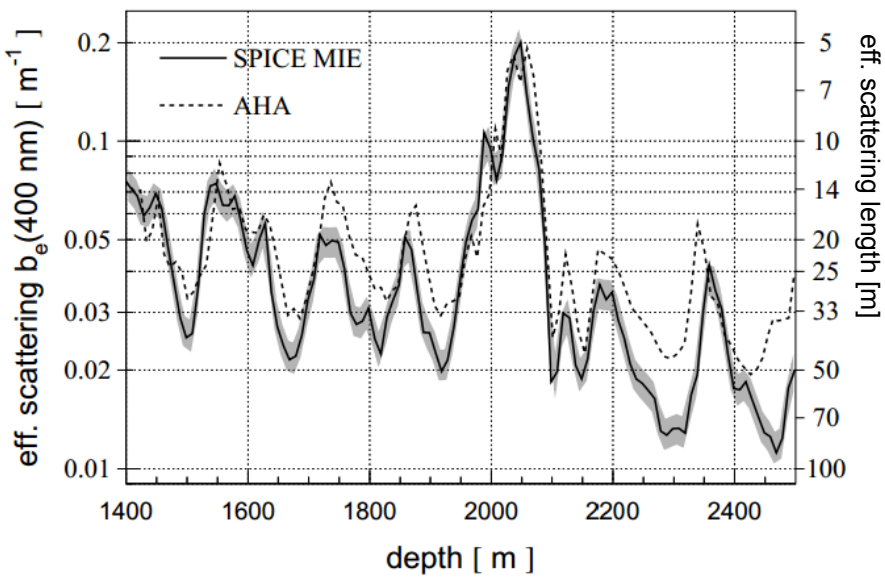


Ice properties





South Pole ice cap

- temperature profile
  -55°C(top) to -10°C (bottom)
- dust layers
  (e.g from volcanic ash)
- low radioactivity
  - Ø(Bq/m³)

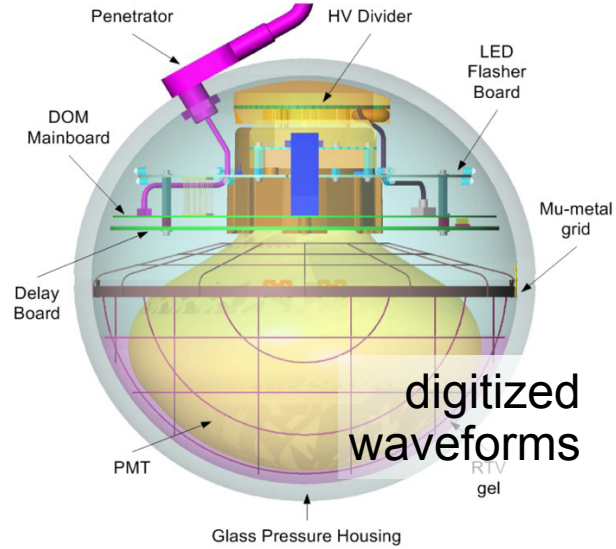
Light propagation

- scattering
- absorption
  - still very clear in optical

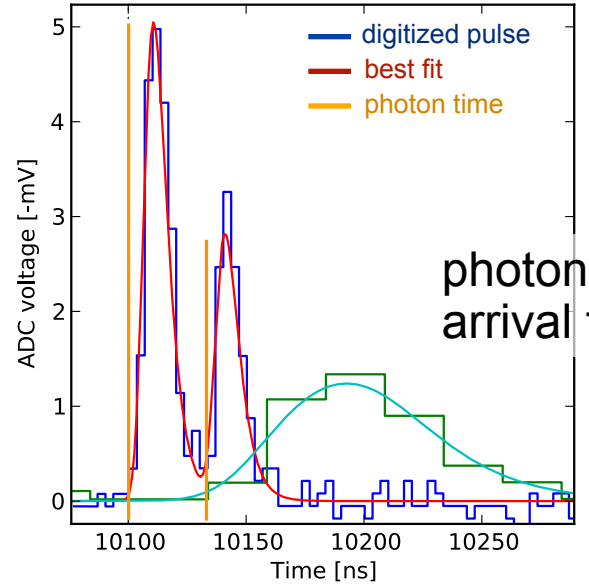
Attenuation length

- $\lambda_{att} \approx 45$m

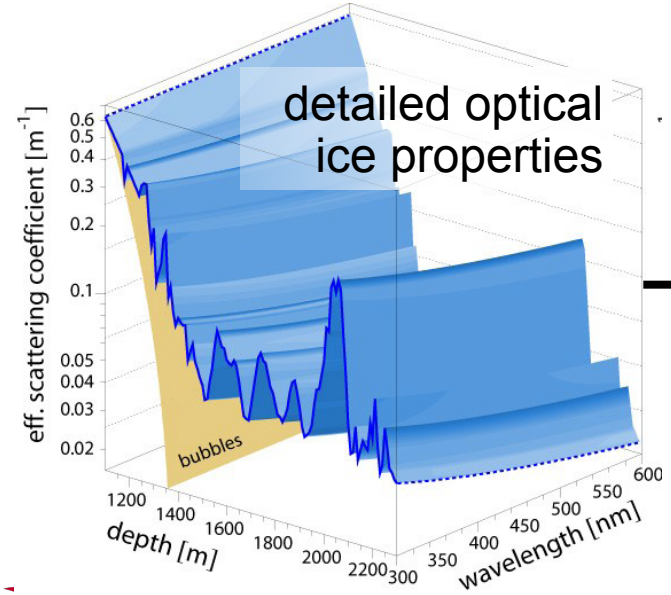
Event reconstruction



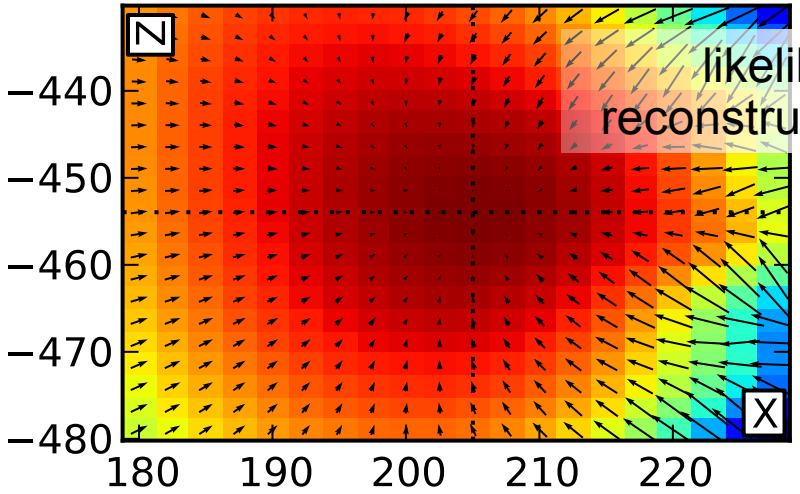
digitized waveforms



photon arrival times



detailed optical ice properties



likelihood reconstruction

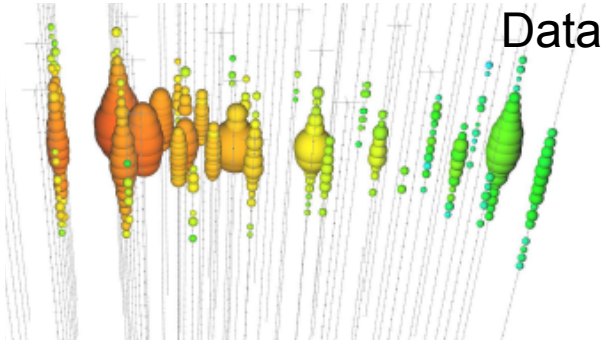
Event signatures

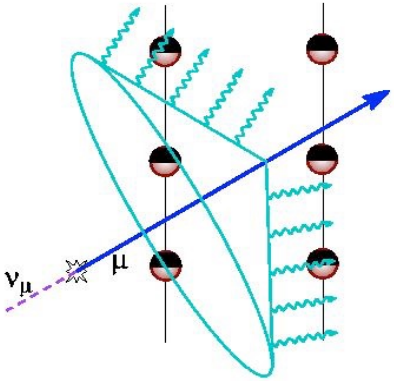
Tracks

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

- pointing resolution

  $\sigma_\Psi \sim 1^\circ$





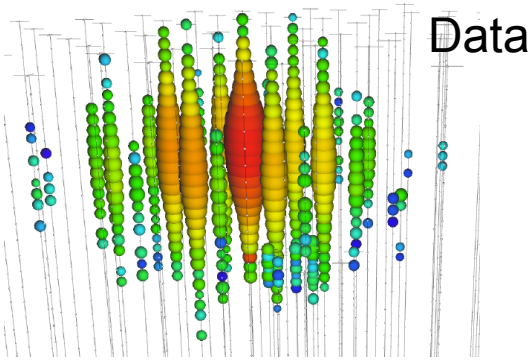
Cascades

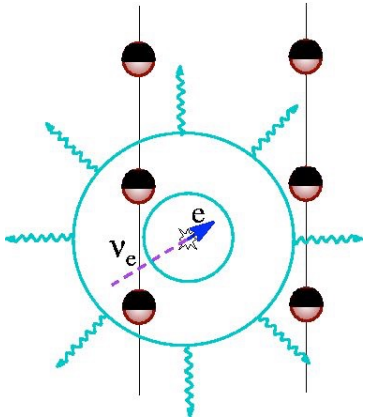
$$\nu_e + N \rightarrow e + X$$

$$\nu_f + N \rightarrow \nu_f + X$$

- energy resolution

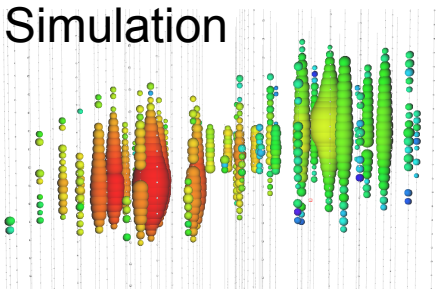
  $\sigma_E \sim 0.1 \log10(E)$



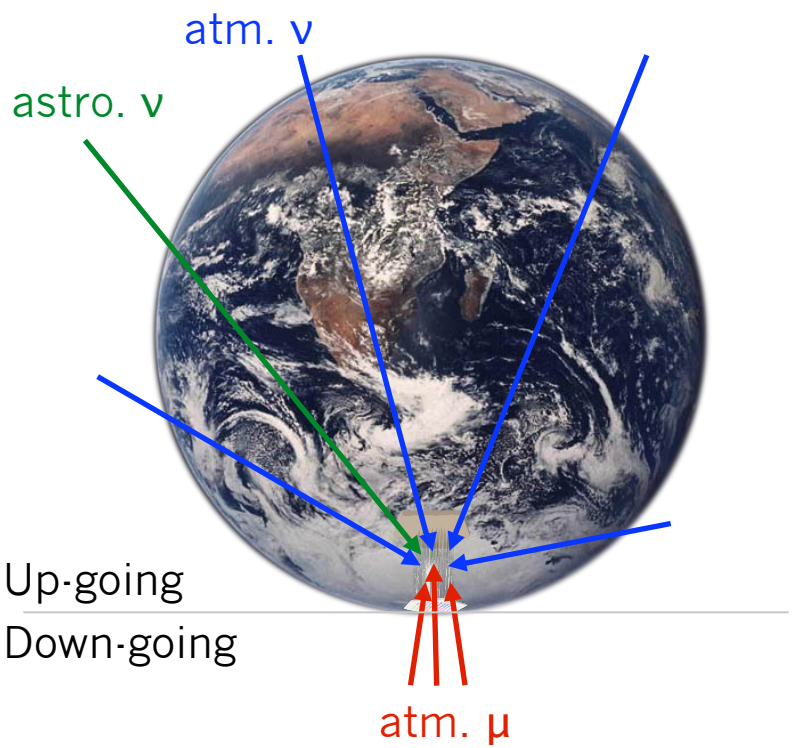


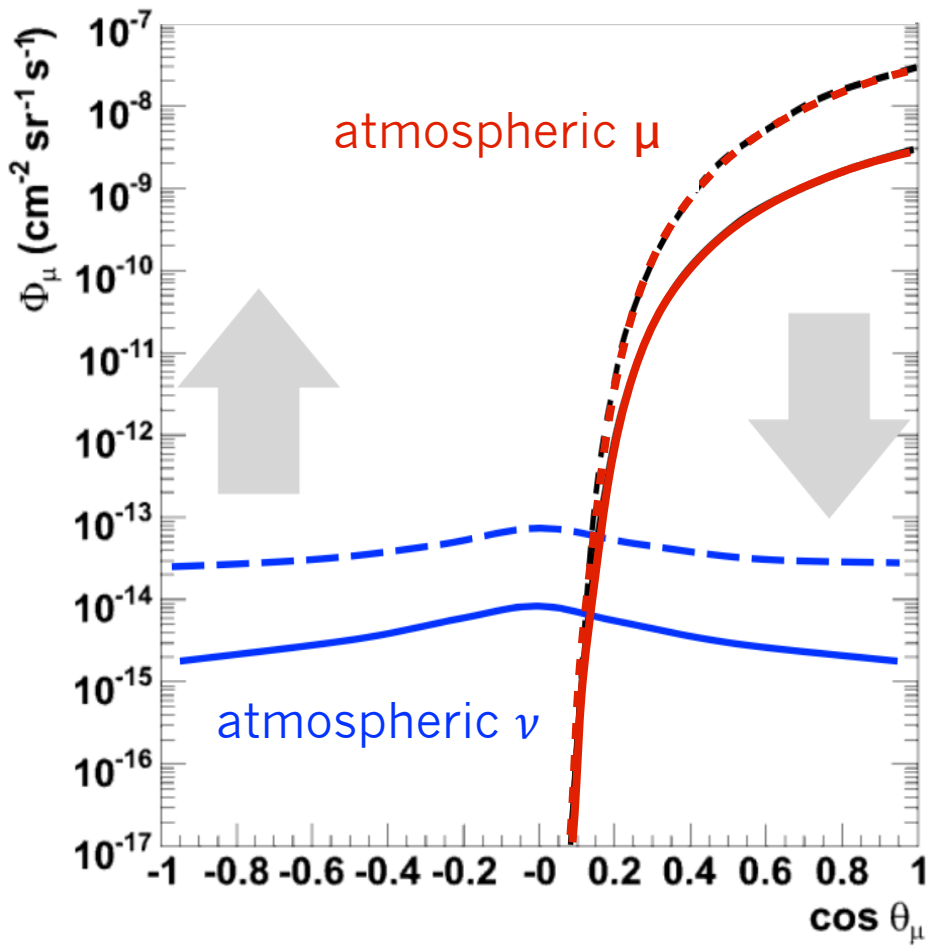
As well as...

- muon bundles (cosmic rays)
- double-bang (ν_τ)
- exotic states (monopoles,...)



Background

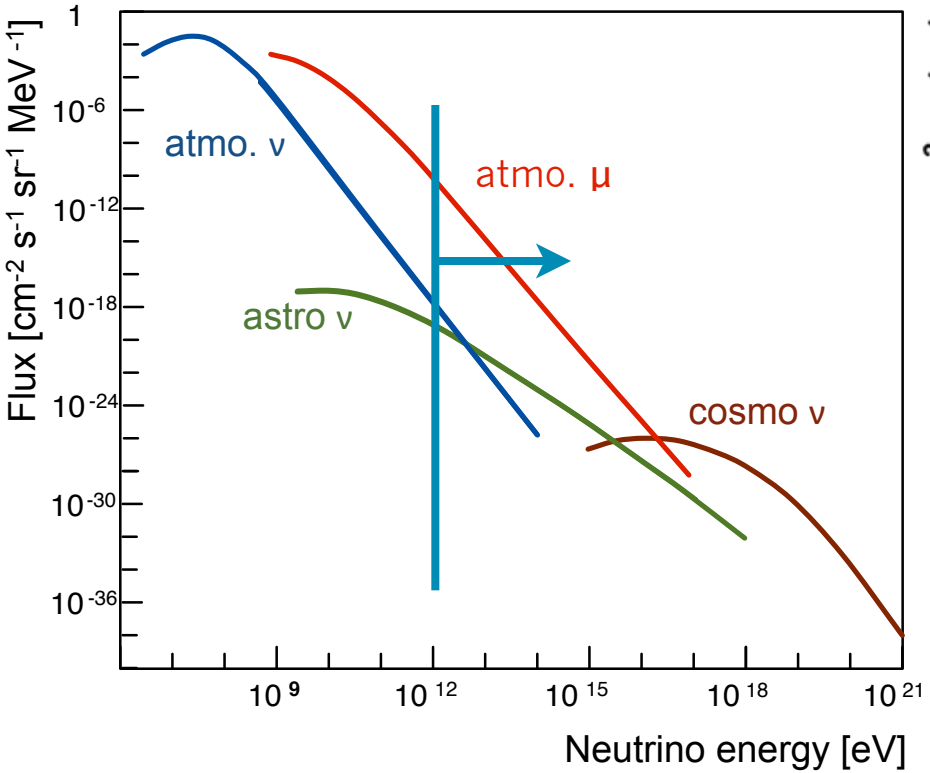


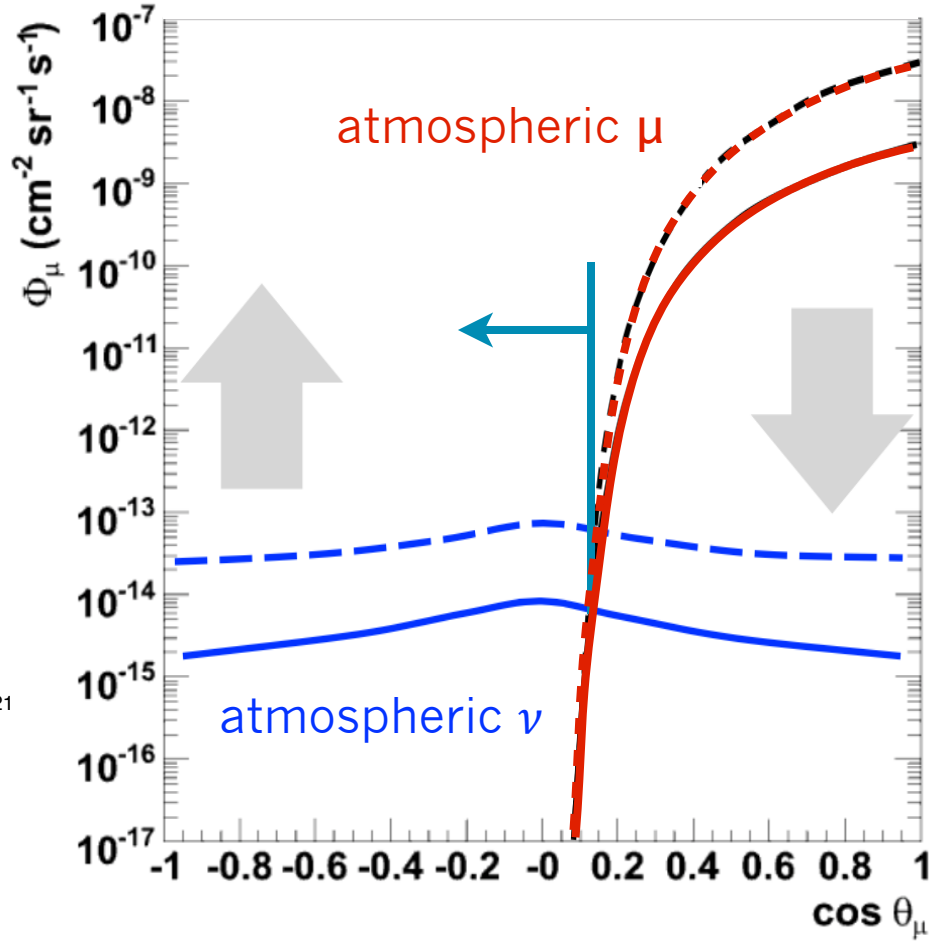


Rates

- atm. μ: 2800 per second
- atm. ν: 0.1 per minute
  - need >10^6 background rejection!

Background rejection



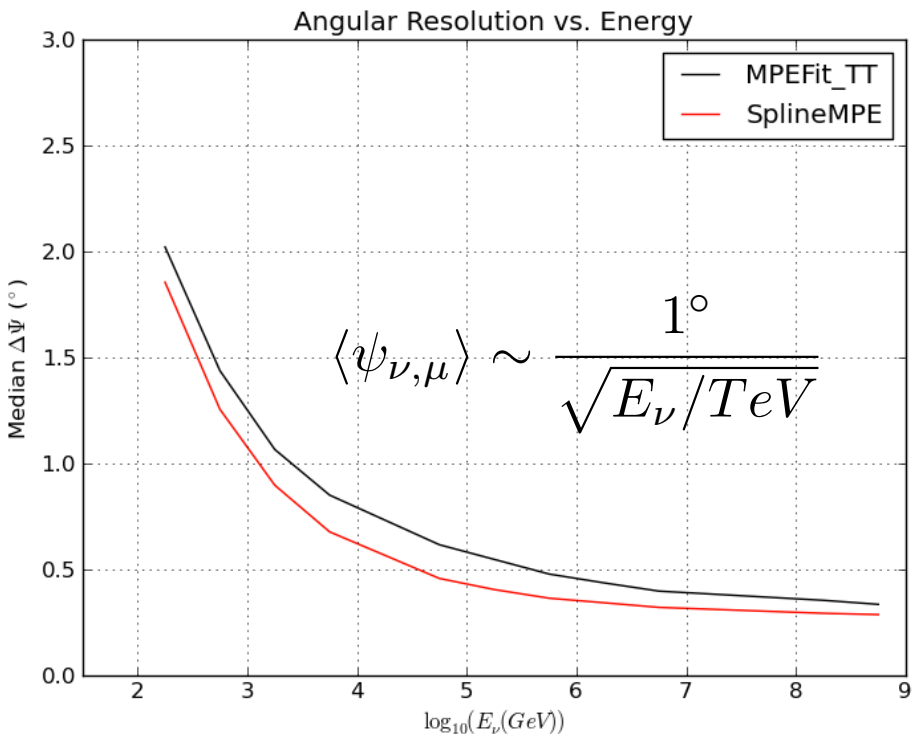


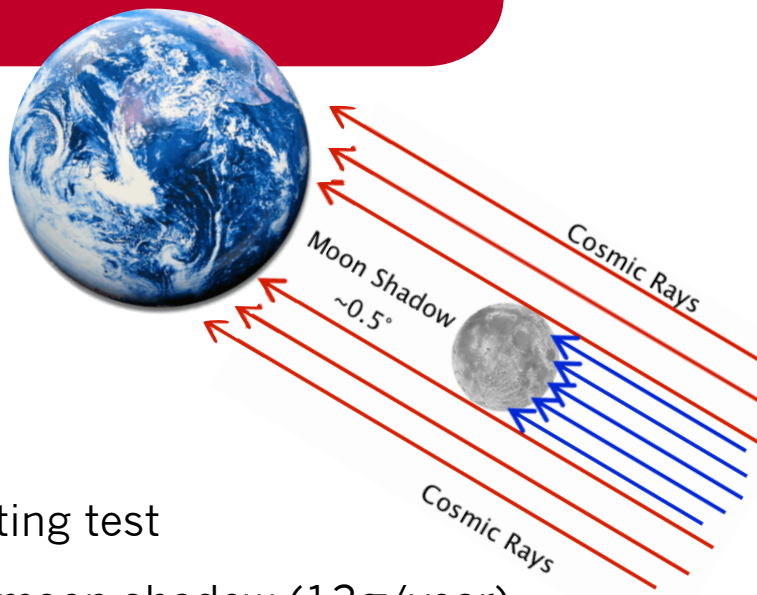
Rejection techniques

- event direction
- energy
- event topology

Point sources

ν_μ pointing resolution



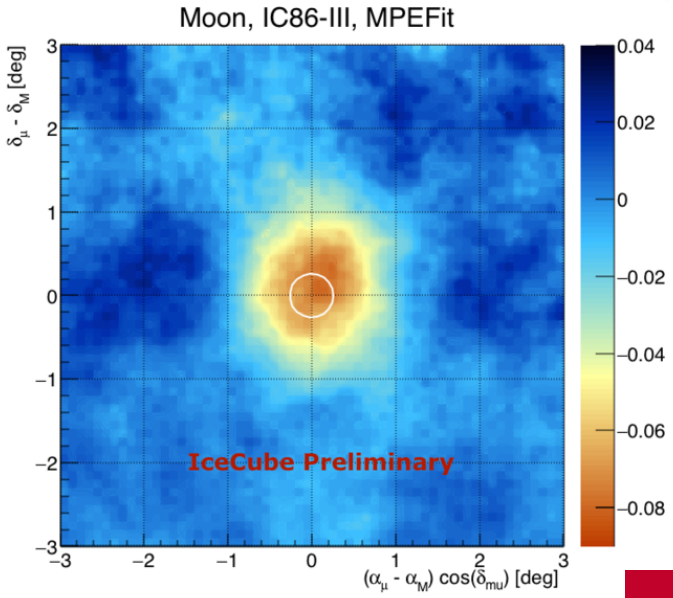


Pointing resolution

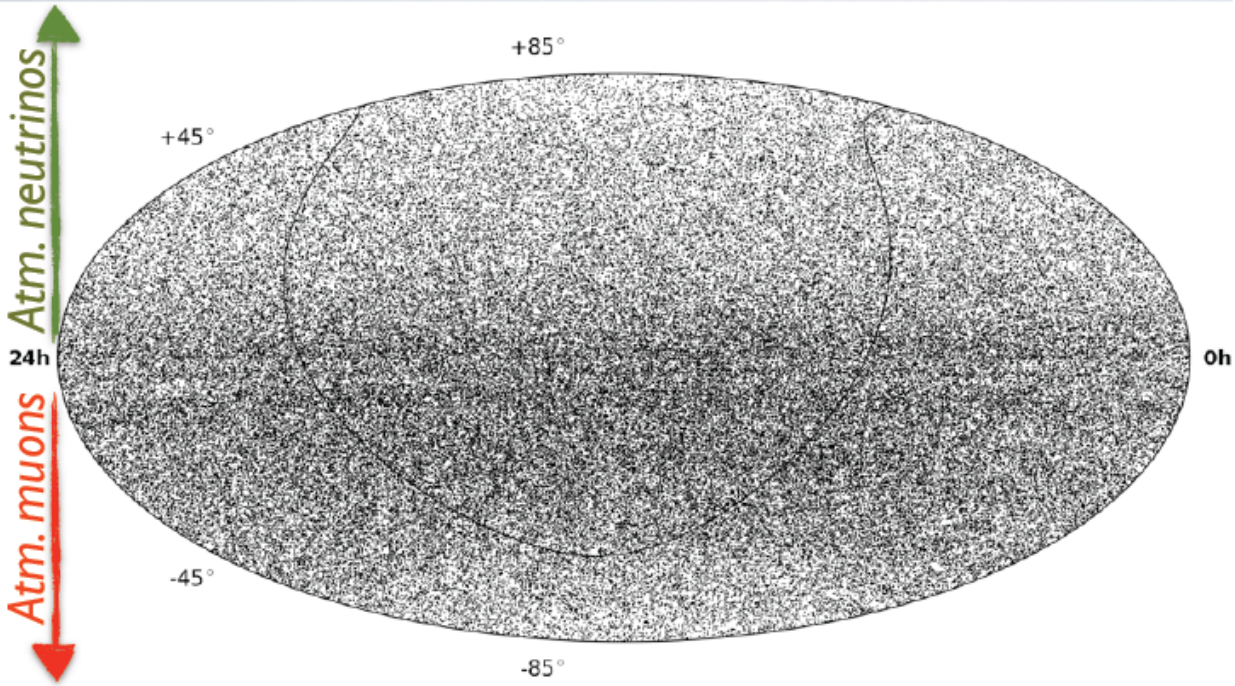
- energy dependent
  - $\sigma(\theta_\nu) \approx 1^\circ$ at 1 TeV
  - dominated by ν-μ scattering angle

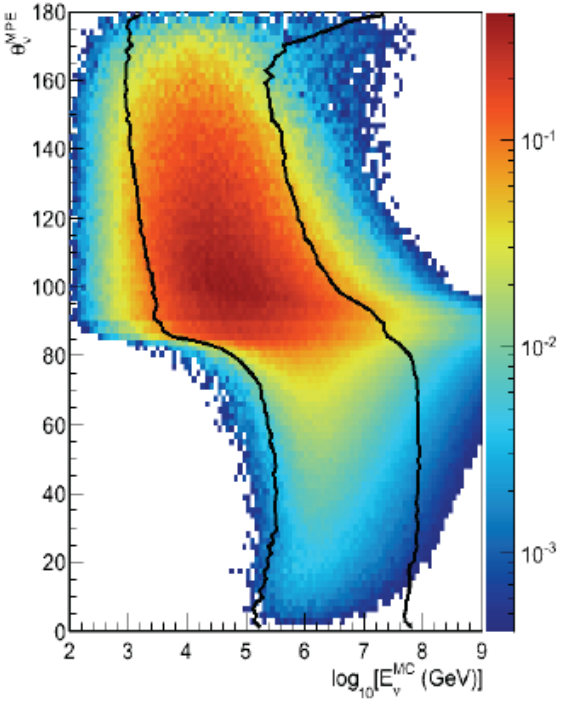
Pointing test

- moon shadow (13σ/year)



Point source searches

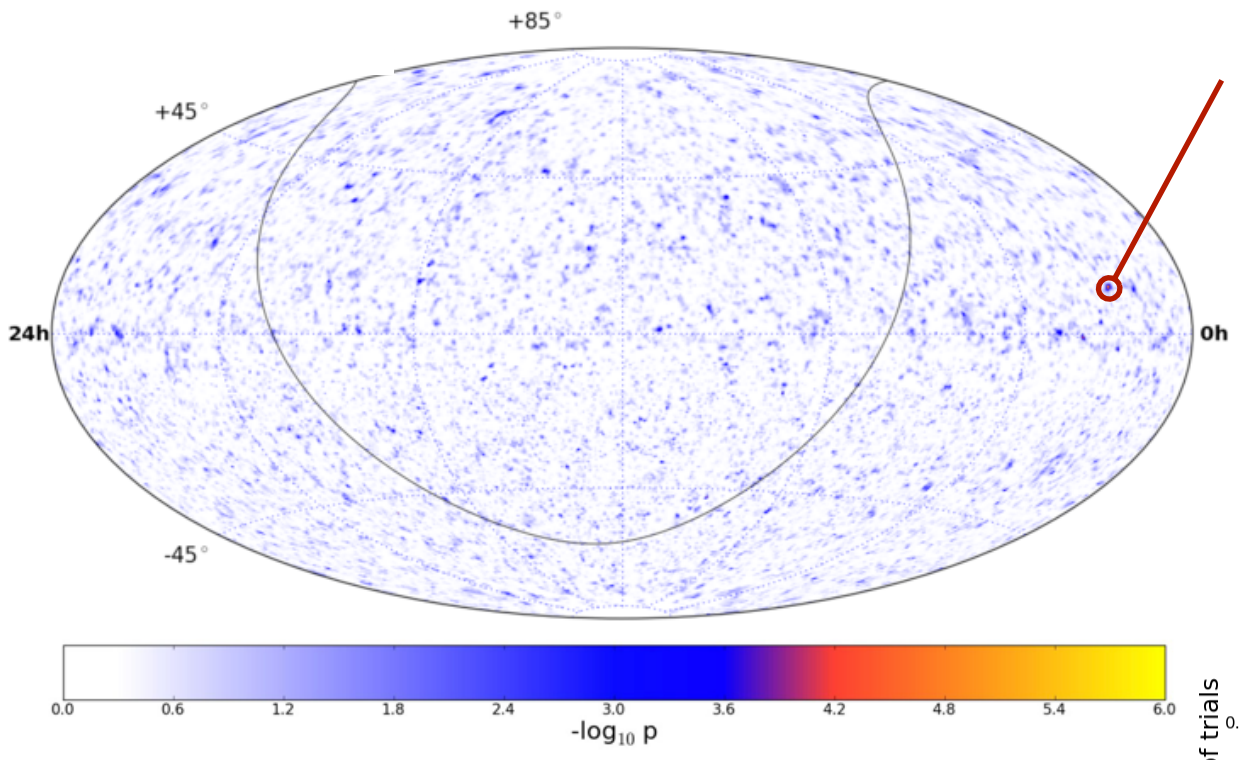




Dataset

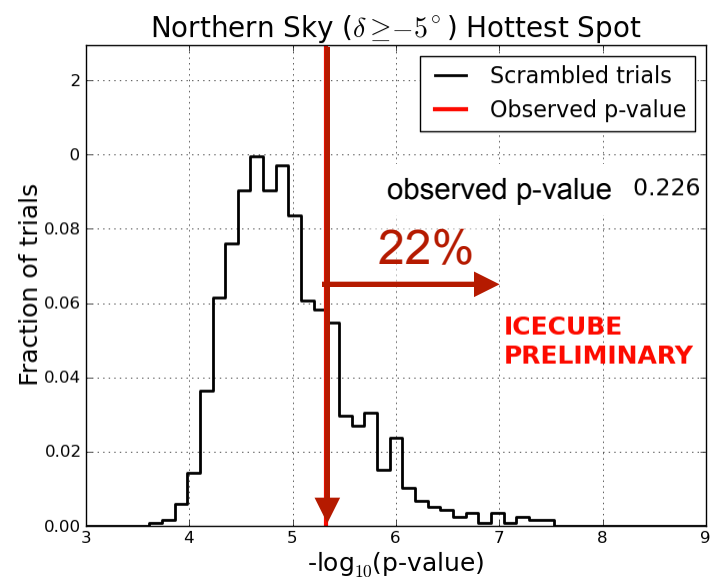
- livetime 1371 days (4 years) ➔ 394,000 events after cuts
  - 40% up-going
  - 60% down-going (at high energy)

Significance skymap



Hottest spot

- DEC: 29.25°
- RA: 10.55°
- $-\log_{10}(p) = 5.318$
- $n_s = 43.04$, $\gamma = 2.88$
  - no close-by candidates

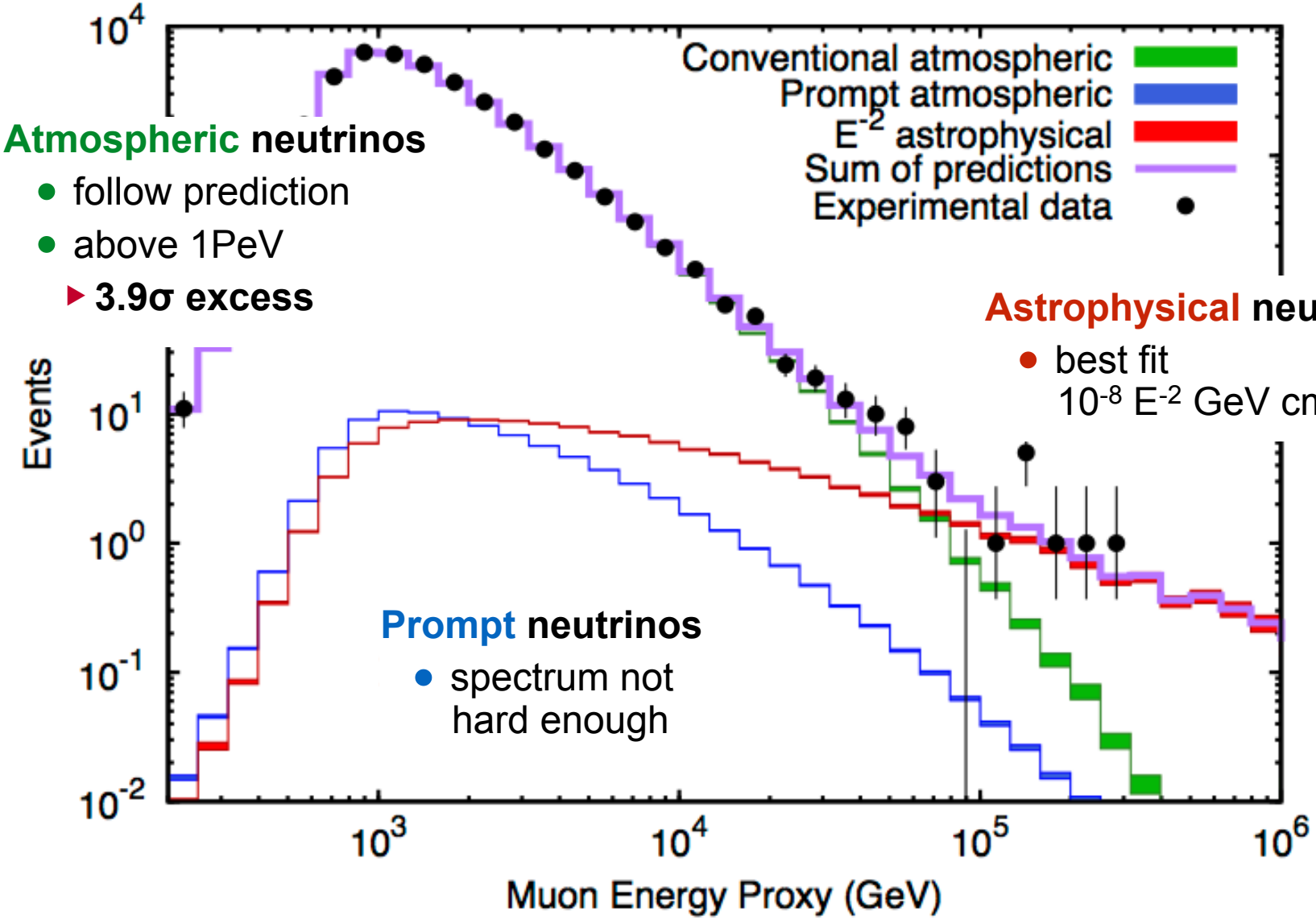


Analysis

- calculate over-density (p-value) of real data
- scramble event directions
- count accidental occurances
  - 22% have equal or larger max. p-value

Unresolved sources

ν_μ energy spectrum



Atmospheric neutrinos

- follow prediction
- above 1PeV
  - **3.9σ excess**

Astrophysical neutrinos

- best fit
  10^{-8} E^{-2} GeV cm^{-2} s^{-1} sr^{-1}

Prompt neutrinos

- spectrum not hard enough

High Energy Starting Events (HESE)

Active veto layer

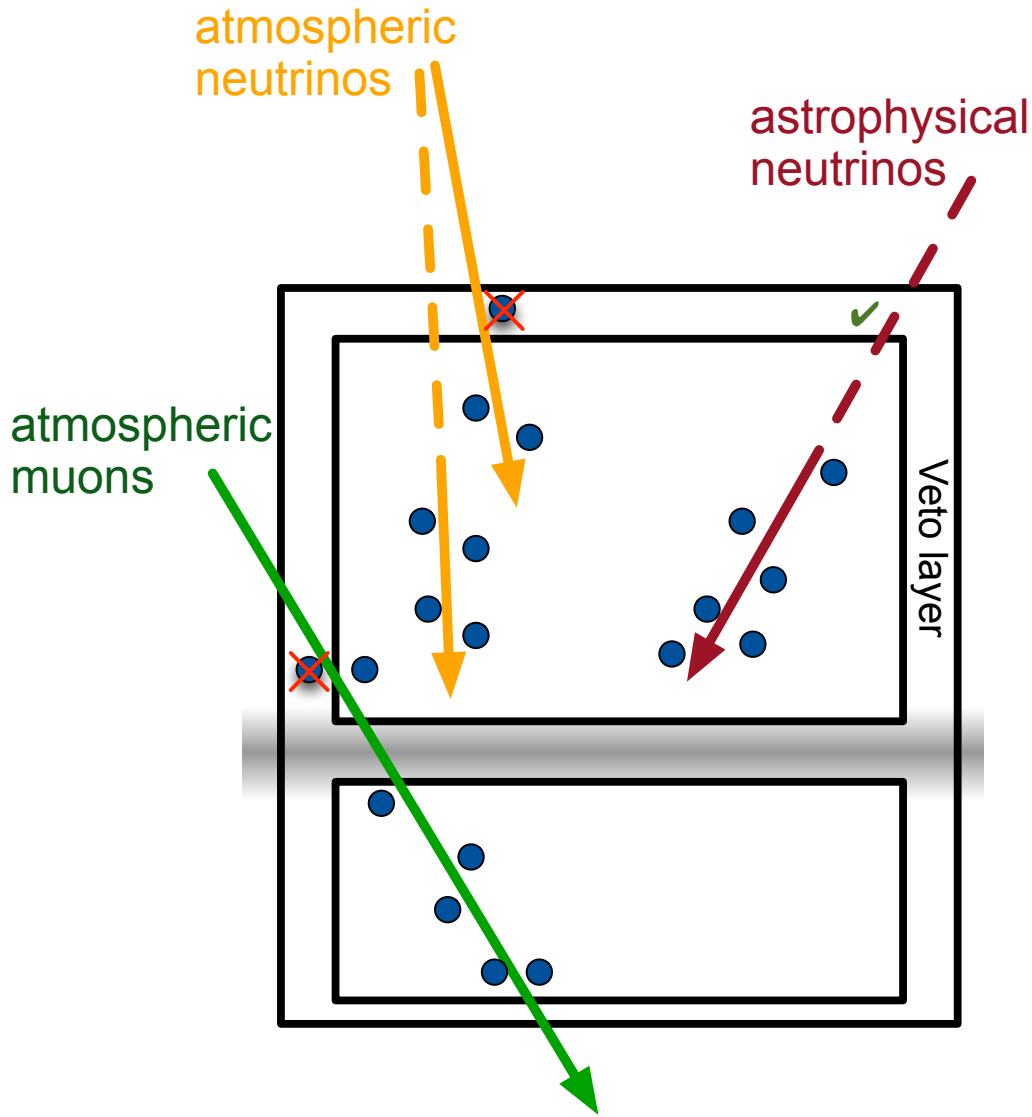
- reject events with early hit in veto layer
- keep *starting* events

Atmospheric flux

- **atmo. μ** rejected in veto
- **atmo. ν** rejected by
  - energy cut
  - μ companion

Result

- Optimized for 1 PeV region
  - factor 3 gain in sensitivity
- Sensitive to all flavors



HESE results

Dataset

- 1347 days (4 yrs) full detector

Events

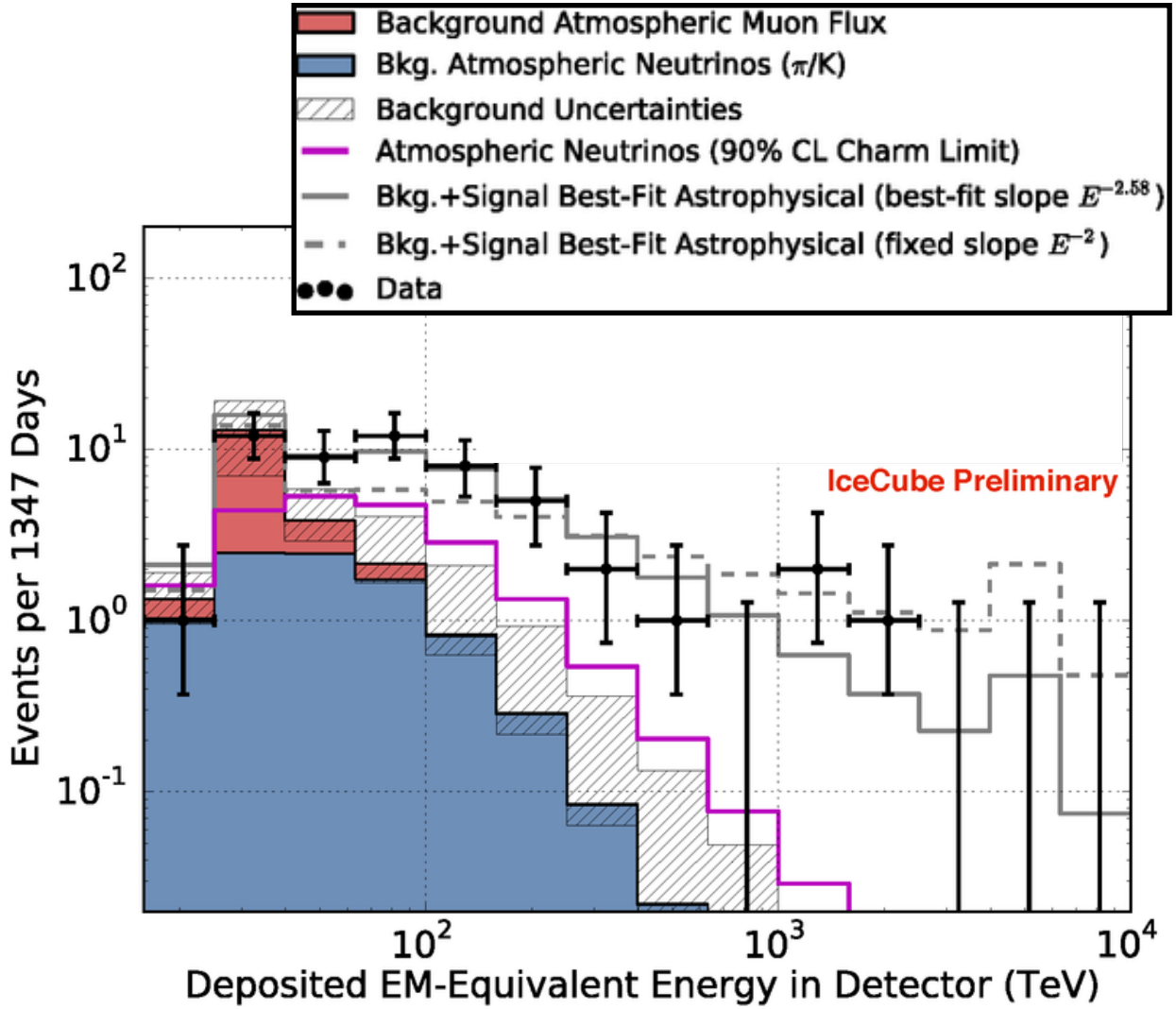
- 54 events
  - 15 track-like
  - 39 cascade-like

Background estimate

- atmo. μ: 12.6±5.1
- atmo. ν: 11.5±5.7

Significance

- well above 5σ



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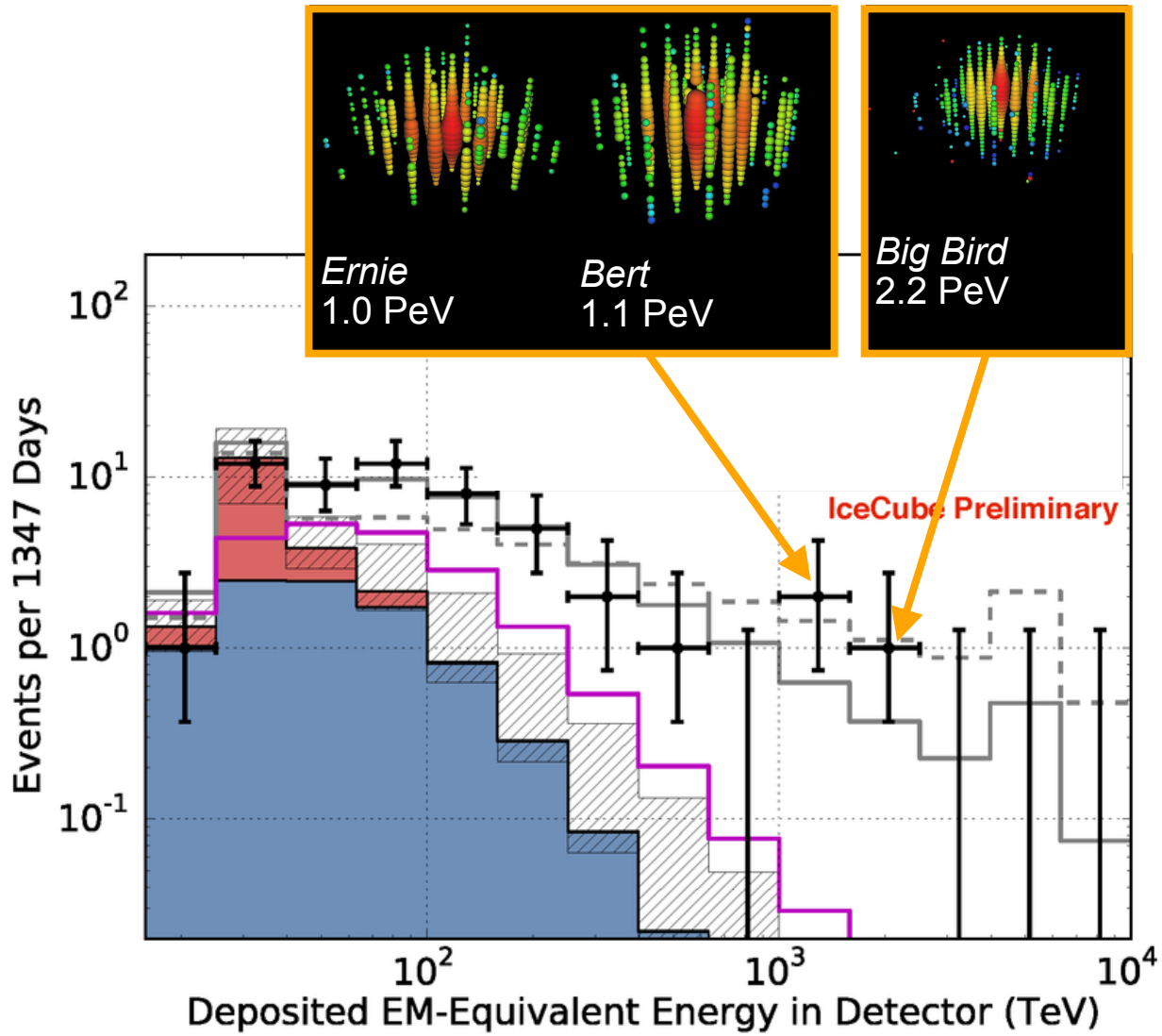
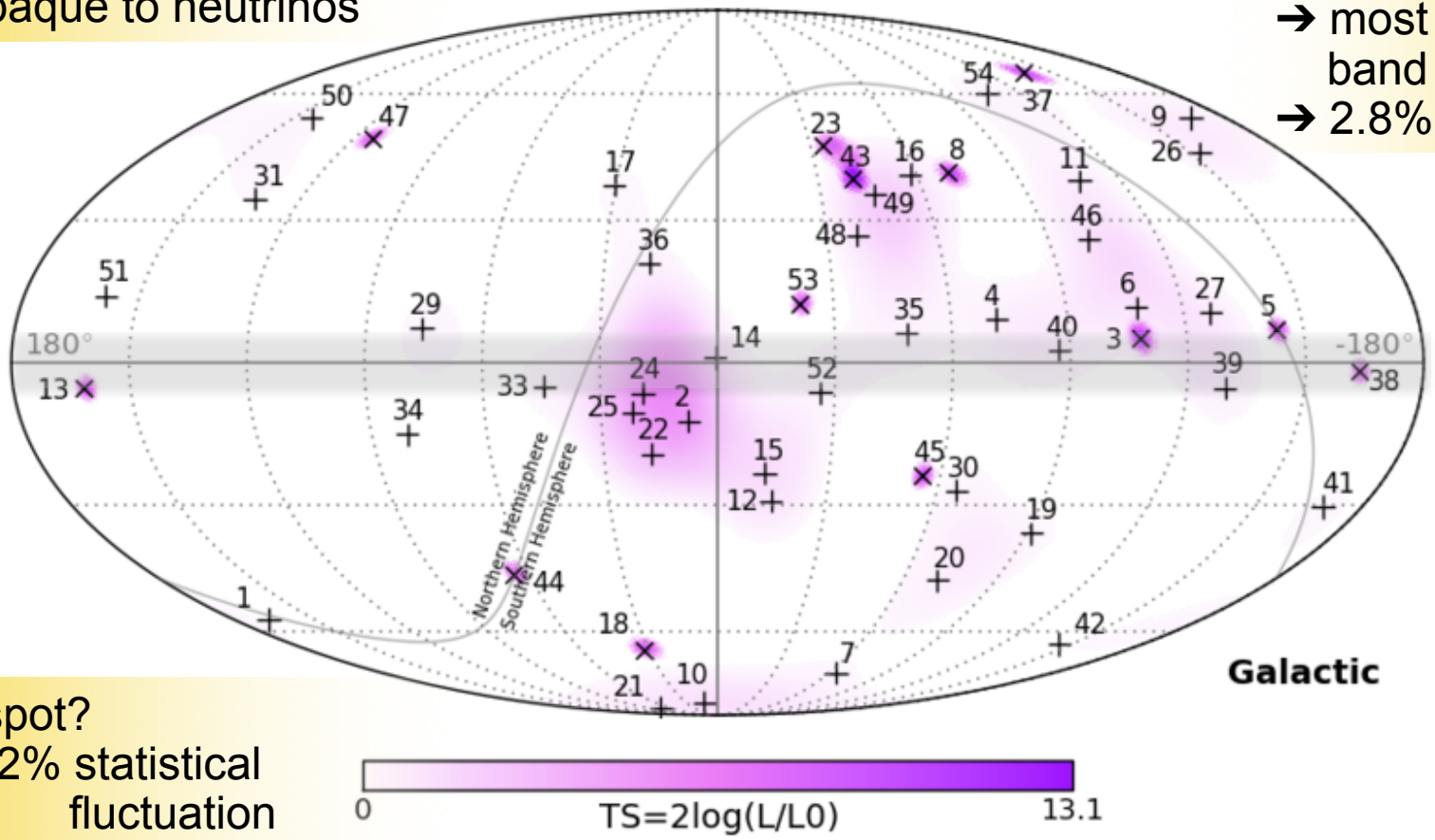


HESE results

north vs. south?
➔ earth becomes opaque to neutrinos

correlation with galactic plane?
➔ most likely band = 7.5º
➔ 2.8% probability



hot spot?
➔ 7.2% statistical fluctuation

Flavour analysis

Flavours at source

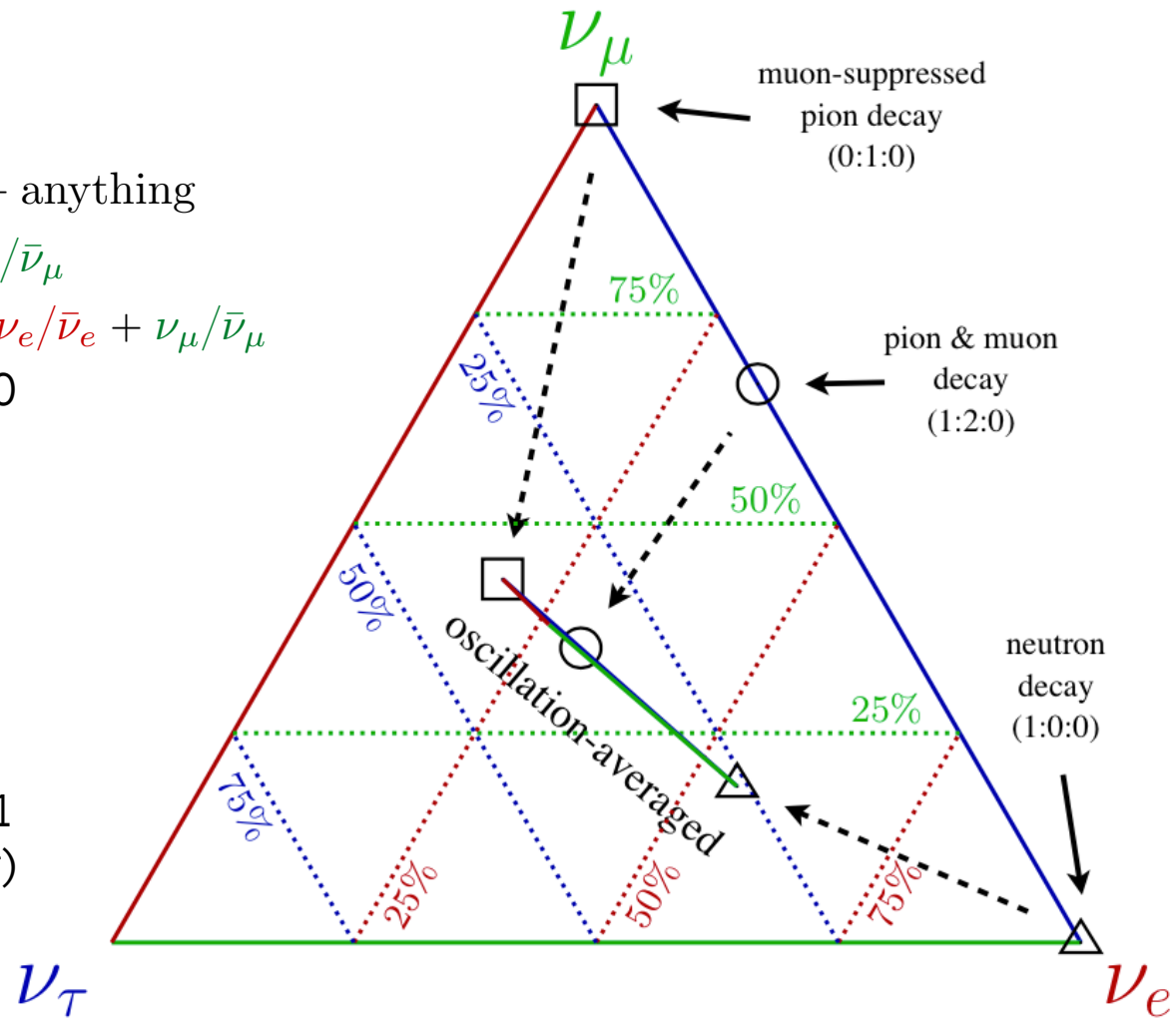
- regular decay

$$p(p/\gamma) \rightarrow \pi^{\pm}/\pi^{0} + \text{anything}$$
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}/\bar{\nu}_{\mu}$$
$$\hookrightarrow e^{\pm} + \nu_{e}/\bar{\nu}_{e} + \nu_{\mu}/\bar{\nu}_{\mu}$$

  - flavour ratio = 1:2:0

Flavours at earth

- altered by **oscillations**
- assume average over many sources
  - flavour ratio ~ 1:1:1 (bi-maximal mixing)



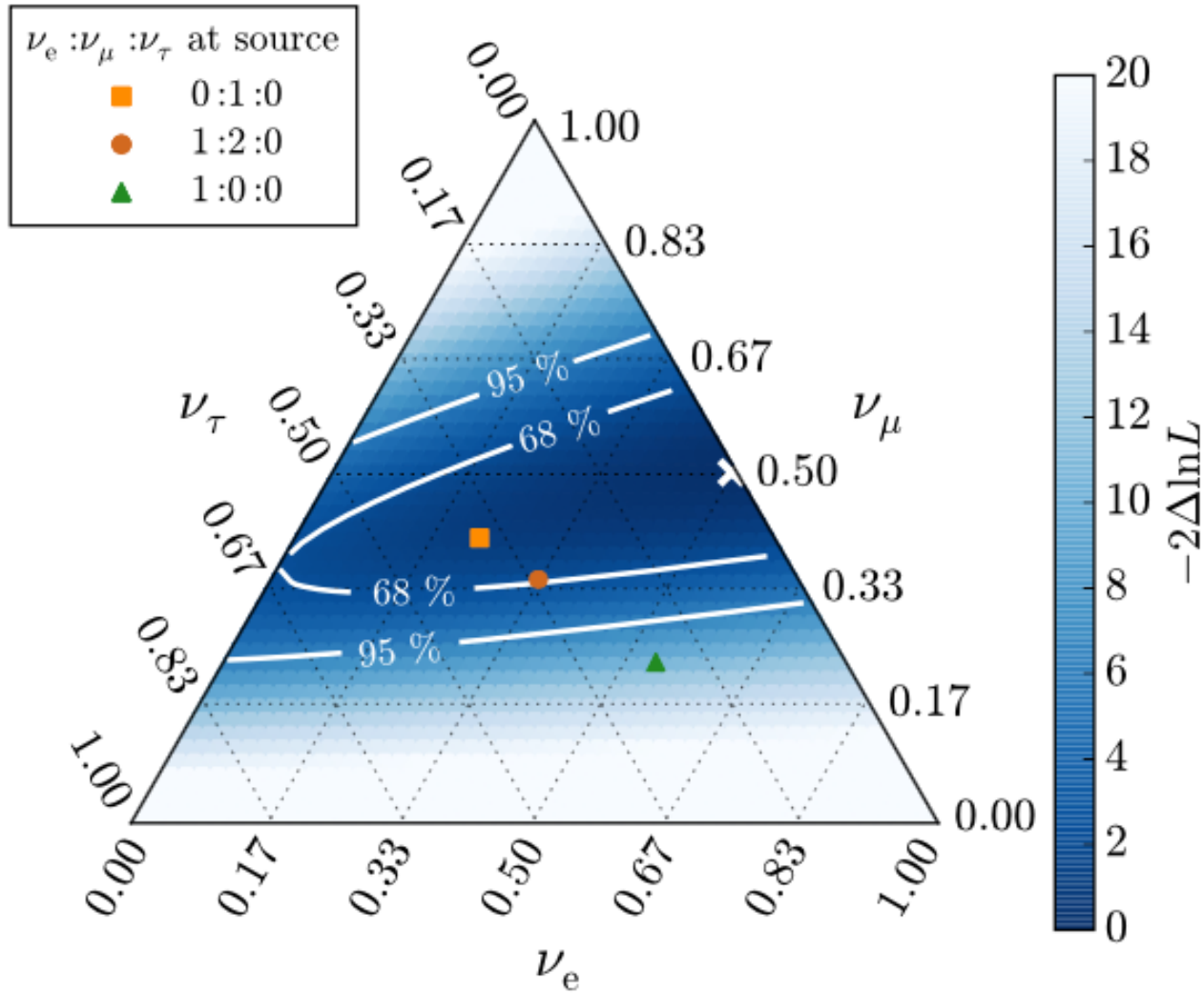
Flavour analysis

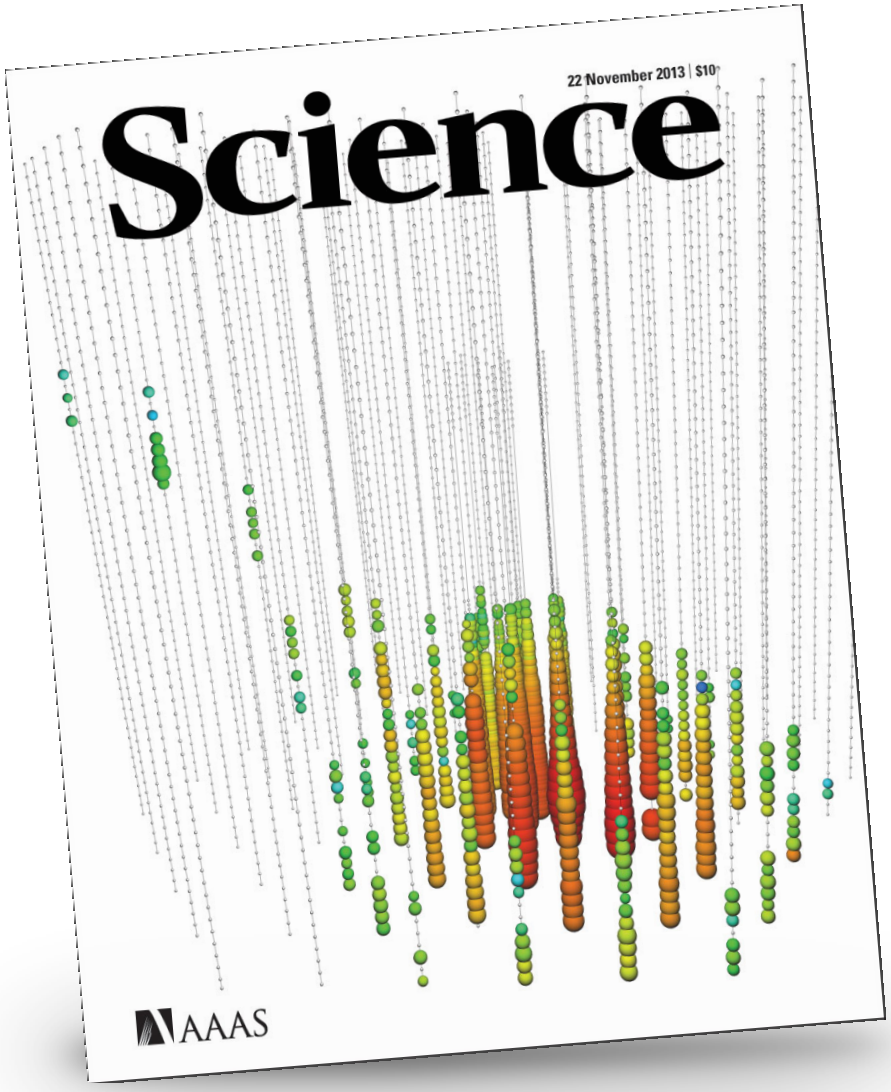
Results

- **regular** decay
  - p-value = 30%
- **muon-suppressed**
  - p-value = 60%
- **neutron** decay
  - excluded at 3.2σ

ν_e - ν_τ degeneracy

- can not resolve ν_τ at TeV energies





Astrophysical neutrinos discovered!

What next?

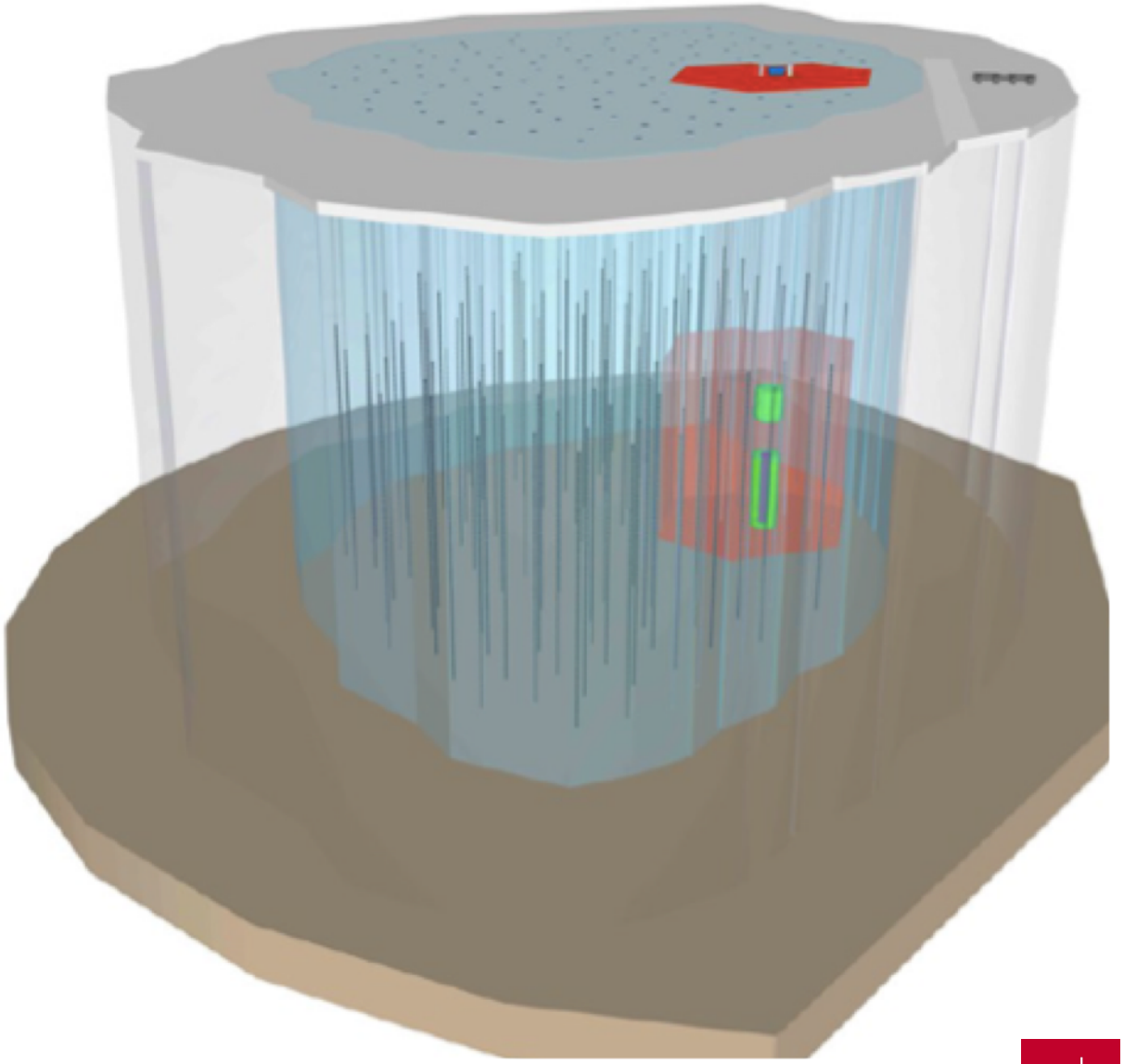
The High Energy Extension (HEX)

Goal

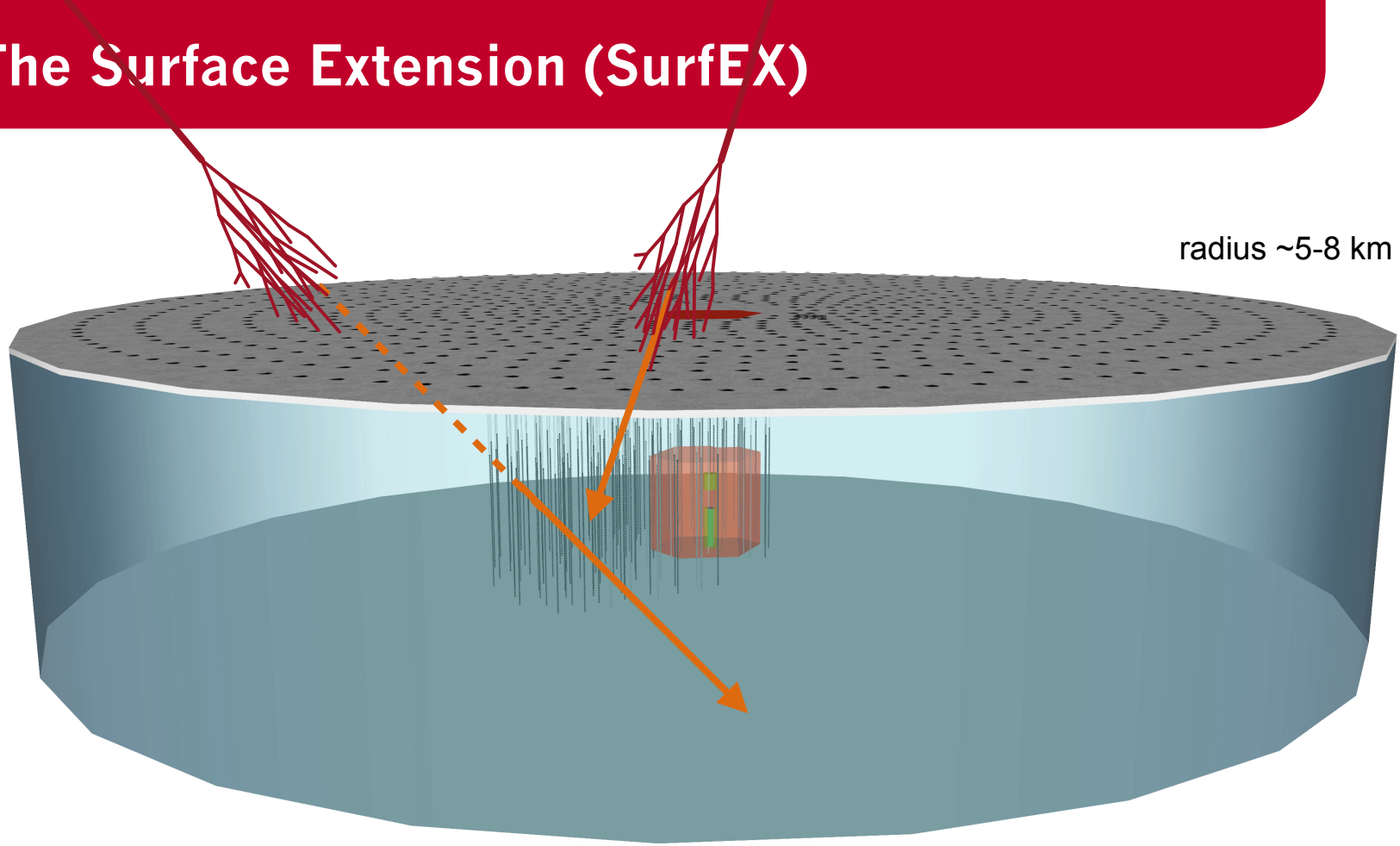
- increase effective area by factor 5
- 50 events / year
  - find point sources

Method

- increase string-spacing
  - raise threshold



The Surface Extension (SurfEX)



Air shower veto

- increase A_{eff} by
  - 50% if effective at 300 TeV
  - 100% if effective at 30 TeV

... plus cosmic ray physics

Neutrinos on Earth

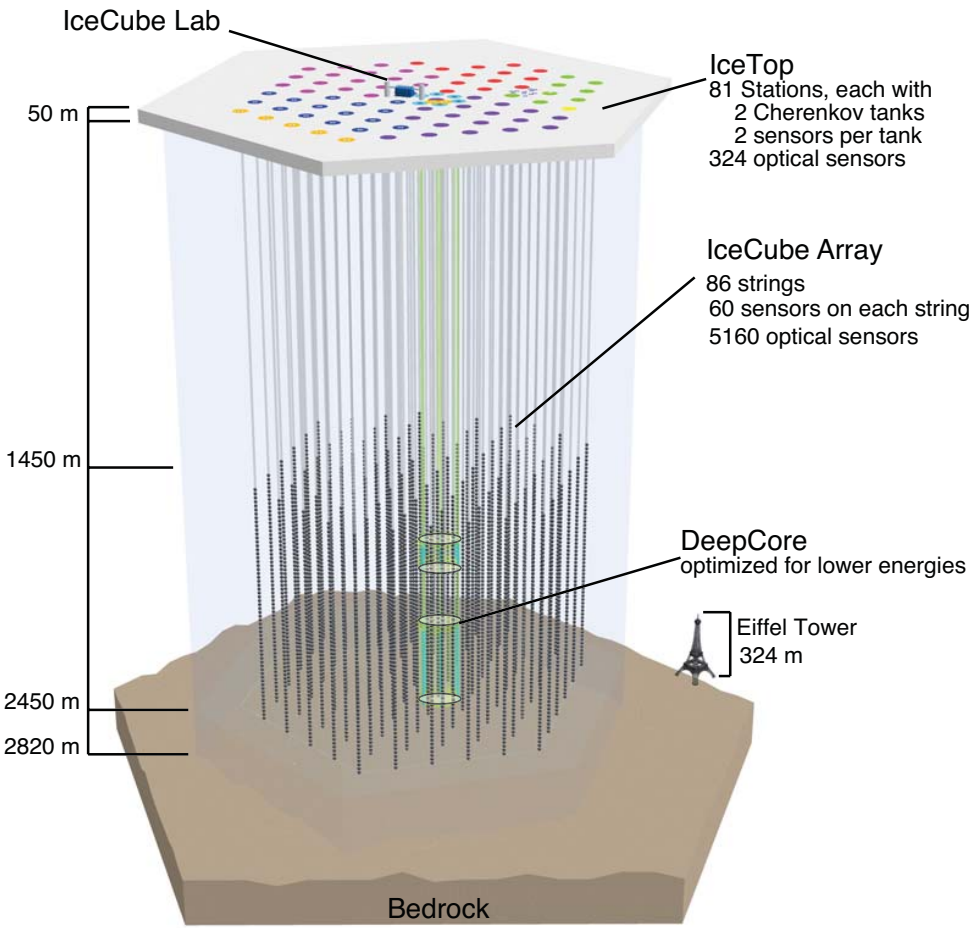
PRISMA

JG|U

IceCube

IceCube (in operation)

- 78 strings, 125m / 17m spacing
- E_{thresh} ~ 100 GeV
  - optimized for astrophysical CR-sources
  - discovered!



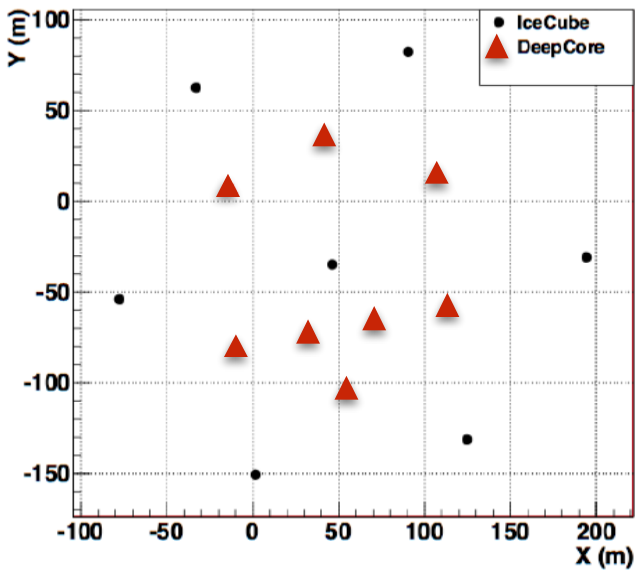
IceCube's low-energy ν detector

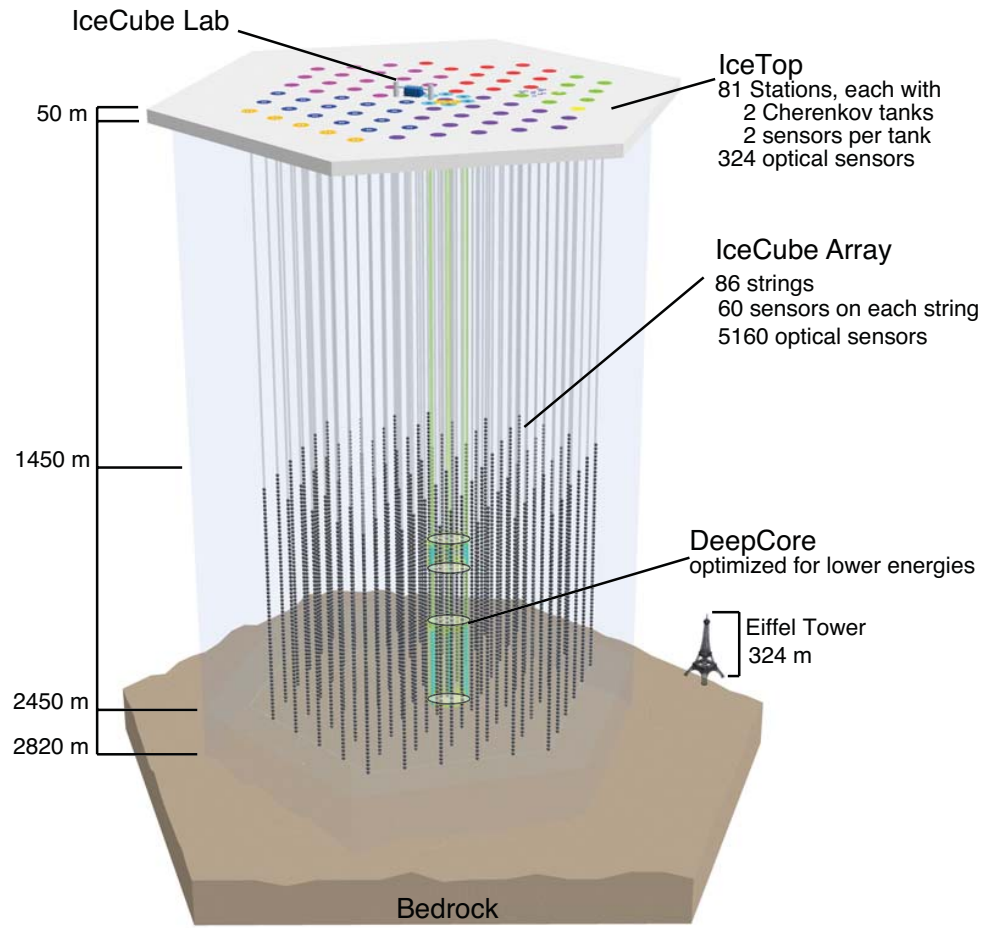
IceCube (in operation)

- 78 strings, 125m / 17m spacing
- E_{thresh} ~ 100 GeV

DeepCore (in operation)

- +8 strings, 72m / 7m spacing
- E_{thresh} ~ 10 GeV





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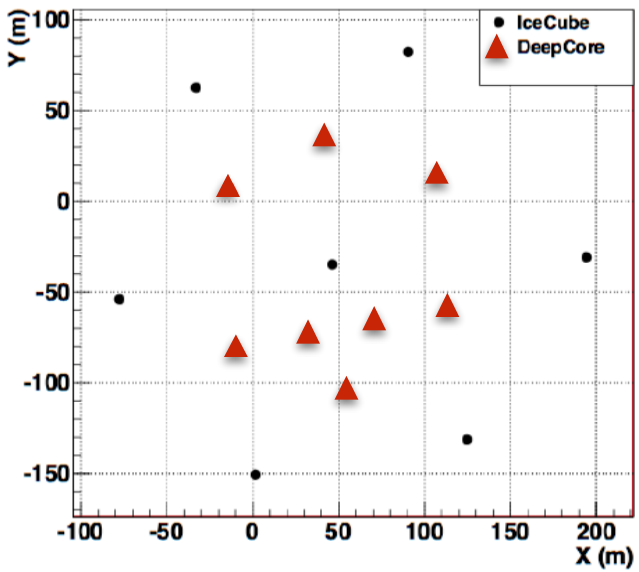
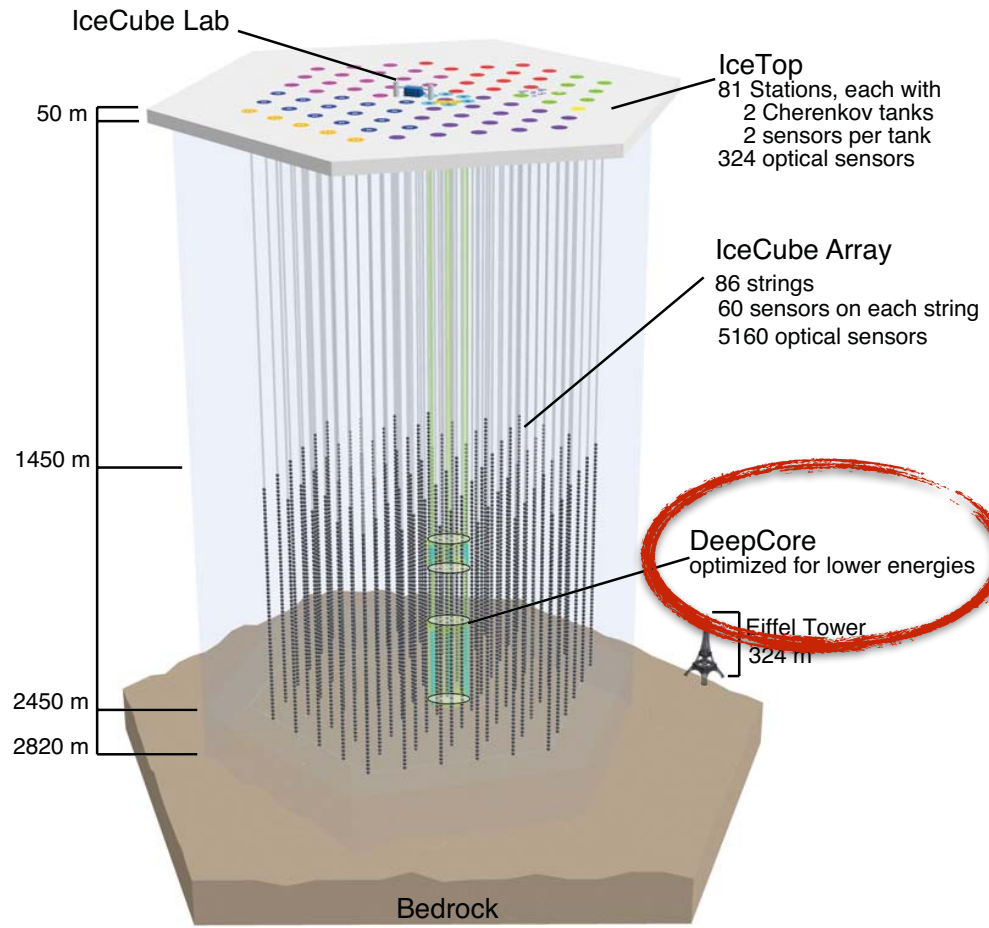




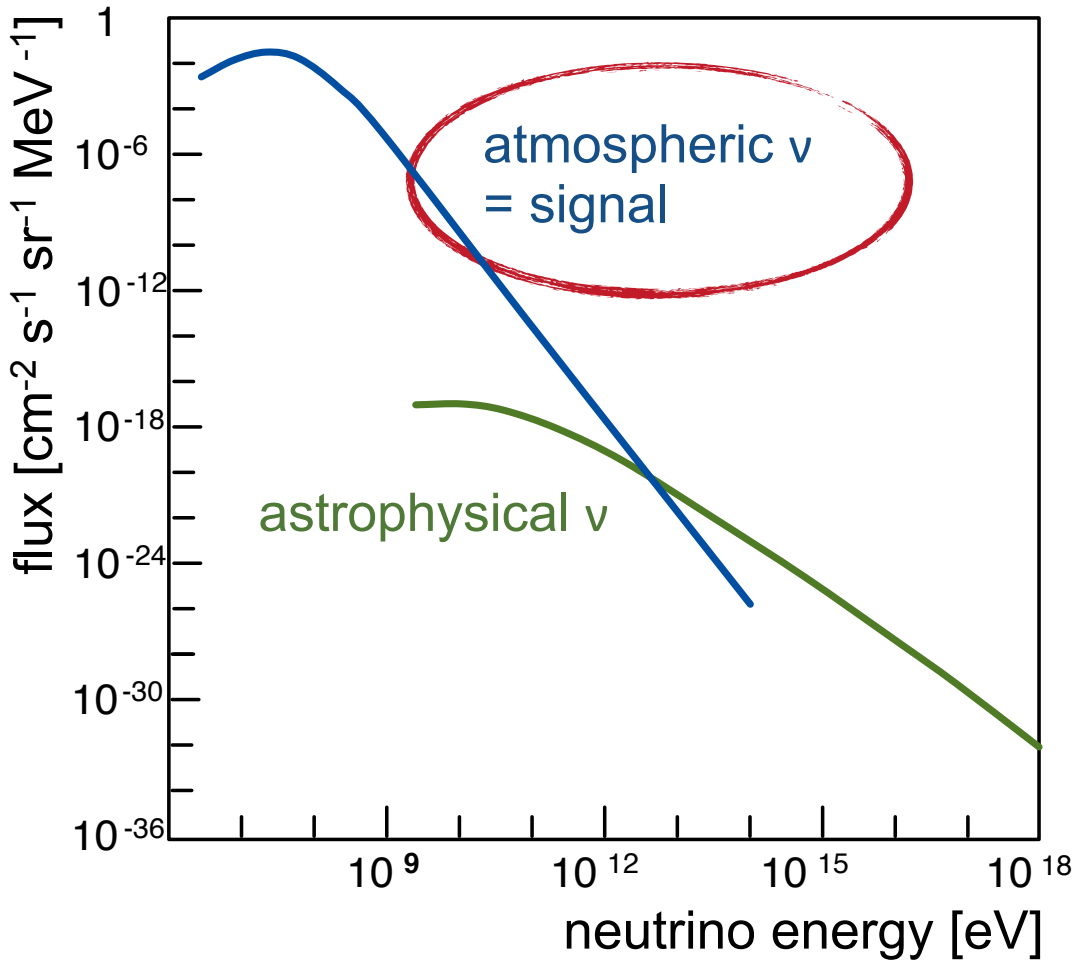
Atmospheric neutrinos

Event rates (trigger level)

- $\nu_\mu \sim 10^5$ / year
- $\nu_e \sim 10^3$ / year

➔ Huge data sample

- cosmic ray physics
- ν-oscillation physics



Neutrino Oscillations

Weak interactions couple to superpositions of neutrino mass eigenstates:

$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

$$|\nu_\mu\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

Time evolution

$$|\nu_{1,2}\rangle \to e^{-iE_{1,2}t}|\nu_{1,2}\rangle$$

Flavor transition probability

$$P_{\mu\to e}(t) \equiv |\langle\nu_e|e^{-i\hat{H}t}|\nu_\mu\rangle|^2$$

$$= \left| -\sin\theta\cos\theta\, e^{-iE_1 t} + \sin\theta\cos\theta\, e^{-iE_2 t}\right|^2$$

$$= \sin^2(2\theta)\sin^2\left(\frac{(E_1 - E_2)t}{2}\right)$$

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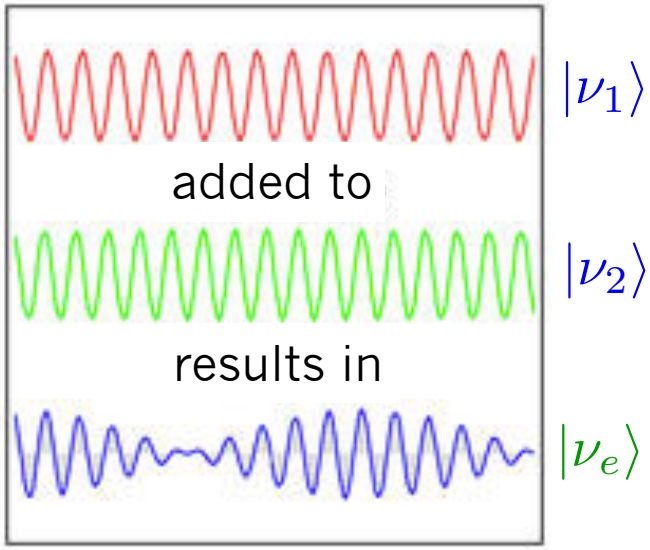
Sound wave analogy



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Neutrino Oscillations

$$P_{e\to\mu}(t) = \sin^2(2\theta)\sin^2\left(\frac{(E_1 - E_2)t}{2}\right)$$

Using $m \ll E$ and $t \simeq L$:

$$P_{e\to\mu}(t) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

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$$\Delta m^2 \equiv m_2^2 - m_1^2$$

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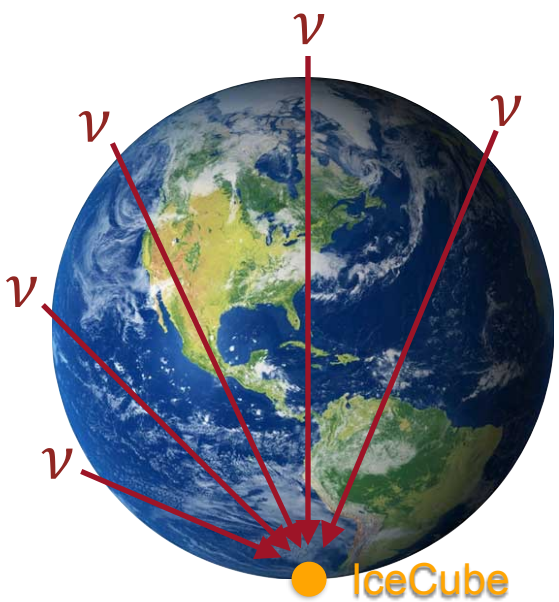
Three neutrino flavours:

- two Δm^2 and two signs (Δm^2_{21}, Δm^2_{32})
- three mixing angles (θ_{12}, θ_{23}, θ_{13})

Neutrinos vs. earth

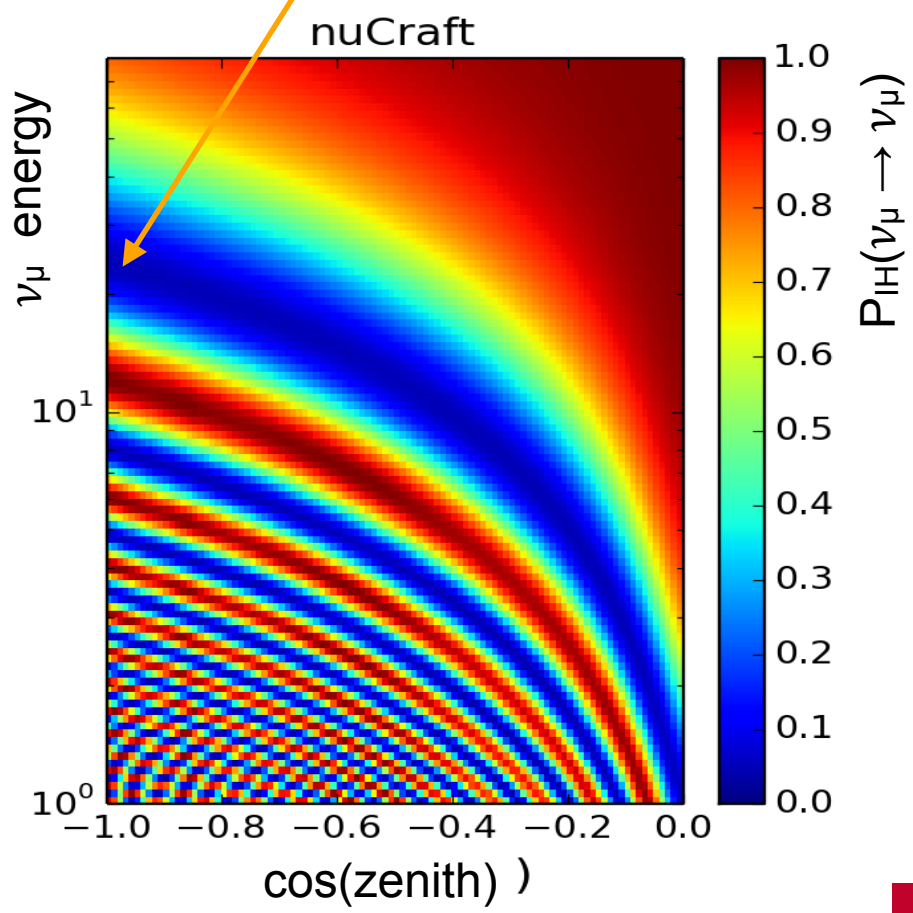
Atmospheric neutrinos

- ν-oscillations in earth
  - wide range of L/E
- measure only ν_μ
  - sensitive to θ_{23}, Δm_{32}^2

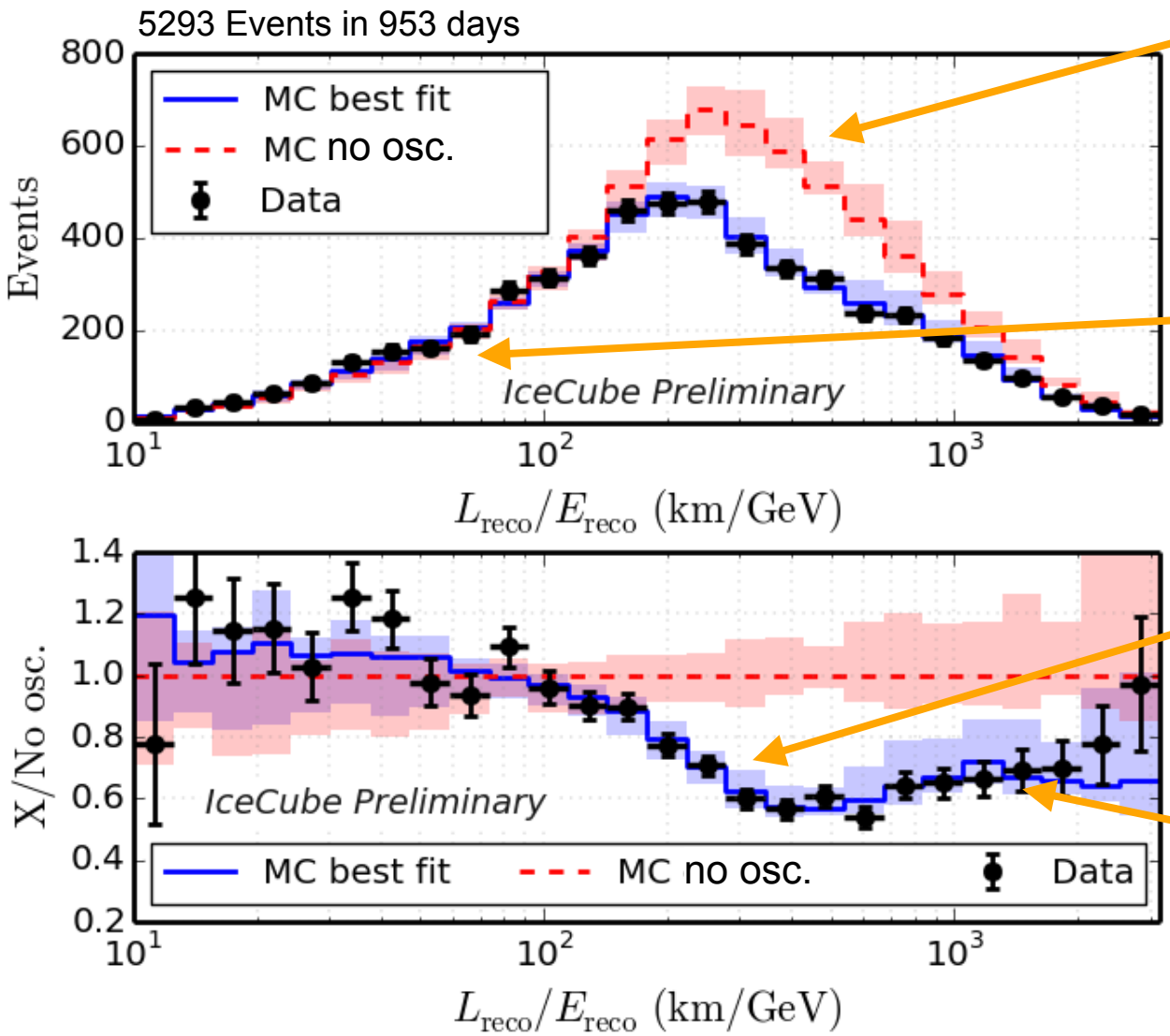


1st oscillation minimum

- $L_{max} = 12 \cdot 10^3$ km
- $E_\nu \sim 20$ GeV



Oscillation analysis



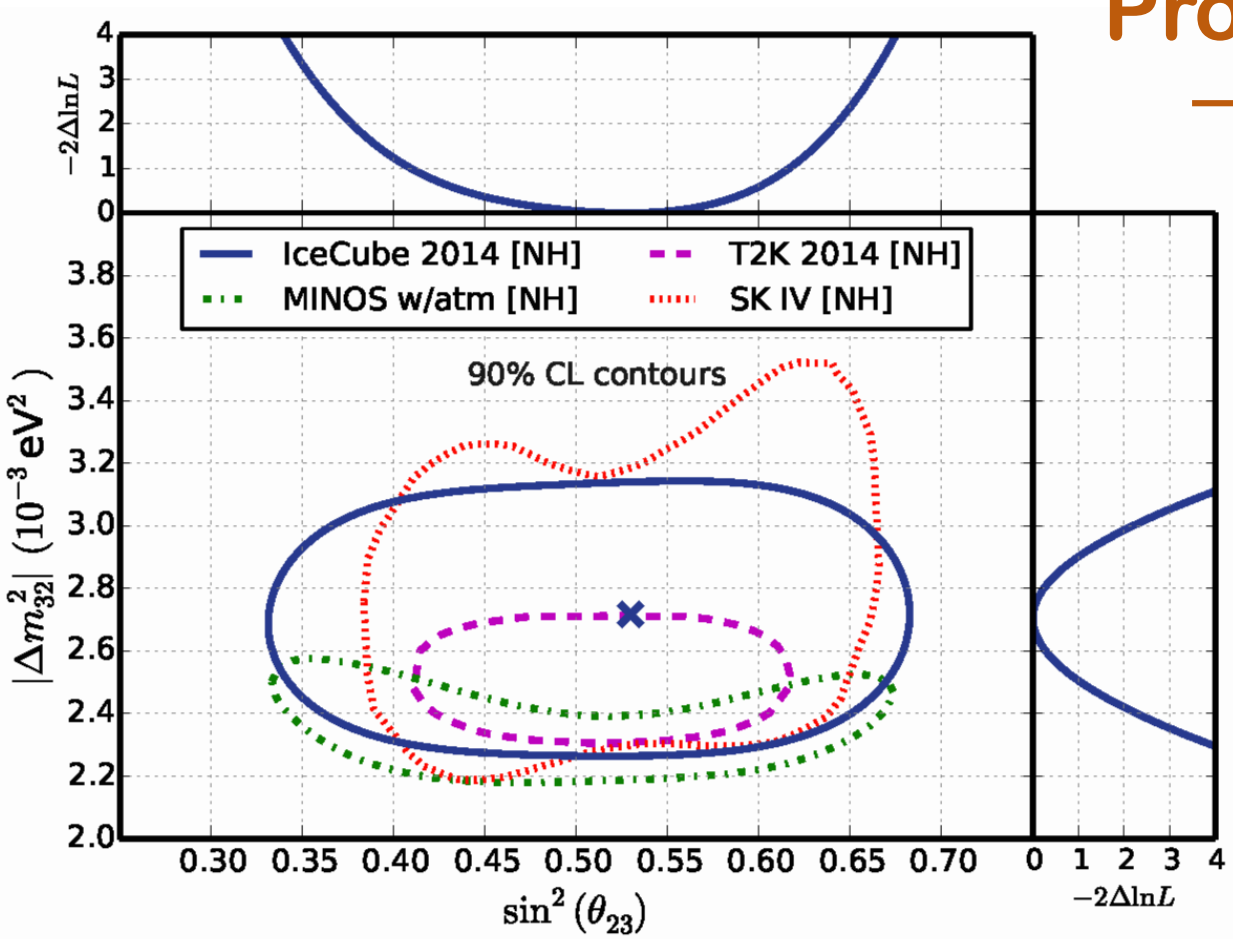
sample peaks
at oscillation minimum

good agreement (limited
statistics) in control region

good description
of oscillation region

observing oscillation
maximum and rise

Oscillation result



Proof of principle → competitive result!

What next?

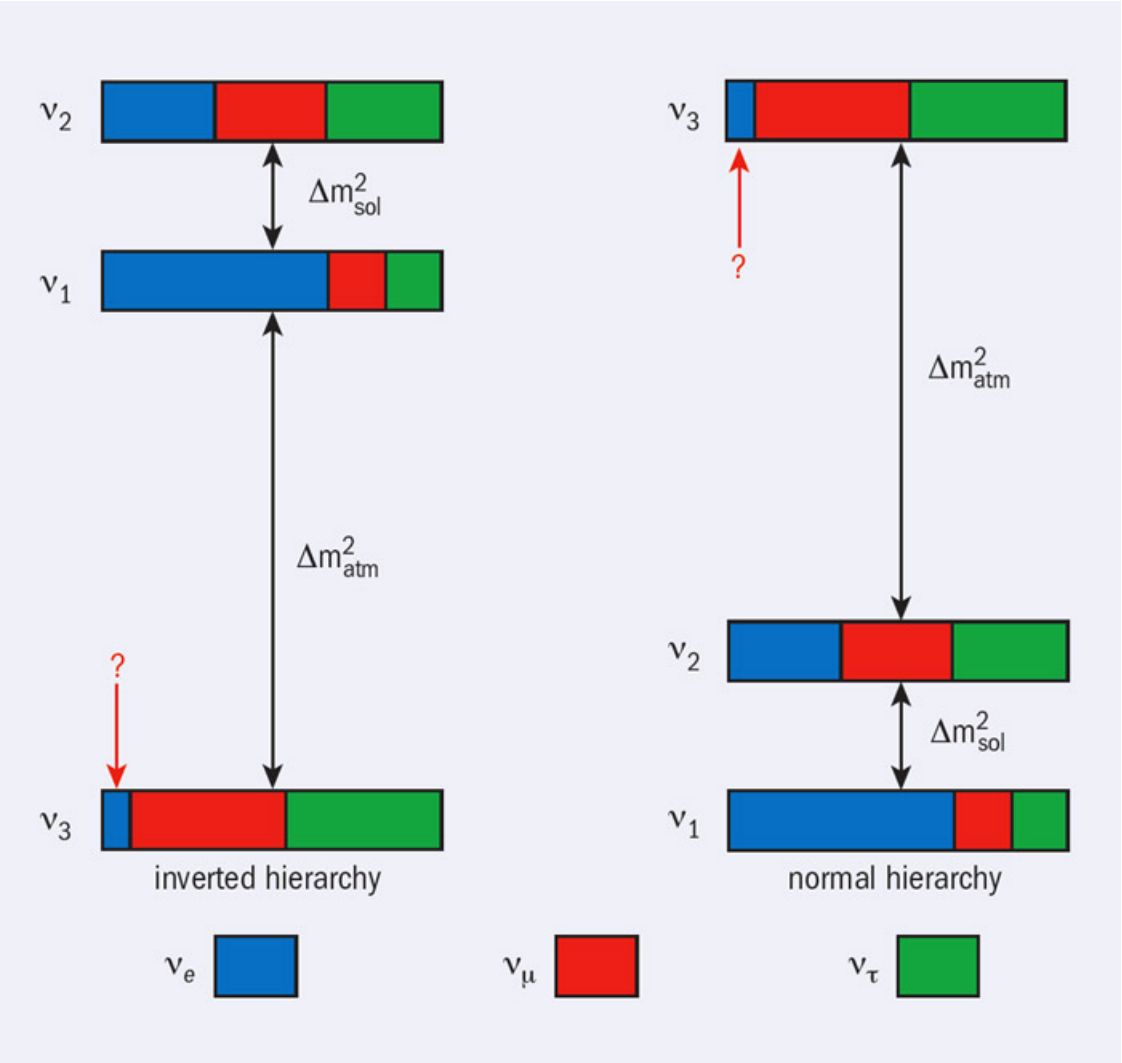
Neutrino mass hierarchy

Oscillation parameters

- amplitude
  - mixing angles
- frequency
  - |mass splitting|

Order of mass eigenstates?

- matter effects
  - break degeneracy
- for $\nu_2 \leftrightarrow \nu_1$
  - solar neutrino oscillations ✔
- for $\nu_3 \leftrightarrow \nu_2$?



Neutrinos vs. earth

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- ν-oscillations in earth
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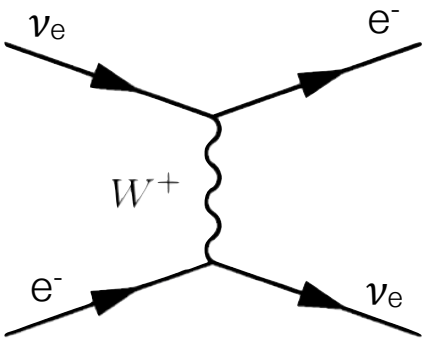
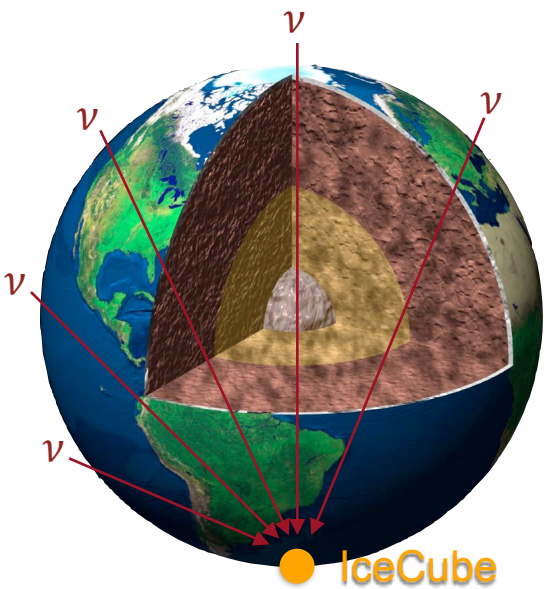
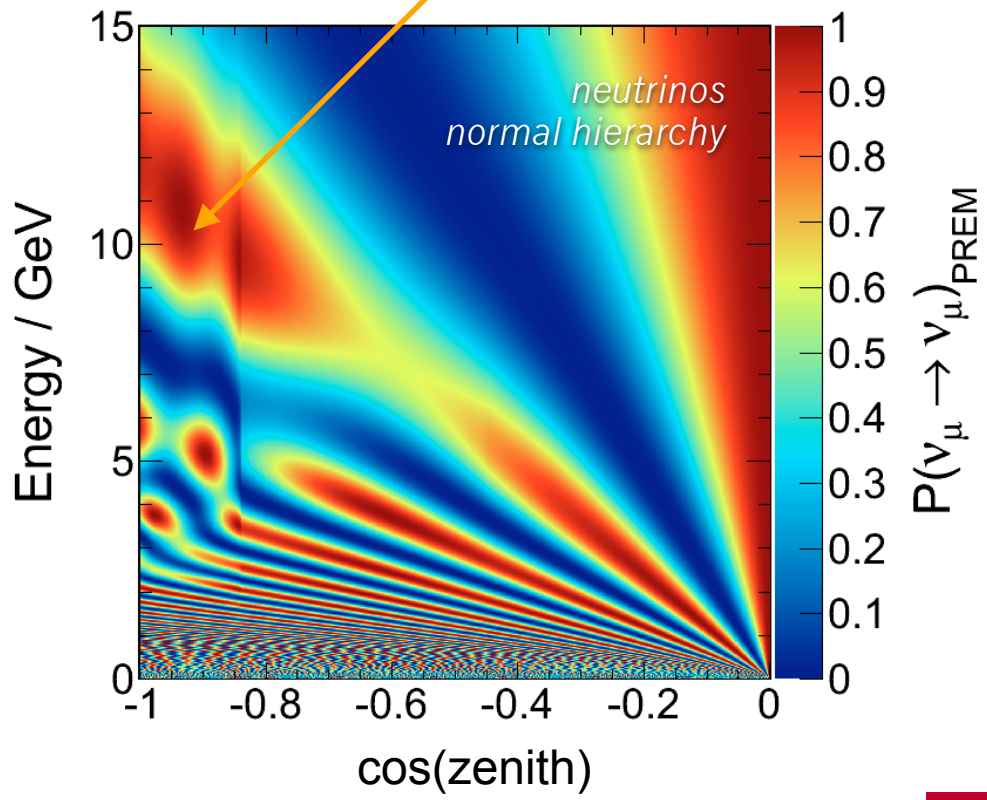
- matter effects
  - mass hierarchy



matter effects

- strongest in core
- E_ν ~ 3-15 GeV





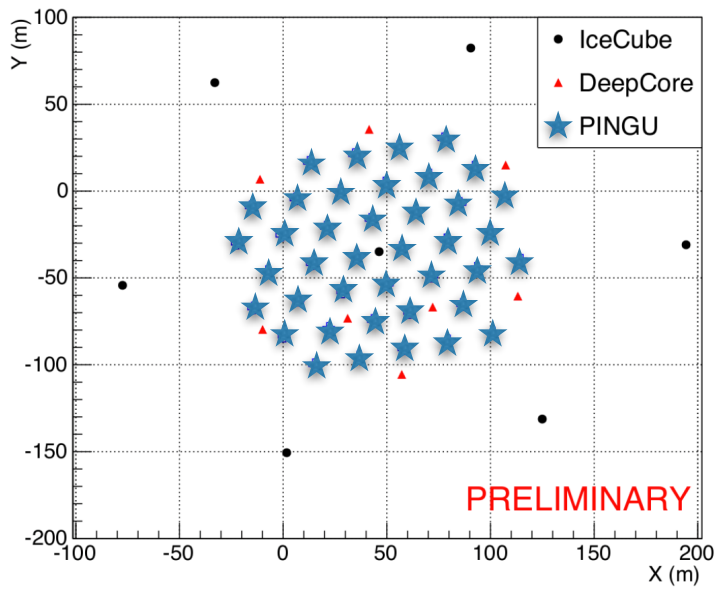
IceCube's low-energy ν extension

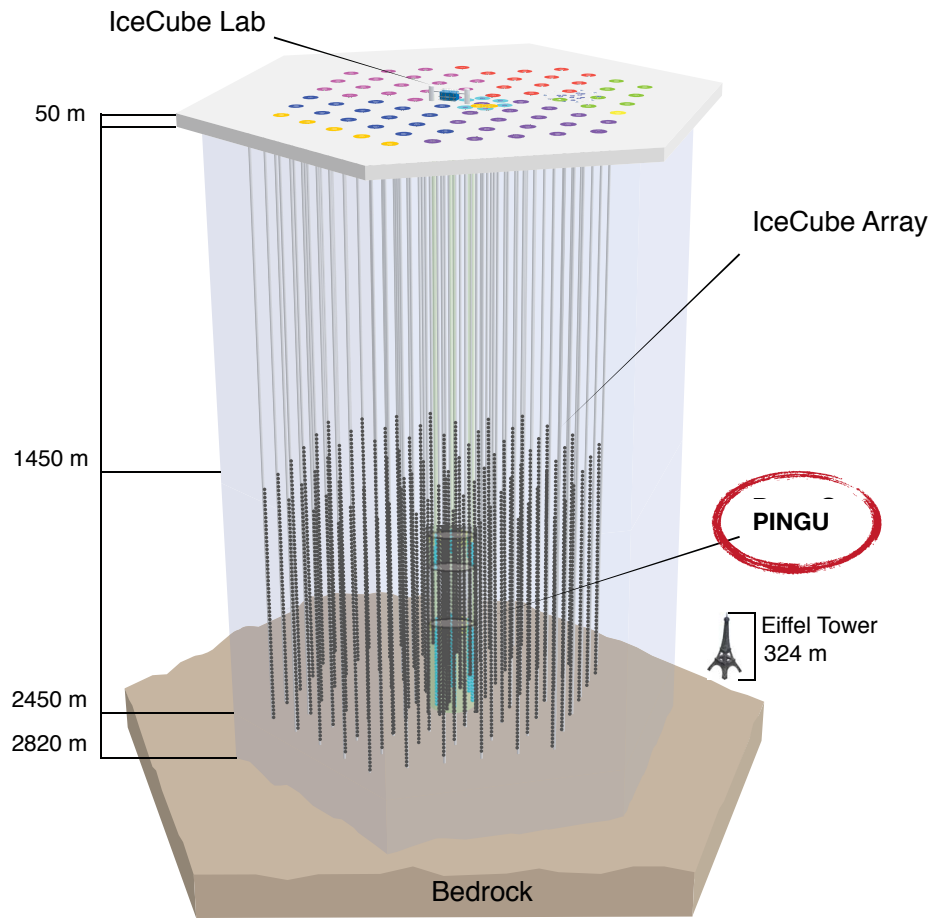
IceCube (in operation)

- 78 strings, 125m / 17m spacing
- E_{thresh} ~ 100 GeV

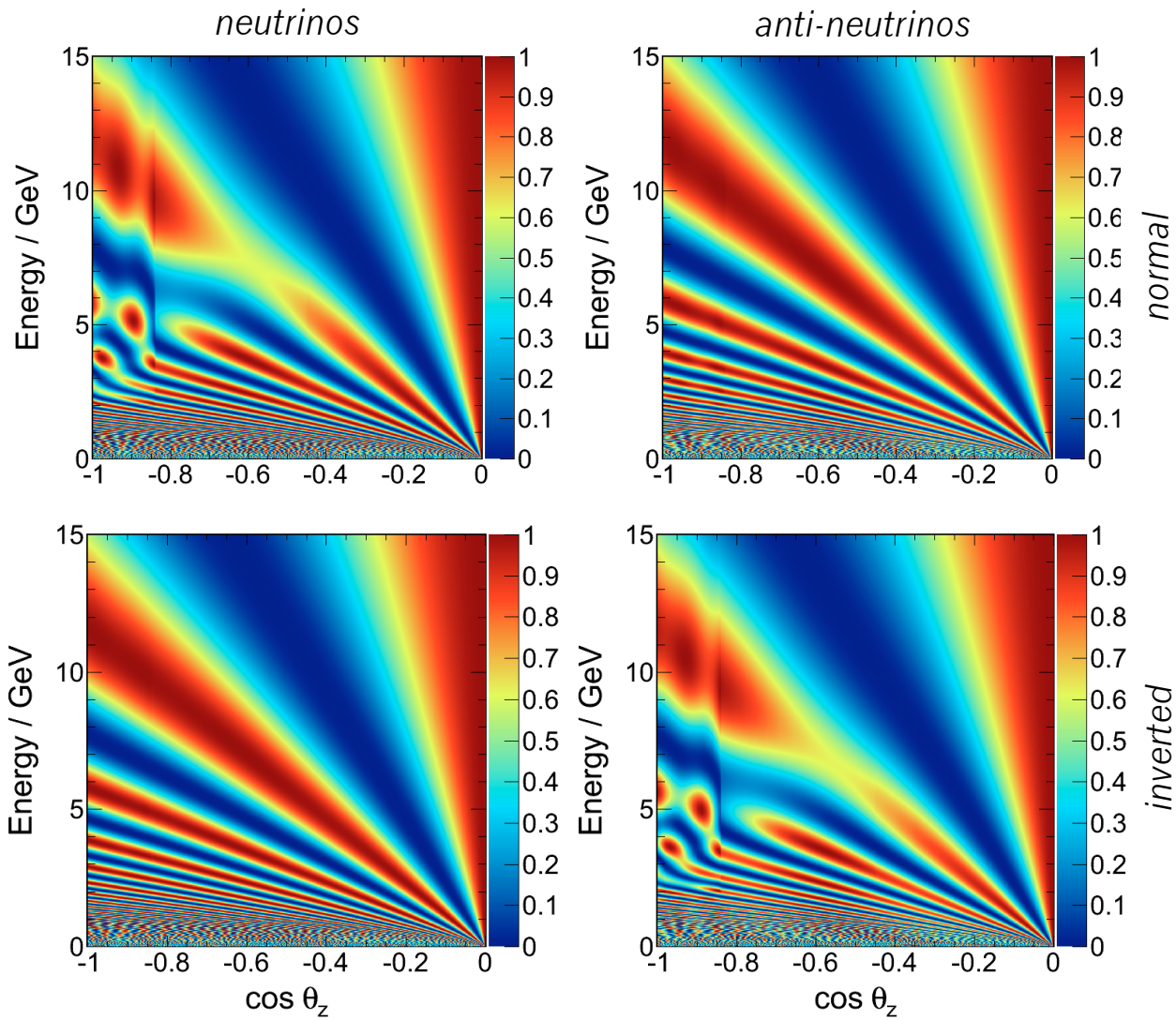
PINGU (proposed)

- +40 strings, 25m / 3m spacing
- E_{thresh} ~ 1 GeV
  - neutrino mass hierarchy





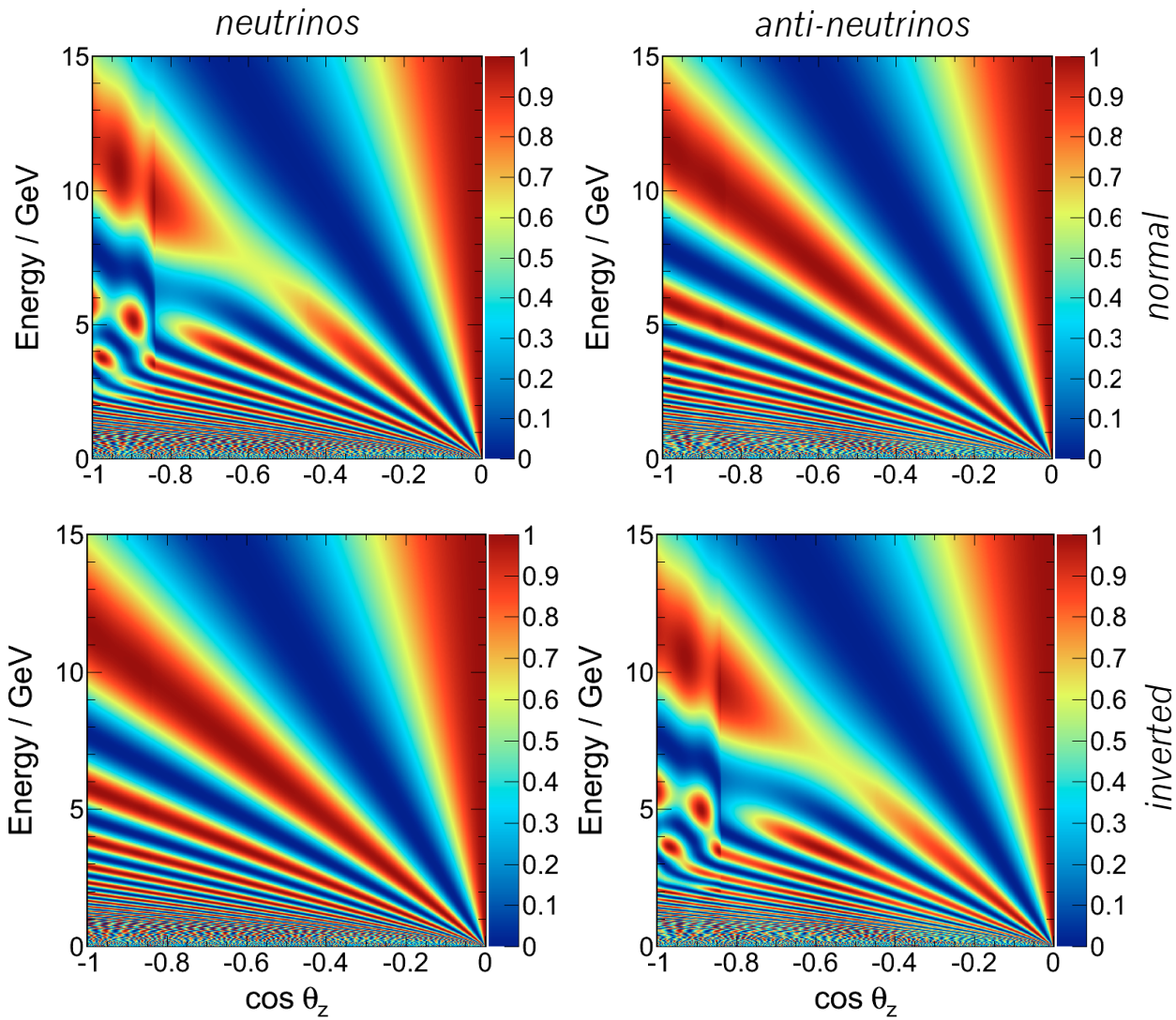
Neutrino Mass Hierarchy



Neutrino Mass Hierarchy

Signal

- matter effects (MSW)
  - inverted for $\nu \leftrightarrow \bar{\nu}$



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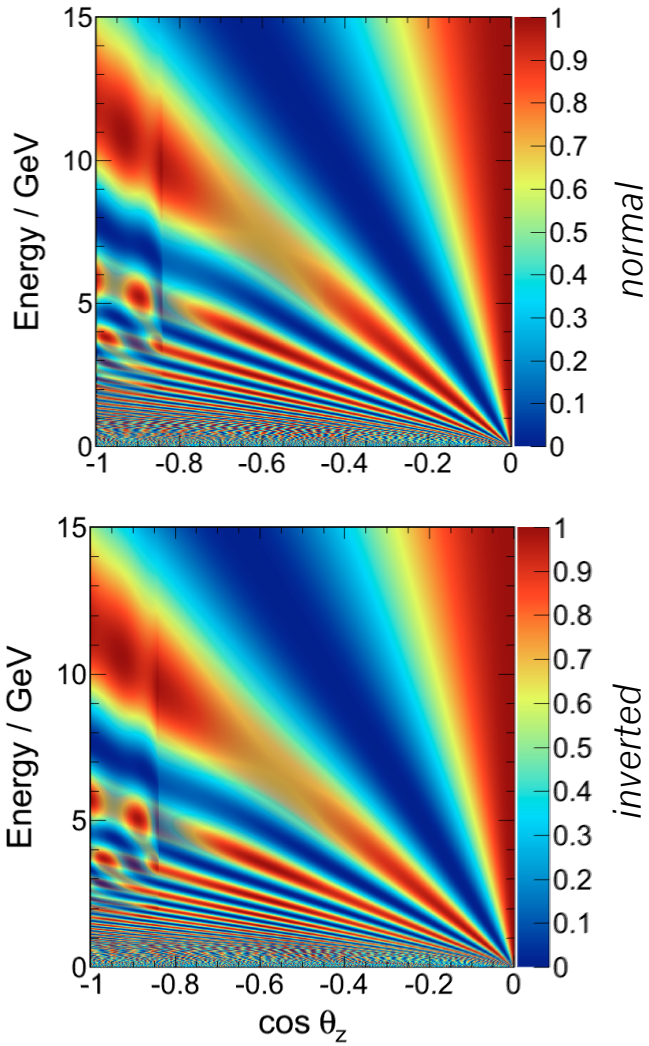
- *similar* flux from atmosphere

  $\Phi(\nu)/\Phi(\bar{\nu}) \sim 1 \pm 0.1$



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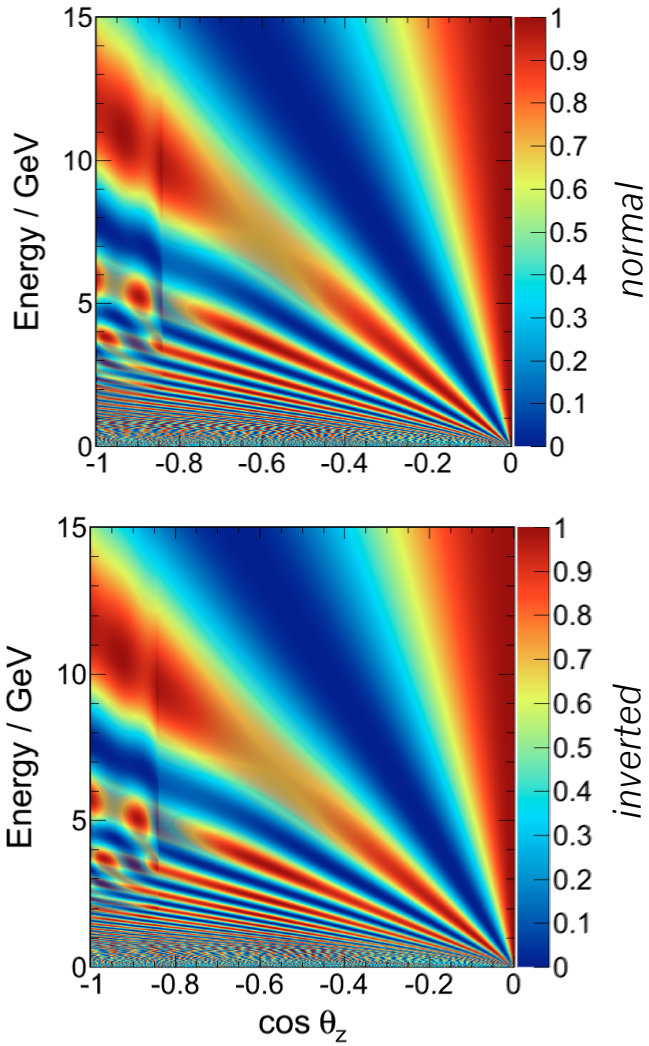
- x-sections *differ*

  $\sigma(\nu N)/\sigma(\bar{\nu} N) \sim 2$

  ➔ few % effect



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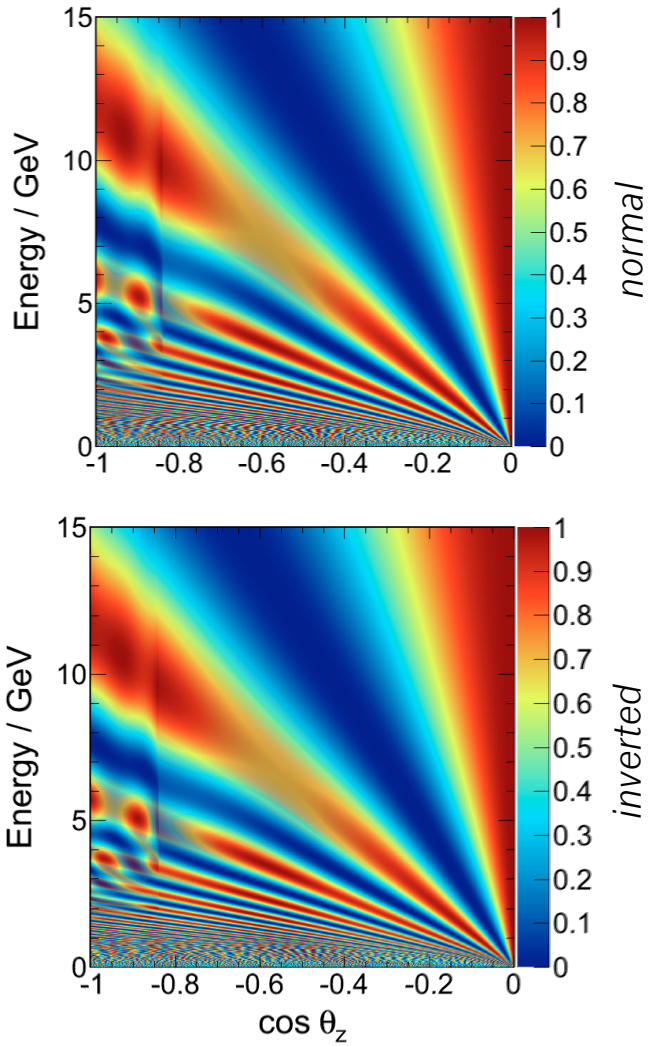
  → few % effect

Requirements

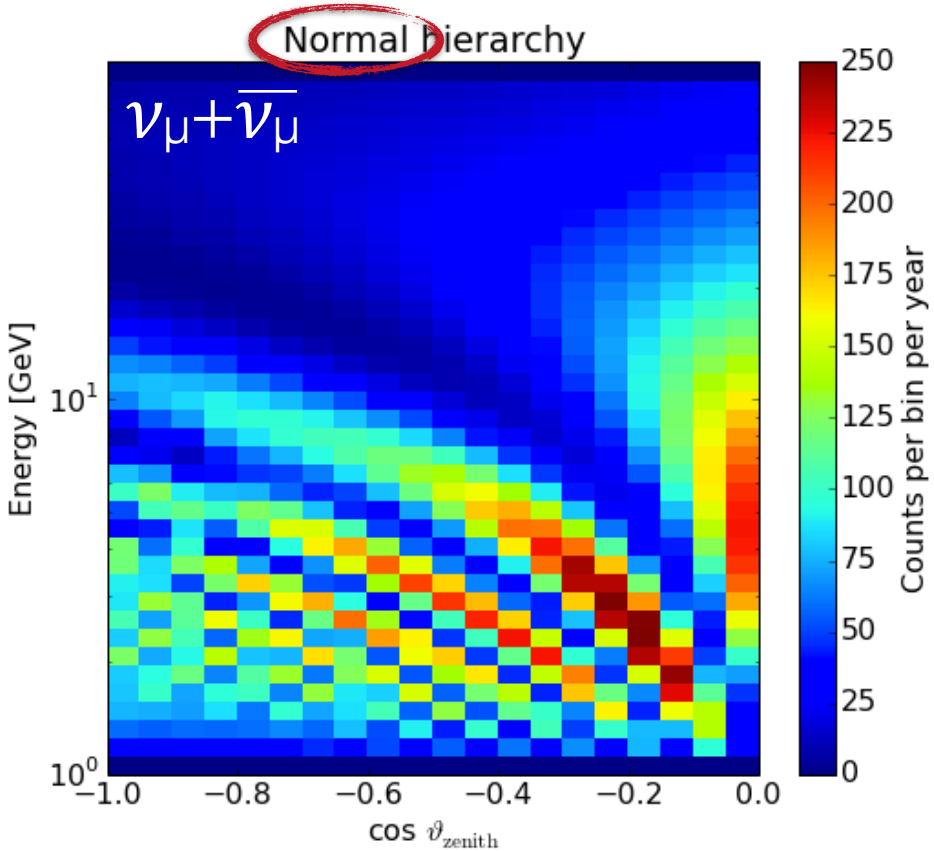
- high statistics
- very good control of systematic effects



Signatures in PINGU

Detected events (1-80GeV, after cuts)

- ~50k ν_μ + anti-ν_μ per year
- ~38k ν_e + anti-ν_e per year
  - small but distinct signature



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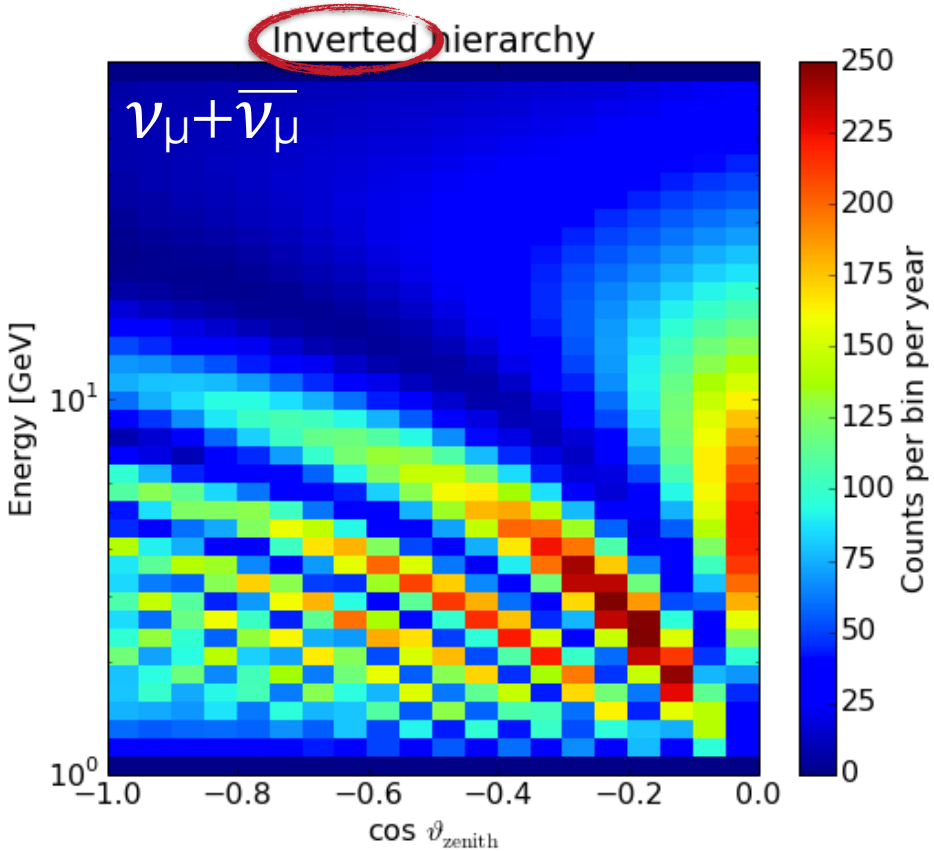

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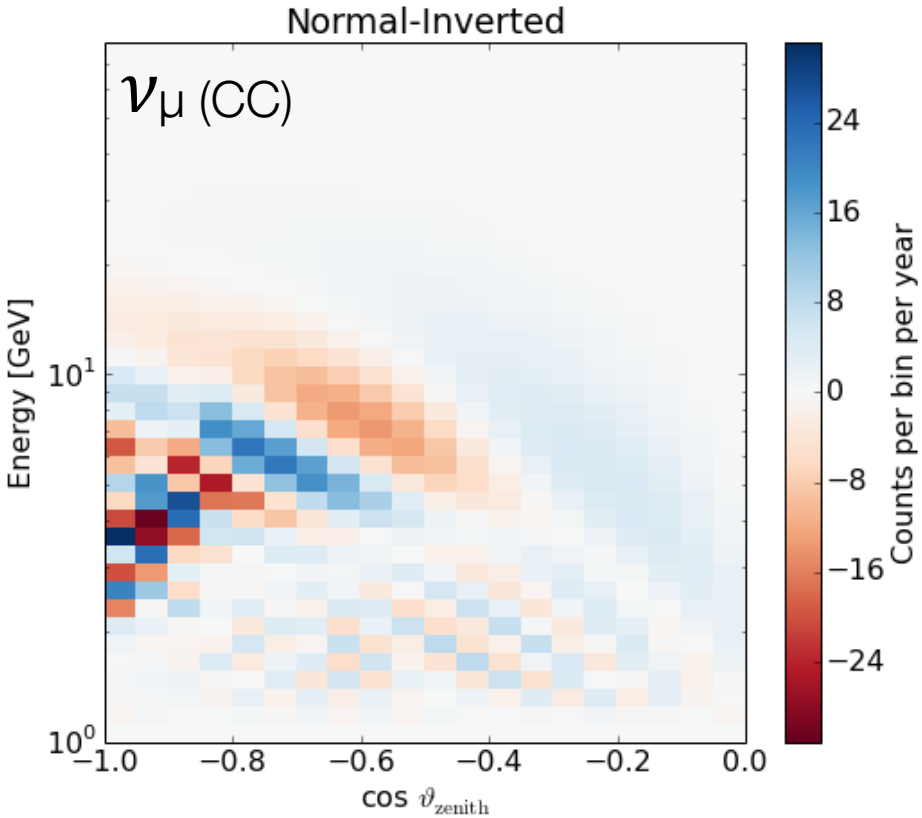


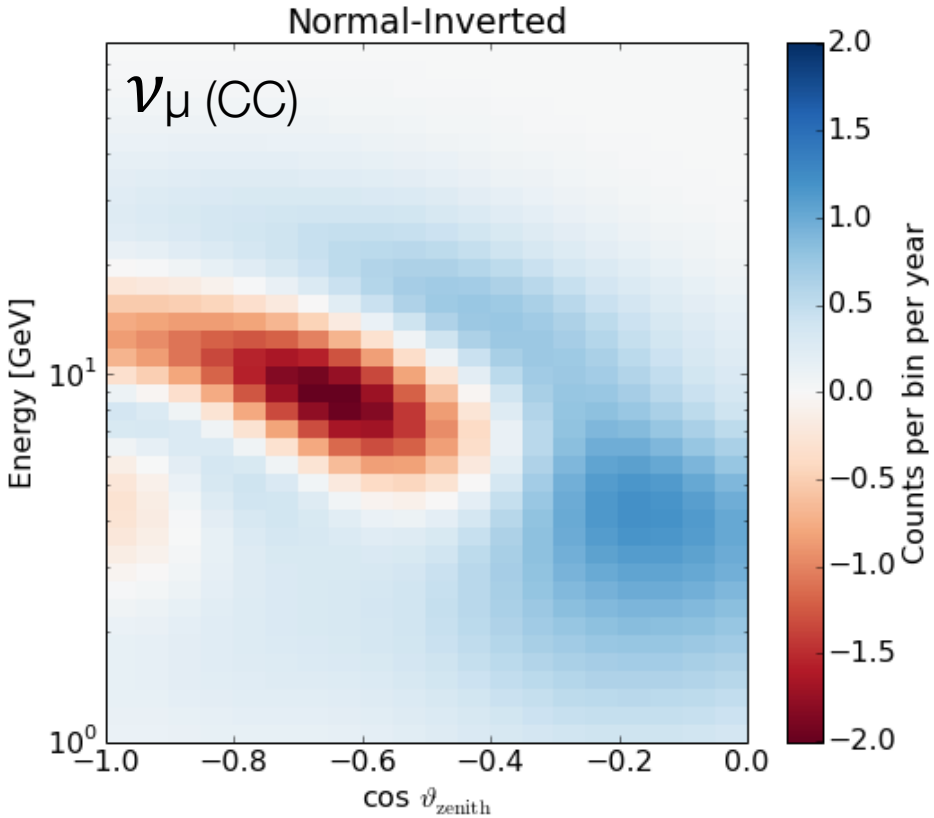
Signatures in PINGU

Detected events (1-80GeV, after cuts)

- ~50k ν_μ + anti-ν_μ per year
- ~38k ν_e + anti-ν_e per year
  - small but distinct signature

Detector effects

- energy resolution
  - ~20% above 10GeV
- directional resolution
  - improving with E



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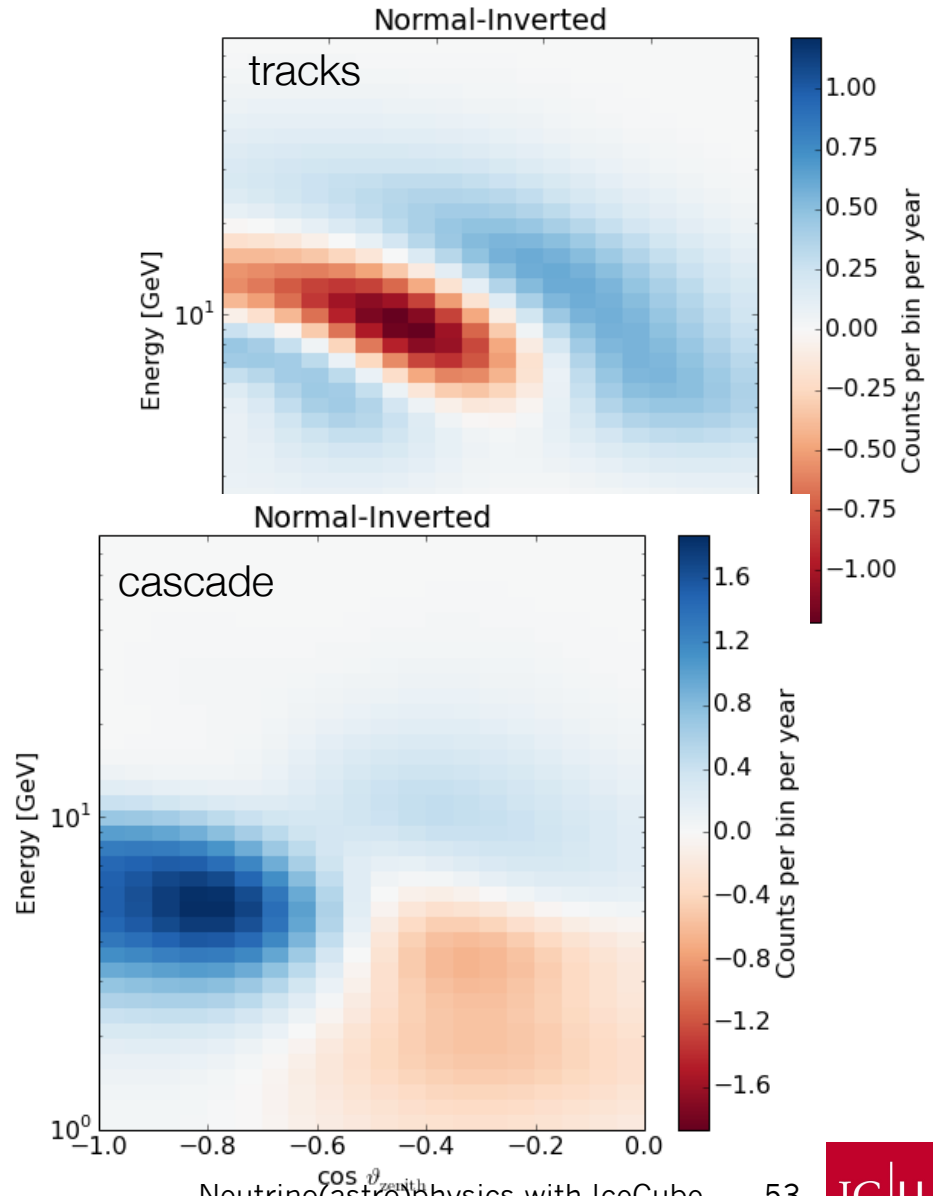
Particle identification

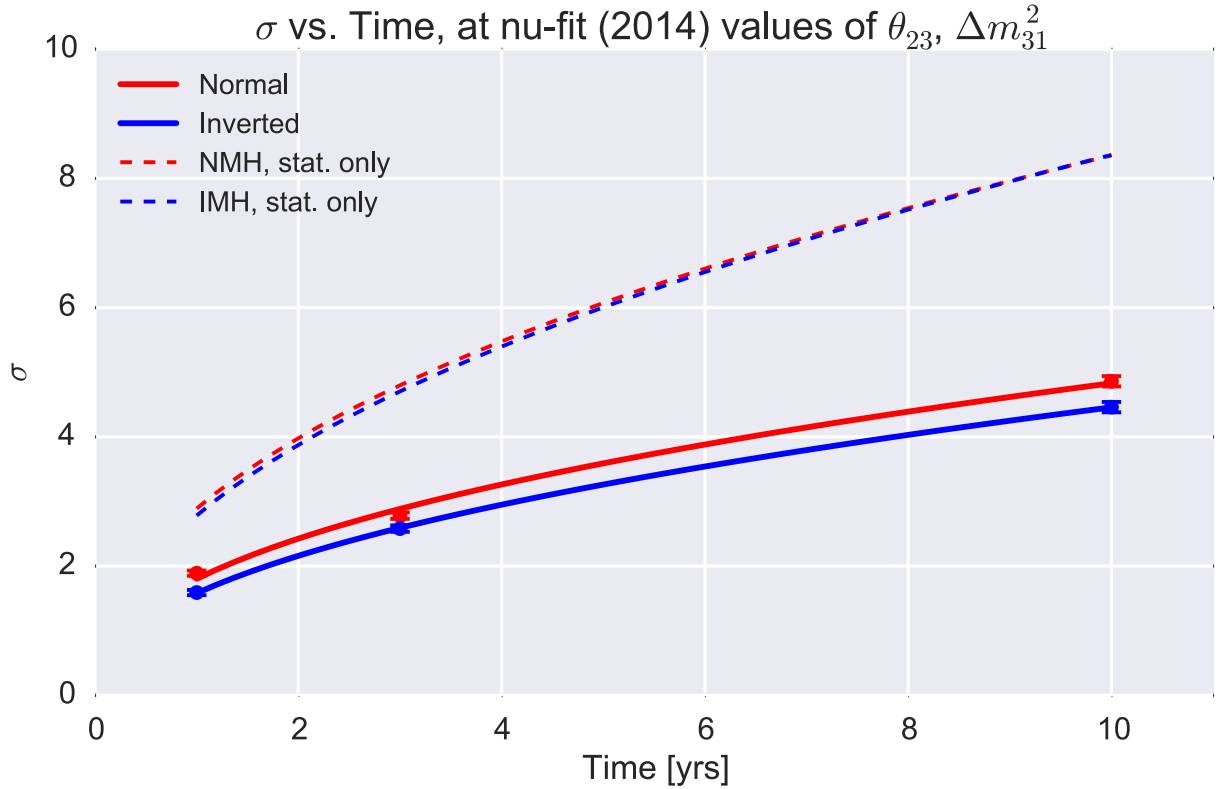
- ν_μ(CC) = *tracks*
- ν_e (CC) + ν_X (NC) = *cascades*
  - quite distinct



Results: neutrino mass hierarchy

Analysis results

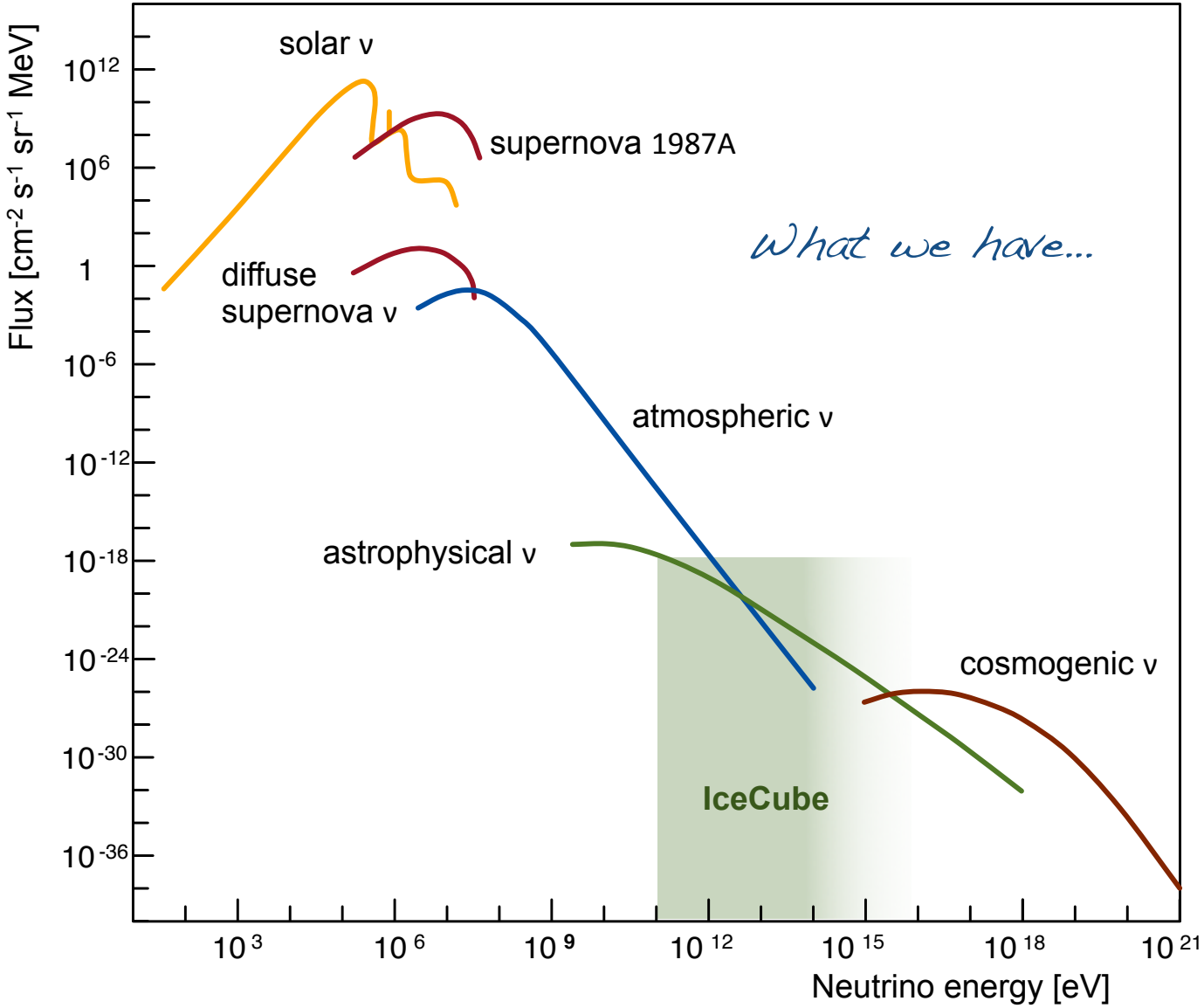
- for worst case
  (θ_{23} = 42.3°)
- hierarchy significance
  - ~3σ in 3.5 years



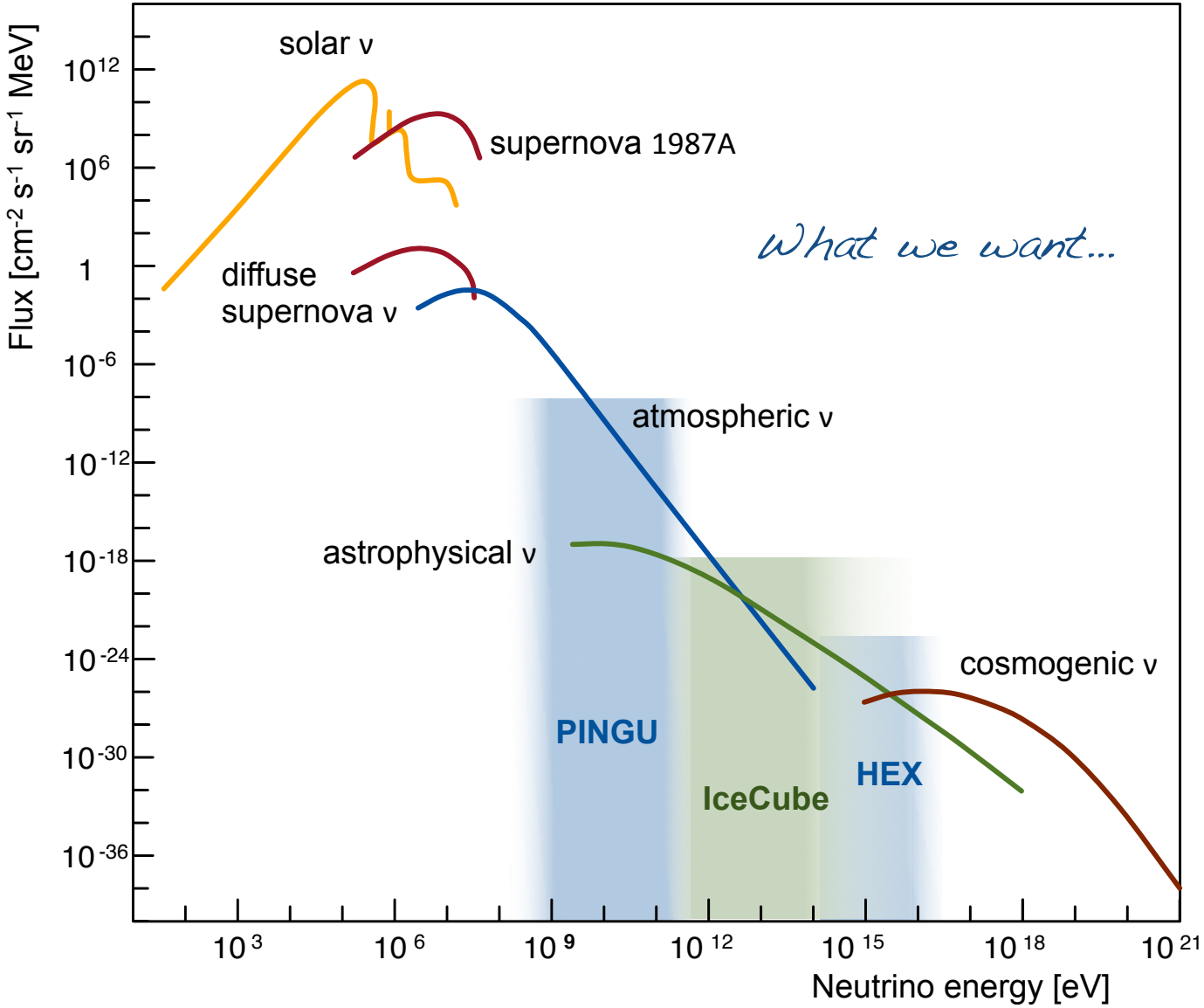
Comparison to others

- PINGU could be the **first** detector
  to make this challenging measurement

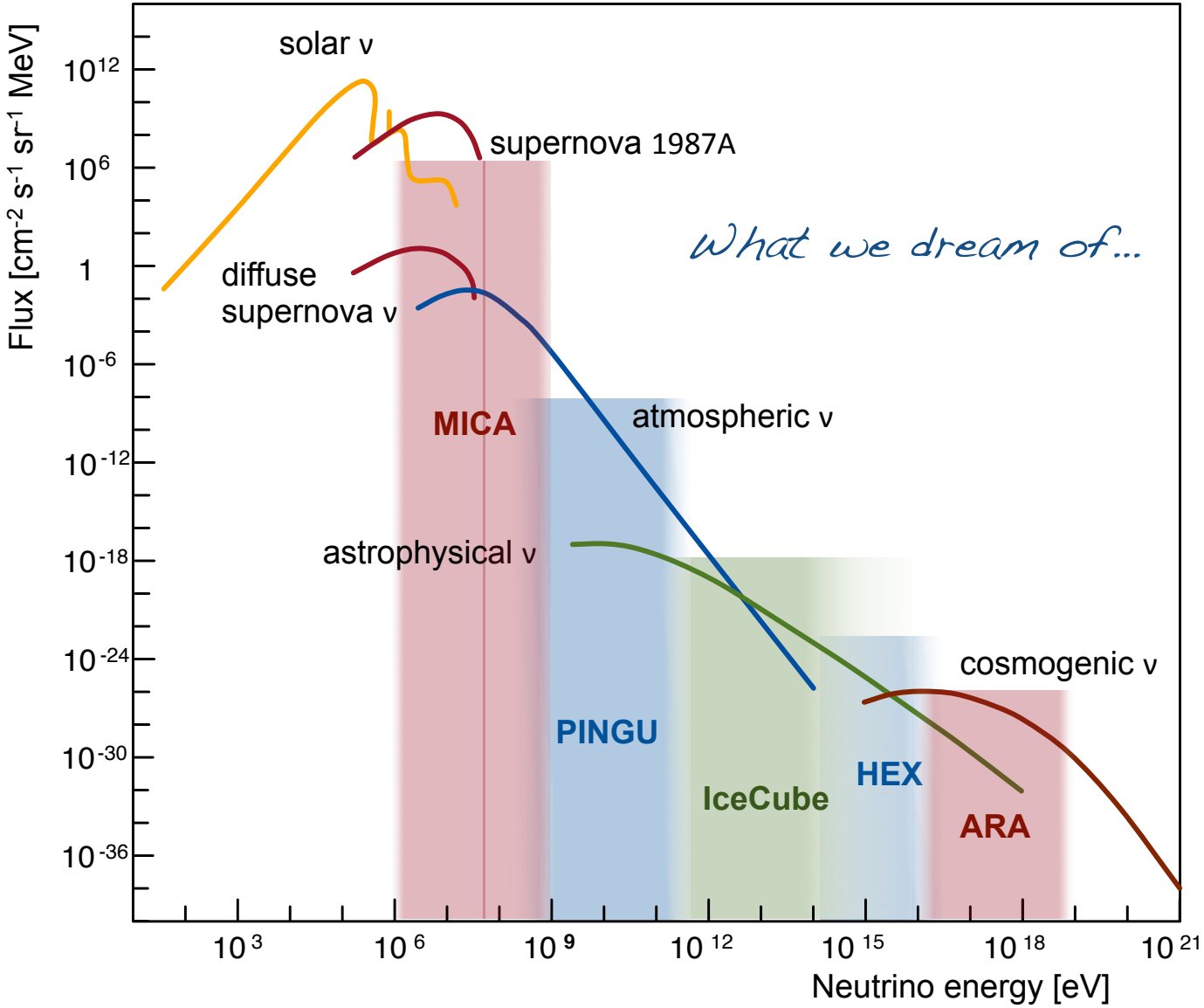
Outlook


Flux [cm-2 s-1 sr-1 MeV]
10^12
10^6
1
10^-6
10^-12
10^-18
10^-24
10^-30
10^-36
solar ν
supernova 1987A
What we have...
diffuse
supernova ν
atmospheric ν
astrophysical ν
cosmogenic ν
IceCube
10^3
10^6
10^9
10^12
10^15
10^18
10^21
Neutrino energy [eV]

Outlook


solar ν
supernova 1987A
What we want...
diffuse
supernova ν
atmospheric ν
astrophysical ν
cosmogenic ν
PINGU
IceCube
HEX
Flux [cm-2 s-1 sr-1 MeV]
10^12
10^6
1
10^-6
10^-12
10^-18
10^-24
10^-30
10^-36
10^3
10^6
10^9
10^12
10^15
10^18
10^21
Neutrino energy [eV]

Outlook


Flux [cm-2 s-1 sr-1 MeV]
10^12
10^6
1
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10^-18
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10^-36
solar ν
supernova 1987A
What we dream of...
diffuse
supernova ν
MICA
atmospheric ν
astrophysical ν
cosmogenic ν
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HEX
IceCube
ARA
10^3
10^6
10^9
10^12
10^15
10^18
10^21
Neutrino energy [eV]

Conclusion

High-energy neutrinos can tell us about the sources of cosmic rays

➔ IceCube just found first neutrinos from outside solar system

Oscillation of low-energy neutrinos can tell us about their fundamental properties

➔ IceCube can also measure these

IceCube-Gen2 will bring major advances for both of these fields

Thank you!

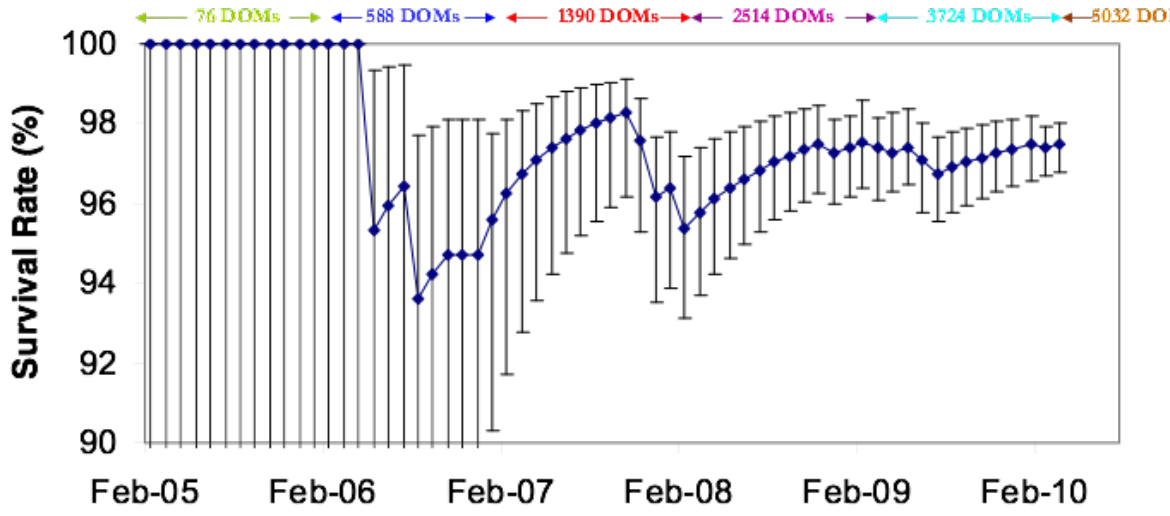
Performance

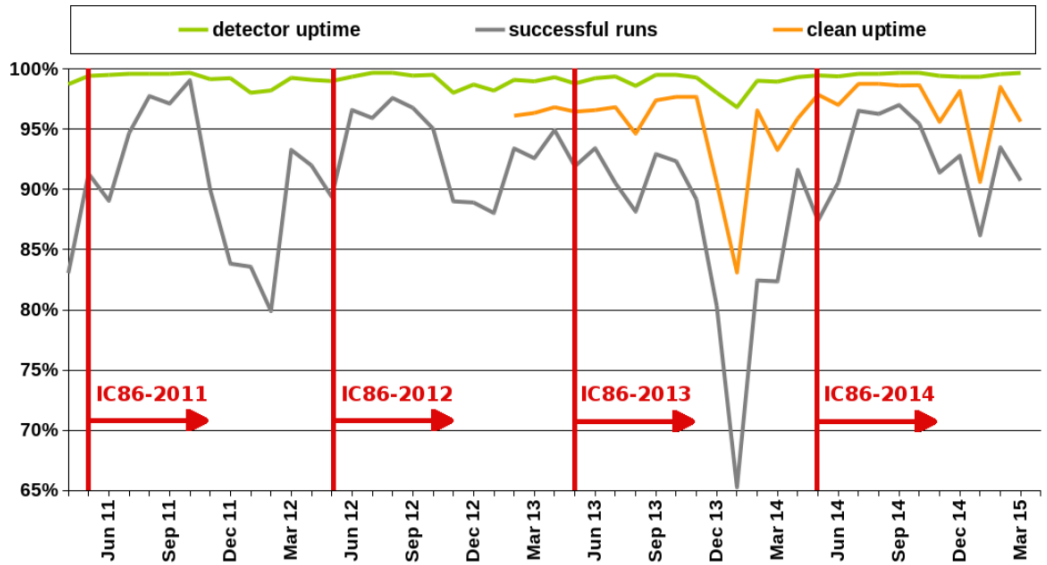
Installation

- 5484 optical modules installed
  - 128 DOMs failed (during installation)
  - 50% fixed again
- expected statistical lifetime
  - 14.000 years

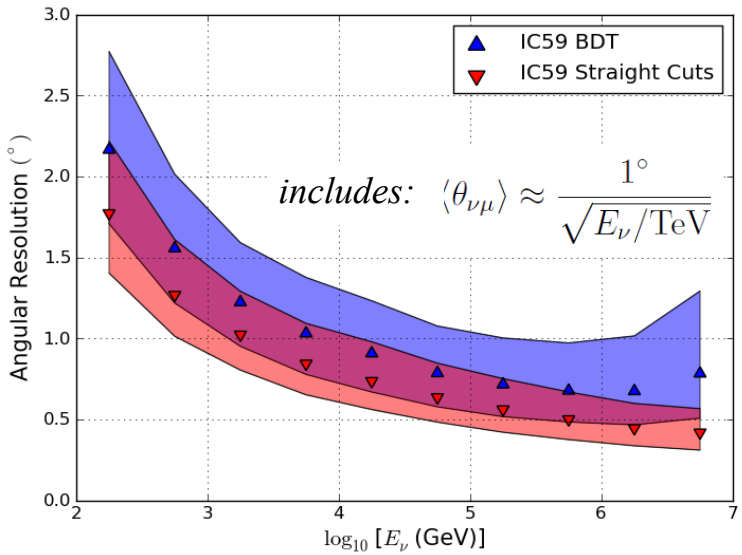
Data-taking

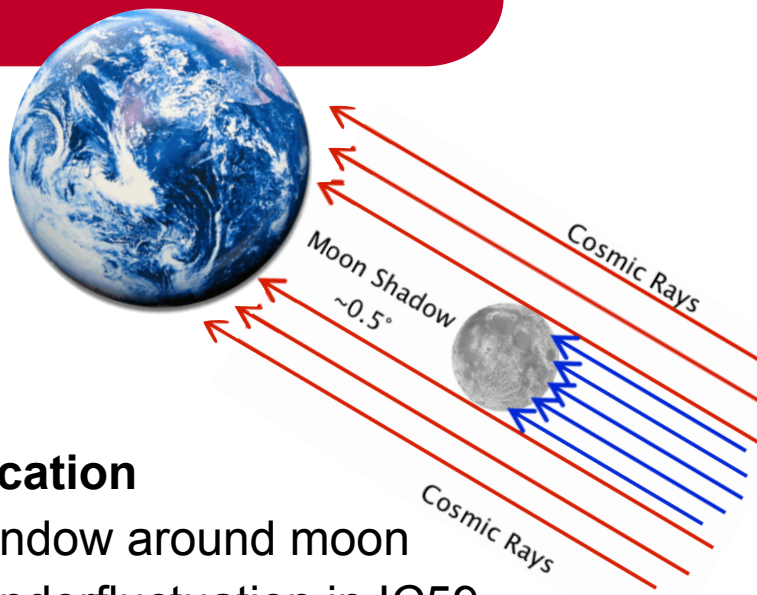
- average detector uptime
  - >99% last years
- used for data analysis
  - >95% over 5 years





ν_μ pointing resolution





Pointing resolution

- improves with energy
- dominated by
  ν-μ scattering angle

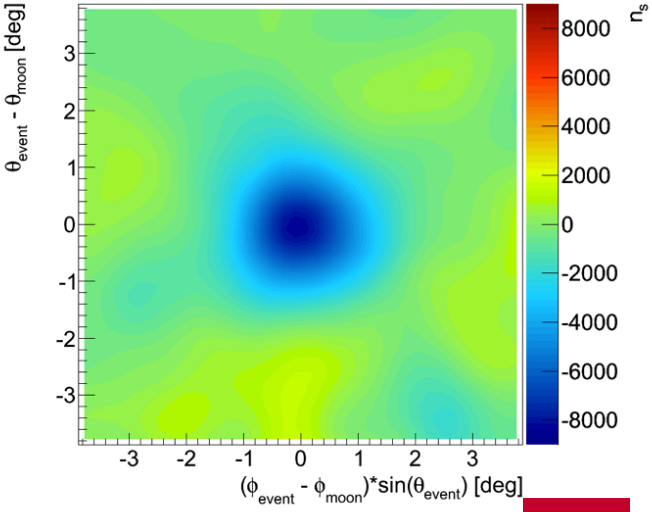
Energy resolution

- estimated from
  dE/dx of muons
- dominated by stochastic losses
  → $\sigma(E_\mu) \approx 0.3 \log_{10}(E_\mu)$

Pointing verification

- ±4° window around moon

→ 13σ underfluctuation in IC59
(14 moon cycles)



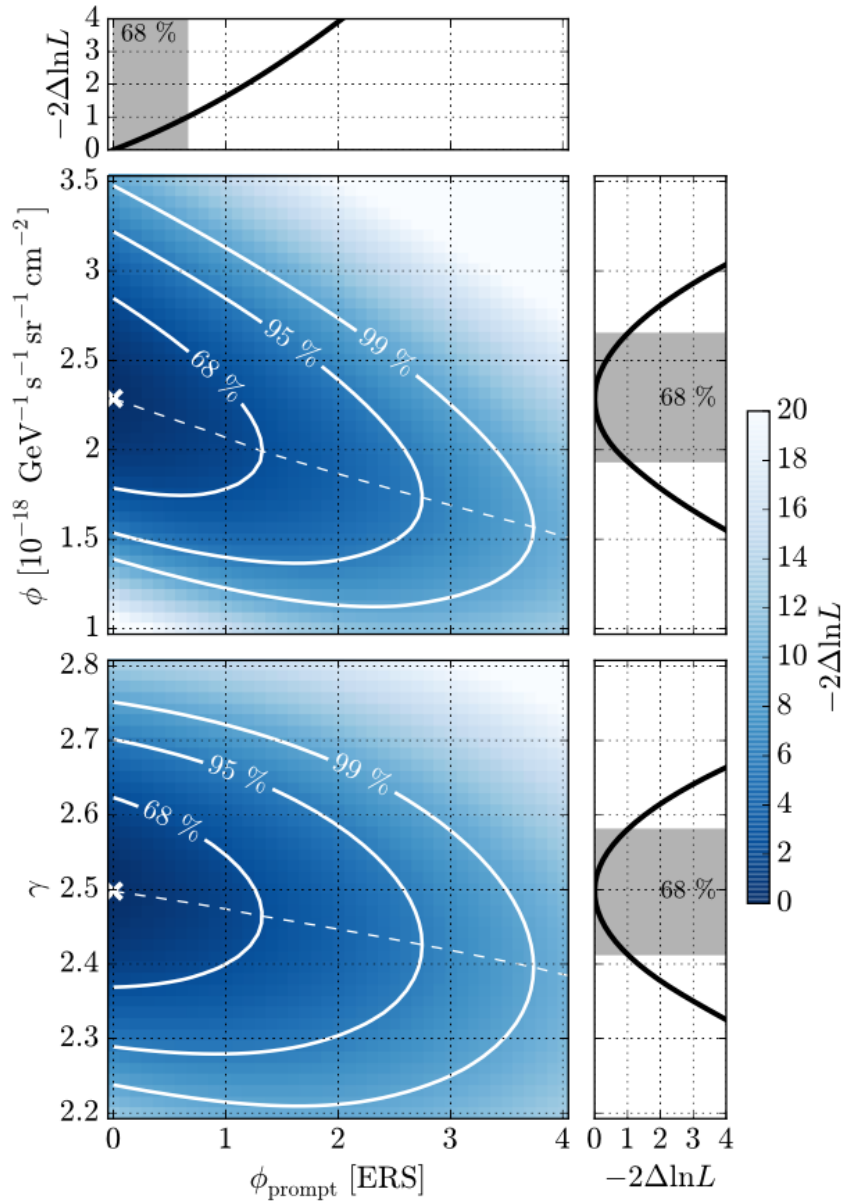
Combined analysis

Results from multiple searches

- 2 dedicated track searches
- 2 dedicated cascade searches
- high- and medium energy starting event searches
  - all are consistent

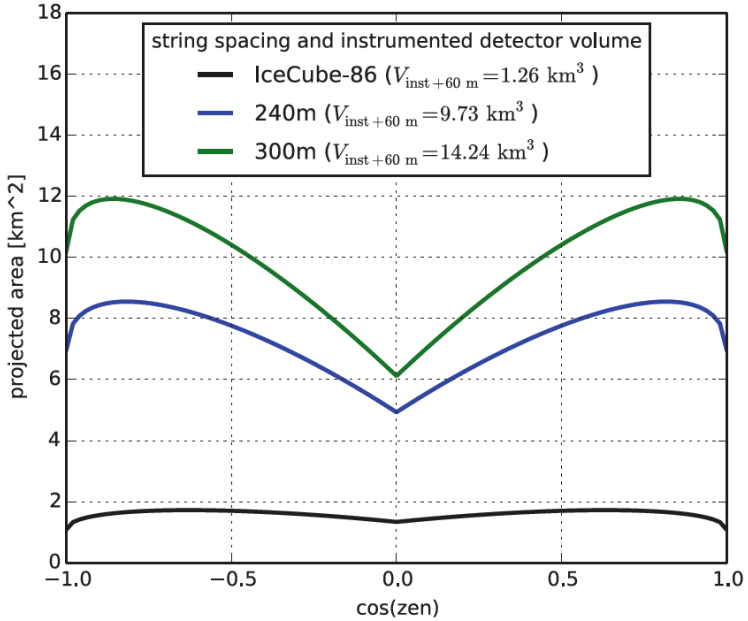
Best fit result

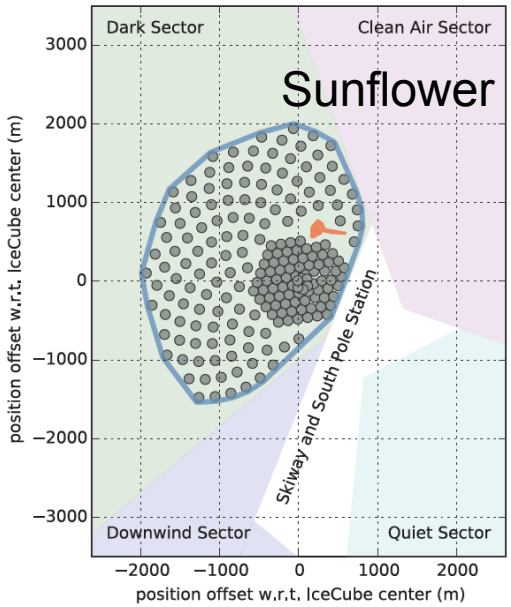
- spectral index
  - **γ = 2.50 ± 0.09**
- matches predictions for Fermi acceleration
- no indication of break in power law

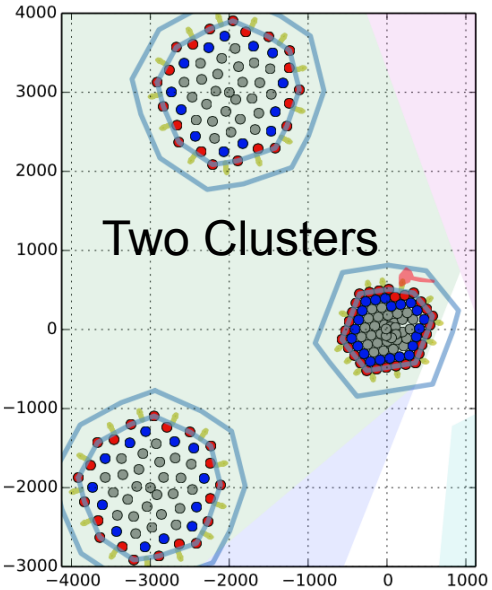


PRISMA

Geometry studies







Constraints

- South Pole sectors
  - radial assymmetrie
- optical ice properties / bedrock
  - only slightly thicker detector
  - polar assymmetrie

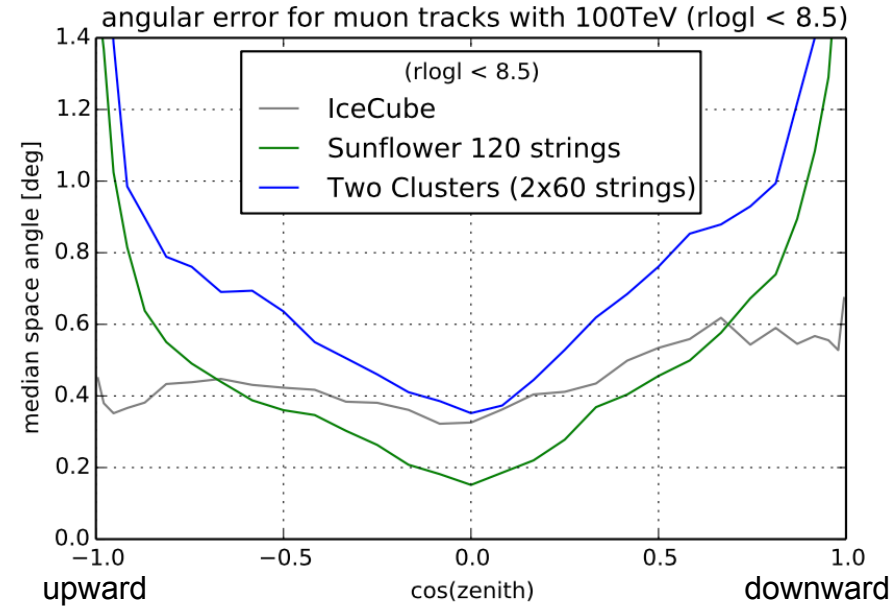
Wish-list

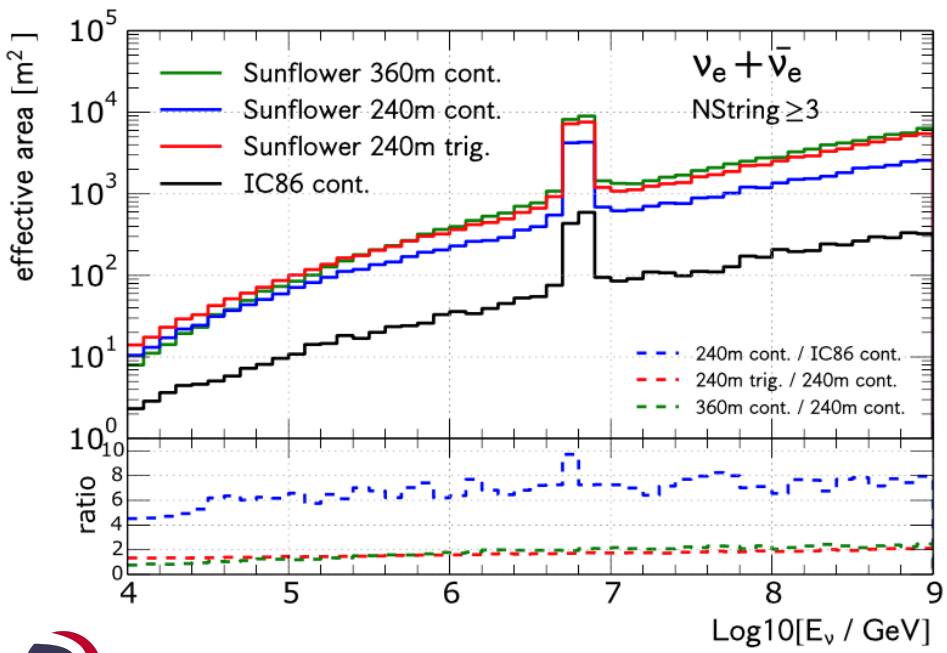
- active veto technique
  - avoid regular grid
    - no *channels* for background

Expected performance

Tracks

- same resolution for horizontal events
  - region with
    - low μ-background ✔
    - little earth absorption ✔





Cascades

- effective area grows with
  - volume
  - veto efficience
- additional help from Glashow resonance

$$\nu_e + e^- \rightarrow W^-$$

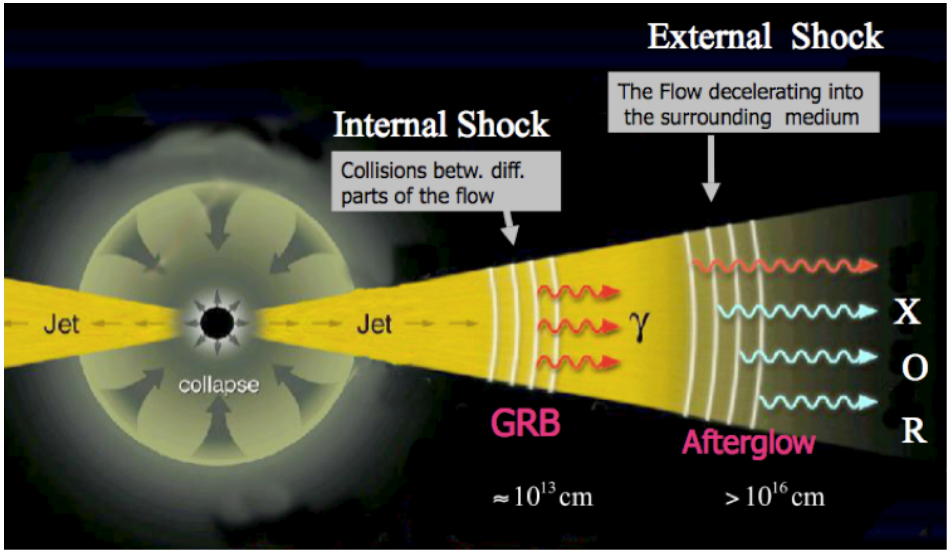
Transient sources

Transient sources

Gamma ray bursts

Fireball model (long GRBs)

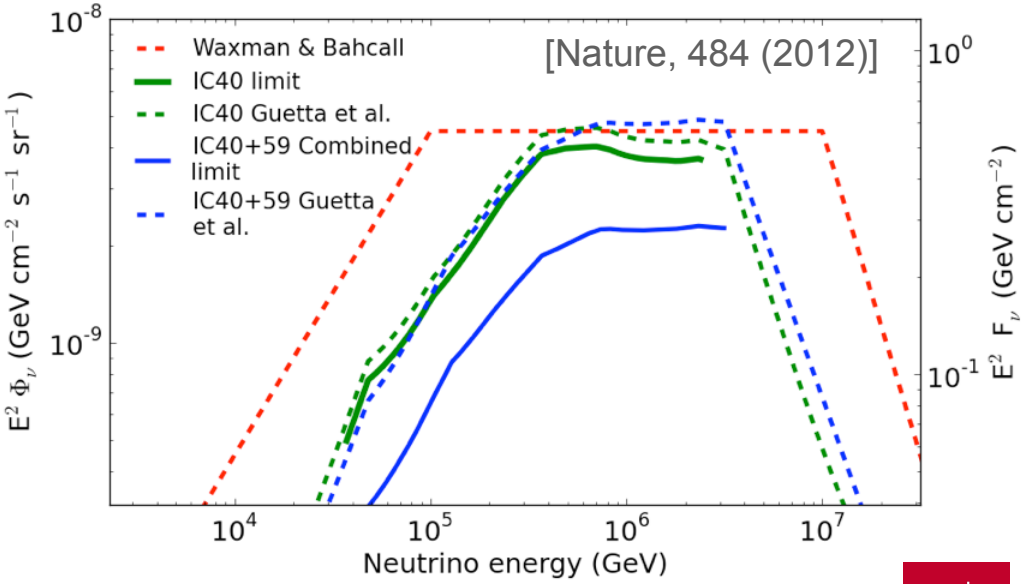
- collapse of massive star
- total energy release ~10^{45} Joules
  - candidate for cosmic rays
- ultra-relativistic jets
  - PeV neutrino emission ??



IceCube GRB search

- coincidence analysis
  - time window ($\Delta T \approx 0.1$-100s)
  - direction ($\Delta\Psi_{\mathrm{IceCube}} \approx 1^{\circ}$)
- per-alert emission model
  - 5.2 events expected
  - **no** events observed

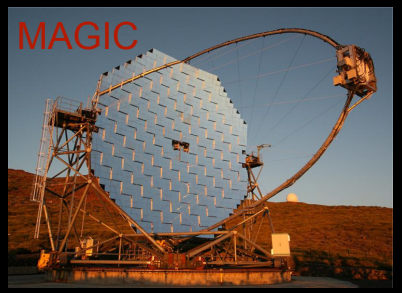
→ starting to constrain GRB models

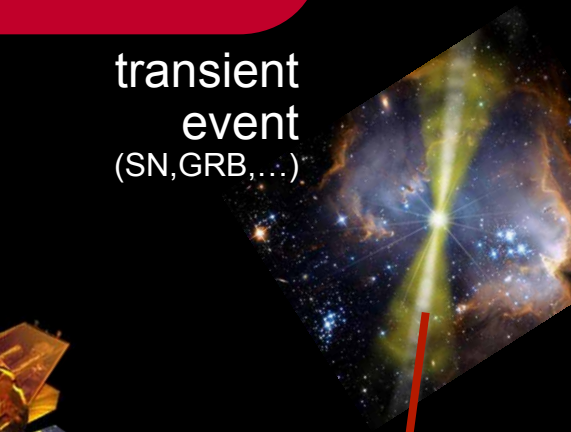


Follow-up program

Idea

- trigger follow-up observation by neutrinos in IceCube
  - ➔ online neutrino analysis





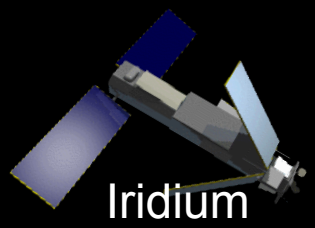
Online alerts

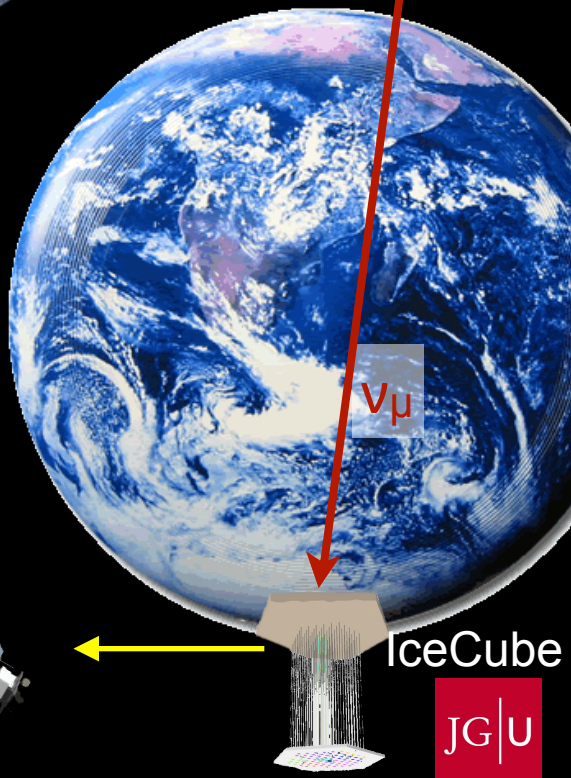
- multiplet trigger
  $N_\nu \geq 2$, $\Delta\Psi \geq 4°$, $\Delta t \leq 100$s separation

Follow-up program

- optical: ROTSE, PTF ➔ first results
- X-rays: SWIFT
- γ-rays: MAGIC, VERITAS

northern hemisphere institute





PRISMA

JG|U

IceCube online neutrino filter

Neutrino multiplets

	N_ν	Measured	Expected
IC 40	2	15	8.53
	3	0	0.003
IC 59	2	19	15.66
	3	0	0.004
IC79	2	32	42.5
	3	0	0.012
IC86	2	24	19.59
	3	0	0.005

Trigger ~3000 Hz

general muon filter

Level 1 ~30 Hz

high-quality up-going events

Level 2 ~3 Hz

neutrino selection

Level 3 ~2 mHz

90% atmospheric neutrinos

Latency

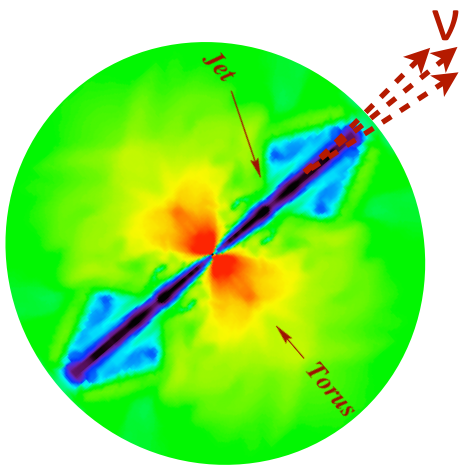
- 3 minutes

Optical follow-up – first results

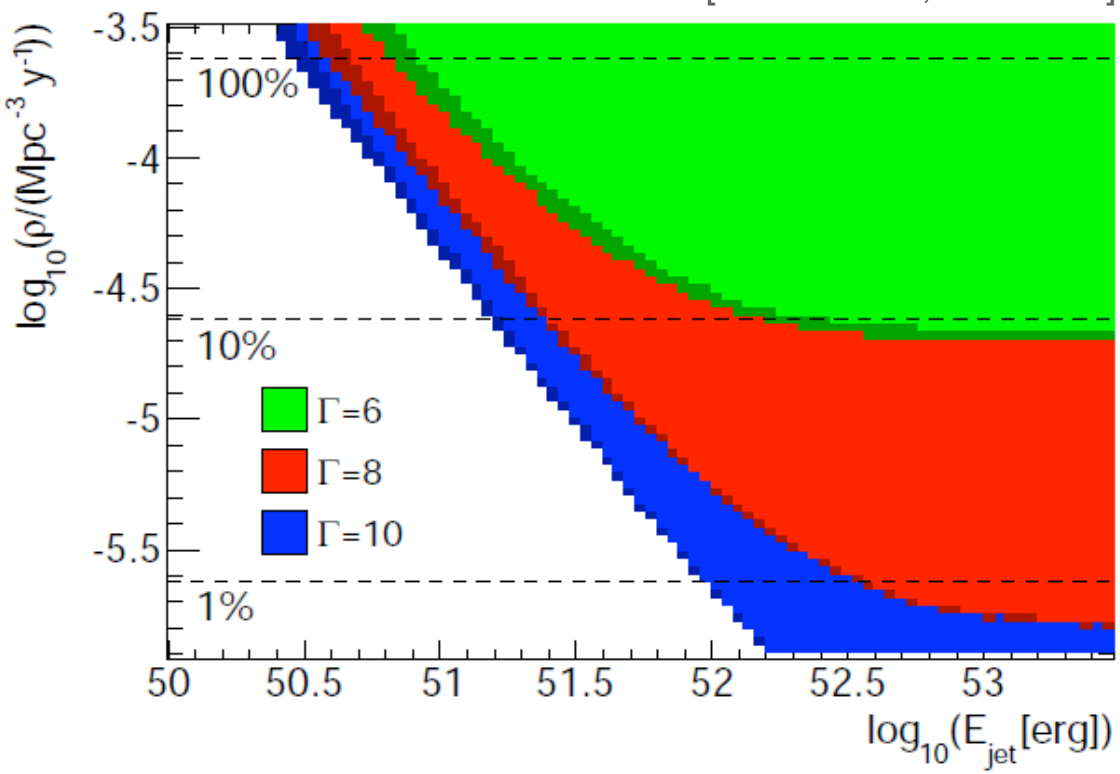
Supernova jet model

- Are there GRB – like jets in core-collapse SNe?

[Ando & Beacom (PRL 95/2005)]



[Abbasi et al., A&A 2012]



First year of optical follow-up

- 34 alerts send to ROTSE
- 0 SN counterparts observed

Summary

Motivation

- Neutrinos & Cosmic rays

Neutrinos from heaven

- Point sources
- Transient sources
- Diffuse flux

➔ High-Energy extension

Neutrino from earth

➔ PINGU