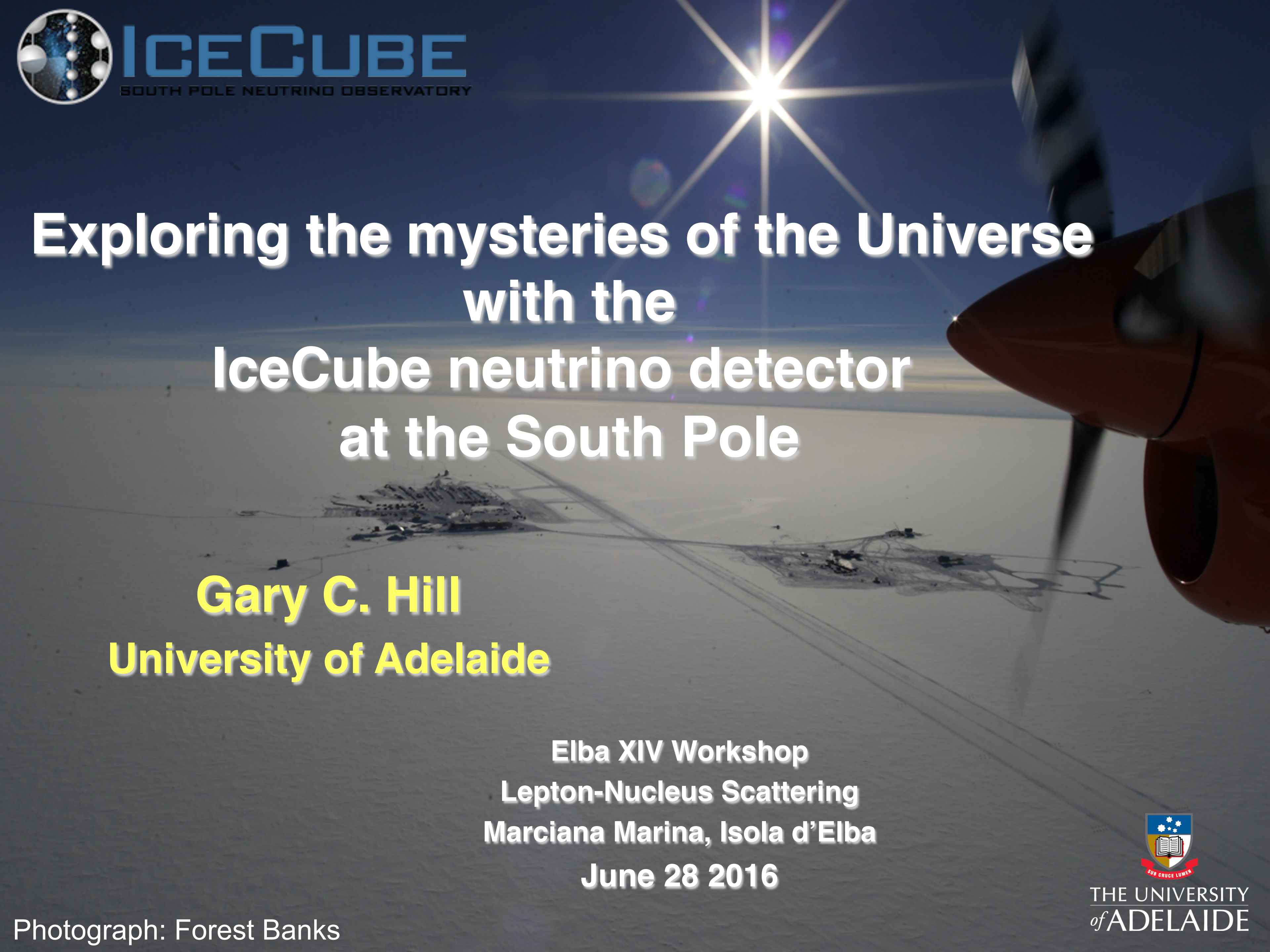
Exploring the mysteries of the Universe with the IceCube neutrino detector at the South Pole

Gary C. Hill

University of Adelaide

Elba XIV Workshop
Lepton-Nucleus Scattering
Marciana Marina, Isola d'Elba
June 28 2016



Photograph: Forest Banks

IceCube South Pole Neutrino Observatory

THE UNIVERSITY of ADELAIDE

IceCube

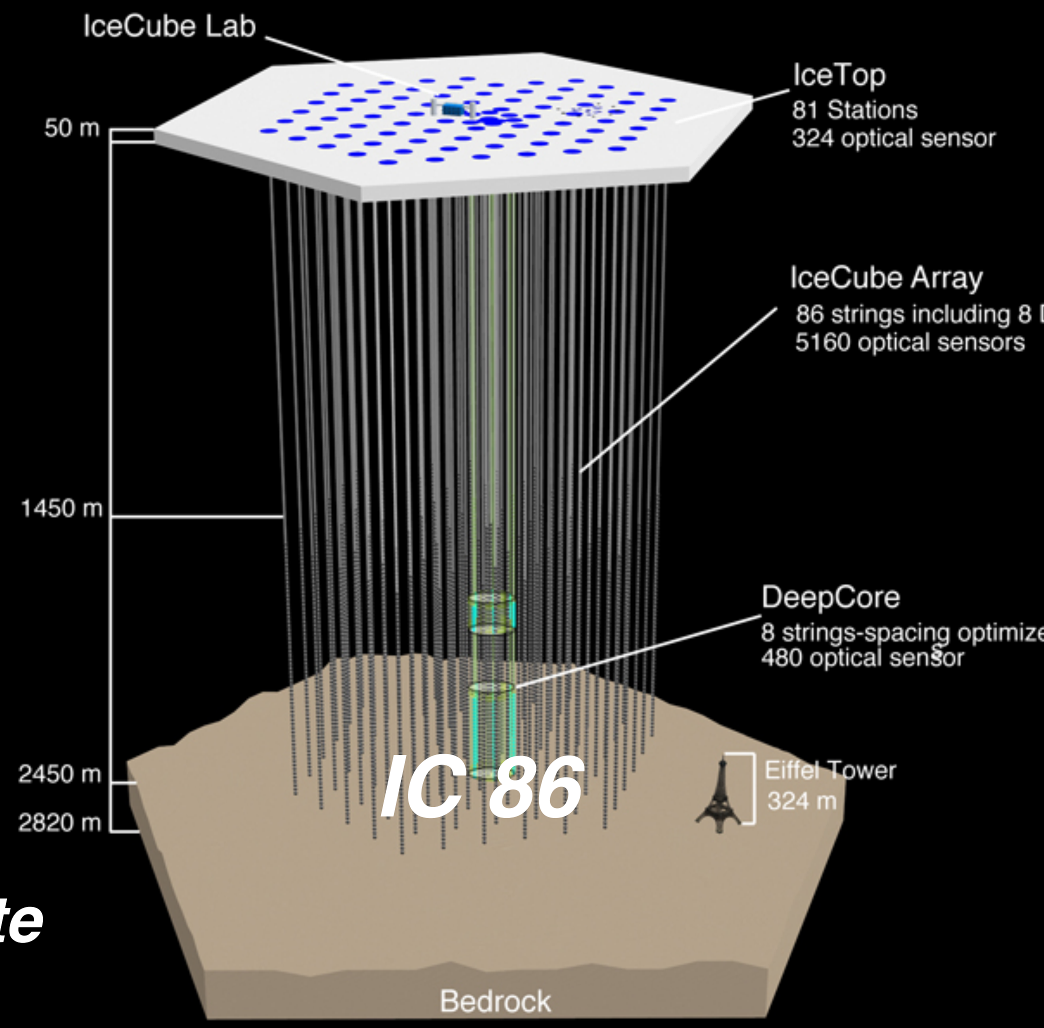
IceTop - cosmic ray studies

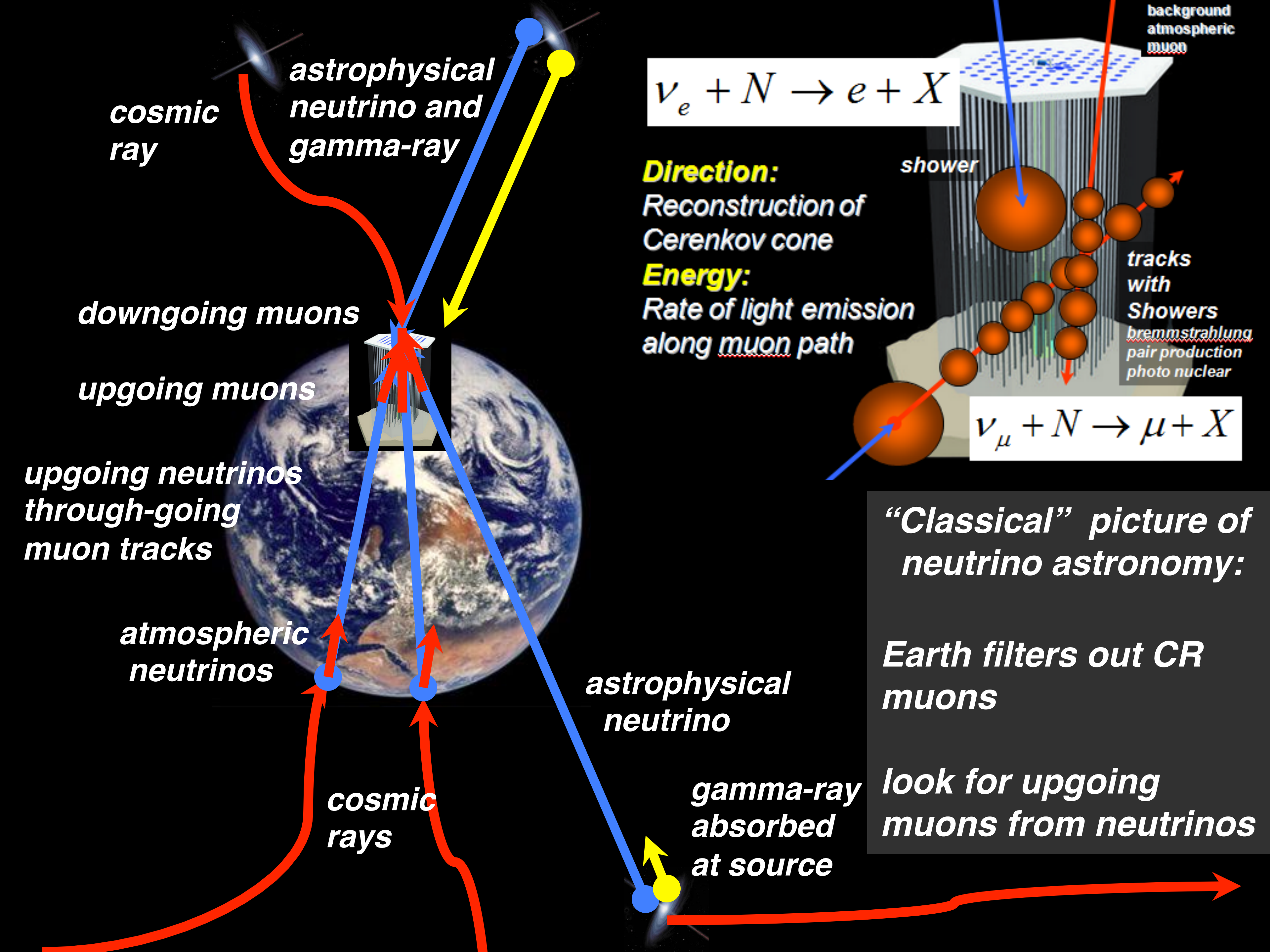
Construction:
Dec 2004 – Dec 2010

86 strings x 60 DOM
IceTop air shower array

Partial detectors analysed:
IC40, IC59, IC79

Full detector:
IC86, 5 years running to date
HESE: IC79/86-1
HESE-4: IC79/86-1/86-2,3,4





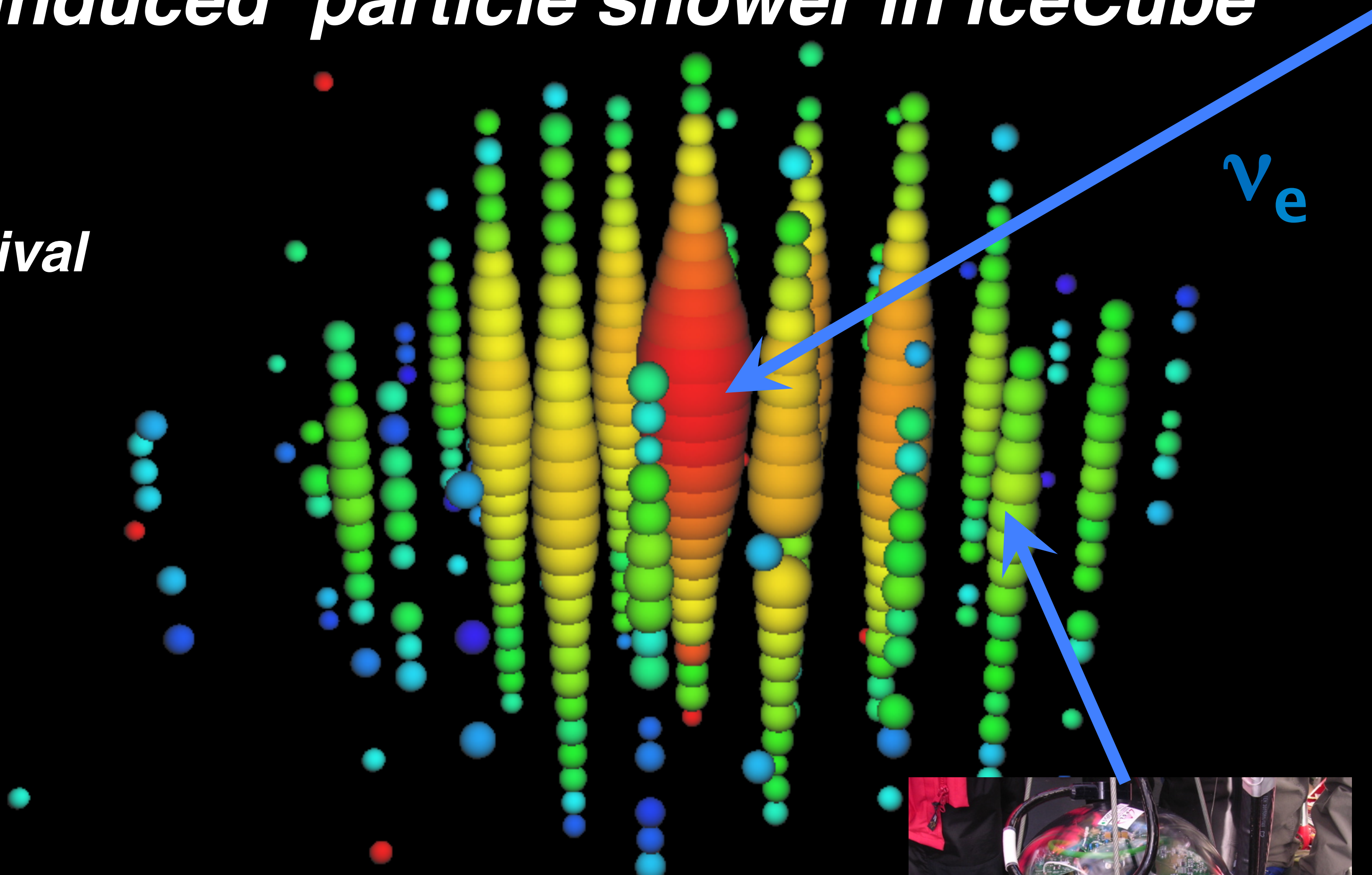
"Classical" picture of neutrino astronomy:

Earth filters out CR muons

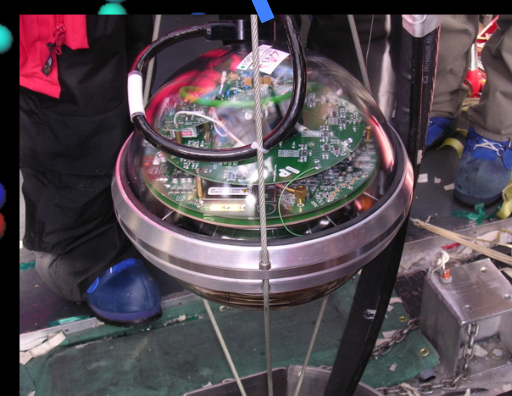
look for upgoing muons from neutrinos

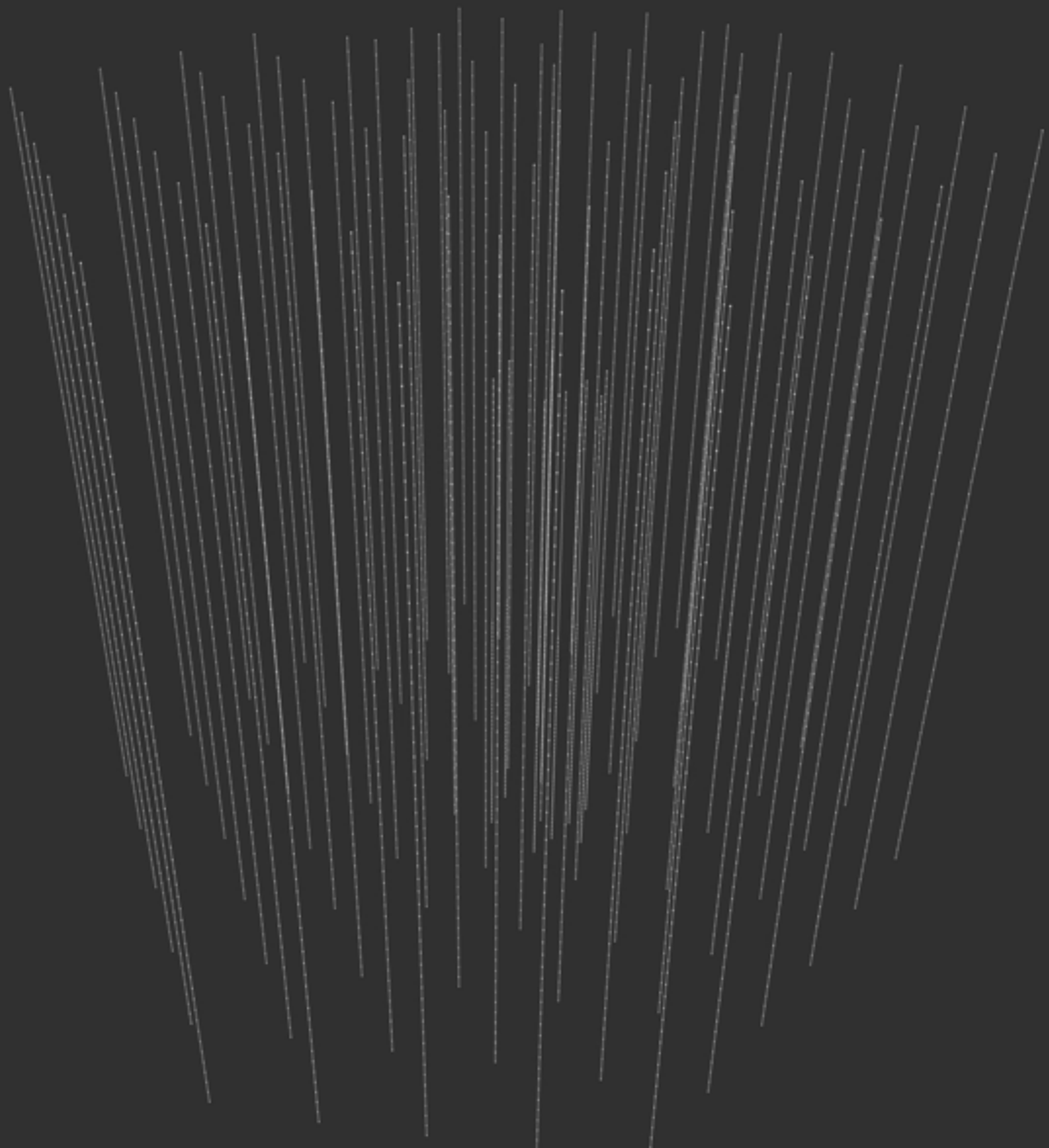
Cherenkov light from a 2 PeV neutrino induced particle shower in IceCube

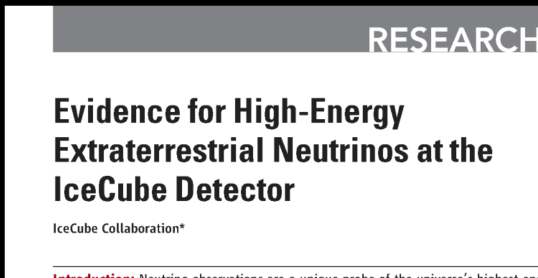
photon arrival timings:
red - early
yellow
orange
green
blue - late



string spacing 125 m
DOM spacing 17 m



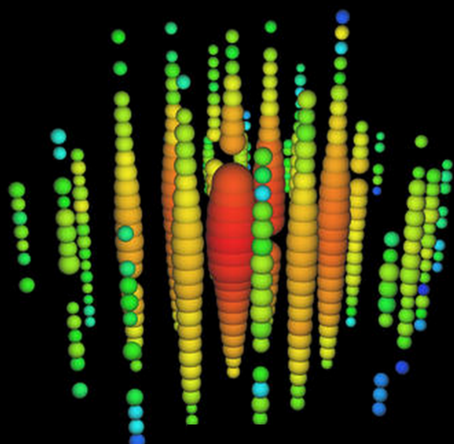



RESEARCH

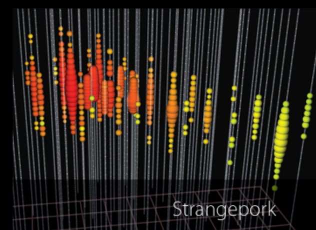
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

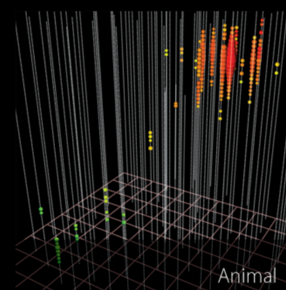
IceCube Collaboration*

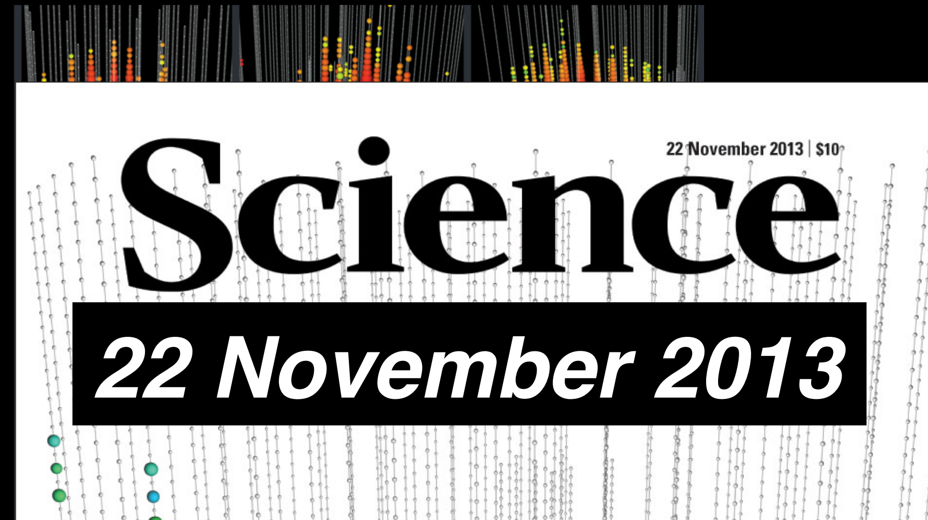
Introduction: Neutrino observations are a unique probe of the universe's highest-en



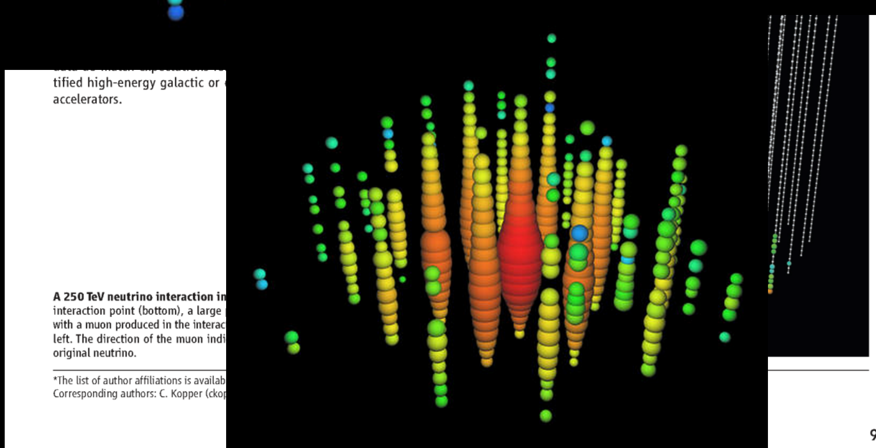
28 High Energy Events

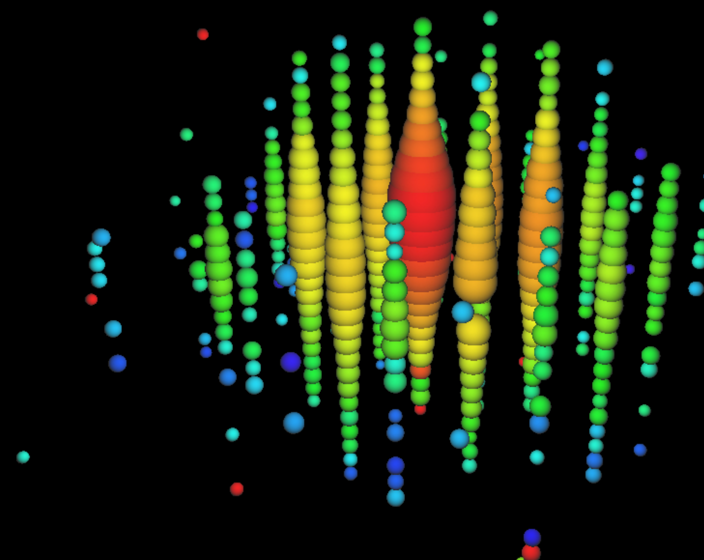






22 November 2013





Sources of neutrinos

The Big Bang

$\rho\nu = 330 / cm^3$

$E_\nu = 0.0004$ eV

(1 MeV = 1.6×10^{-13} Joules)

SN1987

$E_\nu \sim$ MeV

The Sun

ν_e

$\Phi_\nu^{Earth} = 6 \times 10^{10}\ \nu / cm^2 s$

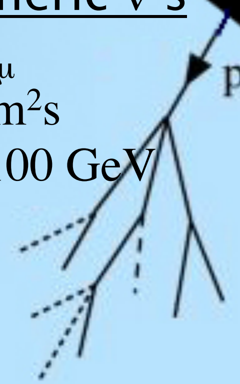
$E_\nu \sim 0.1 - 20$ MeV

Atmospheric ν's

$\nu_e, \nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu$

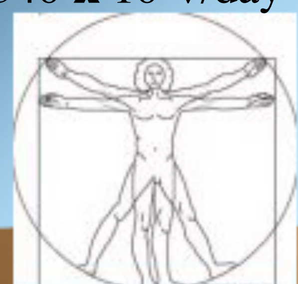
$\Phi_\nu \sim 1\nu / cm^2 s$

$E_\nu \sim 0.1 - 100$ GeV



Human Body

$\Phi_\nu = 340 \times 10^6 \nu/day$



Nuclear Reactors

$E_\nu \sim$ few MeV

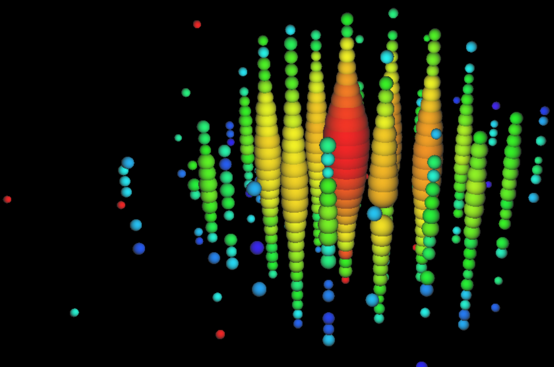
Earth's Radioactivity

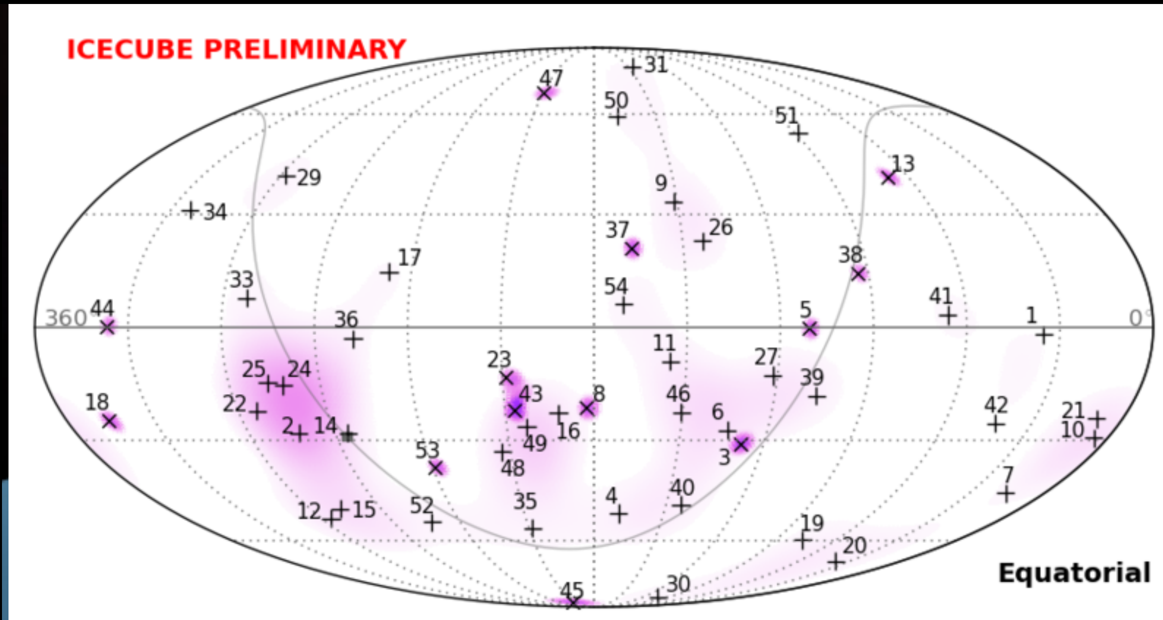
$\Phi_\nu \sim 6 \times 10^6 \nu/cm^2 s$

Accelerators

$E_\nu \simeq 0.3 - 30$ GeV

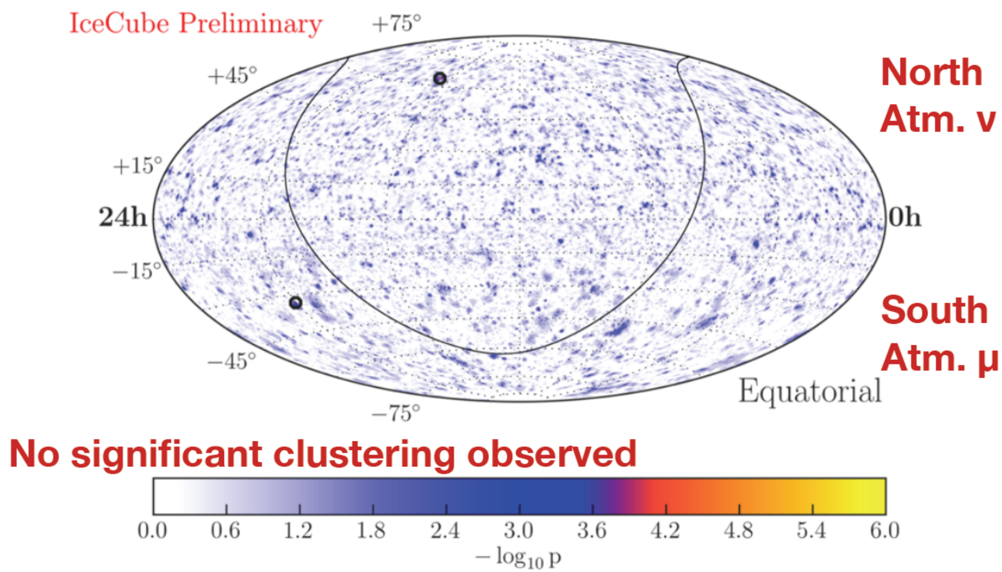
Sources of neutrinos





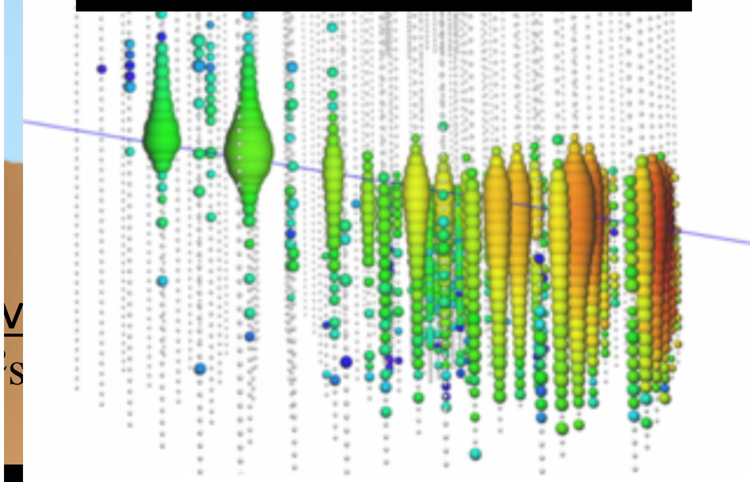
The newest source: the high energy Universe

Results of 6 year analysis



Muon: 2.6 PeV deposited

Neutrino: 3-10 PeV !



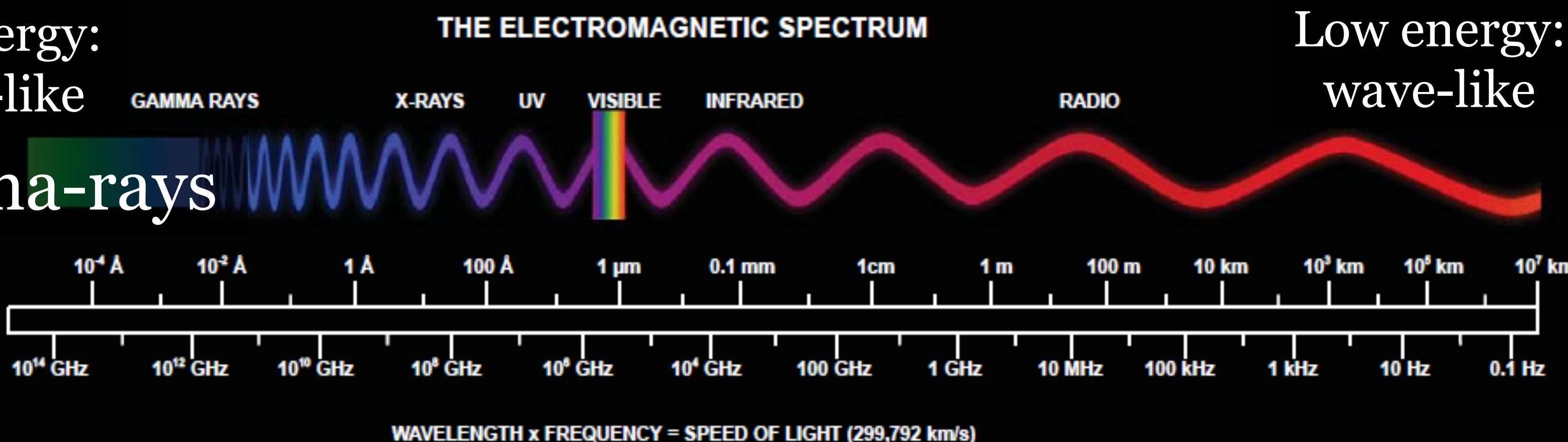
Astronomical messengers:

Light: the electromagnetic spectrum

High energy: particle-like

Low energy: wave-like

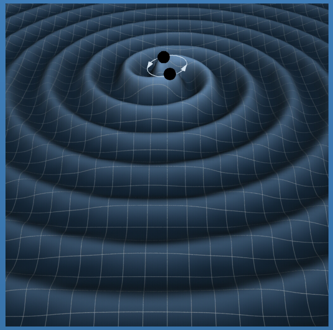
Gamma-rays



Not light: other messengers

Cosmic rays

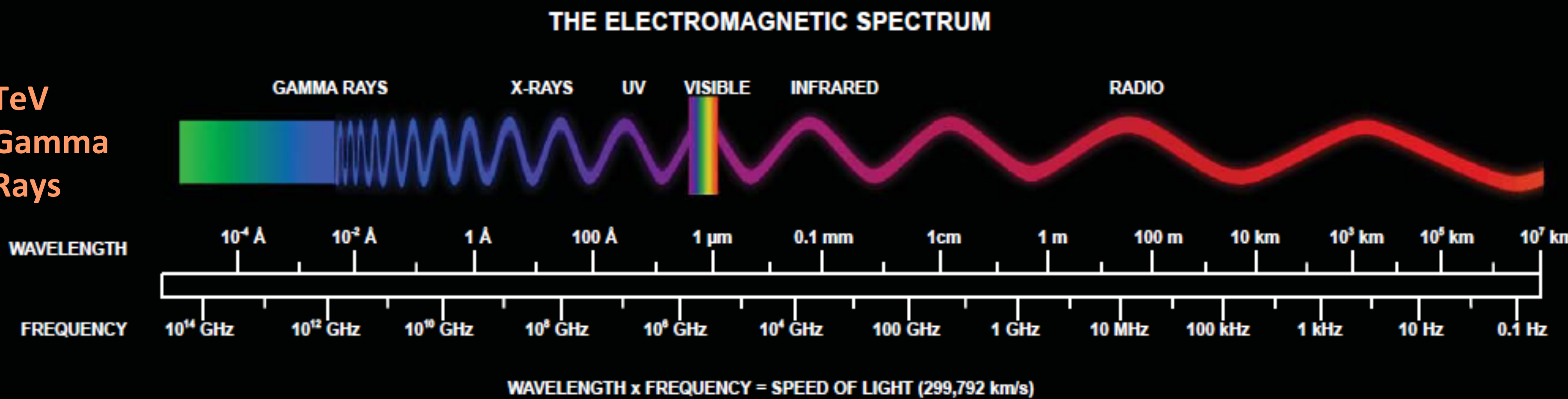
Neutrinos



Gravitational waves

Astronomy with light

TeV Gamma Rays



Low energy Gamma-ray

Space

X-ray

Space

Optical/IR

Ground

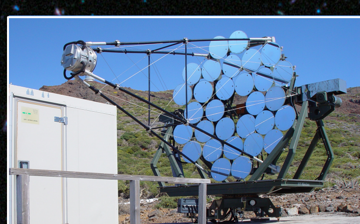
Infrared

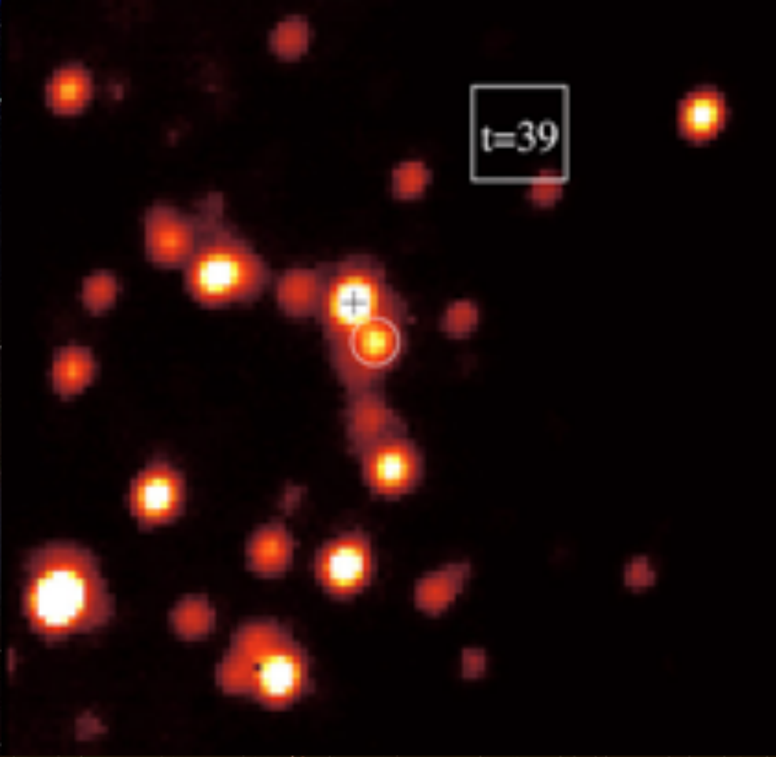
Space

Radio

Ground

Ground

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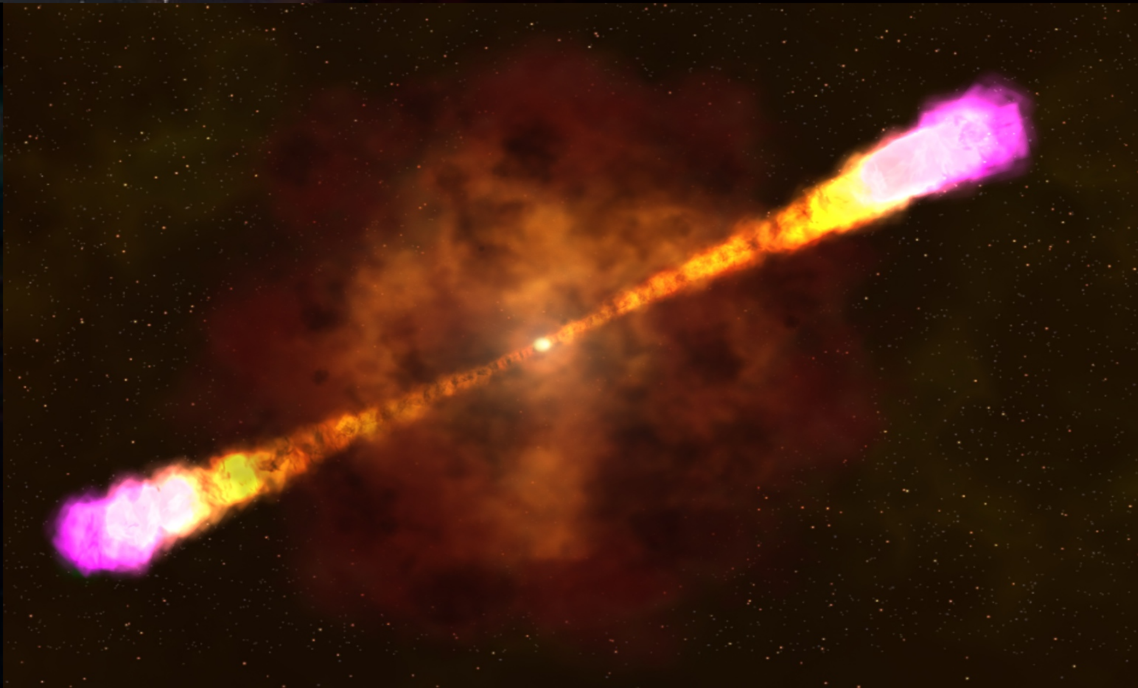
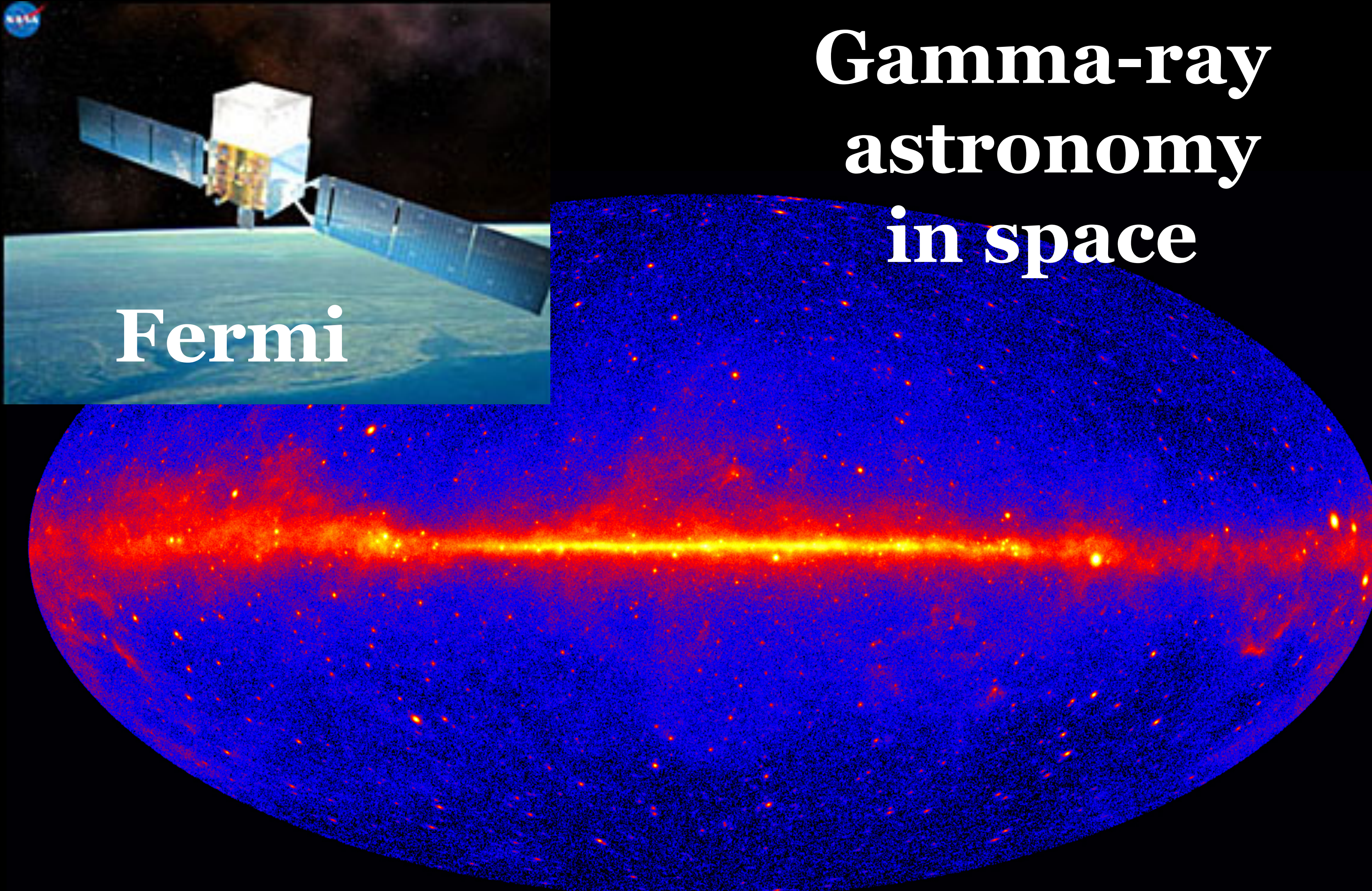
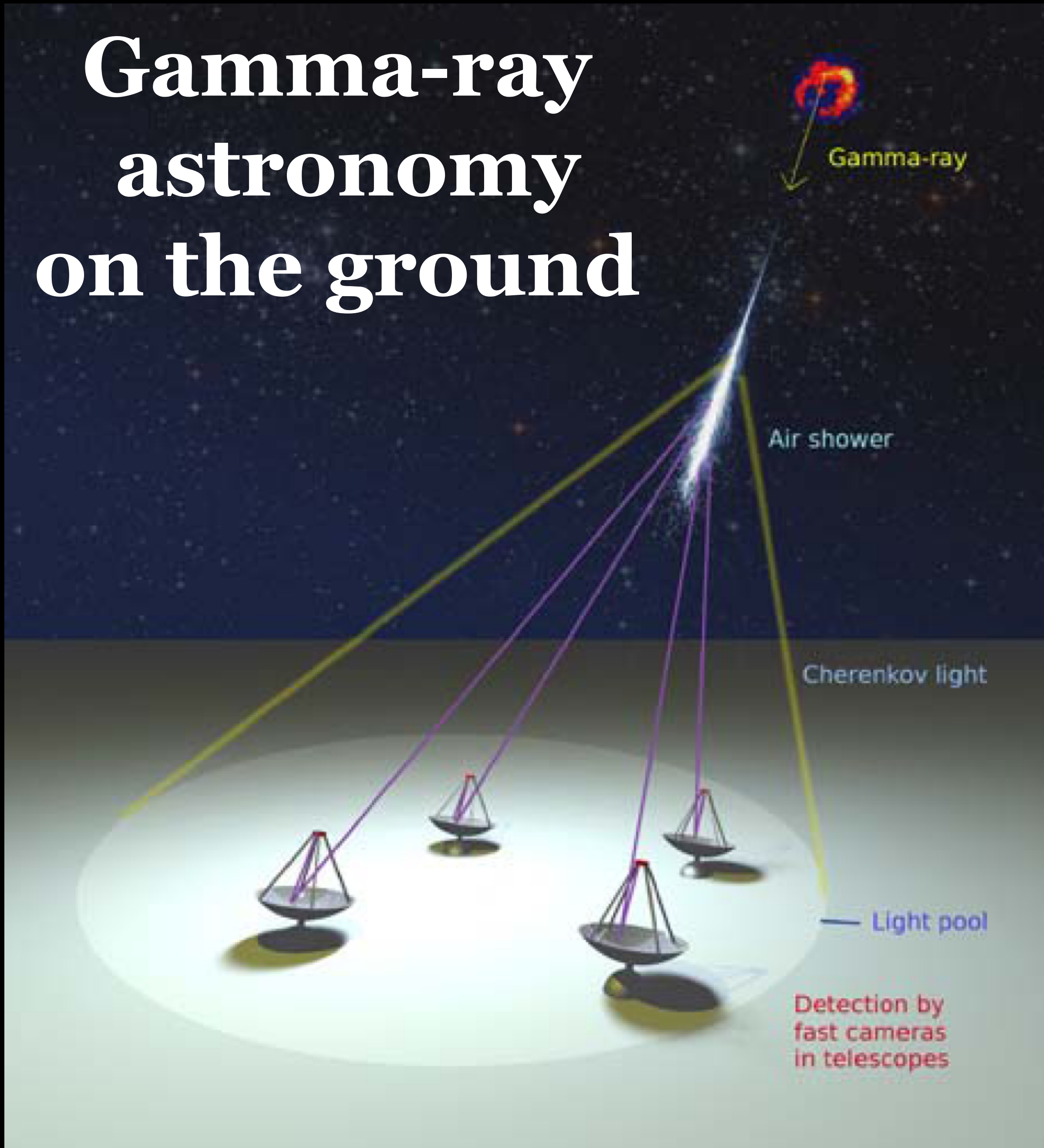
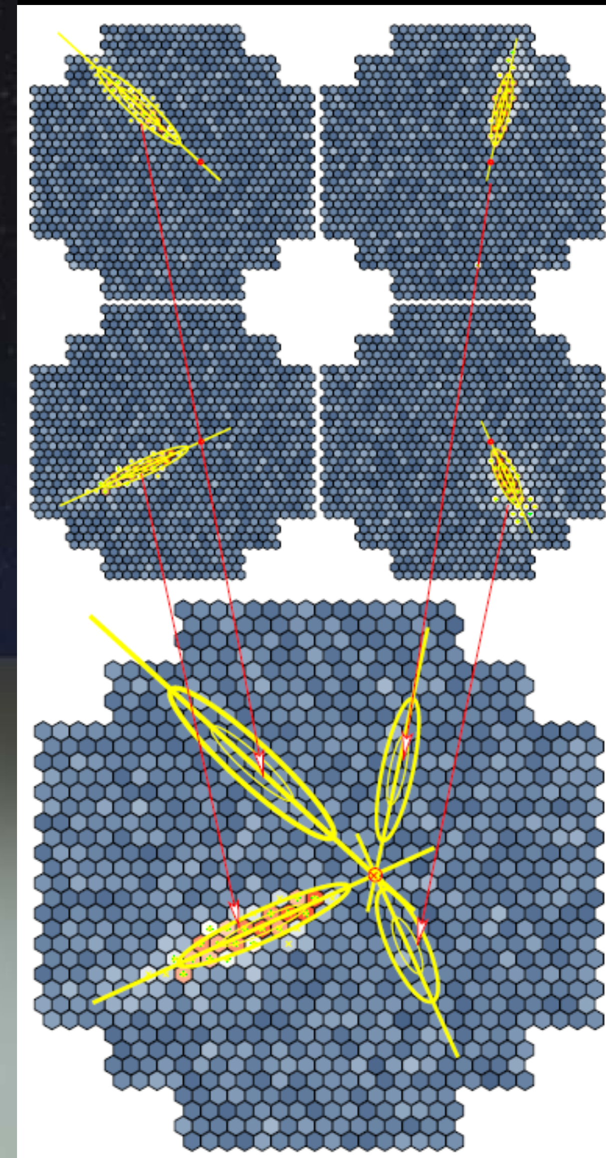


Gamma-ray astronomy in space

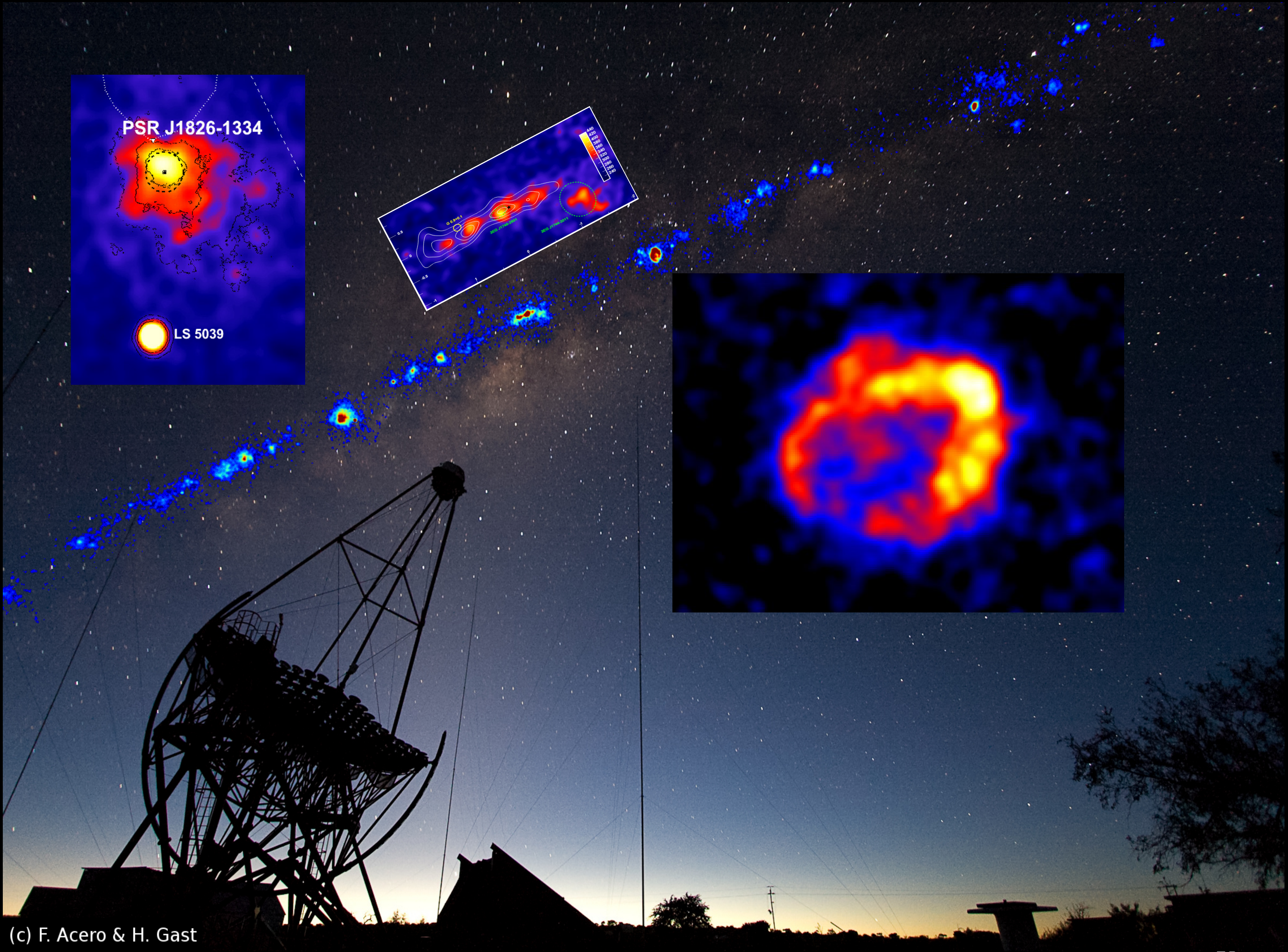


Gamma-ray astronomy on the ground

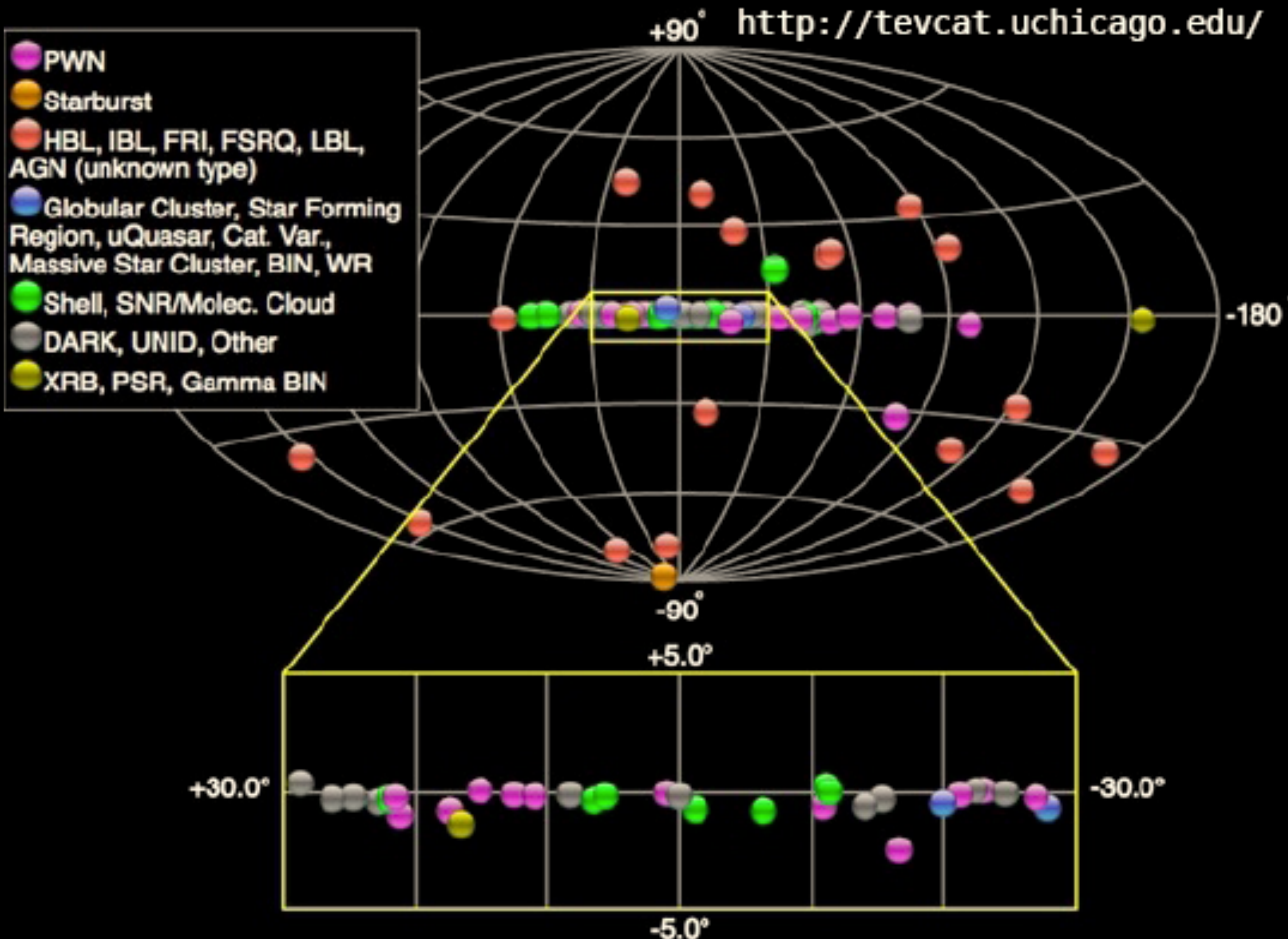




H.E.S.S. telescope, Namibia



(c) F. Acero & H. Gast



http://tevcat.uchicago.edu/
+90°
-90°
-180°
PWN
Starburst
HBL, IBL, FRI, FSRQ, LBL, AGN (unknown type)
Globular Cluster, Star Forming Region, uQuasar, Cat. Var., Massive Star Cluster, BIN, WR
Shell, SNR/Molec. Cloud
DARK, UNID, Other
XRB, PSR, Gamma BIN
+5.0°
-5.0°
+30.0°
-30.0°

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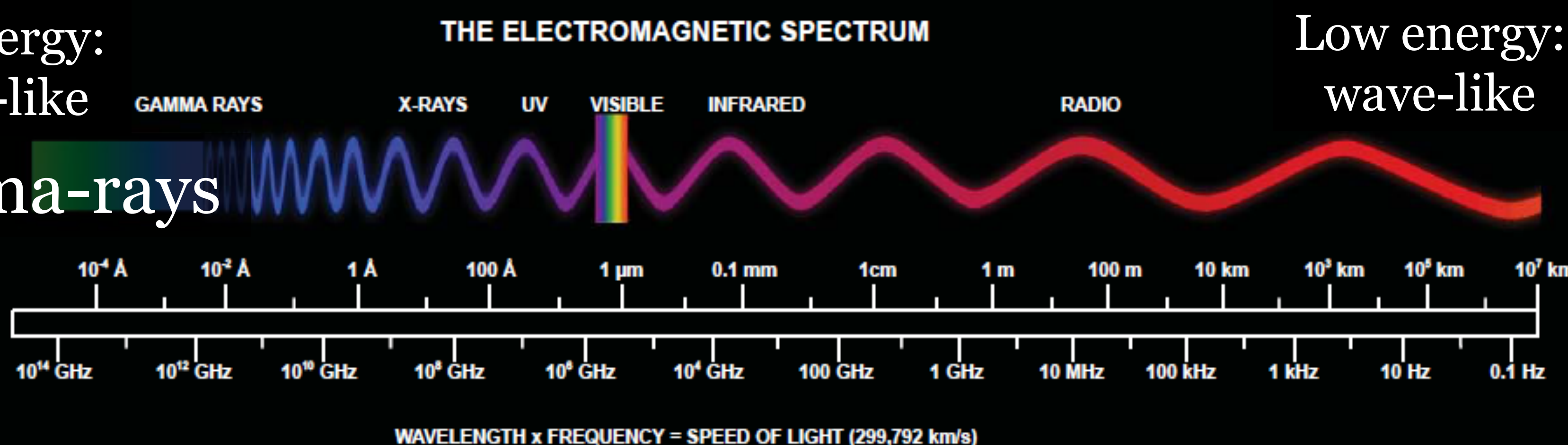
Low energy: wave-like

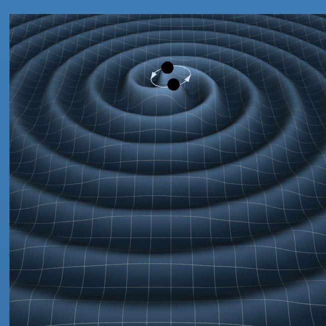
Gamma-rays



Not light: other messengers

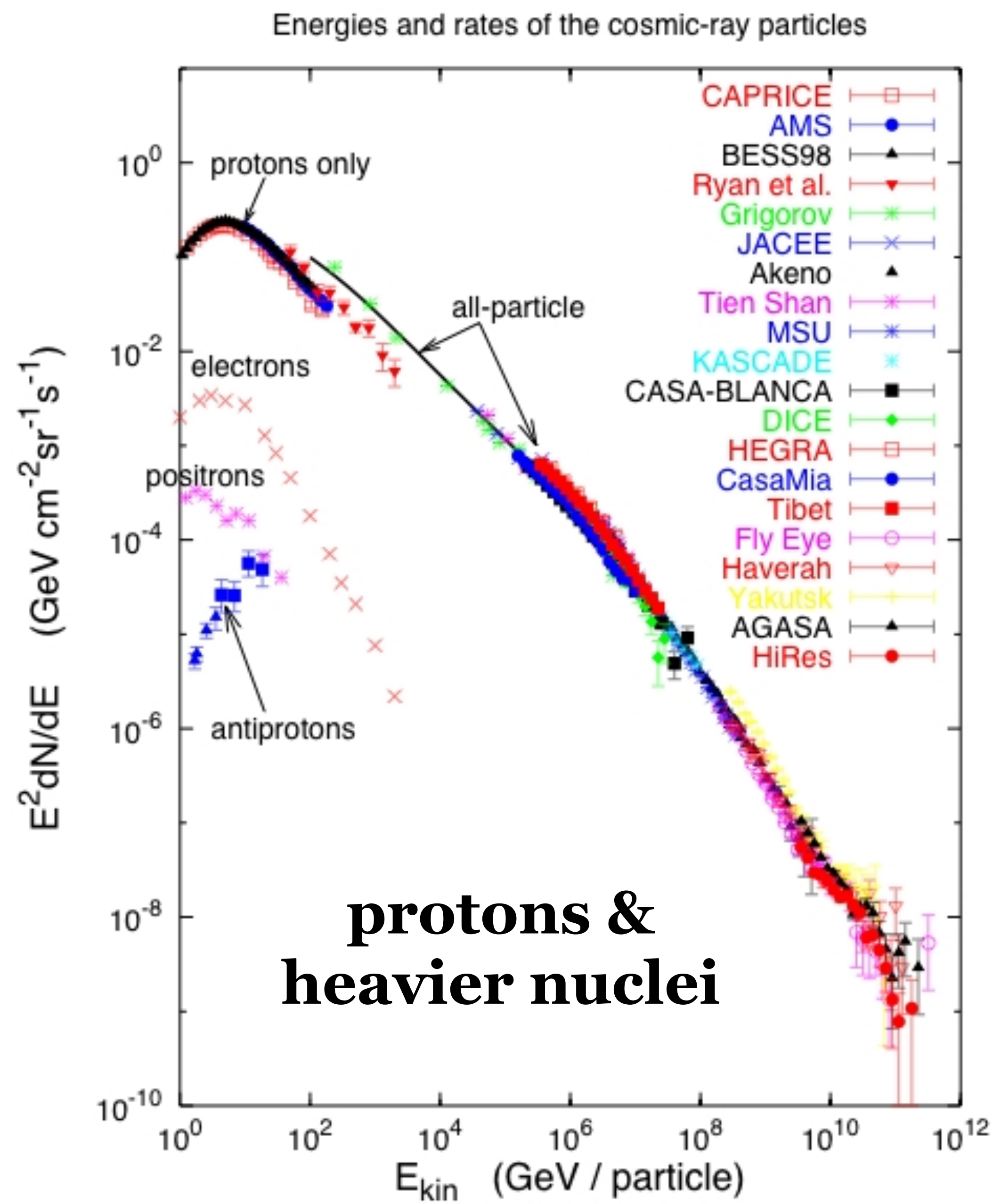
Cosmic rays

Neutrinos

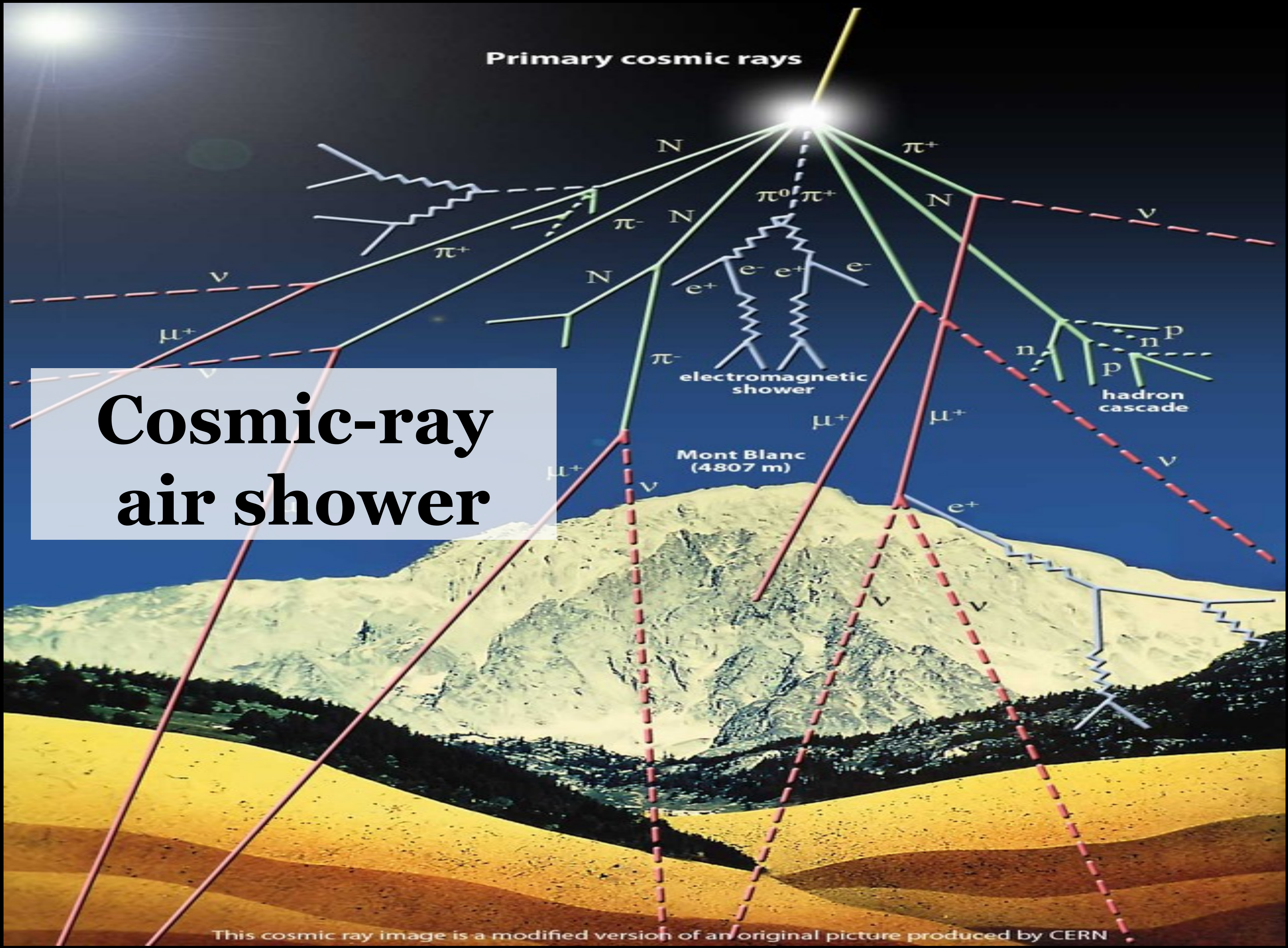


Gravitational waves

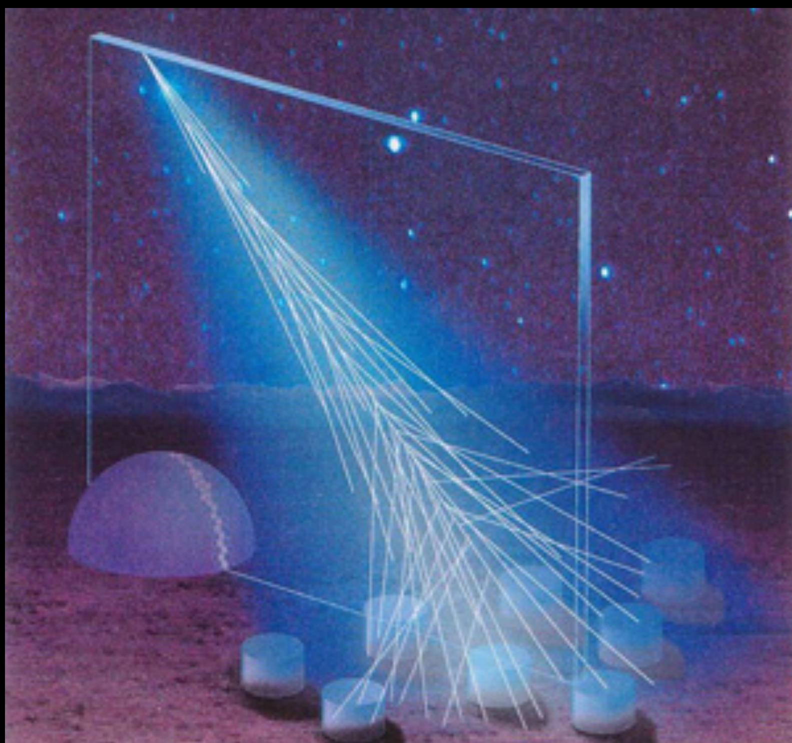
Cosmic-ray astronomy

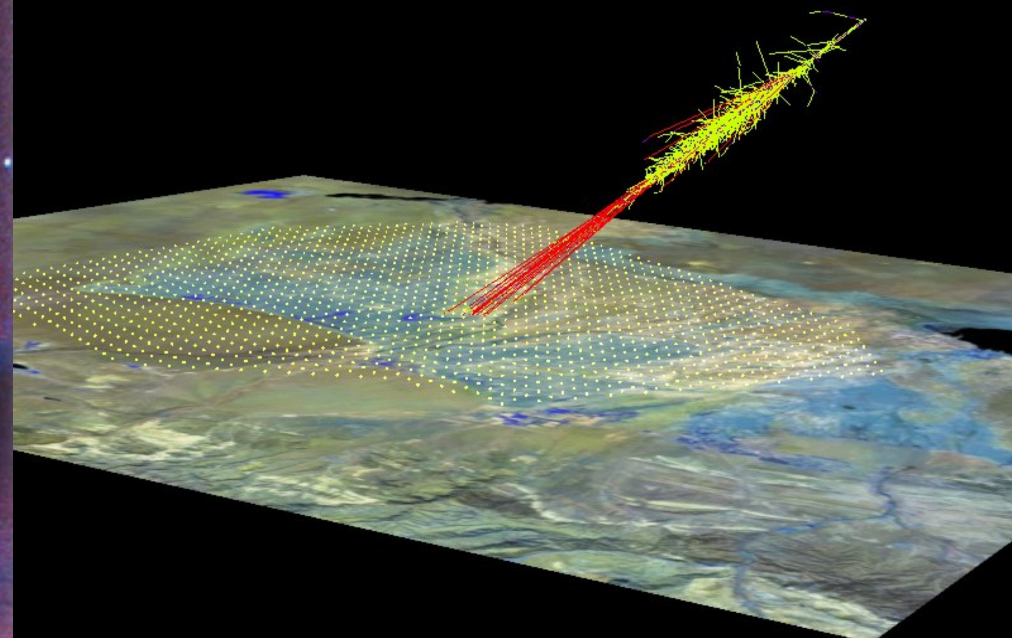


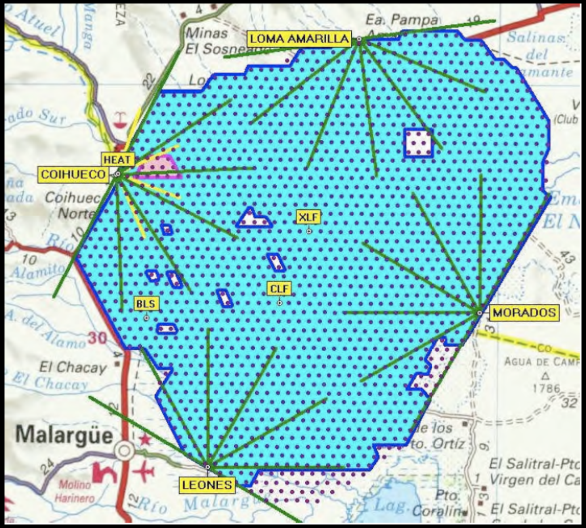
Cosmic-ray air shower



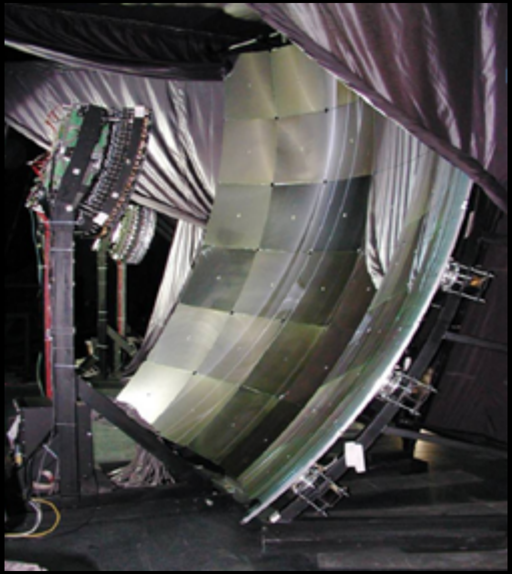
Cosmic air shower detection

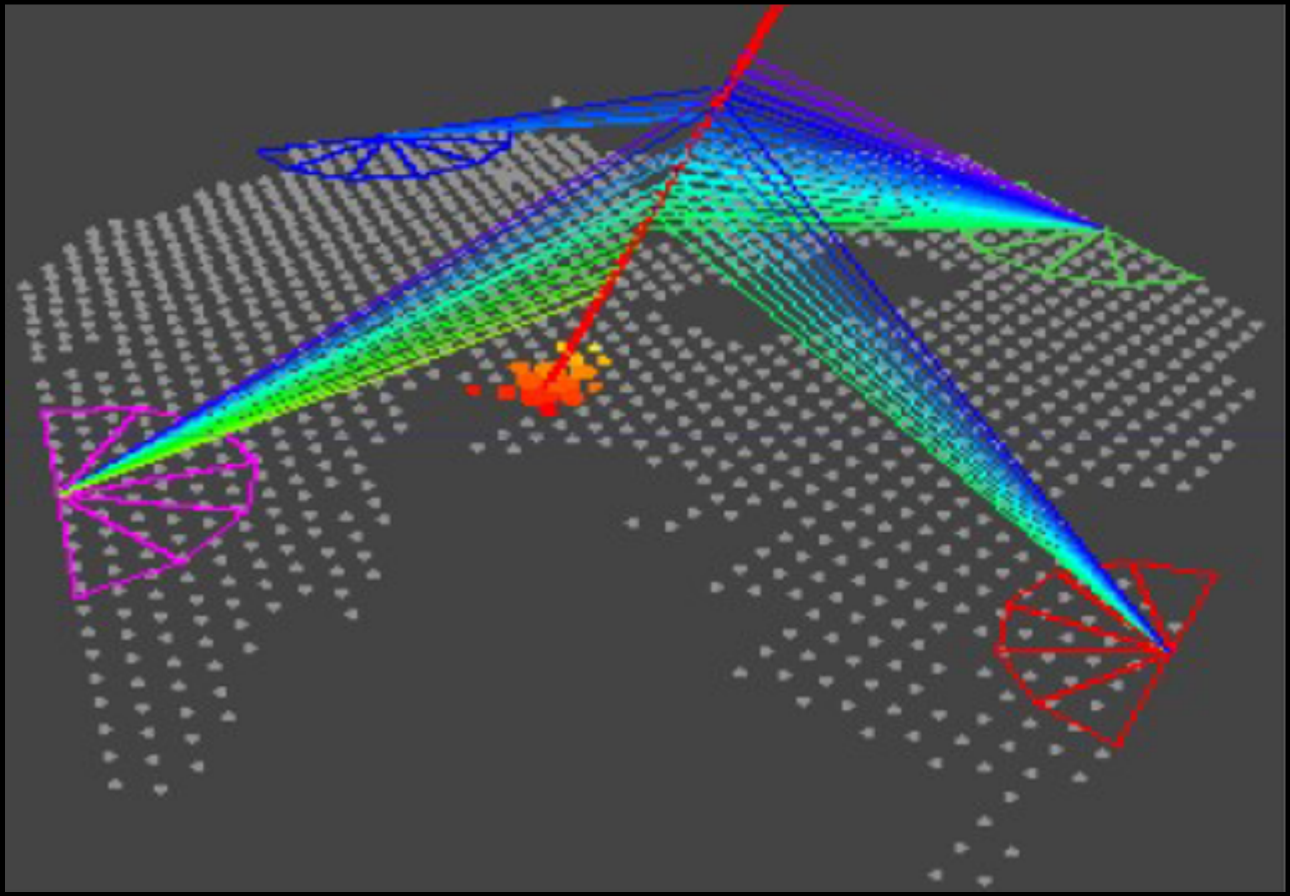






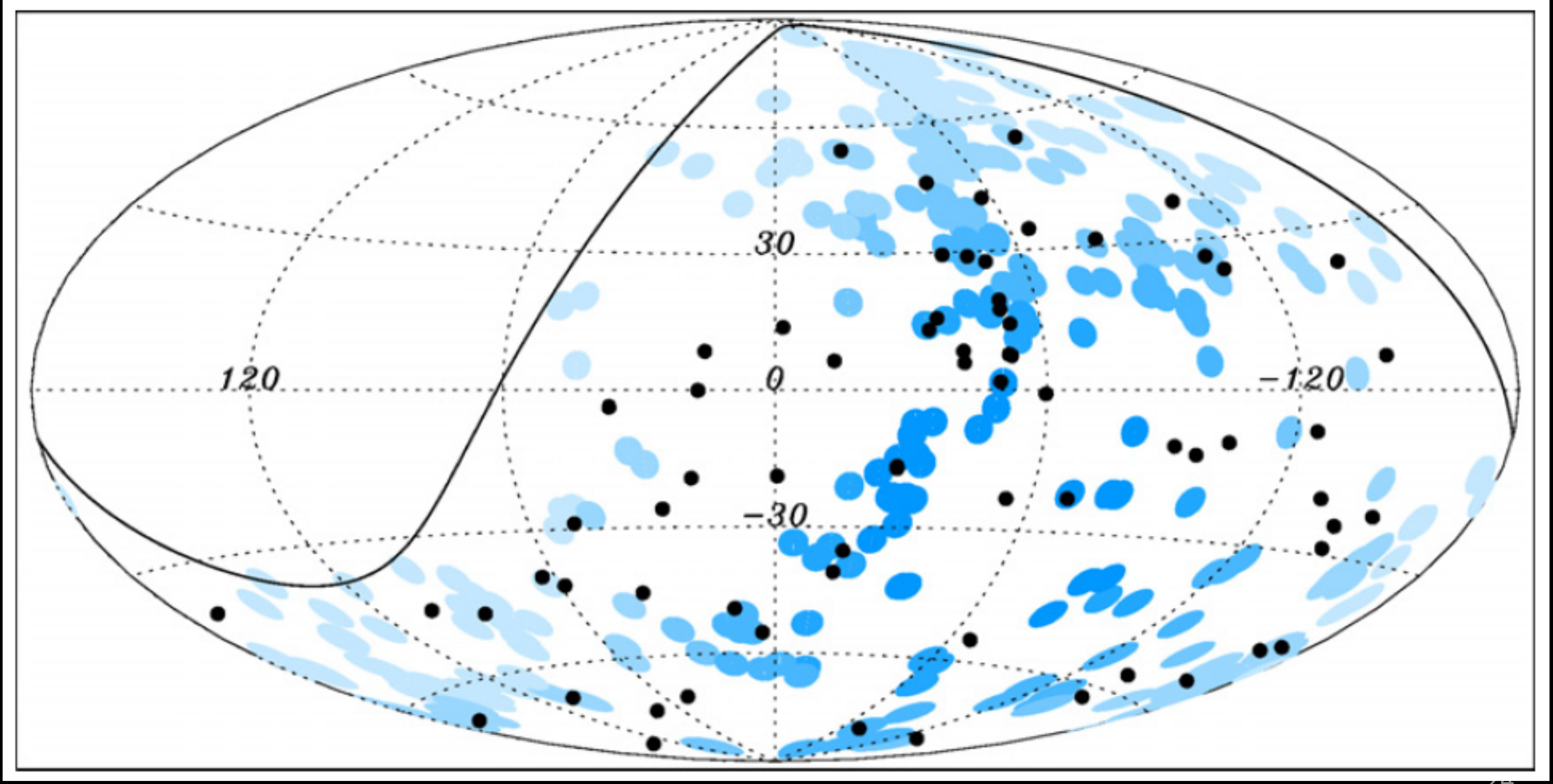
PIERRE
AUGER
OBSERVATORY

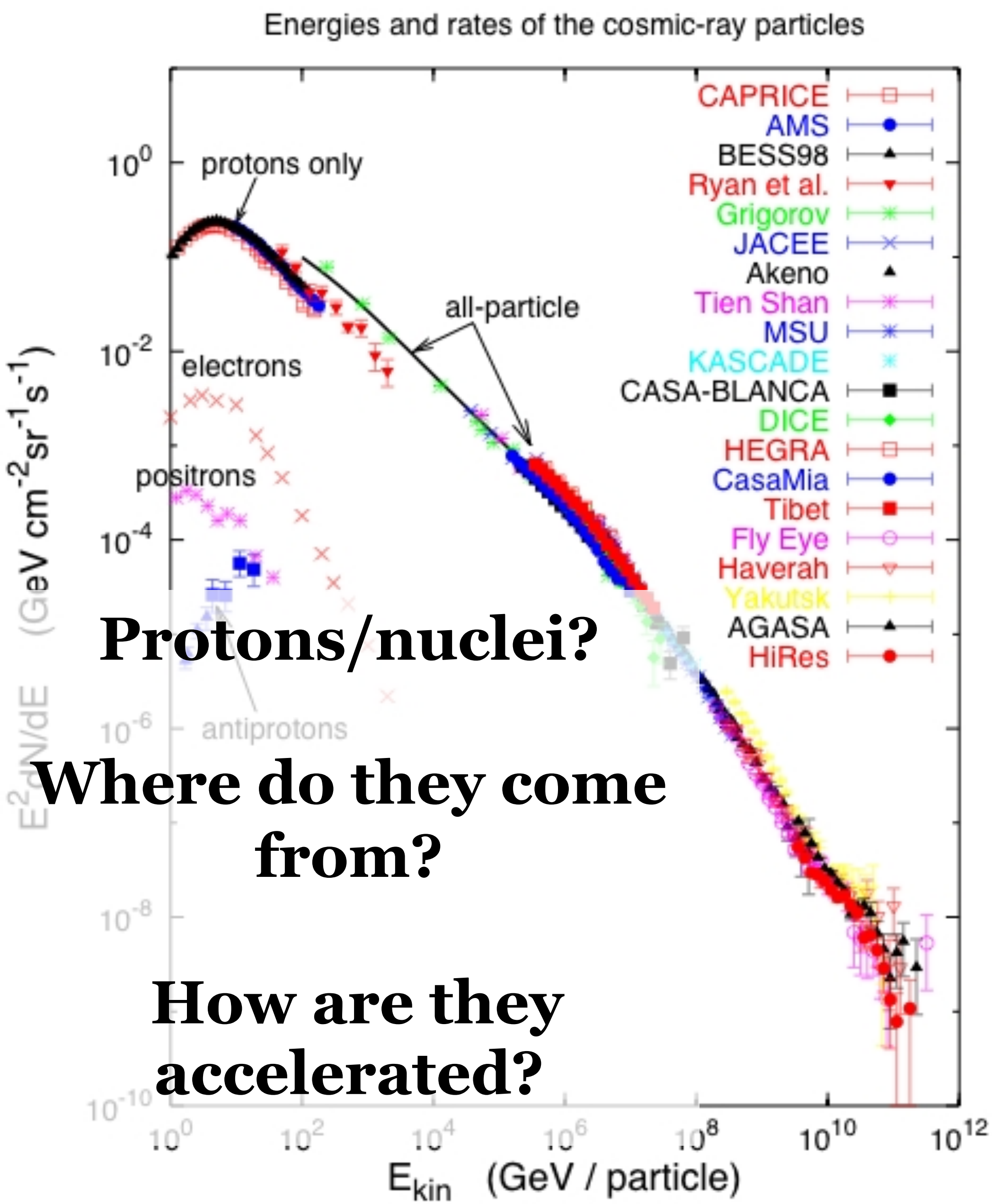




Cosmic-ray astronomy with Auger

Black dots: highest energy cosmic rays
Blue dots: active galaxies

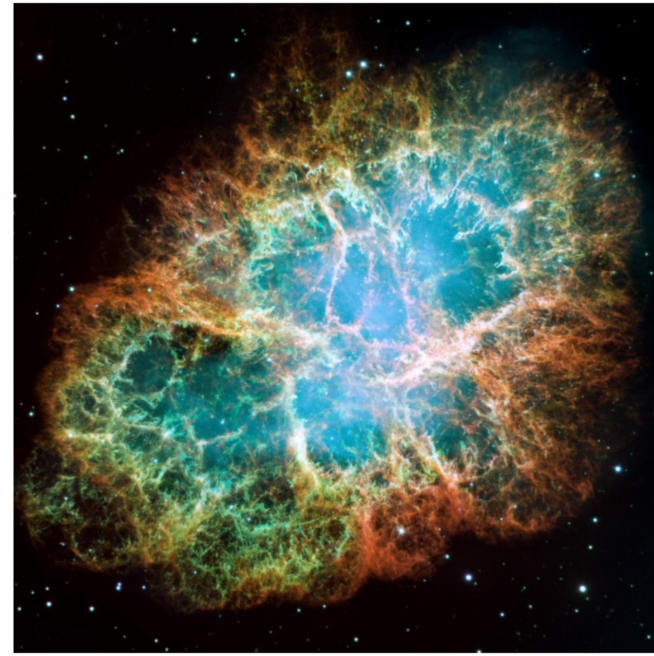


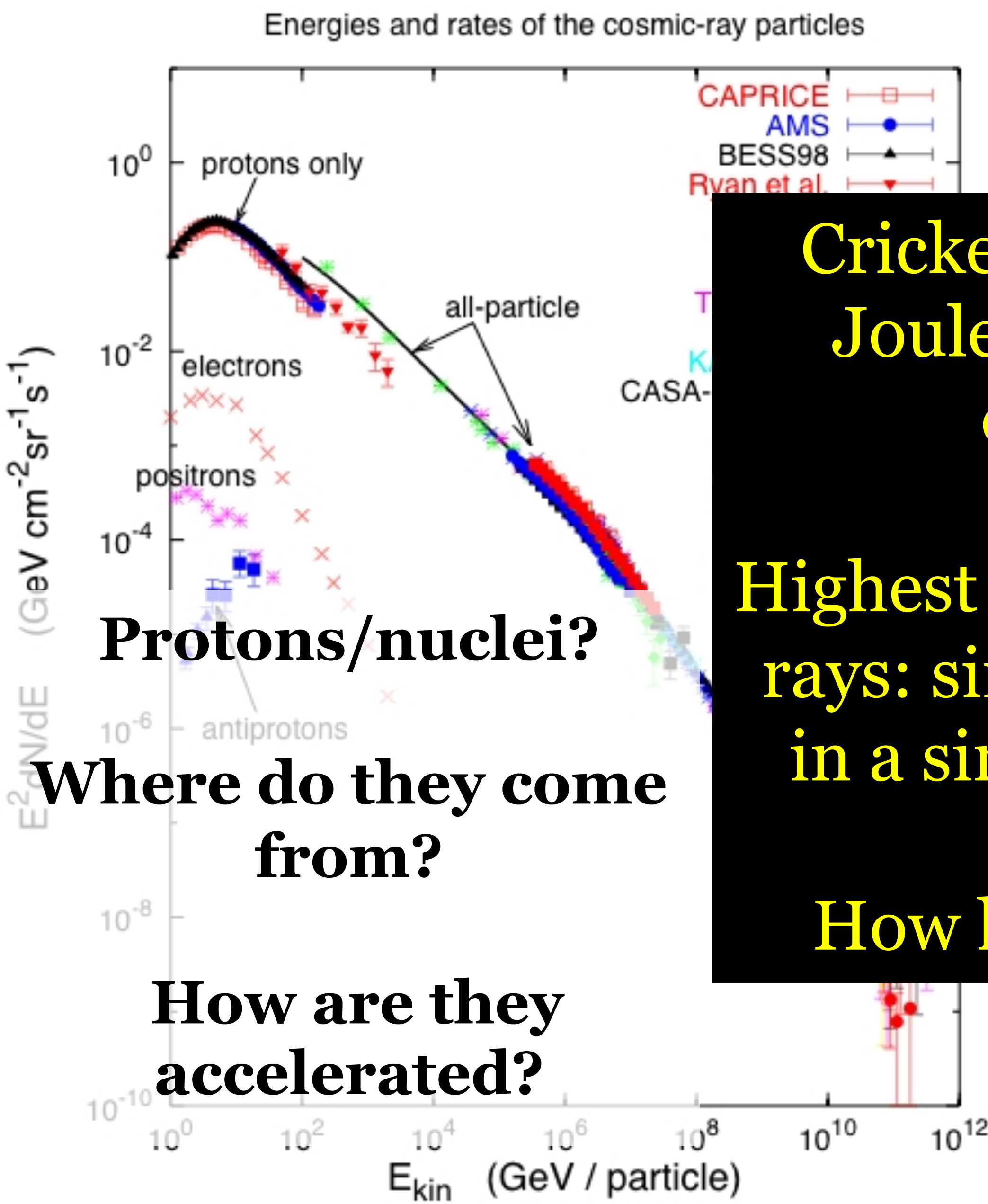


Protons/nuclei?

Where do they come from?

How are they accelerated?





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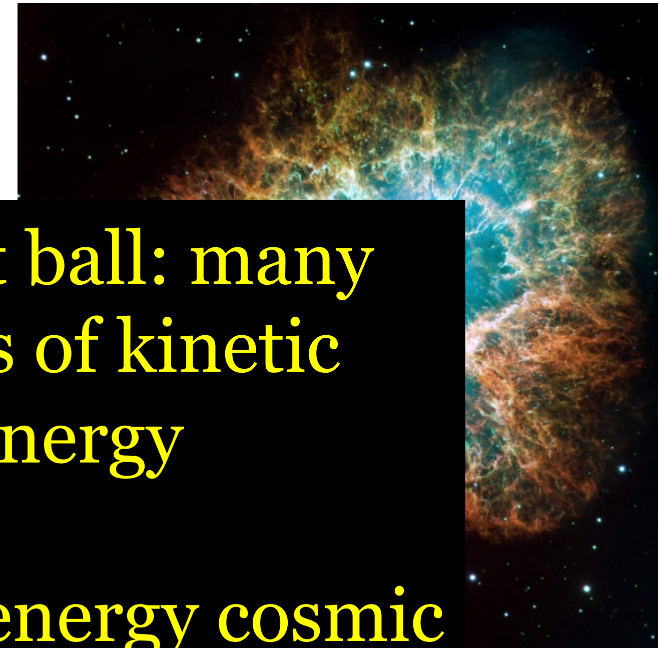
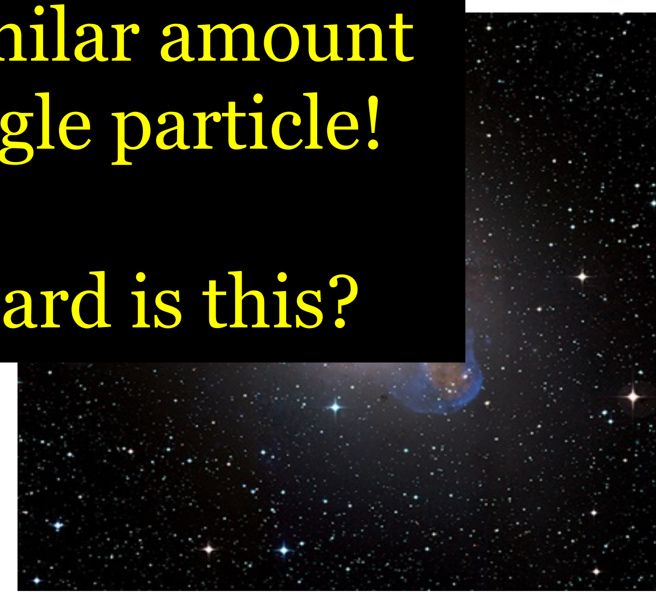
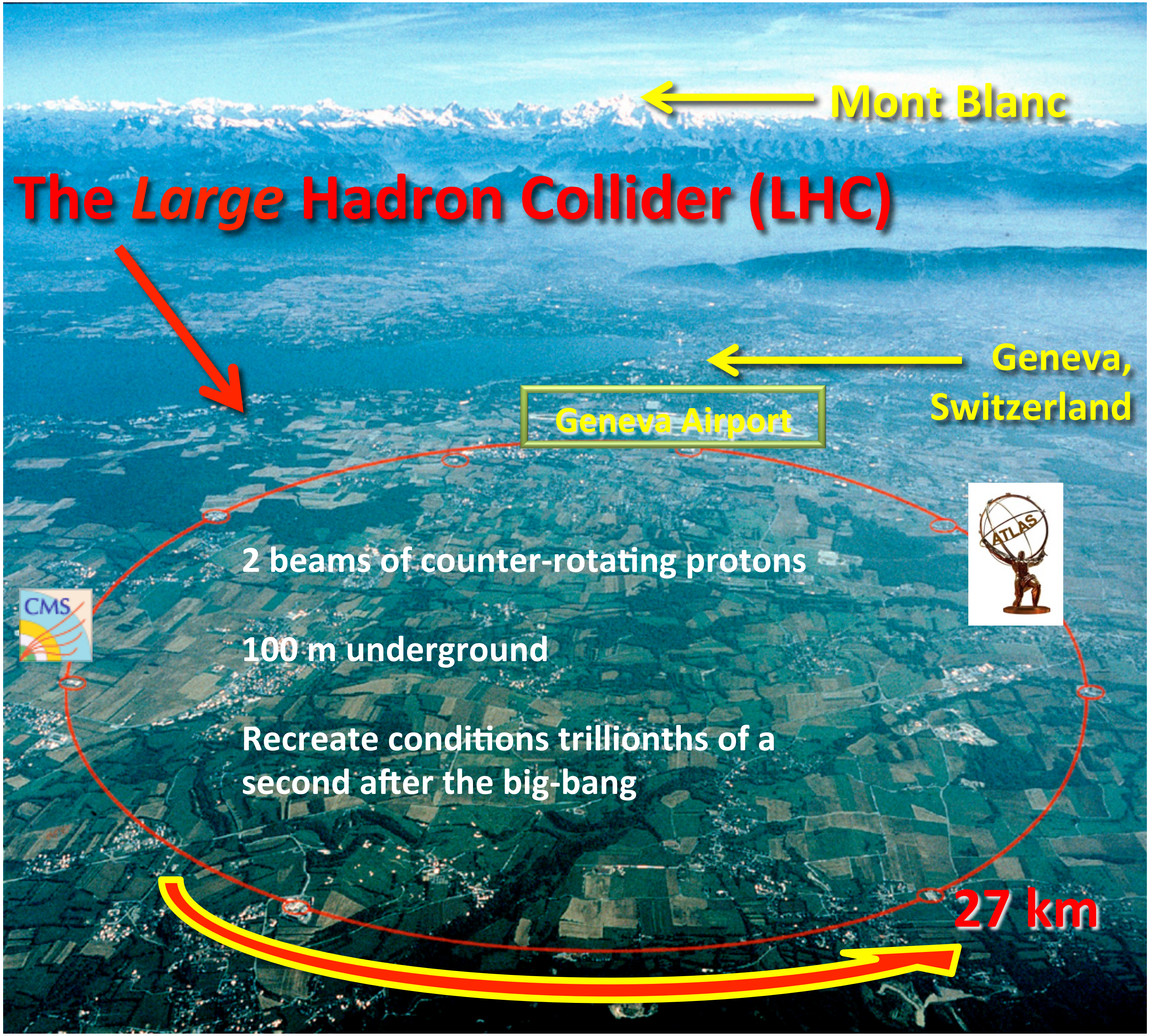




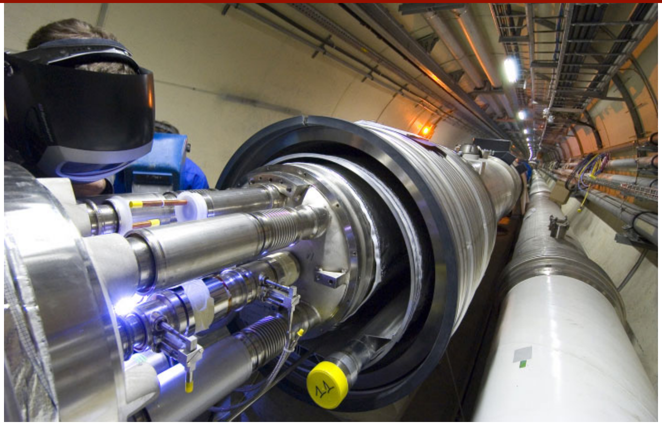
Cricket ball: many Joules of kinetic energy

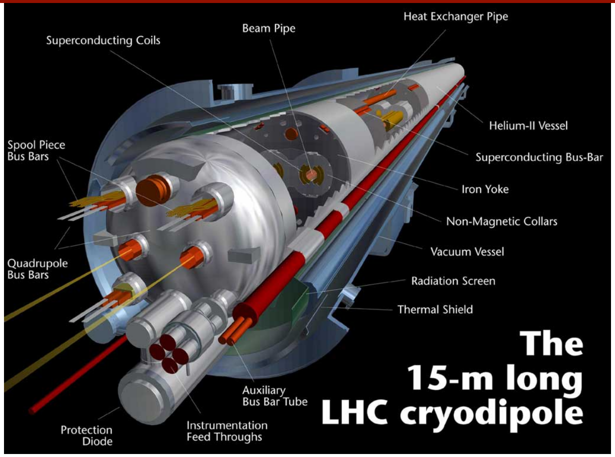
Highest energy cosmic rays: similar amount in a single particle!

How hard is this?


Mont Blanc
The *Large* Hadron Collider (LHC)
Geneva, Switzerland
Geneva Airport
2 beams of counter-rotating protons
100 m underground
Recreate conditions trillionths of a second after the big-bang
CMS
ATLAS
27 km

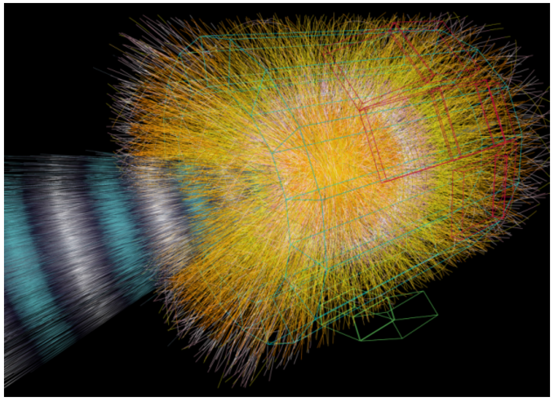
The LHC at CERN





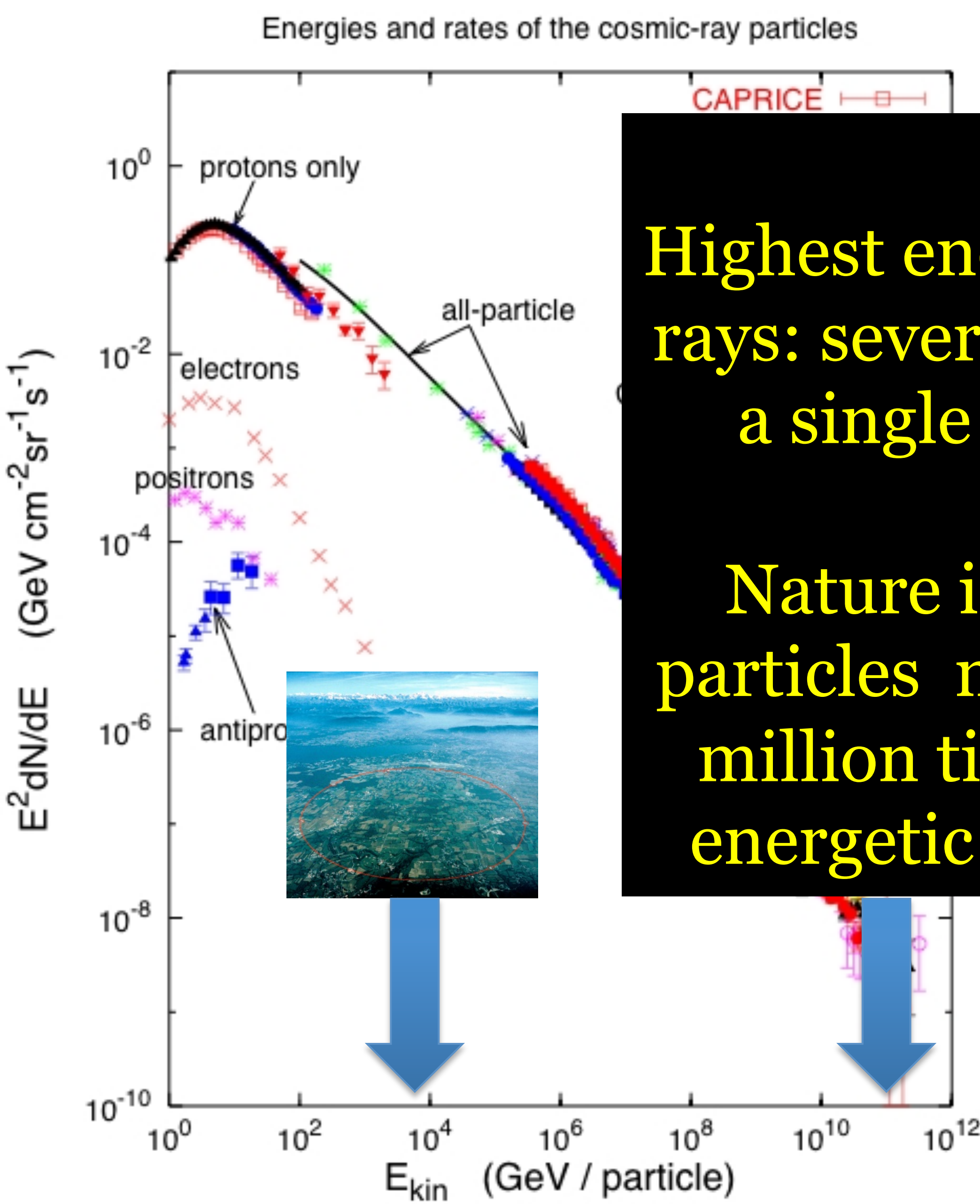
Several thousand billion **protons** travel 27 km at **99.999999%** the speed of light, collide **40,000,000** times a second.

Beam pipe under **same vacuum as outer space**. Pressure is 1/10th that of the surface of the moon.



Superconducting and superfluid liquid helium is maintained at **-271.3 C or 1.9 K**. That is even colder than interstellar space!

Violent collisions ~ temperatures a billion times higher than the core of the sun are produced. That is roughly 160,000,000,000,000,000 C



Highest energy cosmic rays: several Joules in a single particle!

Nature is making particles more than a million times more energetic than LHC

Astronomical messengers:

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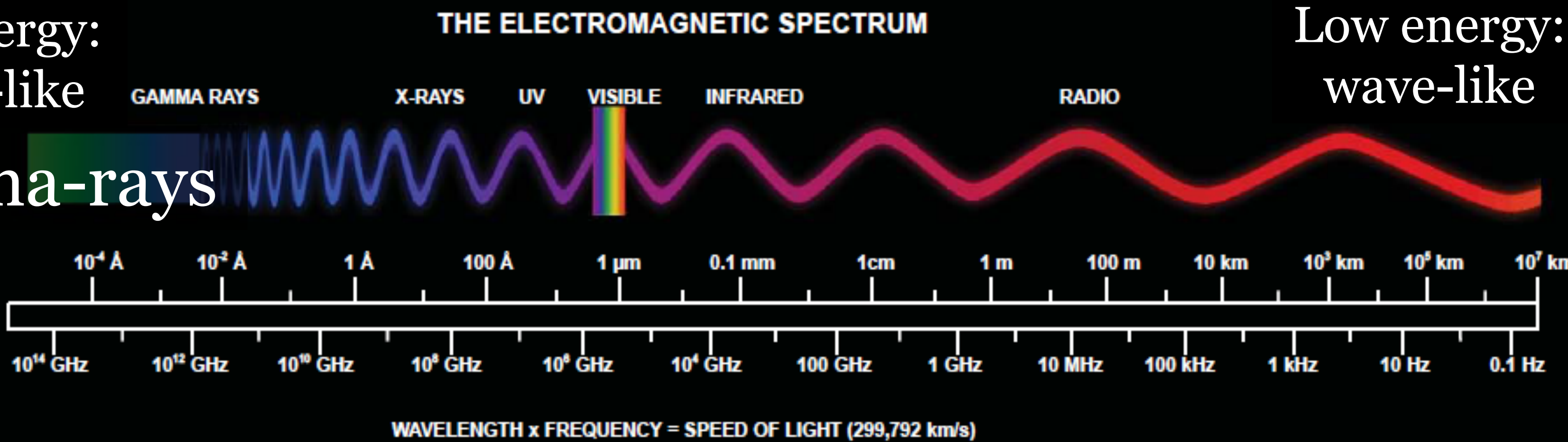
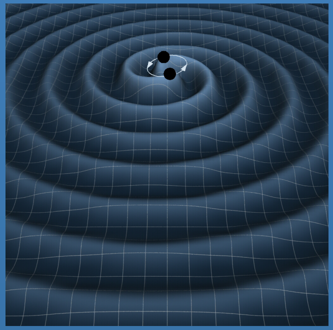
Gamma-rays



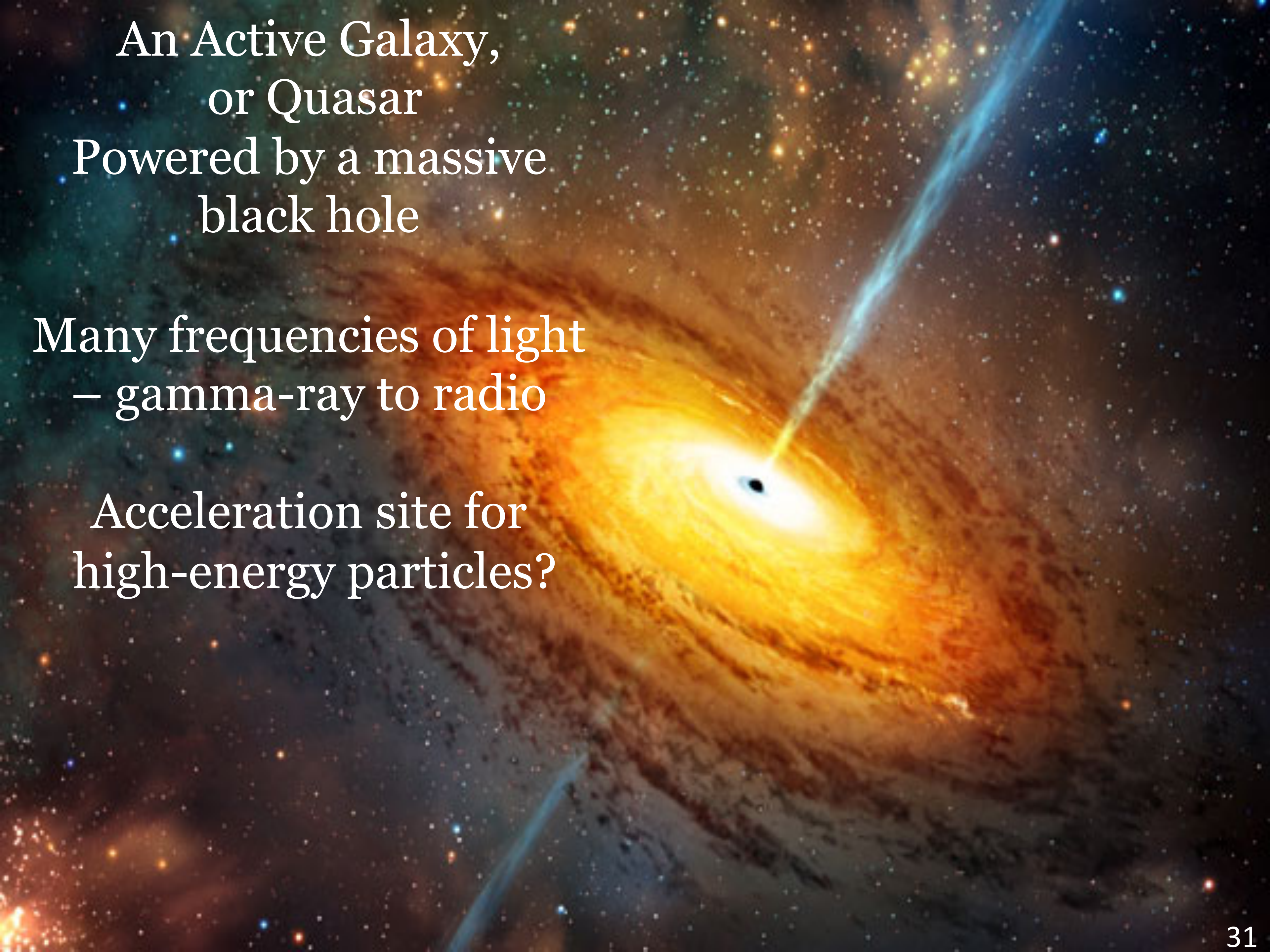
Not light: other messengers

Cosmic rays

Neutrinos



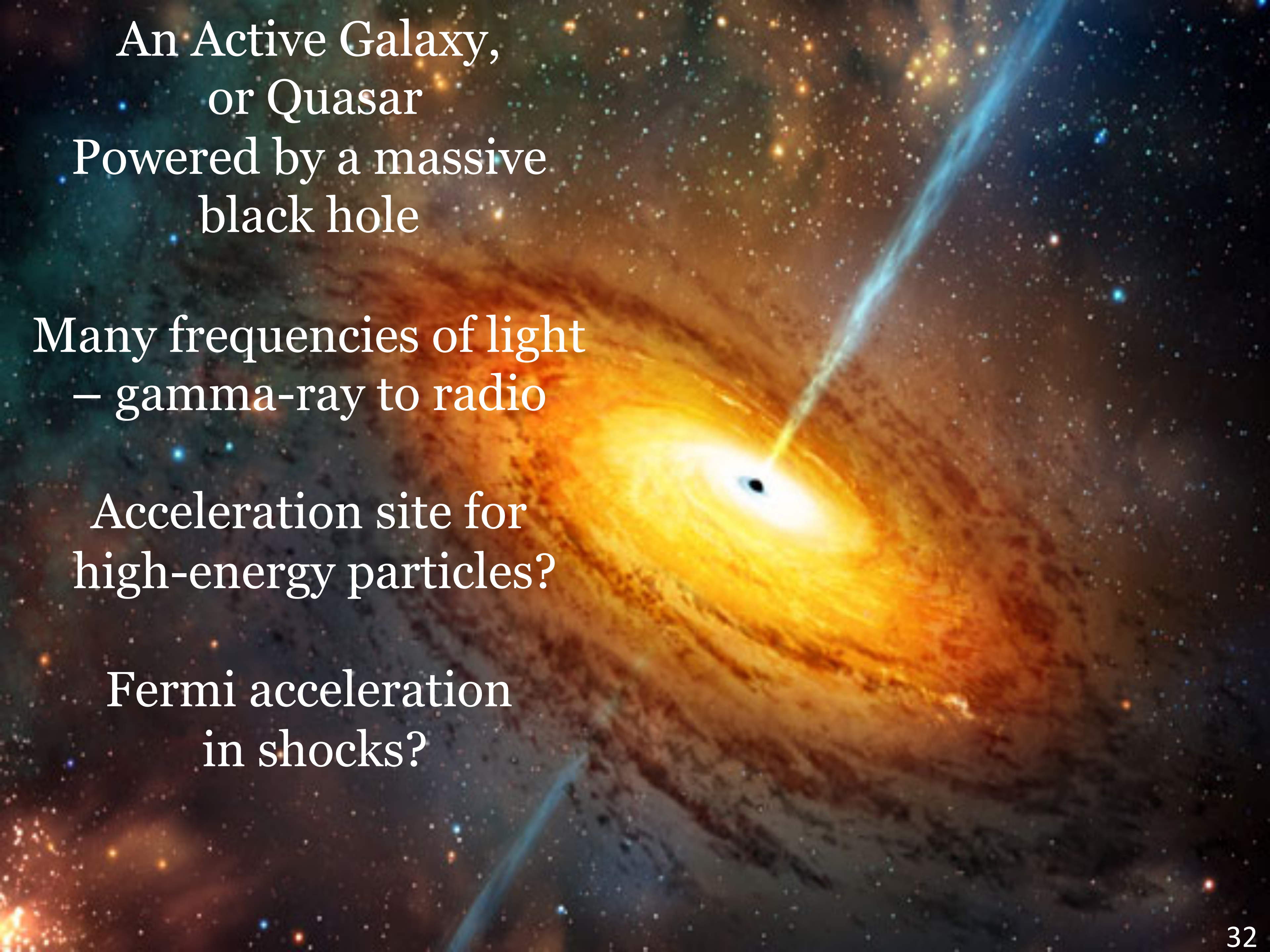
Gravitational waves



An Active Galaxy,
or Quasar
Powered by a massive
black hole

Many frequencies of light
– gamma-ray to radio

Acceleration site for
high-energy particles?


An Active Galaxy,
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Fermi acceleration
in shocks?

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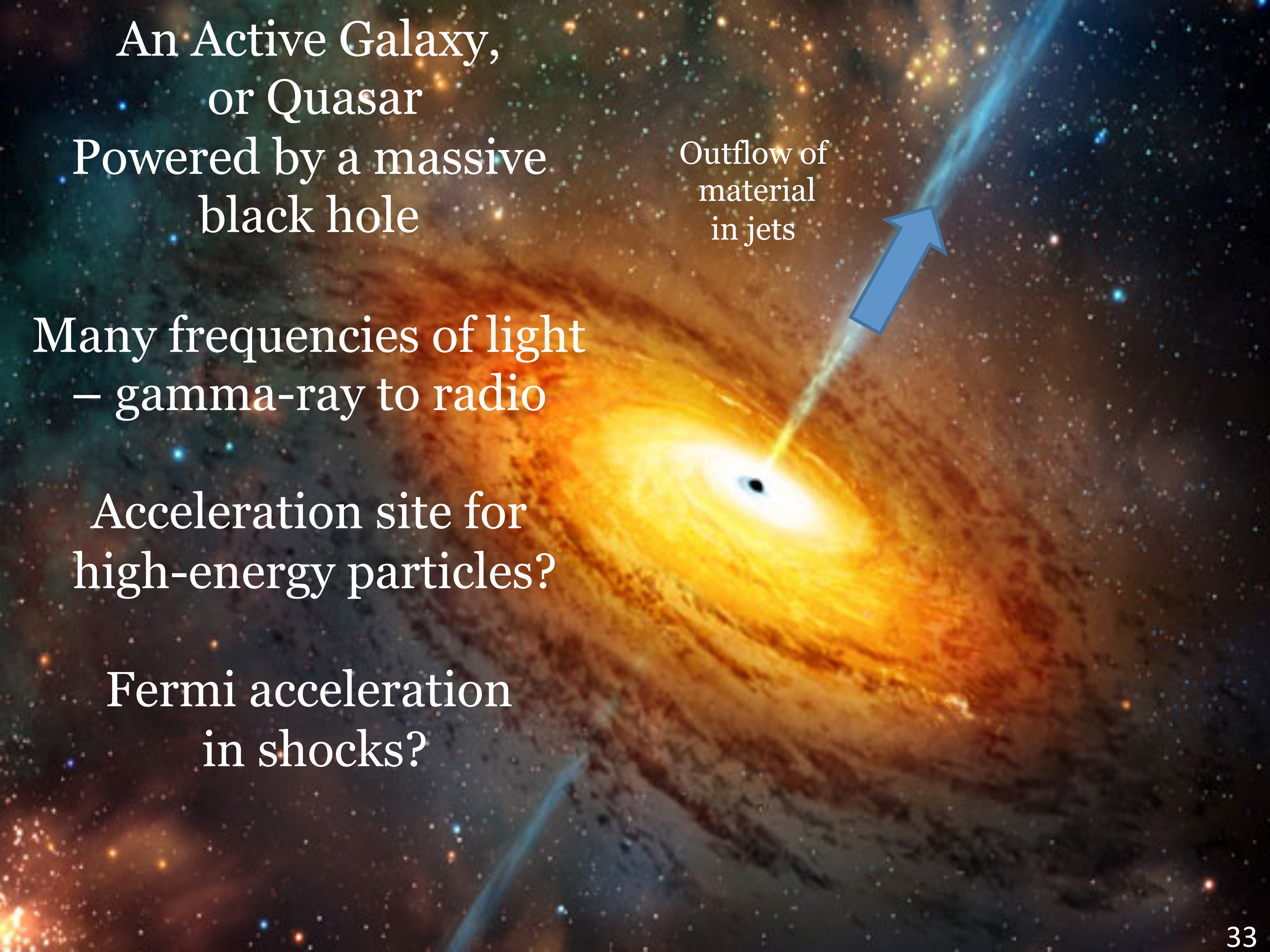

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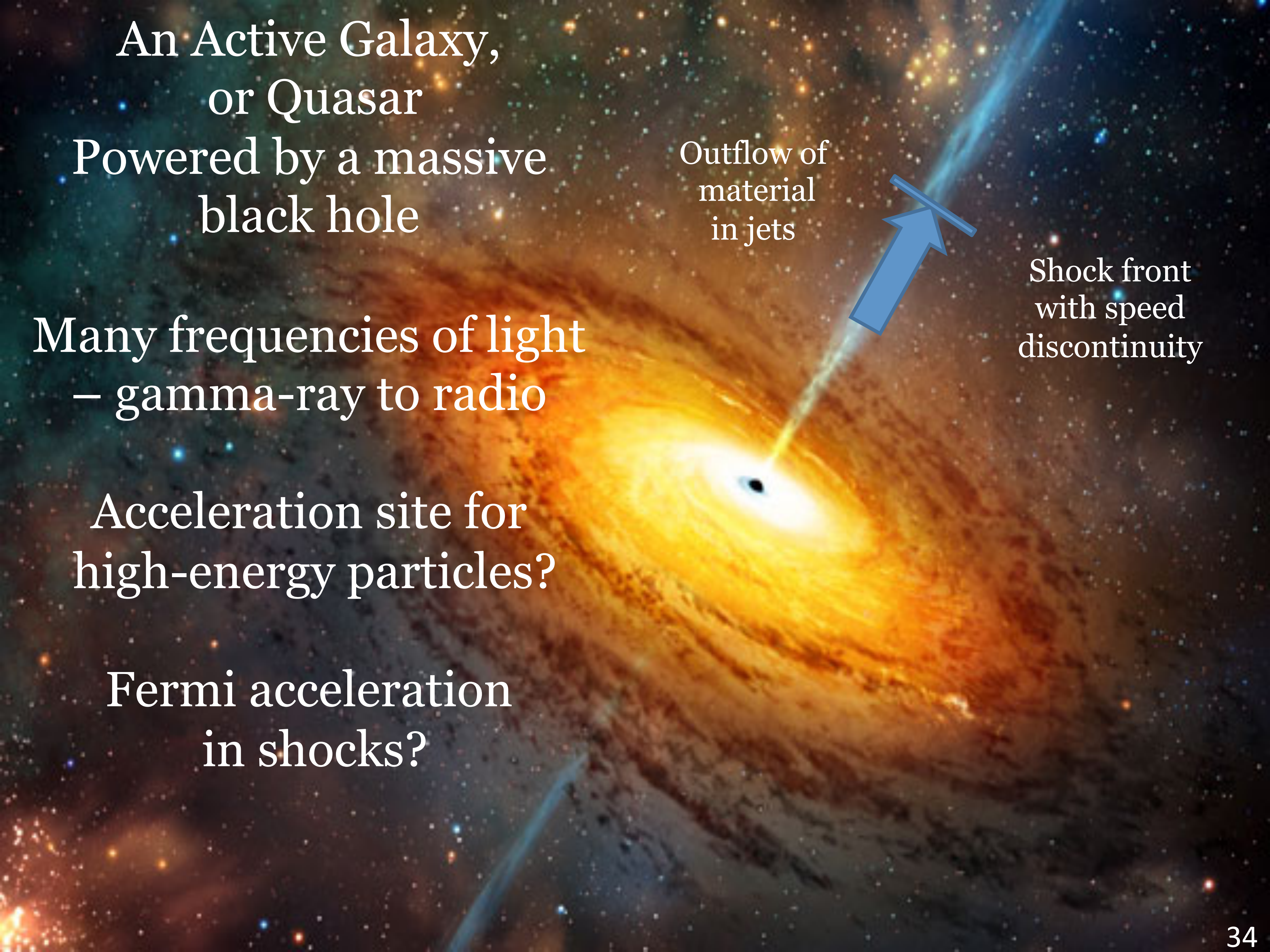
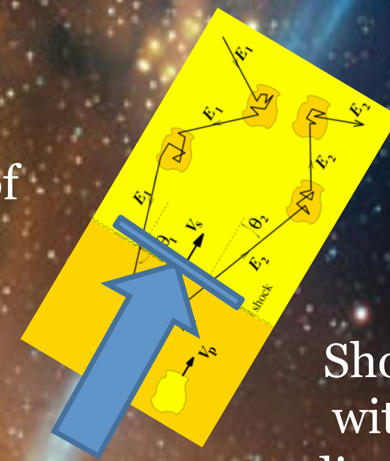


An Active Galaxy,
or Quasar
Powered by a massive
black hole

Outflow of
material
in jets



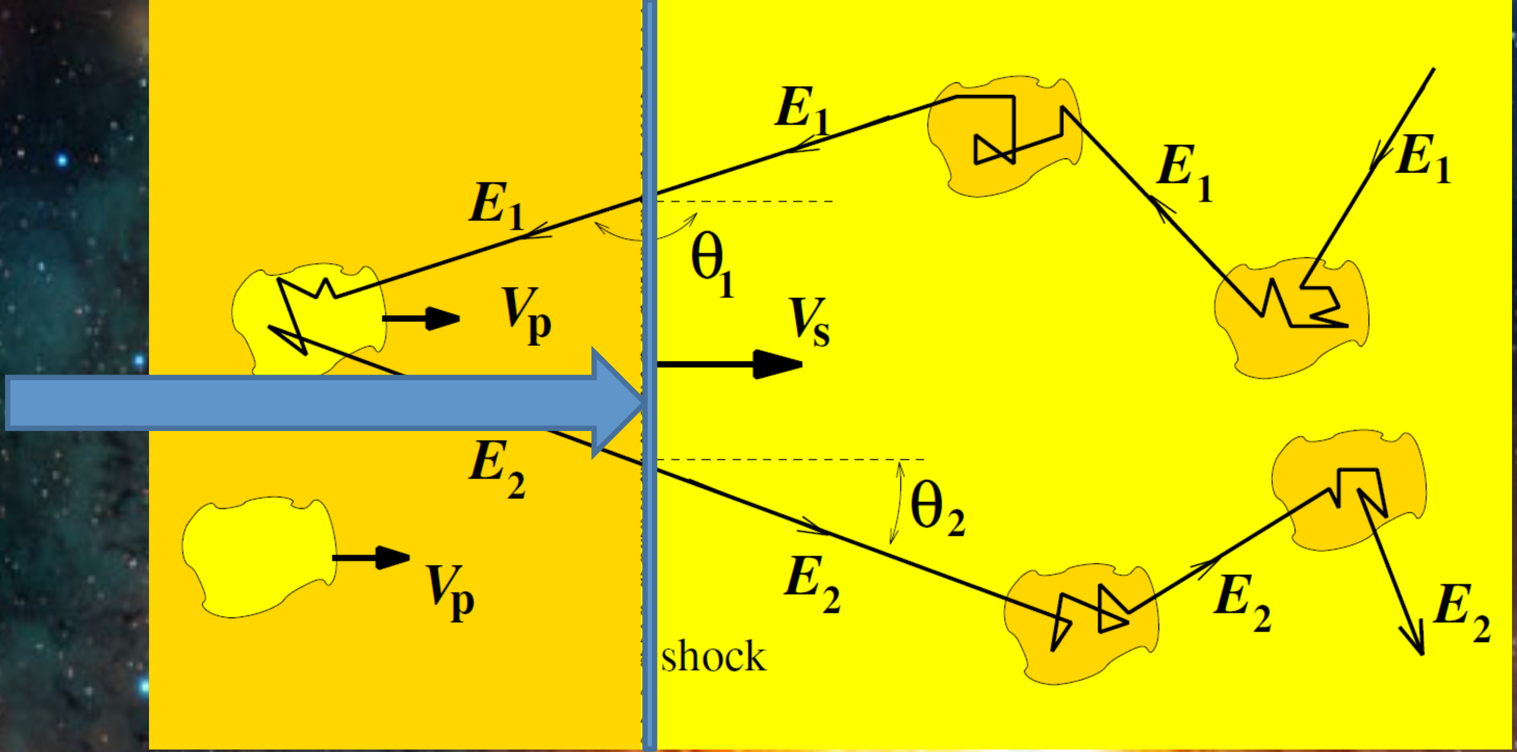
Shock front
with speed
discontinuity

Many frequencies of light
– gamma-ray to radio

Acceleration site for
high-energy particles?

Fermi acceleration
in shocks?

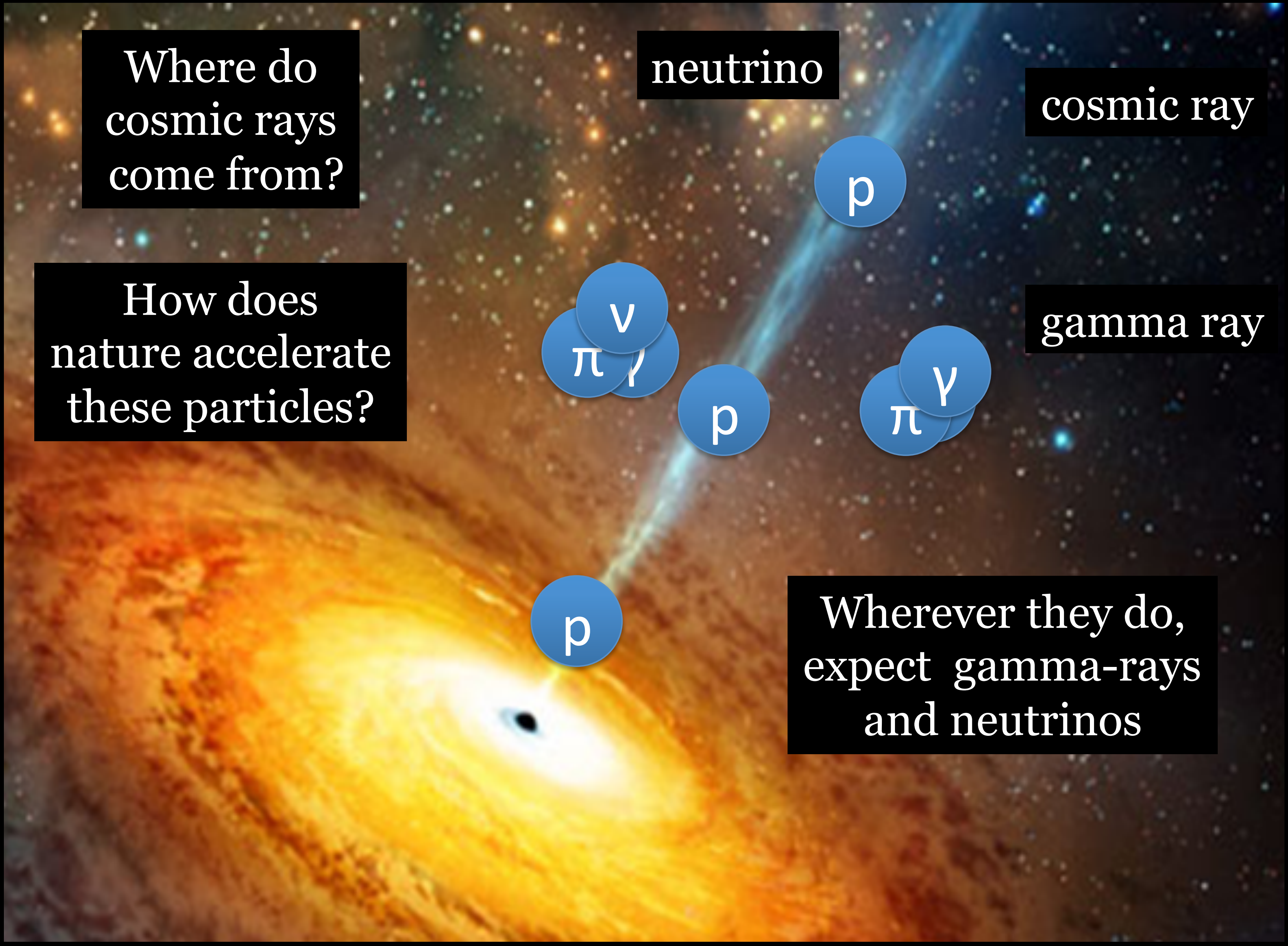
Fermi acceleration as particles bounce back and forth across schock
- small boost in energy each crossing
- confinement by magnetised coulds



Fermi acceleration as particles bounce back and forth across schock

- small boost in energy each crossing: dE/E ~Vs/c
- small chance of escape each crossing: confinement by magnetised coulds
- Energy spectrum of escaping particles:

Power law $N(E) \sim E^{-2}$


Where do cosmic rays come from?
neutrino
cosmic ray
p
How does nature accelerate these particles?
ν
π
γ
p
gamma ray
γ
π
p
Wherever they do, expect gamma-rays and neutrinos

Neutrino and gamma production in cosmic ray accelerators?

The TeV gammas?

$$pp, p\gamma \rightarrow \pi^0 \rightarrow \gamma\,\gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

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

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$e^- + \bar{\nu}_e + \nu_\mu$$

γ-rays also from electrons:

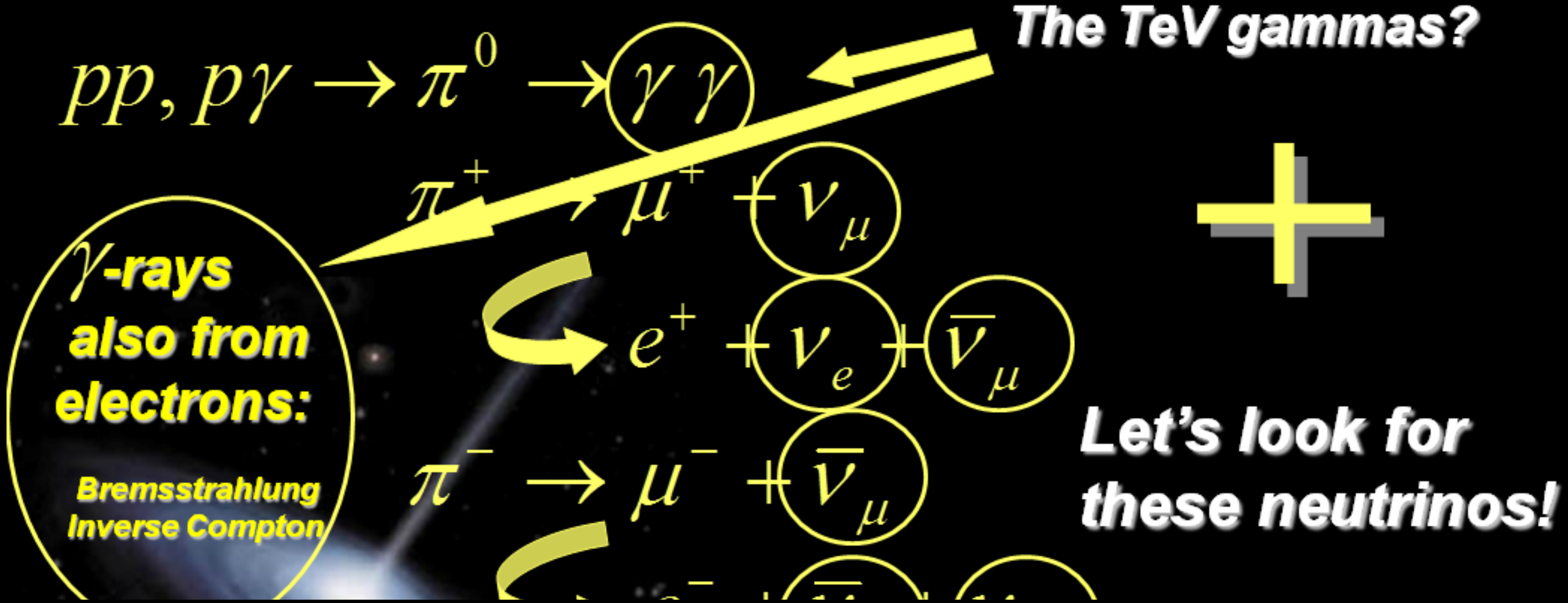
Bremsstrahlung
Inverse Compton

+

Let's look for these neutrinos!

Hadronic accelerator? – cosmic ray origin?

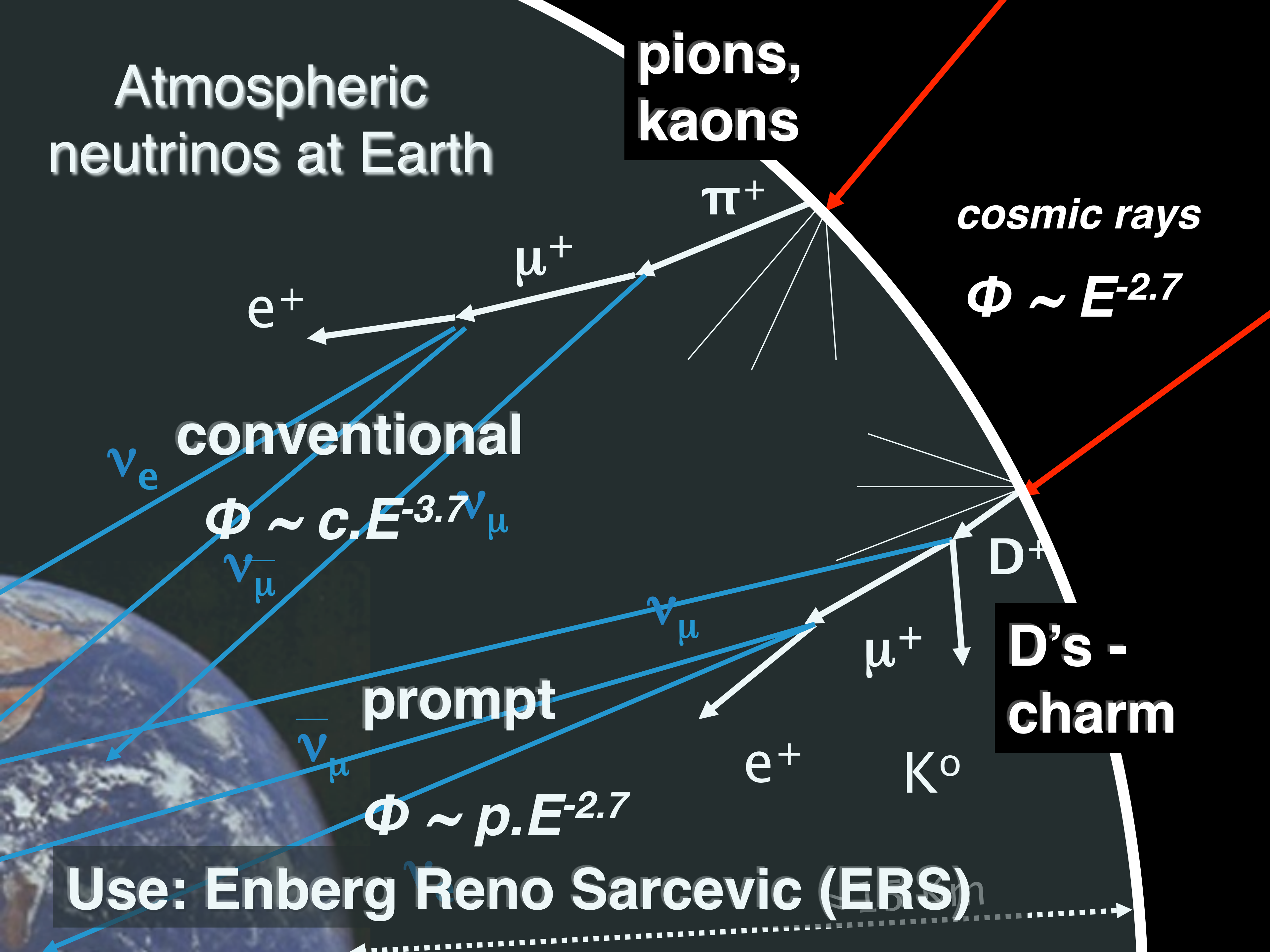
Neutrino and gamma production in cosmic ray accelerators?

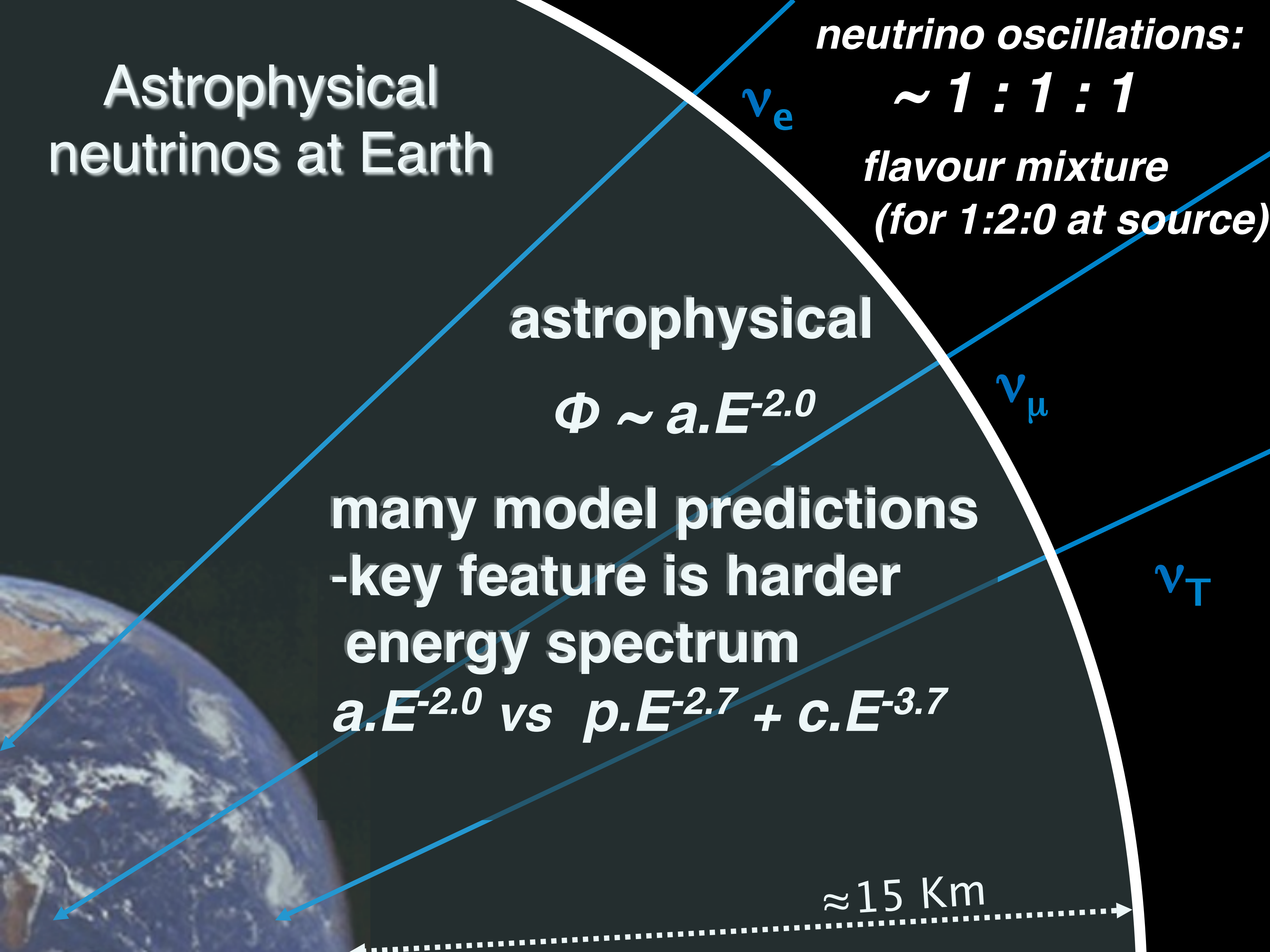


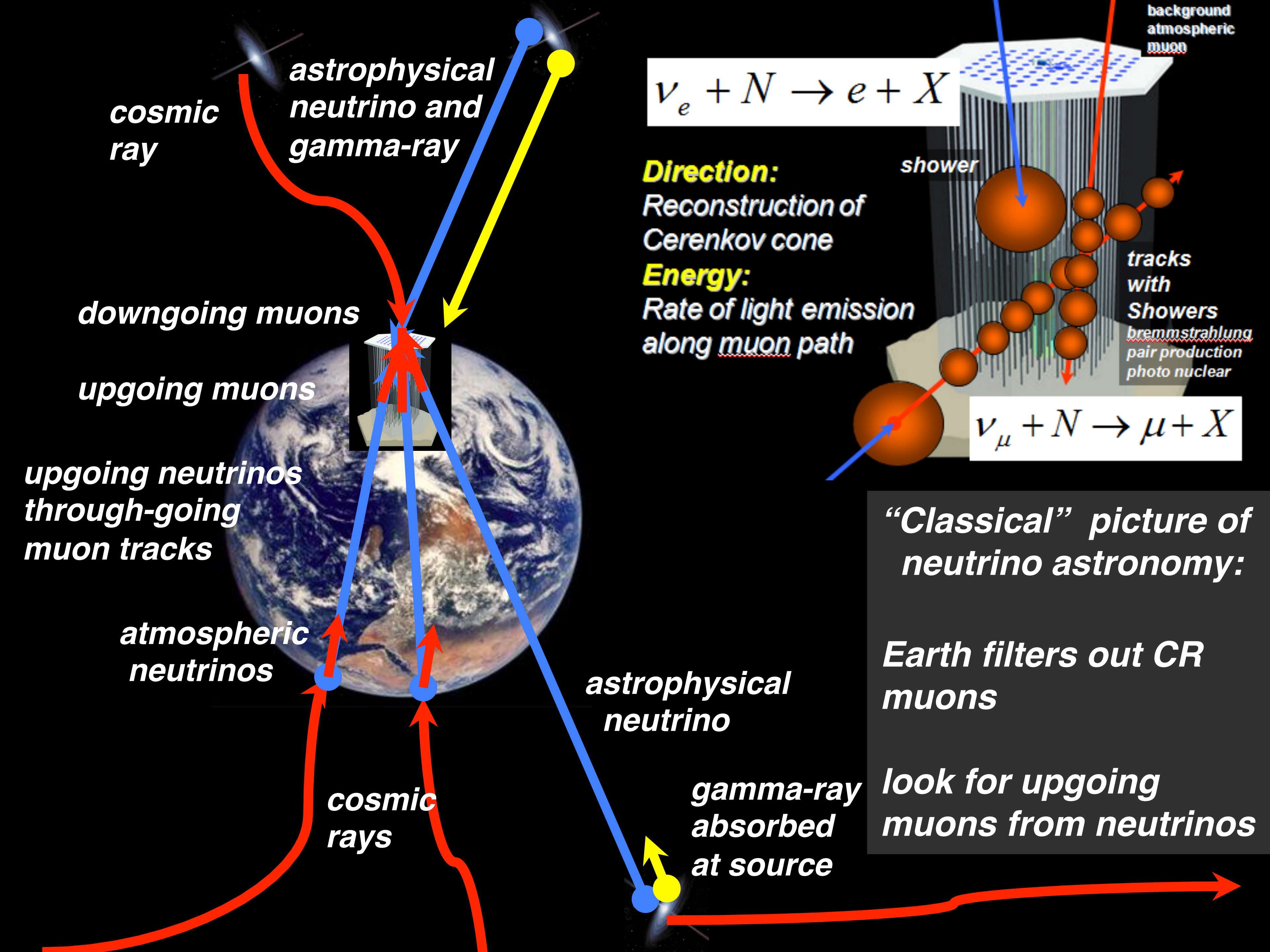
muons decay: e:mu:tau =1:2:0

muons don't decay: e:mu:tau = 0:1:0

neutrons decay: e:mu:tau = 1:0:0


Atmospheric neutrinos at Earth
pions, kaons
π^+
cosmic rays
$\Phi \sim E^{-2.7}$
μ^+
e^+
conventional
ν_e
$\Phi \sim c.E^{-3.7}$
ν_μ
$\bar{\nu}_\mu$
D^+
D's - charm
ν_μ
μ^+
prompt
$\bar{\nu}_\mu$
e^+
K^o
$\Phi \sim p.E^{-2.7}$
Use: Enberg Reno Sarcevic (ERS)


Astrophysical
neutrinos at Earth
neutrino oscillations:
~ 1 : 1 : 1
flavour mixture
(for 1:2:0 at source)
νe
νμ
νT
astrophysical
Φ ~ a.E-2.0
many model predictions
-key feature is harder
energy spectrum
a.E-2.0 vs p.E-2.7 + c.E-3.7
≈15 Km



"Classical" picture of neutrino astronomy:

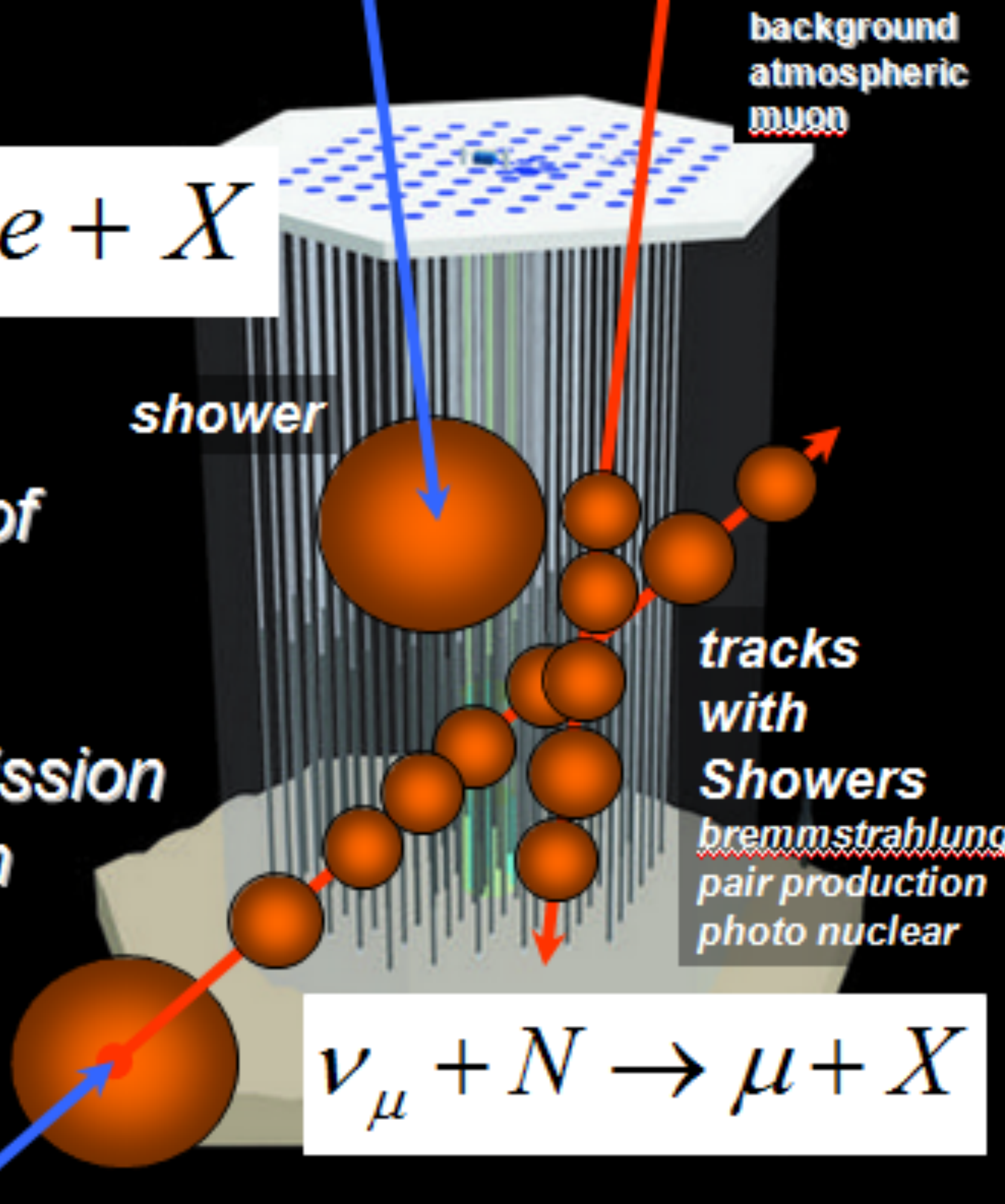
Earth filters out CR muons

look for upgoing muons from neutrinos

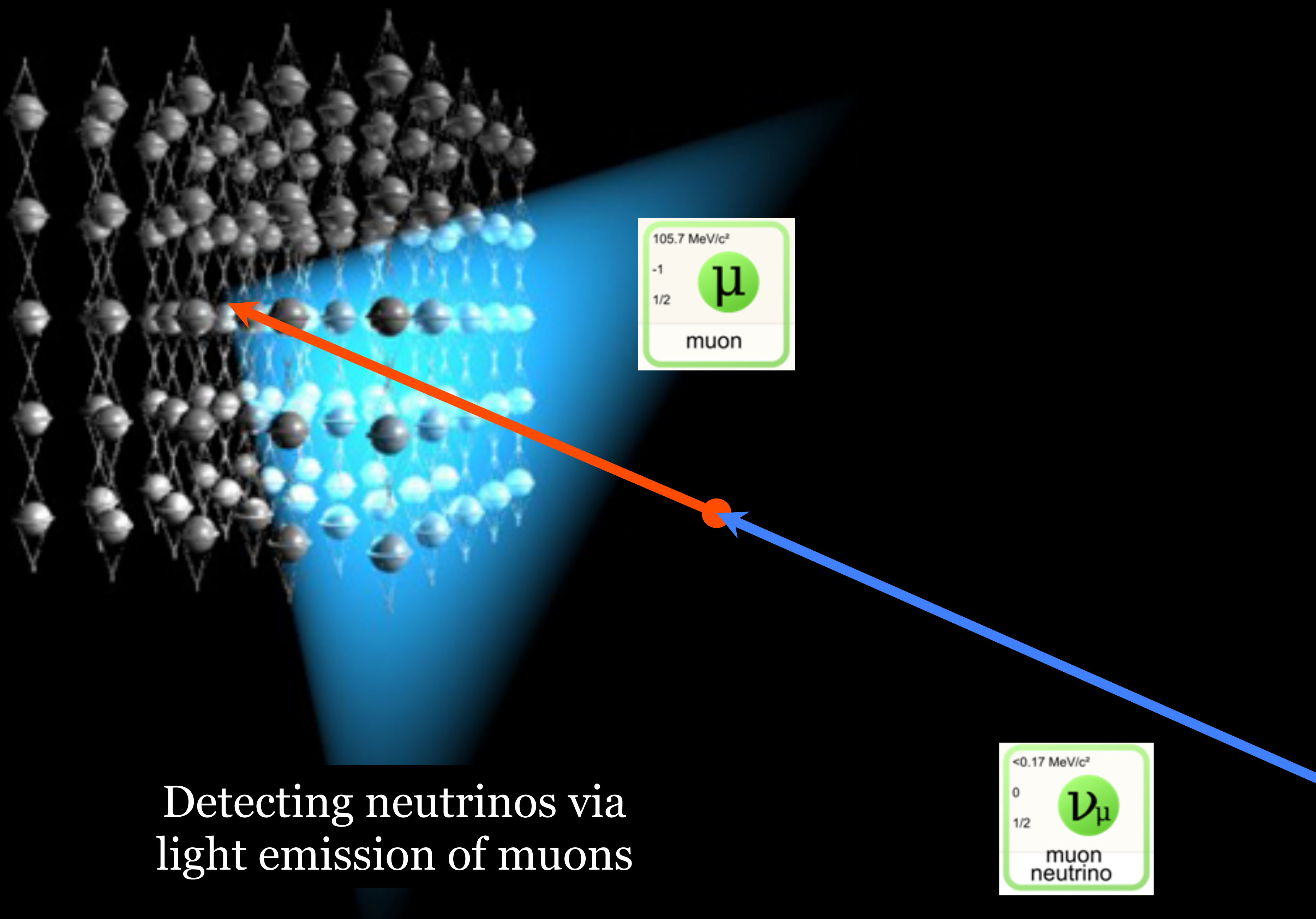
$$\nu_e + N \rightarrow e + X$$

Direction:
Reconstruction of Cerenkov cone

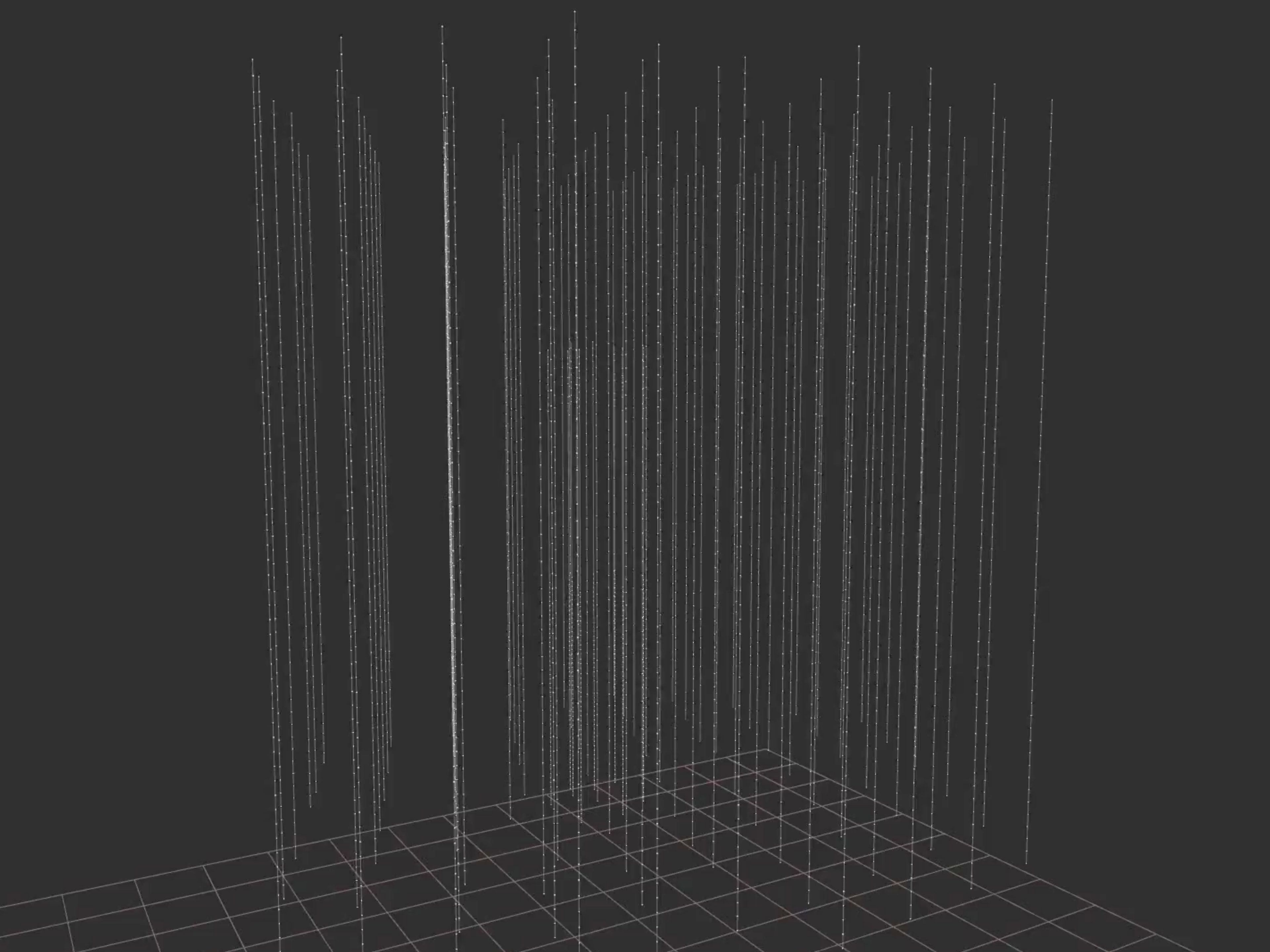
Energy:
Rate of light emission along muon path

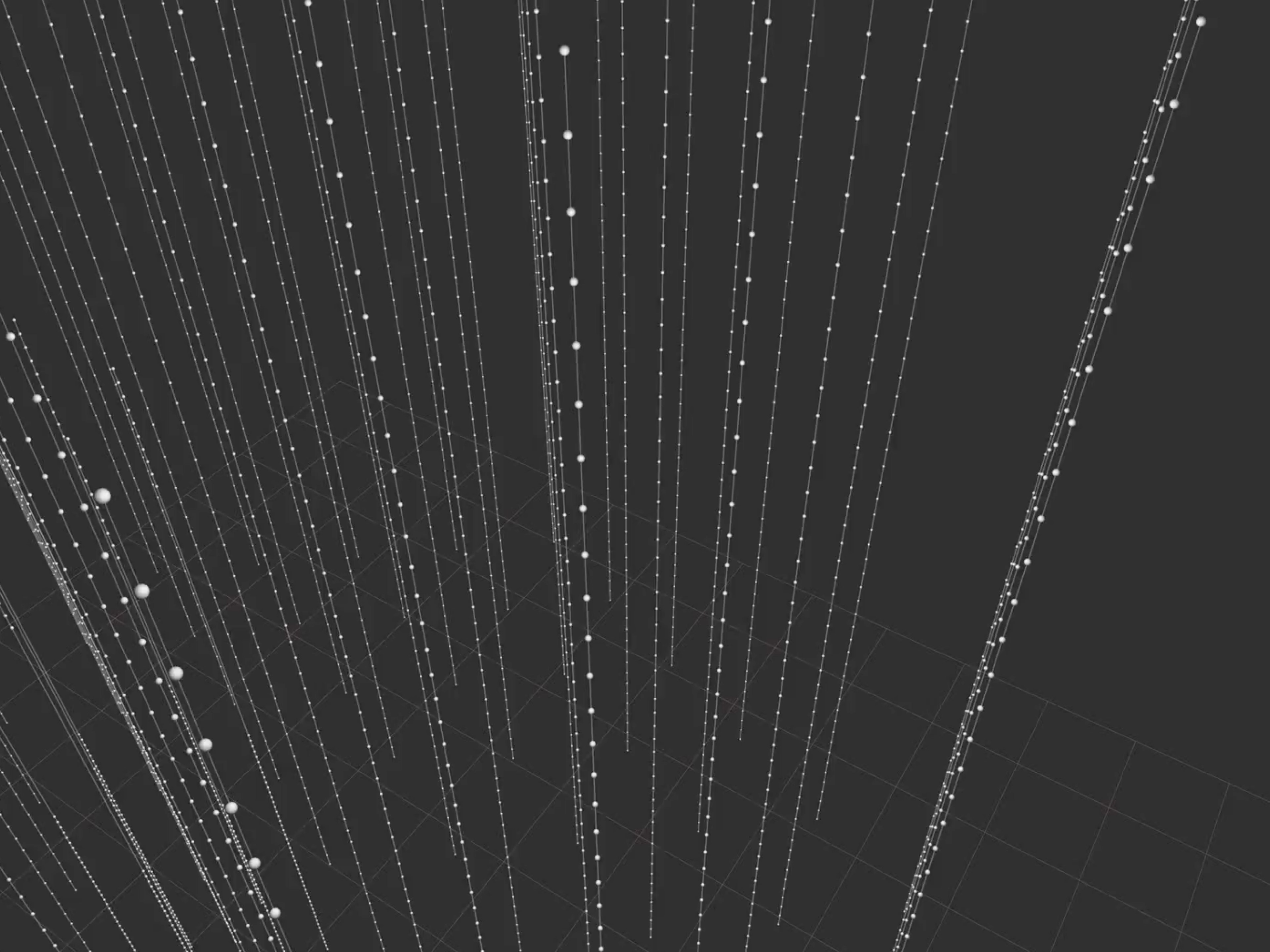


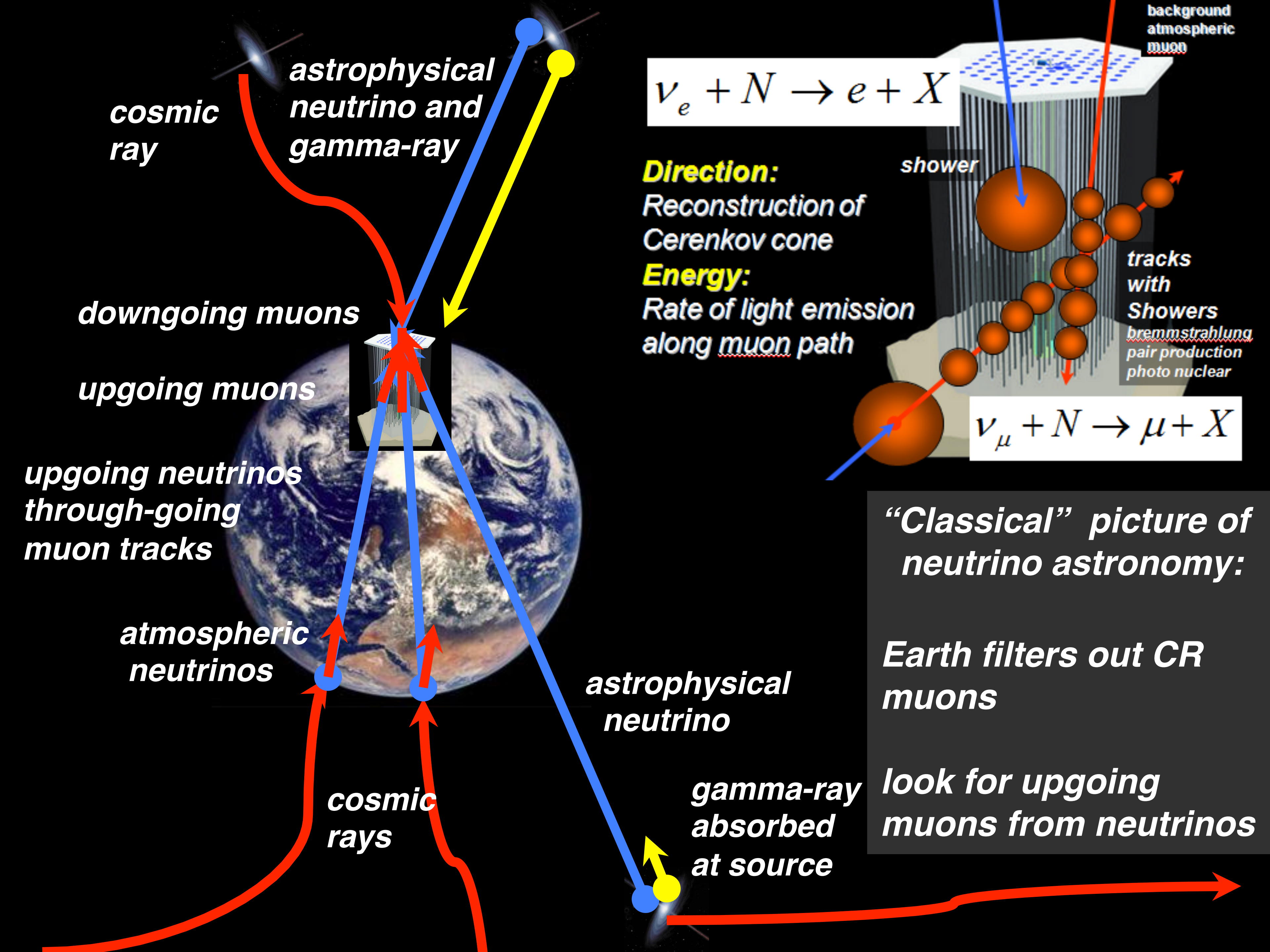
$$\nu_\mu + N \rightarrow \mu + X$$



Detecting neutrinos via light emission of muons





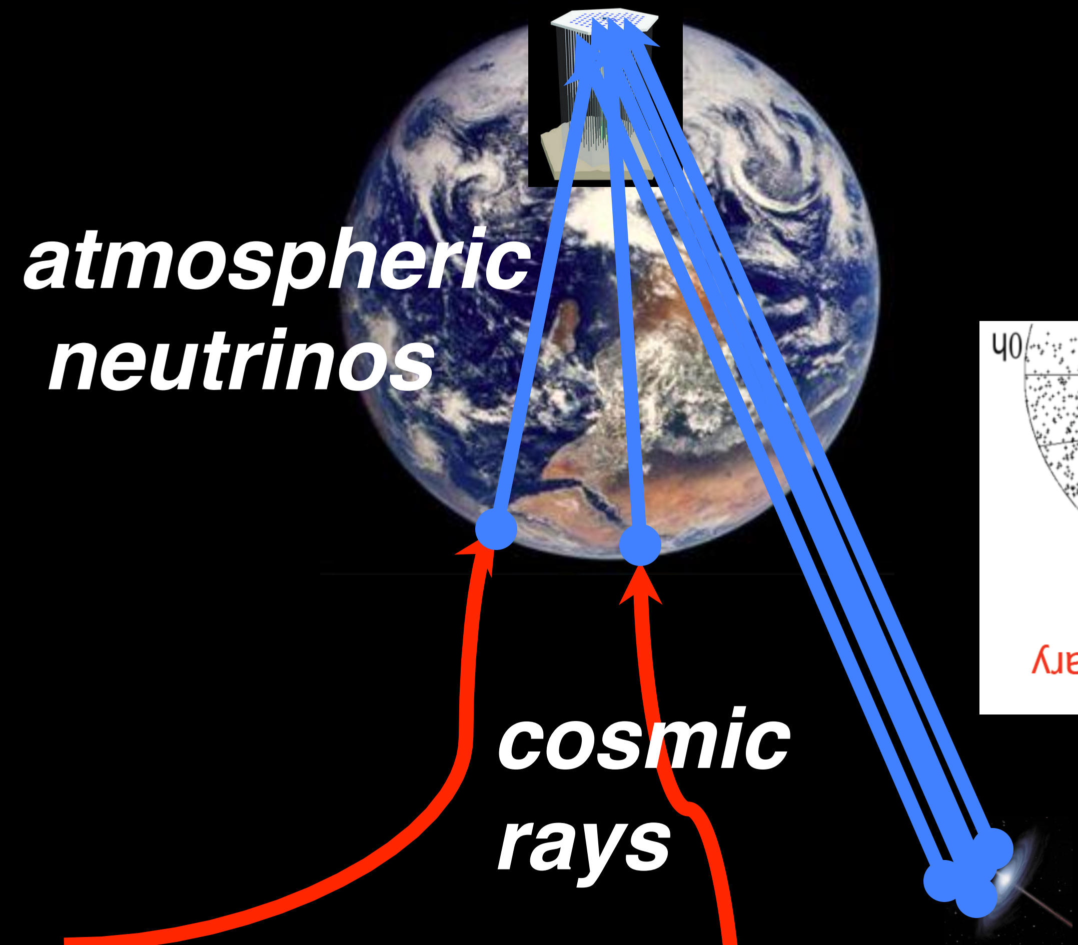


cosmic ray
astrophysical neutrino and gamma-ray
downgoing muons
upgoing muons
upgoing neutrinos through-going muon tracks
atmospheric neutrinos
cosmic rays
astrophysical neutrino
gamma-ray absorbed at source
$\nu_e + N \rightarrow e + X$
background atmospheric muon
Direction:
Reconstruction of Cerenkov cone
Energy:
Rate of light emission along muon path
shower
tracks with Showers
bremmstrahlung
pair production
photo nuclear
$\nu_\mu + N \rightarrow \mu + X$
"Classical" picture of neutrino astronomy:
Earth filters out CR muons
look for upgoing muons from neutrinos

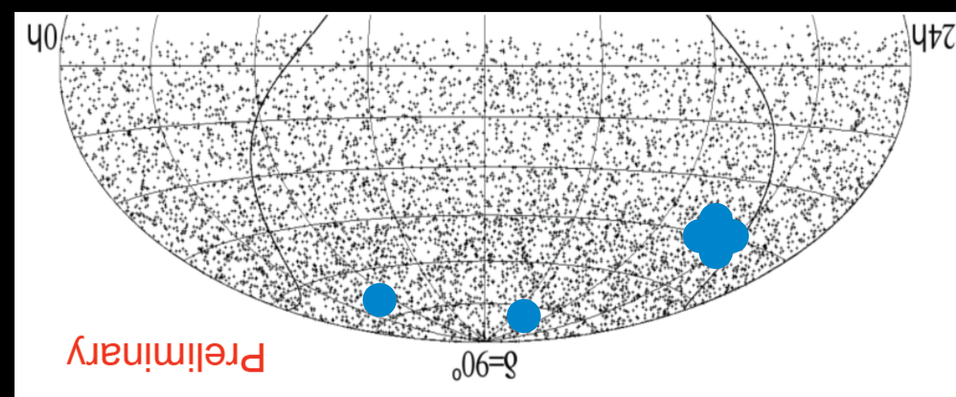
Looking down at the south pole into the northern sky

reject downgoing muons

upgoing neutrinos through-going muon trac



astrophysical neutrino point source as excess on background?

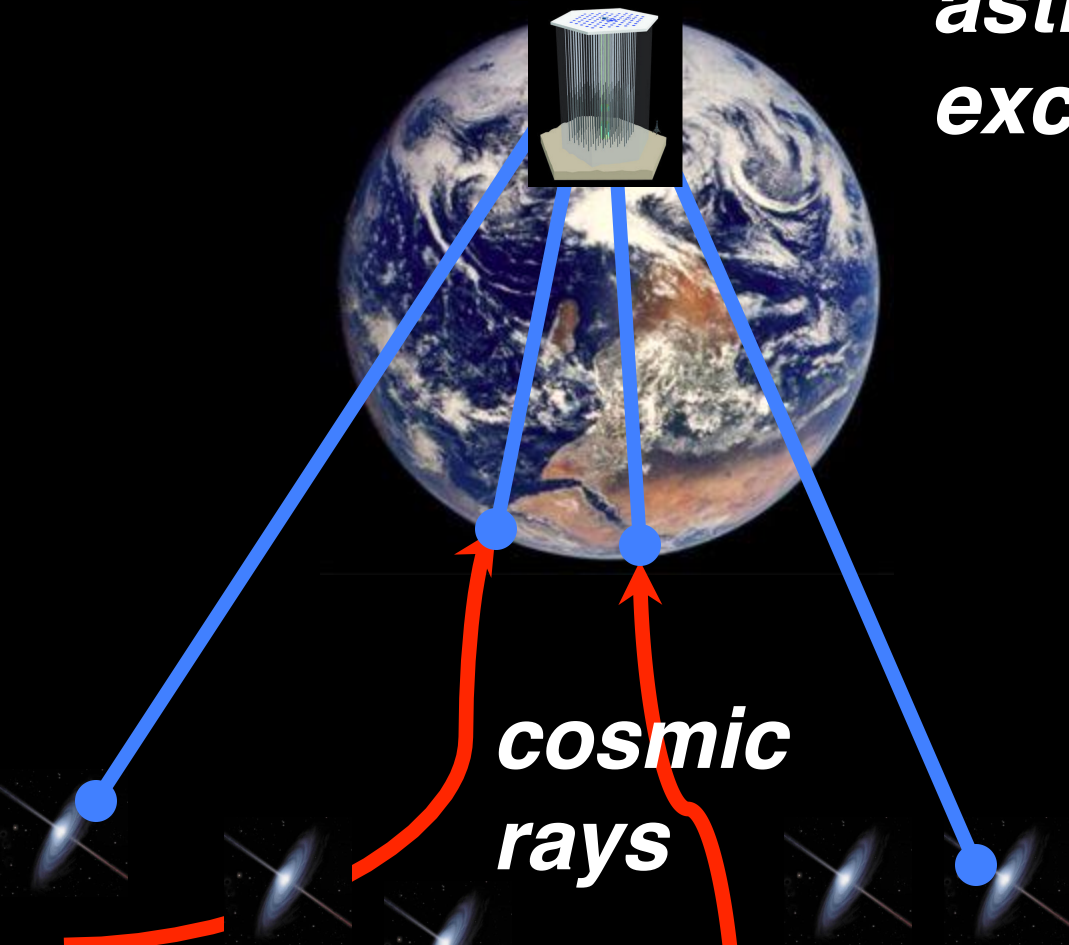


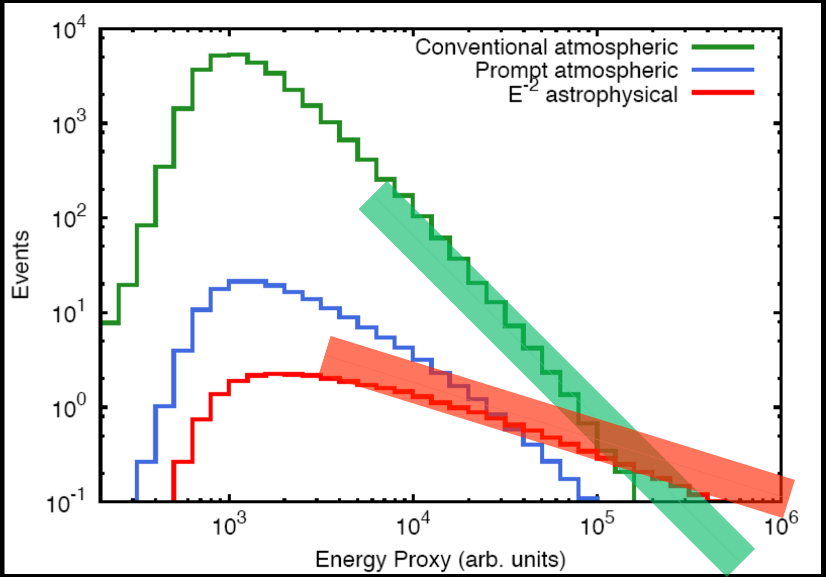
Looking down at the south pole into the northern sky

upgoing neutrinos
through-going muon tra

reject downgoing muons

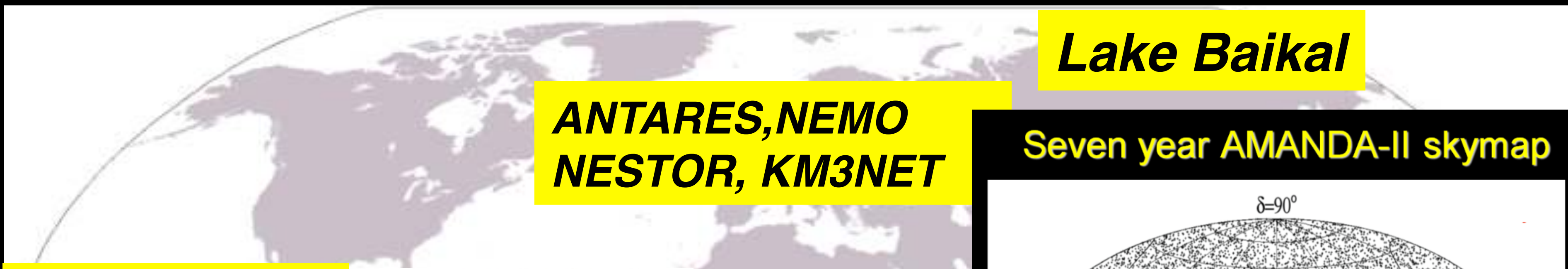
astrophysical neutrino excess at high energy?





muon energy in detector

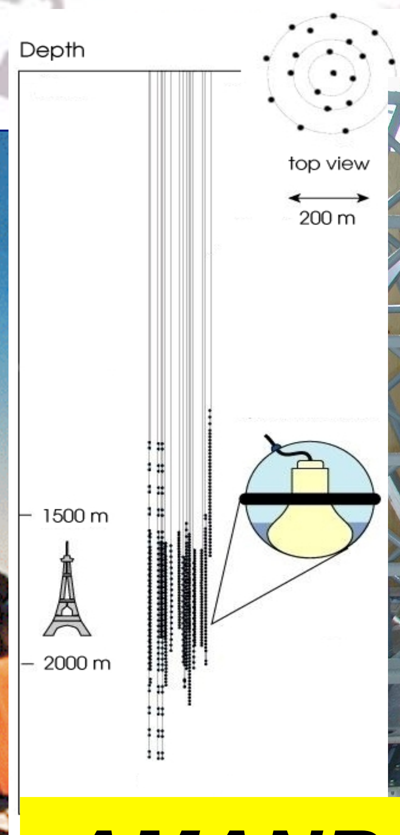
Optical Cherenkov neutrino detectors



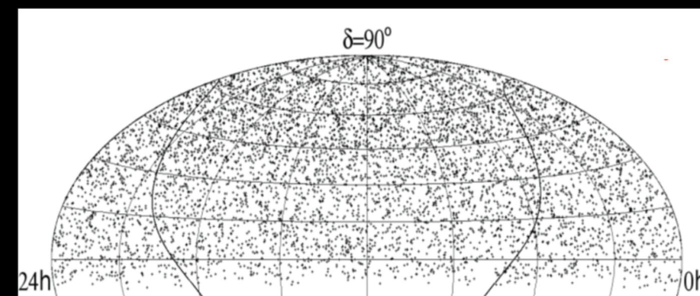
Lake Baikal

ANTARES,NEMO
NESTOR, KM3NET

DUMAND



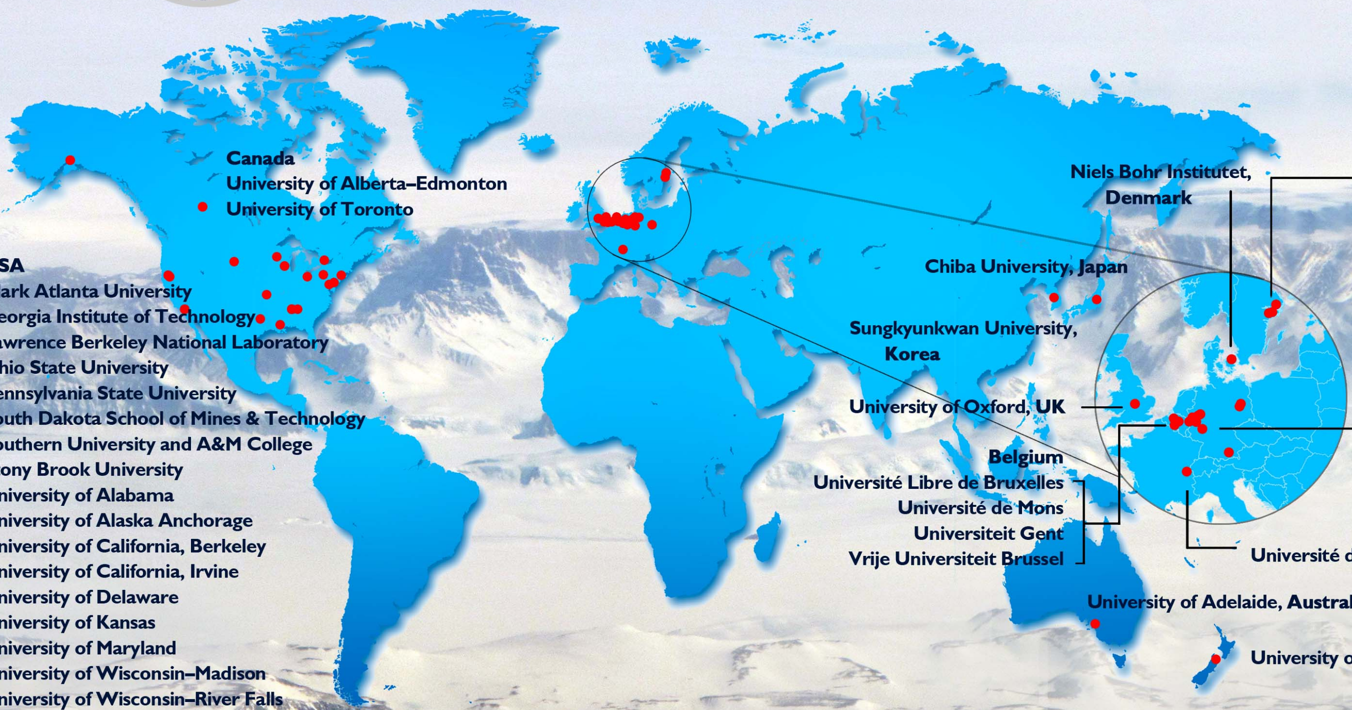
Seven year AMANDA-II skymap



No obvious point source in the map…
nor any evidence for a diffuse flux

AMANDA, IceCube

The IceCube Collaboration



Canada
University of Alberta–Edmonton
University of Toronto

USA
Clark Atlanta University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Ohio State University
Pennsylvania State University
South Dakota School of Mines & Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of Delaware
University of Kansas
University of Maryland
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

Niels Bohr Institutet, Denmark

Chiba University, Japan

Sungkyunkwan University, Korea

University of Oxford, UK

Belgium
Université Libre de Bruxelles
Université de Mons
Universiteit Gent
Vrije Universiteit Brussel

University of Adelaide, **Australia**

University of Canterbury, **New Zealand**

Sweden
Stockholms universitet
Uppsala universitet

Germany
Deutsches Elektronen-Synchrotron
Friedrich-Alexander-Universität Erlangen-Nürnberg
Humboldt-Universität zu Berlin
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RWTH Aachen
Technische Universität München
Universität Bonn
Technische Universität Dortmund
Universität Mainz
Universität Wuppertal

Université de Genève, **Switzerland**

Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

IceCube

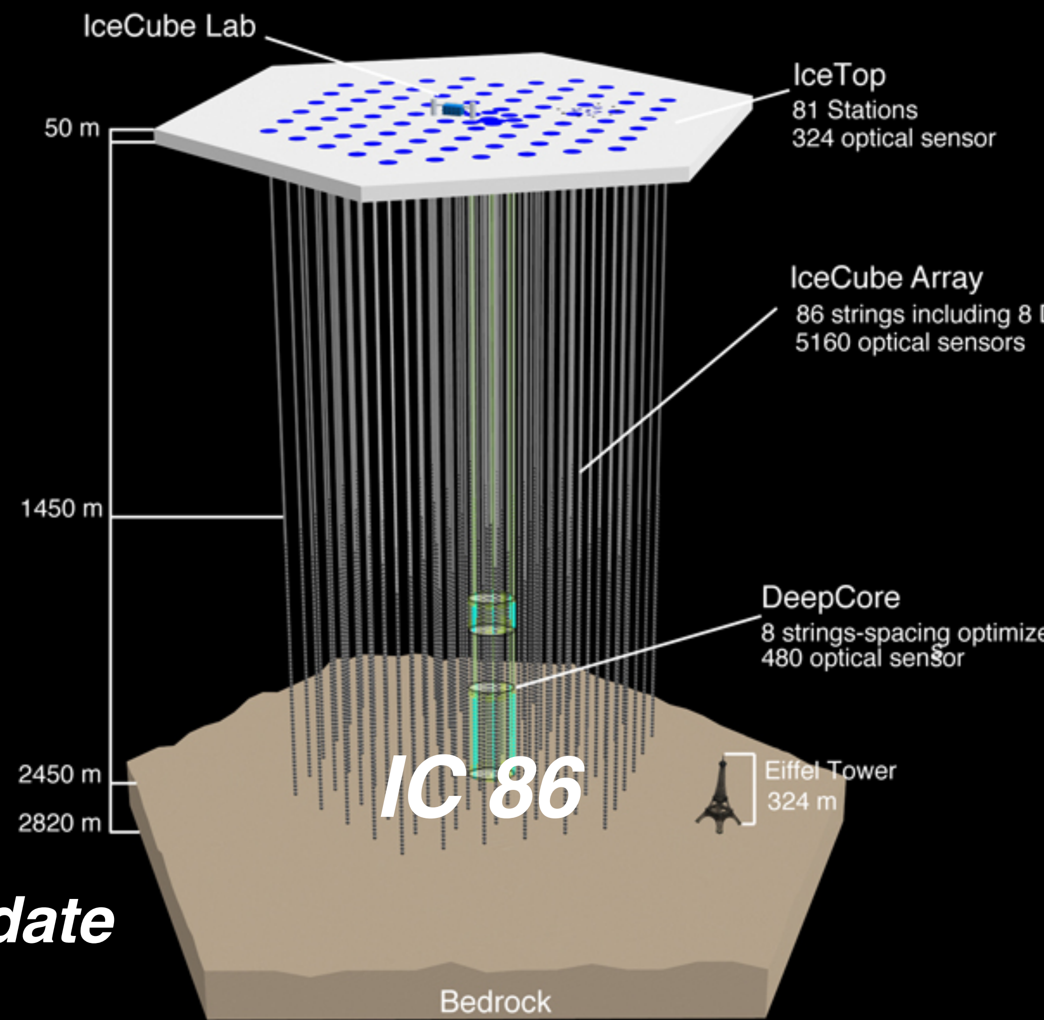
Construction:
Dec 2004 – Dec 2010

86 strings x 60 DOM
IceTop air shower array

Partial detectors analysed:
IC40, IC59, IC79

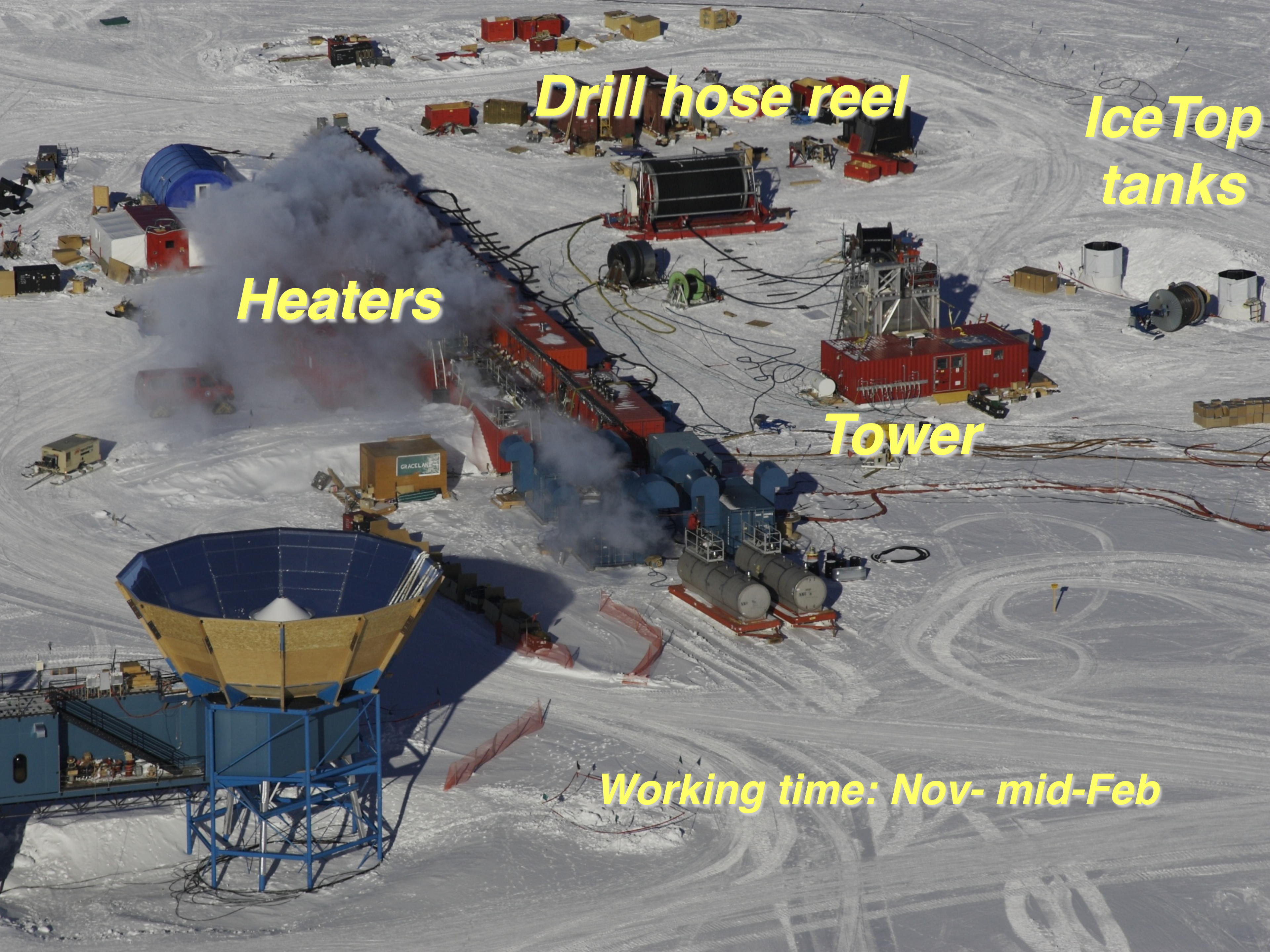
Full detector:
IC86, 3 ½ years running to date
HESE: IC79/86-1
HESE-2: IC79/86-1/86-2

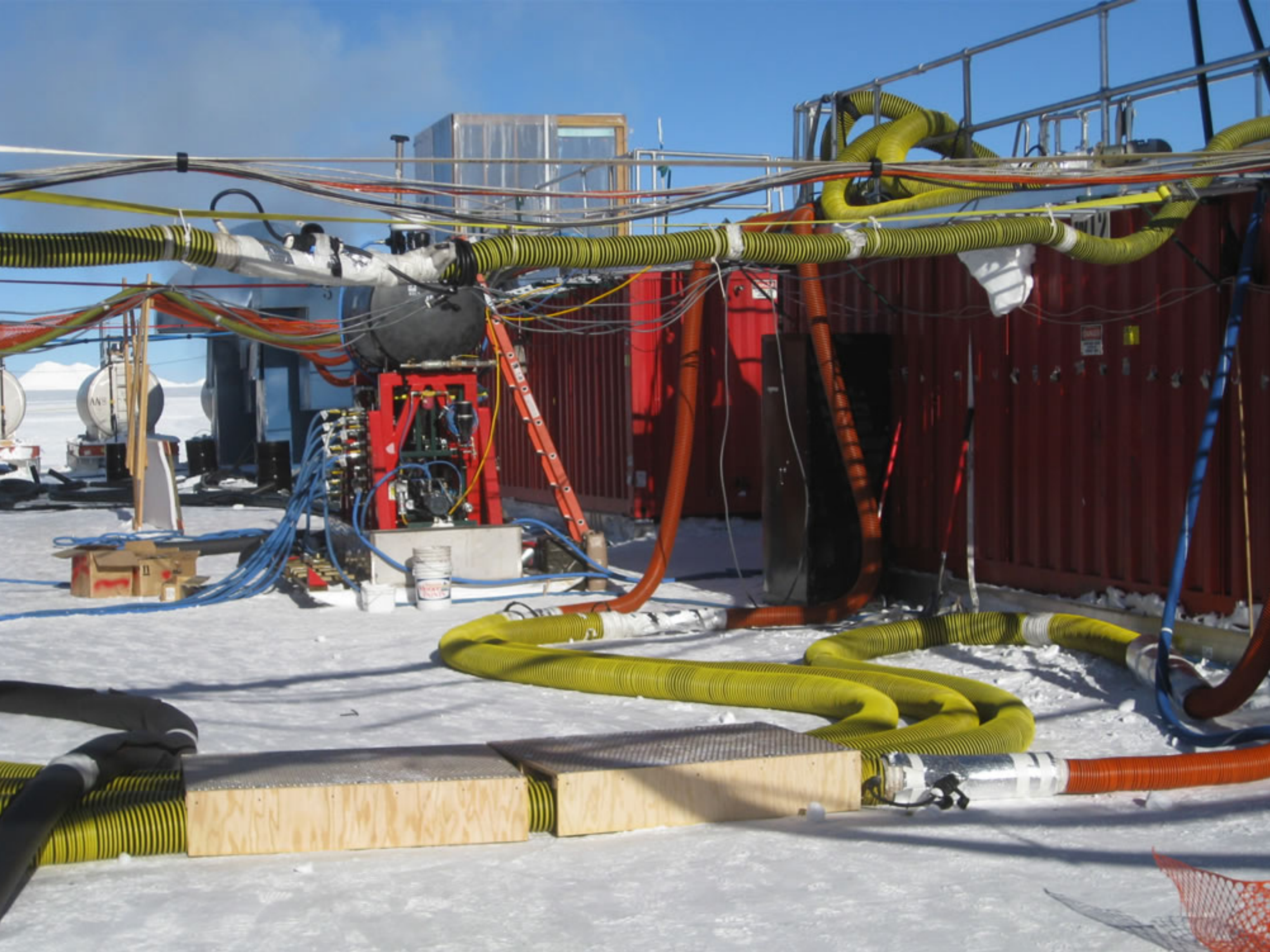
IceTop

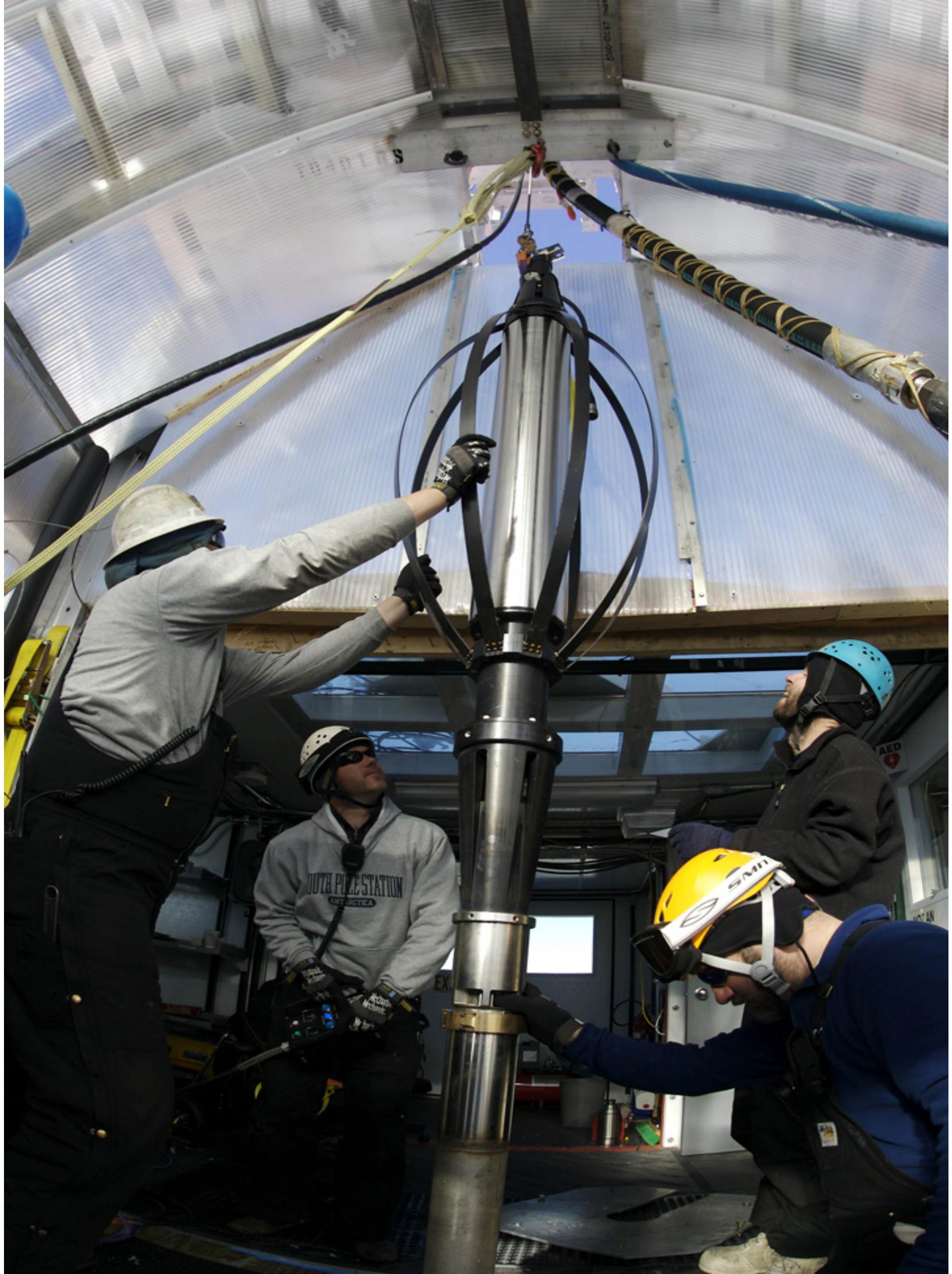



Logistics
9 million pounds of Cargo and fuel
300 Hercules LC 130 missions

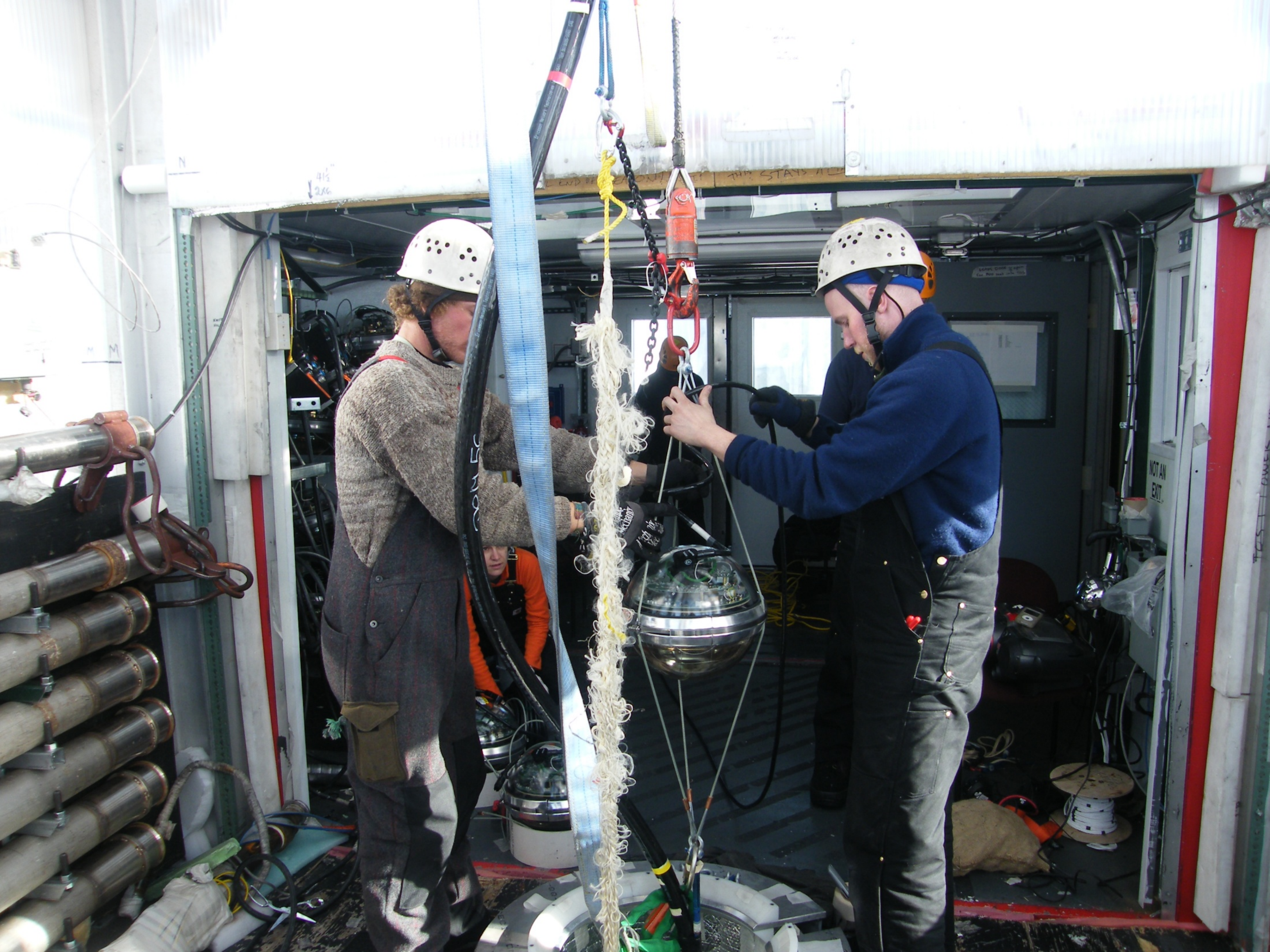

Excellent infrastructure and support:
NSF / Raytheon Polar Services
NSF/ Lockheed Martin (ASC)


Drill hose reel
IceTop
tanks
Heaters
Tower
Working time: Nov- mid-Feb

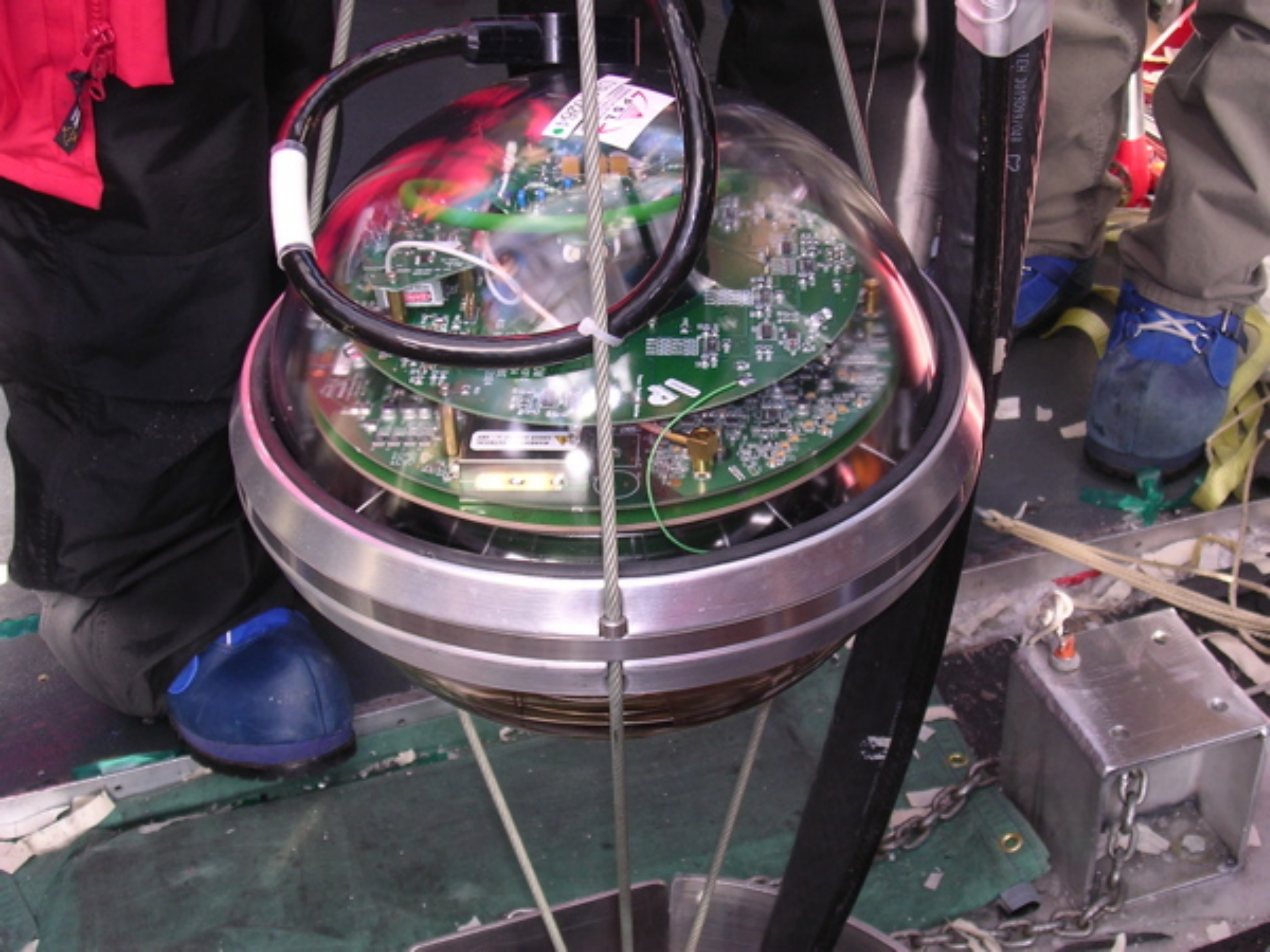


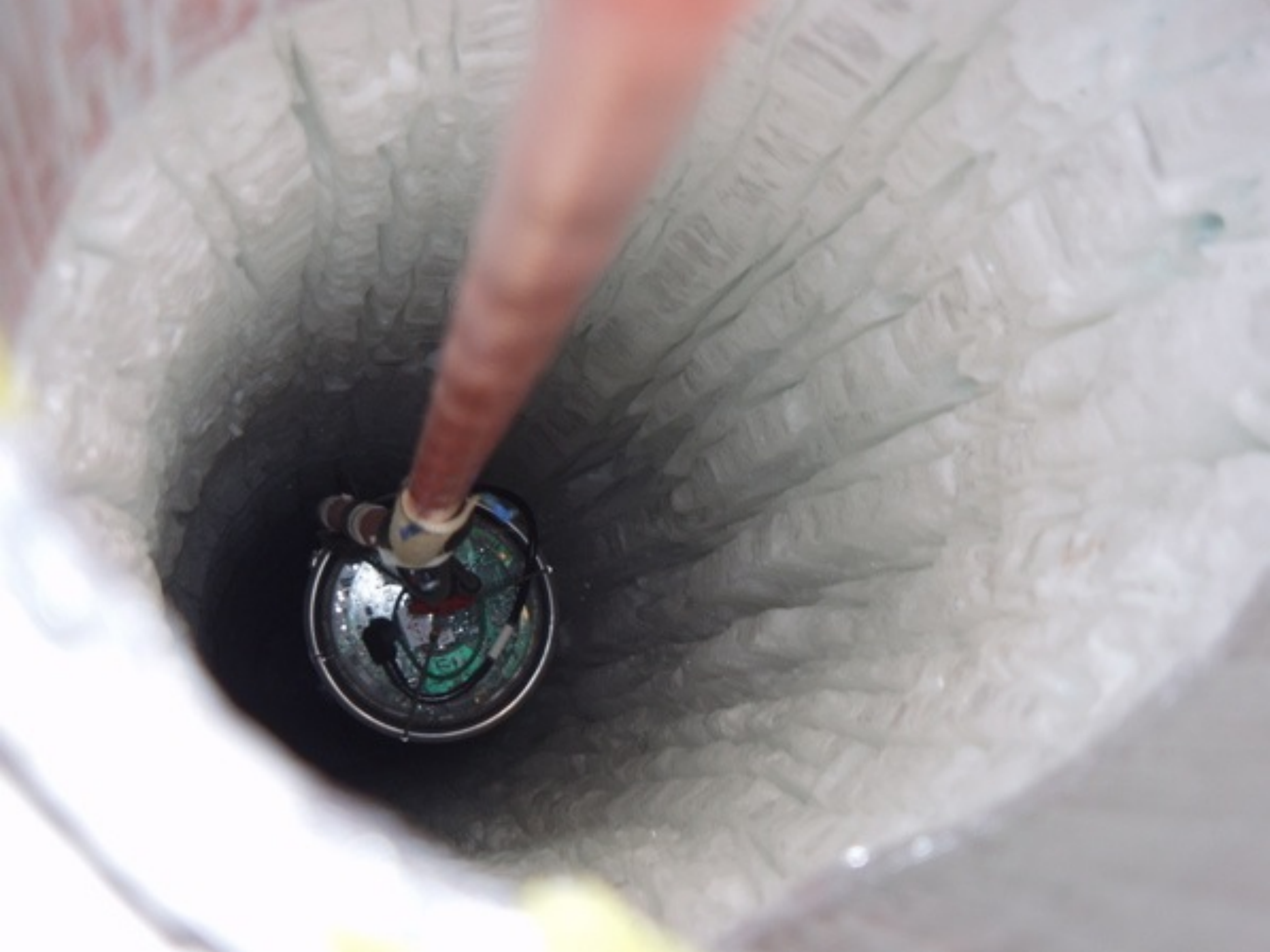

AED


EXIT
TOS 1
2


NOT AN EXIT

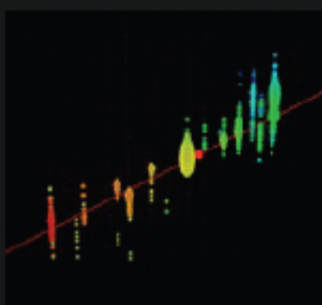

DIGITAL





Neutrino event signatures

CC Muon Neutrino

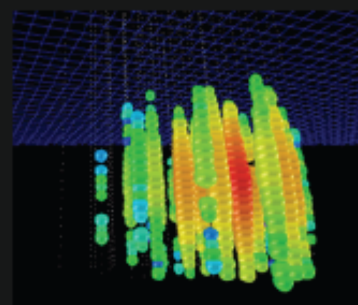


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
$< 1°$ angular resolution

Neutral Current / Electron Neutrino



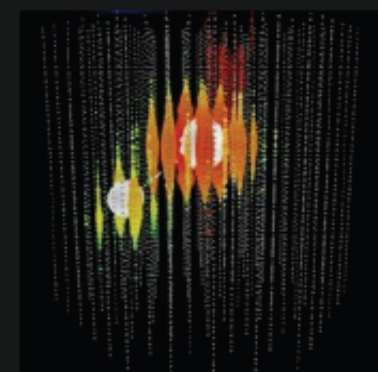
$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

$\approx \pm 15\%$ deposited energy resolution
$\approx 10°$ angular resolution
(at energies $\gtrapprox$ 100 TeV)

CC Tau Neutrino



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

"double-bang" and other signatures (simulation)

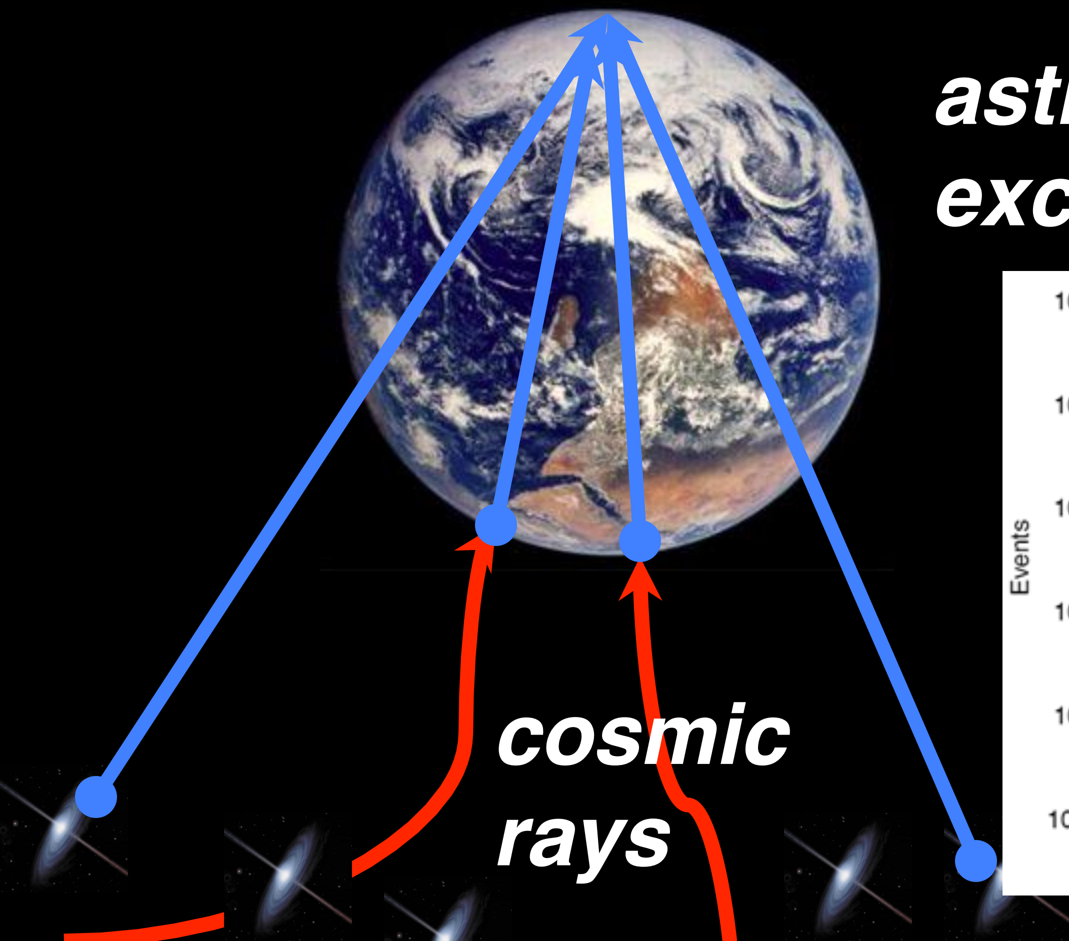
(not observed yet)

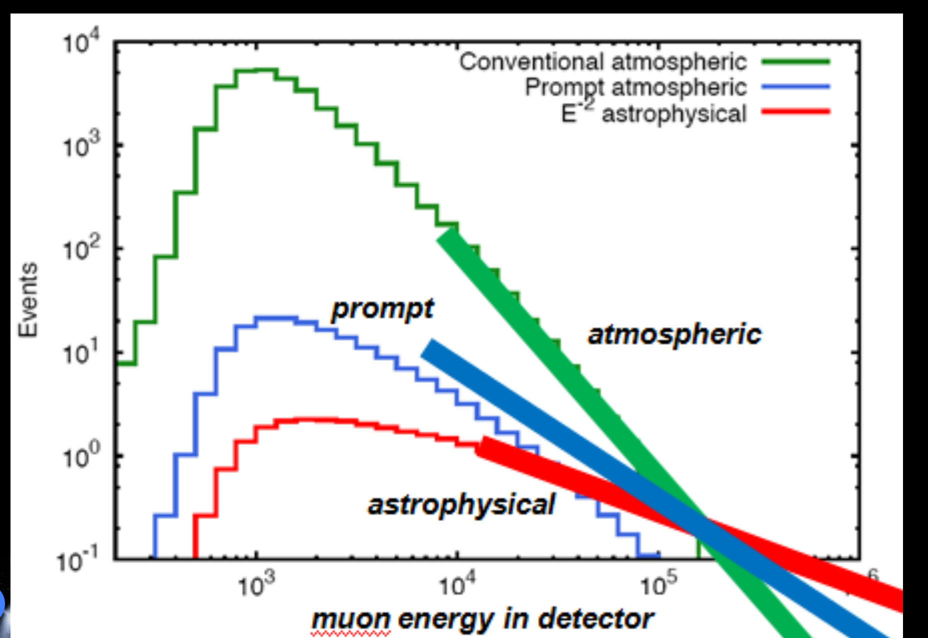
Looking down at the south pole into the northern sky

reject downgoing muons

upgoing neutrinos through-going muon trac

astrophysical neutrino excess at high energy?

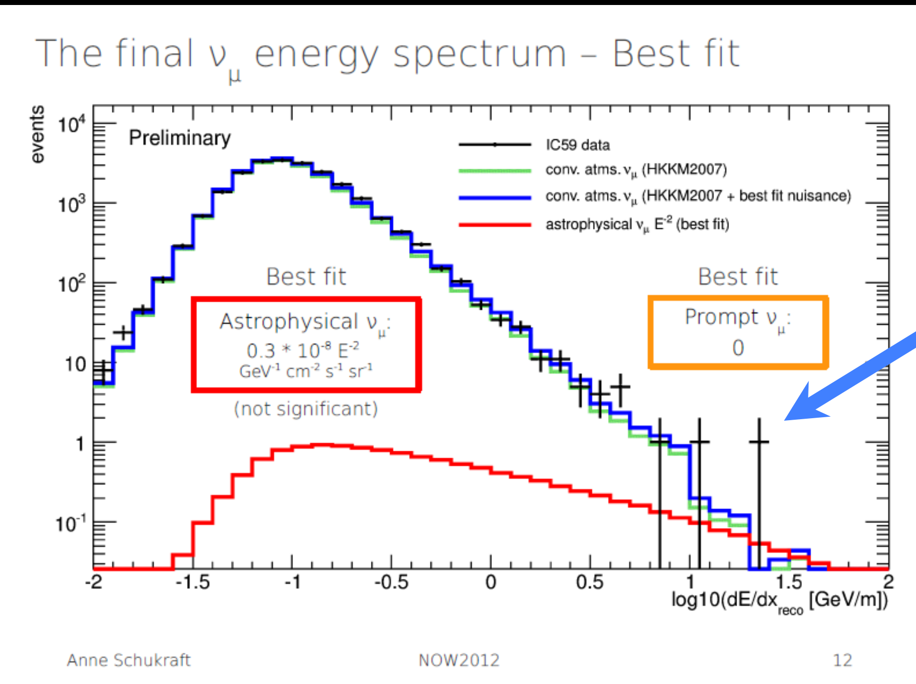


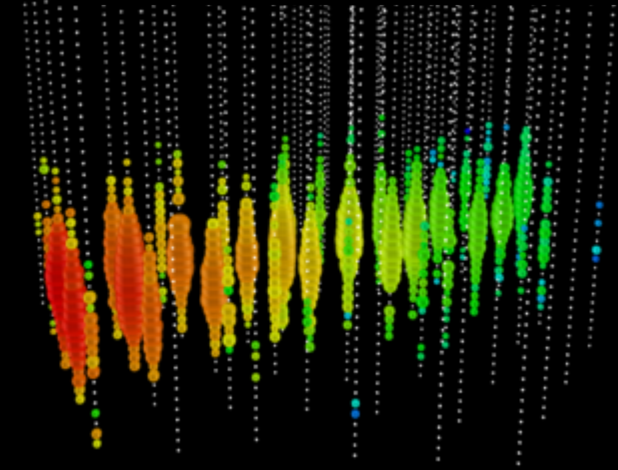


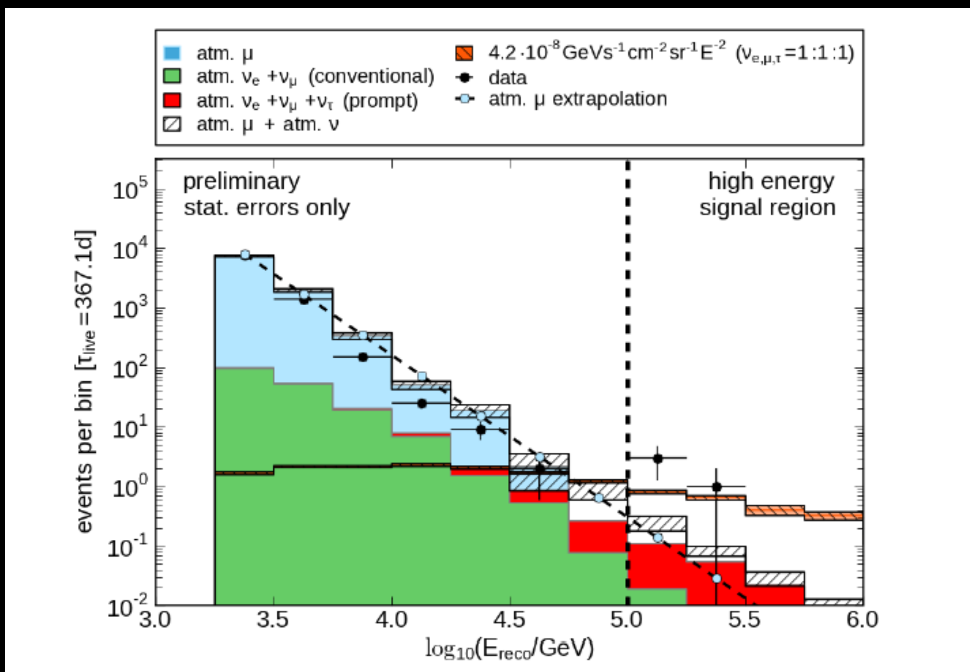
IC59 upgoing muon analysis

1.8 sigma excess

~1 PeV neutrino







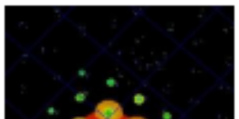
IC40 shower analysis

2.4 sigma excess

Flashback: Neutrino 2012, Kyoto

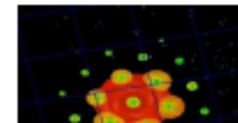
Two events passed the selection criteria

2 events / 672.7 days - background (atm. μ + conventional atm. ν) expectation 0.14 events
preliminary p-value: 0.0094 (2.36σ)

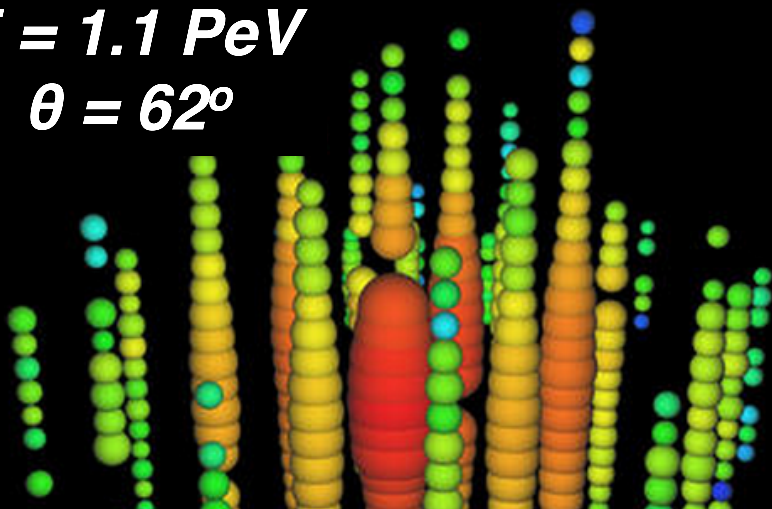


Run119316-Event36556705
Jan 3rd 2012
NPE 9.628×10^4

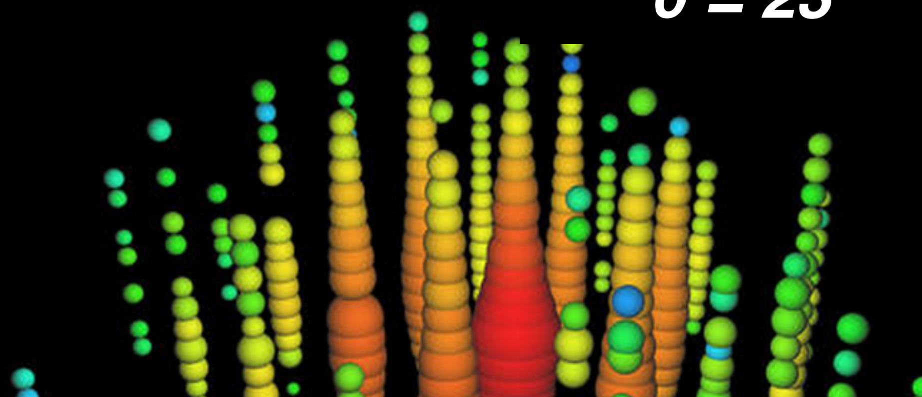
Run118545-Event63733662
August 9th 2011
NPE 6.9928×10^4



E = 1.1 PeV
θ = 62º



E = 1.0 PeV
θ = 23º



These two 1 PeV showers are downgoing!
How were they found amongst billions of atmospheric muons?

These two 1 PeV cascades are downgoing!
Can they be atmospheric neutrinos?

PHYSICAL REVIEW D **79**, 043009 (2009)

Vetoing atmospheric neutrinos in a high energy neutrino telescope

Stefan Schönert,[1] Thomas K. Gaisser,[2] Elisa Resconi,[1] and Olaf Schulz[1]

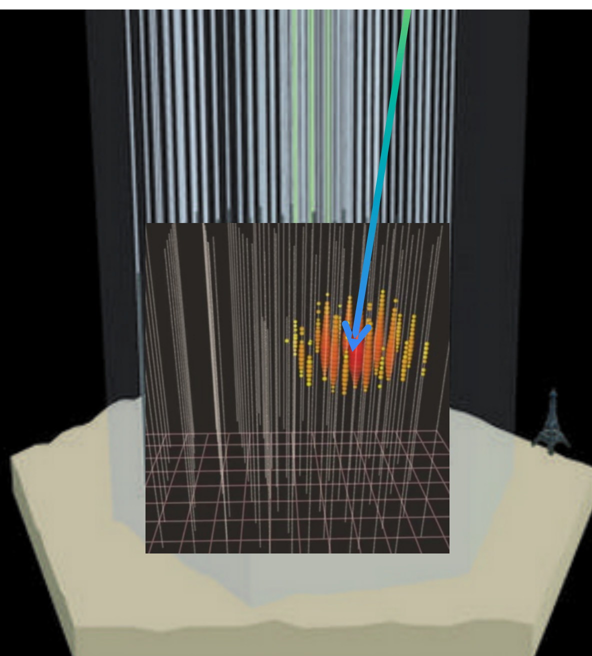
Schönert, Gaisser, Resconi, Schulz

We discuss the possibility to suppress downward atmospheric neutrinos in a high energy neutrino telescope. This can be achieved by vetoing the muon which is produced by the same parent meson decaying in the atmosphere. In principle, atmospheric neutrinos with energies $E_\nu > 10$ TeV and a zenith angle up to 60° can be vetoed with an efficiency of >99%. Practical realization will depend on the depth of the neutrino telescope, on the muon veto efficiency, and on the ability to identify downward-moving neutrinos with a good energy estimation.

"atmospheric neutrino self veto"

for muon-neutrinos:

see muon from same parent meson decay

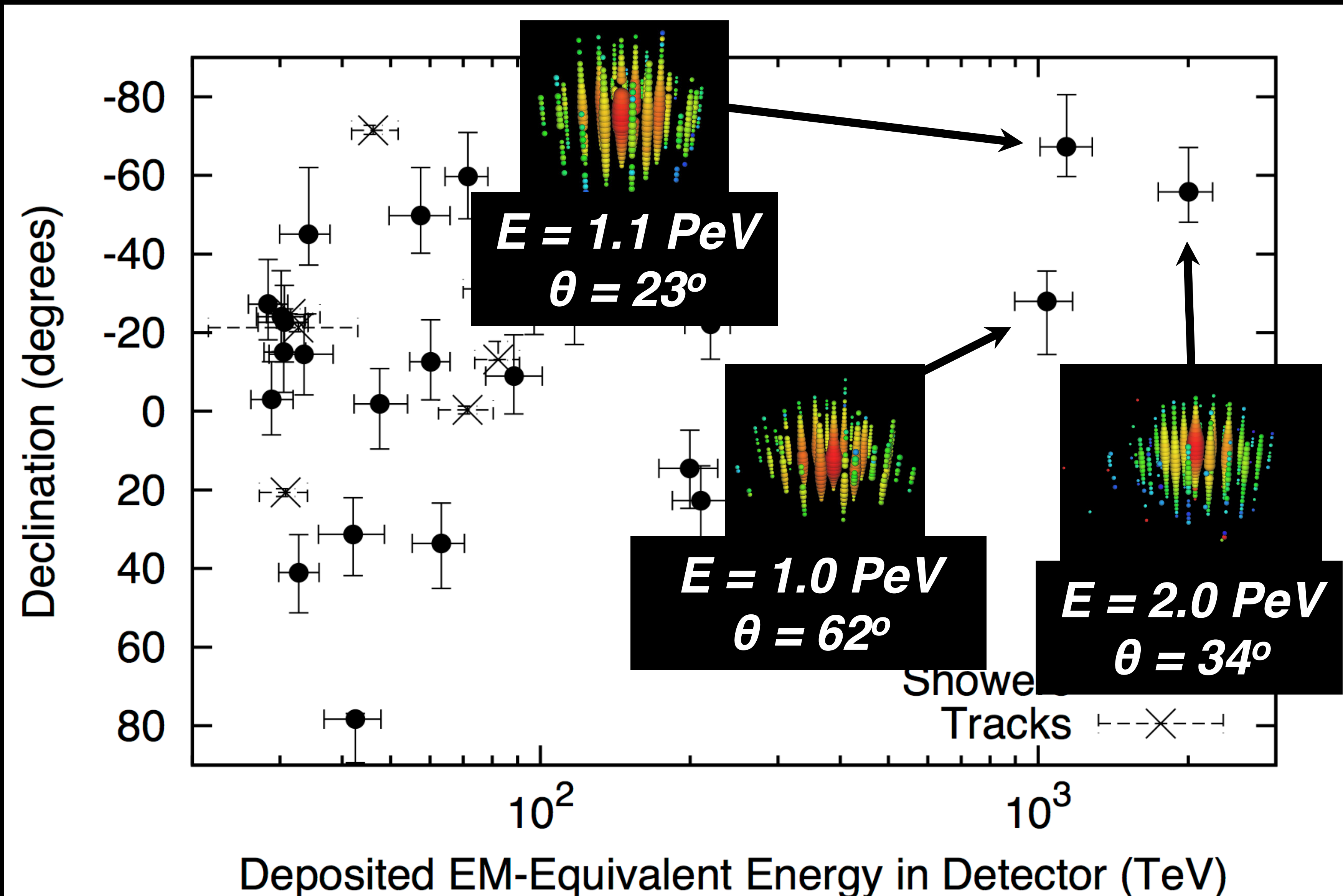


True also for electron and tau neutrinos:

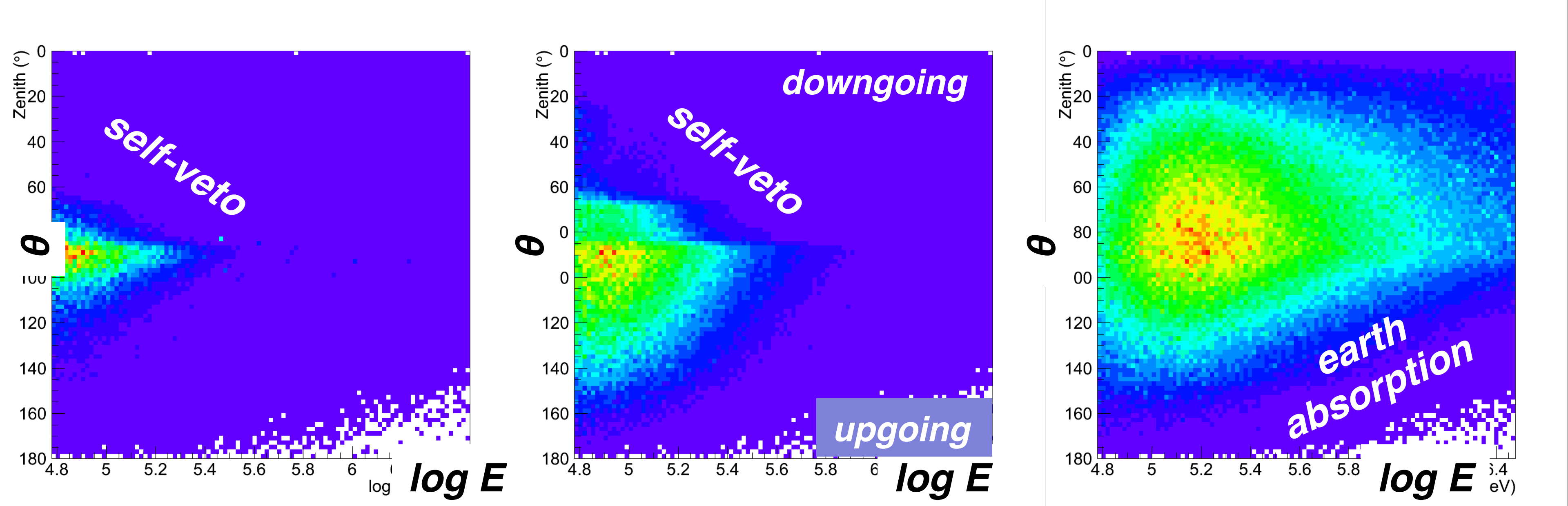
see muons from other decays in the entire air shower

van Santen, Jero, Gaisser, Karle

Primary cosmic rays
105.7 MeV/c^2
-1
1/2
μ
muon
<2.2 eV/c^2
0
1/2
ν_e
electron neutrino
Neutrino from the atmosphere above the south pole
Muon from the atmosphere above the south pole
Rejected!
Neutrino from the distant Universe
Keep!



E = 1.1 PeV
θ = 23°
E = 1.0 PeV
θ = 62°
E = 2.0 PeV
θ = 34°
Tracks
Declination (degrees)
-80
-60
-40
-20
0
20
40
60
80
10^2
10^3
Deposited EM-Equivalent Energy in Detector (TeV)



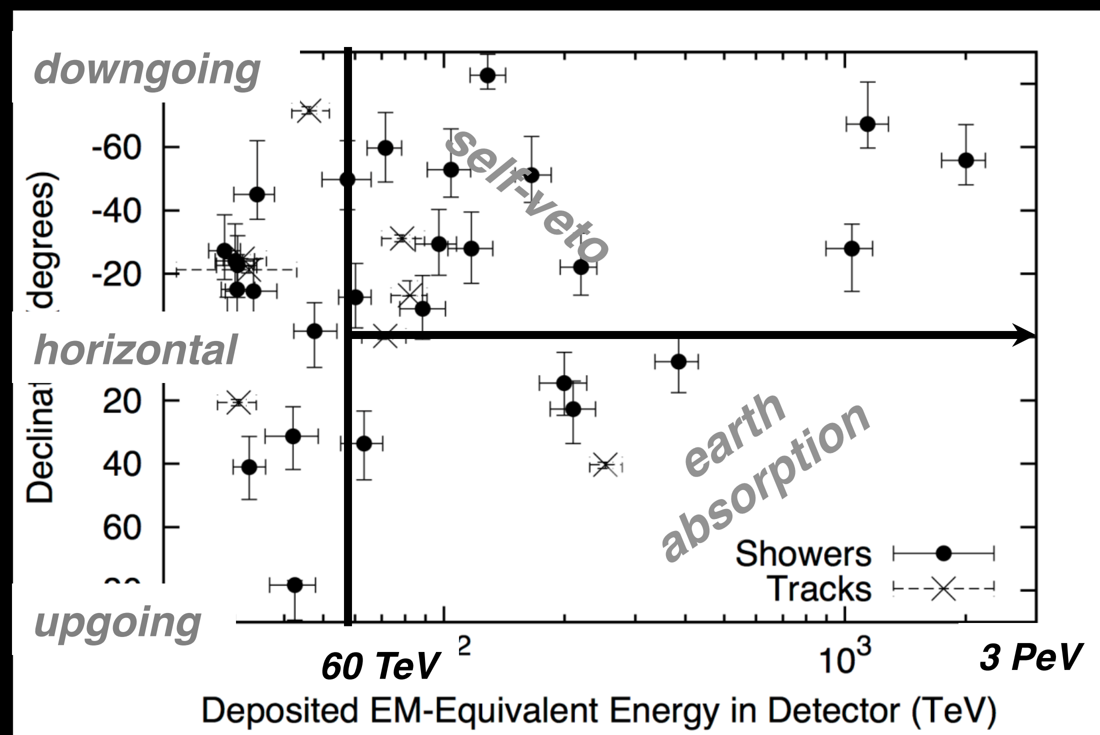
conventional + prompt + astrophysical

IC79/86-1/86-2 diffuse analysis forward folding

Fit (track/shower) data to mixture of

conventional
prompt
astrophysical

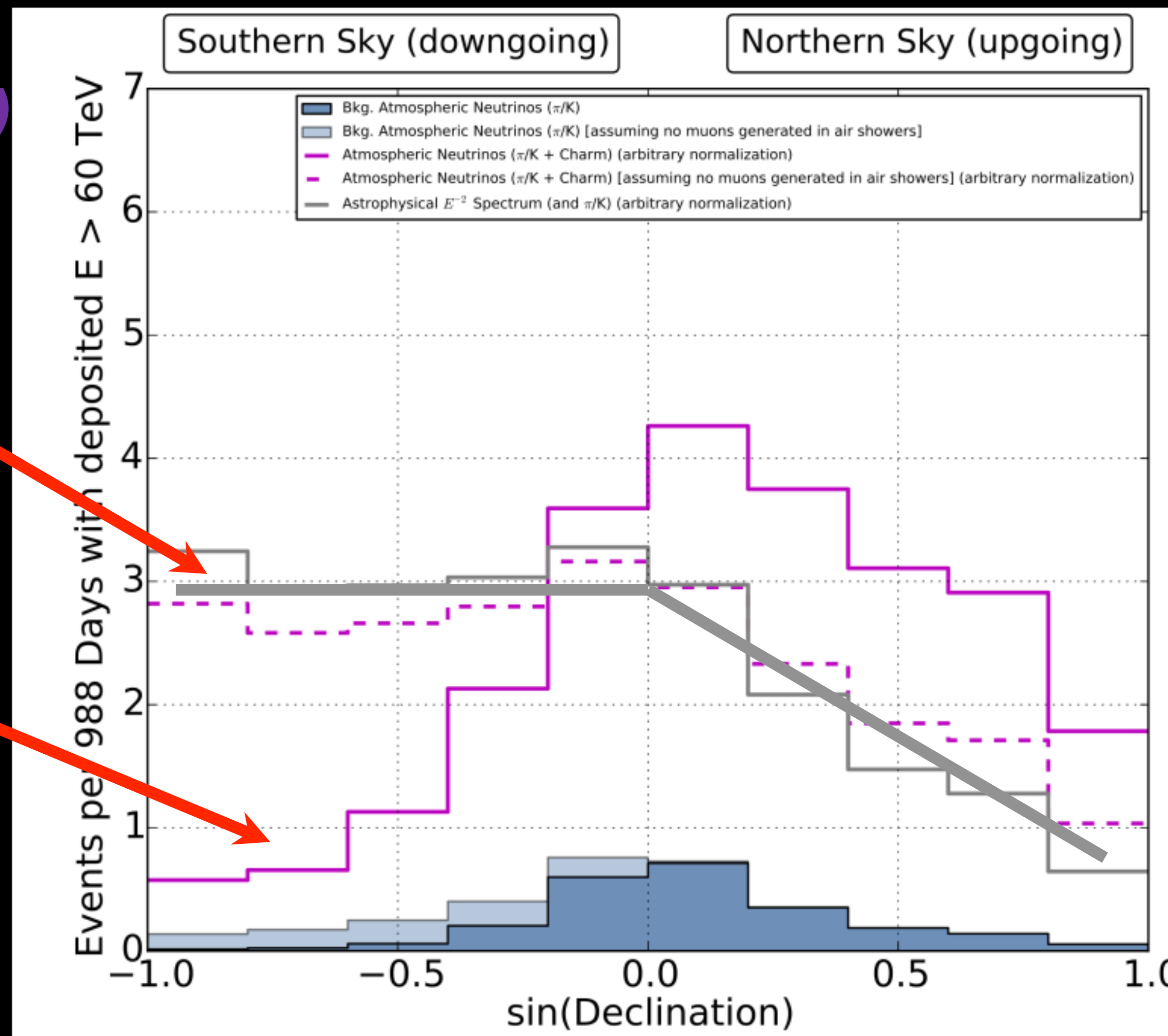
= data



The power of the self-veto

Without self-veto astro (grey) and prompt (dash-purple) have same zenith shape

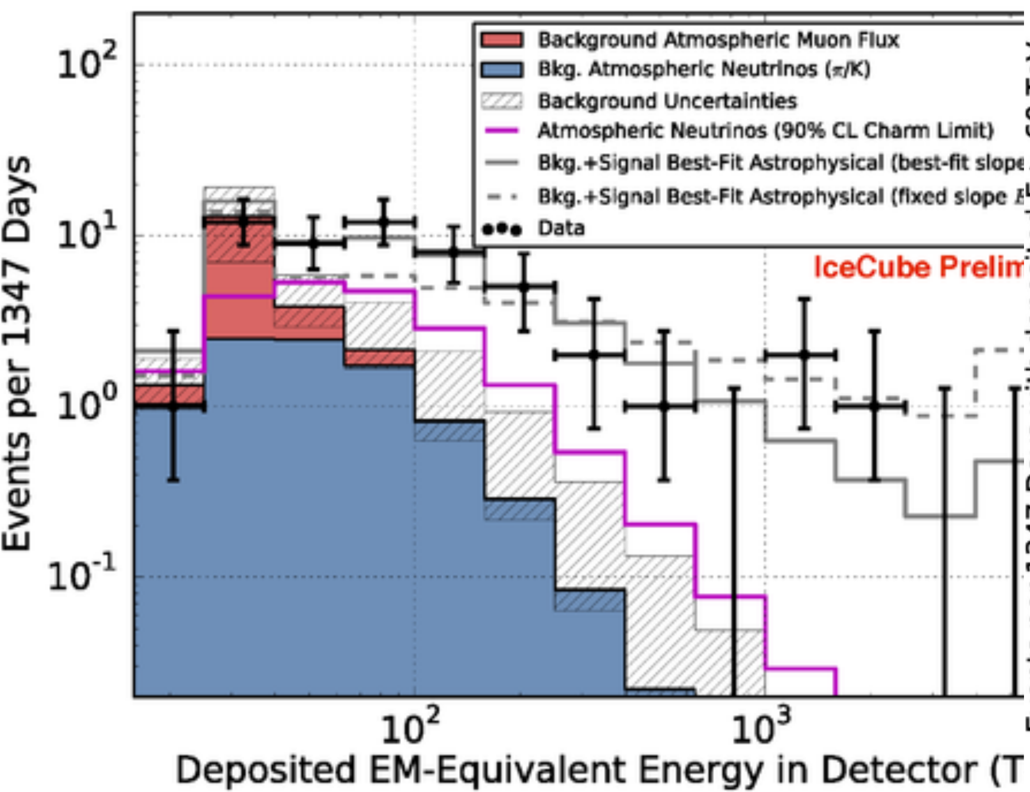
With self-veto prompt (solid-purple) is highly suppressed from above

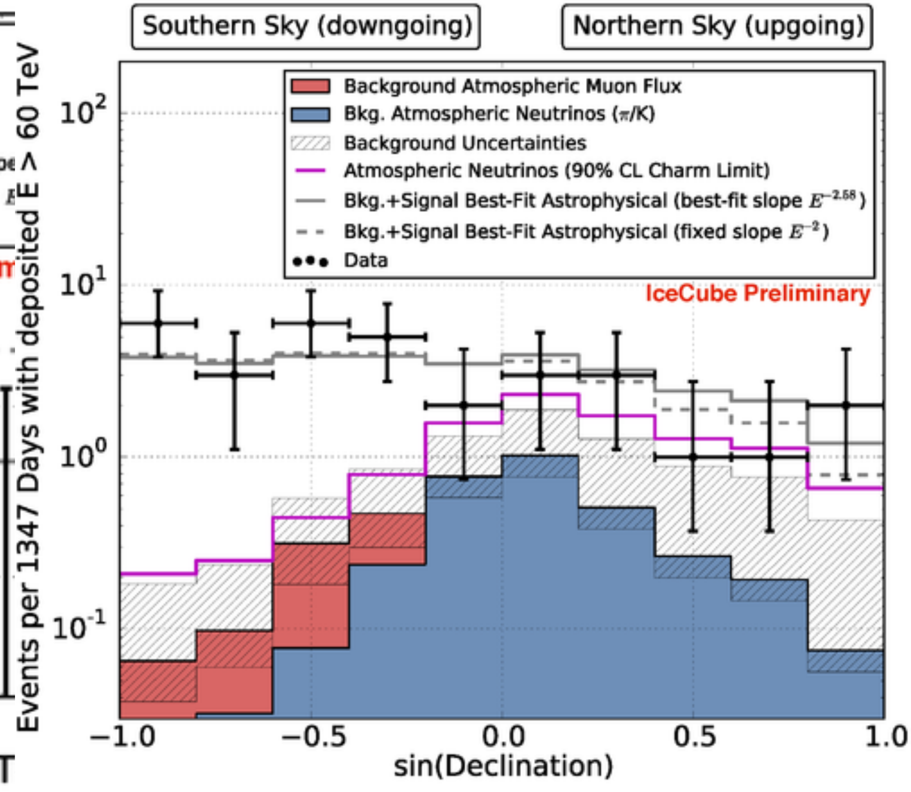


Global fit of energy vs angle to a mixture of atmospheric and astrophysical E^{-2} neutrinos

best fit flux: $E^2\Phi = 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

~7 sigma rejection of atmospheric-only hypothesis

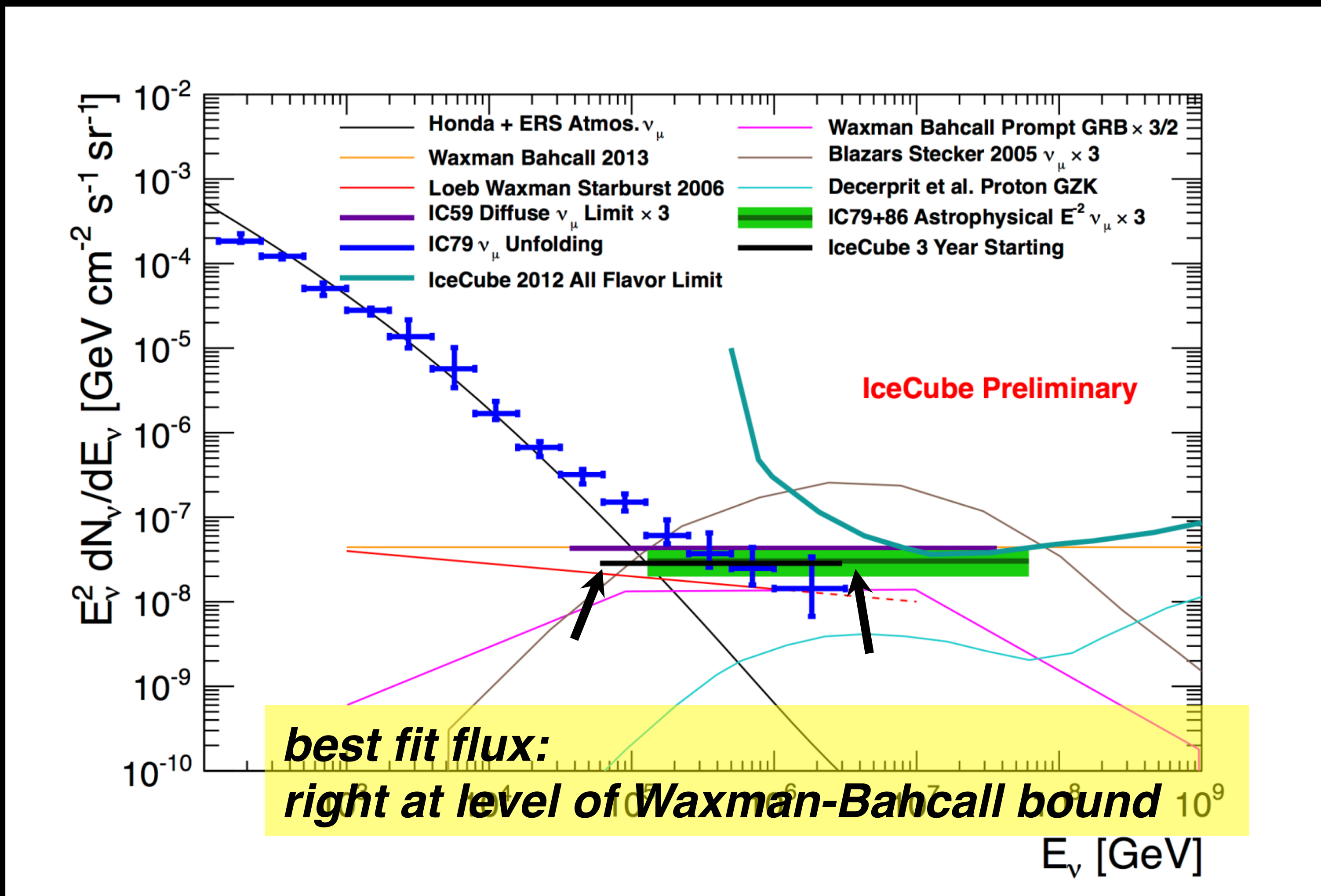




Global fit, energy (60 TeV – 3 PeV) vs angle,

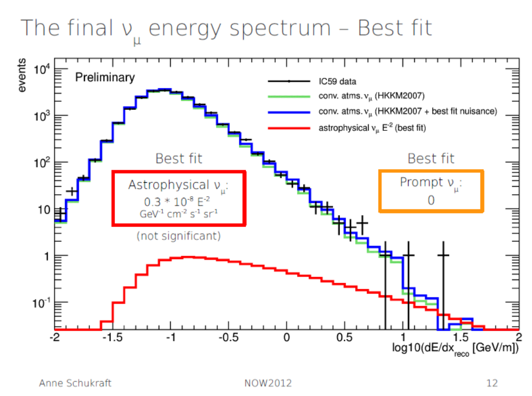
best fit flux: $E^2\Phi = 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} (per flavour)

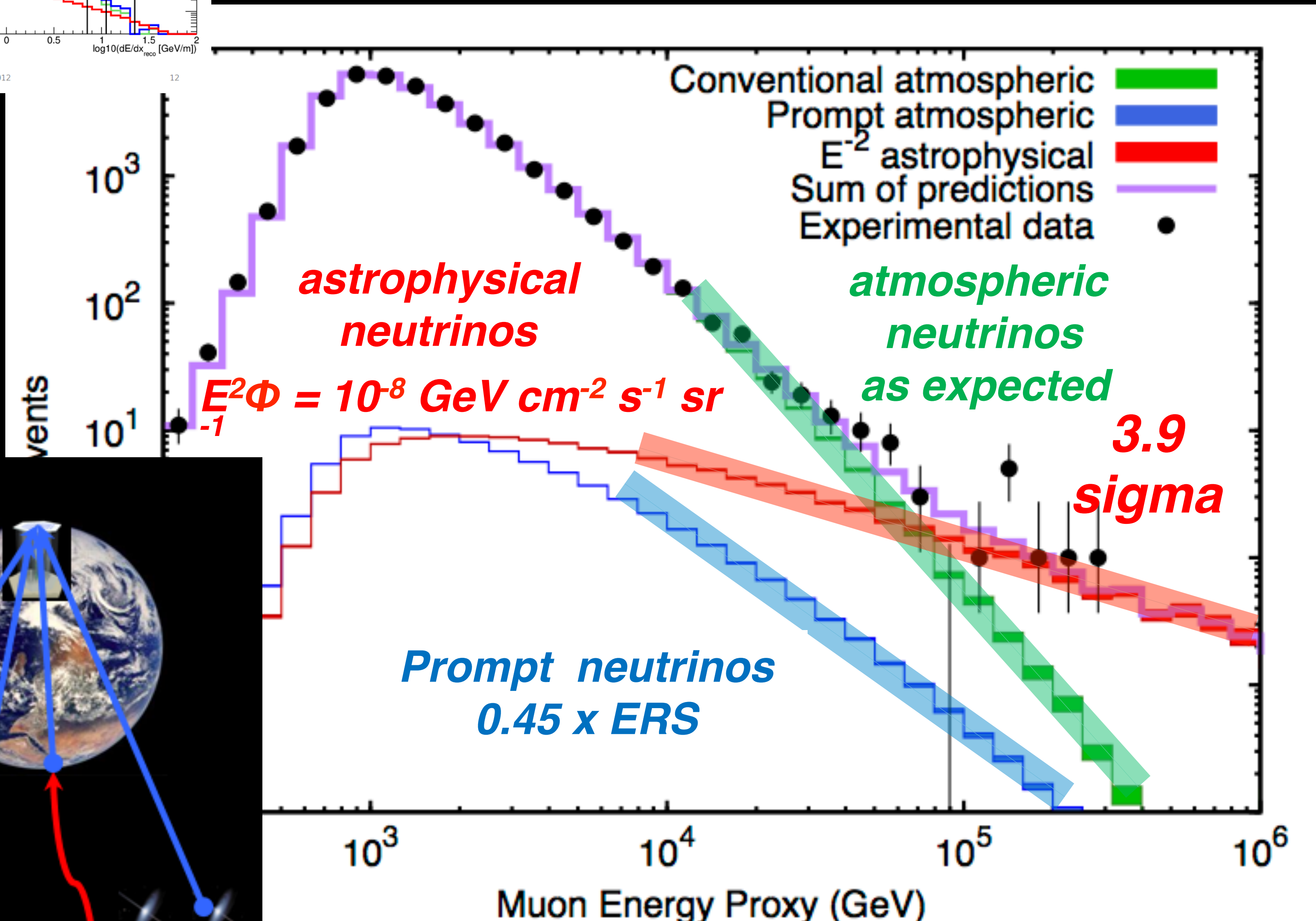
5.7 sigma rejection of atmospheric-only hypothesis

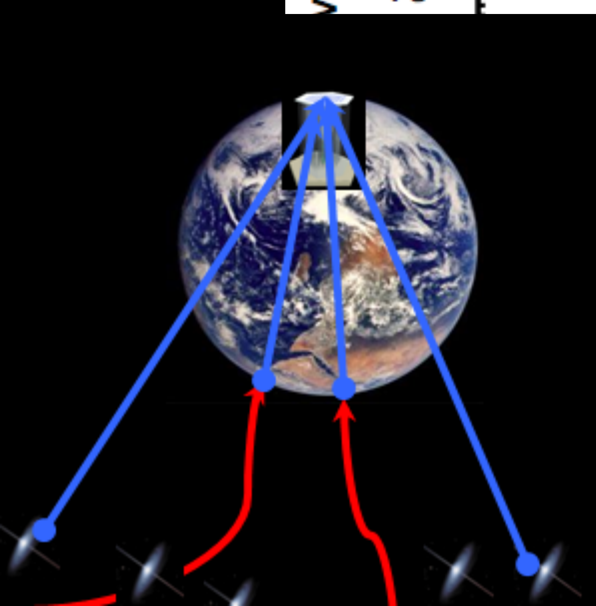


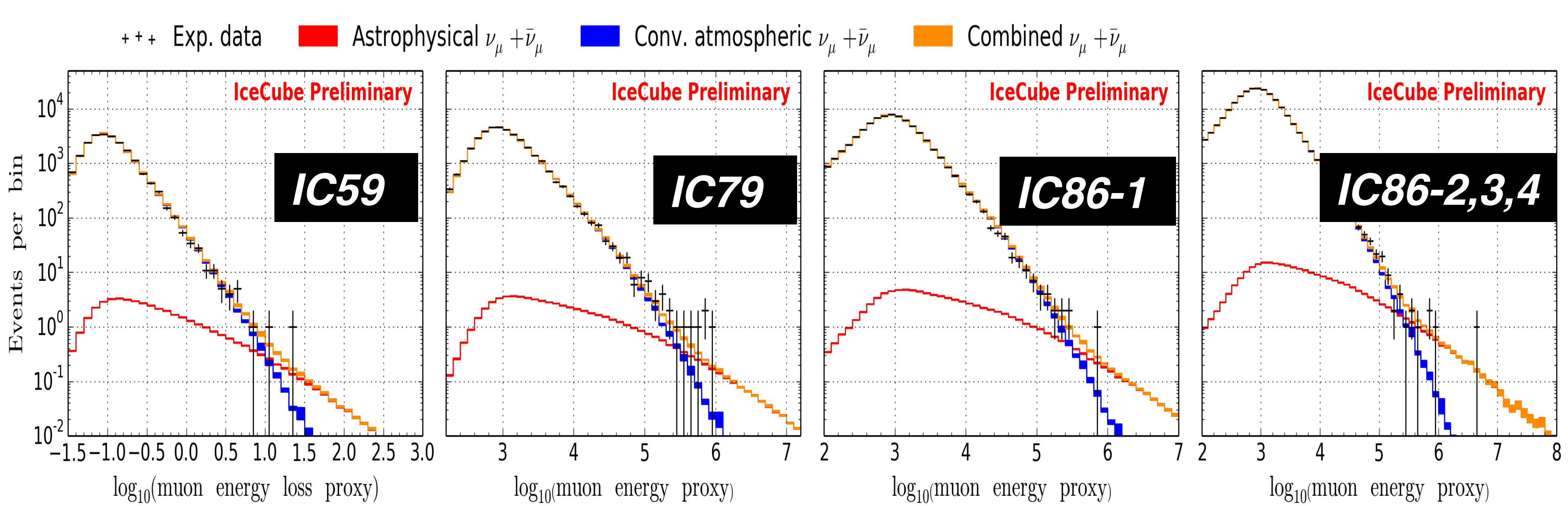
best fit flux:
right at level of Waxman-Bahcall bound

Hint from IC59 (1.8 sigma); now IC79/86-1 upgoing muon neutrinos give 3.9 sigma

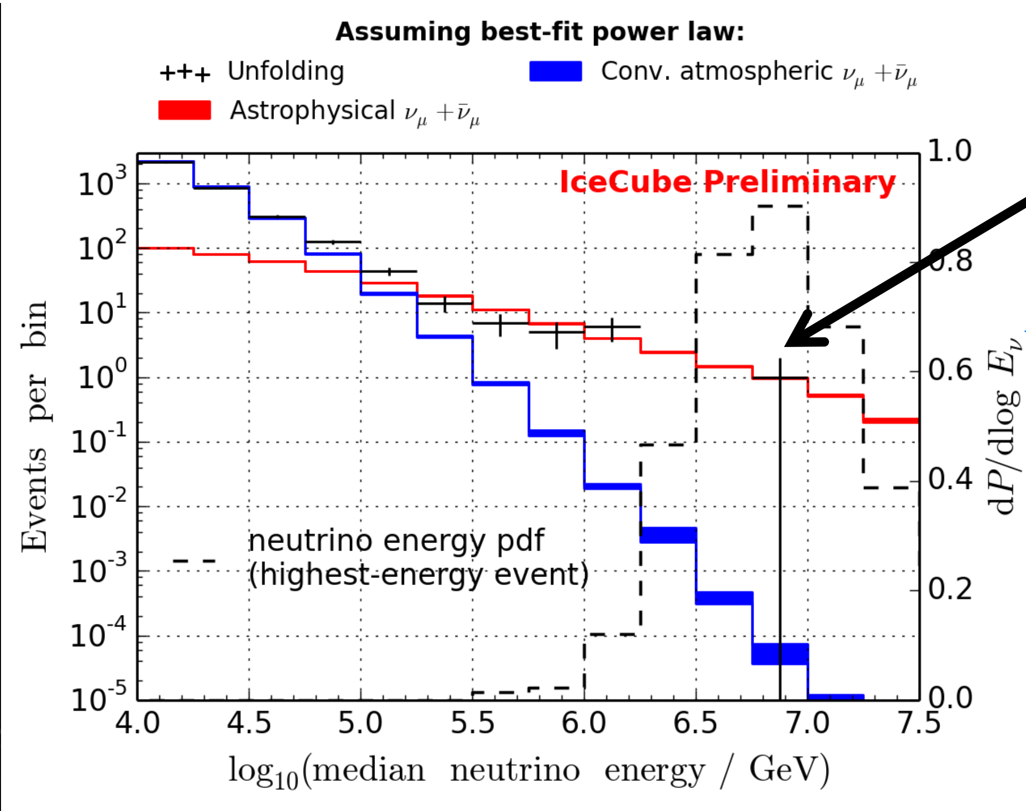




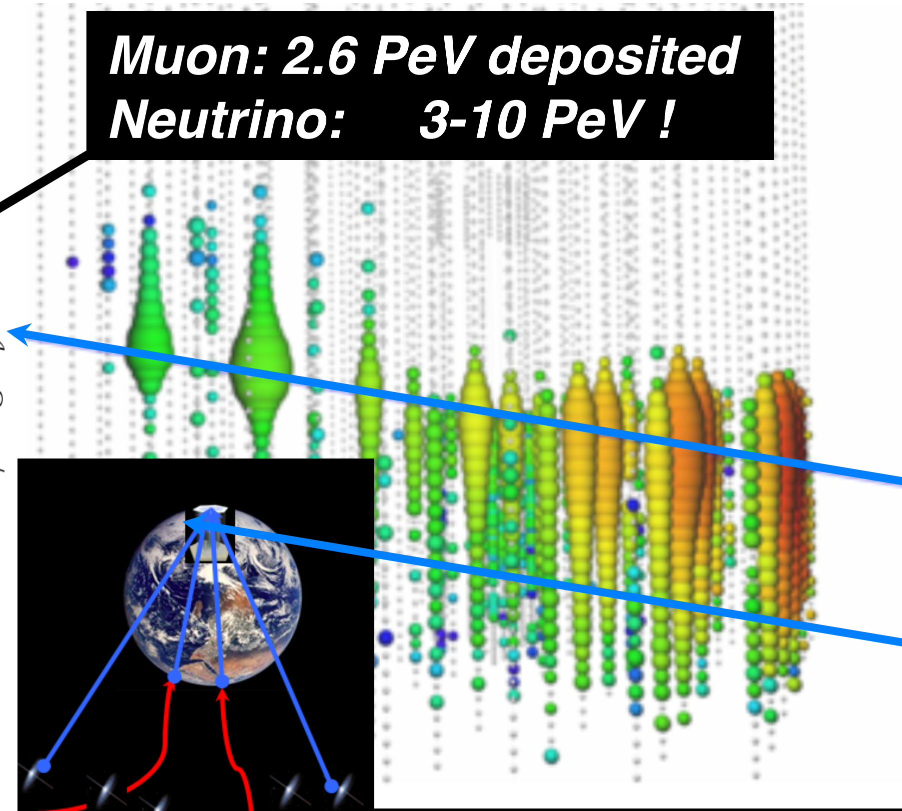




+++ Exp. data
Astrophysical $\nu_\mu + \bar{\nu}_\mu$
Conv. atmospheric $\nu_\mu + \bar{\nu}_\mu$
Combined $\nu_\mu + \bar{\nu}_\mu$
IceCube Preliminary
IC59
IC79
IC86-1
IC86-2,3,4
Events per bin
$\log_{10}$(muon energy loss proxy)
$\log_{10}$(muon energy proxy)

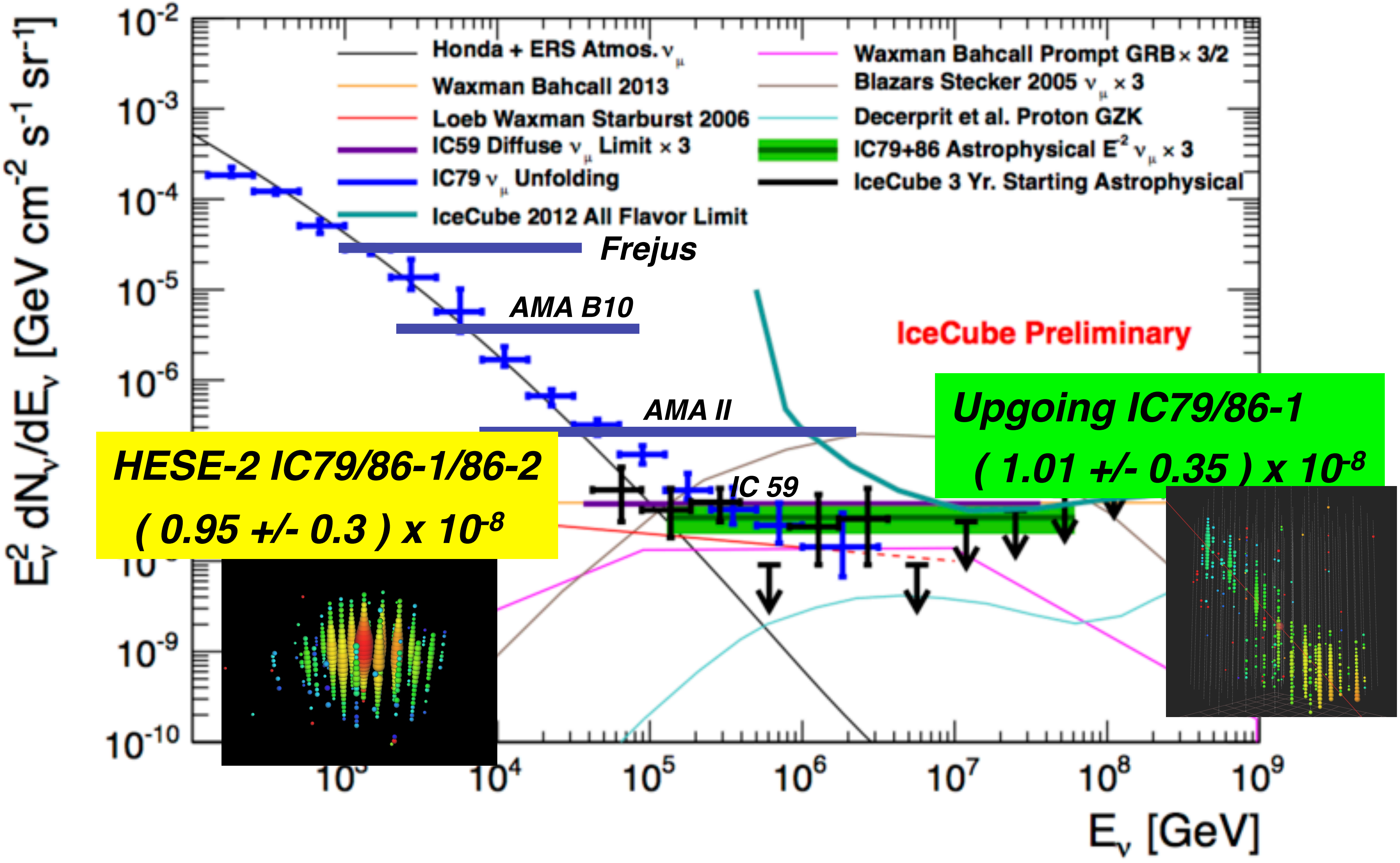


Assuming best-fit power law:
+++ Unfolding
Conv. atmospheric $\nu_\mu + \bar{\nu}_\mu$
Astrophysical $\nu_\mu + \bar{\nu}_\mu$
IceCube Preliminary
neutrino energy pdf
(highest-energy event)
Events per bin
$dP/d\log E_\nu$
$\log_{10}$(median neutrino energy / GeV)



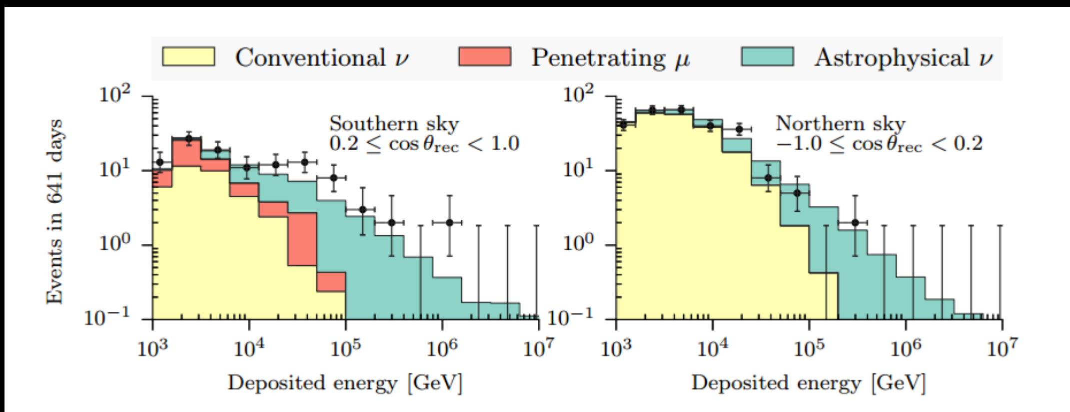
Muon: 2.6 PeV deposited
Neutrino: 3-10 PeV !

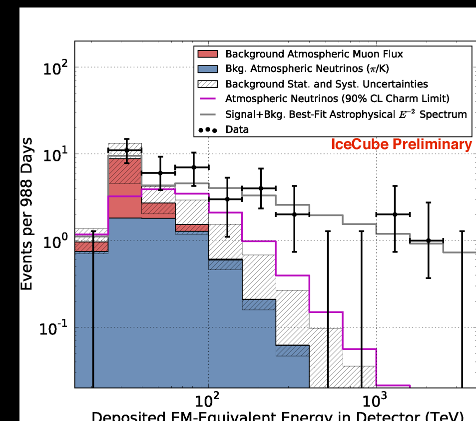
Diffuse flux summary



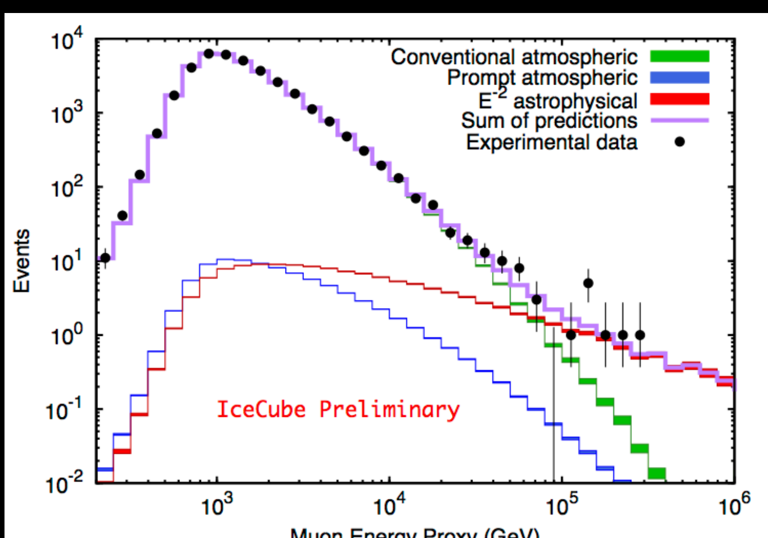
Clear we see an astrophysical flux of neutrinos – muons and showers – from the whole sky

showers/tracks





tracks



What are the properties of the source population from which these have come?

Are there many weak sources, or some stronger than average sources?

Astrophysical neutrinos at Earth

neutrino oscillations:

~ 1 : 1 : 1

flavour mixture

ν_e

ν_μ

ν_T

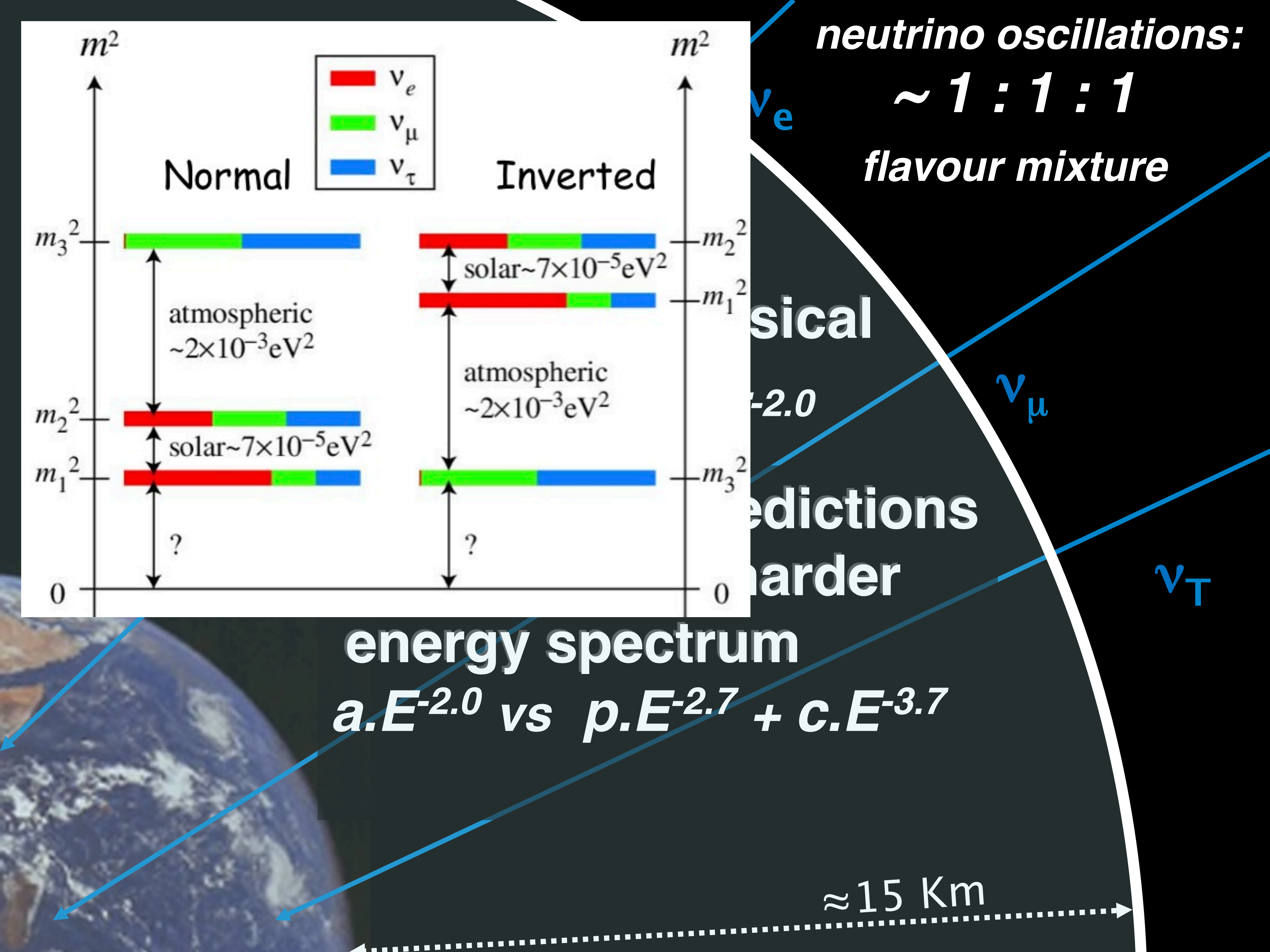
astrophysical

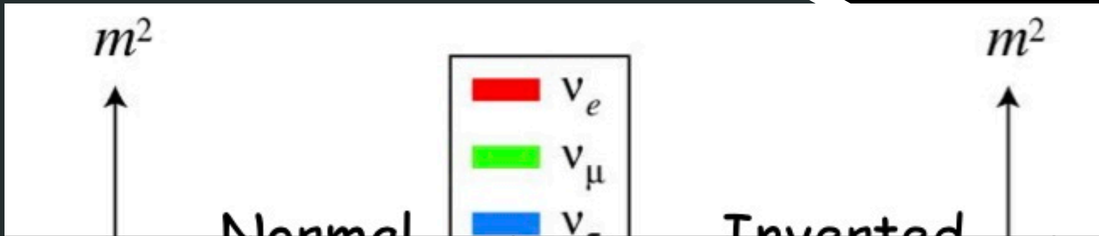
$\Phi \sim a.E^{-2.0}$

many model predictions
-key feature is harder energy spectrum

$a.E^{-2.0}$ vs $p.E^{-2.7} + c.E^{-3.7}$

≈15 Km


neutrino oscillations:
~ 1 : 1 : 1
flavour mixture
ν_e
ν_μ
ν_T
m²
m²
Normal
Inverted
ν_e
ν_μ
ν_τ
m_3^2
m_2^2
m_1^2
m_2^2
m_1^2
m_3^2
atmospheric ~2×10⁻³eV²
solar~7×10⁻⁵eV²
solar~7×10⁻⁵eV²
atmospheric ~2×10⁻³eV²
?
?
0
0
sical
-2.0
edictions
harder
energy spectrum
a.E^-2.0 vs p.E^-2.7 + c.E^-3.7
≈15 Km



<2.2 eV/c² 0 1/2 ν_e electron neutrino		**10**	**4**	**4**
<0.17 MeV/c² 0 1/2 ν_μ muon neutrino		**4**	**7**	**7**
<15.5 MeV/c² 0 1/2 ν_τ tau neutrino		**4**	**7**	**7**
Source				
	Earth	<2.2 eV/c² 0 1/2 ν_e electron neutrino	<0.17 MeV/c² 0 1/2 ν_μ muon neutrino	<15.5 MeV/c² 0 1/2 ν_τ tau neutrino

neutrino oscillations:

~ 1 : 1 : 1

flavour mixture

ν_e

ν_μ

ν_T

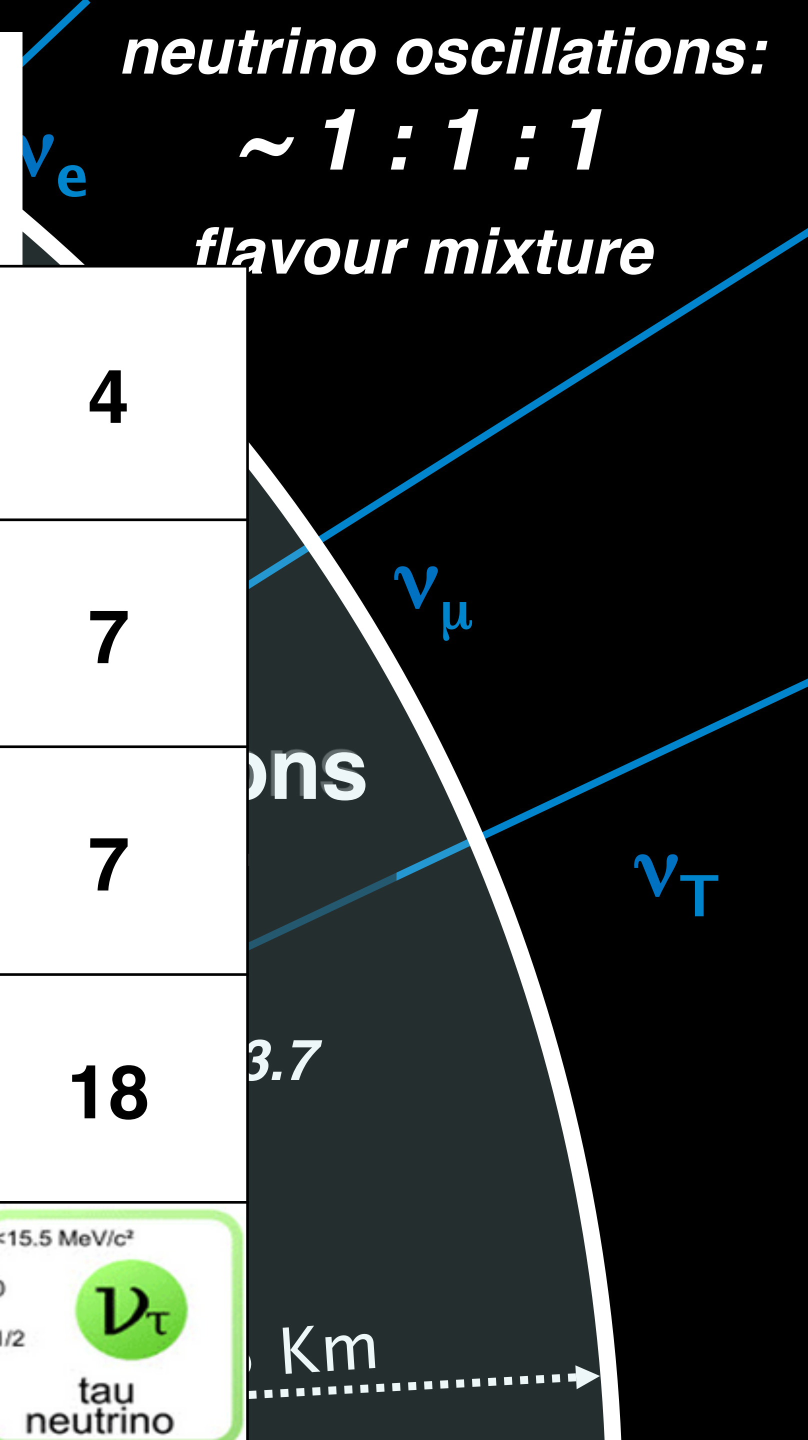
ons

3.7

Km

Muons decay at source

<2.2 eV/c² 0 1/2 ν_e electron neutrino	1	10	4	4
<0.17 MeV/c² 0 1/2 ν_μ muon neutrino	2	4	7	7
<15.5 MeV/c² 0 1/2 ν_τ tau neutrino	0	4	7	7
Source		18	18	18
	Earth	<2.2 eV/c² 0 1/2 ν_e electron neutrino	<0.17 MeV/c² 0 1/2 ν_μ muon neutrino	<15.5 MeV/c² 0 1/2 ν_τ tau neutrino



Muons damped at source ν_e

neutrino oscillations:

~ 4 : 7 : 7

flavour mixture

<2.2 eV/c² 0 1/2 ν_e electron neutrino	0	10	4	4
<0.17 MeV/c² 0 1/2 ν_μ muon neutrino	1	4	7	7
<15.5 MeV/c² 0 1/2 ν_τ tau neutrino	0	4	7	7
Source		4	7	7
	Earth	<2.2 eV/c² 0 1/2 ν_e electron neutrino	<0.17 MeV/c² 0 1/2 ν_μ muon neutrino	<15.5 MeV/c² 0 1/2 ν_τ tau neutrino

ν_μ

ν_T

Neutrons decay at source

neutrino oscillations:

~ 5 : 2 : 2

flavour mixture

<2.2 eV/c^2 0 1/2 ν_e electron neutrino	1	10	4	4
<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	0	4	7	7
<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	0	4	7	7
Source		5	2	2
	Earth	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino

ν_μ

ν_T

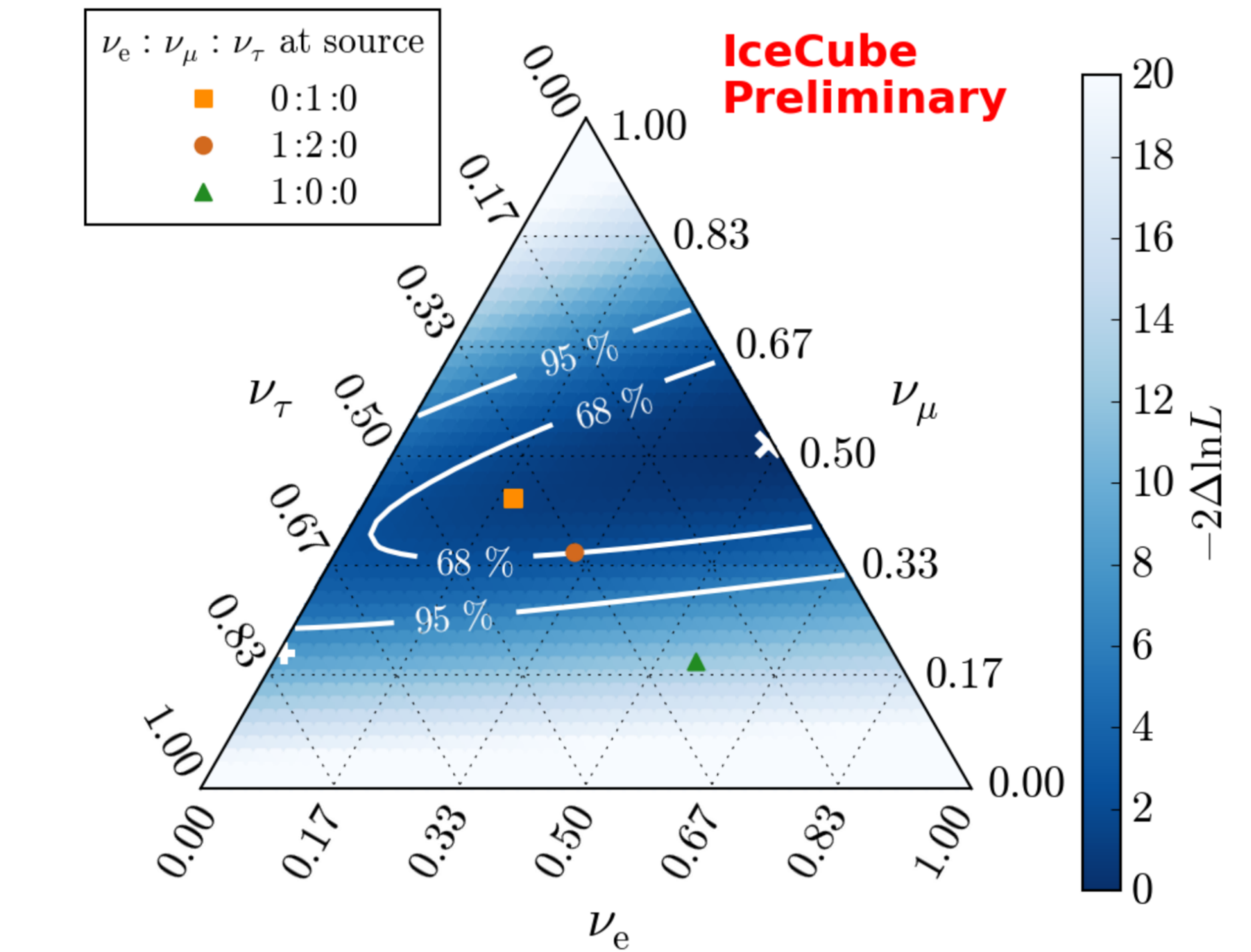
Normal

Inverted

ons

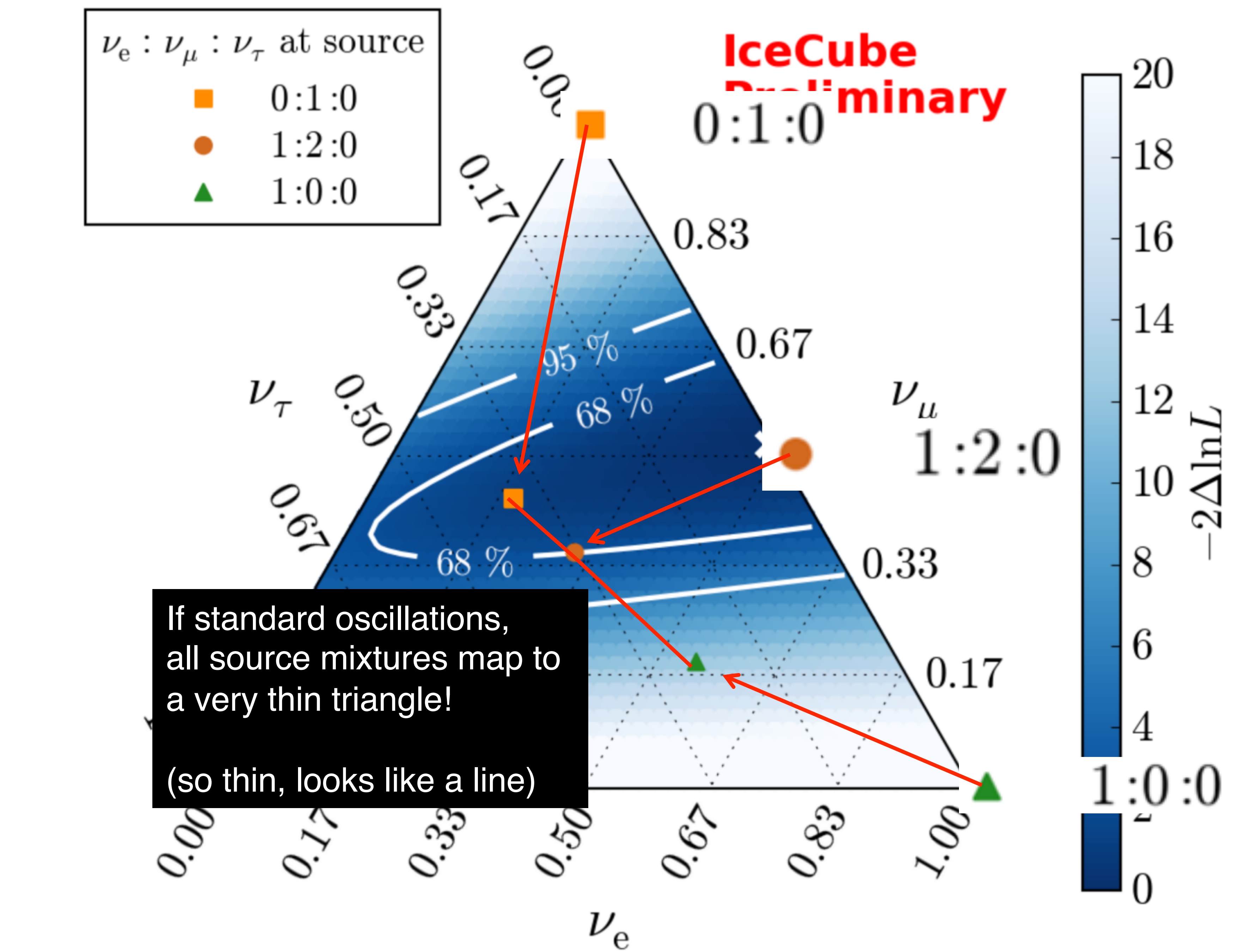
3.7

Km



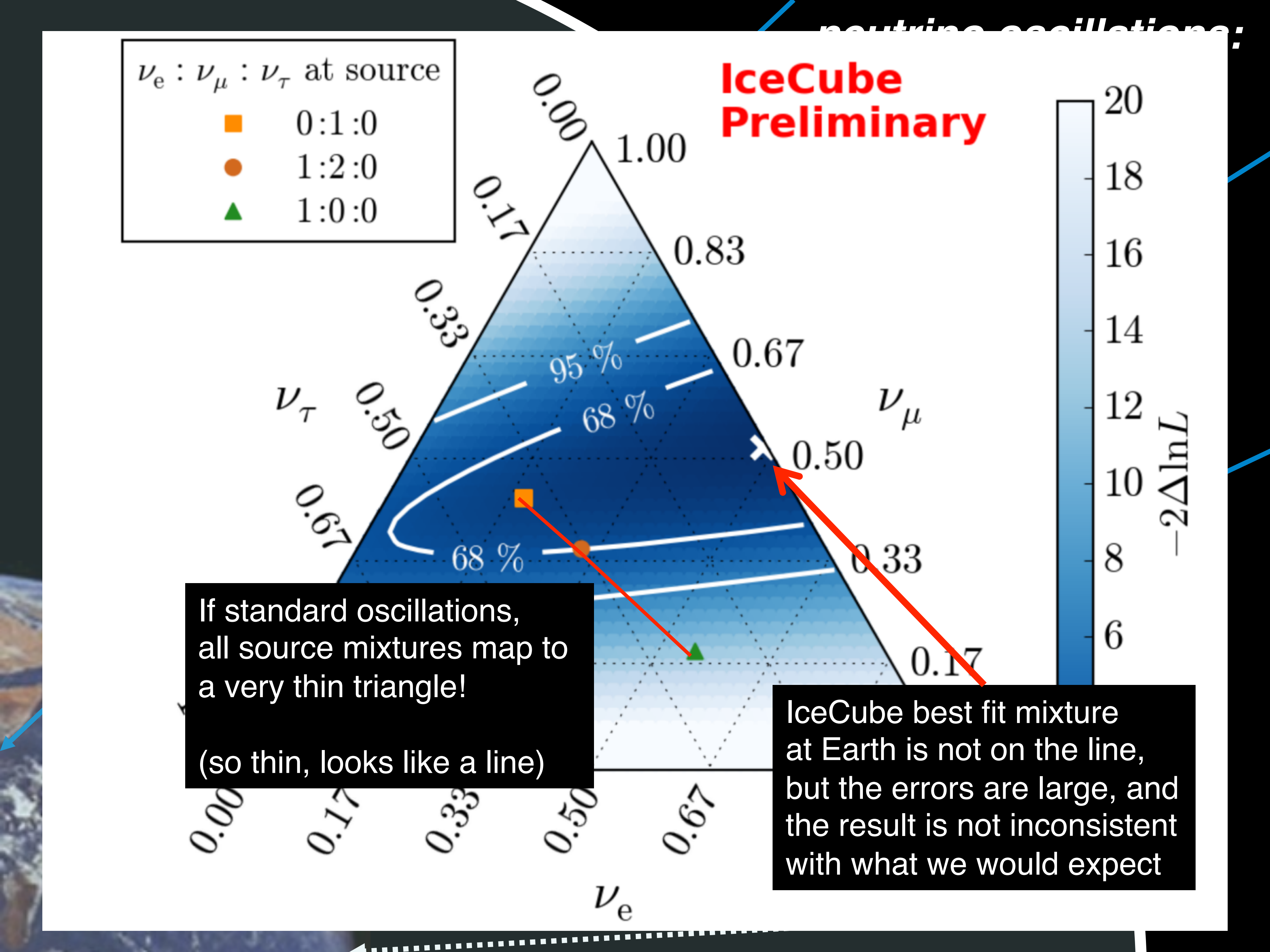
$\nu_e : \nu_\mu : \nu_\tau$ at source
0 : 1 : 0
1 : 2 : 0
1 : 0 : 0
IceCube Preliminary
95 %
68 %
68 %
95 %
ν_τ
ν_μ
ν_e
0.00
0.17
0.33
0.50
0.67
0.83
1.00
$-2\Delta\ln L$
0
2
4
6
8
10
12
14
16
18
20

neutrino oscillations:



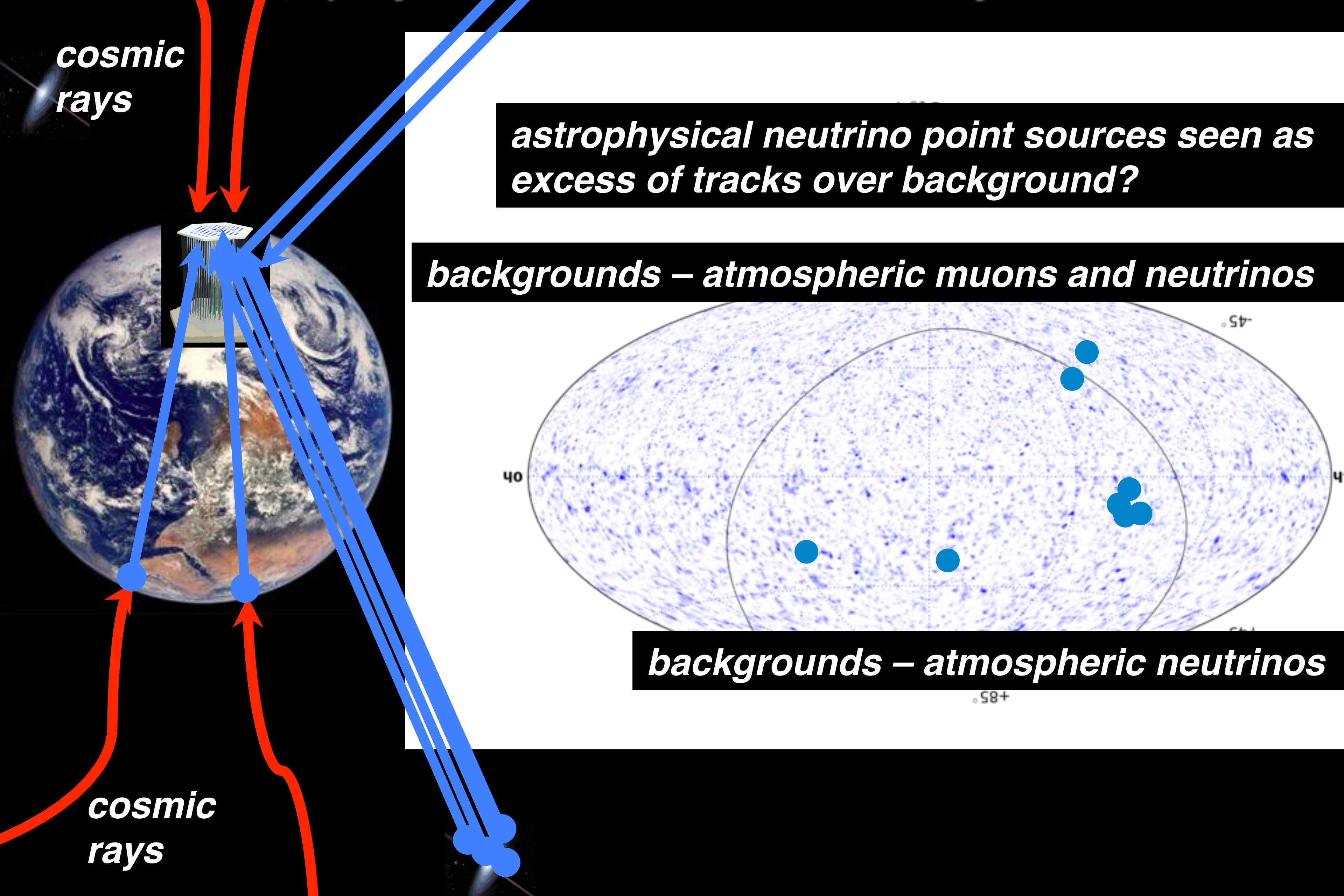
If standard oscillations, all source mixtures map to a very thin triangle!

(so thin, looks like a line)

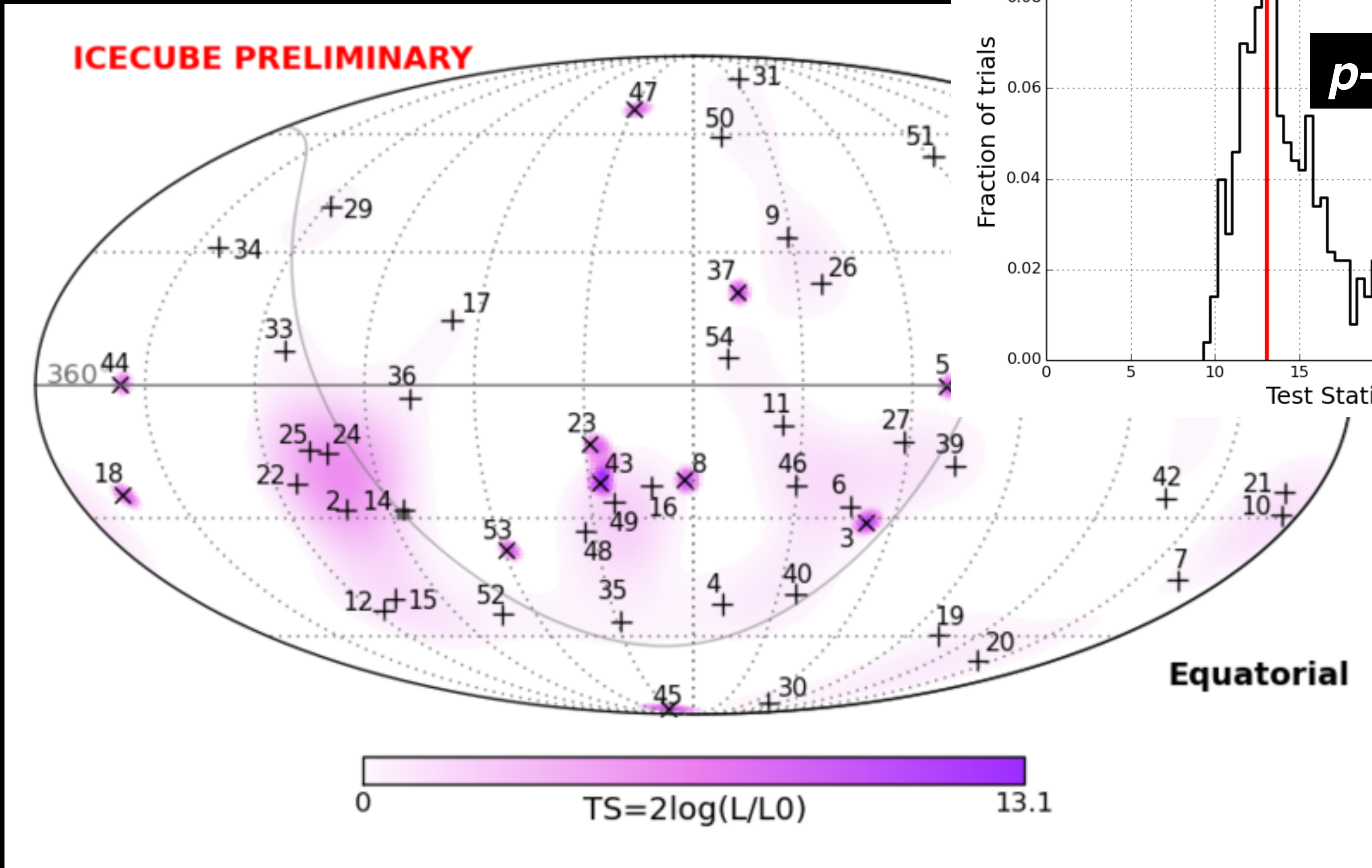


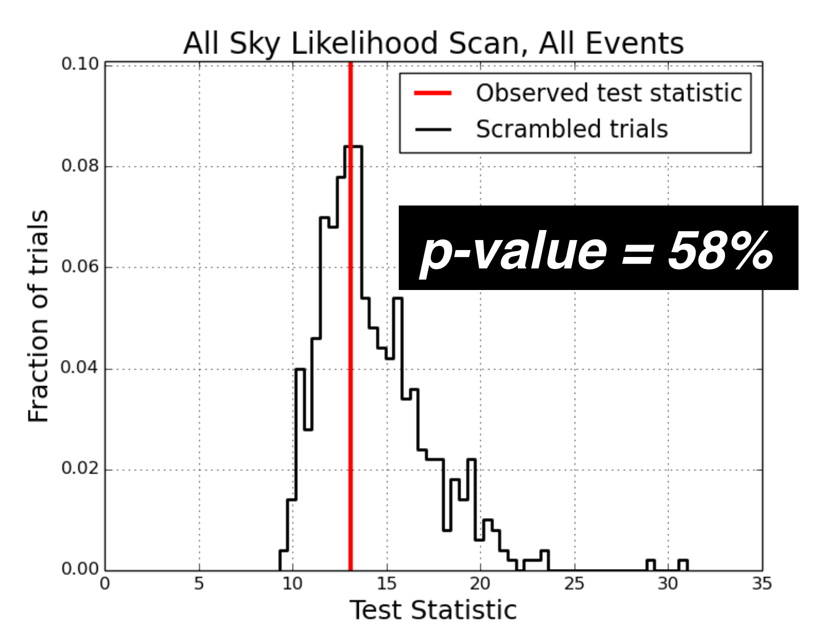
neutrino oscillations:
$\nu_e : \nu_\mu : \nu_\tau$ at source
0 : 1 : 0
1 : 2 : 0
1 : 0 : 0
IceCube Preliminary
95 %
68 %
68 %
ν_τ
ν_μ
ν_e
0.00
0.17
0.33
0.50
0.67
1.00
0.83
0.67
0.50
0.33
0.17
0.00
0.17
0.33
0.50
0.67
20
18
16
14
12
10
8
6
$-2\Delta\ln L$
If standard oscillations, all source mixtures map to a very thin triangle!
(so thin, looks like a line)
IceCube best fit mixture at Earth is not on the line, but the errors are large, and the result is not inconsistent with what we would expect

Have astrophysical neutrinos, all sky



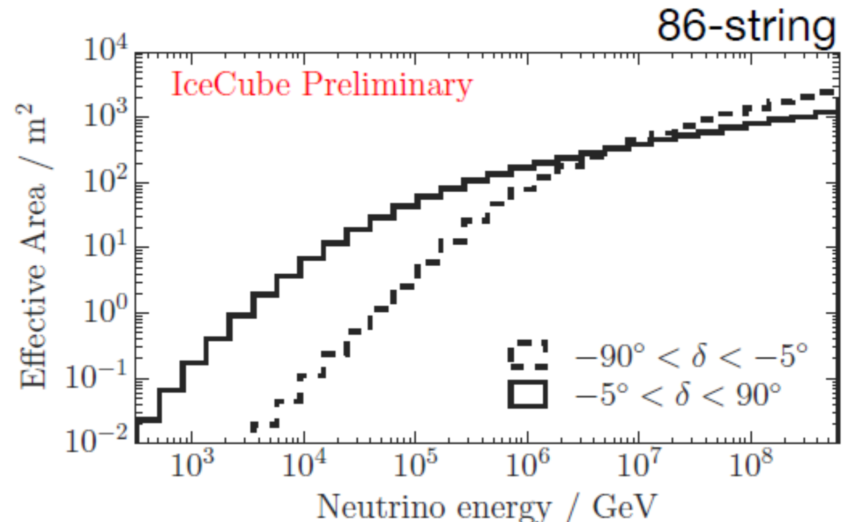
Do the HESE events cluster - is there a brighter than average source?

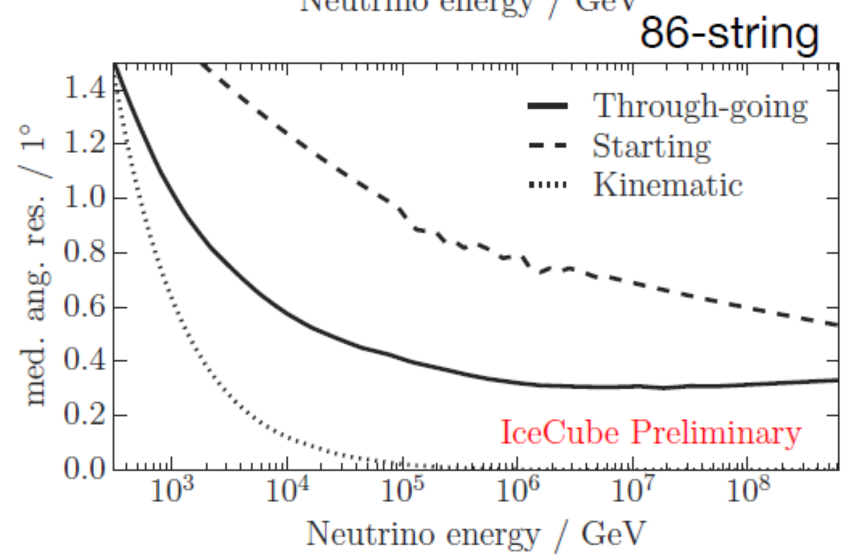




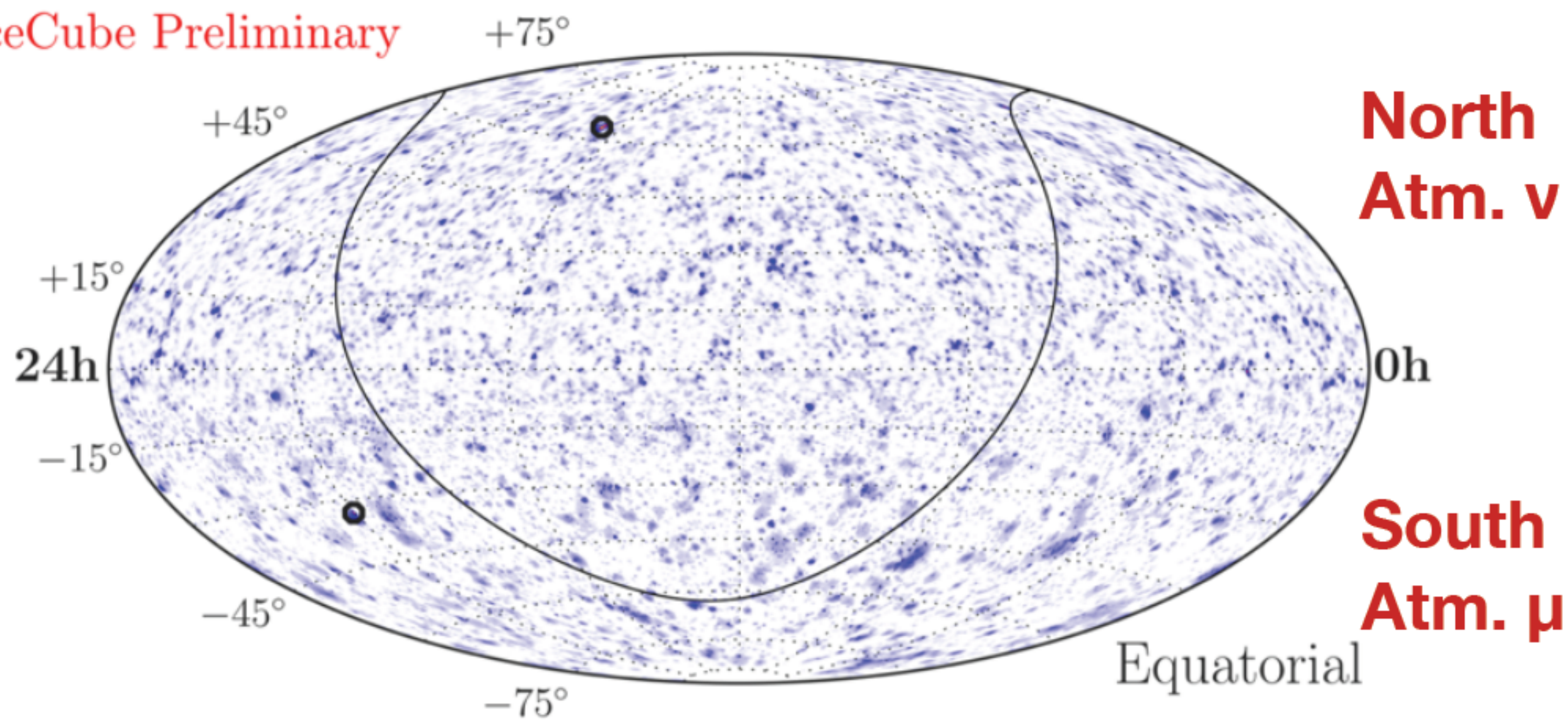
Event Sample of Point Source Searches

- Multivariate event selection to select most promising signal
  - Muons induced by high-energy neutrinos
  - Best reconstruction (long-lever arm)
- North: ~70k ν_μ's per year
- South: ~35k μ's per year
- Total: 6 years = **600,000+** events
  - First 2 years in partial configuration (IC40 & IC59)
  - 4 years with full detector (IC79 + 3xIC86)

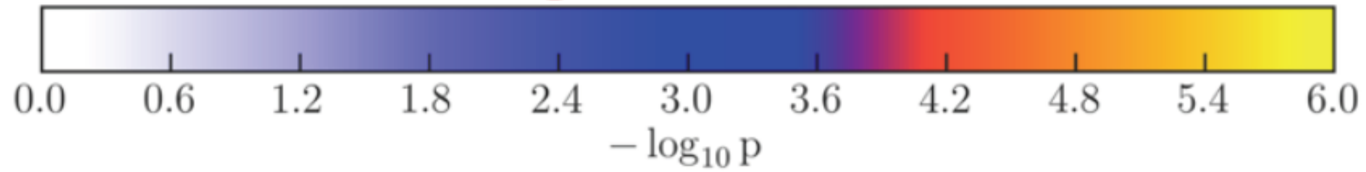




Results of 6 year analysis

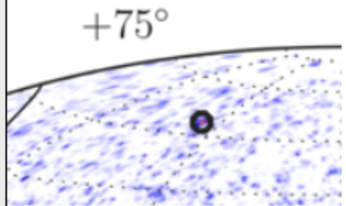


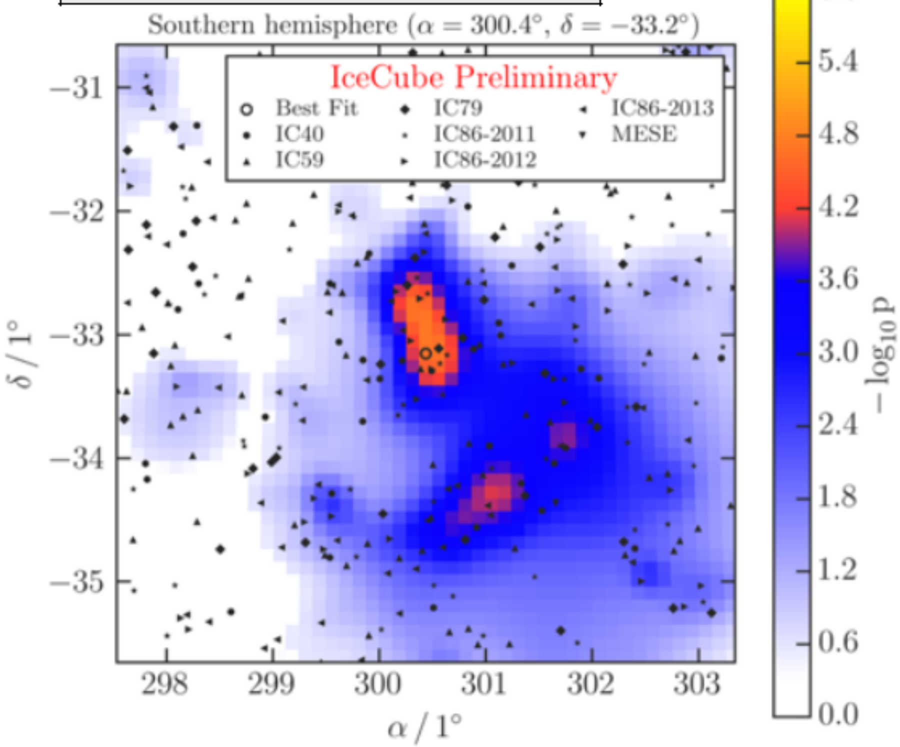
No significant clustering observed

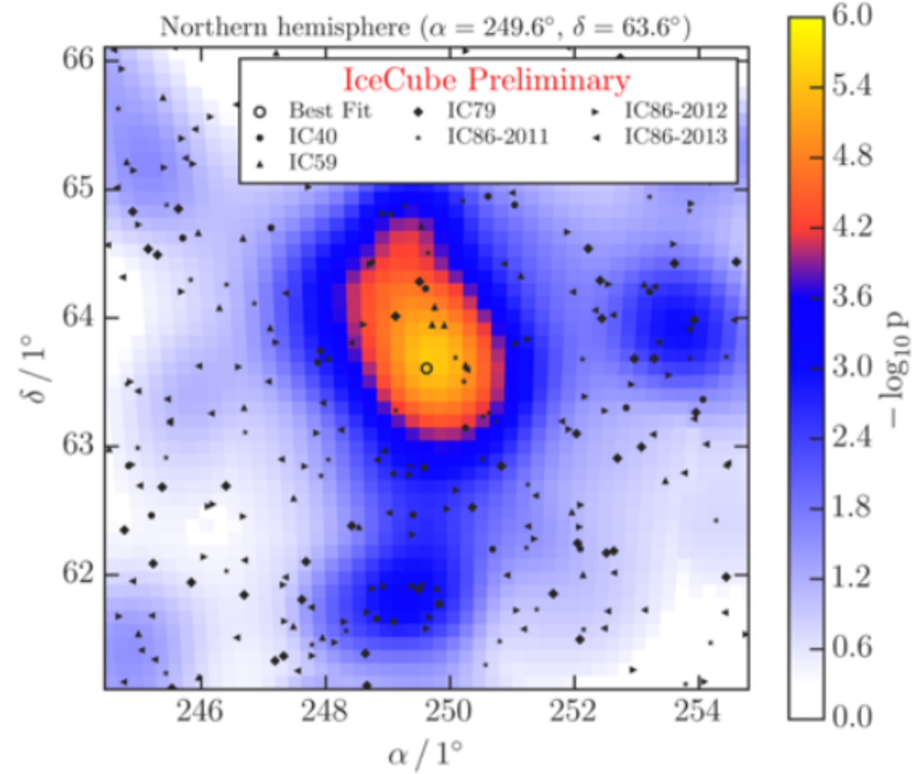


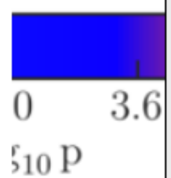
Results of 6 year analysis - Hottest Spots

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





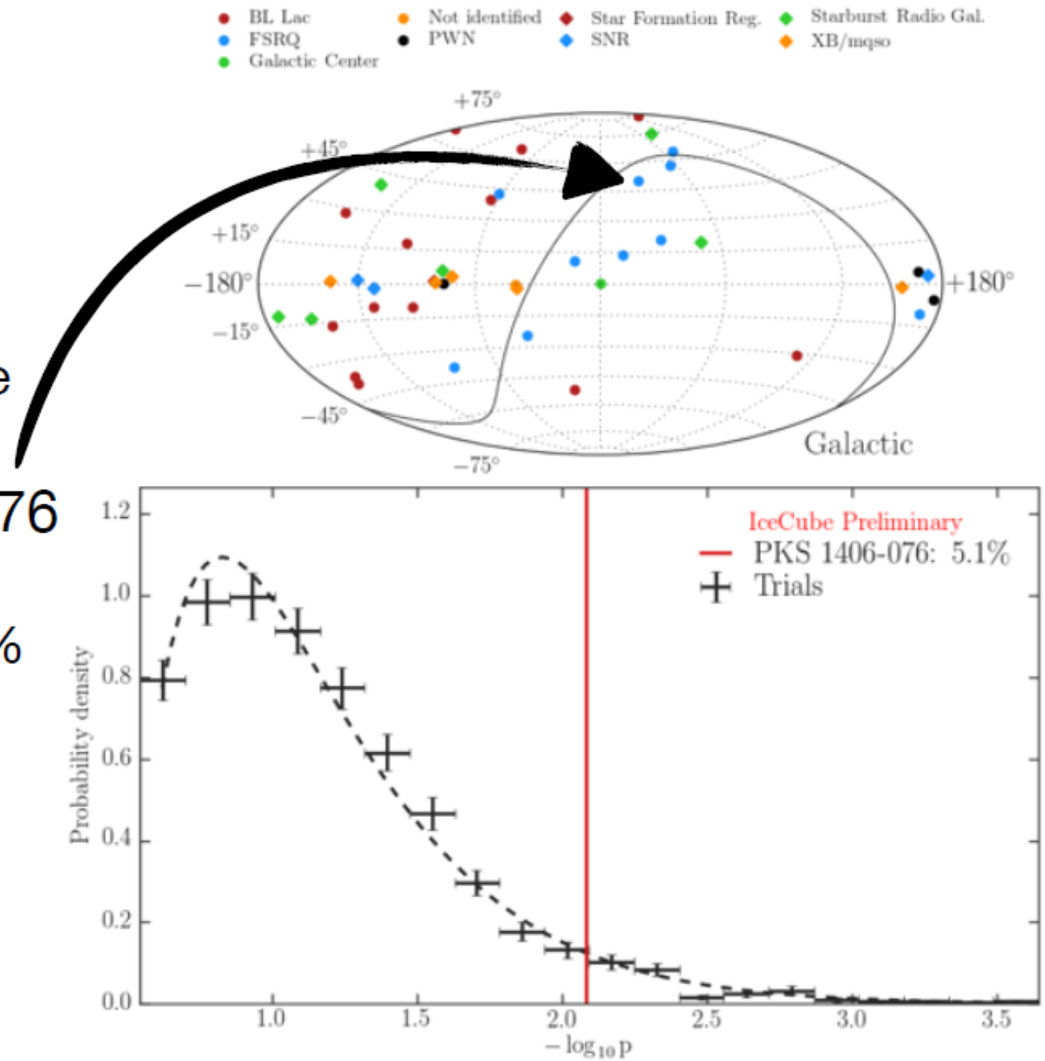




North	
$-\log_{10}(p)$	5.51
Post-Trial	35%
n_s	28.4
γ	

A-Priori Source lists

- Source list of possible neutrino emitters
  - 44 sources of various type
  - Mostly northern hemisphere
- Best Source: PKS1406-076
  - Post Trial Significance: 5.1%
  - n_Src = 12.9, ɣ = 2.8
- Complete source list at ApJ 796, 109 (2014)



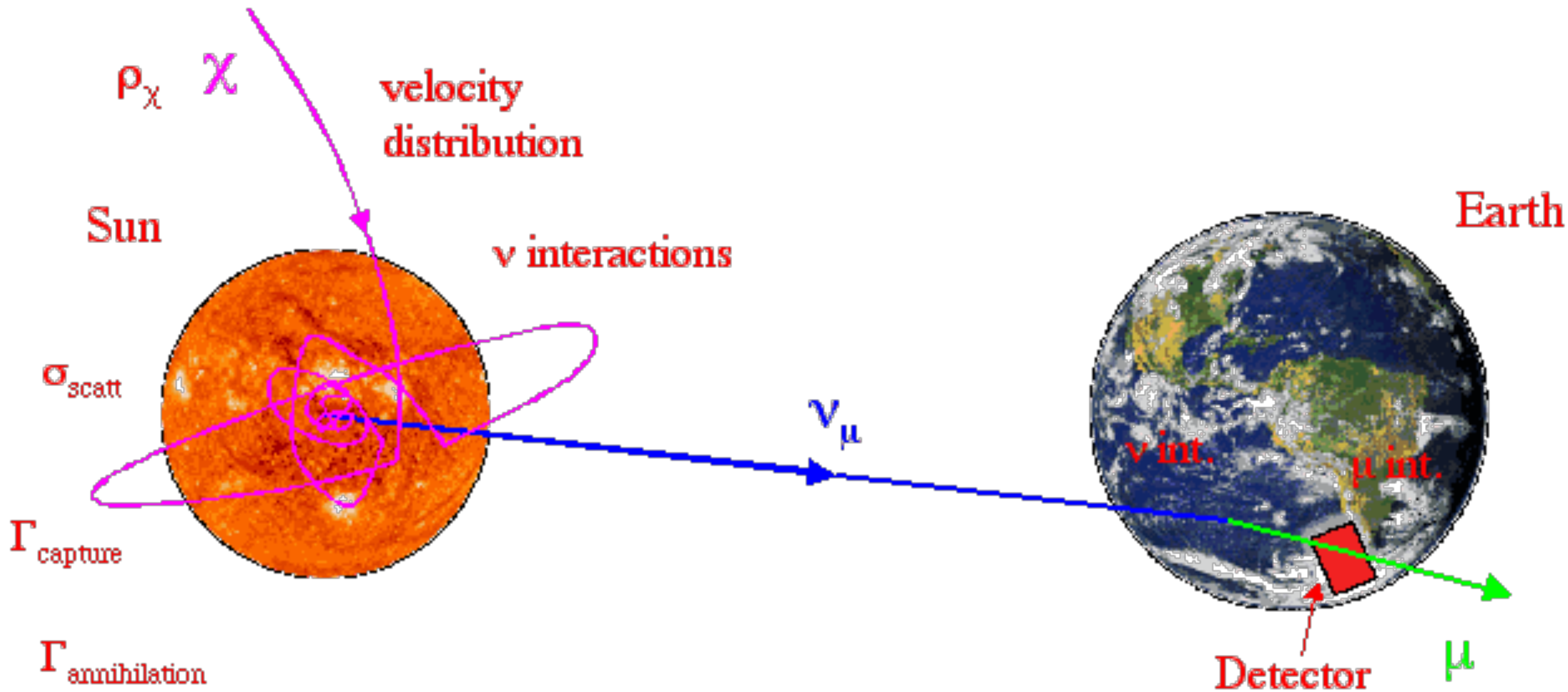
Beyond the Standard Model:

Indirect dark matter detection?

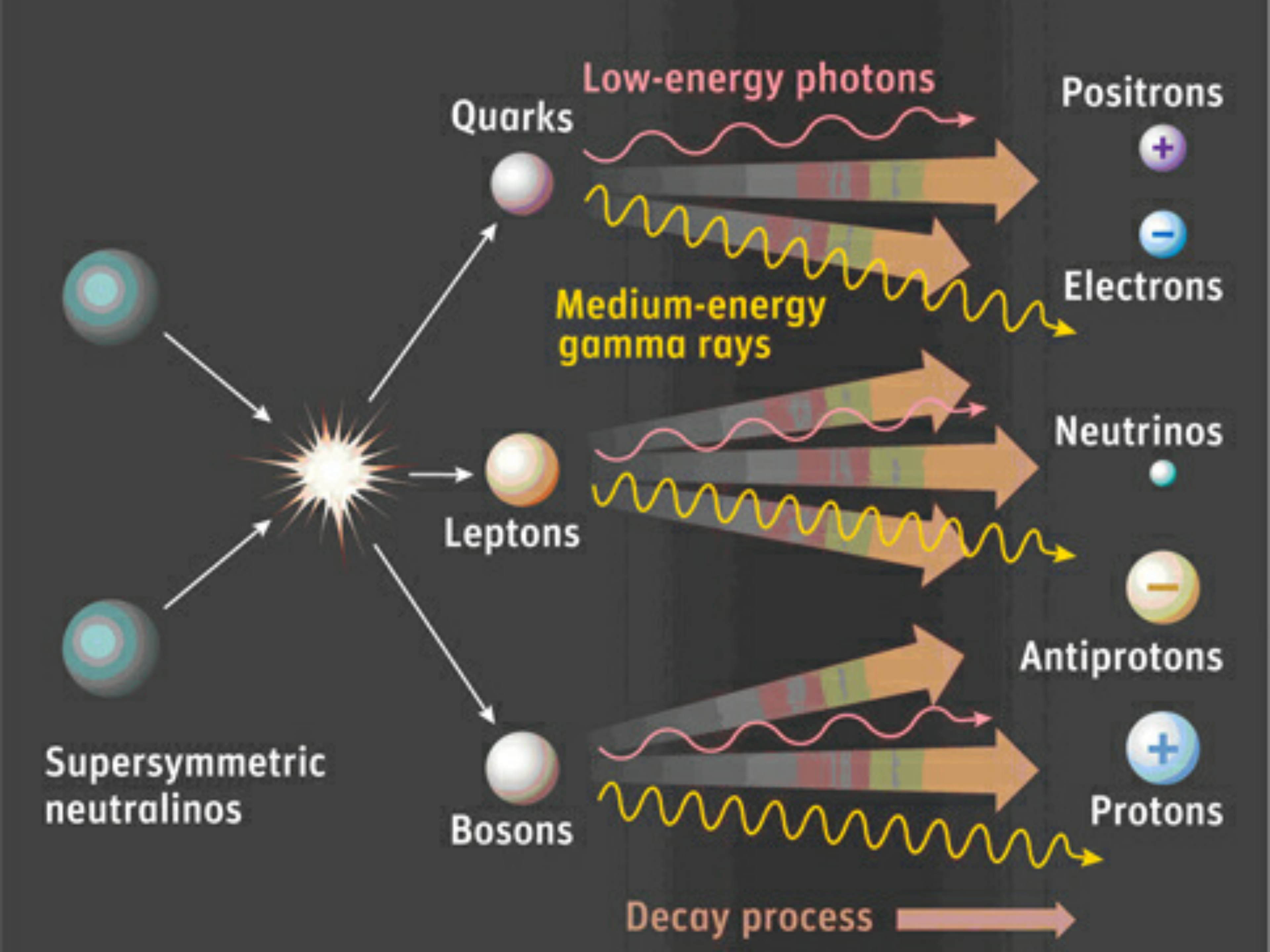
Dark matter accumulation in

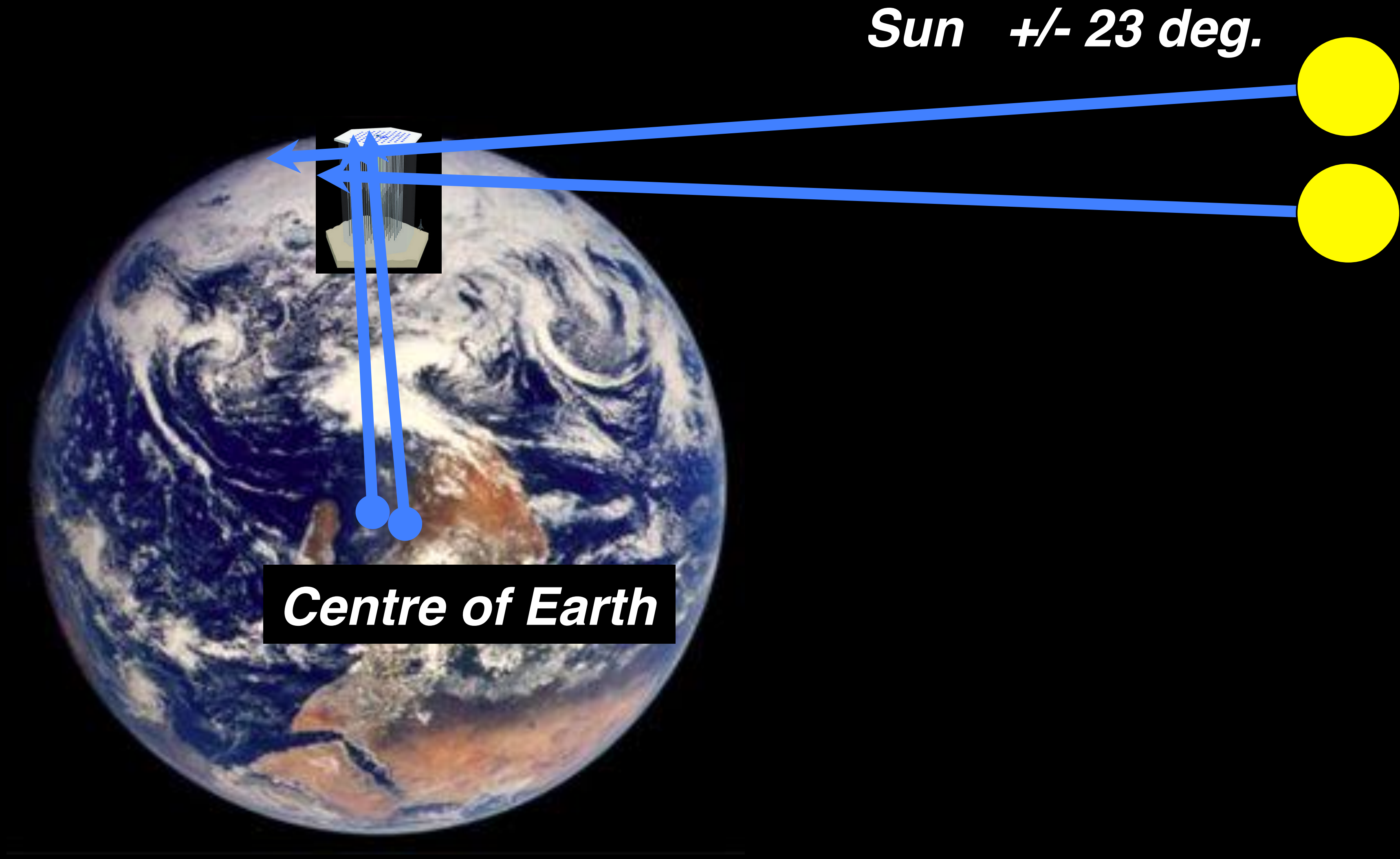
the sun
the earth
galactic halo
other galaxies

Annihilation to neutrinos…



ρ_χ
χ
velocity distribution
Sun
ν interactions
σ_{scatt}
$\Gamma_{capture}$
$\Gamma_{annihilation}$
ν_μ
Earth
ν int.
μ int.
Detector
μ


Low-energy photons
Quarks
Positrons
Electrons
Medium-energy gamma rays
Neutrinos
Leptons
Antiprotons
Supersymmetric neutralinos
Bosons
Protons
Decay process


Sun +/- 23 deg.
Centre of Earth

Search for Dark Matter Annihilations in the Sun with the 79-String IceCube Detector

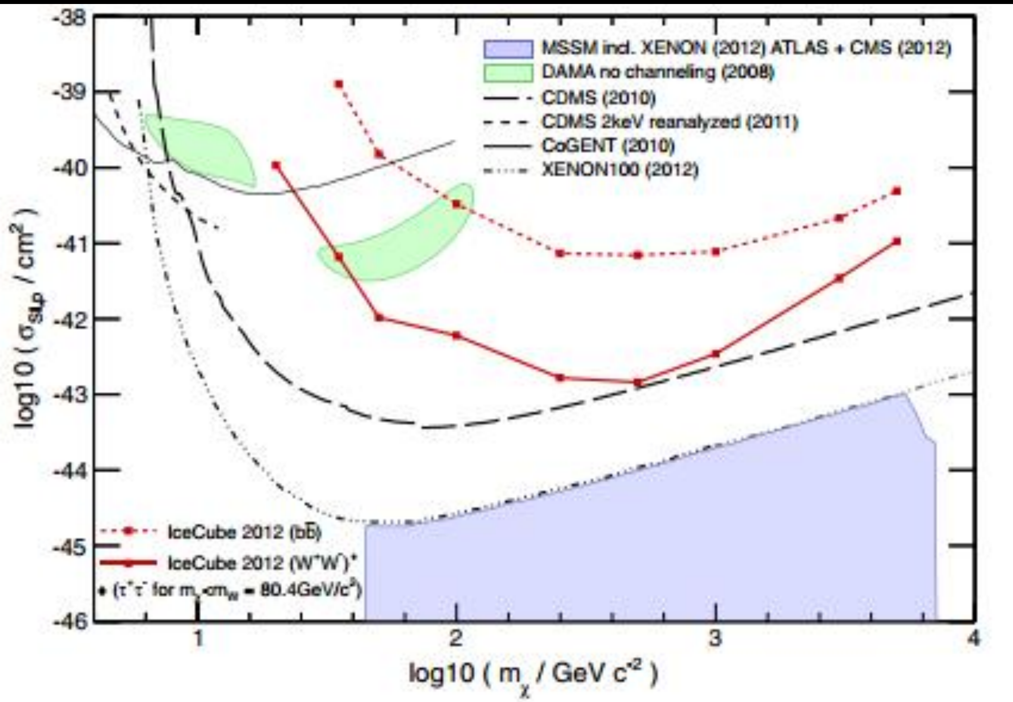
We have performed a search for muon neutrinos from dark matter annihilation in the center of the Sun with the 79-string configuration of the IceCube neutrino telescope. For the first time, the DeepCore subarray is included in the analysis, lowering the energy threshold and extending the search to the austral summer. The 317 days of data collected between June 2010 and May 2011 are consistent with the expected background from atmospheric muons and neutrinos. Upper limits are set on the dark matter annihilation rate, with conversions to limits on spin-dependent and spin-independent scattering cross sections of weakly interacting massive particles (WIMPs) on protons, for WIMP masses in the range 20–5000 GeV/c^2. These are the most stringent spin-dependent WIMP-proton cross section limits to date above 35 GeV/c^2 for most WIMP models.

TABLE I. Results from the combination of the three independent datasets. Upper 90% limits on the number of signal events μ_s^{90}, the WIMP annihilation rate in the Sun Γ_A, the muon flux Φ_μ and neutrino flux Φ_ν, and the WIMP-proton scattering cross-sections (spin-independent, $\sigma_{SI,p}$, and spin-dependent, $\sigma_{SD,p}$), at the 90% confidence level including systematic errors. The sensitivity $\overline{\Phi}_\mu$ (see text) is shown for comparison.

m_χ (GeV/c^2)	Channel	μ_s^{90}	Γ_A (s^{-1})	$\overline{\Phi}_\mu$ (km^{-2}y^{-1})	Φ_μ (km^{-2}y^{-1})	Φ_ν (km^{-2}y^{-1})	$\sigma_{SI,p}$ (cm^2)	$\sigma_{SD,p}$ (cm^2)
20	$\tau^+\tau^-$	162	2.46×10^{25}	5.26×10^{4}	9.27×10^{4}	2.35×10^{15}	1.08×10^{-40}	1.29×10^{-38}
35	$\tau^+\tau^-$	70.2	1.03×10^{24}	1.03×10^{4}	1.21×10^{4}	1.02×10^{14}	6.59×10^{-42}	1.28×10^{-39}
35	$b\bar{b}$	128	1.99×10^{26}	5.63×10^{4}	1.04×10^{5}	6.29×10^{15}	1.28×10^{-39}	2.49×10^{-37}
50	$\tau^+\tau^-$	19.6	1.20×10^{23}	4.82×10^{3}	2.84×10^{3}	1.17×10^{13}	1.03×10^{-42}	2.70×10^{-40}
50	$b\bar{b}$	55.2	1.75×10^{25}	2.06×10^{4}	1.80×10^{4}	5.64×10^{14}	1.51×10^{-40}	3.96×10^{-38}
100	W^+W^-	16.8	3.35×10^{22}	1.49×10^{3}	1.19×10^{3}	1.23×10^{12}	6.01×10^{-43}	2.68×10^{-40}
100	$b\bar{b}$	28.9	1.82×10^{24}	7.57×10^{3}	5.91×10^{3}	6.34×10^{13}	3.30×10^{-41}	1.47×10^{-38}
250	W^+W^-	29.9	2.85×10^{21}	3.04×10^{2}	4.15×10^{2}	9.72×10^{10}	1.67×10^{-43}	1.34×10^{-40}
250	$b\bar{b}$	19.8	1.27×10^{23}	1.85×10^{3}	1.45×10^{3}	4.59×10^{12}	7.37×10^{-42}	5.90×10^{-39}
500	W^+W^-	25.2	8.57×10^{20}	1.46×10^{2}	2.23×10^{2}	2.61×10^{10}	1.45×10^{-43}	1.57×10^{-40}
500	$b\bar{b}$	30.6	4.12×10^{22}	8.53×10^{2}	1.02×10^{3}	1.52×10^{12}	6.98×10^{-42}	7.56×10^{-39}
1000	W^+W^-	23.4	6.13×10^{20}	1.19×10^{2}	1.85×10^{2}	1.62×10^{10}	3.46×10^{-43}	4.48×10^{-40}
1000	$b\bar{b}$	30.4	1.39×10^{22}	4.33×10^{2}	5.99×10^{2}	5.23×10^{11}	7.75×10^{-42}	1.00×10^{-38}
3000	W^+W^-	22.2	7.79×10^{20}	1.09×10^{2}	1.66×10^{2}	1.65×10^{10}	3.44×10^{-42}	5.02×10^{-39}
3000	$b\bar{b}$	26.1	4.88×10^{21}	2.52×10^{2}	3.47×10^{2}	1.89×10^{11}	2.17×10^{-41}	3.16×10^{-38}
5000	W^+W^-	22.8	8.79×10^{20}	1.01×10^{2}	1.58×10^{2}	1.77×10^{10}	1.06×10^{-41}	1.59×10^{-38}
5000	$b\bar{b}$	26.4	6.50×10^{20}	2.21×10^{2}	3.26×10^{2}	1.63×10^{11}	4.89×10^{-41}	7.29×10^{-38}

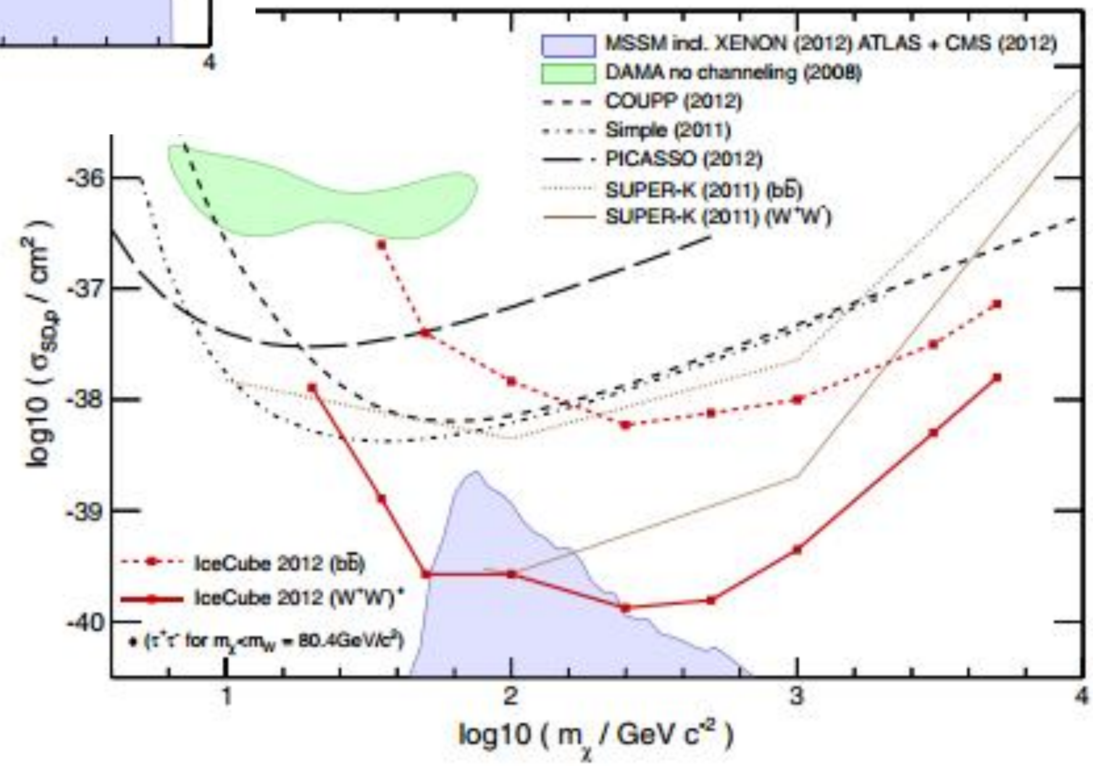
Search for Dark Matter Annihilations in the Sun with the 79-String IceCube Detector

Limits on capture cross sections



Spin-independent

Spin-dependent



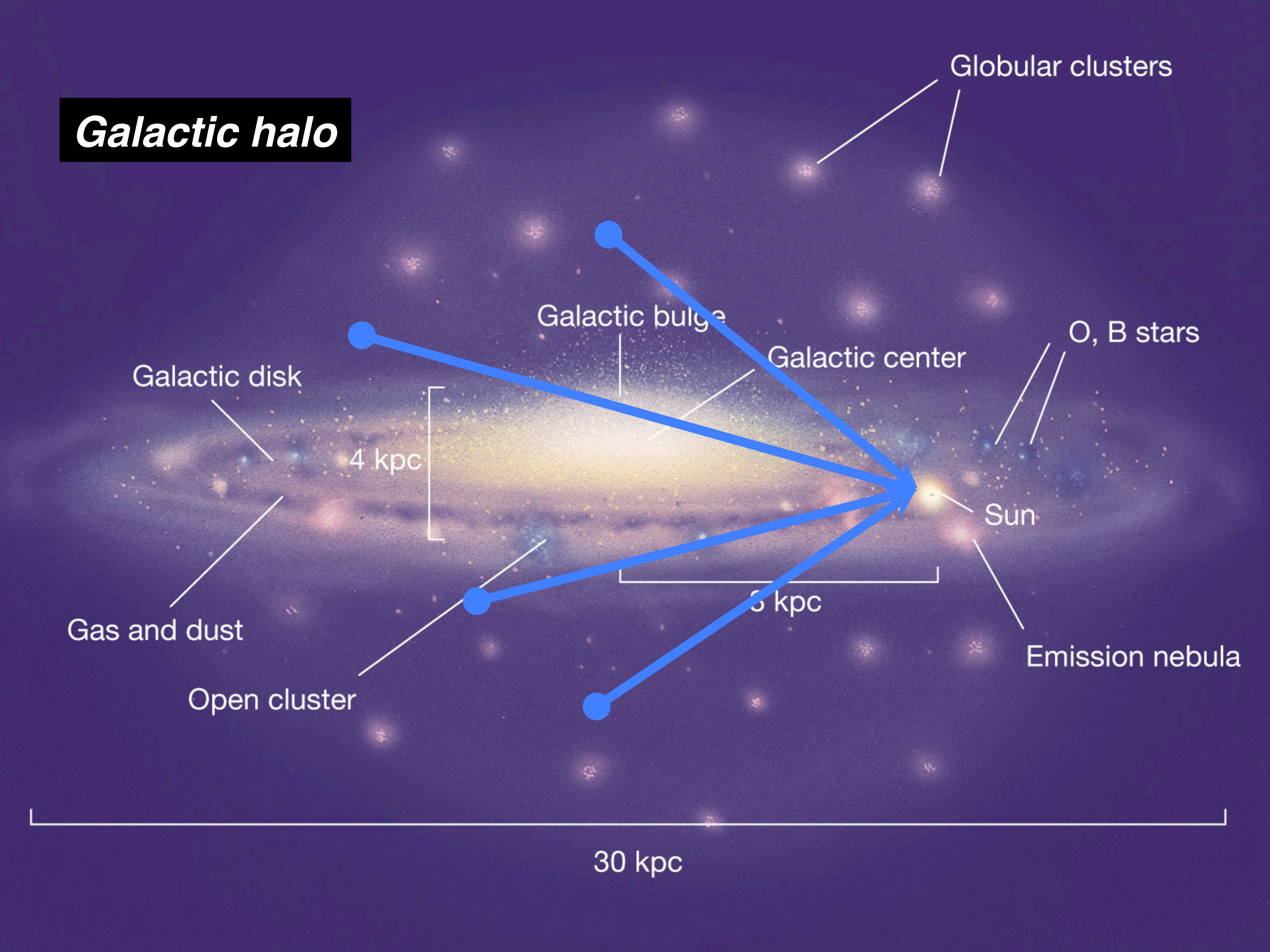
PRL **110**, 131302 (2013)

IceCube search for dark matter annihilation in nearby galaxies and galaxy clusters

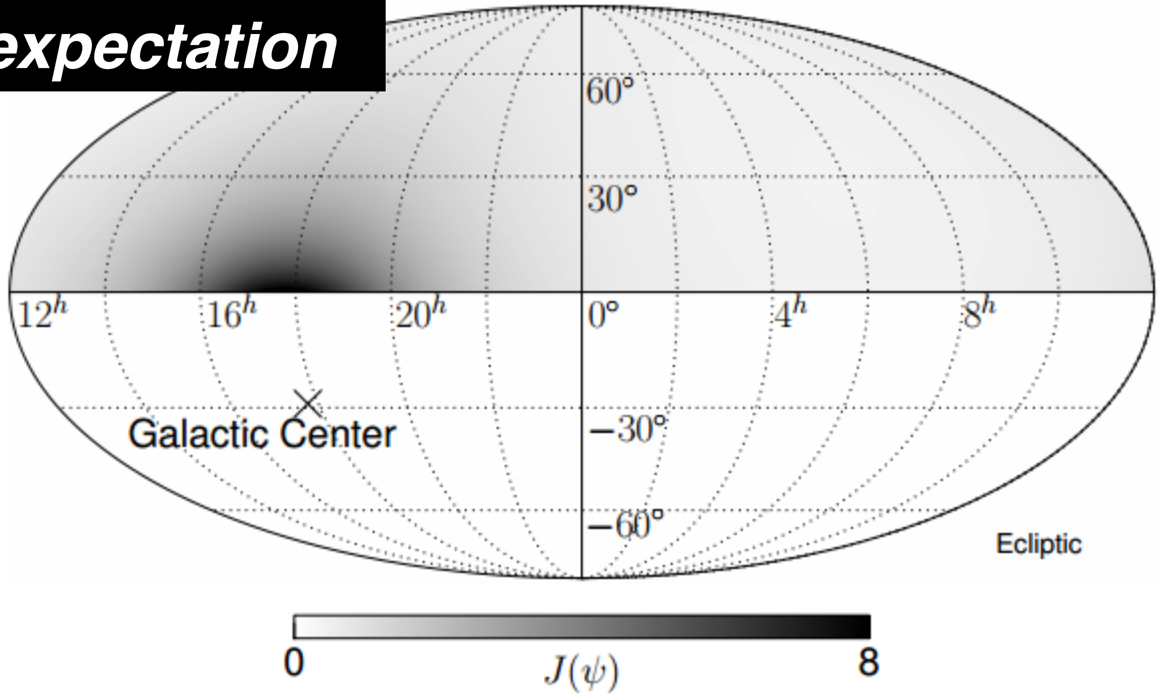
We present the results of a first search for self-annihilating dark matter in nearby galaxies and galaxy clusters using a sample of high-energy neutrinos acquired in 339.8 days of live time during 2009/10 with the IceCube neutrino observatory in its 59-string configuration. The targets of interest include the Virgo and Coma galaxy clusters, the Andromeda galaxy, and several dwarf galaxies. We obtain upper limits on the cross section as a function of the weakly interacting massive particle mass between 300 GeV and 100 TeV for the annihilation into $b\bar{b}$, W^+W^-, $\tau^+\tau^-$, $\mu^+\mu^-$, and $\nu\bar{\nu}$. A limit derived for the Virgo cluster, when assuming a large effect from subhalos, challenges the weakly interacting massive particle interpretation of a recently observed GeV positron excess in cosmic rays.

Source	Right ascension	Declination	Distance [kpc]	Mass [$M_\odot$]	$\log_{10} J_{NFW}$ [$GeV^2 cm^{-5}$]	Boost factor
Segue 1	10h 07m 04s	+16°04'55"	23	1.58×10^7	19.6 ± 0.5 [40]	Not considered
Ursa Major II	08h 51m 30s	+63°07'48"	32	1.09×10^7	19.6 ± 0.4 [40]	Not considered
Coma Berenices	12h 26m 59s	+23°54'15"	44	0.72×10^7	19.0 ± 0.4 [40]	Not considered
Draco	17h 20m 12s	+57°54'55"	80	1.87×10^7	18.8 ± 0.1 [40]	Not considered
Andromeda	00h 42m 44s	+41°16'09"	778	6.9×10^{11}	19.2 [20]*	66
Virgo cluster	12h 30m 49s	+12°23'28"	22300	6.9×10^{14}	18.2 [41]*	980
Coma cluster	12h 59m 49s	+27°58'50"	95000	1.3×10^{15}	17.1 [41]*	1300

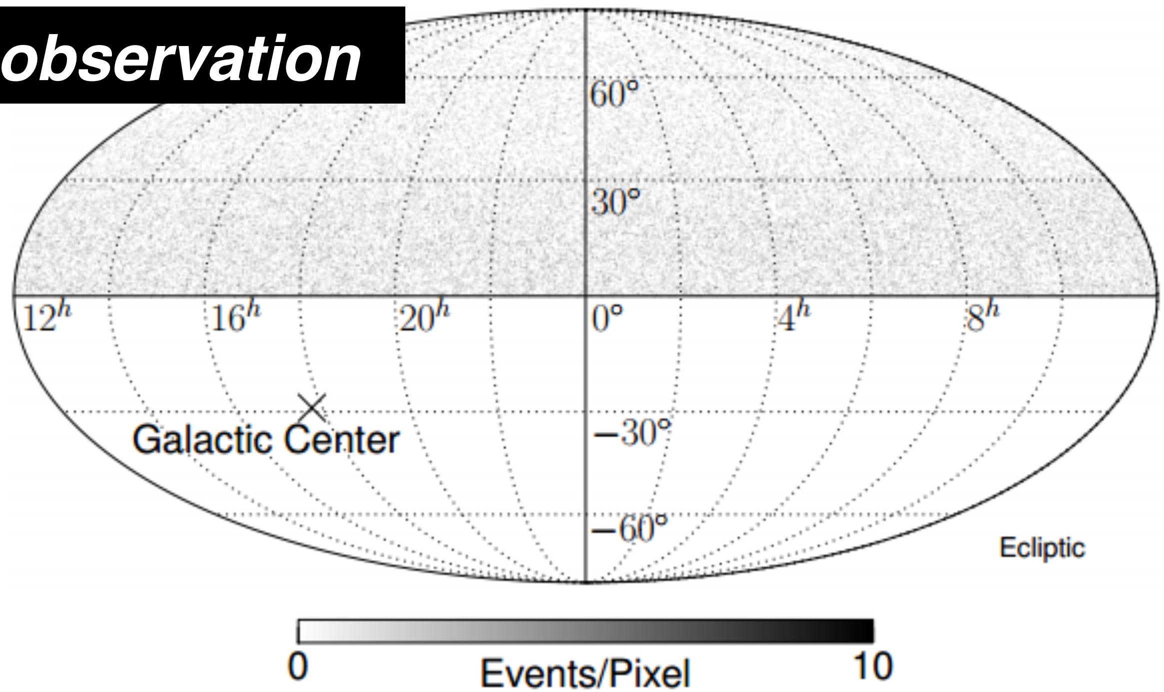
TABLE I. A list of potential astrophysical dark matter targets, their locations [37], distances, and masses [38], as well as J_{NFW} factors (see Sec. III) considered in this paper. Boost factors for Andromeda, Coma, and Virgo are applied, when subclusters are taken into account. According to Ref. [39], subclusters in dwarf galaxies do not usefully boost the signal. For the extended Virgo cluster, M87 was used as the central position. *For Andromeda and the galaxy clusters, no uncertainties are available.


Galactic halo
Globular clusters
Galactic bulge
O, B stars
Galactic center
Galactic disk
4 kpc
Sun
Gas and dust
kpc
Emission nebula
Open cluster
30 kpc

expectation

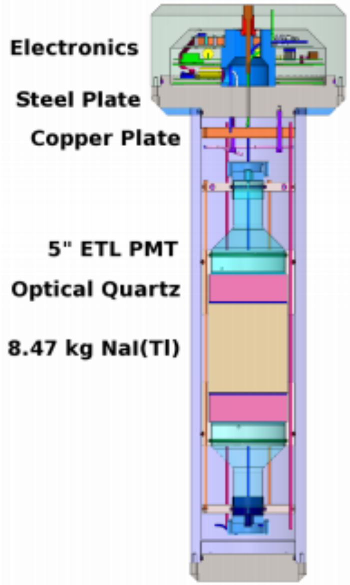


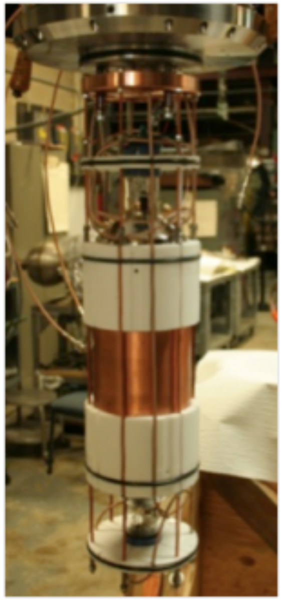
observation



Power spectrum analysis:

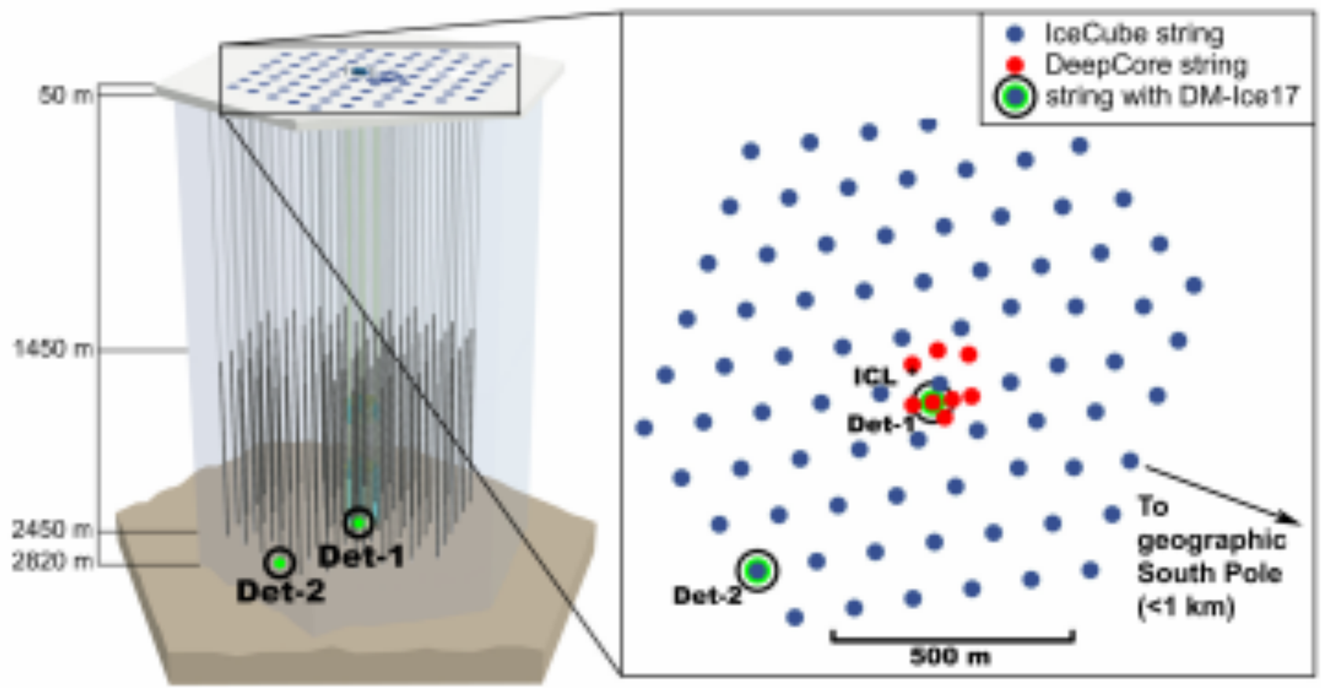
coefficients mapped to single test statistic for clustering





DM-Ice:

direct detection



First data from DM-Ice17

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(The DM–Ice Collaboration)

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[2] *Department of Physics, University of Alberta, Edmonton, Alberta, Canada*
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[4] *Department of Physics, Yale University, New Haven, CT, USA*
[5] *Fermi National Accelerator Laboratory, Batavia, IL, USA*
[6] *Department of Physics and Astronomy, University of Sheffield, Sheffield, UK*
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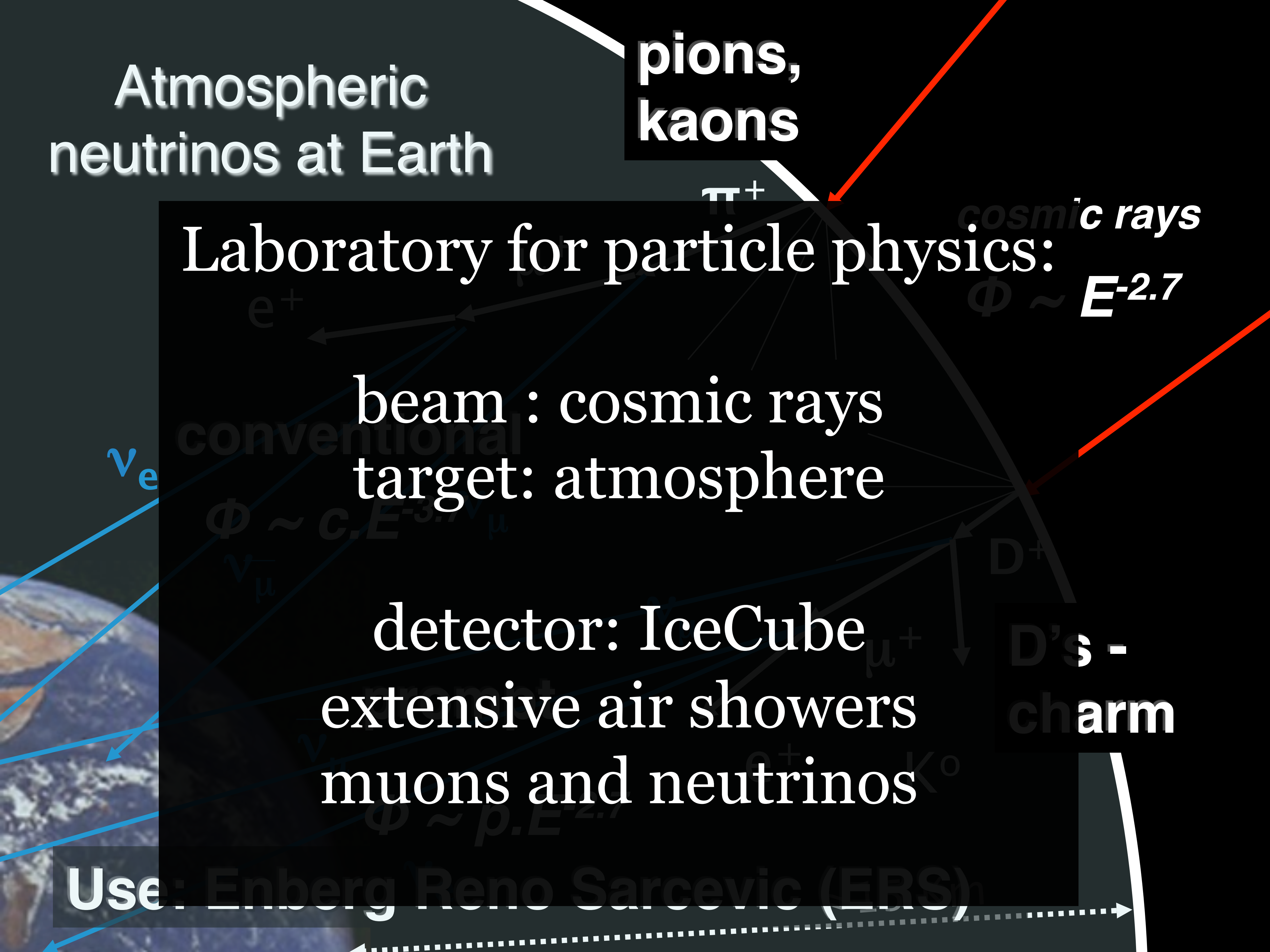
[8] *Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL, USA*

(Dated: August 14, 2014)

We report the first analysis of background data from DM-Ice17, a direct-detection dark matter experiment consisting of 17 kg of NaI(Tl) target material. It was co-deployed with IceCube 2457 m deep in the South Pole glacial ice in December 2010 and is the first such detector operating in the Southern Hemisphere. The background rate in the $6.5-8.0\,\mathrm{keV_{ee}}$ region is measured to be 7.9 ± 0.4 counts/day/keV/kg. This is consistent with the expected background from the detector assemblies with negligible contributions from the surrounding ice. The successful deployment and operation of DM-Ice17 establishes the South Pole ice as a viable location for future underground, low-background experiments in the Southern Hemisphere. The detector assembly and deployment are described here, as well as the analysis of the DM-Ice17 backgrounds based on data from the first two years of operation after commissioning, July 2011 – June 2013.

arxiv.org/pdf/1401.4804v2.pdf

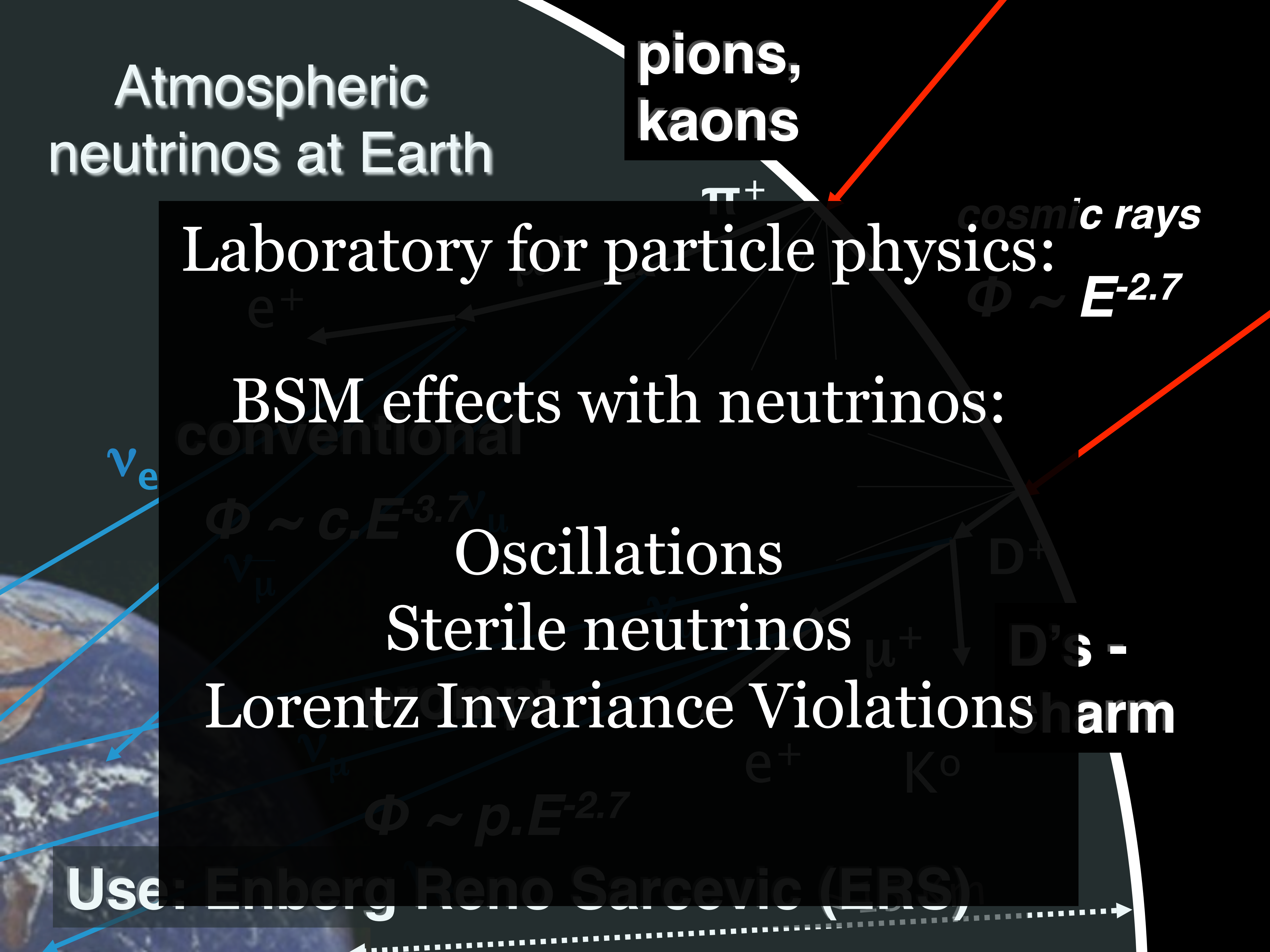
Atmospheric neutrinos at Earth



Laboratory for particle physics:

beam : cosmic rays
target: atmosphere

detector: IceCube
extensive air showers
muons and neutrinos

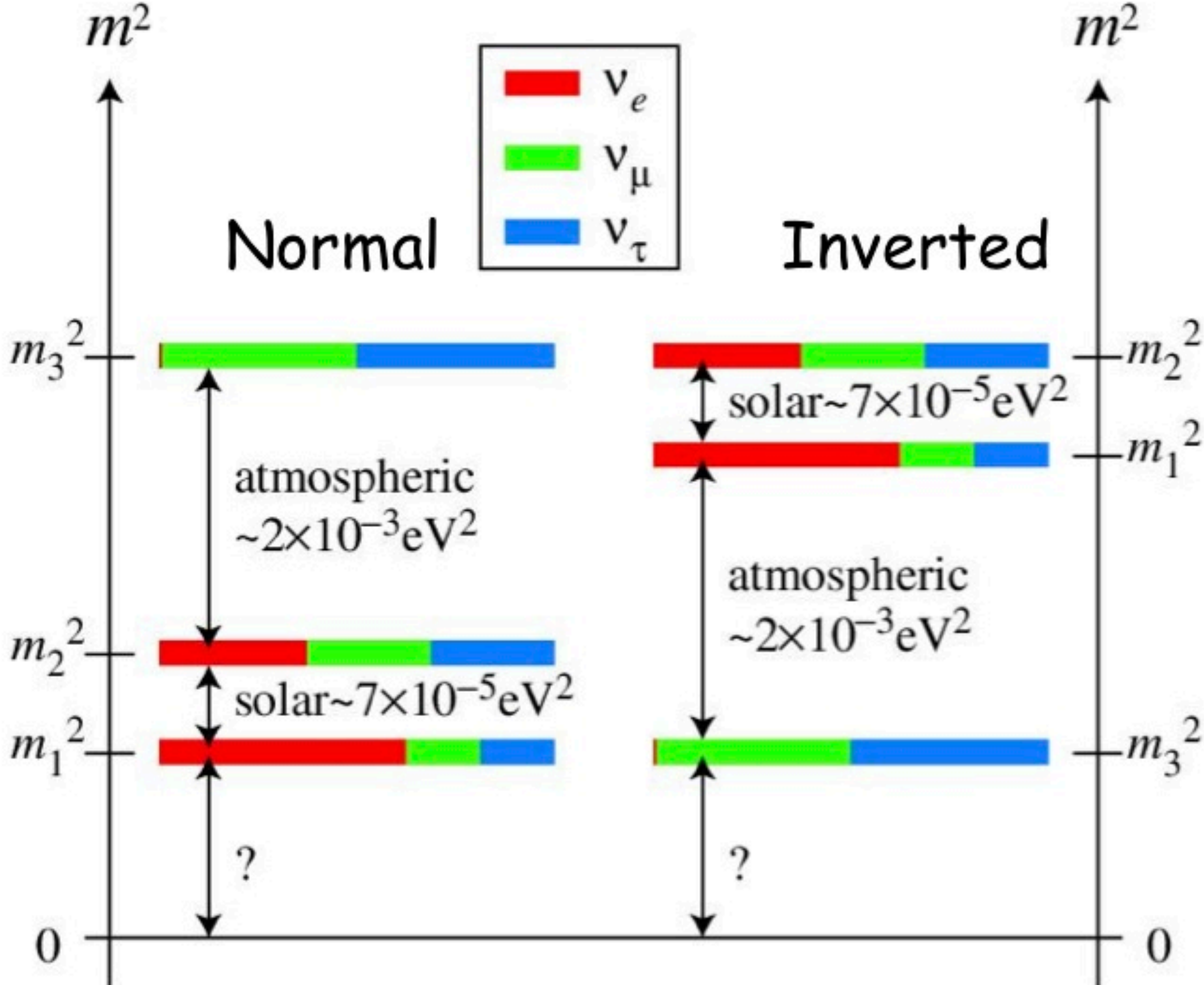


Laboratory for particle physics:

BSM effects with neutrinos:

Oscillations
Sterile neutrinos
Lorentz Invariance Violations

Mass eigenstates not same as flavour eigenstates → neutrinos change flavour



Mass eigenstates not same as flavour eigenstates → neutrinos change flavour

- Neutrinos have peculiar properties
  - **Massive, but not too massive**
  - **Different masses, but not too different***
  - **Mixed, almost maximally mixed**

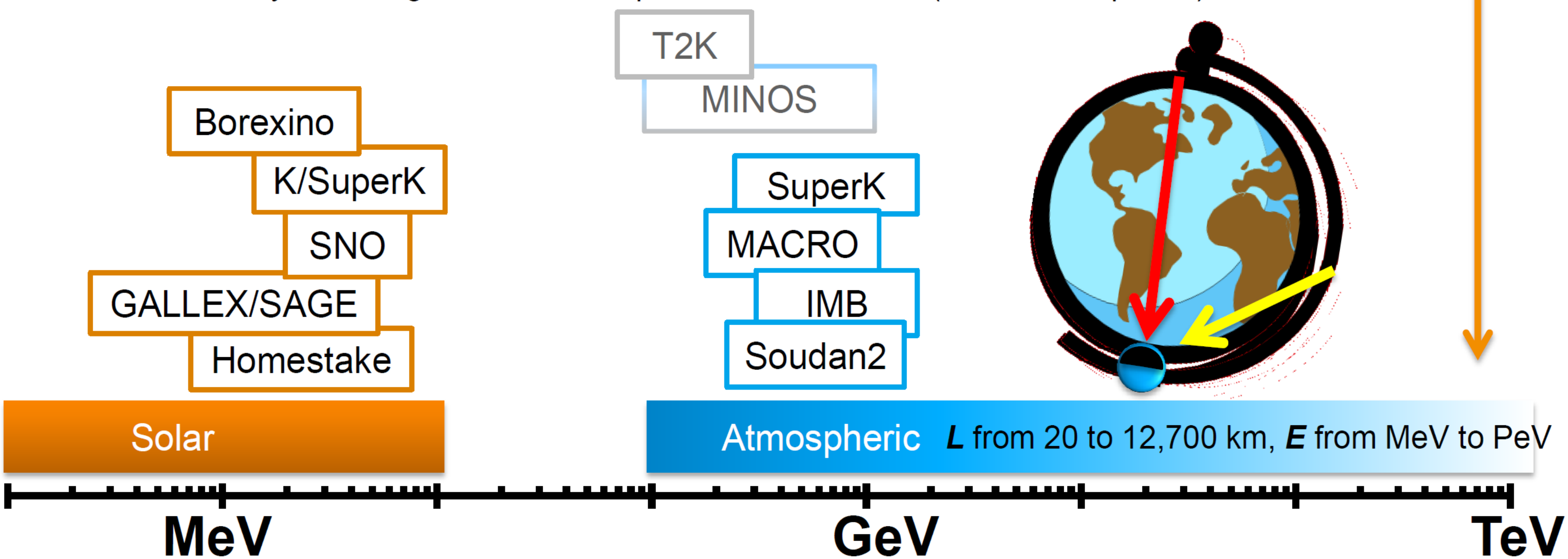
Neutrino oscillations

Described by a sum of factors of the form

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

3+2+1 physics parameters

- Nature has been kind to us
  - Naturally occurring neutrinos as a probe for oscillations (solar, atmospheric)



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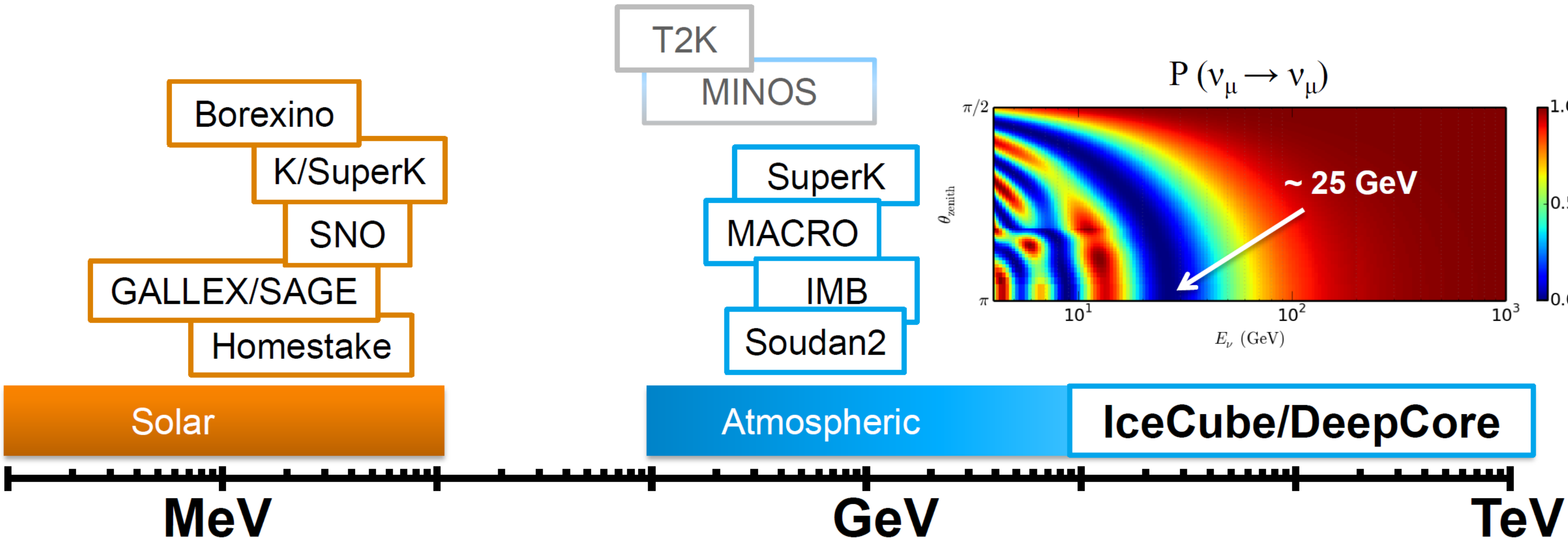

Mass eigenstates not same as flavour eigenstates → neutrinos change flavour

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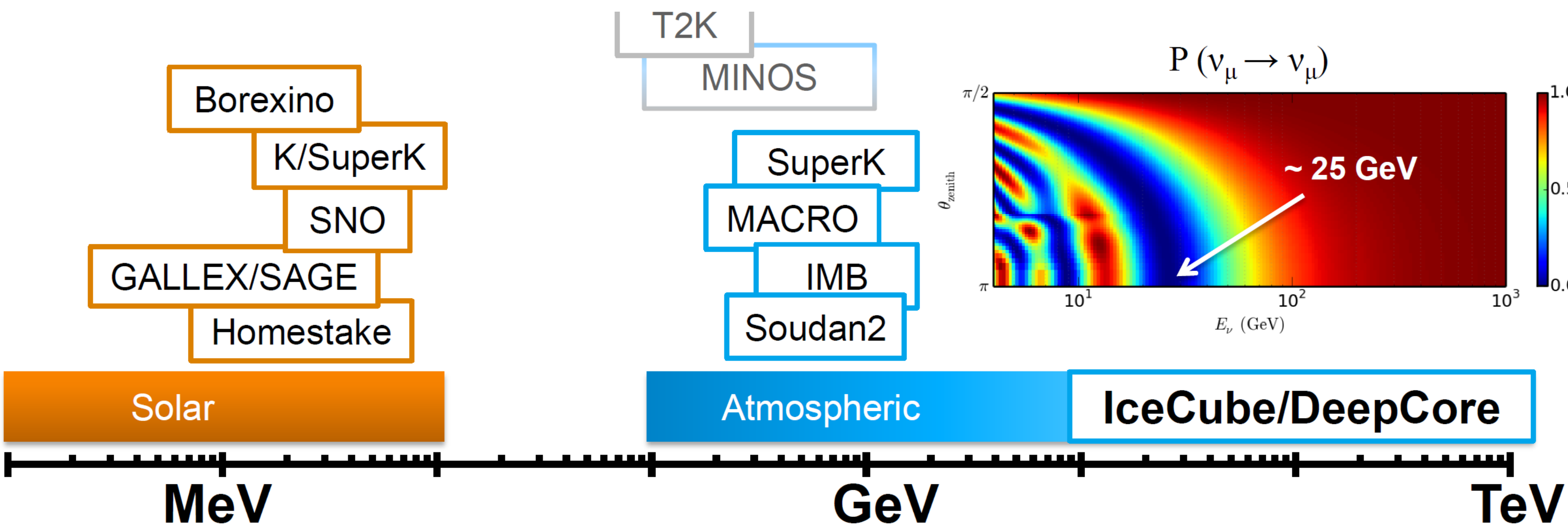
Neutrino oscillations

Described by a sum of factors of the form

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

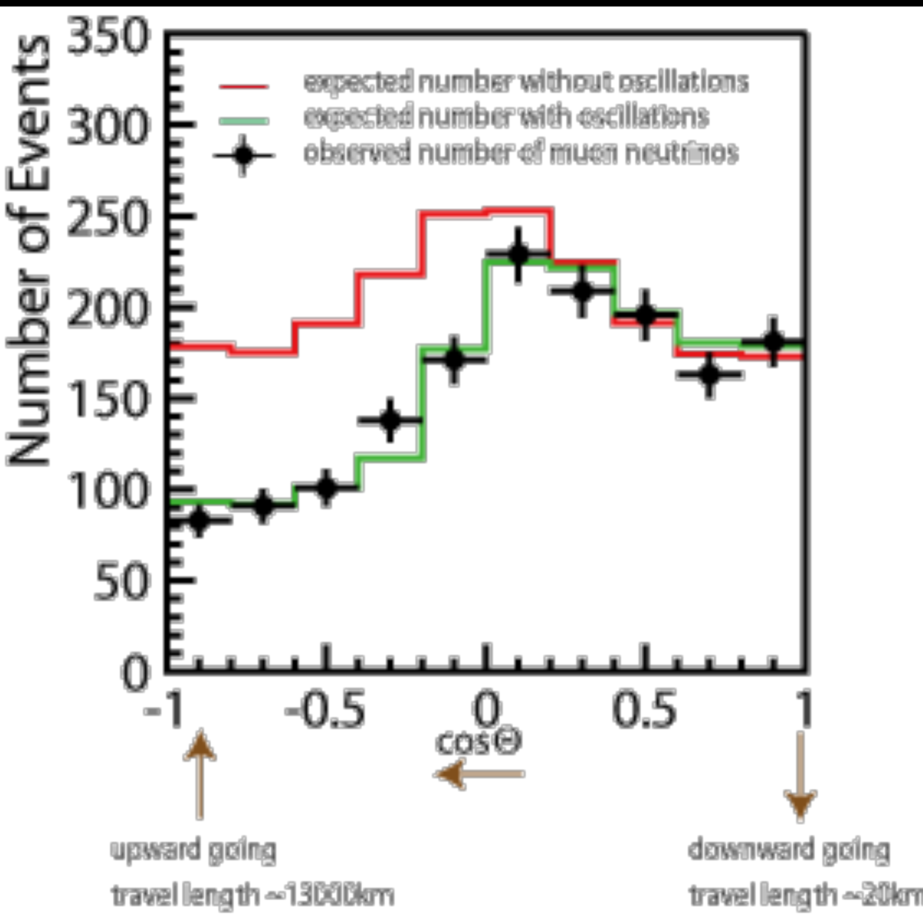
3+2+1 physics parameters

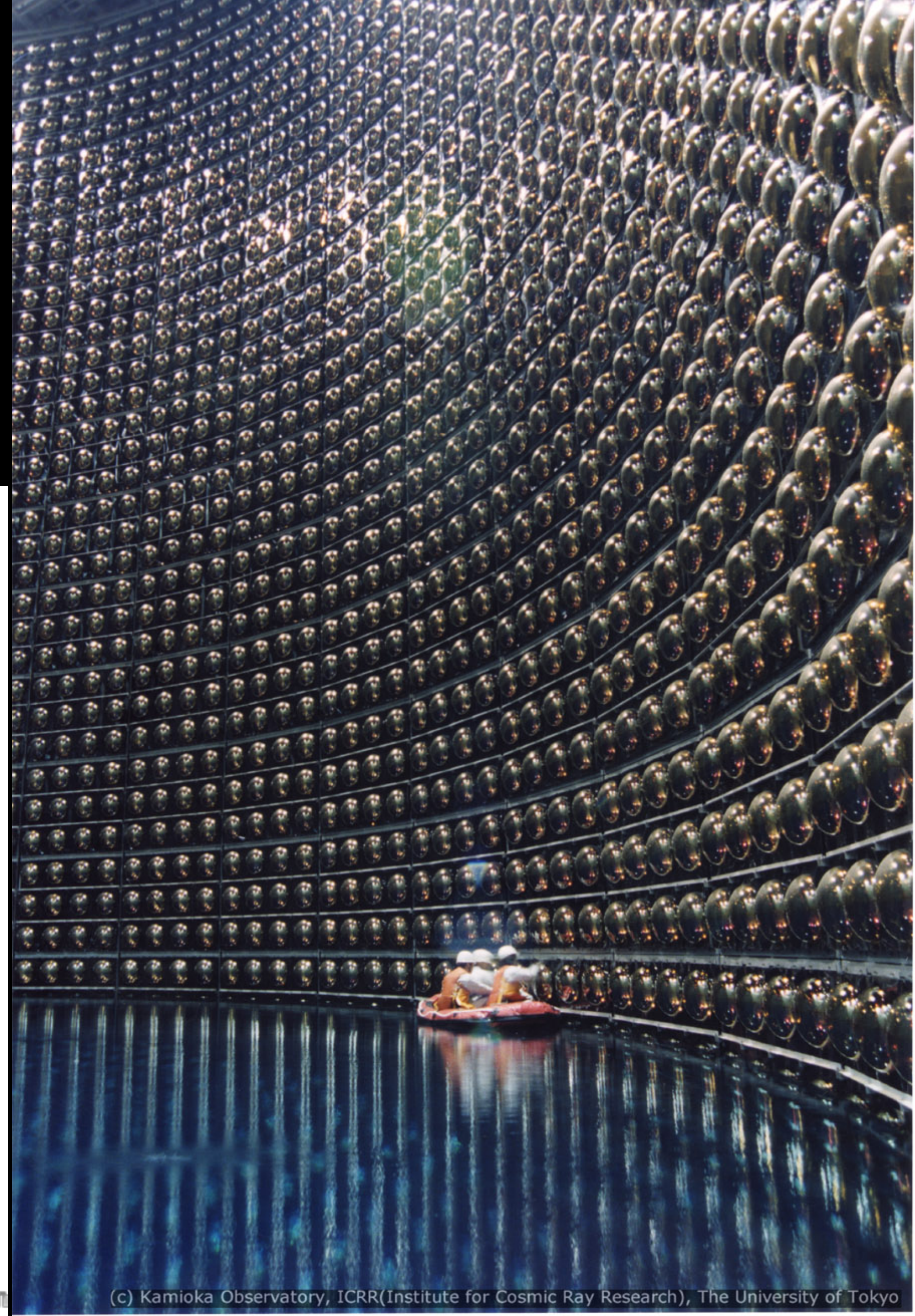
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2(2\theta_{23})\ \sin^2\left(1.27\,\Delta m^2_{32}\, L/E\right)$$



Super Kamiokande

Muon-neutrino disappearance (to tau-neutrinos)

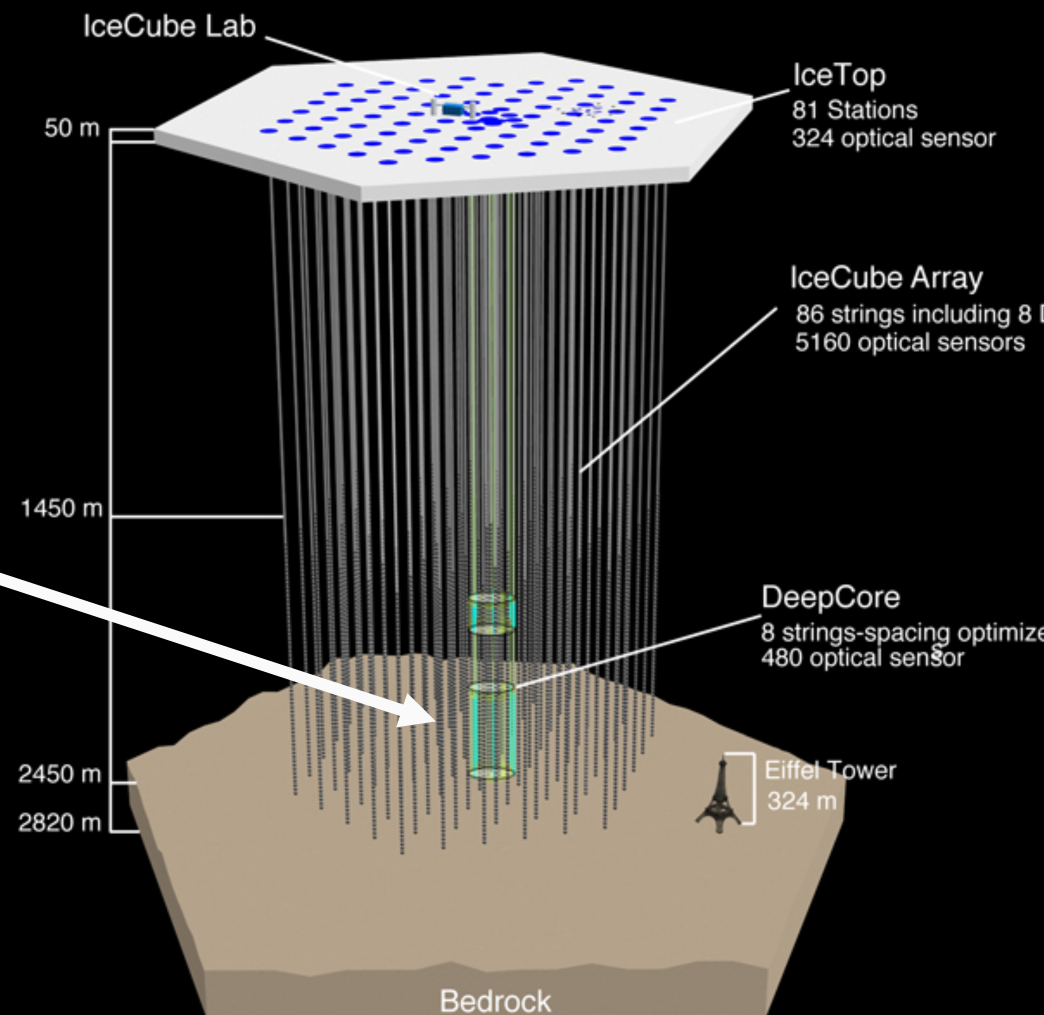


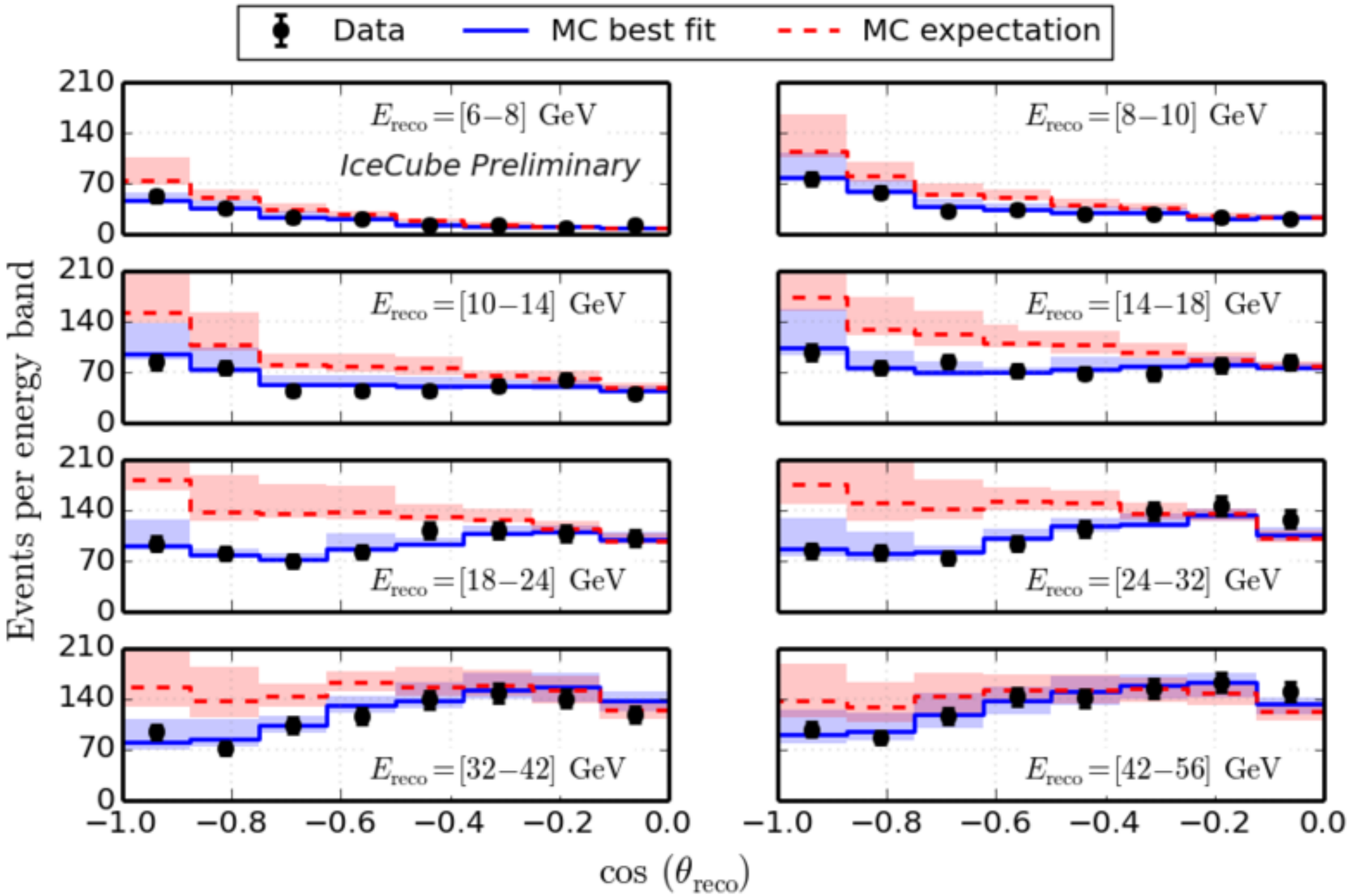


IceCube

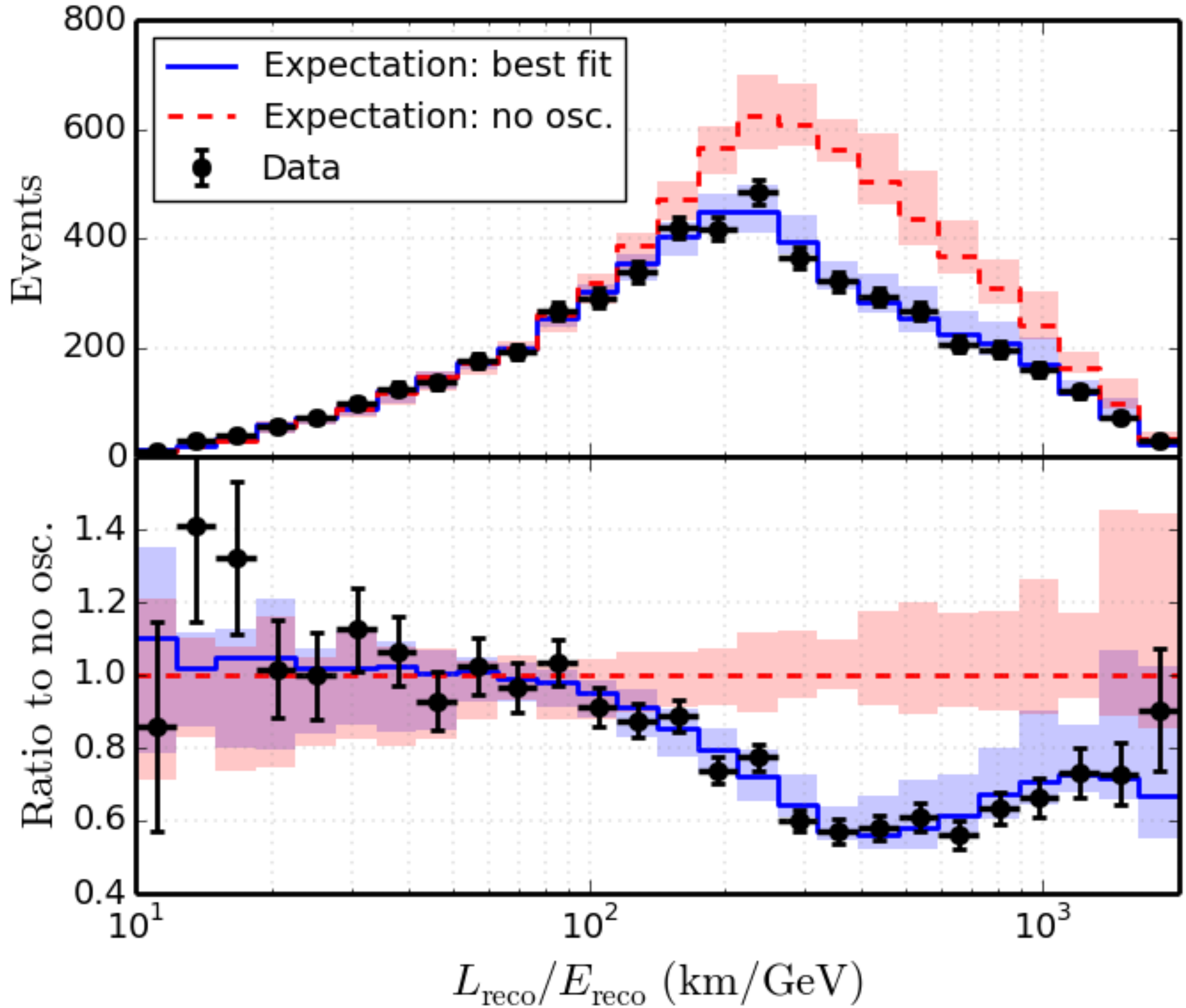
DeepCore:

sensitive to low energy neutrinos

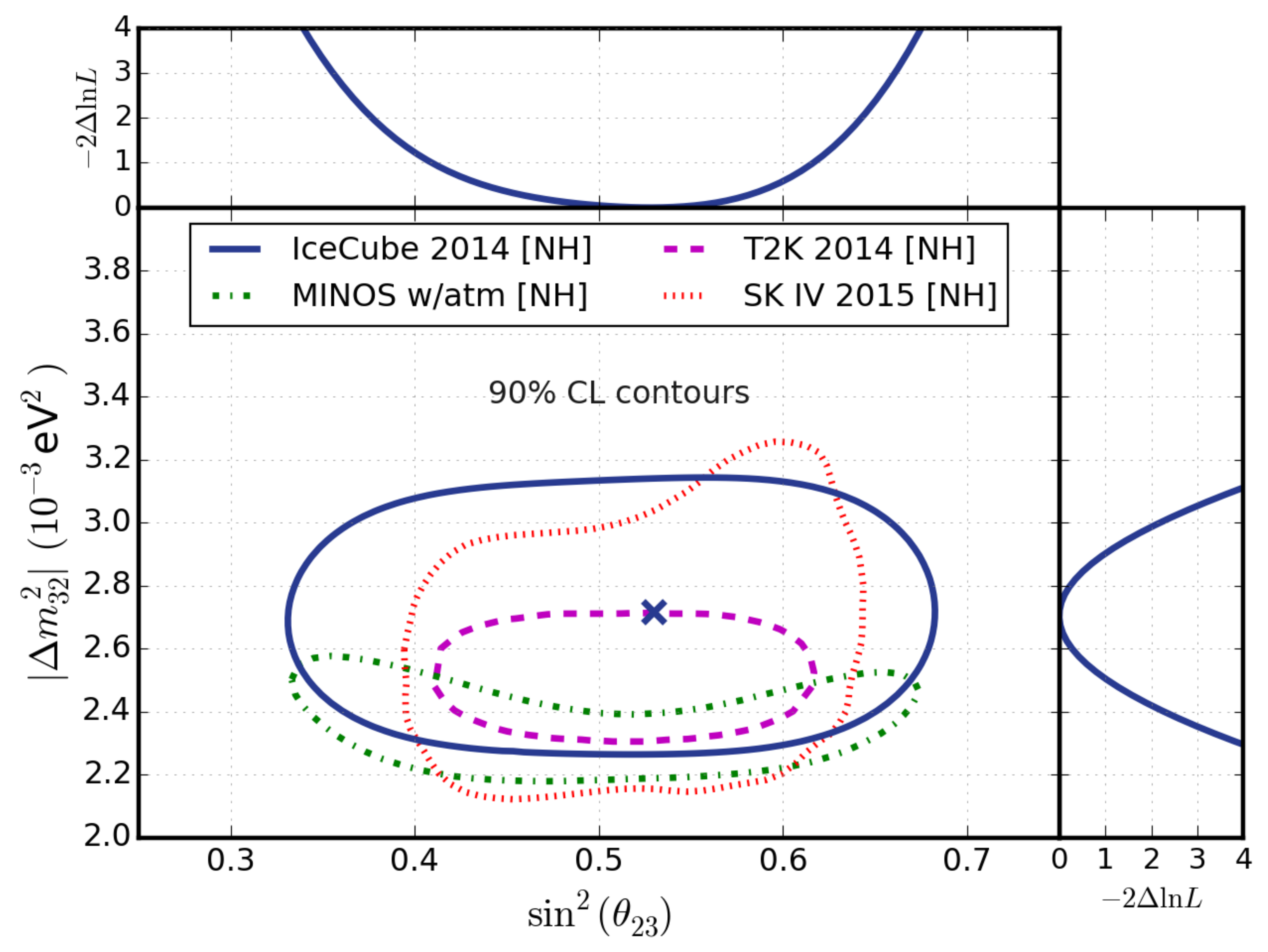




Data
MC best fit
MC expectation
Events per energy band
$E_{reco} = [6-8]$ GeV
IceCube Preliminary
$E_{reco} = [8-10]$ GeV
$E_{reco} = [10-14]$ GeV
$E_{reco} = [14-18]$ GeV
$E_{reco} = [18-24]$ GeV
$E_{reco} = [24-32]$ GeV
$E_{reco} = [32-42]$ GeV
$E_{reco} = [42-56]$ GeV
0
70
140
210
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
$\cos(\theta_{reco})$

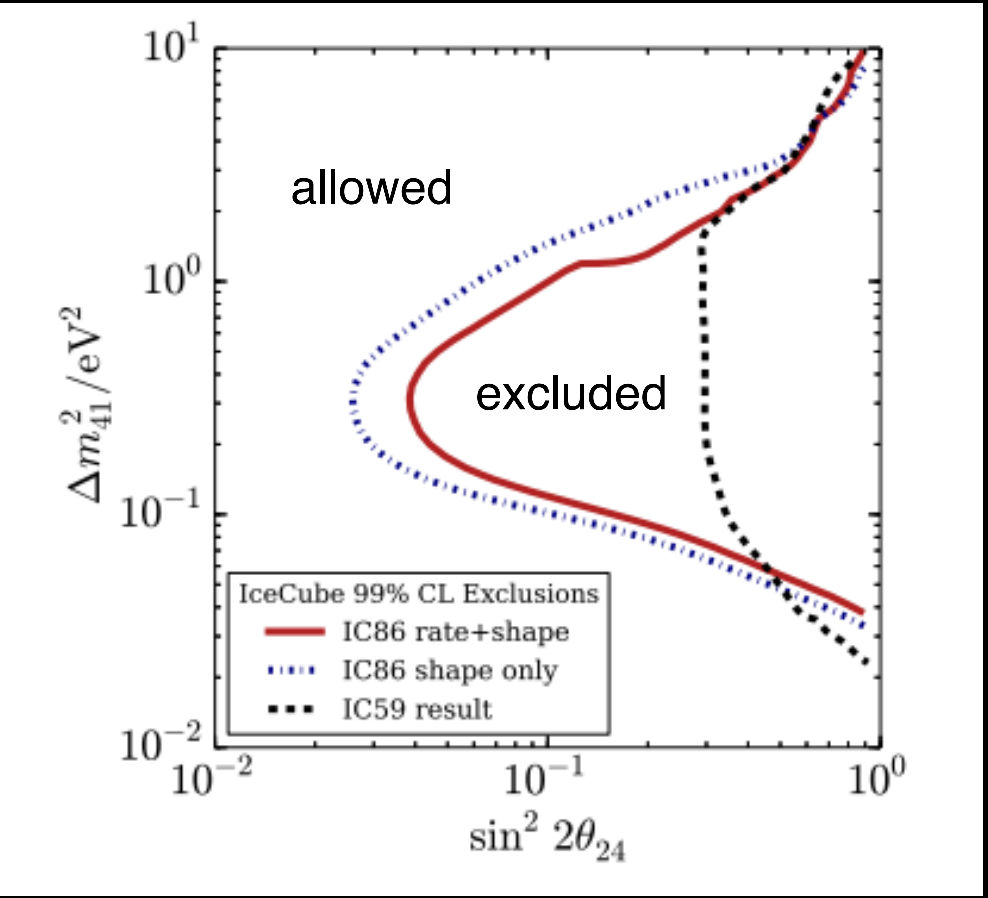


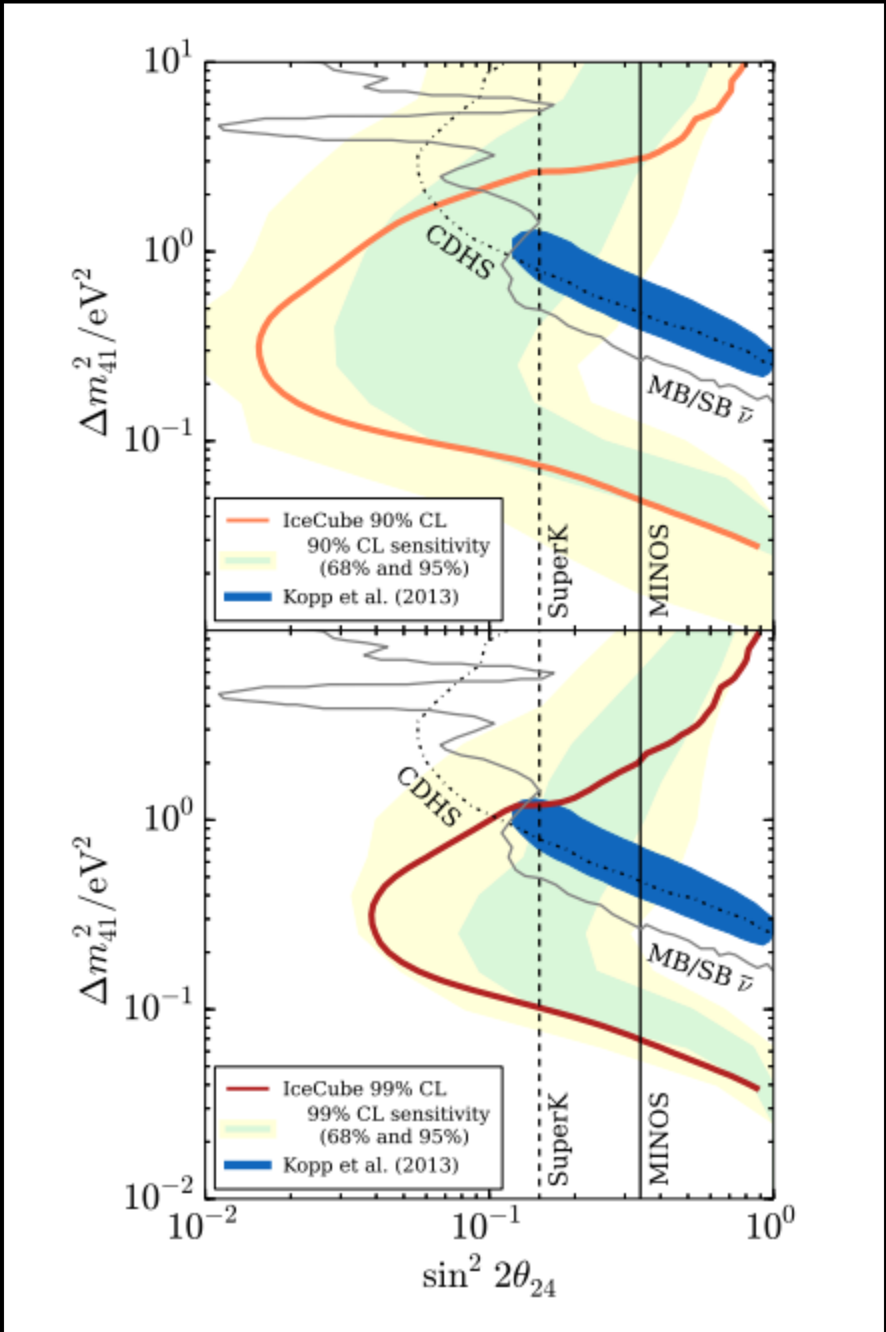
Expectation: best fit
Expectation: no osc.
Data
Events
Ratio to no osc.
$L_{\mathrm{reco}}/E_{\mathrm{reco}}$ (km/GeV)
0
200
400
600
800
0.4
0.6
0.8
1.0
1.2
1.4
10^1
10^2
10^3

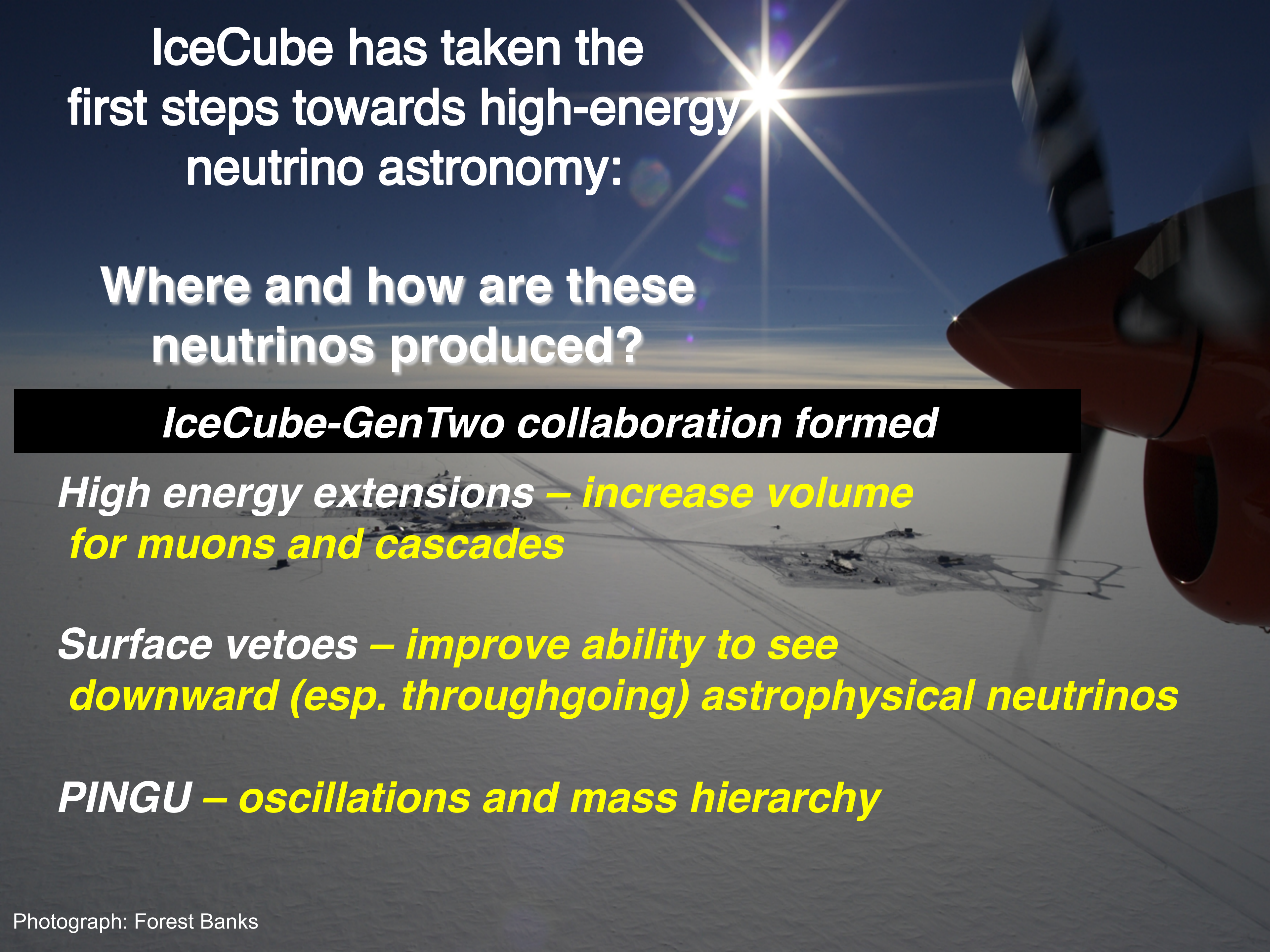


$-2\Delta\ln L$
IceCube 2014 [NH]
T2K 2014 [NH]
MINOS w/atm [NH]
SK IV 2015 [NH]
90% CL contours
$|\Delta m^2_{32}|\ (10^{-3}\mathrm{eV}^2)$
$\sin^2(\theta_{23})$
$-2\Delta\ln L$

Sterile neutrinos :
look for disappearance of atmospheric neutrinos (beyond standard oscillation)







Photograph: Forest Banks

IceCube has taken the first steps towards high-energy neutrino astronomy:

Where and how are these neutrinos produced?

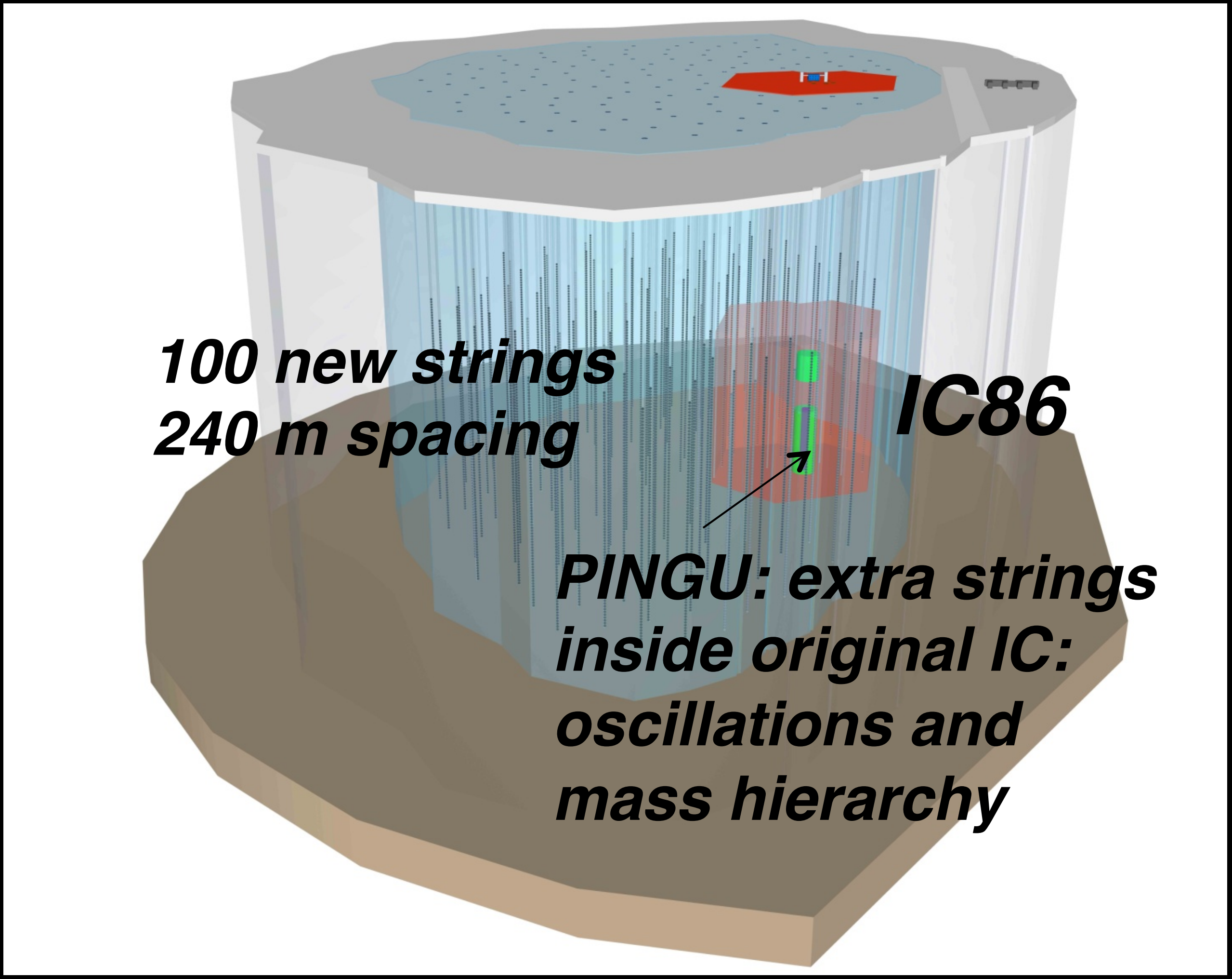
IceCube-GenTwo collaboration formed

High energy extensions – increase volume for muons and cascades

Surface vetoes – improve ability to see downward (esp. throughgoing) astrophysical neutrinos

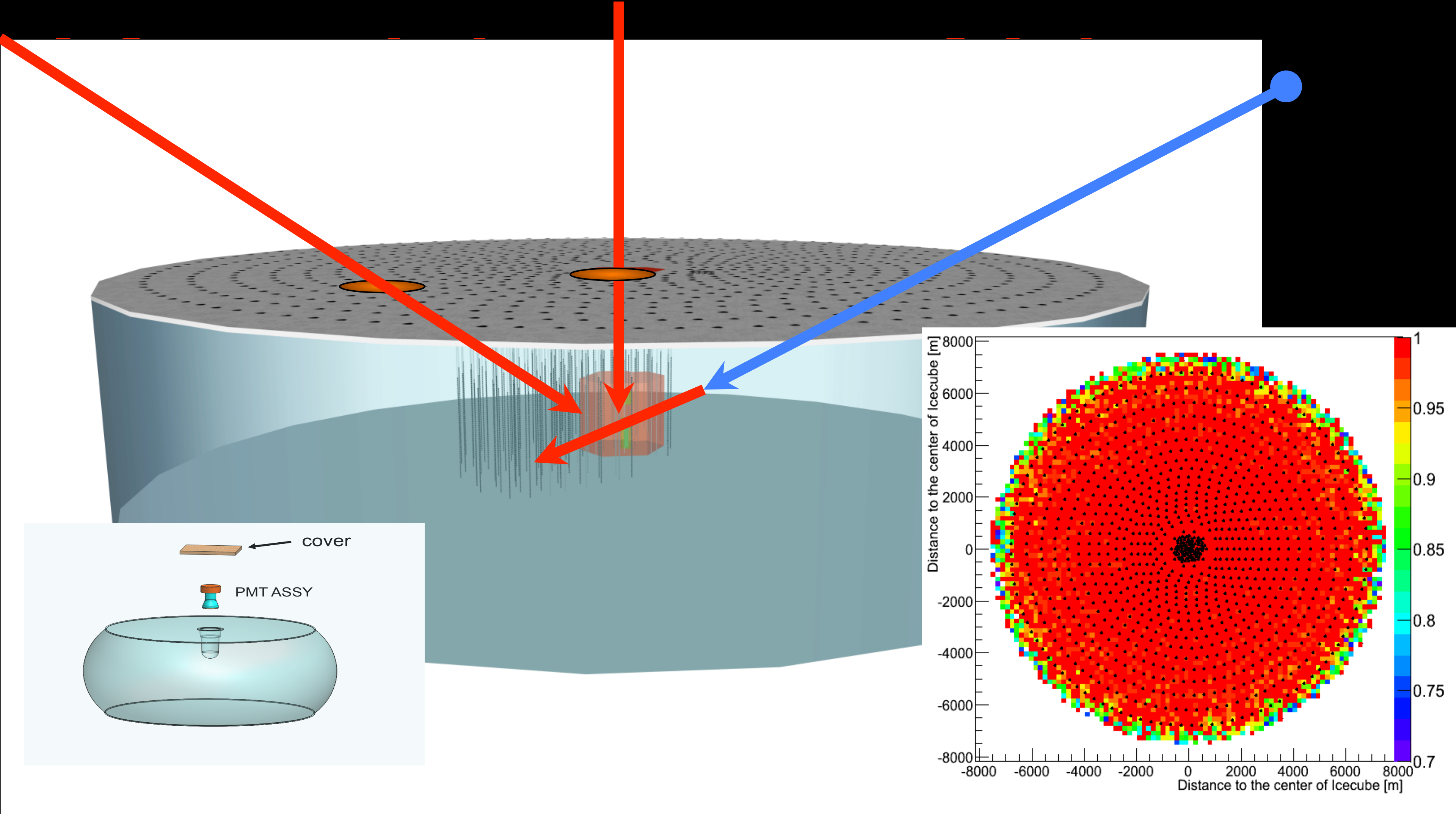
PINGU – oscillations and mass hierarchy

High energy extensions – increase volume for muons and cascades with more strings

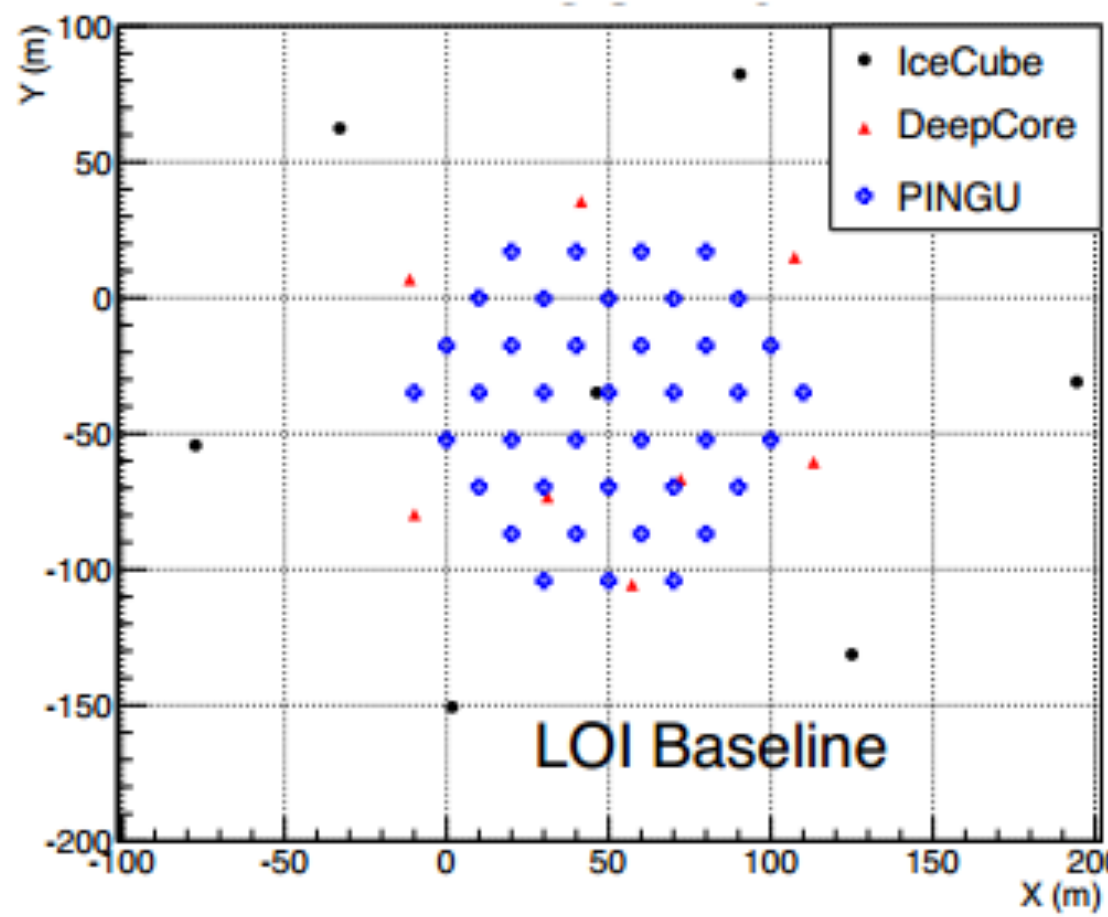


1 PeV (cosmic primary) veto: reject most atmospheric muon AND neutrino background above 100 TeV.

An efficient surface veto, 100 km^2, for 3–5 sr background free cosmic muon neutrino and some shower detection

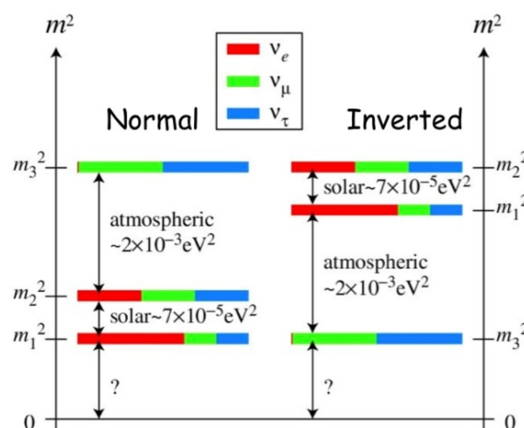


PRECISION ICECUBE NEXT GENERATION UPGRADE



Measure the neutrino mass hierarchy:

subtle change to energy vs arrival direction of atmospheric neutrinos



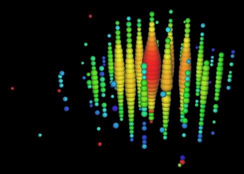
40 strings

96 DOMs per string

3m spacing

IceCube has taken the first steps towards high-energy neutrino astronomy:

- diffuse flux: $\Phi = 10^{-8}\ E^{-2}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$ (1:1:1 flavour)
- contained vertex (7σ), upgoing muons ($>5\sigma$)
- atmospheric prompt origin strongly rejected
- lack of correlation with galactic plane, and events at high galactic latitudes may suggest extra-galactic origin
- many theoretical speculations and attempts to correlate with sources have been proposed



proposal for a next generation detector
- increased in-ice volume
- enhanced surface veto
- PINGU