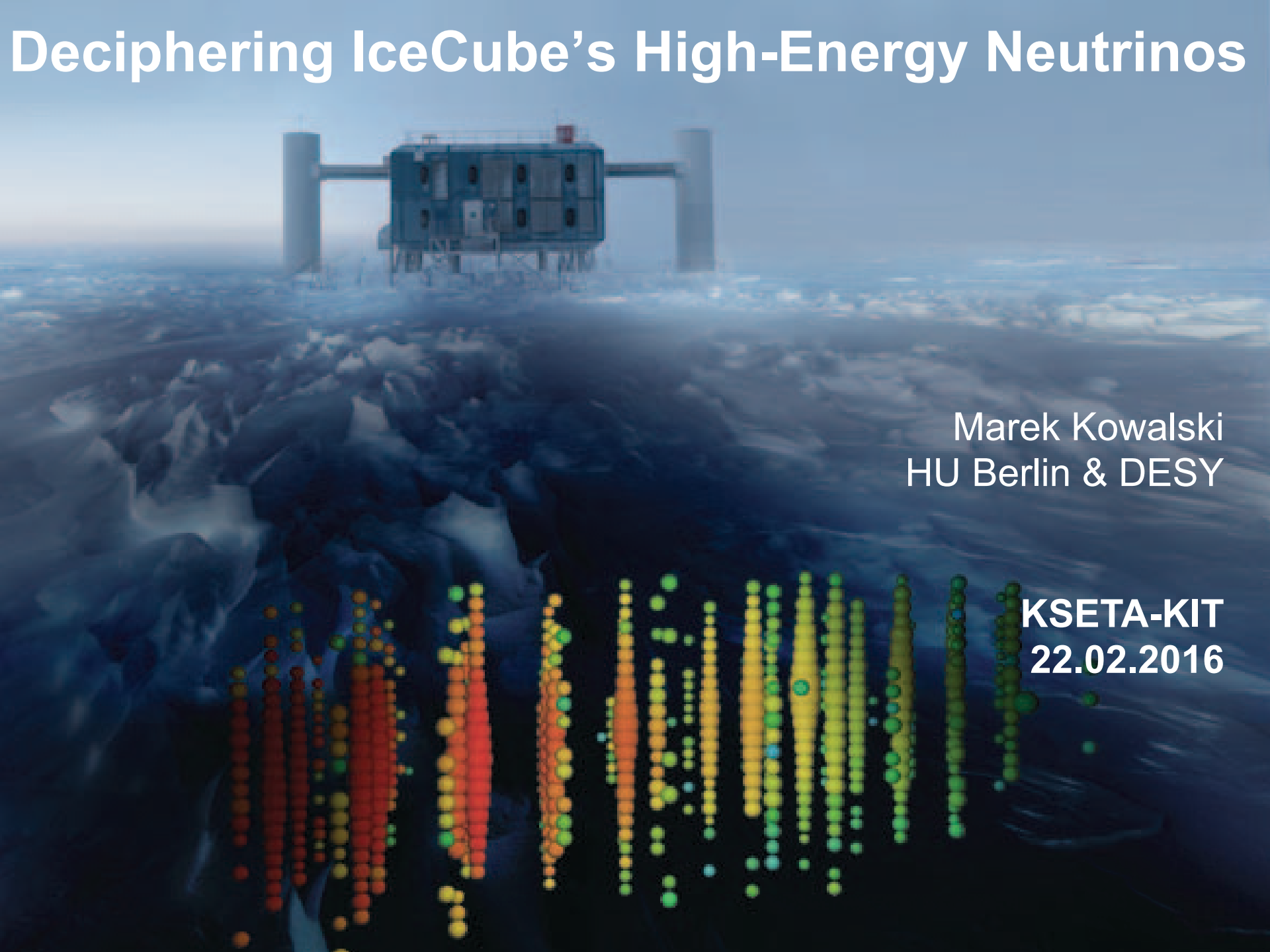
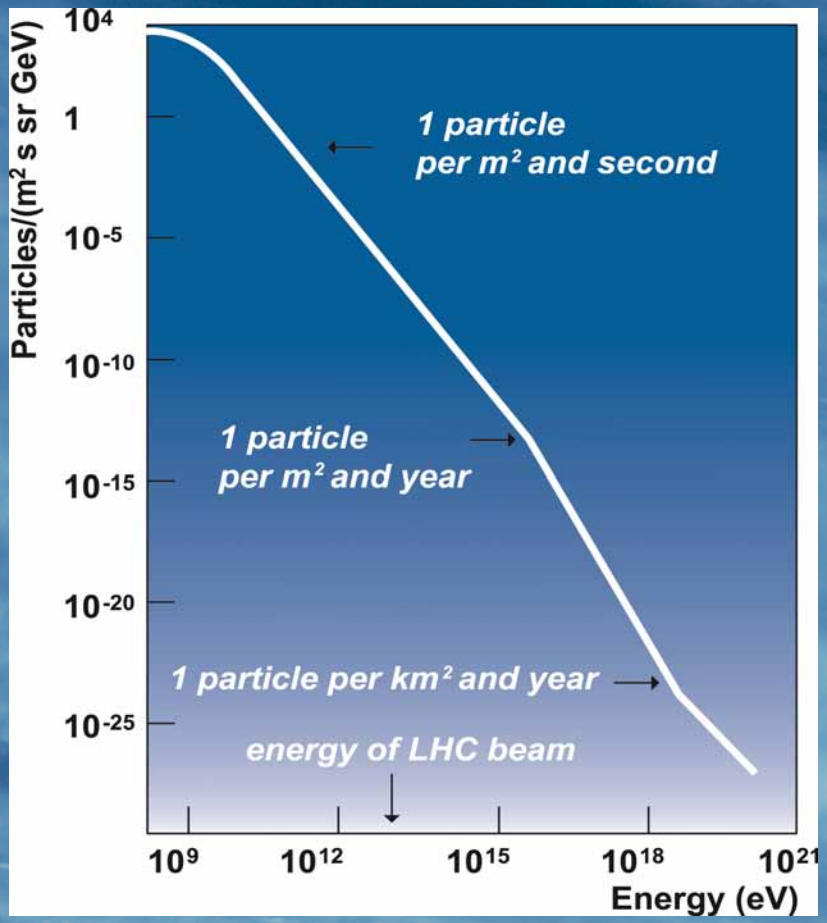
Deciphering IceCube's High-Energy Neutrinos



Marek Kowalski
HU Berlin & DESY

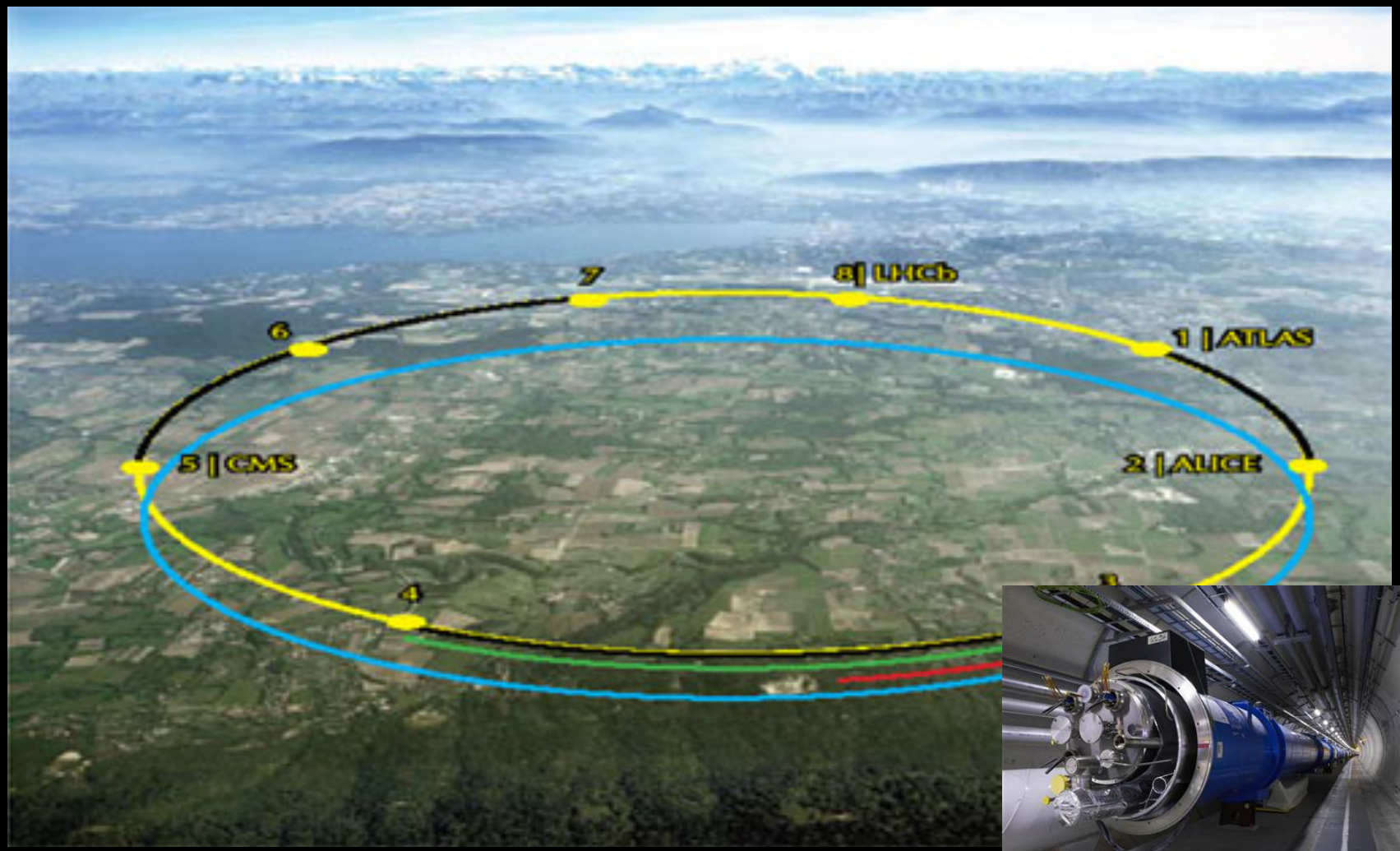
KSETA-KIT
22.02.2016

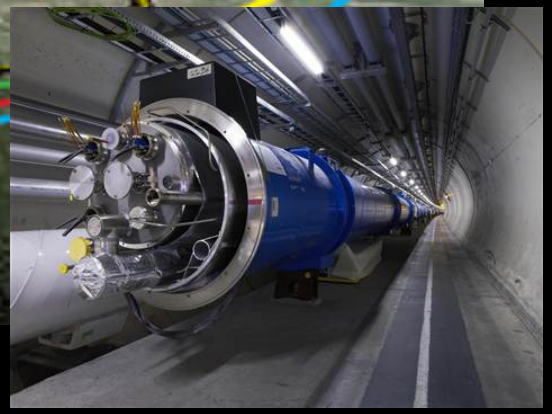


Cosmic Rays observed beyond 10^{20} eV

Large Hadron Collider:

$E_{max} = c \cdot e \cdot B \cdot R = 7 \times 10^{12}$ eV





Potential galactic sources of cosmic rays

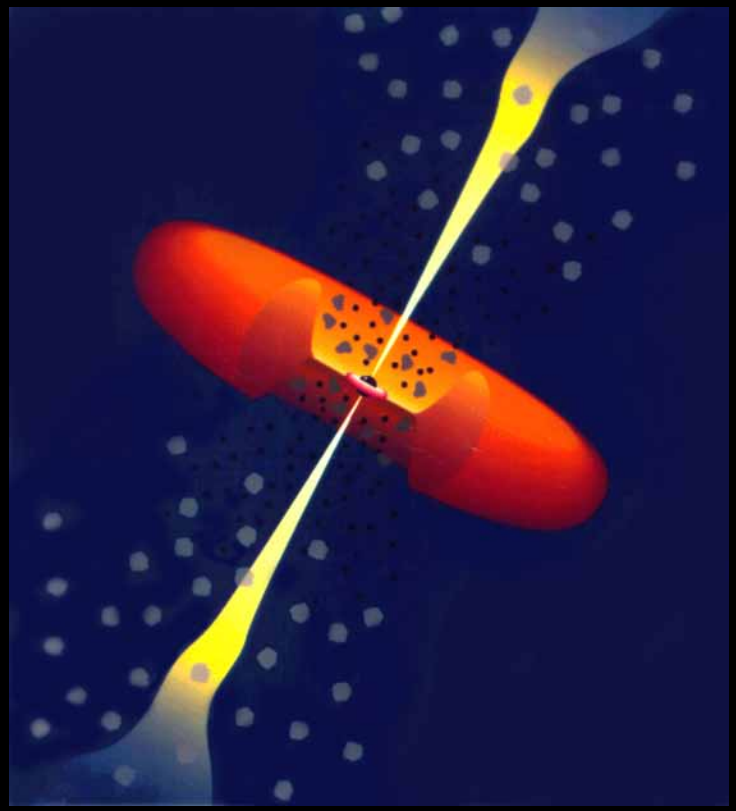
$E_{max} = c \cdot e \cdot B \cdot R \sim 10^{15}$ eV

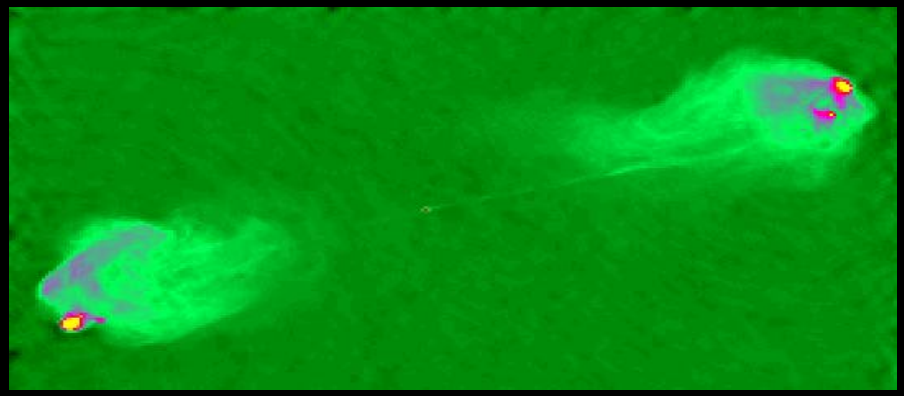
Supernova-Remnants

Microquasars
Pulsars
...

Potential extra-galactic sources of cosmic rays

$E_{max} = c \cdot e \cdot B \cdot R \sim 10^{20}$ eV



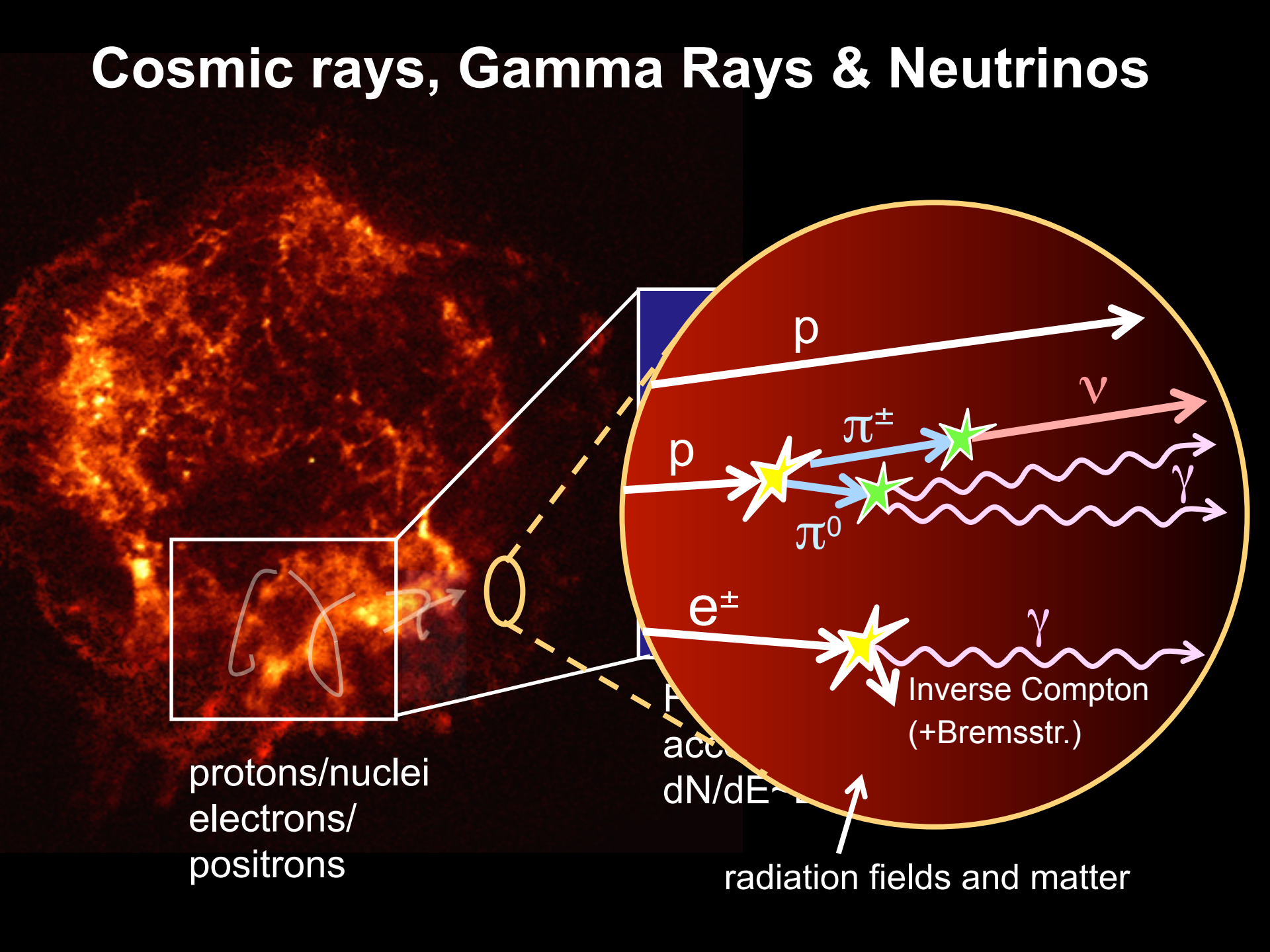


Active Galactic Nuclei

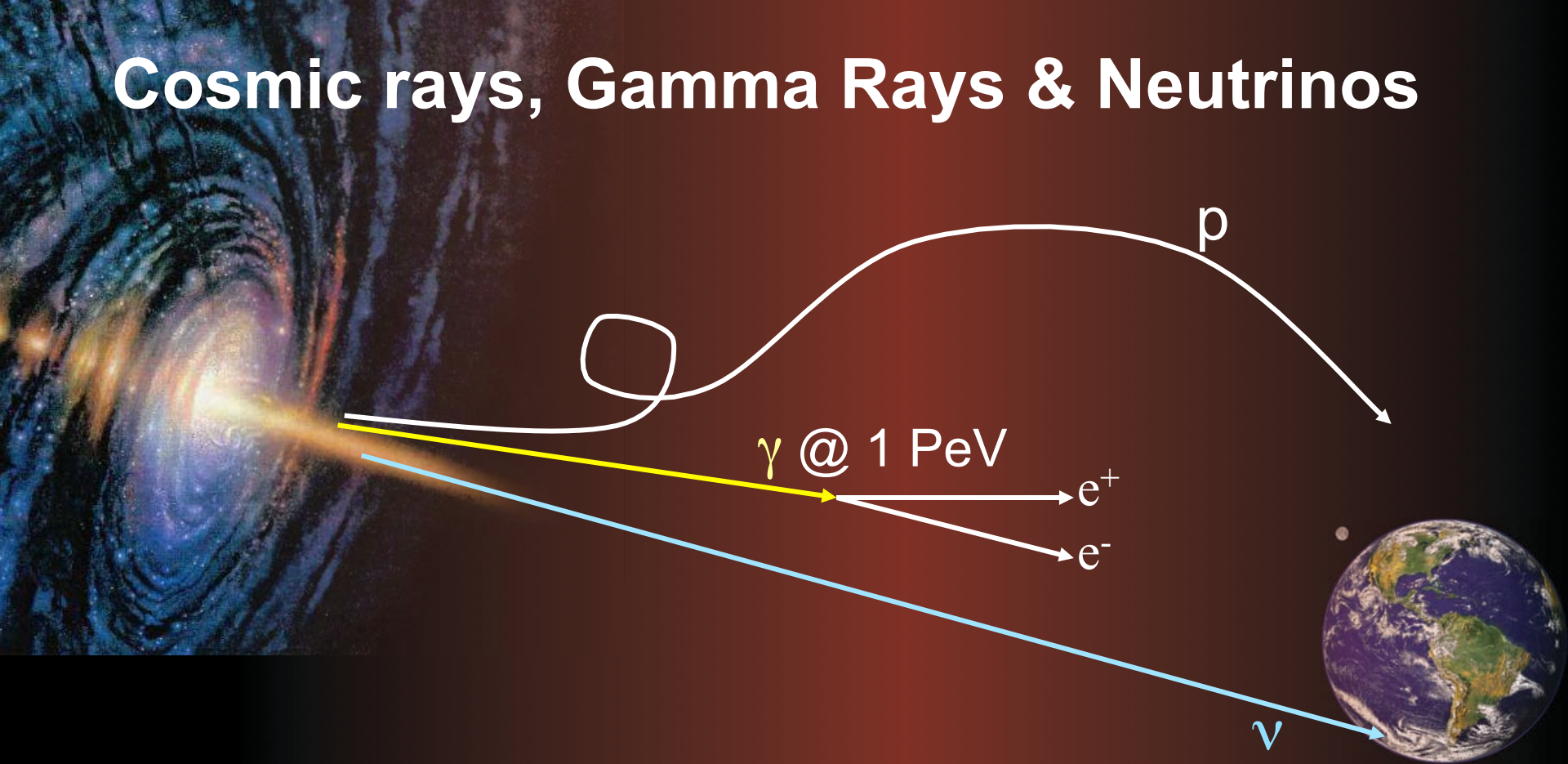
Gamma Ray Bursts

...

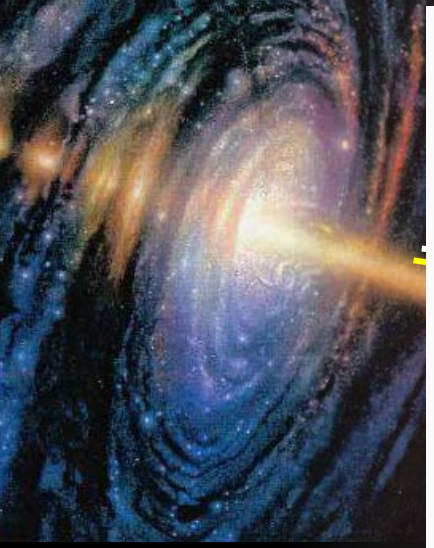
Cosmic rays, Gamma Rays & Neutrinos

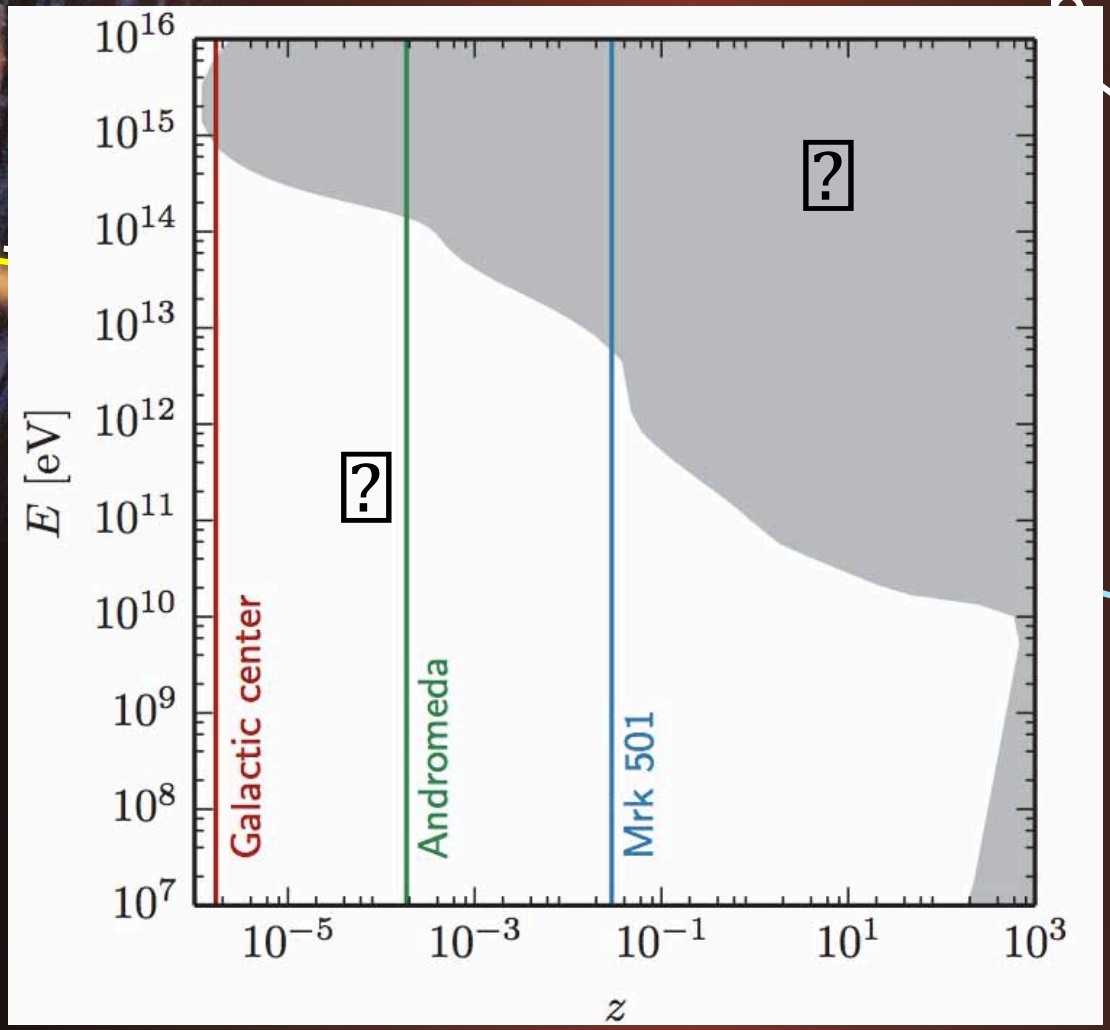


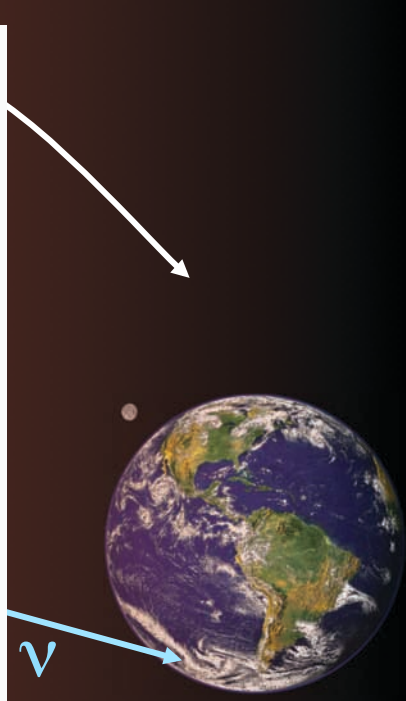
Cosmic rays, Gamma Rays & Neutrinos



Cosmic rays, Gamma Rays & Neutrinos







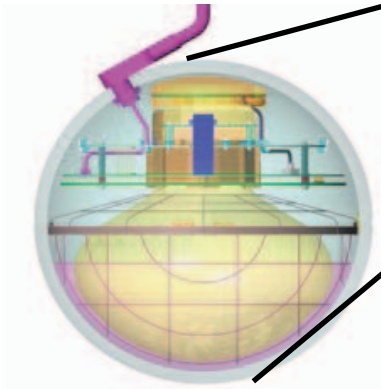
The IceCube Neutrino Observatory

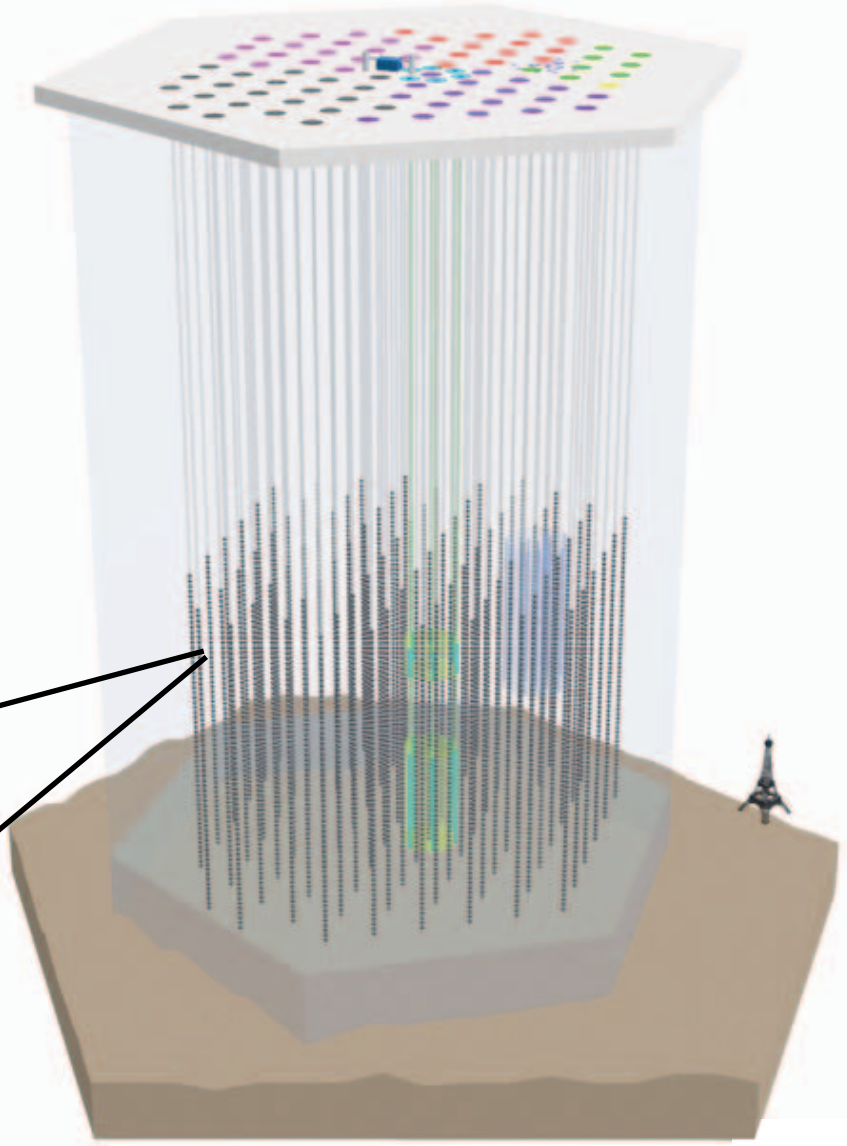
IceCube

- 86 Strings, 5360 DOMs
- Completed in 2011
- $E_{thresh} \sim 100$ GeV

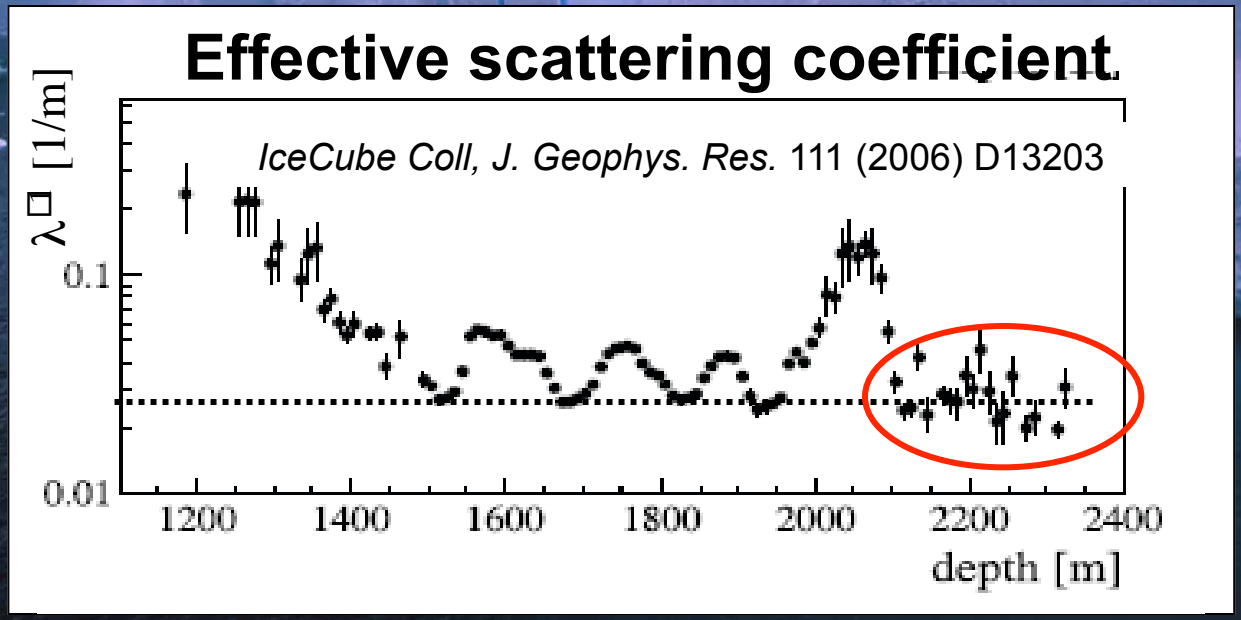
➔ **astrophysical neutrinos** cosmic ray physics, dark matter, neutrino physics,…

digital optical module (DOM) housing 10 inch PMT





Optical properties of the detection medium

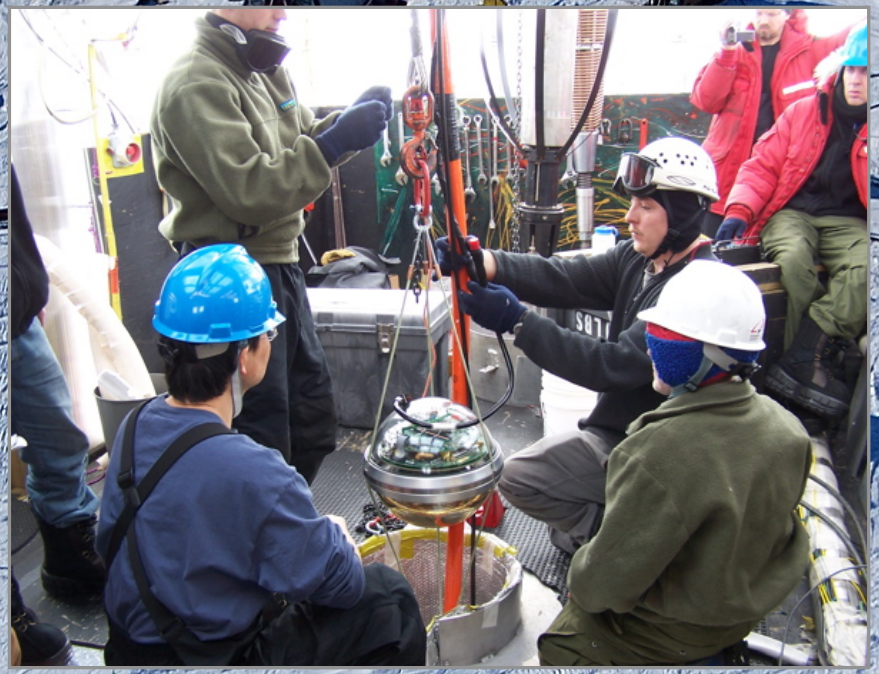


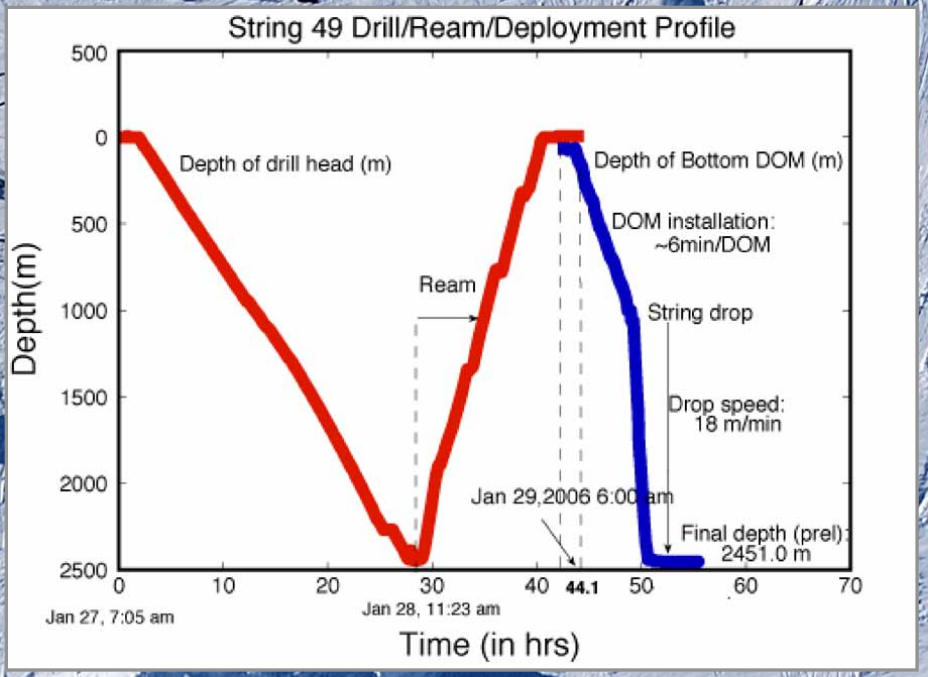
The IceCube Detector

Installation

The IceCube Detector

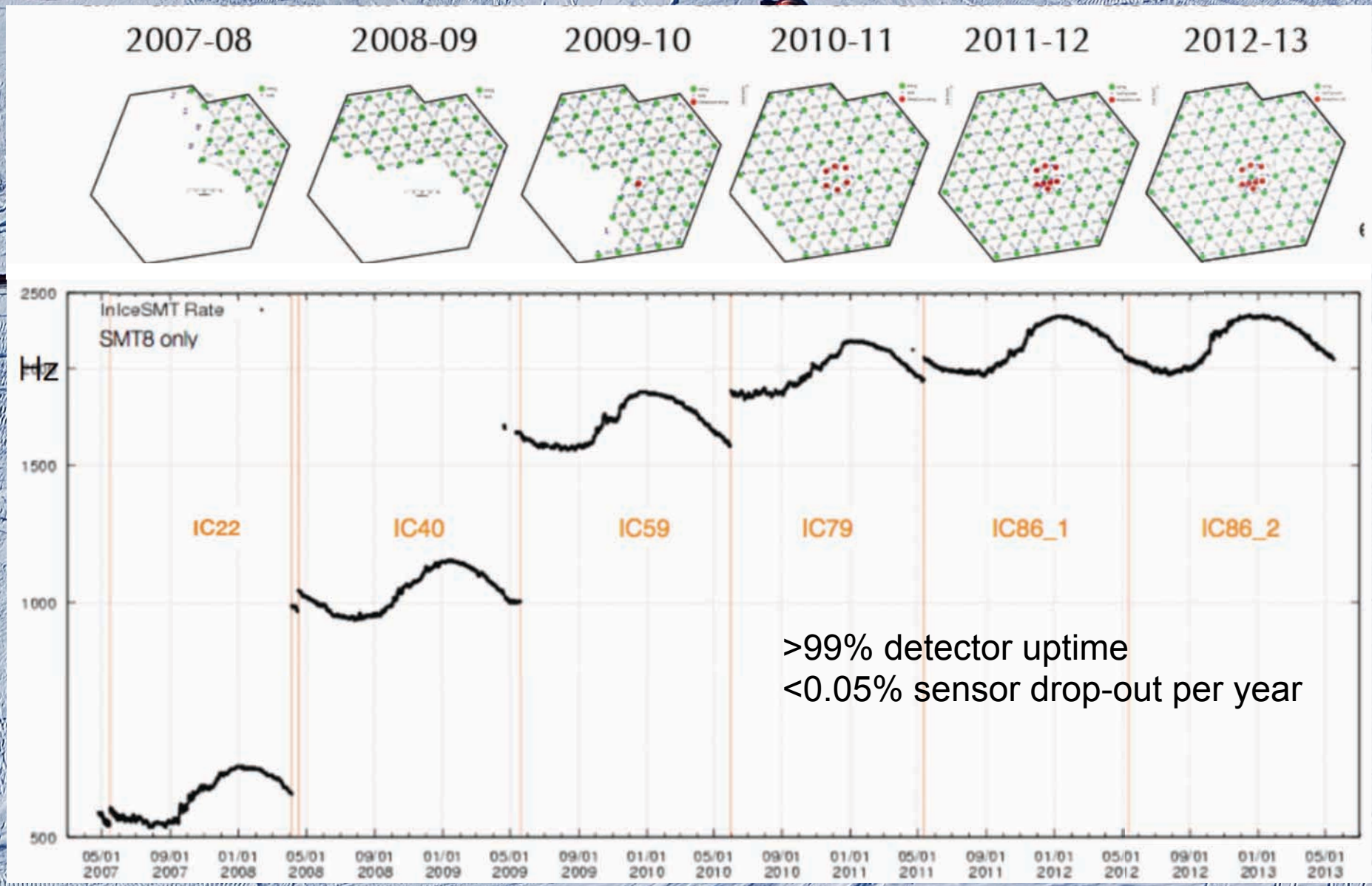
Installation





The IceCube Detector

Installation

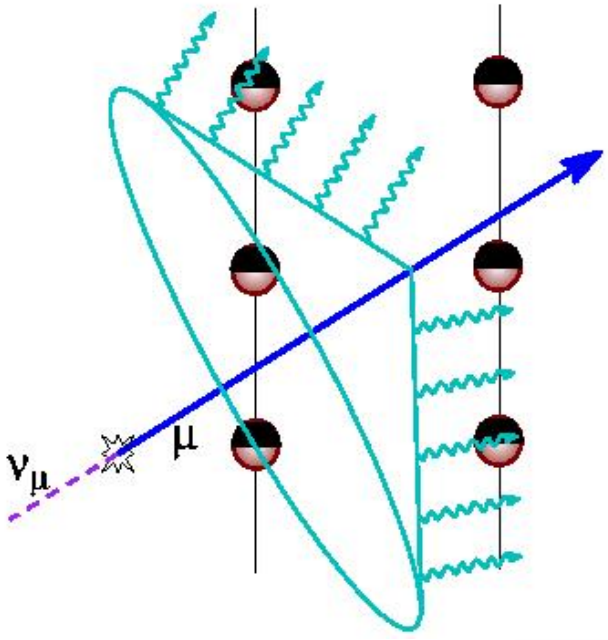


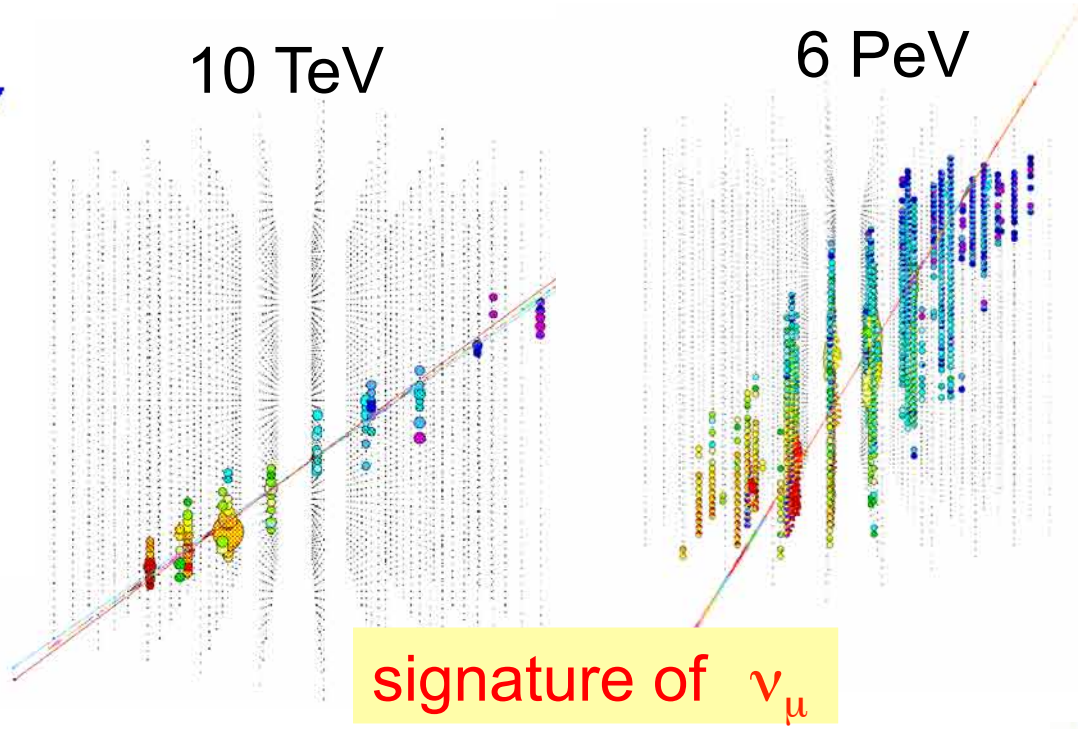
>99% detector uptime
<0.05% sensor drop-out per year


icecube.wisc.edu
Decades ago the aspiration to build a kilometer-scale neutrino detector at the South Pole seemed farfetched. Now, thanks to the support of our collaboration, we are celebrating the five-year anniversary of this incredible scientific achievement. We look forward to our continued relationship and celebrating future discoveries with you!
Marek Kowalski
DESY Zeuthen
Platanenallee 6
D 15738 Zeuthen
Germany
South Pole, Antarctica
JAN 17 2016
Dear Marek,
warmest greetings from the bottom of the world!
ICECUBE
DETECTOR COMPLETION
5years
IceCube Detector Completion

Neutrino signatures

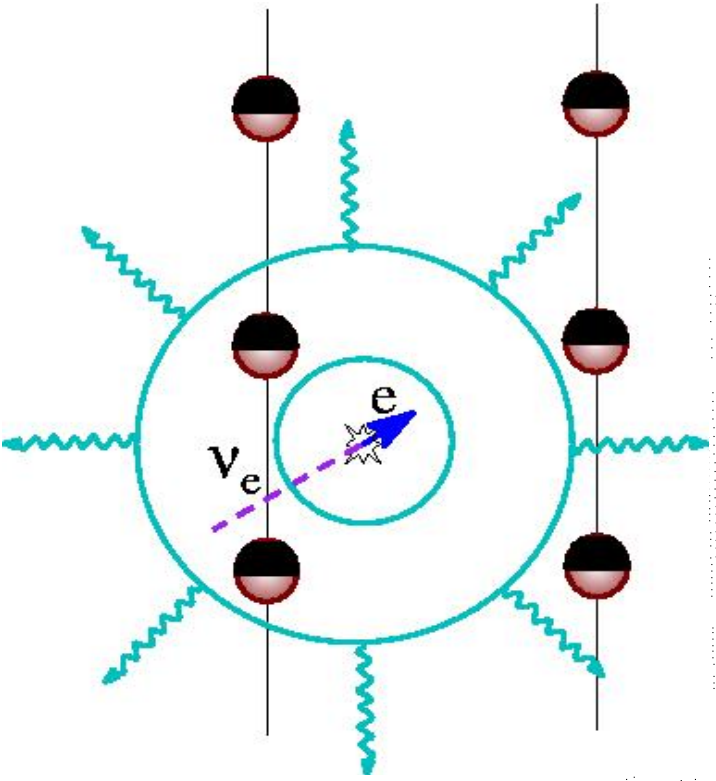
Muon-tracks
+ good pointing (<1 degree)
+ large event rates due long muon range





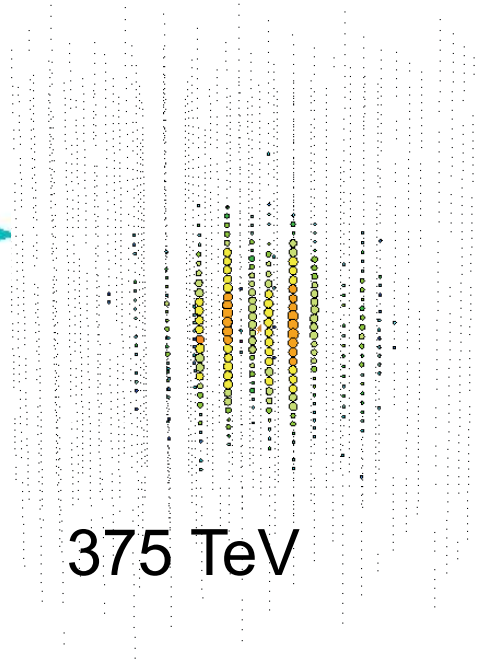
signature of ν_μ

Neutrino signatures

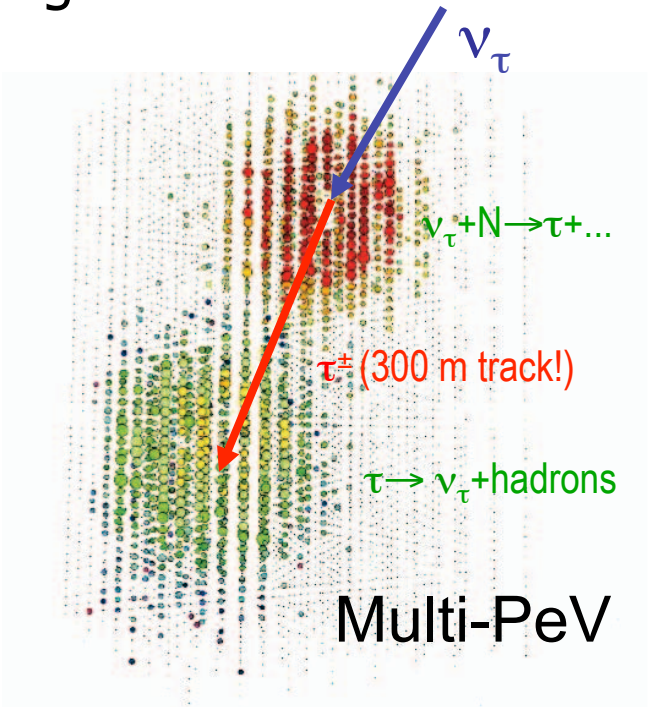


Particle shower (cascade)

+ $\nu_e, \nu_\tau, (\nu_\mu)$
+ good energy resolution
+ little background



375 TeV

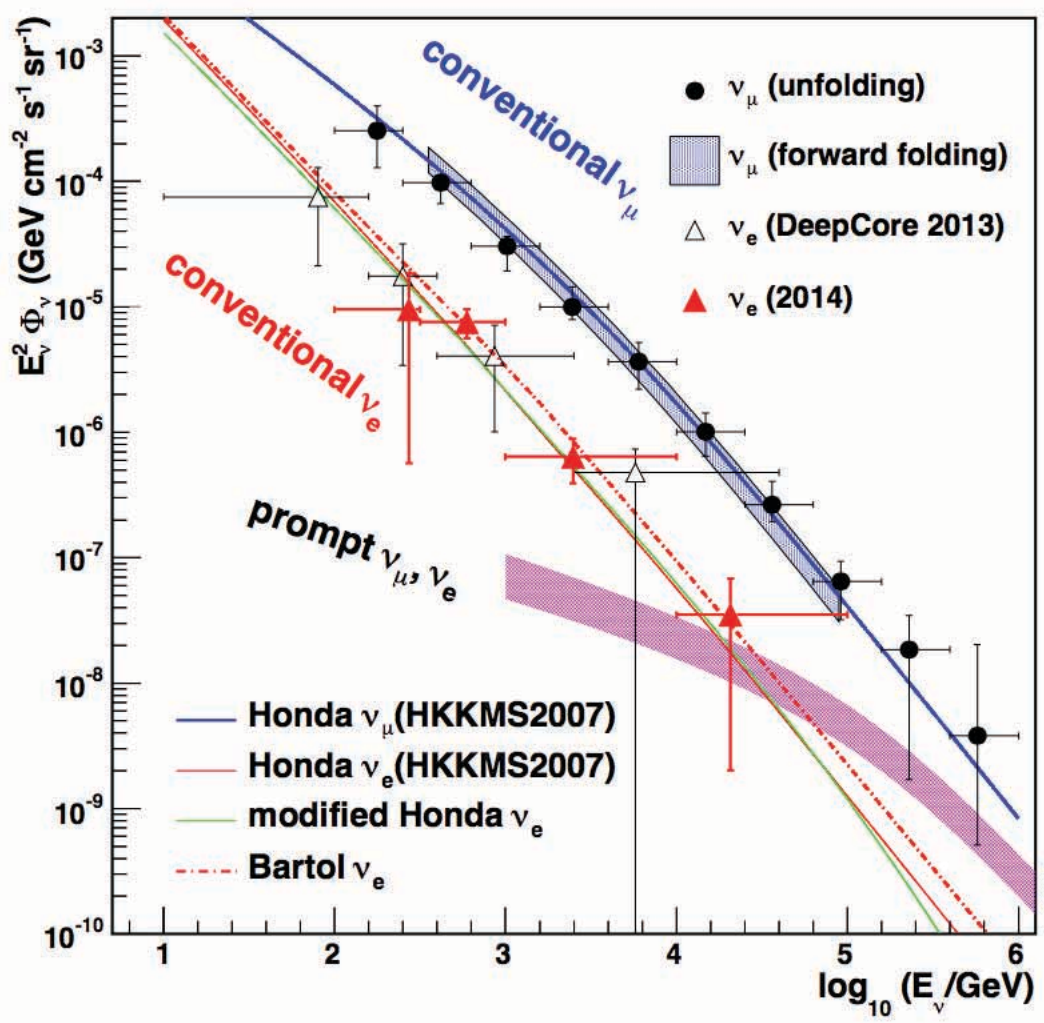


Multi-PeV

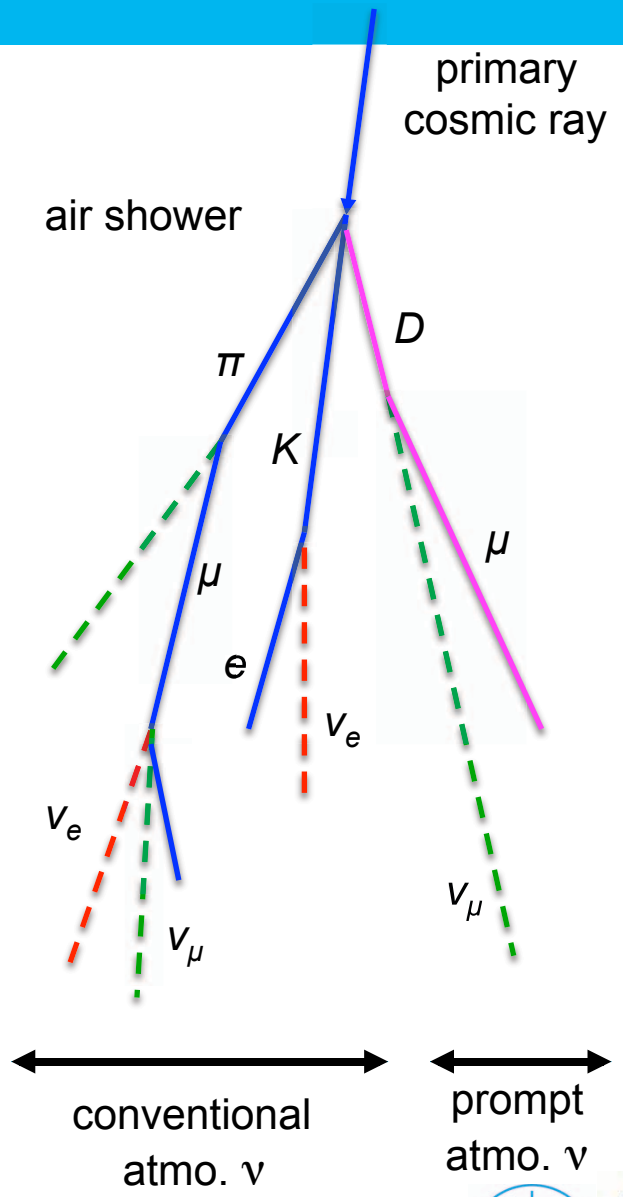
signature of ν_e

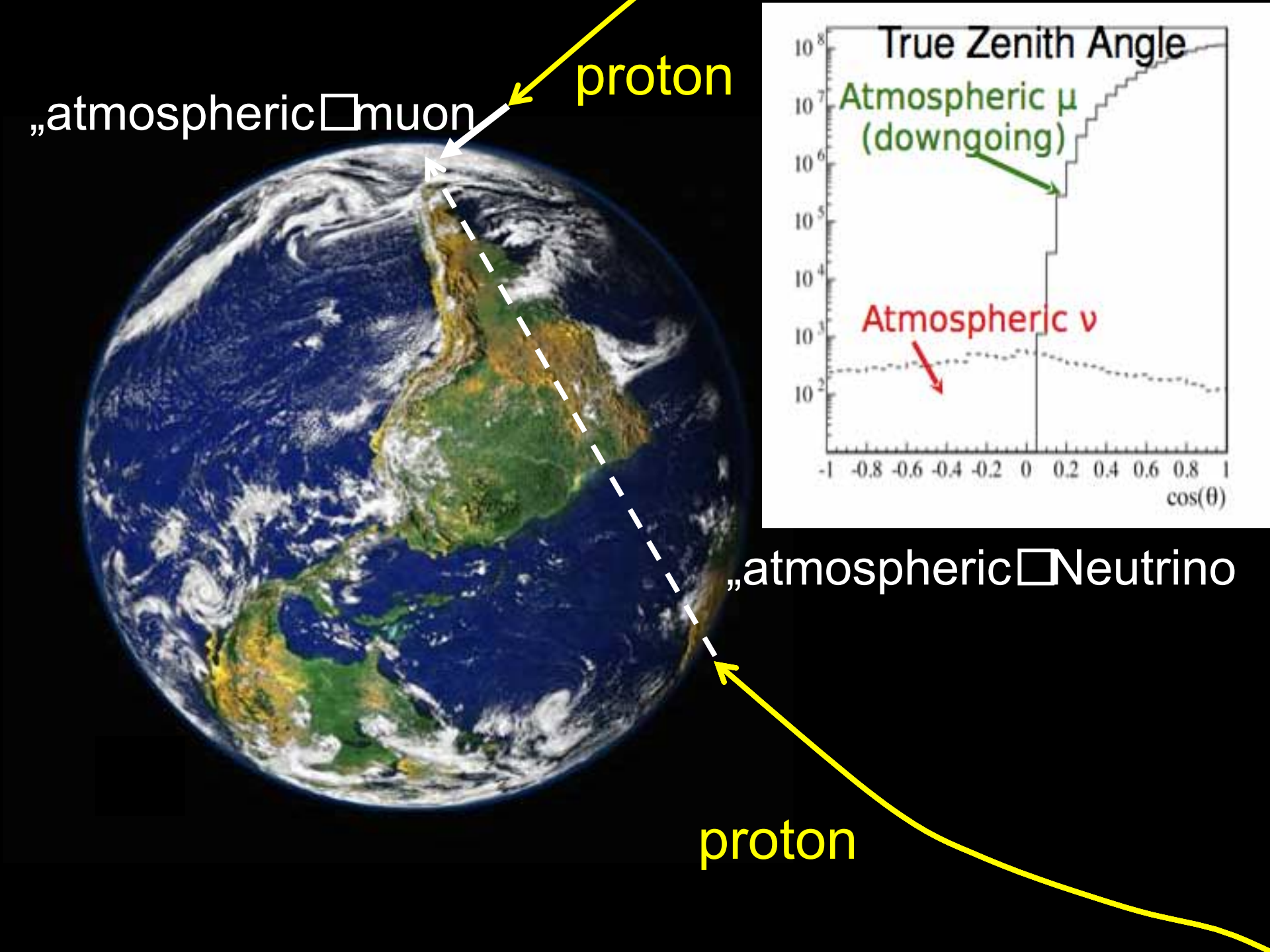
signature of ν_τ

The Backgrounds: Atmospheric Neutrinos & Muons



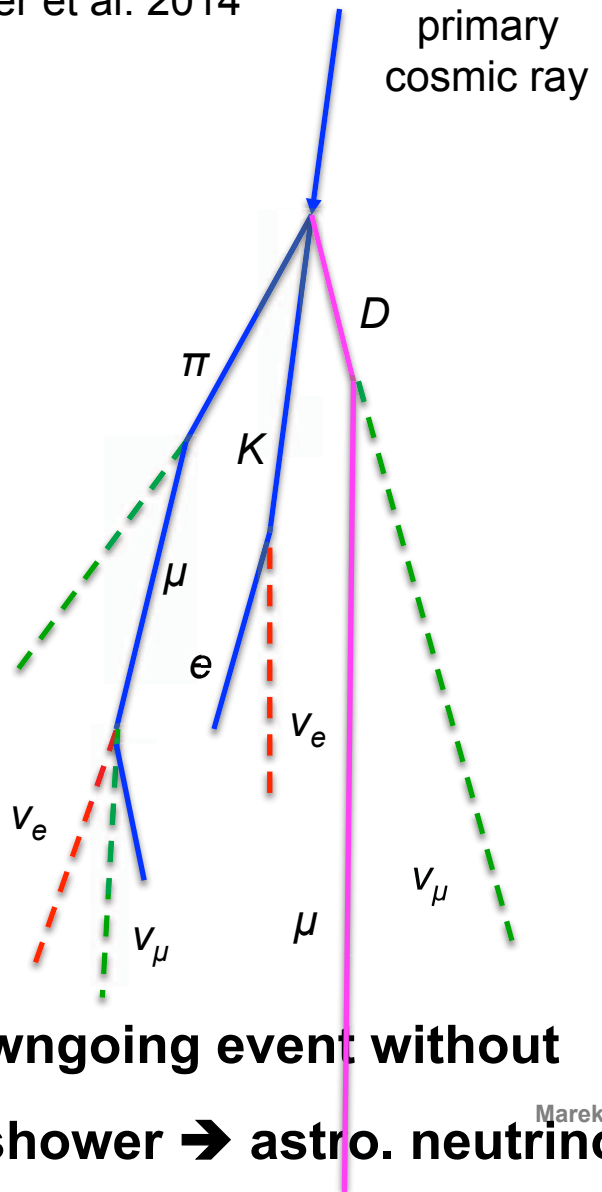
PRD2015



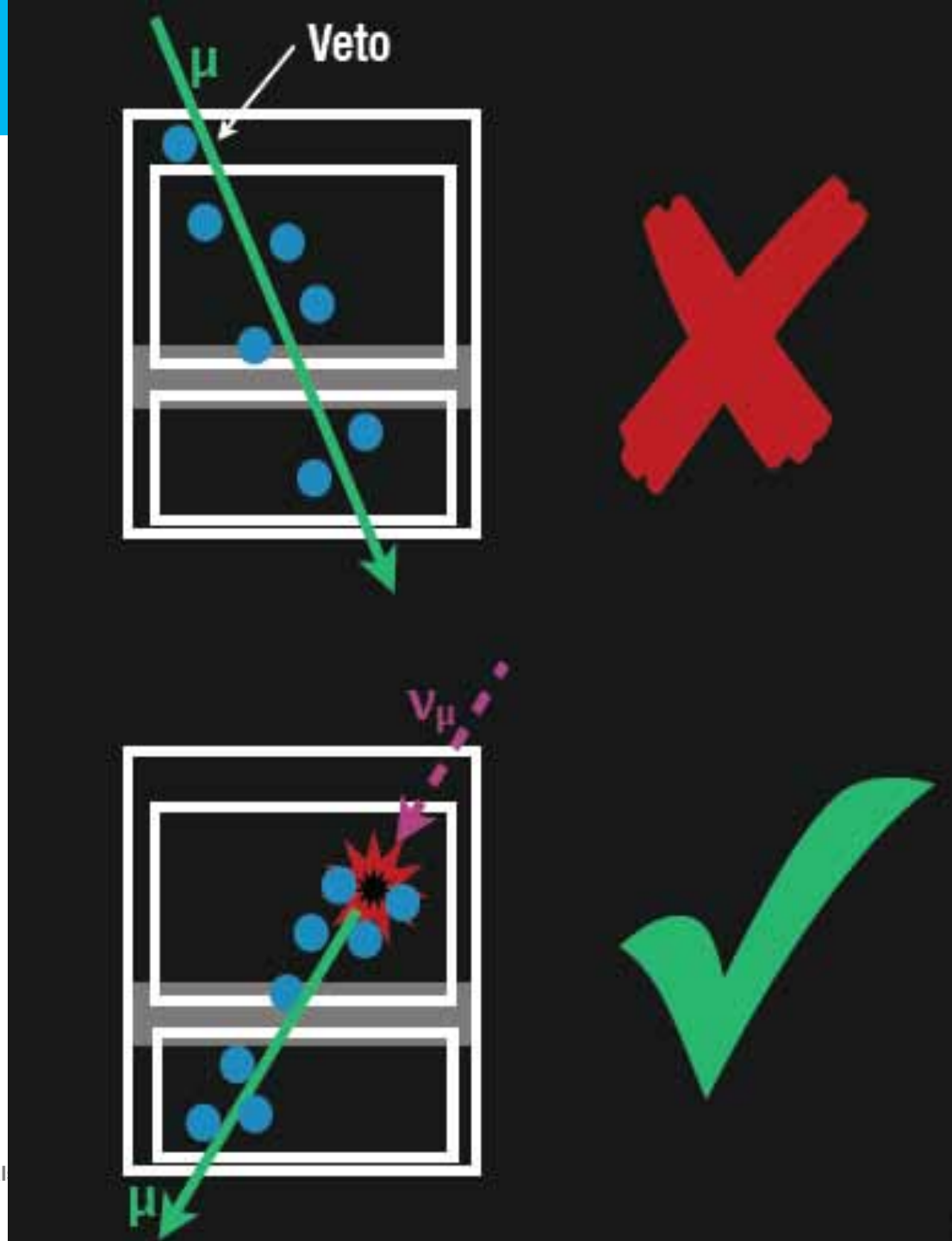

„atmospheric muon“
proton
True Zenith Angle
Atmospheric μ
(downgoing)
Atmospheric ν
10^8
10^7
10^6
10^5
10^4
10^3
10^2
-1 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1
cos(θ)
„atmospheric Neutrino“
proton

Vetoing atmospheric muons and neutrinos

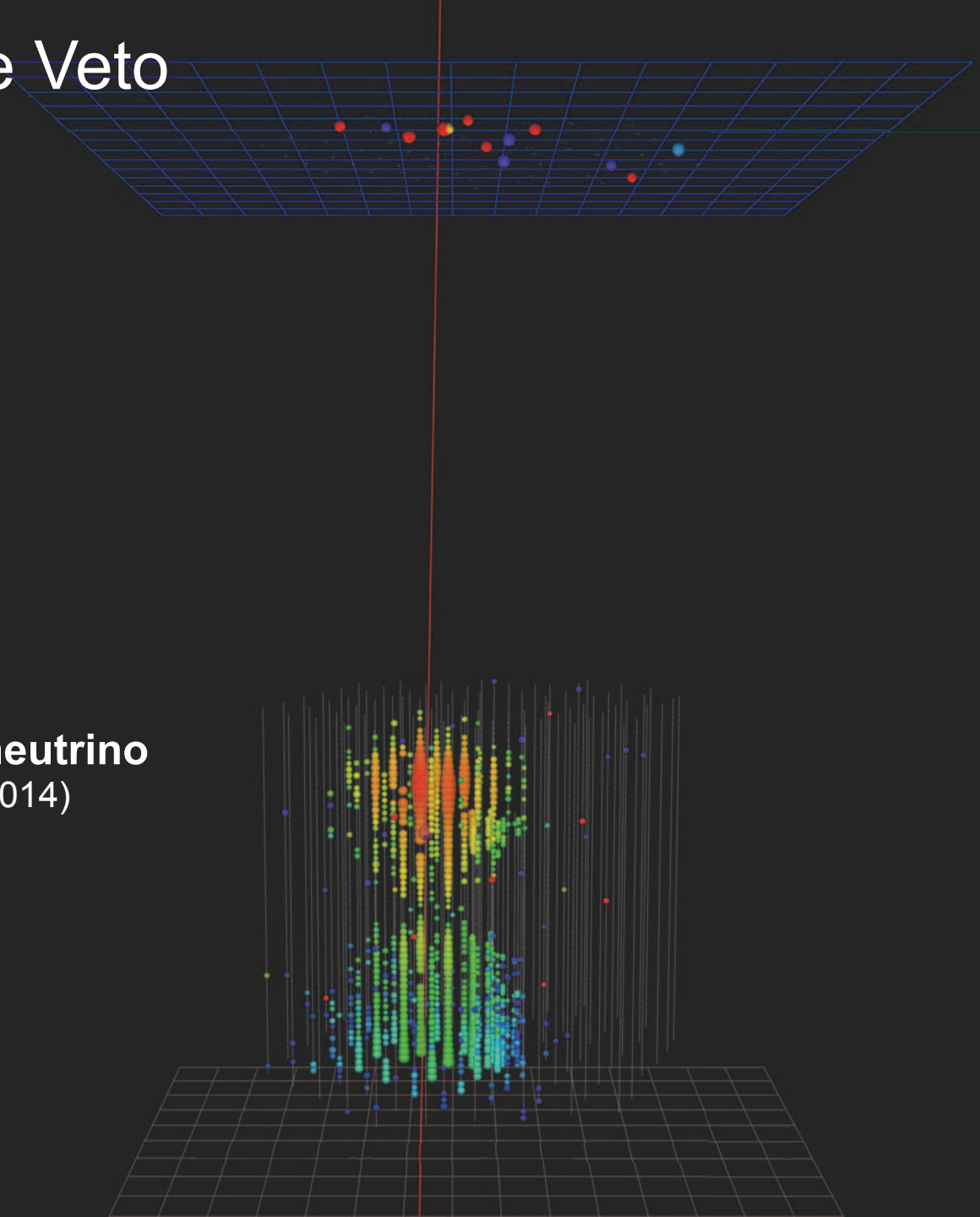
Schönert et al, 2009
Gaisser et al. 2014



Downgoing event without airshower ➔ astro. neutrino!



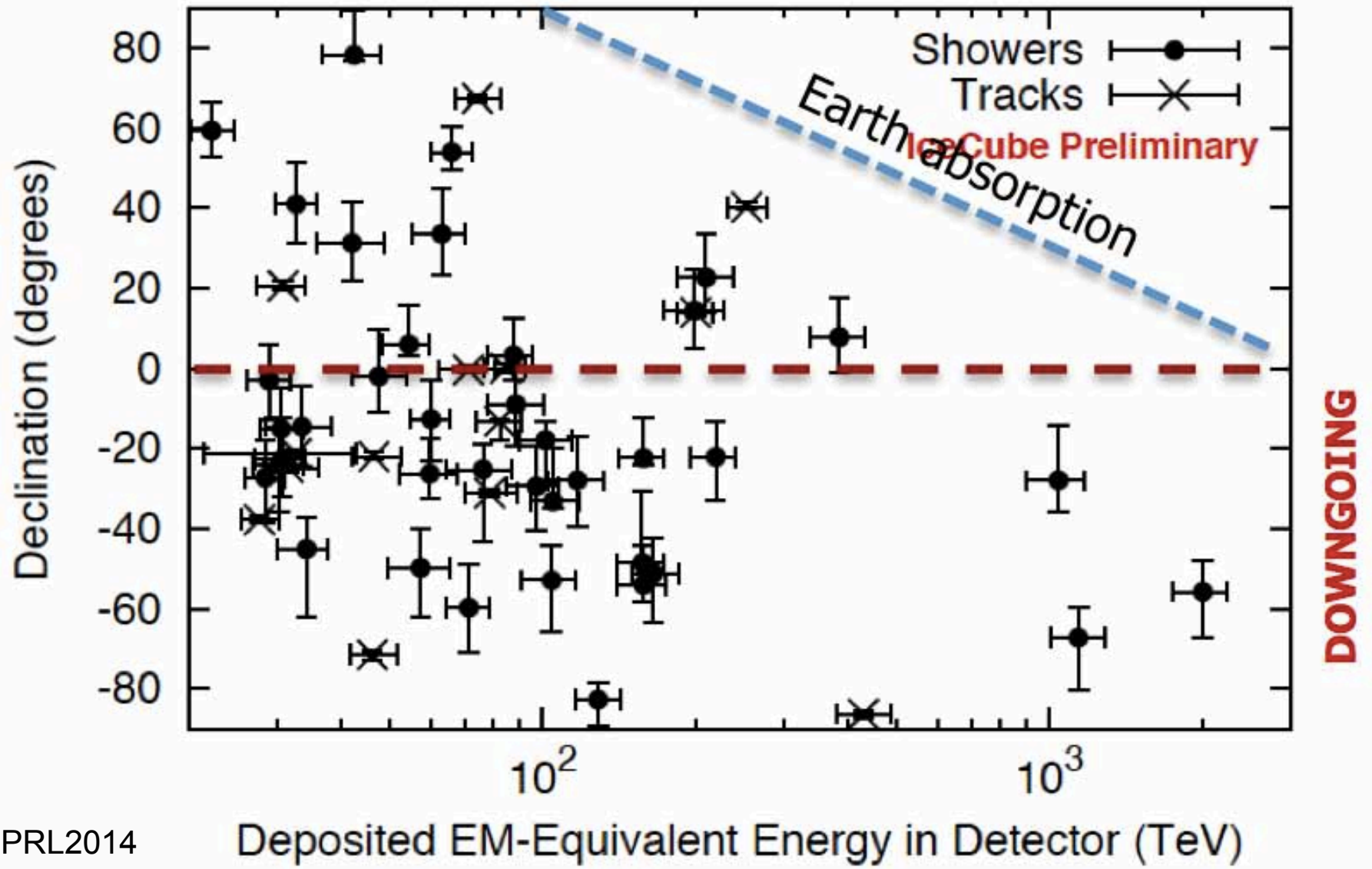
Surface Veto



cosmic neutrino
(detected 2014)

Astrophysical Neutrinos!

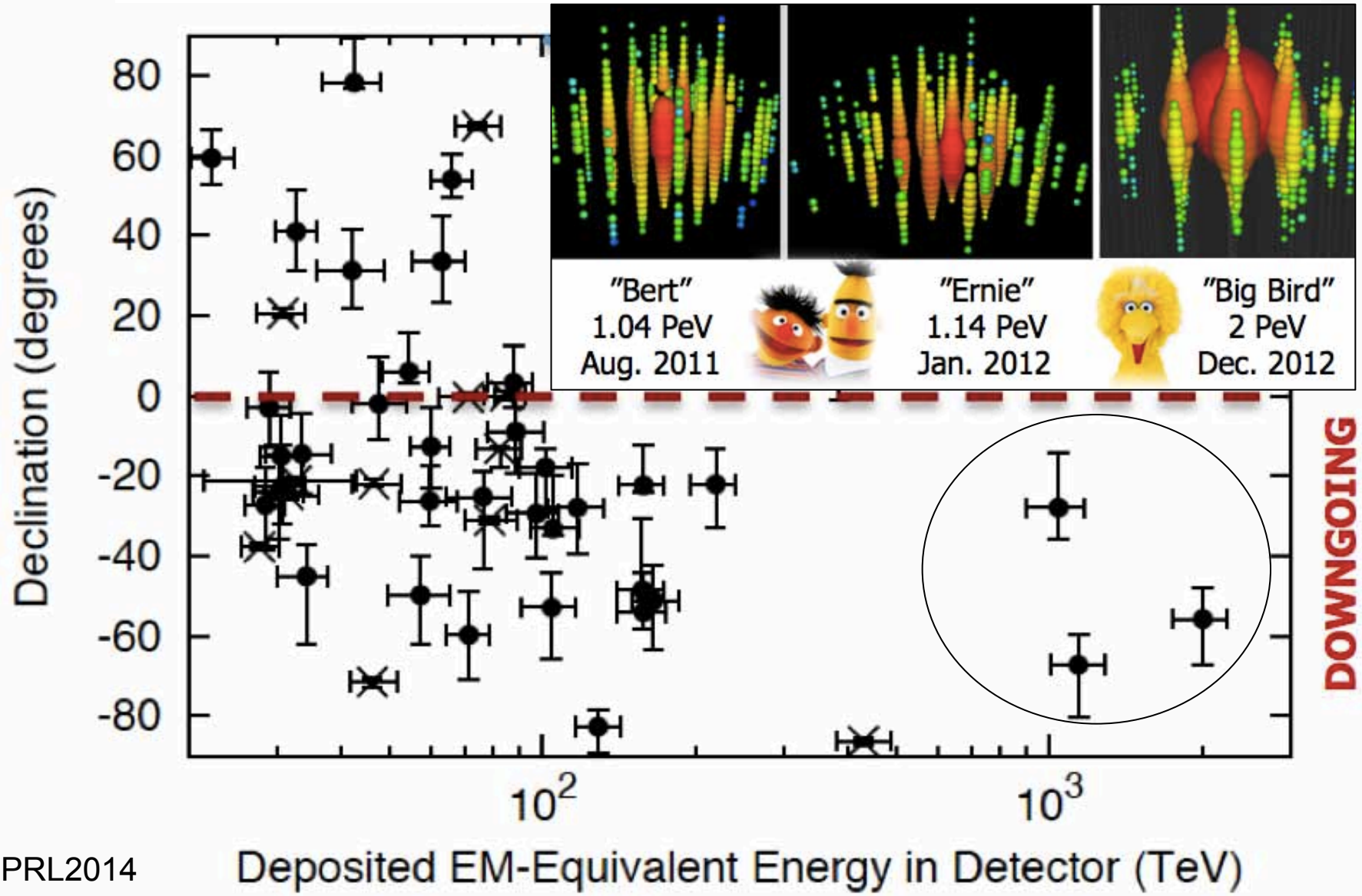
54 events observed with 20±6 expected from atmosphere



PRL2014

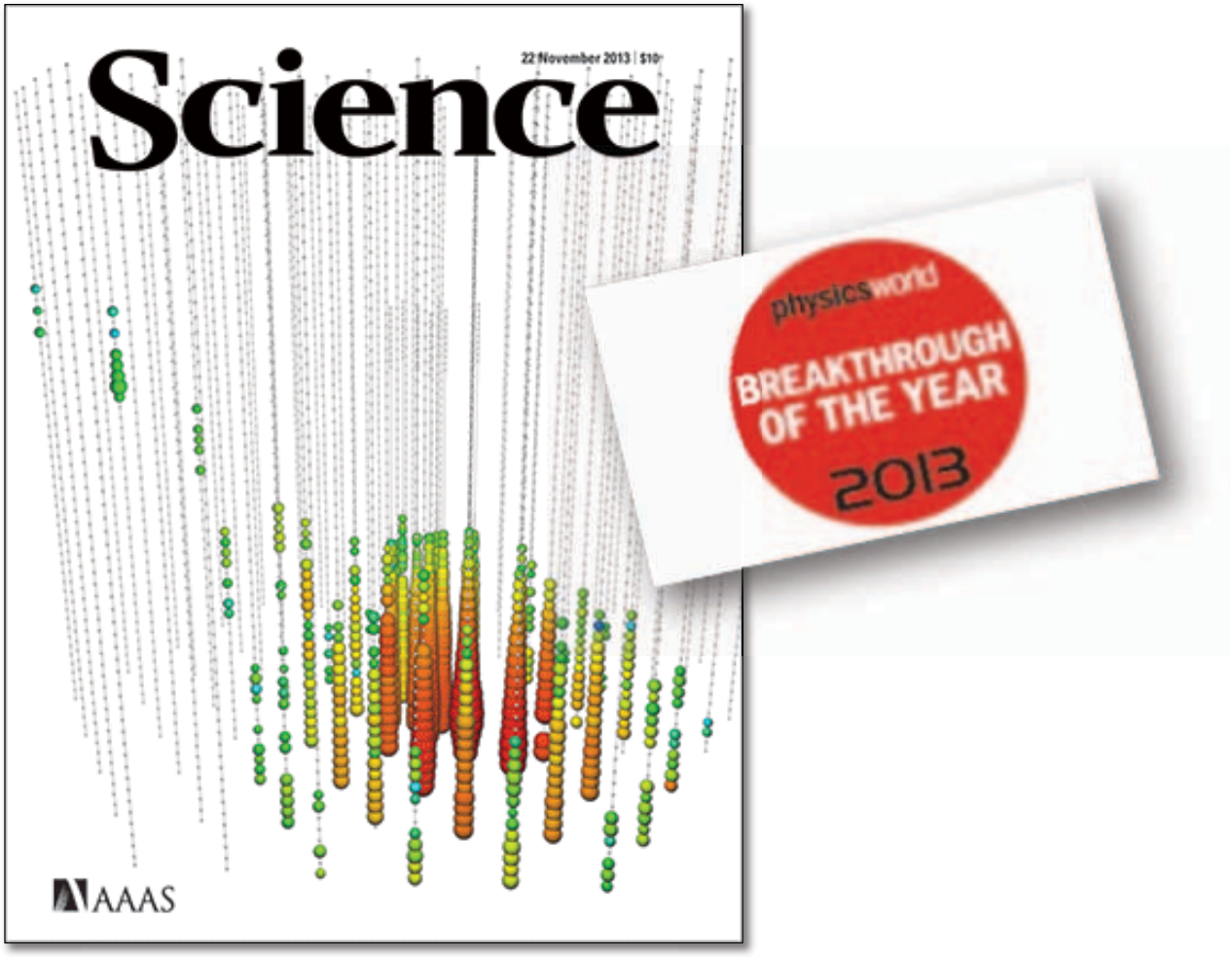
Astrophysical Neutrinos!

54 events observed with 20±6 expected from atmosphere



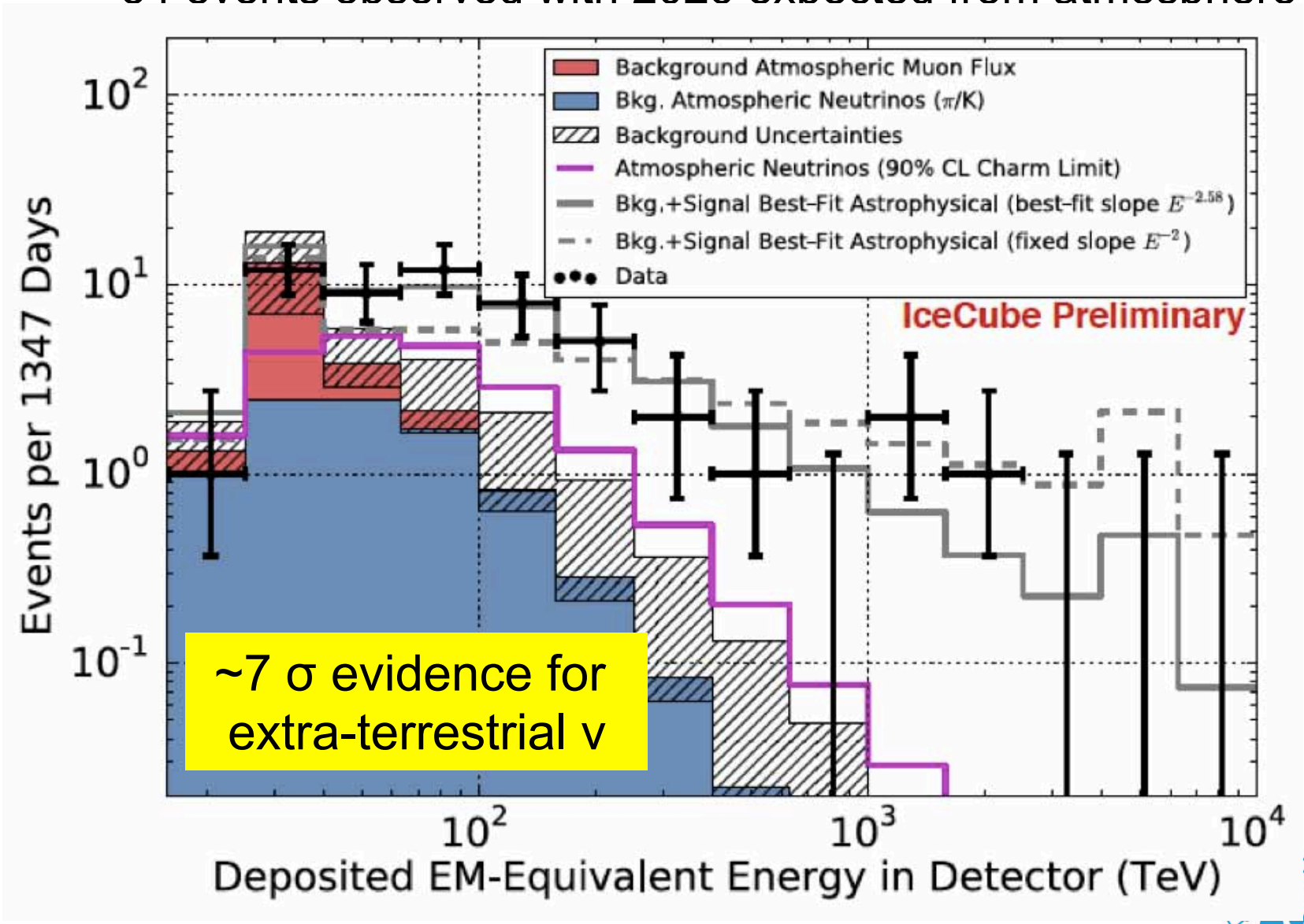
PRL2014

Astrophysical Neutrinos!



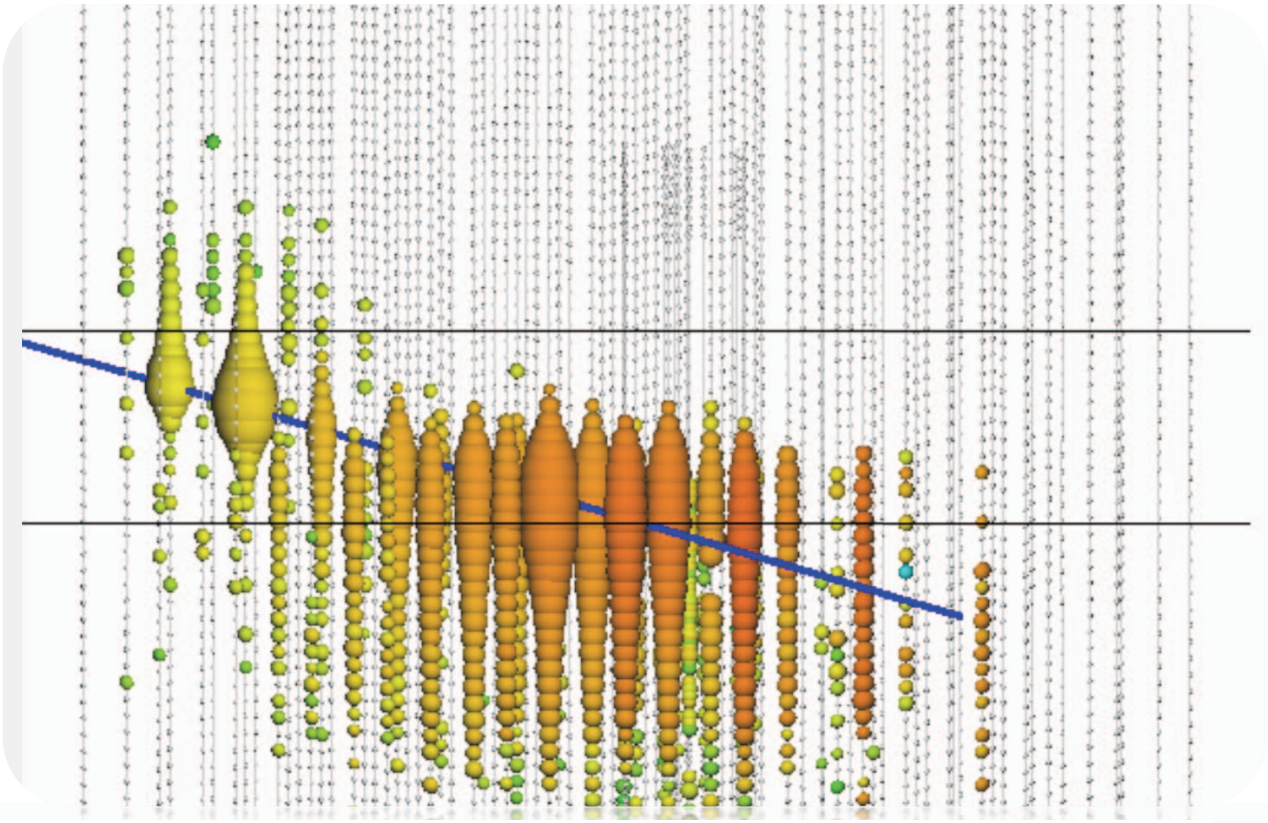
Energy Spectrum

54 events observed with 20±6 expected from atmosphere



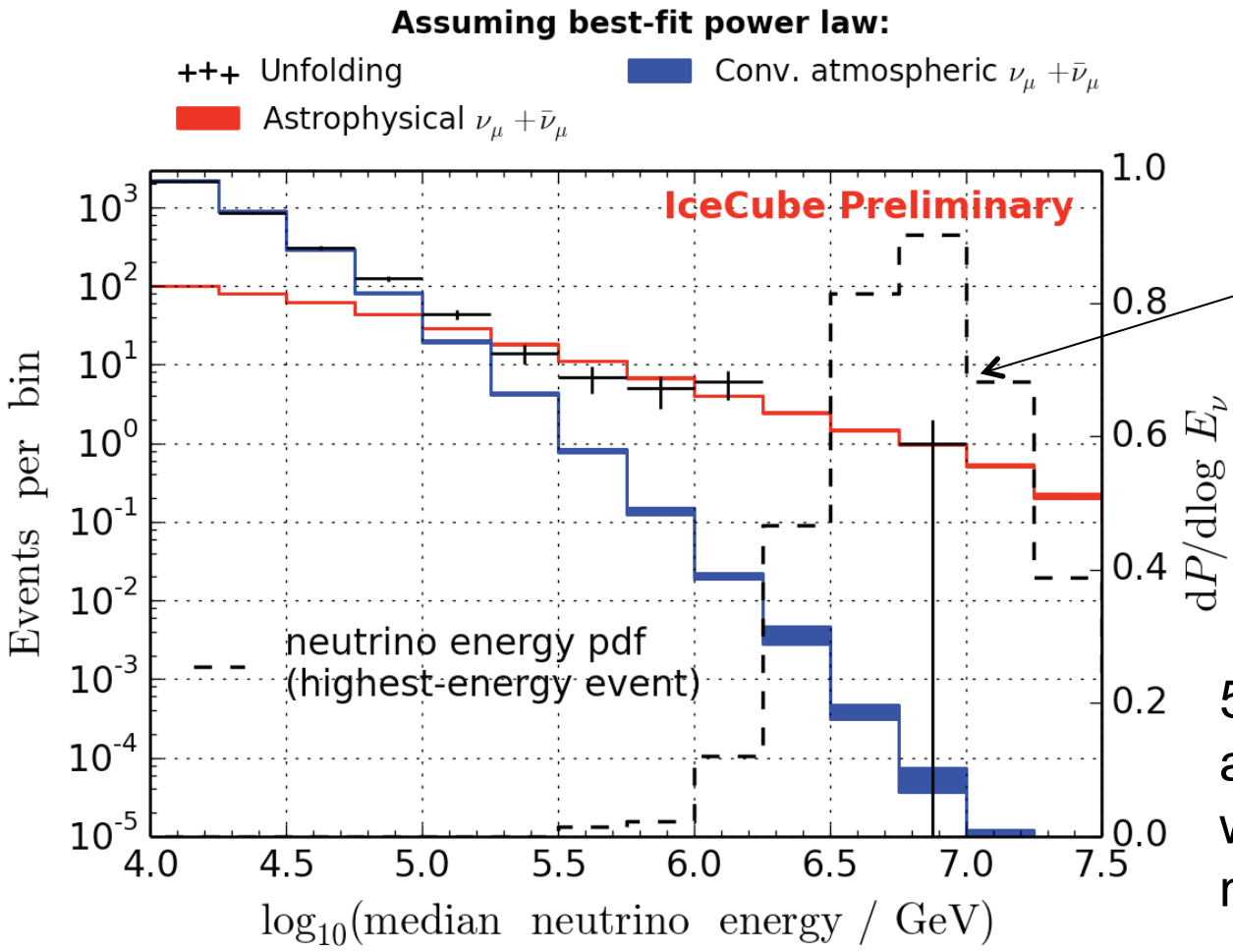
and there is more…

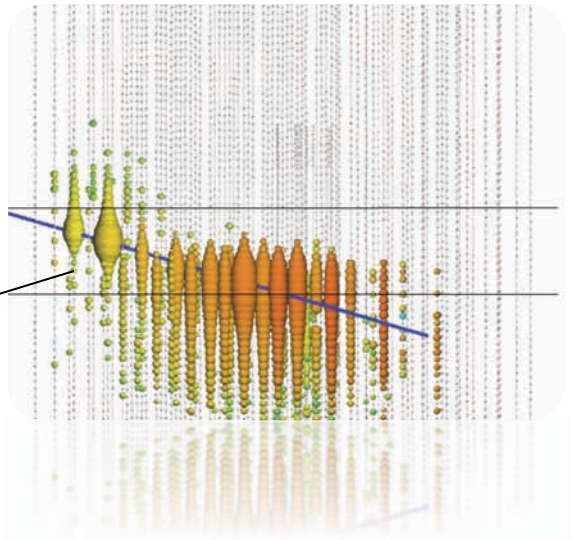
The highest energy event so far,
deposited energy in IceCube: 2.6±0.3 PeV



ICRC2015

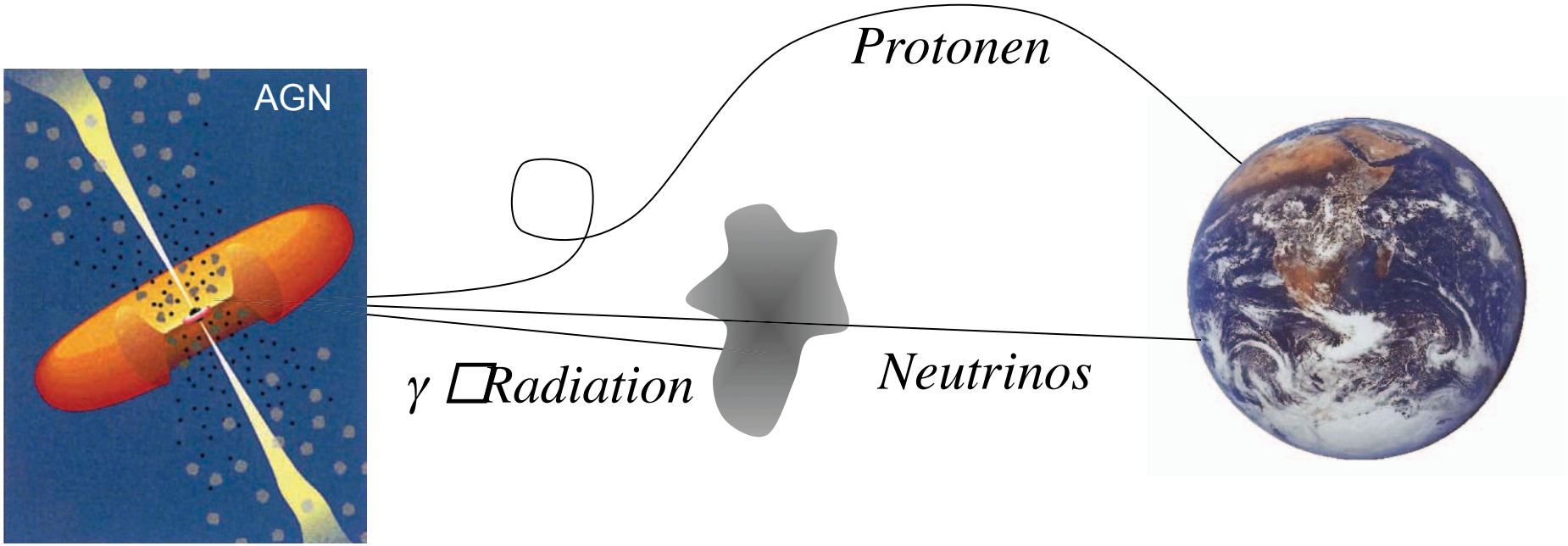
and there is more…





5.9 sigma detection of astrophysical neutrinos with through-going muons analysis

Neutrino Flavor Ratio



$p + X \rightarrow \pi^{+-} + \pi^{0} + \ldots$

$\hookrightarrow \nu + \mu + \ldots$

Flavor ratio at the source

$\nu_e : \nu_\mu : \nu_\tau \approx 1 : 2 : 0$

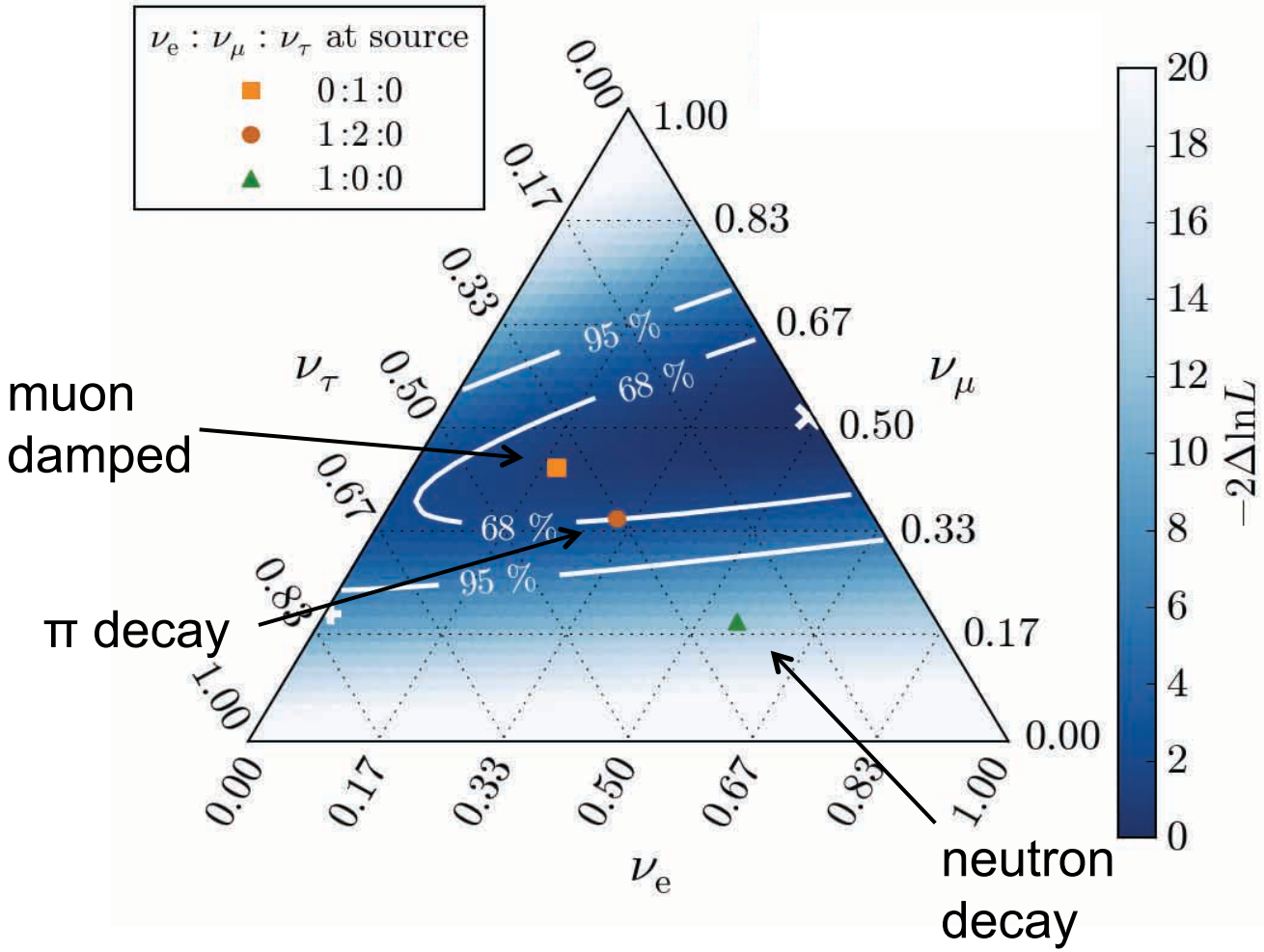
Neutrino oscillation length:

$\lambda_{23} \approx 10^{11}\ (E_\nu/\mathrm{TeV})\ \mathrm{cm}$

Flavor ratio at the Earth:

$\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$

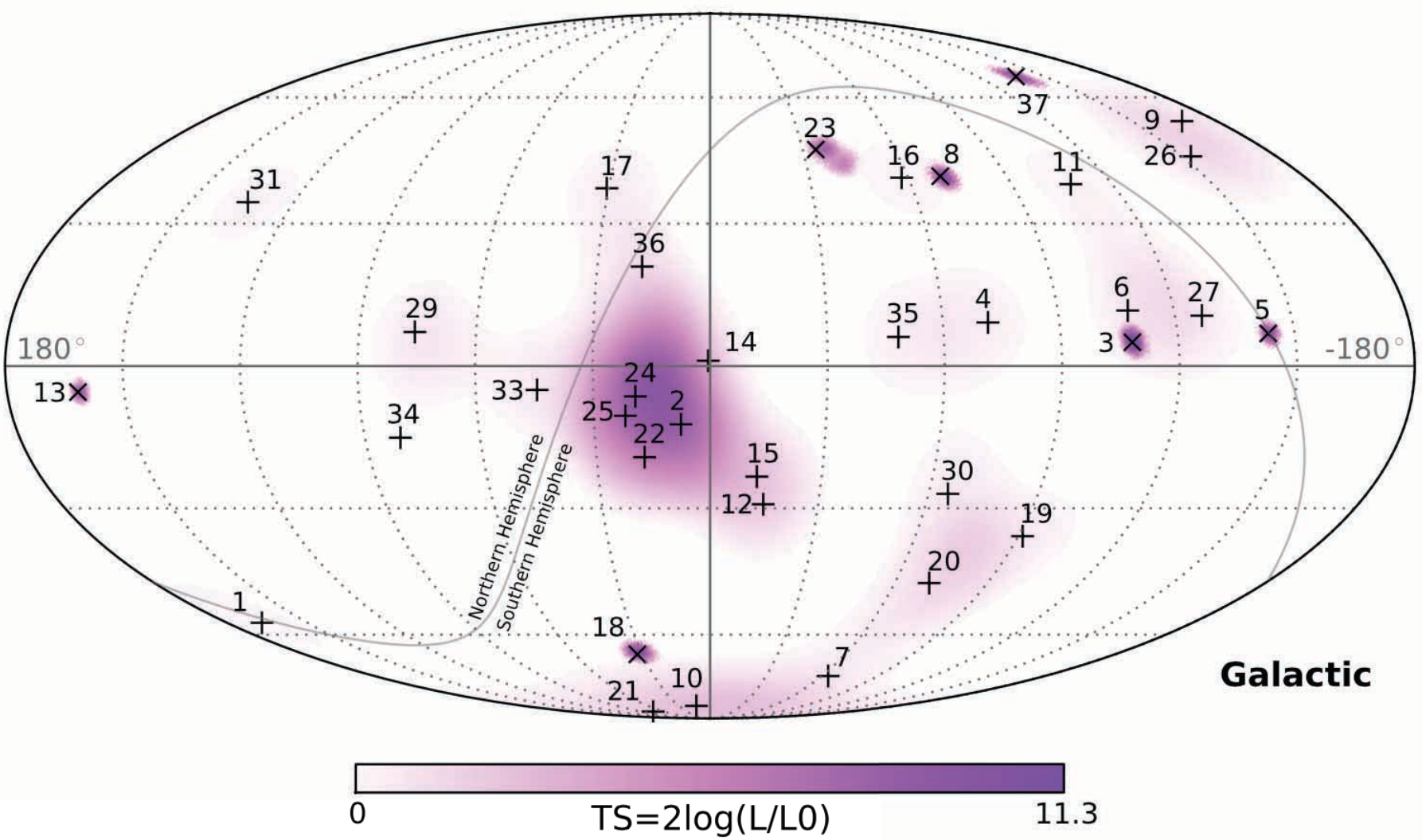
Neutrino Flavor Ratio



Flavor ratio (v_e:v_μ:v_τ) compatible with expectation (1:1:1)

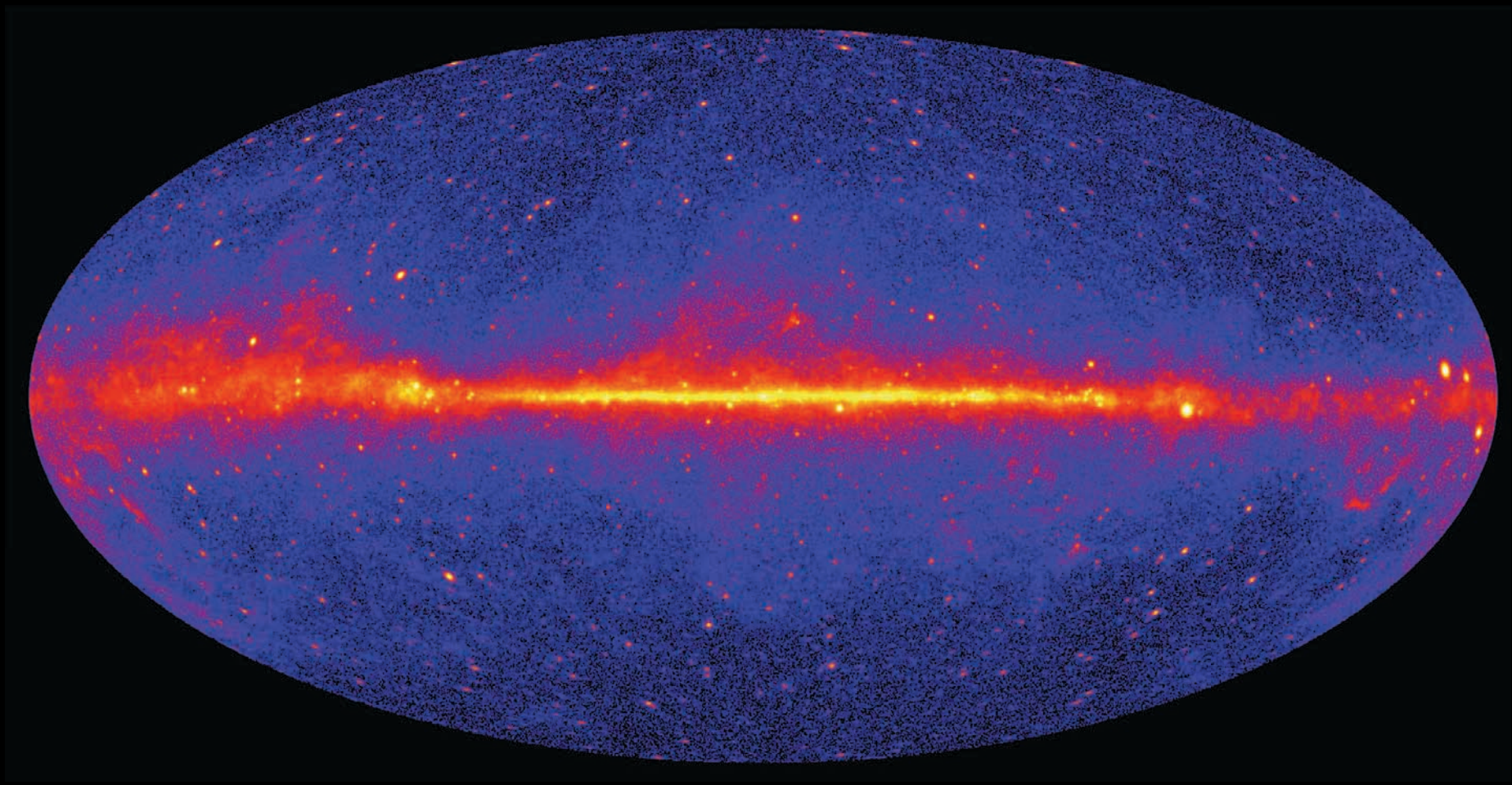
ApJ 2015, PRL 2015

Sky map of 54 High Energy Starting Events

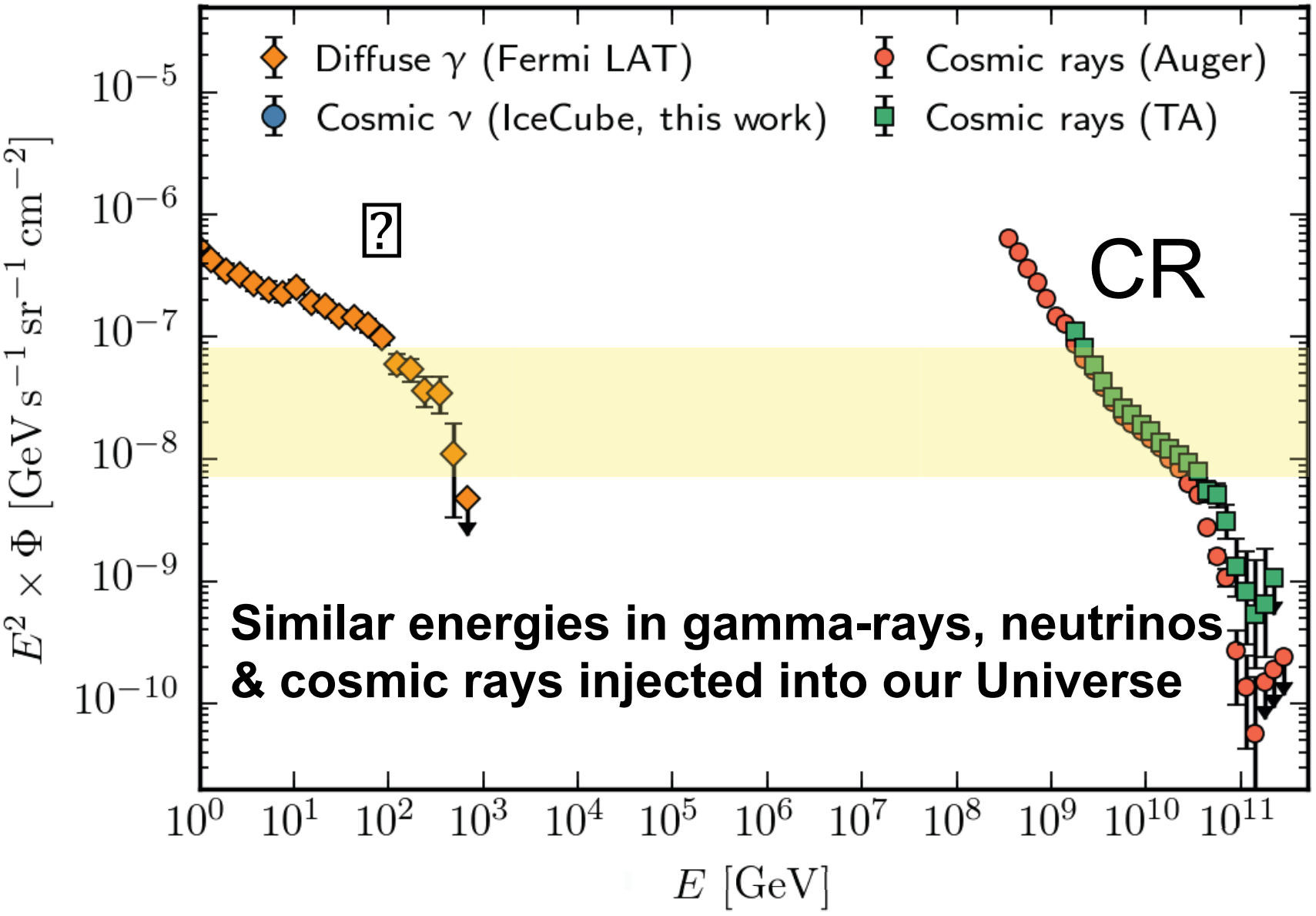


Largely isotropic ☐ extragalatic origin!

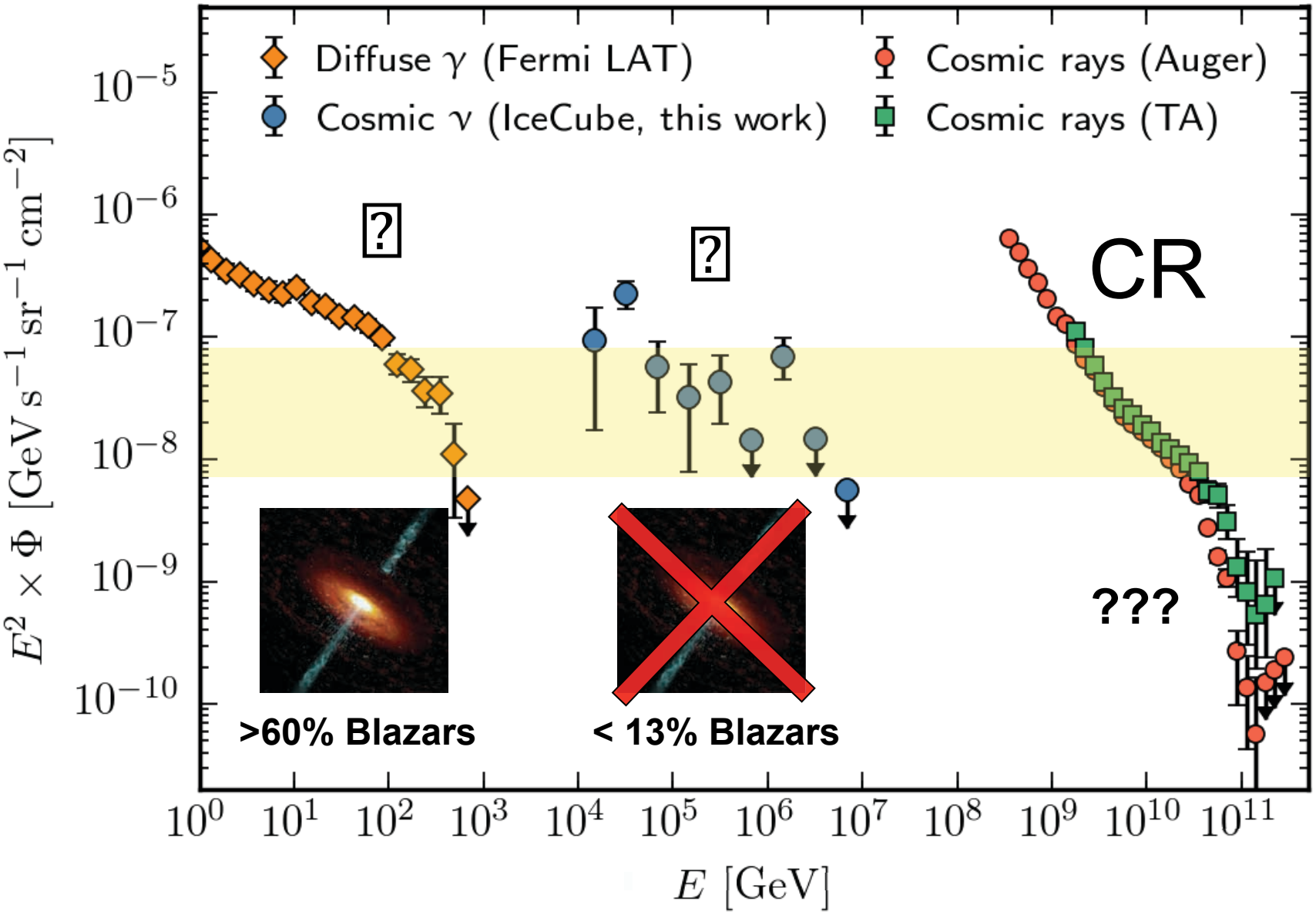
The gamma-ray sky observed by the FERMI satellite



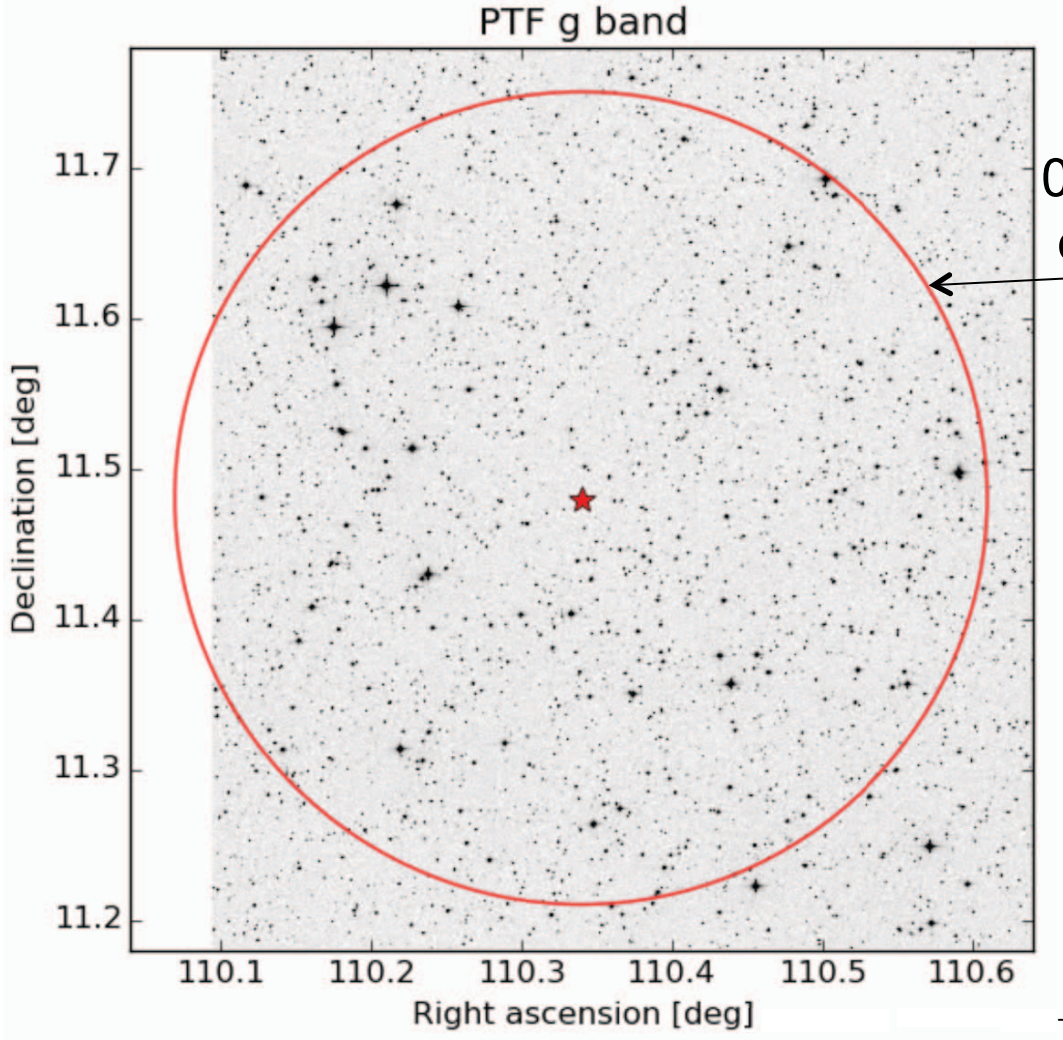
Multi-Messenger Astronomy



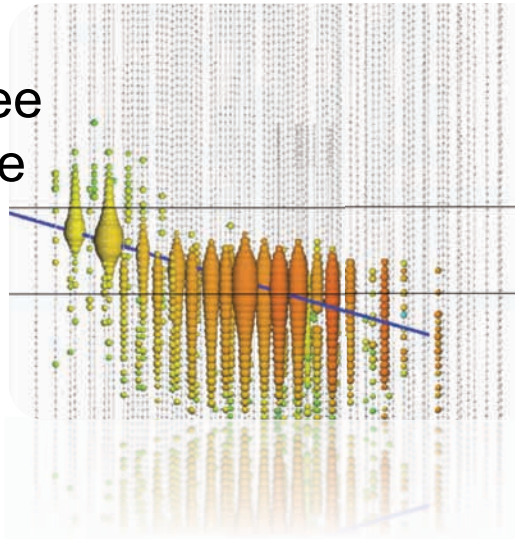
Multi-Messenger Astronomy



Resolving the sources of the diffuse flux



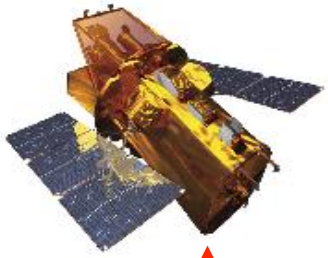
0.27 degree error circle



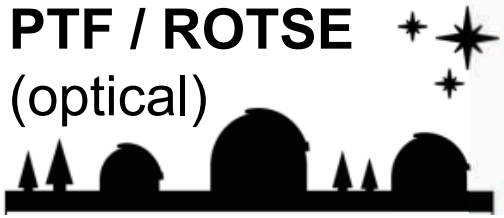
IceCube neutrino follow-up

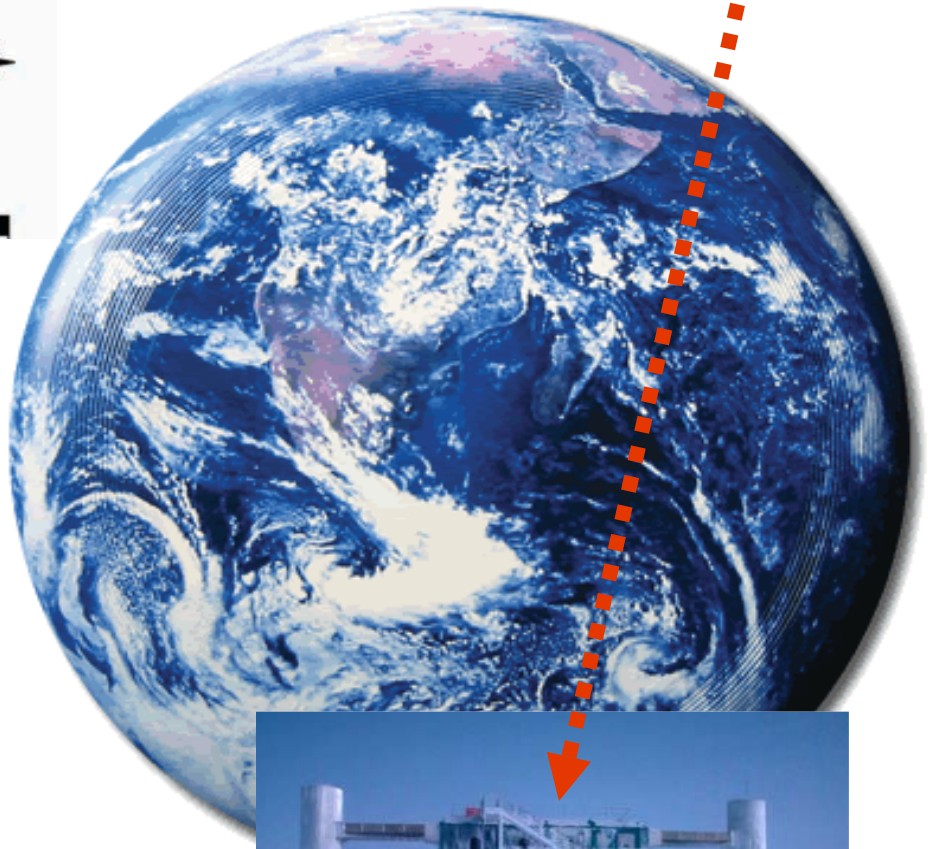
AGN/SN/GRB

Swift (X-Ray)



PTF / ROTSE
(optical)





DESY

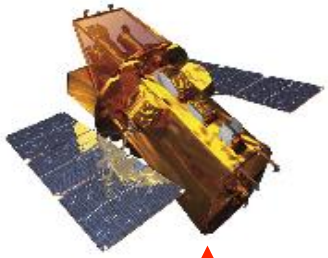
More follow-up with
VERITAS, MAGIC, HESS

iridium

IceCube
SOUTH POLE NEUTRINO OBSERVATORY

IceCube neutrino follow-up

Swift (X-Ray)



PTF / ROTSE
(optical)

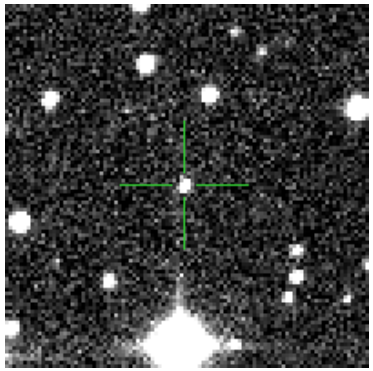
DESY

chance coin. ~2%
ApJ 2015

iridium

IceCubes' first SN

NEW



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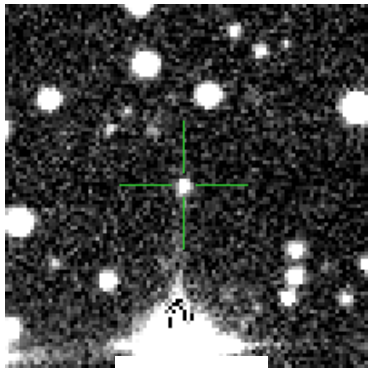
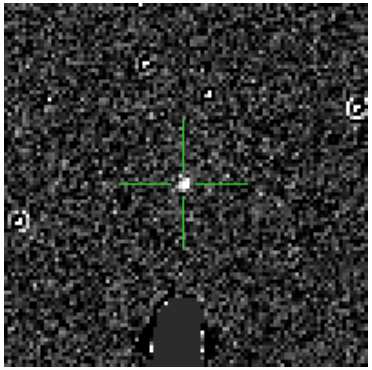
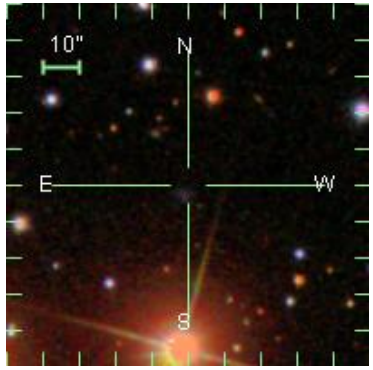


SUB



SDSS

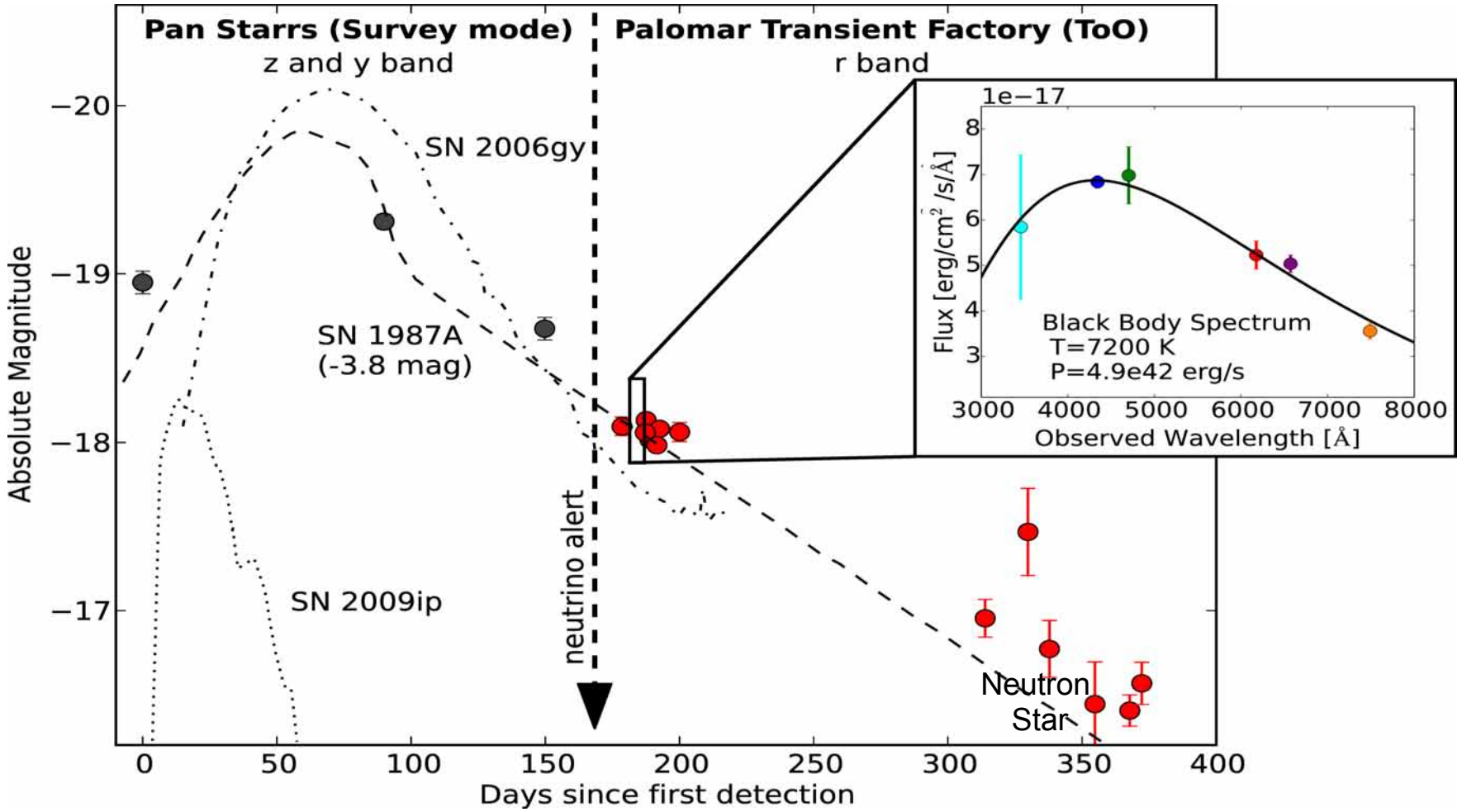


PTF12csy

IceCube
SOUTH POLE NEUTRINO OBSERVATORY

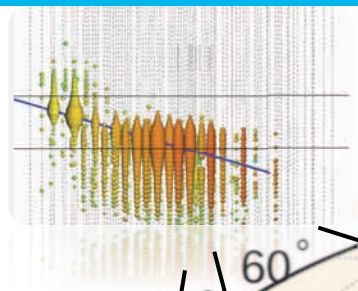
IceCube's first SN

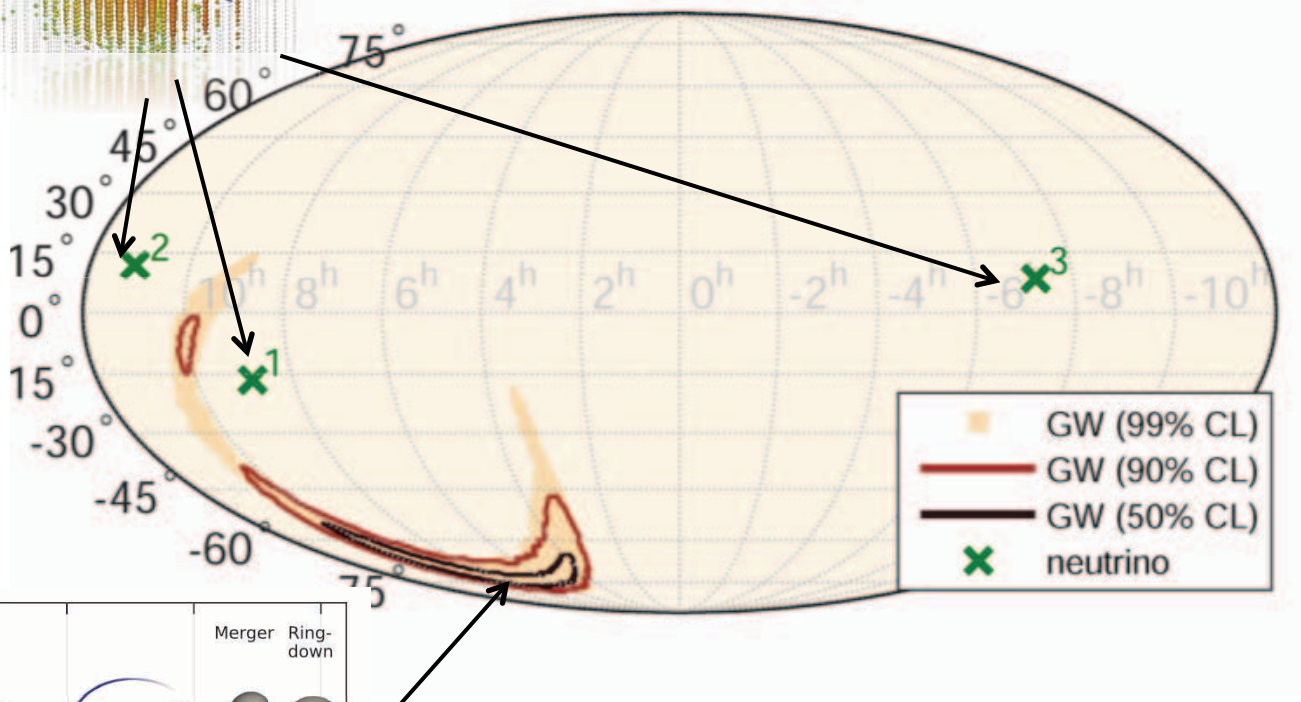
PTF12csy: A bright SN Type IIN @ 300 Mpc

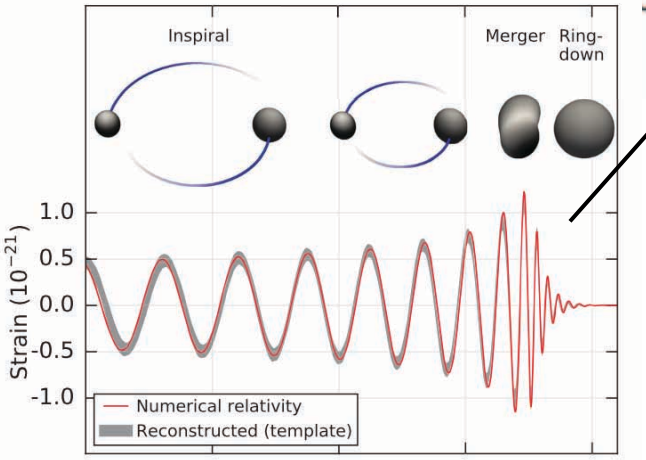


Astrophys. J. (2015)

Neutrino follow-up of LIGO event GW150914

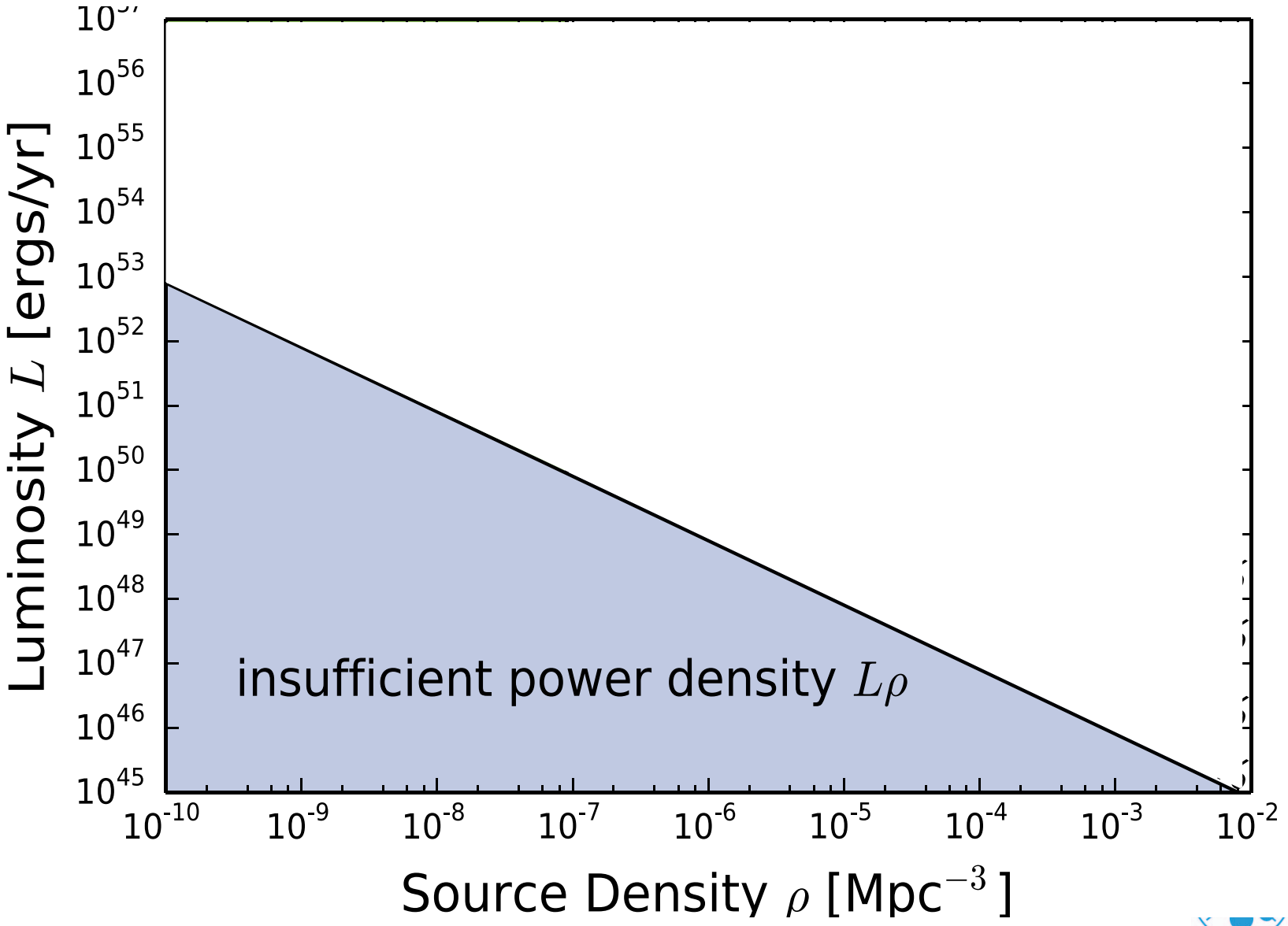




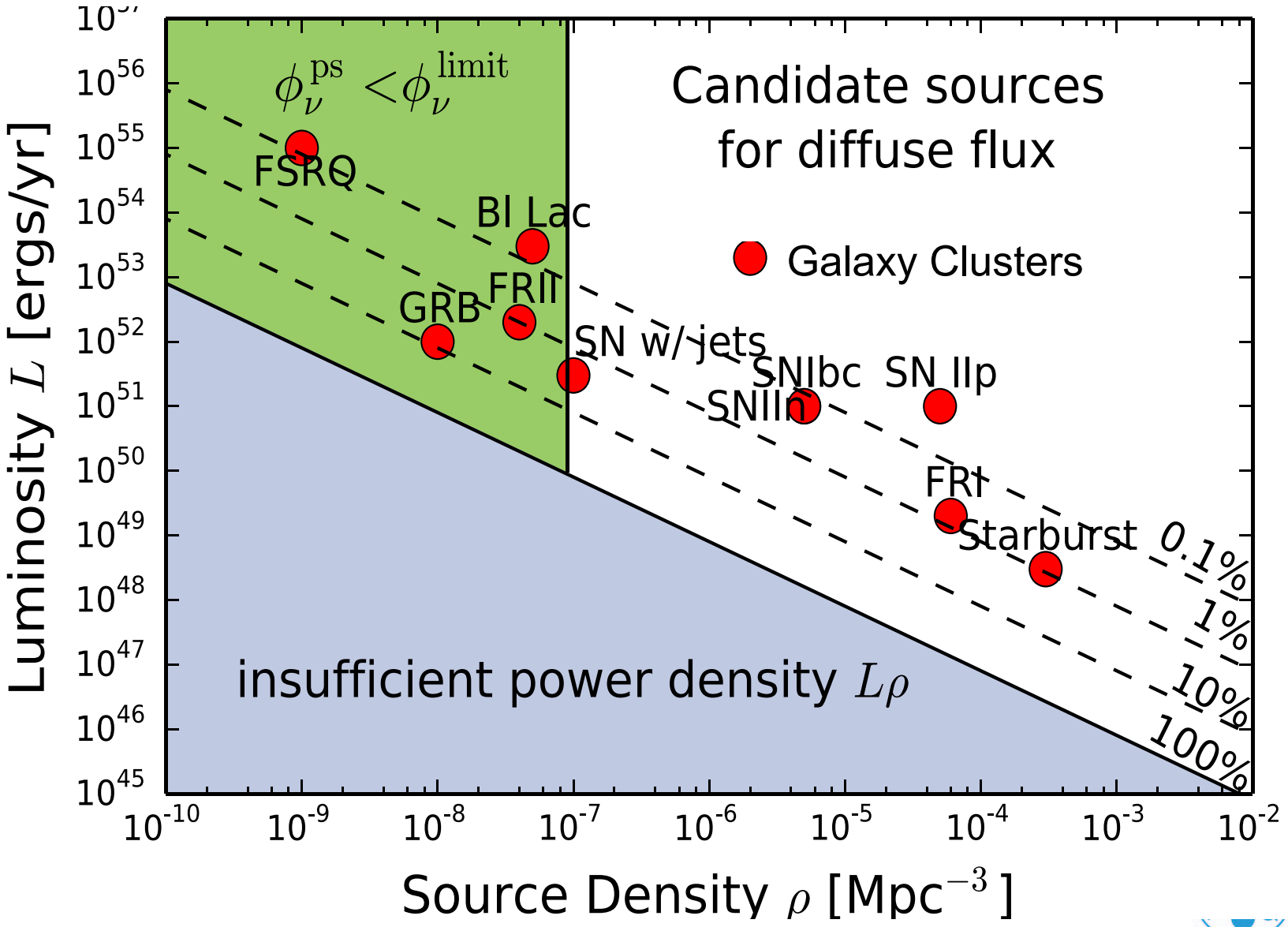


No significant concidence with neutrinos

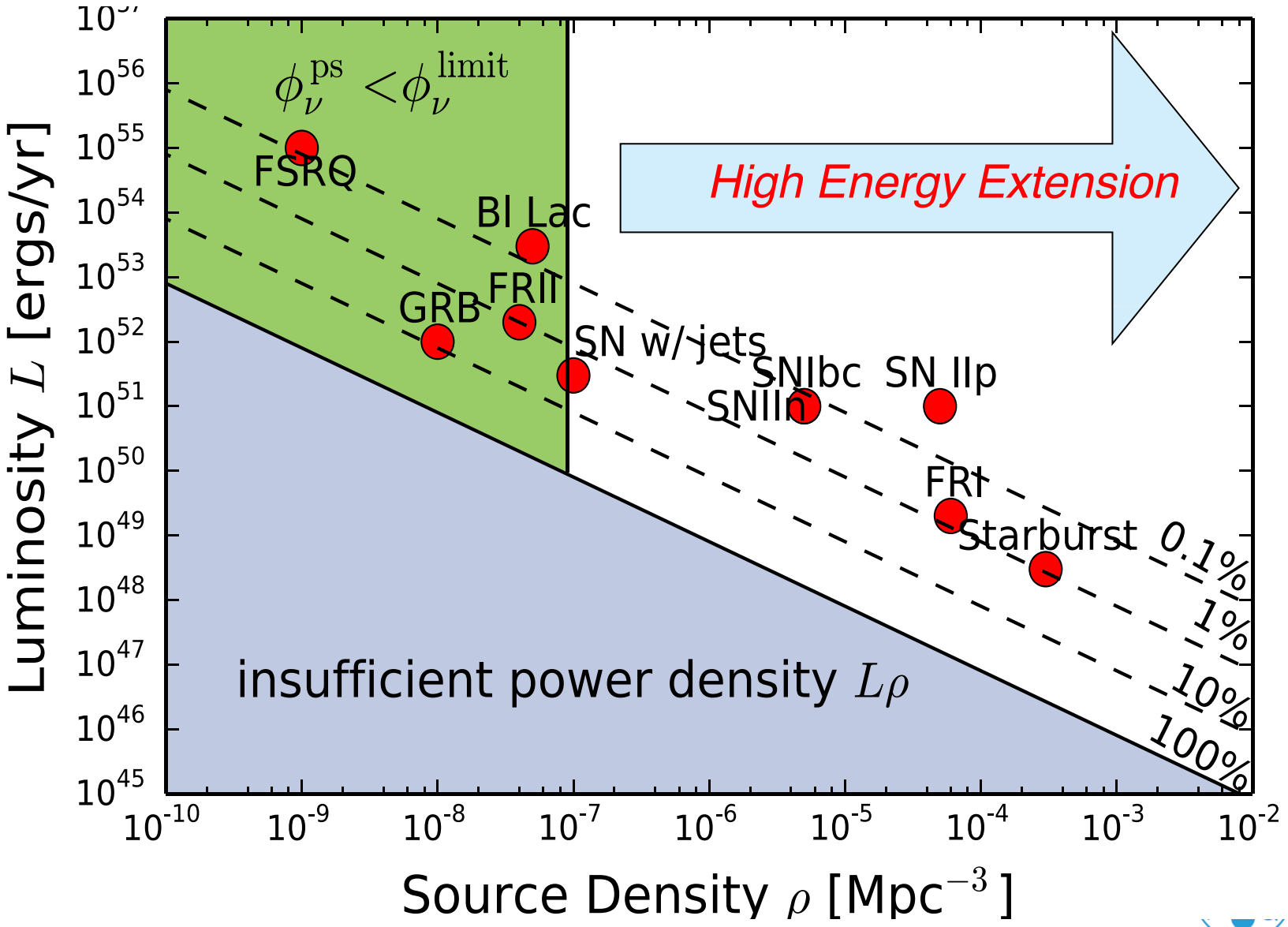
Resolving the sources of the diffuse flux



Resolving the sources of the diffuse flux

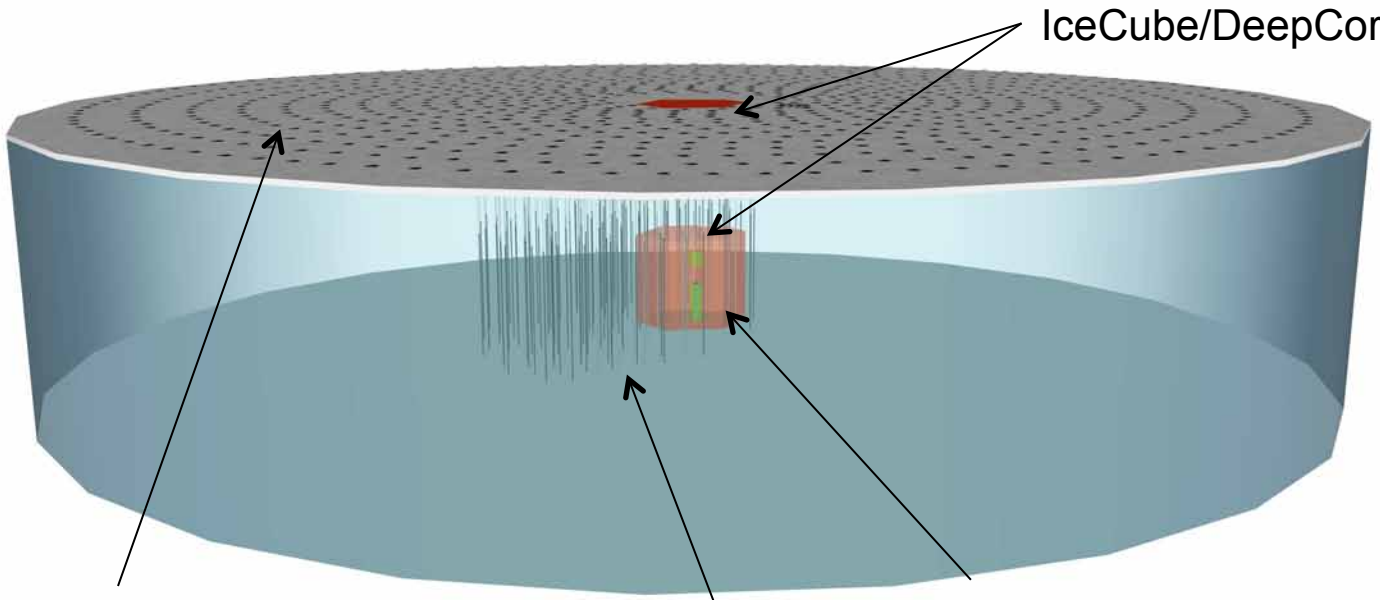


Resolving the sources of the diffuse flux



The IceCube-Gen2 Observatory

A wide band neutrino observatory (MeV – EeV) using several detection technologies – optical, radio, and surface veto – to maximize the science.



Surface veto array
Baseline:
75 km^2 / 100 TeV threshold

High Energy Array
Baseline:
140 strings, 240 m spacing

Low Energy / PINGU
40 strings

arXiv:1412.5106

Conclusion

- IceCube detected high-energy extra-terrestrial neutrinos, offering a unique view on the high-energy Universe
- Sources not yet resolved, consistent with extra-galactic origin
- New (multi-messenger) observation reduce the list of candidates
- As many new questions as old ones answered
- Planning for IceCube-Gen2 has started