Multi-Messenger Astronomy

with Neutrinos

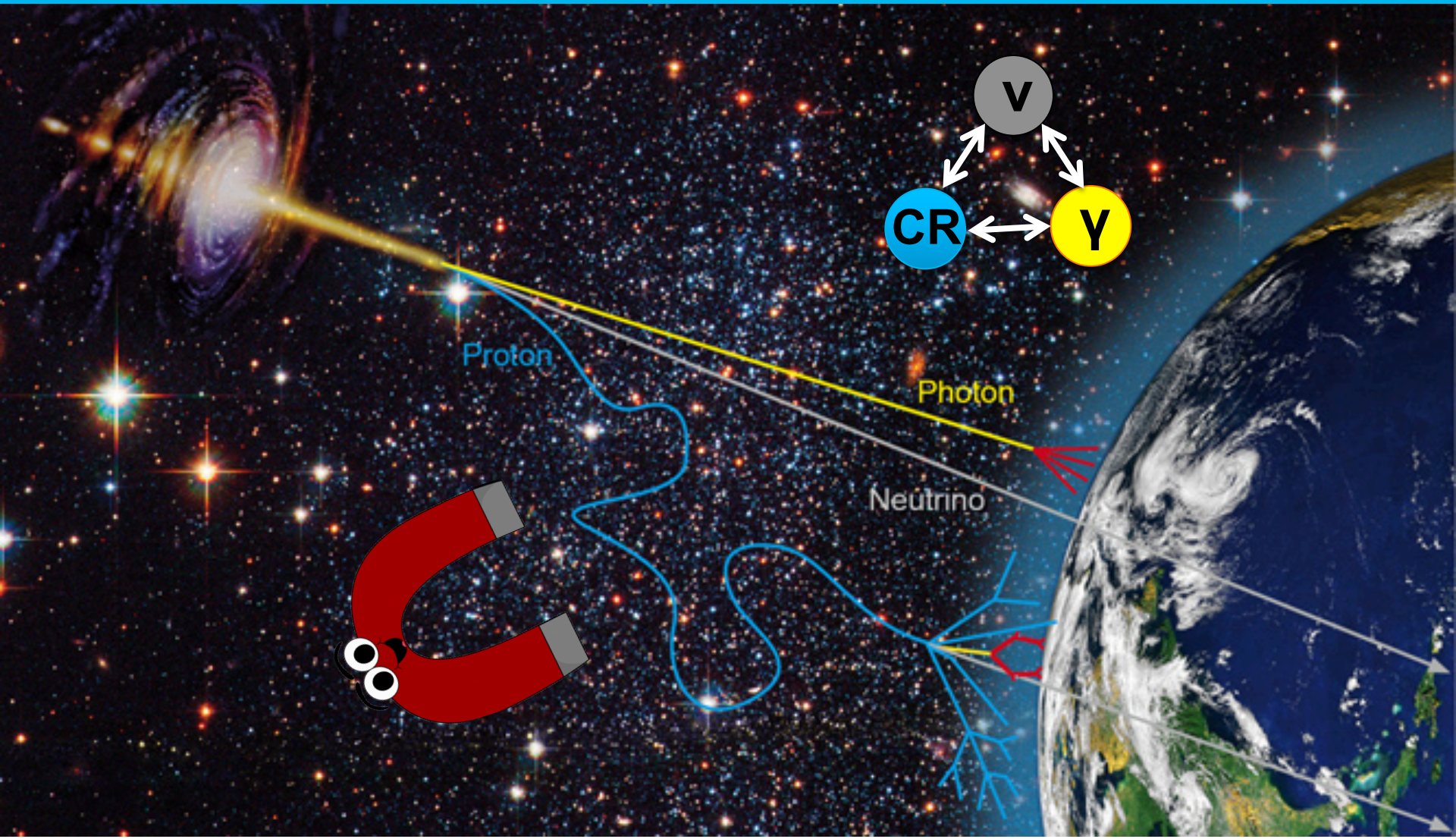
Anna Franckowiak, DESY Zeuthen

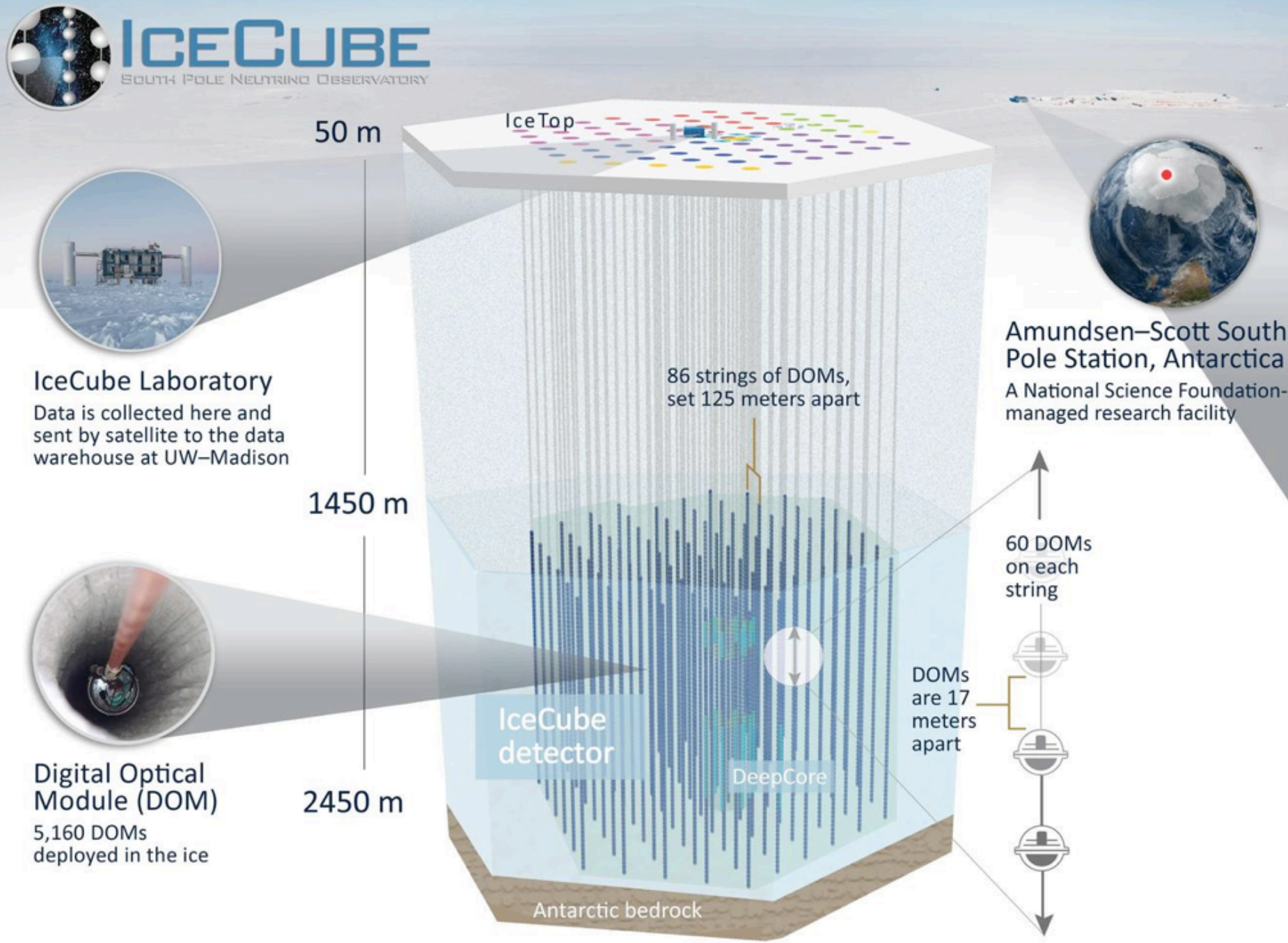
HAP Workshop, Erlangen, 21.9.2016

HELMHOLTZ ASSOCIATION

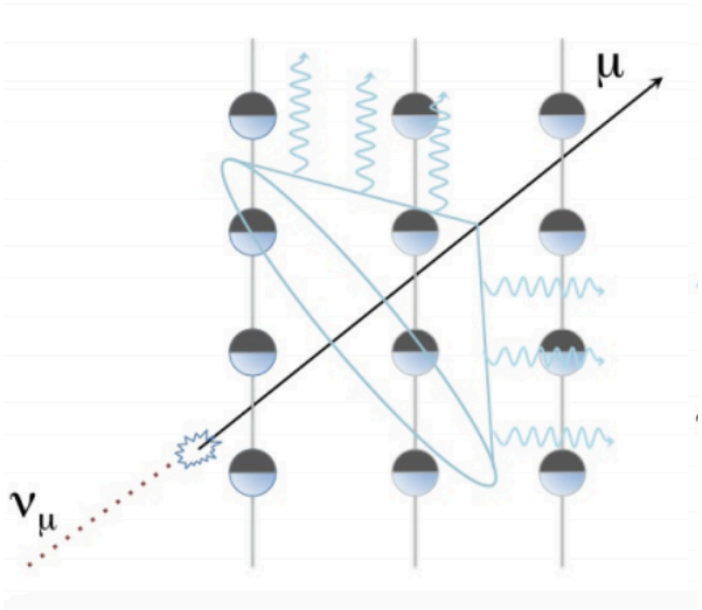
DESY

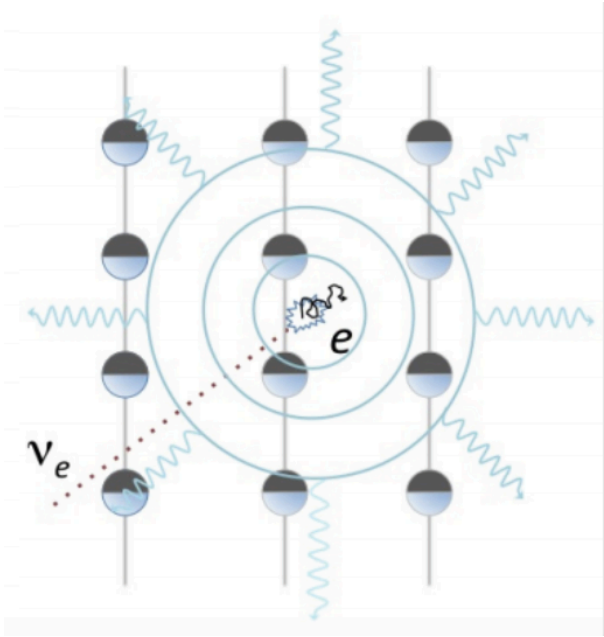
The Multi-Messenger Picture




IceCube
South Pole Neutrino Observatory
50 m
IceTop
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
1450 m
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
2450 m
Antarctic bedrock

IceCube neutrino event signatures

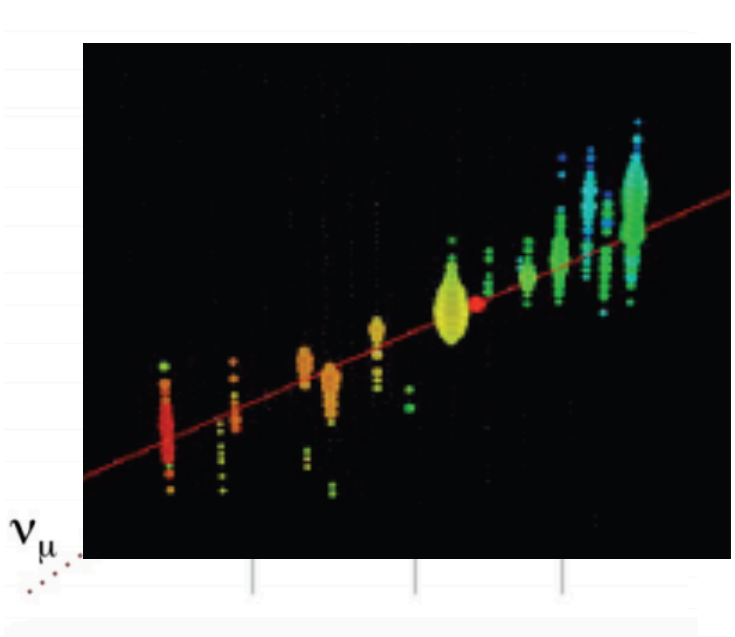


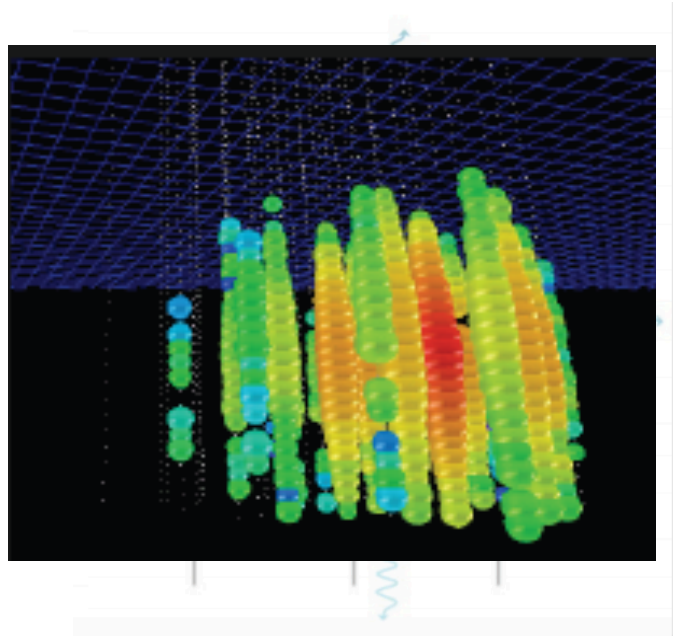


- Muon track from CC muon neutrino interactions
  - Angular resolution < 1°
  - dE/dx resolution factor 2-3

- Cascade from CC electron and NC all flavor interactions
  - Angular resolution ~10-20° at 100 TeV
  - Energy resolution ~15%

IceCube neutrino event signatures





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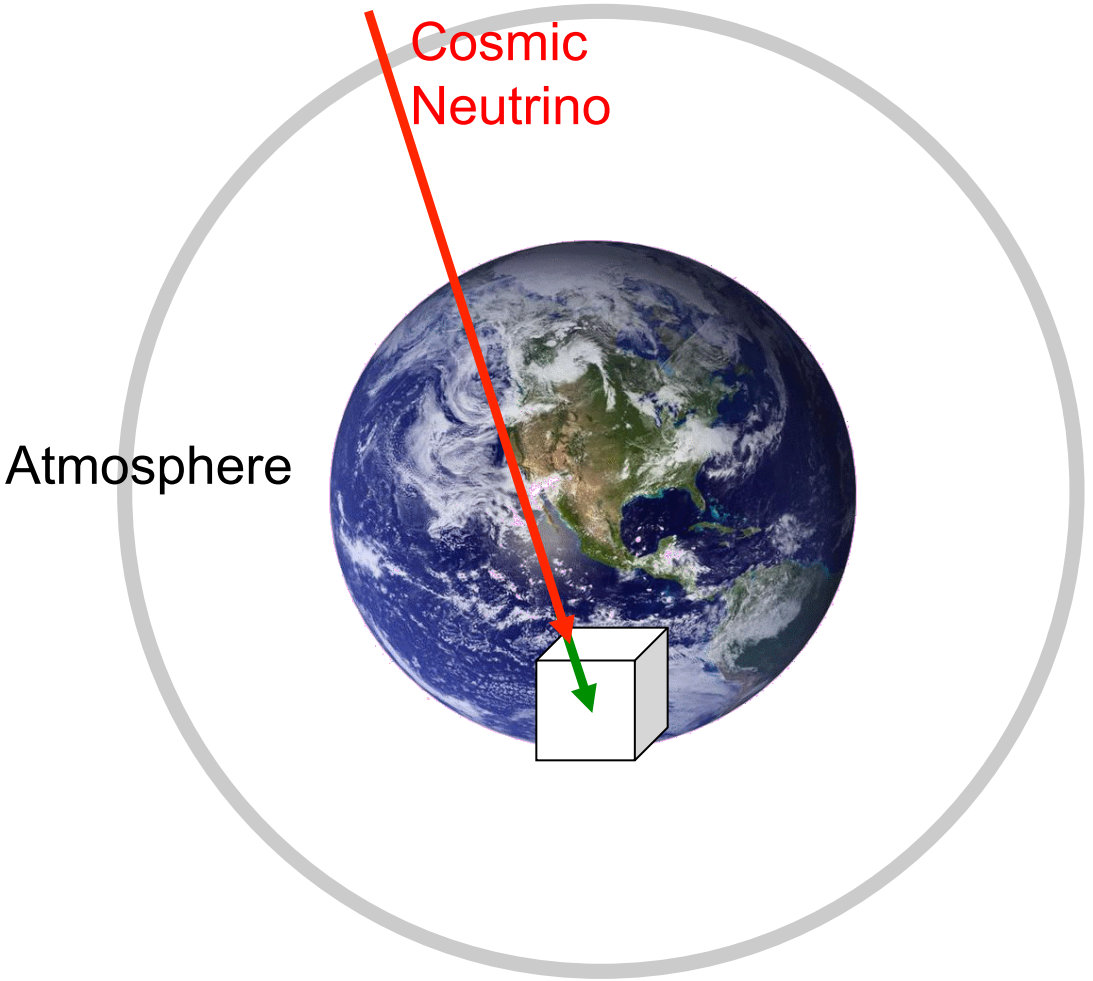

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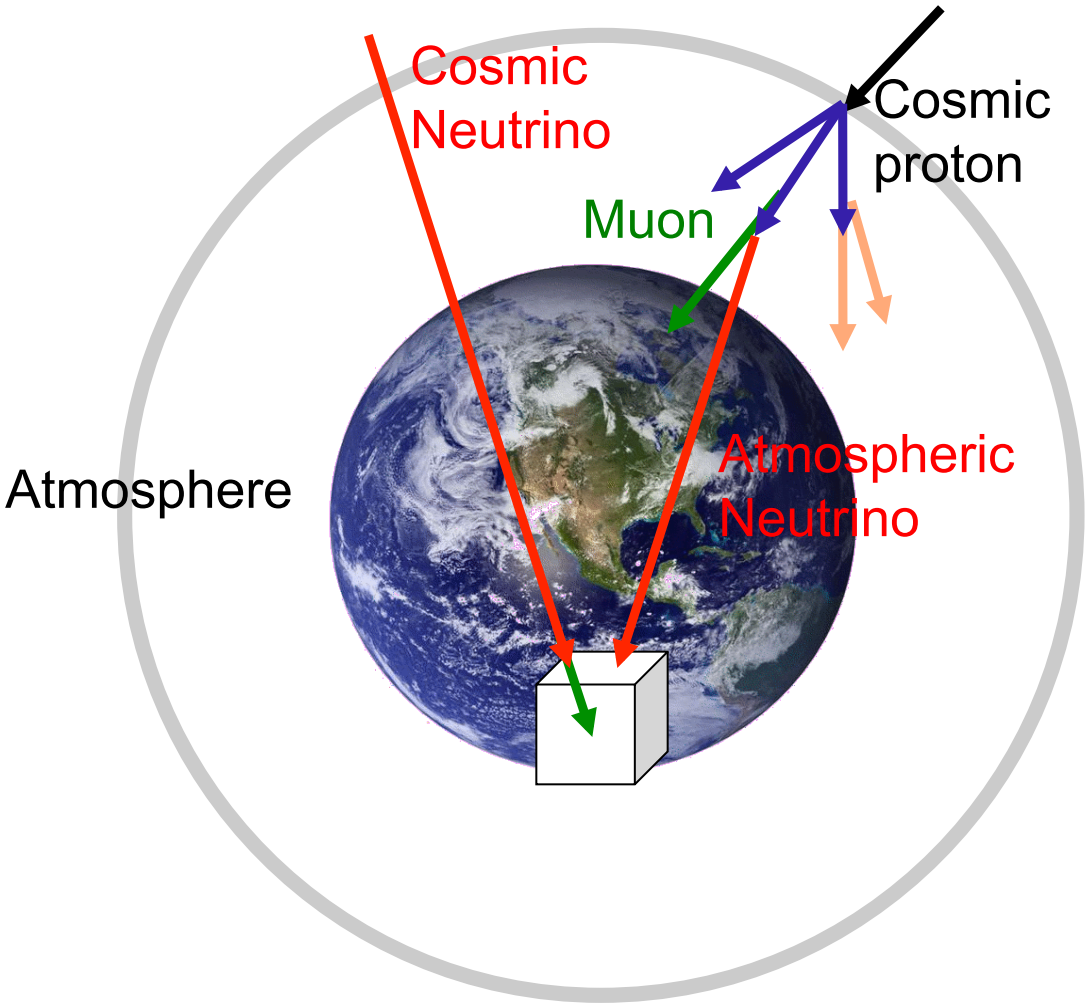

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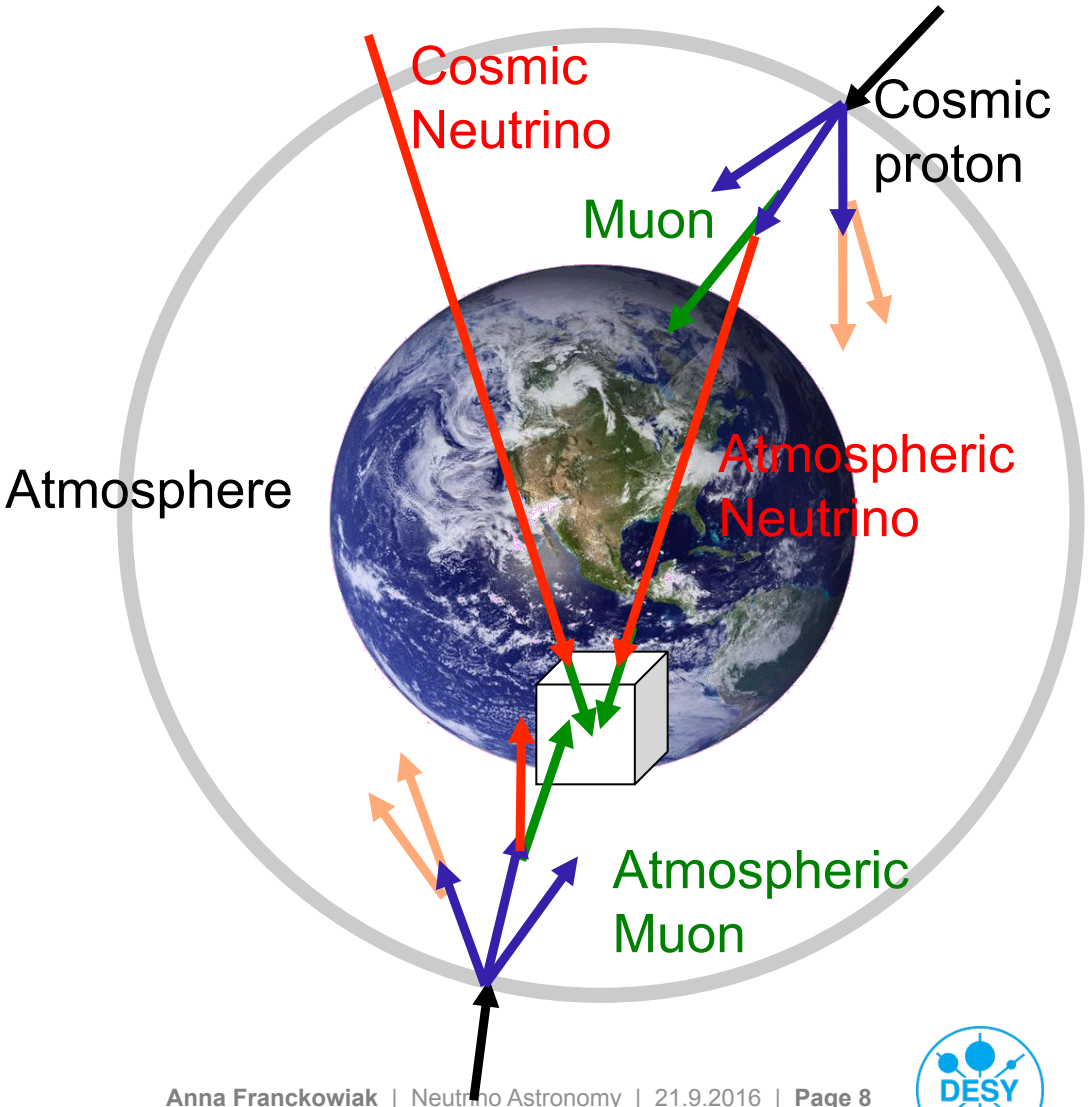

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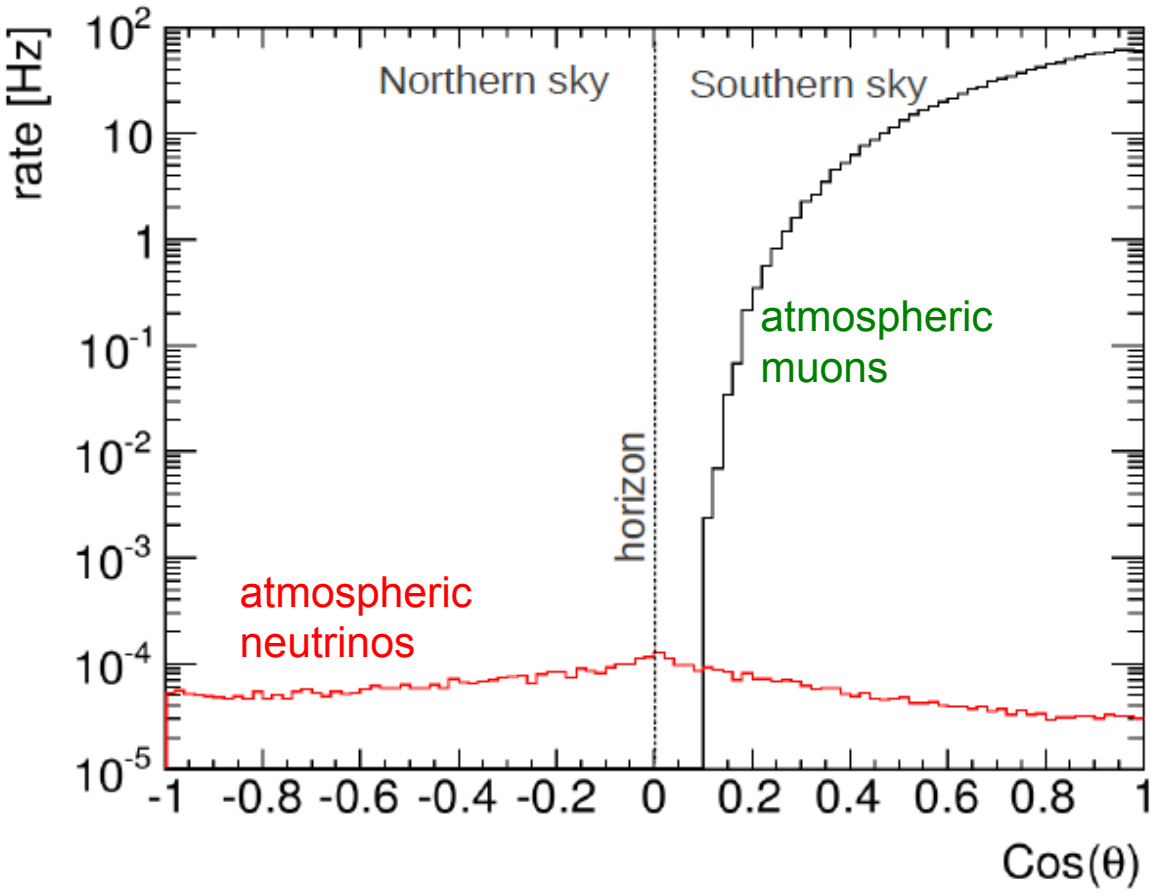
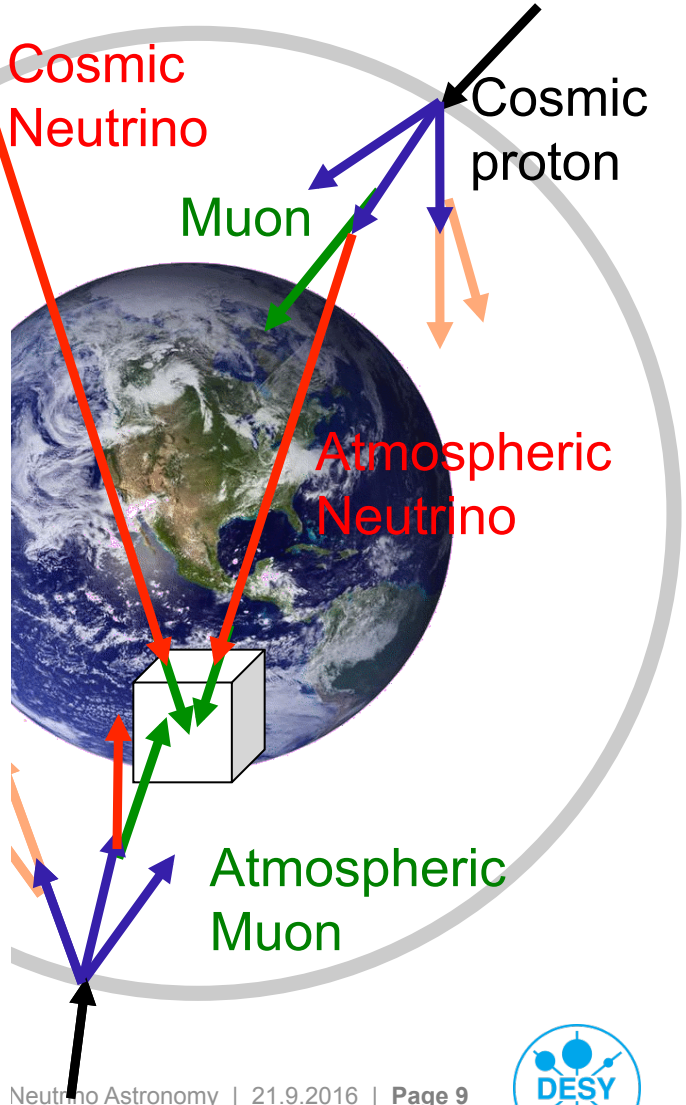
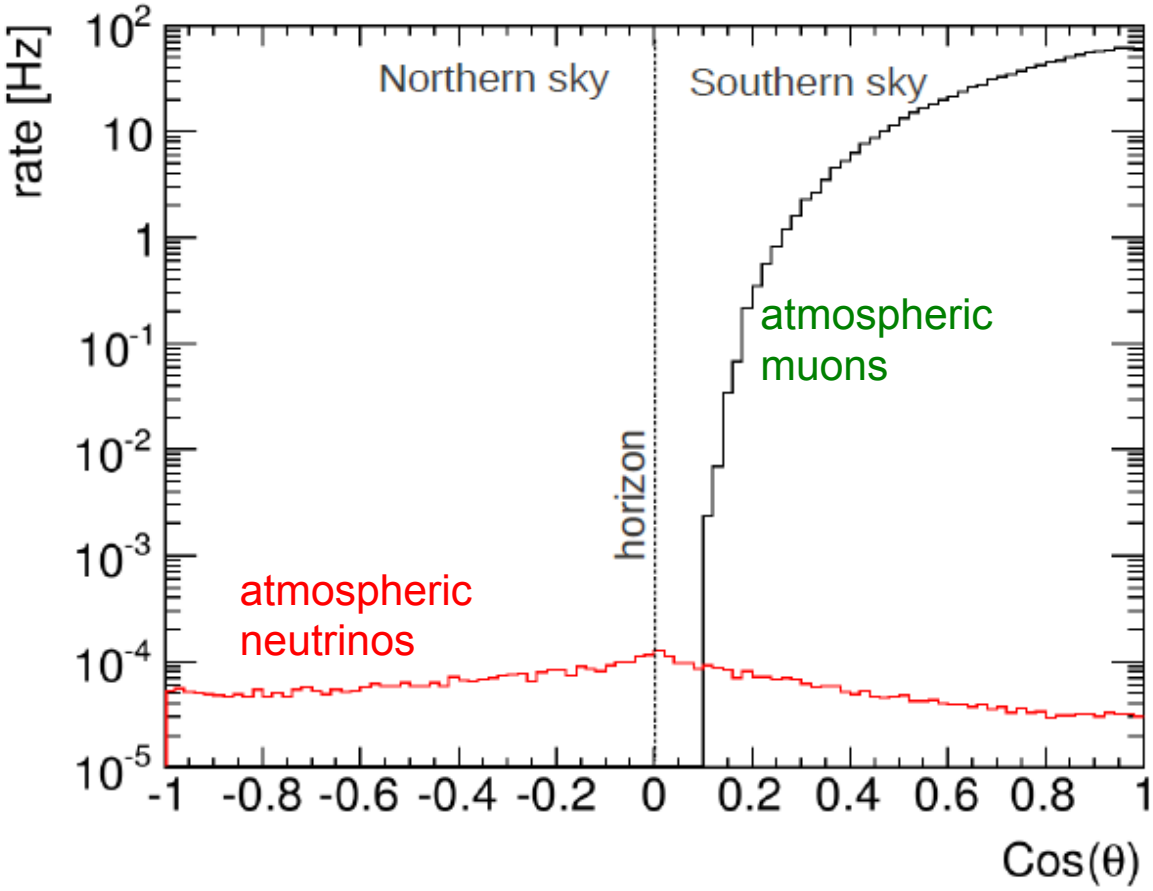
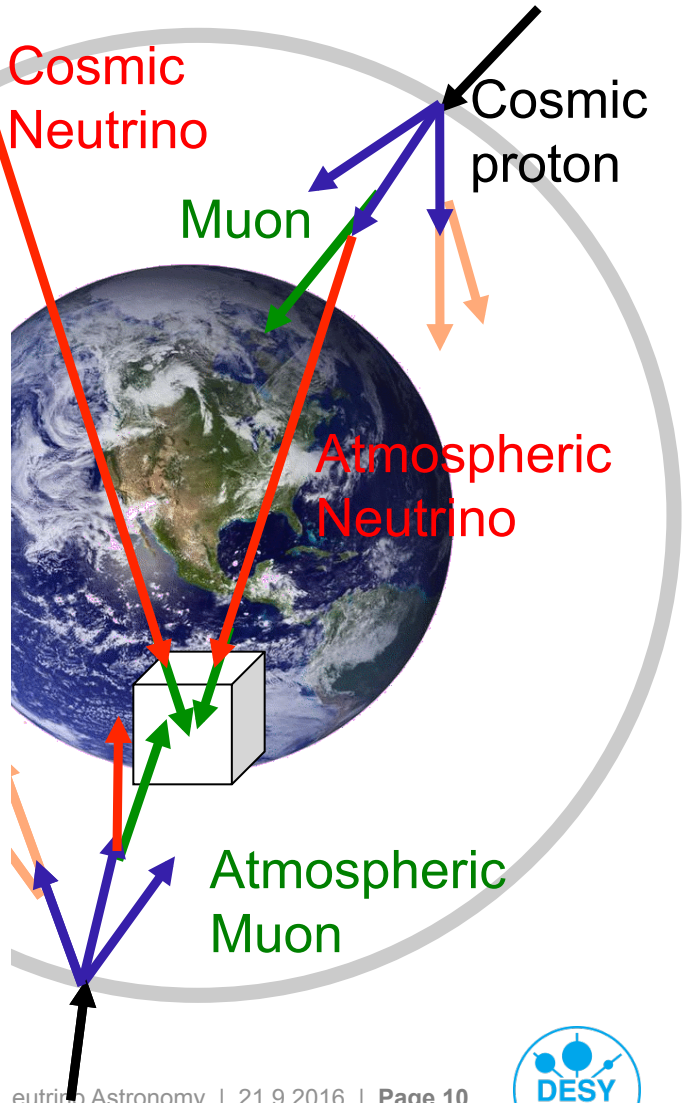




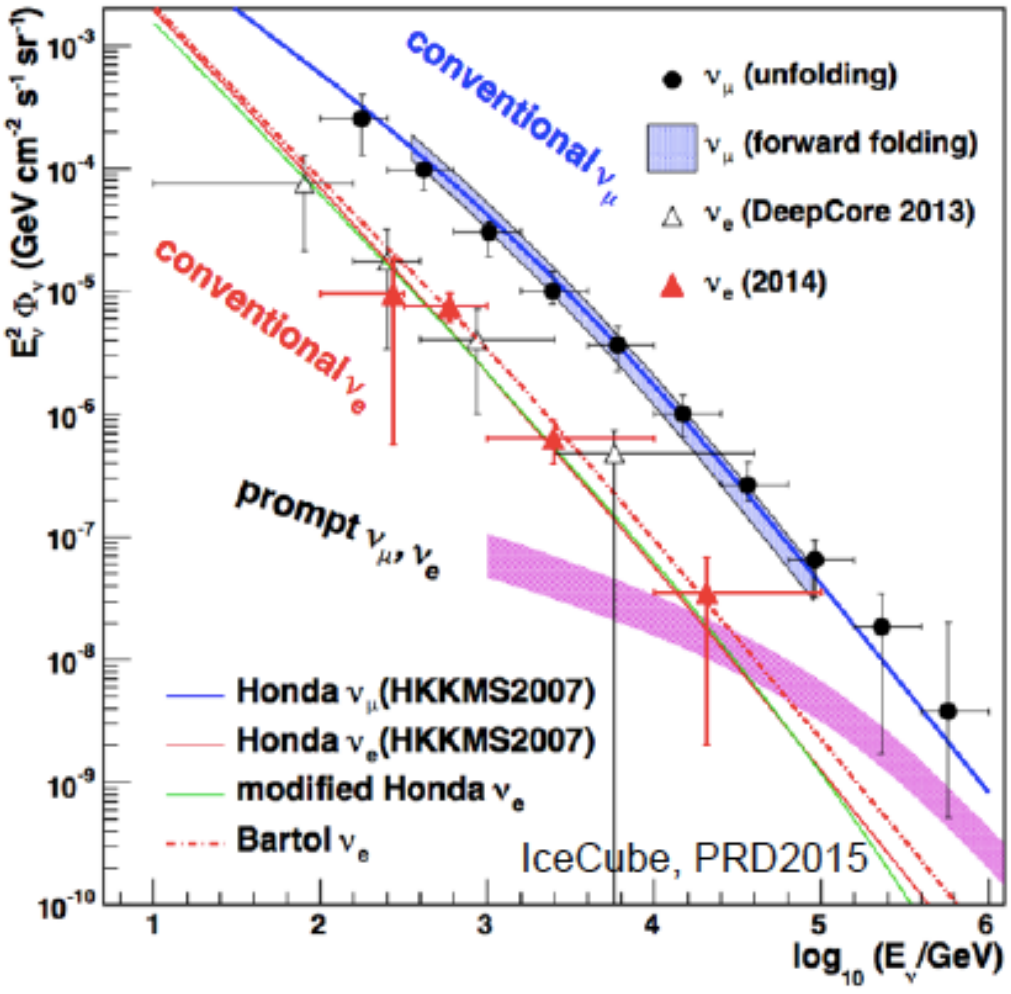
Background in Search for Cosmic Neutrinos

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

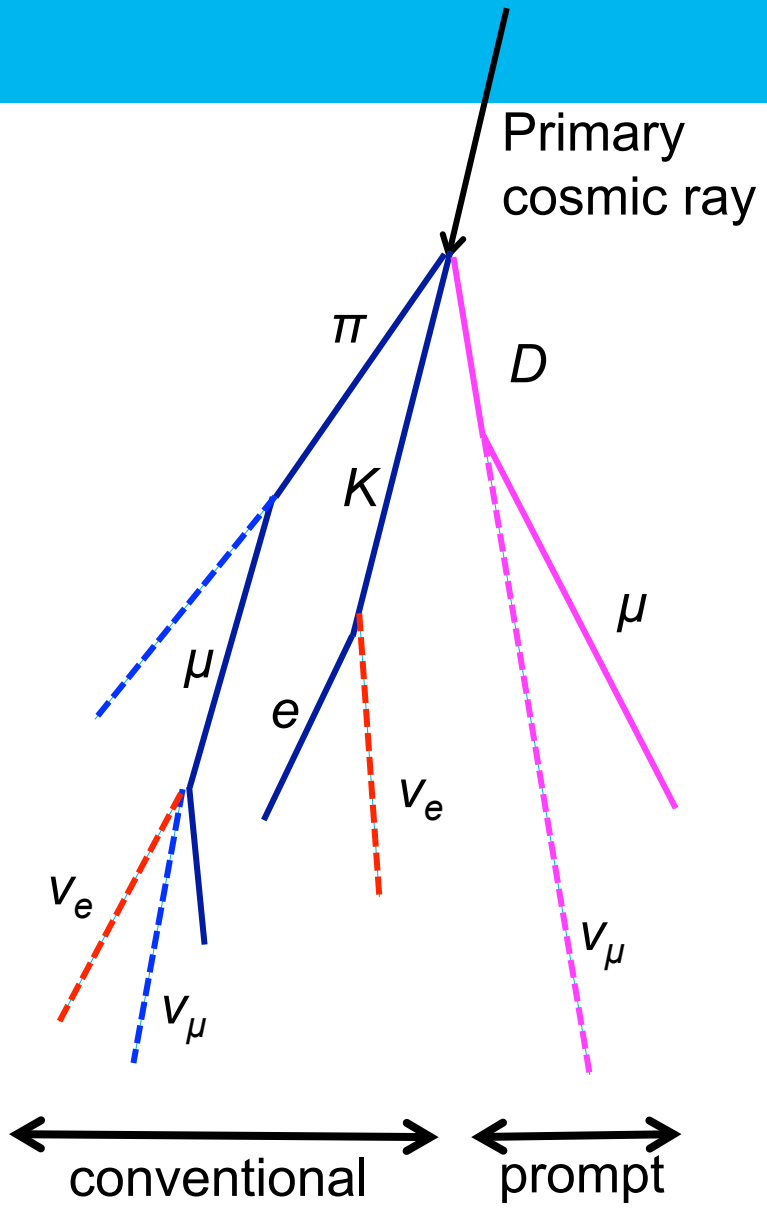




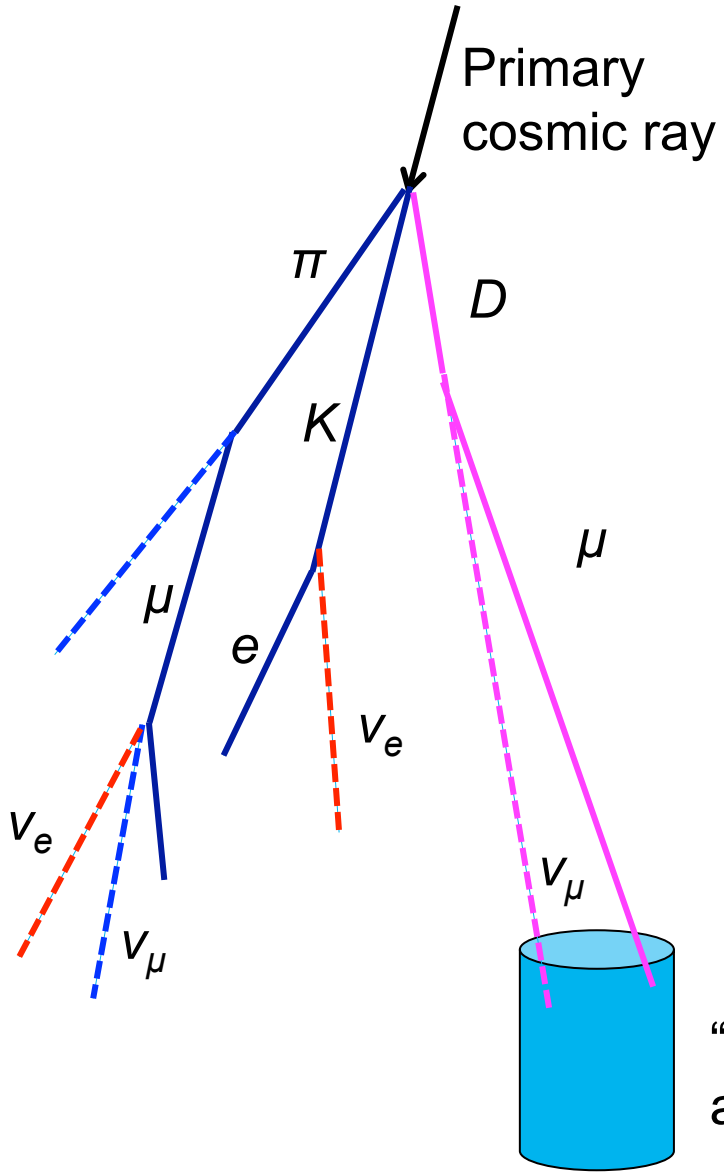
Atmospheric Neutrinos

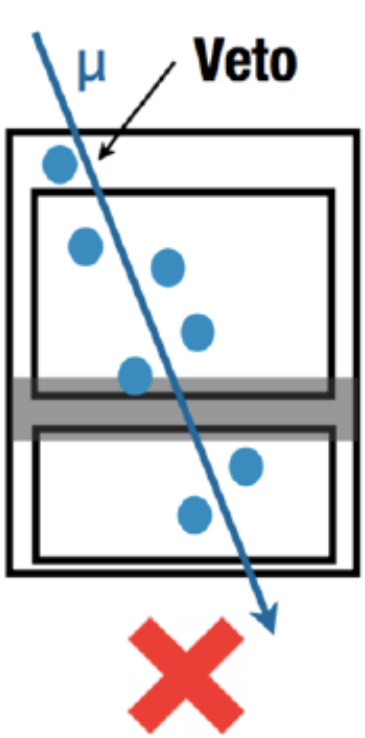


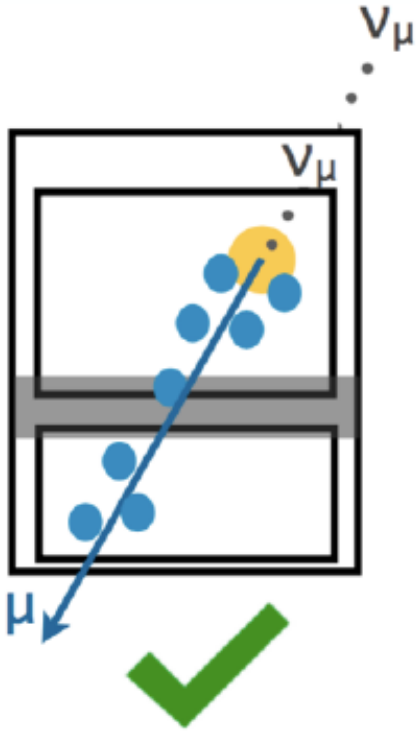
> 70.000 ν_μ / yr



Vetoing Atmospheric Muons and Neutrinos

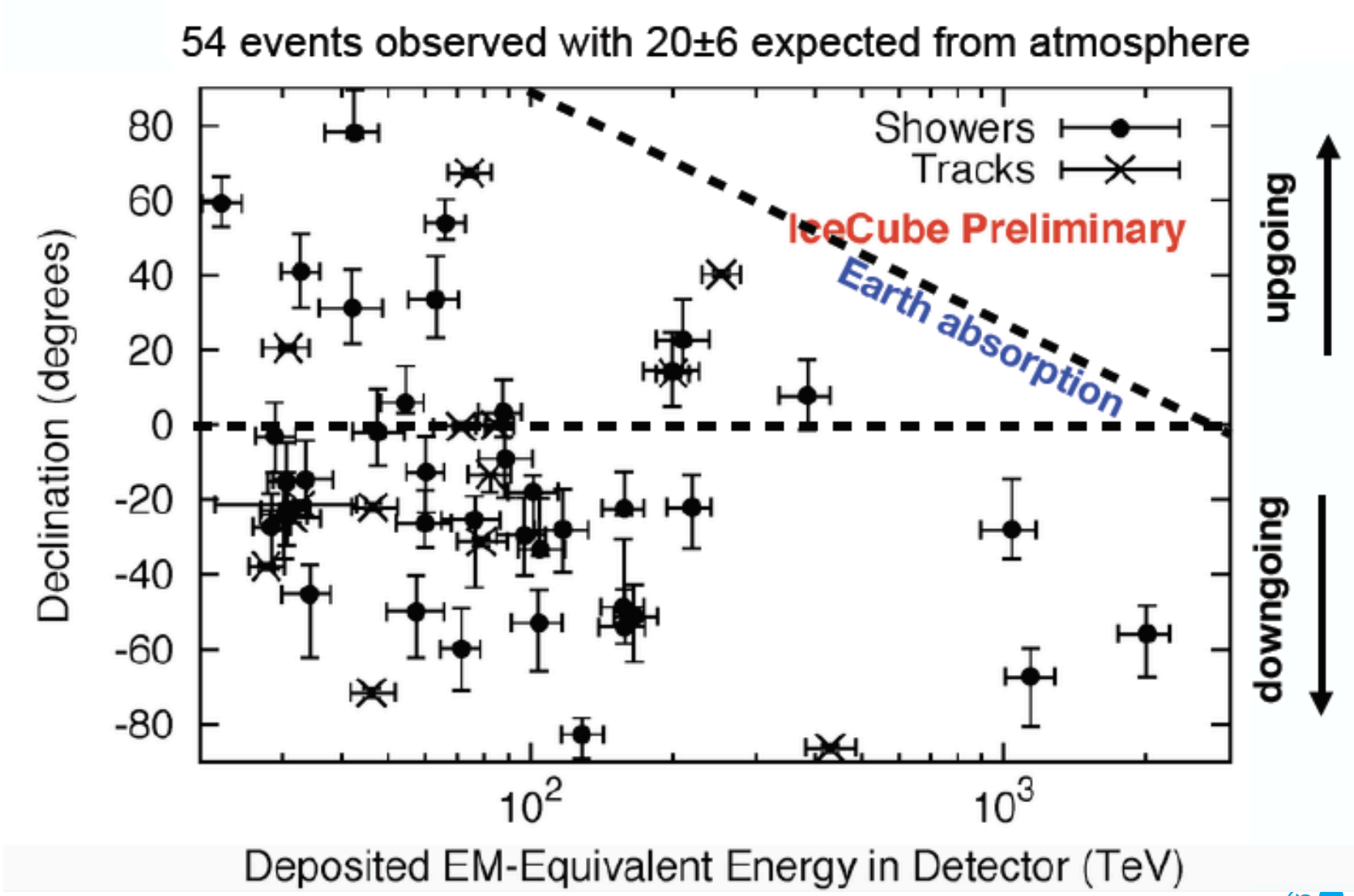






"Self-veto" of
atm. neutrinos

First Astrophysical Neutrinos!



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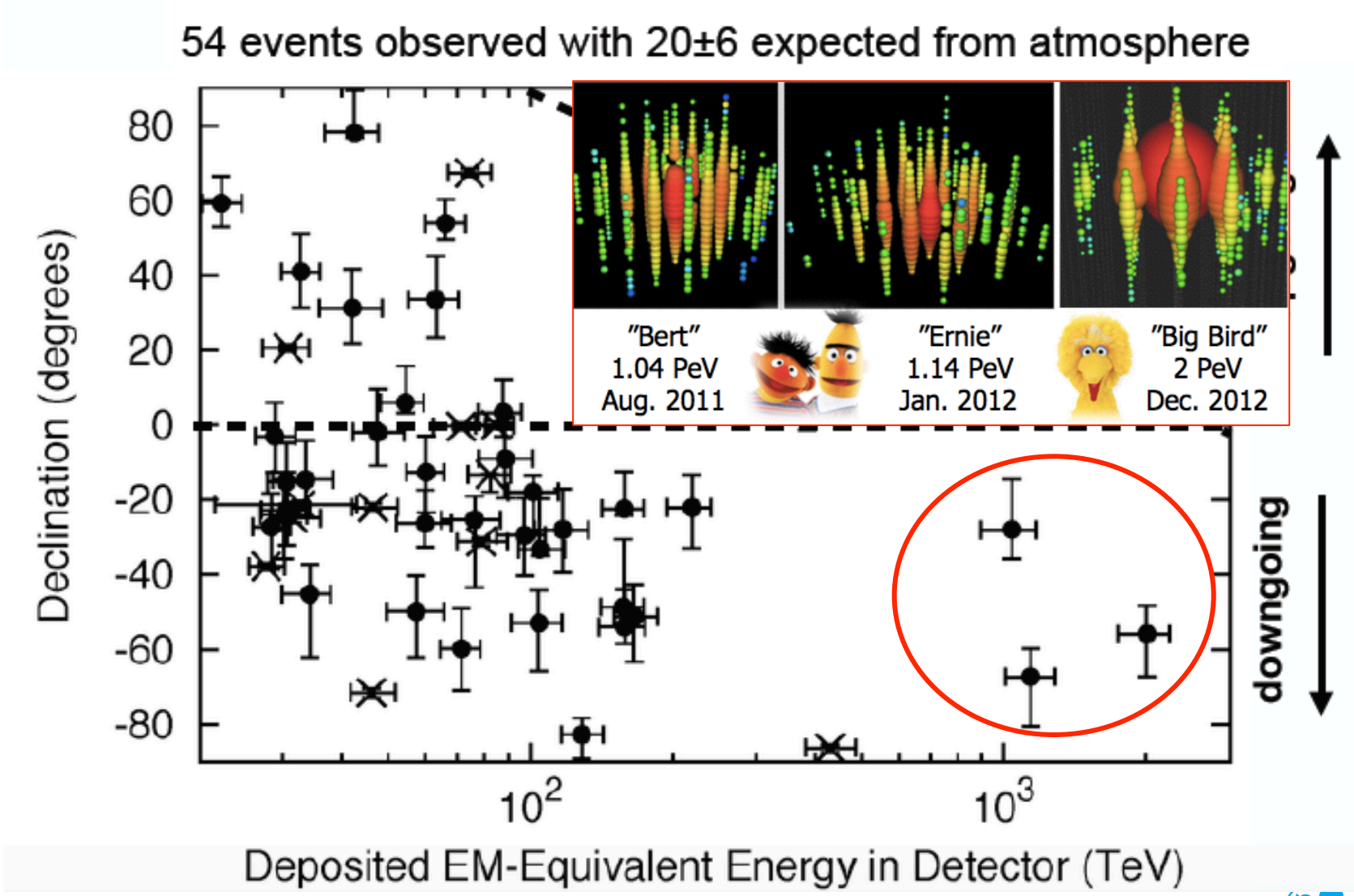
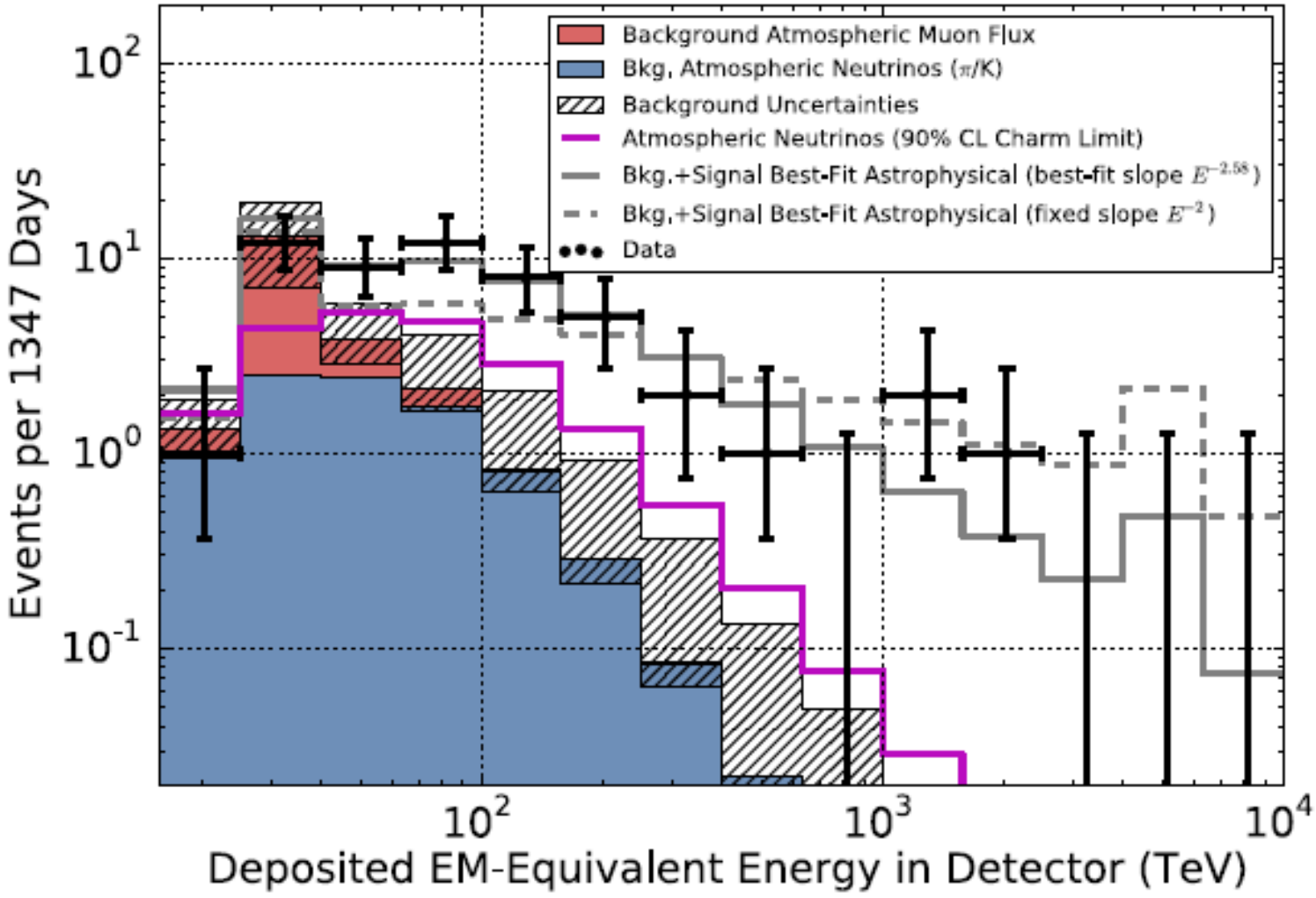


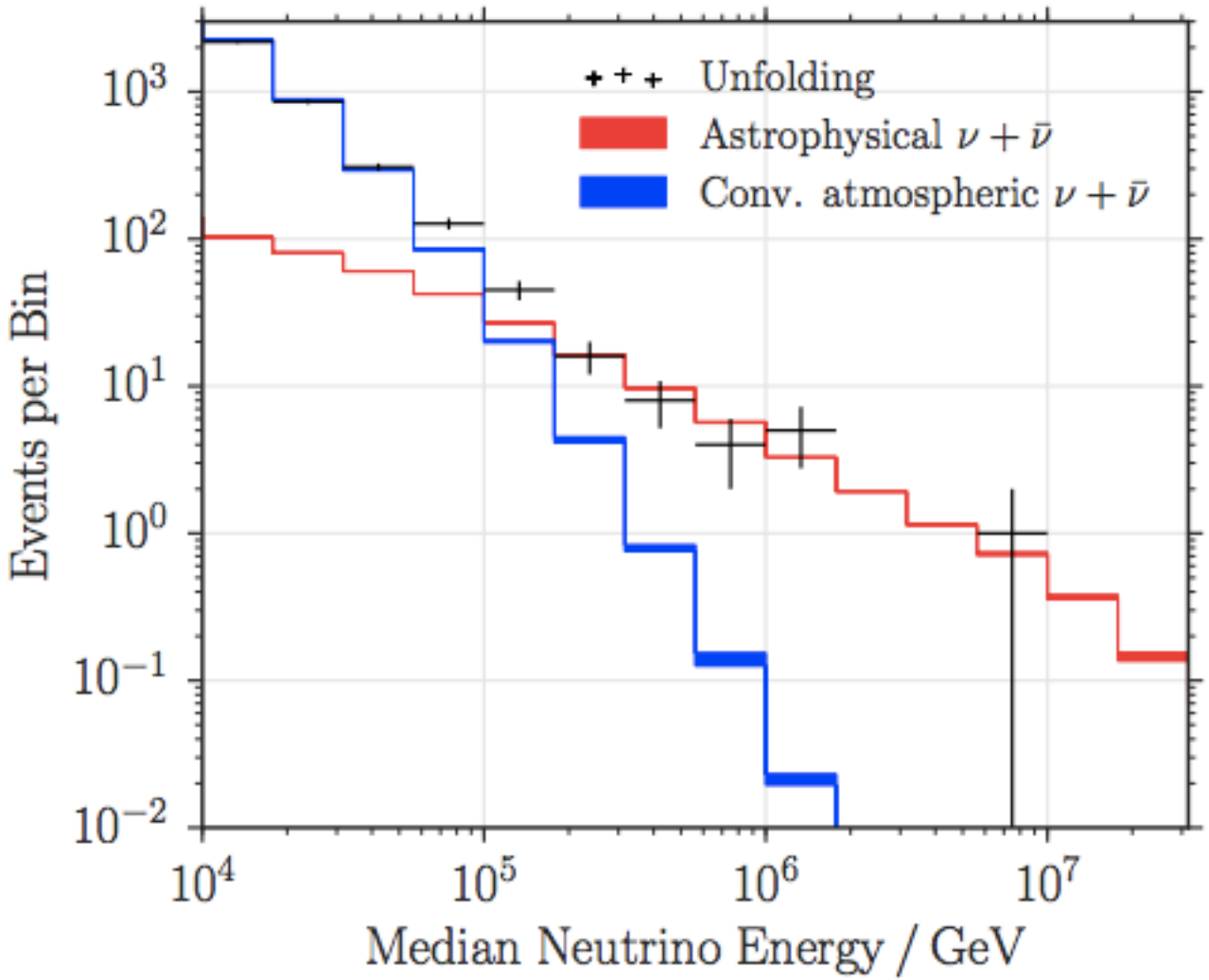
Energy Spectrum

IceCube Coll., Science 342, 2013
PRL 113, 101101 (2014)

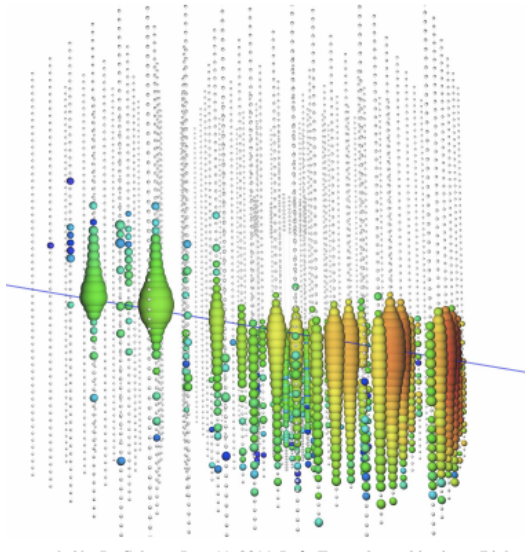


Through-going Events

arXiv:1607.08006



2.6 ± 0.3 PeV



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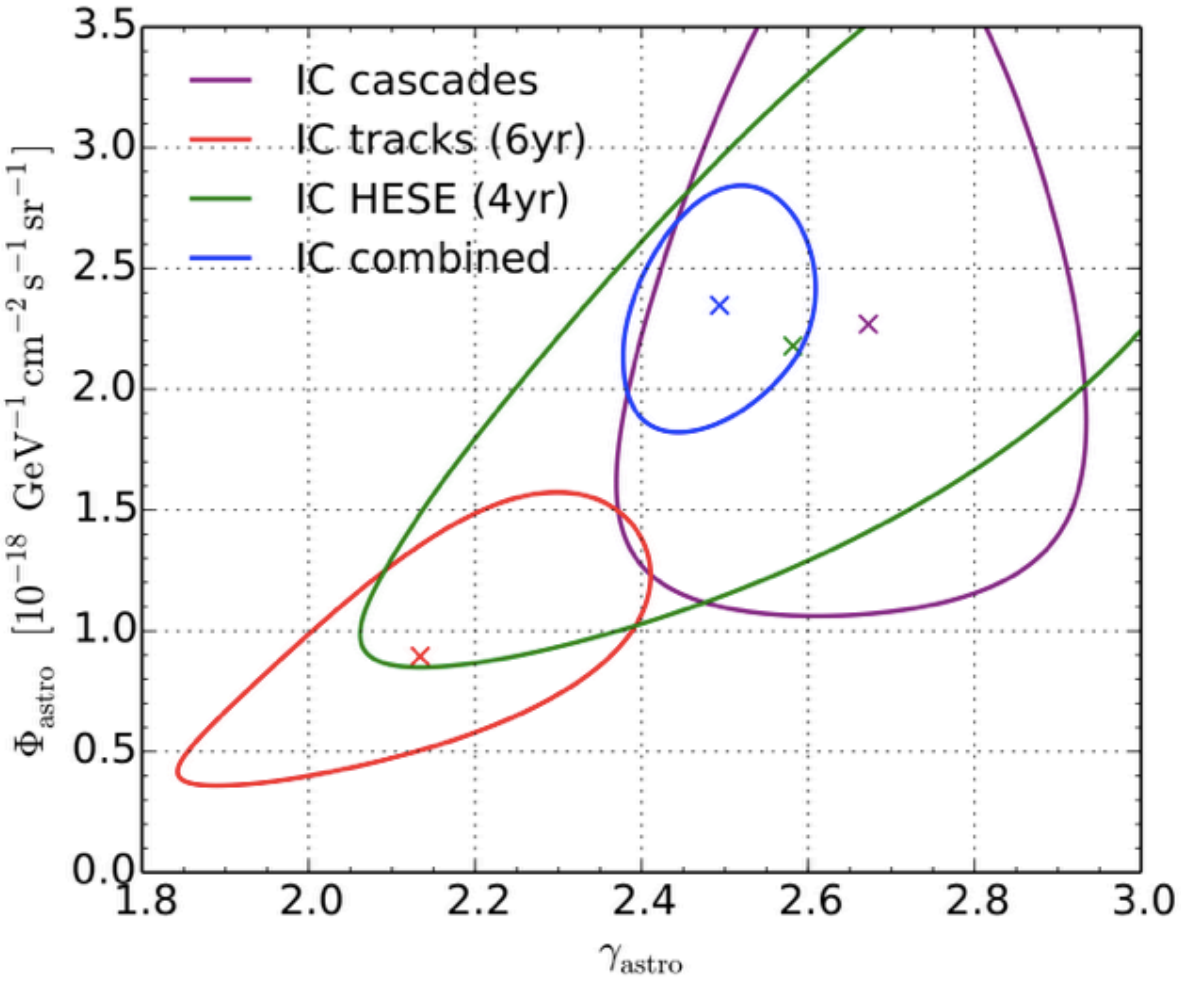
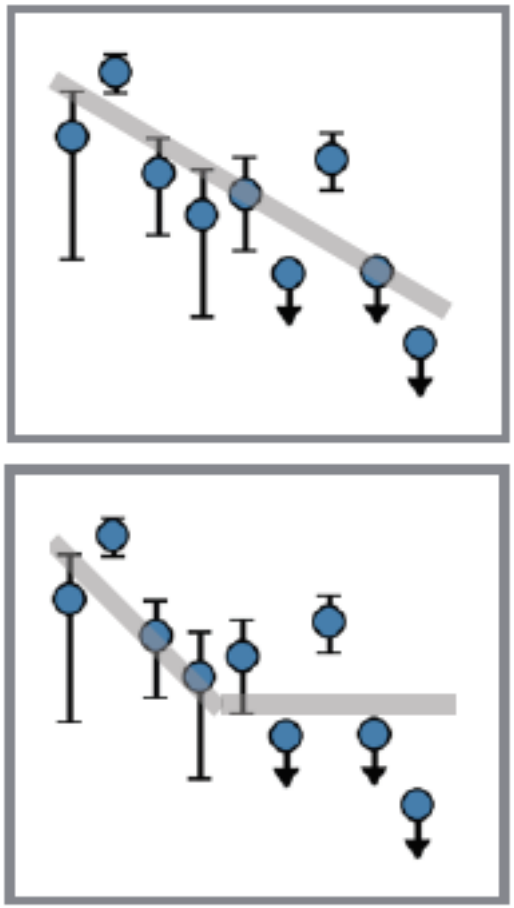
Spectral Shape

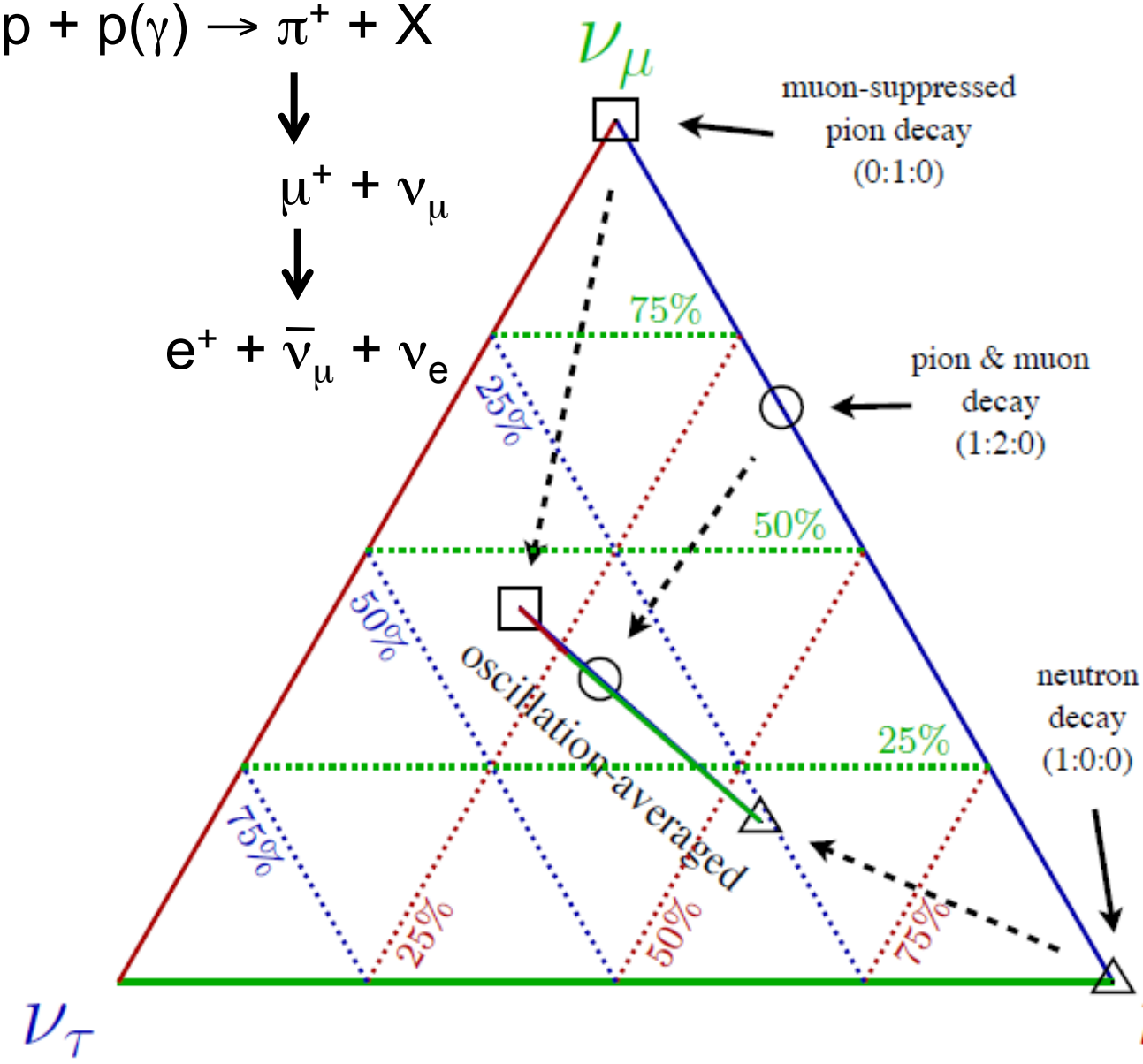




Are we seeing a spectral flattening of astrophysical neutrinos?

Flavor composition: what do we expect?

$$p + p(\gamma) \rightarrow \pi^+ + X$$
$$\downarrow$$
$$\mu^+ + \nu_\mu$$
$$\downarrow$$
$$e^+ + \bar{\nu}_\mu + \nu_e$$



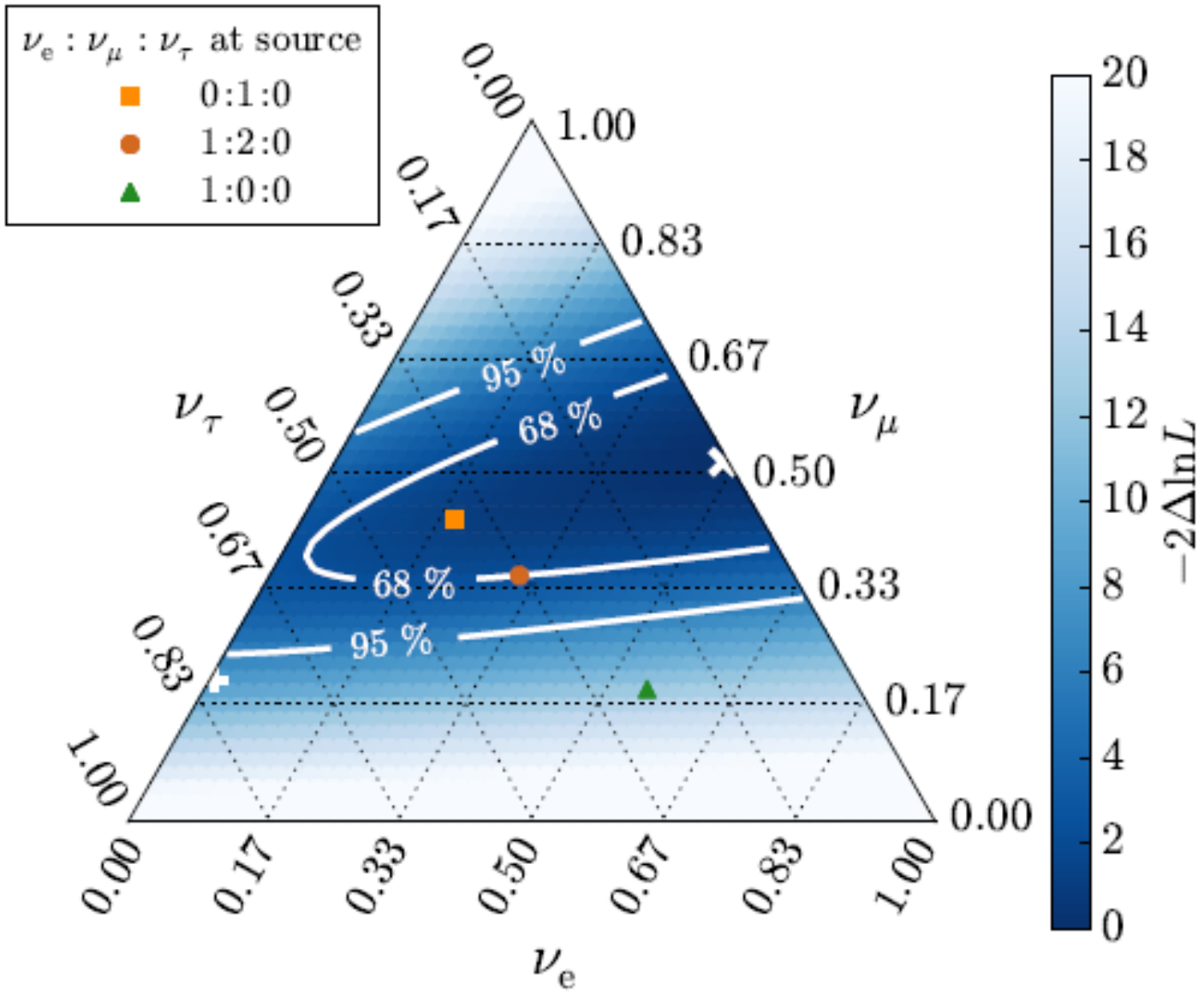
Muon loses energy before it decays due to large magnetic fields

"standard" scenario, pion decay

Neutron sources

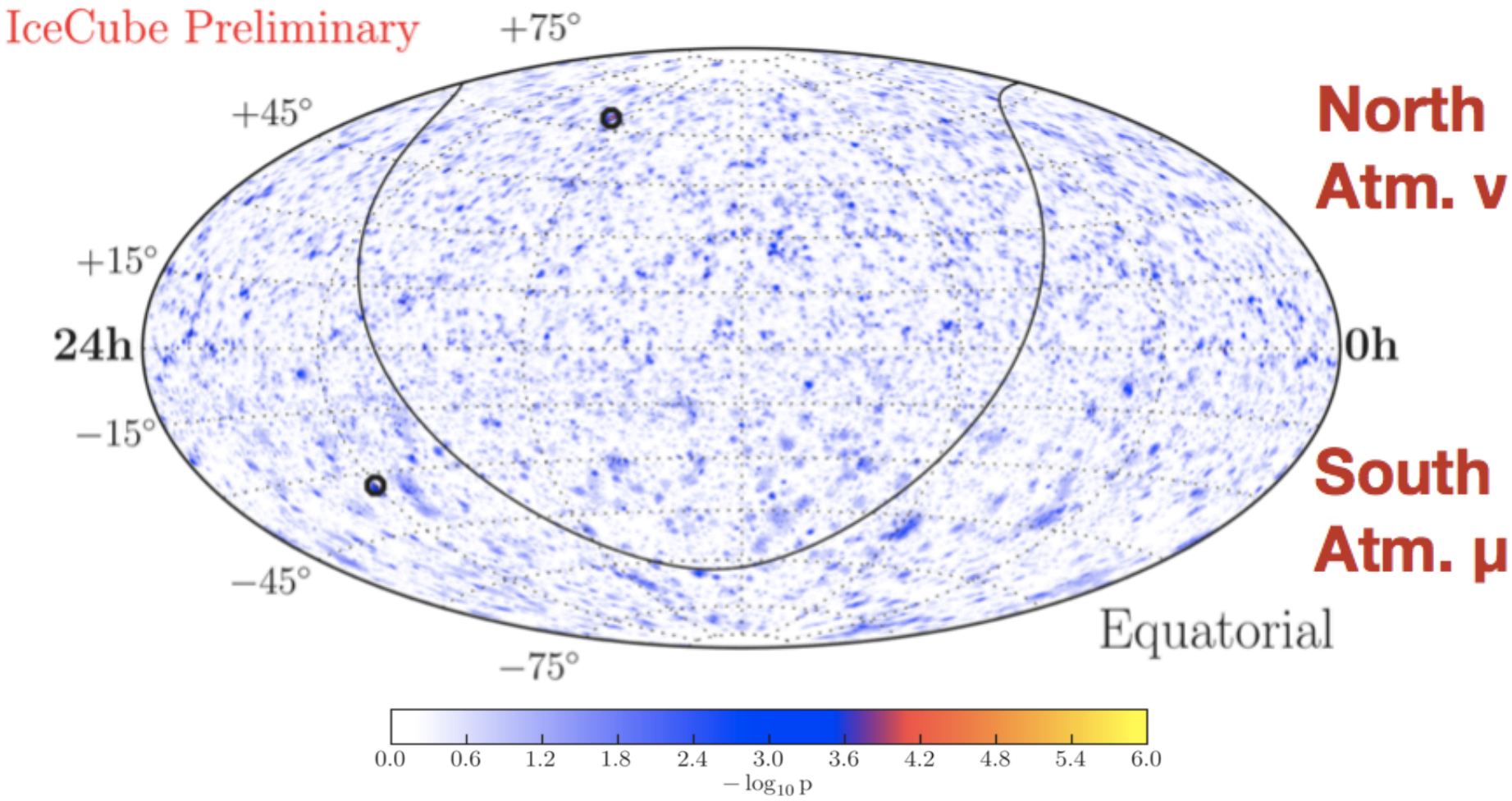
Flavor composition: what do we measure?

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



ApJ 809, 98 (2015)

Looking for Spatial Neutrino Clusters: Point Source Search



presented at ICRC 2015

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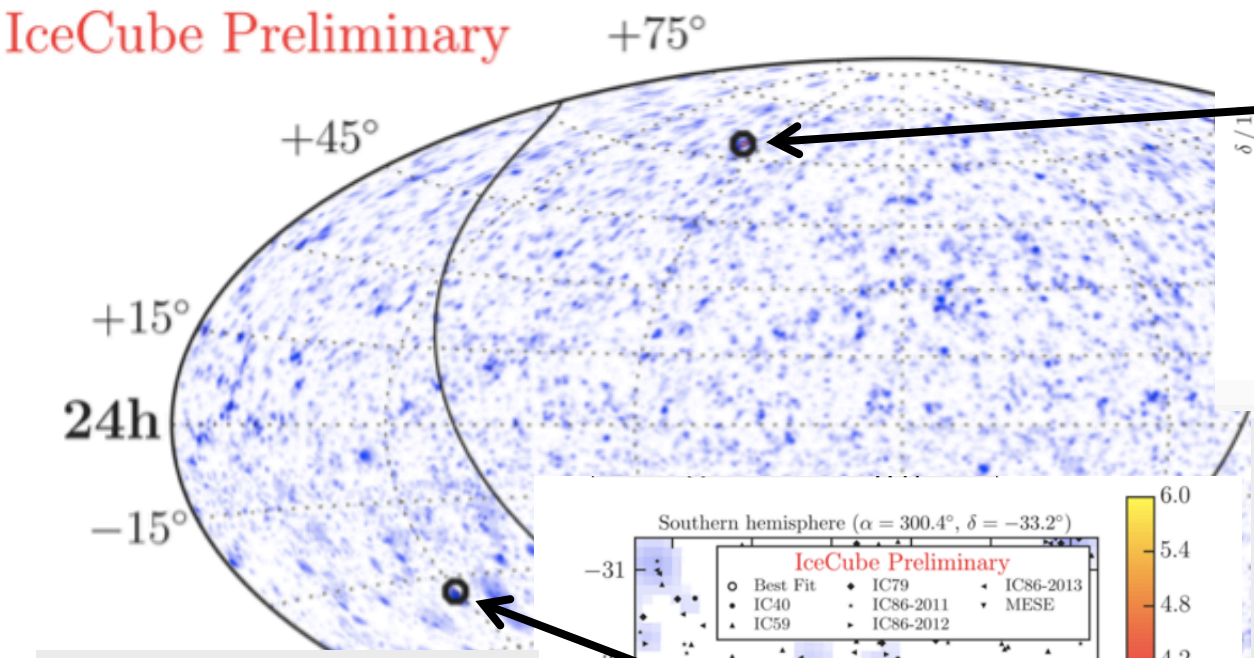
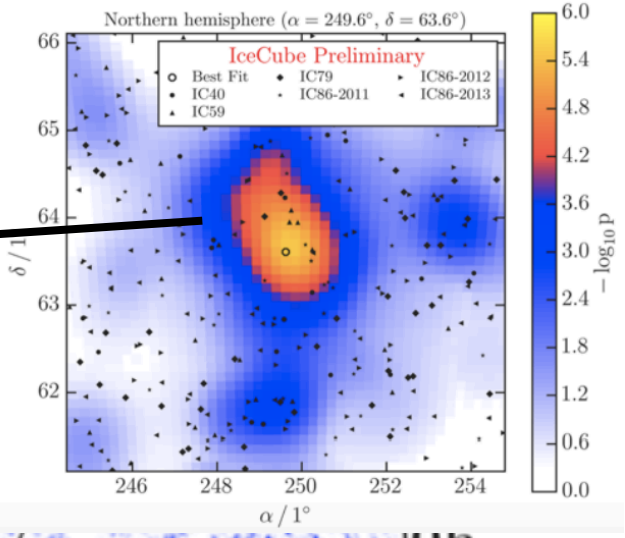
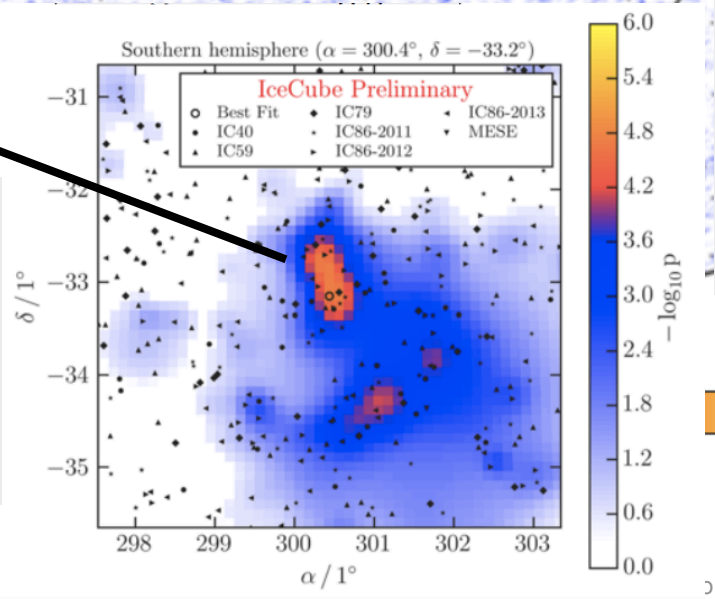




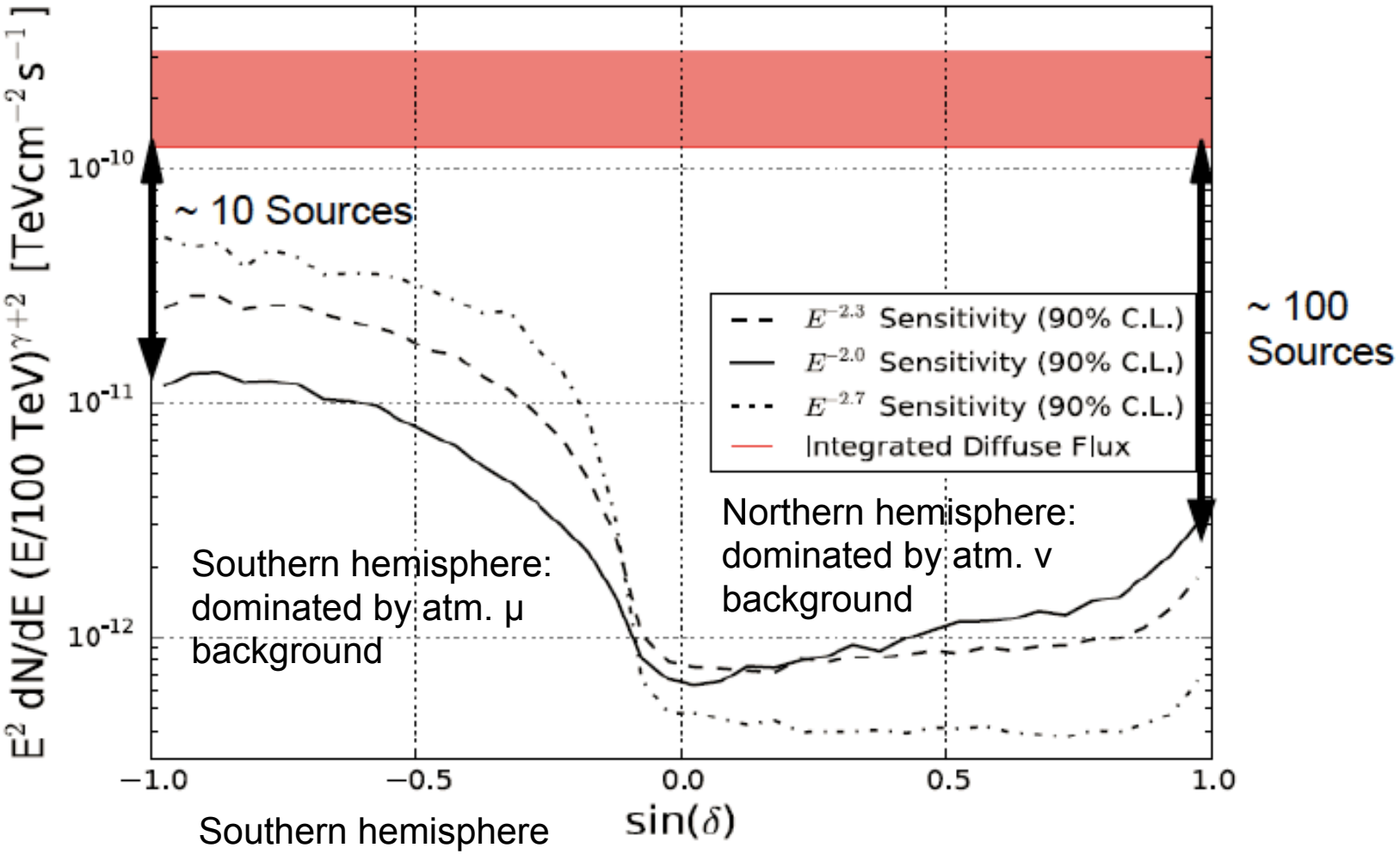


South	
-log10(p)	4.74
Post-Trial	87%
n_s	19.4
γ	2.3

North	
-log10(p)	5.51
Post-Trial	35%
n_s	28.4
γ	2.1

presented at ICRC 2015

Point Source Flux Limit – How many sources?



The Multi-Messenger Ansatz

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

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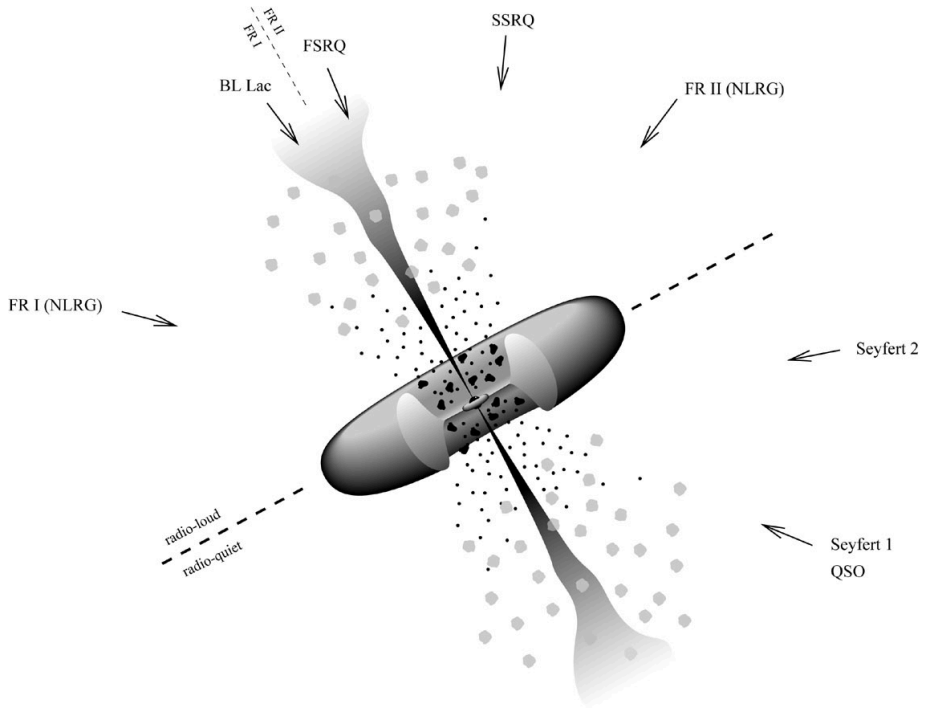
Electro-magnetic data can tell us **WHERE** and/or **WHEN**

Blazars

- Gamma rays tell us WHERE



IceCube Coll., arXiv:1502.03104

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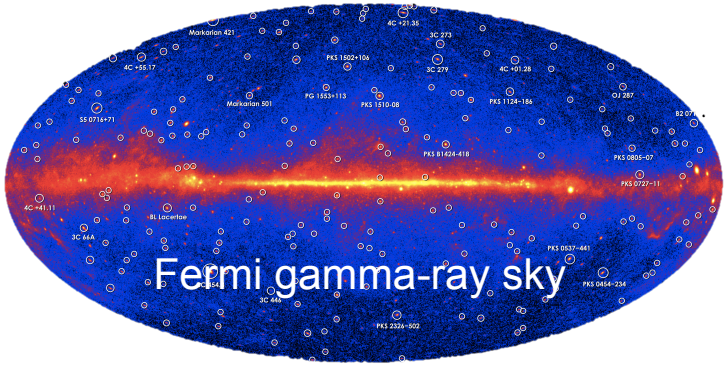
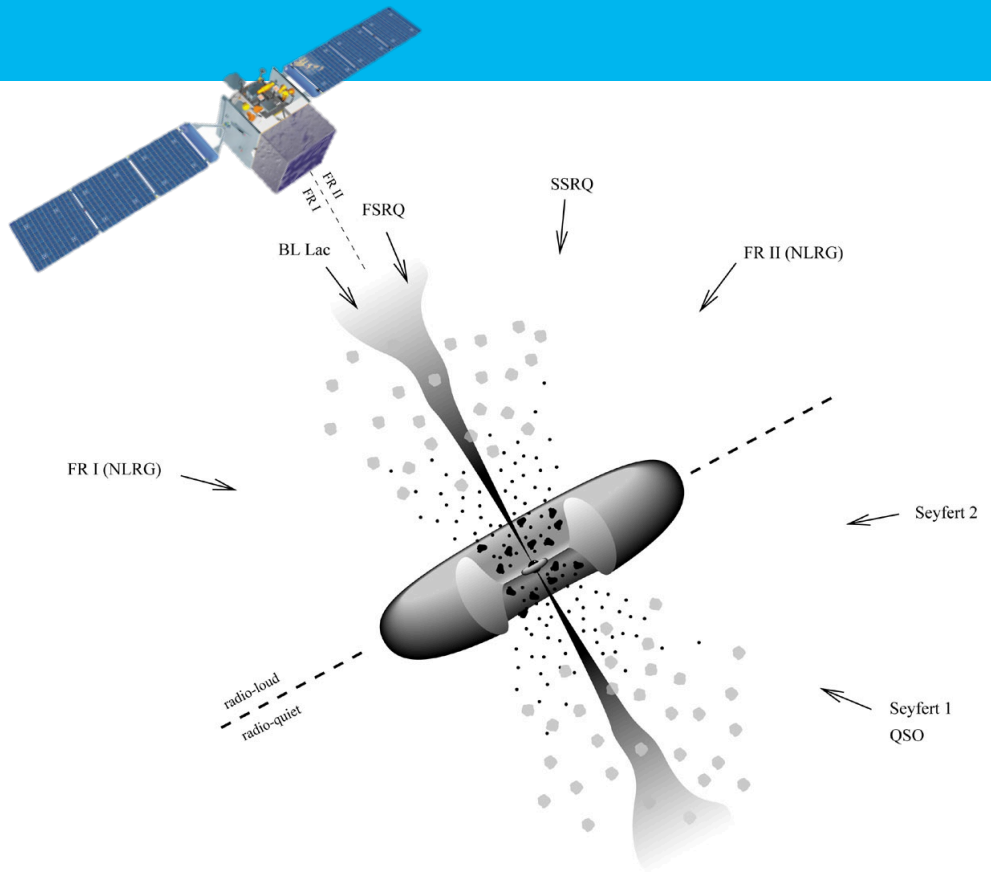


Fermi gamma-ray sky



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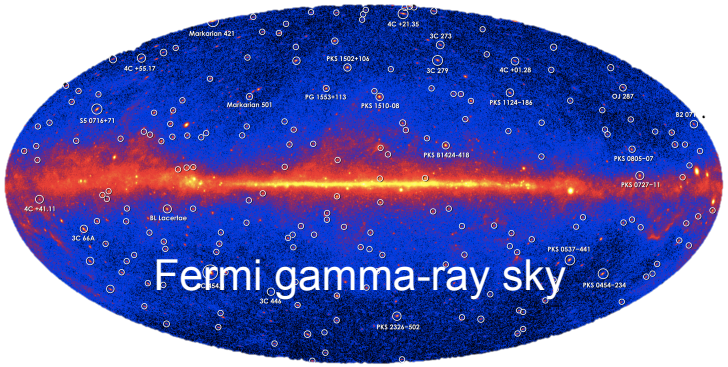
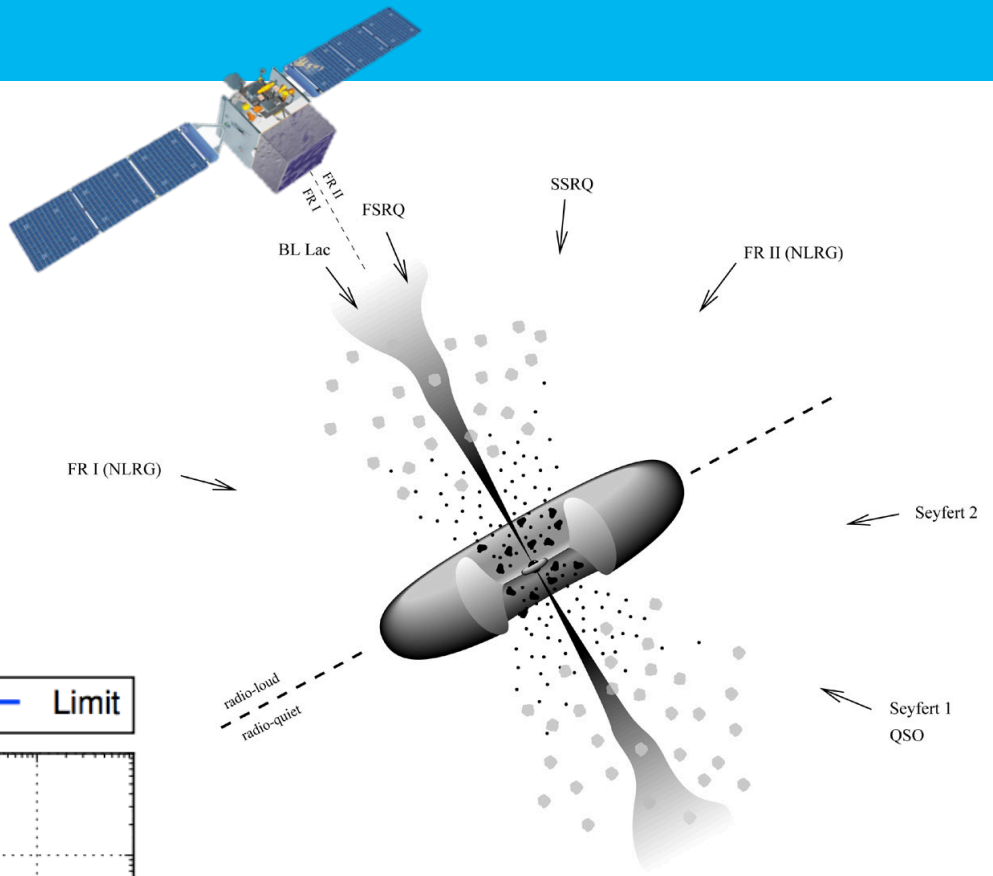
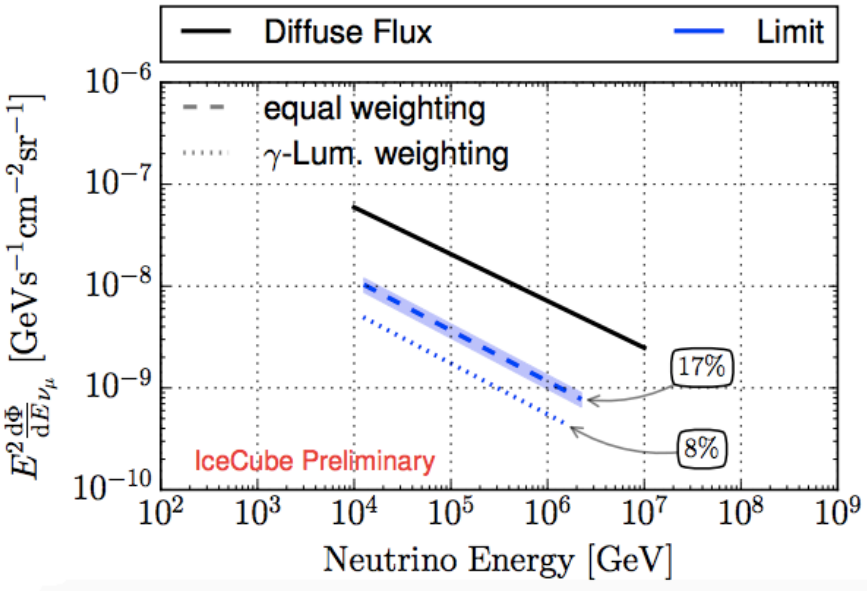




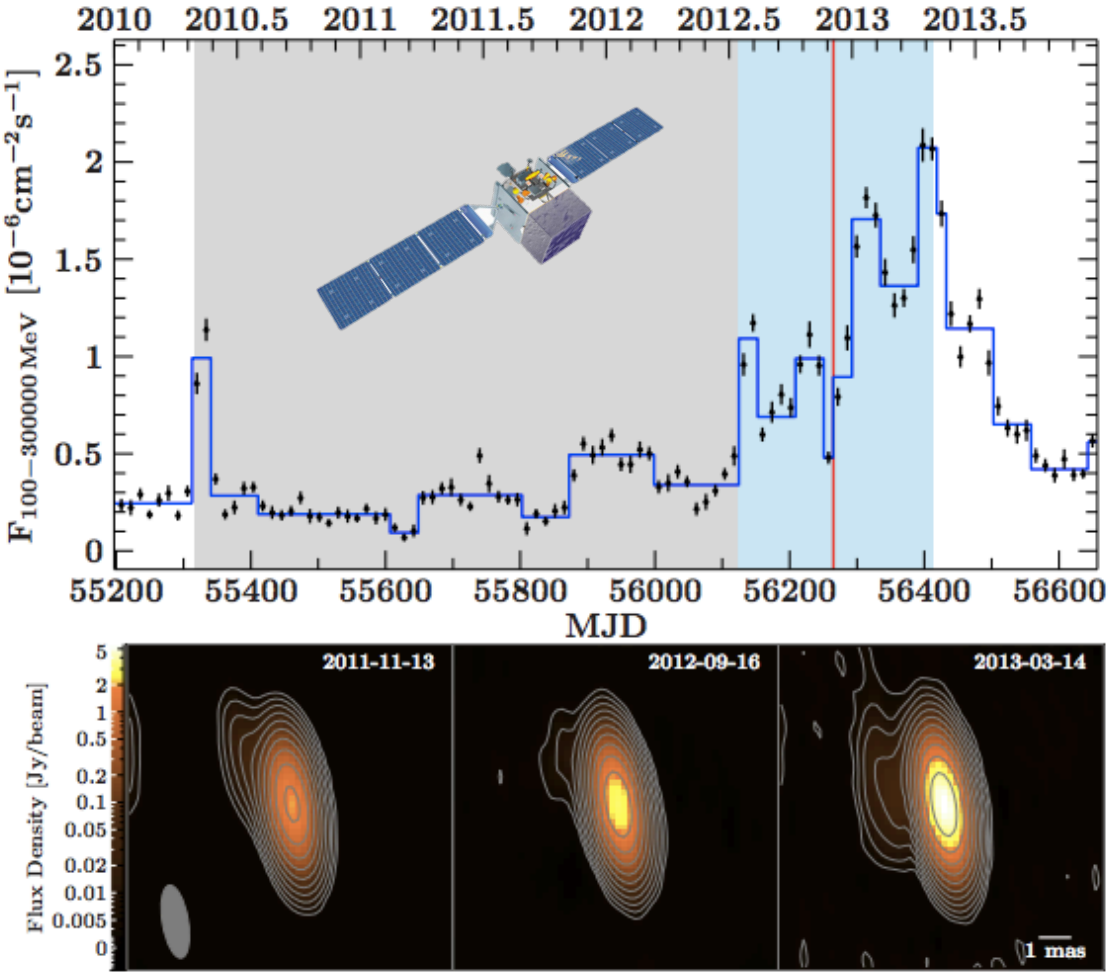


Correlation study of 3 years of IceCube data and 862 Fermi-LAT blazars

IceCube Coll., arXiv:1502.03104

Blazar Flares

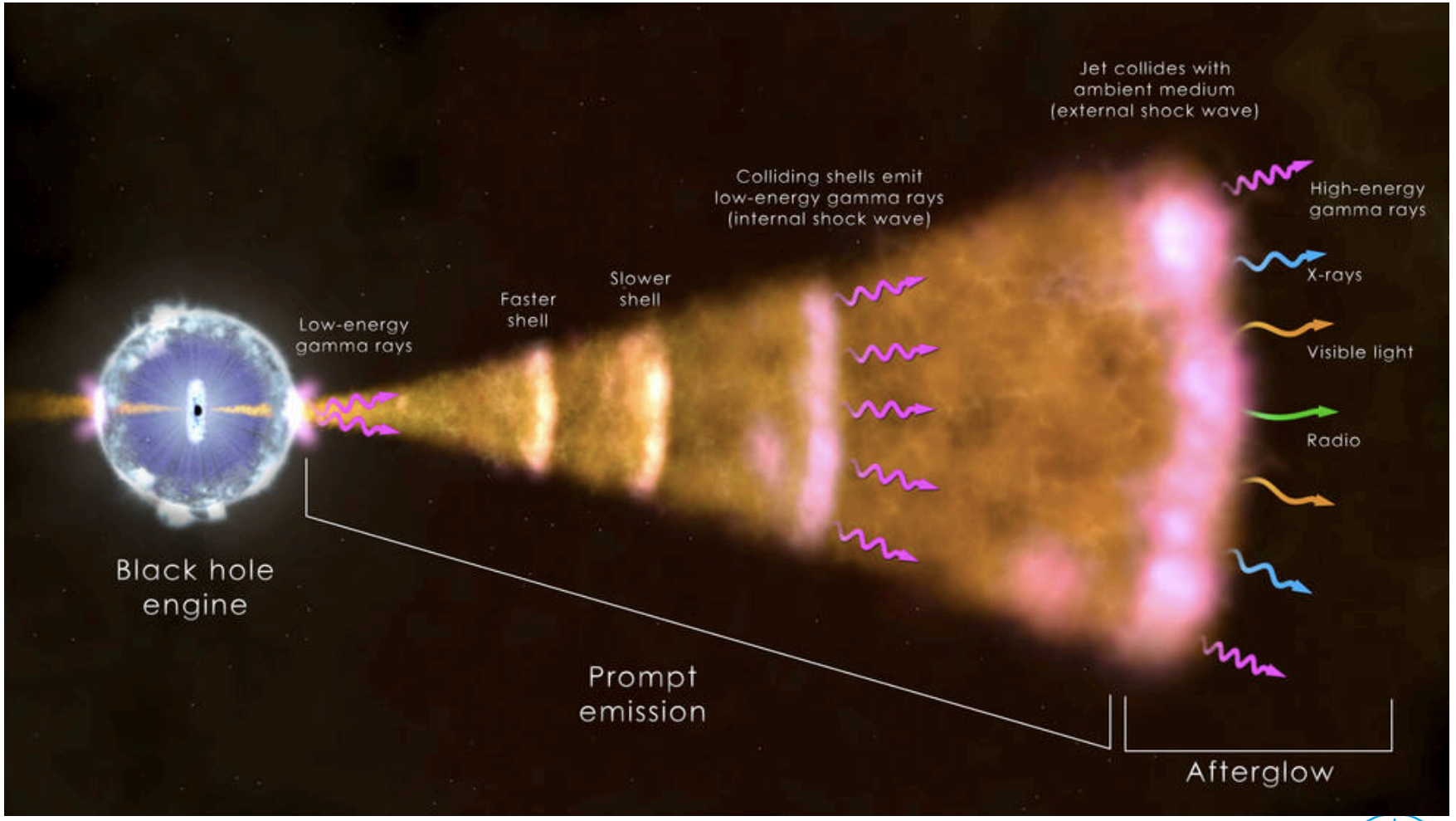
- Gamma rays tell us WHERE and WHEN
- Major outburst of blazar PKS B1424−418 occurred in temporal and positional coincidence PeV neutrino
- single source has sufficiently high fluence to explain an observed coinciding PeV neutrino event
- 5% chance coincidence



Kadler et al., Nature, 2016

Gamma-Ray Bursts (GRBs)

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



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- Extremely large energy release on the time-scale of 0.1-100 seconds
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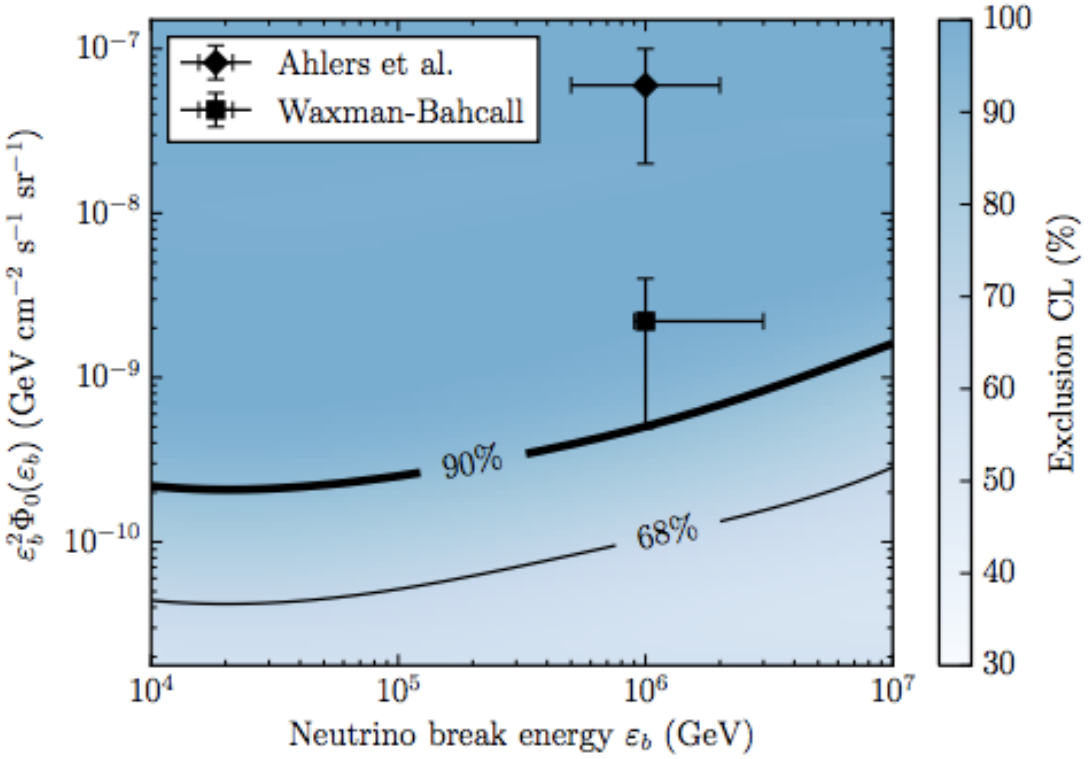
> 800 GRBs correlated with IceCube data



IceCube Coll., ApJ 805, 2015
arXiv:1601.06484

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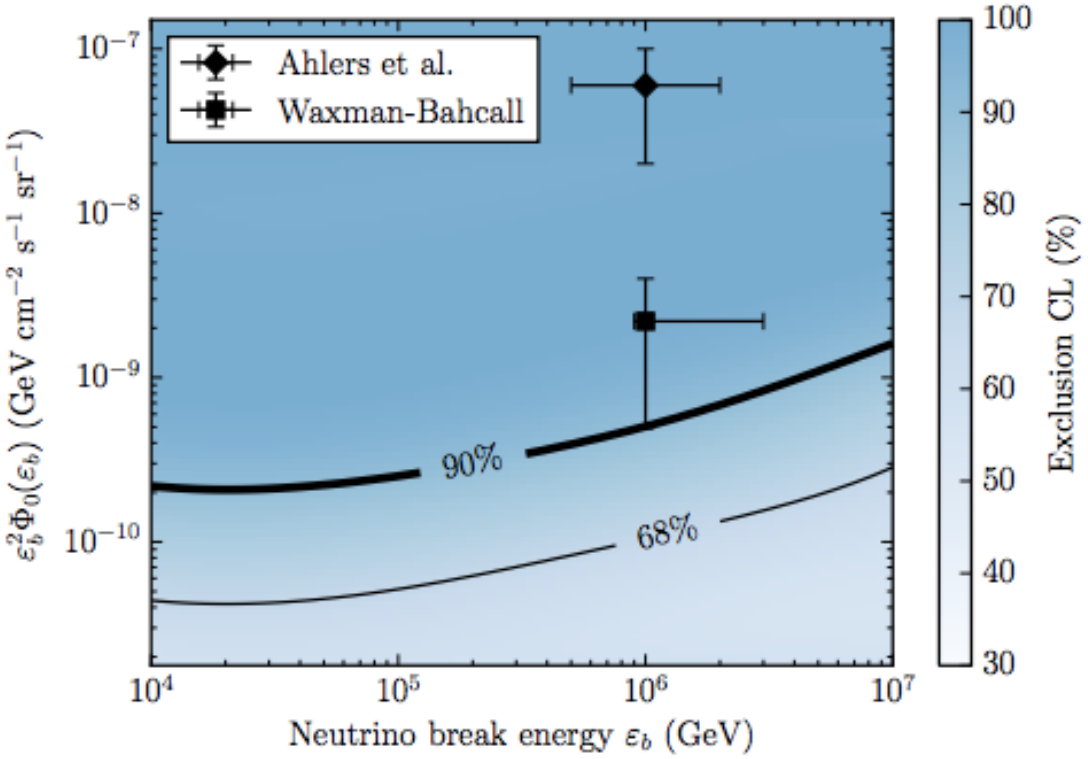
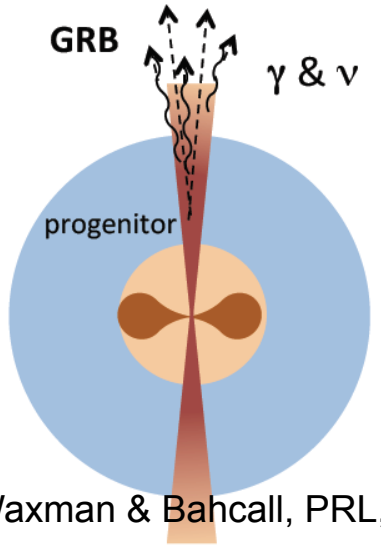


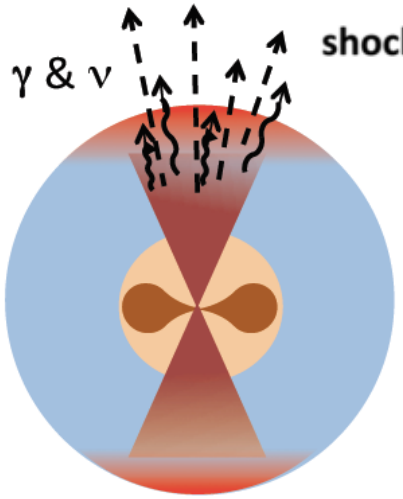
GRBs contribute less than 1% to observed diffuse neutrino flux.
Potential large population of nearby low-luminosity GRBs not constrained.

IceCube Coll., ApJ 805, 2015
arXiv:1601.06484

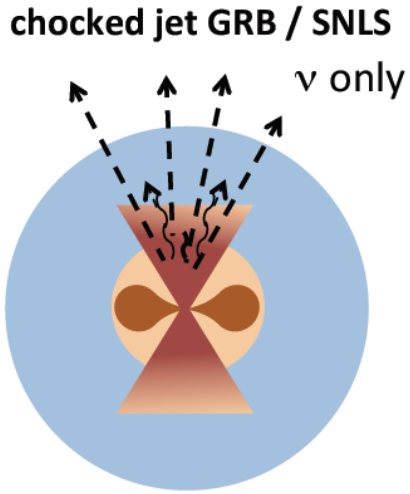
Supernovae (SNe)



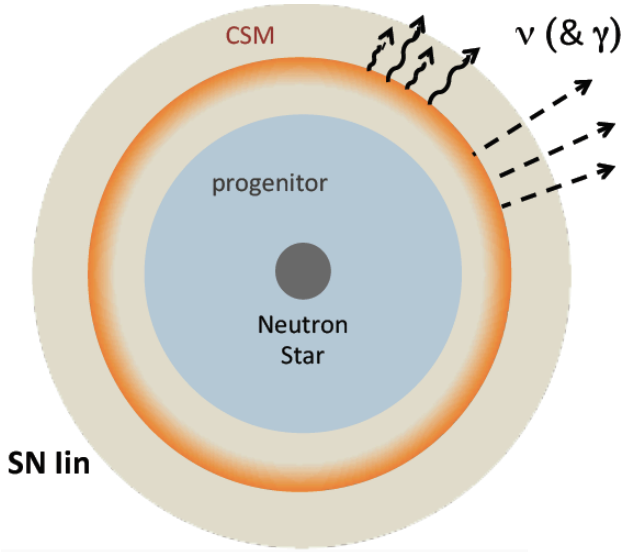
Waxman & Bahcall, PRL, 78 (1997)



Murase et al, ApJL,651 (2006)



Ando & Beacom, PRL 95 (2005)



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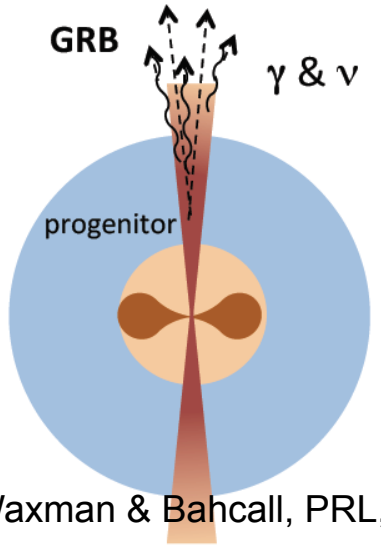

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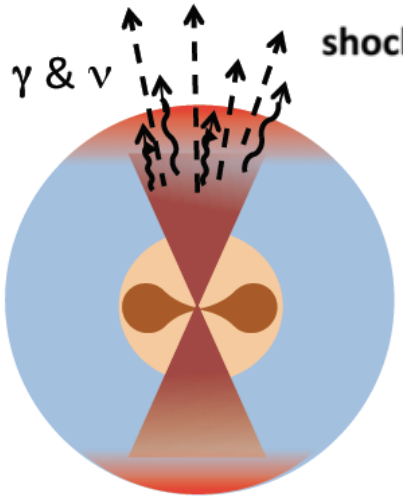

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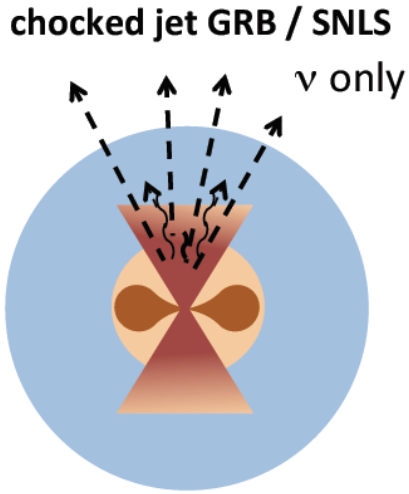

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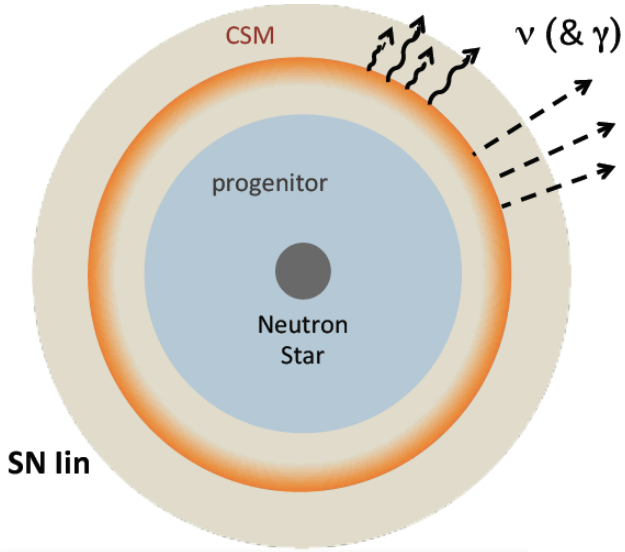

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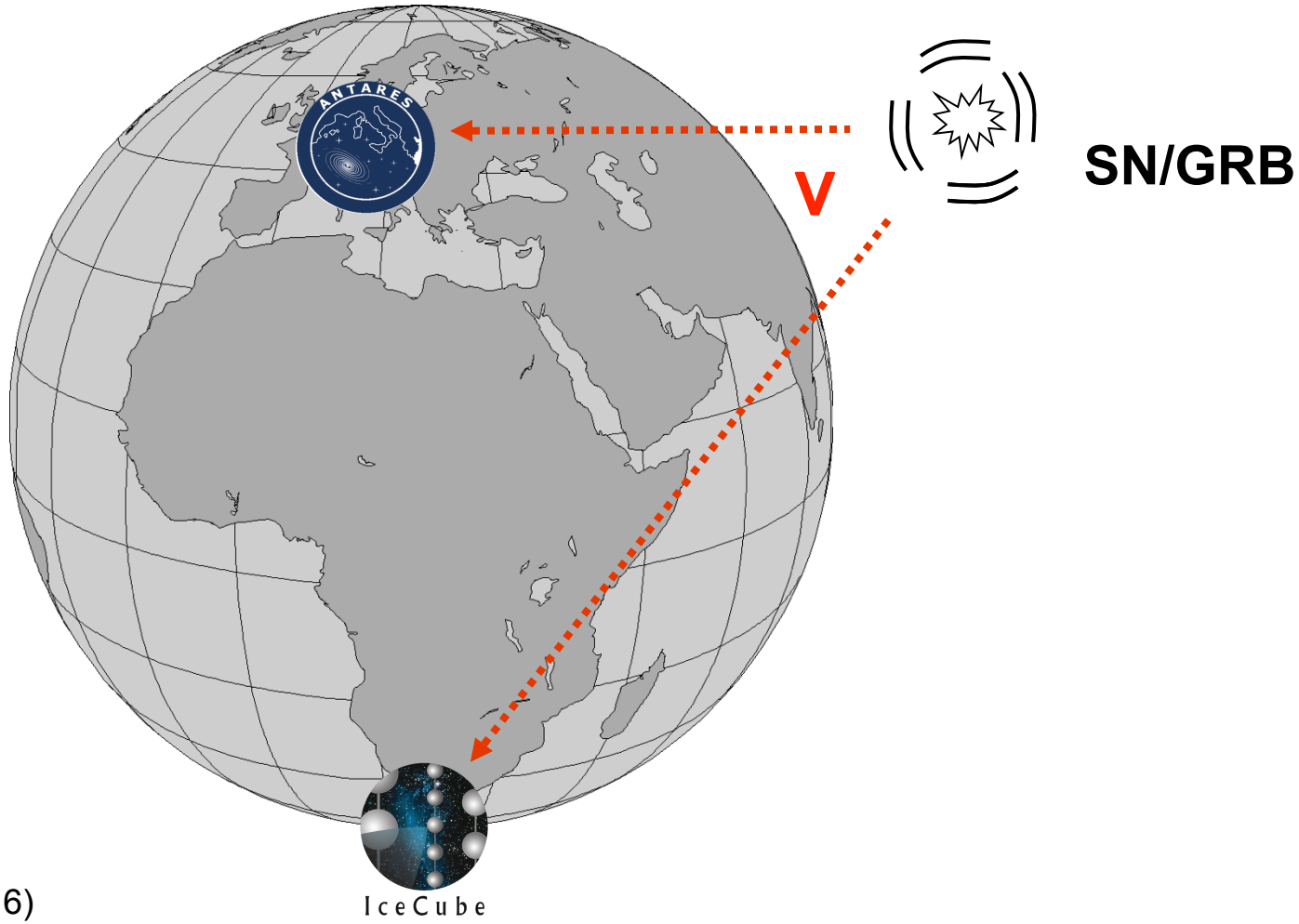
SNe are best discovered in optical

optical surveys do not cover the whole sky

use IceCube to trigger EM follow-up

DESY

Optical Follow-Up

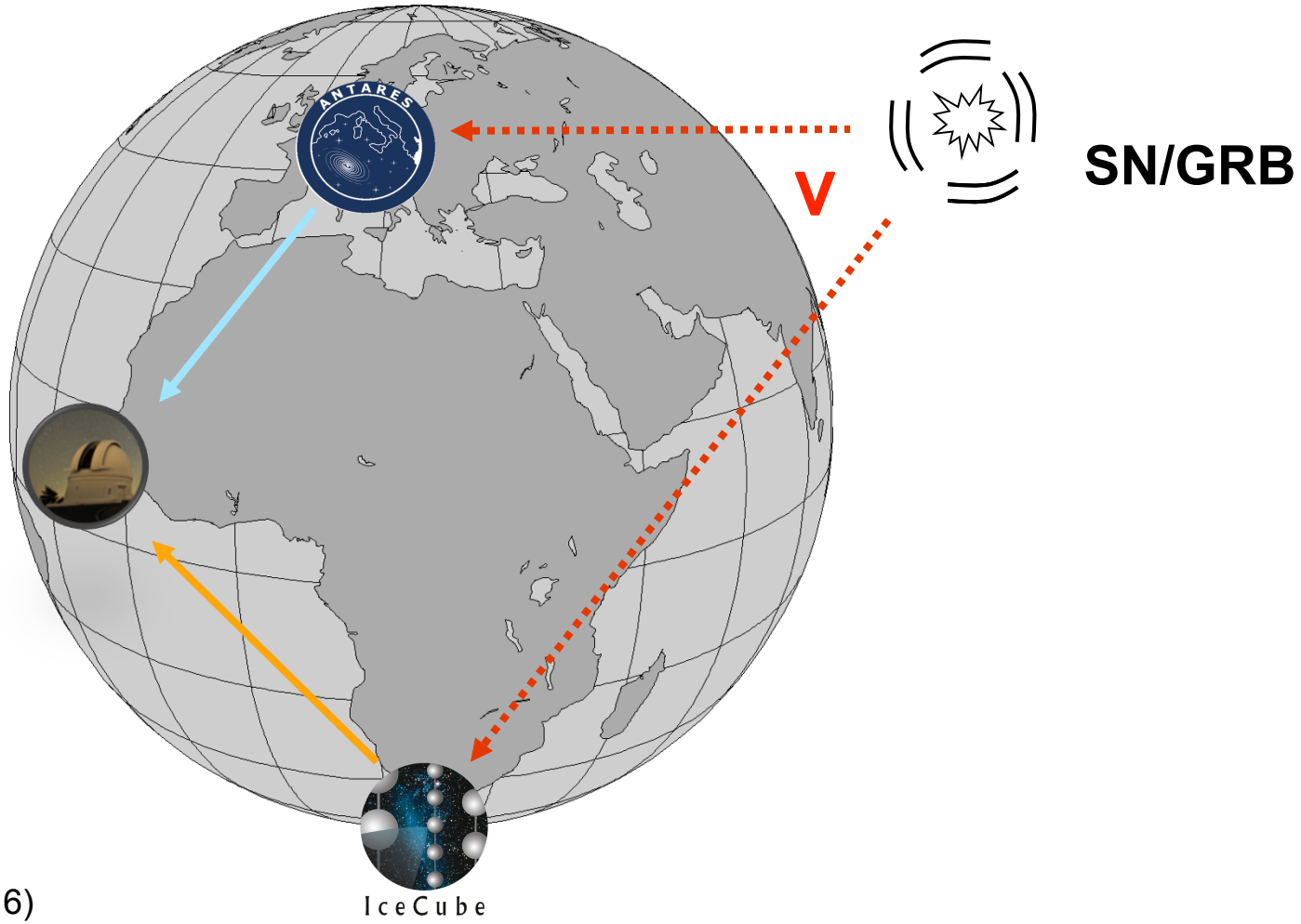


ANTARES JCAP 1602 (2016)
Ackermann et al.arXiv:0709.2640
IceCube A&A 539, A60 (2012)

Thomas Kintscher and IceCube Coll.
2016 *J. Phys.: Conf. Ser.* **718** 062029

Optical Follow-Up

Optical Telescopes
(iPTF, MASTER, Tarot, Pan-STARRS, ASAS-SN)



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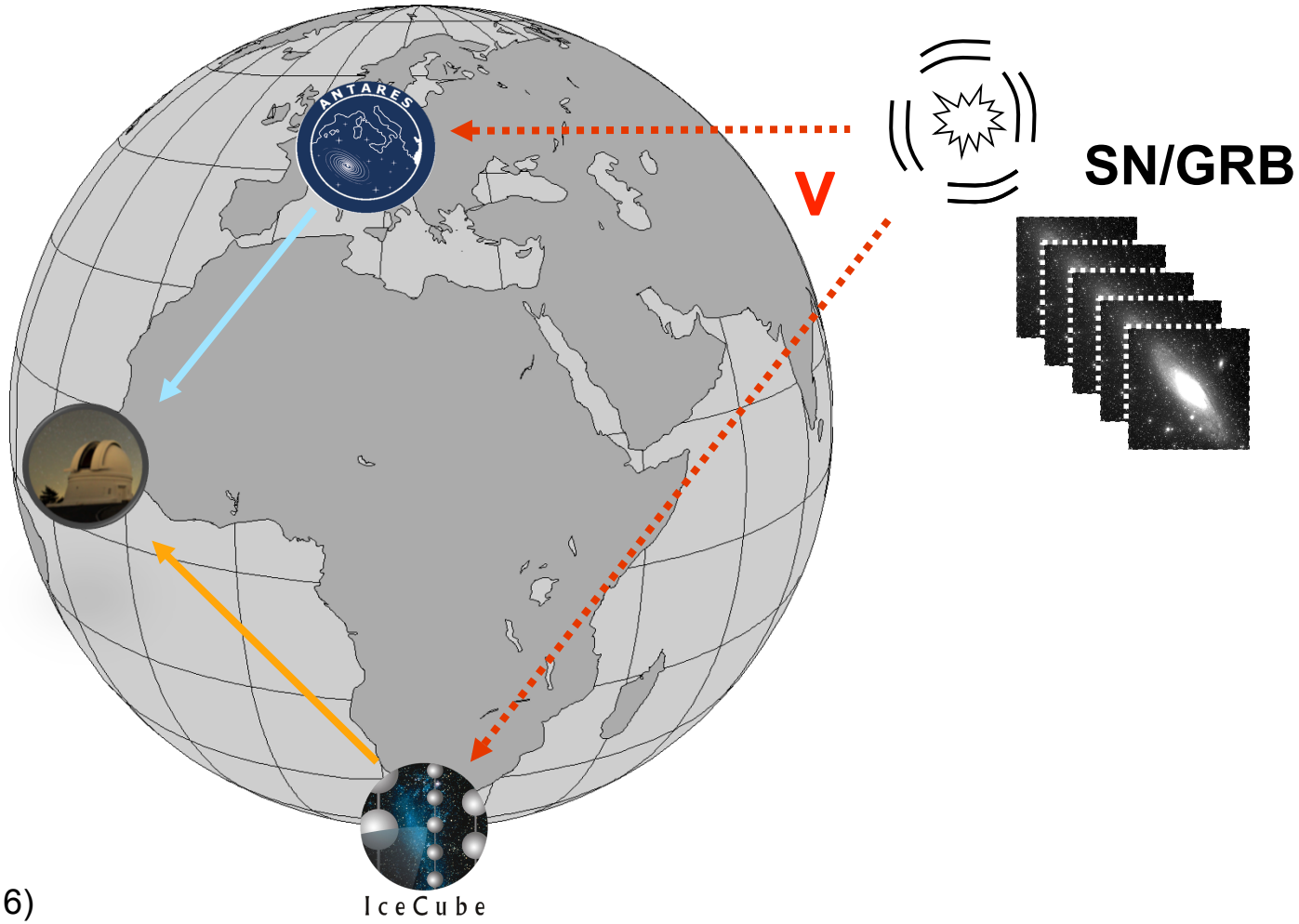

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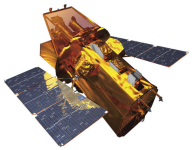
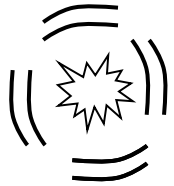
Optical, X-ray, Radio and Gamma-Ray Follow-Up

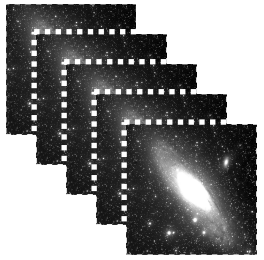
X-ray (Swift)

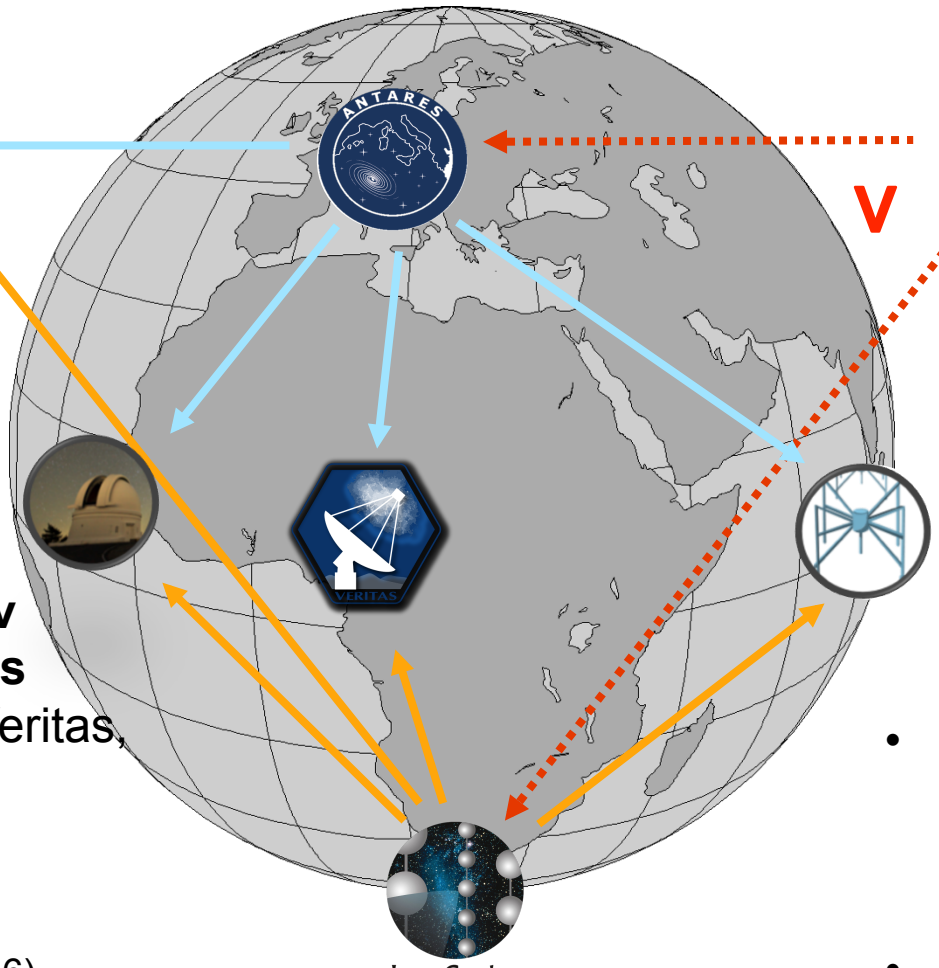


See talk by T. Kintscher



SN/GRB





ν

Optical Telescopes (iPTF, MASTER, Tarot, Pan-STARRS, ASAS-SN)

Cherenkov Telescopes (MAGIC, Veritas, HESS)

Radio Telescopes (MWA)

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

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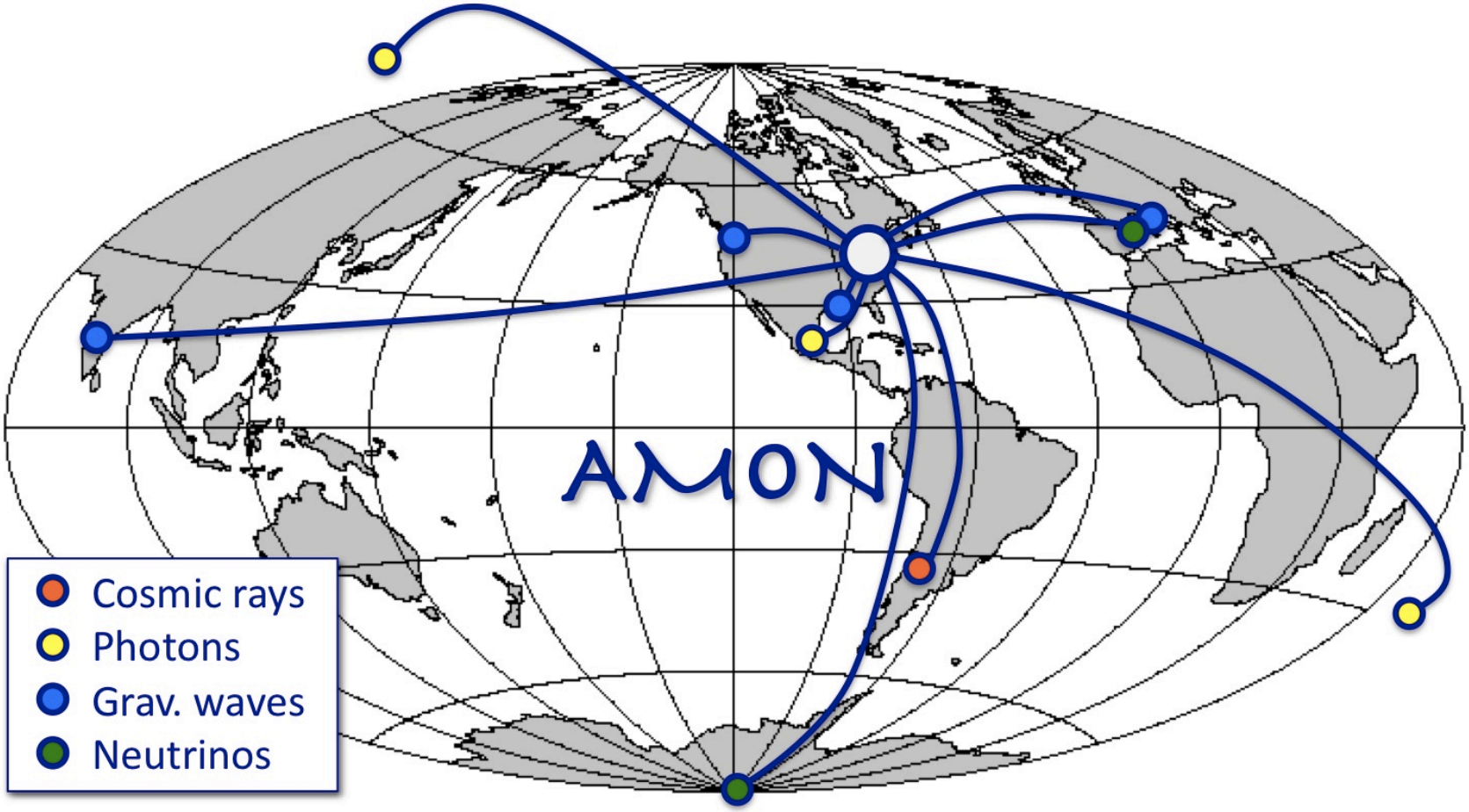
DESY

Astrophysical Multimessenger Observatory Network (AMON)

IceCube track events now available in real-time through GCN



http://amon.gravity.psu.edu

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

Conclusion

"Neutrino physics is largely an art of learning a great deal by observing nothing."

Haim Harari

- First astrophysical high-energy neutrinos detected
- Source still unknown
- Multi-messenger analysis helps to increase sensitivity
  - Some source classes are excluded / disfavored
  - Remaining source classes studied extensively

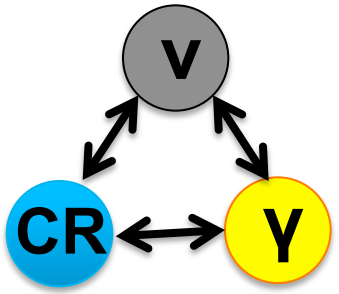

Stay tuned!

Back-up

Neutrino Production Processes

Hadronuclear (e.g. star burst galaxies and galaxy clusters)

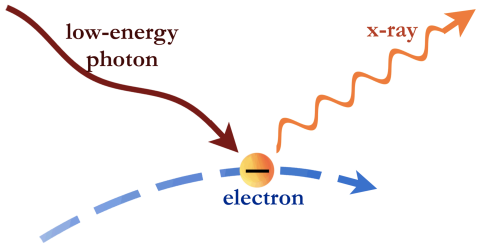
$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\,\gamma \\ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu \\ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

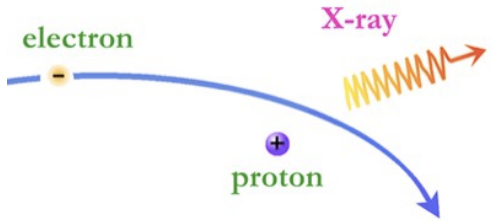


Photohadronic (e.g. gamma-ray bursts, active galactic nuclei)

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\,\pi^0 \rightarrow p\,\gamma\,\gamma \\ n\,\pi^+ \rightarrow n\,\mu^+ \nu_\mu \rightarrow n\,e^+ \nu_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

Gamma-rays are not exclusively produced in hadronic processes

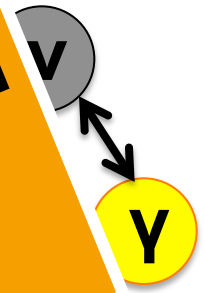




Neutrino Production Processes

Hadronuclear (e.g. star burst galaxies and galaxy clusters)

$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\,\gamma \\ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu \\ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \bar{\nu}_\mu \nu \end{cases}$$



Photohadronic (e… galactic nuclei)

$p\gamma \rightarrow$ … $\nu_\mu \rightarrow n\, e^+ \nu_e \bar{\nu}_\mu \nu_\mu$

Neutrinos are the smoking gun signature for hadronic acceleration

Gamma-ray … not exclusively produced in hadronic processes