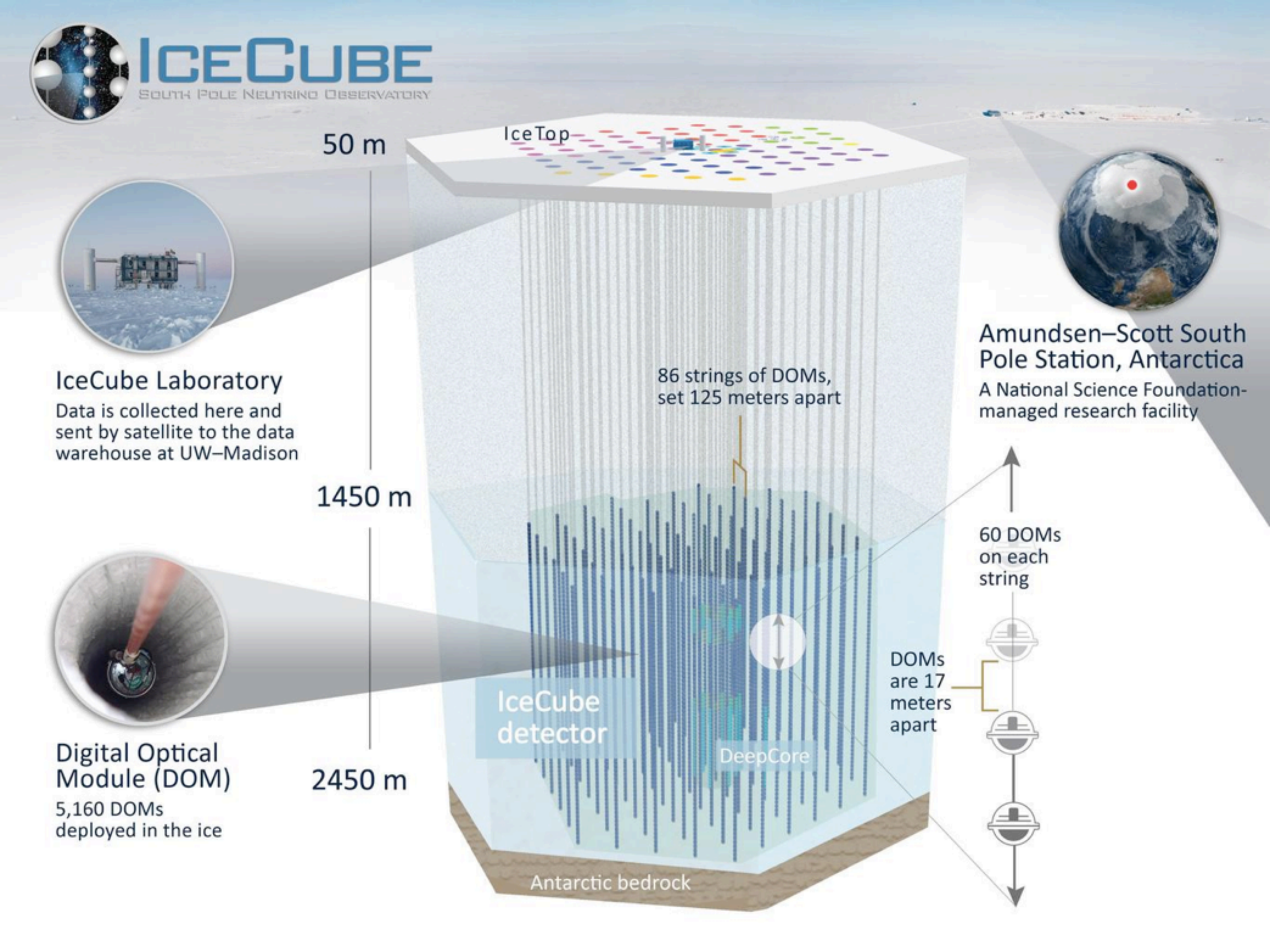
Neutrino Astrophysics at DESY

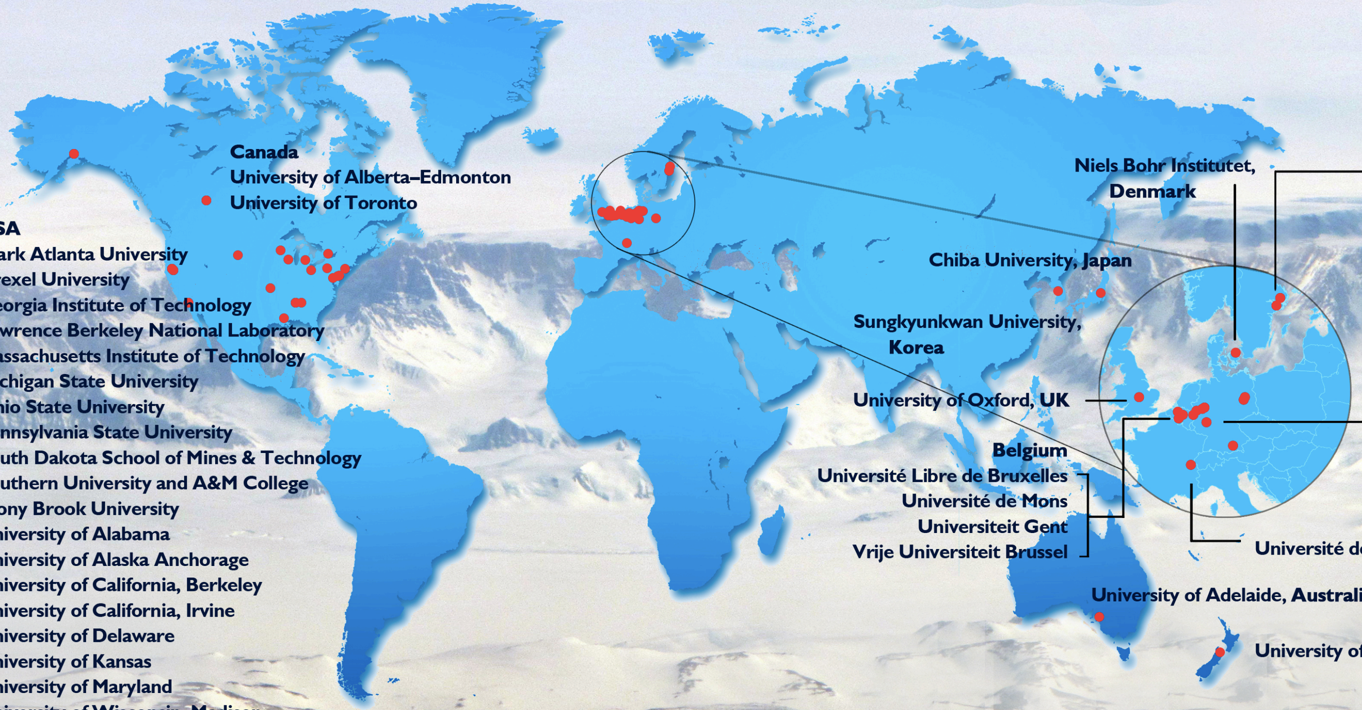
Anna Franckowiak
20.10.2016
PRC 82, DESY, Zeuthen

The Multi-Messenger Picture



IceCube
South Pole Neutrino Observatory
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
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
Antarctic bedrock

The IceCube Collaboration



USA
- Clark Atlanta University
- Drexel University
- Georgia Institute of Technology
- Lawrence Berkeley National Laboratory
- Massachusetts Institute of Technology
- Michigan State University
- 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

Canada
- University of Alberta–Edmonton
- University of Toronto

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

Sweden
- Stockholms universitet
- Uppsala universitet

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

Université de Genève, **Switzerland**

University of Adelaide, **Australia**

University of Canterbury, **New Zealand**

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)

Activities at DESY

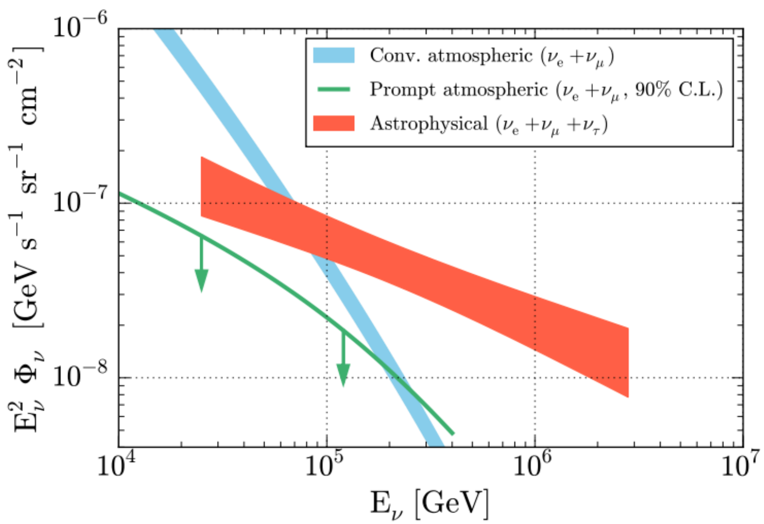
- **Direct searches for astrophysical neutrinos** (M. Ackermann, M. Usner, F. Bradascio, J. Stachurska)
- **Multi-messenger follow-up** (E. Bernardini, A. Franckowiak,T. Kintscher, M. Kowalski, K. Satalecka, A. Stasik, N. Strotjohann)
- **Atmospheric neutrino oscillations, search for sterile neutrinos** (S. Blot, A. Terliuk)
- **Cosmic rays** (H.-P. Bretz, T. Karg)
- **Searches for magnetic monopoles** (E. Jacobi)
- **Gen2/PINGU R&D** (D. Hebecker, T. Karg, S. Kunwar)
- **Gen2 sensitivity** (M. Kowalski, J. von Santen)

5 permanent scientists, 4 postdocs, 10 PhD students

Helmholtz Young Investigator Group of A. Franckowiak will start in 2017

GNN PhD Prize for DESY PhD

- Dr. Lars Mohrmann
- "Characterizing Cosmic Neutrino Sources (A Measurement of the Energy Spectrum and Flavor Composition of the Cosmic Neutrino Flux Observed with the IceCube Neutrino Observatory)"
- Published in ApJ 809, 98 (2015), arXiv:1507.03991



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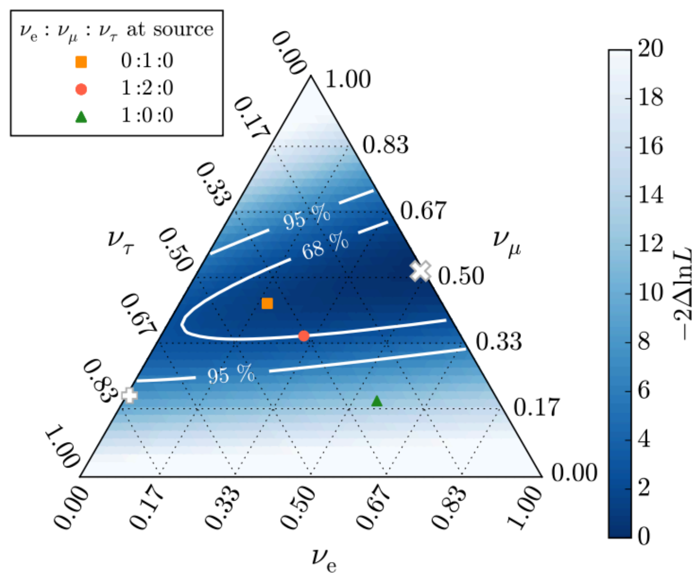
$$\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu$$

Sources → Earth

	ν_e	ν_μ	ν_τ	ν_e	ν_μ	ν_τ
Pion Decay	1	2	0	1	1	1
Muon damped	0	1	0	0.2	0.39	0.39
Neutron decay	1	0	0	0.56	0.22	0.22

$$n \rightarrow p\, e^- \bar{\nu}_e$$

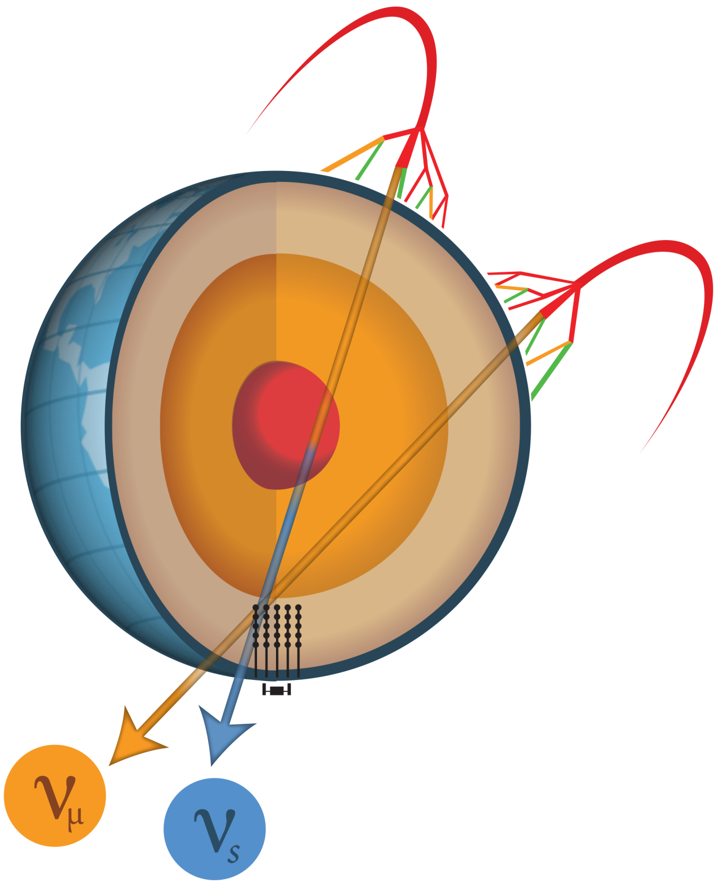


Sterile Neutrinos

ν_e ν_μ ν_τ ν_s

?

> hypothesized particle which would not interact at all with matter except gravity
> Could resolve anomalies found in accelerator neutrino experiments



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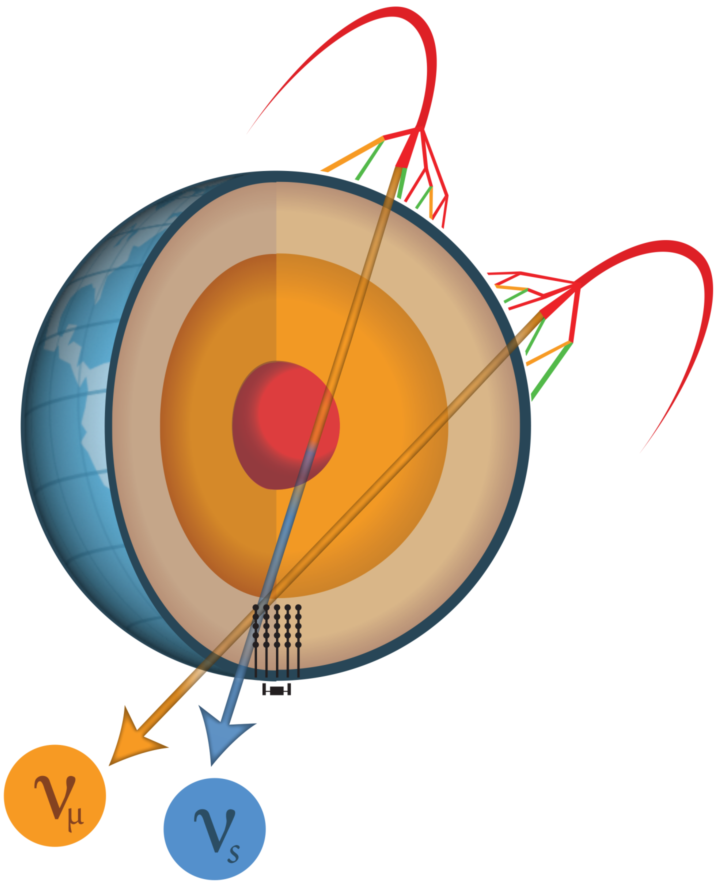

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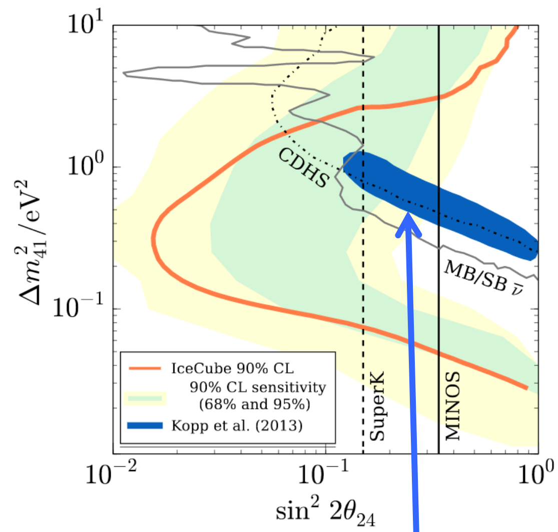
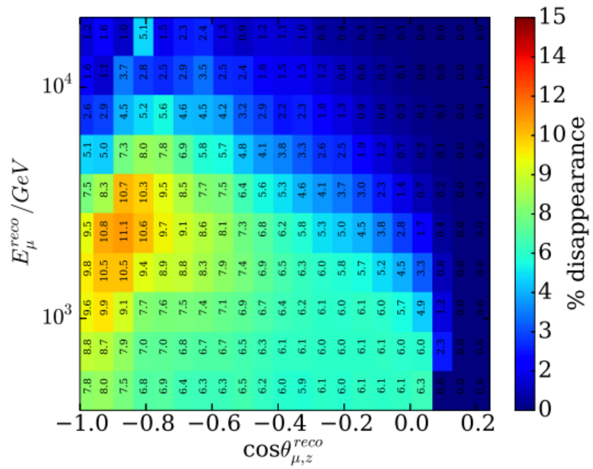
Sterile Neutrinos

- Search for ν_μ ($\overline{\nu}_\mu$) disappearance in the energy range of 320 GeV – 20 TeV
- Sterile neutrinos would produce distortions of the atmospheric neutrino flux in energy and angle
- Phys. Rev. Lett. 117, 071801 (2016)



Allowed region from global fit of appearance experiments



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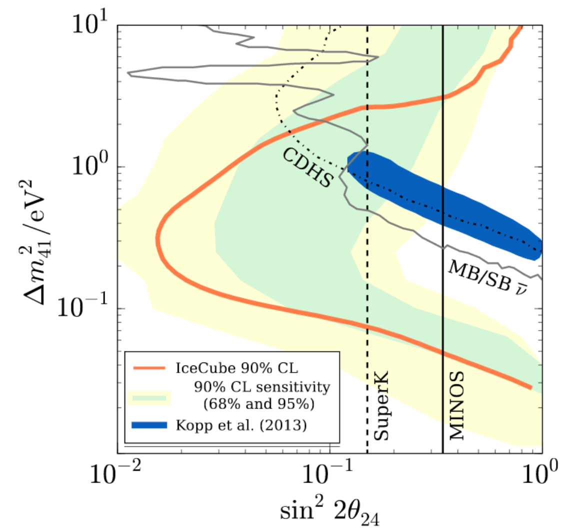
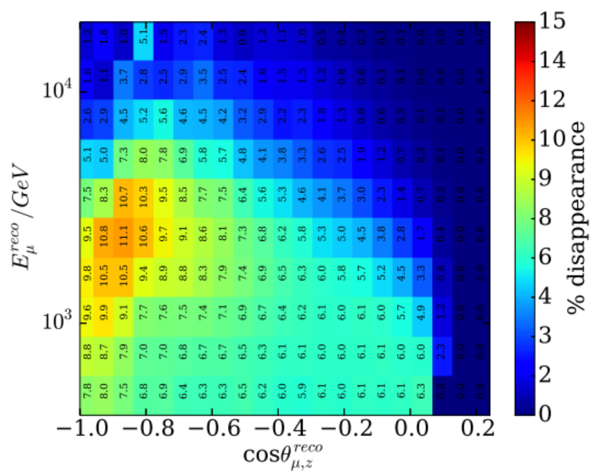
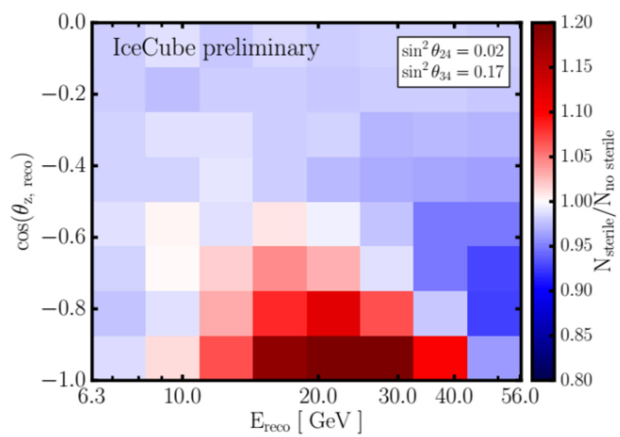






Ungoing-work at DESY lowers the energy threshold from 320 to 10 GeV

A. Terliuk

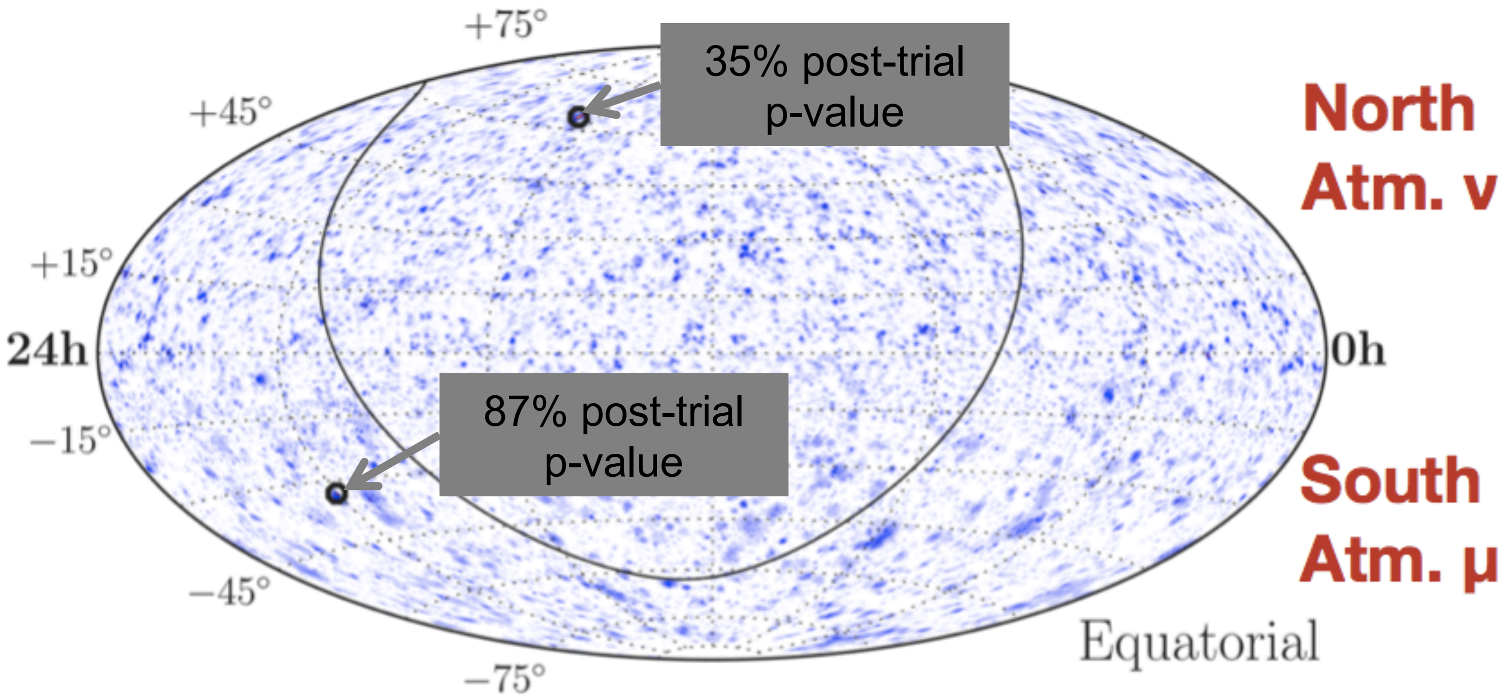
IceCube Low-Energy Systematics Workshop

11-13 July at DESY Zeuthen

S. Blot

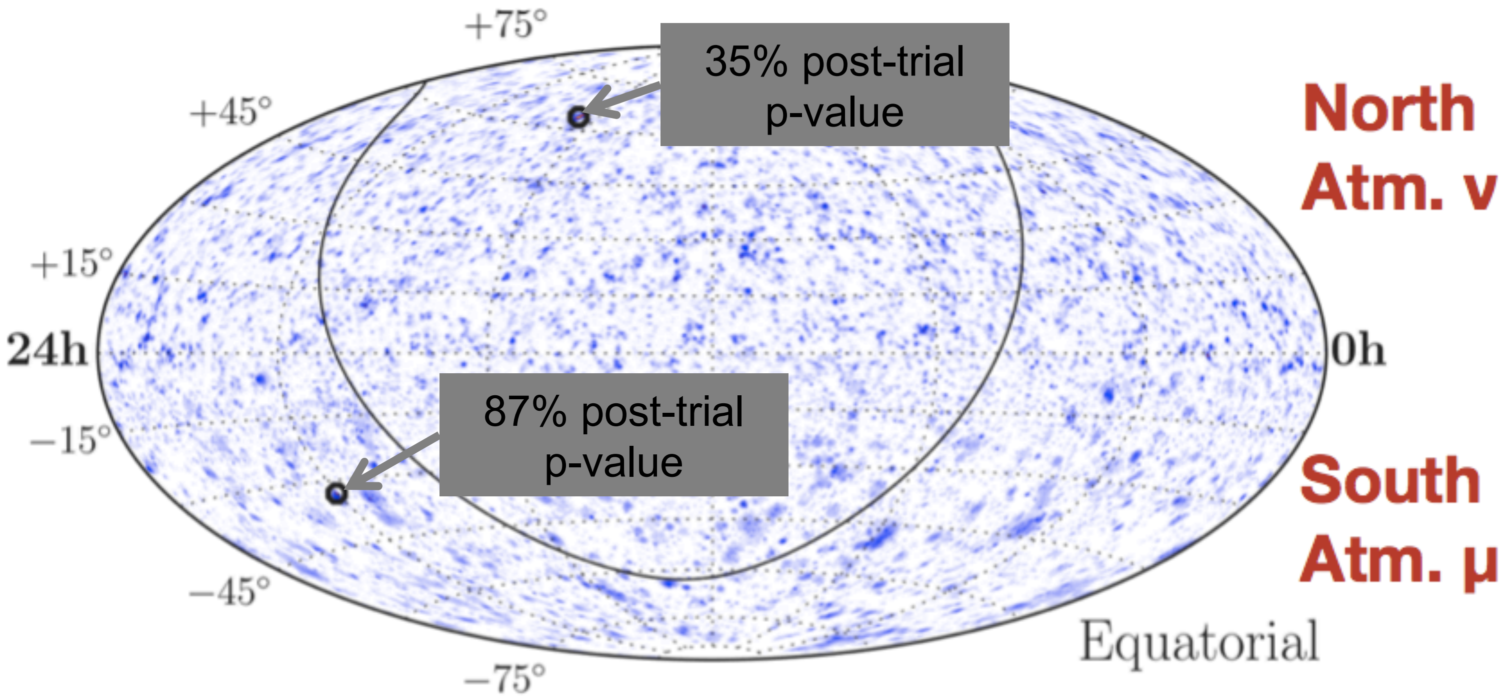
Search for Neutrino Sources

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



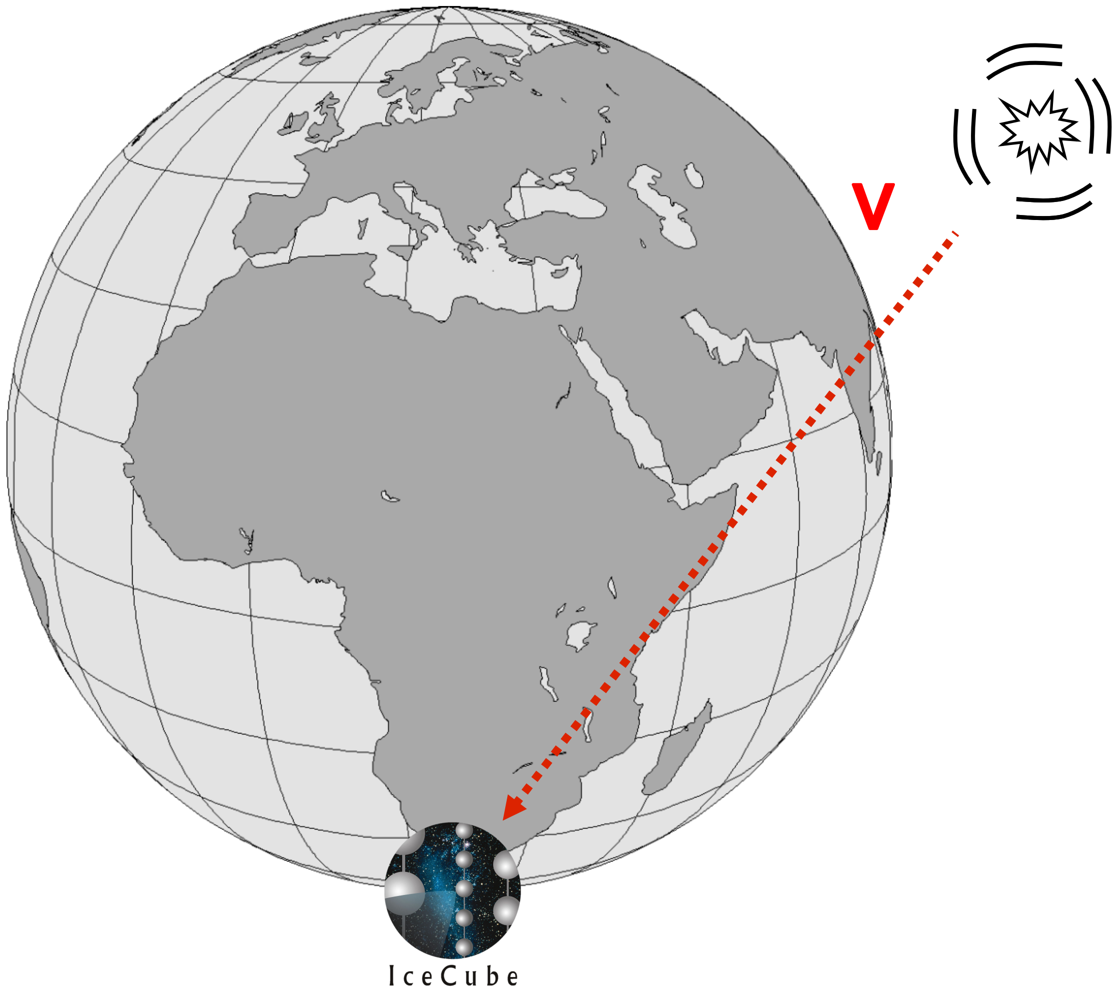
The Multi-Messenger Approach

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



Combining neutrino and **Electro-magnetic** data can increase our sensitivity to identify neutrino sources

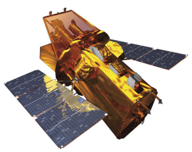
Real-Time Multi-Messenger Program



Ackermann et al. arXiv:0709.2640
IceCube A&A 539, A60 (2012)
IceCube arXiv: 1610.01814

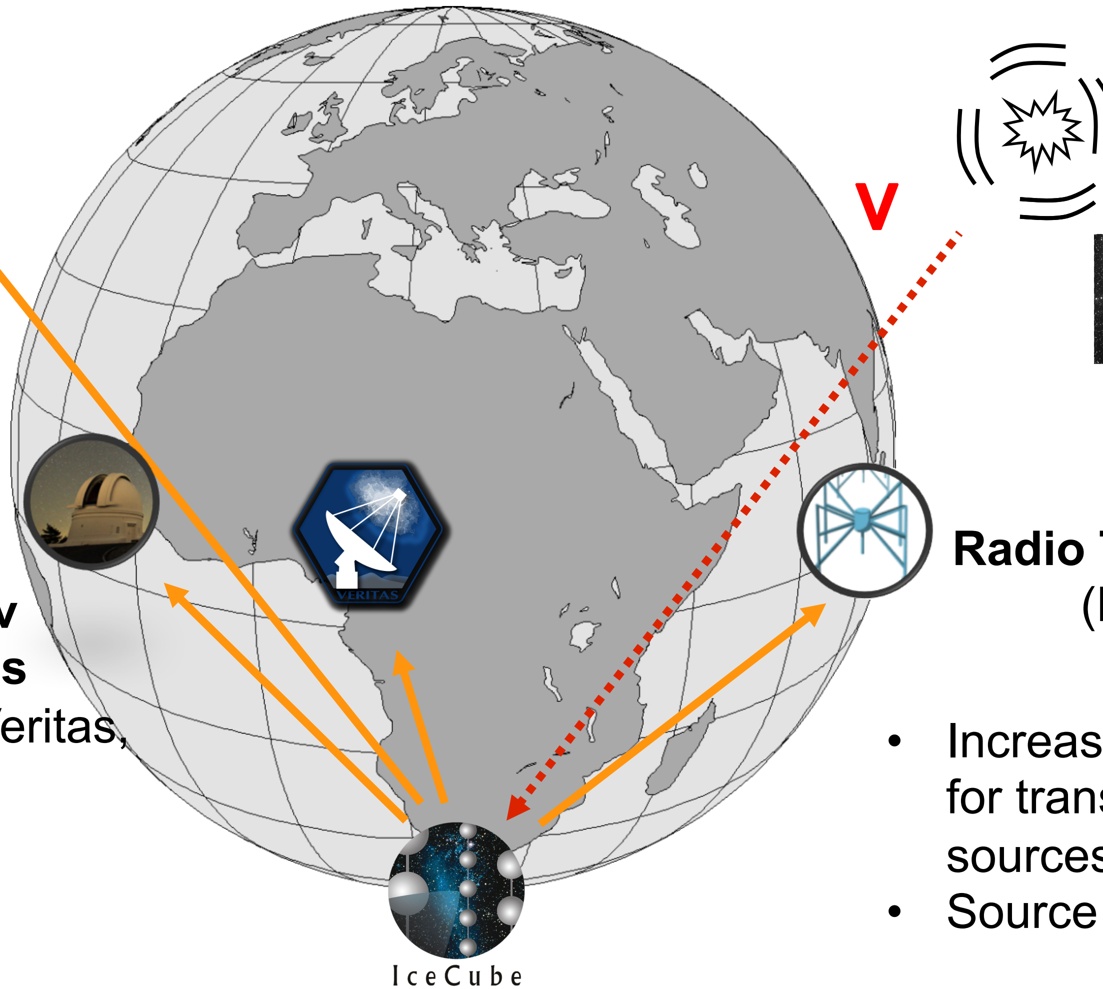
Real-Time Multi-Messenger Program

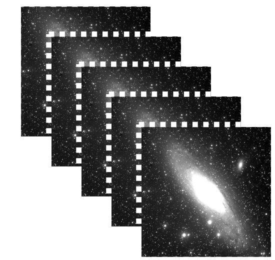
X-ray (Swift)



Optical Telescopes
(iPTF, MASTER,
Pan-STARRS)

Cherenkov Telescopes
(MAGIC, Veritas, HESS)



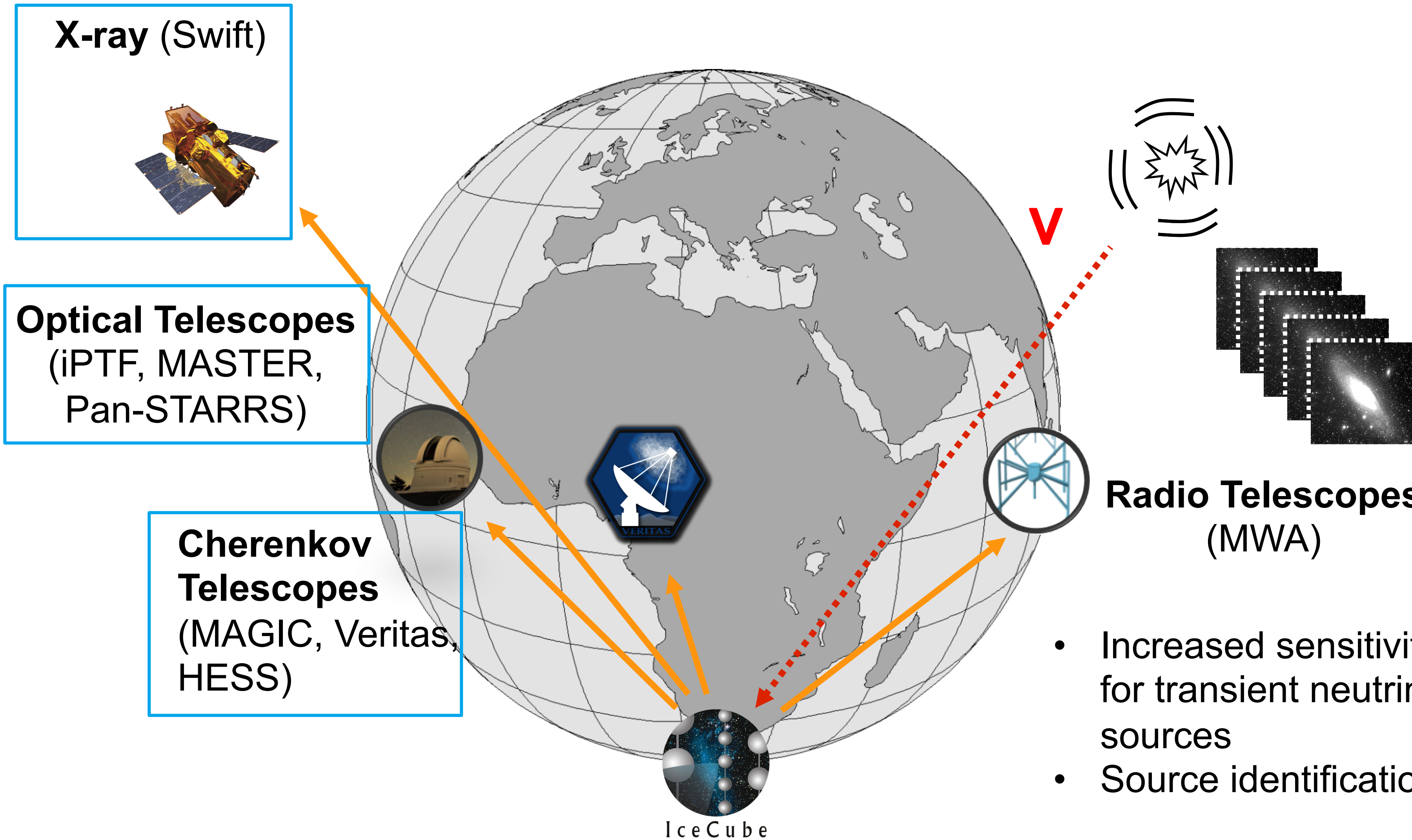


Radio Telescopes
(MWA)

- Increased sensitivity for transient neutrino sources
- Source identification

Ackermann et al. arXiv:0709.2640
IceCube A&A 539, A60 (2012)
IceCube arXiv: 1610.01814

Real-Time Multi-Messenger Program



- Increased sensitivity for transient neutrino sources
- Source identification

Ackermann et al. arXiv:0709.2640
IceCube A&A 539, A60 (2012)
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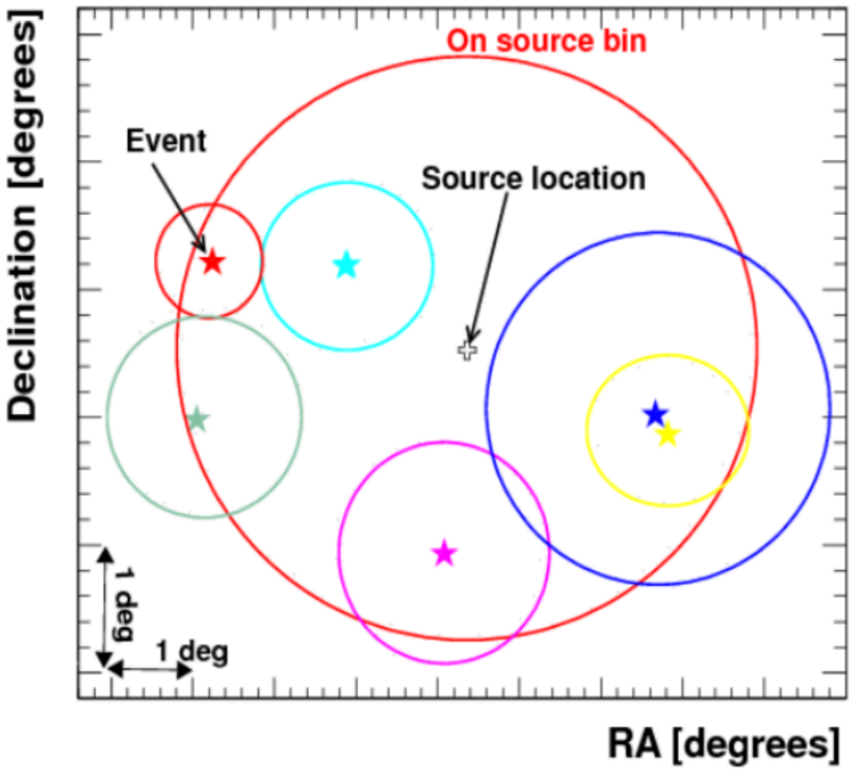
IceCube Gamma-Ray Follow-Up: Results

- Search for excess from predefined list of variable gamma-ray sources
- Most significant alert
  - Nov. 9th 2012
  - 6 events in 4.2 days



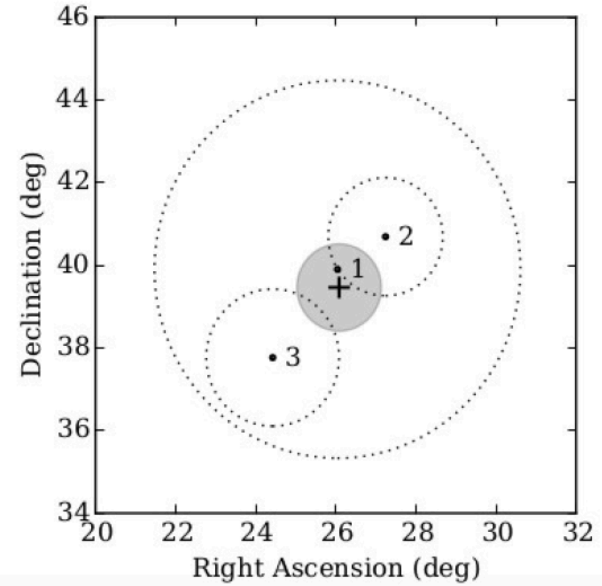
- Alert forwarded to VERITAS
  - No significant gamma-ray emission found

E. Bernardini, D. Gora, T. Kintscher

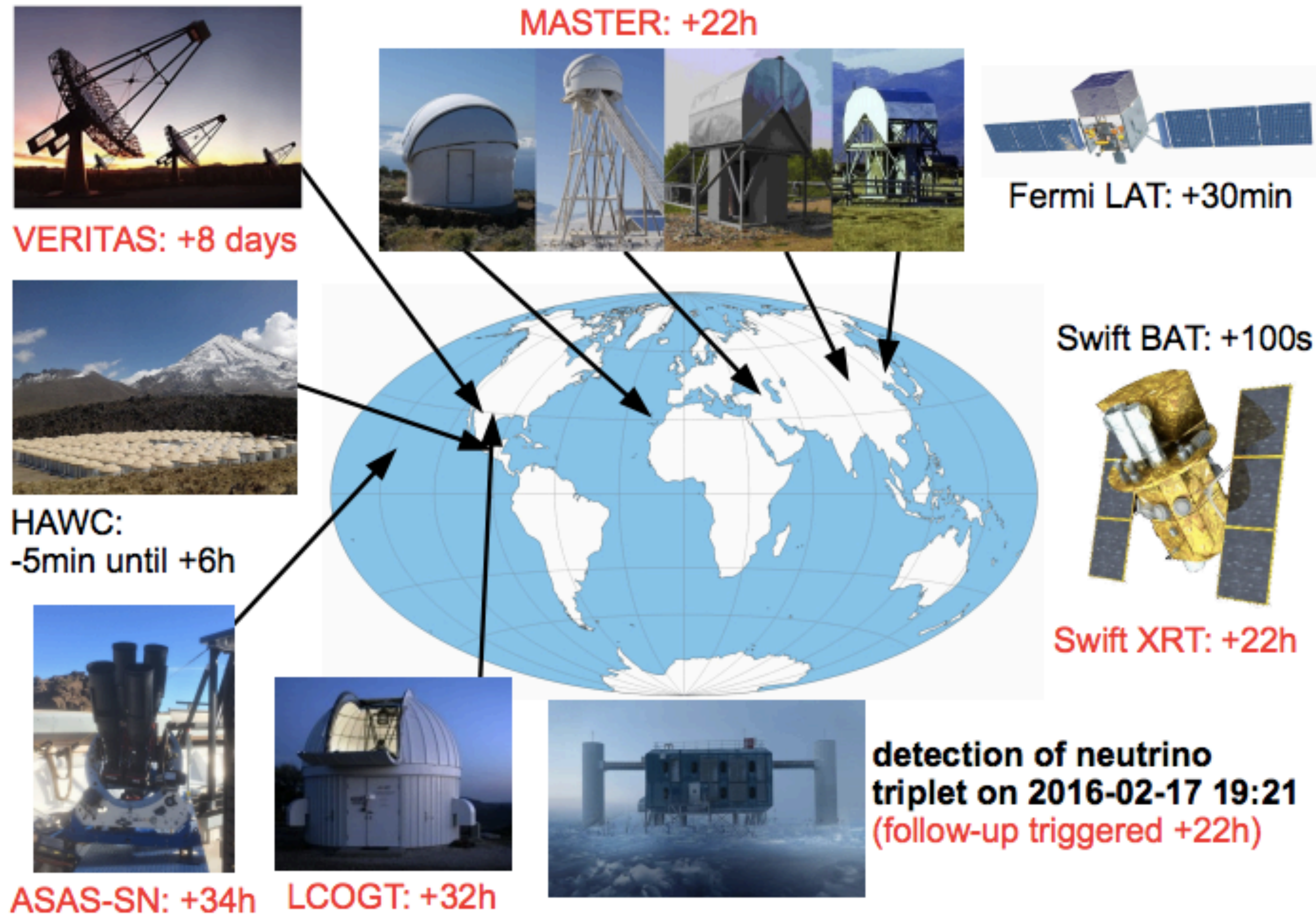
IceCube arXiv: 1610.01814

IceCube Optical Follow-Up: First Triplet Found

- Three neutrino candidates within 100 sec from the same direction
- Once every 14 years from background



N. Strotjohann



N. Strotjohann

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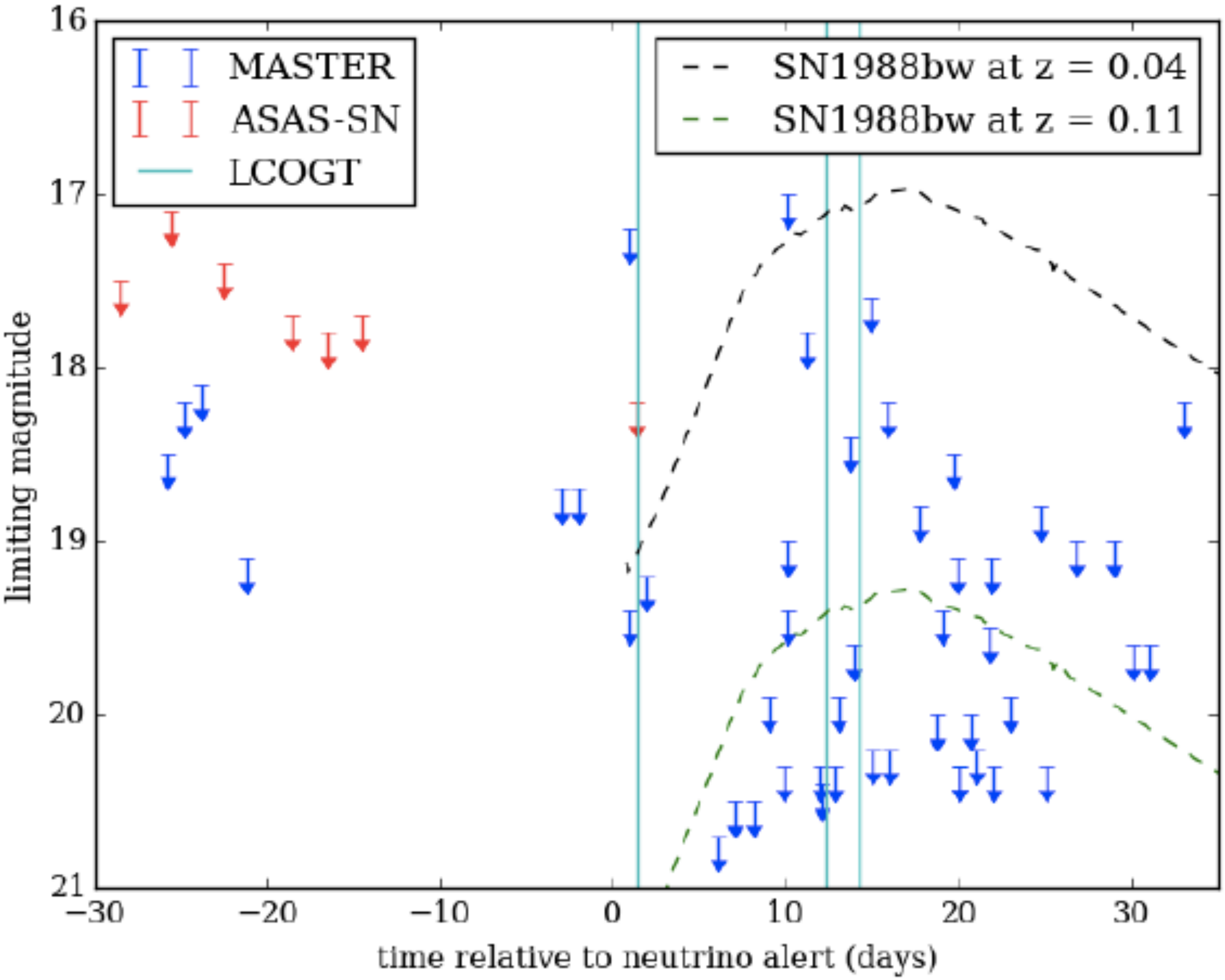
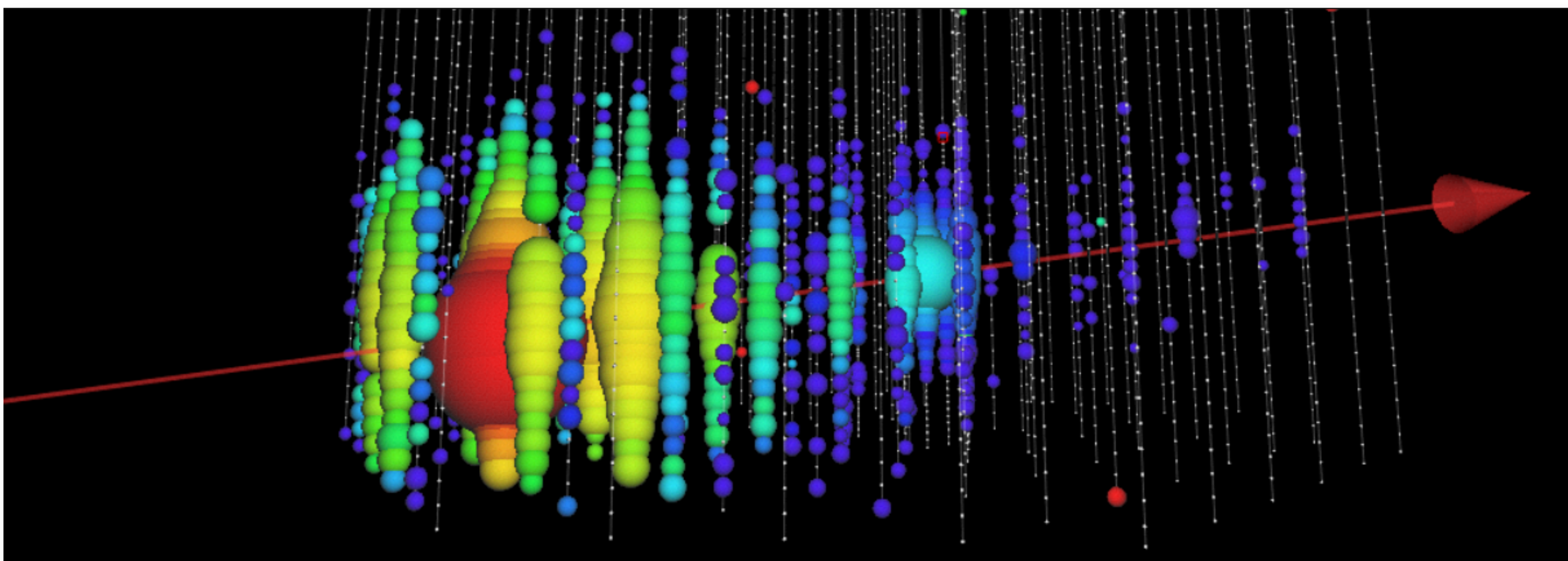


No optical counterpart found → close-by supernova ruled out

N. Strotjohann

IceCube Public Alerts

- 8 high-energy track events per year
- ~50% signal purity
- Since April 2016
- Delay of < 1min

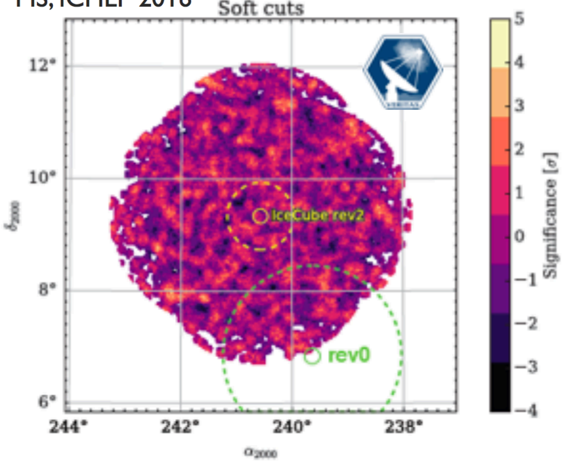


Gamma-Ray Follow-Up of Public Alerts

H.E.S.S.

★ automatic **follow-up < 2 min**
★ duration: 2h (full H.E.S.S.-II array)
2016-04-28: 18min (first position)
2016-04-29: 1.5h (updated position)
2016-04-30: 0.5h (updated position)
★ analysis in progress

MS, ICHEP 2016



VERITAS

★ automatic **follow-up in 112s**
★ duration: 1.2 h (first) + 2 h (updated)
★ moonlight settings - reduced high-voltage
★ UL ~ few % C.U.

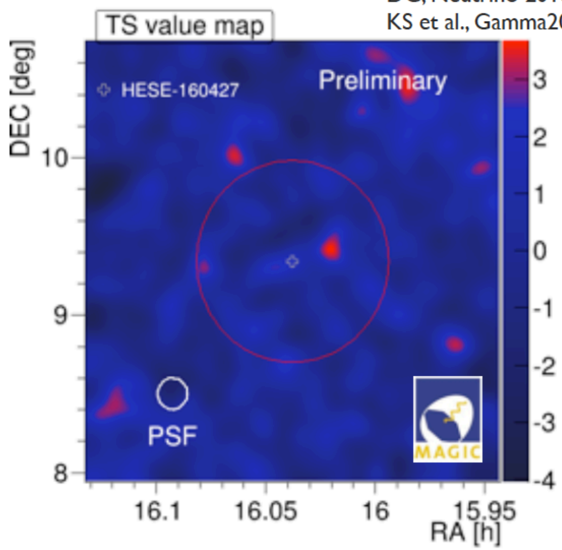
FACT

★ observed updated position
★ duration: 4.24 h
2016-04-28 2:00 – 4:32 UTC
2016-04-29 1:32 – 3:33 UTC
★ zd: 19 – 30°
★ moderate moon light
★ some clouds in the 1st night
★ weather fine in the 2nd night
★ no signal found

MAGIC

★ 2h data taken on 29/04/2016 with moderate moon (updated position)
★ night 27/28 Apr not possible - Moon too bright
★ zenith range:18-26 deg
★ E threshold ~120 GeV
★ hot spot 0.3 deg away, significance: ~ 3.6 sigma (2.1 sigma after trials)
★ UL - analysis ongoing...

DG, Neutrino 2016
KS et al., Gamma2016



K. Satalecka, E. Bernardini

Optical Follow-Up of Public Alerts by Pan-STARRS

```
TITLE:    GCN CIRCULAR
NUMBER:   19381
SUBJECT:  ICECUBE-160427A : Pan-STARRS imaging and optical transients in the field
DATE:     16/05/04 18:43:58 GMT
FROM:     Stephen Smartt at Queen's U/Belfast  <s.smartt@qub.ac.uk>
```

Object	RA (J2000)	DEC (J2000)	Disc Date	i -mag
PS16cgv	15 59 53.84	+09 11 08.4	20160430	22.01
PS16cgw	16 00 39.69	+09 39 21.2	20160430	21.80
PS16cfu	16 01 15.66	+09 25 04.7	20160430	21.14
PS16cgx	16 01 18.60	+09 51 53.1	20160430	21.84 *
PS16cfz	16 02 11.96	+09 54 07.9	20160430	21.27
PS16cgb	16 02 19.12	+09 34 50.1	20160430	22.03
PS16cgi	16 03 27.72	+08 54 05.2	20160430	22.09

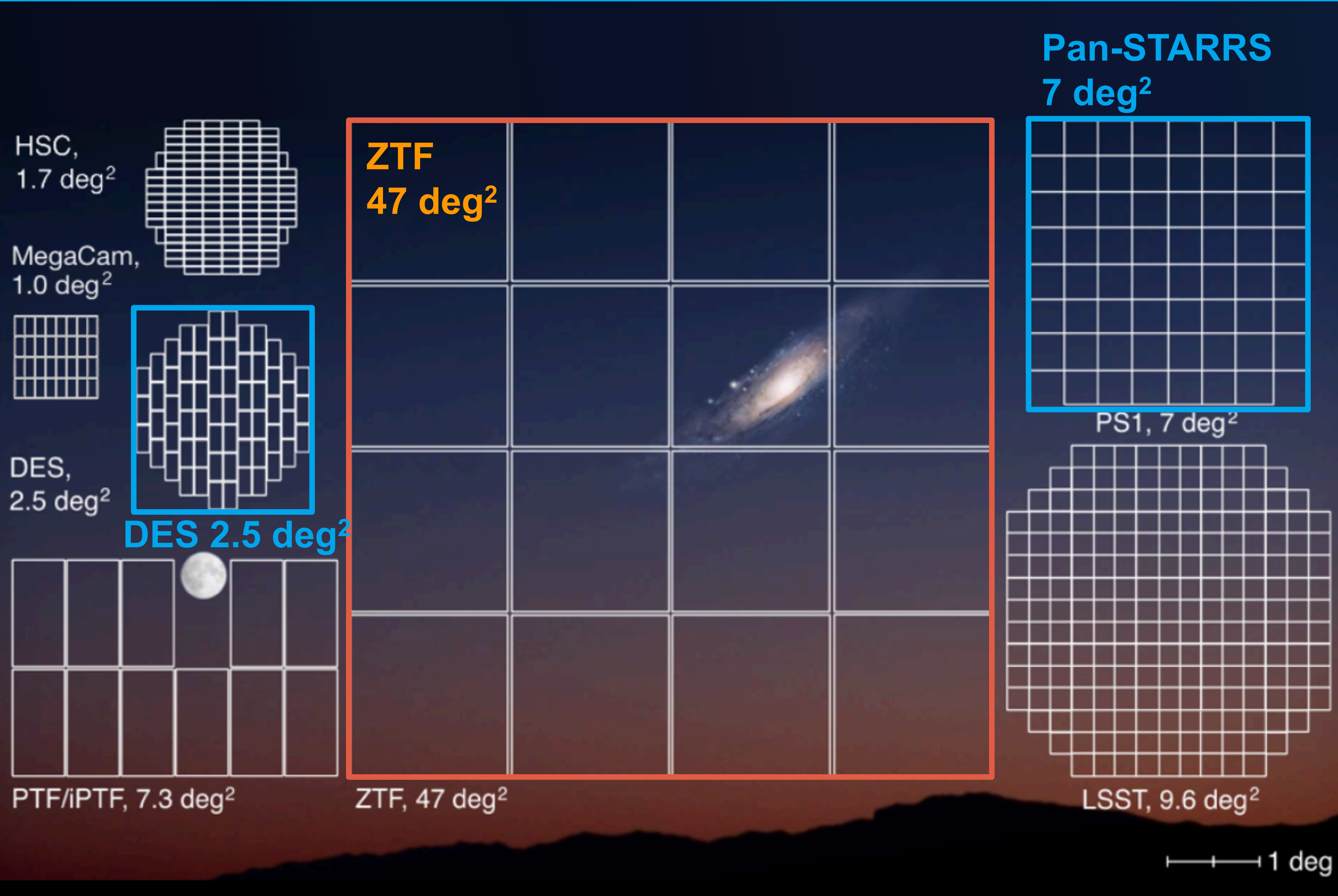
* PS16cgx rose at by 0.4 mag over 2 days. The rise time would be consistent with a type Ic supernova at z ~ 0.1 to 0.2 that exploded on or around 2016 April 27.2 (and possibly an off-axis GRB). However the 4th data point shows it has peaked at i=21.5 +/- 0.1, and is therefore more consistent with a type Ia SN from the normal field population. Spectroscopic follow-up is needed to confirm.

Optical data analysis still on-going → collaboration with cosmology group at HU Berlin

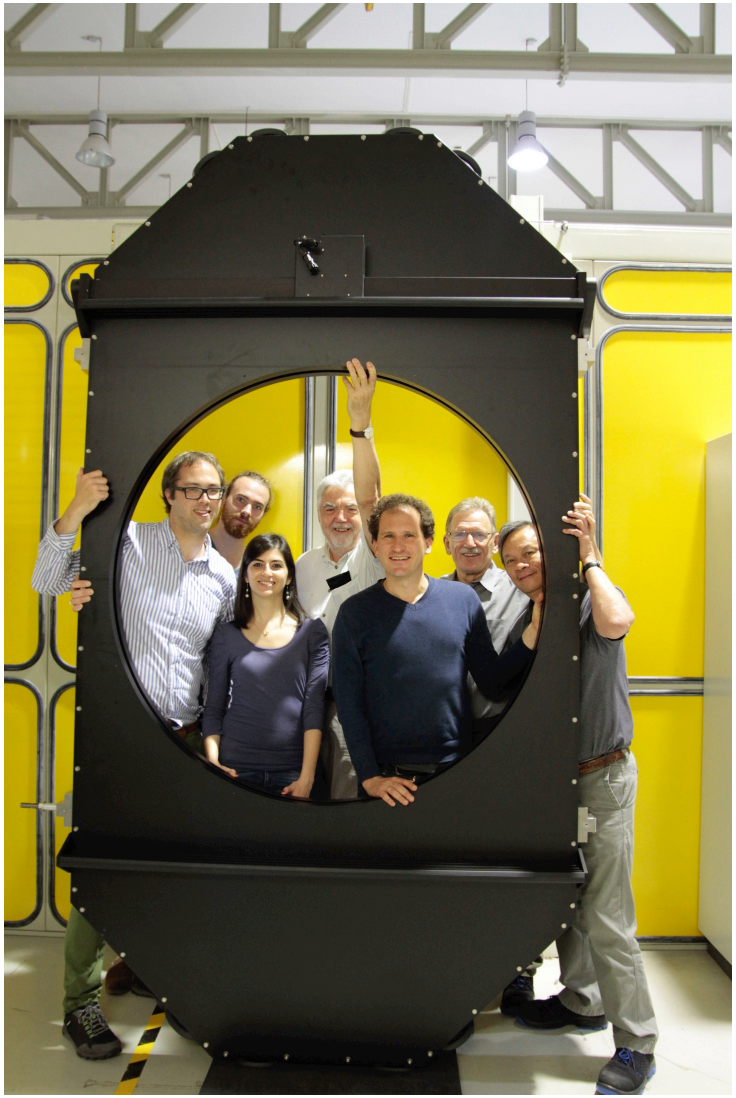
A. Franckowiak, M. Kowalski, J. v. Santen


The Future
NEXT EXIT

The Zwicky Transient Facility (ZTF)

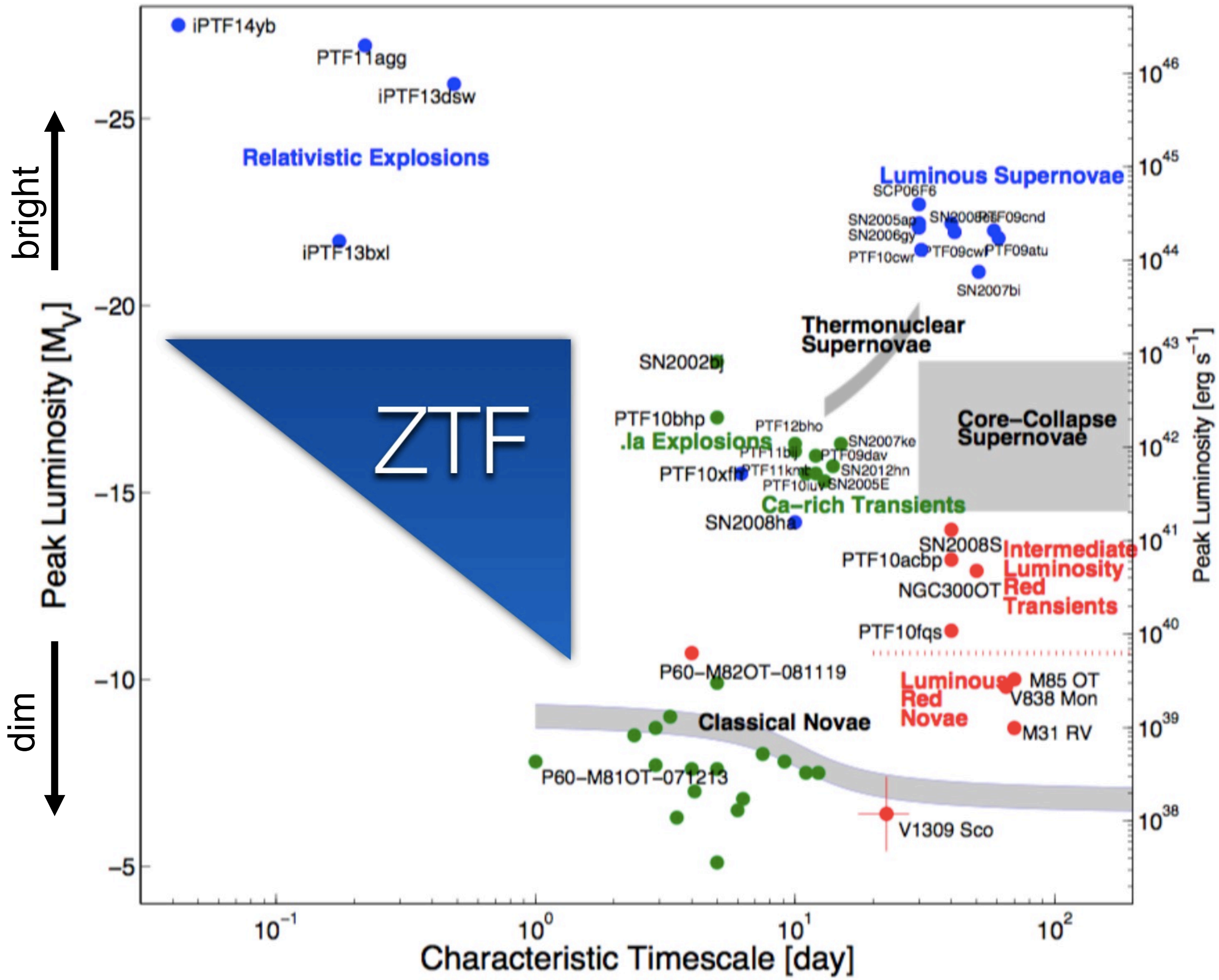


The DESY-Bonn Shutter



Anna Fr

Optical Transients with ZTF



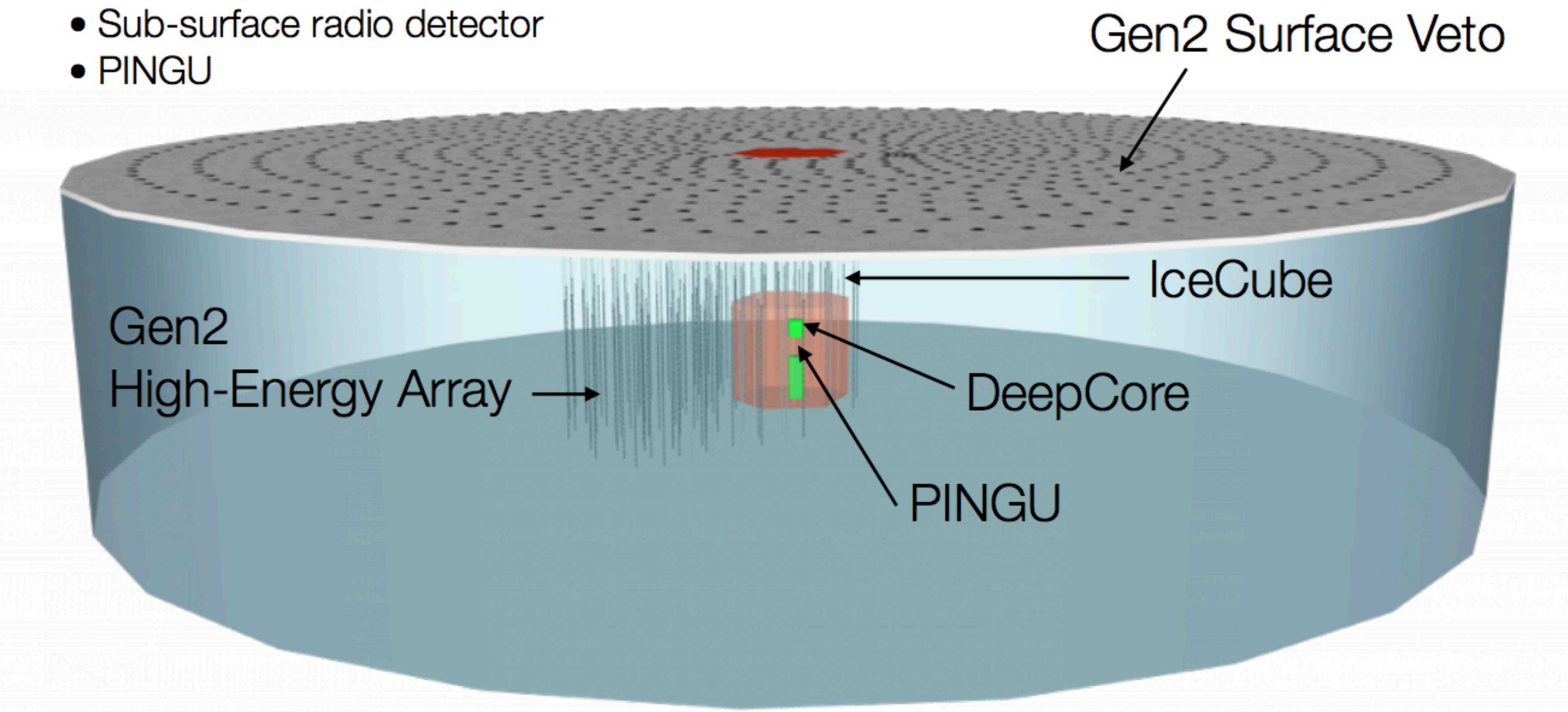
ZTF will scan the entire Northern sky every other day

YIG: integration of ZTF into IceCube multi-messenger program

IceCube Gen2

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

Multi-component observatory:
- Surface air shower detector
- Gen2 High-Energy Array
- Sub-surface radio detector
- PINGU



M. Ackermann, M. Kowalski, J. v. Santen

IceCube Gen2 – Hardware Development

mDOM

36 cm

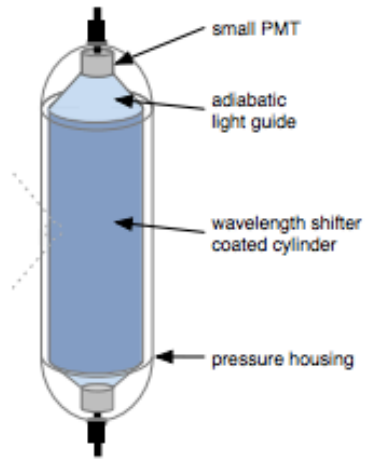
- Directional information
- More sensitive area per module

D-Egg

30 cm

- Directional information
- More sensitive area per module
- Smaller geometry

WOM



11 cm

- more sensitive area per $
- Small diameter
- Lower noise rate

LOM

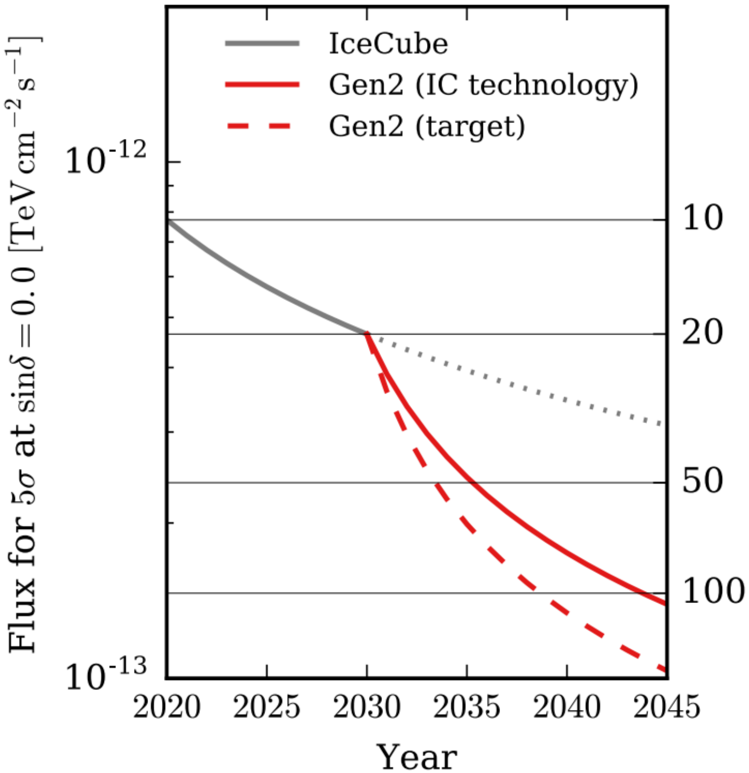
13 cm

- Small diameter
- Directional info.
- More area per module

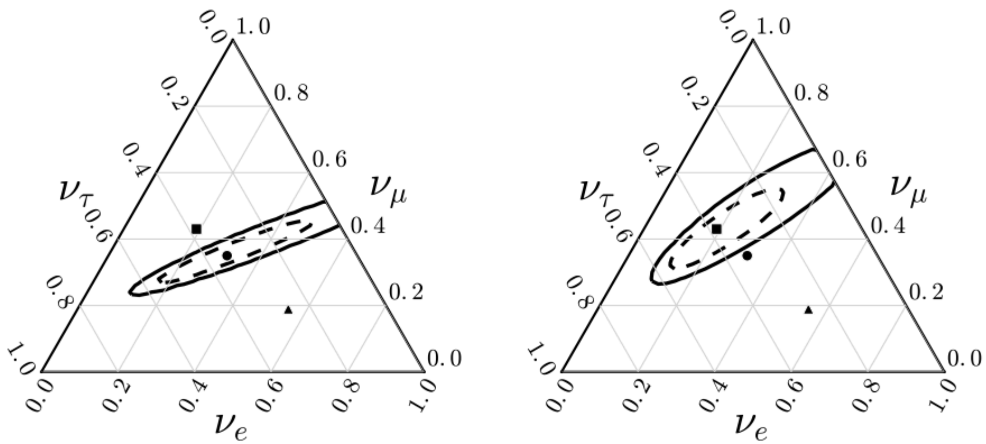
D. Hebecker, T. Karg, S. Kunwar

IceCube Gen2 – Expected Sensitivity

Point Source Sensitivity



Probing acceleration environments



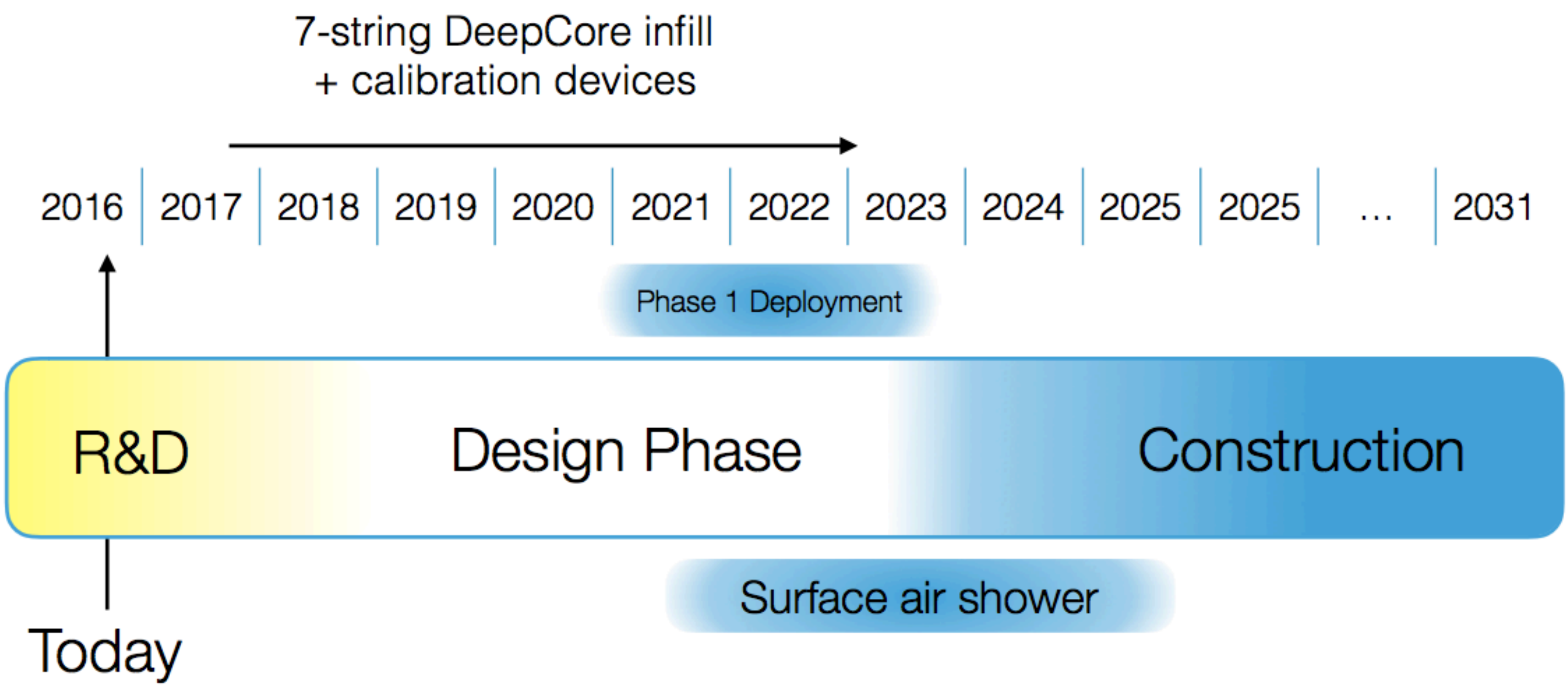
M. Ackermann, M. Kowalski, J. v. Santen

Summary: The IceCube group at DESY

- Covers a broad range of science topics
  - From neutrino astronomy
  - Over particle physics
  - To physics beyond the standard model
- Takes a leading role
  - In preparations for IceCube Gen2
  - In the operations and extension of the IceCube real-time analysis and follow-up programs

Backup

IceCube Gen2 – Time Scale

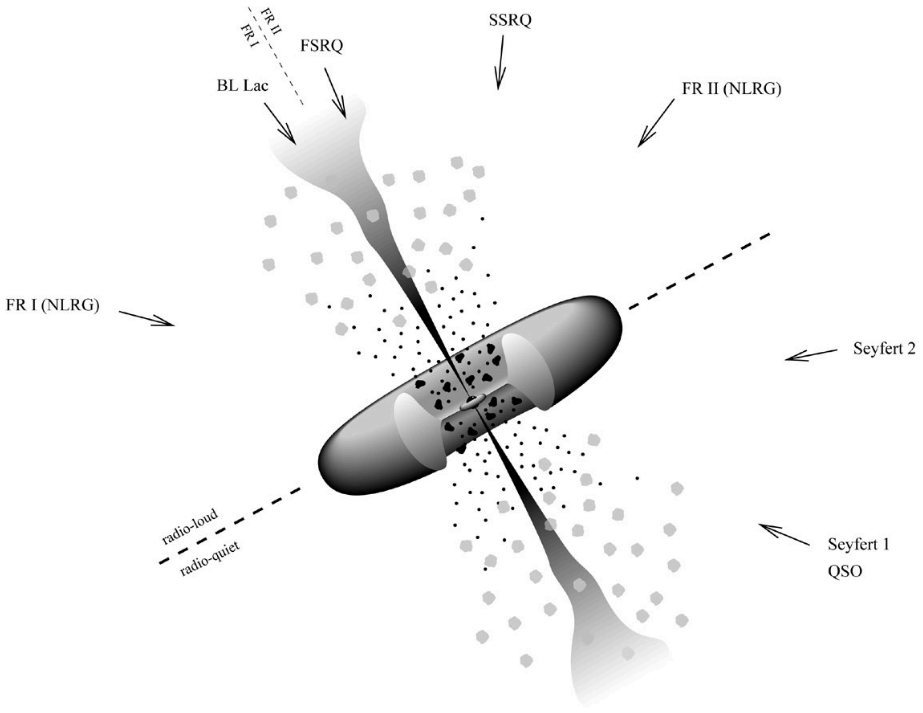


IceCube Gen2 – Motivation

- Resolve the source populations that produce the high energy astrophysical neutrinos detected by IceCube
- Identify the sources of the highest energy cosmic rays
- Learn about the environments responsible for the highest energetic cosmic particles
- Study of galactic and extra-galactic propagation of CR with neutrinos as tracers
- Obtain a unique view into the explosion of stars
- Explore the very high-energy Universe when it was most active

Blazars

- Gamma rays tell us WHERE



IceCube Coll., arXiv:1502.03104

Blazars

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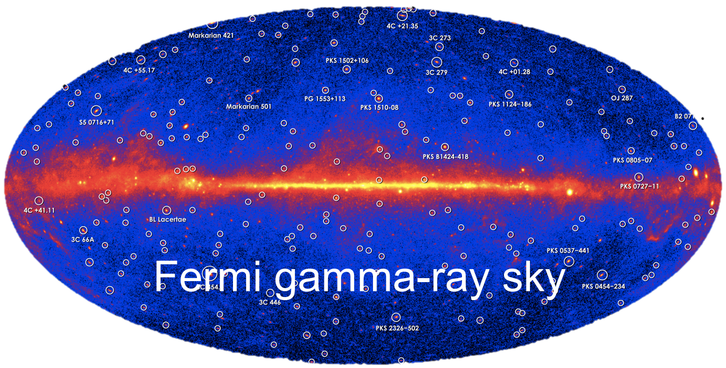

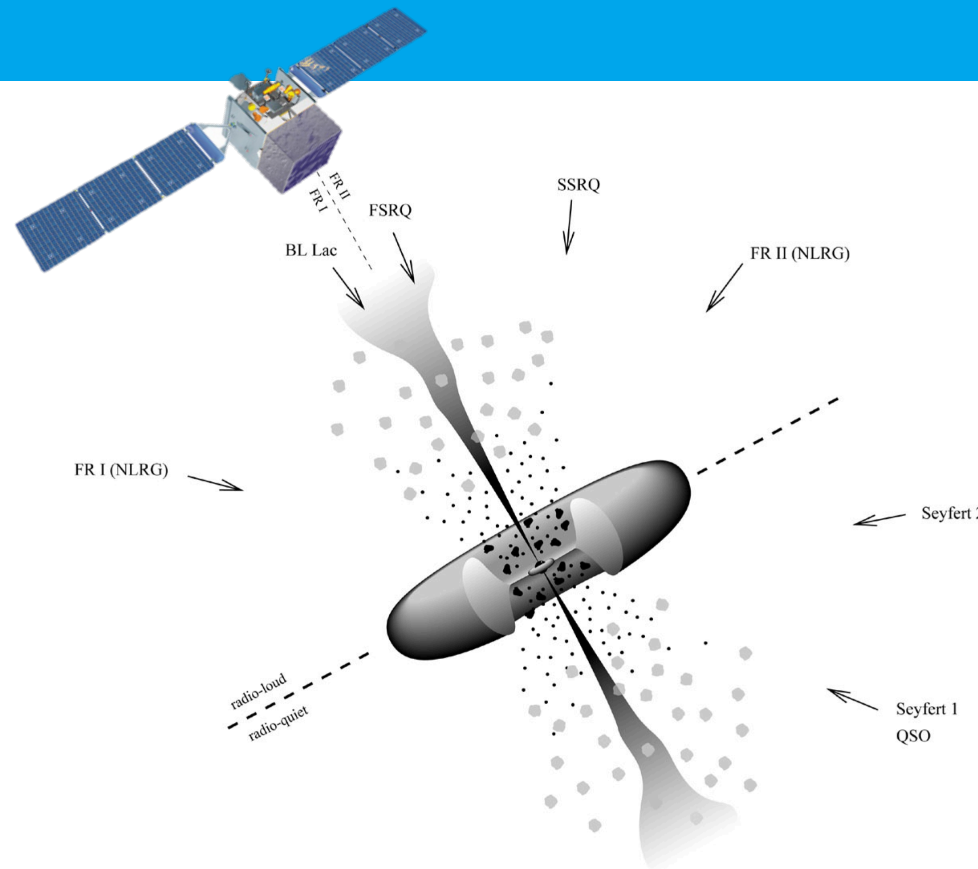

IceCube Coll., arXiv:1502.03104

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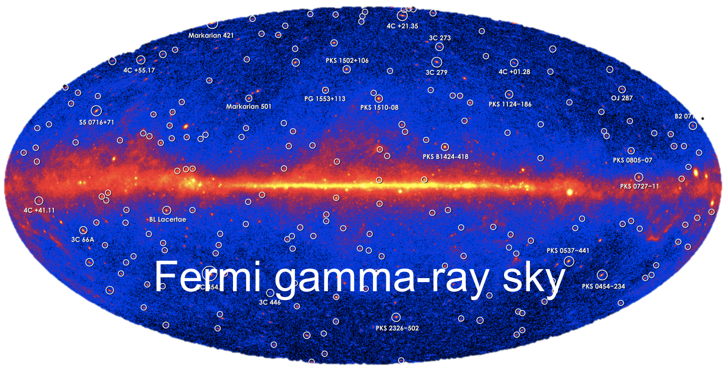
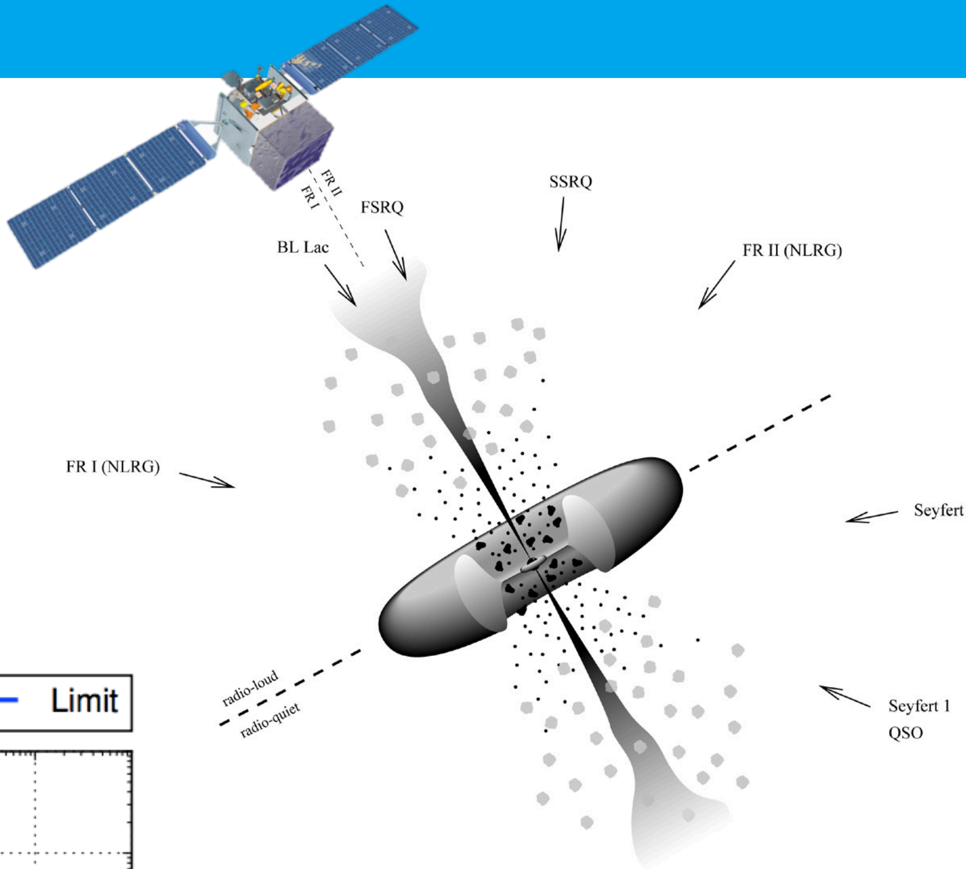
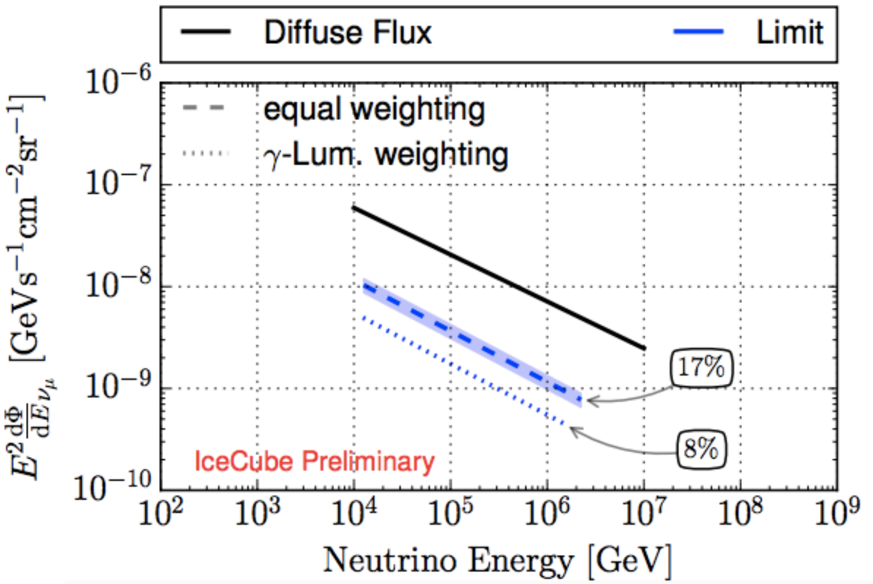




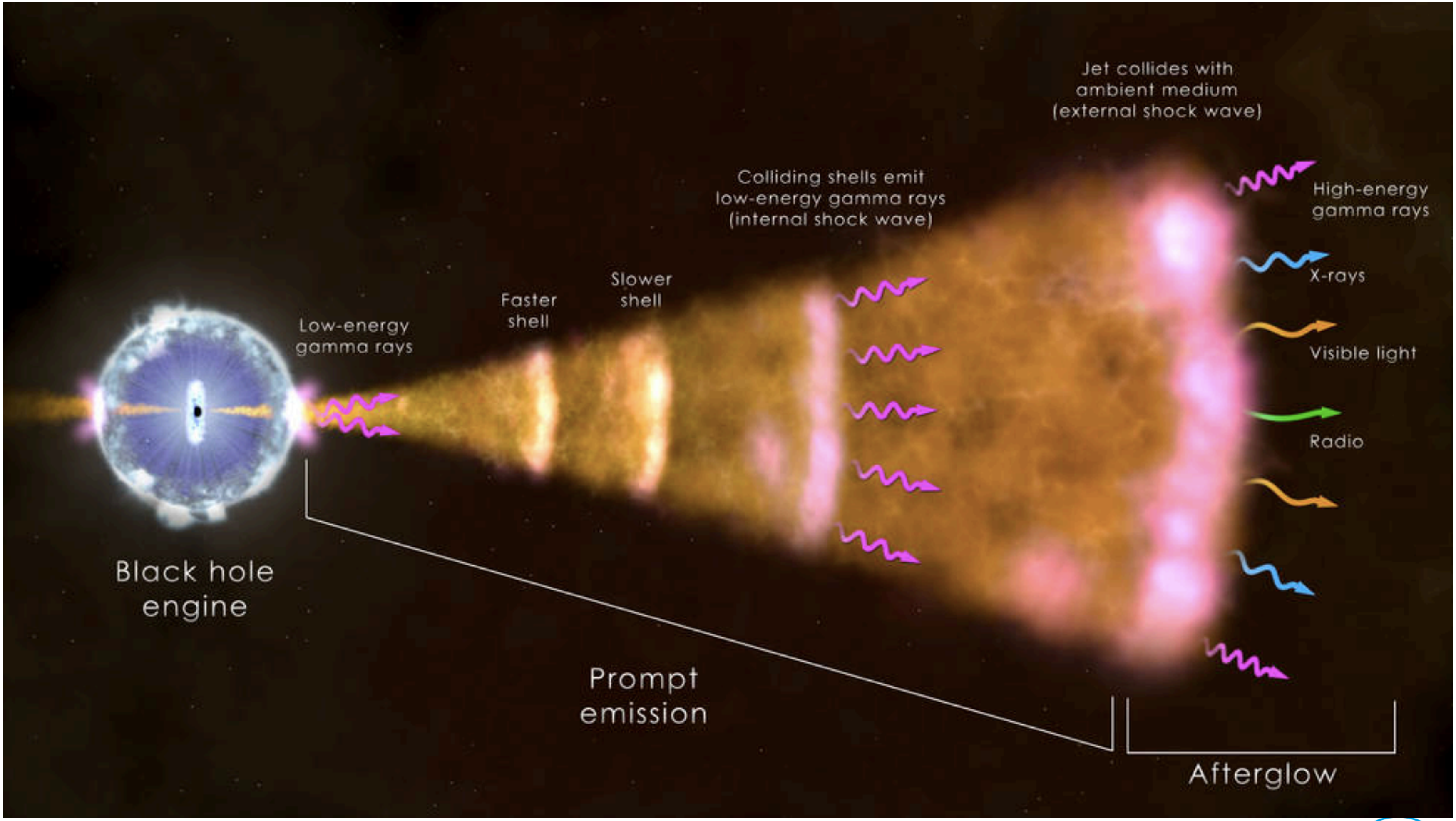


Correlation study of 3 years of IceCube data and 862 Fermi-LAT blazars

IceCube Coll., arXiv:1502.03104

Gamma-Ray Bursts (GRBs)

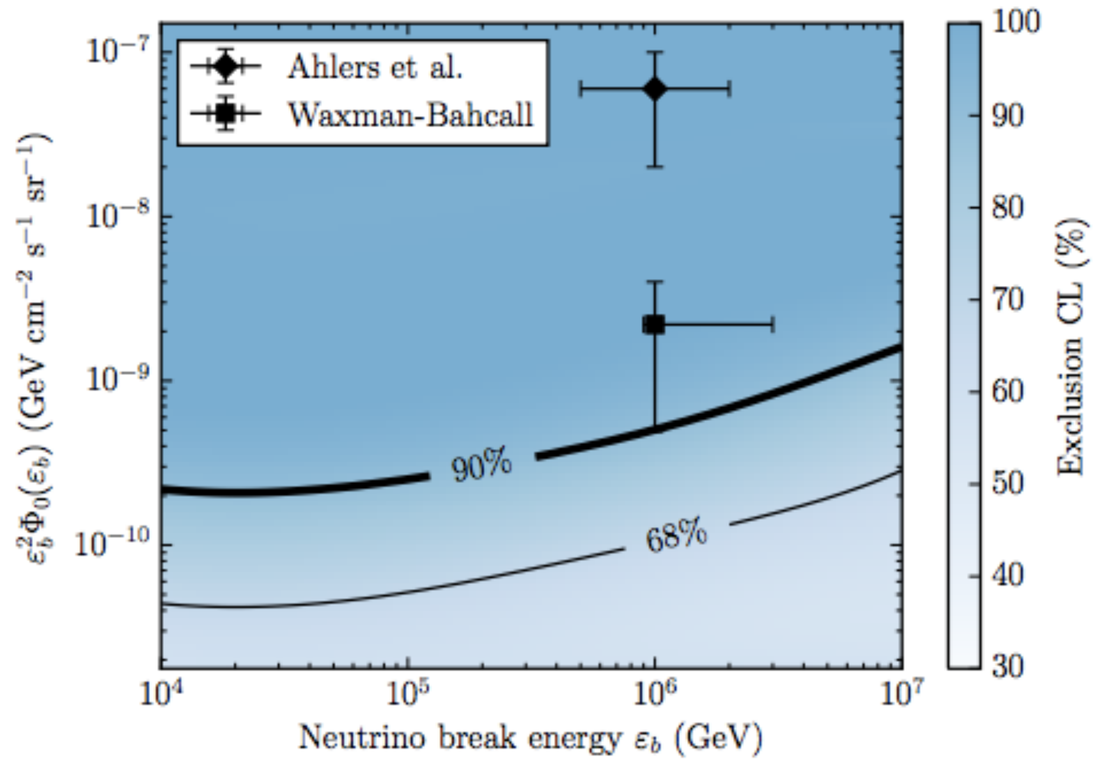
- Gamma rays and X-rays tell us WHERE and WHEN



Gamma-Ray Bursts (GRBs)

- Extremely large energy release on the time-scale of 0.1-100 seconds
- Gamma rays and X-rays tell us WHERE and WHEN

> 800 GRBs correlated with IceCube data



IceCube Coll., ApJ 805, 2015
arXiv:1601.06484

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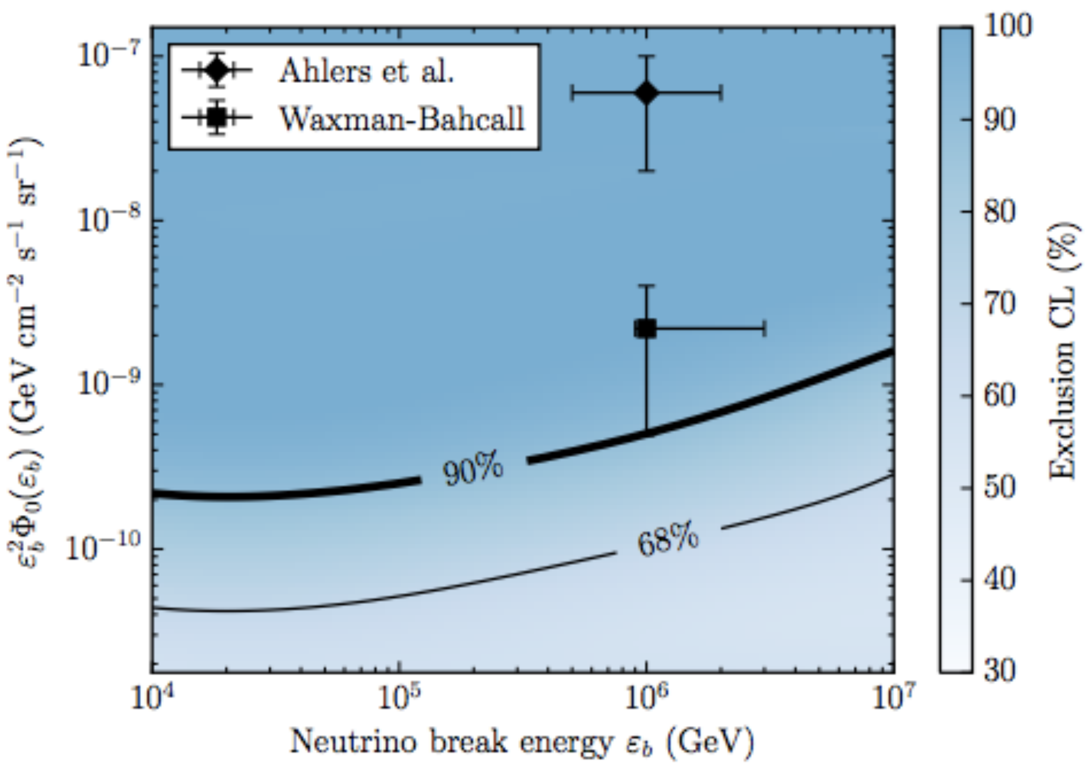
- Gamma rays and X-rays tell us WHERE and WHEN

> 800 GRBs correlated with IceCube data

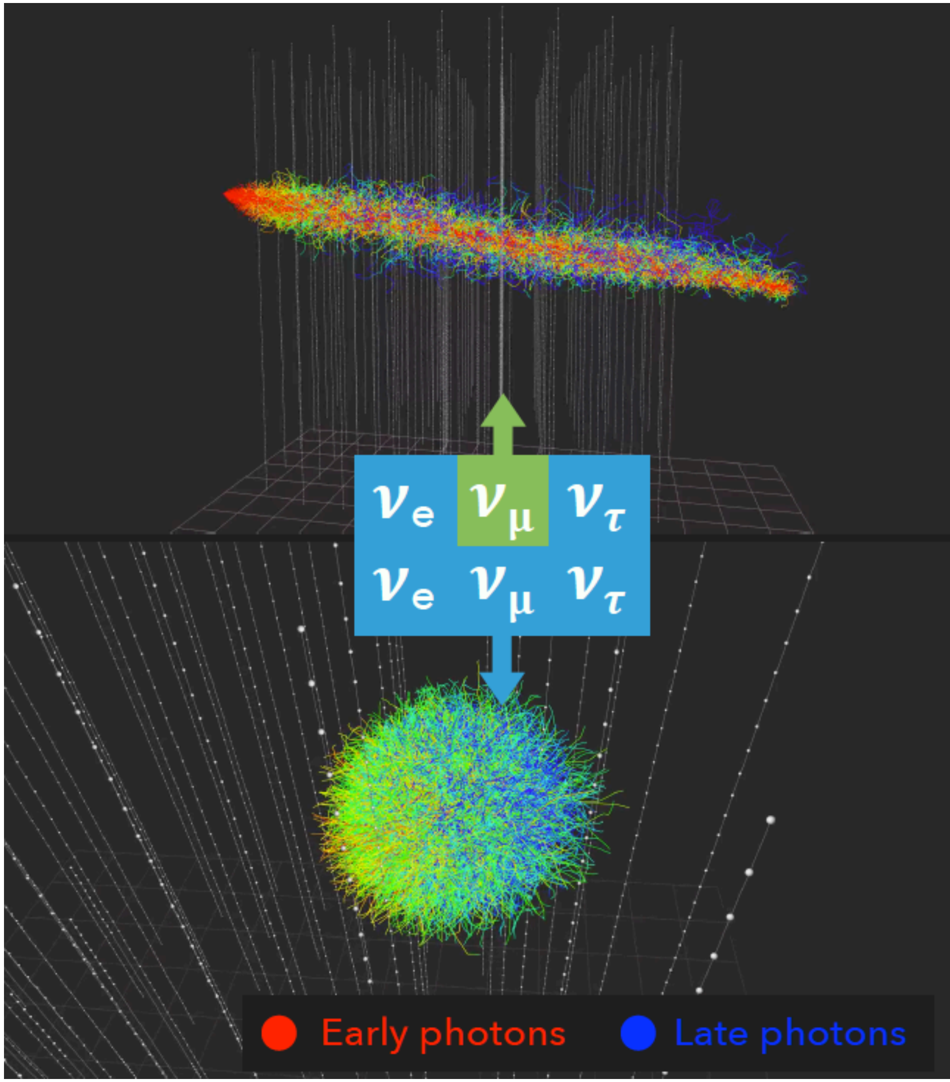


GRBs contribute less than 1% to observed diffuse neutrino flux. Potential large population of nearby low-luminosity GRBs not constrained.

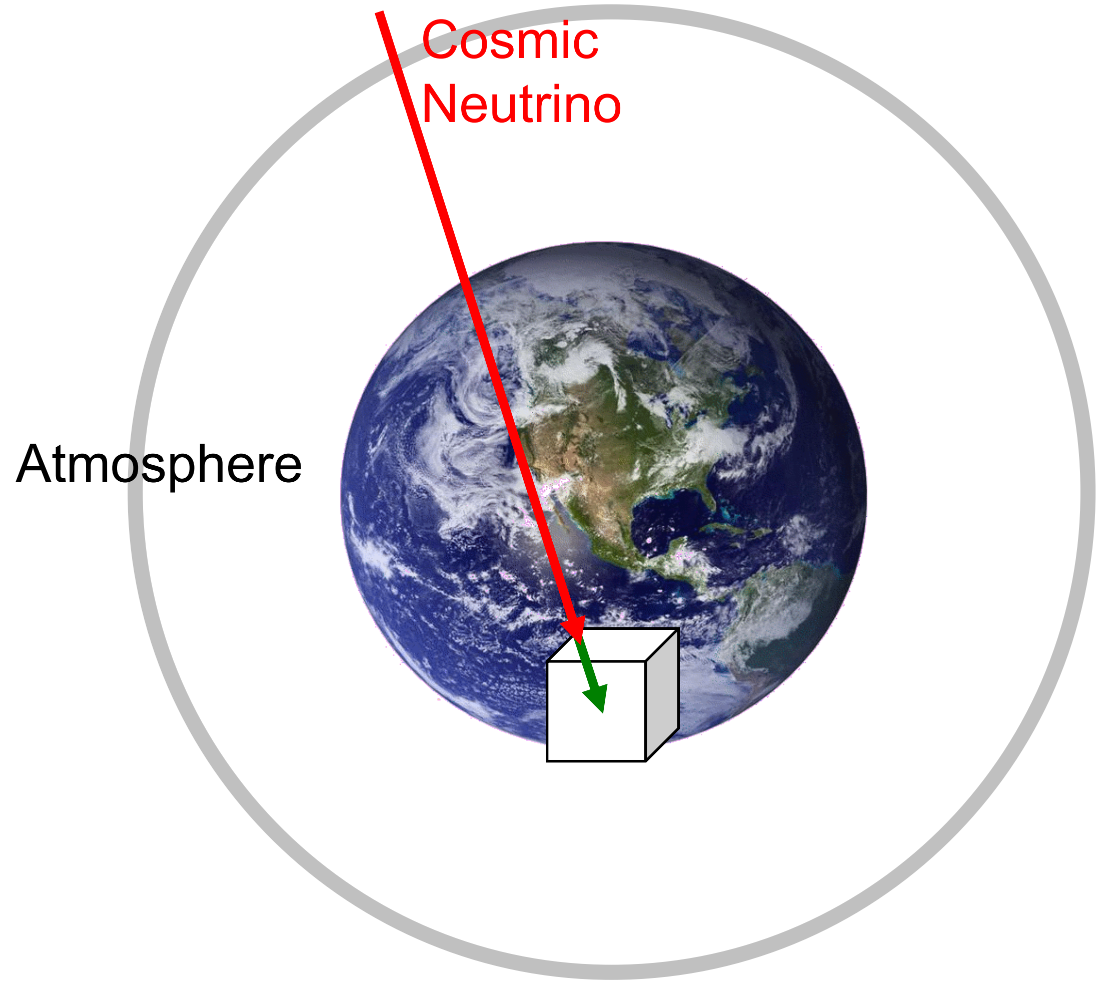
IceCube Coll., ApJ 805, 2015
arXiv:1601.06484

Event Signature

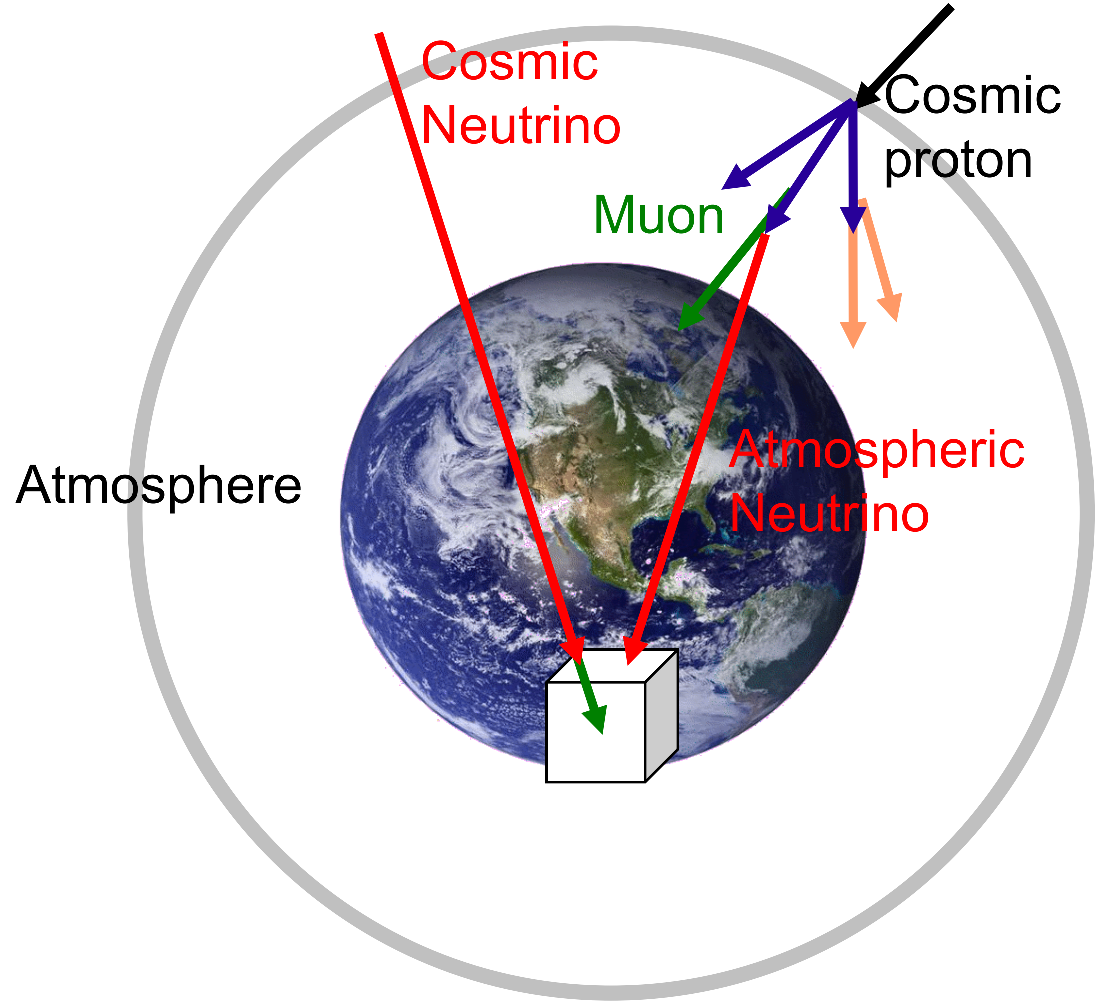
- Tracks events
  - Muon neutrinos
  - Good angular resolution < 1deg
  - Vertex can outside the detector → Increased effective volume
- Shower events
  - All flavors
  - Fully active calorimeter → good energy resolution ±15% deposited energy
  - Poor angular reconstruction ~10 deg (>100 TeV)



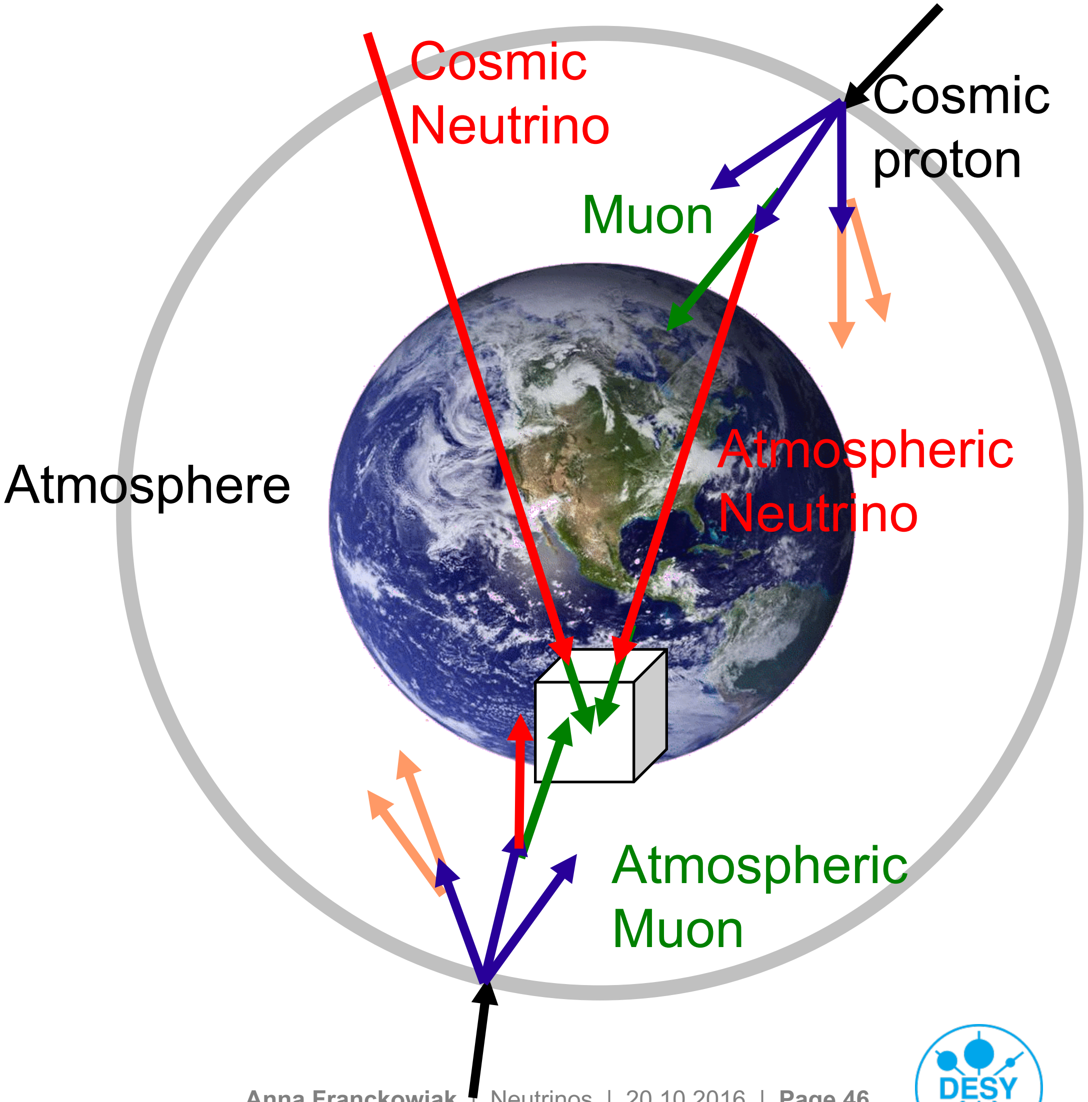
Background in Search for Cosmic Neutrinos



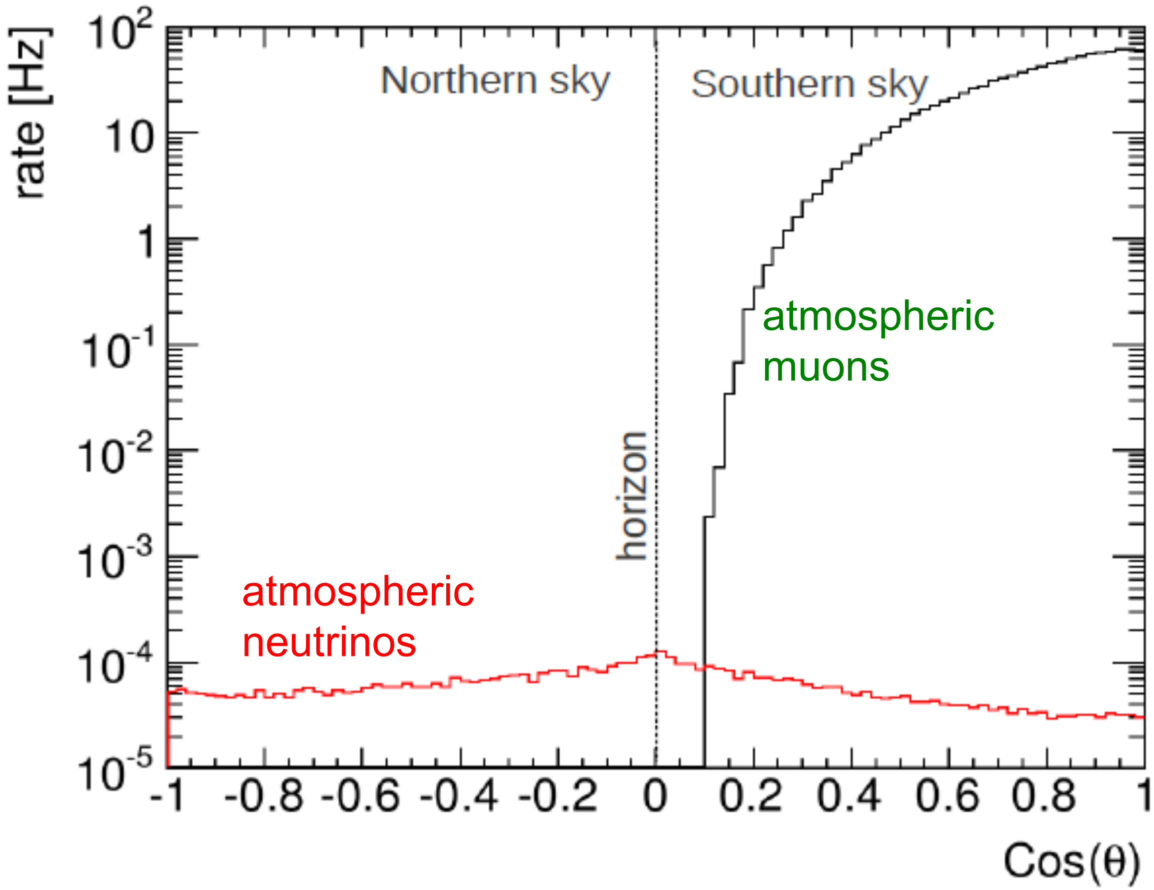
Background in Search for Cosmic Neutrinos

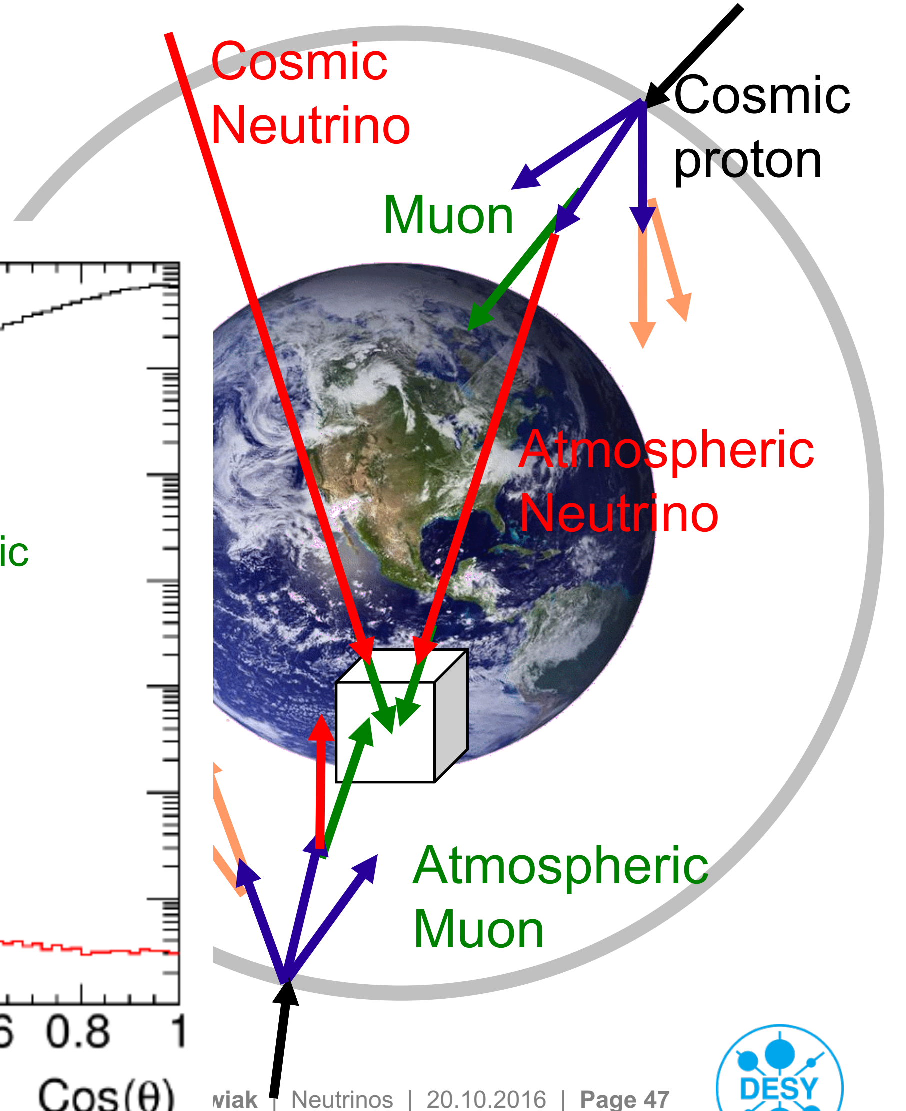


Background in Search for Cosmic Neutrinos



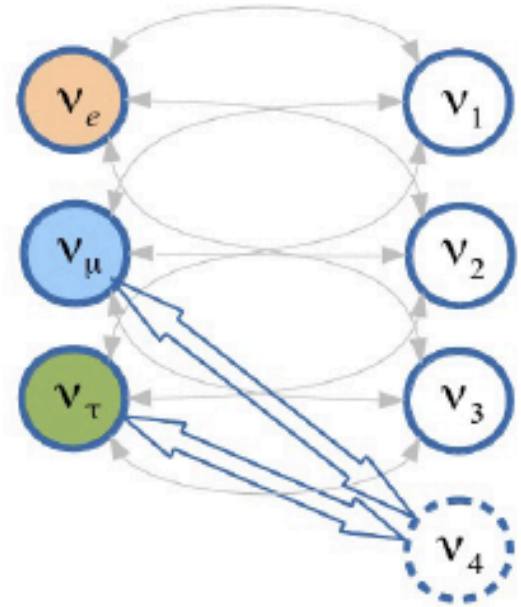
Background in Search for Cosmic Neutrinos





Neutrino mixing in 3+1 model

- Tension between different experiments:
  - Beam experiments, reactor anomaly, early gallium experiments
- Sterile neutrinos might explain the tension
- Problem: sterile neutrinos do not interact



Standard PMNS matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$

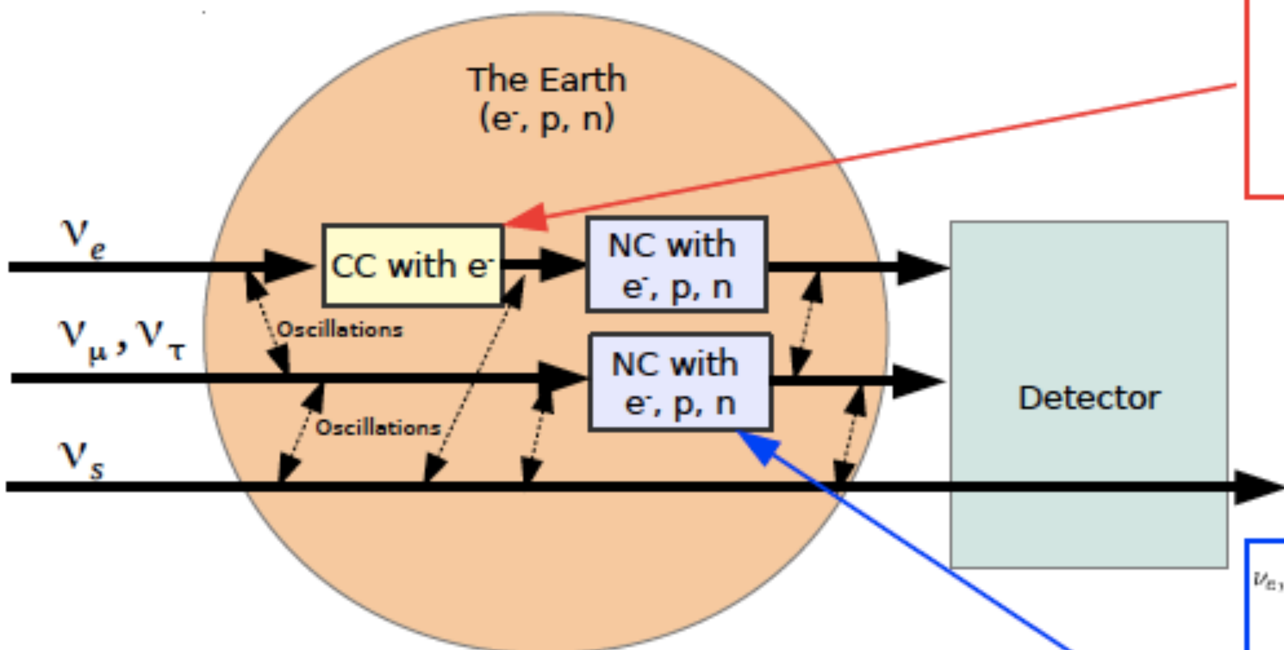
$$|U_{\mu 4}|^2 = \sin^2\theta_{24}$$
$$|U_{\tau 4}|^2 = \sin^2\theta_{34} \cdot \cos^2\theta_{24}$$

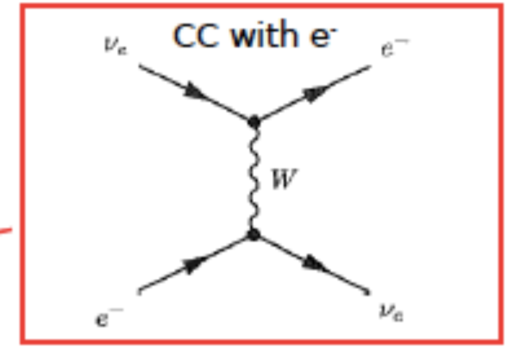
- Changes muon neutrino oscillations

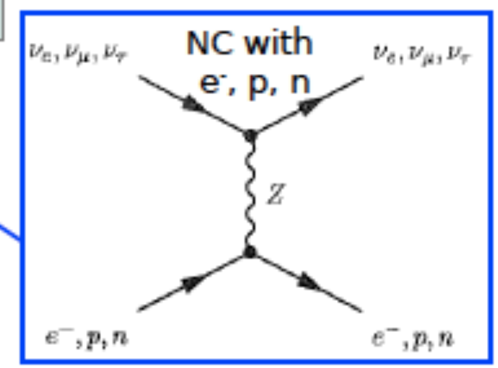
- New parameters:
  - θ_{14}, θ_{24}, θ_{34}, δ_2, δ_3, Δm_{41}^2
- Assumptions:
  - $\delta_2 = \delta_3 = \theta_{14} = 0$

Matter Effects

> Propagation of neutrinos through matter



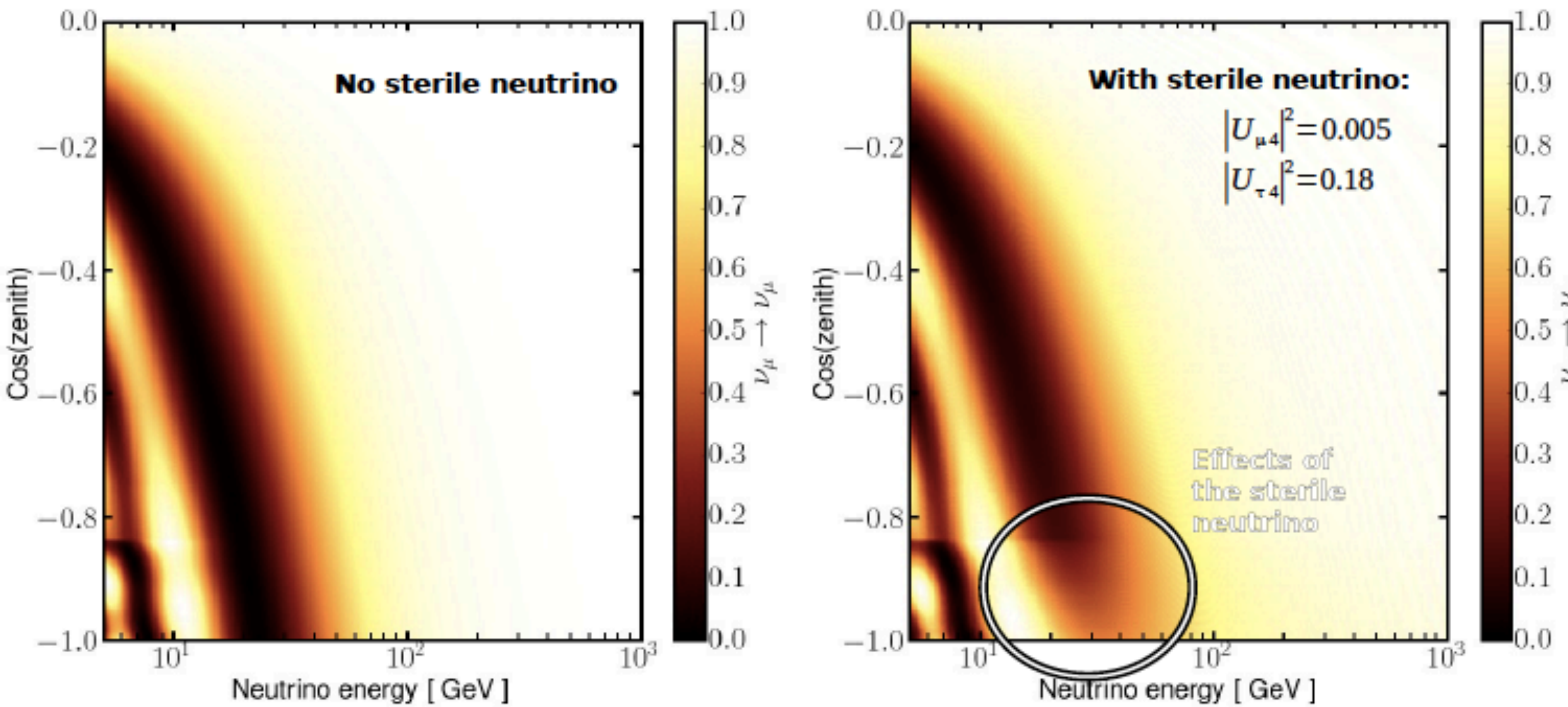




> Presence of matter:

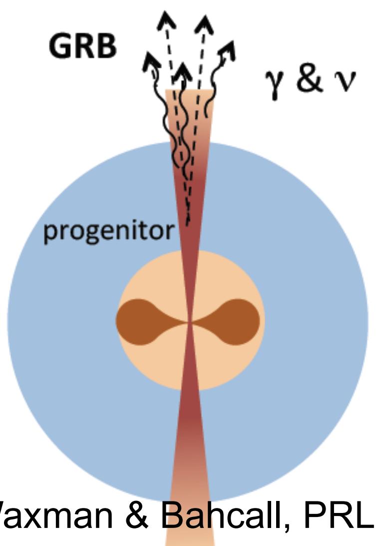
- Modifies effective mixing parameters
- Enhances effects of the sterile neutrino

Sterile neutrino signal below 100 GeV

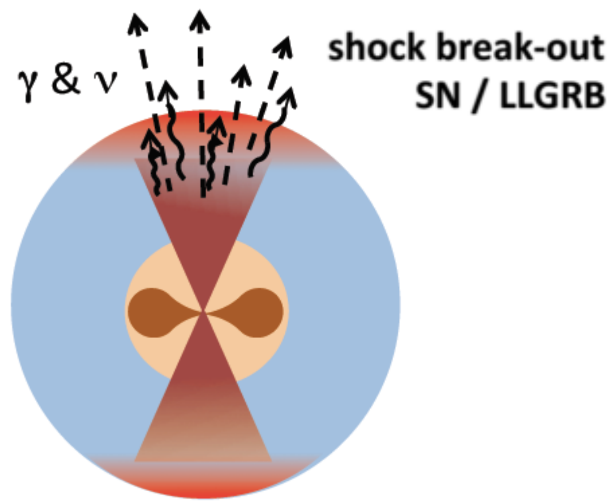


> Changes of the oscillations minimum for neutrinos crossing the Earth

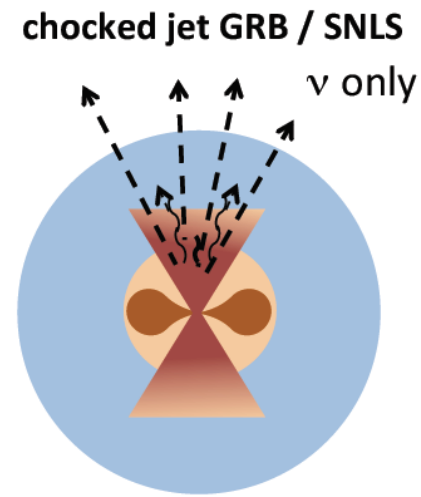
Stellar Collapses – Gamma-Ray Bursts and Supernovae



Waxman & Bahcall, PRL, 78 (1997)

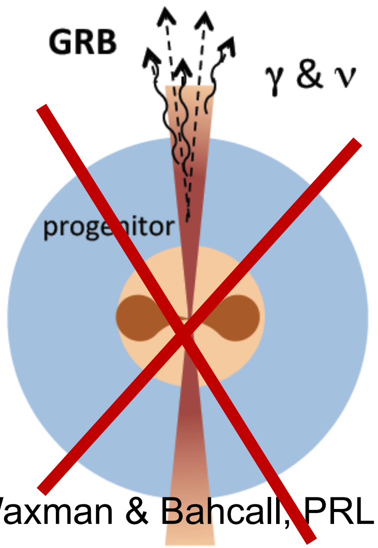


Murase et al, ApJL,651 (2006)



Ando & Beacom, PRL 95 (2005)

Stellar Collapses – Gamma-Ray Bursts and Supernovae



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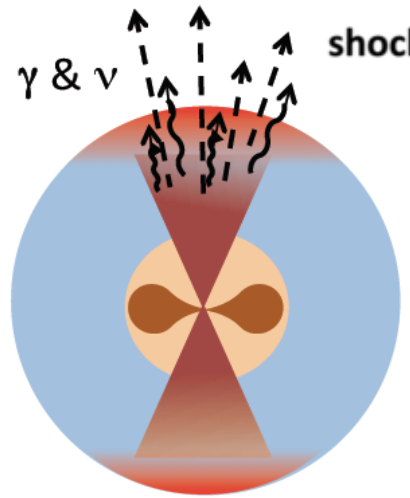
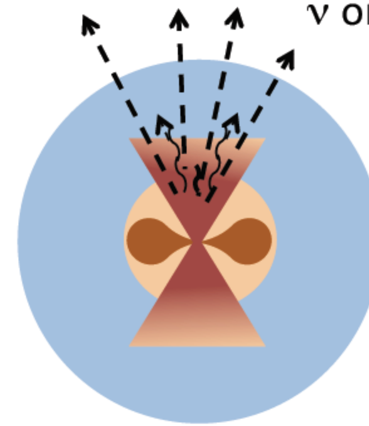


Murase et al, ApJL,651 (2006)

chocked jet GRB / SNLS



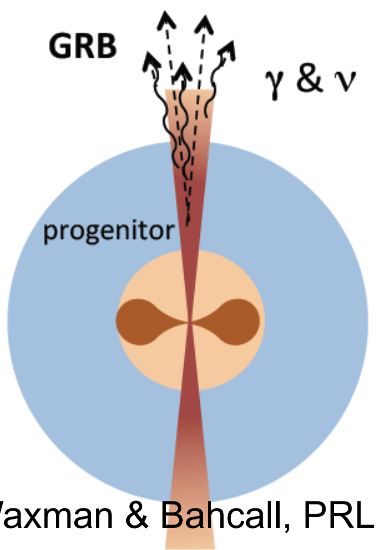
Ando & Beacom, PRL 95 (2005)

>800 GRBs correlated with IceCube data

→ GRB produce less than 1% of the diffuse neutrino flux

IceCube Coll., ApJ 805, 2015

Stellar Collapses – Gamma-Ray Bursts and Supernovae



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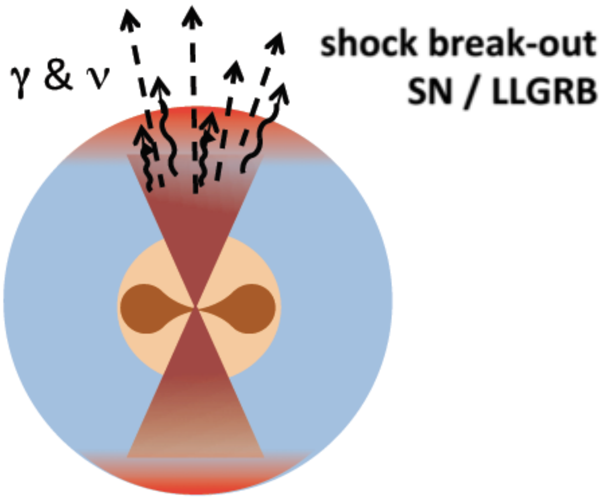
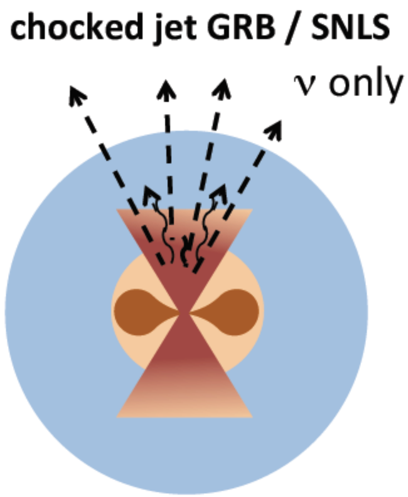


Murase et al, ApJL,651 (2006)



Ando & Beacom, PRL 95 (2005)

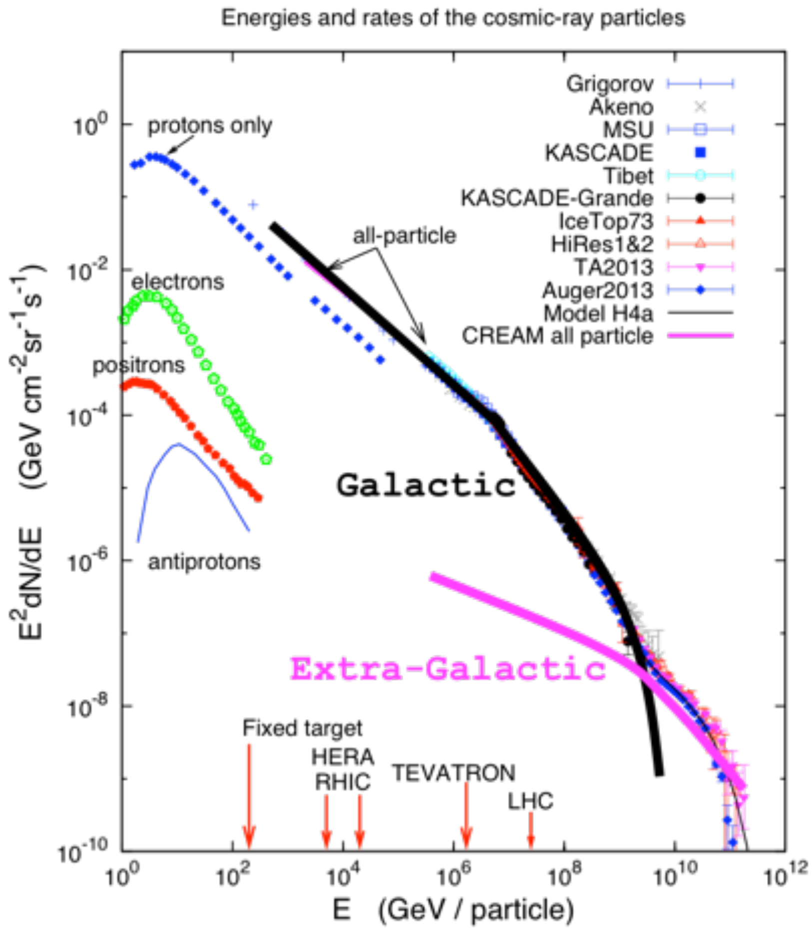
SNe are best discovered in optical

optical surveys do not cover the whole sky

use IceCube to trigger EM follow-up

The Cosmic-Ray Mystery

- Cosmic Rays discovered by Victor Hess in 1912
- Cosmic Rays spectrum spans 10 decades of energy
  - Origin still unknown



Located at Mt. Palomar, California