Multi-Messenger Astronomy

with Neutrinos

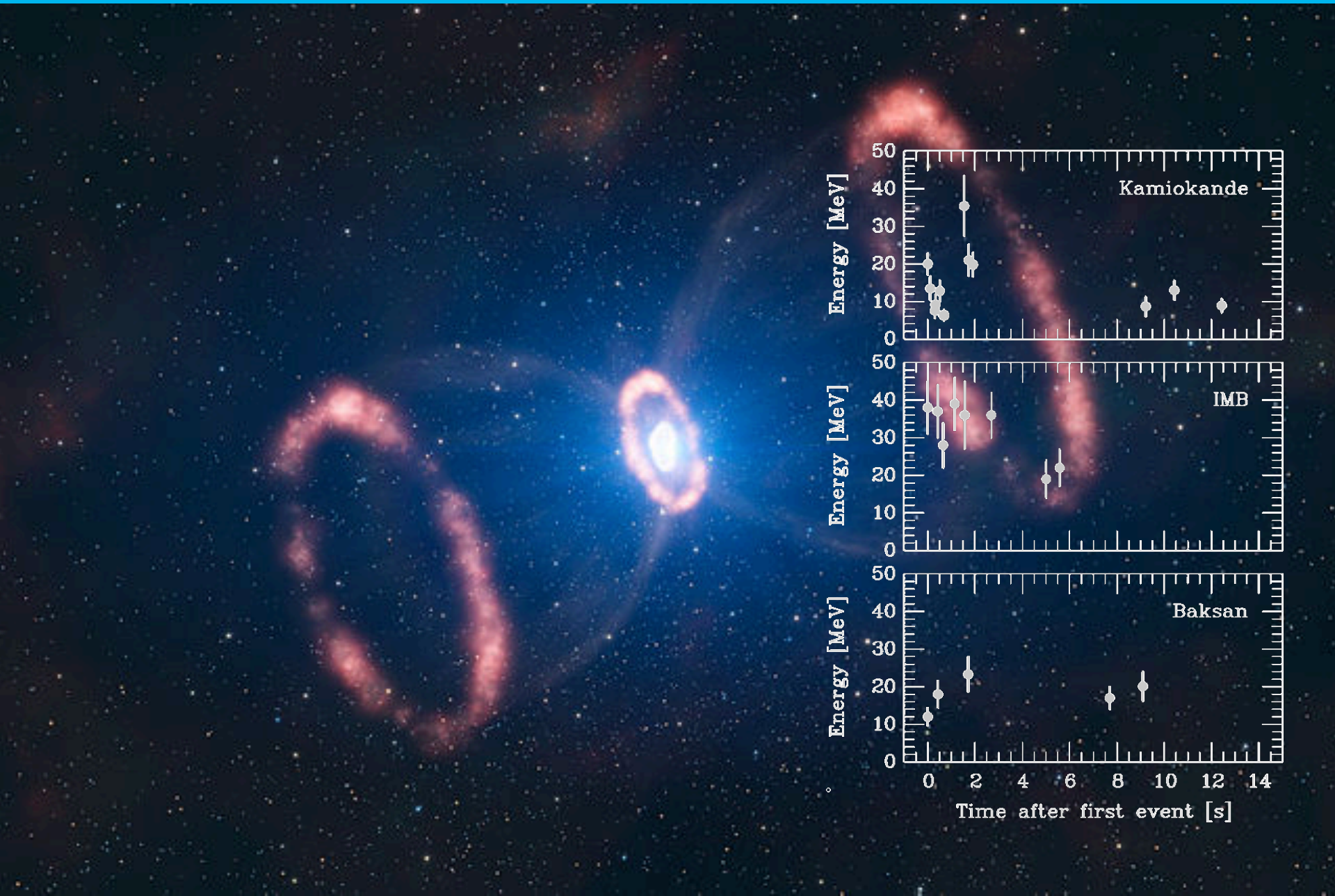
Anna Franckowiak

Neutrino 2016, London
4.7.2016

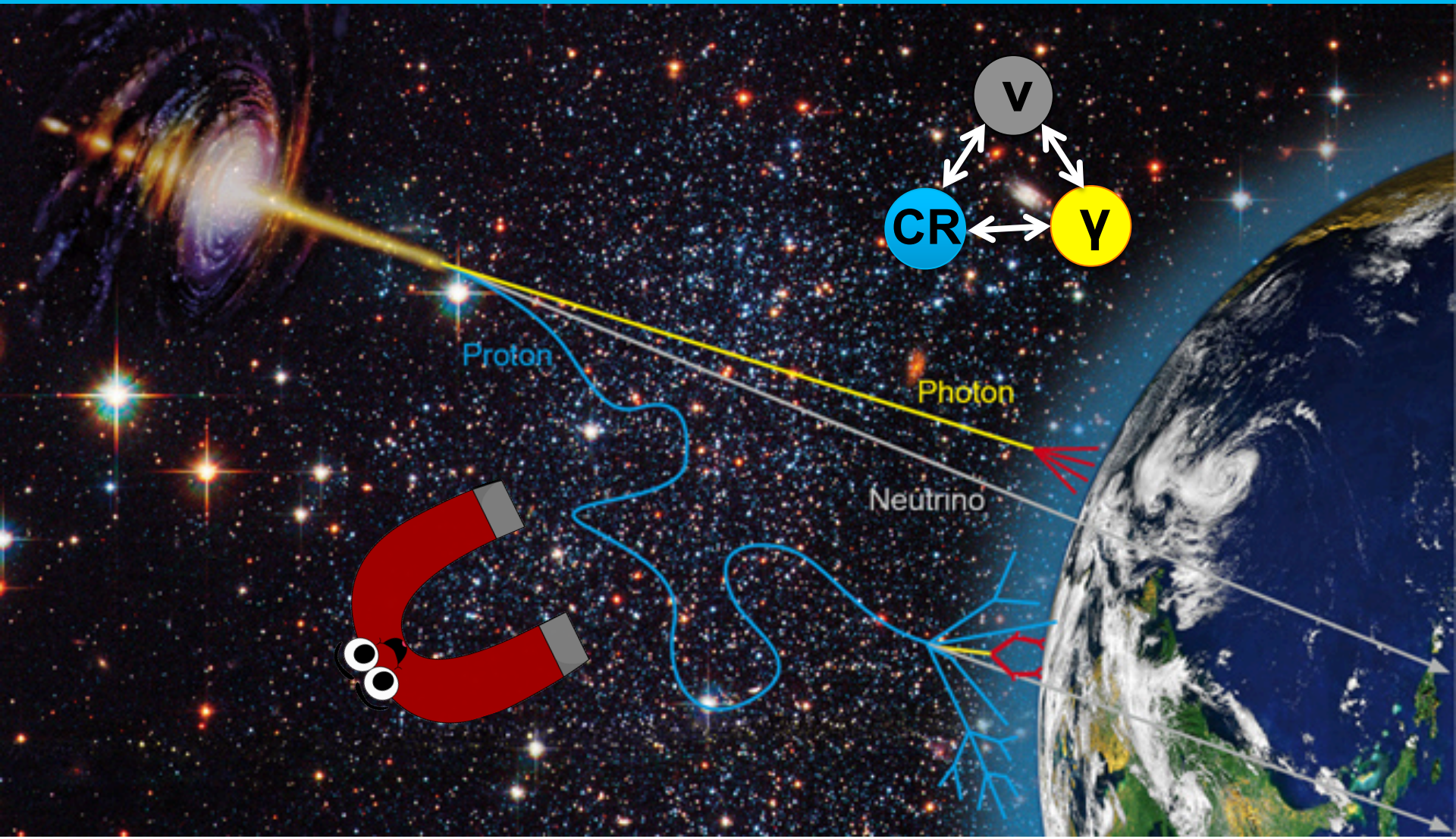
HELMHOLTZ ASSOCIATION

DESY

MeV Neutrinos from SN1987A



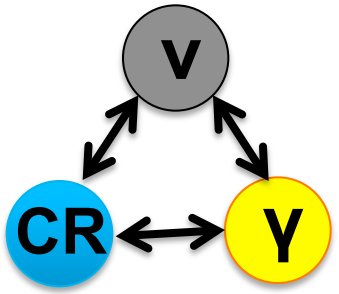
The Neutrino Cosmic-Ray Connection



Neutrino Production Processes

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

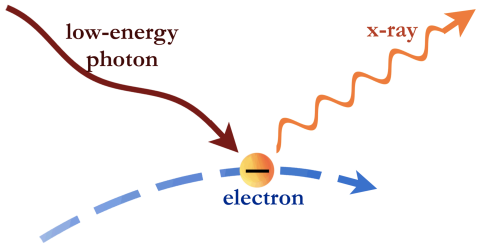
$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\,\gamma \\ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu \\ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

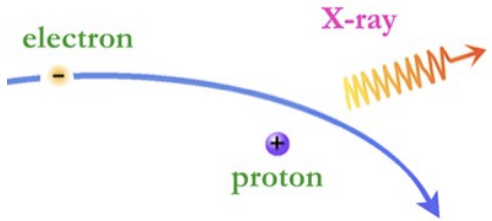


Photohadronic (e.g. gamma-ray bursts, active galactic nuclei)

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

Gamma-rays are not exclusively produced in hadronic processes

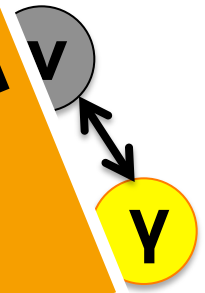




Neutrino Production Processes

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

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

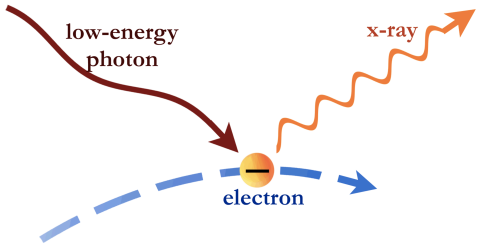


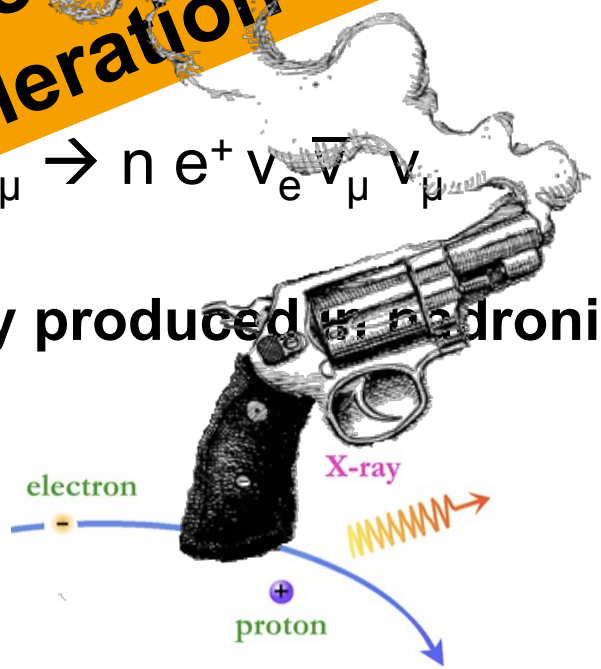
Neutrinos are the smoking gun signature for hadronic acceleration

Photohadronic (e… …alactic nuclei)

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

Gamma-ray … not exclusively produced in hadronic processes

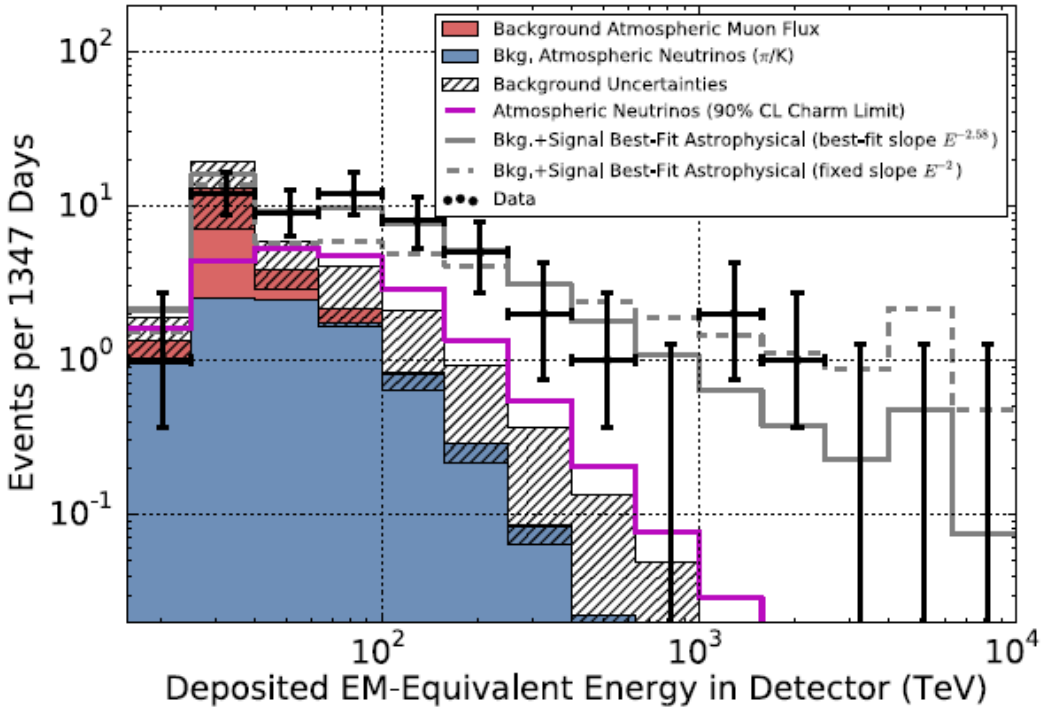


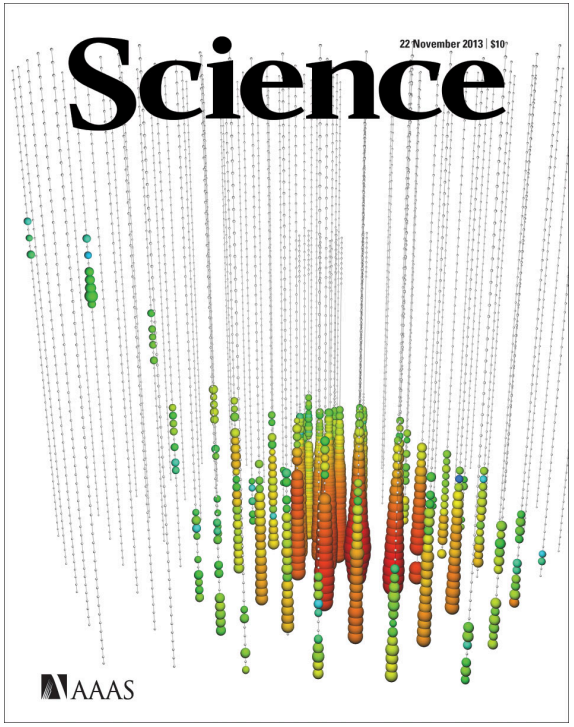


DESY

First Detection of High-Energy Astrophysical Neutrinos

See talk by M. Kowalski



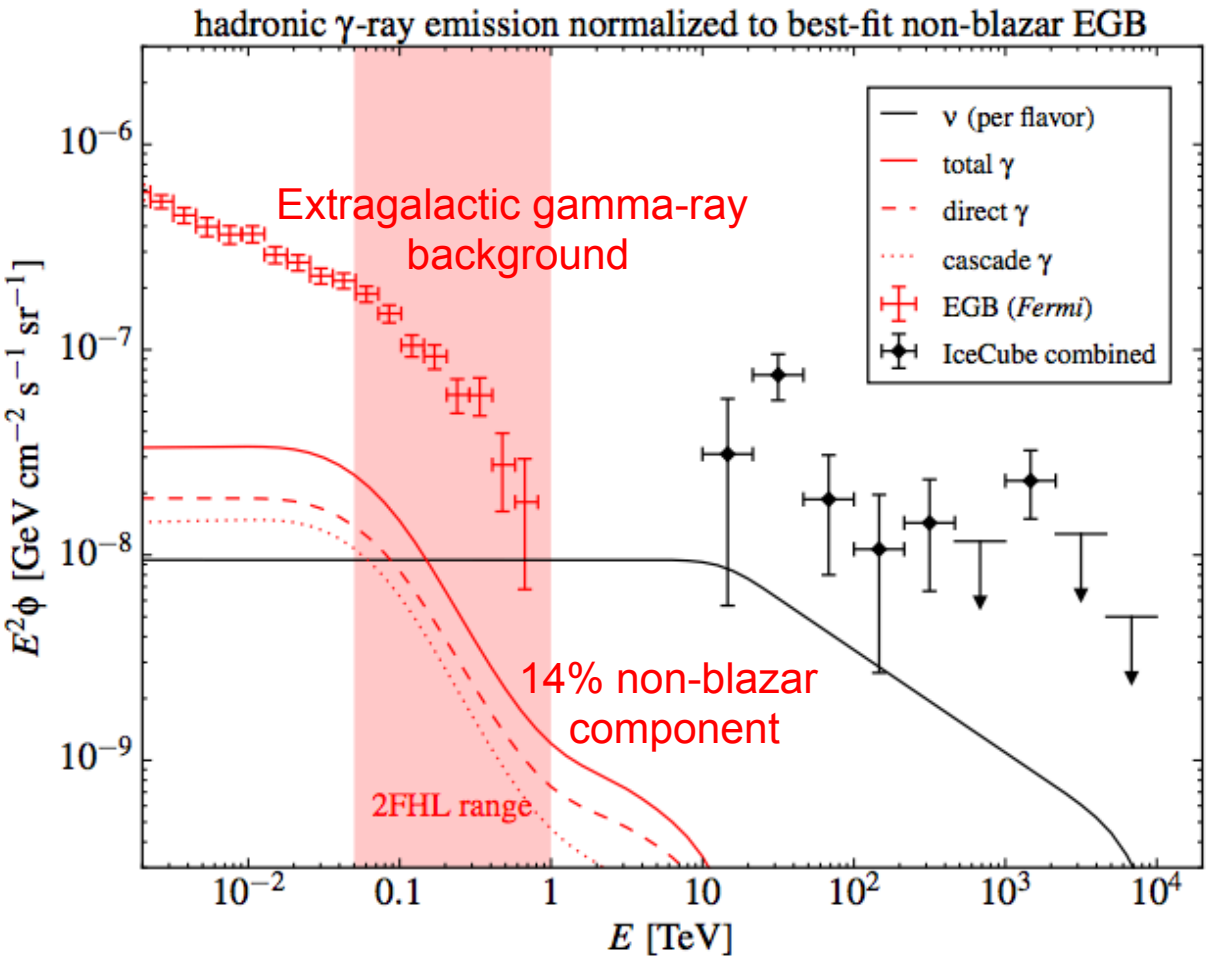


Origin still unknown

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

DESY

Gamma-ray background disfavors pp Neutrino Sources



Starburst galaxies contribute less than 30% to the diffuse neutrino flux

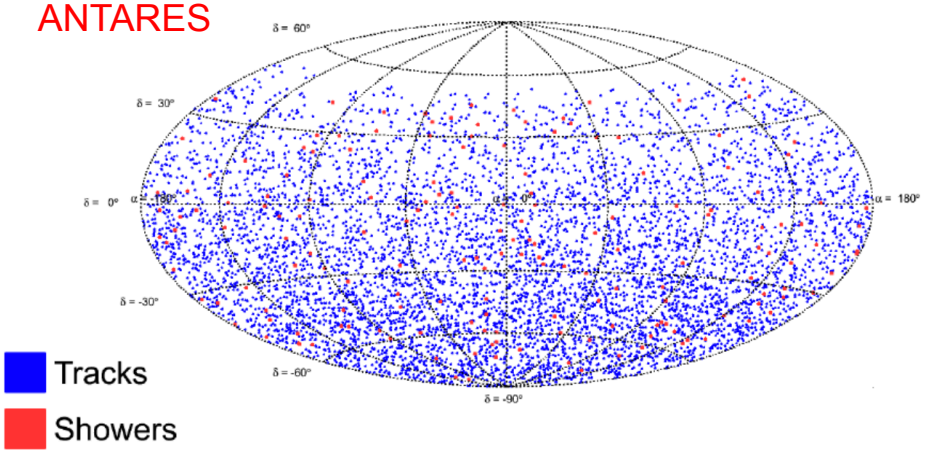
Bechtol et al. arXiv:1511.00688

DESY

The Multi-Messenger Ansatz

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

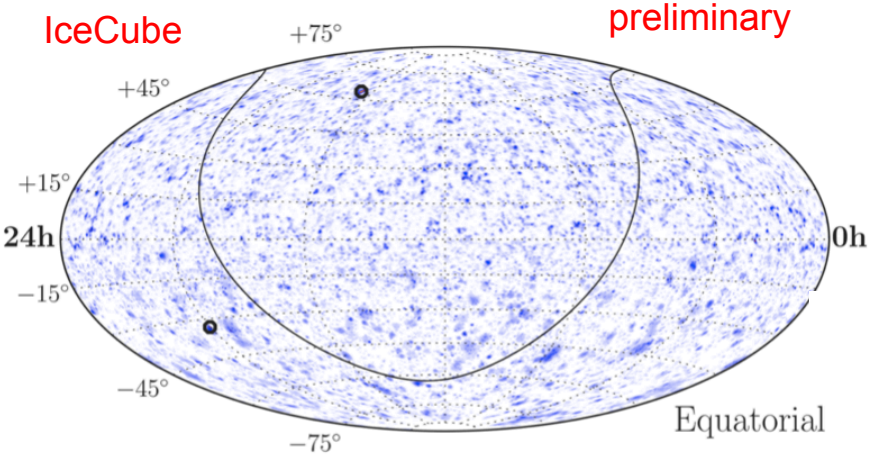
ANTARES



ANTARES ApJ 786 2014

IceCube

preliminary



IceCube presented at ICRC 2015

DESY

The Multi-Messenger Ansatz

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

If we know **WHERE** and/or **WHEN** to look we can increase our sensitivity

DESY

The Multi-Messenger Ansatz

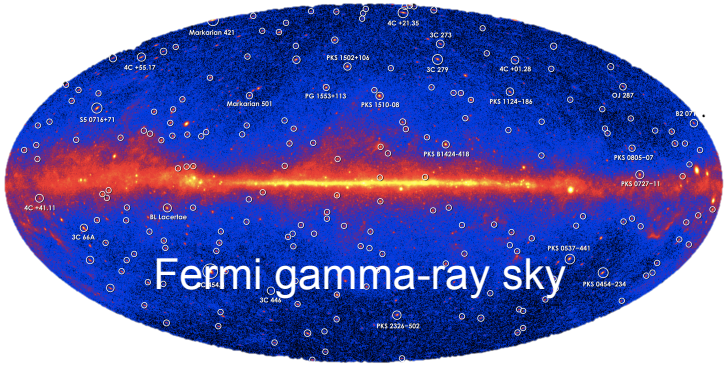
No significant cluster of neutrinos found: Neutrinos alone do not (yet) reveal a source

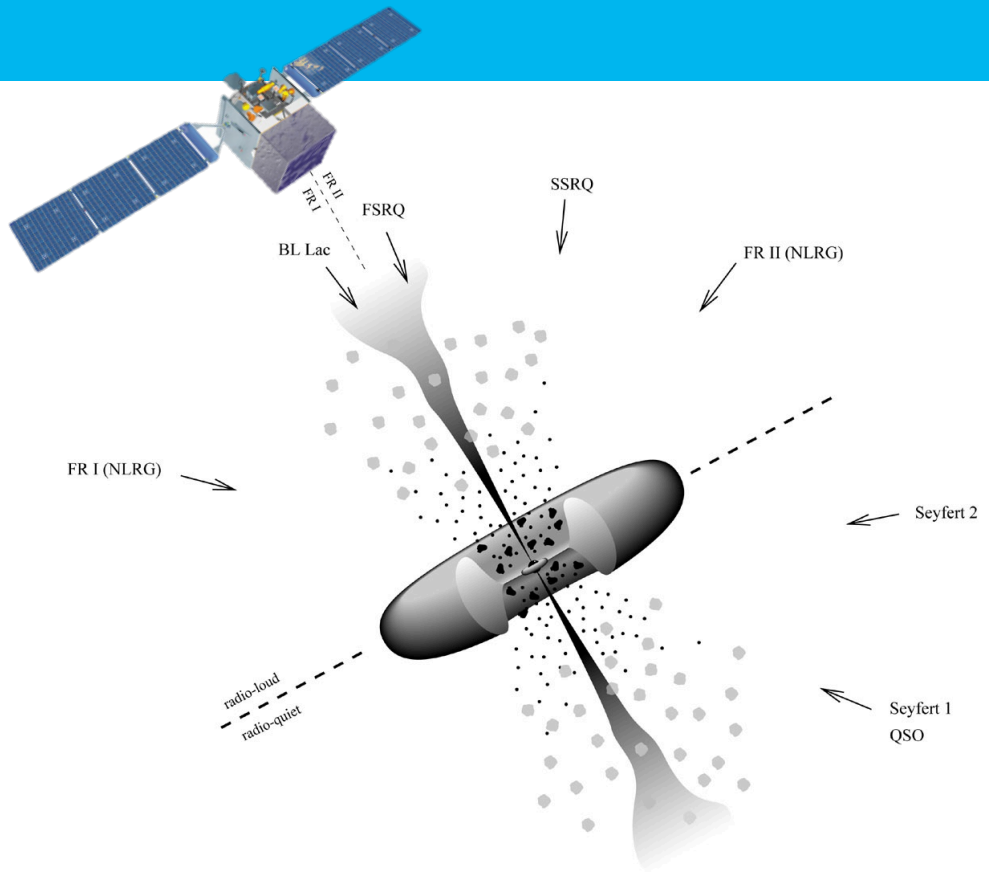
If we know **WHERE** and/or **WHEN** to look we can increase our sensitivity

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

Blazars

- Gamma rays tell us WHERE





IceCube Collaboration (arXiv: 1502.03104): Contribution from blazars to diffuse flux < ~20%

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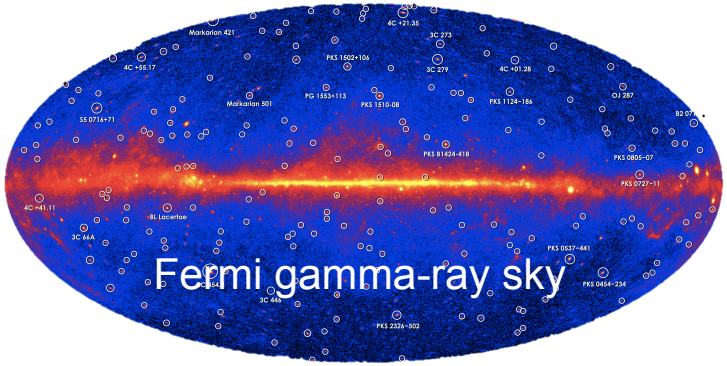

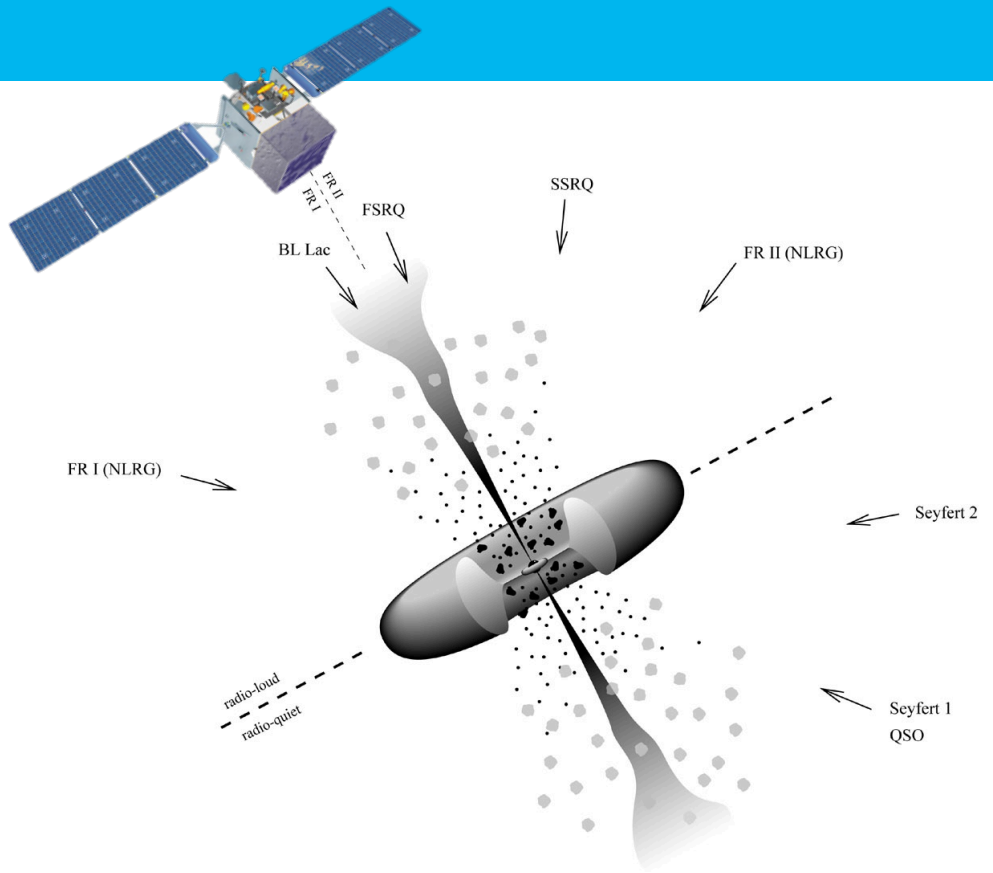

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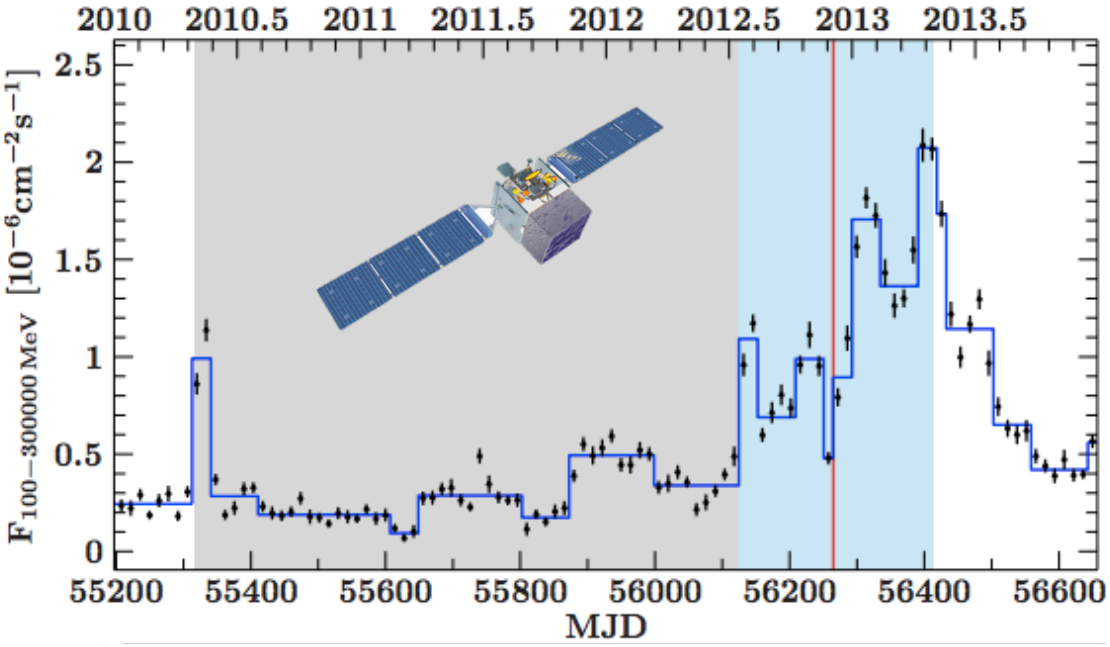
P. Padovani & E. Resconi et al. MNRAS, 457, 3582 (2016) find correlation with bright high-frequency peaked blazars (1.3% chance prob.), suggest 10-20% contribution to diffuse flux

Blazar Flares

RA 208.4°
Dec -55.8°

- Gamma rays tell us WHERE and WHEN
- Major outburst of FSRQ PKS B1424−418 occurred in temporal and positional coincidence PeV neutrino
- 5% chance coincidence

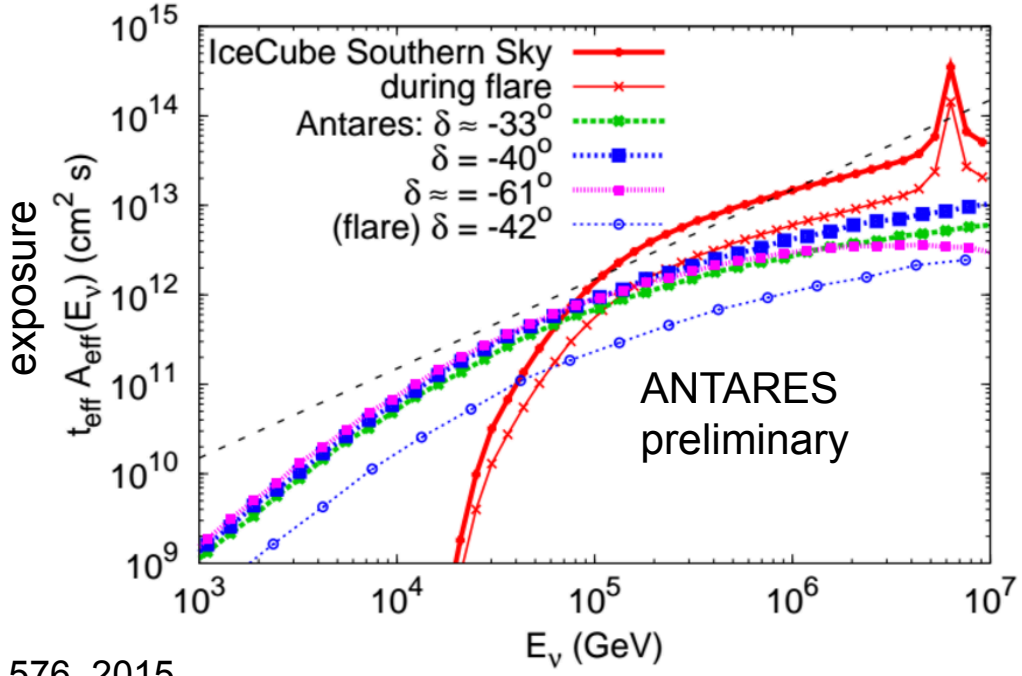


Kadler et al., Nature 520, 266 (2016)

DESY

Constraining the Possible Neutrino Spectra of High-Fluence Blazars with ANTARES

- Point-source search with 406-days of ANTARES data at position of PKS B1424−418
  - Flux limit (90% CL): 4.2×10^{-8} GeV cm^{-2} s^{-1}
  - very steep neutrino spectrum excluded



ANTARES, A&A Lett. 576, 2015
M. Kadler on behalf of the TANAMI and ANTARES Coll. presented at ICRC 2015

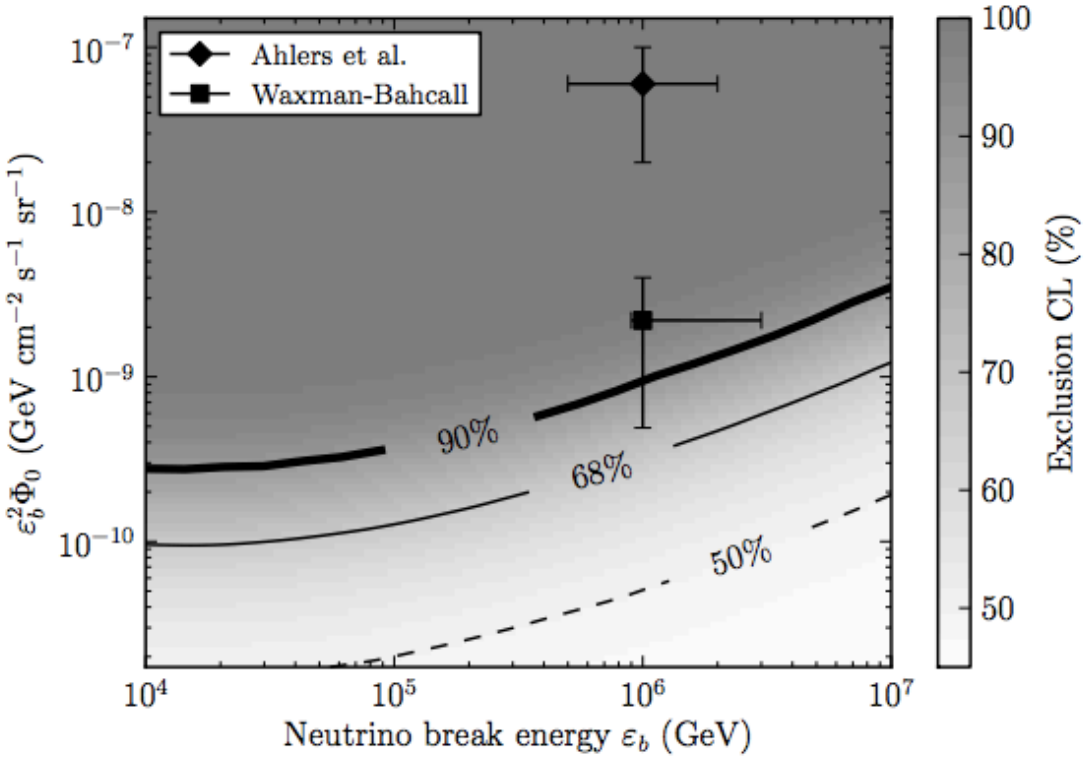
Gamma-Ray Bursts (GRBs)

- Extremely large energy release on the typical time-scale of ~100 sec
- Gamma rays and X-rays tell us WHERE and WHEN

4 years of IceCube Northern sky data correlated with 506 GRBs

Searches for neutrinos from GRBs with ANTARES (see poster S. Celli, P2.001)

See also: R. Maunu P2.013



IceCube Coll., ApJ 805, 2015

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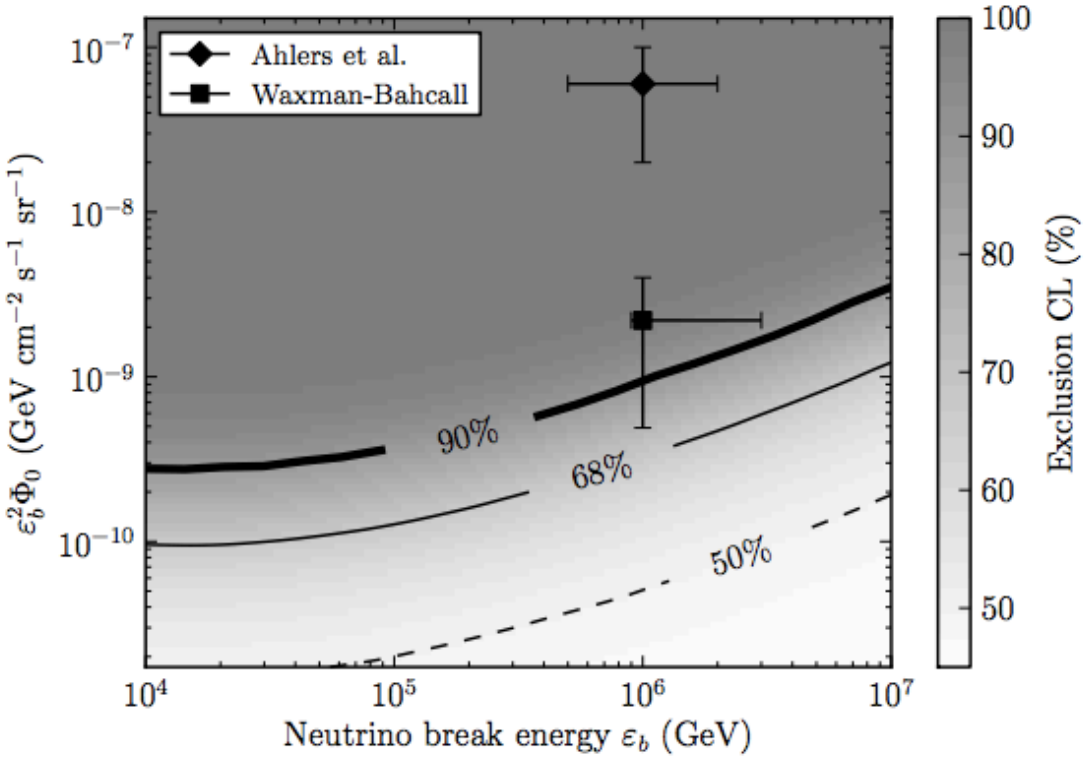
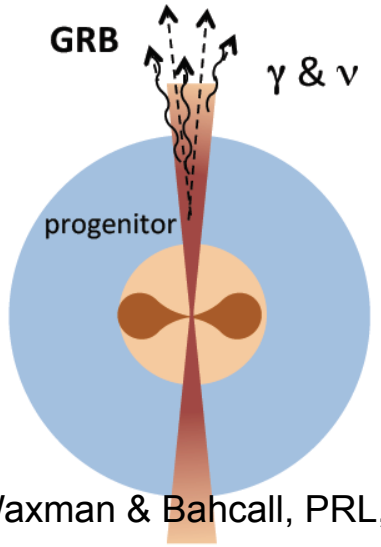


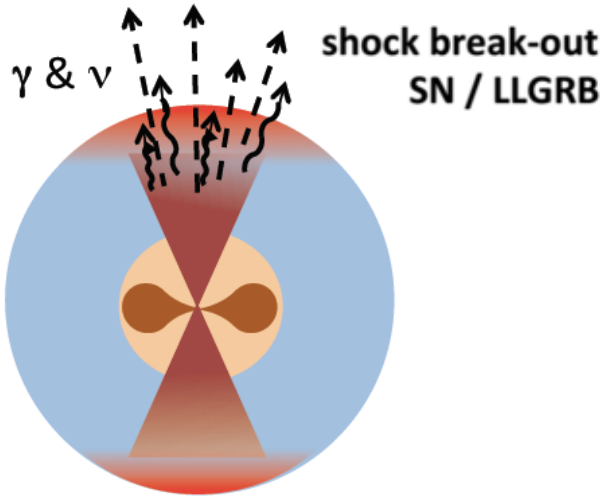
GRBs contribute less than 1% to observed diffuse neutrino flux.
Potential large population of nearby low-luminosity GRBs not constrained.

IceCube Coll., ApJ 805, 2015

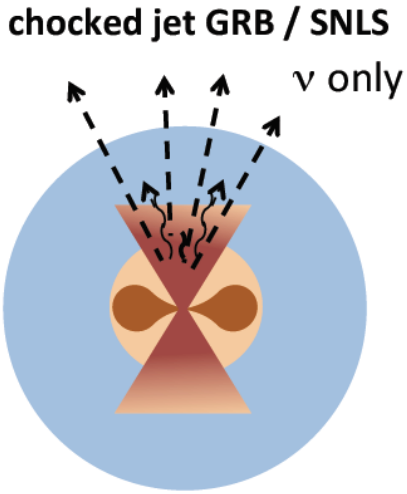
GRBs / Supernovae (SNe)



Waxman & Bahcall, PRL, 78 (1997)



Murase et al, ApJL,651 (2006)



Ando & Beacom, PRL 95 (2005)

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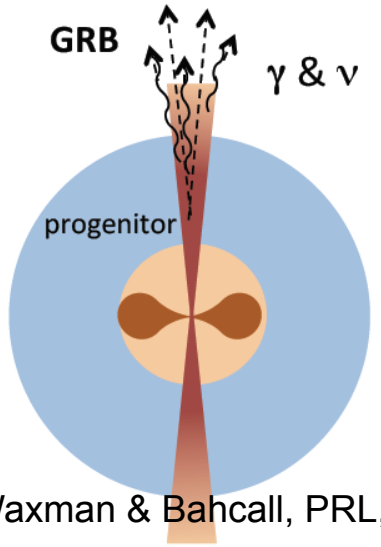

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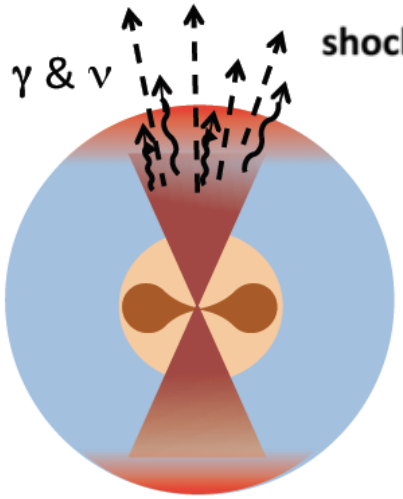

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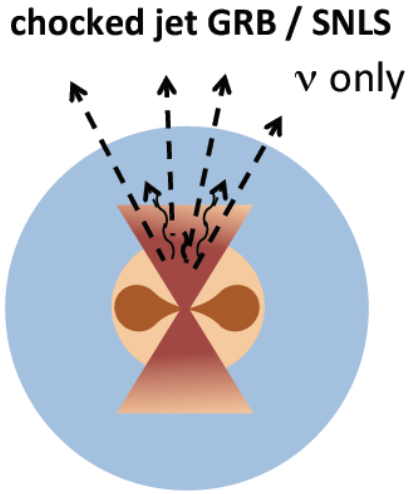


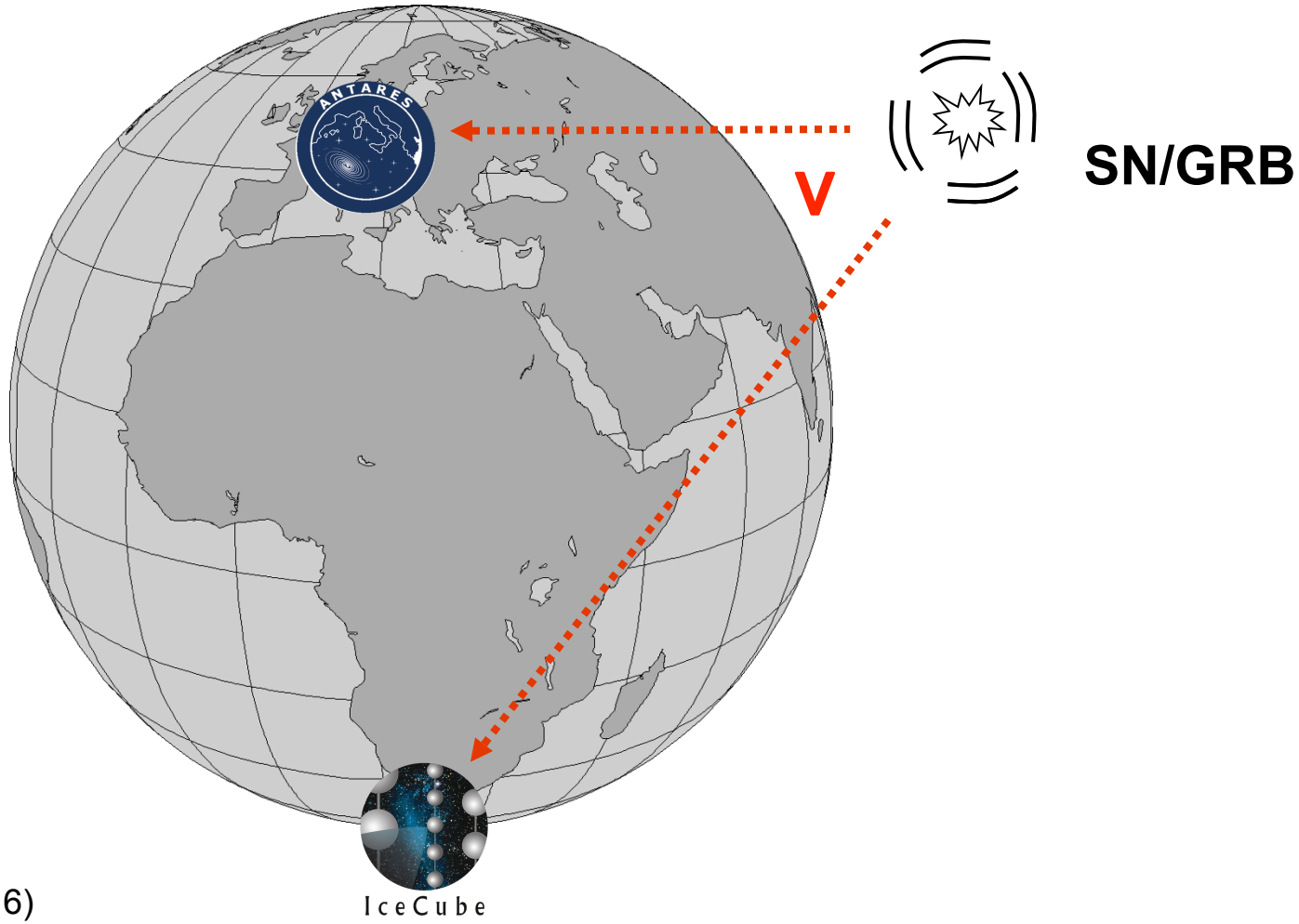
Ando & Beacom, PRL 95 (2005)

SNe are best discovered in optical

optical surveys do not cover the whole sky

Use neutrinos to trigger EM follow-up

Optical Follow-Up

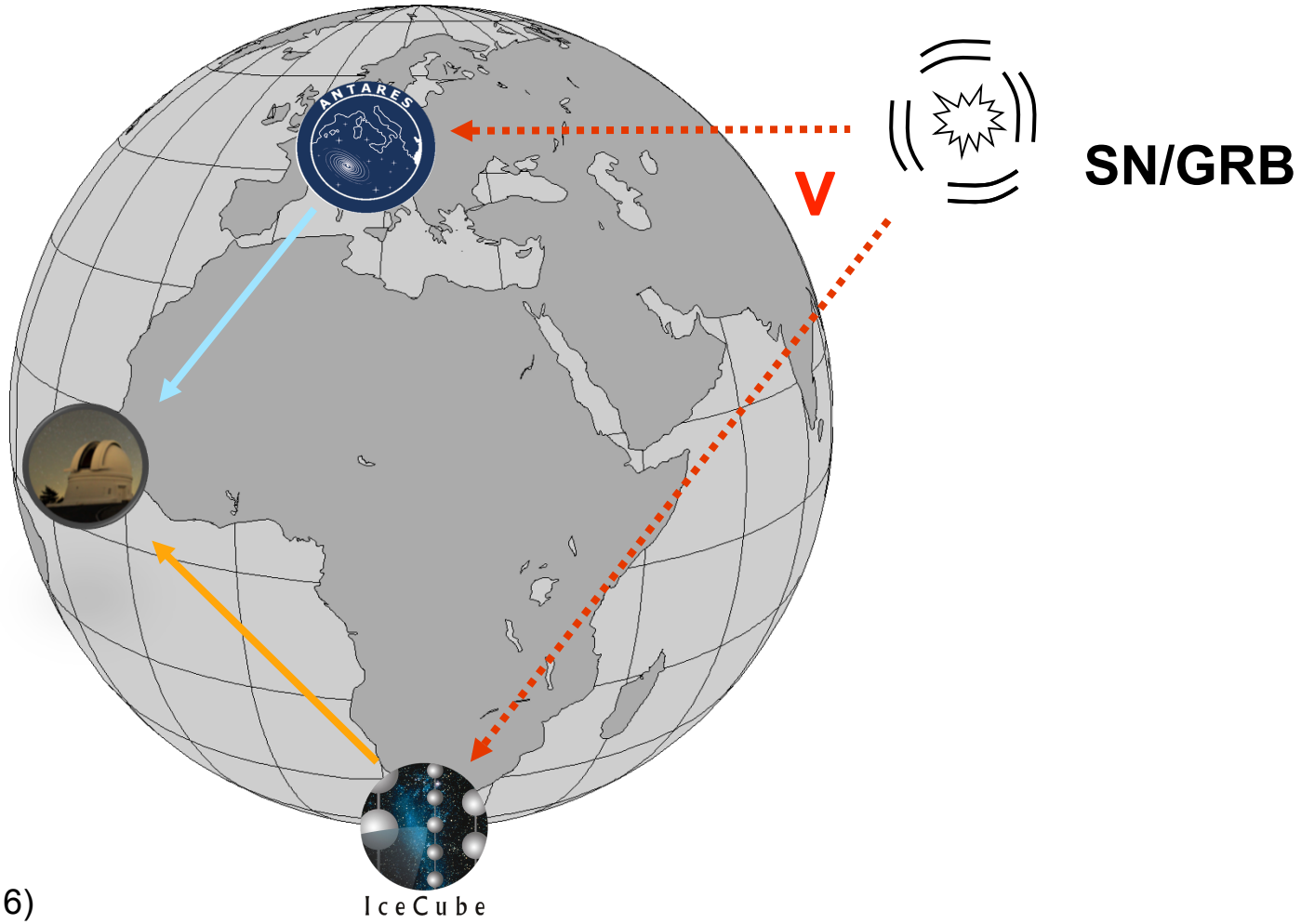


ANTARES JCAP 1602 (2016)
Ackermann et al.arXiv:0709.2640
IceCube A&A 539, A60 (2012)

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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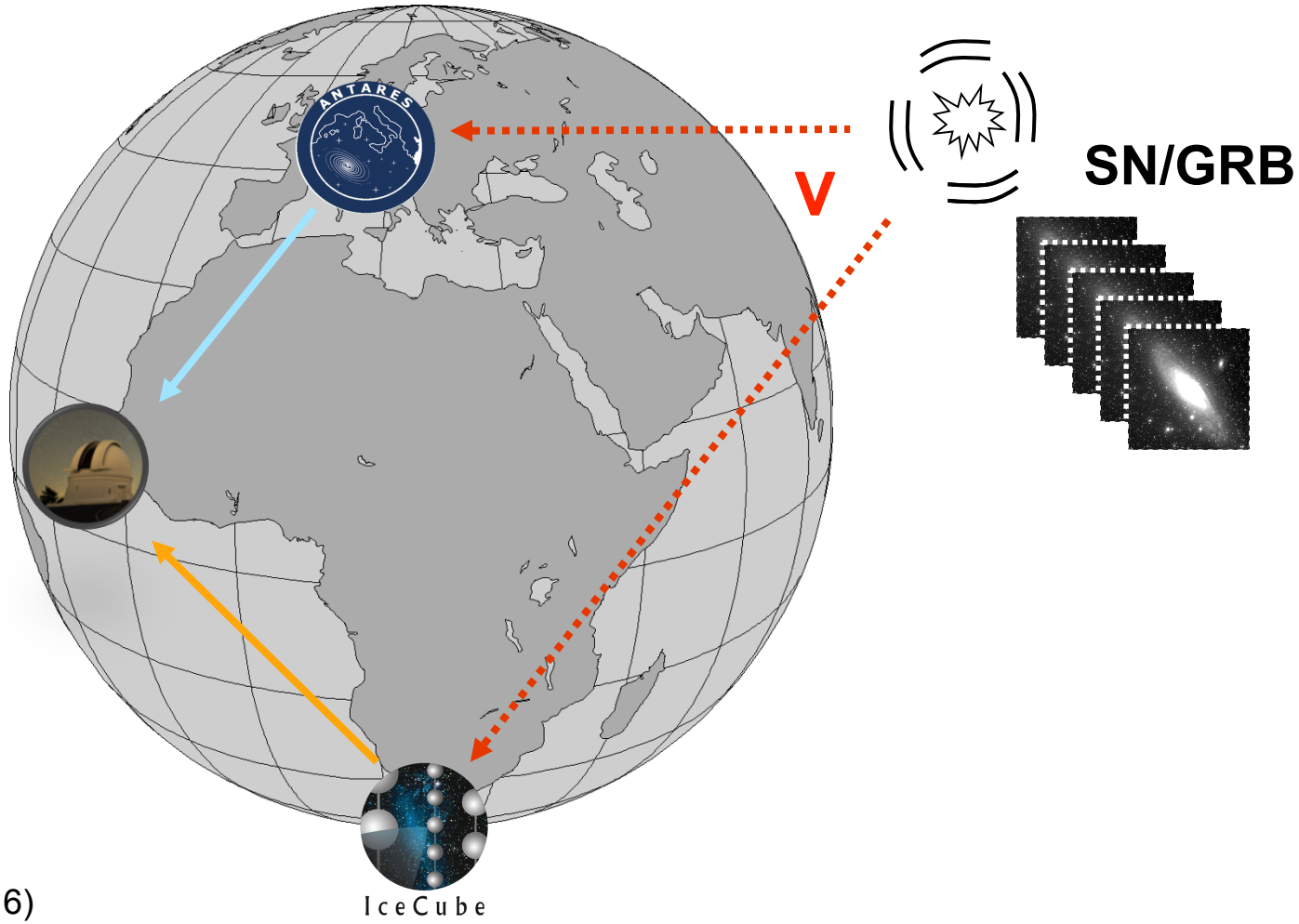

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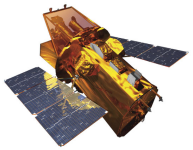
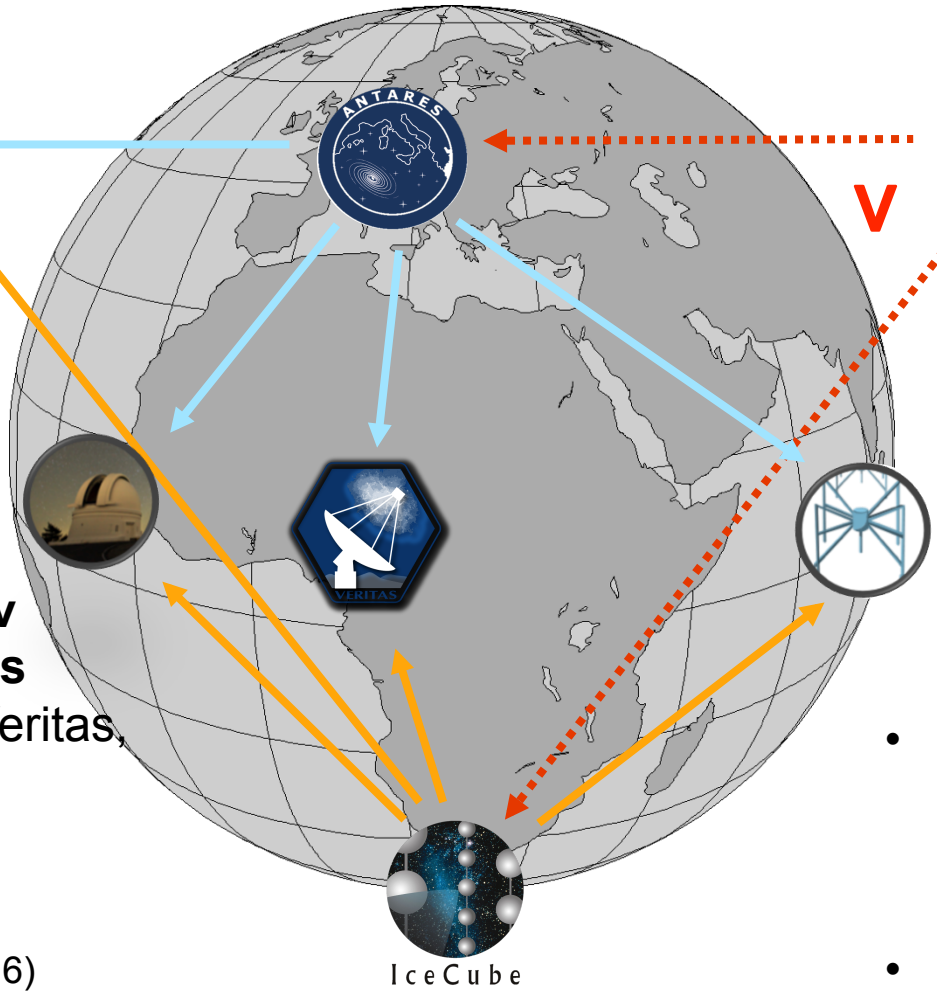
Optical, X-ray, Radio and Gamma-Ray Follow-Up

X-ray (Swift)





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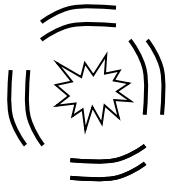
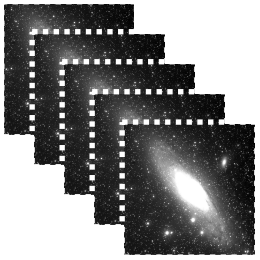


SN/GRB



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

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

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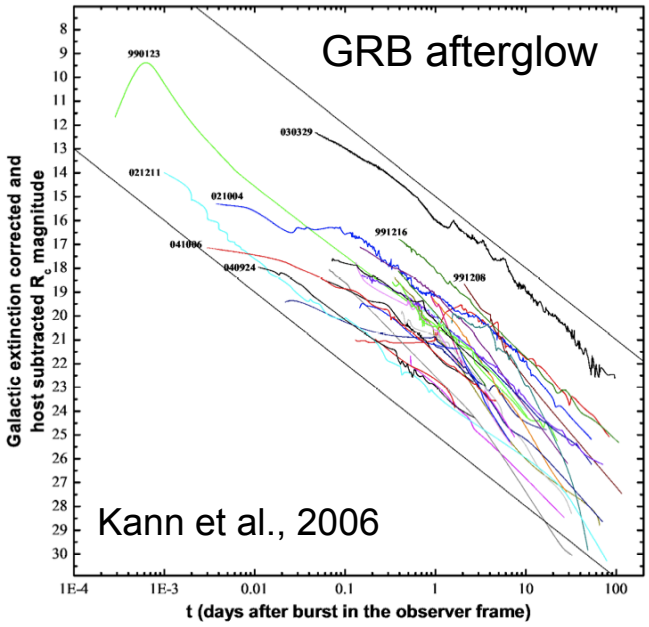
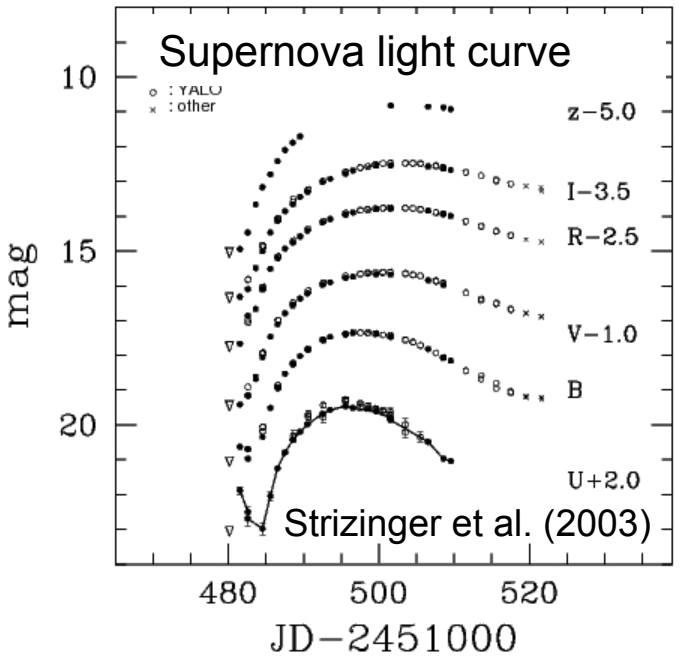
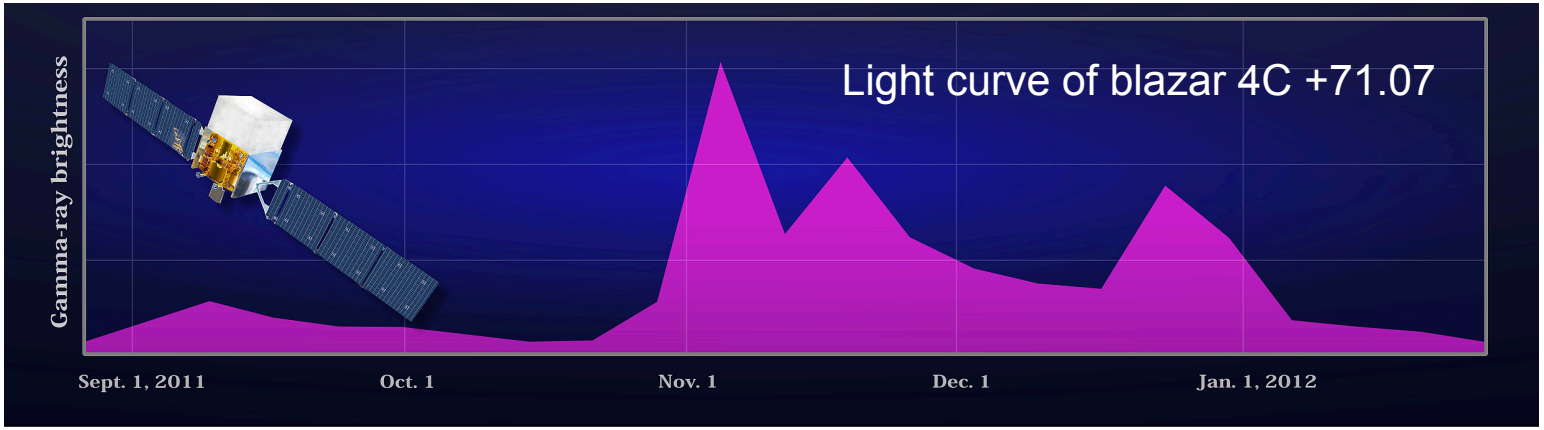
DESY

Expected EM Counterparts

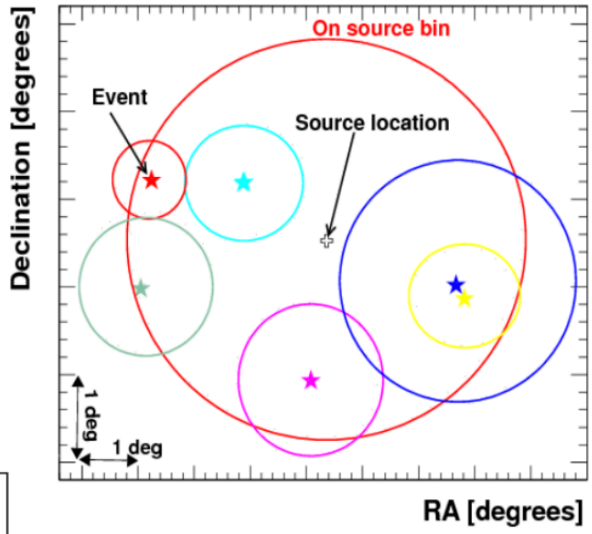




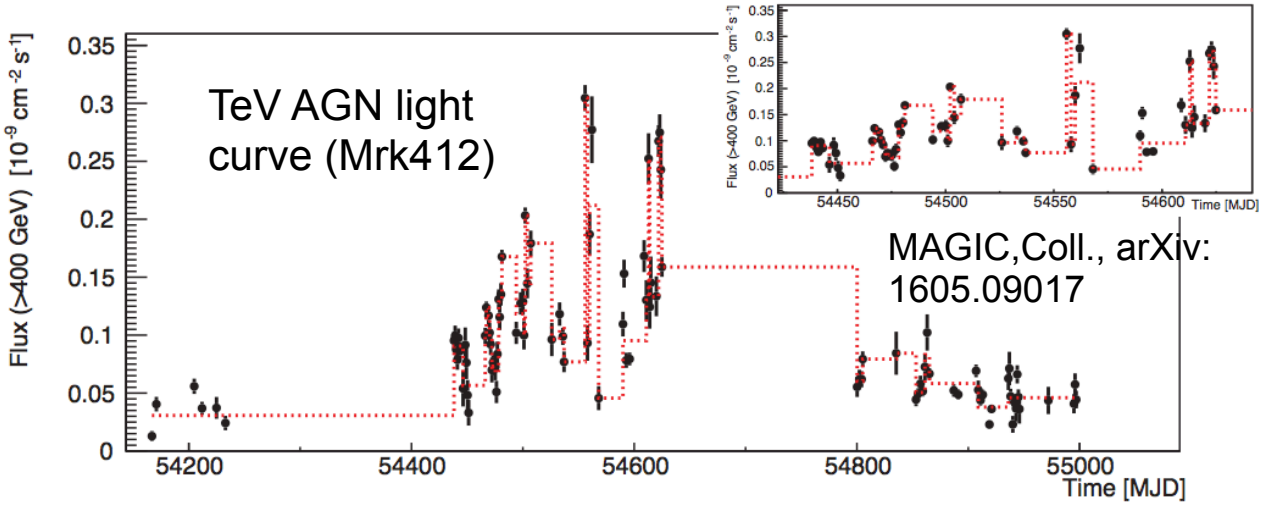


Real-time Search for Neutrinos and TeV flare Correlation

- Aiming for detection of flaring sources on time scales of up to 3 weeks
- Follow-up with MAGIC, Veritas, (HESS)
- Predefined source list
  - Bright, hard and variable GeV gamma-ray sources
  - 180 sources: mostly blazars



Posters by D. Gora P2.085, F. Schüssler P2.010

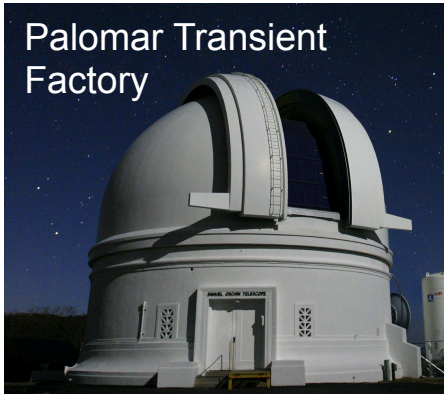


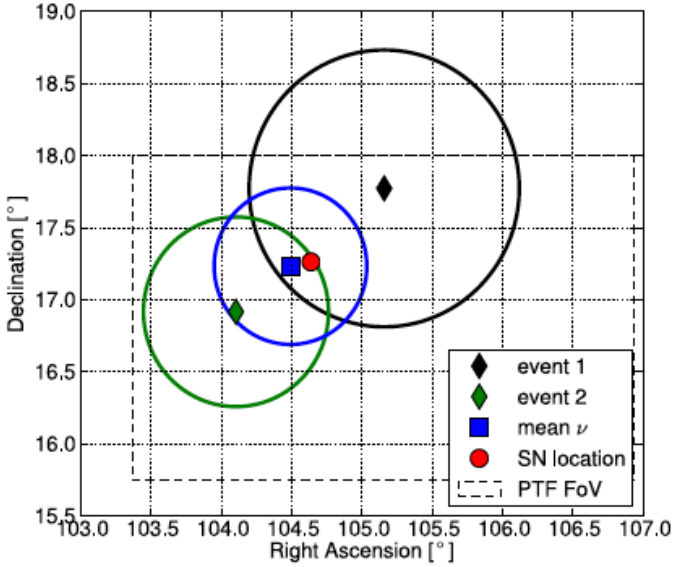
Most significant alert:
Nov. 9th 2012
6 events in 4.2 days, followup by VERITAS
Log10(p-value) = -4.46 (not corrected for trials)

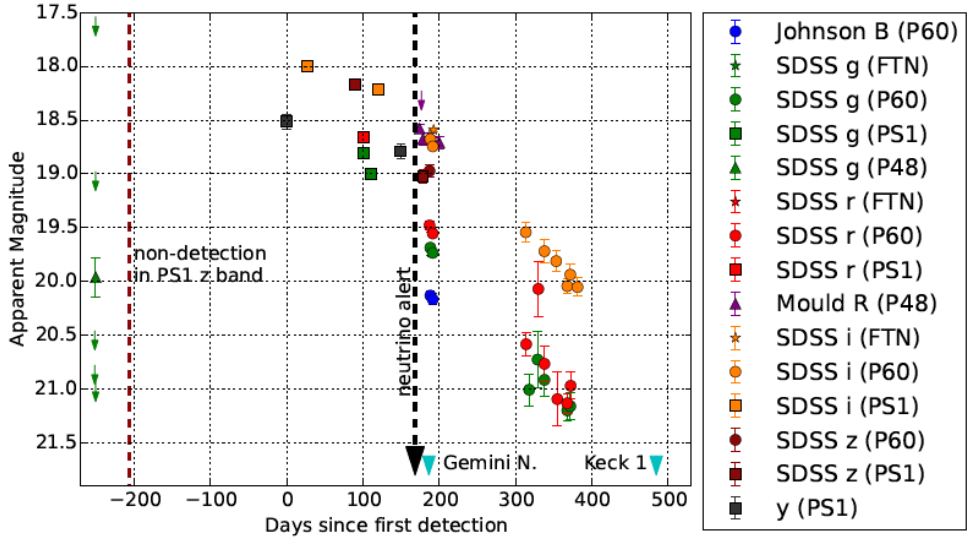
Thomas Kintscher and IceCube Coll. 2016 *J. Phys.: Conf. Ser.* **718** 062029

IceCube Optical Follow-up Program: Supernova Detection

- Sensitive to short bursts of neutrinos (<100sec)
- PTF12csy, a very bright supernova type IIn at 300 Mpc
- Coincident with the most significant neutrino alert (two neutrinos detected only 1.6 s apart)
- Chance probability 1.6%
- Supernova 150 days old at time of neutrino detection



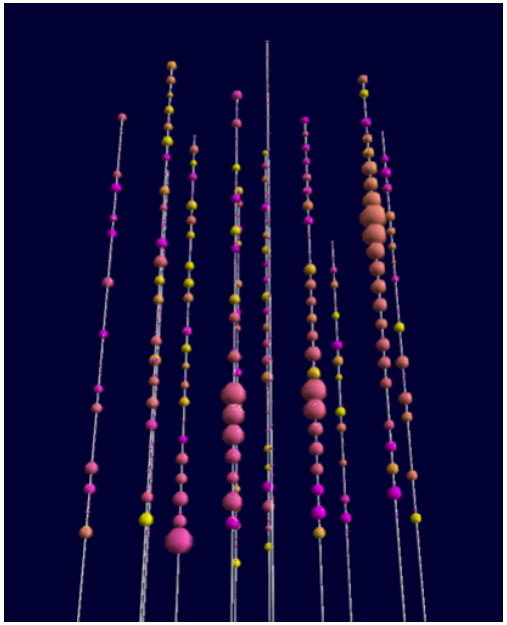


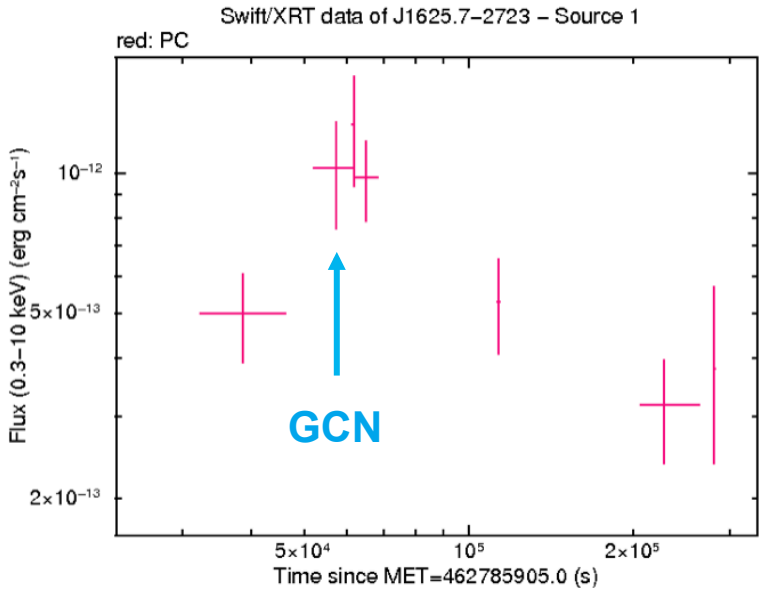


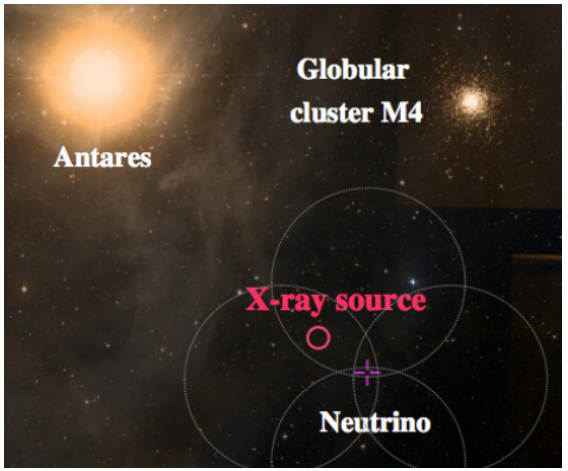
IceCube & PTF Coll. ApJ, 811 (2015)

ANTARES Optical / X-ray Follow-up: ANT150109A

- Single Neutrino at 60 TeV
- Triggered optical (MASTER, Tarot, Zadko) and X-ray observations (Swift)
- Variable X-ray source found → ATel 7987
- Follow-up observations identified source as a variable star







ANTARES Coll., presented at AMON workshop 2015

DESY

ANTARES Optical Follow-up: ANT150109A (ATel 7987/ GCN 18231)

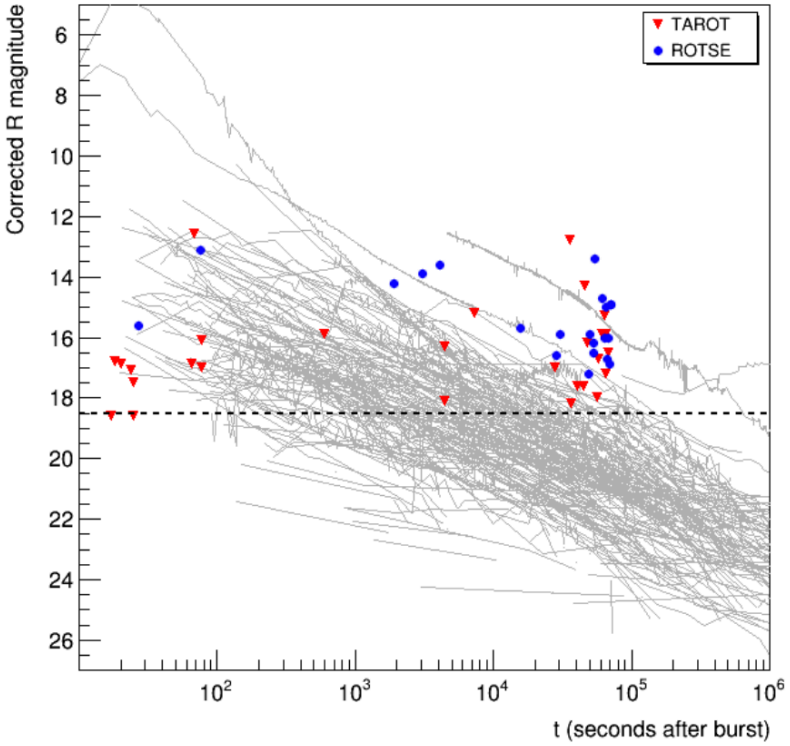
- Neutrinos
  - IceCube: ATel 8097
- Optical
  - Pan-STARRS: ATel 7992, 8027
  - SALT: ATel 7993
  - NOT: ATel 7994 GCN18236
  - WiFeS: ATel 7996
  - CAHA: ATel 7998, GCN18241
  - MASTER: ATel 8000 GCN18240
  - LSGT: ATel 8002
  - NIC: ATel 8006
  - ANU: GCN18242
  - GCM: GCN18239
  - VLT/X-shooter
- X-rays
  - Integral: ATel 7995
  - MAXI: ATel 8003
  - Swift: ATel 8124, GCN18231
- Radio
  - Jansky VLA: ATel 7999, 8034
- Gamma-rays
  - MAGIC: ATel 8203
  - Fermi-GBM: GCN18352
  - HAWC
  - HESS

Great interest by astro-community

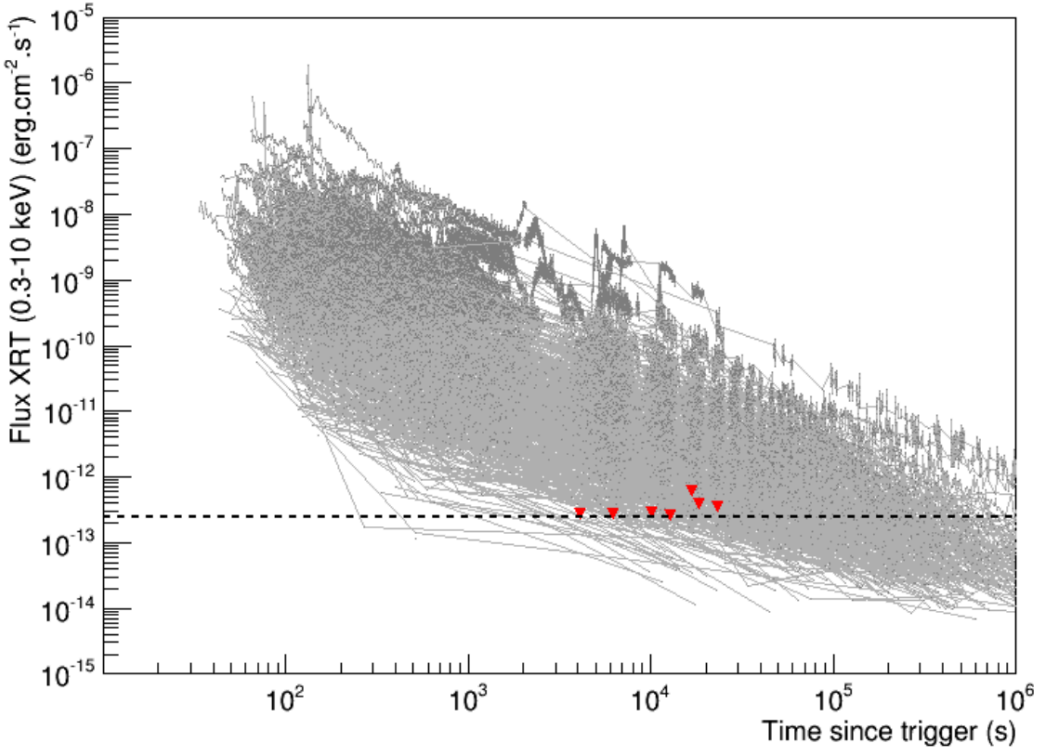
ANTARES follow-up – Search for GRB counterpart

- Fast reaction by follow-up instruments are required to detect rapidly declining GRB afterglow

Optical GRB afterglows compared to upper limits following ANTARES alerts



X-ray GRB afterglows compared to upper limits following ANTARES alerts

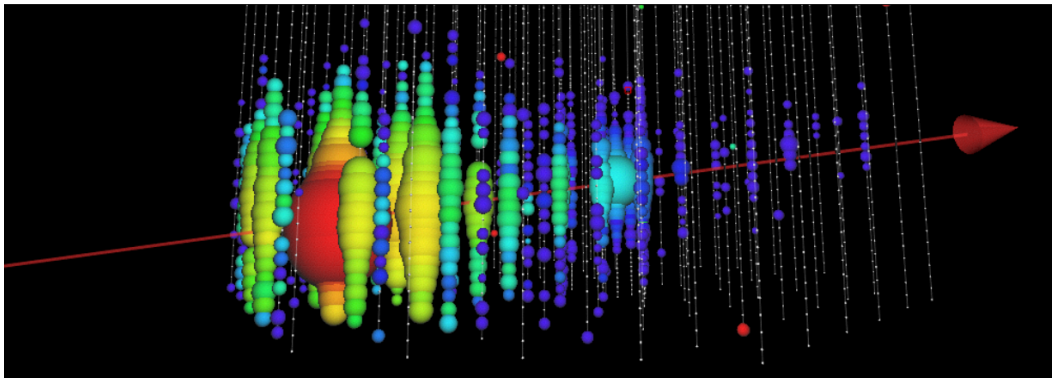


ANTARES JCAP 1602 (2016)

IceCube HESE Track Events now Public ICECUBE-160427A

- High-Energy Starting Events (HESE) Tracks (total: 4/y, signal: 1/y)
- Energy threshold ~60TeV
- Angular resolution: 0.4-1.6 deg (50% containment), 1.2-8.9 deg (90%)
- Improved resolution available after *O*(h)
- First alert: April 27th 2016

Through-going muon events (EHE), total 4/y, signal 2/y public soon



	Time	RA	DEC	Err (50%)	Err (90%)
First direction	April 27	239.66°	6.85°	1.6°	8.9°
Updated direction	April 29	240.57°	9.34°	--	0.6°

Poster by K. Jero P2.012

Followup of First Public HESE Event (GCN 19381)

> Optical

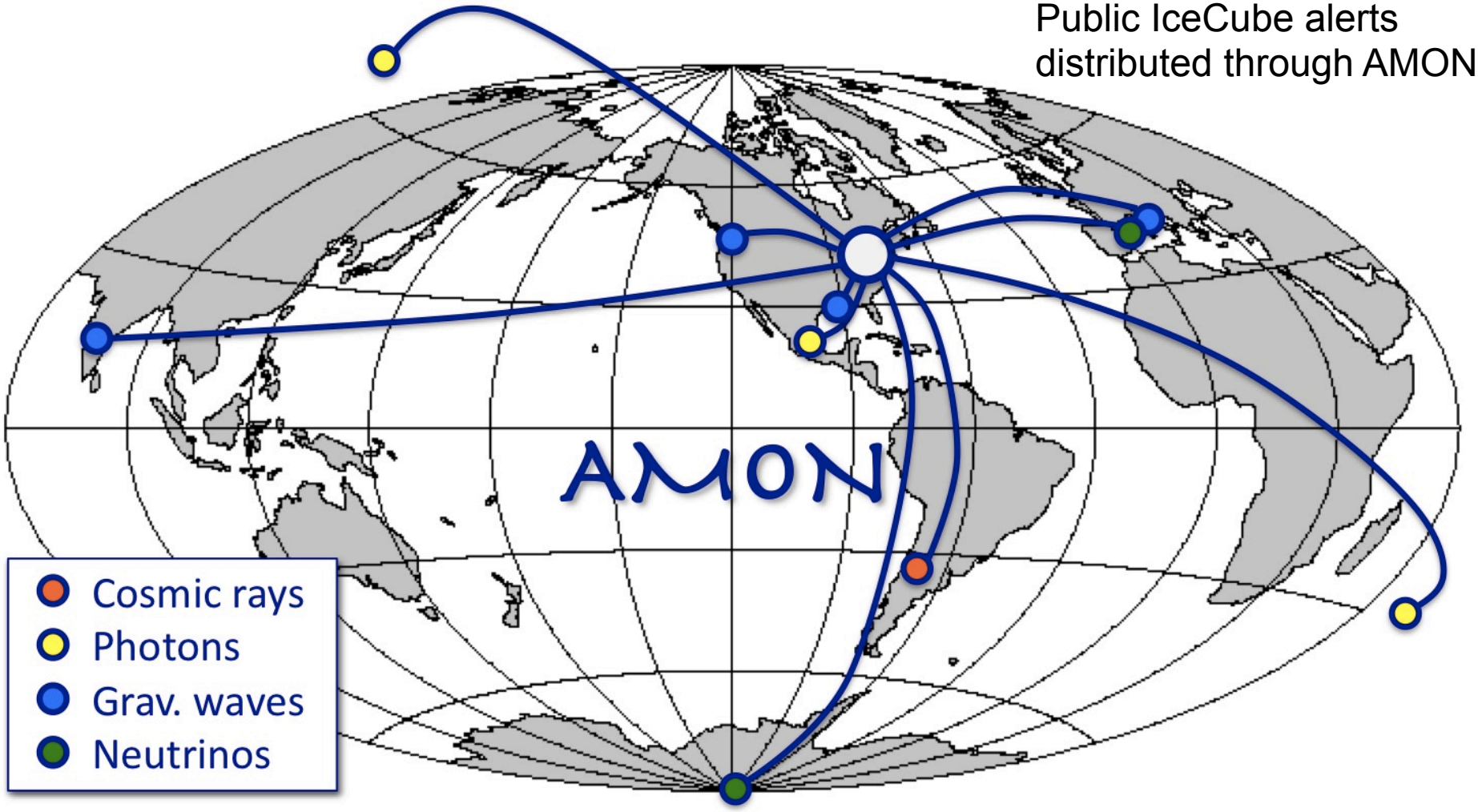
- iPTF (GCN 19392) – 3 transients, all AGN
- Master (GCN 19362) – no detection
- Pan-STARRS (GCN 19381) – 7 supernovae candidates

> Gamma-ray

- IPN (GCN 19426) – no detection
- Fermi-LAT (GCN 19360) – 5 unrelated blazars
- Fermi-GBM (GCN 19364) – no detection
- FACT (GCN 19427) – no detection
- Veritas (GCN 19377) – no detection
- HAWC (GCN 19361) – no detection
- MAGIC (see poster by D. Gora P2.085)

Great interest by astro-community

Astrophysical Multimessenger Observatory Network (AMON)



http://amon.gravity.psu.edu

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

DESY

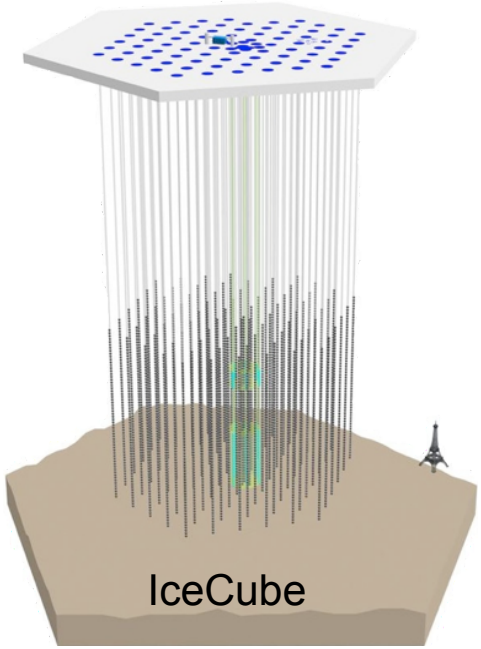
Conclusion

- Neutrinos are
  - unique messengers for from the high-energy universe
  - the smoking gun signature for the origin of high-energy cosmic rays
- 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
- New neutrino real-time channels available
  - Distribution of alerts through AMON


Stay tuned!

Backup

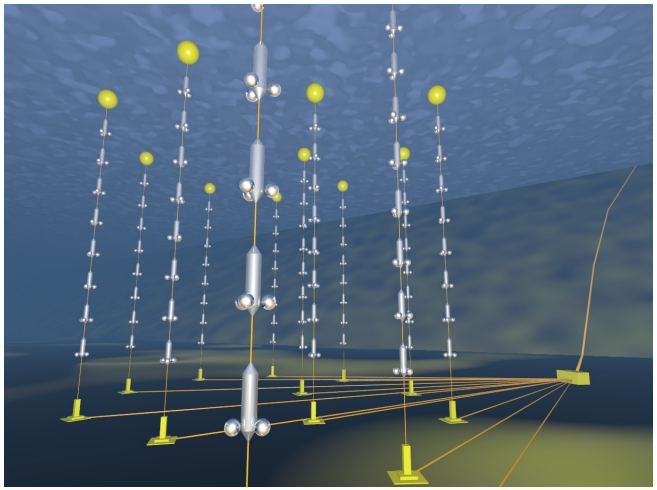
Ice/Water Cherenkov Neutrino Detectors



Volume: 1 Gton
Energy threshold: 100 GeV

See talk by M. Kowalski

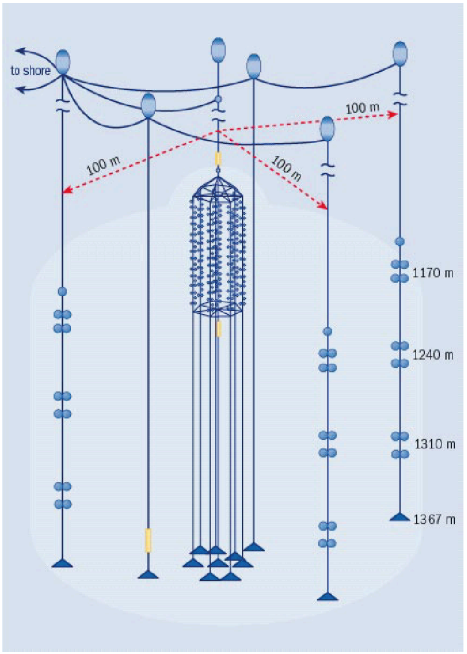
ANTARES



See talk by A. Kouchner

Volume: 10 Mtons
Energy threshold: 10 GeV

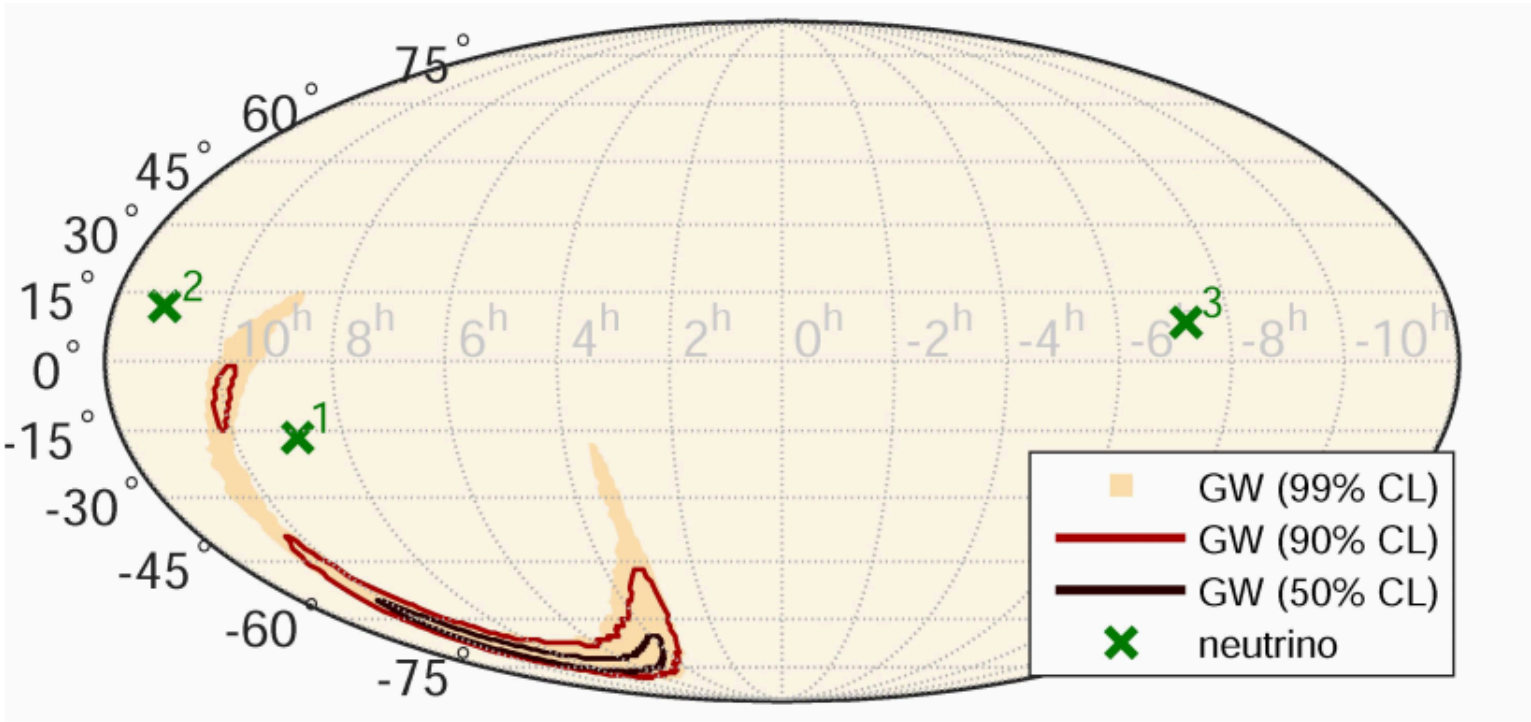
Baikal



Volume: 100 ktons
Energy threshold: 10 GeV

Gravitational Waves and Neutrinos

Search for neutrinos from GW150914 in ANTARES and IceCube data
→ no counterpart found

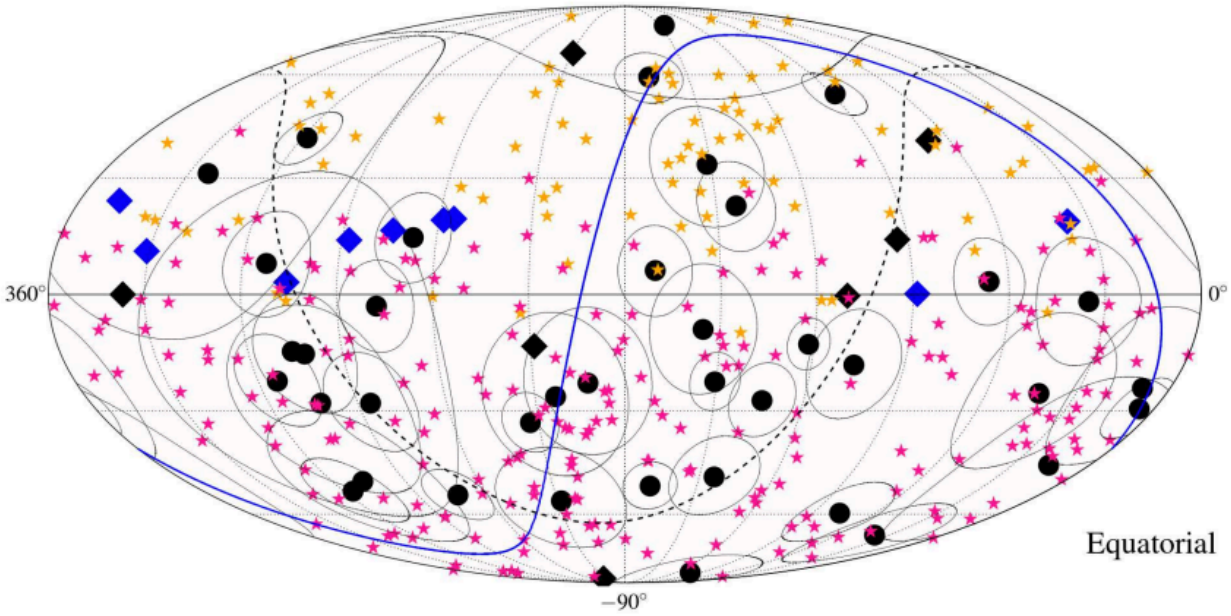


Neutrino could help to constrain direction and teach us about the GW source environment

See talk by Imre Bartos

Neutrinos and UHE Cosmic-Rays

- Correlation of IceCube neutrinos with UHE cosmic-rays (E>50 EeV) from Auger and Telescope Array

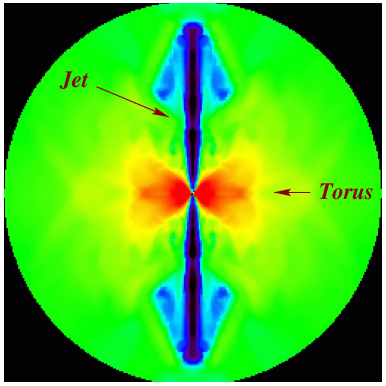


★ Telescope Array
★ Auger
● IceCube HESE cascades
◆ Icecube HESE tracks
◆ IceCube through-going muon tracks

No significant correlation found

IceCube Coll. JCAP01 (2016) 037

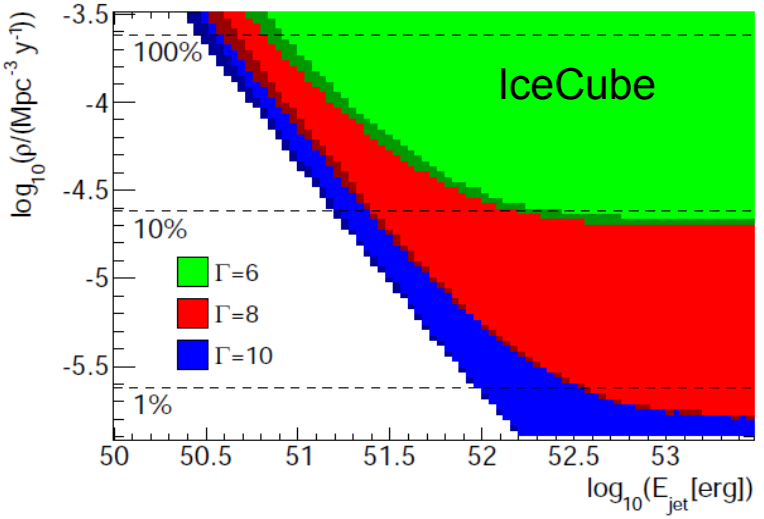
Limits on Chocked Jet Supernova Models

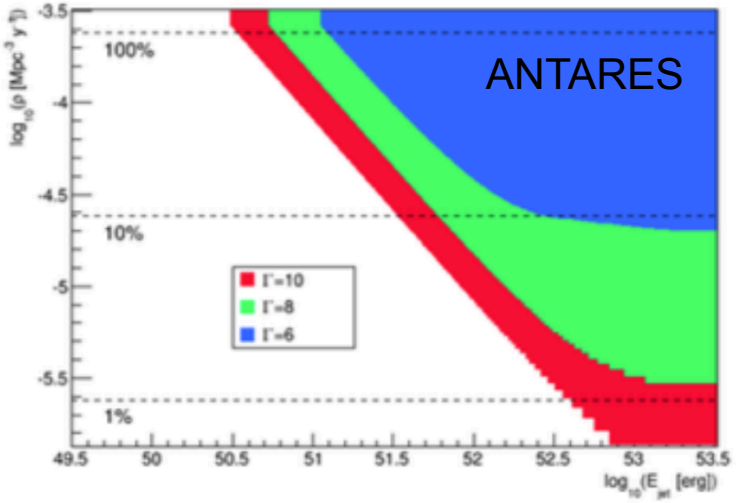


Core-collapse SNe (CCSN) with Jets, Ando & Beacom PRL 95, 2005

Model parameters:

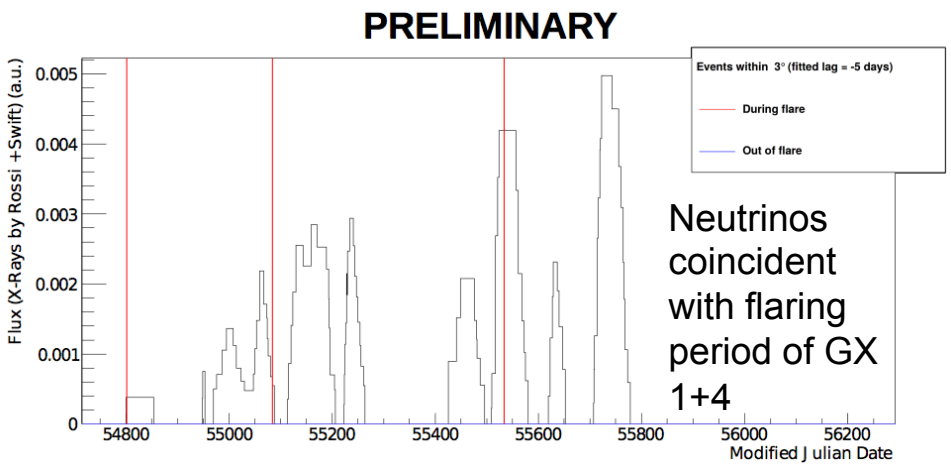
- Rate of CCSN with jets ρ
- Jet energy E_{jet}
- Lorentz boost factor Γ





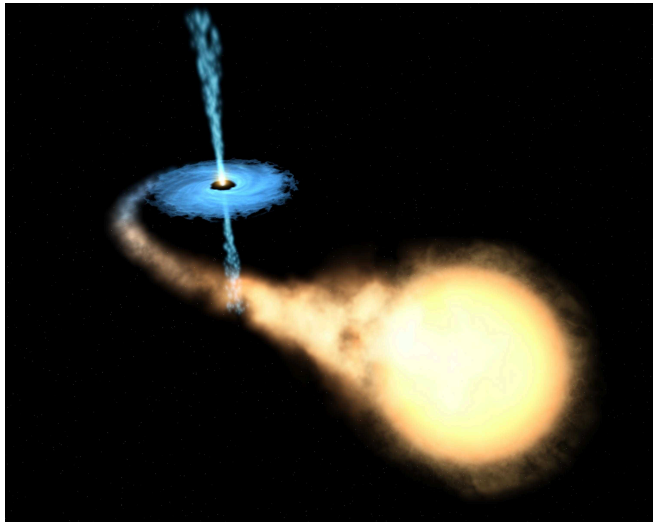
IceCube A&A 539, A60 (2012)
ANTARES …

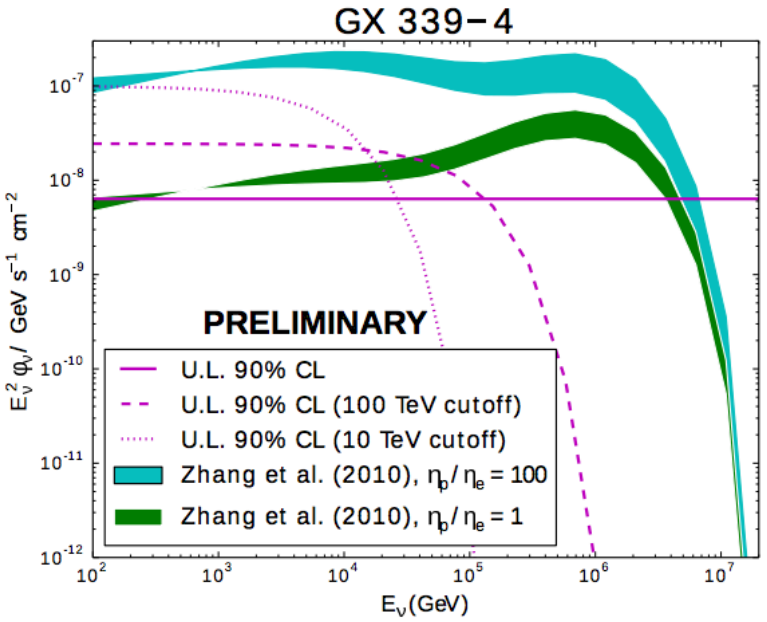
Search for Neutrinos from X-ray Binaries with ANTARES

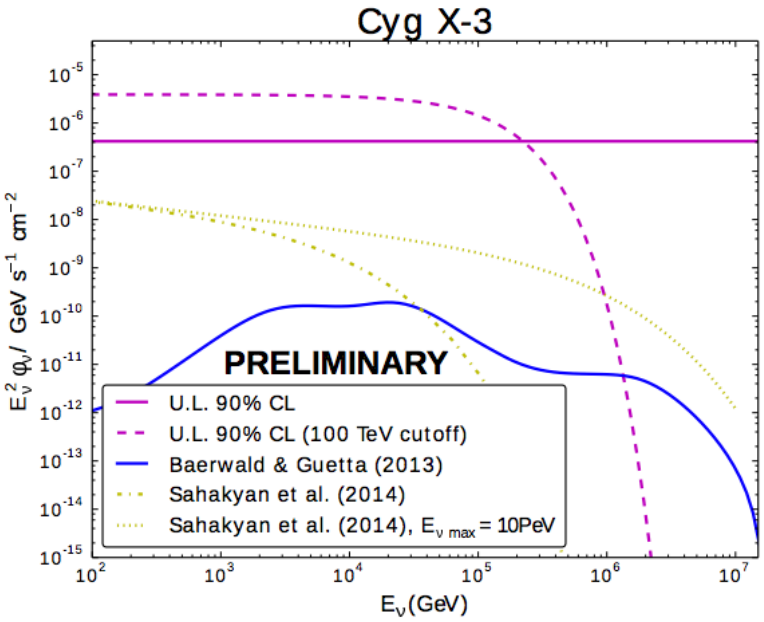


Neutrinos coincident with flaring period of GX 1+4

34 X-ray binaries

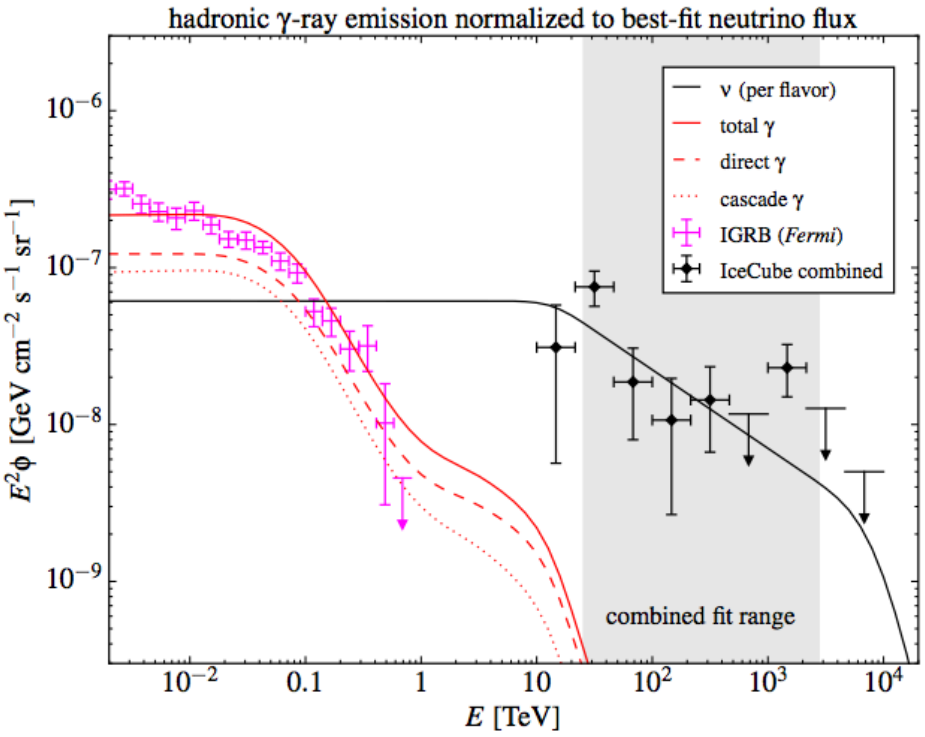


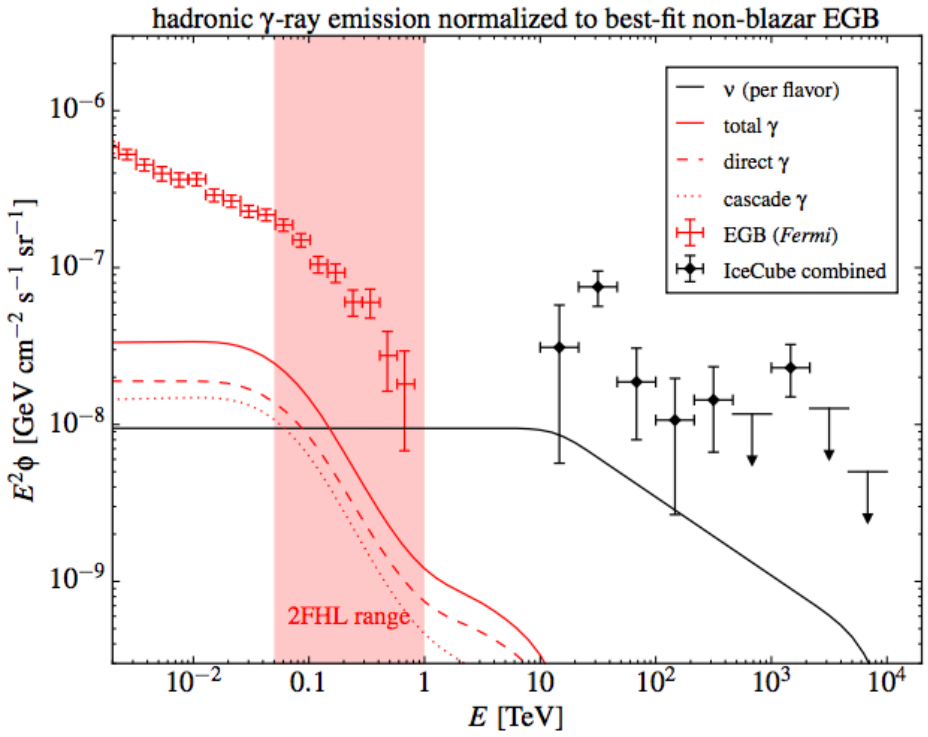




Antares Coll., presented at ICRC 2015

Constraints on pp Sources from Gamma-Ray Background



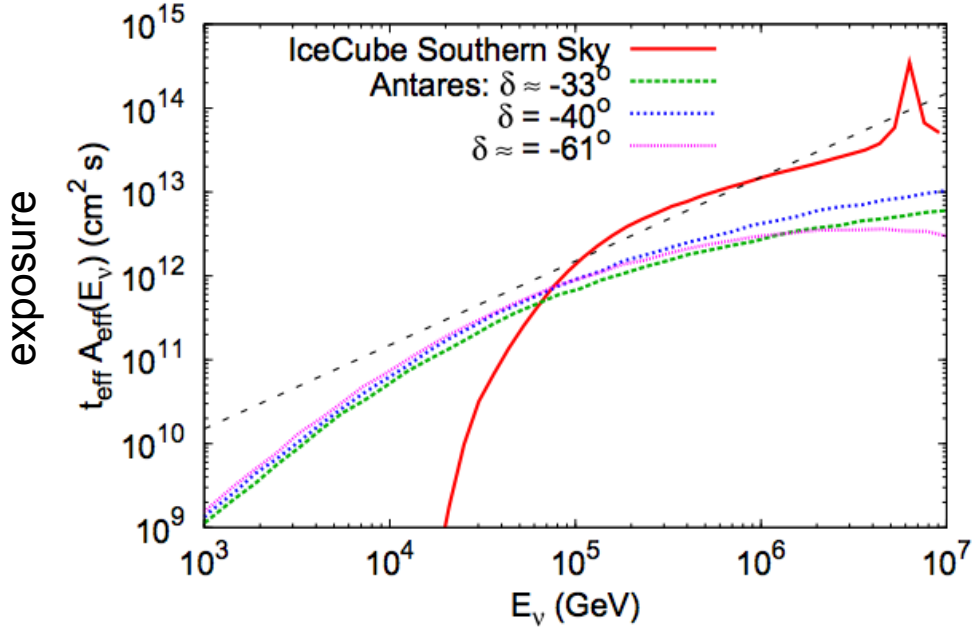


Starburst galaxies disfavored

Bechtol et al. arXiv:1511.00688

ANTARES constrains a blazar origin of two IceCube PeV neutrino events

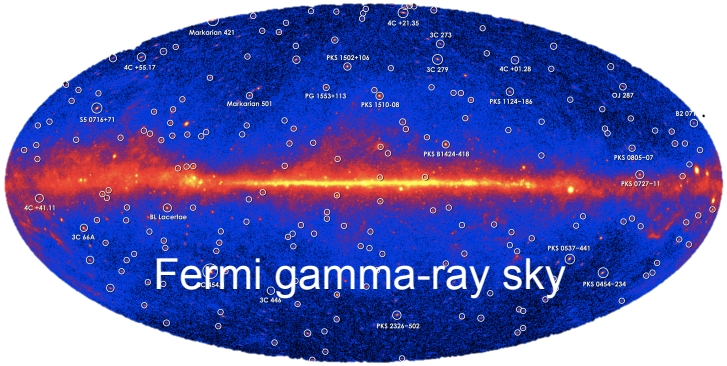
- TANAMI Coll.: six bright, variable blazars found positionally coincident with two of the most energetic IceCube events (Krauss et al. A&A 566 2014)
- ANTARES: search for neutrinos from 6 suggested blazars in 6 years of data → relevant constraints on spectral index of potential source

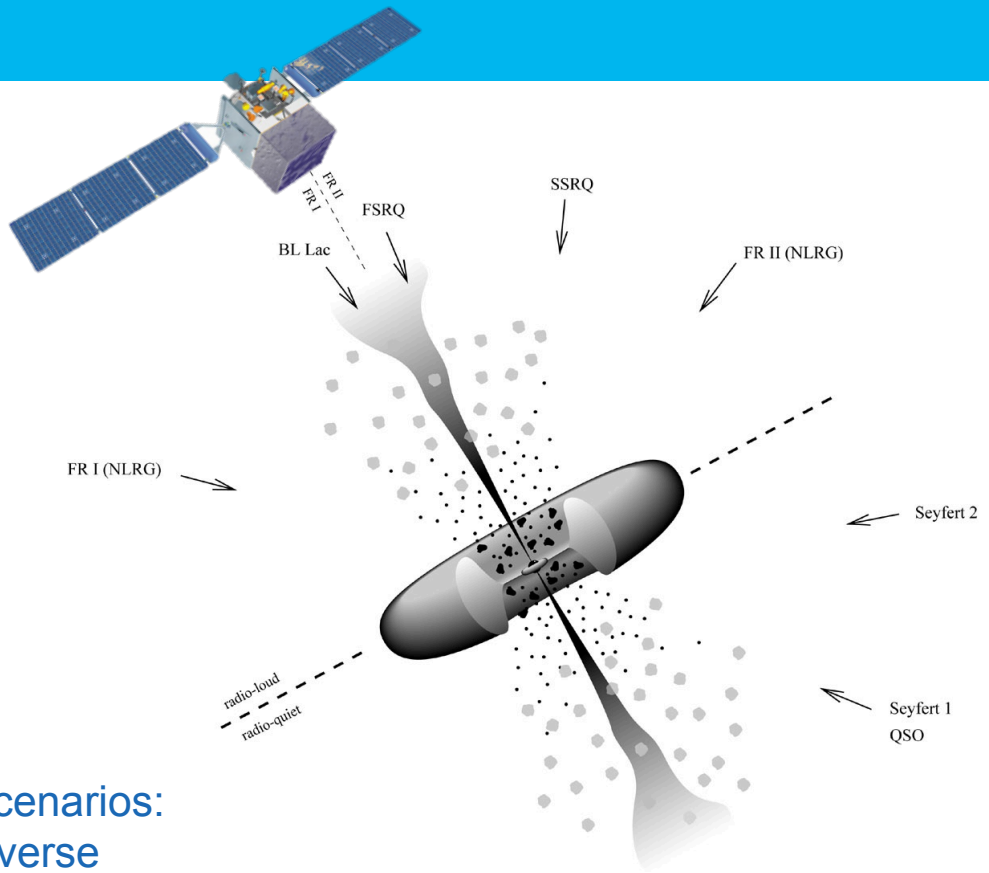


ANTARES, A&A Lett. 576, 2015

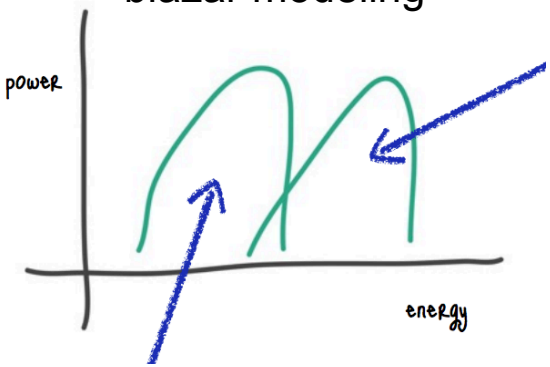
Blazars

> Gamma rays tell us WHERE





blazar modeling



Two different scenarios:

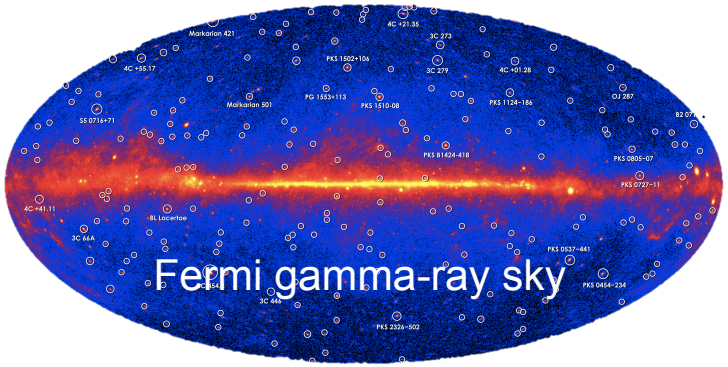
- Leptonic: Inverse Compton
- Hadronic: π^0 decay (or proton synchrotron in strong magnetic fields)

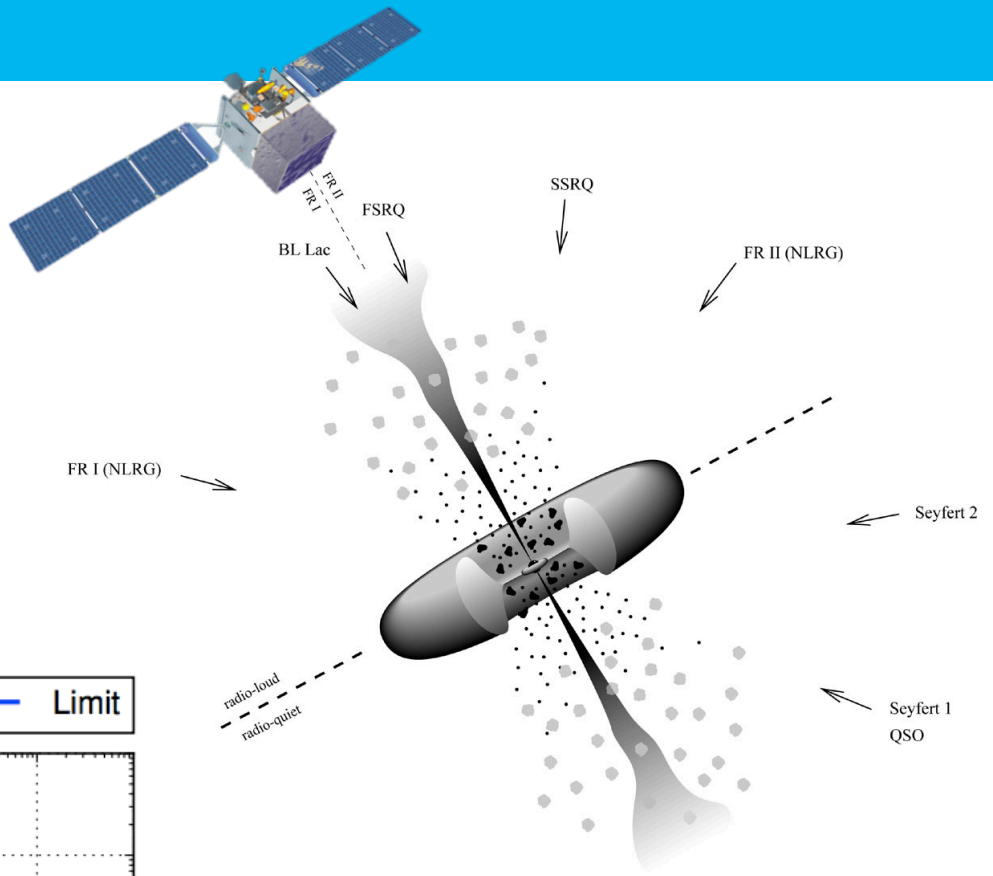
Lower energy emission due to synchrotron emission from relativistic electrons in the jet

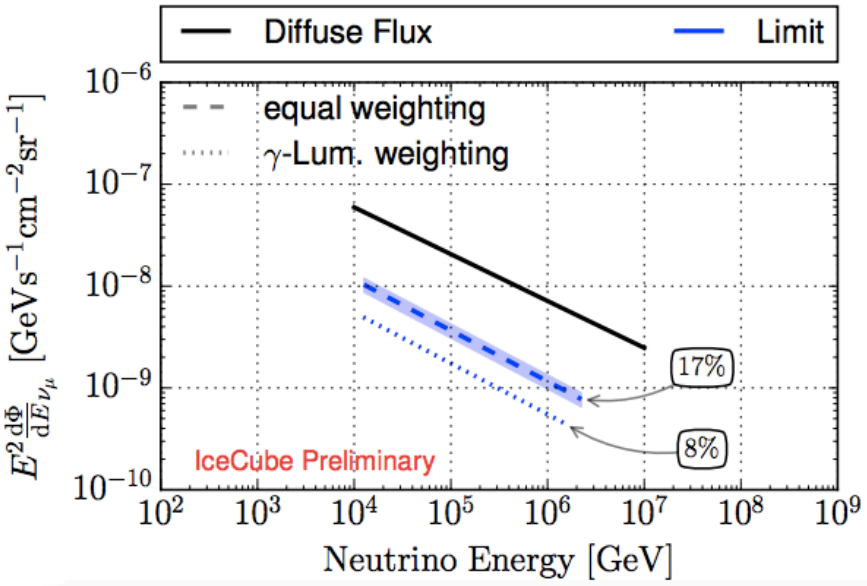
DESY

Blazars

- Gamma rays tell us WHERE







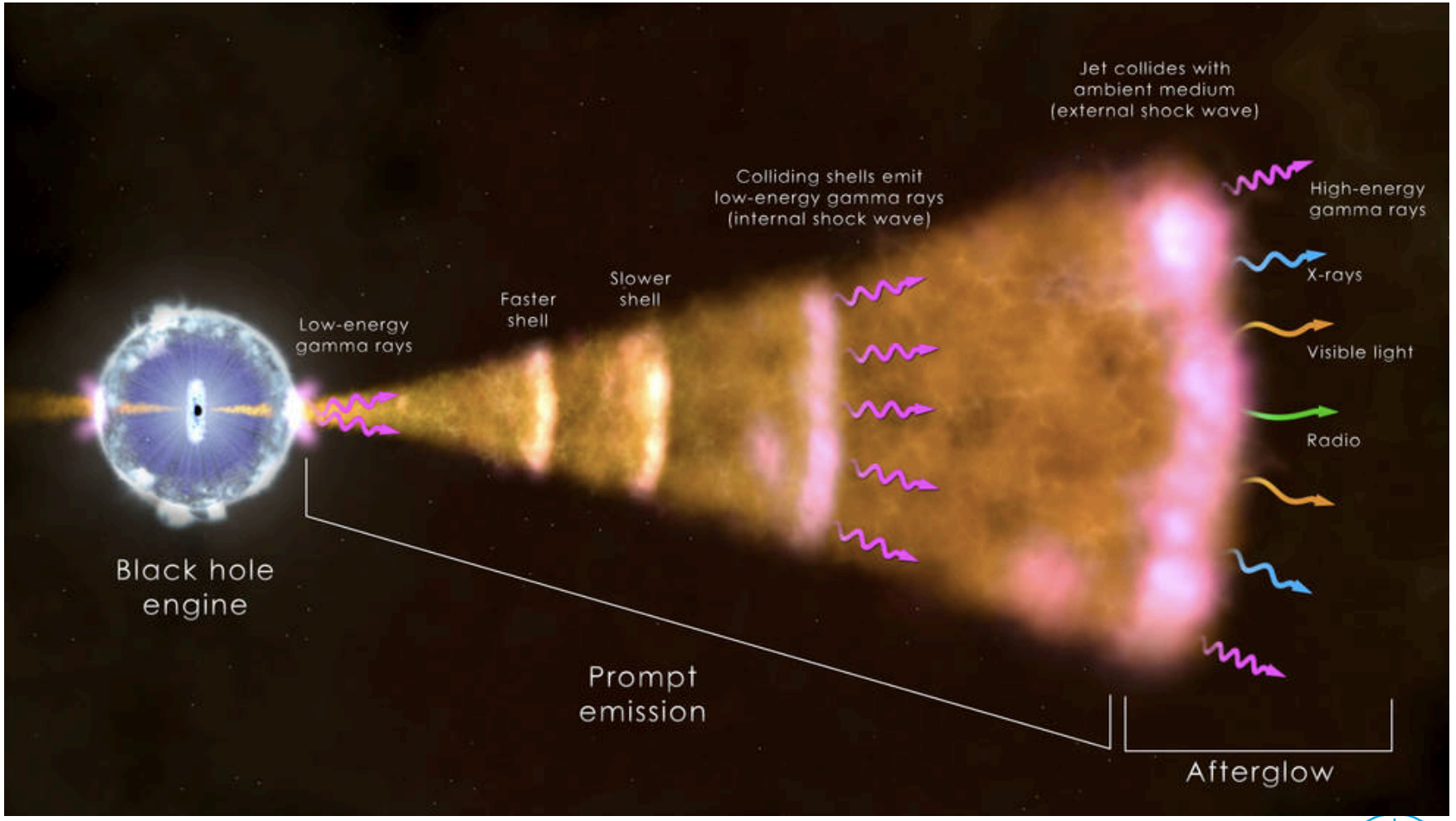
Correlation study of 3 years of IceCube data and 862 Fermi-LAT blazars

See talk by M. Kowalski

IceCube Coll., arXiv:1502.03104

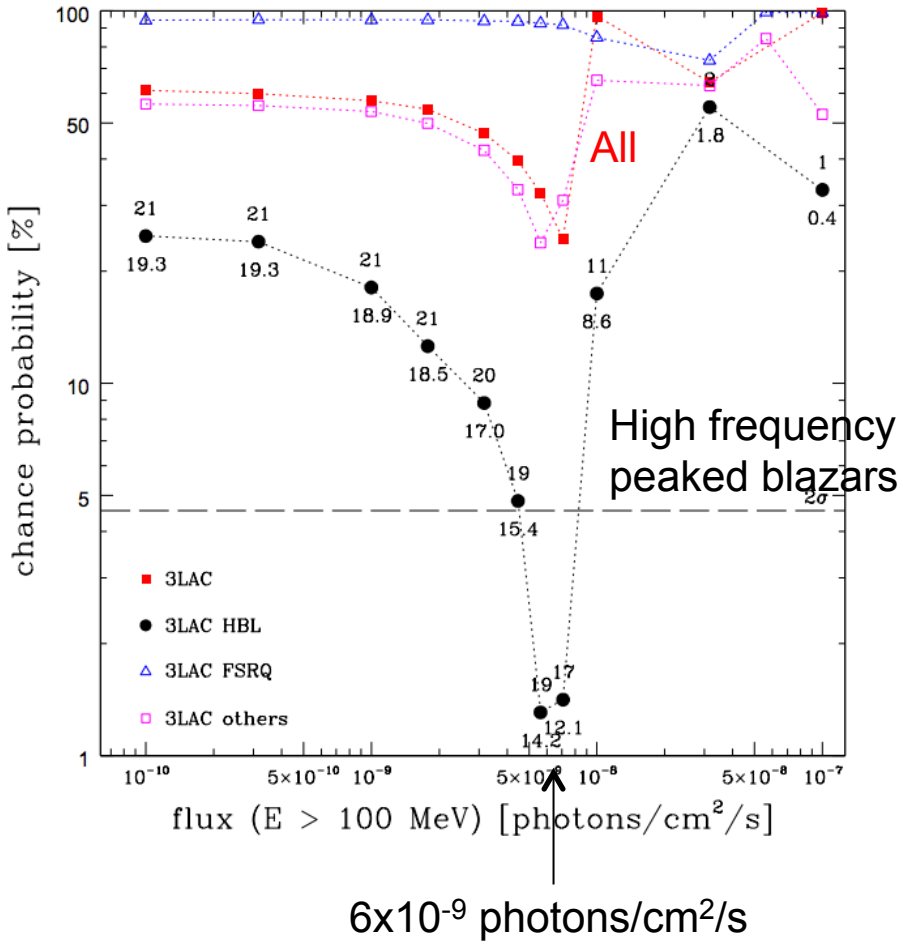
Gamma-Ray Bursts (GRBs)

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



Blazars

- Hint for correlation of extreme blazars and high-energy neutrinos
- 10-20% of diffuse flux could be produced by high frequency peaked blazars (not in tension with IceCube limit)
- Chance probability 1.3%



P. Padovani & E. Resconi et al.
MNRAS, 457, 3582 (2016)