# Multi-Messenger Astronomy

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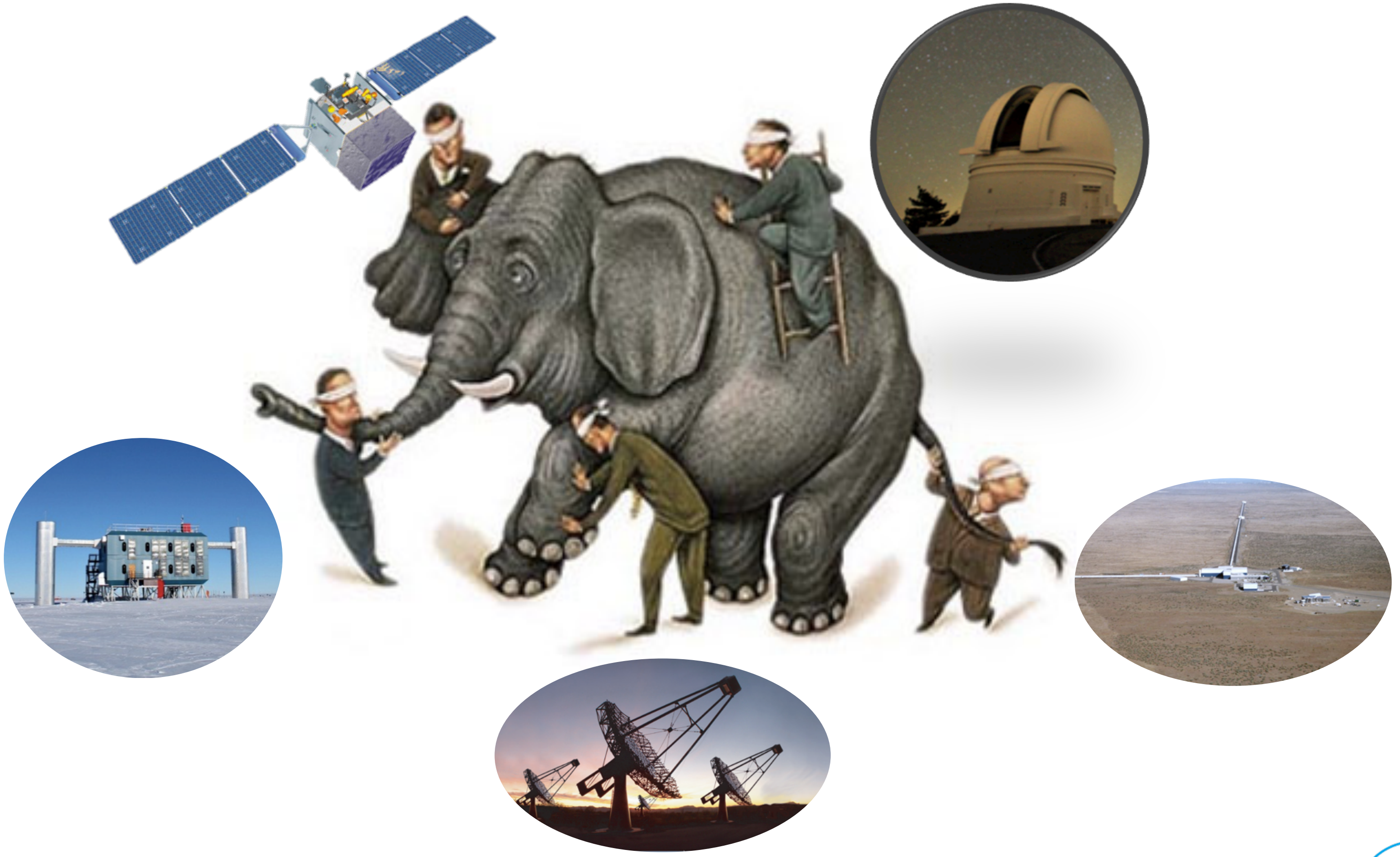
DESY, Zeuthen
International School of Nuclear Physics, Erice
September 23, 2017

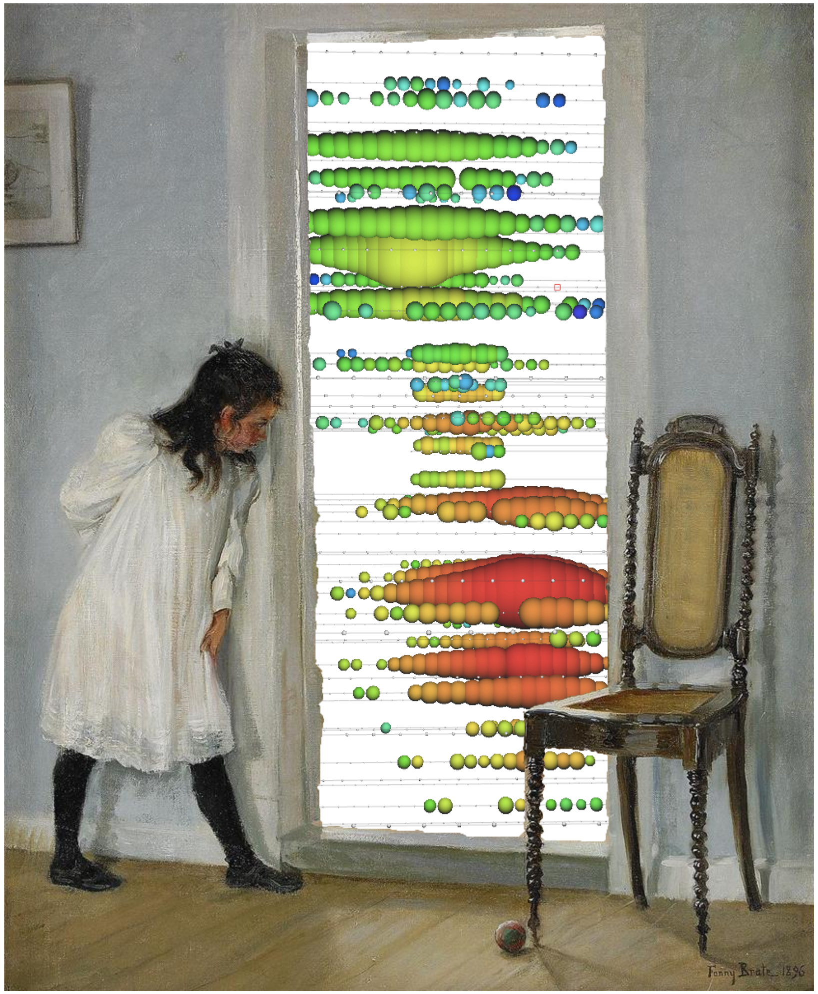
HELMHOLTZ ASSOCIATION

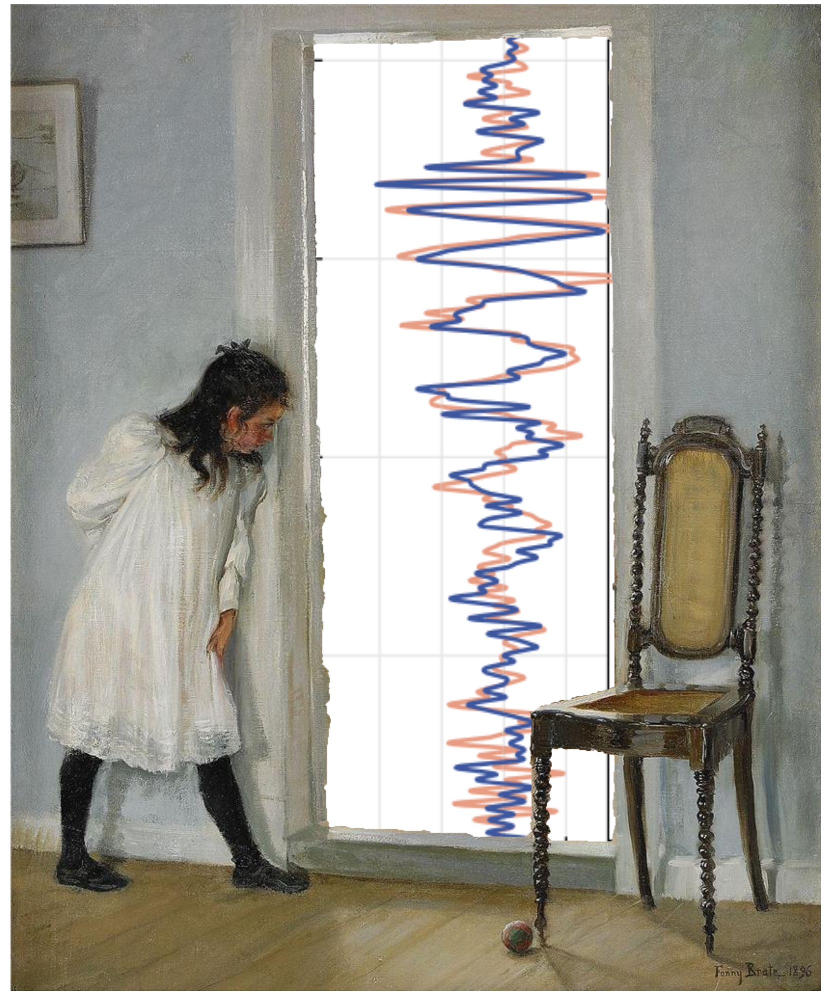
DESY

# The High-Energy Universe

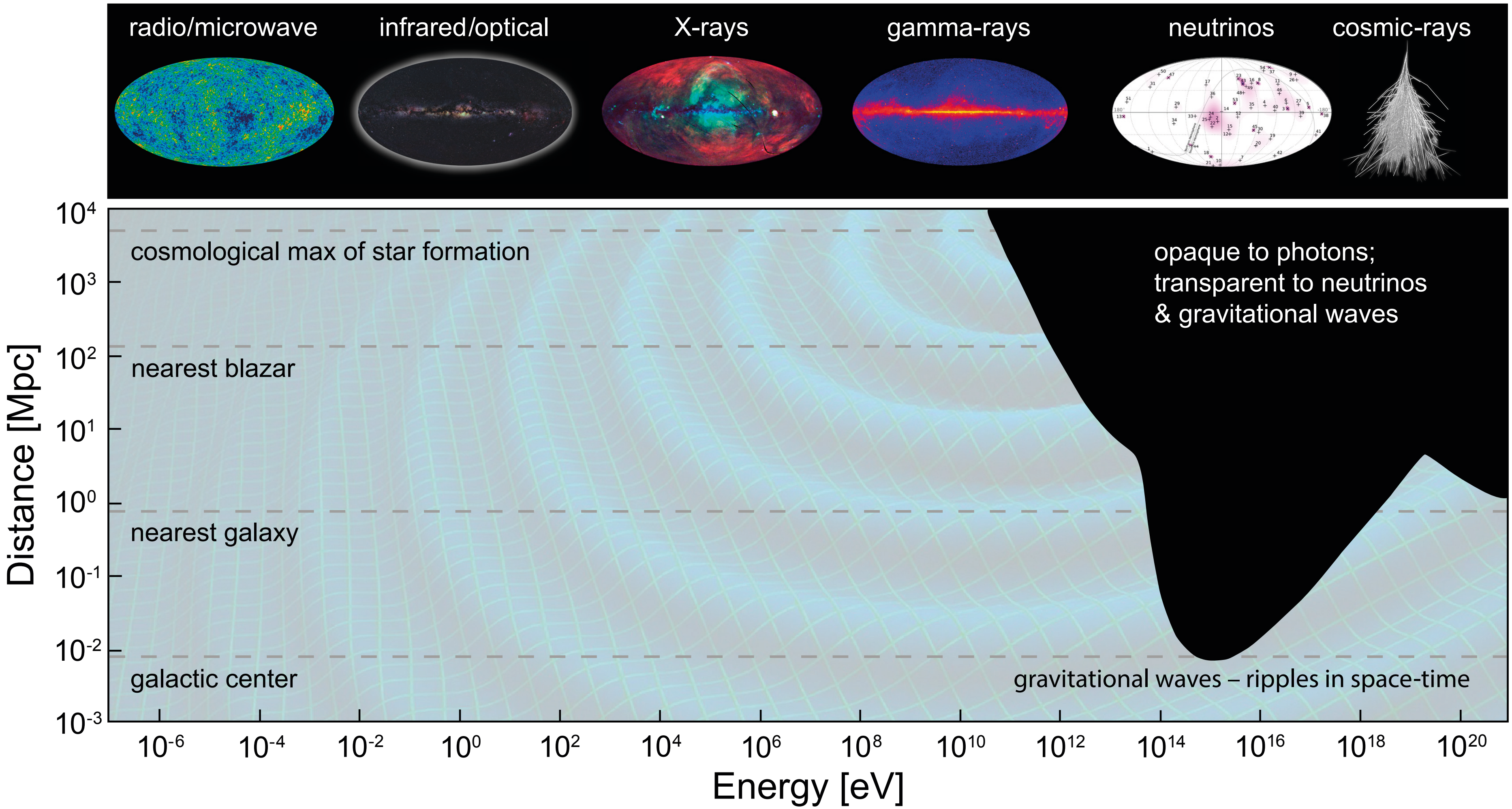


# Two New Windows to the Universe

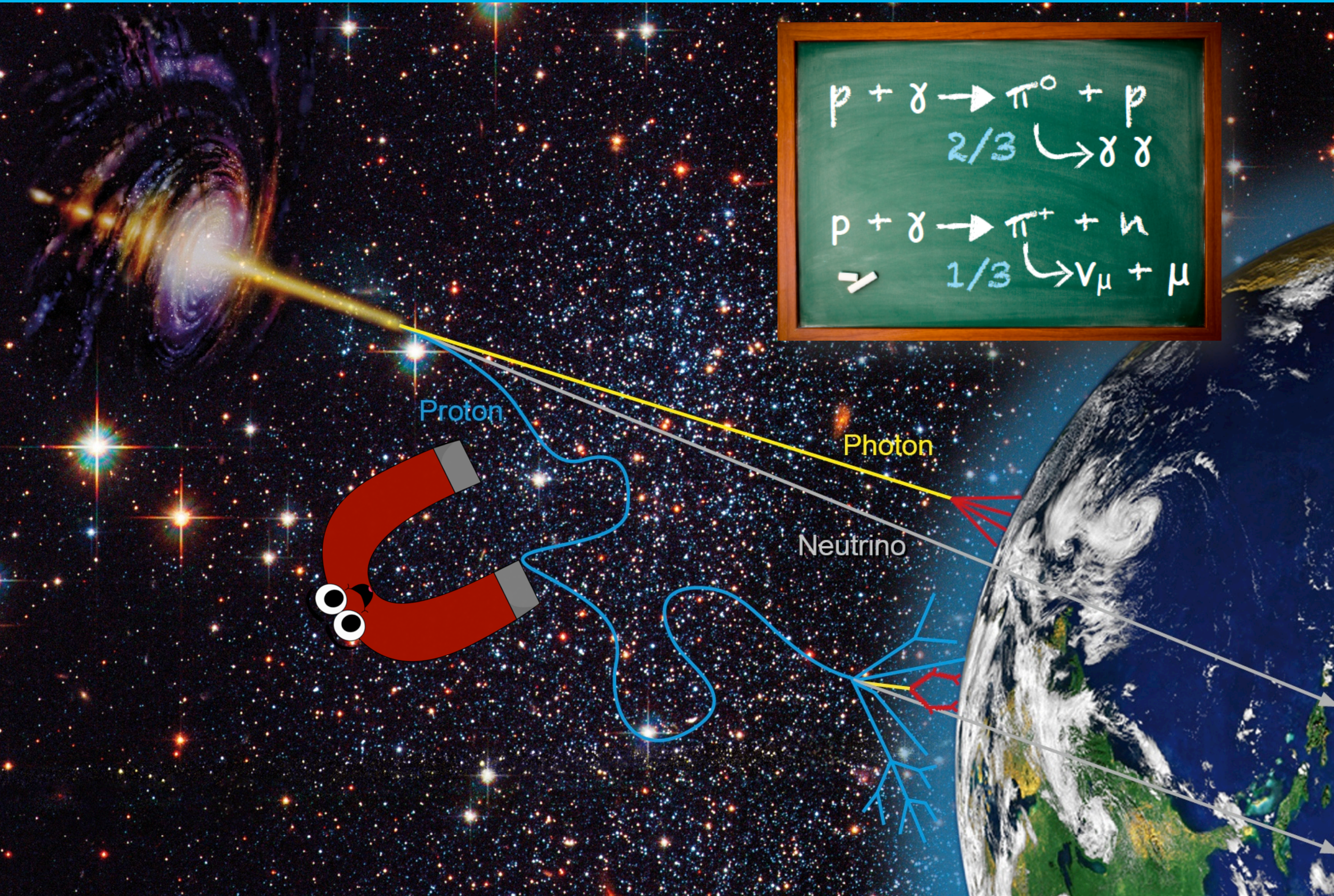




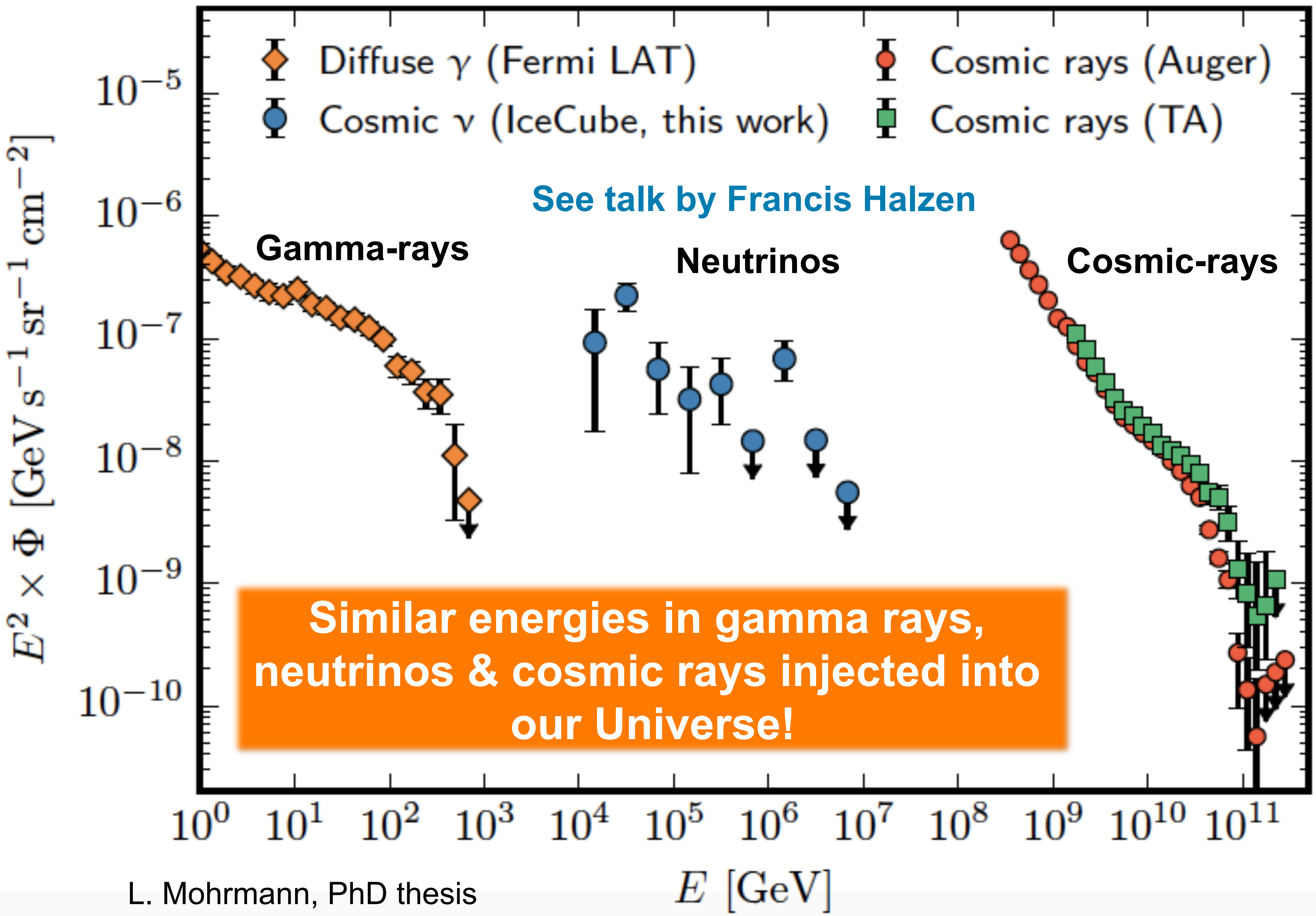
# Where Can We Look?



# What are the Cosmic-Ray Sources?



# Diffuse Neutrino Flux detected!




L. Mohrmann, PhD thesis

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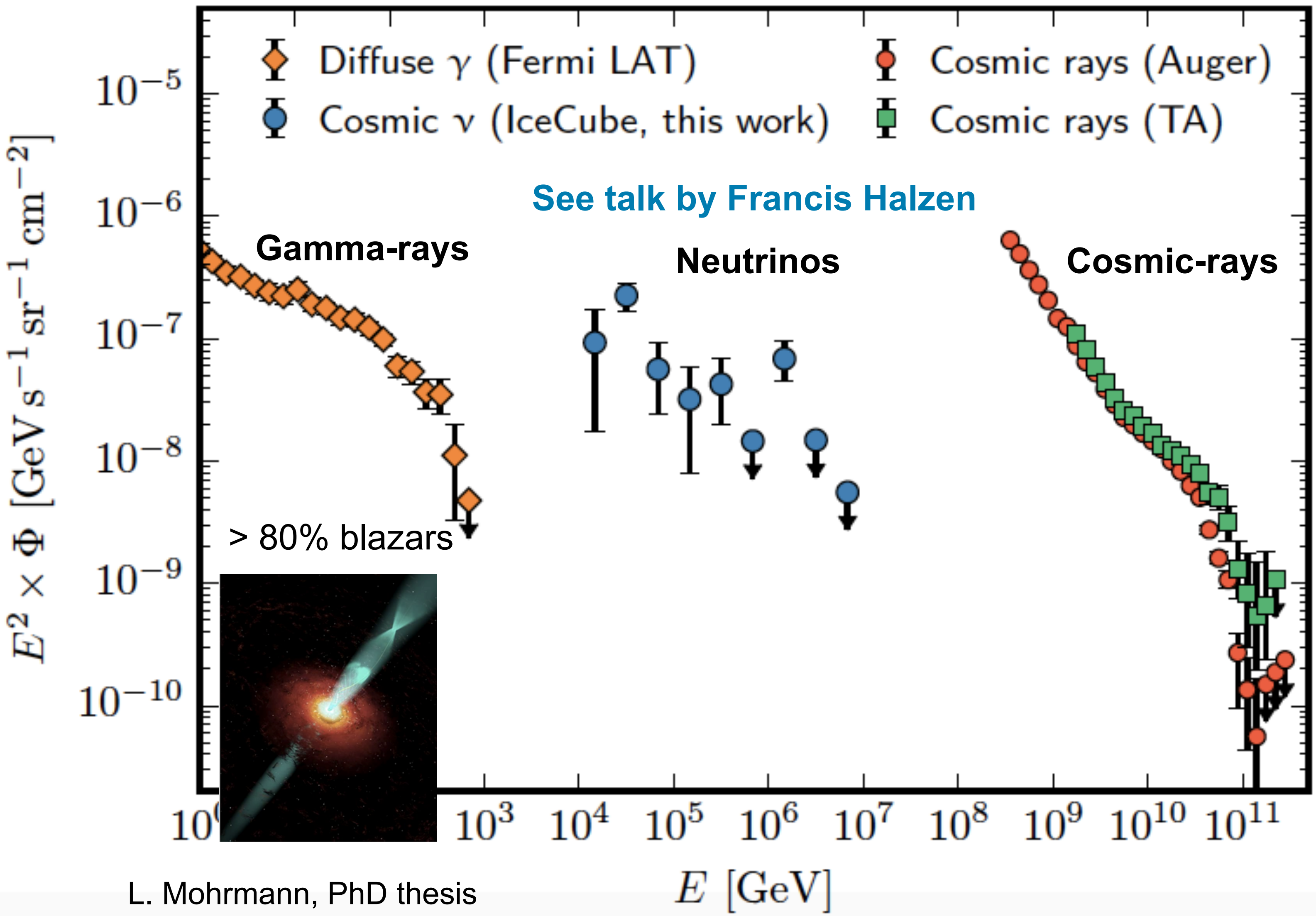
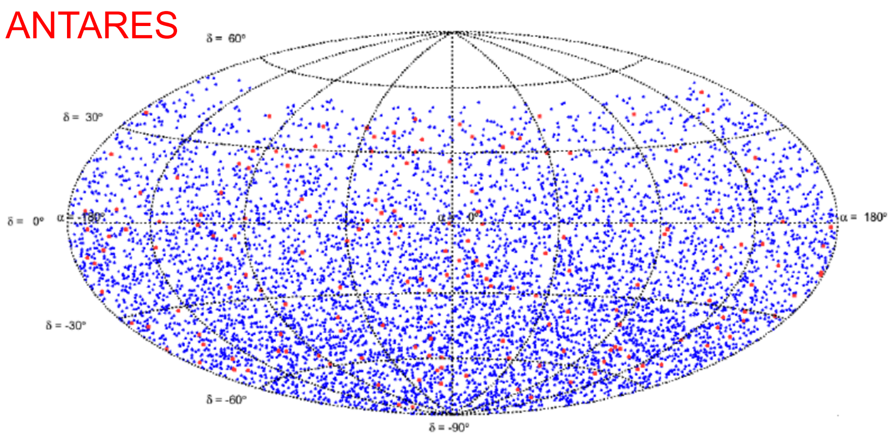
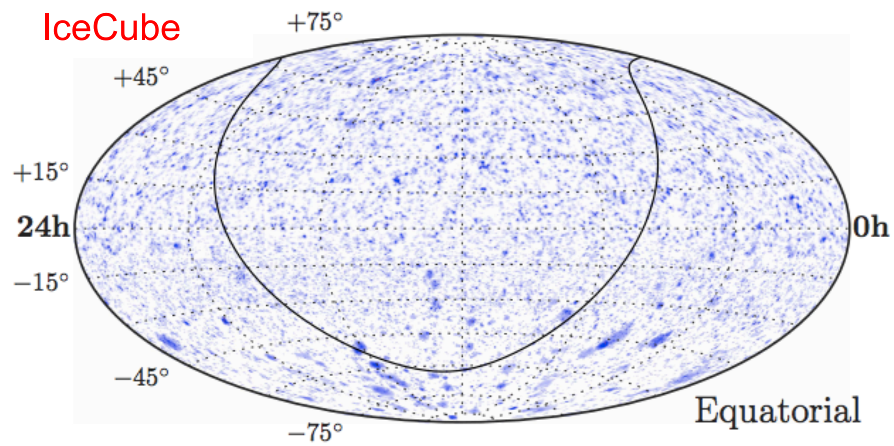



L. Mohrmann, PhD thesis

# Search for Neutrino Clusters in Space




ANTARES ApJ 786 (2014)

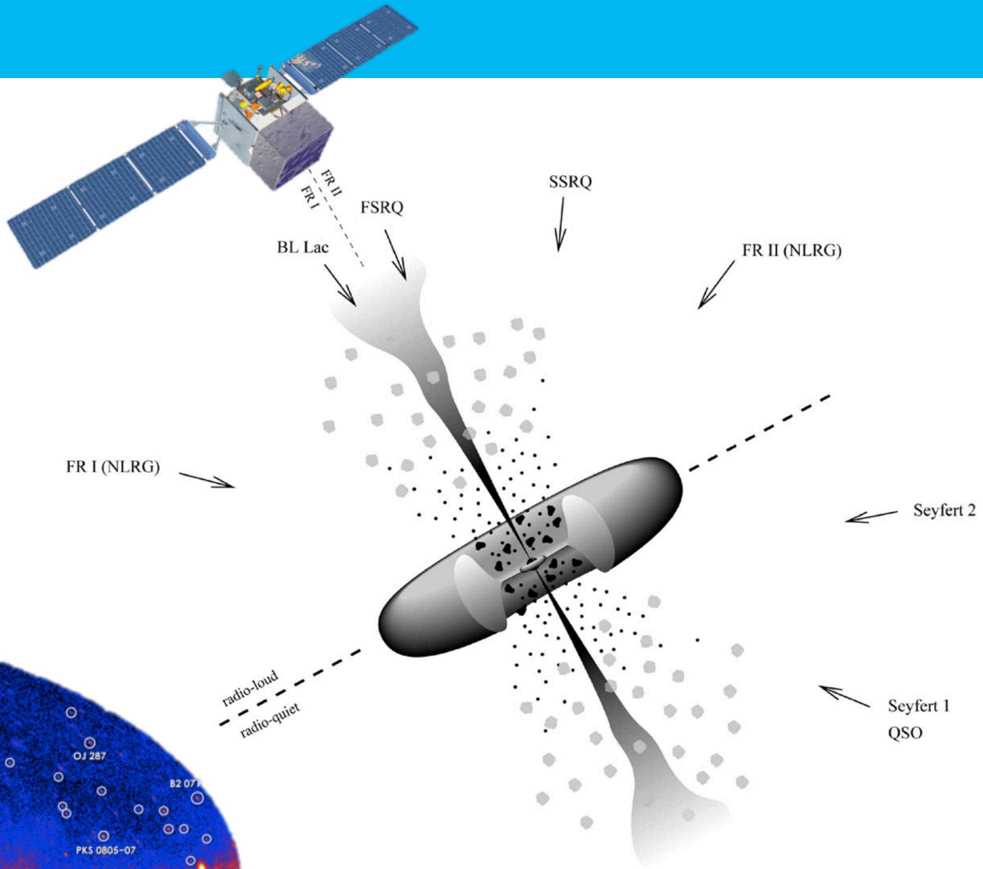



IceCube ApJ 835 (2017)

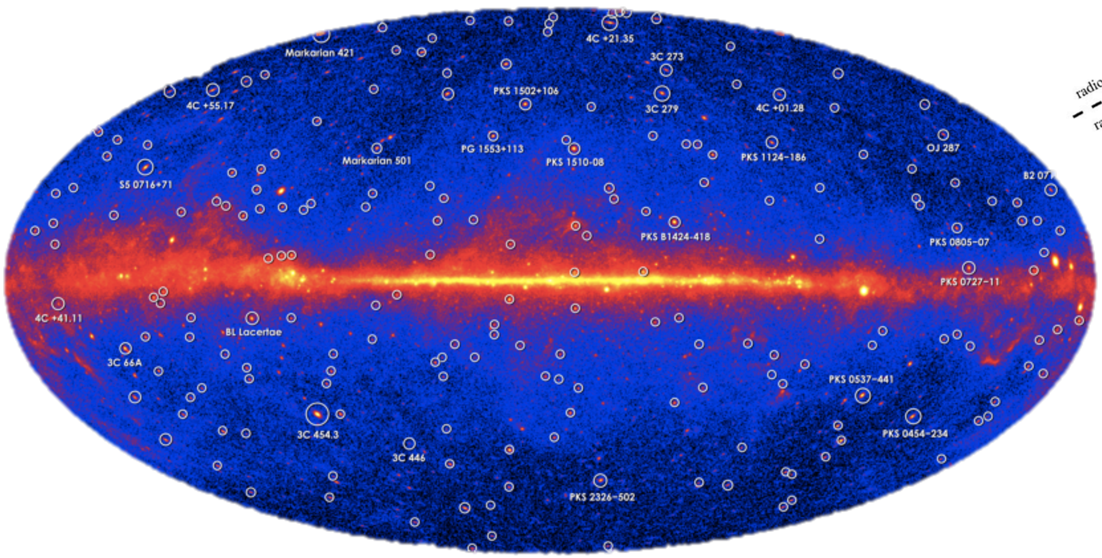
**Large trials factor → Multiwavelength data can tell us where and when to look for neutrinos**

# Blazars

- Gamma rays tell us WHERE

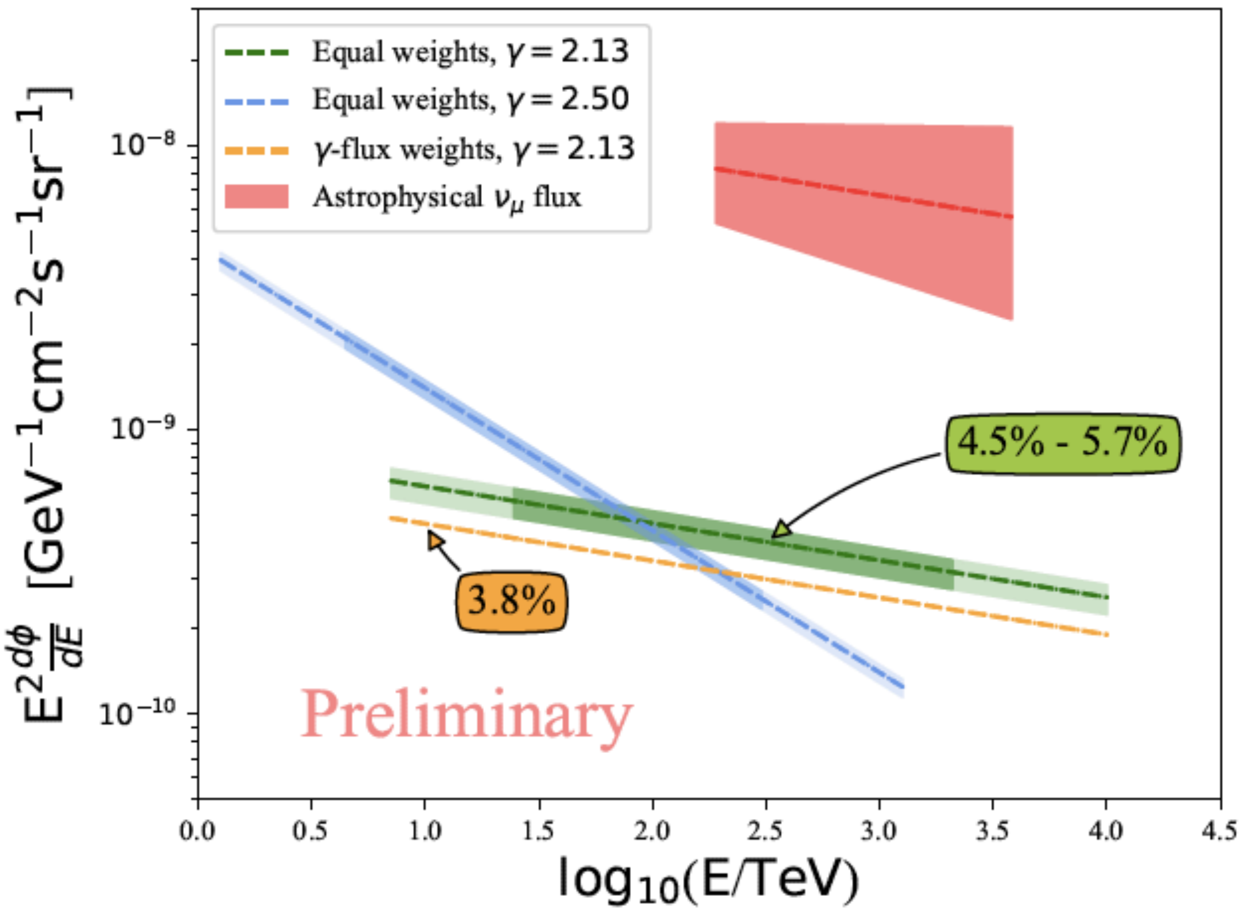


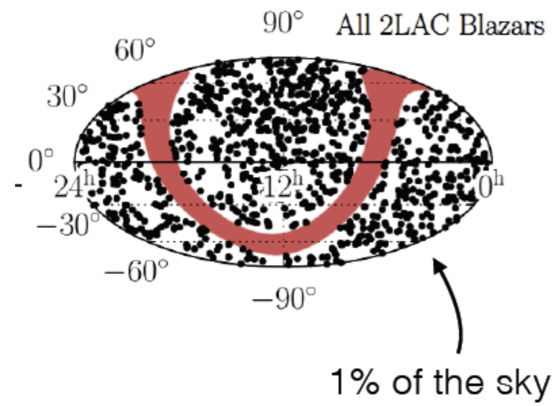

Fermi gamma-ray sky




IceCube Collaboration, ICRC 2017
Fermi-LAT PRL 116(15) 151105
Astrophys.J. 835 (2017) no.1, 45

# Blazars




Correlation study of 7 years of IceCube data and 862 Fermi-LAT blazars

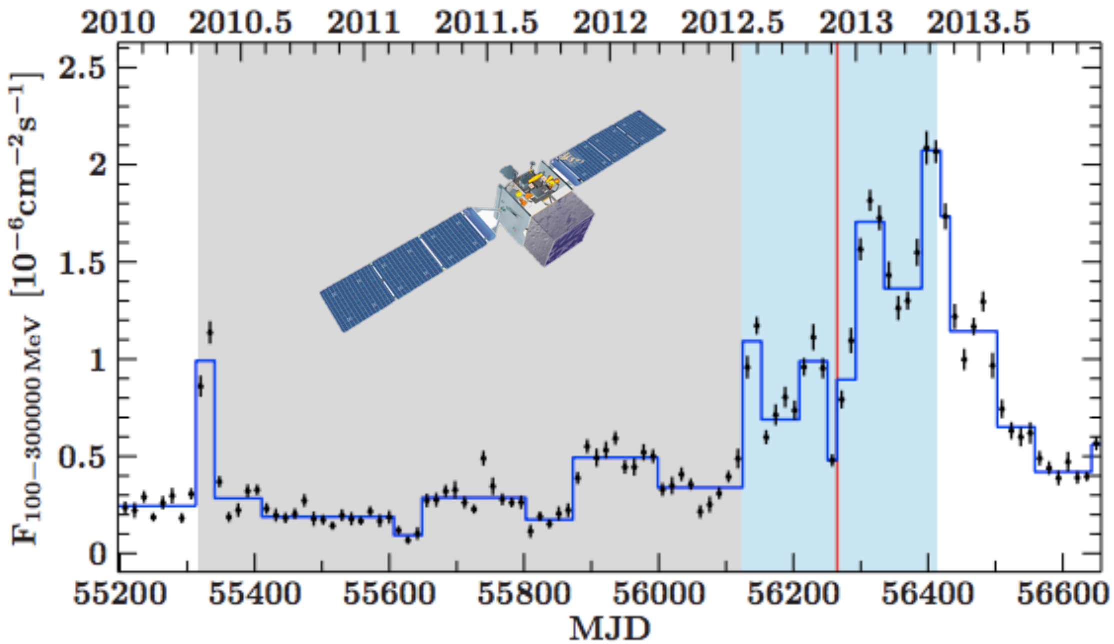
**Blazars contribute >80% to the gamma-ray background but less than 6% to the diffuse neutrino flux**

IceCube Collaboration, ICRC 2017
Fermi-LAT PRL 116(15) 151105
Astrophys.J. 835 (2017) no.1, 45

# Blazar Flares

RA 208.4°
Dec -55.8°

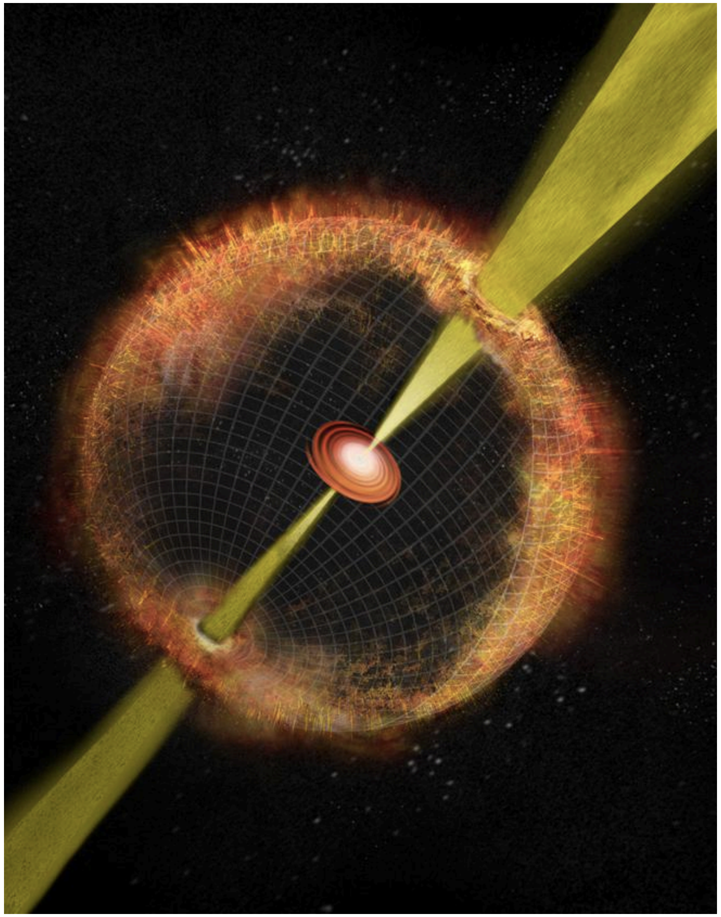
- Gamma rays tell us WHERE and WHEN
- Major outburst of blazar PKS B1424−418 occurred in temporal and positional coincidence with a PeV neutrino
- 5% chance coincidence




Kadler et al., Nature Physics, 2016

# Gamma-Ray Bursts (GRBs)

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



1172 GRBs correlated with IceCube data

563 GRBs correlated with ANTARES data

IceCube ApJ 843 (2017), 112
ANTARES Eur.Phys.J. C77 (2017) no.1, 20

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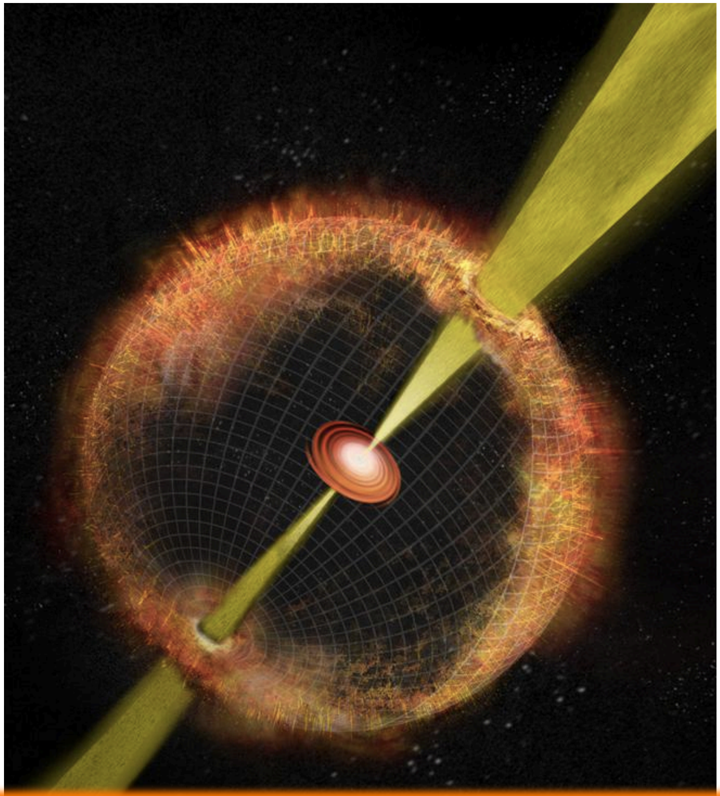


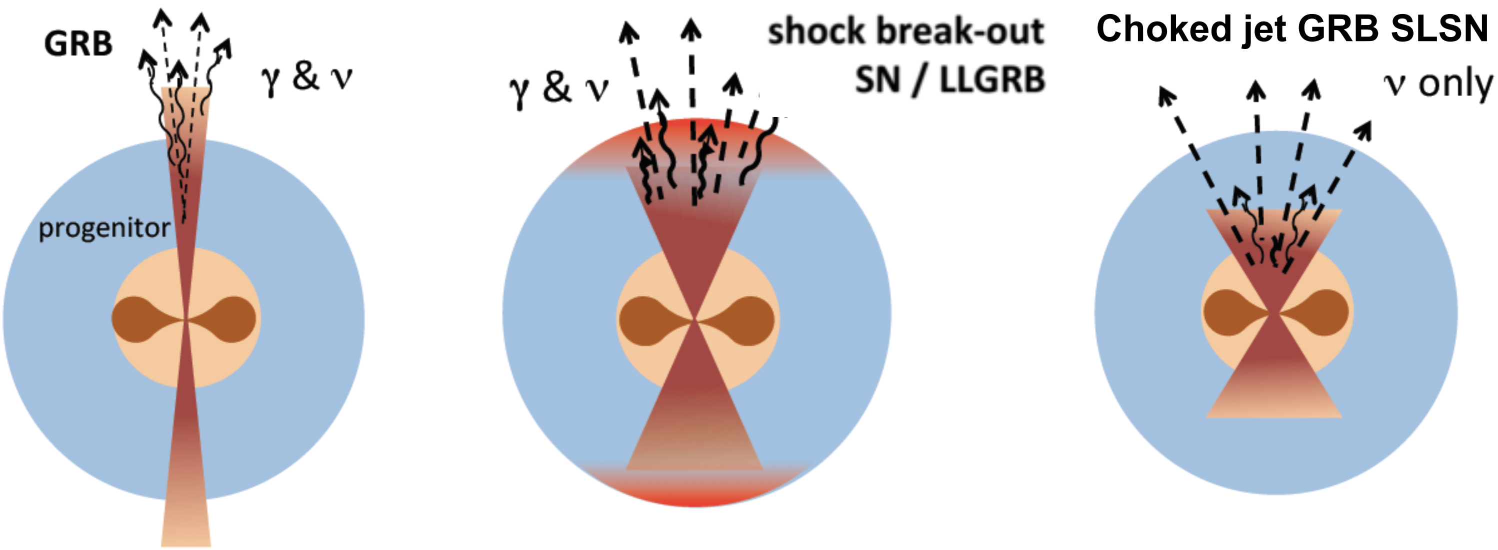
1172 GRBs correlated with IceCube data

563 GRBs correlated with ANTARES data

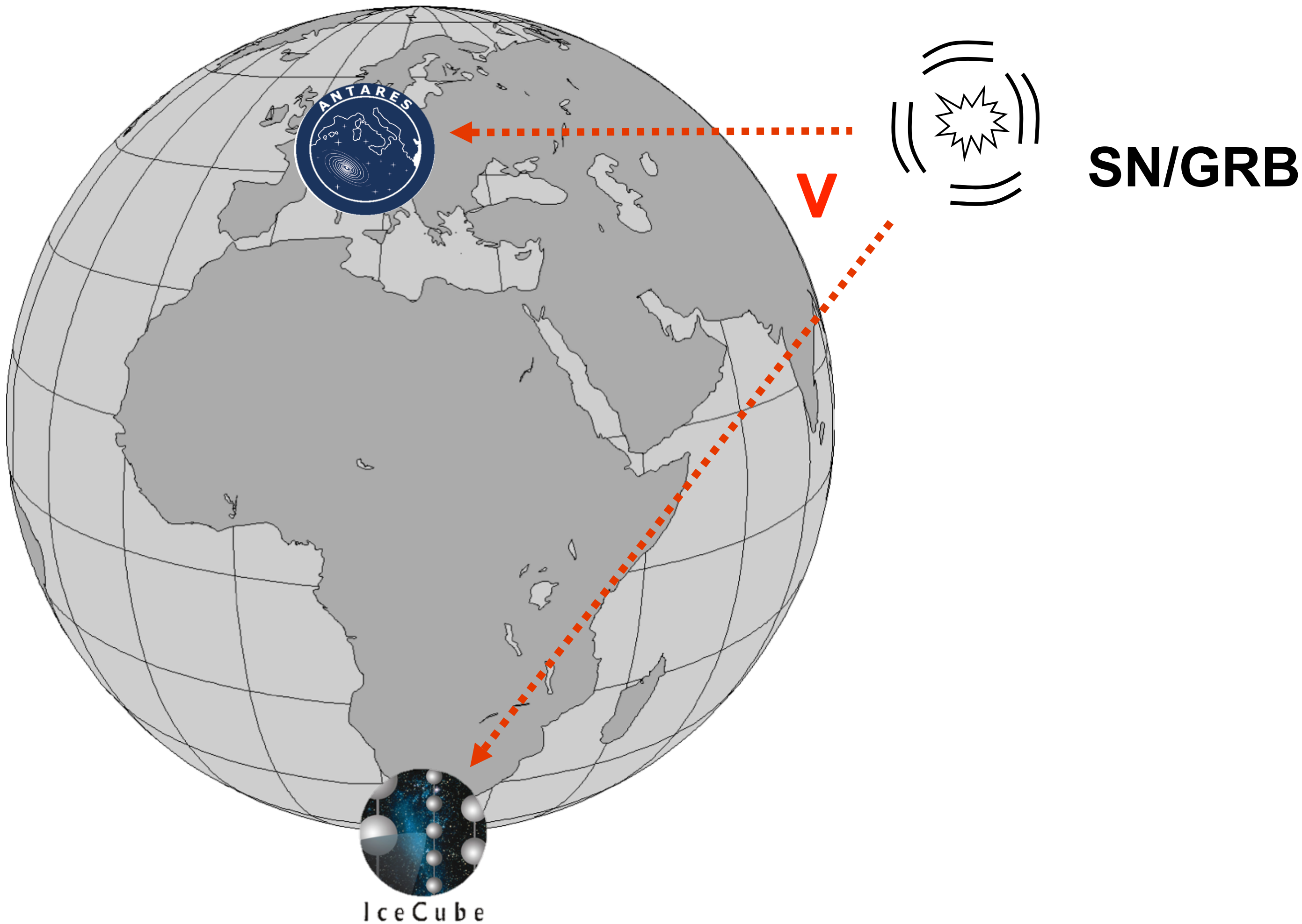
**GRBs contribute less than 1% to observed diffuse neutrino flux. Potential large population of nearby low-luminosity GRBs not constrained**

IceCube ApJ 843 (2017), 112
ANTARES Eur.Phys.J. C77 (2017) no.1, 20

# GRB-Supernova Connection



# Target of Opportunity Program




ANTARES JCAP 1602 (2016)
Ackermann et al.arXiv:0709.2640
IceCube A&A 539, A60 (2012)
IceCube, MAGIC, VERITAS, 2016 JINST 11 P11009

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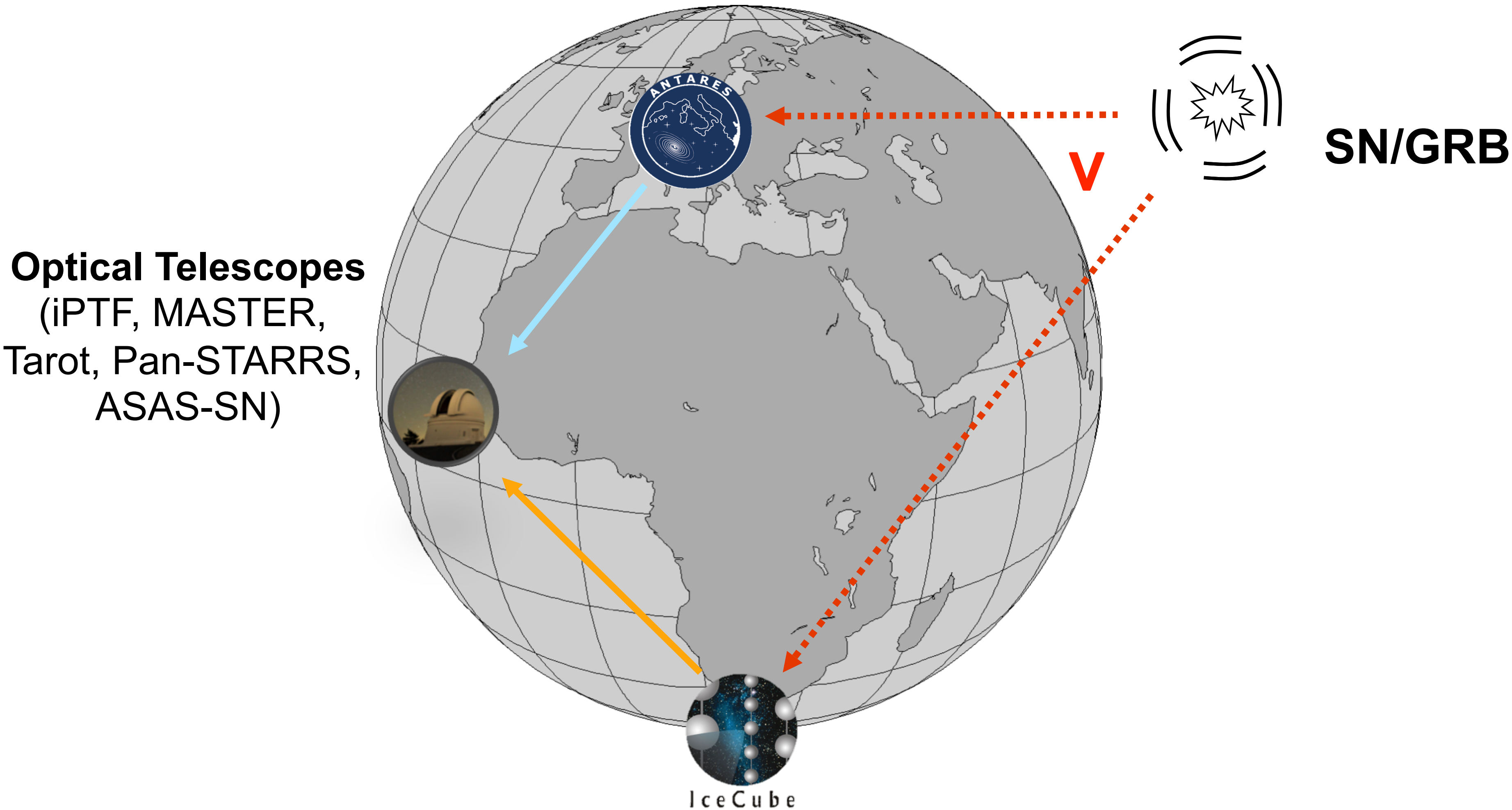


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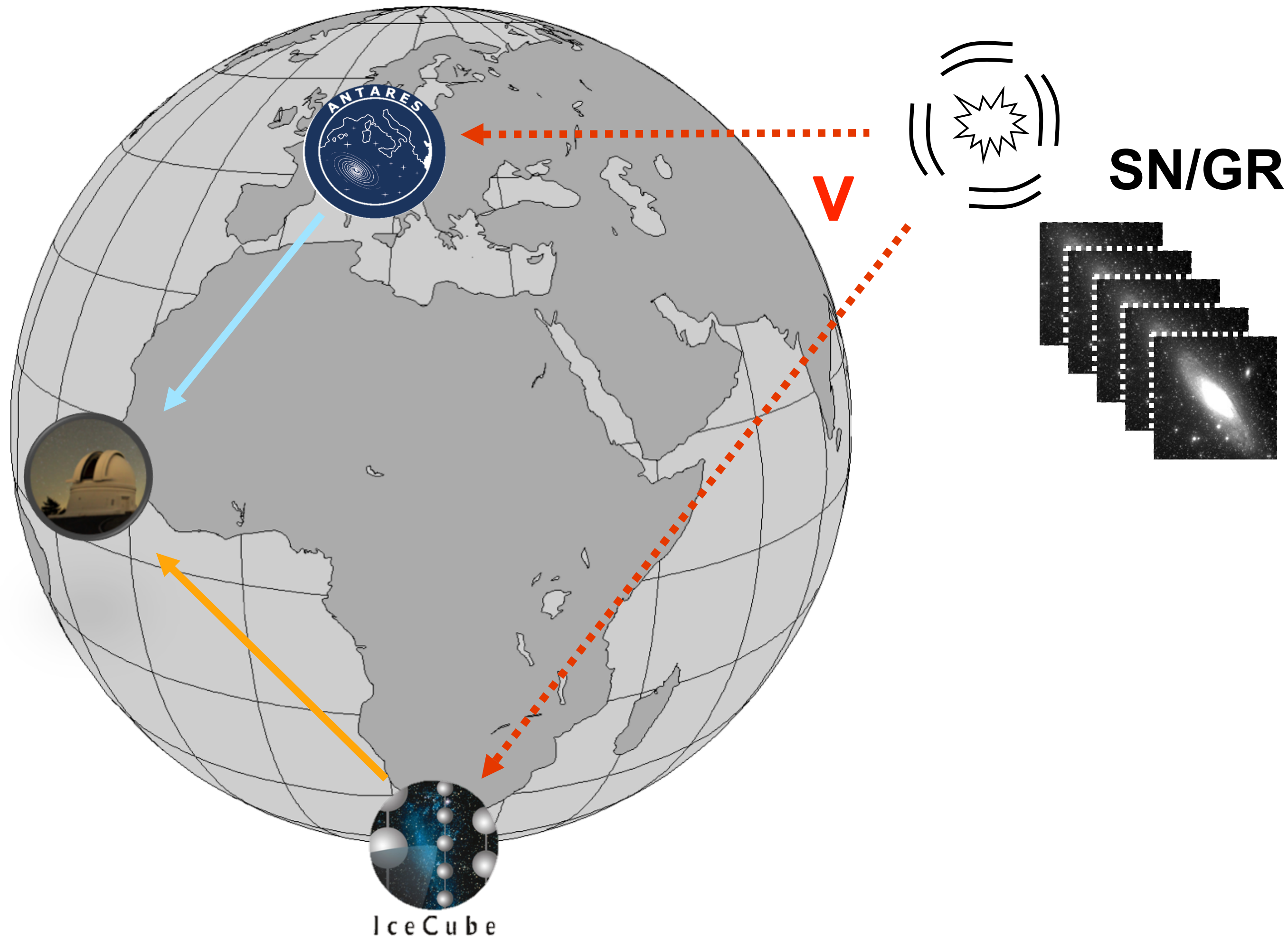
IceCube, MAGIC, VERITAS, 2016 JINST 11 P11009

# Target of Opportunity Program

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

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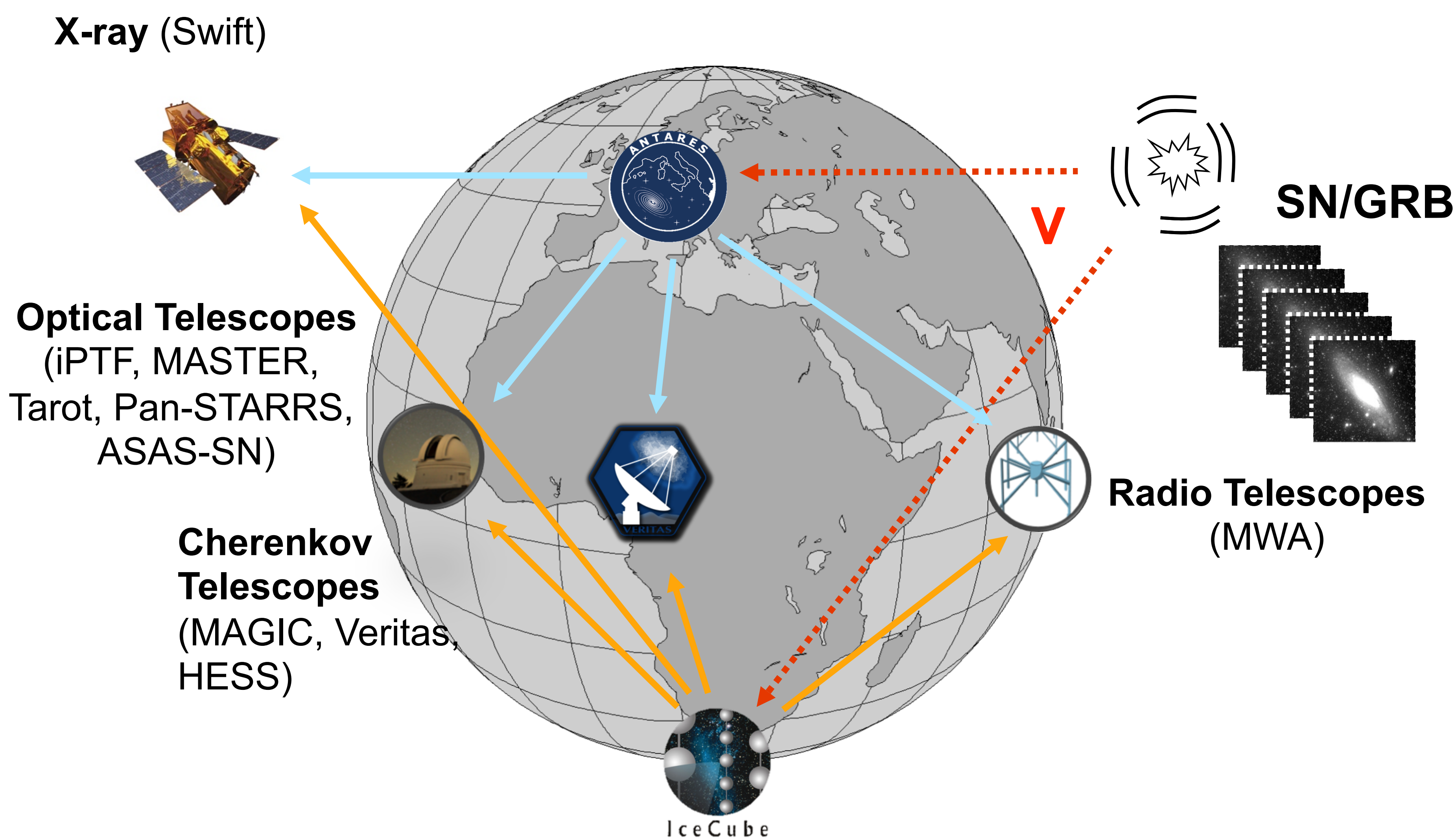


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DESY

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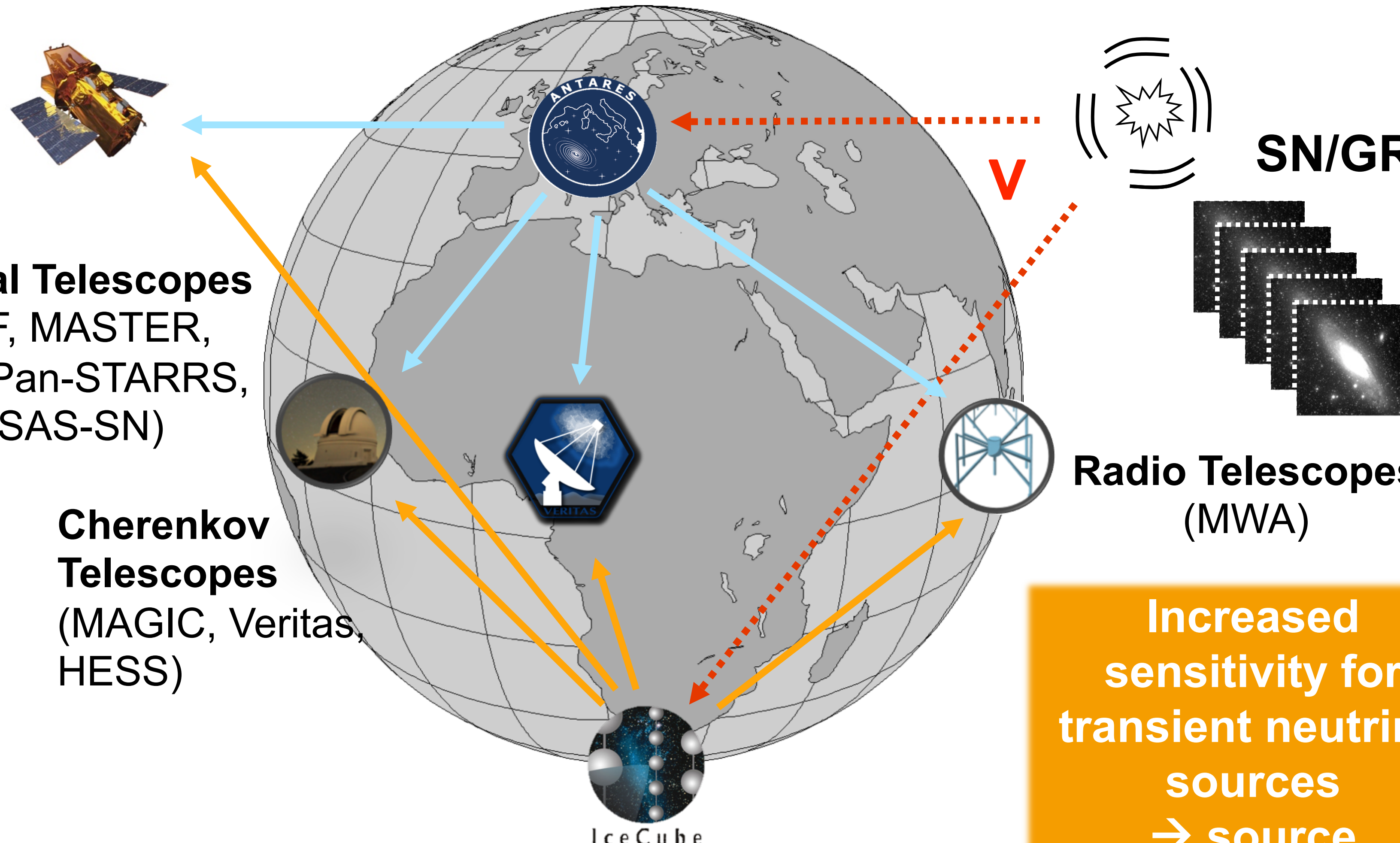
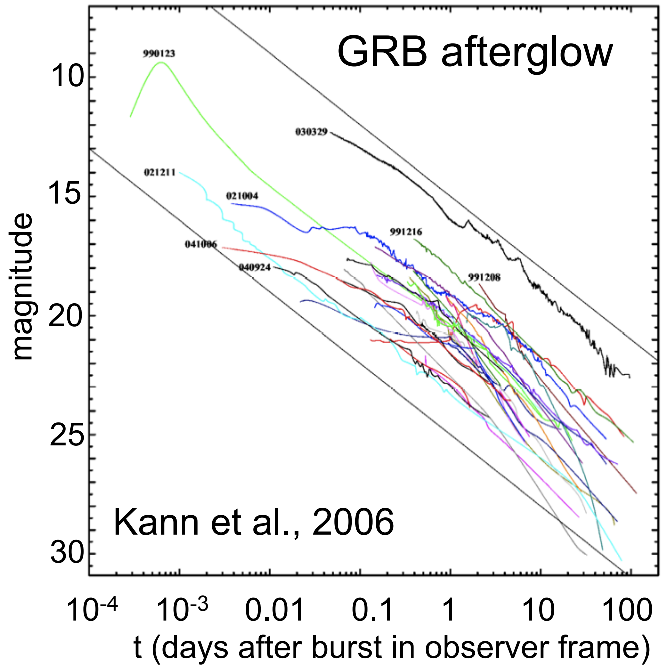
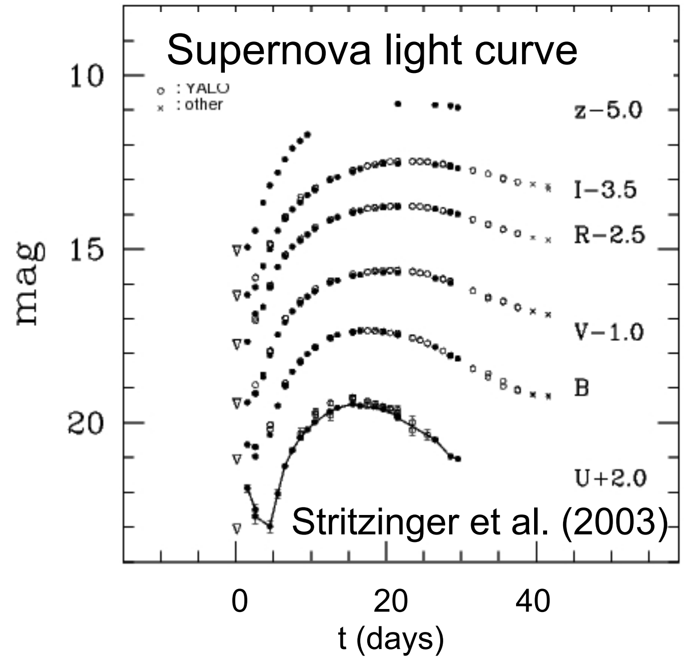


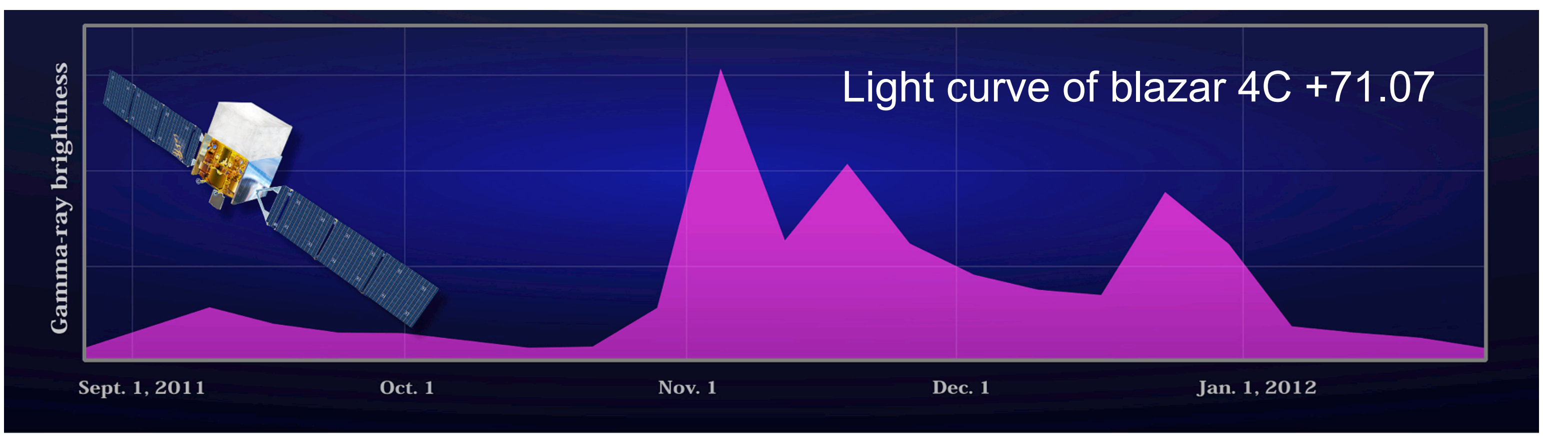

**Increased sensitivity for transient neutrino sources → source identification**

ANTARES JCAP 1602 (2016)
Ackermann et al.arXiv:0709.2640
IceCube A&A 539, A60 (2012)
IceCube, MAGIC, VERITAS, 2016 JINST 11 P11009

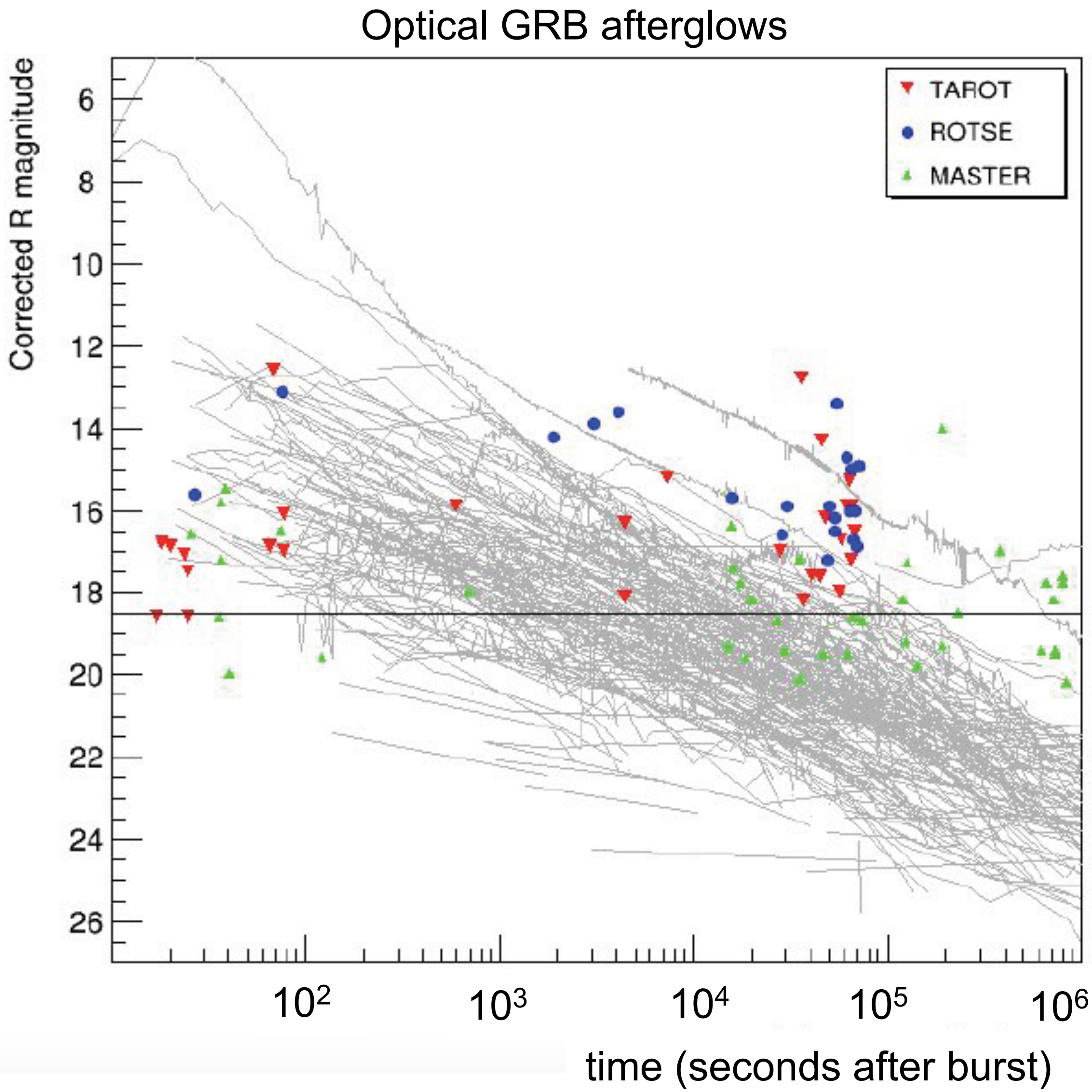
# Expected EM Counterparts



# Fast Follow-Up Possible!

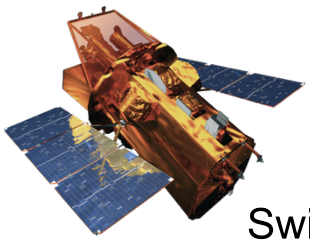



**Fast reaction by follow-up instruments are required to detect rapidly declining GRB afterglow**

ANTARES JCAP 1602 (2016)

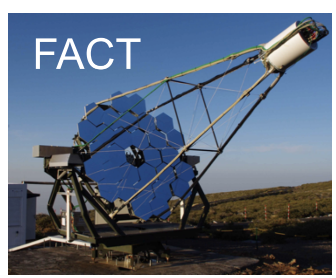
# Public IceCube Alerts since April 2016

- Single high-energy events (> ~100TeV)
- 8 / year, ~3 / year of astrophysical origin
- First alert on 2016/04/27 → **large interest by astro community**

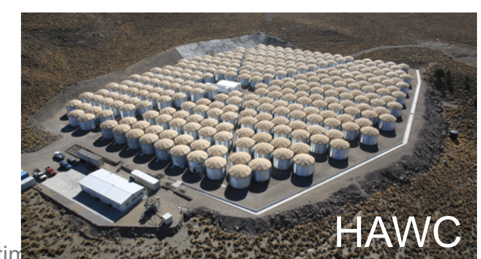


Swift





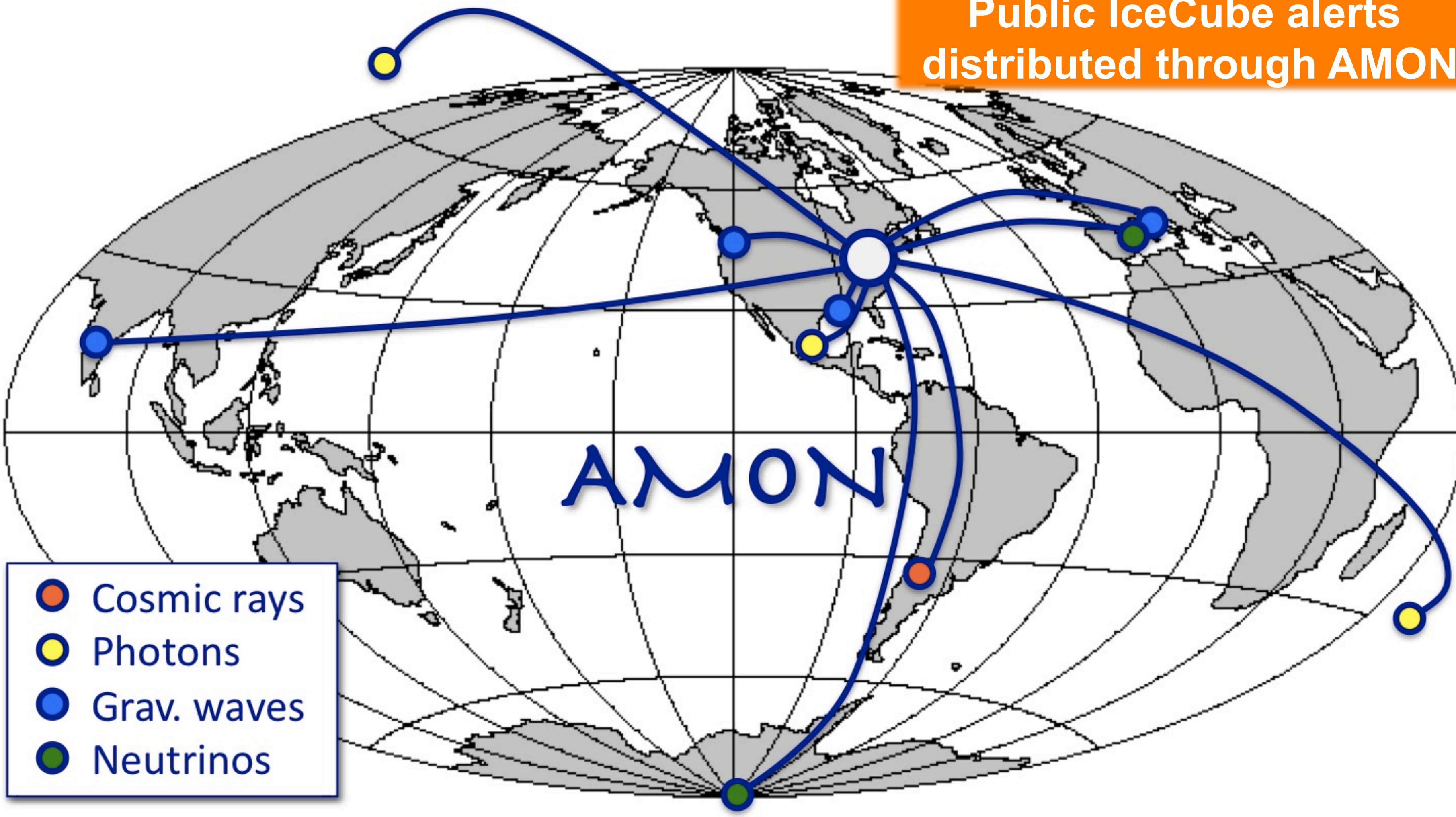







# Astrophysical Multimessenger Observatory Network (AMON)

**Public IceCube alerts distributed through AMON**

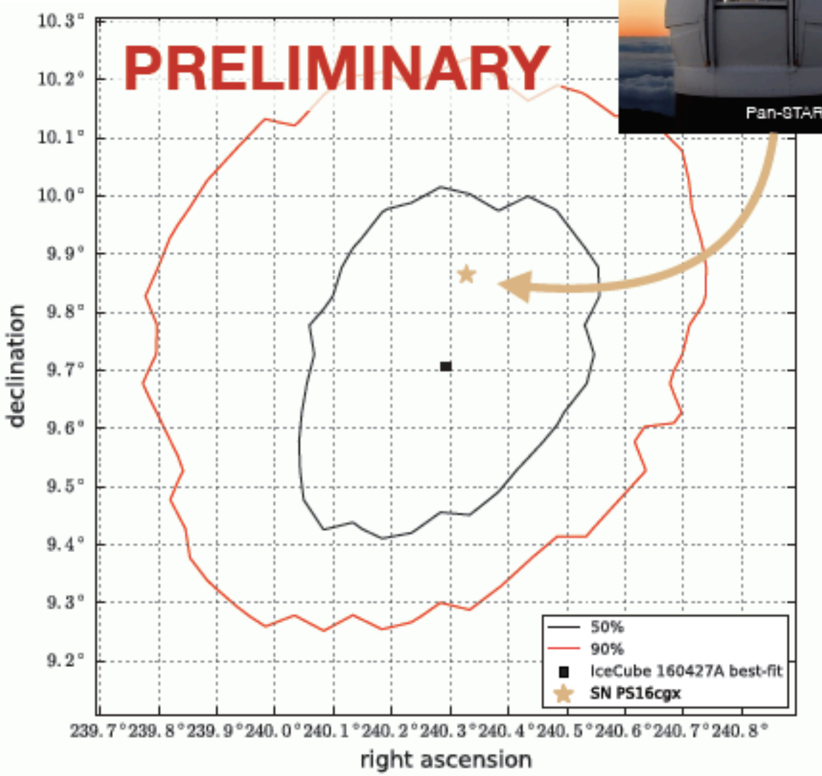



http://sites.psu.edu/amon/
Keivani, et al., PoS(ICRC2017) 629

# Supernova found by Pan-STARRS in public IceCube Alert

IceCube, ICRC 2017

Pan-STARRS followed up IceCube alert on 2016-04-27 and found a recent supernova at z=0.3:


Light curve consistent with explosion days before neutrino alert

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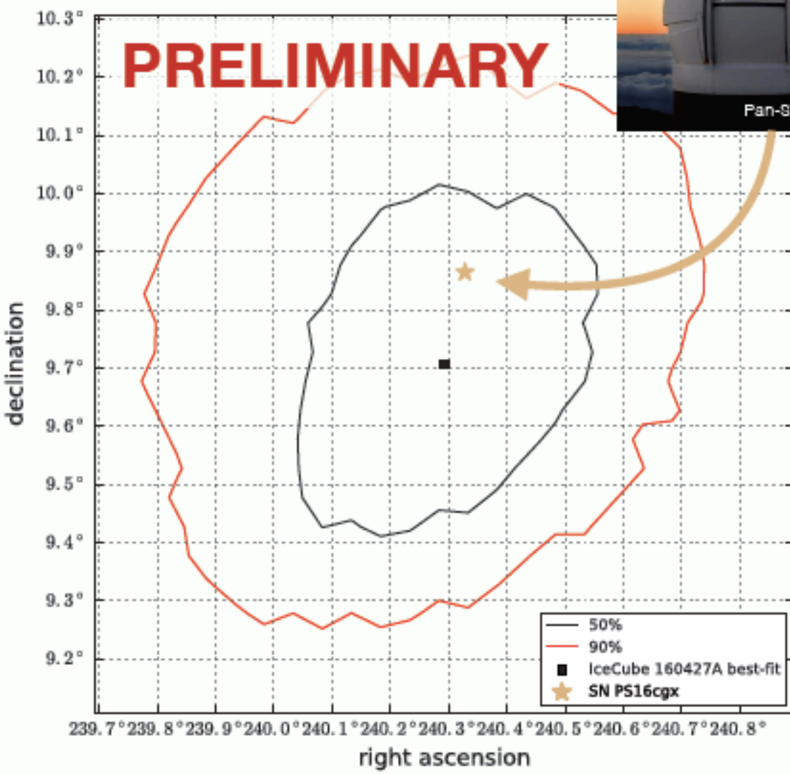
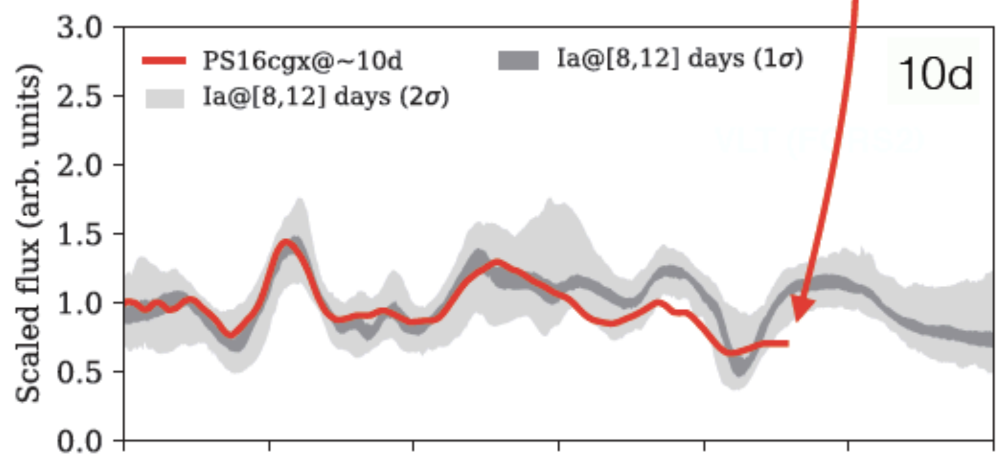




Optical spectroscopy taken 10, 20 days post peak


Features atypical for SNIa but not sufficient to exclude

Light curve consistent with explosion days before neutrino alert

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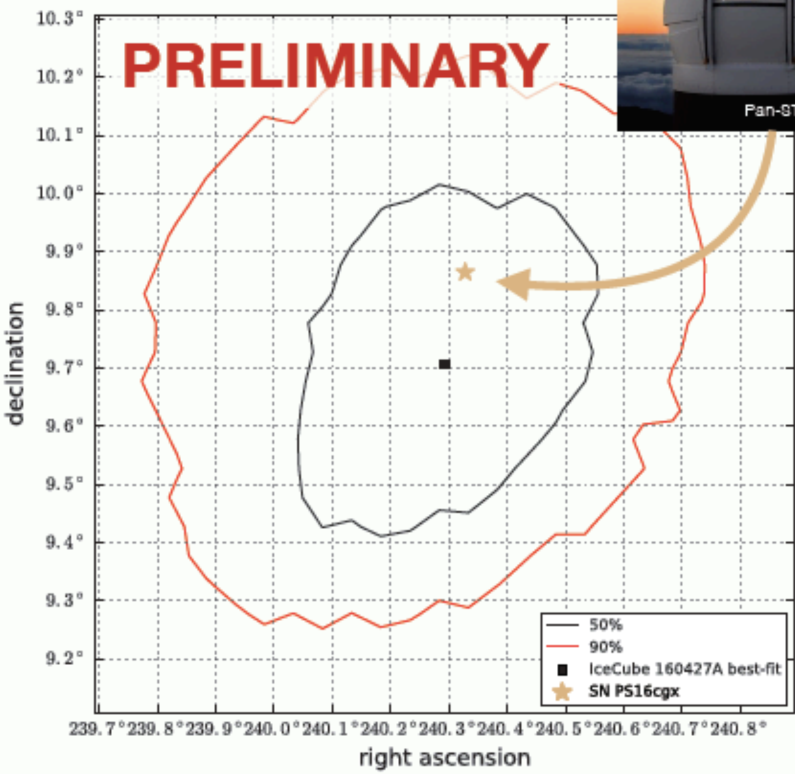



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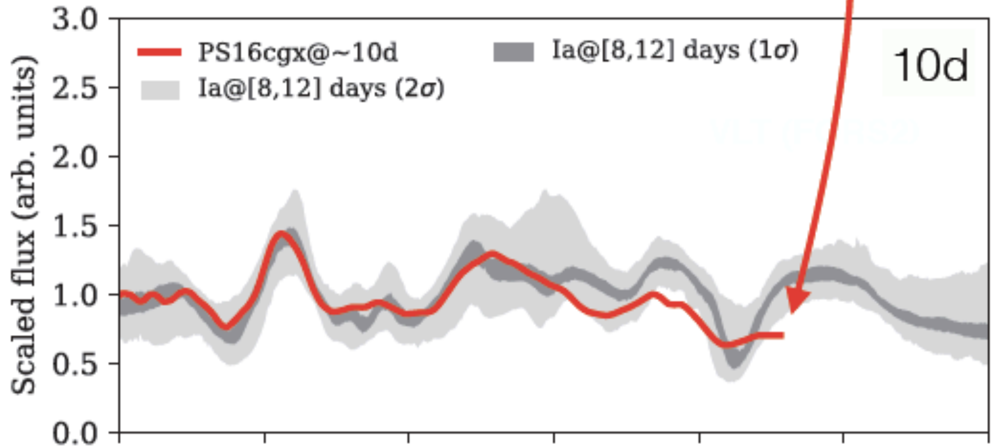


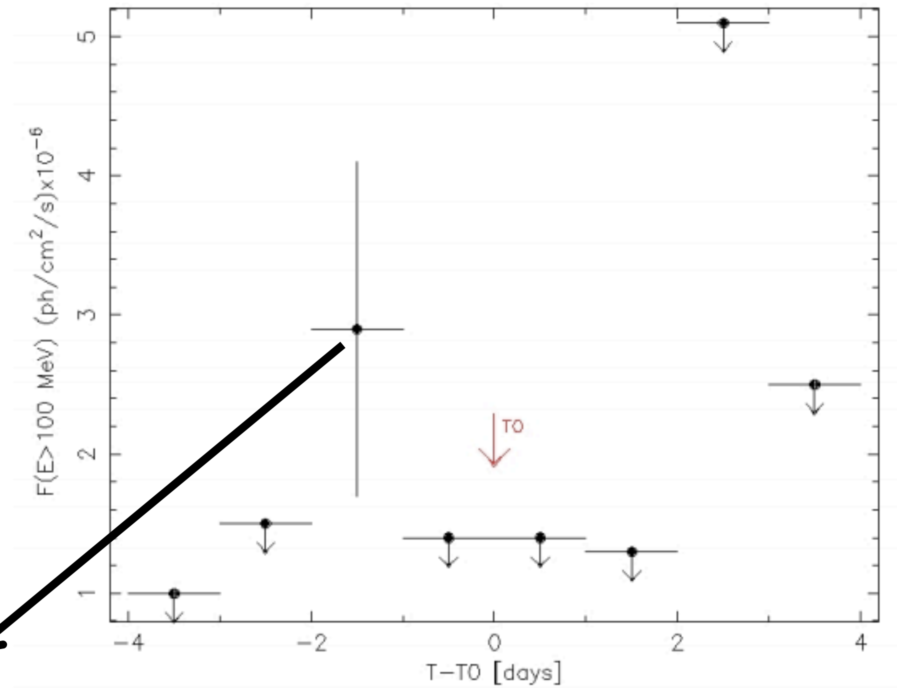

Features atypical for SNIa but not sufficient to exclude

Light curve consistent with explosion days before neutrino alert

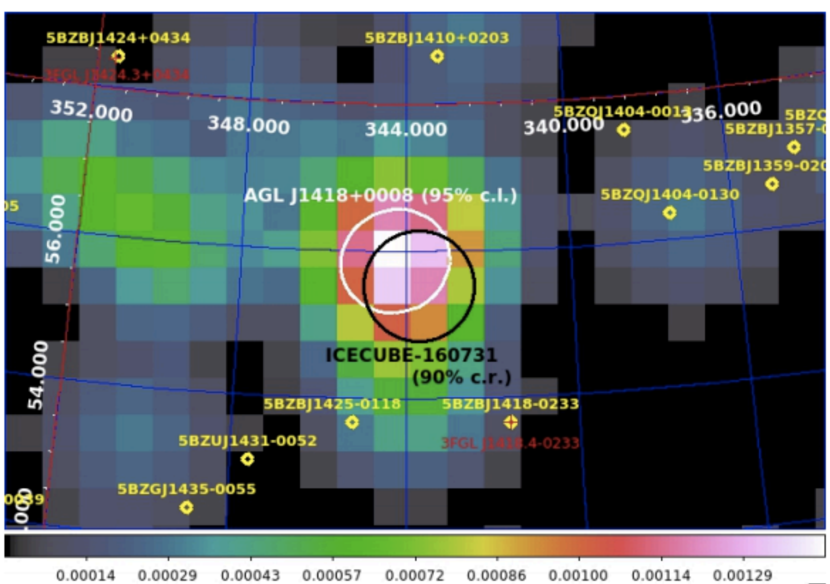
Chance probability { if **Ic** (associated with GRBs): **<1%**; if **Ia** (no HE neutrinos exp.): **<10%**

# Gamma-ray Counterpart to ICECUBE-160731

- AGILE gamma-ray signal:
  - No prompt emission in +/-1000 sec
  - Gamma-ray signal 2 days before the neutrino event (~4σ post-trial significance)
  - Possibly HBL blazar

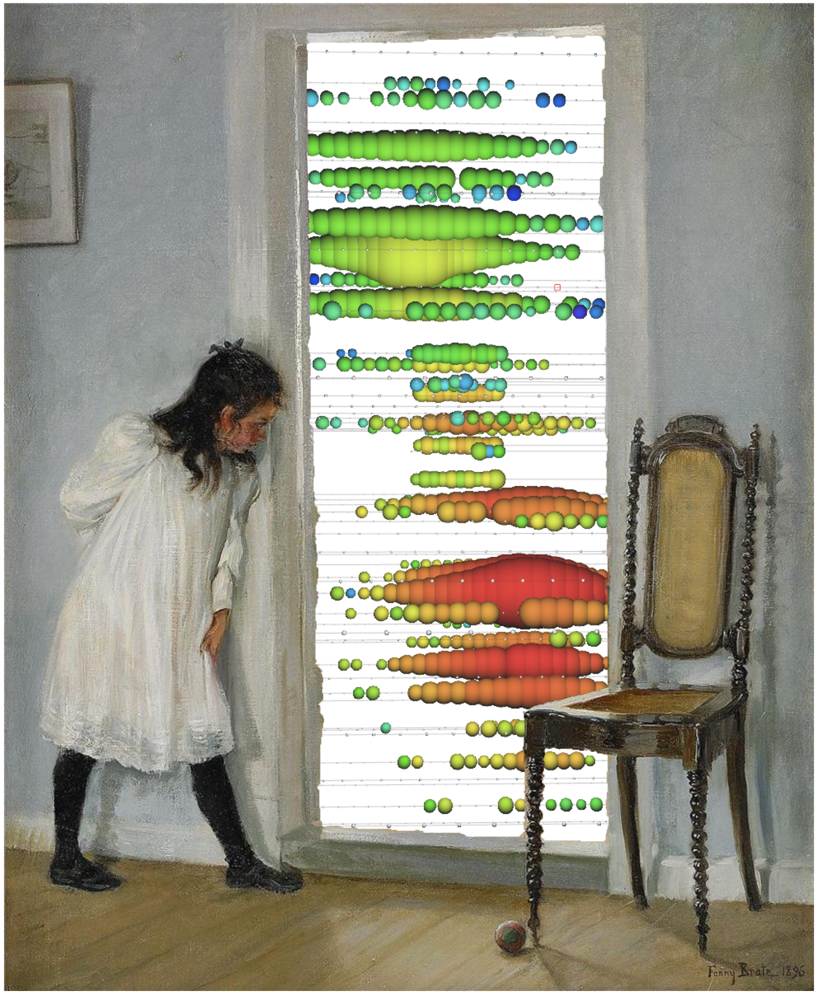


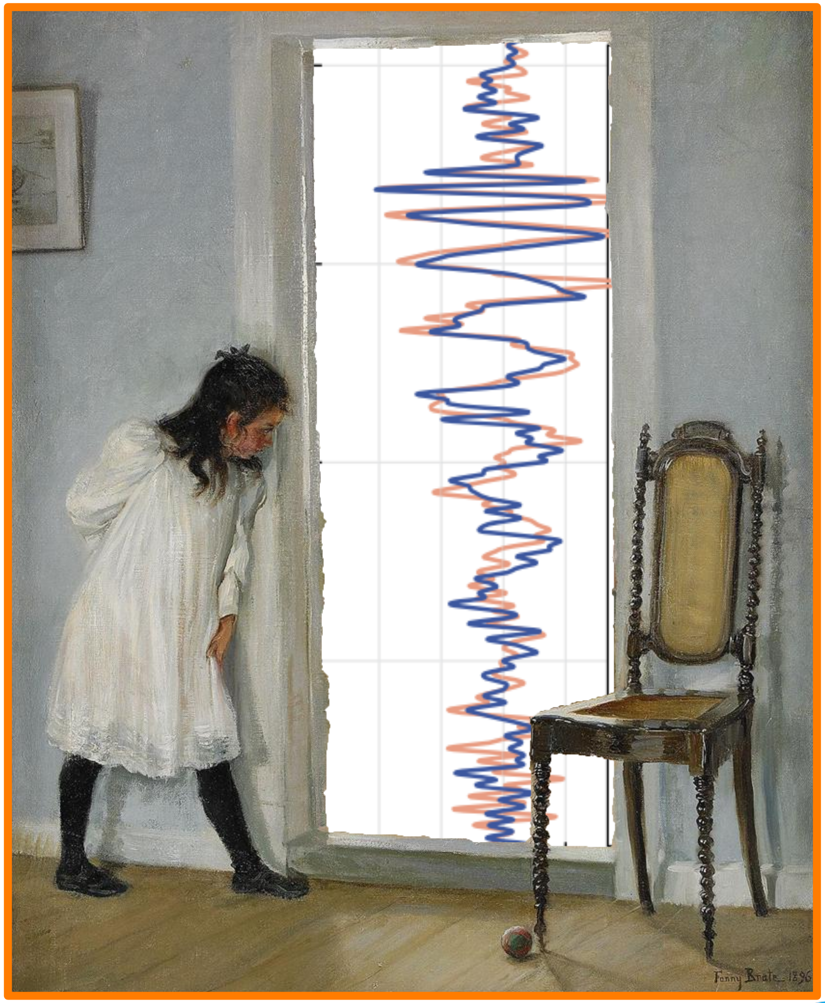

AGILE intensity map (>100MeV)



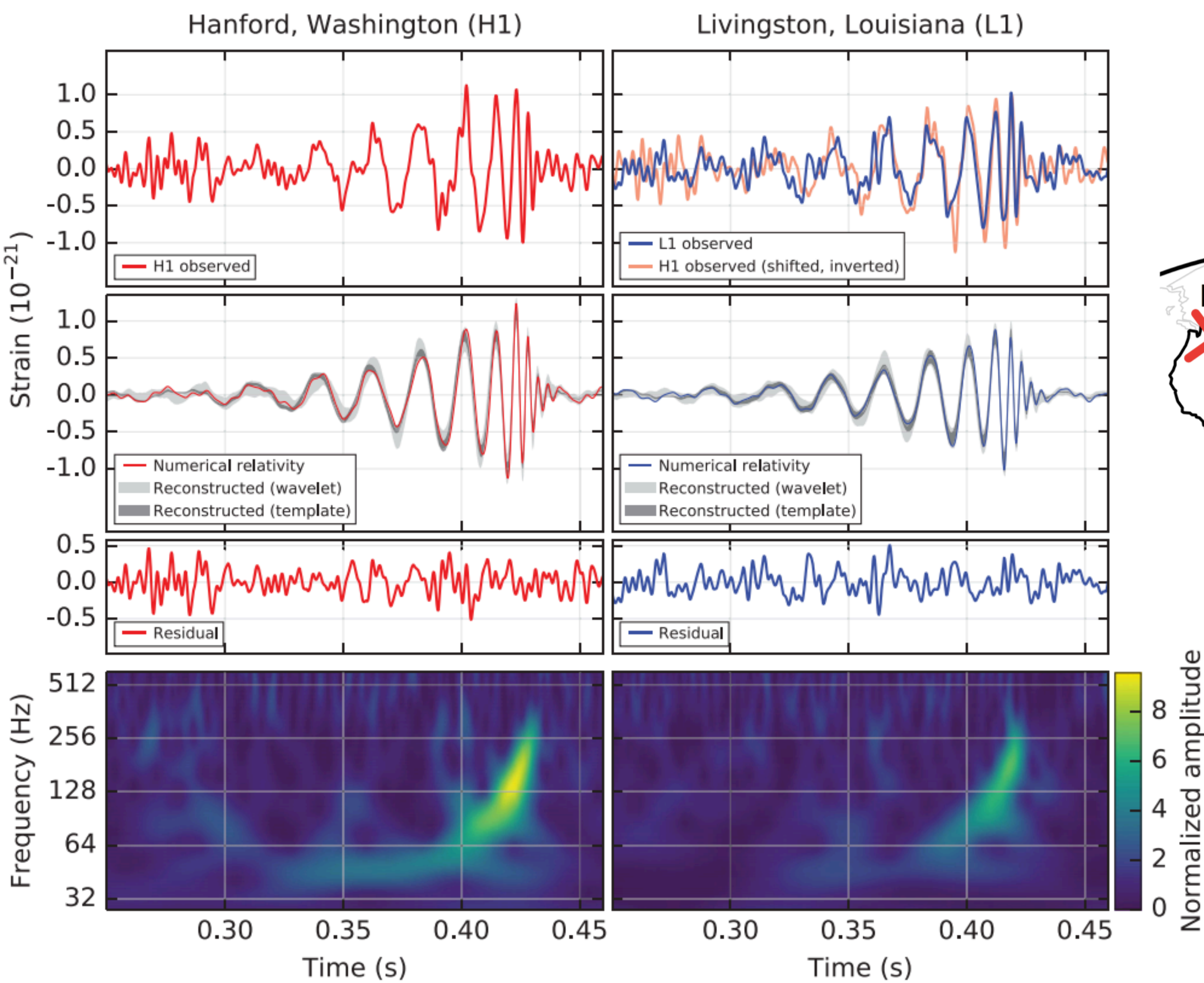

F. Lucarelli et al, ApJ 846, Vol. 2, p. 121 (2017)

# Two New Windows to the Universe

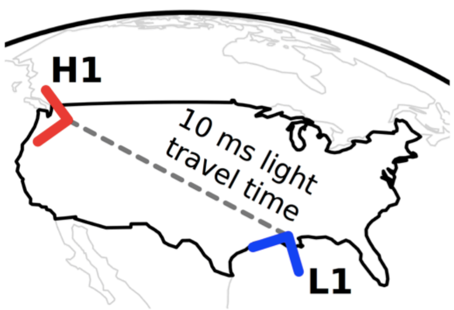




# Another new Window to the Universe: Gravitational Waves



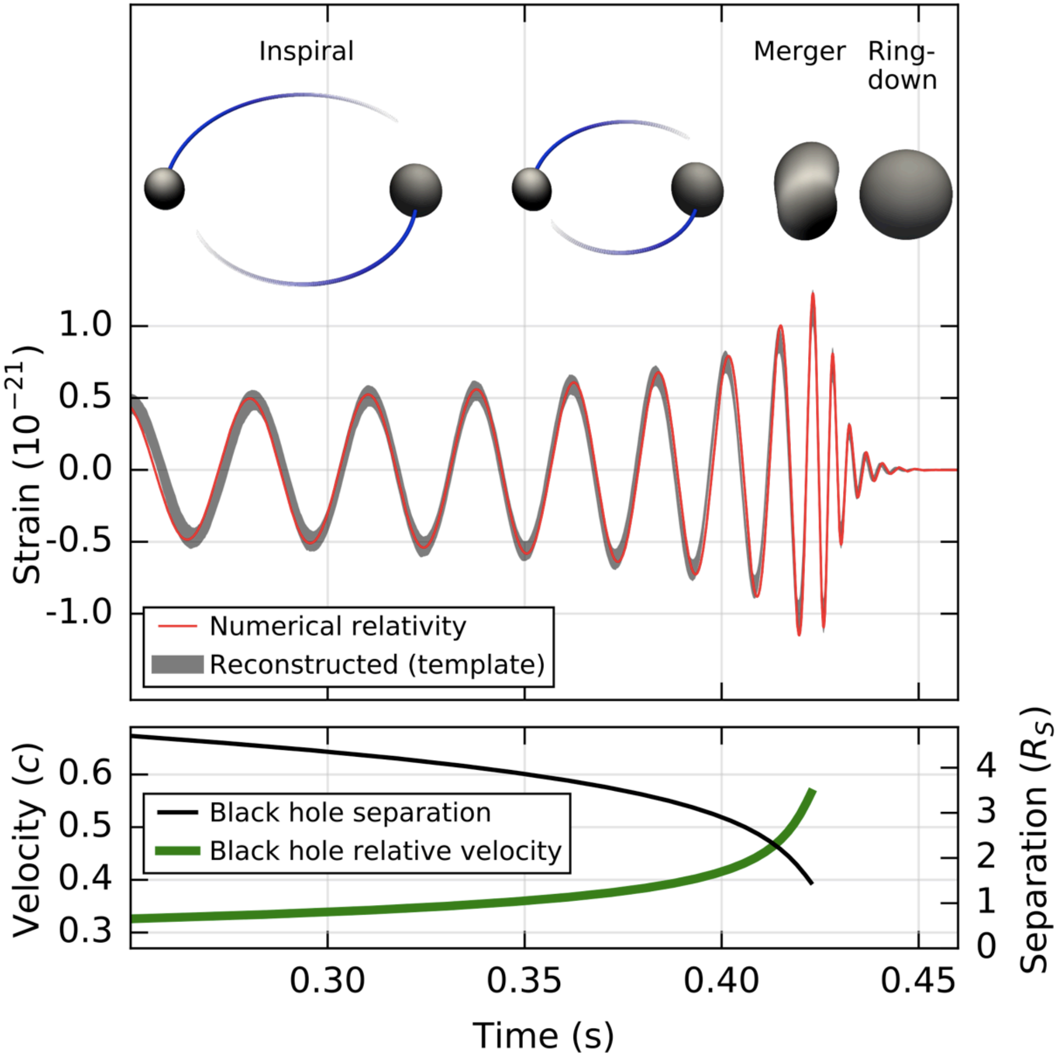

**Sept. 14, 2015**




Abbott et al. (LIGO, Virgo Coll.), PRL (2016) 116, 061102


Courtesy of Corey Gray

# Black-hole Black-hole Merger




Merger of two black holes

$36^{+5}_{-4} M_\odot$

$29^{+4}_{-4} M_\odot$

Energy radiated in gravitational waves:

$3.0^{+0.5}_{-0.5} M_\odot c^2$

Distance:

$410^{+160}_{-180}$ Mpc



Abbott et al. (LIGO, Virgo Coll.), PRL (2016) 116, 061102

# Black Holes of Known Mass

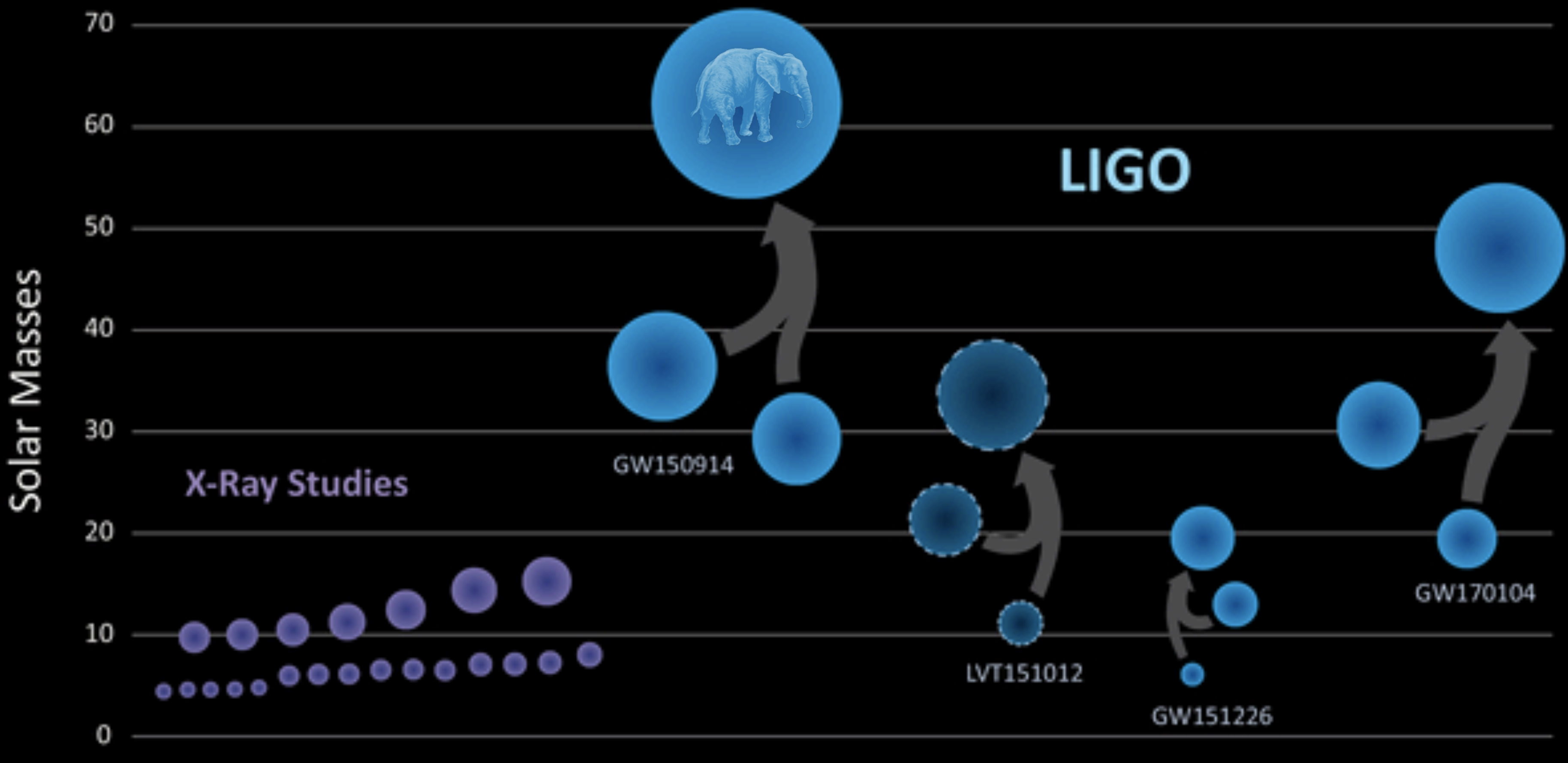
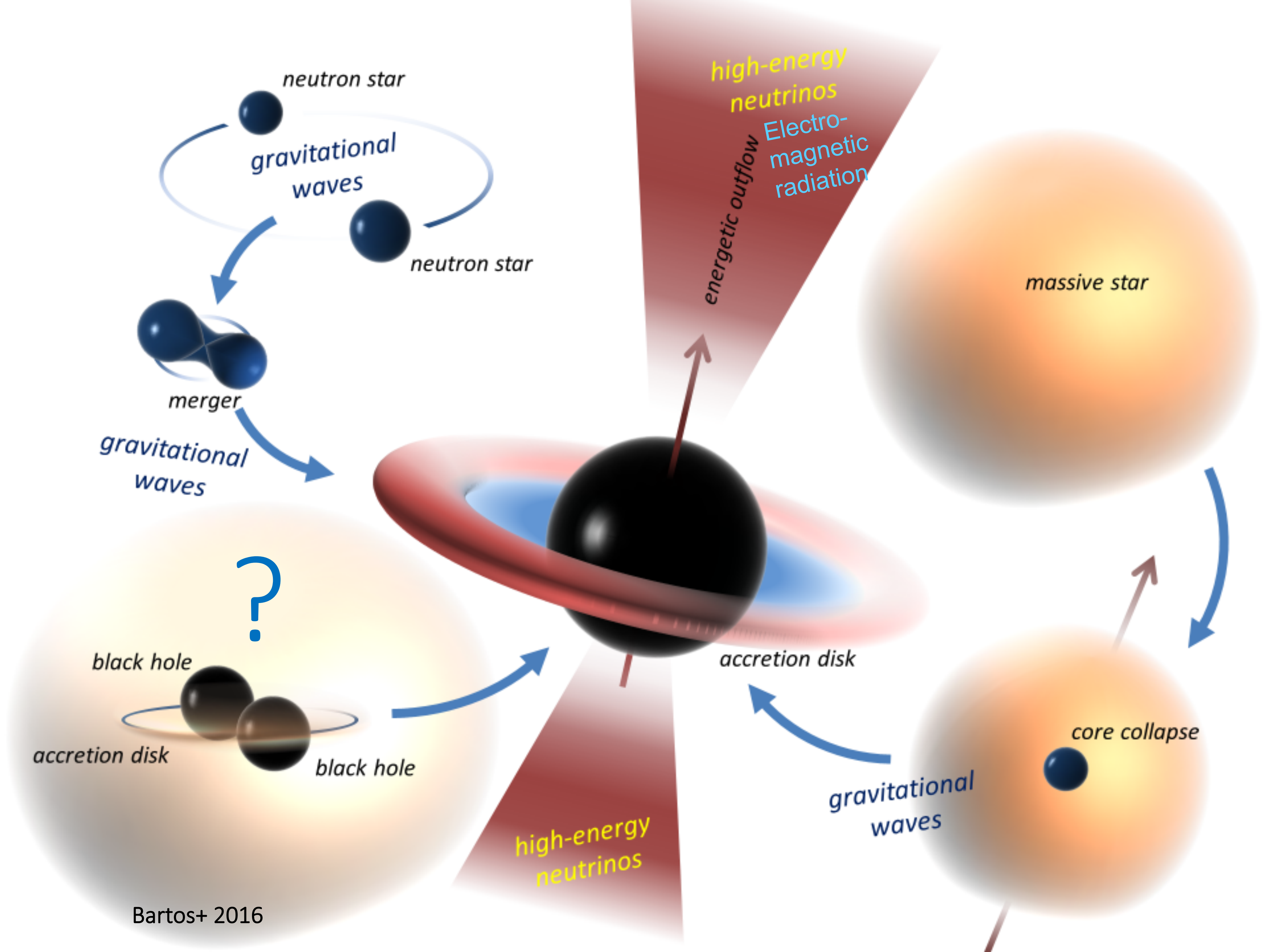
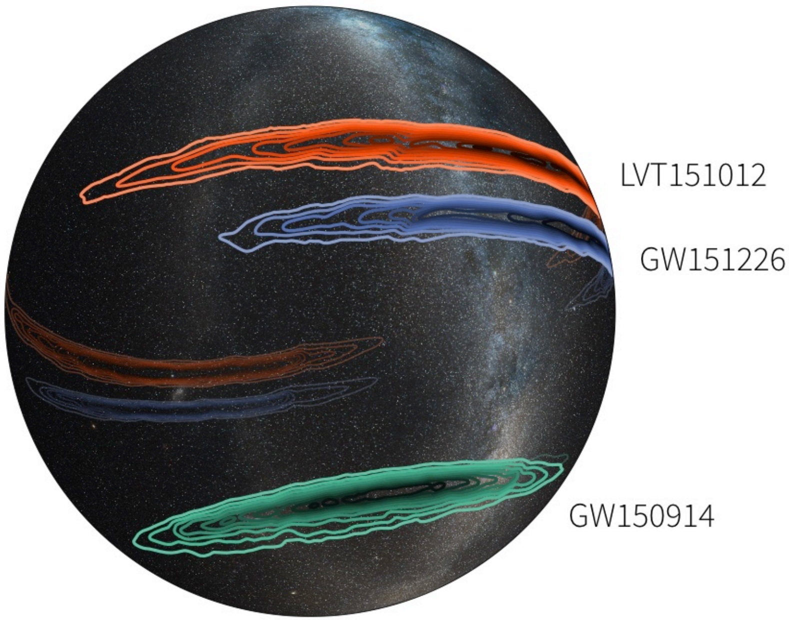


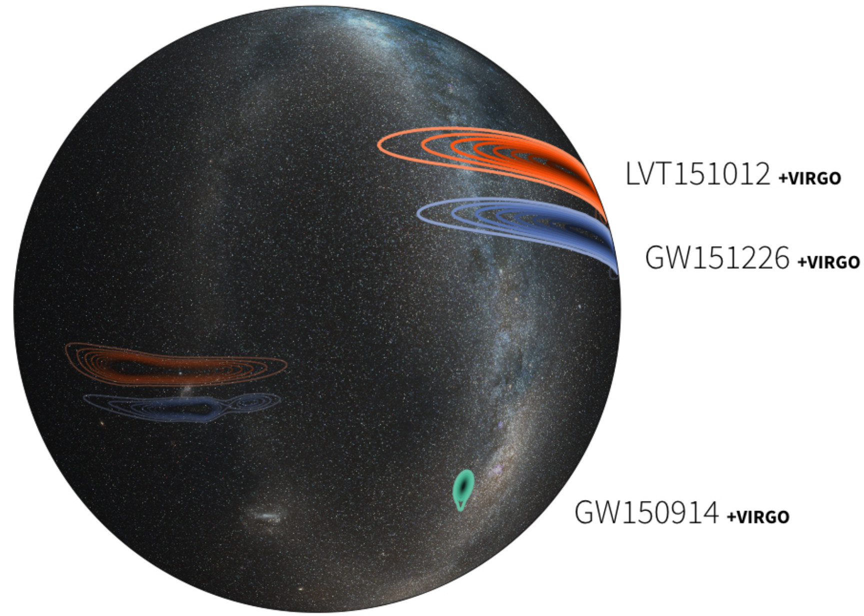

Image credit: LIGO


neutron star
gravitational waves
neutron star
merger
gravitational waves
?
black hole
accretion disk
black hole
Bartos+ 2016
high-energy neutrinos
Electro-magnetic radiation
energetic outflow
massive star
accretion disk
high-energy neutrinos
core collapse
gravitational waves

# Sky Localization



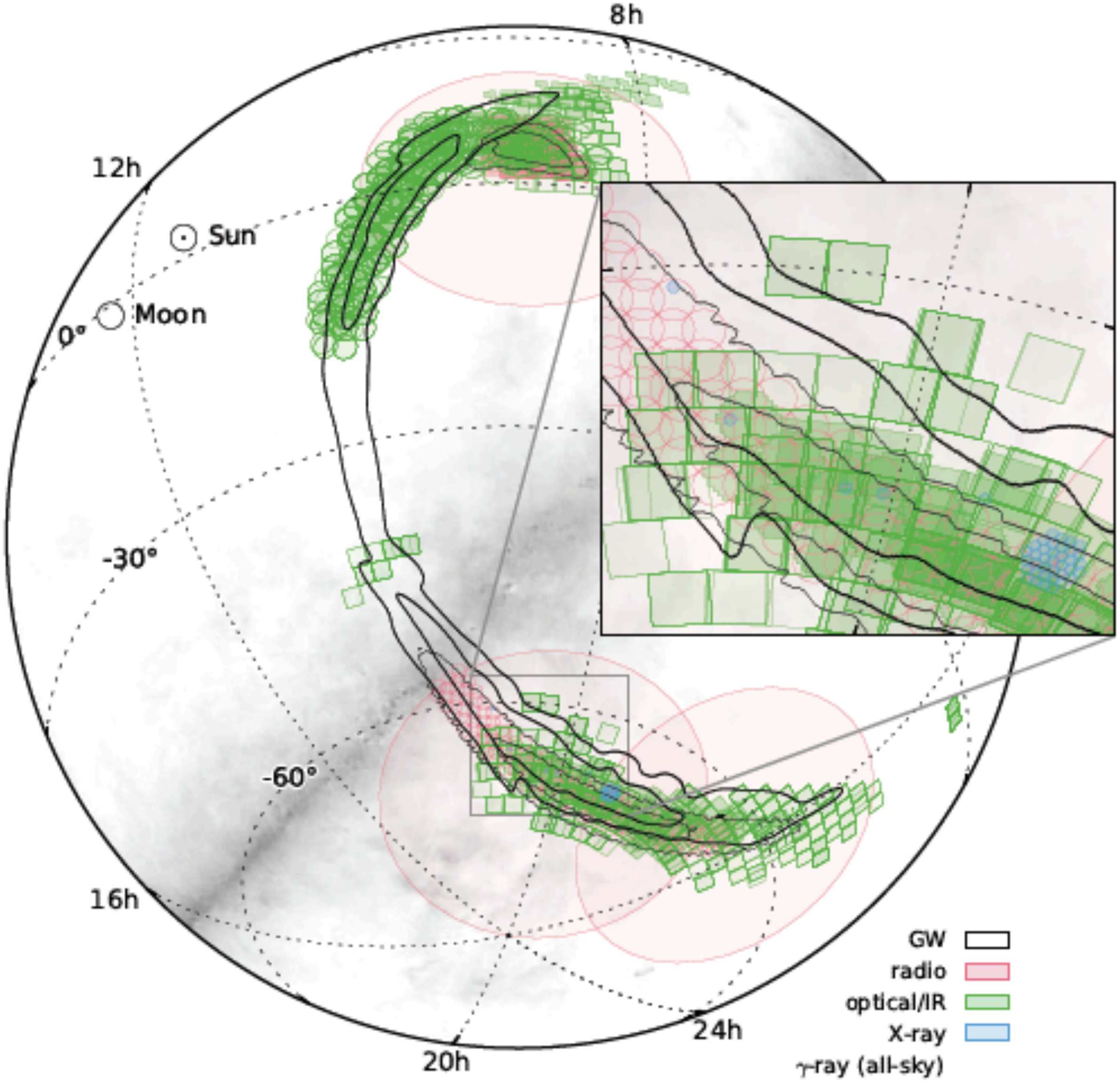

LIGO localizations




Simulated estimates with Virgo

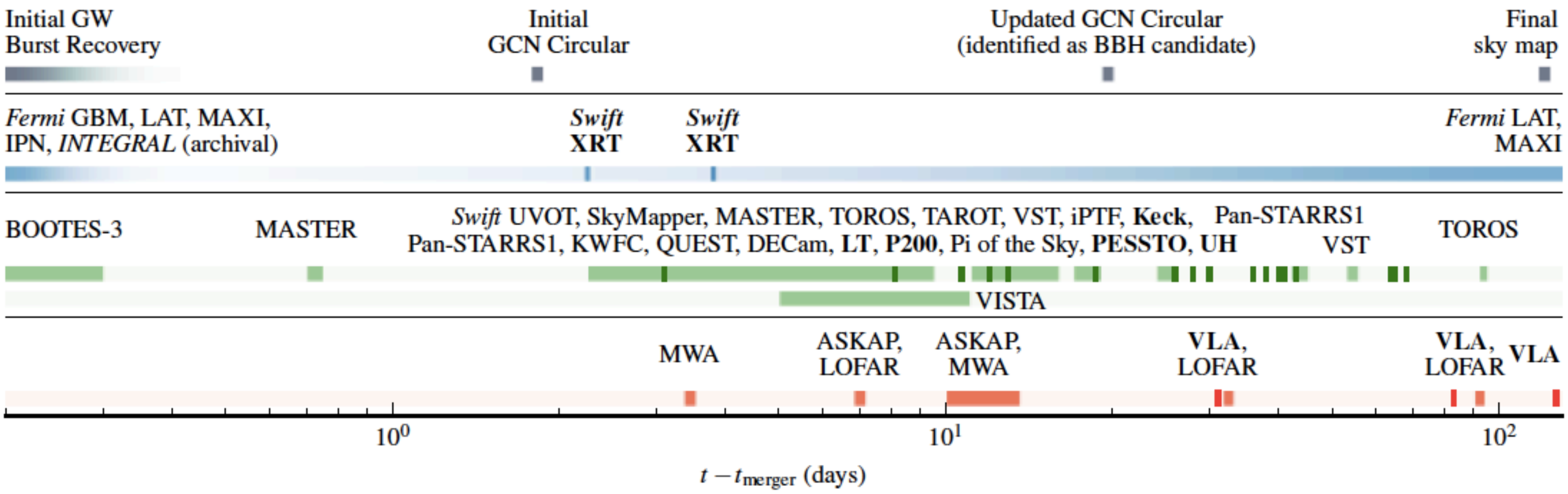
Image credit: LIGO/Leo Singer (Milky Way image: Axel Mellinger)

# Multi-Wavelength Follow-Up




Abbott et al., ApJ Letters (2016), 826

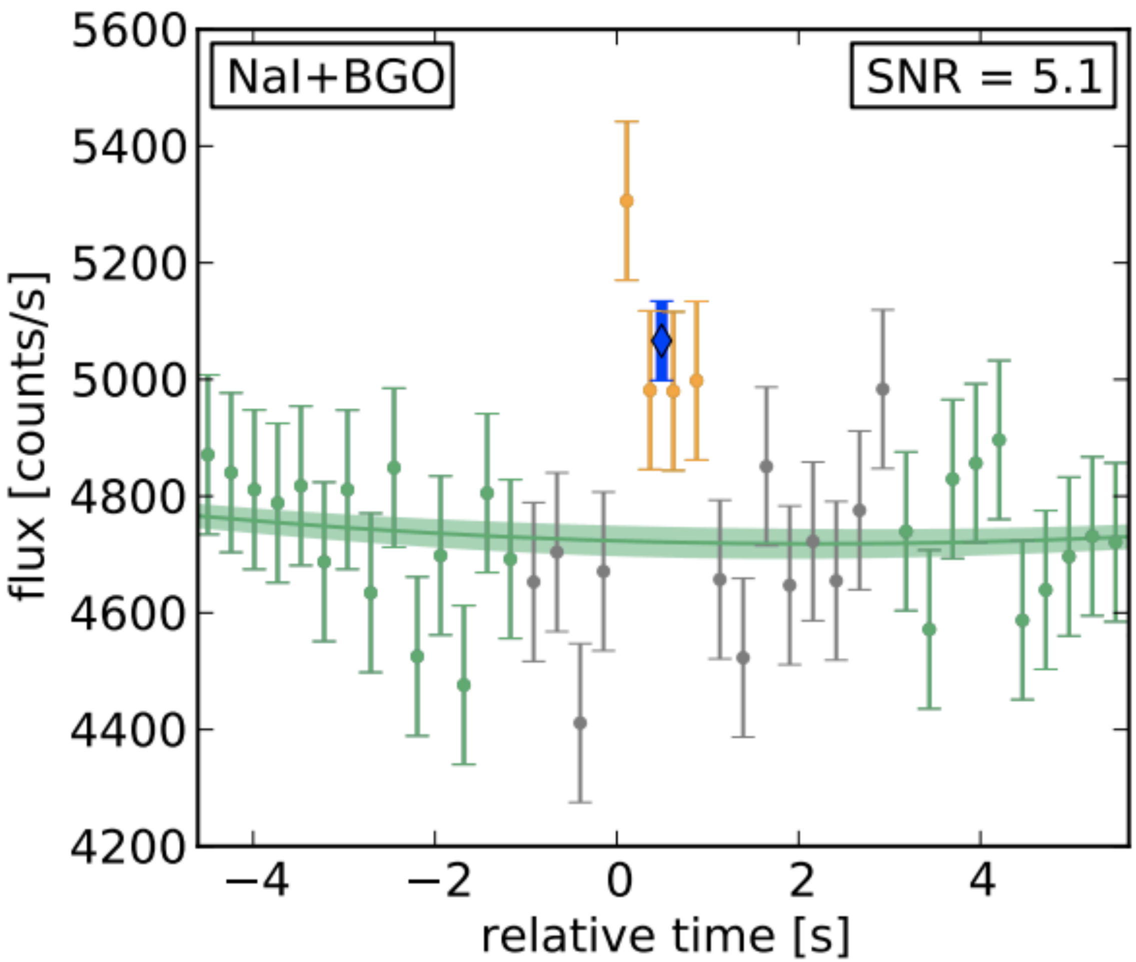
# Multi-Wavelength Follow-Up




**No electro-magnetic signature expected for black-hole black-hole mergers**

Abbott et al., ApJ Letters (2016), 826

# Hint for Gamma-ray Signal?



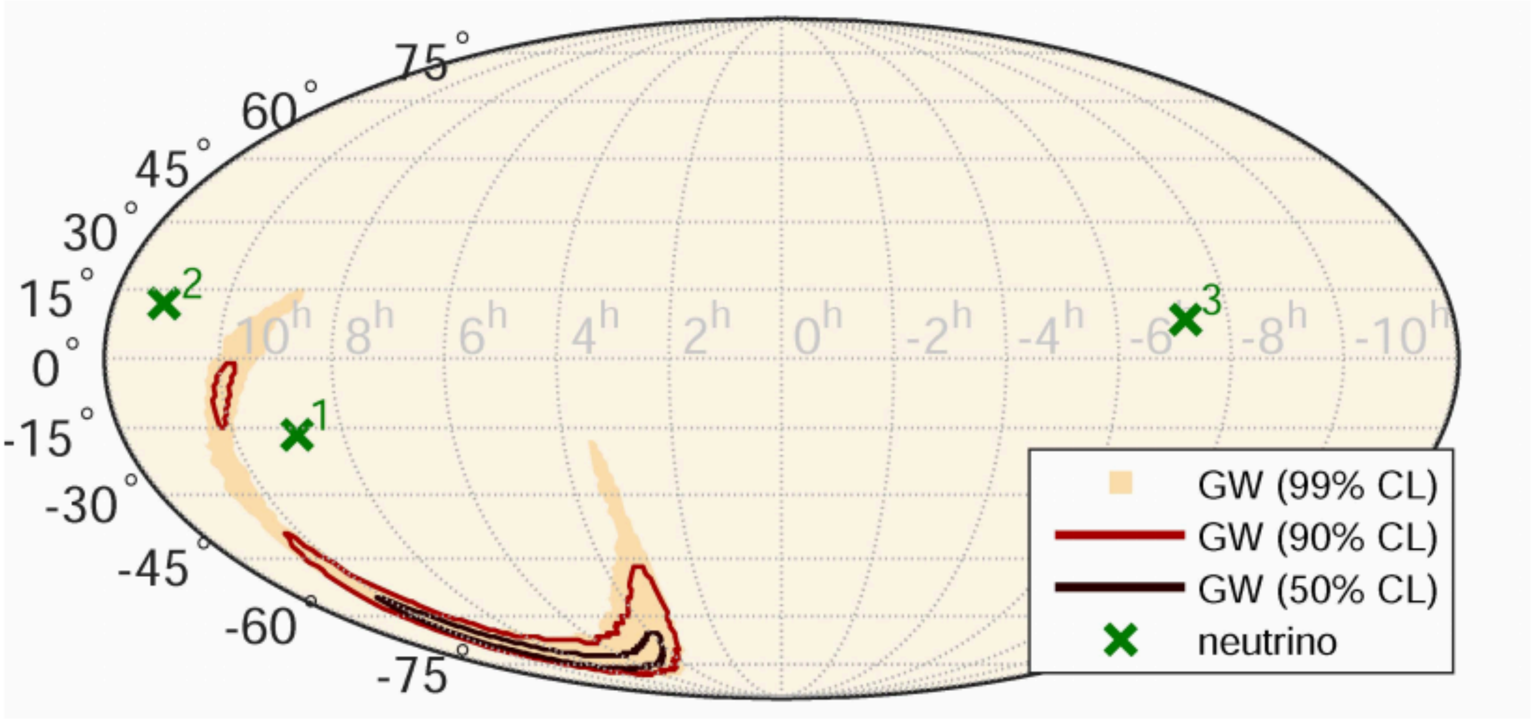

Gamma-Ray Burst Monitor finds short gamma-ray bursts coincident with gravitational wave signal
**0.2% p-value**

- A. Loeb, ApJ Letters (2016) 819
- B. Zhang, ApJ (2016) 827
- R. Moharana, S. Razzaque, N. Gupta, P. Meszaros, PRD (2016) 93
- …

Connaughton et al. (GBM Coll.) ApL 826 (2016)

# Gravitational Waves (GW) and Neutrinos

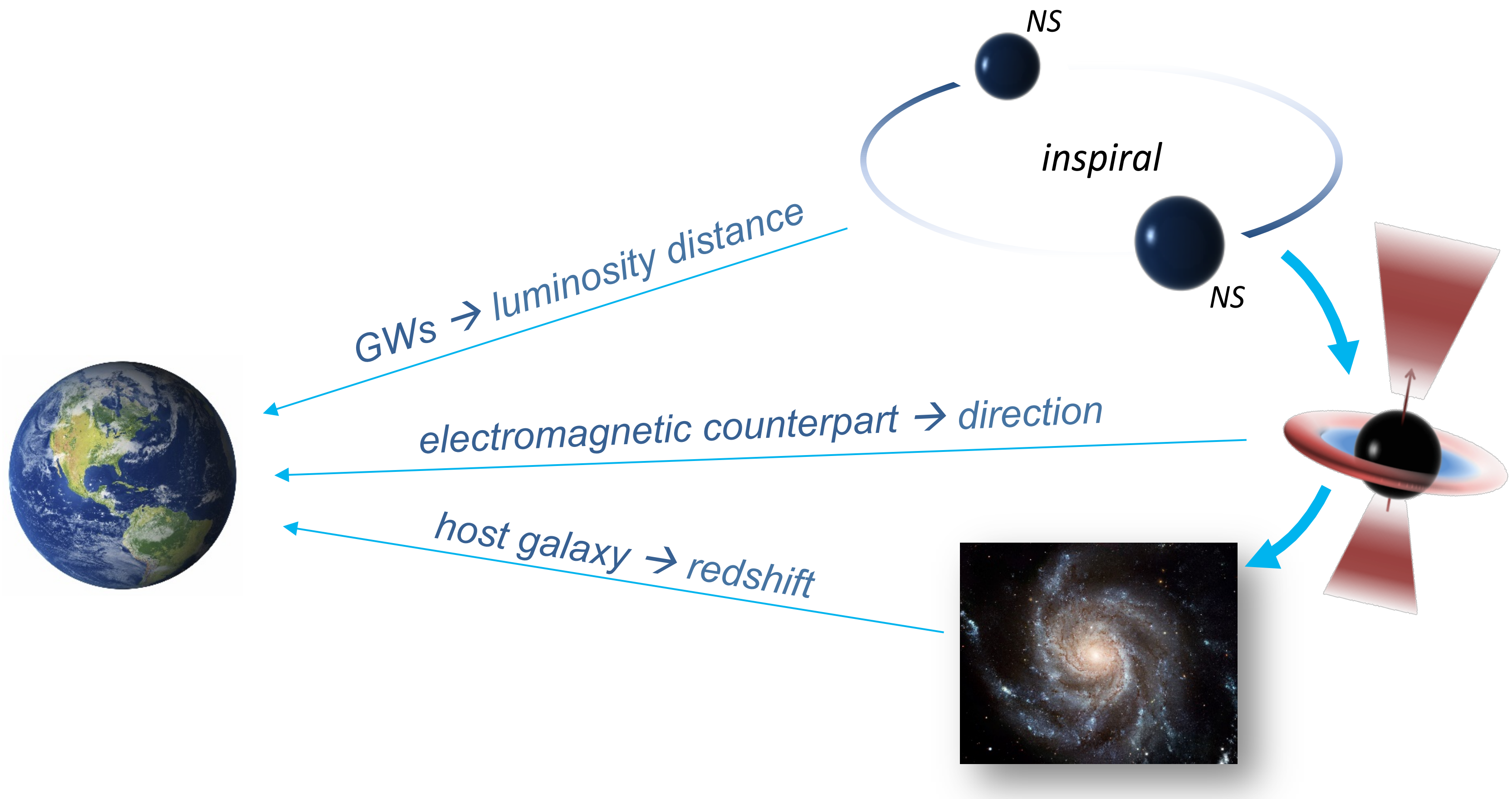
Search for neutrinos from GW150914 in ANTARES and IceCube data in +/-500 sec → no counterpart found




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

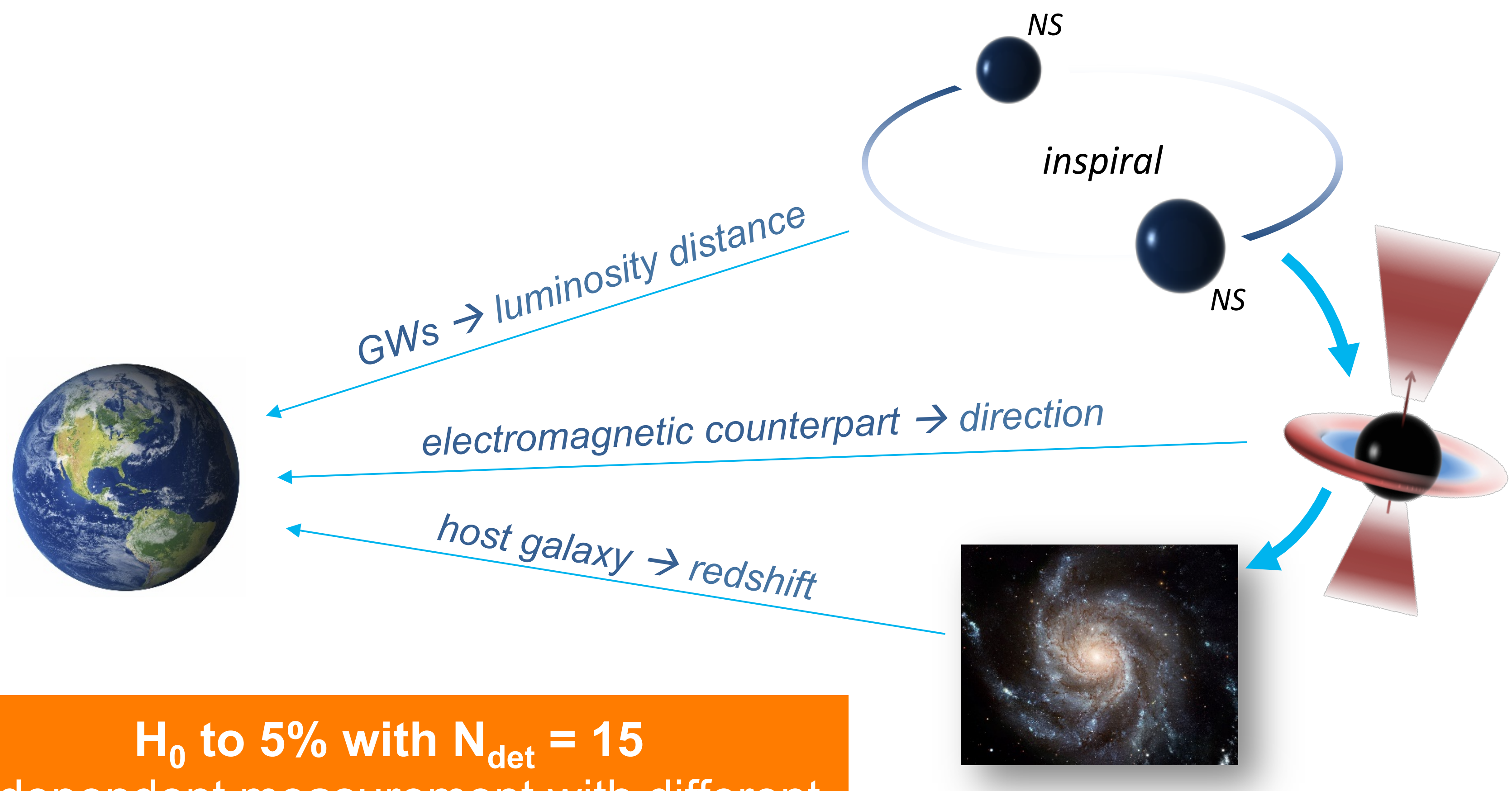
LIGO, Virgo, ANTARES, IceCube
Phys. Rev. D 93, 122010 (2016)

# Cosmology with GW Sources




Schulz Nature (1986)
D. Holz & s. Hughes ApJ (2005) 629
Nissanke+ 2010

# Cosmology with GW Sources



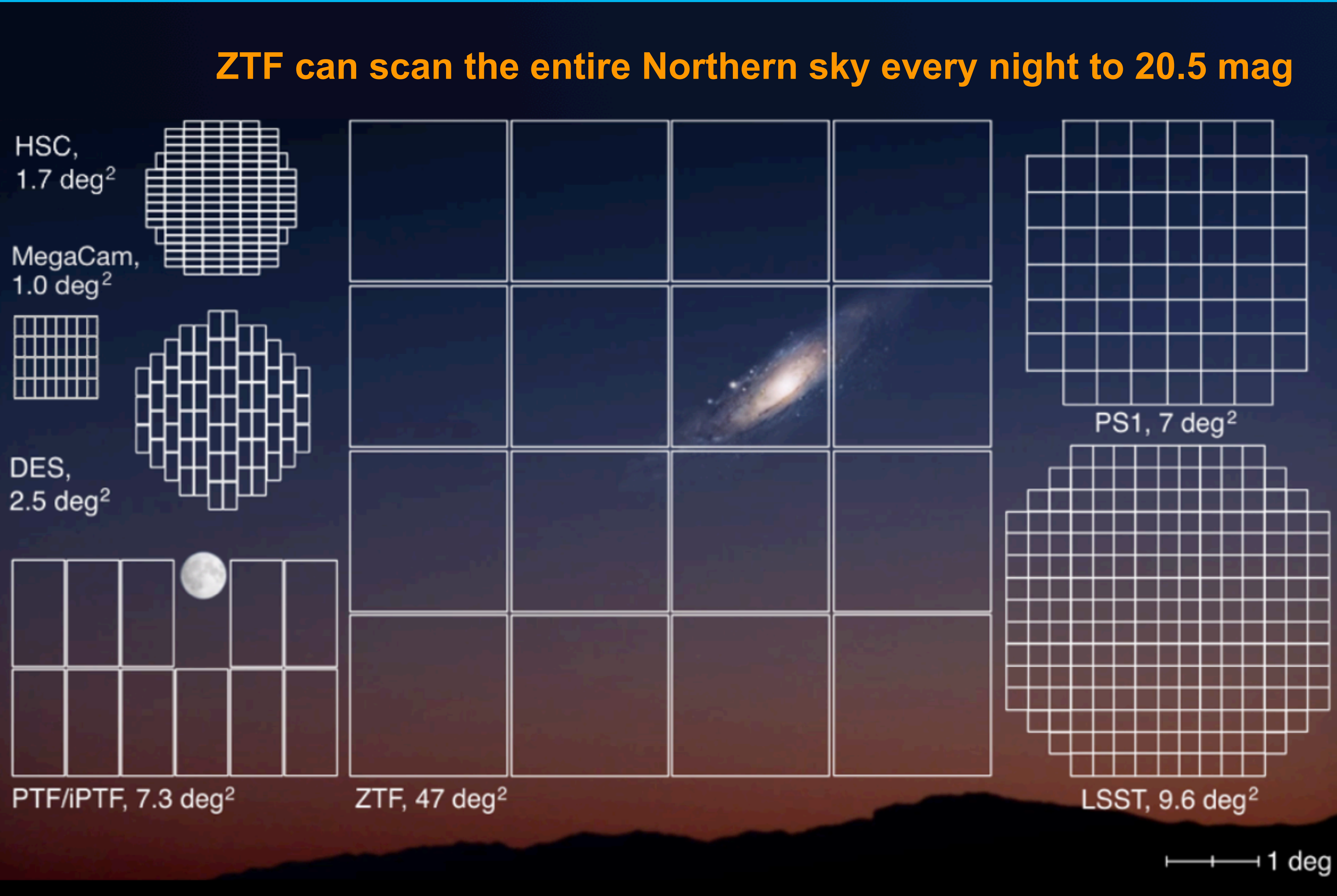

**$H_0$ to 5% with $N_{det}$ = 15**
Independent measurement with different systematics!

Schulz Nature (1986)
D. Holz & s. Hughes ApJ (2005) 629
Nissanke+ 2010

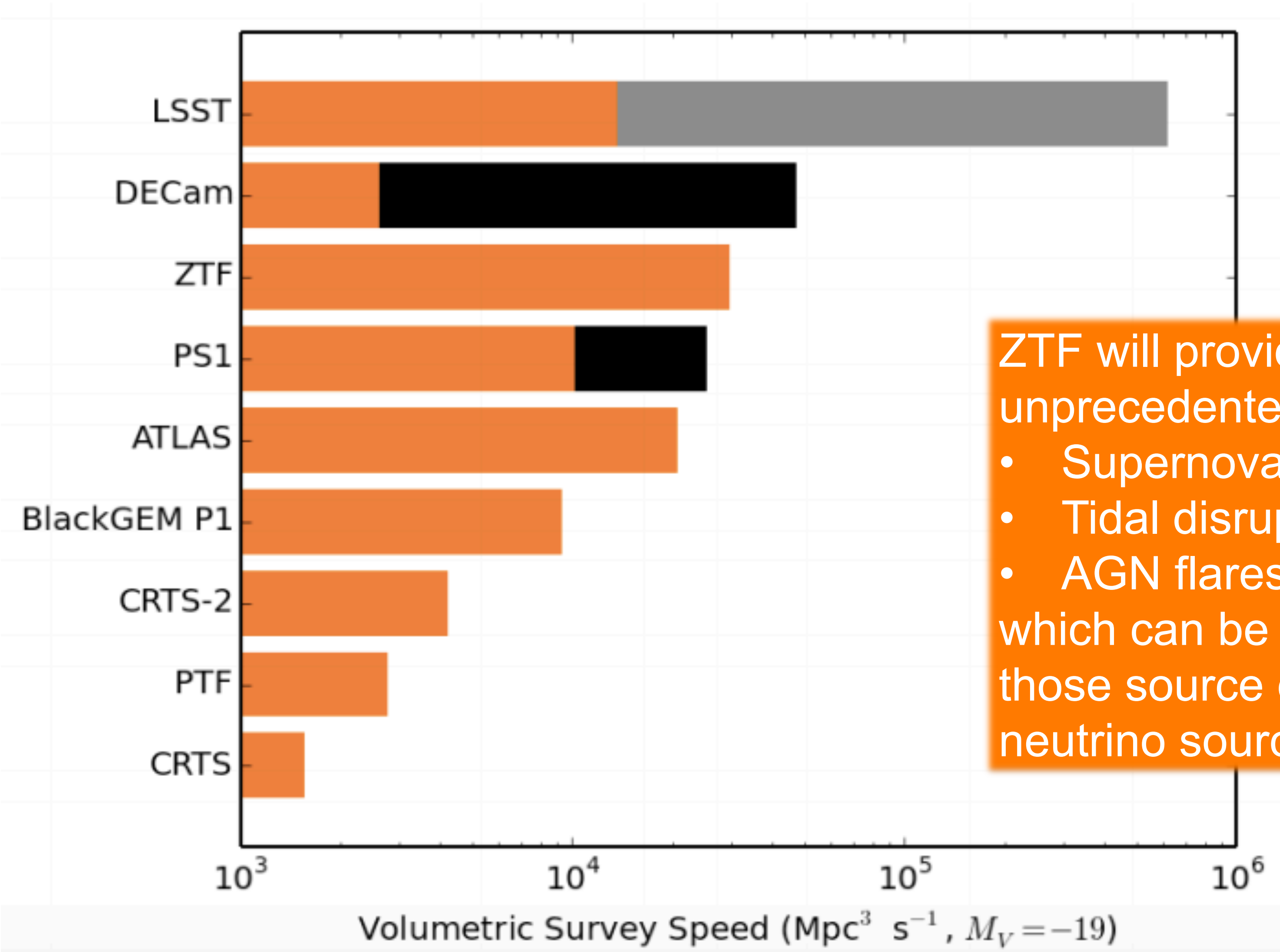
# Future Improvements

- Next generation of neutrino detectors (KM3Net, IceCube Gen2)
  - Larger volume
  - Better angular resolution
- Next generation GW detectors
  - Improved sensitivity
  - Better angular resolution
- New electro-magnetic surveys
  - Gamma-rays: CTA
  - X-rays: eROSITA
  - Radio: SKA
  - Optical: ZTF, LSST

# Optical Surveys



# ZTF will reach world-leading speed in finding spectroscopically-accessible transients

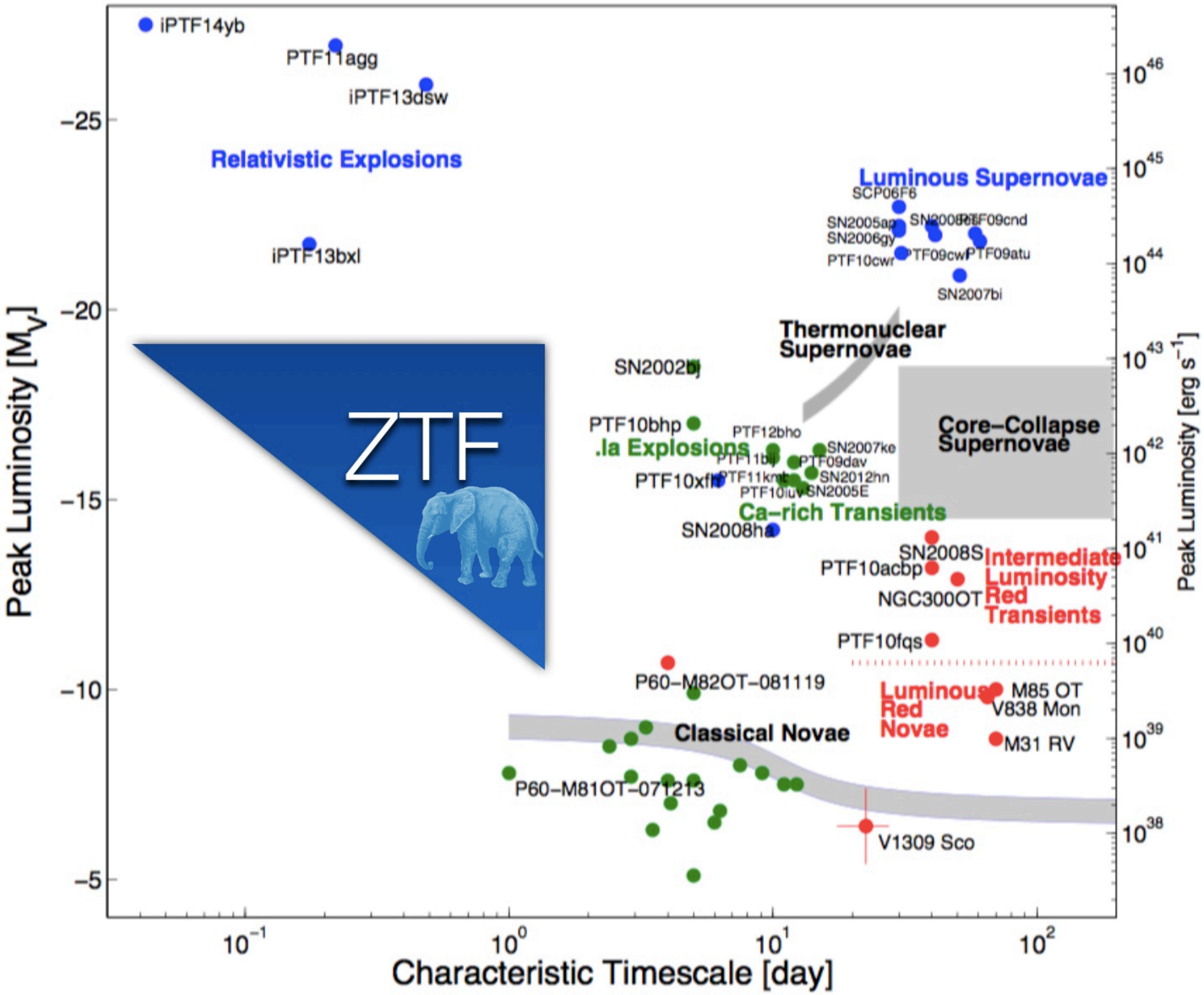



ZTF will provide an unprecedented catalog of

- Supernova
- Tidal disruption events
- AGN flares

which can be used to probe those source classes as neutrino sources

# New Transients will be Accessible



# Summary

- Neutrinos and GW are two unique new messengers from the high-energy Universe
- Neutrino sources still unknown
  - Multimessenger observations have been used to exclude / disfavor some source candidates
  - Others extensively studied
- GW sources are known
  - Multimessenger observations could teach us about host environment
  - Future applications to cosmology
- More data and new instruments to come

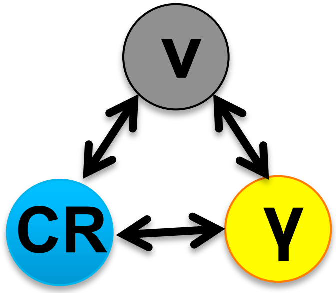

Stay tuned!

# 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)

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

# Neutrino Production Processes

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

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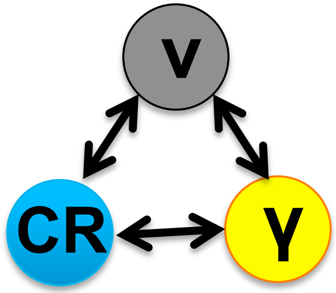


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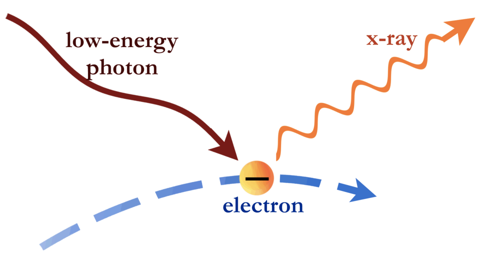
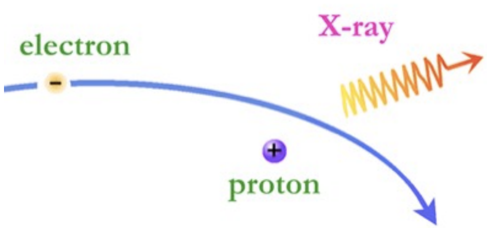
## Gamma-rays are not exclusively produced in hadronic processes



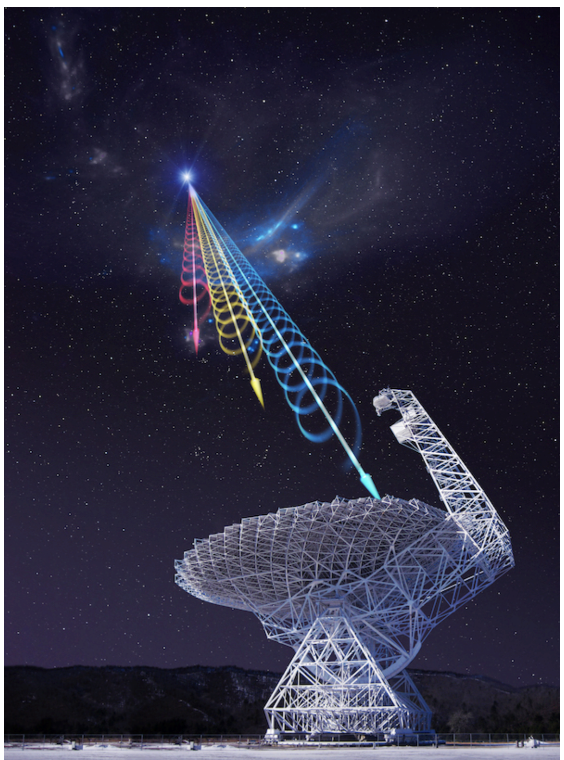



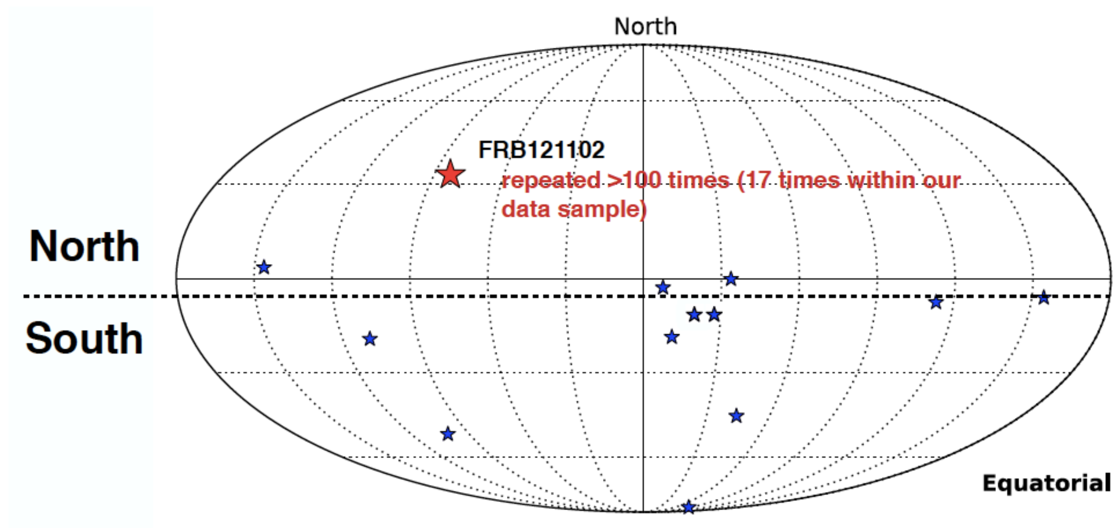
# Fast Radio Bursts

Many possible models: some are possible neutrino sources (e.g. magnetar/SGR hyperflares)

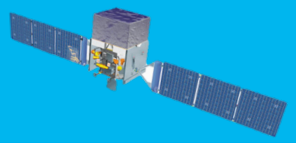
S. B. Popov and K. A. Postnov, arXiv1307.4924
Halzen *et al.*(2005) asto-ph/0503348

**No excess found from 29 bursts (13 unique locations)**
25 time windows tested: 10 ms, 20 ms, 40 ms, … , 0.97 days, 1.94 days

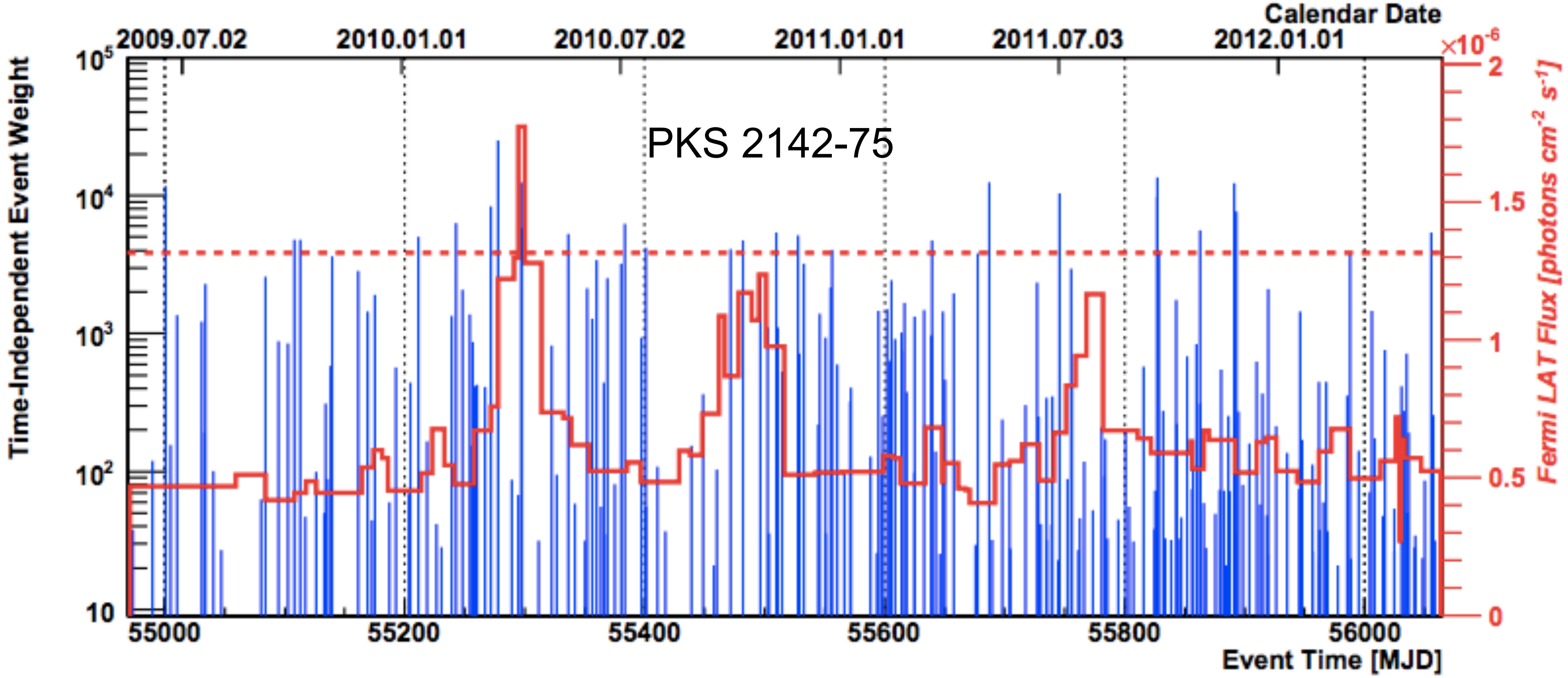




# Using Full Blazar Light Curves



- Search for neutrinos correlated with GeV gamma-ray emission
- Denoised Fermi-LAT light curves as input time PDF




**No correlation found in 3 years of IceCube data and ~50 variable gamma-ray sources**

IceCube Coll. ApJ 807 (2015) 46

# First HESE/EHE Alerts

| Date | Type | RA | Dec | 50% Error |
|---|---|---|---|---|
| 2016/04/27 | HESE | 240.6° | 9.3° | 0.6° |
| 2016/07/31 | EHE + HESE | 214.5° | -0.3° | 0.35° |
| 2016/08/06 | EHE | 122.8° | -0.7° | 0.11° |
| 2016/08/14 | HESE | 200.3° | -32.4° | 0.48° |
| 2016/11/03 | HESE | 40.8° | 12.6° | 0.42° |
| 2016/12/10 | EHE | 46.6° | 15.0° | 0.3° |
| 2017/03/03 | HESE | 305.2° | -26.6° | 0.5° |
| 2017/03/21 | EHE | 98.3.1° | -14.5° | 0.3° |
| 2017/05/06 | HESE | 221.8° | -26.0° | 1.2° |

Alerts sent publicly via GCN through AMON

# First HESE/EHE Alerts

| Date | Type | RA | Dec | 50% Error |
|---|---|---|---|---|
| 2016/04/27 | HESE | 240.6° | 9.3° | 0.6° |
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| 2016/11/03 | HESE | 40.8° | 12.6° | 0.42° |
| 2016/12/10 | EHE | 46.6° | 15.0° | 0.3° |
| 2017/03/03 | HESE | 305.2° | -26.6° | 0.5° |
| 2017/03/21 | EHE | 98.3.1° | -1 | |
| 2017/05/06 | HESE | 221.8° | -2 | |

Alerts sent publicly via GCN through AMON

**optical**

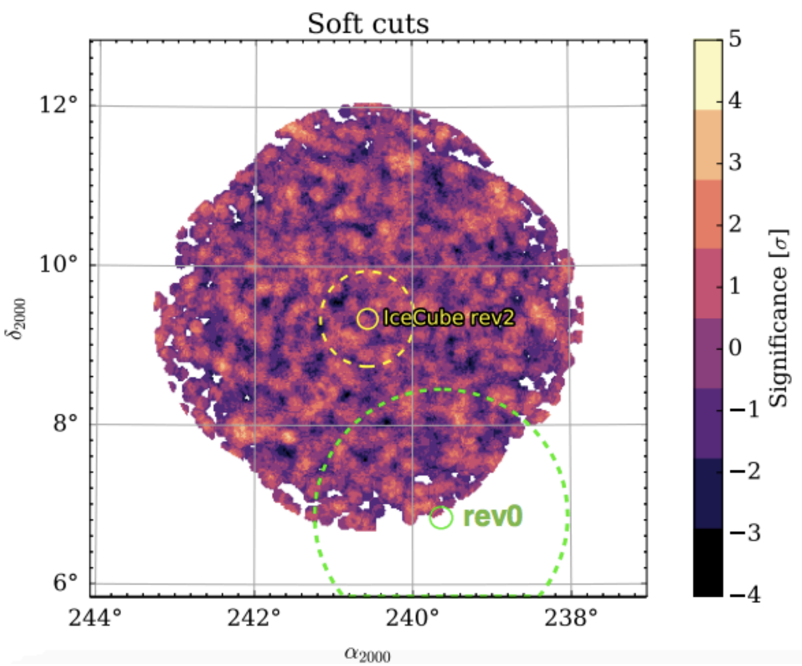
| Telescope | Results |
|---|---|
| iPTF | 3 transients, all AGN |
| MASTER | No detection |
| Pan-STARRS | 7 SN candidates |

**gamma-rays**

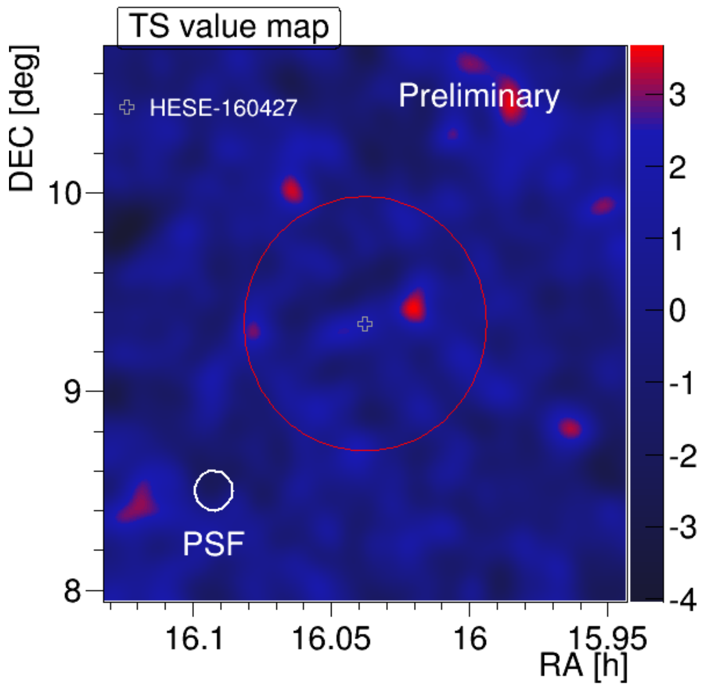
| Telescope | Results |
|---|---|
| IPN | No detection |
| Fermi-LAT | 5 unrelated blazars |
| Fermi-GBM | No detection |
| FACT | No detection |
| VERITAS | No detection |
| HAWC | No detection |
| MAGIC | No detection |

# Gamma-Ray Follow-Up of Public Alerts

- All operating Cherenkov Telescopes observed
  - H.E.S.S.: automatic follow-up in < 2min
  - VERITAS: automatic follow-up in 112 sec
  - FACT
  - MAGIC



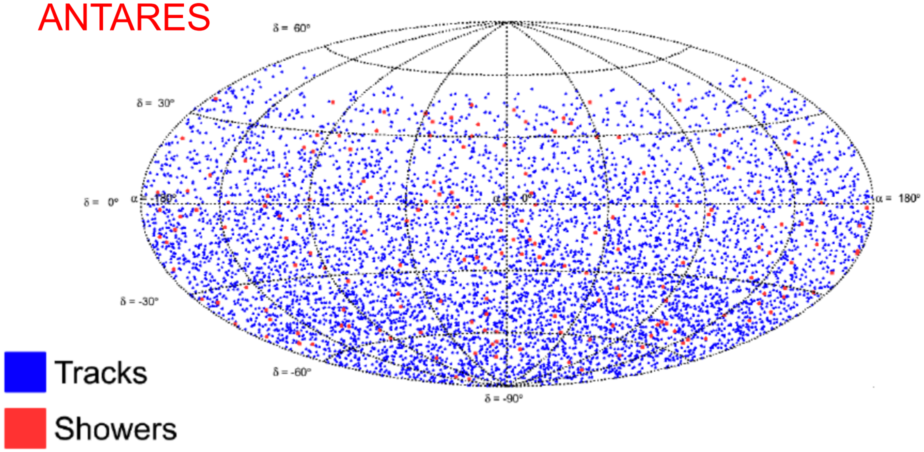

M. Santander for the VERITAS Coll., ICHEP 2016



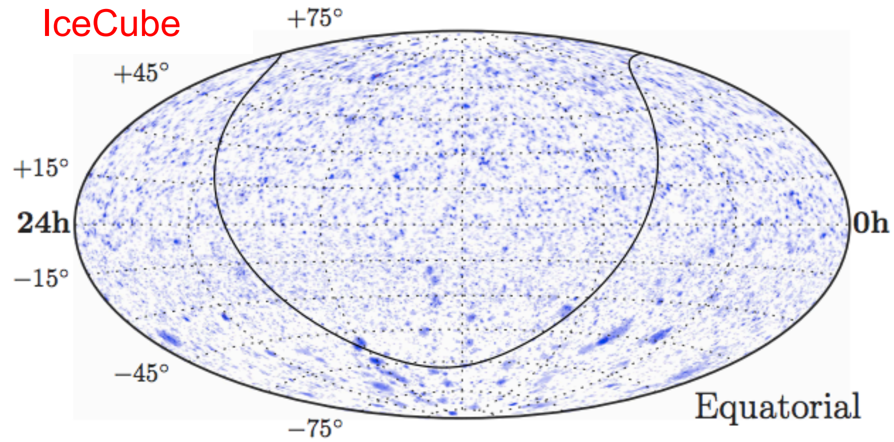

D. Gora et al. for the MAGIC Coll., Neutrino 2016

DESY

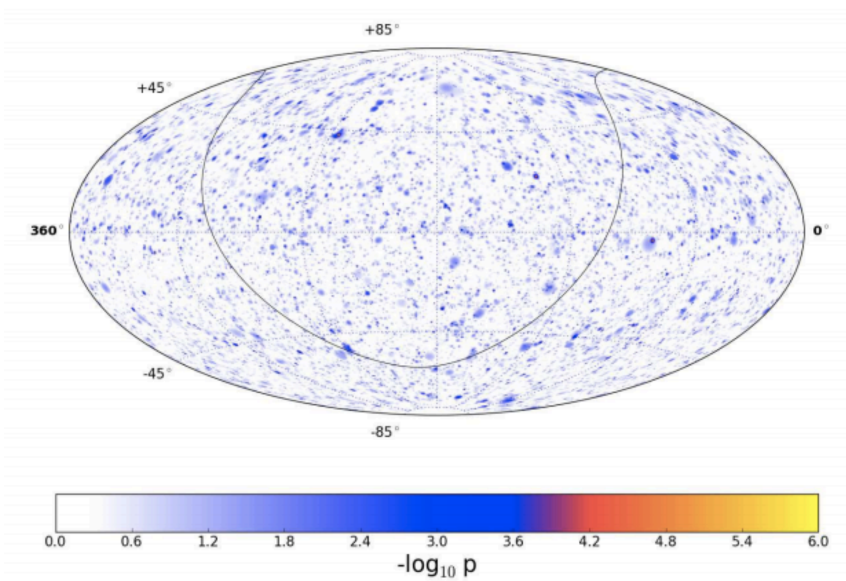
# Search for Neutrino Clusters in Space and Time




ANTARES ApJ 786 (2014)



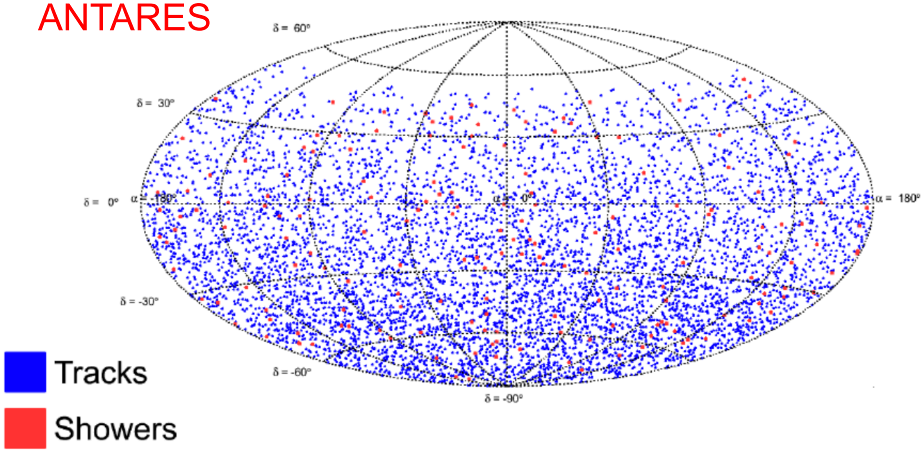

IceCube ApJ 835 (2017)




IceCube ApJ 807 (2015)

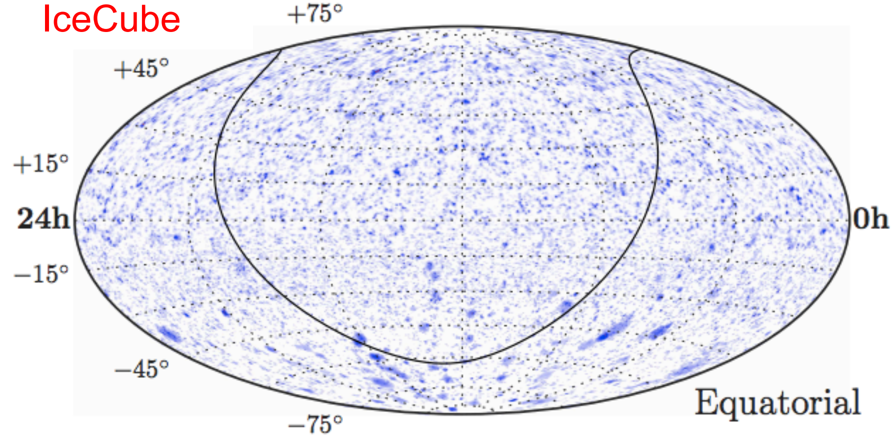
# Search for Neutrino Clusters in Space and Time

ANTARES



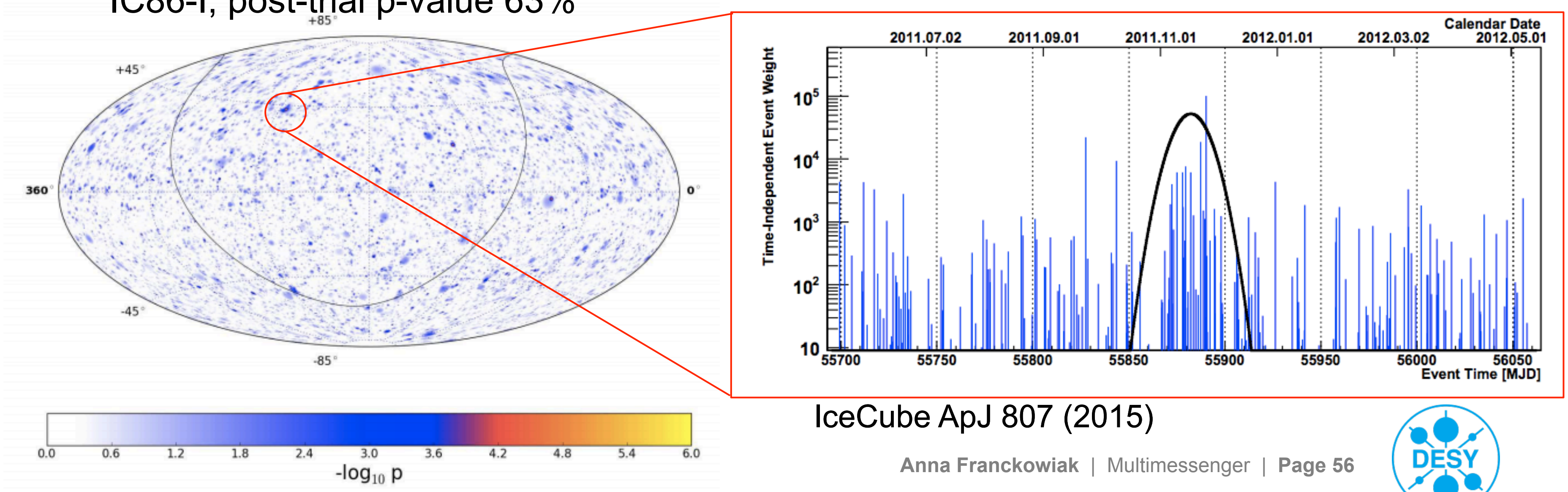

ANTARES ApJ 786 (2014)

IceCube

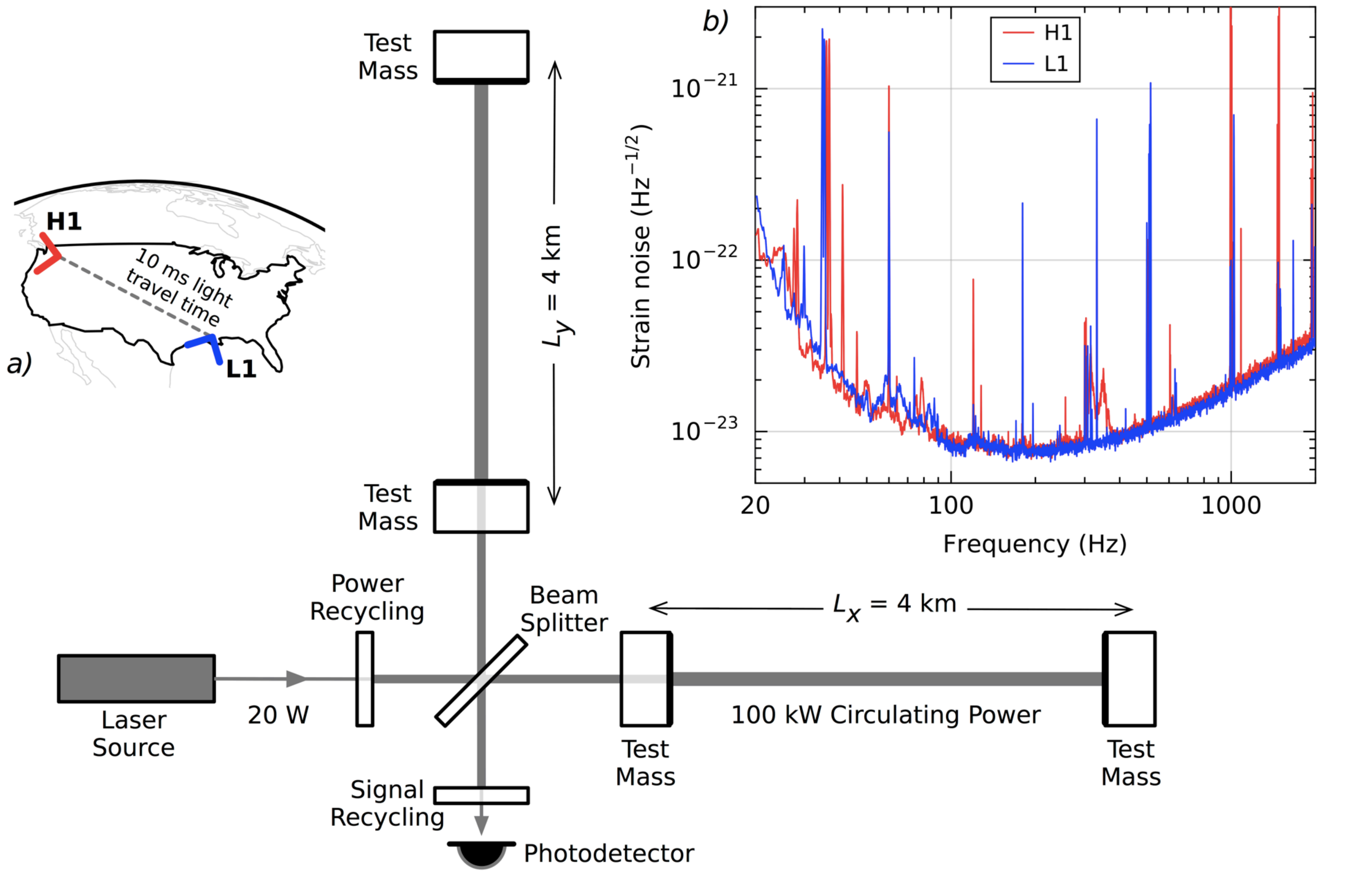



IceCube ApJ 835 (2017)

IC86-I, post-trial p-value 63%

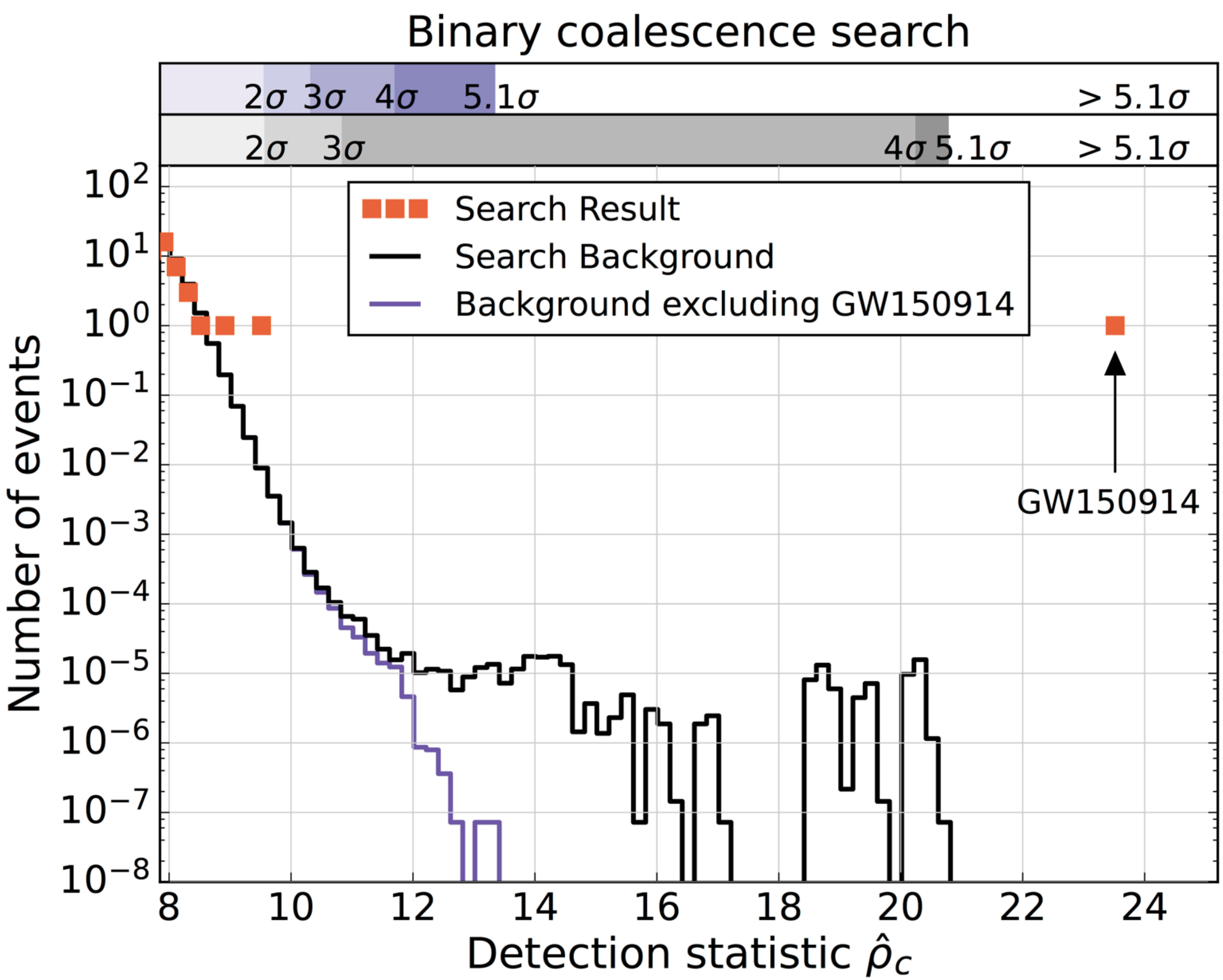



IceCube ApJ 807 (2015)



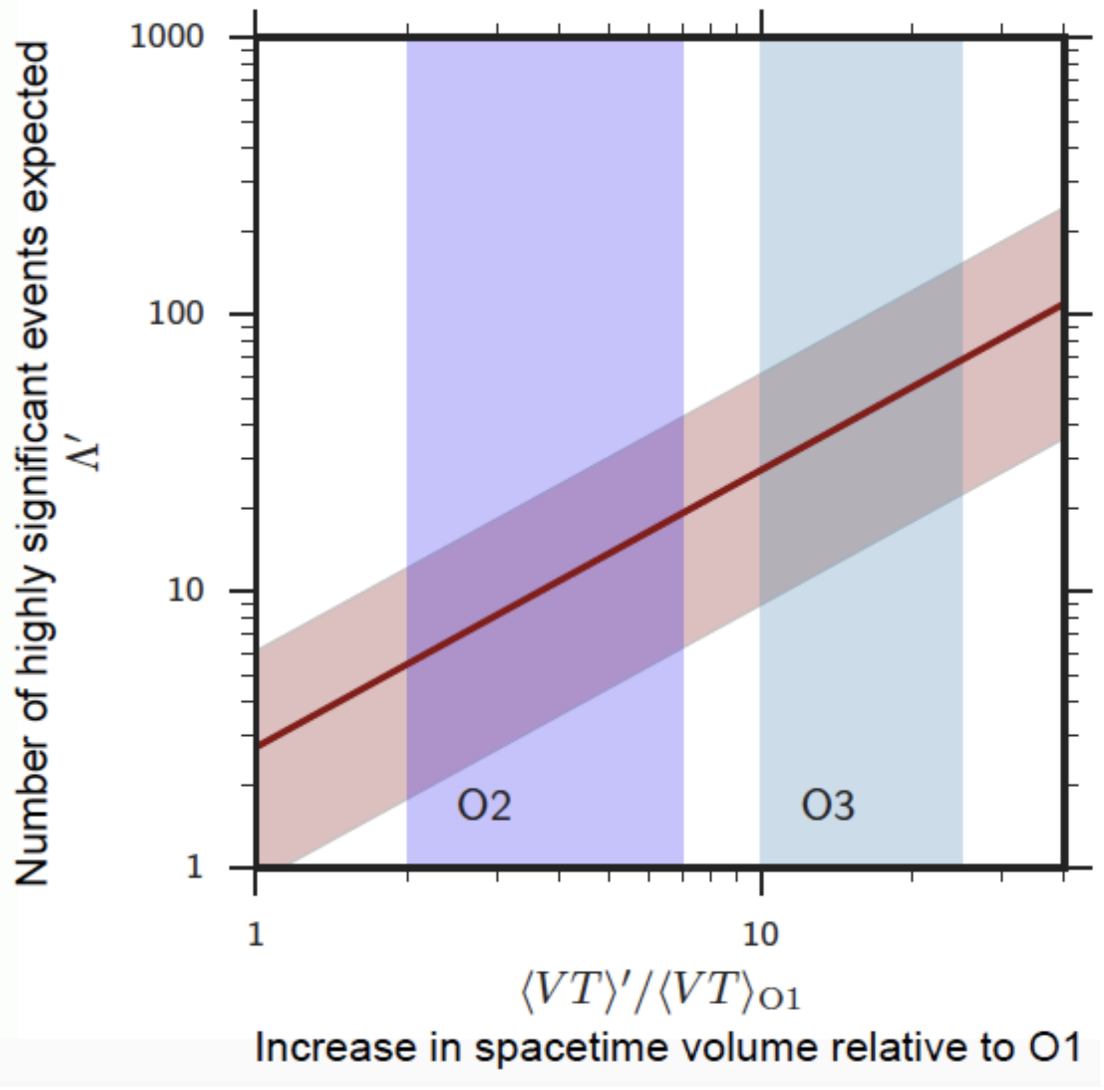
H1
10 ms light travel time
L1
a)
Test Mass
$L_y$ = 4 km
Test Mass
Power Recycling
Beam Splitter
$L_x$ = 4 km
Laser Source
20 W
Test Mass
100 kW Circulating Power
Test Mass
Signal Recycling
Photodetector
b)
H1
L1
Strain noise (Hz$^{-1/2}$)
$10^{-21}$
$10^{-22}$
$10^{-23}$
20
100
1000
Frequency (Hz)

# Gravitational Wave Events in First Observing Run




Abbott et al. (LIGO, Virgo Coll.), PRL (2016) 116, 061102

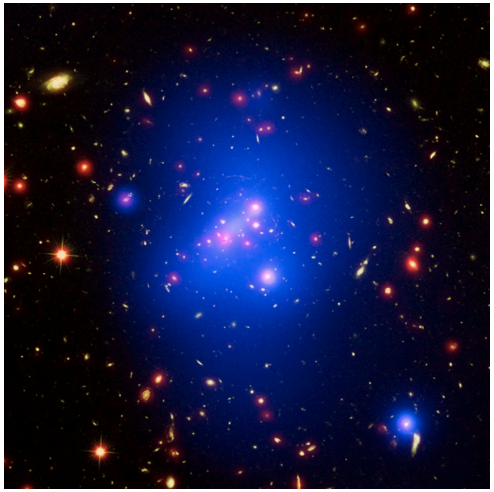
# Expected Number of GW Events



# Extra-Galactic Neutrino Sources

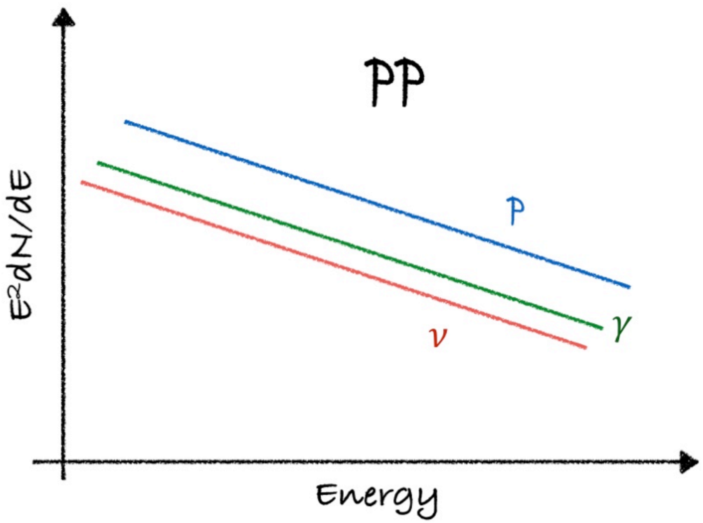
- Star forming galaxies

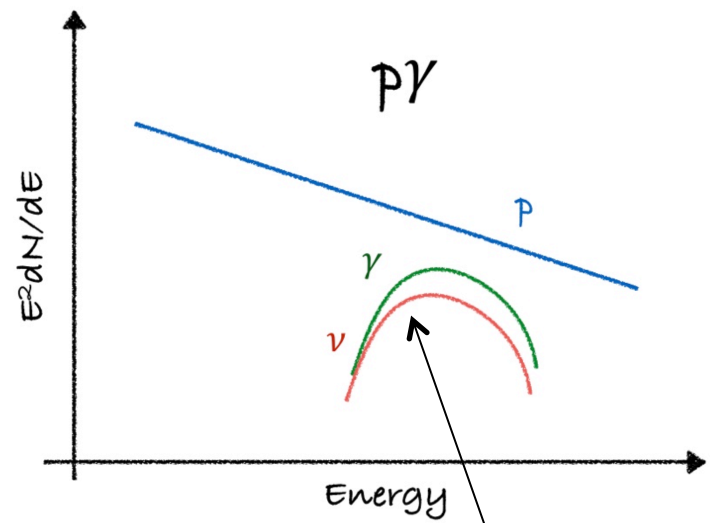
- Galaxy clusters



# Neutrino Production Processes

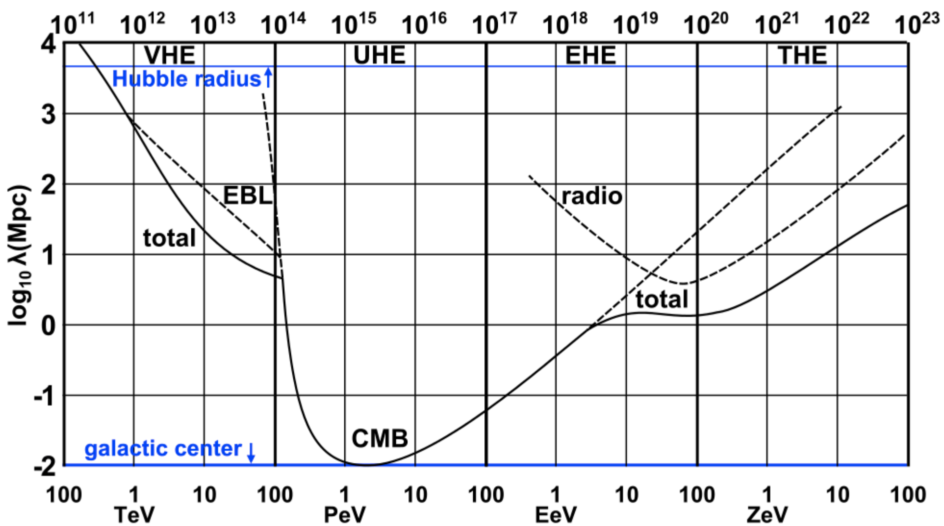
At the source



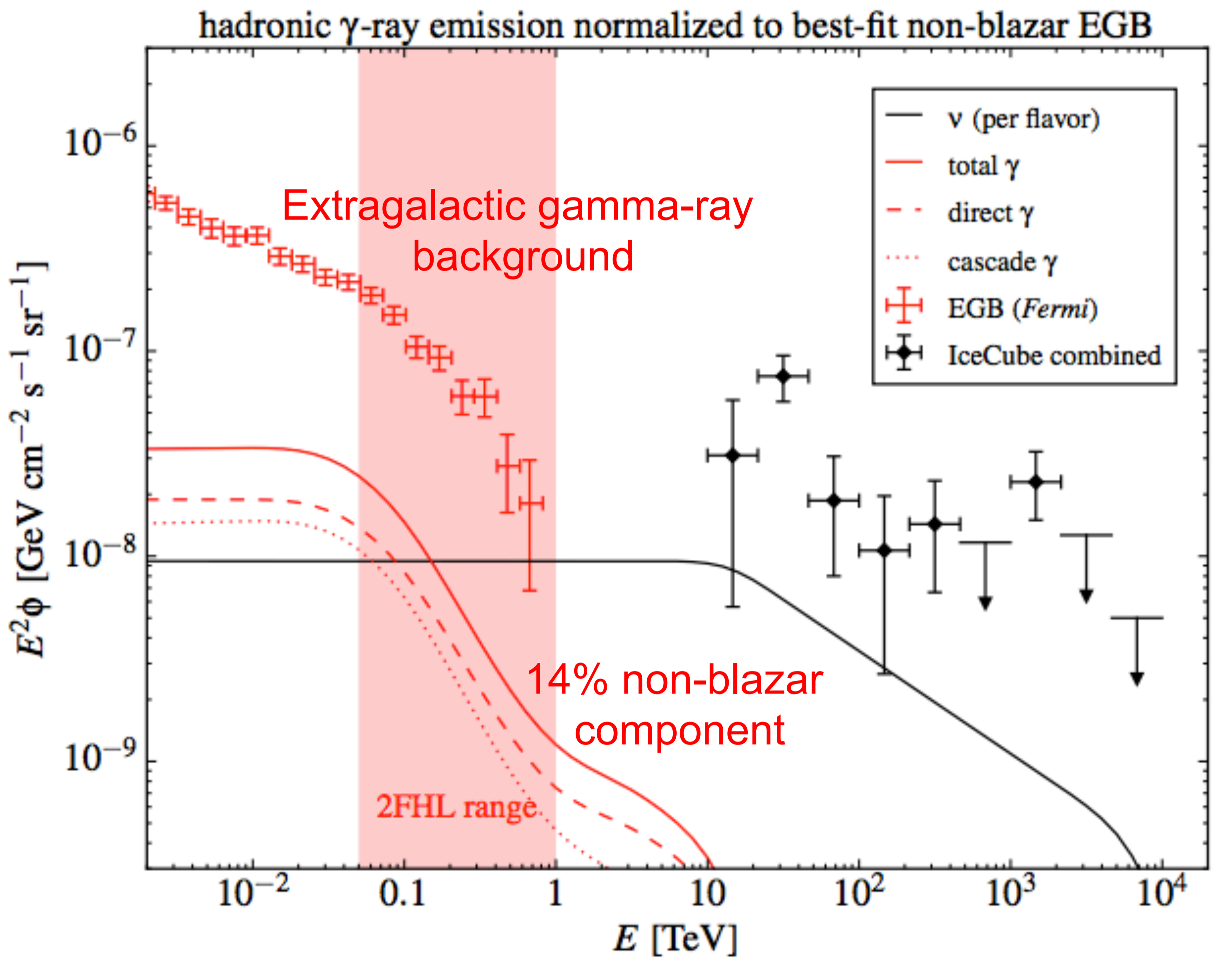




Peak position depends on photon field

High-energy photons will cascade down



# Gamma-ray background disfavors pp Neutrino Sources



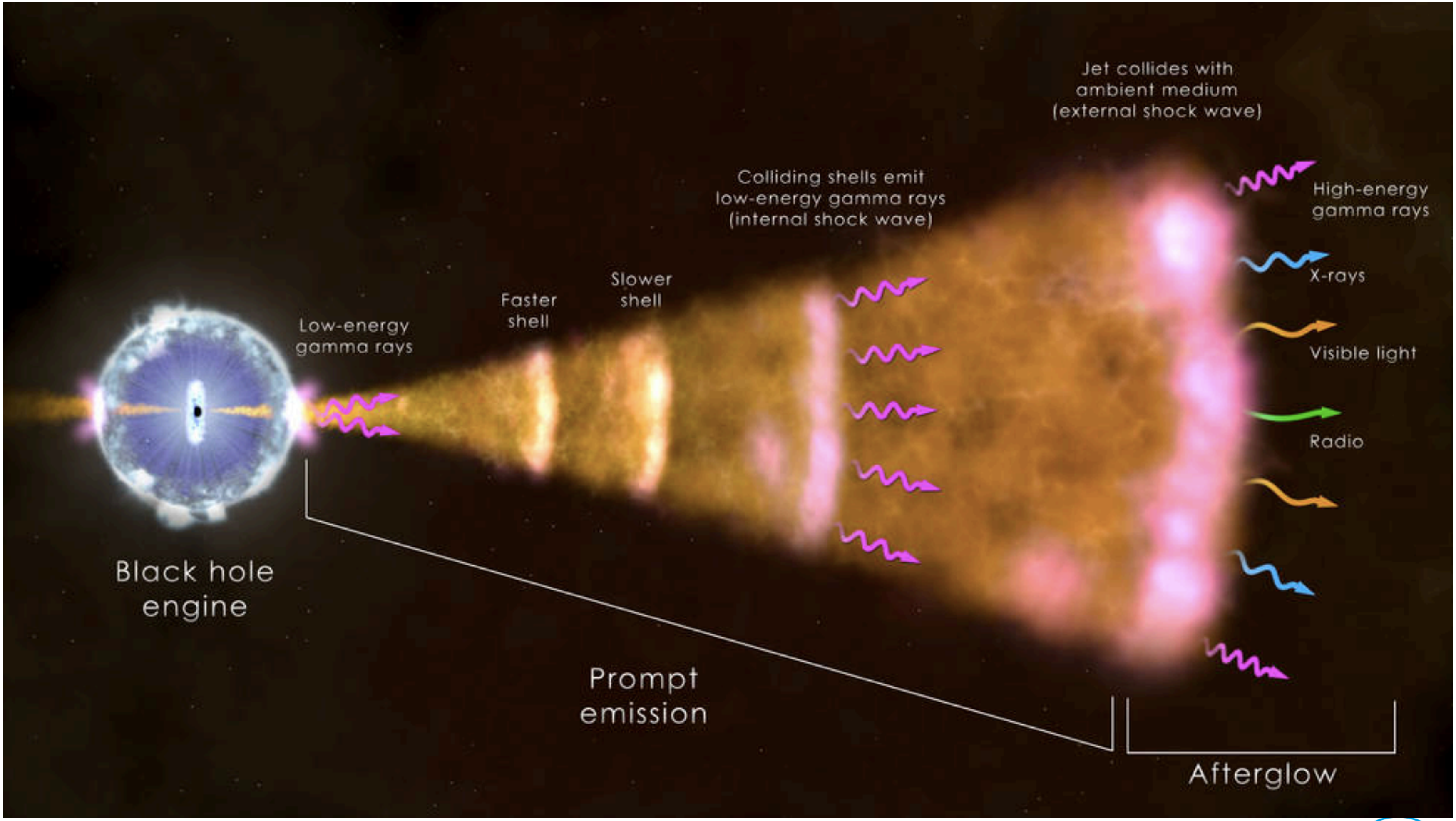

**Starburst galaxies and galaxy clusters contribute less than 30% to the diffuse neutrino flux**

In the future Fermi-LAT will improve measurement of EGB and resolve more source → better constraints

Bechtol et al. arXiv:1511.00688

# Gamma-Ray Bursts (GRBs)

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

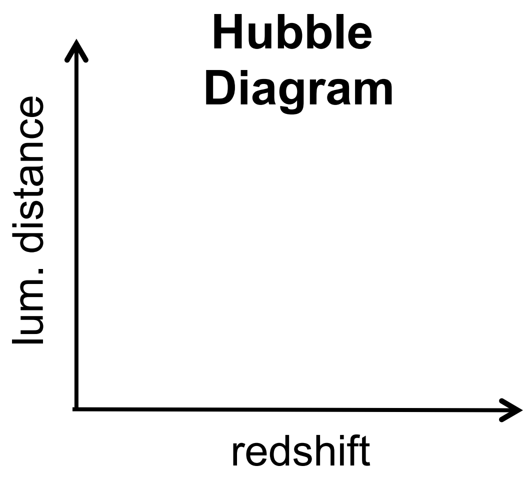


# Cosmology with GW Sources

> "Standard candle"
- Type Ia supernova
- equal intrinsic luminosity → luminosity distance

> "Standard siren"
- GW signal delivers luminosity distance
- Counterpart identification could deliver redshift

> Independent measurement with different systematics!




D. Holz & s. Hughes ApJ (2005) 629