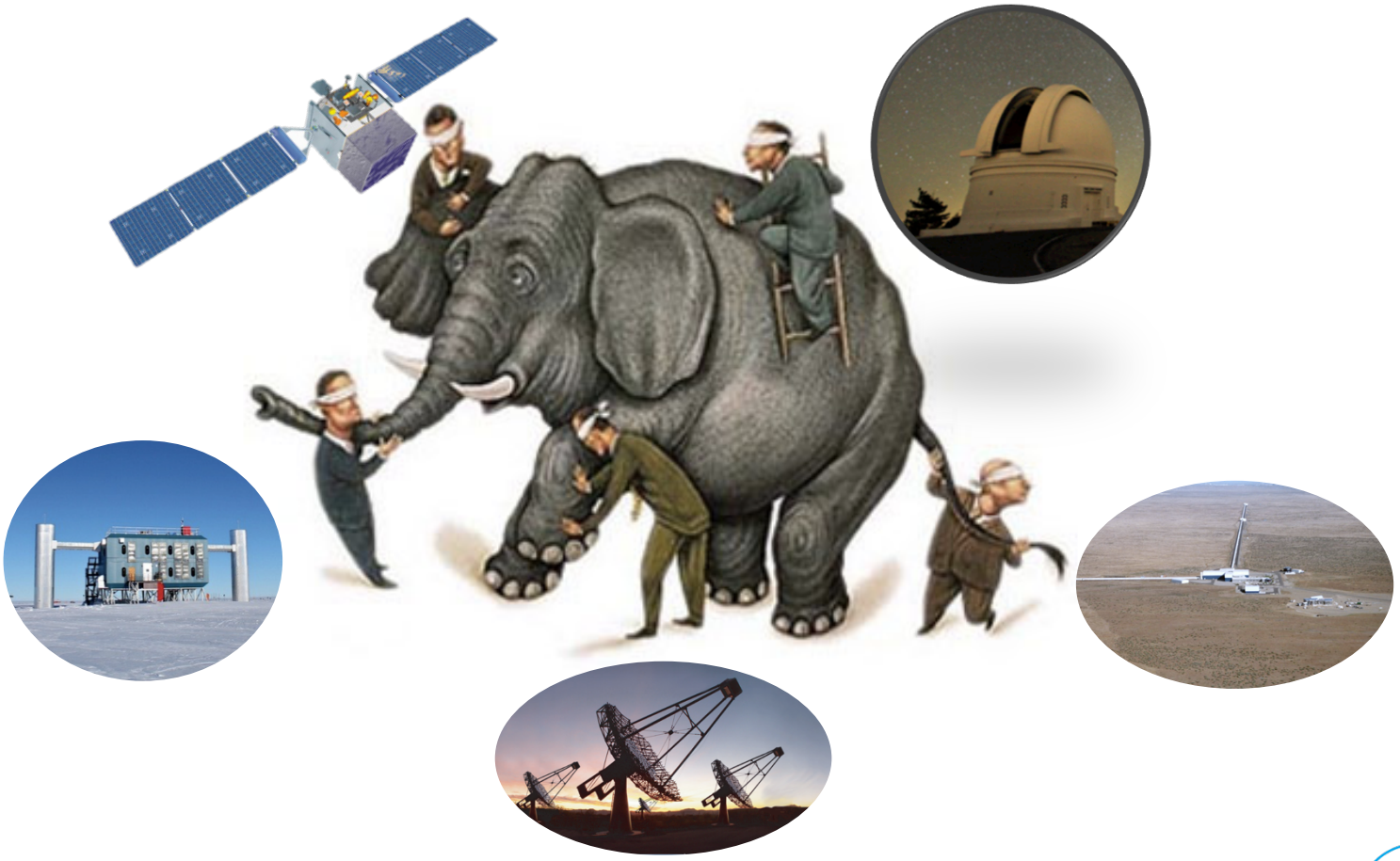
Multimessenger Astrophysics

Anna Franckowiak
29th Rencontres de Blois
June 2, 2017

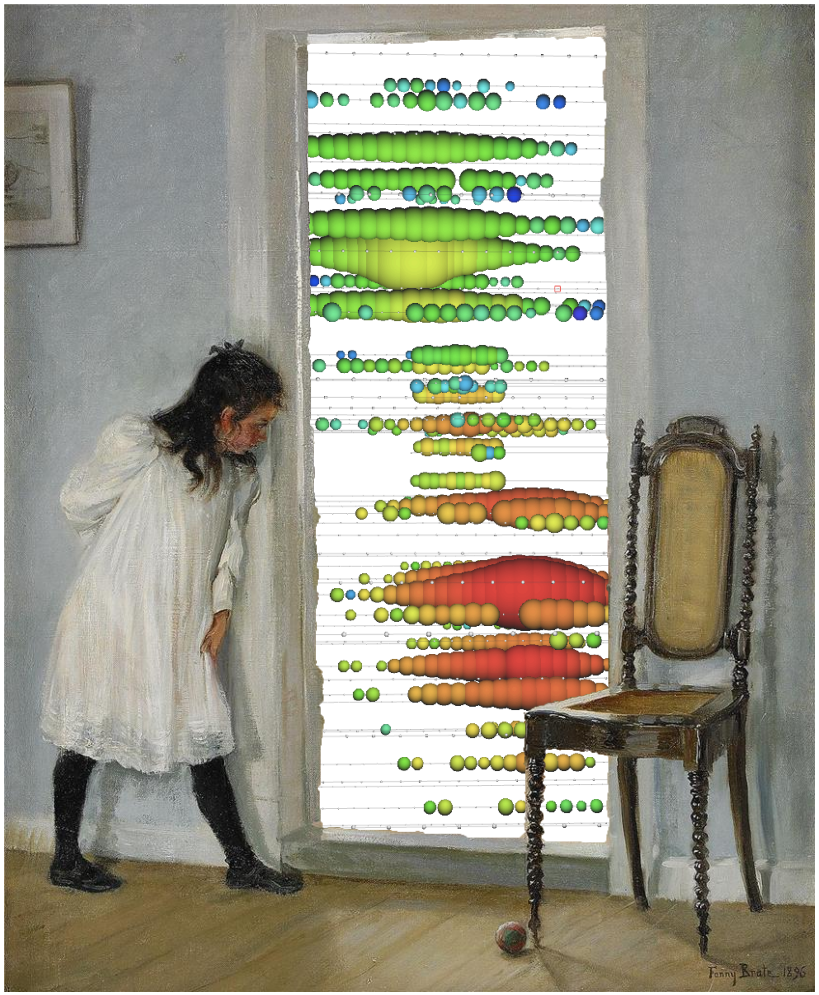
HELMHOLTZ ASSOCIATION

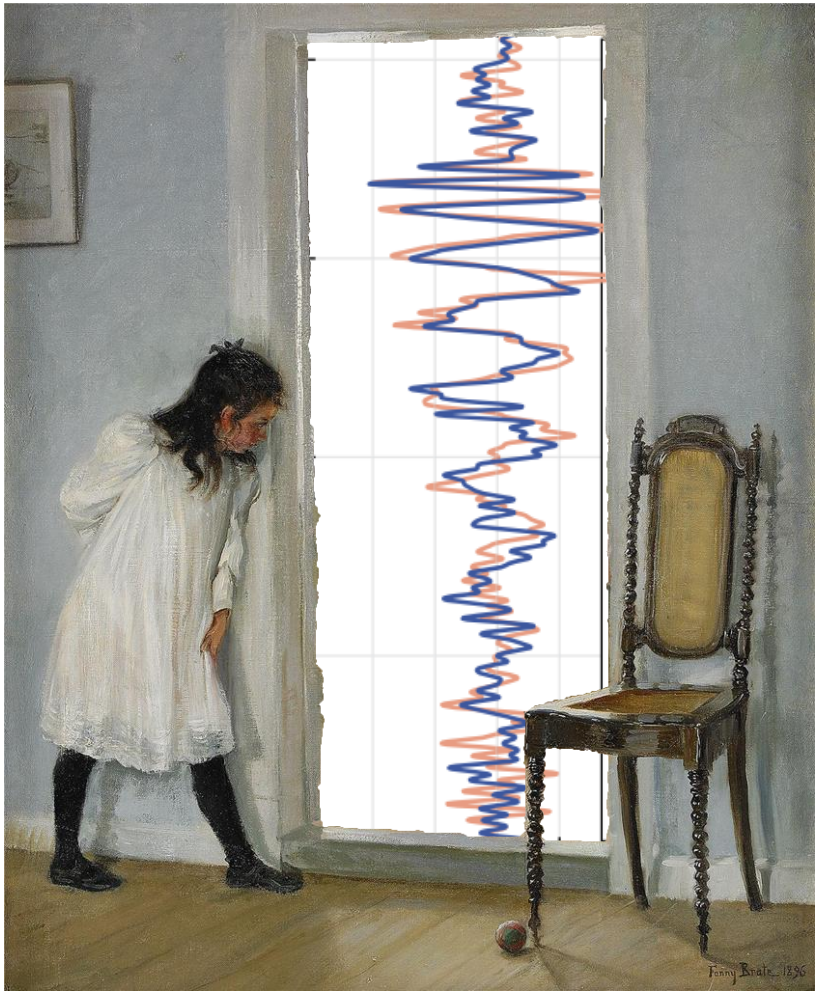
DESY

The High-Energy Universe

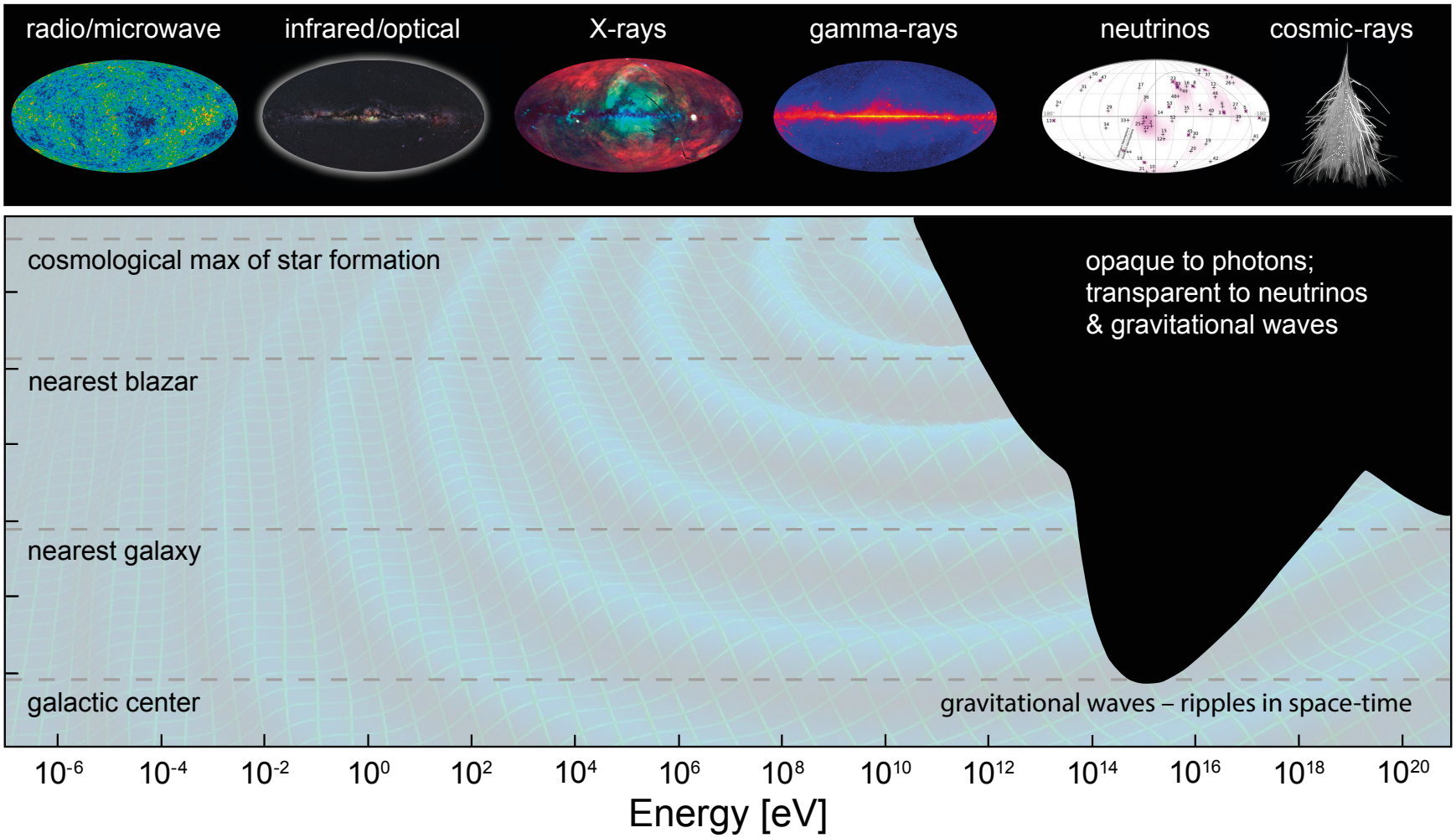


Two New Windows to the Universe

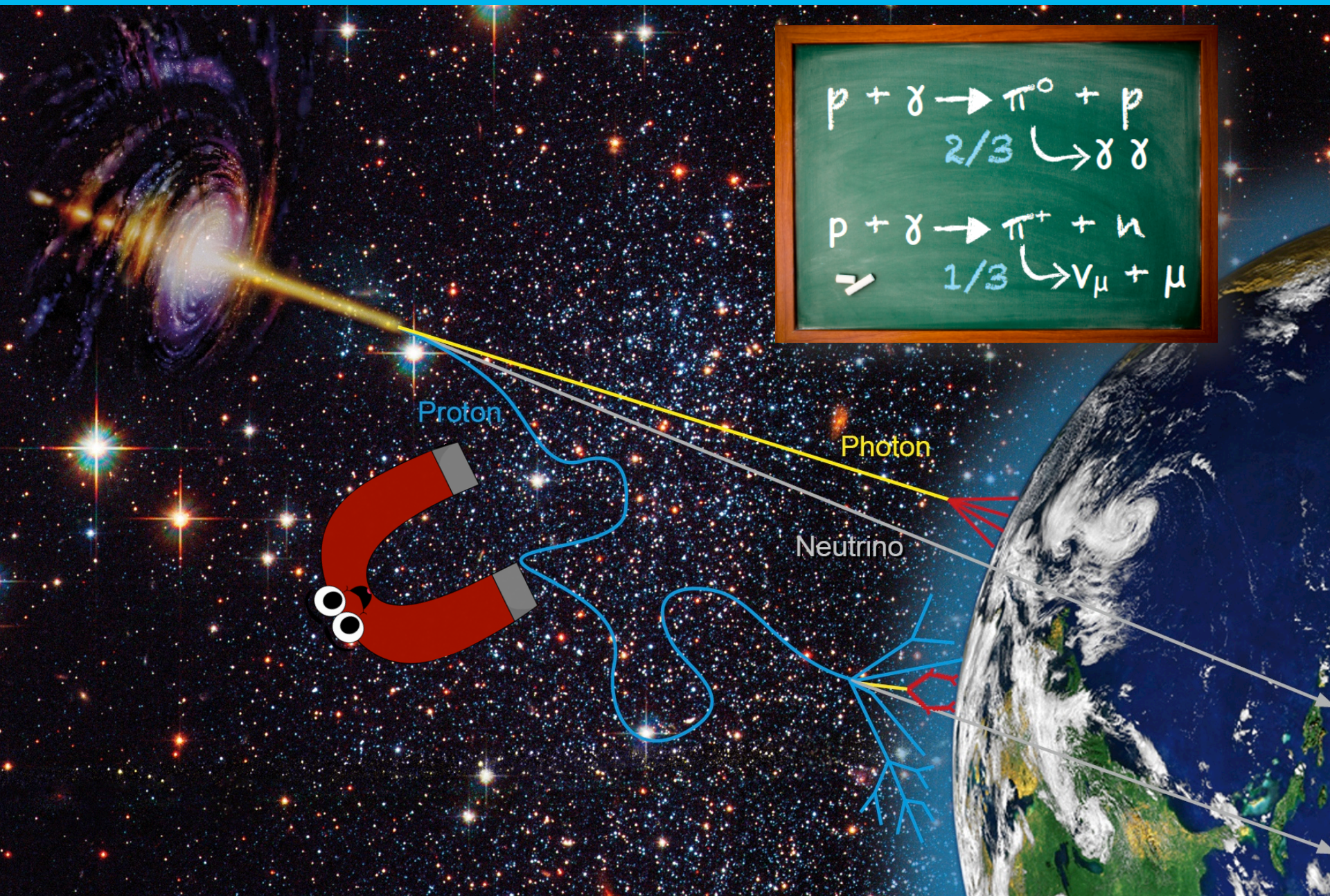




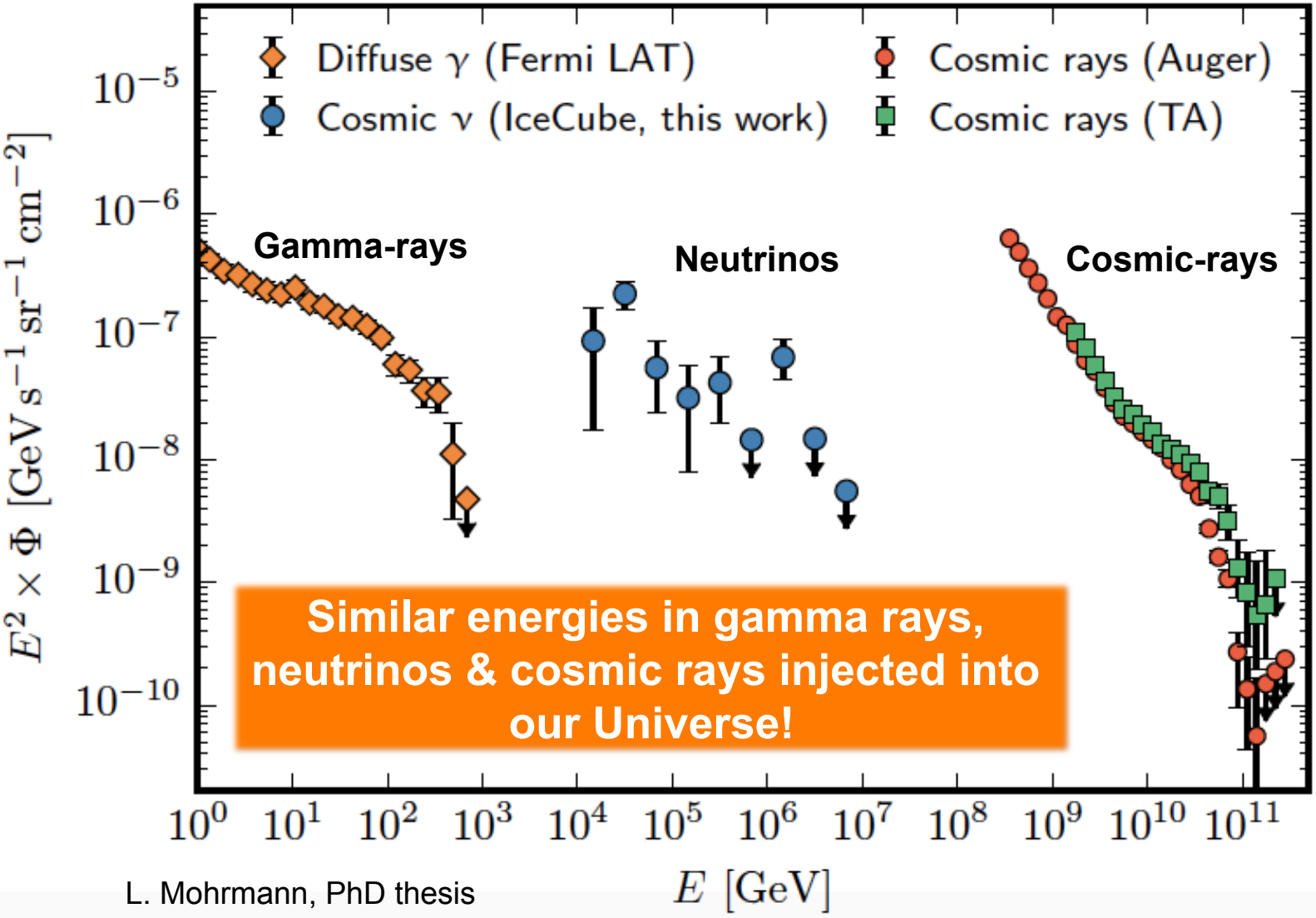
Where Can We Look?



What are the Cosmic-Ray Sources?

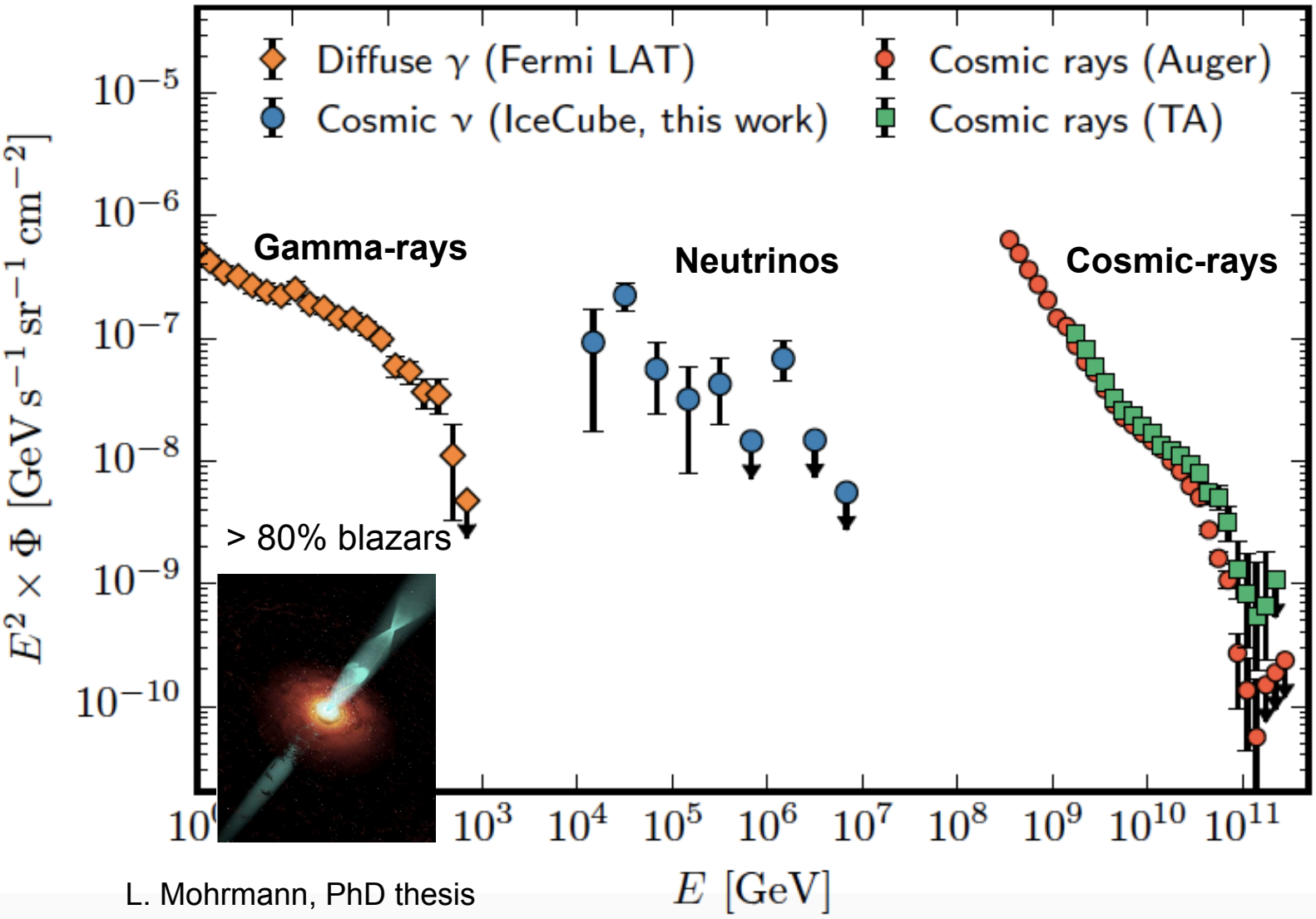


The High-Energy Universe



L. Mohrmann, PhD thesis

The High-Energy Universe

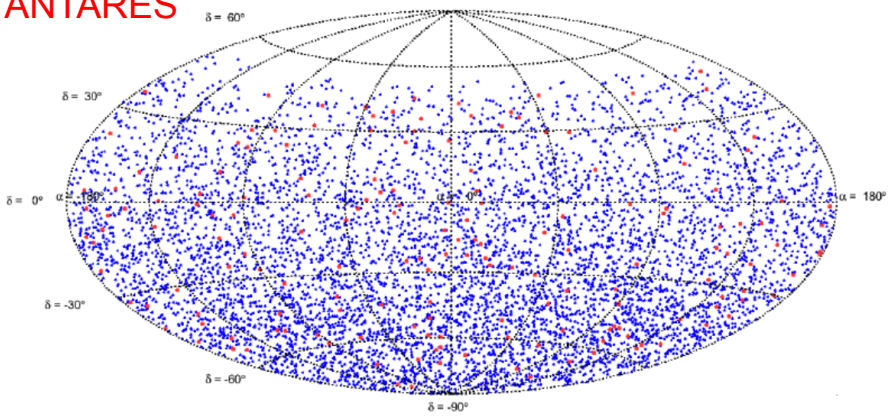


L. Mohrmann, PhD thesis

Search for Neutrino Clusters in Space

ANTARES

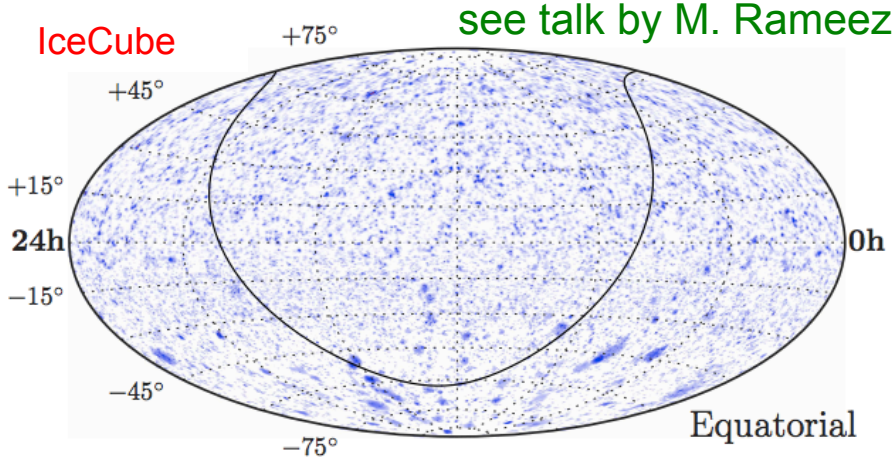
see talk by S. Navas



ANTARES ApJ 786 (2014)

IceCube

see talk by M. Rameez



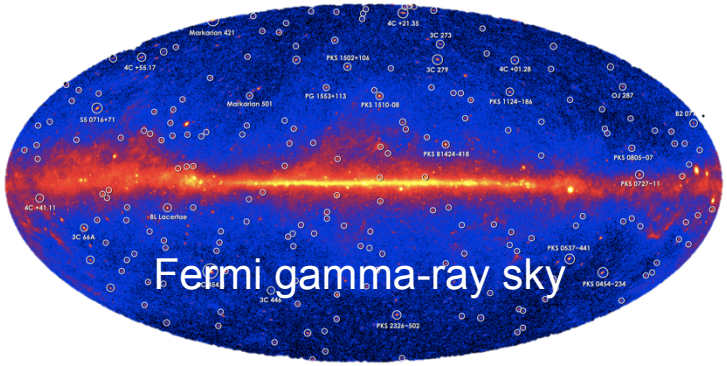
IceCube ApJ 835 (2017)

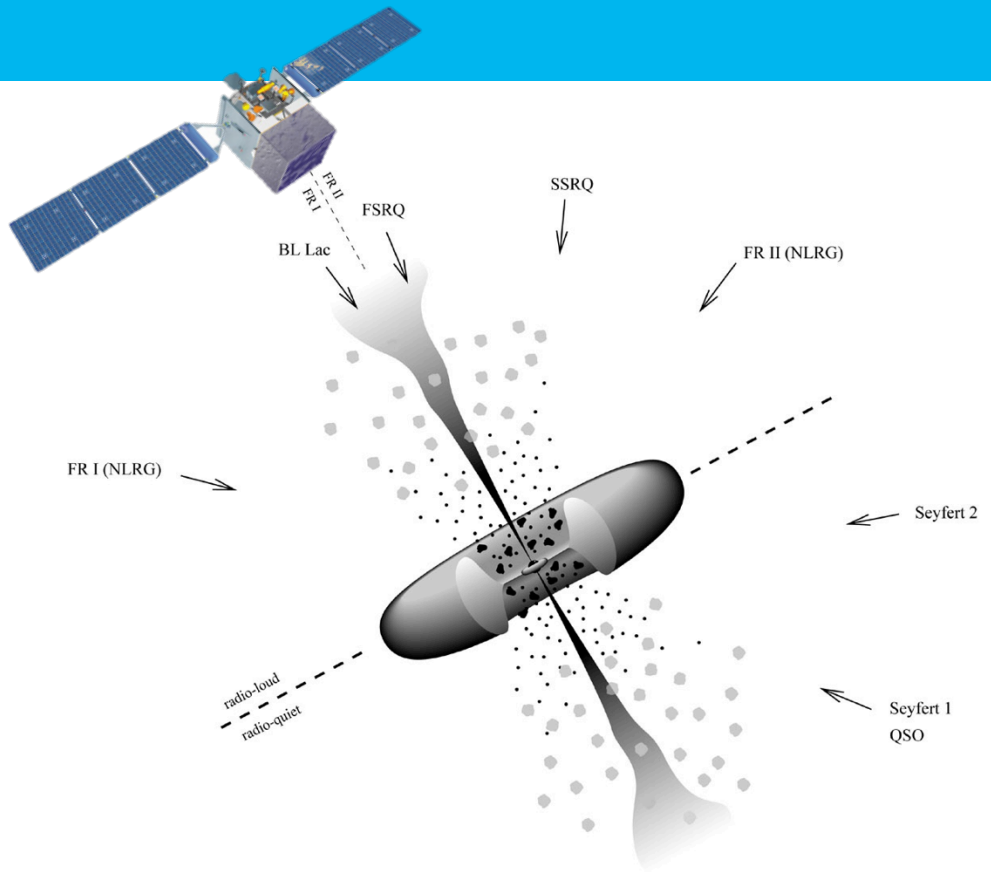
Large trials factor → Multiwavelength data can tell us where and when to look for neutrinos

DESY

Blazars

- Gamma rays tell us WHERE





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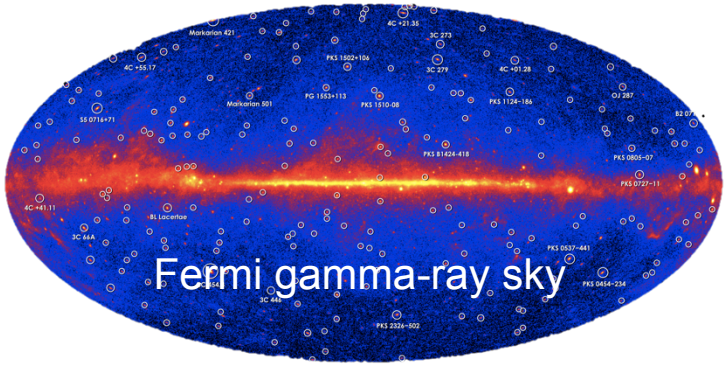
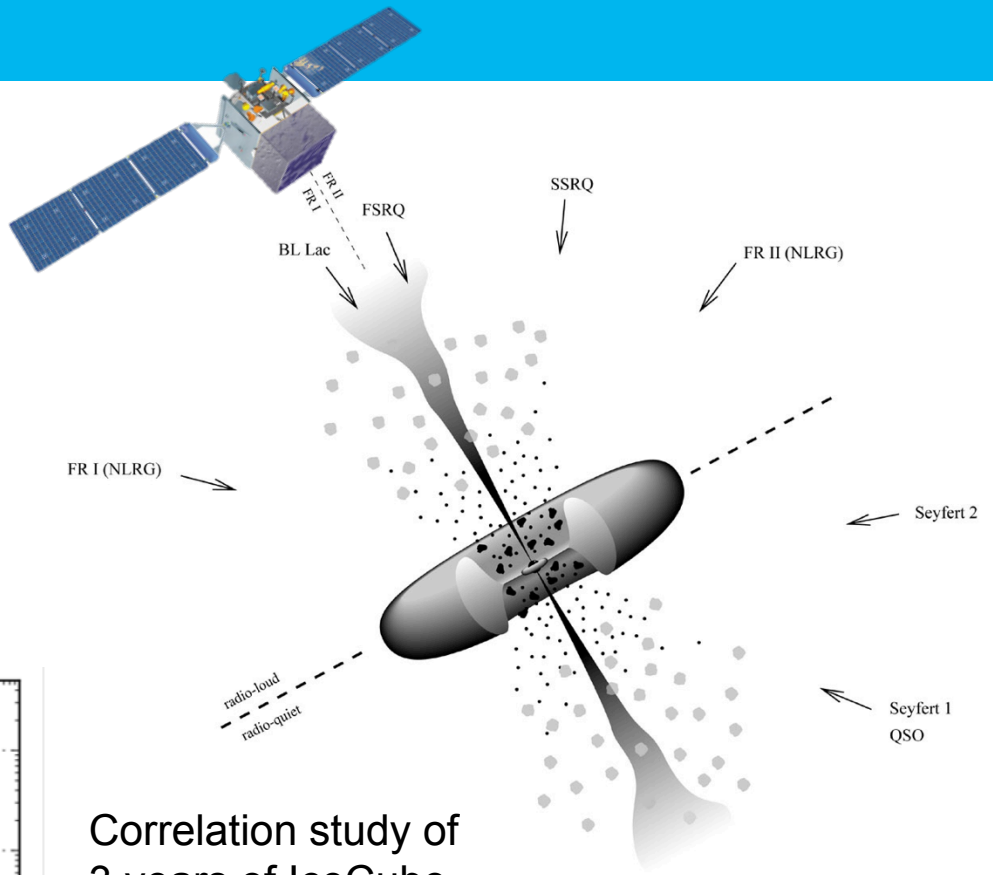
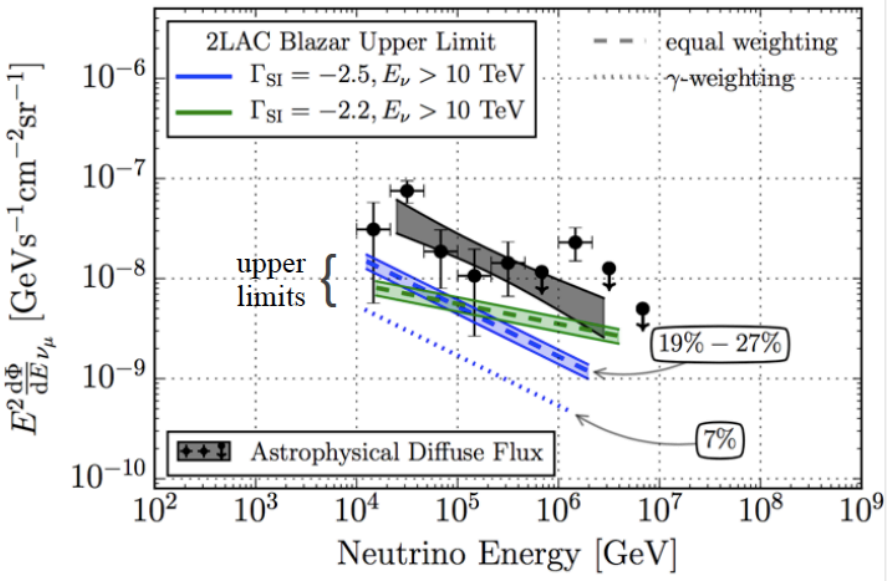






Correlation study of 3 years of IceCube data and 862 Fermi-LAT blazars

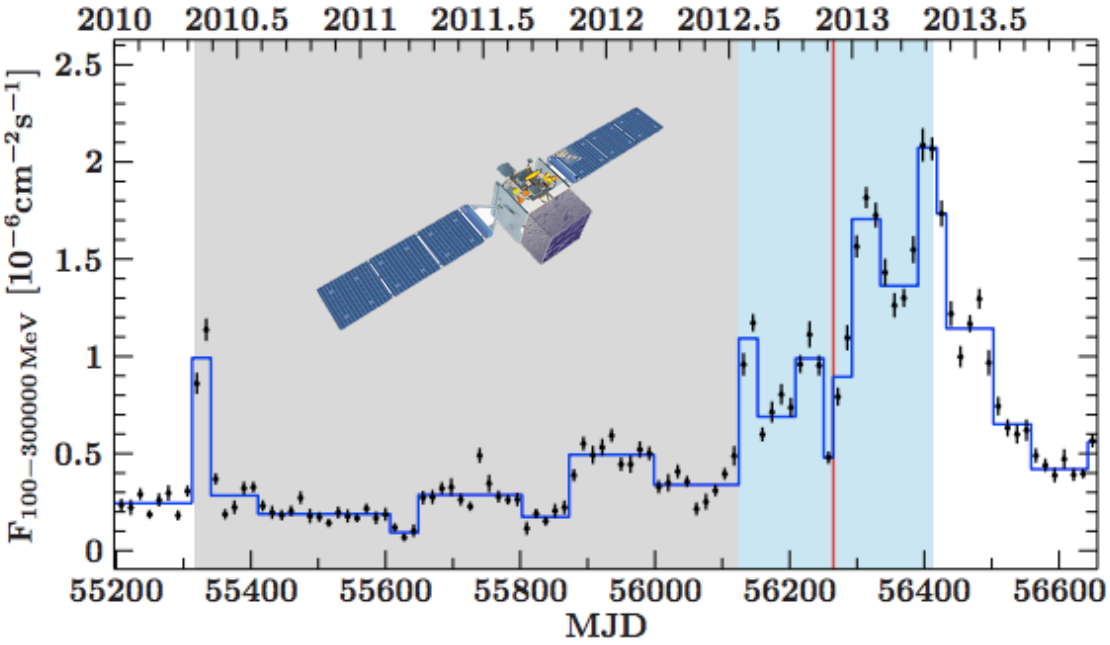
Blazars contribute less than 30% to the diffuse neutrino flux

IceCube Coll., ApJ 835, 2017

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 PeV neutrino
- 5% chance coincidence

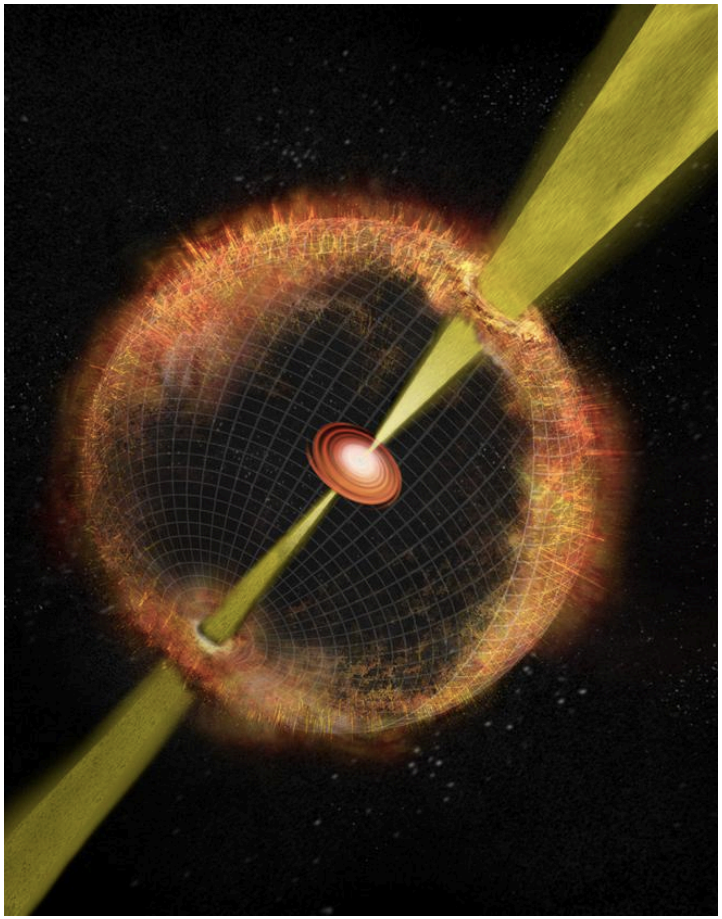


Kadler et al., Nature Physics, 2016

DESY

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



1172 GRBs correlated with IceCube data

563 GRBs correlated with ANTARES data

IceCube arXiv:1702.06868
ANTARES Eur.Phys.J. C77 (2017) no.1, 20

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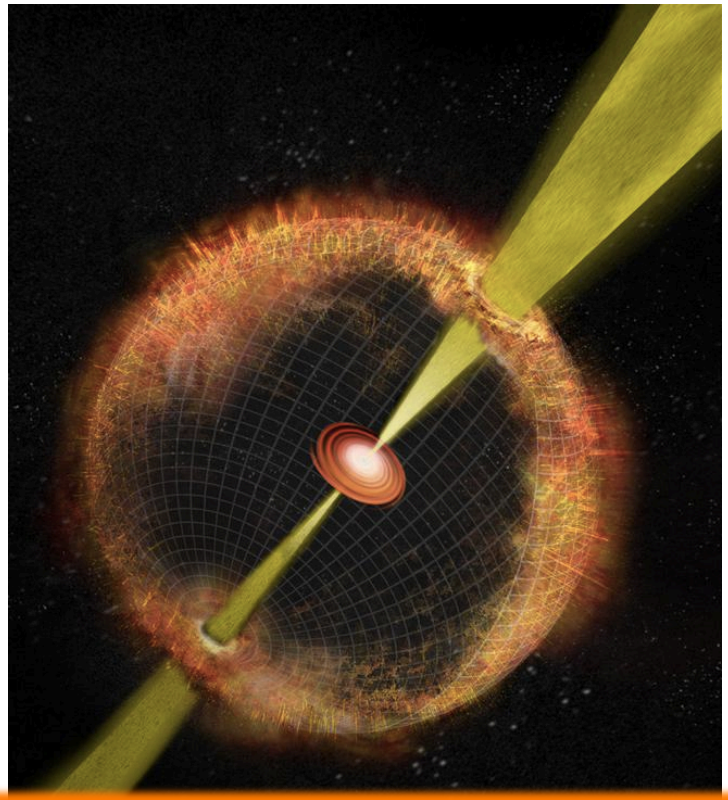


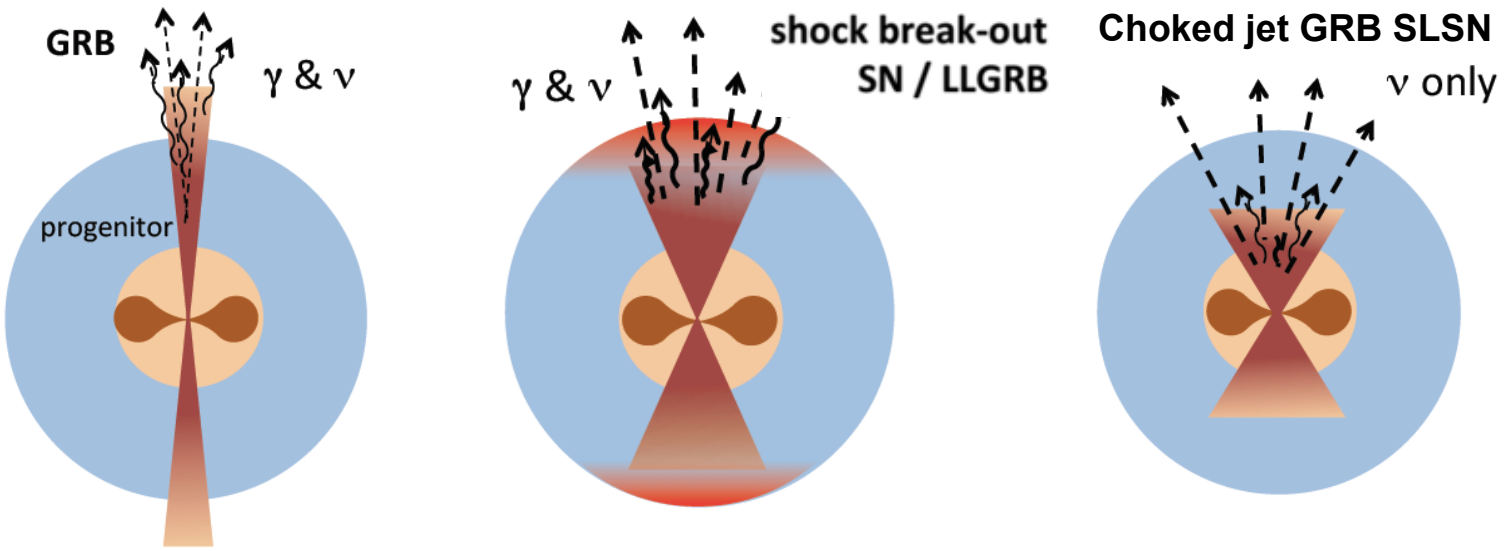
1172 GRBs correlated with IceCube data

563 GRBs correlated with ANTARES data

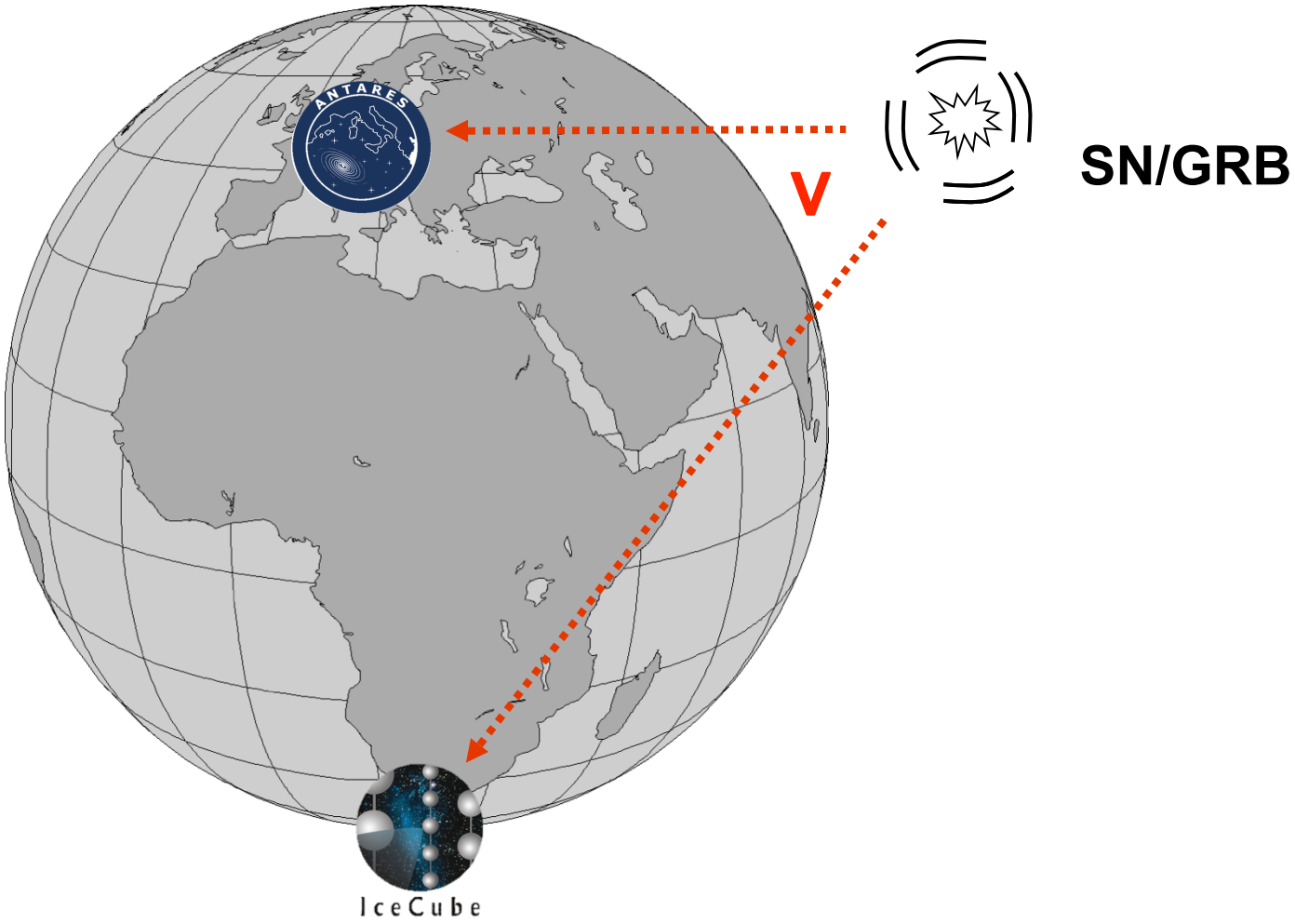
GRBs contribute less than 1% to observed diffuse neutrino flux. Potential large population of nearby low-luminosity GRBs not constrained

IceCube arXiv:1702.06868
ANTARES Eur.Phys.J. C77 (2017) no.1, 20

GRB-Supernova Connection



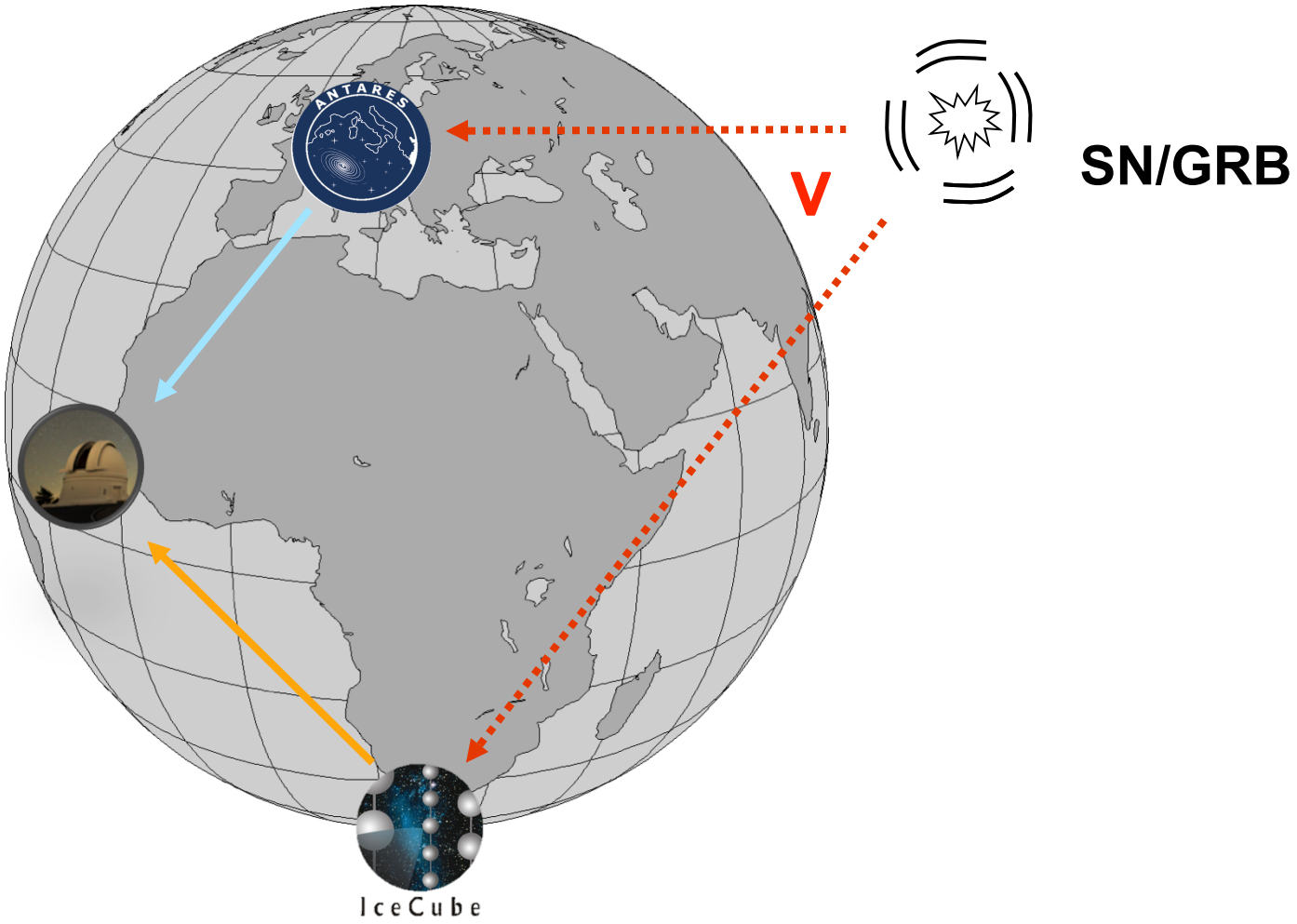
Target of Opportunity Program



IceCube, MAGIC, VERITAS, arXiv:1610.01814
ANTARES JCAP 1602 (2016)
Ackermann et al.arXiv:0709.2640
IceCube A&A 539, A60 (2012)

Target of Opportunity Program

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



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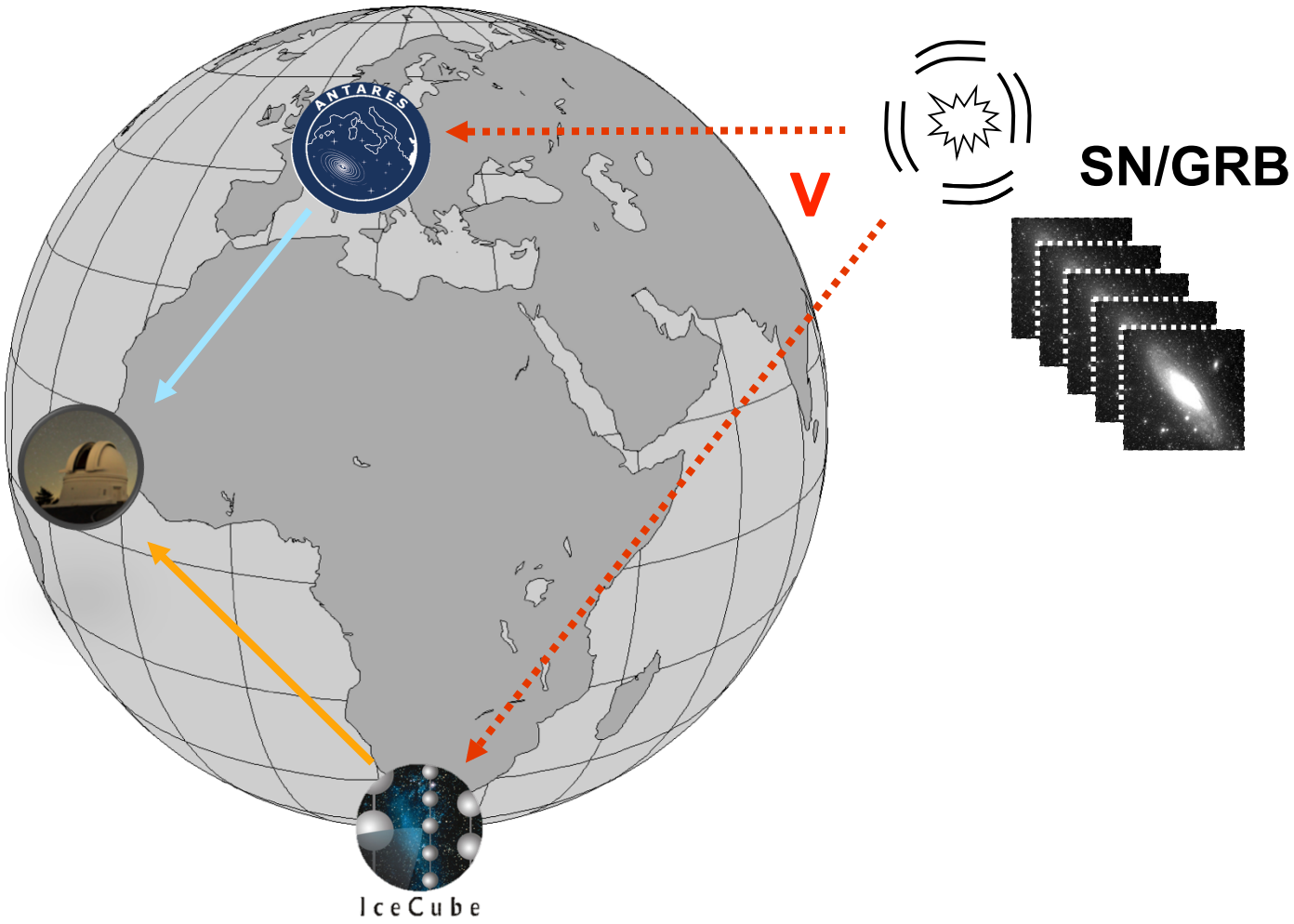

IceCube, MAGIC, VERITAS, arXiv:1610.01814
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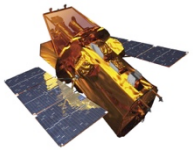
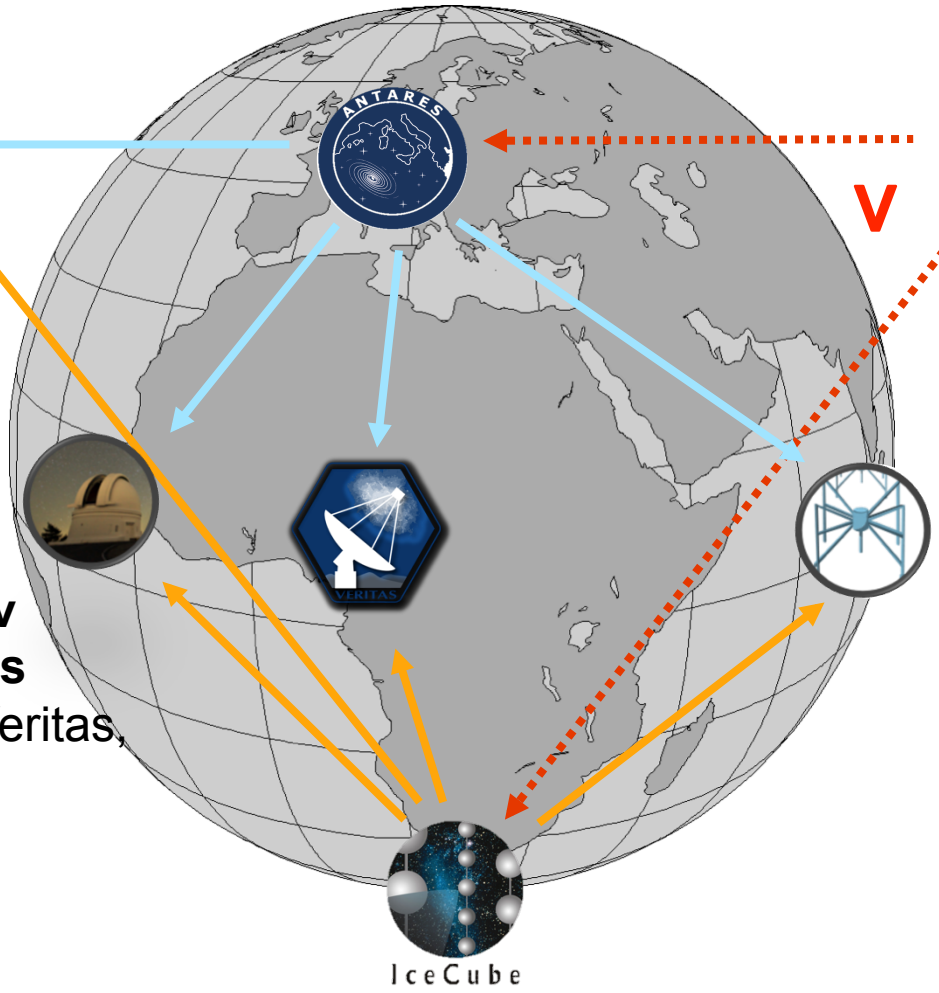
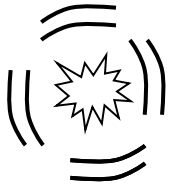
Target of Opportunity Program

X-ray (Swift)

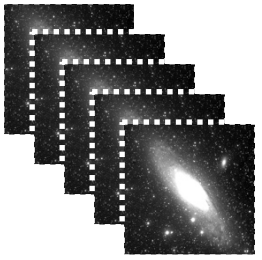




ν



SN/GRB



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

Cherenkov Telescopes
(MAGIC, Veritas, HESS)

Radio Telescopes
(MWA)

IceCube, MAGIC, VERITAS, arXiv:1610.01814
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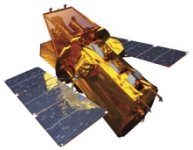
Target of Opportunity Program

X-ray (Swift)



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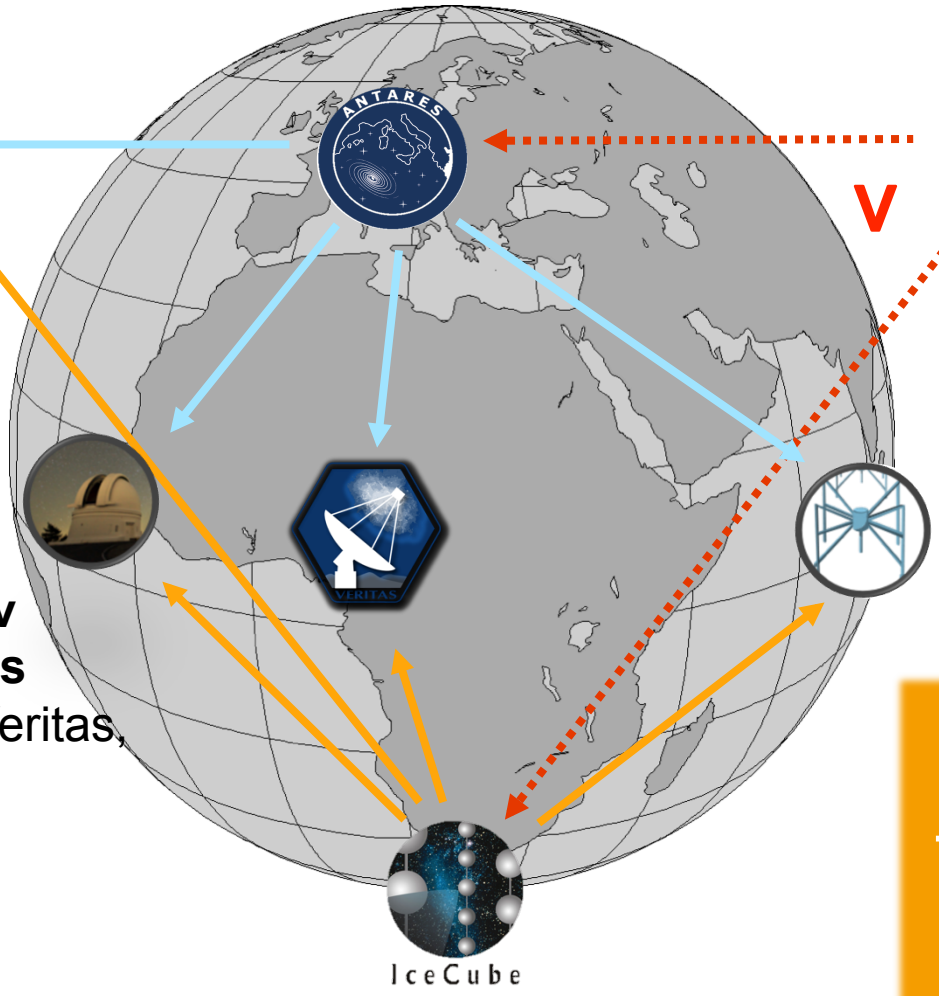
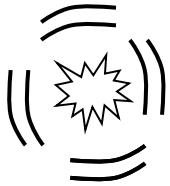


ν



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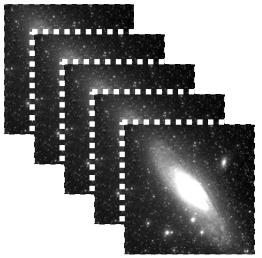
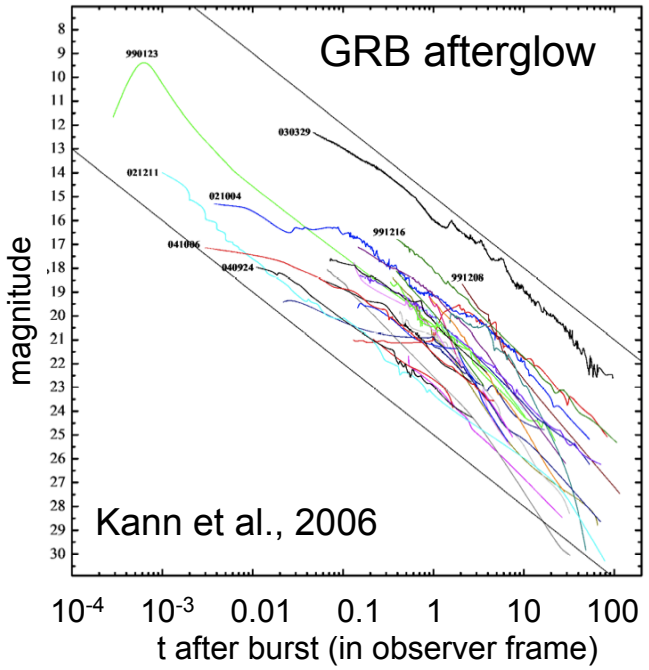


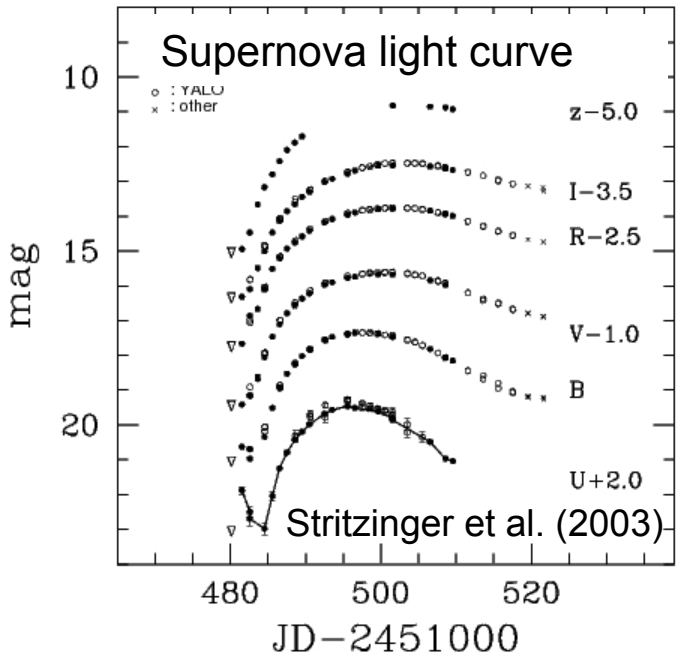
Radio Telescopes
(MWA)

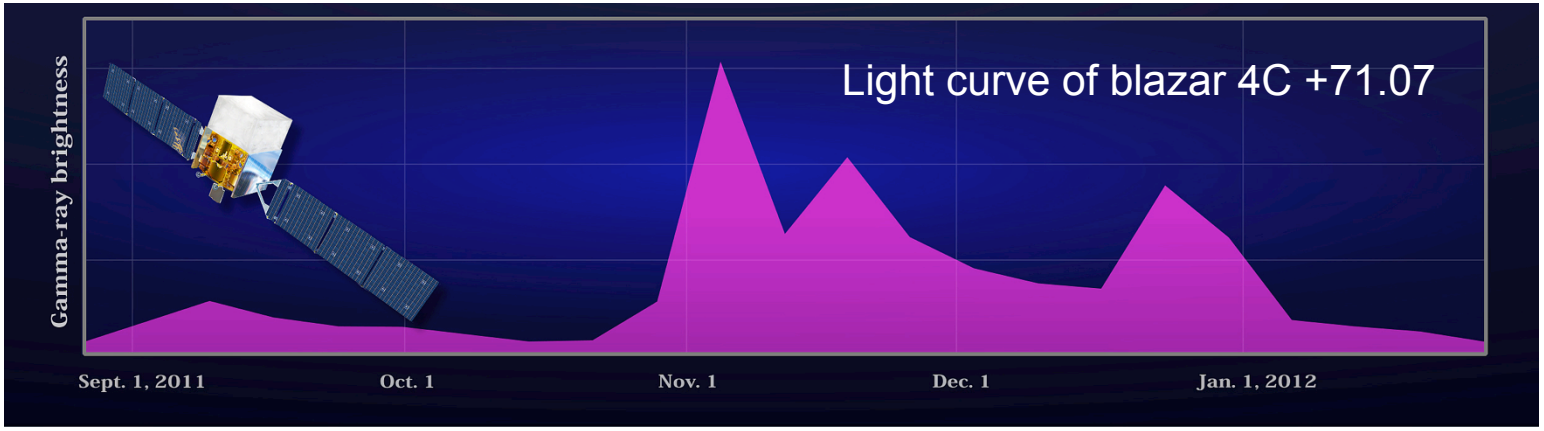
Increased sensitivity for transient neutrino sources → source identification

IceCube, MAGIC, VERITAS, arXiv:1610.01814
ANTARES JCAP 1602 (2016)
Ackermann et al.arXiv:0709.2640
IceCube A&A 539, A60 (2012)

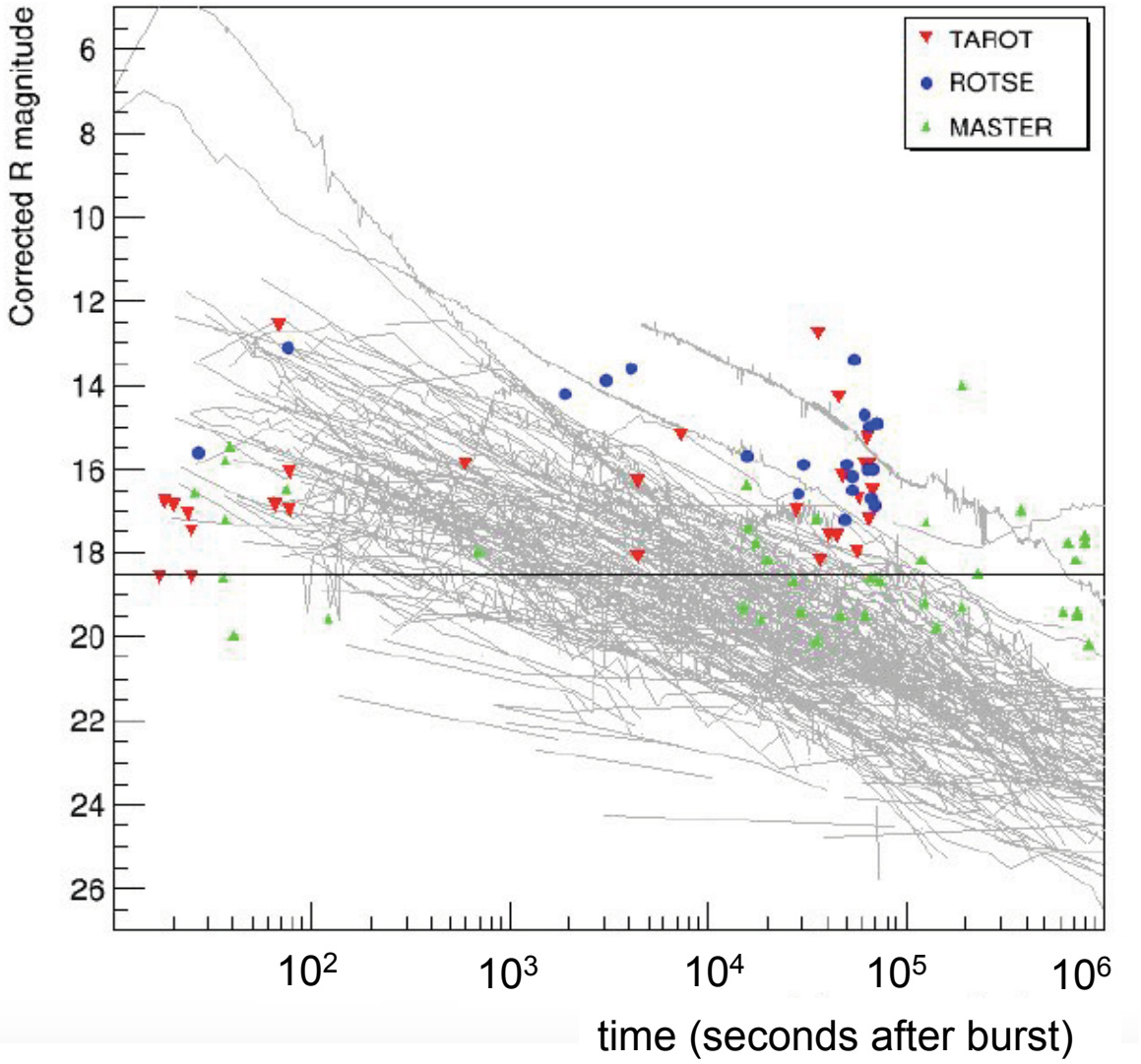
Expected EM Counterparts







Fast Follow-Up Possible!

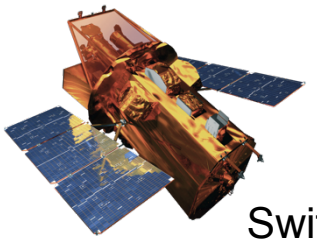


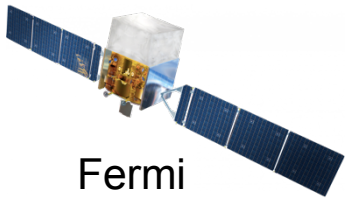
Fast reaction by follow-up instruments are required to detect rapidly declining GRB afterglow

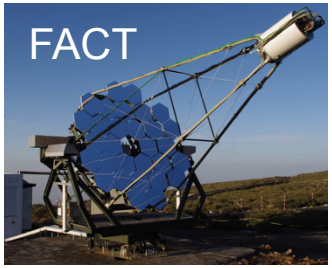
ANTARES JCAP 1602 (2016)

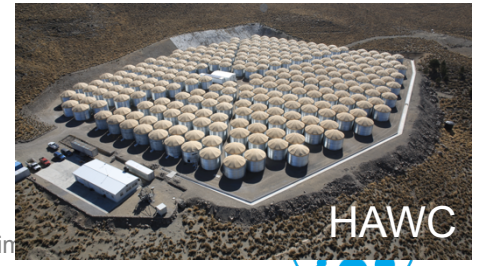
Public IceCube Alerts since April 2016

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

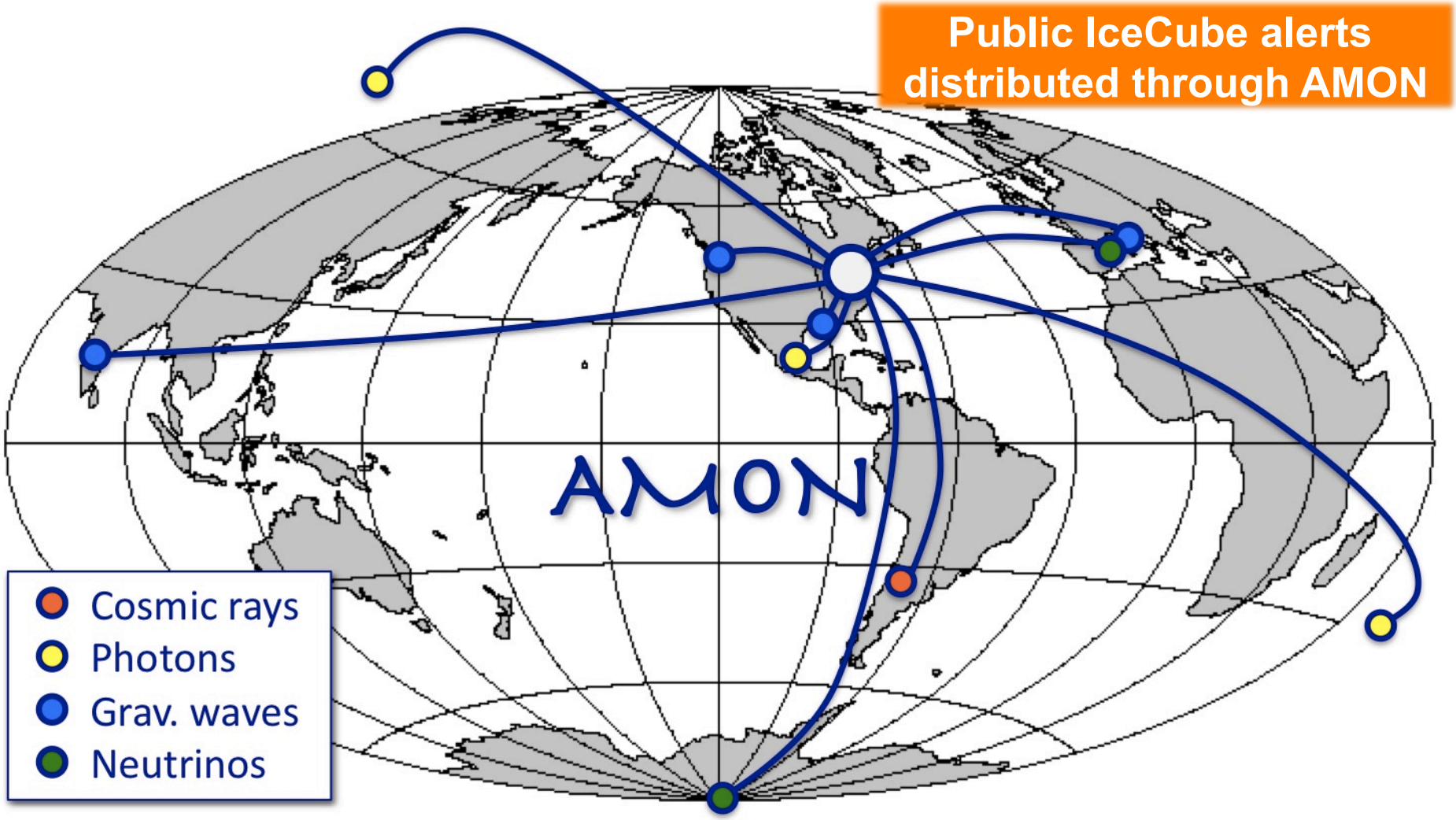

Swift


Fermi





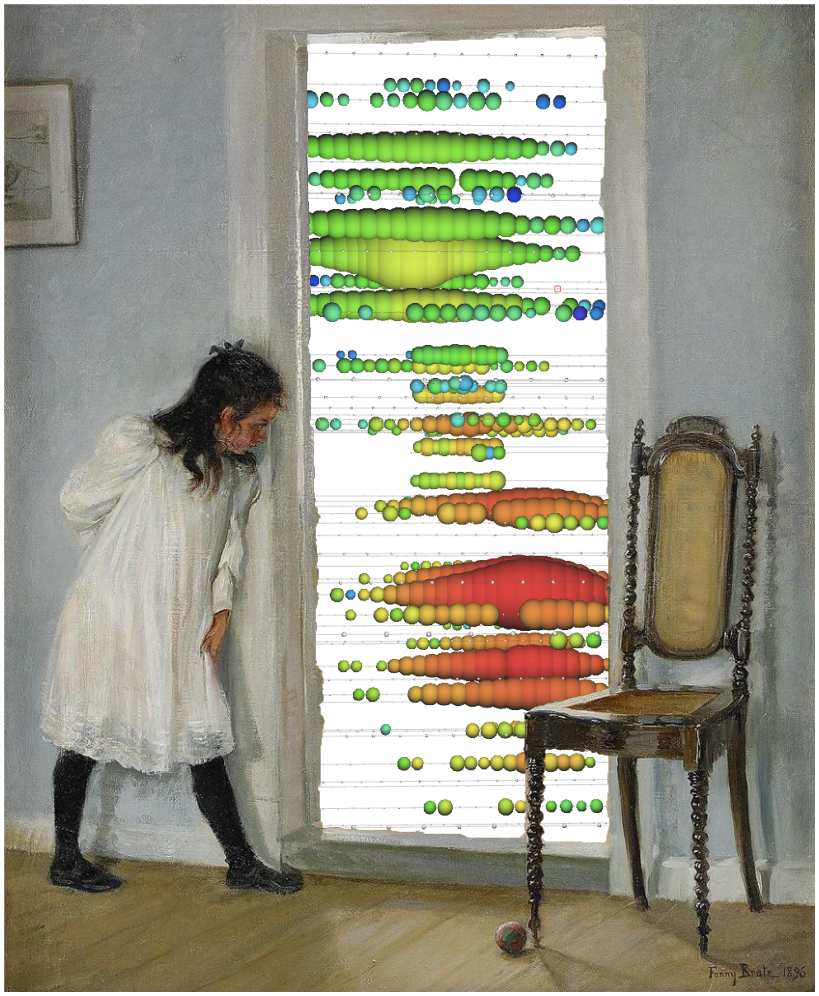
Astrophysical Multimessenger Observatory Network (AMON)

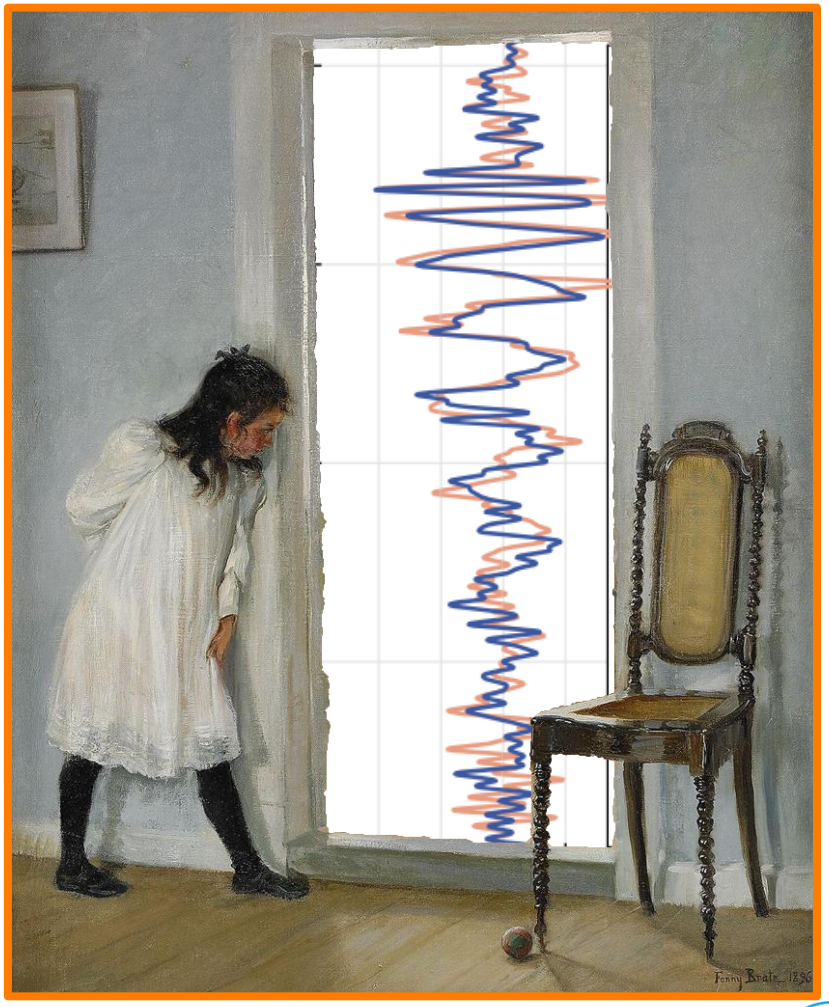


http://amon.gravity.psu.edu

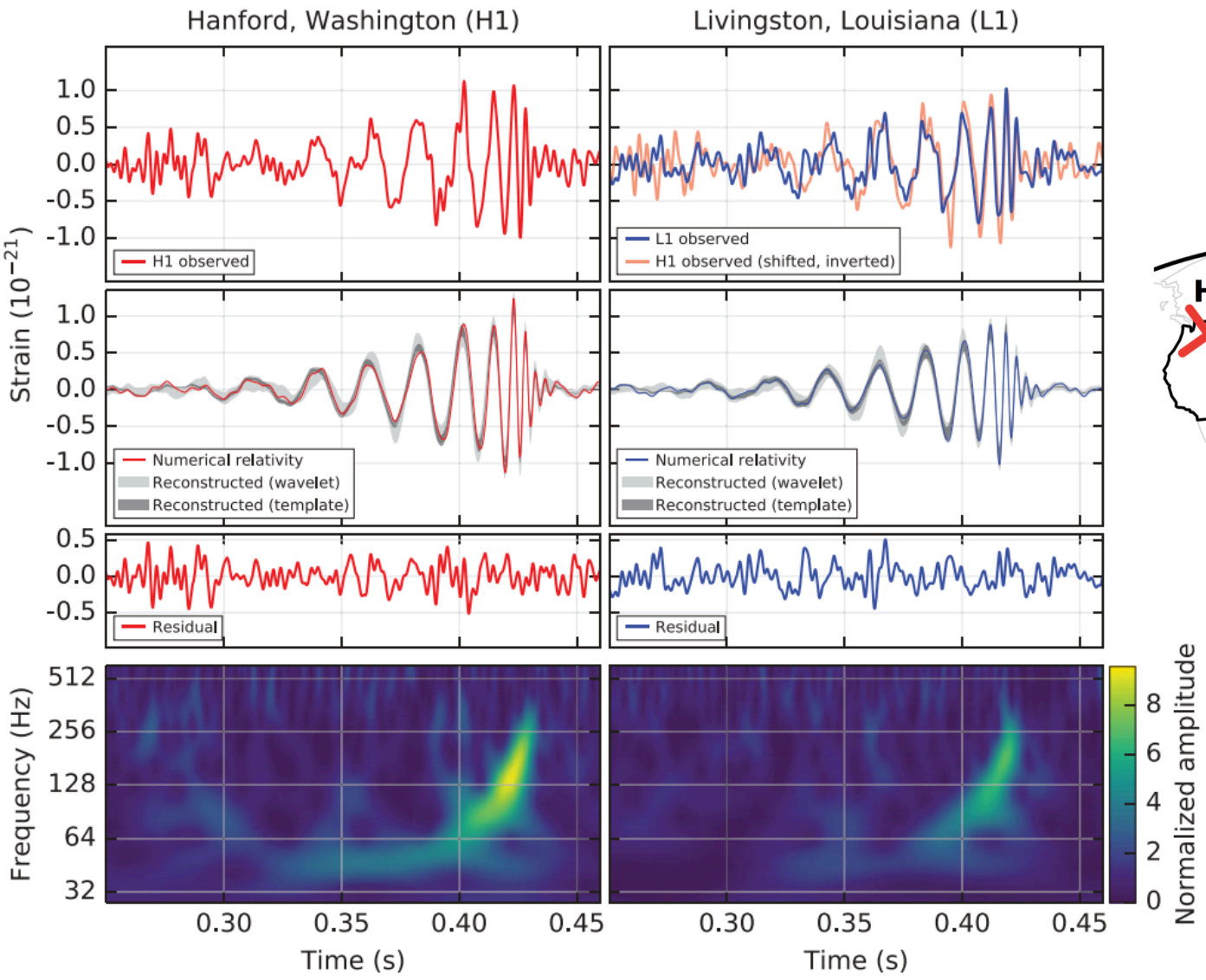
Smith et al., Astropart. Phys., 45 (2013)

Two New Windows to the Universe

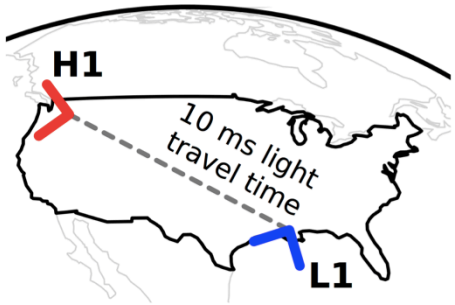




Another new Window to the Universe: Gravitational Waves



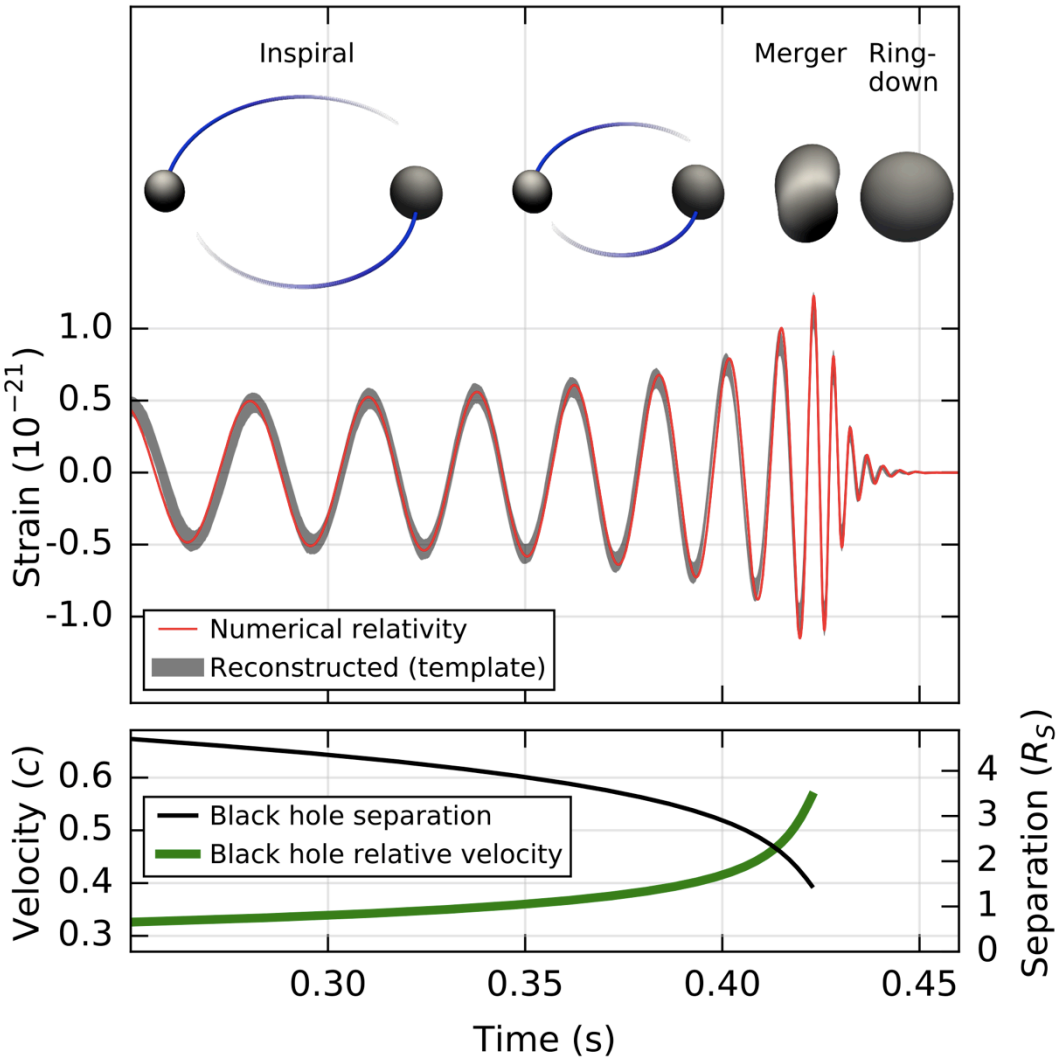
Sept. 14, 2015



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

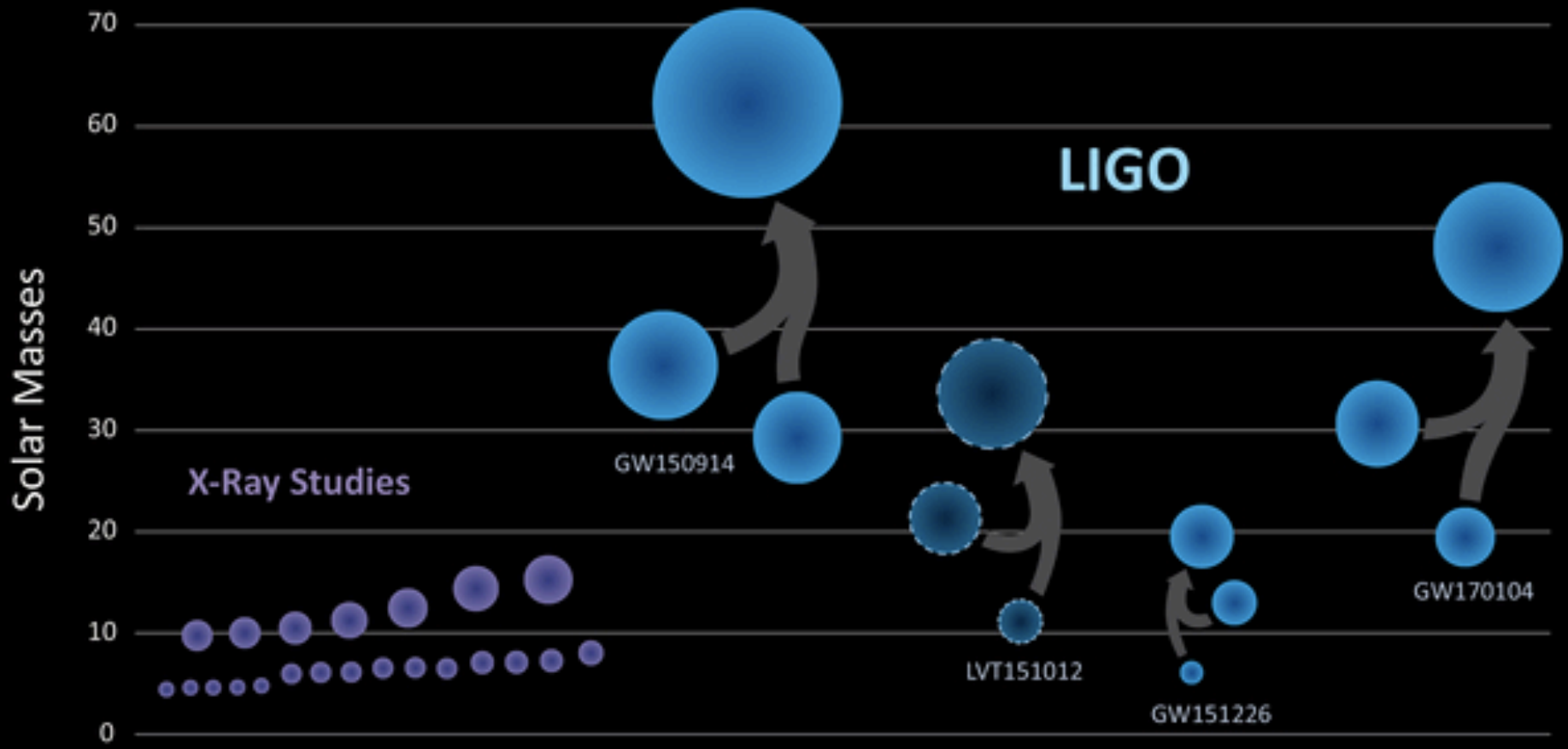
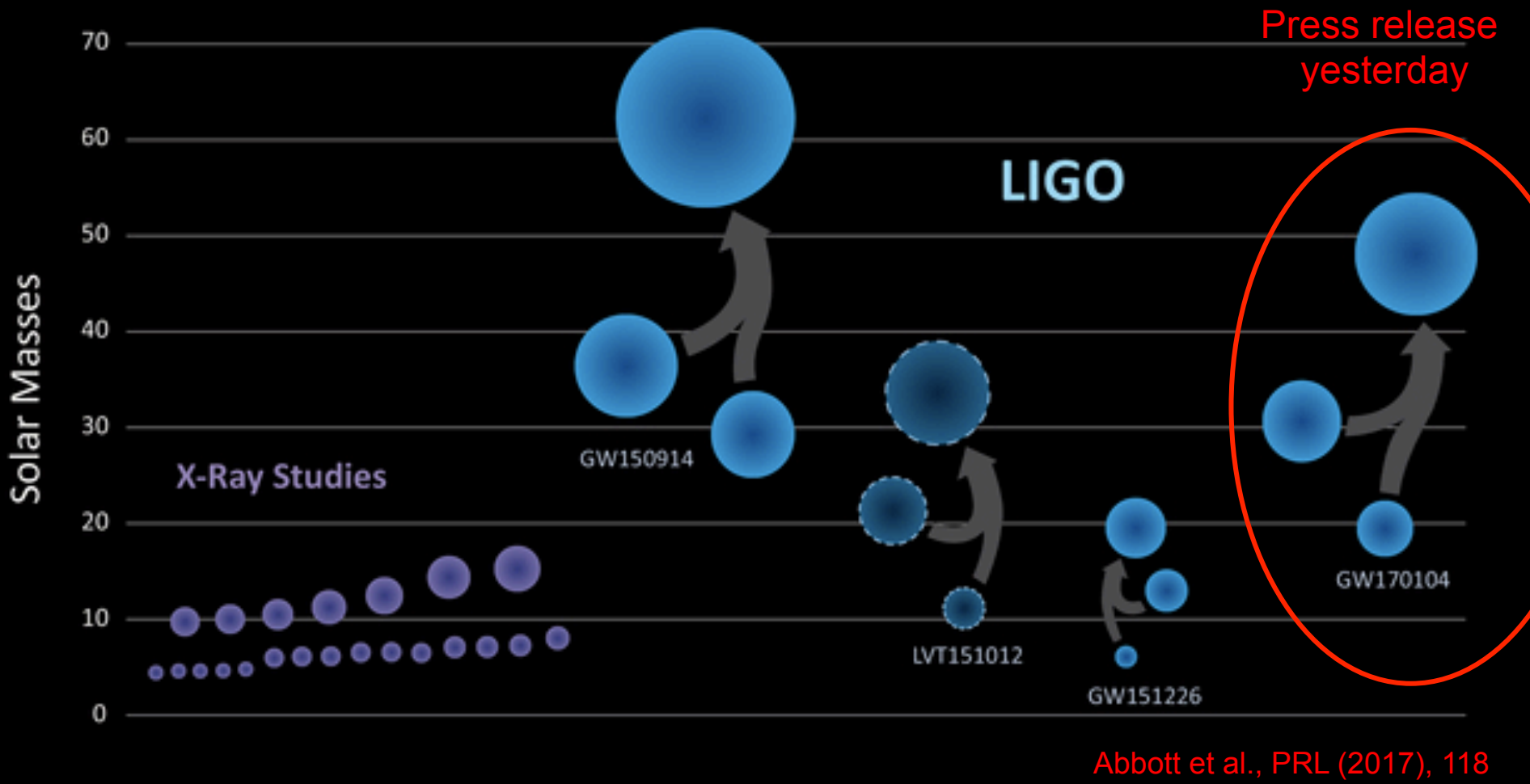


Image credit: LIGO

Black Holes of Known Mass



Abbott et al., PRL (2017), 118

Image credit: LIGO

Neutron Star Merger

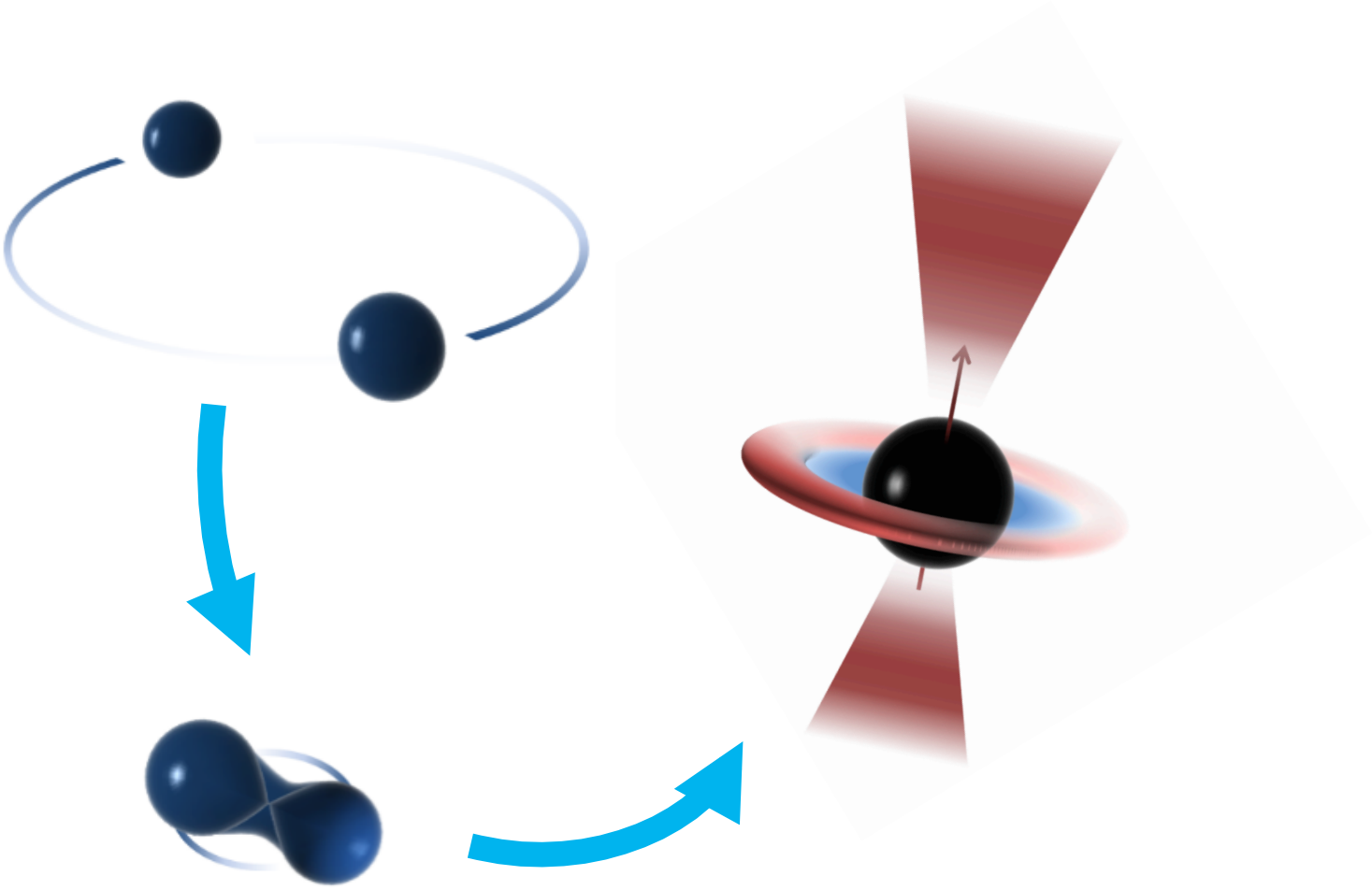


Image credit: I. Bartos

Supernova

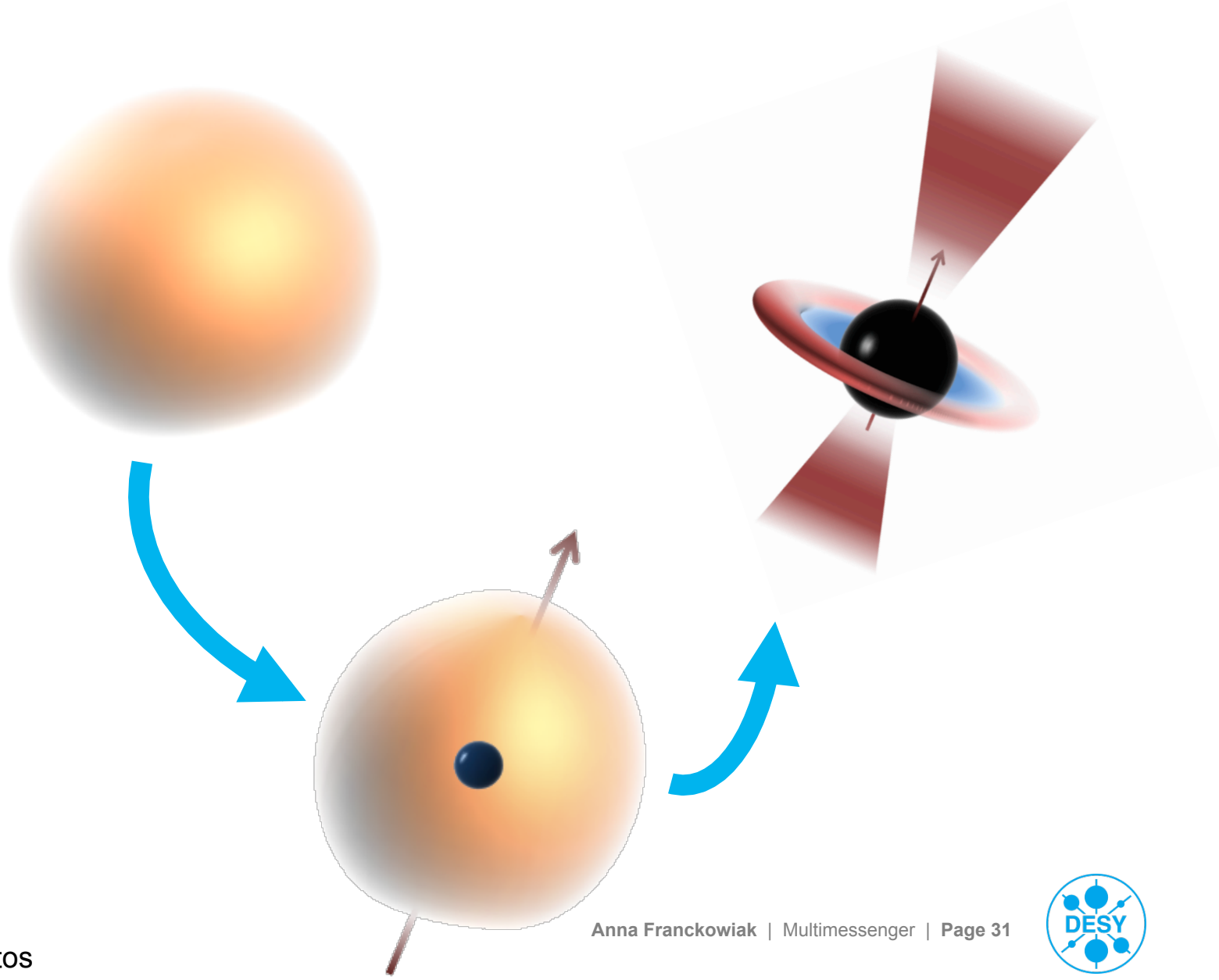
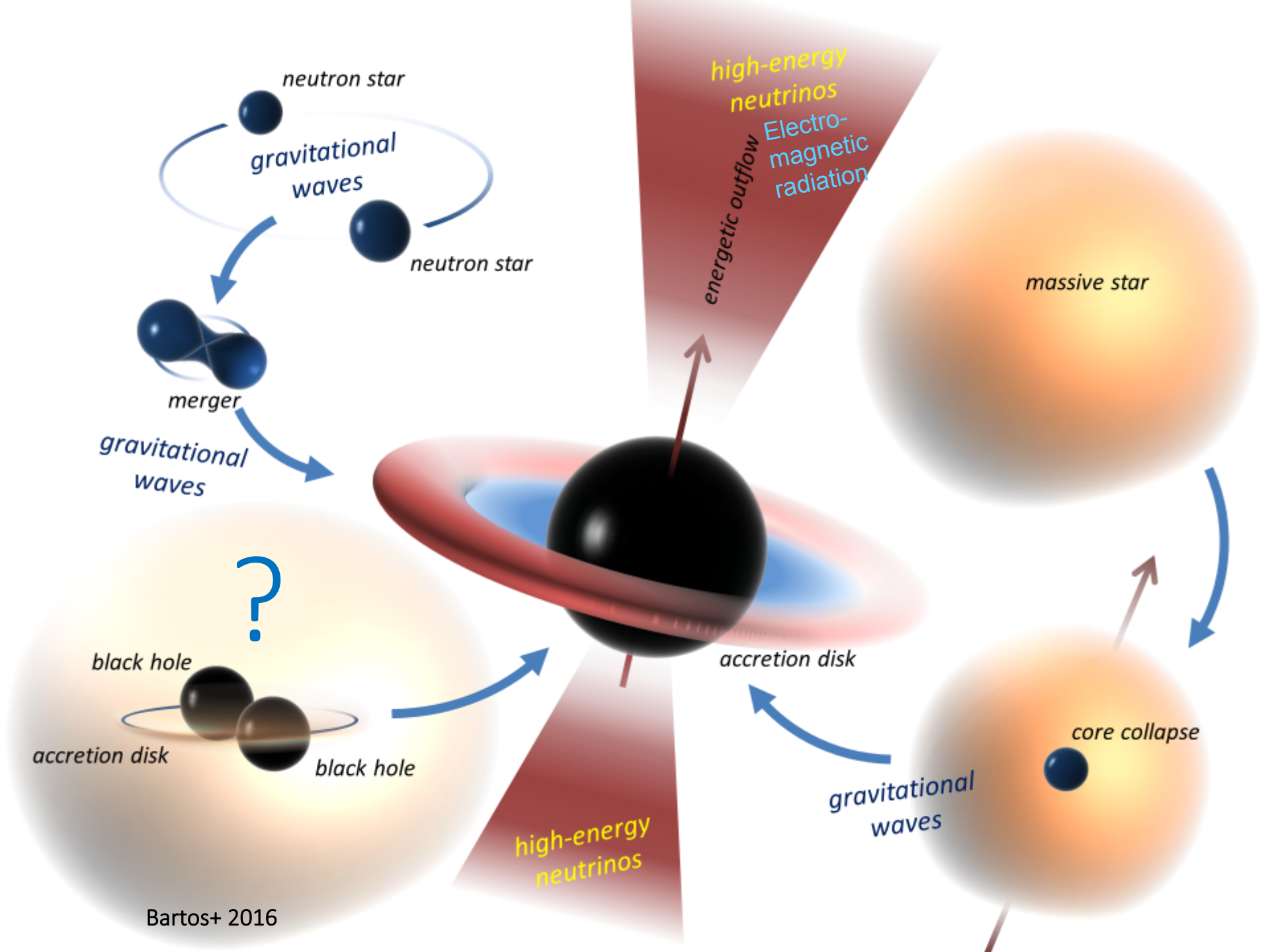
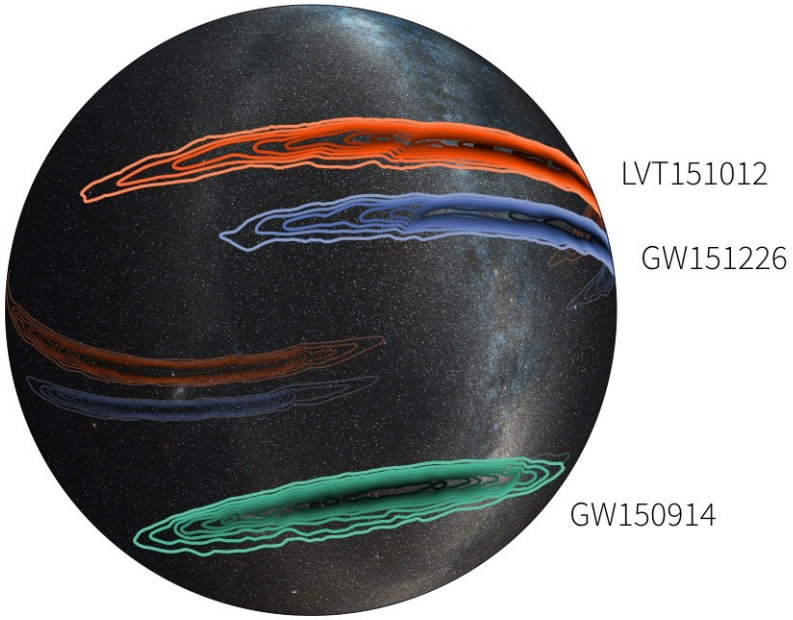


Image credit: I. Bartos

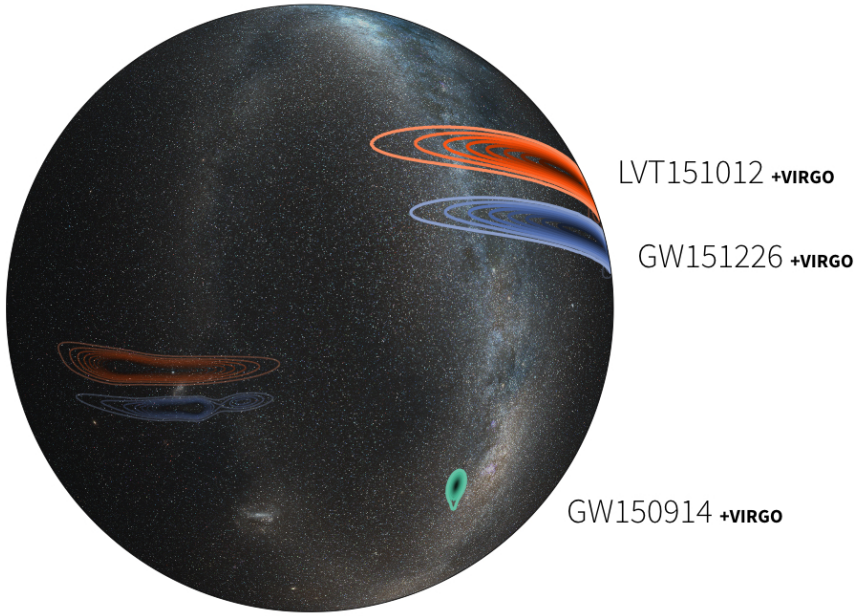

neutron star
gravitational waves
neutron star
merger
gravitational waves
high-energy neutrinos
energetic outflow
Electro-magnetic radiation
massive star
accretion disk
?
black hole
accretion disk
black hole
high-energy neutrinos
core collapse
gravitational waves

Bartos+ 2016

Sky Localization



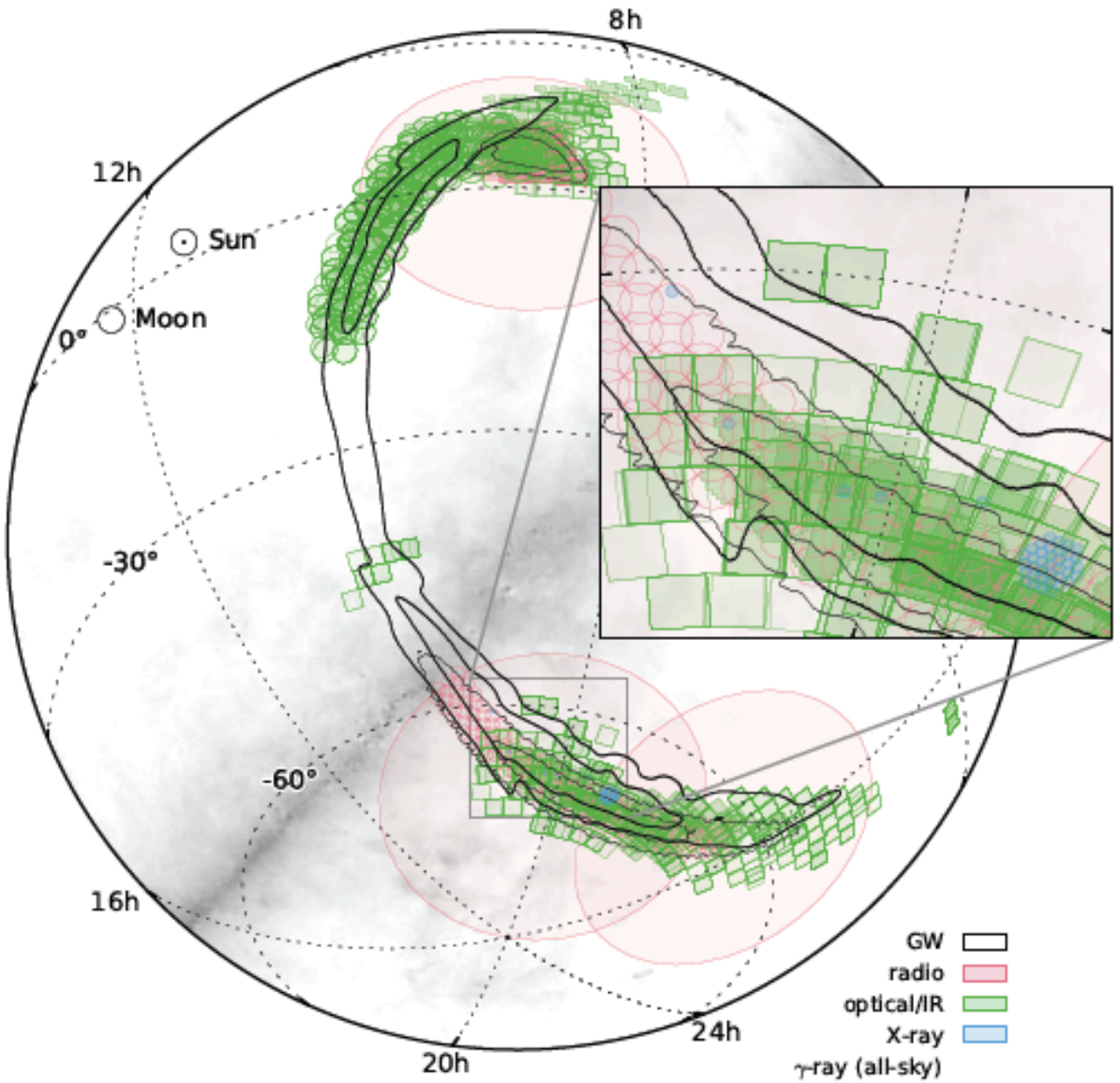
LIGO localizations



Simulated estimates with Virgo

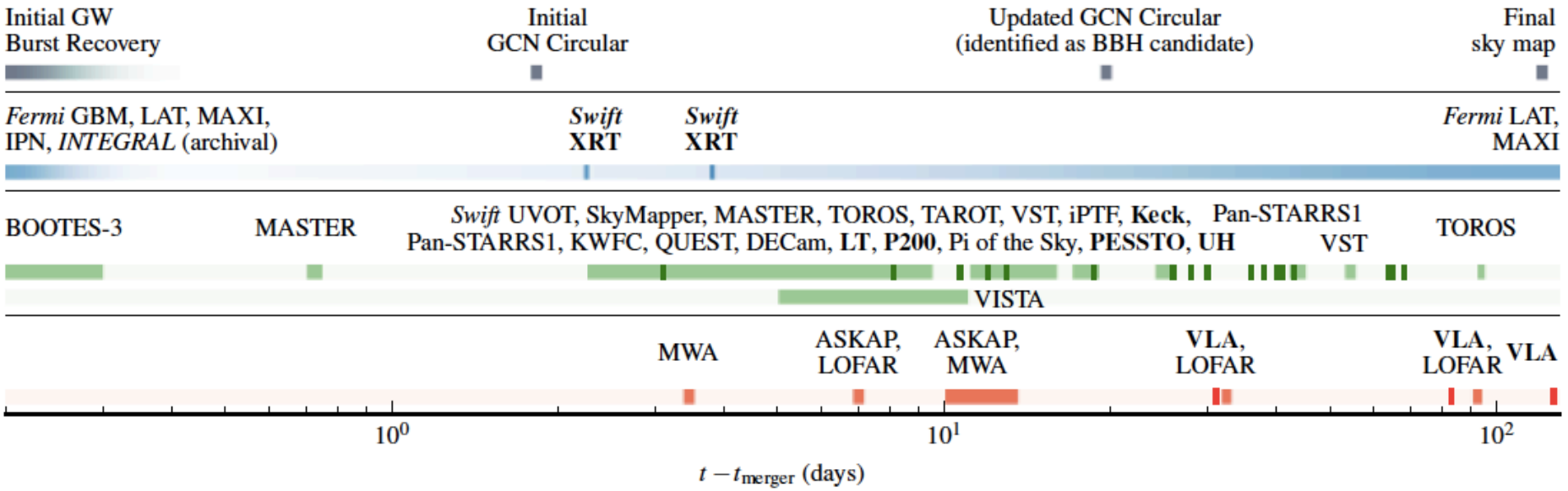
Image credit: LIGO/Leo Singer (Milky Way image: Axel Mellinger)

Multi-Wavelength Follow-Up



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

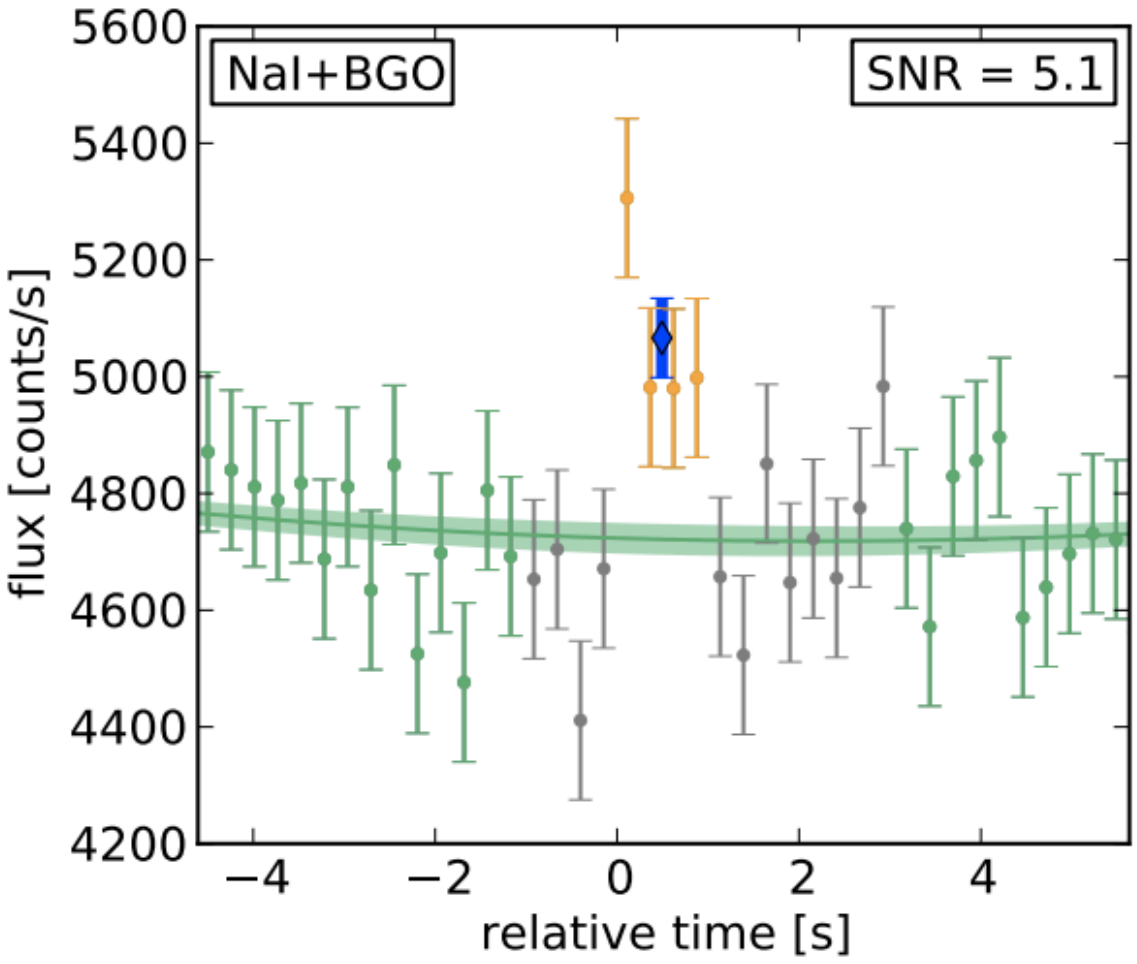
Multi-Wavelength Follow-Up



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

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

Hint for Gamma-ray Signal?



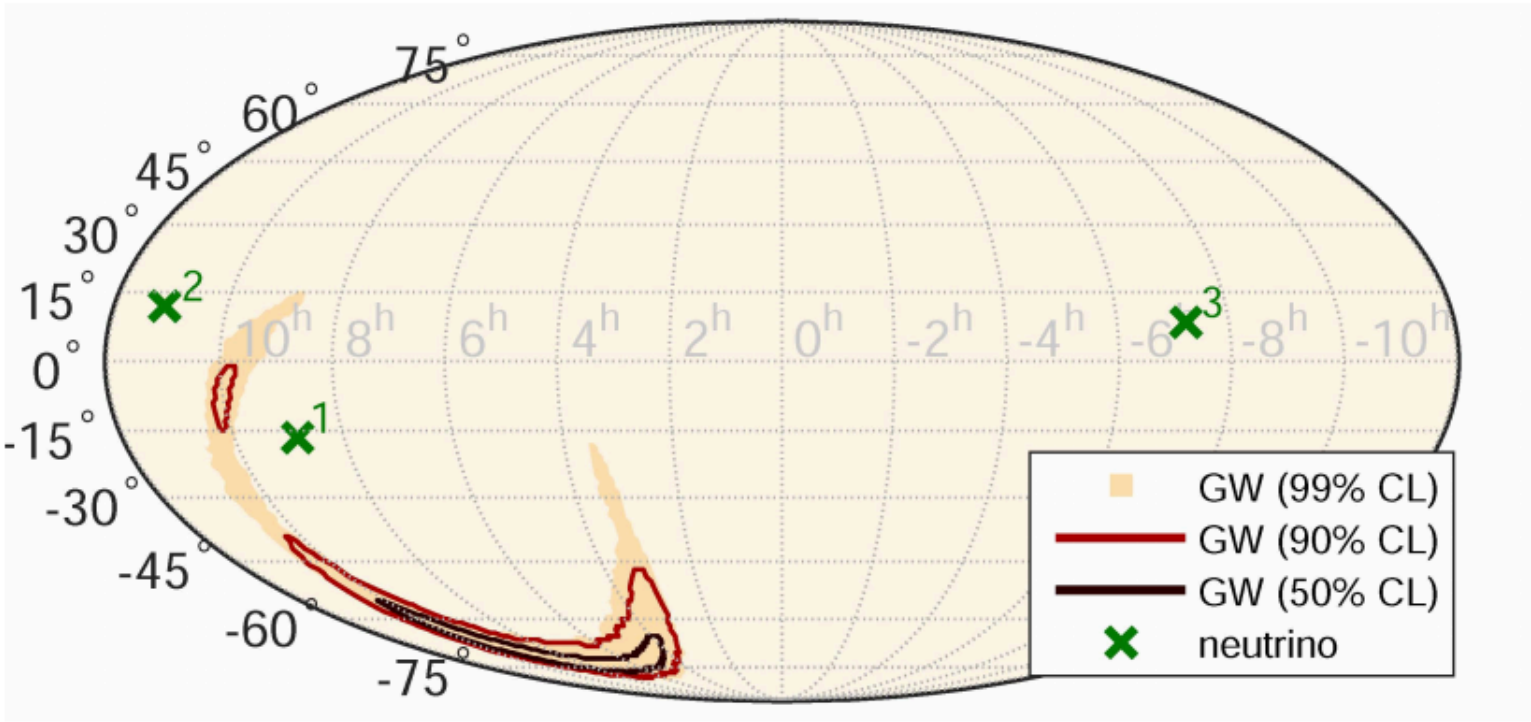
Gamma-Ray Burst Monitor finds short gamma-ray bursts coincident with gravitational wave signal
0.2% p-value

- 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

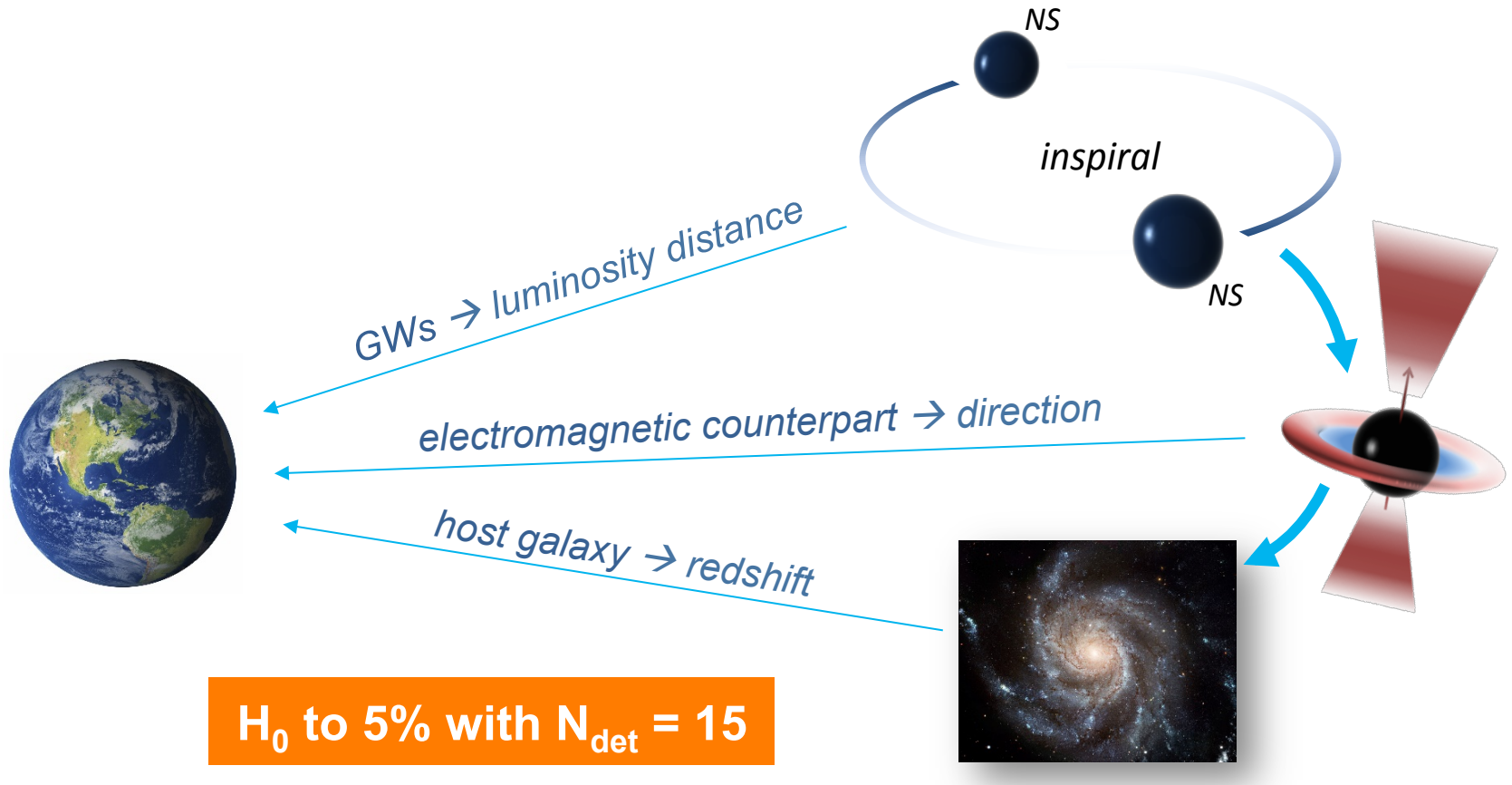
Search for neutrinos from GW150914 in ANTARES and IceCube data
→ no counterpart found



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



H_0 to 5% with N_{det} = 15

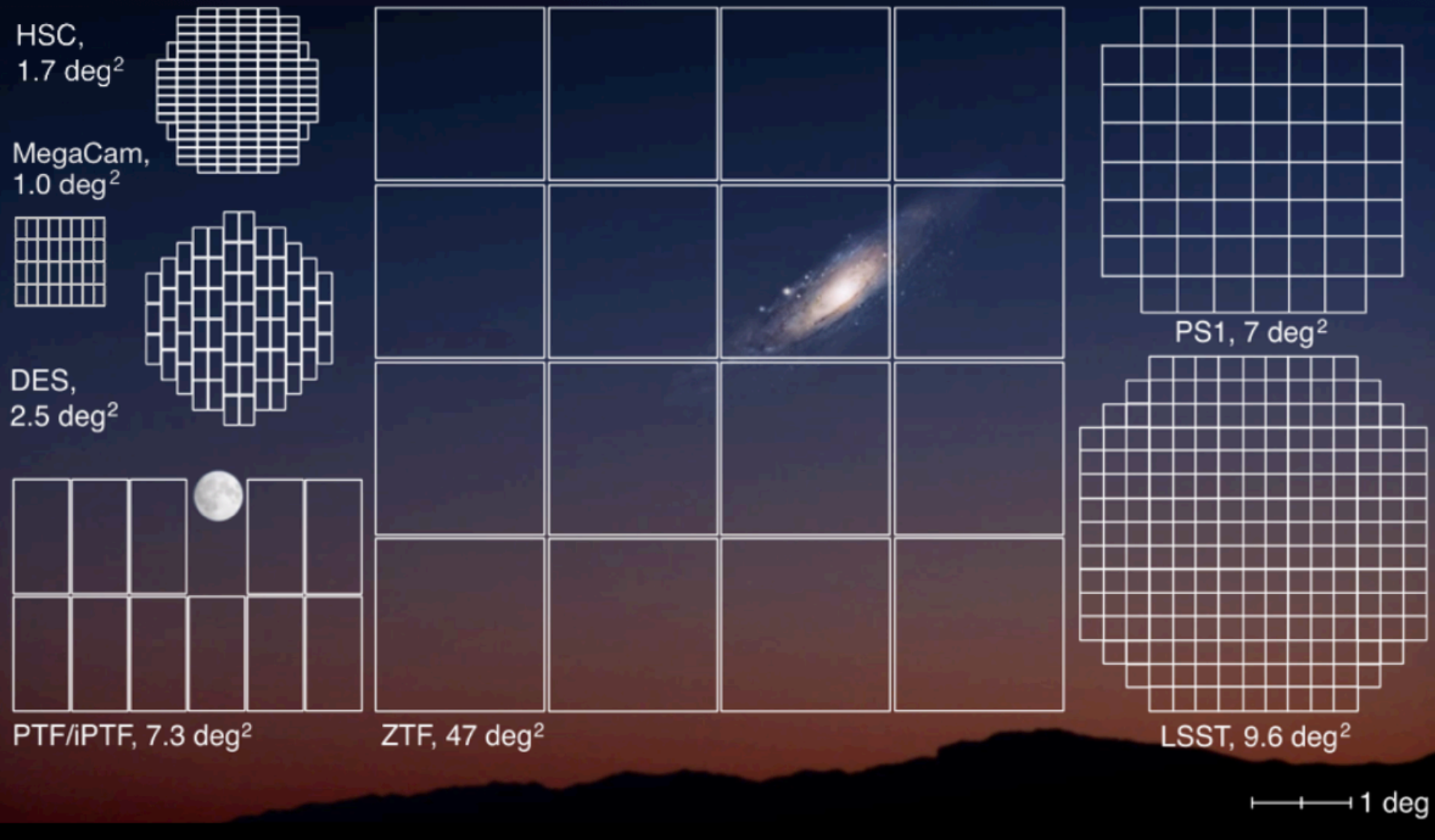
Schulz Nature (1986)
D. Holz & s. Hughes ApJ (2005) 629
Nissanke+ 2010

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 can scan the entire Northern sky every night to 20.5 mag



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!

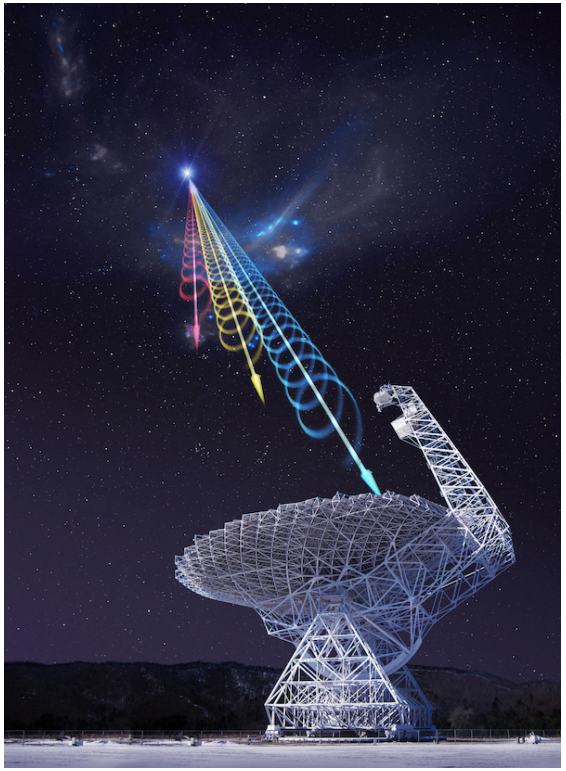
Back-up

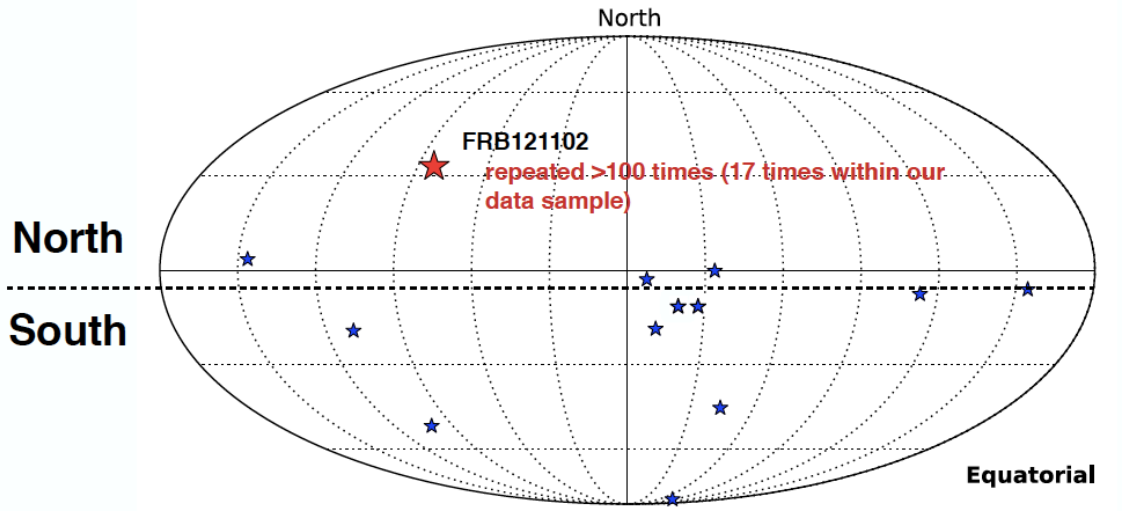
Fast Radio Bursts

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

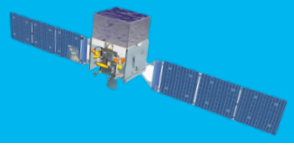
S. B. Popov and K. A. Postnov, arXiv1307.4924
Halzen *et al.*(2005) asto-ph/0503348

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

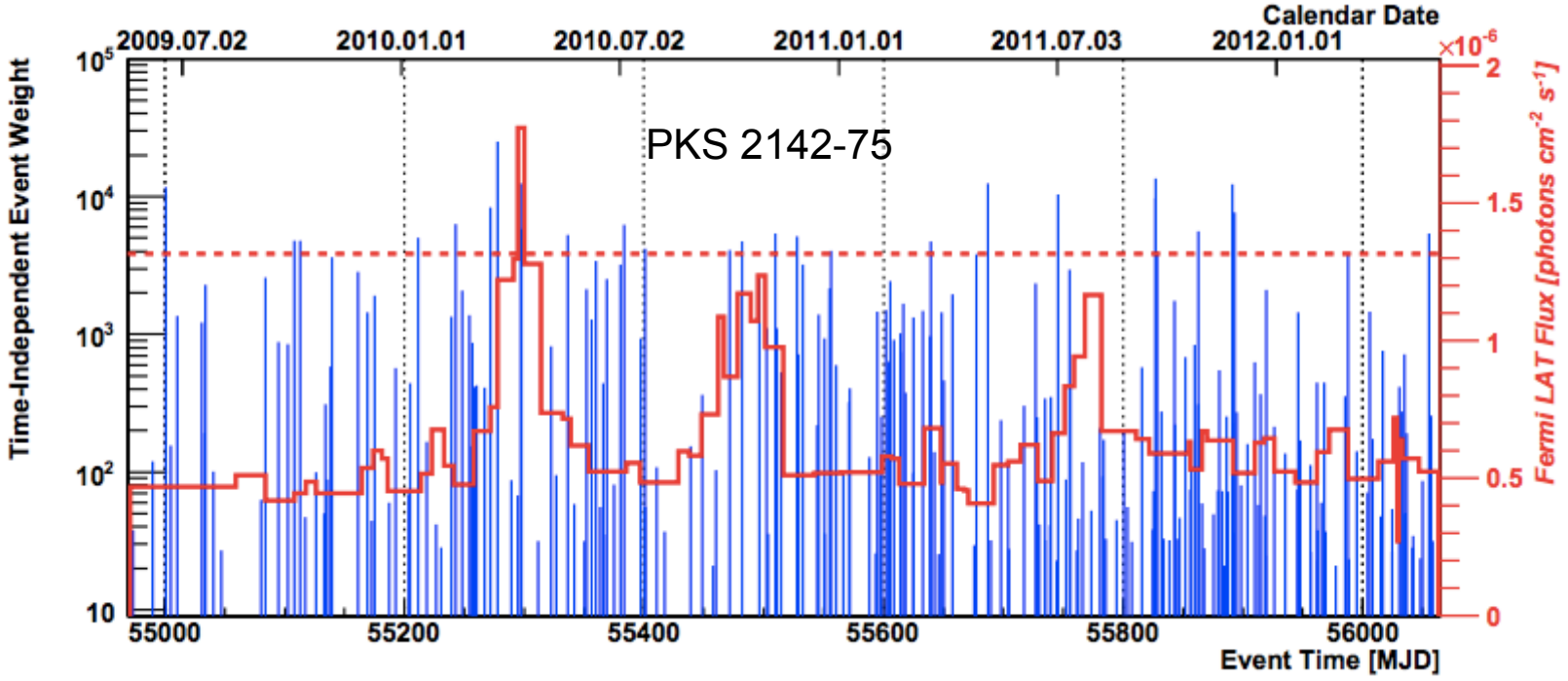




Using Full Blazar Light Curves



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



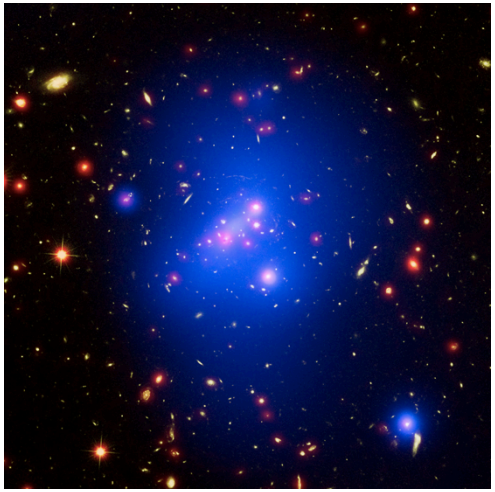
No correlation found in 3 years of IceCube data and ~50 variable gamma-ray sources

IceCube Coll. ApJ 807 (2015) 46

Extra-Galactic Neutrino Sources

- Star forming galaxies

- Galaxy clusters



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

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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

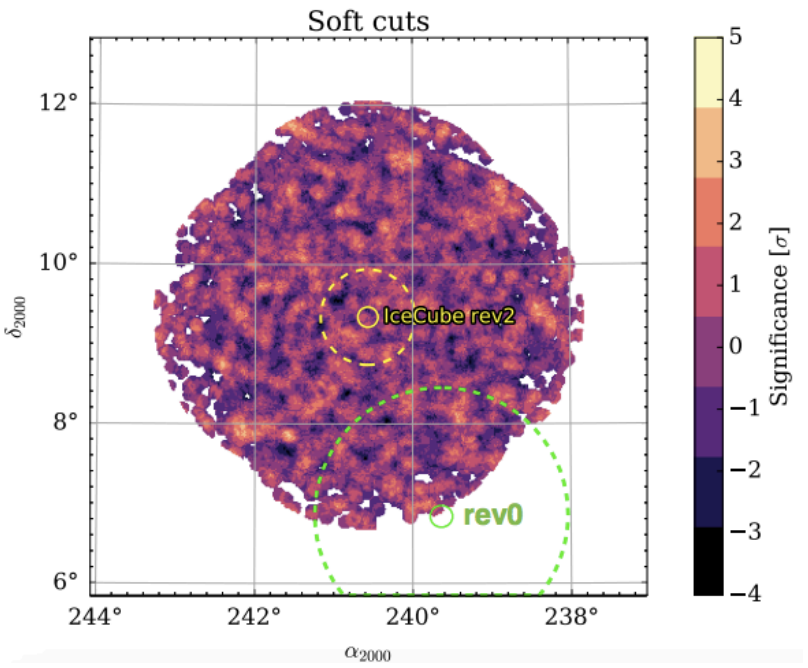
Telescope	Results
iPTF	3 transients, all AGN
MASTER	No detection
Pan-STARRS	7 SN candidates

gamma-rays

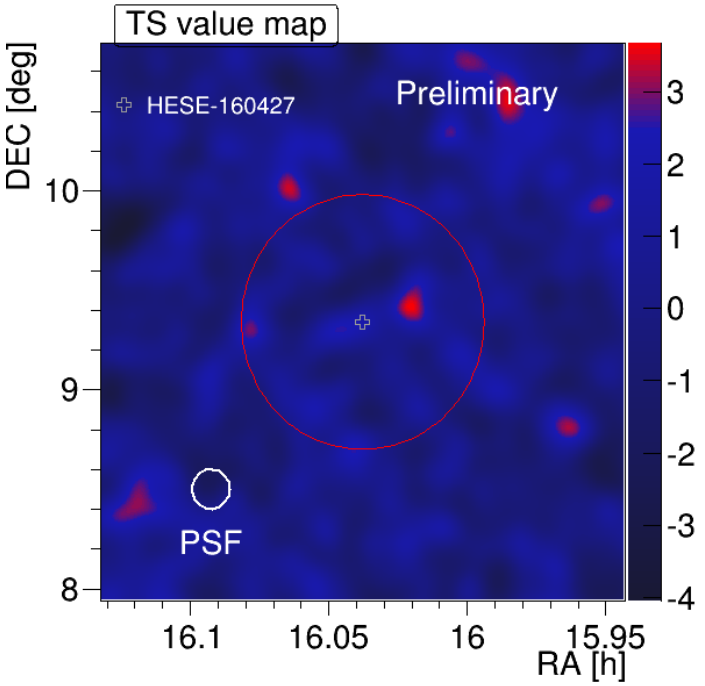
Telescope	Results
IPN	No detection
Fermi-LAT	5 unrelated blazars
Fermi-GBM	No detection
FACT	No detection
VERITAS	No detection
HAWC	No detection
MAGIC	No detection

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



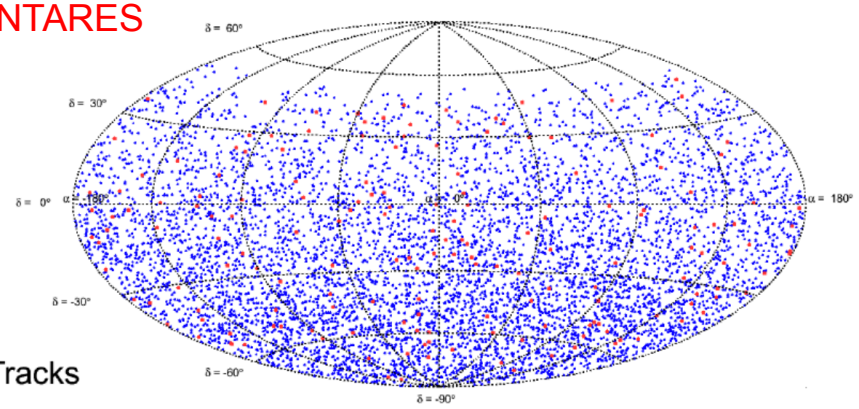
M. Santander for the VERITAS Coll., ICHEP 2016



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

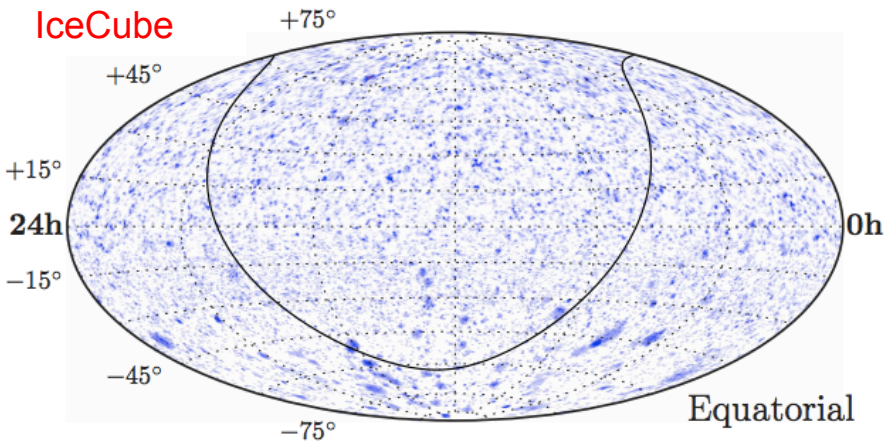
Search for Neutrino Clusters in Space and Time

ANTARES

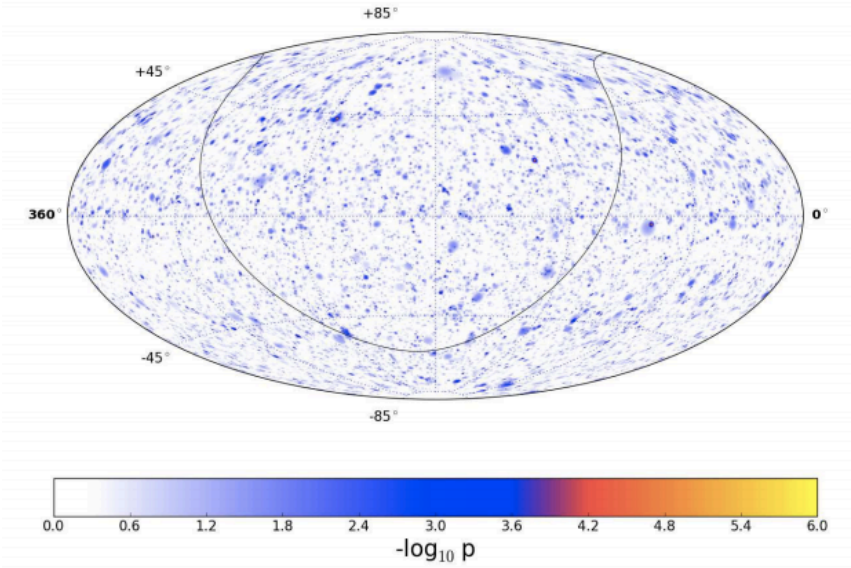


ANTARES ApJ 786 (2014)

IceCube



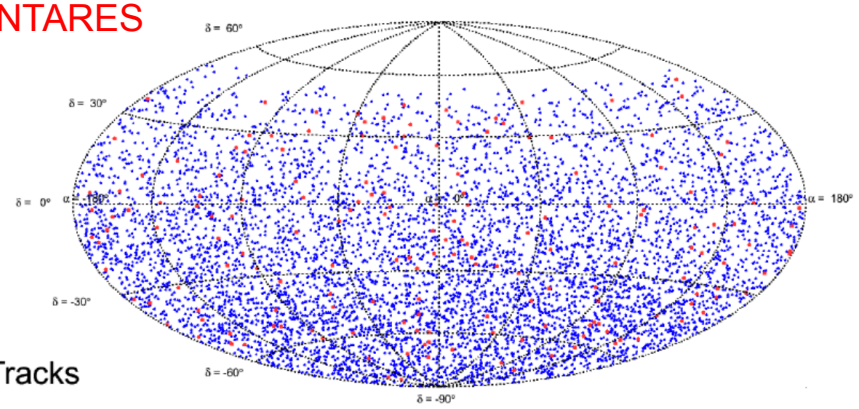
IceCube ApJ 835 (2017)



IceCube ApJ 807 (2015)

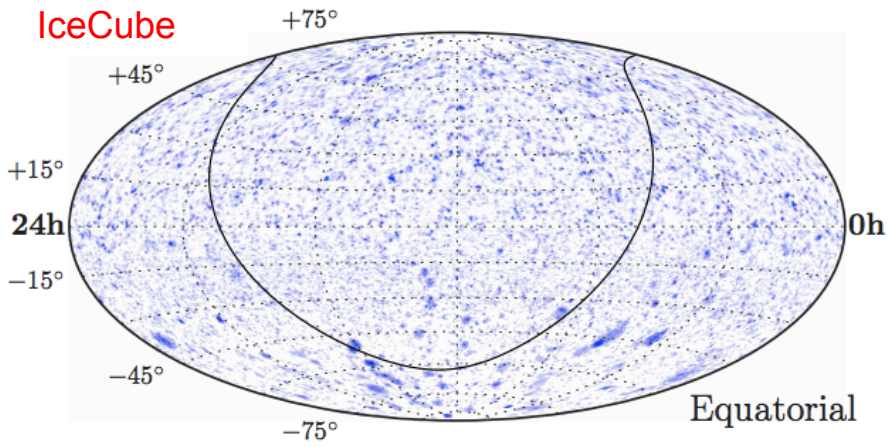
Search for Neutrino Clusters in Space and Time

ANTARES



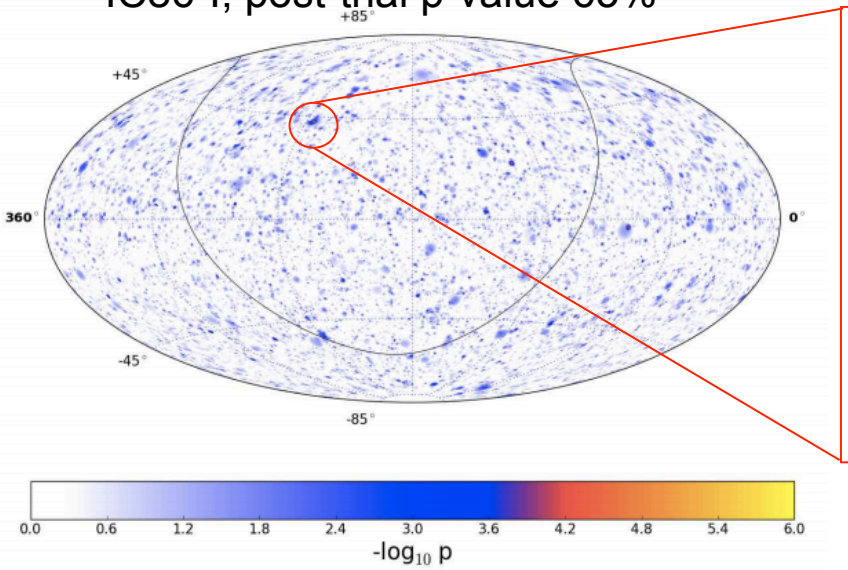
ANTARES ApJ 786 (2014)

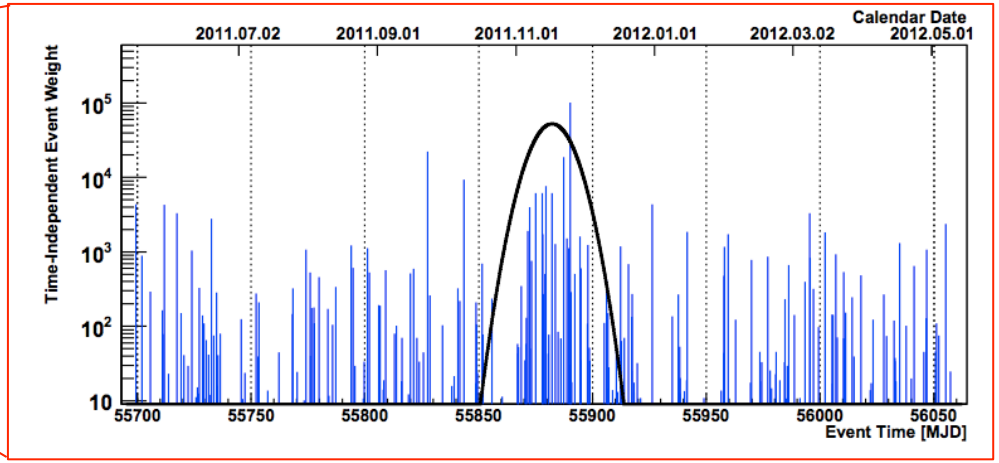
IceCube



IceCube ApJ 835 (2017)

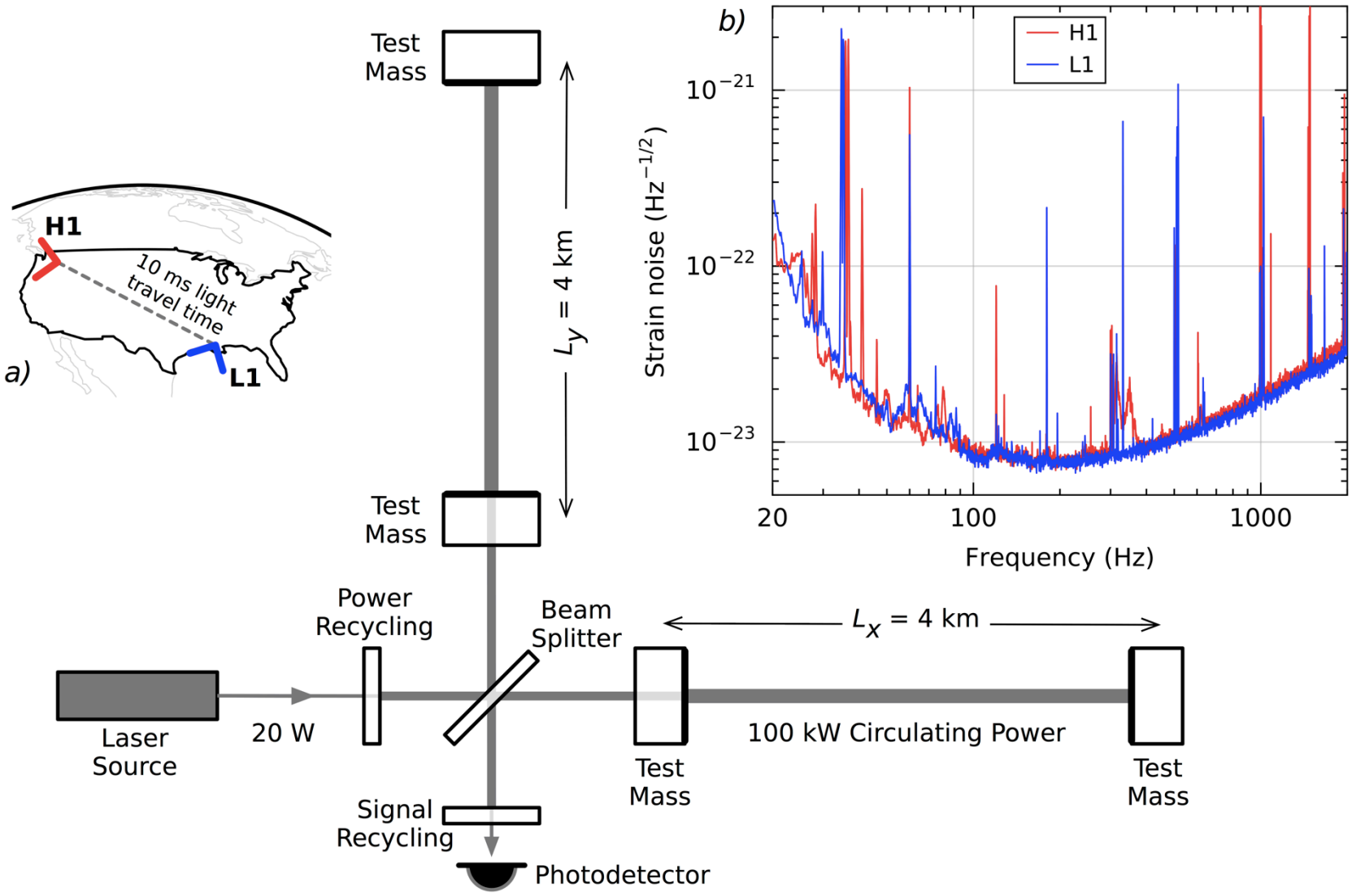
IC86-I, post-trial p-value 63%



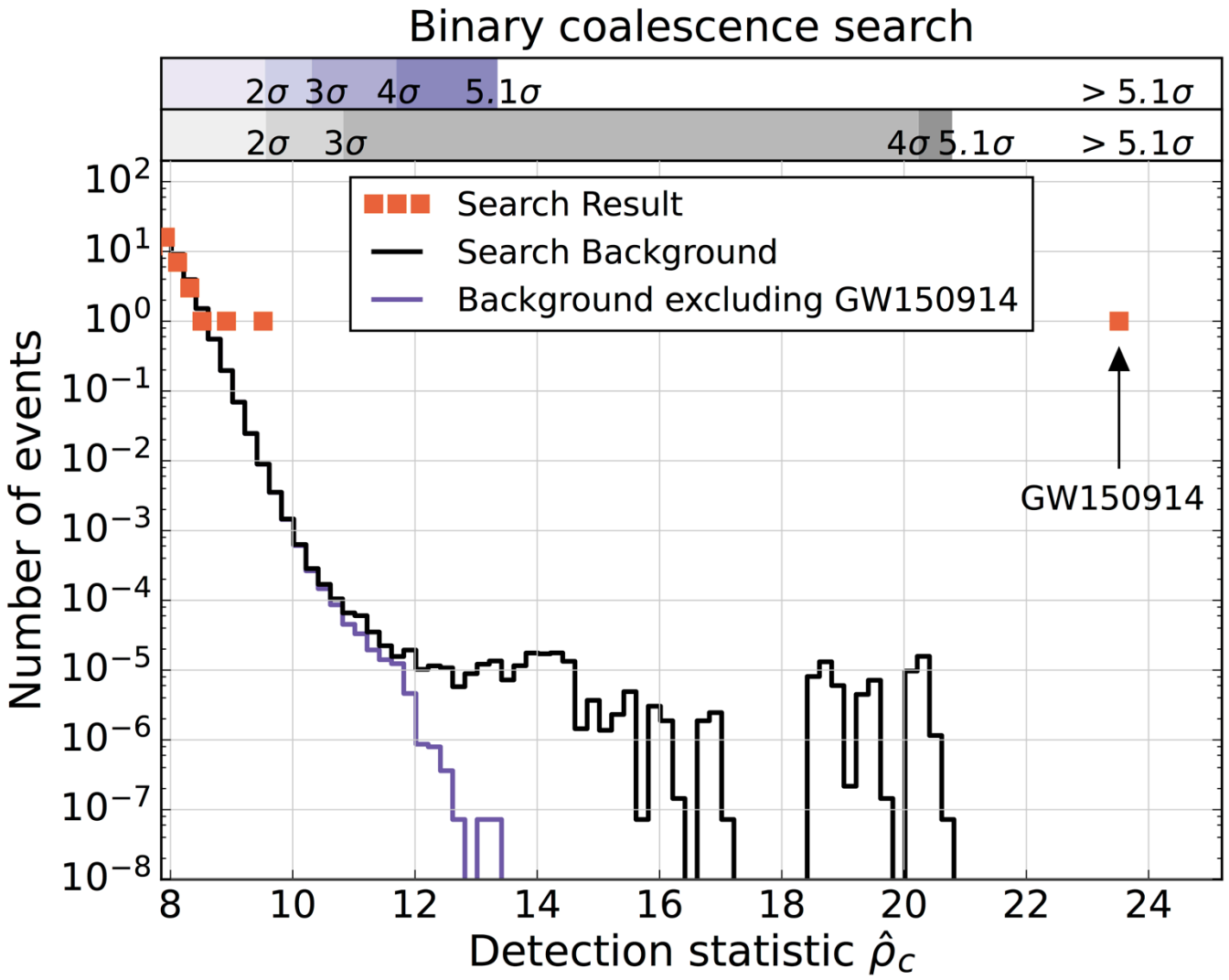


IceCube ApJ 807 (2015)

DESY

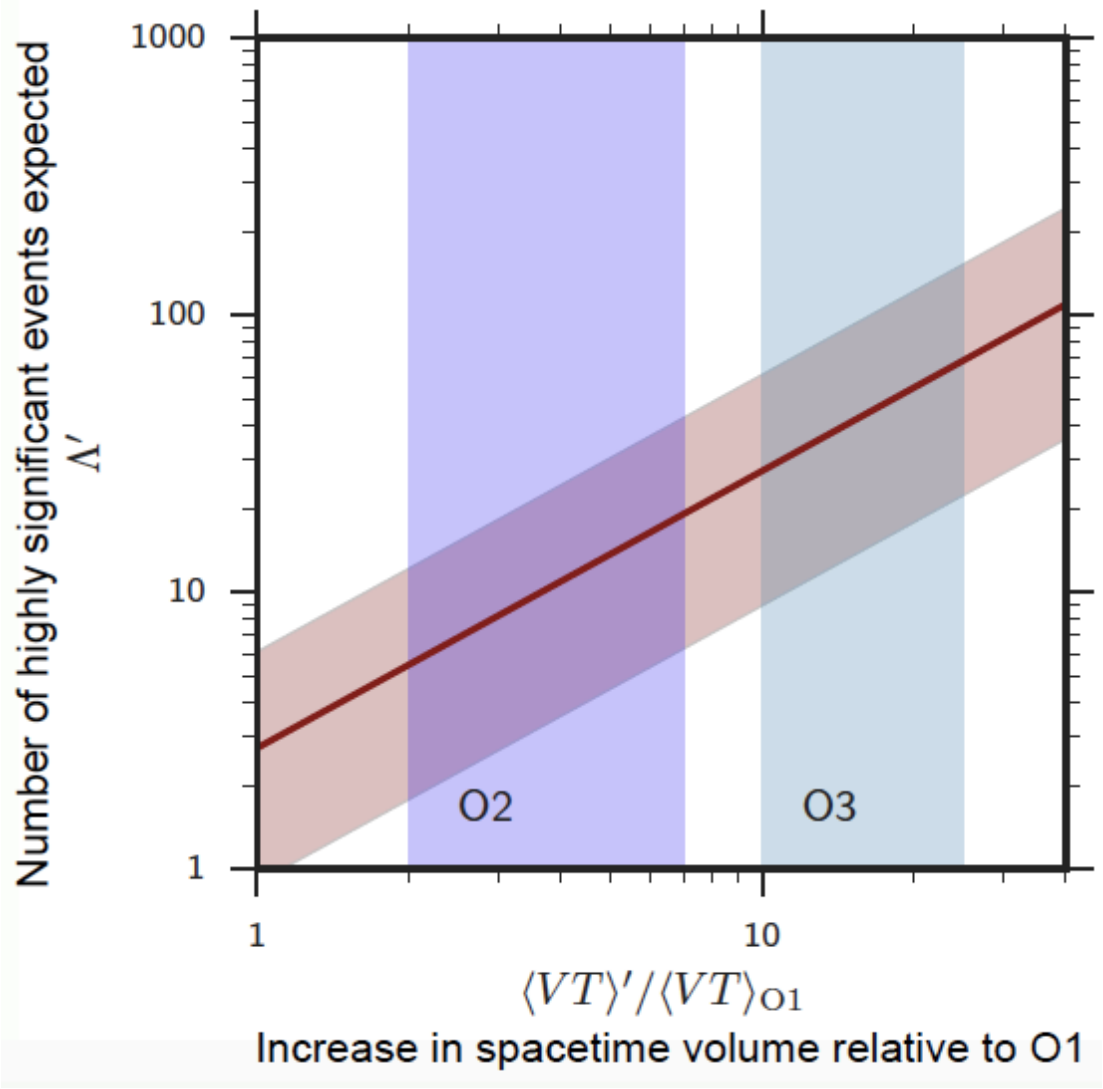

a)
H1
L1
10 ms light travel time
b)
H1
L1
Strain noise (Hz$^{-1/2}$)
10^{-21}
10^{-22}
10^{-23}
20
100
1000
Frequency (Hz)
Test Mass
Test Mass
L_y = 4 km
Power Recycling
Beam Splitter
L_x = 4 km
Laser Source
20 W
100 kW Circulating Power
Test Mass
Test Mass
Signal Recycling
Photodetector

Gravitational Wave Events in First Observing Run



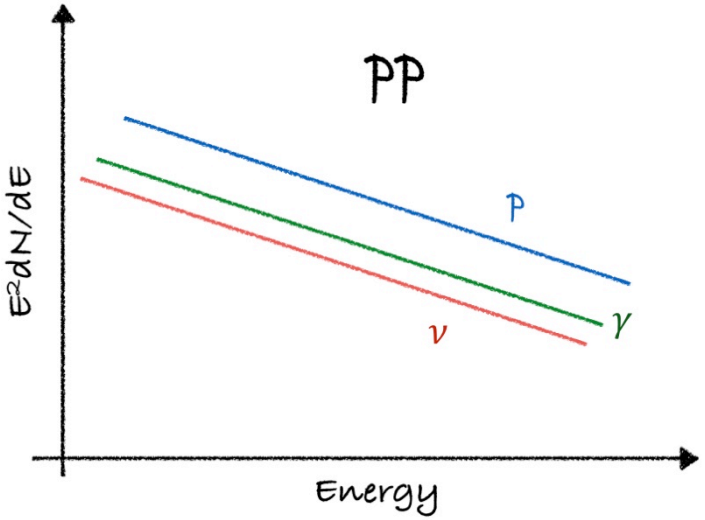
Abbott et al. (LIGO, Virgo Coll.), PRL (2016) 116, 061102

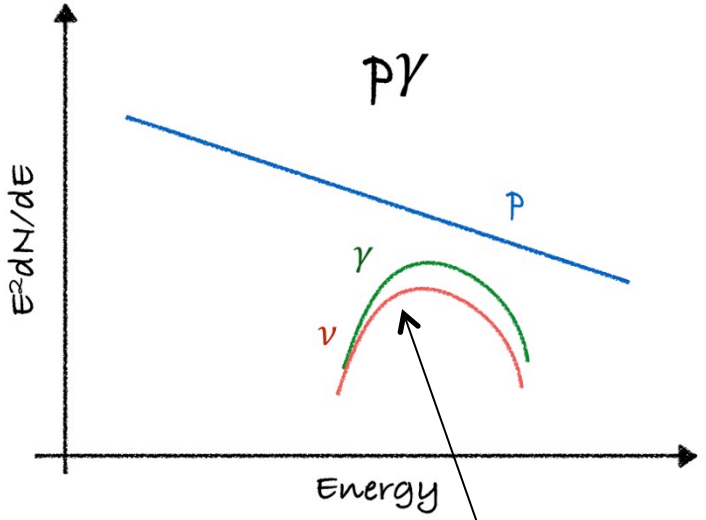
Expected Number of GW Events



Neutrino Production Processes

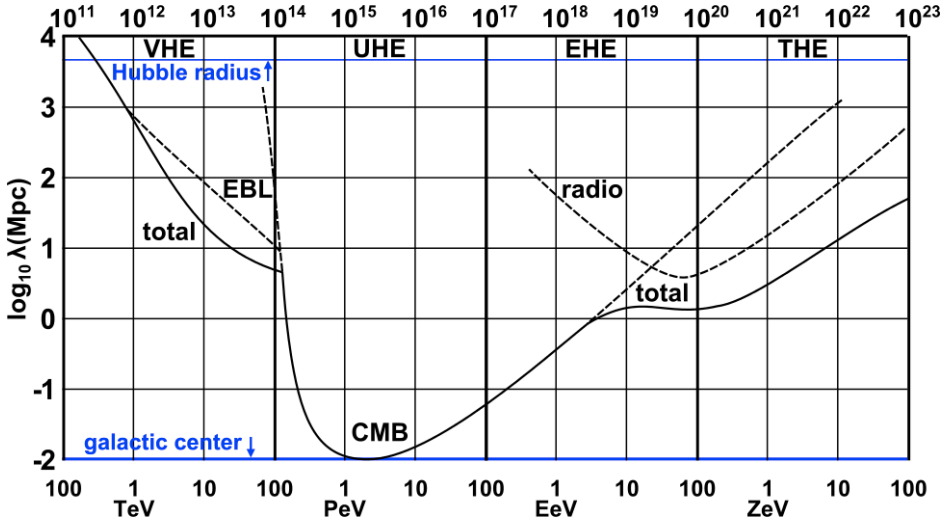
At the source



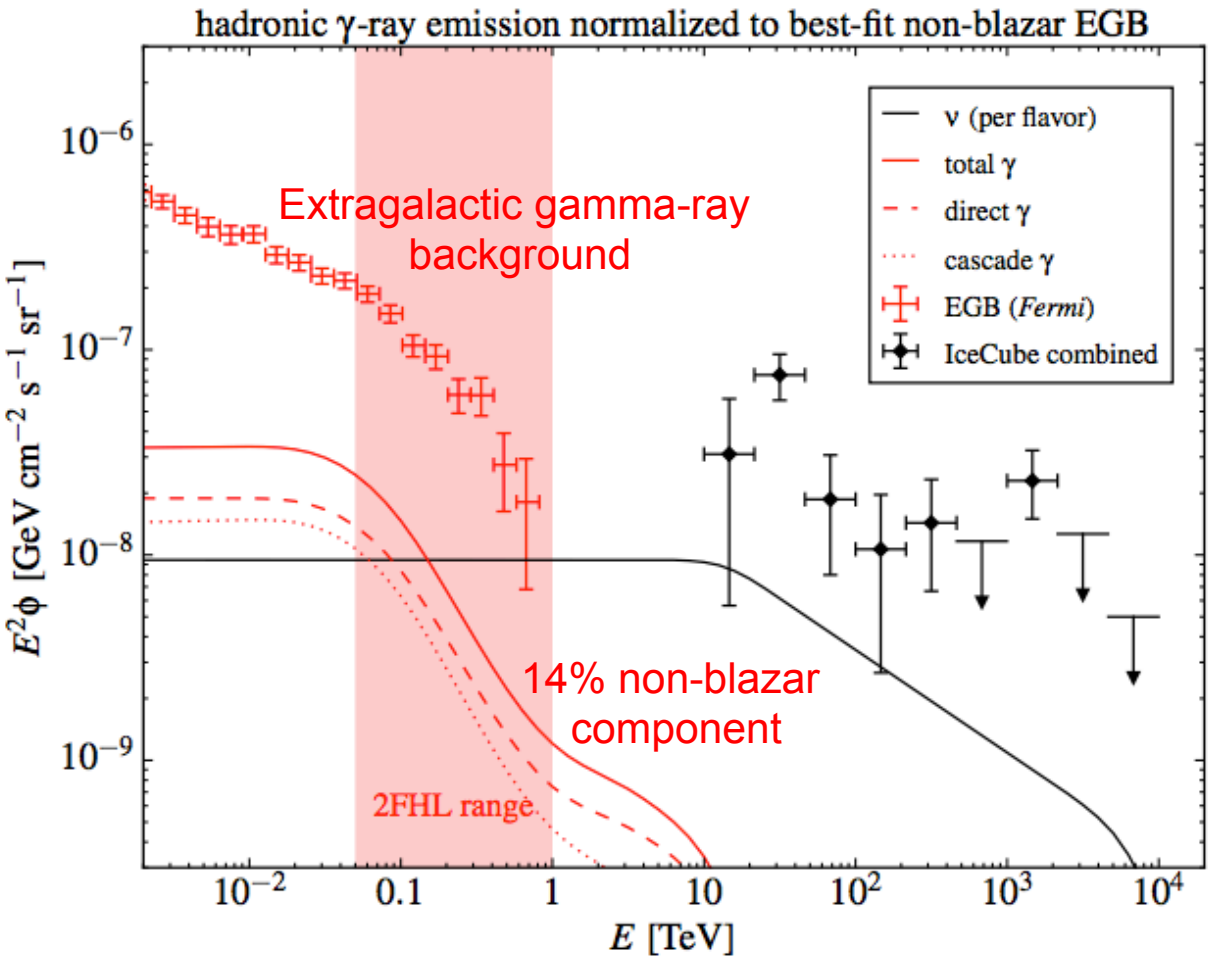


Peak position depends on photon field

High-energy photons will cascade down



Gamma-ray background disfavors pp Neutrino Sources



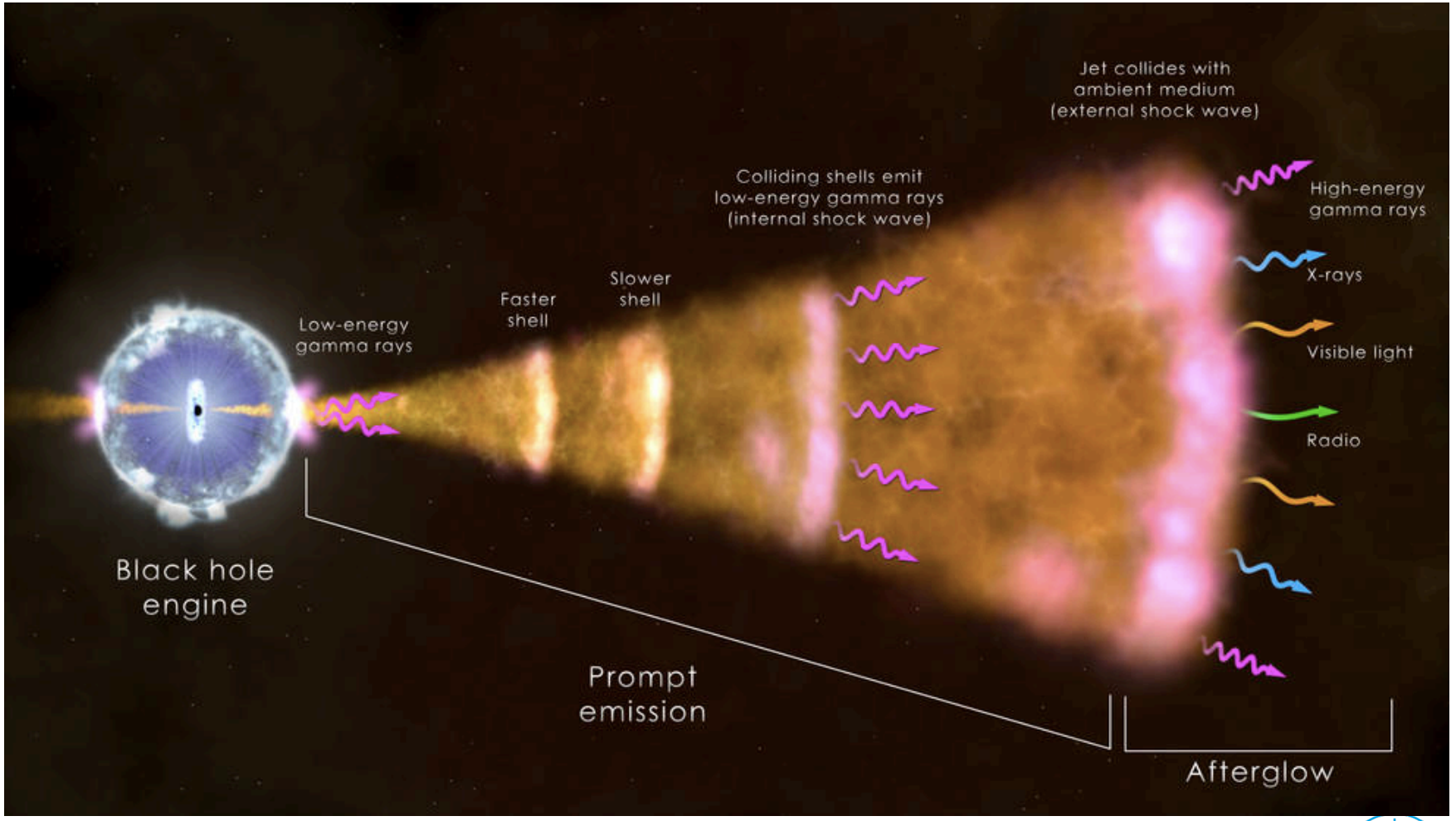
Starburst galaxies and galaxy clusters contribute less than 30% to the diffuse neutrino flux

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

Bechtol et al. arXiv:1511.00688

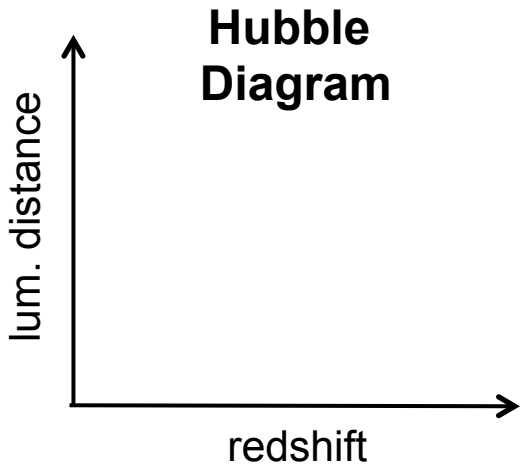
Gamma-Ray Bursts (GRBs)

> 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