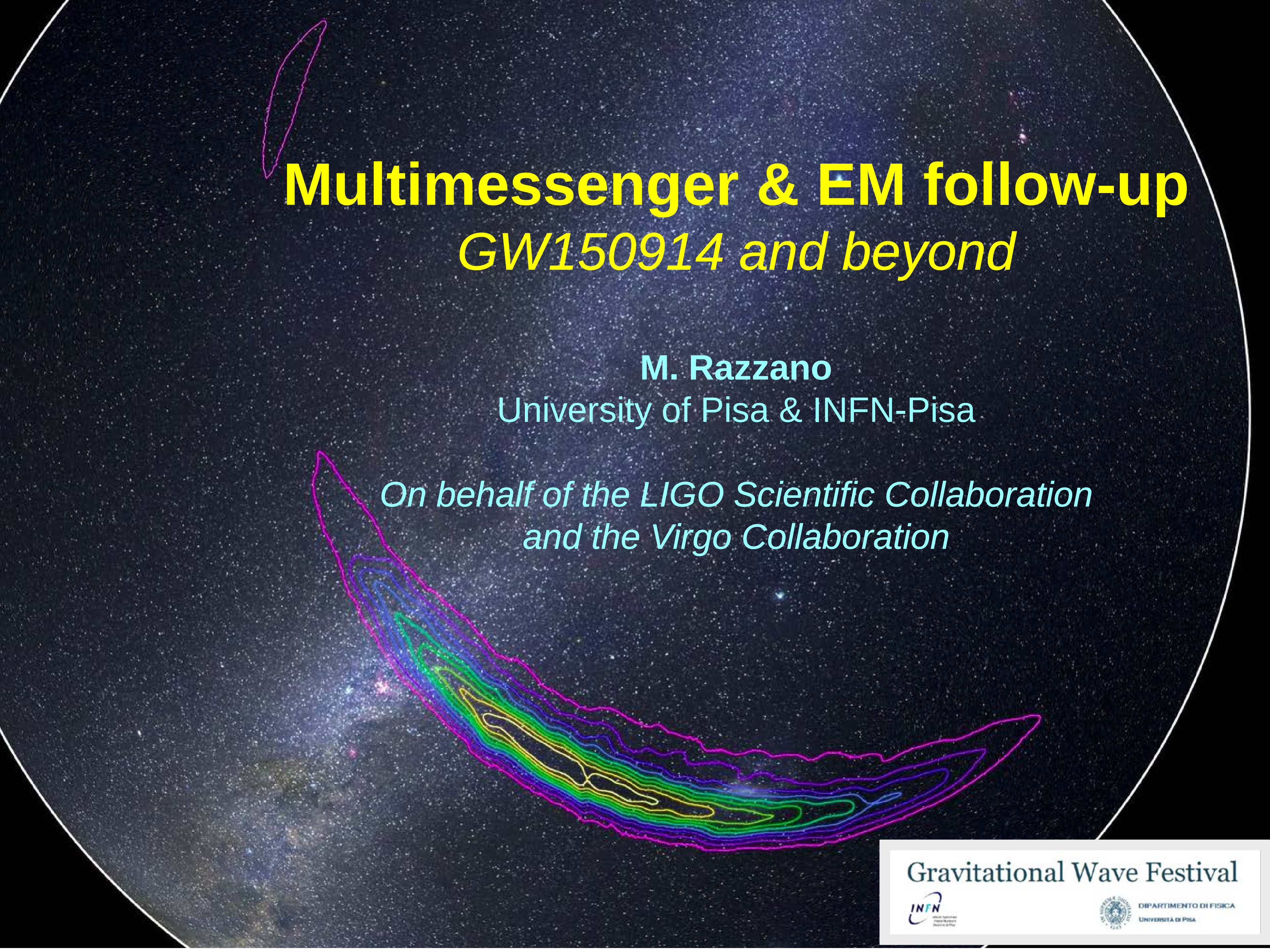


Multimessenger & EM follow-up

GW150914 and beyond

M. Razzano

University of Pisa & INFN-Pisa

On behalf of the LIGO Scientific Collaboration and the Virgo Collaboration

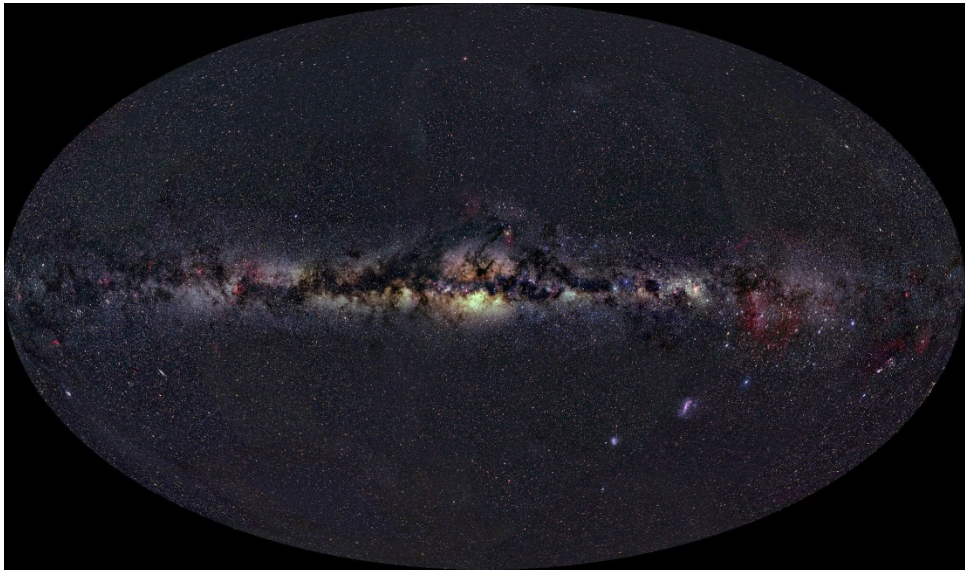
Gravitational Wave Festival

INFN

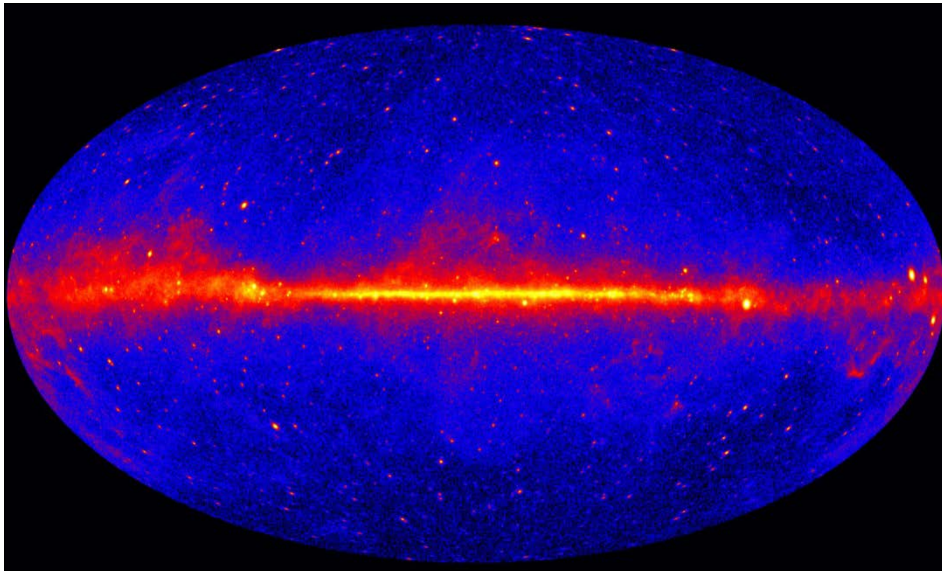
DIPARTIMENTO DI FISICA
UNIVERSITÀ DI PISA

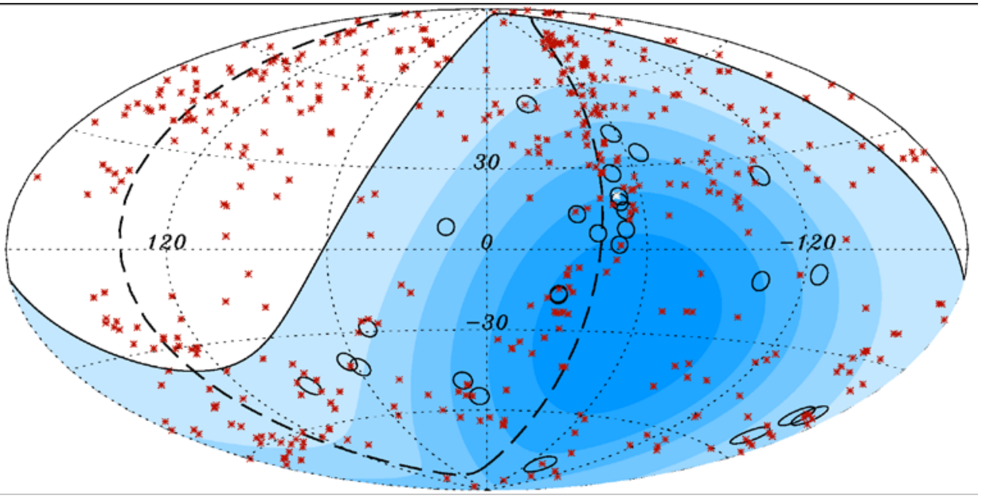
The multi-messenger sky today

Optical (APOD)

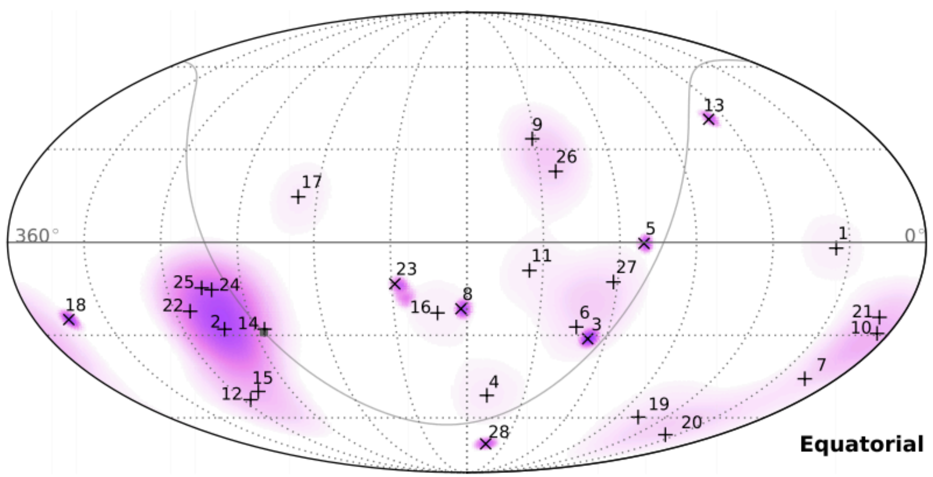


Gamma rays > 0.1 GeV (Fermi-LAT, 2013)





Cosmic rays > 57 Eev (Auger, 2007)



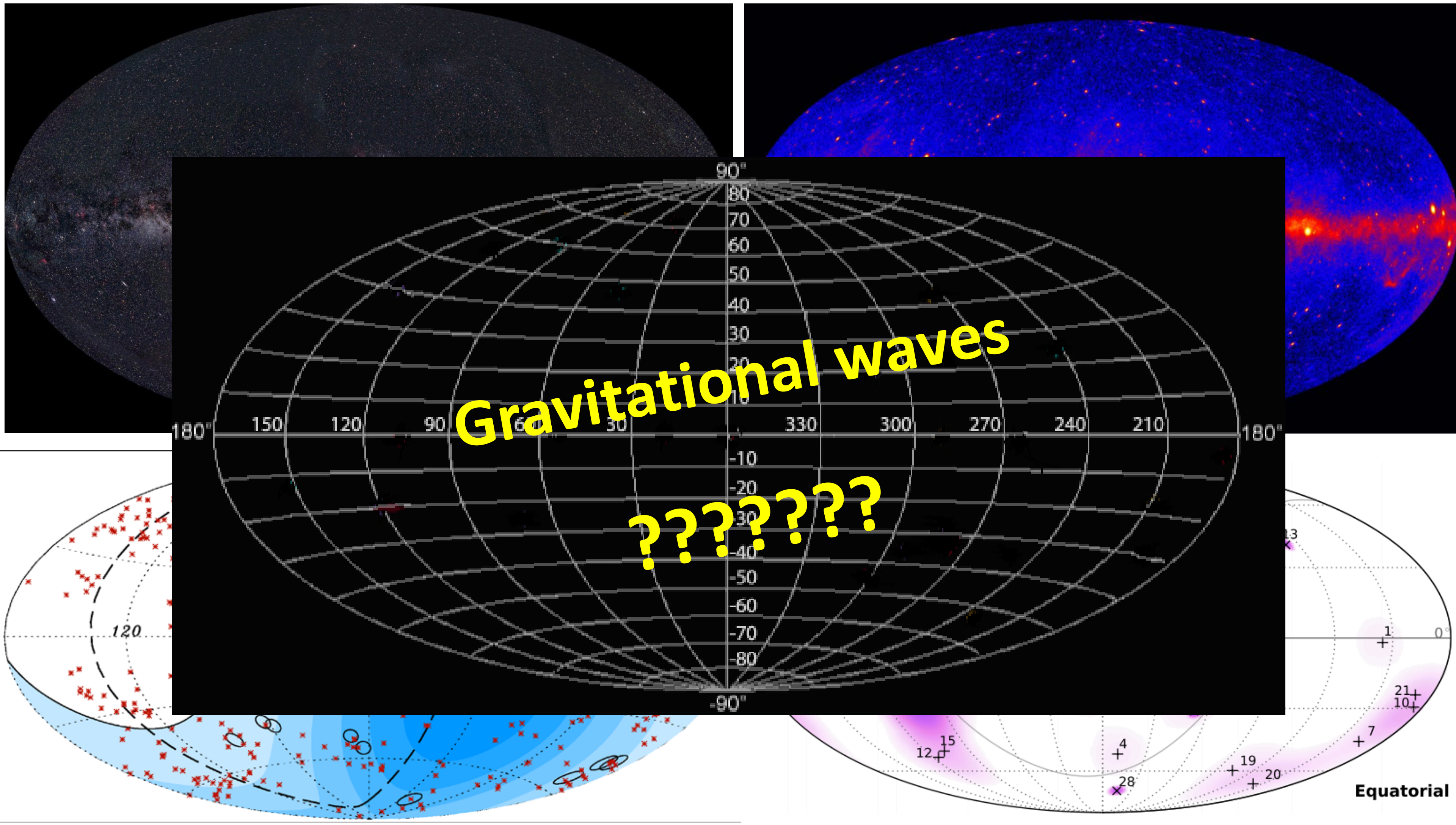
Neutrinos > 30 Tev (Icecube, 2013)

*

The multi-messenger sky today

Optical (APOD)

Gamma rays > 0.1 GeV (Fermi-LAT, 2013)



Cosmic rays > 57 Eev (Auger, 2007)

Neutrinos > 30 Tev (Icecube, 2013)

*

M. Razzano

Why joint multimessenger observations?

- **Complementary information:**
  - **GW→ mass distribution**
  - **EM → emission processes, environment**
  - **Neutrinos→ hadronic/nuclear processes, etc**

- **Give a precise (arcmin/arcsecond) localization (EM but not only)**
  - **Localize host galaxy of a merger**
  - **Identify an EM counterpart with timing signature (e.g. pulsars)**

- **Provide a more complete insight into the most energetic events in the Universe**

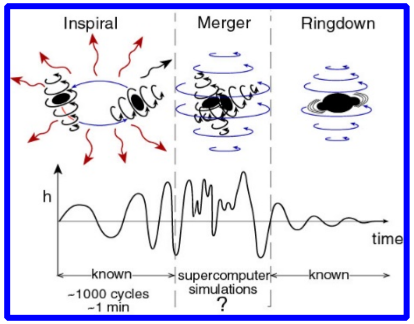
- **Explore the physics of the progenitors (mass, spin, distance..) and their environment (temperature, density, redshift..)**

- **Open a new era of multi-messenger (GW, photons, neutrinos, CR) physics**

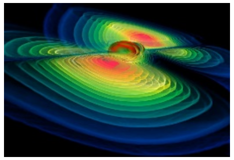
Expected multimessengers sources detectable by LIGO/Virgo

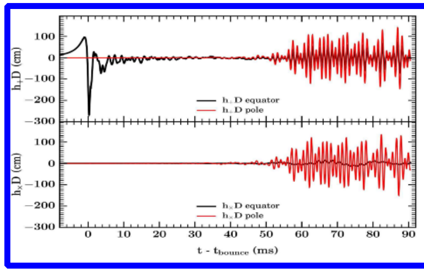
Transients

- **Coalescence of compact binary systems (NSs and/or BHs)**
  - Known waveforms (template banks)
  - $E_{gw} \sim 10^{-2}\ Mc^2$



- **Core-collapse of massive stars**
  - Uncertain waveforms
  - $E_{gw} \sim 10^{-8} – 10^{-4}\ Mc^2$

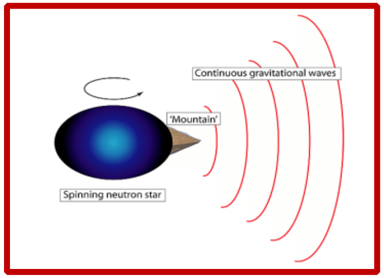




Ott, C. 2009

Non transients

- **Rotating neutron stars**
  - Quadrupole emission from star's asymmetry
  - Continuous and Periodic
- **Stochastic background**
  - Superposition of many signals (mergers, cosmological, etc)
  - Low frequency

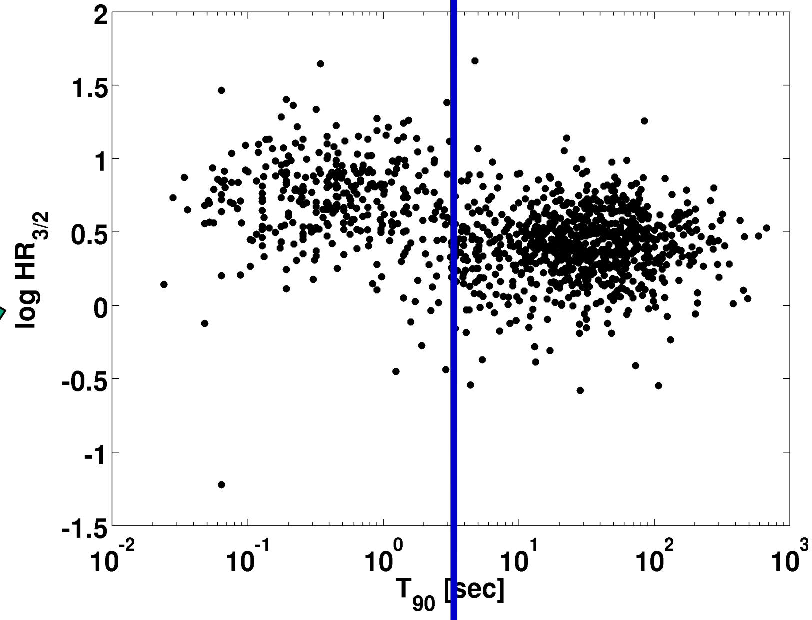


Multimessnger GW/EM: the GRB connection

Gamma Ray Bursts are intense flashes of gamma rays
Very Energetic (up to E_{iso} 10^{53} erg)

- **Short GRBs (<2 s)**

believed to be associated with mergers



Multimessenger observations
Key to test associations!

- **Long GRBs (>2 s)**
- **Believed to be associated with core-collapse of massive star**

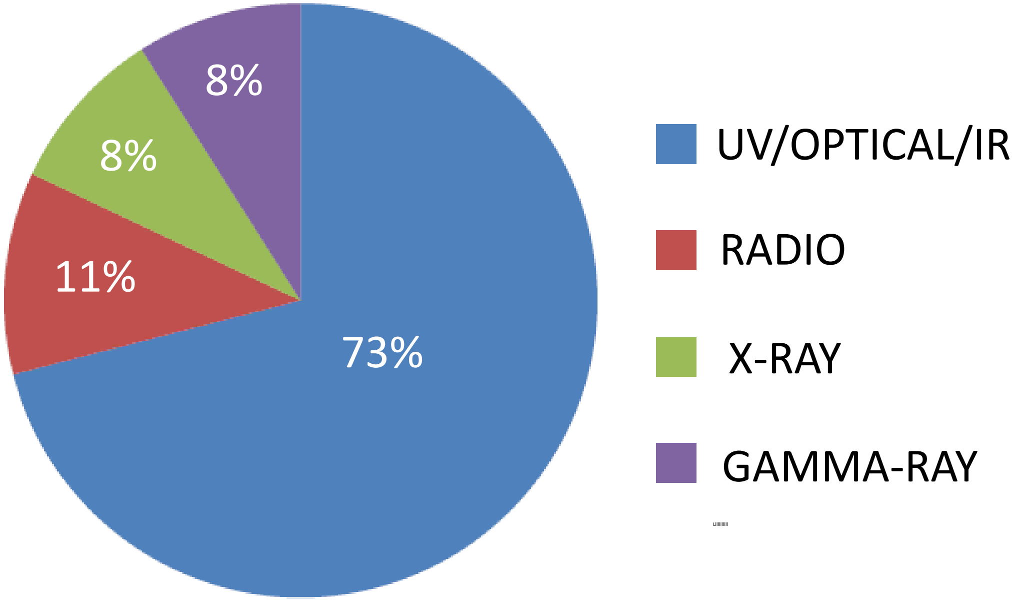
Why an EM follow-up program?

- **EM follow-up is key to find counterparts and do great science**
  - **GW analysis and checks will require time**
  - **Need to avoid misinformation/rumors**
  - **Encourage multiwavelength coverage**

- **EM follow-up program**
  - **Standard MoU to share information promptly while mantaining confidentiality for event candidates**
  - **Once first few (>=4) detections, prompt alerts will be made public for high-confidence detections**

- **Status**
  - **More than 70 groups have signed MoU with LIGO & Virgo**
  - **From radio to gamma rays**
  - **Special LVC GCN Notices and Circulars with distribution limited to partners**

LVC GW-EM follow-up program



74 MoUs involving

- **160 instruments**

(space and ground-based facilities)
Full coverage, radio - VHE

- **Astronomical institutions, agencies and large/small groups of astronomers** (20 countries)

In 2012, **LVC agreed policy on releasing GW alerts**

“Initially, ***triggers*** *(partially-validated event candidates) will be* ***shared promptly only with astronomy partners who have signed a Memorandum of Understanding*** *(MoU) with LVC involving an agreement on deliverables, publication policies, confidentiality, and reporting.*

After four GW events have been published*, further event candidates with high confidence will be* ***shared immediately with the entire astronomy community****, while lower-significance candidates will continue to be shared promptly only with partners who have signed an MoU.”*

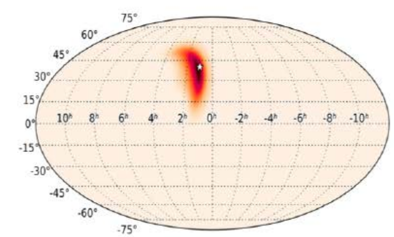
- The first (2014) and second (2015) open call for participation in GW-EM follow-up program (last year) **74 MoUs signed**

- **Third call issued, deadline 7 February 2016**
  http://www.ligo.org/scientists/GWEMalerts.php

The EM follow-up steps

- Past experience (2009-2010)
  - 30 min latency, optical telescopes+Swift
  - Centralized organization
- Now
  - Few mins latency
  - GCN for MoU partners
  - 74 participating in O1, 63 operating, 25 followed the event
  - 19 orders of magnitude

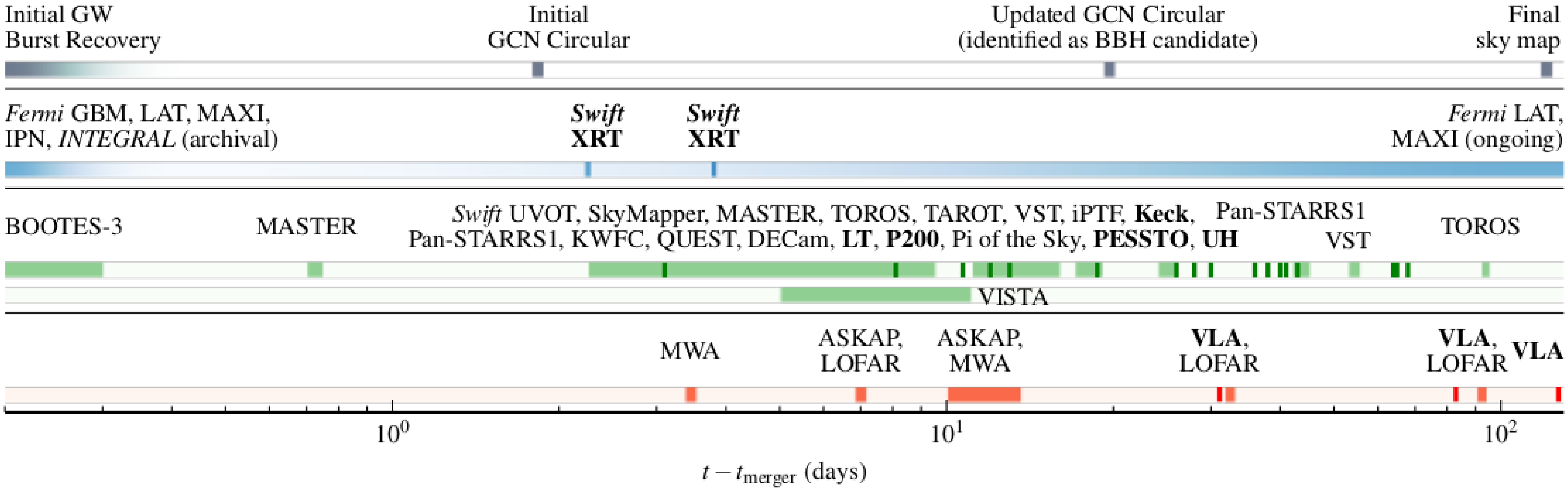
GW alert → Sky localization → EM follow-up



EM event	EM band	timescale
Prompt emission	Gamma rays	<s.
Afterglow	X-ray, optical, radio	Hours-days
Kilonova-macronova	Optical-near IR	Days-months
Radio blast wave	Radio	Monhts-years

GW150914 follow-up timeline

- t+3 minutes: cWB & oLIB pipelines
    - T+17 min – 14 hr (skymaps)
        - T+2d: first GCN
            - T+3w: BBH identification
                - T+4m: updated FAR (<1/100 yr)



Abbott+16 (arXiv:1602.08492)

GW150914 sky maps

Skymaps pipelines

- cWB: constrained ML
- OLIB: bayesian
- BAYESTAR: triangulation (based on CBC pipelines)
- LALInference: full details

	Area[a]			$\theta_{\rm HL}$[b]	Comparison[c]			
	10%	50%	90%		cWB	LIB	BSTR	LALInf
cWB	10	100	310	43^{+2}_{-2}	—	190	180	230
LIB	30	210	750	45^{+6}_{-5}	0.55	—	220	270
BSTR	10	90	400	45^{+2}_{-2}	0.64	0.56	—	350
LALInf	20	150	620	46^{+3}_{-3}	0.59	0.55	0.90	—

[a] Area of credible level ($\deg^2$). Note that the LALInference area is consistent with but not equal to the number reported in Abbott et al. (2016e) due to minor differences in sampling and interpolation.

[b] Mean and 10% and 90% percentiles of polar angle in degrees.

[c] Fidelity (below diagonal) and the intersection in $\deg^2$ of the 90% confidence regions (above diagonal).

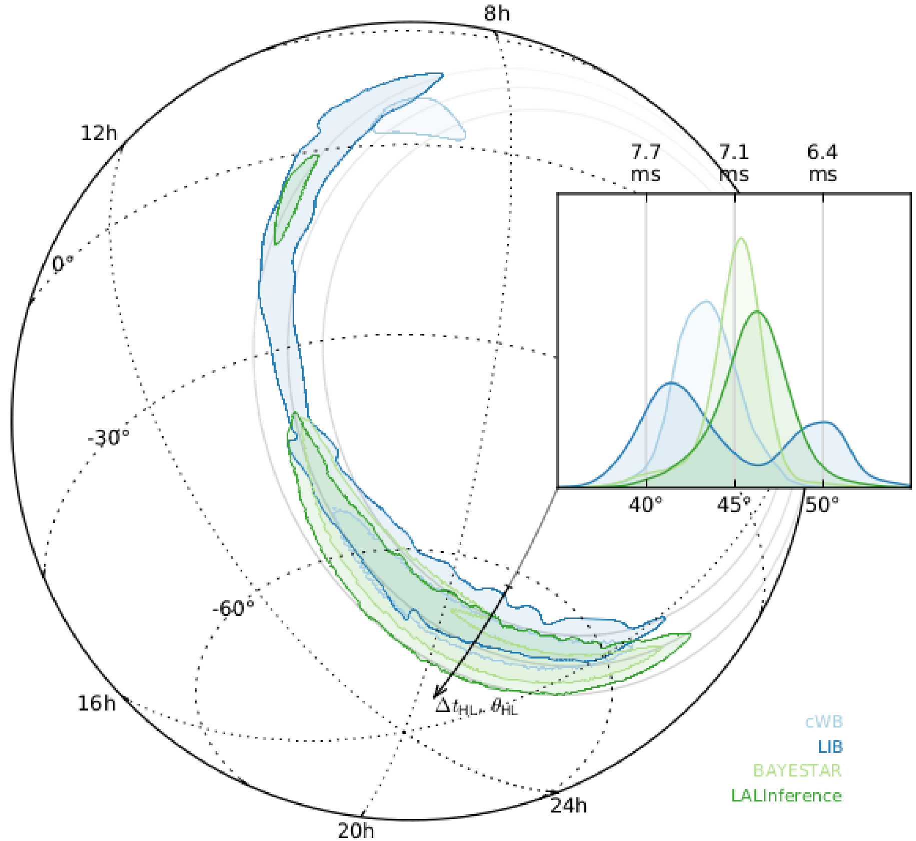
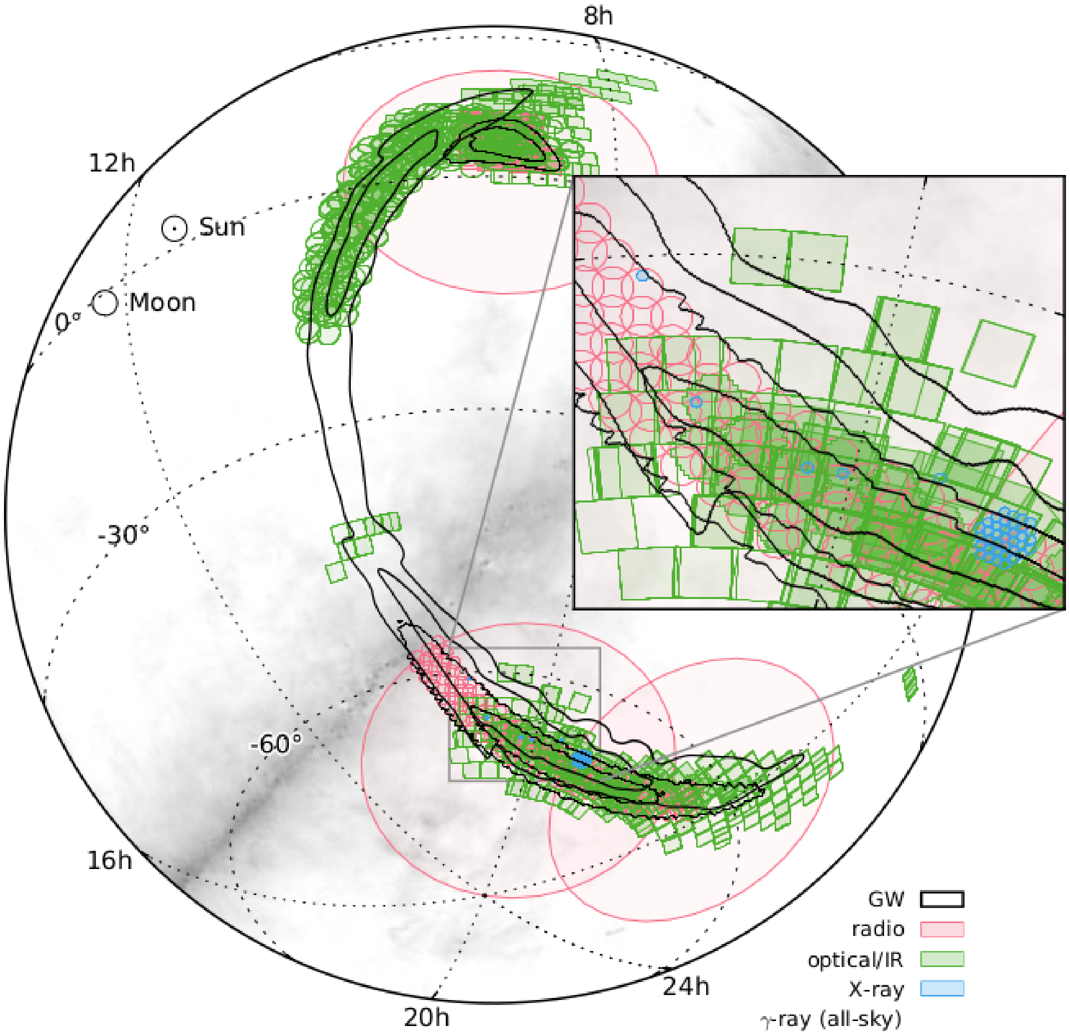


Figure 2. Comparison of different GW sky maps, showing the 90% credible level contours for each algorithm. This is an orthographic projection centered on the centroid of the LIB localization. The inset shows the distribution of the polar angle $\theta_{\rm HL}$ (equivalently, the arrival time difference $\Delta t_{\rm HL}$).

Abbott+16 (arXiv:1602.08492)

GW150914 coverage

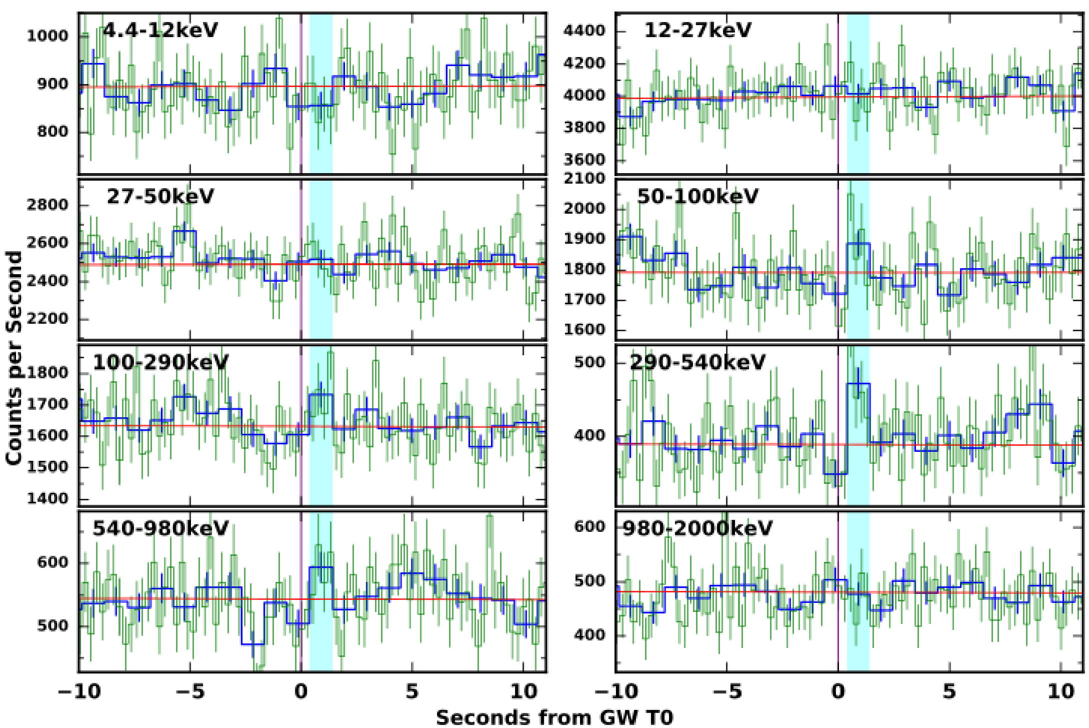
- 19 teams involved
- Repointing (optical)
- Archival (X & gamma)
- Deep follow-up (optical/radio)

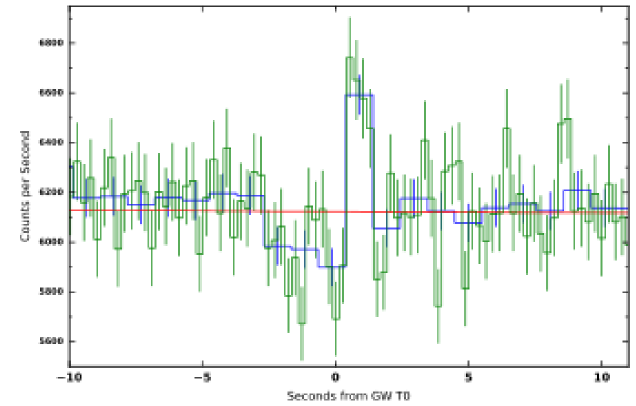


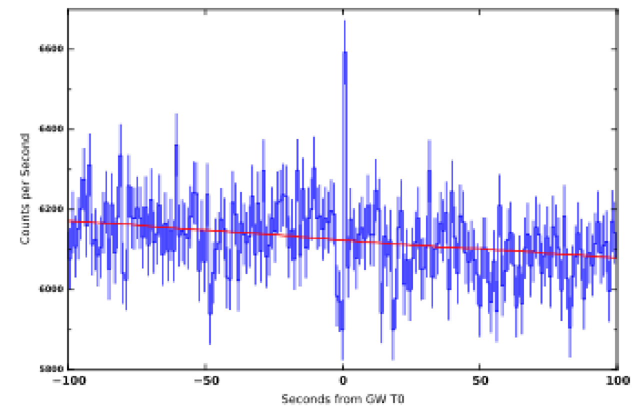
Abbott+16 (arXiv:1602.08492)

The GBM transient

- Detector:
  - Full unocculted sky
  - Scintillators, from keV to ~30MeV
  - No triggers from standard onboad or offline pipelines
- Results
  - Specific “subthreshold” pipeline (Blackburn+15)
  - dt ~0.4s, lasting ~1 sec
  - Estimated FAR = 0.002
  - Localization 199 sq deg, close to Earth limb
  - Spectrum: PL + cutoff
  - Estimated flux: 1.8e49 erg/s
  - Trial factors?



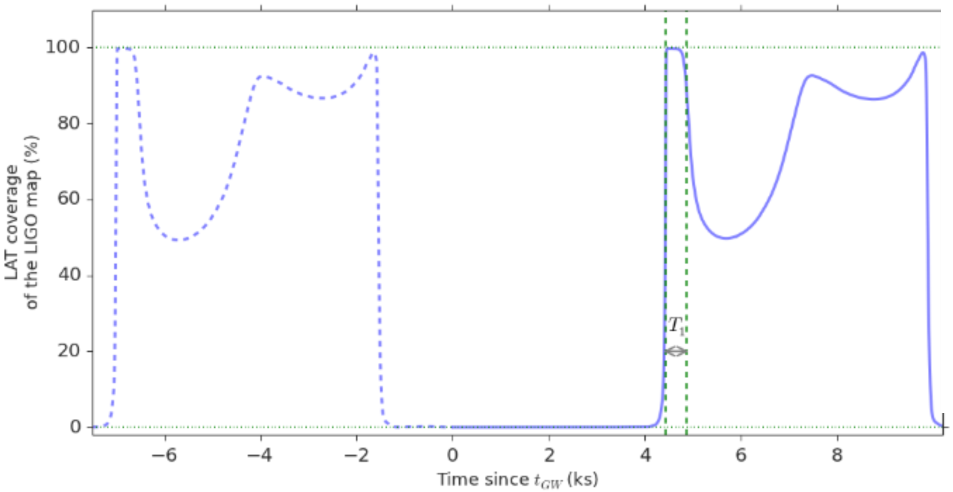




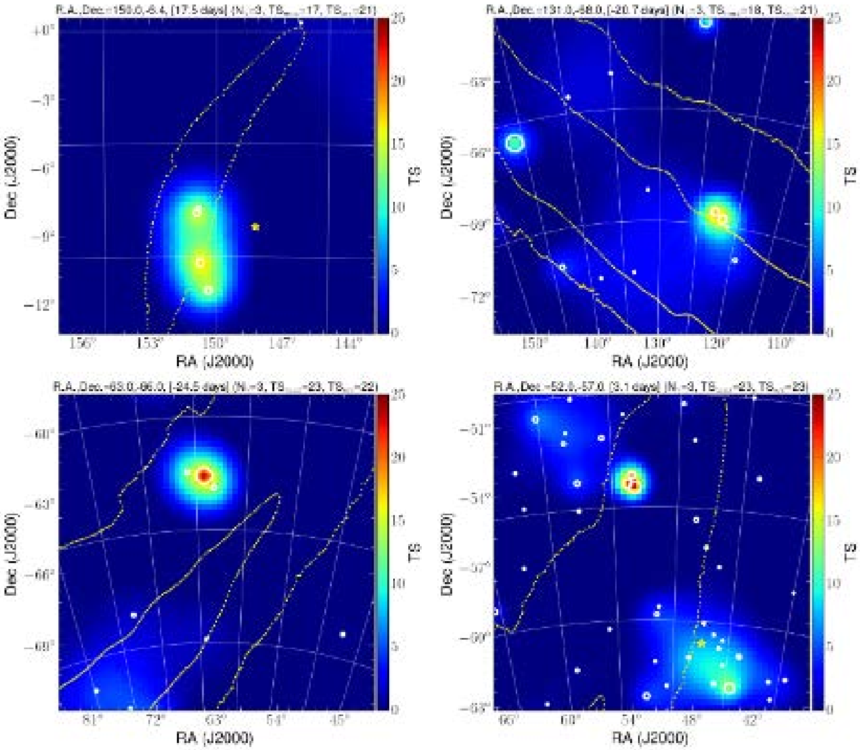
Connaughton+16
(arxiv:1602.03920)

The view of the Fermi-LAT

- **Other analysis by high-energy facilities to confirm/disprove GBM transient**
- Fermi LAT
  - Large fov (2.4 sr), survey mode (t=95 m)
  - High-energy (>100 MeV) gamma rays
  - Results:
    - Coverage started from t+70 m
    - No triggers on automatic pipeline
    - No significant excesses on short and long-based ad hoc pipelines



LAT coverage

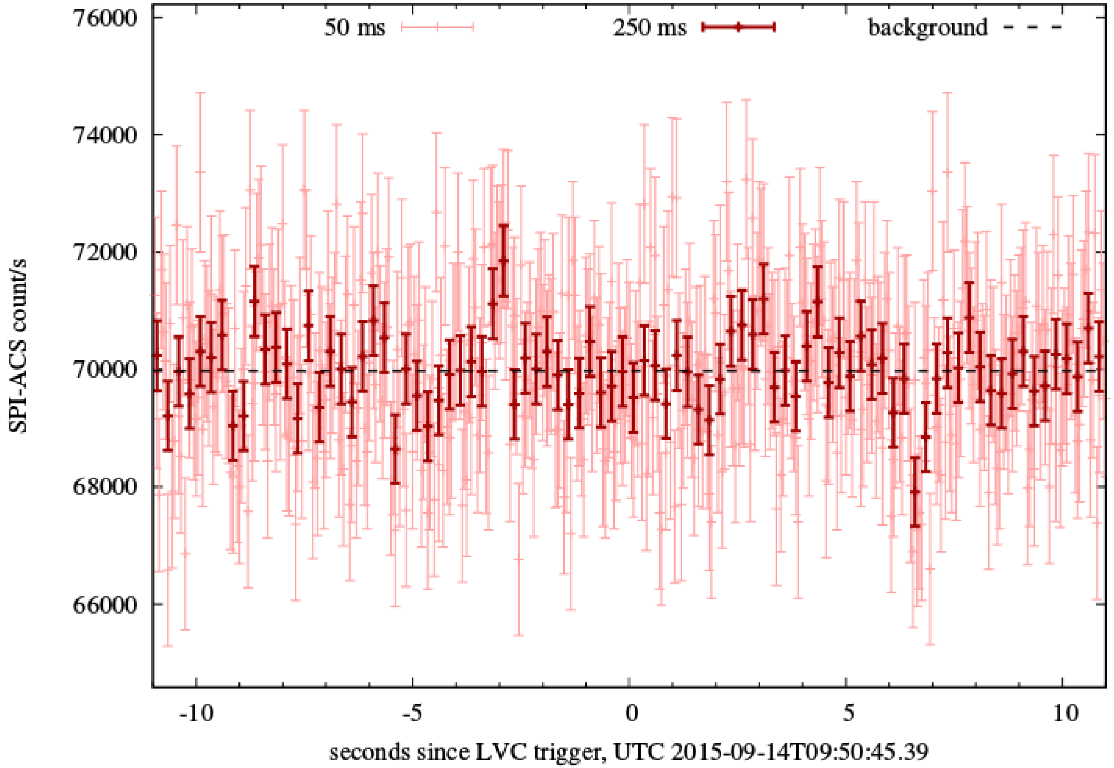


Top sources in 60-day window

Ackermann+16 (arxiv:1602.04488)

The view of INTEGRAL and Swift

- INTEGRAL
  - SPI-ACS: all-sky monitor, E>75 keV
  - Operating during the GW trigger
  - Peak of 0.5 s at t+26.4 s
  - Effective area 30-40 x GBM one
  - F<1e48 erg/s
- Swift
  - 2% oLIB
  - No new sources
  - Evans+16 (arxiv:1602.04735)



LAT coverage

Savchenko+16
(arxiv:1602.04180)

Optical, IR, radio

- Optical
  - Tiled and galaxy-oriented
  - Tens of candidates, later observed deeper
  - Candidates compatible with normal population of SN, AGN, etc..
- Radio coverage up to t+4 months

				Optical					
DECam	i, z	$i < 22.5$, $z < 21.5$	3.9, 5, 22	100	38	14	14	11	18344, 18350
iPTF	R	$R < 20.4$	3.1, 3, 1	140	3.1	2.9	0.0	0.2	18337
KWFC	i	$i < 18.8$	3.4, 1, 1	24	0.0	1.2	0.0	0.1	18361
MASTER	C	< 19.9	-1.1, 7, 7	590	56	35	55	49	18333, 18390, 18903, 19021
Pan-STARRS1	i	$i < 19.2 - 20.8$	3.2, 21, 42	430	28	29	2.0	4.2	18335, 18343, 18362, 18394
La Silla–QUEST	g, r	$r < 21$	3.8, 5, 0.1	80	23	16	6.2	5.7	18347
SkyMapper	i, v	$i < 19.1$, $v < 17.1$	2.4, 2, 3	30	9.1	7.9	1.5	1.9	18349
Swift UVOT	u	$u < 19.8$ (gal.)	2.3, 1, 1	3	0.7	1.0	0.1	0.1	18331
	u	$u < 18.8$ (LMC)	3.4, 1, 1						18346
TAROT	C	$R < 18$	2.8, 5, 14	30	15	3.5	1.6	1.9	18332, 18348
TOROS	C	$r < 21$	2.5, 7, 90	0.6	0.03	0.0	0.0	0.0	18338
VST	r	$r < 22.4$	2.9, 6, 50	90	29	10	14	10	18336, 18397
				Near Infrared					
VISTA	Y, J, K_S	$J < 20.7$	4.8, 1, 7	70	15	6.4	10	8.0	18353
				Radio					
ASKAP	863.5 MHz	5–15 mJy	7.5, 2, 6	270	82	28	44	27	18363, 18655
LOFAR	145 MHz	12.5 mJy	6.8, 3, 90	100	27	1.3	0.0	0.1	18364, 18424, 18690
MWA	118 MHz	200 mJy	3.5, 2, 8	2800	97	72	86	86	18345

Theoretical interpretations

- General consensus
  - Stellar BBH do not produce EM emission
- However..
  - Very dense environments
  - Maybe not BHs? (strange stars, etc..)
  - Fragmentation of a massive core
  - 12 papers citing GBM (and counting)

Draft version February 24, 2016
Preprint typeset using LaTeX style emulateapj v. 5/2/11

ELECTROMAGNETIC COUNTERPARTS TO BLACK HOLE MERGERS DETECTED BY LIGO

Abraham Loeb[1]

Draft version February 24, 2016

ABSTRACT

Mergers of stellar-mass black holes (BHs), such as GW150914 observed by LIGO, are not expected to have electromagnetic counterparts. However, the Fermi GBM detector identified a γ-ray transient 0.4 s after the gravitational wave (GW) signal GW150914 with consistent sky localization. I show that the two signals might be related if the BH binary detected by LIGO originated from two clumps in a dumbbell configuration that formed when the core of a rapidly rotating massive star collapsed. In that case, the BH binary merger was followed by a γ-ray burst (GRB) from a jet that originated in the accretion flow around the remnant BH. A future detection of a GRB afterglow could be used to determine the redshift and precise localization of the source. A population of standard GW sirens with GRB redshifts would provide a new approach for precise measurements of cosmological distances as a function of redshift.

Loeb+16
(arxiv:1602.04735)

Fermi GBM signal contemporaneous with GW150914 - an unlikely association

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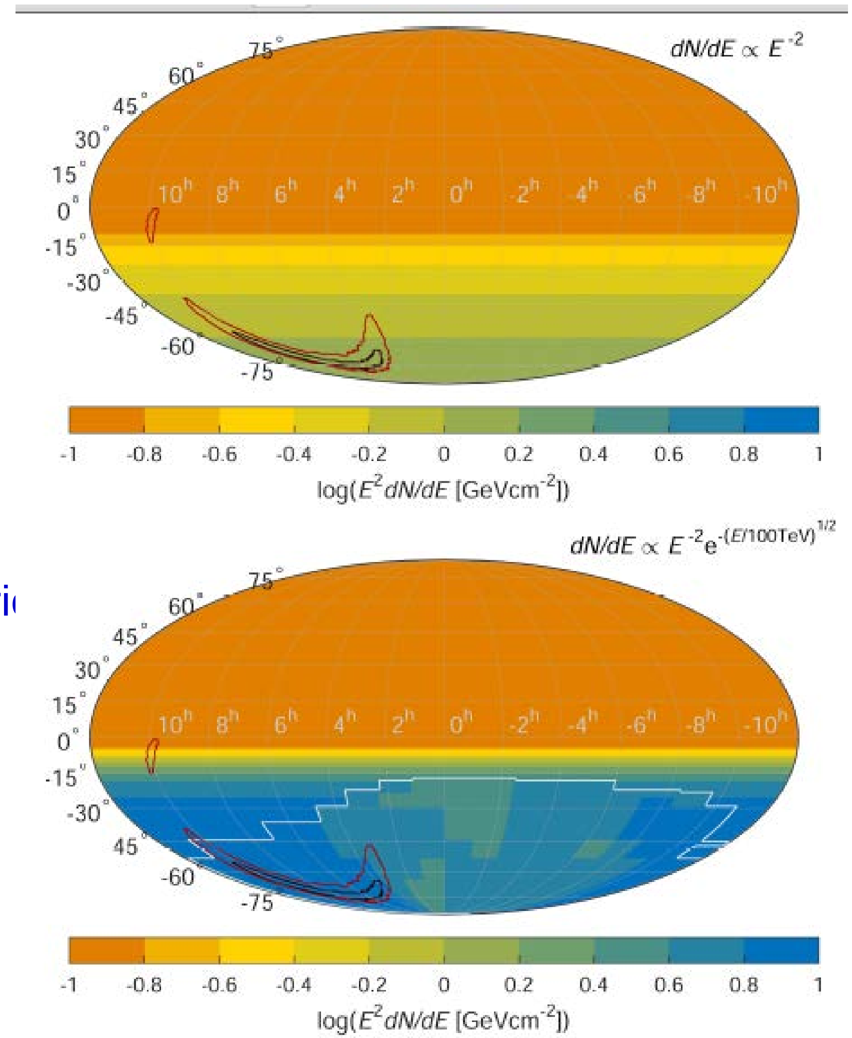
ABSTRACT

The physical constraints required by the association of the Fermi GBM signal contemporaneous with GW150914 - radiative power of 10^{49} erg s^{-1}, and corresponding magnetic fields on the black hole of the order of 10^{12} Gauss - are astrophysically highly implausible. Combined with the relatively high random probability of coincidence of 0.22 percents, we conclude that the electromagnetic signal is likely unrelated to the BH merger.

Lyutikov+16
(arxiv:1602.07352)

Multimessenger: GW+neutrinos

- IceCube and ANTARES operational
  - Search for coincident emission
  - Joint detection would provide good angular resolution
- Results
  - No neutrinos coincident with GW150914
  - Within 500 s, 3(0) neutrinos detected by IceCube(ANTARES), consistent with atmospheric neutrino
  - Constrain the source → E_{vtot}<1e52-1e54 erg



ANTARES+IceCube+LSC+Virgo
(arxiv:1602.05411)

Conclusions

- GW and photons provide complementary information
  - Multimessenger observations extremely promising
- Multimessenger approach is key to study the most extreme objects in the Universe
  - Natural laboratories to probe fundamental physics
  - Transients (e.g. GRBs)
  - Also, other sources (e.g. neutron stars)
- GW150914 provided a first test for EM follow-up campaign
  - Great synergy and coverage
  - Suggested interesting theoretical scenarios
- Future
  - Not just BBH: what about BNS/NSBH?
  - Order 1e5 galaxies: EM counterpart is key to understand the source
  - Virgo contribution crucial to improve localization

A new, growing community*

ready for the new challenges of the gravitational wave physics

*New perspectives on the violent Universe: unveiling the physics of compact objects with joint observations of gravitational waves and electromagnetic radiation (FIRB 2012, Branchesi, Razzano, Mapelli)