Cosmic Sounds
the multimessenger revolution

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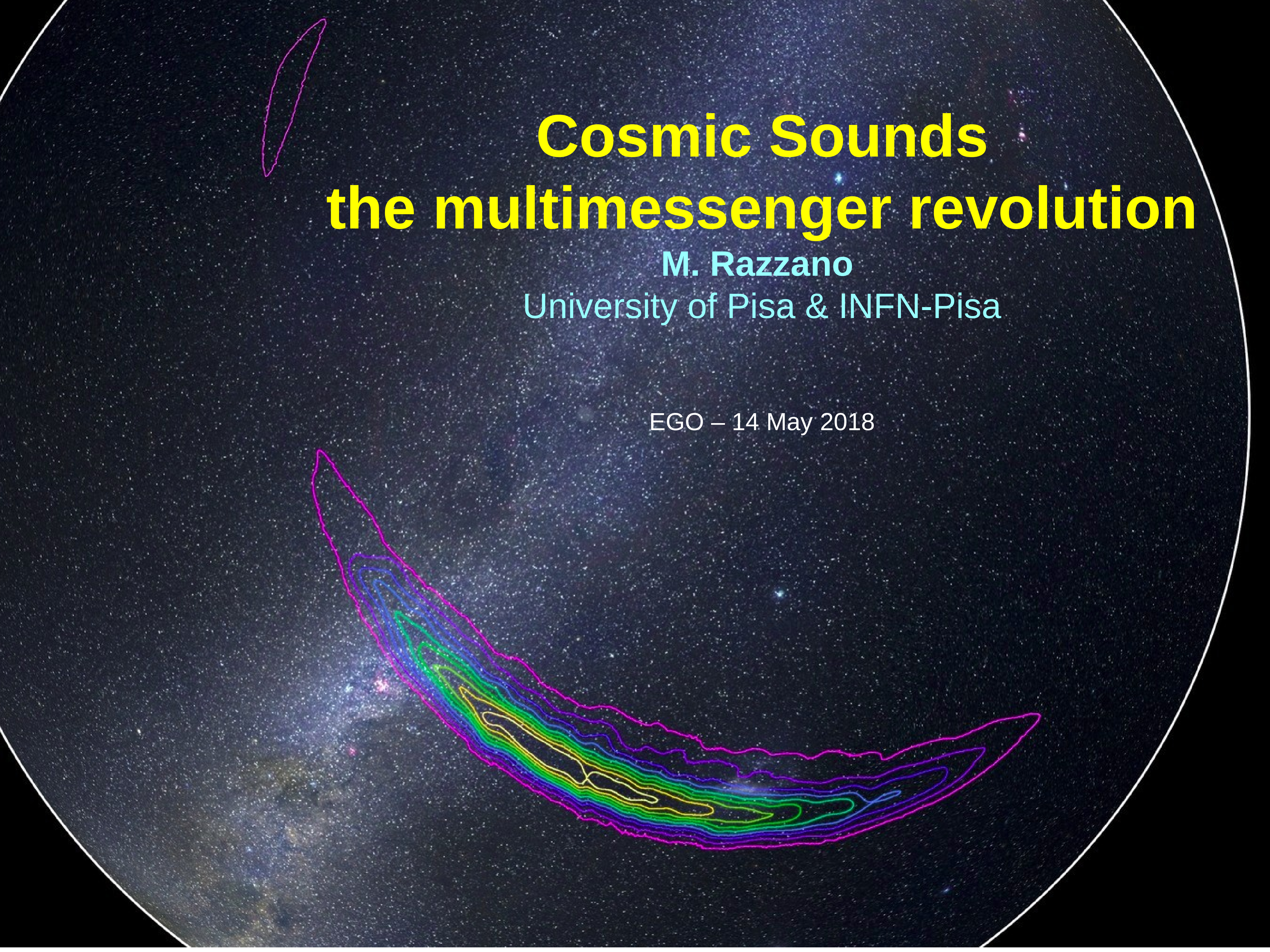
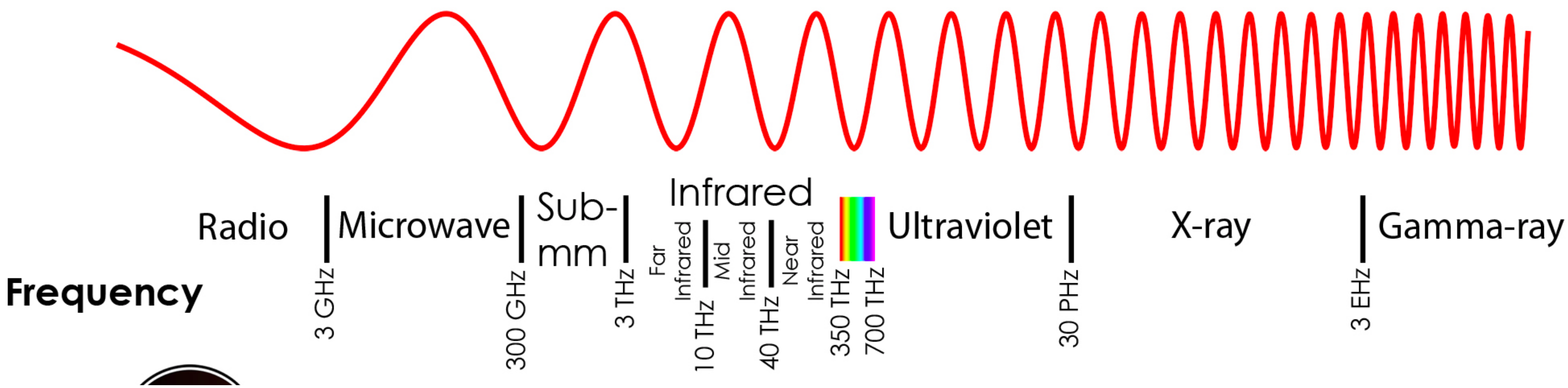
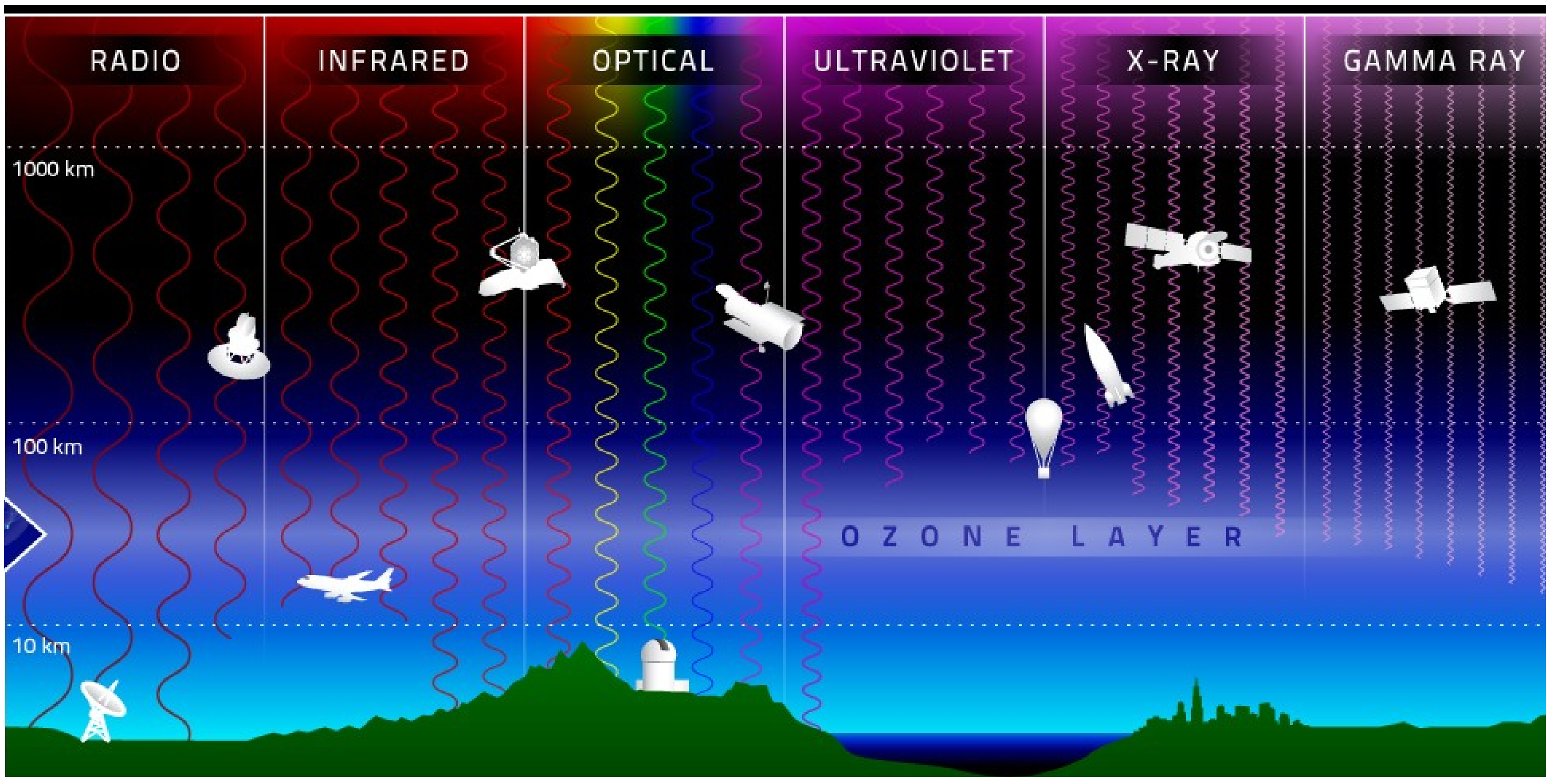
EGO – 14 May 2018



The multiwavelength sky





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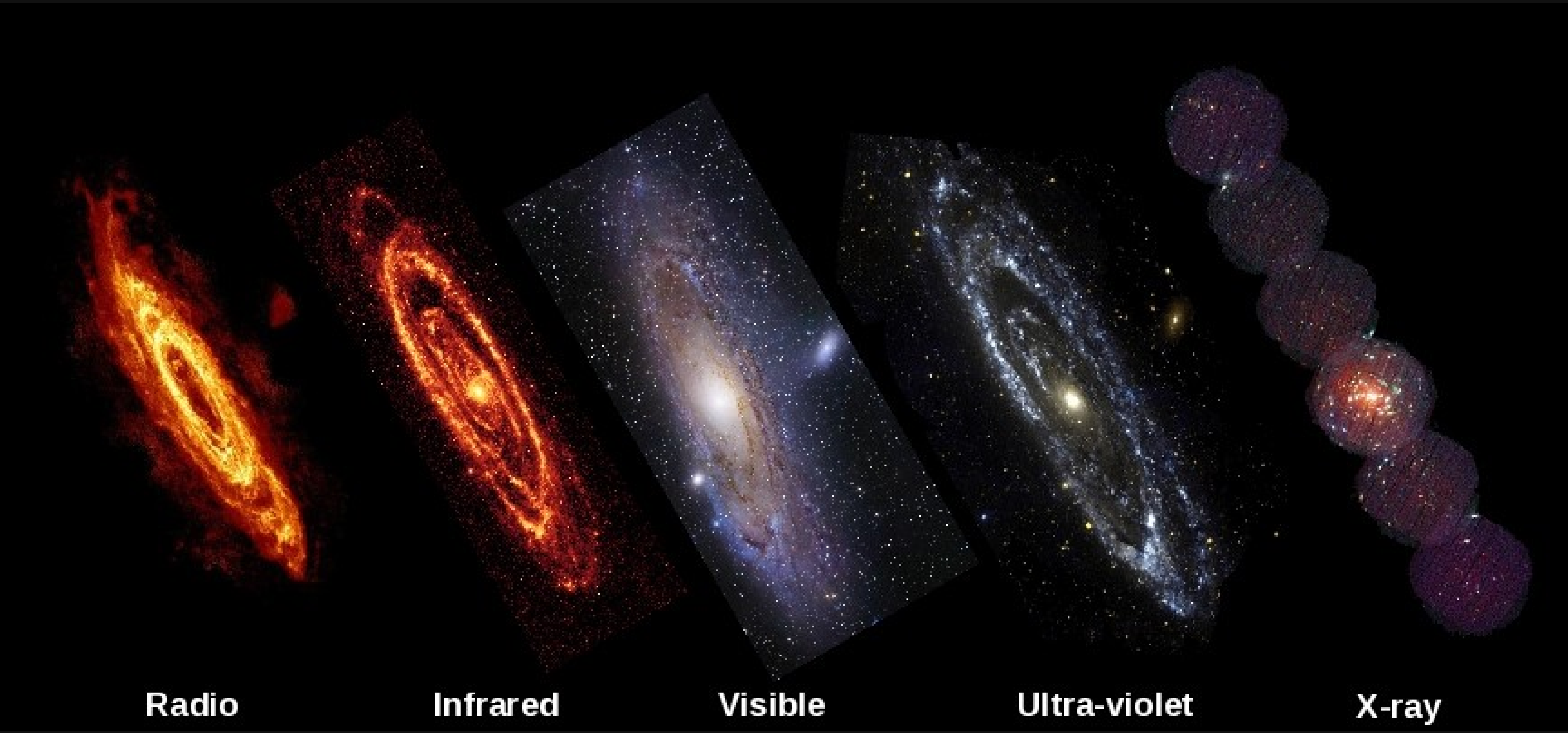
M31 (Andromeda Galaxy) in visible...

...and at other wavelengths



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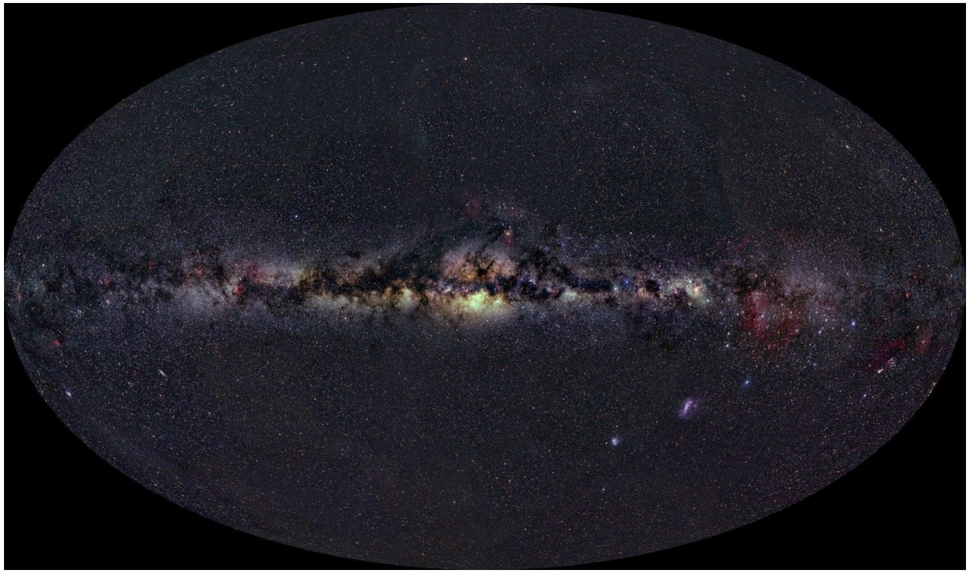
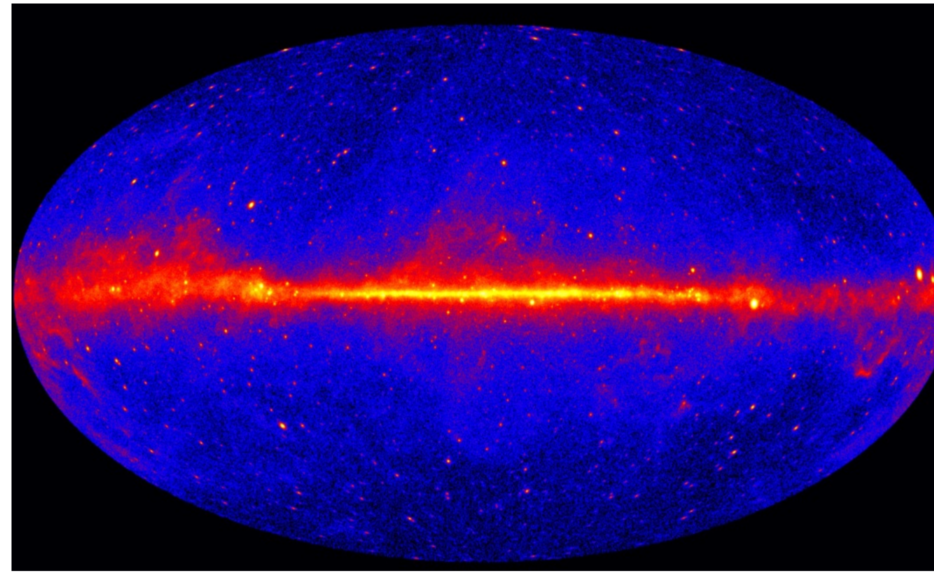
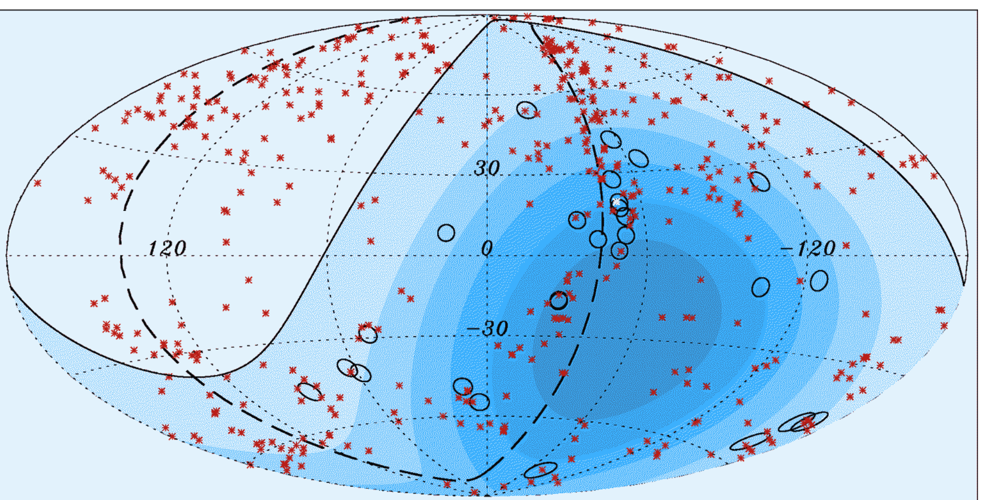
The multi-messenger sky today

Optical (APOD)

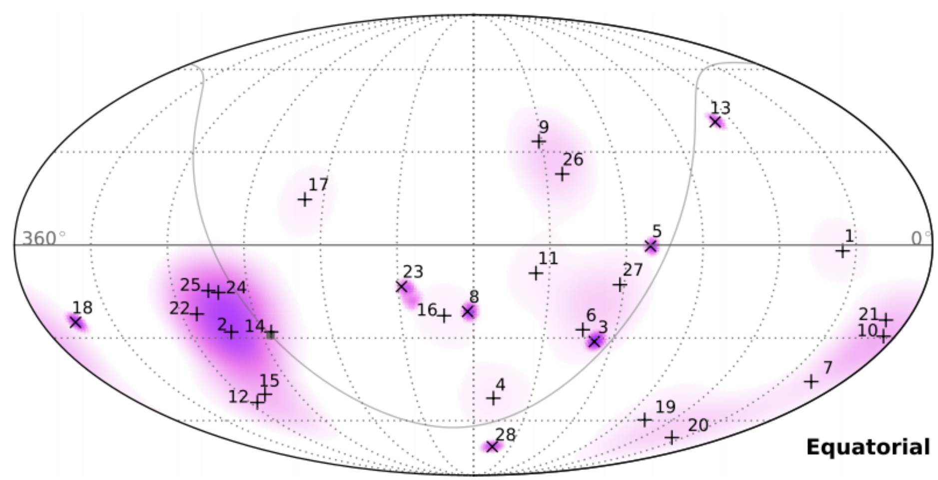


Gamma rays > 0.1 GeV (Fermi-LAT)





Cosmic rays > 57 Eev (Auger, 2007)



Neutrinos > 30 Tev (Icecube, 2013)

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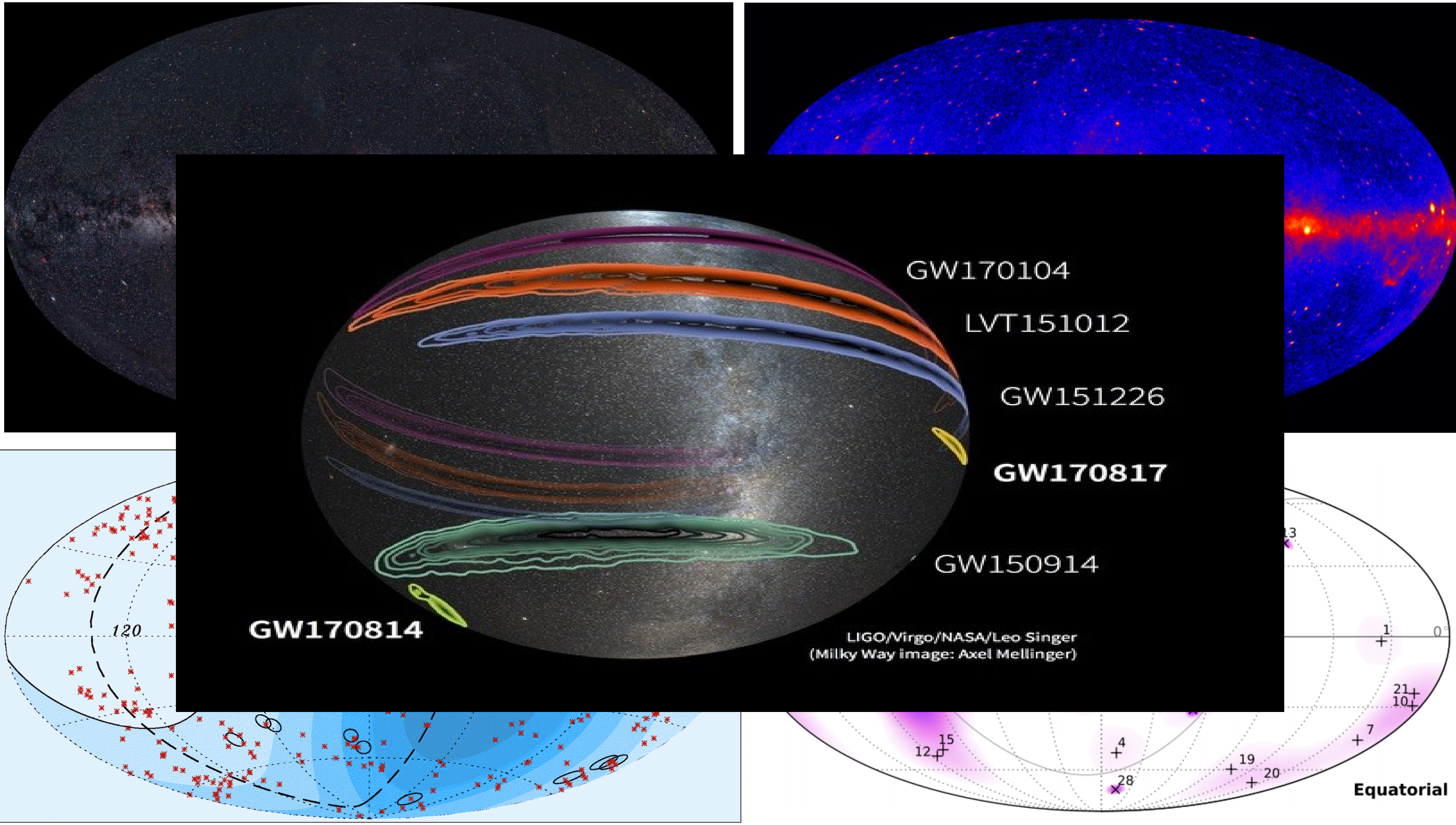
The multi-messenger sky today

Optical (APOD)

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



Cosmic rays > 57 Eev (Auger, 2007)

Neutrinos > 30 Tev (Icecube, 2013)

*

M. Razzano

The new frontiers of multimessenger astronomy

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

- **Give a precise (arcmin/arcsecond) localization**
  - **Localize host galaxy of a merger**
  - **Identify an EM counterpart with timing signature (e.g. pulsars)**
  - **EM follow-up is crucial**

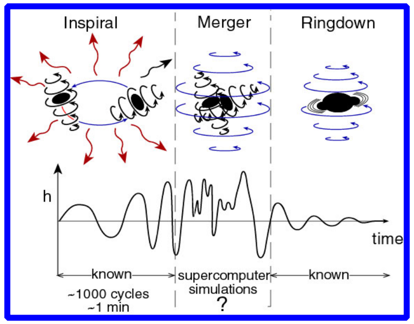
- **Provide a more complete insight into the most extreme events in the Universe**

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

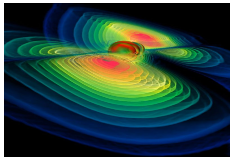
Expected multimessengers sources detectable by LIGO/Virgo

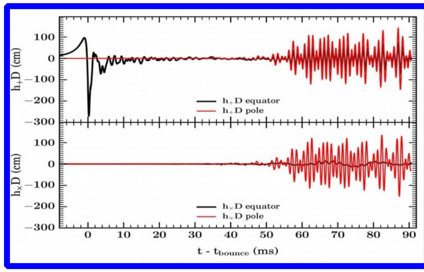
Transients

- **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
  - $E_{gw} \sim 10^{-8} – 10^{-4}\ Mc^2$



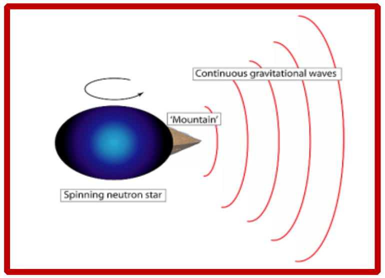


Ott, C. 2009

Non transients

- **Rotating neutron stars**
  - Quadrupole emission from star's asymmetry
  - Continuous and Periodic

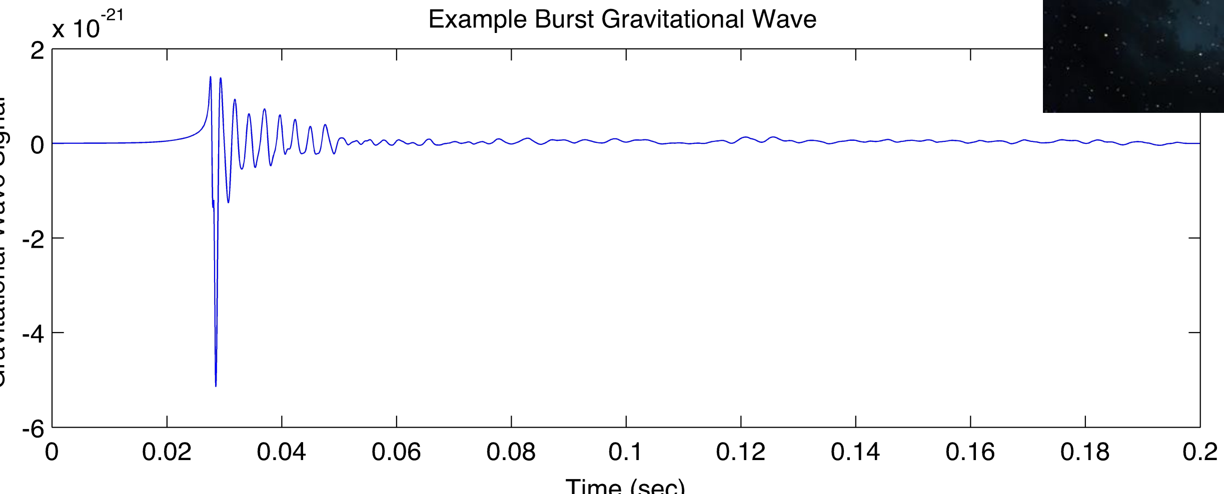
- **Stochastic background**
  - Superposition of many signals (mergers, cosmological, etc)
  - Low frequency



Multimessenger Physics – Supernovae

Stellar explosions

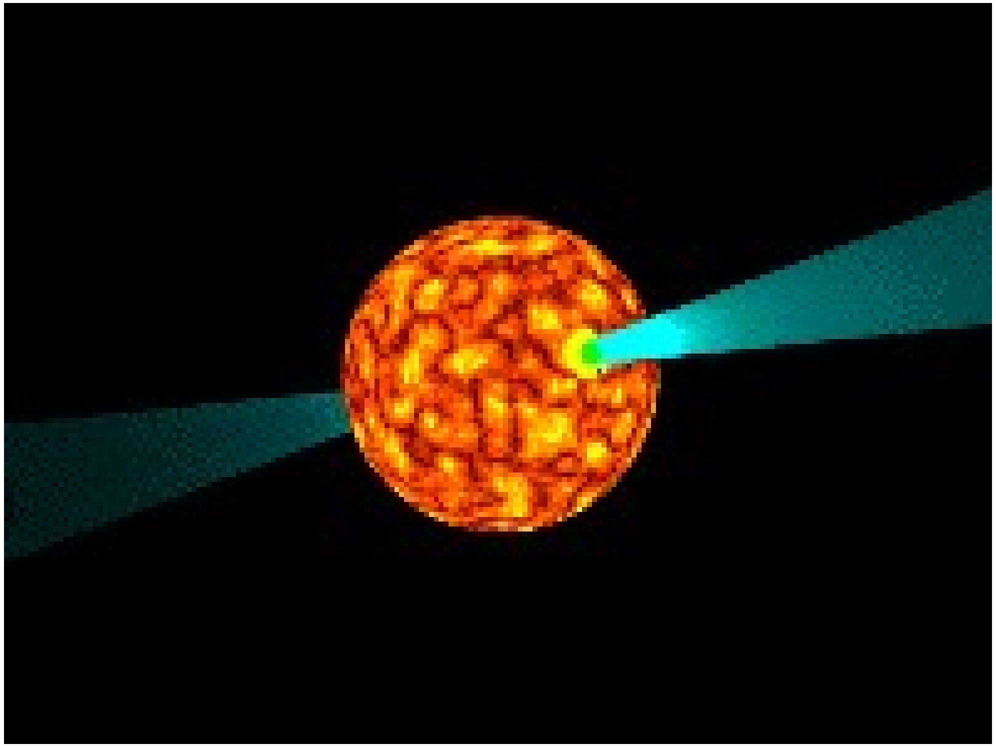
- What is the physical mechanisms behind Supernovae?
- What is the structure/asymmetry during collapse?
- Many inputs beyond GW are required

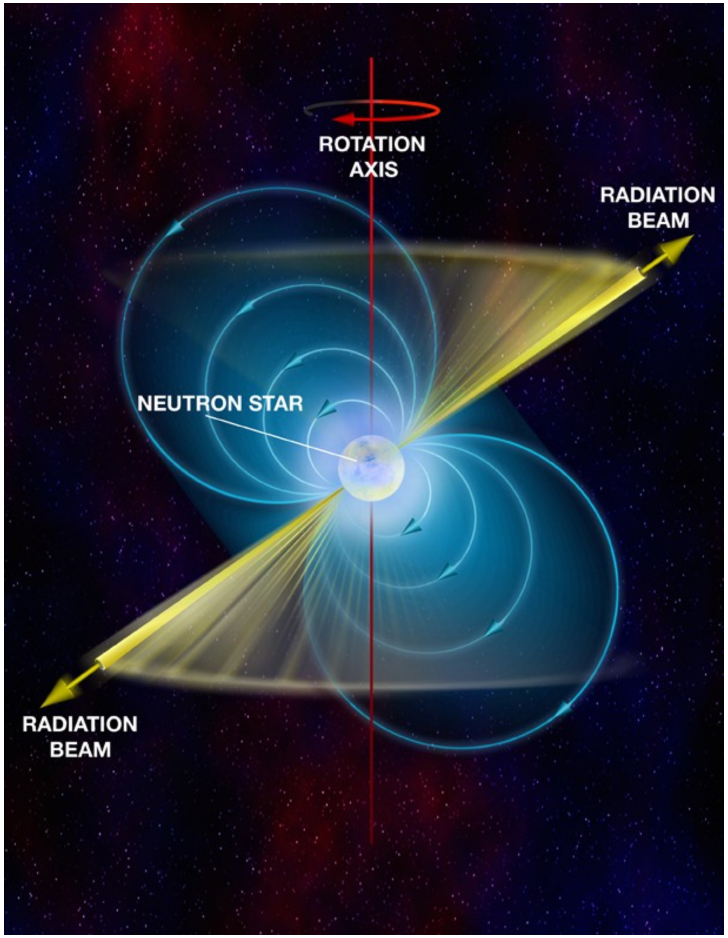


Multimessenger Physics – Neutron Stars

Continuous Waves

- Non-linear instabilities and NS evolution
- Explore the nature of the NS crust
- Glitch

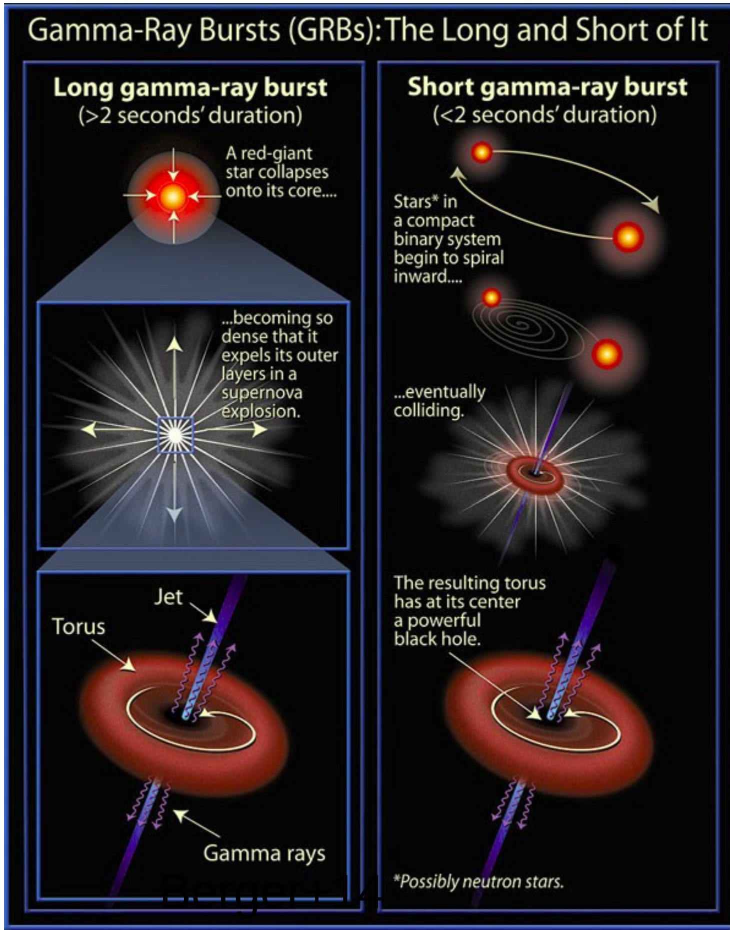




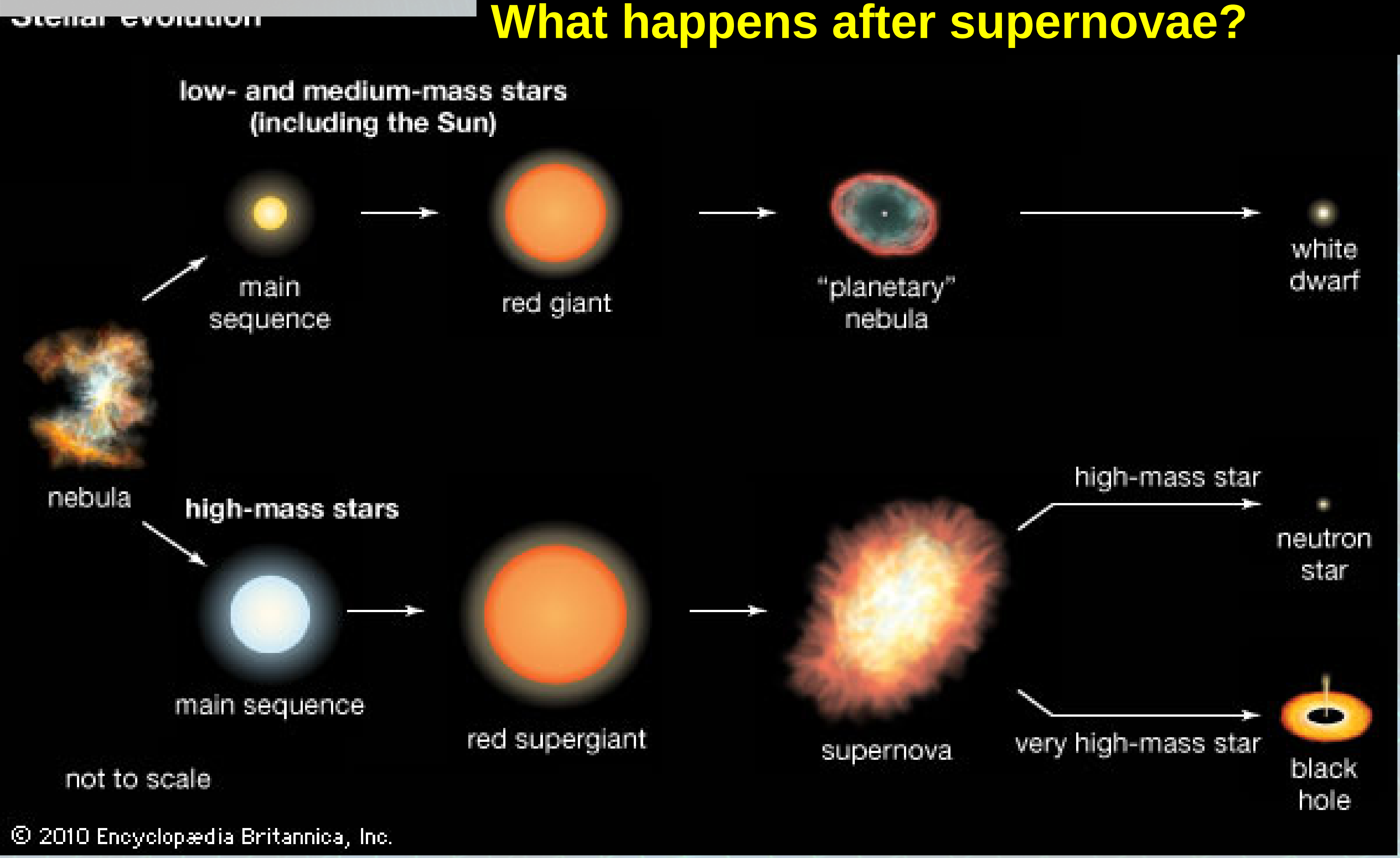
Multimessenger Physics - Mergers

Mergers of binary objects (NSs and/or BHs)

- Believed to be progenitors of short GRBs
  - Follow-up observations, find EM counterparts
- Populations of compact objects
  - Evolution
  - Mass function



Massive stars go supernova
What happens after supernovae?

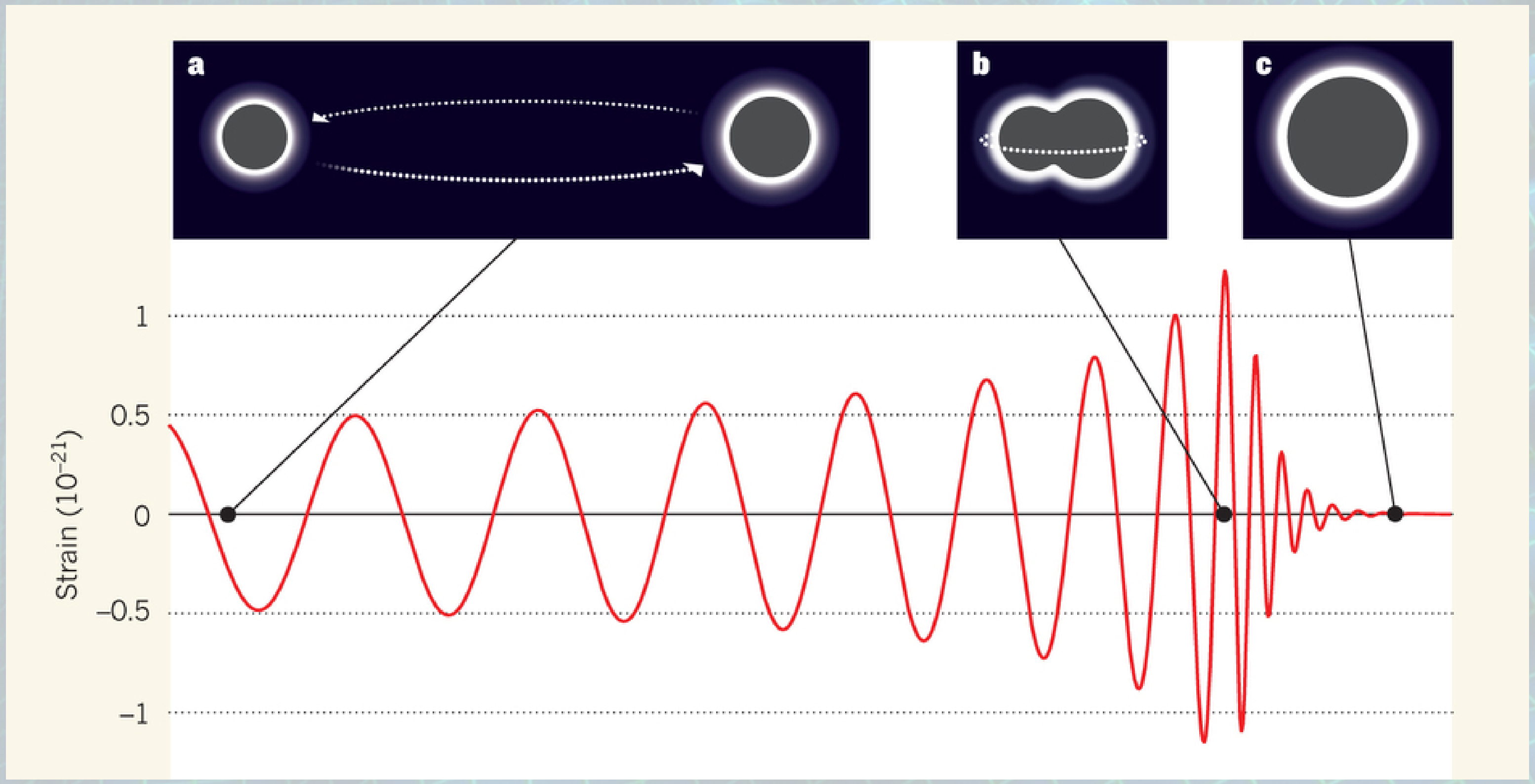


Coalescence of binary systems

«Ringdown»

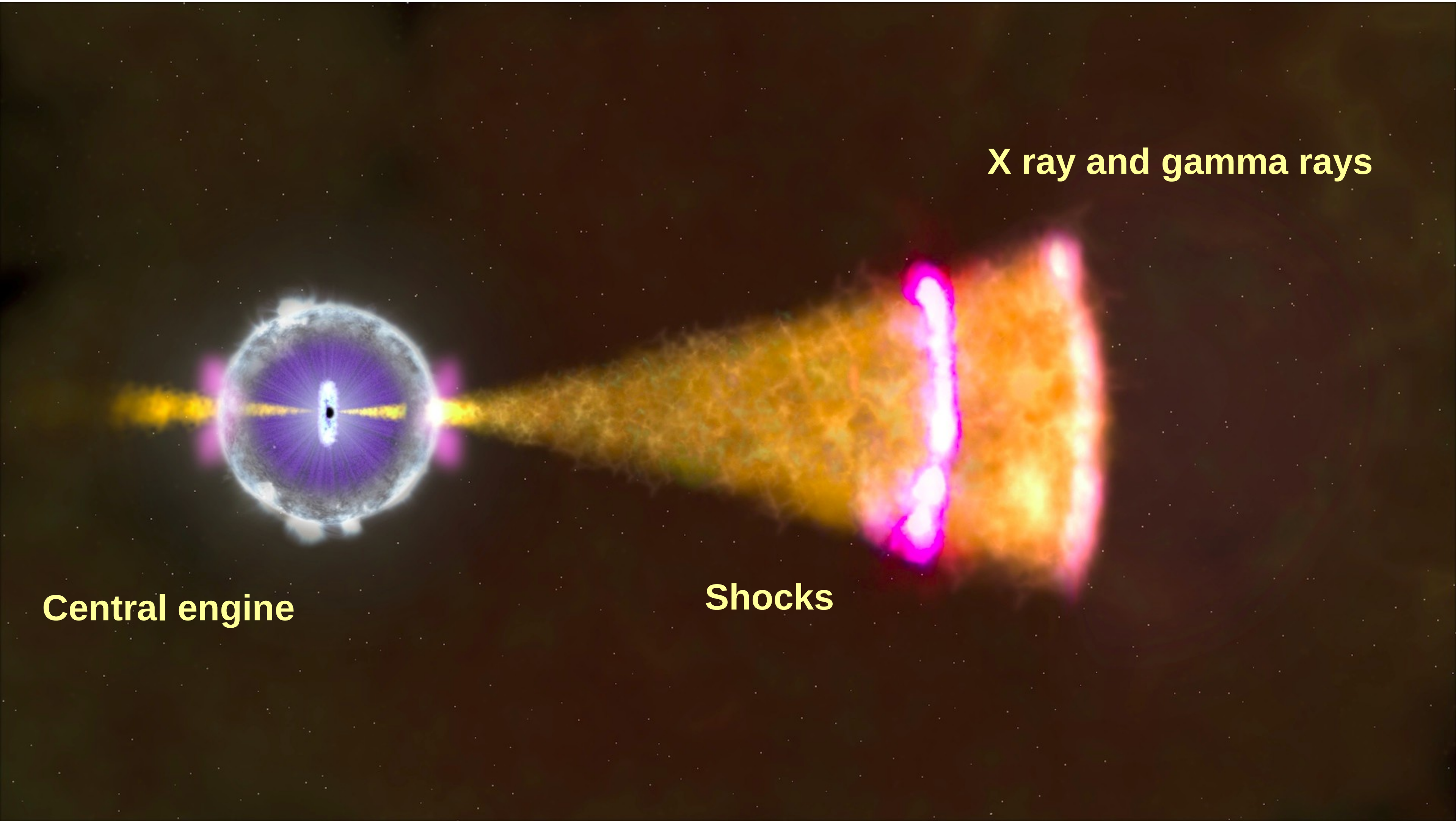
Merger

Inspiral

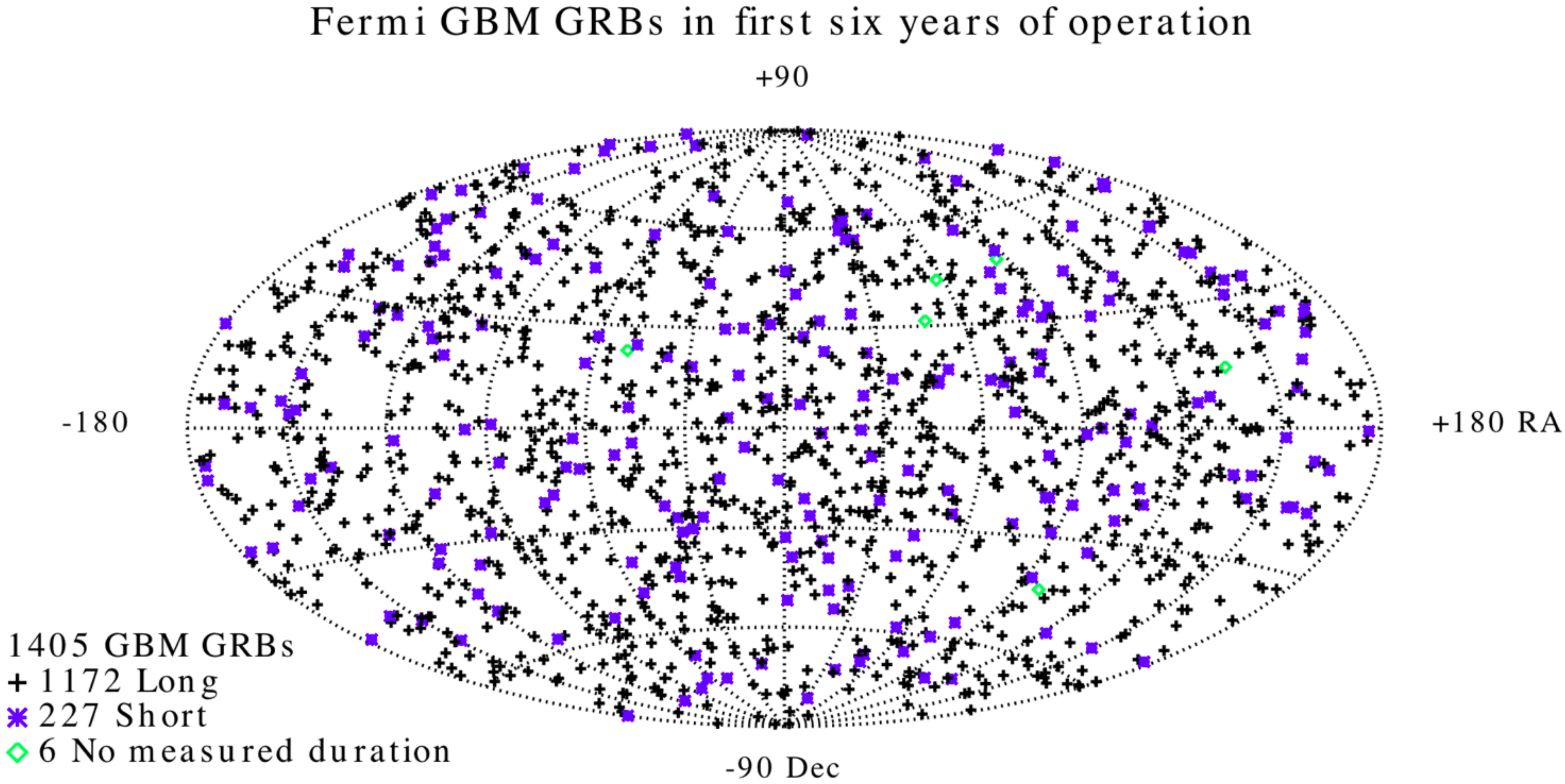


Multimessenger: the case of GRB

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



Multimessenger: the case of GRB

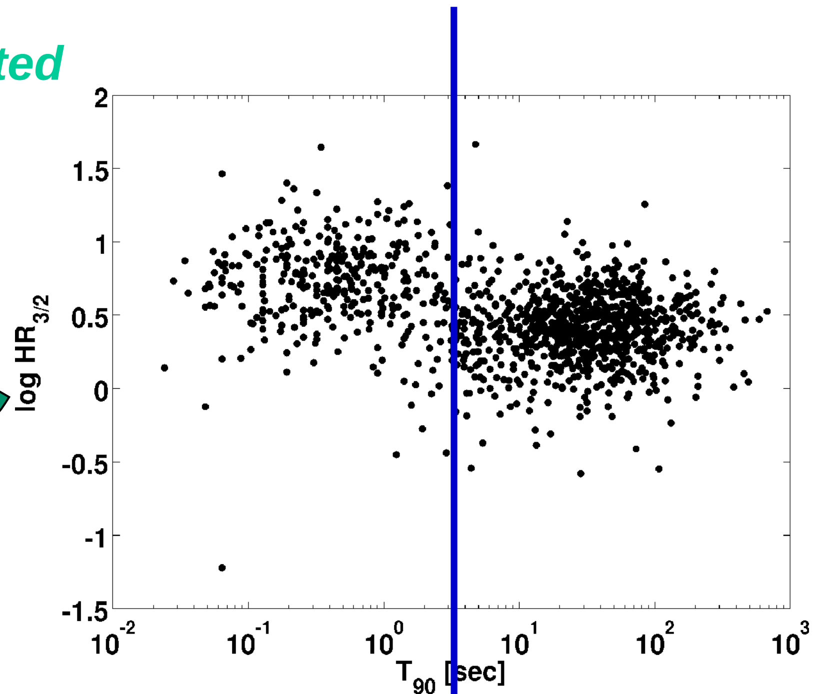


Science case for EM follow-up: the GRB connection

Gamma Ray Bursts are intense flashes of gamma rays
Multimessenger is key to study progenitors

Short GRBs (<2 s)

believed to be associated with mergers



Long GRBs (>2 s)

Believed to be associated with core-collapse of massive star

A needle in a haystack: an example from the past

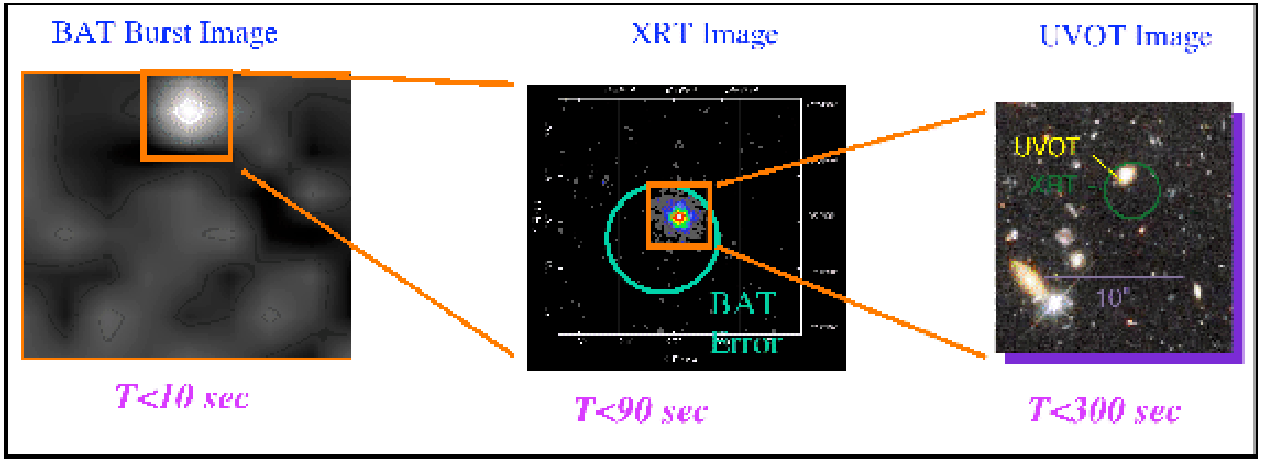
Find a counterpart is not easy!

•EM Transients might be

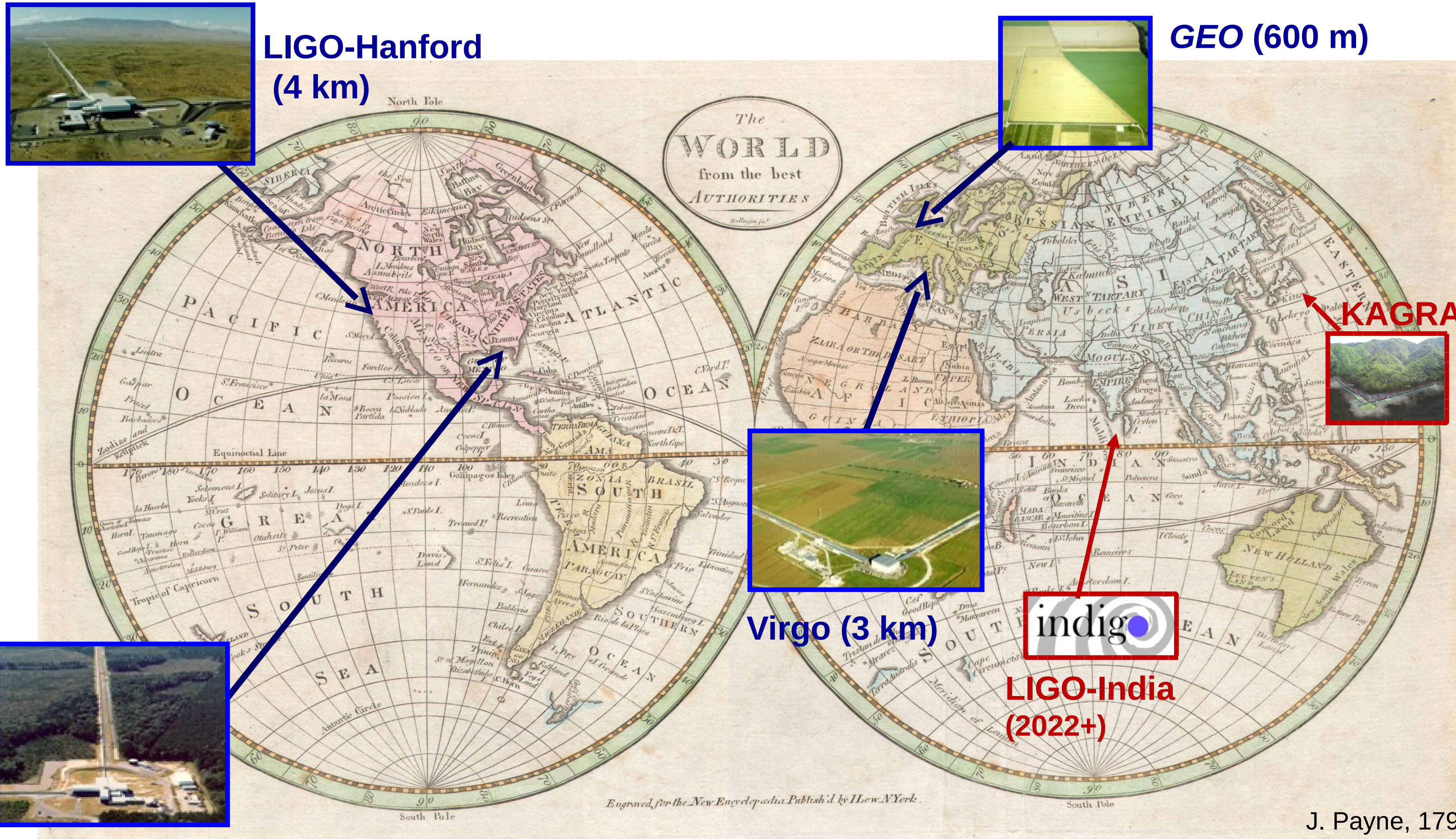
- **Fast**
- **Faint**
- **Too many**

•Findind counterparts of GRBs was very difficult

•For GWs, the situation is worse...



The era of Advanced GW detectors

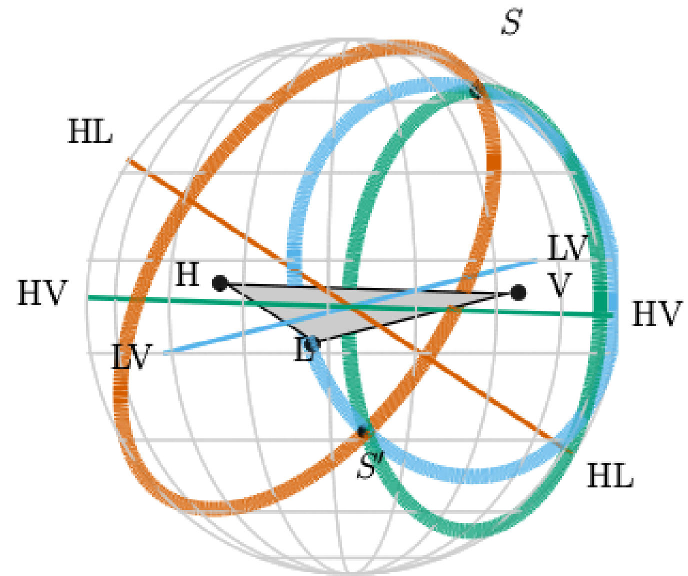


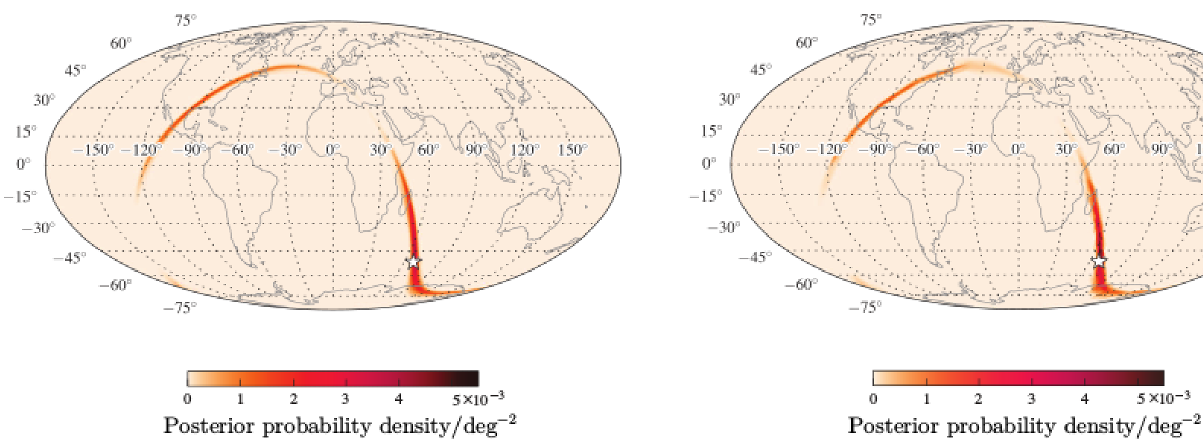
J. Payne, 1798

Advanced LIGO + Advanced Virgo
First joint run in 2016 (O2)

Sky Localization of GW transients

- “Triangulation” using temporal delays
- Depends on the SNR
- Low SNR → large error box (tens – hundreds sq deg)
- Wide-fov telescopes are required!



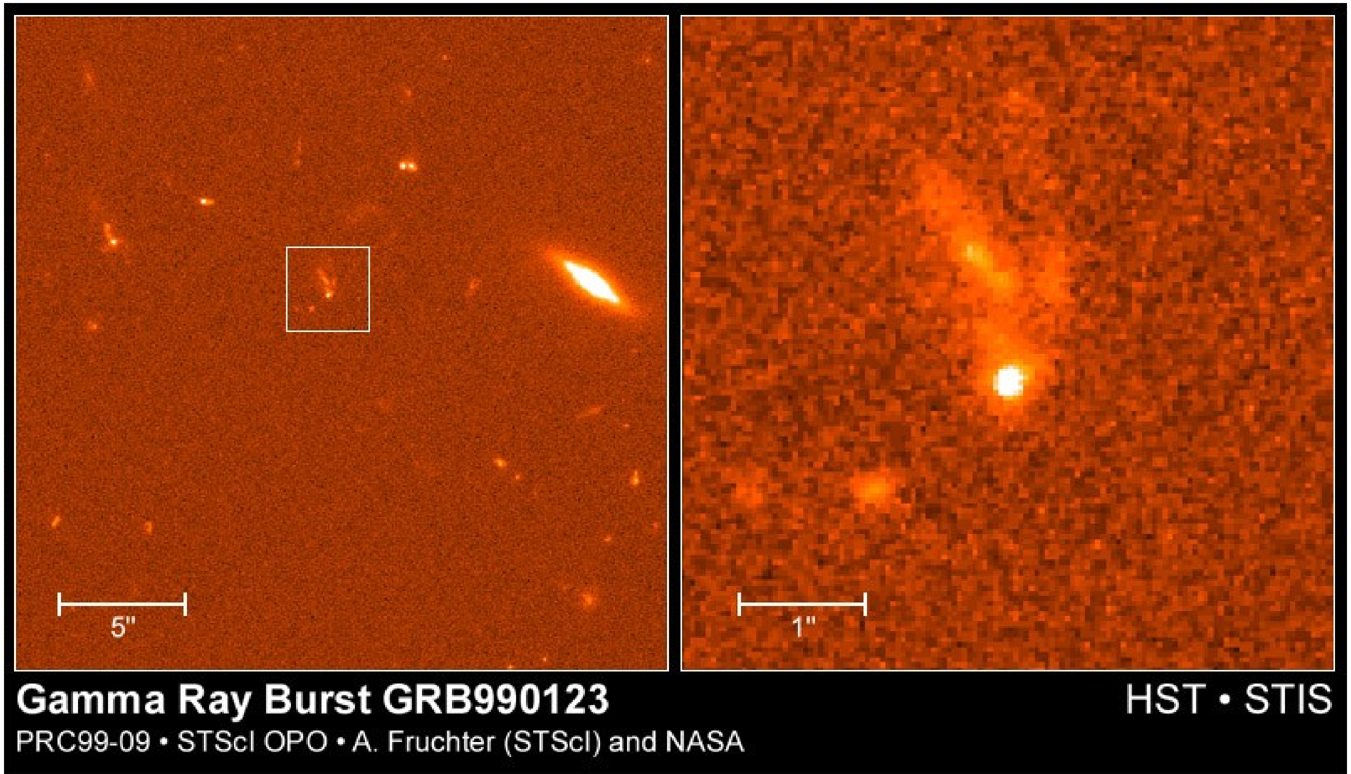


Abbott+16, LRR 19,1

BNS system, SNR ~13.2
LALINFERENCE (left), BAYESTAR (right)

EM follow-up : key challenges

- What is the best observing strategy?
  - Scan the full error box?
  - Look only to specific regions (e.g. potential galaxy hosts?
  - How to identify the potential host?
- If there is more than one candidate…
  - How can we uniquely identify it?
  - How can models help us?



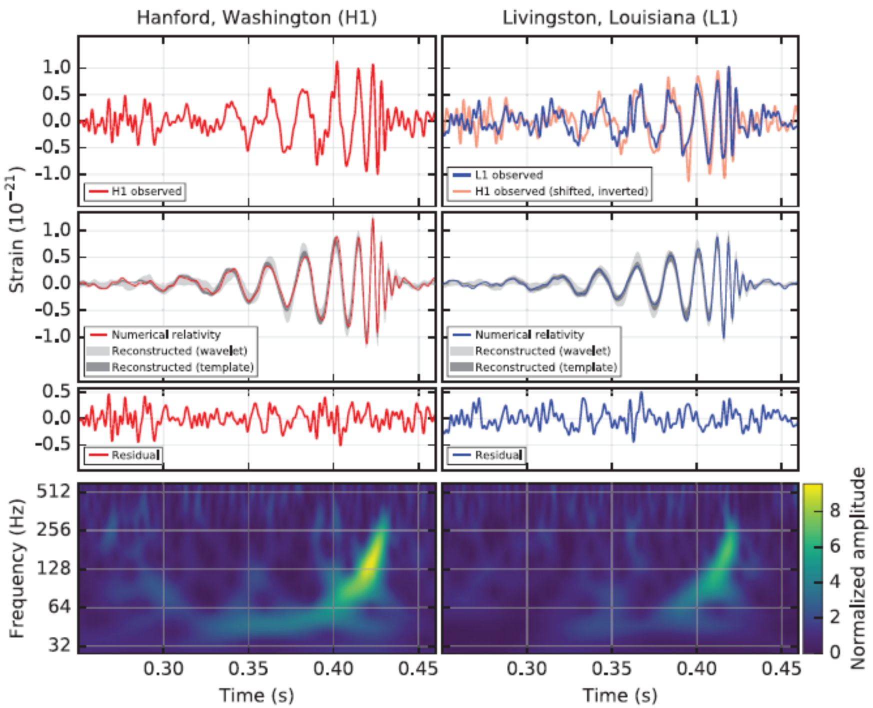
Why an EM follow-up program?

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

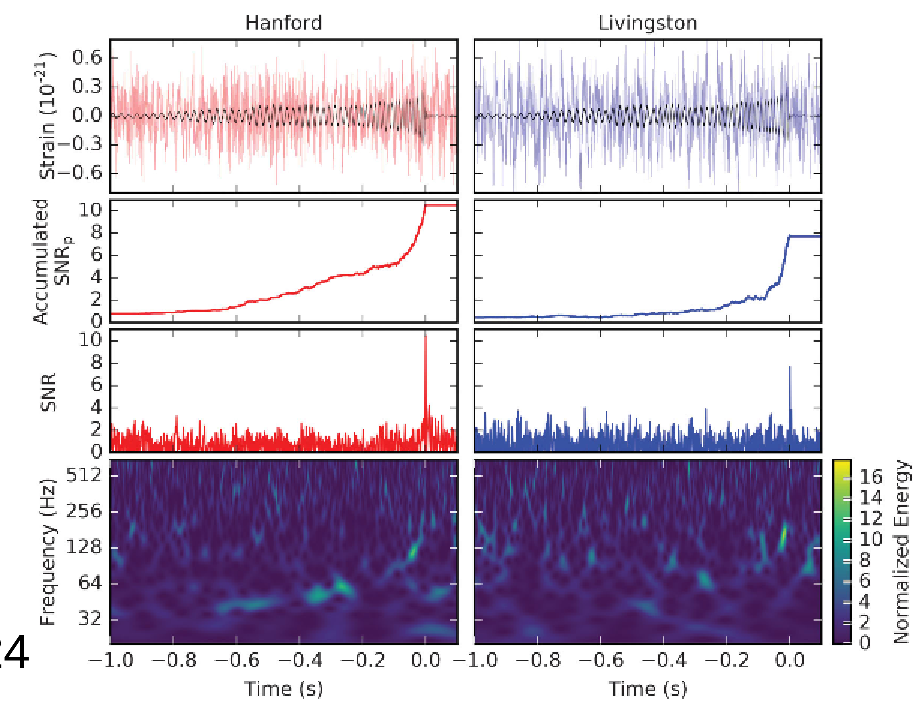
- EM follow-up program
  - Standard MoU to share information promptly while mantaining confidentiality for event candidates
  - GW alerts sent to partners through private GCN notices/circulars
  - Once first few (>=4) detections, prompt alerts will be made public for high-significance detections (FAR<1/100 yrs)

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

First detections!

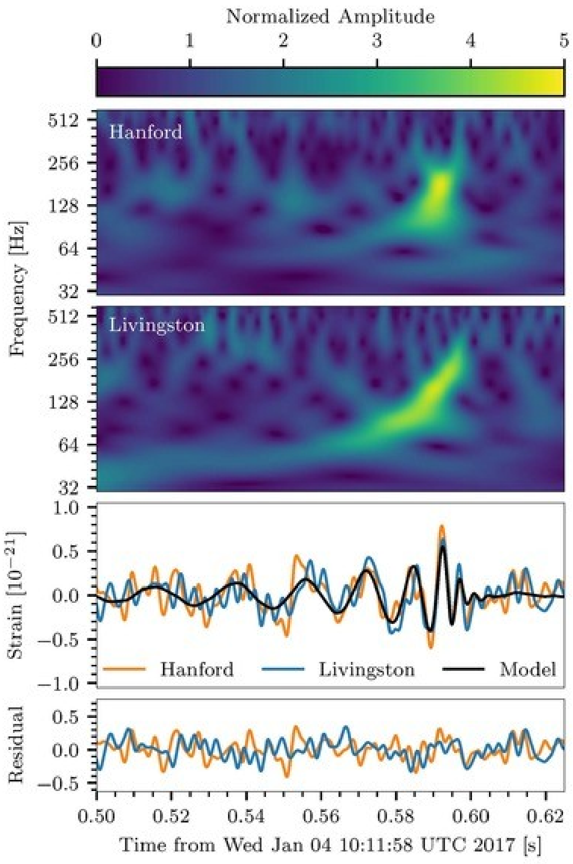


GW15109
Abbott+16, PRL116,6



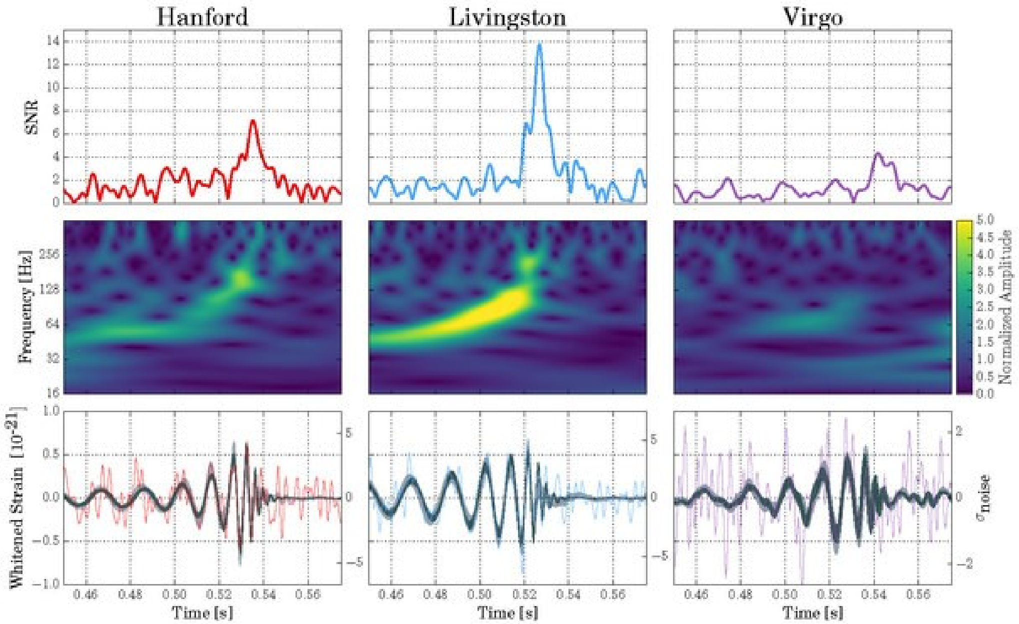
GW151226
Abbott+16, PRL116,24

First detections!

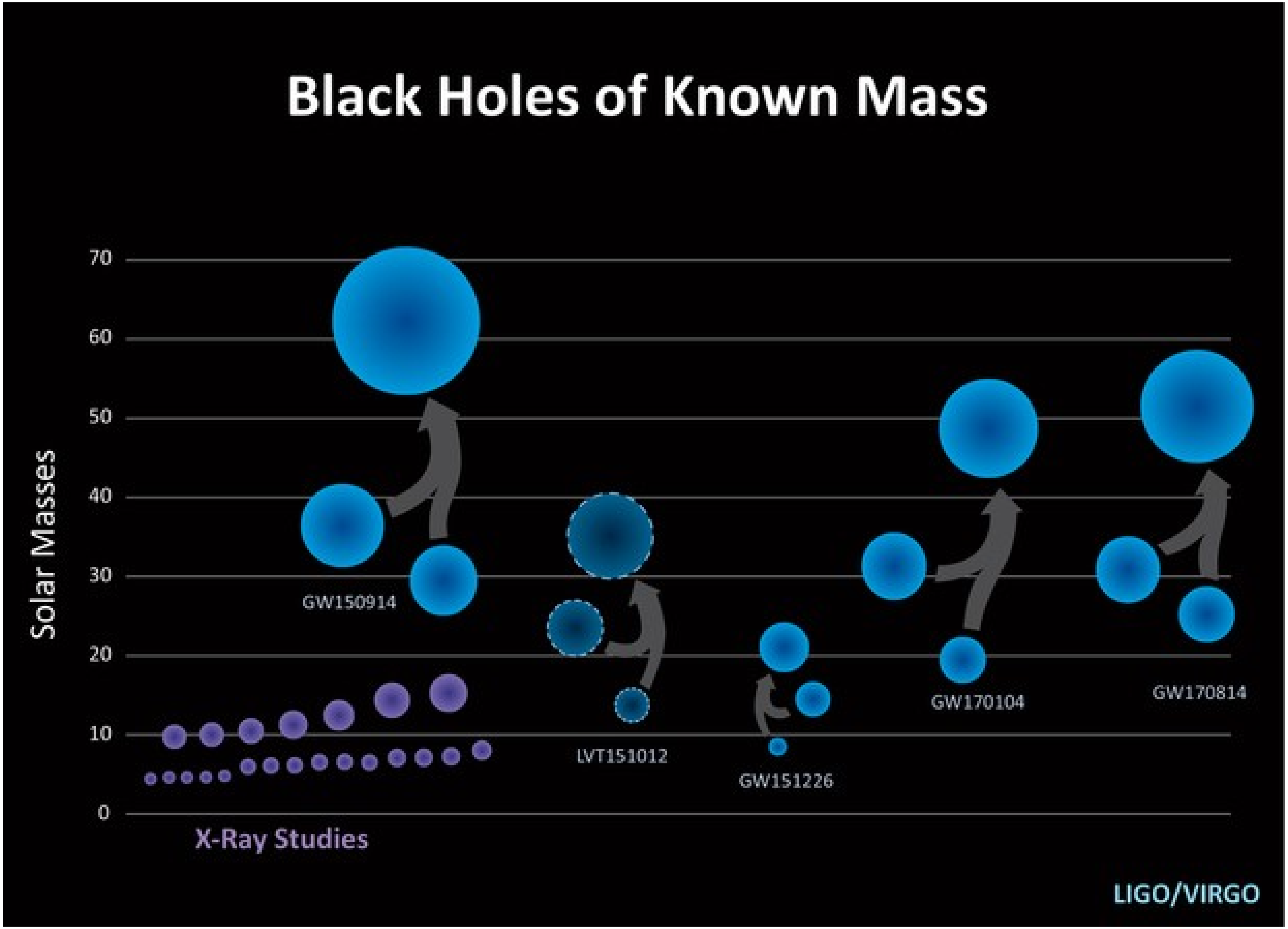


GW170104

GW170814,
The first “triple”

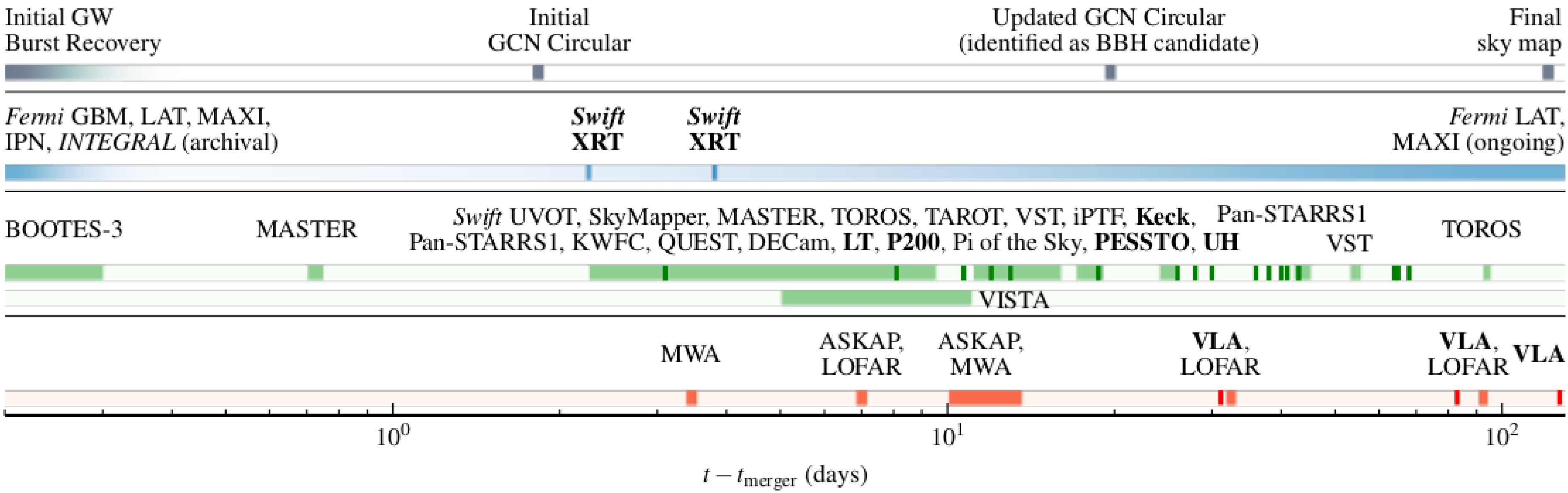


Black hole populations



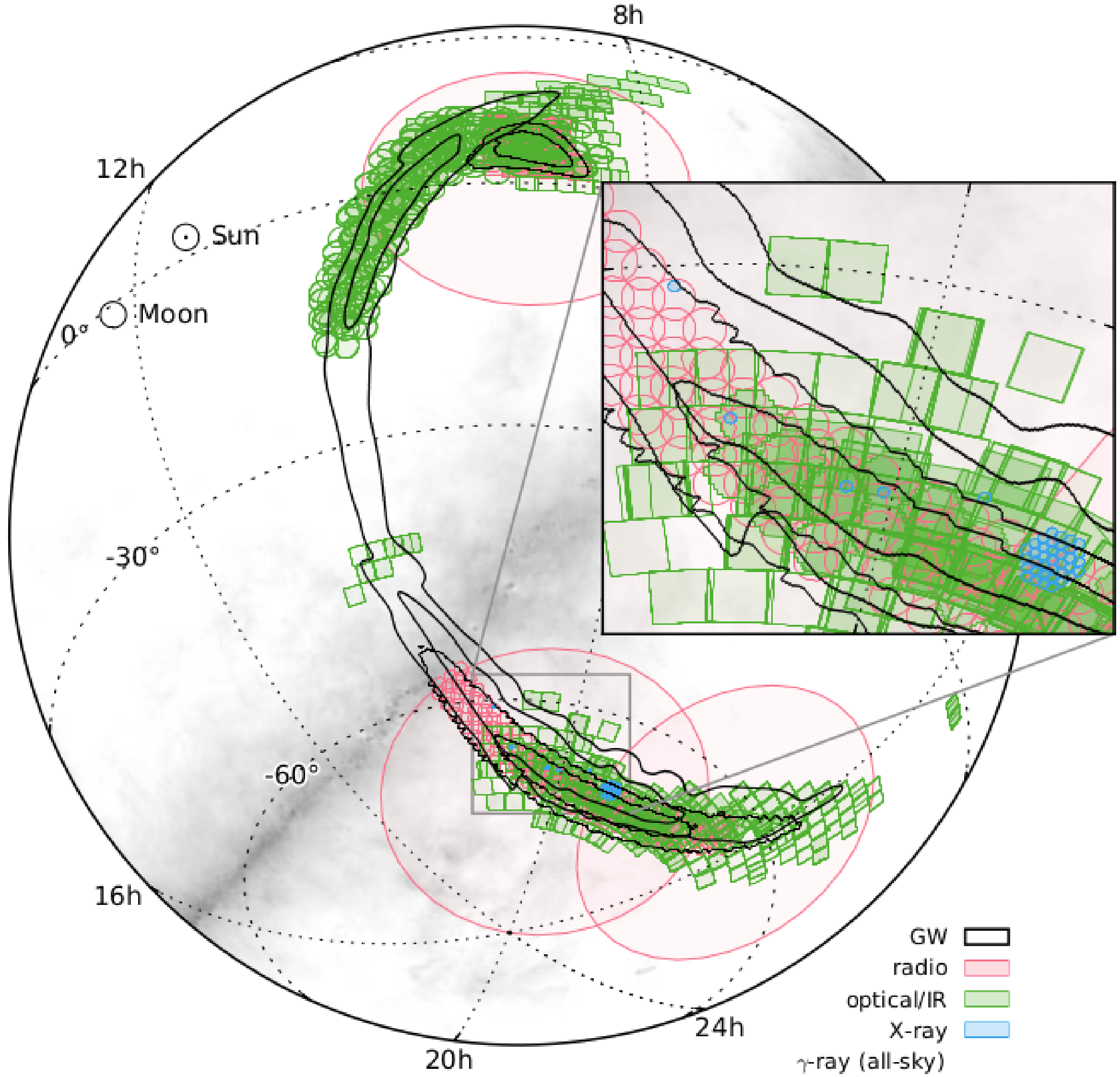
GW150914 follow-up timeline

- t+few minutes: cWB & oLIB pipelines
  - T+17 min – 14 hr (skymaps)
    - T+2d: first alert (after many checks)
      - T+3w (Oct 3): BBH identification
        - T+4m (Oct 20) updated FAR (<1/100 yr)



Abbott+16 (arXiv:1602.08492)

GW150914 coverage



- 25 teams involved
- 19 orders of magnitudes in wavelenghts
- Repointing (optical)
- Archival (X & gamma)
- Deep follow-up (optical/radio)

Abbott+16 (arXiv:1602.08492)

X-rays and gamma rays

Facility/ Instrument	Band[a]	Depth[b]	Time[c]	Area (deg^2)	Contained Probability (%) cWB	LIB	BSTR[d]	LALInf	GCN
			Gamma-ray						
Fermi LAT	20 MeV–300 GeV	1.7×10^{-9}	(every 3 hr)	—	100	100	100	100	18709
Fermi GBM	8 keV–40 MeV	$0.7–5 \times 10^{-7}$ (0.1–1 MeV)	(archival)	—	100	100	100	100	18339
INTEGRAL	75 keV–1 MeV	1.3×10^{-7}	(archival)	—	100	100	100	100	18354
IPN	15 keV–10 MeV	1×10^{-7}	(archival)	—	100	100	100	100	—
			X-ray						
MAXI/GSC	2–20 keV	1×10^{-9}	(archival)	17900	95	89	92	84	19013
Swift XRT	0.3–10 keV	5×10^{-13} (gal.)	2.3, 1, 1	0.6	0.03	0.18	0.04	0.05	18331
		$2–4 \times 10^{-12}$ (LMC)	3.4, 1, 1	4.1	1.2	1.9	0.16	0.26	18346

- Fermi GBM: 1 candidate ~1.9σ, ~0.4 s (Connaughton+16)
- Fermi LAT : no candidates (Ackermann+16)
- INTEGRAL: no candidates (Sevechenko+16)
- Swift: candidates, but no new sources (Ewans+16)

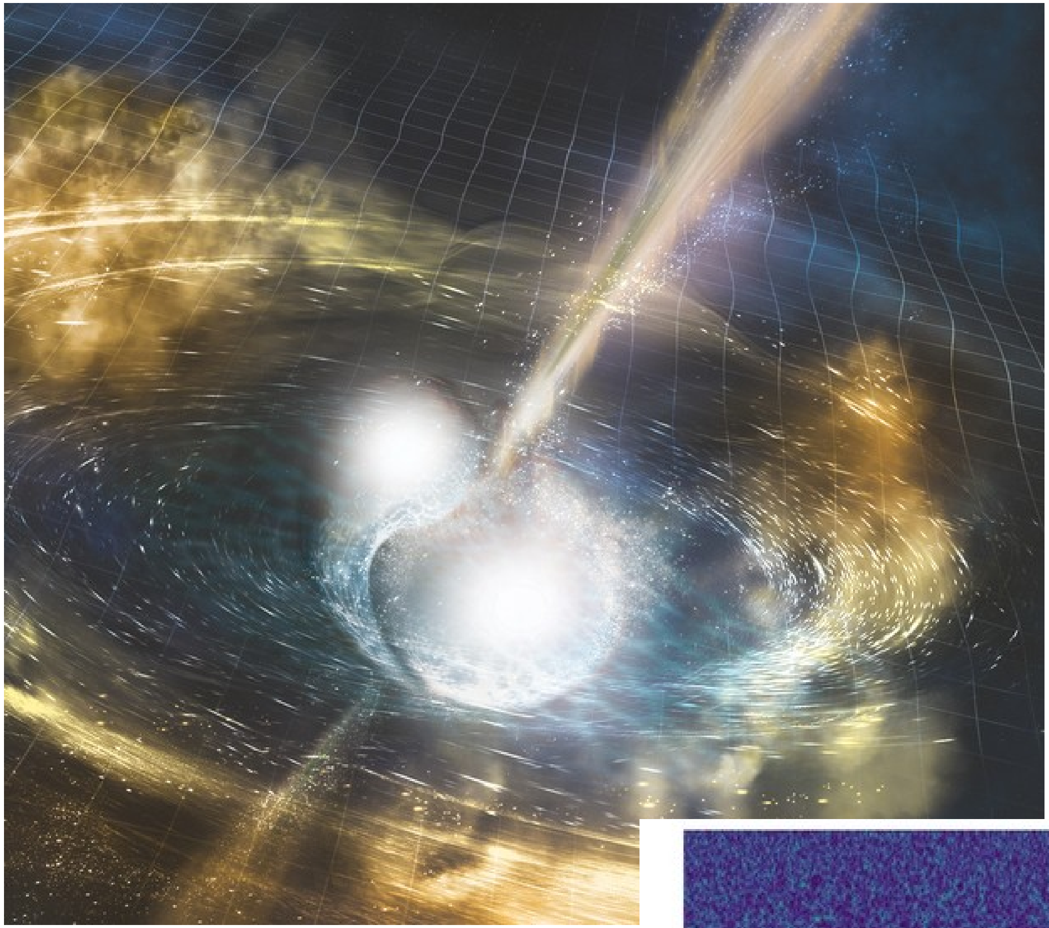
Abbott+16 (arXiv:1602.08492)

Optical, IR, radio

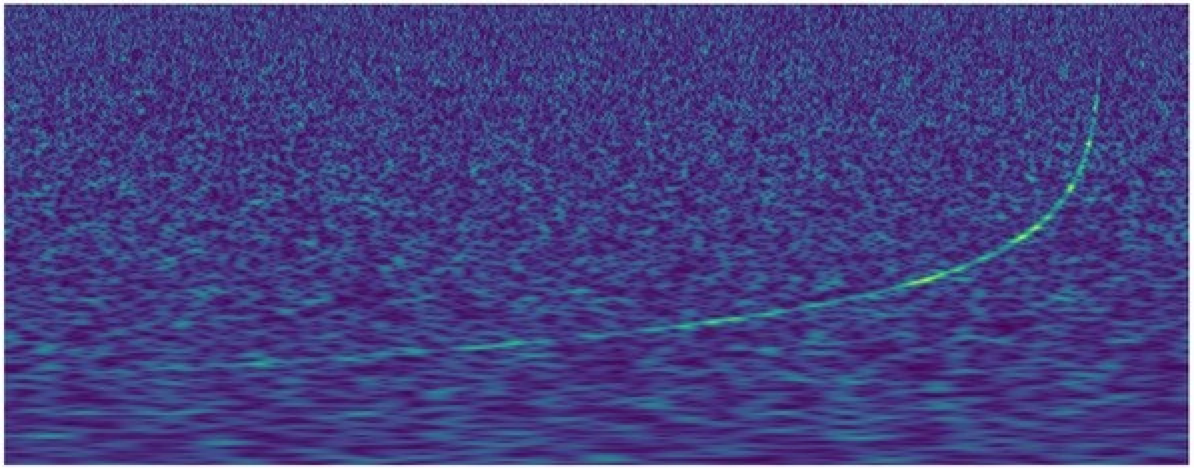
- Optical
  - Tiled and galaxy-oriented
  - Tens of candidates, later observed deeper
  - Candidates compatible with normal population of SN, AGN, etc..
- Radio coverage up to t+4 months

				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

The case of GW170817

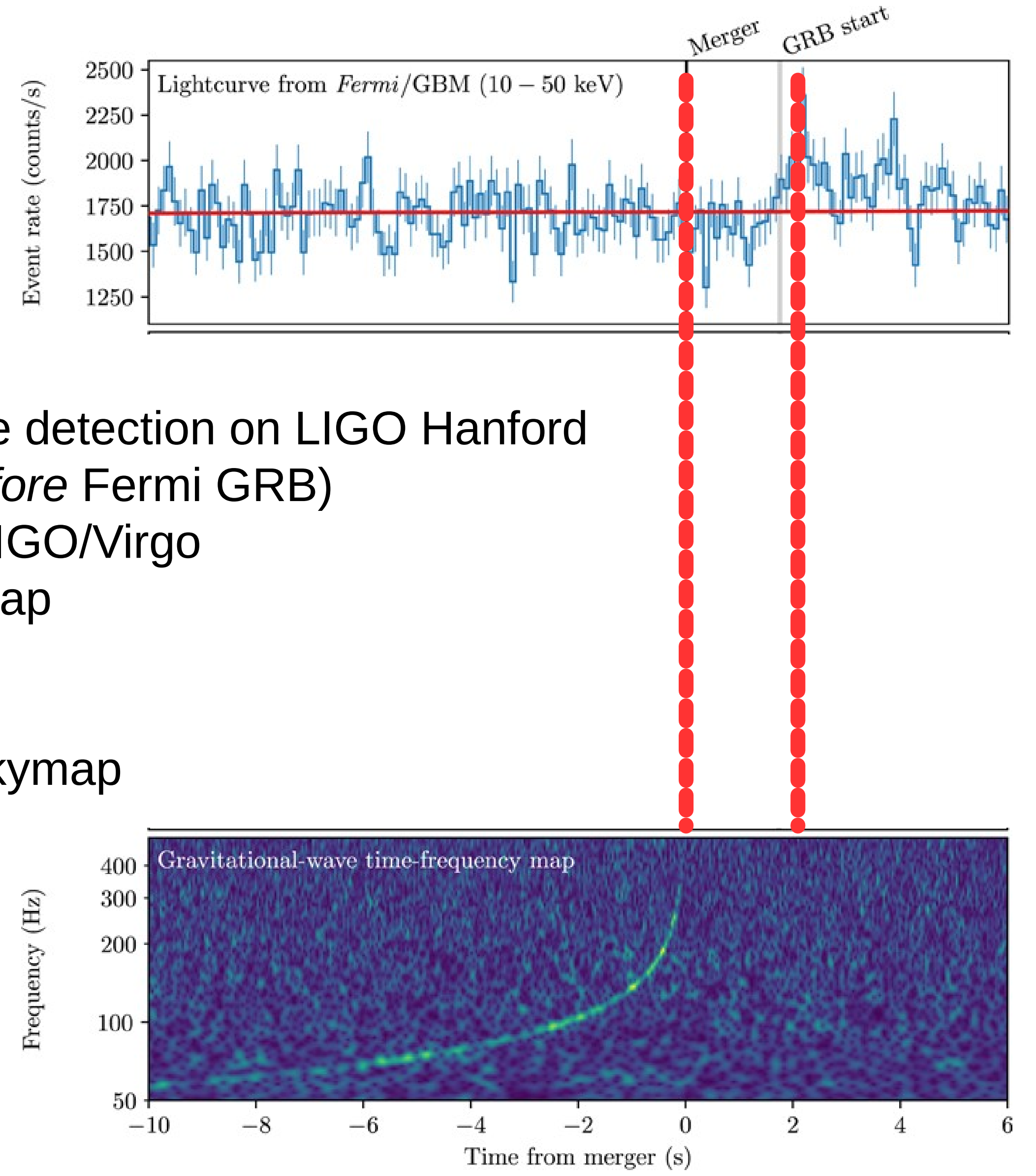


- M1=1.36-2.26 Msol
- M2 = 0.86-1.36 Msol
- Estimated distance: 40 Mpc



Timeline of the GW170817 discovery

- **12:41:06 UTC** : onboard *Fermi*-GBM trigger
- **12:14:20 UTC** : Automatic Fermi Gamma-ray Coordinates Network (GCN)

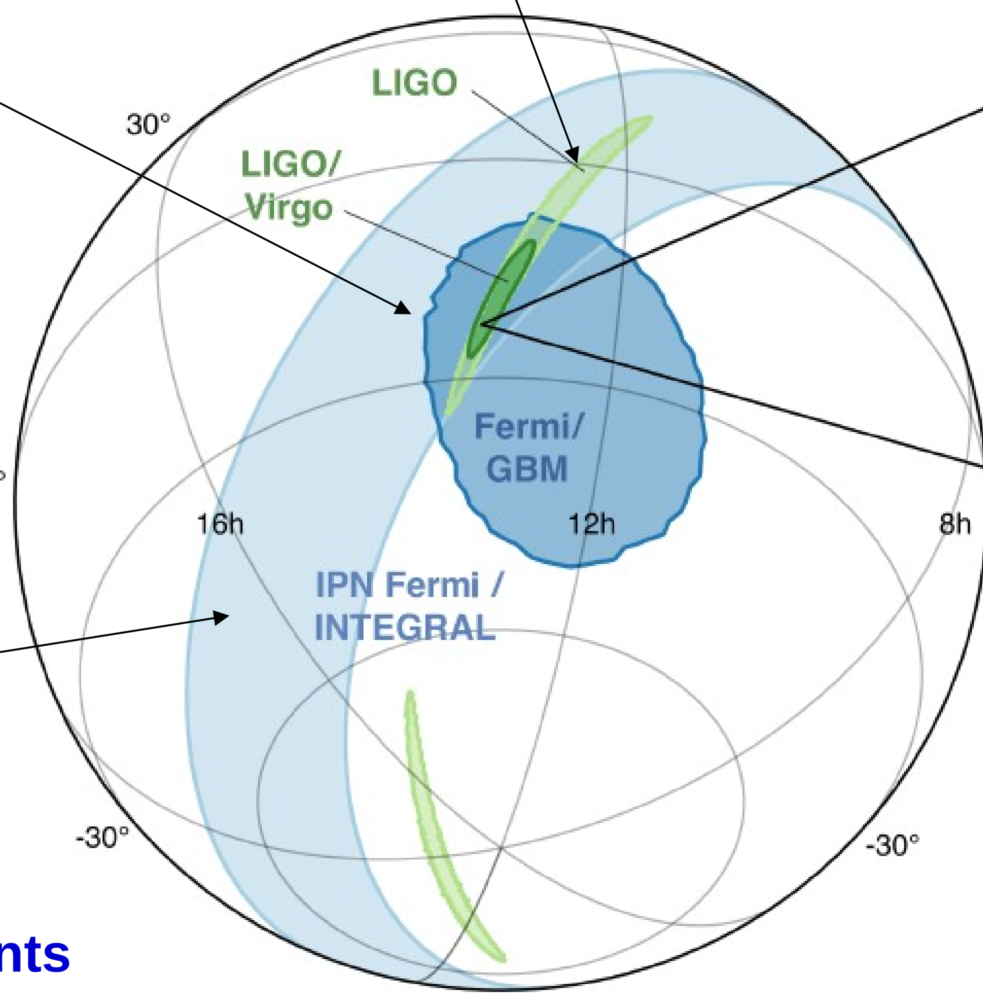


- **~12:47 UTC** : low-latency GW pipeline detection on LIGO Hanford
  - Detected time 12:41:04 (1.7 sec *before* Fermi GRB)
- **13:21:42 UTC** : First alert sent from LIGO/Virgo
- **17:54:51 UTC**: First LIGO-Virgo skymap
  - Error region ~31 deg^2
  - Distance 40 Mpc
- **23:54:40 UTC**: Refined LIGO-Virgo skymap
  - Error region ~34 deg^2

Sky localization

LIGO: 190 deg^2

Fermi GBM:
1100 deg^2



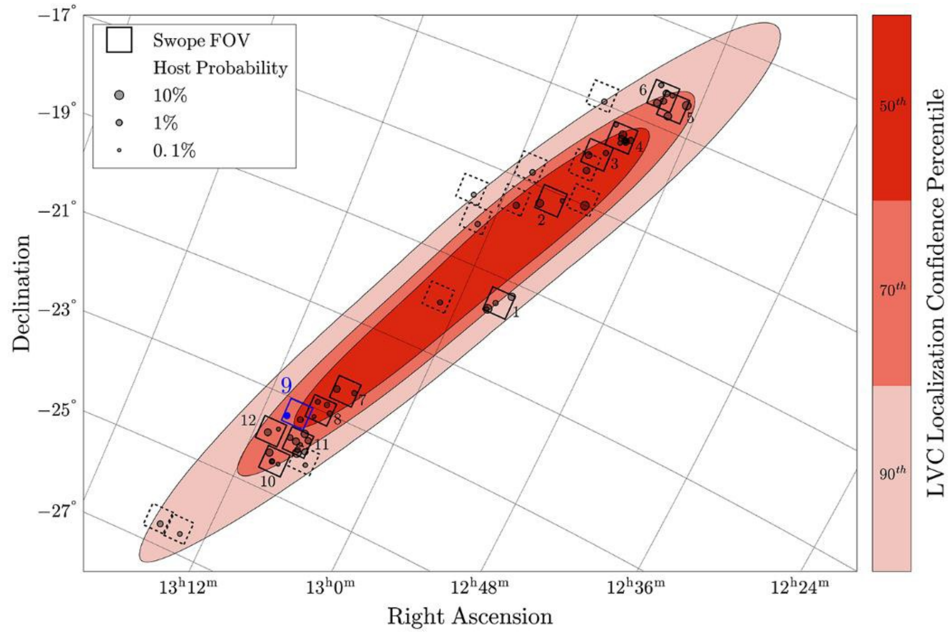
LIGO
+
Virgo
=
31 deg^2

Fermi GBM
+
INTEGRAL SPI
(Interplanetary
Network)
Additional constraints

M. Razzano

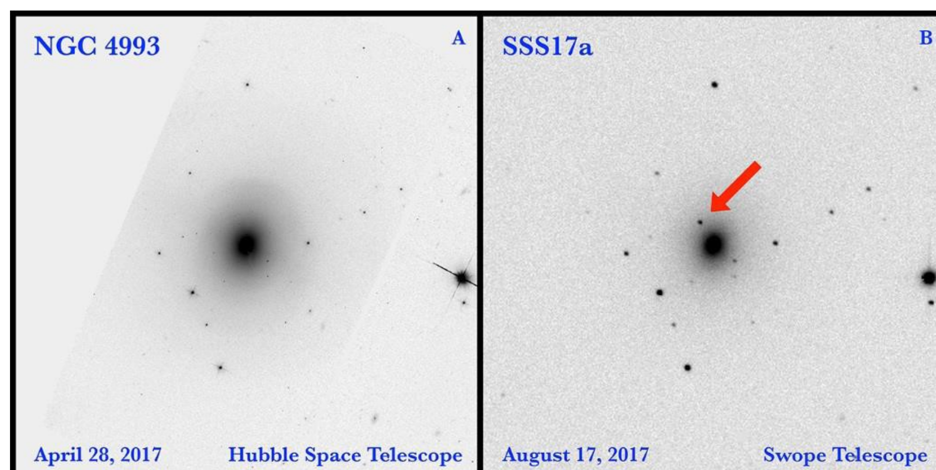
The optical transient

One-Meter, Two-Hemisphere (1M2H) team
1-m Swope telescope, Las Campanas (Chile)



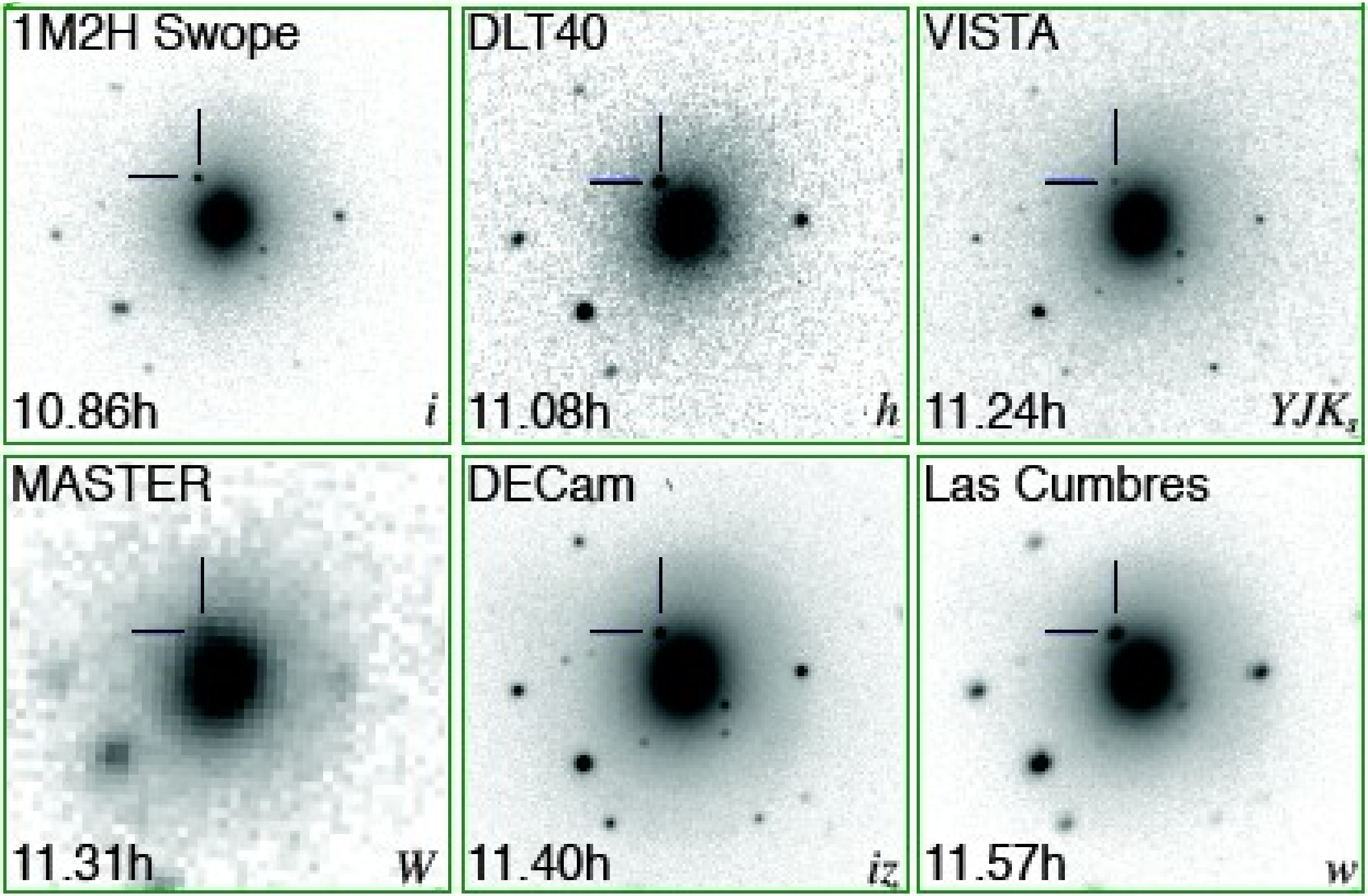
- Observation at t_0+10.8 hr
- mag(i) ~17
- Names SSS17a
- later AT2017gfo
- ESO 508 cluster at 40 Mpc

- *(Coulter et al. 2017)*



The fab six

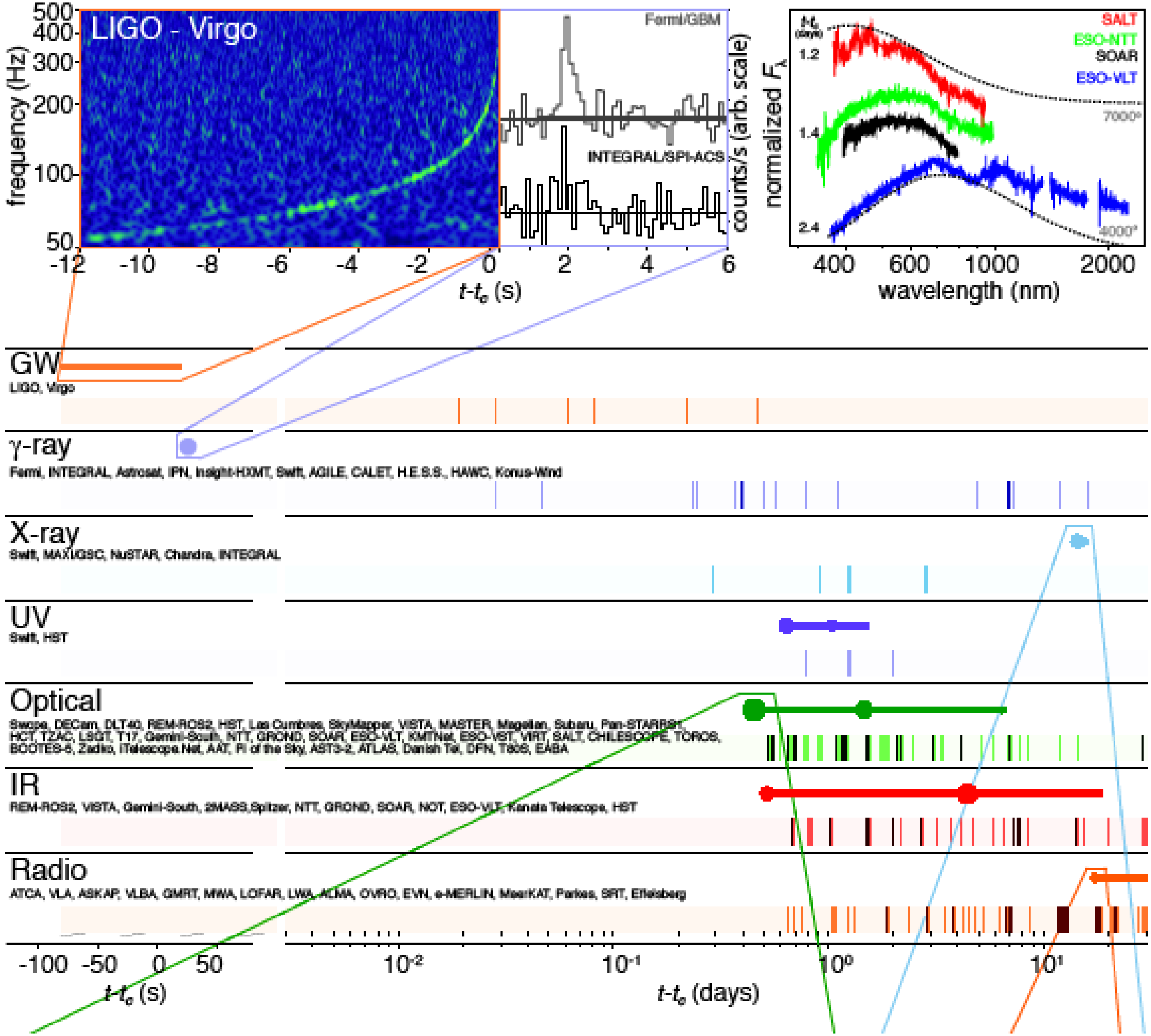
- *(Coulter et al. 2017)*
- *(Yang et al. 2017)*
- *(Tanvir et al. 2017)*



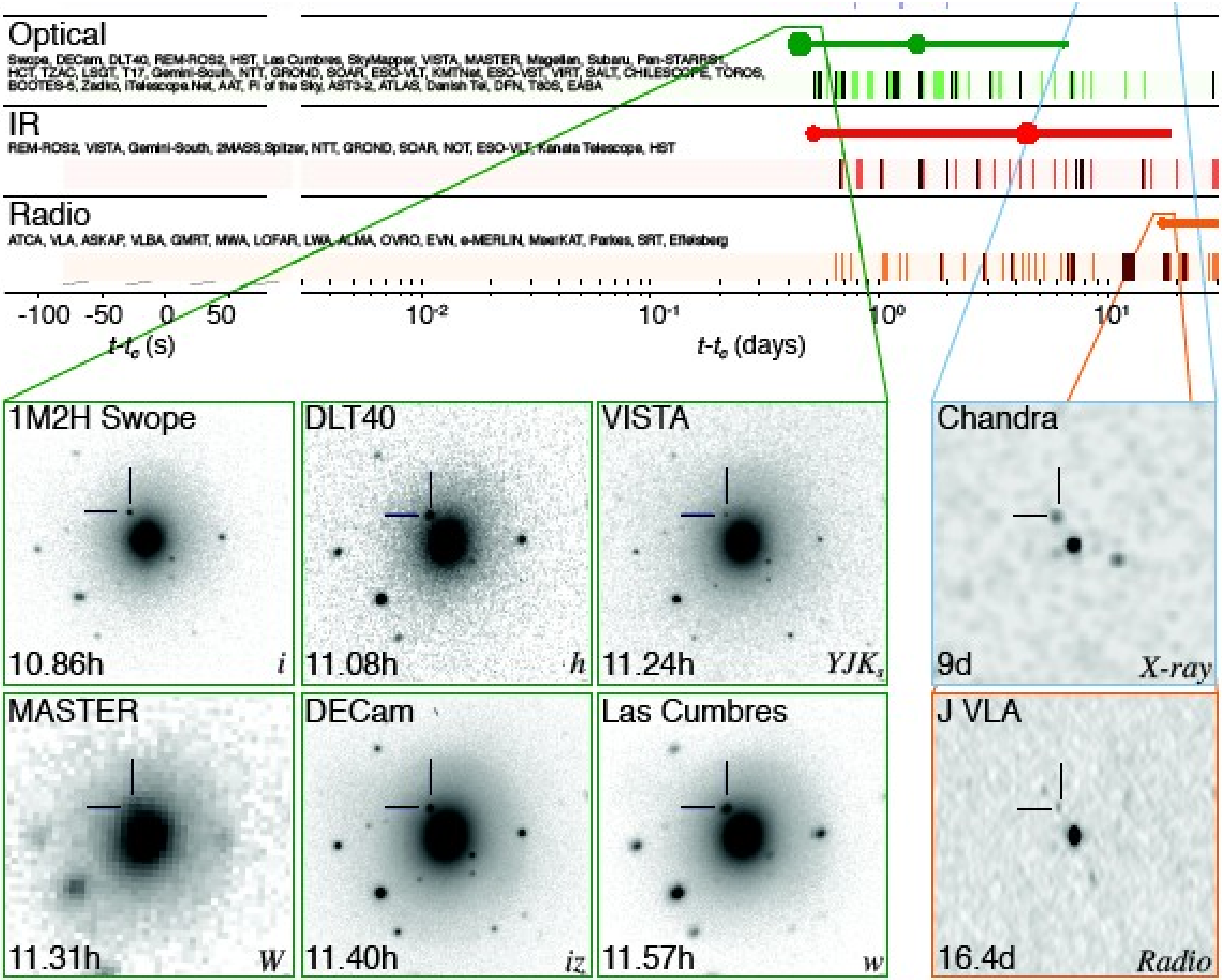
- *(Lipunov et al. 2017)*
- *(Allam et al. 2017)*
- *(Accavi et al. 2017)*

M. Razzano

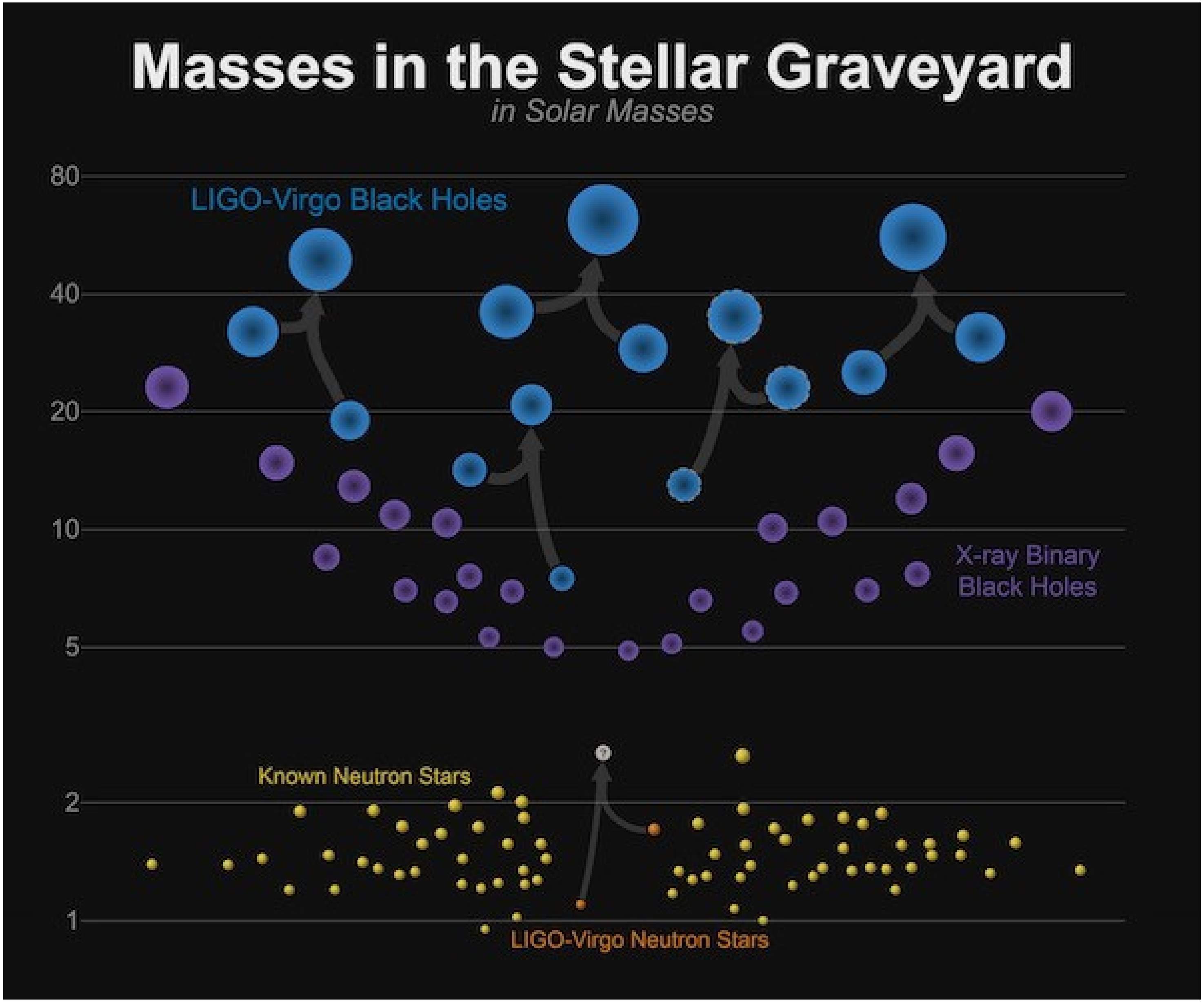
Summary of observations



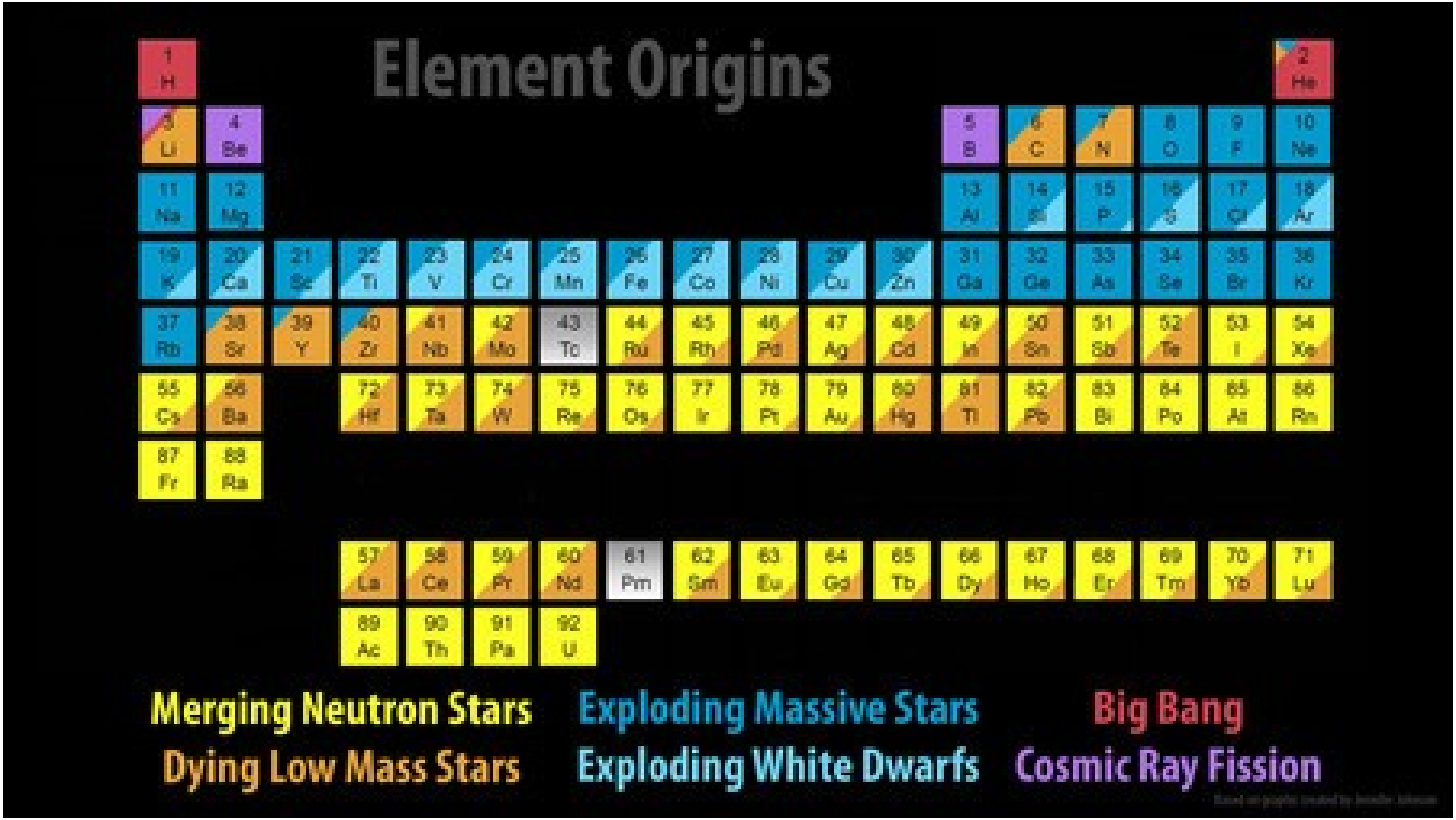
Summary of observations



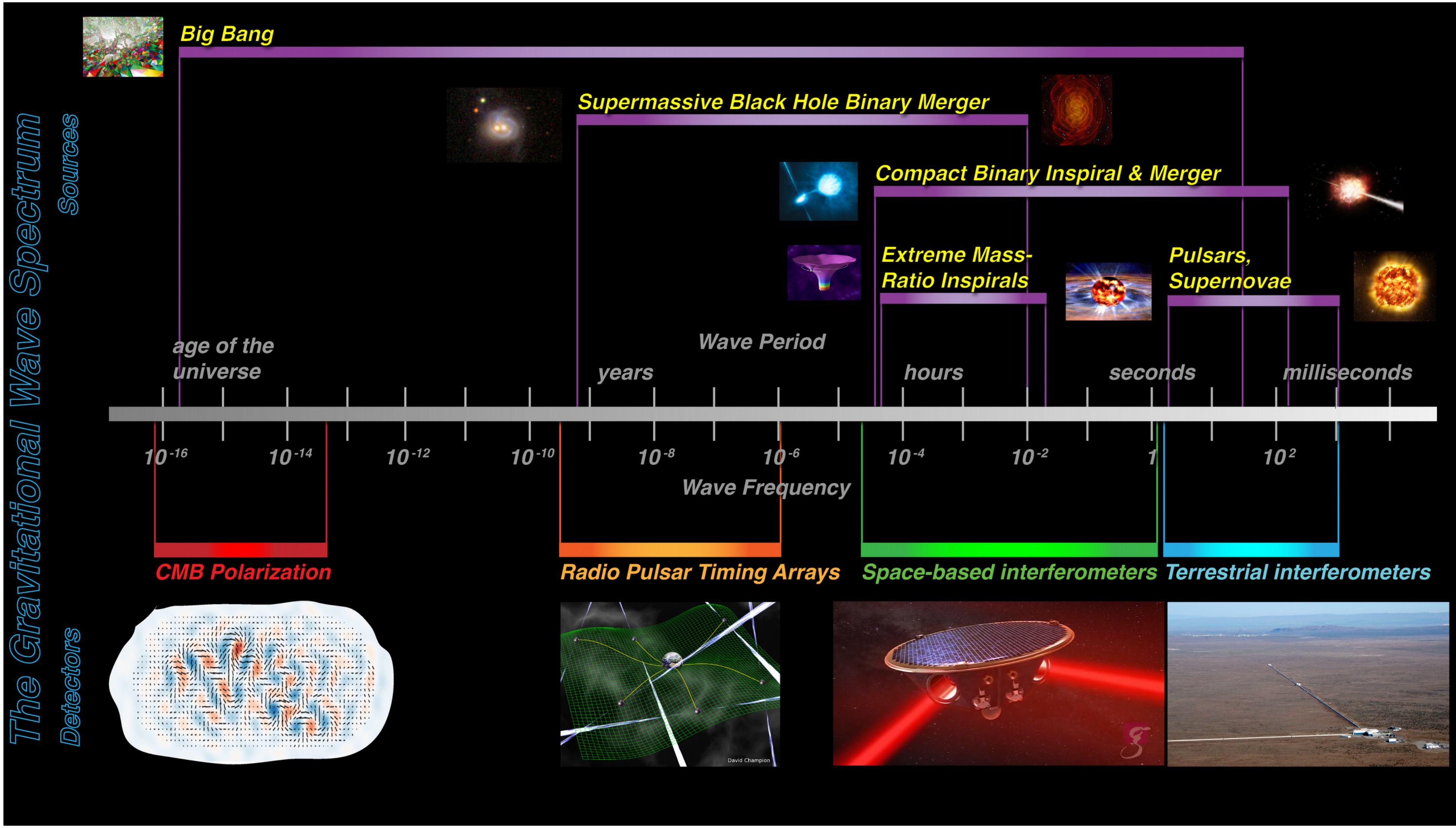
Neutron star populations



The origin of gold



Not just Virgo/LIGO...



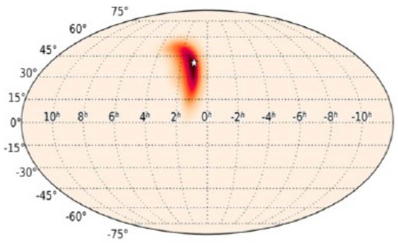
Conclusions

- 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)
- First GW events provided first tests for EM follow-up campaign
  - Great synergy and coverage
  - No expected EM emission from BBHs, but new interesting models arising
- Multimessenger astronomy has just begun
  - Not just BBH: now we have NS-NS
  - Virgo contribution important to improve localization & parameter estimation
  - Prospects for unexpected sources

EM follow-up: past and present

- Past experiences (2009-2010)
  - ~30 min latency, optical telescopes+Swift
  - Centralized organization
- Now (2015-)
  - Few mins latency
  - GCN alerts for EM partners (MoU)
  - Broadband coverage

GW alert → Sky localization → EM follow-up



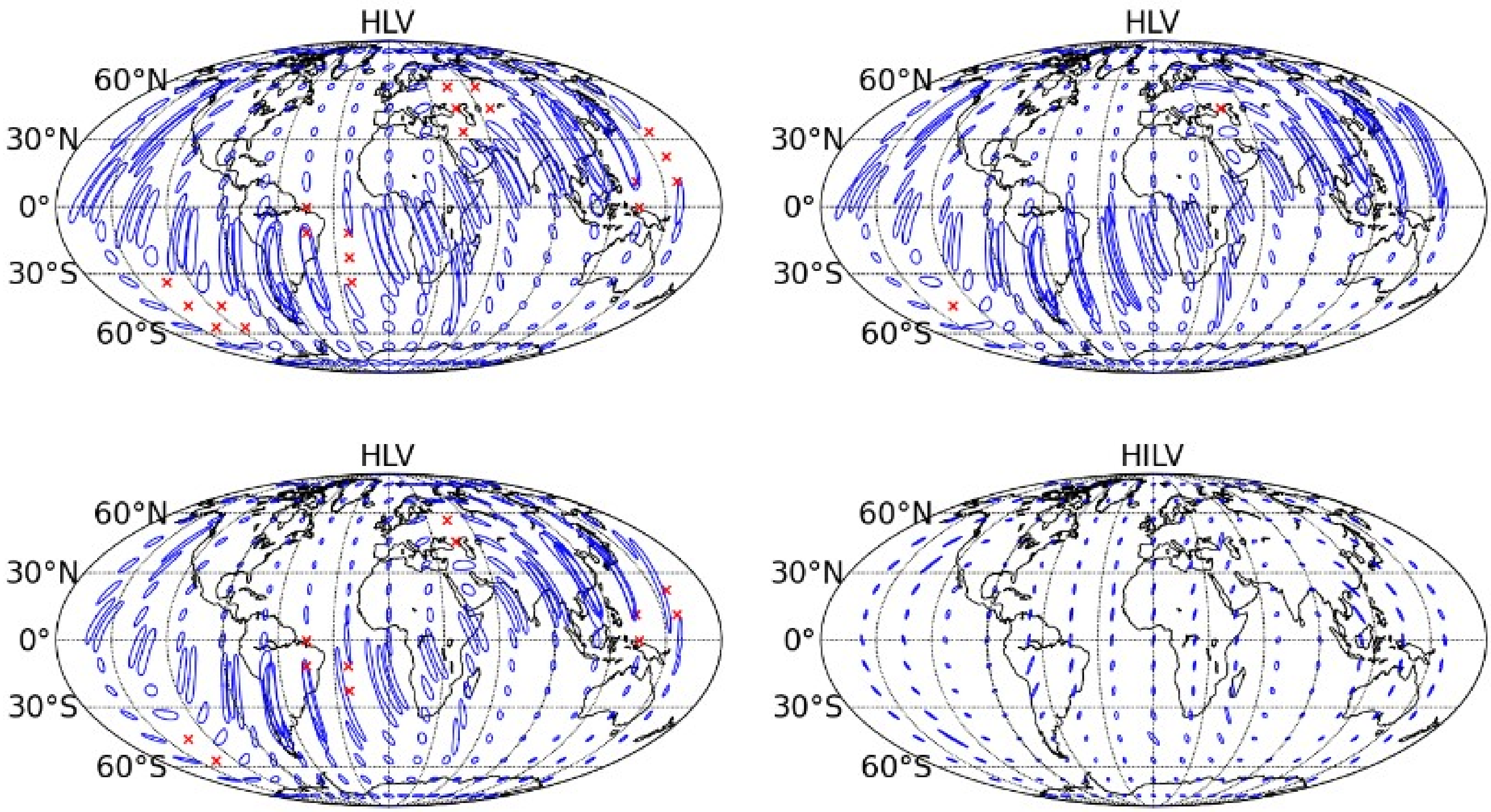
EM event	EM band	Timescale
Prompt emission	Gamma rays	<seconds

Sky Localization

BNS, 80 Mpc

2016-17

2017-18



2019+

2022+

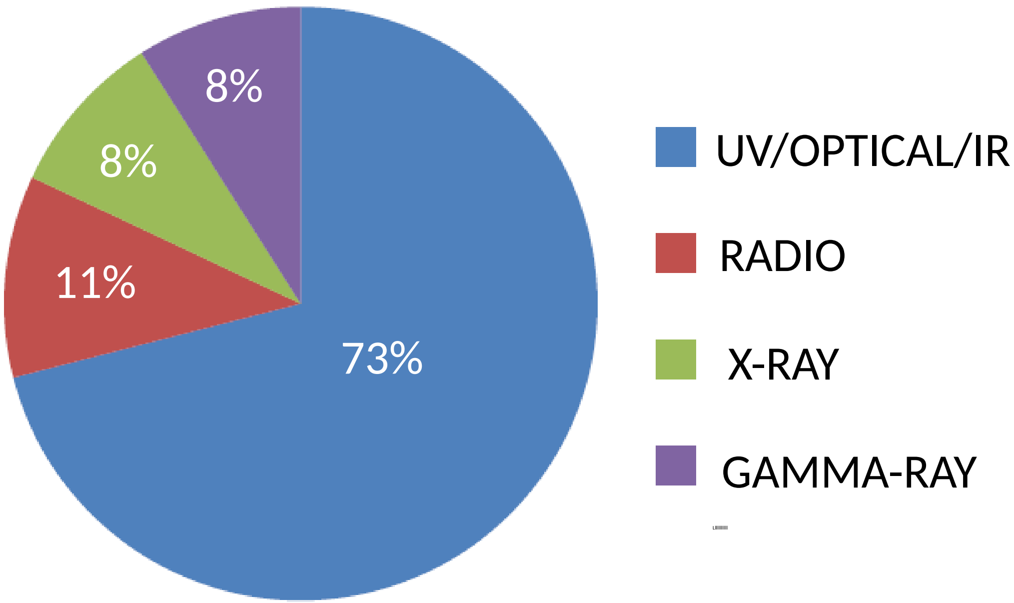
BNS, 160 Mpc

→ **90% CL**

X → **No detection**

Abbott+16, LRR 19,1

LIGO and Virgo EM follow-up program



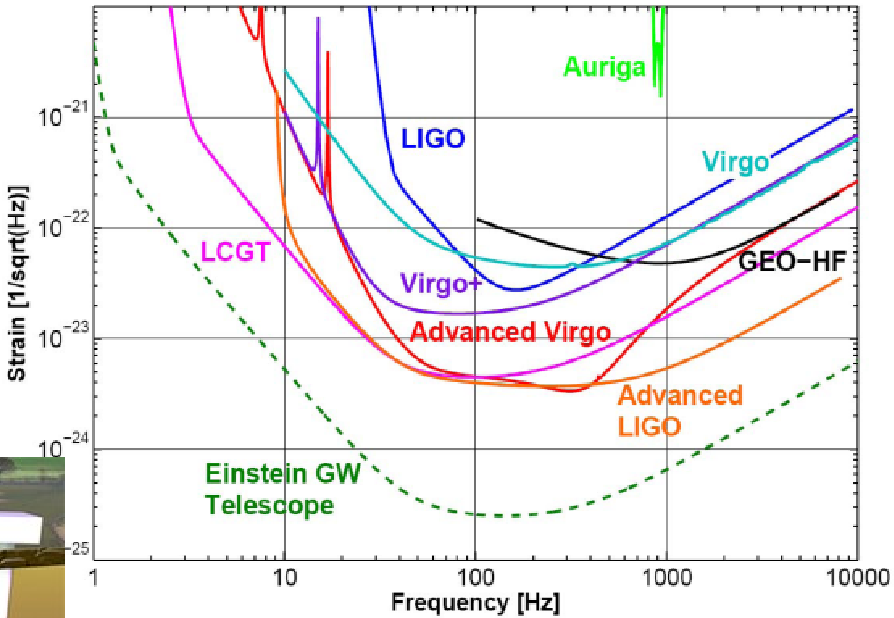
Now 80 MoUs involving

- **160 instruments**
(space and ground-based facilities)
Broadband, radio – VHE gamma rays

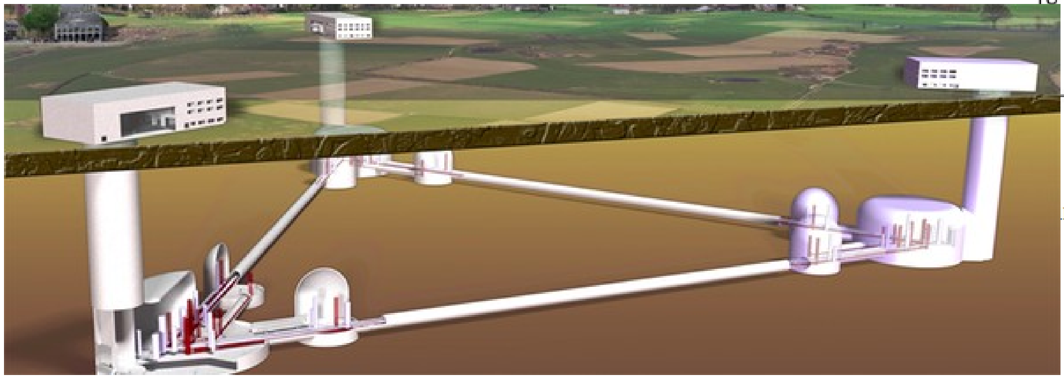
- **Astronomical institutions, agencies and large/small groups of astronomers** (20 countries)

Einstein Telescope (3rd generation)

- more sensitive than Advanced Detectors
- Extend to lower frequency window (3-100 Hz)
- Complementary with eLISA sensitivity at very low frequency

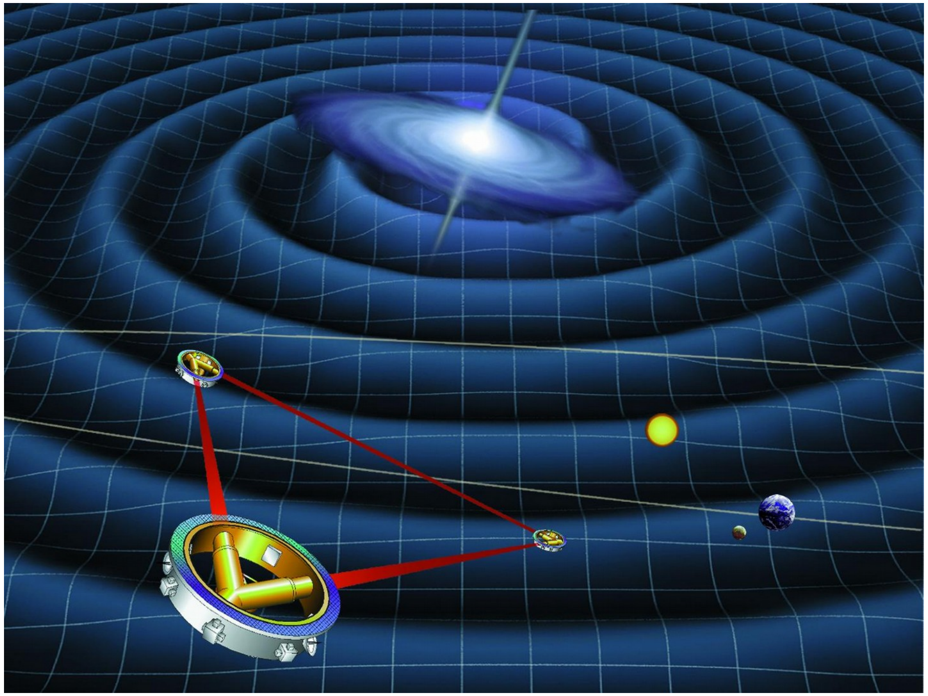


re 5: Sensitivities of gravitational wave detectors from the first to the third generation.



Even more in future: eLISA science (2034 -)

- Open 0.1 – 100 mHz window
- 3 spacecrafts, millions km separation)
- Main Topics
  - Astrophysics of black holes and galaxy formation
  - Merging massive black holes in galaxies at all distances
  - Massive BHs swallowing matter
  - known binary compact stars and stellar remnants
  - known populations of more distant binaries
  - probably other sources
  - possibly relics of the extremely early Big Bang
  - Test gravity in strong regime



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."*

- First (2014), second (2015) and third (2016) open calls for participation in GW-EM follow-up program (last year) **80 MoUs signed**

- **http://www.ligo.org/scientists/GWEMalerts.php**

GW150914 sky maps

Localization pipelines

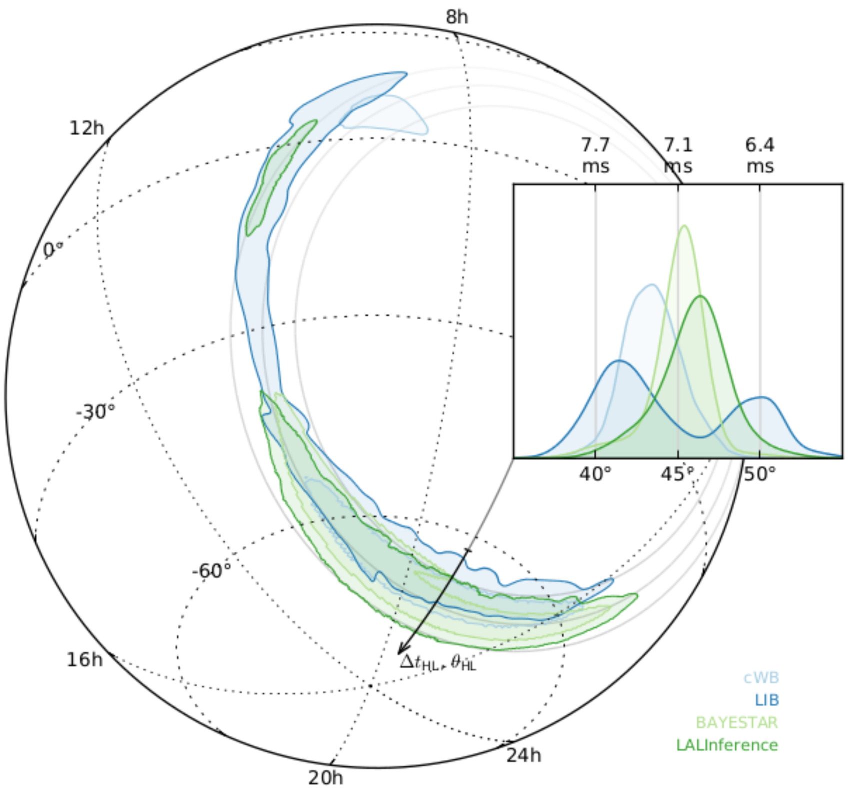
- cWB: constrained ML on sky grid
- LIB: bayesian inference
- BAYESTAR: triangulation (based on CBC pipelines, here offline)
- LALInference: full details

	Area[a]				Comparison[c]			
	10%	50%	90%	θ_{HL}[b]	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.

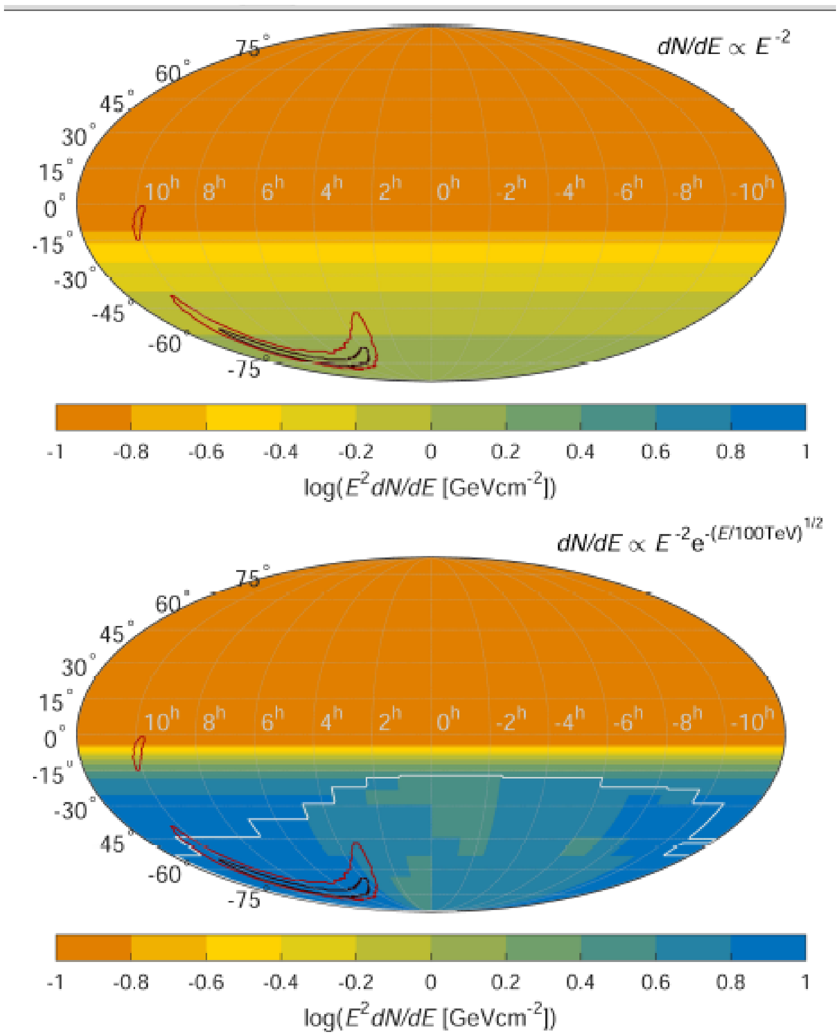
[c] Fidelity (below diagonal) and the intersection in deg^2 of the 90% confidence regions (above diagonal).



Abbott+16 (arXiv:1602.08492)

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 atmospheri neutrino
  - Constrain the source → E_{vtot}<1e52-1e54 erg



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