The new era of multimessenger astronomy

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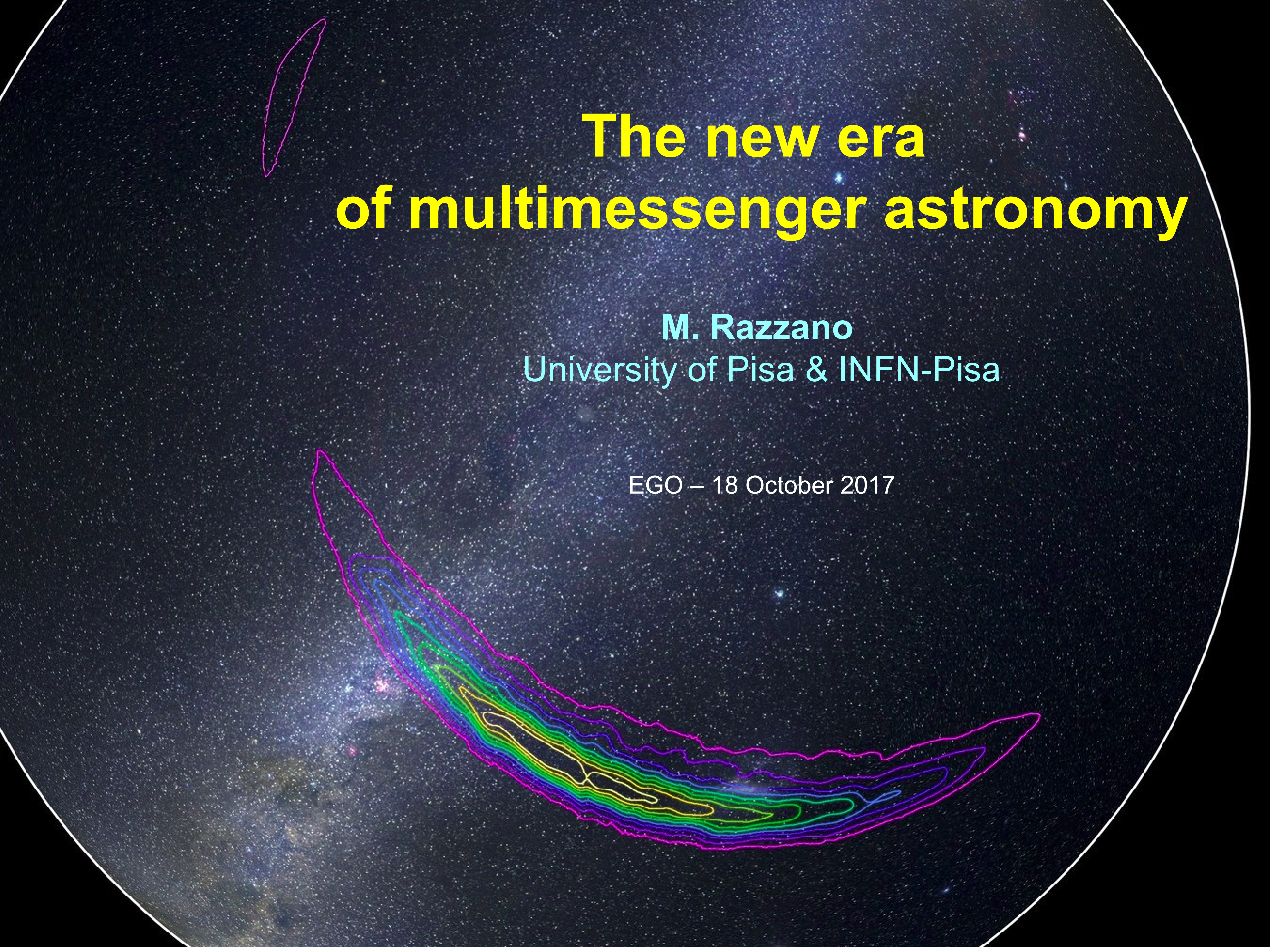
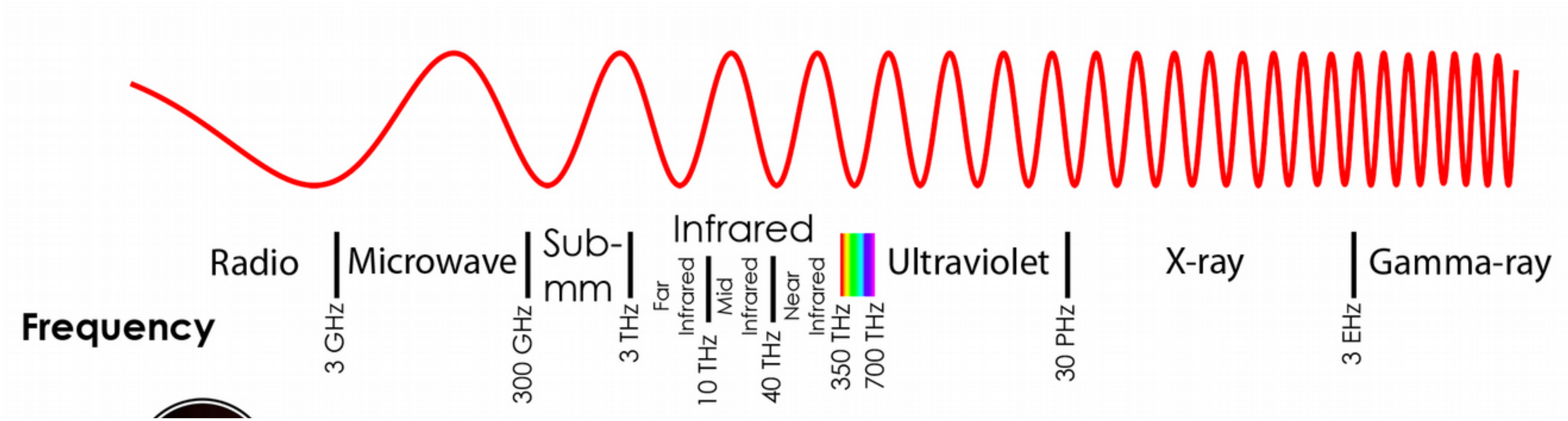
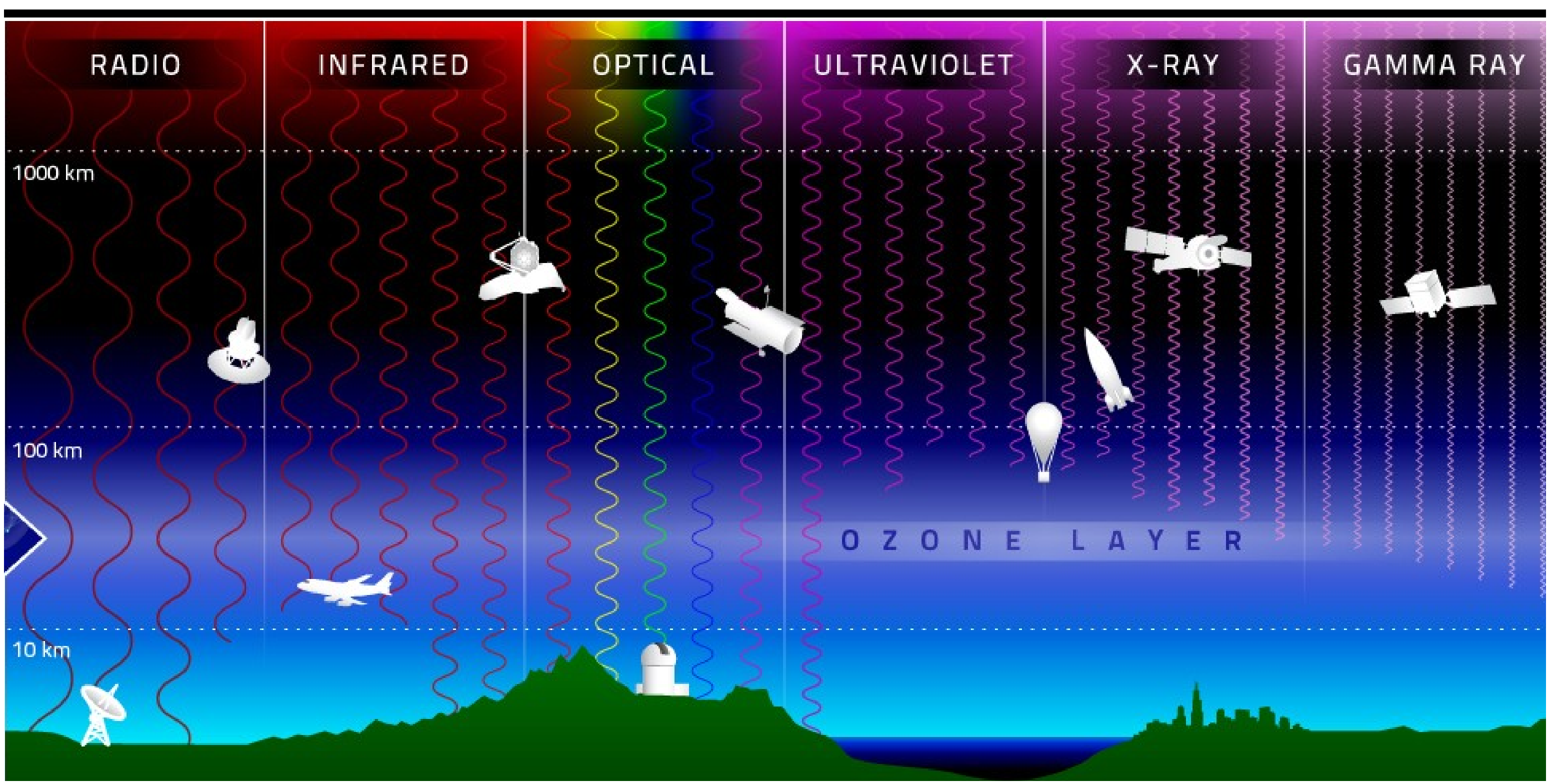
EGO – 18 October 2017



The multiwavelength sky





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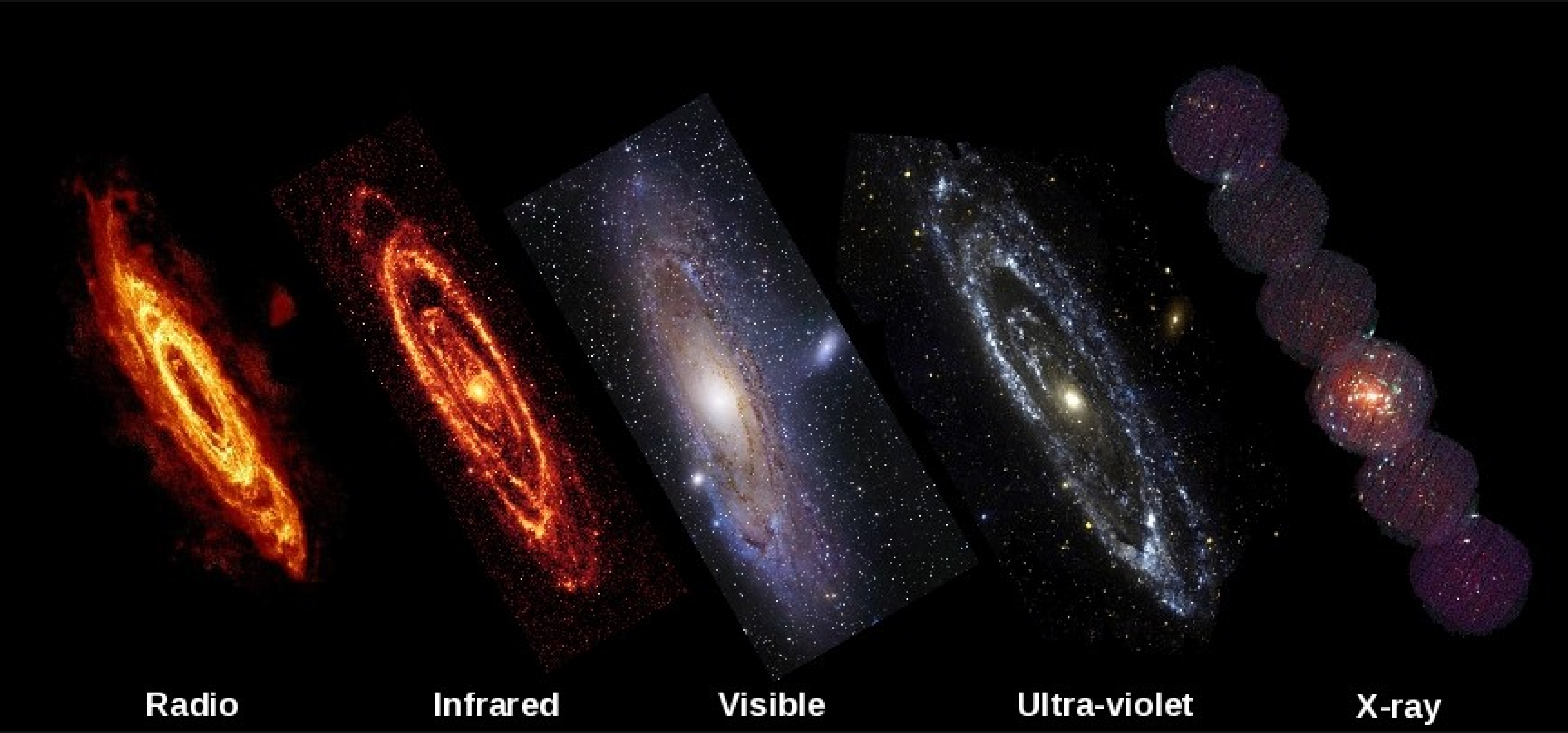
M31 (Andromeda Galaxy) in visible...

...and at other wavelengths



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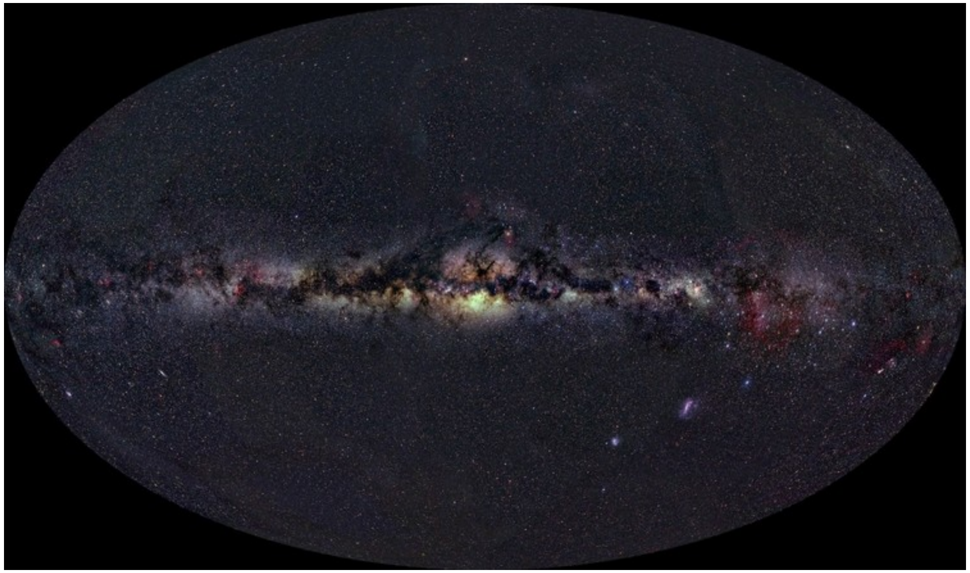
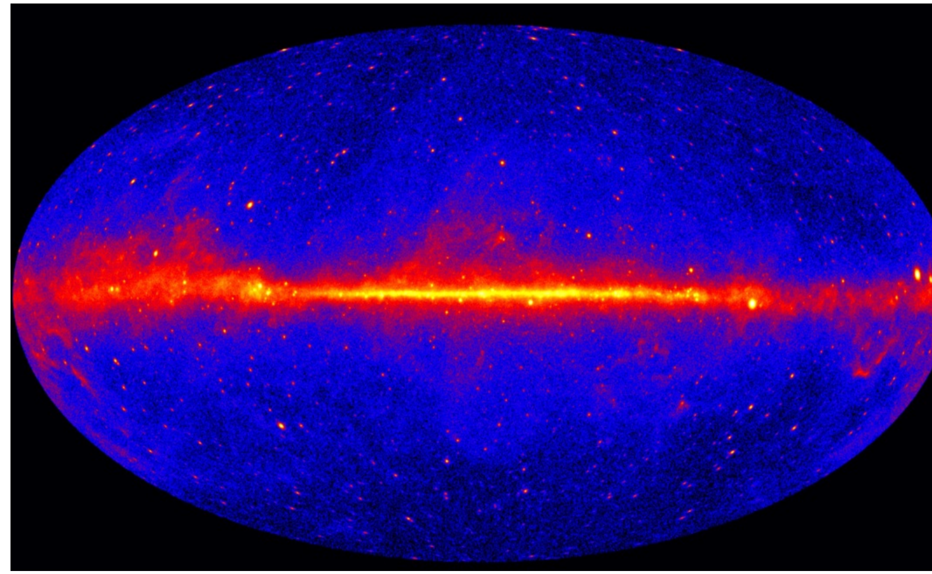
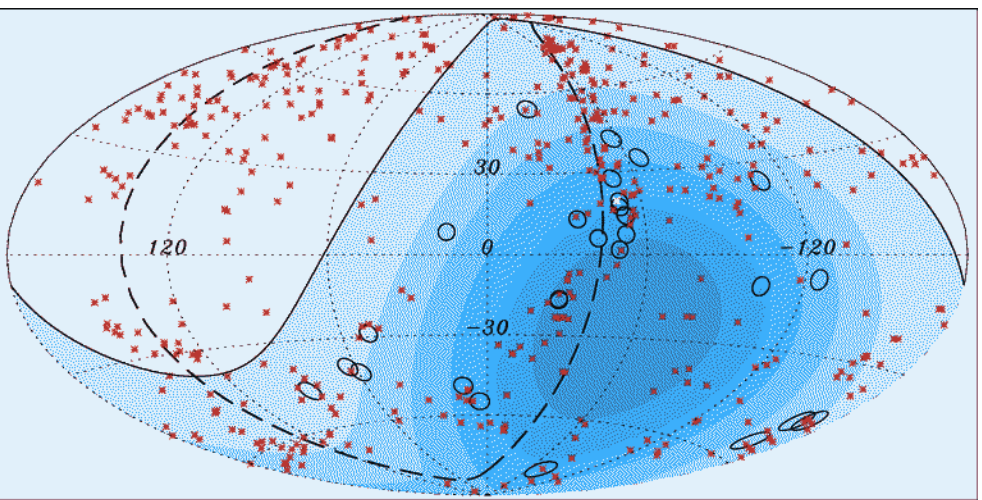
The multi-messenger sky today

Optical (APOD)

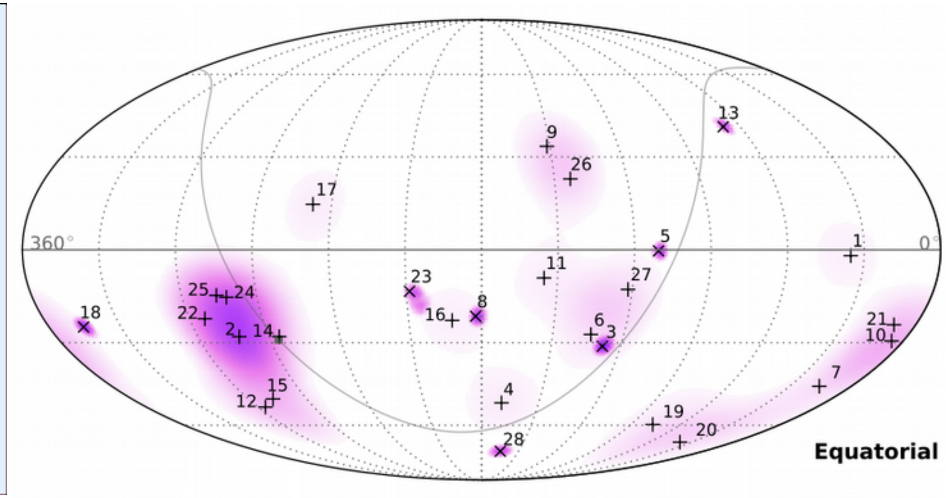


Gamma rays > 0.1 GeV (Fermi-LAT)





Cosmic rays > 57 Eev (Auger, 2007)



Neutrinos > 30 Tev (Icecube, 2013)

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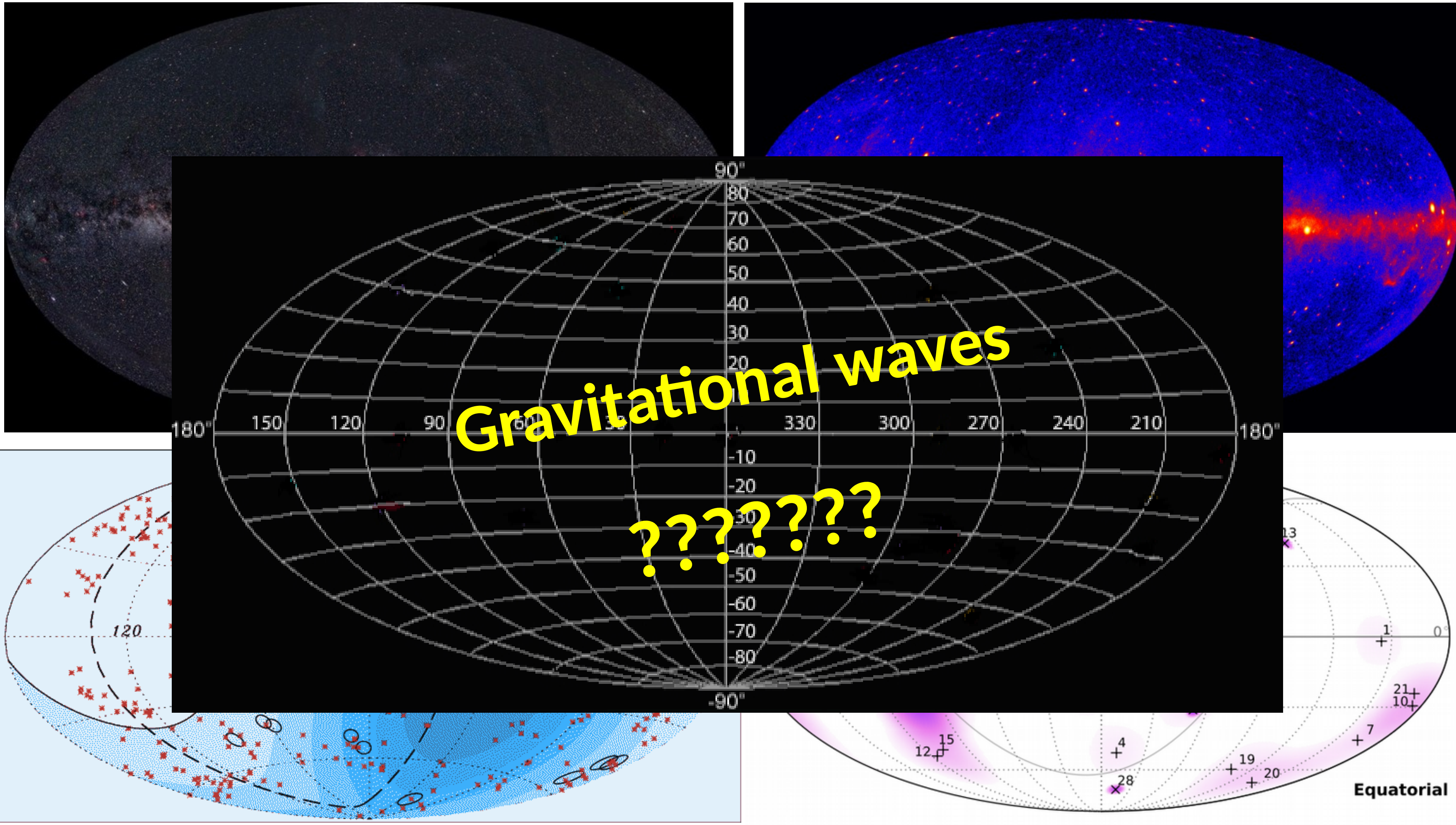
The multi-messenger sky today

Optical (APOD)

Gamma rays > 0.1 GeV (Fermi-LAT)



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A multi-messenger sky

Optical (APOD)

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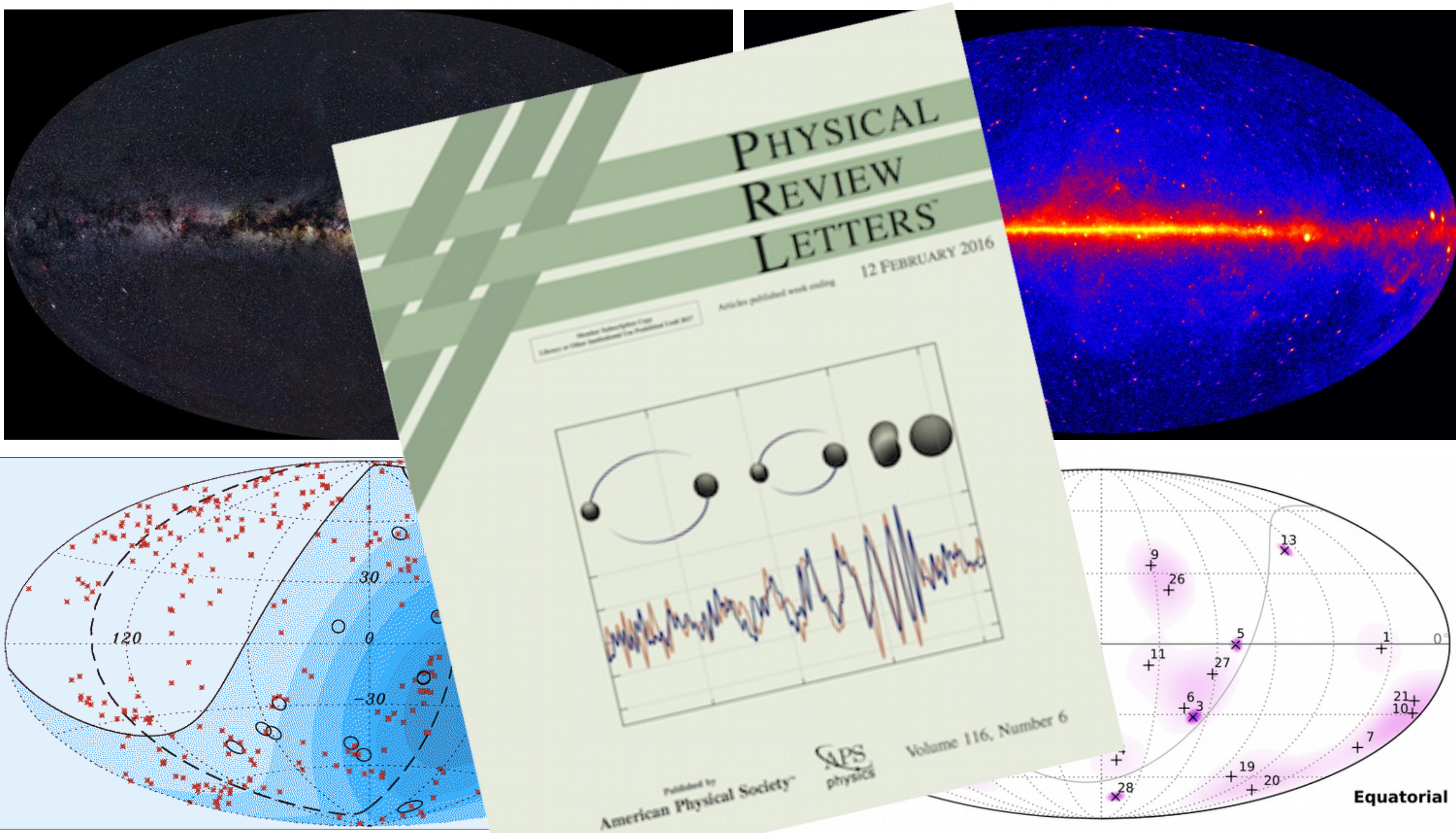

Cosmic rays > 57 Eev (Auger,

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The multi-messenger sky today

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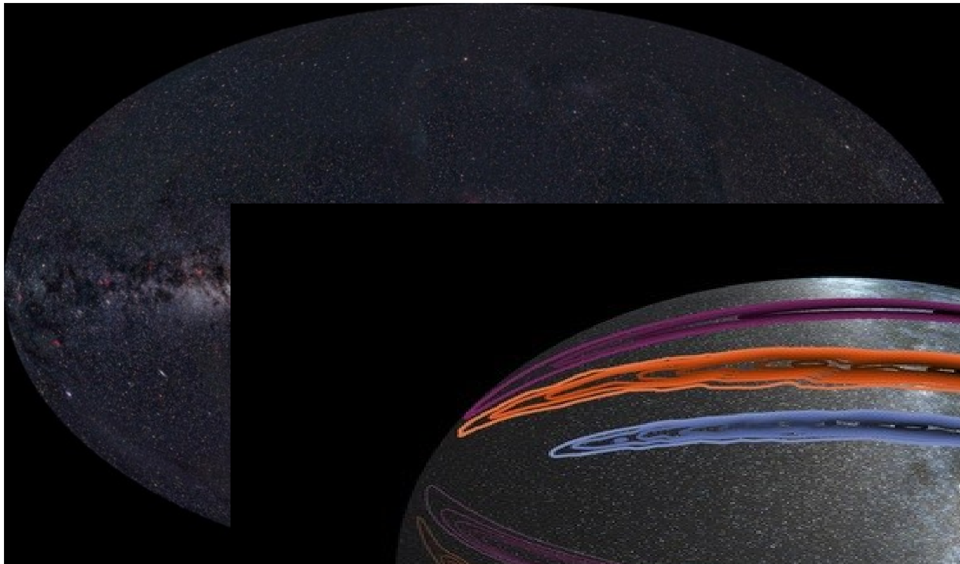

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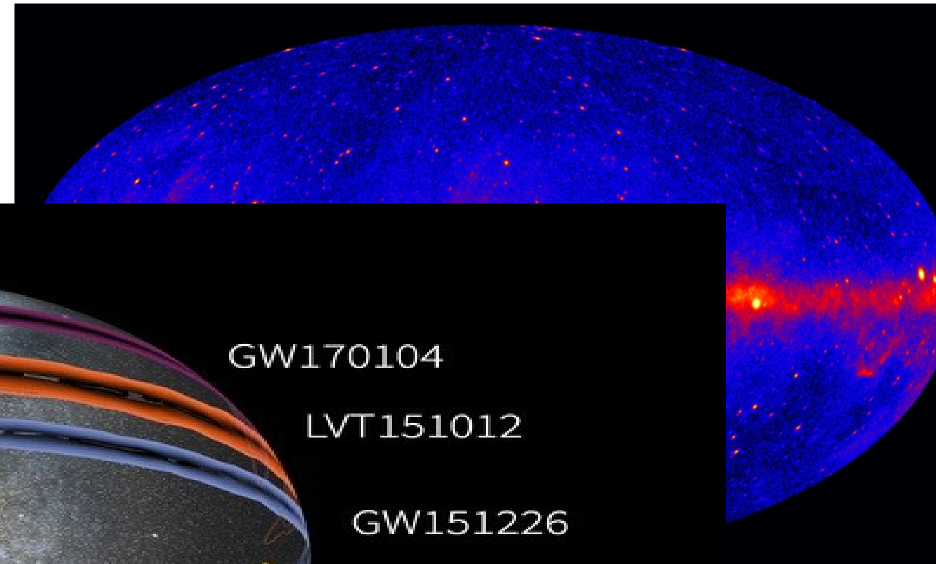

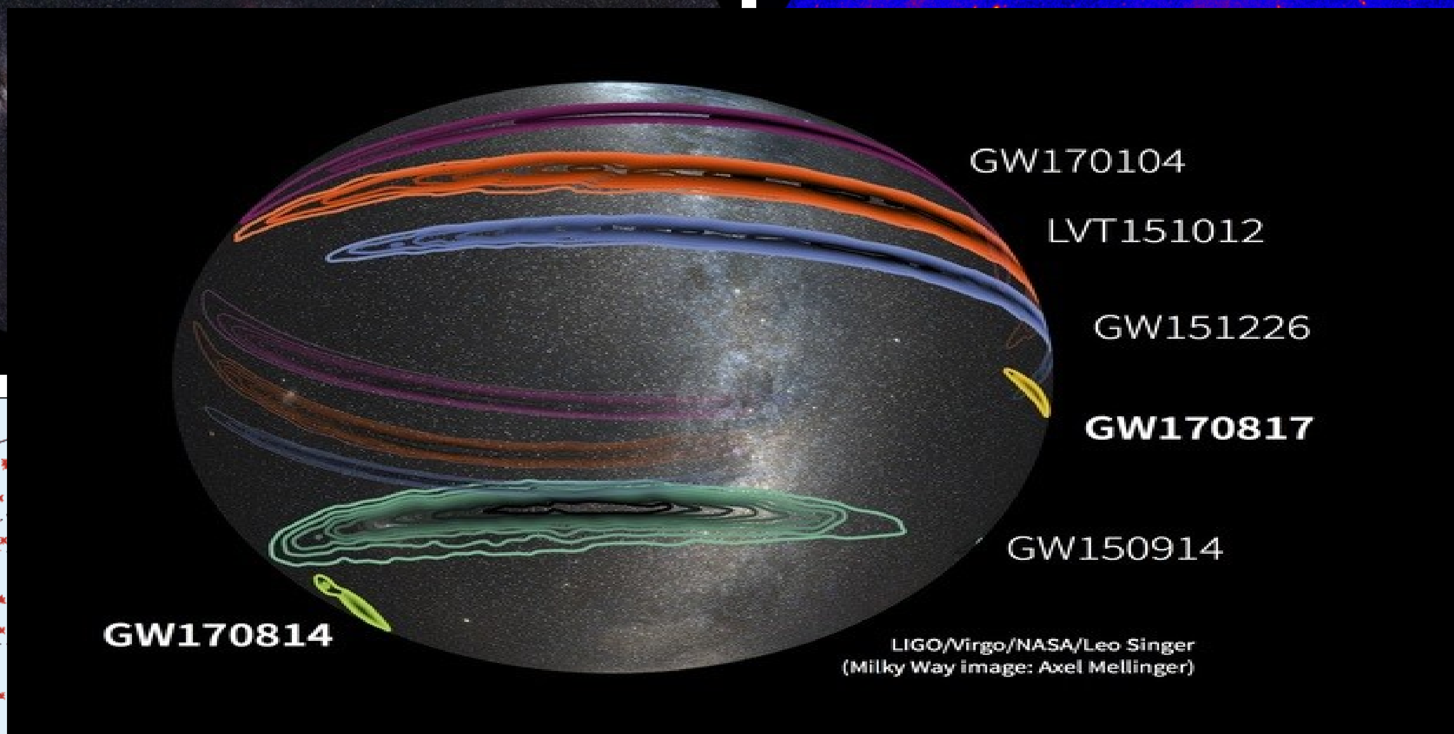

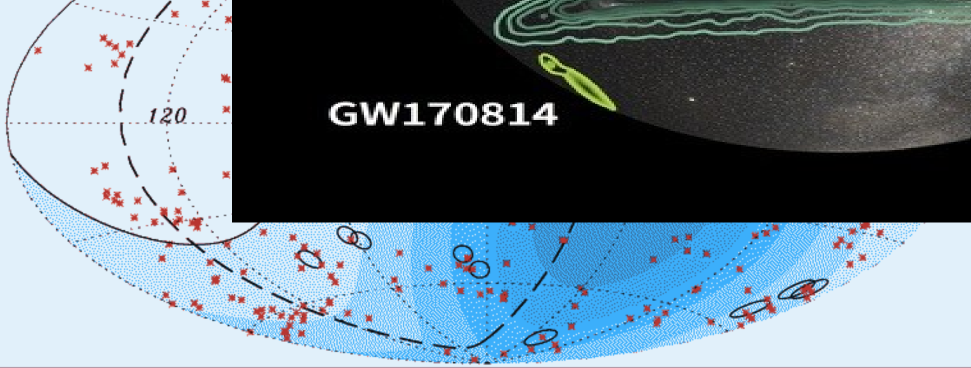

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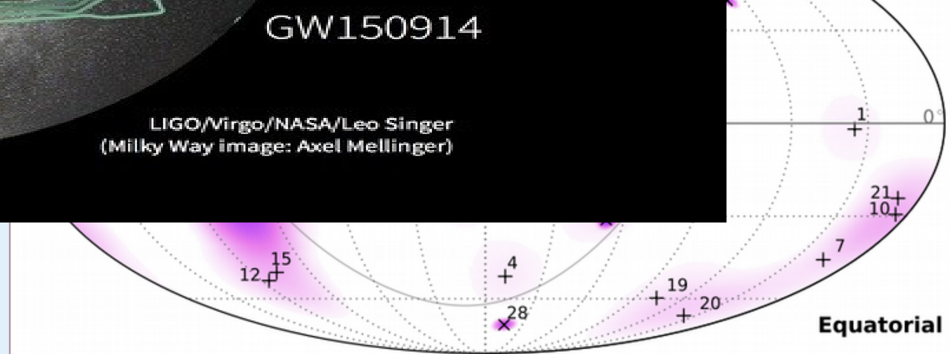

Neutrinos > 30 Tev (Icecube, 2013)

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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

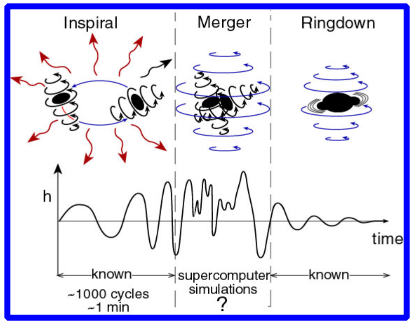
- Provide a more complete insight into the most extreme events in the Universe

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

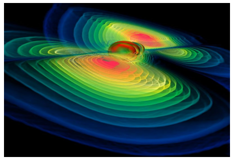
Expected multimessengers sources detectable by LIGO/Virgo

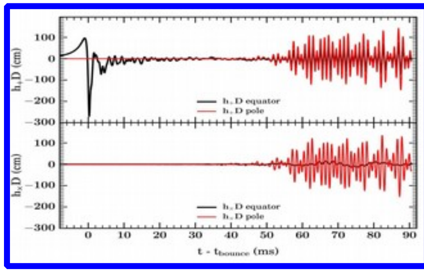
Transients

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



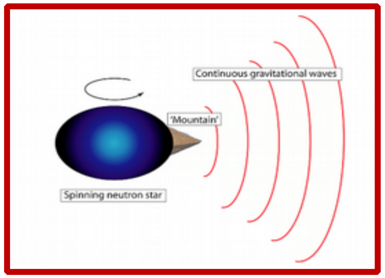


Ott, C. 2009

Non transients

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

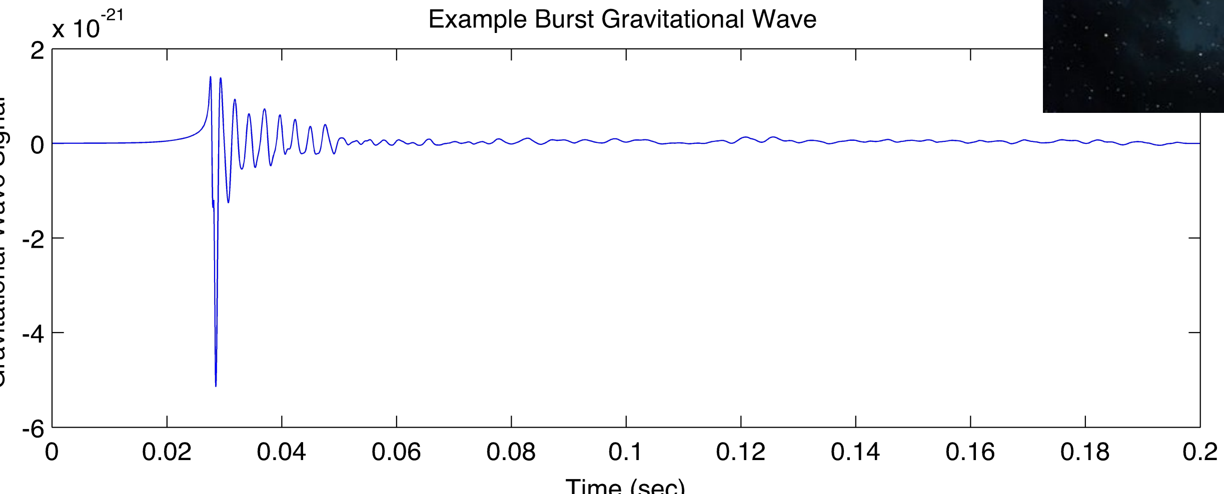
- **Stochastic background**
  - Superposition of many signals (mergers, cosmological, etc)
  - Low frequency



Multimessenger Physics – Supernovae

Stellar explosions

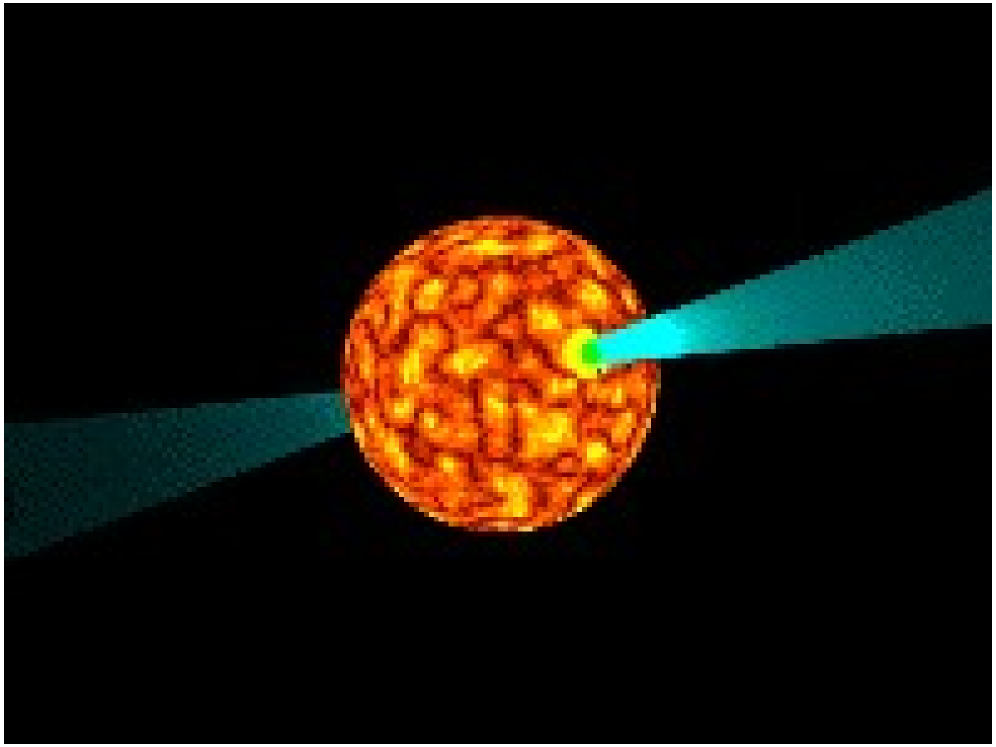
- What is the physical mechanisms behind Supernovae?
- What is the structure/asymmetry during collapse?
- Many inputs beyond GW are required

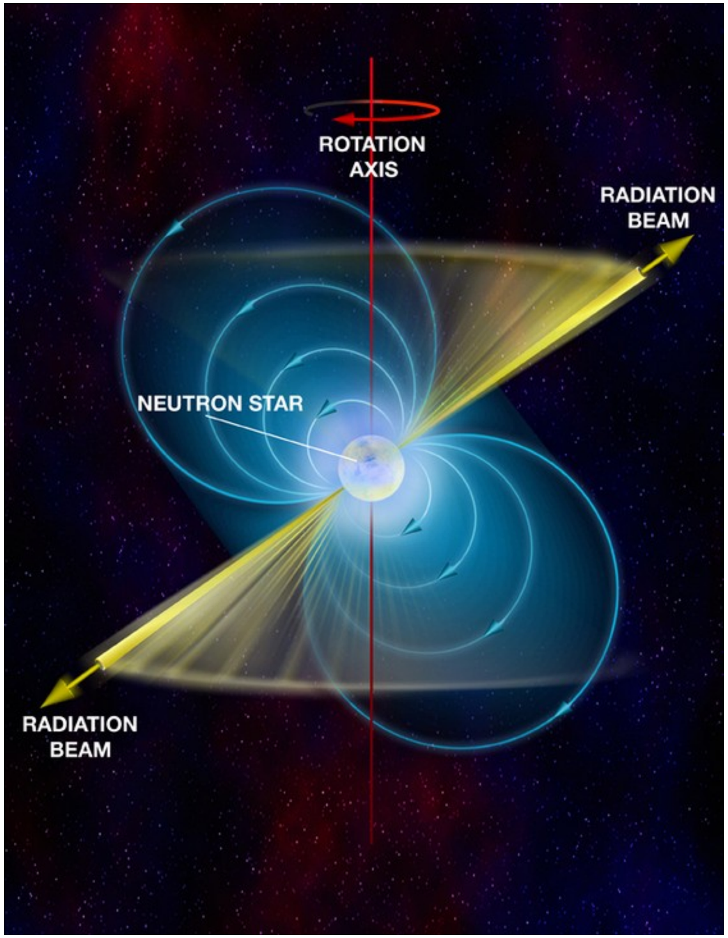


Multimessenger Physics – Neutron Stars

Continuous Waves

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

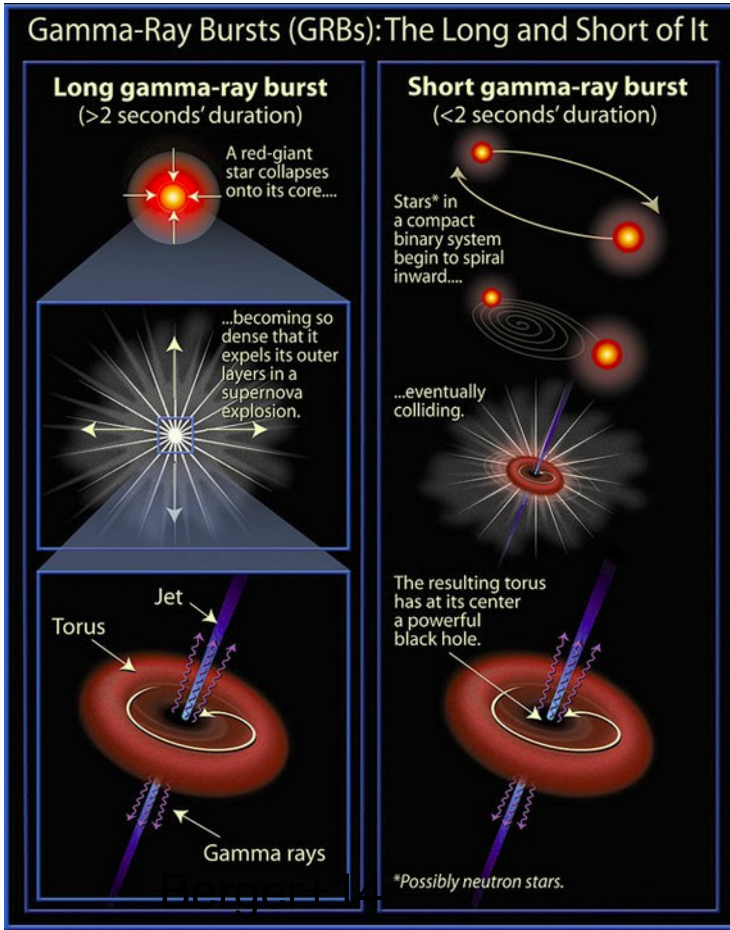




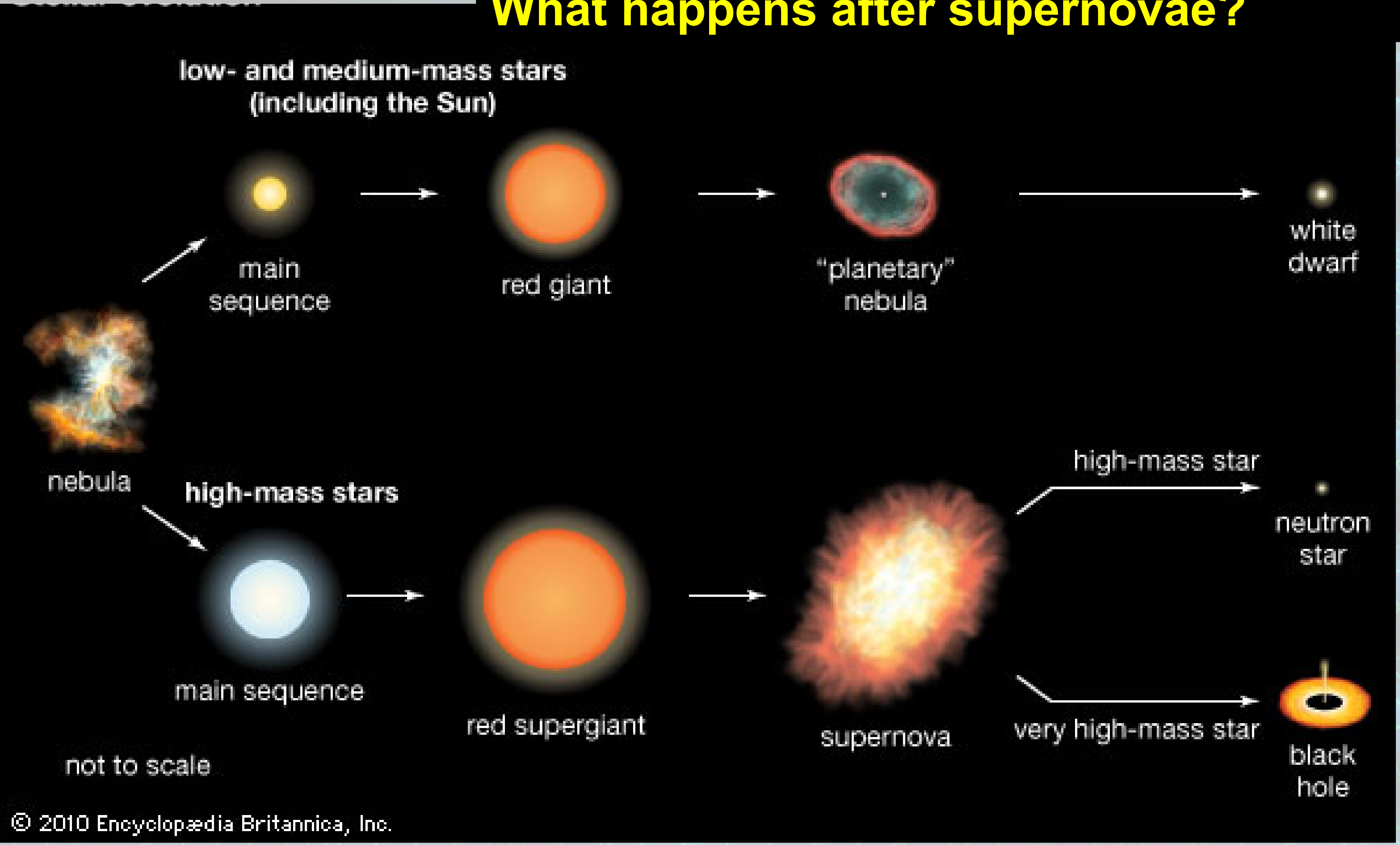
Multimessenger Physics - Mergers

Mergers of binary objects (NSs and/or BHs)

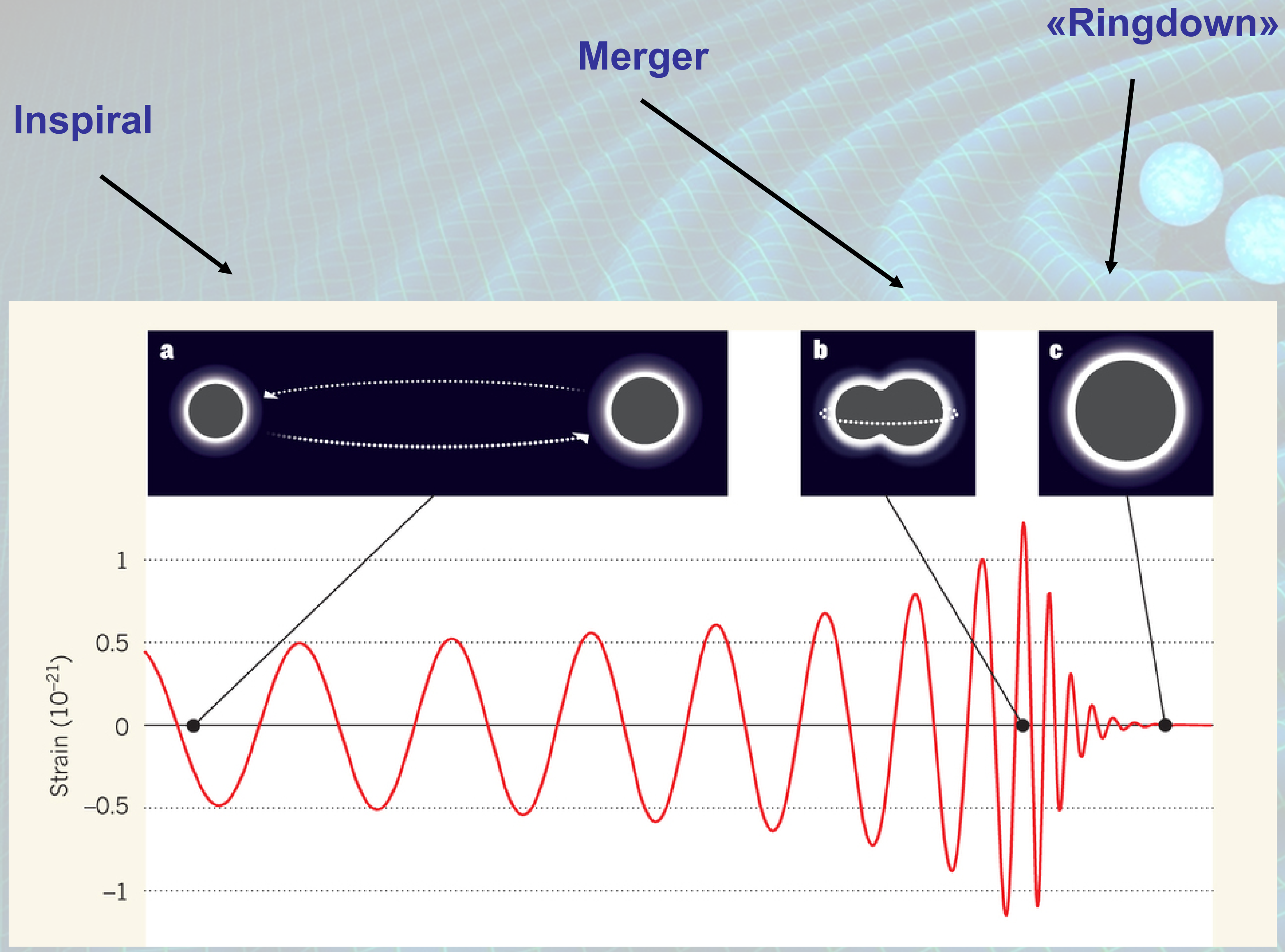
- Believed to be progenitors of short GRBs
  - Follow-up observations, find EM counterparts
- Populations of compact objects
  - Evolution
  - Mass function



Massive stars go supernova
What happens after supernovae?

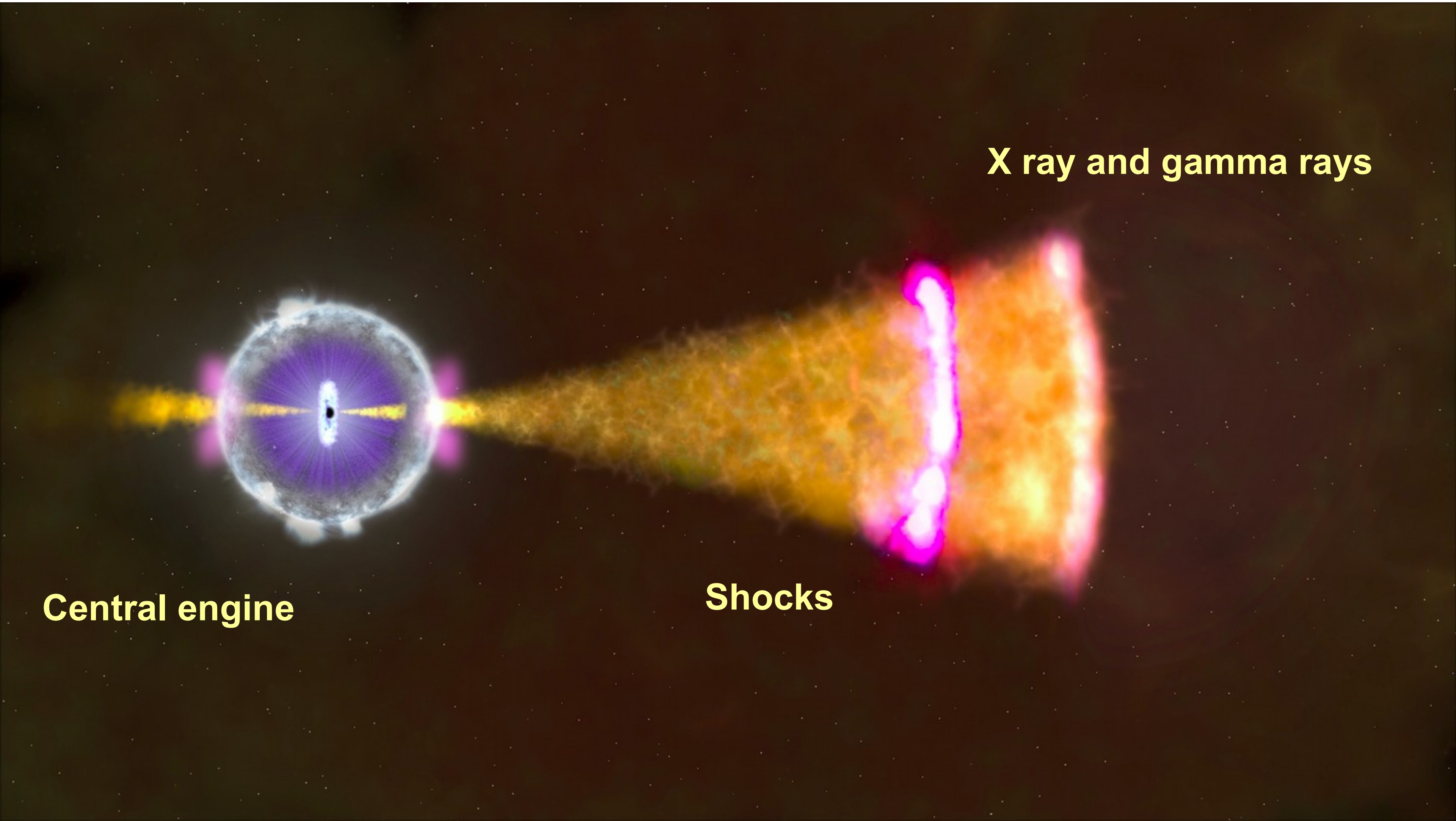


Coalescence of binary systems



Multimessenger: the case of GRB

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



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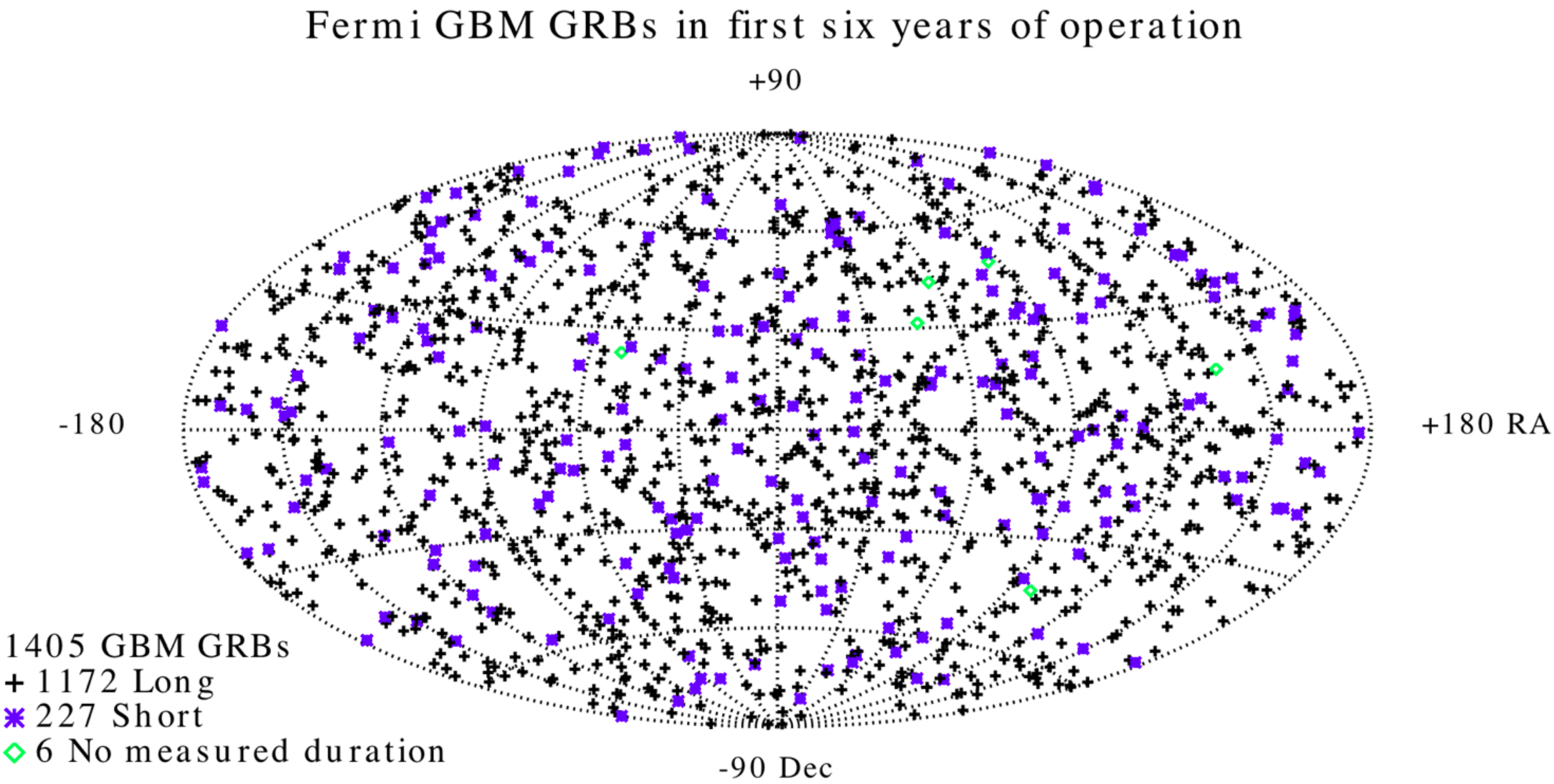
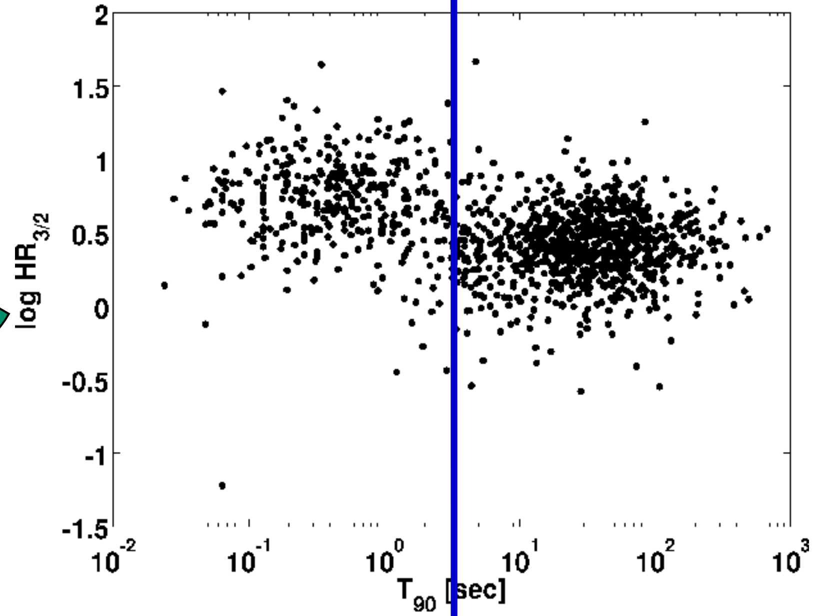


Science case for EM follow-up: the GRB connection

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

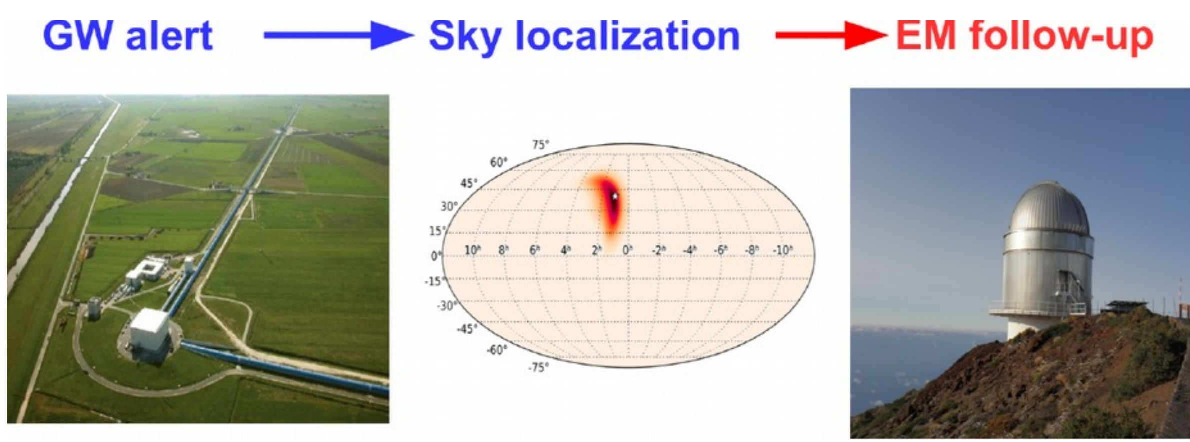


Long GRBs (>2 s)

Believed to be associated with core-collapse of massive star

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



EM event	EM band	Timescale
Prompt emission	Gamma rays	<seconds

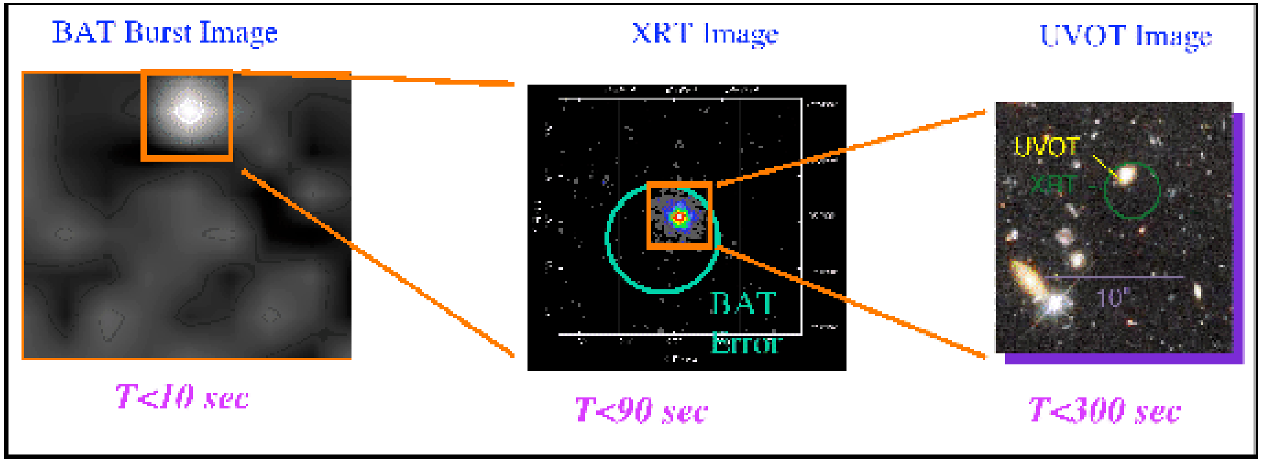
A needle in a haystack: an example from the past

Find a counterpart is not easy!

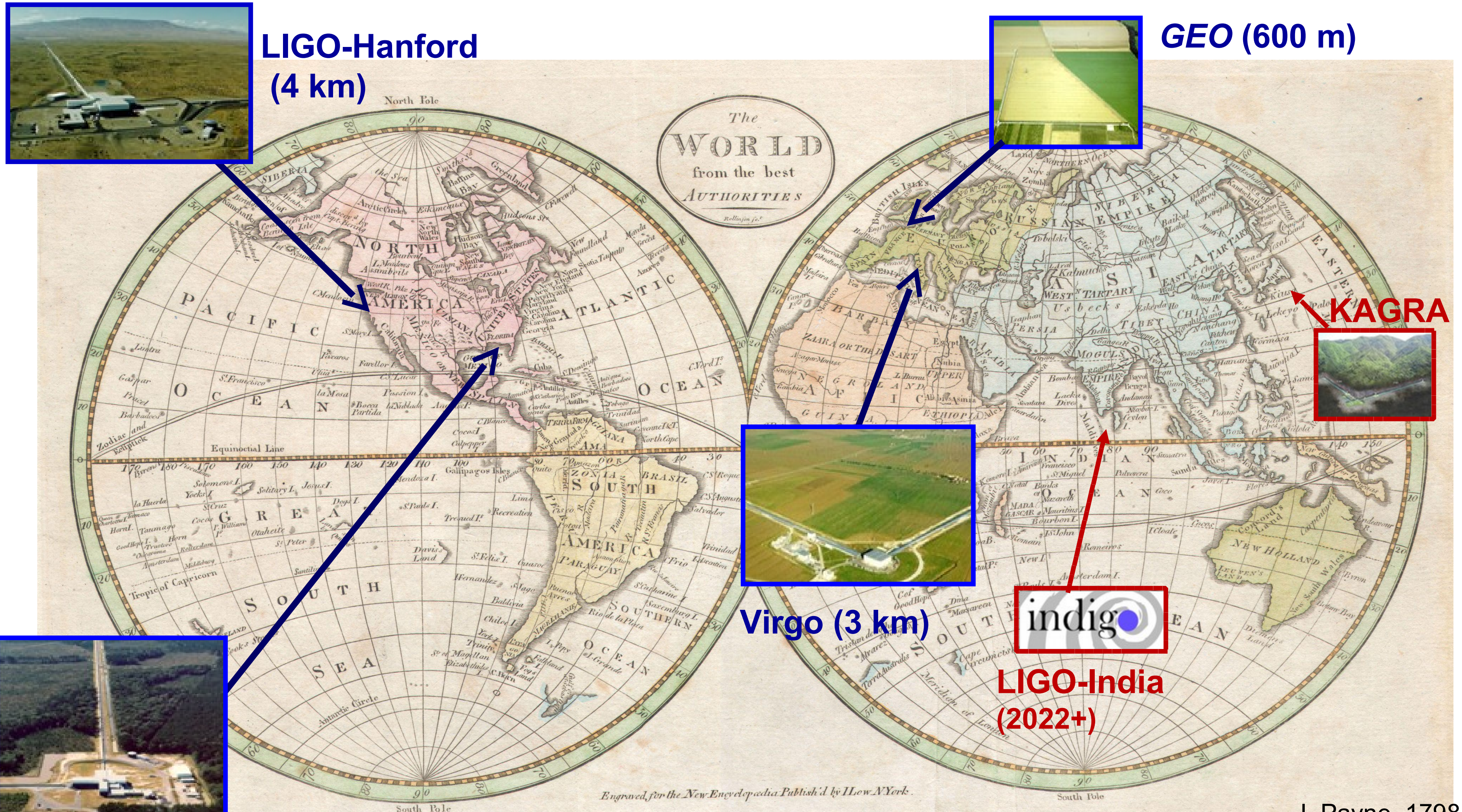
- **EM Transients might be**
  - **Fast**
  - **Faint**
  - **Too many**

- **Findind counterparts of GRBs was very difficult**

- **For GWs, the situation is worse…**



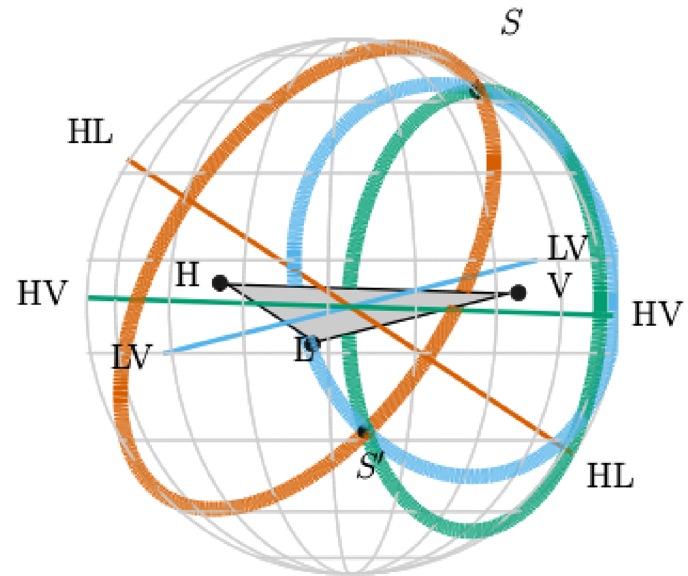
The era of Advanced GW detectors

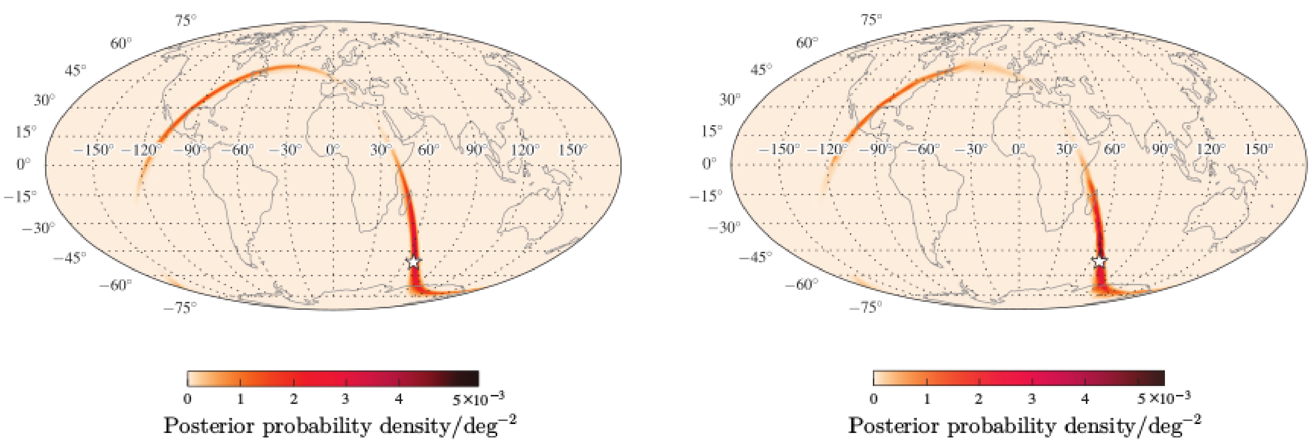


Advanced LIGO + Advanced Virgo
First joint run in 2016 (O2)

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

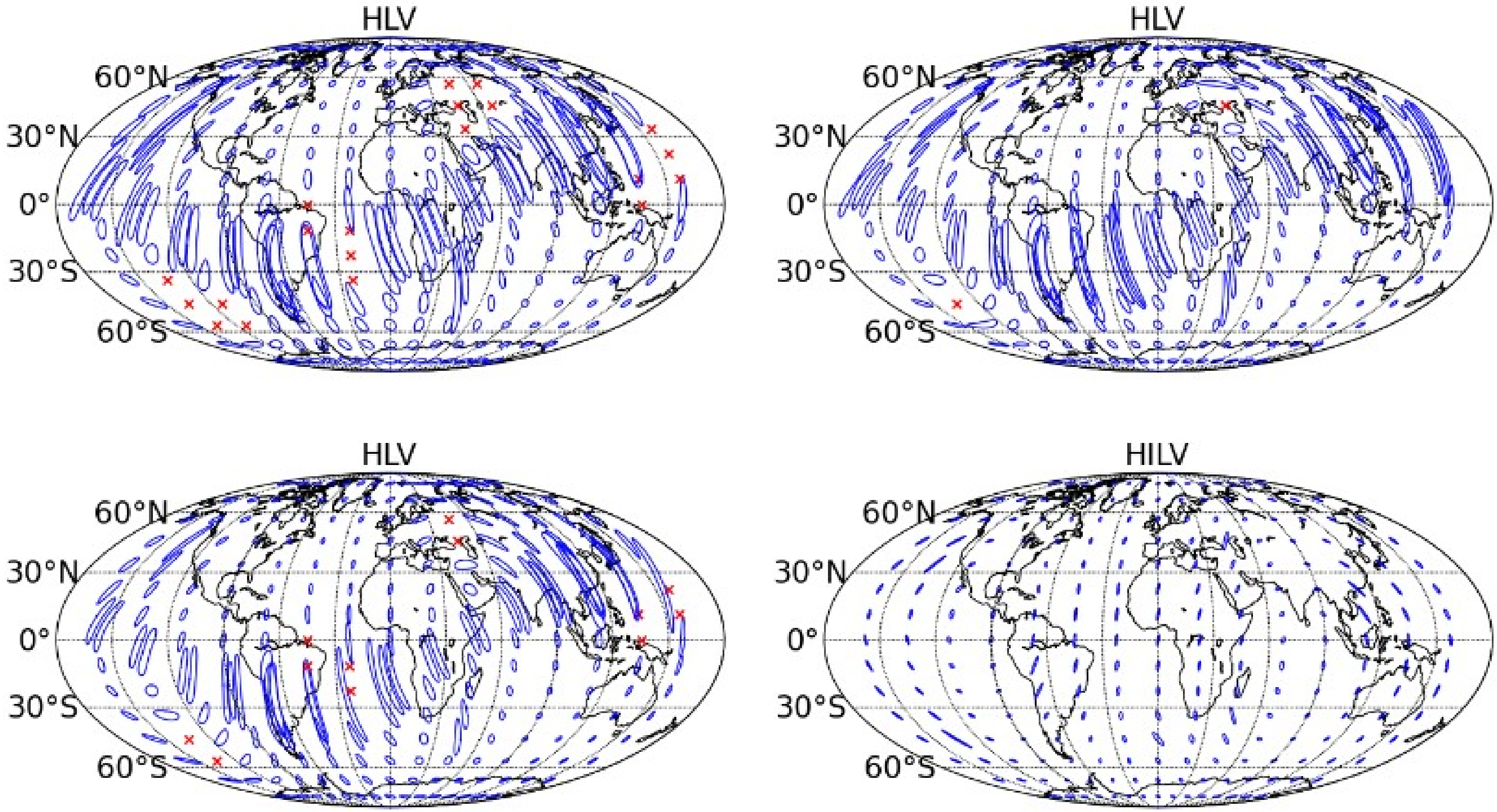
BNS system, SNR ~13.2
LALINFERENCE (left), BAYESTAR (right)

Sky Localization

BNS, 80 Mpc

2016-17

2017-18



2019+

2022+

BNS, 160 Mpc

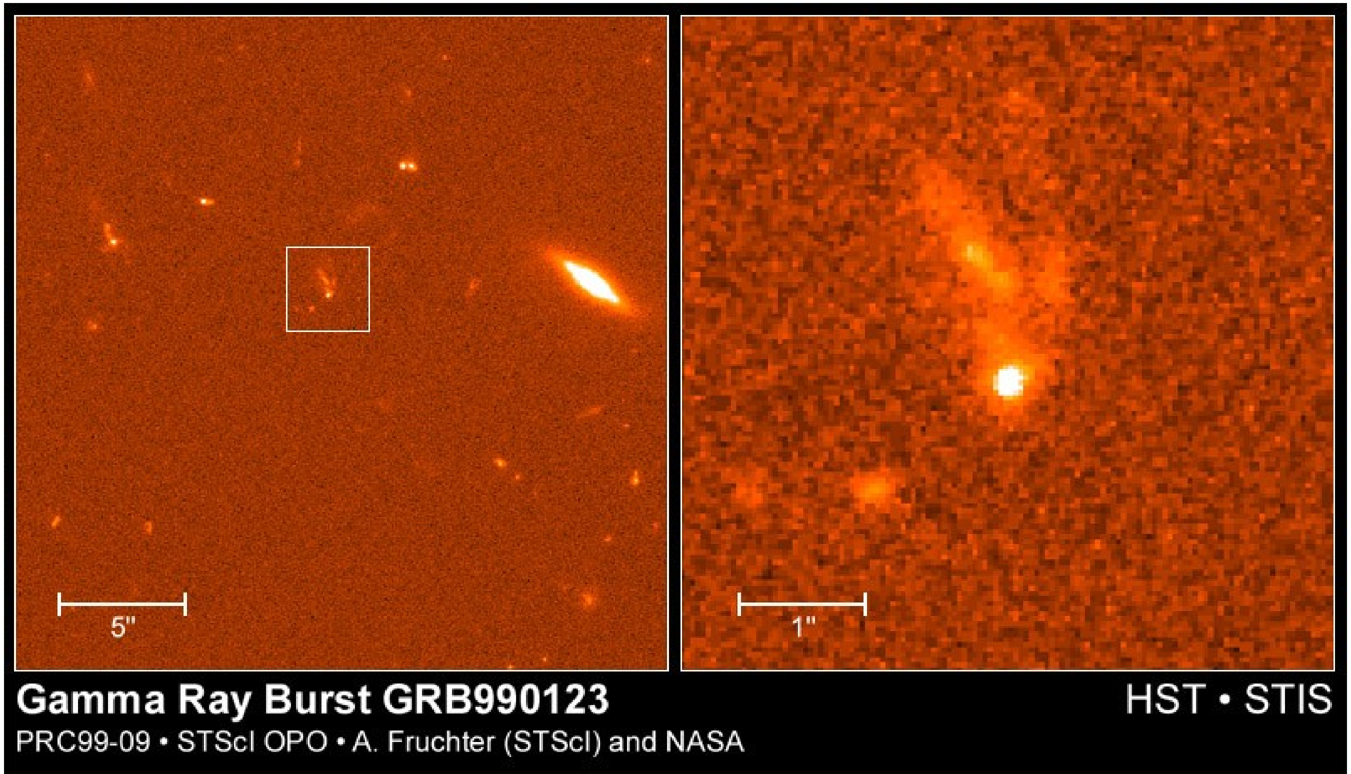
→ **90% CL**

X → **No detection**

Abbott+16, LRR 19,1

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?



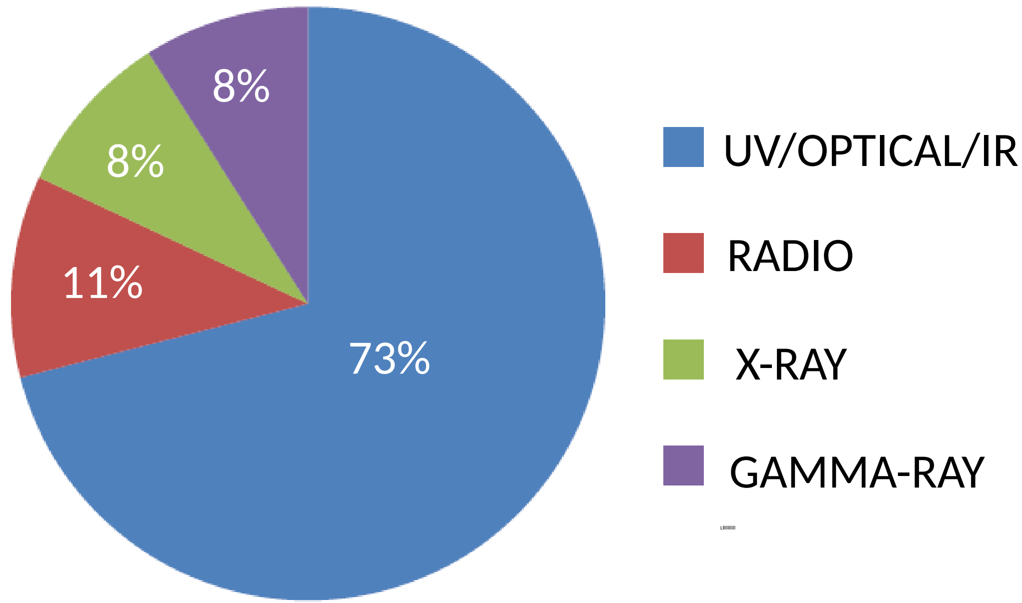
Why an EM follow-up program?

- 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

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)

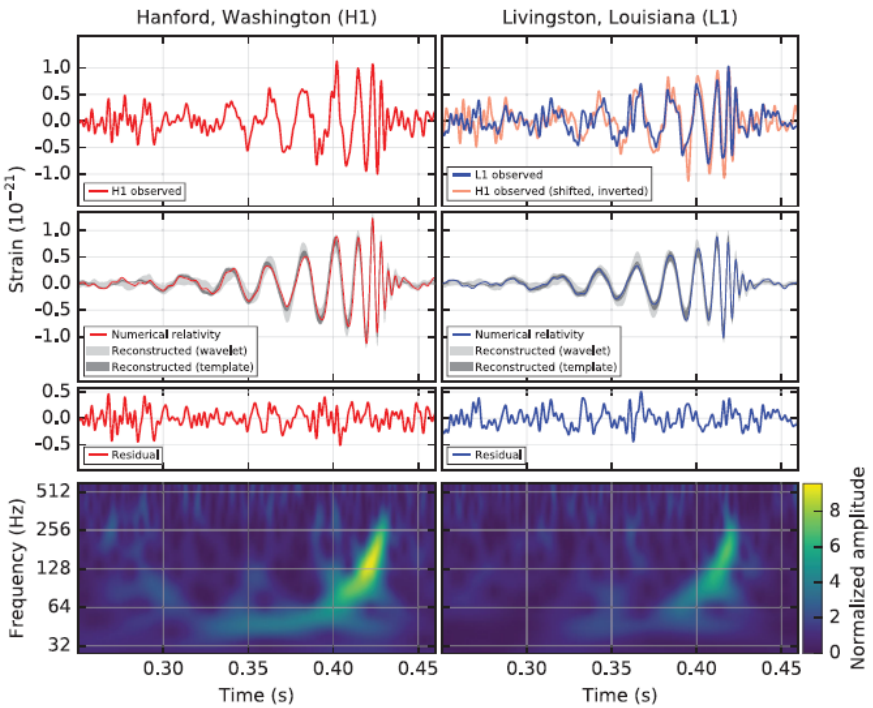
In 2012, **LVC agreed policy on releasing GW alerts**

*"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.*

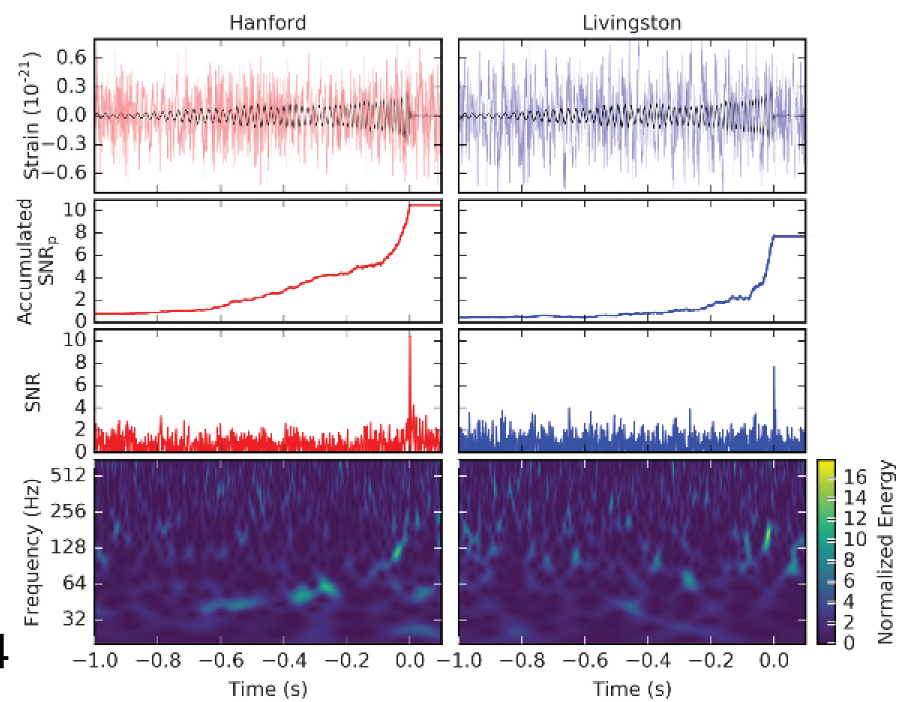
***After four GW events have been published**, further event candidates with high confidence will be **shared immediately with the entire astronomy community**, while lower-significance candidates will continue to be shared promptly only with partners who have signed an MoU."*

- 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**

First detections!

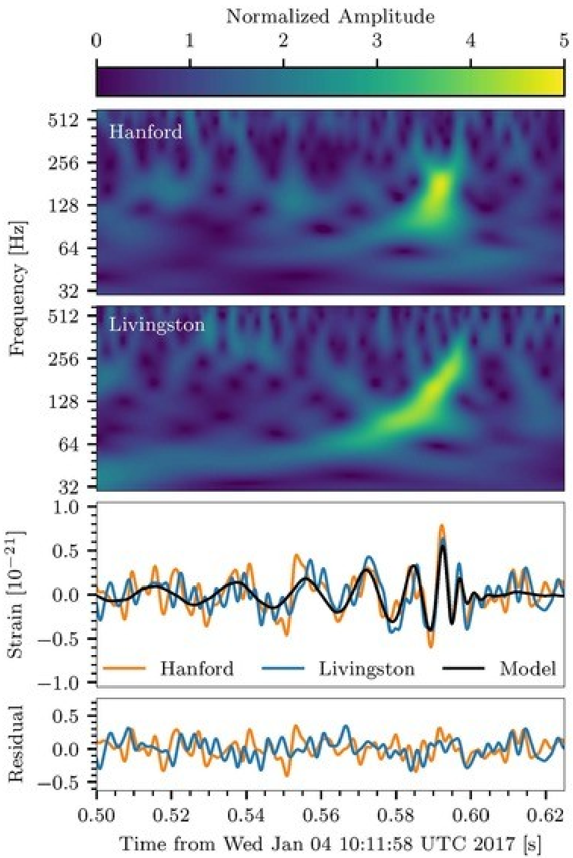


GW15109
Abbott+16, PRL116,6



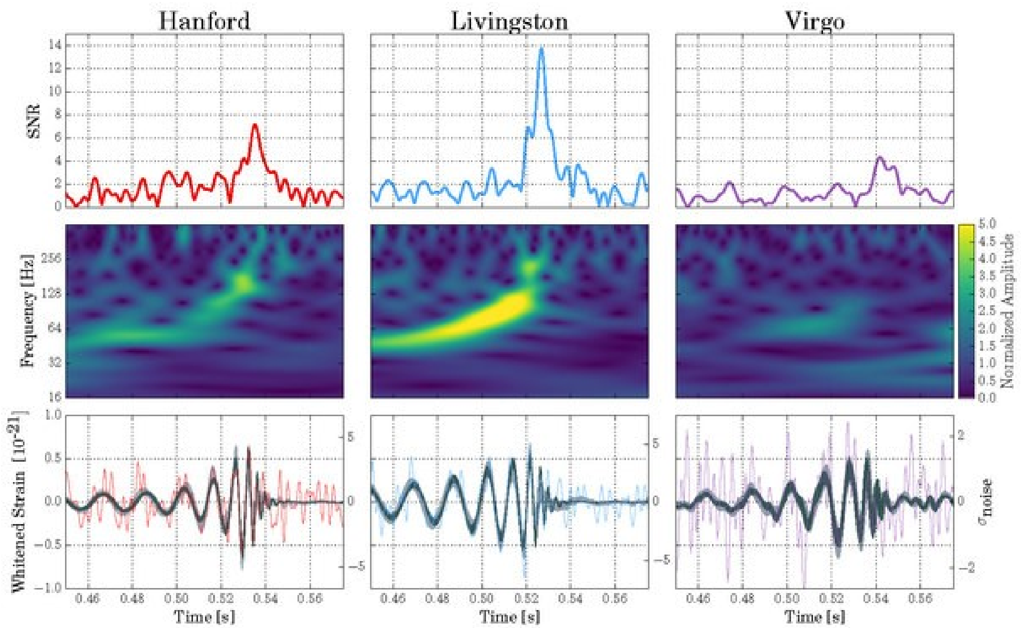
GW151226
Abbott+16, PRL116,24

First detections!

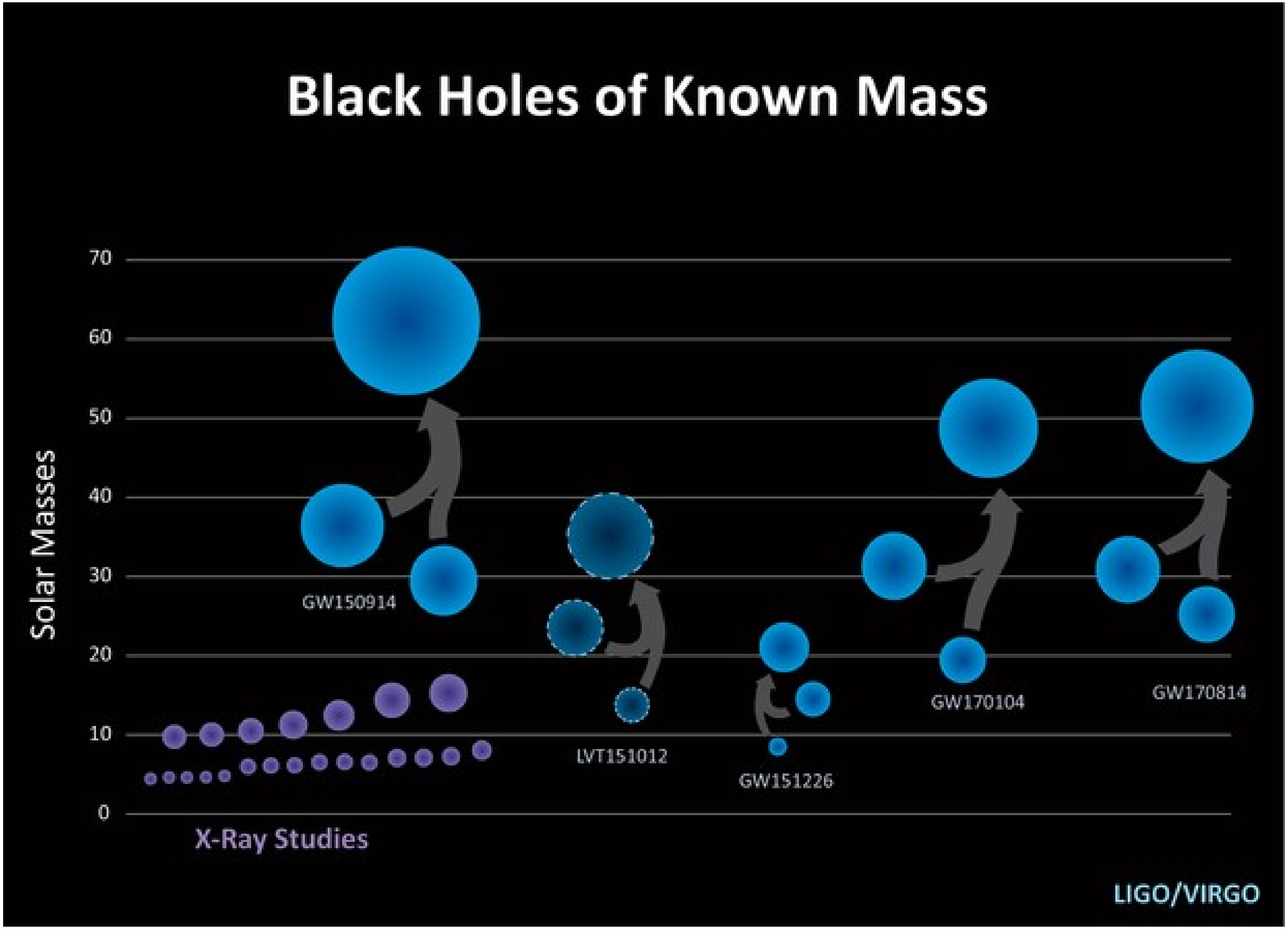


GW170104

GW170814,
The first "triple"

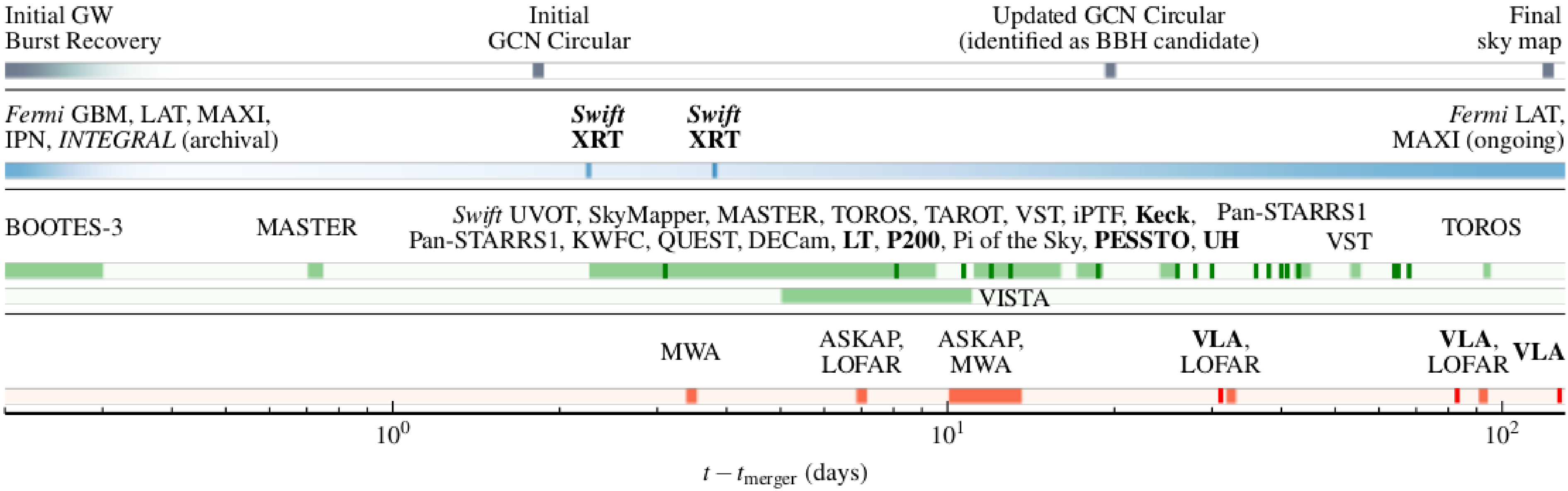


Black hole populations



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 sky maps

Localization pipelines

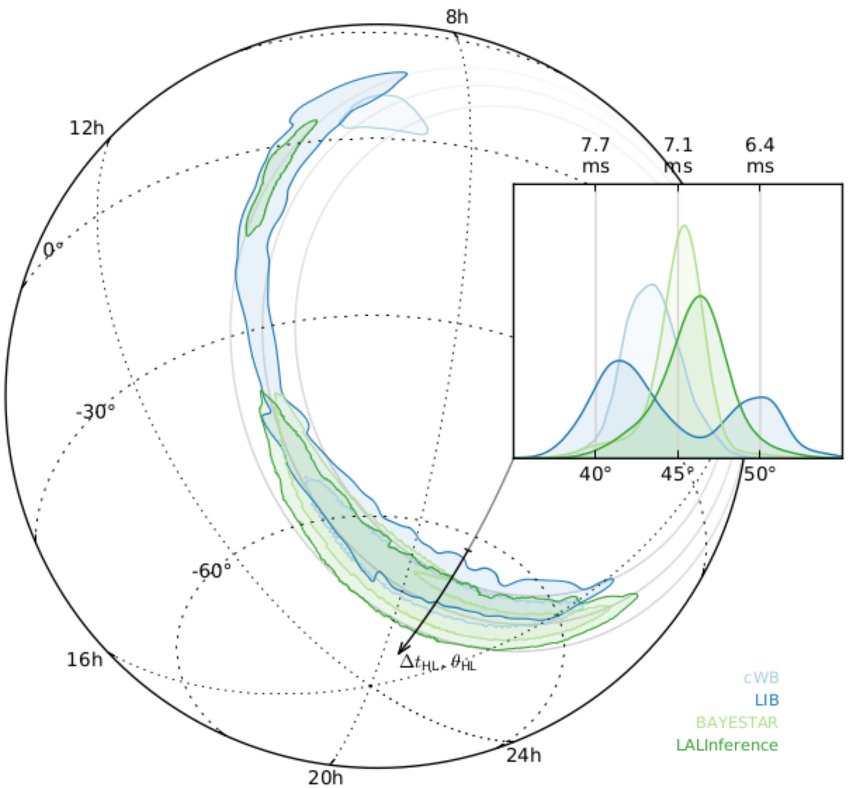
- cWB: constrained ML on sky grid
- LIB: bayesian inference
- BAYESTAR: triangulation (based on CBC pipelines, here offline)
- LALInference: full details

	Area[a]			θ_{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.

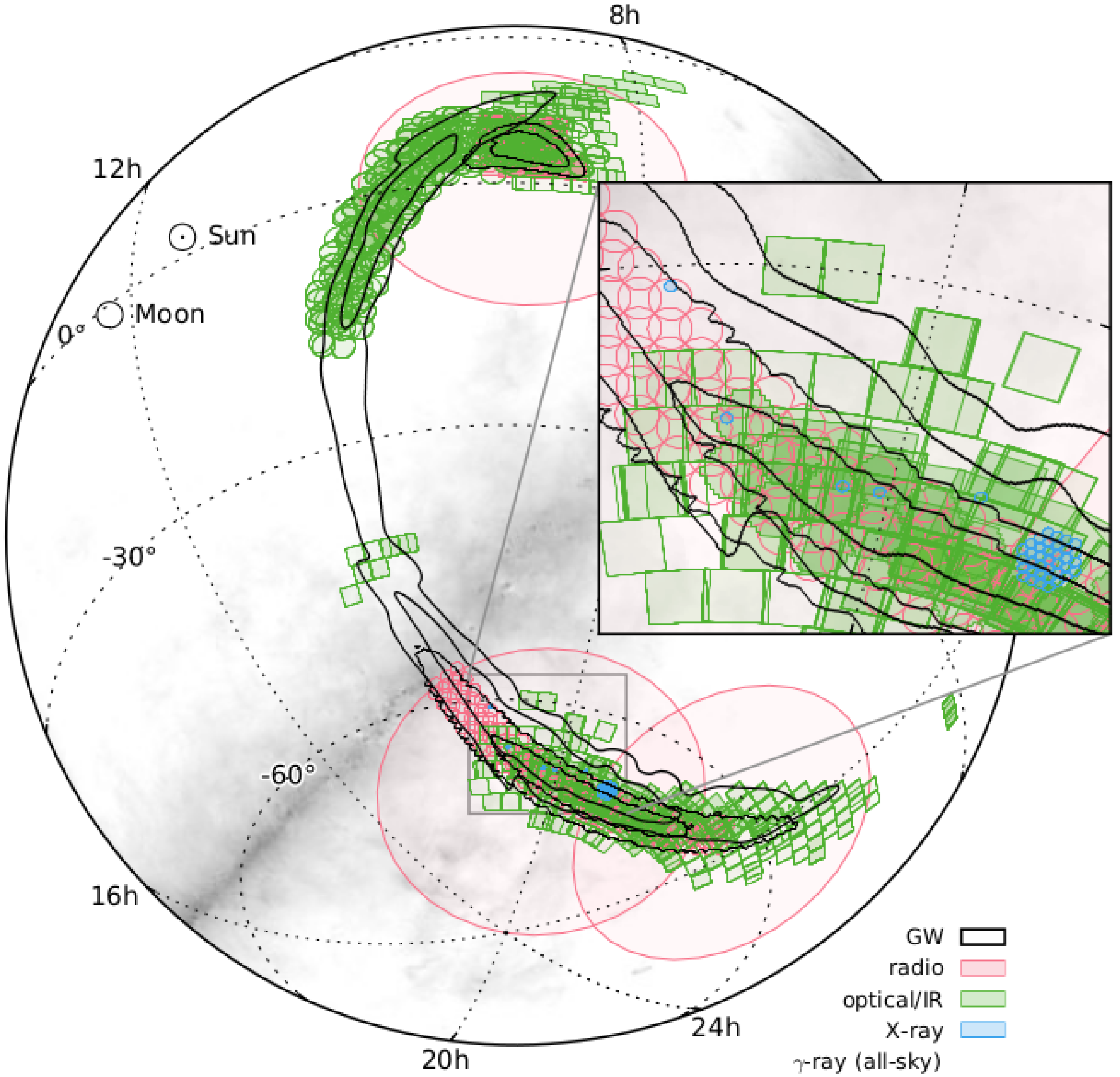
[b] Mean and 10% and 90% percentiles of polar angle in degrees.

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



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)

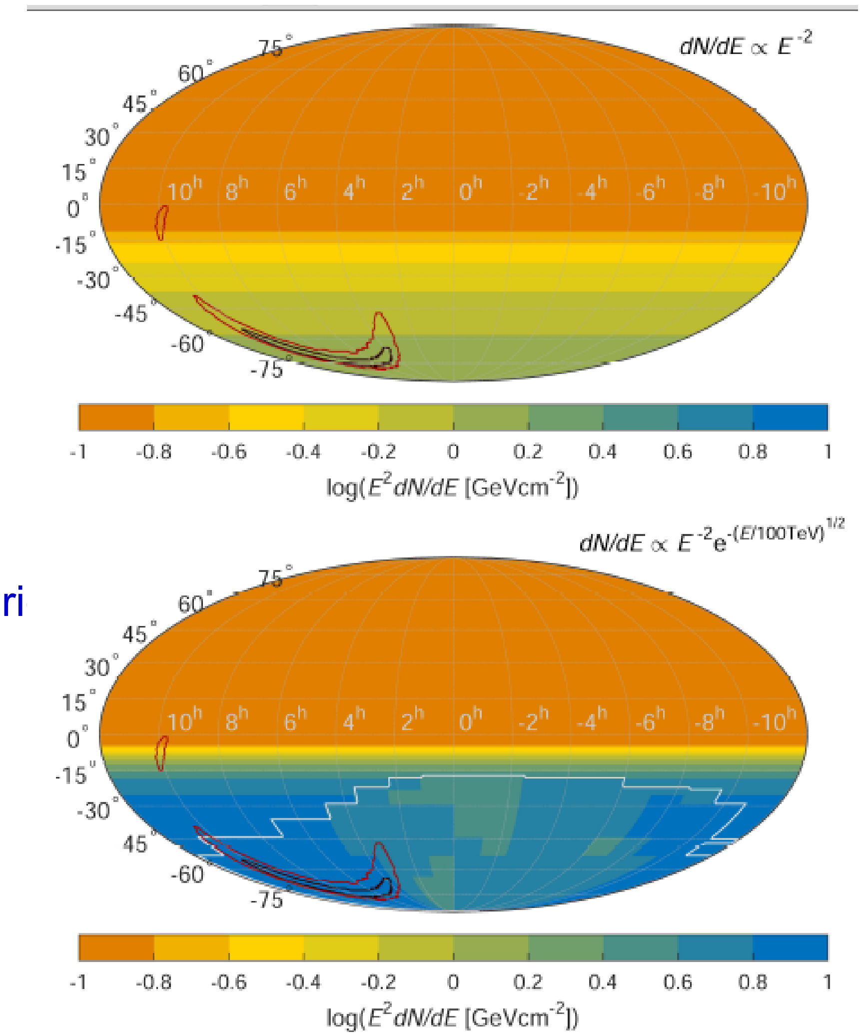
Abbott+16 (arXiv:1602.08492)

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

Multimessenger: GW+neutrinos

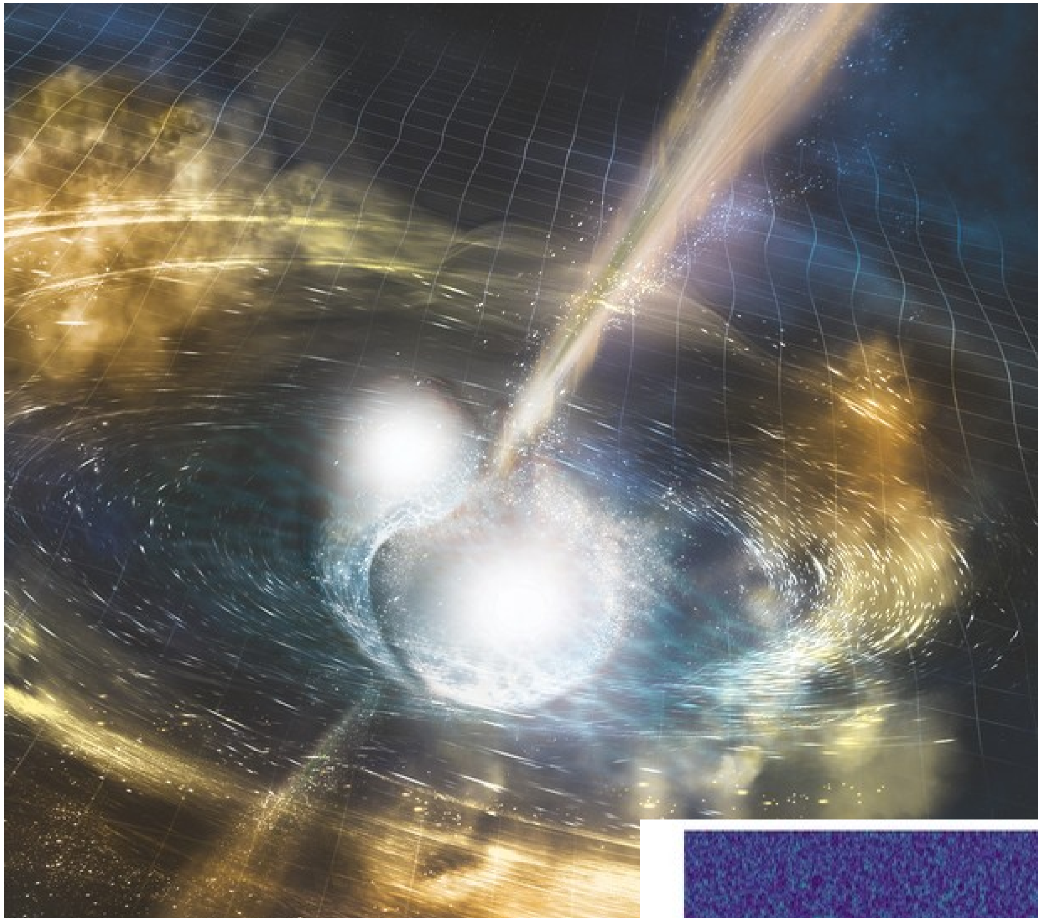


- IceCube and ANTARES operational
  - Search for coincident emission
  - Joint detection would provide good angular resolution
- Results
  - No neutrinos coincident with GW150914
  - Within 500 s, 3(0) neutrinos detected

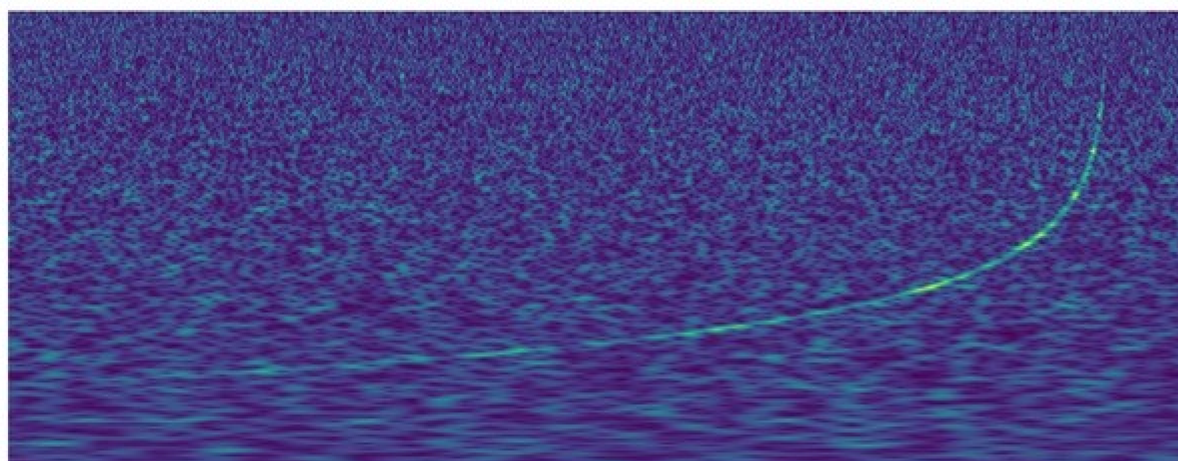
  by IceCube(ANTARES), consistent with atmospheri neutrino
  - Constrain the source → E_{vtot}<1e52-1e54 erg

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

The case of GW170817



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



The case of GW170817

Chirp Video

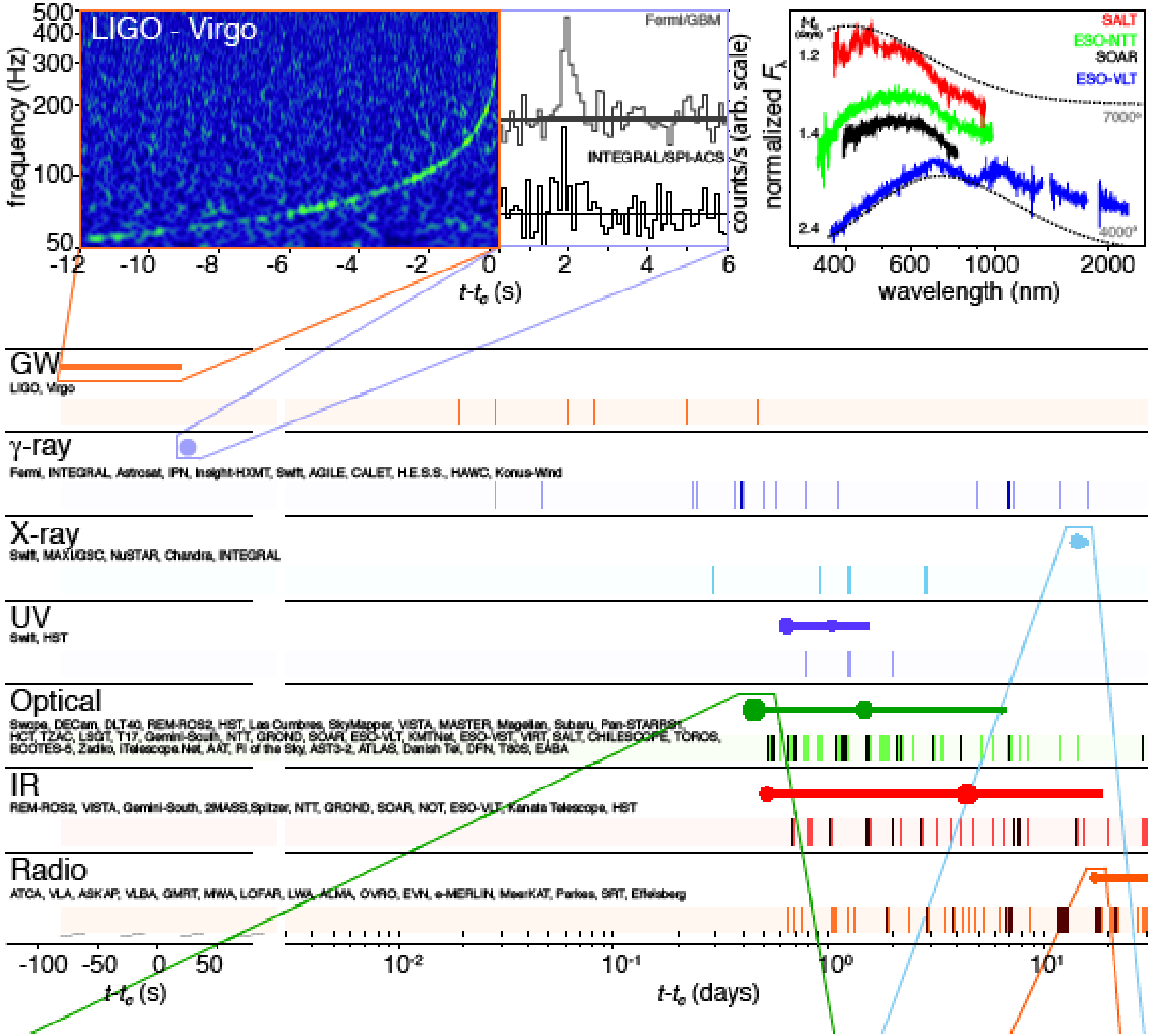
The case of GW170817

GRB video

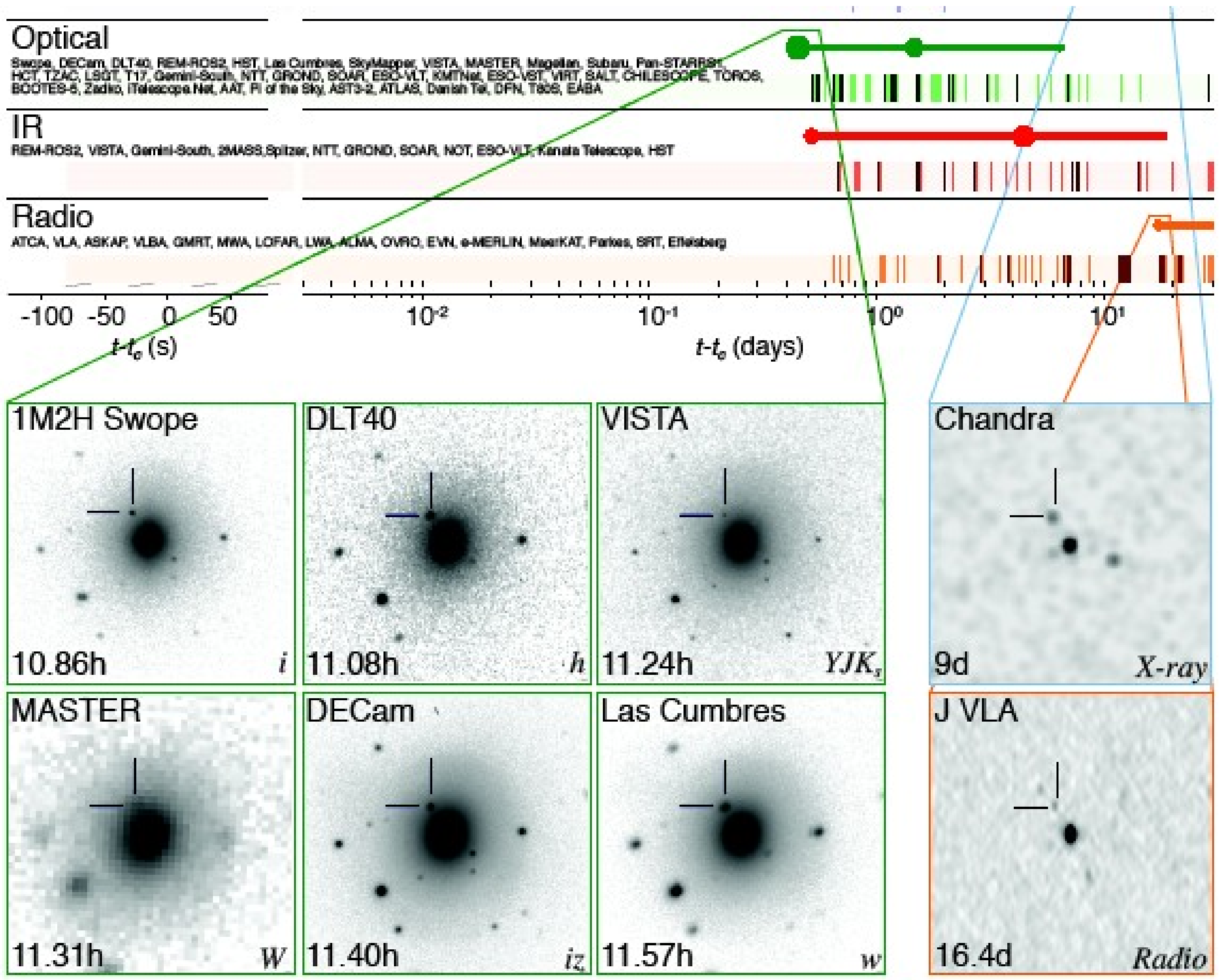
The case of GW170817

GRB video

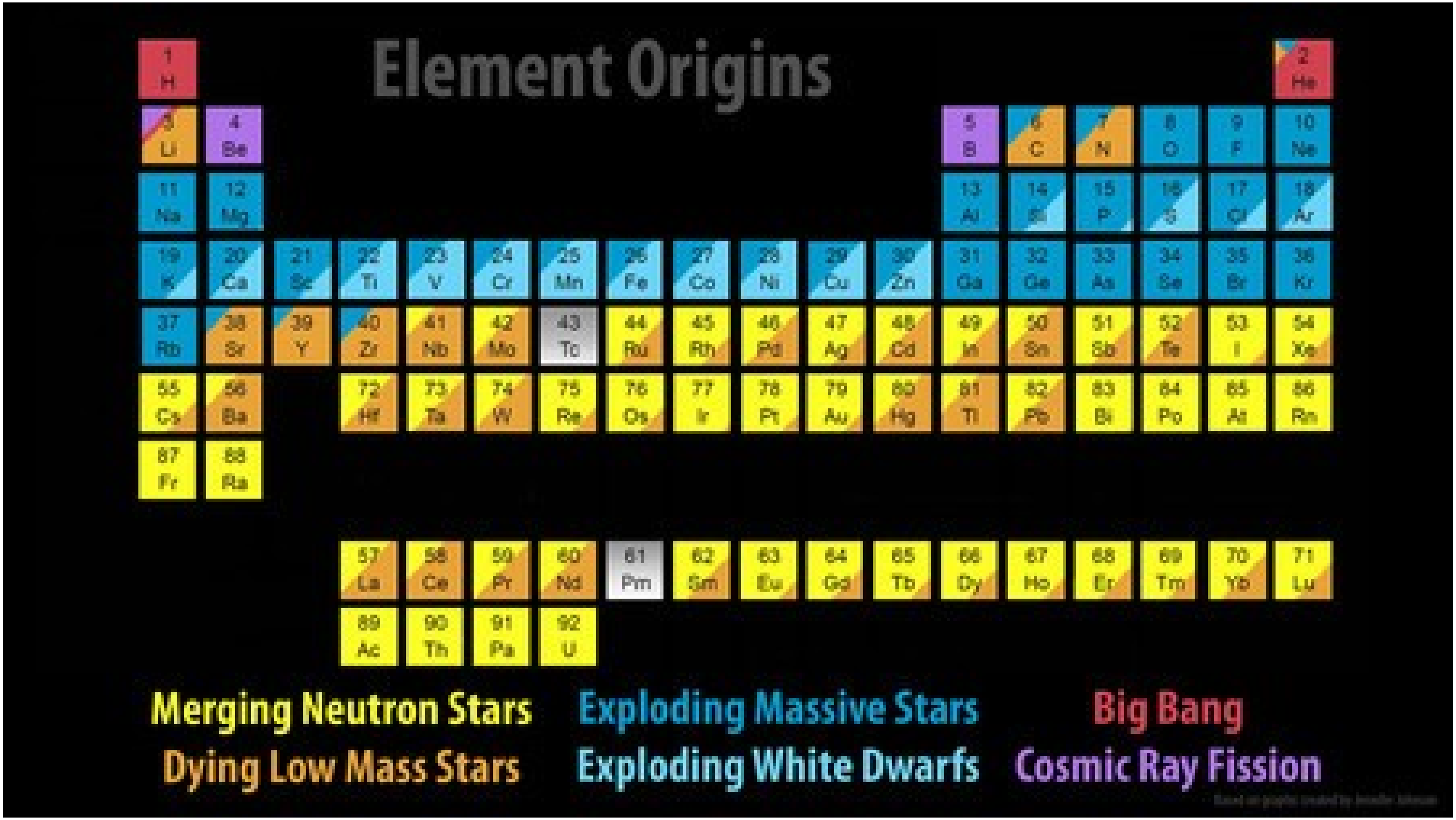
Summary of observations



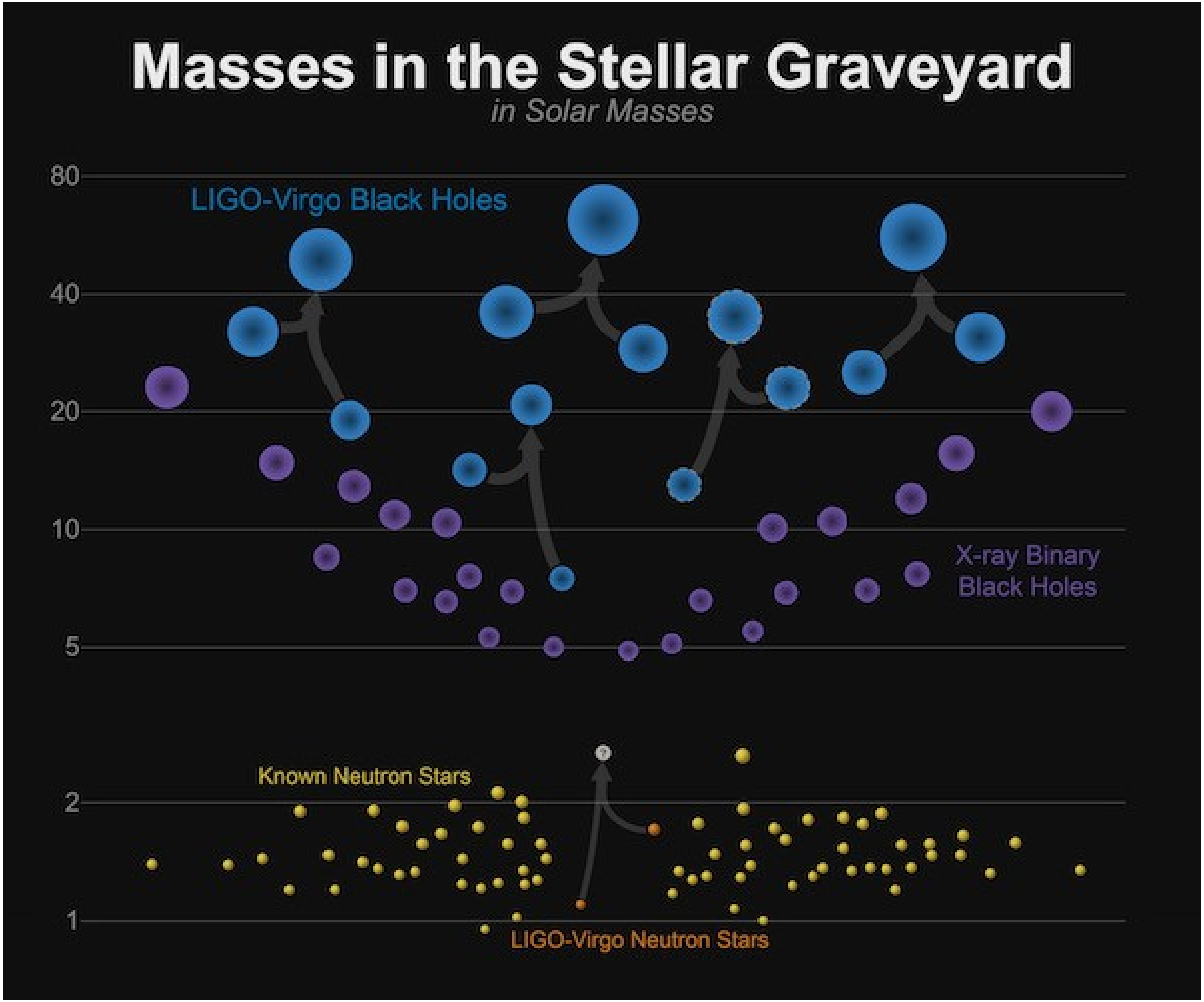
Summary of observations



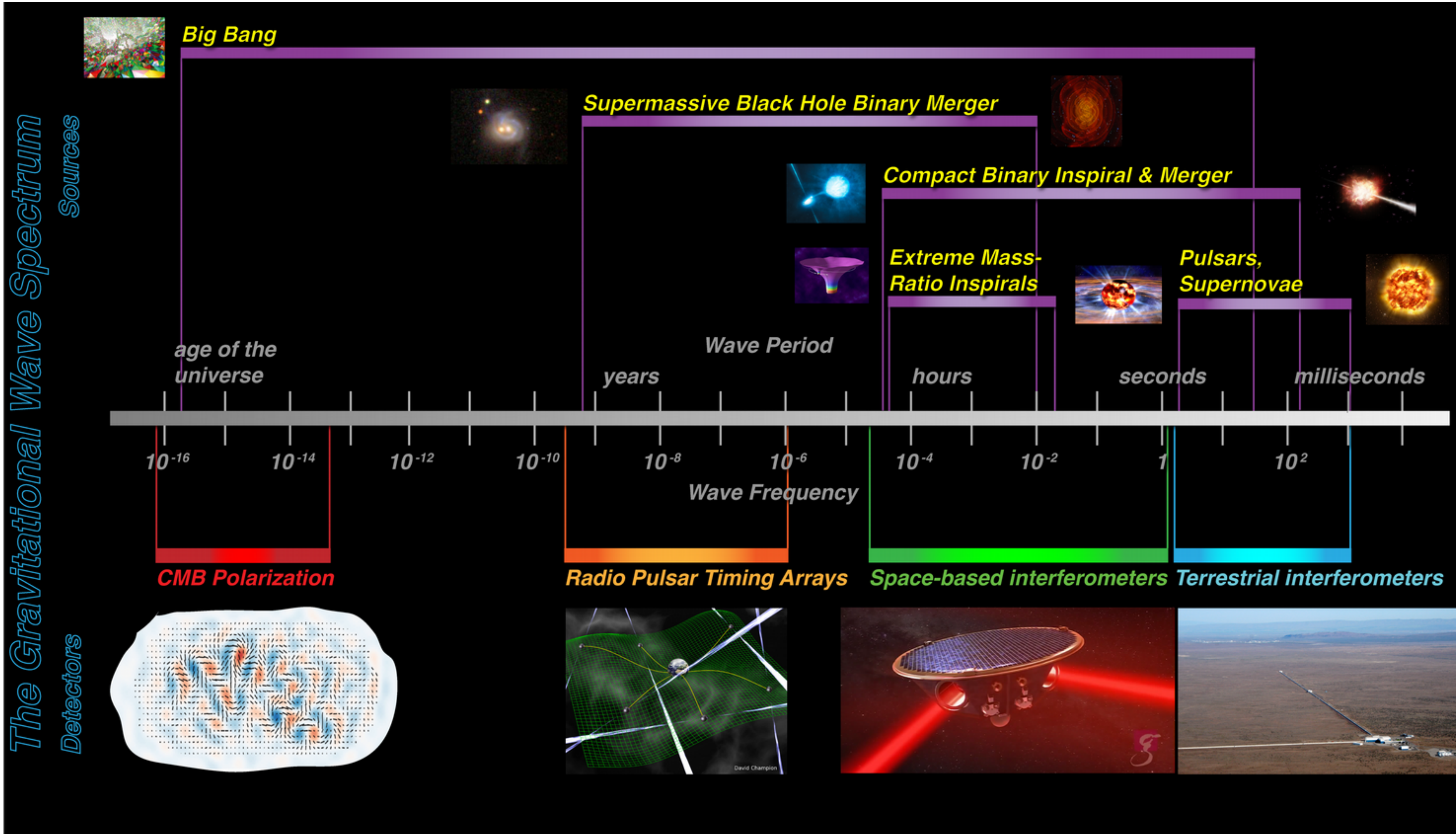
The origin of gold



Neutron star populations

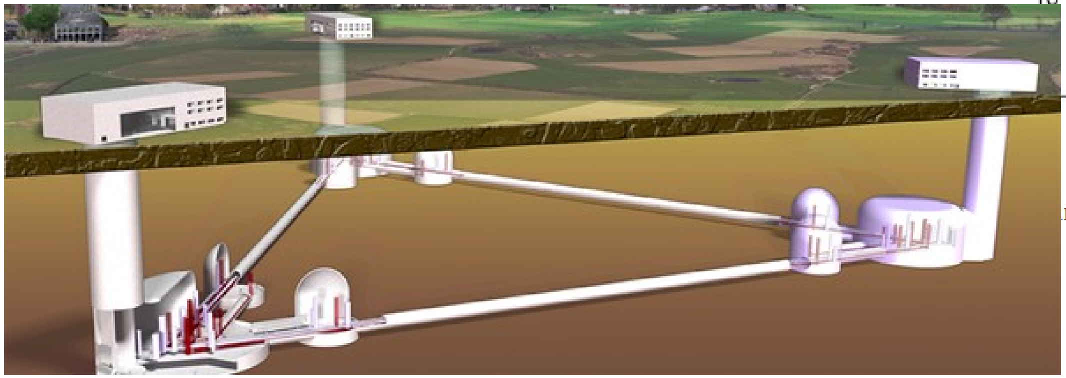


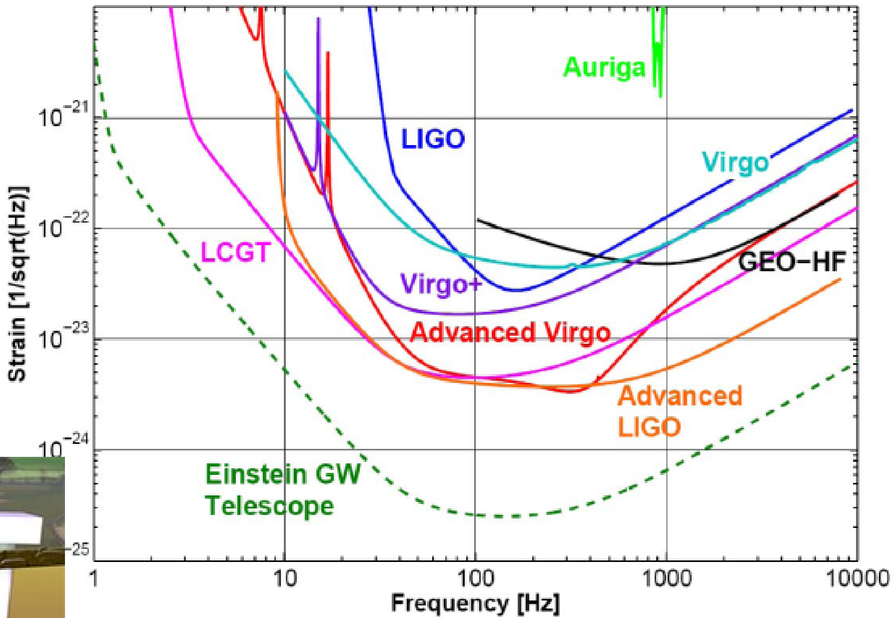
Not just Virgo/LIGO...



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

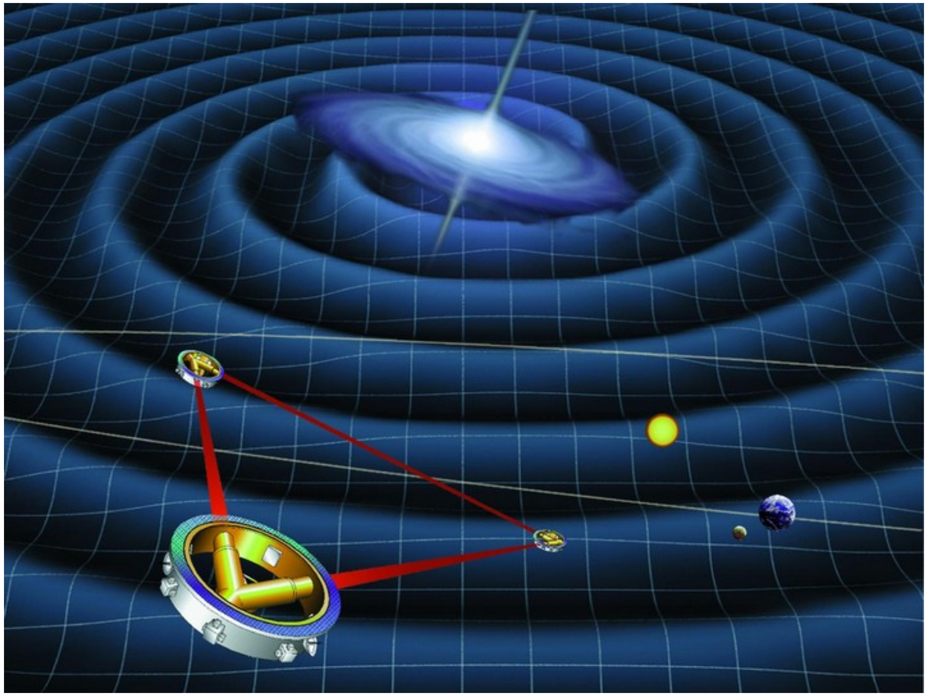




re 5: Sensitivities of gravitational wave detectors from the first to the third generation.

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



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