Gravitational Waves

and the dawn of multimessenger astrophysics

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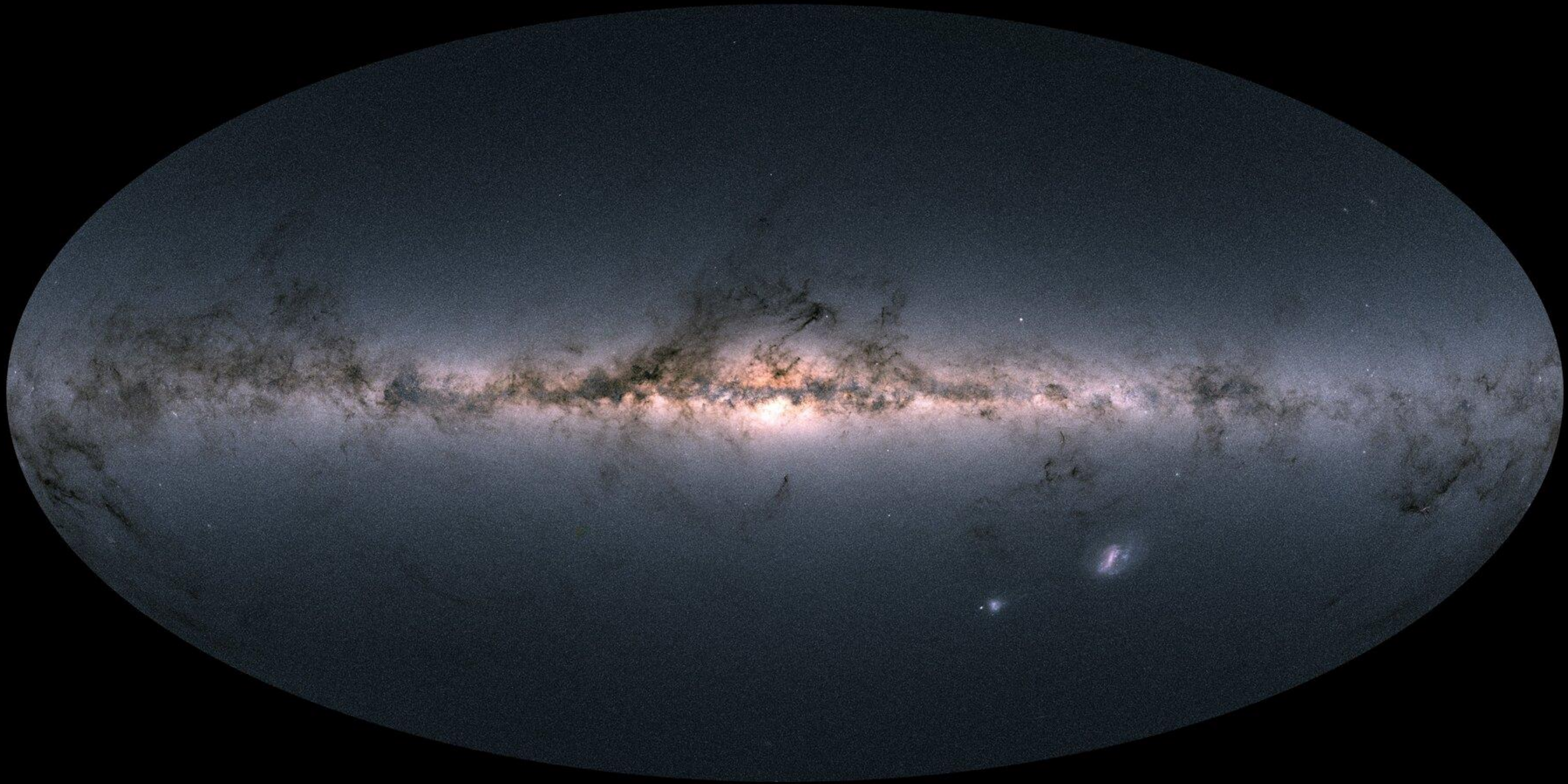
University of Pisa & INFN-Pisa

Colloquium, Università di Pavia
March 22, 2021

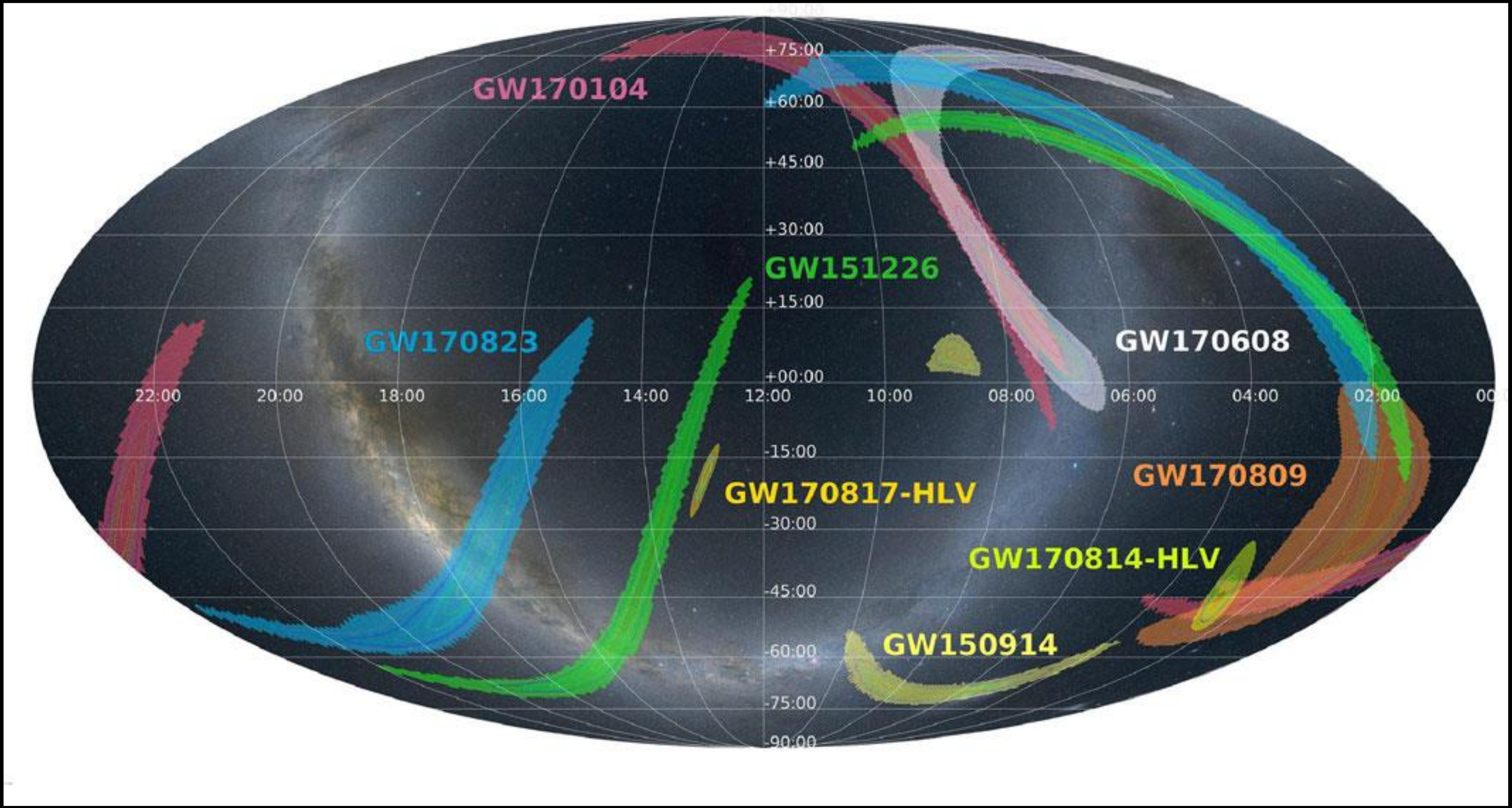
Credits: LIGO/Axel Mellinger

From here….



Credits: ESA/Gaia/DPAC

…to here !

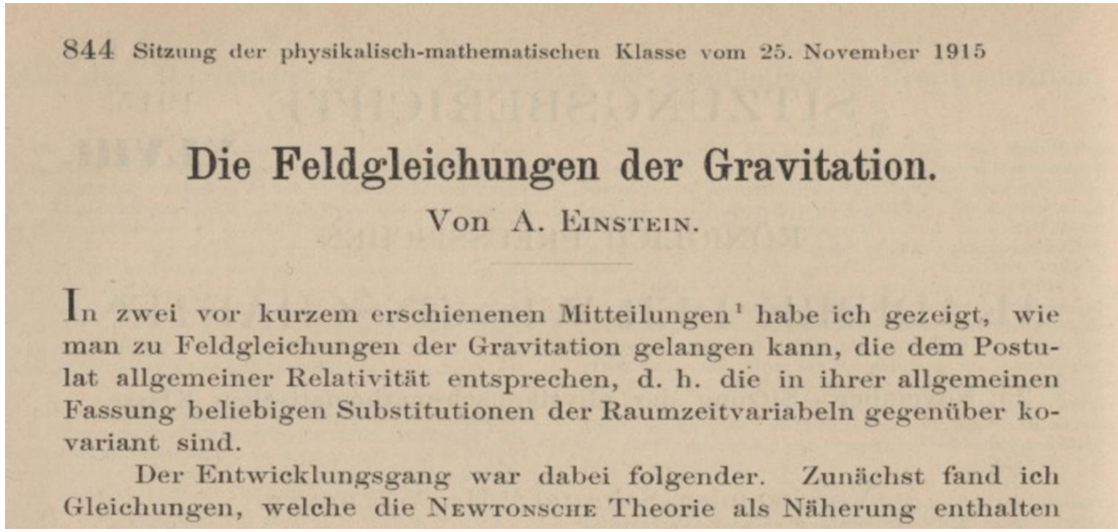


Credits: LIGO/Virgo
Abbott et al, (LVK collaborations) 2020, LRR, 23, 3

Basics: What are Gravitational Waves?

- **A consequence of Einstein's General Relativity**
  - **Gravity as a manifestation of the geometry of the spacetime**

"Spacetime tells matter how to move;
matter tells spacetime how to curve"
(J. Wheeler)


844 Sitzung der physikalisch-mathematischen Klasse vom 25. November 1915

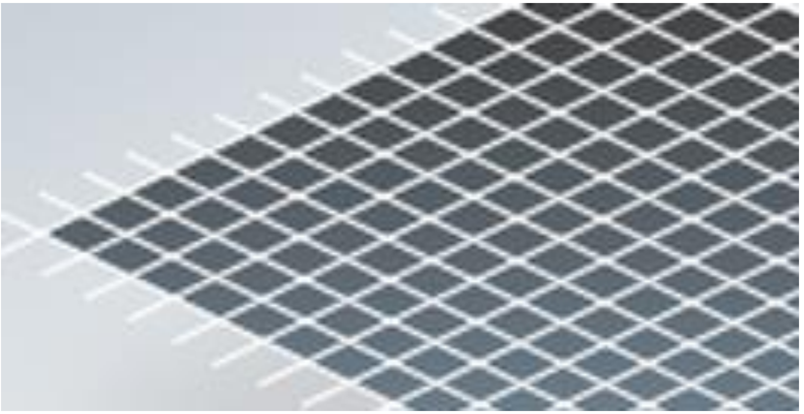
Die Feldgleichungen der Gravitation.

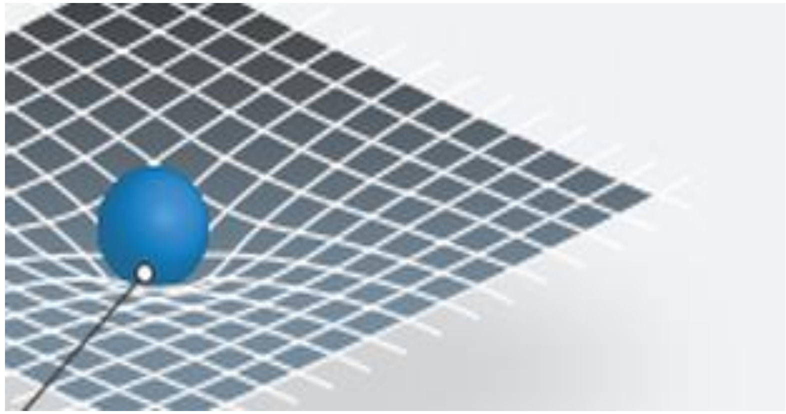
Von A. Einstein.

In zwei vor kurzem erschienenen Mitteilungen[1] habe ich gezeigt, wie man zu Feldgleichungen der Gravitation gelangen kann, die dem Postulat allgemeiner Relativität entsprechen, d. h. die in ihrer allgemeinen Fassung beliebigen Substitutionen der Raumzeitvariabeln gegenüber kovariant sind.

Der Entwicklungsgang war dabei folgender. Zunächst fand ich Gleichungen, welche die Newtonsche Theorie als Näherung enthalten

Credits: Preussische Akademie der Wissenschaften, Sitzungsberichte, 1915





What are gravitational waves?

The core are Einstein's equation of field

$$\boxed{R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu}} = \boxed{\frac{8\pi G}{c^4} T_{\mu\nu}}$$

We write

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Flat, Minkovski metric

Small perturbation

Geometric part
(aka Einstein's tensor $G_{\mu\nu}$)
=
Geometry of spacetime

Stress-Enery part
(aka momentum-energy tensor)
=
Matter distribution

Let's start from the beginning

- Einstein equations become a wave equation in h(t) → wave solution, gravitational waves!
- GW are ripples in spacetime that travel at speed of light
- 2 polarizations, + and x
- Generated by accelerating masses, violent phenomena

- Under condition of slow motion and weak field,
- when we have a non-vanishing quadrupole momentum of the mass distribution, we have GW emission

$$h_{ij}^{TT}(t,z) \simeq \frac{2G}{c^4 r} \ddot{I}_{ij}^{TT}(t - r/c)$$

- h(t) ~dL/L
- BUT……………………h(t) ~ 10^{-21} →Even for L ~ km , dL ~ 10^{-18} m ☹

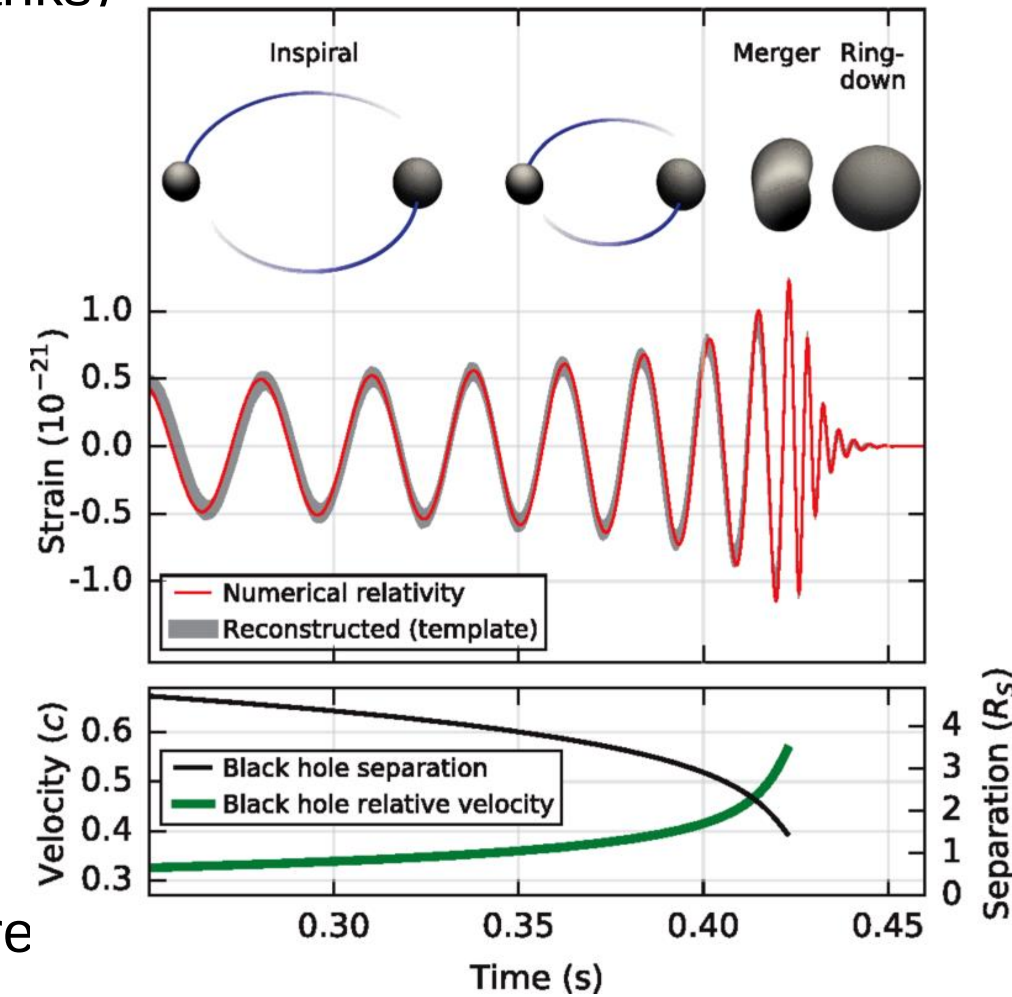
Expected GW sources

Transients

- **Coalescence of compact binary systems (NSs and/or BHs)**
  - Known waveforms (matched filter with template banks)
  - Only source class detected so far
- **Core-collapse of massive stars**
  - Uncertain waveforms
  - Unmodeled searches less sensitive
  - than matched filter

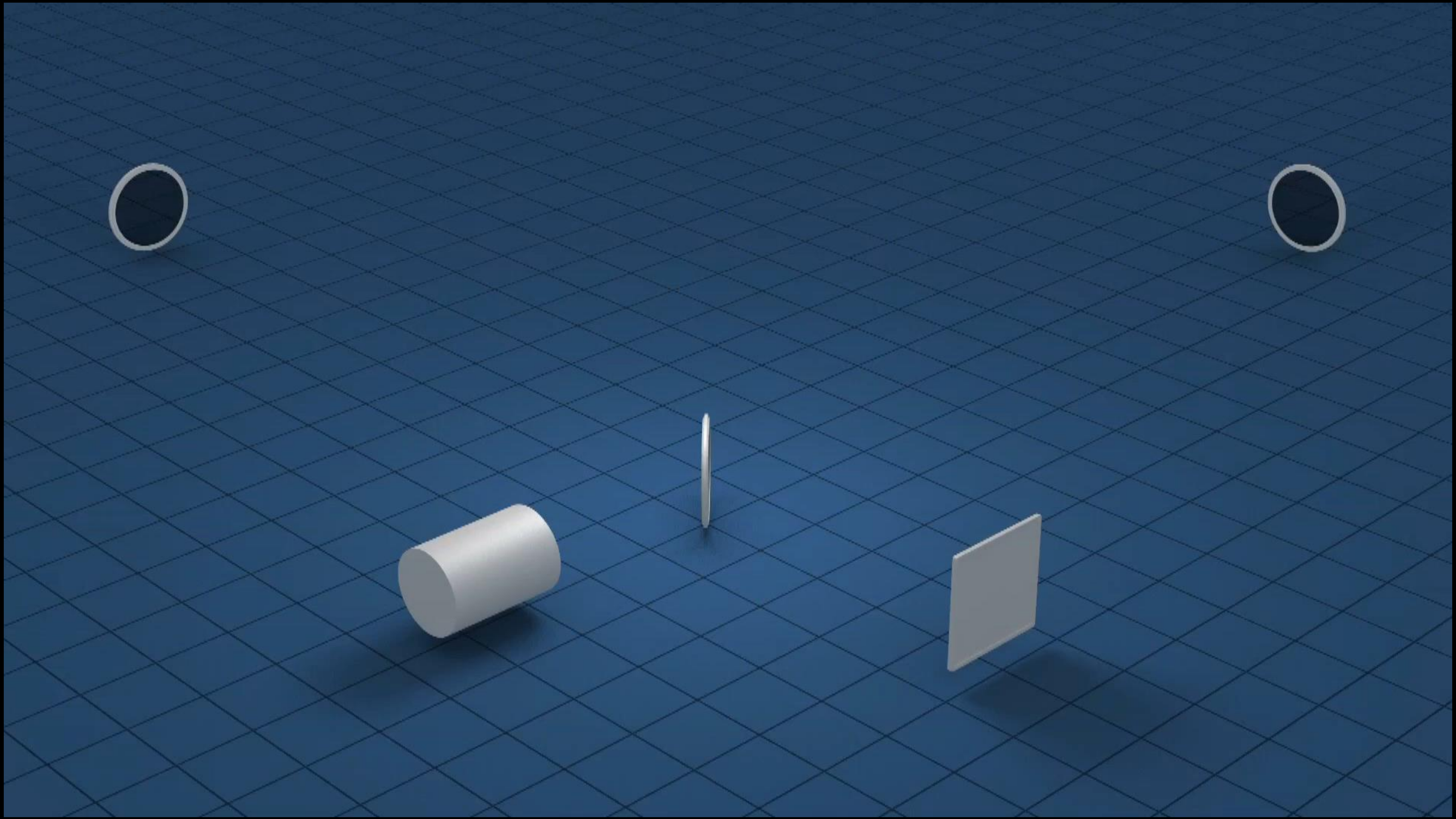
Non transient

- **Rotating neutron stars**
  - Quadrupole emission from stellar asymmetry
  - Continuous and periodic
- **Stochastic background**
  - Continuous, due to unresolved sources/Big Bang re

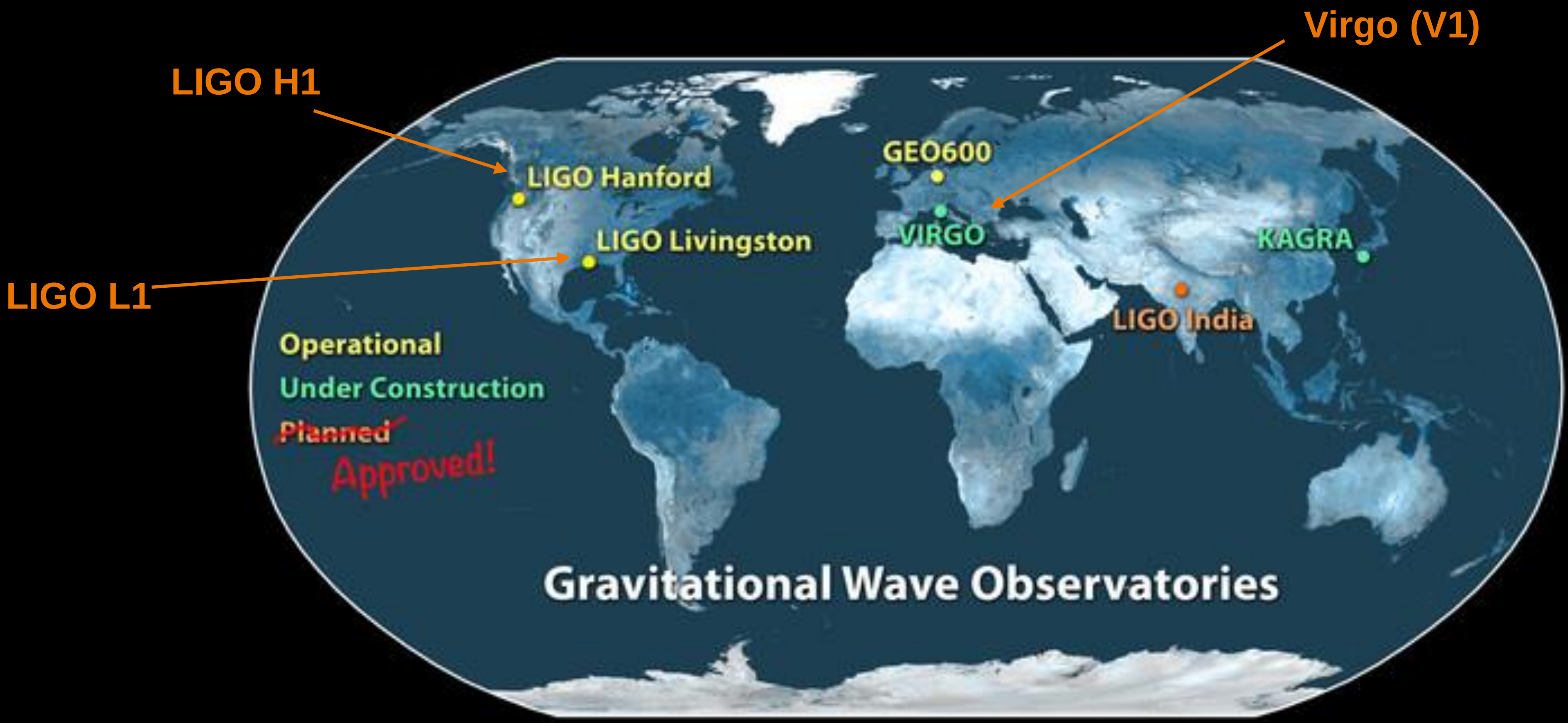


Abbott et al 2016, PRL, 116, 101103

How do we detect these tiny GWs?



The Advanced Detectors

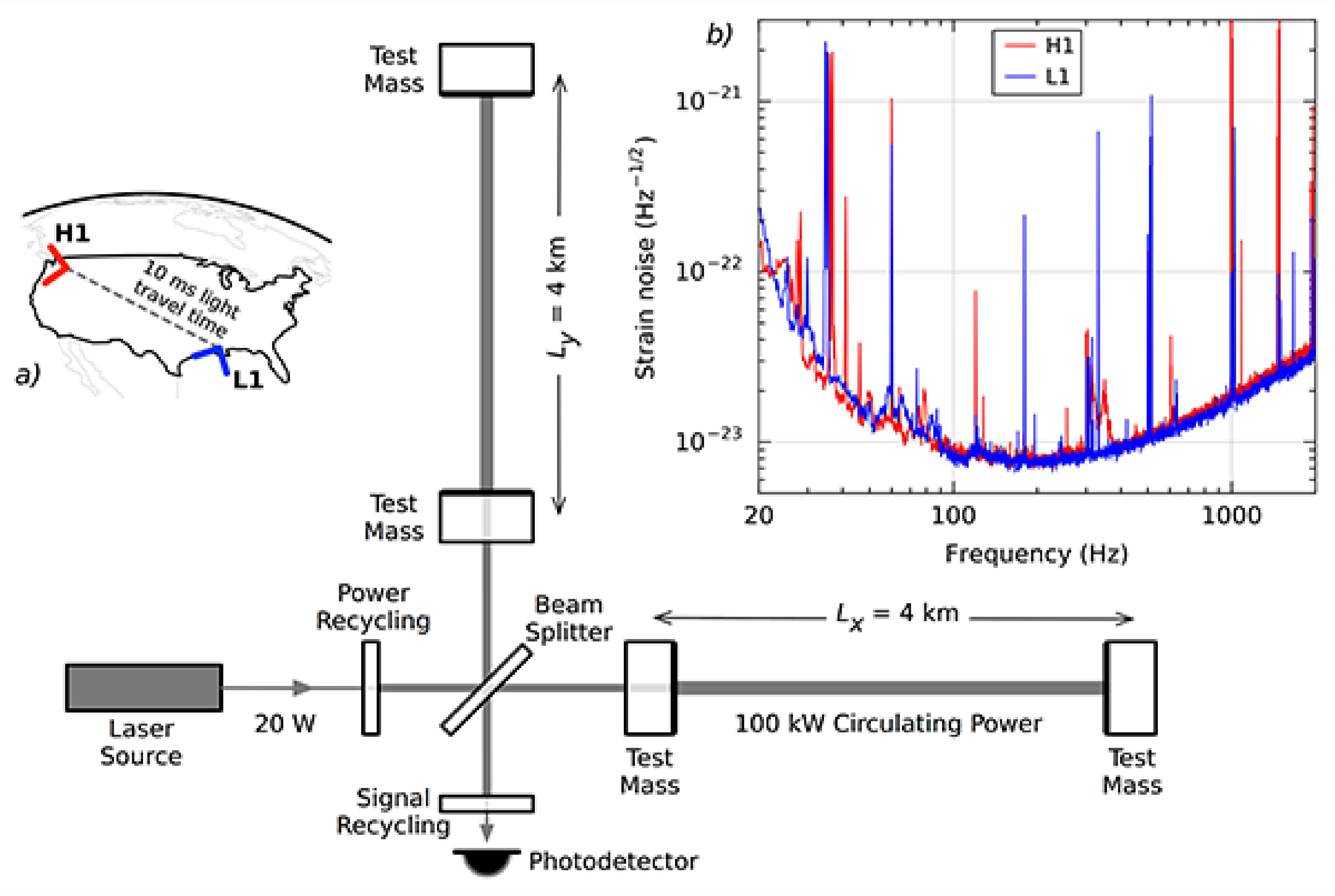


Credit: Caltech/MIT/LIGO Lab

Detection method
- km-scale Michelson interferometers
- Fabry-Perot cavities
- hw and sw methods to suppress noise

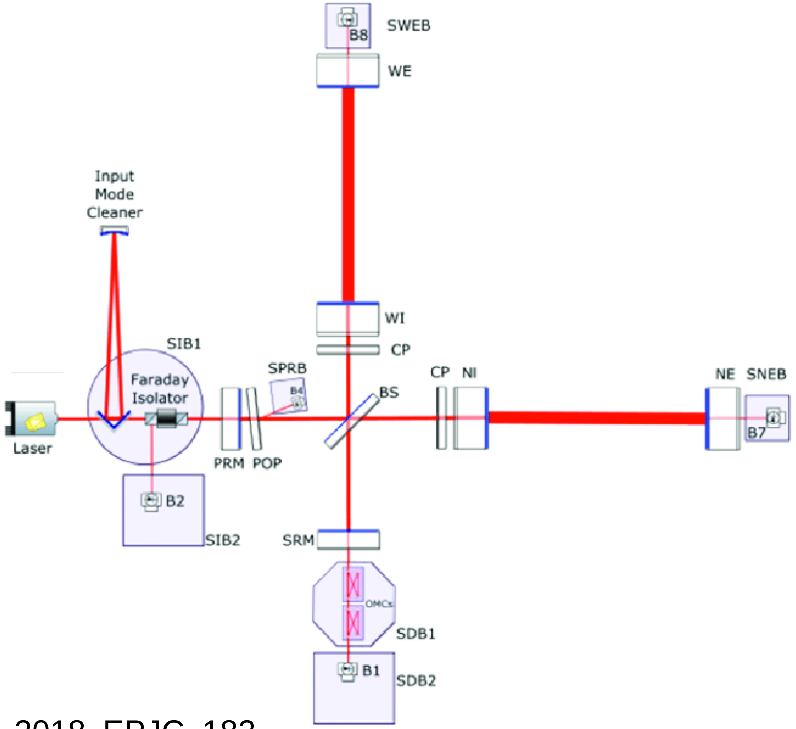
Better sensitivity
- ~10x wrt previous generation (2002-2011)
- ~1000x more volume → ~1000x higher rates

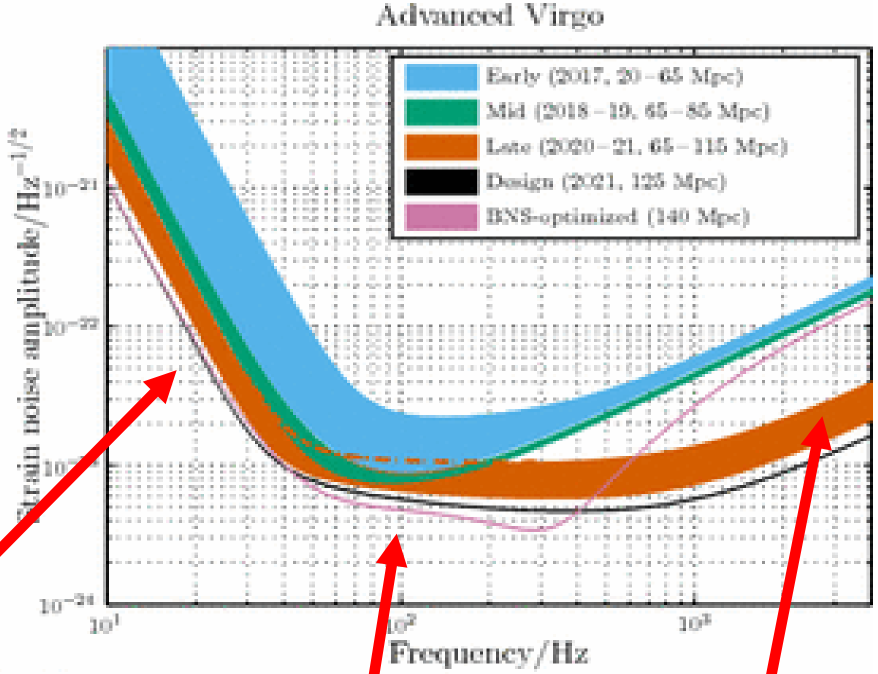
GW laser interferometers: Advanced LIGO



Abbott et al. 2016, PRL 116, 061102

Advanced Virgo





Newtonian noise
+ seisme noise

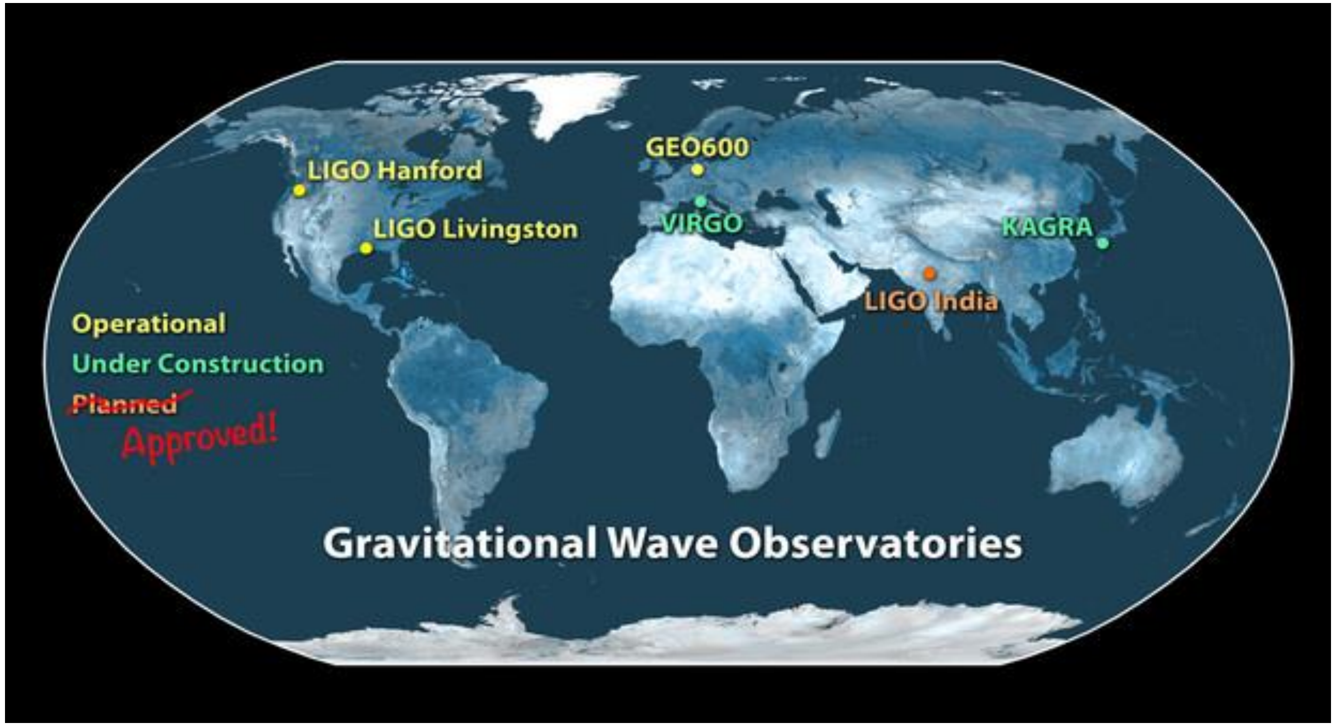
Thermal noise

Quantum noise

Acernese et al., 2018, EPJC, 182

The story so far

- **Advanced LIGO and Virgo completed**
- **3 joint runs**
  - O1 (H1+L1) - Sep 12, 2015 - Jan 19, 2016
  - O2 (H1+L1+V1) - Nov 30, 2016 - Aug 25, 2017
  - O3a (H1+L1+V1) - Apr 1 - Oct 1, 2019
  - O3b (H1+L1+V1) - Nov 1, 2019 - Mar 27, 2020



Credit: Caltech/MIT/LIGO Lab

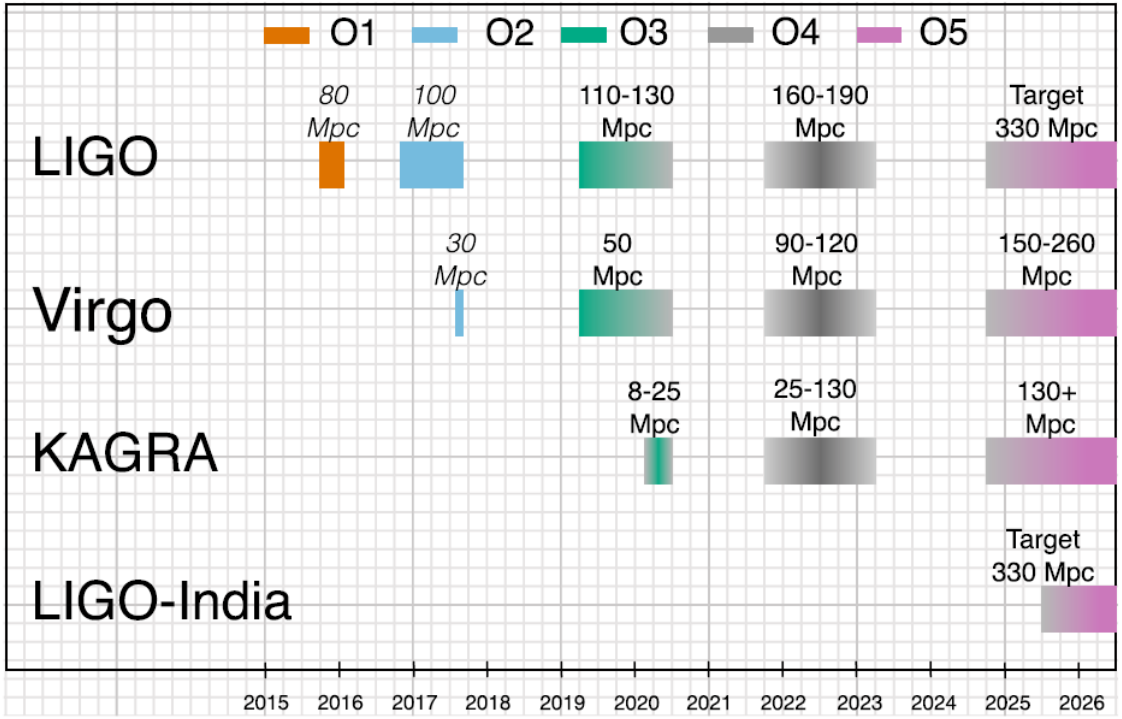
Observing scenario

- **Run schedule**
  - Each run longer and more sensitive
  - Commissioning breaks (e.g. 1 month in O3 in Oct 2019)
  - Adv Virgo joined in O2
  - Oct 2019 KAGRA signed MoU with LIGO/Virgo

  - Network duty cycle of 43% (46%) in O1 (O2)

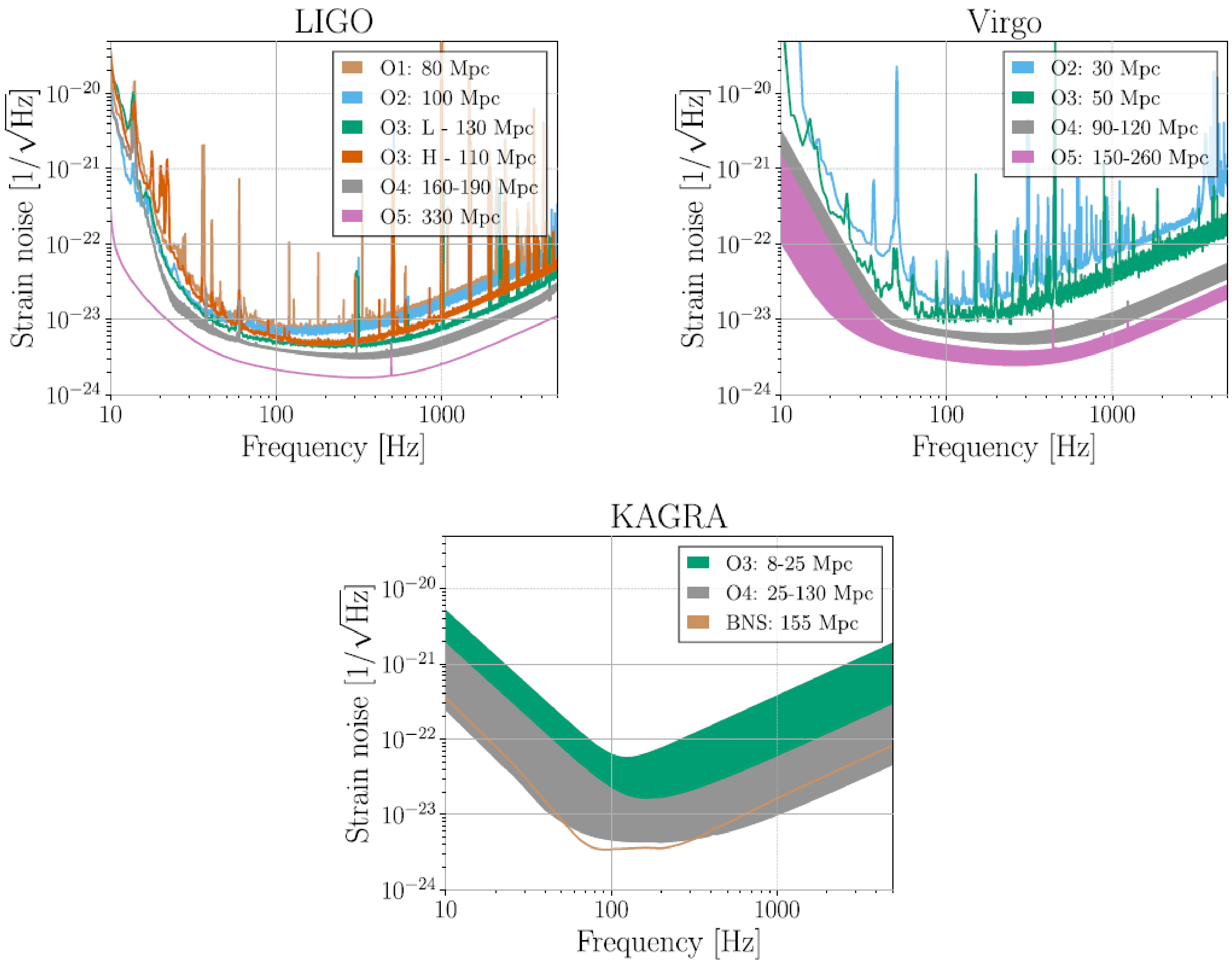
Table 1 Percentage of time during the first and second observing runs that the aLIGO and AdV detectors spent in different operating modes as recorded by the on-duty operator

	O1		O2		
	Hanford	Livingston	Hanford	Livingston	Virgo
Operating mode %					
Observing	64.6	57.4	65.3	61.8	85.1
Locking	17.9	16.1	8.0	11.7	3.1
Environmental	9.7	19.8	5.8	10.1	5.6
Maintenance	4.4	4.9	5.4	6.0	3.1
Commissioning	2.9	1.6	3.4	4.7	1.1
Planned engineering	0.1	0.0	11.9	5.5	–
Other	0.4	0.2	0.2	0.2	2.0



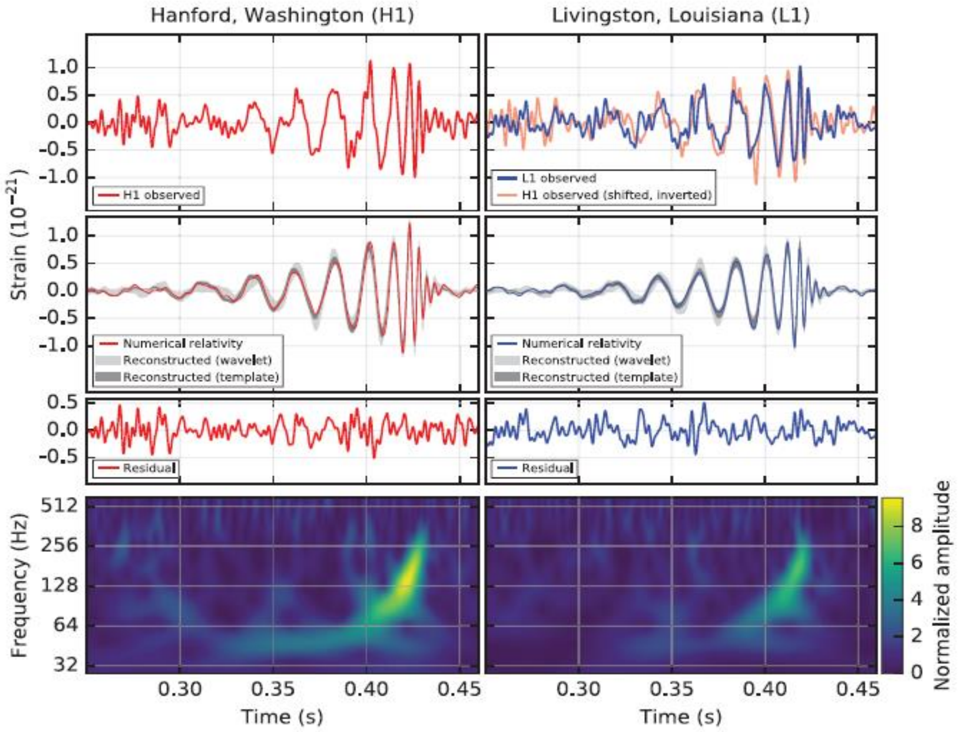
More details in "Observing Scenario" paper Abbott et al, (LVK collaborations) 2020, LRR, 23, 3

Sensitivity curves

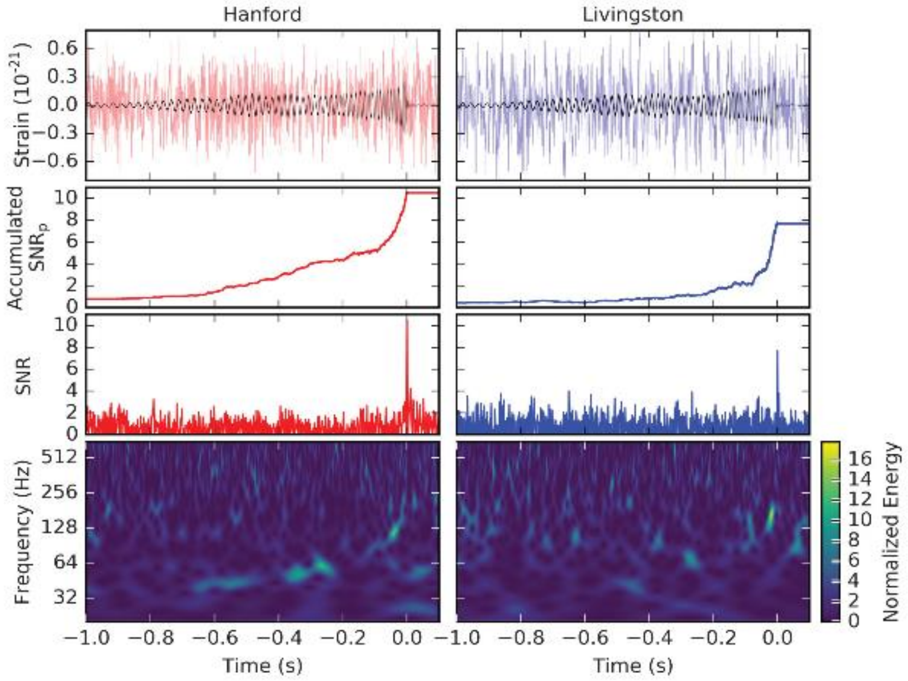


Abbott et al, (LVK collaborations) 2020, LRR, 23, 3

The first detections…



GW150914
Abbott+16, PRL116,6

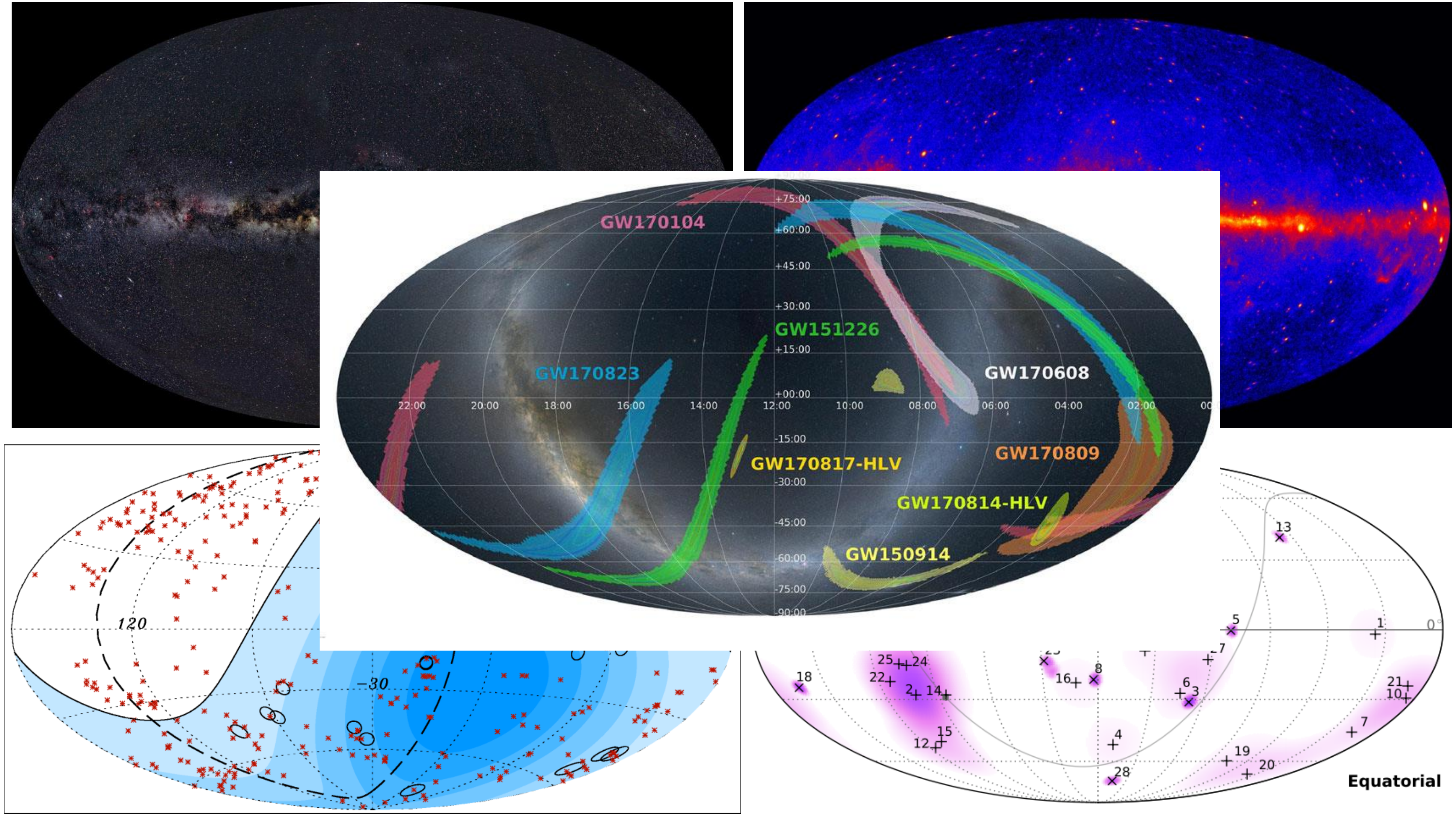


GW151226
Abbott+16, PRL116,24

The multimessenger frontier

Optical (collage, APOD, A. Mellinger)

Gamma rays > 0.1 GeV (Fermi-LAT)



Cosmic rays > 57 Eev (Auger, 2007)

Neutrinos > 30 Tev (Icecube, 2013)

*

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Why go multimessenger?

NASA NASA

- Providing a deeper insight into the most extreme events in the Universe

LIGO

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

- Accessing complementary information:
  - EM → emission processes, acceleration mechanisms, environment
  - GW→ mass distribution
  - Neutrinos→ hadronic/nuclear processes, etc.

- How? Relying on a precise (arcmin/arcsecond) localization
  - Pinpoint host galaxy of a merger
  - Identify an EM counterpart with timing signature (e.g. pulsars)
  - EM follow-up to get simultaneous observations

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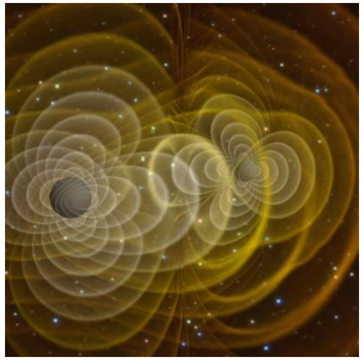
Multimessenger strategies

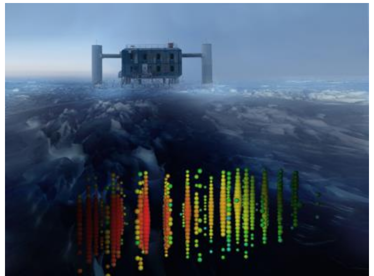
Electromagnetic radiation

Gravitational Waves



Follow-up (find a counterpart)

External-triggered searches



Astrophysical neutrinos

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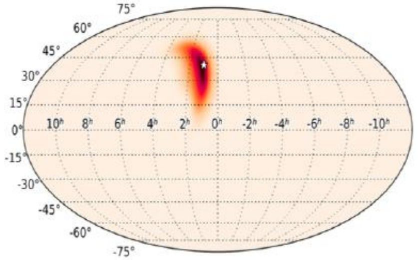
The follow-up strategy

- Past experiences (2009-2010)
  - ~30 min latency, optical telescopes+Swift
  - Centralized organization

GW alert → Sky localization → EM follow-up



EM event	EM band	Timescale
Prompt emission	Gamma rays	<seconds
Afterglow	X-ray, optical, radio	Hours-days
Kilonova-macronova	Optical-near IR	Days-weeks
Radio blast wave	Radio	Months-years

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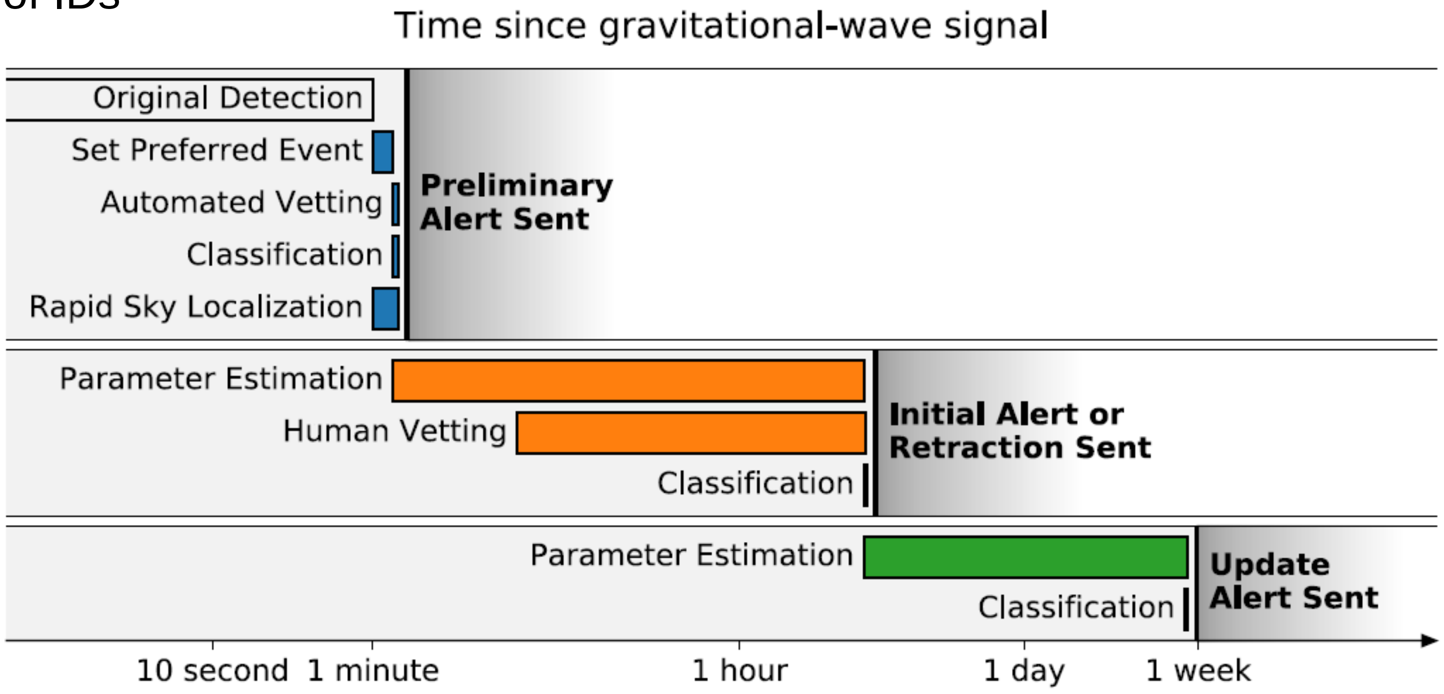
Multimessenger follow-up

- ## O1 & O2 follow-up program
  - Sent privately to groups that signed MoU with LIGO/Virgo
  - 95 groups at the end of O2
  - Alerts sent via GCN for False Alarm Rate <2/month
  - GCN included time, 3D localization, probability of IDs
  - 17 alerts sent, 7BBHS+1BNS (GW170817)



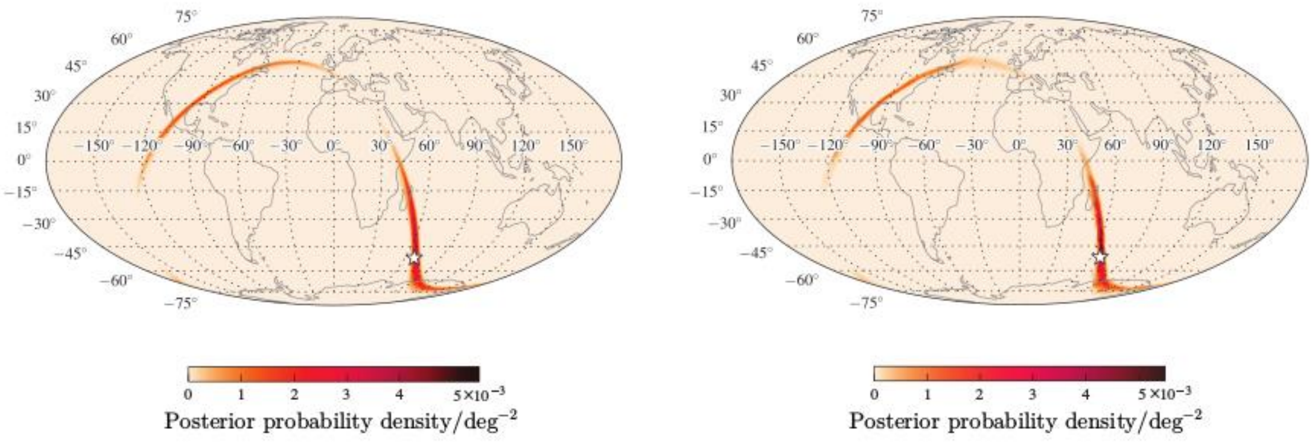
Abbott et al, (LVK collaborations) 2020, LRR, 23, 3

LV Public Alerts User Guide
https://emfollow.docs.ligo.org/userguide

- ## O3: public alerts
  - Preliminary GCN Notice within minutes
  - Rapid Response Team confirms or retracts
  - More details in following GCNs
  - Overall purity of 90% across categories of mergers
  - 41 GW candidate events released in low-latency in O3a, 8 retracted, 3 terrestrial

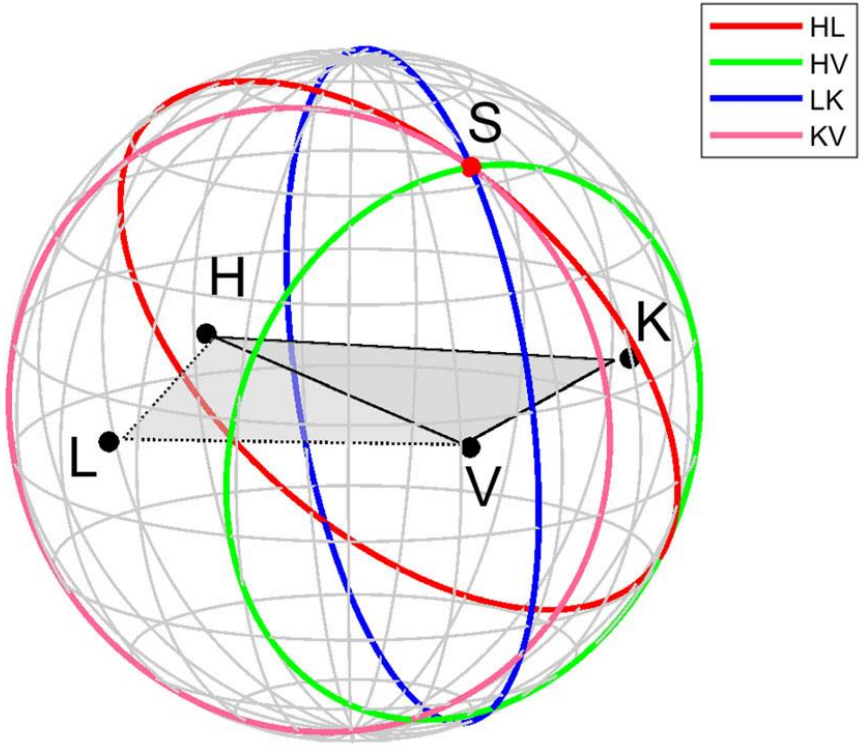
Sky Localization of GW transients

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



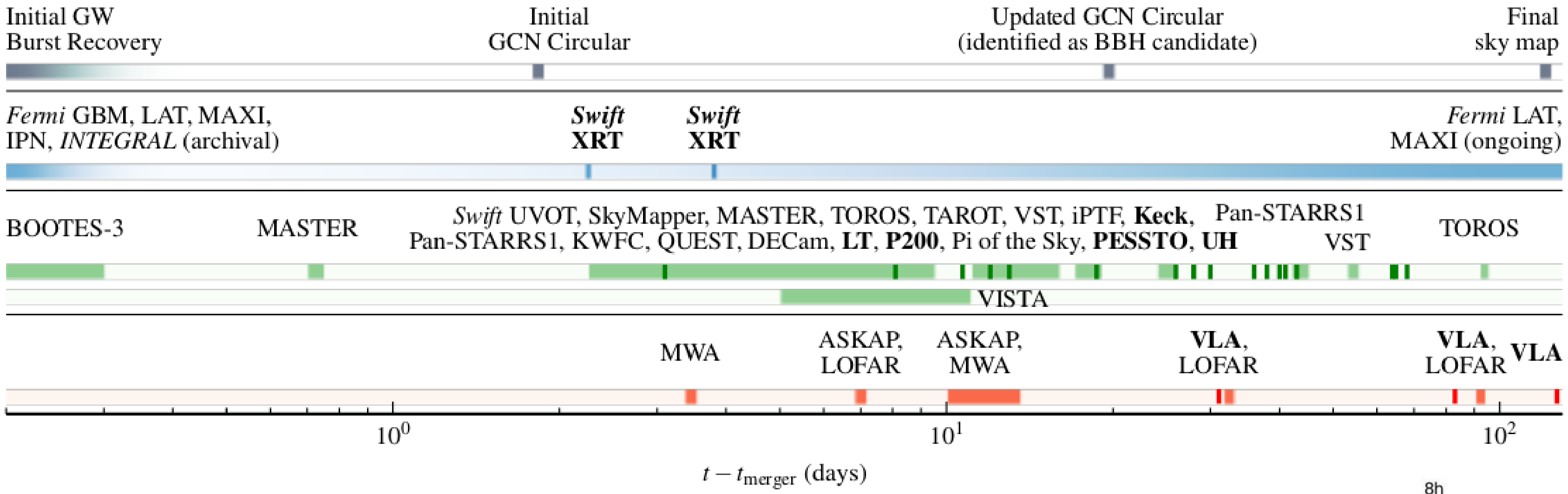
Abbott+16, LRR 19,1

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

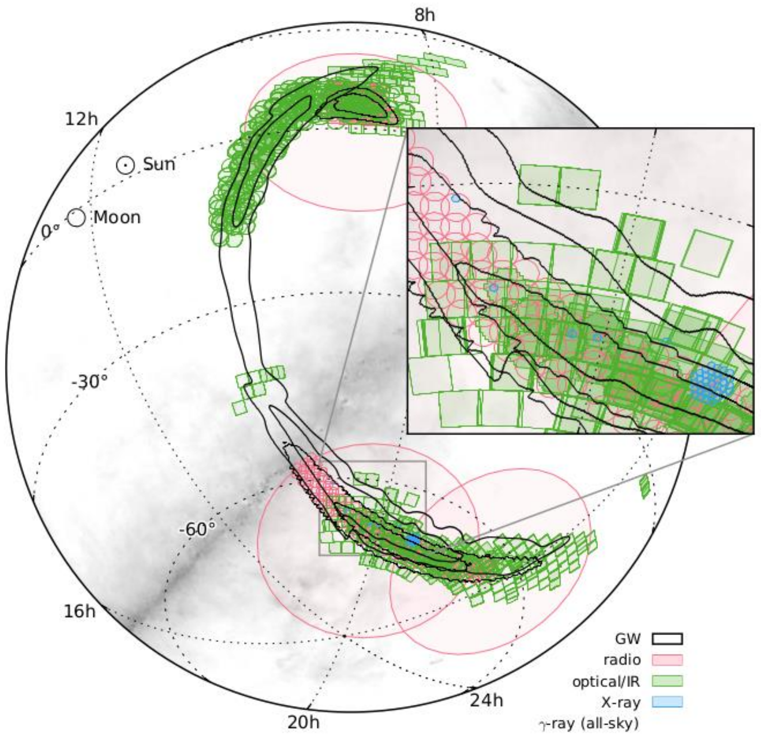


Abbott et al 2020, LRR, 23, 3

The case of GW150914 follow-up

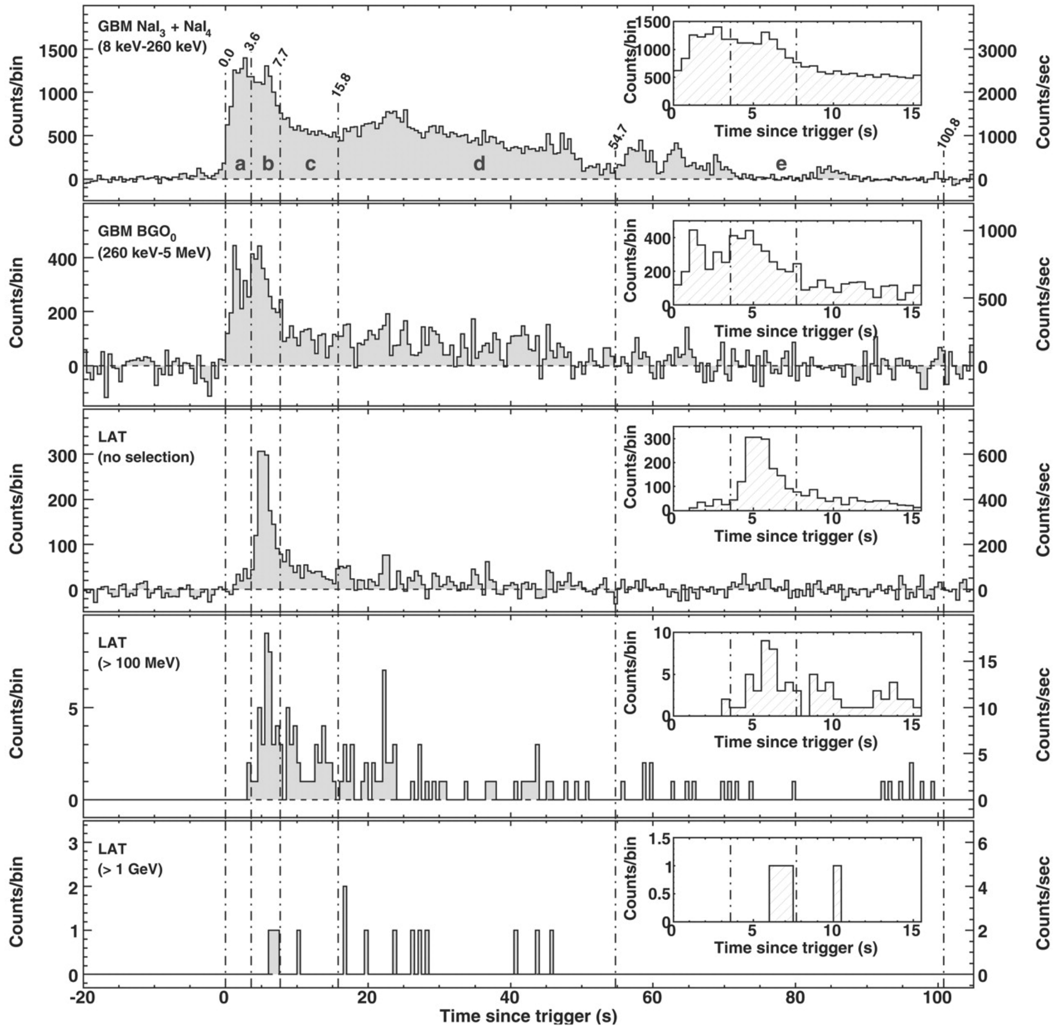


Abbott+16, ApJ 826, 13

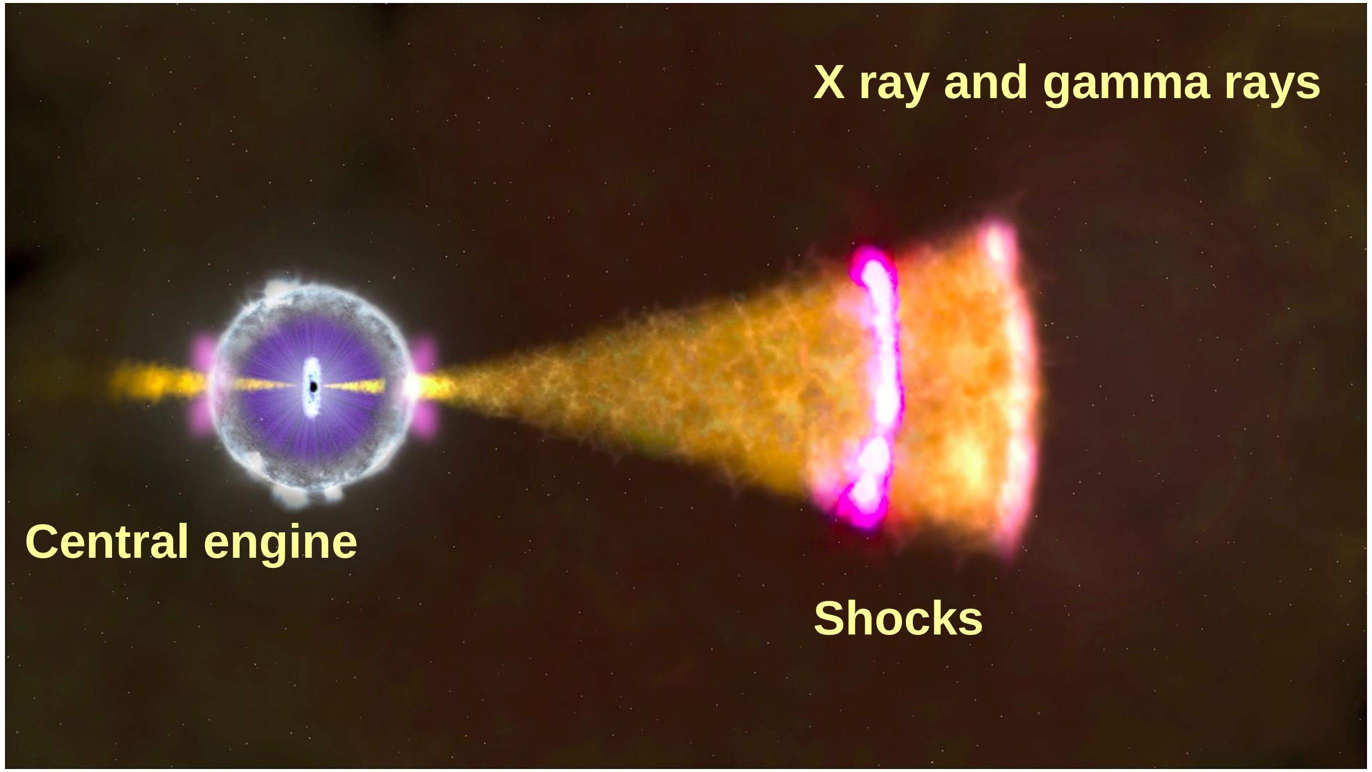


- 25 teams involved
- 19 orders of magnitudes in wavelenghts
- Repointing (optical)
- Archival (X & gamma)
- Deep follow-up (optical/radio)

A multimessenger science case: Gamma Ray bursts



GRB 080916C Observed by Fermi LAT & GBM
Fermi LAT & GBM collaborations, 2009, Science, 323,5922

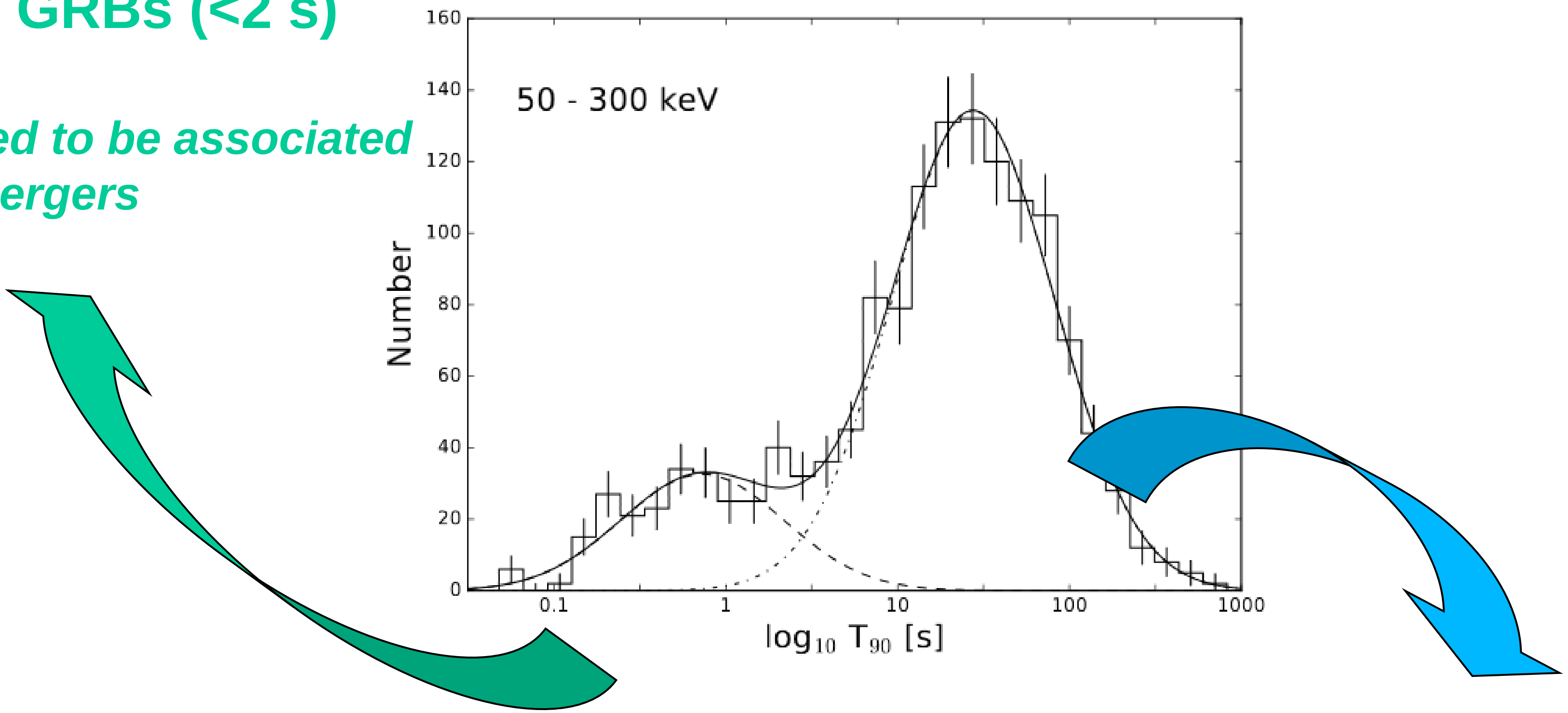


Credits: D. Darling

Science case for EM follow-up: the GRB connection

Short GRBs (<2 s)

believed to be associated with mergers

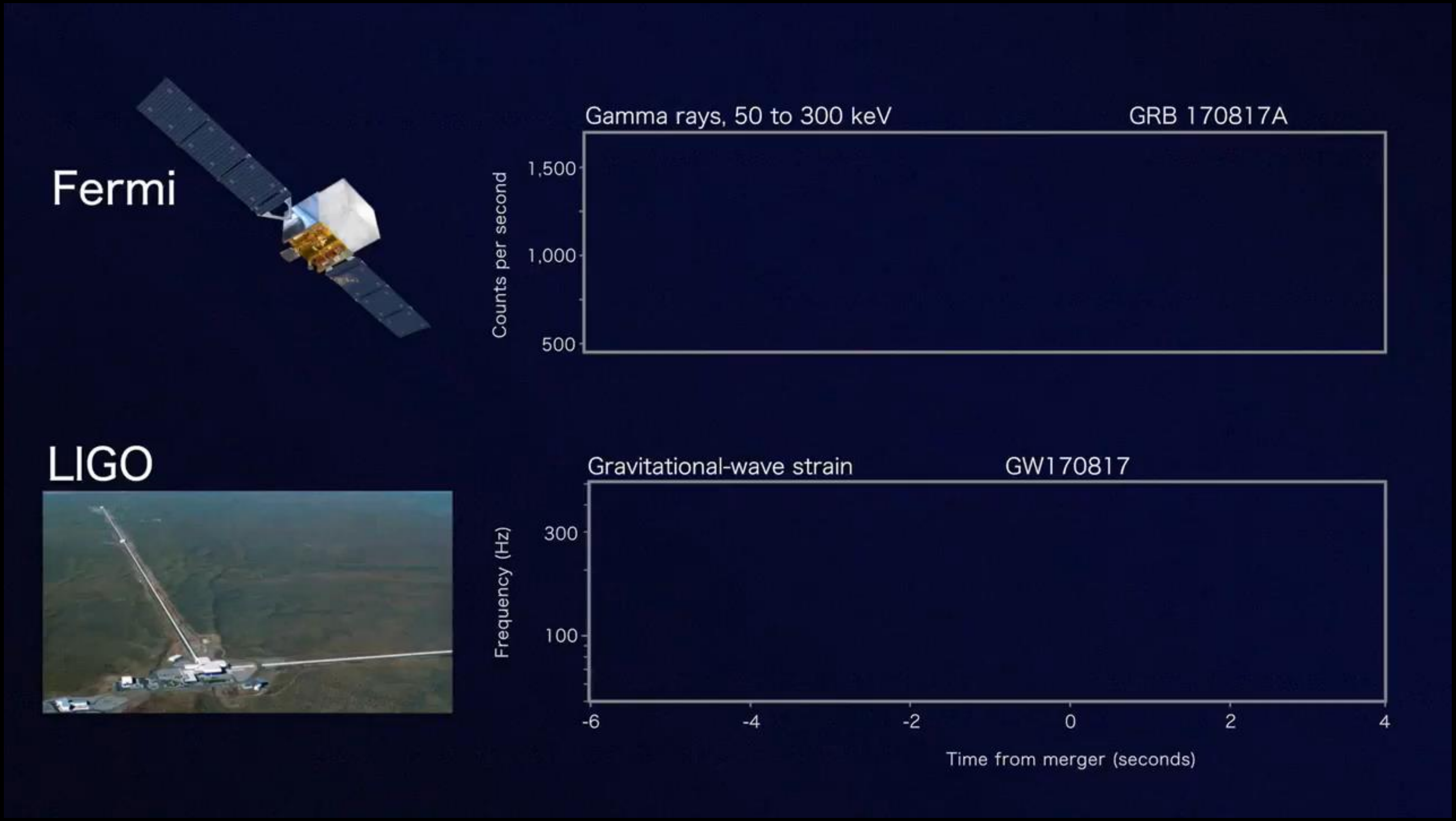


Long GRBs (>2 s)

Believed to be associated with core-collapse of massive star

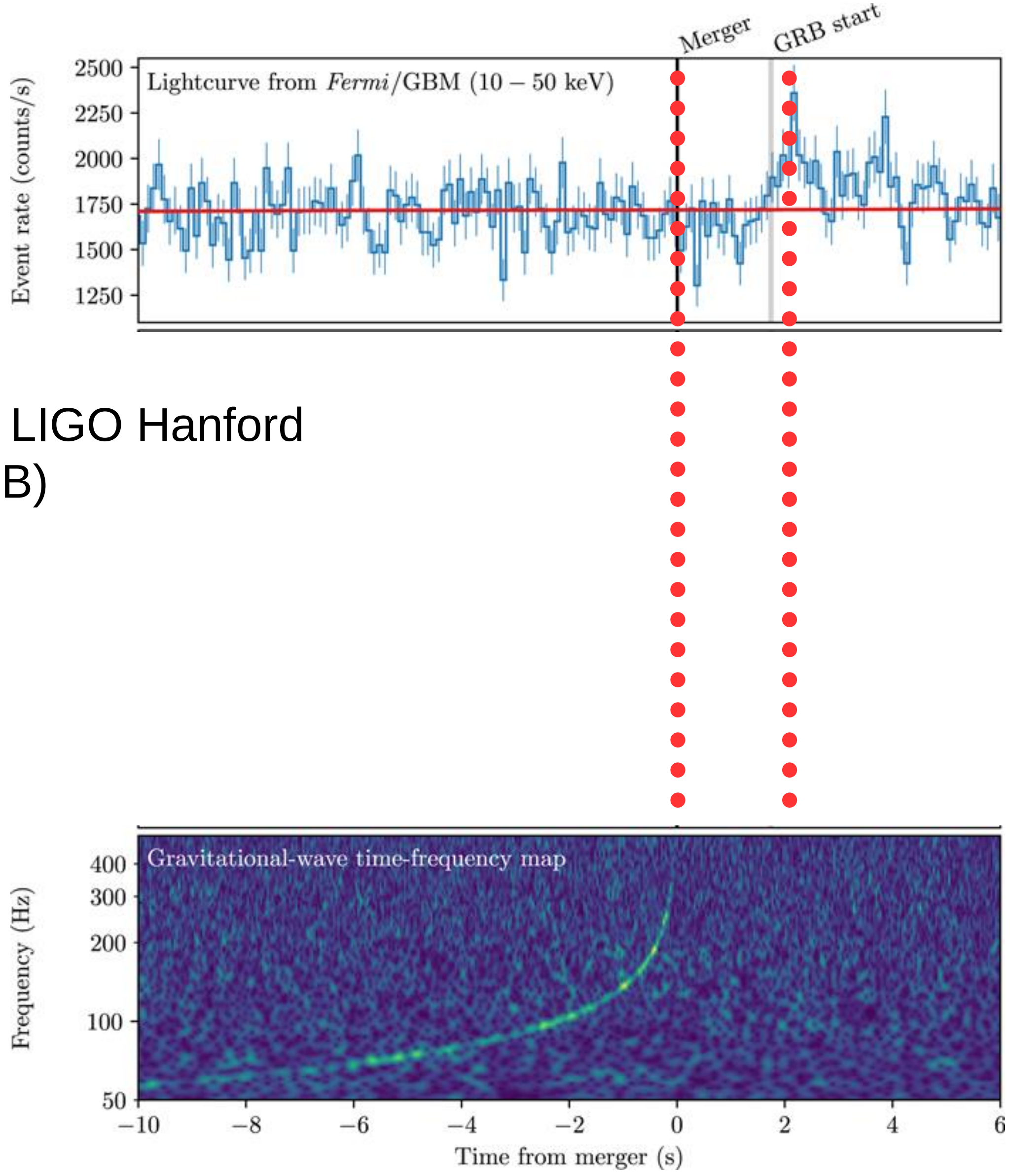
3rd GBM catalog
Narayana Bhat+, ApJS,223 (2016)

August 17, 2017



Timeline of the GW170817 discovery

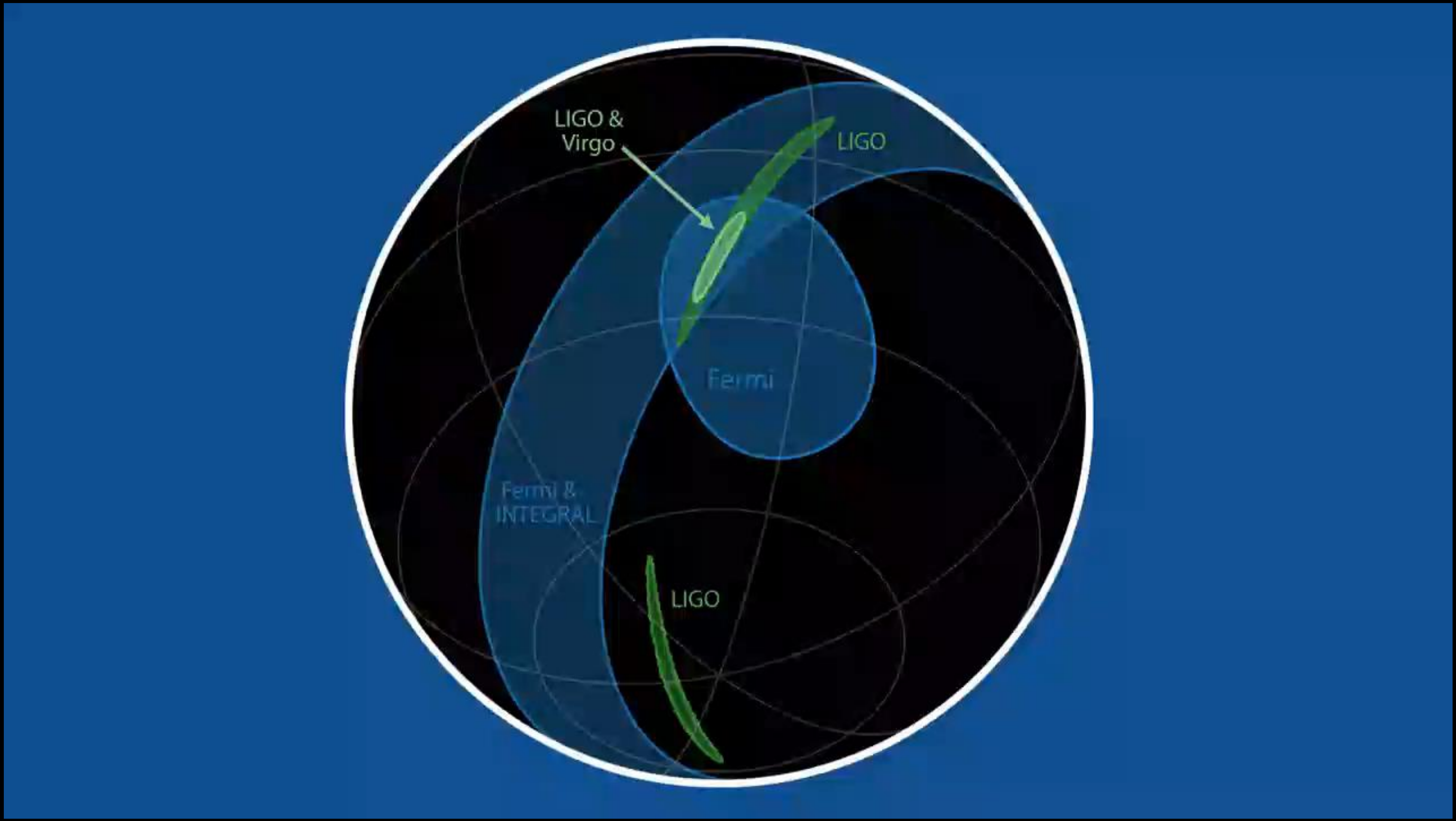
- **12:41:06 UTC** : onboard *Fermi*-GBM trigger
- **12:41:20 UTC** : Automatic Fermi Gamma-ray Coordinates Network (GCN)



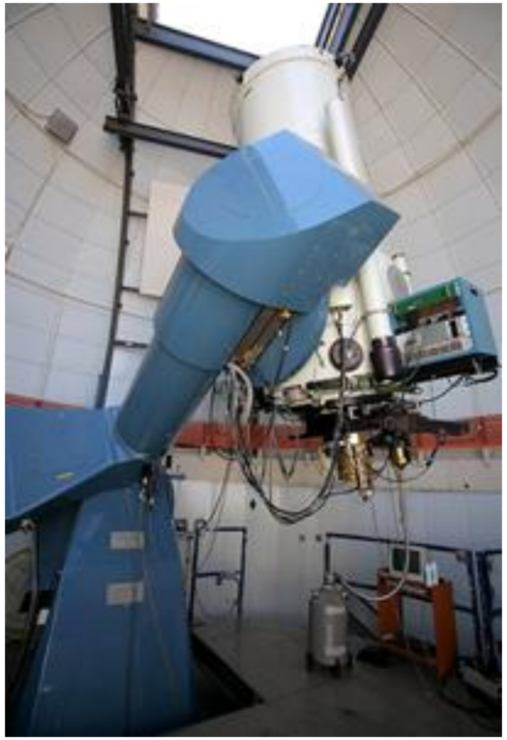
- **~12:47 UTC** : low-latency GW pipeline detection on LIGO Hanford
  - Detected time 12:41:04 (1.7 sec *before* Fermi GRB)
- **13:21:42 UTC** : First alert sent from LIGO/Virgo
- **17:54:51 UTC**: First LIGO-Virgo skymap
  - Error region ~31 deg^2
  - Distance 40 Mpc
- **23:54:40 UTC**: Refined LIGO-Virgo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

Abbott+17, ApJ 848,2

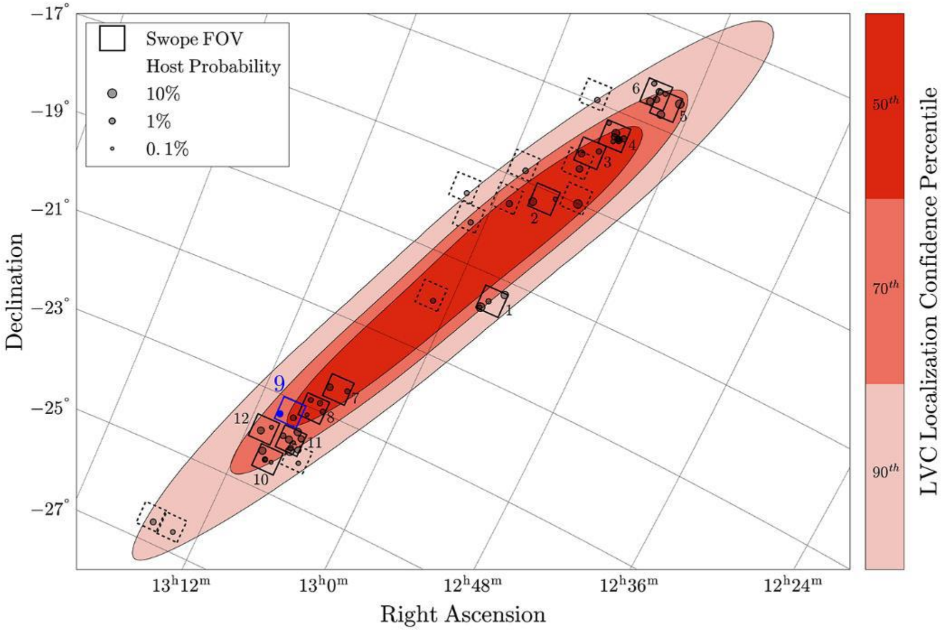
Sky localization



The optical transient

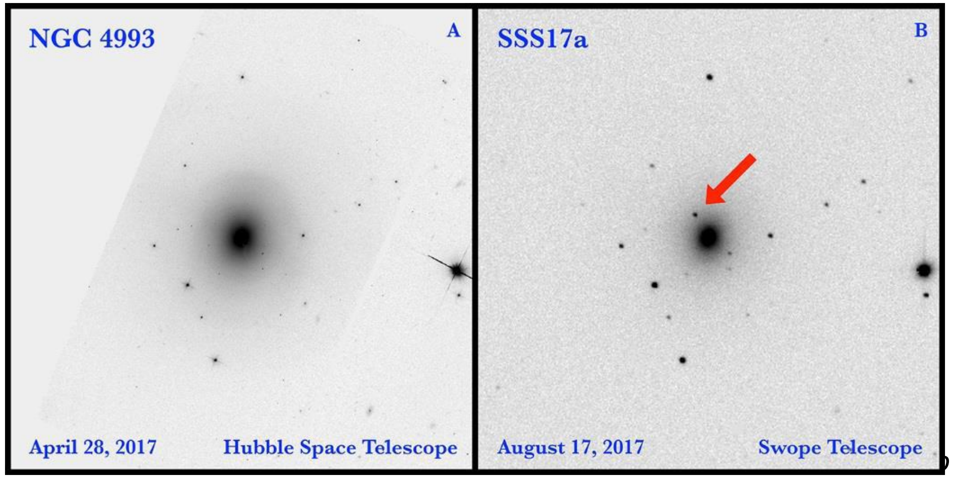


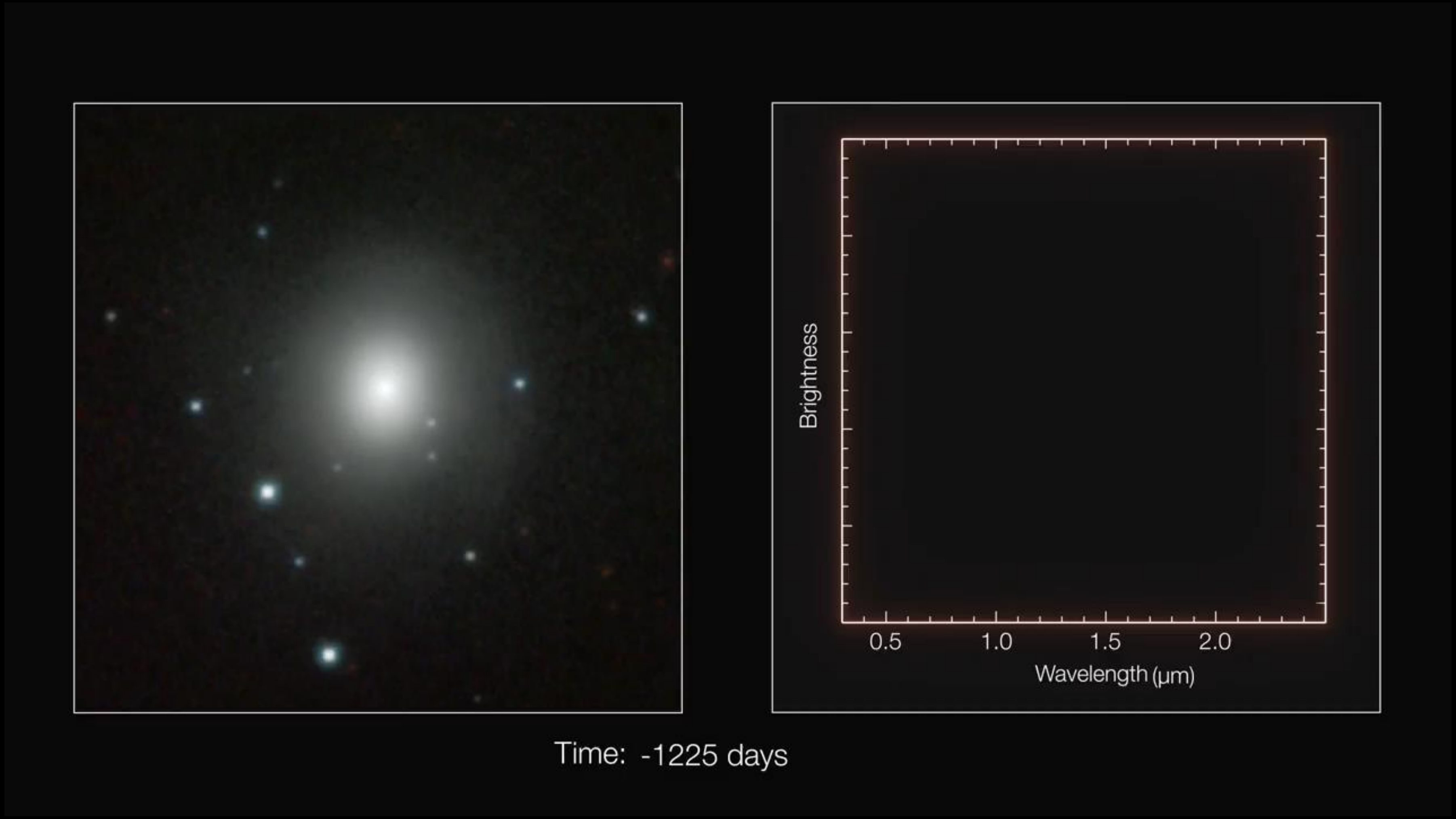
One-Meter, Two-Hemisphere (1M2H) team
1-m Swope telescope, Las Campanas (Chile)



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

- *(Coulter et al. 2017)*

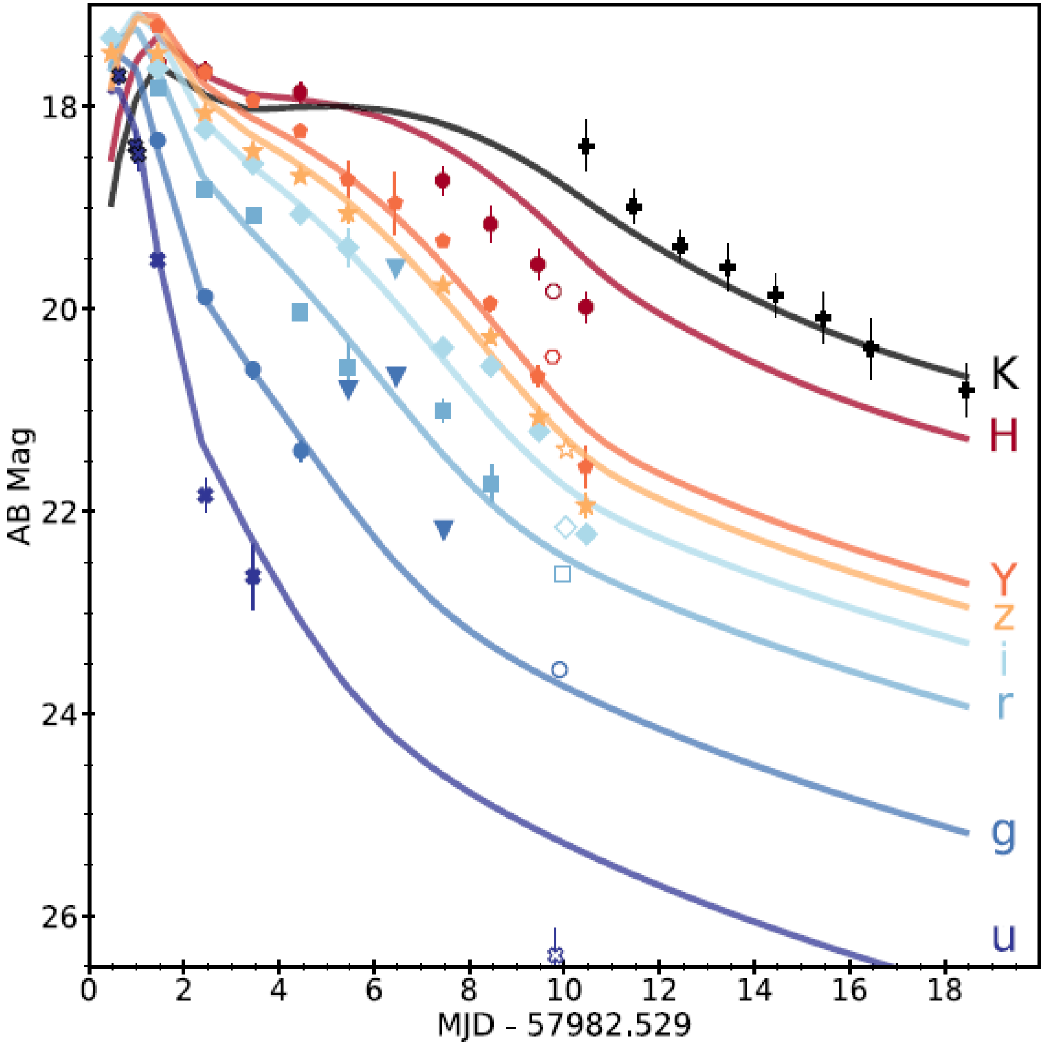



Brightness
0.5
1.0
1.5
2.0
Wavelength (μm)
Time: -1225 days

Broadband follow-up: UV, optical, IR

Next days, follow-up observations to rule out chance coincidences
Photometry using DECam, HST, Gemini-south, Swift, from IR to UV

Confirmation of kilonova



Cowperthwaite et al. 2017

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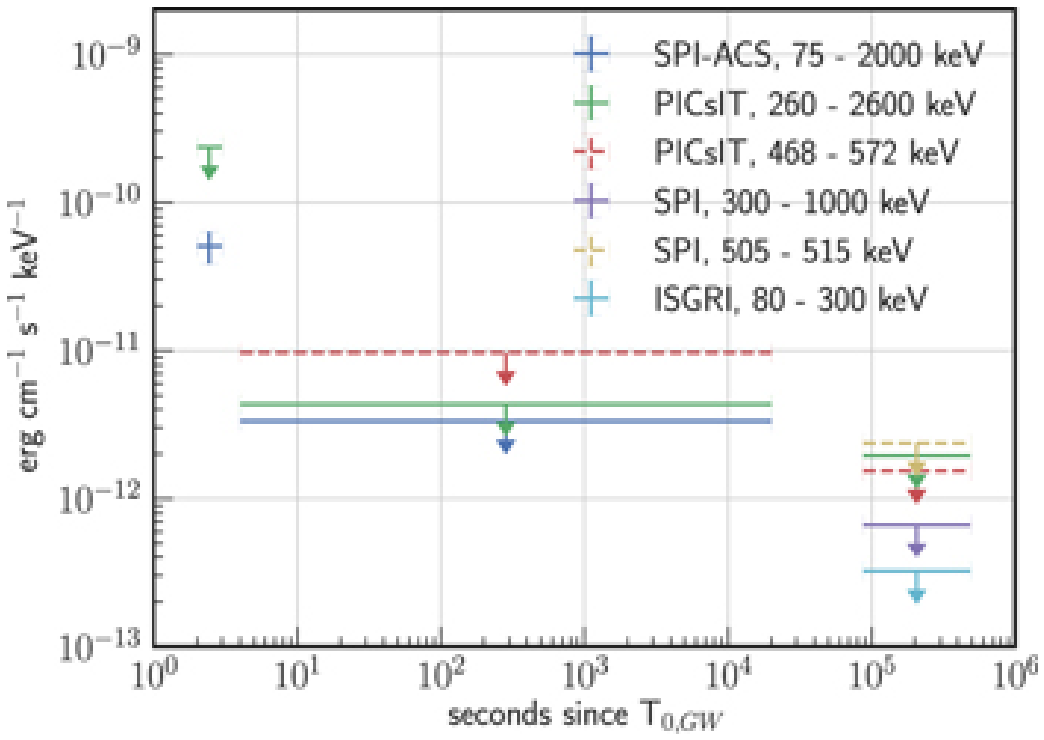
Broadband follow-up: gamma rays

Gamma rays probe highly relativistic processes
Many high-energy facilities online (IPN)

- Fermi GBM+Fermi LAT
- AGILE
- INTEGRAL
- HXMT
- CALET
- AstroSat
- HESS
- HAWC



INTEGRAL upper limits
(Savchenko et al, 2017)

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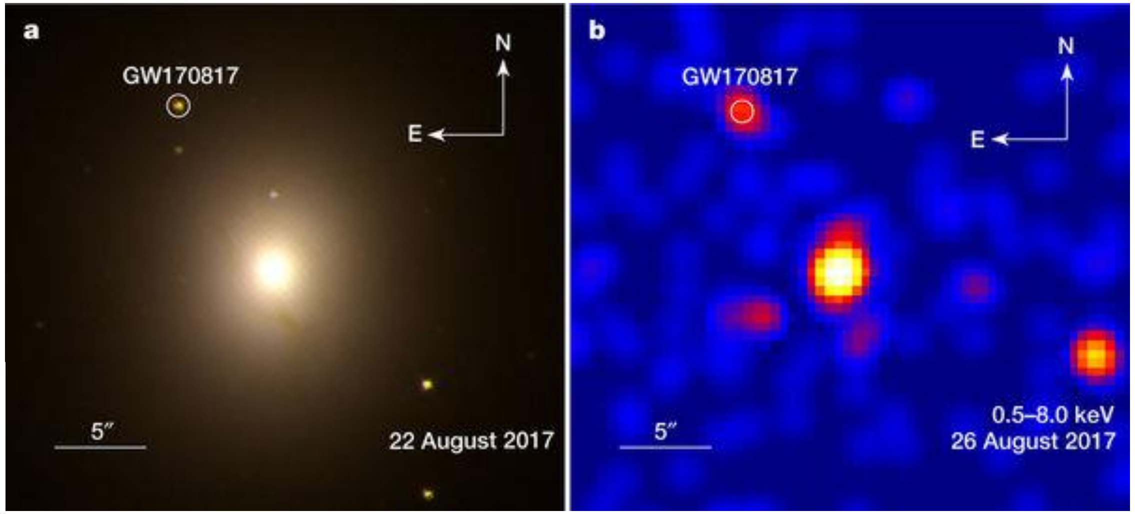
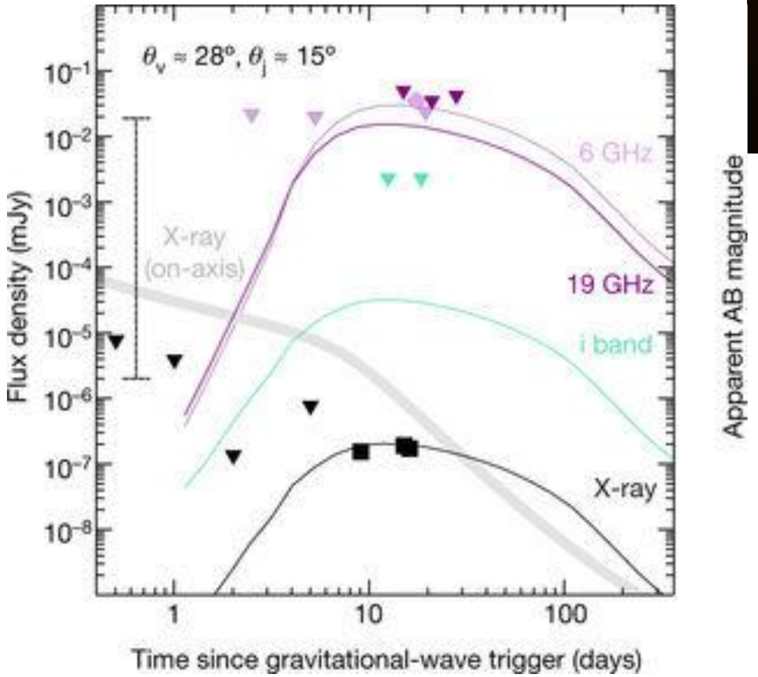
Broadband follow-up: X-rays

- No detections until t_0+9 days
- First detection by Chandra (Troja et al., 2017)
- Emission up to t0+15 days (occulted by Sun)





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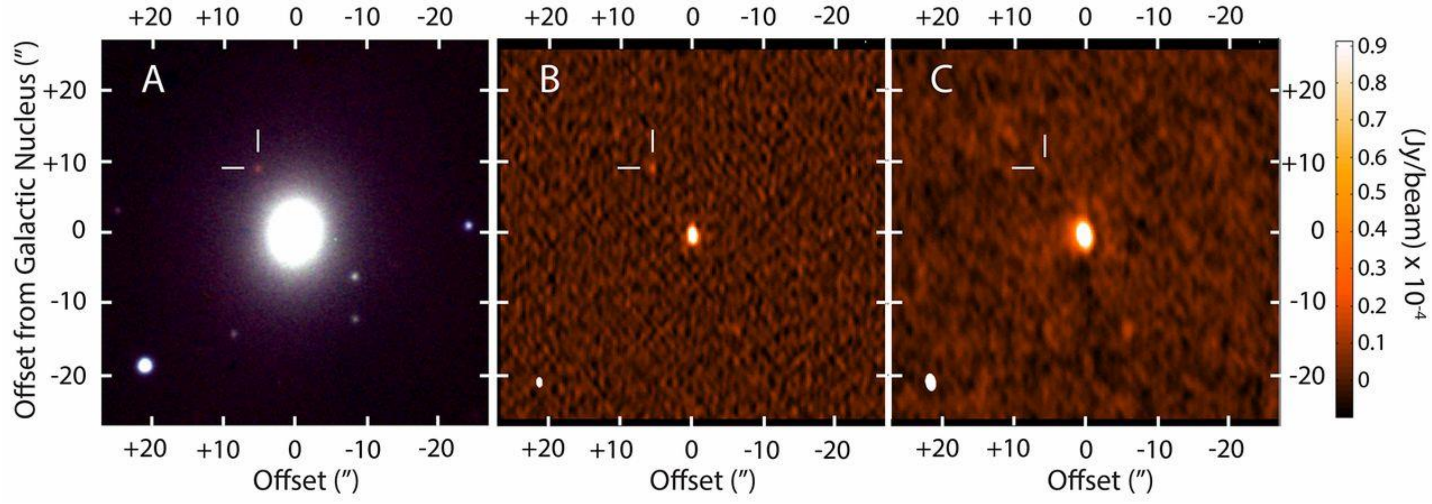
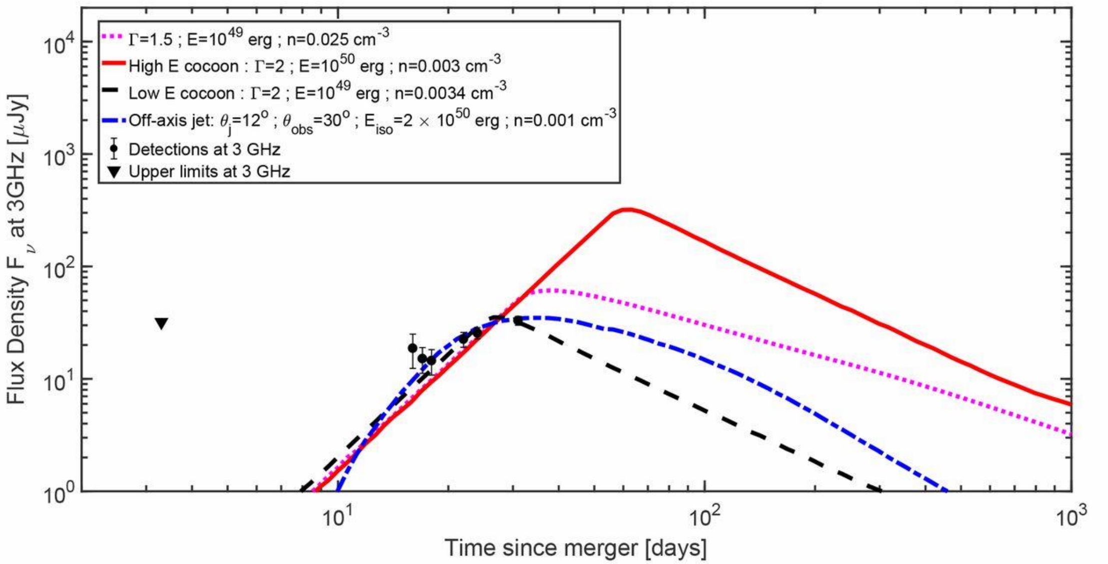
Broadband follow-up: radio

- First detection at t_0+16 days by VLA, confirmed by ATCA



6 GHz image @VLA

Consistent with cocoon or off-axis emission

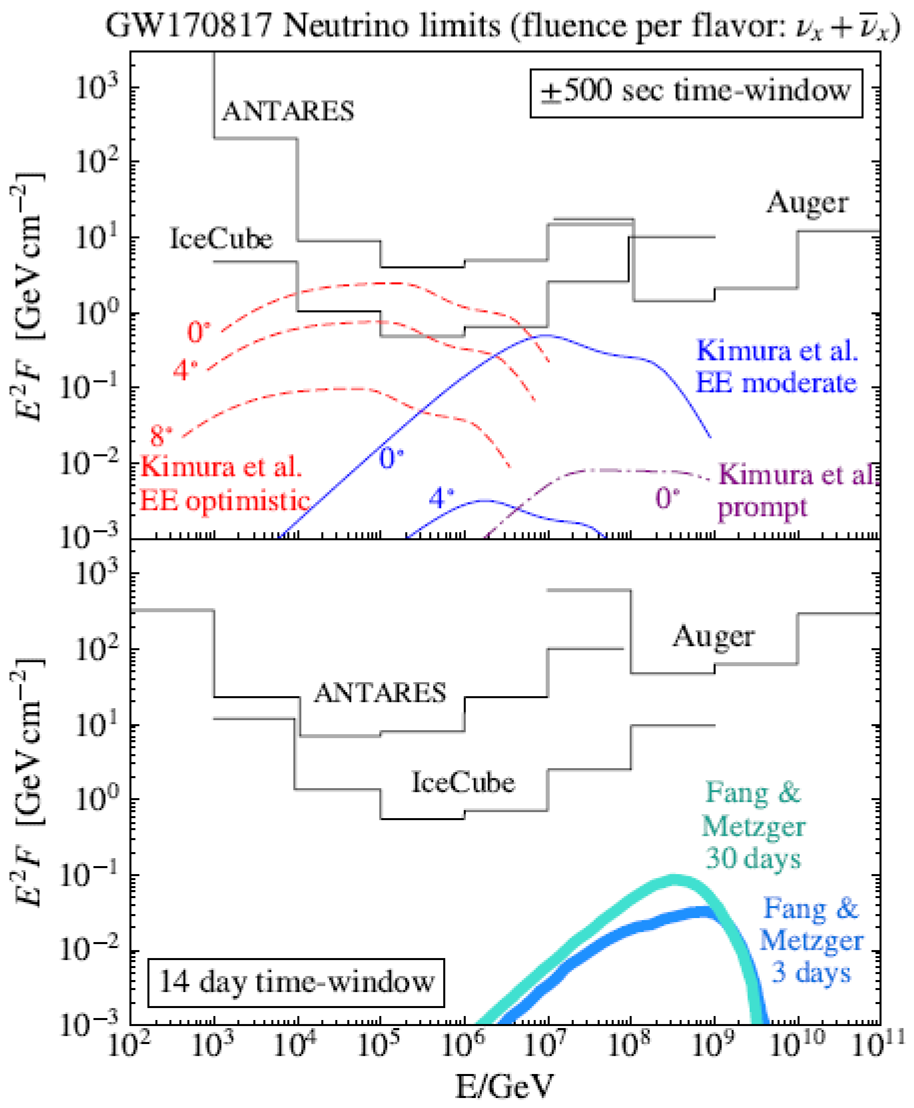


Hallinan et al 2017

Broadband follow-up: neutrinos

- Icecube
- ANTARES
- Pierre Auger Observatory

No detection
Upper limits computed



Albert et al 2017

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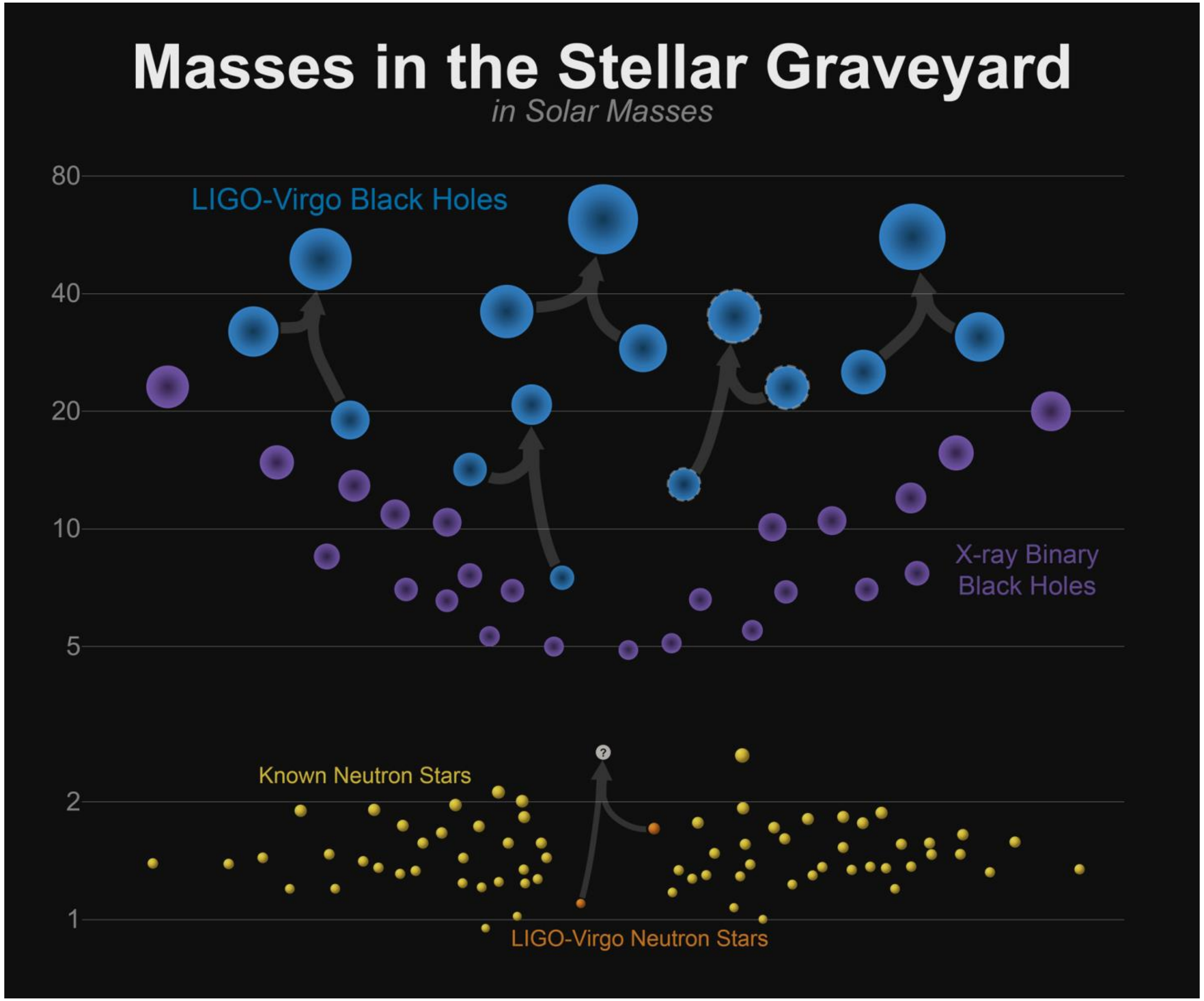
Lessons learned: NS physics

- NS masses and constraints on EoS
- Explored new mass range with GWs



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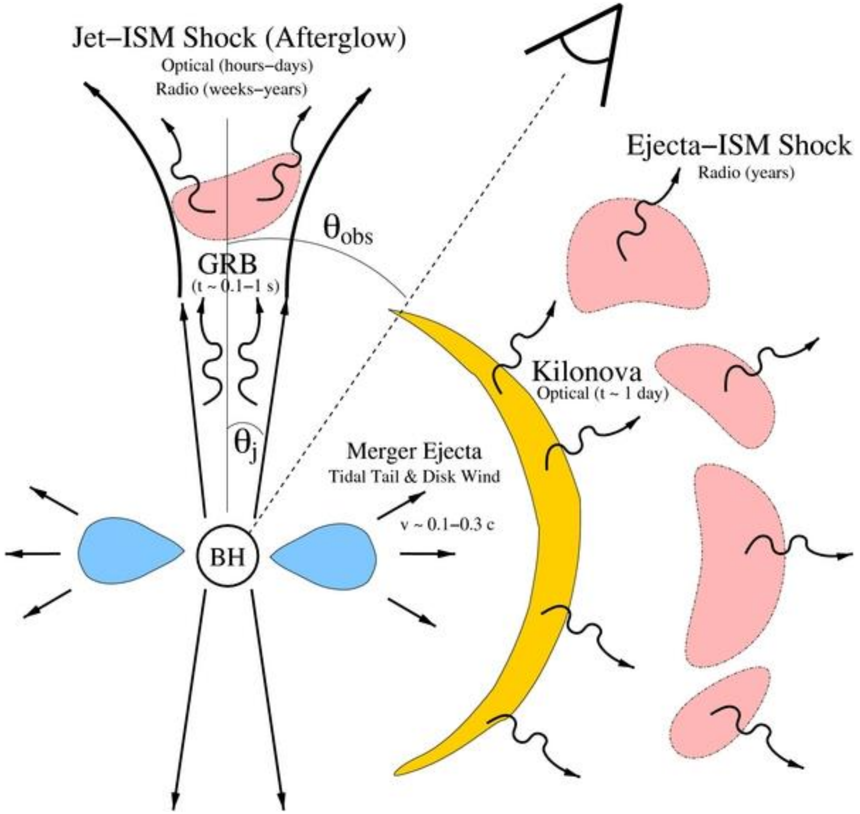
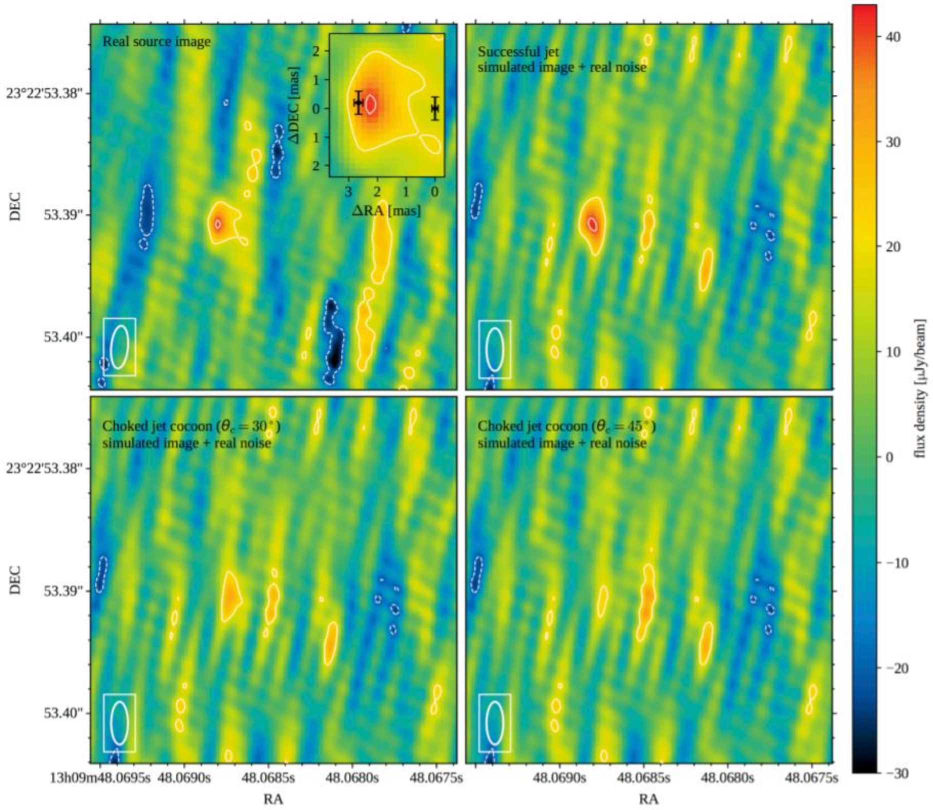
Lessons learned: GRB physics

- NS mergers – short GRBs association
  (Abbott et al. 2017, ApJ 848,13)
- GRB EM emission: few models, including
  1. Jet seen off-axis
  2. Structured core+outer cocoon
  3. Isotropic fireball
- VLBI radio imaging pointing toward (1)



Metzger & Berger 2012, ApJ,746,1

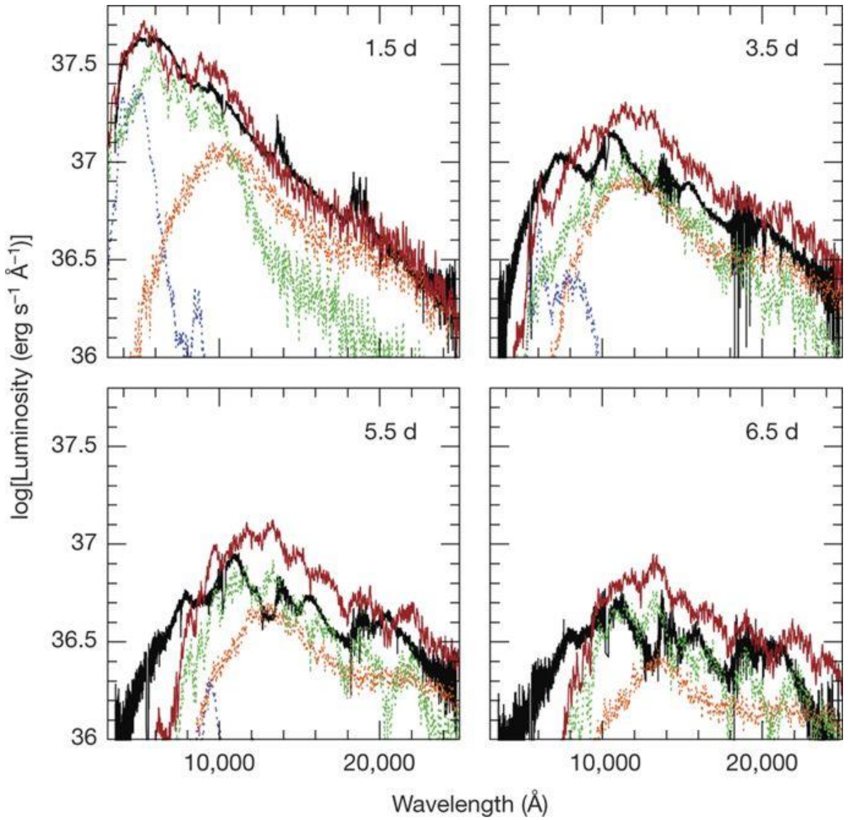


Ghirlanda et al. 2018, arxiv1808.00469

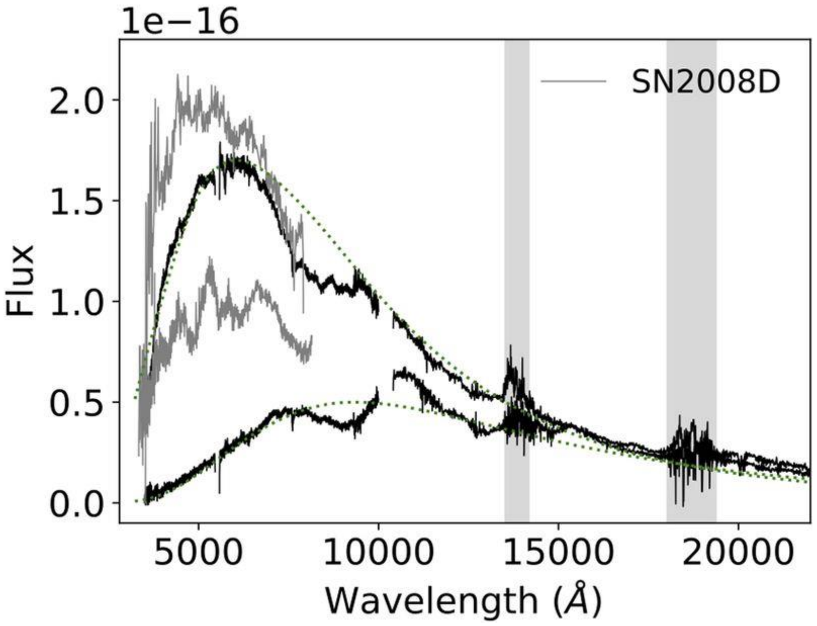
M. Razzano

Lessons learned:
origin of heavy elements

- Confirmation of a kilonova transient(1/10 SN luminosity)
- Evidence of heavy element production via r-processes



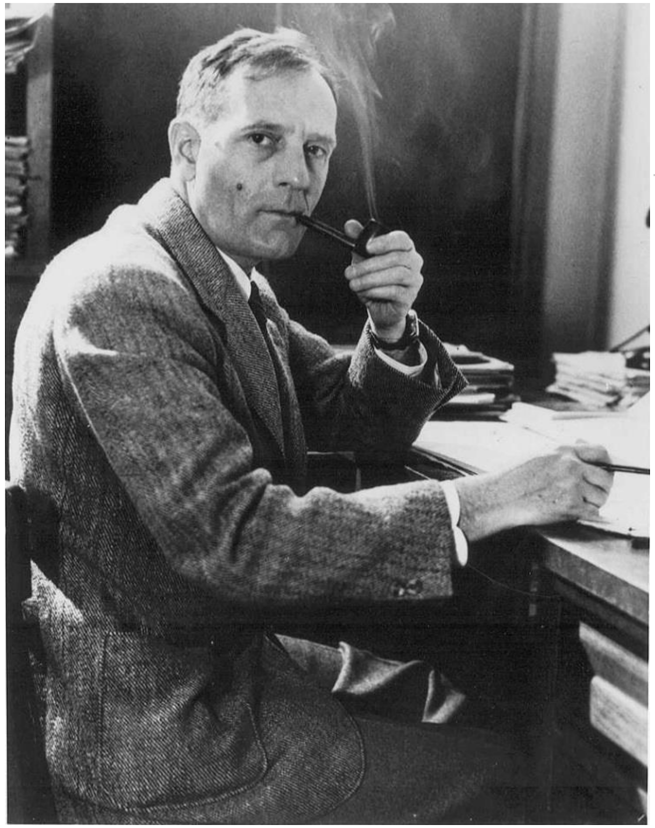
1.5-3.5 d
2-5 d



Pian et al. 2017, Nature, 551,67

M. Razzano

Lesson learned: cosmology



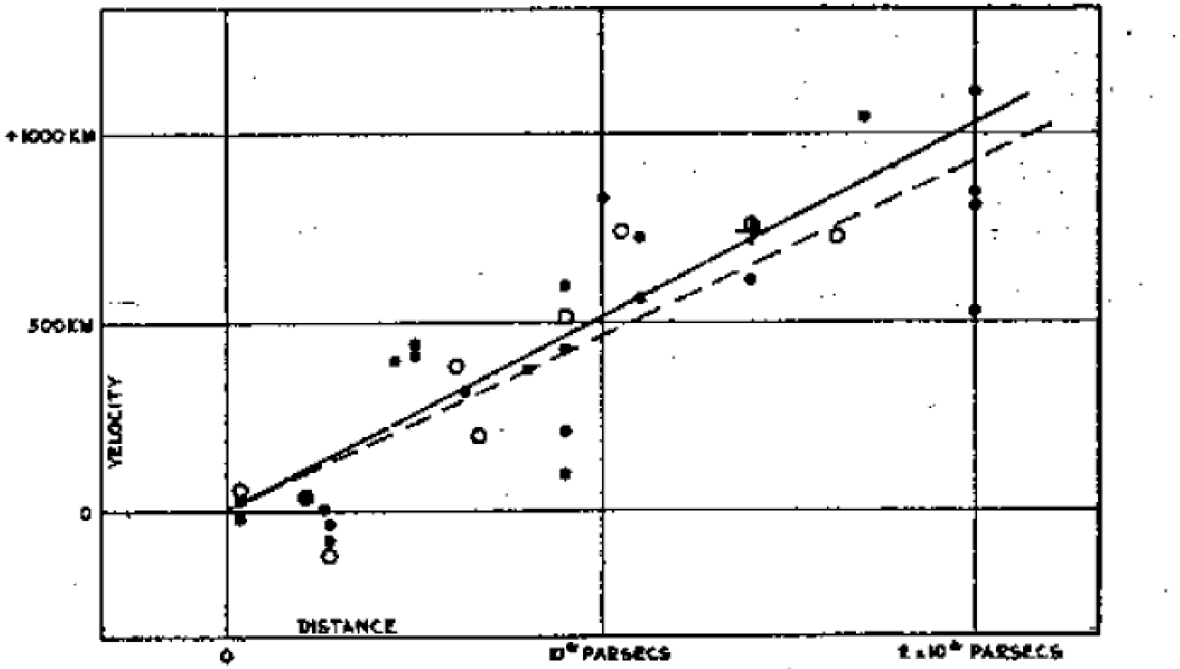


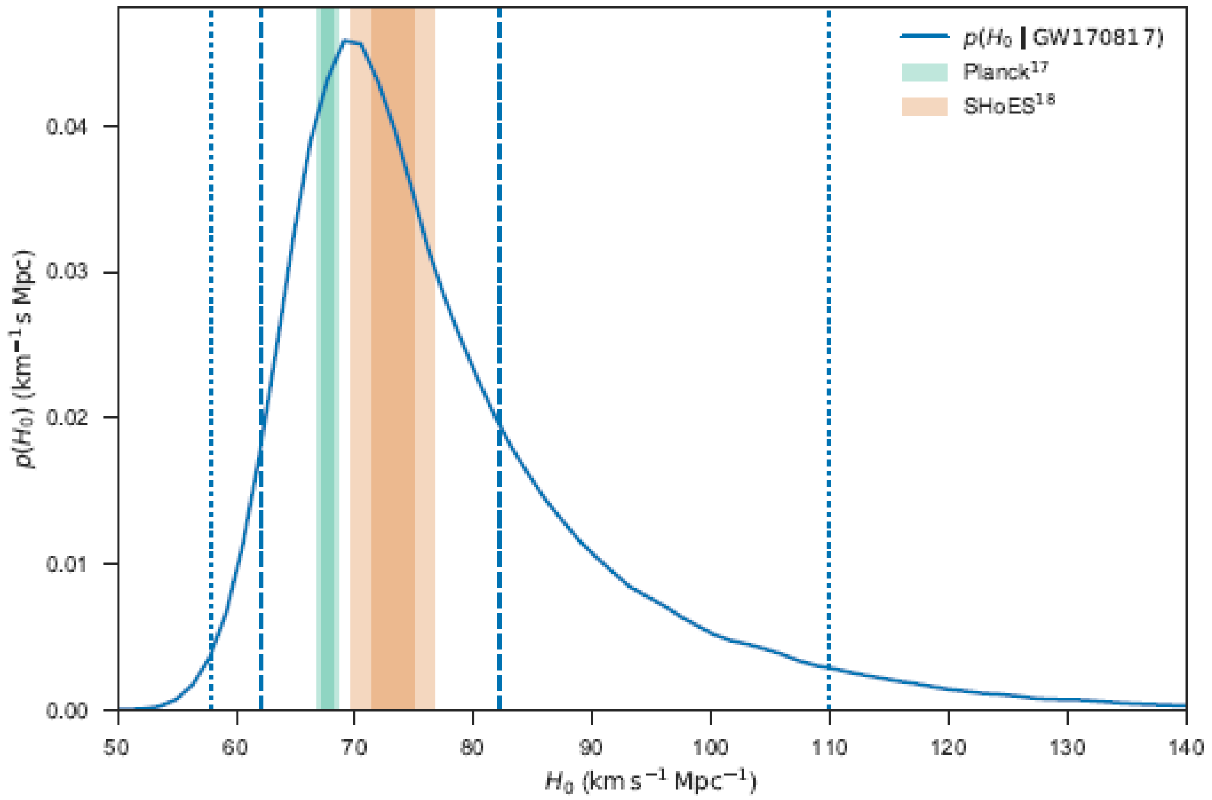
FIGURE 1

$$V = H_0 \, d$$

- Gravitational waves → d («standard syrens»)
- IF we know the galaxy counterpart → Redshift → V

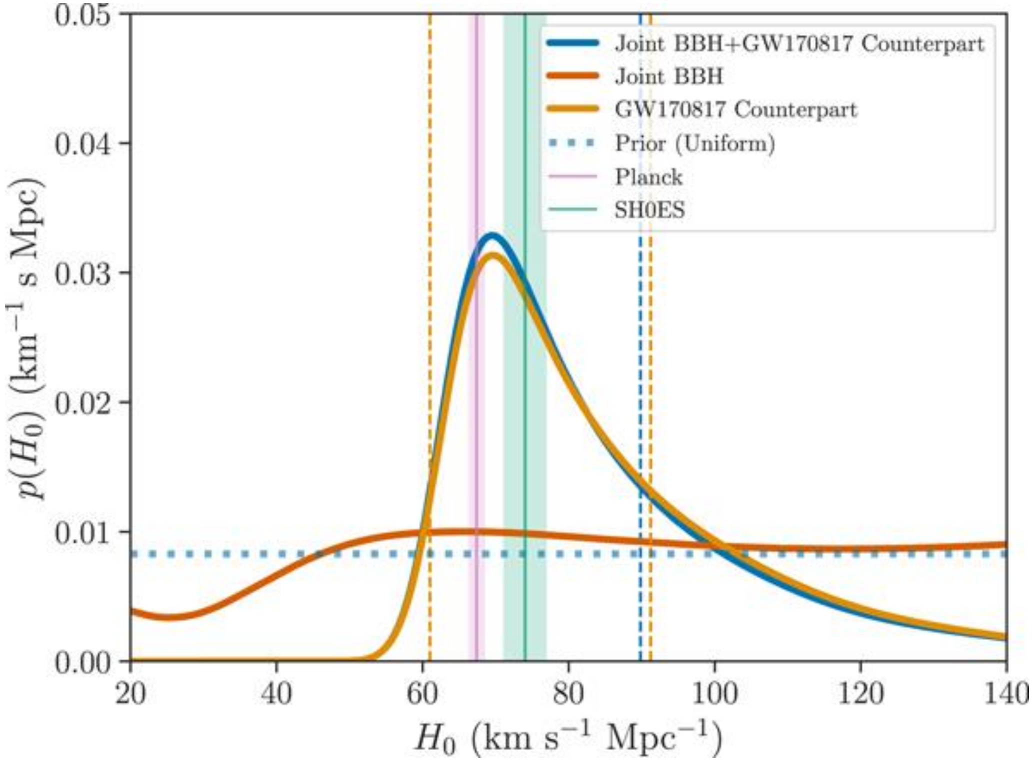
M. Razzano

Multimessenger H_0



$$H_0 = 70^{+12}_{-8} \text{ Km s}^{-1} \text{ Mpc}^{-1}$$

Abbott et al 2017, Nature, 551, 85



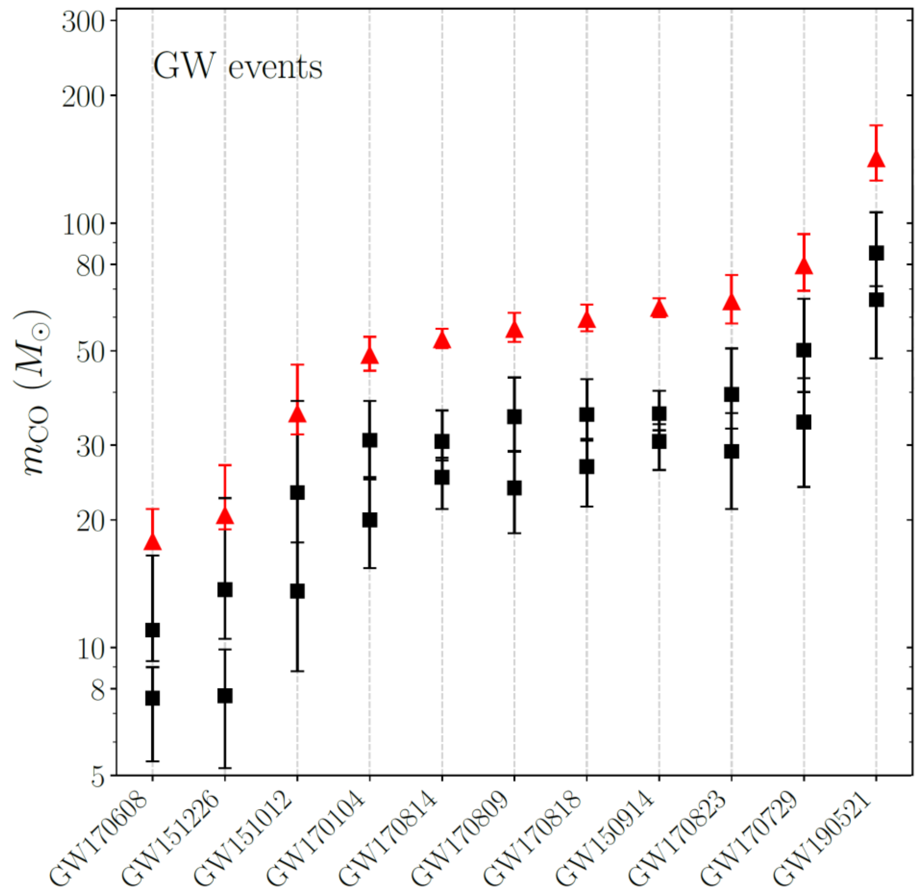
Abbott et al, ApJ,909,2

M. Razzano

Beyond GW170817: Most interesting events

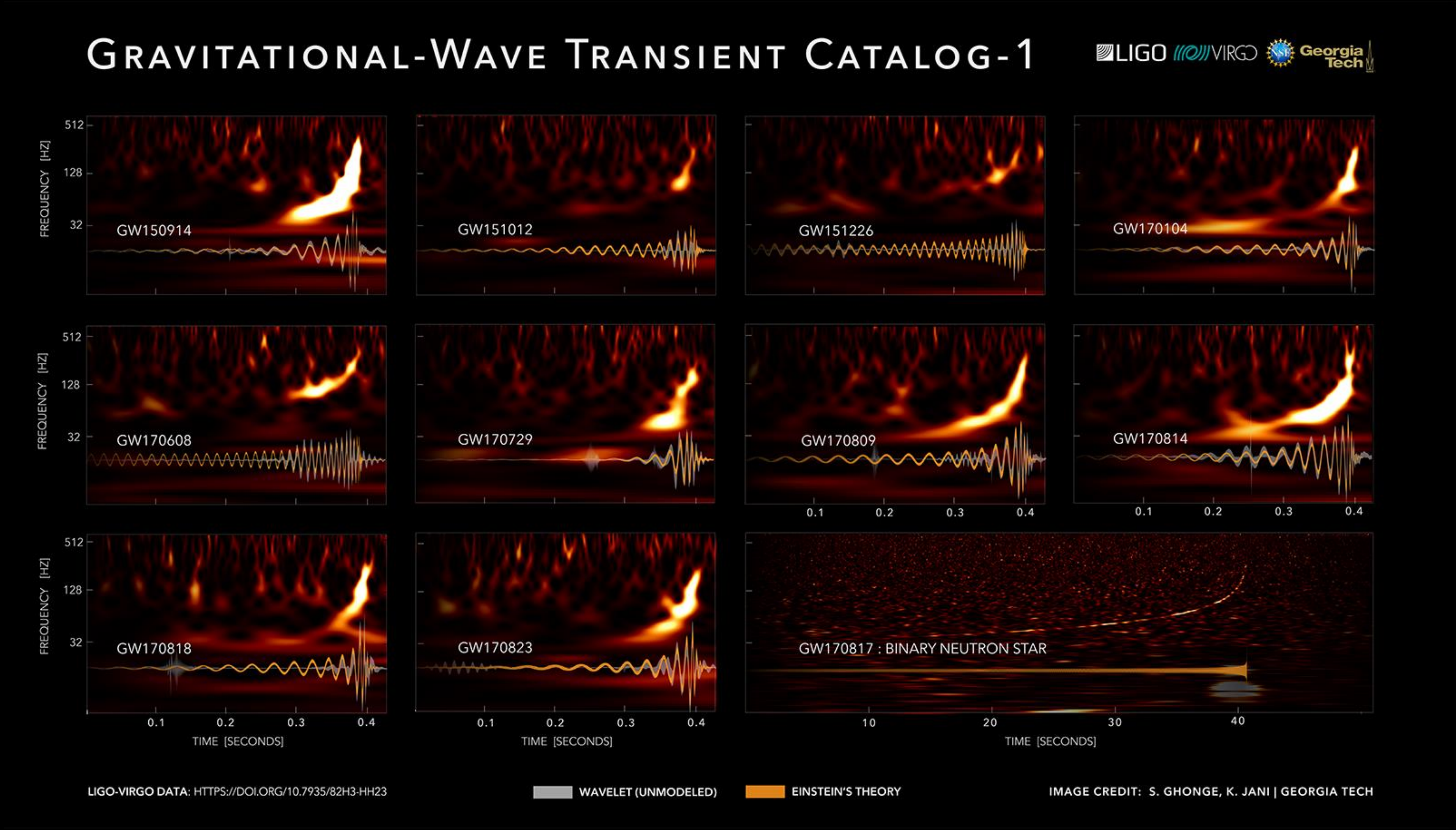
- **GW150914**
  - First detection, BBH
  - Abbott et al 2016, PRL, 116, 101103

- **GW170814**
  - BBH, First triple detection LIGO+Virgo
  - localization from 1000 deg^2 to 60 deg^2
  - Abbott et al 2017,PRL,119,141101
- **GW170817**
  - The first BNS!
  - Detected by Fermi-GBM, First GRB-BNS connection
  - Lots and lots of great science
  - Abbott et al 2017, PRL,119,161101
- **GW190425**
  - Second BNS
  - Abbott et al. 2020, ApJL, 892, 3
- **GW190521**
  - BBH, total mass 150 Msun
  - Abbott et al., 2020 PRL, 125, 101102
- **GW190814**
  - BH+ NS(?)
  - Abbott et al 2020, ApJL,896,44



Adapted from Abbott et al 2020, ApL 900,13

The First Catalog of GW Transients (GWTC-1)



GWTC-1
Abbott et al 2019, arXiv:1811.12907

Toward GW catalogs

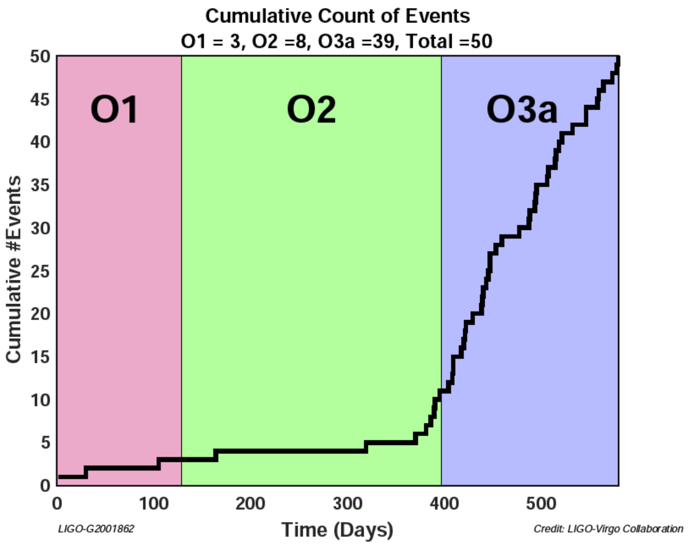
- **From single publication to a catalog-based paradigm**

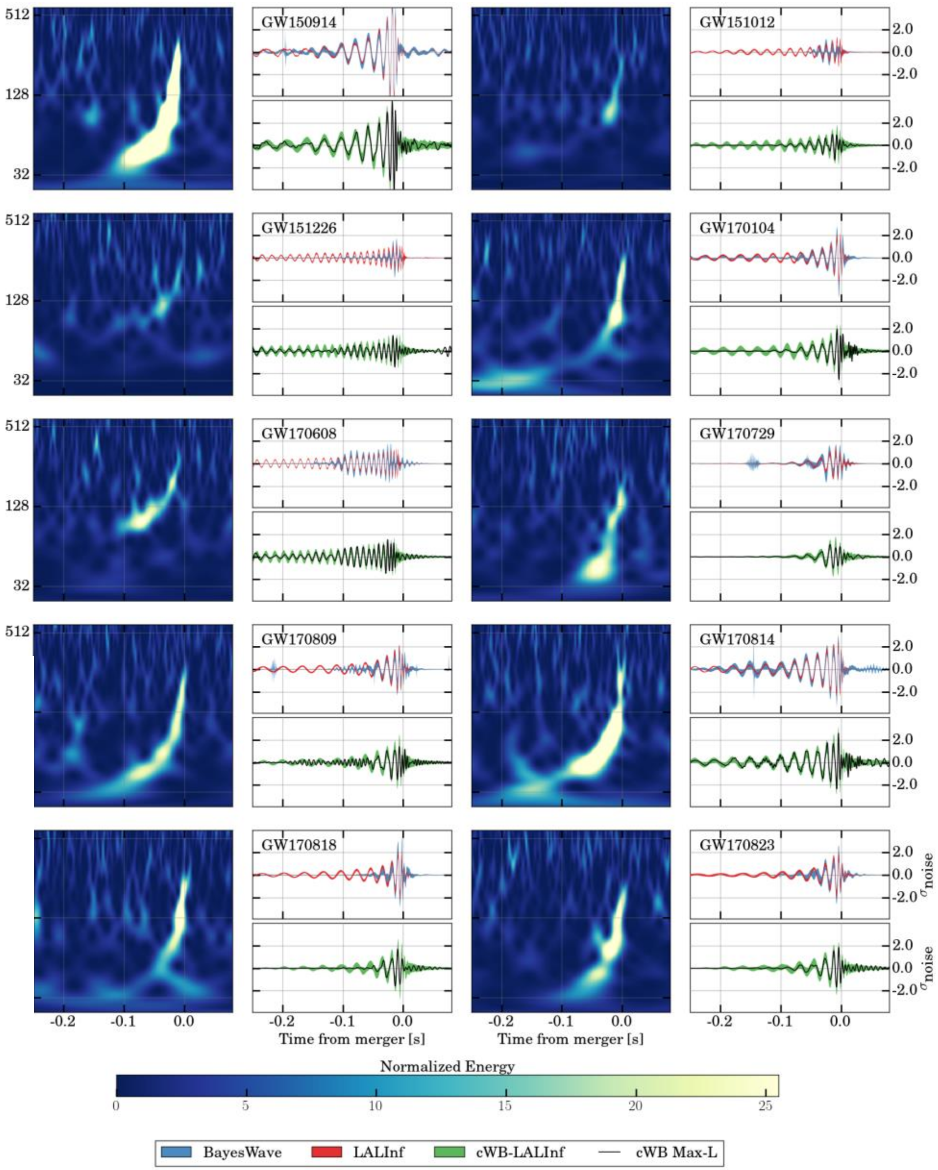
Gravitational Wave Transient Catalog 1 (GWTC-1)

- 10 BBH+1 BNS + marginal events
- O1+O2 detections
- Abbott et al 2019, PRX, 9, 031040

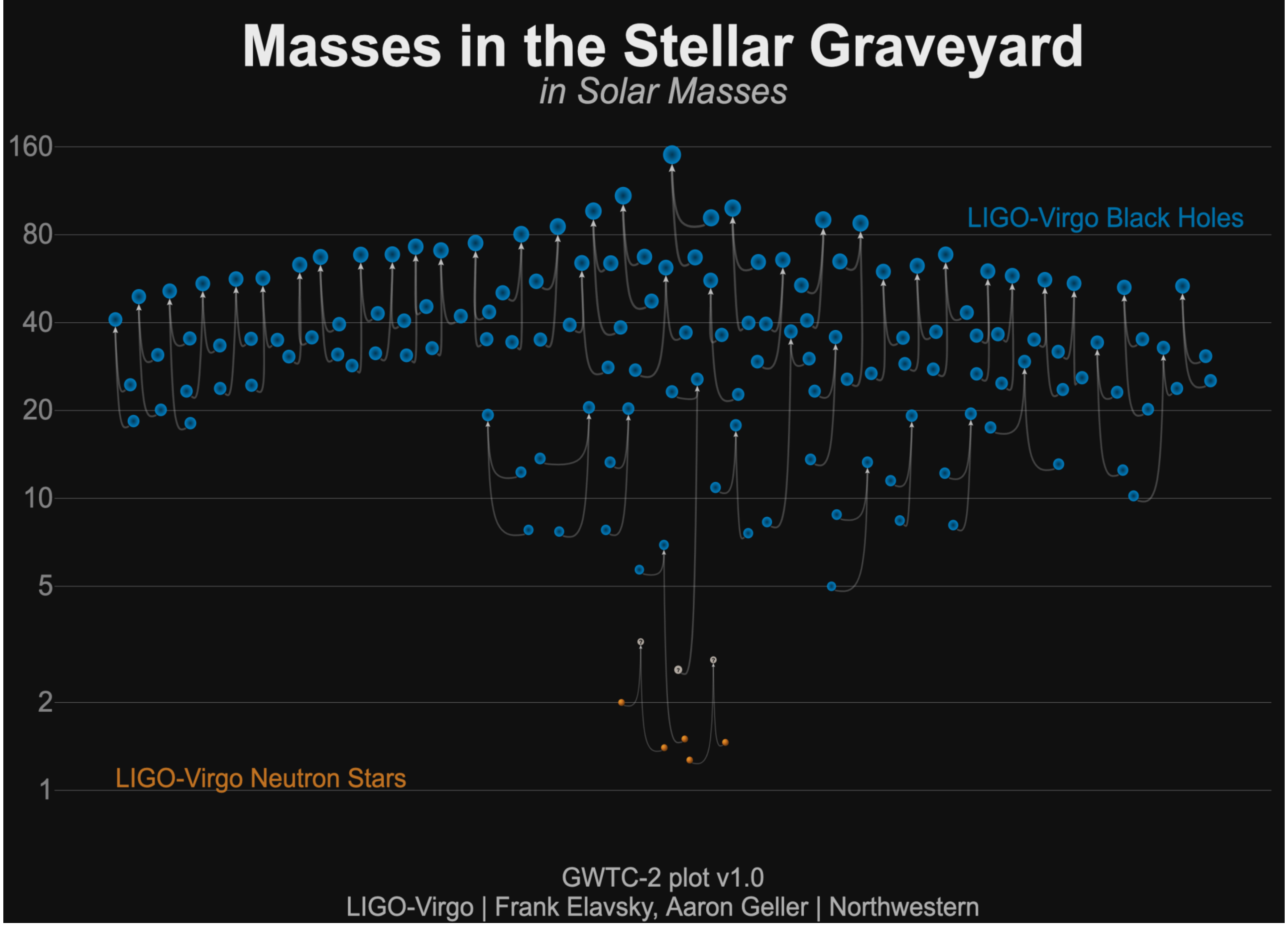
Gravitational Wave Transient Catalog 2 (GWTC-2)

- +39 events
- O1+O2+O3a detections
- Abbott et al 2020,
- (arxiv2010.14527)





Adapted from Abbott et al 2019, PRX, 9, 031040


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

New opportunities: GW open data

Hosted at the Gravitational Wave Open Science Center (GWOSC)
https://www.gw-openscience.org/

GW Public Data

- **Gravitational Wave Open Science Center**
  - Joint LIGO+Virgo effort (KAGRA will join)
  - Released according to Data Management Plan (Last update 2017)
  - Releases every 6 months, 6-month block, latency 18 months
  - 2 type of released data
    - Strain data and parameters of detected events
    - “bulk” data release of observing runs (O1,O2 and previous)
  - More details in Abbott et al 2021, SoftwareX,13,100658

- **Engaging the community**
  - Lots of material (tools, tutorials)
  - Periodic Open Data Workshops (ODW)
  - Next ODW (remote) in May

More info at
https://www.gw-openscience.org/

Abbott et al 2021,

The road ahead: O4 and beyond

- **O4**
  - 1 year, projected >2022
  - 4-detector network (LIGO 160-190 Mpc,
  - Virgo 90-120 Mpc, KAGRA 25-130Mpc)
- **O5**
  - projected >2024
  - 4-detector network (LIGO A+, AdV+ Phase2, KAGRA)
- **2025+**
  - LIGO India joins, 5-detector network

- **Further upgrades**
- LIGO A+
  - higher power
  - frequency-dependent squeezing
  - upgraded coatings
  - In place by O5
- Virgo Adv+
  - Phase 1: signal recycling higher power
  - Phase 2: higher power, larger test masses

Table 2 Achieved and projected detector sensitivities for a $1.4\,M_\odot + 1.4\,M_\odot$ BNS system, a $30\,M_\odot + 30\,M_\odot$ BBH system, a $1.4\,M_\odot + 10\,M_\odot$ NSBH system, and for two unmodeled burst signals

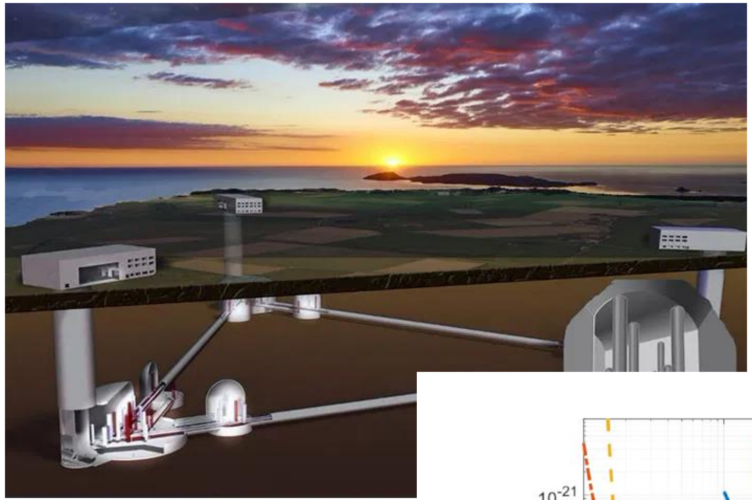
		O1	O2	O3	O4	O5
BNS range (Mpc)	aLIGO	80	100	110–130	160–190	330
	AdV	–	30	50	90–120	150–260
	KAGRA	–	–	8–25	25–130	130+
BBH range (Mpc)	aLIGO	740	910	990–1200	1400–1600	2500
	AdV	–	270	500	860–1100	1300–2100
	KAGRA	–	–	80–260	260–1200	1200+
NSBH range (Mpc)	aLIGO	140	180	190–240	300–330	590
	AdV	–	50	90	170–220	270–480
	KAGRA	–	–	15–45	45–290	290+
Burst range (Mpc) $[E_{GW} = 10^{-2}\,M_\odot c^2]$	aLIGO	50	60	80–90	110–120	210
	AdV	–	25	35	65–80	100–155
	KAGRA	–	–	5–25	25–95	95+
Burst range (kpc) $[E_{GW} = 10^{-9}\,M_\odot c^2]$	aLIGO	15	20	25–30	35–40	70
	AdV	–	10	10	20–25	35–50
	KAGRA	–	–	0–10	10–30	30+

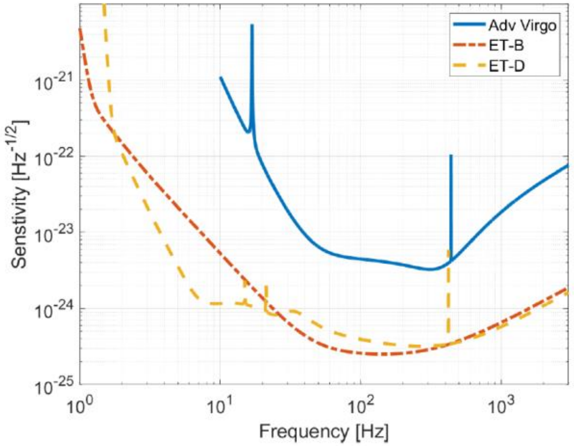
The quoted ranges correspond to the orientation-averaged spacetime volumes surveyed per unit detector time. For the burst ranges, we assume an emitted energy in GWs at 140 Hz of $E_{GW} = 10^{-2}\,M_\odot c^2$ and of $E_{GW} = 10^{-9}\,M_\odot c^2$. The later is consistent with the order of magnitude of the energy expected from core-collapse of massive stars (see footnote 4). Both compact binary coalescence (CBC) and burst ranges are obtained using a single-detector SNR threshold of 8. The O1 and O2 numbers are representative of the best ranges for the LIGO detectors: Hanford in O1 and Livingston in O2. The O3 numbers for aLIGO and AdV reflect recent average performance of each of the three detectors. Range intervals are quoted for future observing runs due to uncertainty about the sequence and impact of upgrades

Abbott et al, (LVK collaborations) 2020, LRR, 23, 3

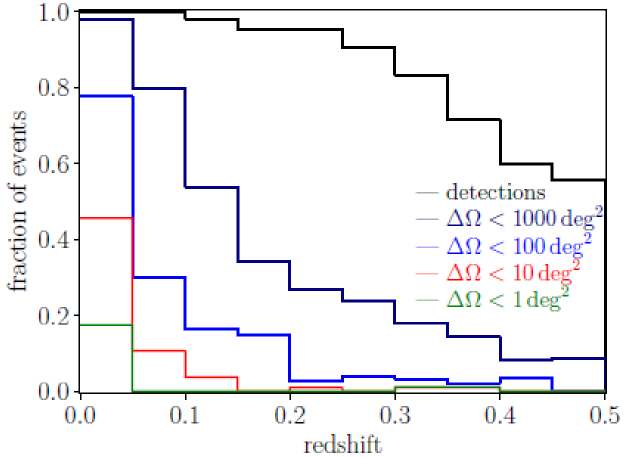
3G: Einstein Telescope

- **Einstein Telescope (EU-based)**
  - 2 underground, 10-km, underground triangle-shaped
  - 2 possible sites, Sardinia and Meuse-Rhine
  - Proposal submitted for ESFRI roadmap
  - Probing larger horizon, black hole history with z,
  - cosmology

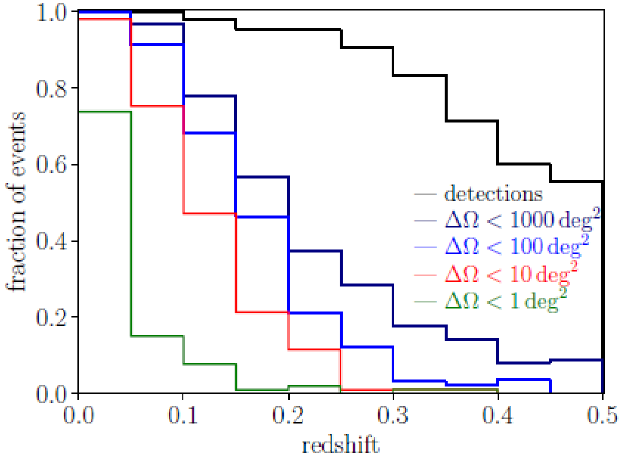




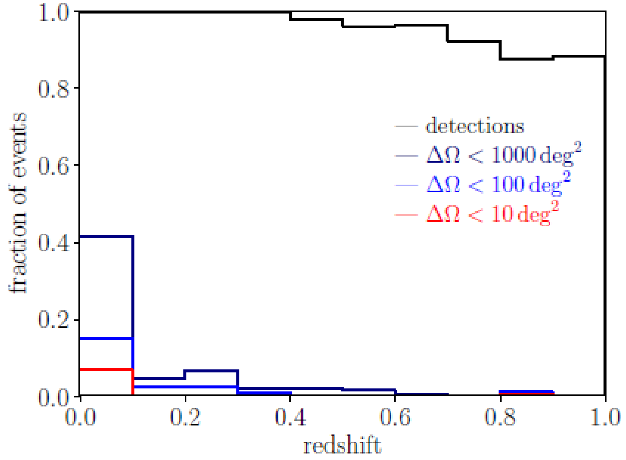
BNS, ET alone



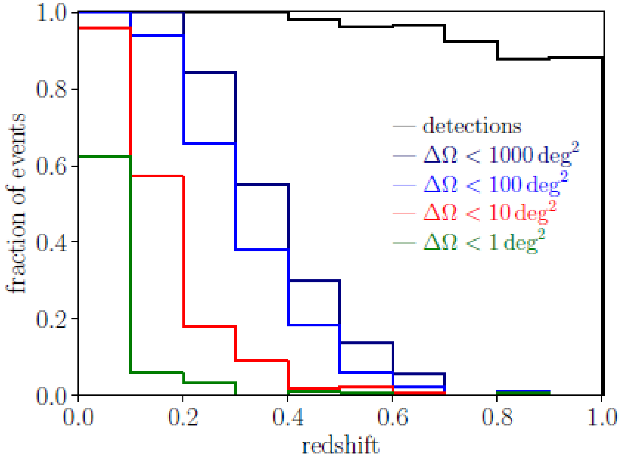
BNS, ET+LVKI



BBH, ET alone

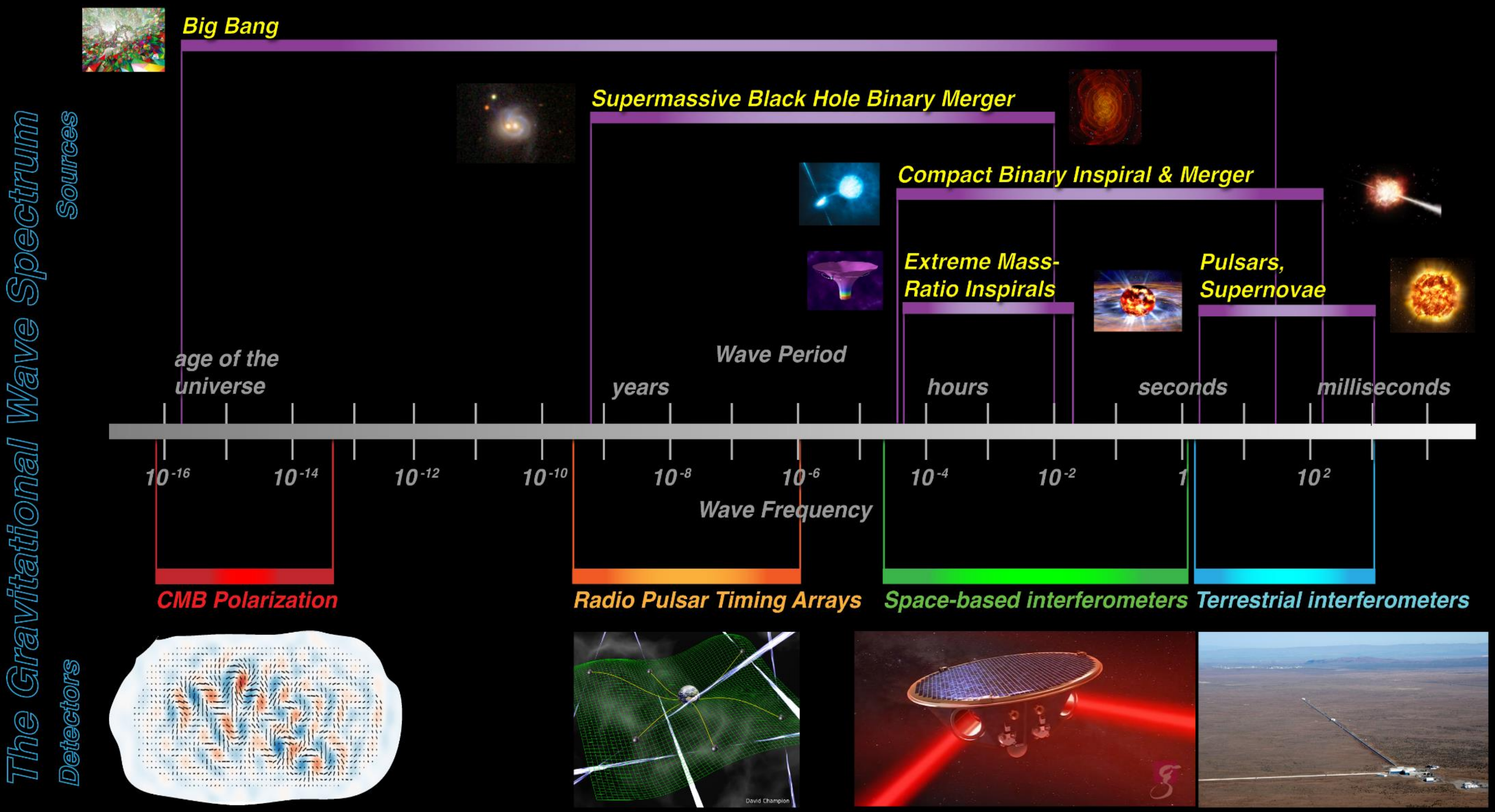


BBH, ET + LVKI



Maggiore et al 2020, arxiv 1912.02622

Beyond advanced detectors



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)

- GW170817 provided a first successful multimessenger story
  - Great synergy and coverage
  - >70 teams involved, EM+neutrinos
  - Kilonova counterpart discovered
  - Astrophysics & fundamental physics

- Present & Future
  - Not just BBH: what about new new sources?
  - New opportunities from OPA and Open Data

Thanks for the attention!