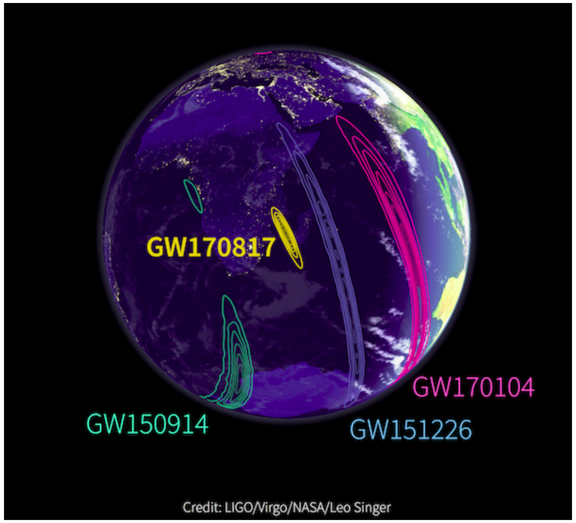
Gravitational wave transient sources

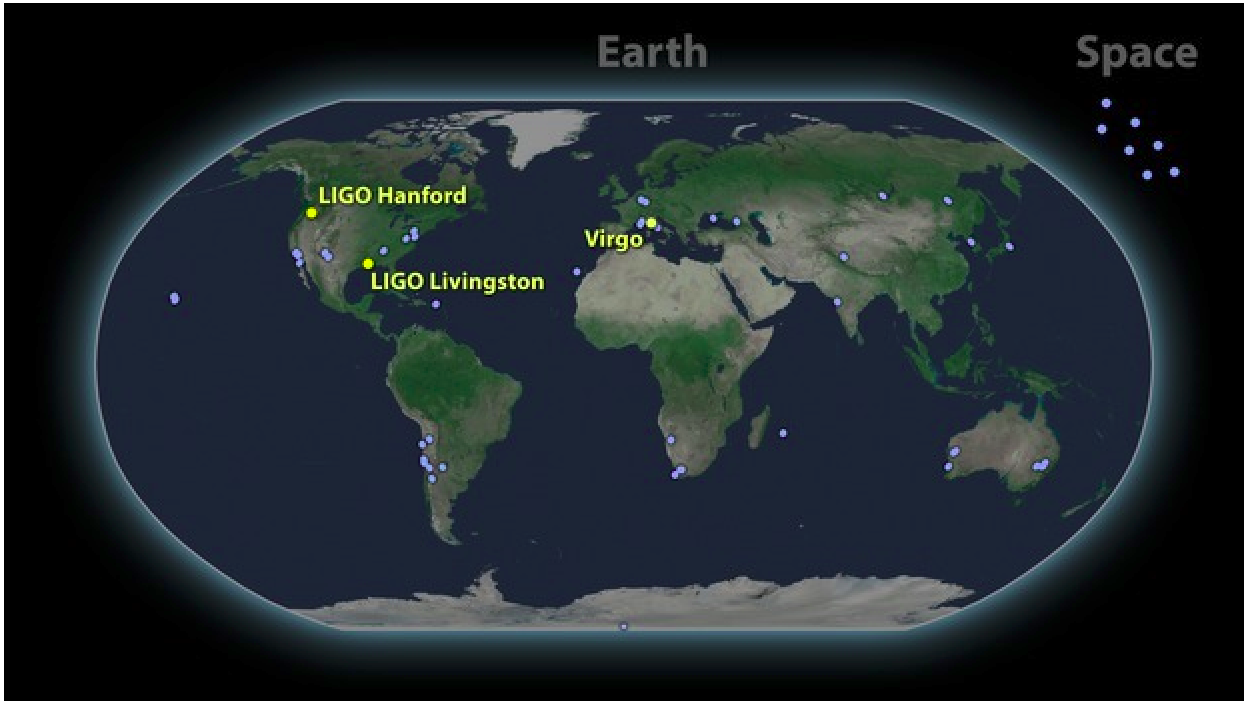


Marie Anne Bizouard, LAL

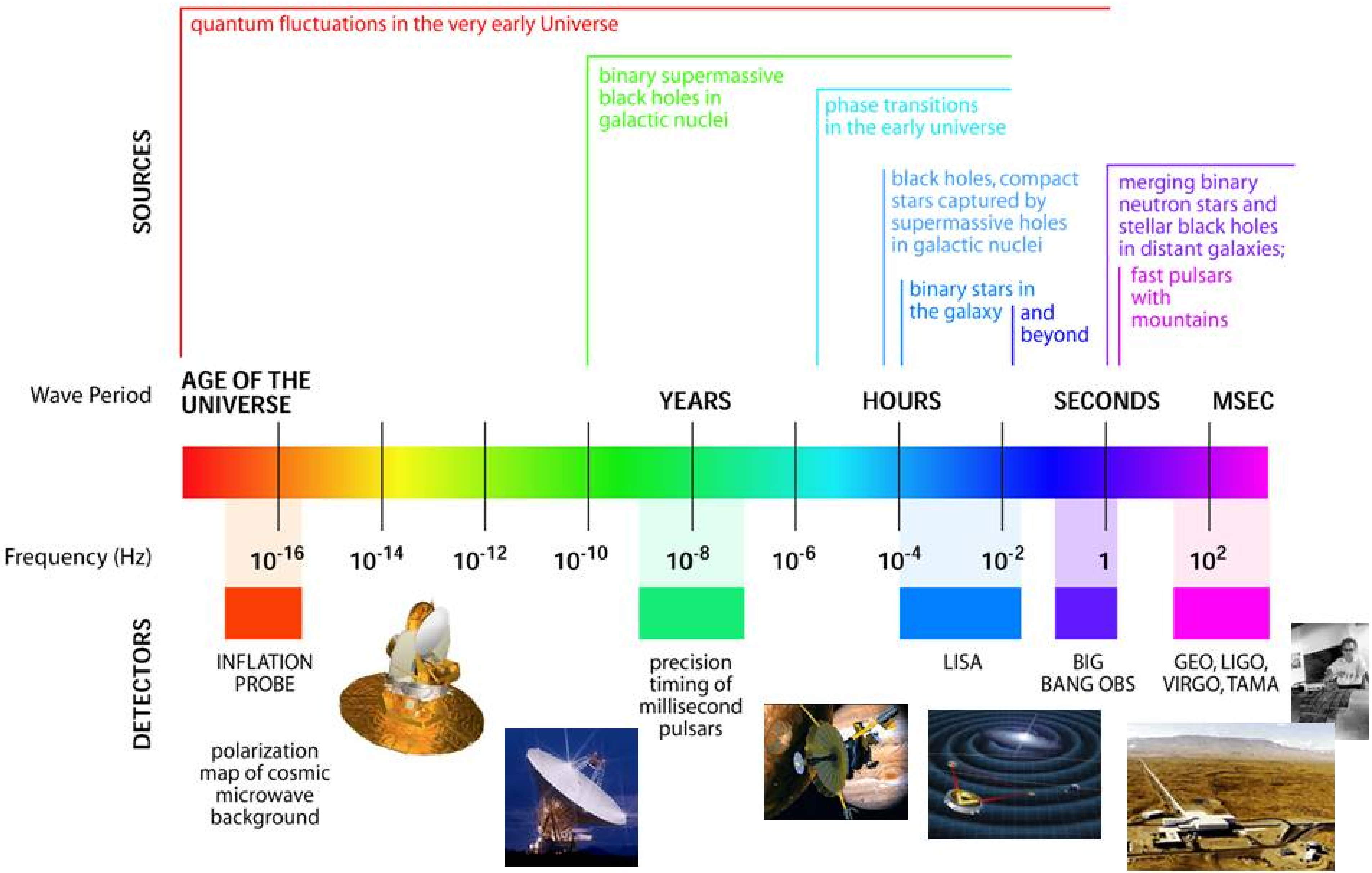
PNHE TS2020 2nd workshop
June 4th 2018, Montpellier

Outline

- Transient sources & the LVC physics program:
  - Compact binary coalescence, core collapse supernova, magnetars/SGR/giant flares, NS instabilities, BH accretion disk instabilities, NS fallback, ….
  - O3 predictions.
- GW detector network timeline

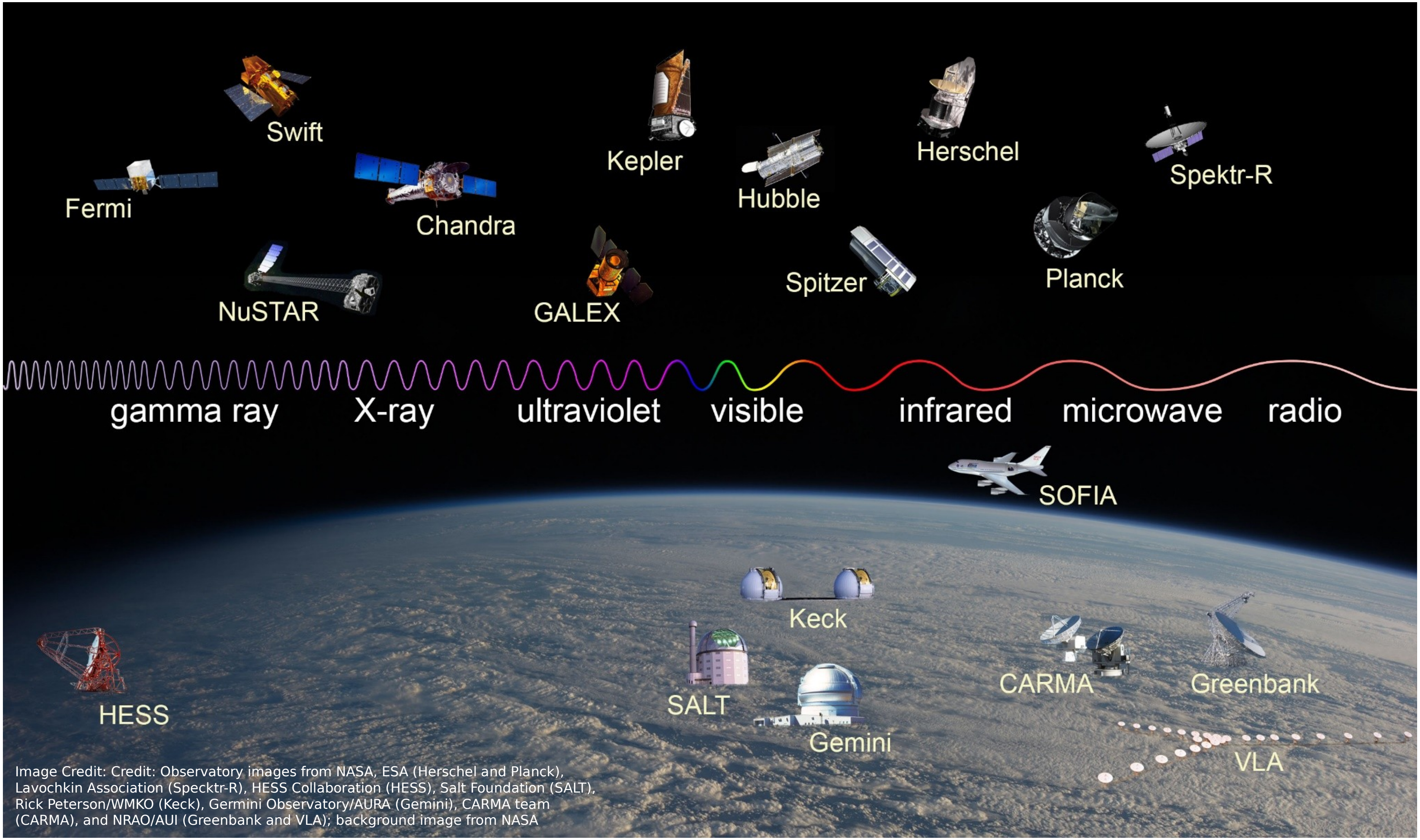


THE GRAVITATIONAL WAVE SPECTRUM

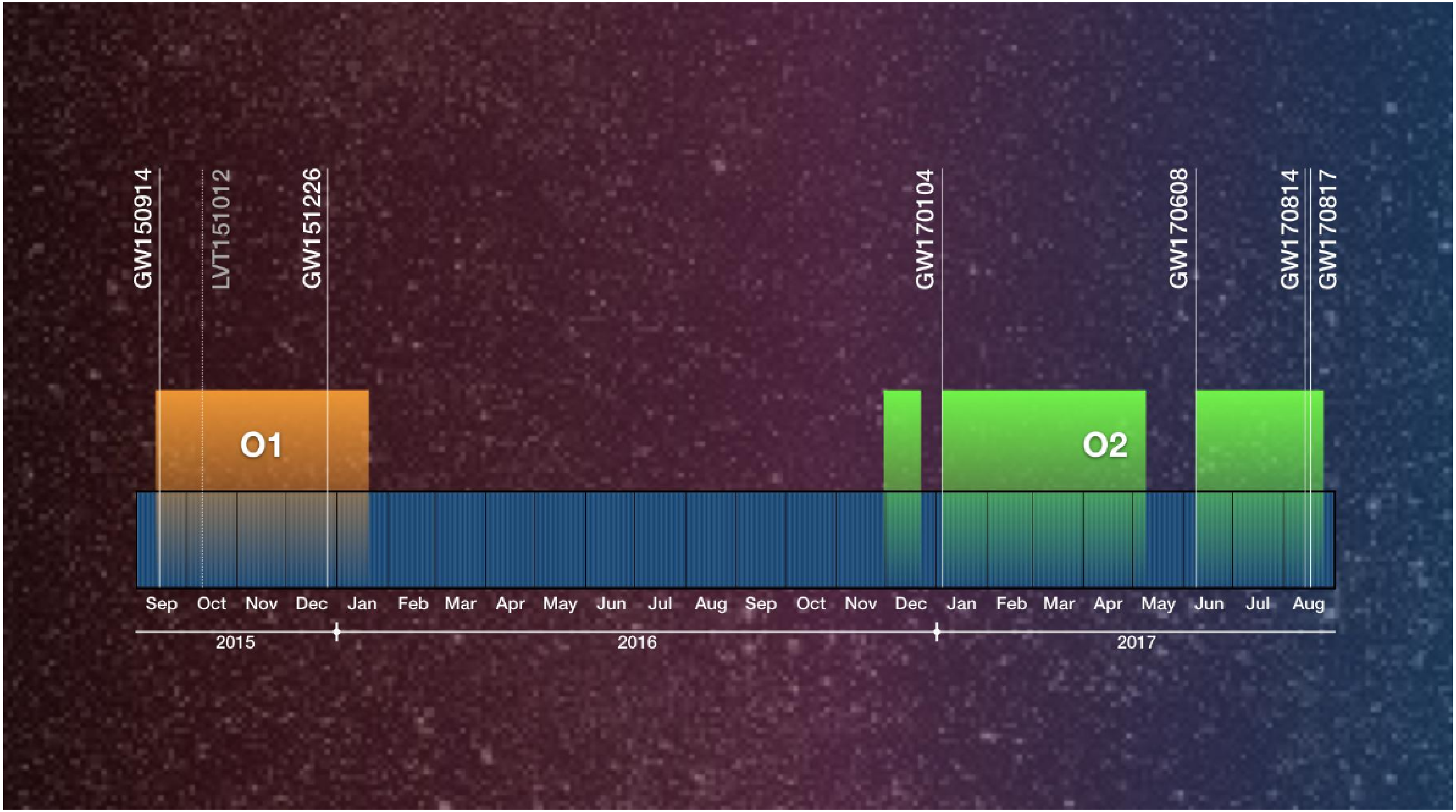


Time-domain transient astronomy

Astronomical transients events are mostly associated to the violent Universe …
… and can be observed along the whole electromagnetic spectrum



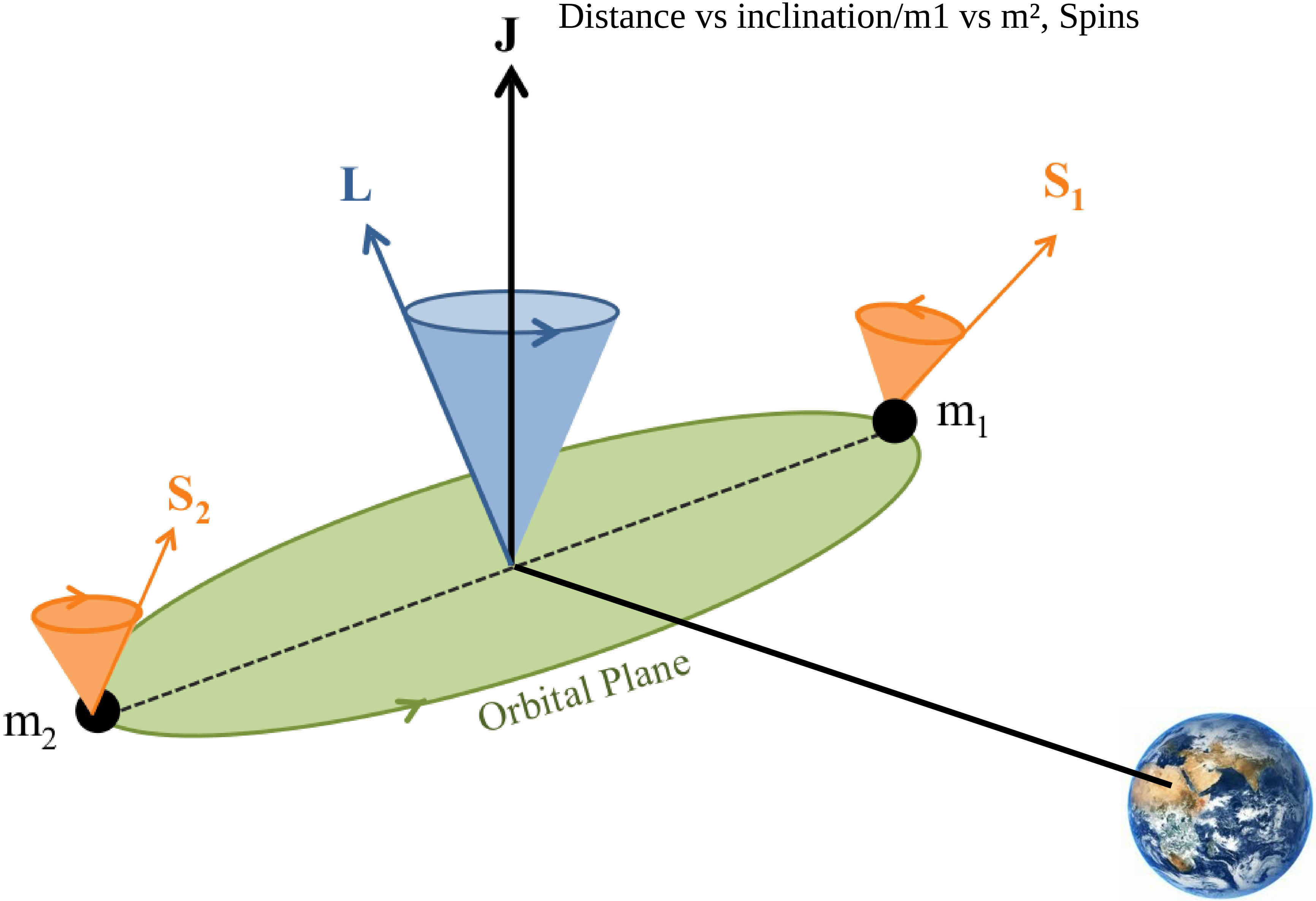
Compact binary systems : observed !



- What do we measure ?
- Which implications ?
- Which GW astronomy ?
- What can we expect during O3 ?

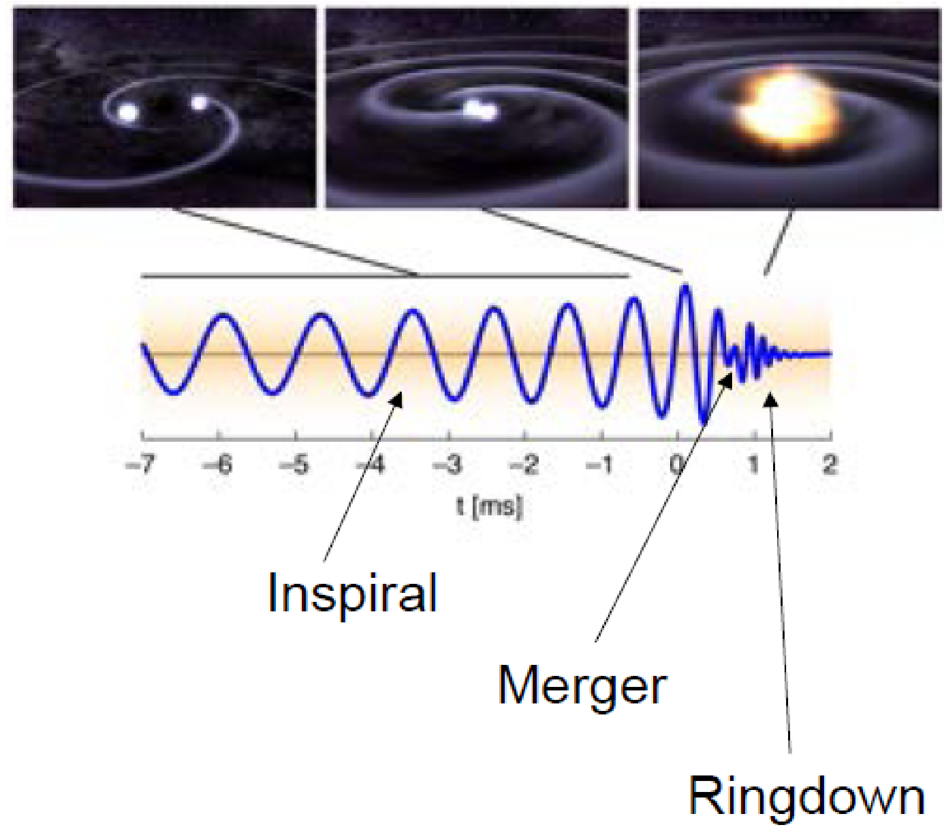
Compact binary system

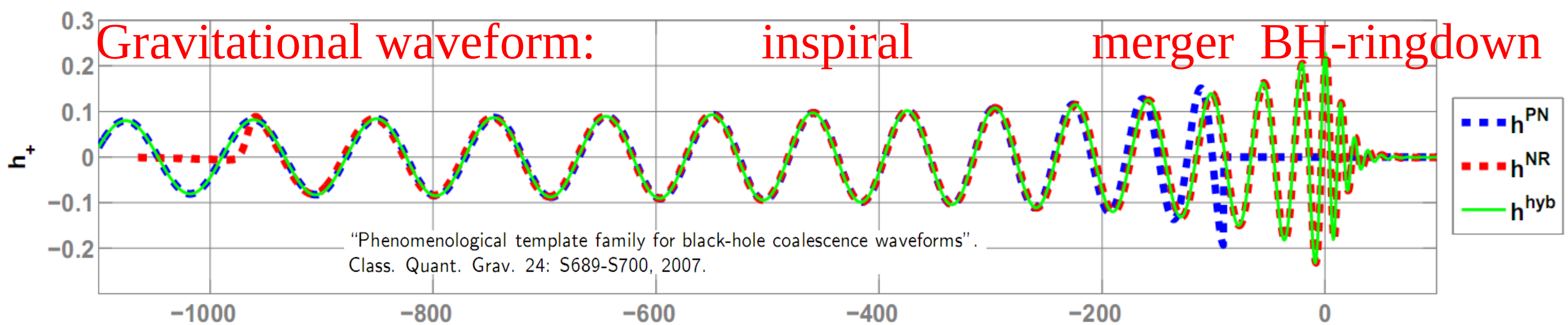
We measure all parameters but some are degenerated.
Distance vs inclination/m1 vs m², Spins



Compact binary coalescence

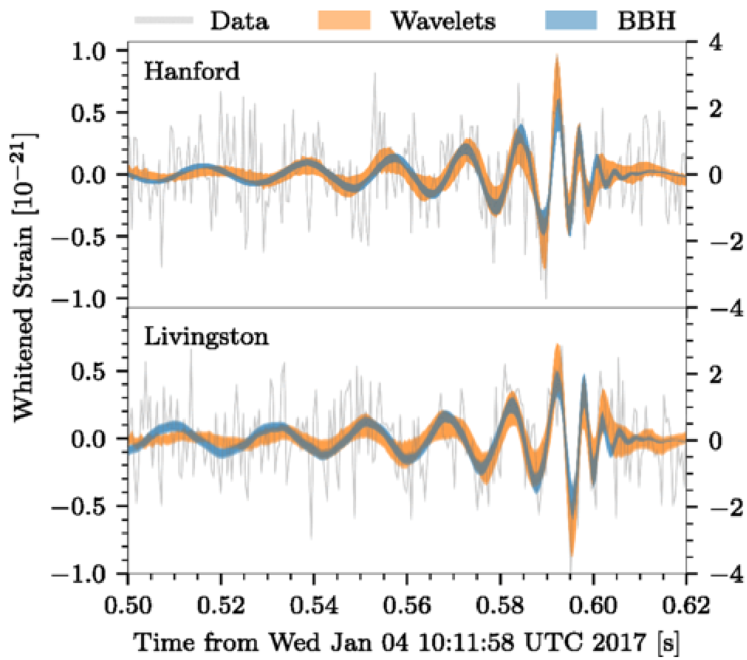
- Compact binary objects: Two neutron stars and/or black holes.
- Inspiral toward each other. Emit gravitational waves as they inspiral.
- Amplitude and frequency of the waves increases over time, until the merger.
- Waveform relatively well understood, → matched template searches.
- Unique way to study string field gravity and the structure of the nuclear matter in the most extreme conditions

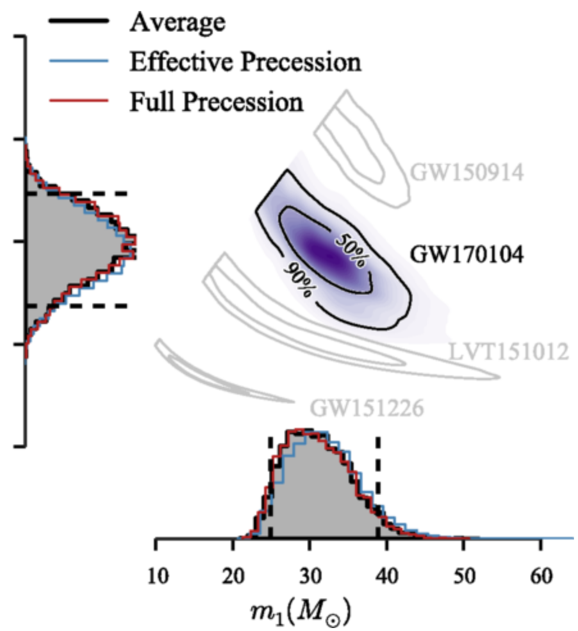


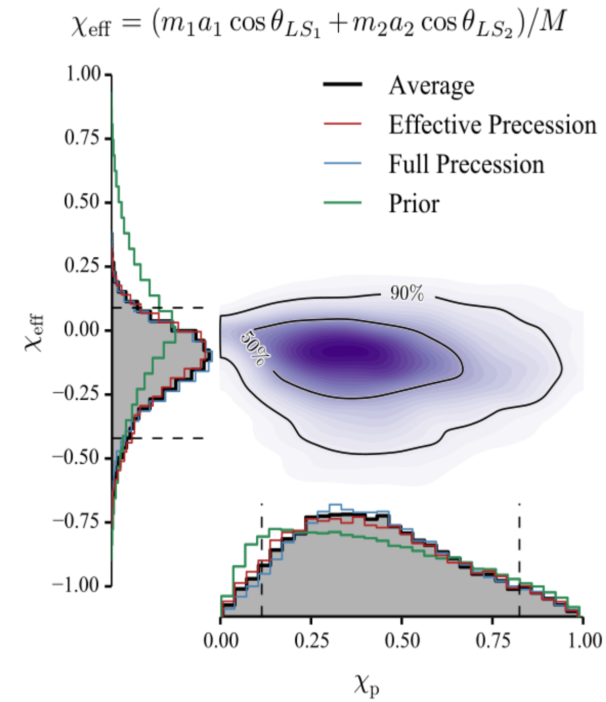


Waveform carries lots of information about binary masses, orbit, merger, spins, ...

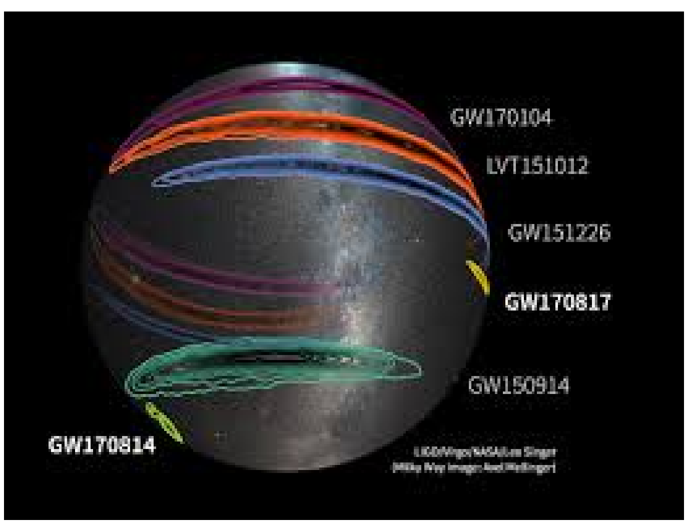
GW astronomy with BBH







[Phys. Rev. Lett. 118, 221101]



Measured rate : 12 -213 Gpc^{-3} yr^{-1}
Several BBH mergers per hour in the observak universe

Astrophysics implication :
Chirp mass & spins measurements can help to infer which scenarios of formation and evolution compact binaries follow

Isolated binary vs dynamical processes in dense stellar clusters ts2020ll

Mass of graviton

- Hypothetical massive graviton theory: Yukawa type correction in the Newtonian potential.
- Massive graviton propagates at speed that depends on the frequency/energy (dispersion: lower frequencies propagate slower than high frequencies → phase distortion at 1PN order).
- GW150914+GW151226

$$\lambda_g > 1 \times 10^{13}\, km$$

$$m_g \leq 1.2 \times 10^{-22}\, eV/c^2$$

$$\frac{v_g^2}{c^2} = 1 - \frac{h^2 c^2}{\lambda_g^2 E^2}$$

$$\lambda_g = \frac{h}{m_g c}$$

- GW150914+GW151226+GW170104

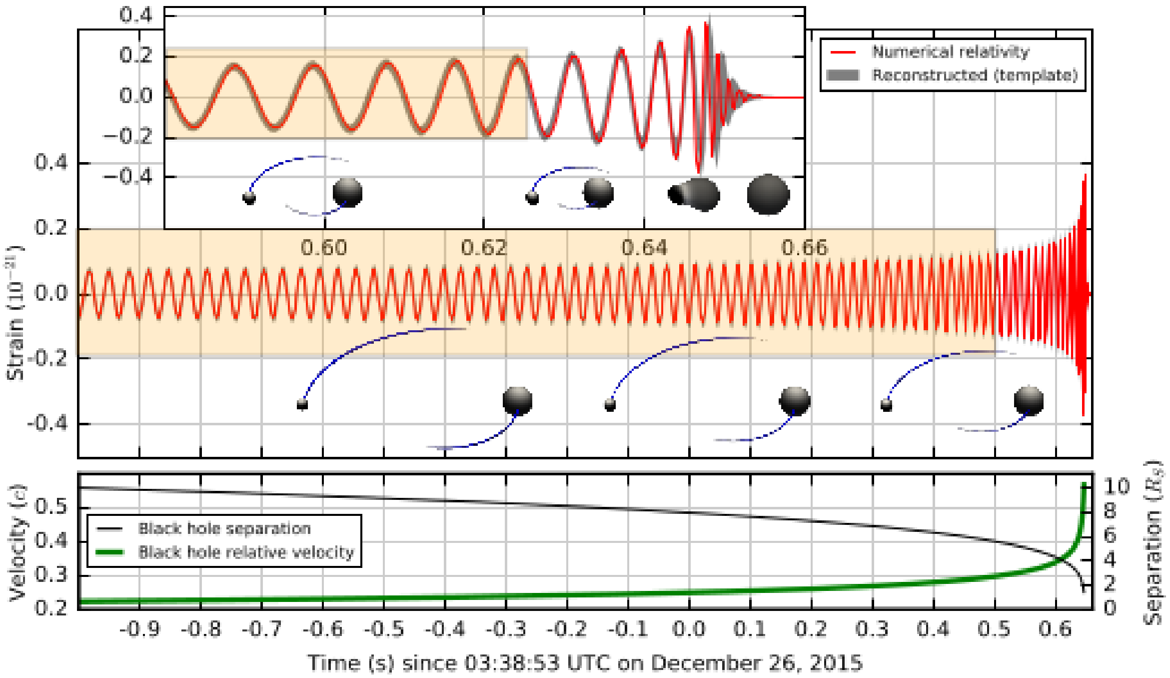
$$\lambda_g > 1.6 \times 10^{13}\, km$$

[Phys. Rev. Lett. 118, 221101]

$$m_g \leq 7.7 \times 10^{-23}\, eV/c^2$$

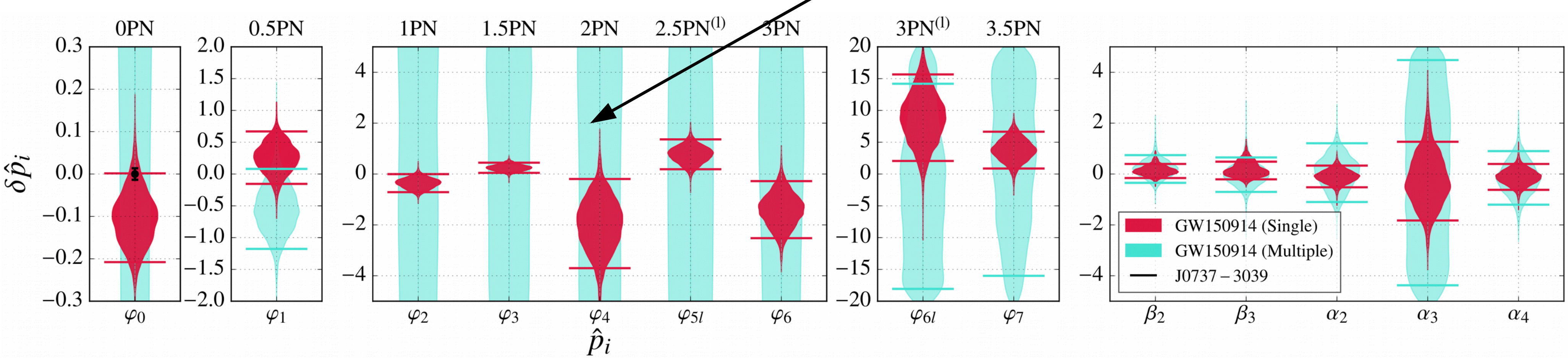
- Not as good as some static bounds ($\lambda_g > 10^{22}$ km from weak lensing) but still better than solar systems ($\lambda_g > 10^{12}$ km) and binar pulsar tests ($\lambda_g > 10^{10}$ km).

Testing GR GWs

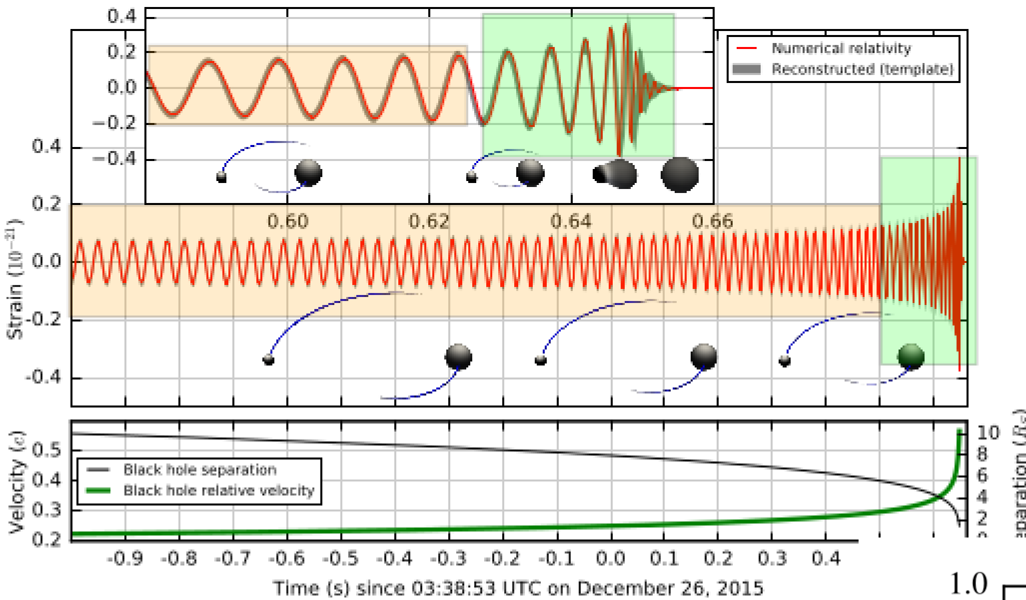


- Waveform:
  $h(f,\theta) = A(f;\theta)e^{i\phi(f;\theta)}$,
- $\phi = \phi_o + \sum \phi_k(\theta)(\pi M f)^{(k-5)}$
  $\theta = \{m_1, m_2, \mathbf{s_1}, \mathbf{s_2}\}$
- $\phi_k = \phi_k^{GR}(1 + \delta\phi_k)$

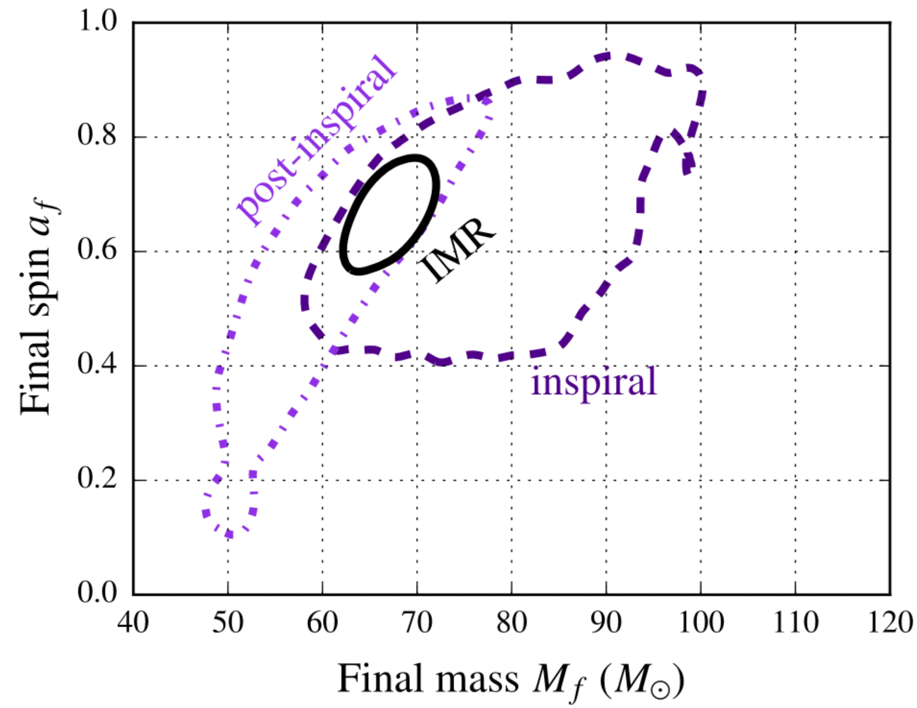
[LVC PRL(2016), PRX(2016), PRL(2017)]



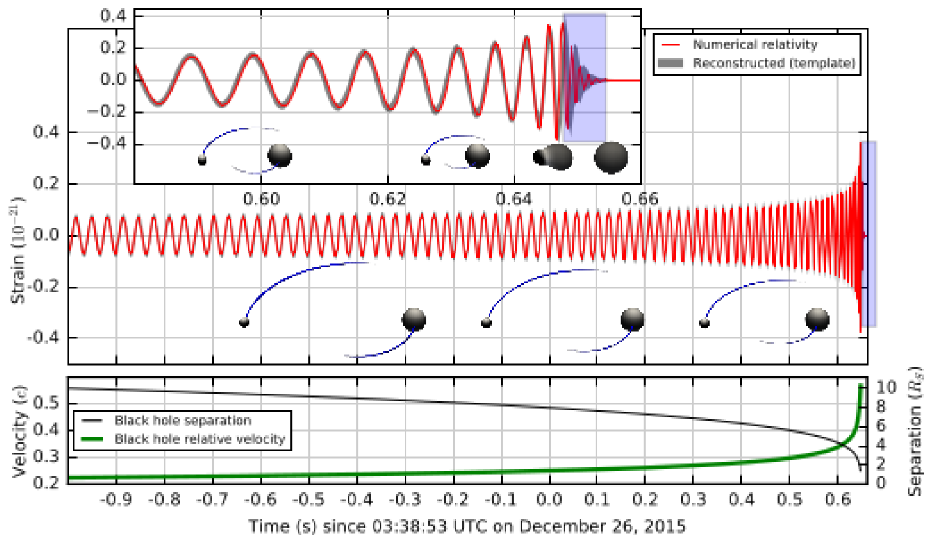
Consistency test for inspiral, merger and ringdown



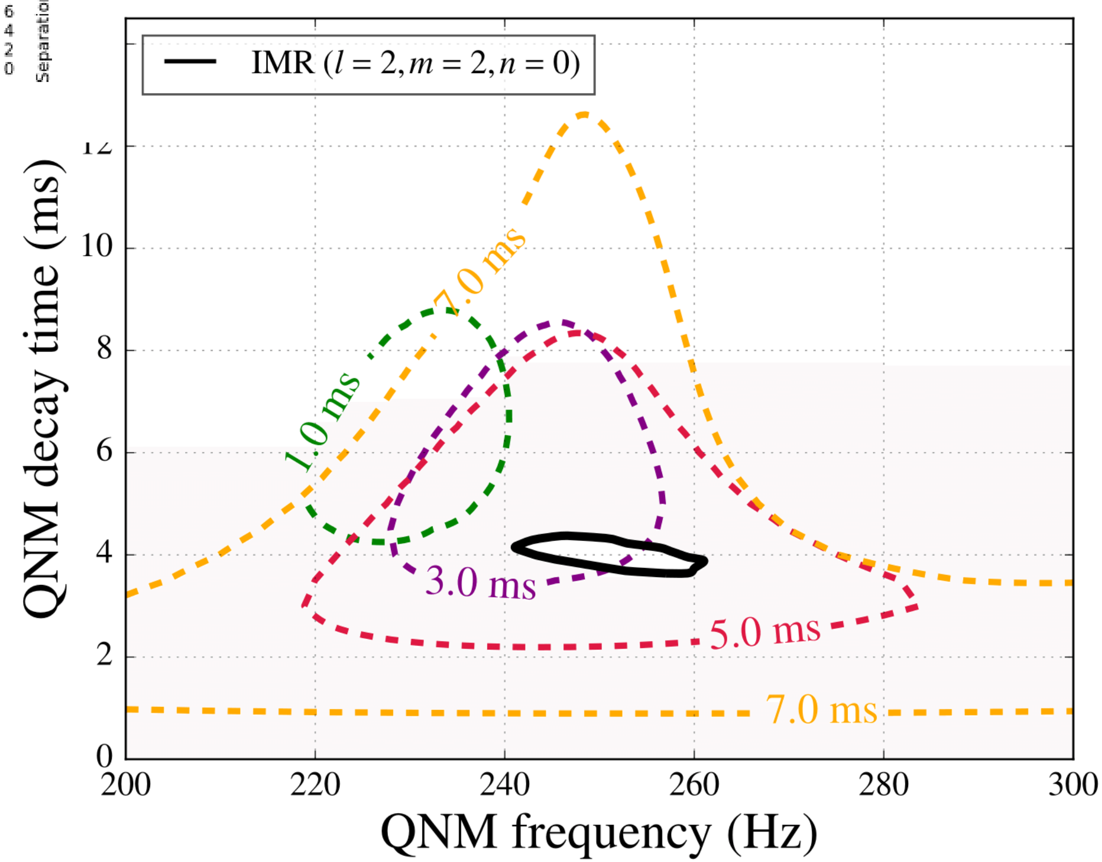
Verify self-consistency by comparing final mass and spin predicted from the "inspiral" and from the "post-inspiral" [Ghosh+, 2016] [LVC PRL(2016)]



Testing the QNM of the final BH

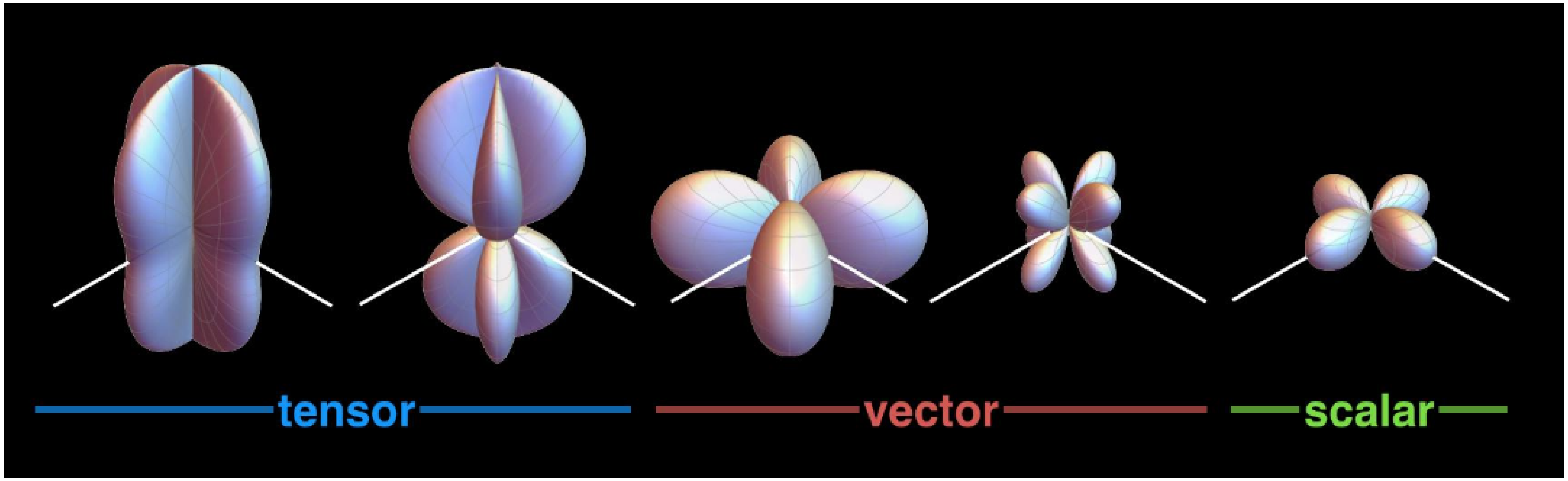


$$h(t) = Ae^{-t(t-t_0)/\tau} cos(2\pi f_0(t-t_0) + \phi_0)$$



From the IMR parameter estimation, the l=2,m=2,n=0 f^{QNM} = 251 Hz & τ=4 ms @90% CL.

Test of polarizations with GW170814



- Tenseur- vector : 200:1
- Tenseur-scalar : 1000:1

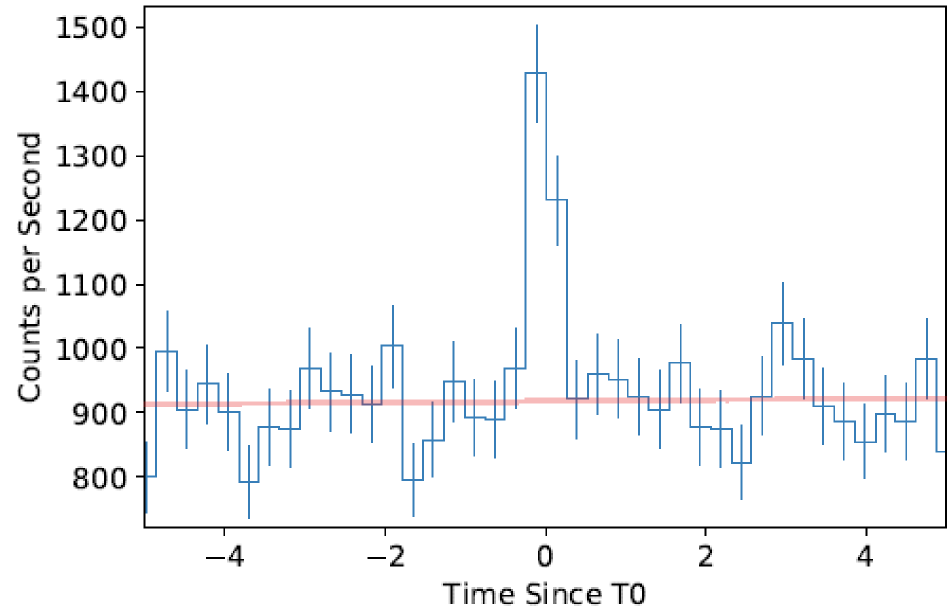
→ pure vector or pure scalar excluded.

→ GR templates match the phase of the data extremely well.

Binary neutron star merger

Artist's depiction of a neutron star collision after inspiral. (Credit: NASA/Swift/Dana Berry)

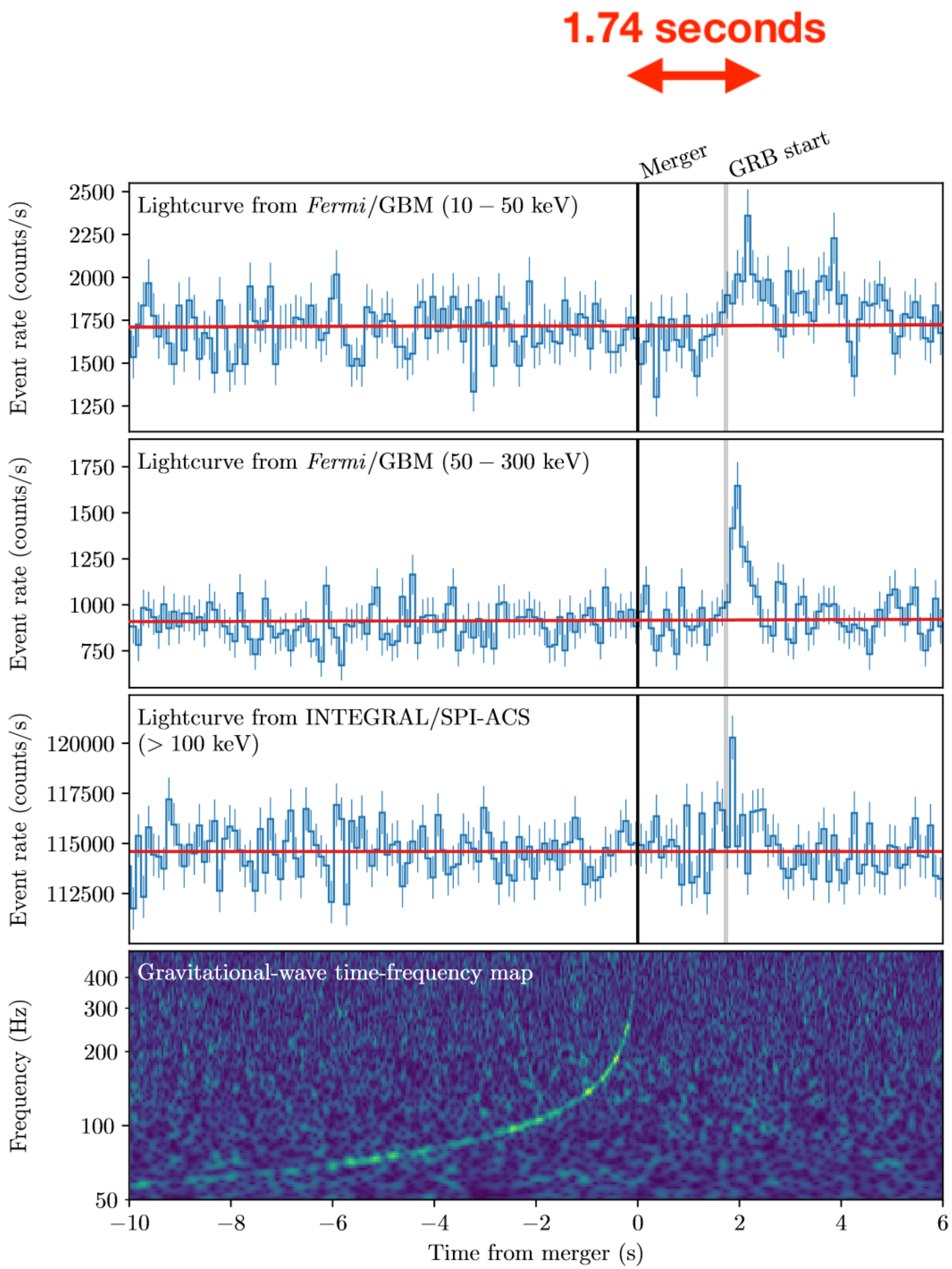
GW170817 – The Birth of Multi-Messenger Astronomy



17 August 2017, 12:41…

```
//////////////////////////////////////////////////////////////////////
TITLE:           GCN/FERMI NOTICE NOTICE_DATE:     Thu 17 Aug 17 12:41:20 UT
NOTICE_TYPE:     Fermi-GBM Alert RECORD_NUM:      1
TRIGGER_NUM:     524666471
GRB_DATE:        17982 TJD;    229 DOY;    17/08/17
GRB_TIME:        45666.47 SOD {12:41:06.47} UT
TRIGGER_SIGNIF:  4.8 [sigma]
TRIGGER_DUR:     0.256 [sec]
E_RANGE:         3-4 [chan]    47-291 [keV]
...
COMMENTS:        Fermi-GBM Trigger Alert.
COMMENTS:        This trigger occurred at longitude,latitude = 321.53,3.90 [deg].   COMMENTS:        The
LC_URL file will not be created until ~15 min after the trigger.
//////////////////////////////////////////////////////////////////////
```

GW170817/GRB170817A : gravity speed constraint



Over 1.3x10^8 light years :

$$\Delta t = (1.74 \pm 0.05)\, s$$

$$\frac{c_g - c}{c} \approx c \frac{\Delta t}{D_L}$$

$$-3 \times 10^{-15} \leq \frac{\Delta c}{c} \leq 7 \times 10^{-16}$$

GW170817 – Host galaxy found

T_0 + ~12 hours :
Alert (GCN) sent
From 1m2H Swope

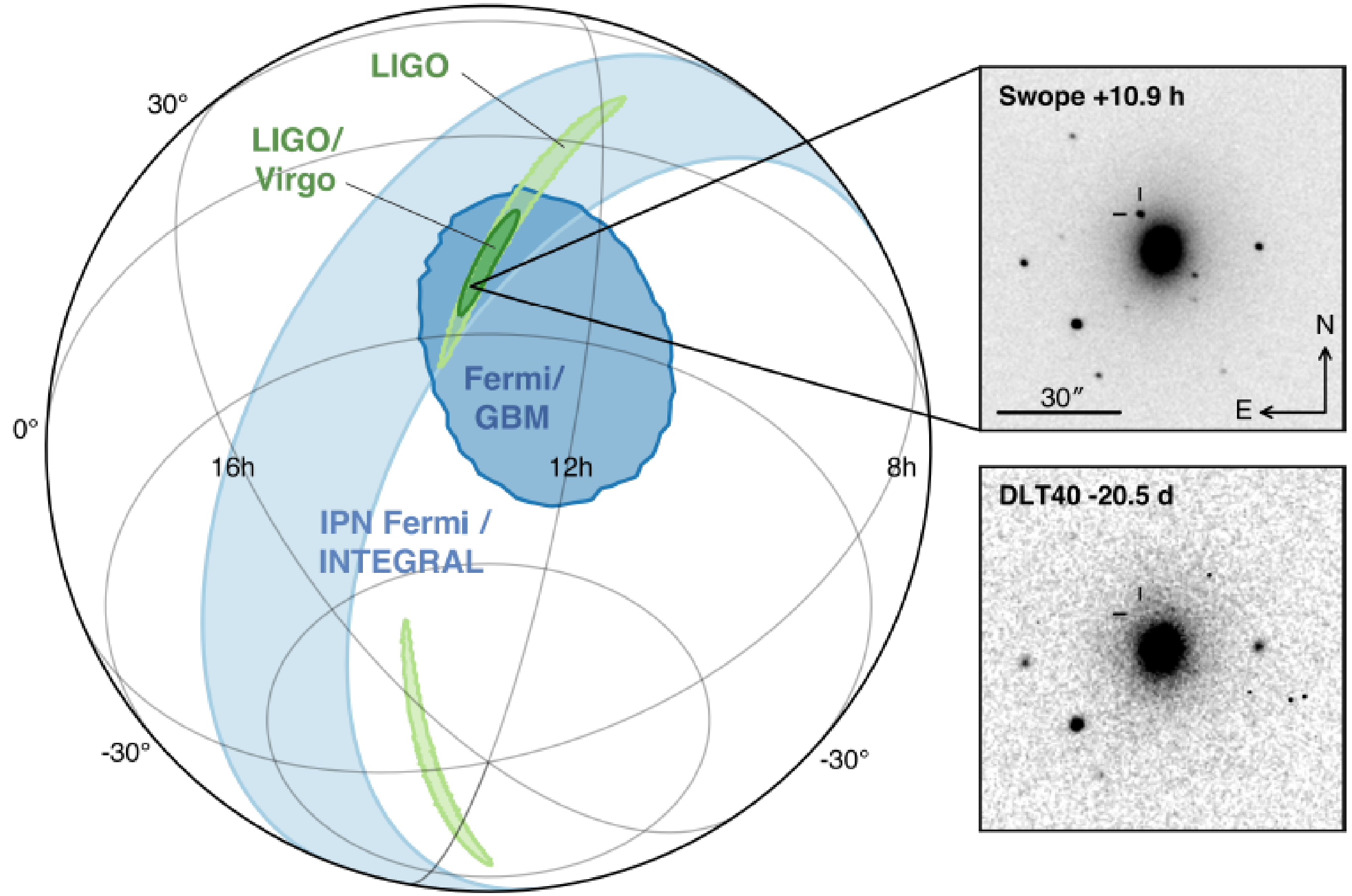


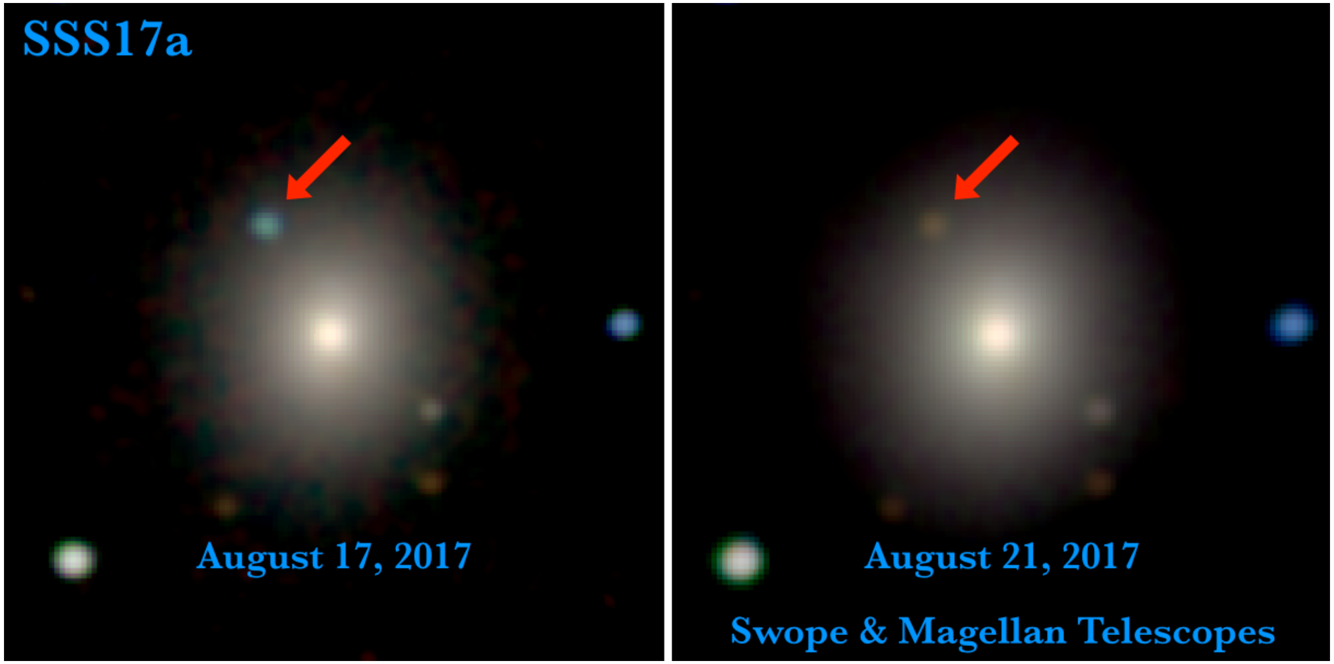
Figure 1. Localization of the gravitational-wave, gamma-ray, and optical signals. The left panel shows an orthographic projection of the 90% credible regions from LIGO (190 deg^2, light green), the initial LIGO-Virgo localization (31 deg^2, dark green), IPN triangulation from the time delay between *Fermi* and *INTEGRAL* (light blue), and *Fermi* GBM (dark blue). The inset shows the location of the apparent host galaxy NGC 4993 in the Swope optical discovery image at 10.9 hours after the merger (top right) and the DLT40 pre-discovery image from 20.5 days prior to merger (bottom right). The reticle marks the position of the transient in both images.

GW170817/GRB170817A : kilonova model confirmed !

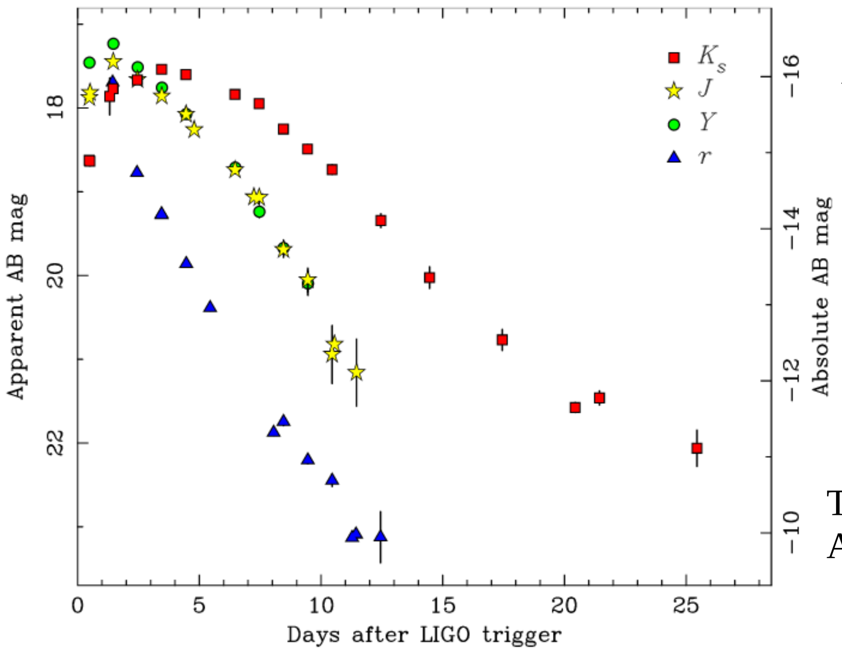
An initially blue signal that fades and turns to red.

- Ejected mass of 0.04 Msun
- Velocity 0.2 c
- Line features with « light » elements 90<A<140

« Inferring the ejected mass and a merger rate from GW170817 implies that such mergers are a dominant mode of r-process production in the Universe. » (Kasen et al. Nature 551 (2017) 80)

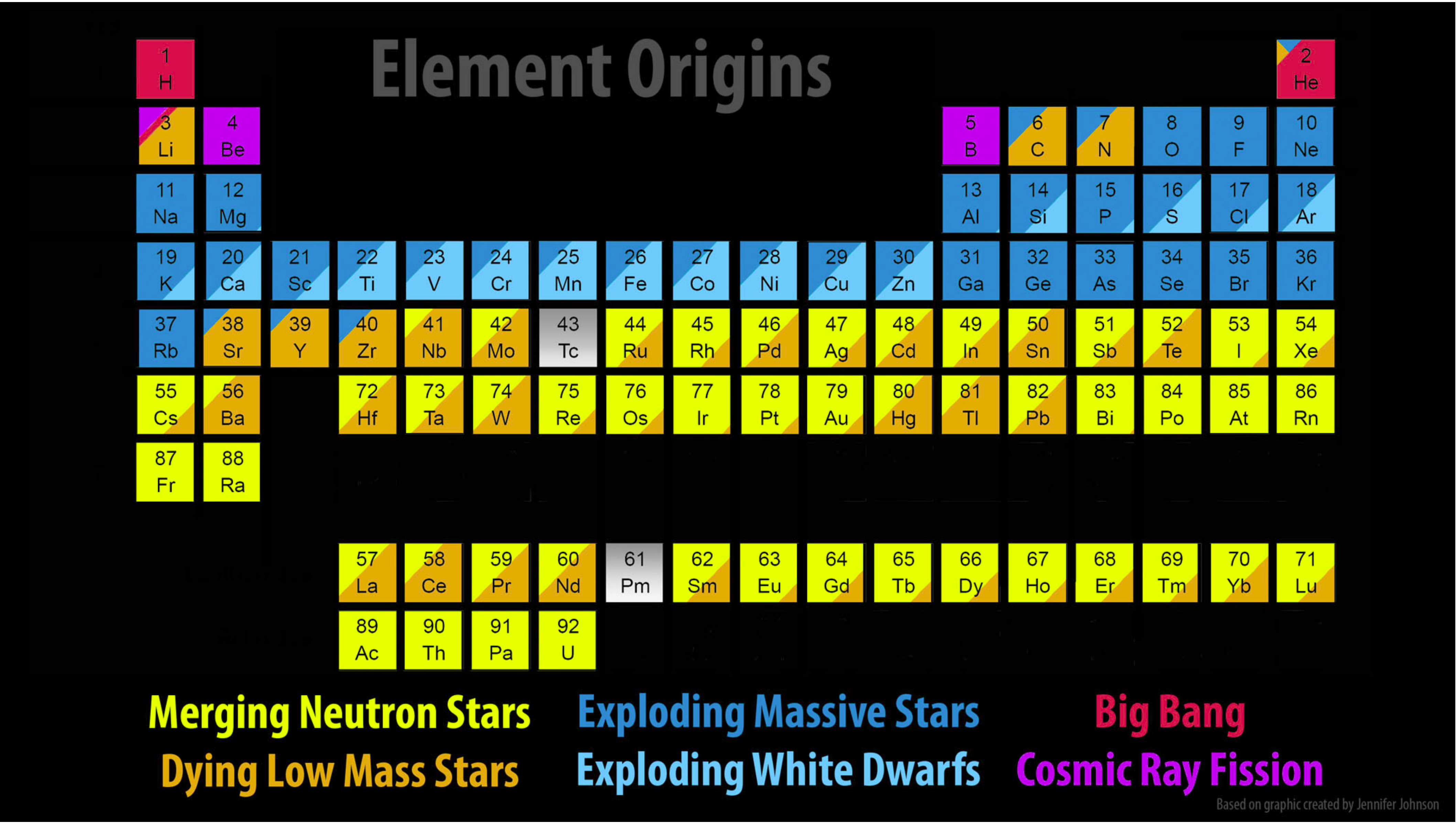


Drout et al ArXiv:1710.05443



Tanvir et al Astrophys.J. 848 (2017) no.2, L27

GW170817 : heavy elements production



Tidal effects and equation of state of nuclear matter

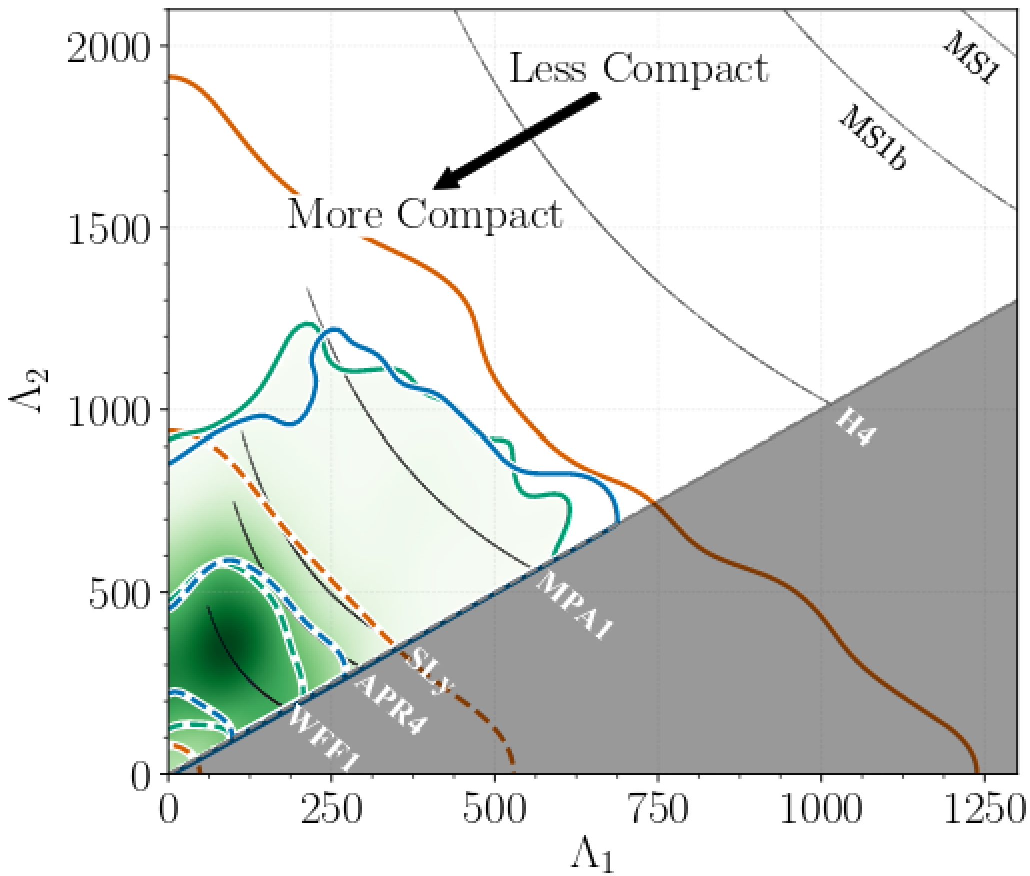
Dimensionless tidal deformability

$$\Lambda = \frac{2}{3} k_2 (\frac{c^2 R}{GM})^5$$

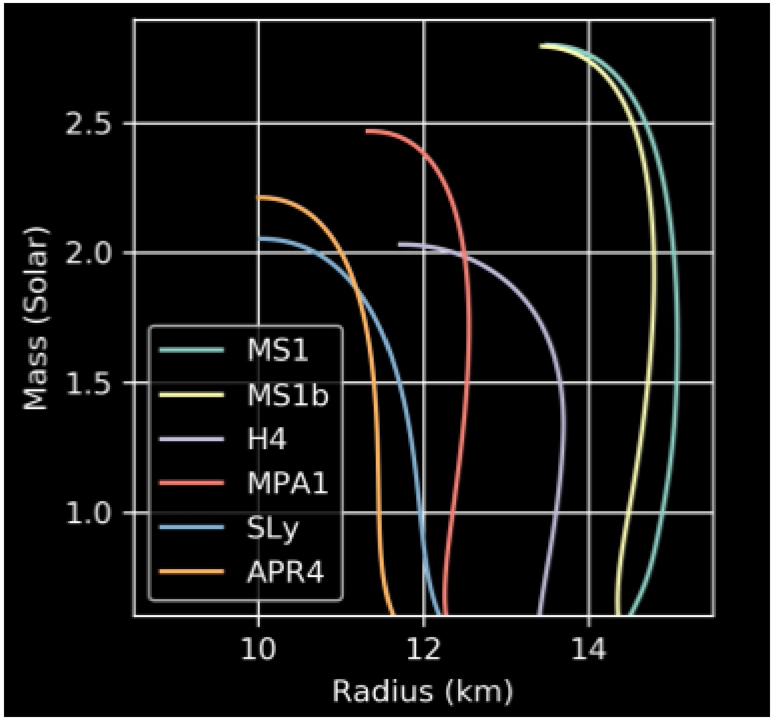
$$R \sim 11km(\frac{M}{1.44M_{\odot}})(\frac{k_2}{0.1})^{-1/5}(\frac{\Lambda}{300})^{1/5}$$

Tigher constrains obtained with :

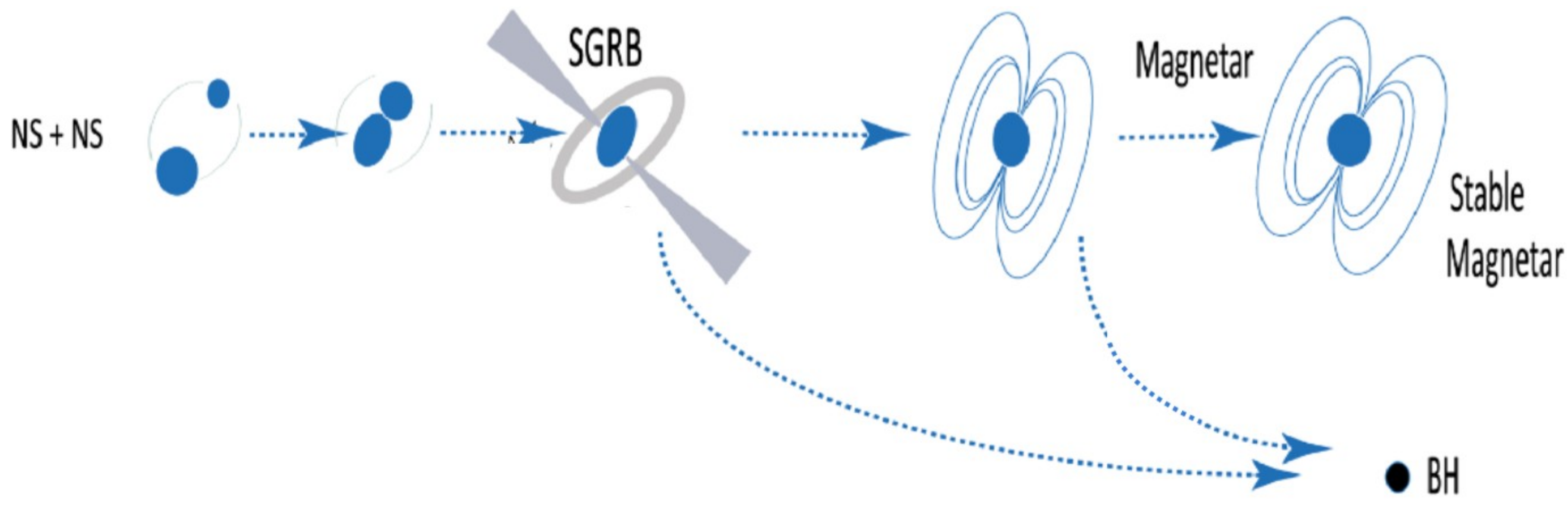
- NS hypothesis
- Low spins



[arXiv:1805.11581]



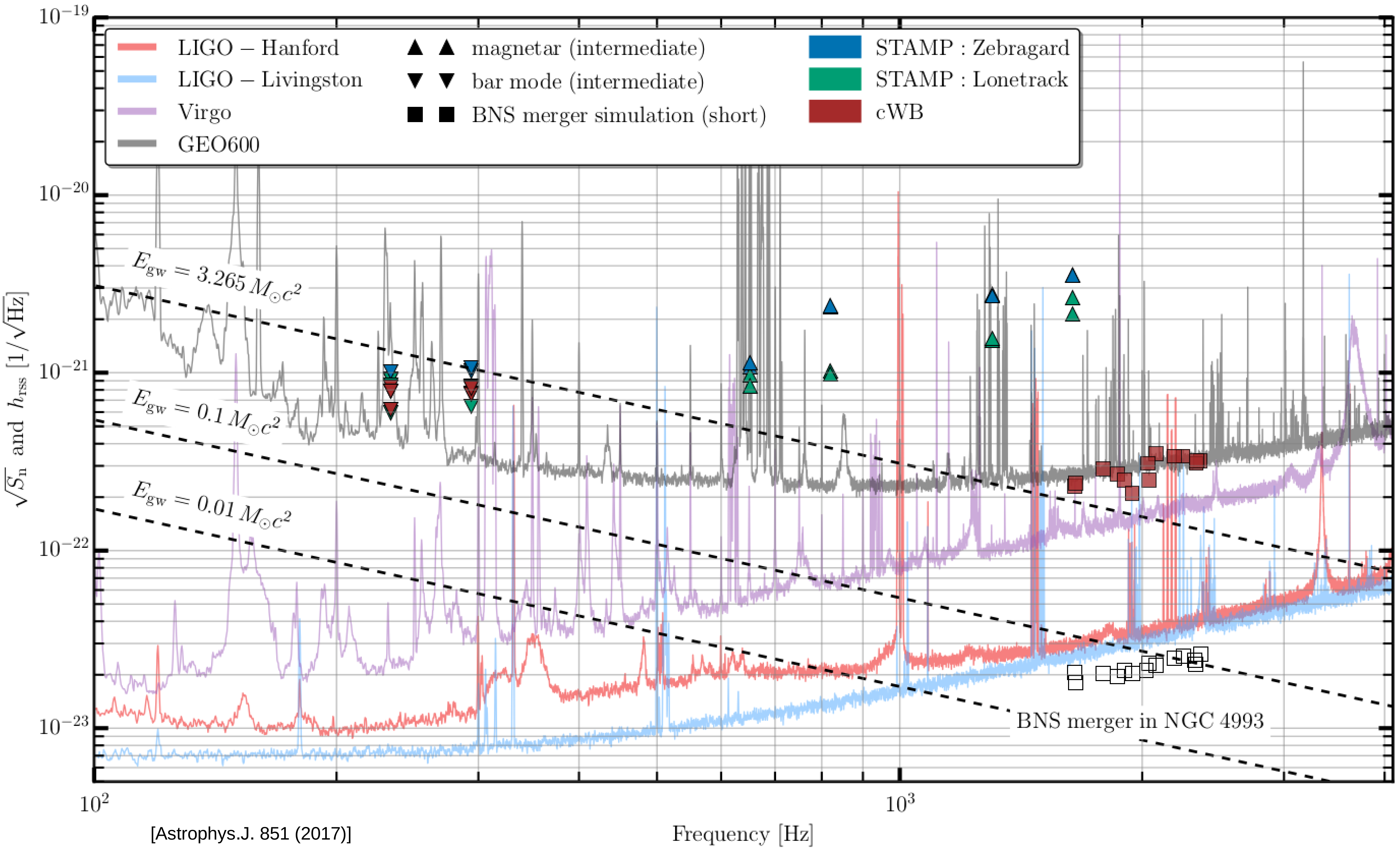
GW170817 : nature of the remnant



The outcome of the BNS can be :

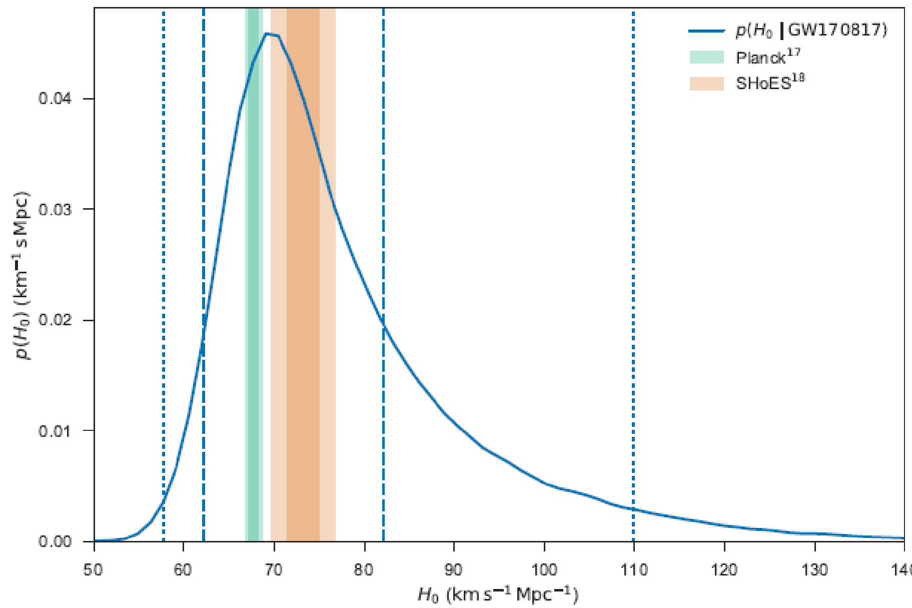
- BH prompt formation, favored by soft EOS
- Hypermassive NS, that collapses to a BH in < 1s
- Supremassive NS, that collapses to a BH in 100-10000s (long-lived transient)
- Stable NS

GW170817 : nature of the remnant



[Astrophys.J. 851 (2017)]

Hubble constant measurement



Planck : 67.74 ± 0.46 km/s/Mpc

SNIa : 73.8 ± 1.74 km/s/Mpc

→ 3σ tension.

With GW170817 :

$$H_0 = 70^{+12}_{-8} kms^{-1} Mpc^{-1}$$

<u>Advantage</u> : GW astronomy measures luminosity distance over cosmic scales.

No need of cosmic ladder (compact binaries are standard candle).

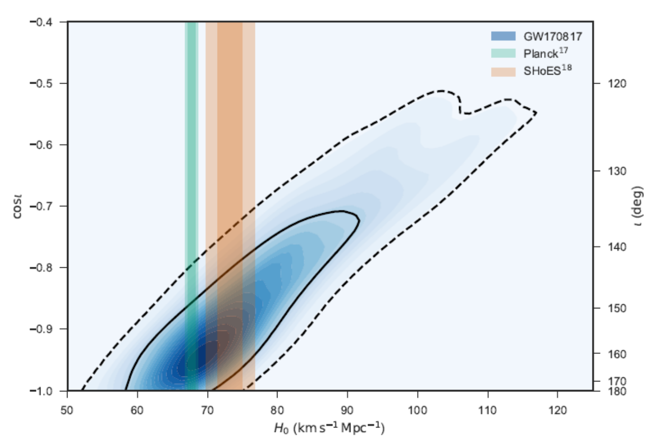
<u>How to improve H0 uncertainty?</u>

- More BNS events with host galaxy identified & redshift measurement.

  Better constrain the inclination angle.

  Use of the numerous BBH + galaxy catalogue.

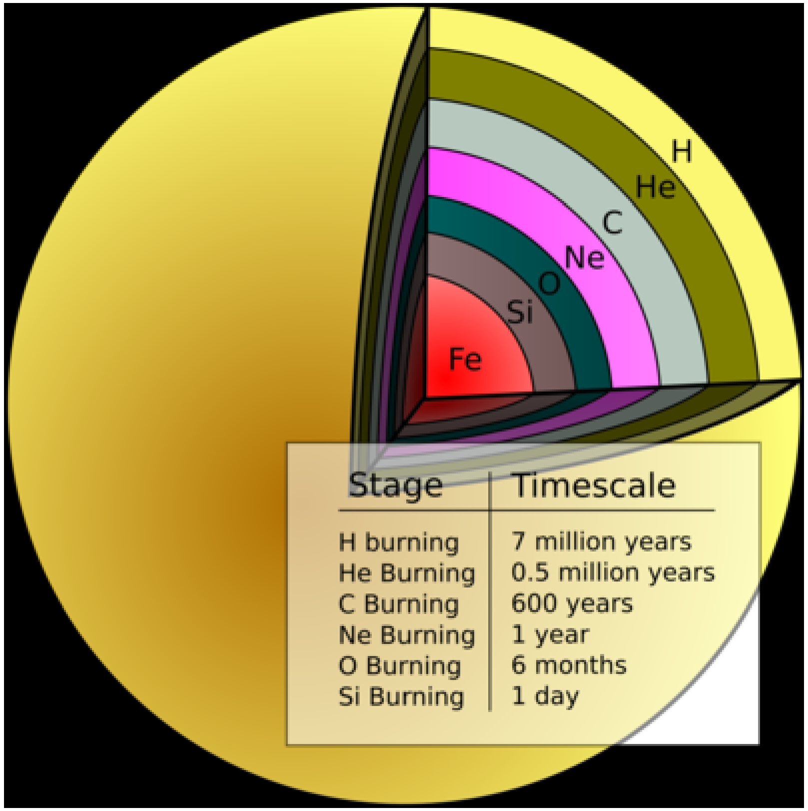
[Nature 551 (2017) no.7678]



Other transient sources

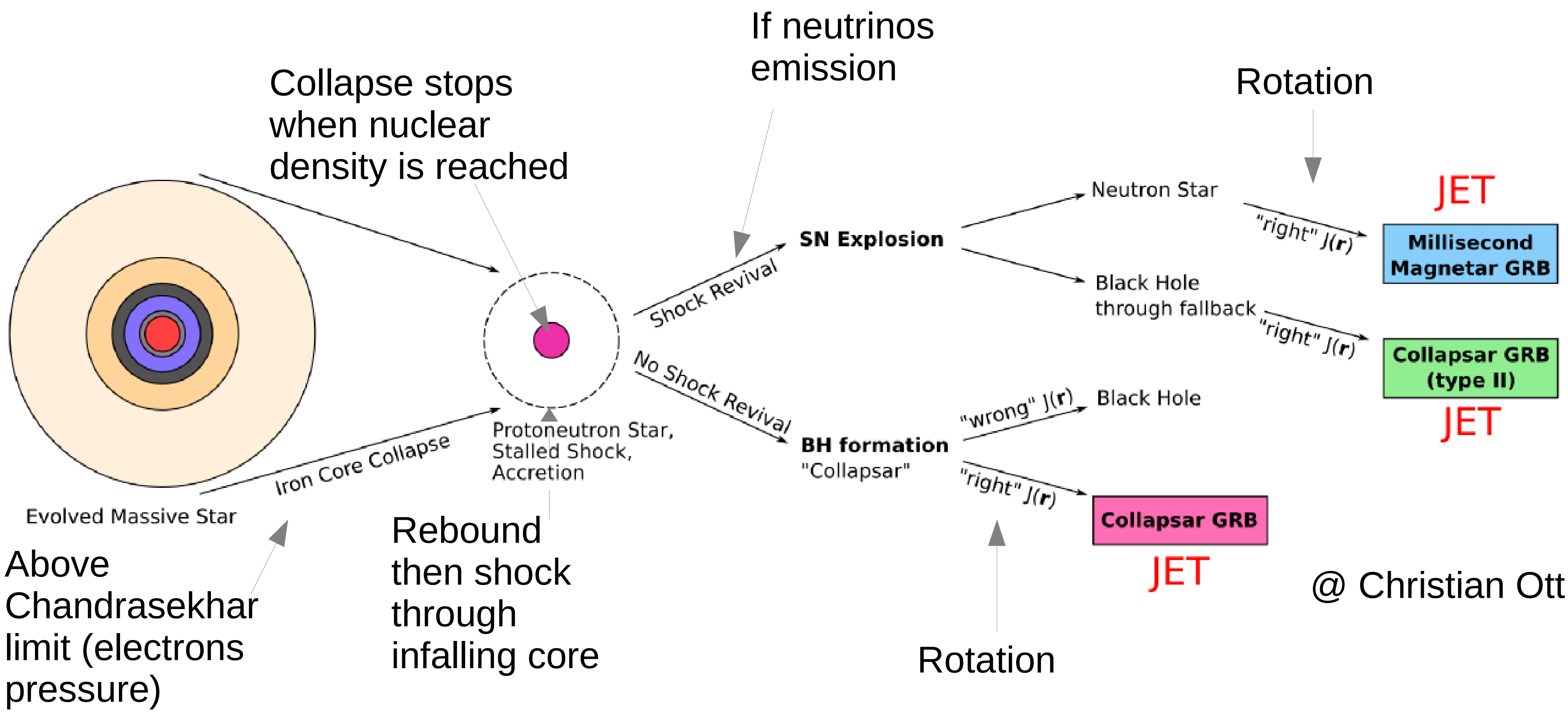
Other transient GW source: stellar core collapse

- Stars spend most of their lives burning hydrogen.
- Helium settles in the core and will burn when temperatures increase sufficiently $(M > 8 - 10 M_{\odot})$
- For massive stars , the process continues through Carbon, Oxygen, … up to Iron.
- This process does not continue past iron as iron is one of the most tightly bound nuclei.
- Iron core builds up in center of star.



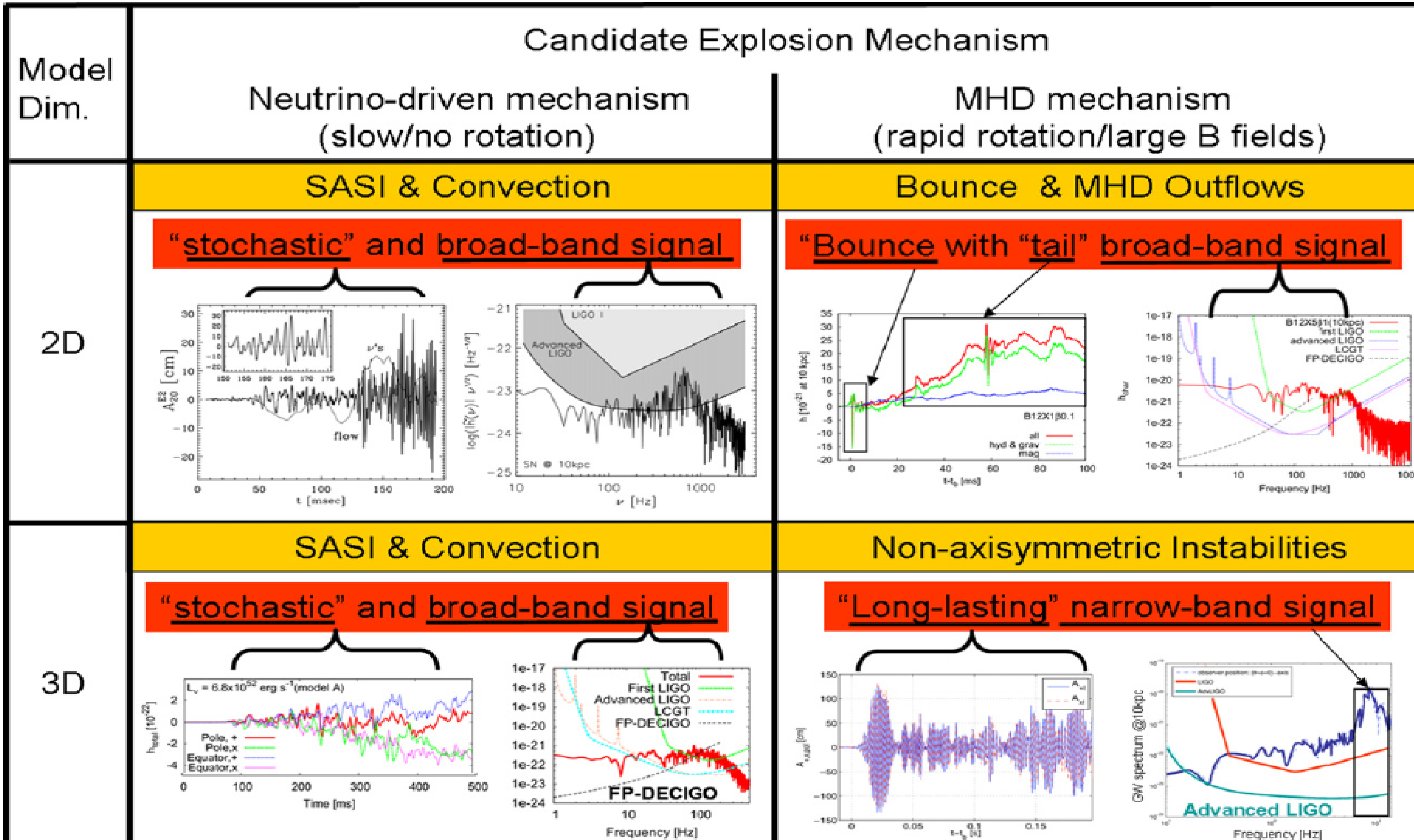
Stage	Timescale
H burning	7 million years
He Burning	0.5 million years
C Burning	600 years
Ne Burning	1 year
O Burning	6 months
Si Burning	1 day

Stellar core collapse in a nutshell



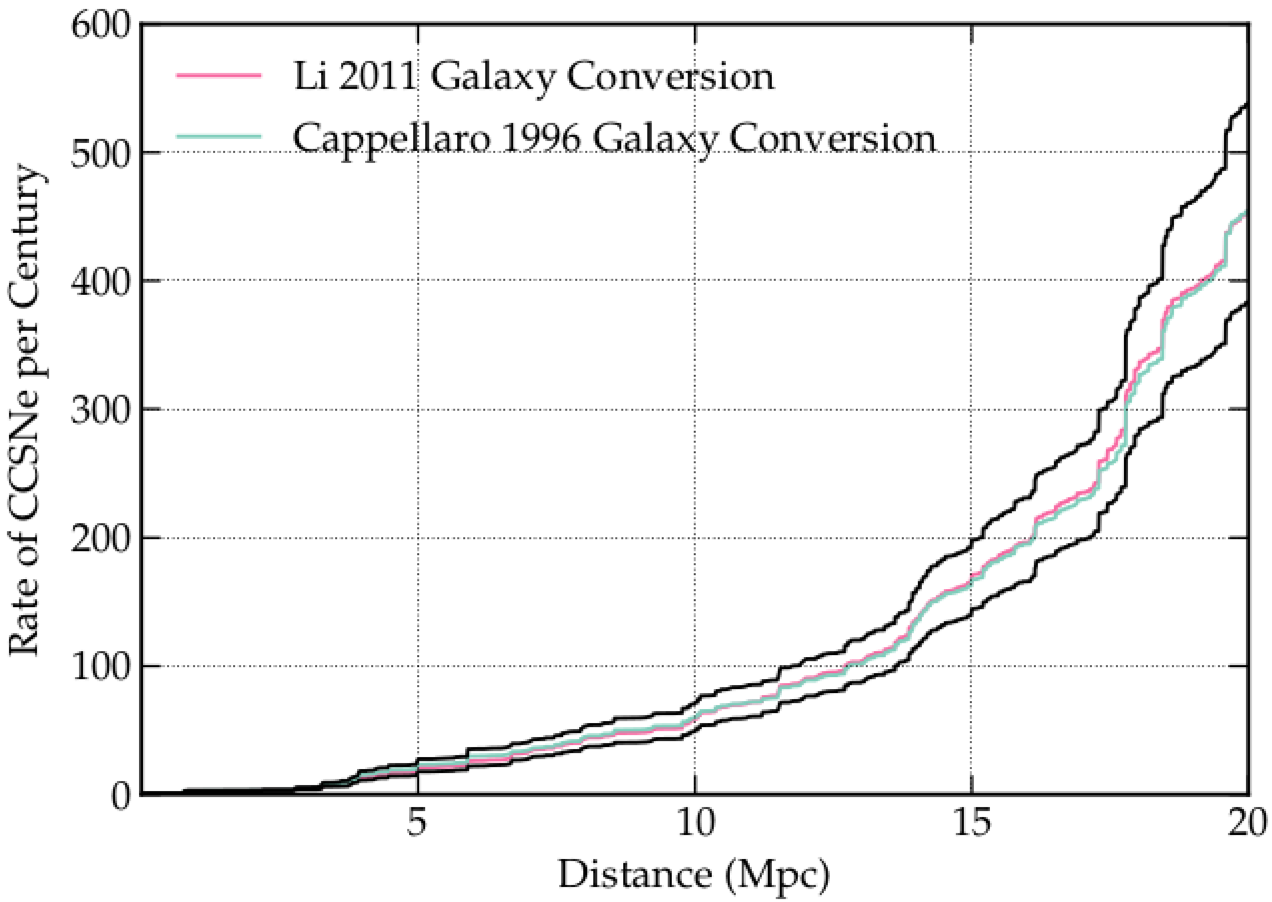
CCSN: post-bounce waveform summary

[Kotake C.R. Physique 14 (2013) 318-351]



Core collapse supernova: how far can we go & how many?

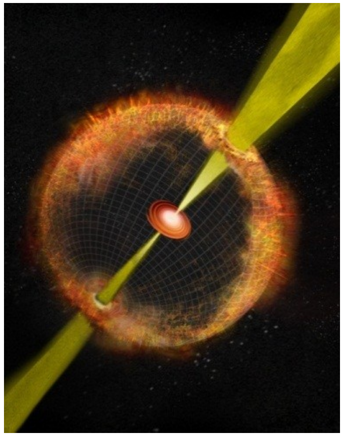
- At LIGO/Virgo design sensitivity : distance range: between 100 kpc (SASI and MHD) and 20 Mpc (extreme model like disk fragmentation and bar mode) [Gossan et al arxiv:1511.02836]
- Low energy neutrino emssion will help a lot GW searches.



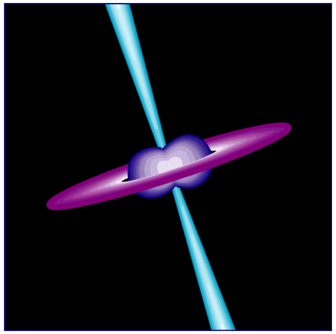
Other transient searches

- Rapidly rotating NS (SN remnants) → dynamical instabilities
  - Acoustic pressure mode (f-mode), rotation modes (r-modes), bar mode instabilities
- GW & EM transients: SGRs, AXPs, star quake may excite non radial oscillation modes that couple to GW emission.
- GW and GRBs (short & long).
- Pulsar glitches.
- Cosmic string kinks and cups.

Long - Soft GRBs



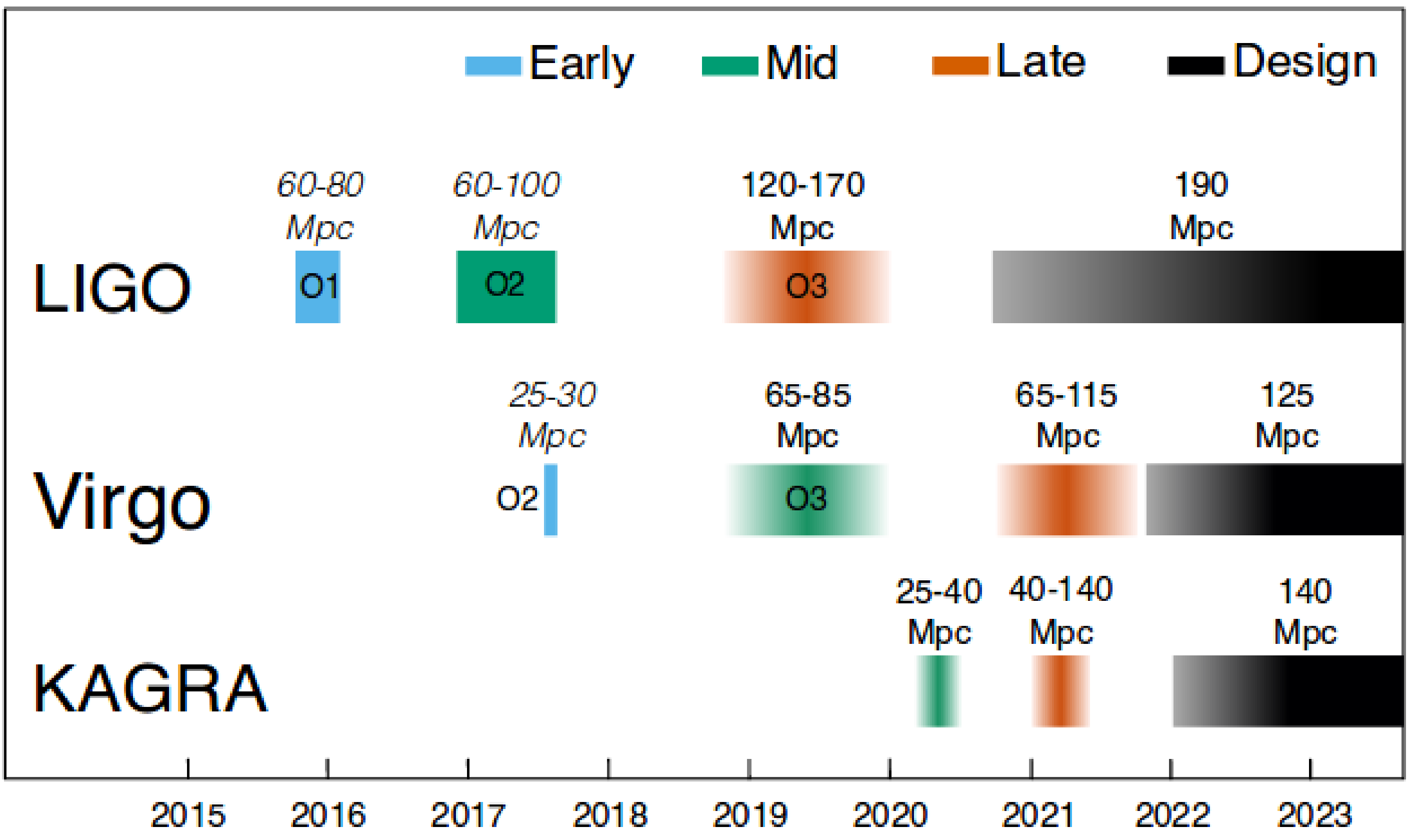
Short - Hard GRBs



NS-NS merger

O3 source rates prediction

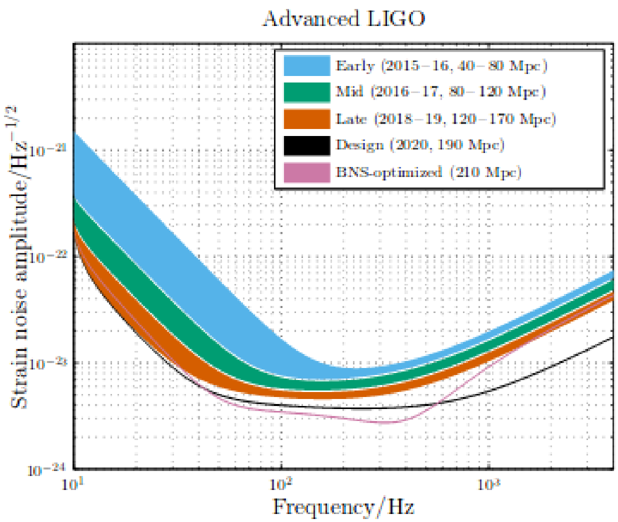
- An even larger network at the end of O3

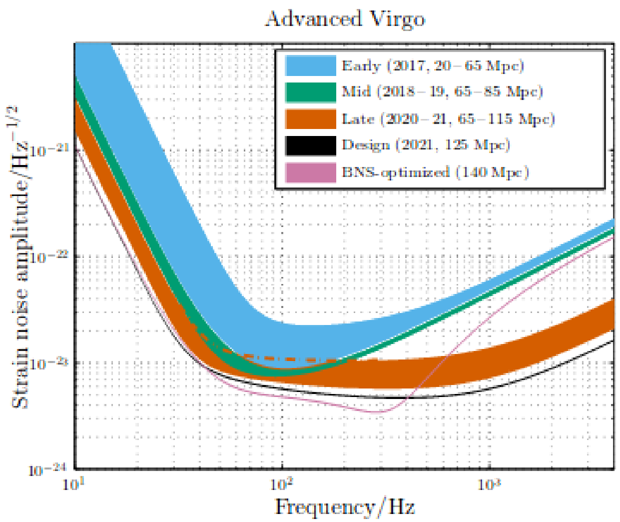


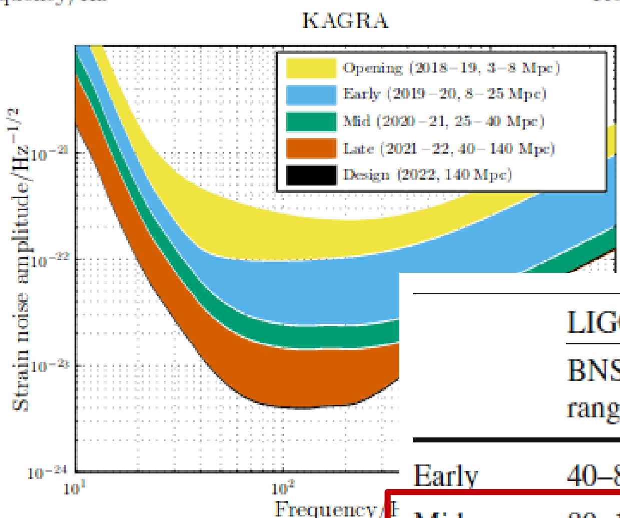
[Living Rev.Rel. 21 (2018) 3]

O3 source rates prediction

[Living Rev.Rel. 21 (2018) 3]







	LIGO		Virgo		KAGRA	
	BNS range/Mpc	BBH range/Mpc	BNS range/Mpc	BBH range/Mpc	BNS range/Mpc	BBH range/Mpc
Early	40–80	415–775	20–65	220–615	8–25	8–250
Mid	80–120	775–1110	65–85	615–790	25–40	250–405
Late	120–170	1110–1490	65–115	610–1030	40–140	405–1270
Design	190	1640	125	1130	140	1270

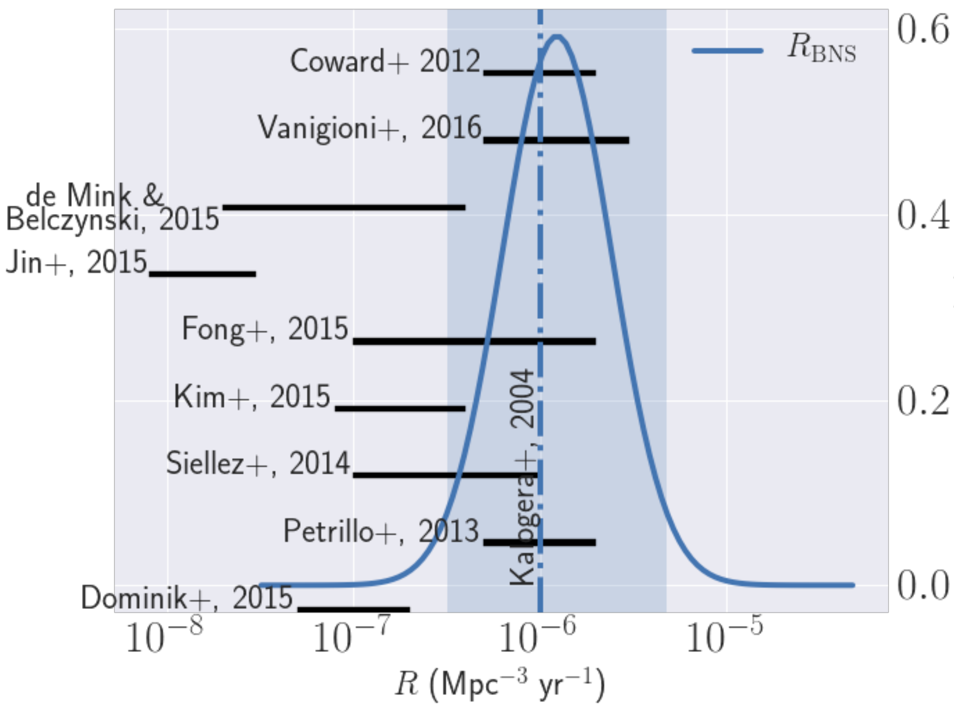
The different phases match those in Fig. 1. We quote the range, the average distance to which a signal could be detected, for a 1.4 $M_\odot$+1.4 $M_\odot$ binary neutron star (BNS) system and a 30 $M_\odot$+30 $M_\odot$ binary black hole (BBH) system

O3 source rates prediction

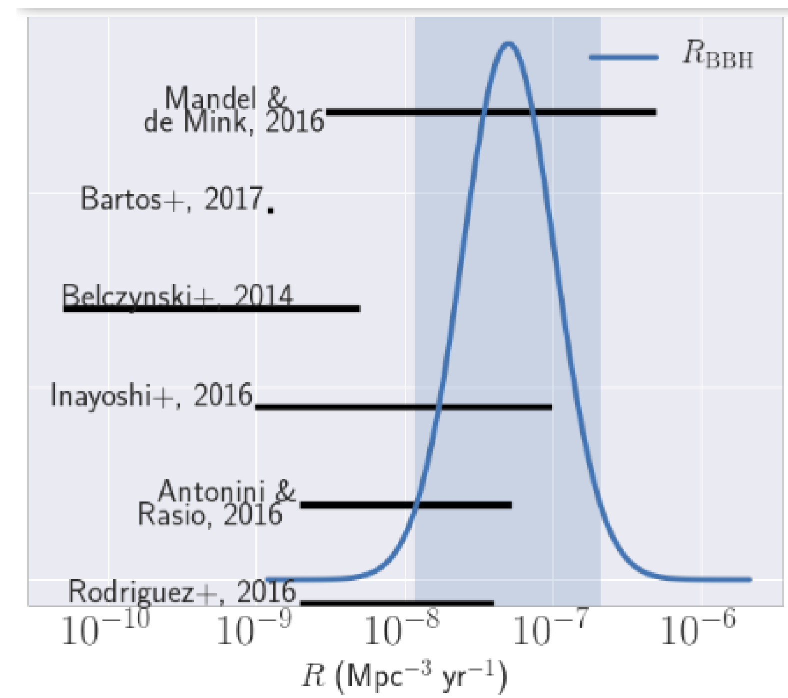
- Plan to start at the end of January 2019
- Run will last for one year
- KAGRA may join near the end if they achieve sufficient sensitivity
- Public alerts will be issued
- GW transient triggers below the detection standard that may improve a specific science/source search when analyzed jointly with the EM/neutrino sectors
- Several MOUs with this scope exercised are still in place:
  - High Energy Neutrinos (Antares, Icecube)
  - Gamma-Ray/X-ray transients sources (Fermi-GBM)
  - Core-collapse Supernova low energy neutrinos (Borexino, Icecube, KamLAND, LVD)

O3 source rates prediction

BNS



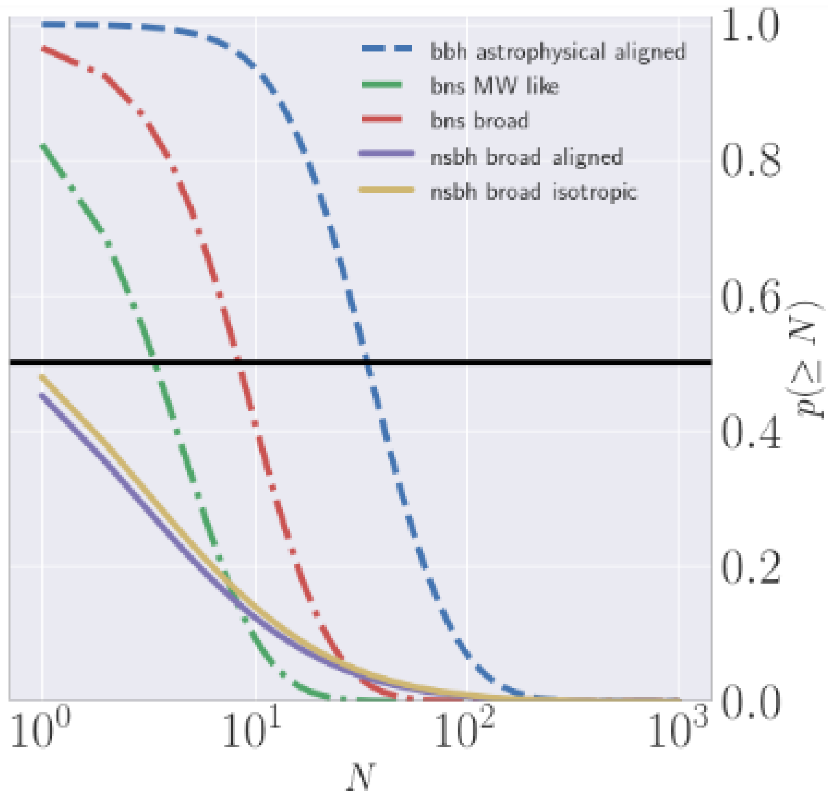
BBH



- Key factor : mass distribution pdf (log uniform vs power law).

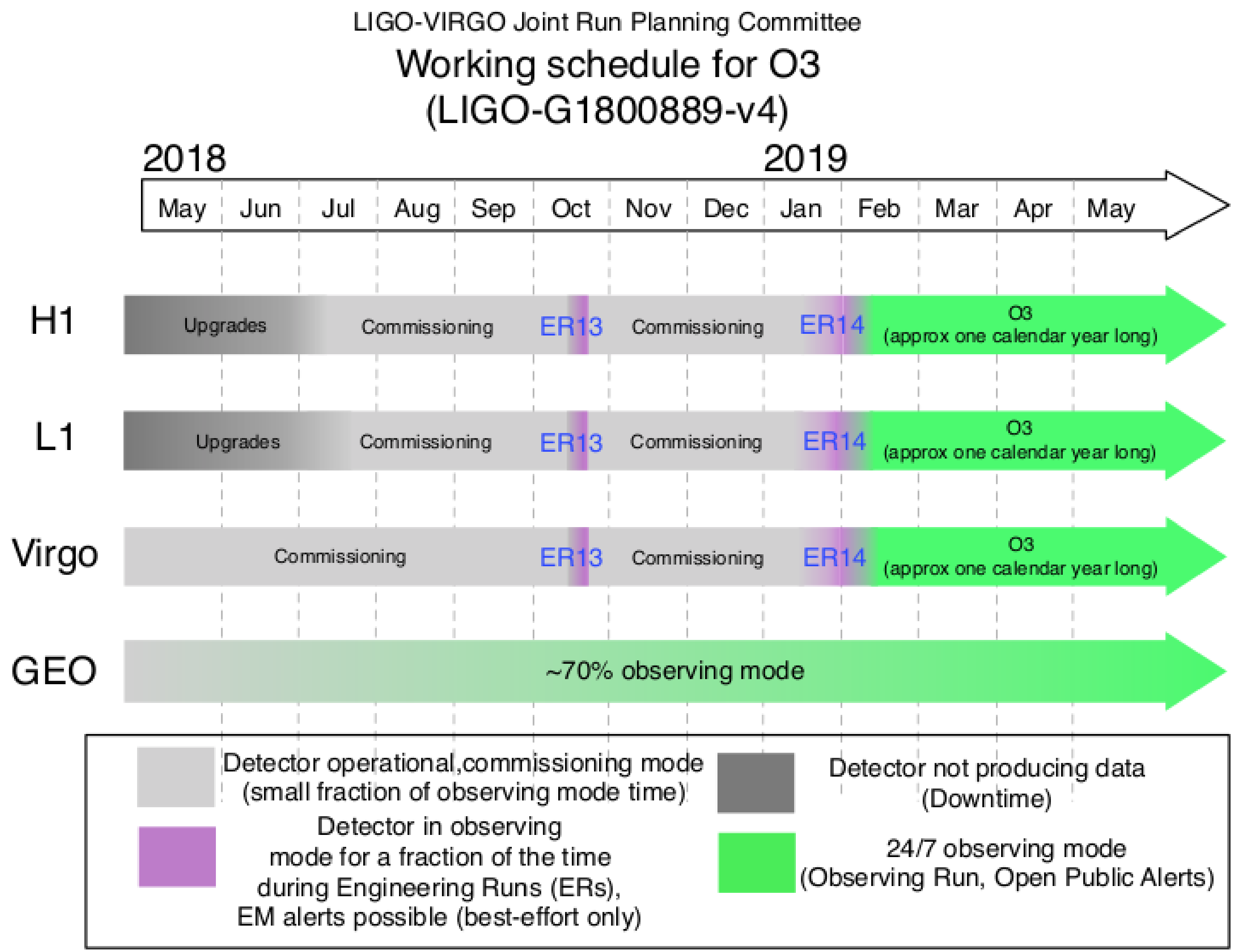
- BBH rate will dominate : up to ~few/week at least ~few/month.
- 1-10 BNS mergers over the year, possibly up to 1/month.
- Most models for a NS-BH merger give ~50 % chance that there will be an event in O3

O3 source rates prediction



source category	full year VT	N_d
BBH / bbh_astrophysical_aligned	6.8×10^8 Mpc^3 yr	35^{+78}_{-26}
BNS / bns_mw_like	3.2×10^6 Mpc^3 yr	4^{+9}_{-4}
BNS / bns_broad	7.3×10^6 Mpc^3 yr	9^{+19}_{-7}
NSBH / nsbh_broad_aligned	4.9×10^7 Mpc^3 yr	1^{+24}_{-1}
NSBH / nsbh_broad_isotropic	5.7×10^7 Mpc^3 yr	1^{+28}_{-1}

Timeline

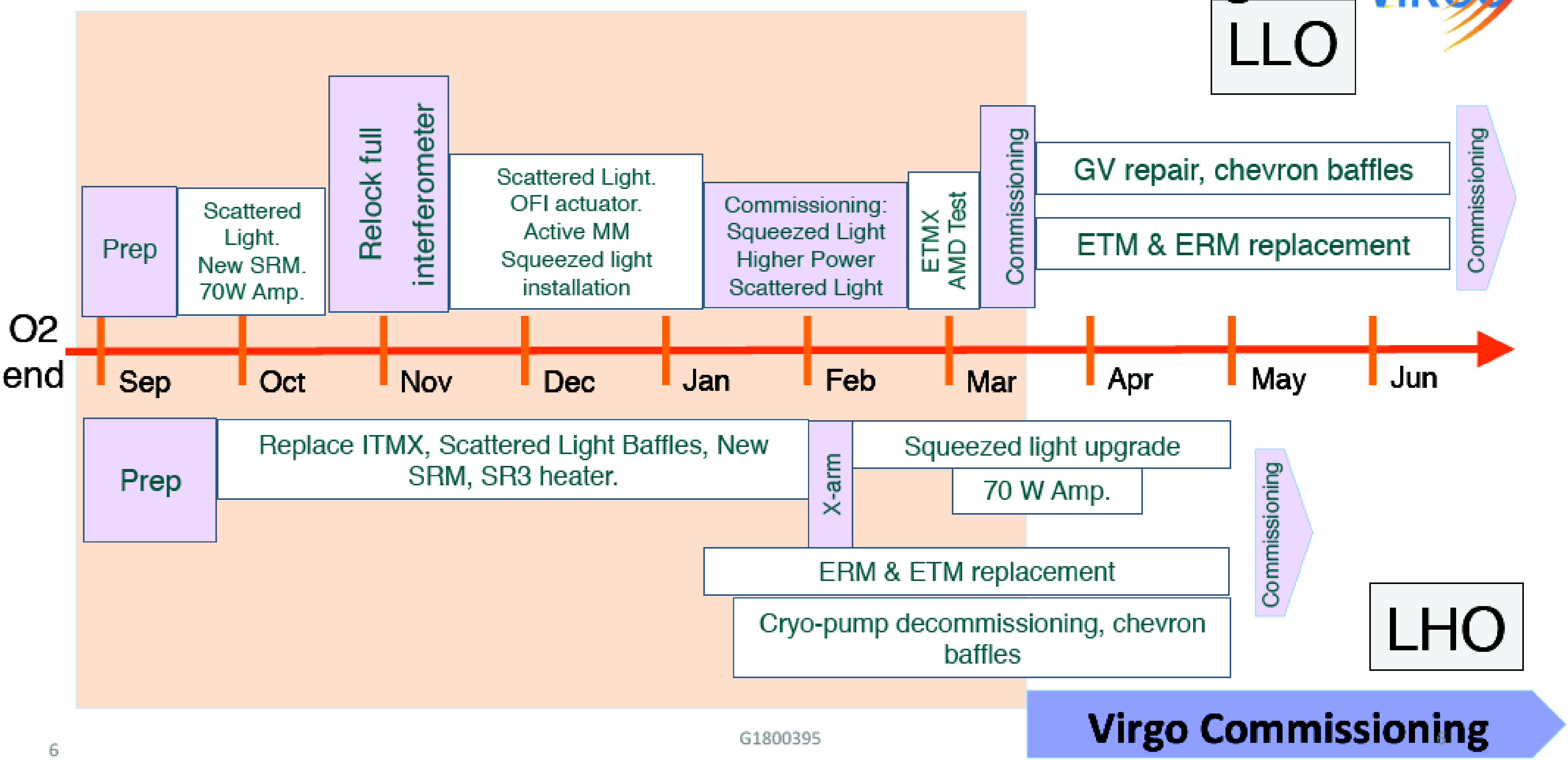

LIGO-VIRGO Joint Run Planning Committee
Working schedule for O3
(LIGO-G1800889-v4)
2018
2019
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
H1
Upgrades
Commissioning
ER13
Commissioning
ER14
O3
(approx one calendar year long)
L1
Upgrades
Commissioning
ER13
Commissioning
ER14
O3
(approx one calendar year long)
Virgo
Commissioning
ER13
Commissioning
ER14
O3
(approx one calendar year long)
GEO
~70% observing mode
Detector operational,commissioning mode
(small fraction of observing mode time)
Detector not producing data
(Downtime)
Detector in observing
mode for a fraction of the time
during Engineering Runs (ERs),
EM alerts possible (best-effort only)
24/7 observing mode
(Observing Run, Open Public Alerts)

Conclusion

- LVC missions
  - Find all GW sources in LIGO/Virgo/GEO detectors data.
  - Extract all possible physics results : Fundamental physics tests and measurements : H_0, graviton celerity, test of equivalence principle, constrain the nuclear matter EOS, …
  - Provide alerts to the outside world and especially to « observers » and perform multi-messenger analysis.
- O3 preparations
  - Open public alerts
  - See Michal Was talk !

https://www.ligo.org/scientists/GWEMalerts.php

Post O2 Installation and Commissioning



PNHE ts2020ll

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Epoch			2015 – 2016	2016 – 2017	2018 – 2019	2020+	2024+
Planned run duration			4 months	9 months	12 months	(per year)	(per year)
Expected burst range/Mpc		LIGO	40 – 60	60 – 75	75 – 90	105	105
		Virgo	—	20 – 40	40 – 50	40 – 70	80
		KAGRA	—	—	—	—	100
Expected BNS range/Mpc		LIGO	40 – 80	80 – 120	120 – 170	190	190
		Virgo	—	20 – 65	65 – 85	65 – 115	125
		KAGRA	—	—	—	—	140
Achieved BNS range/Mpc		LIGO	60 – 80	60 – 100	—	—	—
		Virgo	—	25 – 30	—	—	—
		KAGRA	—	—	—	—	—
Estimated BNS detections			0.05 – 1	0.2 – 4.5	1 – 50	4 – 80	11 – 180
Actual BNS detections			0	1	—	—	—
90% CR	% within	5 deg^2	< 1	1 – 5	1 – 4	3 – 7	23 – 30
		20 deg^2	< 1	7 – 14	12 – 21	14 – 22	65 – 73
	Median/deg^2		460 – 530	230 – 320	120 – 180	110 – 180	9 – 12
Searched area	% within	5 deg^2	4 – 6	15 – 21	20 – 26	23 – 29	62 – 67
		20 deg^2	14 – 17	33 – 41	42 – 50	44 – 52	87 – 90