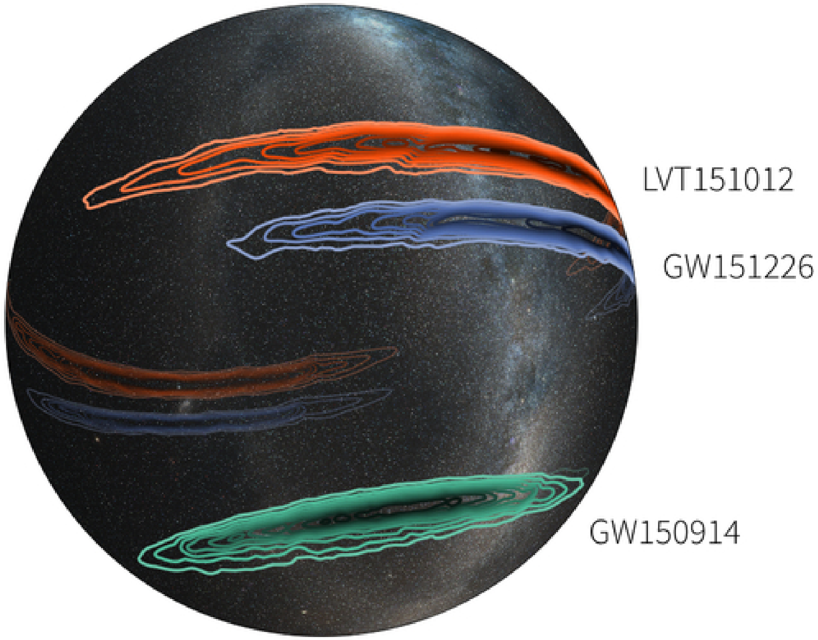

# Gravitational Wave Transients

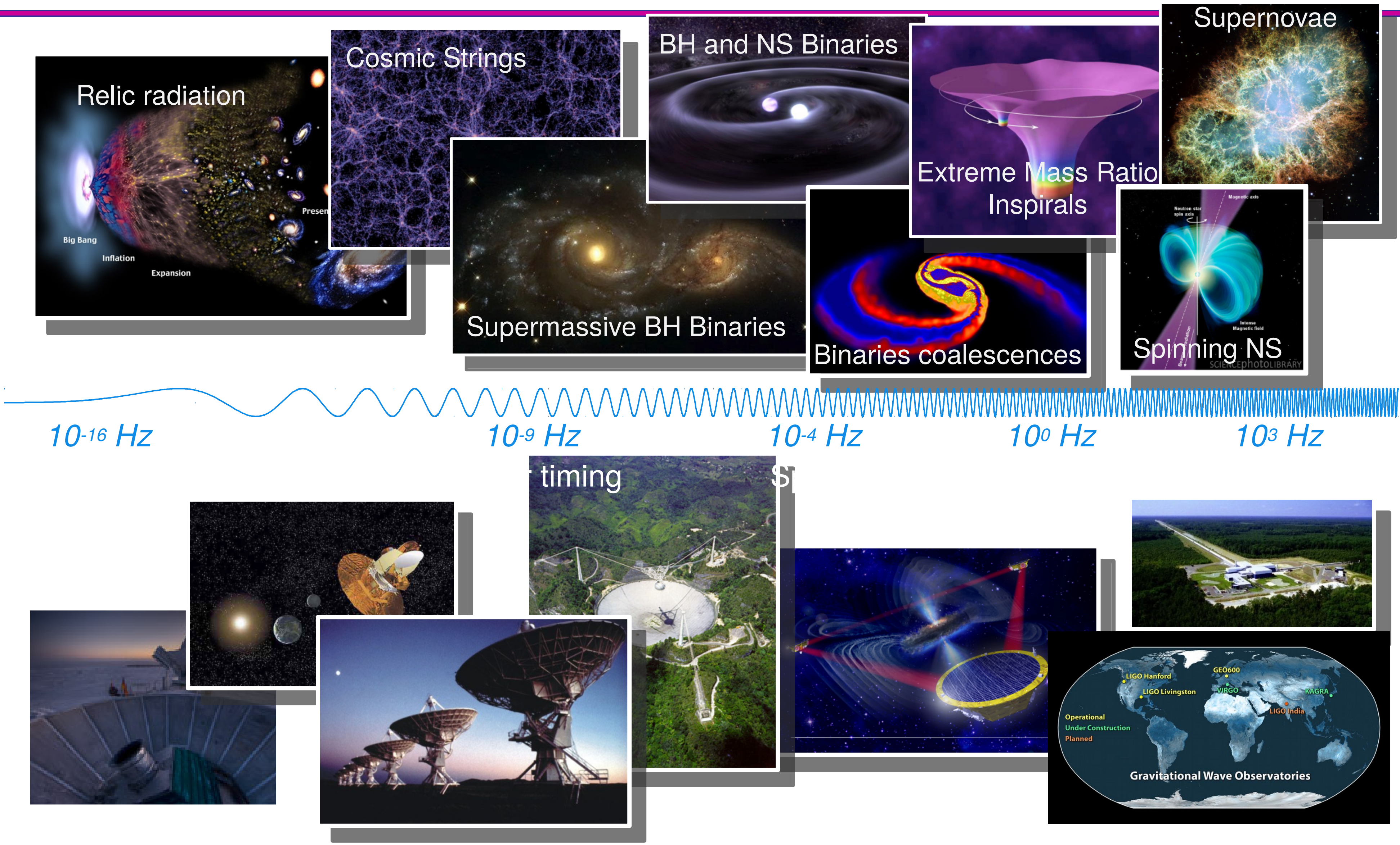



Marie Anne Bizouard – LAL Orsay – IN2P3 / Univ. Paris Sud

# Outline

- GW transient sources
- What has been detected / what is known / what is unknown
- Multi-messenger astronomy
- Online searches
- Observation planning / detectors network

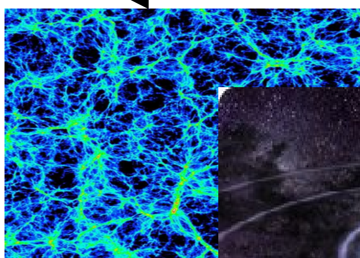
# The gravitational wave spectrum

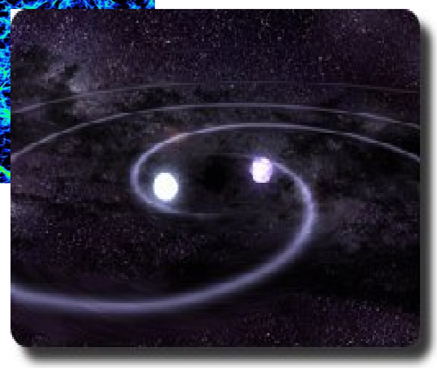


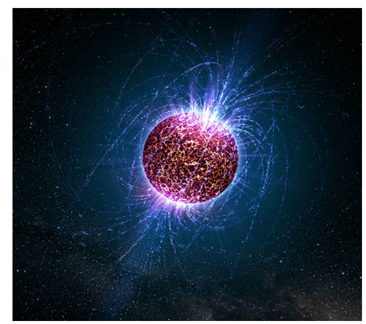
# LIGO-Virgo GW searches zoology

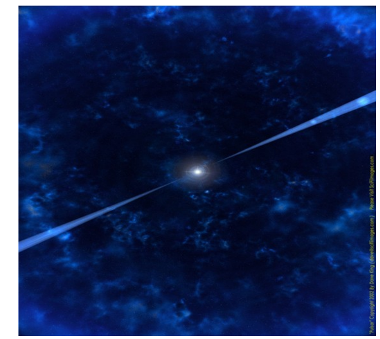
Short duration (~1s) Long duration (∞)

Waveform known

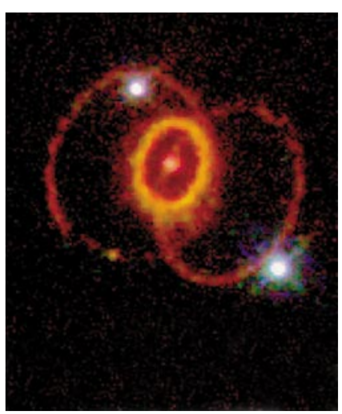




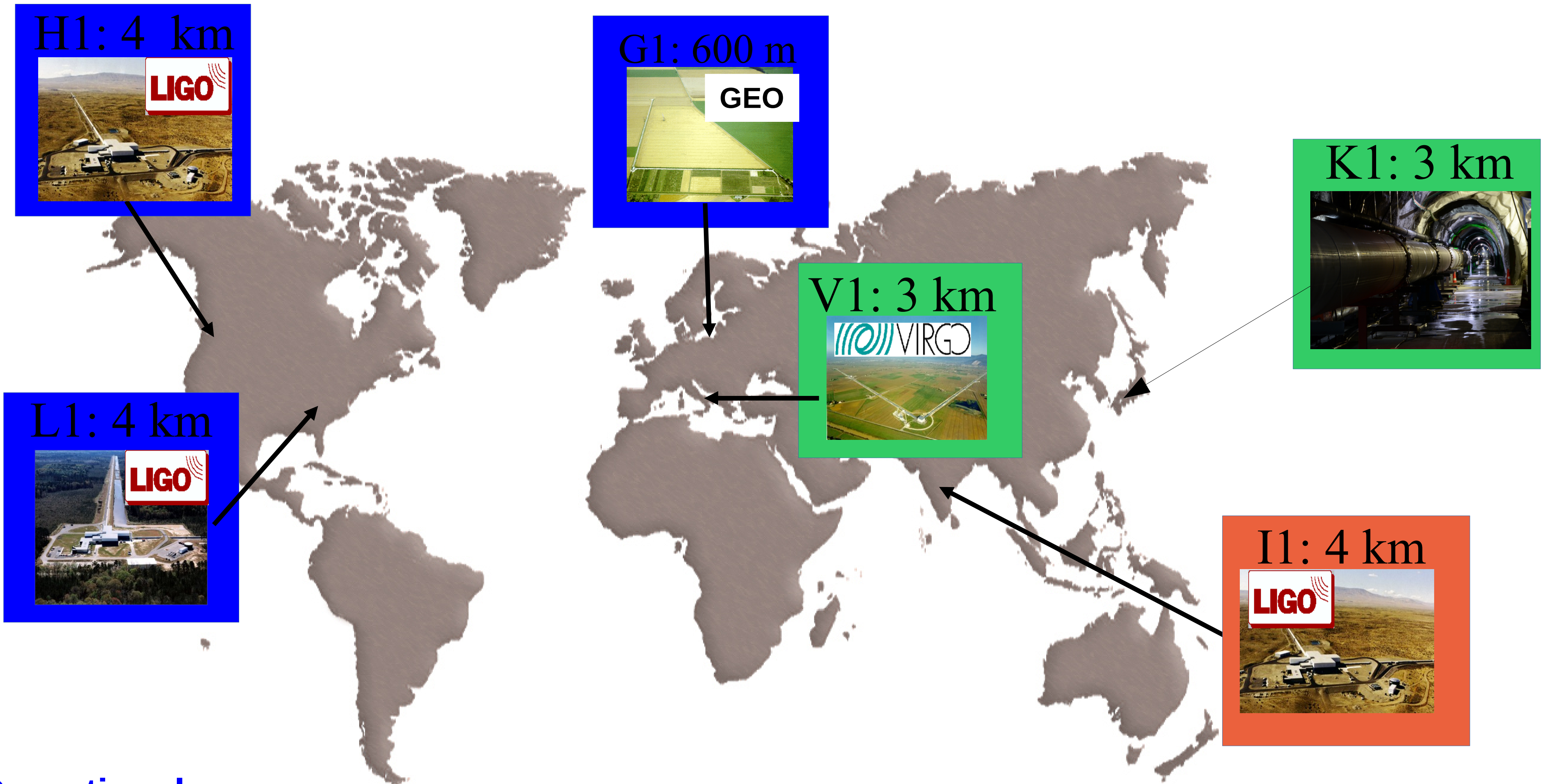




Waveform unknown



# Network of ground-based advanced detectors

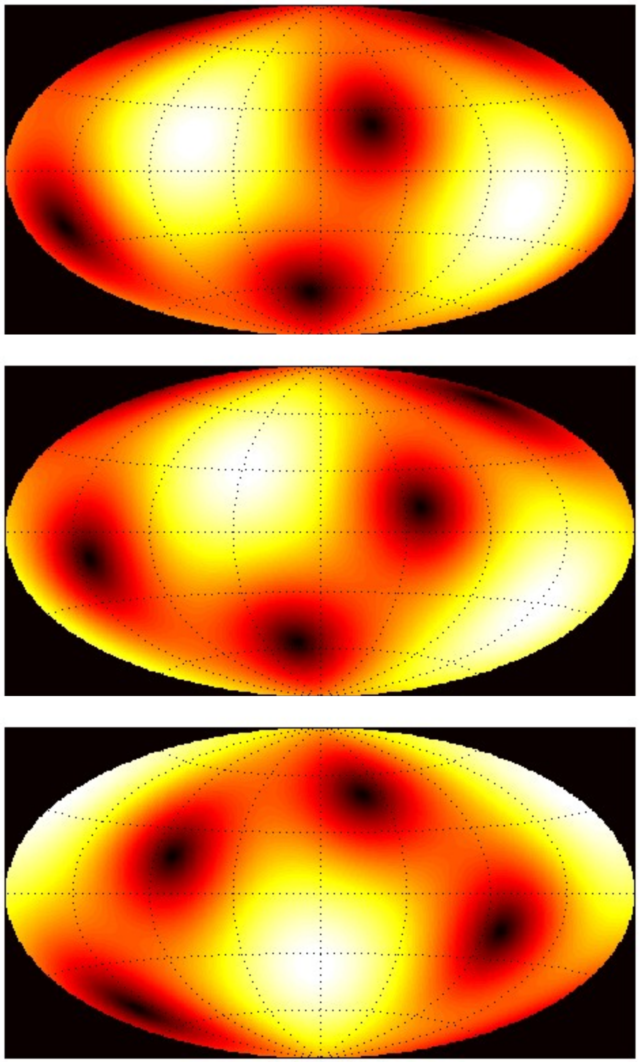



Operational
Commissioning/construction
Planned

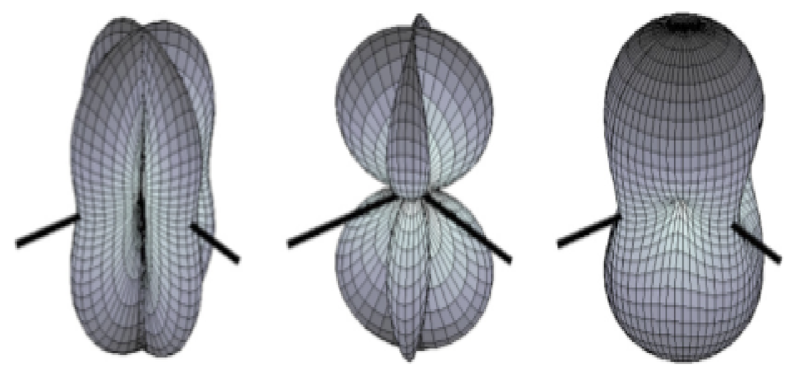
**Since 2007, LIGO, GEO & Virgo data are jointly analyzed by the LIGO Scientific Collaboration and the Virgo Collaboration.**

# Multi-detectors search

H1
L1
V1

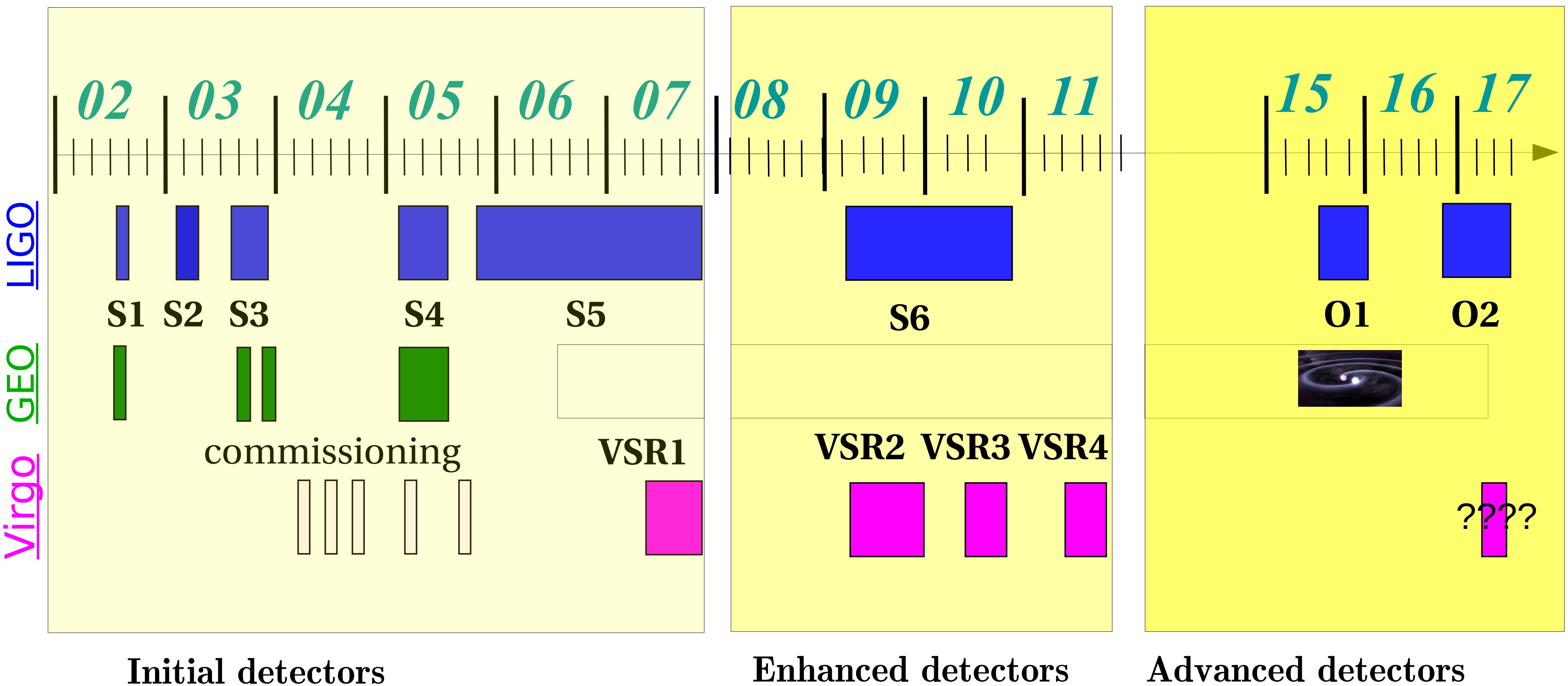


- Earth rotation allows to cover almost the full sky
- Effective experience livetime can be increased by time shifting one detector wrt others → improve the background estimation/significance of an event.



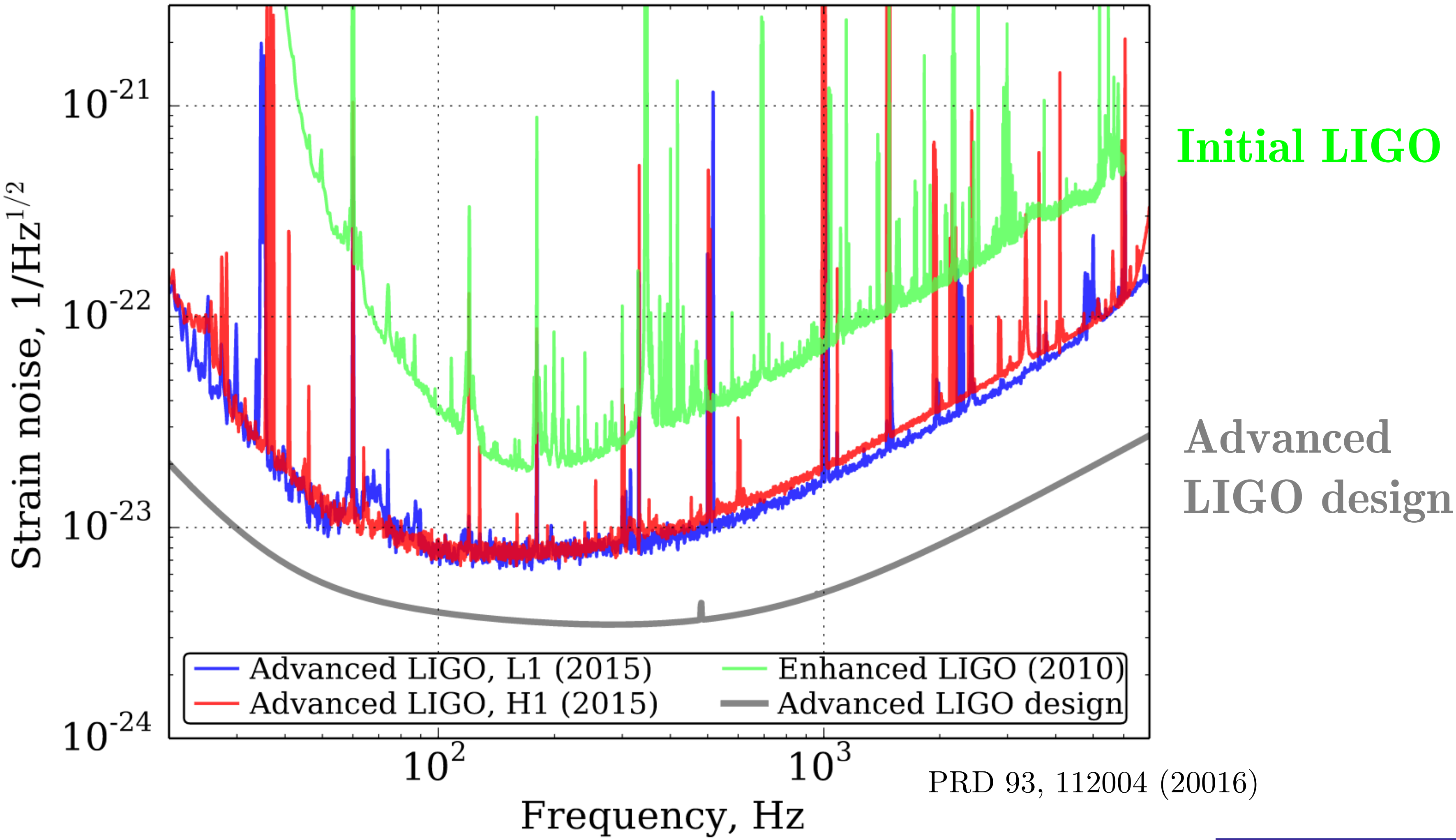
$F_+$ $F_\times$ $\sqrt{F_+^2 + F_\times^2}$

# LIGO-GEO-Virgo joint runs



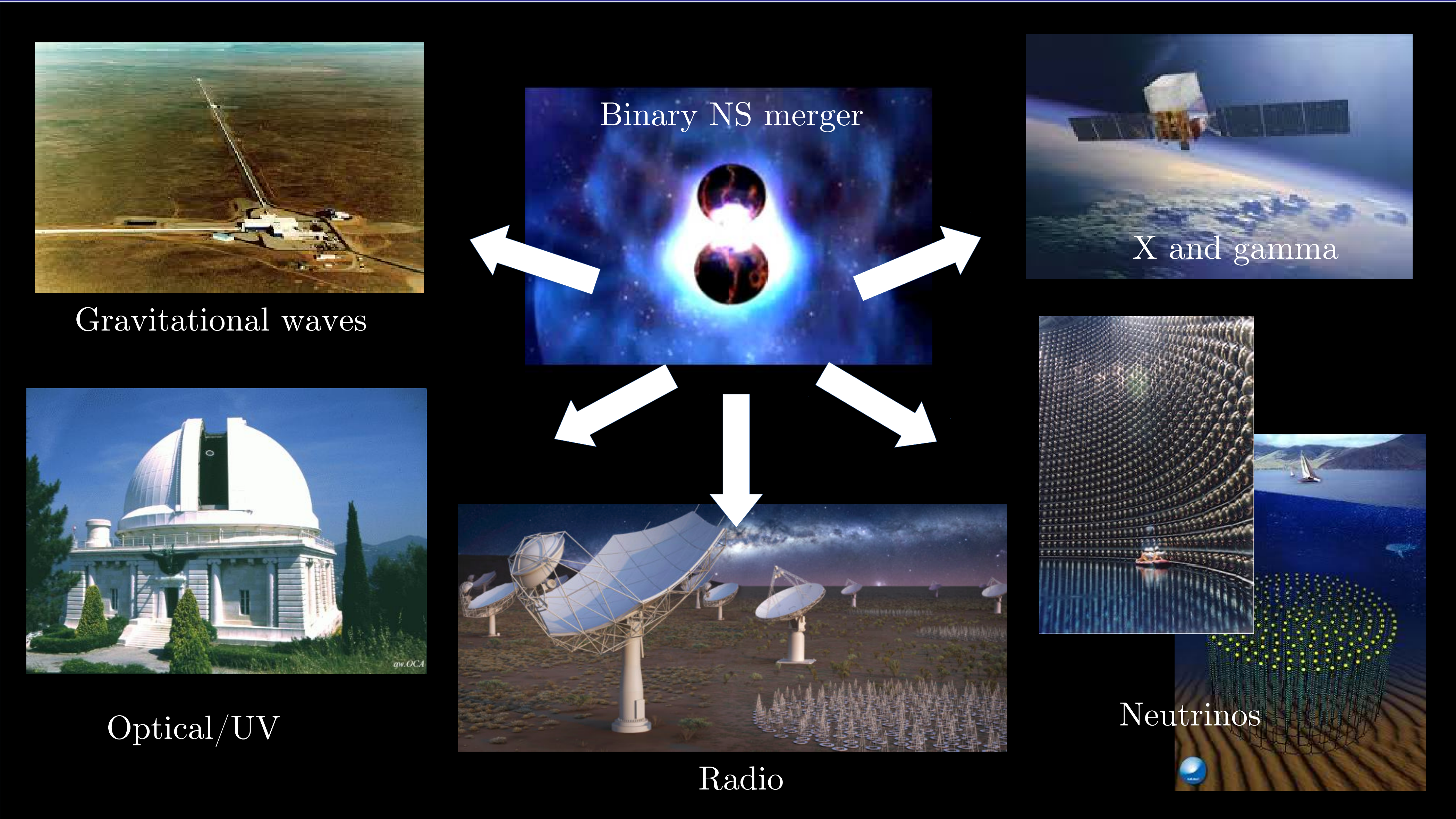
# Strain noise during O1

**Better than ever not yet at sensitivity !**




PRD 93, 112004 (20016)

# Multi-messenger astronomy with GWs



# What the GW network is doing now

**All-sky / all-time transient searches**

→ low latency (1 min)
→ submit **private** GCN notices & circulars the “most significant” triggers
→ 74 MOU currently active
→ all triggers kept in a private LVC data base
→ LIGO data public release 18 months after data taking

**Targeted searches (external triggers)**

→ GRB, SGR, AXP, magnetars
→ medium latency (GRB only)

**Multi-messenger searches**

→ neutrinos (HEN & LEN), FRB, GRB, ...
→ sub-threshold triggers

**Latest — as of 20 June 2017 16:22 CDT**

Query:

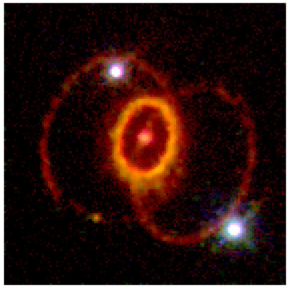
Get neighbors:

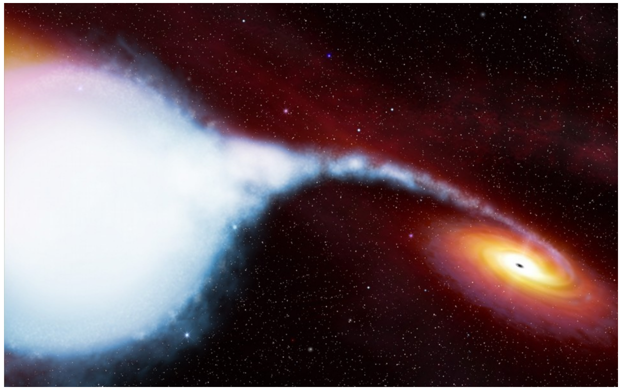
| UID | Labels | Group | Pipeline | Search | Instruments |
|---|---|---|---|---|---|
| G250089 | | CBC | gstlal | HighMass | H1,L1 |
| G250088 | | CBC | gstlal | HighMass | H1,L1 |
| G250087 | | CBC | gstlal | HighMass | H1,L1 |
| G250086 | | CBC | gstlal | HighMass | H1,L1 |
| G250085 | | CBC | gstlal | HighMass | H1,L1 |
| G250078 | | CBC | MBTAOnline | | H1,V1 |
| G250077 | | CBC | MBTAOnline | | H1,V1 |
| G250076 | | CBC | gstlal | HighMass | H1,L1 |
| G250075 | | CBC | MBTAOnline | | H1,V1 |

# GW transient sources

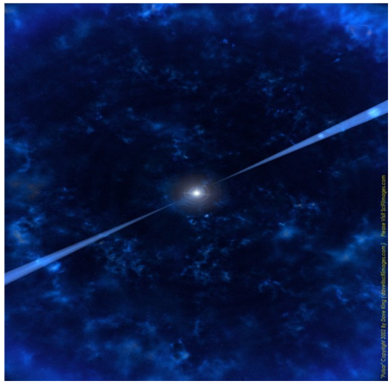
- To emit GW a source must be compact, relativistic and asymmetric
- Astrophysical sources
  - Stellar core collapse
  - Black holes
  - Neutron star instabilities

associated with other messengers: (photons/neutrinos) GRB, SGR, pulsar glitches, supernova, ….

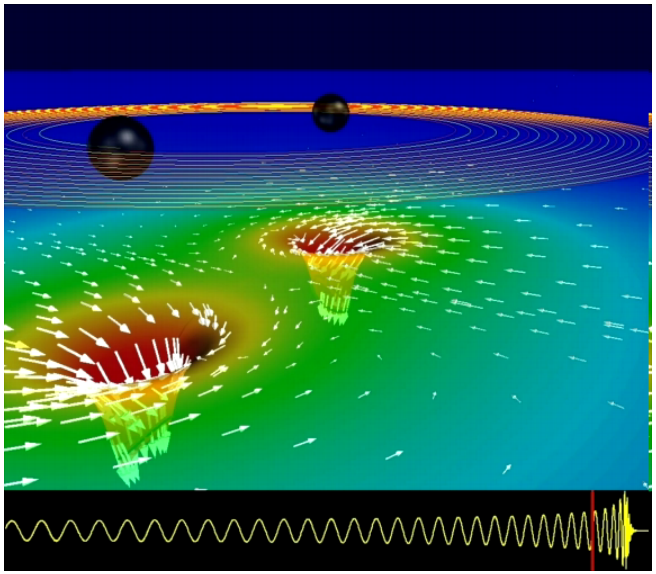




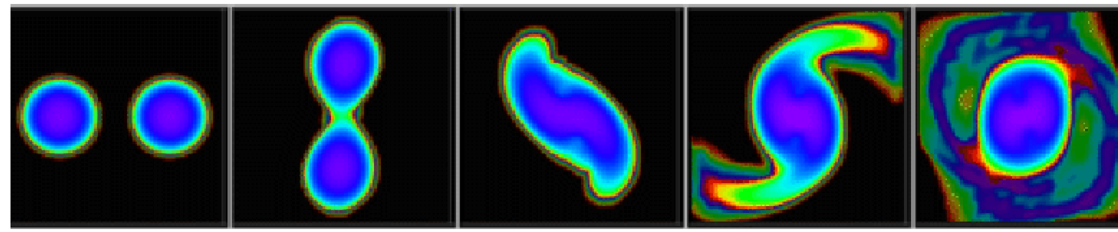
- Exotic objects: cosmic (super-)string, …
- Which information matters?
  - Astrophysical events rate
  - Signal waveform
  - Background / signal disentanglement
  - Other messenger association?



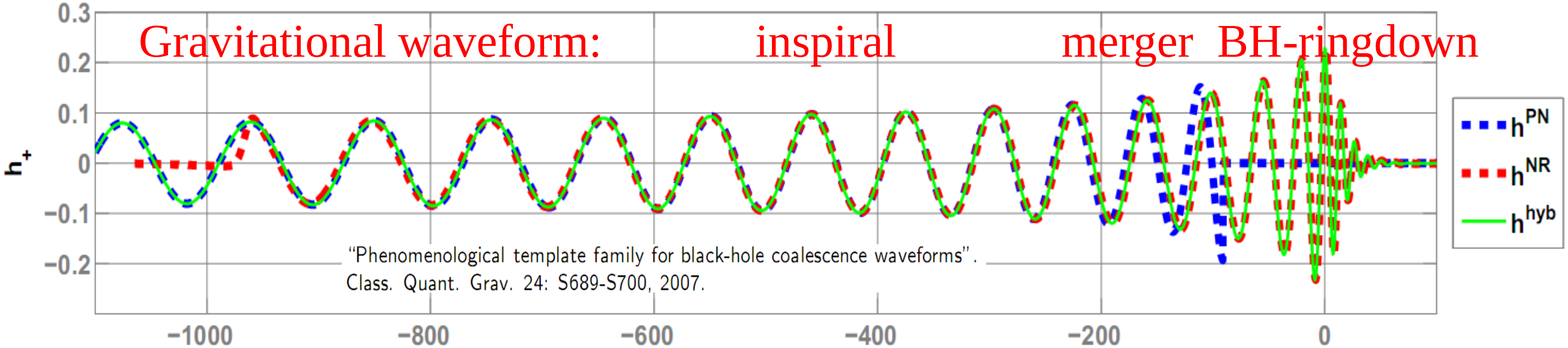
# Compact Binary Coalescence



- Neutron star – neutron star (Centrella et al.)

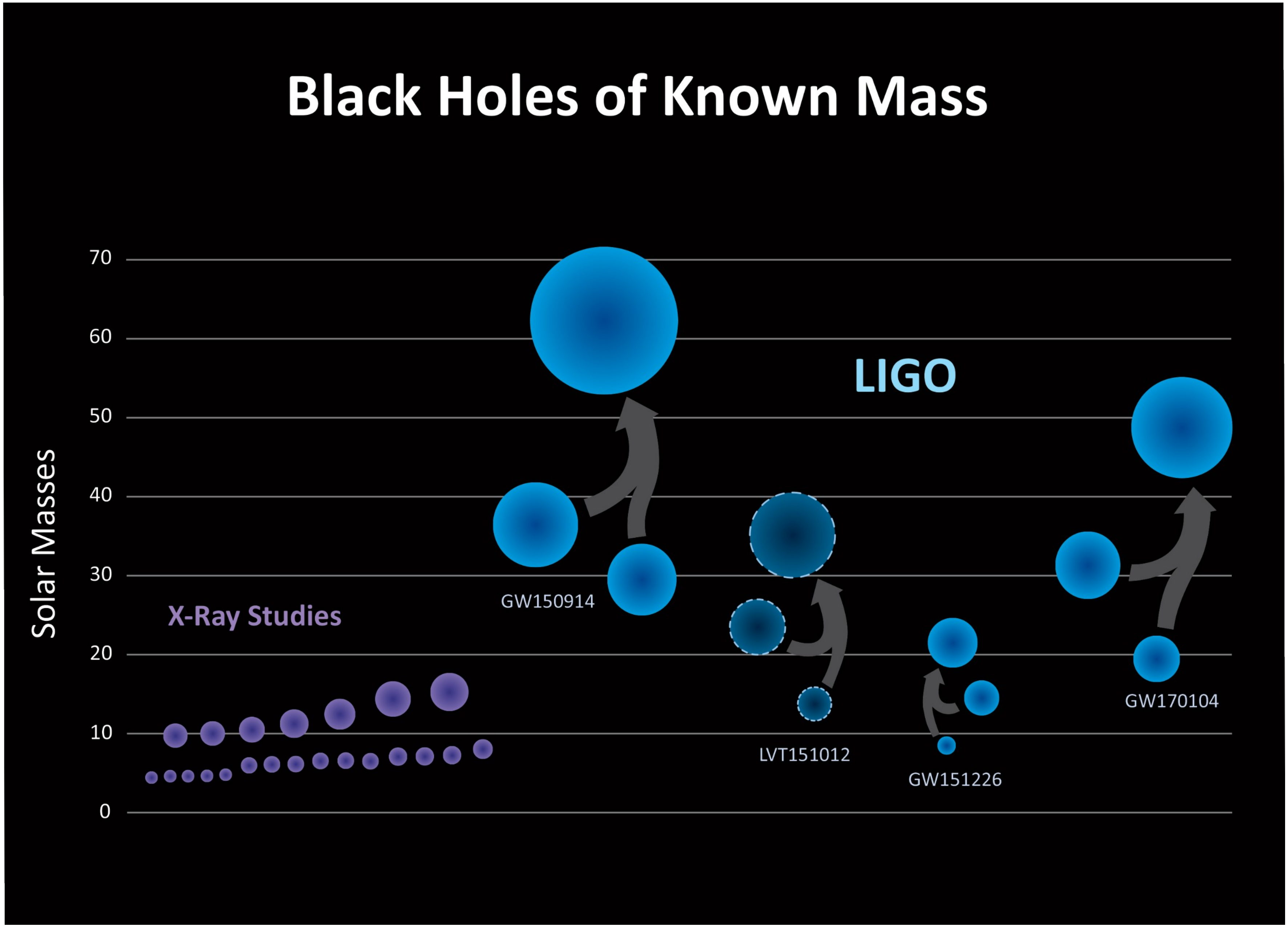


Unique way to study string field gravityy and the structure of the nuclear matter in the most extreme conditions



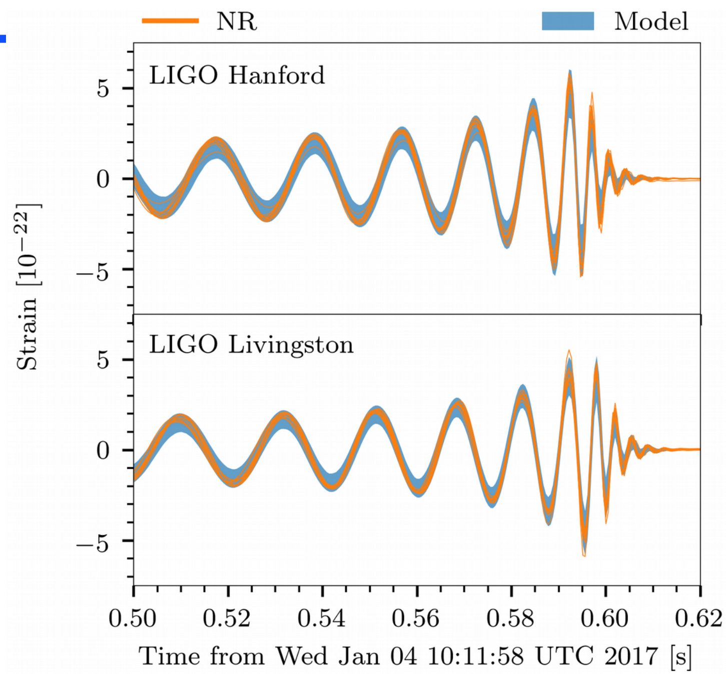

Waveform carries lots of information about binary masses, orbit, merger, spins, ...

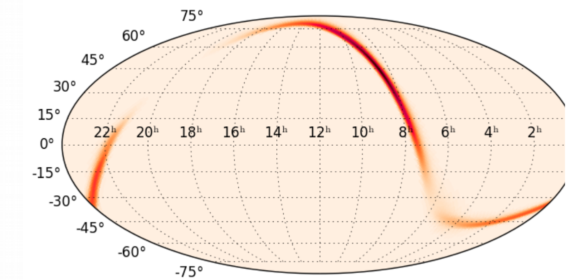
# Detected BBH events

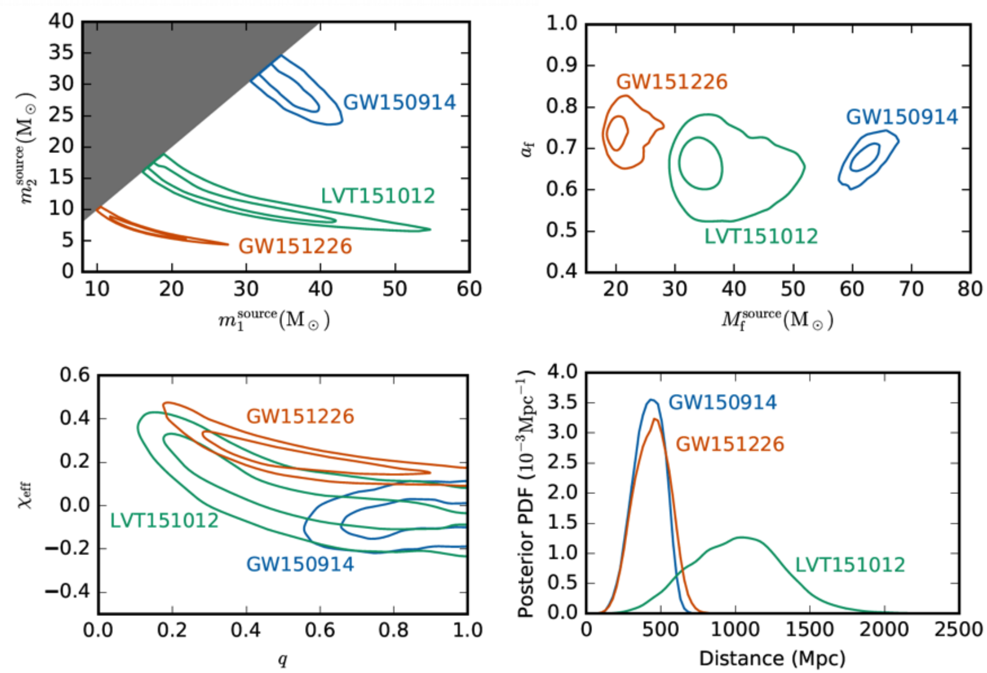


# Extracting the parameters

| Event | GW150914 | GW151226 | LVT151012 |
|---|---|---|---|
| Signal-to-noise ratio $\rho$ | 23.7 | 13.0 | 9.7 |
| False alarm rate FAR/yr$^{-1}$ | $< 6.0 \times 10^{-7}$ | $< 6.0 \times 10^{-7}$ | 0.37 |
| p-value | $7.5 \times 10^{-8}$ | $7.5 \times 10^{-8}$ | 0.045 |
| Significance | $> 5.3\sigma$ | $> 5.3\sigma$ | $1.7\sigma$ |
| Primary mass $m_1^{\text{source}}/\mathrm{M}_\odot$ | $36.2^{+5.2}_{-3.8}$ | $14.2^{+8.3}_{-3.7}$ | $23^{+18}_{-6}$ |
| Secondary mass $m_2^{\text{source}}/\mathrm{M}_\odot$ | $29.1^{+3.7}_{-4.4}$ | $7.5^{+2.3}_{-2.3}$ | $13^{+4}_{-5}$ |
| Chirp mass $\mathscr{M}^{\text{source}}/\mathrm{M}_\odot$ | $28.1^{+1.8}_{-1.5}$ | $8.9^{+0.3}_{-0.3}$ | $15.1^{+1.4}_{-1.1}$ |
| Total mass $M^{\text{source}}/\mathrm{M}_\odot$ | $65.3^{+4.1}_{-3.4}$ | $21.8^{+5.9}_{-1.7}$ | $37^{+13}_{-4}$ |
| Effective inspiral spin $\chi_{\text{eff}}$ | $-0.06^{+0.14}_{-0.14}$ | $0.21^{+0.20}_{-0.10}$ | $0.0^{+0.3}_{-0.2}$ |
| Final mass $M_{\text{f}}^{\text{source}}/\mathrm{M}_\odot$ | $62.3^{+3.7}_{-3.1}$ | $20.8^{+6.1}_{-1.7}$ | $35^{+14}_{-4}$ |
| Final spin $a_{\text{f}}$ | $0.68^{+0.05}_{-0.06}$ | $0.74^{+0.06}_{-0.06}$ | $0.66^{+0.09}_{-0.10}$ |
| Radiated energy $E_{\text{rad}}/(\mathrm{M}_\odot c^2)$ | $3.0^{+0.5}_{-0.4}$ | $1.0^{+0.1}_{-0.2}$ | $1.5^{+0.3}_{-0.4}$ |
| Peak luminosity $\ell_{\text{peak}}/(\text{erg}\,\text{s}^{-1})$ | $3.6^{+0.5}_{-0.4} \times 10^{56}$ | $3.3^{+0.8}_{-1.6} \times 10^{56}$ | $3.1^{+0.8}_{-1.8} \times 10^{56}$ |
| Luminosity distance $D_{\text{L}}/\text{Mpc}$ | $420^{+150}_{-180}$ | $440^{+180}_{-190}$ | $1000^{+500}_{-500}$ |
| Source redshift $z$ | $0.09^{+0.03}_{-0.04}$ | $0.09^{+0.03}_{-0.04}$ | $0.20^{+0.09}_{-0.09}$ |
| Sky localization $\Delta\Omega/\text{deg}^2$ | 230 | 850 | 1600 |





# Radiated energy & luminosity

- GW150914

$$E_{rad} = 3.0^{+0.5}_{-0.4} \mathrm{M}_\odot c^2$$
$$l_{peak} = 3.6^{+0.5}_{-0.4} \times 10^{56} \mathrm{erg/s}$$

- LVT151012

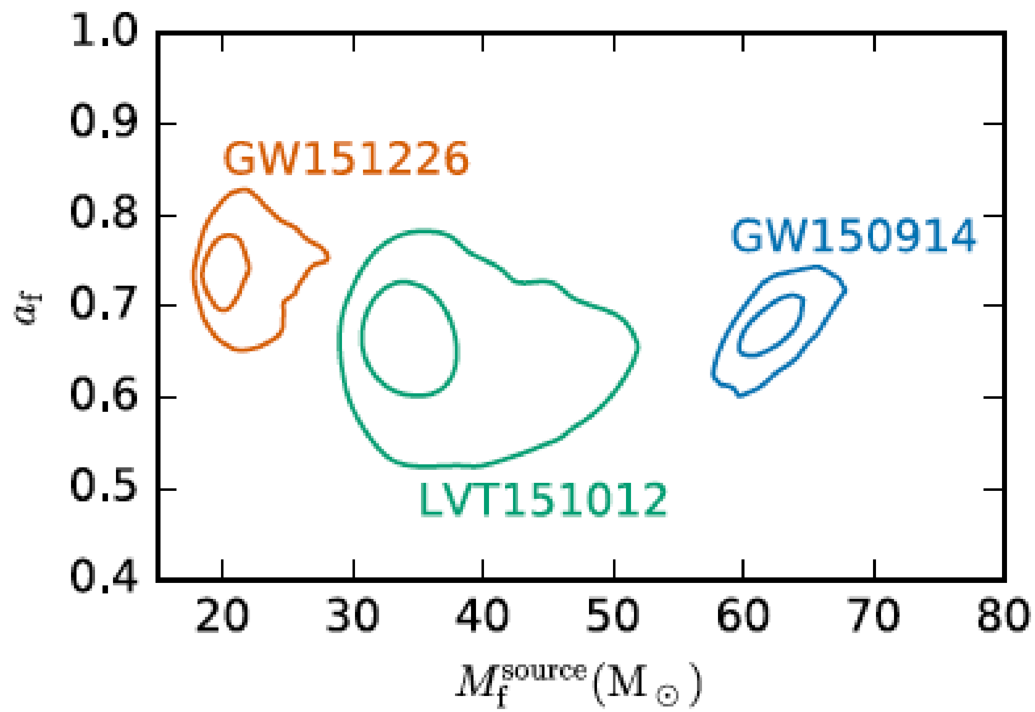
$$E_{rad} = 1.5^{+0.3}_{-0.4} \mathrm{M}_\odot c^2$$
$$l_{peak} = 3.1^{+0.8}_{-1.8} \times 10^{56} \mathrm{erg/s}$$

- GW151226

$$E_{rad} = 1.0^{+0.1}_{-0.2} \mathrm{M}_\odot c^2$$
$$l_{peak} = 3.3^{+0.8}_{-1.6} \times 10^{56} \mathrm{erg/s}$$

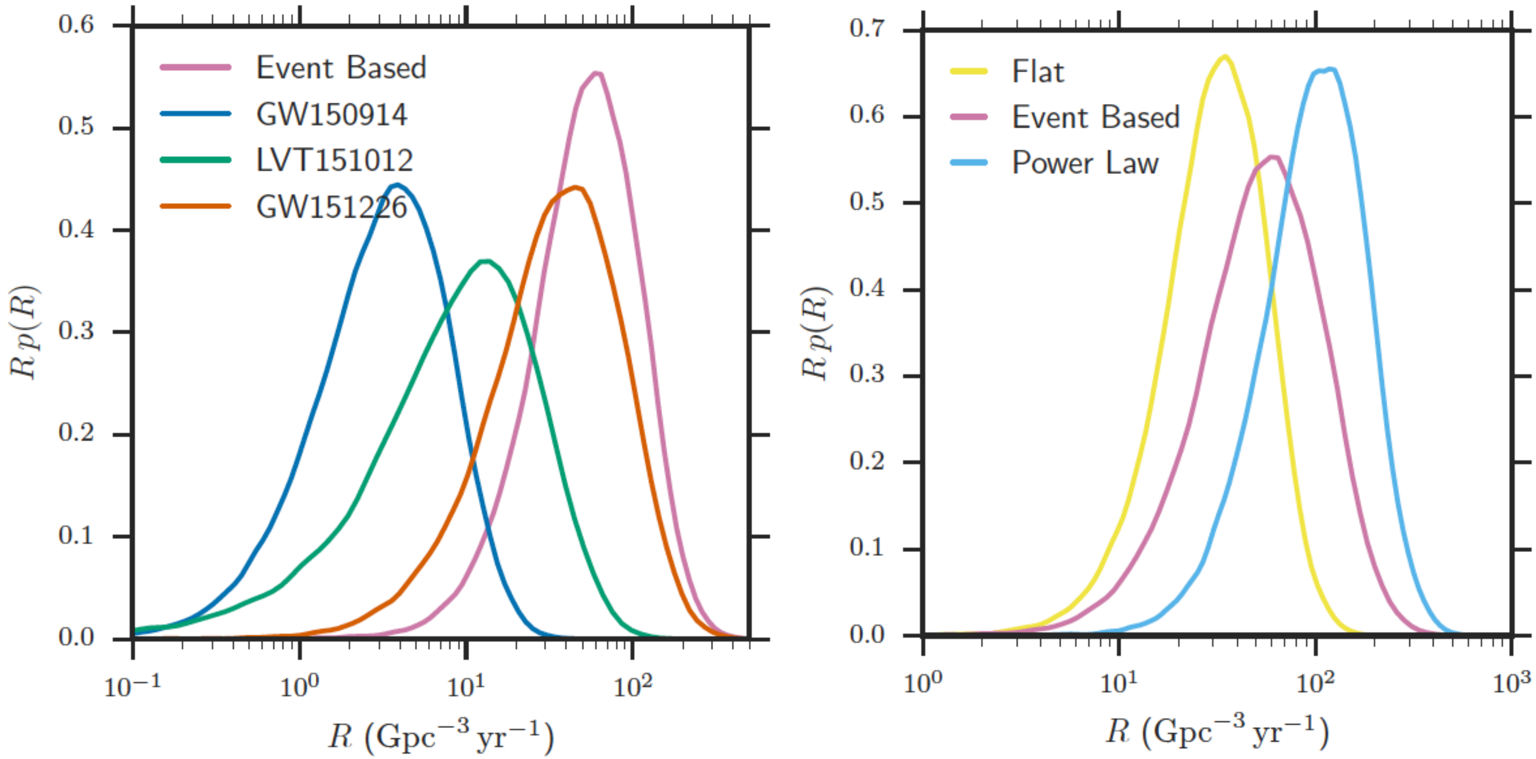
- GW170104

$$E_{rad} = 2.0^{+0.6}_{-0.7} \mathrm{M}_\odot c^2$$
$$l_{peak} = 3.1^{+0.7}_{-1.3} \times 10^{56} \mathrm{erg/s}$$




- GW150914: $E_{GW} \approx 3\ Mc^2$, or ~4.5% of the total mass-energy of the system.
- Roughly $10^{80}$ gravitons.
- Peak luminosity $L_{GW} \sim 3.6 \times 10^{54}\ erg/s$, briefly outshining the EM energy output of all the stars in the observable universe (by a factor > 20).

# Astrophysical rate density



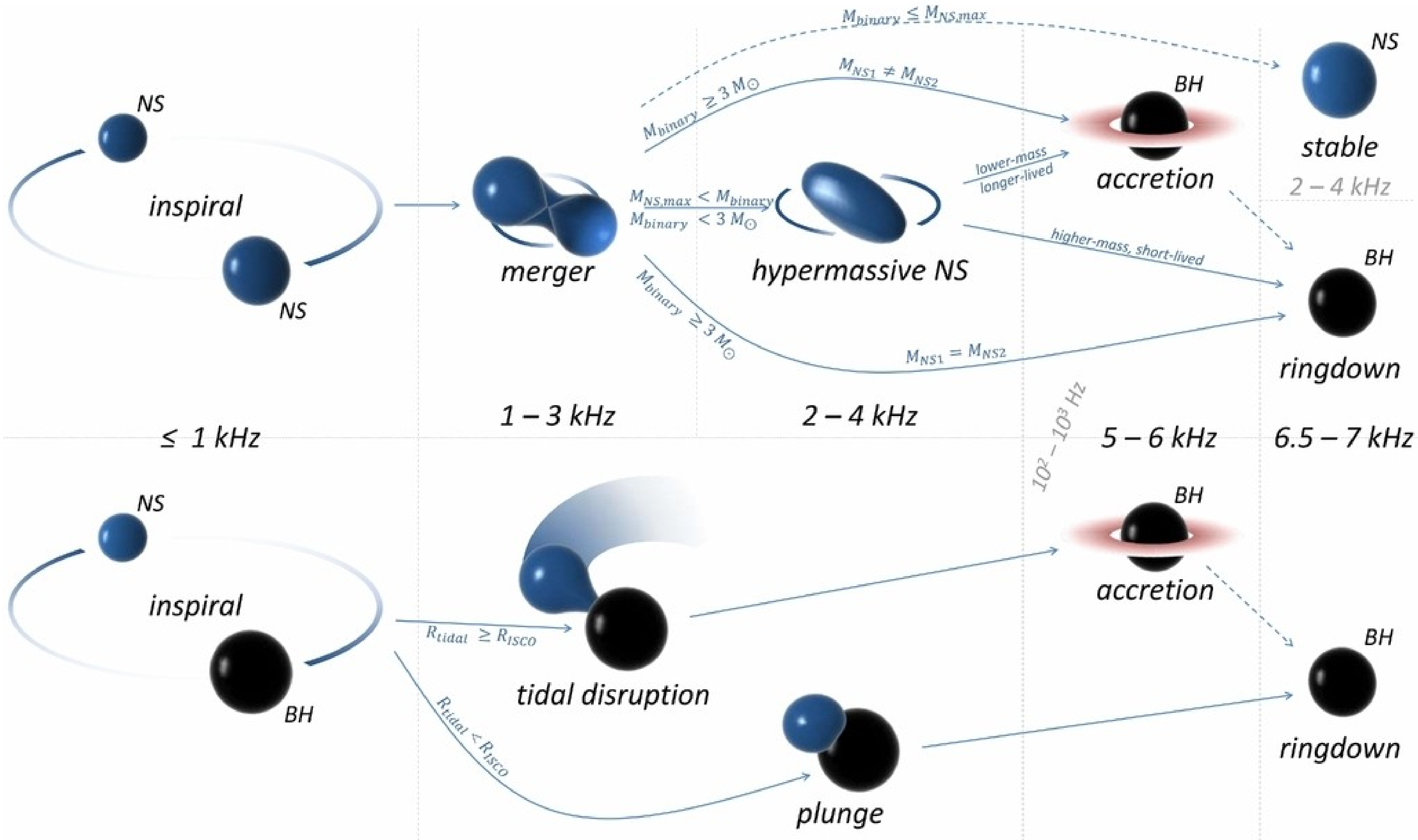

Updated rate: 12-213 Gpc$^{-3}$ yr$^{-1}$ (9-240 Gpc$^{-3}$ yr$^{-1}$)

Roughly consistent with astrophysical expectations from:

- Core collapse supernova rate
- Short GRB rate
- Astrophysical modeling of compact binary formation ("population synthesis")
- A half-dozen BNS systems in our galaxy (including Hulse-Taylor)

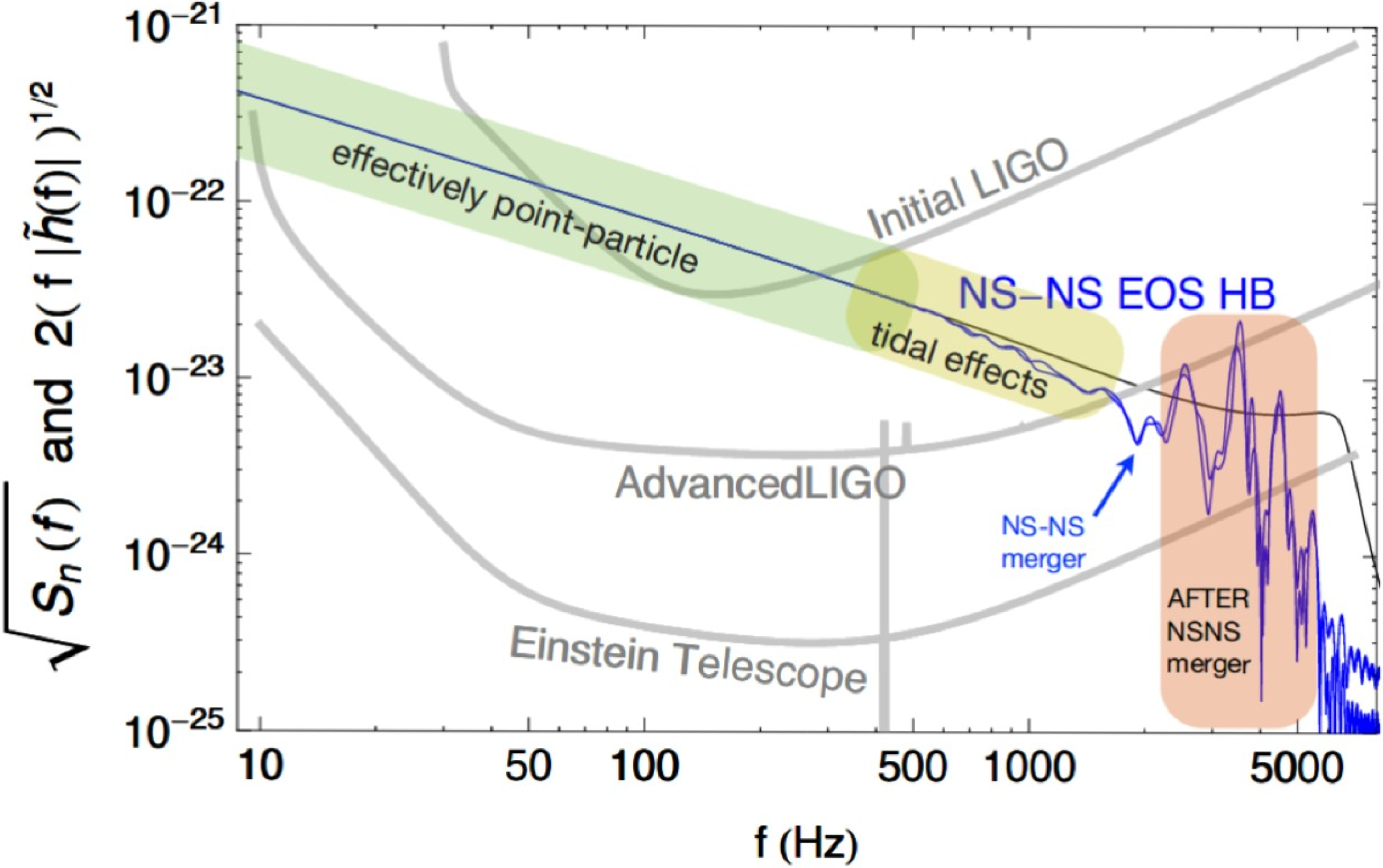
# Binary involving a NS

Figure 1 from I Bartos et al 2013 Class. Quantum Grav. 30 123001



# NS-NS – matter effect

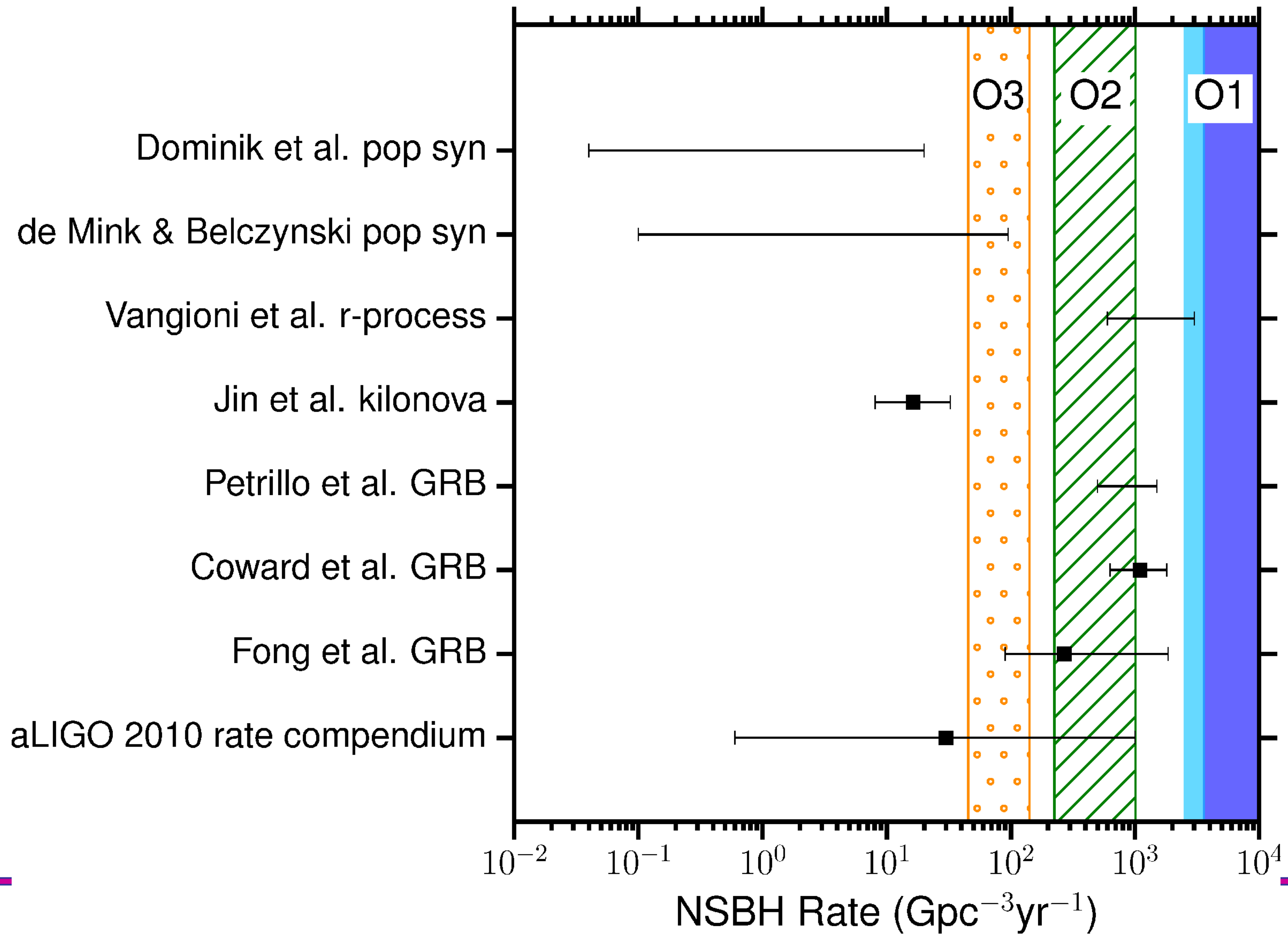
Read et al, Phys.Rev.D 88,044042 (2013)



# Binary neutron stars & neutron star-black hole

**NS-BH predictions**

gr-qc:1607.07456



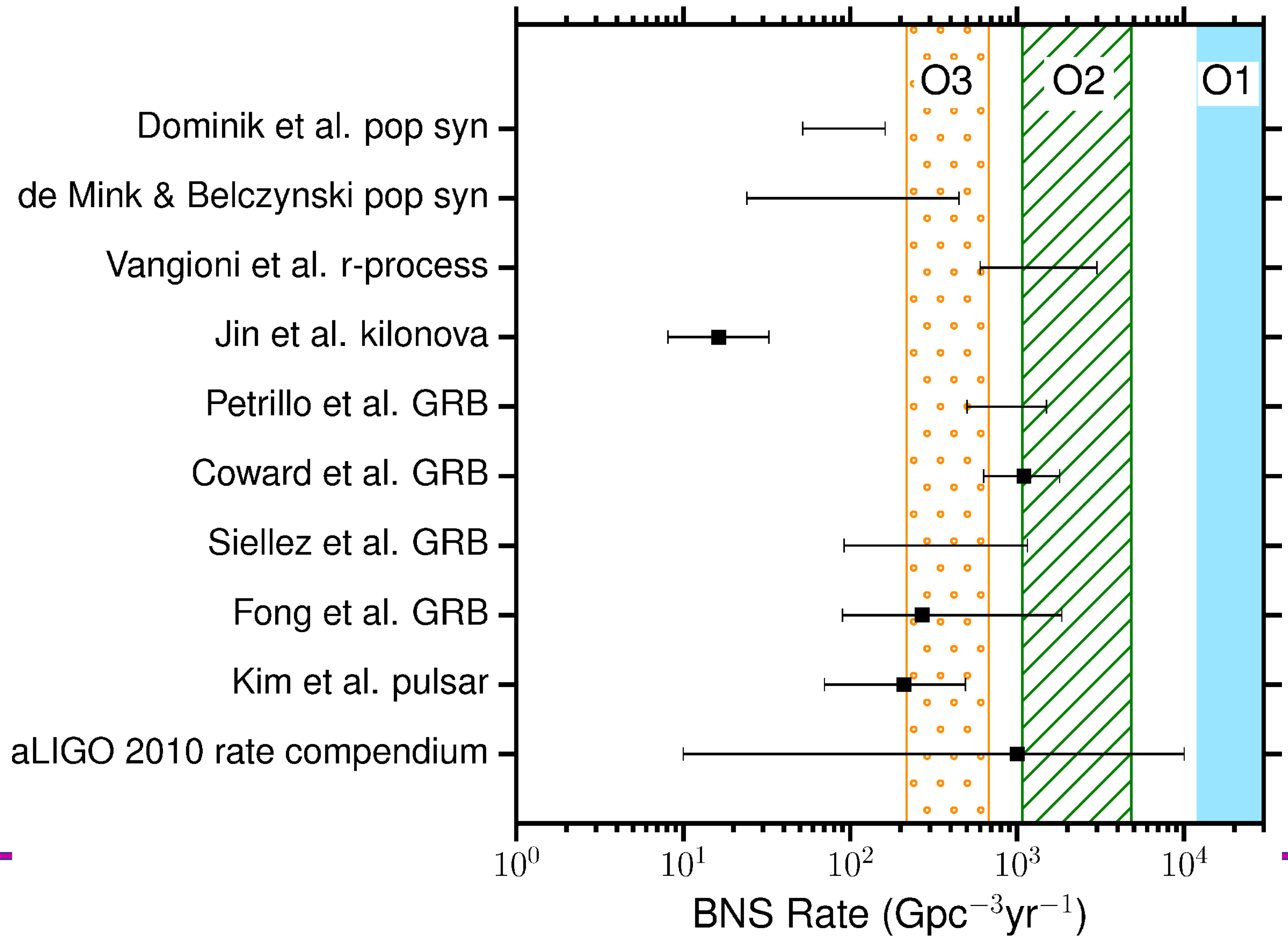

10-1.4 Msun

5-1.4 Msun

# Binary neutron stars & neutron star-black hole

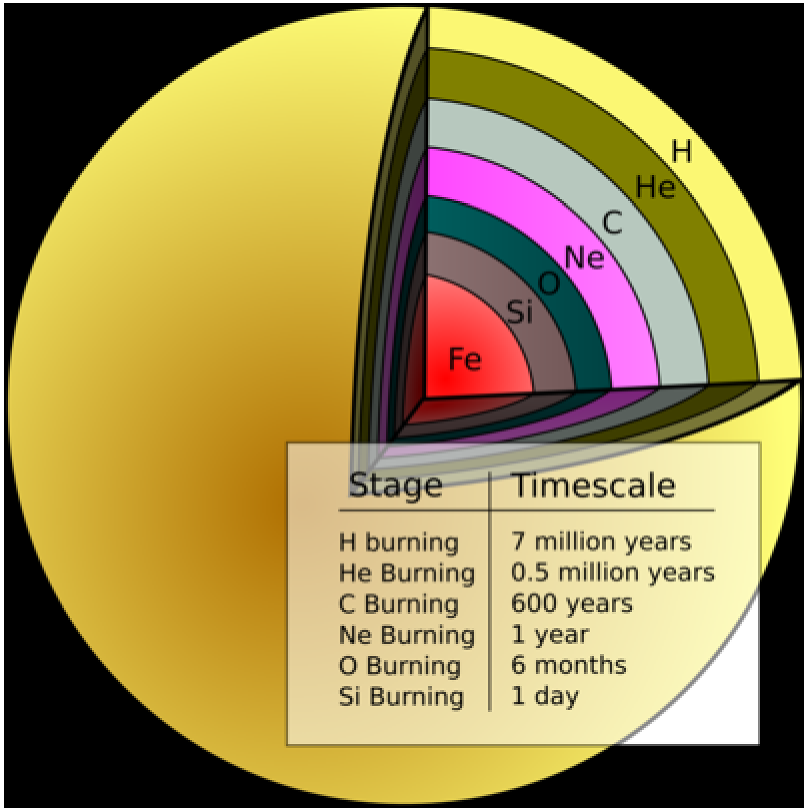
gr-qc:1607.07456

**BNS predictions**

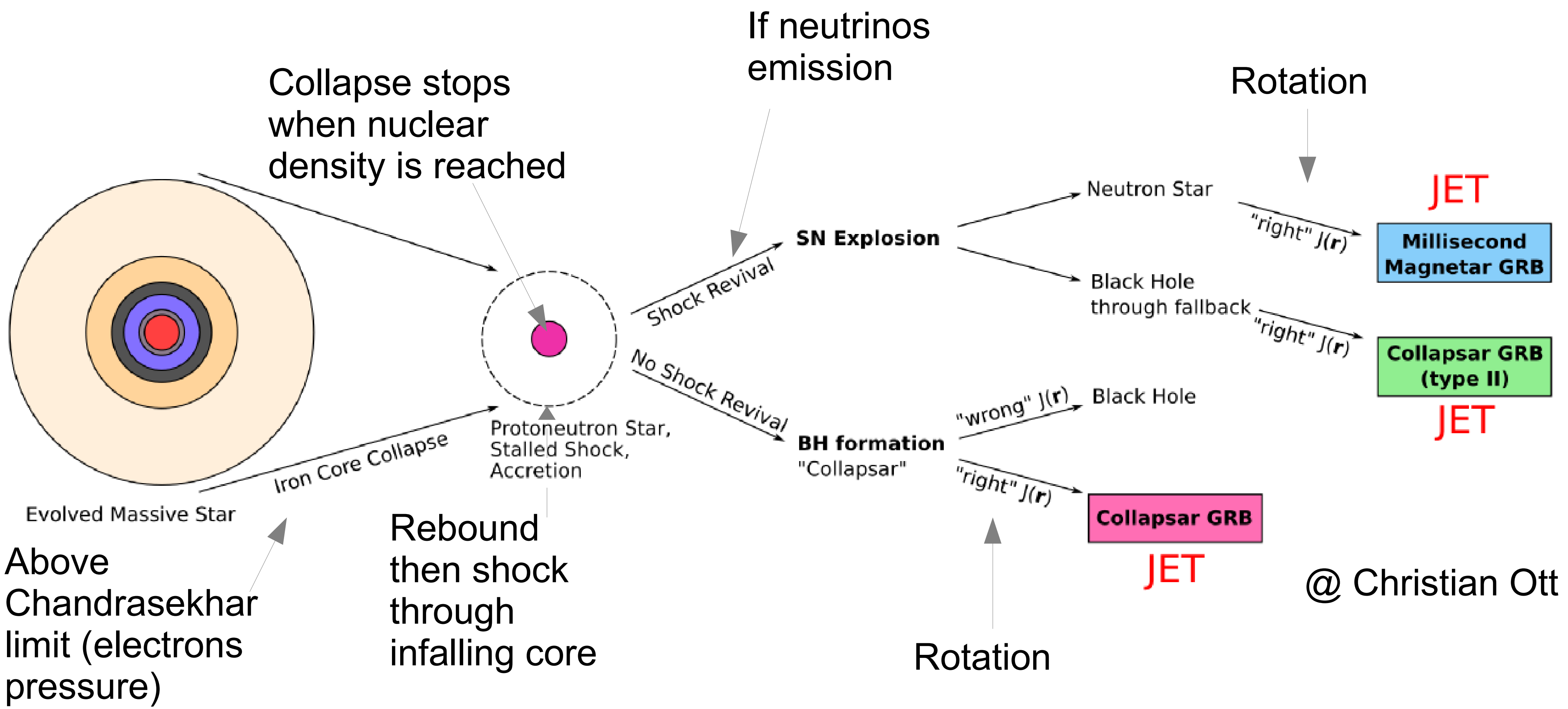


# Stellar core collapse

- Stars spend most of their lives burning hydrogen.
- Helium settles in the core and will burn when temperatures increase sufficiently
- For massive stars $(M > 8 - 10 M_{\odot})$ 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.

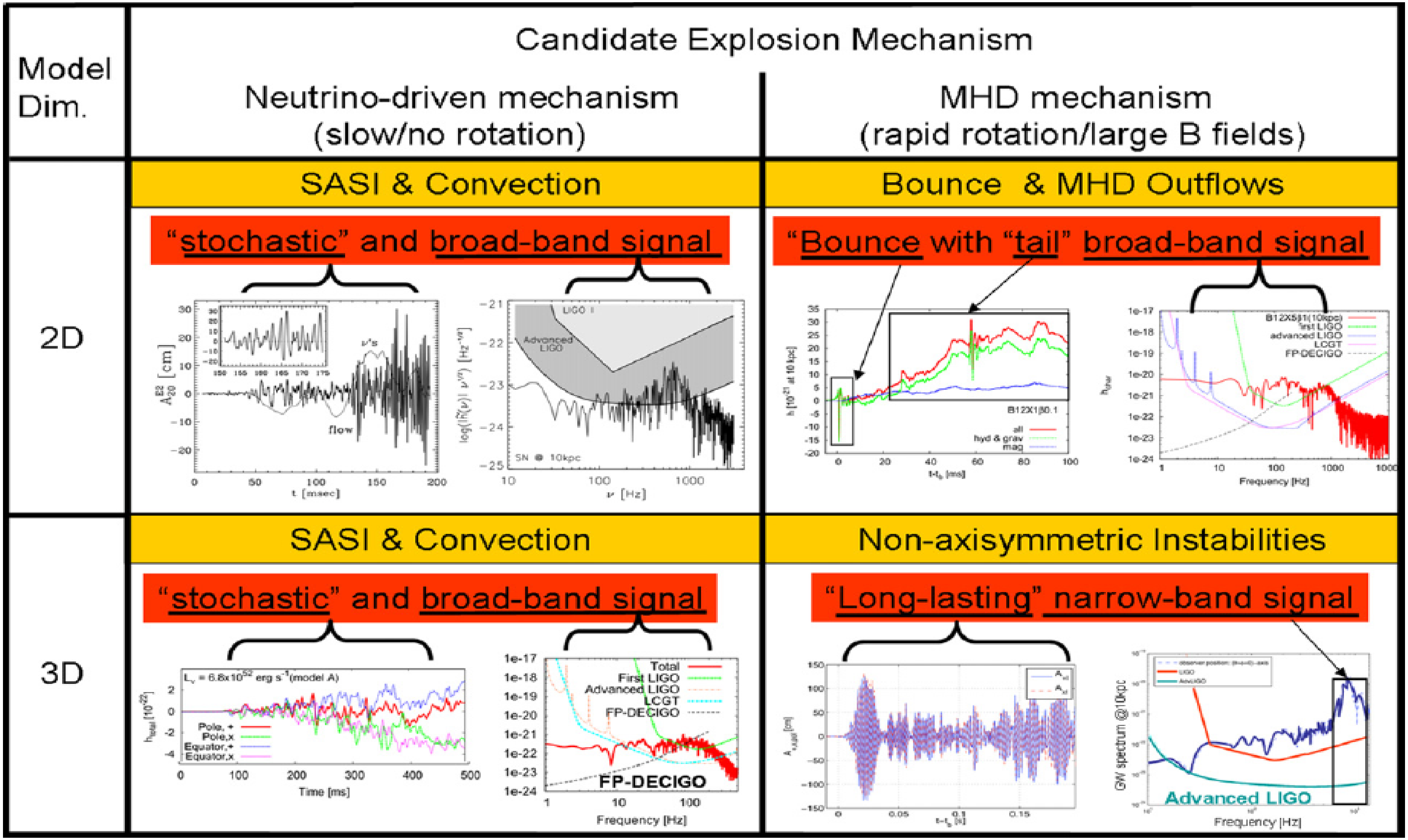


# Stellar core collapse in a nutshell



# CCSN: post-bounce waveform summary

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

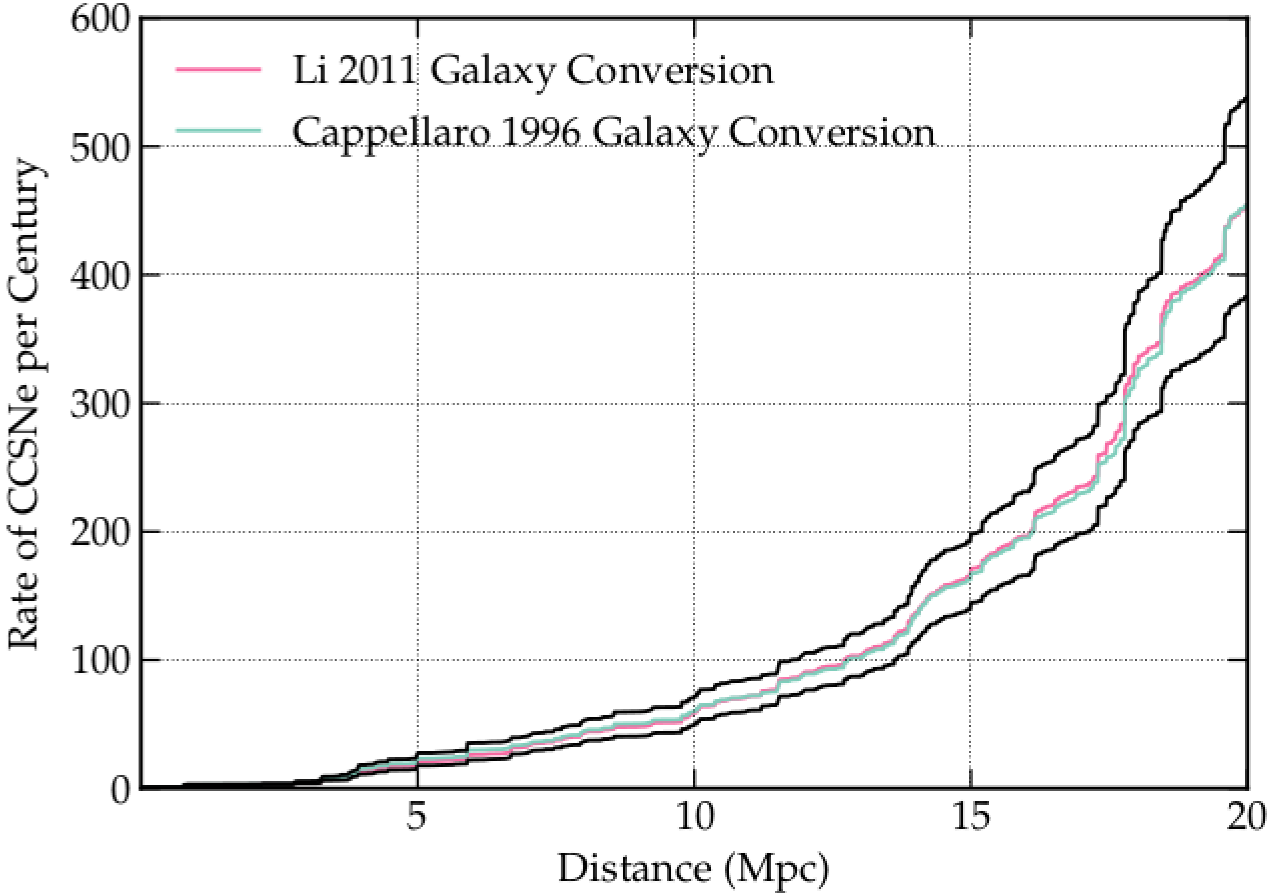


# Core collapse supernova: how far can we go & how many?

After 2020:

Distance: between 100 kpc (SASI and MHD) and 20 Mpc (extreme model like disk fragmentation and bar mode) [Gossan et al arxiv:1511.02836]

Rate : [J. Gill et al in preparation]



# Neutron star instabilities

- Supernova remnants or accreting white dwarf collapse → very rapidly rotating NS will develop non axisymetric dynamical instabilities
- The physics of NS is far from being simple. Many parameters play a role on the NS stability: equation of state for high density matter, matter superfluidity / superconducting, presence of proton, strange quarks, …)
- Pulsation normal modes: f and r modes are the most promising modes for GW emission ?
  - f-mode: fundamental (acoustic) pressure mode of the star (2-4 kHz). Rotation change frequencies. GW emission damps f-modes within ~ a tenth of a second.
  - r-modes: inertial modes due to rotation (Coriolis force). Lots of work around because have been thought to lead to high amplitude GW emission (GW radiation was thought to increase the amplitude of the mode)
  - bar mode instabilities occur when rotational kinetic ratio exceeds $\beta$=0.27
  - w-modes: pure GR effects (7 kHz) damped in a fraction of millisecond.
- GW Amplitude ? Last predictions are quite pessimistic.
- Rate? Very unclear. The fraction of very rapidly NS after a SN is not known ($10^{-6}$ /yr/galaxy ?)

# Black hole ringdown

- A BH that is distorted from its stationary Kerr configuration will radiate GW that drive it back to the stationary state (hair loss theorem)
- A BH formed in core collapse will certainly be distorted: if large amounts of matter accrete onto it, it will continually driven into new states of distortion.
- Waveform (perturbation theory): Quasi-normal mode $e^{-t/\tau}\sin(2\pi f t)$
- BH spectroscopy: deduce the BH parameters (mass M, spin a) from QNM parameters (f, τ).

$$2\pi f = \frac{1}{M}\left[1-0.63\left(1-\frac{a}{M}\right)^{0.3}\right] \qquad \tau = \frac{4}{2\pi f\left(1-\frac{a}{M}\right)^{0.45}}$$

- GW amplitude: $h \approx 5.10^{-22}\left(\frac{E}{10^{-3}M_{\otimes}c^2}\right)^{1/2}\left(\frac{1kHz}{f}\right)^{1/2}\left(\frac{15Mpc}{r}\right)$

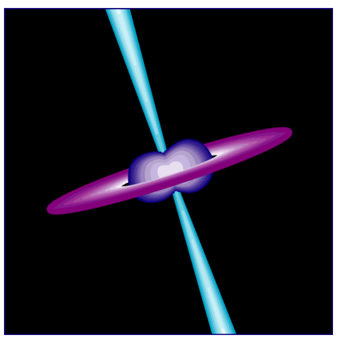
# Multi-messenger searches – what for?

- 2 modes: EM events "triggered" GW searches & GW transient EM follow-ups
- Triggered searches: one knows time, position (sometimes distance) and some info about the putative GW signal to search → tune an "all-sky/all-time" generic unmodelled burst search. What do we gain?
  - Background reduction (parameter space reduction) → tackle weaker GW signals.
  - Combined information may infer astrophysical information about the source
  - Non detection GW results may rule out models
- EM follow-ups: prompt (<1mn) GW searches to identify possible GW candidates and reconstruct their sky position to send alerts for EM transient follow-ups that would be missed

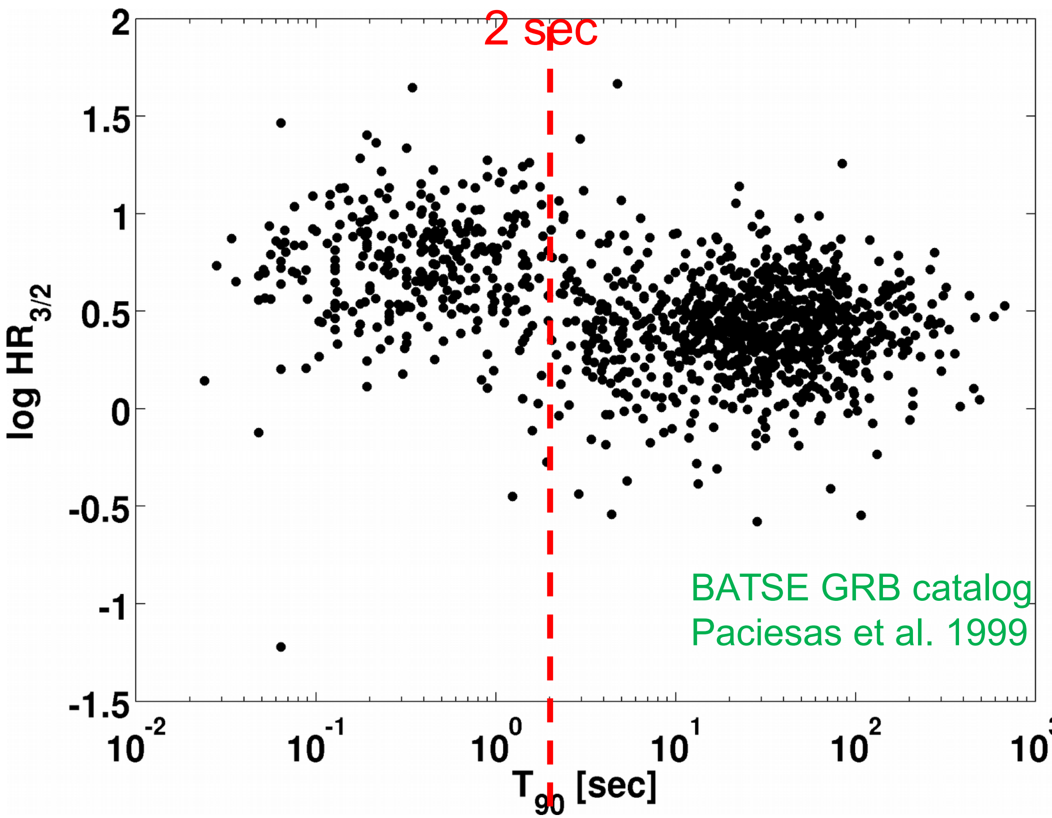
# Transient GW events & “electro-magnetic” transients

GRBs

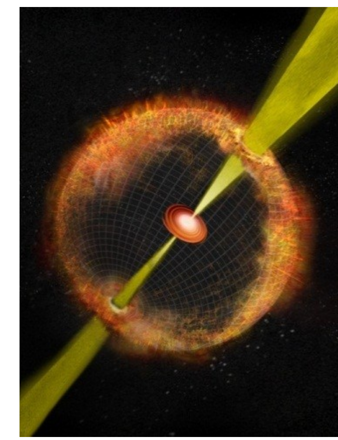
## Short - Hard GRBs



NS-NS merger




## Long - Soft GRBs



Most thought to be from binary mergers involving a neutron star

Some from giant flares from soft gamma repeaters (magnetars)

Most thought to be from the collapse of high-mass stars with rapidly rotating cores

Supernovae seen in some cases

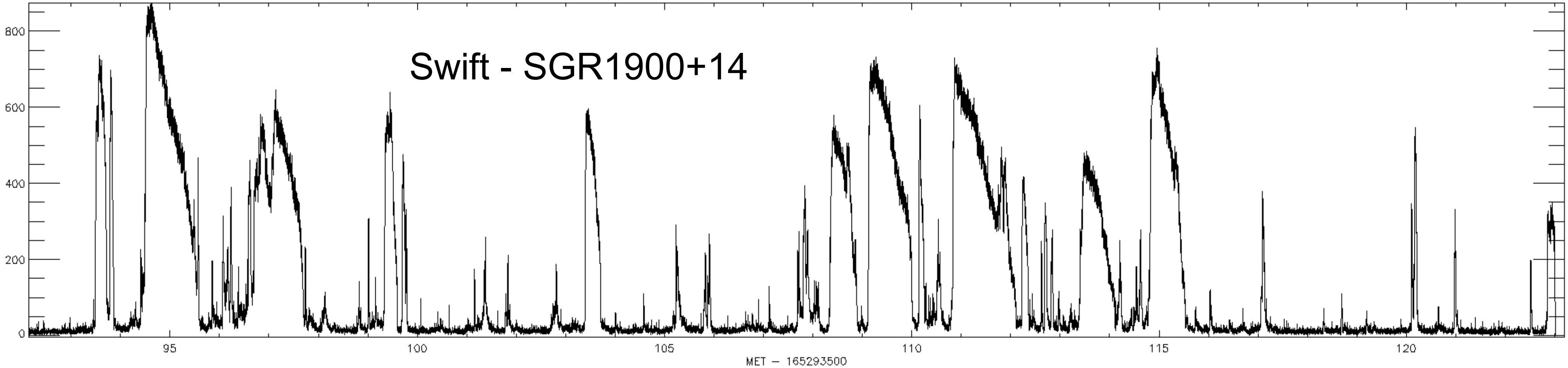
# Transient GW events & “electro-magnetic” transients

Magnetar flares: Soft Gamma Ray Repeaters (SGRs) & anomalous X-ray pulsars (AXPs) are believed to be magnetars (NS with $B>10^{15}$ G):

- Occasionally emit flares of soft gamma-rays $E_{EM}=10^{42}$ erg.
- Some SGRs produce giant flare with energy up to $10^{46}$ erg (burst <0.2 s)
- Giant flare could be related to cracking of the crust (star quake). Possible excitation of vibrational modes (quasi-periodic oscillations seen in X-ray detectors)

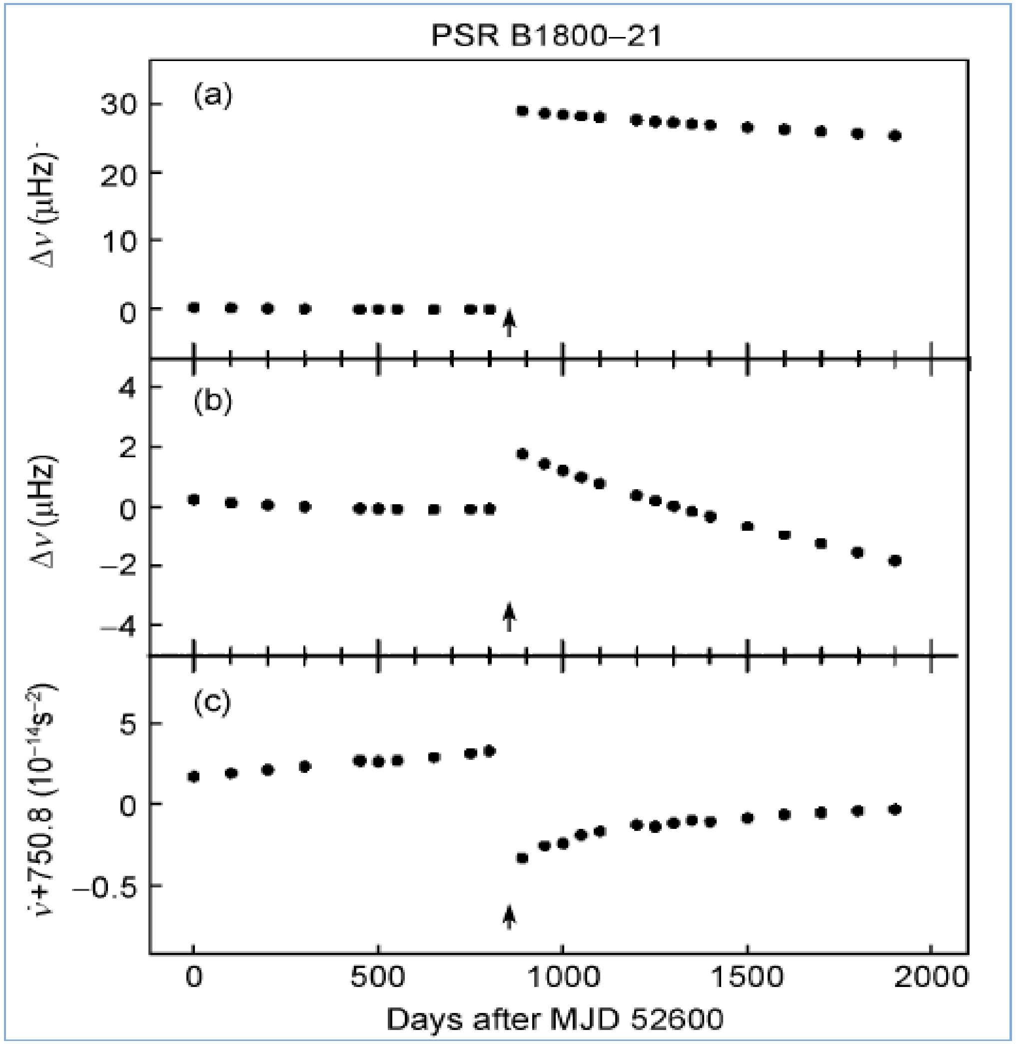
→ may excite non-radial oscillation modes that couple to GW emission.

40 bursts in 30 s



# Transient GW events & “electro-magnetic” transients

Pulsar glitches: frequency glitch observed in some young pulsars.




The mechanism is not clear but some scenario has been proposed:

- crust craking (star quake)

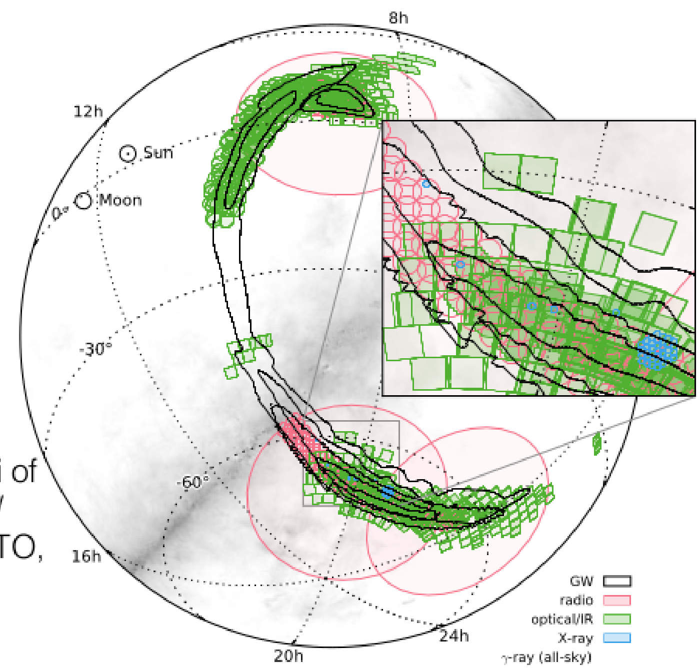
- superfluid-crust interaction

→ normal mode of the NS excitation that couples with GW emission.

→ GW search assuming damped normal mode waveforms

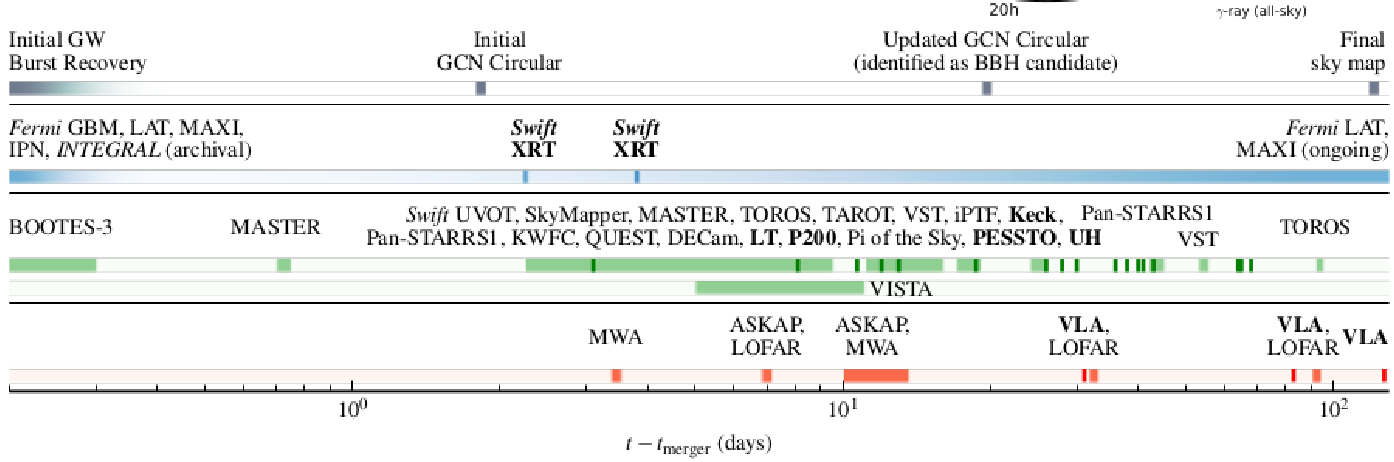
# EM follow up

LOCALIZATION AND
BROADBAND FOLLOW-UP
OF THE GRAVITATIONAL-WAVE
TRANSIENT GW150914

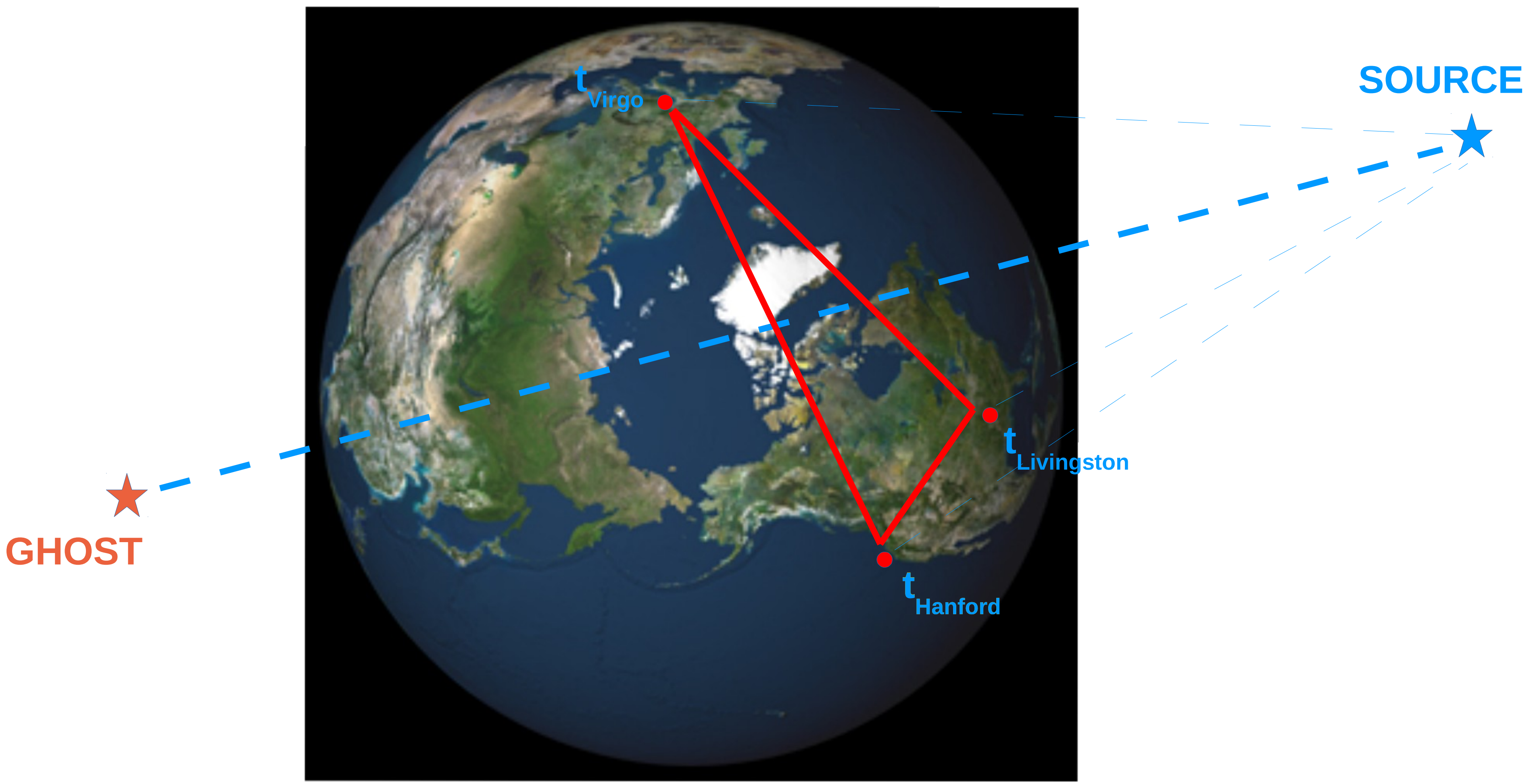



25 observing teams

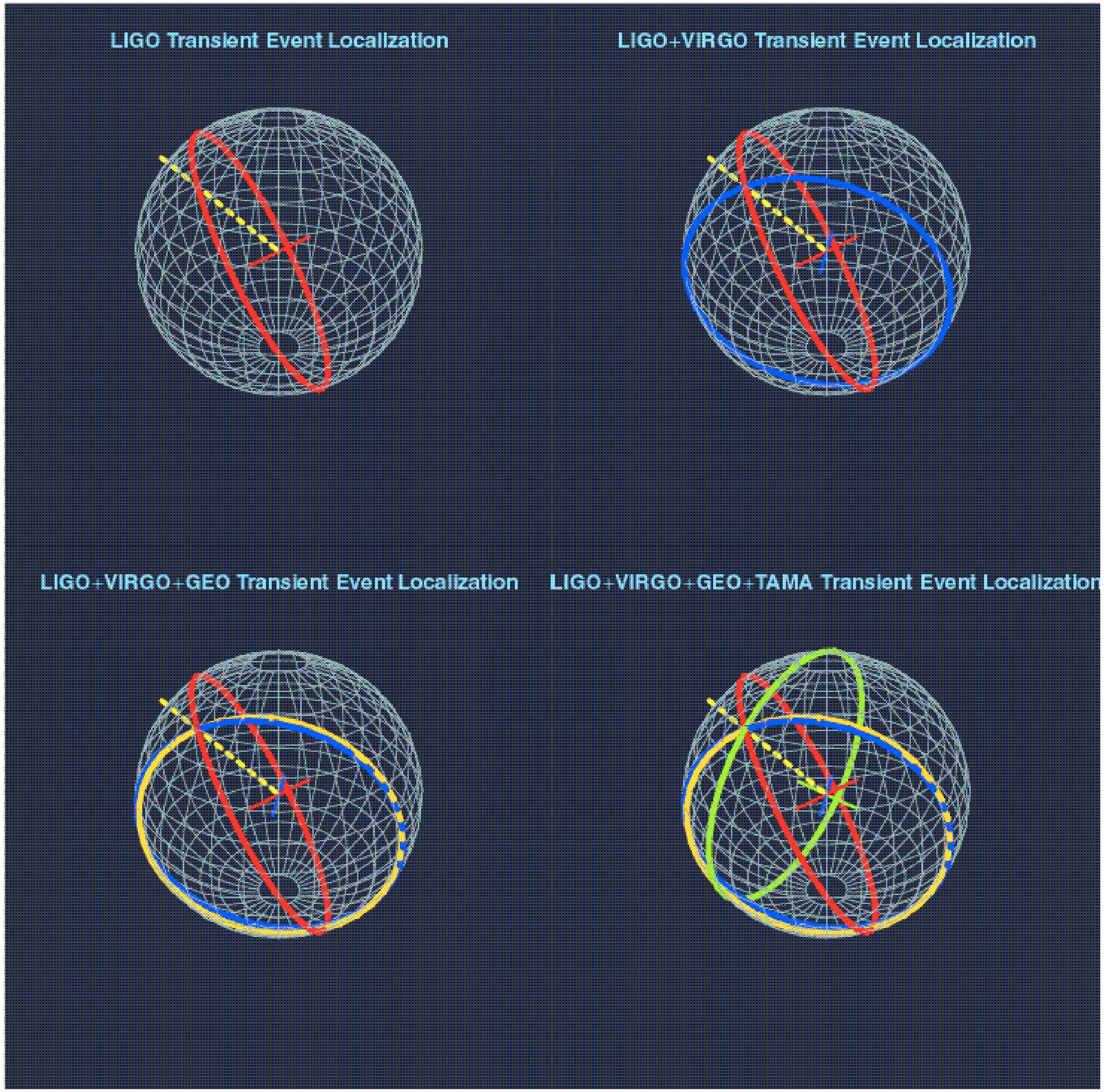
ASKAP, LOFAR, MWA, Fermi/GBM, Fermi/LAT, INTEGRAL, IPN, Swift, MAXI, BOOTES, MASTER, Pi of the Sky, DES/DECam, INAF/GRAWITA, iPTF, J-GEM/KWFC, La Silla–QUEST, Liverpool Telescope, PESSTO, Pan-STARRS, SkyMapper, TAROT, Zadko, TOROS, VISTA



# Source sky localisation



# Source sky localisation

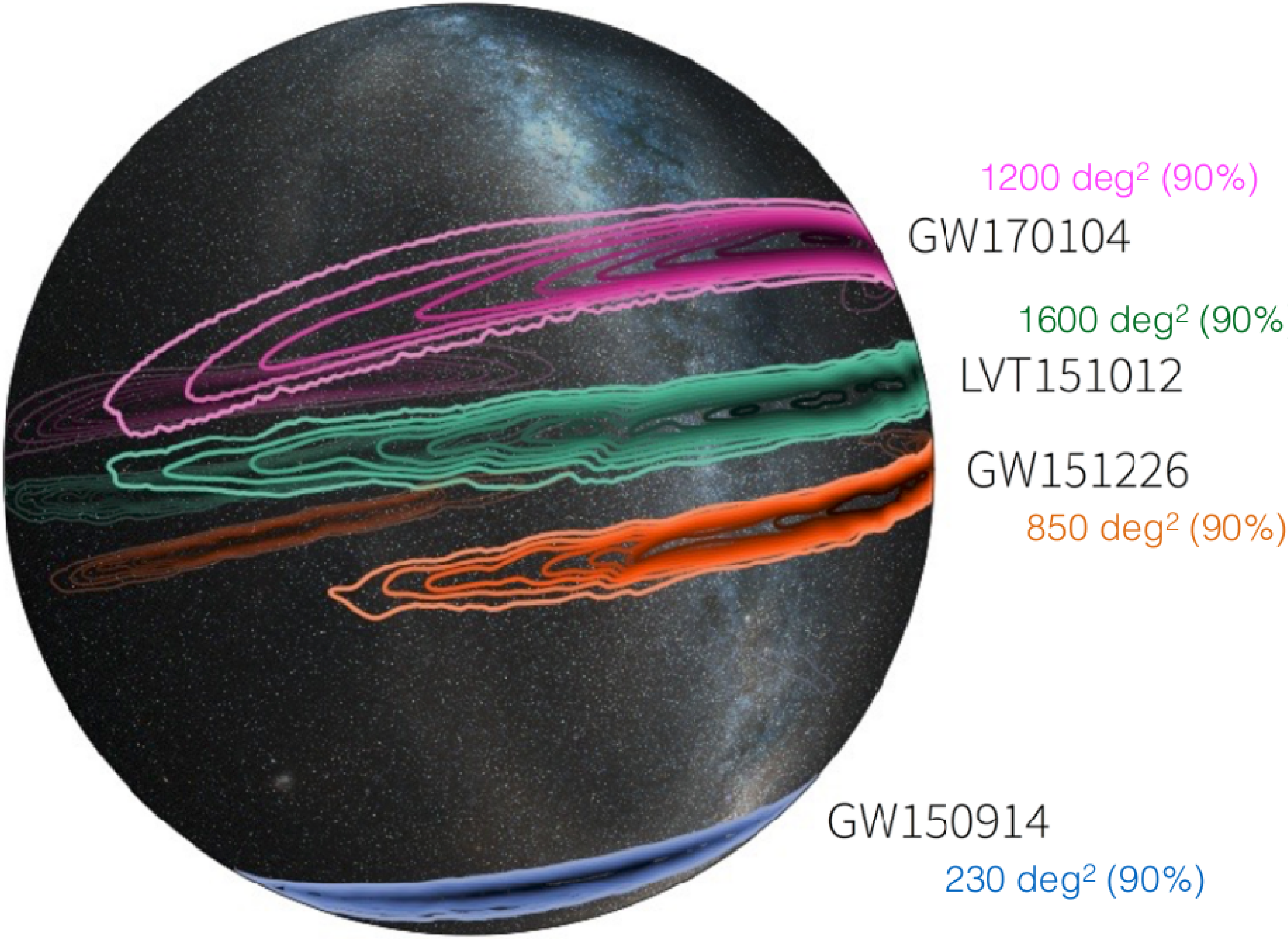



- 2 detectors → circle in sky
- Timing triangulation provides leading order estimates: error dominated by timing uncertainty: $\sigma_t \sim \frac{1}{2\pi\rho\sigma_f}$

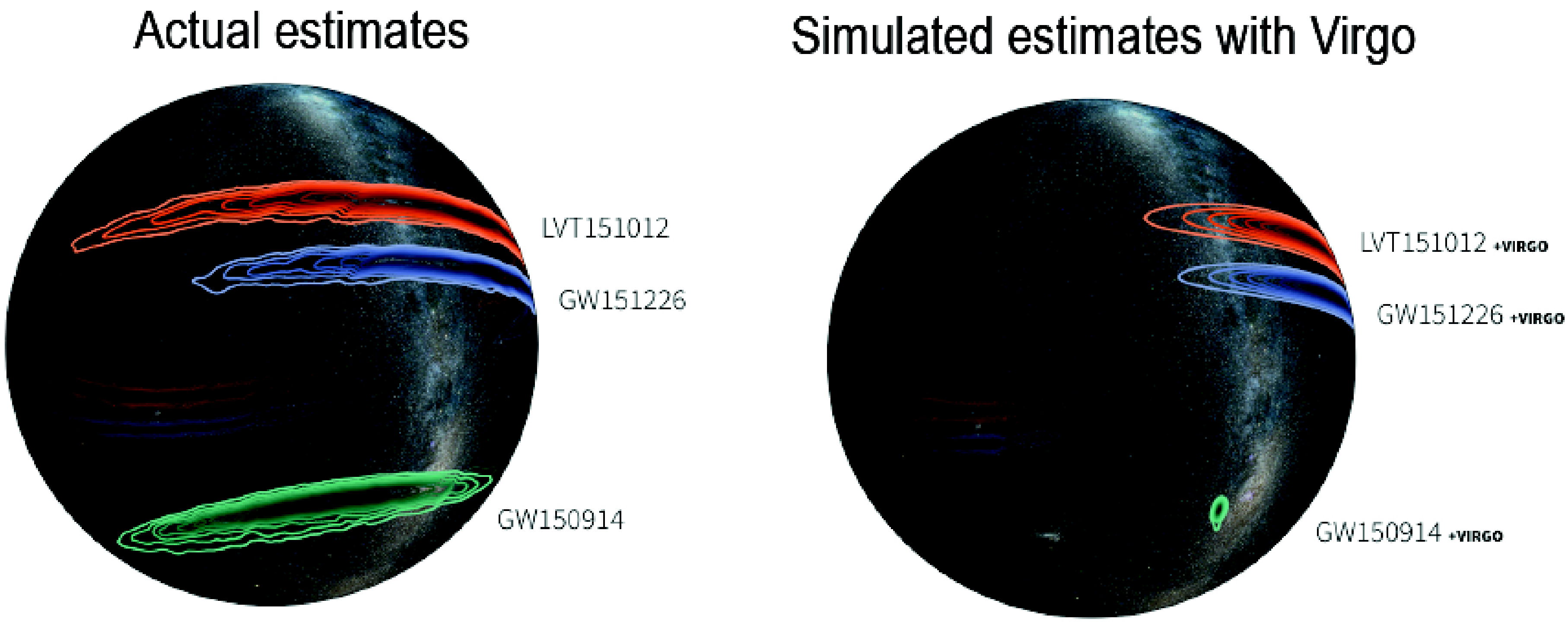
  → tens of square degrees

  → better resolution at high frequency
- Coherent analysis inverse problem by-product

# Sky localization – 2 detectors case

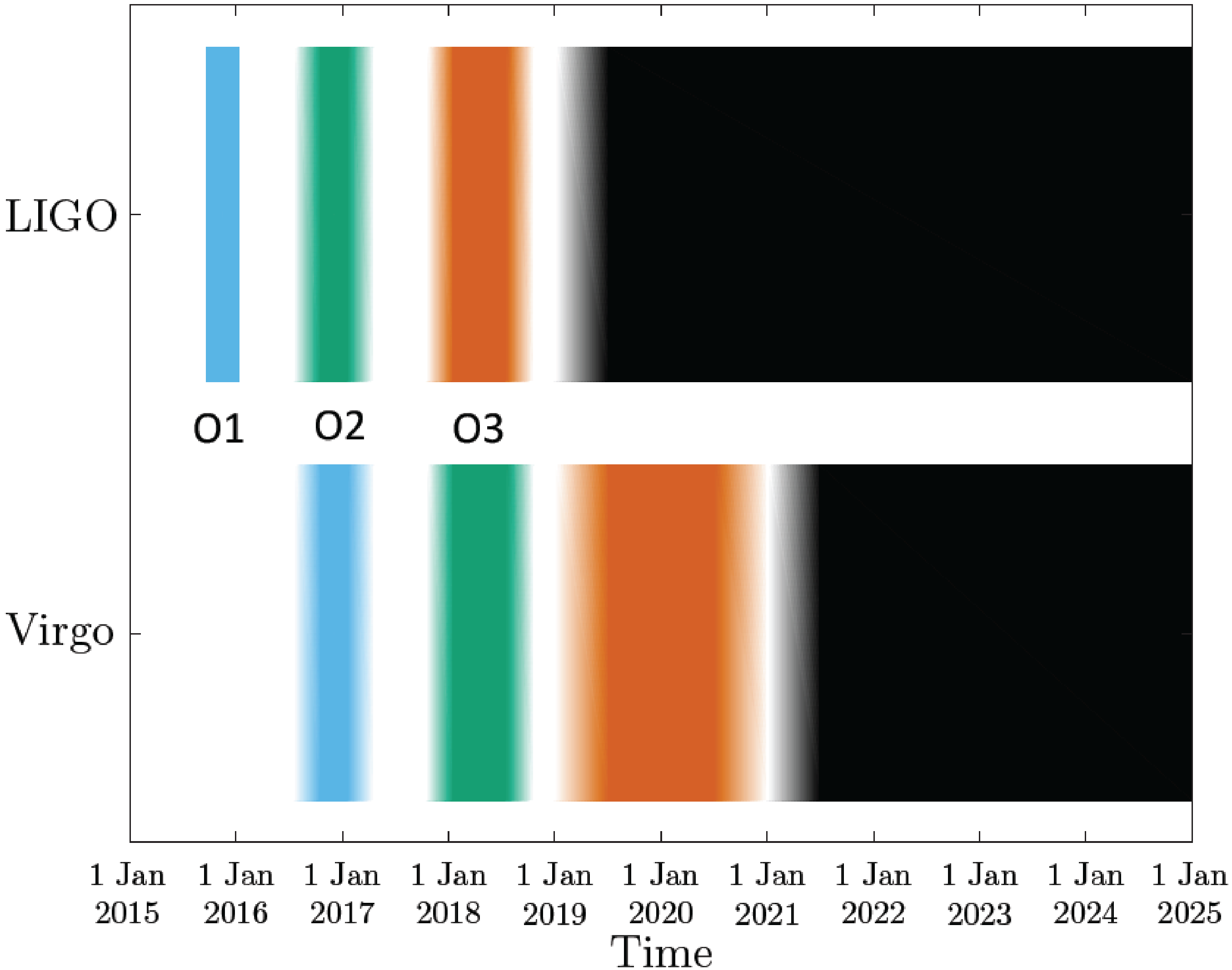


# Sky localization: more detectors needed!




3-D projection of the Milky Way onto a transparent globe shows the probable locations of confirmed detections GW150914 (green), and GW151226 (blue), and the candidate LVT151012 (red). The outer contour for each represents the 90 percent confidence region while the innermost contour is the 10 percent region.
Image credit: LIGO/Axel Mellinger

# Near term observing plan



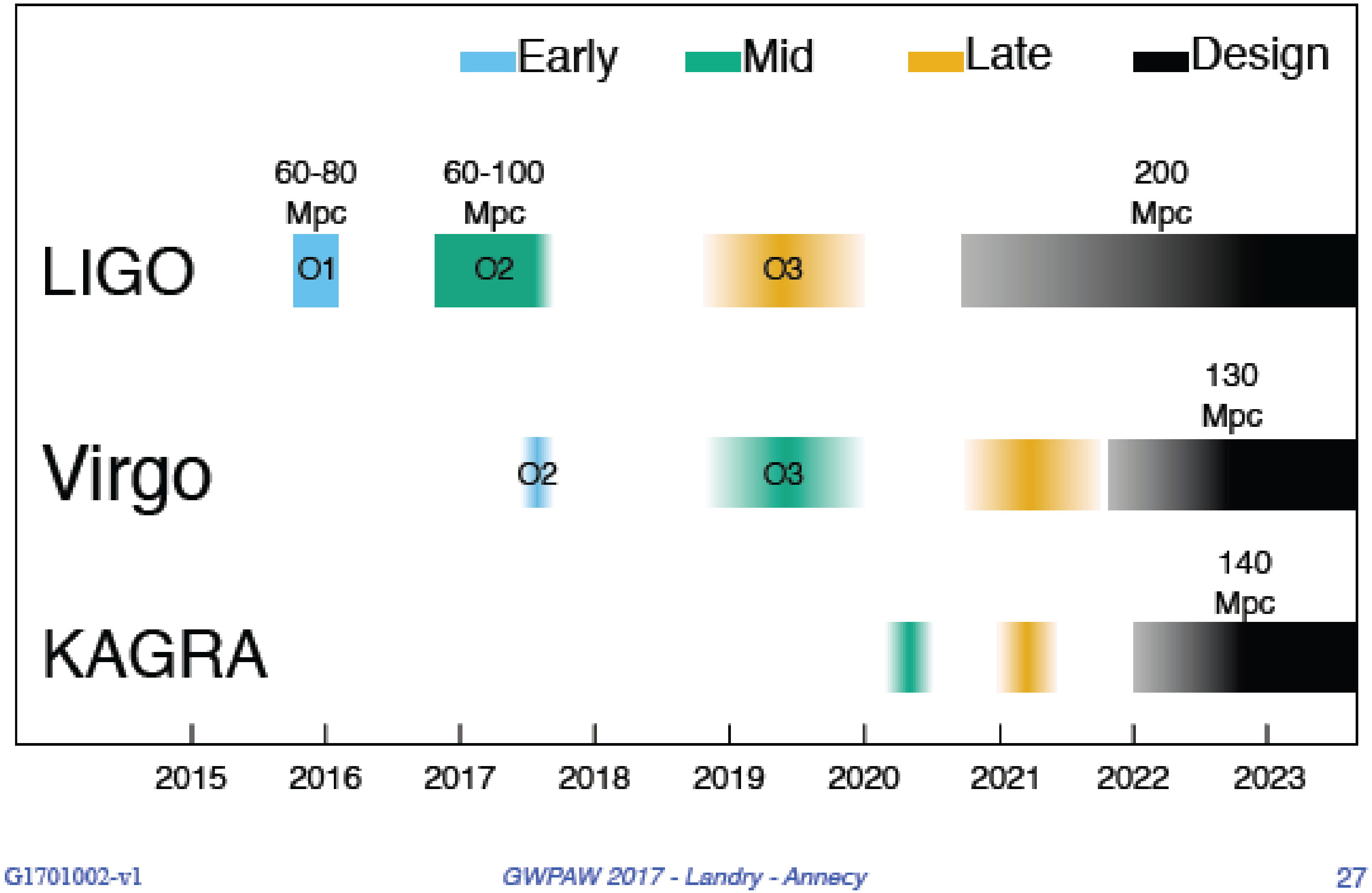

- Early (2015 – 16, 40 – 80 Mpc)
- Mid (2016 – 17, 80 – 120 Mpc)
- Late (2017 – 18, 120 – 170 Mpc)
- Design (2019, 200 Mpc)
- BNS-optimized (215 Mpc)

orientation-averaged distance for BNS detection with SNR = 8

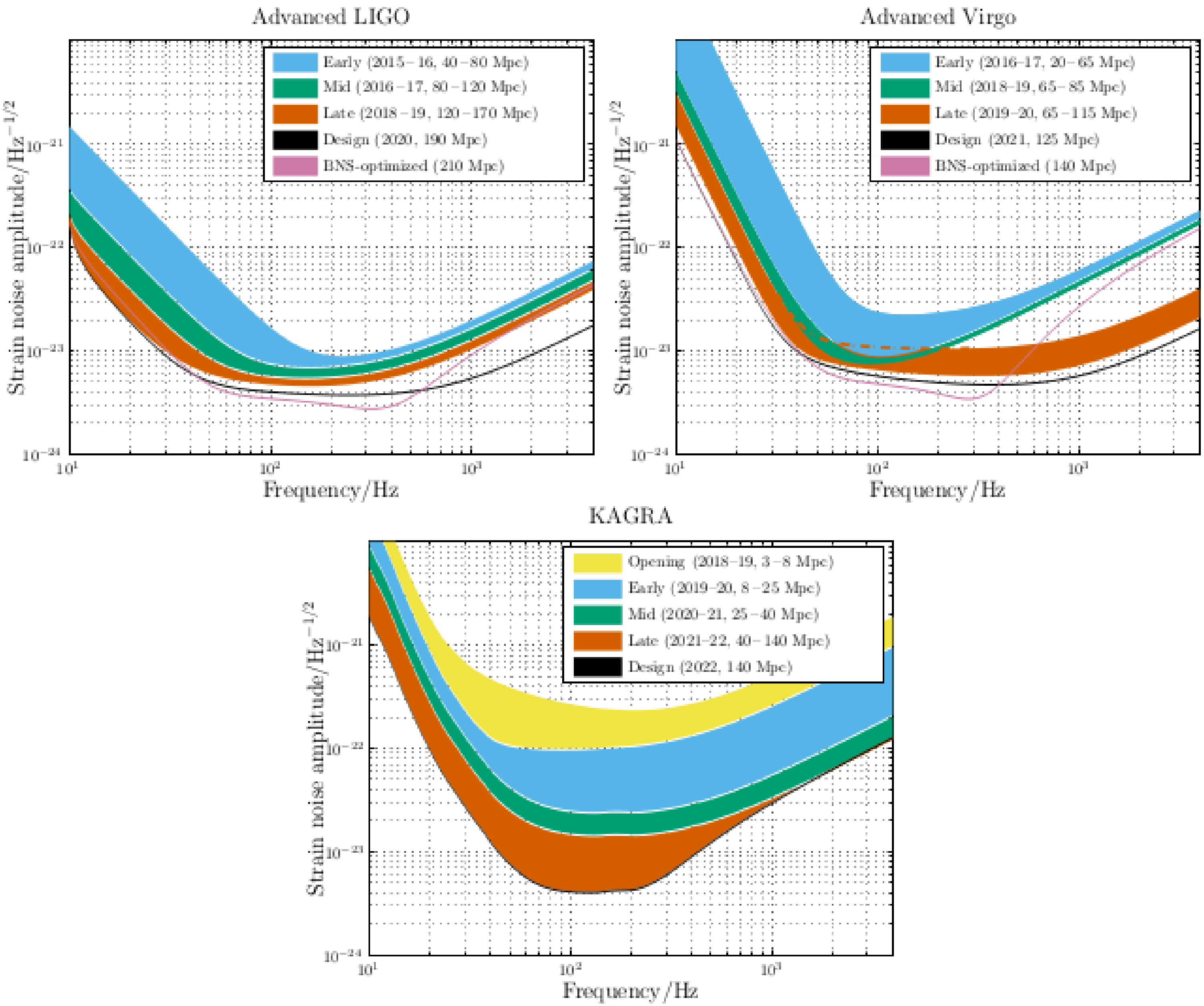
- Early (2016–17, 20 – 60 Mpc)
- Mid (2017–18, 60 – 85 Mpc)
- Late (2018–20, 65 – 115 Mpc)
- Design (2021, 130 Mpc)
- BNS-optimized (145 Mpc)

Living Rev. Relativity 19 (2016), 1

# LIGO – Virgo - KAGRA



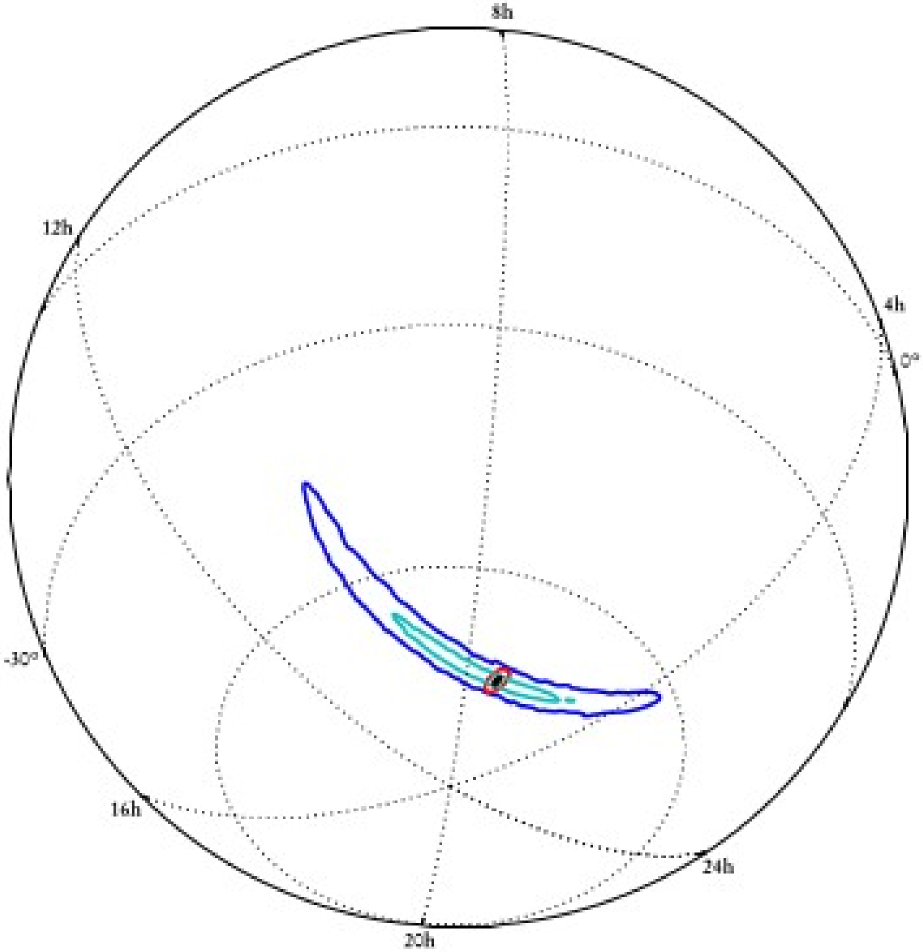
# Network performance



# Network performance

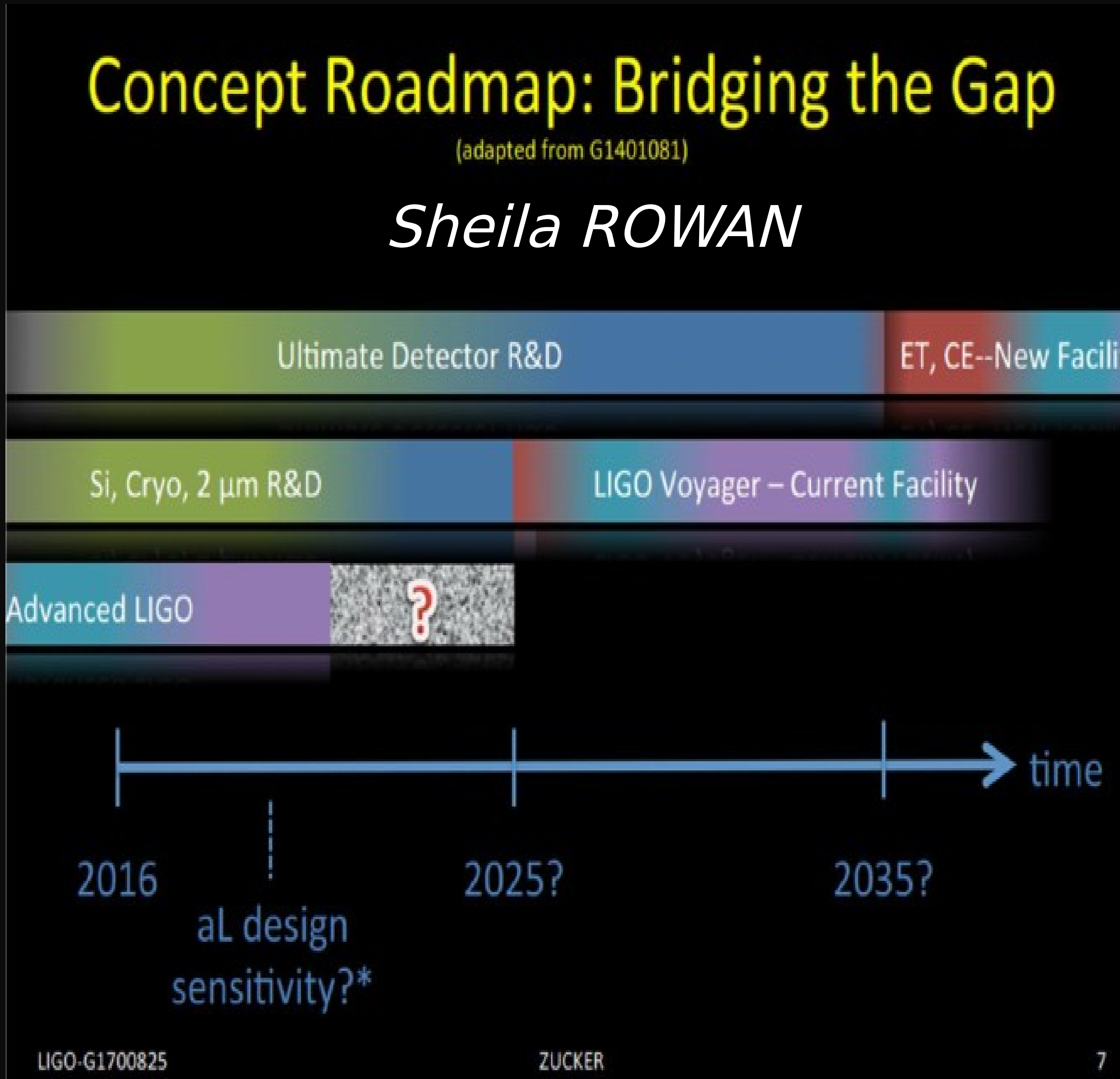
| Epoch | | | 2015 – 2016 | 2016 – 2017 | 2018 – 2019 | 2020+ | 2024+ |
|---|---|---|---|---|---|---|---|
| Planned run duration | | | 4 months | 9 months | 12 months | (per year) | (per year) |
| Expected burst range/Mpc | | LIGO | 40 – 60 | 60 – 75 | 75 – 90 | 105 | 105 |
| | | Virgo | — | 20 – 40 | 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 | 68 – 78 | — | — | — | — |
| | | Virgo | — | — | — | — | — |
| | | KAGRA | — | — | — | — | — |
| Estimated BNS detections | | | 0.002 – 2 | 0.007 – 30 | 0.04 – 120 | 0.1 – 200 | 0.4 – 400 |
| Actual BNS detections | | | 0 | — | — | — | — |
| 90% CR | % within | 5 $\mathrm{deg}^2$ | $< 1$ | 2 | $> 1 – 2$ | $> 3 – 8$ | $> 20$ |
| | | 20 $\mathrm{deg}^2$ | $< 1$ | 14 | $> 10$ | $> 8 – 30$ | $> 50$ |
| | | median/$\mathrm{deg}^2$ | 480 | 230 | — | — | — |
| Searched area | % within | 5 $\mathrm{deg}^2$ | 6 | 20 | — | — | — |
| | | 20 $\mathrm{deg}^2$ | 16 | 44 | — | — | — |
| | | median/$\mathrm{deg}^2$ | 88 | 29 | — | — | — |

# Network performance



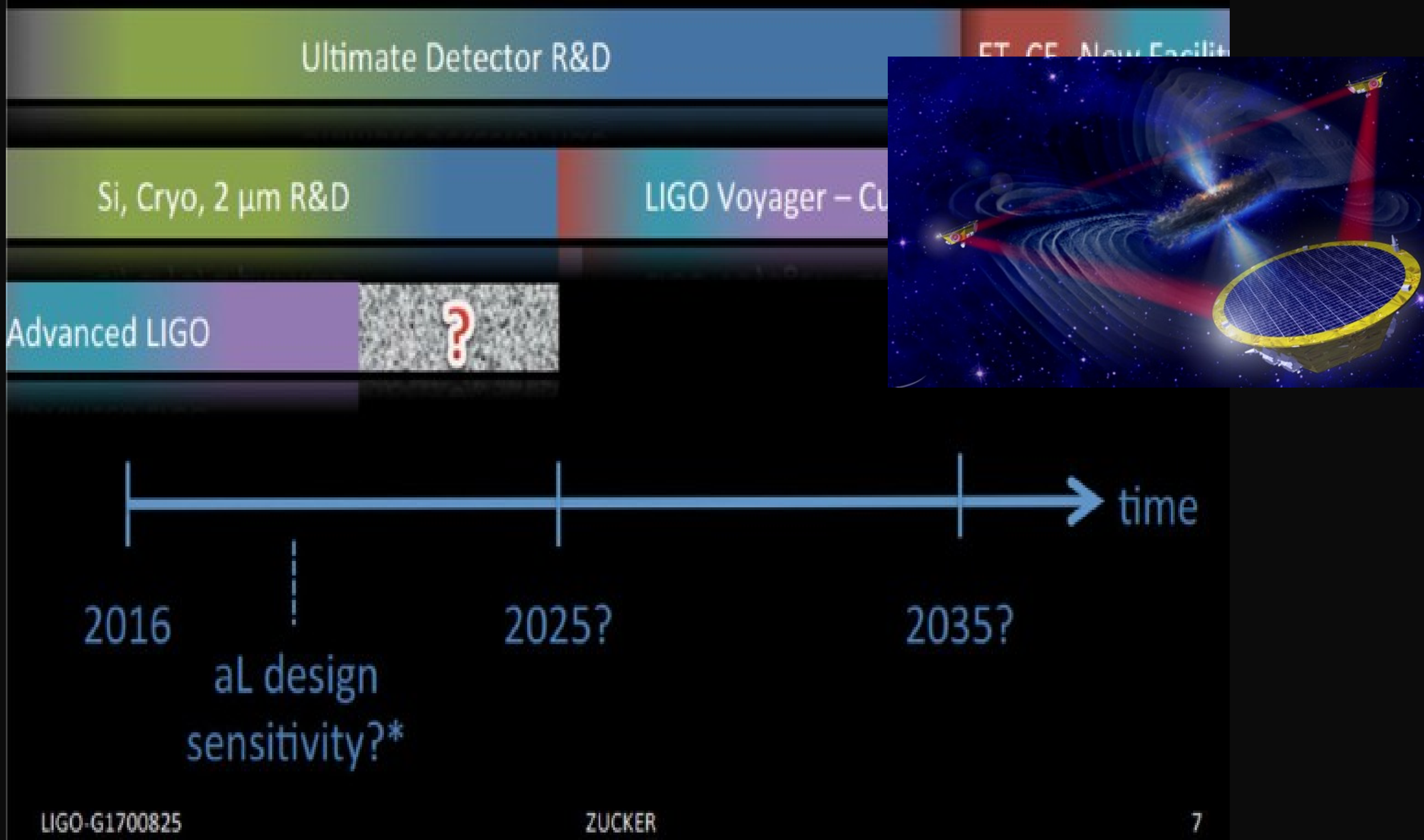

GW150914 like signal

O1 H + L
Design H + L
O2 H + L + V
Design H + L + V




*Sheila ROWAN*

# . . . and LISA


Ultimate Detector R&D
Si, Cryo, 2 µm R&D
LIGO Voyager –
Advanced LIGO
?
time
2016
2025?
2035?
aL design
sensitivity?*
LIGO-G1700825
ZUCKER
7