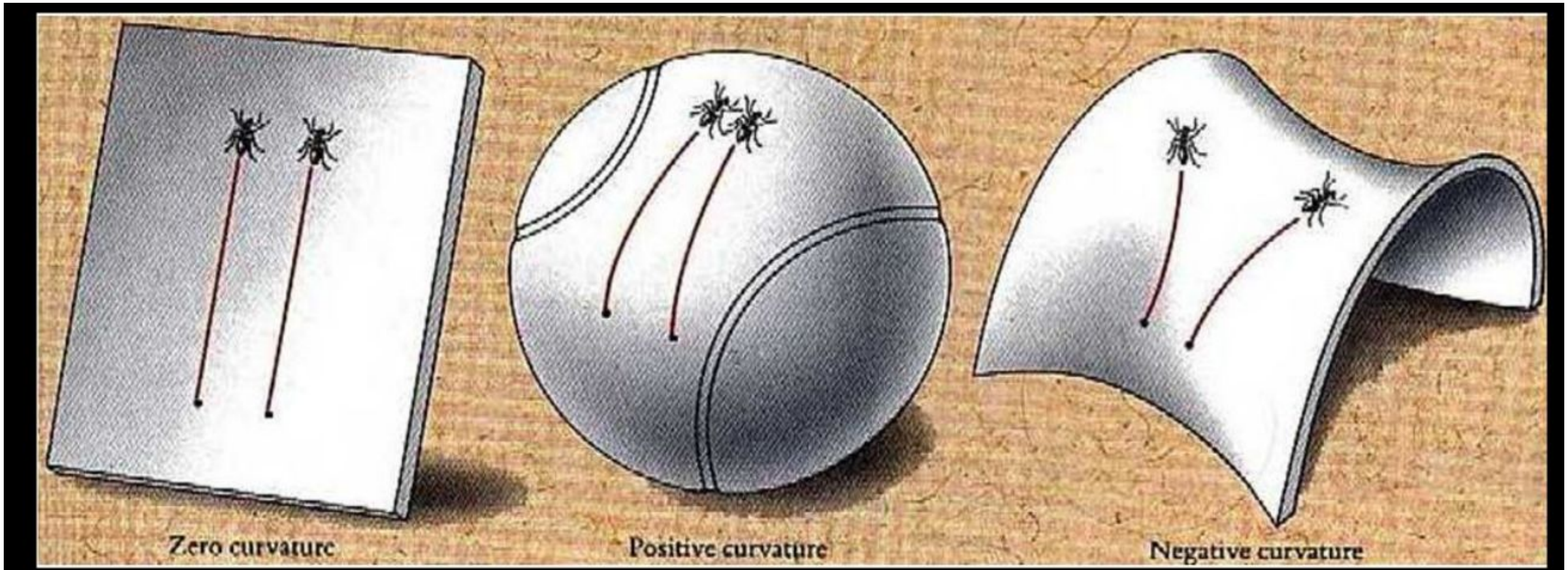
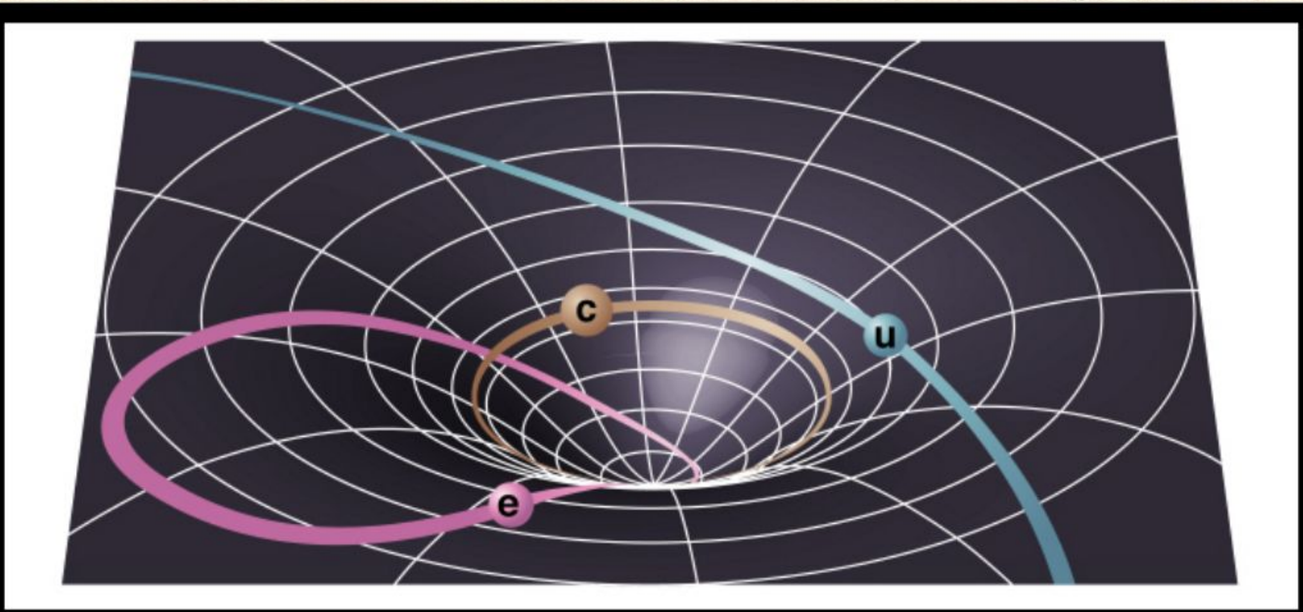
LIGO-Virgo-KAGRA gravitational-wave sources and observational results

Michal Bejger (for the LIGO-Virgo-KAGRA collaboration)
GEMMA2 16–19 September 2024 Rome, Italy

Gravity = geometry



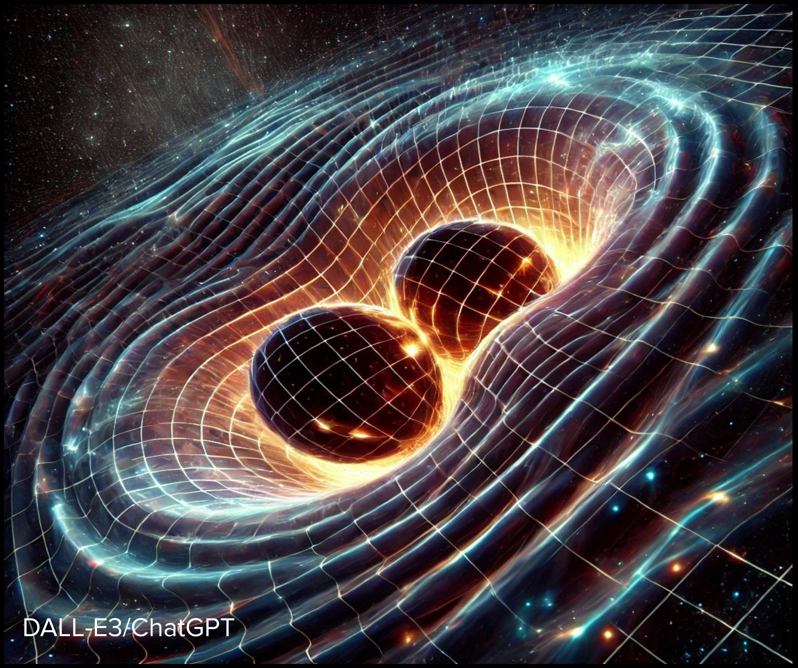


Gravitational waves

$$\underbrace{R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu}}_{\text{geometry}} = \underbrace{\frac{8\pi G}{c^4} T_{\mu\nu}}_{\text{mass-energy}}$$

Einstein (1916) - solution to GR equations that looks like waves *(time-varying changes of curvature propagating with the speed of light)*:

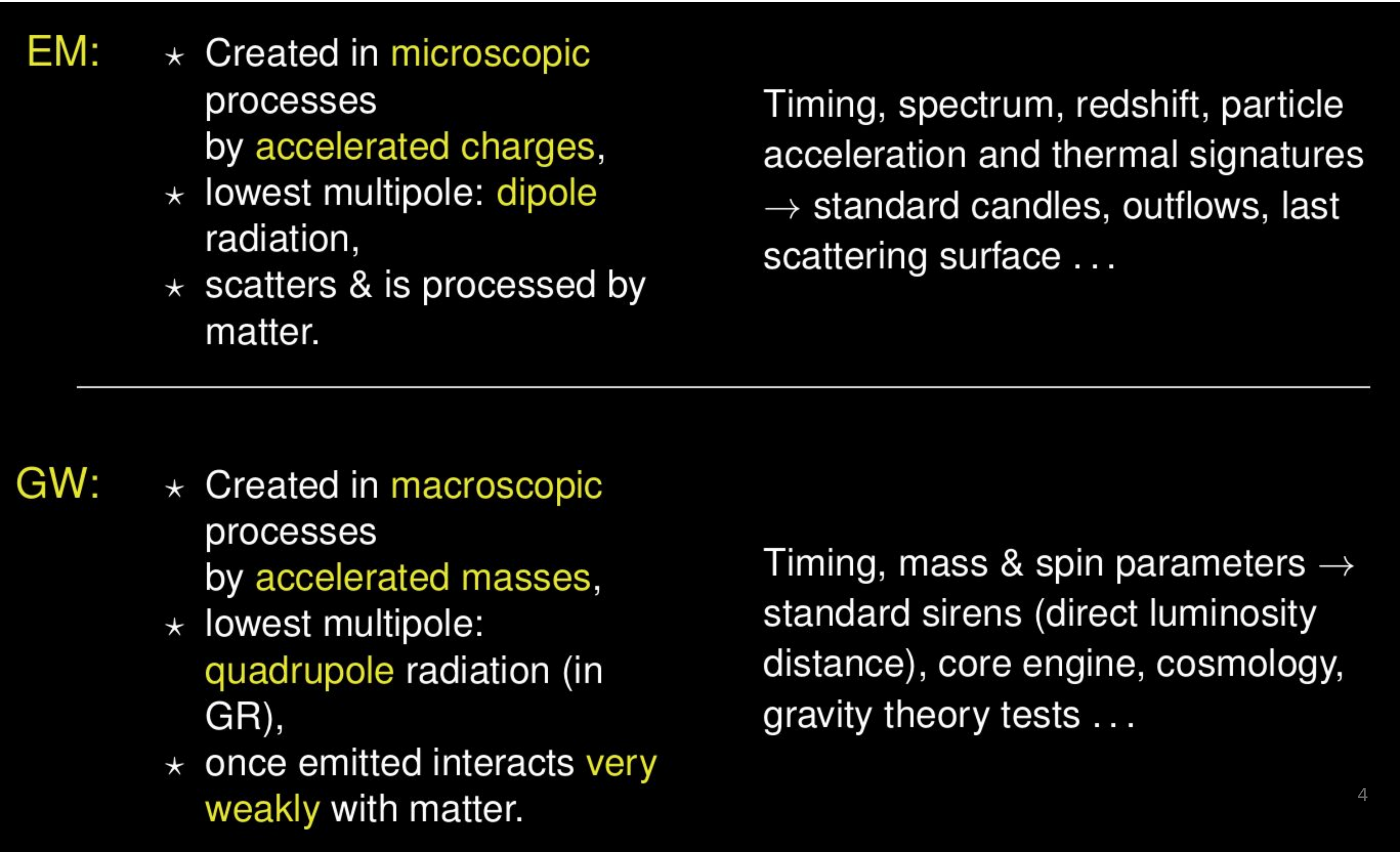
- ⋆ quadrupole nature,
- ⋆ transverse waves,
- ⋆ generated by accelerated movement of charges (masses),
- ⋆ two independent polarizations (+ and ×).



DALL-E3/ChatGPT

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

Electromagnetic vs gravitational waves



EM:

- ⋆ Created in microscopic processes by accelerated charges,
- ⋆ lowest multipole: dipole radiation,
- ⋆ scatters & is processed by matter.

Timing, spectrum, redshift, particle acceleration and thermal signatures → standard candles, outflows, last scattering surface . . .

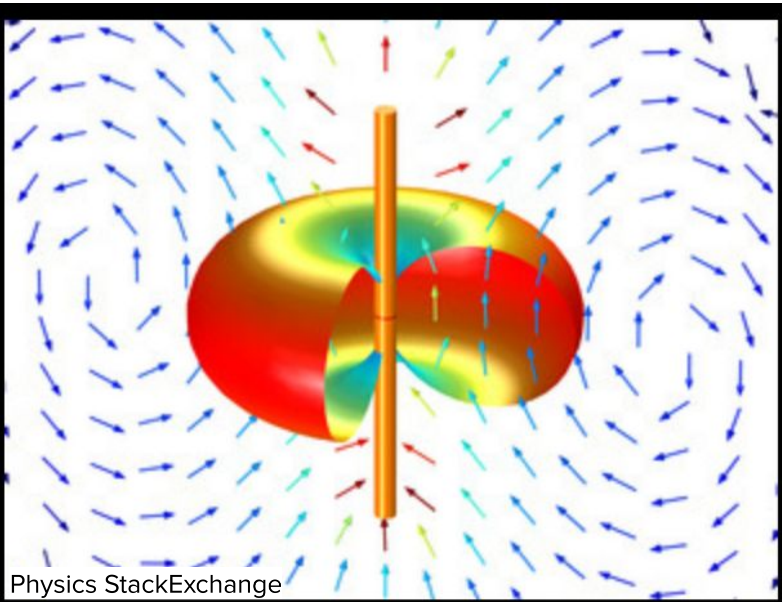
GW:

- ⋆ Created in macroscopic processes by accelerated masses,
- ⋆ lowest multipole: quadrupole radiation (in GR),
- ⋆ once emitted interacts very weakly with matter.

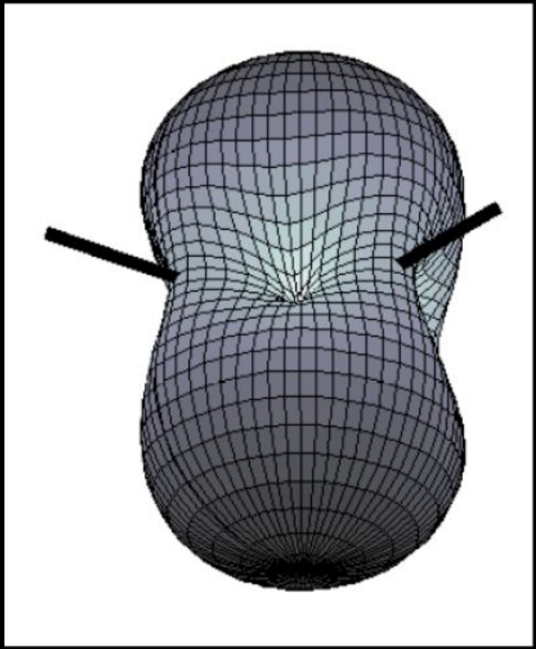
Timing, mass & spin parameters → standard sirens (direct luminosity distance), core engine, cosmology, gravity theory tests . . .

Interferometer = GW antenna

Very precise ruler to measure distances between free-falling bodies using laser light



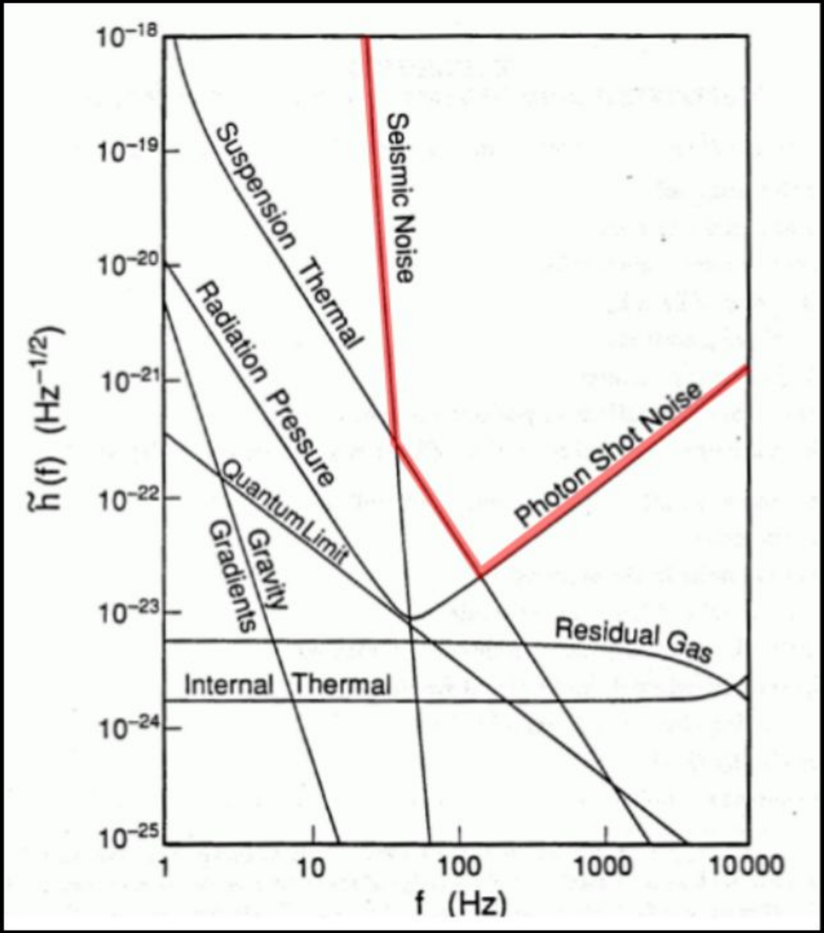
Physics StackExchange



Wikimedia Commons,
Schwarzbeck Mess-Elektronik

© LIGO Hanford, LIGO Livingston, Virgo, KAGRA, GEO600

Ground-based detector broadband sensitivity



Initial LIGO proposal (1989)

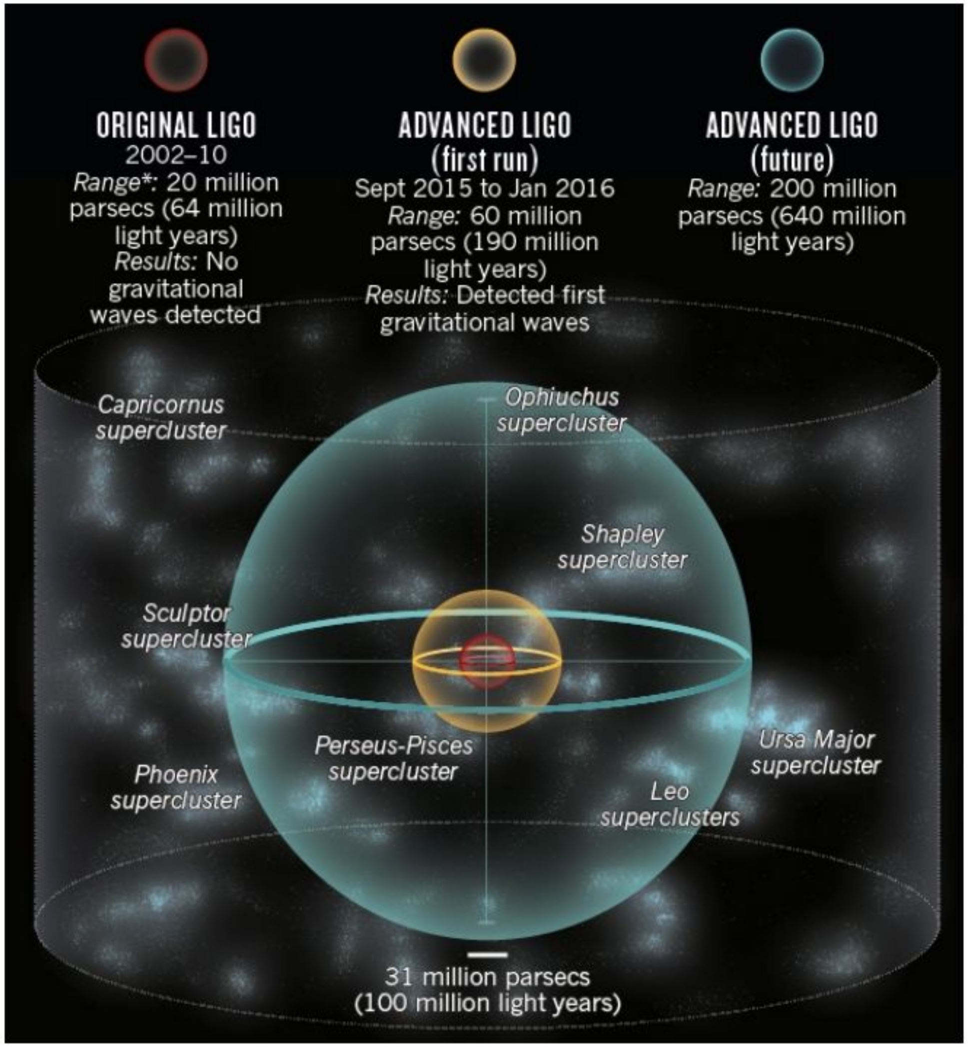
- ★ Range of frequencies similar to human ears:

Wikimedia Commons

From 20 Hz (H0) to a few thousands Hz (3960 Hz, H7) - 8 octaves.

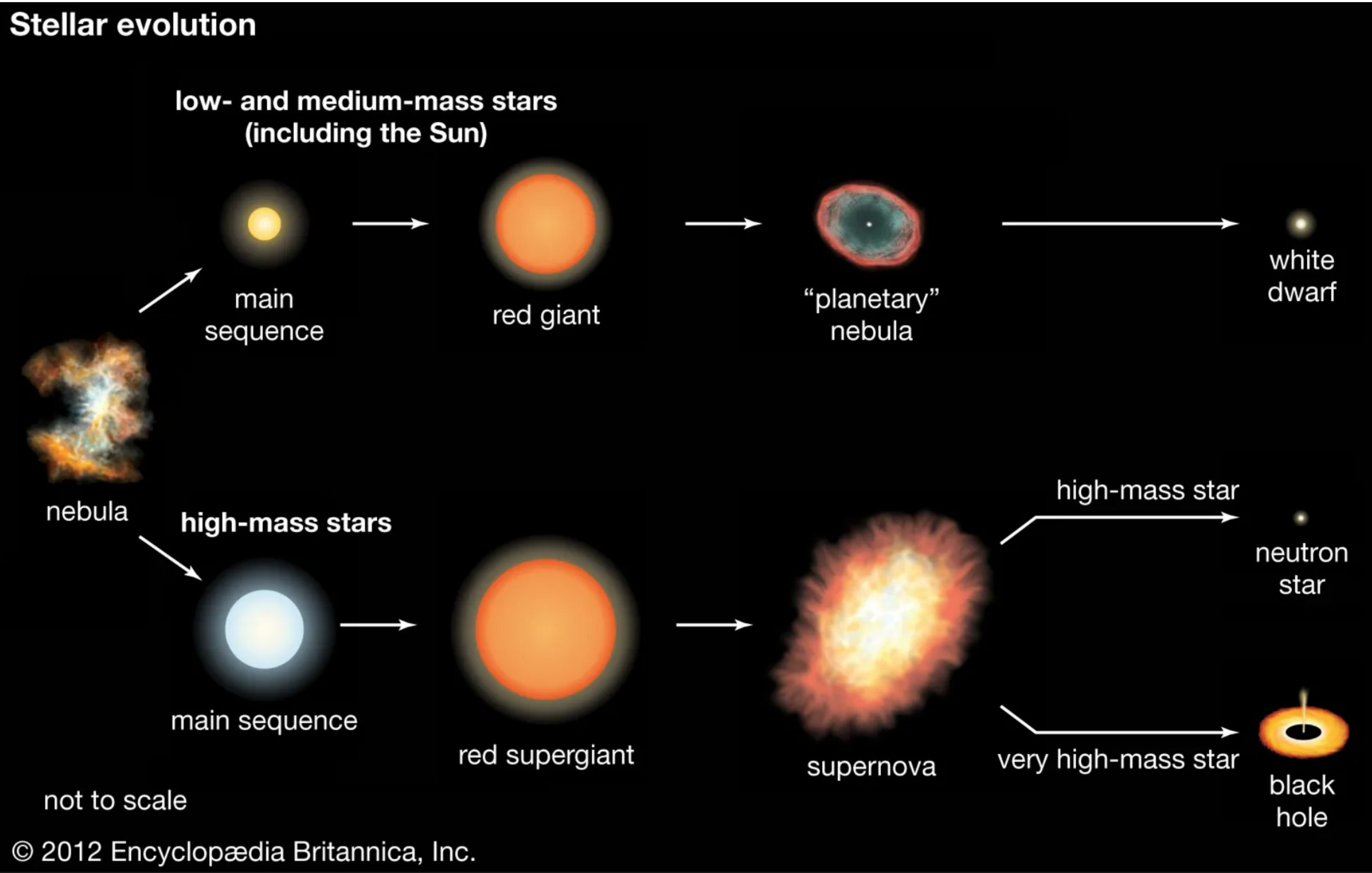
- ★ Poor, like for an ear, angular resolution.

Sensitivity → amplitude → volume



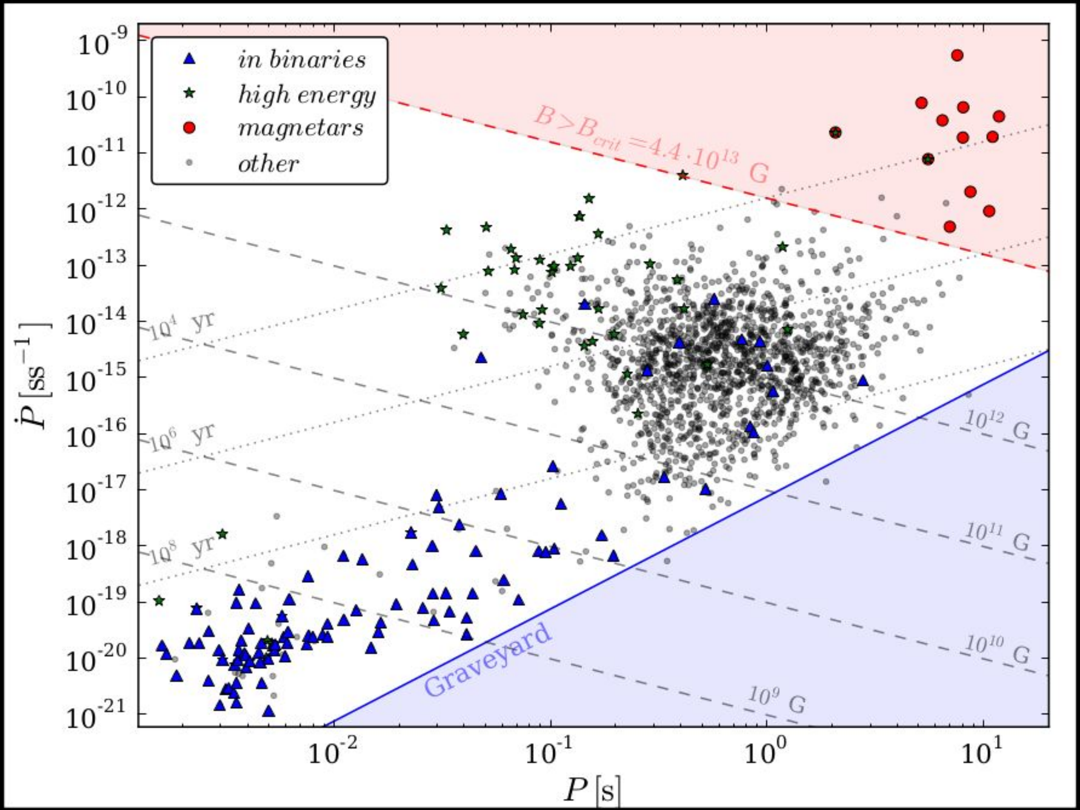
- ⋆ Detector's sensitivity (registering waves of amplitude h) is related to maximal range r, $h \propto 1/r$
- ⋆ Reachable cosmic volume $V \propto r^3$
- ⋆ Increase of sensitivity $h \to 0.1h$ gives $r \to 10r$, that is $V \to 1000V$.

LVK targets are compact stellar remnants



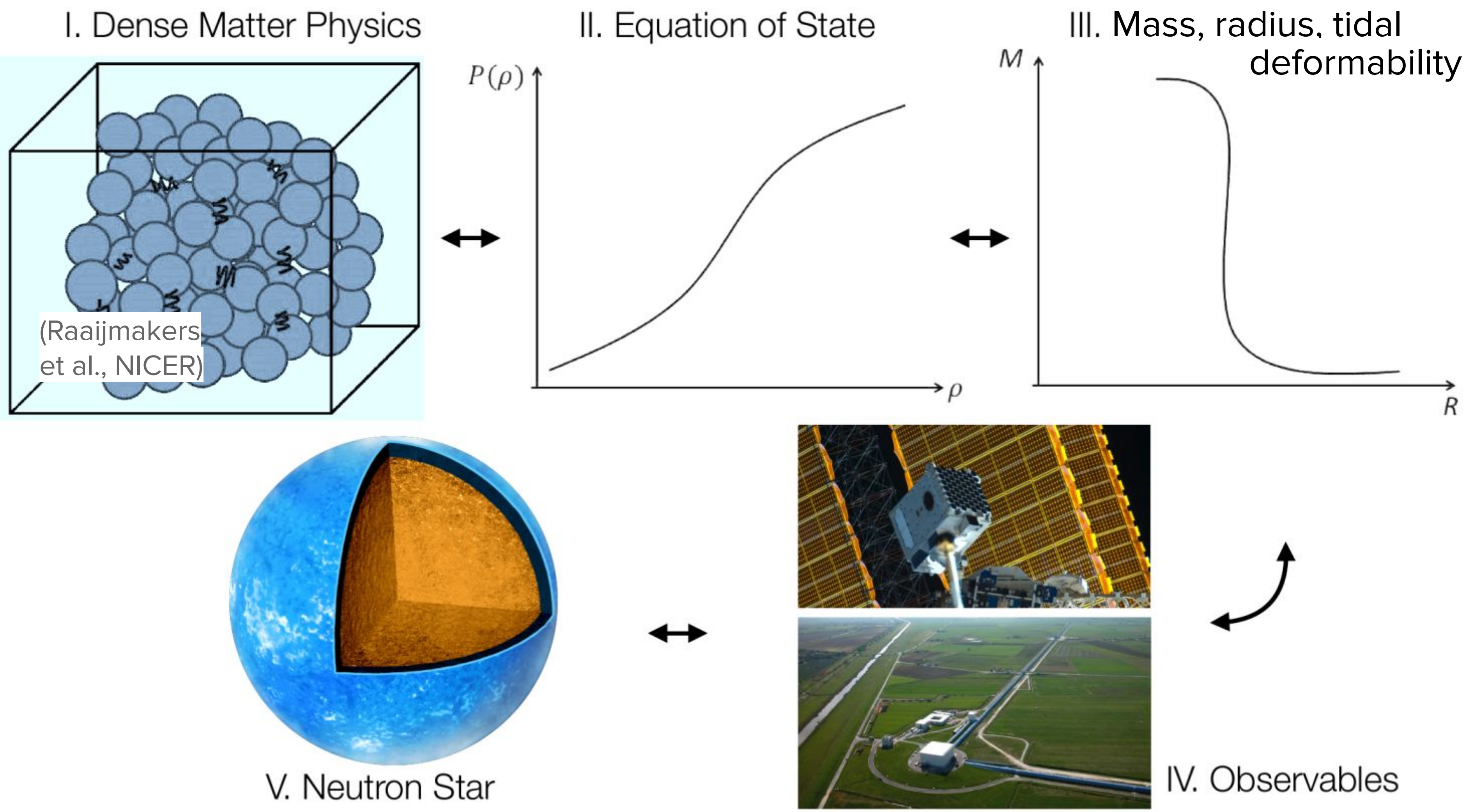
Neutron stars: extremely dense, magnetized stellar remnants

The most relativistic **material** objects in the Universe: compactness $M/R \simeq 0.5$, observed in all EM spectrum as pulsars, magnetars, in supernovæ remnants, in accreting systems, in double neutron star binaries...



About 3000 NSs observed to date, estimated $\sim 10^{8} - 10^{9}$ in the Galaxy.

From nuclear physics to astrophysics (and back)


I. Dense Matter Physics

(Raaijmakers et al., NICER)

II. Equation of State

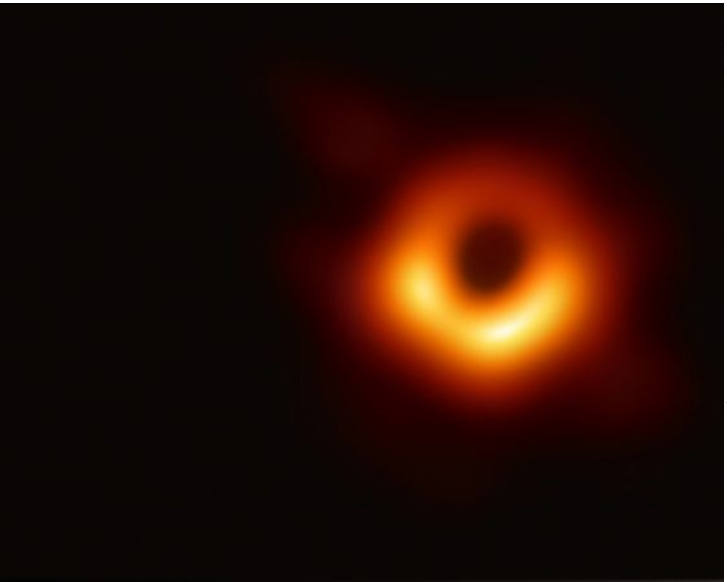
III. Mass, radius, tidal deformability

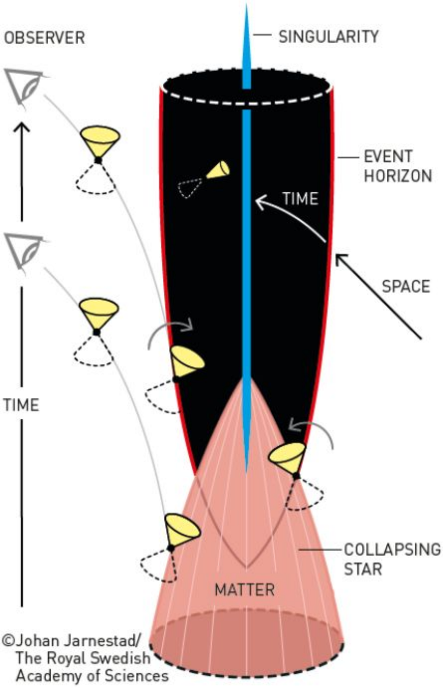
IV. Observables

V. Neutron Star

Important: every equation of state is related to a maximum mass neutron stars built of this matter can reach - heavier objects collapse to black holes

Black holes





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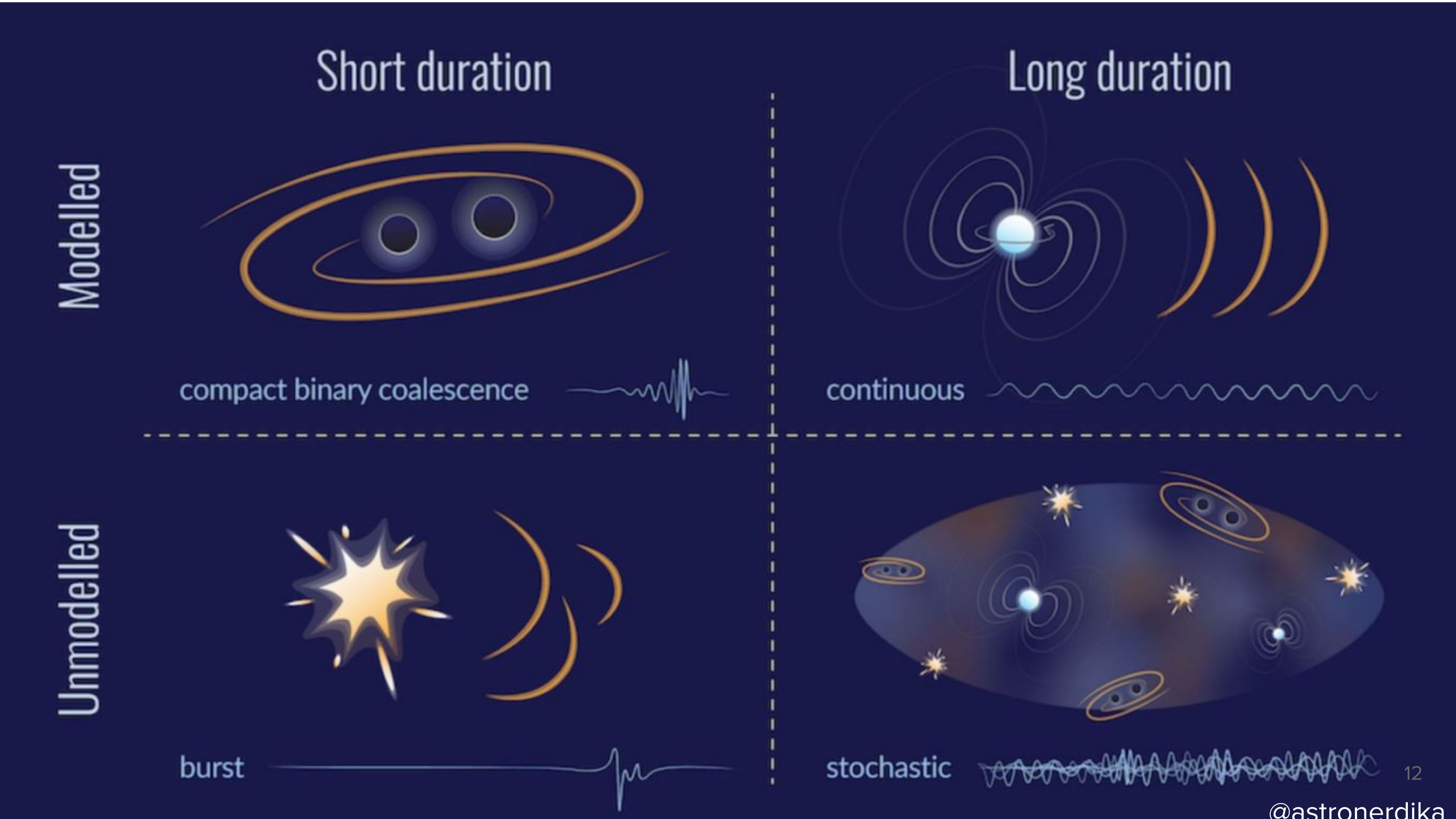
The Royal Swedish
Academy of Sciences

Black hole is a region of spacetime with curvature so large, it curves on itself trapping everything inside (even light)

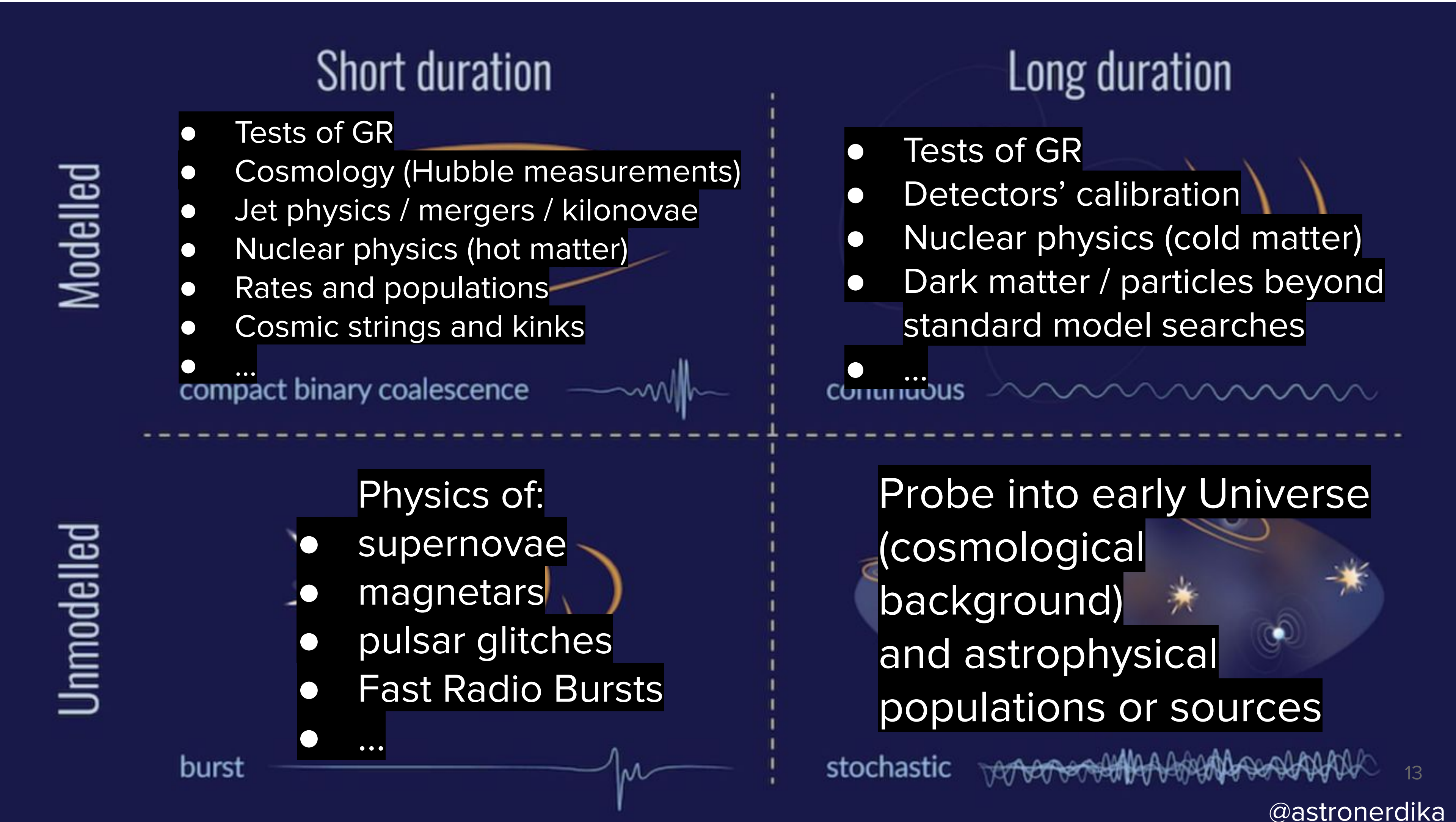
(Event Horizon Telescope 2019, Interstellar 2014)

Gravitational-wave signal types of interest to LVK...



@astronerdika

…and why they are interesting and useful



- Tests of GR
- Cosmology (Hubble measurements)
- Jet physics / mergers / kilonovae
- Nuclear physics (hot matter)
- Rates and populations
- Cosmic strings and kinks
- …

- Tests of GR
- Detectors' calibration
- Nuclear physics (cold matter)
- Dark matter / particles beyond standard model searches
- …

Physics of:

- supernovae
- magnetars
- pulsar glitches
- Fast Radio Bursts
- …

Probe into early Universe (cosmological background) and astrophysical populations or sources

Testing gravity theories with inspiral-merger-ringdown signals

Karl Popper (1902-1994): falsifiability of the theory is the fundamental scientific criterion.

With hundreds of significant events already, one may think of various tests:

- ★ „residual” (does the data contain anything unexpected after subtracting the signal model?)
- ★ „astrophysical parameters” (are the parameters consistent with each other in various regimes?)
- ★ „parameters of the theory” (are the coefficient values consistent with the theory?)
- ★ „dispersion relation” (do gravitational waves propagate like photons?)
- ★ „ringdown” (are we observing horizons as predicted by GR?)
- ★ „echoes” (are observed objects really GR black holes?)
- ★ „polarizations” (do gravitational waves interact with matter as GR predicts?)

Compact binaries and their GW properties

- ⋆ Chirp mass $\mathcal{M} = \left(\mu^3 M^2\right)^{1/5} = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$,
- ⋆ Mass ratio $q = m_2/m_1$ (at 1PN), alternatively $\nu = m_1 m_2/(m_1 + m_2)^2$,
- ⋆ Spin-orbit and spin-spin coupling (at 2PN and 3PN, resp.) →

$$\chi_{eff} = (m_1 \chi_{1z} + m_2 \chi_{2z})/(m_1 + m_2)$$

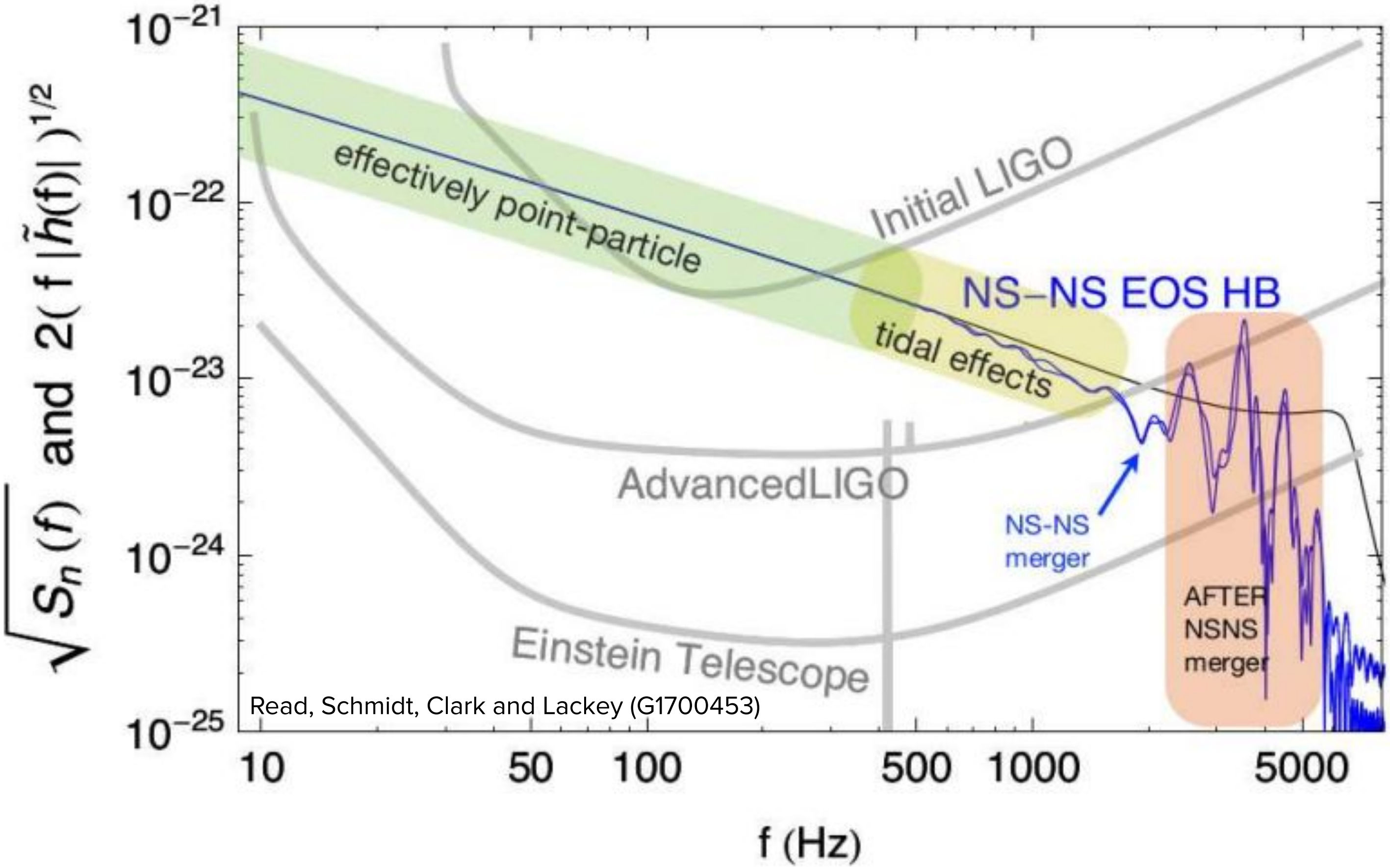
where χ_{iz} are spin components along system's total angular momentum,

- ⋆ Tidal deformability Λ (at 5PN) →

$$\tilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12 m_2) m_1^4 \Lambda_1}{(m_1 + m_2)^5} + (1 \leftrightarrow 2)$$

- ⋆ Direct ”luminosity” (”loudness”) distance: binary systems are ”standard sirens”.

GW spectrum of 'material' binaries (for example, binary neutron stars)

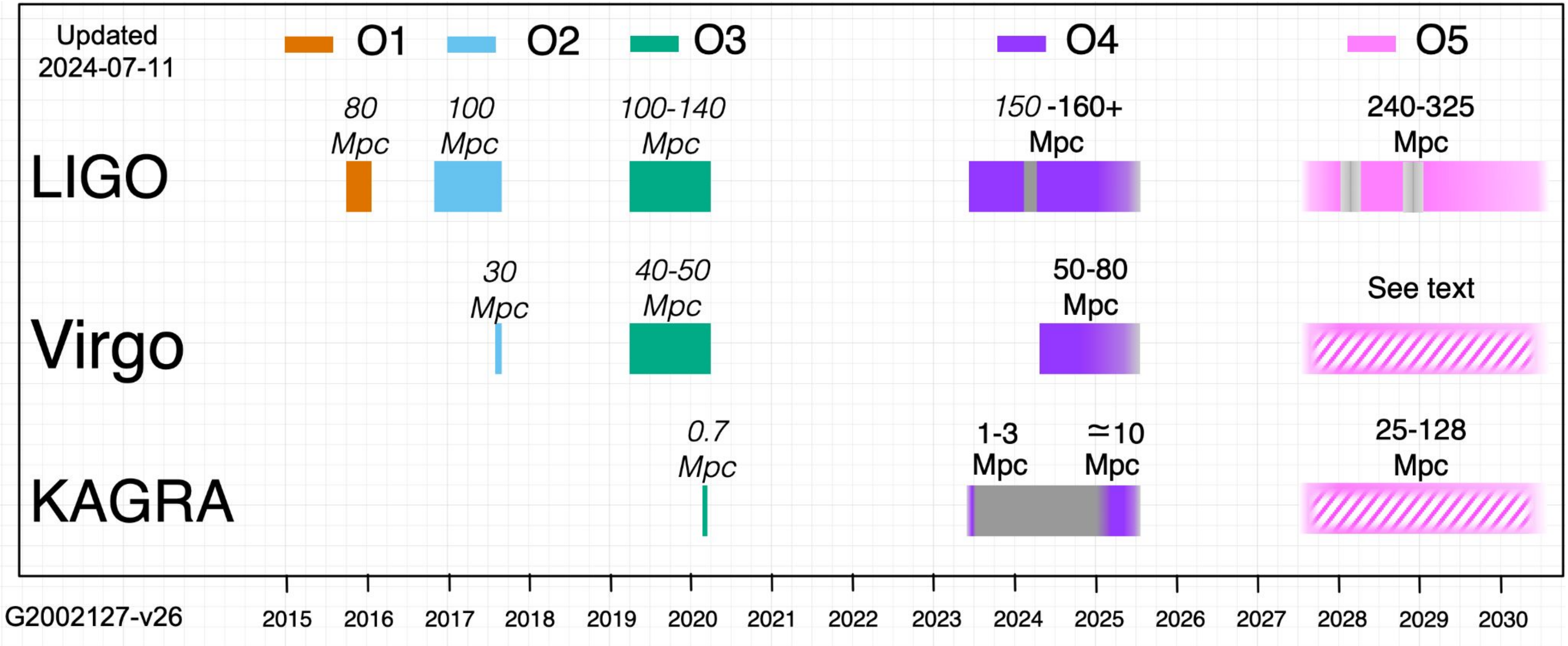


Read, Schmidt, Clark and Lackey (G1700453)

For extended-body interactions, phase evolution differs from point-particle description,

$$\Psi(f) = \Psi_{PP}(f) + \Psi_{tidal}(f)$$

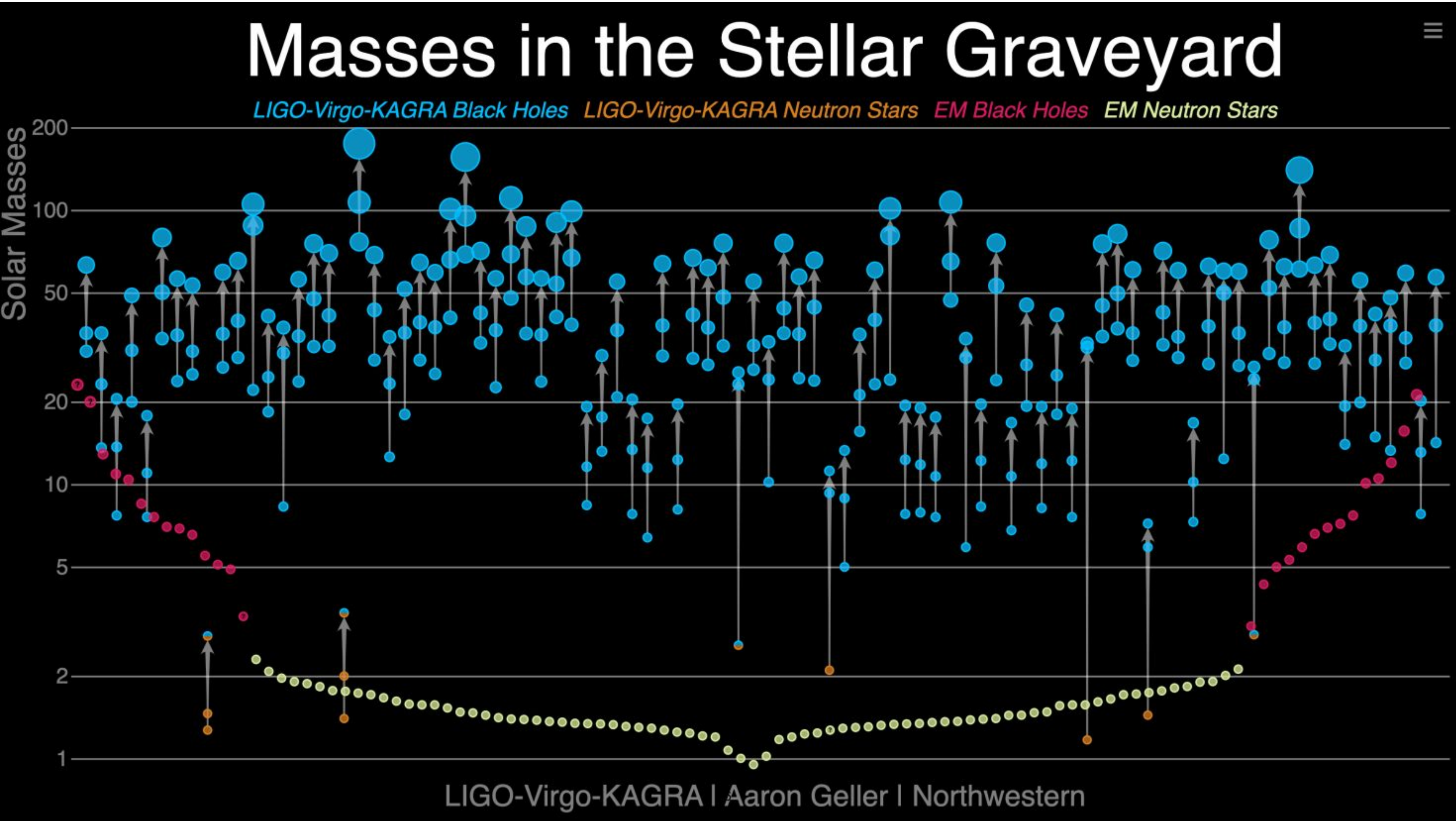
Observing runs (https://observing.docs.ligo.org/plan)



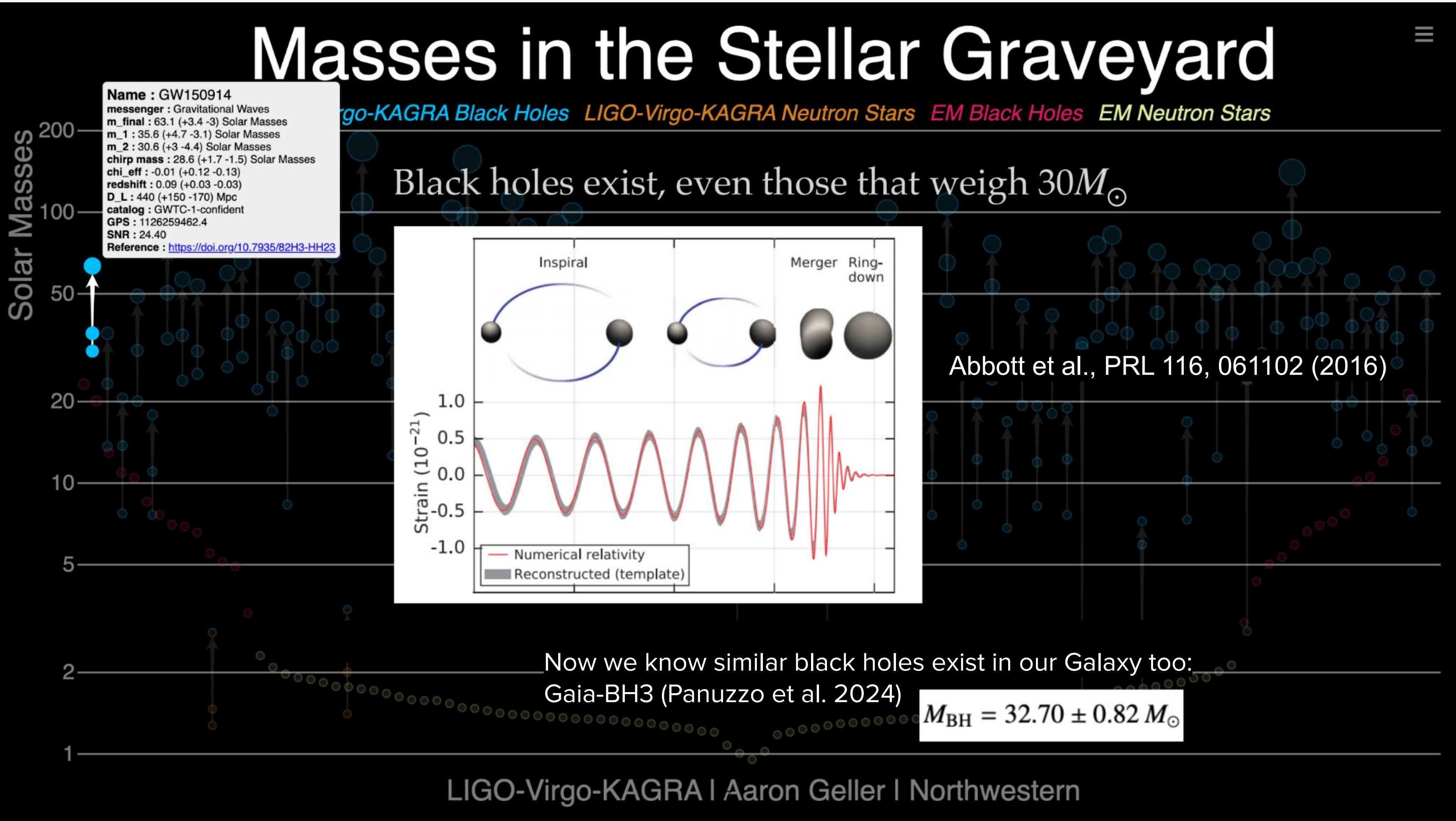
- O4a (LIGO detectors): 24 May 2023 - 16 Jan 2024
- O4b started 15:00 UTC on 10 April 2024
    - Virgo joined O4b
- O4b ends 9 June 2025

(see G. Losurdo talk on Tuesday)

The story so far



First detection: GW150914



Name : GW150914
messenger : Gravitational Waves
m_final : 63.1 (+3.4 -3) Solar Masses
m_1 : 35.6 (+4.7 -3.1) Solar Masses
m_2 : 30.6 (+3 -4.4) Solar Masses
chirp mass : 28.6 (+1.7 -1.5) Solar Masses
chi_eff : -0.01 (+0.12 -0.13)
redshift : 0.09 (+0.03 -0.03)
D_L : 440 (+150 -170) Mpc
catalog : GWTC-1-confident
GPS : 1126259462.4
SNR : 24.40
Reference : https://doi.org/10.7935/82H3-HH23

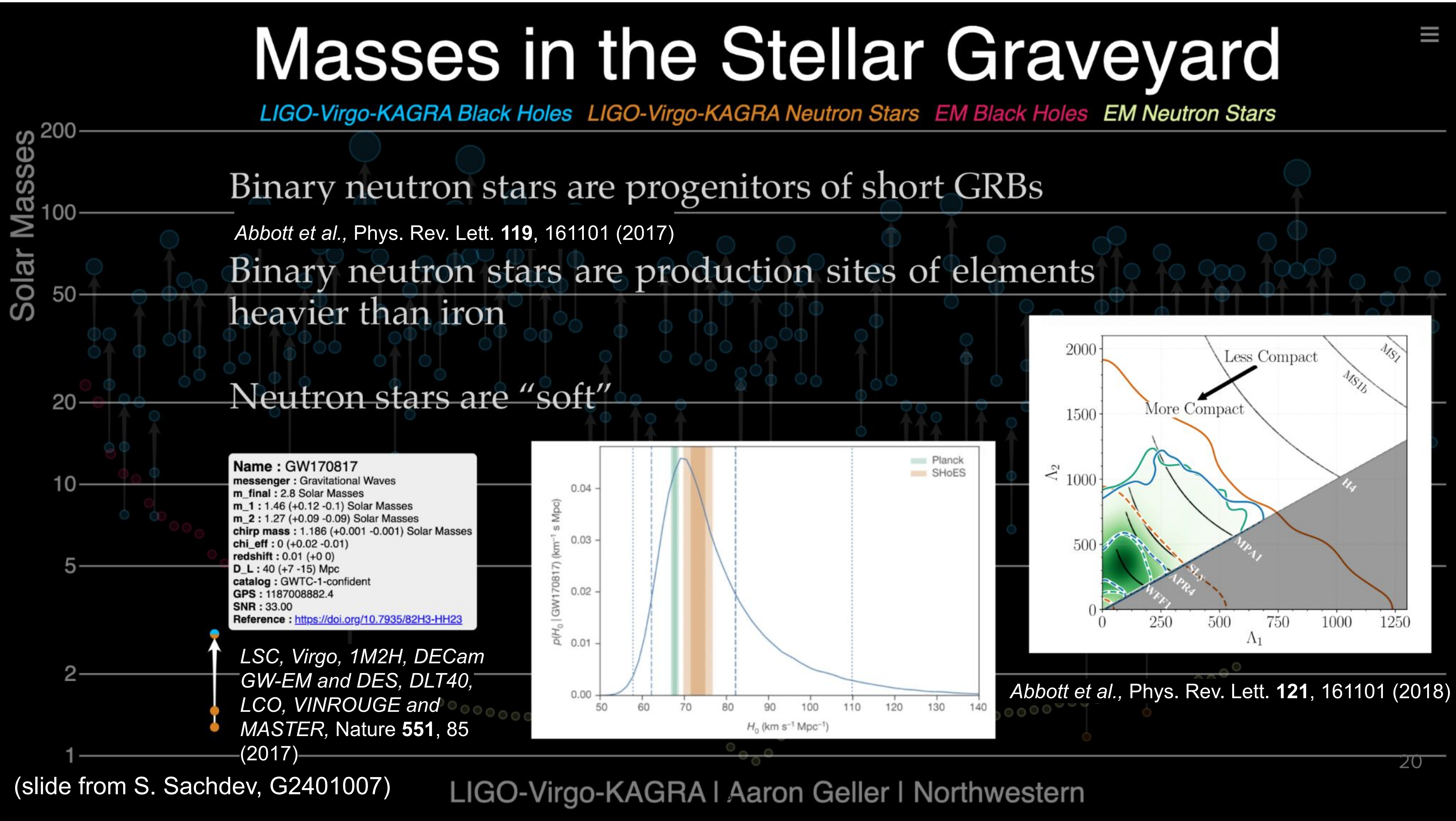
Black holes exist, even those that weigh $30M_\odot$

Abbott et al., PRL 116, 061102 (2016)

Now we know similar black holes exist in our Galaxy too:
Gaia-BH3 (Panuzzo et al. 2024)

$$M_{\rm BH} = 32.70 \pm 0.82\, M_\odot$$

Binary neutron star system: GW170817



Masses in the Stellar Graveyard

Binary neutron stars are progenitors of short GRBs

Abbott et al., Phys. Rev. Lett. **119**, 161101 (2017)

Binary neutron stars are production sites of elements heavier than iron

Neutron stars are “soft”

Name : GW170817
messenger : Gravitational Waves
m_final : 2.8 Solar Masses
m_1 : 1.46 (+0.12 -0.1) Solar Masses
m_2 : 1.27 (+0.09 -0.09) Solar Masses
chirp mass : 1.186 (+0.001 -0.001) Solar Masses
chi_eff : 0 (+0.02 -0.01)
redshift : 0.01 (+0 0)
D_L : 40 (+7 -15) Mpc
catalog : GWTC-1-confident
GPS : 1187008882.4
SNR : 33.00
Reference : https://doi.org/10.7935/82H3-HH23

LSC, Virgo, 1M2H, DECam GW-EM and DES, DLT40, LCO, VINROUGE and MASTER, Nature **551**, 85 (2017)

Abbott et al., Phys. Rev. Lett. **121**, 161101 (2018)

(slide from S. Sachdev, G2401007)

LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

GW170817: speed of gravitation

Relative speed difference between GWs and photons:

$$\frac{v_{GW} - c}{c} = \frac{\Delta v}{c} \approx \frac{c\Delta t}{d}.$$

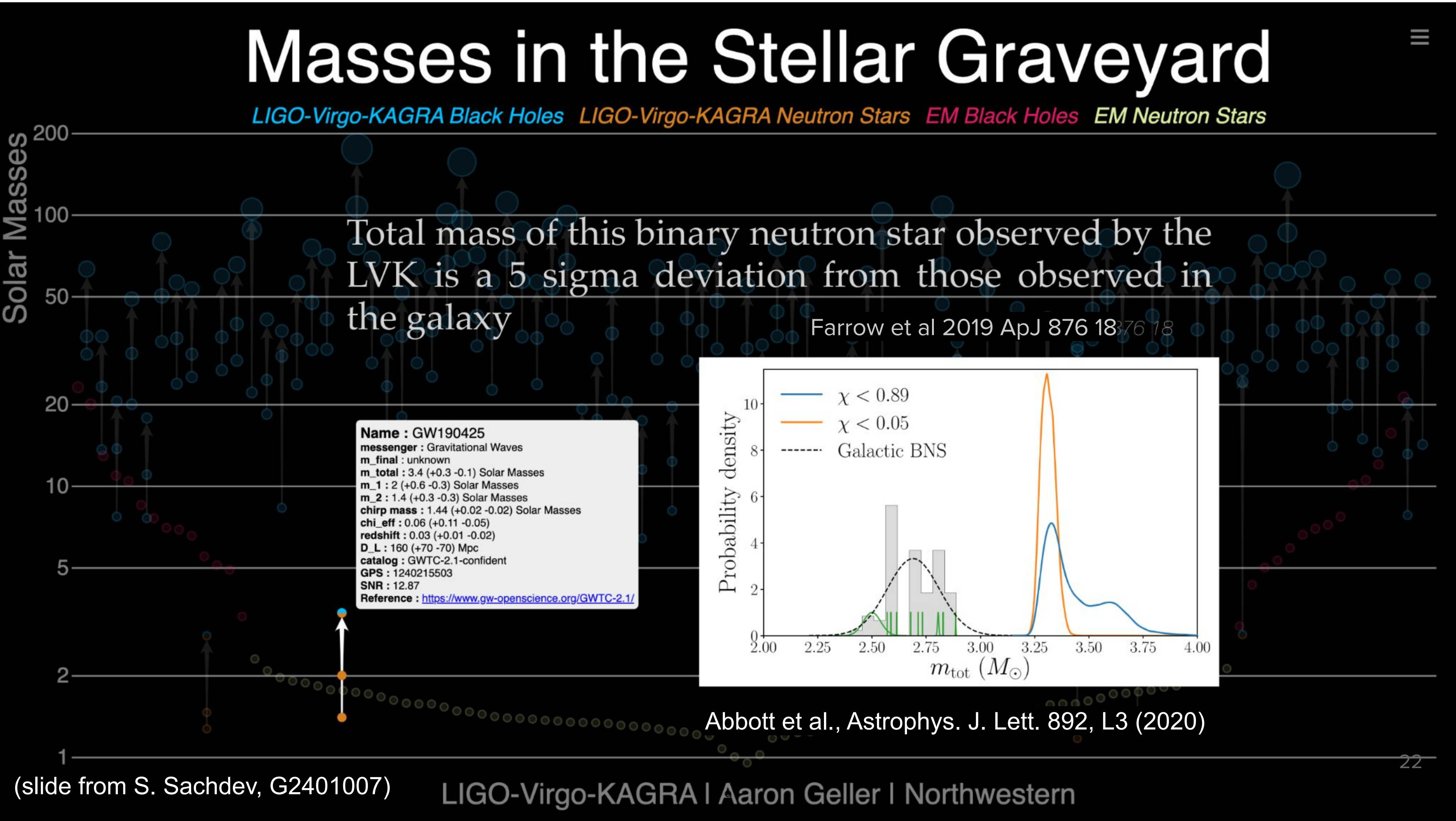
Assuming very conservative values:

- ⋆ Distance $d = 26$ Mpc (lower bound from 90% credible interval on luminosity distance derived from the GW signal),
- ⋆ Time delay $\Delta t = 10$ s (actual delay between GW170817 and GRB170817A was $\simeq 1.7$ s)

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

$$\boxed{v_{GW} = 299792458^{+0.000001}_{-0.000006}\ \mathrm{m/s} = c^{+0.000001}_{-0.000006}\ \mathrm{m/s}}$$

Heavy binary NS system: GW190425



Masses in the Stellar Graveyard

Total mass of this binary neutron star observed by the LVK is a 5 sigma deviation from those observed in the galaxy

Farrow et al 2019 ApJ 876 18

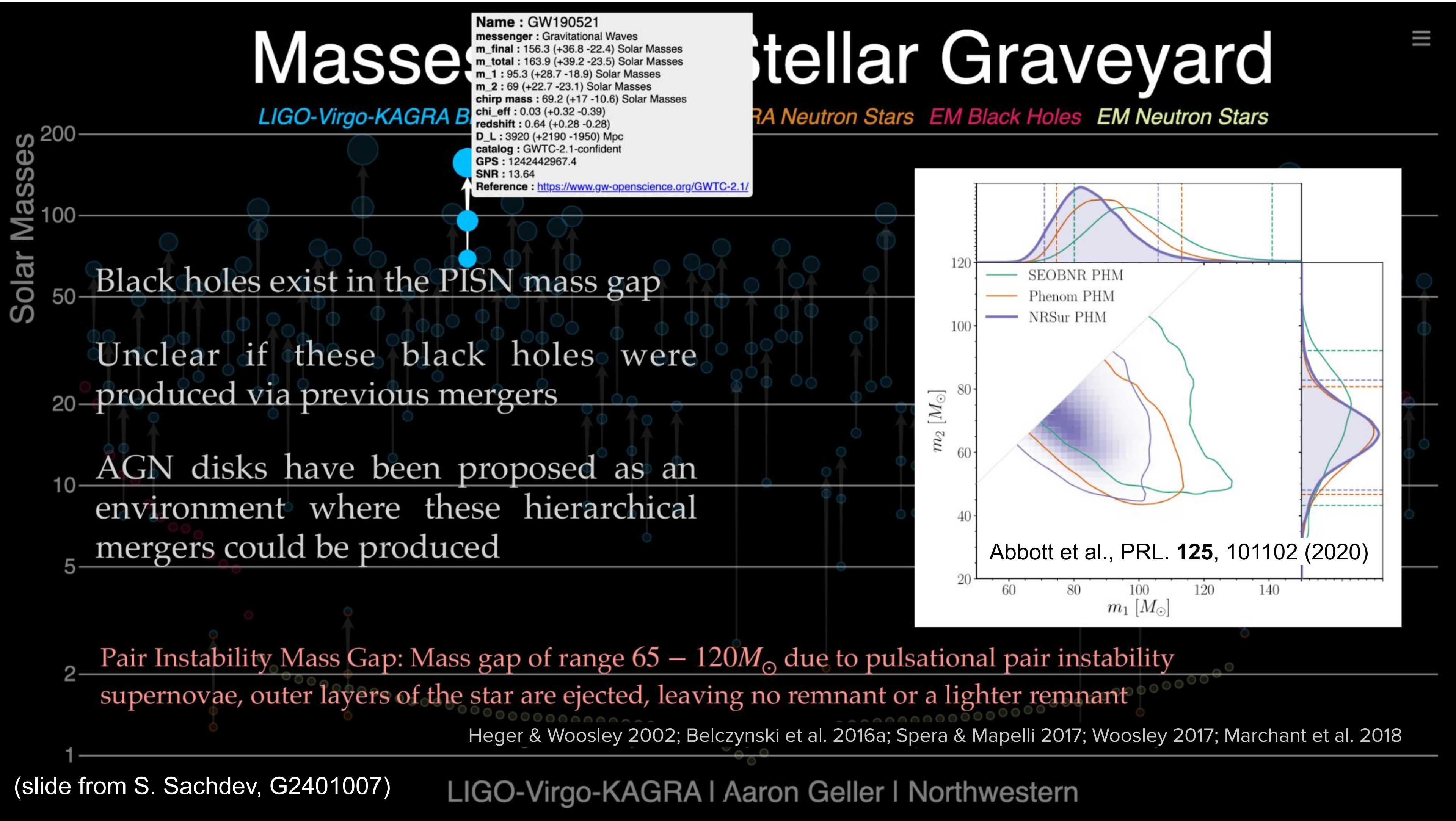
Name : GW190425
messenger : Gravitational Waves
m_final : unknown
m_total : 3.4 (+0.3 -0.1) Solar Masses
m_1 : 2 (+0.6 -0.3) Solar Masses
m_2 : 1.4 (+0.3 -0.3) Solar Masses
chirp mass : 1.44 (+0.02 -0.02) Solar Masses
chi_eff : 0.06 (+0.11 -0.05)
redshift : 0.03 (+0.01 -0.02)
D_L : 160 (+70 -70) Mpc
catalog : GWTC-2.1-confident
GPS : 1240215503
SNR : 12.87
Reference : https://www.gw-openscience.org/GWTC-2.1/

Abbott et al., Astrophys. J. Lett. 892, L3 (2020)

(slide from S. Sachdev, G2401007)

LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Very heavy black holes: GW190521



Name : GW190521
messenger : Gravitational Waves
m_final : 156.3 (+36.8 -22.4) Solar Masses
m_total : 163.9 (+39.2 -23.5) Solar Masses
m_1 : 95.3 (+28.7 -18.9) Solar Masses
m_2 : 69 (+22.7 -23.1) Solar Masses
chirp mass : 69.2 (+17 -10.6) Solar Masses
chi_eff : 0.03 (+0.32 -0.39)
redshift : 0.64 (+0.28 -0.28)
D_L : 3920 (+2190 -1950) Mpc
catalog : GWTC-2.1-confident
GPS : 1242442967.4
SNR : 13.64
Reference : https://www.gw-openscience.org/GWTC-2.1/

Black holes exist in the PISN mass gap

Unclear if these black holes were produced via previous mergers

AGN disks have been proposed as an environment where these hierarchical mergers could be produced

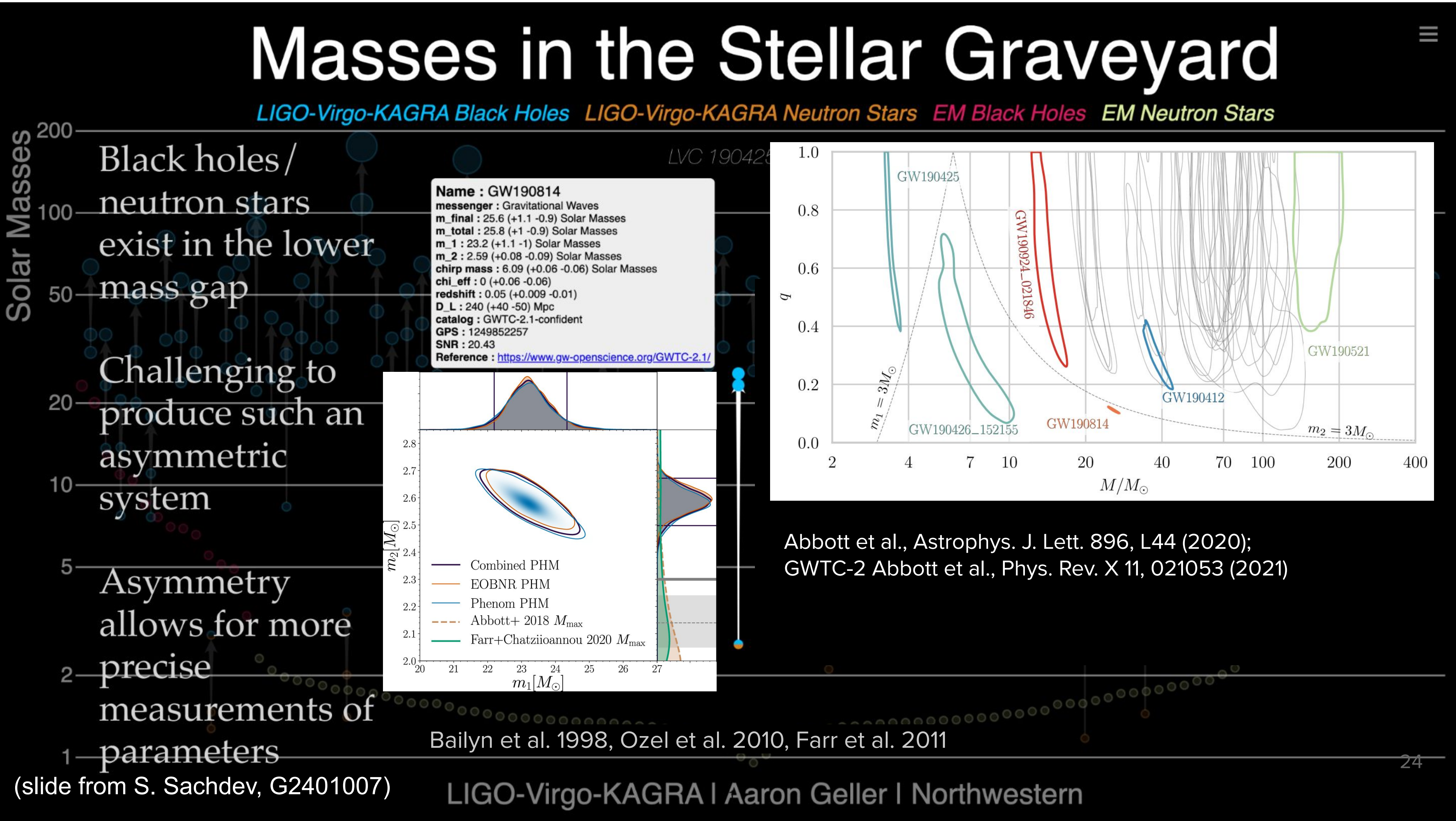
Abbott et al., PRL. **125**, 101102 (2020)

Pair Instability Mass Gap: Mass gap of range $65 - 120M_\odot$ due to pulsational pair instability supernovae, outer layers of the star are ejected, leaving no remnant or a lighter remnant

Heger & Woosley 2002; Belczynski et al. 2016a; Spera & Mapelli 2017; Woosley 2017; Marchant et al. 2018

(slide from S. Sachdev, G2401007)

Very asymmetric binary system: GW190814



Black holes / neutron stars exist in the lower mass gap

Challenging to produce such an asymmetric system

Asymmetry allows for more precise measurements of parameters

Name : GW190814
messenger : Gravitational Waves
m_final : 25.6 (+1.1 -0.9) Solar Masses
m_total : 25.8 (+1 -0.9) Solar Masses
m_1 : 23.2 (+1.1 -1) Solar Masses
m_2 : 2.59 (+0.08 -0.09) Solar Masses
chirp mass : 6.09 (+0.06 -0.06) Solar Masses
chi_eff : 0 (+0.06 -0.06)
redshift : 0.05 (+0.009 -0.01)
D_L : 240 (+40 -50) Mpc
catalog : GWTC-2.1-confident
GPS : 1249852257
SNR : 20.43
Reference : https://www.gw-openscience.org/GWTC-2.1/

Abbott et al., Astrophys. J. Lett. 896, L44 (2020);
GWTC-2 Abbott et al., Phys. Rev. X 11, 021053 (2021)

Bailyn et al. 1998, Ozel et al. 2010, Farr et al. 2011

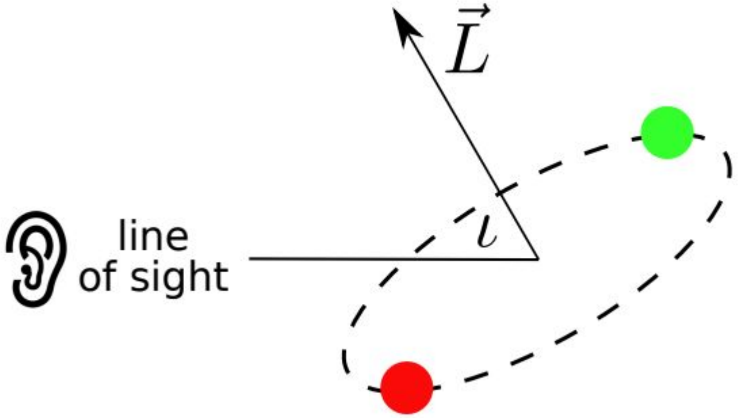
(slide from S. Sachdev, G2401007)

Binary system: distance-inclination degeneracy

Luminosity distance $\sim 1/h$, and

$$h = h_+ F_+ + h_\times F_\times$$

depends on the inclination of the binary with repect to the "line of sight".



Two independent polarizations h_+ and $h_\times$:

$$\begin{aligned} h_+ &= \frac{2\mu}{r}(\pi M f_{GW})^{2/3}\left(1+\cos^2\iota\right)\cos(2\phi(t)), \\ h_\times &= \frac{4\mu}{r}(\pi M f_{GW})^{2/3}\cos\iota\,\sin(2\phi(t)). \end{aligned}$$

Effects of various parameters on inspiral waveform

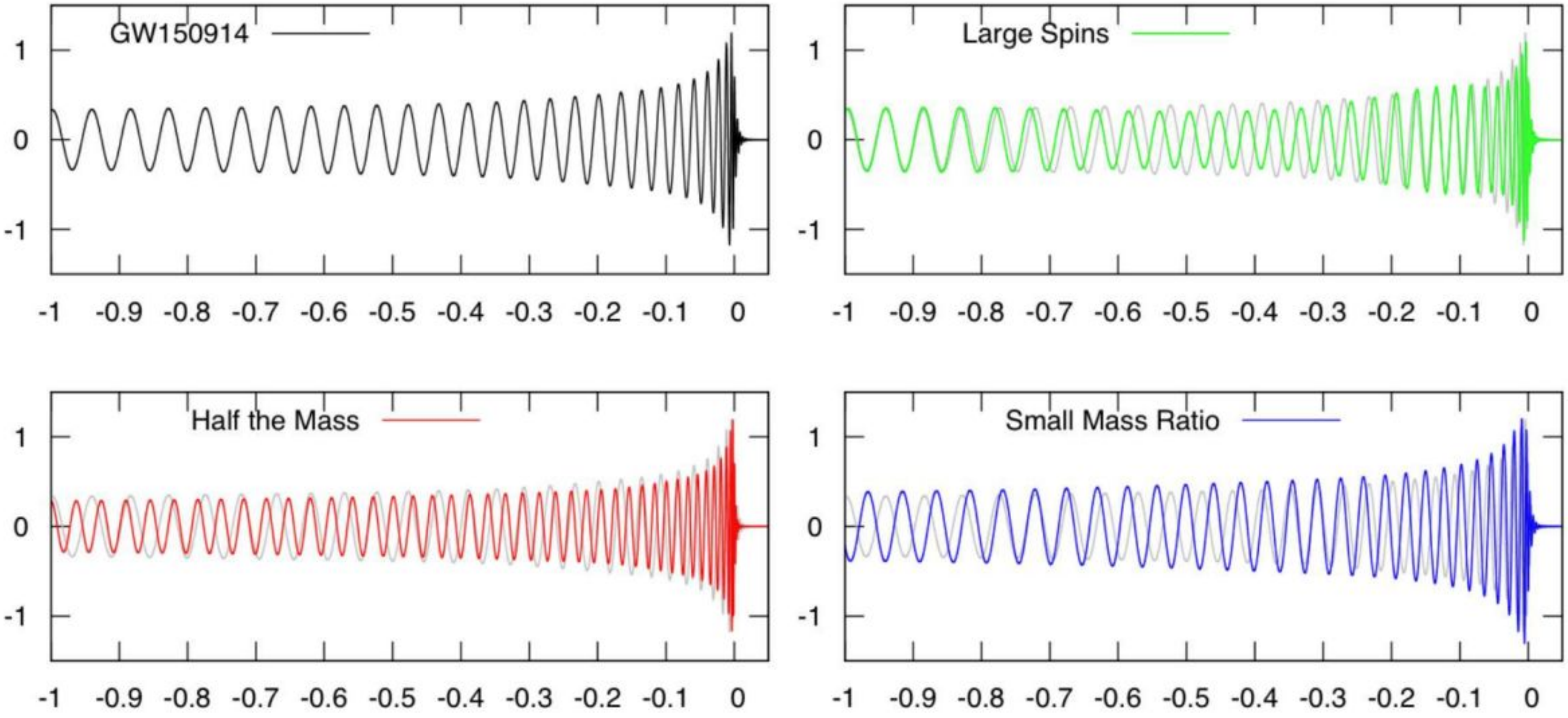
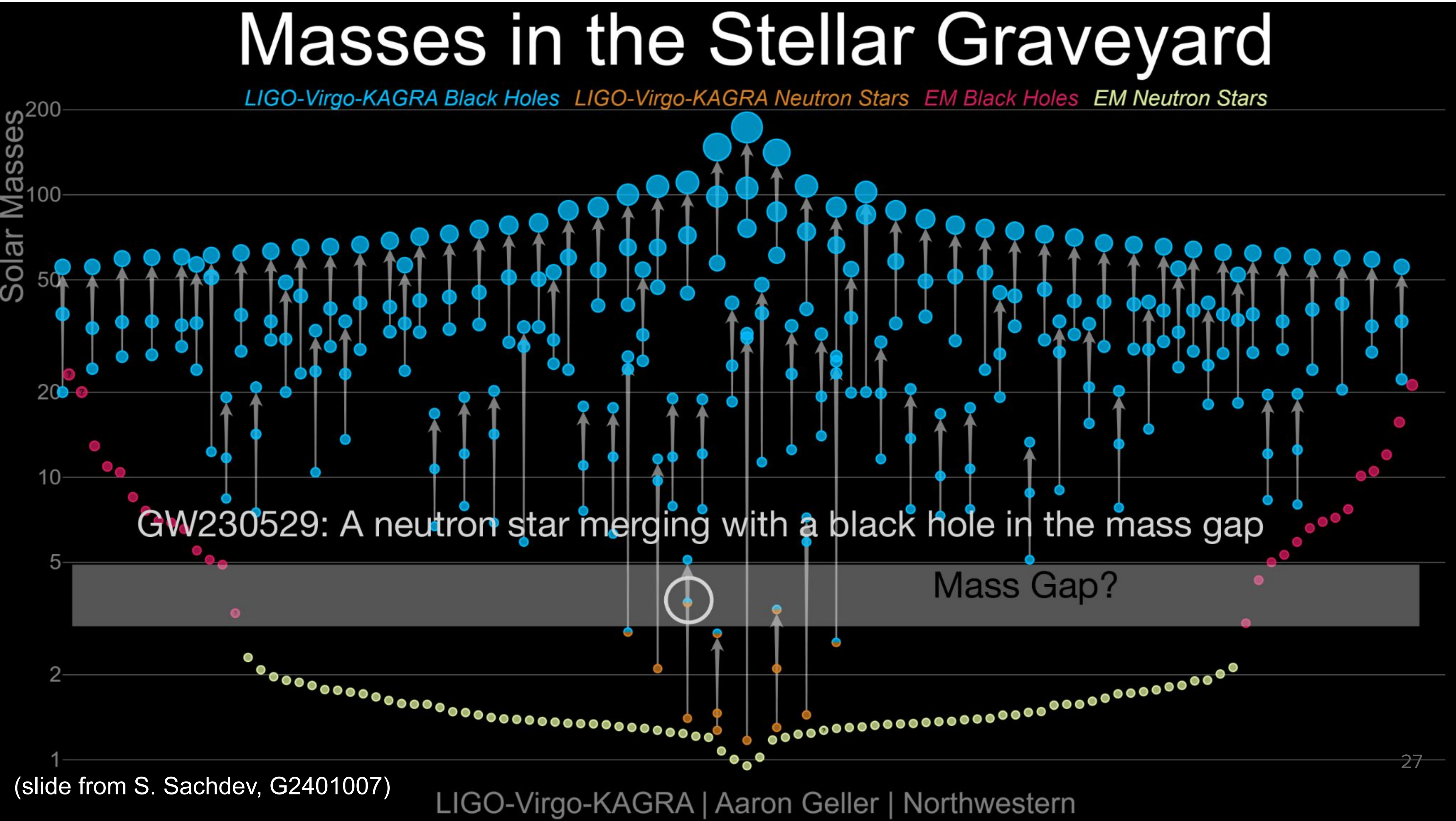


Illustration by N. Cornish and T. Littenberg

04: GW230529 and mass gap objects



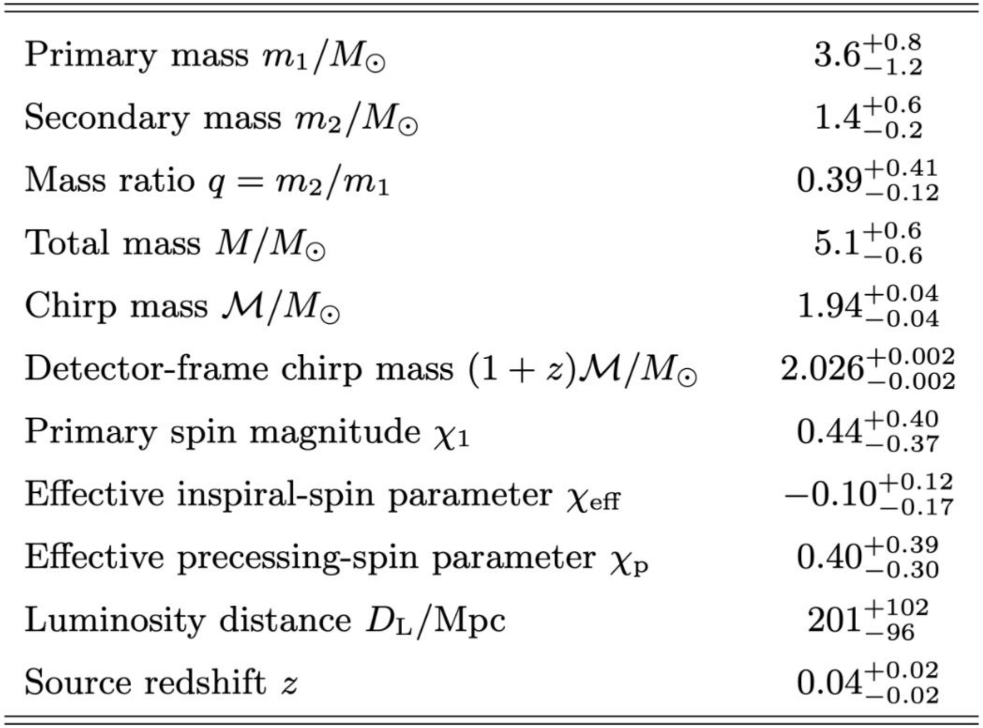
(slide from S. Sachdev, G2401007)

GW230529 properties

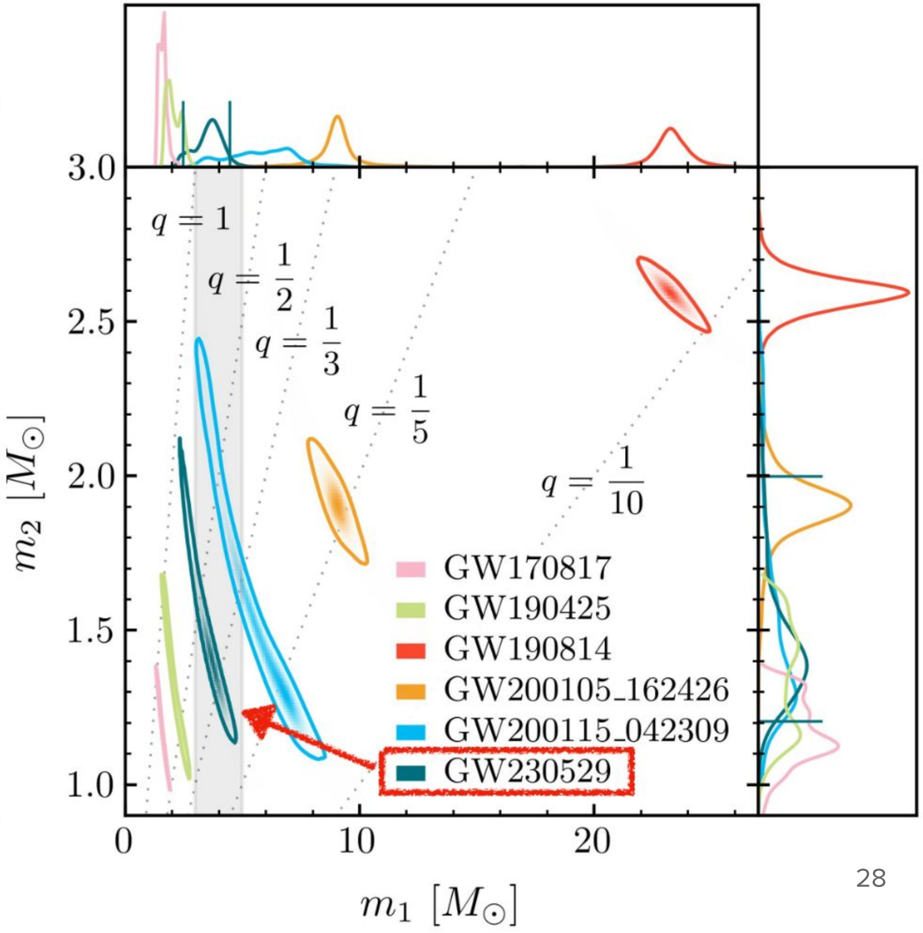
Online L1-only detection with GstLAL, MBTA, PyCBC (IFAR > 60 yr)

No confirmed EM counterpart, no clear tidal constraints

SNR ~11.5



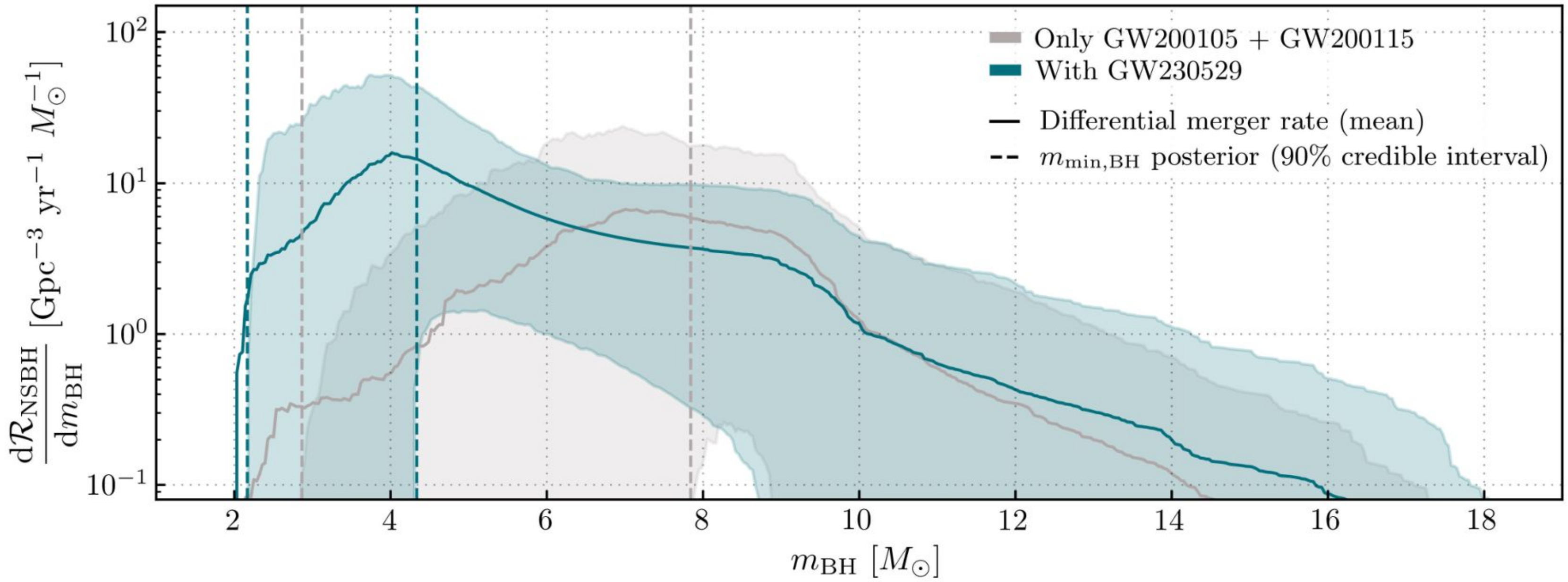
Primary mass $m_1/M_\odot$	$3.6^{+0.8}_{-1.2}$
Secondary mass $m_2/M_\odot$	$1.4^{+0.6}_{-0.2}$
Mass ratio $q = m_2/m_1$	$0.39^{+0.41}_{-0.12}$
Total mass $M/M_\odot$	$5.1^{+0.6}_{-0.6}$
Chirp mass $\mathcal{M}/M_\odot$	$1.94^{+0.04}_{-0.04}$
Detector-frame chirp mass $(1+z)\mathcal{M}/M_\odot$	$2.026^{+0.002}_{-0.002}$
Primary spin magnitude χ_1	$0.44^{+0.40}_{-0.37}$
Effective inspiral-spin parameter χ_{eff}	$-0.10^{+0.12}_{-0.17}$
Effective precessing-spin parameter χ_{p}	$0.40^{+0.39}_{-0.30}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	201^{+102}_{-96}
Source redshift z	$0.04^{+0.02}_{-0.02}$



Abac et al., Astrophys. J. Lett. 970, L34 (2024)

GW230529: minimum black hole mass

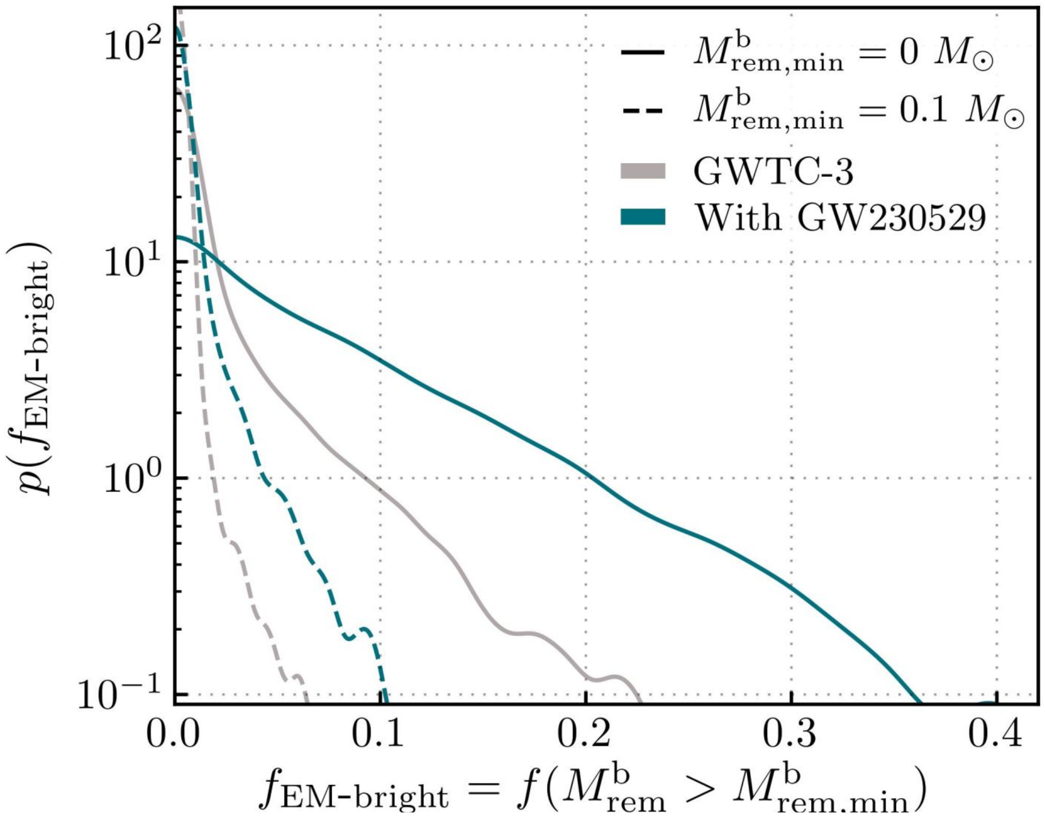
- inferred minimum mass of black holes in the NSBH population decreases with the inclusion of GW230529
- GW230529 increases the inferred rate of compact binary mergers with a component in the 3–5 $M_\odot$ range



Minimum inferred BH mass in NSBH systems: $m_{\rm min,BH} = 3.4^{+1.0}_{-1.2}\ M_\odot$ with GW230529
$m_{\rm min,BH} = 6.0^{+1.8}_{-3.2}\ M_\odot$ without.

Abac et al., Astrophys. J. Lett. 970, L34 (2024)

GW230529: influence on EM brightness



Posterior on the fraction of NSBH systems detected with GWs that may be EM bright, $f_{\mathrm{EM\text{-}bright}}$, depending on the threshold remnant mass required to power a counterpart, $f(M^{\mathrm{b}}_{\mathrm{rem}} > M^{\mathrm{b}}_{\mathrm{rem,min}})$. The solid and dashed curves represent different values of the minimum remnant mass $M^{\mathrm{b}}_{\mathrm{rem,min}}$.

- Fraction of EM bright NSBHs increases if we include GW230529 in the population
    - less massive black holes are more likely to tidally disrupt neutron stars

Abac et al., Astrophys. J. Lett. 970, L34 (2024)

LIGO/Virgo/KAGRA Public Alerts: https://gracedb.ligo.org/superevents/public/O4/

O4a ended January 2024, providing 81 new high-confidence gravitational wave candidates

LIGO/Virgo/KAGRA Public Alerts

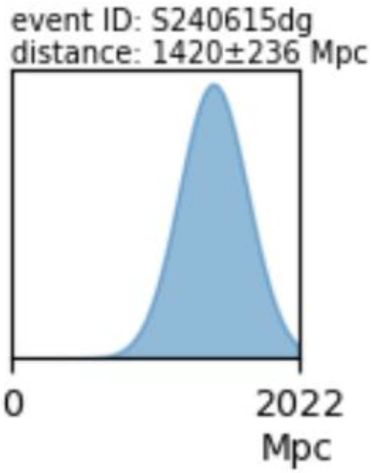
- More details about public alerts are provided in the LIGO/Virgo/KAGRA Alerts User Guide.
- Retractions are marked in red. Retraction means that the candidate was manually vetted and is no longer considered a candidate of interest.
- Less-significant events are marked in grey, and are not manually vetted. Consult the LVK Alerts User Guide for more information on significance in O4.
- Less-significant events are not shown by default. Press "**Show All Public Events**" to show significant and less-significant events.

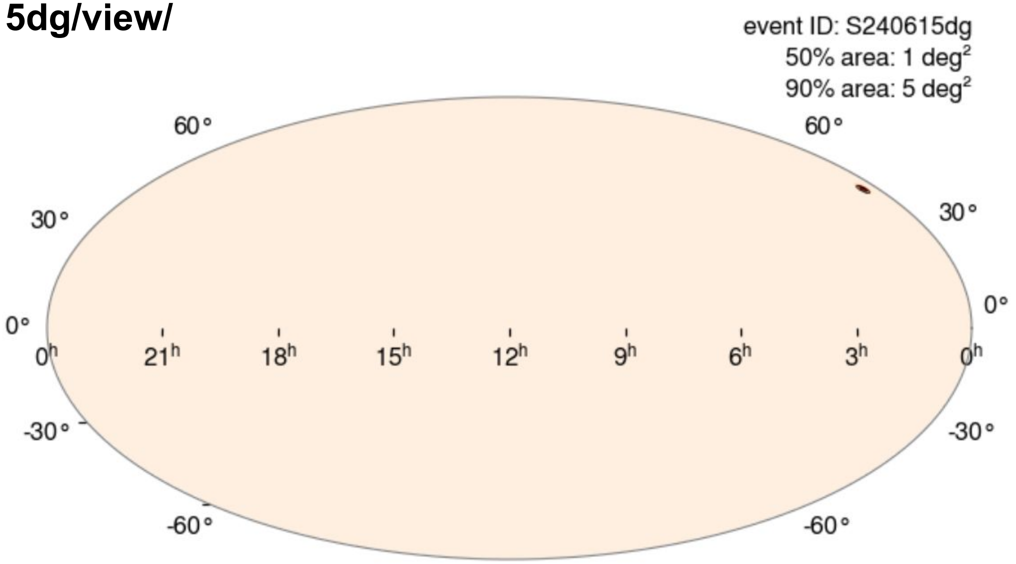
O4 Significant Detection Candidates: **130** (146 Total - 16 Retracted)

O4 Low Significance Detection Candidates: **2368** (Total)

Example of a well localized candidate event in O4:
https://gracedb.ligo.org/superevents/S240615dg/view/

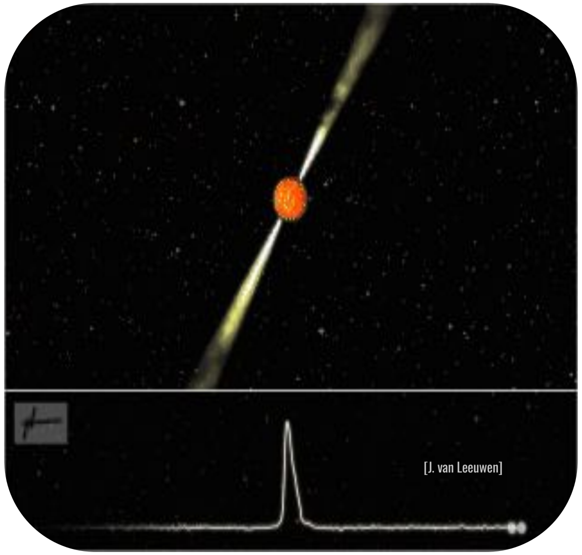
Bilby constraints:



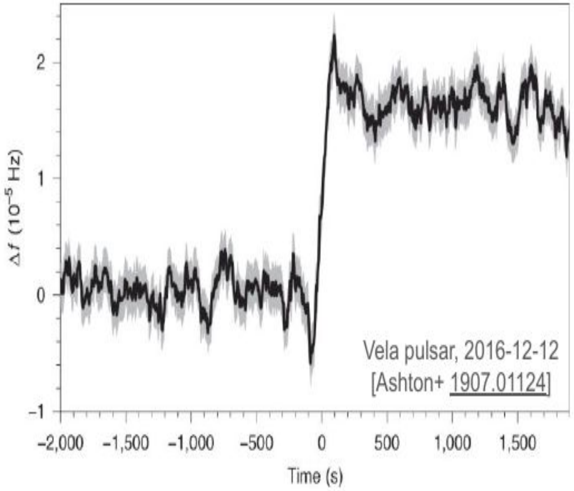


Pulsar glitches and their relation to GWs

Some pulsars experience sudden **spin-up events**, caused by - we hope - internal redistribution of energy and angular momentum (starquakes and/or superfluid recoupling).



[J. van Leeuwen]



Vela pulsar, 2016-12-12
[Ashton+ 1907.01124]

Possible GW signatures:

- Short-duration bursts: mainly from f-modes (high-frequency)
- “tCWs” (long-duration monochromatic transients): Whatever goes on in the neutron star at the glitch, it might cause a temporarily augmented quadrupole moment (instability or ‘’mountain’’)

The Vela pulsar (J0835–4510)

- One of LVK standard target for CW searches: young, nearby (287 pc), frequency low but in sensitivity range (f_{rot} ~11 Hz, f_{gw} ~22 Hz). Indirect spindown upper limit for persistent CWs already beaten with initial LIGO-Virgo (Abadie et al., 2011a).
- Strong glitches ($\Delta f / f \sim 10^{-6}$) every 1.5 years or so. Not as frequent or regular as J0537–6910 (the ''big glitcher''), but much closer.
- First LSC search for short bursts from 2006 glitch (Abadie et al., 2011b).
- First tCW search on O2 open data for 2016 glitch (Keitel et al., 2019).
- No glitch during O3.
- Last glitch in 2021.
- **Now a glitch during O4b with all three (LHV) detectors online!**

[Chandra/NASA]

Summary and outlook

One more year observations in O4 - exciting data to explore and signals to detect:

- ~100 more compact binary coalescence events (hopefully an EM bright one?) to broaden our understanding on astrophysics of compact objects, cosmology, gravity theory.

We search for

- short transient signals
  - very heavy (primordial, intermediate mass?) binary black holes
  - supernovae, magnetar outbursts, GRBs, FRBs…
- intermediate duration signals
  - post-glitch, r-modes from rotating neutron stars
- long/persistent signals
  - stochastic background, asymmetric rotating neutron stars
  - very light (primordial, asteroid/planetary mass?) binary black holes
  - dark matter and exotic particles - as astrophysical sources, but also directly interacting with interferometers (‘’direct detection’’)
- lensed gravitational waves

using various state-of-the-art data analysis methods, including machine learning.