Multi-messenger astronomy with gravitational waves

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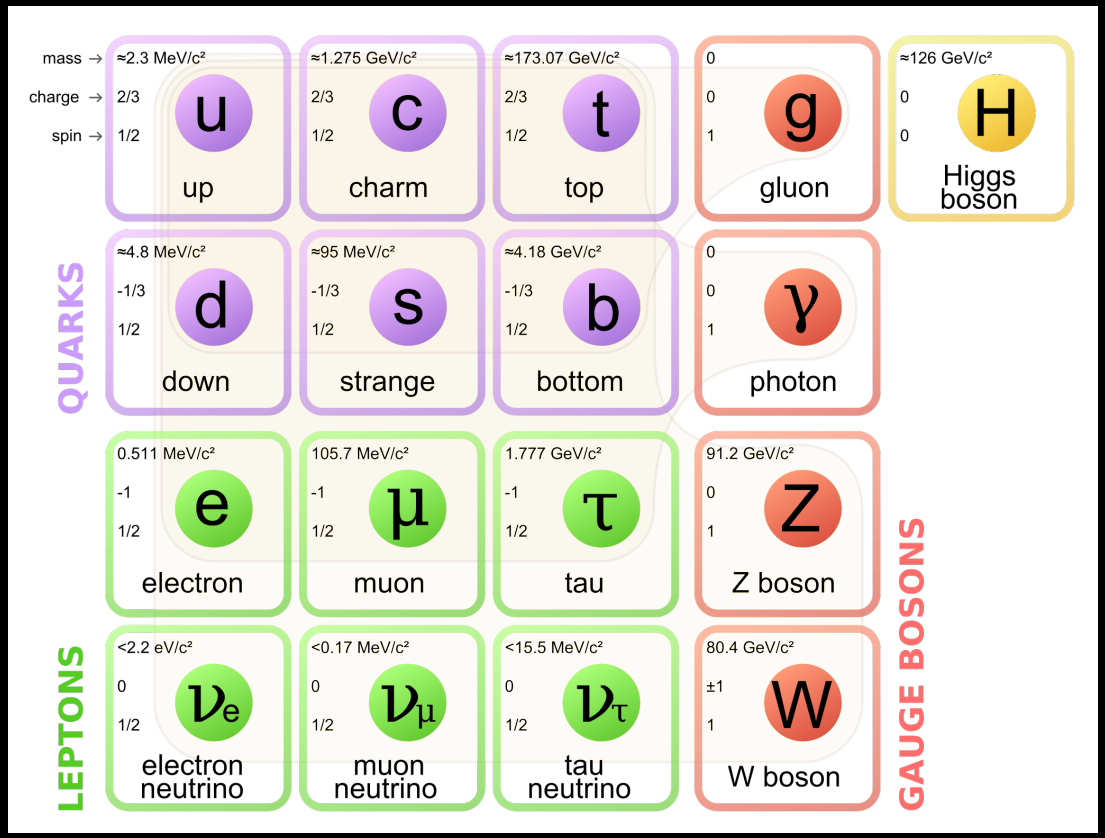
IDPASC, 25.6.20

Fundamental interactions

Standard Model:



- ⋆ Strong interactions (1),
- ⋆ Electromagnetism ($1/137$),
- ⋆ Weak interactions (10^{-9}),

- ⋆ Gravitation (10^{-38})
  - ⋆ the weakest ”force”,
  - ⋆ not described in the Standard Model,
  - ⋆ does the ”graviton” really exist?

Gravitation: Newton vs Einstein

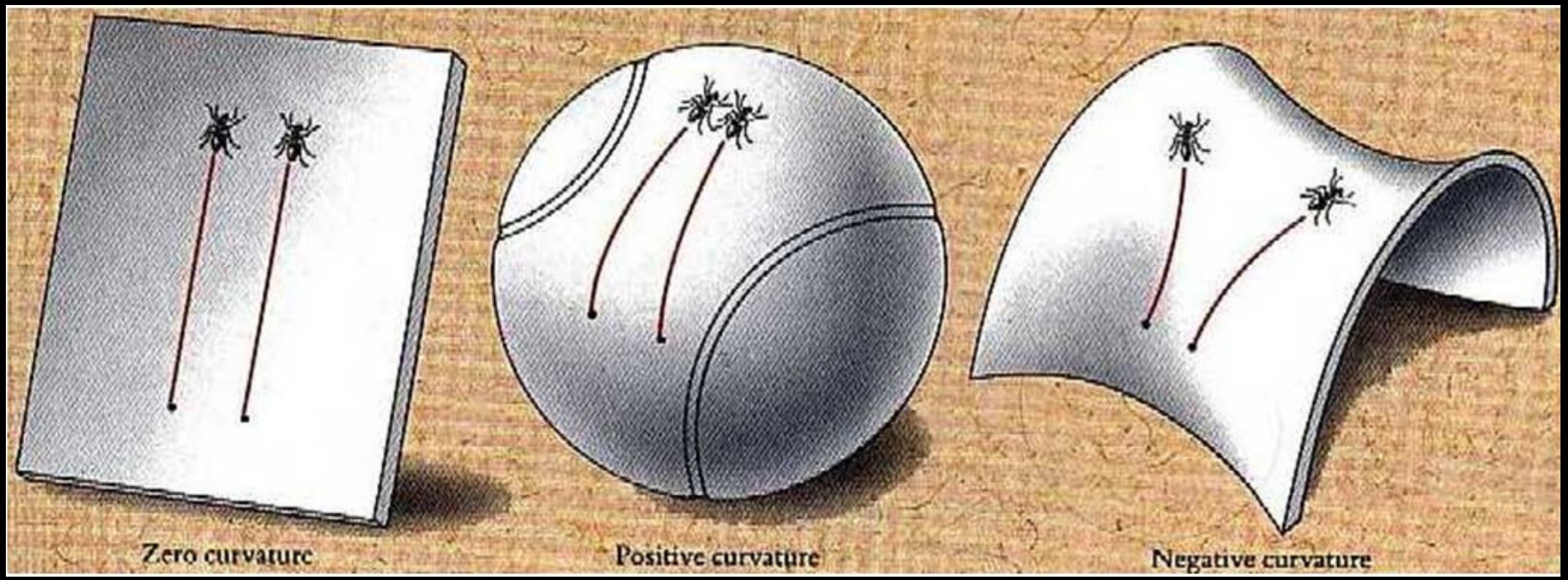
Newton:

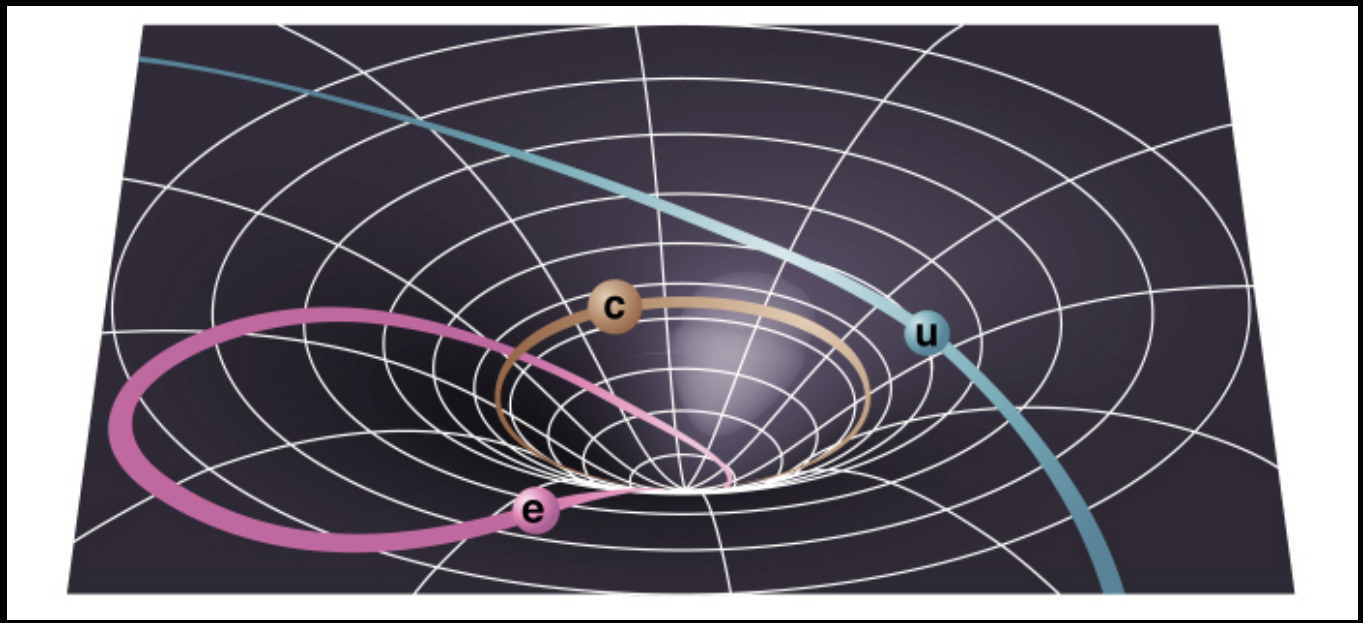
- ⋆ Space is euclidean, time is absolute, there is no relation between them
- ⋆ Gravitation is a force acting between masses
- ⋆ Force of gravitation acts immediately at any distance

Einstein:

- ⋆ Space and time are related
- ⋆ 4-dimensional space-time is curved by masses, and gravitation is an effect of this curvature
- ⋆ Effects of gravitation travel with a finite speed (speed of light)

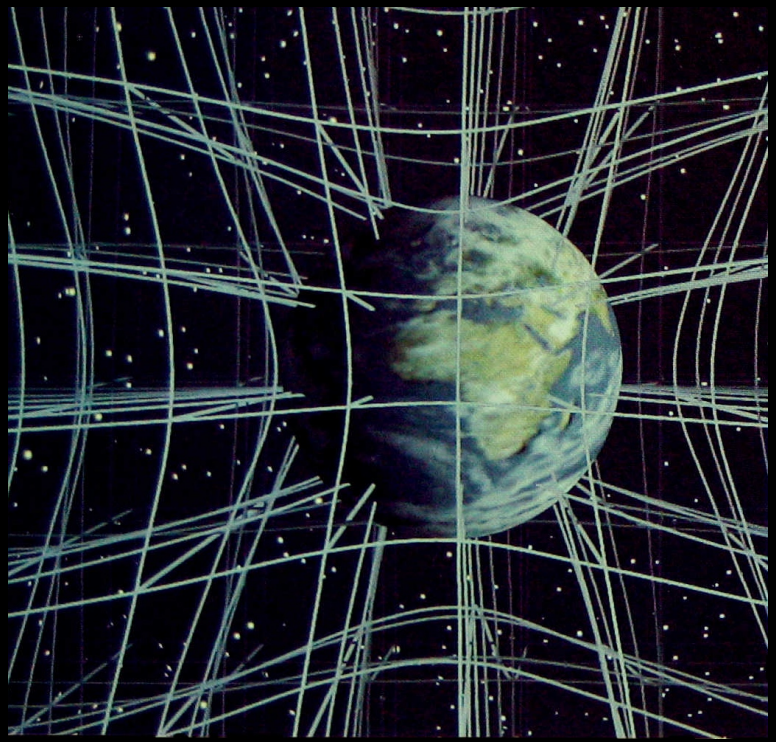
The role of curvature





Einstein (1915): gravitation $\equiv$ spacetime geometry

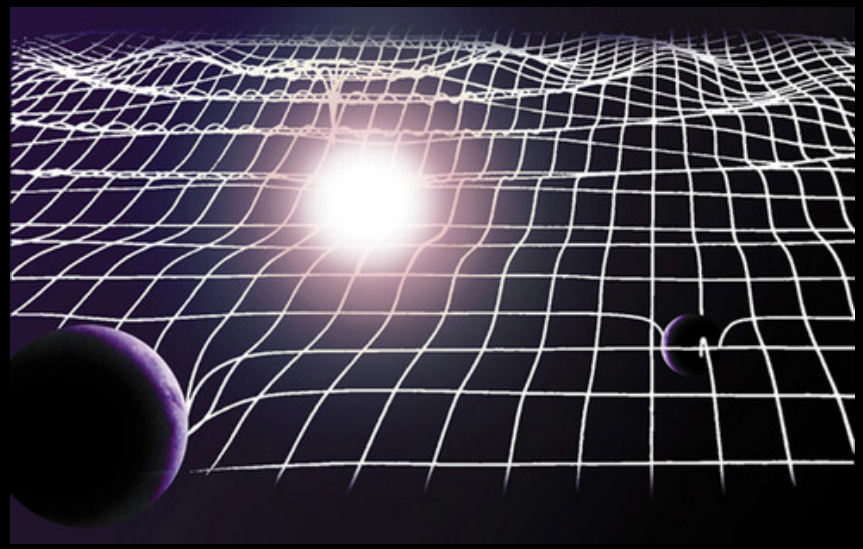
$$\underbrace{R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu}}_{\text{geometry}} = \underbrace{\frac{8\pi G}{c^4} T_{\mu\nu}}_{\text{mass-energy}}$$



”Spacetime grips mass, telling it how to move. . . Mass grips spacetime, telling it how to curve”

(*John A. Wheeler*)

Einstein (1916): wave-like solutions in general theory of relativity: time-dependent changes of curvature propagating with the speed of light

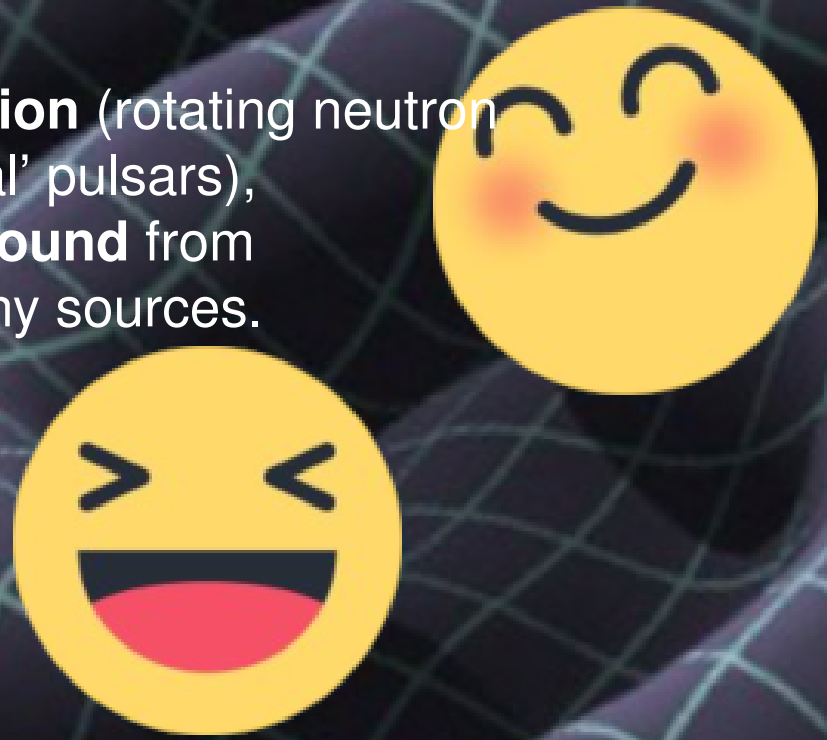


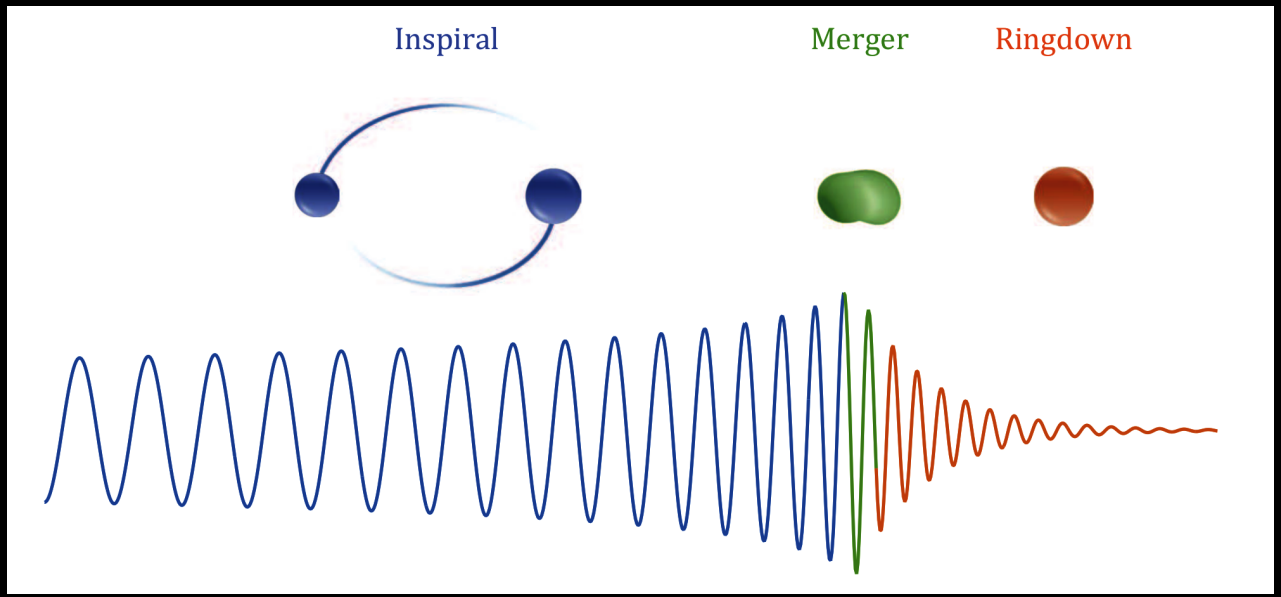
Astrophysical sources

Non-axisymmetric (rapid) movement of (large) masses
$\Longrightarrow$ detectable gravitational-wave emission

- ⋆ Transient signals (cataclysms):
  - ⋆ **in binary systems** (black holes, neutron stars),
  - ⋆ **explosions** (e.g. core-collapse supernovæ).

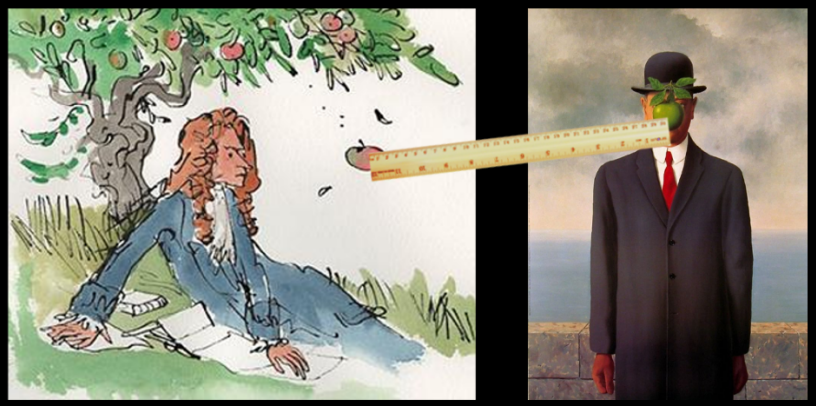
- ⋆ Long-lasting signals:
  - ⋆ **continuous emission** (rotating neutron stars = 'gravitational' pulsars),
  - ⋆ **stochastic background** from a population of many sources.




Inspiral
Merger
Ringdown

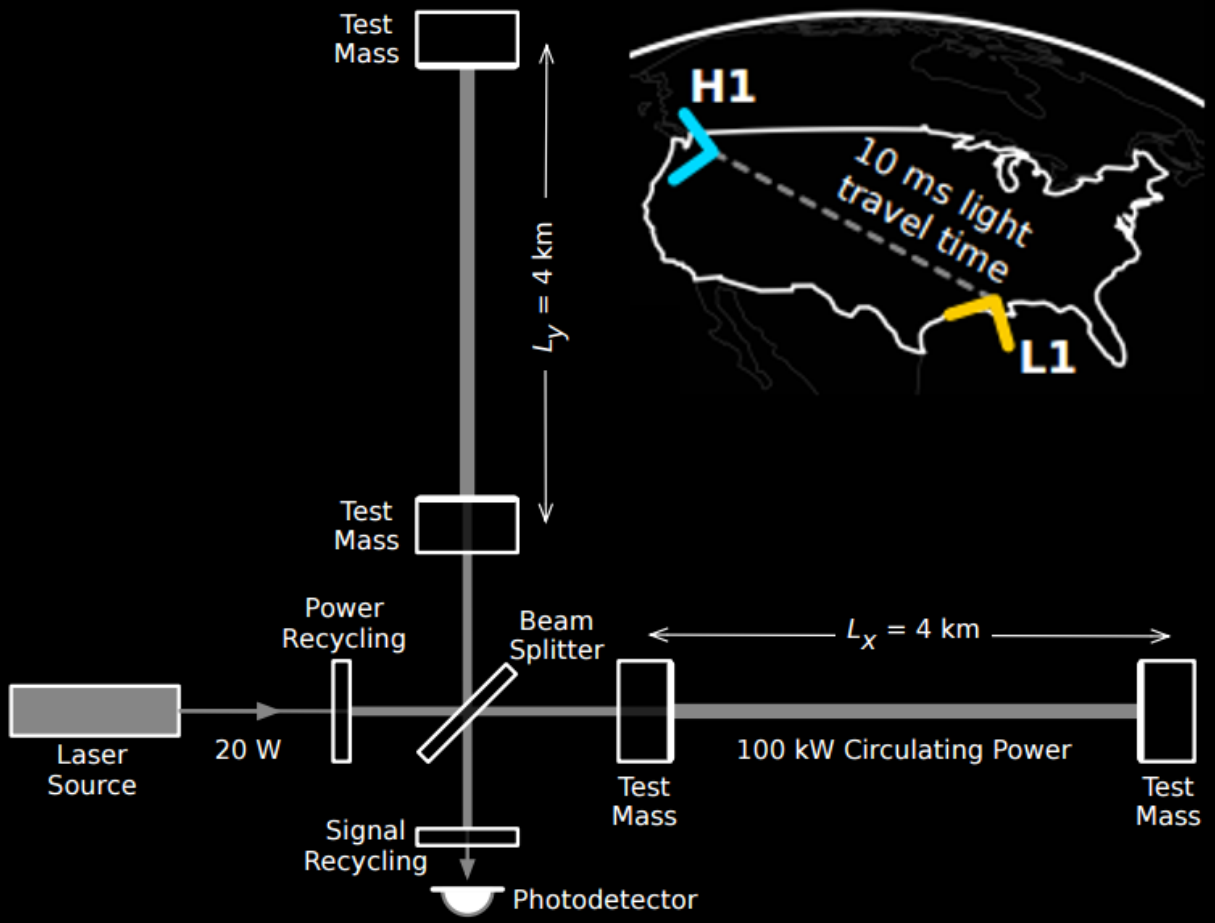
LIGO-Virgo global detector network

Very precise rulers: measuring distances between free-falling bodies with laser light.



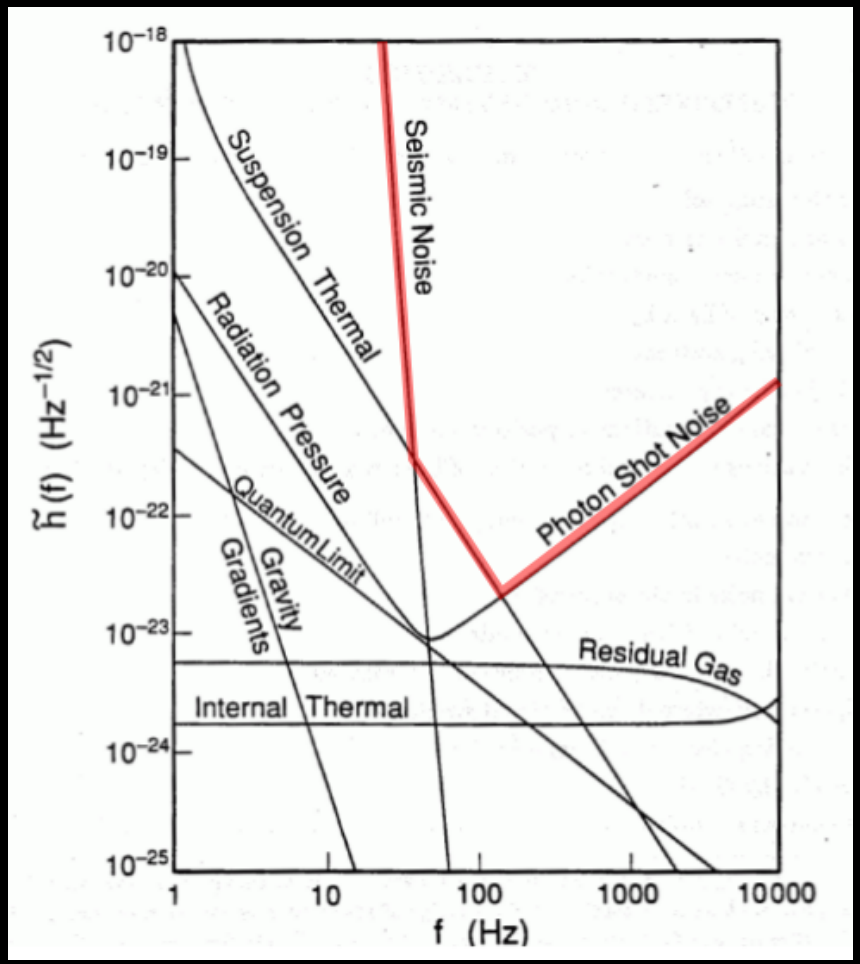
Detection principle. Laser interferometry

"How to measure distance when the ruler also changes length?"



Changes in arms length are **very** small: $\delta L_x - \delta L_y = \Delta L < 10^{-18}$ m (smaller than the size of the proton). Wave amplitude $h = \Delta L / L \leq 10^{-21}$.

LIGO-Virgo broadband sensitivity curves



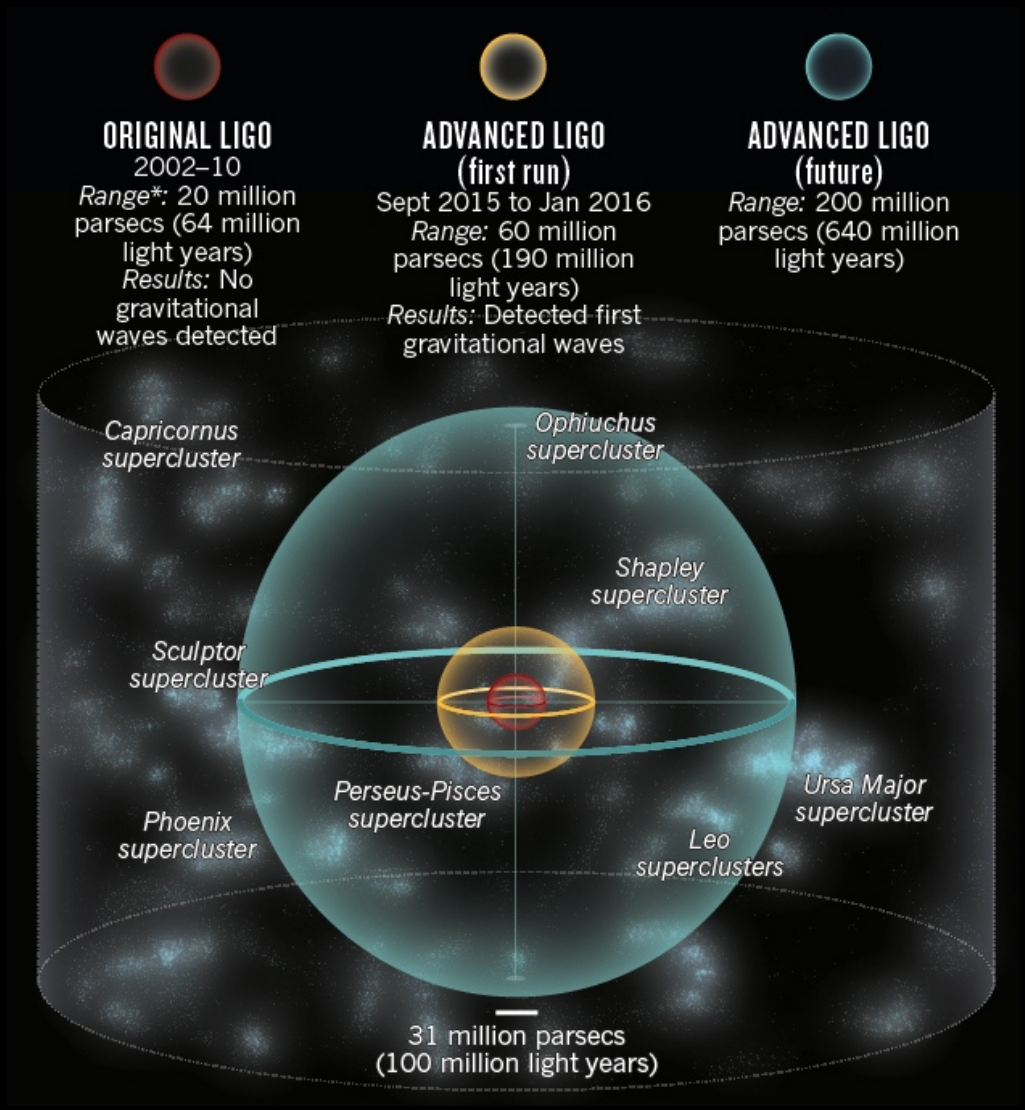
Initial LIGO proposal (1989)

- ⋆ Range of frequencies similar to human ears:

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

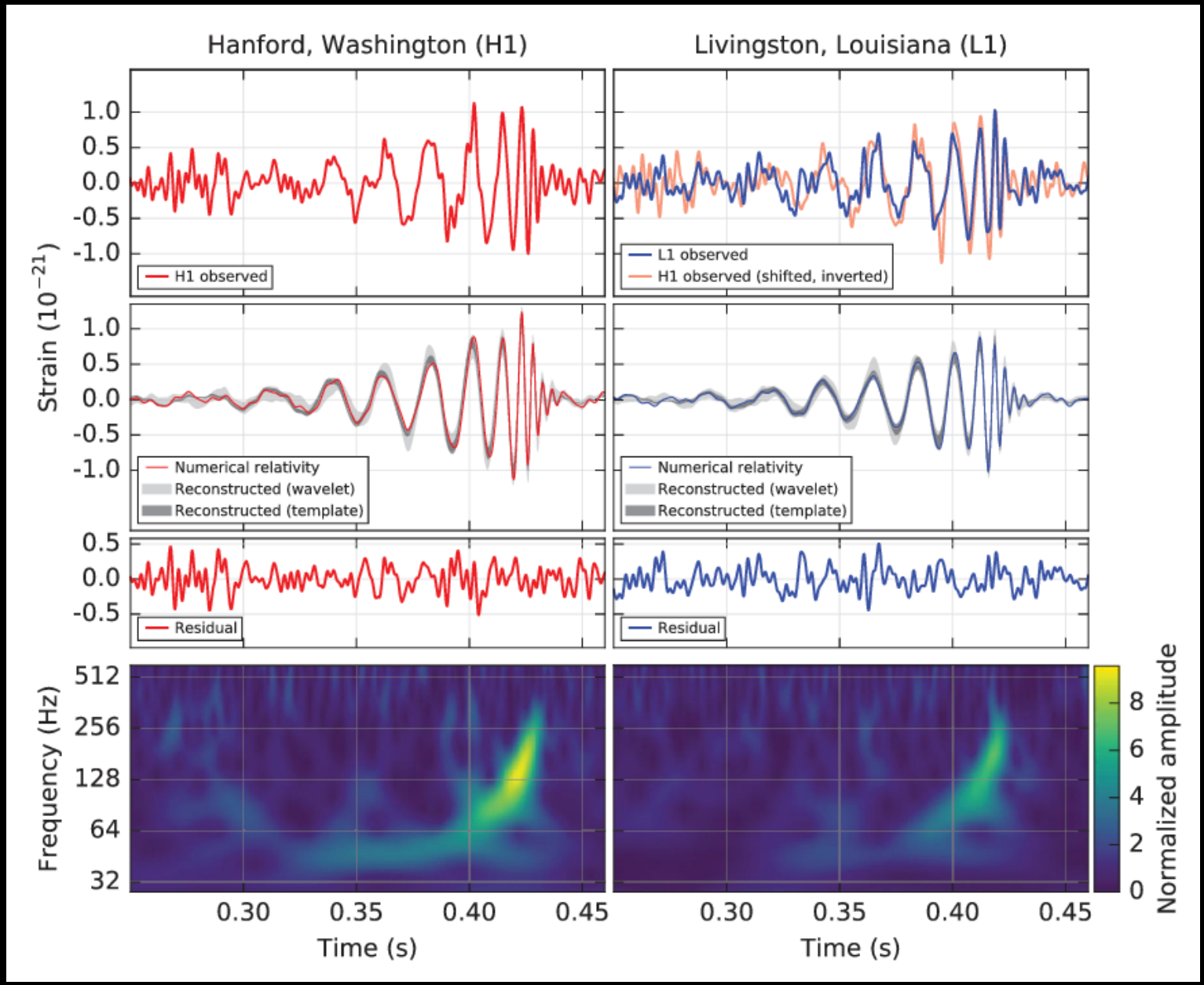
- ⋆ Poor, like for an ear, angular resolution.

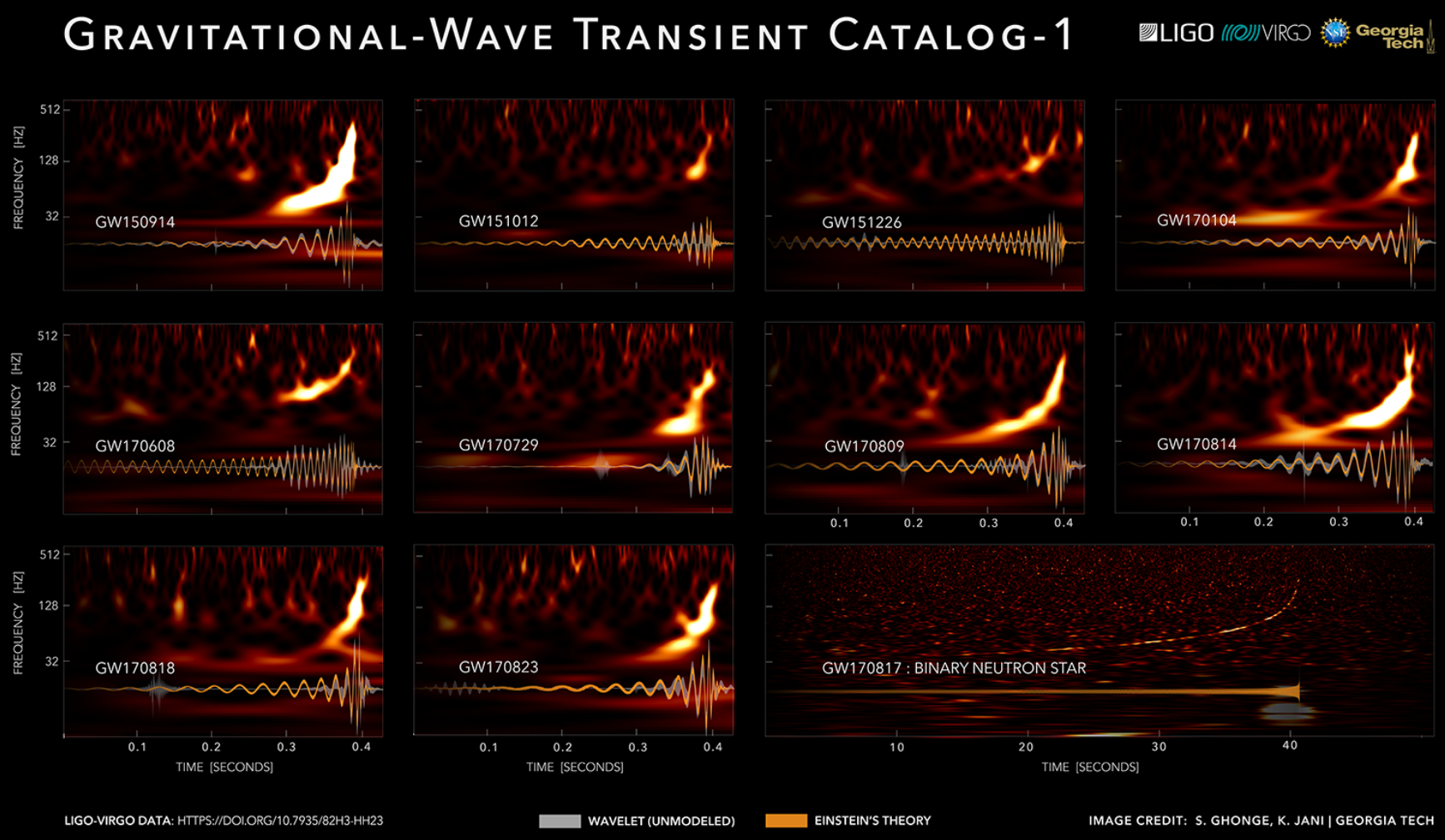
Sensitivity $\rightarrow$ amplitude $\rightarrow$ volume



- ⋆ 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 $h \rightarrow 0.1h$ gives $r \rightarrow 10r$, that is $V \rightarrow 1000V$.

GW150914: 14 September 2015, 11:50:45 CEST





GWTC-1 - O1 & O2 detections (Phys. Rev. X 9, 031040 2019)

Astrophysically-interesting parameters of the binary

Intrinsic:

- ⋆ 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.) $\rightarrow$

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

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

- ⋆ Tidal deformability Λ (at 5PN) $\rightarrow$

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

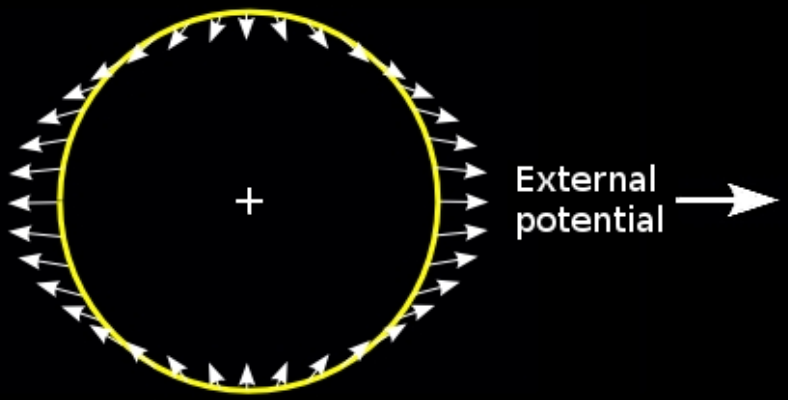
Extrinsic:

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

Signature of matter in binary NS waveforms

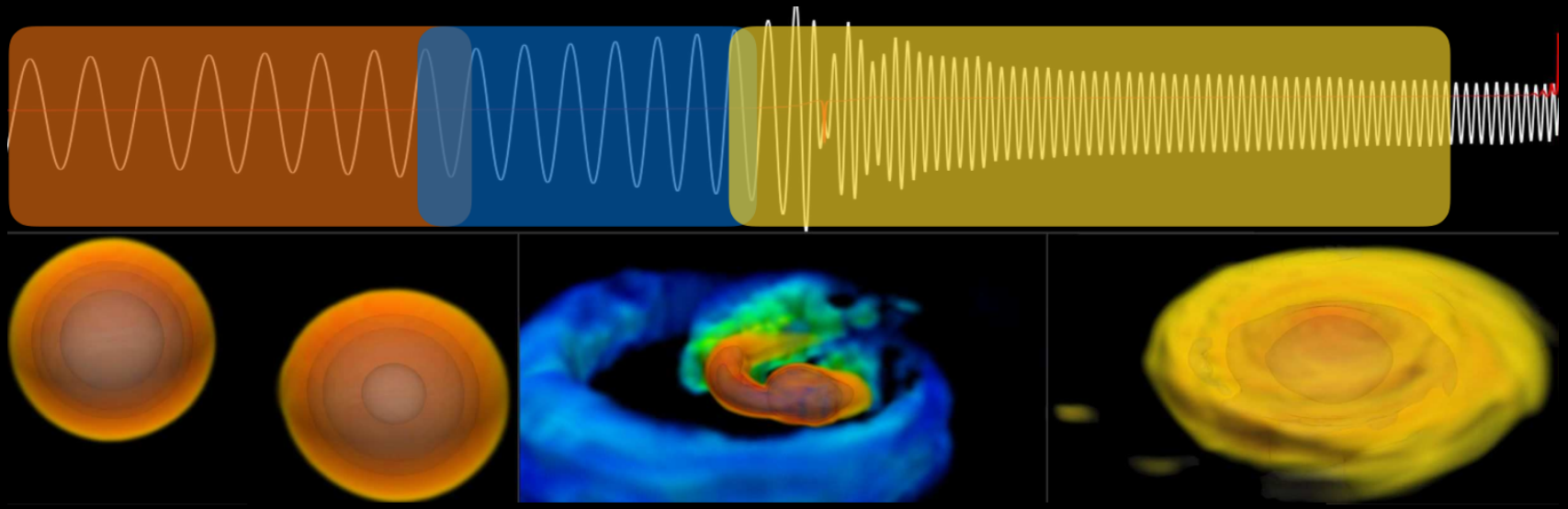
Tidal tensor $\mathcal{E}_{ij}$ of one of the components induces quadrupole moment Q_{ij} in the other:

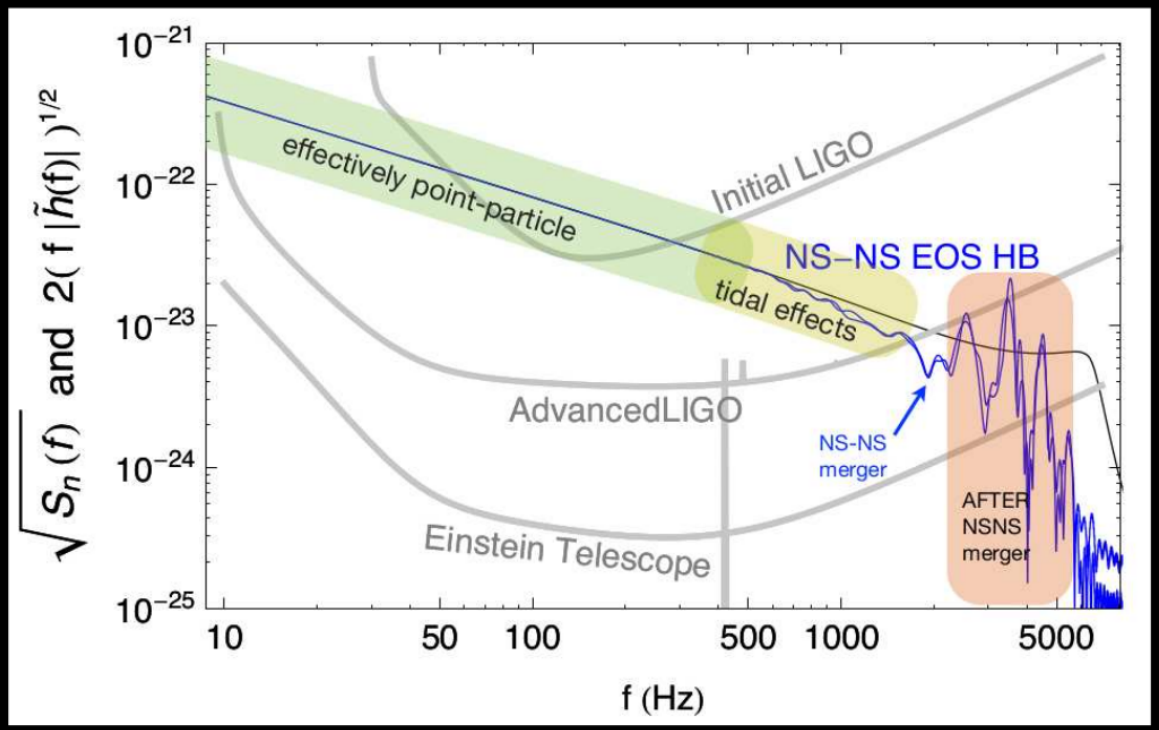
$$Q_{ij} = -\lambda \mathcal{E}_{ij} \quad \rightarrow \quad \lambda = \frac{\text{size of quadrupole deformation}}{\text{strength of external tidal field}} \quad \rightarrow \quad \lambda = \frac{2}{3} k_2 R^5$$



λ tidal deformability,
$k_2 \in (0.05, 0.15)$ - the Love number (dependent on M and equation of state).

- ⋆ Convenient redefinition: $\Lambda = G\lambda \left(\frac{GM}{c^2}\right)^{-5} \in (100, 1000)$
- ⋆ Weighted sum: $\tilde{\Lambda} = \frac{16}{13} \frac{(M_1+12M_2)M_1^4\Lambda_1+(M_2+12M_1)M_2^4\Lambda_2}{(M_1+M_2)^5}$
- ⋆ From the scaling tidal interaction is subtle (5PN) effect $(v/c)^{10}$




$\sqrt{S_n(f)}$ and $2(f\,|\tilde{h}(f)|\,)^{1/2}$
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10
50
100
500
1000
5000
f (Hz)
effectively point-particle
Initial LIGO
NS–NS EOS HB
tidal effects
AdvancedLIGO
NS-NS merger
AFTER NSNS merger
Einstein Telescope

EM vs GW

EM:

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

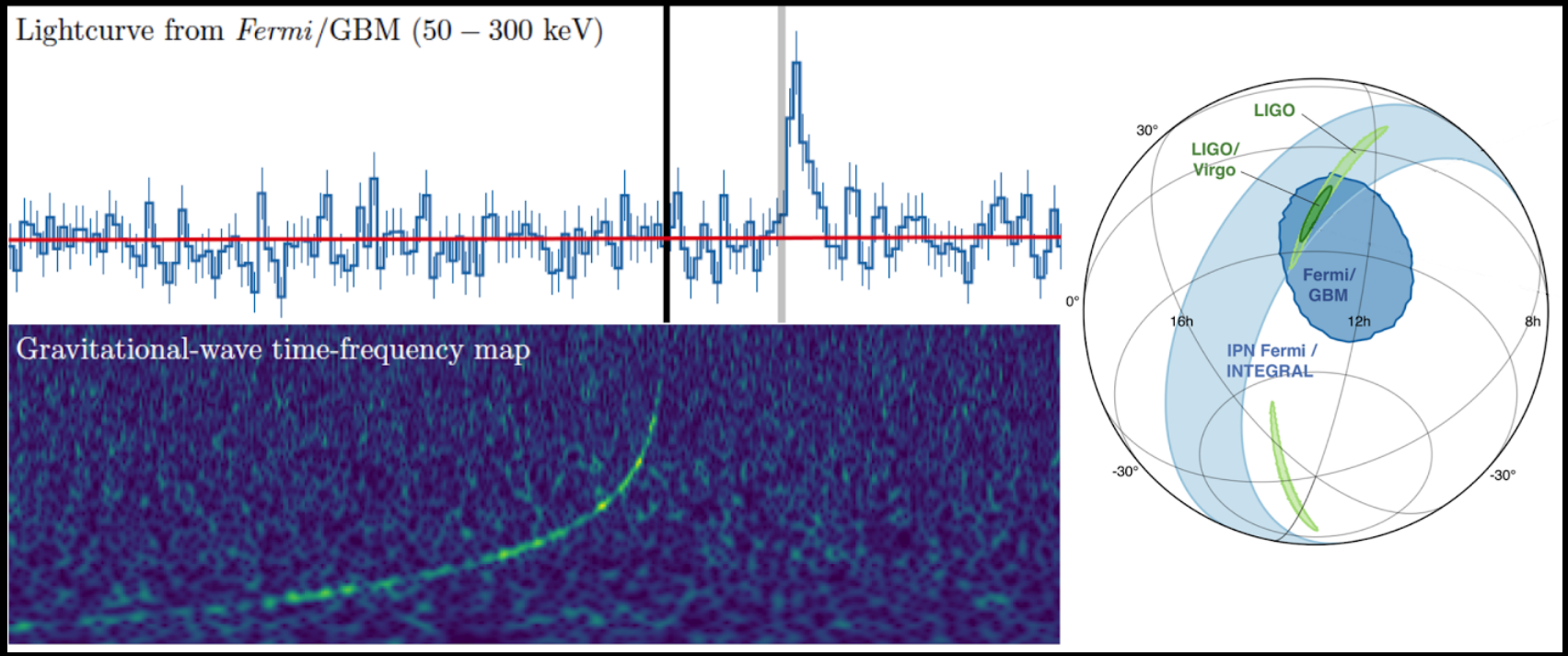
Timing, spectrum, redshift, particle acceleration and thermal signatures $\rightarrow$ standard candles, outflows, last scattering surface ...

GW:

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

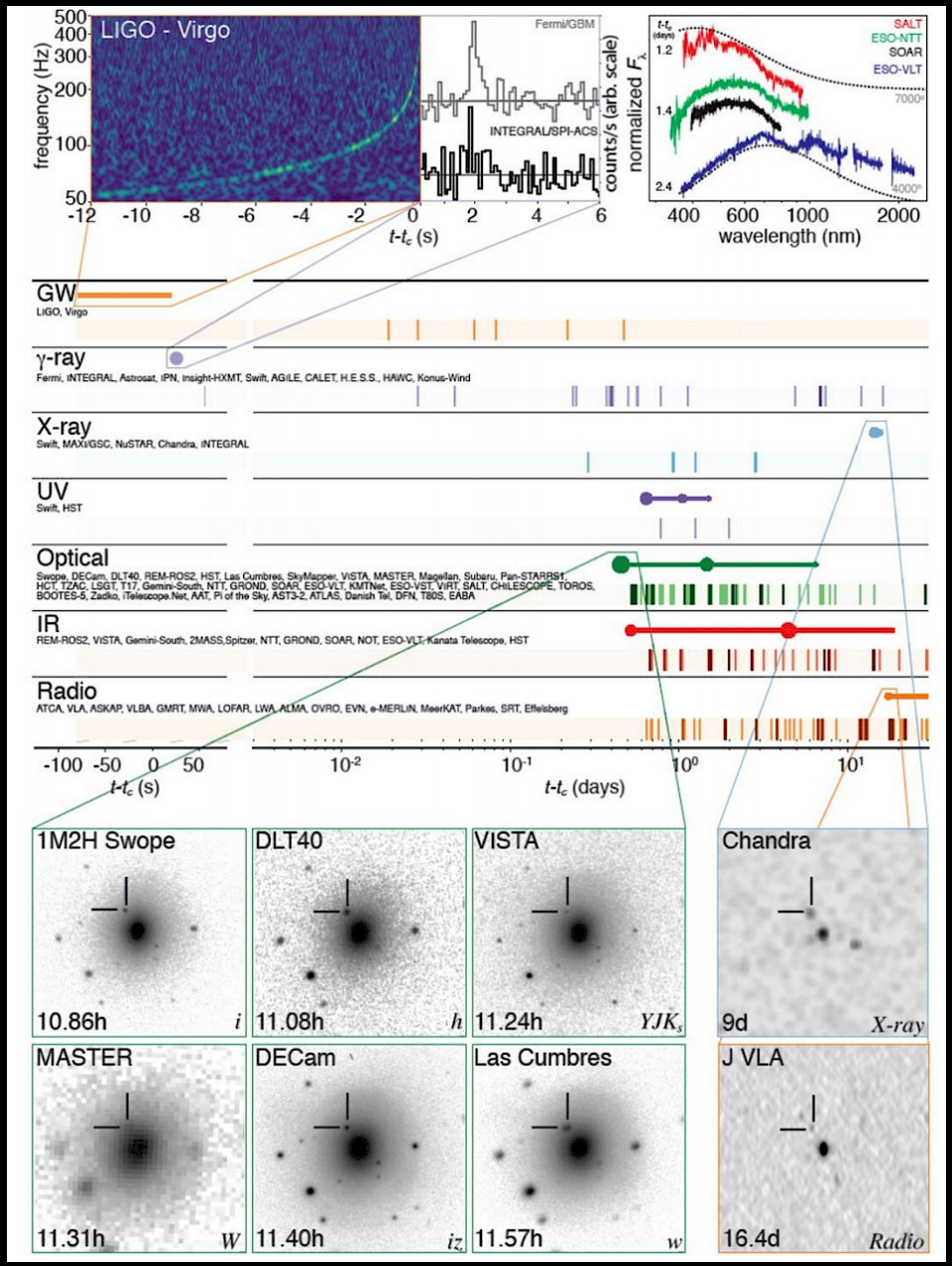
Timing, mass & spin parameters $\rightarrow$ standard sirens (direct luminosity distance), core engine, cosmology, gravity theory tests ...

GW170817: 17 August 2017, 14:41:04 CEST



- ⋆ Combined LIGO-Virgo signal-to-noise ratio: SNR=32.4,
- ⋆ False alarm rate: less than one in 80000 years,
- ⋆ Chirp mass $\mathcal{M} = \frac{(M_1 M_2)^{3/5}}{(M_1+m_2)^{1/5}} = 1.186^{+0.001}_{-0.001}\ M_\odot$
- ⋆ Distance $d = 40^{+8}_{-14}$ Mpc (90% credible intervals)
- ⋆ High-spin prior $\tilde{\Lambda} \leq 800$, low-spin prior: $\tilde{\Lambda} \leq 900$

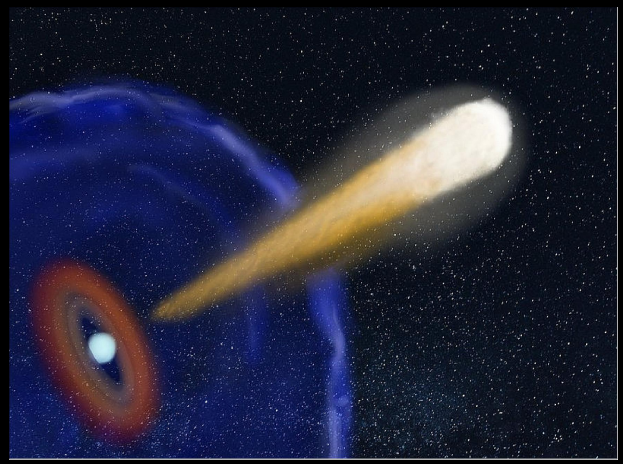
EM-followup multi-messenger observations



'Kilonova' - UV-optical-IR glow powered by radioactive decay of isotopes:

- ⋆ Luminosity $10^8\ L_\odot$ in visual 1 day after the merger,
- ⋆ IR bright for nearly two weeks,
- ⋆ Black-body spectrum → thermal source.

All consistent with radioactive r-process heating.



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

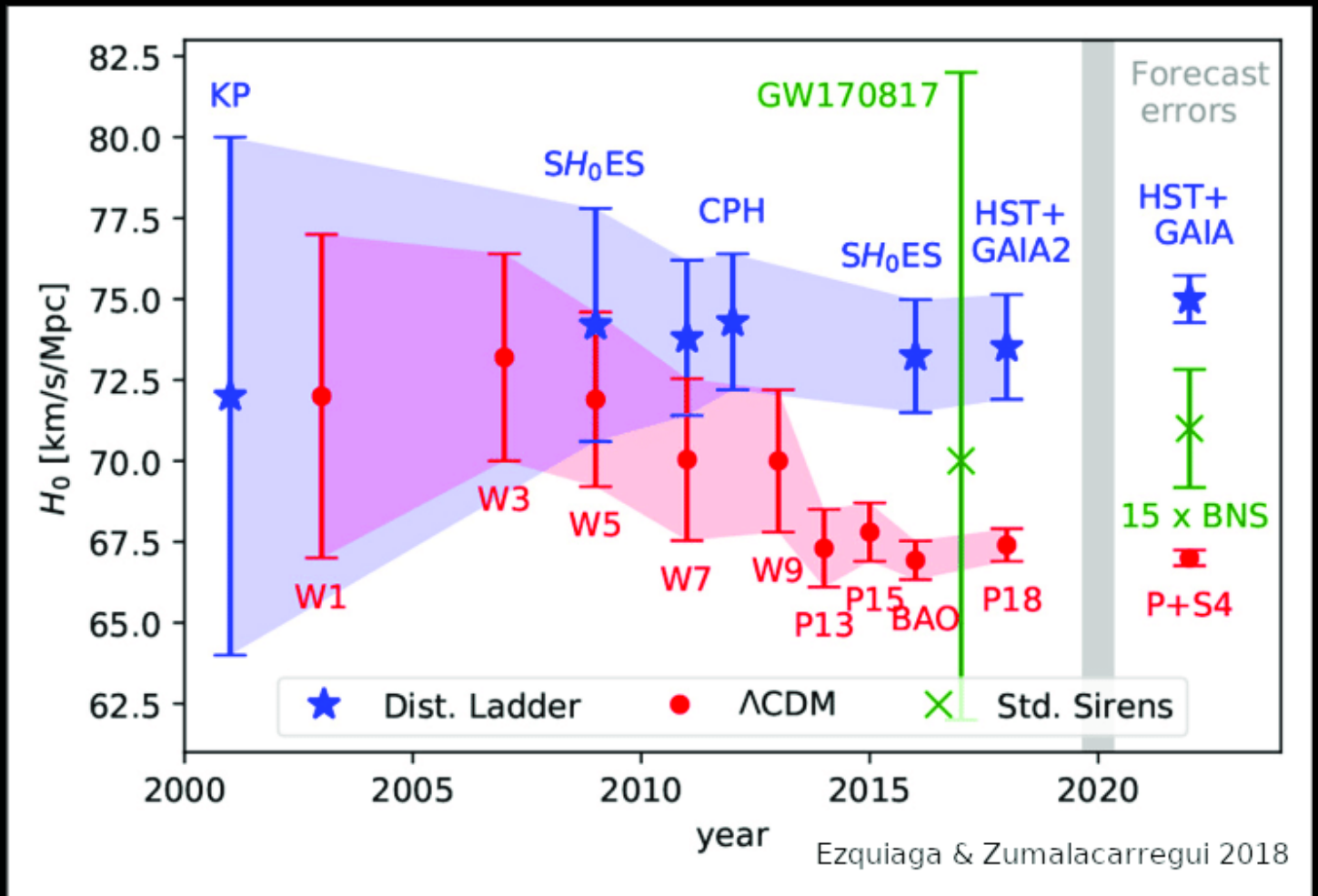
$$-3 \times 10^{-15} \leq \frac{\Delta v}{c} \leq 7 \times 10^{-16}$$

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

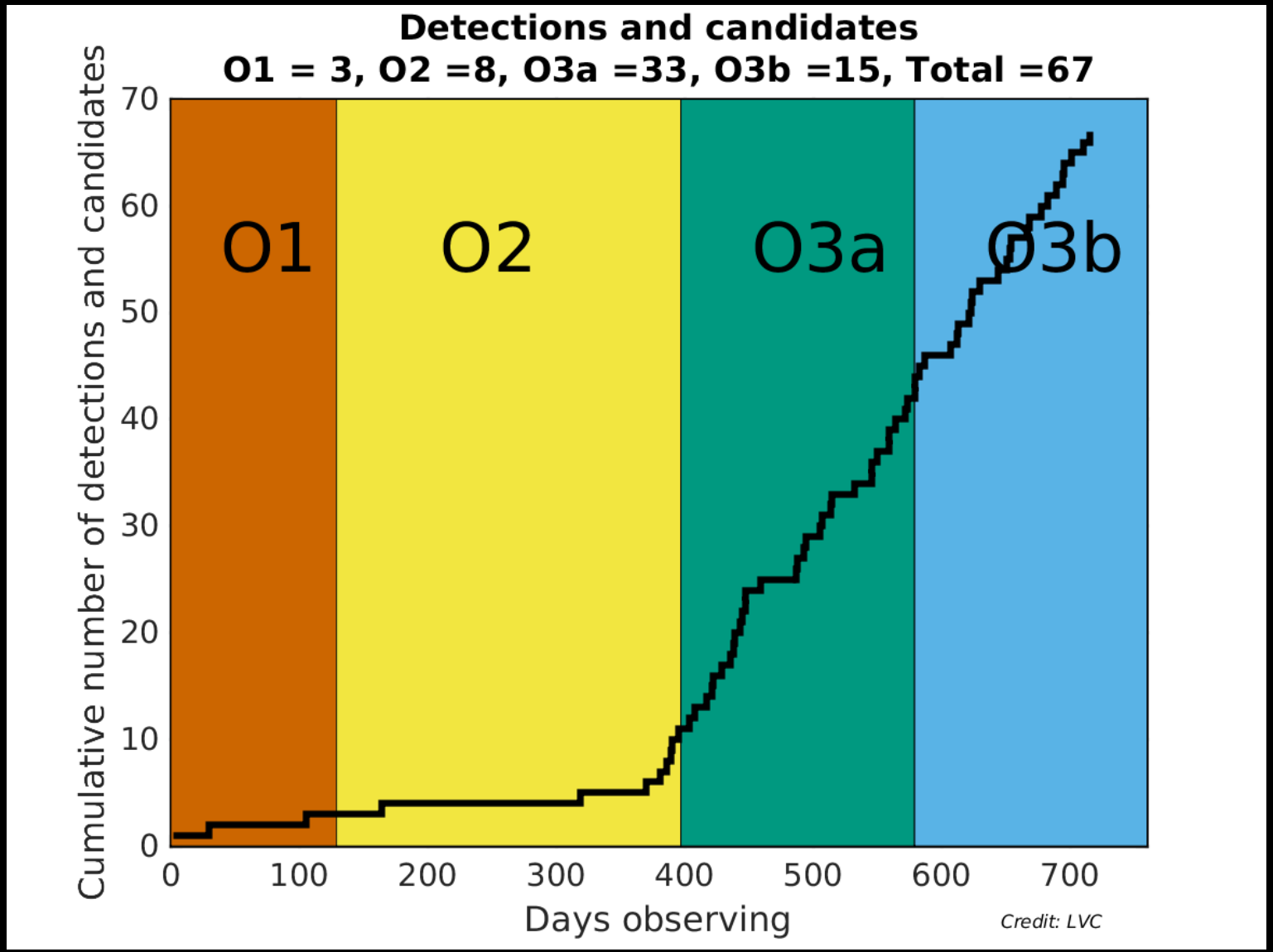
GW170817: Hubble parameter with ”standard siren”

Hubble parameter defined as $v_H = H_0 d$

- $H_{0,GW} = 70^{+12}_{-8}$ km s^{-1} Mpc^{-1}
- Planck: 67.74 ± 0.46, SH0ES: 73.24 ± 1.74 km s^{-1} Mpc^{-1}



LIGO-Virgo O3 run: 56 signals since 01 April 2019

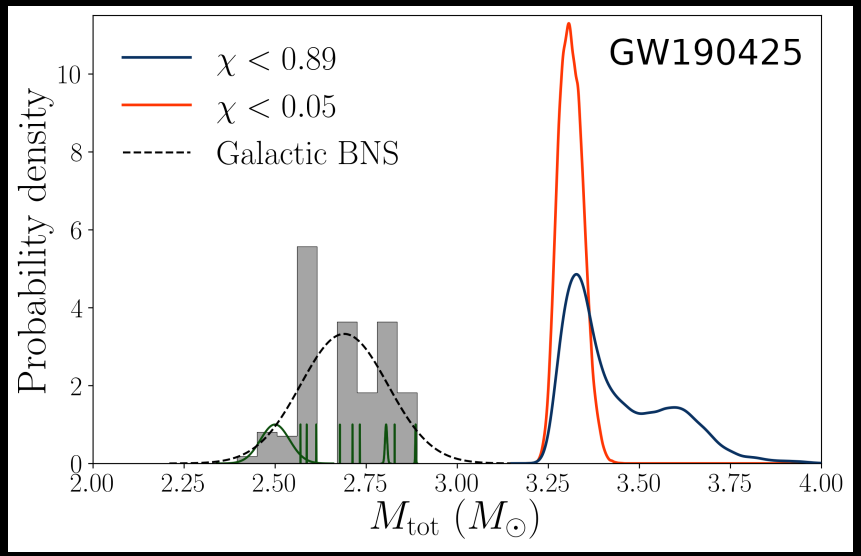


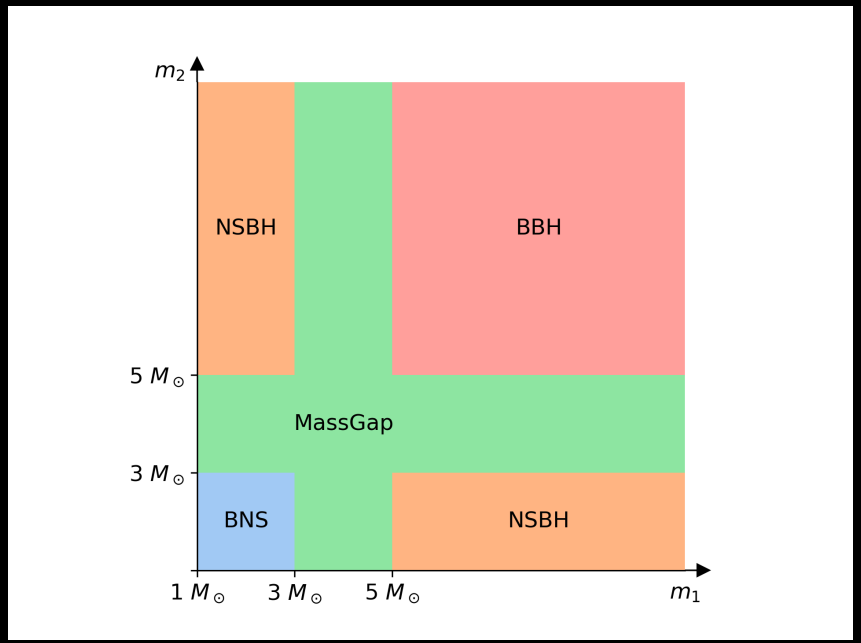
(O3 suspended 25 March 2020 because of COVID-19 :/)

LIGO-Virgo O3 run: 56 signals since 01 April 2019

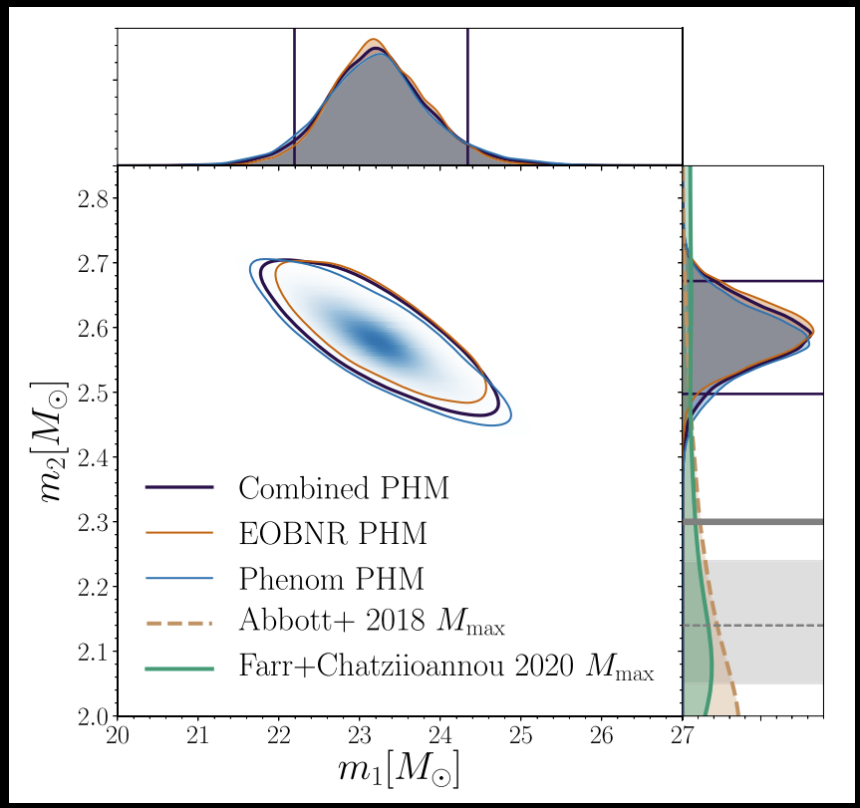
Among others:

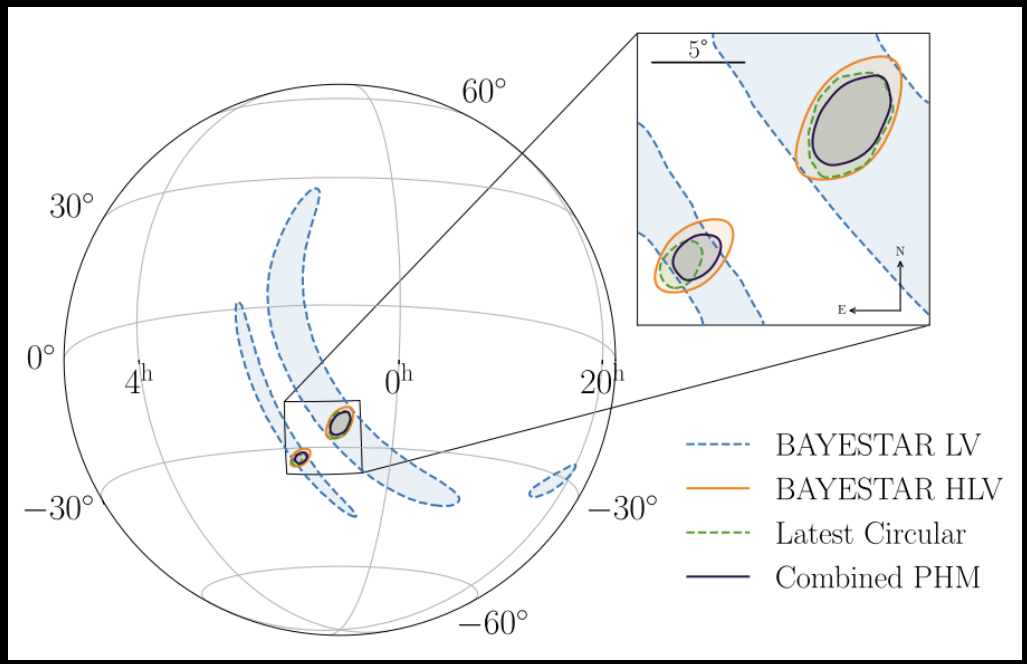
- ⋆ **GW190425**: BNS, massive binary neutron star system, $r = 156 \pm 41$ Mpc (arXiv:2001.01761),
- ⋆ **GW190412**: BBH coalescence with asymmetric masses (arXiv:2004.08342),
- ⋆ **GW190814**: first detection of a NSBH system? (arXiv:2006.12611),
- ⋆ S190521g: very distant (and massive) BBH, $r = 3931 \pm 953$ Mpc,
- ⋆ S200115j: NSBH with BH in the "mass gap"?





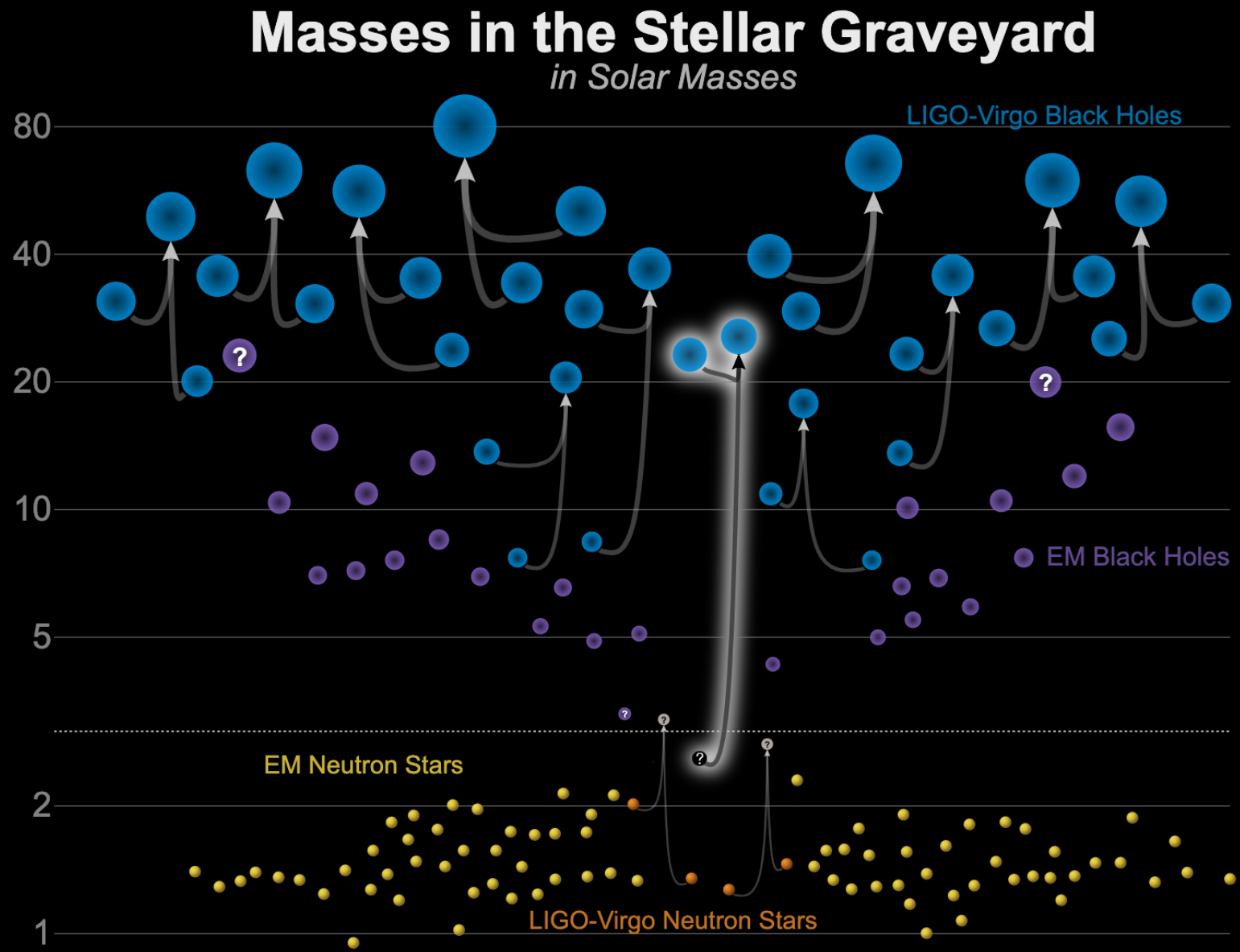
GW190814: 23 $M_\odot$ BH + 2.6 $M_\odot$ compact object





Distance 241^{+41}_{-45} Mpc, sky localisation to within 18.5 deg^2.

Best localized "dark siren" so far: $H_0 = 75^{+59}_{-13}$ km s^{-1} Mpc^{-1}
(with GW170817: $H_0 = 70^{+17}_{-8}$ km s^{-1} Mpc^{-1})


Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
?
Updated 2020-05-16
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

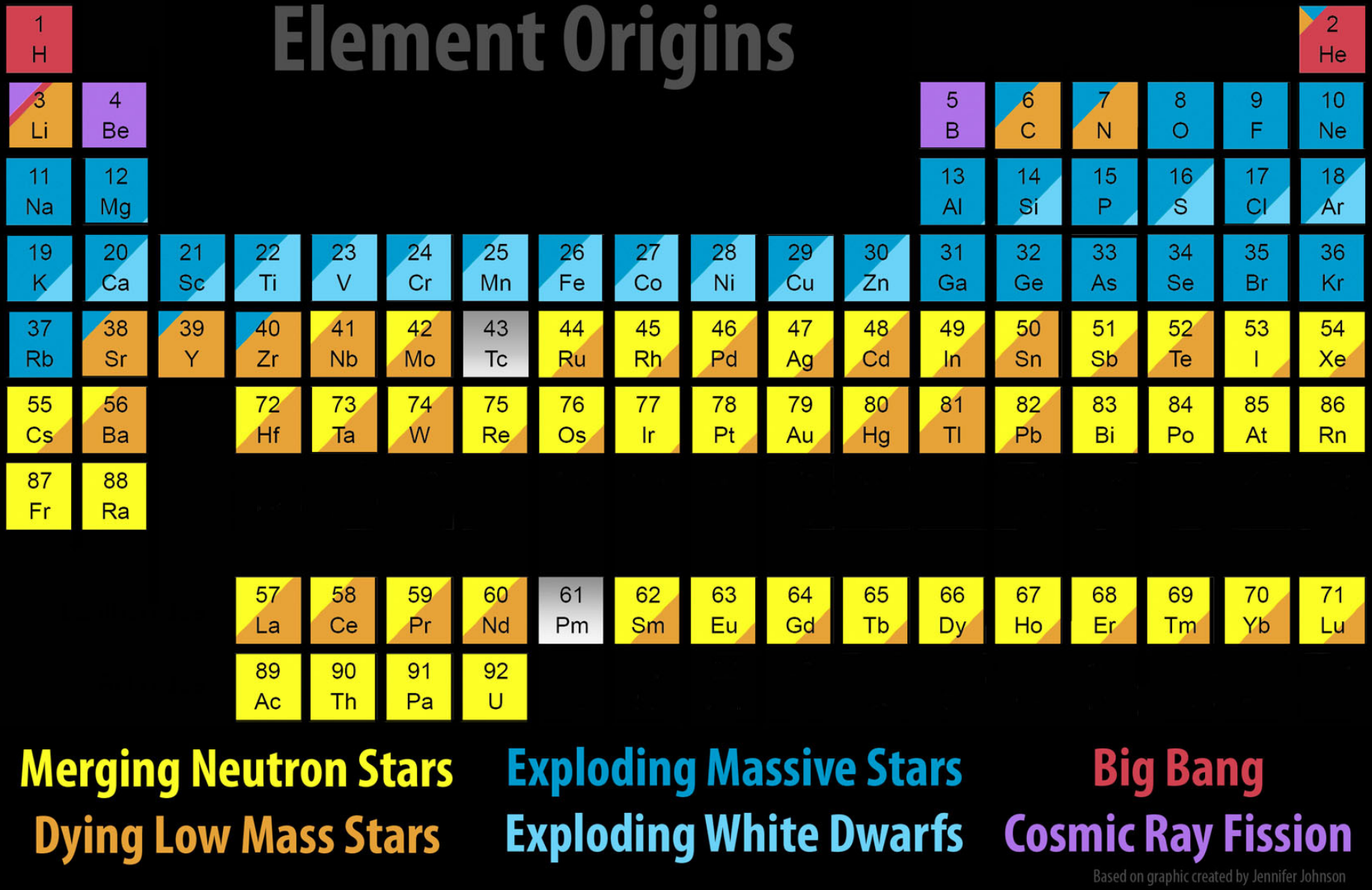
Soon

Neutron stars: dense matter equation of state, mass-tidal deformability relationship, maximum mass $\leftrightarrow$ mass gap, phase transitions to quark-gluon plasma, additional fields and particles / exotic matter, elastic properties matter and phases, viscosity, magnetic field, oscillations and stability of stars, glitches, superfluidity and superconductivity, . . .

Multi-messenger astronomy: gamma-ray bursts, production of elements, mass function of black holes and neutron stars, environment in host galaxies, various channels for creating binary systems, . . .

Cosmology: Hubble parameter, dark energy equation of state, interaction with dark matter particles, large-scale structure, stochastic gravitational-wave background, lensing, . . .

Tests of gravity theories: higher harmonics, black hole spectroscopy (ring-down), no-hair theorem, echoes, scalar & vector polarizations, strong field tests outside the quadrupole approximation, spin precession, Lorentz invariance, massive gravity, gravitational-wave memory, . . .



Most of gold, platinum is produced in neutron-star mergers, in r-process (rapid neutron capture)!