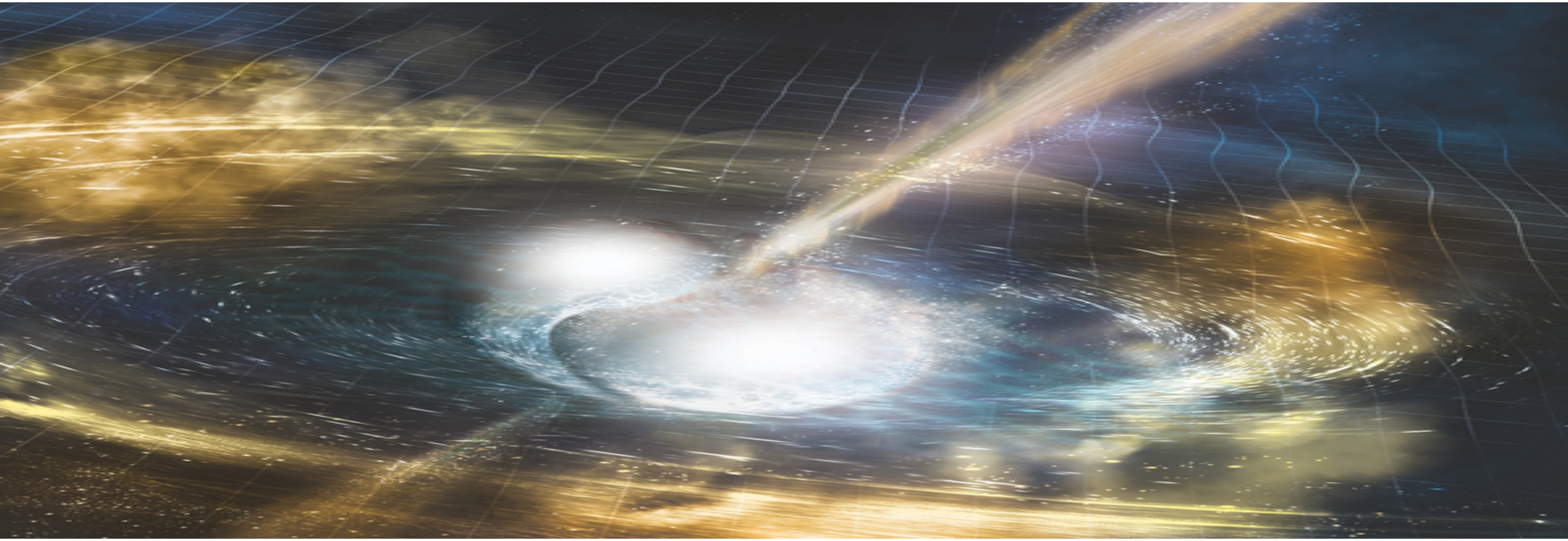
Implications of the LIGO/Virgo gravitational wave detections for fundamental physics and cosmology.

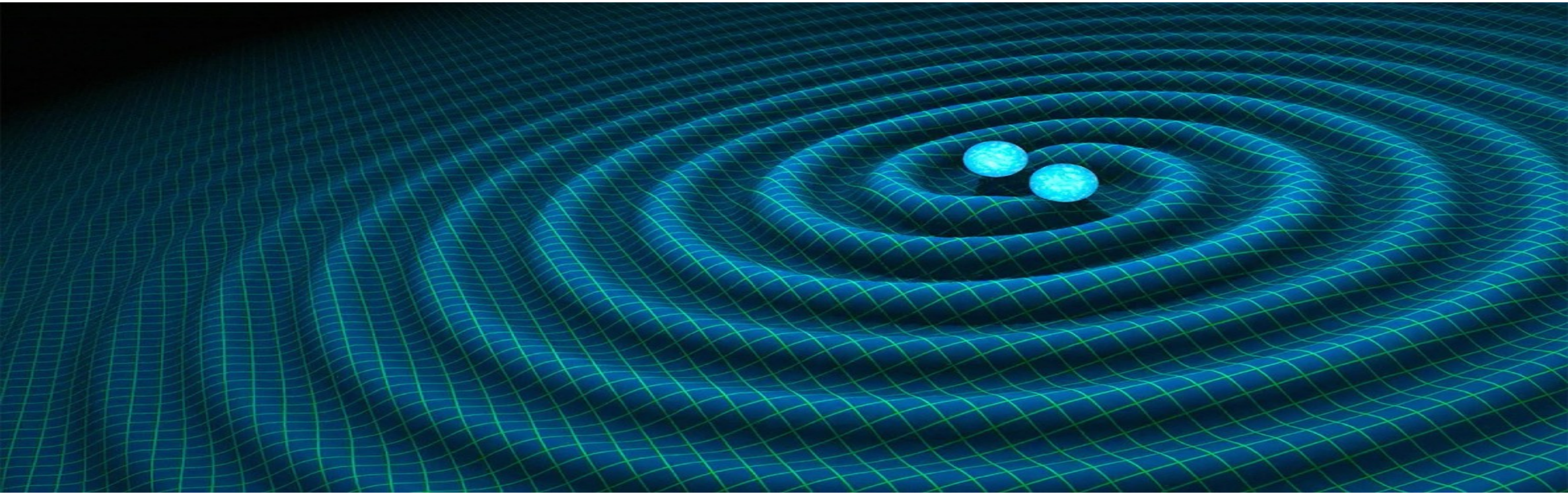


Ed Porter (APC/CNRS) for the LIGO/Virgo Collaboration
30th Rencontres de Blois, 4-8 June 2018

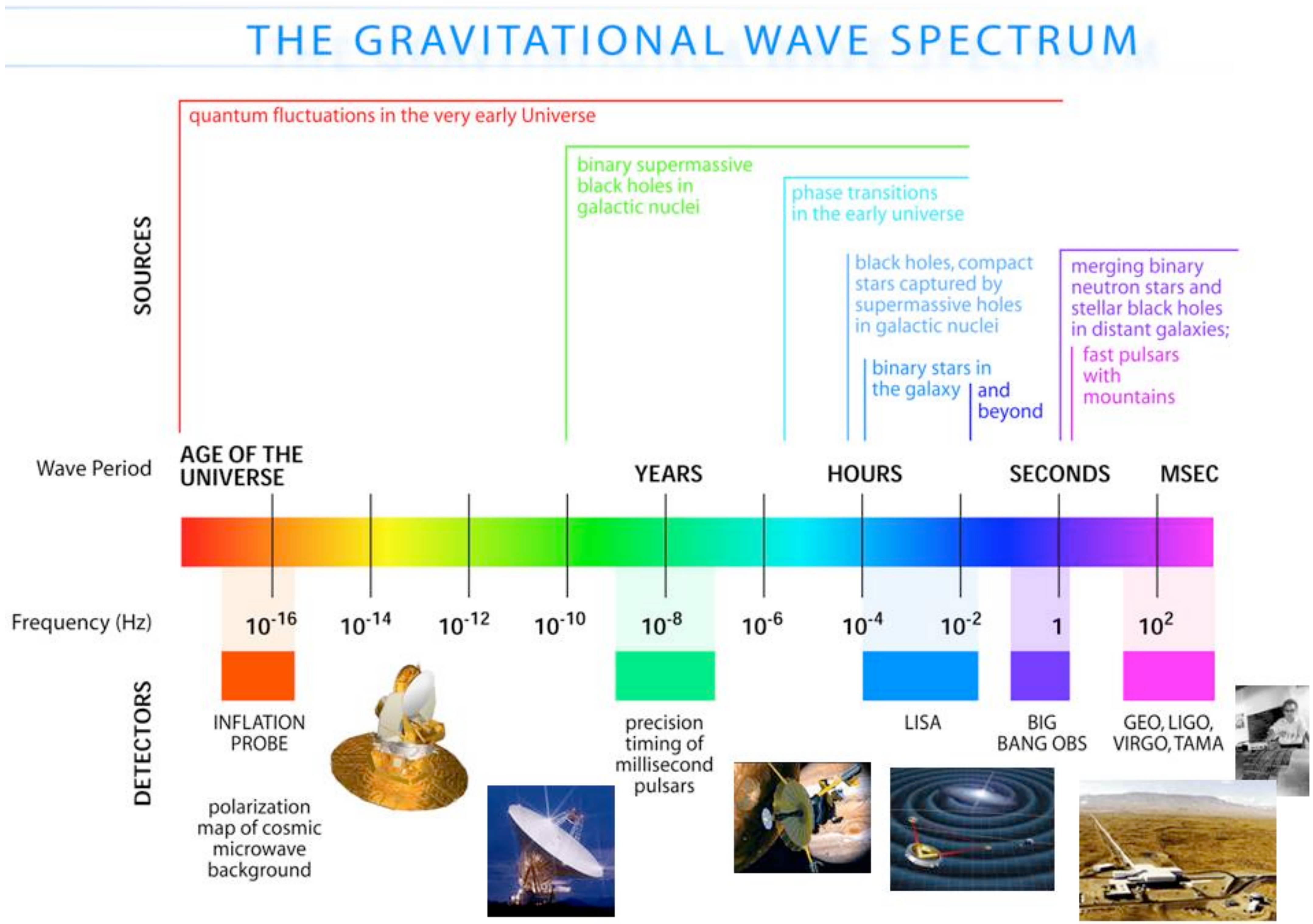
Overview

- GW Astronomy
- Advanced Detector Observation Runs
- Fundamental physics using BBH mergers
- Fundamental physics and cosmology using a BNS merger
- Neutron star equation of state

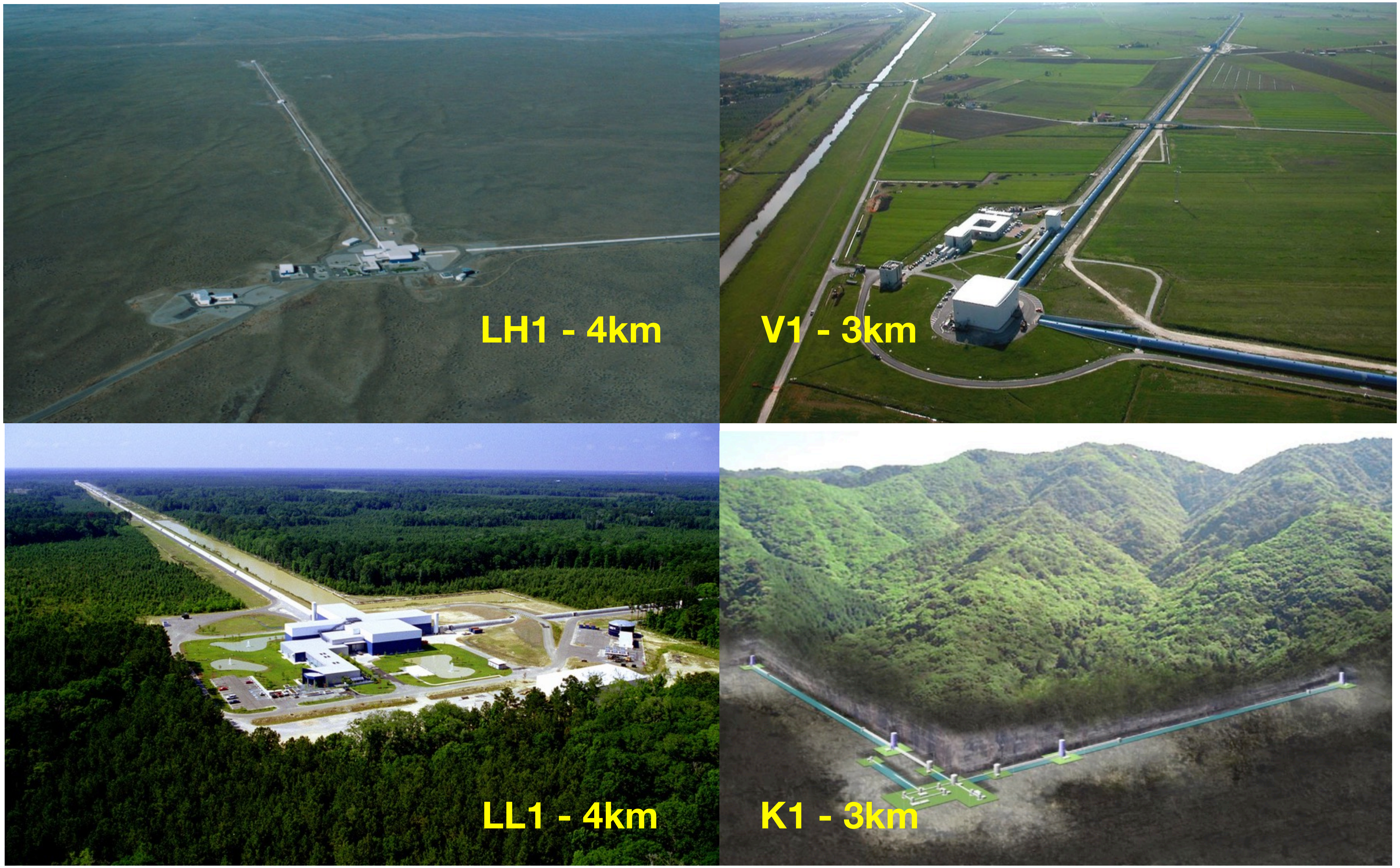
Gravitational Wave Astronomy



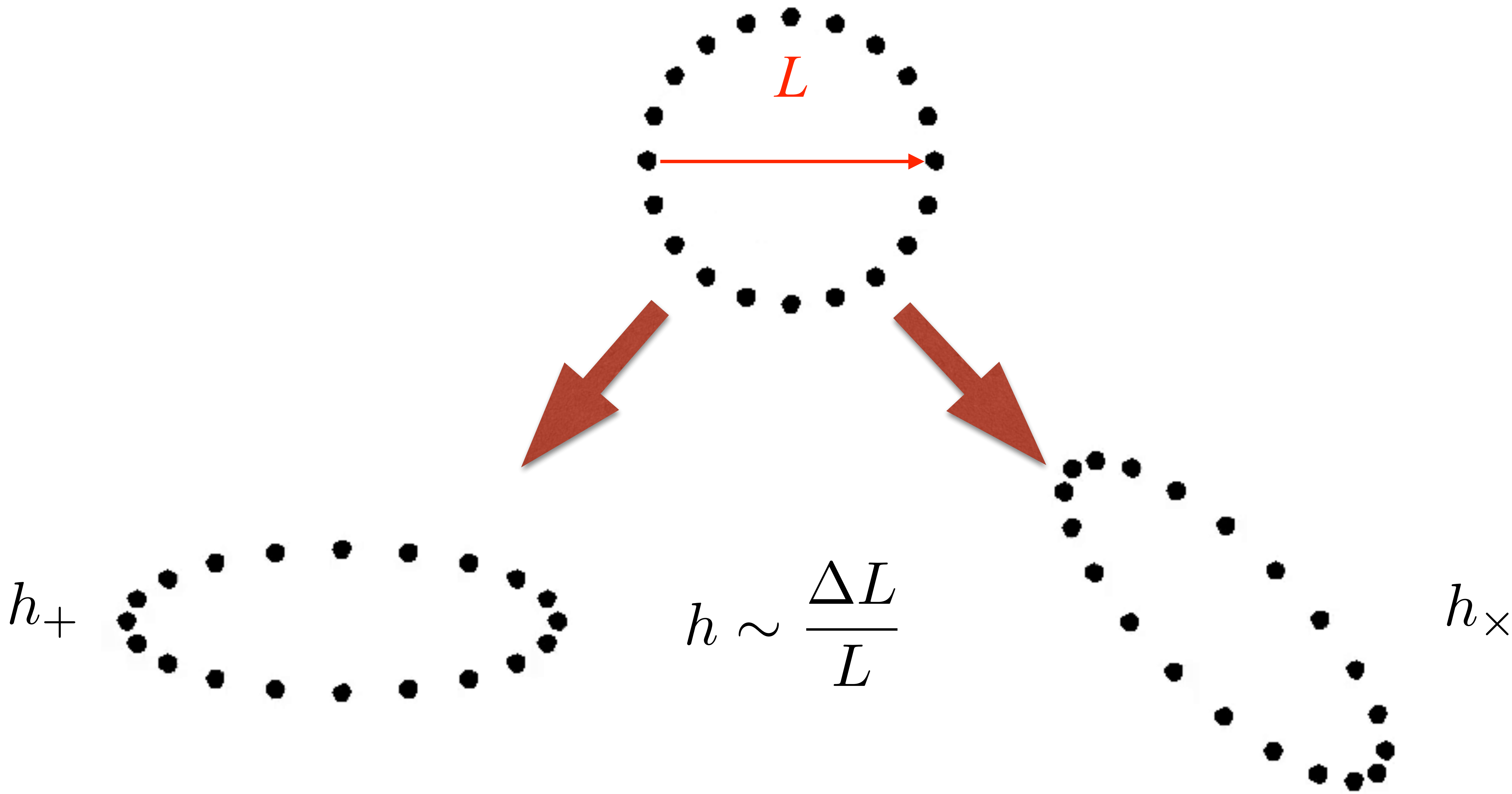
GWs and GW detection



Ground-based GW Interferometers

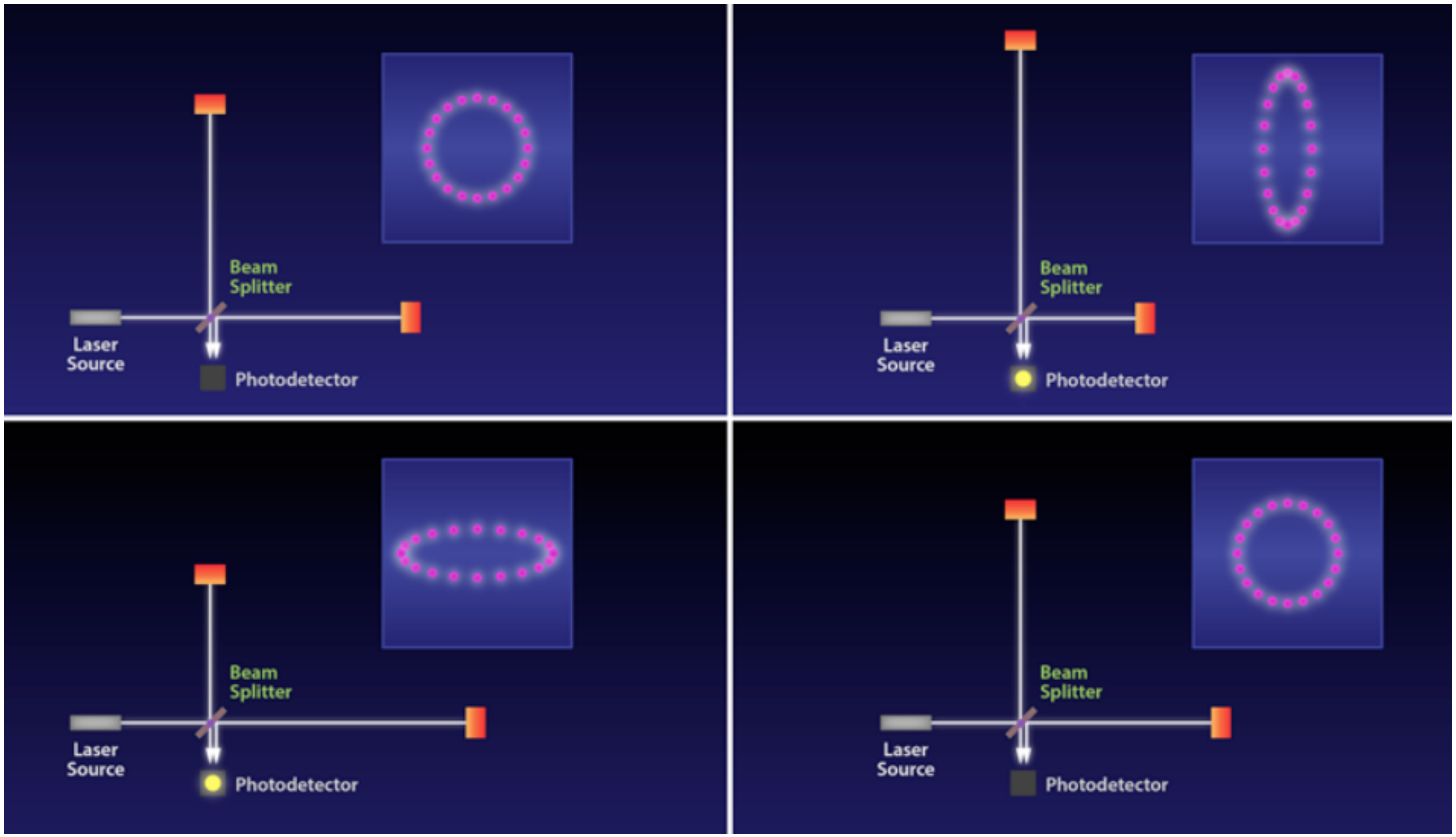


GWs and GW detection



GW Interferometers

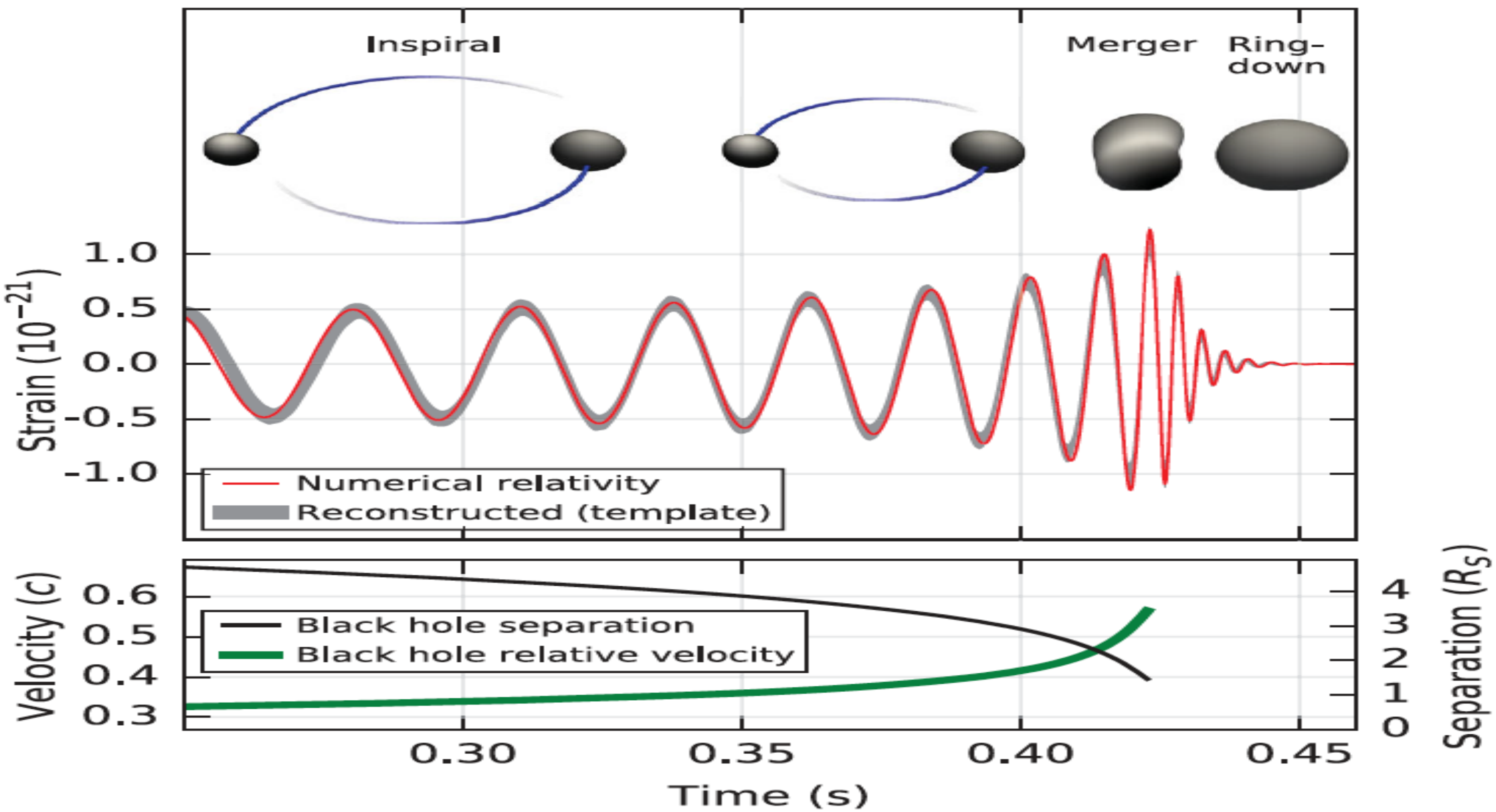
$$\Delta L \sim hL \sim 10^{-21} 10^{3} m \sim 10^{-18} m$$



$$h_i(t) = h_+(t+\tau_i)F_i^+ + h_\times(t+\tau_i)F_i^\times$$

Compact Binary Coalescence

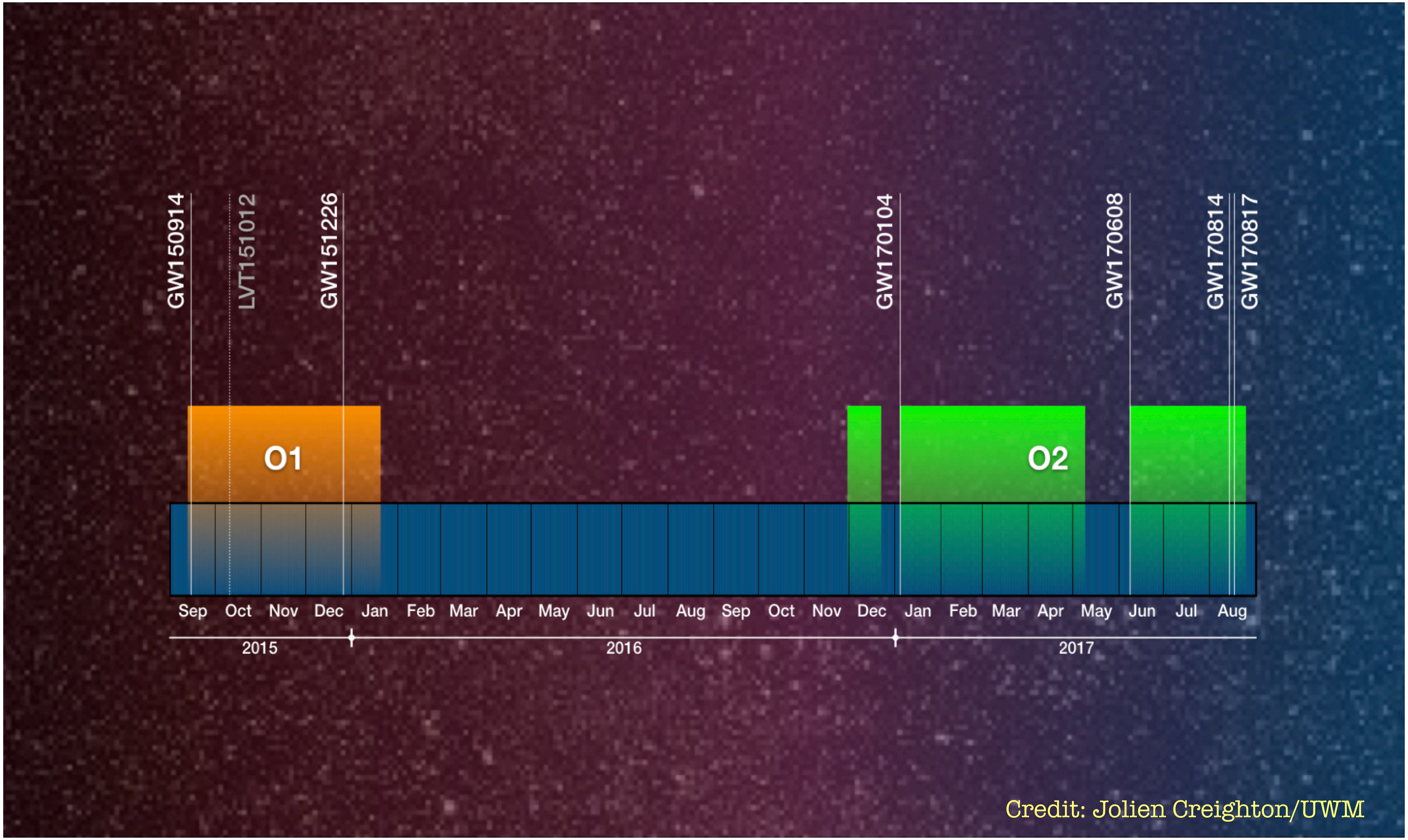
We use matched filtering as a method for both detection and parameter estimation. This method is phase sensitive and requires waveform models from both analytical and numerical relativity.



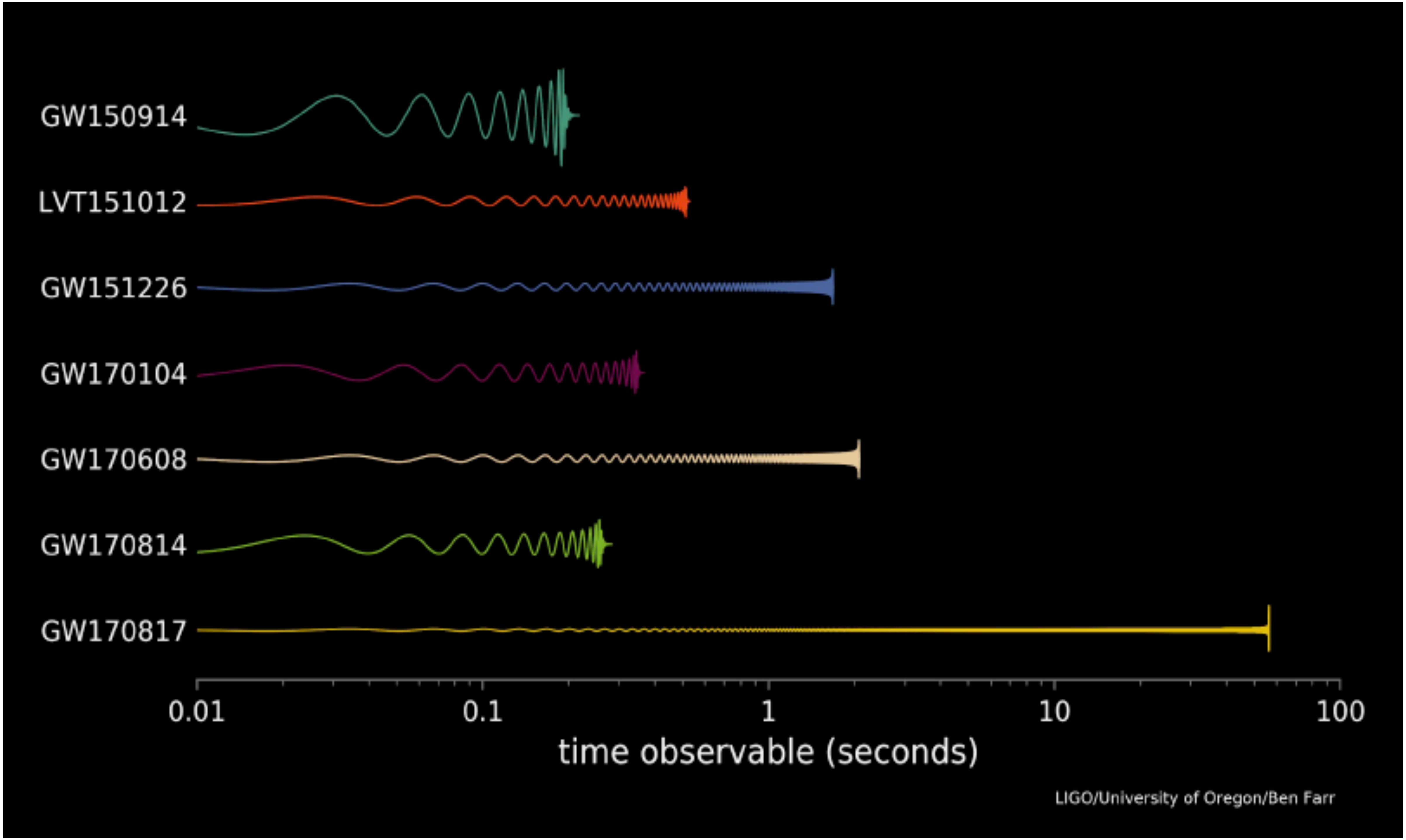
Abbott et al, PRL 116, 061102 (2016)

Advanced detector observation runs

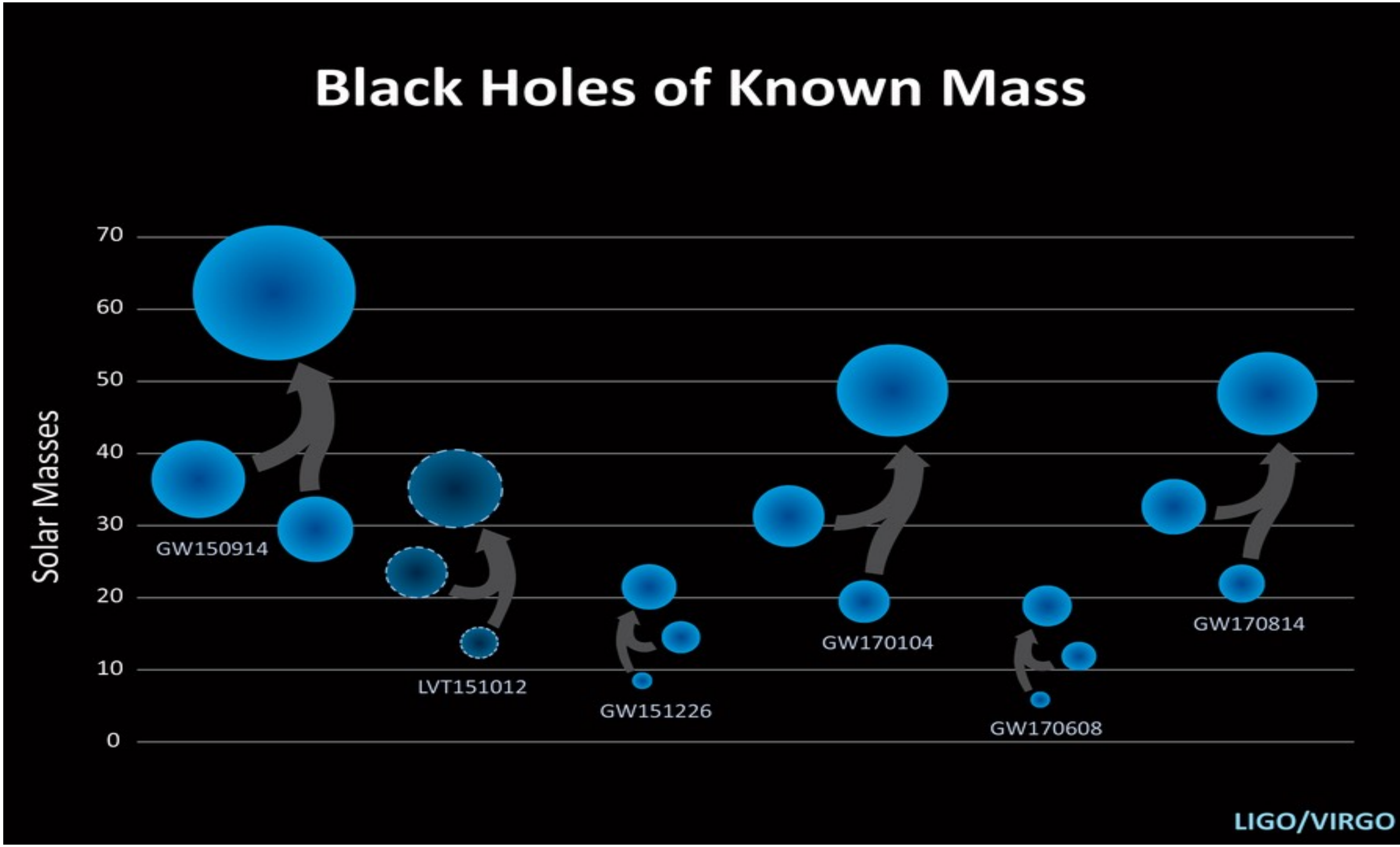
O1/O2


GW150914
LVT151012
GW151226
GW170104
GW170608
GW170814
GW170817
O1
O2
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
2015
2016
2017
Credit: Jolien Creighton/UWM

O1/O2

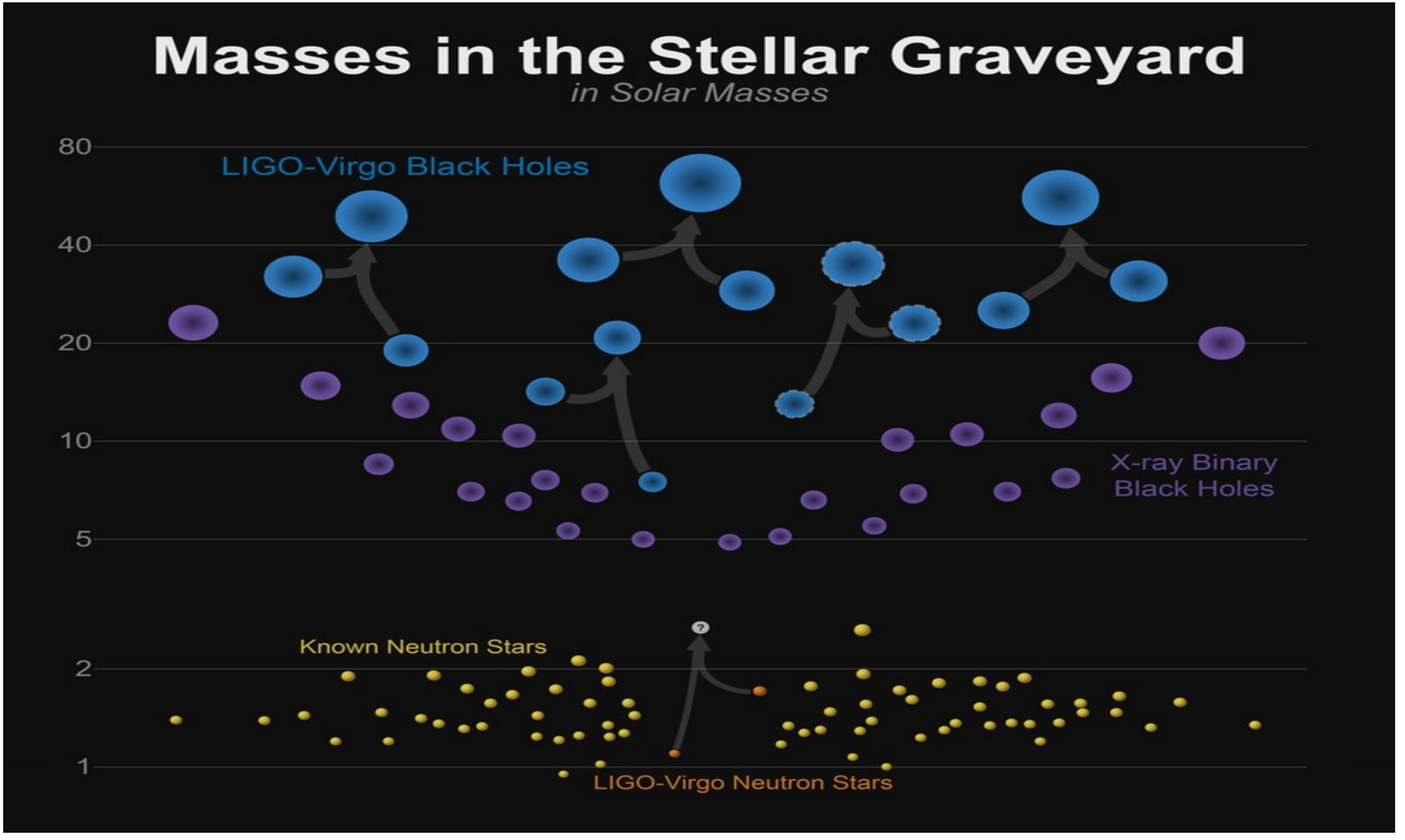

GW150914
LVT151012
GW151226
GW170104
GW170608
GW170814
GW170817
0.01
0.1
1
10
100
time observable (seconds)
LIGO/University of Oregon/Ben Farr

O1/O2



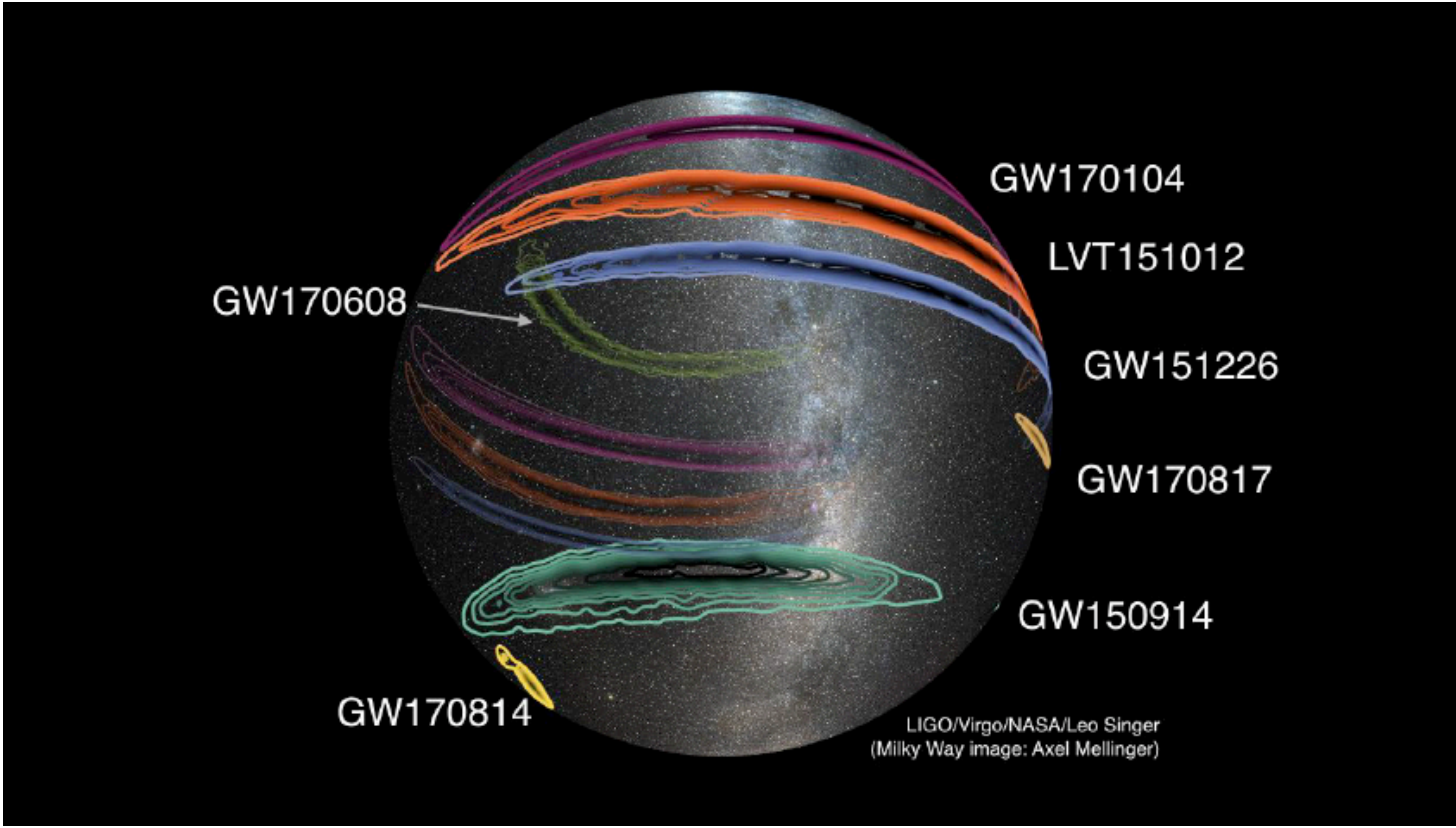
www.ligo.caltech.edu/images

GW170817

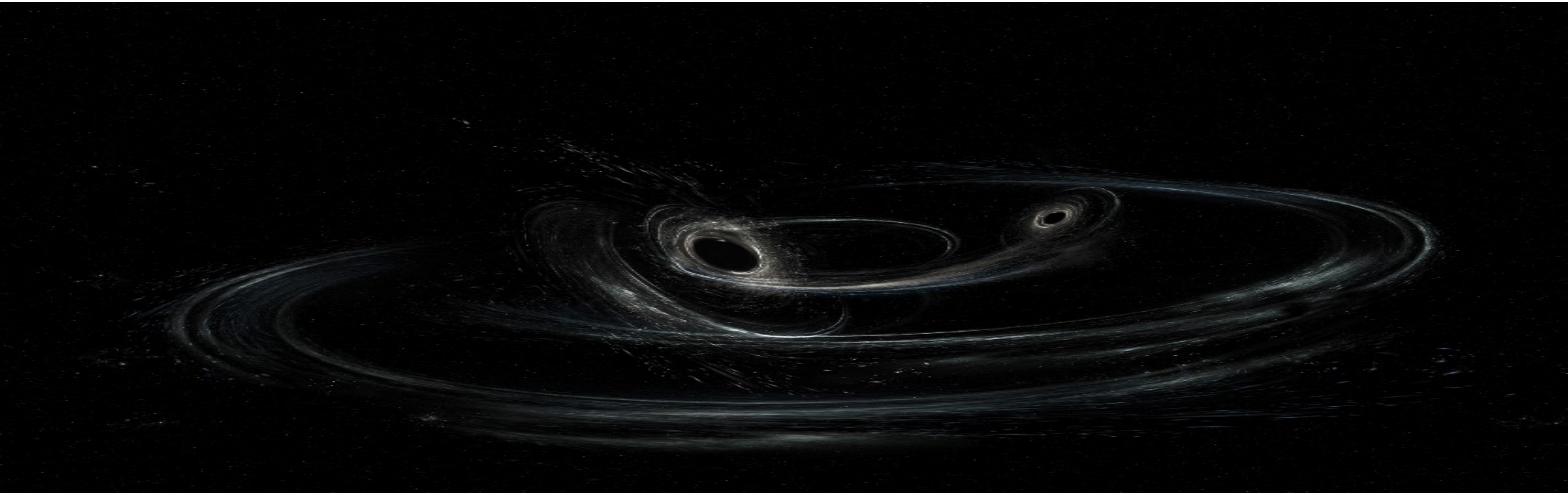


www.ligo.caltech.edu/images

O1/O2


GW170104
LVT151012
GW170608
GW151226
GW170817
GW150914
GW170814
LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

Binary Black Hole Mergers



Binary Pulsars vs GWs

- EM observations of binary pulsars give $dP_{orb}/dt \sim 10^{-14} - 10^{-12}$
- Confirm GW luminosity at leading order with excellent precision
- Most relativistic (J0737-3039) has almost constant dP_{orb}/dt
- $v_{orb}/c \sim 2x10^{-3}$ and $t_c \sim 85$ *Myrs*
- GW150419 had $dP_{orb}/dt \sim -0.1$ *(30Hz)* $\Rightarrow -1$ *(132 Hz)*
- Just before merger the two BHs orbited each other 75 times/sec
- $v_{orb}/c \sim 0.5$ just before merger

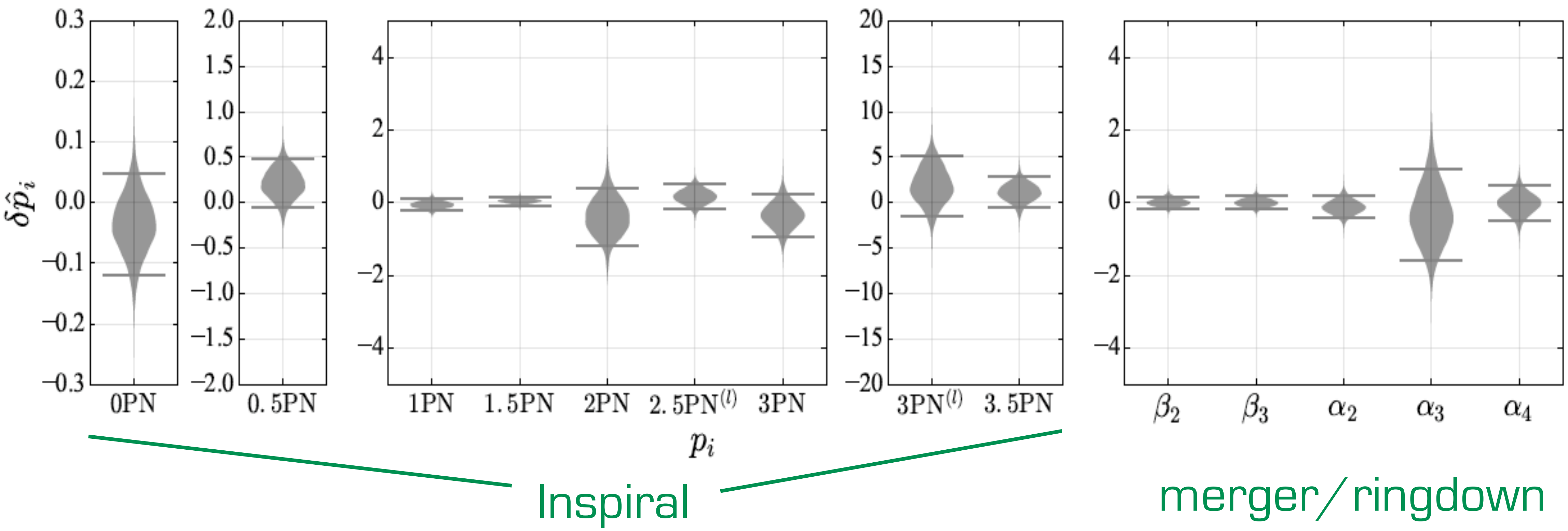
Phenomenological IMR test

- Look for dominant effect deviations from GR at different PN orders

$$\tilde{h}_{\mathrm{GR}}(f) = \tilde{A}(f;\vec{\vartheta}_{\mathrm{GR}})e^{i\Psi(f;\vec{\vartheta}_{\mathrm{GR}})}$$

$$\tilde{h}(f) = \tilde{A}(f;\vec{\vartheta}_{\mathrm{GR}})e^{i\left[\Psi(f;\vec{\vartheta}_{\mathrm{GR}})+\delta\Psi(f;\vec{\vartheta}_{\mathrm{GR}},X_{\mathrm{modGR}})\right]}$$

GW150914+GW151226+GW170104



Modified Dispersion

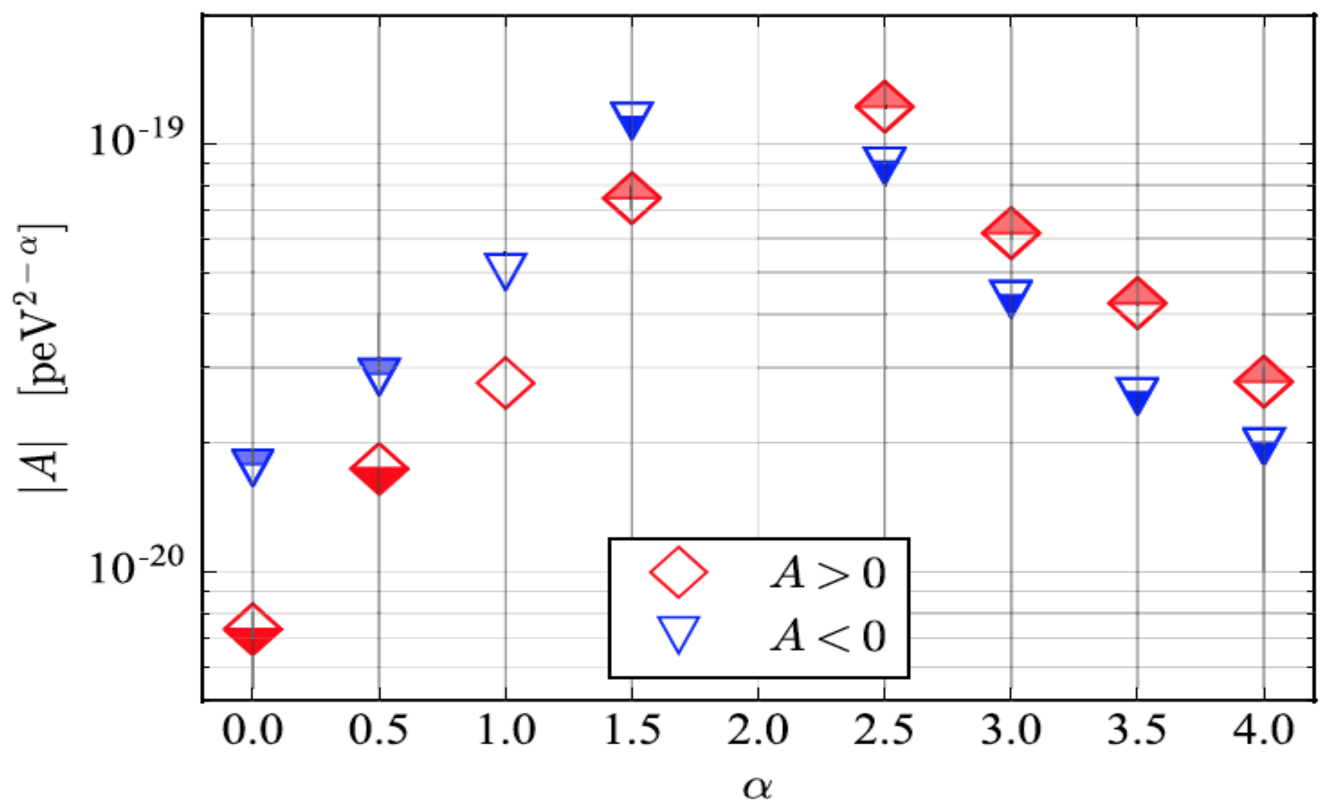
- Assume a dispersion relationship of the form

$$E^2 = p^2c^2 + Ap^\alpha c^\alpha, \ \alpha \geq 0$$

- modifying the GW group velocity as

$$v_g/c = 1 + (\alpha - 1)AE^{\alpha-2}/2$$

- which changes the phase of the GW



Abbott et al, PRL 118, 221101 (2017)

Massive Graviton

- **GW150914+GW151226**

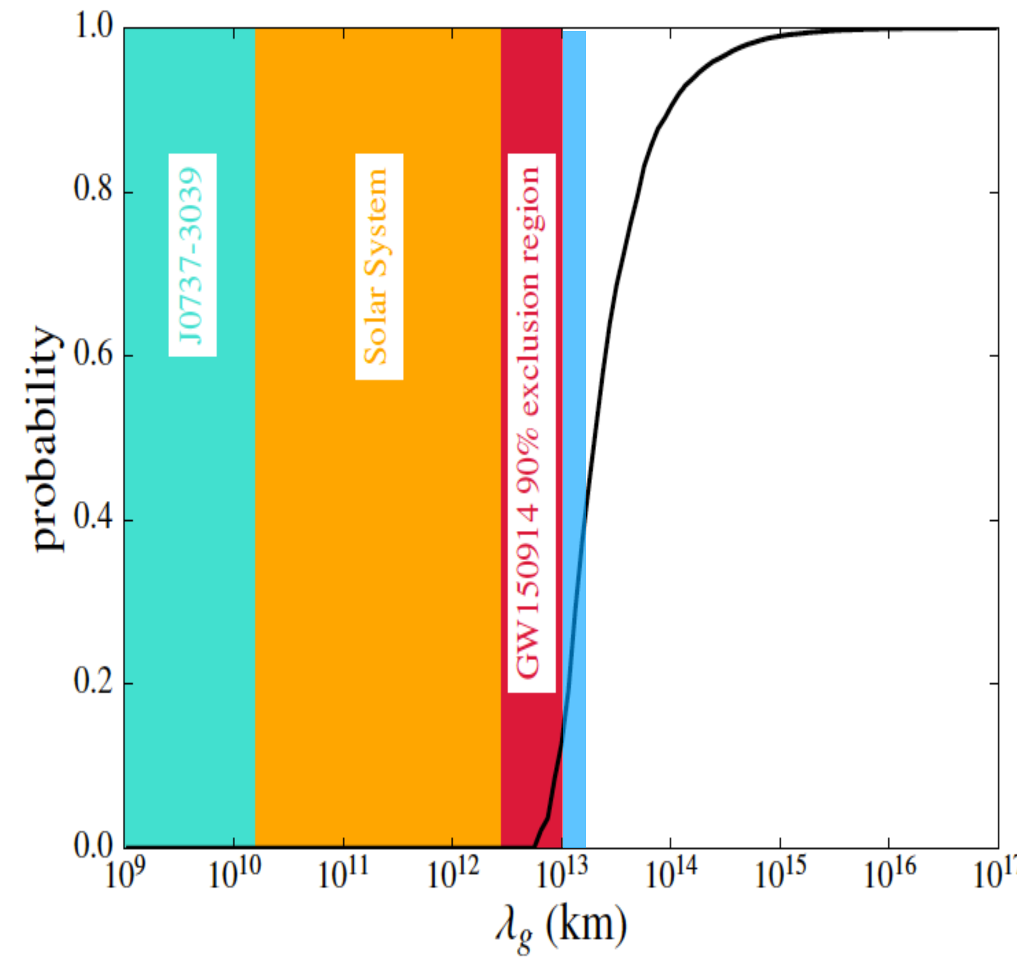
$$\lambda_g > 1 \times 10^{13}\, km$$

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

- **GW150914+GW151226+GW170104**

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

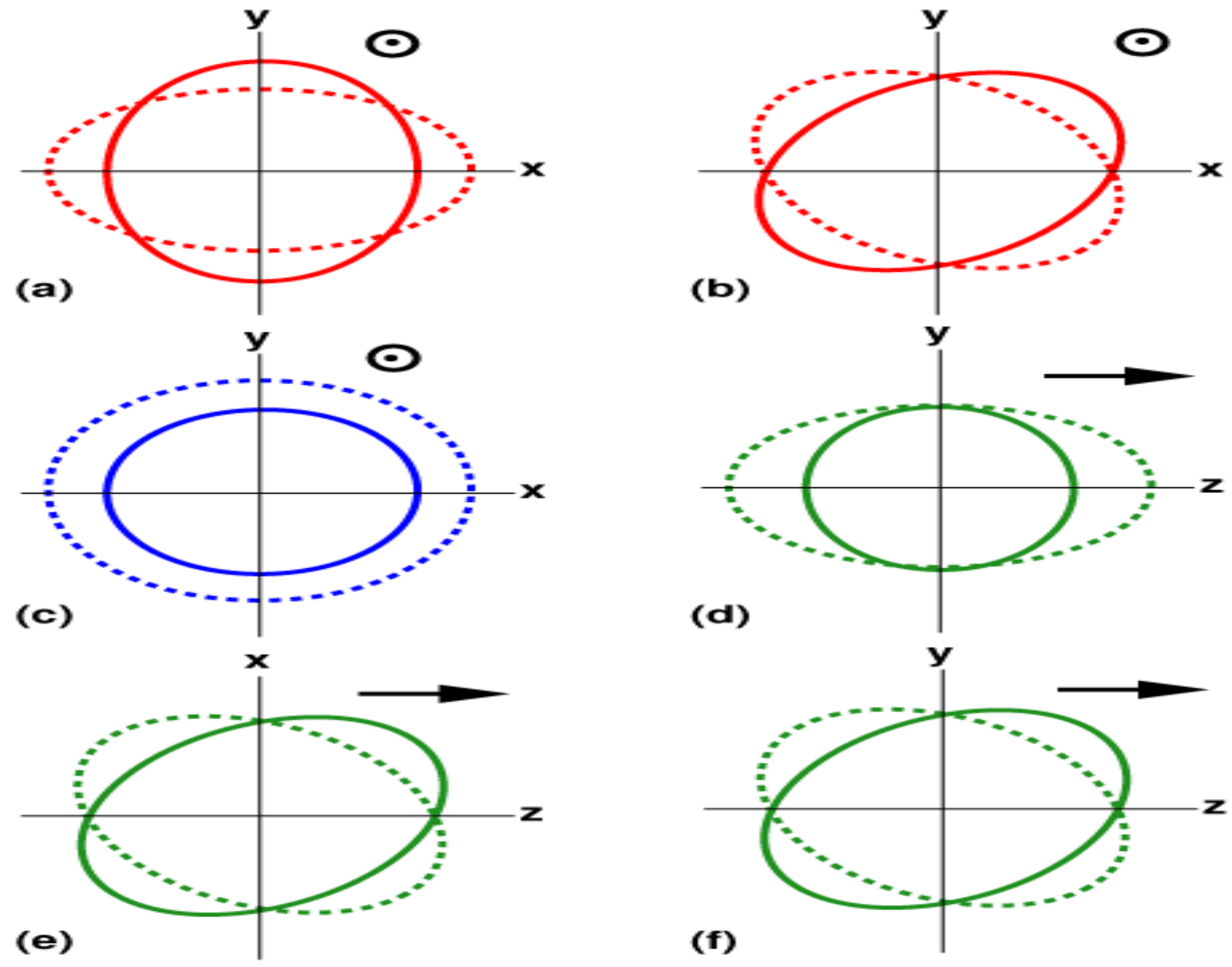
$$m_g \leq 7.7 \times 10^{-23}\, eV/c^2$$



- **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 binary pulsar tests ($\lambda_g > 10^{10}$ km)**

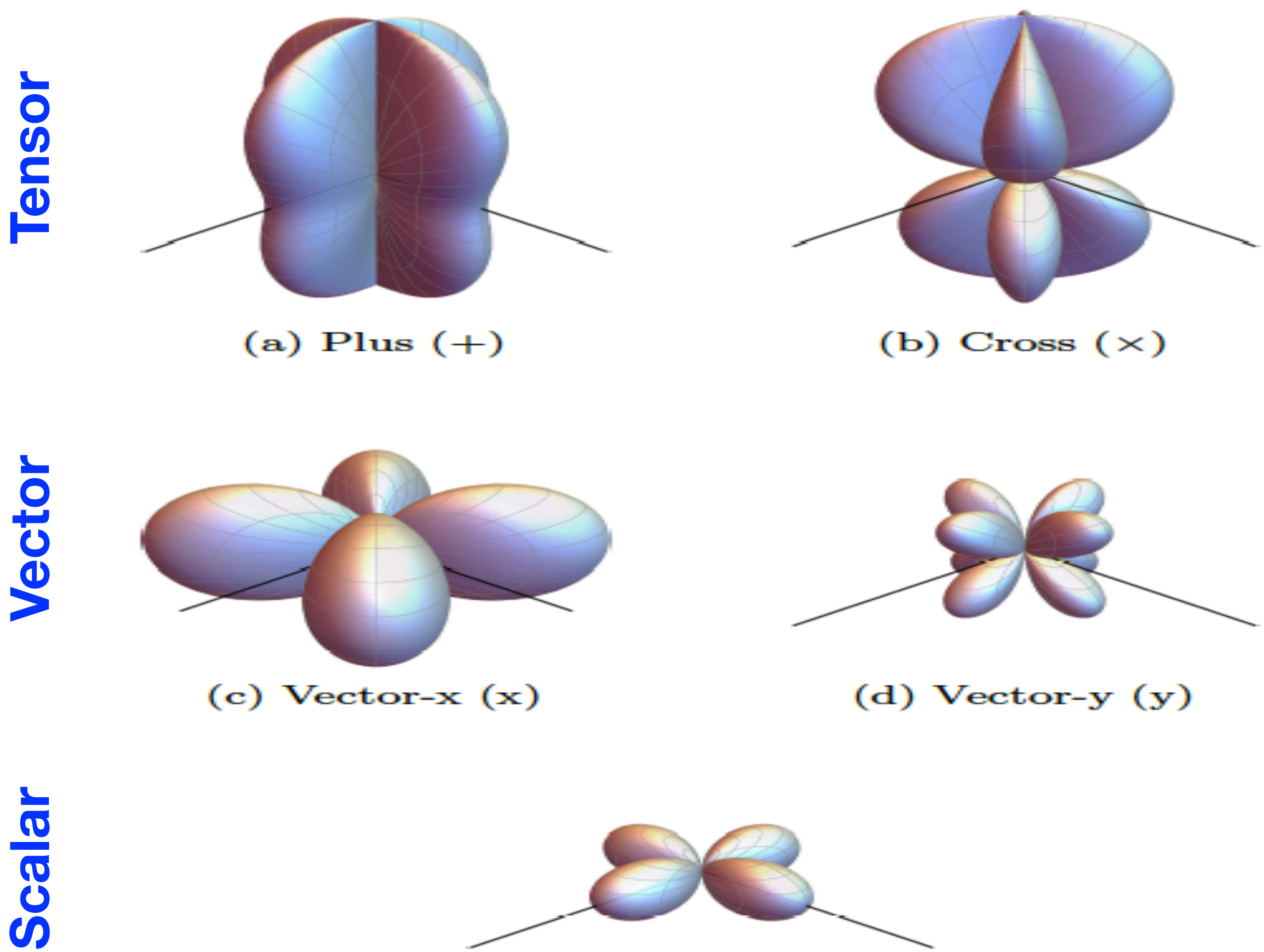
GW Polarisations

- In generic metric theories, GWs can have up to 6 polarisations coming from the 6 independent components of the Riemann tensor.
- Test possible due to inclusion of Advanced Virgo



GW Polarisations

Different polarisations produce a different response at the detector



(a) Plus (+) (b) Cross (×)

(c) Vector-x (x) (d) Vector-y (y)

(e) Scalar (s)

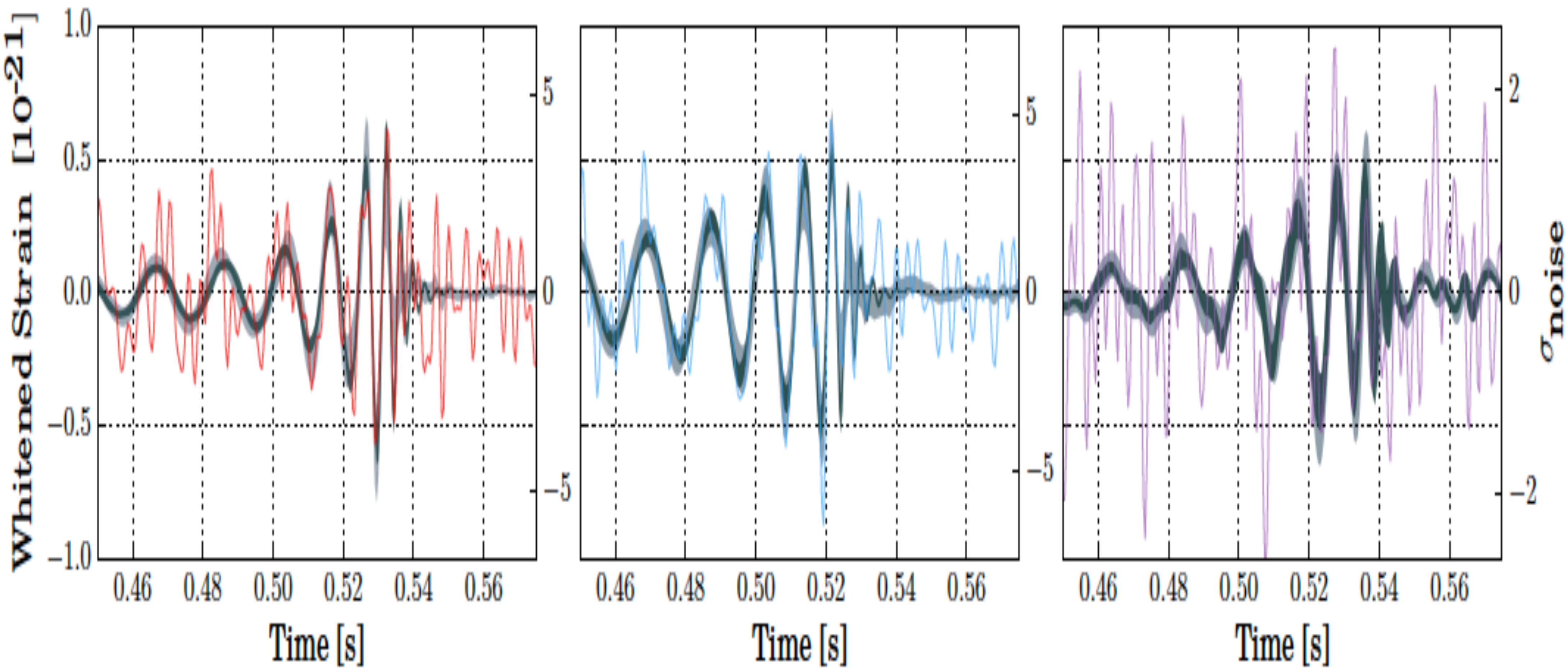
Credit: Max Isi

T:V = 200:1

T:S = 1000:1

GW Polarisations

Is this really surprising...?

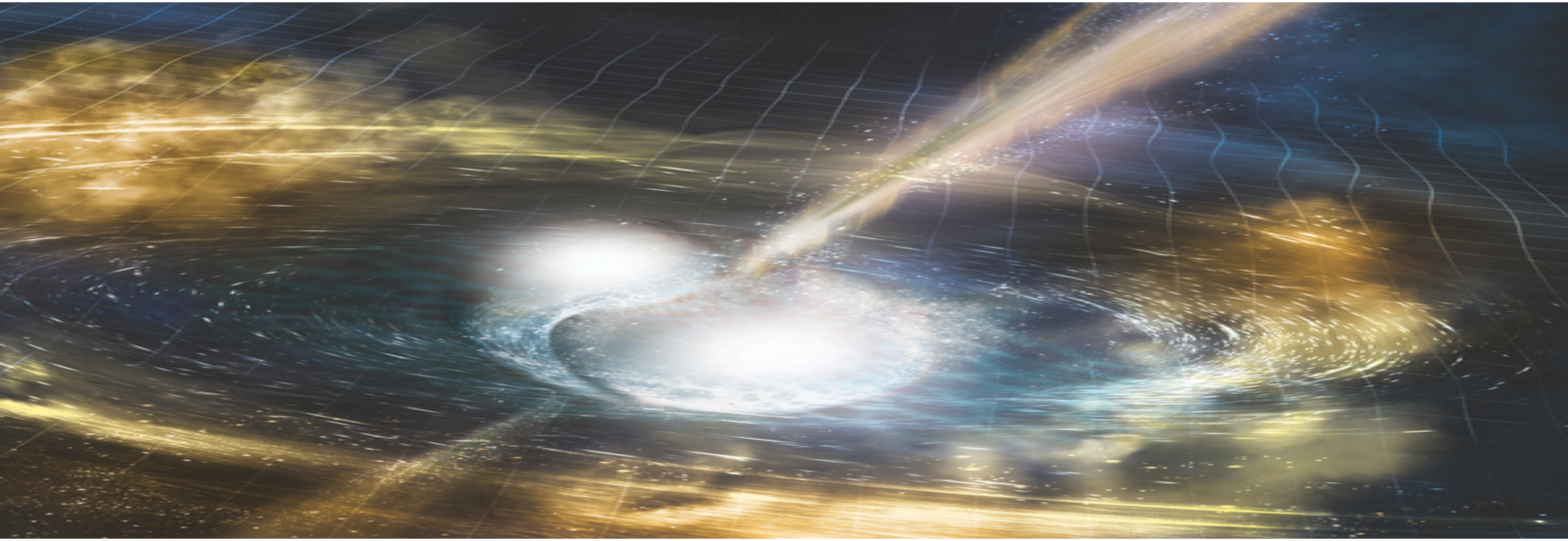


Abbott et al, PRL 119, 141101 (2017)

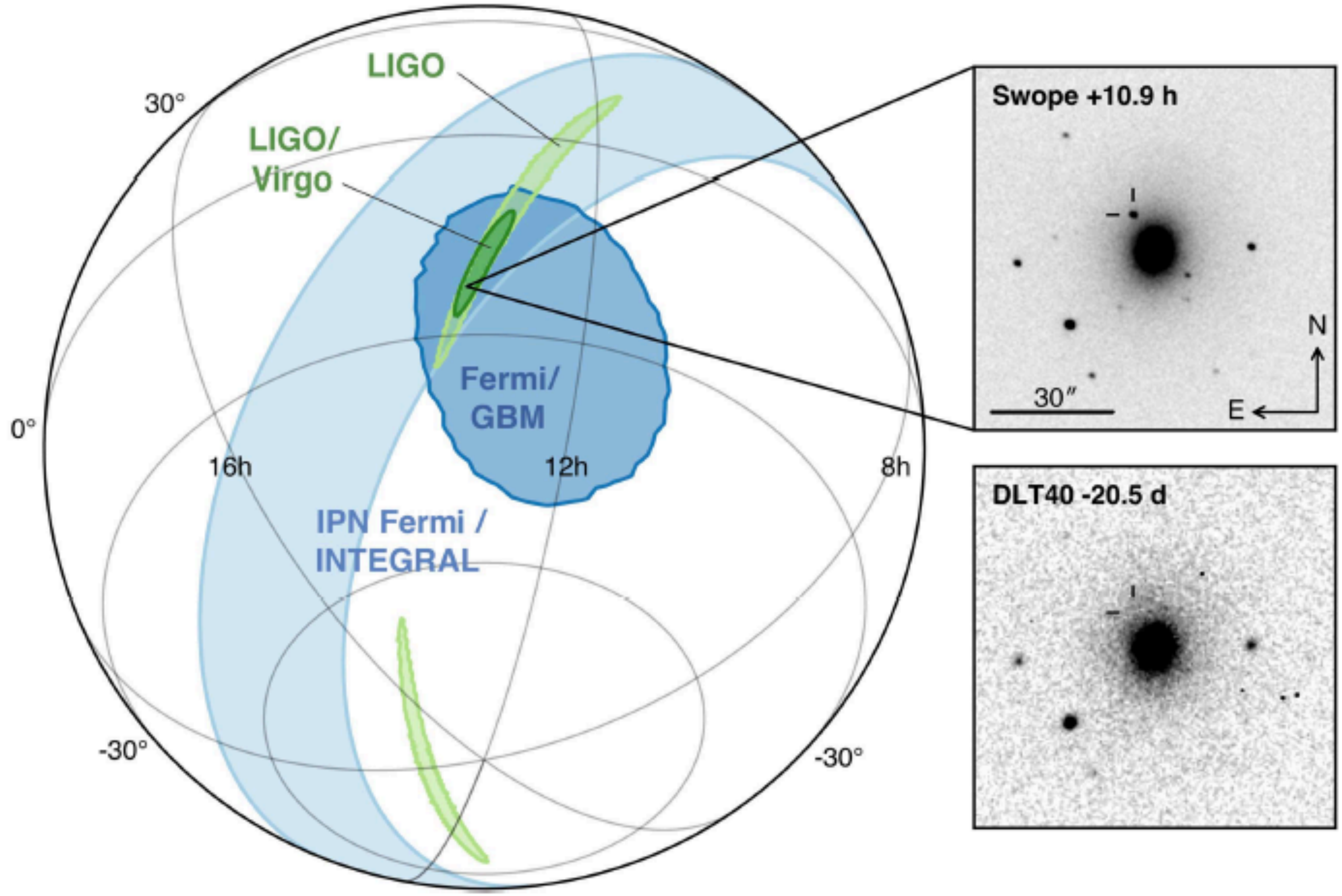
GR templates match the phase of the data extremely well!!

Already heavily constrains how much non-tensorial polarisation there can be!

Binary Neutron Star Mergers



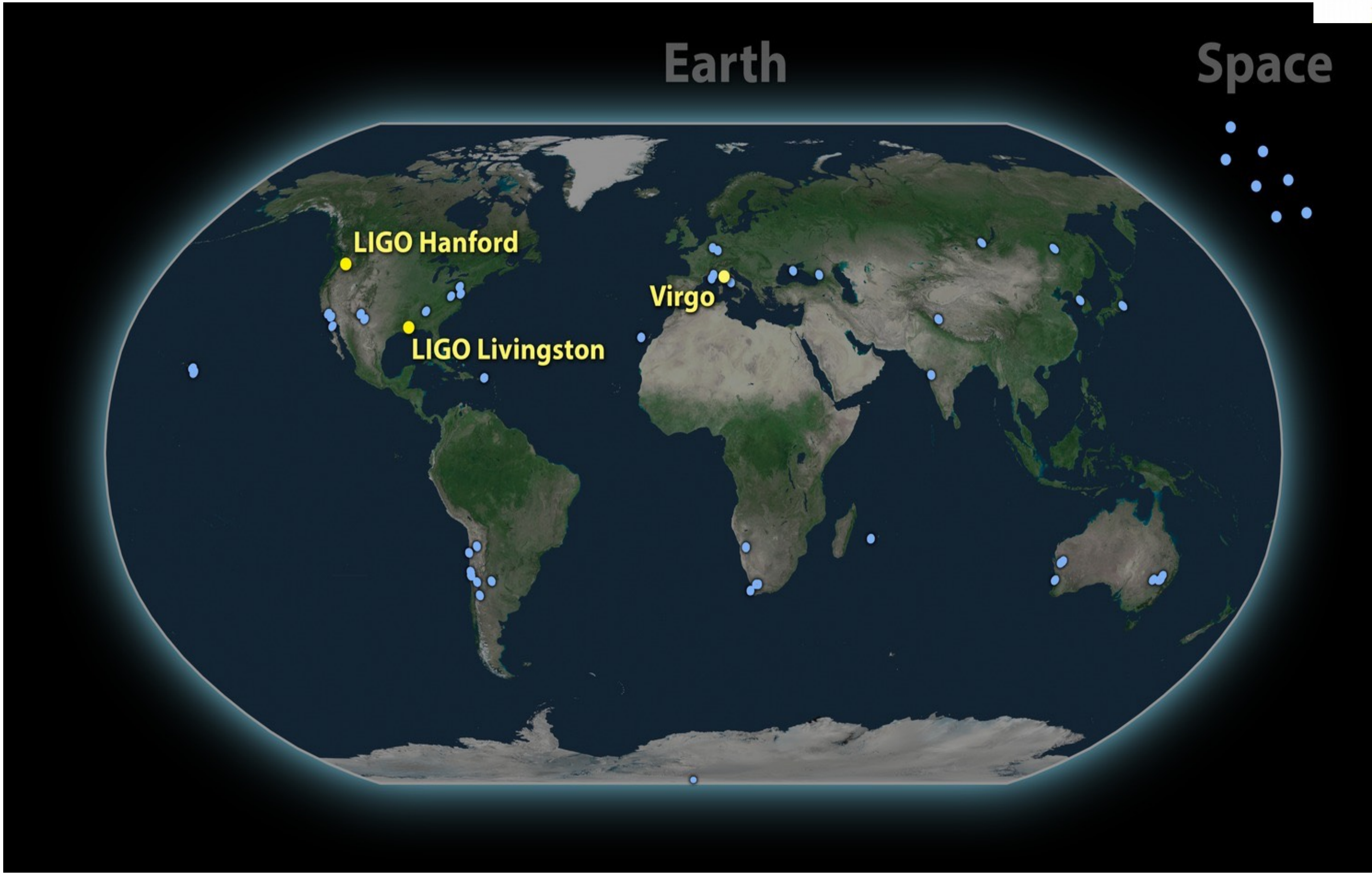
GW170817



GW sky-error = 28 deg^2

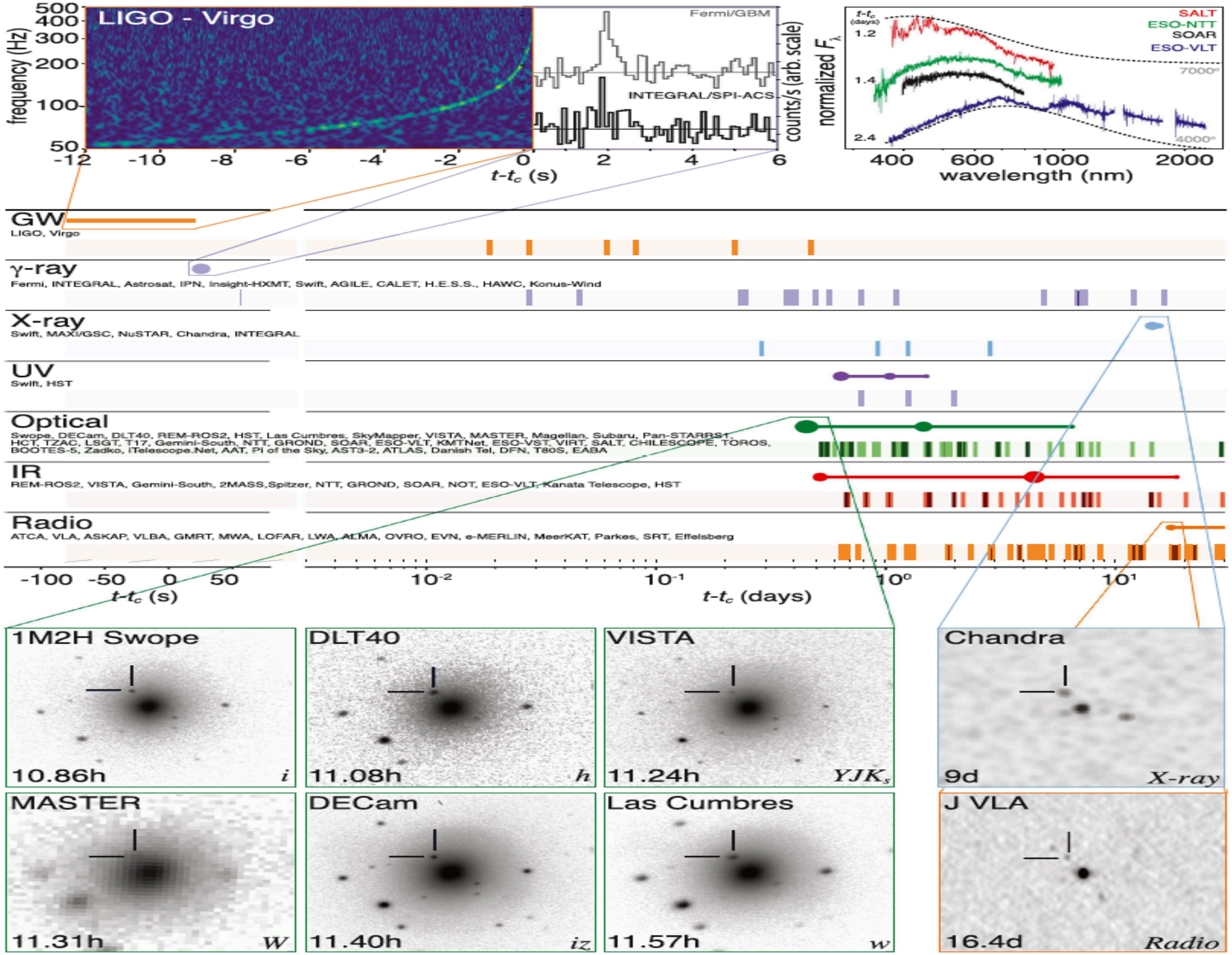
Abbott et al, PRL 119, 161101 (2017)

GW170817



www.ligo.caltech.edu/images

GW170817

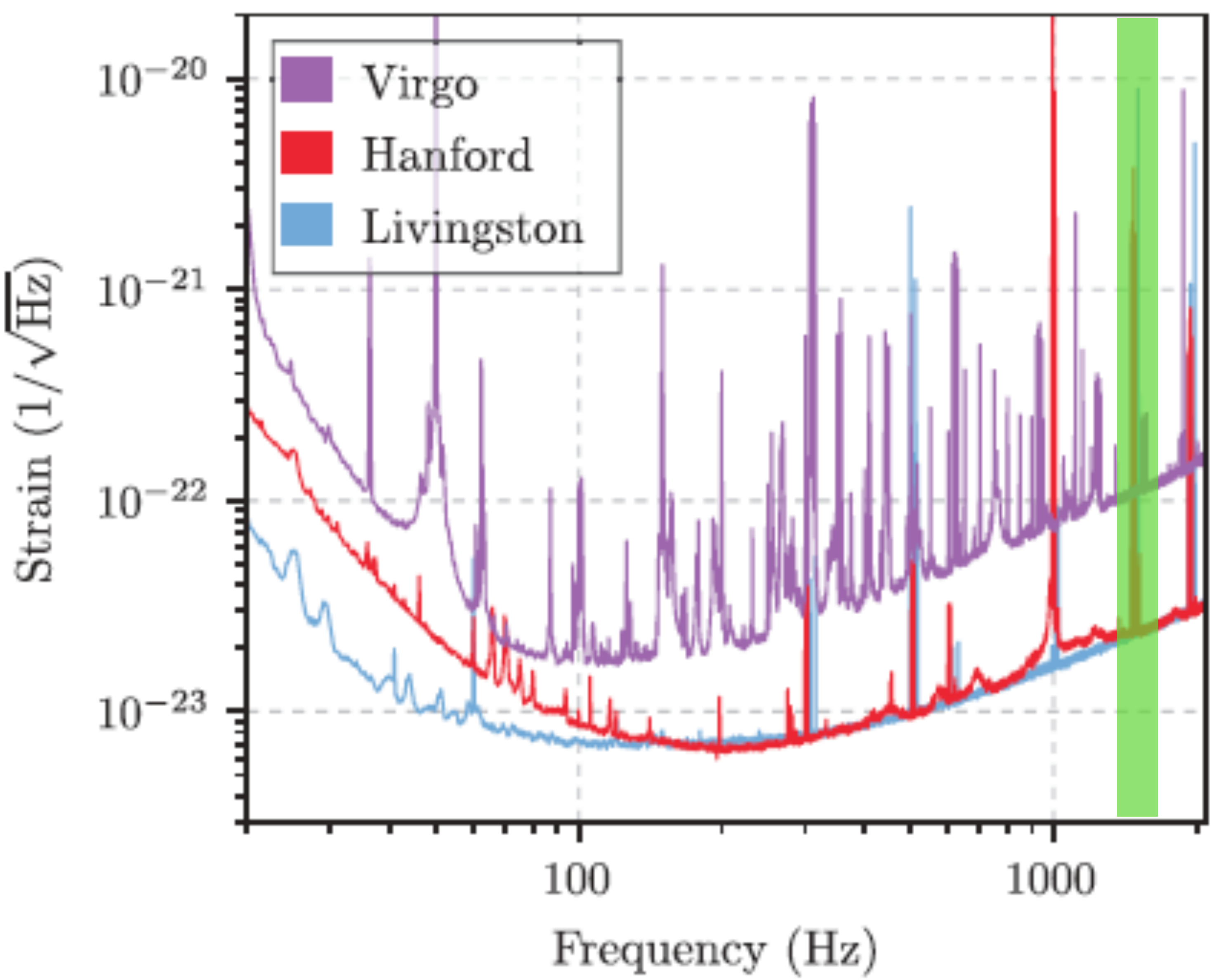


Abbott et al, ApJ Letters 848, L13 (2017)

BNS Remnant

Q:So what is the remnant of the merger?

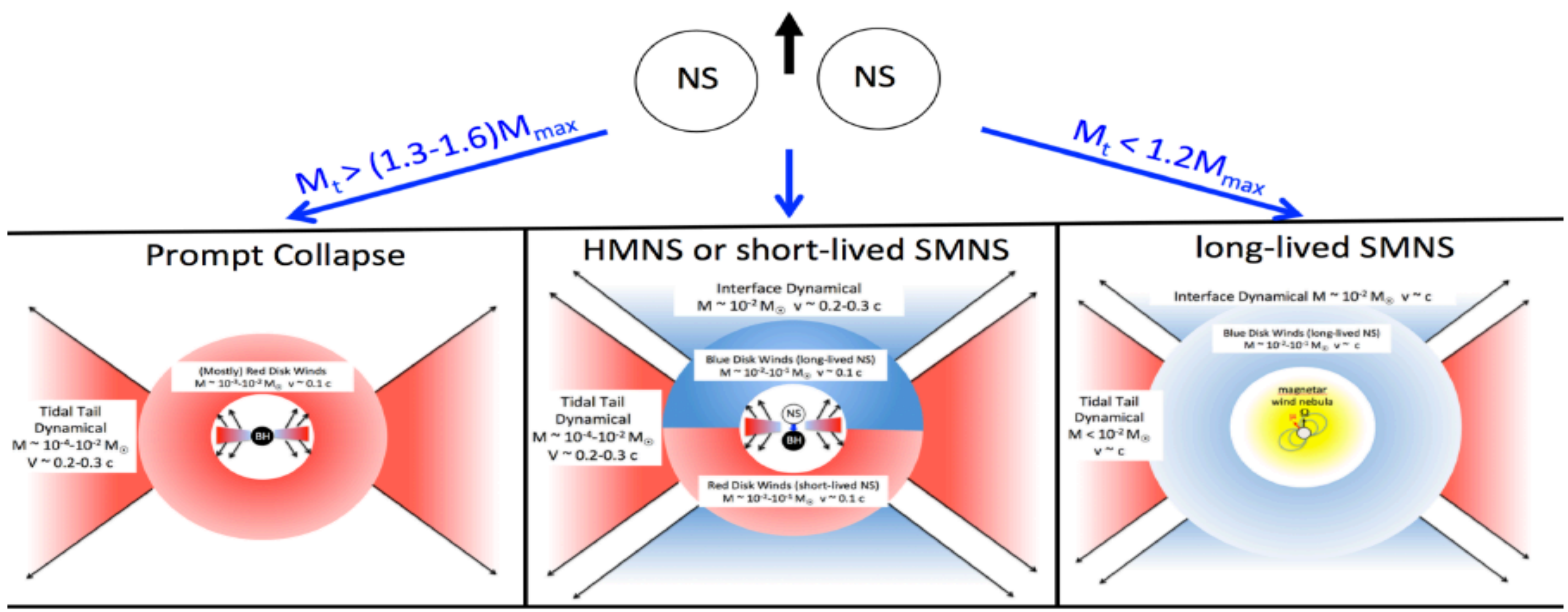
A:From GWs - we don't know. High frequency signal dominated by photon shot noise



BNS Remnant

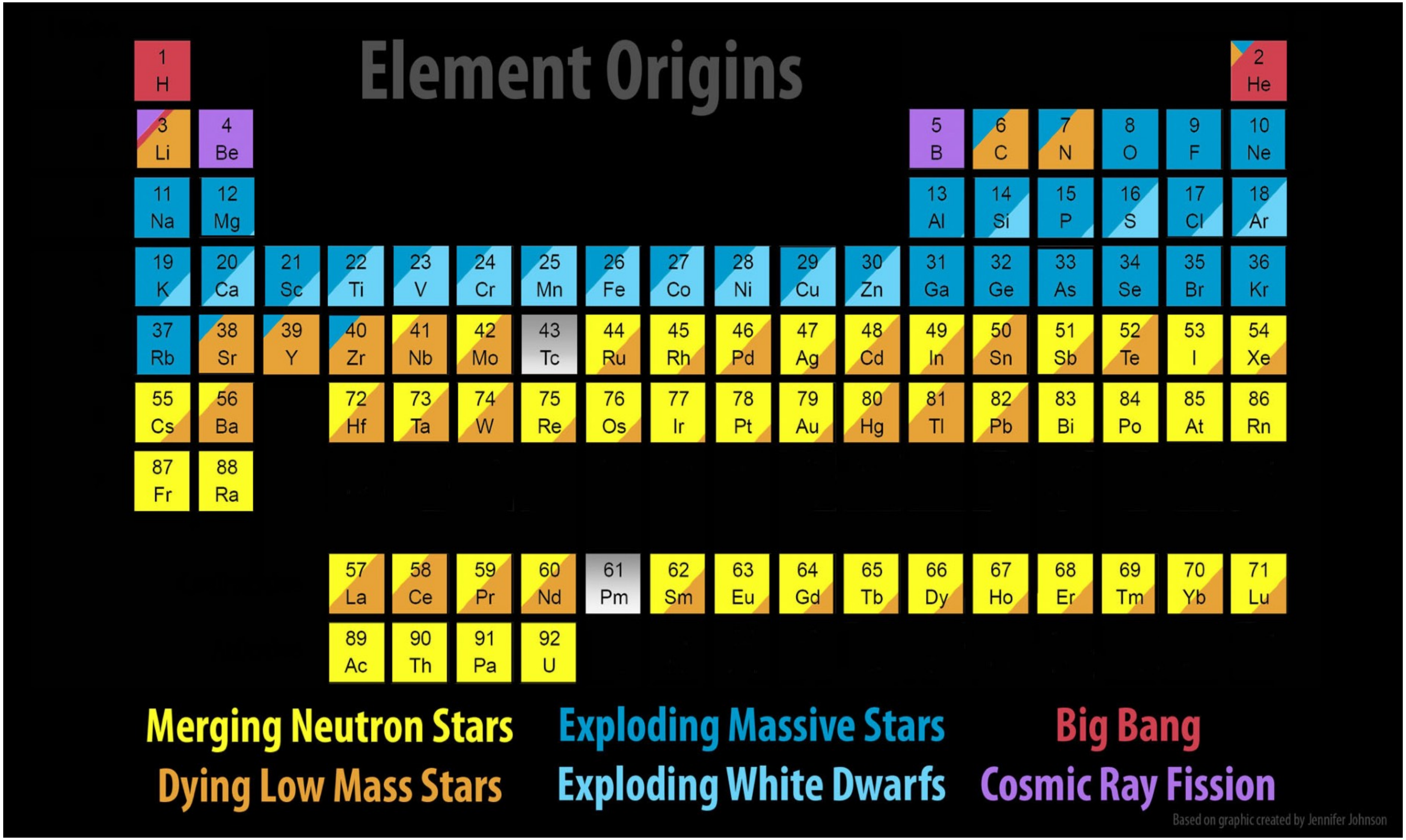
Q: So what is the remnant of the merger?

A: From EM - unclear! Some people believe prompt collapse to BH, others believe in the formation of a transient hypermassive NS



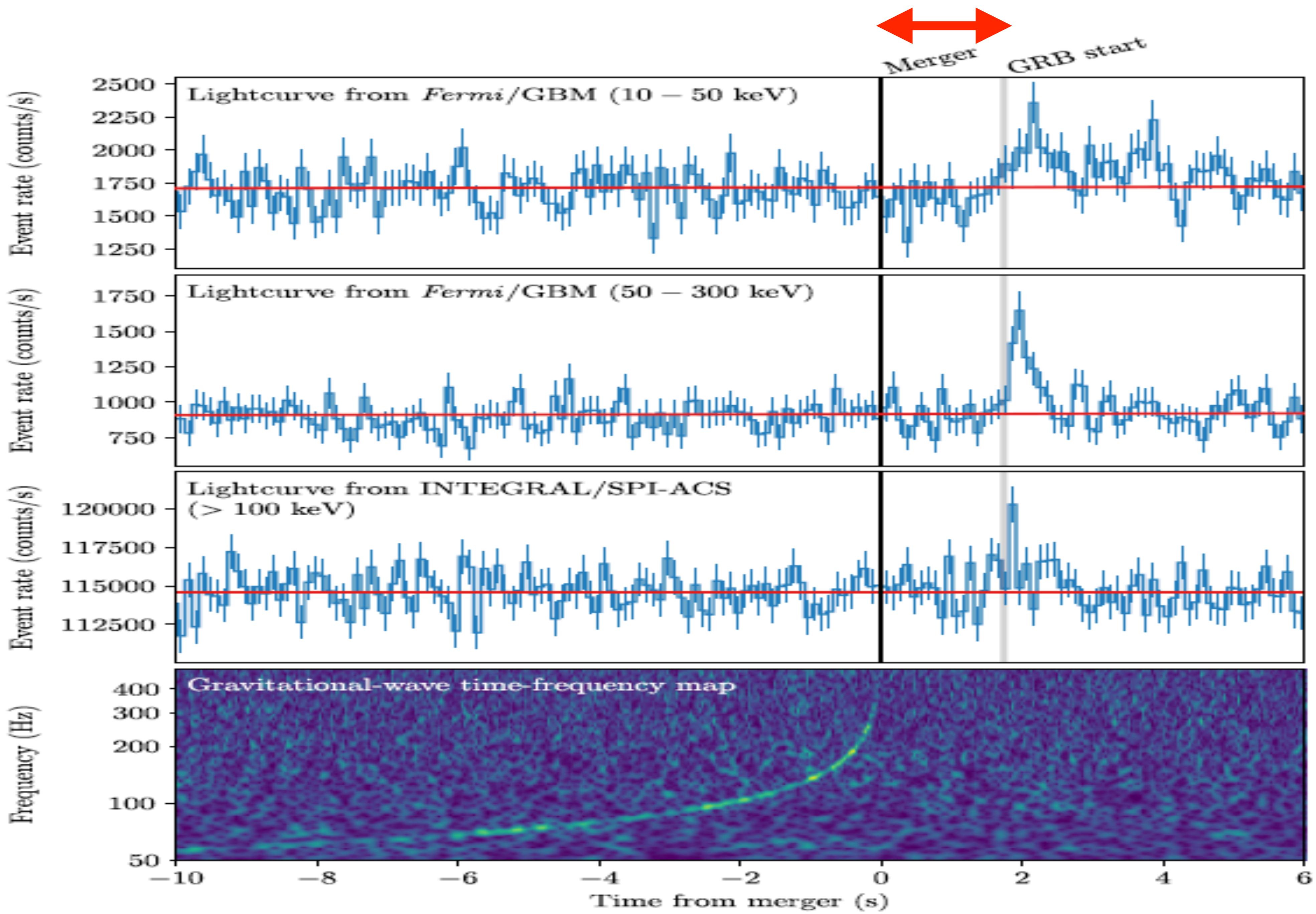
Margalit et al (2017)

Heavy Element Production



Credit: Jennifer Johnson/SDSS

GW170817 & GRB170817A



Abbott et al, ApJ Letters 848, L13 (2017)

Speed of GWs

- The time delay between the GW and GRB detections over 1.3×10^8 Lyrs was (N.B. analysis allows for +/- 10 secs)

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

- Defining the fractional difference between the speed of light and GWs as

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

- We find the following constraint

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

- Large consequences for cosmological theories

Abbott et al, ApJ Letters 848, L13 (2017)

Speed of GWs : implications

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [42] Brans-Dicke/$f(R)$ [43, 44] Kinetic Gravity Braiding [46]	quartic/quintic Galileons [13, 14] Fab Four [15, 16] de Sitter Horndeski [45] $G_{\mu\nu}\phi^\mu\phi^\nu$ [47], Gauss-Bonnet
beyond H.	Derivative Conformal (20) [18] Disformal Tuning (22) DHOST with $A_1 = 0$	quartic/quintic GLPV [19] DHOST [20, 48] with $A_1 \neq 0$
	Viable after GW170817	Non-viable after GW170817

- **with extension to: Einstein-Aether, Horava gravity, Generalised Proca, TeVeS, massive gravity, bigravity, multi-gravity, MOND-like theories**

arXiv:1710.05901, 1710.06394, 1710.05893, 1710.05877....

Equivalence Principle

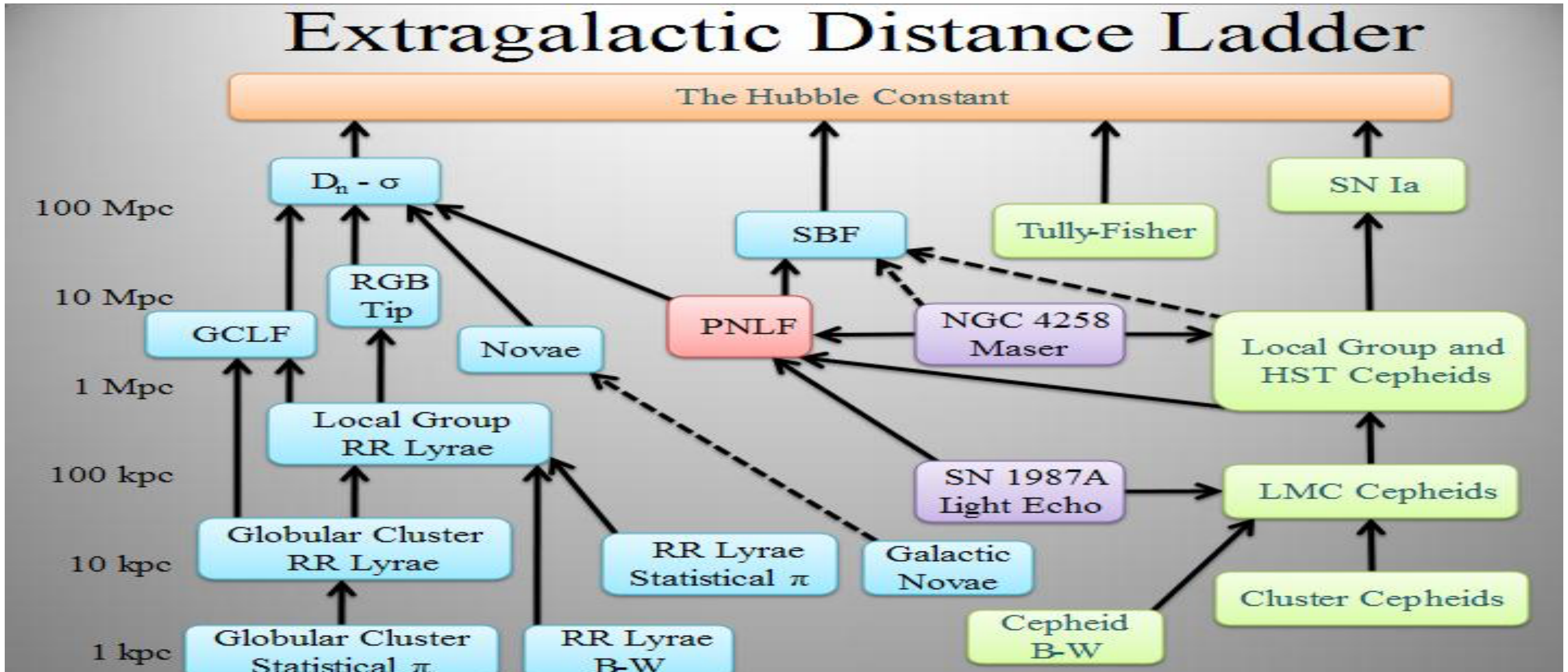
- Shapiro delay is defined as $\Delta t_s = -\frac{1+\gamma}{c}\int_{r_e}^{r_o} U(r(l))dl$
- γ is the PPN parameter parameterising a deviation from Einstein-Maxwell theory
- Conservative bound on $\Delta\gamma = |\gamma_{GW} - \gamma_{EM}| \leq 2\frac{\Delta t}{\Delta t_s}$
- is $-2.6 \times 10^{-7} \leq \Delta\gamma \leq 1.2 \times 10^{-6}$
- Newer result (S. Boran et al, 1710.06168) using more sophisticated dark matter halo model gives

$$\Delta\gamma \leq 3.9 \times 10^{-8}$$

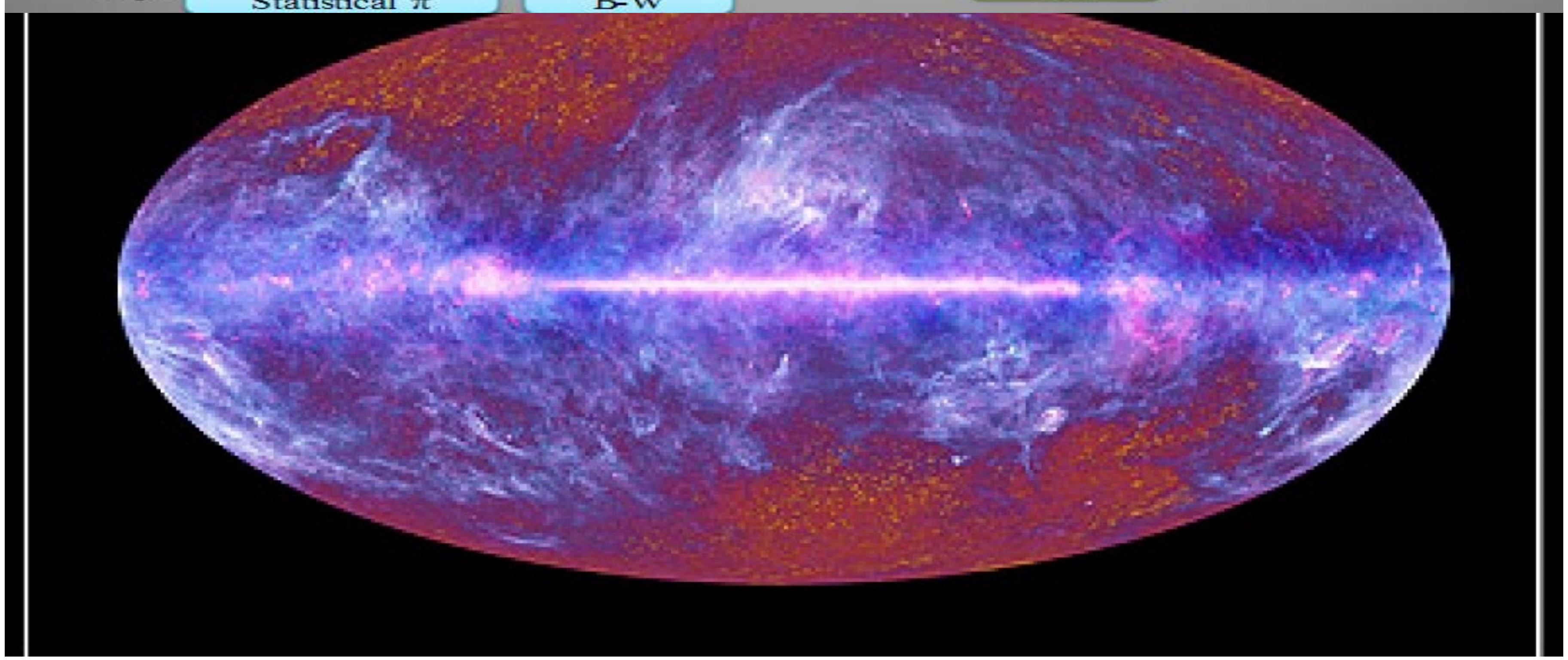
- implying that MOND-like dark matter emulator theories are ruled out, as the GWs would have arrived 1000 days before the EM emission

Hubble's Constant

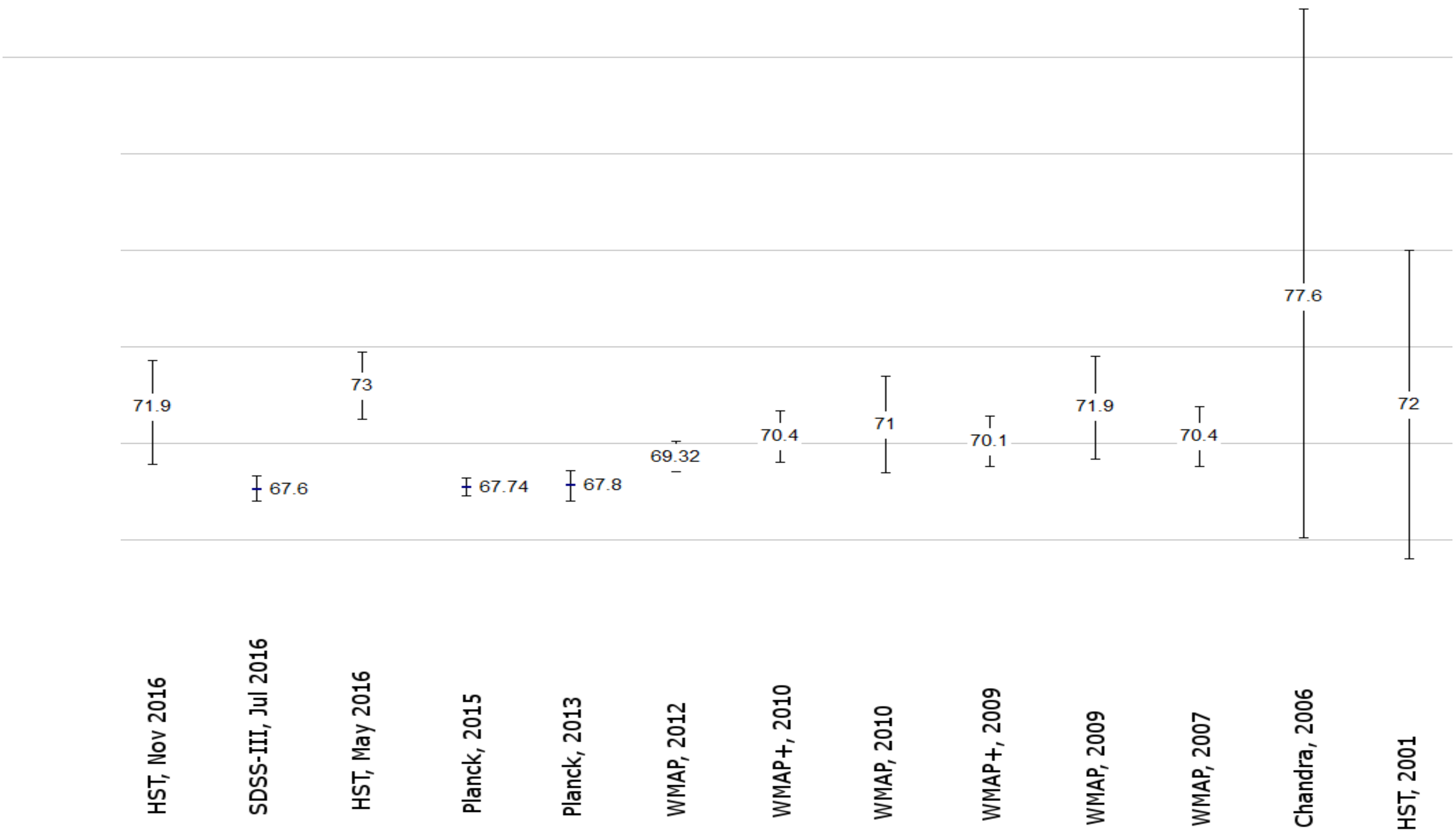
Astrophysics



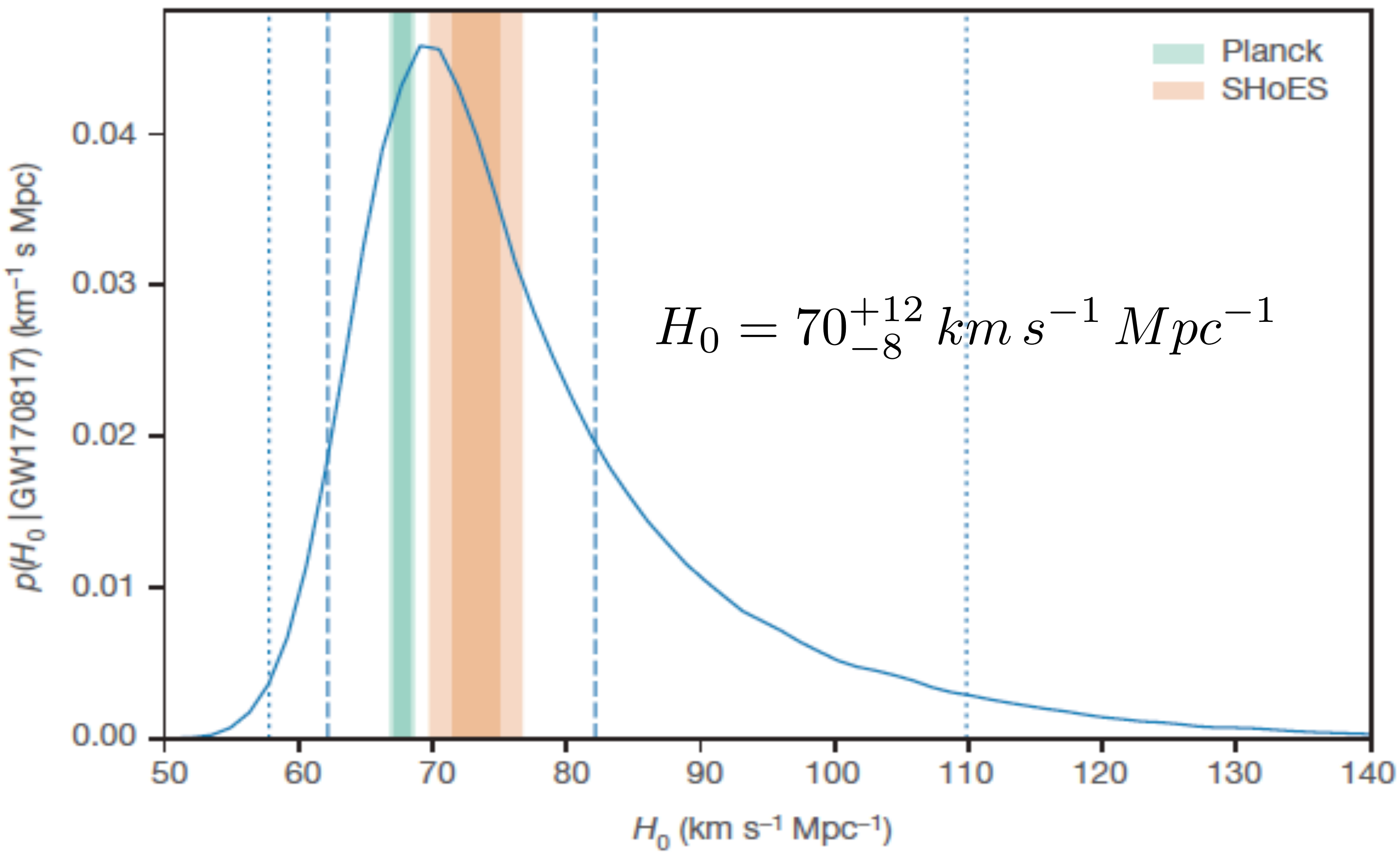
Cosmology



Hubble's Constant



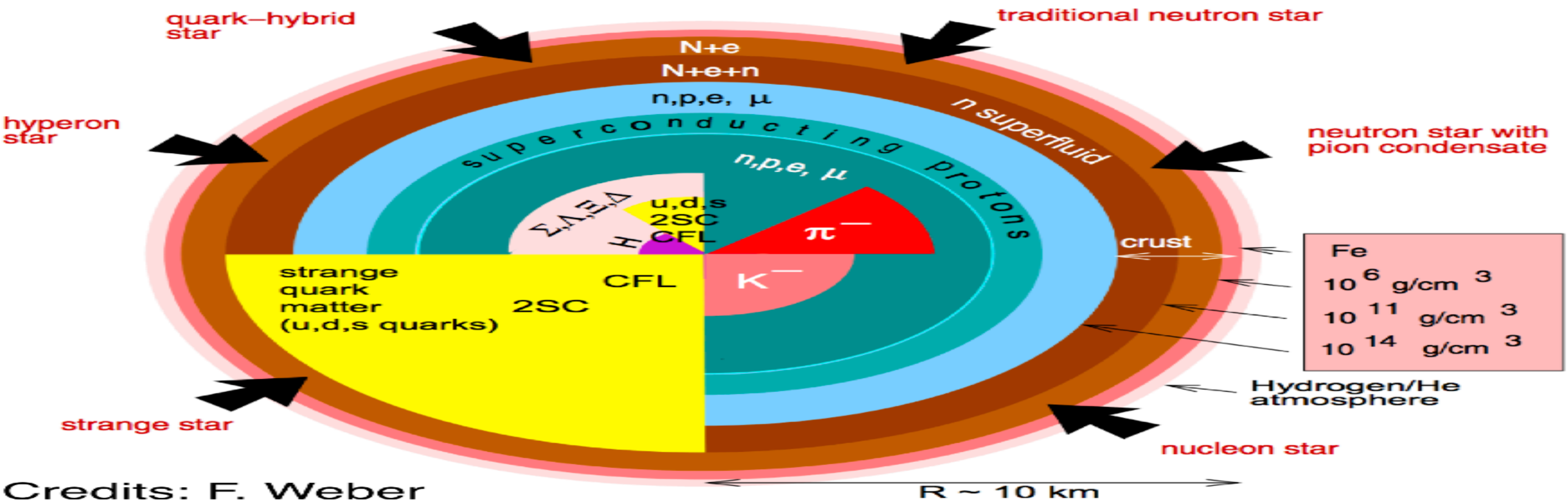
Hubble's Constant



- **N.B. No cosmic distance ladder needed!!**
- **GW astronomy measures luminosity distance directly over cosmic scales**

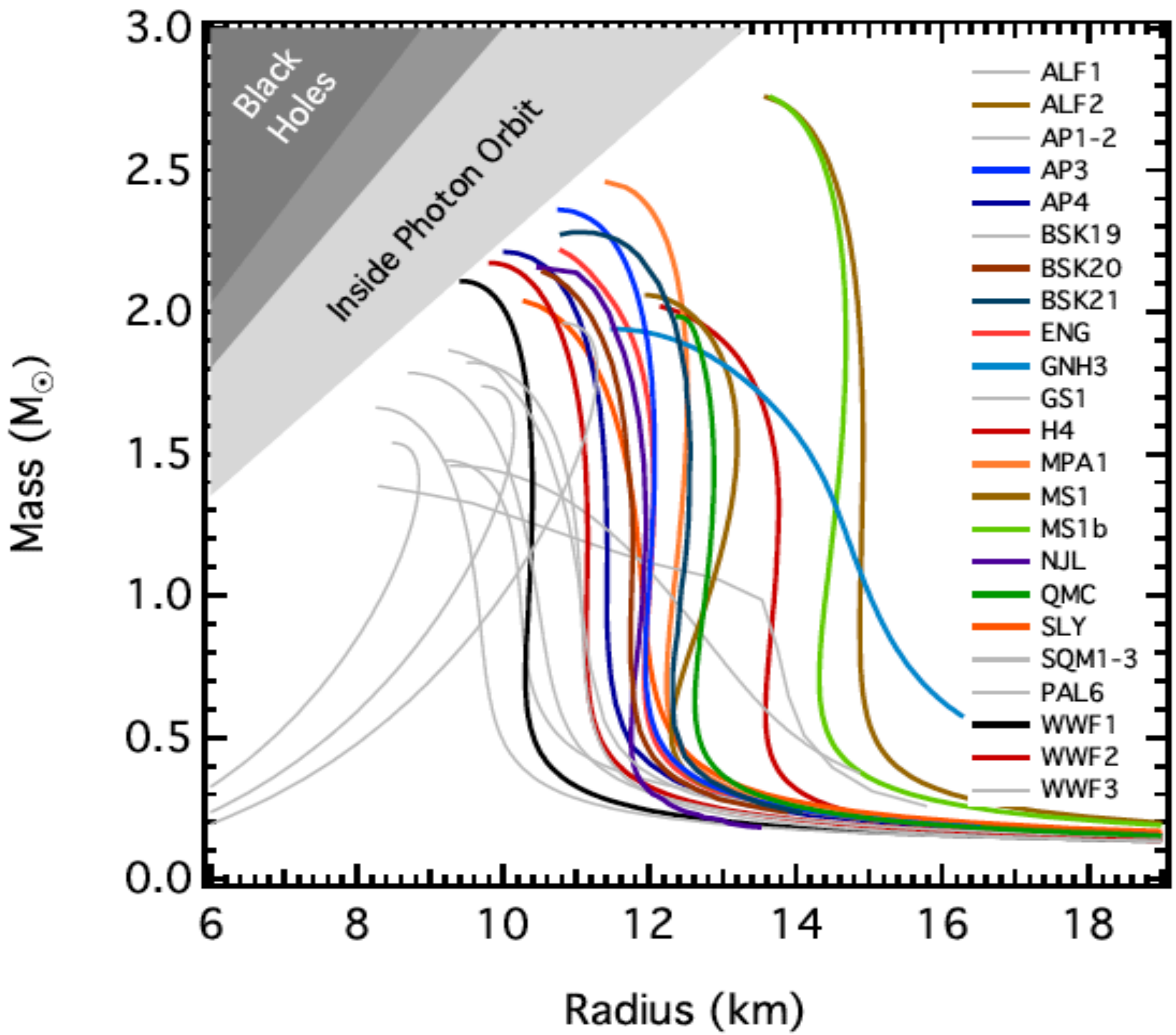
Abbott et al, Nature (2017)

Neutron Star Equation of State



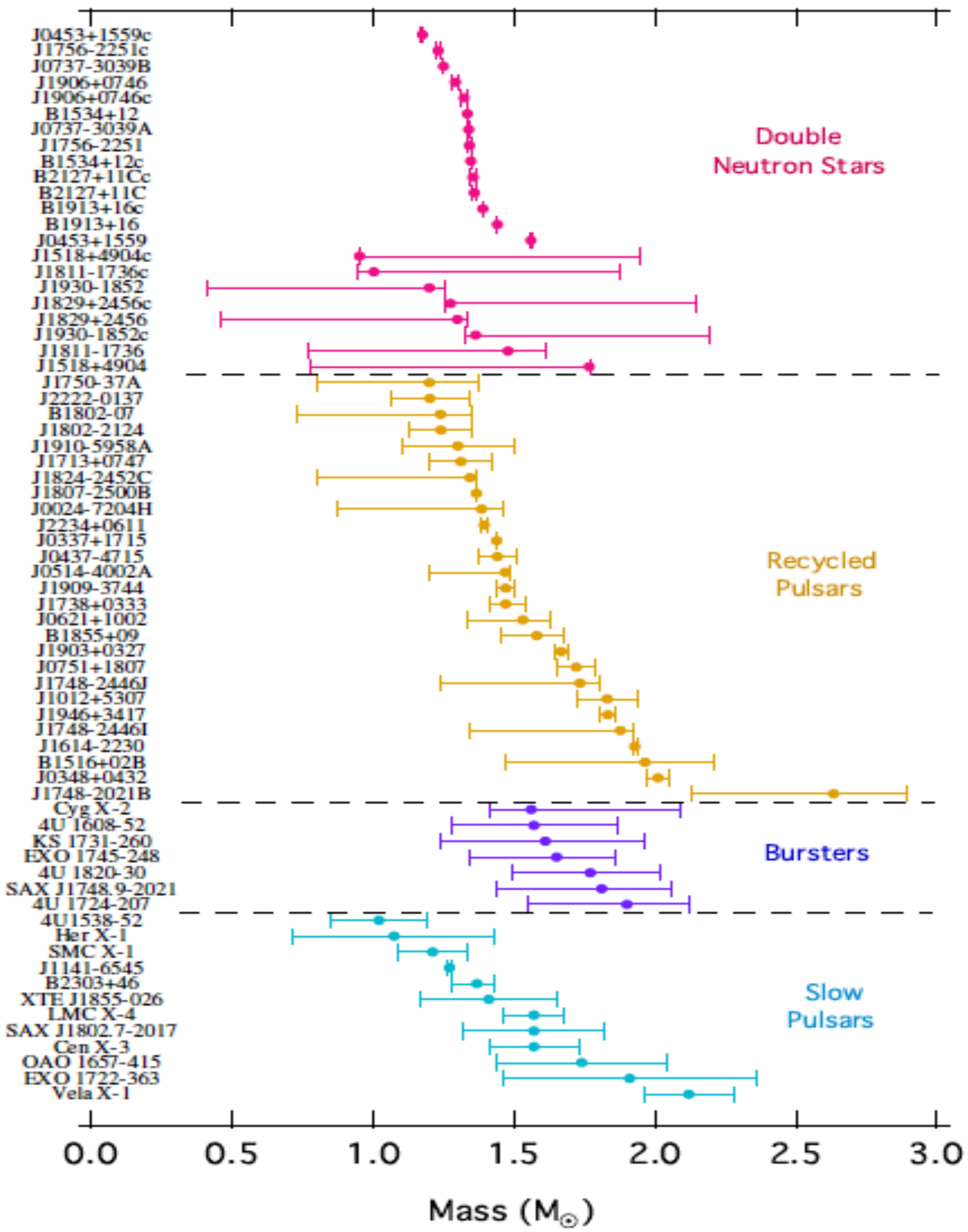
Credits: F. Weber

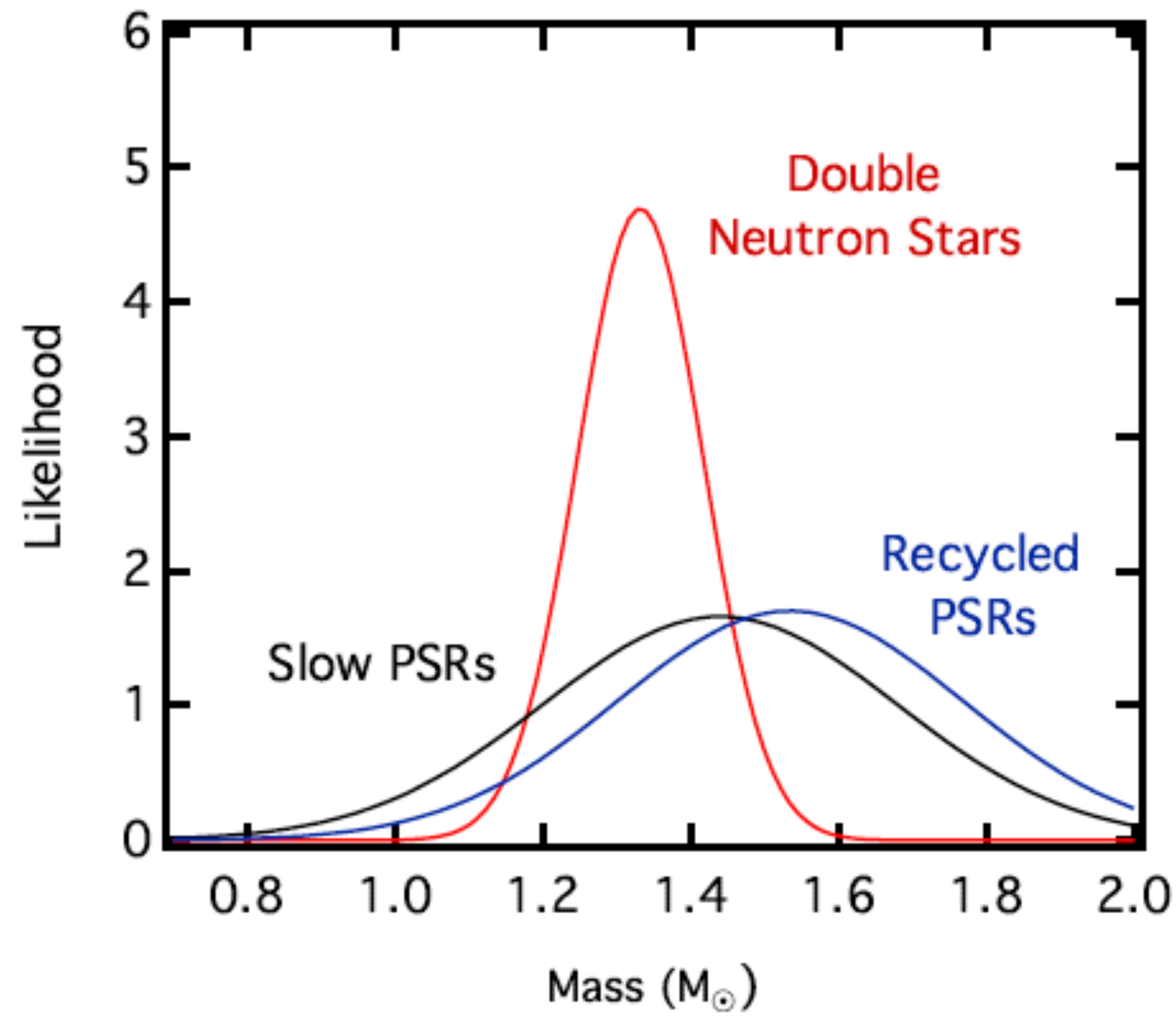
Equation of State



Özel & Freire, Ann.Rev.Astron.Astrophys 54, 401 (2017)

Maximum NS Mass

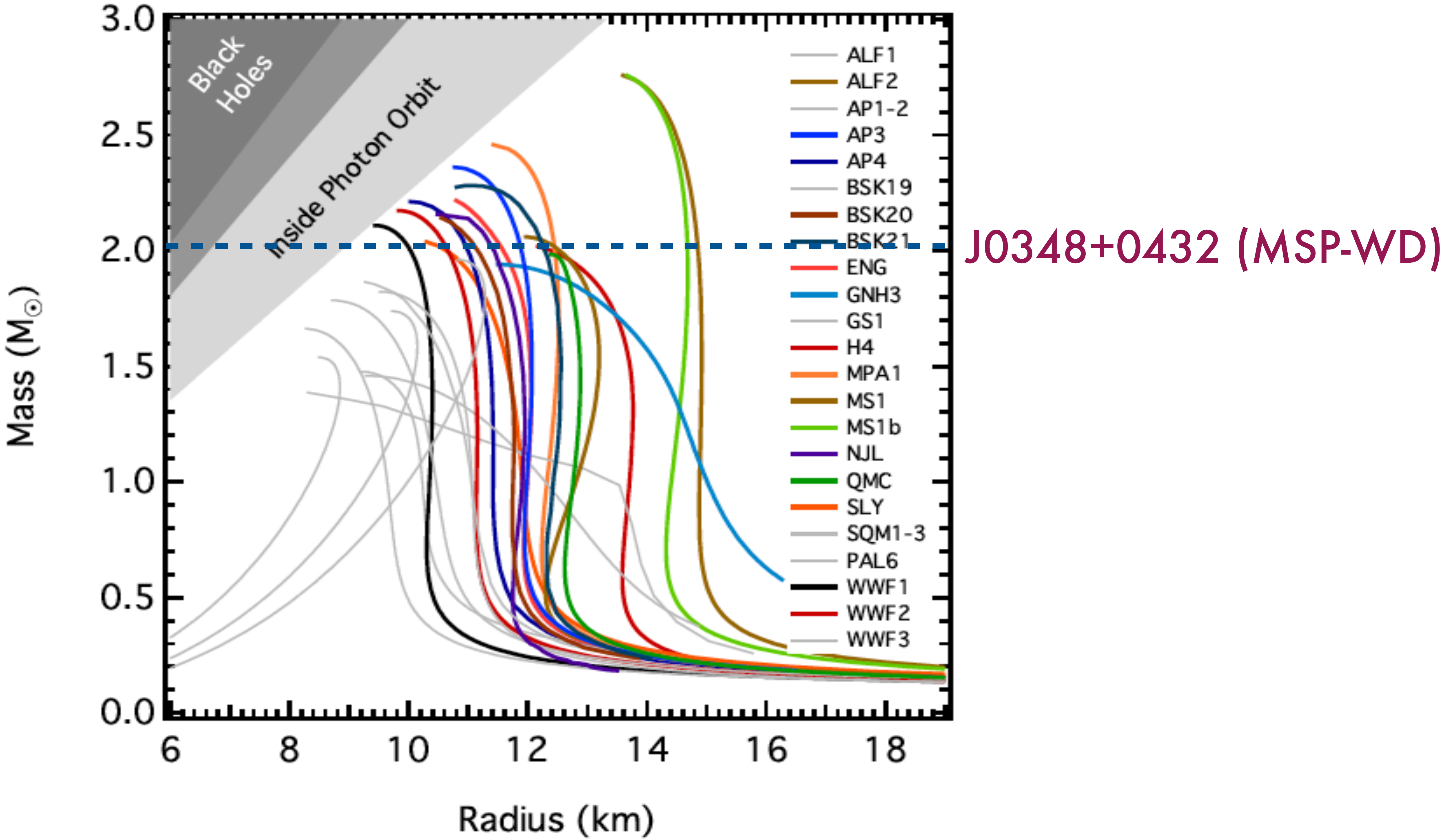




J0348+0432 : 2.01±0.04 M⊙

Özel & Freire, Ann.Rev.Astron.Astrophys 54, 401 (2017)

Equation of State



BNS Waveforms

For BBH systems, we can use a point particle approximation

- Inspiral comes from post-Newtonian theory
- Merger comes from numerical relativity
- Ringdown comes from black hole perturbation theory

For BNS systems, the pp-approximation breaks down early in the inspiral

- Need to include tidal effects of matter into the GW phase

$$\tilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12m_2)m_1^4 \Lambda_1 + (m_2 + 12m_1)m_2^4 \Lambda_2}{(m_1 + m_2)^5}$$

$$\Lambda = (2/3)k_2[(c^2/G)(R/m)]^5$$

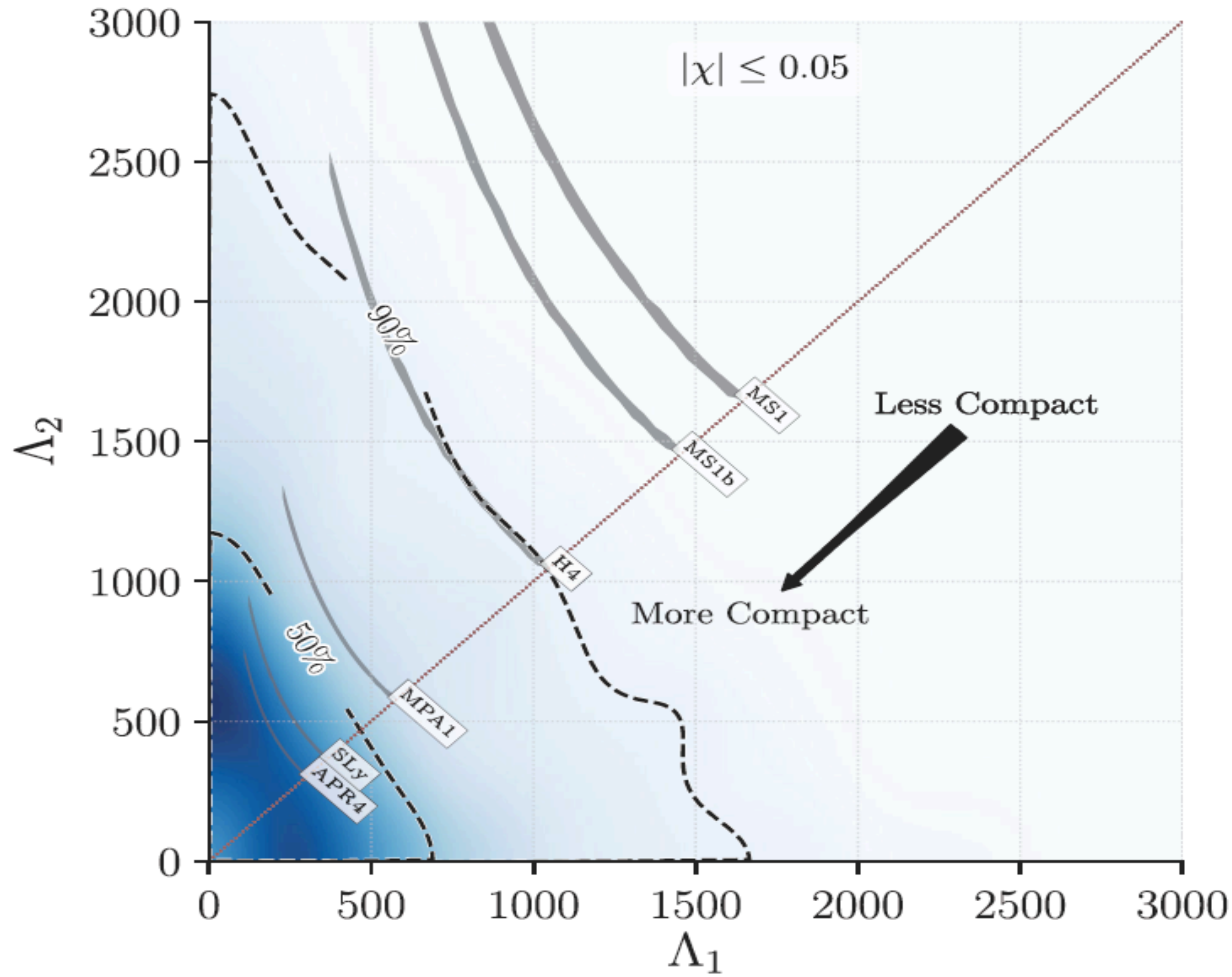
Equation of State

$$30 \leq f/Hz \leq 2048$$

$$m_1 \in (1.36, 1.6)\, M_\odot$$

$$m_2 \in (1.17, 1.36)\, M_\odot$$

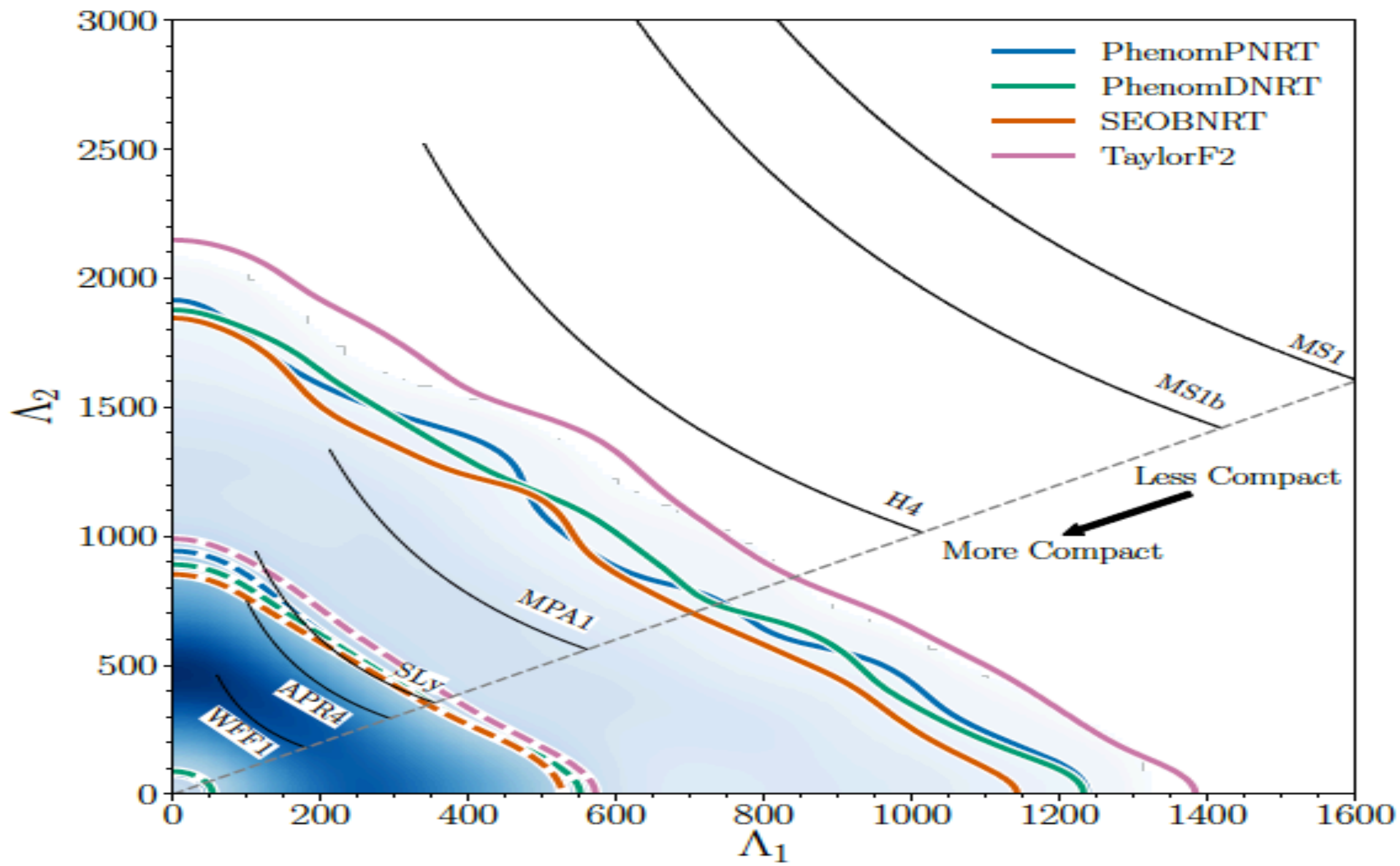
$$\tilde{\Lambda}_{1.4} \leq 900$$



Assume low spins - consistent with NS observations

Abbott et al, PRL 119, 161101 (2017)

Equation of State

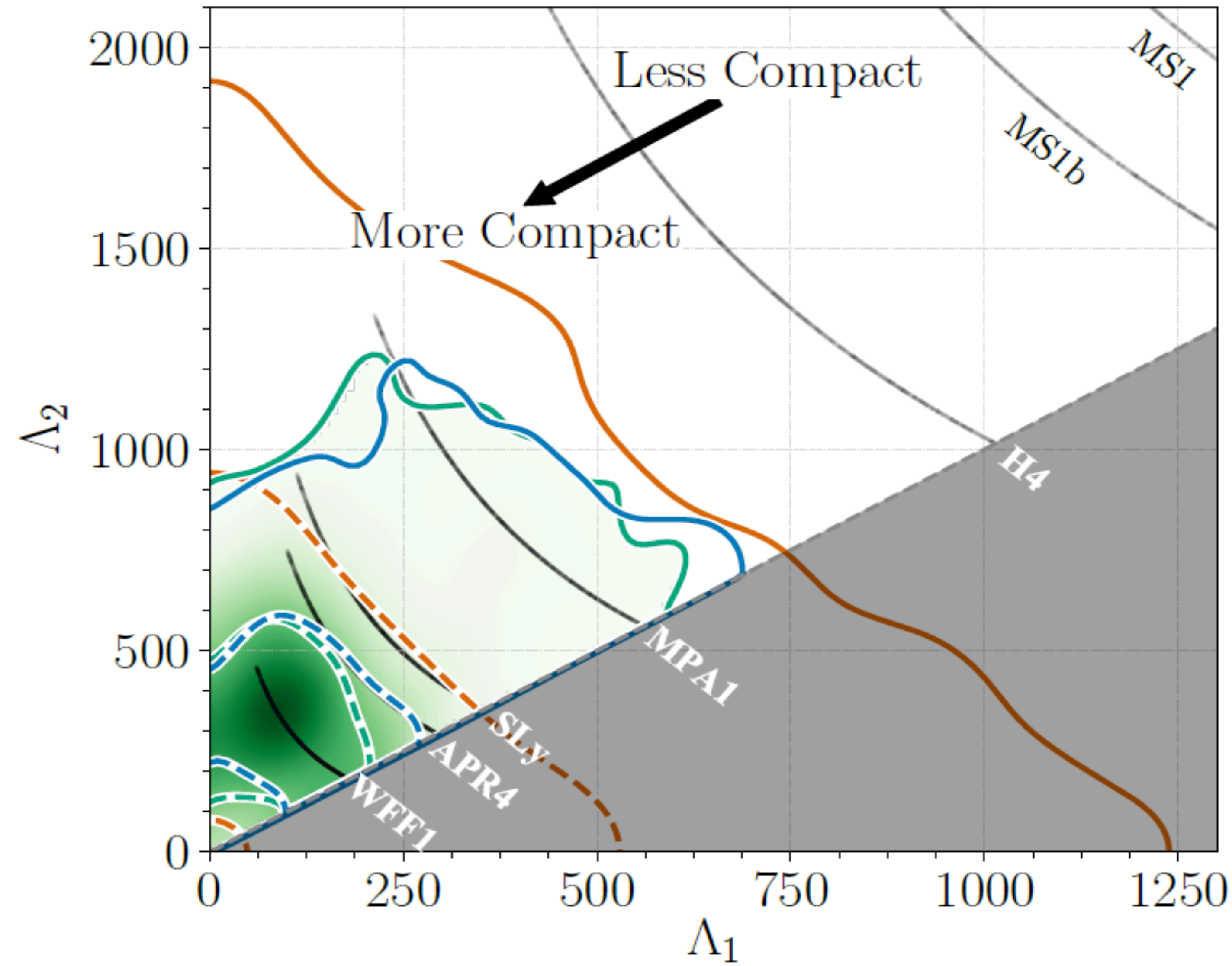


- New analysis beginning at 23 Hz with better modelling
- sky error reduced to 16 deg^2
- Bound on Λ_1 - Λ_2 is 20% smaller
- 2-sided 90% CI does not contain 0

Abbott et al, arXiv:1805.11579 (2018)

Equation of State

- Assume 2 NSs with identical EOS
- 2 EOS methodologies
  - EOS-insensitive :
    i. $\Lambda_a(\Lambda_s, q)$
    ii. Λ - C
  - Parameterised EOS :
    i. Spectral parameterisation
- 90% CI for Λ_1 - Λ_2 shrinks by ~3

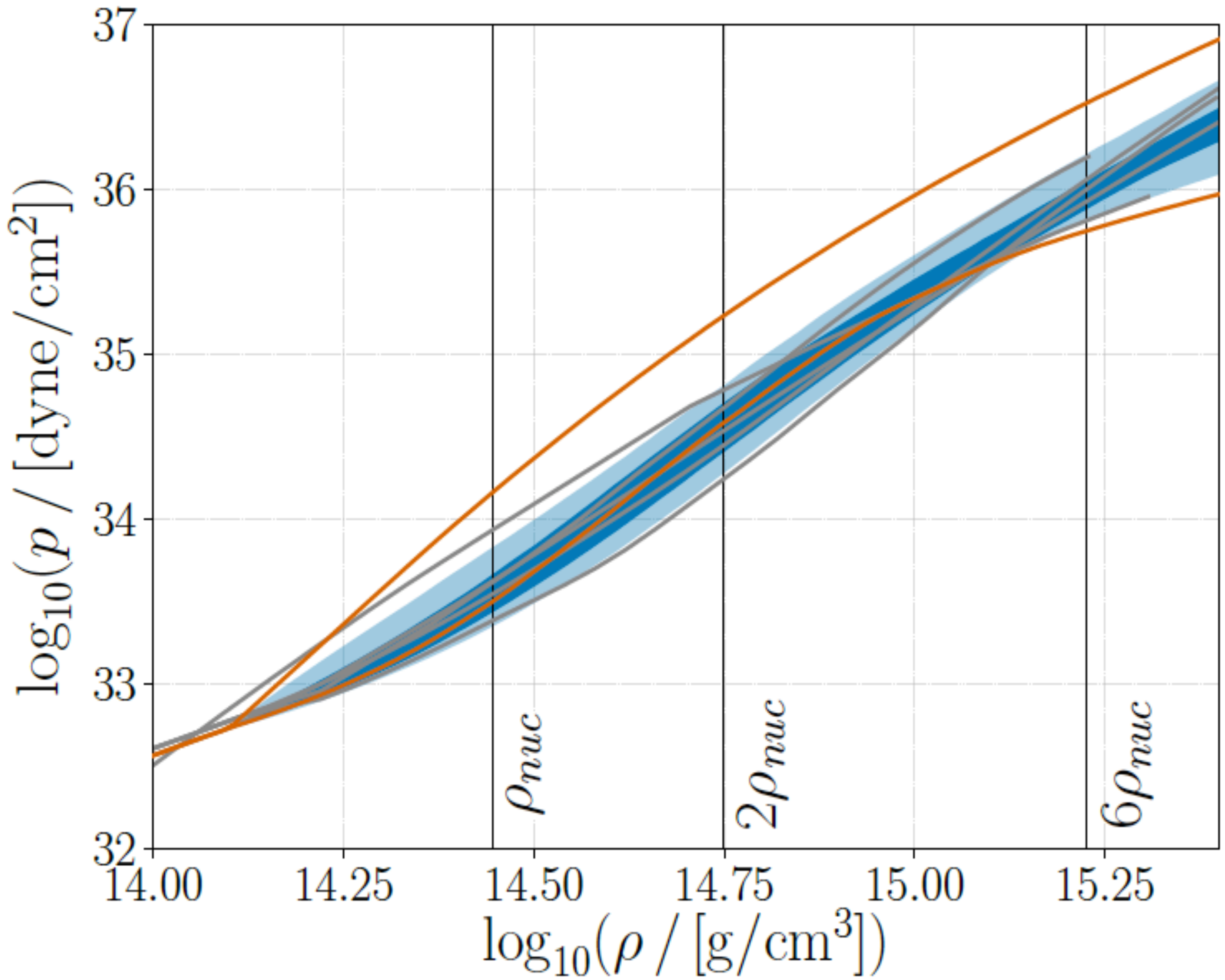


$$\Lambda_{1.4} = 190^{+390}_{-120}$$

Abbott et al, arXiv:1805.11581 (2018)

Equation of State

Now assume spectral parameterisation + minimum NS mass = 1.97 $M_\odot$

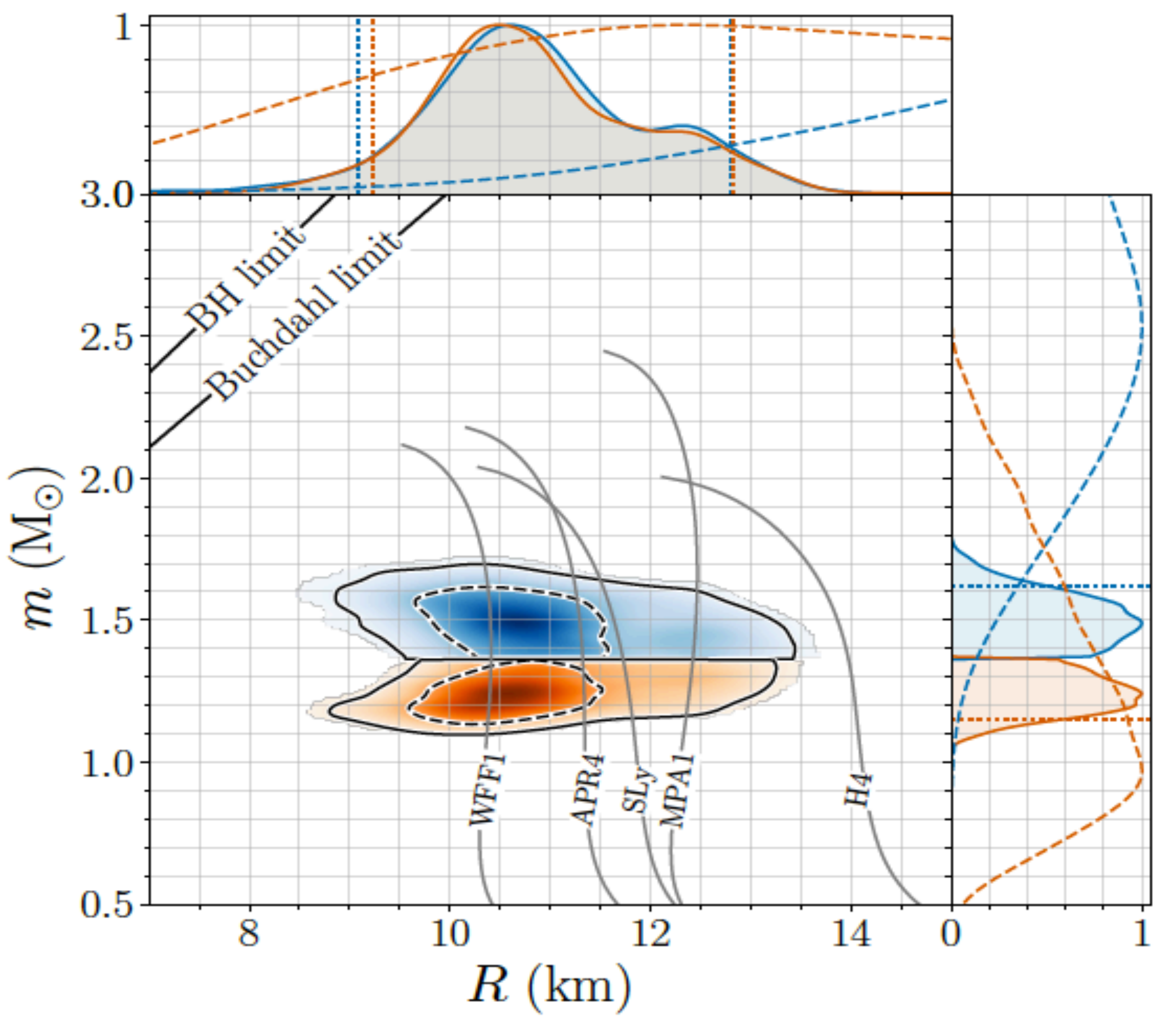


$$p(2\rho_{nuc}) = 3.5^{+2.5}_{-1.7} \times 10^{34}\, dyne\, cm^{-2}$$

Abbott et al, arXiv:1805.11581 (2018)

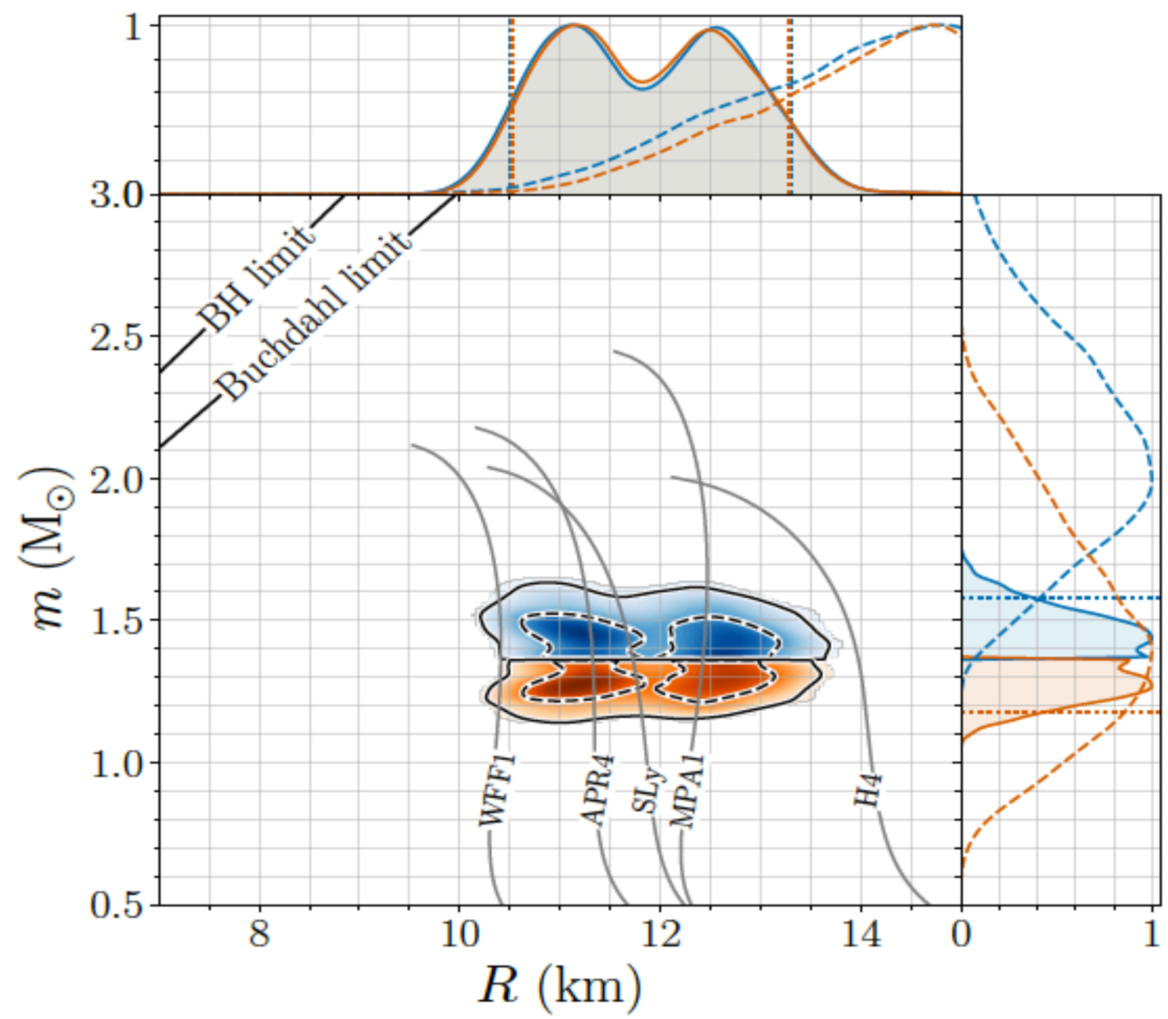
Equation of State

EOS-ins



$$R_1 = 10.8^{+2.0}_{-1.7}\,km$$
$$R_2 = 10.7^{+2.1}_{-1.5}\,km$$

Spec.Param + min. NS mass

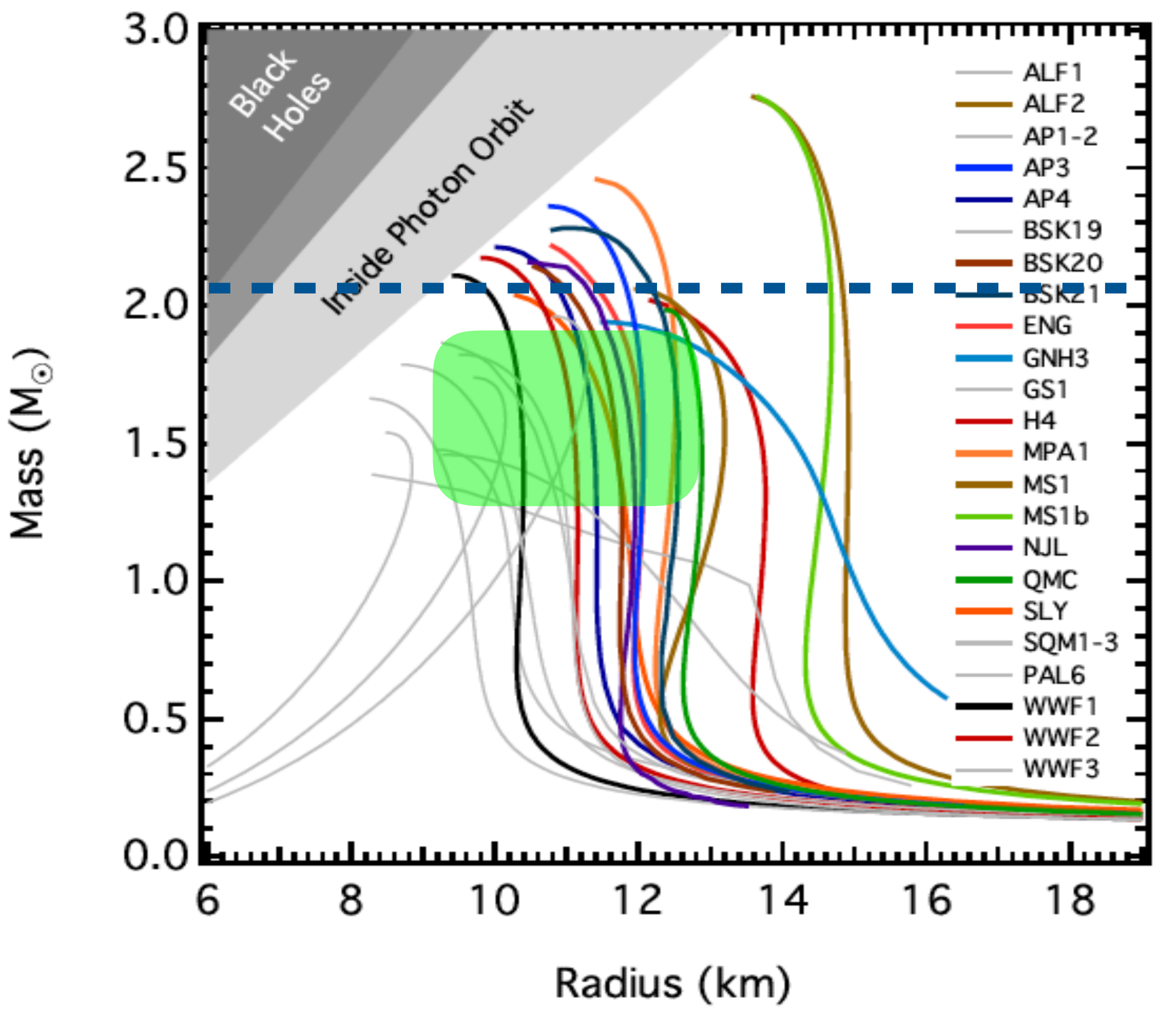


$$R_1 = 11.9^{+1.4}_{-1.4}\,km$$
$$R_2 = 11.9^{+1.4}_{-1.4}\,km$$

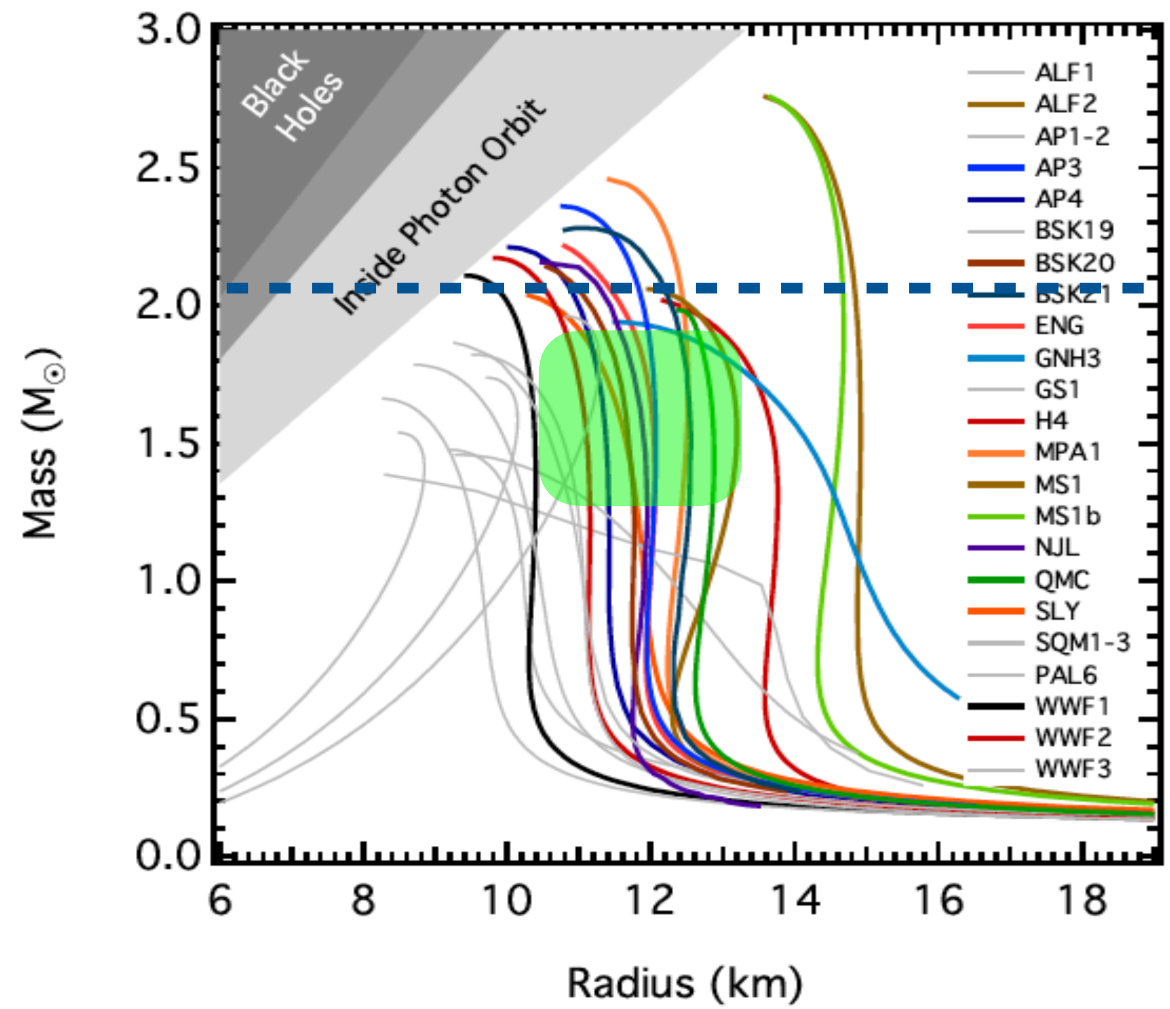
Abbott et al, arXiv:1805.11581 (2018)

Equation of State

EOS-ins



Spec.Param + min. NS mass



GW + EM gives much tighter constraint

Conclusions

- 6 BBH mergers (including first triple detection with Advanced Virgo) + First detection of a BNS merger
- Confirmed that BNS mergers ⇛ SGRBs ⇛ kilonova
- Multi-wavelength follow-up: the era of MMA has truly begun
- $c_g \approx c$
- Consequences for dark energy cosmology and dark matter emulator theories
- Measured Hubble's constant
- No deviations from GR observed!
- GW observations now allow investigation of NS-EOS - already a number of models ruled out!
- More to come in O3…