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NWO Netherlands Organisation for Scientific Research

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on behalf of the LIGO Scientific and Virgo Collaborations

Gravitational Wave Observations: Black Holes, Neutron Stars & Tests of General Relativity

14th Rencontres du Vietnam:
Very High Energy Phenomena in the Universe
August 12-18, 2018
ICISE, Quy Nhon

DCC-G1801553

VIRGO

LIGO VIRGO

Gravitational Waves - New Messengers

Probe the **densest, most dynamical** regions of the universe

Explore **extremes of gravity, astrophysics** & **fundamental physics**

Key **multi-messenger** channel

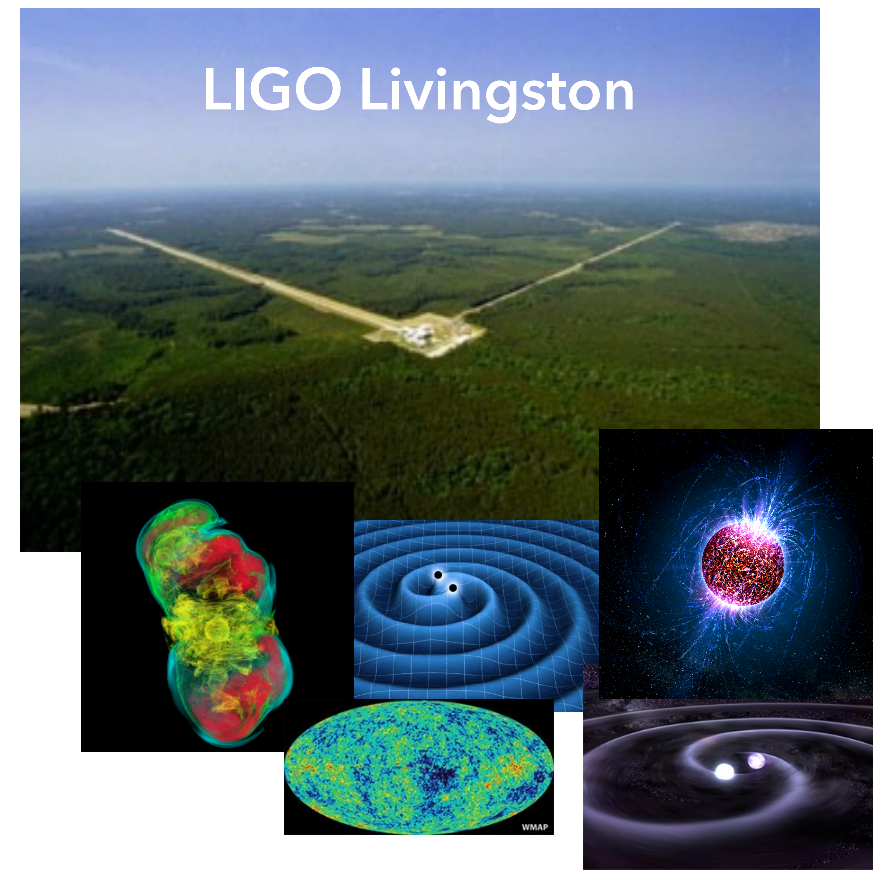
Where & how do black holes form?

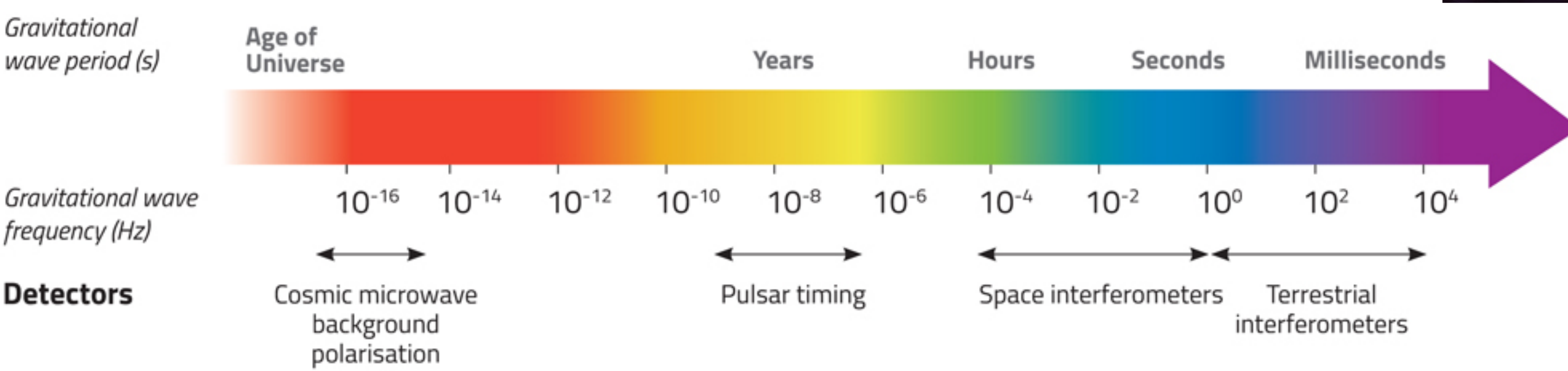
Is General Relativity correct?

What are neutron stars made of?

Ground-based GW observatories

- Interferometric GW observatories
  - Operating: LIGO Livingston, LIGO Hanford, Virgo, GEO600
  - Under construction: KAGRA (~2020)
  - Planned: LIGO India

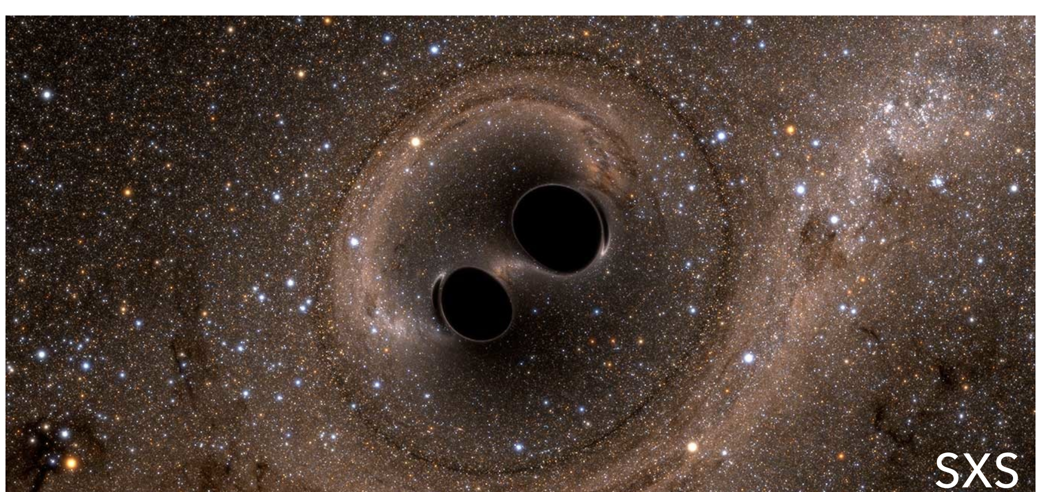




O1 & O2: Summary

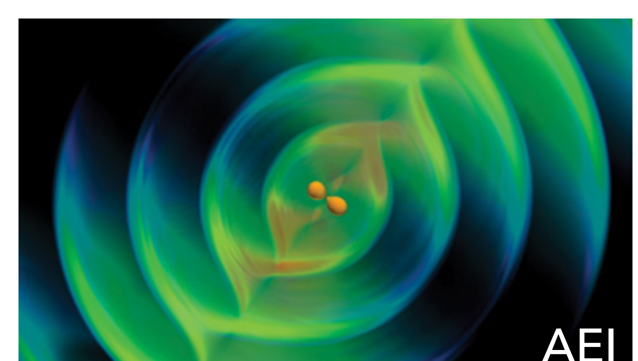
First Observing run (O1):

- 12/09/2015 - 19/01/2016
- ~ 49 days of coincident LIGO data
- 2 BBH detections: GW150914, GW151226
- 1 BBH candidate: LVT151012



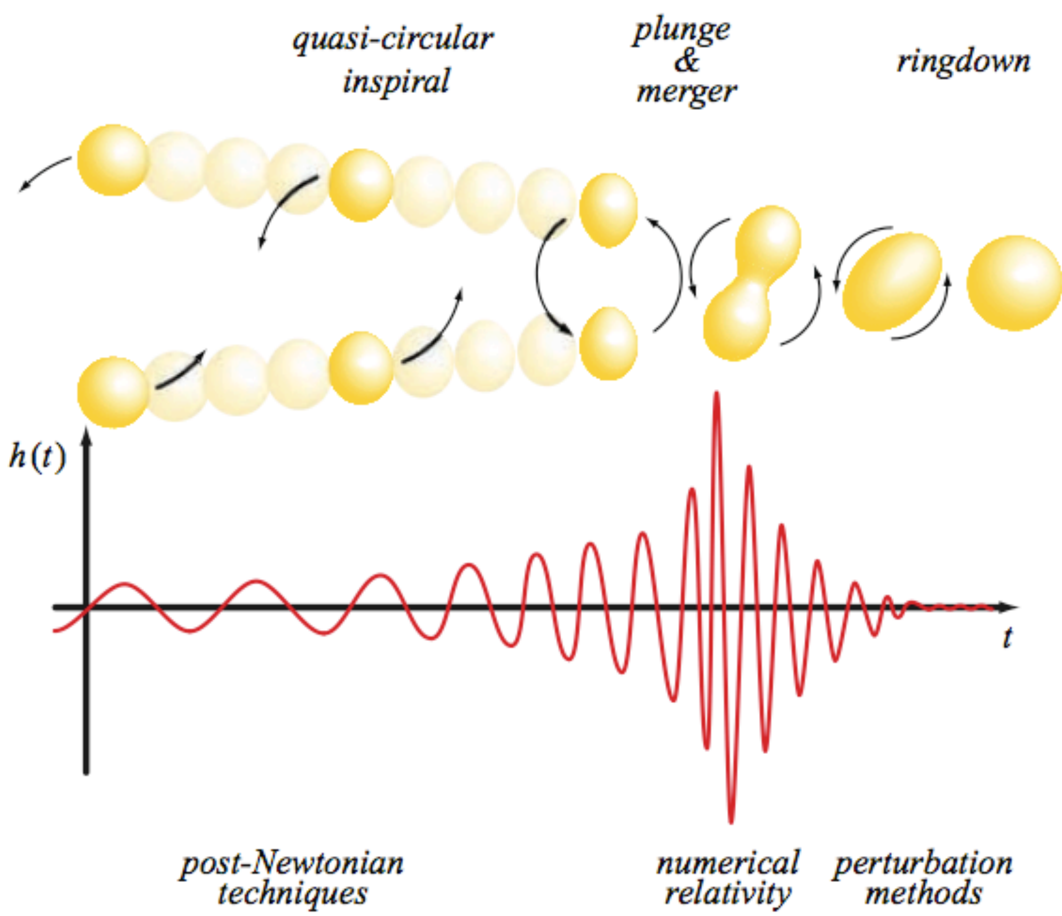
Second Observing run (O2):

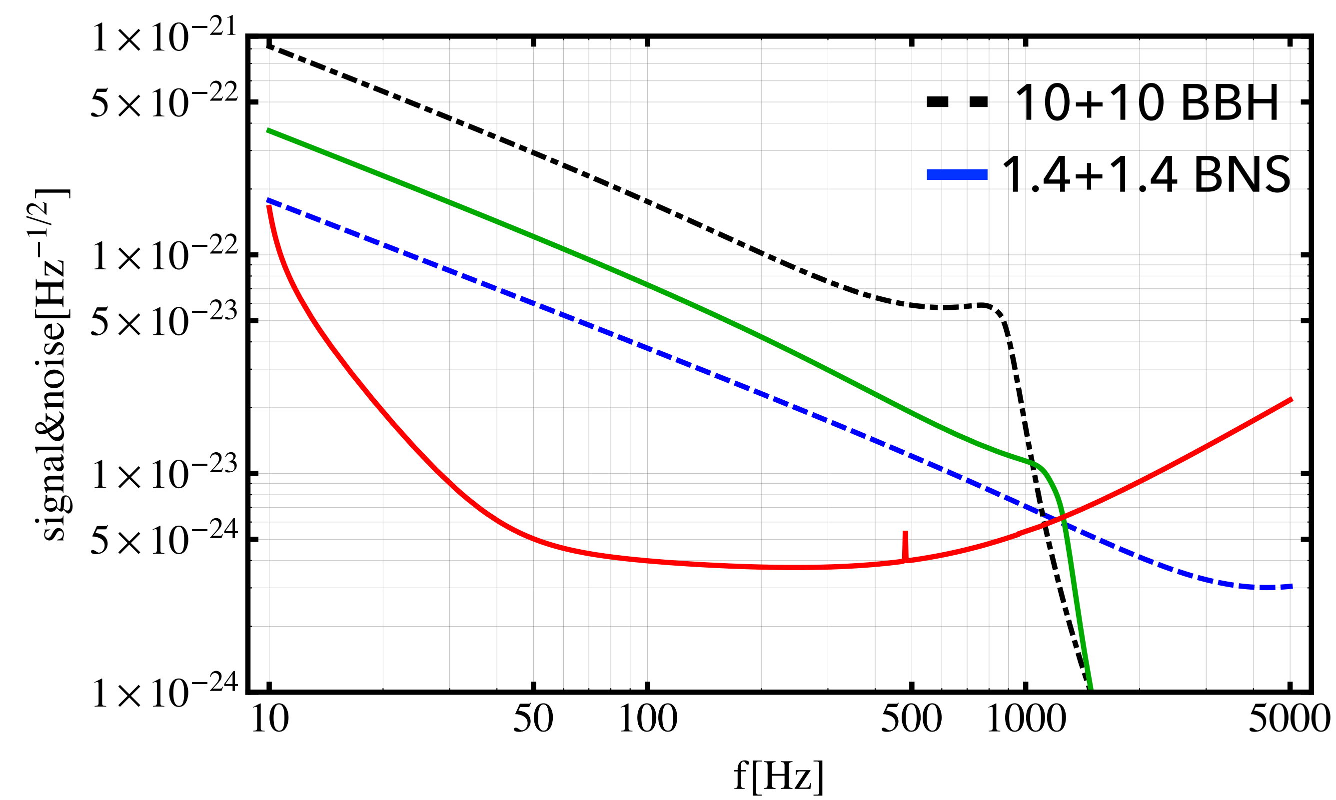
- 30/11/2016 - 25/08/2017
- Virgo joined on August 1st 2017
  - BNS range of ~27 Mpc
- ~ 117 days of coincident LIGO data
- ~ 15 days of coincident LIGO-Virgo data
- 3 BBH detections: GW170104, GW170608, GW170814
- 1 BNS detection: GW170817

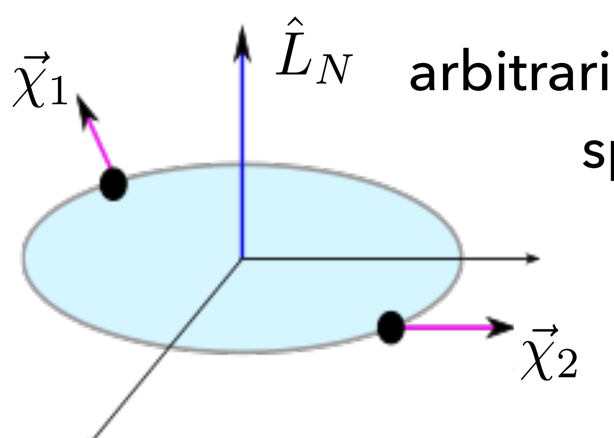


Decoding the chirp signal from coalescing binaries

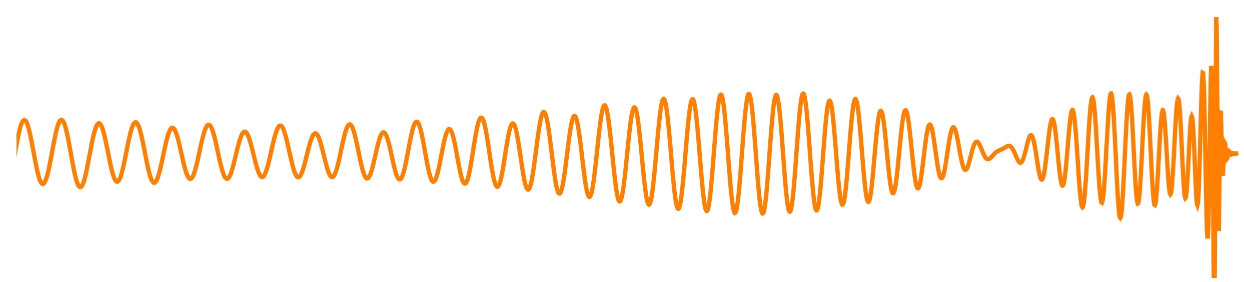
- GWs encode the characteristic properties of the source, esp. masses & spins
  - **Require accurate gravitational waveform models**





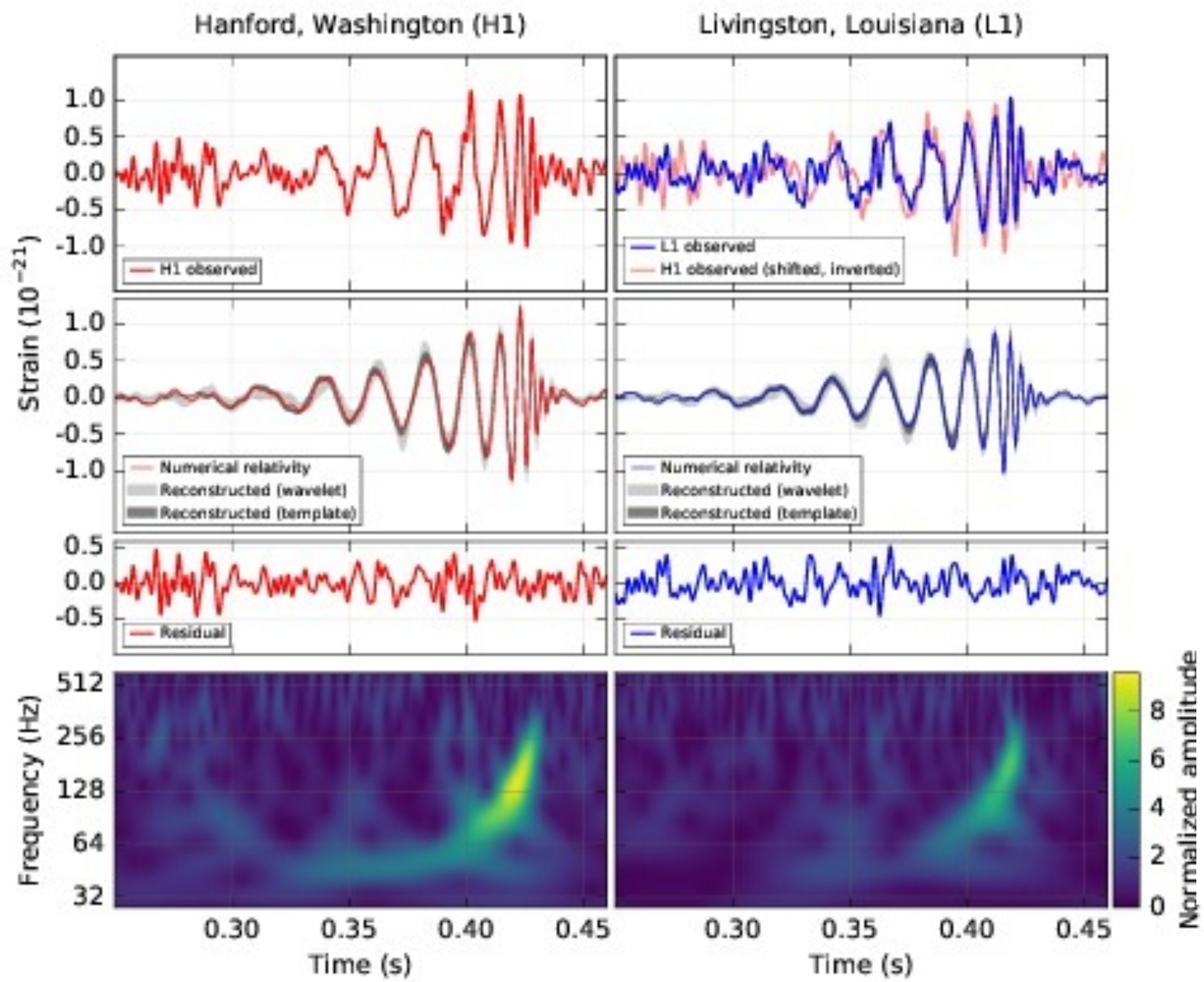


arbitrarily oriented spins

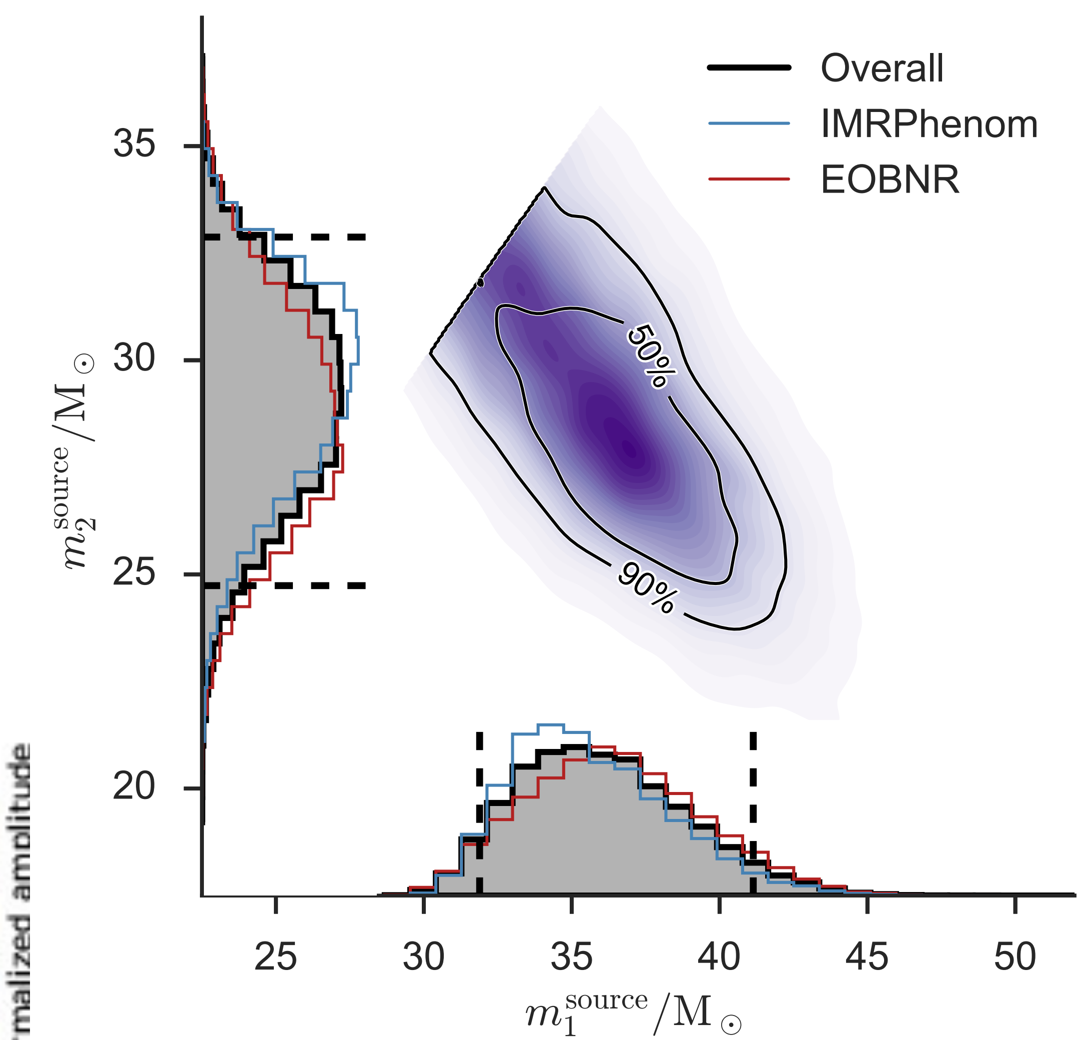


$$\lambda = \{\underbrace{m_1, m_2, \vec{\chi}_1, \vec{\chi}_2}_{intrinsic}, \underbrace{D_L, \theta_{\rm JN}, \iota, \alpha, \delta, \phi_C, t_C, \psi}_{extrinsic}\}$$

- On **September 14, 2015** Advanced LIGO detected the first binary black hole coalescence with a signal-to-noise ratio (SNR) of **~25**

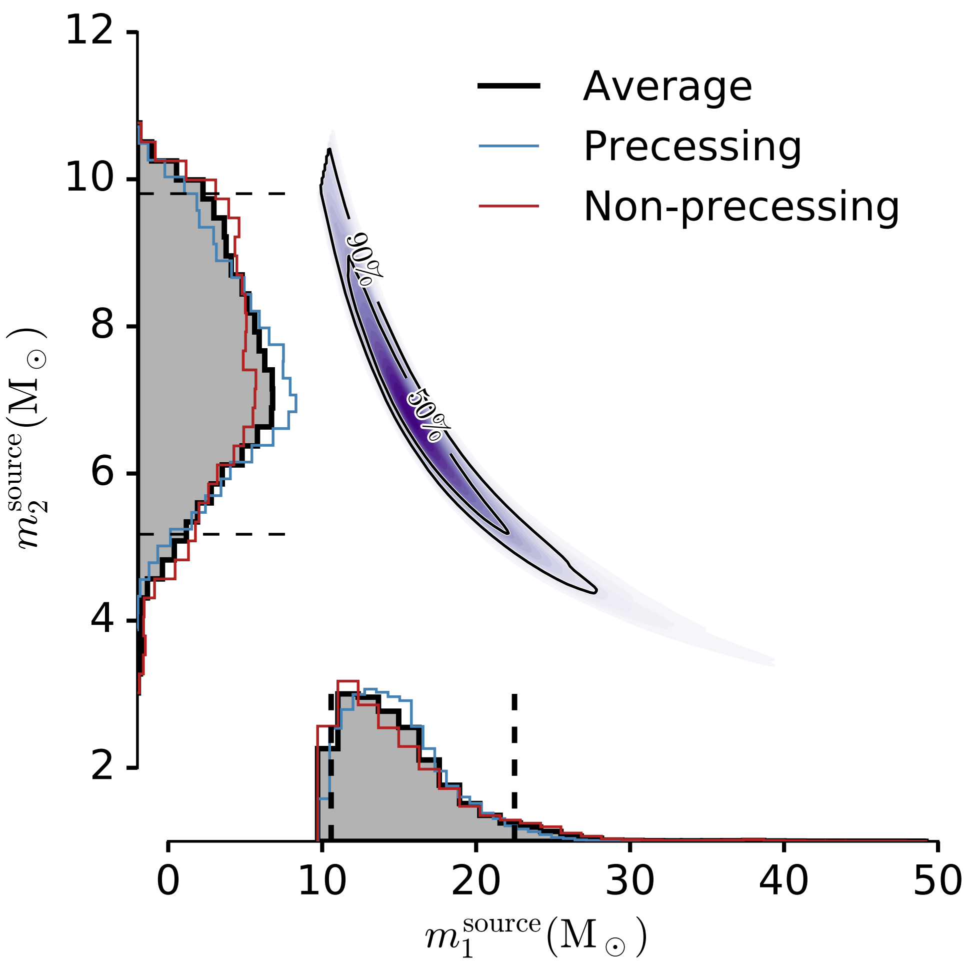


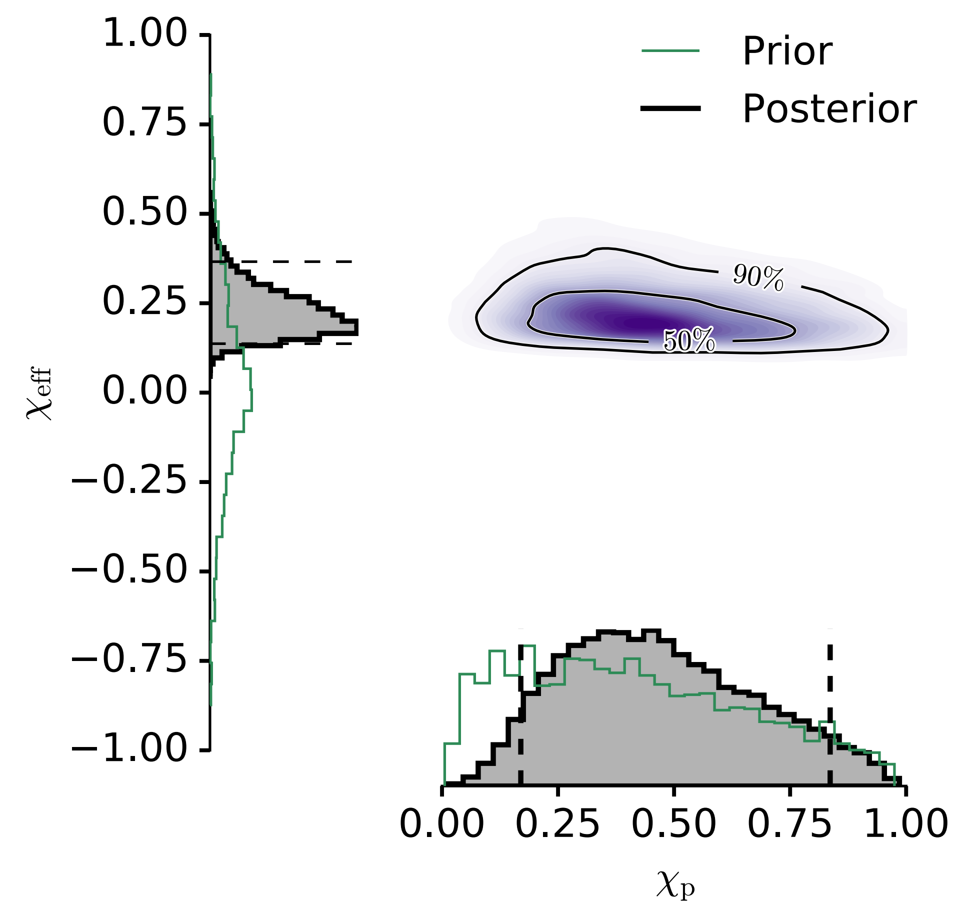
LVC, PRL 116, 061102 (2016)



LVC, PRL, 116, 241102 (2016)

- Recorded on **December 26th, 2015** at 03:38:53 UTC, SNR **~13**





Chirp mass:

$$\mathcal{M} := \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

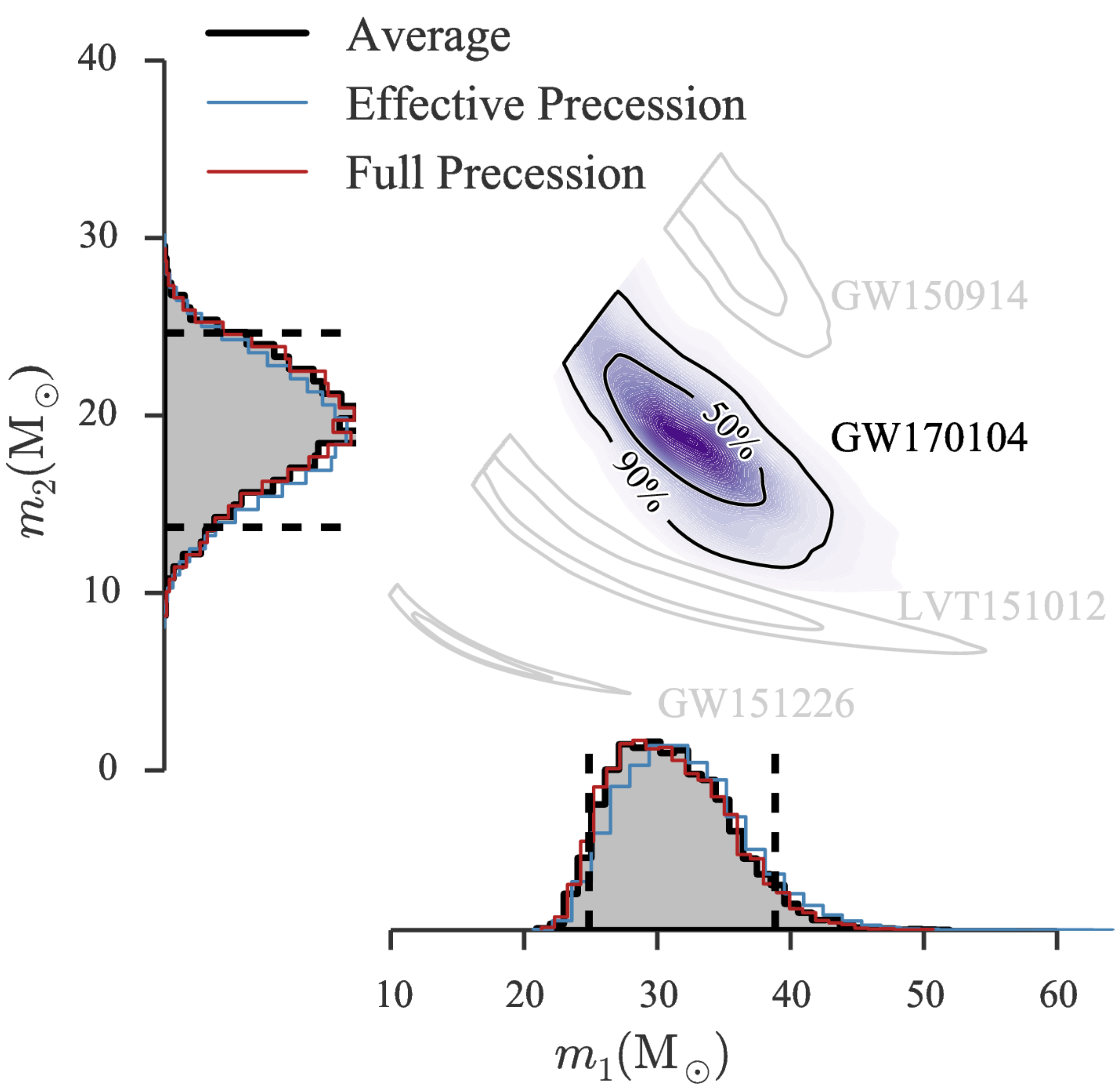
Effective inspiral spin: $\chi_{\rm eff} = \dfrac{m_1 a_{1,\parallel} + m_2 a_{2,\parallel}}{m_1 + m_2}$

Effective precession spin: $\chi_{\rm p} \sim (a_{1,\perp}, a_{2,\perp})$

Phys. Rev. Lett. 116, 241103 (2016)

GW170104: Another massive BBH

- On **January 4th, 2017** at 10:11:58 UTC Advanced LIGO recorded the GW of another high mass BBH with an SNR of **~13**



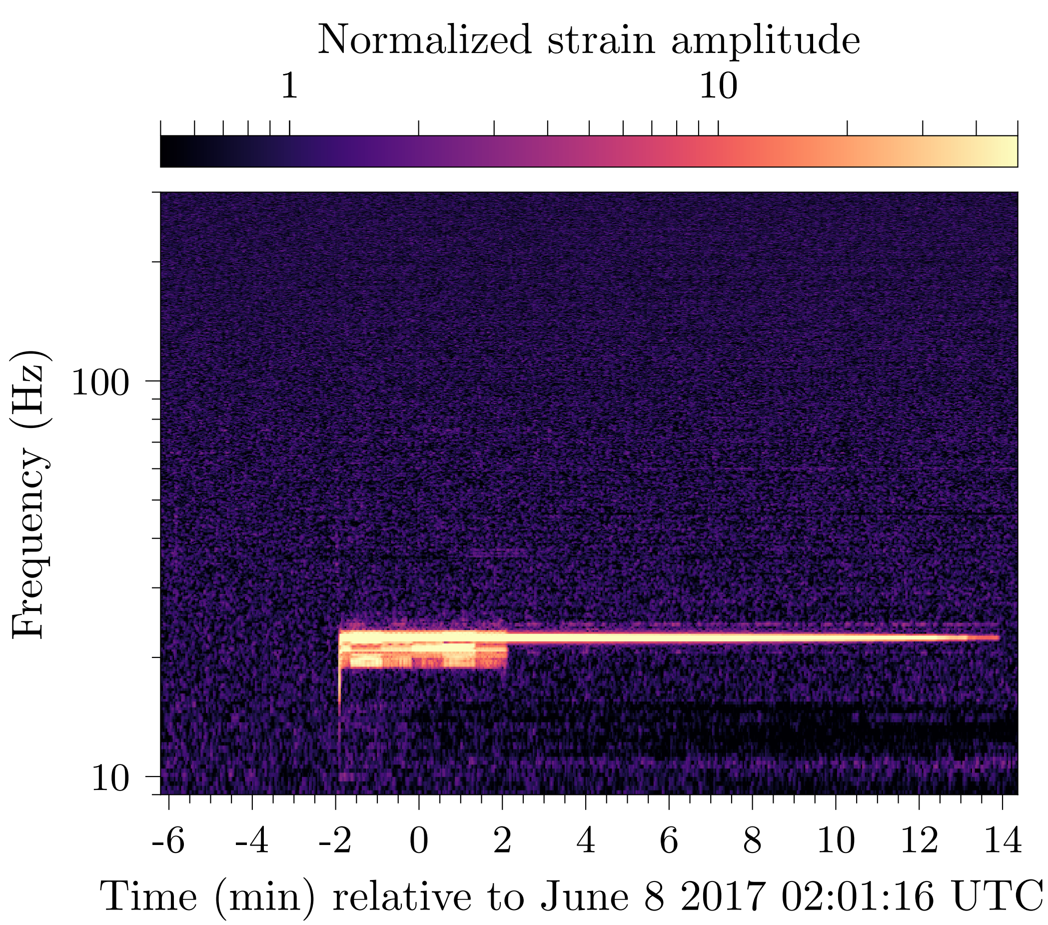
Primary black hole mass m_1	$31.2^{+8.4}_{-6.0} M_\odot$
Secondary black hole mass m_2	$19.4^{+5.3}_{-5.9} M_\odot$
Chirp mass $\mathcal{M}$	$21.1^{+2.4}_{-2.7} M_\odot$
Total mass M	$50.7^{+5.9}_{-5.0} M_\odot$
Final black hole mass M_f	$48.7^{+5.7}_{-4.6} M_\odot$
Radiated energy E_{rad}	$2.0^{+0.6}_{-0.7} M_\odot c^2$
Peak luminosity ℓ_{peak}	$3.1^{+0.7}_{-1.3} \times 10^{56} \mathrm{erg\ s}^{-1}$
Effective inspiral spin parameter χ_{eff}	$-0.12^{+0.21}_{-0.30}$
Final black hole spin a_f	$0.64^{+0.09}_{-0.20}$
Luminosity distance D_L	880^{+450}_{-390} Mpc
Source redshift z	$0.18^{+0.08}_{-0.07}$

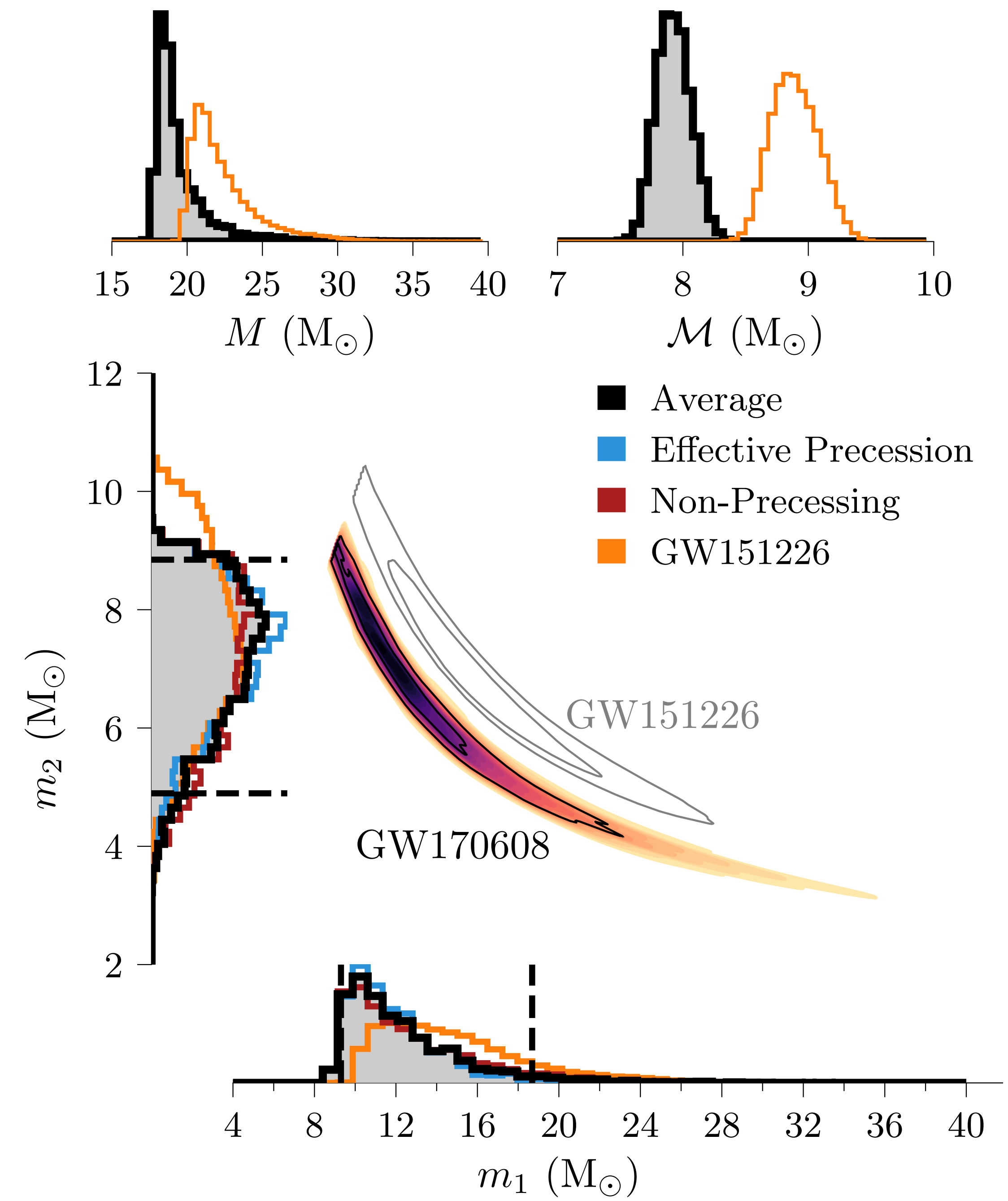
disfavours two large positive spins components along L

Phys. Rev. Lett. 118, 221101, (2017)

GW170608: The (almost) elusive low mass BBH

- On **June 8th, 2017** Advanced LIGO detected its *lightest* black hole binary yet (SNR ~13)
- Single detector trigger in L1
- H1 was not in observing mode due to beam re-centering procedure

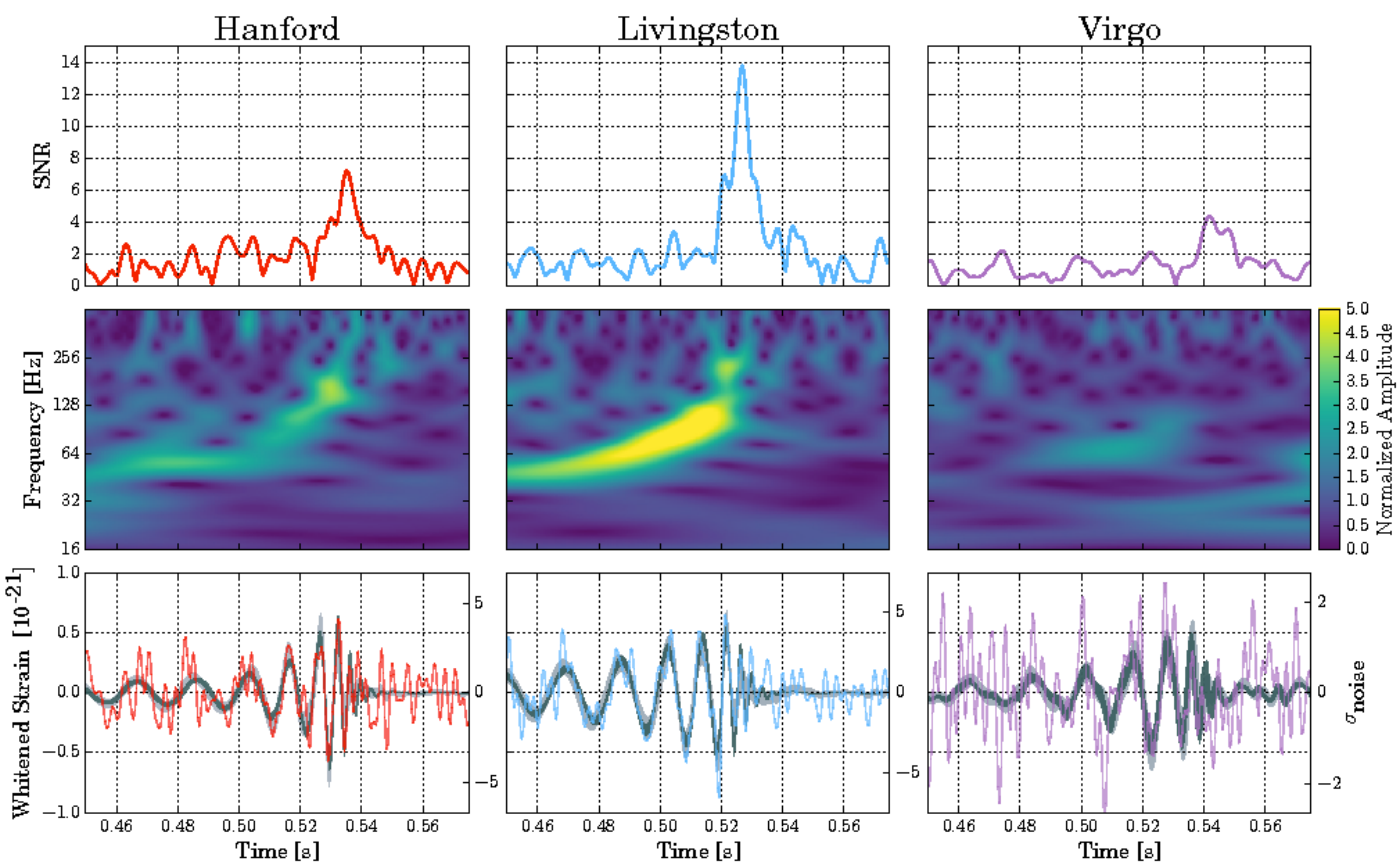




LVC, Astrophys. J. Lett. 851, L35

GW170814: The first HLV binary

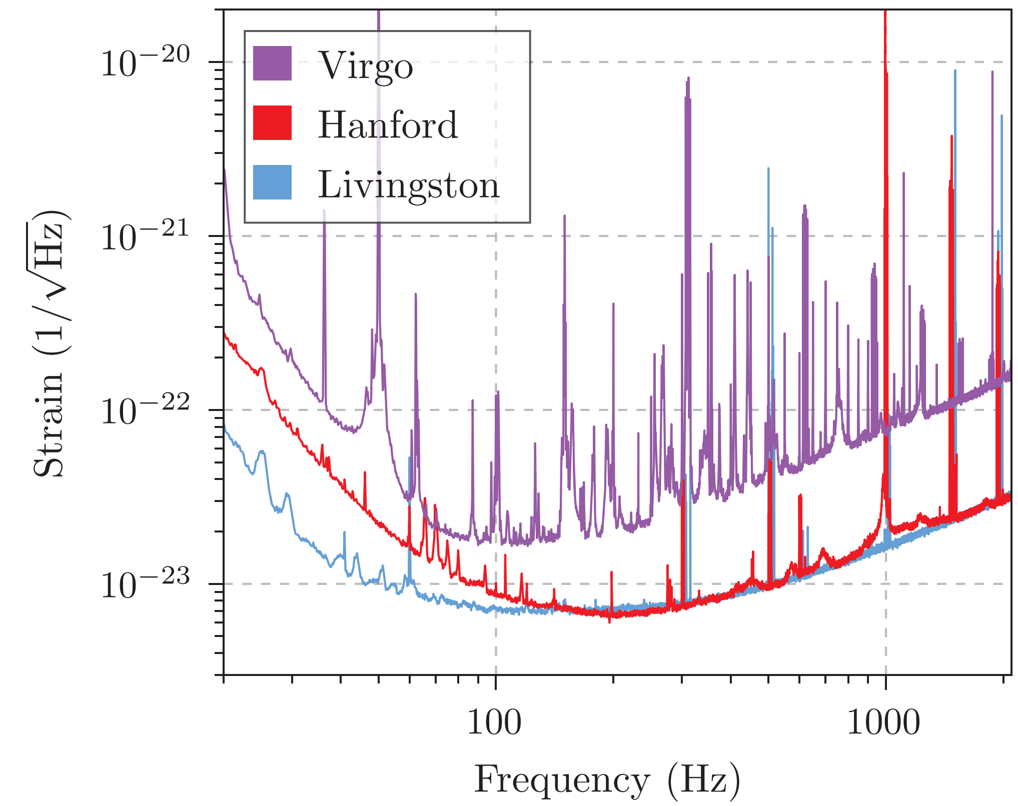
- On **August 14th, 2017** at 10:30:43 UTC Advanced LIGO and Advanced Virgo coincidentally detected the signal of a high mass binary black hole coalescence

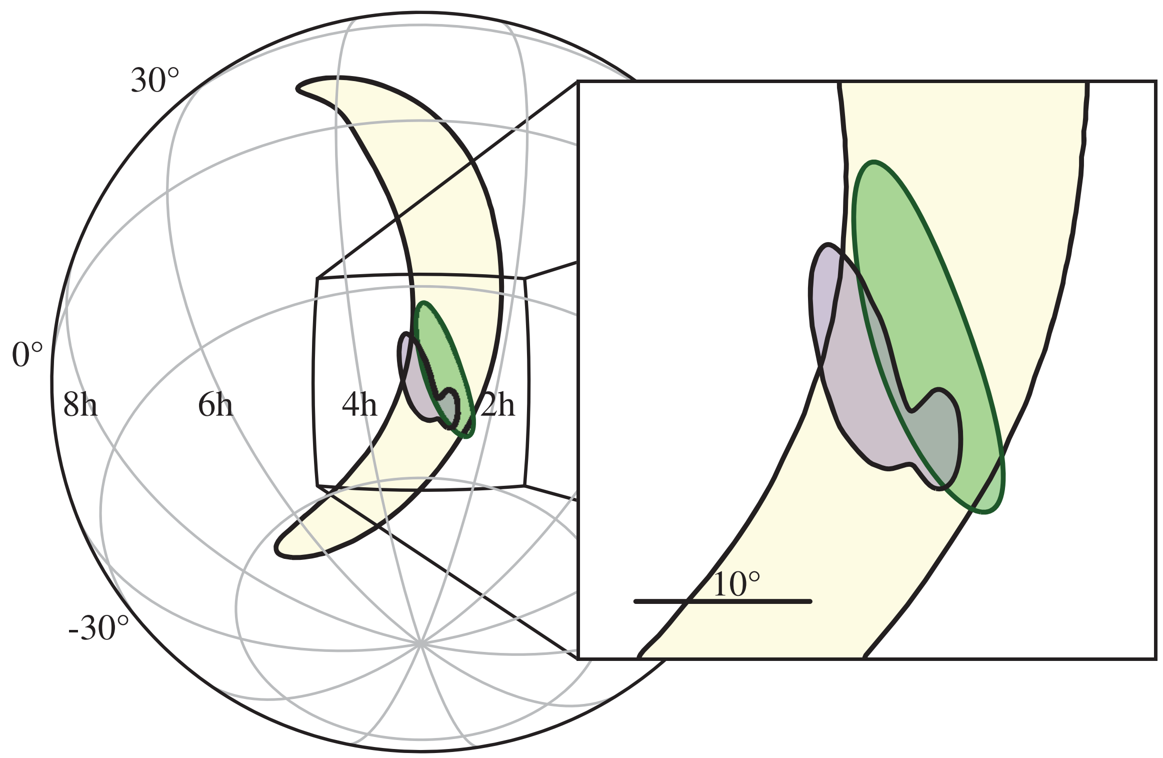


PRL, 119, 141101 (2017)

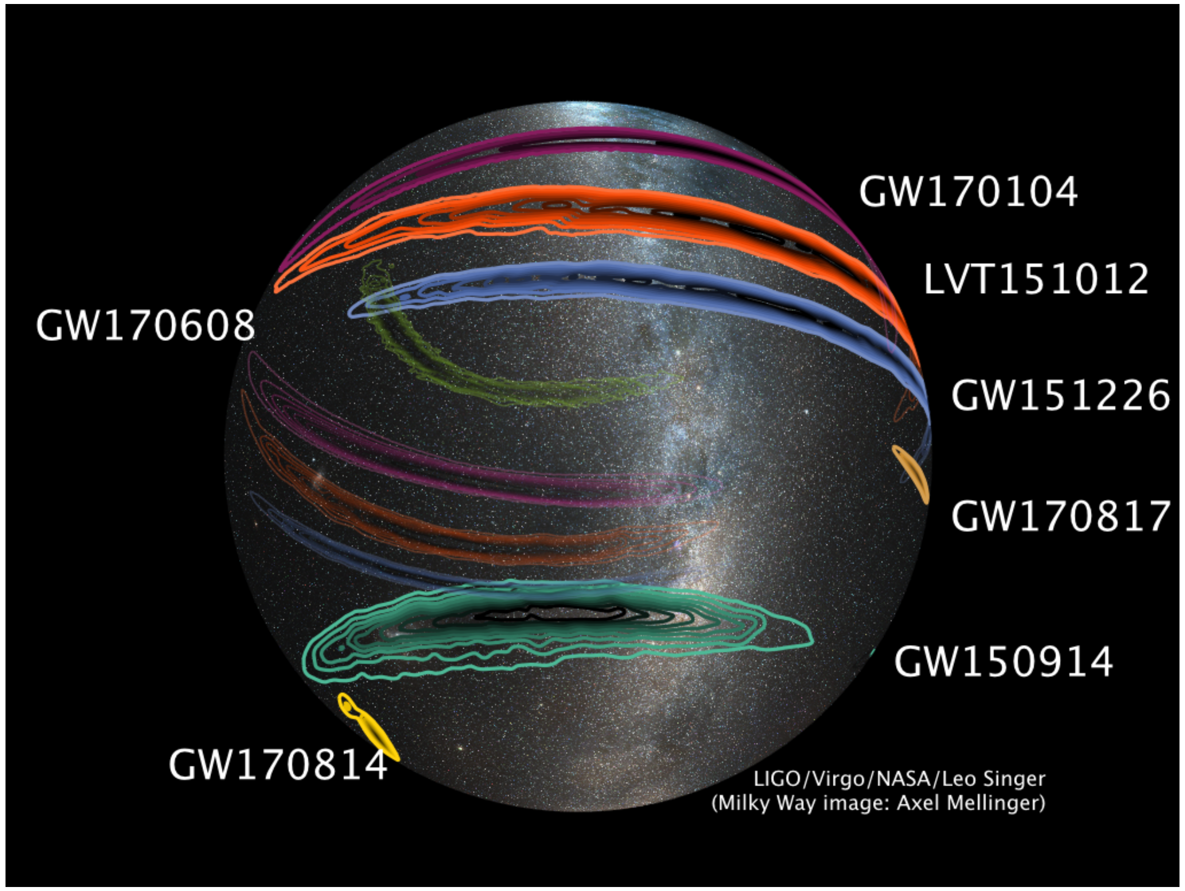
GW170814: The first HLV binary

- 3-detector network SNR ~18
- The addition of Advanced Virgo allows for much tighter sky localisation
  - **1160 deg² to ~60 deg²**

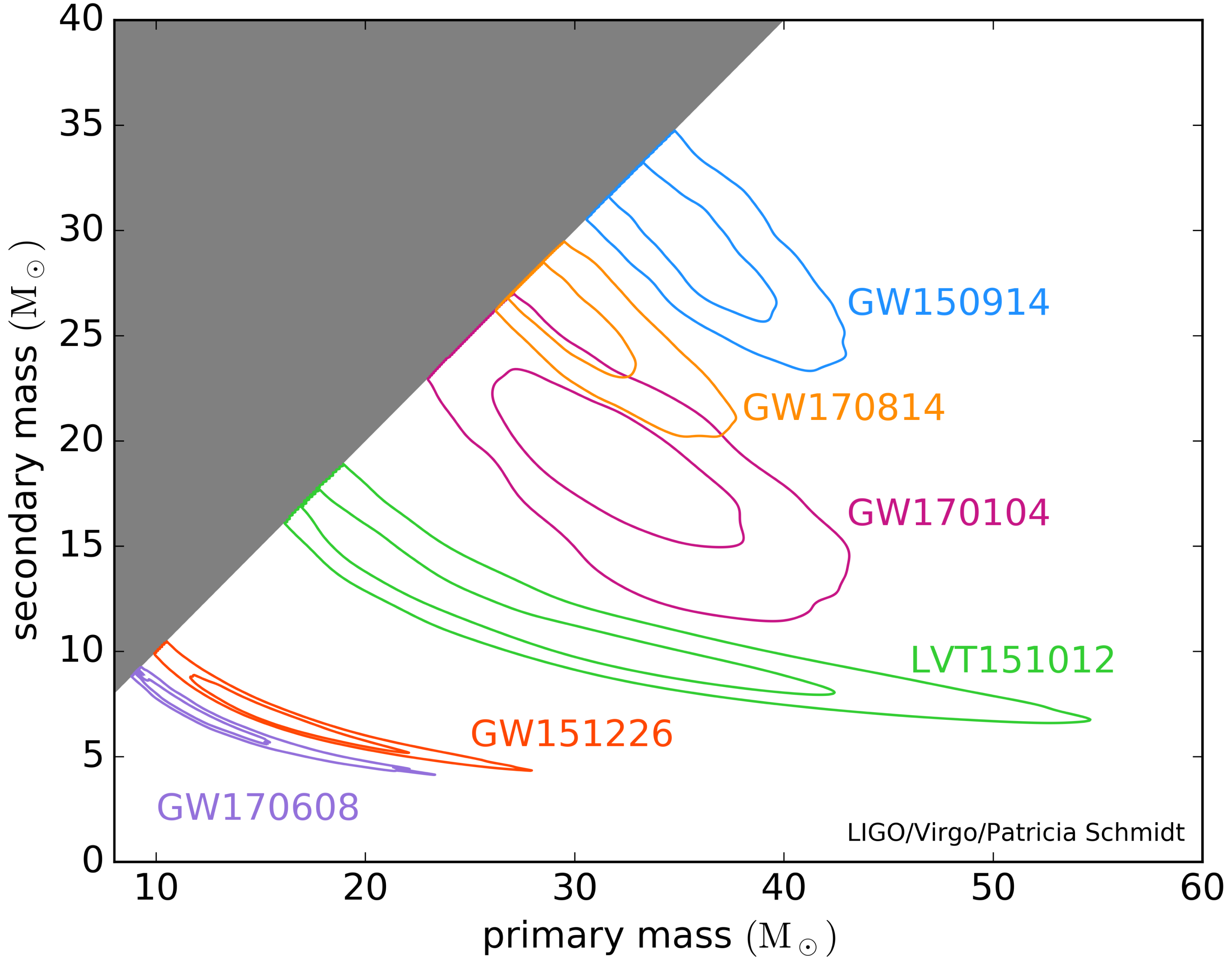




PRL, 119, 141101 (2017)



LIGO's & Virgo's BBH

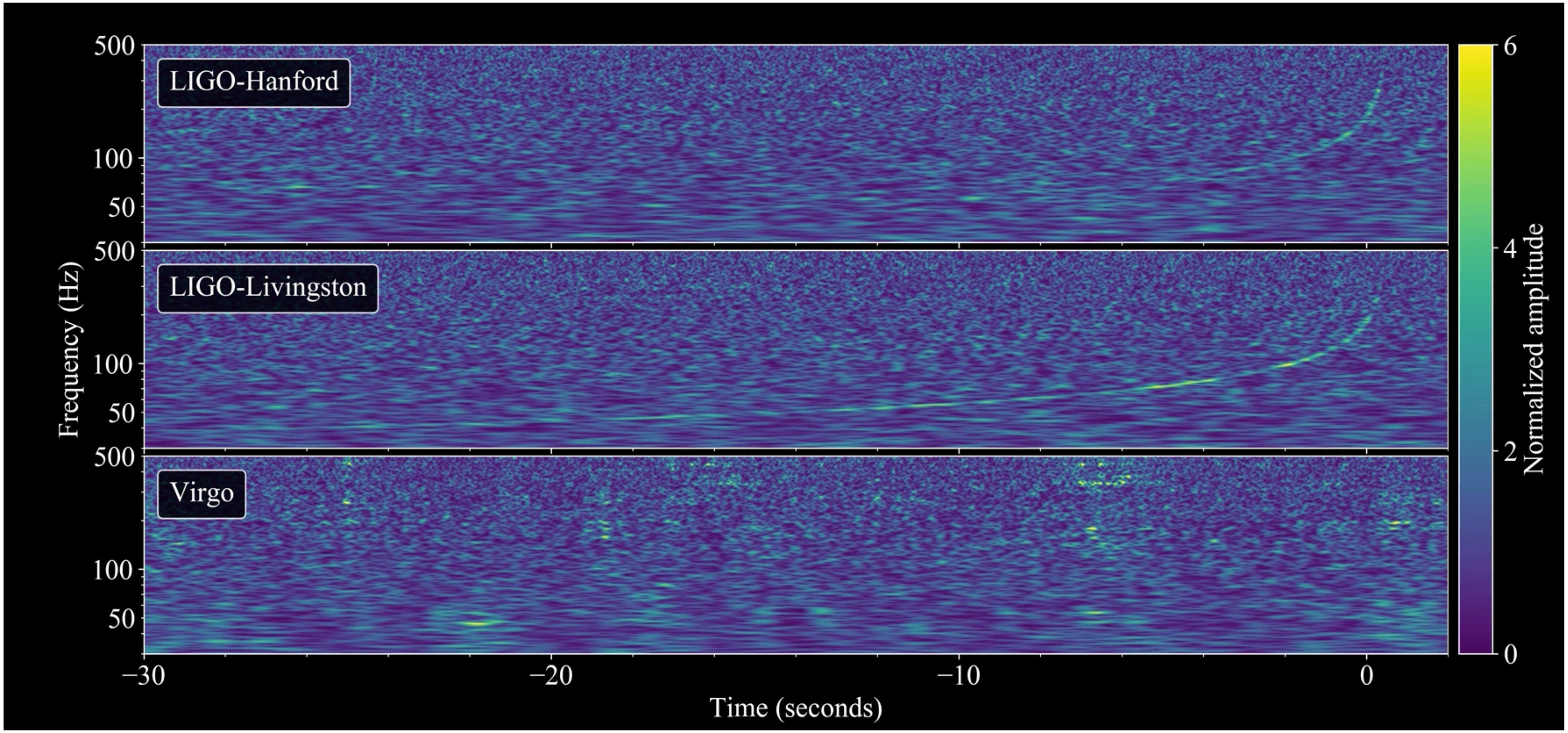


- Distinct populations?
  - Different environments
- Spin constraints are weak
  - Could help distinguish formation channels
  - Individual spins are difficult to measure
- Statistical errors dominate measurements in O1&O2!
- More statistics needed!
  - BBH merger rate:

$$12 - 213\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

GW170817: A binary neutron star inspiral

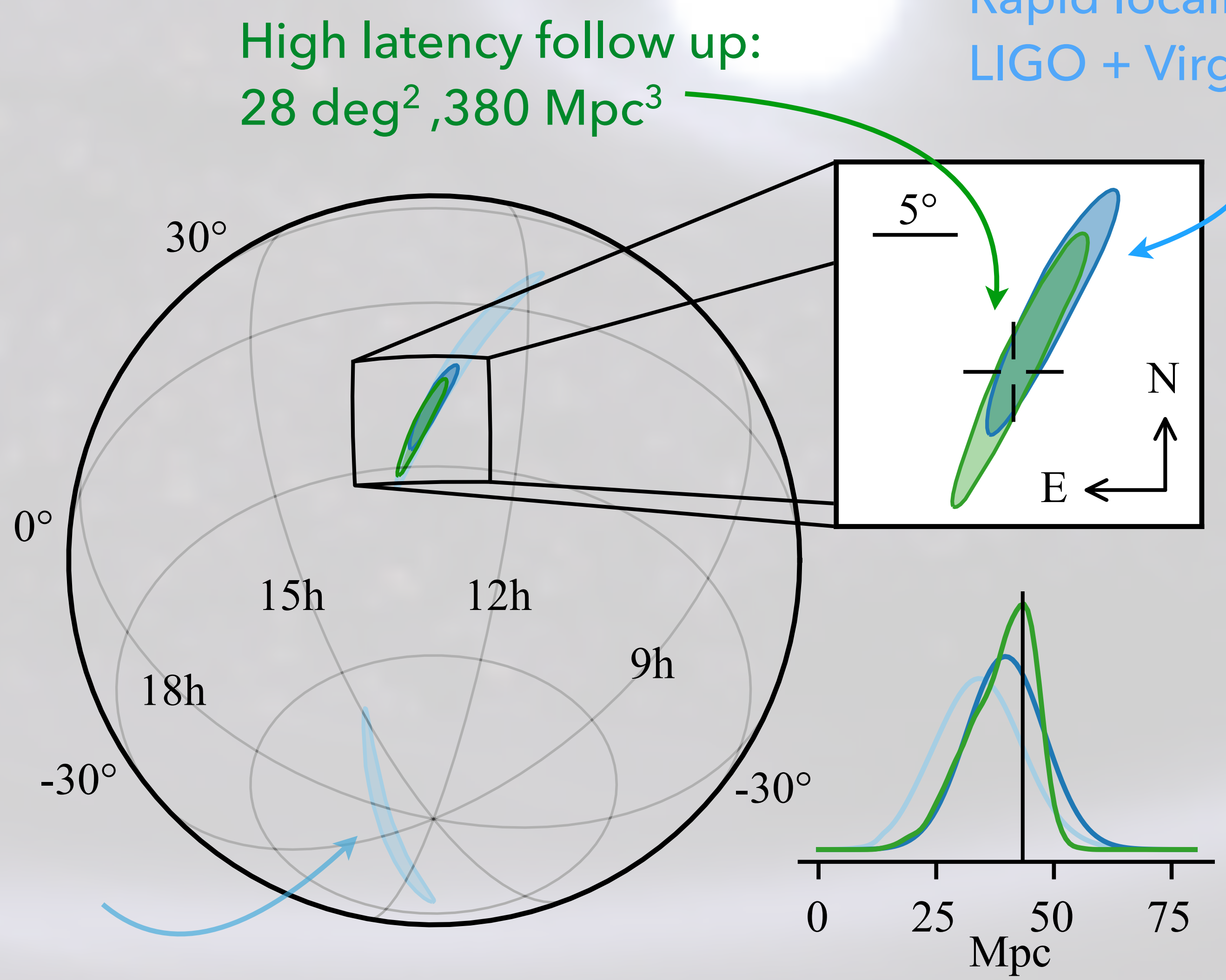
- On **August 17, 2017** at 12:41:04 UTC the signal from a ***binary neutron star*** was detected by Advanced LIGO & Virgo



GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral
PRL., 119, 161101 (2017)

GW170817: A binary neutron star inspiral

- Network SNR: 32.4 - loudest signal seen by Advanced LIGO & Virgo
- Duration of signal ~100s making it the longest signal to date
- False alarm rate in 5.9 days of data is < than 1 per 8 x 10^4 years - highly significant event!



best localised GW

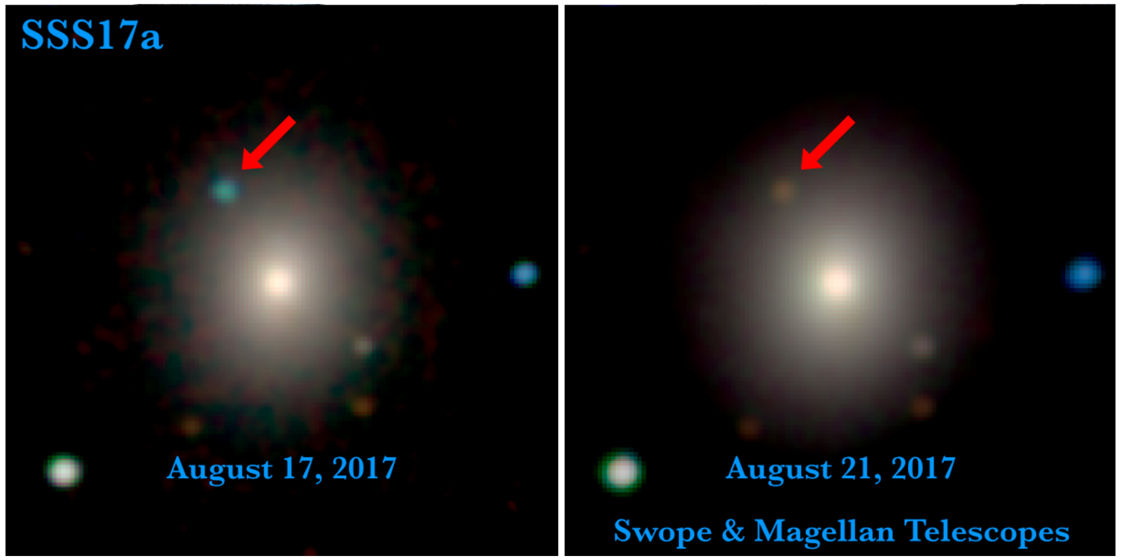
Rapid localisation with LIGO: 190 deg²

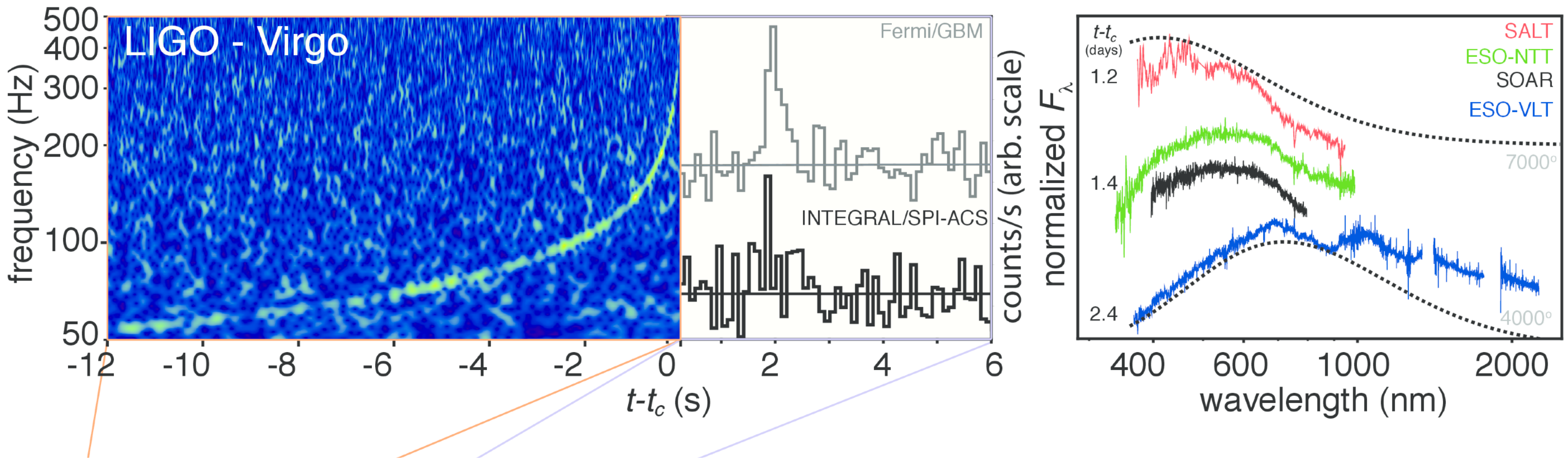
Luminosity distance: ~40Mpc
closest GW

LVC, PRL 119 161101 (2017)

GW170817: A new era is born

- Fermi detects sGRB 1.7s after the GW
- GCN alert sent ~27 minutes after GW detection
- First observation of optical counterpart ~11h later by the Swope telecope
- Localised to NGC 4993





- Rapid fading of blue component
- Redward evolution for ~10 days
- No UHE gamma-rays or neutrinos
- No initial X-ray and radio emission

First GW + EM observation!!

Astrophys. J. 848 (2017) L12

- Chirp mass:

$$\mathcal{M}_c = 1.186^{+0.001}_{-0.001}$$

- Constraints on component masses :

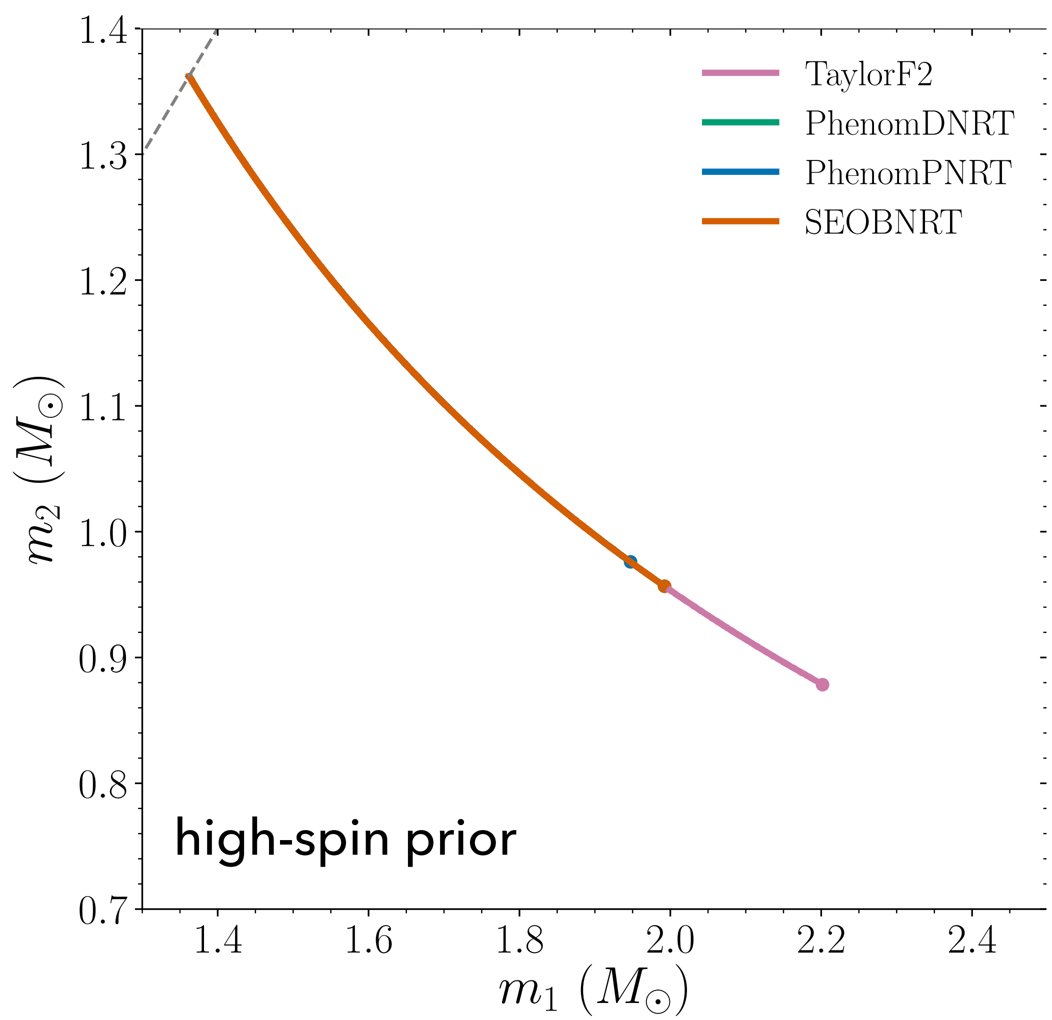
$$1.00M_{\odot} \leq m_i \leq 1.89M_{\odot}$$

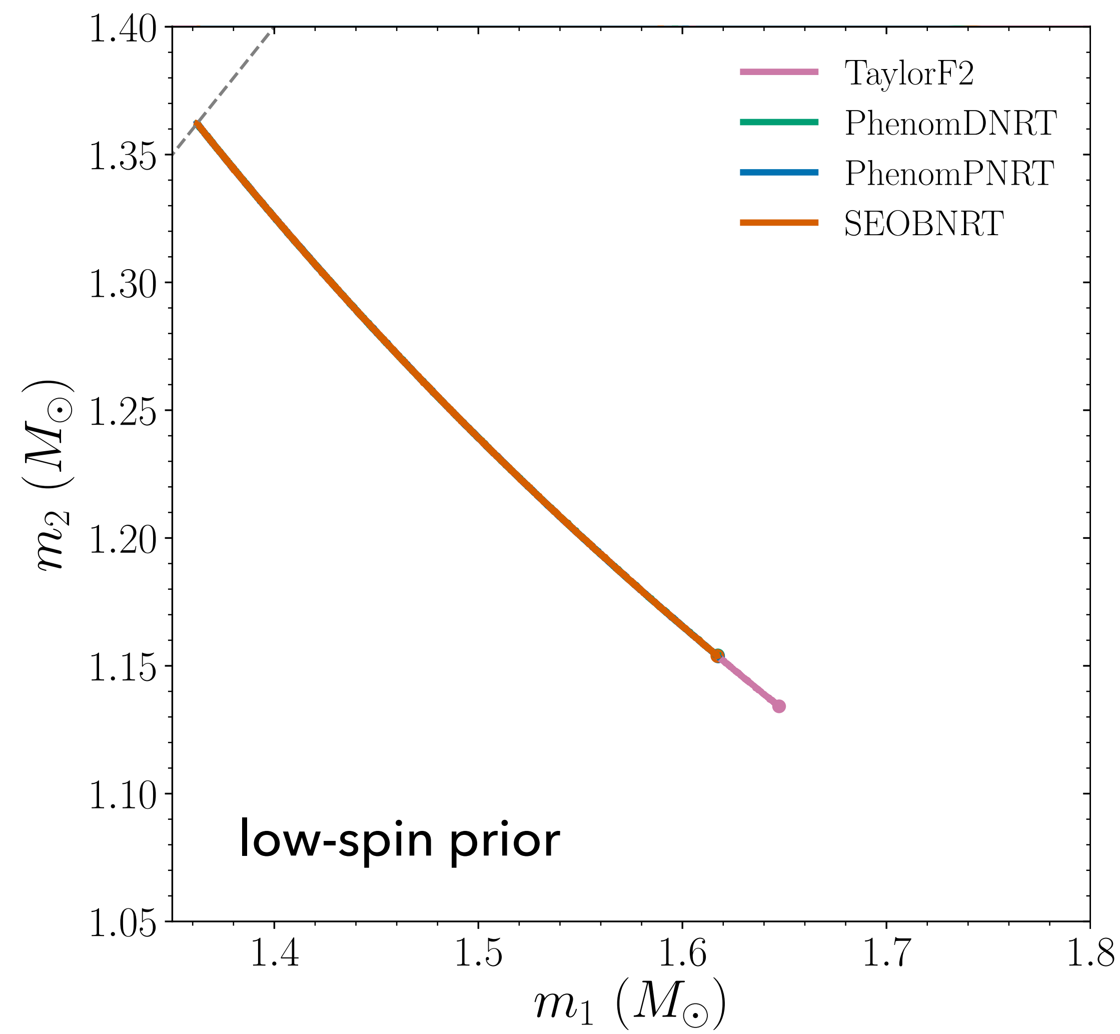
- The total mass

$$2.72M_{\odot} \leq M \leq 2.99M_{\odot}$$

- Inclination angle: face-off

$$119^{\circ} \leq \theta_{\rm JN} \leq 173^{\circ}$$



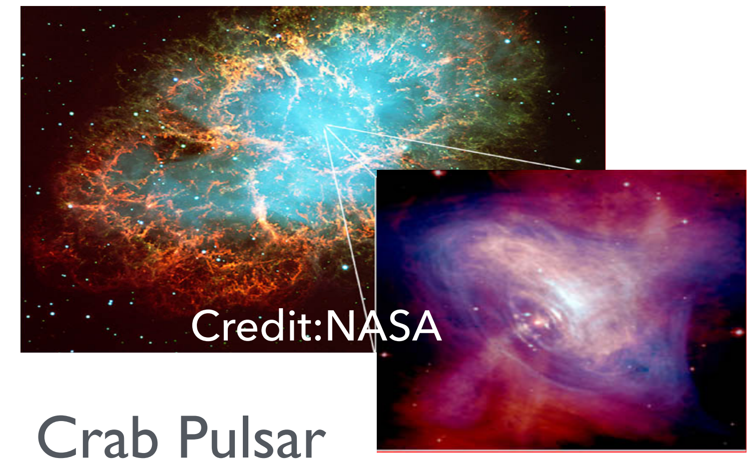


LVC, arXiv:1805.11579

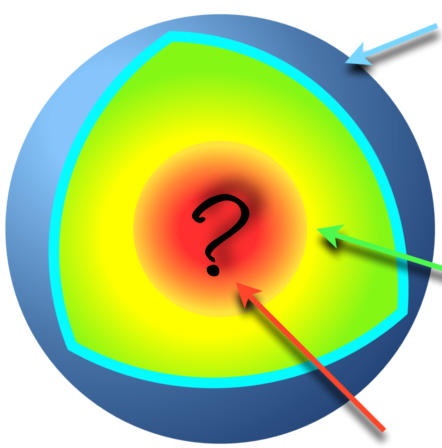
GW170817: Probing matter at its extreme

- Neutron stars: densest objects in the universe
- O(1000s) observed to date

debris from a supernova explosion in 1054



Crab Pulsar



crust ~ *km*

neutron rich ions,

free neutrons

outer core ~ *few km*

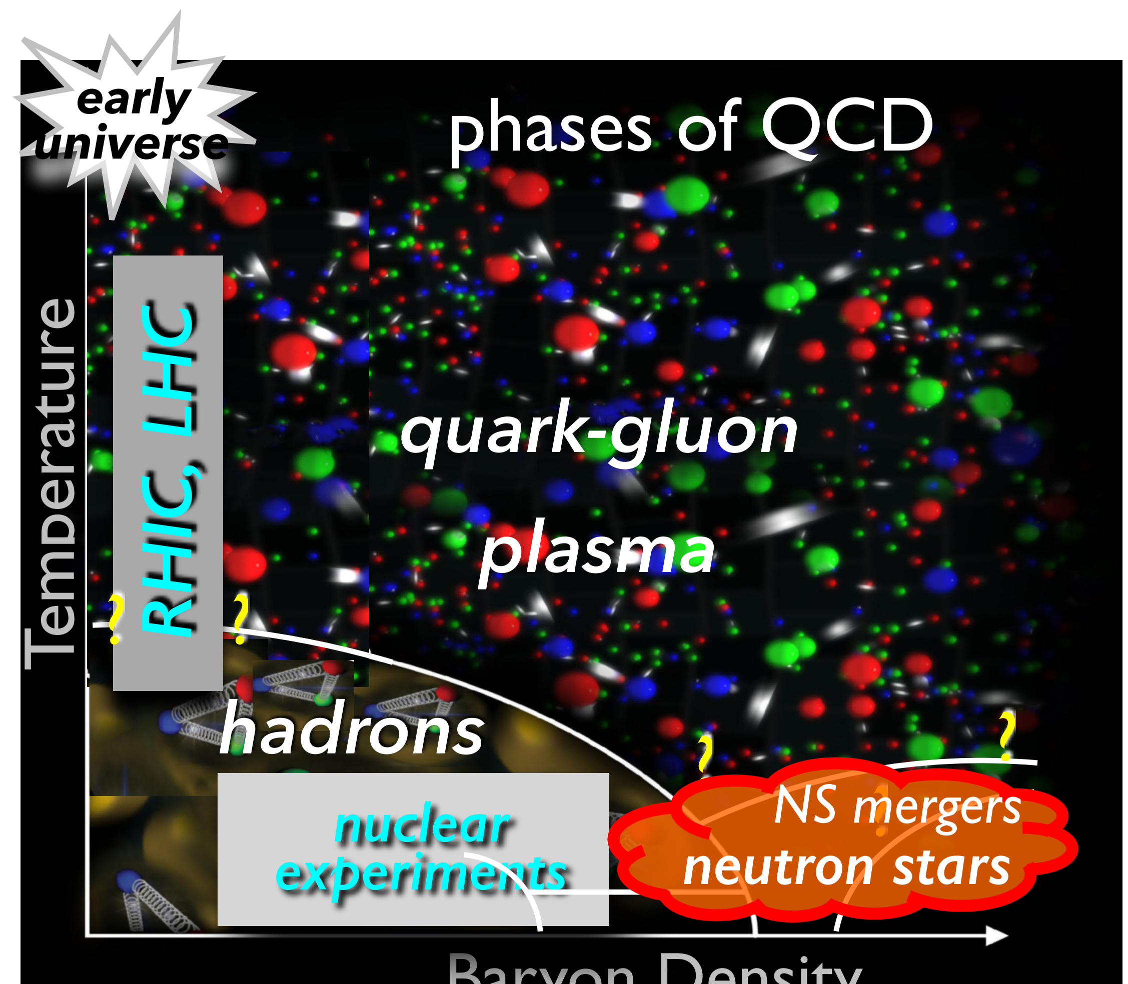
uniform liquid

deep core

~2-10x nuclear density

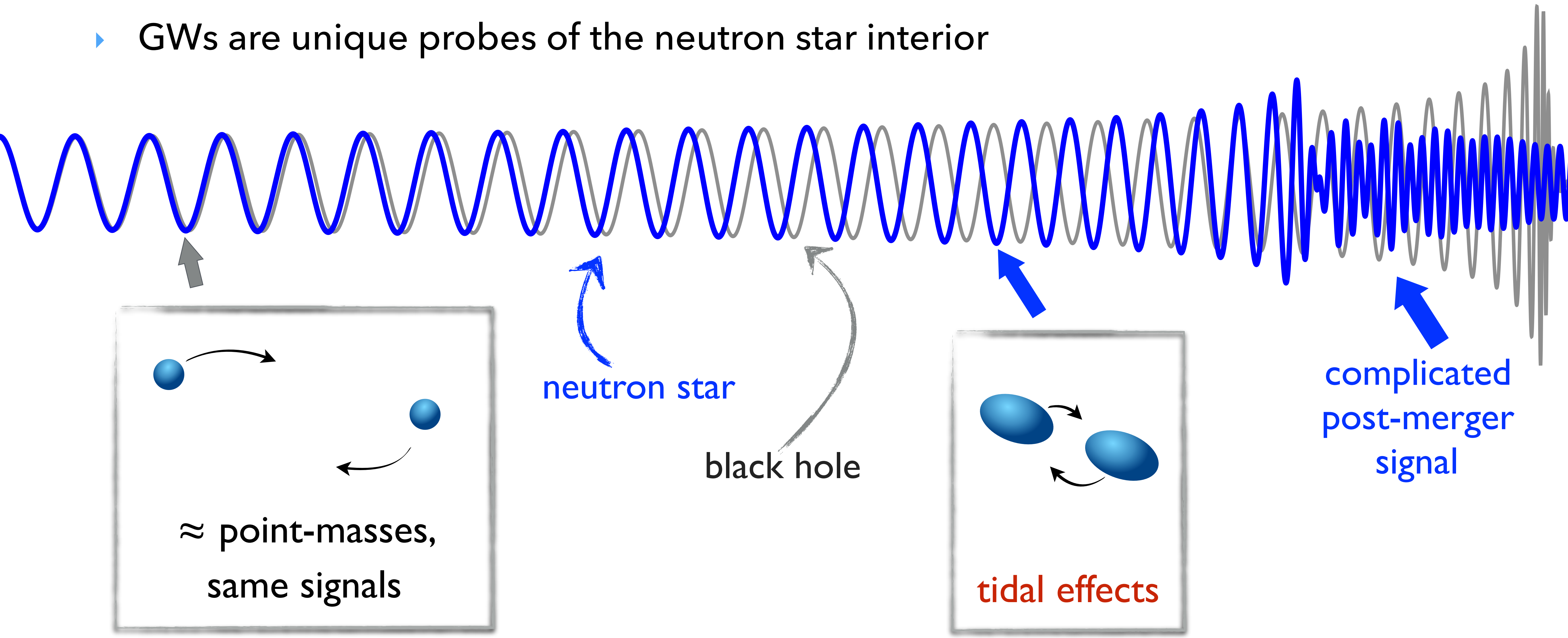
Exotic states of matter?

What is the nature of matter under such extreme conditions?



Credit: F. Linde

- GWs are unique probes of the neutron star interior



Some energy used to deform the NS

Moving tidal bulges produce GWs

$$\dot{E}_{\rm GW} \sim \left[\frac{d^3}{dt^3}\left(Q_{\rm orbit} + Q_{\rm NS}\right)\right]^2$$

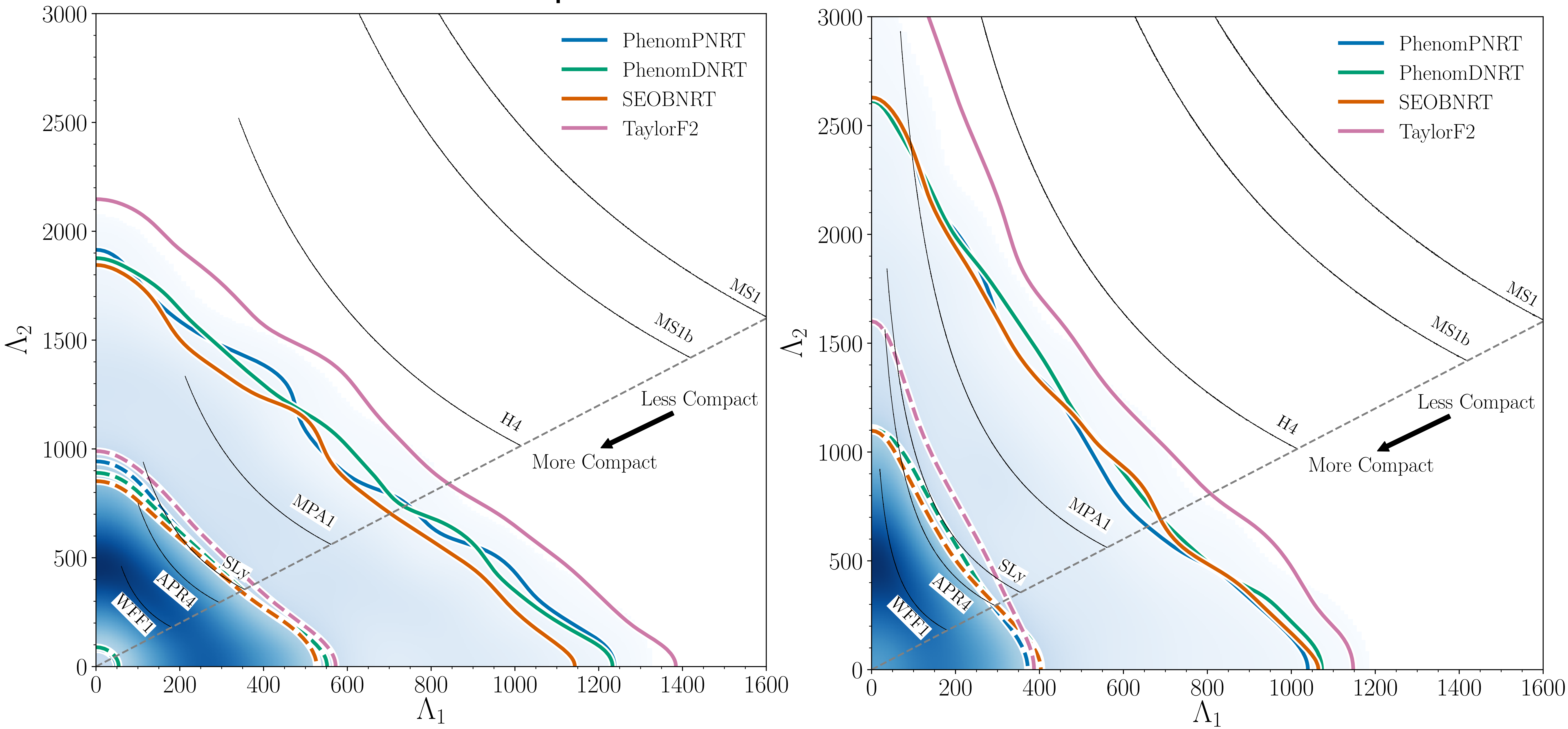
NR Data: T. Dietrich

GW170817: Tidal Measurements

- Leading GW phase determined by:

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

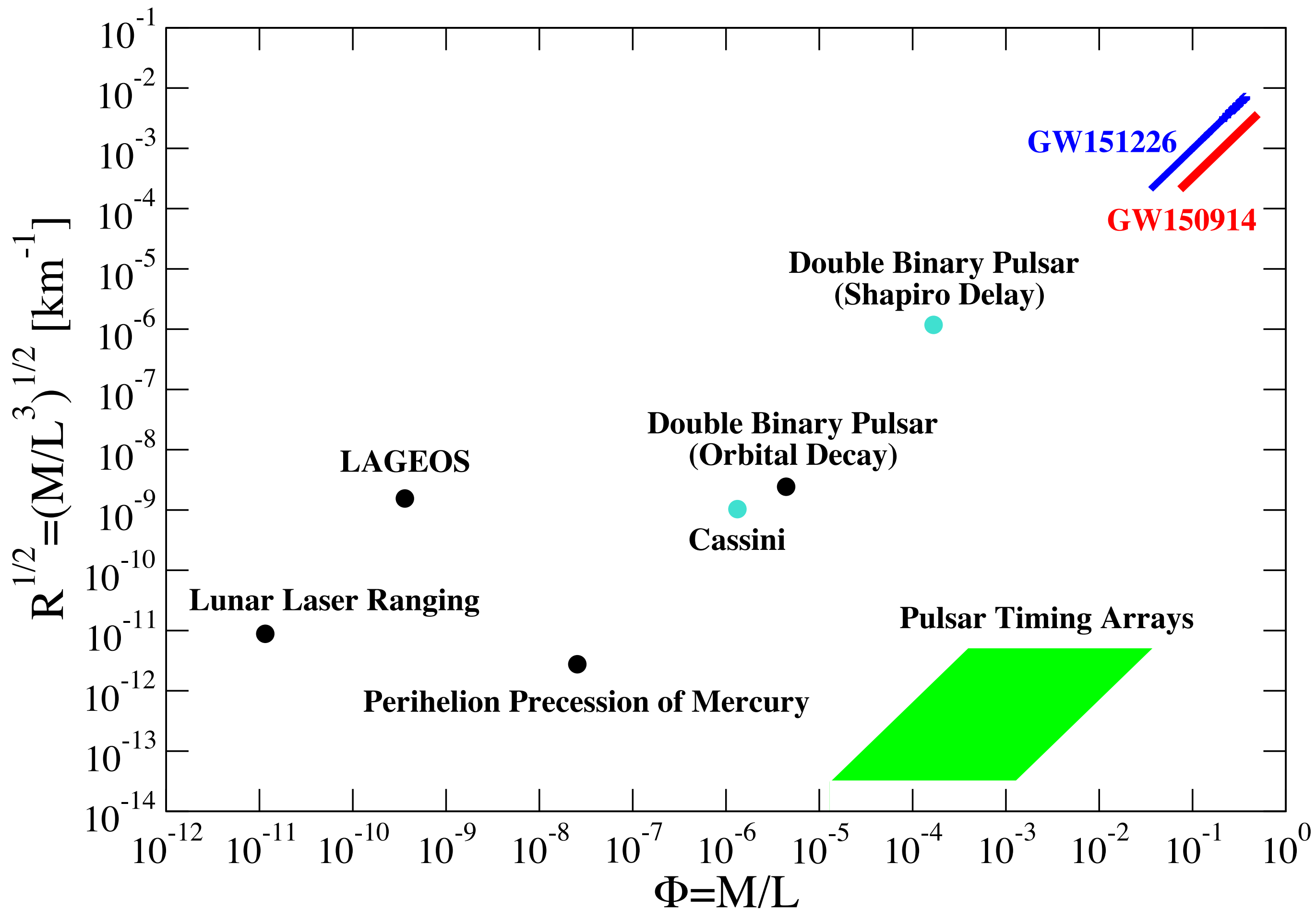
- Most consistent with compact stars: R < 14km



LVC, arXiv:1805.11579

- GWs are a unique probe of the strong-field regime of GR
- Alternative theories introduce extra fields, curvature terms, …
  - Modified dynamics
  - Modified propagation
  - Non-GR black holes
  - Horizon effects
  - …
- Can deviations from GR be observed with GW detections?
  - Very tight solar system constraints
- Almost no full solution to the two-body problem in modified theories of gravity known!

Yunes et al., PRD 2016



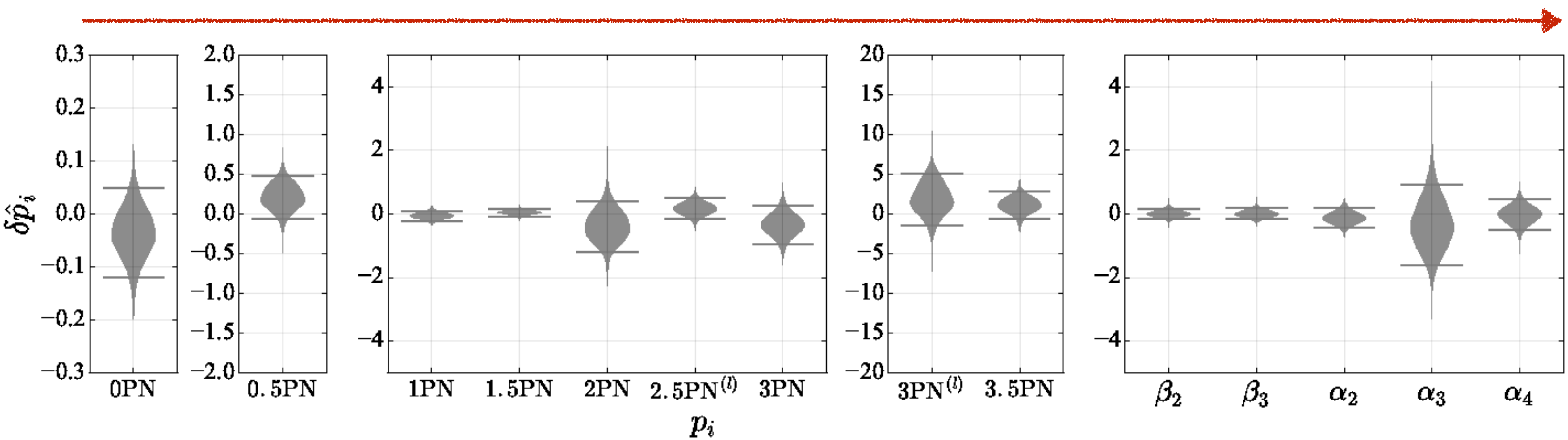
Parameterised Tests

- Perturbation of the GW phase around GR: $h(f) = A(f)e^{-i\phi(f)}$

$$\phi(f) = \phi_c + 2\pi f t_c + \phi_N (Mf)^{-5/3} + \phi_{0.5\mathrm{PN}}(Mf)^{-4/3} + \dots$$
$$+ \beta_2 \log(Mf) + \dots + \alpha_4 \tan^{-1}(aMf + b)$$

- Combined results (GW150914 , GW151226, GW170104) show consistency with General Relativity

low frequency high frequency



$$p_i \rightarrow p_i(1 + \delta\hat{p}_i)$$

LVC, Phys. Rev. Lett. 118, 221101, (2017): Supplementary Material

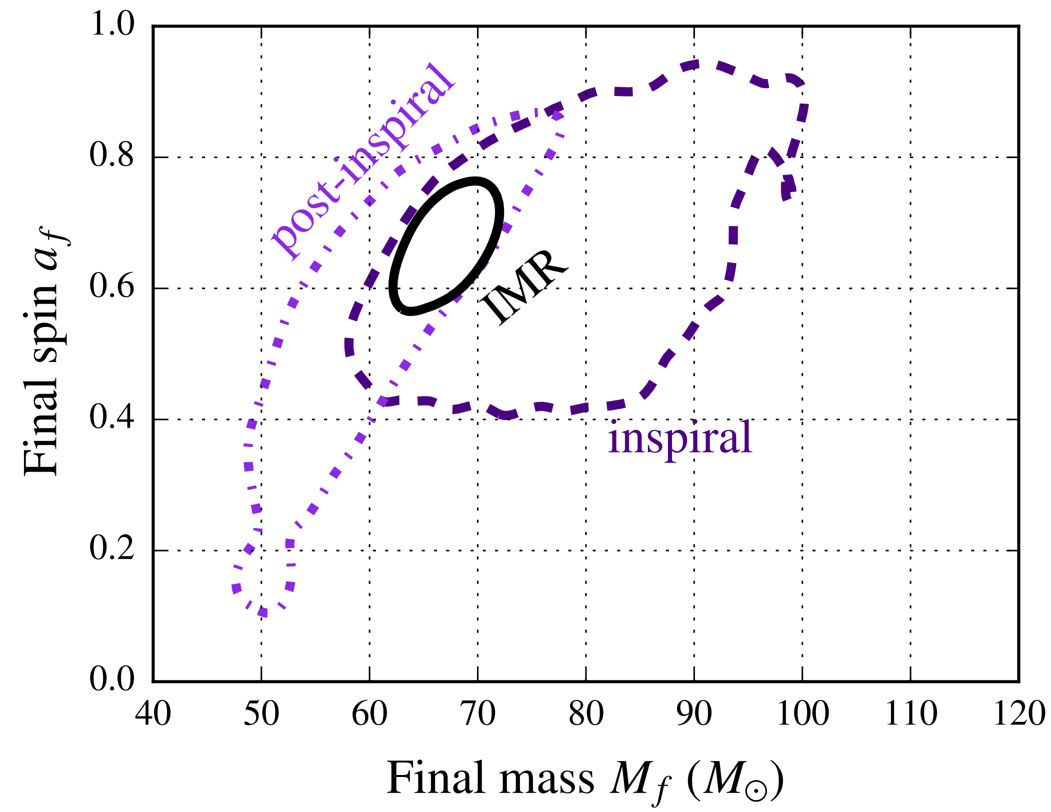
- Perturbed BHs in GR:

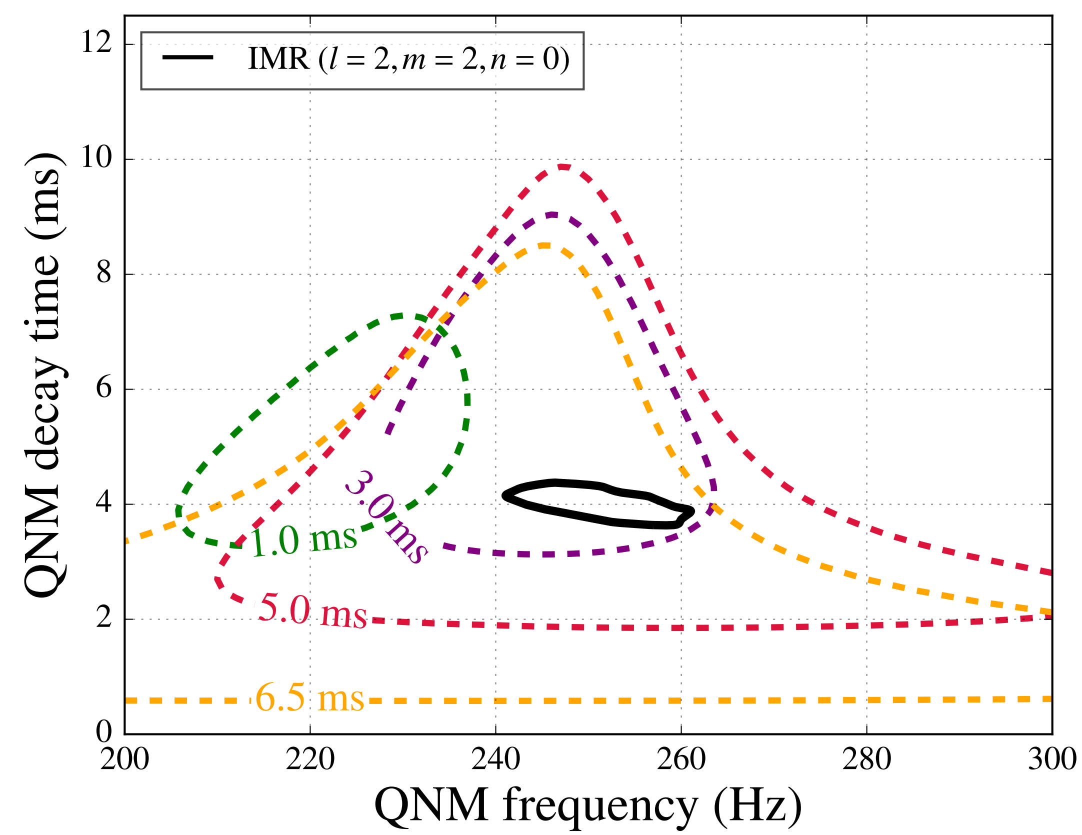
$$h^{\mathrm{RD}}(t) = \sum_{n,\ell,m} A_{n\ell m} e^{\frac{t-t_0}{\tau_{n\ell m}}} \cos(\omega_{n\ell m} + \varphi_{n\ell m})$$

- Inspiral-merger-ringdown (IMR) consistency test
  - Infer final mass and spin from inspiral and merger-ringdown separately
- Measure decay time and QNM frequency using damped sinusoids

Everything is consistent with GR!

LVC, PRL 116 (2016)

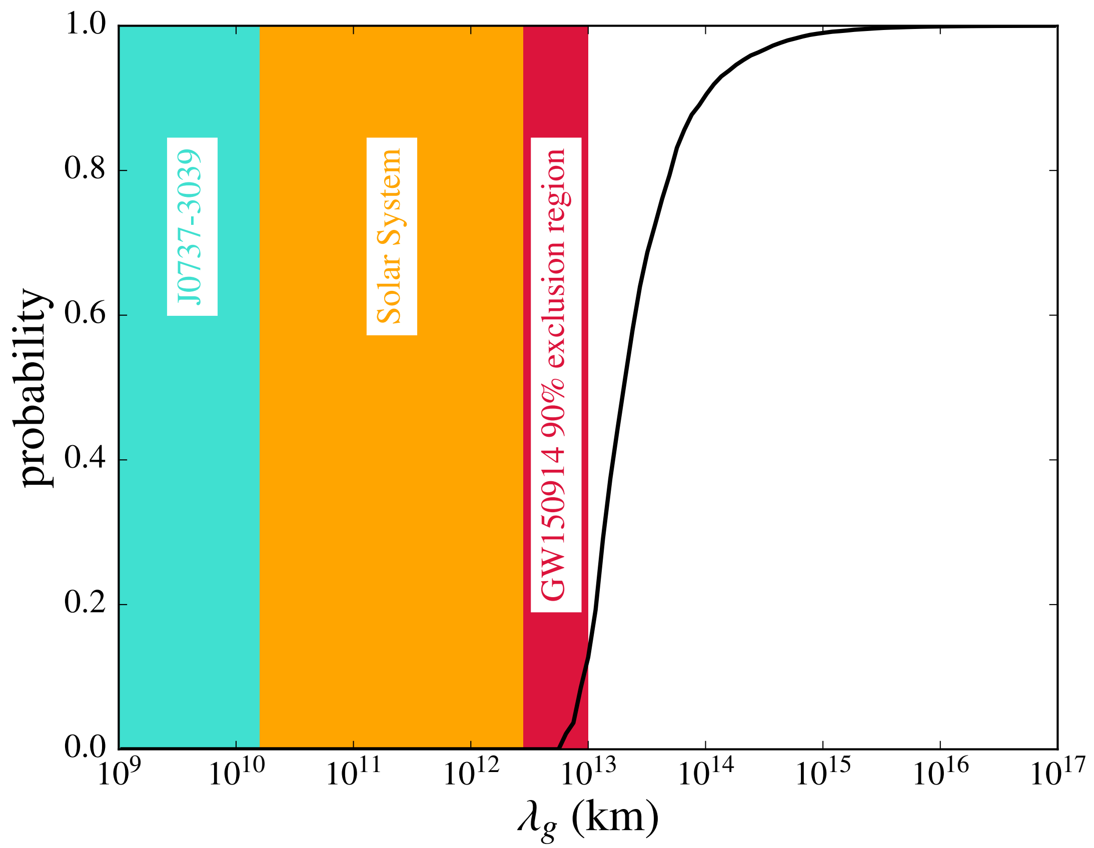




- Families of theories modify the propagation of GWs
- Phenomenological approach: modified dispersion relation $v_g \neq c$

- Massive gravity:

$$E^2 = p^2 v_g^2 + m_g^2 c^4$$



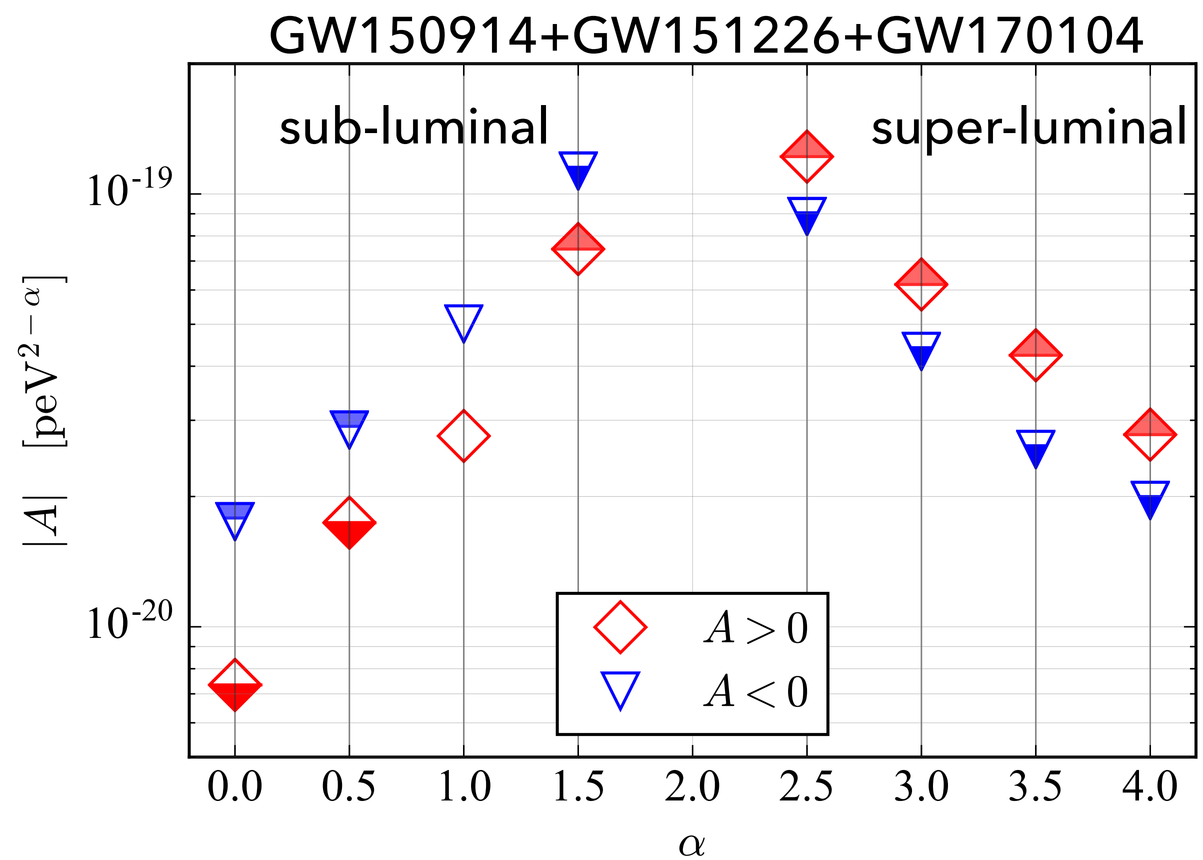
$$m_g \leq 1.2 \times 10^{-22} \mathrm{eV/c^2}$$

$$\lambda_g \geq 10^{13} \mathrm{km}$$

LVC, PRL 116 (2016)

- Generalisation (Lorentz violations):

$$E^2 = p^2 c^2 + A p^\alpha c^\alpha$$



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

$$\alpha = 0, A > 0$$

LVC, PRL 118 (2017) Supplement

Additional Polarisation States

- Generic metric theories of gravity predict 6 polarisation states
- GW detectors respond differently to different polarisations

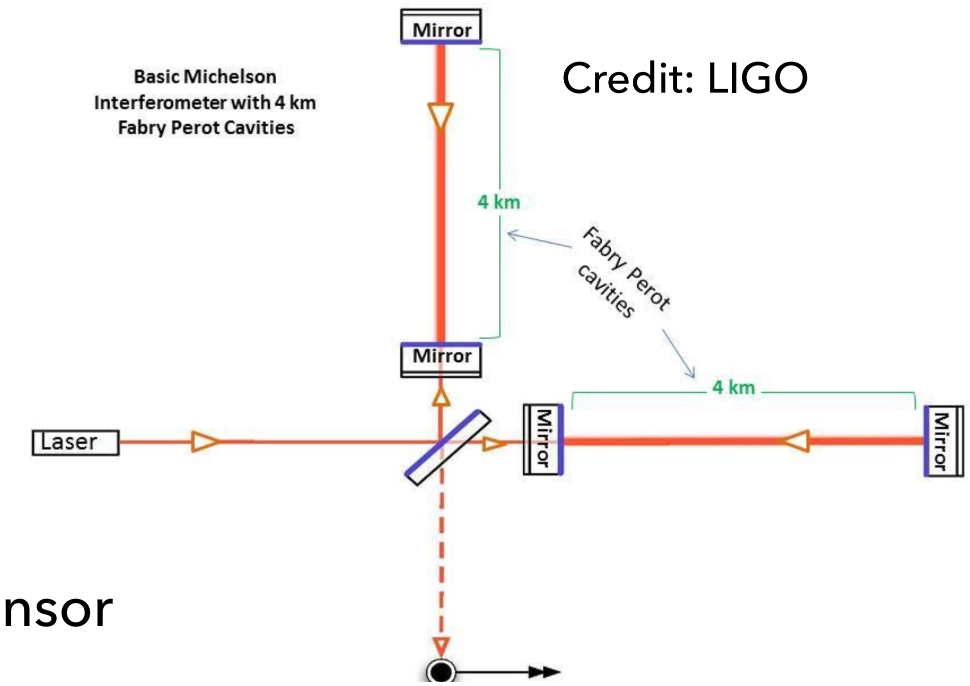
$$h_I(t, \vec{x}_I) = h_A(t, \vec{x}_I) D_I^{ab} e_{ab}^A$$

observed strain — amplitude — detector tensor — polarisation tensor

detector tensor, polarisation tensor: depend on geometry (antenna pattern)

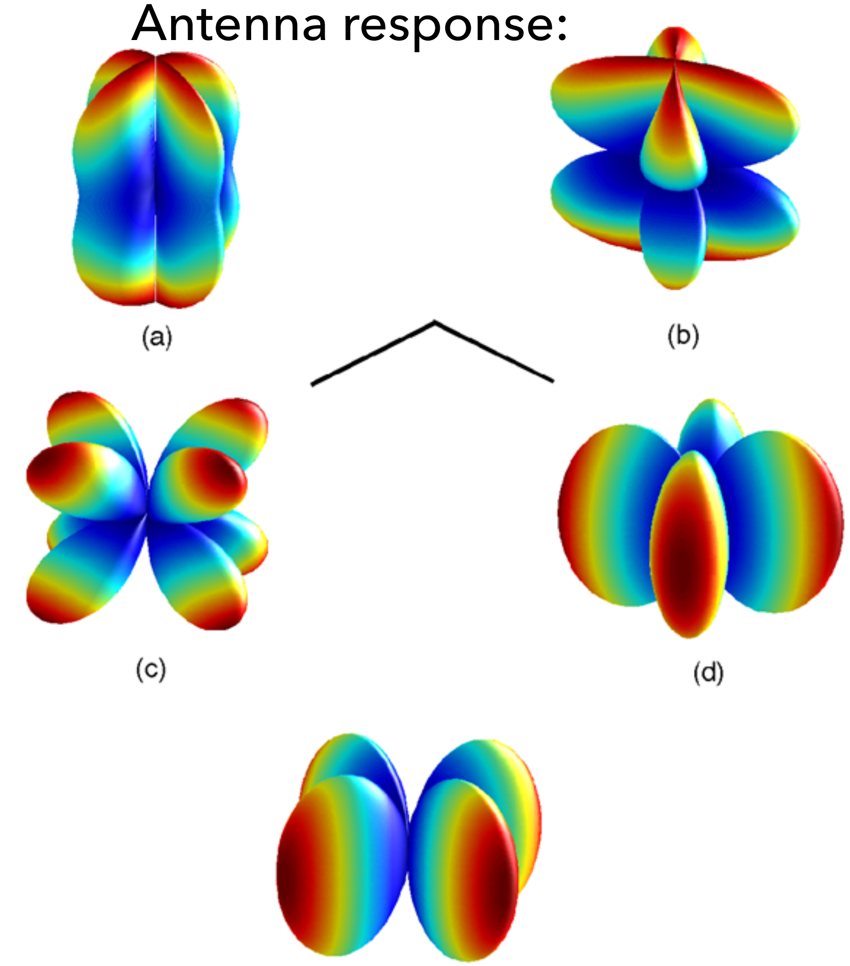
- Two (nearly) co-aligned detectors
  - approximately sensitive to the same linear combination of polarisations
- Observation of GW170814 in LIGO & Virgo
  - test pure scalar (vector) polarisations against tensor polarisations
  - Hypothesis test favours tensor over scalar (vector) polaristions

LVC, PRL 118 (2017)



Credit: LIGO

Antenna response:



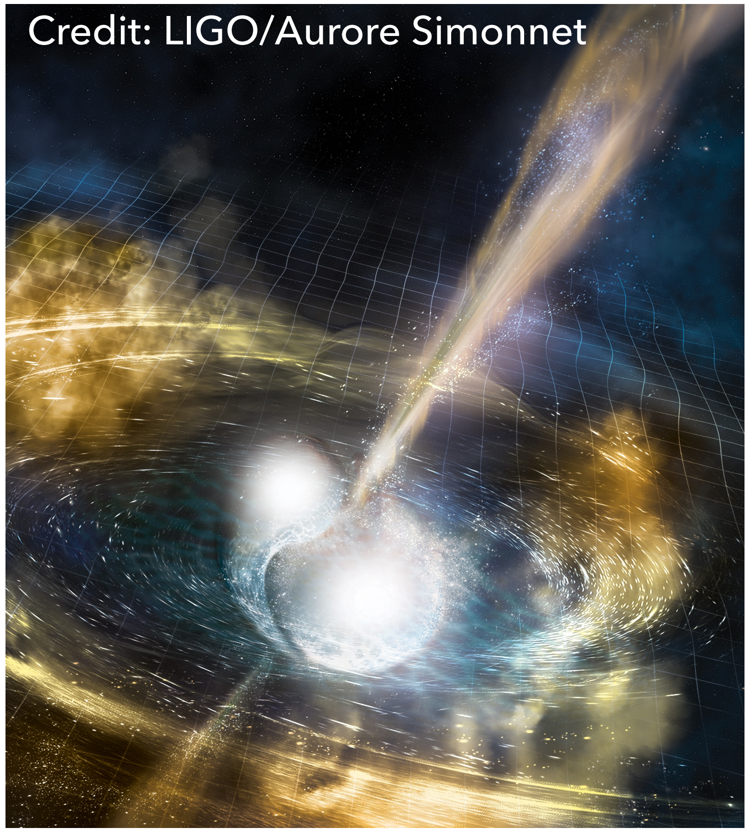
Yunes&Siemens, LRR

Tests with gravity & light

- Constraining the *speed of gravity*
  - GRB observed 1.7s after the GW signal
  - Little to no delay expected over cosmological distances

$$\Delta v / v_{\rm EM} \sim v_{\rm EM} \Delta t / D$$

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



- Test of the equivalence principle: *Shapiro delay*
  - GW and EM affected the same way by background potential
  - Both move along the same geodesic

parameterises deviations from Einstein-Maxwell

$$\delta t_S = \frac{1+\gamma}{c^3} \int_{r_c}^{r_0} U(r(l)) dl$$

$$-2.6 \times 10^{-7} \leq \gamma_{\rm GW} - \gamma_{\rm EM} \leq 1.2 \times 10^{-6}$$

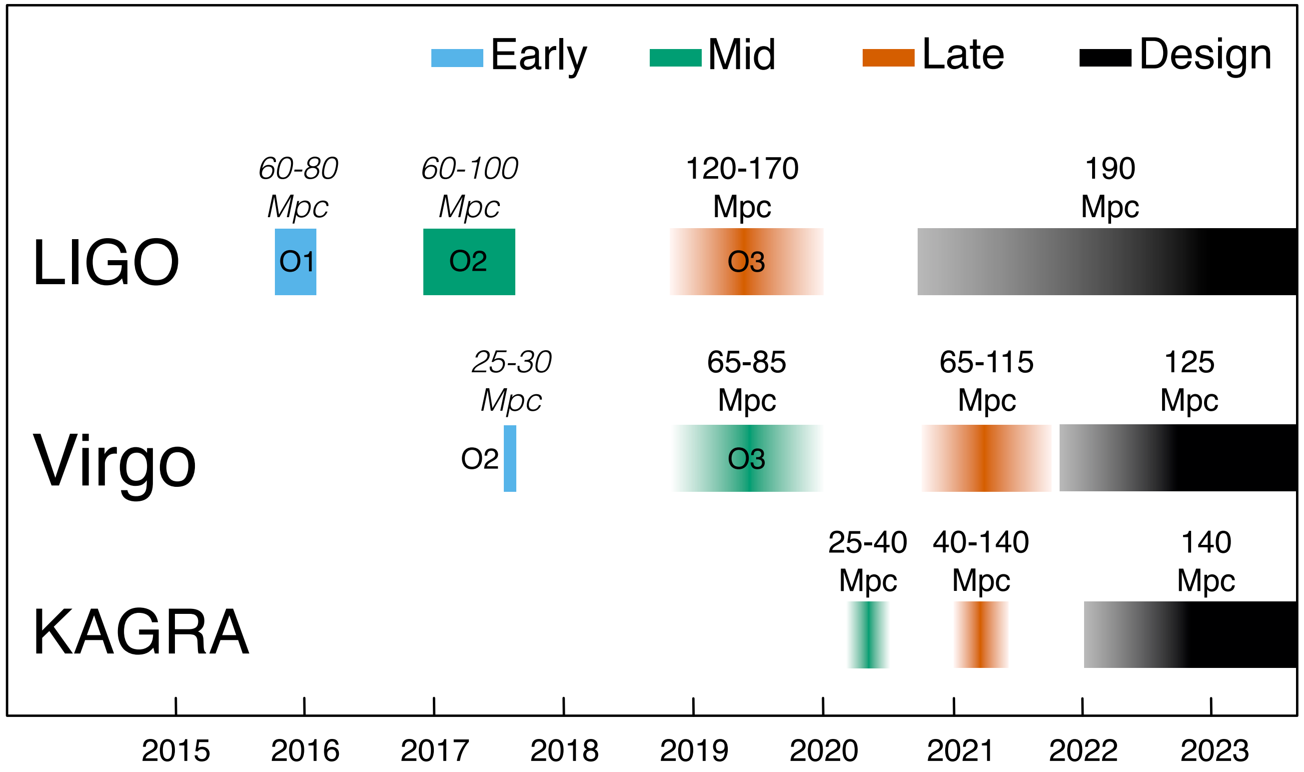
LVC, Fermi &Integral, ApJL (2017)

Outlook

- O2 has finished but data are still being analysed
- O3 is anticipated to start in early 2019
    - aLIGO BNS range: 120-170 Mpc
    - aVirgo BNS range: 65-85 Mpc
- KAGRA is projected to join the ground-based detector network in ~ 2020
- See public Observing Scenarios document for more details:

https://dcc.ligo.org/LIGO-P1200087/public

LVC, Living Rev. Relativity (2018) 21: 3



The future is loud & bright!