Tidal deformabilities and radii of neutron stars from gravitational-wave observations

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ECT* workshop

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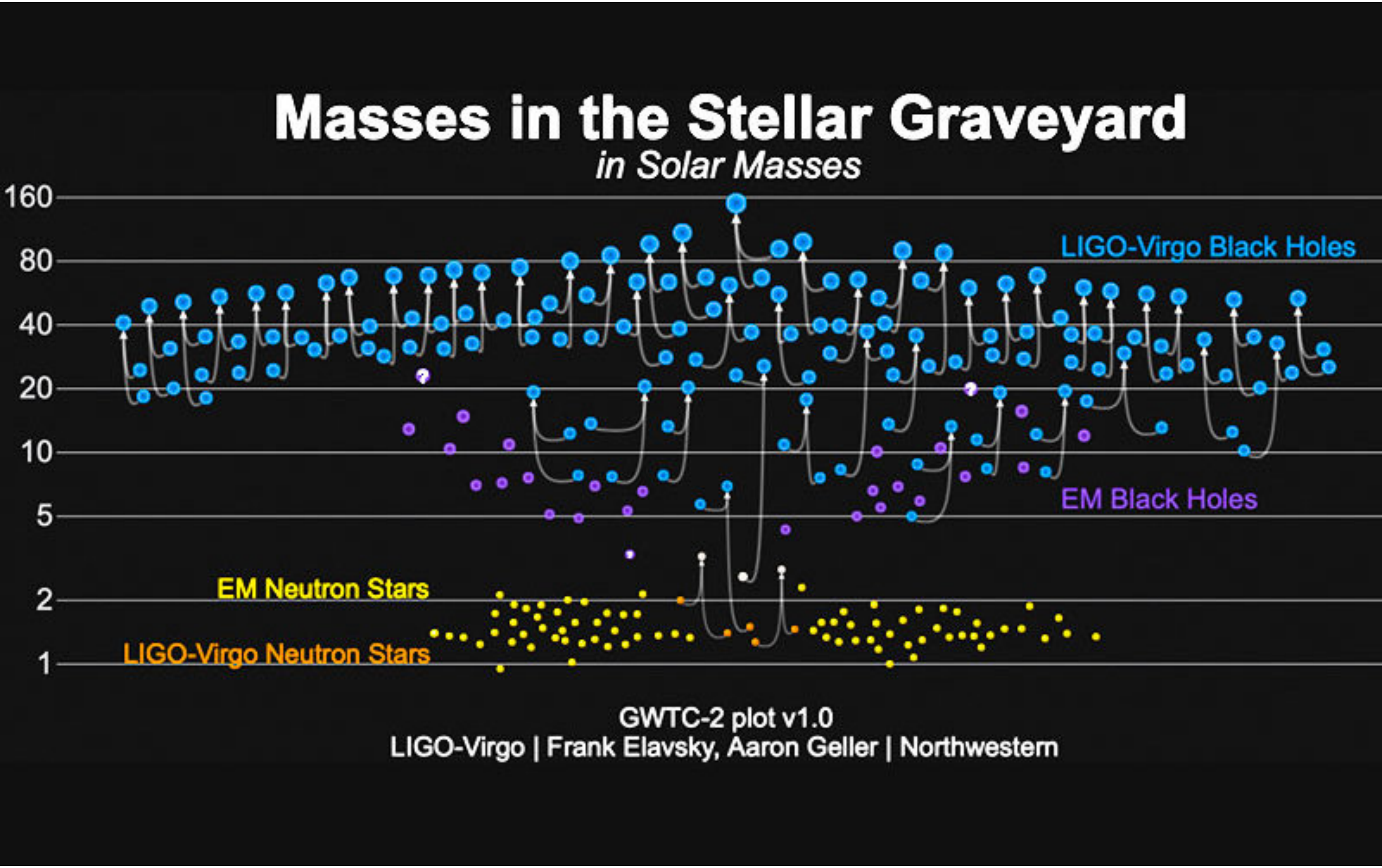

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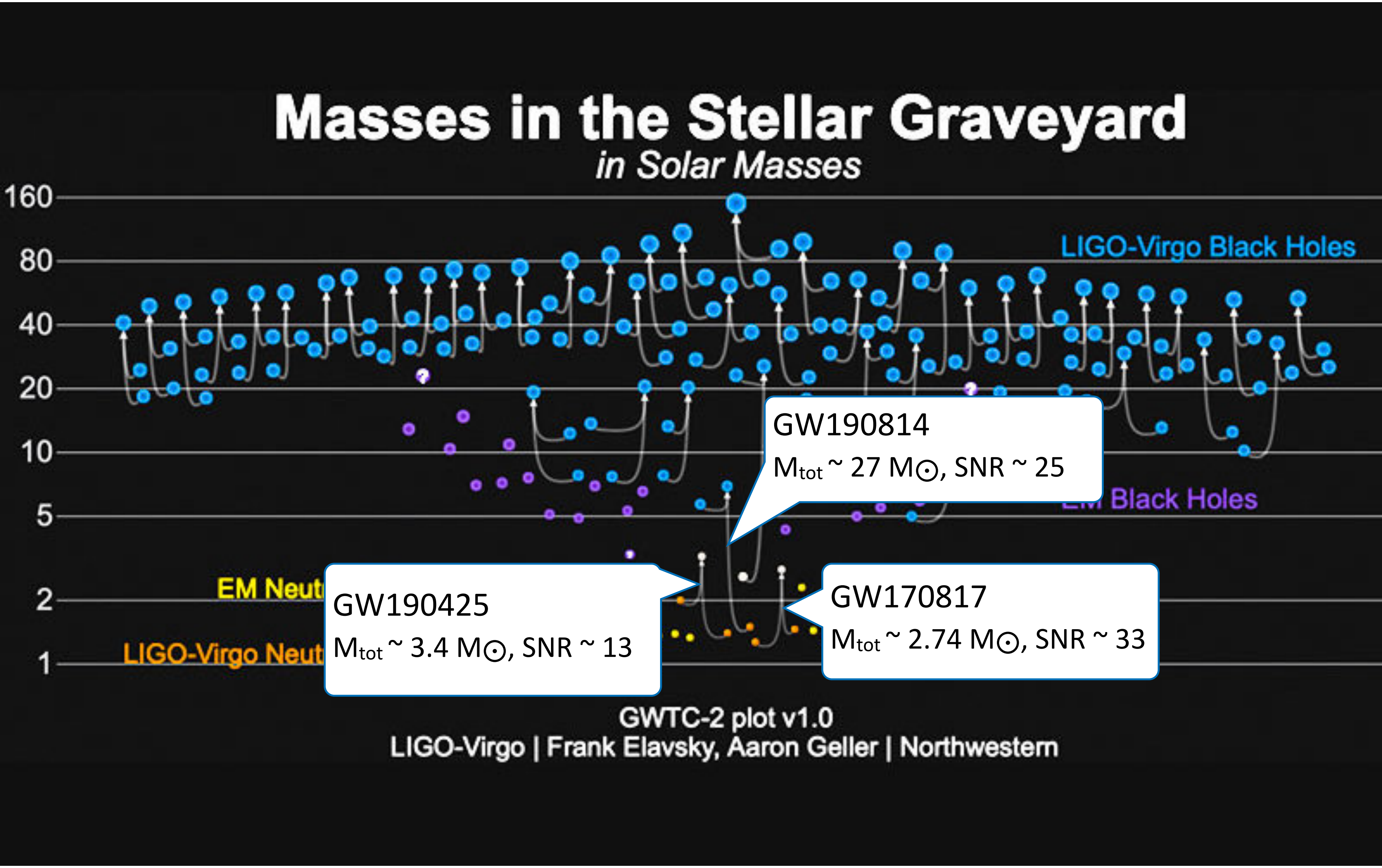
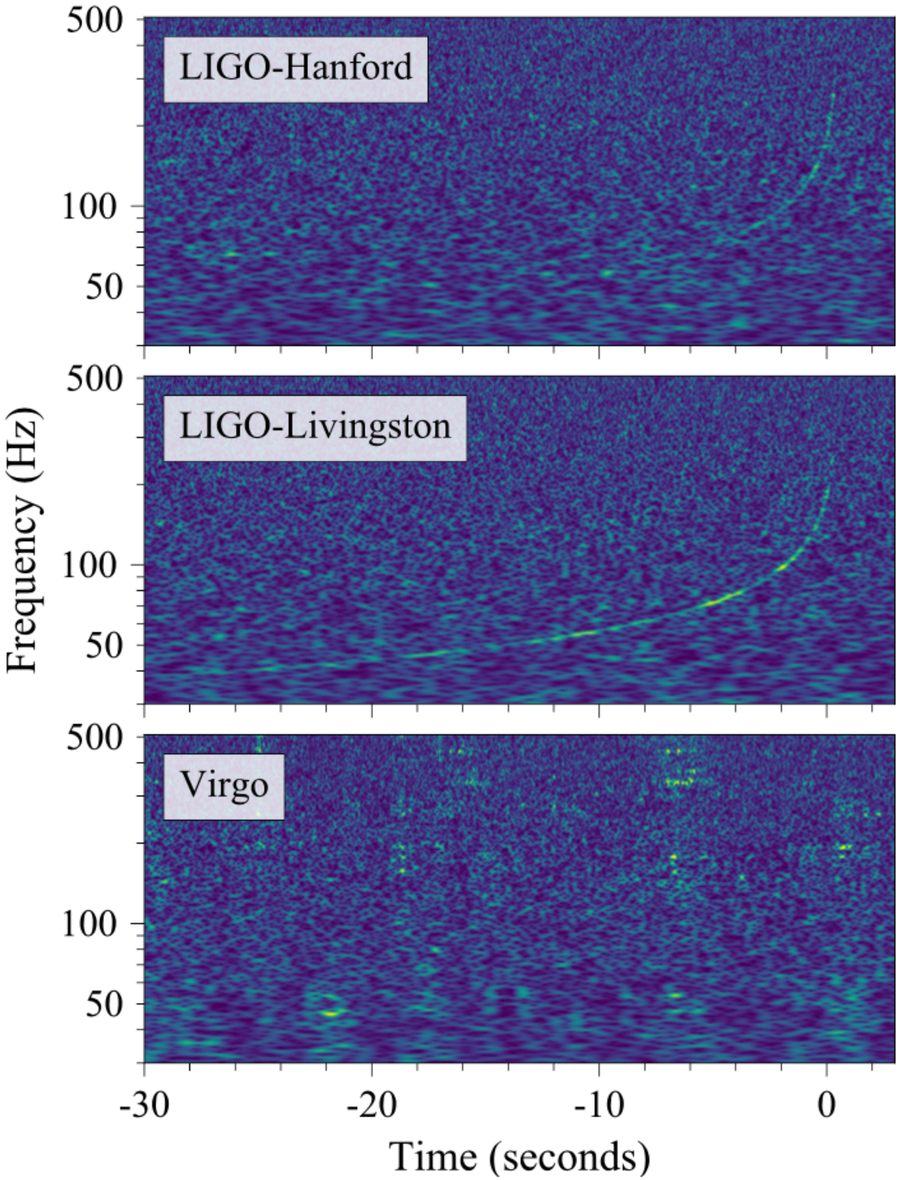

Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
Black Holes
GW190814
M_{tot} ~ 27 M⊙, SNR ~ 25
GW190425
M_{tot} ~ 3.4 M⊙, SNR ~ 13
GW170817
M_{tot} ~ 2.74 M⊙, SNR ~ 33
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

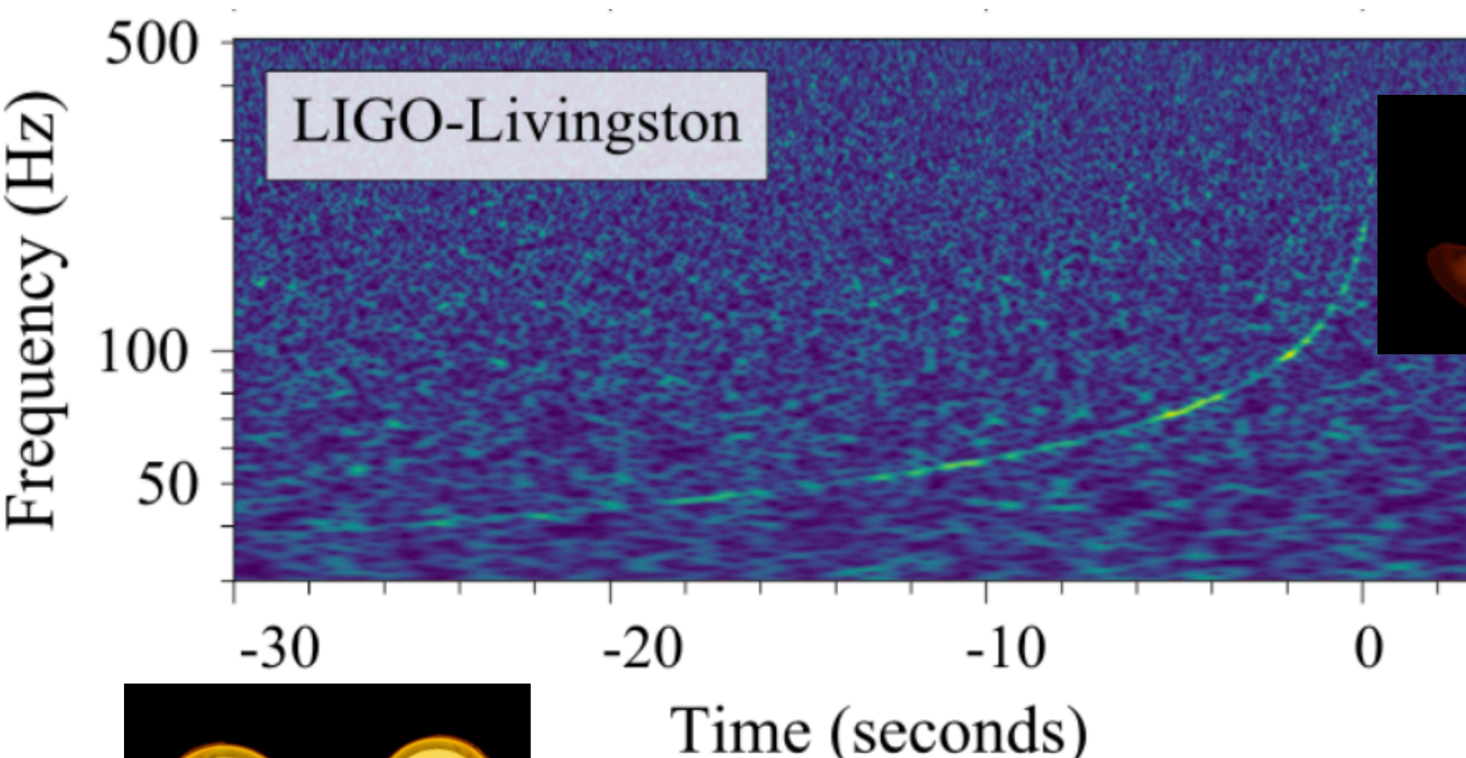
GW170817

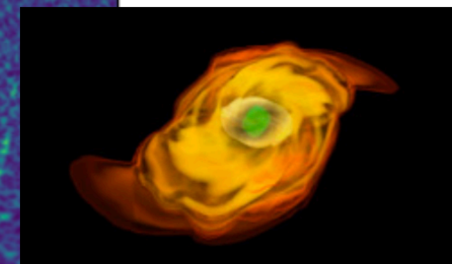


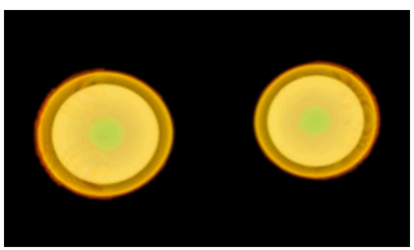
- Only one with electromagnetic counterpart observations
- Loudest gravitational-wave event with a neutron star component

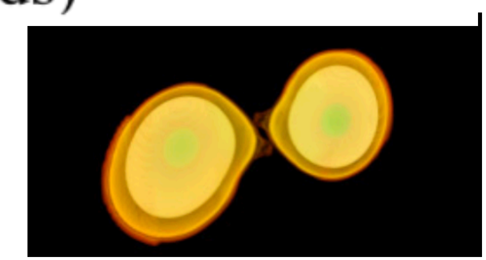
Abbott,…, **SD** et al. ApJL **848**, 2 (2017)

Tidal deformations in binary neutron star inspirals



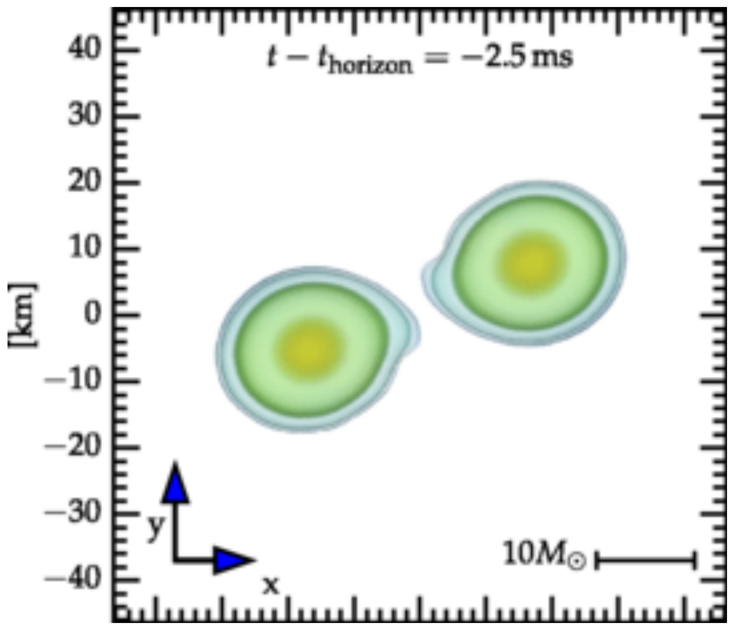






The tidal deformation of each star can be parameterized as $\Lambda = f(m, R, EOS)$

Tidal deformability

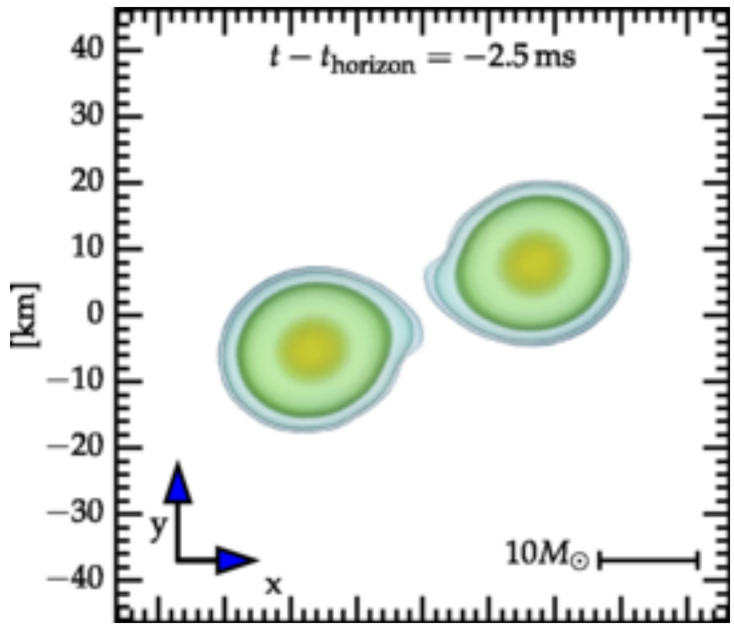


Haas et al (2016)

$\epsilon_{i,j}$

gravitational field of each component star

Tidal deformability



Haas et al (2016)

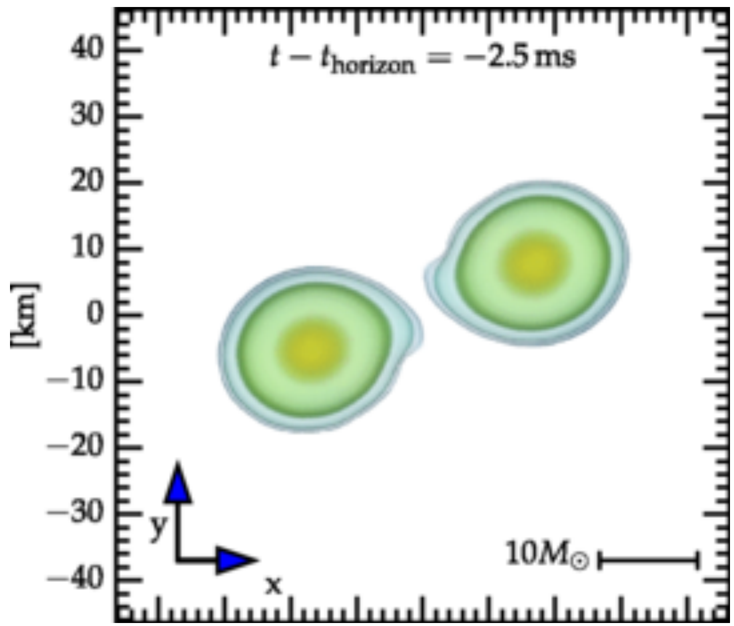
$Q_{i,j}$

$\epsilon_{i,j}$

gravitational field of each component star

induced quadrupole moment on companion

Tidal deformability



Haas et al (2016)

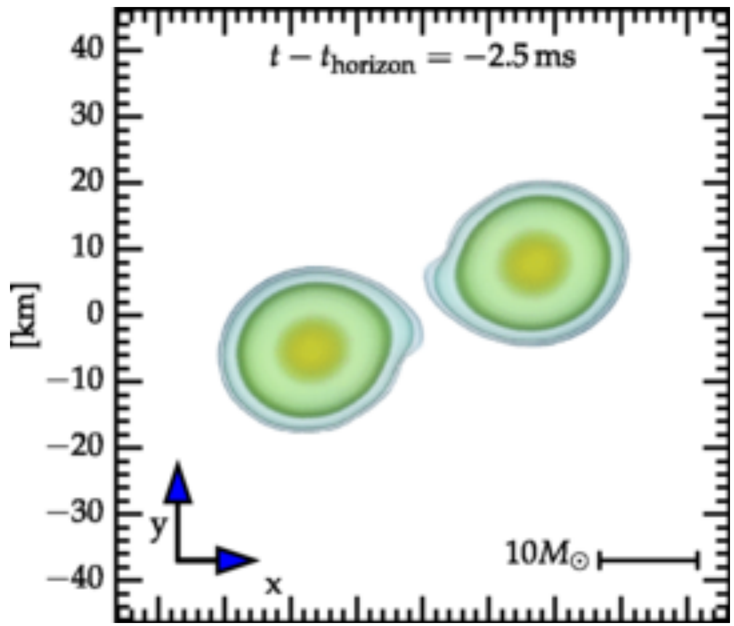
$$Q_{i,j} = -\lambda \epsilon_{i,j}$$

gravitational field of each component star

tidal deformability

induced quadrupole moment on companion

Tidal deformability



Haas et al (2016)

$$Q_{i,j} = -\lambda \epsilon_{i,j}$$

gravitational field of each component star

tidal deformability

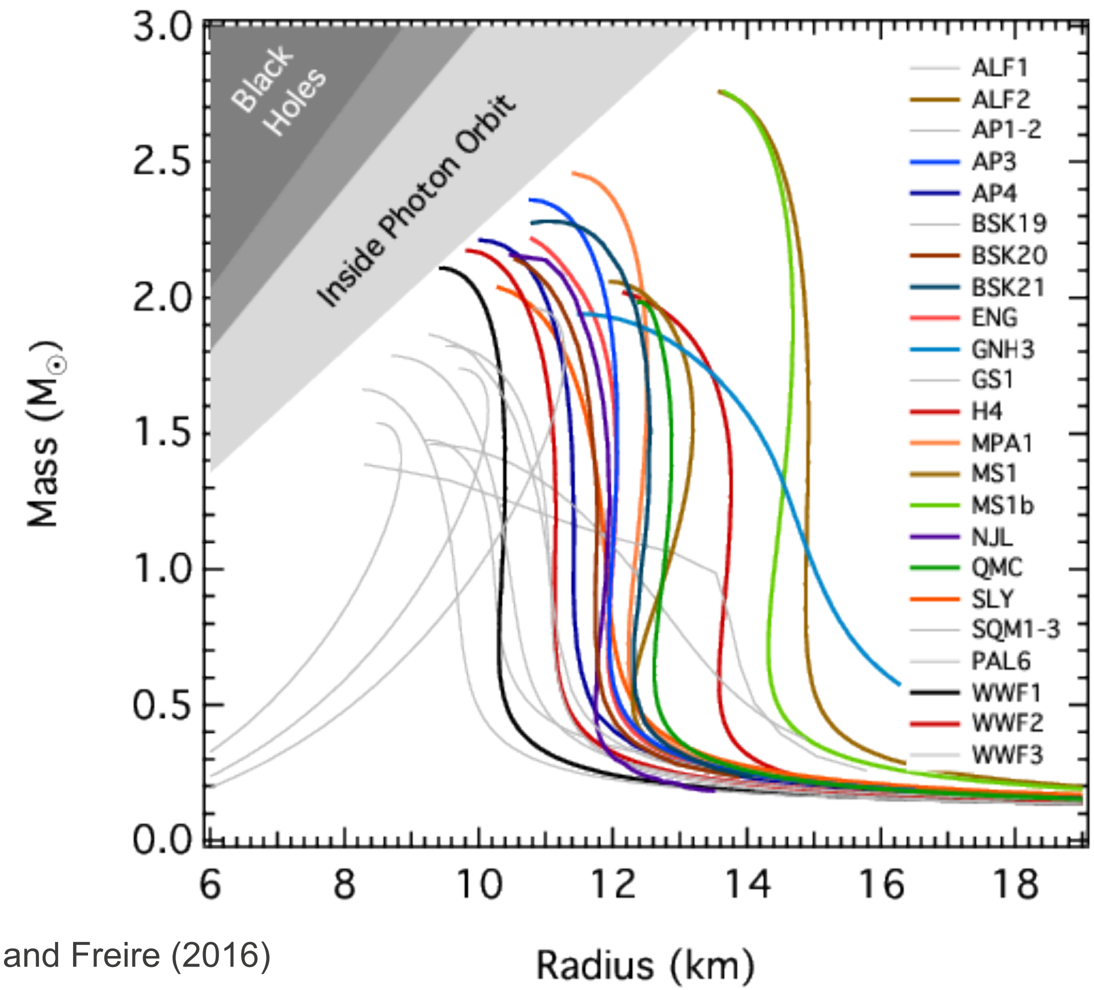
induced quadrupole moment on companion

dimensionless tidal deformability:

$$\Lambda = \lambda / m^5 \qquad \Lambda_{1,2} = \frac{2}{3} k_2 \left(\frac{R_{1,2} c^2}{G m_{1,2}} \right)^5$$

Λ is a measurement of how deformable the neutron star is

How does the tidal deformation connect to the nuclear equation of state?



Ozel and Freire (2016)

$$\Lambda = f(m, R, EOS)$$

Each proposed equation of state generates a specific mass radius curve

We are trying to find what the nuclear equation of state is using GW170817

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Effect of tidal deformability on gravitational waves

Information about the tidal deformability is encoded in the phase of the gravitational-wave signal

$$\Phi(t) \sim \phi_0(\mathcal{M};t)\Big[1 + \phi_1(\eta;t)\left(\frac{v}{c}\right)^2 + \quad ... + \phi_5(\tilde{\Lambda};t)\left(\frac{v}{c}\right)^{10}\Big]$$

chirp mass

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

symmetric mass ratio

$$\eta = \frac{(m_1 m_2)}{(m_1 + m_2)^2}$$

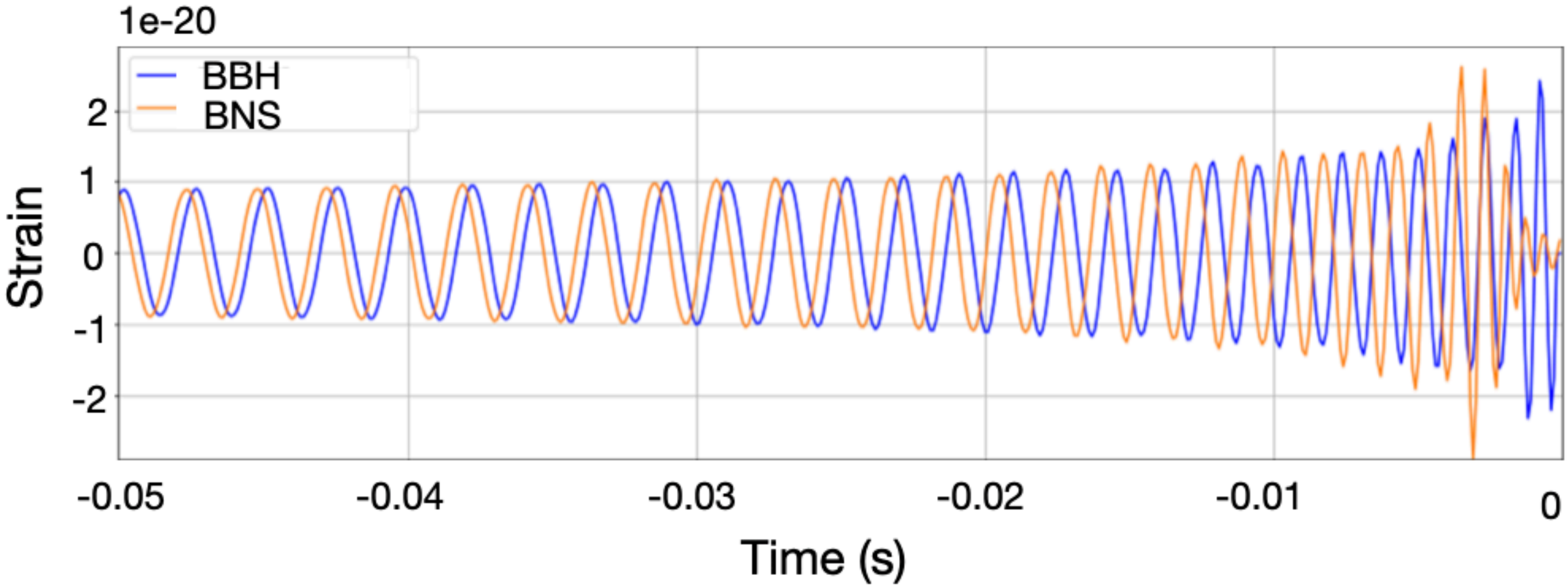
binary deformability

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

Effect of tidal deformability on gravitational waves

Information about the tidal deformability is encoded in the phase of the gravitational-wave signal

$$\Phi(t) \sim \phi_0(\mathcal{M};t)\Big[1 + \phi_1(\eta;t)\Big(\frac{v}{c}\Big)^2 + \quad ... + \phi_5(\tilde{\Lambda};t)\Big(\frac{v}{c}\Big)^{10}\Big]$$



What else is encoded in the gravitational wave data

Parameter space $\vec{\theta}$

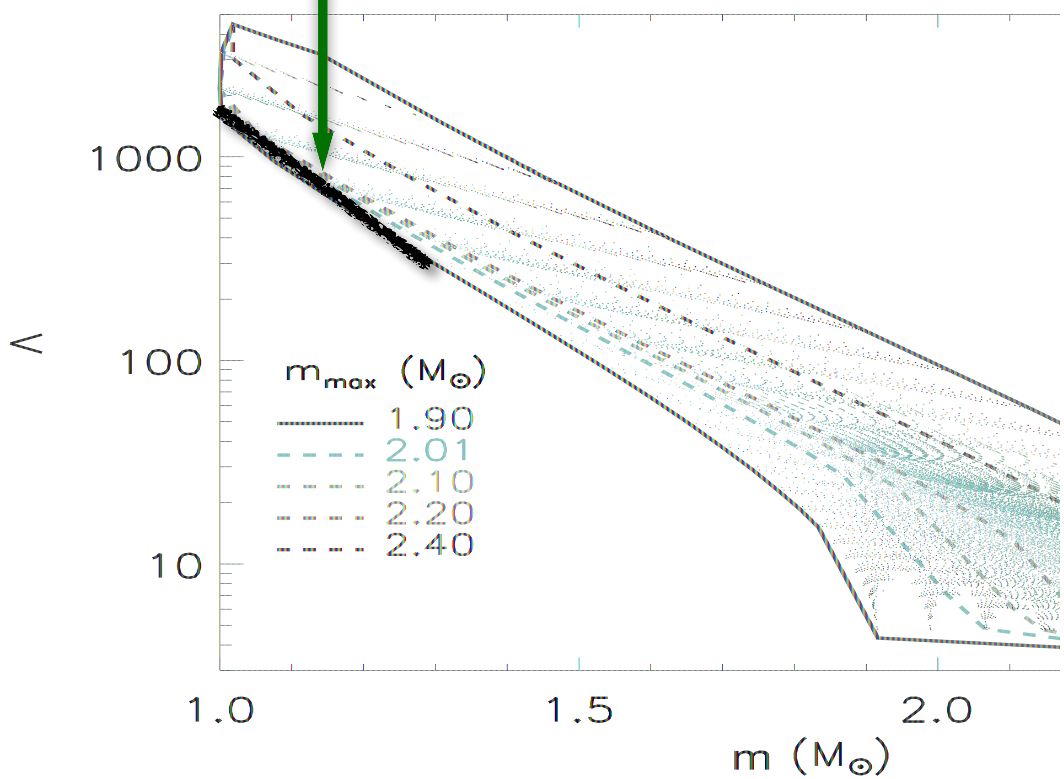
- Component masses : m_1, m_2
- Component spins : $\vec{s_1}, \vec{s_2}$
- Distance to the source : d_L
- Source location and orientation : $\alpha, \delta, \psi, \iota$
- Coalescence time and phase : t_c, ϕ_c
- Component tidal deformabilities : Λ_1, Λ_2

Bayesian inference analysis of GW data to extract these parameters

Common equation of state for GW170817

$\Lambda \propto m^{-6}$

TOV integrations for thousands of physically realistic EOSs



$$\Lambda = a \left(\frac{Gm}{Rc^2} \right)^{-6}$$

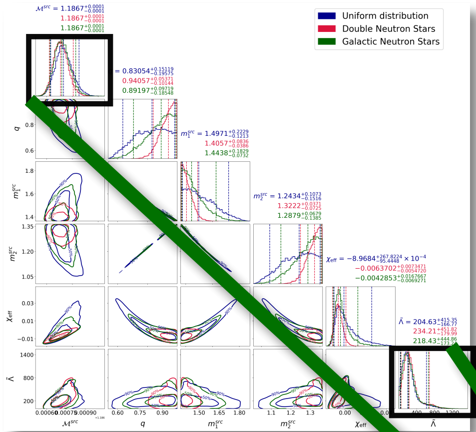
Every equation of state allows a very small variation of radius.

$R_1 \simeq R_2$ $\Lambda_1 \simeq q^6 \Lambda_2$

Common EOS constraint

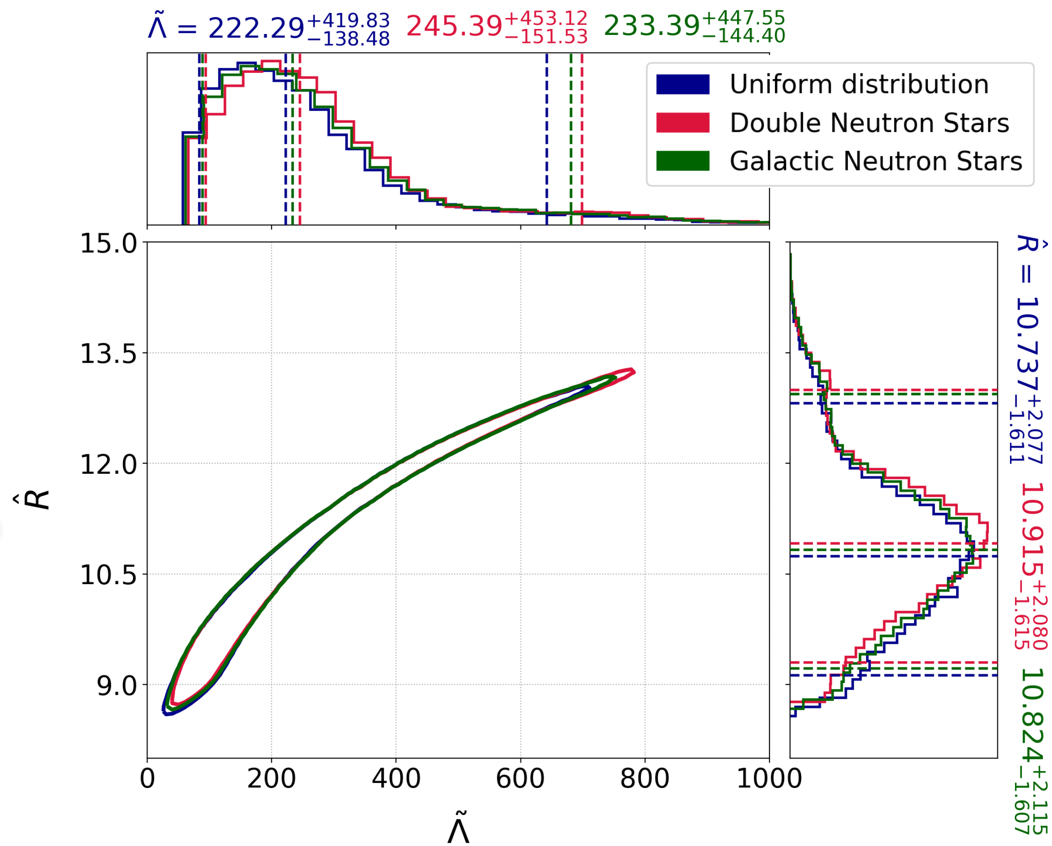
SD et al., Phys. Rev. Lett. 121, 091102 (2018)

Measurement of neutron star tidal deformabilities and radii from GW170817



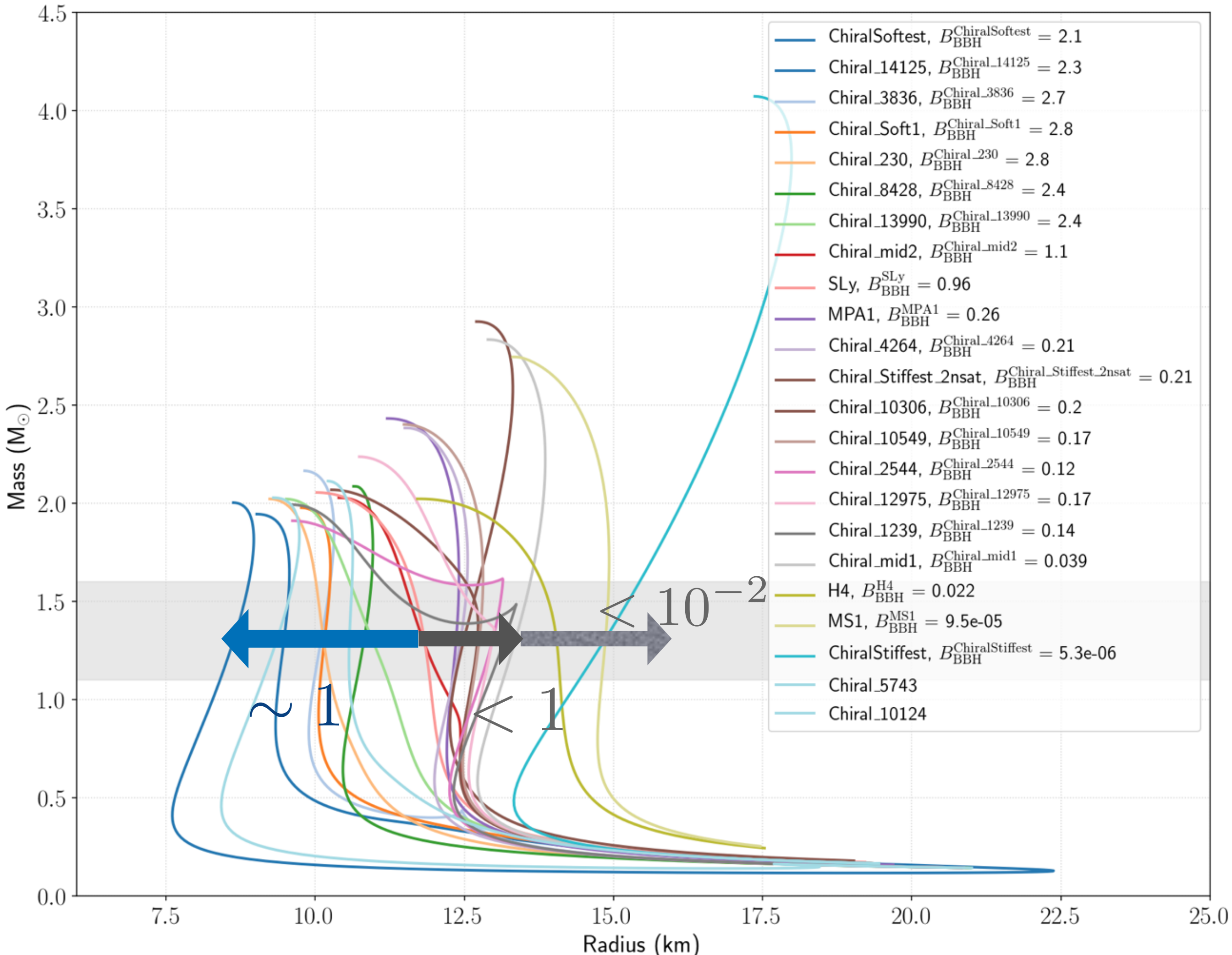
$\tilde{\Lambda} < 500$

$8.9 < \hat{R} < 13.2$ km



SD et al., Phys. Rev. Lett. 121, 091102 (2018)

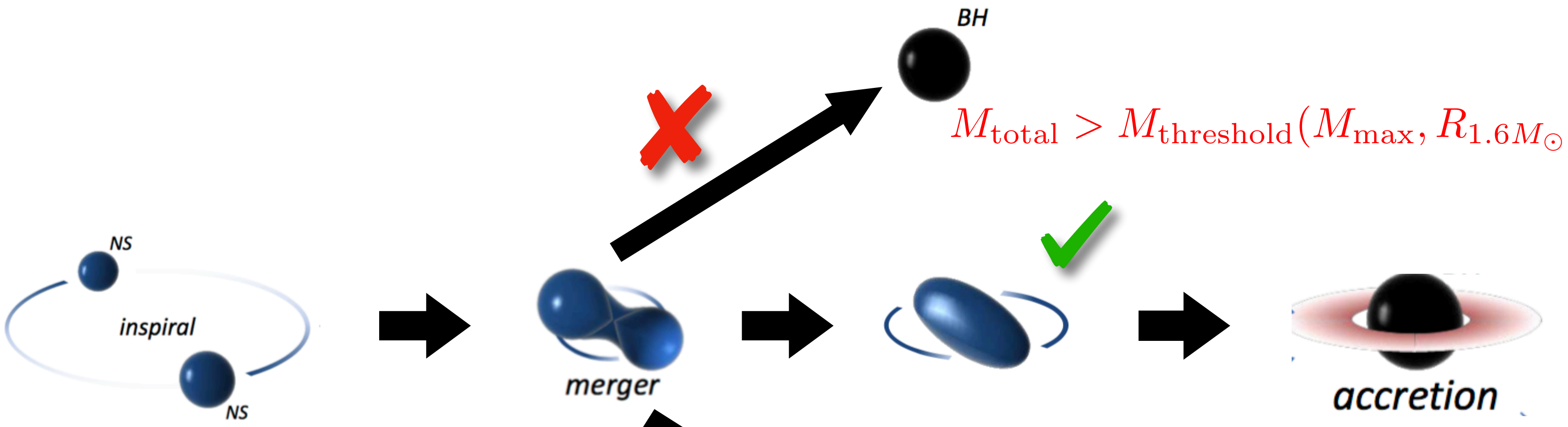
GW170817 constraints on equations of state

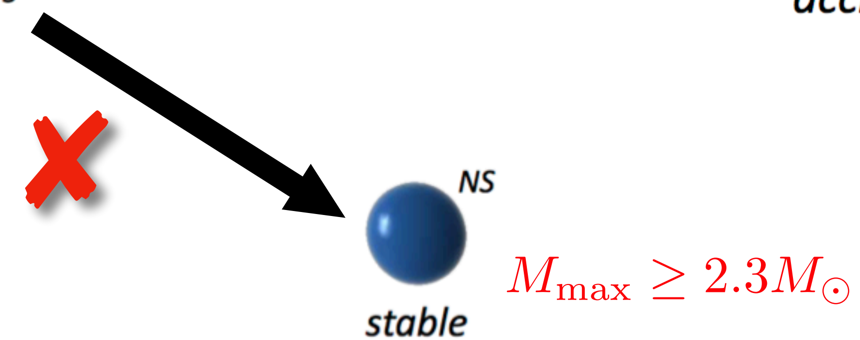


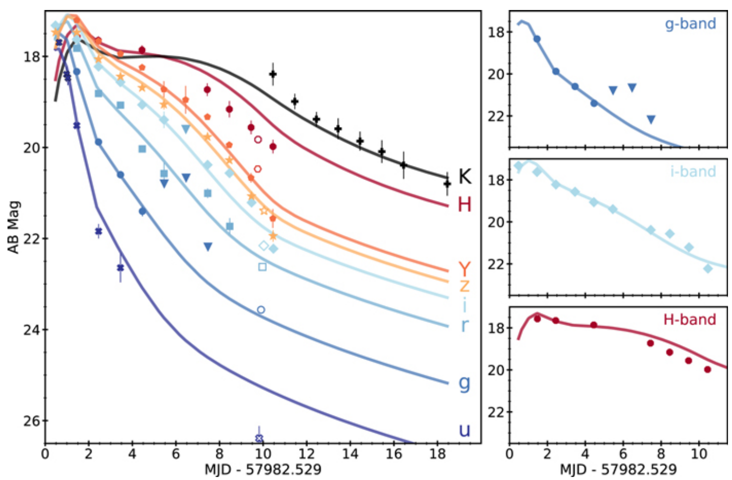
For GW170817, gravitational waves alone cannot distinguish between a binary black hole and a binary neutron star merger

See also: Abbott et al 2020, CQG 37 045006

Information from electromagnetic counterparts of GW170817



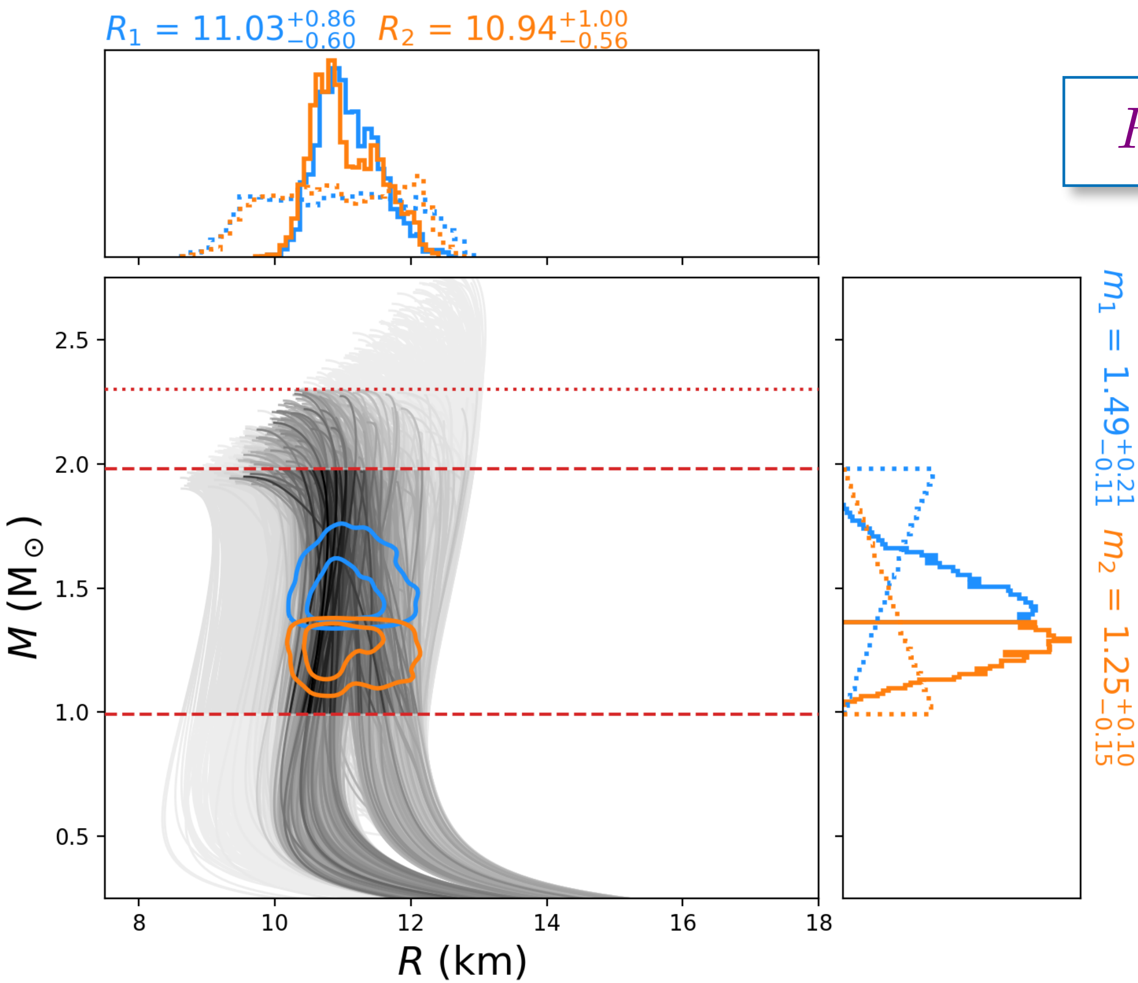




Cowperthwaite et al (2017), ApJL 848 L17

Diagram adapted from: Bartos et al. (2013) CQG 30, 123001

Multimessenger constraints on allowed equations of state

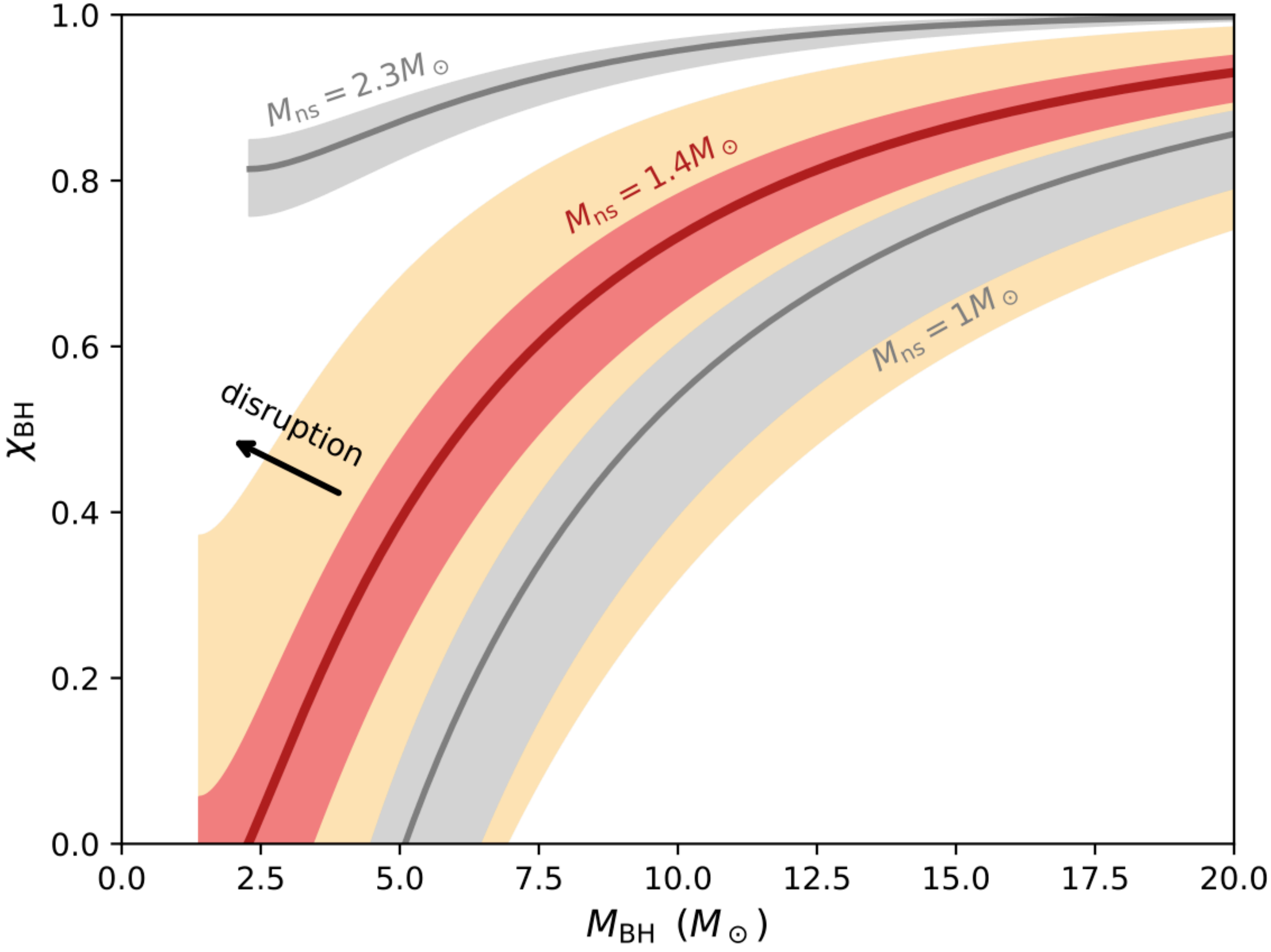


$$R_{1.4} = 11.2^{+1.2}_{-0.8}\ \text{km}$$

Capano, Tews, Brown, Margalit, **SD** et al, Nature Astronomy 4 (2019)

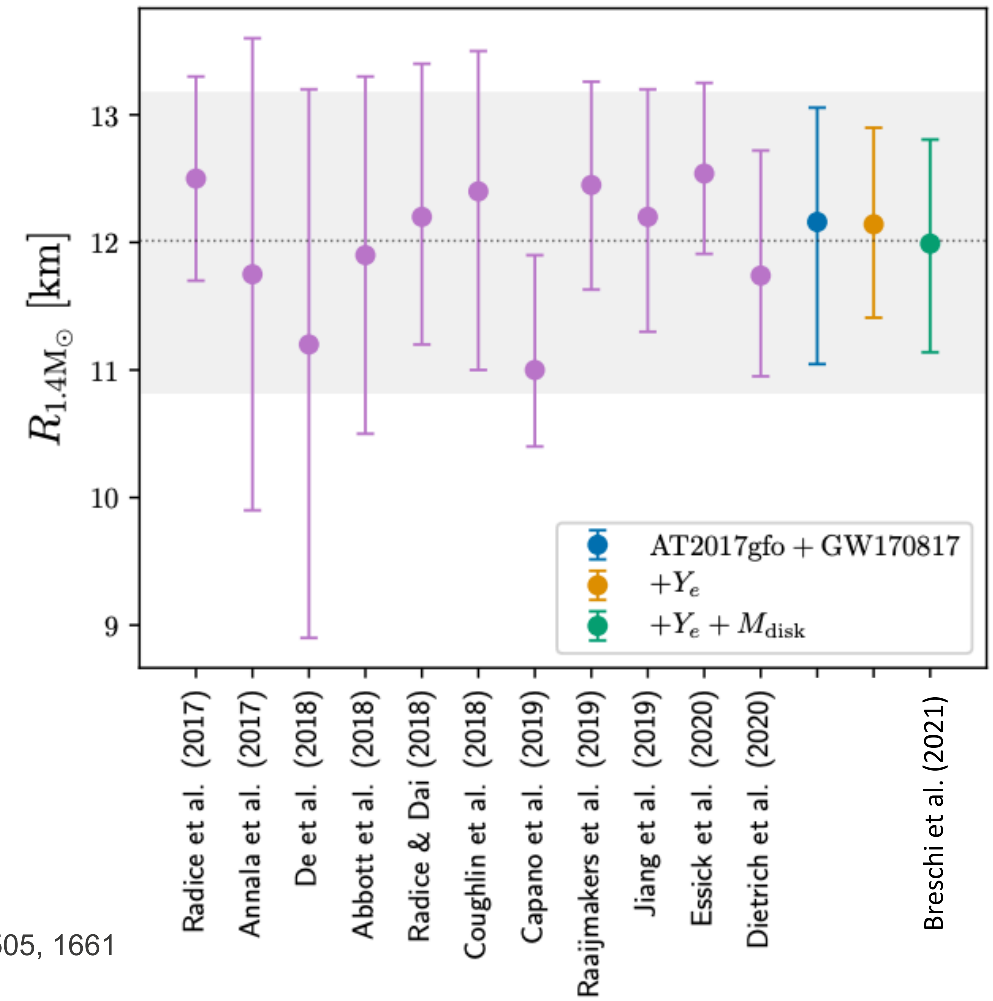
Implications of the radius measurement:

Prospects of observing a neutron star - black hole merger



Capano, Tews, Brown, Margalit, **SD** et al, Nature Astronomy 4 (2019)

Comparison of radius measurements for a 1.4M⊙ neutron star



Breschi et al. (2021) MNRAS 505, 1661

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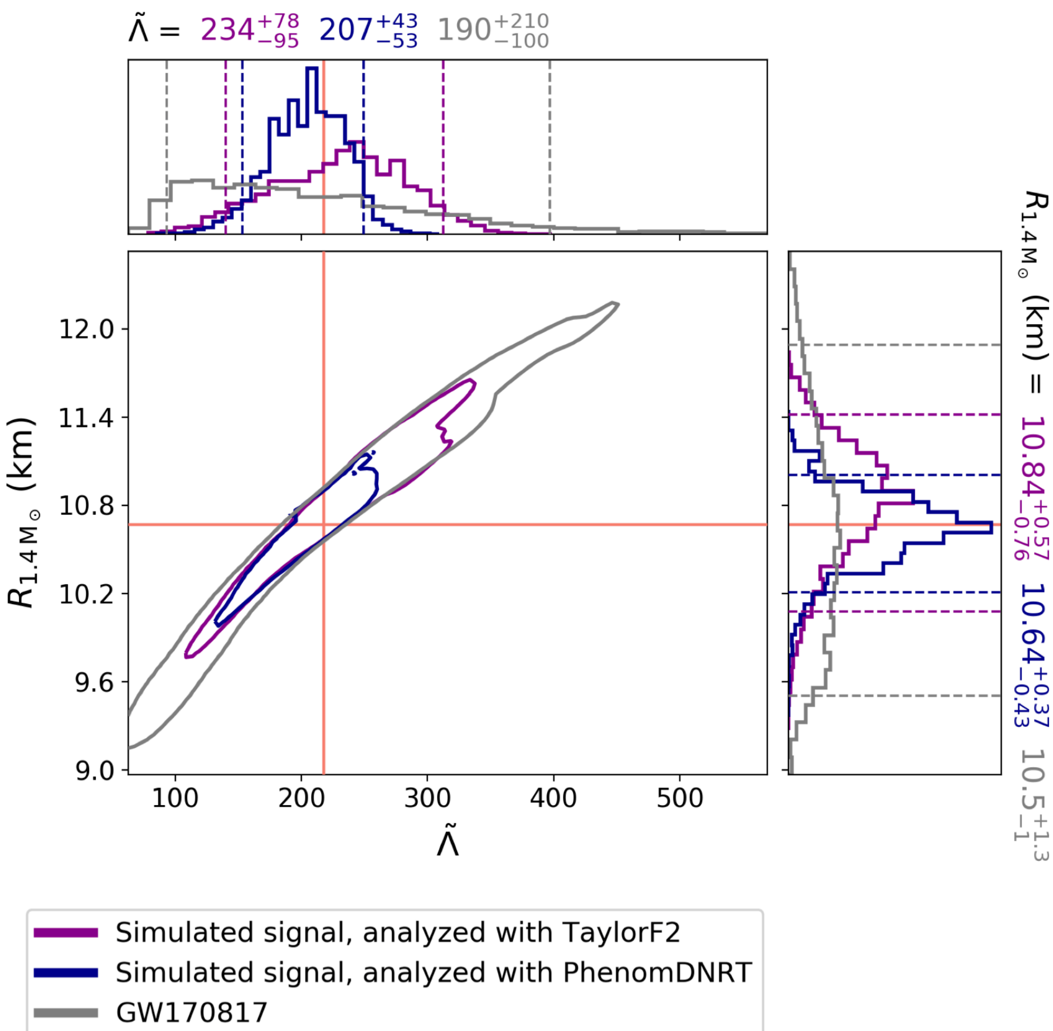
Prospects of improving constraints with future observations



- Using simulated signals at SNR ~100 we find ~2.9x improvement in measurement uncertainty
- Gravitational waves alone will be able to constrain upper and lower bounds of tidal deformability and radii for high SNR signals
- Low SNR signals would need combination of information from GW + EM + nuclear theory

Capano, Tews, Brown, Margalit, **SD** et al, Nature Astronomy 4 (2019)

Thank you for your attention!

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Image credit: NASA & ESA