Neutron star tides and quasi-universal relations

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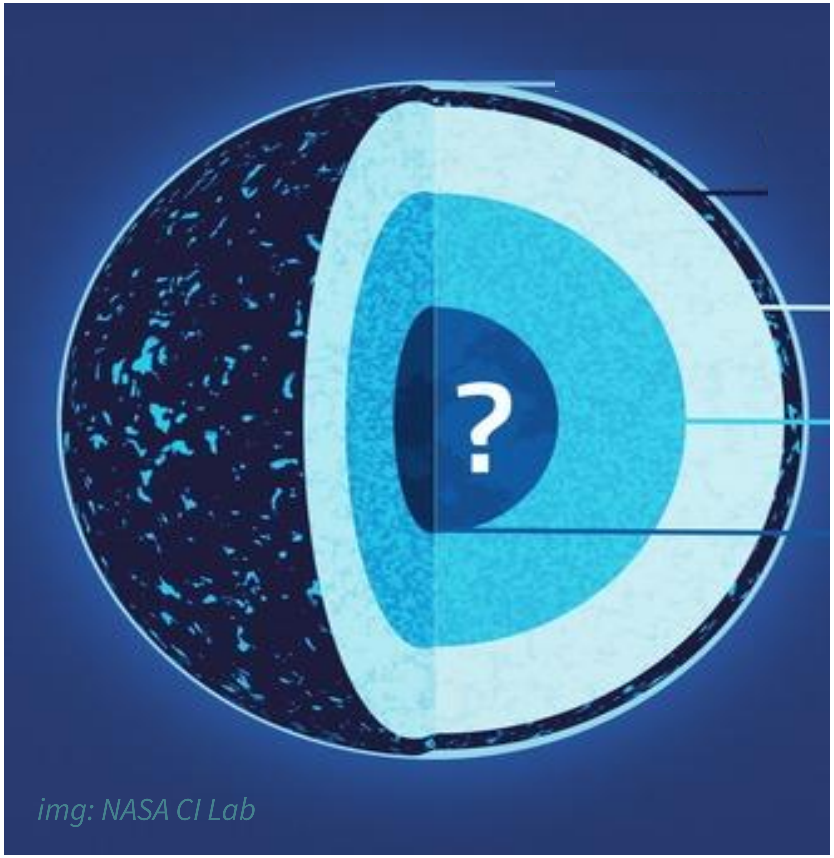
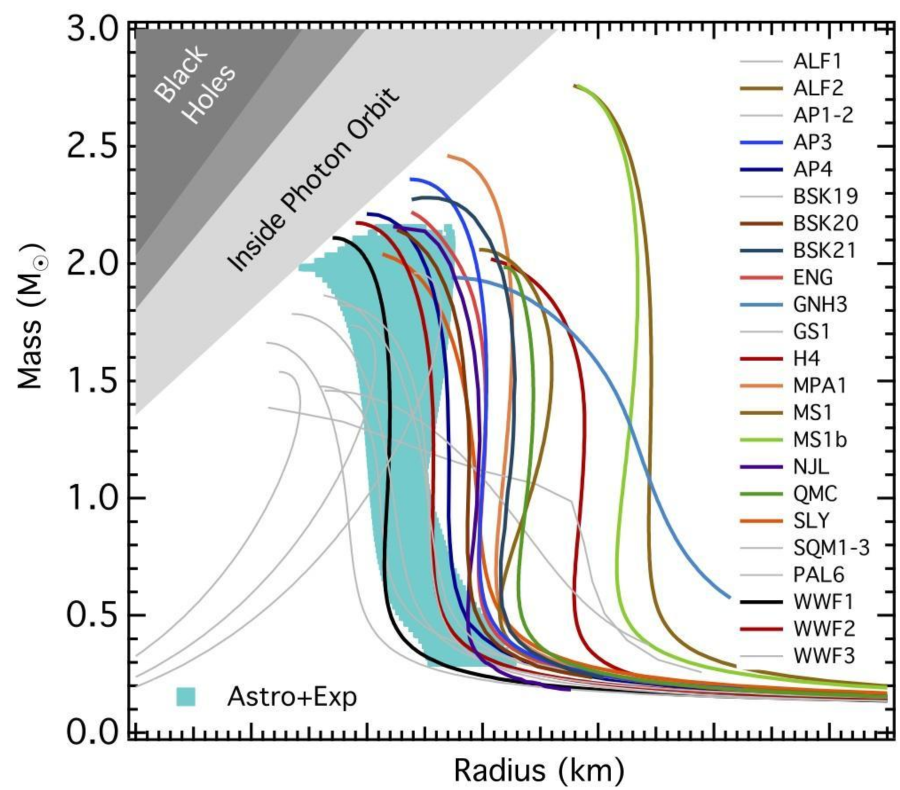
KITP 2019

Neutron star structure and tides



img: Ozel+Freire '16



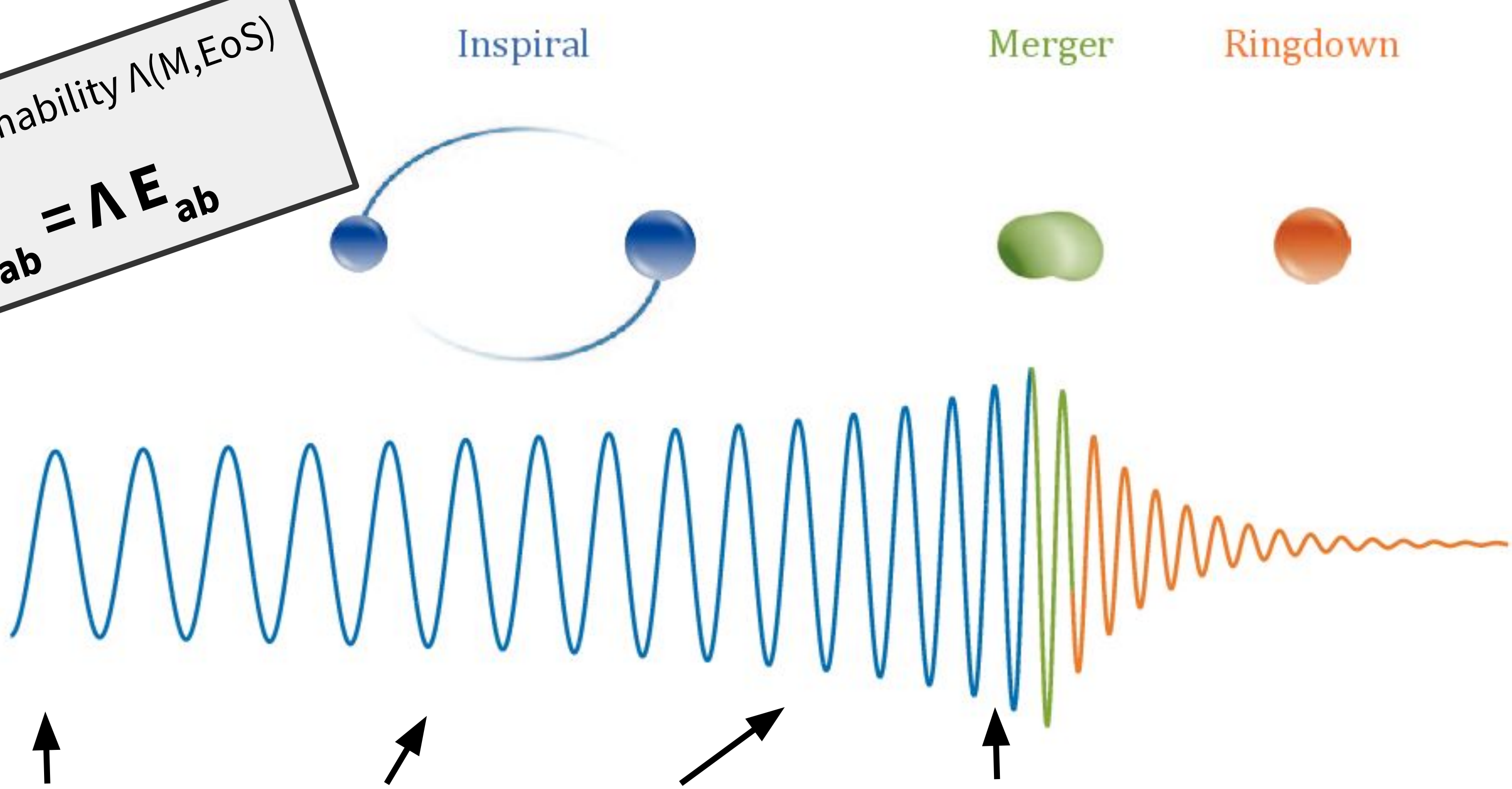
Macroscopic observables are sensitive to nuclear microphysics

Neutron star structure and tides

- Tides imprint internal structure on phasing of the compact binary waveform

Tidal deformability $\Lambda(M,\mathrm{EoS})$

$$Q_{ab} = \Lambda \, E_{ab}$$



~100 Hz
nonlinear tides?

~500 Hz
static tides

~1 kHz
dynamical tides

>1 kHz
tidal disruption?

img: Antelis+Moreno ‘16

Neutron star structure and tides

- Static tides produce both conservative and radiative phase corrections

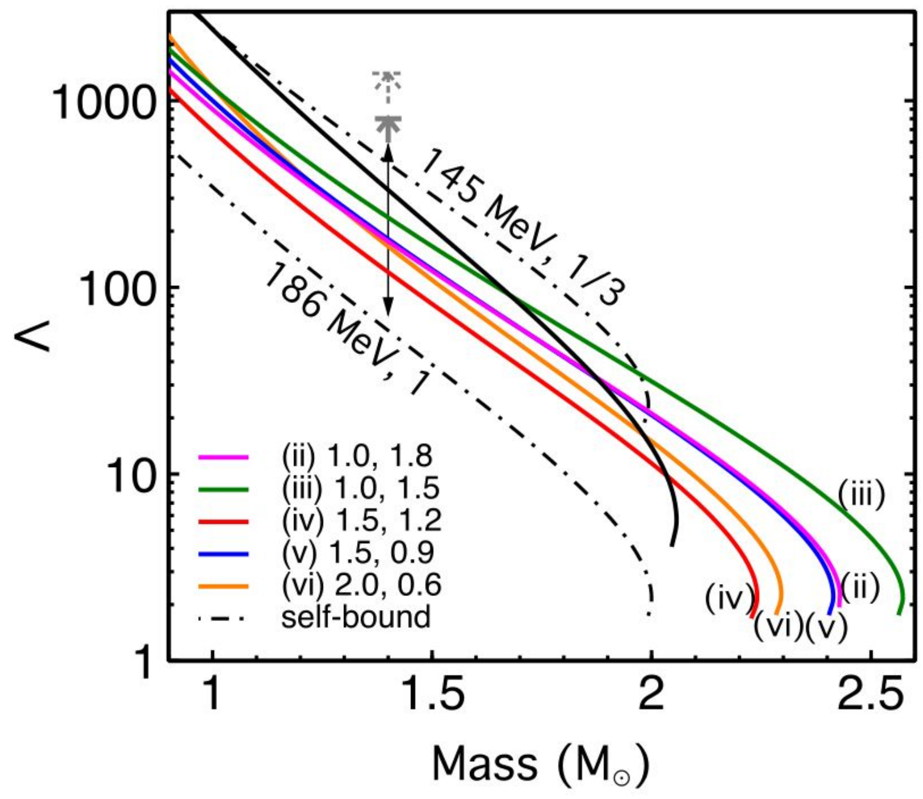
Flanagan+Hinderer '08

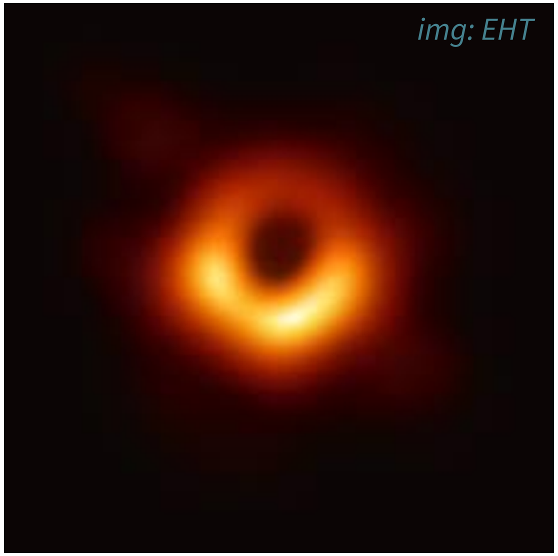
$$P_{gw} \sim -(d^3\bar{Q}/dt^3)^2$$
$$\bar{Q}_{ab} = Q_{ab}^{orb} + Q_{ab}$$

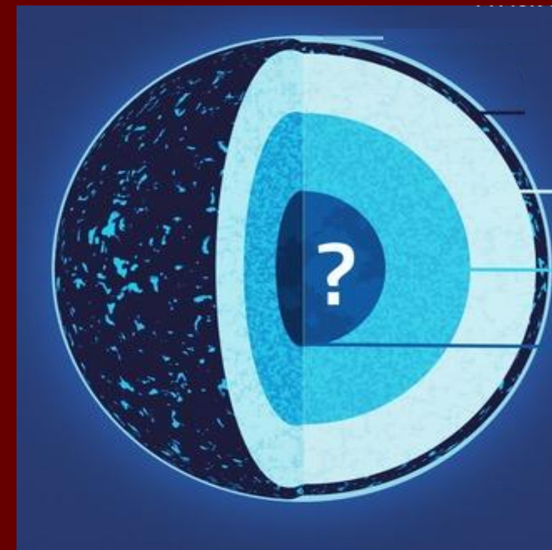
- Deformability enters the waveform at 5PN ($\propto v^{10}/c^{10}$) as

$$\tilde{\Lambda} = 16[(1+12q)M_1^5\Lambda_1 + 1 \leftrightarrow 2]/13M_{tot}^5$$

img: Han+Steiner '18







No-hair theorems

- Mass
- Spin
- R = 2M (Schwarzschild)
- Λ = 0

Binnington+Poisson '09

Gurlebeck '15

Approximate no-hair theorems?

- Mass
- Spin
- R(EoS)
- Λ(EoS)
- I(EoS)
- Q_{rot}(EoS)
- ω_f(EoS)
- ...

I-Love-Q

Yagi+Yunes Science (2013) 1302.4499

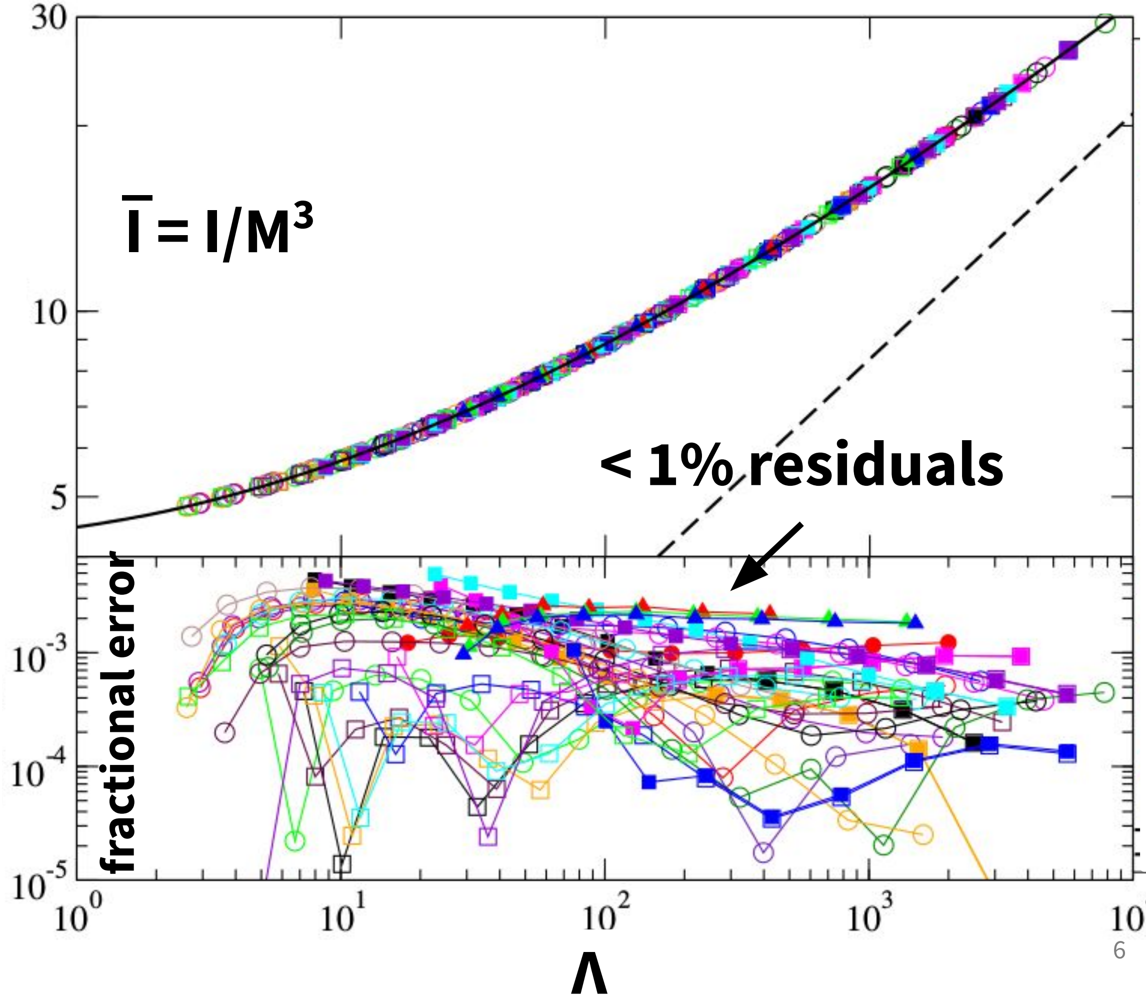
$\bar{I},\ \Lambda,\ Q_{rot}$

Despite depending individually on the EoS, certain combinations of observables are insensitive to internal structure

Other quasi-universal relations:

- **M/R , Λ** *e.g. Maselli+ '13*
- I , M/R *e.g. Lattimer+Prakash '00*
- ω_f , M/R *e.g. Chirenti+ '15*
- …

img: Yagi+Yunes '17



I-Love-Q

Yagi+Yunes Science (2013) 1302.4499

$$\bar{I},\ \Lambda,\ Q_{rot}$$

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I, M/R *e.g. Lattimer+Prakash '00*

ω_f, M/R *e.g. Chirenti+ '15*

...

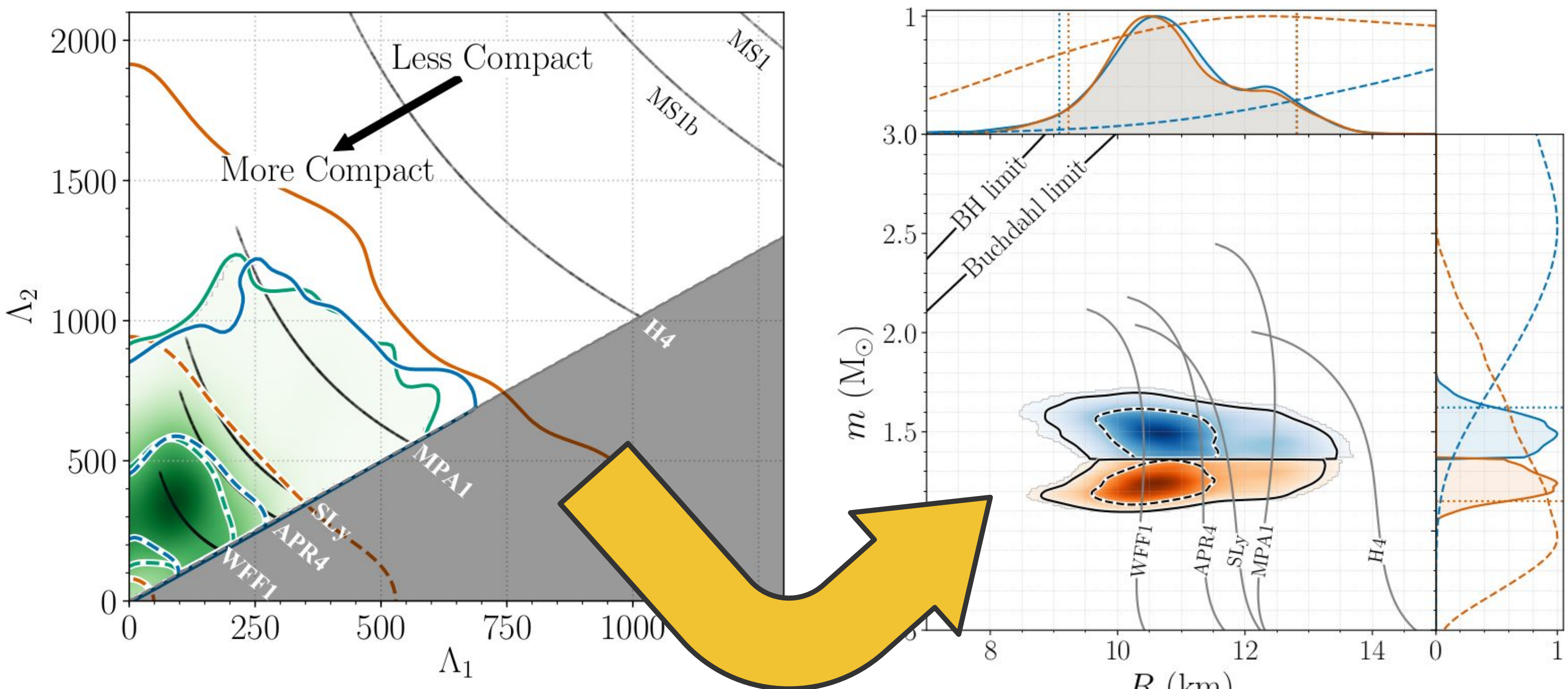
Useful for...

- **Inferring unobservable properties**
- Testing gravity
- Breaking degeneracies

Application: GW170817 radii inference

LVC PRL (2018) 1805.11581

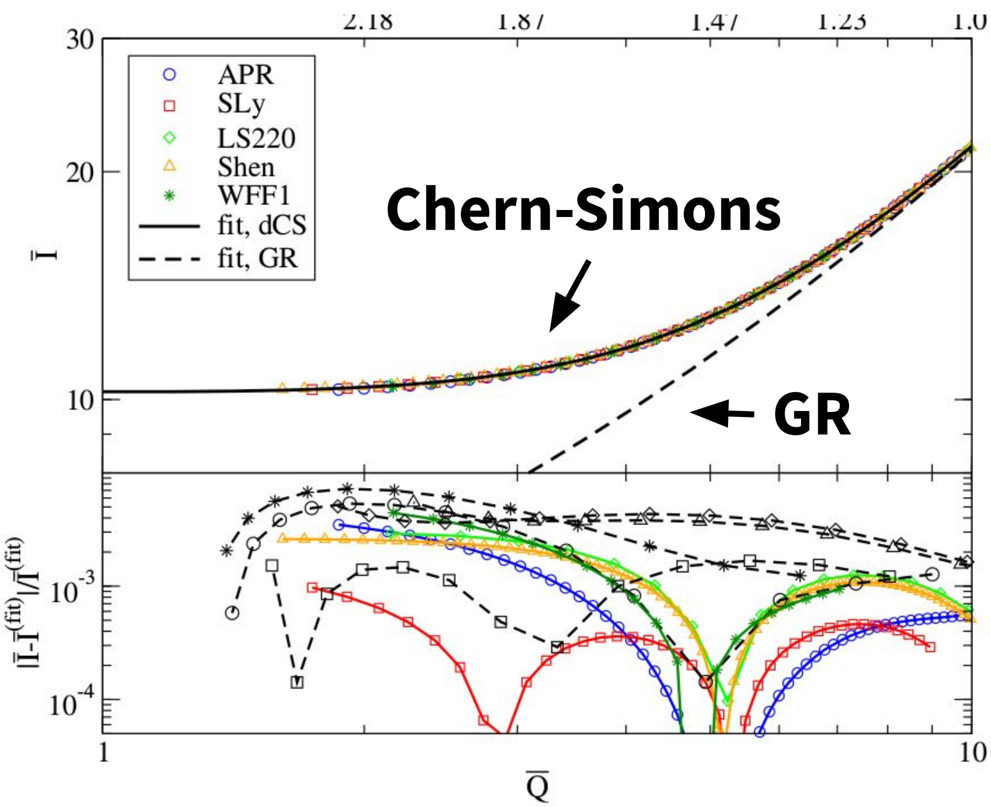
$$P_R(R|\,\mathrm{GW}) = \frac{G}{c^2}\int \frac{P_C(GM/c^2R|\Lambda)P(M,\Lambda|\,\mathrm{GW})}{R^2} M\, dM\, d\Lambda$$



C-Love relation

Application: testing gravity

Yagi+Yunes PhysRep (2017) 1608.02582



Useful for...

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- **Testing gravity**
- Breaking degeneracies

Binary Love relations

Yagi+Yunes CQG (2016) 1512.02639

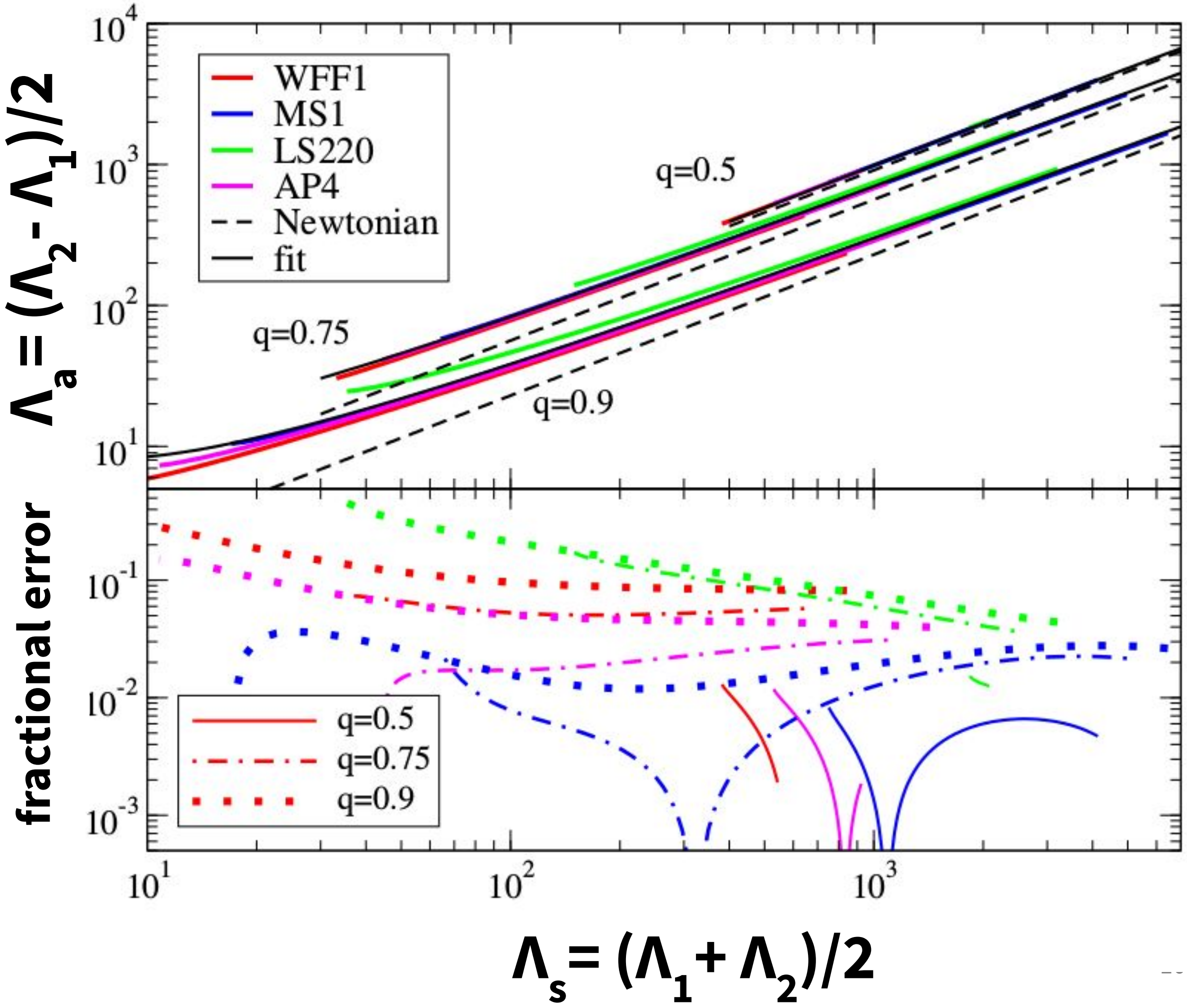
Λ_s, Λ_a, q

residuals

~ 1% for q = 0.5

~ 50% for q = 0.9

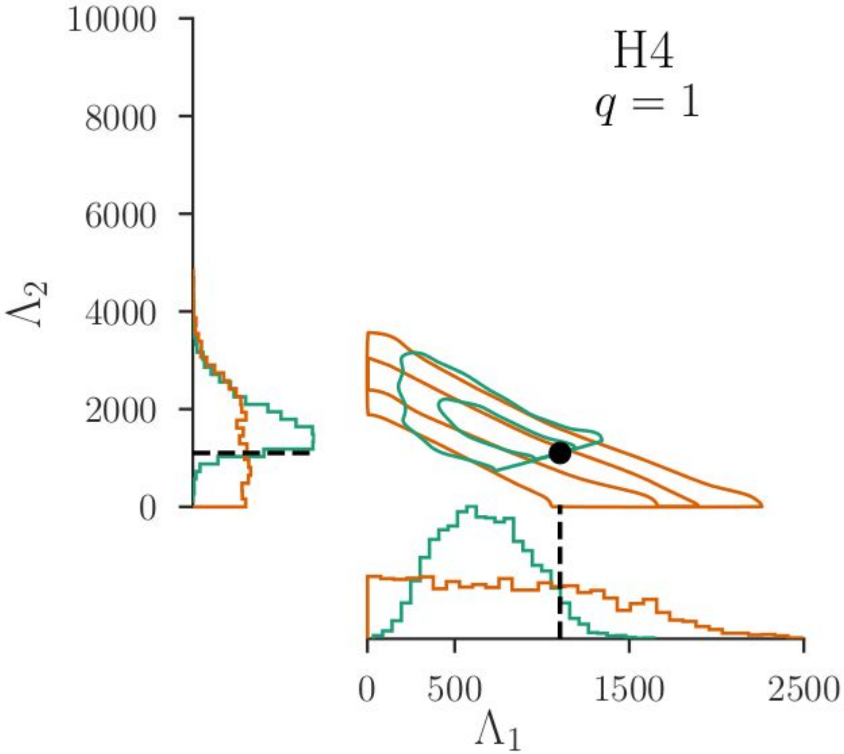
Assuming a common EoS, the tidal deformabilities of two neutron stars are tightly correlated



Application: GW170817 tidal inference

Chatziioannou+ PRD (2018) 1804.03221

$$\Lambda_a = \Lambda_a^{fit}(\Lambda_s, q) + \mathcal{N}(\, \mu(\Lambda_s, q), \sigma(\Lambda_s, q)\,)$$



Useful for...

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- **Breaking degeneracies**

Application: GW170817 tidal inference

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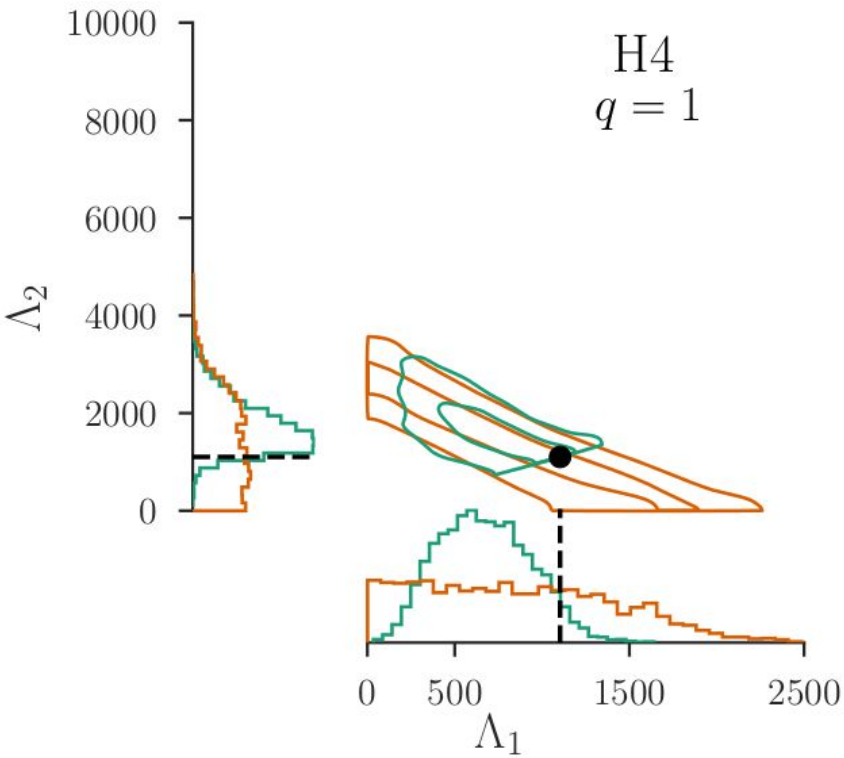
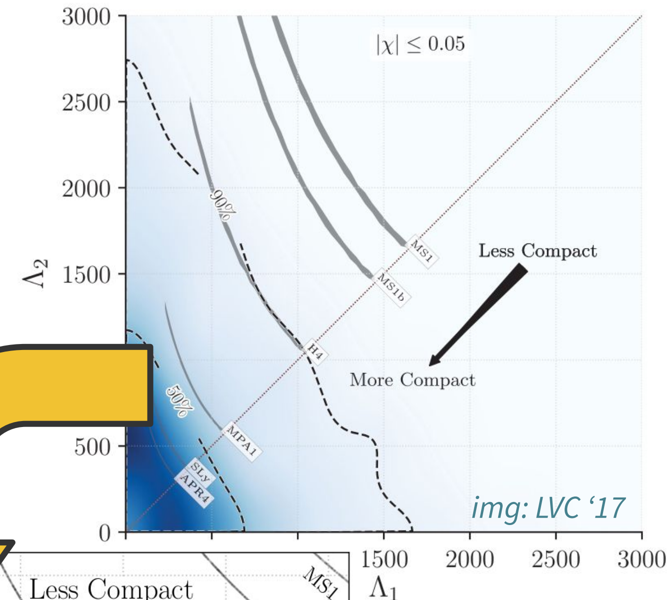
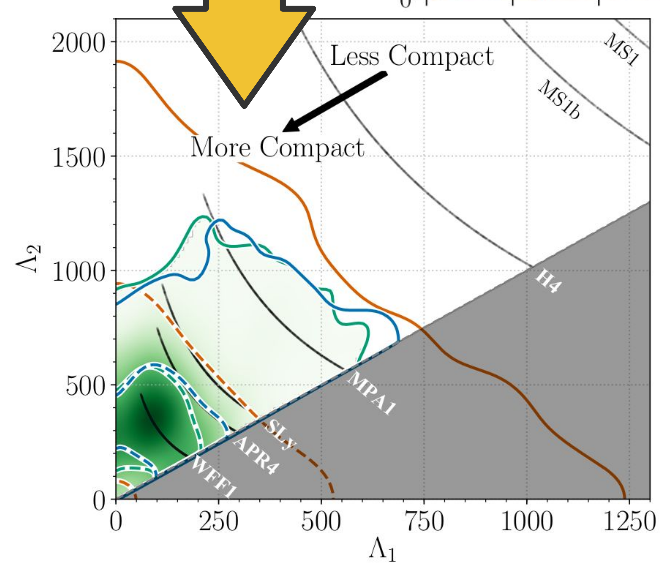


Binary Love relation





Combining quasi-universal relations

Landry+Kumar ApJL (2018) 1807.04727

$$P_I(I|\,\mathrm{EM,GW}) = \frac{c^4}{G^2}\int \frac{P_{\bar{I}}(c^4 I/G^2M^3|\,\Lambda)P_\Lambda(\Lambda|\,\mathrm{EM,\,GW})P(M|\,\mathrm{EM})}{M^3}\,dM\,d\Lambda$$

$$P_\Lambda(\Lambda|\,\mathrm{EM,GW}) = \int P(\Lambda|\,M,\Lambda_{1.4})P(M|\,\mathrm{EM})P(\Lambda_{1.4}|\,\mathrm{GW})\,dM\,d\Lambda_{1.4}$$

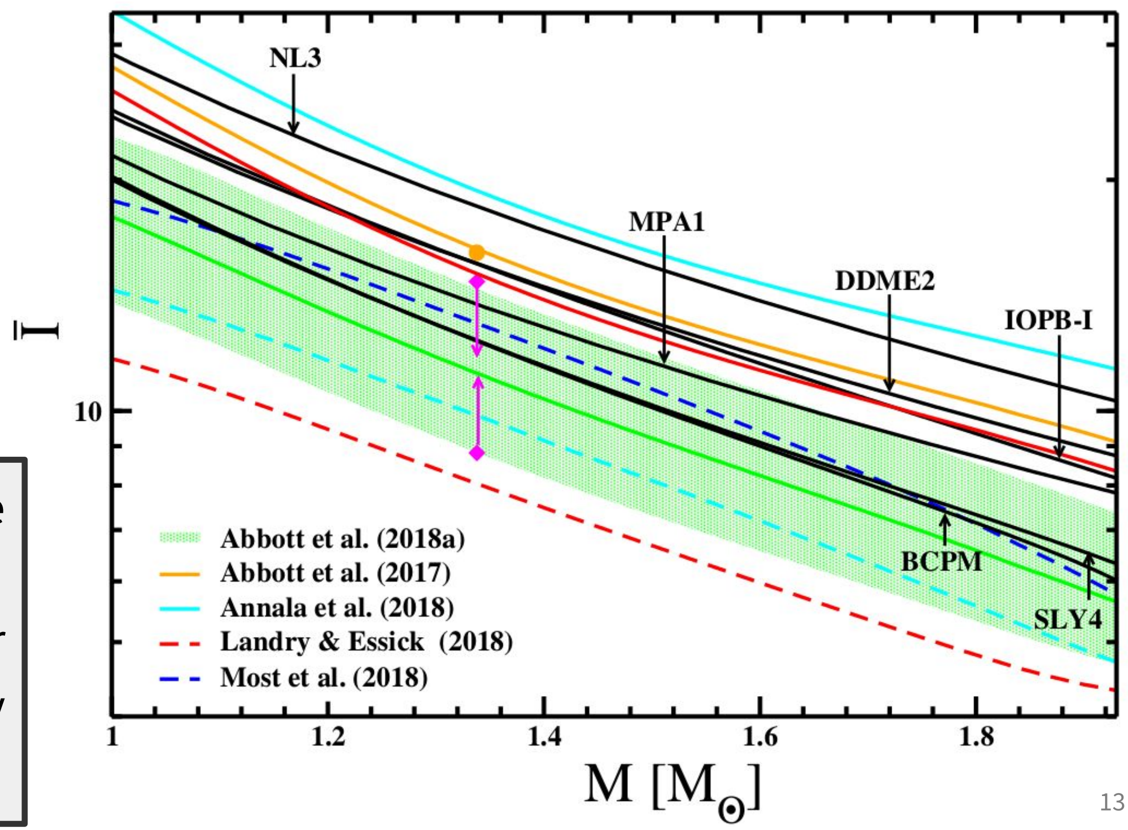
Binary Love + I-Love relations

PSR J0737-3039A
"the double pulsar"

$I = 1.16^{+0.33}_{-0.25} \times 10^{45}$ g cm^2

$\chi = 0.020^{+0.006}_{-0.004}$

Kumar+Landry '19



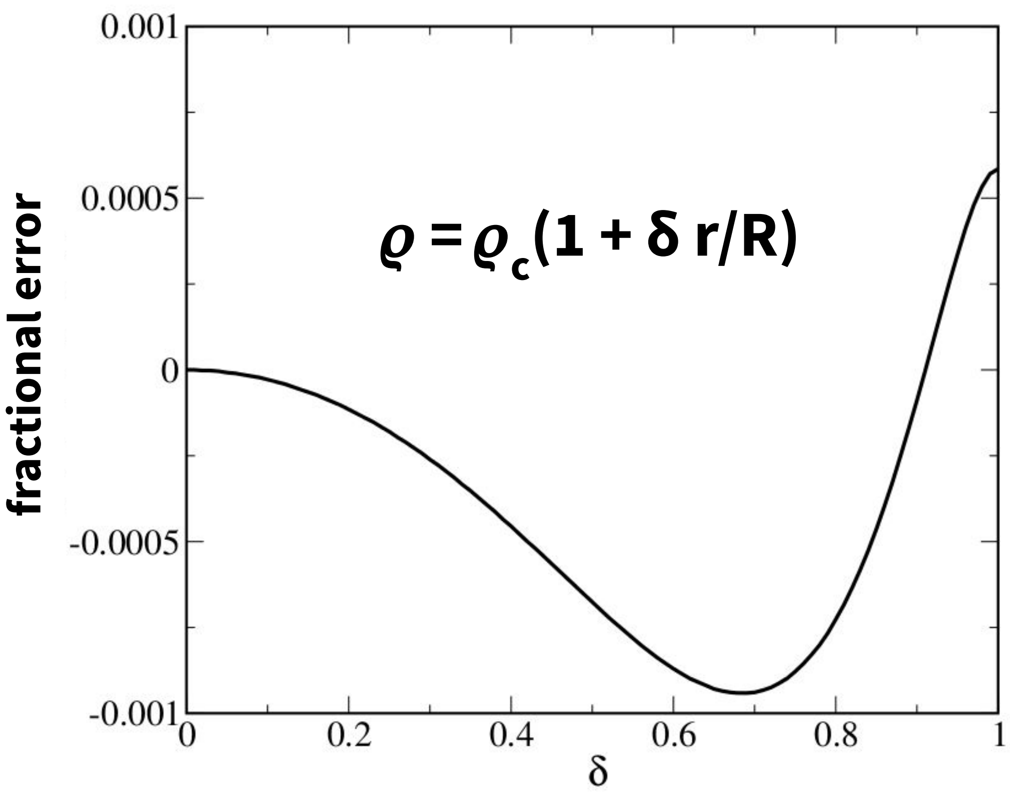
A GW measurement of Λ can be translated into constraints on the properties of NSs in other systems via combined binary Love and I-Love-Q relations

Why I-Love-Q?

Sham+ ApJ (2015) 1410.8271

Yagi+ PRD (2014) 1406.7587

I-Love residuals



Universality caused by emergent symmetry in compact stars: isodensity contour self-similarity

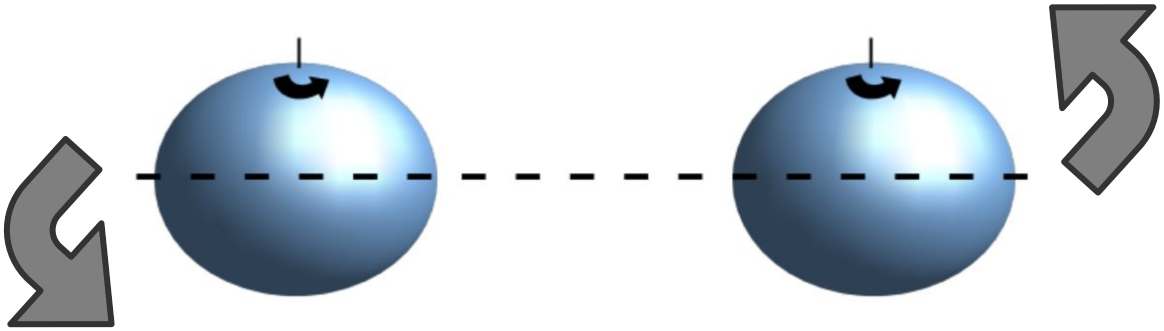
Chan+ PRD (2016) 1511.08566

- I-Love relation is stationary w.r.t. small perturbations away from incompressibility
- Incompressibility $\Rightarrow$ uniform eccentricity profile

Gravitomagnetic and spin-coupled tides

Beyond leading order, many other tidal effects contribute to the waveform.

- 5PN: Tidal deformability Λ
- 6PN: Gravitomagnetic deformability Σ *Damour+Nagar ‘09, Landry+Poisson ‘15*
- 6.5PN: Rotational-tidal deformabilities $\delta\Lambda_{2,3}$, $\delta\Sigma_{2,3}$ *Abdelsalhin ‘18, Landry ‘18*
- 7PN: Octupole tidal deformability Λ_3 *Yagi ‘14*

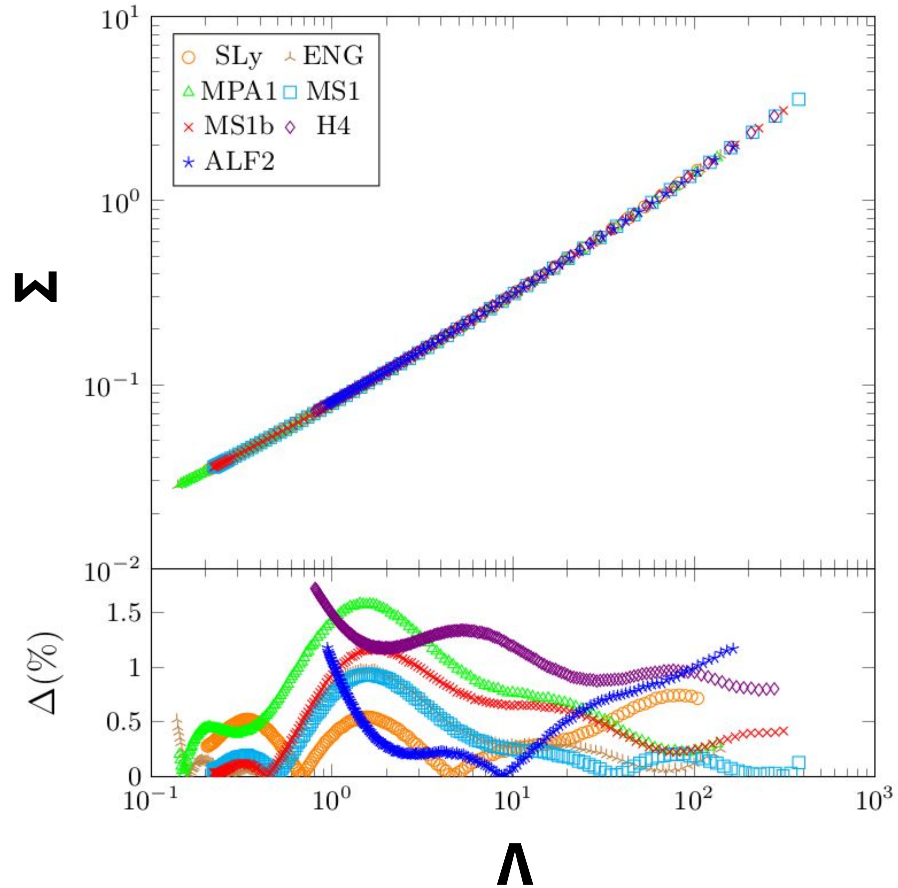


Multipole Love relations

Yagi PRD (2014) 1311.0872

Gagnon-Bischoff+ PRD (2018) 1711.05694

Higher-order tidal coefficients can all be expressed in terms of the tidal deformability virtually independently of the EoS



- Gravitomagnetic and higher multipole tides included in some EOB waveforms (e.g. TEOBResum) via quasi-universal relations

e.g. Akcay+ '19

What’s next?

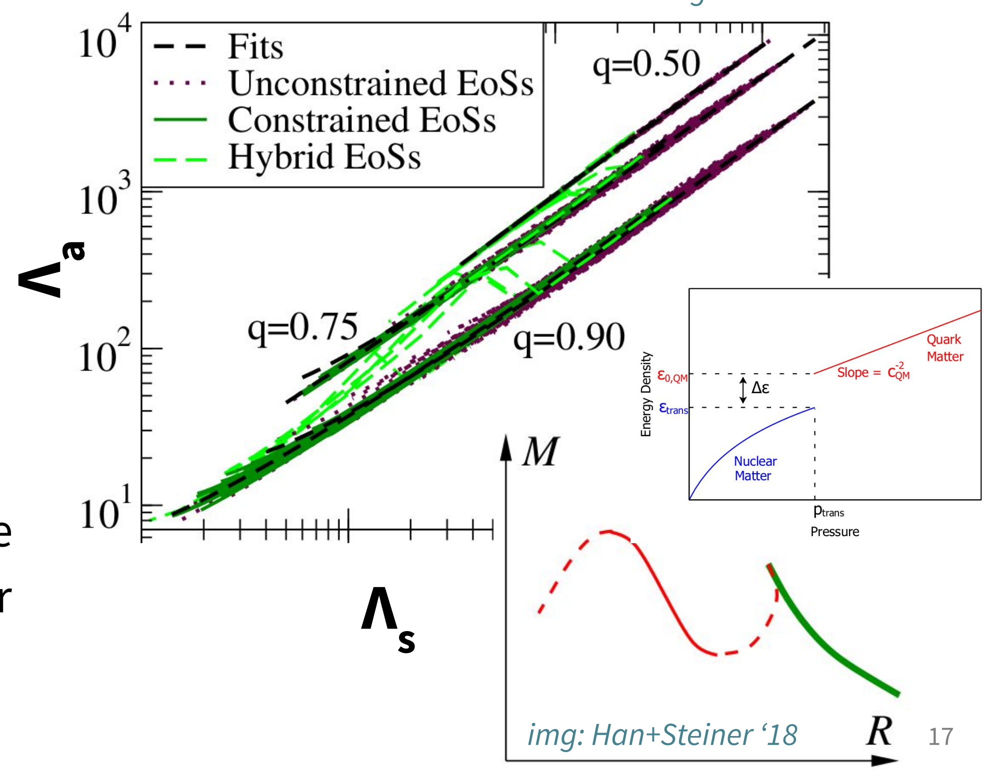
- Universal relations are a useful tool for making inferences about NS properties despite uncertain knowledge of the EoS
- GW measurement of tidal deformability from static tides during binary inspiral can serve as input for these inferences

However, there are recent indications that twin-branch-supporting EoSs may violate the binary Love relations

Han+Steiner ‘18, Carson+ ‘19

↳ This could be an opportunity to use quasi-universal relations to hunt for strong phase transitions in nature

img: Carson+ ‘19



img: Han+Steiner ‘18