Applications of Neutron-Star Universal Relations to Gravitational Wave Observations

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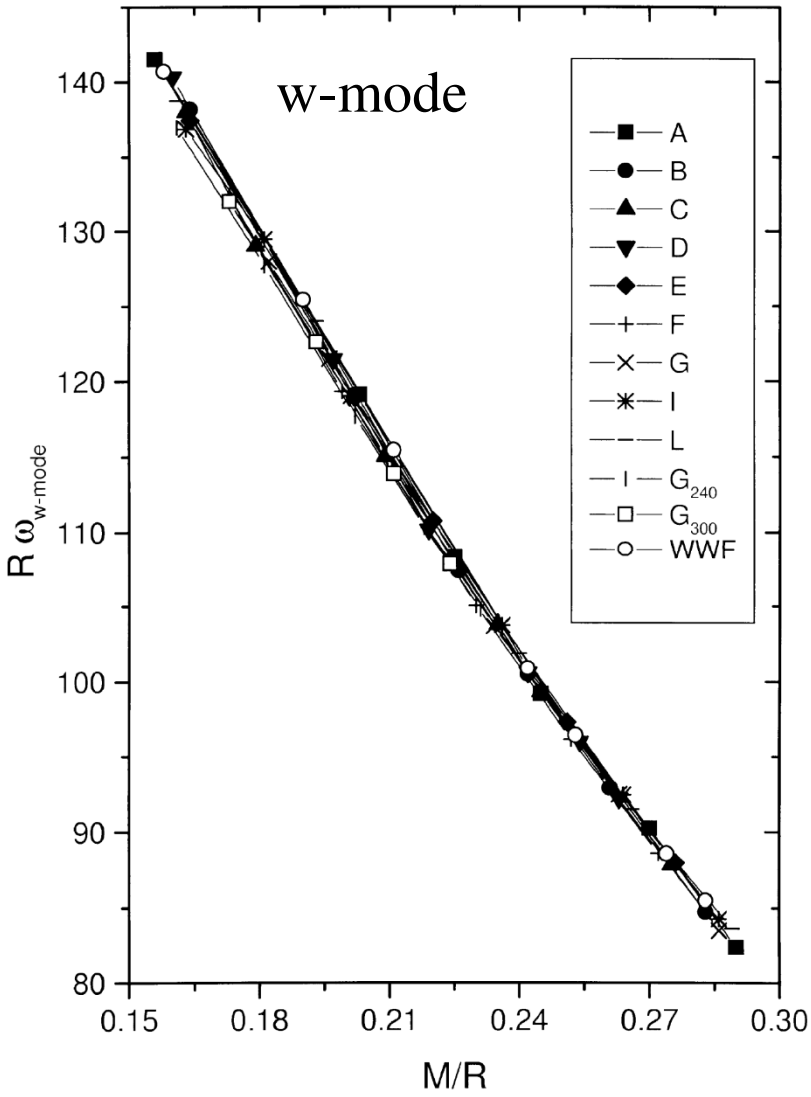
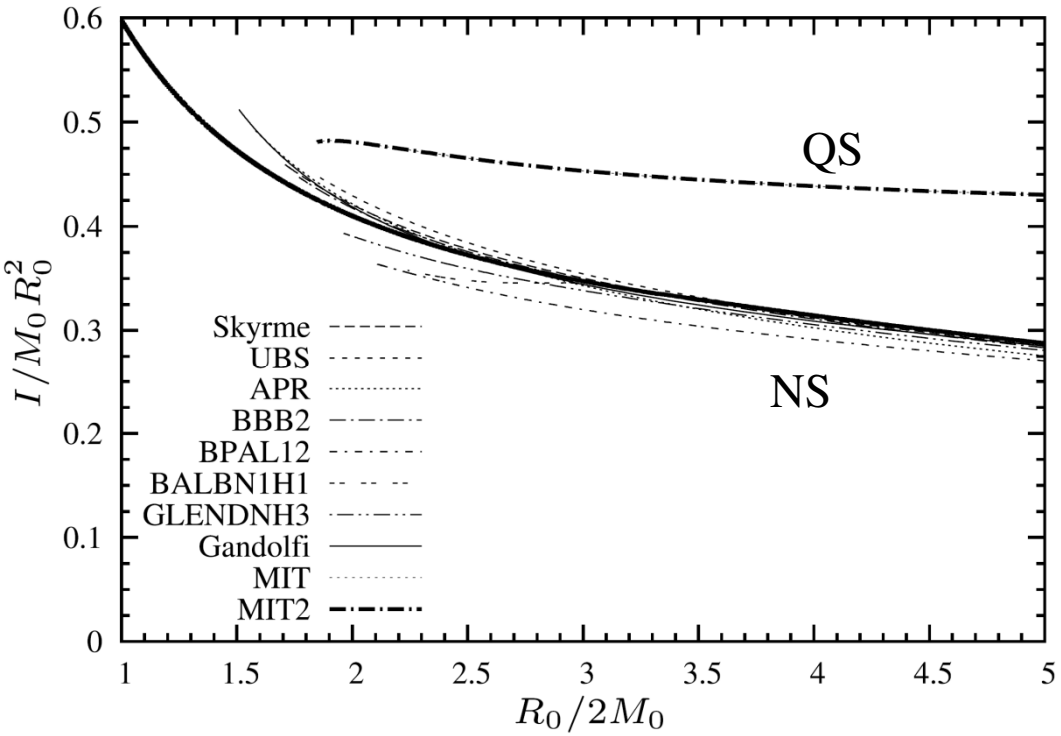
Universal Relations: Isolated NSs



[Andersson & Kokkotas (1998)]



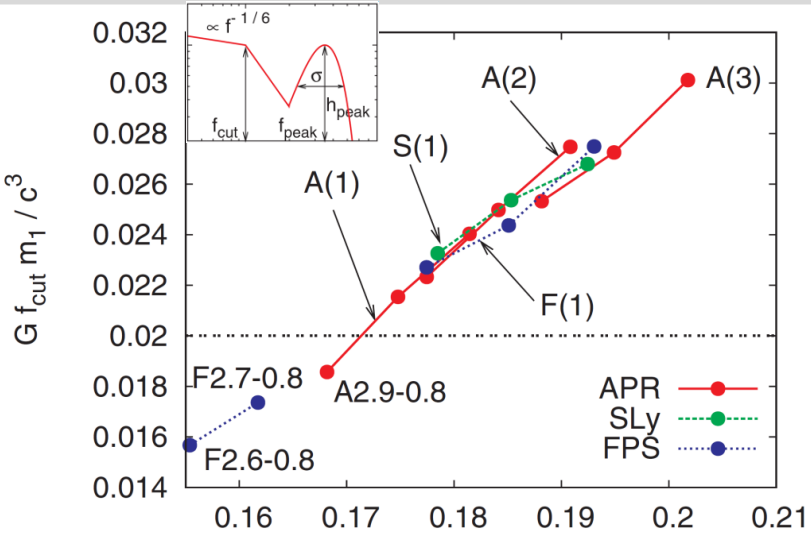
[Lattimer & Prakash (2001)]
[Urbanec+ (2013)]

Many others

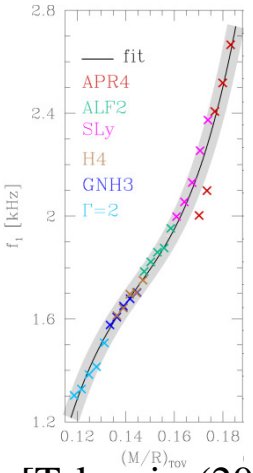
Universal Relations: Binary NSs

[Stergioulas' talk on Tuesday]

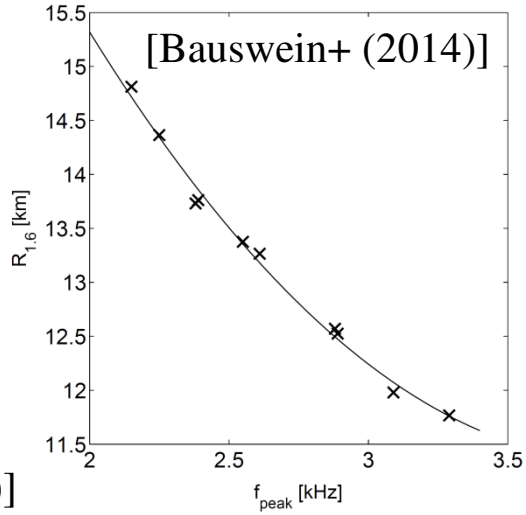
[Read's talk on Thursday]

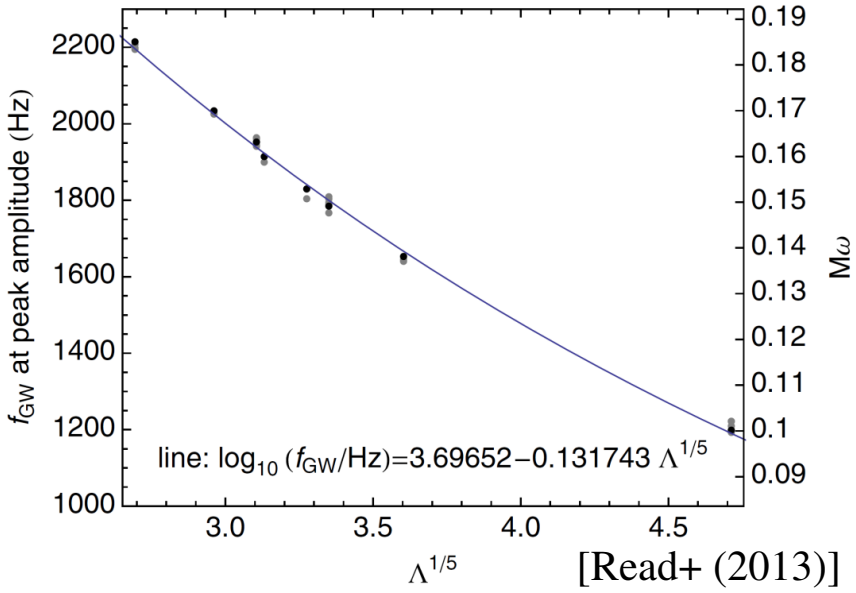


[Kiuchi+ (2010)]

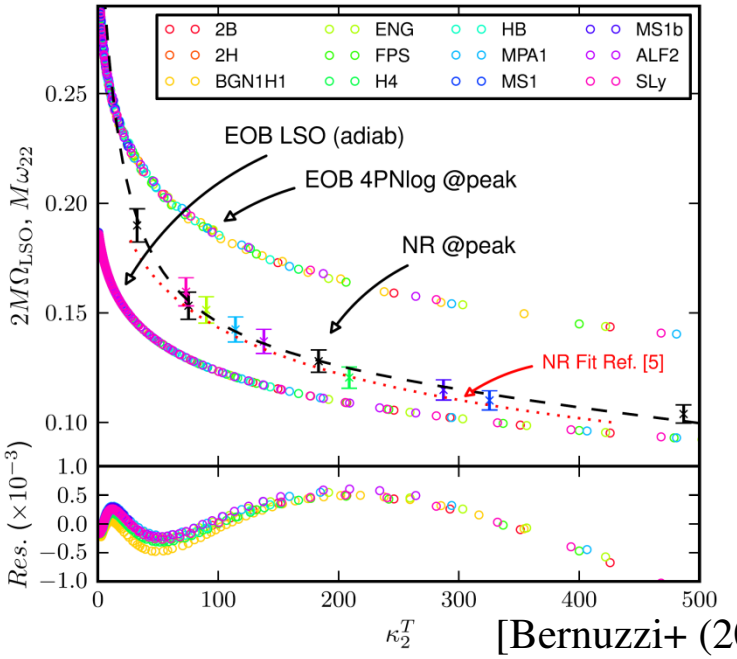


[Takami+ (2014)]





[Read+ (2013)]

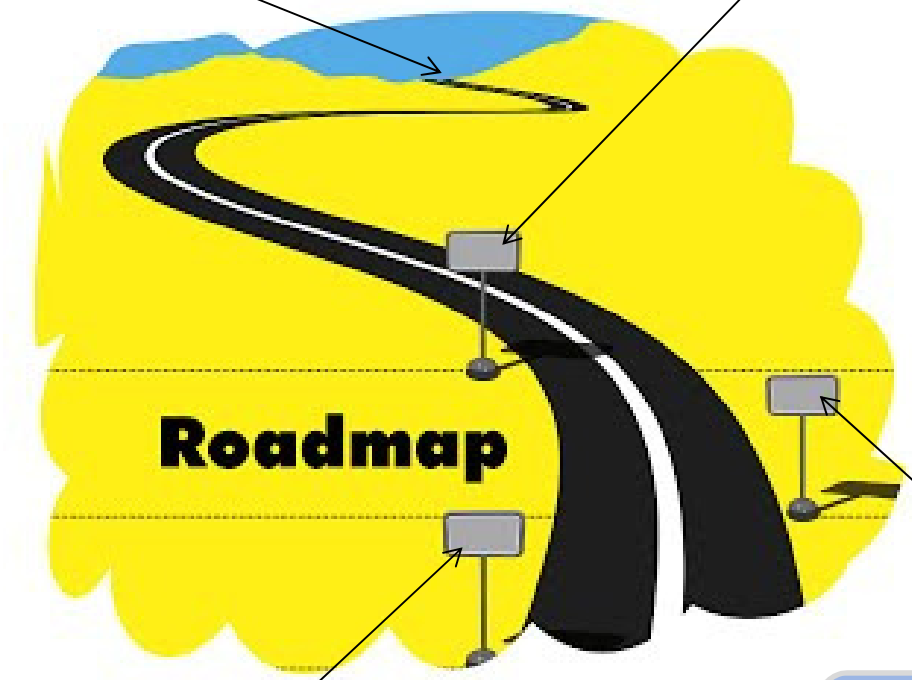


[Bernuzzi+ (2014)]

Roadmap

(IV) Open Questions

(III) Other Related Topics



(I) I-Love-Q & Multipole Love Relations

(II) Applications to GW Observations

I-Love-Q & Multipole Love Relations

Kent Yagi

I-Love-Q Relations

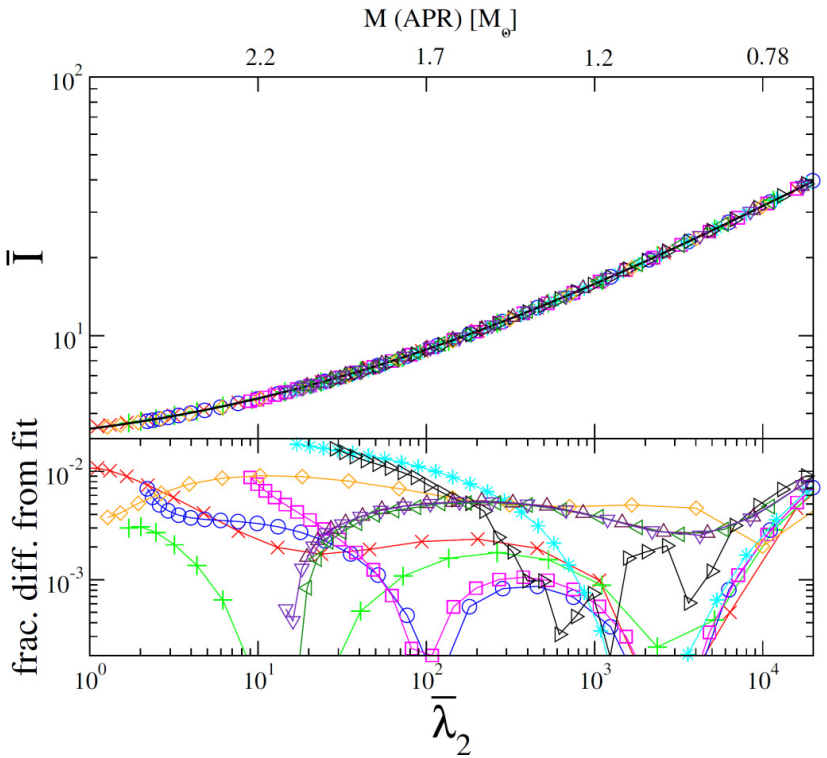
[KY & Yunes, Science, PRD (2013)]

(i) small/static tidal deformation ⇒ Maselli+ (2013)

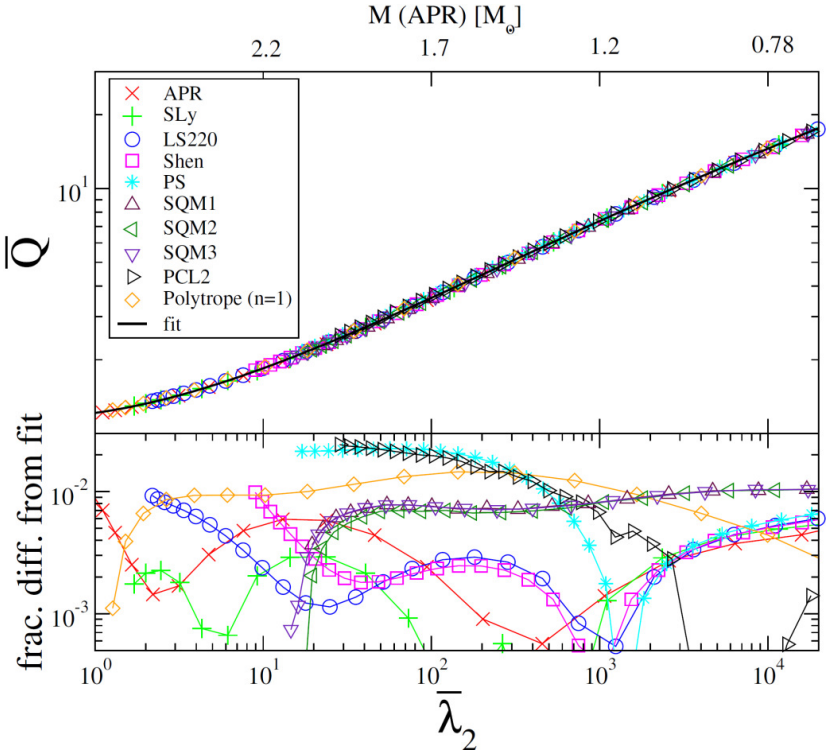
(ii) unmagnetized ⇒ Haskell+ (2014)

(iii) uniform/slow-rotation ⇒ Doneva+ (2013), Papps+ (2014), Chakrabarti+ (2014), KY+ (2014)

(iv) barotropic ⇒ Martinon+ (2014)



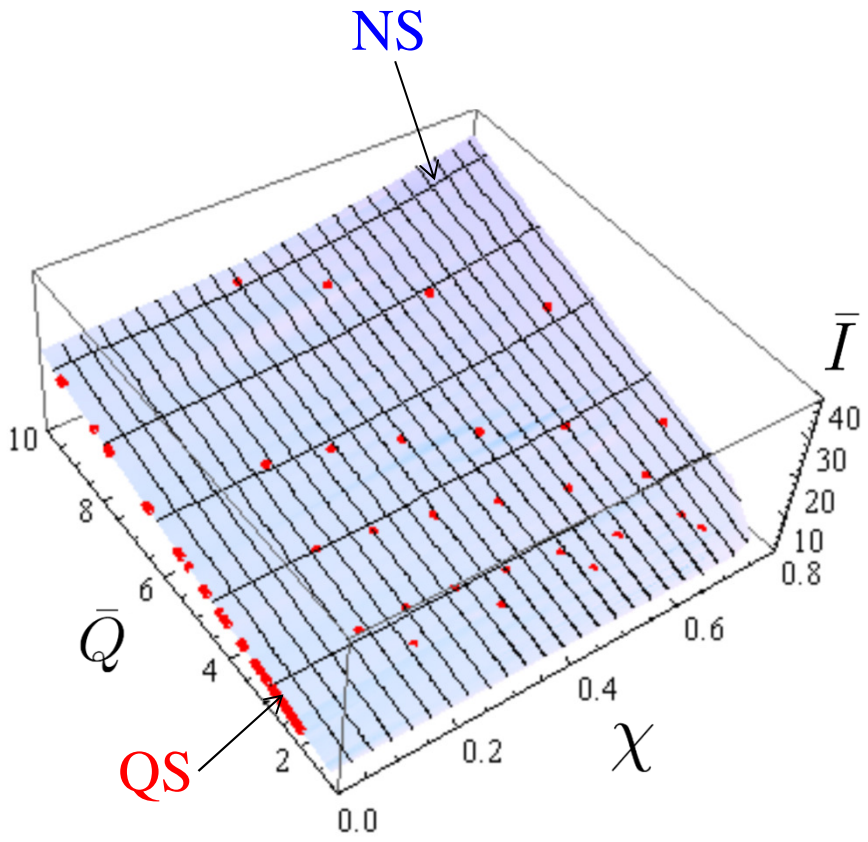
$\bar{I} \equiv I/M_*^3 \qquad \bar{\lambda}_2 \equiv \lambda_2/M_*^5$



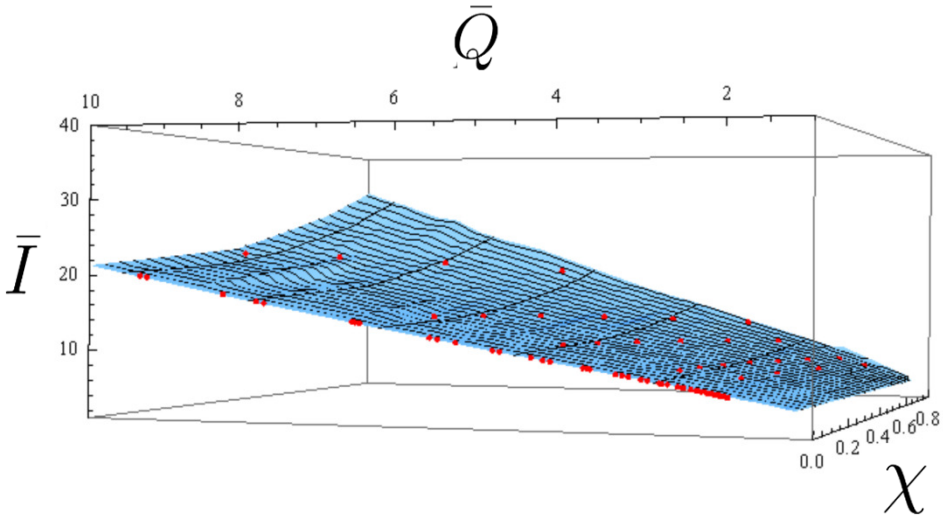
$\bar{Q} \equiv -Q/(M_*^3\chi^2) \qquad \chi \equiv S_1/M_*^2$

Universal I-Q Plane

[Pappas & Apostolatos (2014)]
[KY+ (2014)]



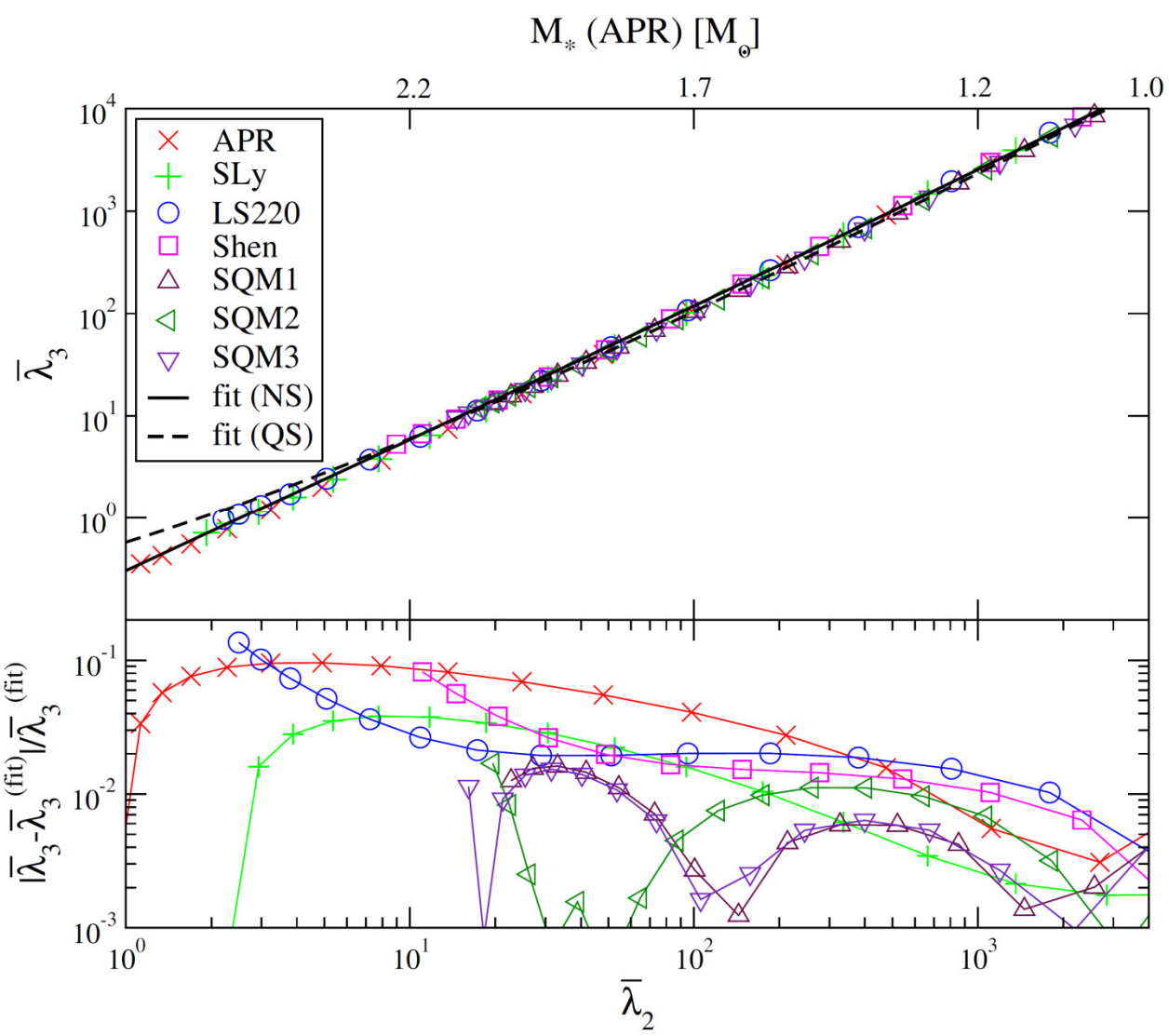
Universality still holds for a fixed χ $(= S_1/M^2)$



QS plane is almost identical to the NS one

Multipole Love Relations

[KY (2014)]



multipole moment

tidal tensor

$$M_L = -\lambda_\ell G_L$$

$$\bar{\lambda}_\ell \equiv \frac{\lambda_\ell}{m^{2\ell+1}}$$

Similar relation holds for

$$\bar{\lambda}_4 - \bar{\lambda}_2$$

Applications to GW Observations

(I) GW Astrophysics

(II) Gravitational Physics

(III) Nuclear Physics

(I) GW Astrophysics

NS/NS gravitational waveform phase

$$\Psi(f) \approx \Psi_0 f^{-5/3}\left[1 + ... + \Psi_3(\beta) f + \Psi_4(\sigma) f^{4/3} + ... + \Psi_{10}(\lambda) f^{10/3}\right]$$

$$\sigma = \sigma_{SS} + \sigma_Q$$

Q-Love relation breaks the degeneracy between spins and Q

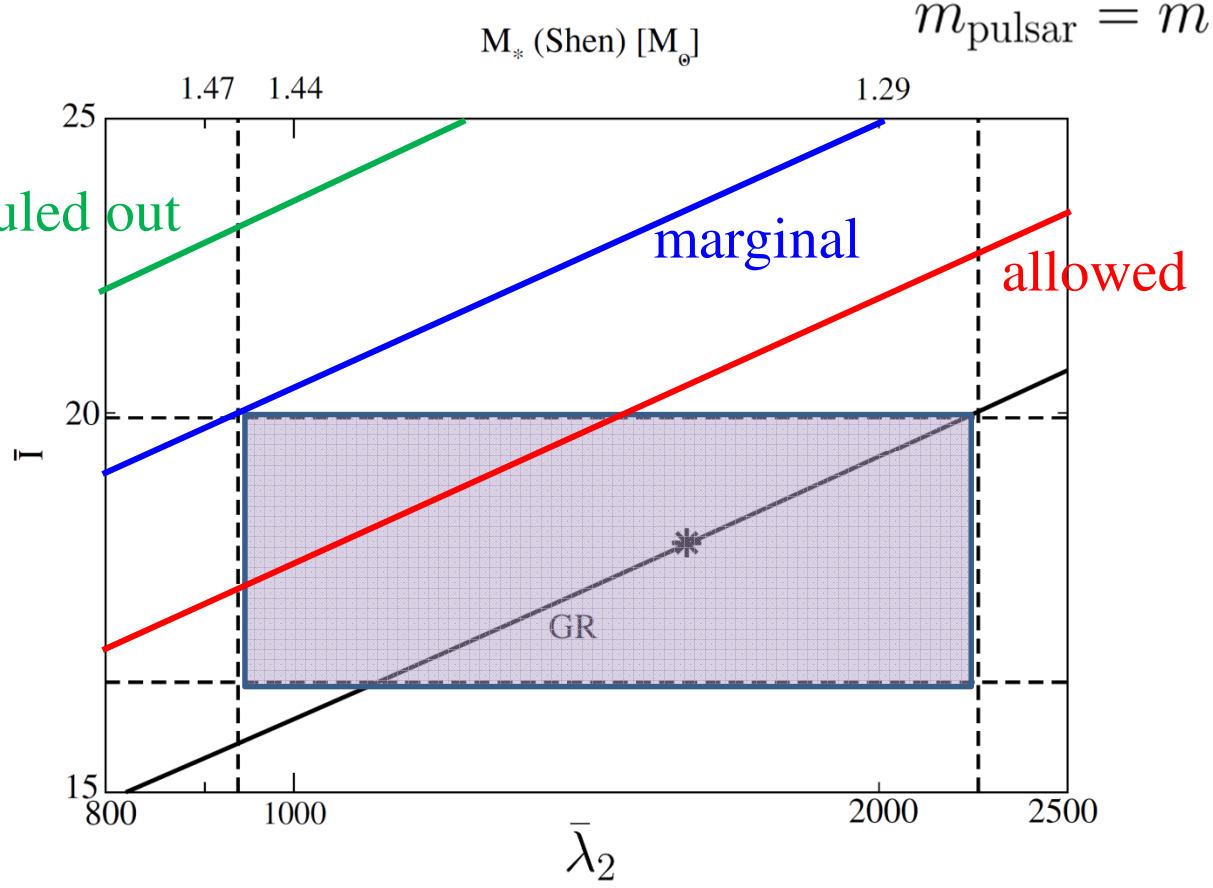
➡ Allows us, in principle, to measure independent spins

(II) Gravitational Physics

-double binary pulsar ➡ $\Delta\bar{I}/\bar{I} = 10\%$

-GWs ➡ $\Delta\bar{\lambda}_2/\bar{\lambda}_2 = 60\%$

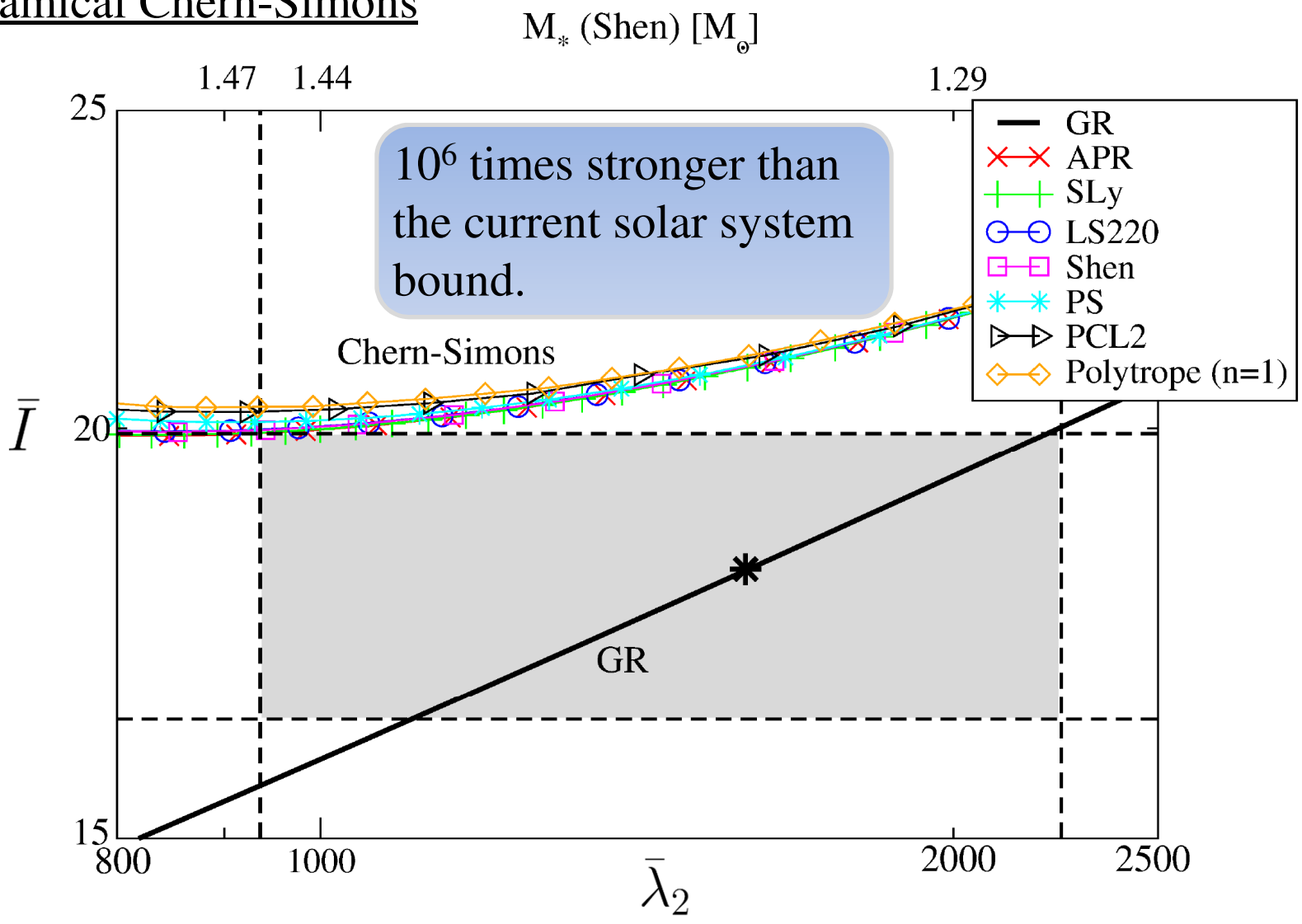
$m_{\rm pulsar} = m_1 = m_2$



Strong-field Tests of Gravity

[KY & Yunes, Science, PRD (2013)]

Dynamical Chern-Simons



(iii) Nuclear Physics

[KY (2014)]

$$\Psi_{\bar{\lambda}_\ell} \sim \bar{\lambda}_\ell^{(1)} X_1^{2\ell-1} x^{2\ell-3/2} + (1 \leftrightarrow 2)$$

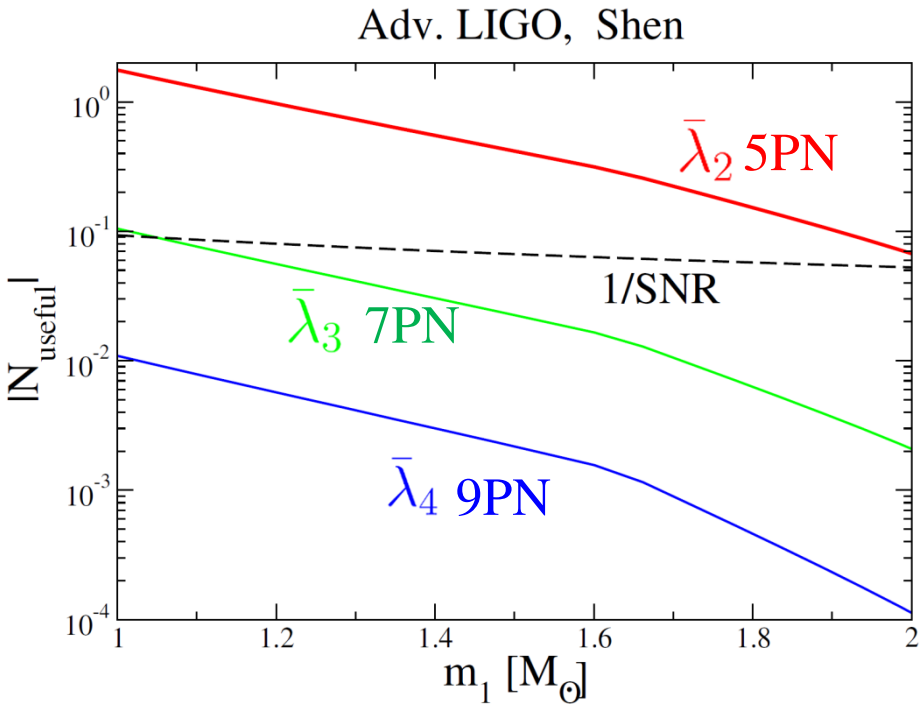
$\Rightarrow$ $(2\ell+1)$ PN

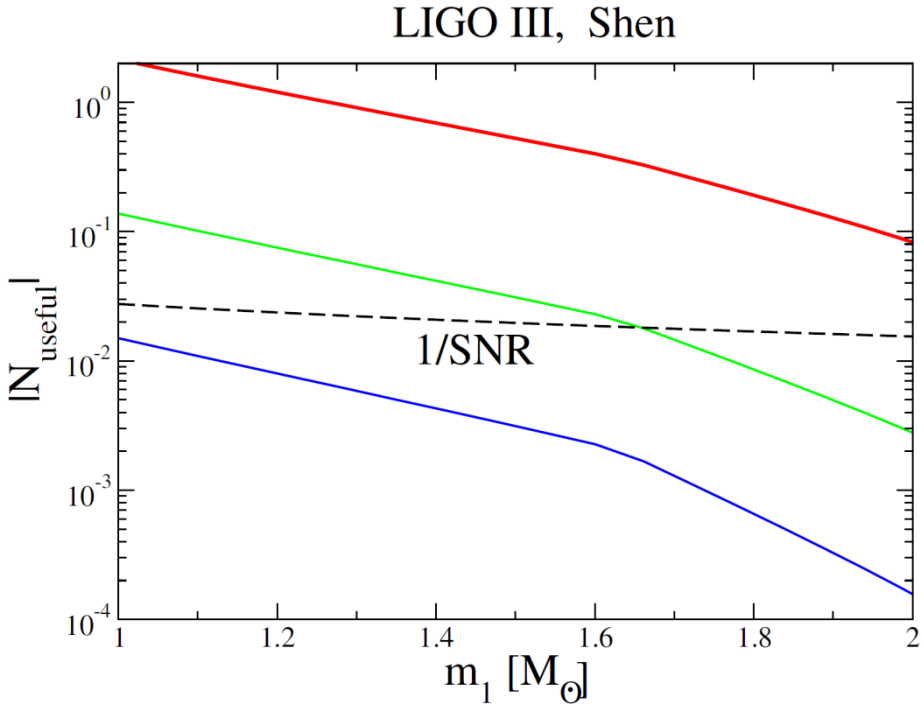
$$\bar{\lambda}_\ell \equiv \frac{\lambda_\ell}{m^{2\ell+1}} \qquad X_A \equiv \frac{m_A}{M}$$

$$x \equiv (\pi M f)^{2/3} \qquad M \equiv m_1 + m_2$$

Useful number of cycles

$D_L = 100\mathrm{Mpc}$ $\quad m_1 = m_2$



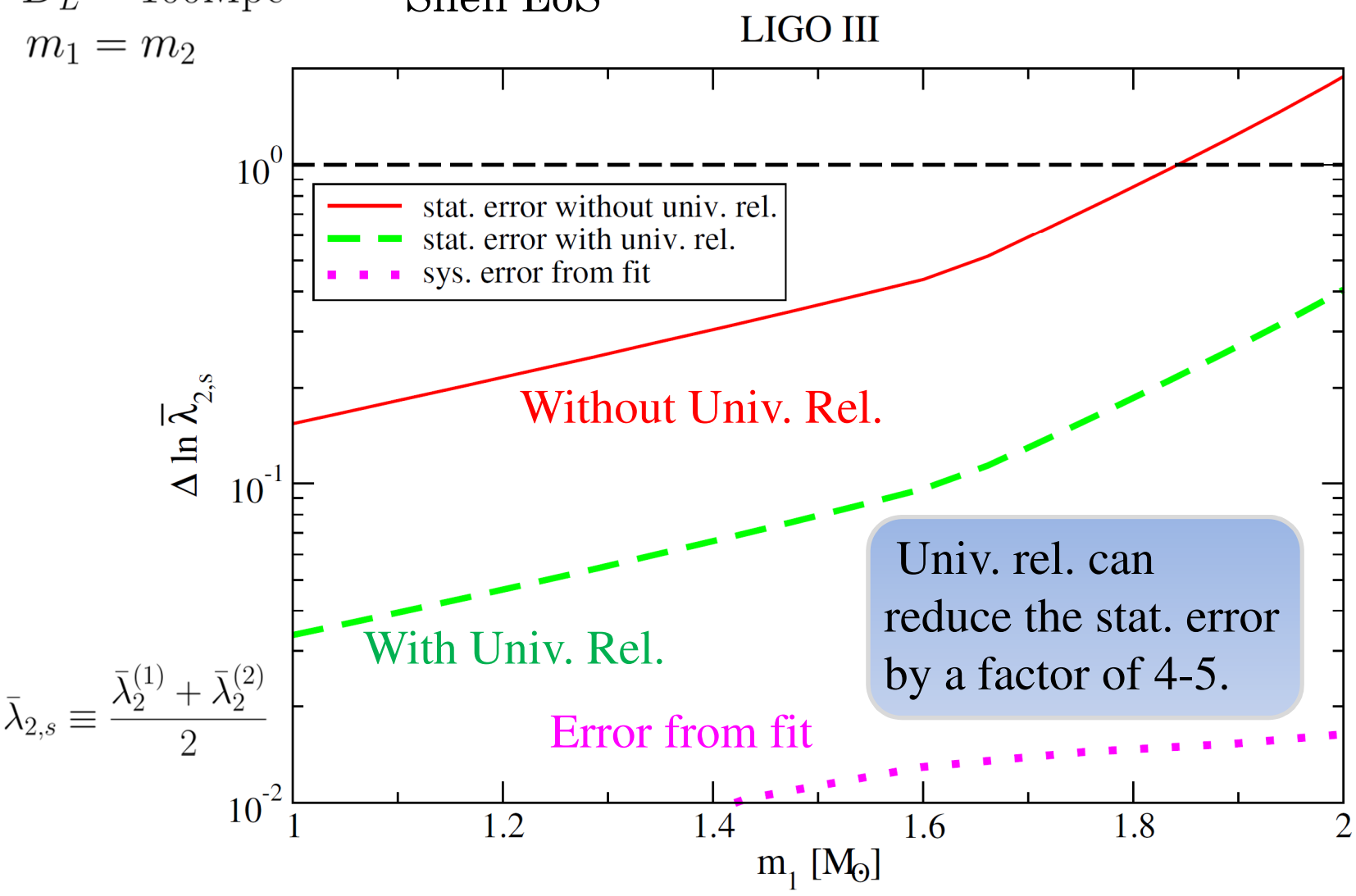


Impact of Multipole Love Relations

[KY (2014)]

$D_L = 100\mathrm{Mpc}$
$m_1 = m_2$

Shen EoS



$$\bar{\lambda}_{2,s} \equiv \frac{\bar{\lambda}_2^{(1)} + \bar{\lambda}_2^{(2)}}{2}$$

Other Related Topics

(I) Applications to X-ray Observations

(II) 3-Hair Relations for Newtonian Polytropes

(III) Why I-Love-Q

(I) Applications to X-ray Observations

Parameters:

$(M, R, I, Q, \cdots)$

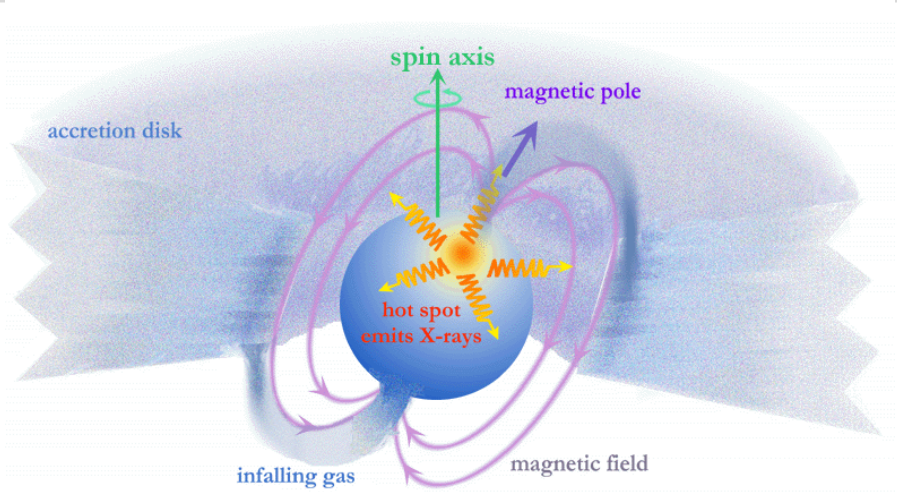
Strong degeneracies among parameters

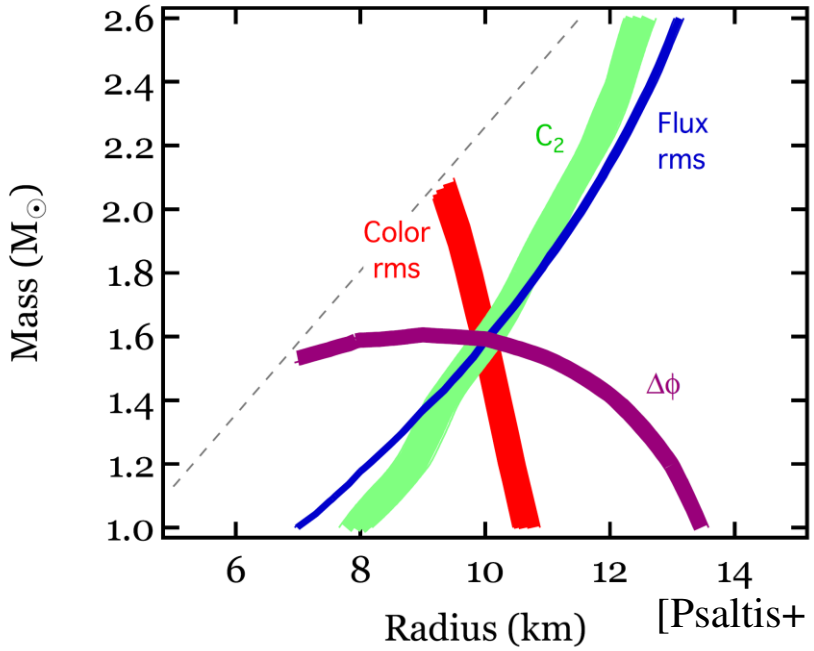
⇓ universal relations

Reduce the number of parameters

⇓

Allows one to measure mass and radius accurately!





[Psaltis+ (2014)]

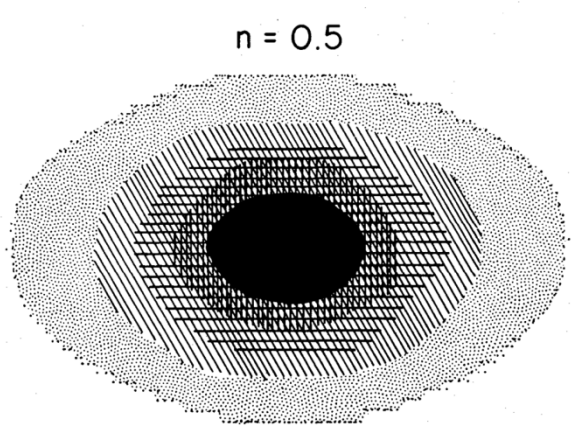
(II) Newtonian 3-Hair Relations

[Stein, KY & Yunes (2014)]

-Newtonian
-rigid rotation
-unmagnetized
- $p = K\rho^{1+1/n}$
-elliptical isodensity

$$M_\ell + i\frac{q}{a}S_\ell = \bar{B}_{n,\lfloor\frac{\ell-1}{2}\rfloor} M(iq)^\ell$$

$$S_1 = aM \qquad M_2 = -q^2 M$$



[Butterworth (1976)]

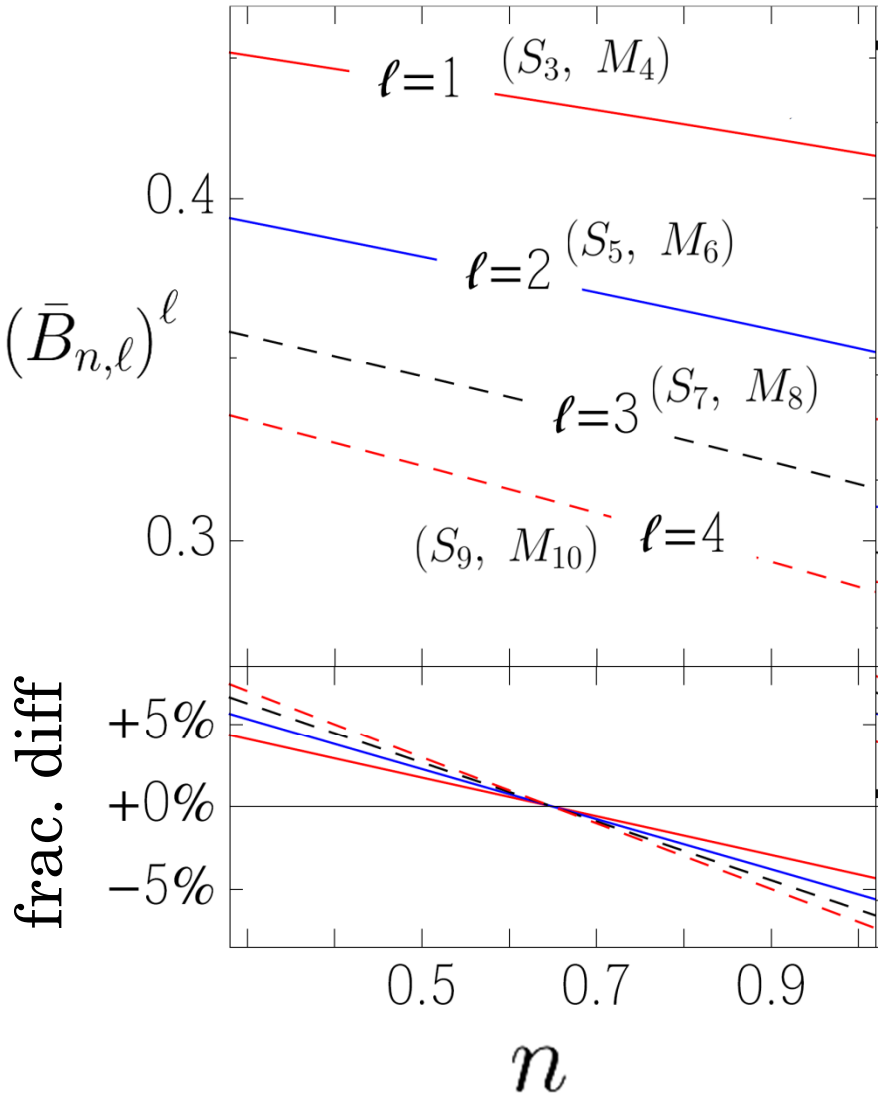
Black Hole No-hair Relation

[Hansen (1974)]

$$M_\ell + iS_\ell = M(ia)^\ell$$

Once the polytropic index *n* is specified, all the higher moments can be expressed in terms of the first three.

Equation of State Dependence



$$M_\ell + i\frac{q}{a}S_\ell = \overline{B}_{n,\lfloor\frac{\ell-1}{2}\rfloor} M(iq)^\ell$$

Coefficient is equation of state insensitive within ~5% for low-l modes

Effective NS No-hair Property

[KY+ (2014)]

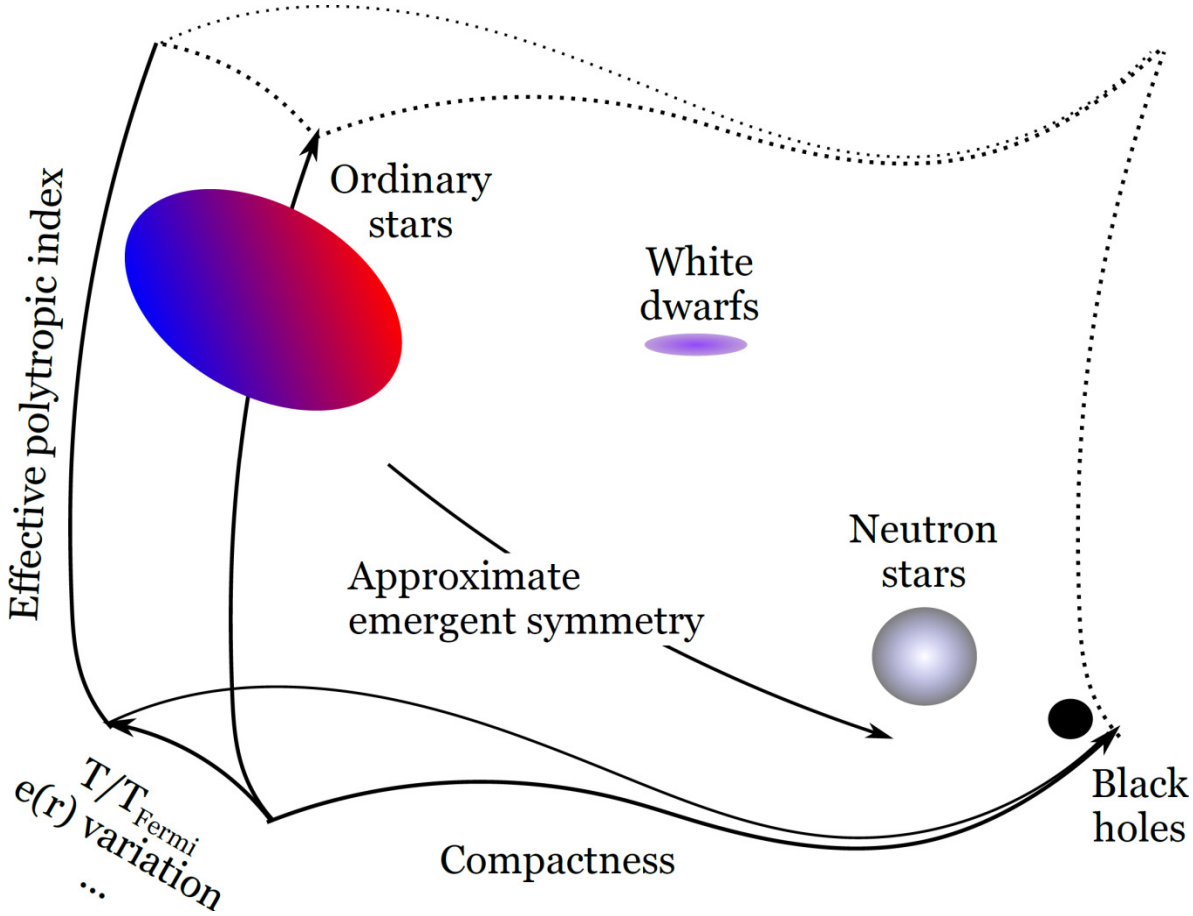
-NS lower multipole moments can be given in terms of the first three.

-confirmed up to M_4

(III) Why I-Love-Q

[KY+ (2014)]

Near self-similarity of isodensity contours plays a crucial role in the universality



Open Questions

Open Questions

(i) Improving parameter estimation:

-Fisher ➡ Bayesian

(ii) Universal relations & Tests of GR in other non-GR theories:

e.g. -Lorentz-violation in gravity

Einstein-Aether, Horava-Lifshitz

-curvature correction

Einstein-dilaton Gauss-Bonnet

f(R)

(iii) Universal relations in differentially-rotating NSs

-Naturally breaks the isodensity self-similarity

-4-hair relation?

(iv) Newtonian analysis

-multipole Love relation

-NS oscillation modes?
Other universal relations?

(v) Love numbers for spinning NSs?

Discussion from Monday Afternoon +α

-Can we construct a hybrid inspiral-merger-ringdown waveform with just one tidal parameter?

Universal relations between the damping time and compactness?

Universal relations among other parameters and compactness?

-How much post-merger oscillations further help constrain the EoS on top of the inspiral?

Which is better?

(i) Rewrite Λ and f_2 into a single parameter (R?) and constrain it strongly.

(ii) Treat Λ and f_2 independently and constrain different part of EoS.