Title: Probing Fundamental Physics with Universal Relations for Neutron Stars

Date: Nov 19, 2015 01:00 PM

URL: http://pirsa.org/15110064

Abstract: Neutron stars offer us an excellent testbed to probe fundamental physics, such as nuclear physics and strong-field gravity. Unlike the well-studied mass-radius relation for neutron stars that depends strongly on their internal structure, I first report unexpected universal relations that we found among the moment of inertia, tidal Love number and quadrupole moment ("I-Love-Q" relations) that are insensitive to the internal structure. Such universal relations help us break the degeneracy among neutron star parameters when probing fundamental physics with radio, X-ray or gravitational wave observations. In the second part of my talk, I explain similar universal relations among neutron star multipole moments, which resemble the no-hair property of black holes. I also mention how one can increase the amount of universality, and discuss that the transition from a "follicly-challenged" neutron star to a "bald" black hole may be related to second order phase transitions in condensed matter physics. In the final part of my talk, I report yet another universal relations among tidal parameters in gravitational waves from neutron star binaries. Such relations allow us to improve the measurability of the tidal effect with future observations, which increases the ability of probing astrophysics, nuclear physics, gravitational physics and even cosmology.

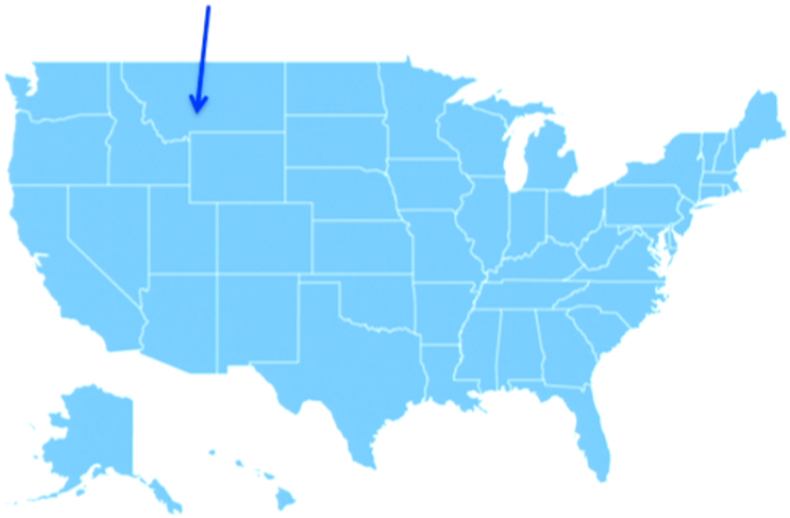
Probing Fundamental Physics with Universal Relations for Neutron Stars

Kent Yagi
Department of Physics, Princeton University

Perimeter Institute
19th Nov. 2015

Who is Kent Yagi???

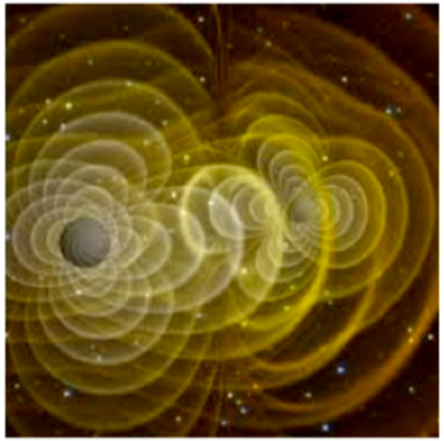
Montana State University



What does Kent work on?

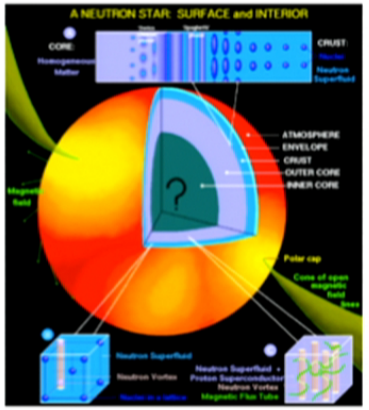
(I) Testing strong-field gravity with binary pulsar and gravitational wave observations

- -scalar-tensor theories
- -massive graviton theories
- -extra dimension theories
- -Einstein-dilaton Gauss-Bonnet gravity
- -dynamical Chern-Simons gravity
- -Lorentz-violating gravity



(II) Neutron star properties in General Relativity

- -universal relations among observables
- -approximate no-hair relations



What are Neutron Stars?

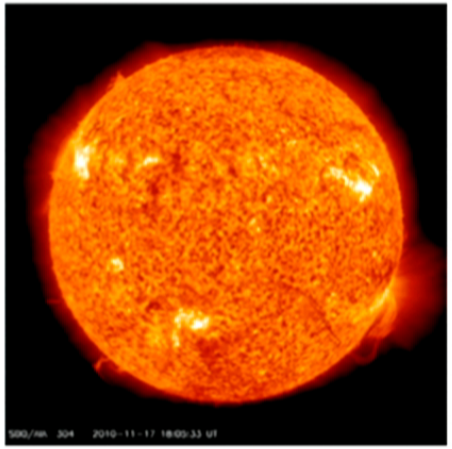
-final fate of massive stars

-mass: 1-2M_{sun}

-radius: 10-14km

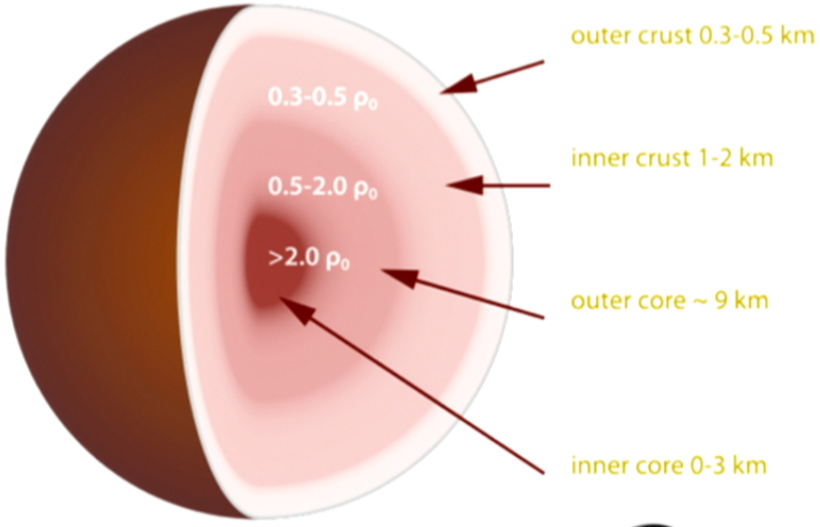
-compactness: 0.1-0.2

$\frac{GM}{c^2 R}$ 0.5 (black hole)



-consist of n, p, e, μ, …

-internal structure currently unknown



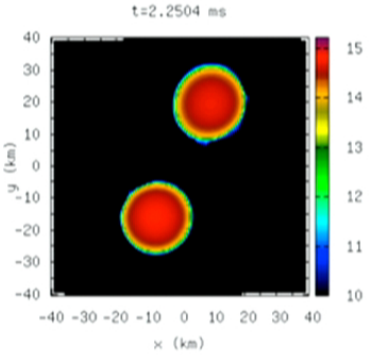
$\rho_0 \approx 7 \times 10^{14} \mathrm{g/cm}^3$

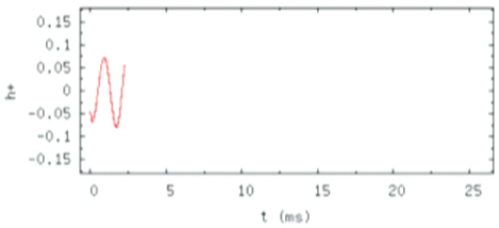
Why are Neutron Stars cool?

(i) probing nuclear physics

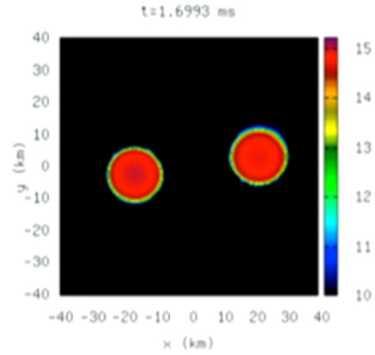
$(m_1, m_2) = (1.2, 1.5) M_\odot$

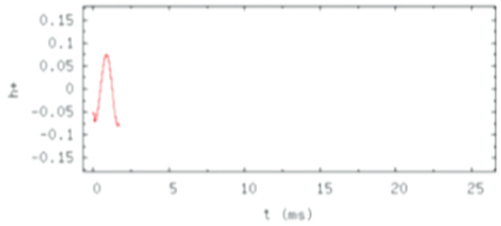
H (stiff)





APR (soft)

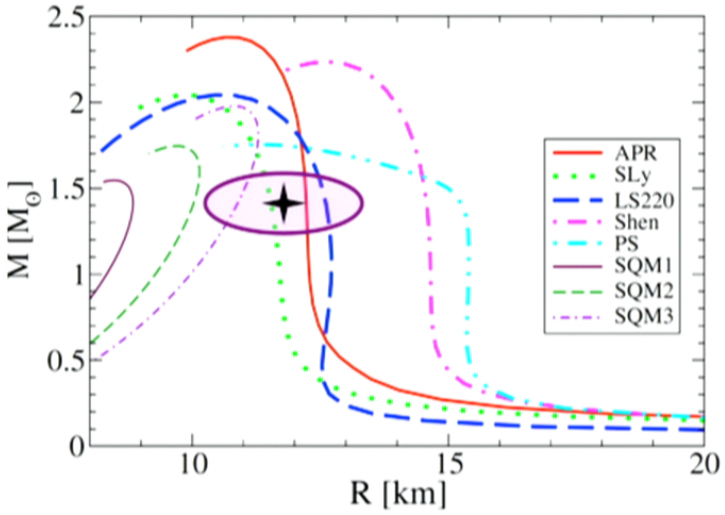




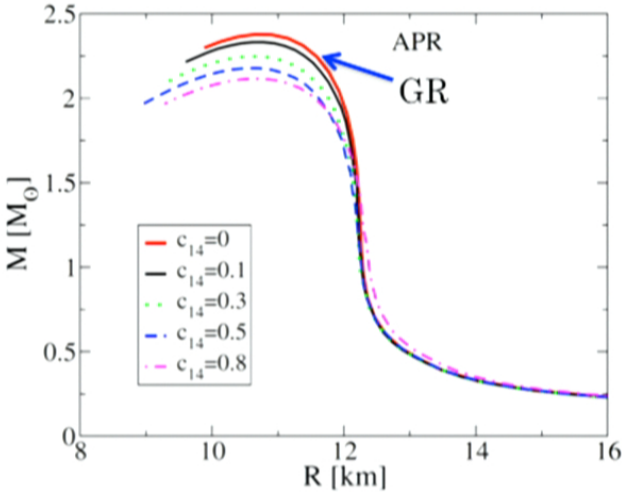
Simulations by Kenta Hotokezaka

Why are Neutron Stars cool?

(i) probing nuclear physics



(ii) probing strong-field gravity



Einstein-EAther theory

[Yagi, et al. (2014)]

Problems

-Degeneracies among parameters

-Degeneracies between uncertainties in nuclear and gravitational physics

universal relations!!

Roadmap

(IV) Discussions & Conclusions

(III) Binary Love Relations

(I) I-Love-Q Relations

(II) Approximate NS No-hair Relations

I-Love-Q Relations

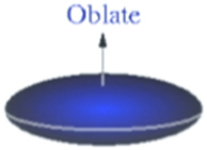
KY & Yunes, Science 341, 365 (2013)
KY & Yunes, PRD 88, 023009 (2013)

Kent Yagi

I-Love-Q

I moment of inertia

Q (spin-induced) quadrupole moment



λ_2 tidal Love number (tidal deformability)

$$\lambda_2 = \frac{\text{(tidally induced) Q}}{\text{tidal field}}$$

Construct slowly-rotating/tidally-deformed NS solutions by solving the Einstein equations numerically.

Extract I, Love & Q from the asymptotic behavior of the metric at spatial infinity.

I-Love-Q Relations

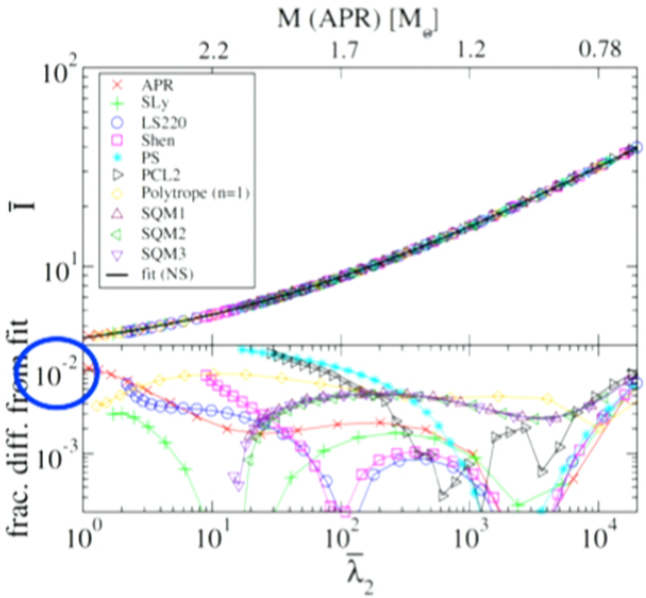
[KY & Yunes, Science, PRD (2013)]

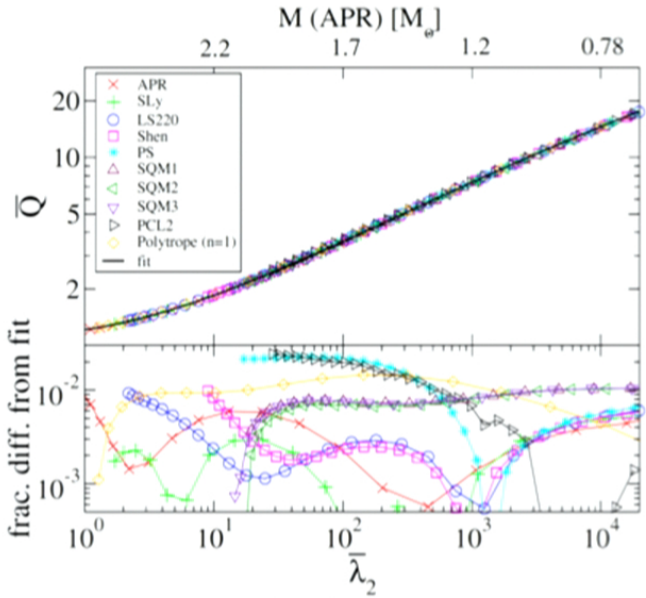
(i) small/static tidal deformation ⇒ Maselli+ (2013)

(ii) unmagnetized ⇒ Haskell+ (2014)

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

(iv) barotropic, isotropic ⇒ Martinon+ (2014), KY & Yunes (2015)





$$\bar{I} \equiv I/M^3 \quad \bar{\lambda}_2 \equiv \lambda_2/M^5 \quad \bar{Q} \equiv -Q/(M^3\chi^2) \quad \chi \equiv S_1/M^2$$

Applications (I): Nuclear Physics

Parameters:

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

I-Q relation

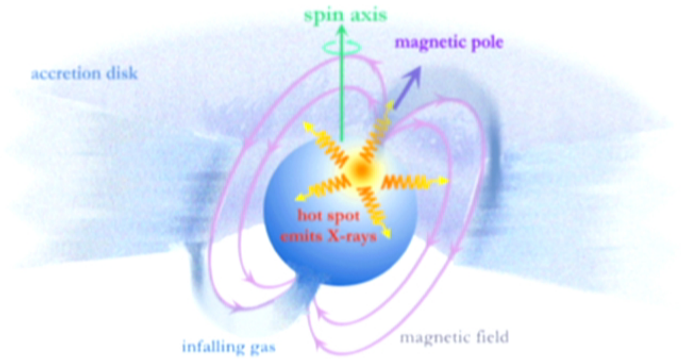
Strong degeneracies among parameters

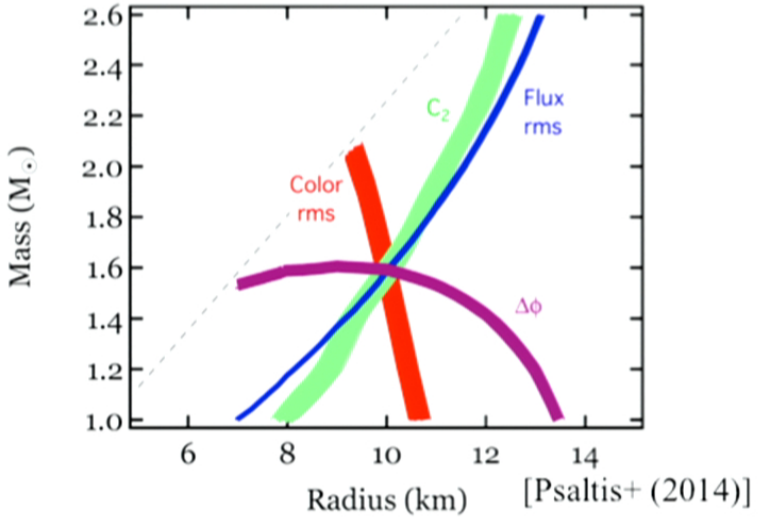
⇓ universal relations

Reduce the number of parameters

⇓

Allows one to measure mass and radius accurately!





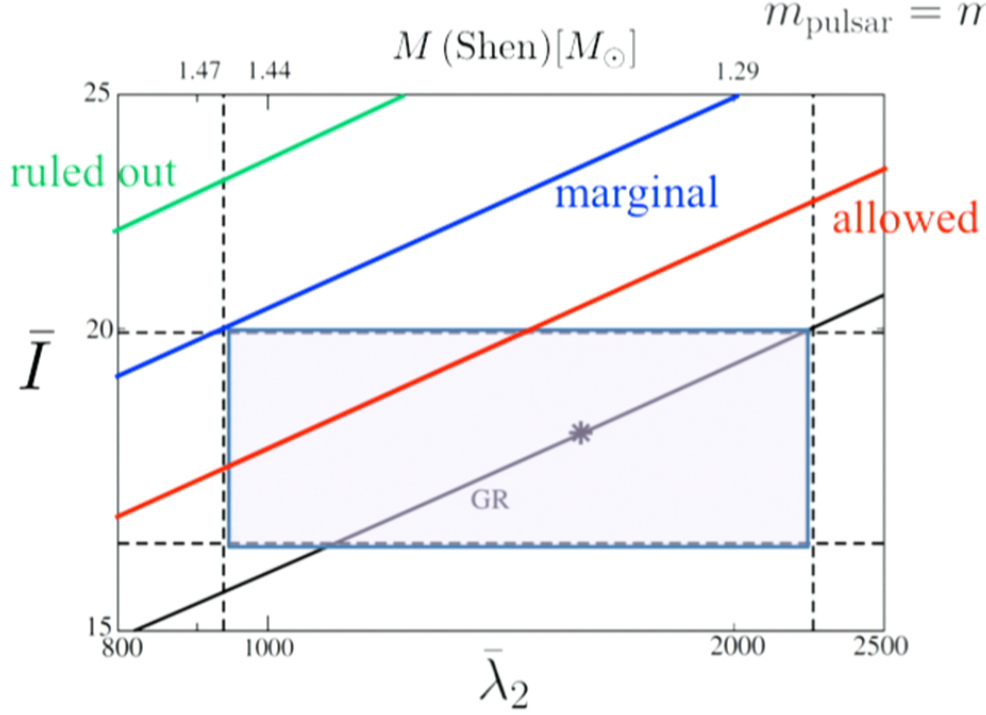
[Psaltis+ (2014)]

Applications (II): Gravitational Physics

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

-gravitational waves ➡ $\Delta\bar{\lambda}_2/\bar{\lambda}_2 = 40\%$

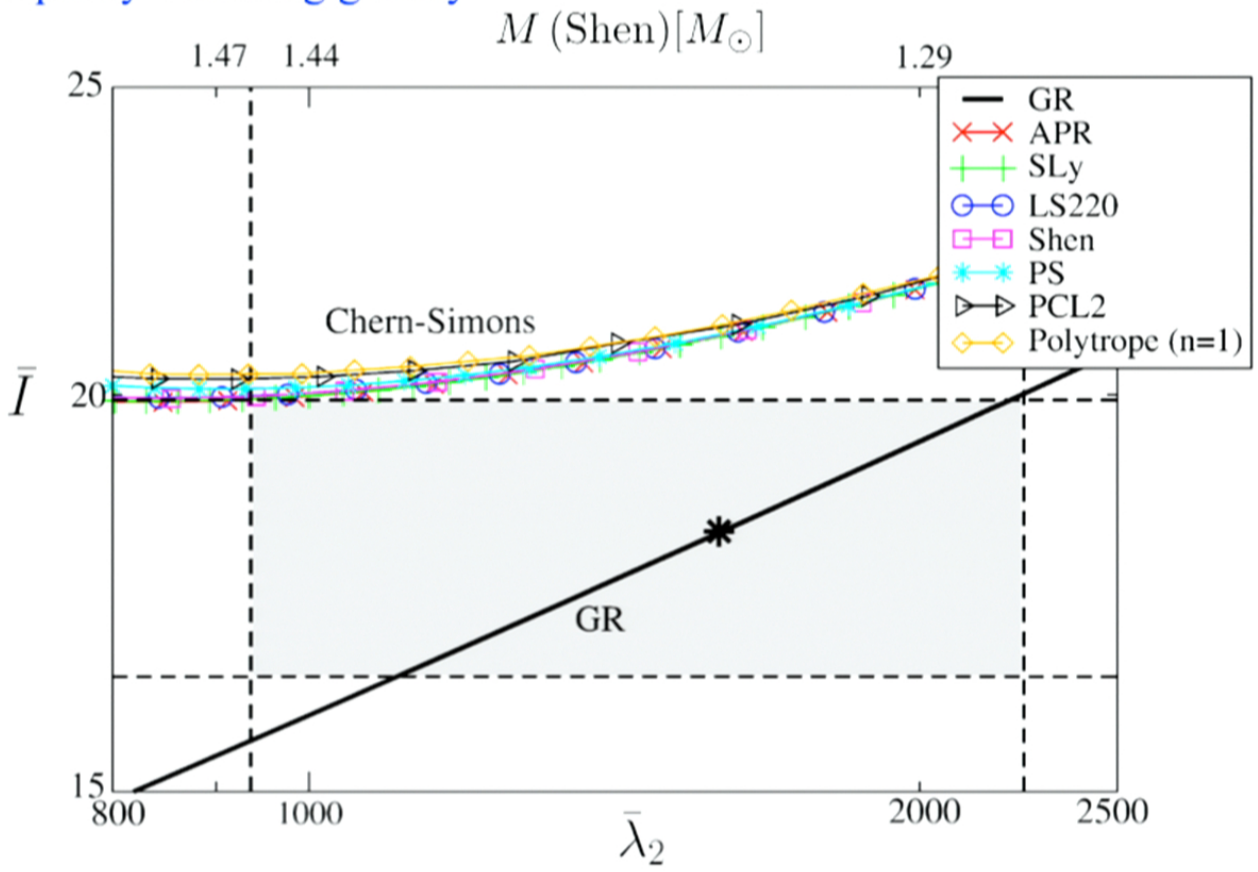
$m_{\rm pulsar} = m_1 = m_2$



Strong-field Tests of Gravity

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

Testing a parity-violating gravity



Approximate No-hair Relations for Neutron Stars

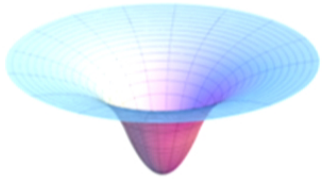
Stein, KY & Yunes, ApJ 788, 15 (2014)
KY et al., PRD 89, 124013 (2014)

Kent Yagi

Multipole Moments

Exterior spacetime of an object is characterized by multipole moments

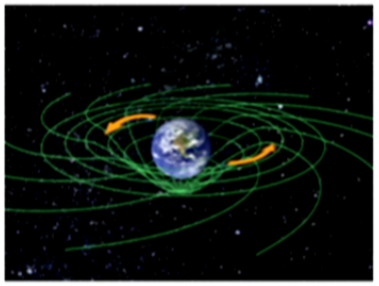
Gravitational potential



$$g_{tt} \sim -1 - 2\sum_{\ell=0}\left[\frac{M_\ell}{r^{\ell+1}} + \mathcal{O}\left(\frac{1}{r^{\ell+2}}\right)\right] P_\ell(\cos\theta)$$

$$g_{t\phi} \sim -2\sin^2\theta \sum_{\ell=1}\left[\frac{1}{\ell}\frac{S_\ell}{r^\ell} + \mathcal{O}\left(\frac{1}{r^{\ell+1}}\right)\right] P'_\ell(\cos\theta)$$

"spacetime" dragging



Black Holes are Bald

BHs only have two hairs, mass and spin

Black Hole No-hair Relation

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

$a = S/M (\equiv S_1/M_0)$ [Hansen (1974)]

Are Neutron Stars also Bald?

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

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

[Stein, KY & Yunes (2014)] $\left(a = S/M \quad q^2 = -Q/M\right)$

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

Q-taro

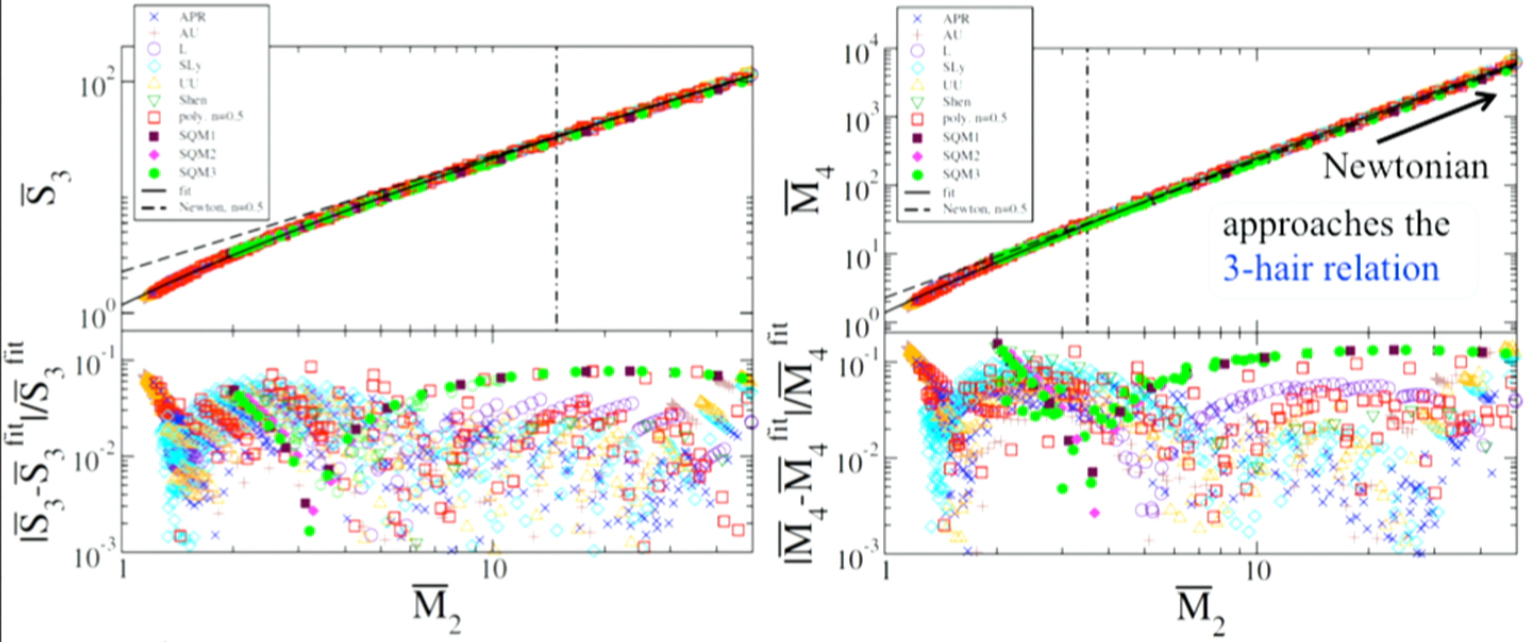
Once the polytropic index n is specified, all the higher moments can be expressed in terms of the first three.

NSs are Follicly-challenged!

[KY+ (2014)]

Calculations in full GR with realistic EoSs

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



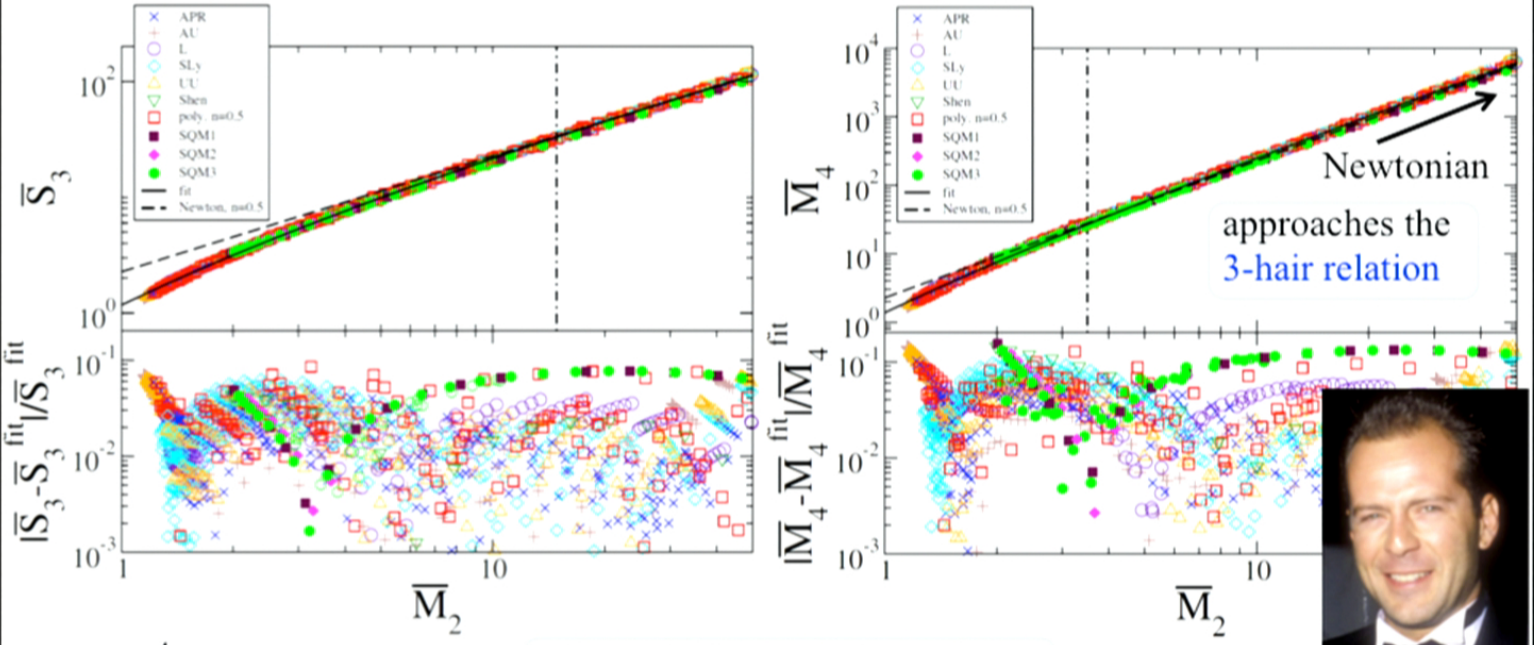
$$\bar{A} \equiv \frac{A}{A_{\rm RH}}$$

NSs are Follicly-challenged!

[KY+ (2014)]

Calculations in full GR with realistic EoSs

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



$$\bar{A} \equiv \frac{A}{A_{\rm RH}}$$

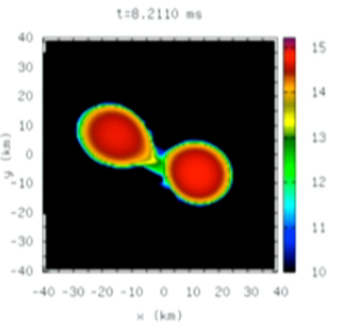
NSs are follicly challenged!

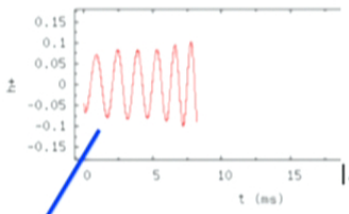
Binary Love Relations

KY & Yunes (in prep.)

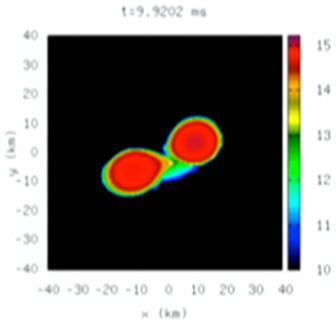
Kent Yagi

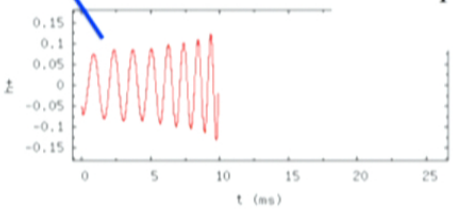
Tidal Effect on Gravitational Waves

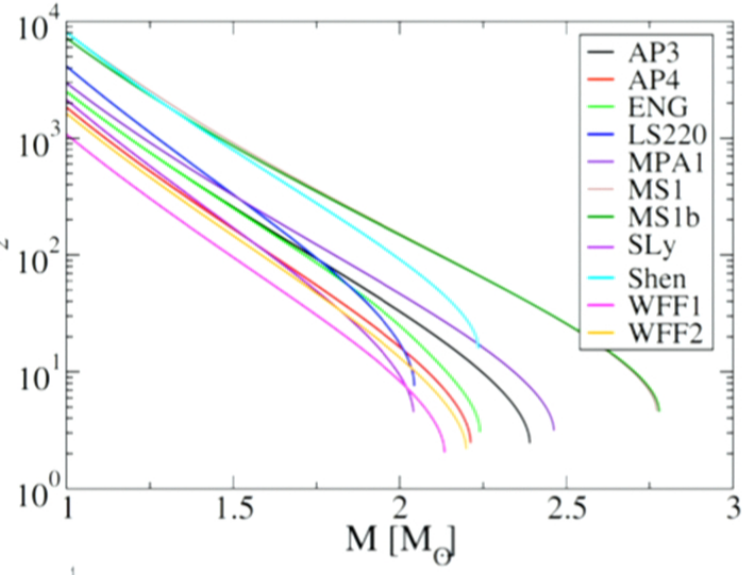




$M,\ \bar{\lambda}_2$

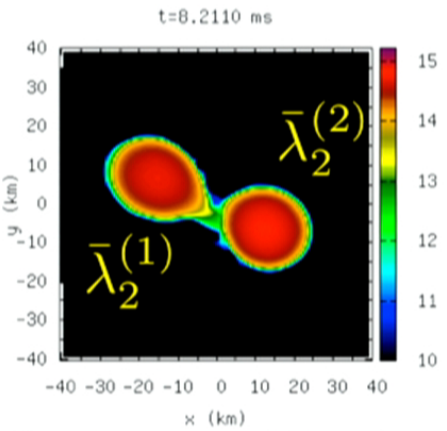


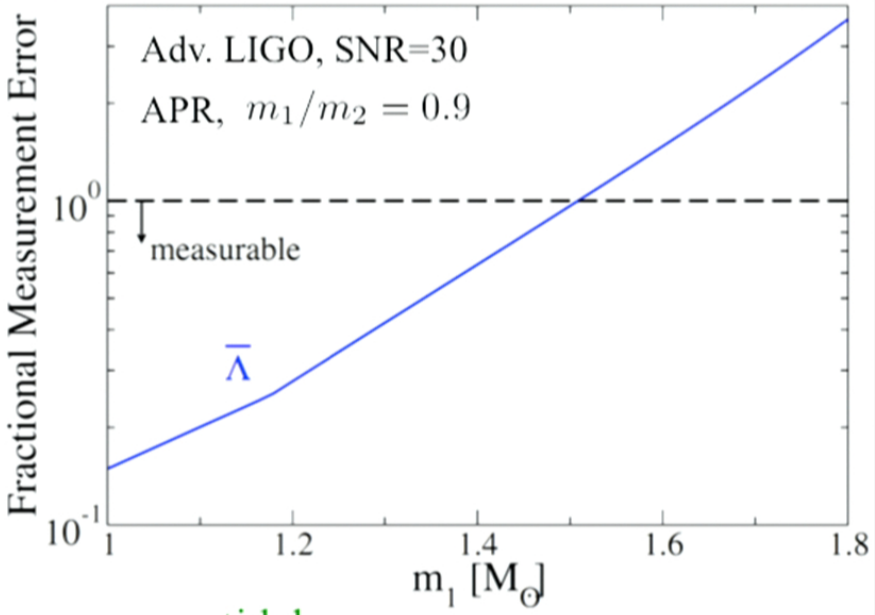




Independent measurement of the Love number and mass with GWs constrains the EoS!

Tidal Parameters and Measurement Accuracy





Gravitational Waveform Phase

Flanagan & Hinderer (2007)
Vines Flanagan & Hinderer (2011)

point particle tidal

$$\Psi = \Psi_{0\mathrm{PN}}\left[1 + \cdots + C_5\bar{\Lambda}x^5 + \left(C_6^{(\bar{\Lambda})}\bar{\Lambda} + C_6^{(\delta\bar{\Lambda})}\delta\bar{\Lambda}\right)x^6 + \cdots\right]$$

$$\bar{\Lambda} = \bar{\Lambda}\left(\bar{\lambda}_2^{(1)}, \bar{\lambda}_2^{(2)}, \frac{m_1}{m_2}\right) \quad \delta\bar{\Lambda} = \delta\bar{\Lambda}\left(\bar{\lambda}_2^{(1)}, \bar{\lambda}_2^{(2)}, \frac{m_1}{m_2}\right) \quad x = [\pi(m_1+m_2)f]^{2/3} \sim v^2$$

Questions

(I) Can we measure tidal parameters that are physically more meaningful?
(Can we measure tidal Love numbers of individual bodies?)

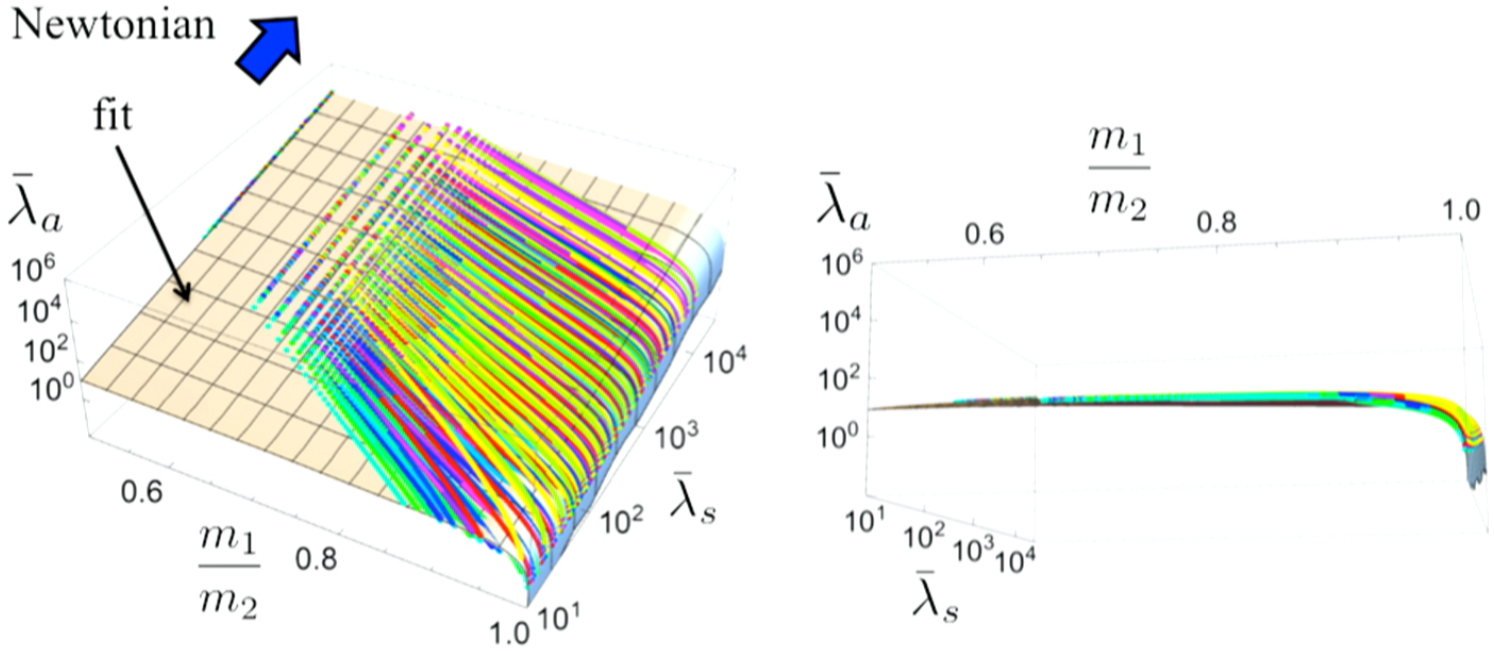
(II) Can we improve the measurement accuracy of tidal parameters?

universal relations!

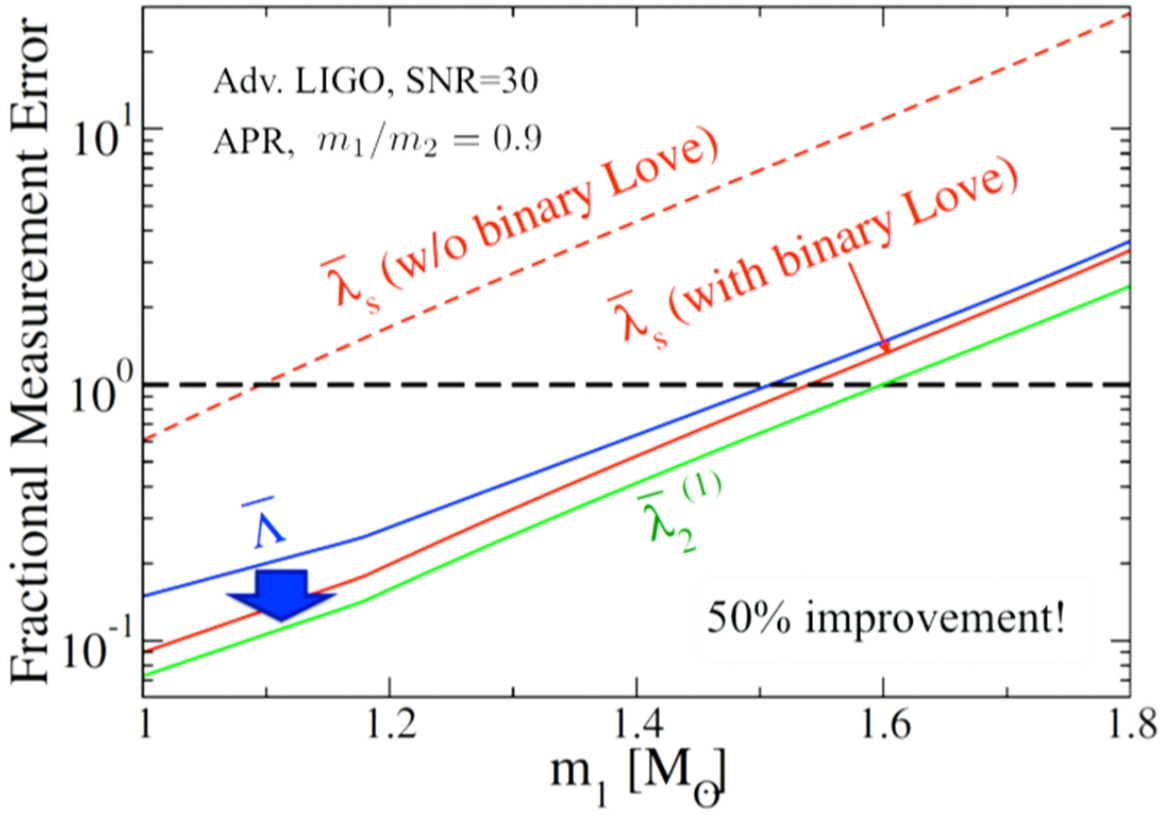
Such relations between two tidal parameters allow us to break the degeneracy between them.

Binary Love Relation

$$\bar{\lambda}_s \equiv \frac{\bar{\lambda}_2^{(1)} + \bar{\lambda}_2^{(2)}}{2} \qquad \bar{\lambda}_a \equiv \frac{\bar{\lambda}_2^{(1)} - \bar{\lambda}_2^{(2)}}{2} \qquad \bar{\lambda}_a = \bar{\lambda}_a\left(\bar{\lambda}_s, \frac{m_1}{m_2}\right)$$



Impact of Binary Love Relation

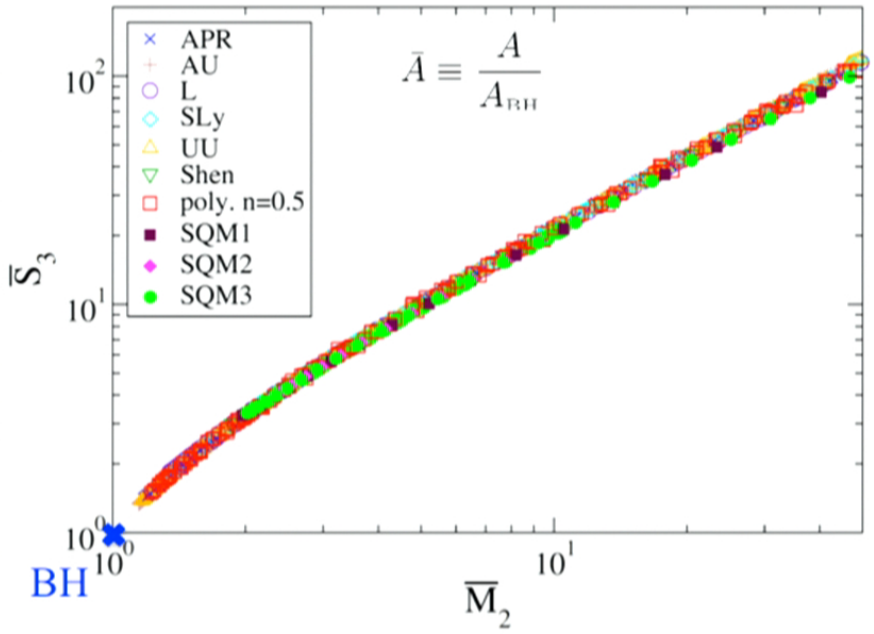


Discussions and Conclusions

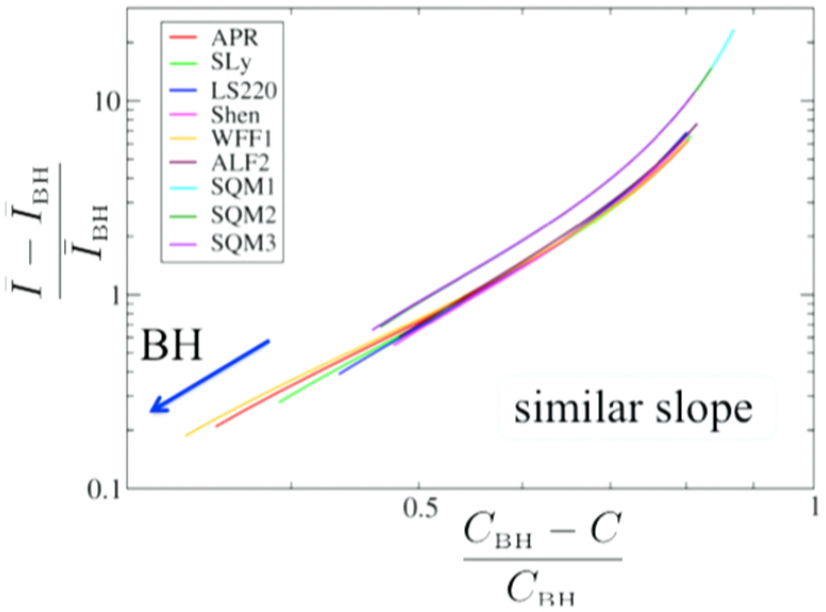
KY & Yunes, PRD 91, 103003 (2015)

Kent Yagi

How do NSs lose their hair…?



Phase Transition…?



$$\bar{I}-\bar{I}_{\rm BH} \propto |C-C_{\rm BH}|^{k_{\bar{I}}}$$

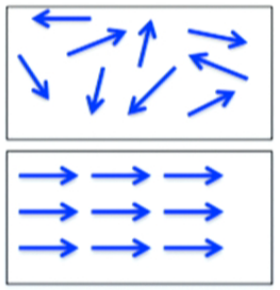
EoS variation

$k_{\bar{I}}$	$3.90(\pm 0.49)$
$k_{\bar{Q}}$	$4.22(\pm 0.45)$
$k_{\bar{S}_3}$	$4.19(\pm 0.49)$

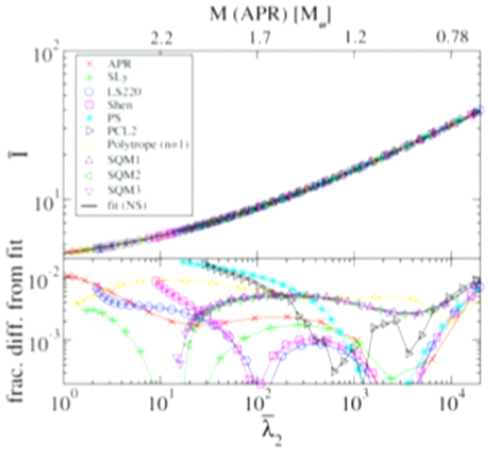
EoS universality of ~10% in the scaling exponent

Relations to 2nd order phase transition?

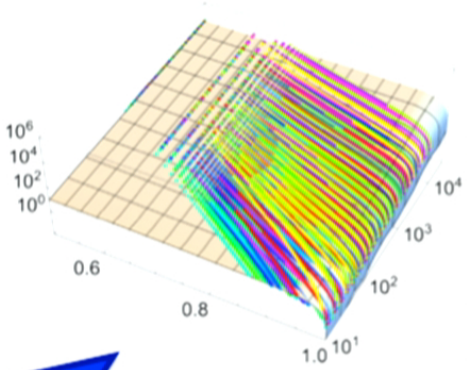
e.g. ferromagnetism



Takeaway



I-Love-Q Relations



Nuclear Physics

Gravitational Physics

NS No-hair Relations

Universal relations are useful in probing fundamental physics!!

Binary Love Relations

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