Universal Relations in Neutron Stars: Implications in Gravitational-wave Astronomy

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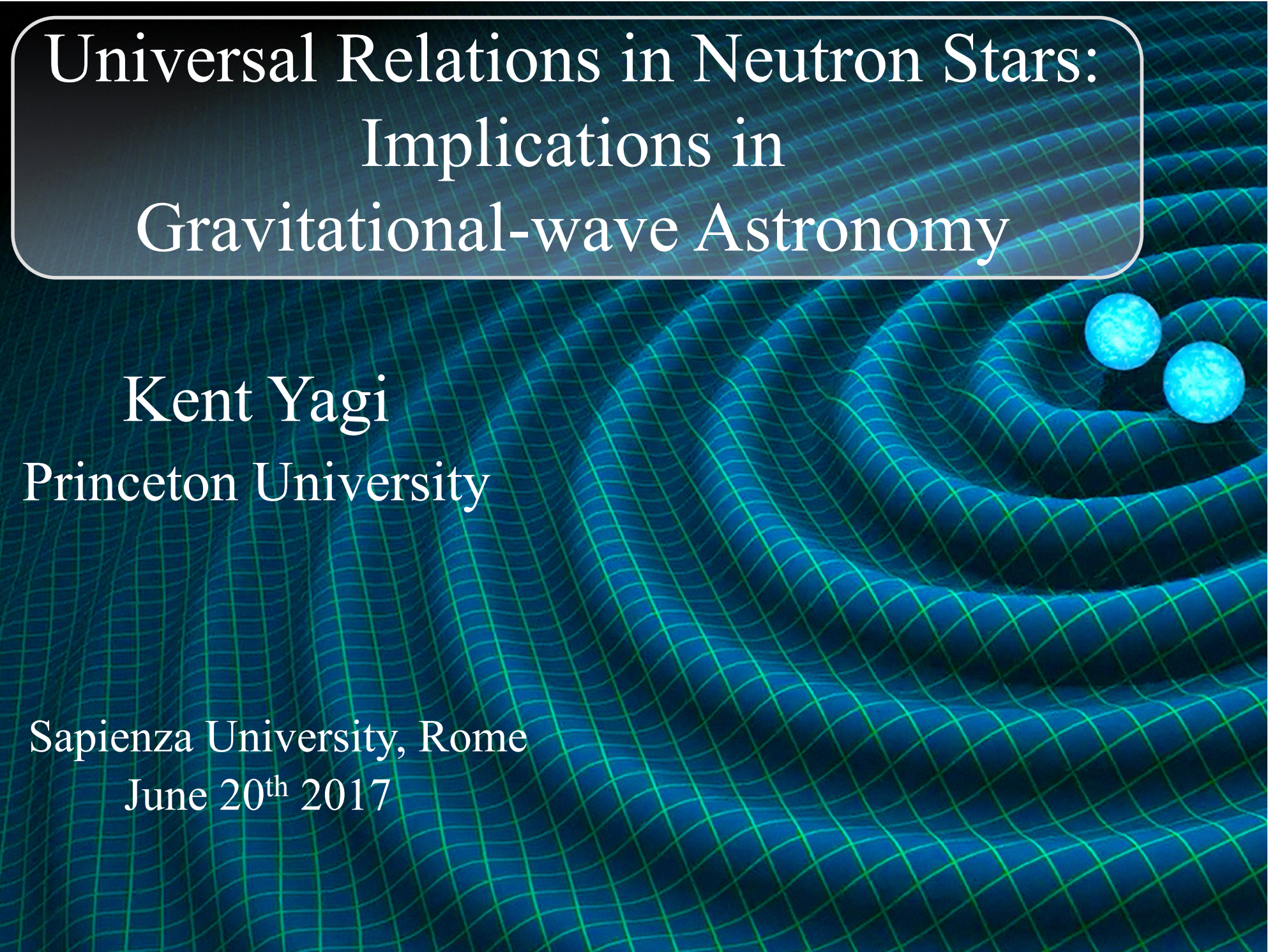
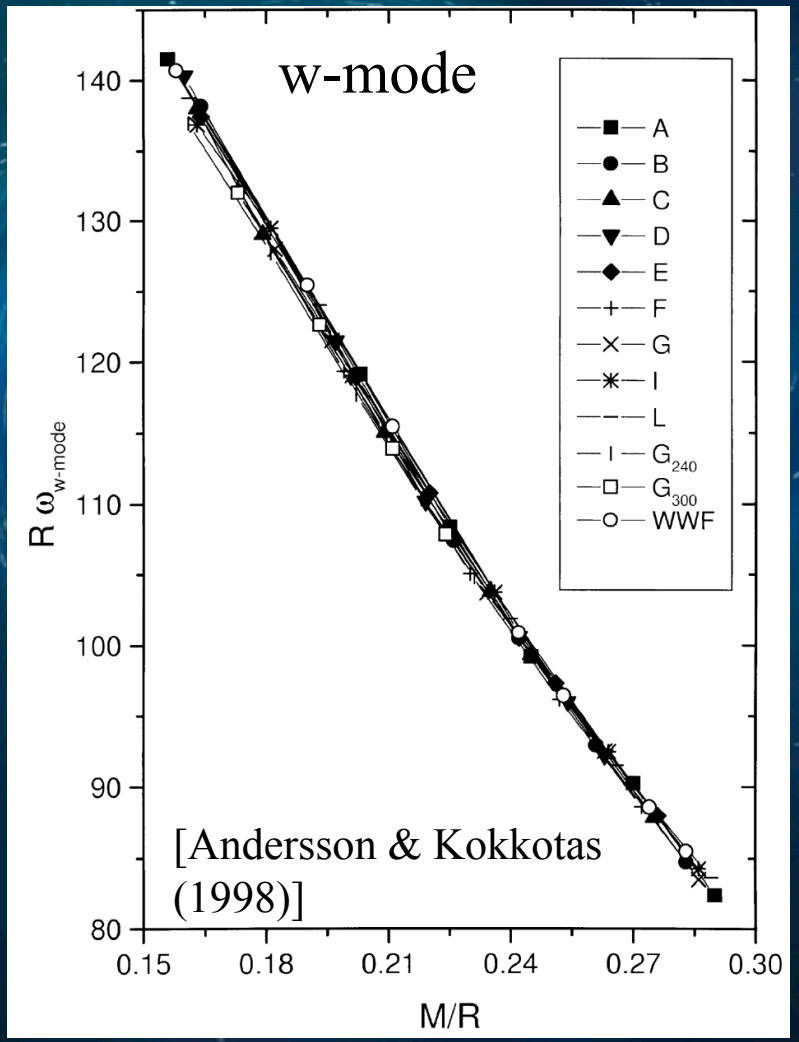
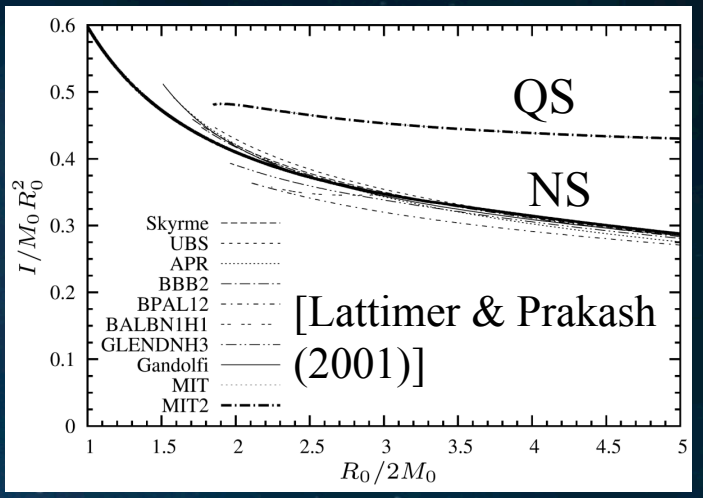
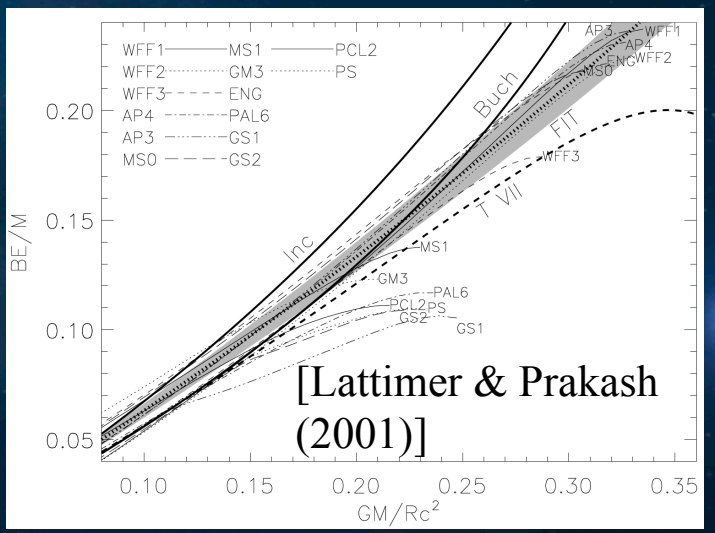


Universal Relations: Isolated NSs

relations among NS observables that do not depend strongly on the equation of state





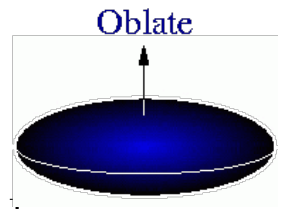


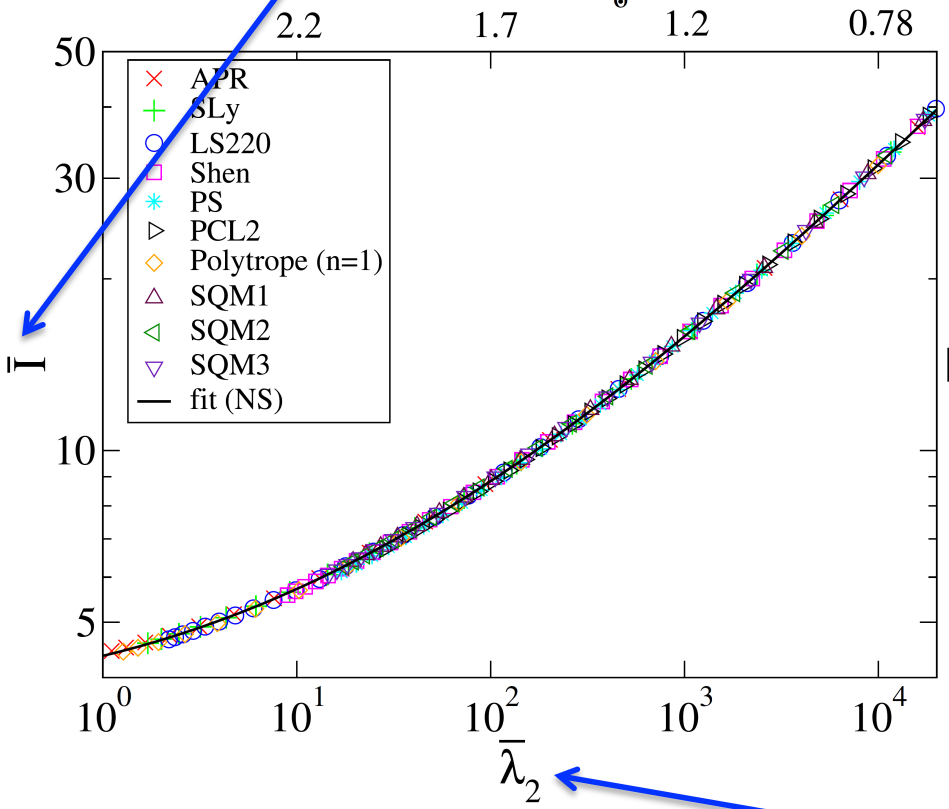
I-Love-Q Relations

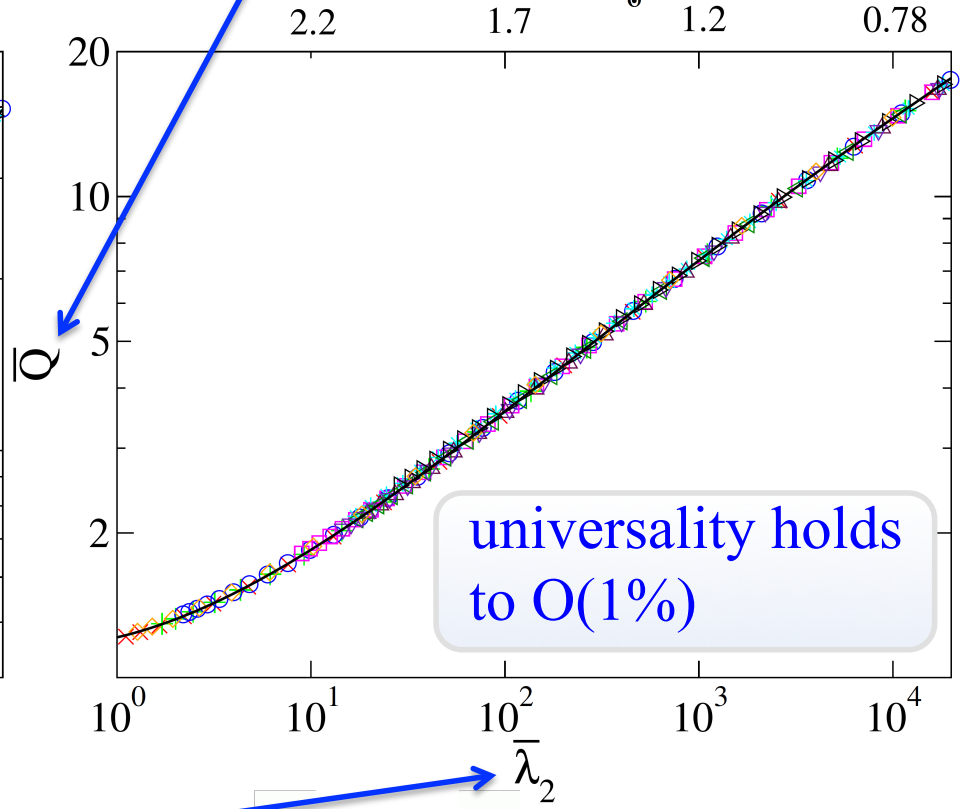
[KY & Yunes, Science 341 365 (2013)]

moment of inertia

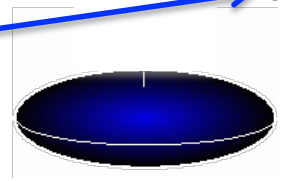
(spin-induced)
quadrupole moment



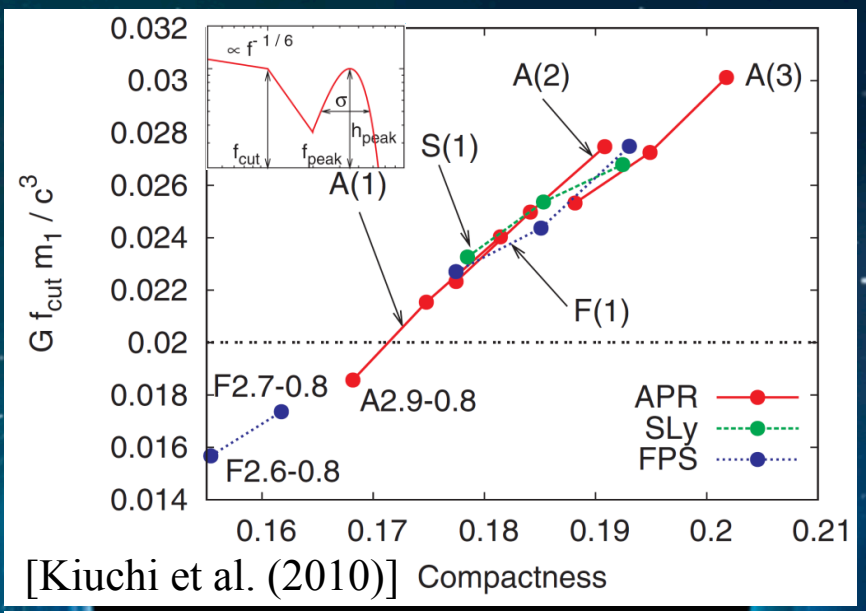




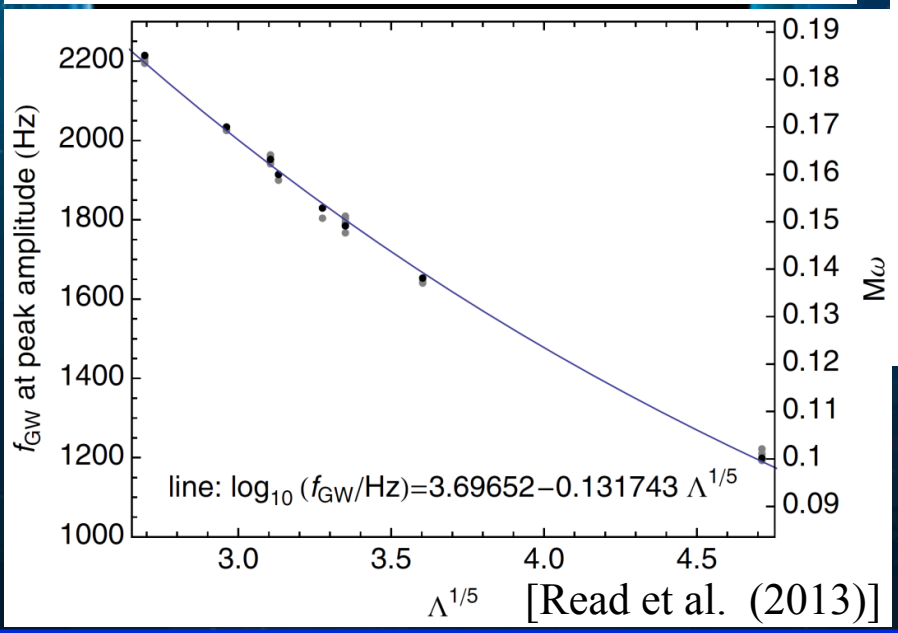
tidal Love number
(tidal deformability)



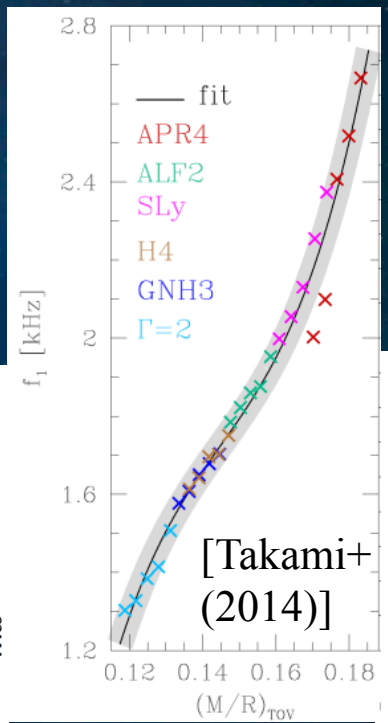
Universal Relations: Binary NS Mergers



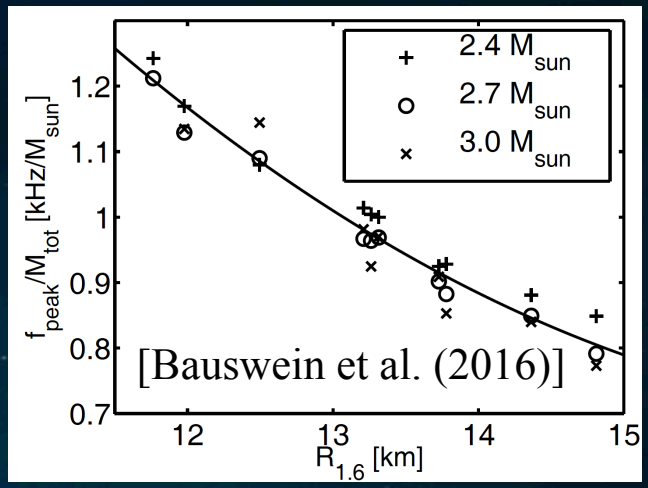
[Kiuchi et al. (2010)]



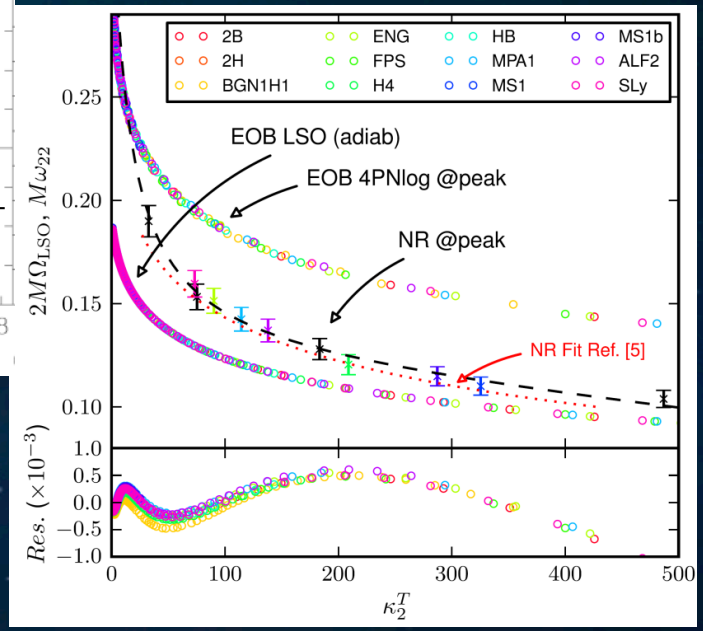
[Read et al. (2013)]



[Takami+ (2014)]



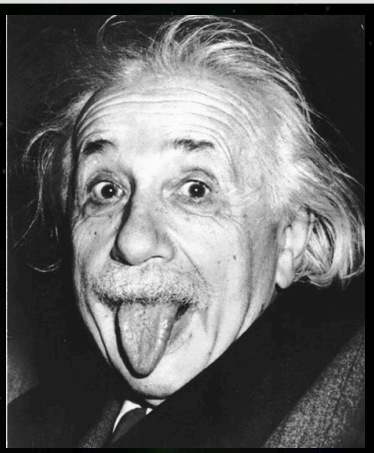
[Bernuzzi et al. (2014)]

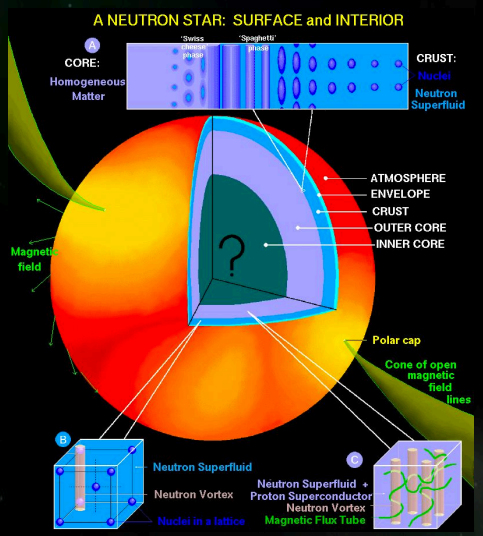


Outline

Astrophysics

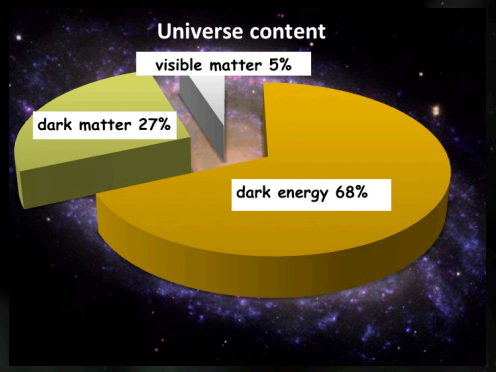
Gravitational Physics





Universal Relations

review article [KY & Yunes, Phys. Rept. (2017)]



Nuclear Physics

Cosmology

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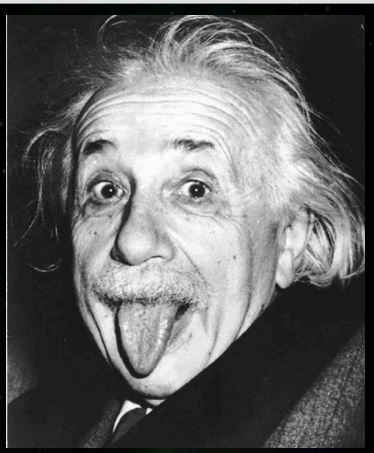

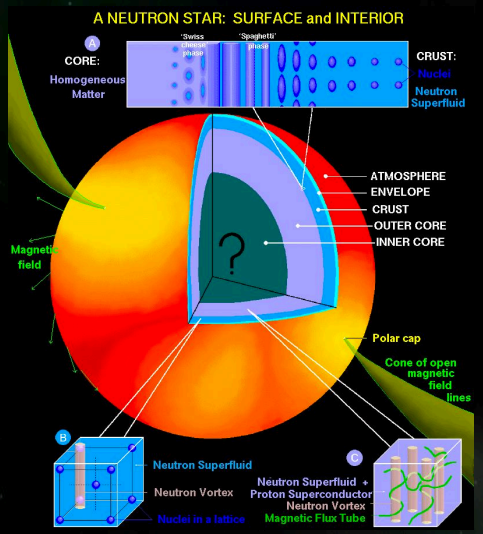

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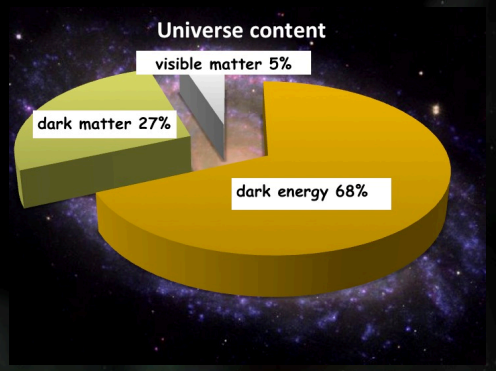


Nuclear Physics

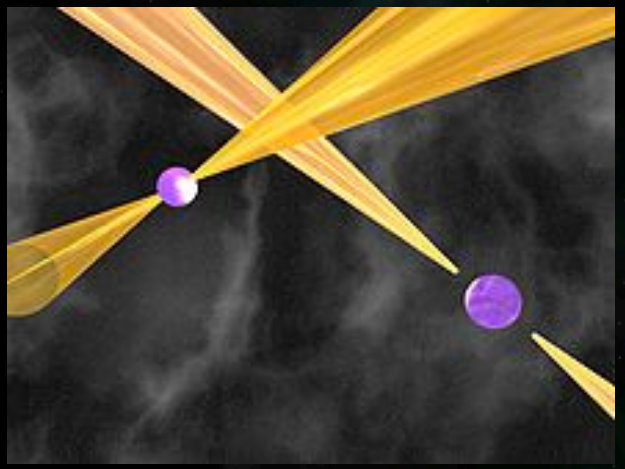
Cosmology

Supernova Scenario

[Newton, Steiner & KY (2016)]

double binary pulsar J0737-3039

- ✓ low eccentricity
- ✓ primary pulsar spin & orbital angular momentum nearly aligned
- ✓ small system velocity



J0737-3039B

- ✓ small kick velocity
- ✓ symmetric explosion
- ✓ short time scale

electron-capture supernova

- ✓ unique core mass for instability onset $[1.366, 1.377]M_\odot$ [Miyaji et al. (1980), Nomoto (1984,87)]
- ✓ small mass loss $\lesssim 0.01M_\odot$

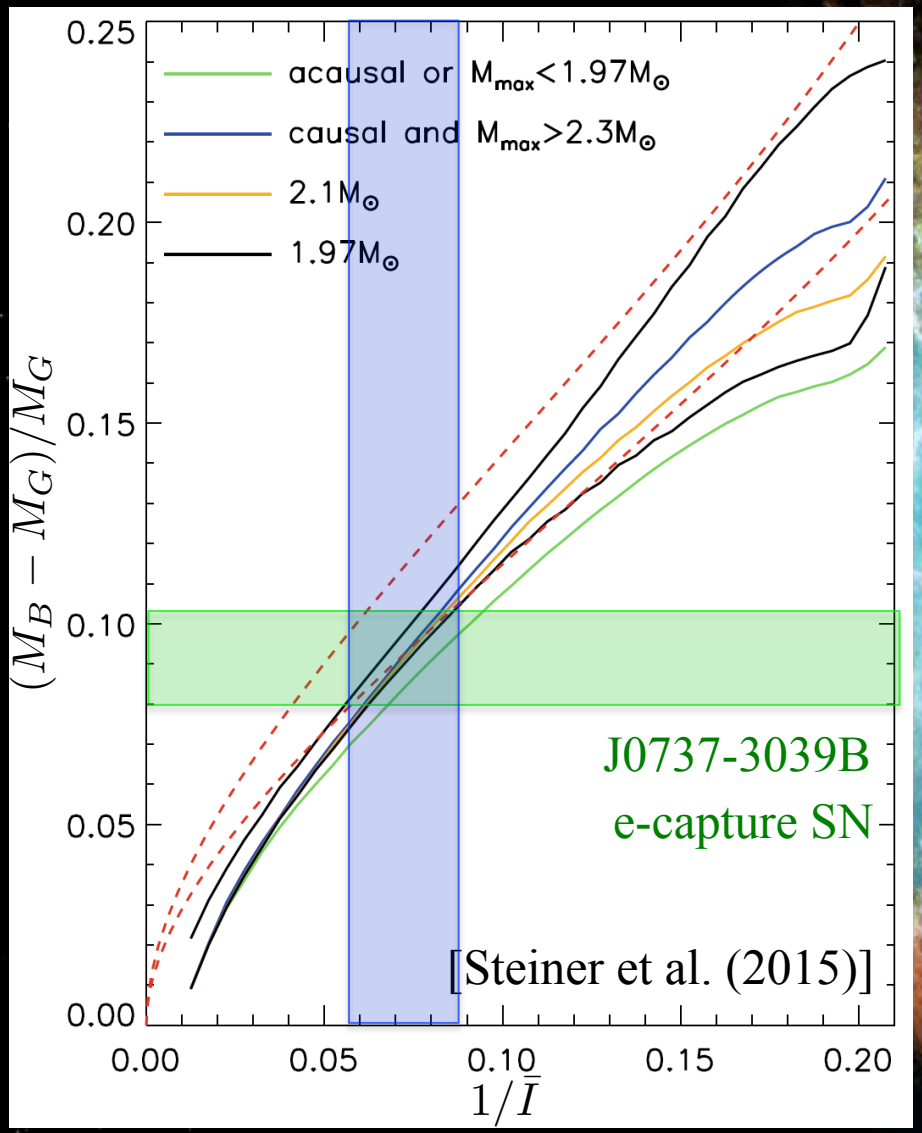
$M_G = 1.25M_\odot$ [Podsiadlowski et al. (2005), Kitaura et al. (2006)]

baryon mass: $M_B \approx [1.366, 1.377]M_\odot$

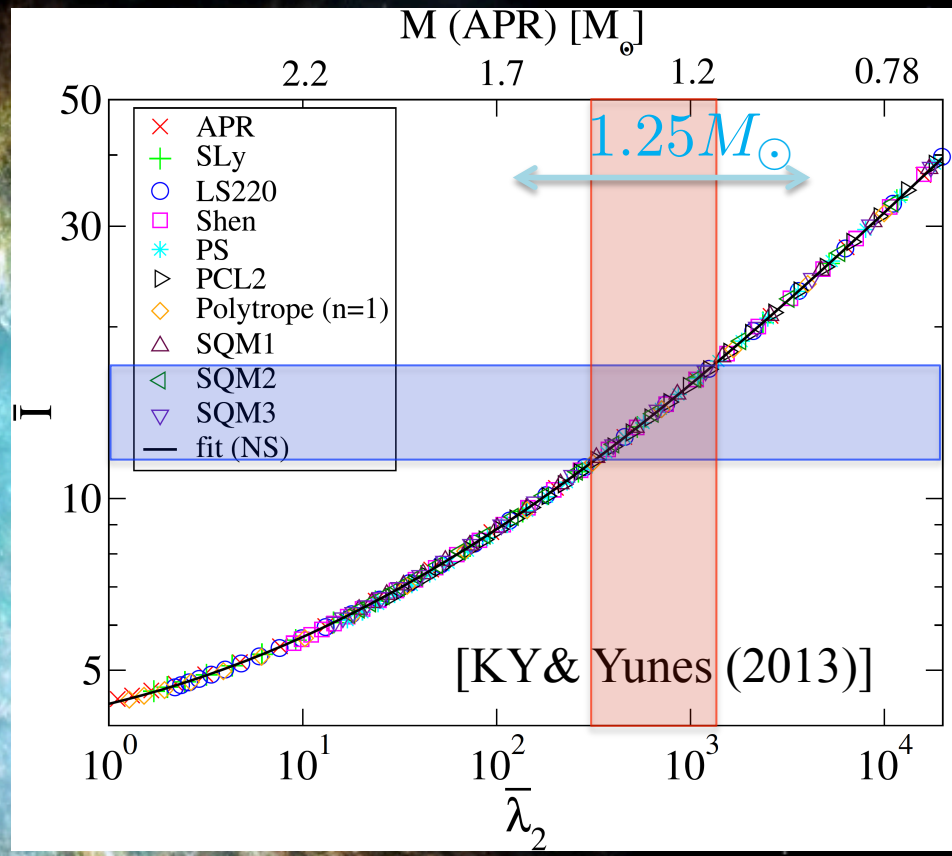
Supernova Scenario

[Newton, Steiner & KY (2016)]

binding energy vs moment of inertia



moment of inertia vs tidal deformability



GW tidal measurement can probe formation scenario of NSs!

Kent Yagi

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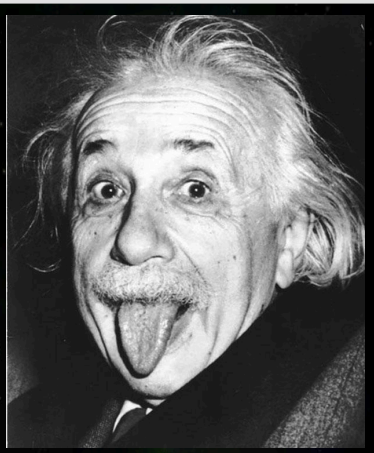

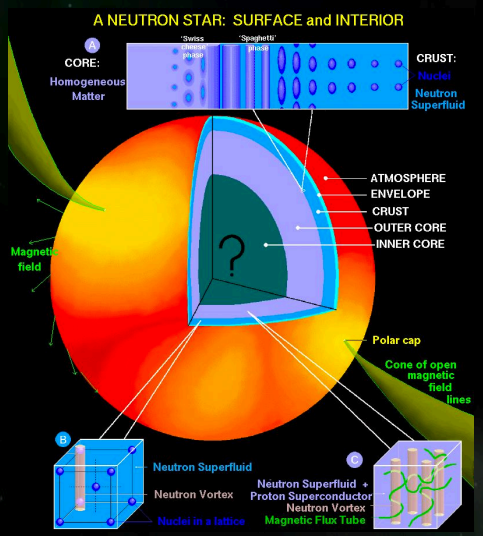

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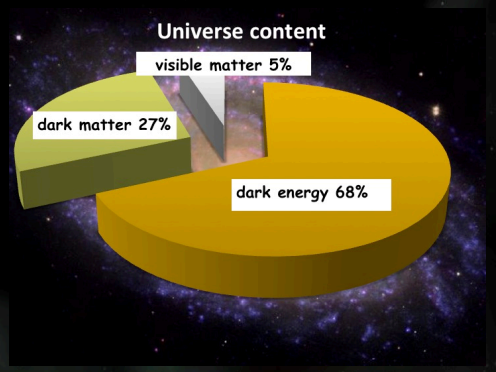

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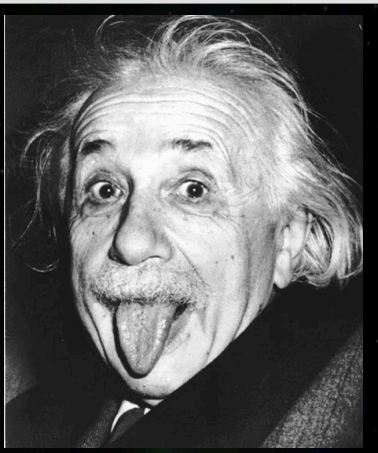

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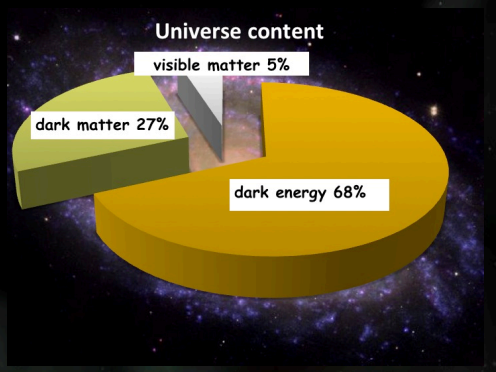
- ✓ Binary NS inspiral
- ✓ Binary NS post-merger



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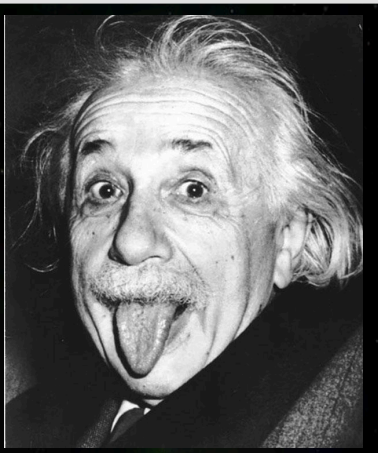

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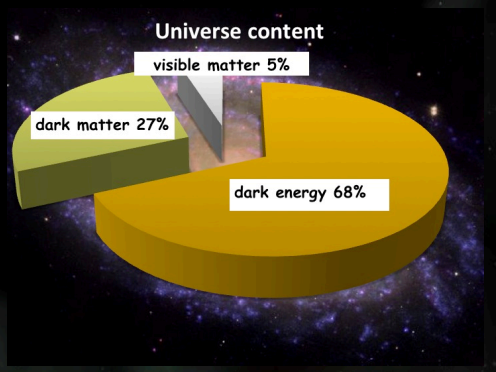
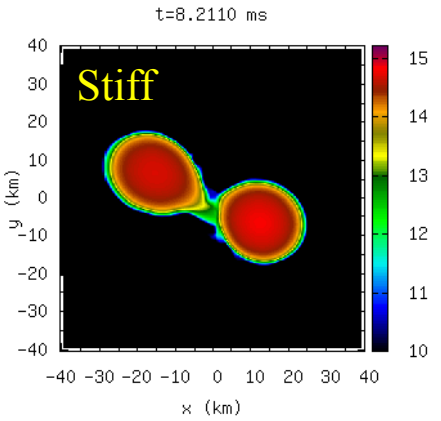
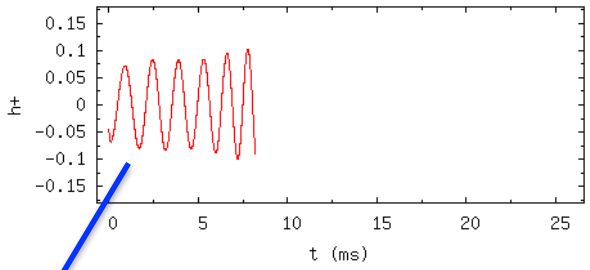


Nuclear Physics

Cosmology

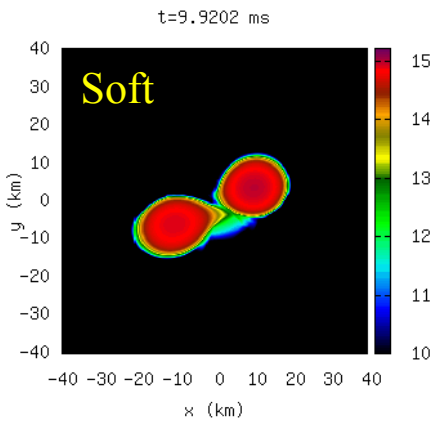
GW Nuclear Astrophysics

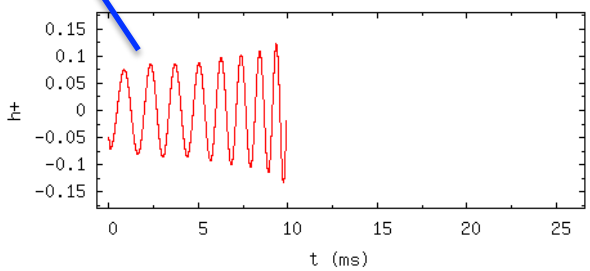




Love number

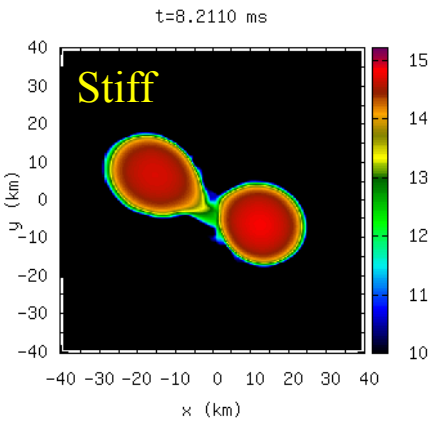
$$m_A,\ \bar{\lambda}_2^{(A)}$$

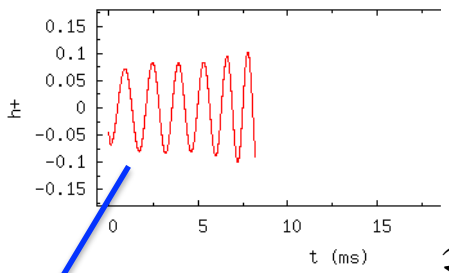




Simulations by Kenta Hotokezaka

GW Nuclear Astrophysics





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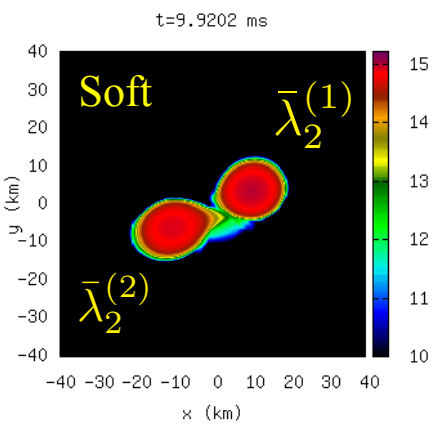
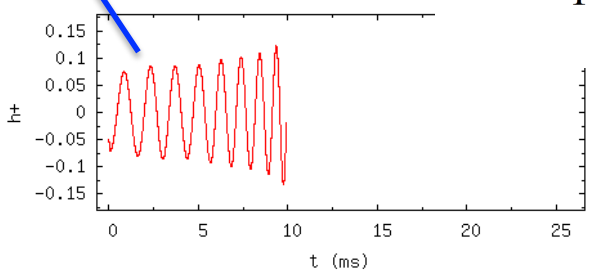
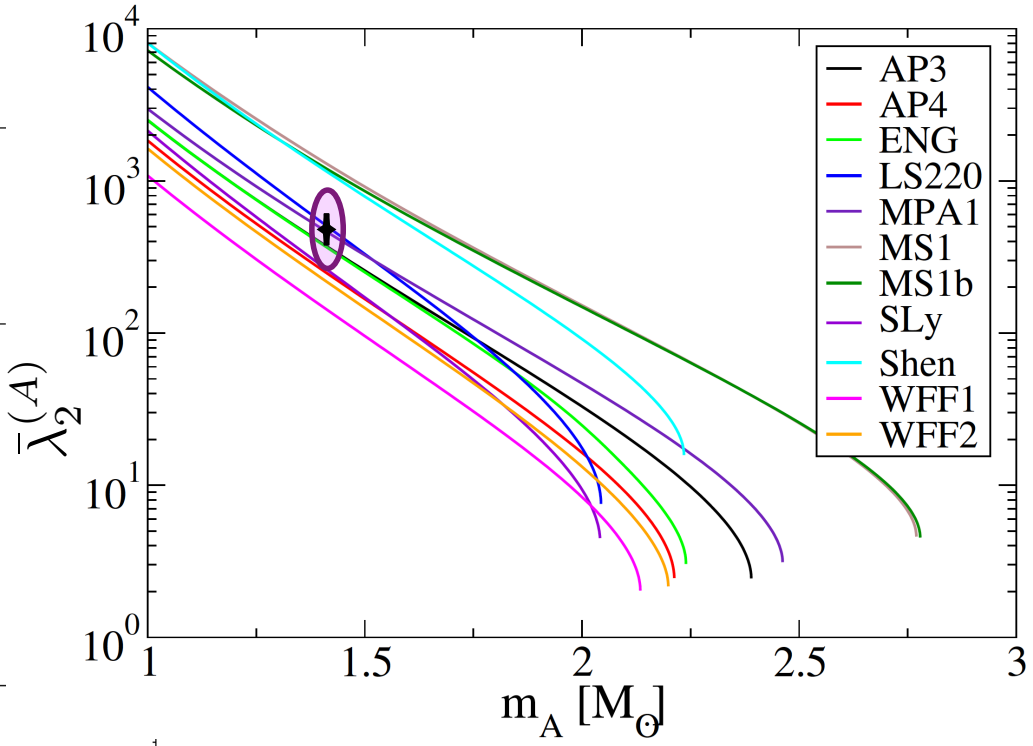






degeneracies between individual Love numbers

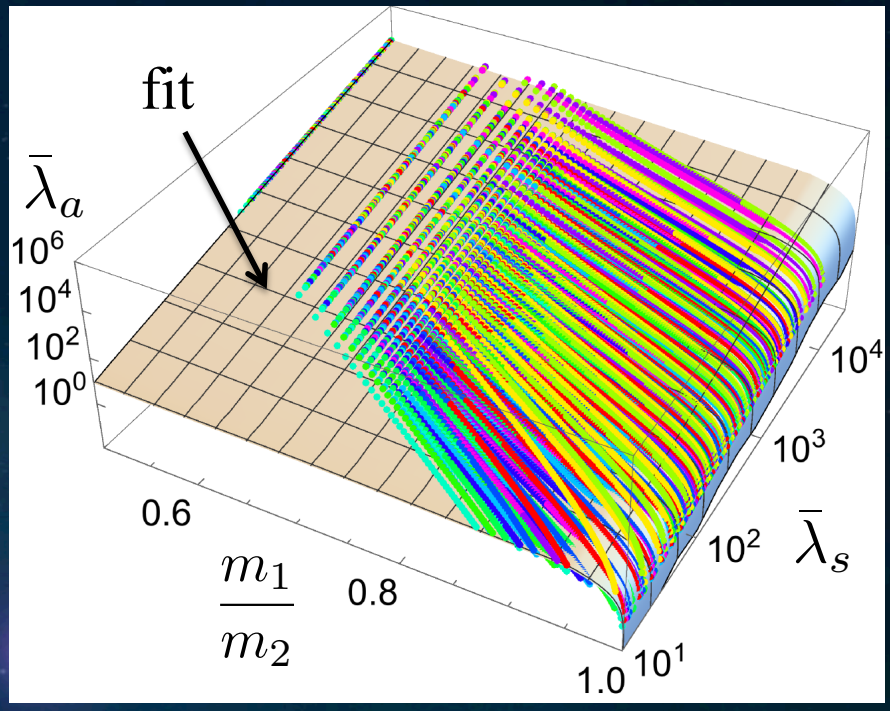
Simulations by Kenta Hotokezaka

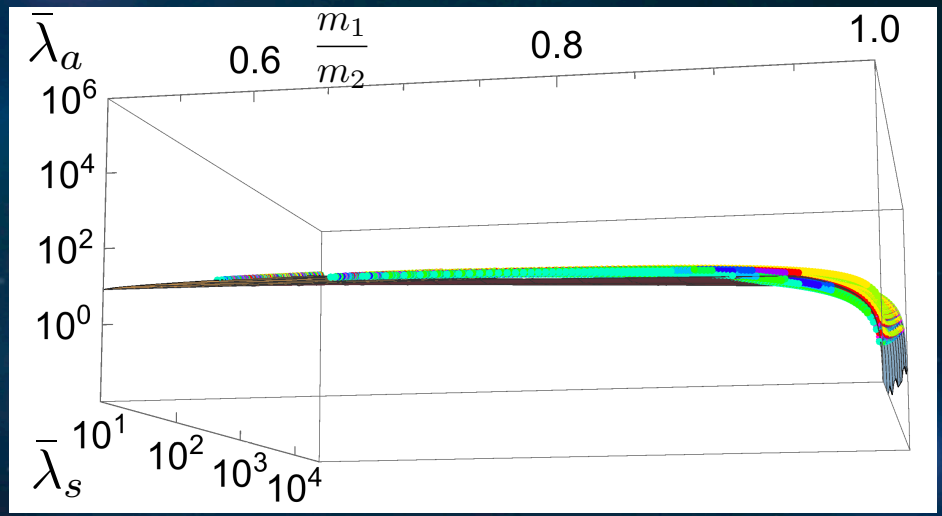
Binary Love Relations

symmetric/anti-symmetric

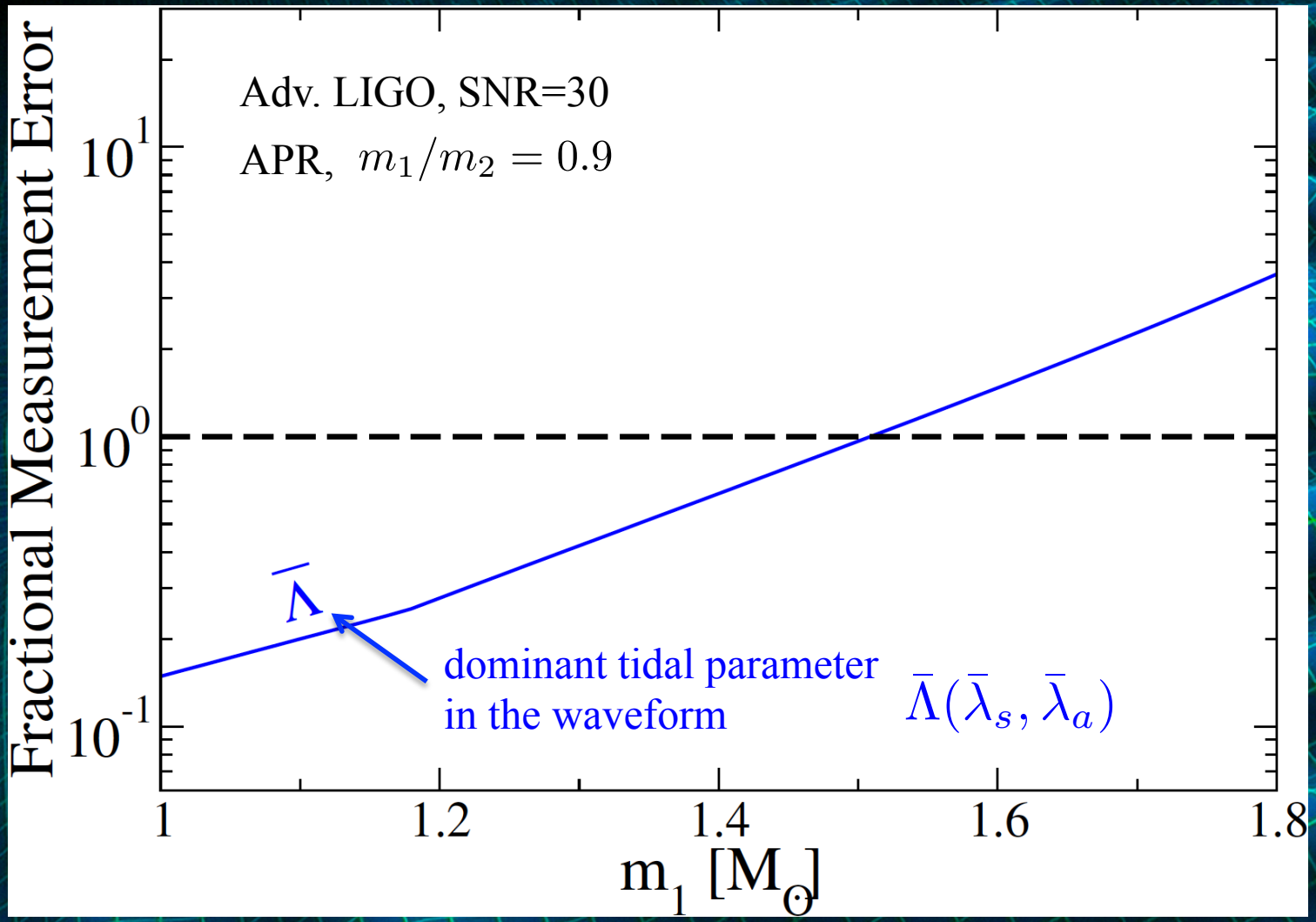
$$\bar{\lambda}_s = \frac{\bar{\lambda}_2^{(1)} + \bar{\lambda}_2^{(2)}}{2}, \quad \bar{\lambda}_a = \frac{\bar{\lambda}_2^{(1)} - \bar{\lambda}_2^{(2)}}{2}$$

Universal to $\mathcal{O}(10\%)$





Impact of Binary Love Relations



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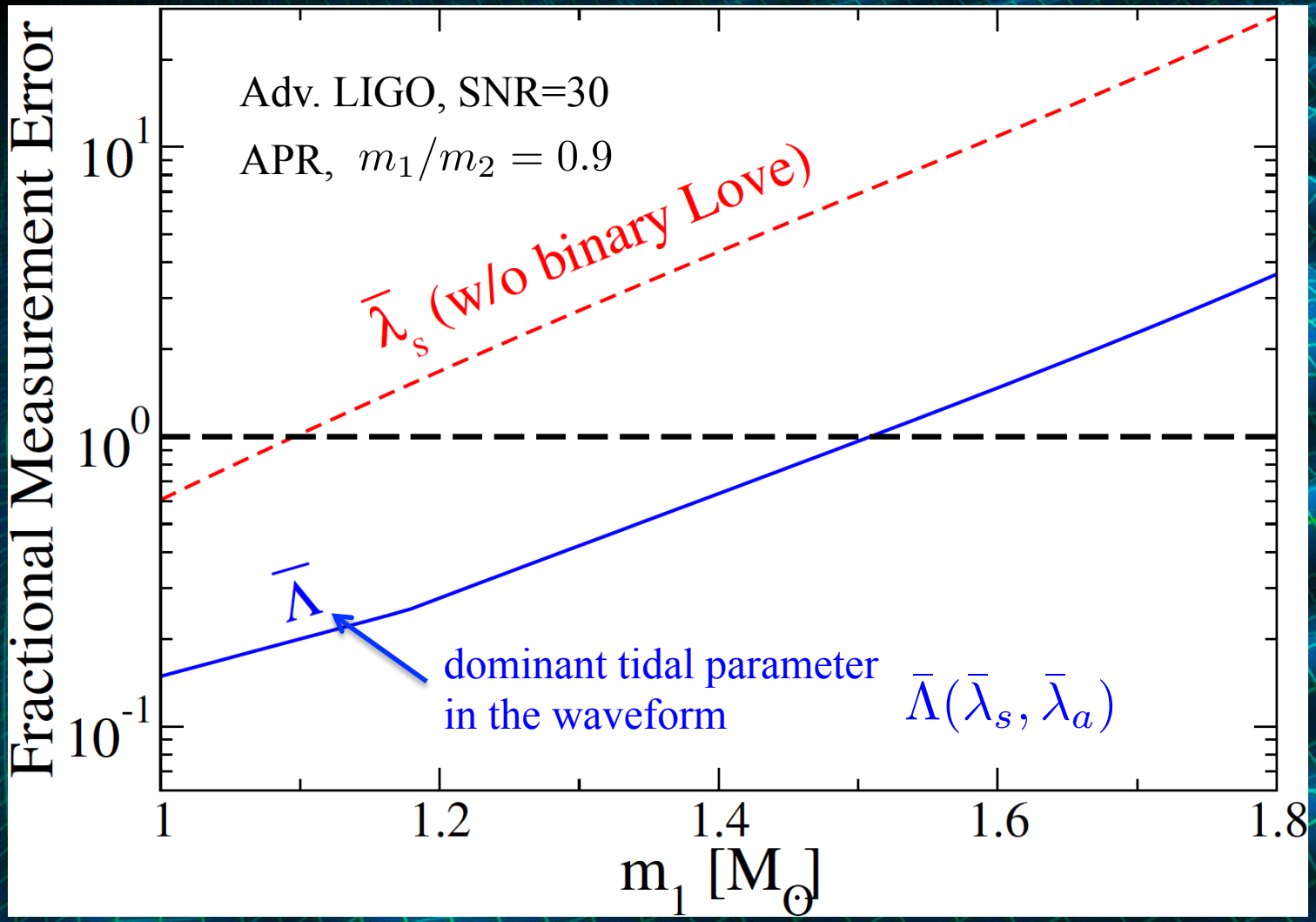

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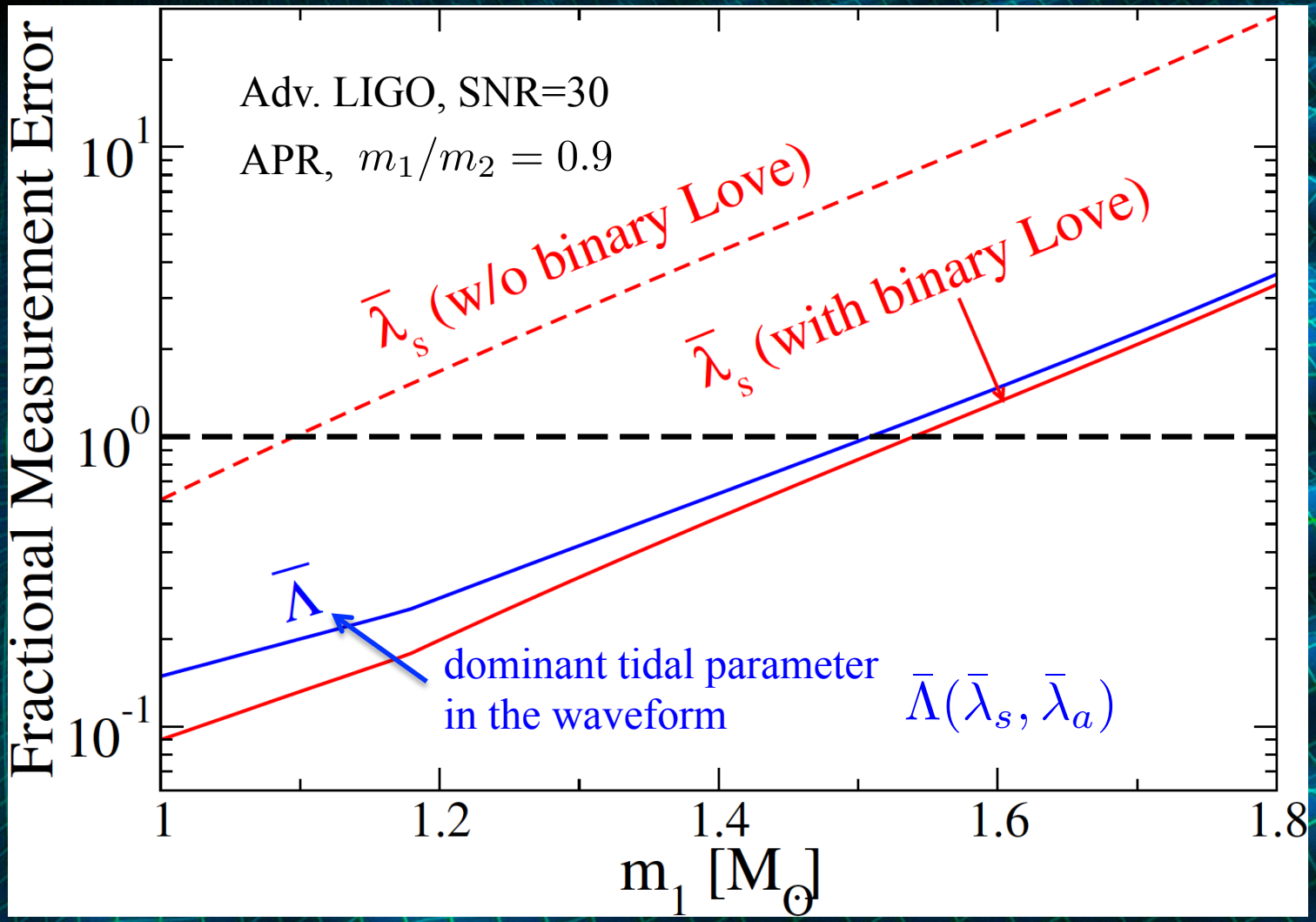

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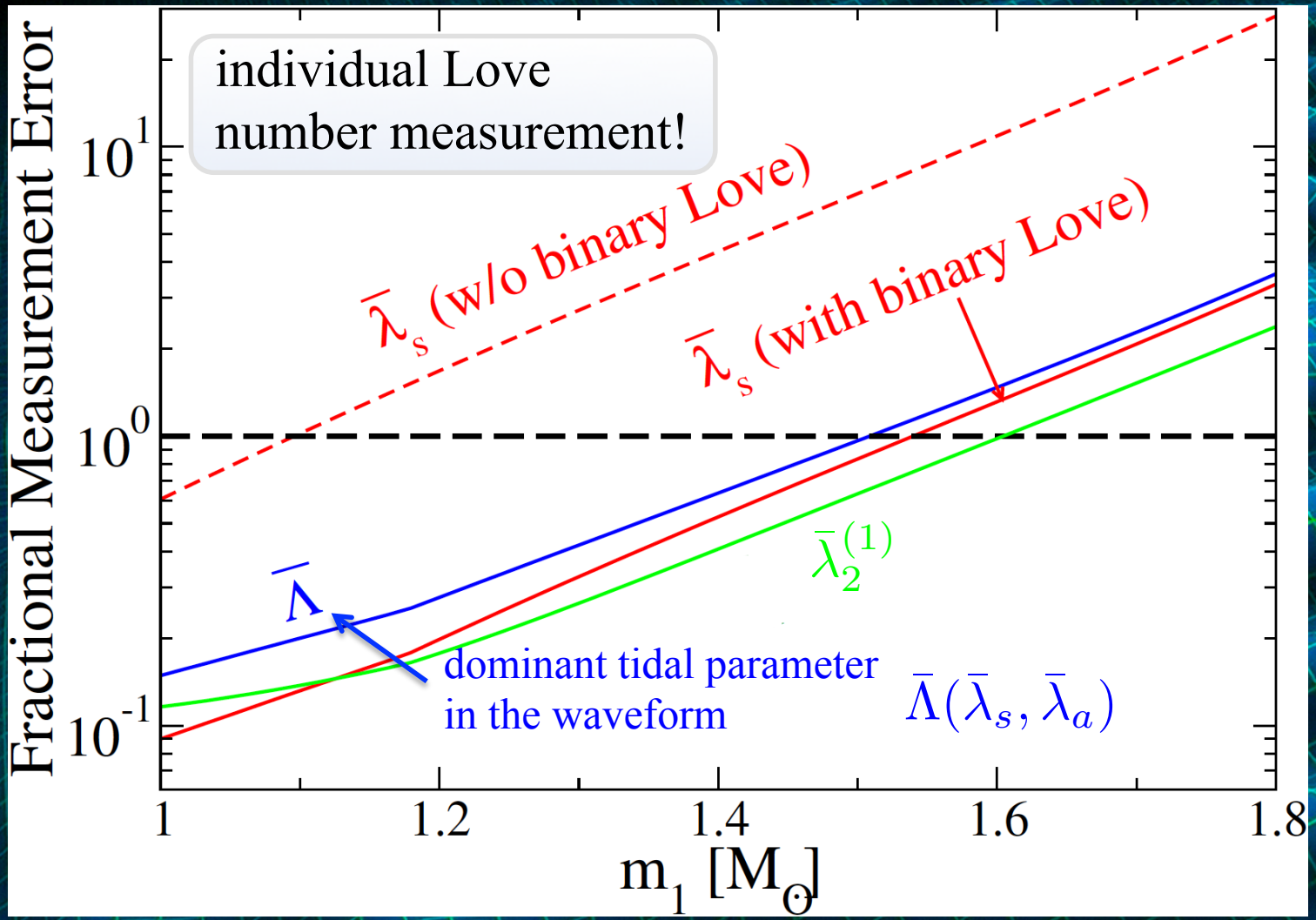

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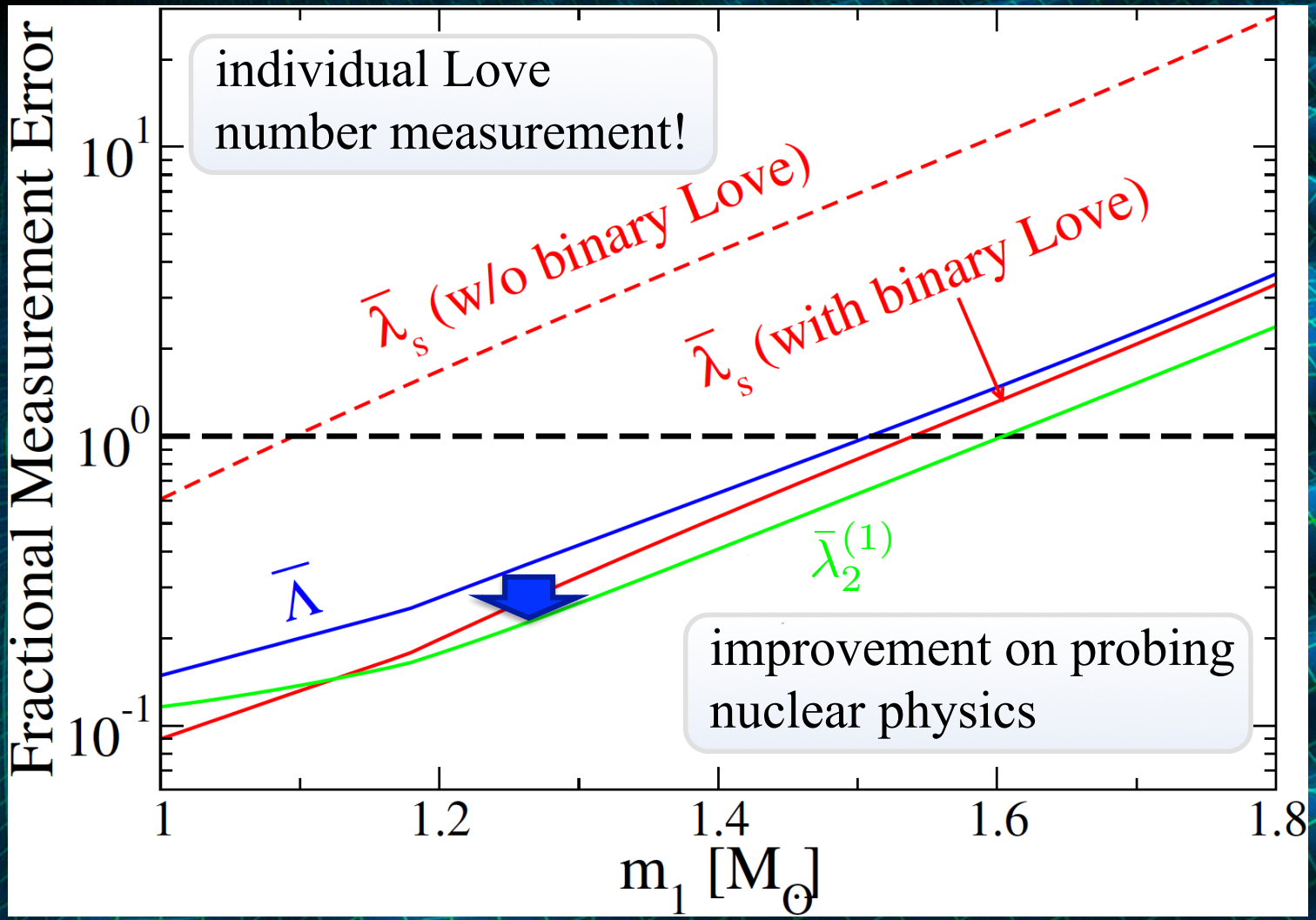

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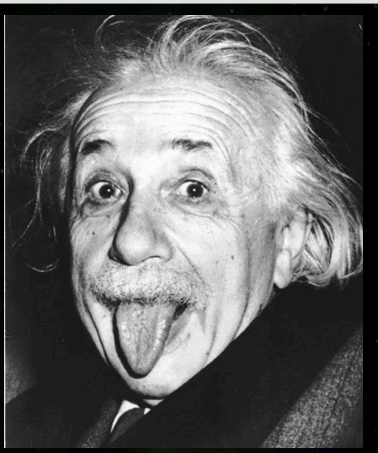

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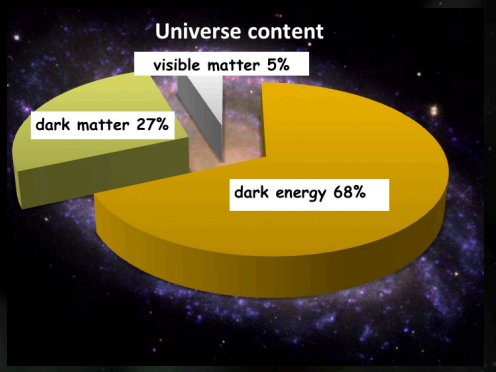
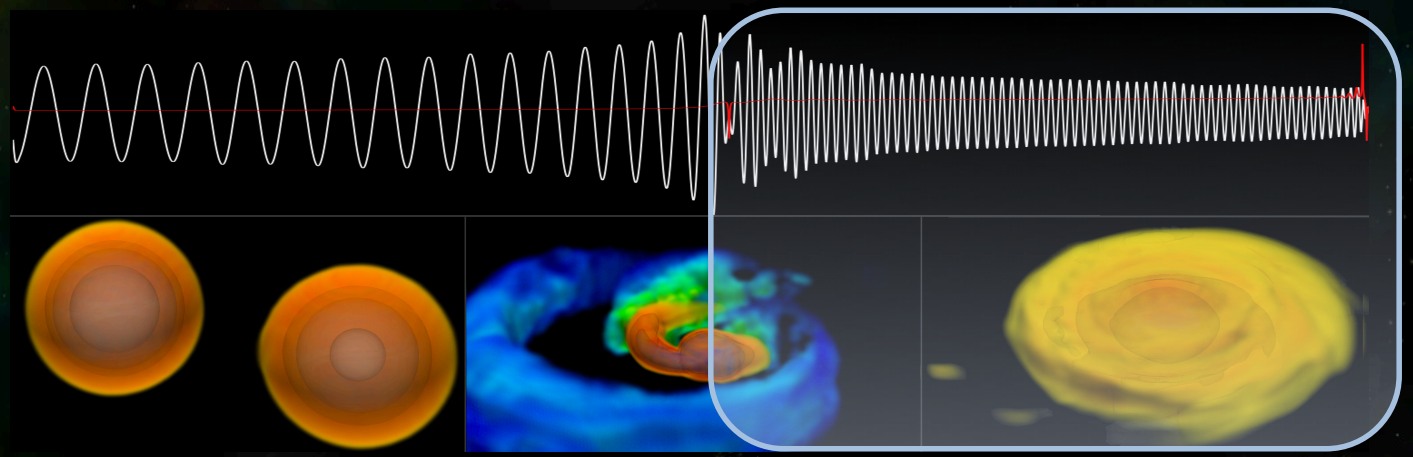


Nuclear Physics

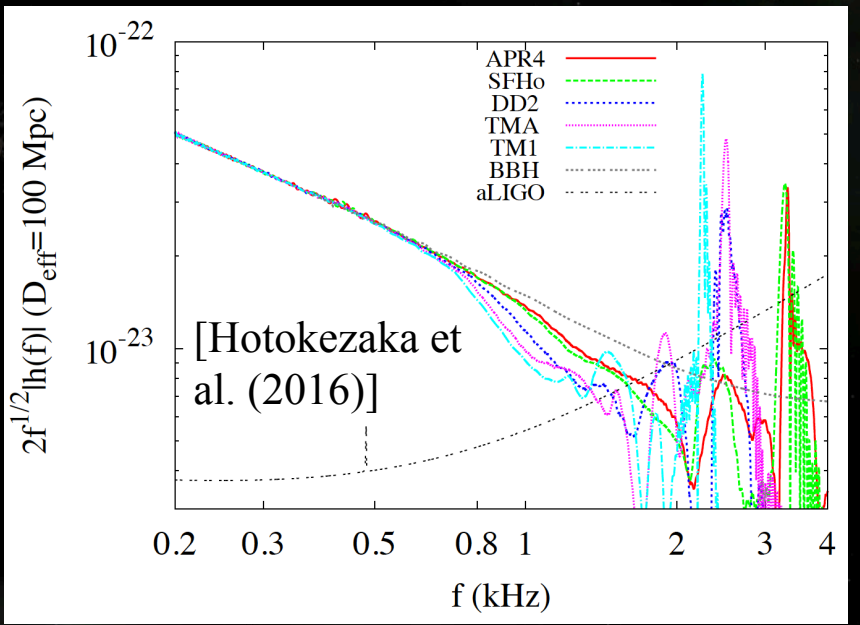
Cosmology

Probing Nuclear Physics with Post-merger GWs



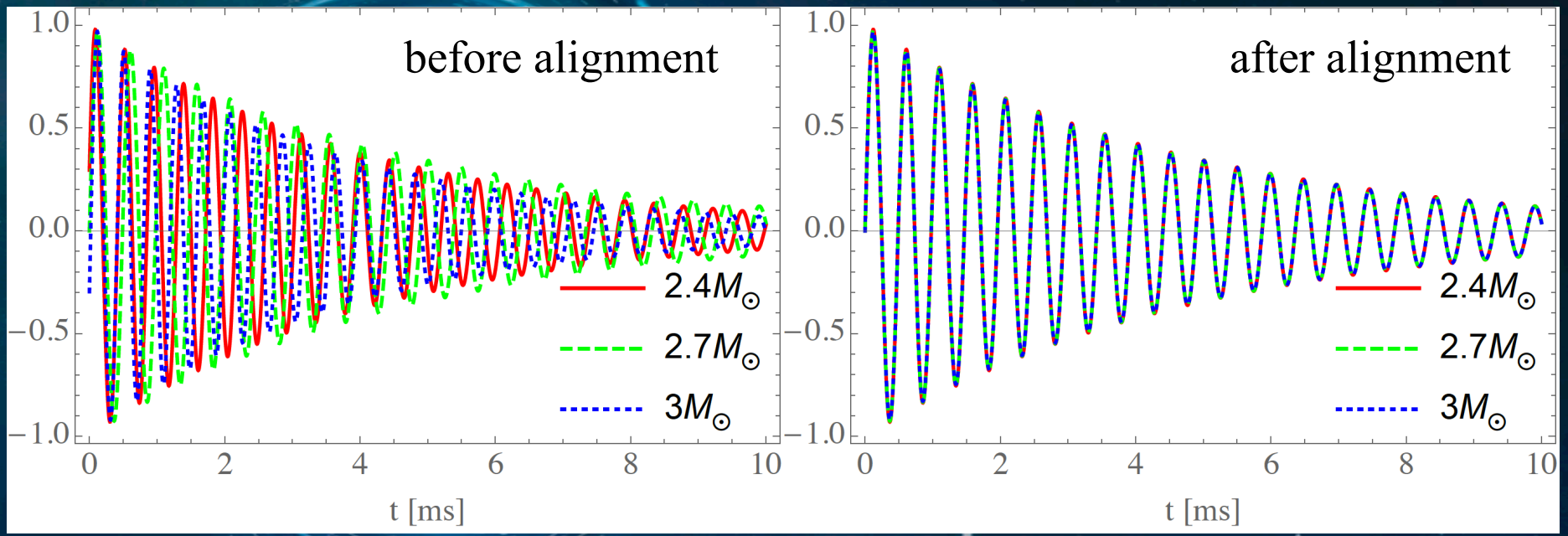
- Contains rich information on nuclear physics
- Detection is challenging
- Coherently stack multiple events!

[Bose et al. (2017)]
[Yang, Paschalidis, KY et al. (in prep.)]



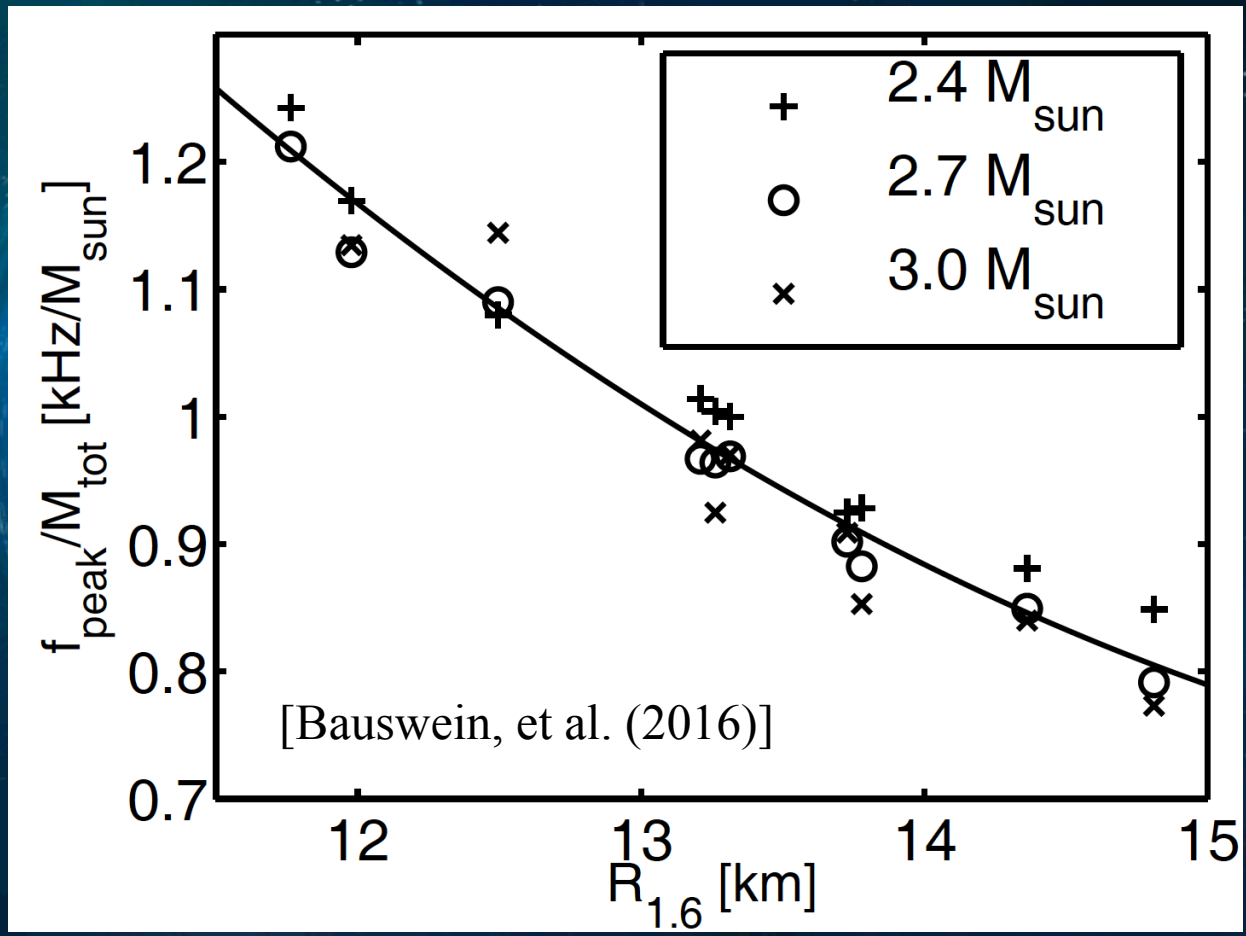
Coherent Mode Stacking [Yang, Paschalidis, KY et al. (in prep.)]

Phase alignment is crucial!



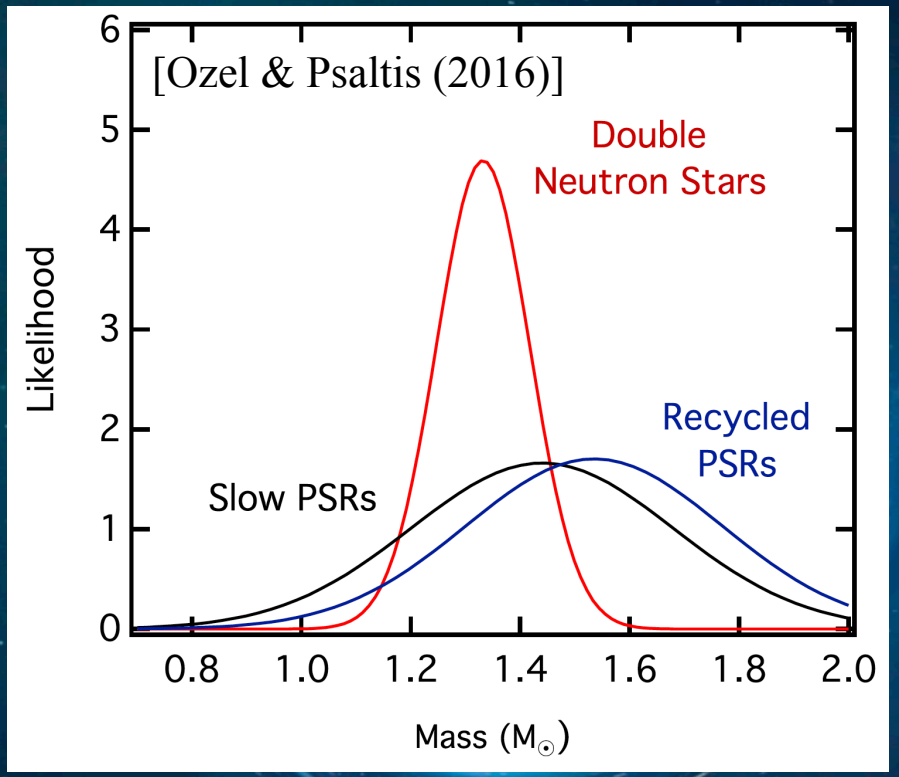
Coherent Mode Stacking [Yang, Paschalidis, KY et al. (in prep.)]

Align frequency with universal relation!

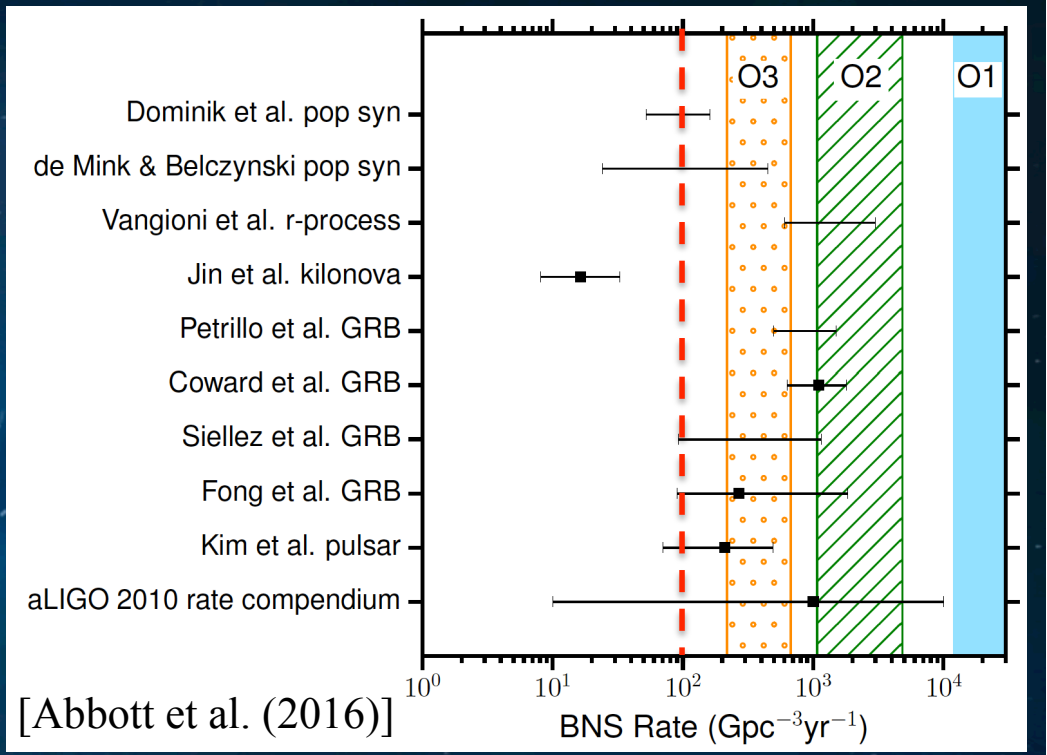


Monte Carlo Simulations [Yang, Paschalidis, KY et al. (in prep.)]

mass distribution



merger rate



[Abbott et al. (2016)]

SNR reduction due to phase misalignment caused by measurement uncertainties in the constant phase offset

$$\delta\phi \sim \frac{1}{\mathrm{SNR}}$$

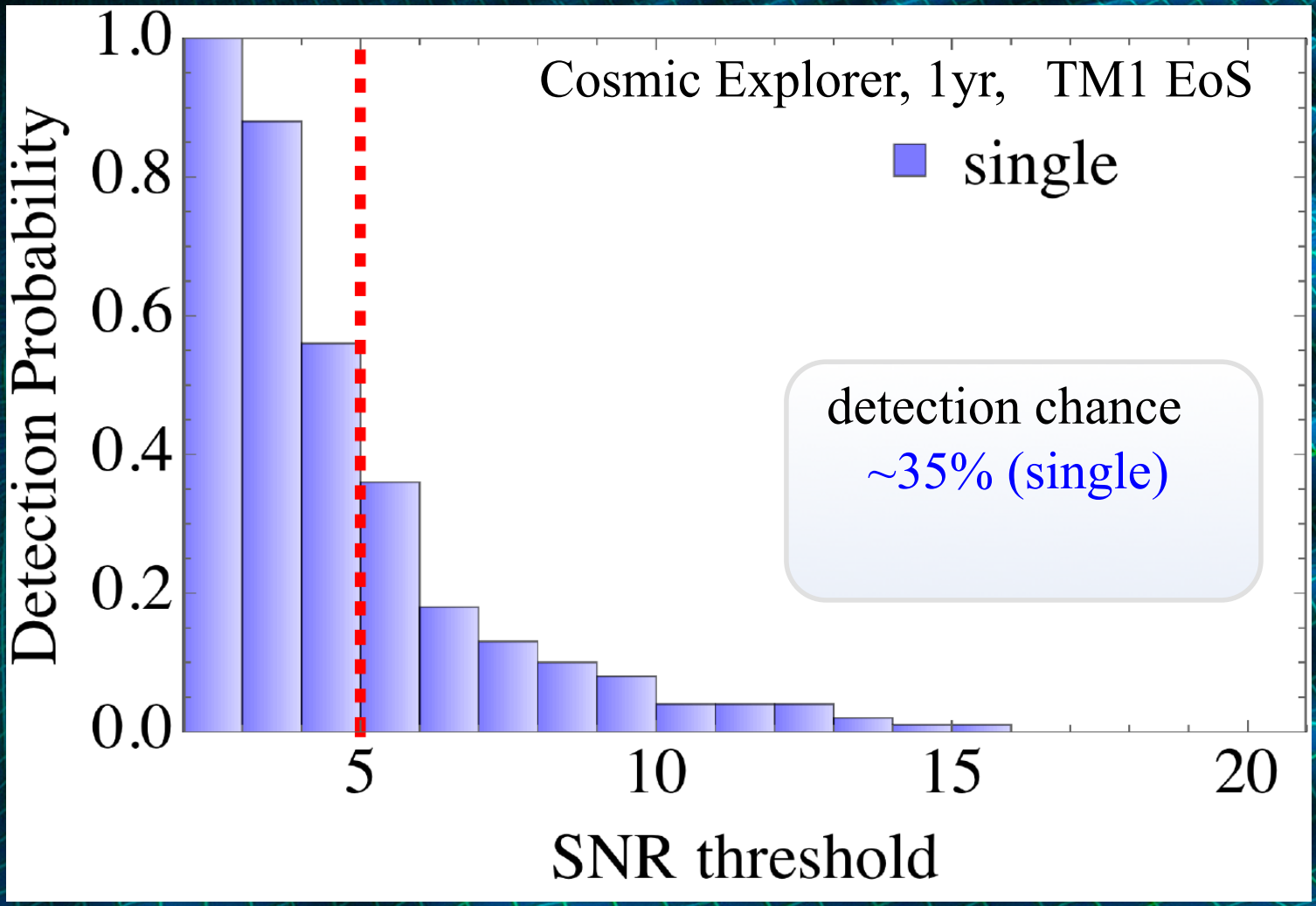
difficult to detect post-merger GWs with aLIGO even after stacking

⇨ need 3rd generation detectors like Cosmic Explorer

Single vs Stacking

[Yang, Paschalidis, KY et al. (in prep.)]

detection probability of post-merger GWs



Single vs Stacking

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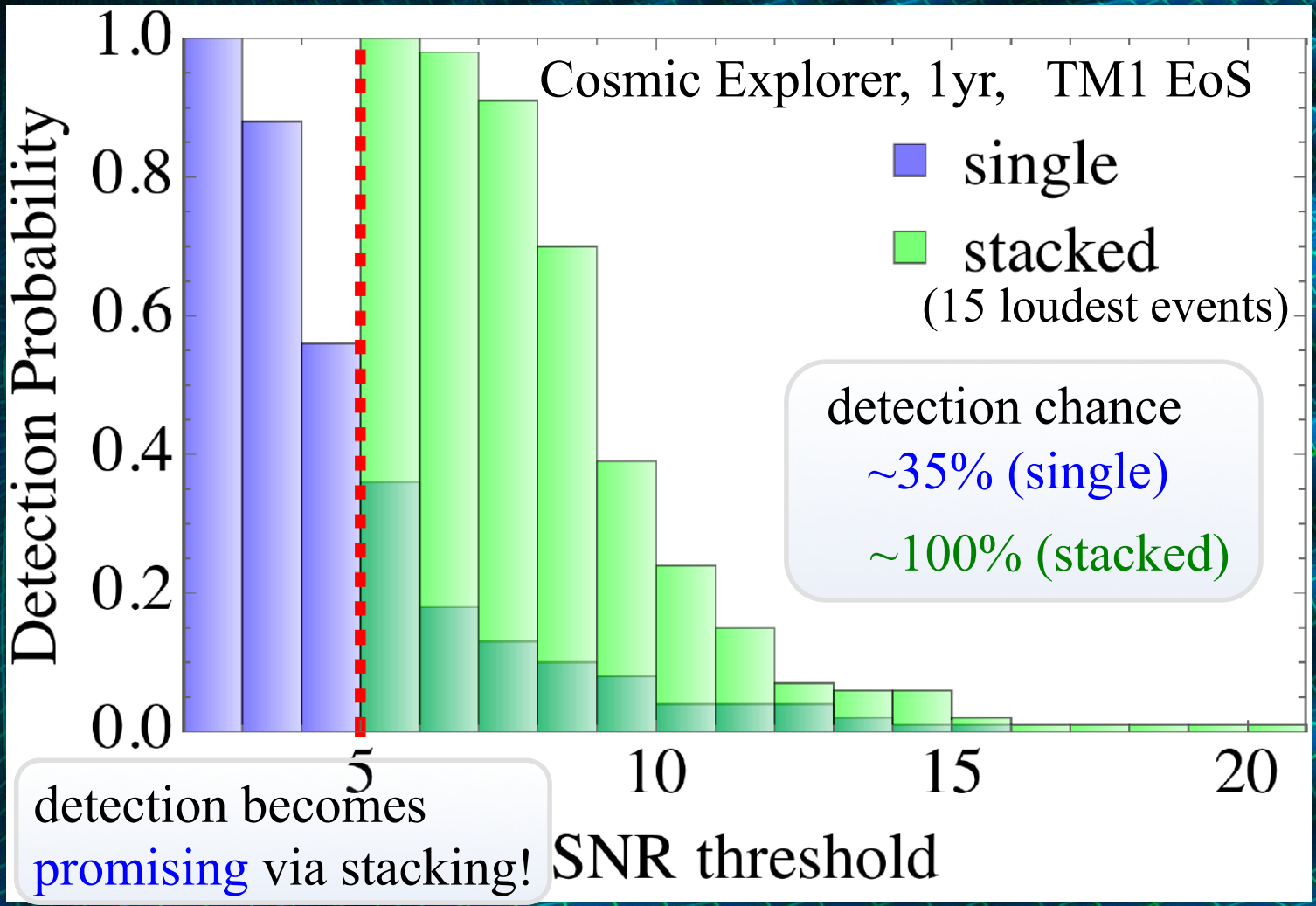

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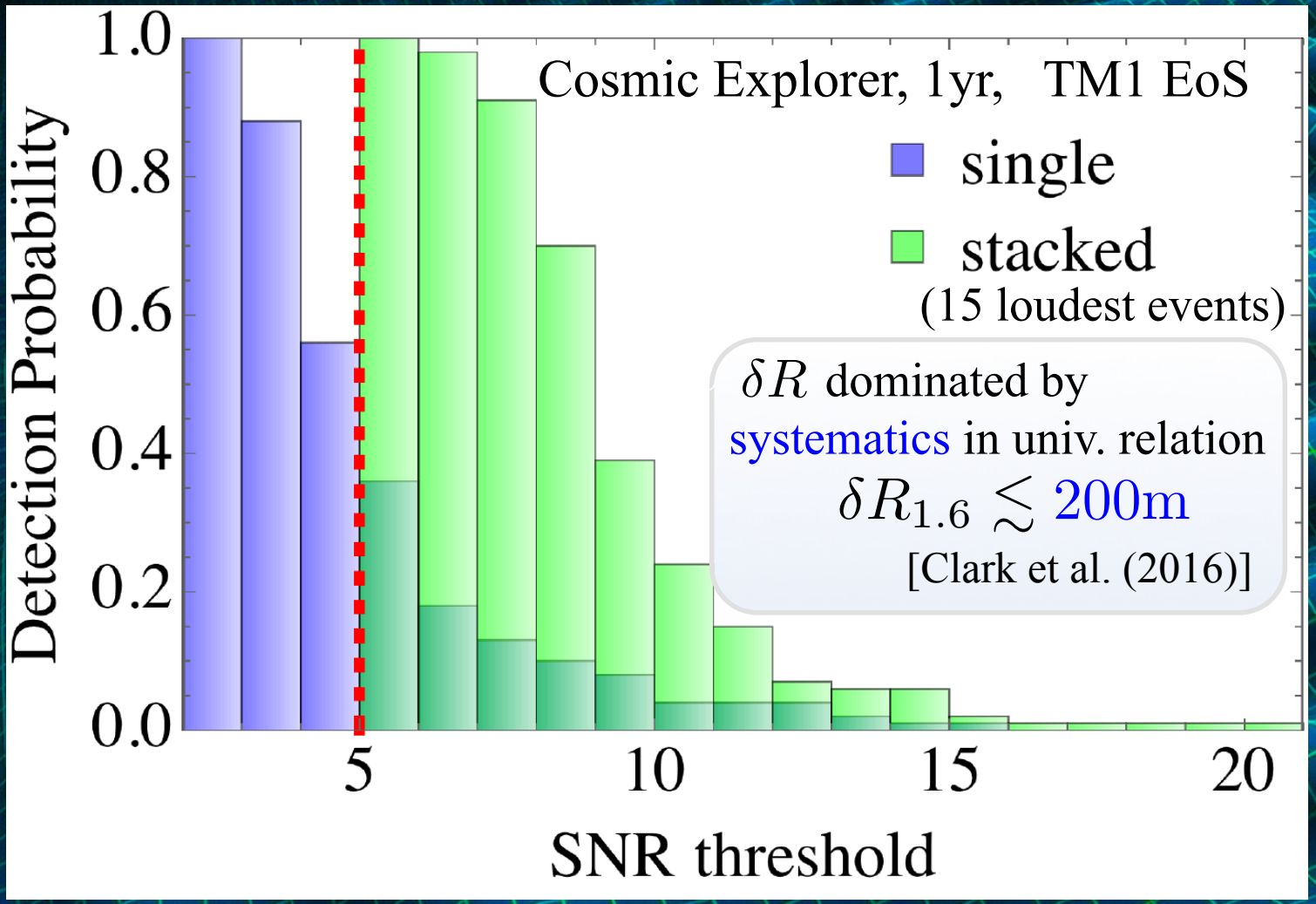
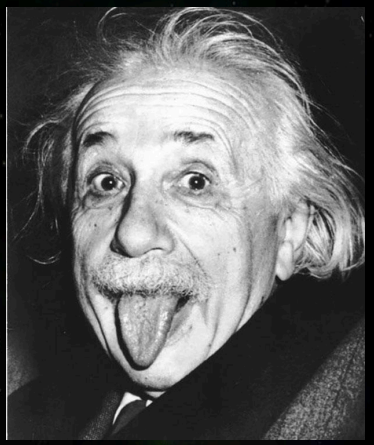
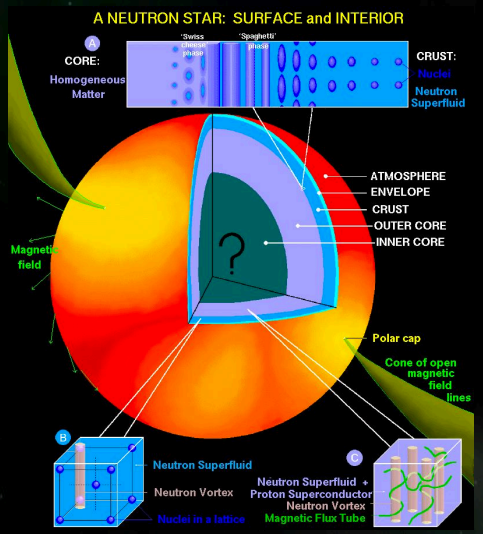


Outline

Astrophysics

Gravitational Physics





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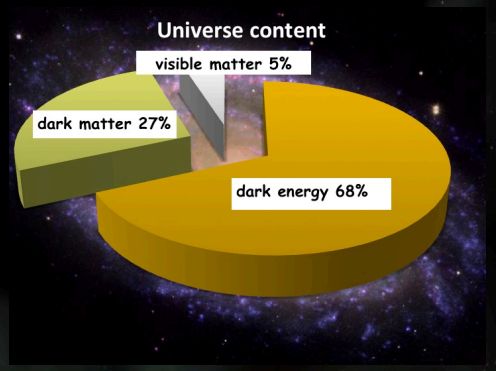
review article [KY & Yunes, Phys. Rept. (2017)]

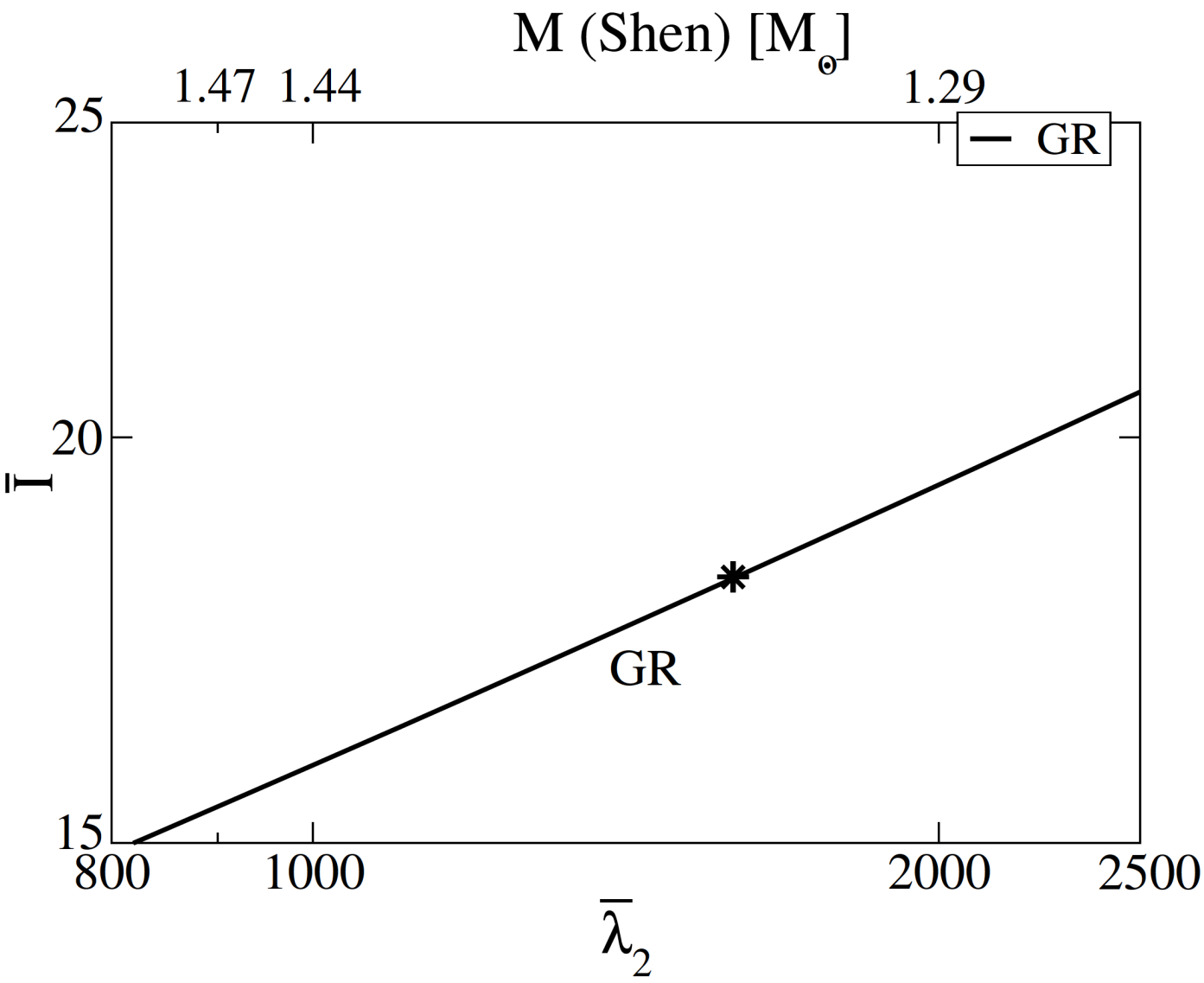


Nuclear Physics

Cosmology

Strong Gravity Tests

[KY & Yunes, Science 341 365 (2013)]



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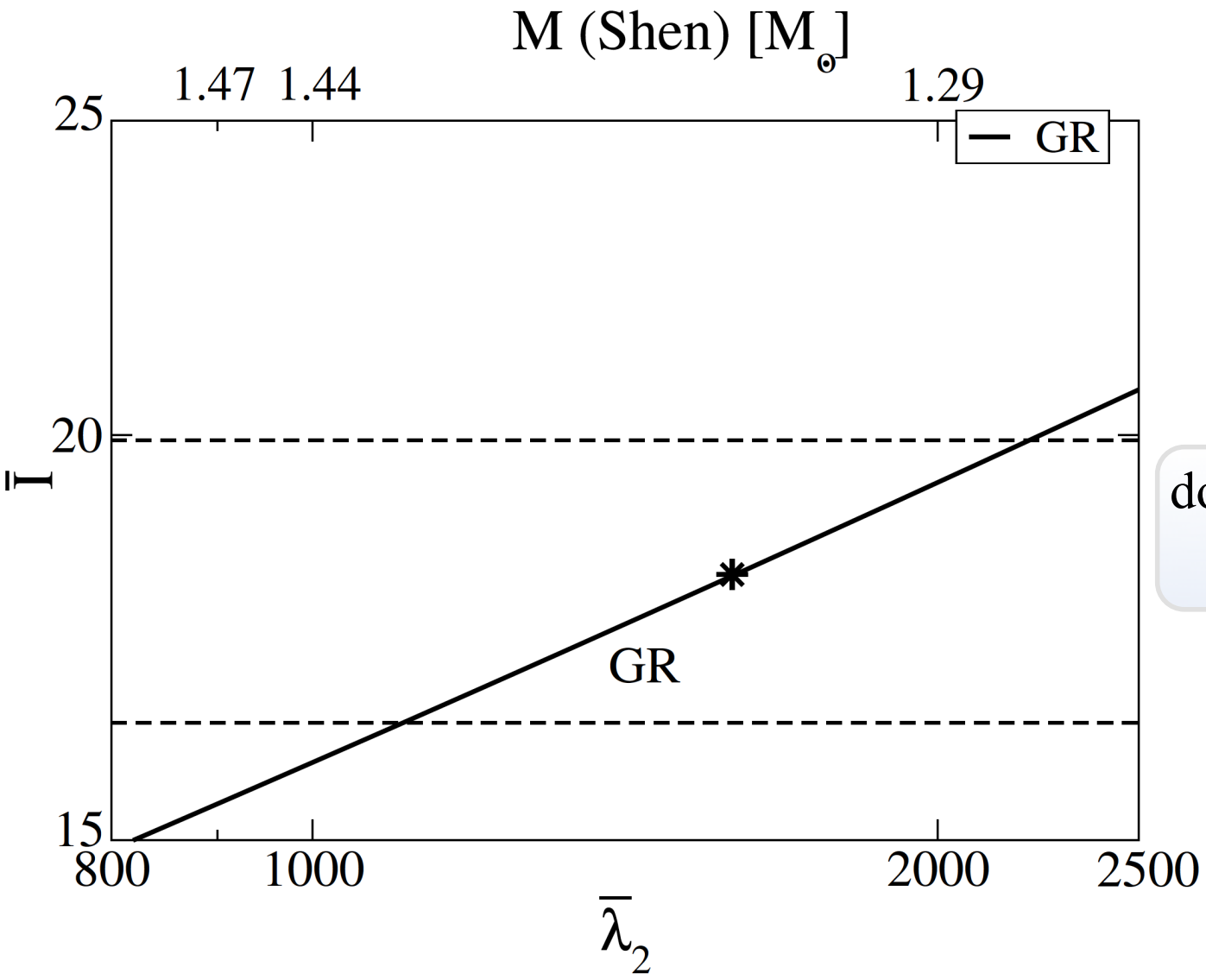

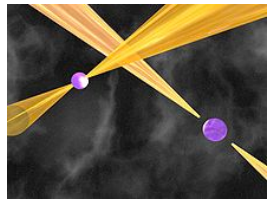

double binary pulsar

$\Delta\bar{I}/\bar{I} = 10\%$

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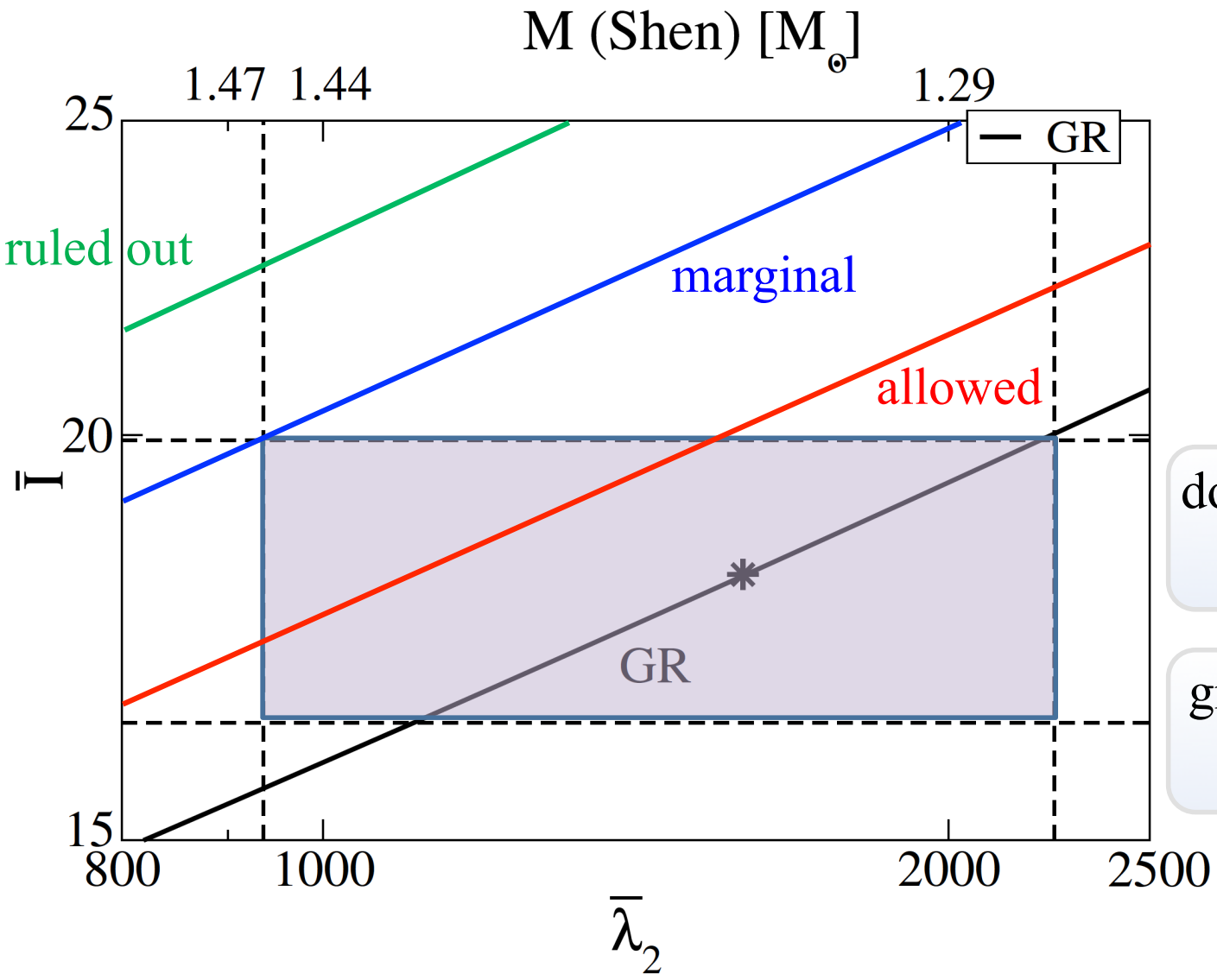

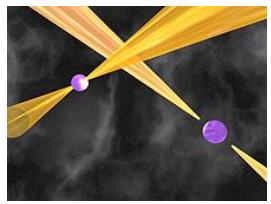

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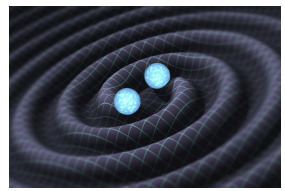
gravitational waves

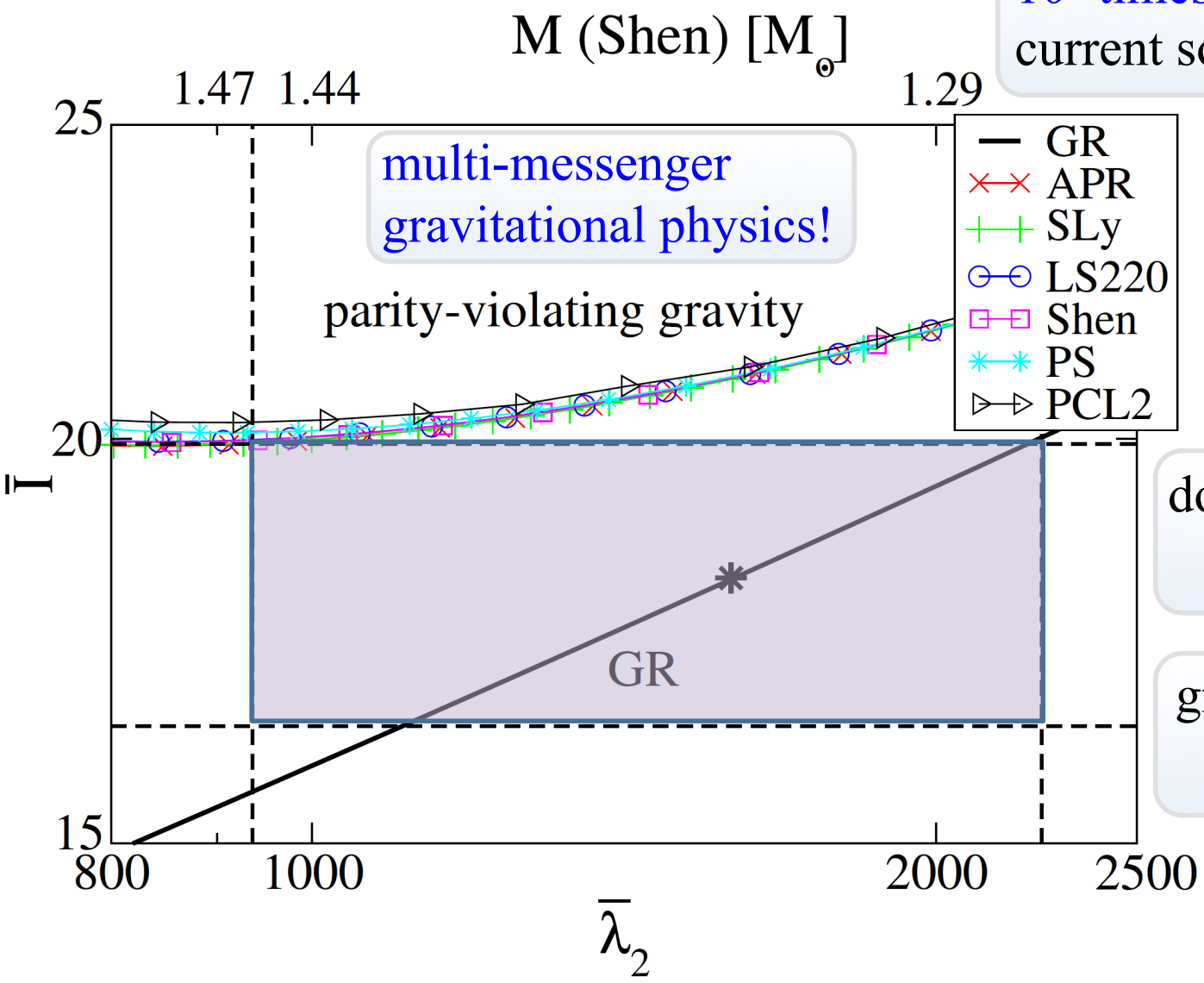
$\Delta\bar{\lambda}_2/\bar{\lambda}_2 = 40\%$

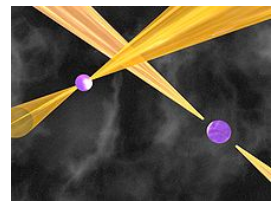


Strong Gravity Tests

[KY & Yunes, Science 341 365 (2013)]

10^6 times stronger than the current solar system bound!





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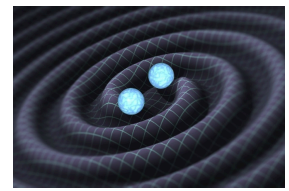

I-Love-Q in Modified Theories of Gravity

Modified Theories of Gravity

- ✓ (massless) scalar-tensor
  [Pani & Berti (2014)]
- ✓ (massive) scalar-tensor
  [Doneva & Yazadjiev (2016)]
- ✓ f(R)
  [Doneva et al. (2015)]
- ✓ Einstein-dilaton Gauss-Bonnet
  [Kleihaus et al. (2014, 2016)]
- ✓ dynamical Chern-Simons
  [Yagi & Yunes (2013)]
- ✓ Eddington-inspired Born-Infeld
  [Sham et al. (2014)]

Exotic Compact Objects

- ✓ boson star / dark star
  [Maselli et al. (2017)]
- ✓ gravastar
  [Pani (2015),
  Uchikata et al. (2016)]

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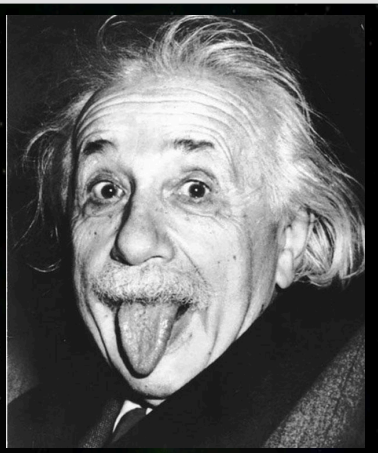

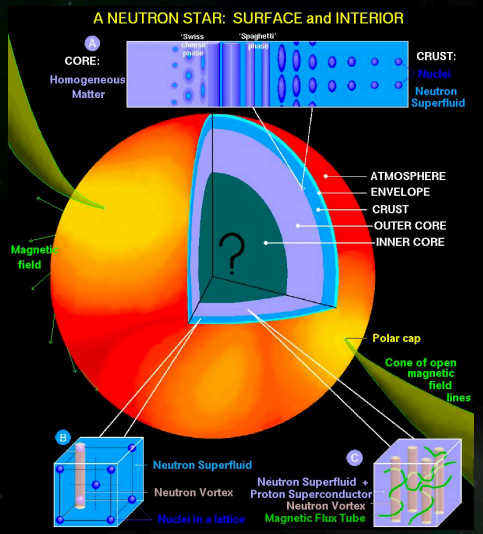

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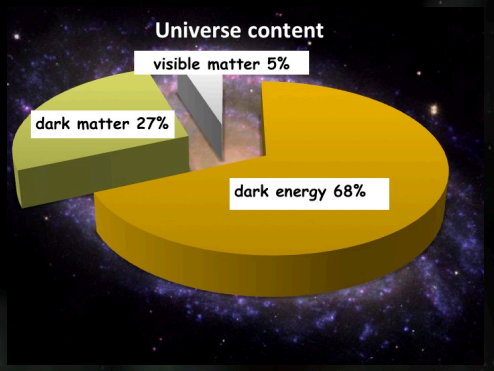


Nuclear Physics

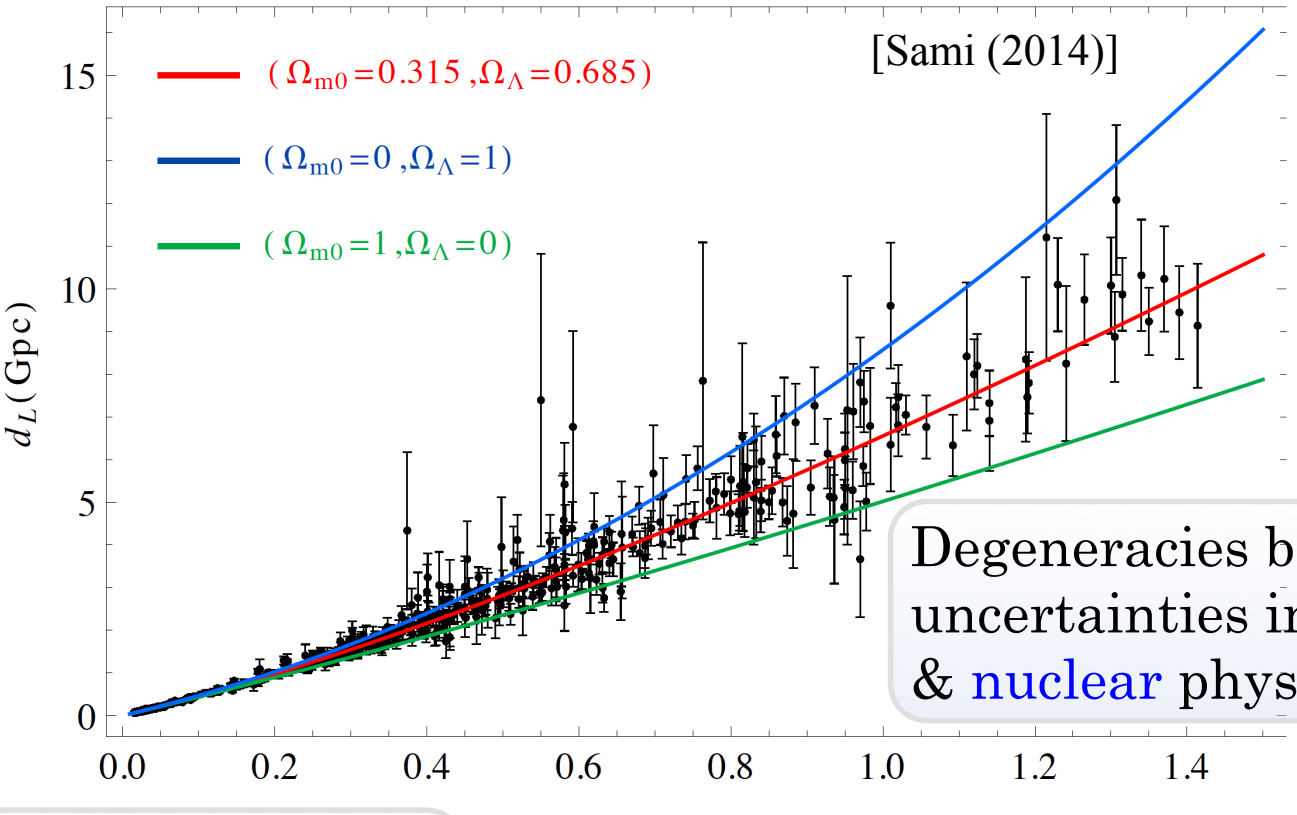
Cosmology

GW Cosmology

[Messenger & Read (2012)]

type Ia SNe ⇨ standard candles

NS/NSs ⇨ standard sirens



GW amplitude

Degeneracies between uncertainties in cosmology & nuclear physics

Correct EoS known

⇨ Break the degeneracy between mass and z

$m(1+z)$

$\bar{\lambda}_2(m, \mathrm{EoS})$

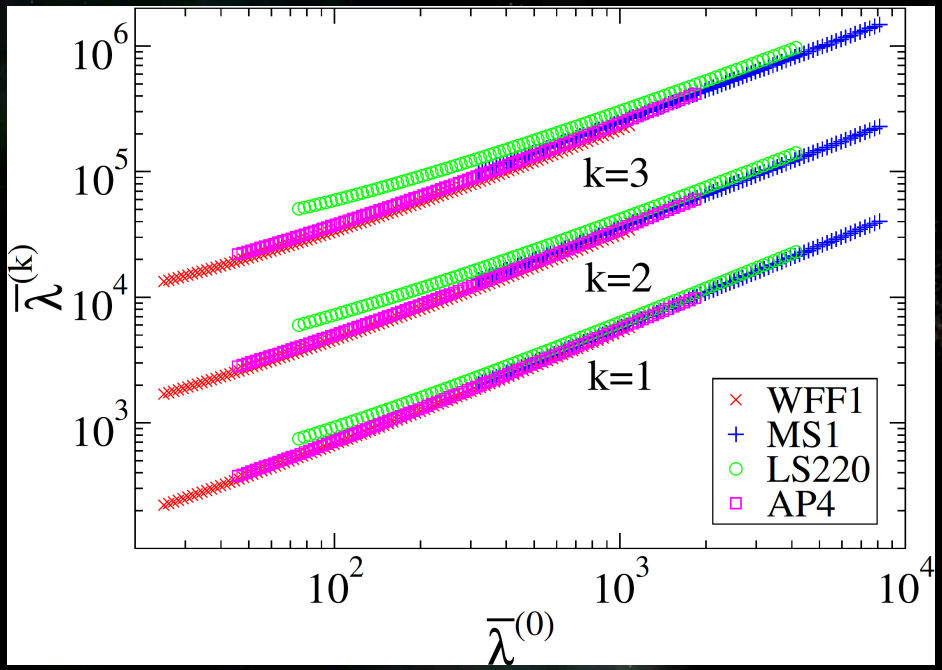
Perfect knowledge of EoS…?

Taylor expanded tidal deformability

[Messenger & Read (2012)]

fiducial mass

$$\bar{\lambda}_2(m) = \sum_{k=0} \frac{\bar{\lambda}^{(k)}}{k!} \left(1 - \frac{m}{m_0}\right)^k$$

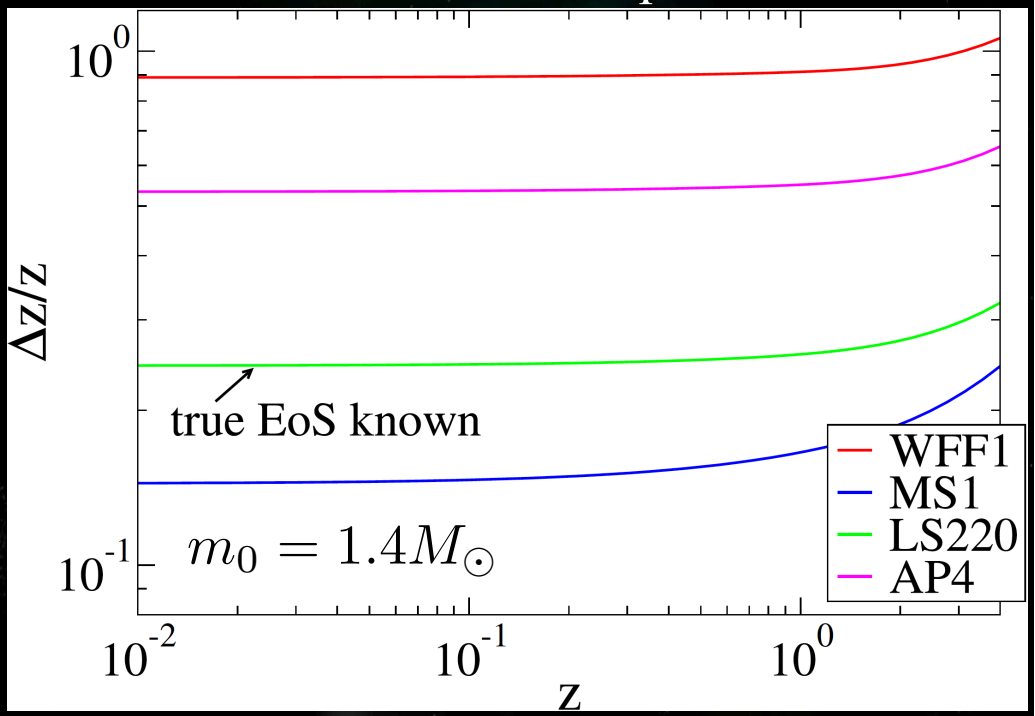


Universal to $\mathcal{O}(10\%)$

Redshift measurement

$(m_1, m_2) = (1.4, 1.4)M_\odot$

Einstein Telescope



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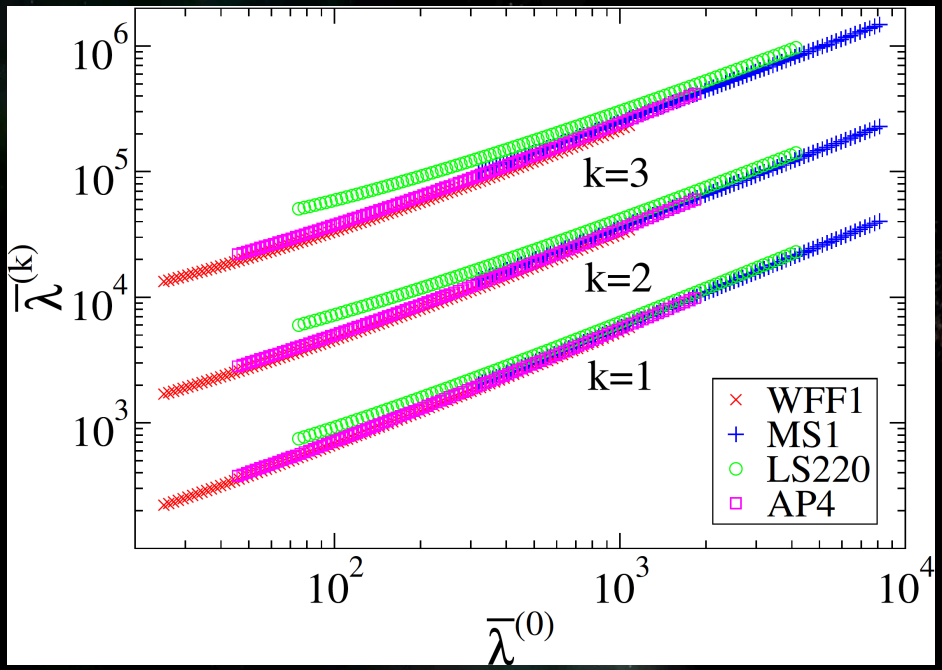

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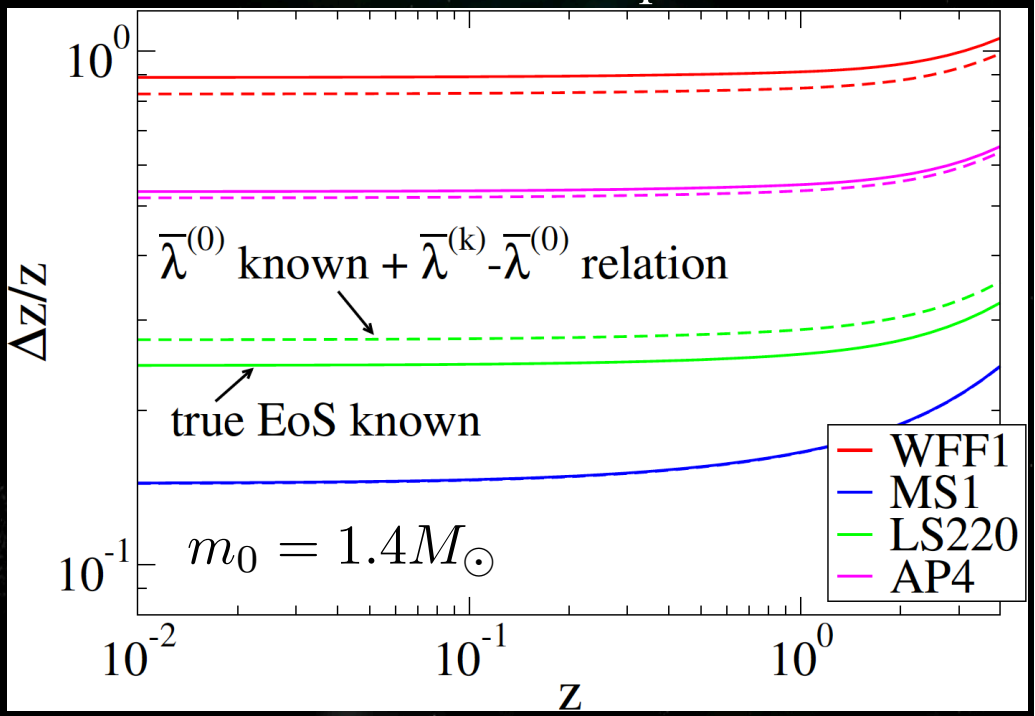


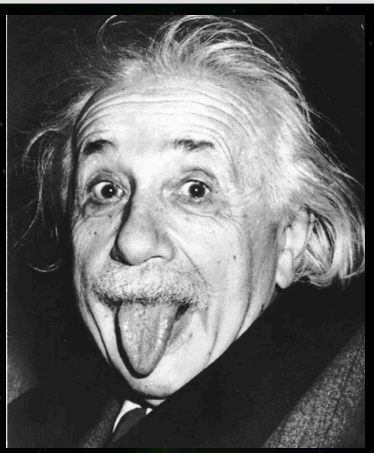
- ✓ difference ~10% at most
- ✓ possible to perform GW cosmology even if only $\bar{\lambda}^{(0)}$ is known

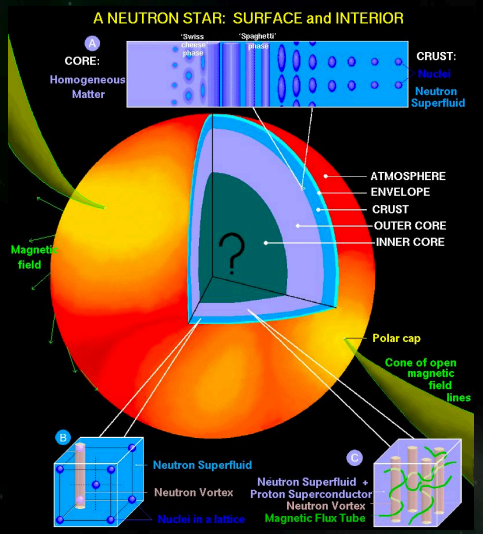
Conclusions

Takeaway

Astrophysics

Gravitational Physics





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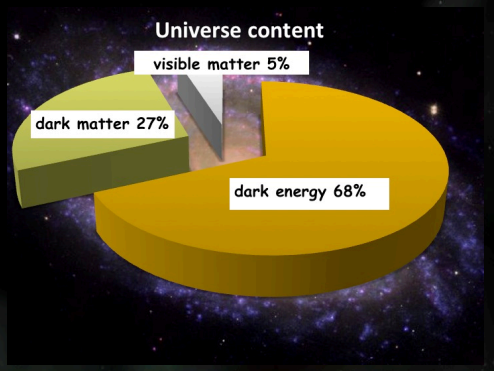
review article [KY & Yunes arXiv:1608.02582]



Nuclear Physics

Cosmology

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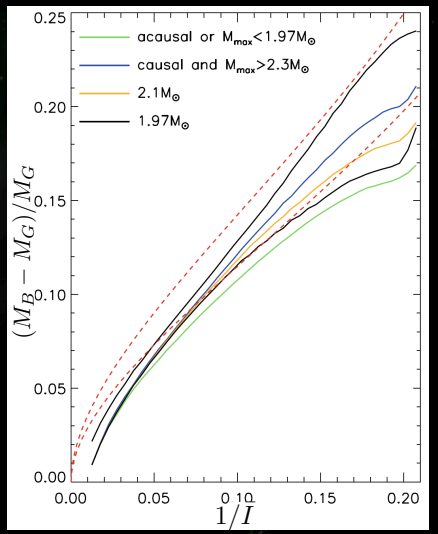

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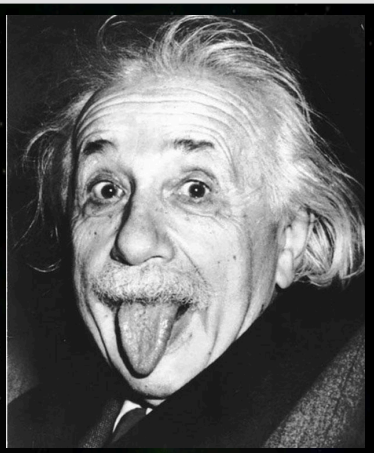

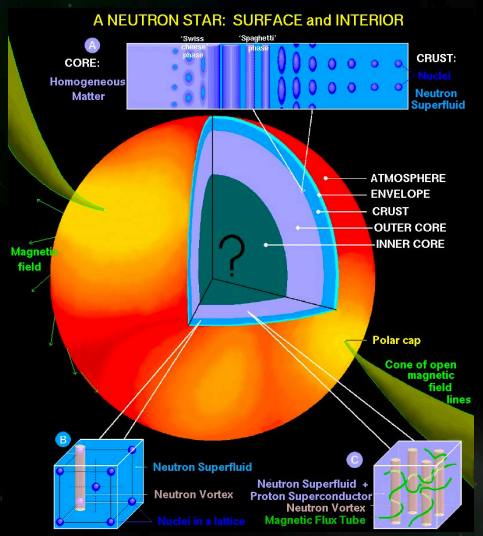

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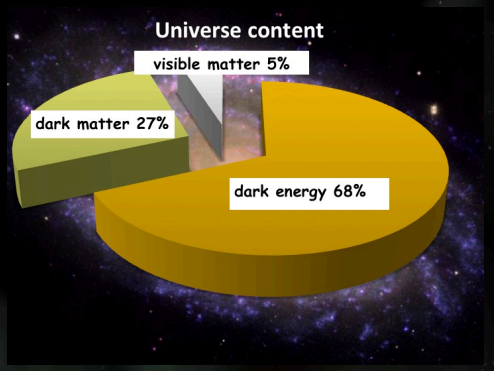

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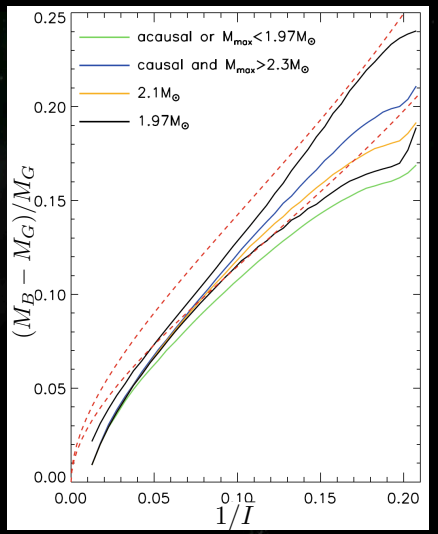
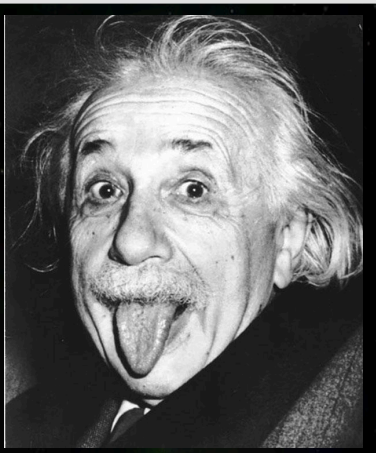
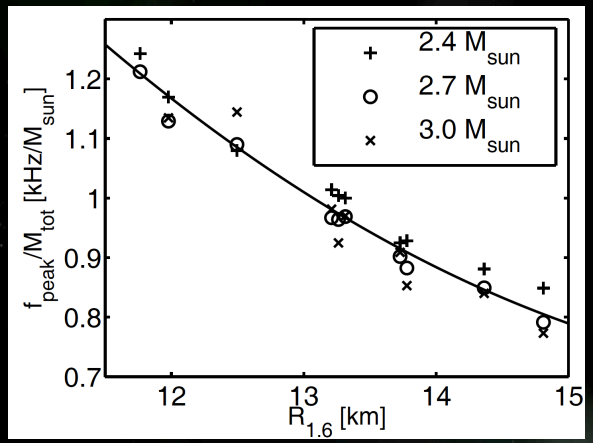


Gravitational Physics





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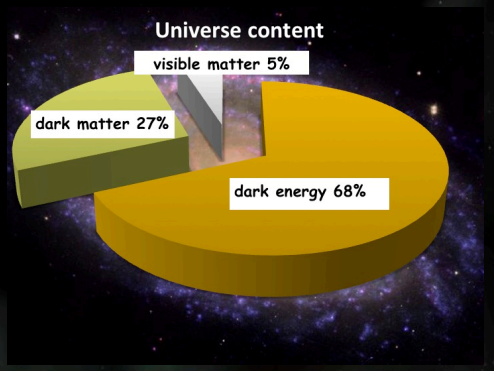

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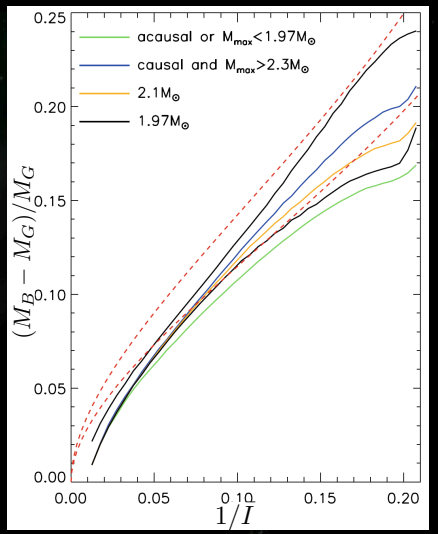

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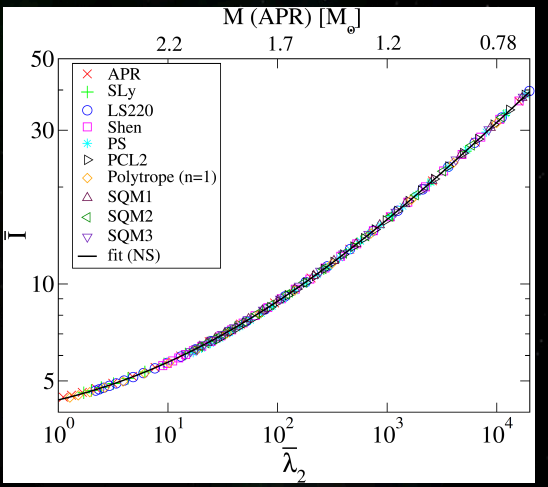

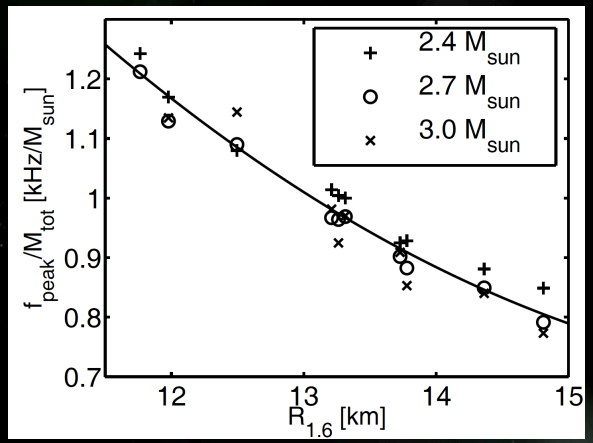

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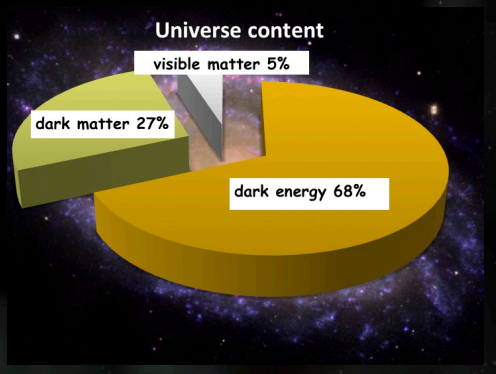

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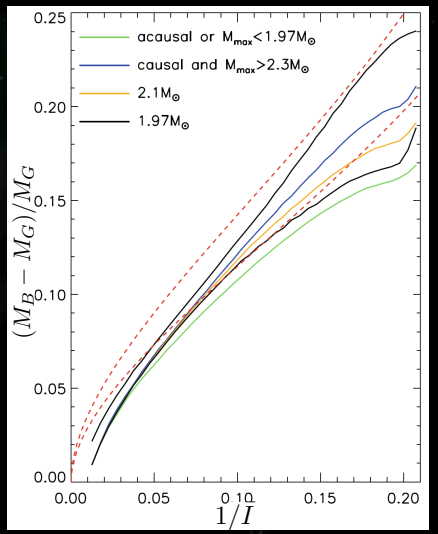

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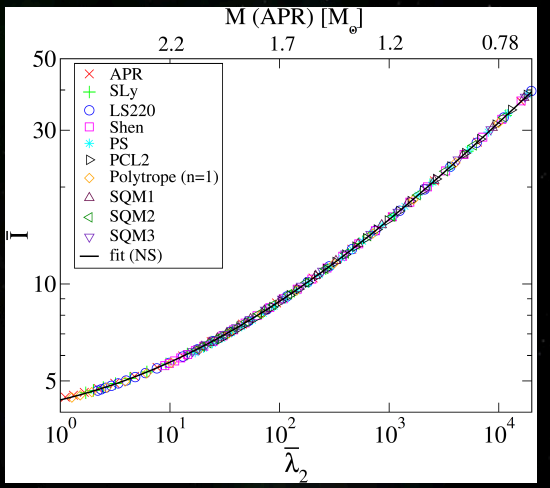

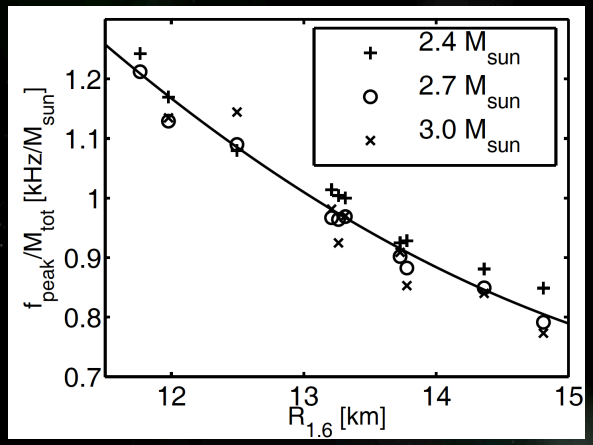

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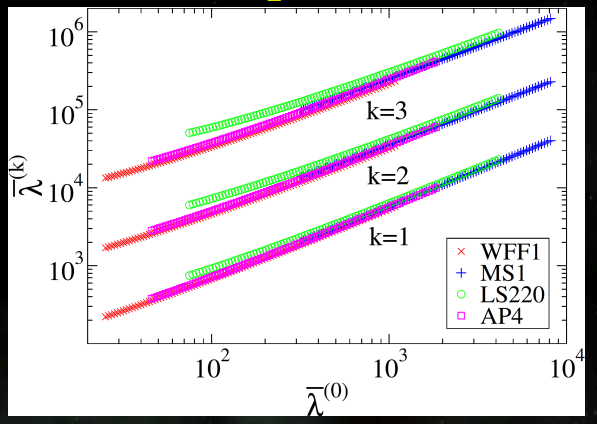

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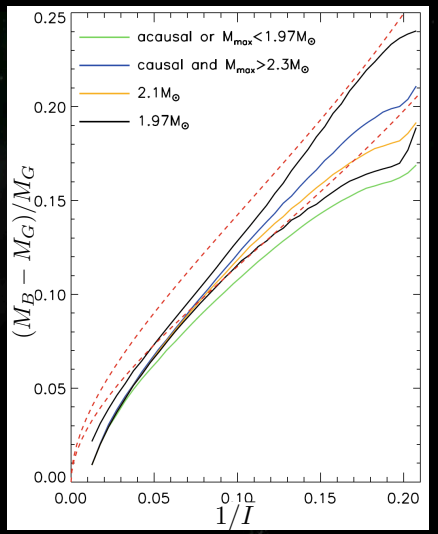

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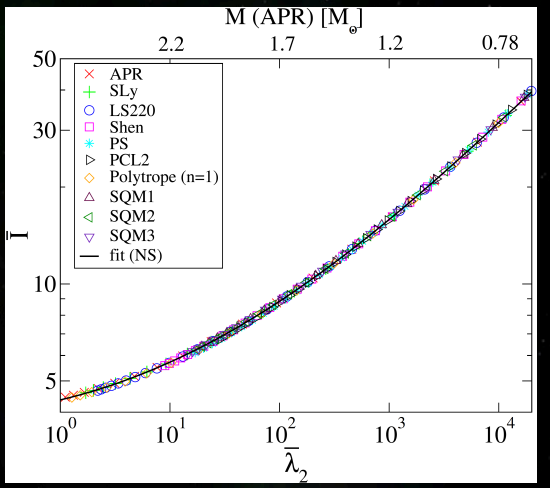

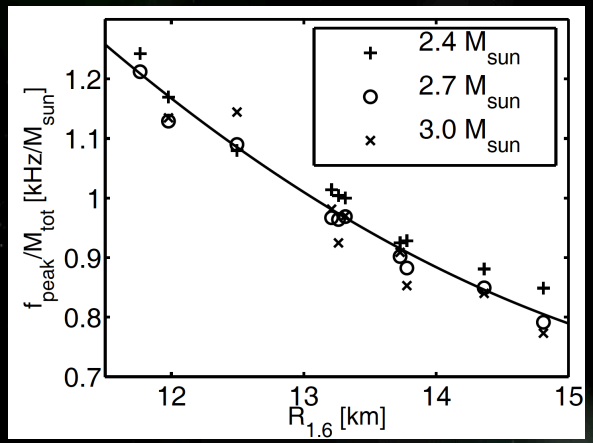

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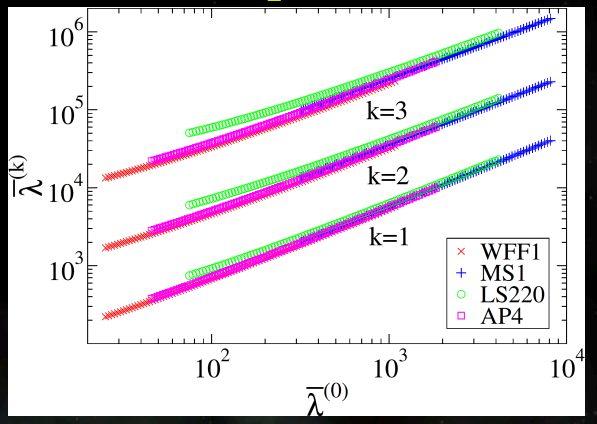

Thank You

Nuclear Physics

Cosmology