Probing Nuclear Physics with Gravitational Waves

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Jefferson Lab., March 5th 2019

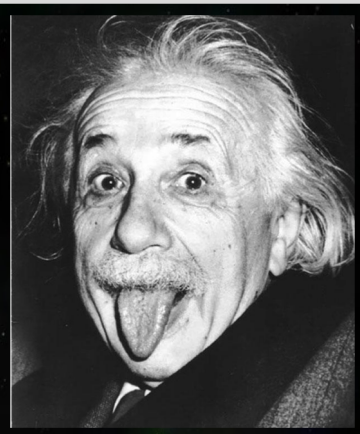
Binary Neutron Star Merger (Aug.17, 2017)

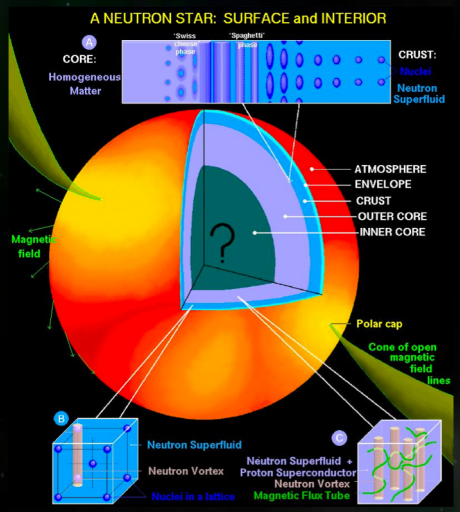
[LIGO]

Leaned Lots of Physics!

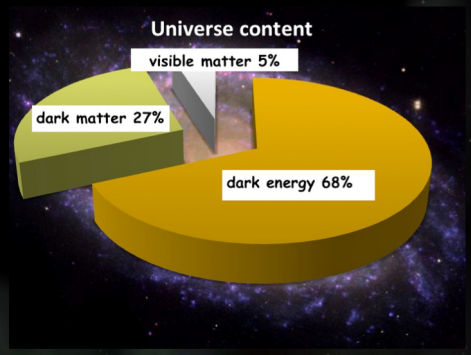
Astrophysics

Gravitational Physics





GW170817

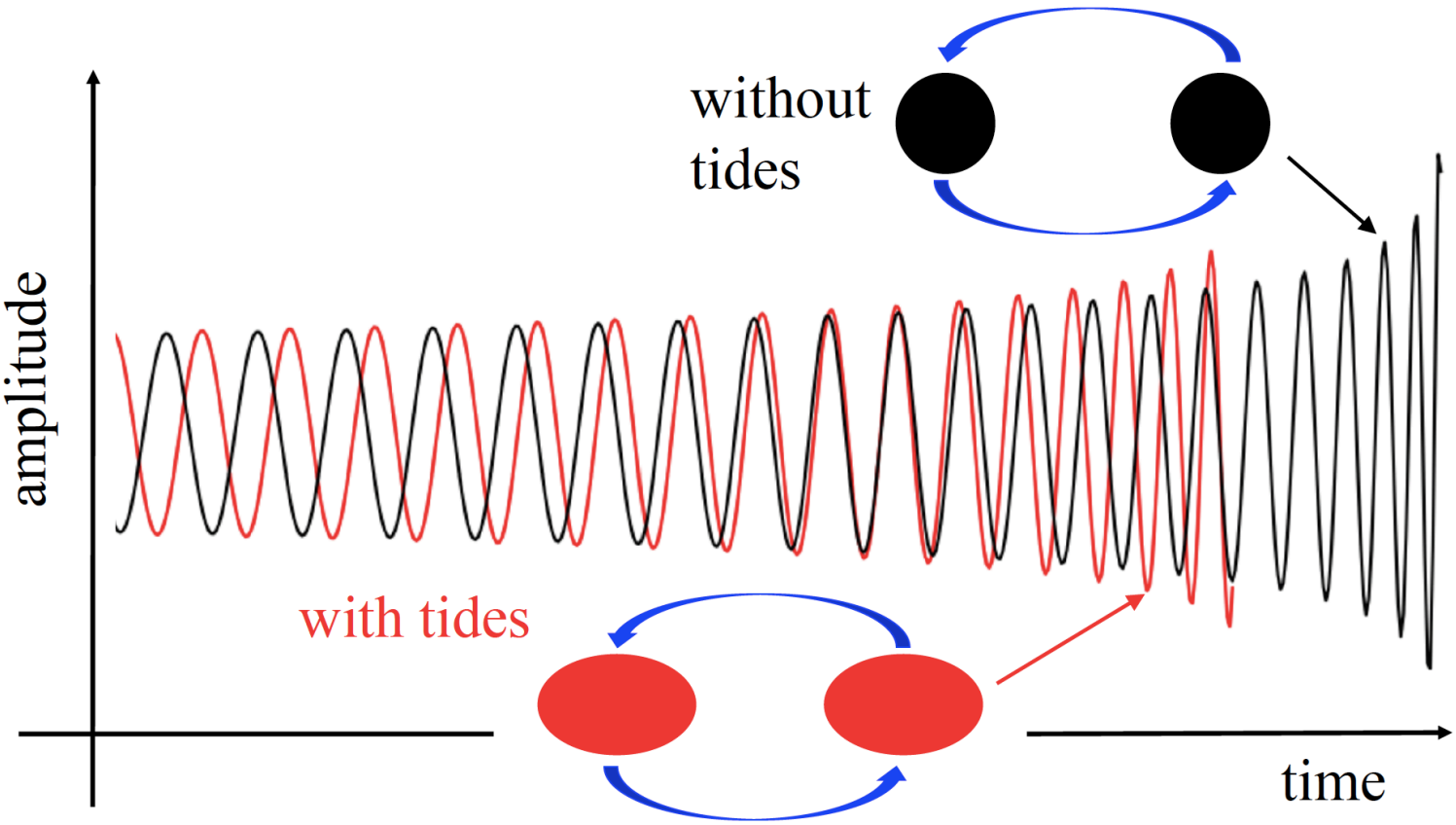


Nuclear Physics

Cosmology

Kent Yagi

Tidal Effect



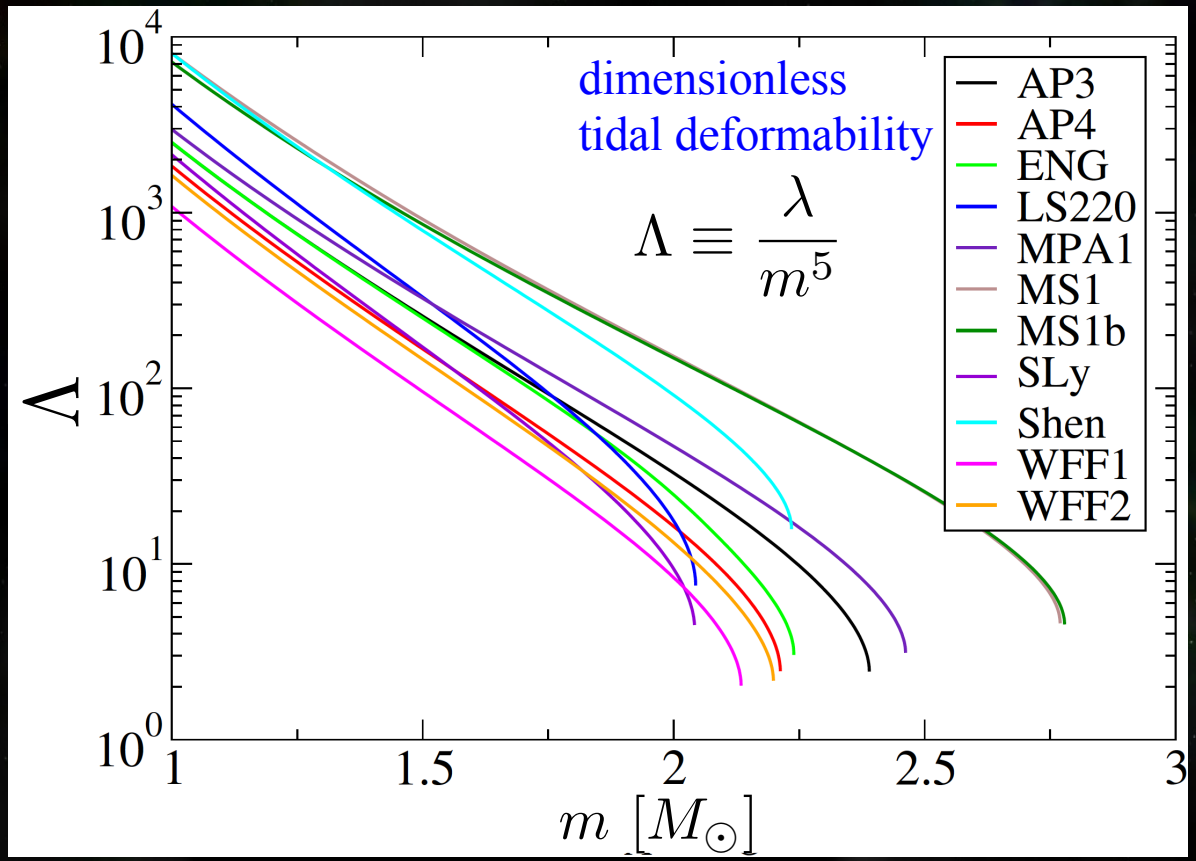
NS internal structure controls the amount
of tides that is encoded in the waveform.

Love

tidal deformability
(tidal Love number)

$$\lambda = \frac{\text{quadrupole moment}}{\text{tidal field}}$$

Love



tidal deformability
(tidal Love number)

$$\lambda = \frac{\text{quadrupole moment}}{\text{tidal field}}$$

LIGO Posterior on the Tidal Deformability

Leading tidal parameter in the waveform:

[LVC, arXiv:1805.11579]

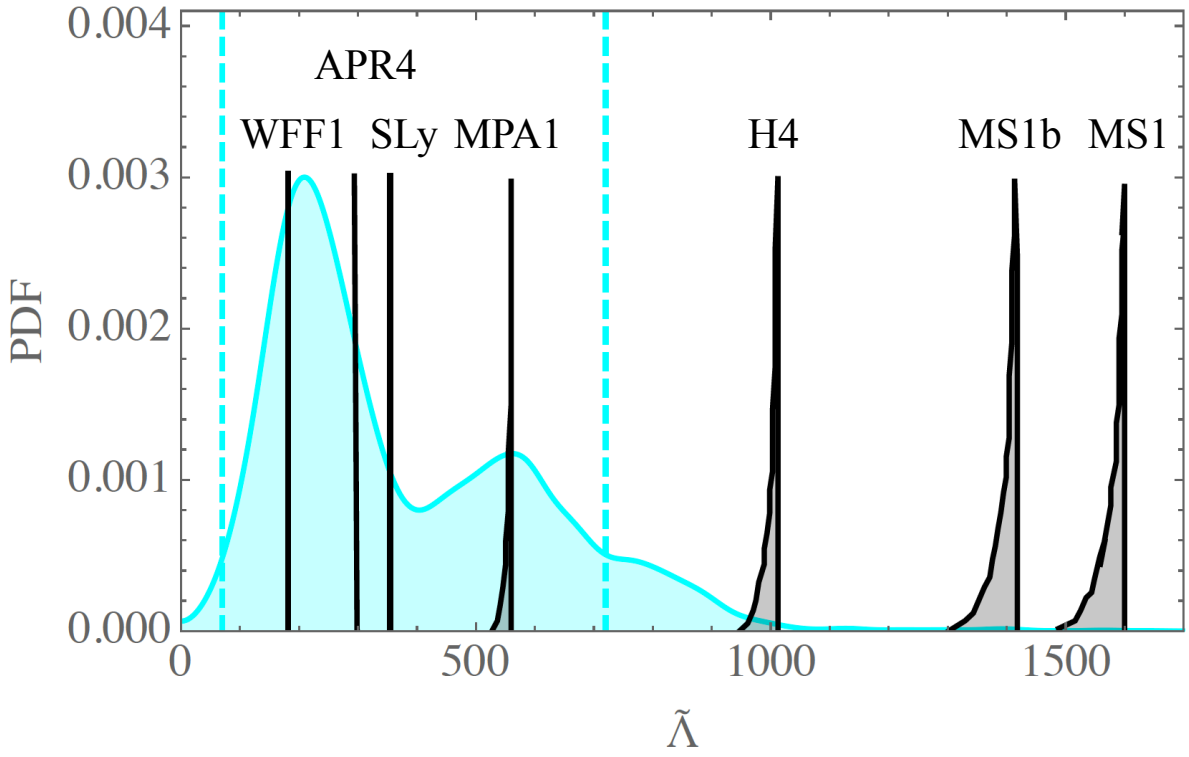
$$\tilde{\Lambda} = \frac{16}{13}\frac{(1+12q)\Lambda_1 + (12+q)q^4\Lambda_2}{(1+q)^5},$$

softer EoSs are preferred

$q = m_1/m_2$

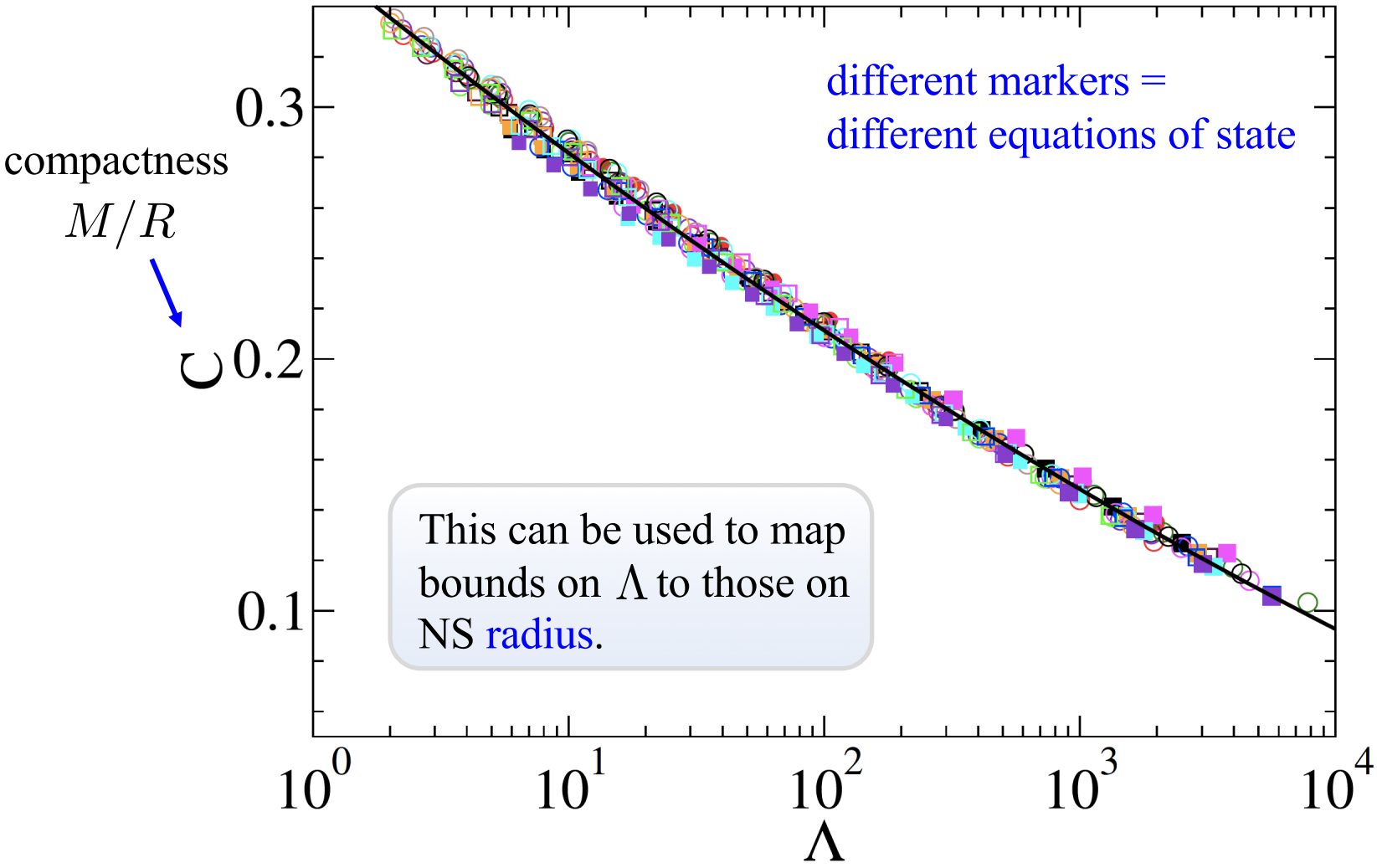
soft

stiff



Universal Love-C Relation

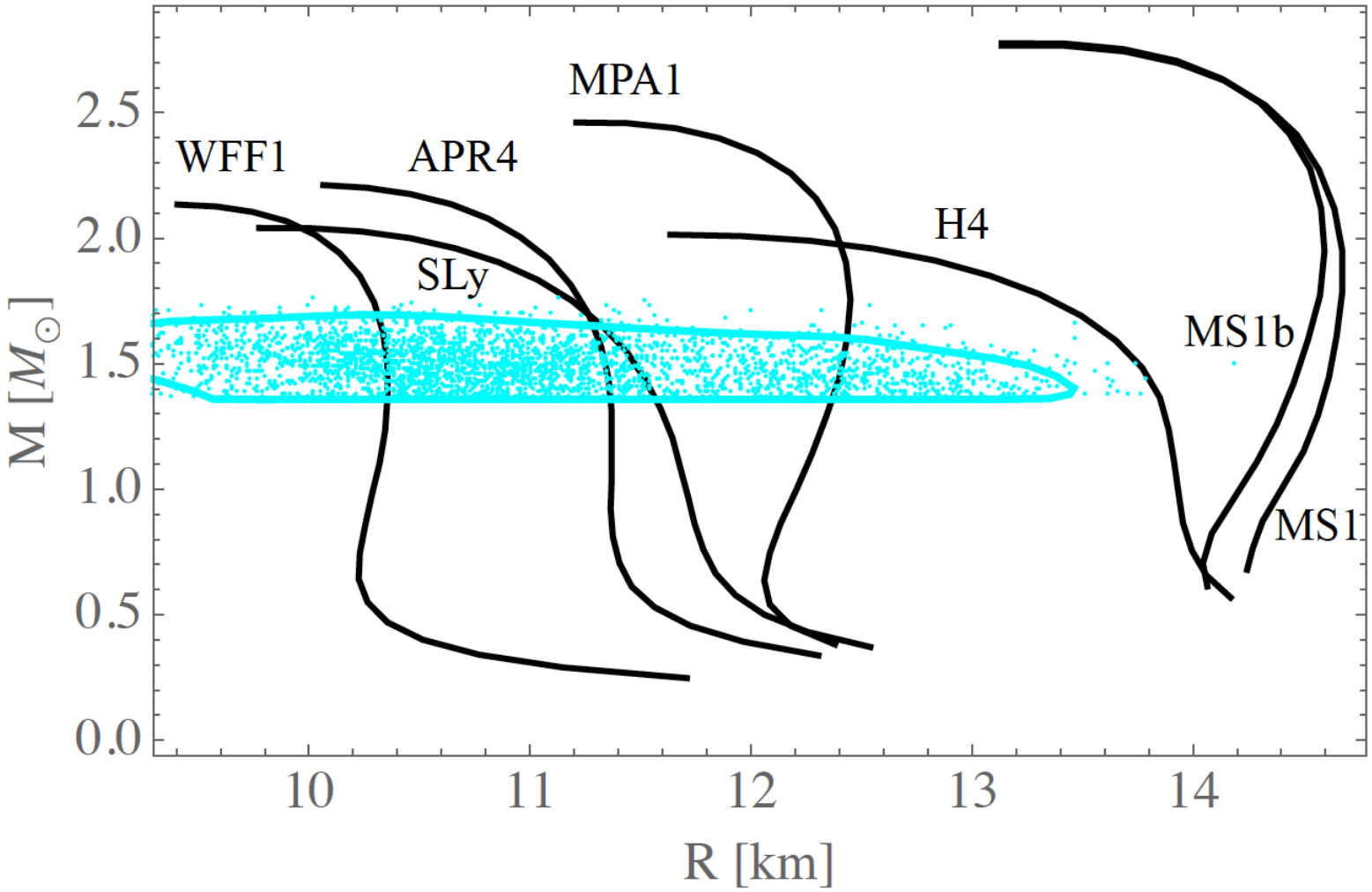
[Maselli et al. (2013)]



[KY & Yunes (2017)]

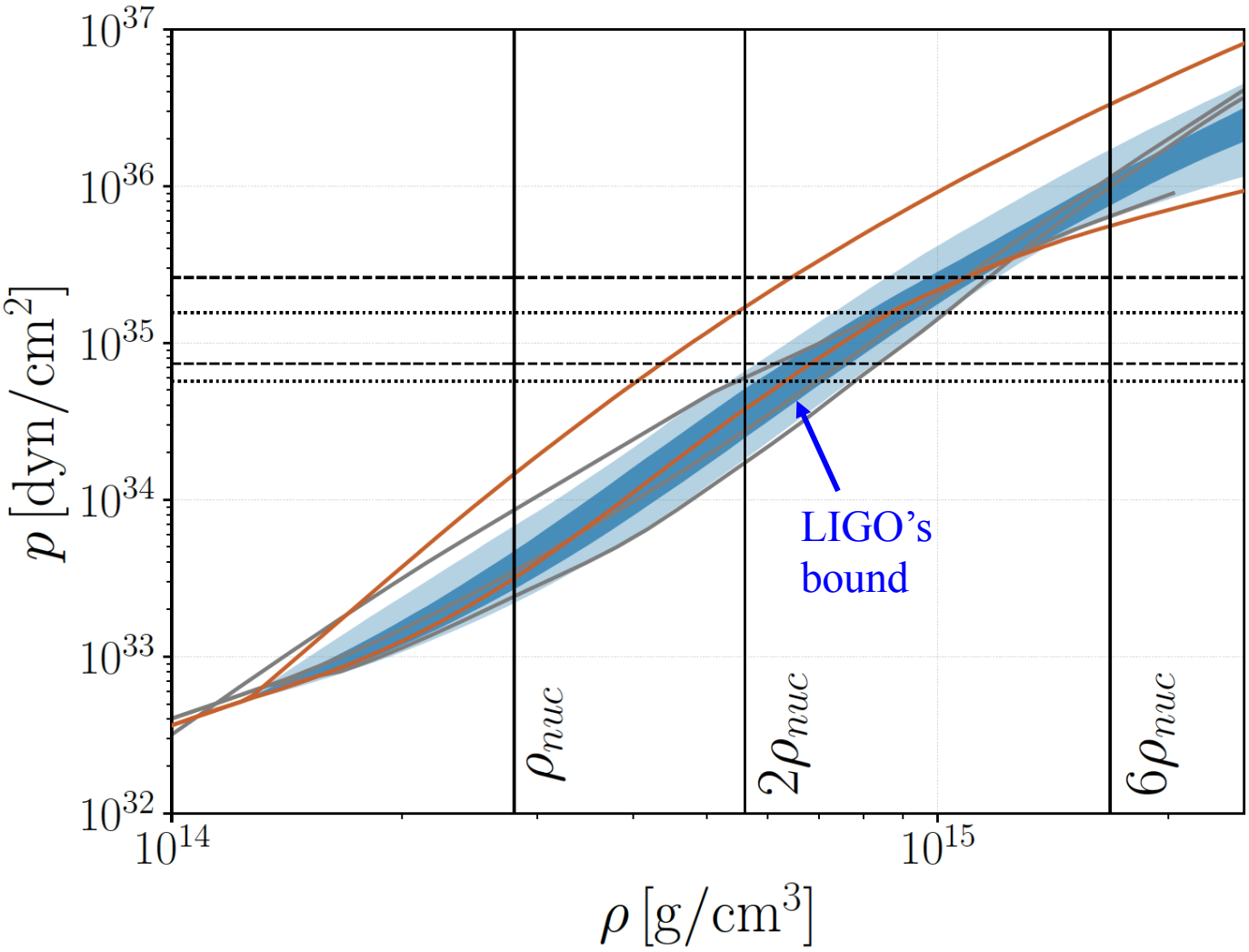
NS Radius Bound

[LVC, arXiv:1805.11581]



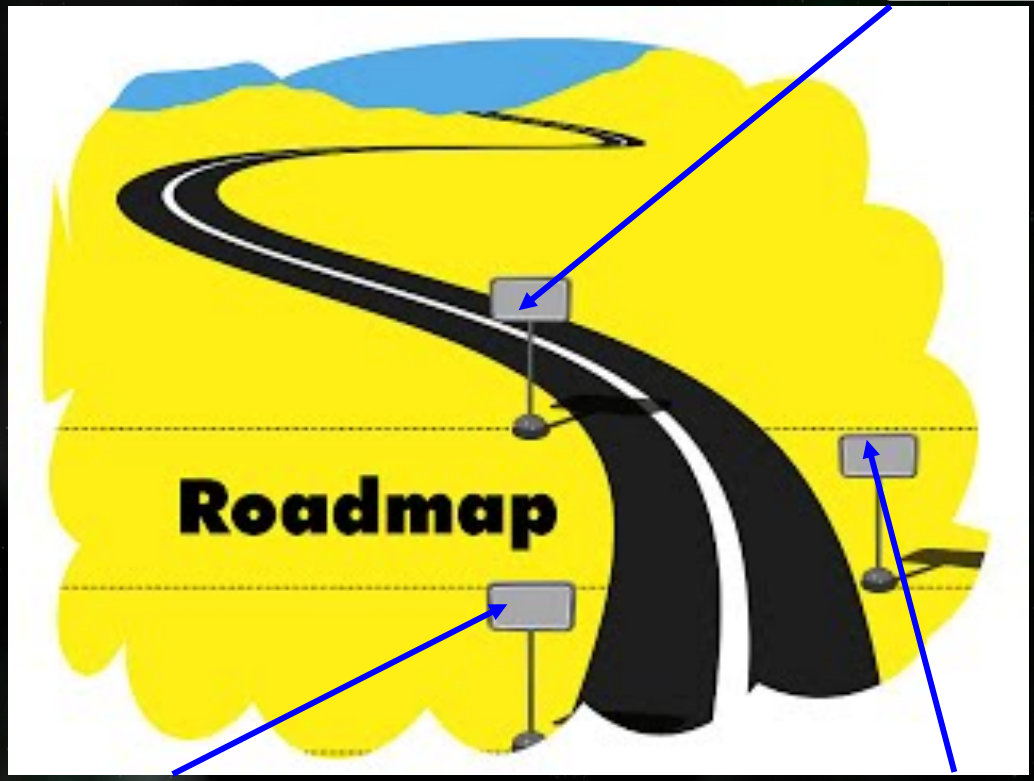
Reconstructing EoS

[LVC, arXiv:1805.11581]



Roadmap

Nuclear Parameter Bounds



Hybrid EoSs

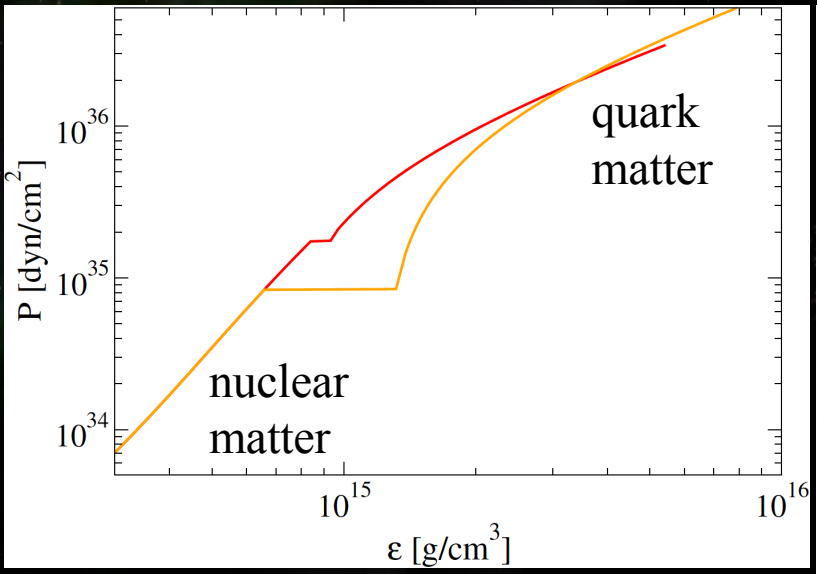
New quark-gluon EoS

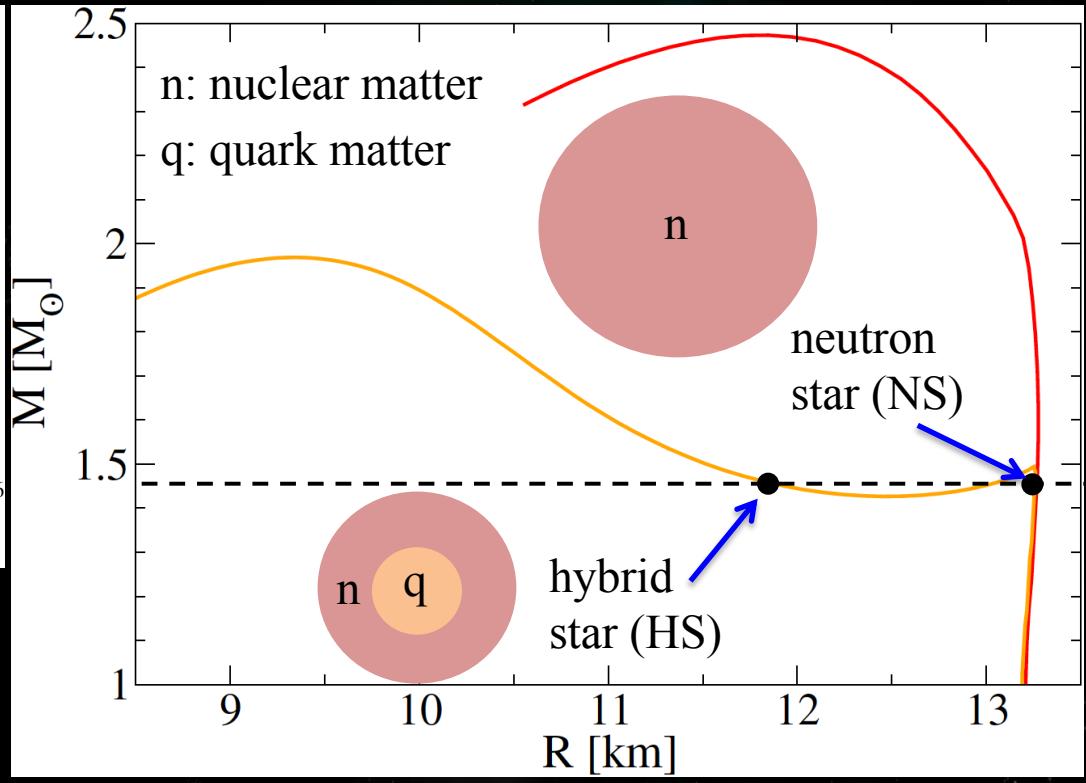
Twin Stars

[Paschalidis, KY, et al. (2018)]

[see e.g. Glendenning & Kettner (2000)]

equations of state with phase transitions



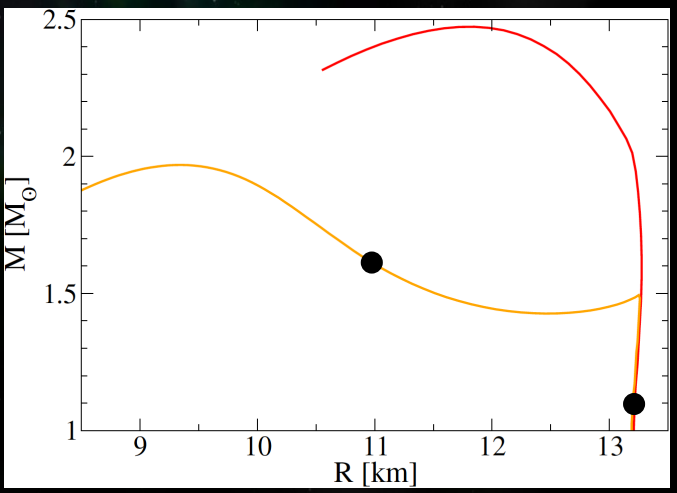


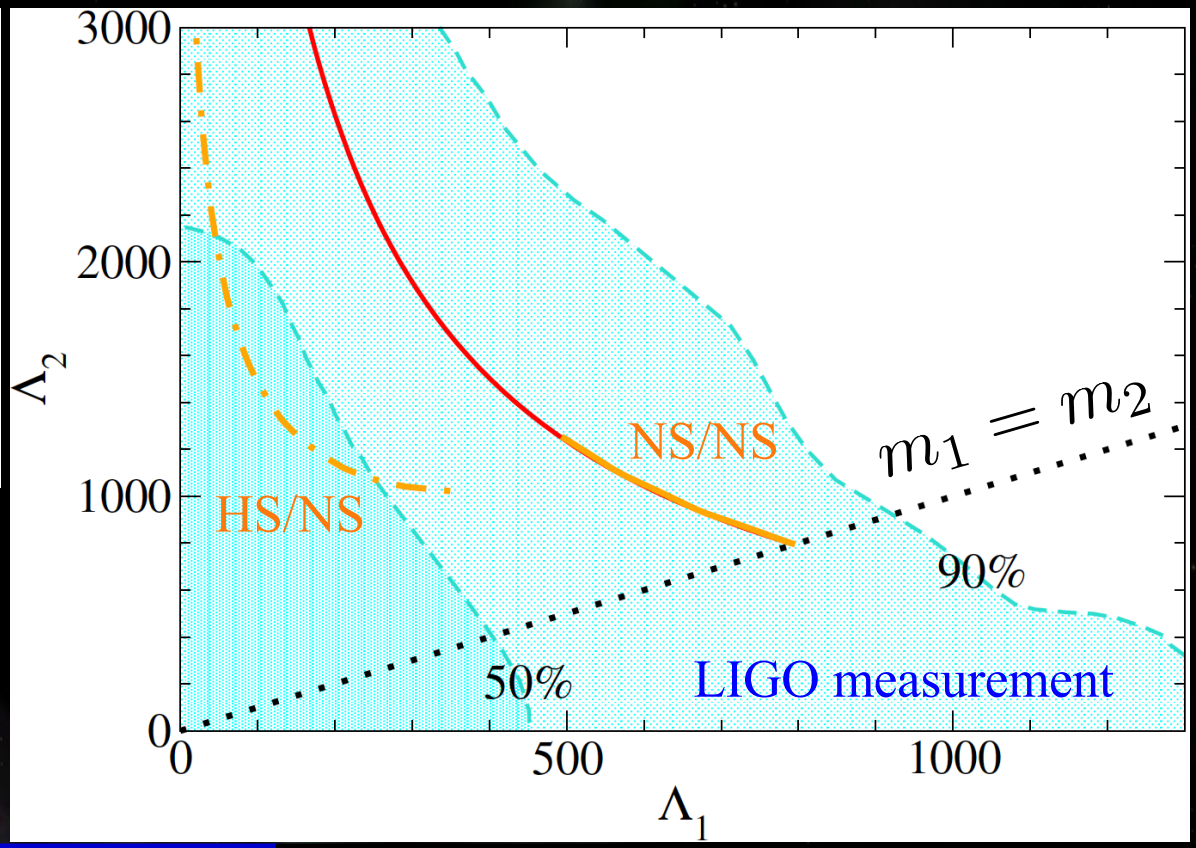
2 compact stars with the same mass but different radii

GW170817 as Hybrid Star / Neutron Star Binary?

[Paschalidis, KY, et al. (2018)]

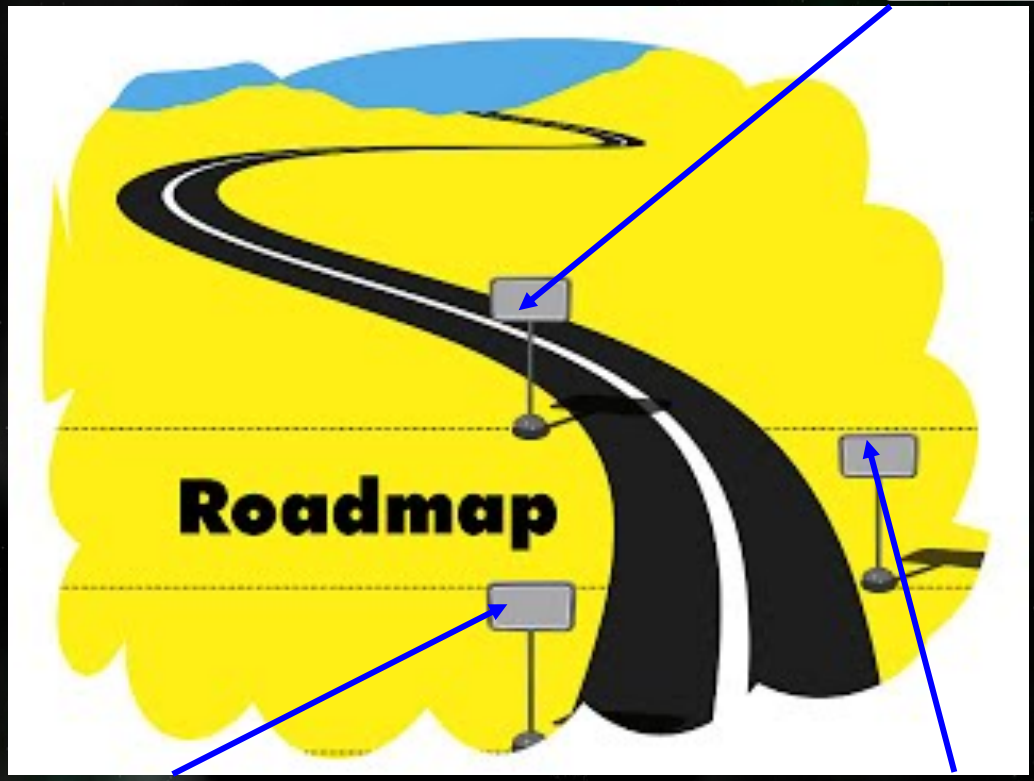
- ✓ consistent with NS/NS
- ✓ also consistent with HS/NS (more favored?)





Roadmap

Nuclear Parameter Bounds

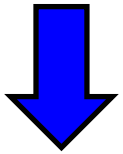


Hybrid EoSs

New quark-gluon EoS

Energy-Momentum Tensor

QCD Lagrangian



Energy-momentum tensor

2nd Mellin moments of generalized parton distributions (observable)

- ✓ JLab [Mazouz et al. (2007) Burkert et al. (2018)]
- ✓ Deep Inelastic Scattering
- ✓ Lattice QCD [Hagler et al. (2008), Shanahan et al. (2019)]

$$\langle p'|T^{\mu\nu}|p\rangle \sim A\gamma^{(\mu}P^{\nu)} + C\left(\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2\right) + \cdots$$

[Ji et al. (1997)]

Fourier transform

$$P = \frac{p+p'}{2}$$

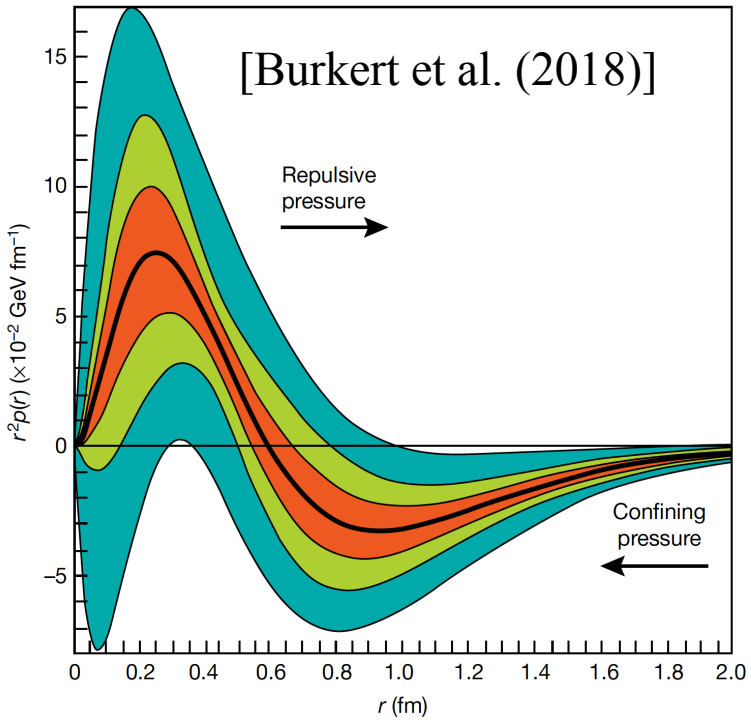
$$\Delta = p' - p$$

energy density

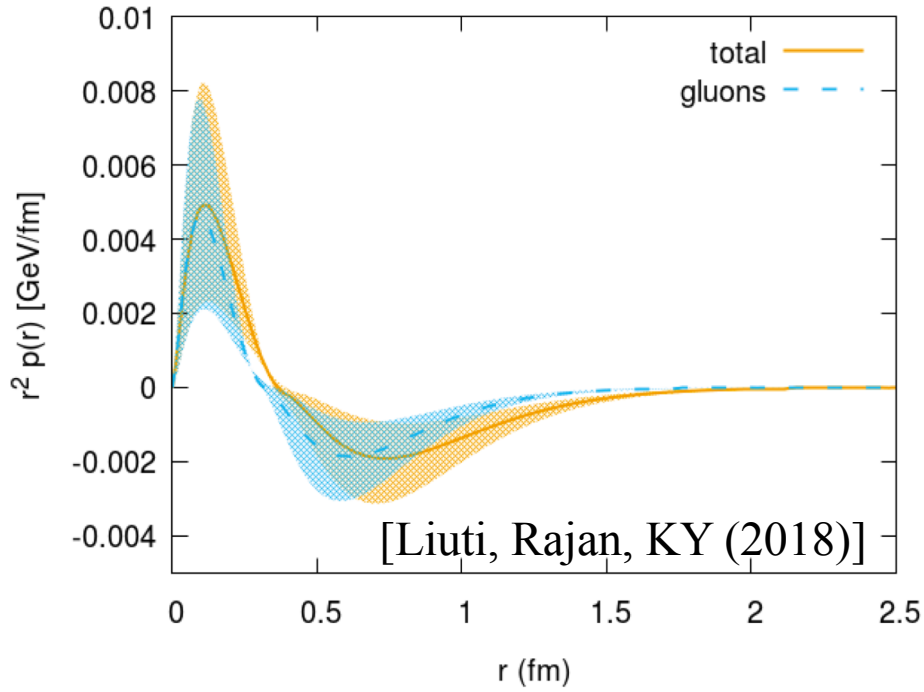
pressure

Pressure profile inside a proton

J-Lab Hall B



based on lattice simulations

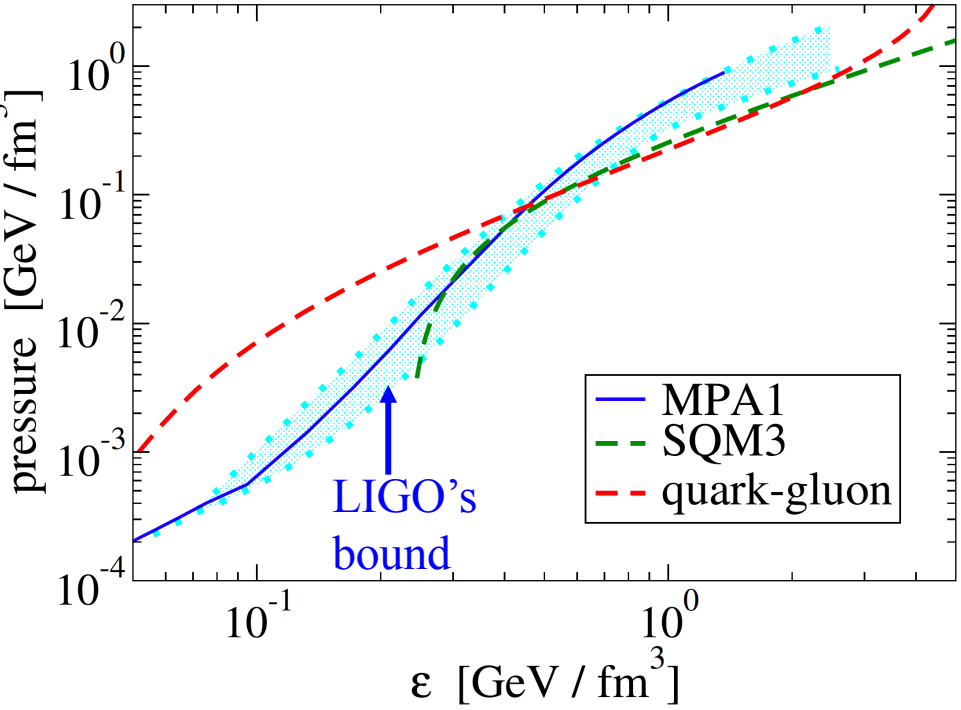


✓ wider range of Δ available

✓ gluons > quarks

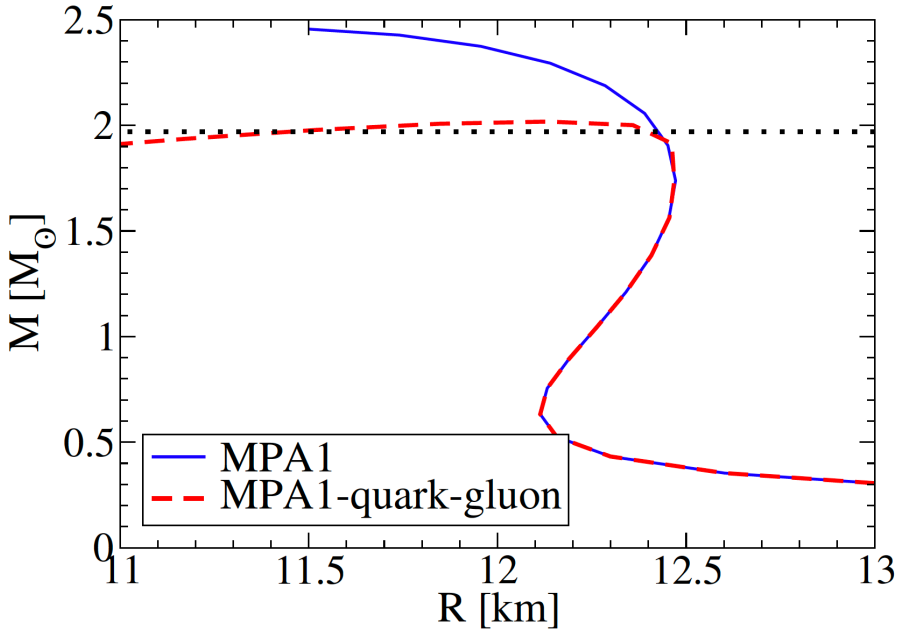
Quark-Gluon Equation of State [Liuti, Rajan, KY (2018)]

Equation of State



high density part marginally consistent with LIGO's result

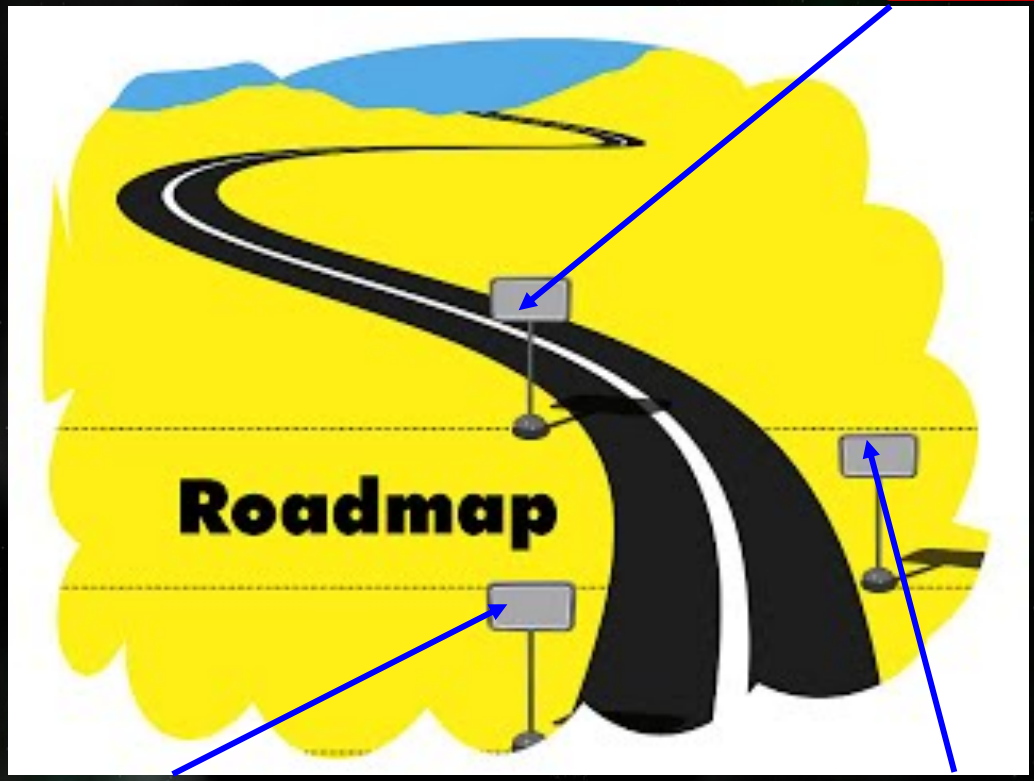
Mass vs Radius



Stitching new quark EoS to some nuclear EoS

Roadmap

Nuclear Parameter Bounds



Hybrid EoSs

New quark-gluon EoS

Nuclear Parameters

Generic way of parameterizing EoS: Taylor expand about symmetric matter and nuclear saturation density

energy per nucleon: $e(n,\delta) = e(n,0) + S(n)\delta^2 + \mathcal{O}(\delta^4)$

symmetric

asymmetric

$n \equiv n_n + n_p$

$\delta \equiv (n_n - n_p)/n$

neutron number density

proton number density

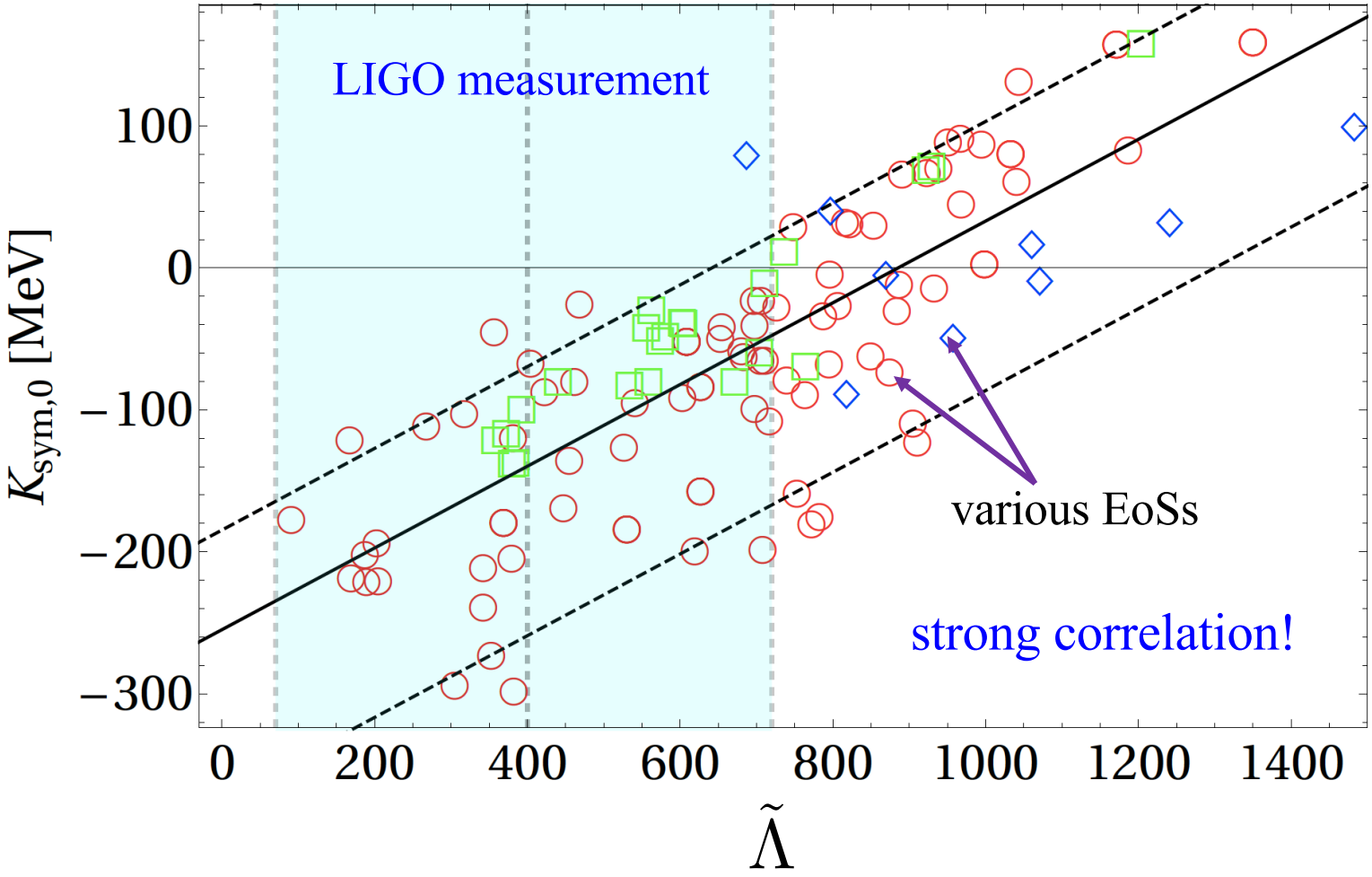
$$S(n) = J_0 + L_0\, y + \frac{K_{\rm sym,0}}{2} y^2 + \mathcal{O}(y^3)$$

$y \equiv (n - n_0)/3n_0$

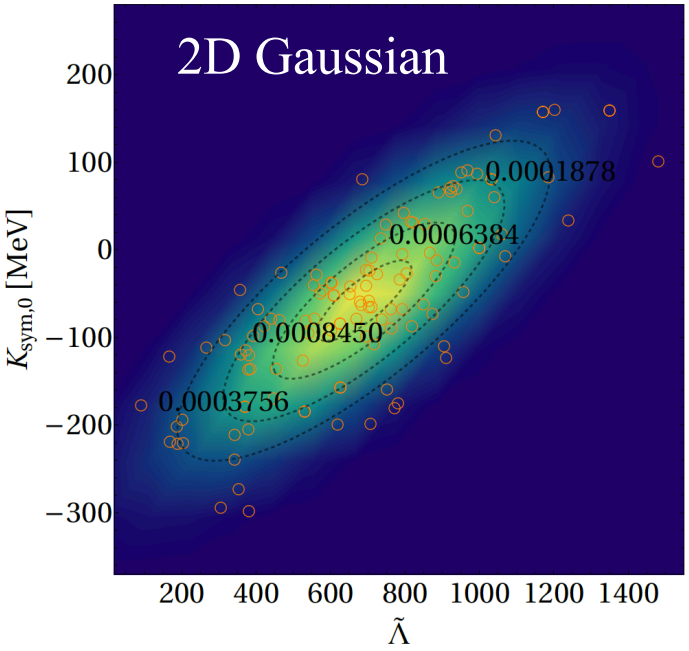
nuclear saturation density

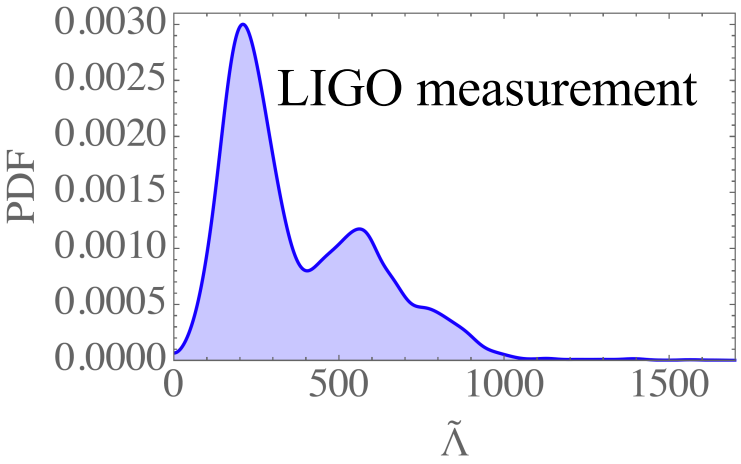
Nuclear Parameter Correlation

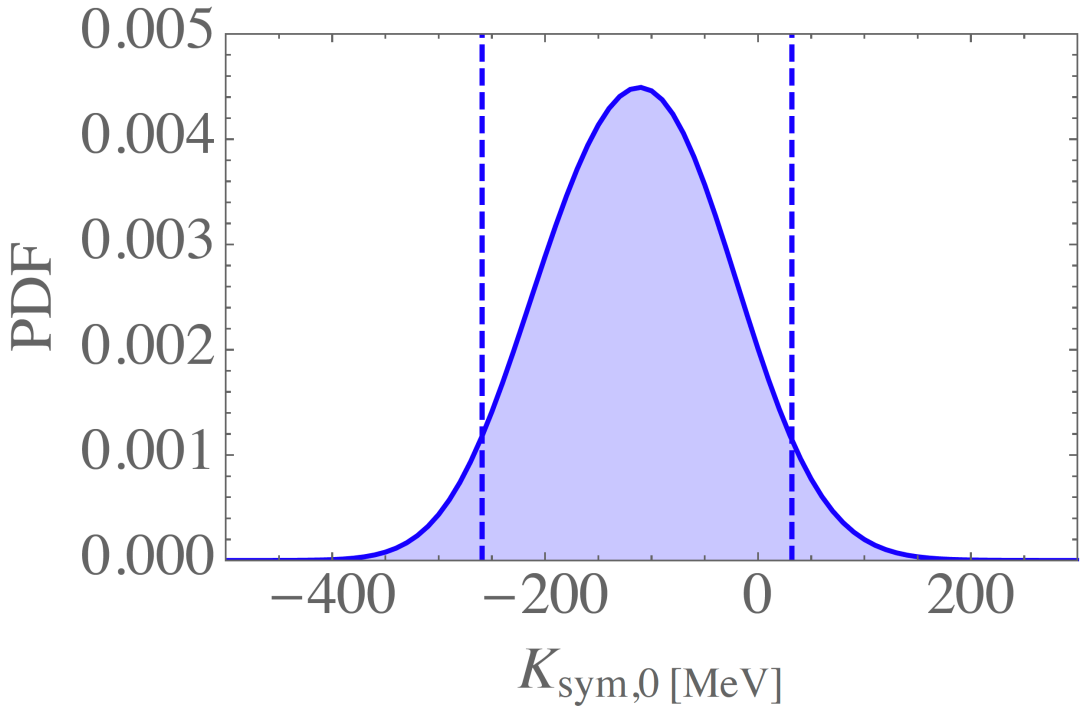
[Malik et al. (2018)]
[Carson, Steiner & KY, arXiv:1812.08910]



Nuclear Parameter Correlation



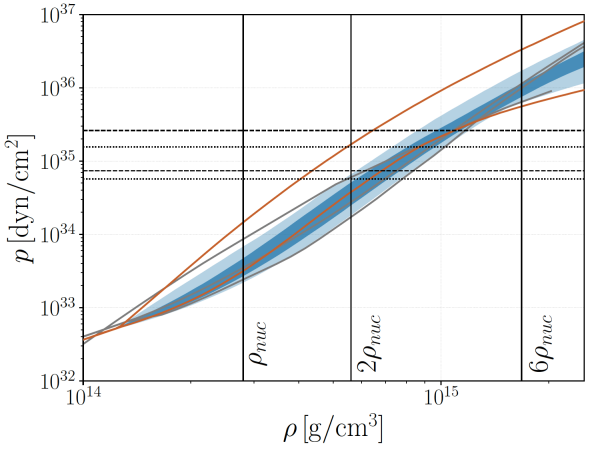




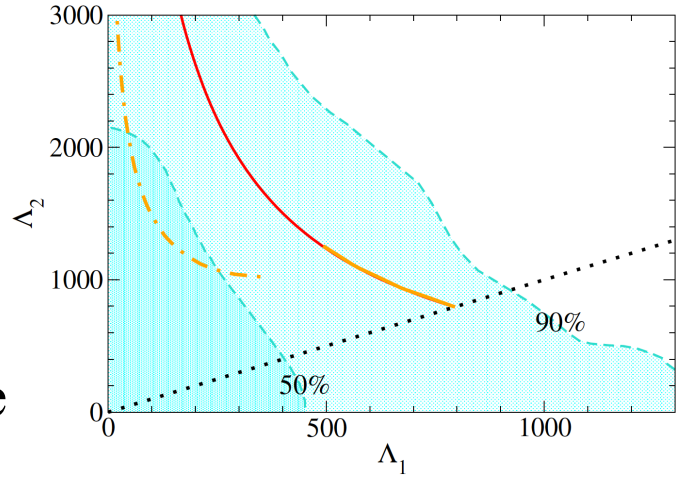
[Carson, Steiner & KY, arXiv:1812.08910]

Conclusions

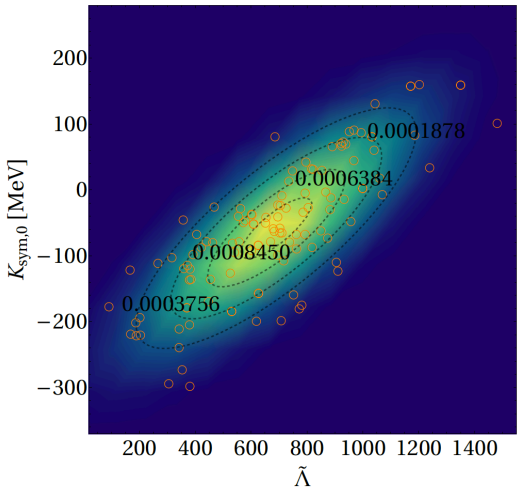
Takeaway



- ✓ Bounds on EoS from LIGO
- ✓ Hybrid EoSs consistent with the GW measurement



Thank You!



- ✓ New bounds on nuclear parameters from correlation with tidal deformability