Equation of state constraints from modern nuclear interactions and observation

Kai Hebeler

Seattle, March 12, 2018

First multi-messenger observations of a neutron star merger and its implications for nuclear physics

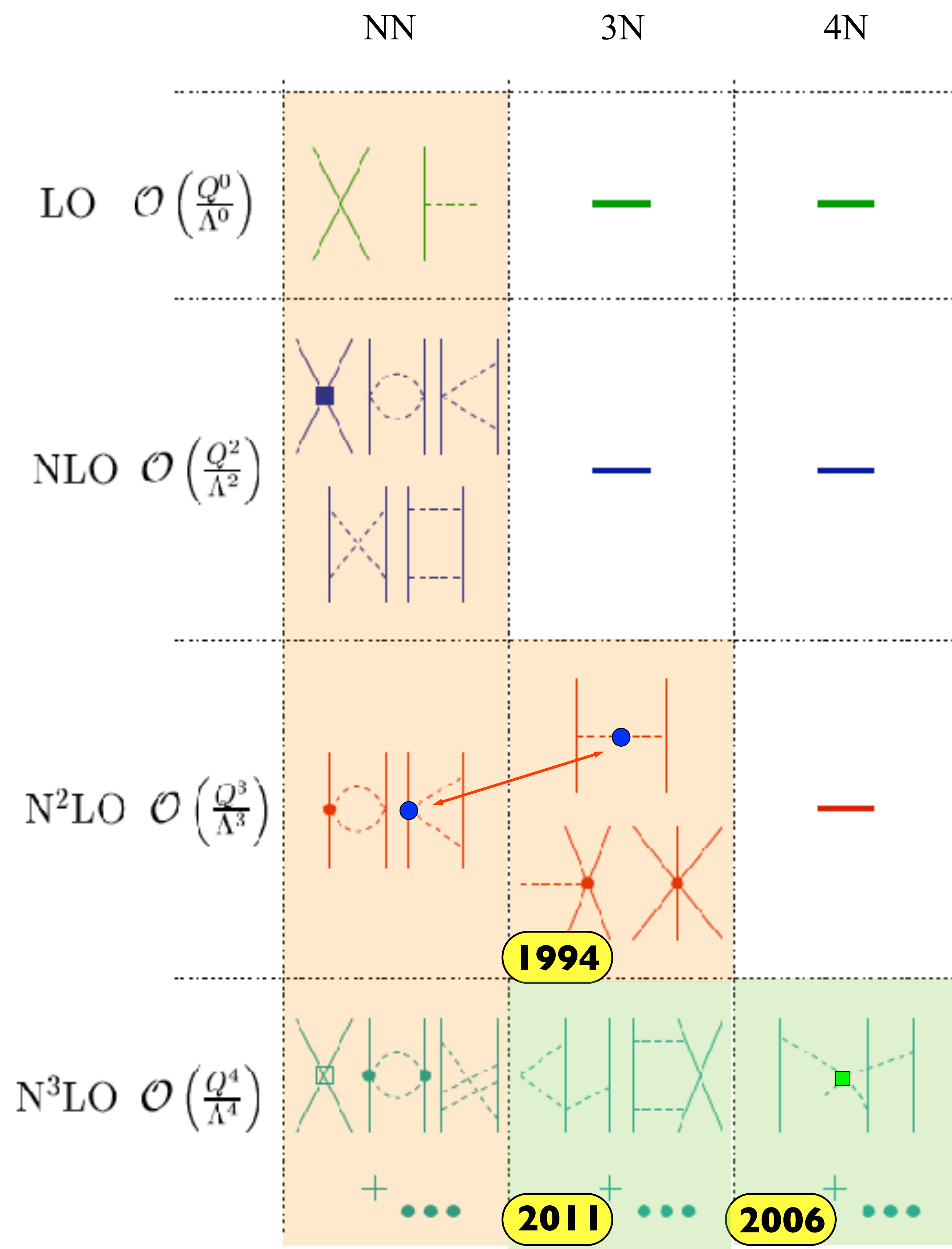
in collaboration with
Svenja Greif, Jim Lattimer, Chris Pethick and Achim Schwenk

SFB 1245

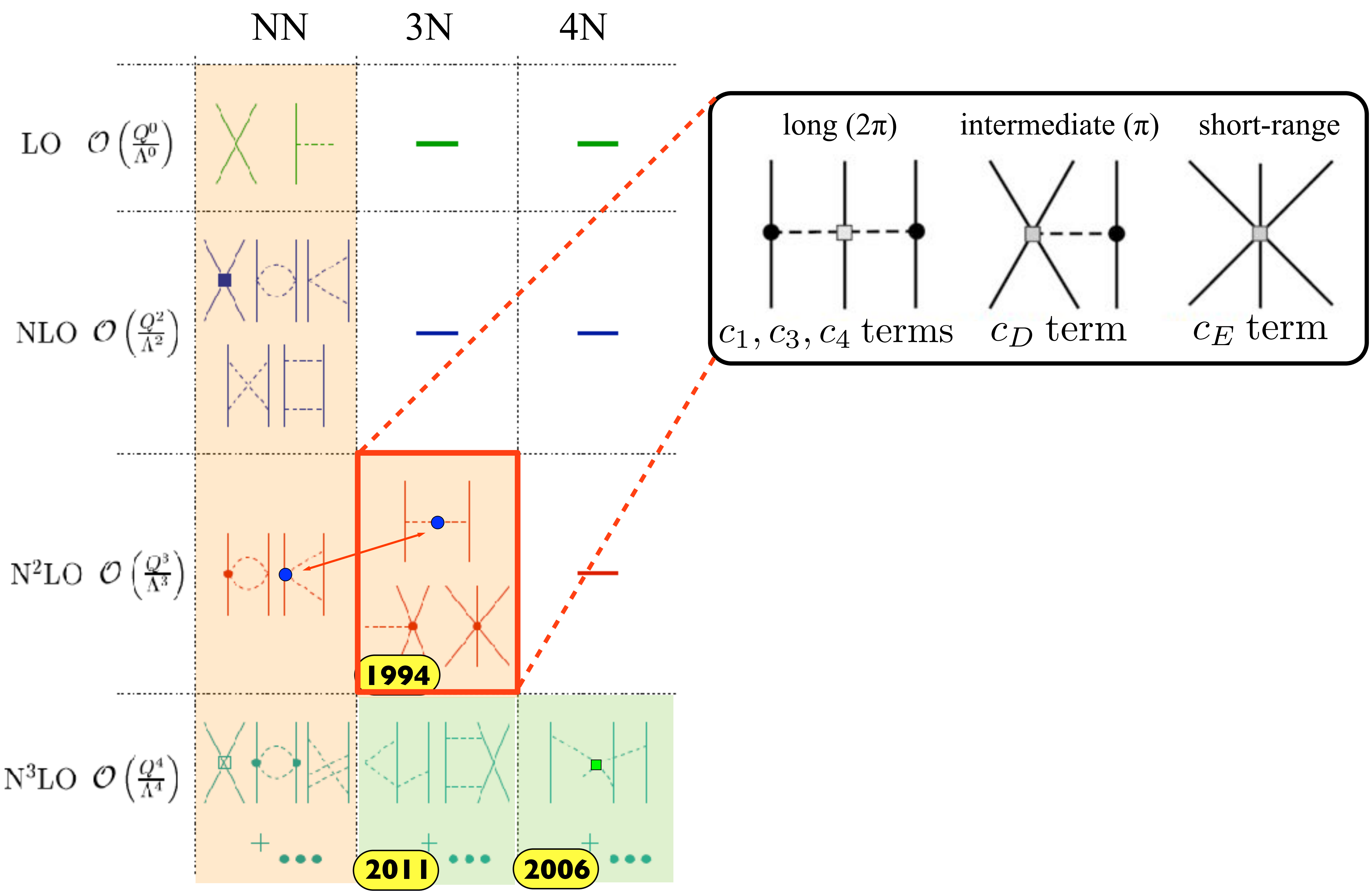
TECHNISCHE UNIVERSITÄT DARMSTADT

Chiral effective field theory for nuclear forces

- choose relevant degrees of freedom: here nucleons and pions
- operators constrained by symmetries of QCD
- short-range physics captured in few short-range couplings
- separation of scales: Q << Λ_b, breakdown scale Λ_b~500 MeV
- power-counting: expand in powers Q/Λ_b
- systematic: work to desired accuracy, obtain error estimates



Many-body forces in chiral EFT



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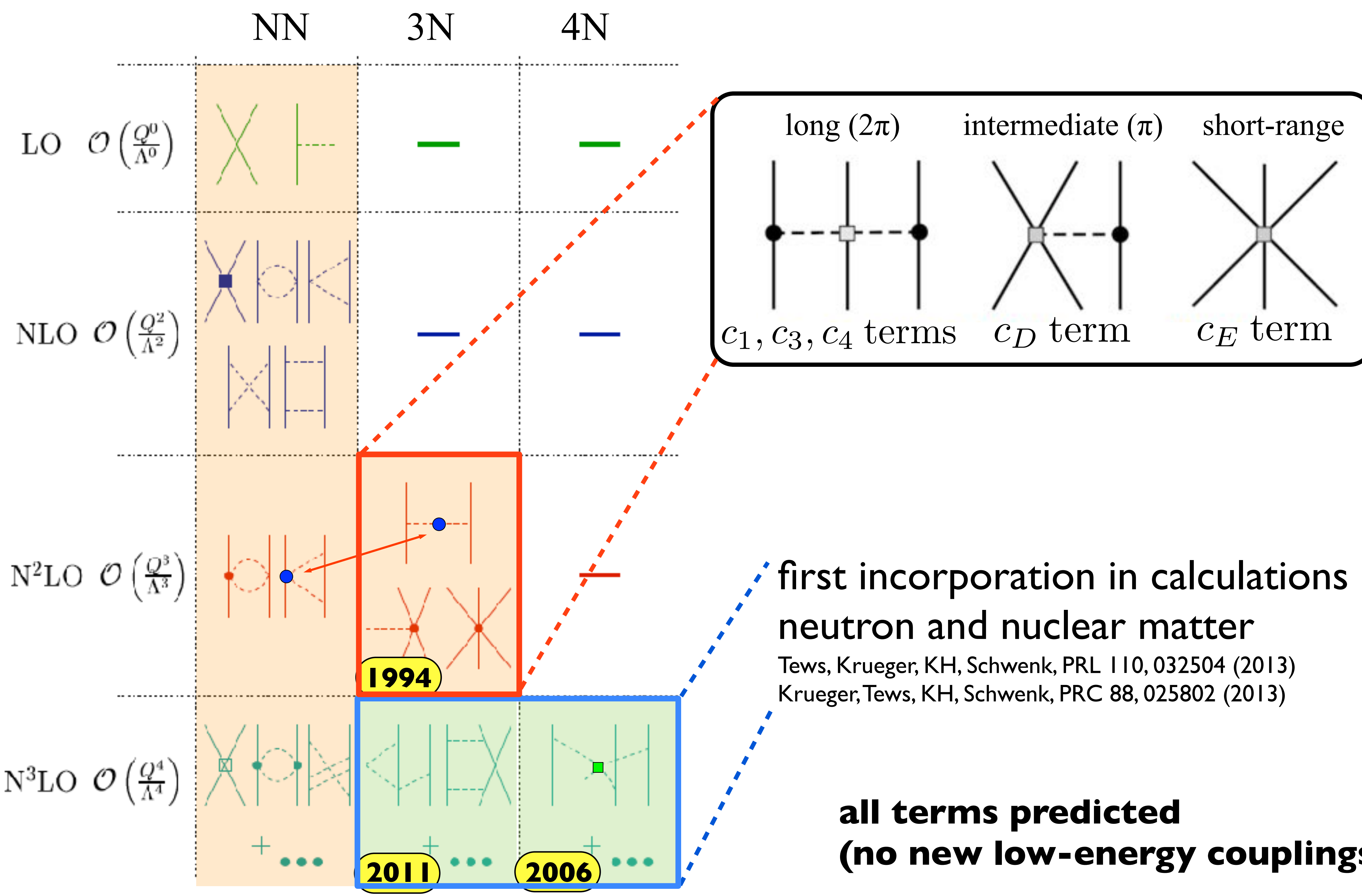


first incorporation in calculations of neutron and nuclear matter

Tews, Krueger, KH, Schwenk, PRL 110, 032504 (2013)

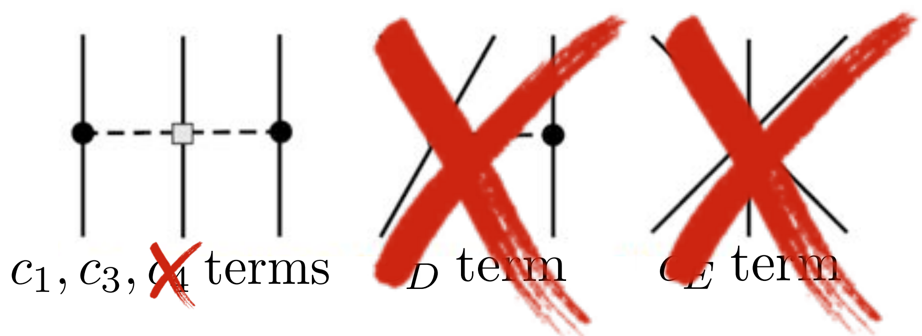
Krueger, Tews, KH, Schwenk, PRC 88, 025802 (2013)

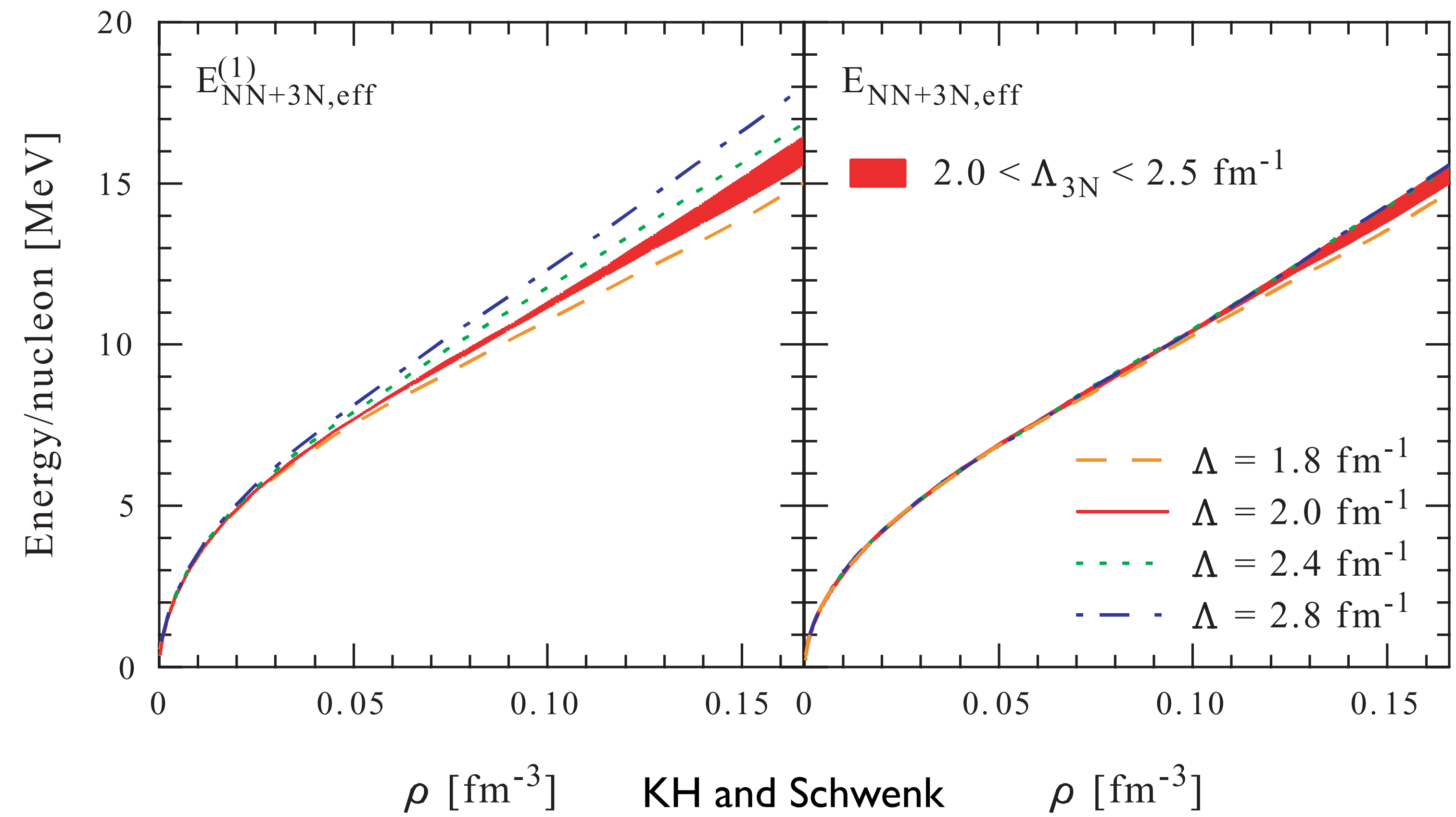
all terms predicted (no new low-energy couplings)

Results for the neutron matter equation of state

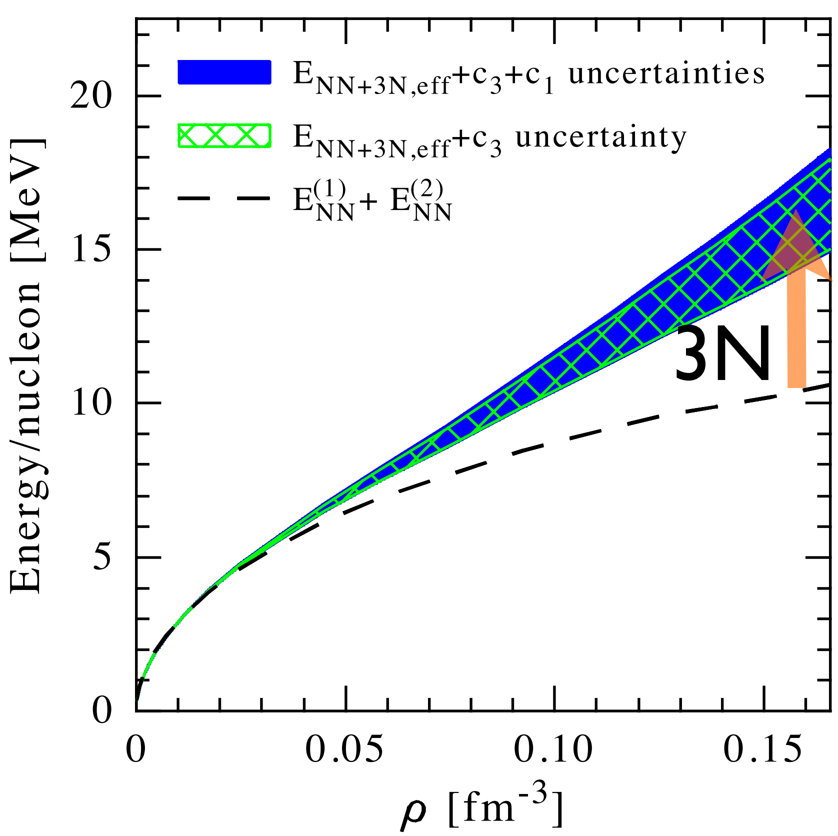
neutron matter is a **unique system** for chiral EFT:

only long-range 3NF contribute in leading order



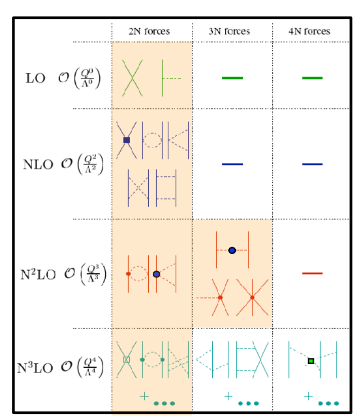


KH and Schwenk
PRC 82, 014314 (2010)



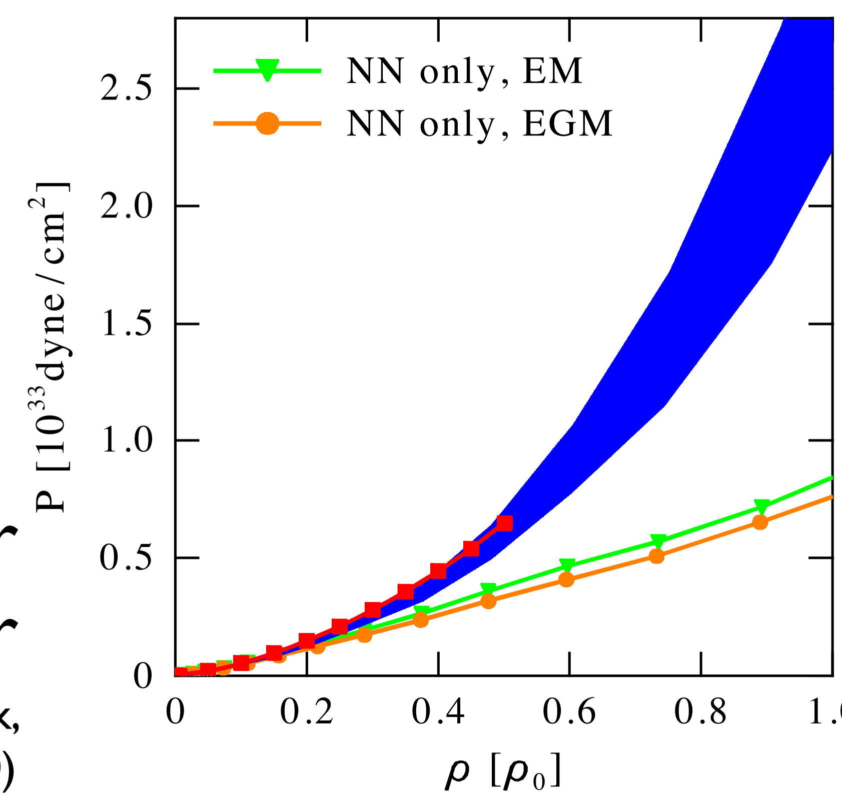
pure neutron matter

KH and Schwenk PRC 82, 014314 (2010)

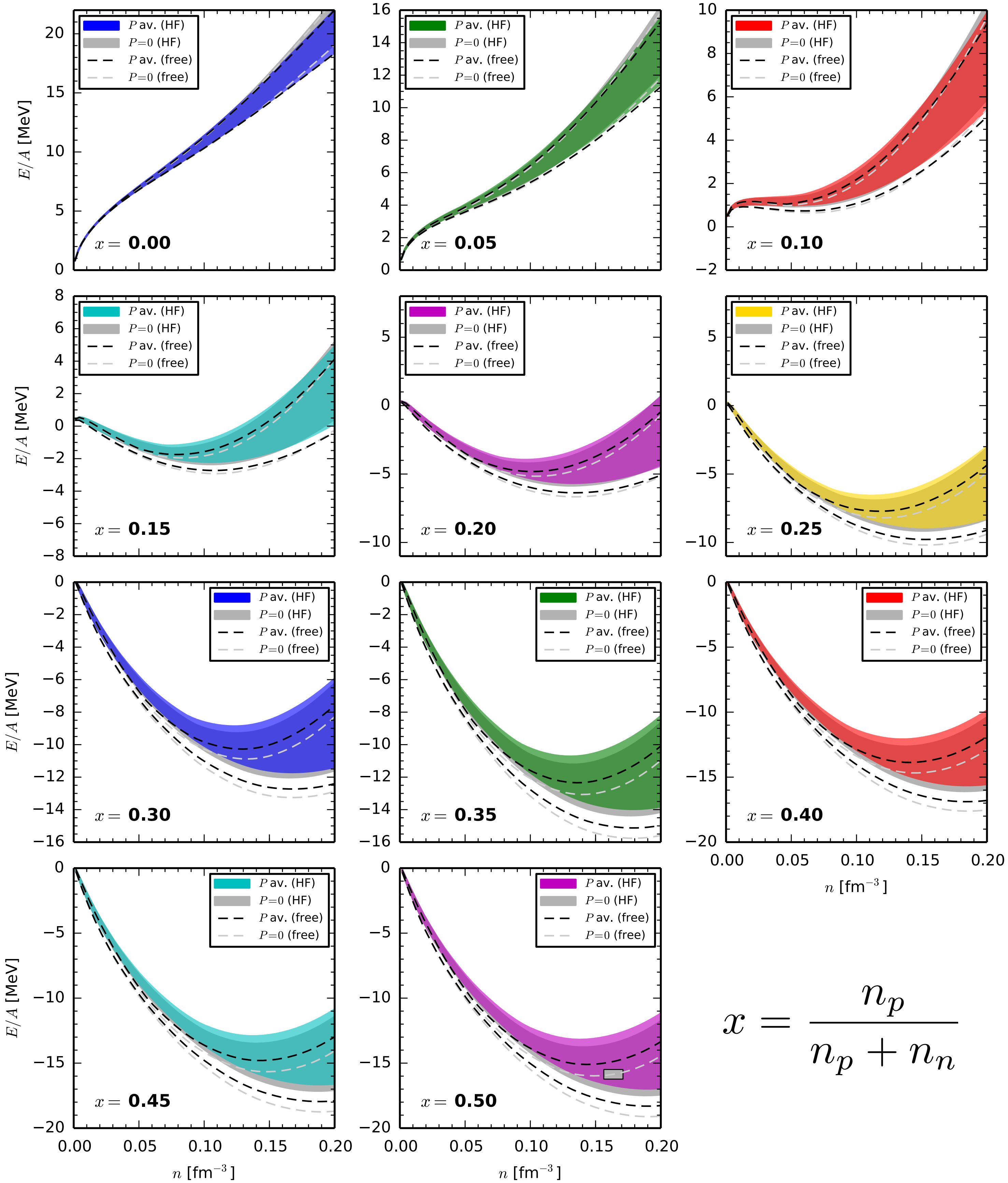


neutron star matter

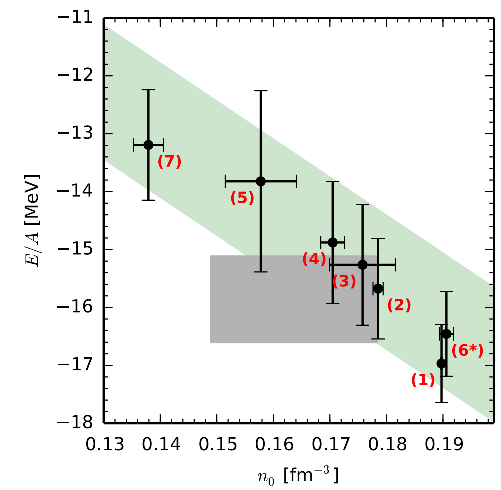
KH, Lattimer, Pethick, Schwenk,
PRL 105, 161102 (2010)



Calculation of general isospin-asymmetric nuclear matter



- uncertainty bands determined by set of 7 Hamiltonians

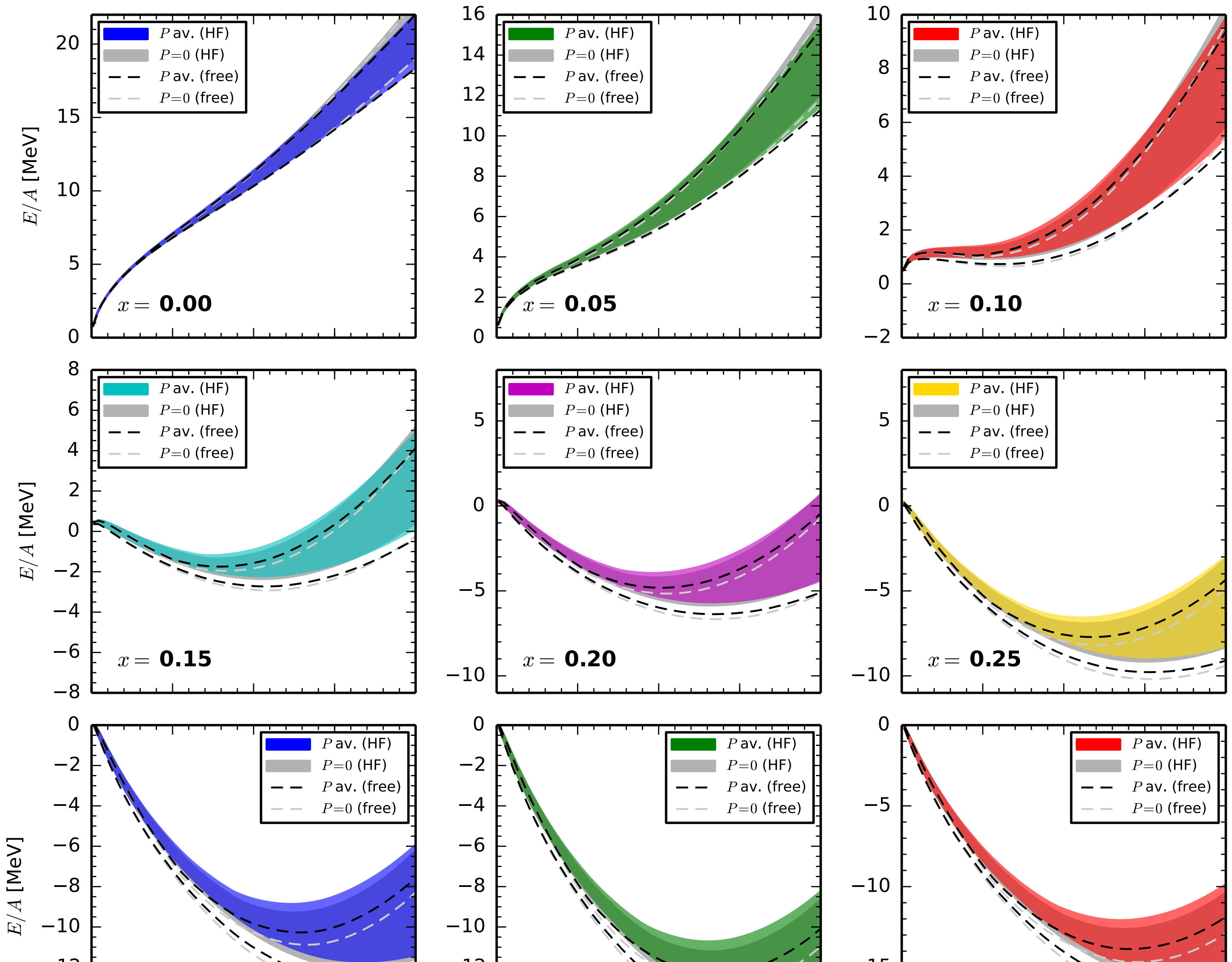


- many-body framework allows treatment of any decomposed 3N interaction

$$x = \frac{n_p}{n_p + n_n}$$

Drischler, KH, Schwenk,
PRC 054314 (2016)

Calculation of general isospin-asymmetric nuclear matter



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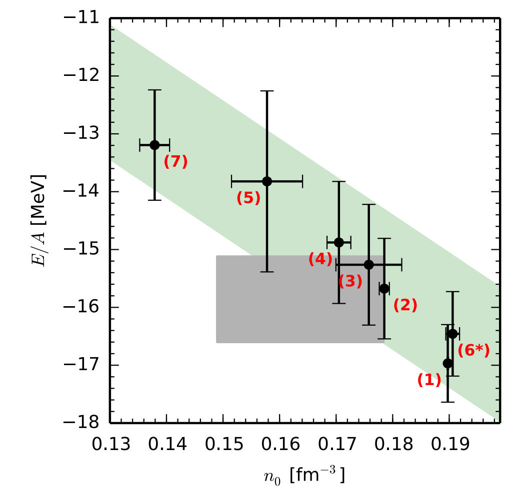


- many-body framework allows treatment of any decomposed 3N interaction

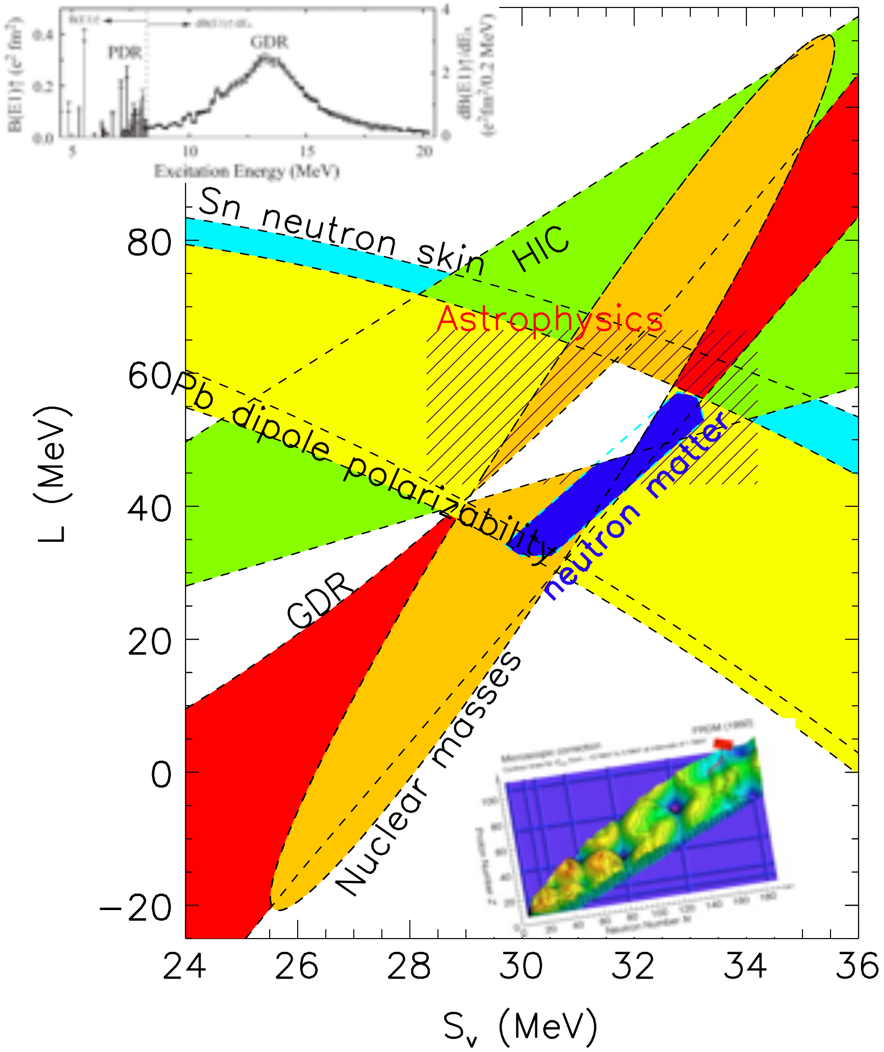
Problem:

Calculation of neutron star properties require EOS up to high densities.
Microscopic calculations limited to 1-2 nuclear saturation density.

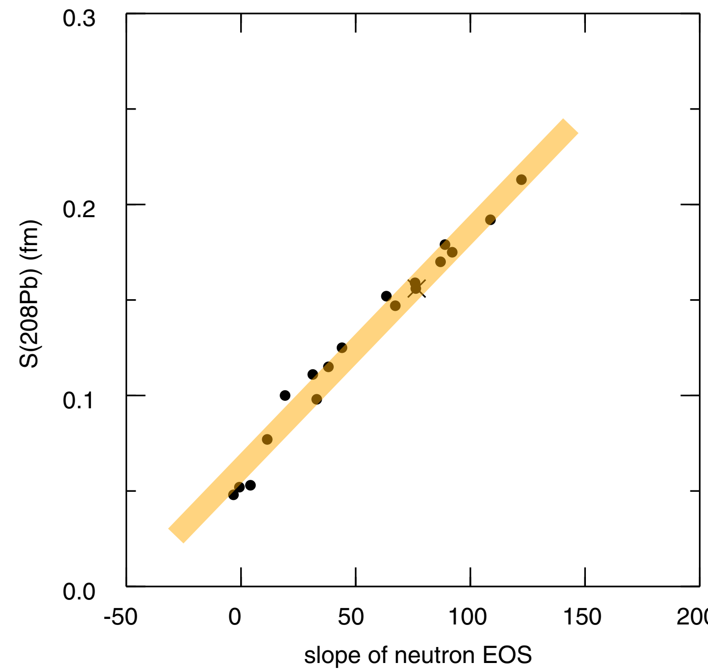
Strategy:

Use observations to constrain the high-density part of the nuclear EOS.

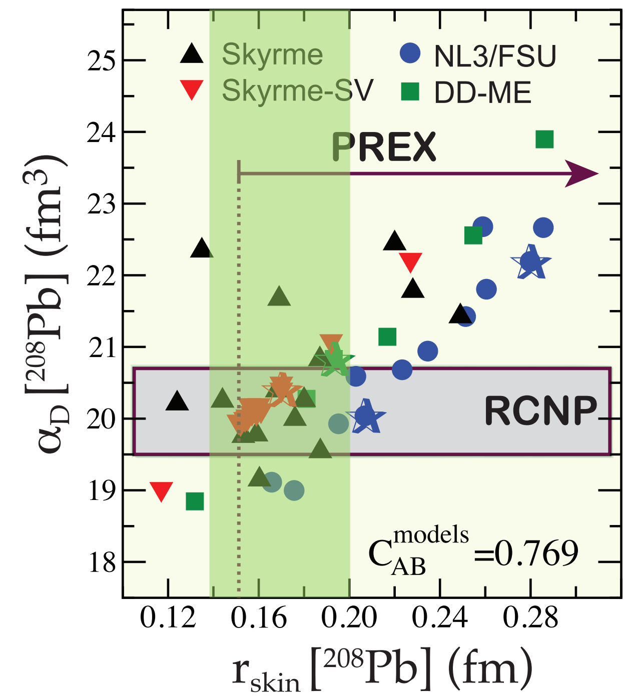
Symmetry energy and neutron skin constraints



KH, Lattimer, Pethick, Schwenk, ApJ 773, 11 (2013)



Brown,
PRL 85, 5296 (2000)



Piekarewicz,
PRC 85, 041302 (2012)

$$S_v = \left.\frac{\partial^2 E/N}{\partial^2 x}\right|_{\rho=\rho_0, x=1/2}$$

$$L = \frac{3}{8}\left.\frac{\partial^3 E/N}{\partial\rho\partial^2 x}\right|_{\rho=\rho_0, x=1/2}$$

neutron skin constraint from neutron matter results:

$$r_{\rm skin}[^{208}{\rm Pb}] = 0.14 - 0.2\ {\rm fm}$$

KH, Lattimer, Pethick, Schwenk, PRL 105, 161102 (2010)

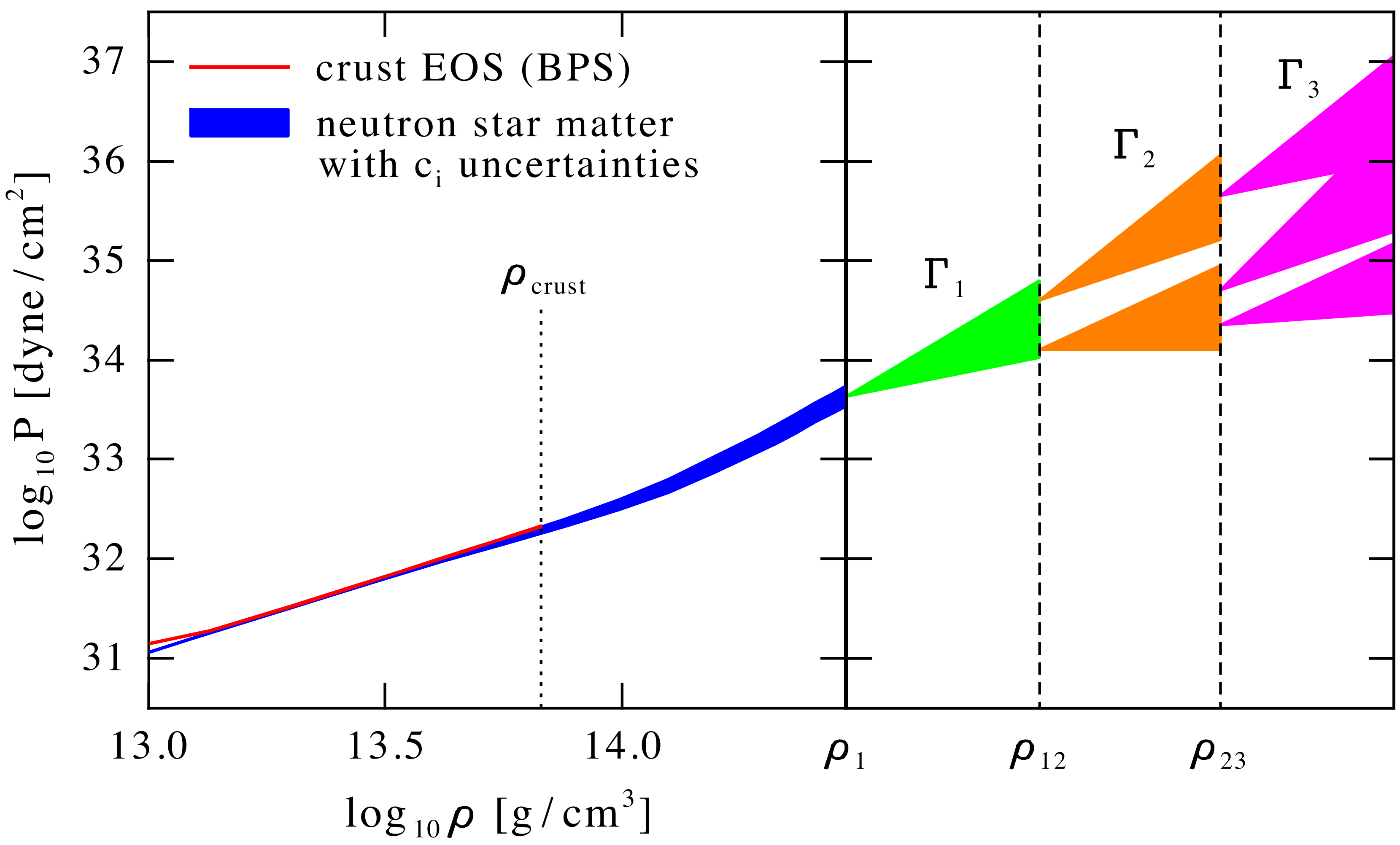
- neutron matter give tightest constraints
- in agreement with all other constraints

Neutron star radius constraints

incorporation of beta-equilibrium: neutron matter $\longrightarrow$ neutron star matter

parametrize piecewise high-density extensions of EOS:

- use polytropic ansatz $p \sim \rho^\Gamma$
- range of parameters $\Gamma_1, \rho_{12}, \Gamma_2, \rho_{23}, \Gamma_3$ limited by physics



KH, Lattimer, Pethick, Schwenk, ApJ 773, 11 (2013)
KH, Lattimer, Pethick, Schwenk, PRL 105, 161102 (2010)

Constraints on the nuclear equation of state

use the constraints:

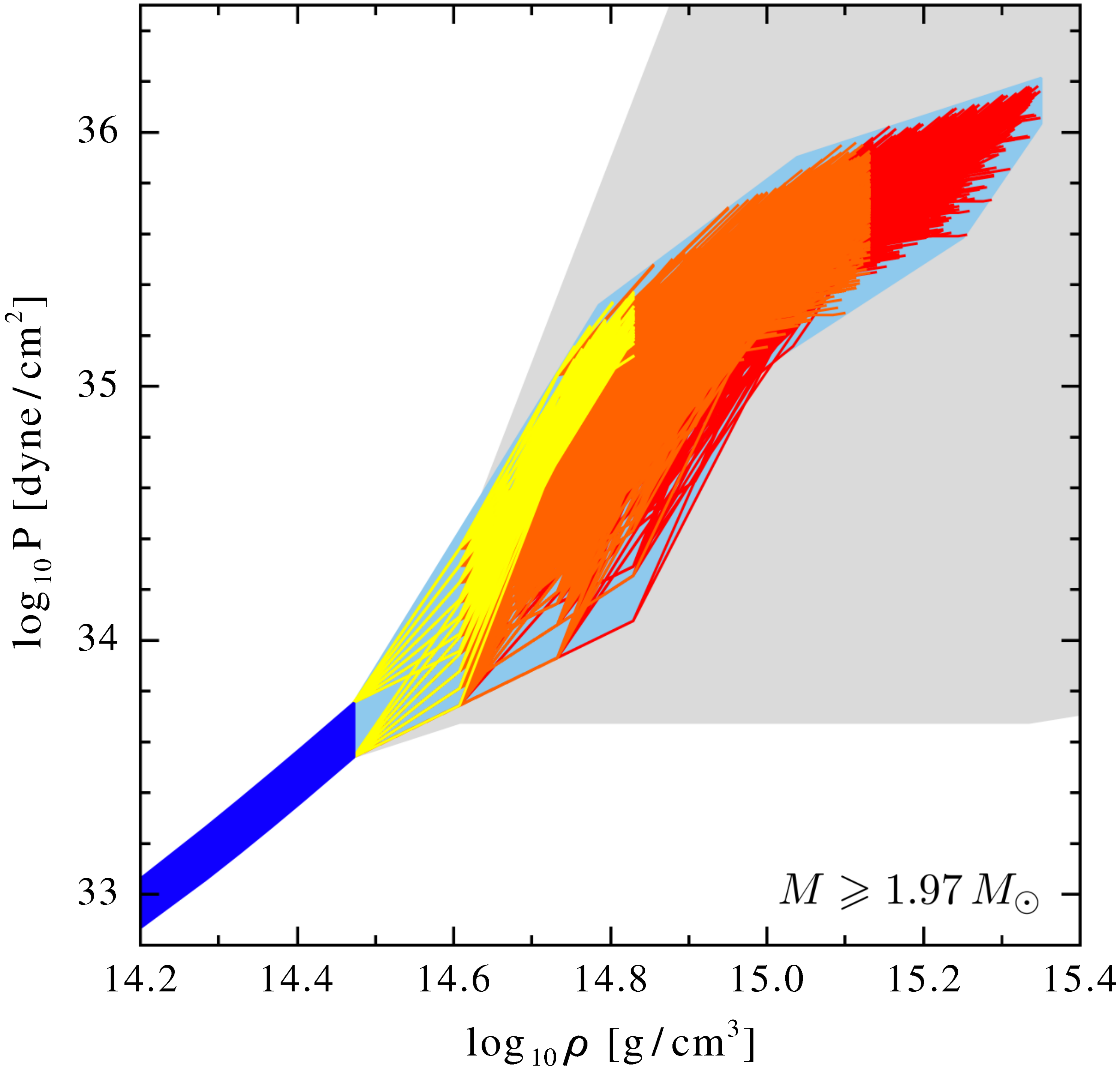
recent NS observations

$$M_{\max} > 1.97\, M_\odot$$

causality

$$v_s(\rho) = \sqrt{dP/d\varepsilon} < c$$

KH, Lattimer, Pethick, Schwenk, ApJ 773, 11 (2013)



constraints lead to significant reduction of EOS uncertainty band

Constraints on the nuclear equation of state

use the constraints:

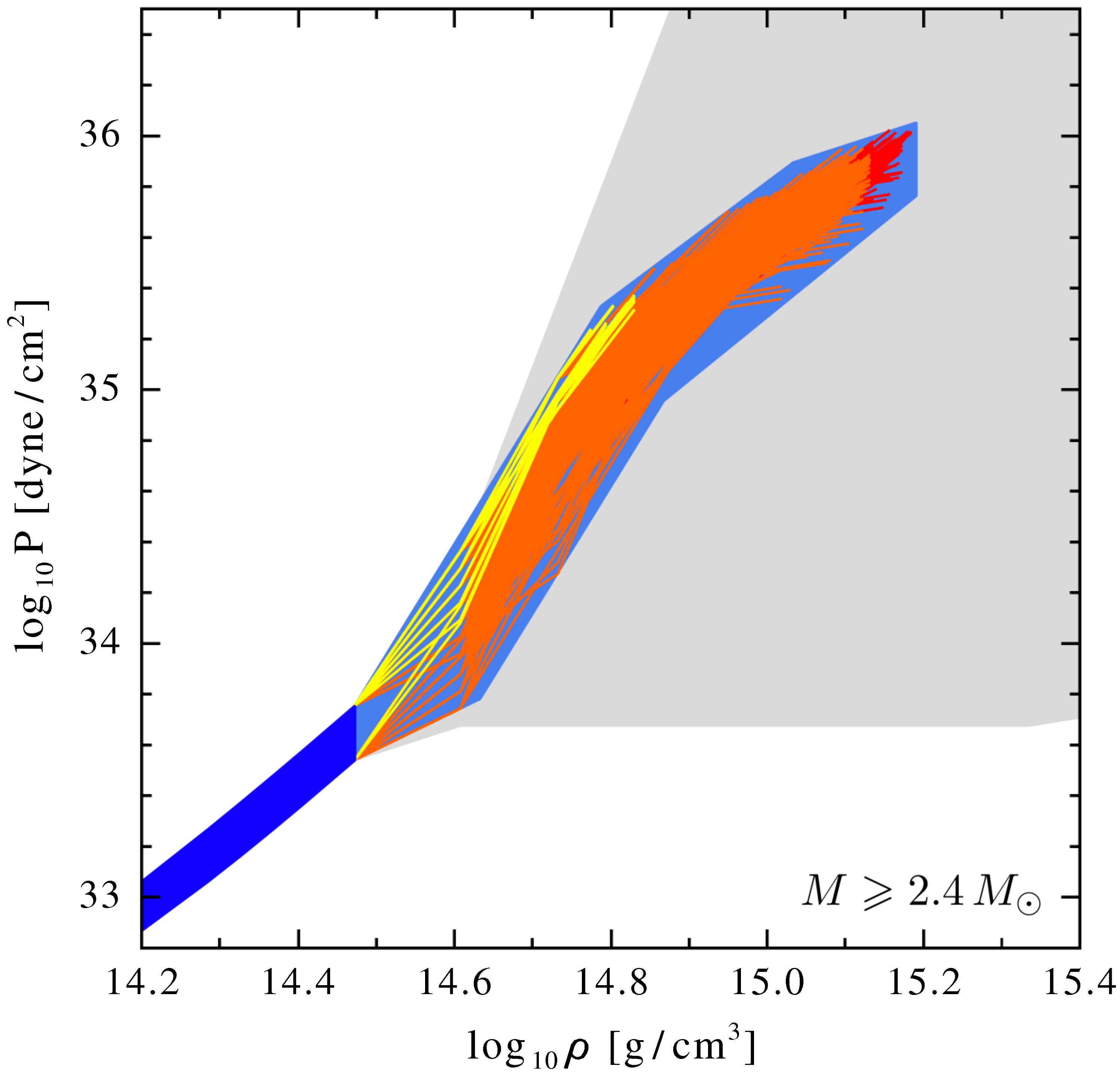
fictitious NS mass

$$M_{\max} > 2.4\,M_\odot$$

causality

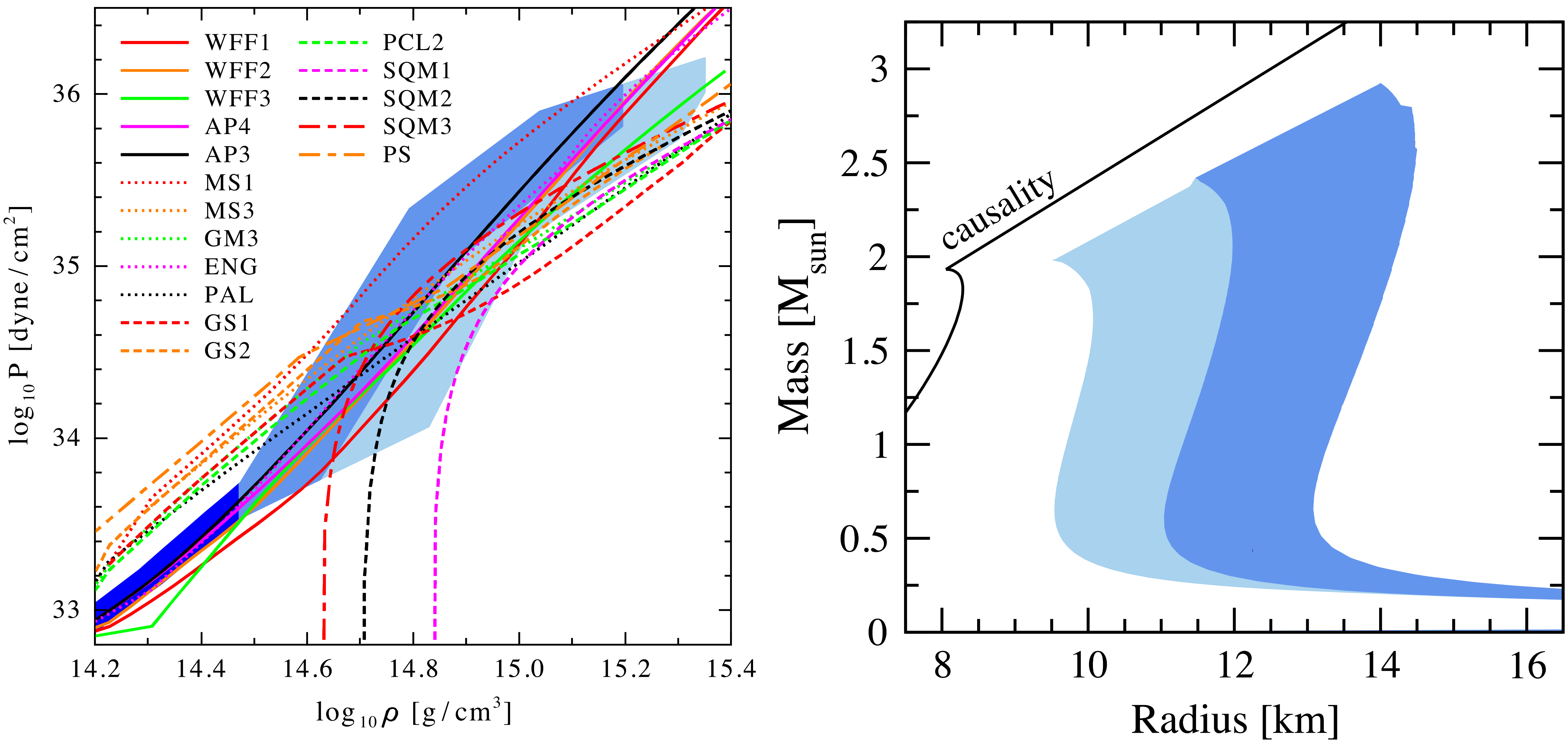
$$v_s(\rho) = \sqrt{dP/d\varepsilon} < c$$

KH, Lattimer, Pethick, Schwenk, ApJ 773, 11 (2013)



increased $M_{\max}$ systematically reduces width of band

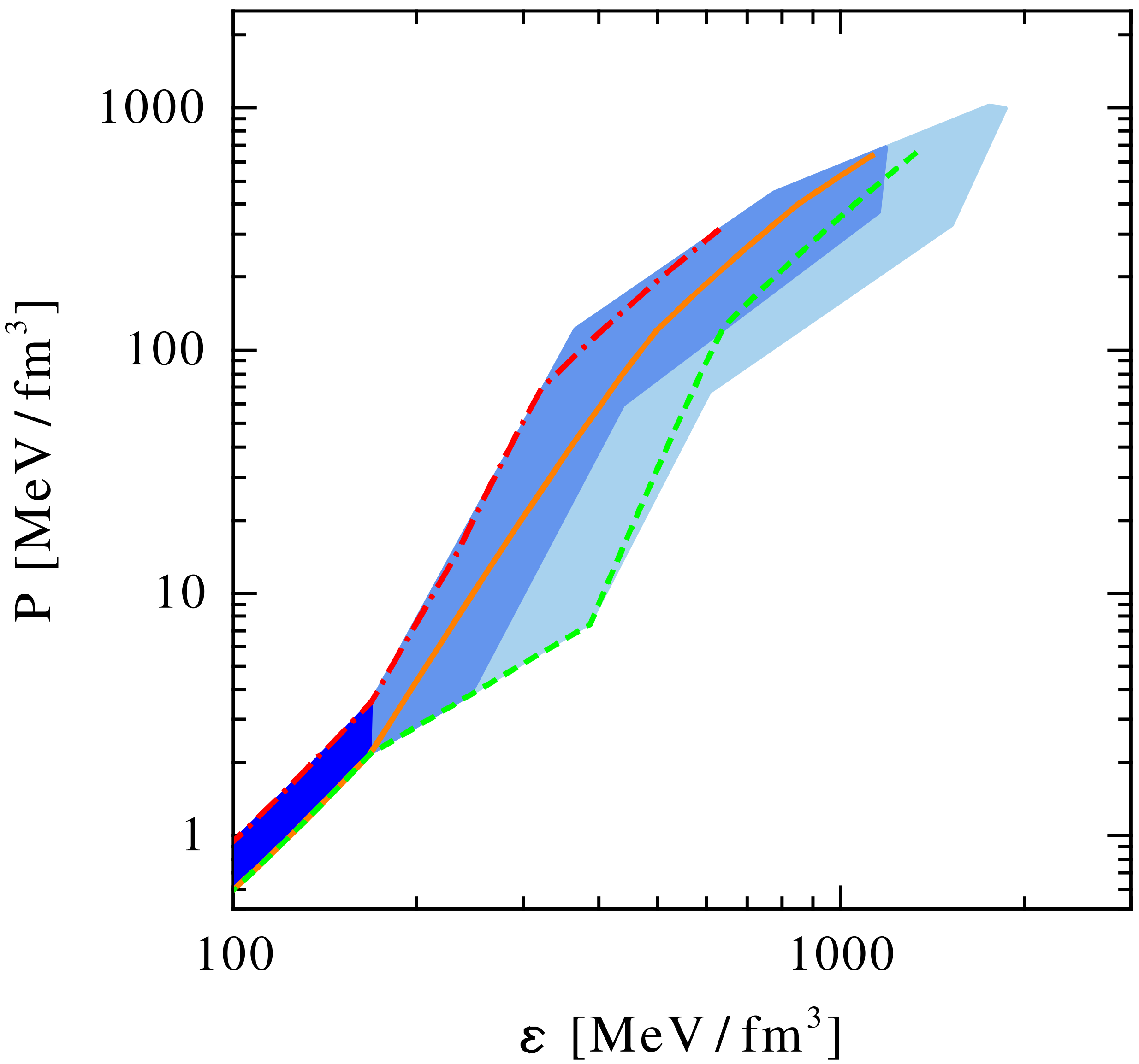
Constraints on neutron star radii

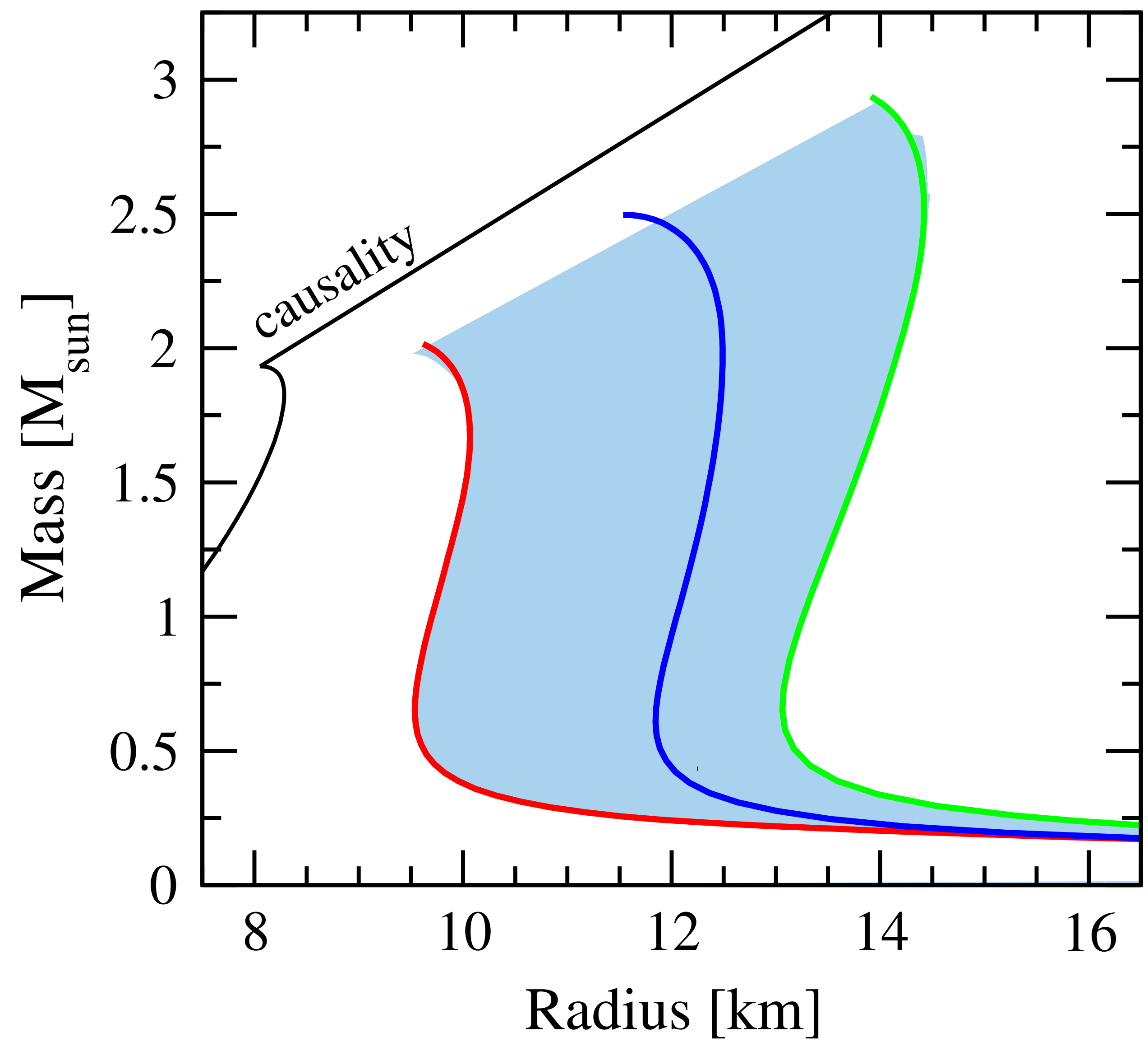


KH, Lattimer, Pethick, Schwenk, ApJ 773, 11 (2013)
see also KH, Lattimer, Pethick, Schwenk, PRL 105, 161102 (2010)

- low-density part of EOS sets scale for allowed high-density extensions
- current radius prediction for typical $1.4\,M_\odot$ neutron star: $9.7 - 13.9\,\mathrm{km}$

Representative set of EOS

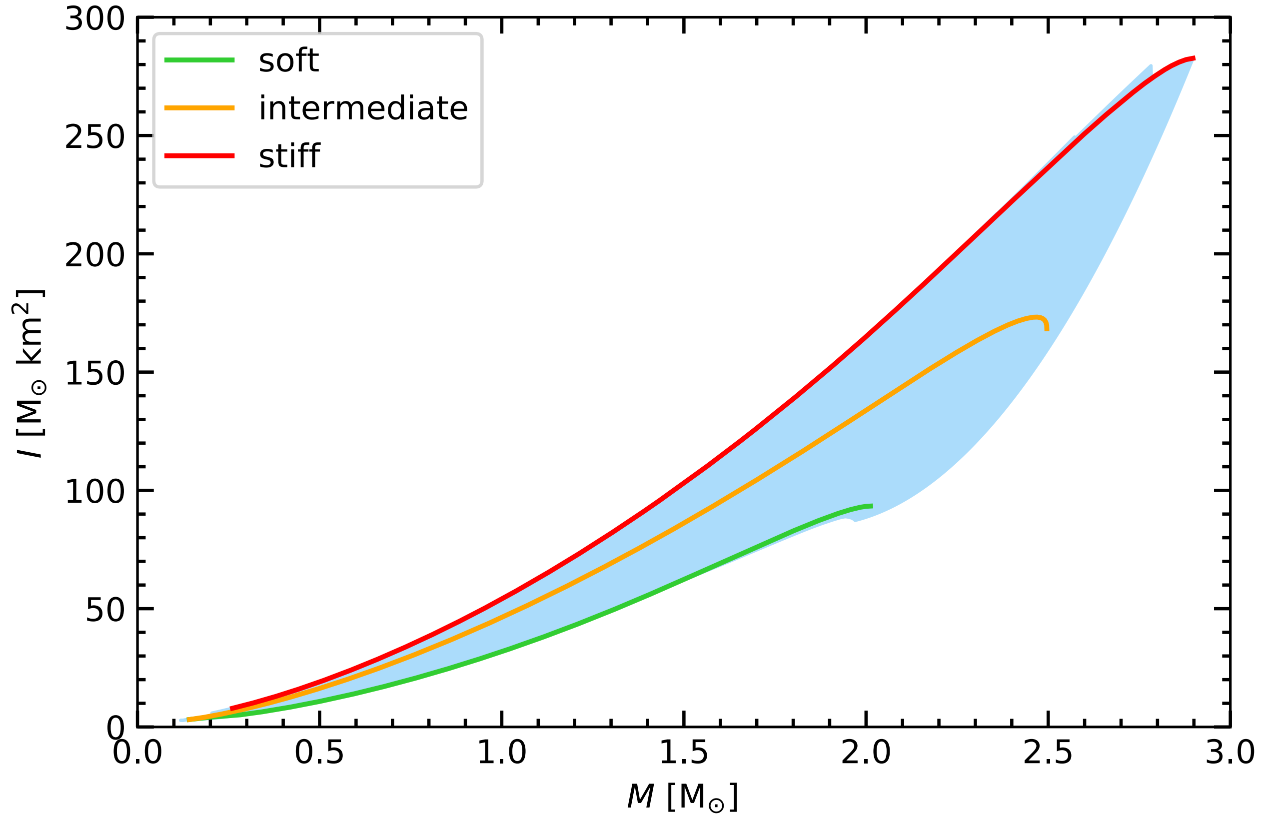


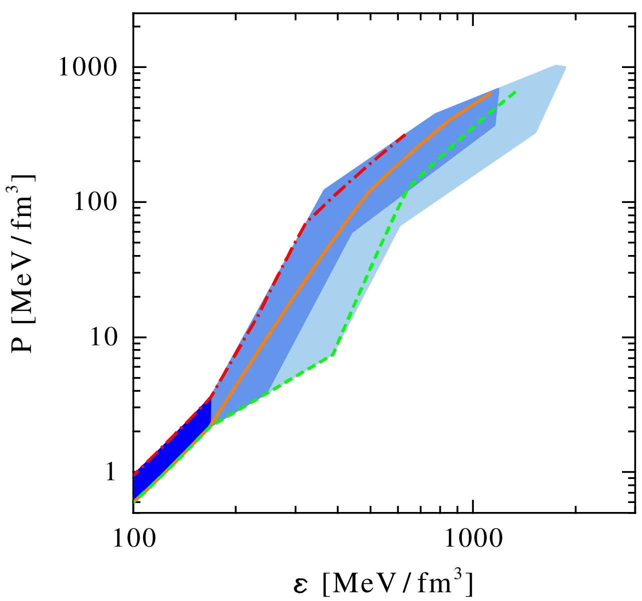


KH, Lattimer, Pethick, Schwenk, ApJ 773, 11 (2013)

- constructed 3 representative EOS compatible with uncertainty bands for astrophysical applications: soft, intermediate and stiff
- allows to probe impact of current theoretical EOS uncertainties on astrophysical observables

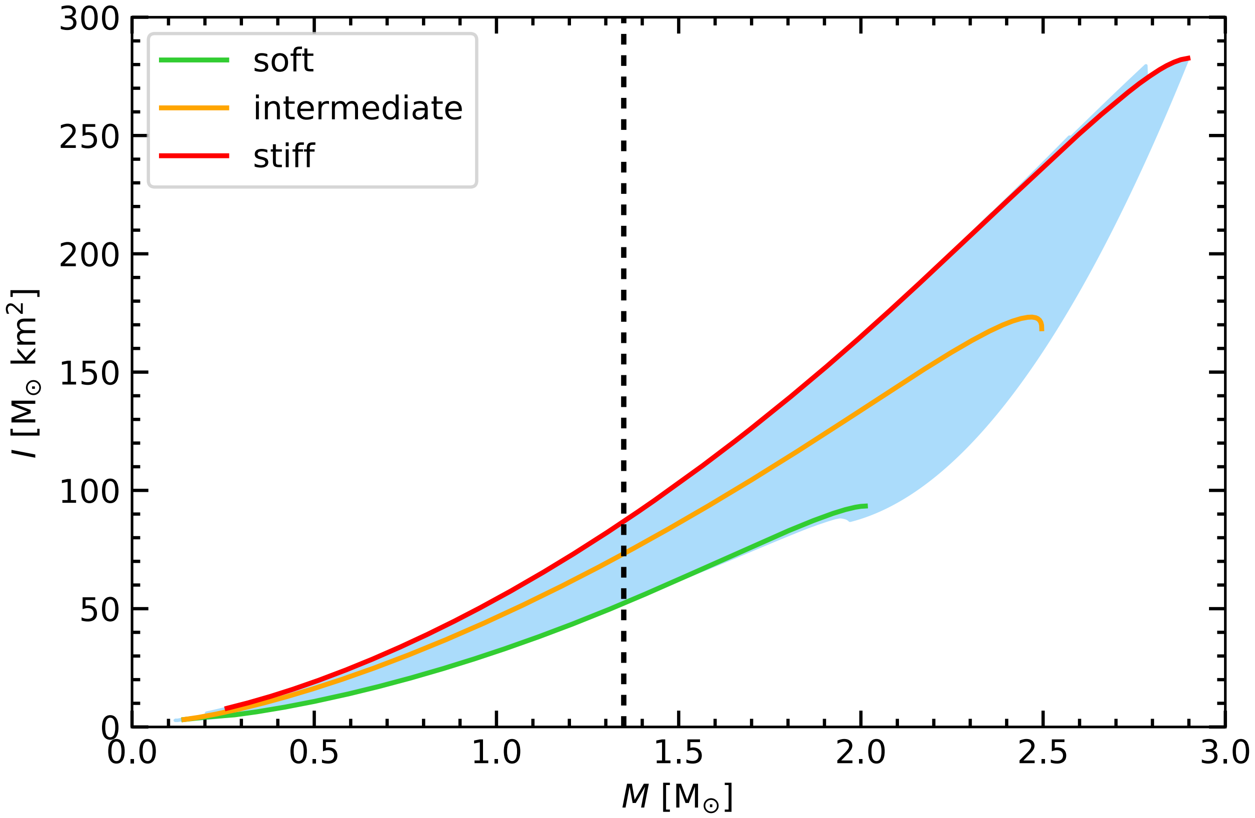
Constraints from moment of inertia measurements

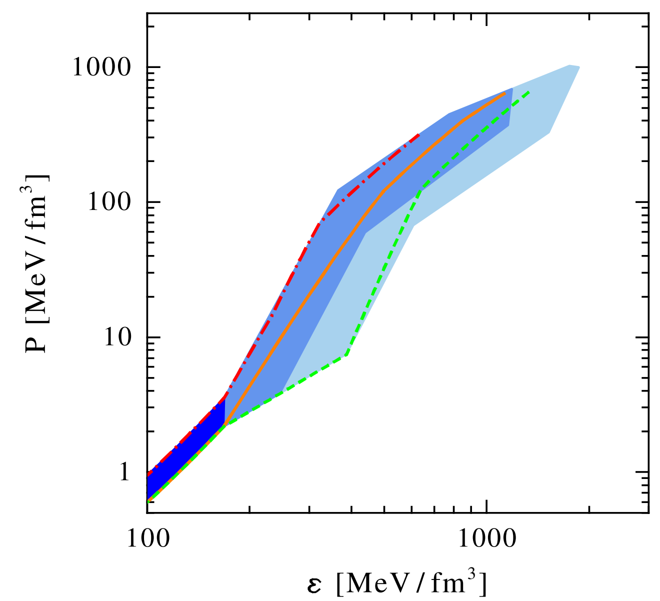




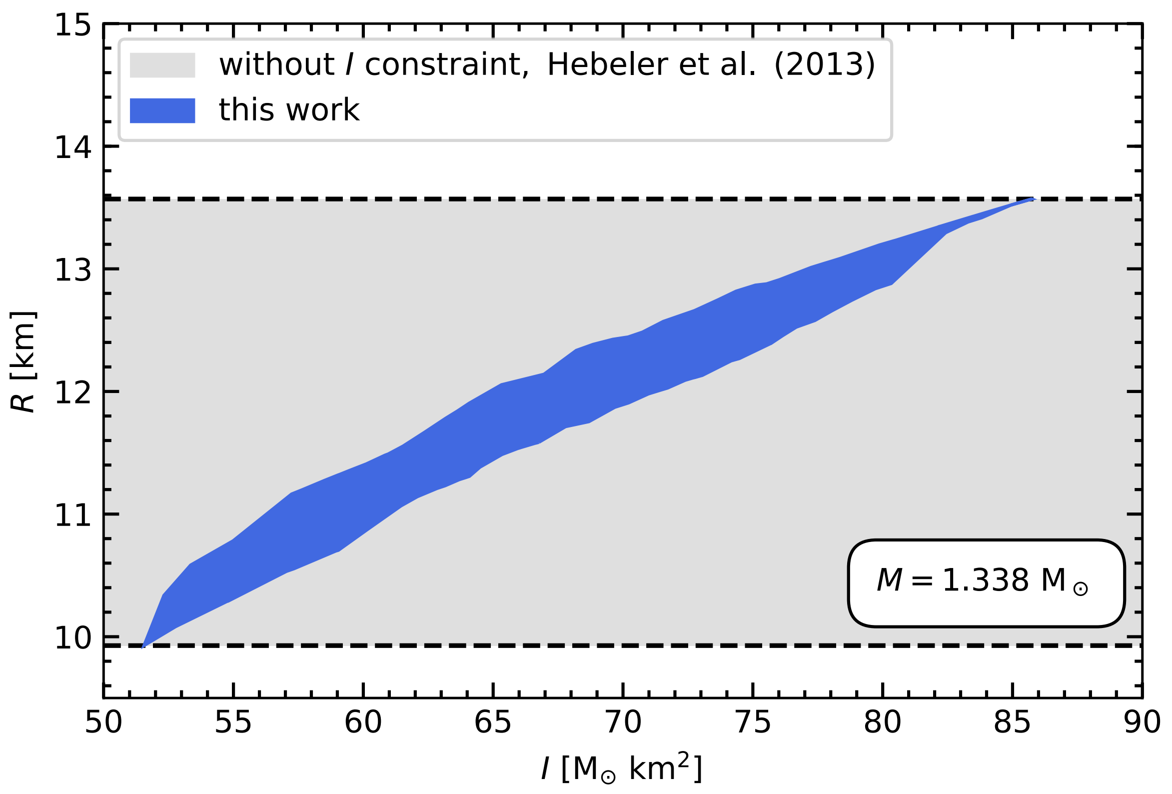
Greif, KH, Lattimer, Pethick, Schwenk,
in preparation

Constraints from moment of inertia measurements





Greif, KH, Lattimer, Pethick, Schwenk, in preparation



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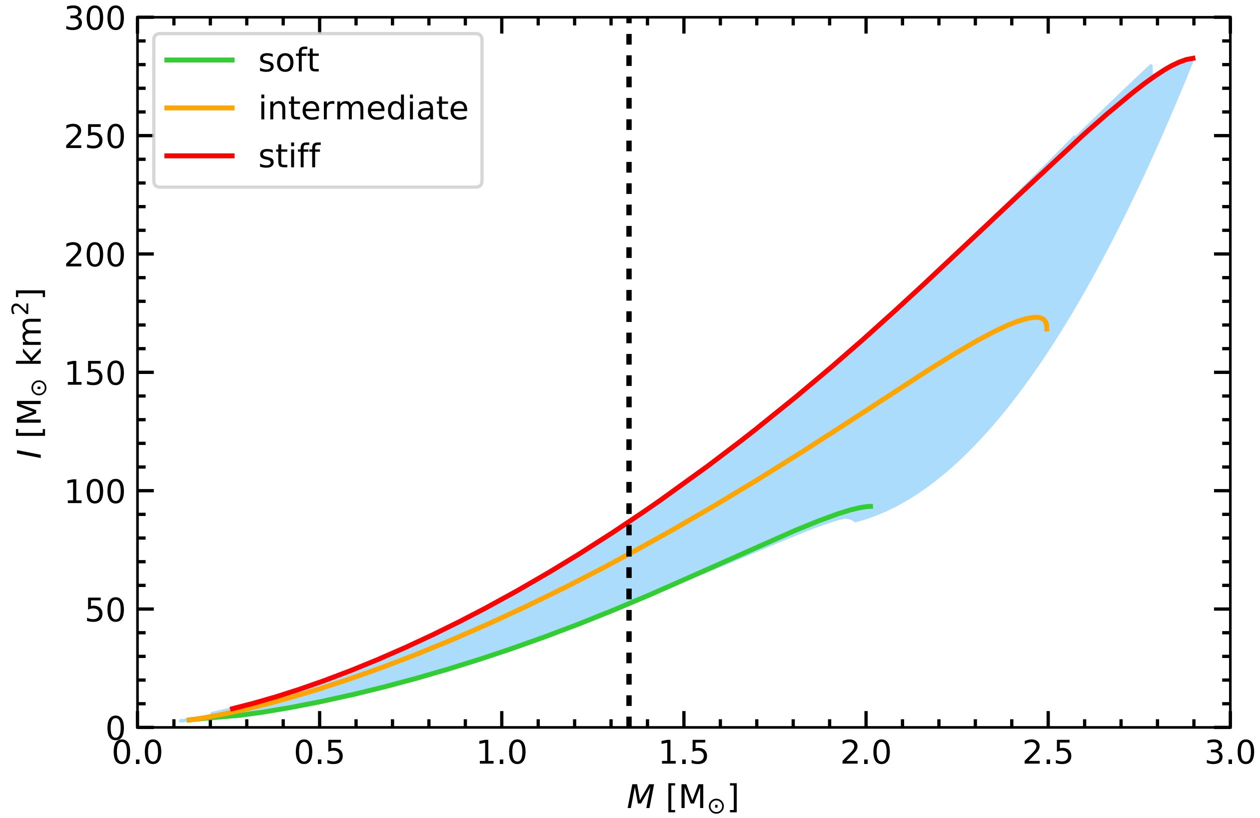
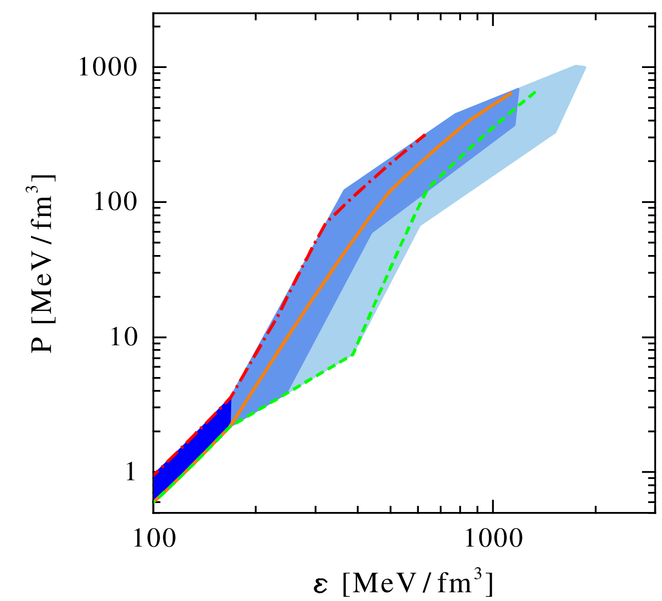
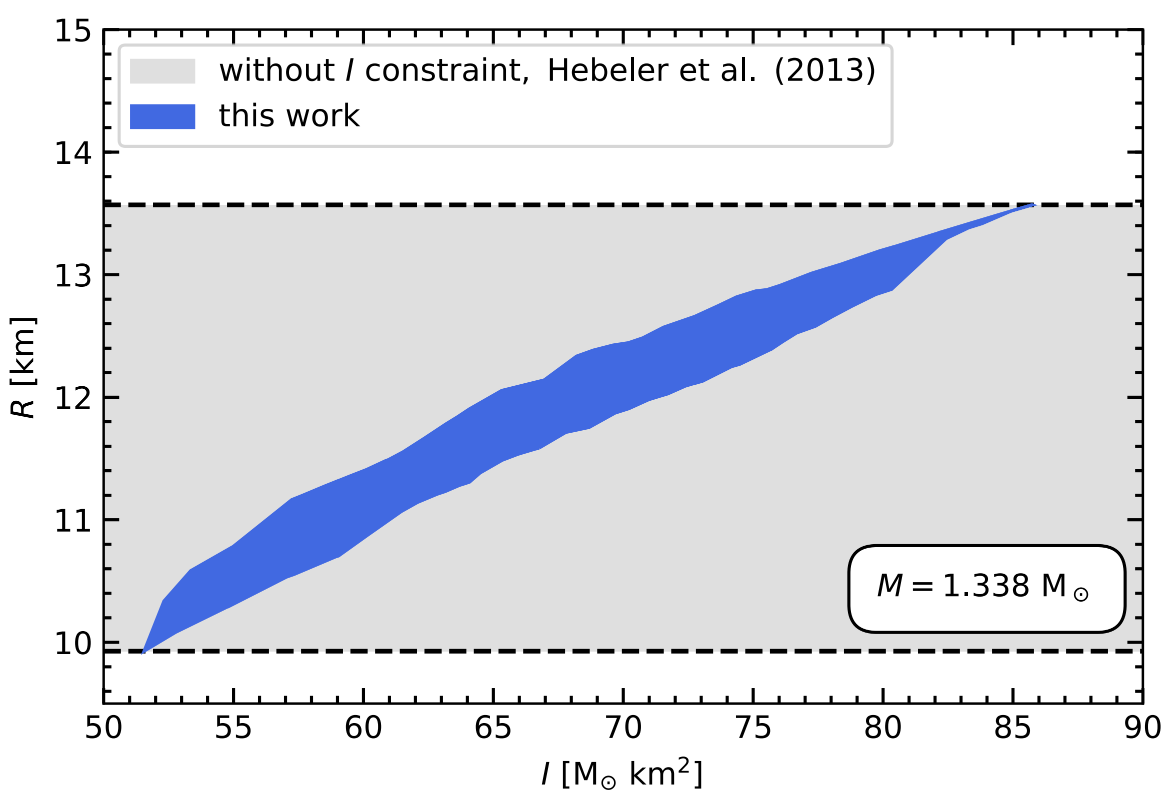
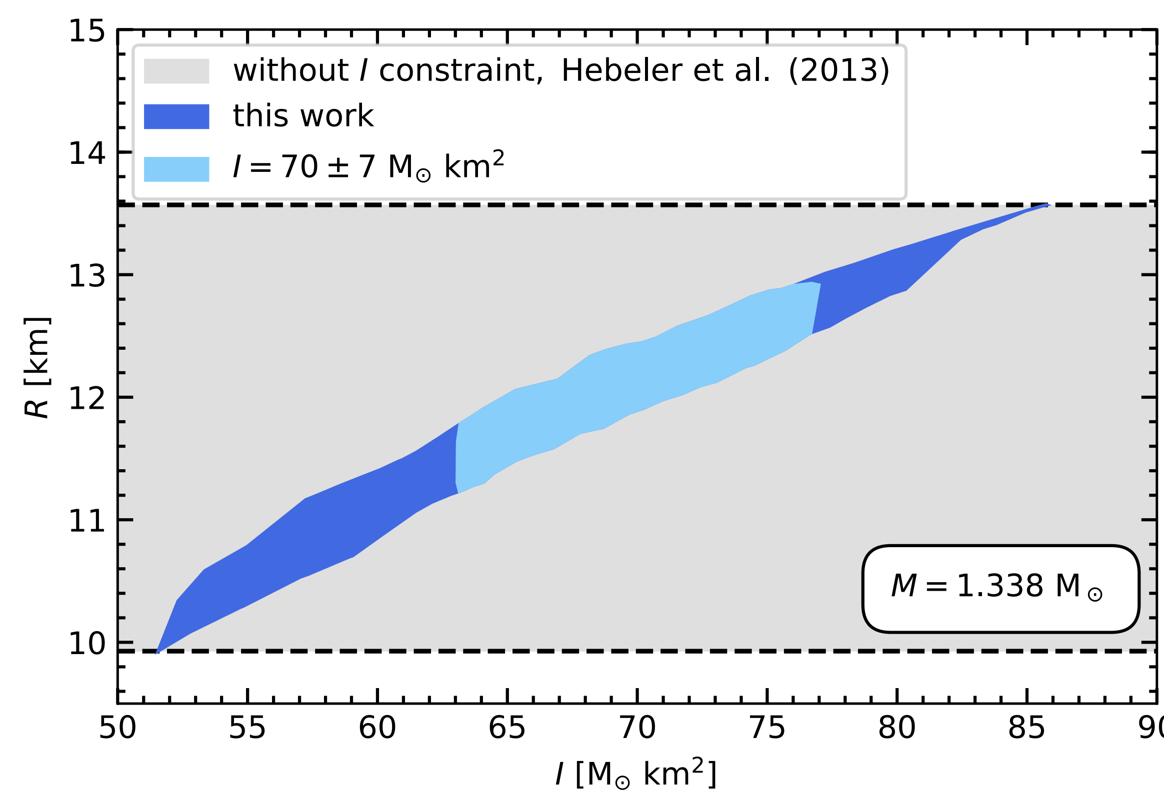




Greif, KH, Lattimer, Pethick, Schwenk, in preparation

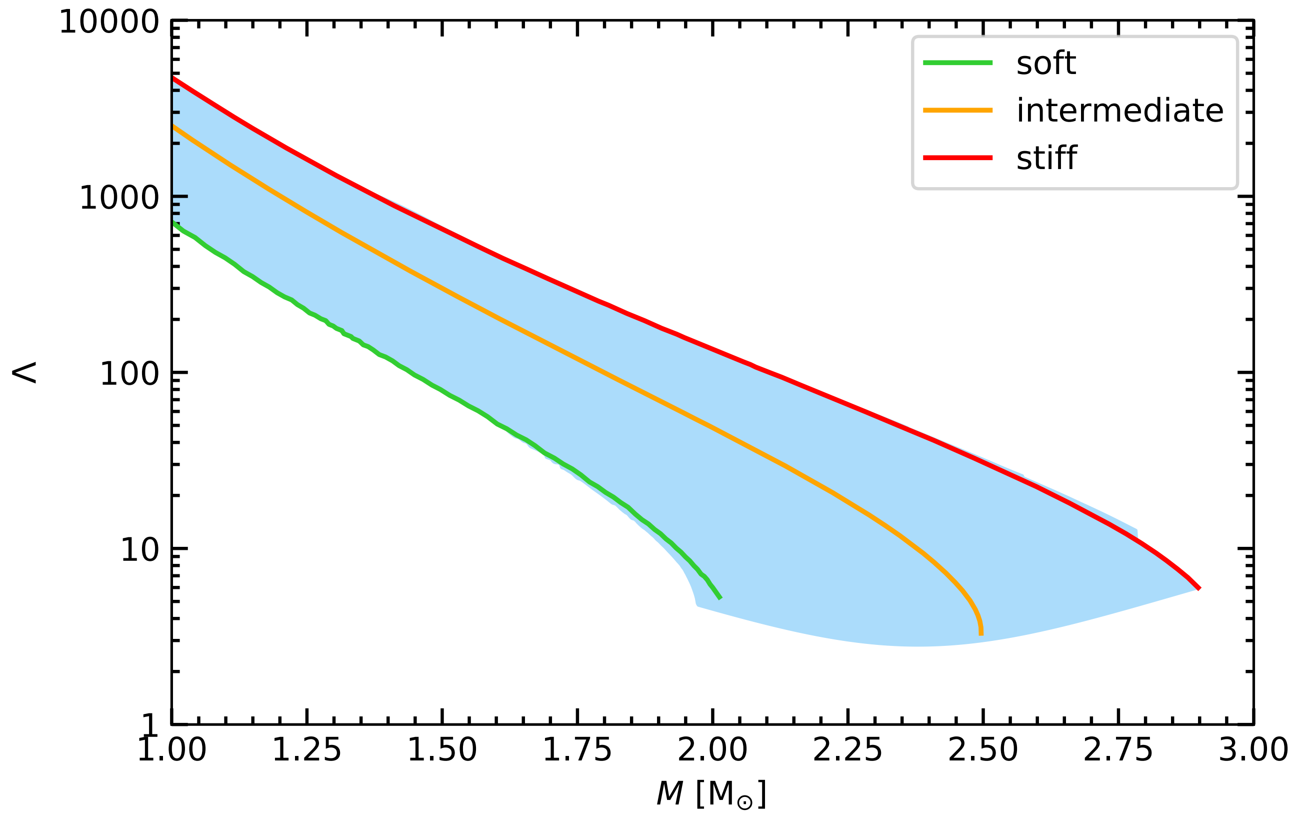


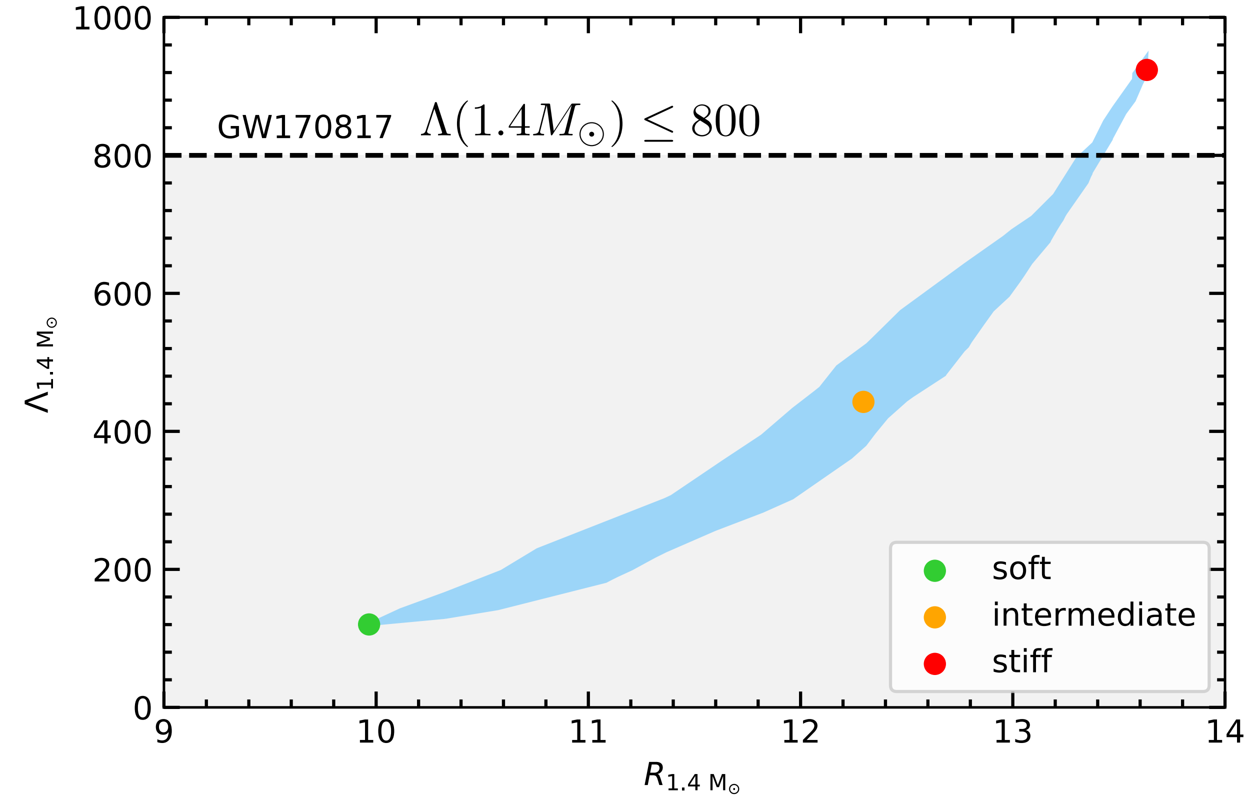
$I_0 \pm 10\%$



reduction in radius uncertainty by $\sim 50\%$

Constraints from tidal deformability measurements





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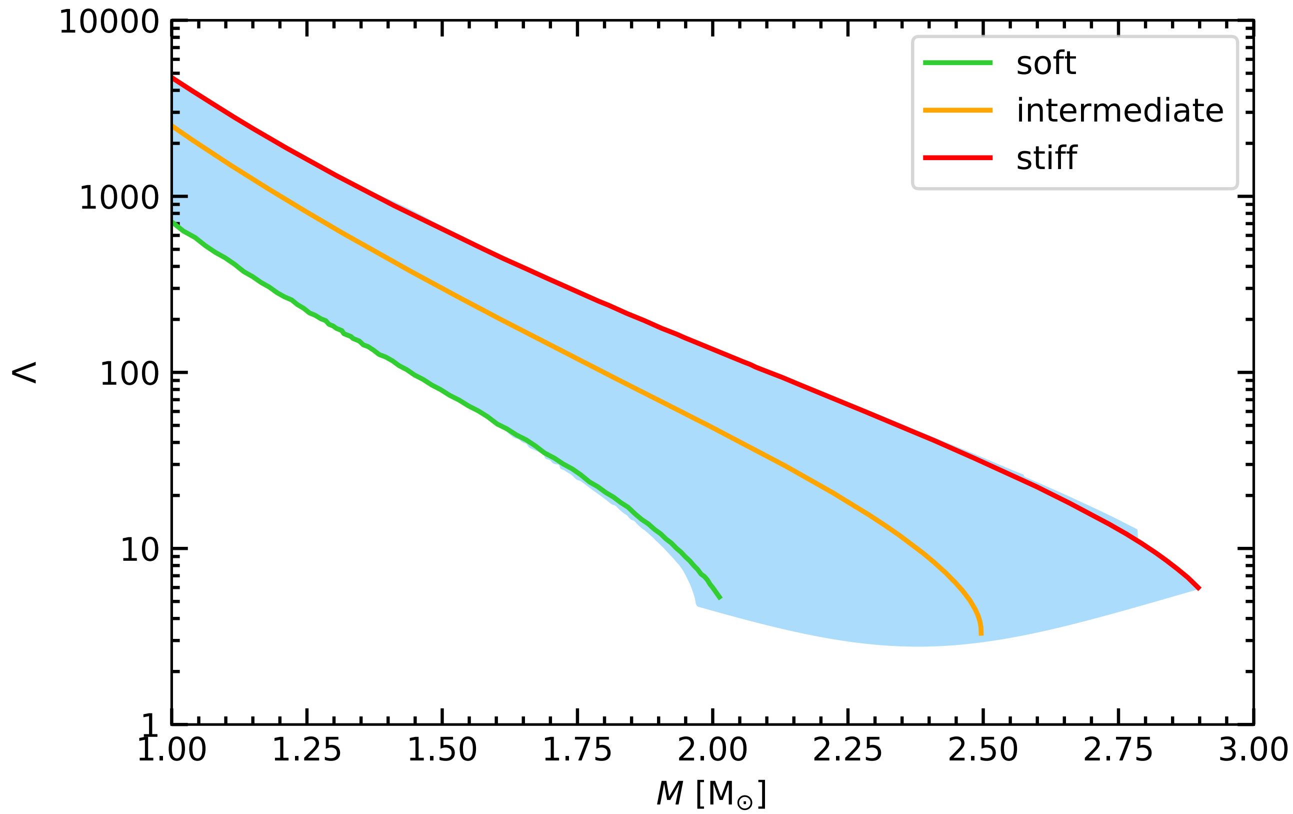
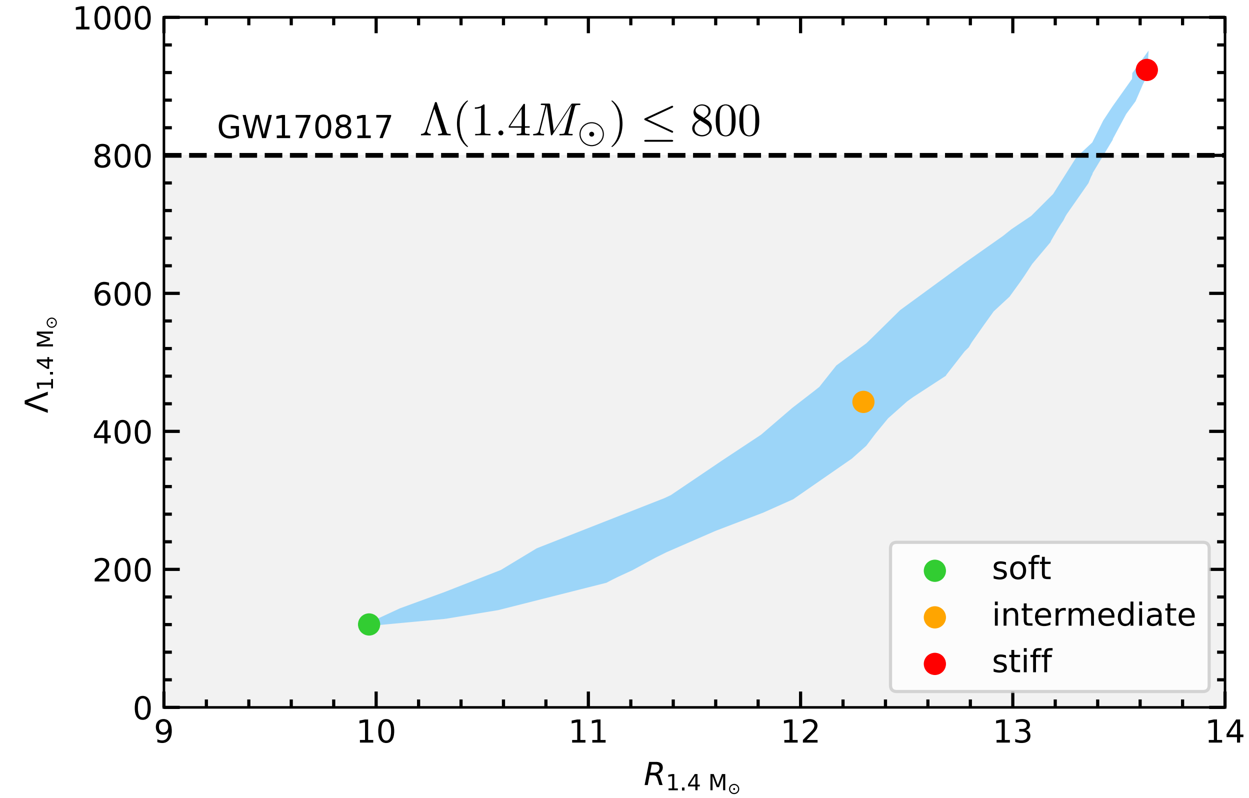




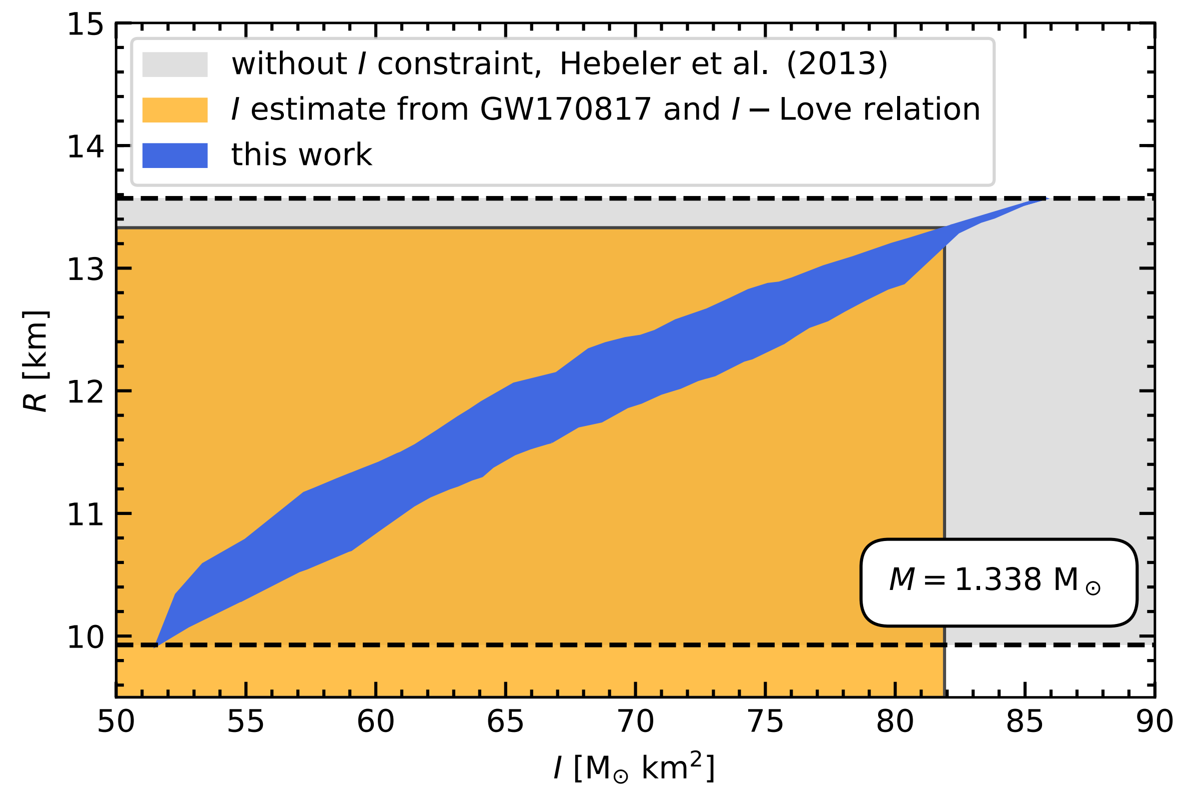
$\Lambda(1.4M_\odot) \leq 800$

↓ I-love-Q Yagi, Yunes, Science (2013)

$I(1.4M_\odot) \leq 88.6\,\mathrm{km}^2\ M_\odot$

↓ I(M) uncertainty band

$I(1.338M_\odot) \leq 81.9\,\mathrm{km}^2\ M_\odot$



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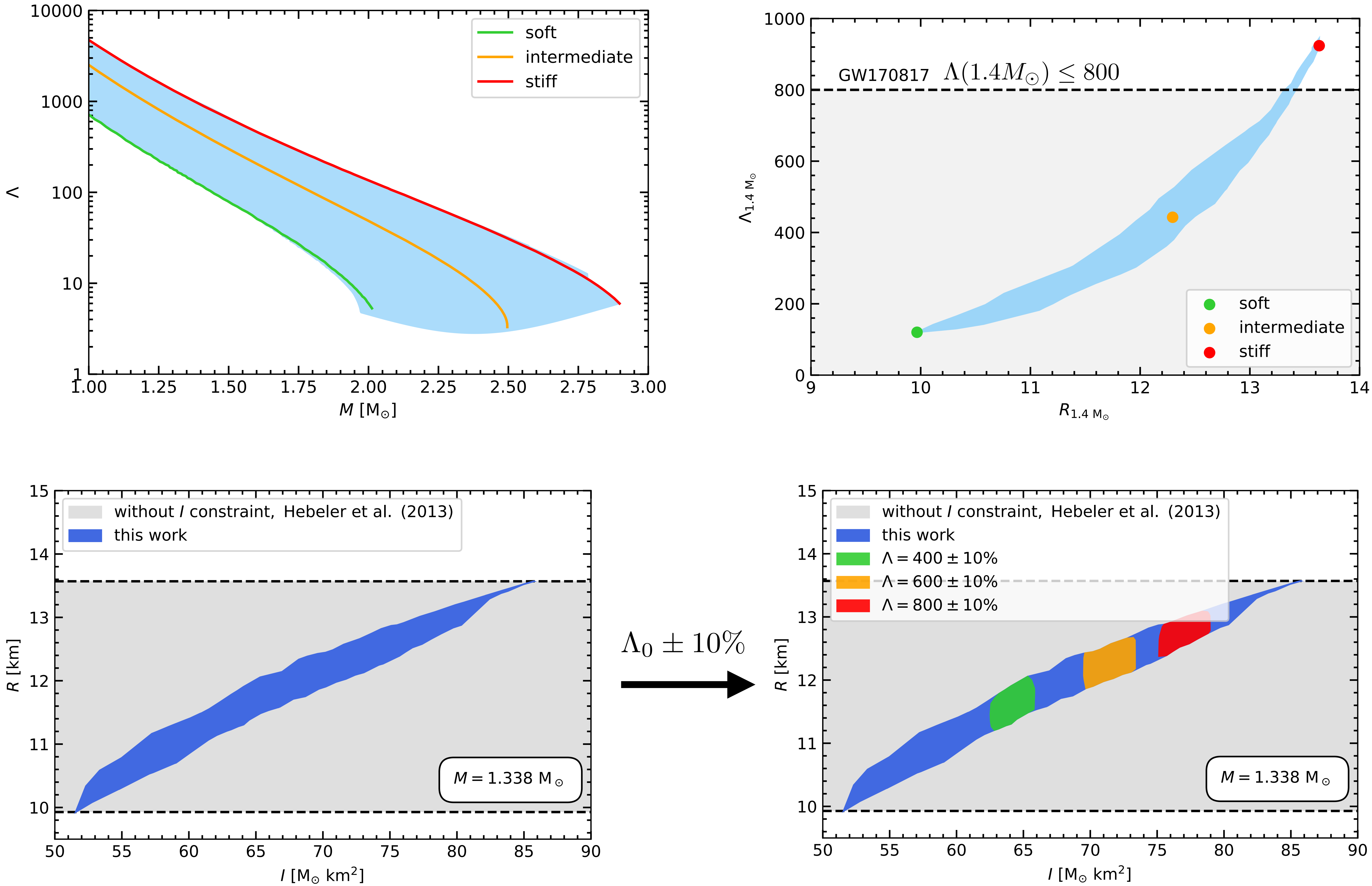
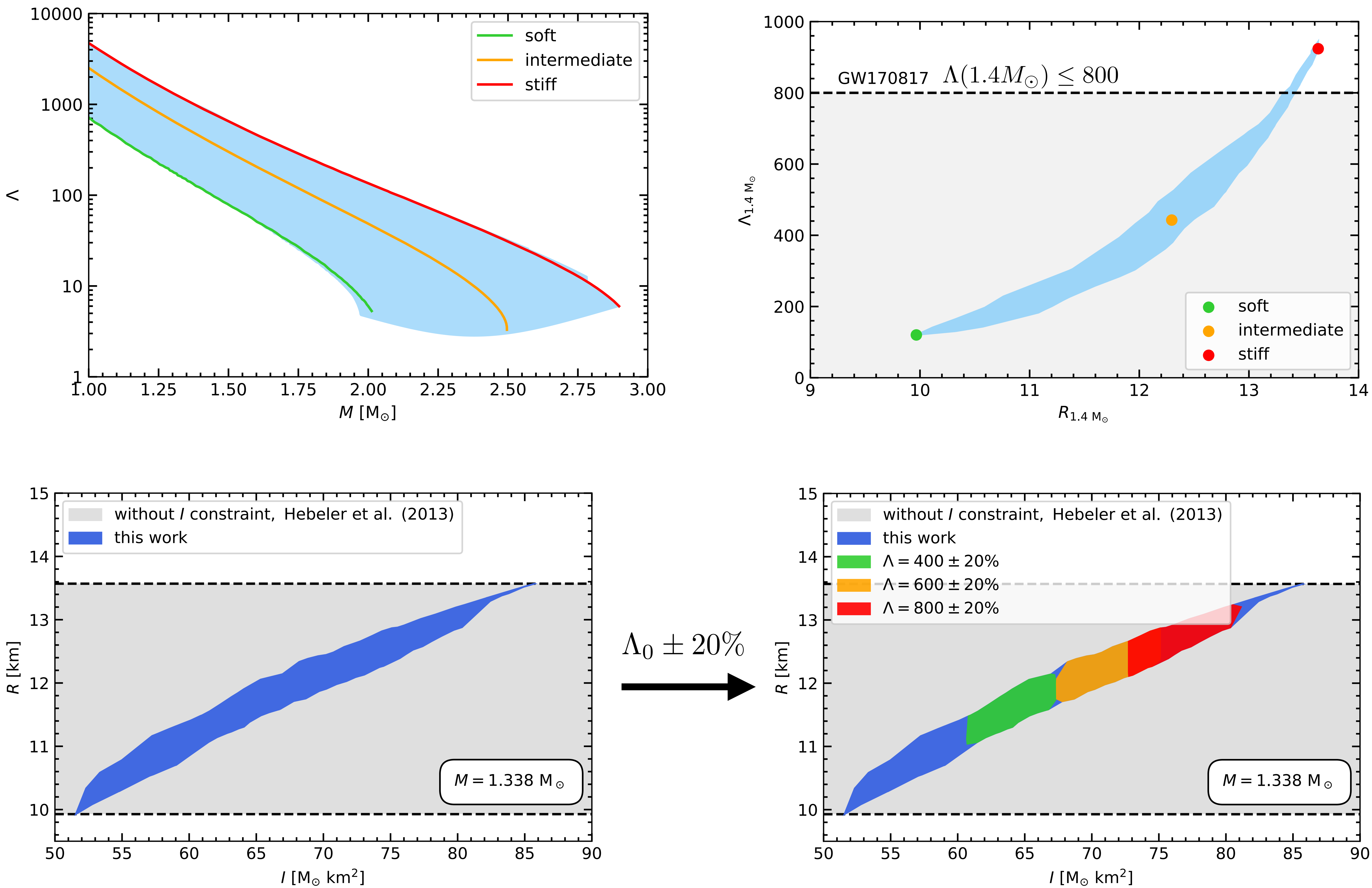


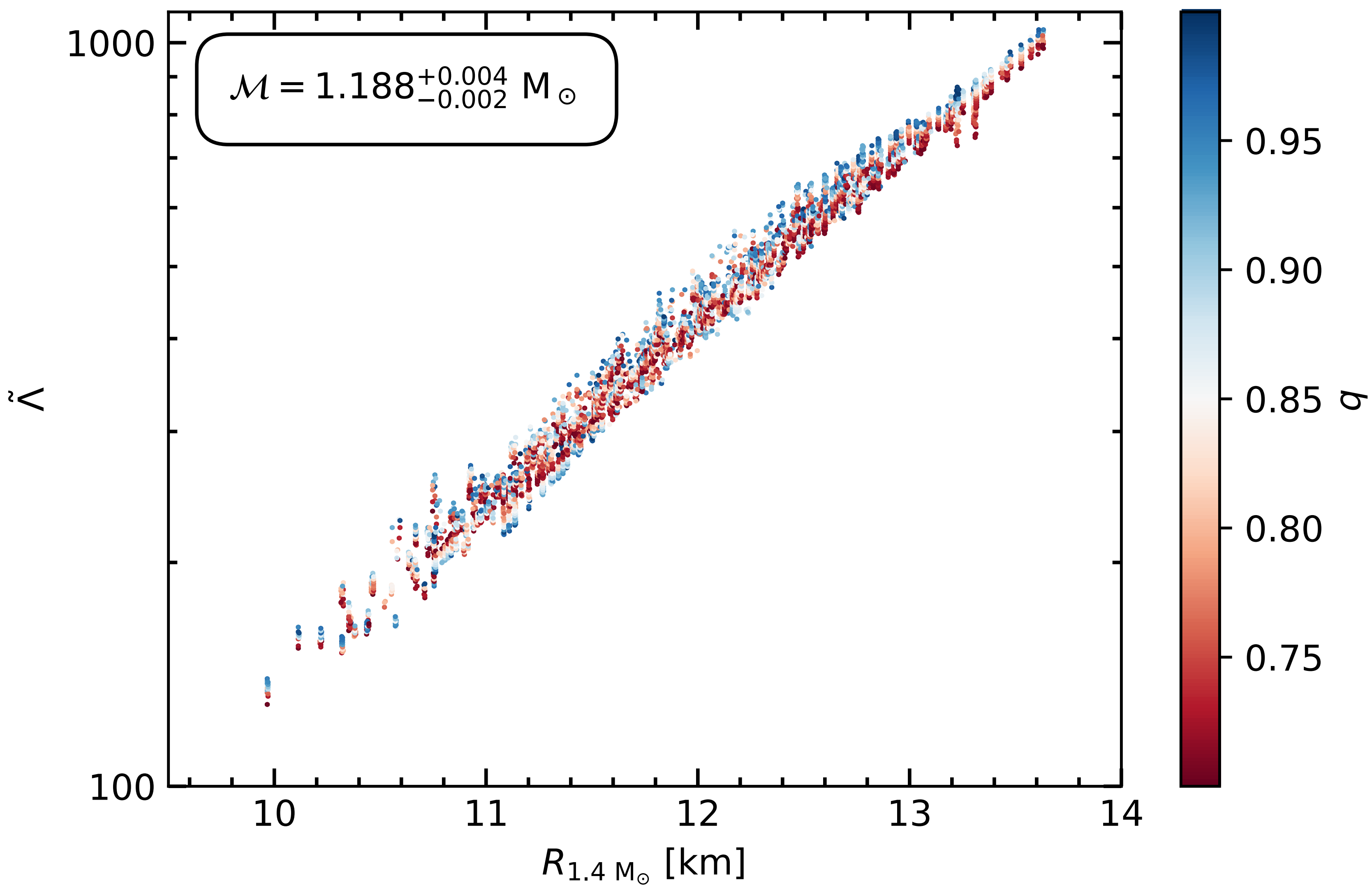
Constraints from tidal deformability measurements



Constraints from tidal deformability measurements

$$\tilde{\Lambda} = \frac{16}{13}\frac{(M_1 + 12M_2)M_1^4\Lambda_1 + (M_2 + 12M_1)M_2^4\Lambda_2}{(M_1 + M_2)^5}$$

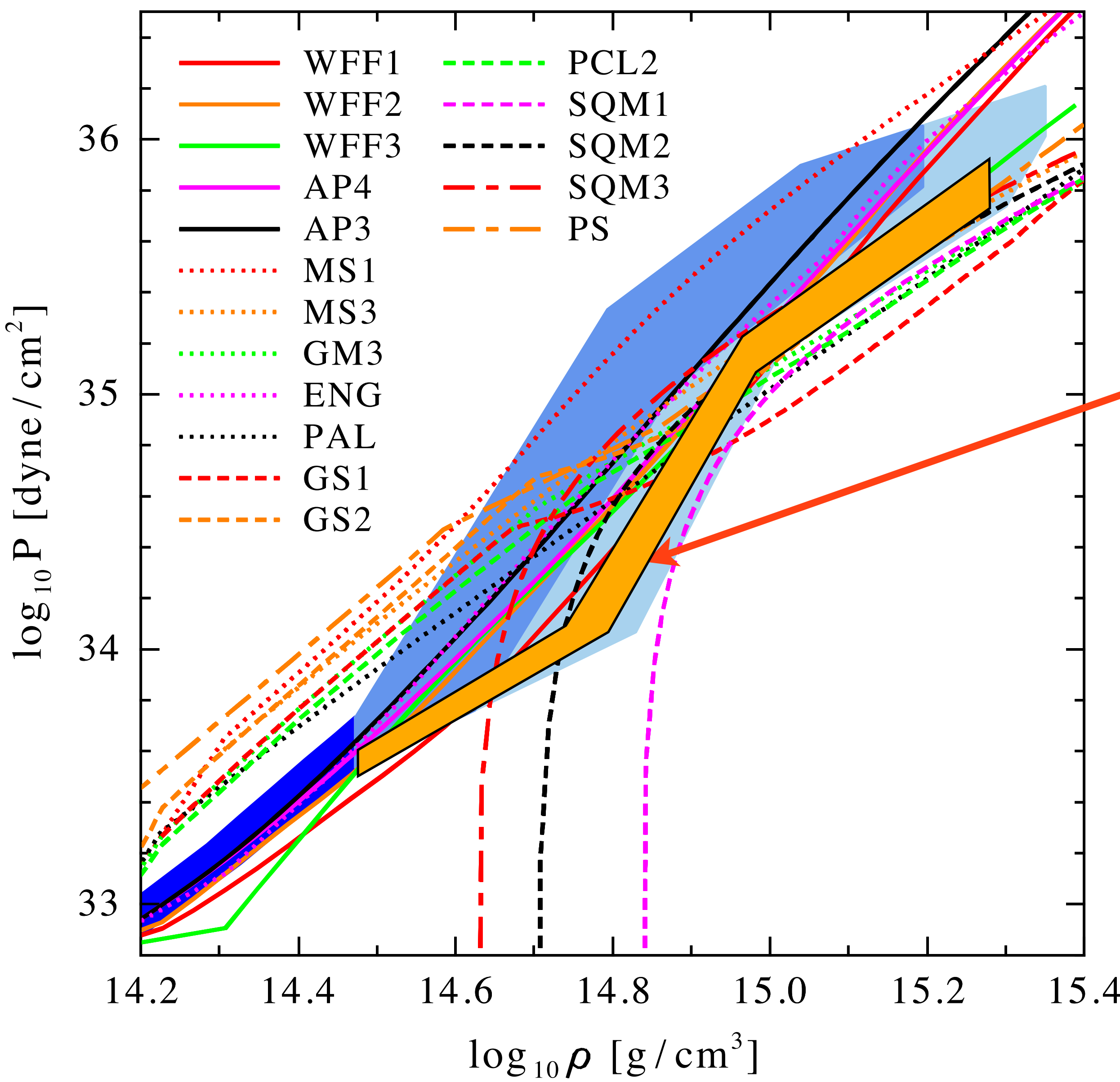
$$\mathcal{M} = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}$$

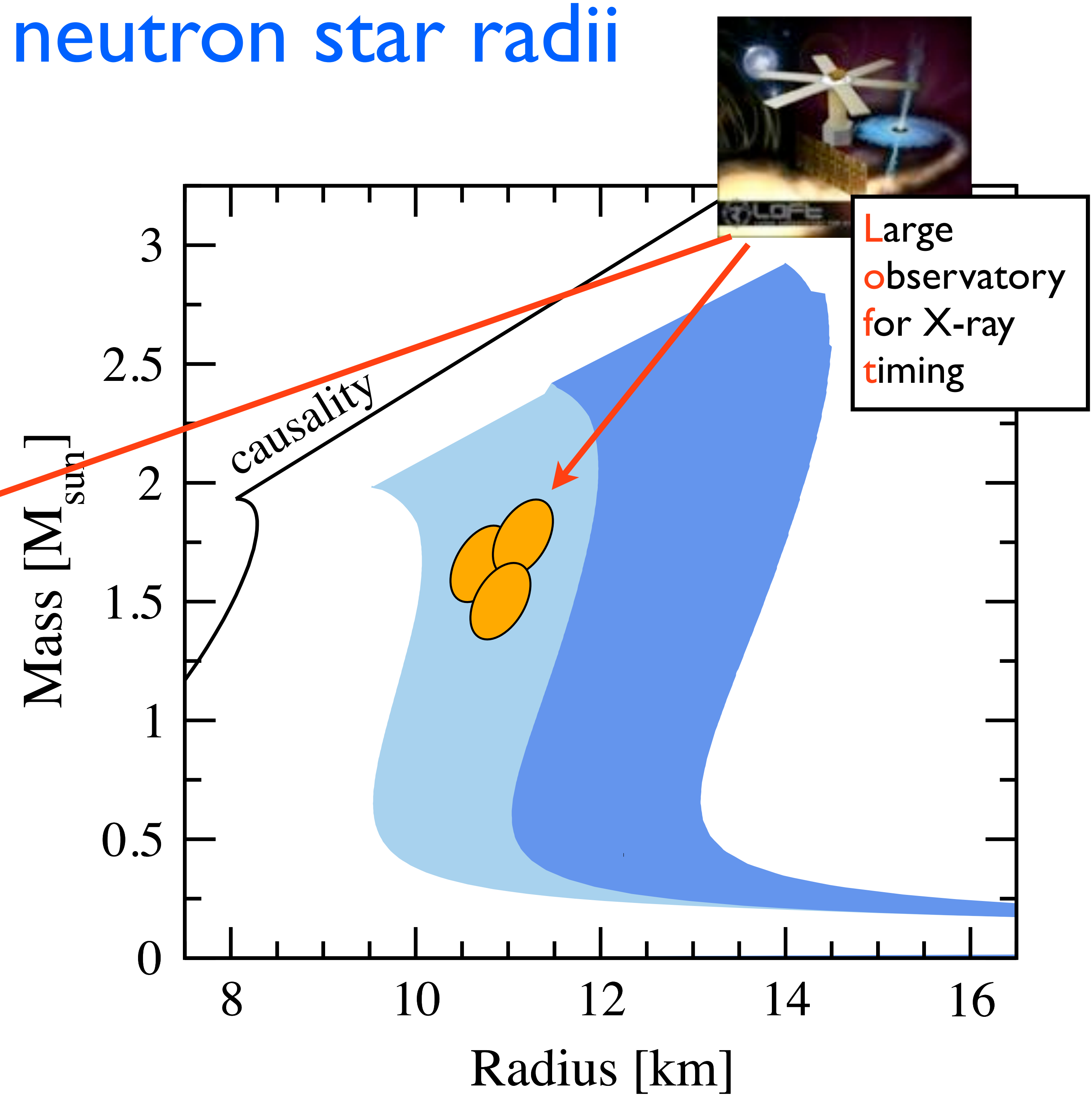


radius constraints for $1.4\,M_\odot$ relatively insensitive to mass ratio $q = \frac{M_1}{M_2}$

Backup slides

Constraints on neutron star radii

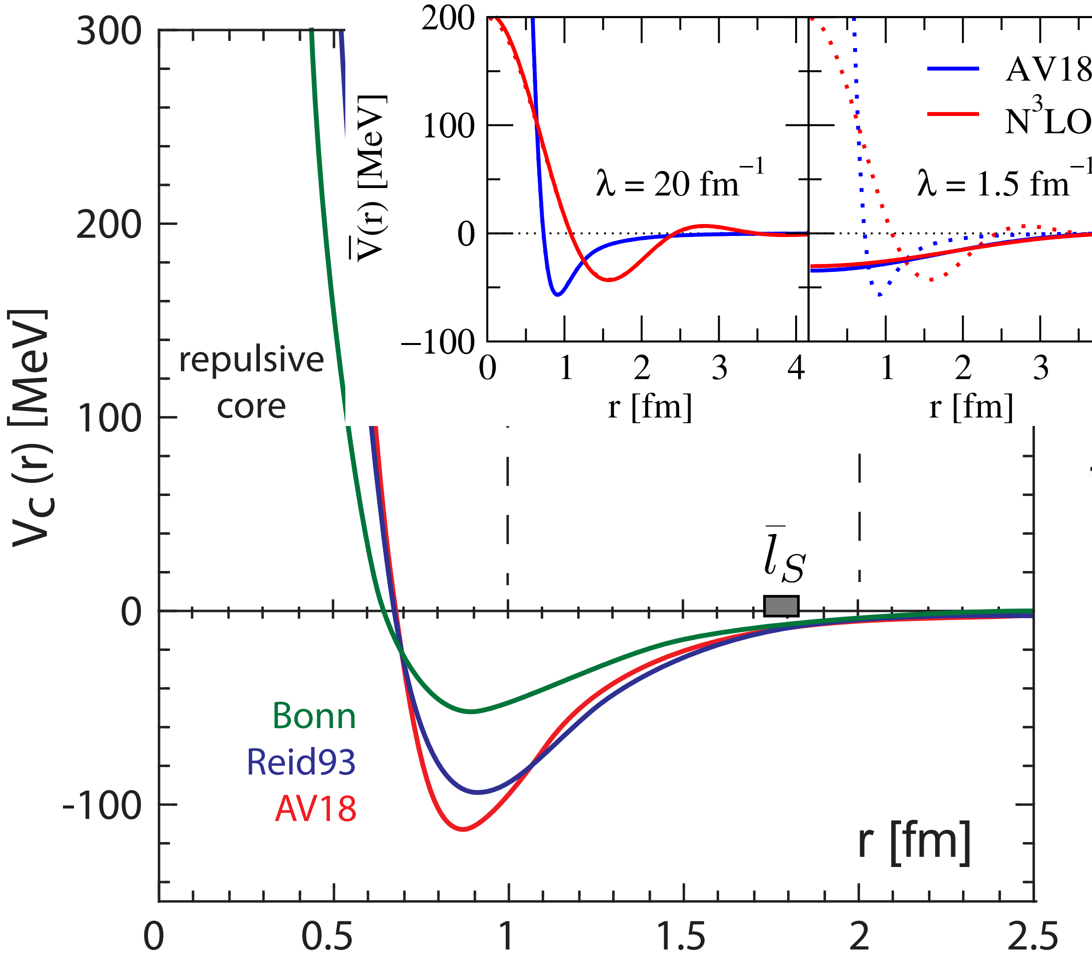


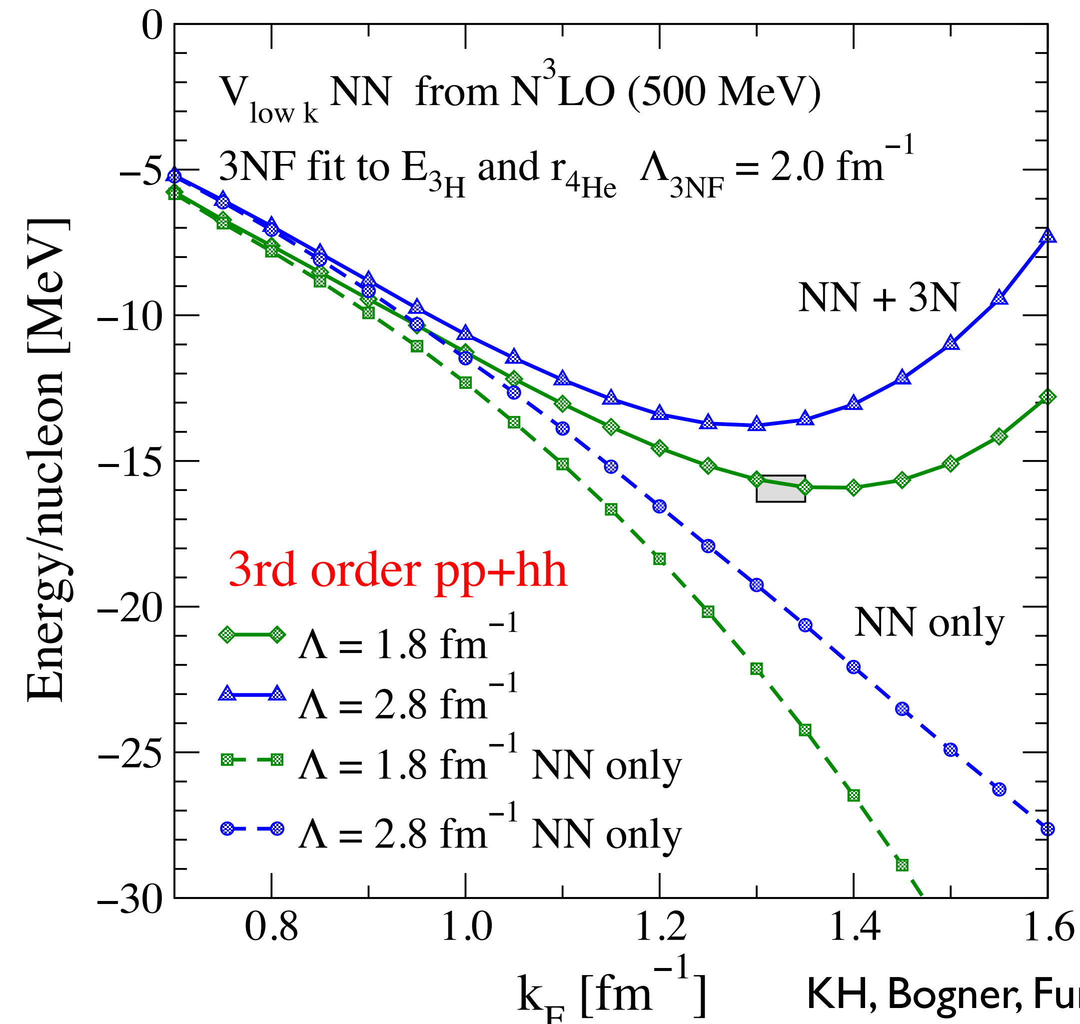


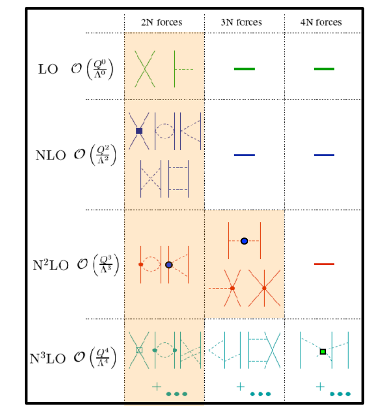
KH, Lattimer, Pethick, Schwenk, ApJ 773, 11 (2013)
see also KH, Lattimer, Pethick, Schwenk, PRL 105, 161102 (2010)

- low-density part of EOS sets scale for allowed high-density extensions
- current radius prediction for typical $1.4\,M_\odot$ neutron star: $9.7 - 13.9\,\mathrm{km}$
- new observatories could significantly improve constraints

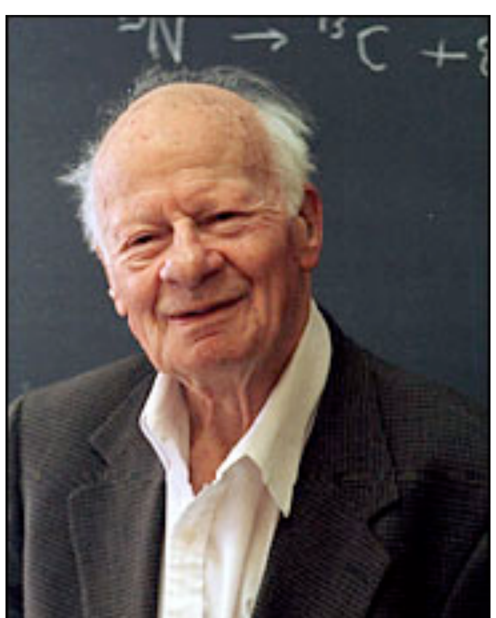
Results for symmetric nuclear matter







KH, Bogner, Furnstahl, Nogga, PRC(R) 83, 031301 (2011)

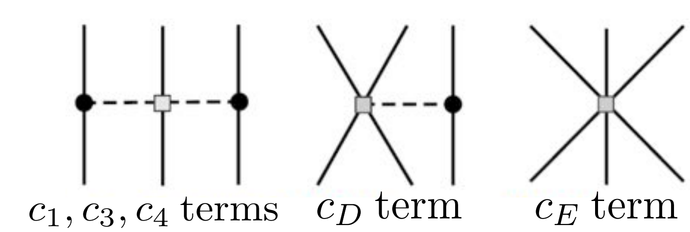


"Very soft potentials must be excluded because they do not give saturation; they give too much binding and too high density. In particular, a substantial tensor force is required."

Hans Bethe (1971)

intermediate (c_D) and short-range (c_E) 3NF couplings fitted to few-body systems at different resolution scales:

$$E_{^3\mathrm{H}} = -8.482\,\mathrm{MeV} \qquad r_{^4\mathrm{He}} = 1.464\,\mathrm{fm}$$



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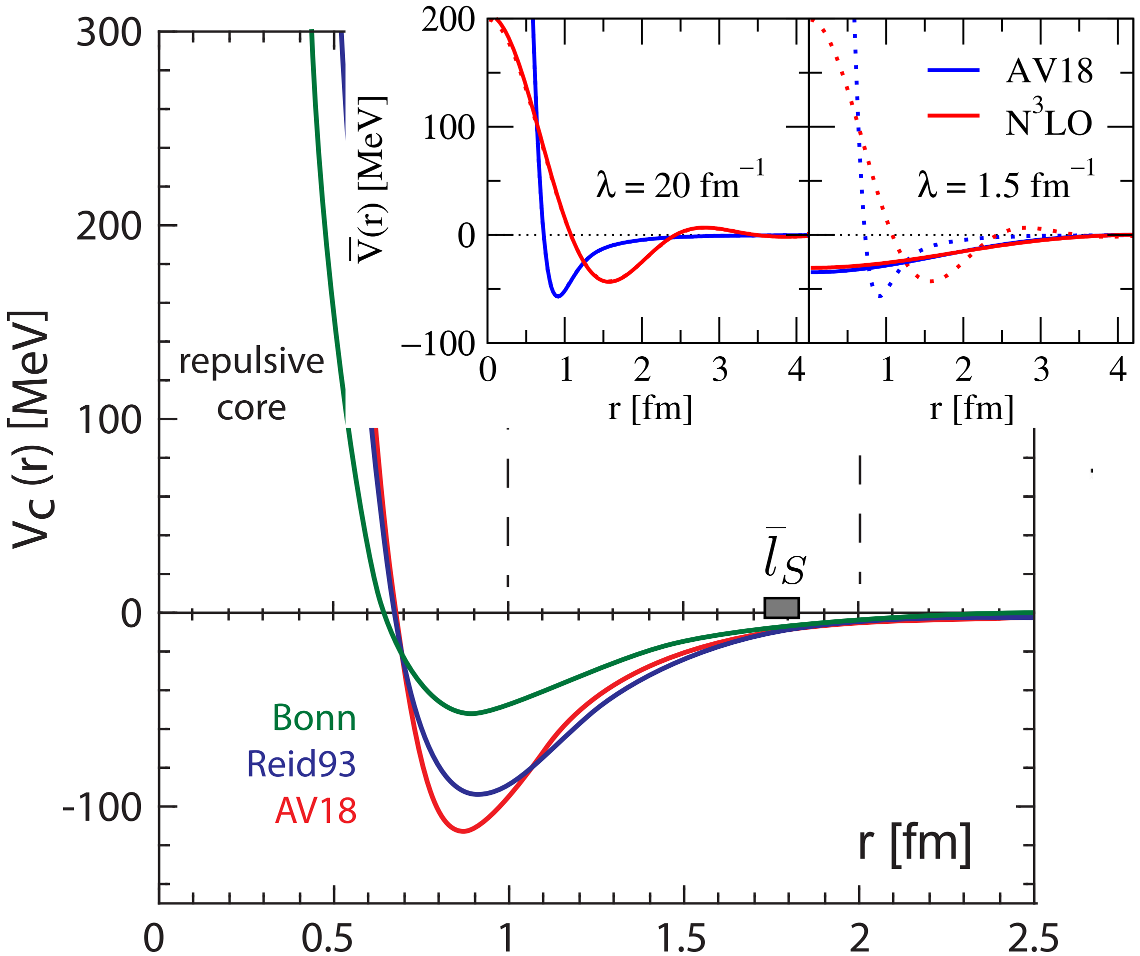
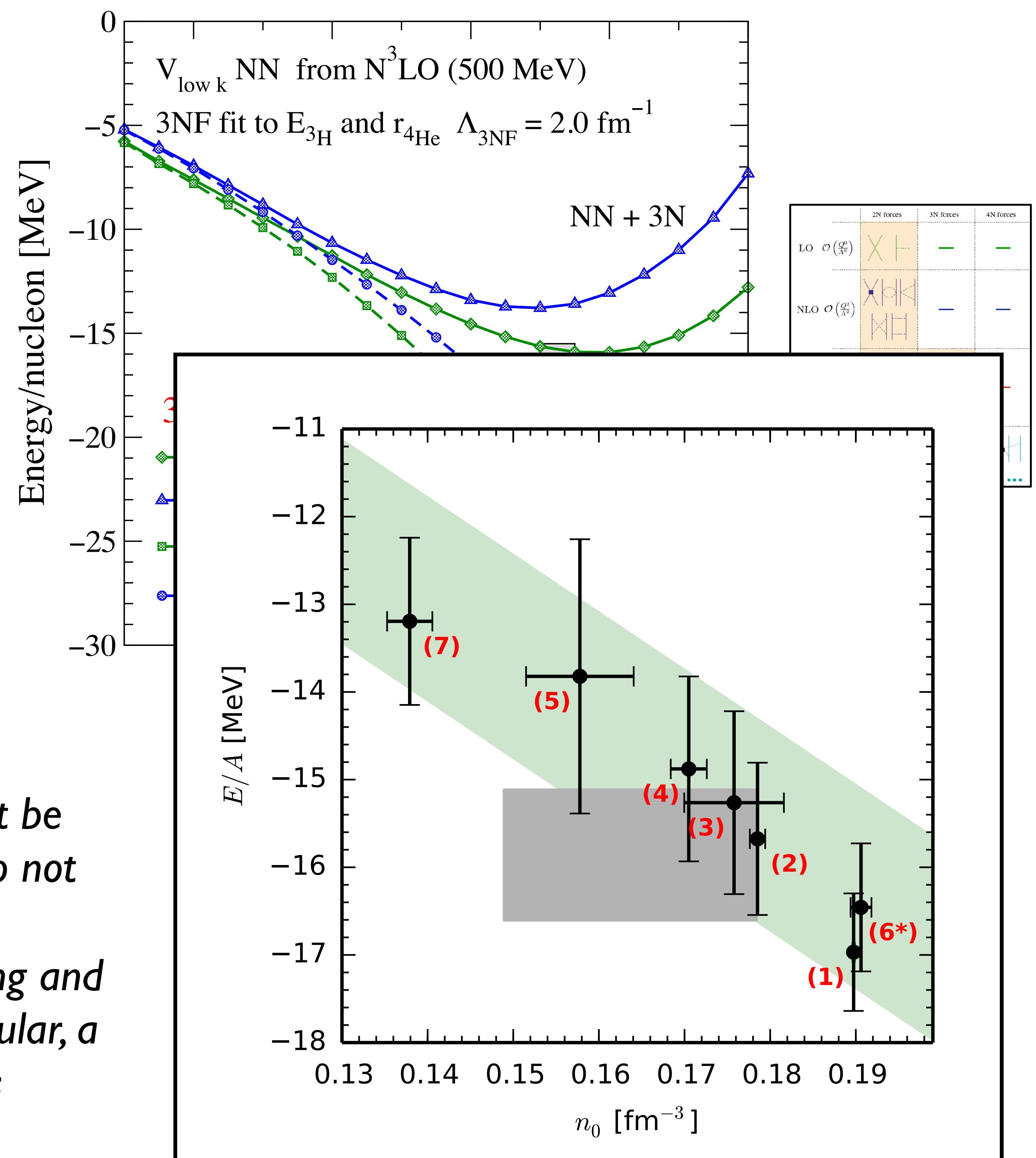


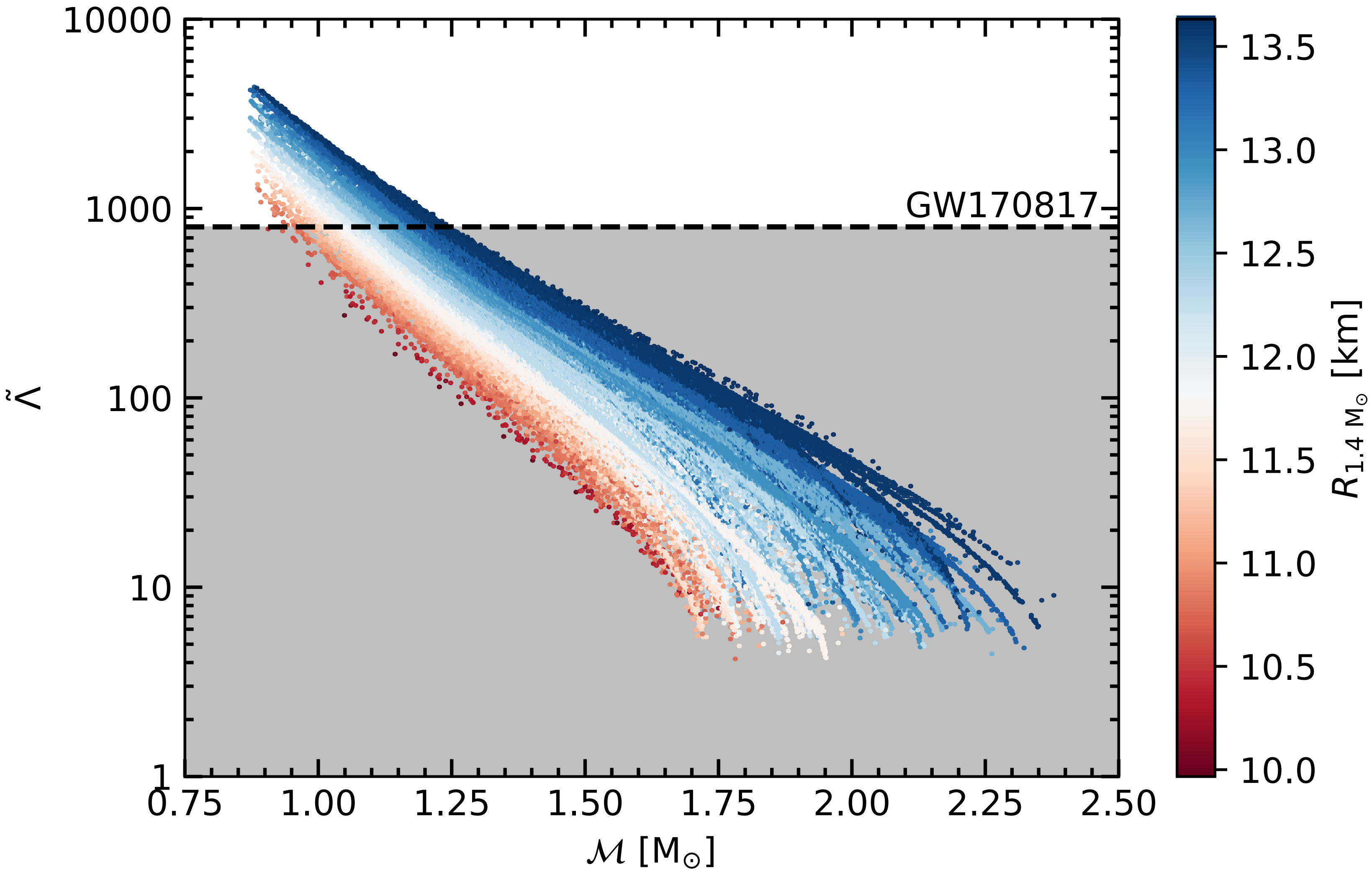


Drischler, KH, Schwenk, PRC93, 054314 (2016)

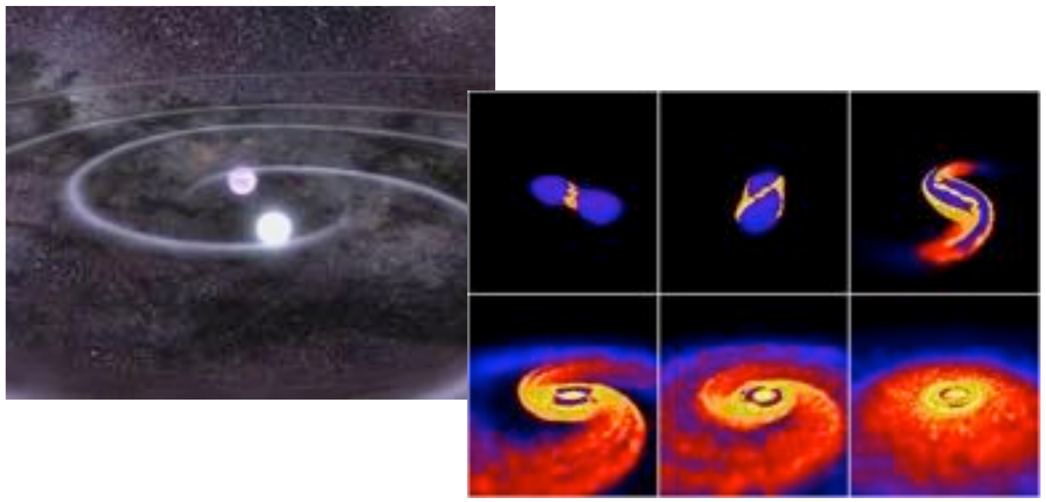
“Very soft potentials must be excluded because they do not give saturation; they give too much binding and too high density. In particular, a substantial tensor force is required.”

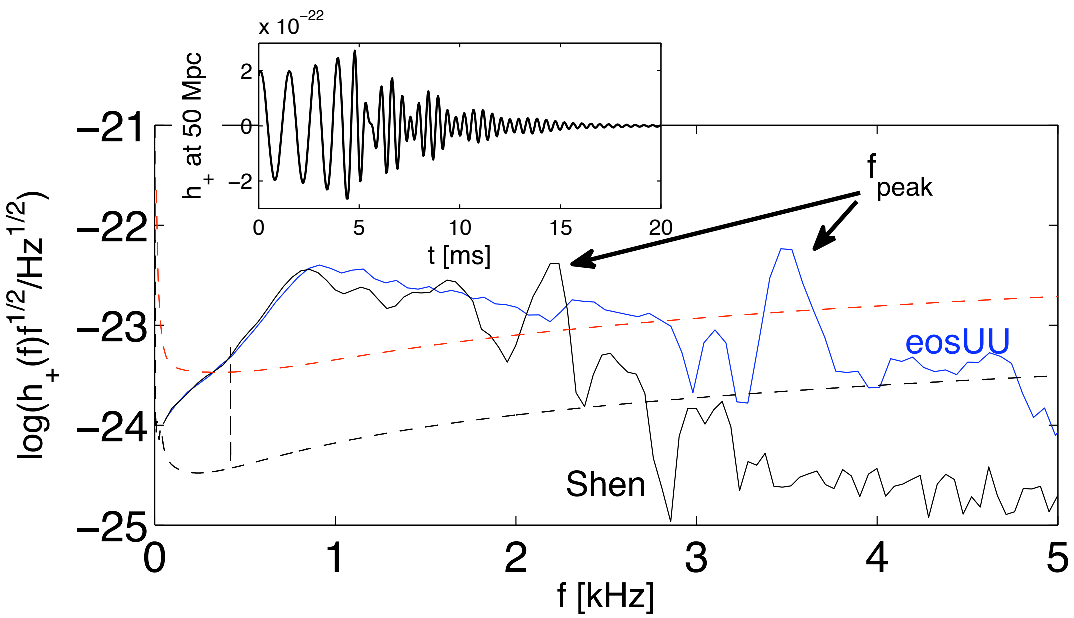
Hans Bethe (1971)

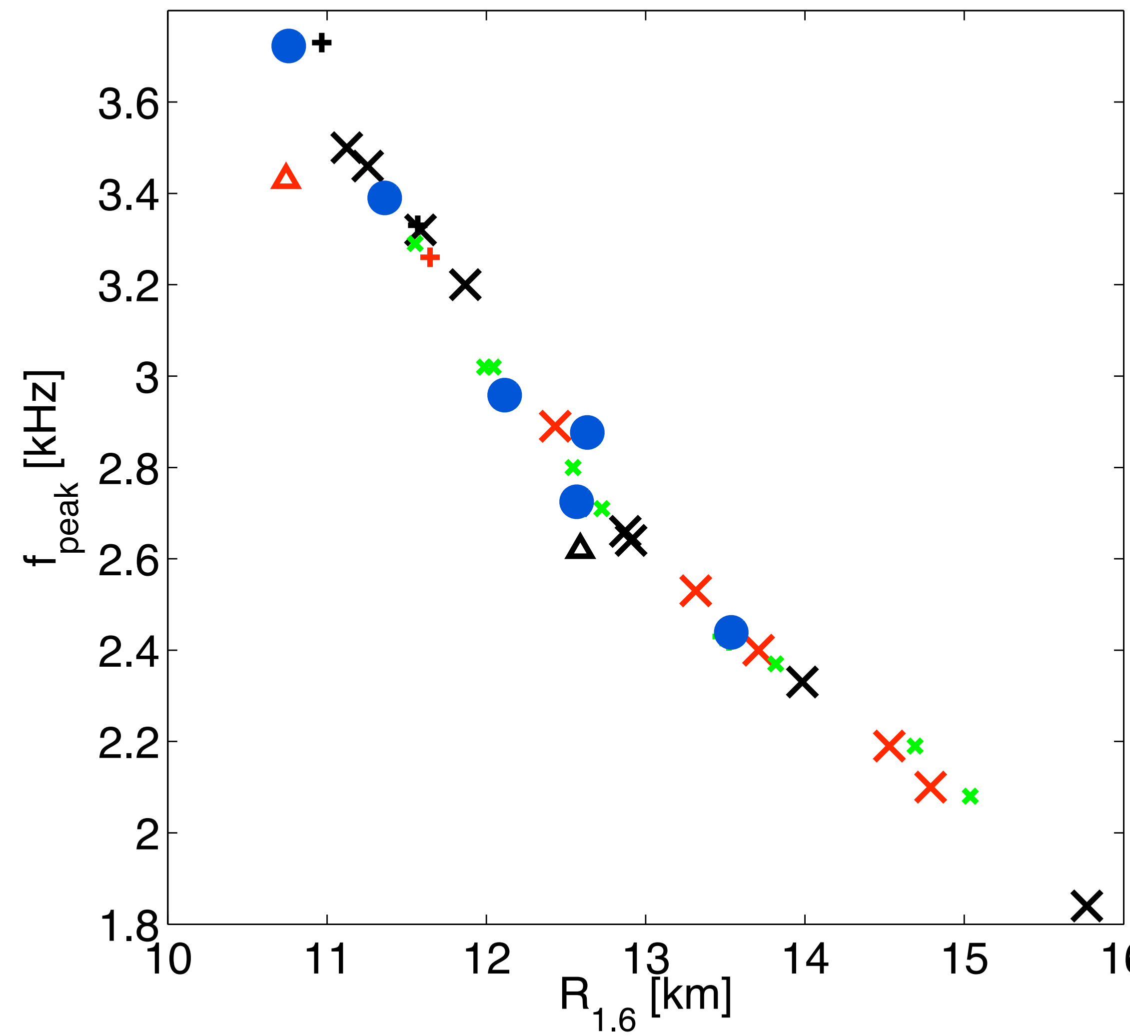
Constraints from tidal deformability measurements



Gravitational wave signals from neutron star binary mergers







Bauswein and Janka, PRL 108, 011101 (2012),
Bauswein, Janka, KH, Schwenk, PRD 86, 063001

- simulations of NS binary mergers show strong correlation between between f_{peak} of the GW spectrum and the radius of a NS
- measuring f_{peak} is key step for constraining EOS systematically at large ρ