Lower Bound on the Tidal Deformability of Neutron Stars

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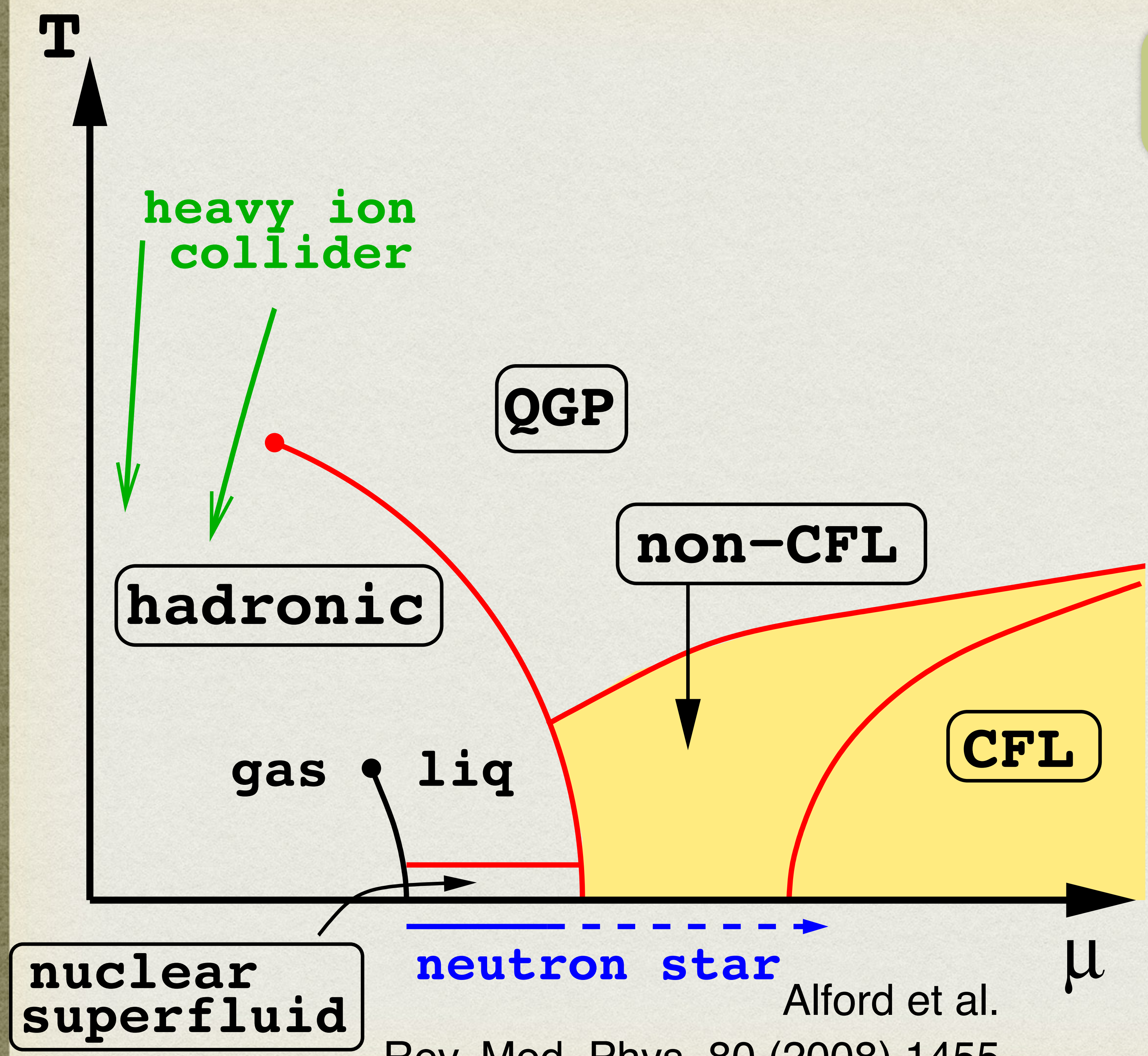
In collaboration with Andrew Steiner, UTK/ORNL

Topical Program: FRIB and the GW170817 kilonova

Wednesday Jul. 18th, 2018 @East Lansing

QCD Phase Diagram



Alford et al.
Rev. Mod. Phys. 80 (2008) 1455

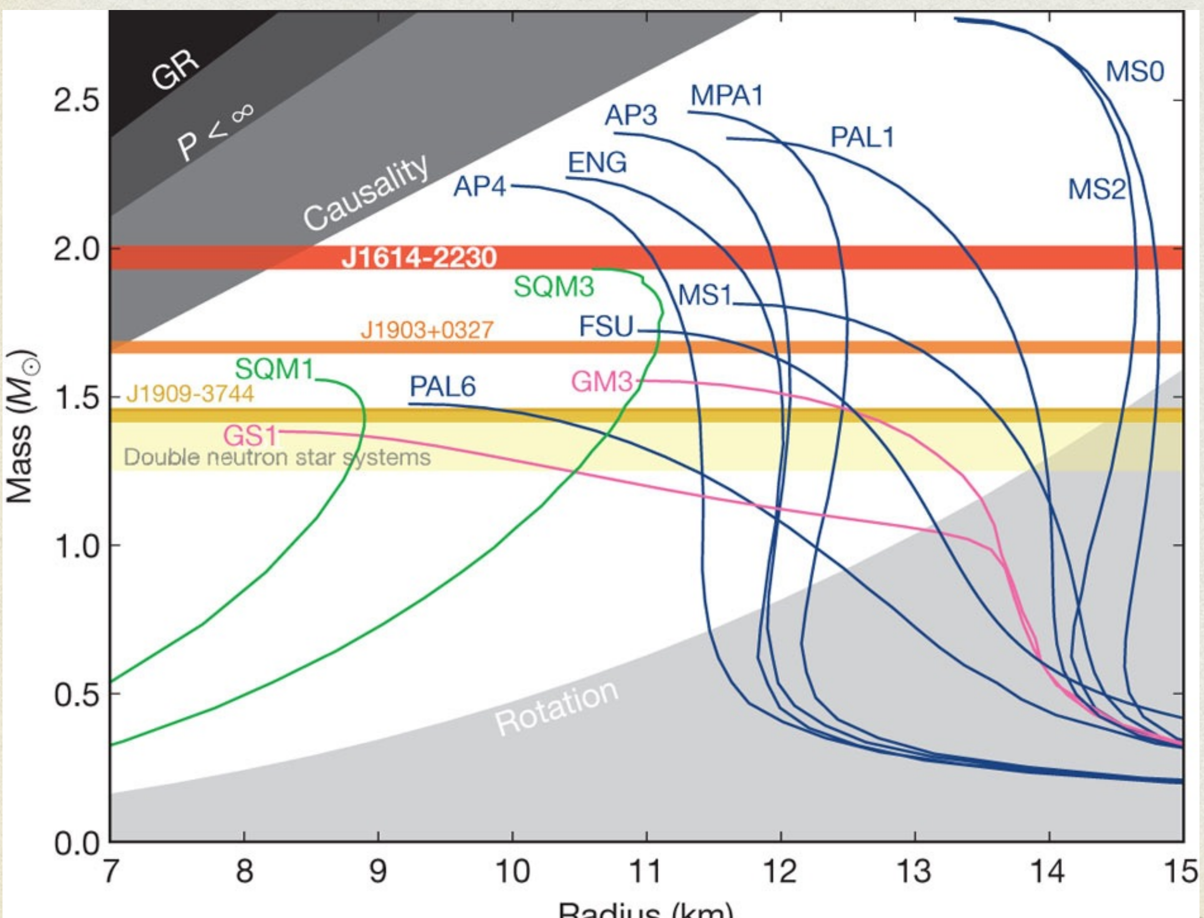
Limits on computations for cold dense matter

- lattice QCD gives good result at finite temperature, but is stymied currently at finite density
- perturbative QCD: only valid at asymptotically high densities
- can't calculate properties of cold dense matter, must observe!

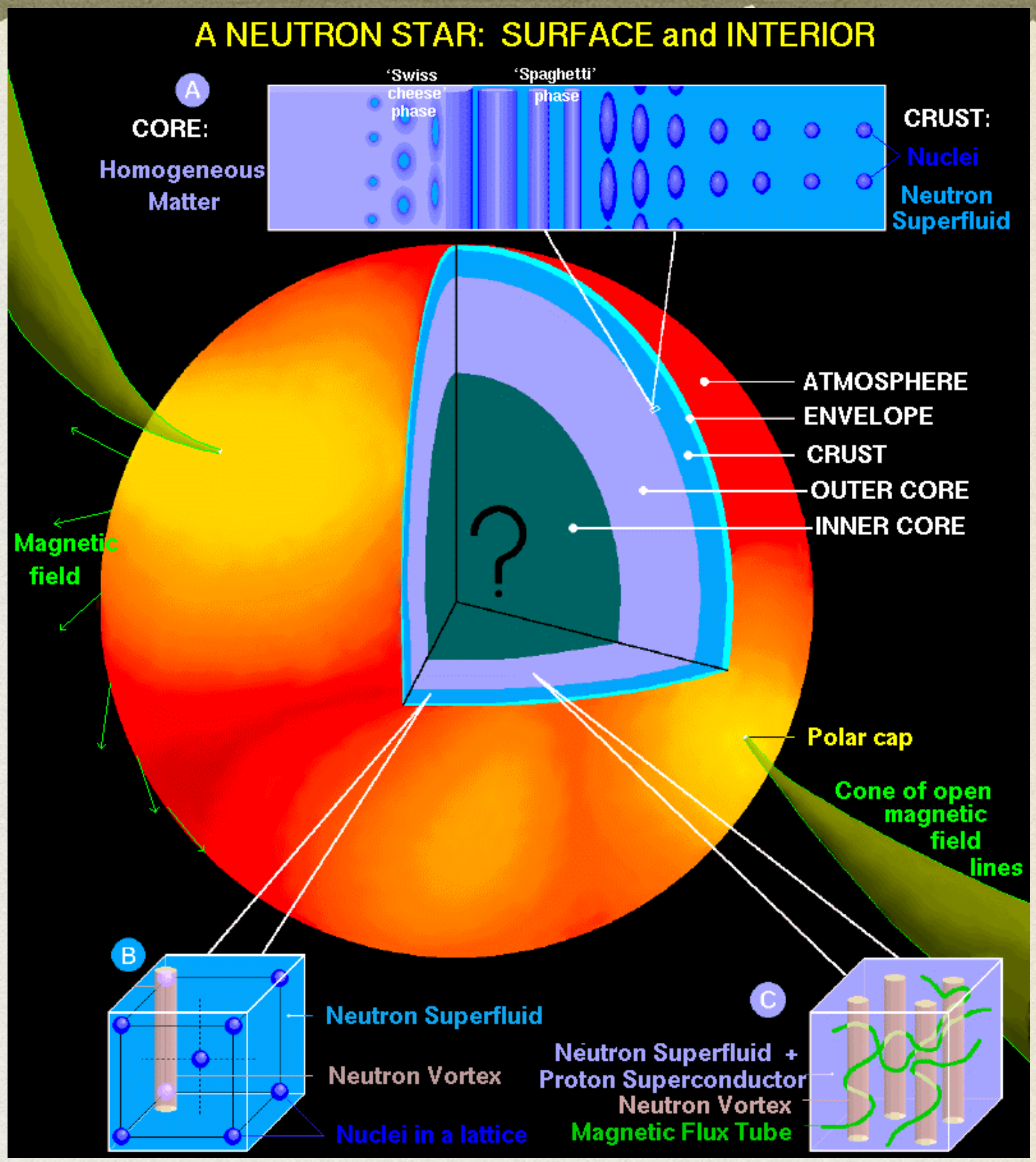
Compact Stars

Unique laboratory for extreme physics

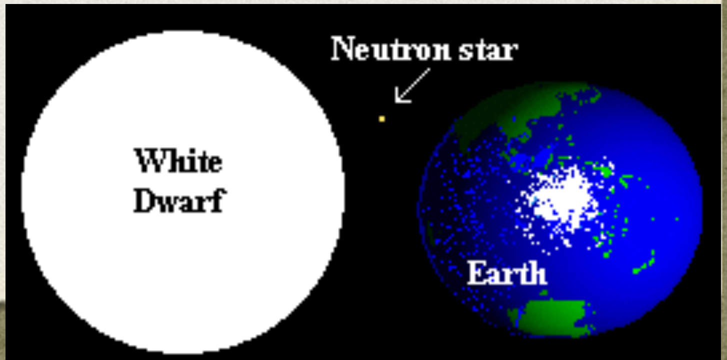
- formed from the collapse of a massive star in a supernova explosion
- static structure determined by Equation of State (pressure vs. density)



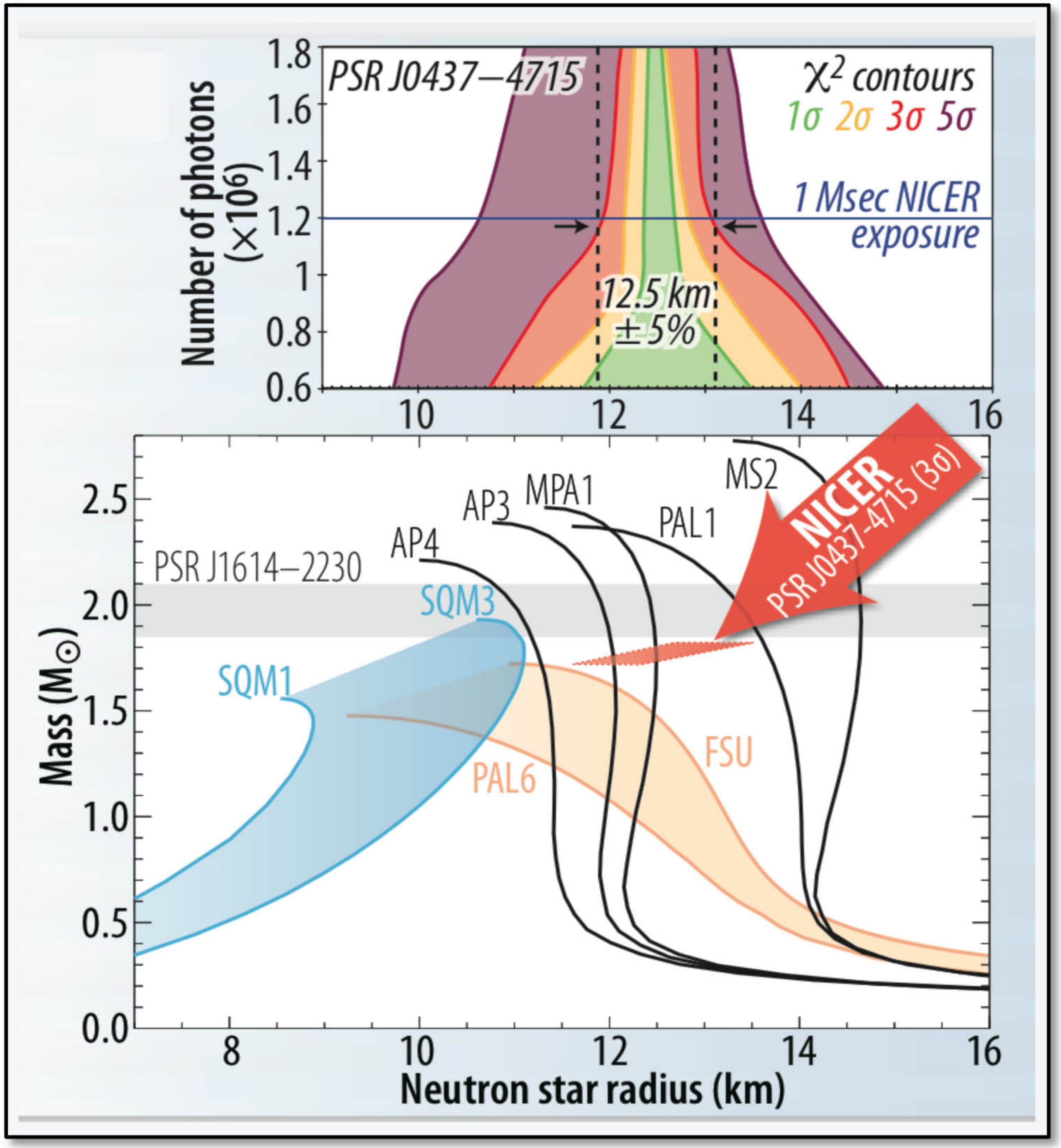
Demorest et al. (2010)

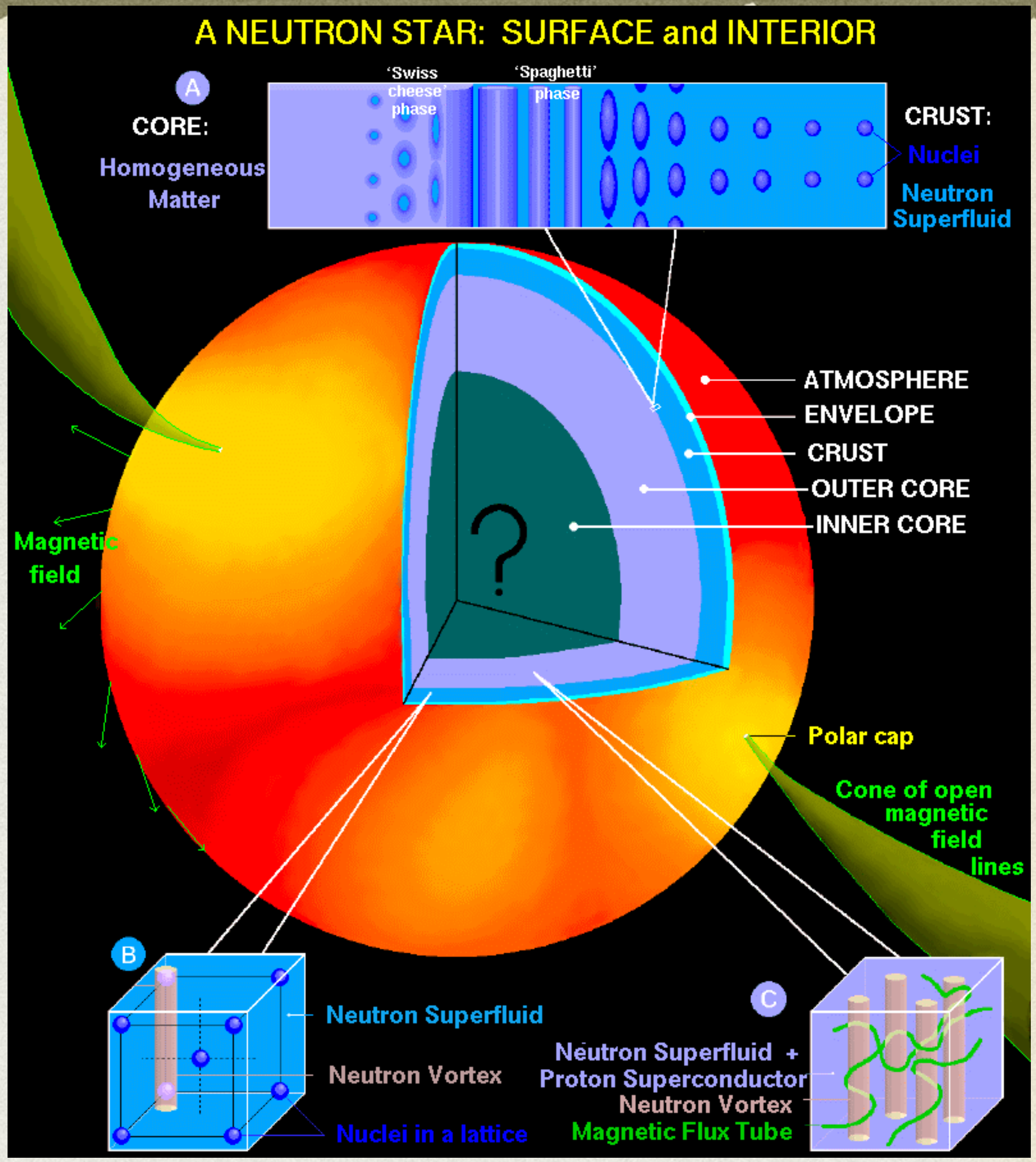


credit: D. Page

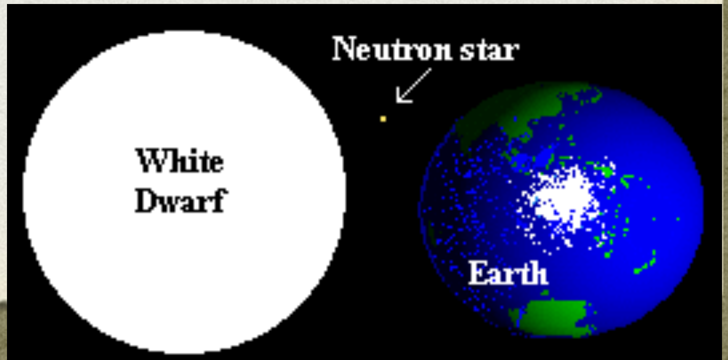


Compact Stars



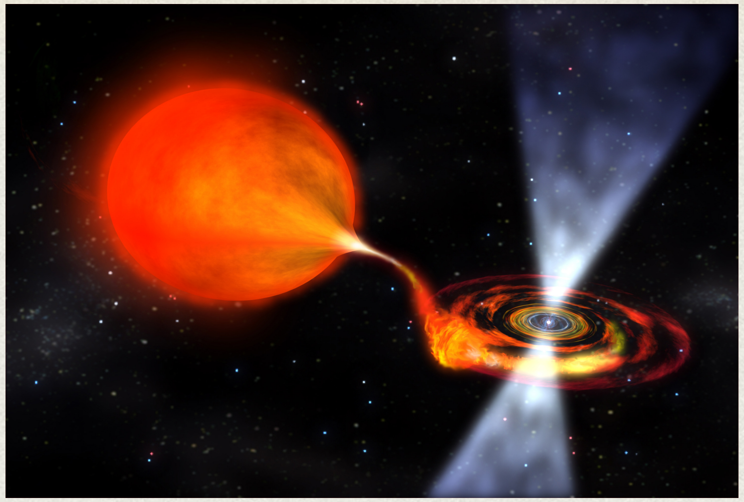


NICER mission

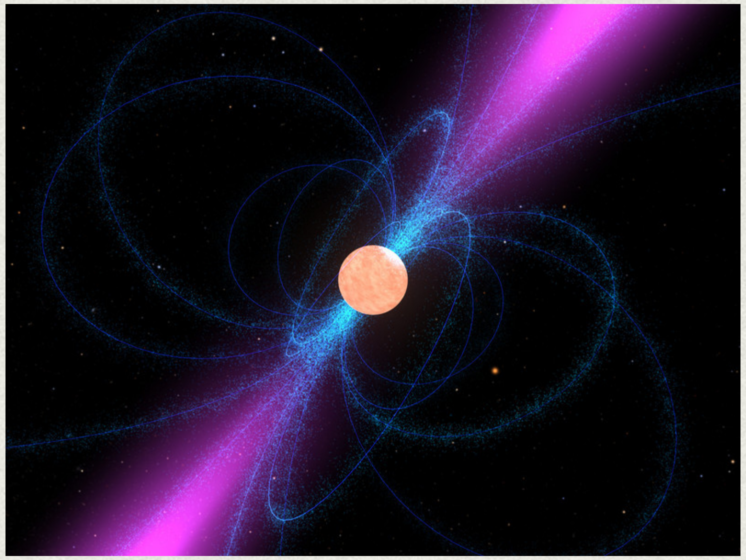


Dense matter in neutron stars

Properties	Observables
equations of state	mass, radius, tidal deformation, MoI...
thermal & transport properties, vortex pinning	cooling, spin-down, glitches, neutrinos, GW...



©NASA



Best constraints from observation so far

-Massive pulsars observed ~2 solar masses

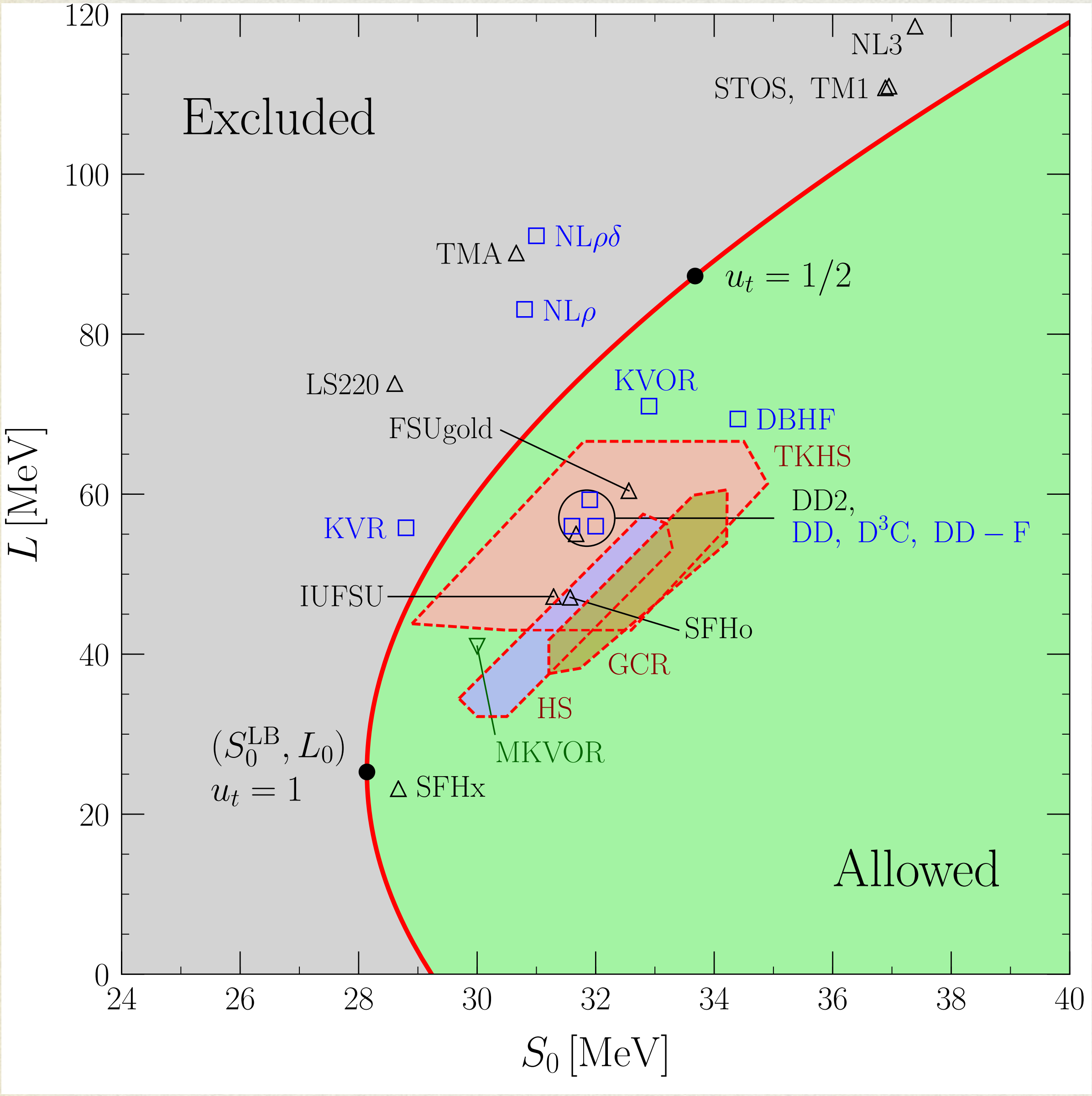
-Pre-merger GW signals detected limit tidal deformability

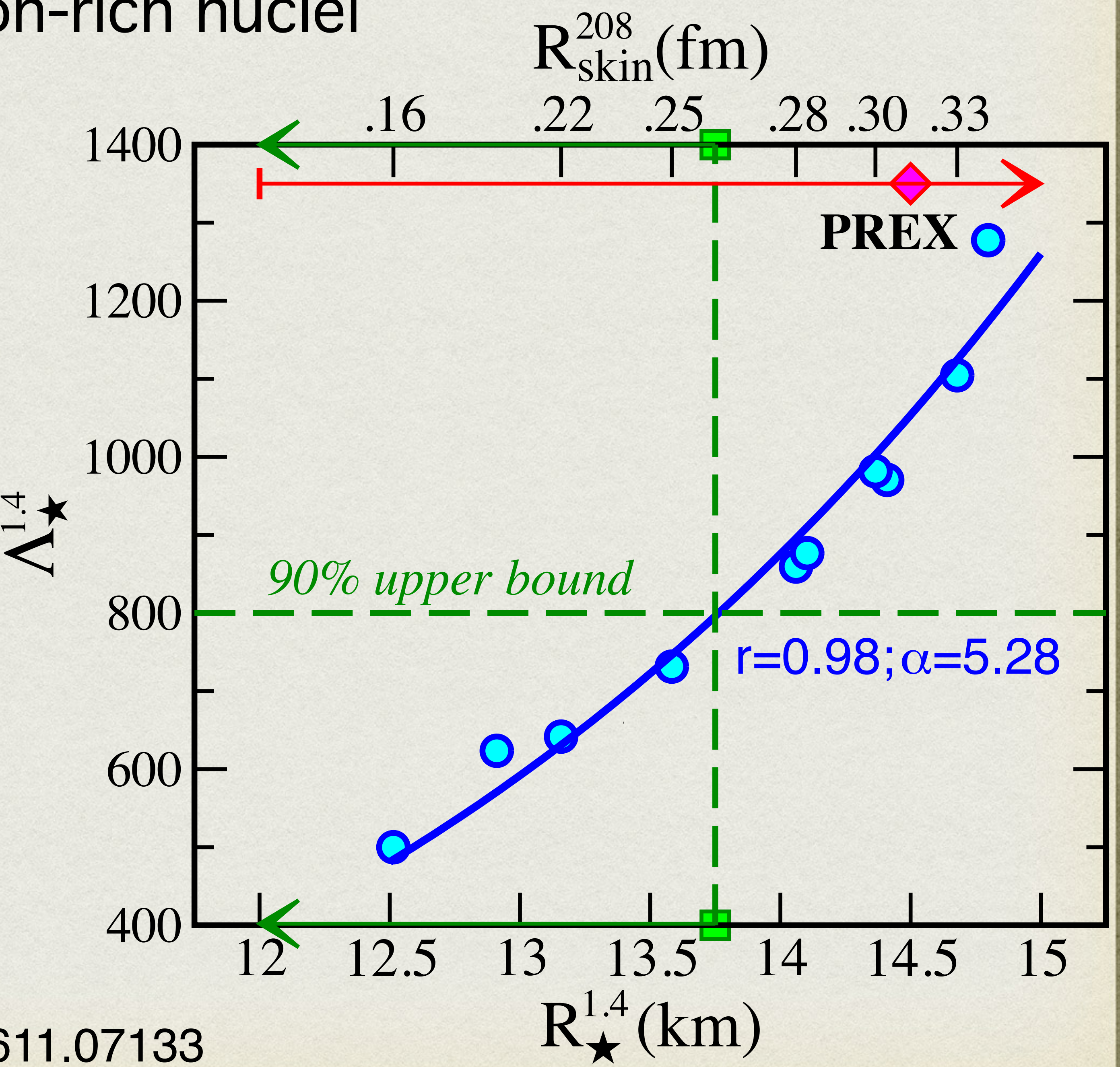
Low-energy Theory/Experiment

-Nuclear symmetry parameter constraints

-Neutron-skin thickness of neutron-rich nuclei

Fattoyev, Piekarewicz & Horowitz, arXiv:1711.06615





Tews, Lattimer, Ohnish & Kolomeitsev, arXiv:1611.07133

Three Scenarios of NS

Normal hadronic stars ⟷ Nuclear matter EoS

-continuous and smooth density profile

-stiffness (symmetry energy)

Self-bound strange quark stars ⟷ Strange matter EoS (assumed as true ground state of QCD)

-“bare” surface with a finite density discontinuity

-bag constant; quark interaction; pairing

Hybrid stars with quark core & nuclear mantle ⟷ EoS with phase transition at critical pressure

-abrupt density change inside the star at phase boundary

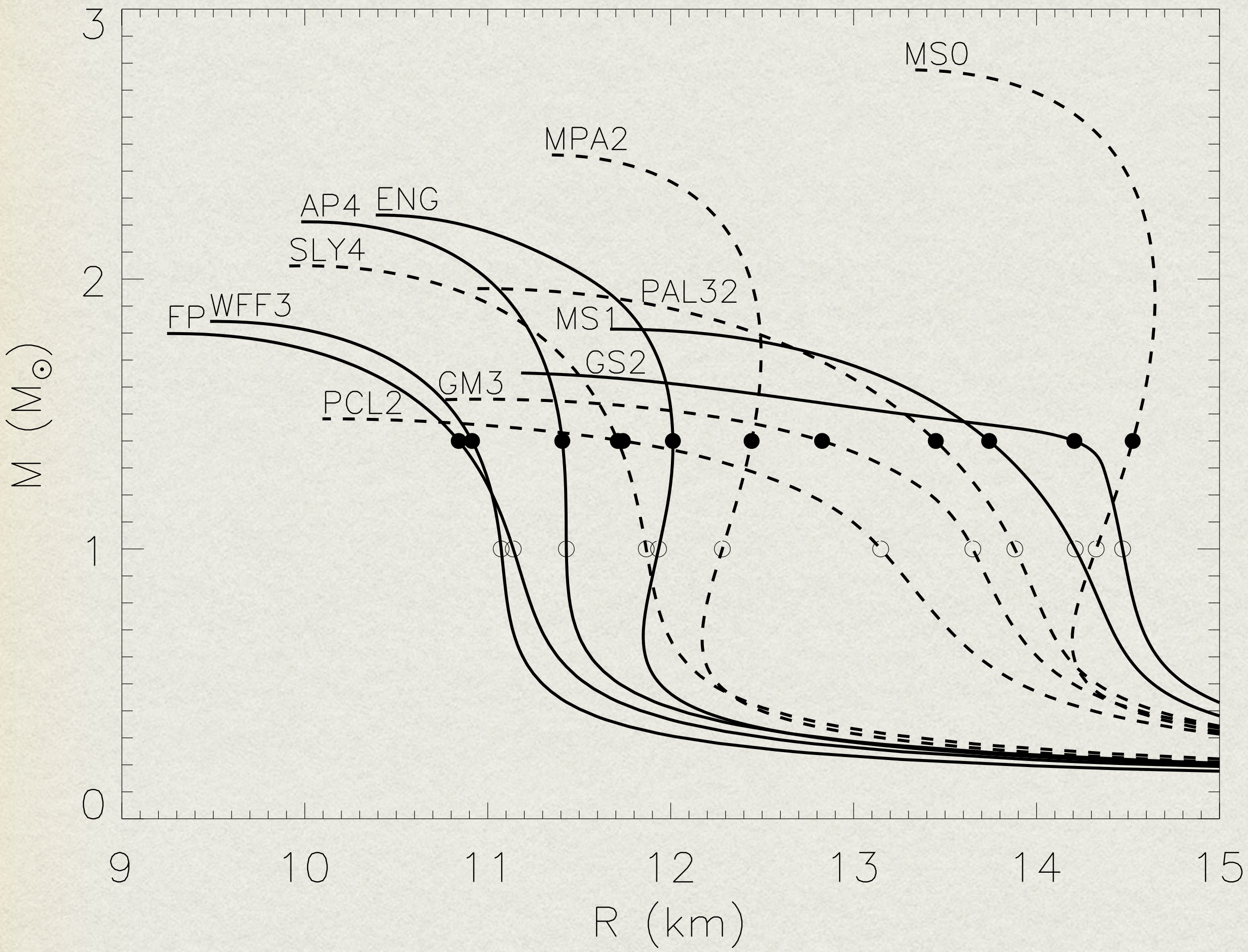
-phase transition parameters

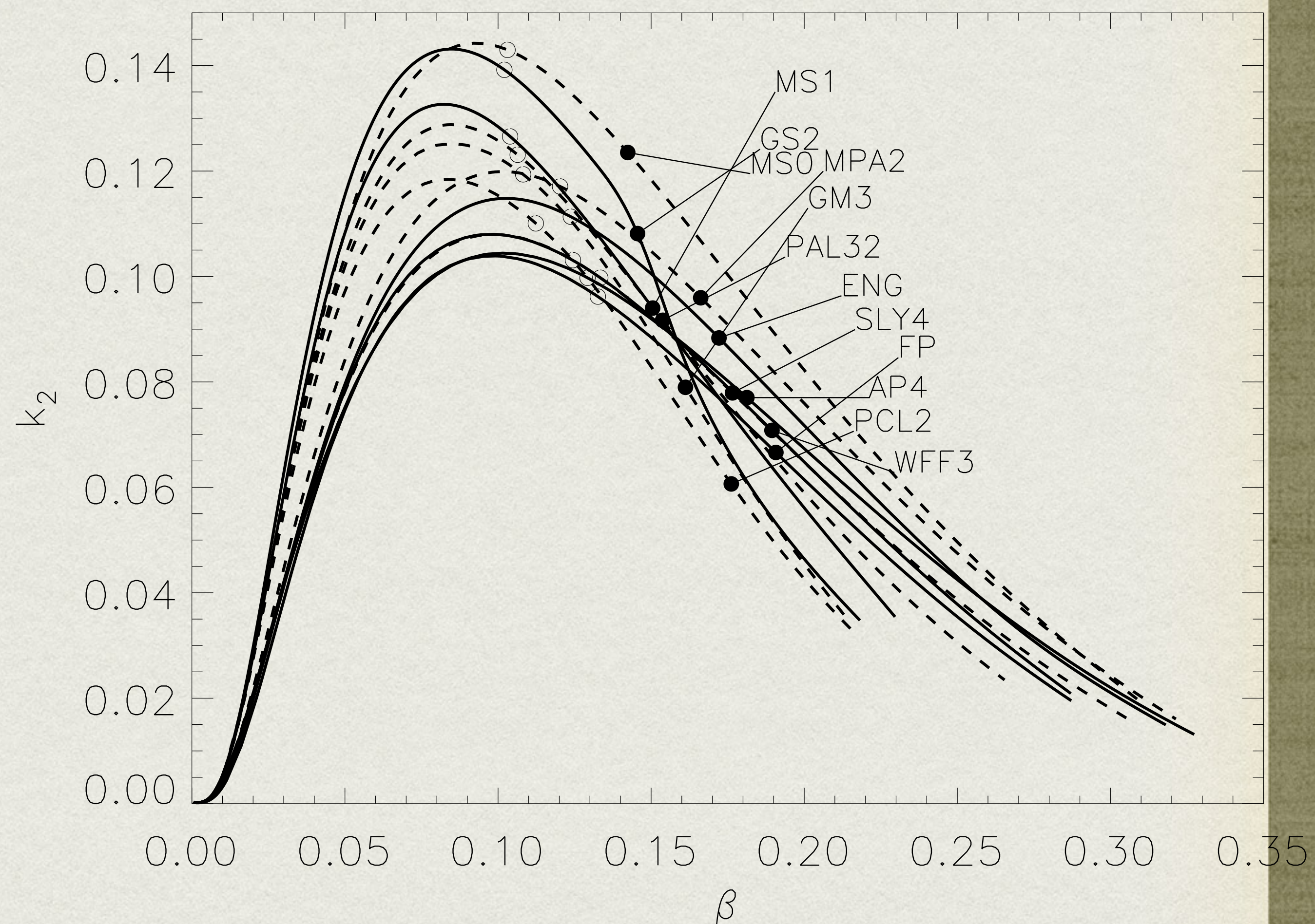
Normal hadronic EoSs

-Tidal Love numbers 0.05~0.15

$c_s^2 = \mathrm{d}p/\mathrm{d}\varepsilon$

-Speed of sound monotonically increasing with pressure from zero





$$\Lambda \equiv \frac{\lambda}{M^5} \equiv \frac{2}{3} k_2 \left(\frac{Rc^2}{GM} \right)^5$$

Postnikov, Prakash & Lattimer,
arXiv:1004.5098

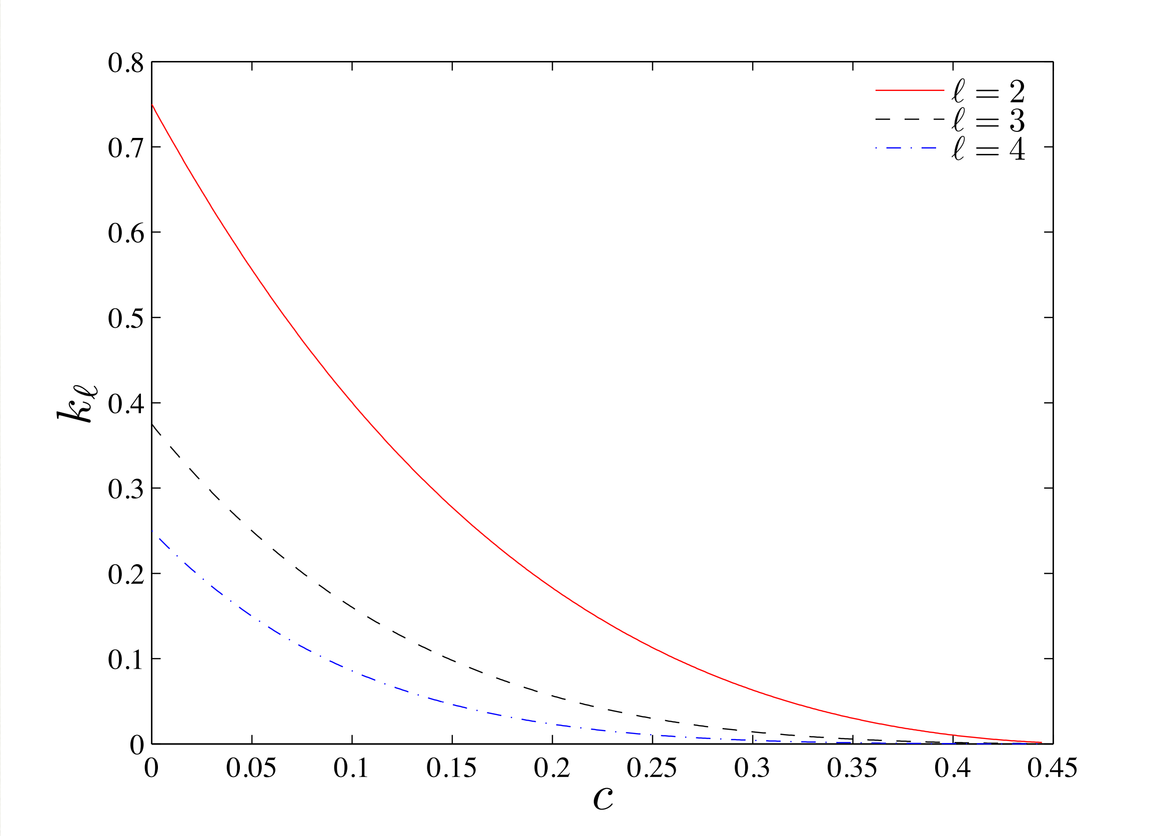
EoSs with discontinuity

-Technical problem: matching boundary conditions properly

-First studied in the incompressible limit:
energy density is constant everywhere inside the star, but jump to zero at the surface

$$C_0^{\text{sing}} = -\frac{4\pi G r^2}{m(r) + 4\pi G r^3 p}\frac{d\varepsilon}{dr}$$

$$\frac{d\varepsilon}{dr} = -\varepsilon_0 \delta(r - R)$$



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delta-function singular term proportional to 3/R

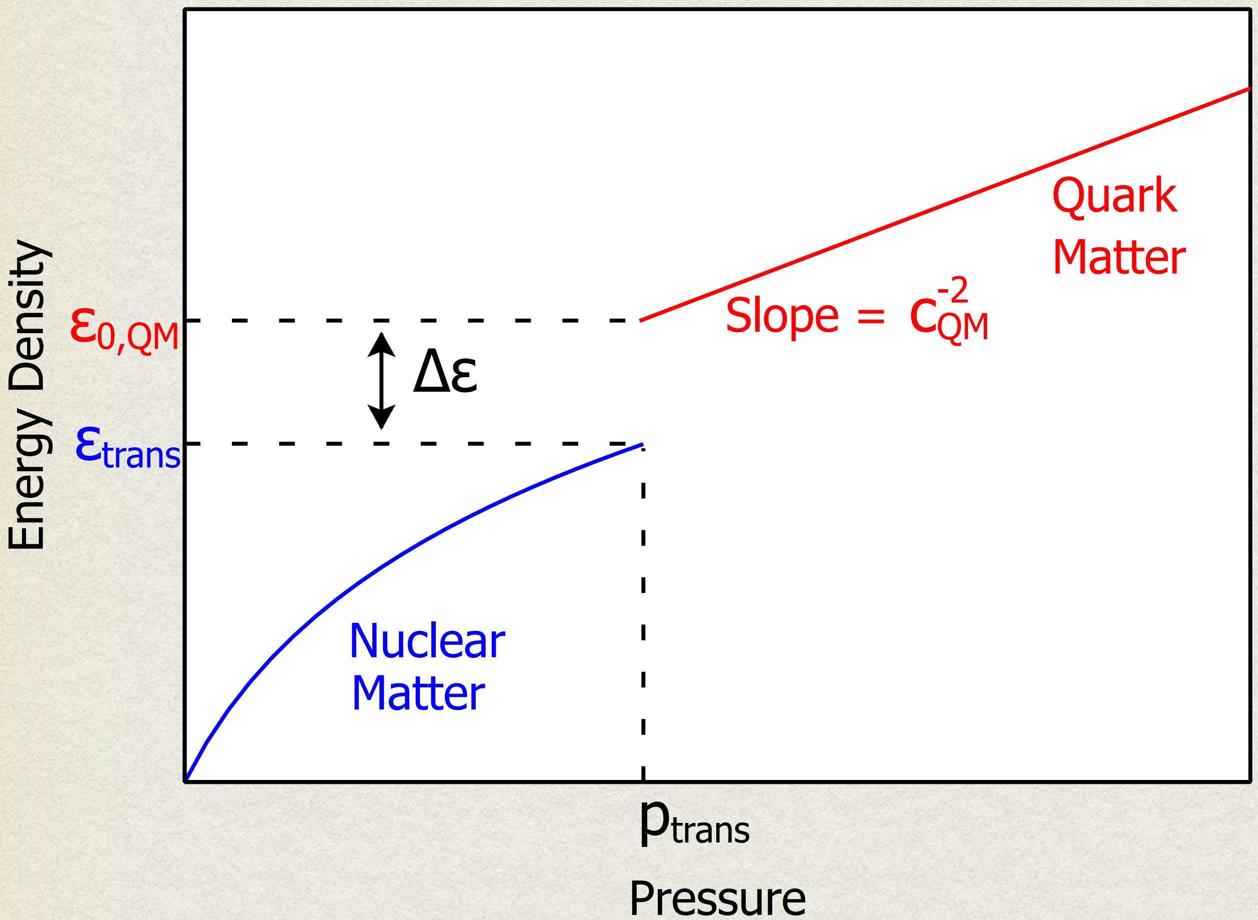
Damour & Nagar, arXiv:0906.0096

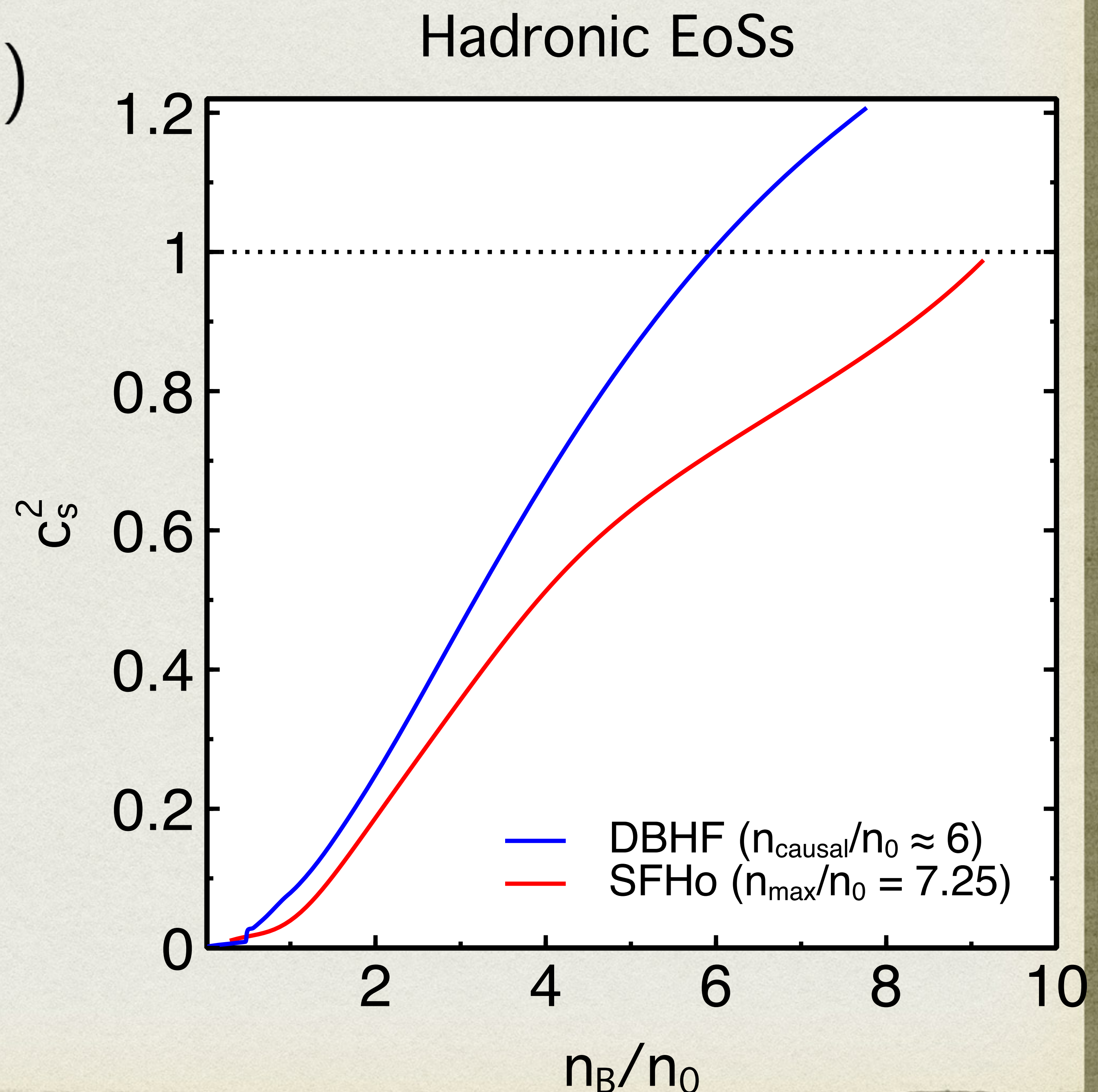
-Applicable to any sharp interface with abrupt density change

Generalize to PTs in hybrid stars

-Model-independent parametrization of high-density matter

$$(p_{\rm trans}/\varepsilon_{\rm trans},\ \Delta\varepsilon/\varepsilon_{\rm trans},\ c^2_{\rm QM})$$





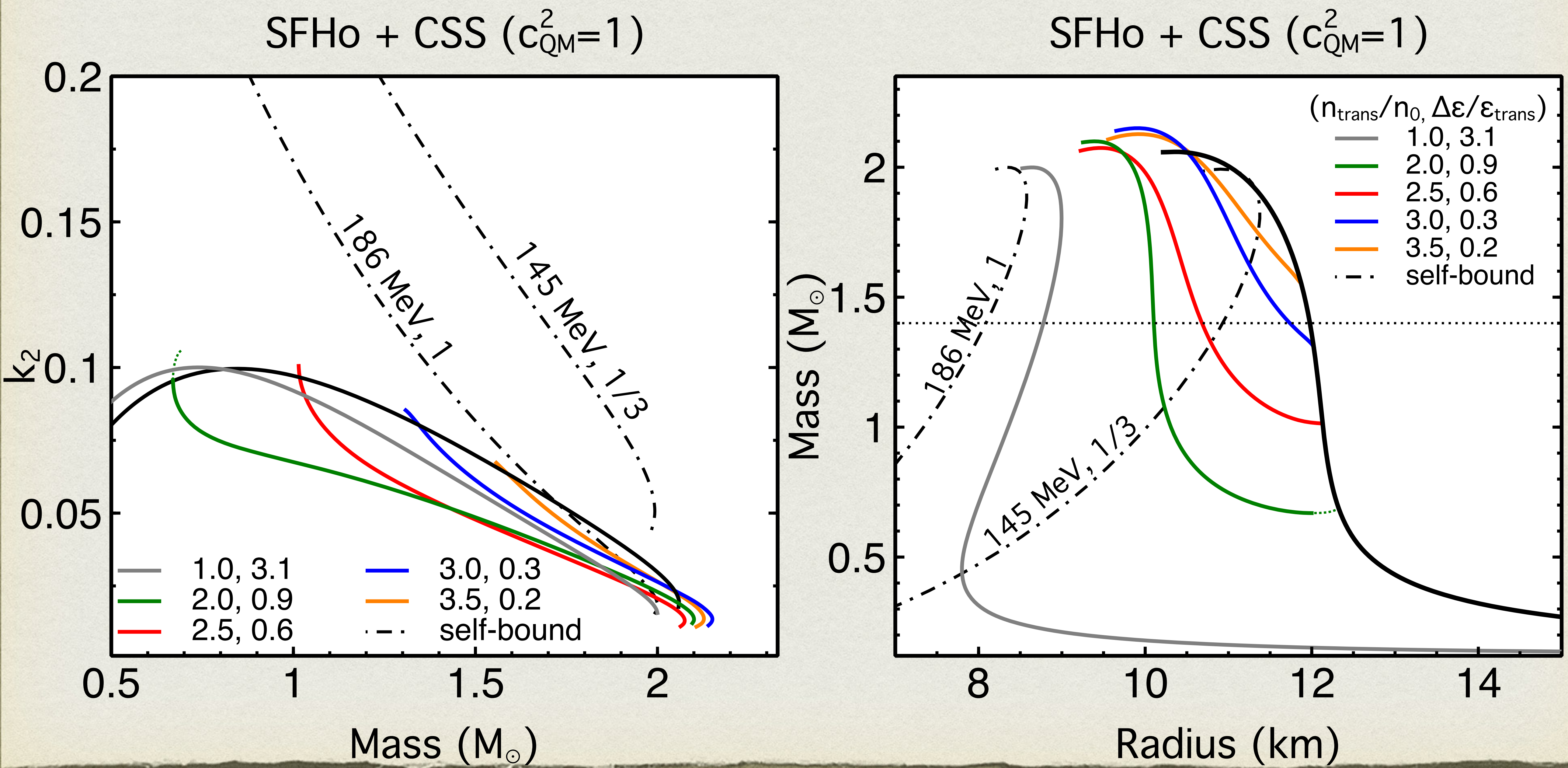
Zdunik & Haensel, arXiv:1211.1231

Alford, SH & Prakash, arXiv:1302.4732

Tidal Parameters with PT

-Model-independent parametrization of high-density matter

-Sizable decrease in both k2 and R above PT: deviated trajectories



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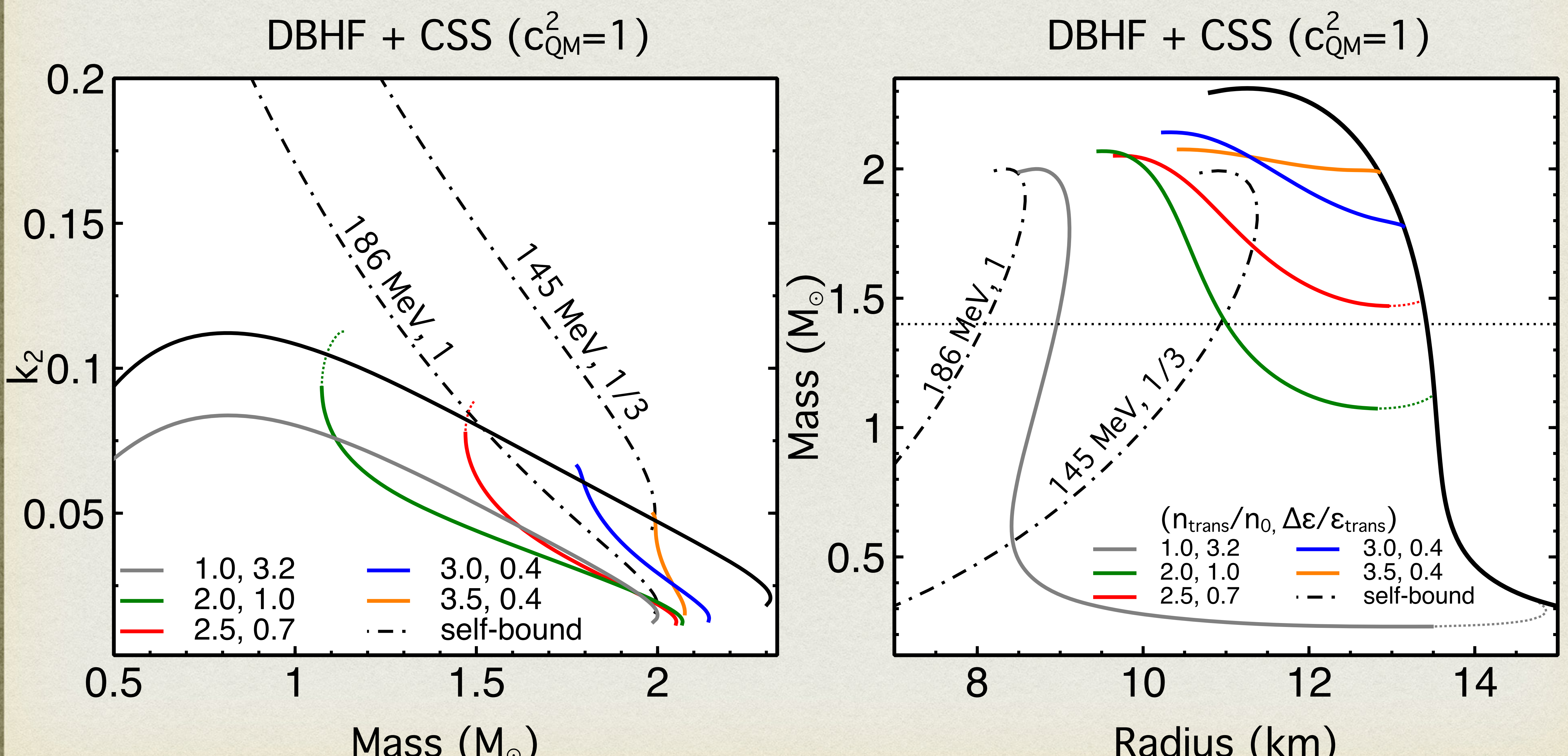
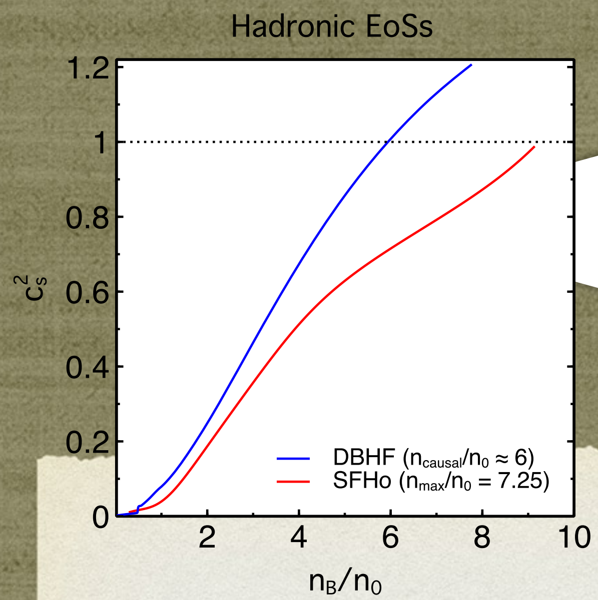


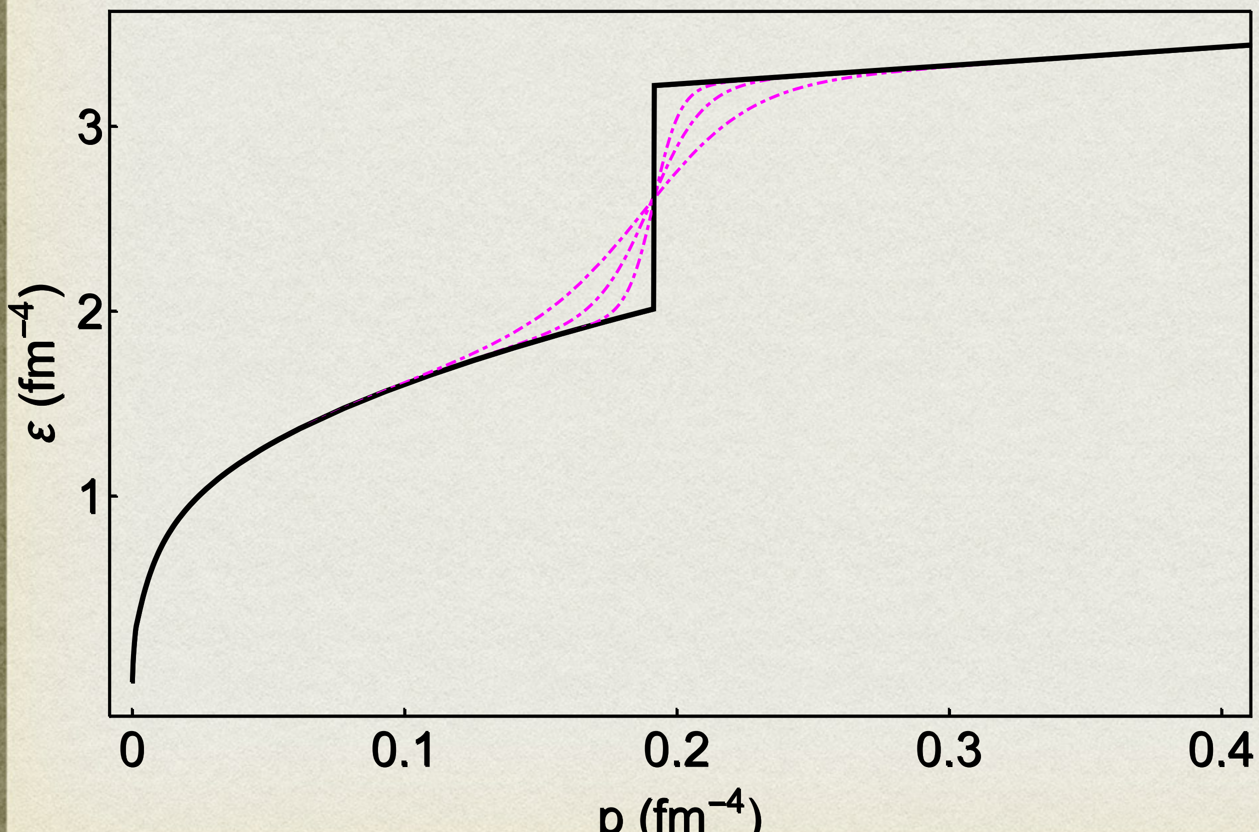


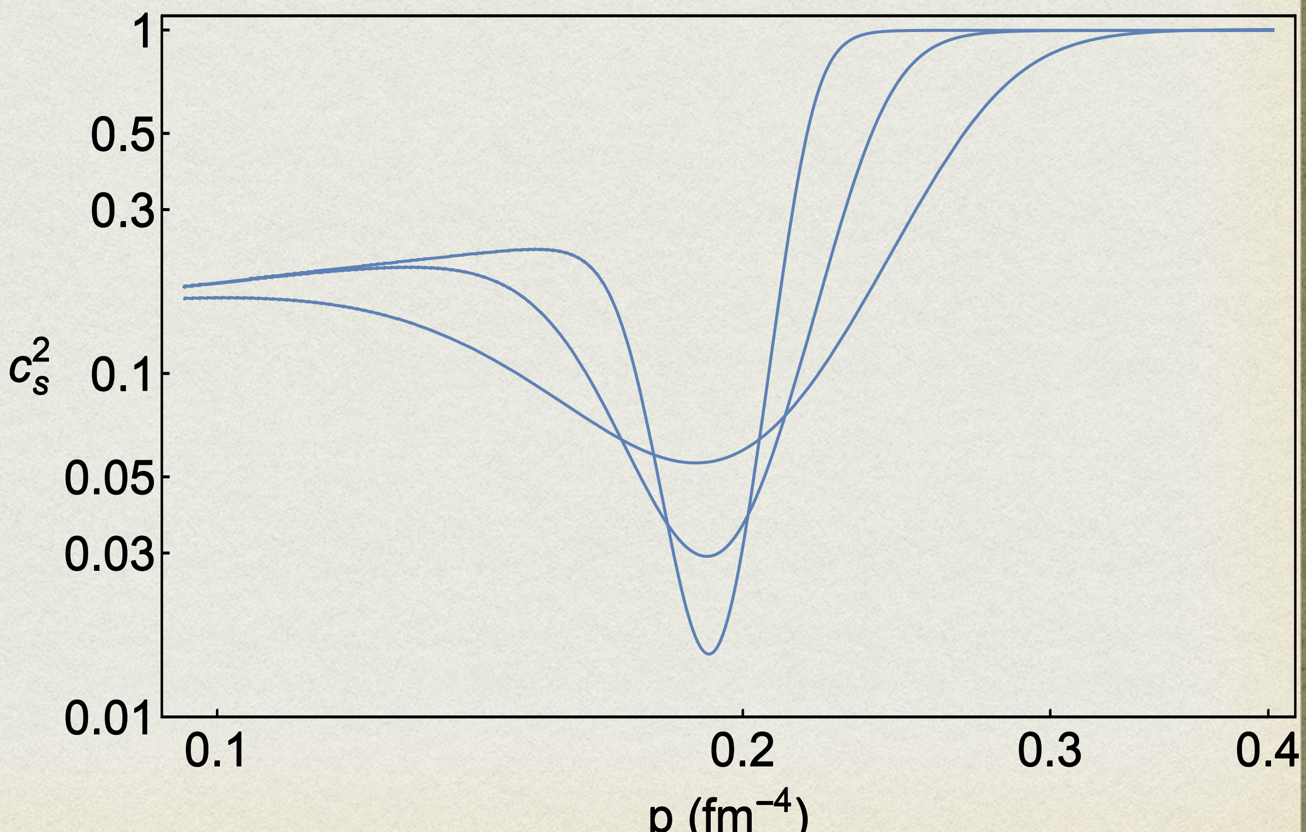
Smoothing to a crossover

-No singularity (good for simulations!), but rapidly changing behavior

$$\varepsilon(p) = \frac{1}{2}\left(1 - \tanh\left(\frac{p - p_{\rm trans}}{\delta p}\right)\right)\varepsilon_{\rm NM}(p) + \frac{1}{2}\left(1 + \tanh\left(\frac{p - p_{\rm trans}}{\delta p}\right)\right)\varepsilon_{\rm QM}(p)$$

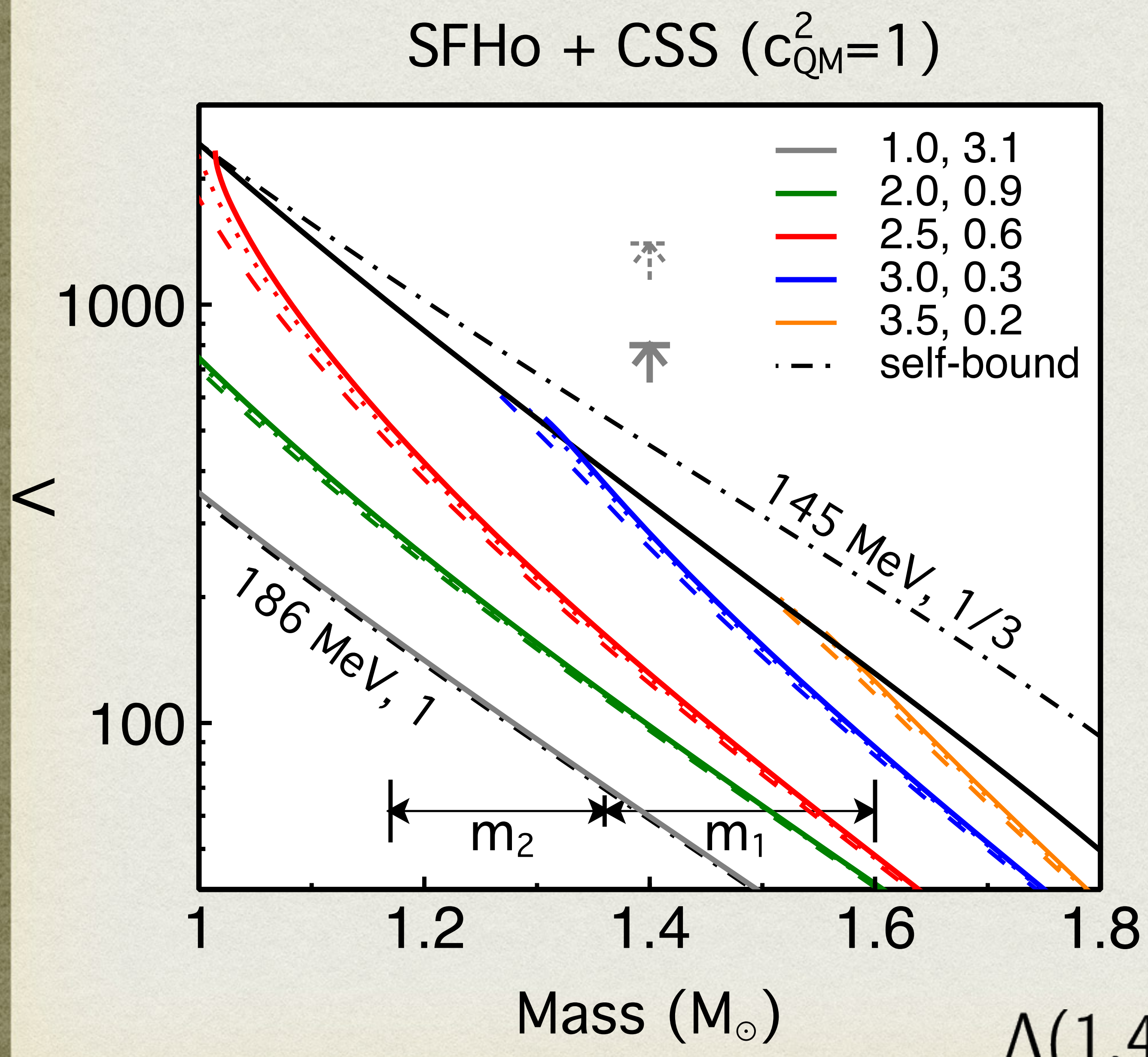
Alford, Harris & Sachdeva, arXiv:1705.09880

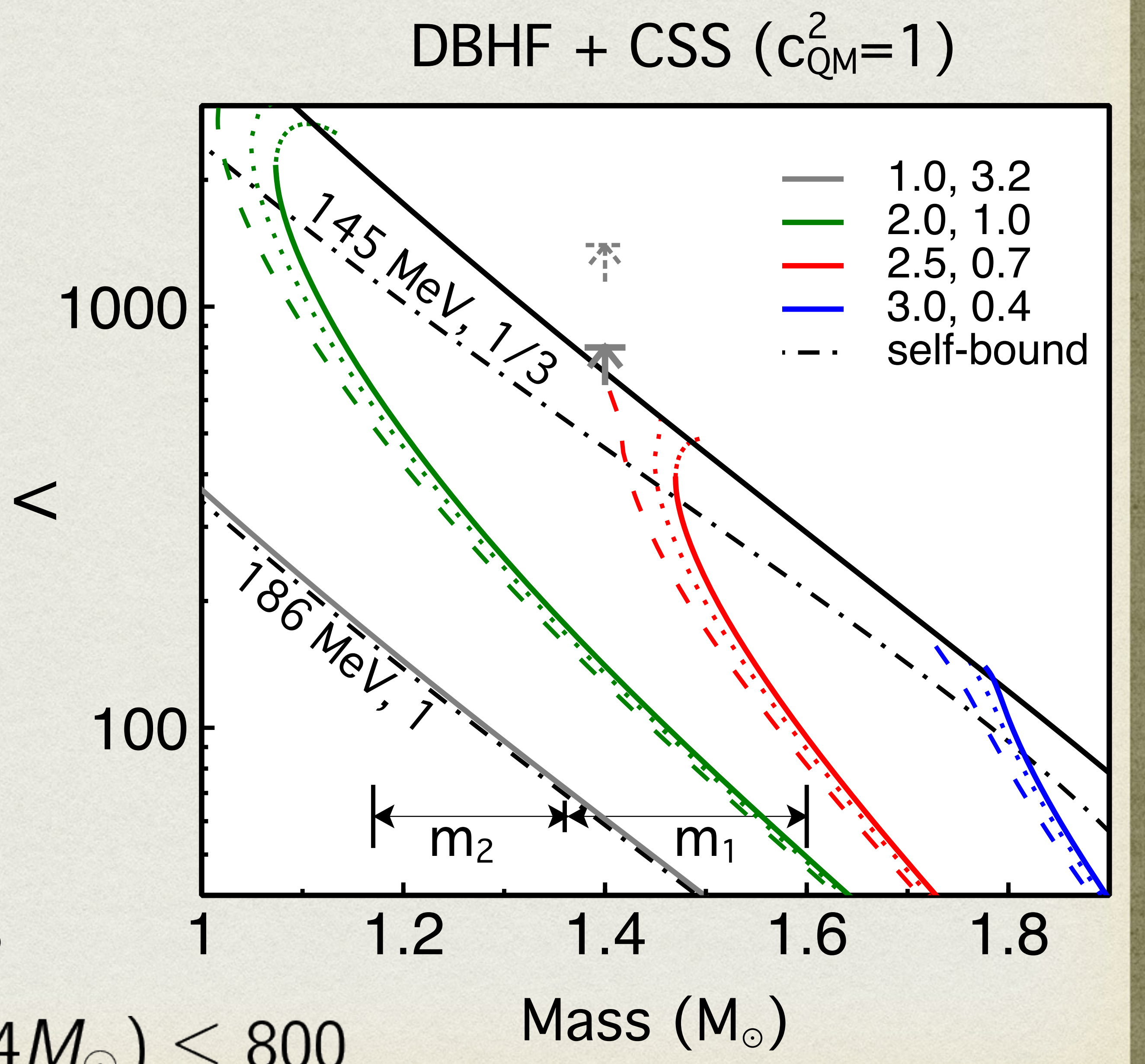




Smoothing to a crossover

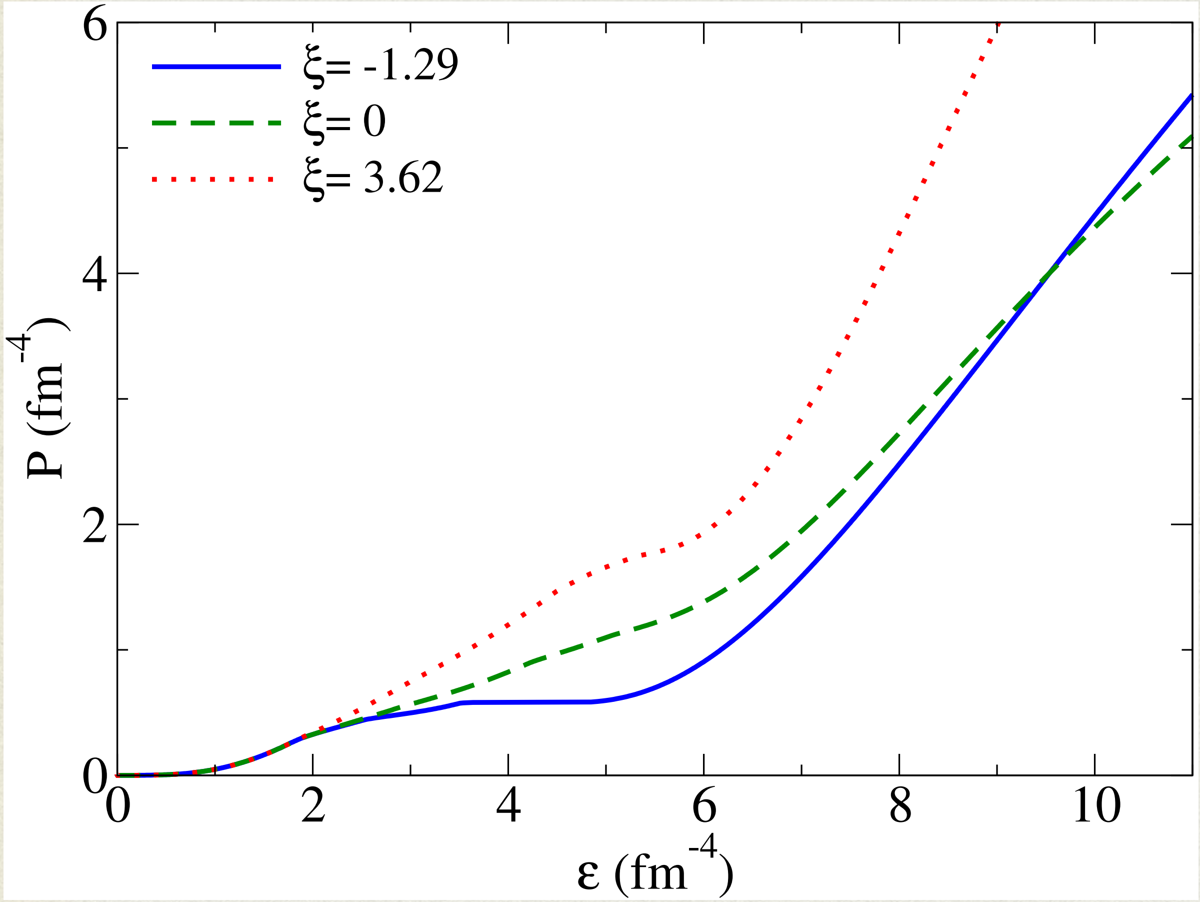
- Λ values slightly lower compared to sharp 1st-order transition
- Agrees with the discontinuous limit as $\delta p \to 0$

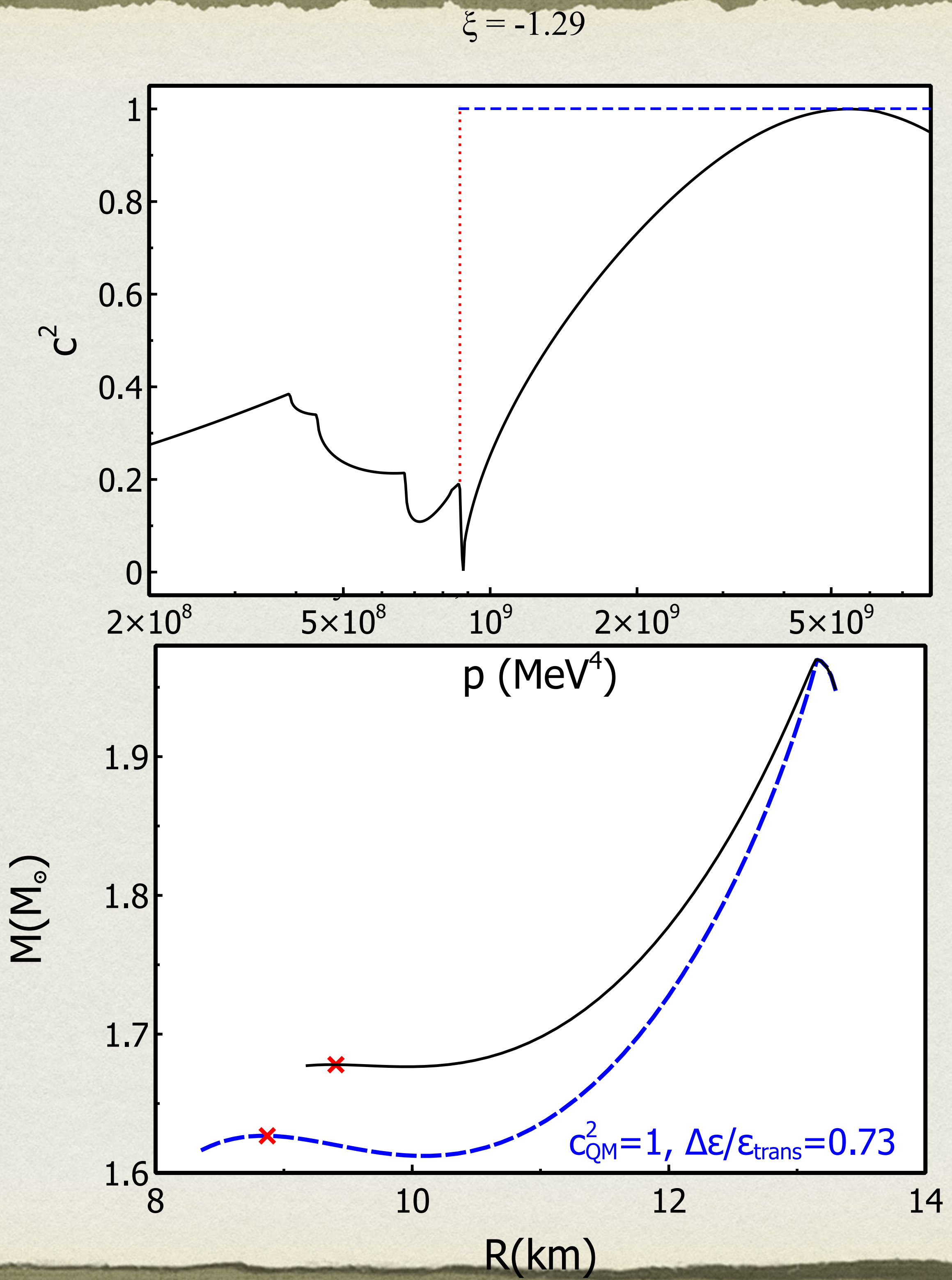




$\Lambda(1.4 M_\odot) \leq 800$

e.g Mimic quark models with PT

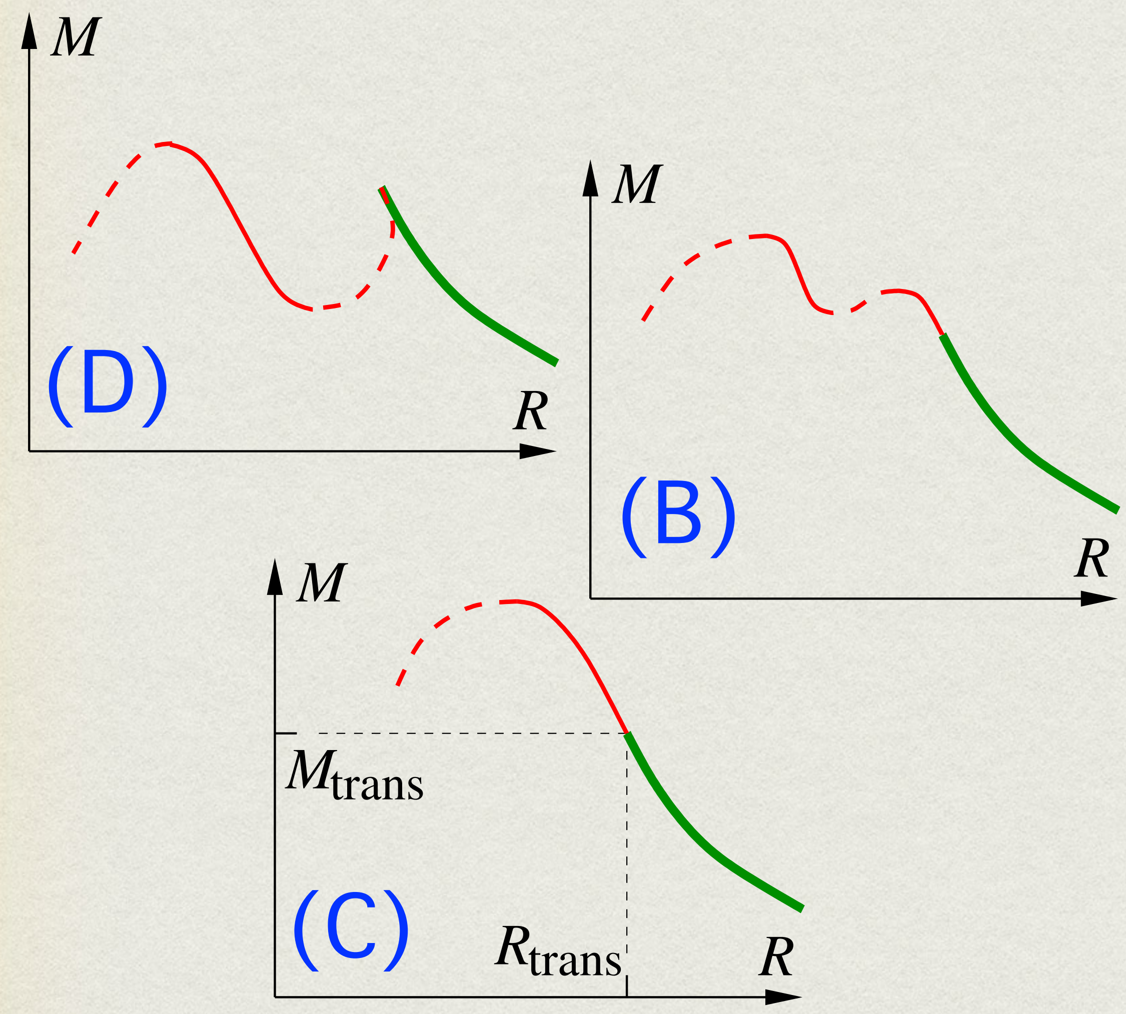


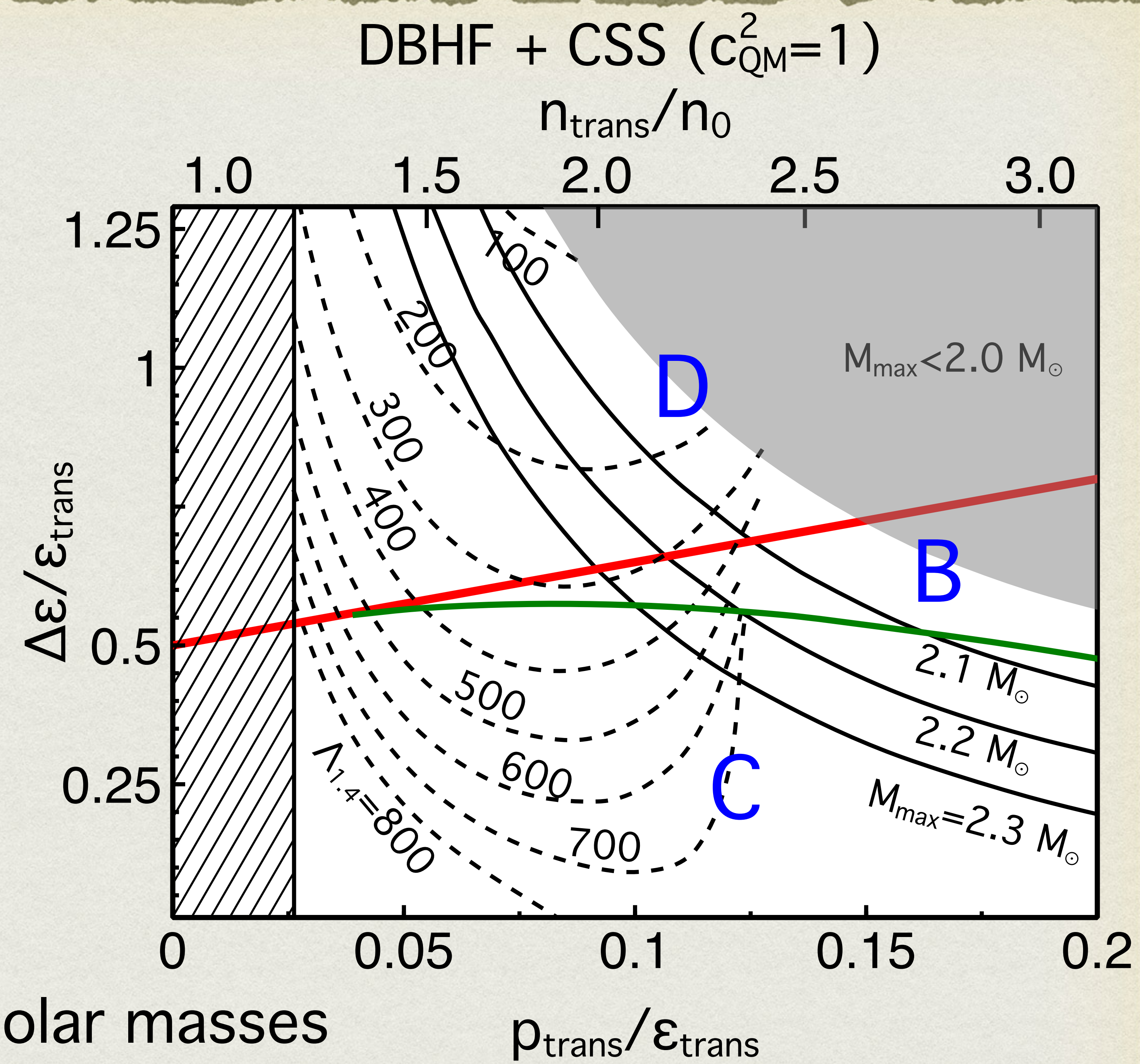


Dexheimer, Negreiros & Schramm,
arXiv:1411.4623

Constraints on PT-like EoSs

Better knowledge of nuclear matter helps



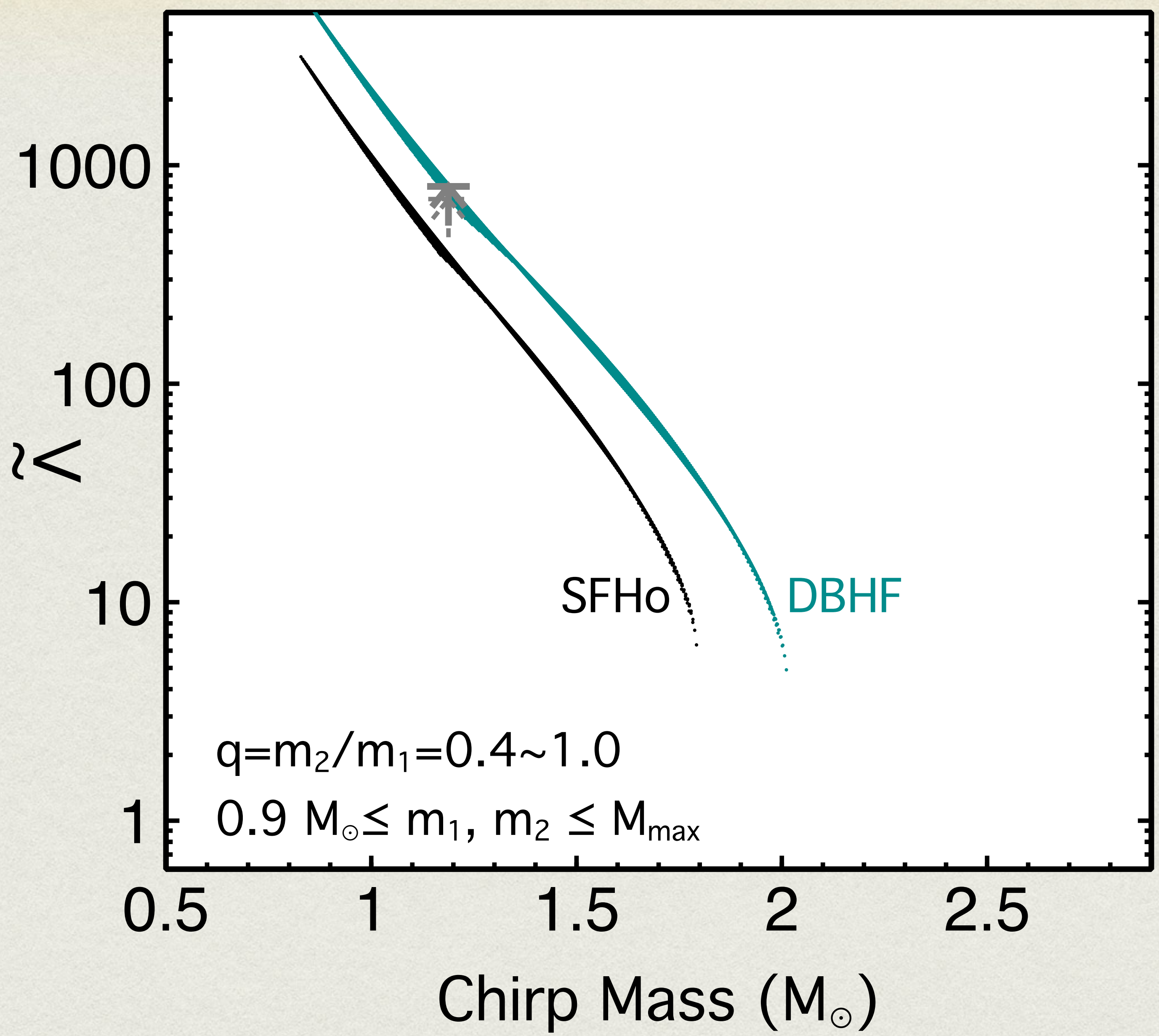


-Massive pulsars observed ~2 solar masses

-Pre-merger GW signals detected limit tidal deformability

Combined tidal deformability

Soft/Stiff Hadronic EoS

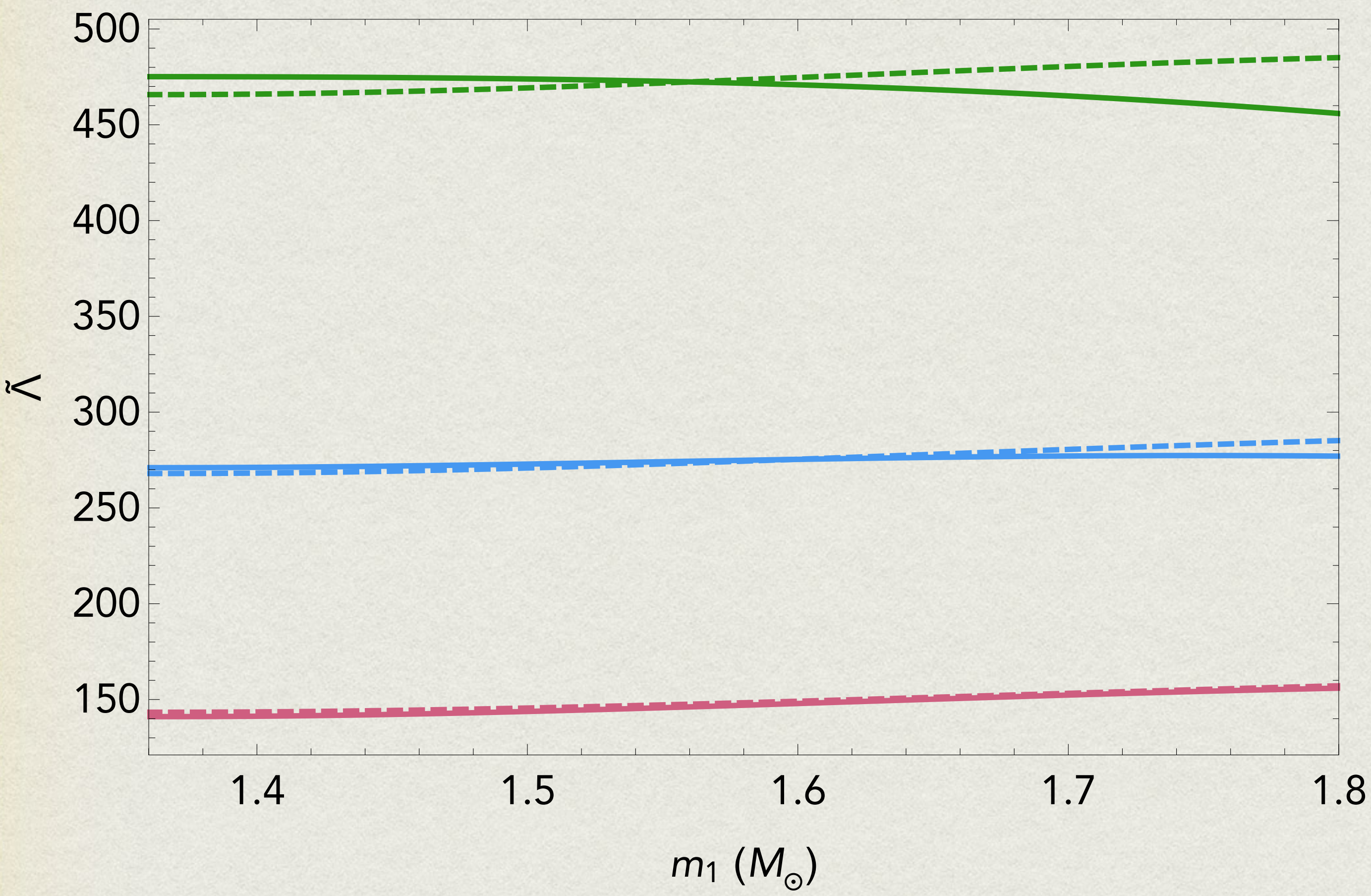


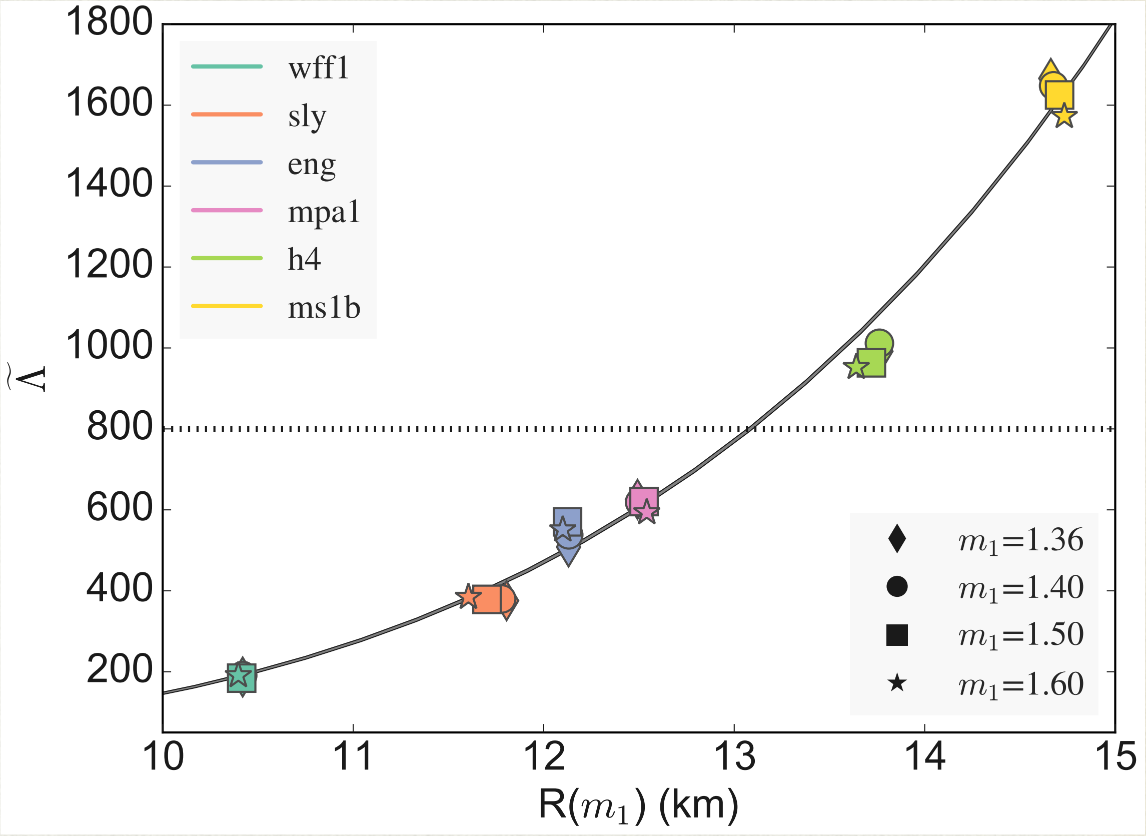
-Strikingly insensitive to the mass ratio $q = m_2 / m_1$ for nuclear matter

-Chirp mass measured to high accuracy -> estimate range of $\tilde{\Lambda}$

Combined tidal deformability

Raithel, Özel & Psaltis,
arXiv:1803.07687



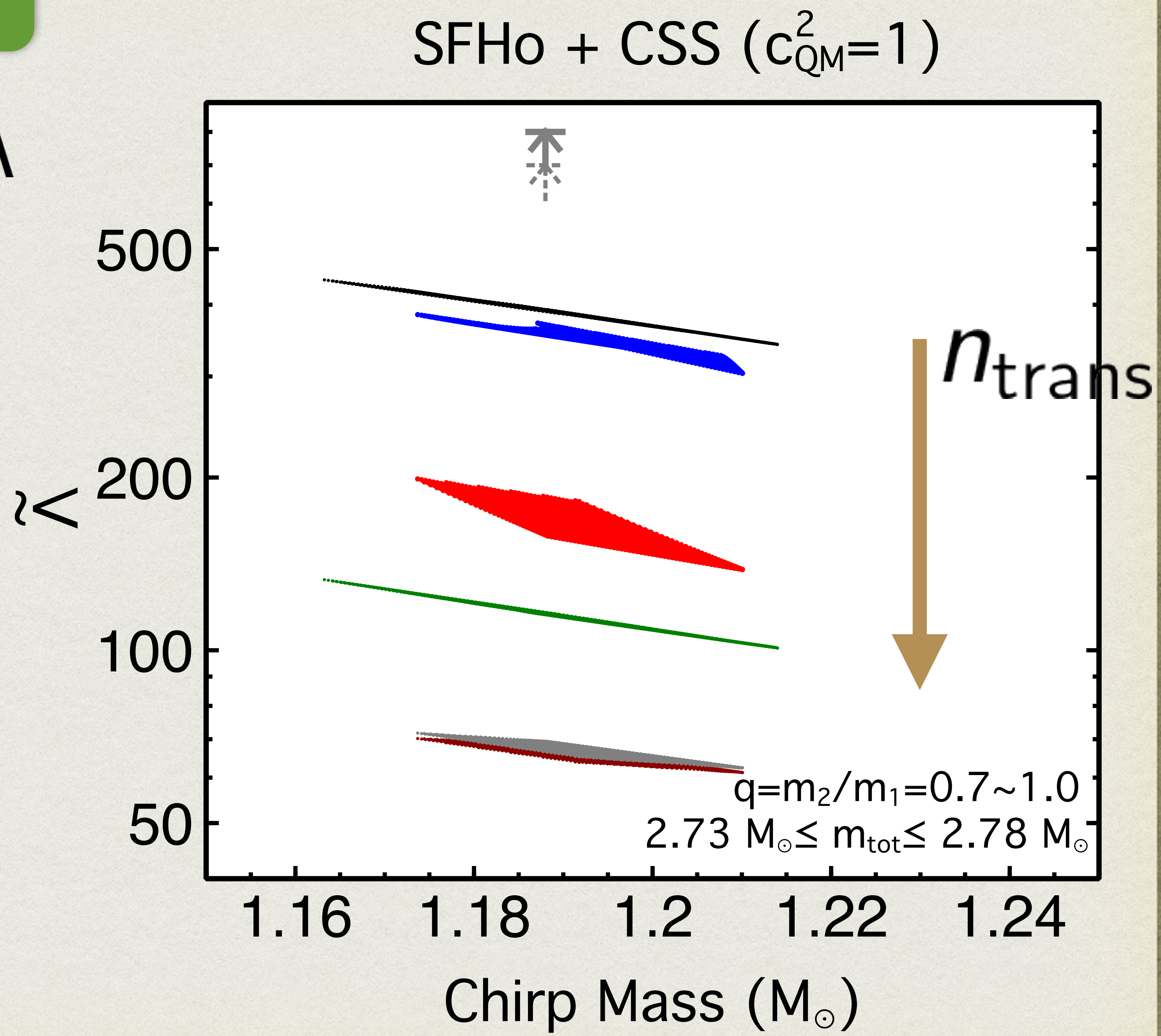


-Allows for direct probe of NS radius for purely-hadronic models

-Chirp mass measured to high accuracy -> estimate range of $\tilde{\Lambda}$

Theoretical lower bound

Soft nuclear matter + strong phase transition immediately above saturation -> lowest Λ



Theoretical lower bound

Soft nuclear matter + strong phase transition immediately above saturation

	$\left(\frac{n_{trans}}{n_0}, \frac{\Delta\varepsilon}{\varepsilon_{trans}}\right)$	M_{trans}	$R_{1.4}$/km	$\tilde{\Lambda}_{1.188}$
SFHo + CSS (c^2_{QM} = 1)	(3.0, 0.3)	1.31 $M_\odot$	11.73	[354.1, 369.7]
	(2.5, 0.6)	1.01 $M_\odot$	10.67	[158.7, 185.4]
	(2.0, 0.9)	0.68 $M_\odot$	10.09	[115.3, 116.5]
	(1.0, 3.1)	0.20 $M_\odot$	8.78	[66.51, 69.45]
	(B, c^2_{QM})		$R_{1.4}$/km	$\tilde{\Lambda}_{1.188}$
SQS	(186 MeV, 1)		8.09	[64.97, 68.08]
SFHo			11.97	[388.8, 392.2]

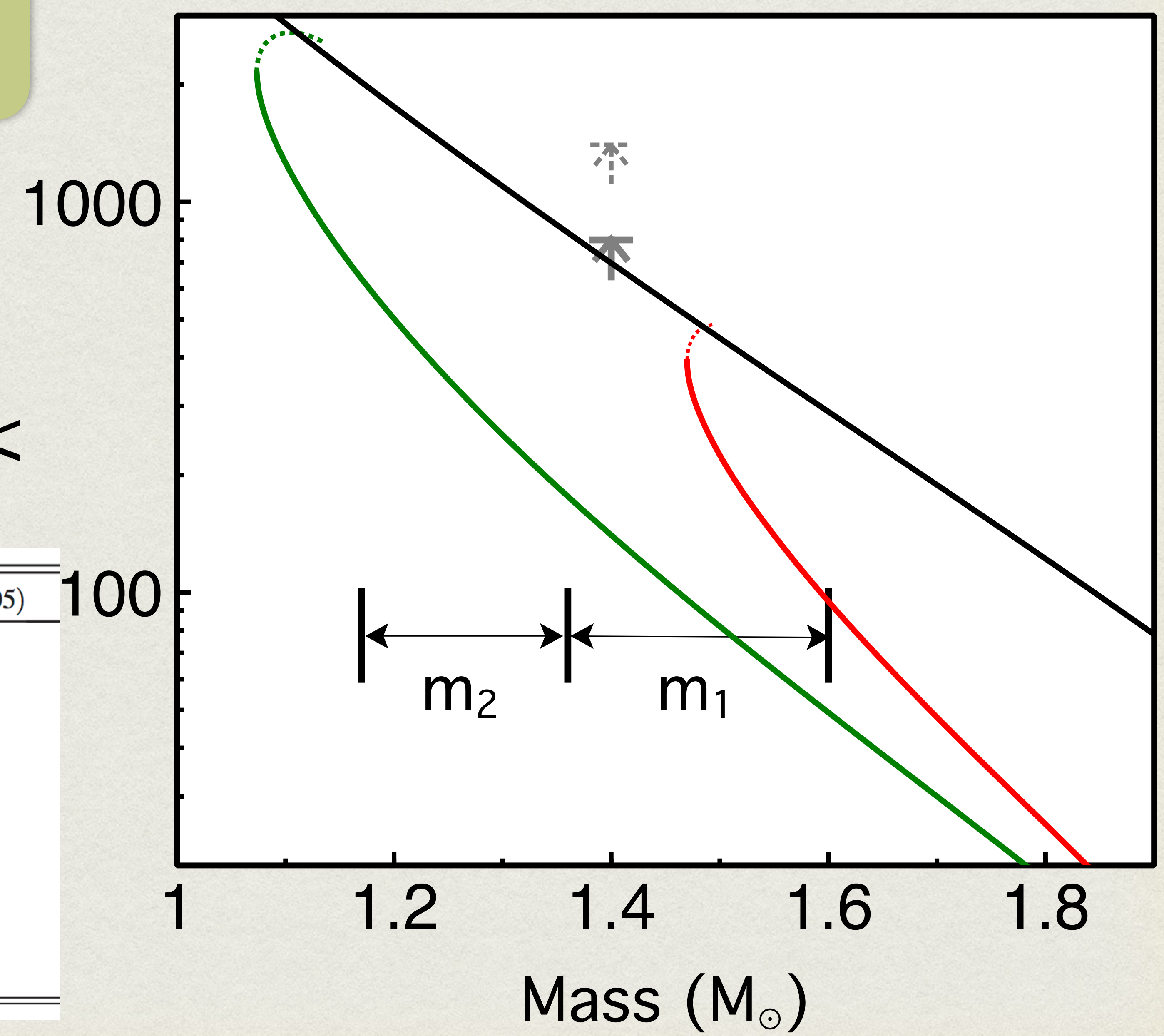
Theoretical lower bound

Soft nuclear matter + strong phase transition immediately above saturation

-NSs obey the same EoS (!)
Is stiffer EoS like DBHF completely ruled out?

<

DBHF + CSS (c^2_{QM}=1)



	Low-spin priors ($\|\chi\| \leq 0.05$)
Primary mass m_1	1.36–1.60 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$
Luminosity distance D_L	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$
Using NGC 4993 location	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800

Phys. Rev. Lett. 119, 161101

Theoretical lower bound

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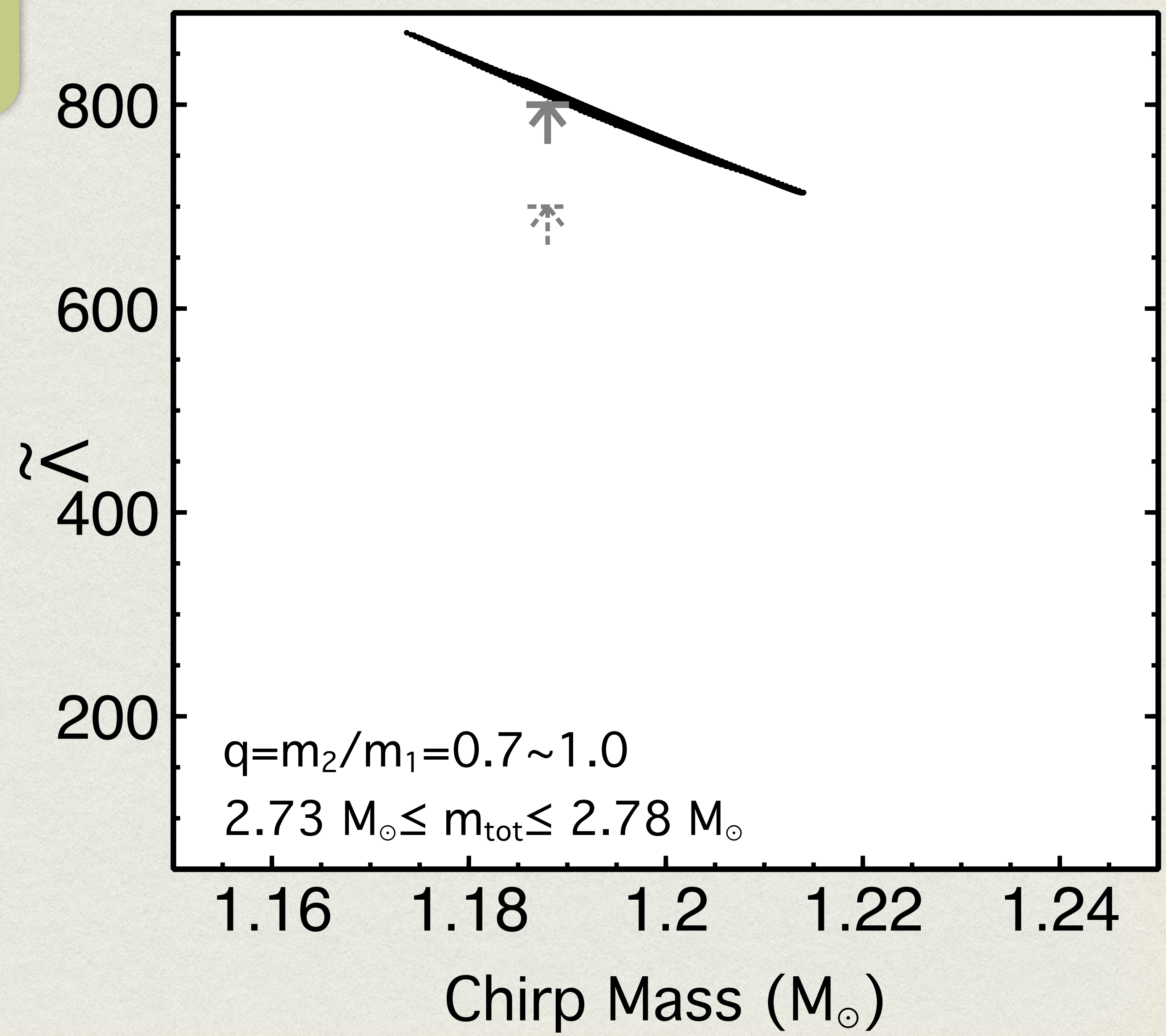

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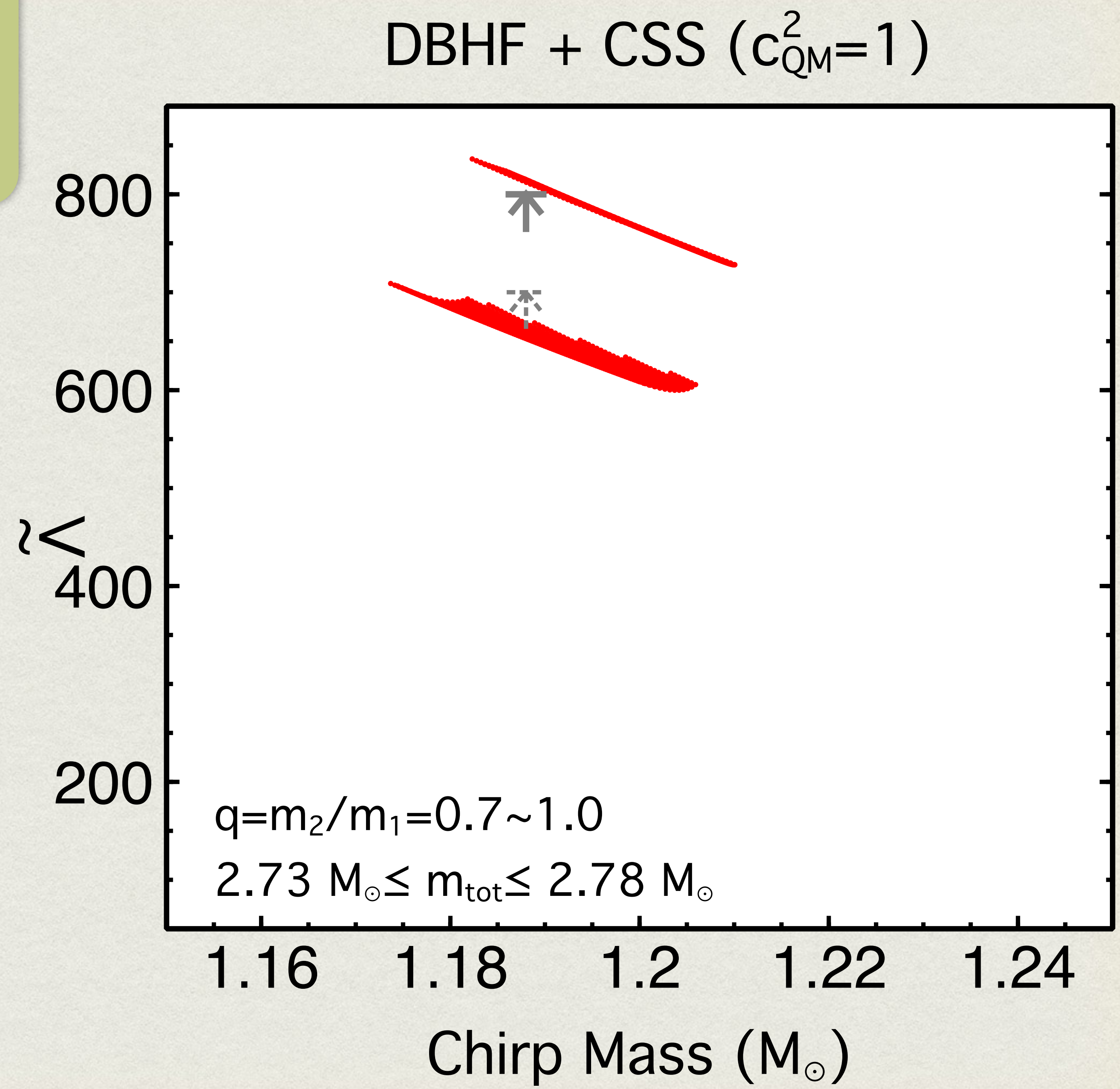
Not necessarily



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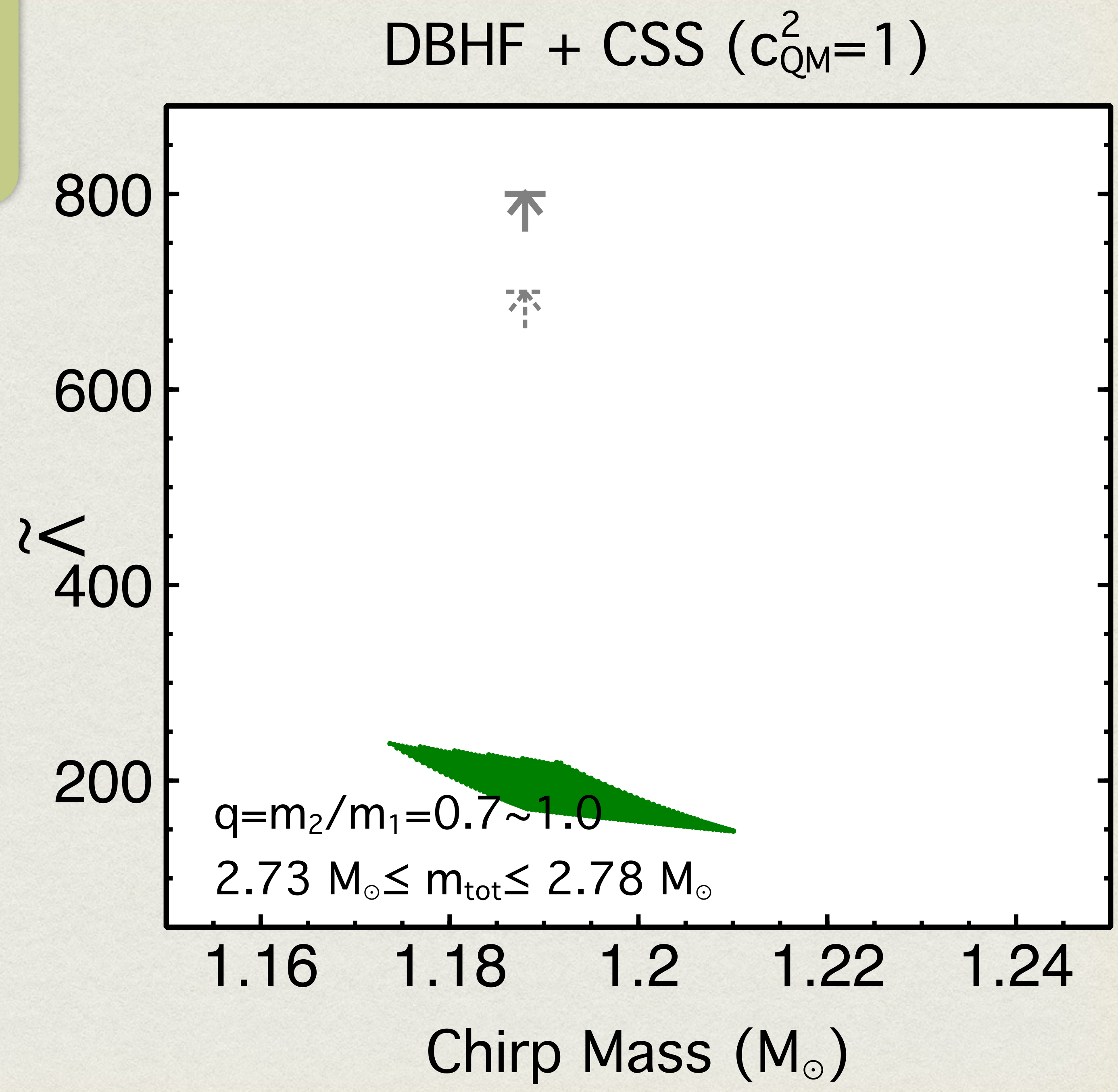
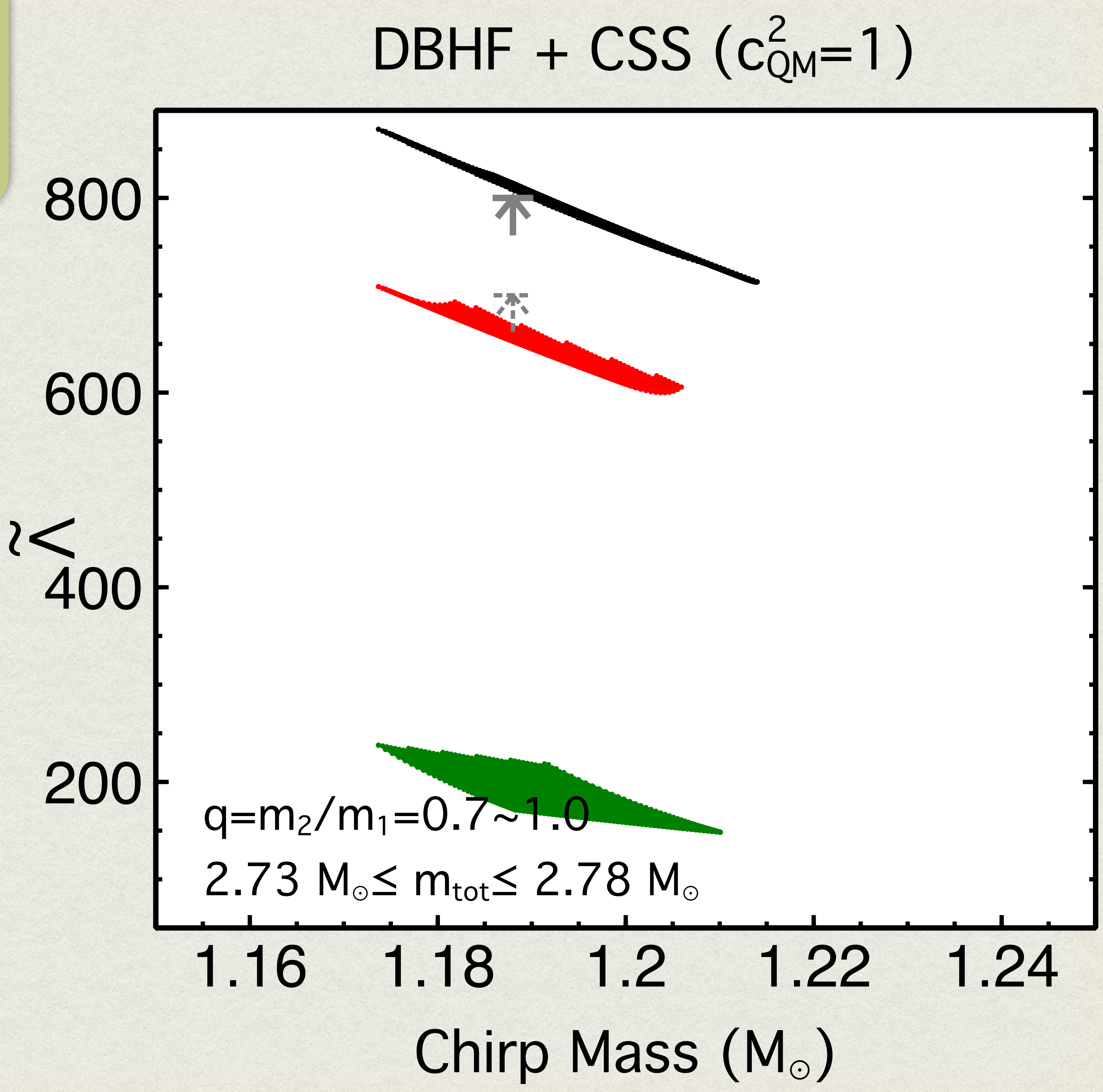


Theoretical lower bound

Soft nuclear matter + strong phase transition immediately above saturation

-NSs obey the same EoS (!)
Is stiffer EoS like DBHF ruled out?

-Could we identify phase transition through future detections?



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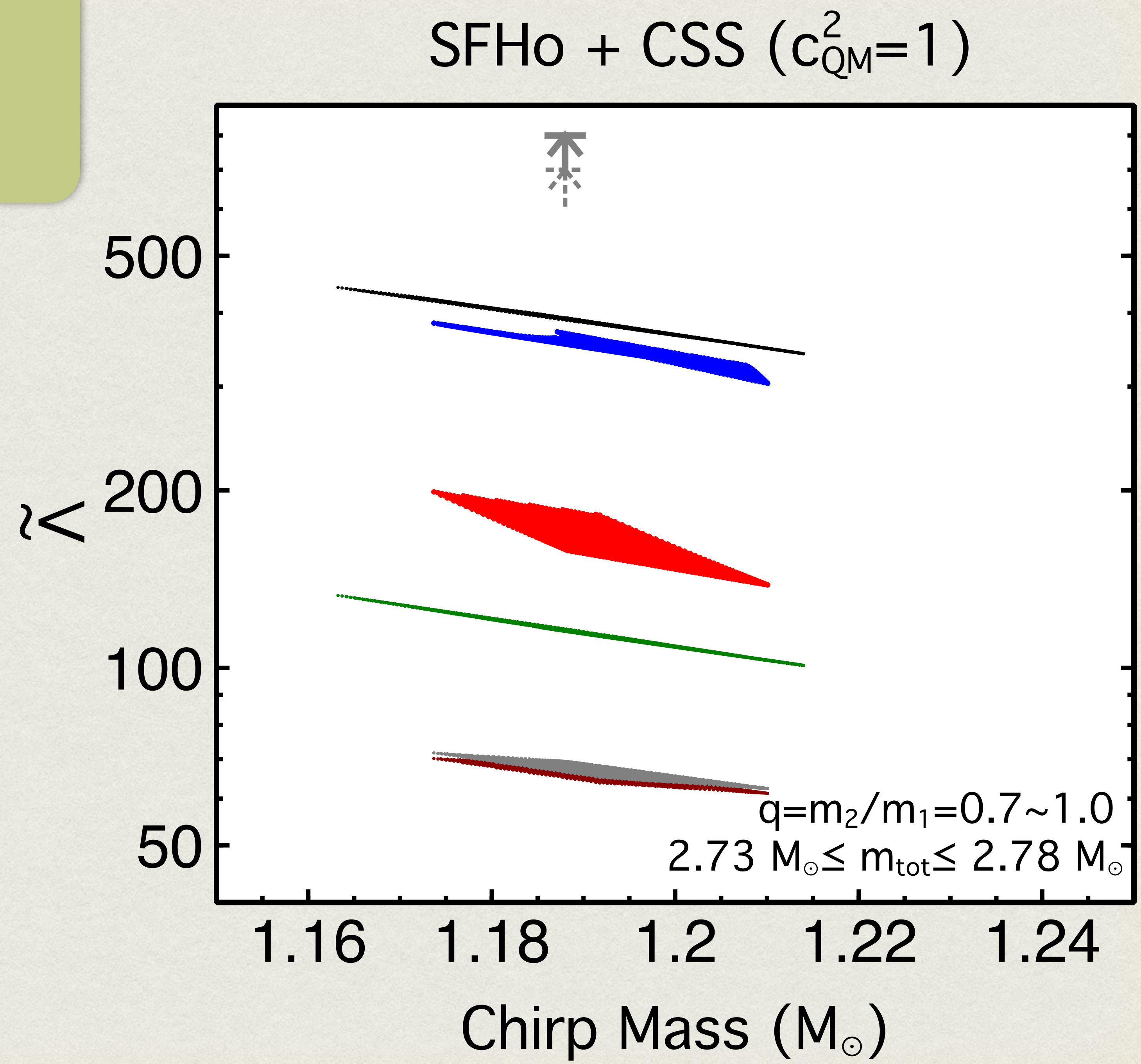


-NSs obey the same EoS (!)
Is stiffer EoS like DBHF ruled out?

-Could we identify phase transition through future detections?

-Is it possible to distinguish NS-NS, HS-HS and NS-HS mergers?

Summary

- Dense matter EoSs categorized in terms of $c_s^2 = \mathrm{d}p/\mathrm{d}\varepsilon$

  a) monotonically increasing and smooth

  b) abrupt discontinuity

  c) smooth but varies rapidly in short range of pressures

  (novel feature to emerge in simulations?)

- Theoretical lowest value of NS tidal deformability is determined by phase transition from soft NM to stiffest QM

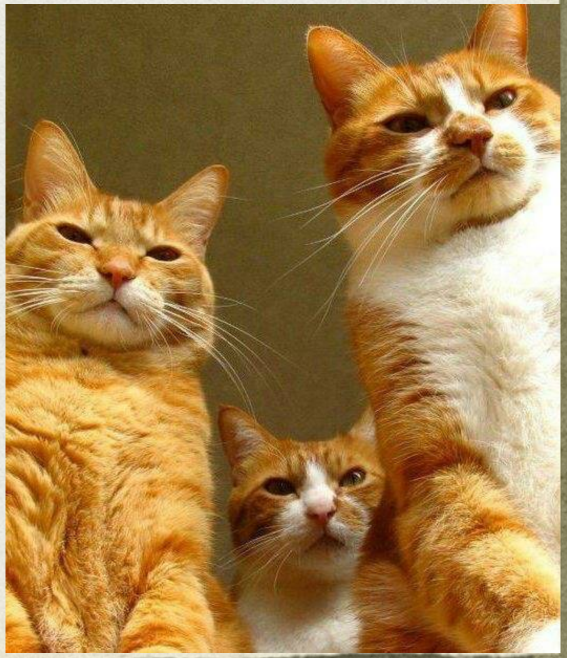
- Better constraints to expect

  a) narrow down uncertainties in NM: theory & experiment

  b) multiple detections to map $\tilde{\Lambda}(M_{\mathrm{chirp}})$

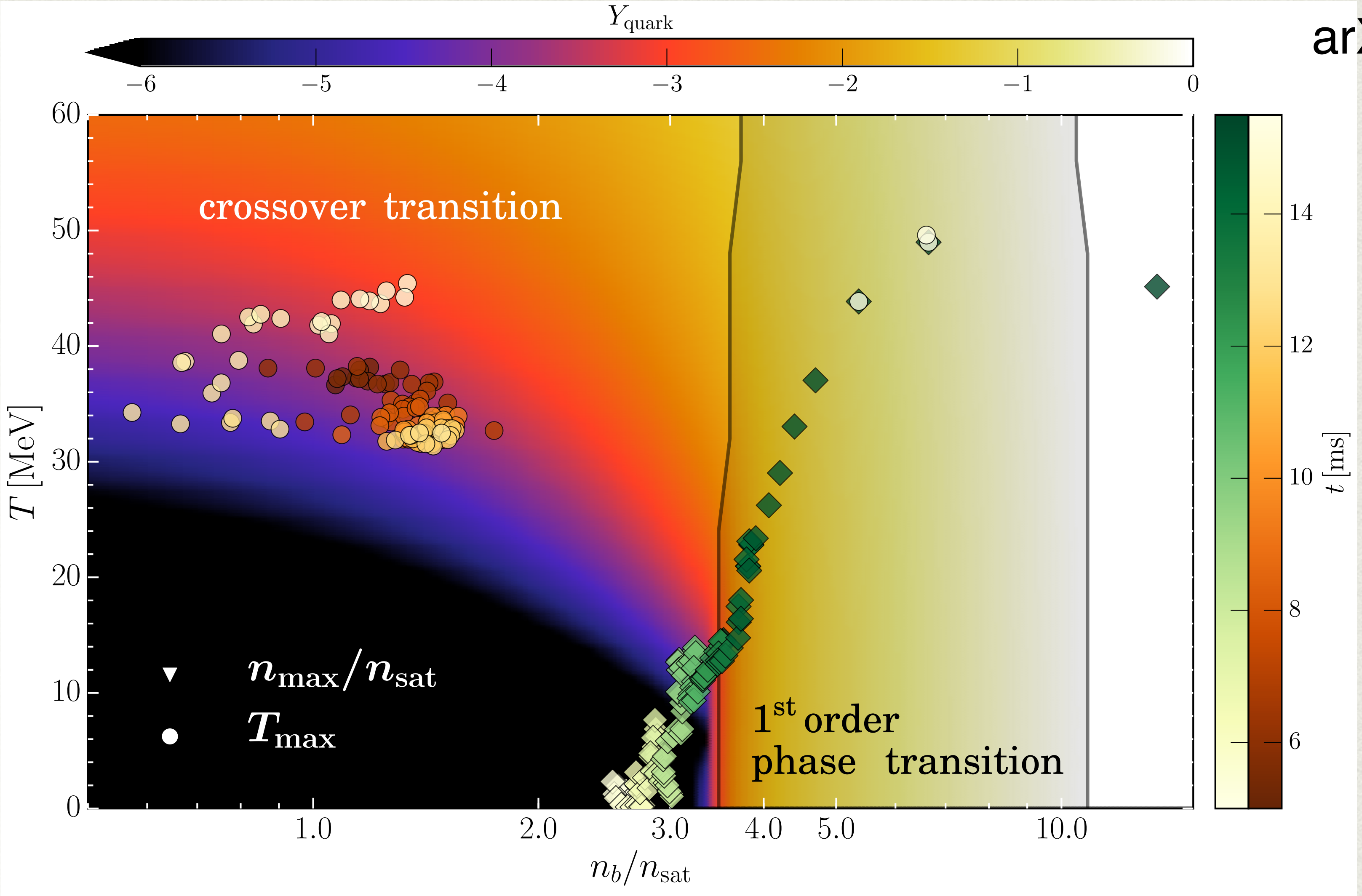
- Future work

  role of PTs in properties other than (zero-T) EoS



e.g. First simulation with quarks

Most et al.,
arXiv:1807.03684



-Evolution of temperature and density of the remnant

-Different post-merger GW signal

e.g. First simulation with quarks

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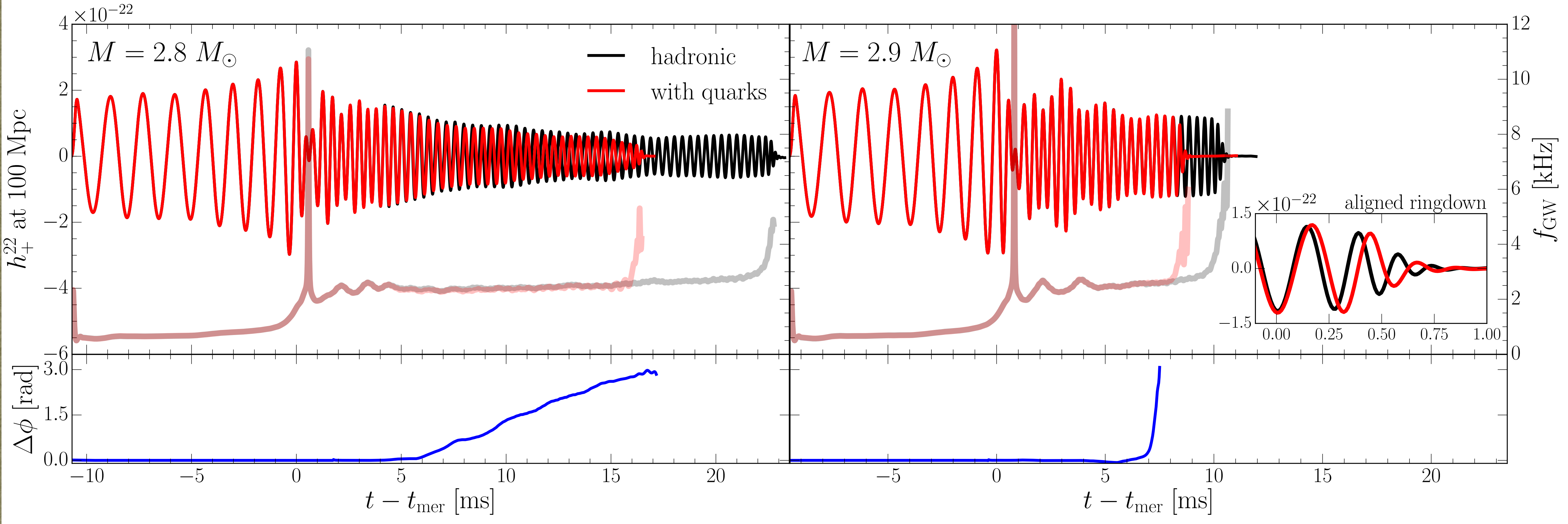


-Evolution of temperature and density of the remnant

-Different post-merger GW signal

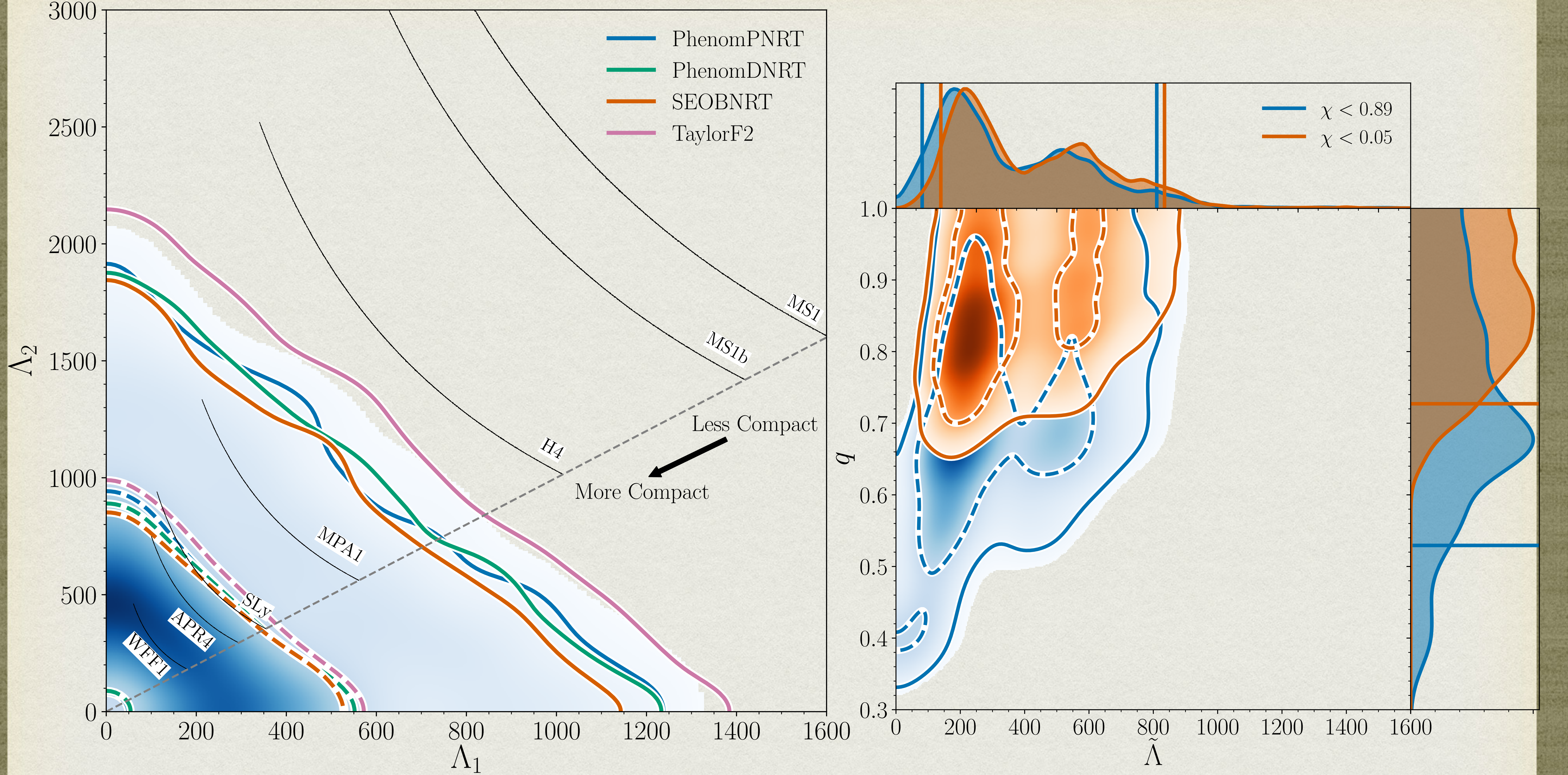
THANK YOU!

Q & A

BACKUP

SLIDES

Updated LIGO Analysis



LVC Collaboration, arXiv:1805.11579

Tolman-Oppenheimer-Volkoff Equation

For the interior of a spherical, static, relativistic star,

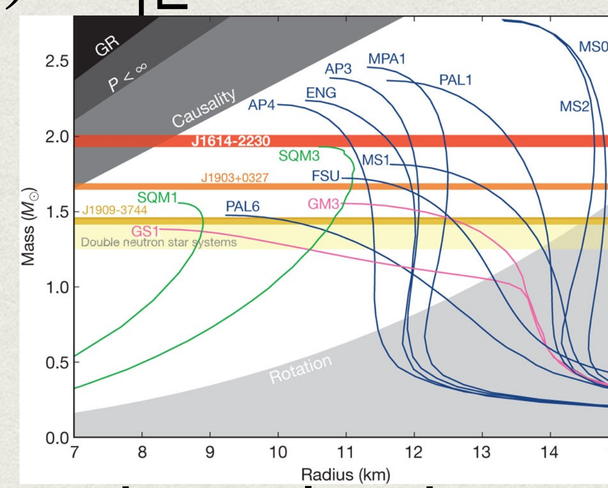
$$\frac{dp}{dr} = -\varepsilon(r)\frac{GM(r)}{r^2}\left[1+\frac{p(r)}{\varepsilon(r)}\right]\left[1+\frac{4\pi r^3 p(r)}{M(r)}\right]\left[1-\frac{2GM(r)}{r}\right]^{-1}$$

$p_{central}$

$\varepsilon(p)$

where the included mass is defined as

$$M(r) \equiv 4\pi\int_0^r \varepsilon(r) r^2 dr$$



For a given equation of state (EoS), TOV can be solved simultaneously for the radial distribution of pressure and that of energy density.

$$p(r=0) = p_{\text{central}}$$

-star surface at zero pressure $\quad p(r=R)=0$

-gravitational mass of the star $\quad M \equiv M(r=R)$

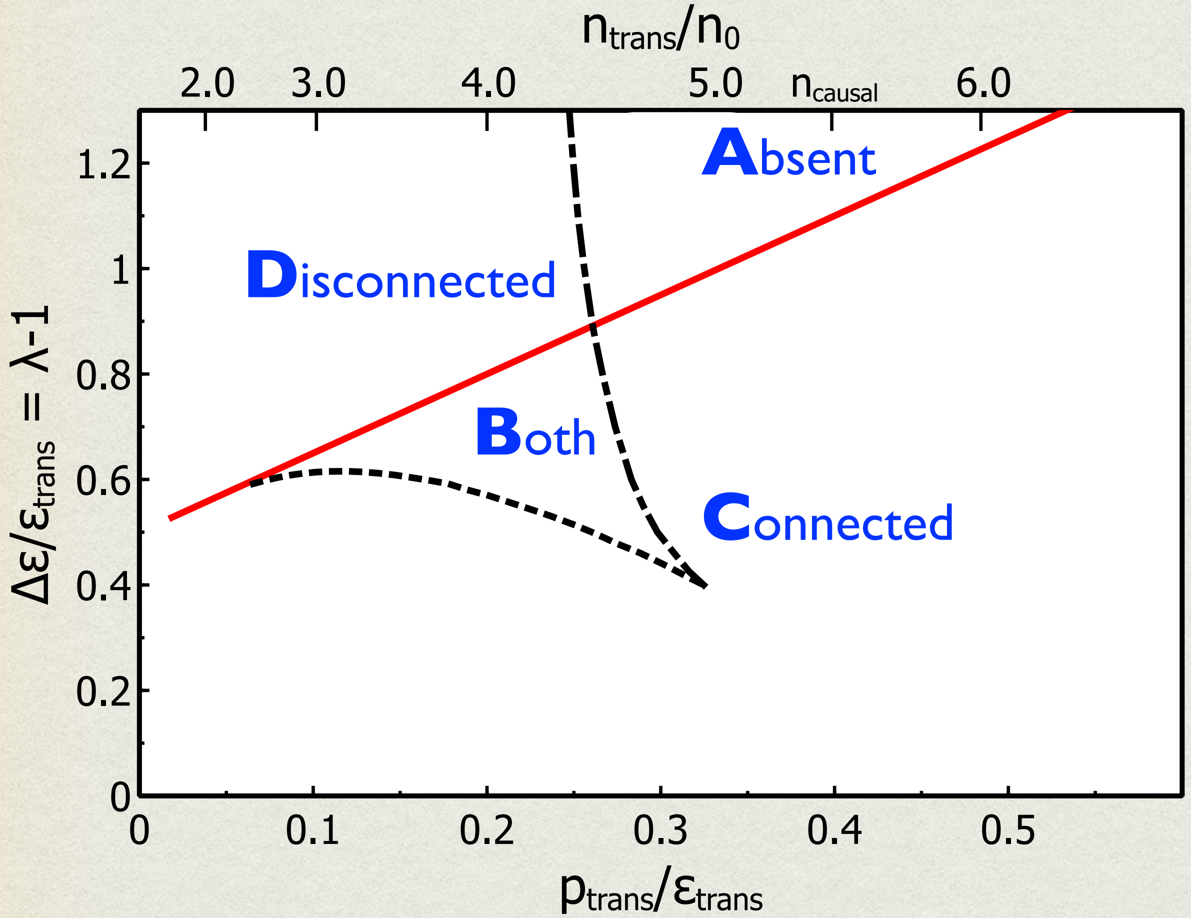
$R(p_{central})$

$M(p_{central})$

$M(R)$

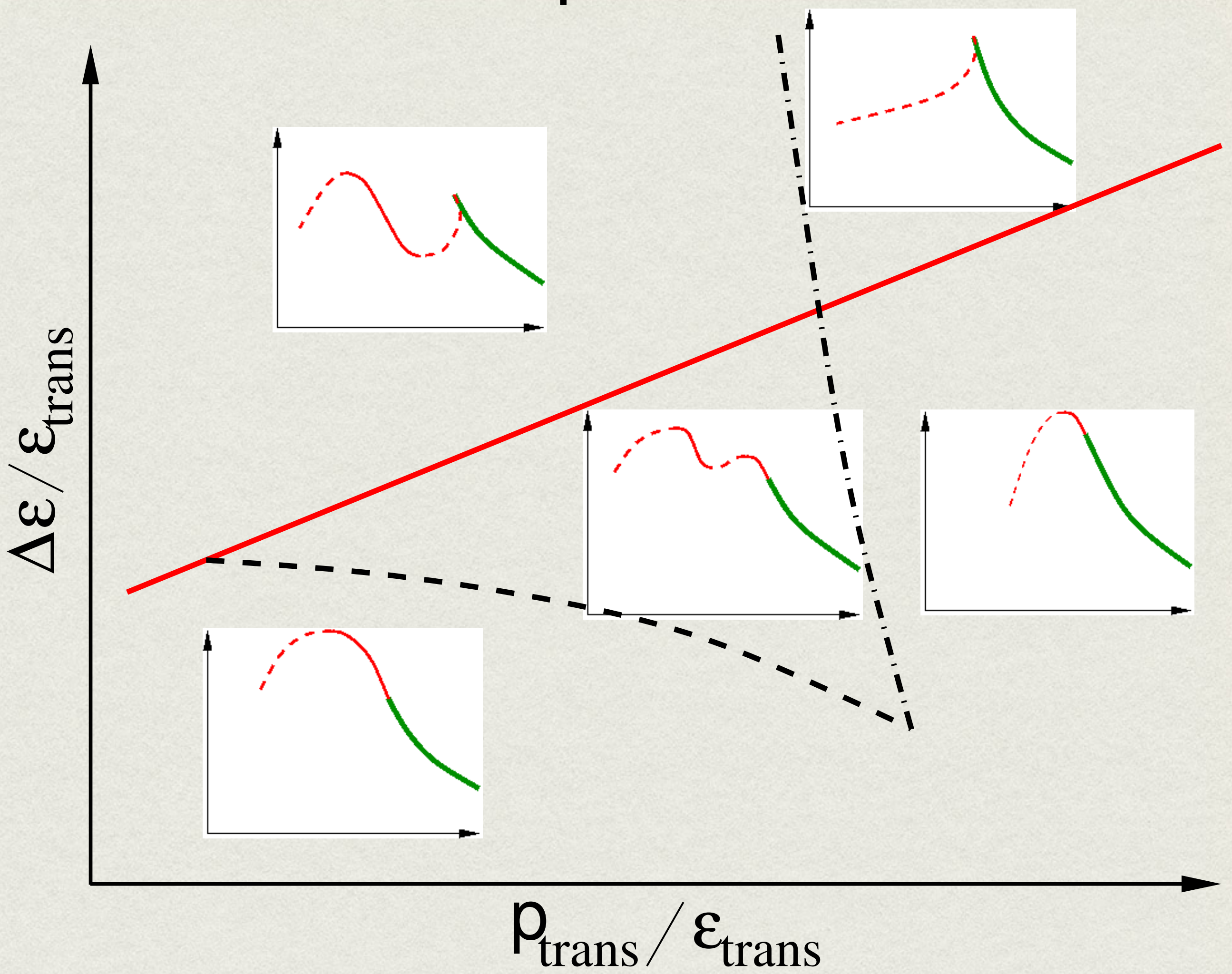
Third-family NSs

Soft NM (HLPS) + QM $c^2_{QM} = 1$



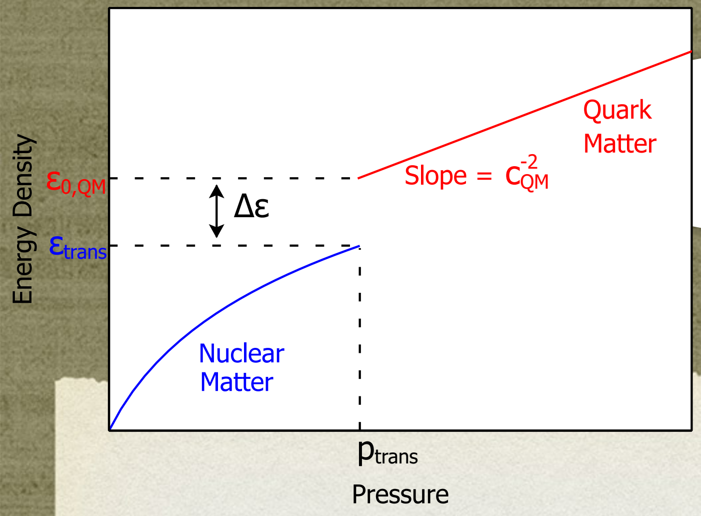
-Below the red line in regions B and C, there is a <u>connected</u> hybrid star branch

-with CSS parametrization

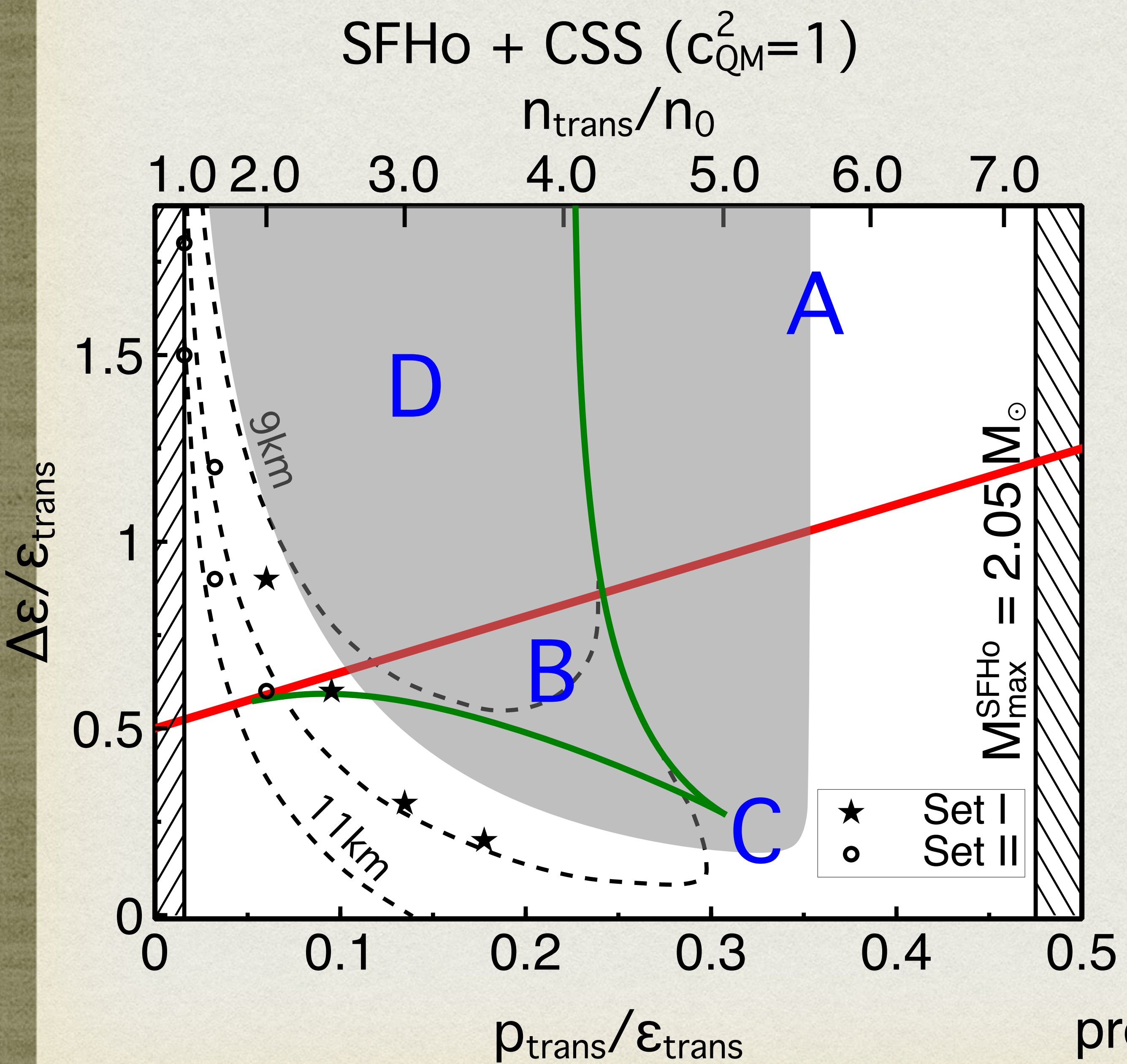


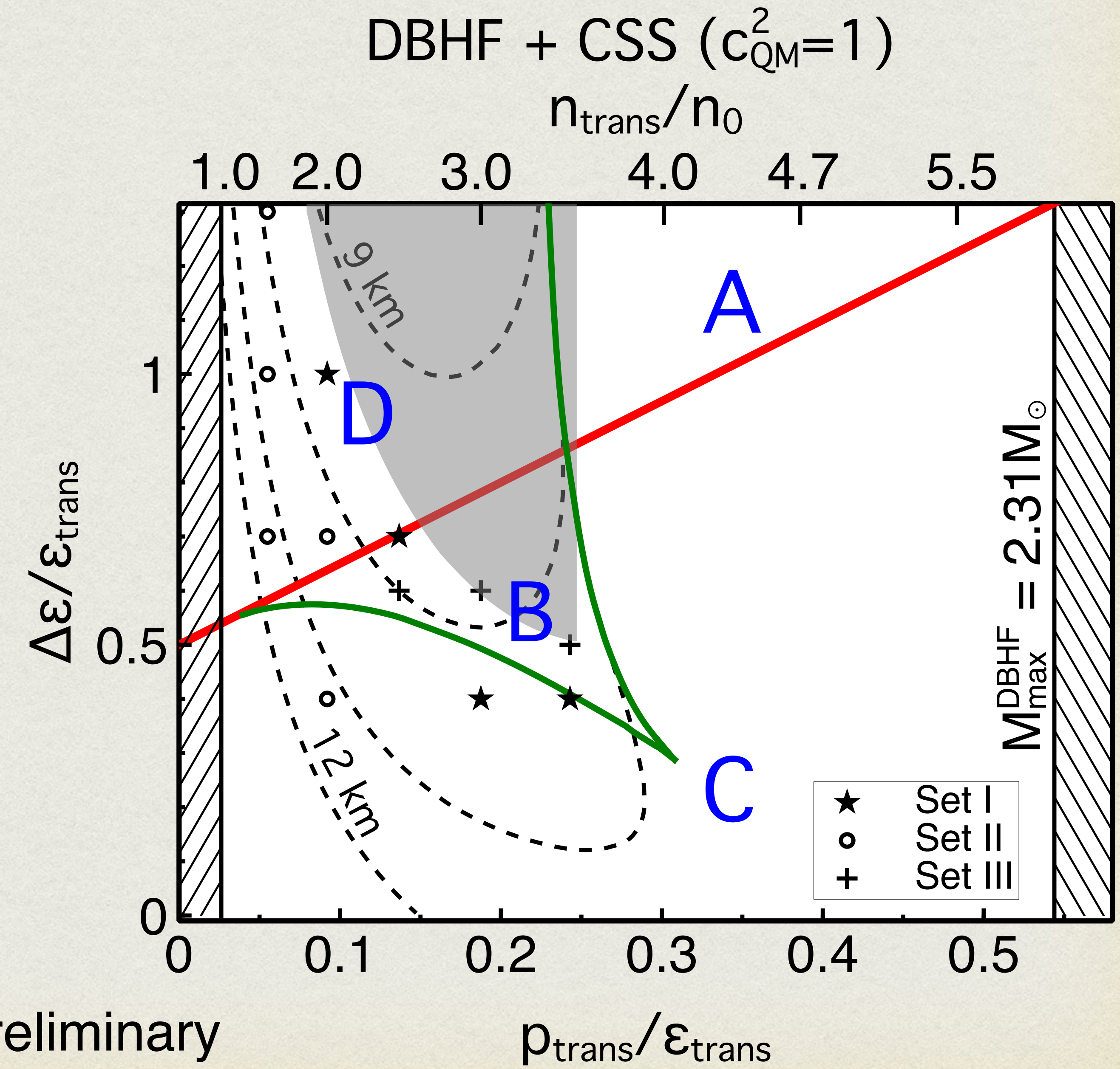
-In regions B and D, there is a <u>disconnected</u> hybrid star branch

Alford, SH & Prakash, arXiv:1302.4702



CSS Phase Diagram





preliminary