Lower Bound on the Tidal Deformability of Neutron Stars

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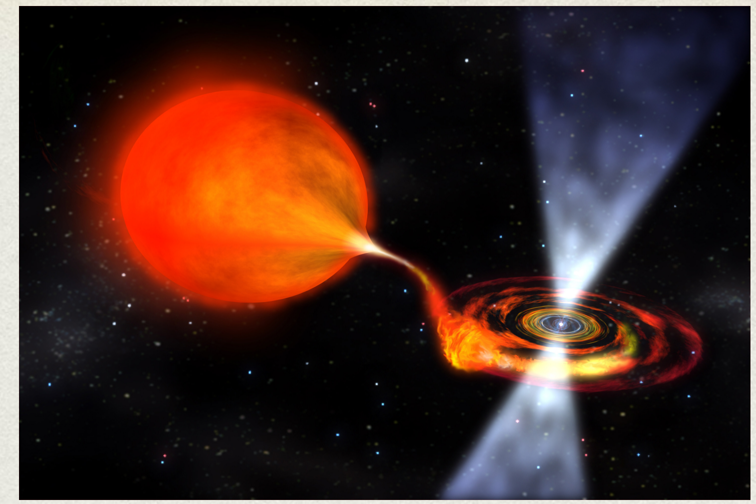
Dense matter in neutron stars

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



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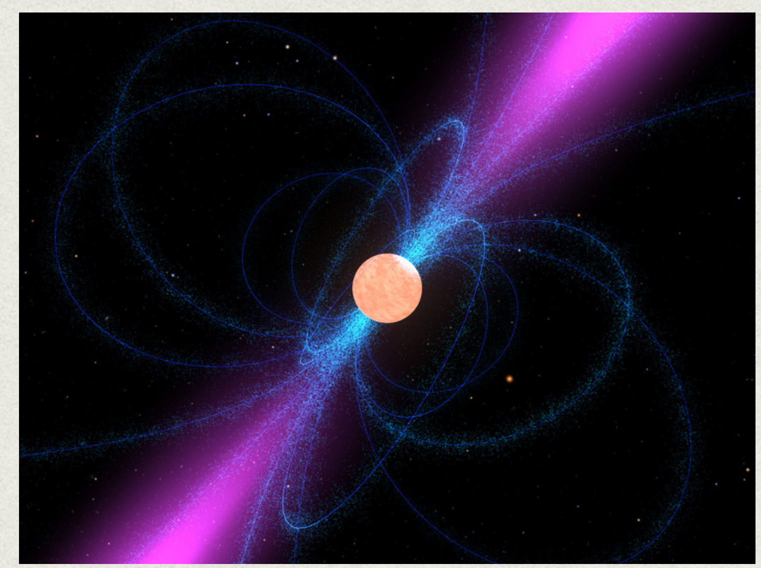


Best constraints so far

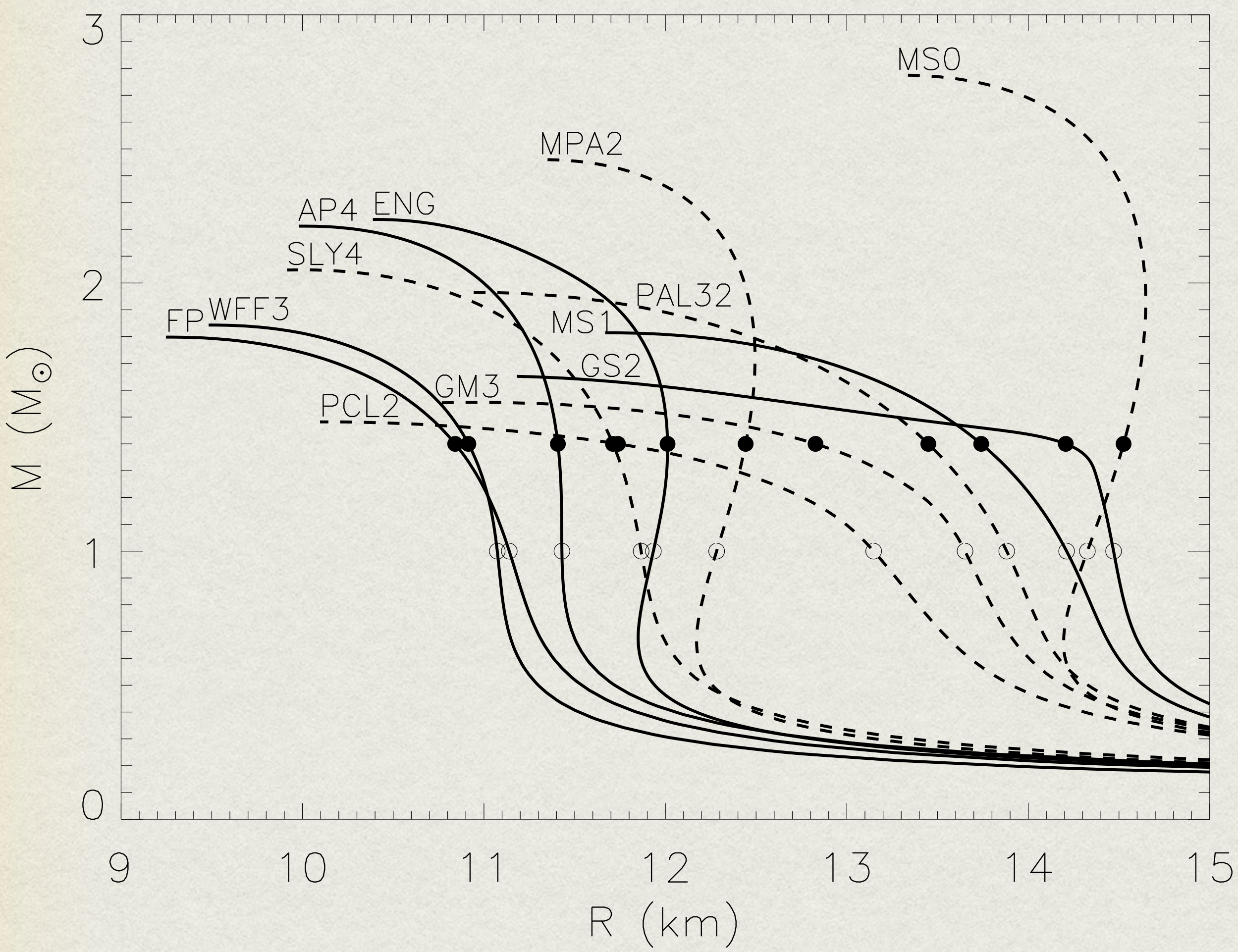
-Massive pulsars observed ~2 solar masses

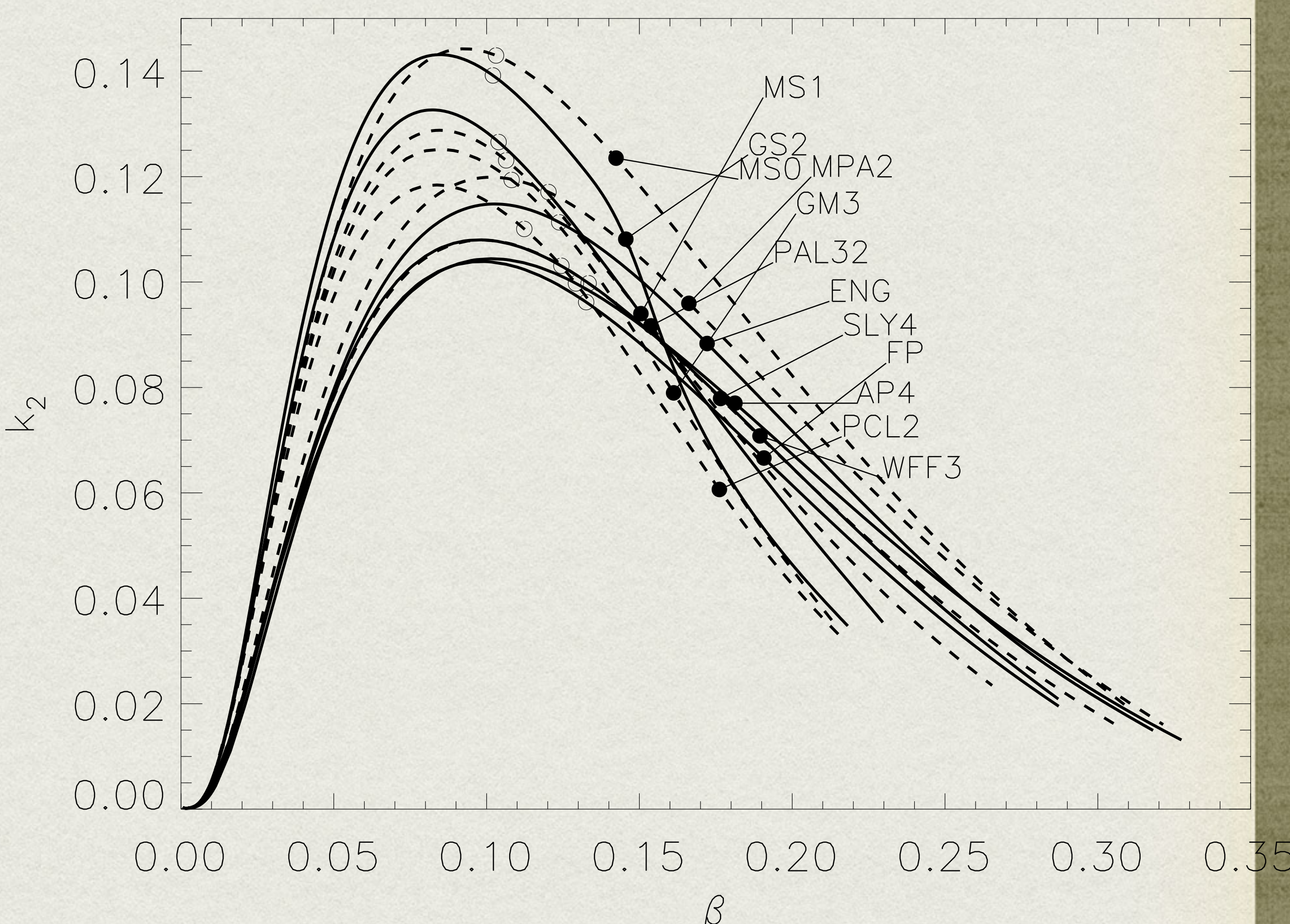
-Pre-merger GW signals detected limit tidal deformability

Normal hadronic EoSs

-Tidal Love numbers 0.05~0.15

-Speed of sound monotonically increasing with pressure from zero





Postnikov, Prakash & Lattimer,
arXiv:1004.5098

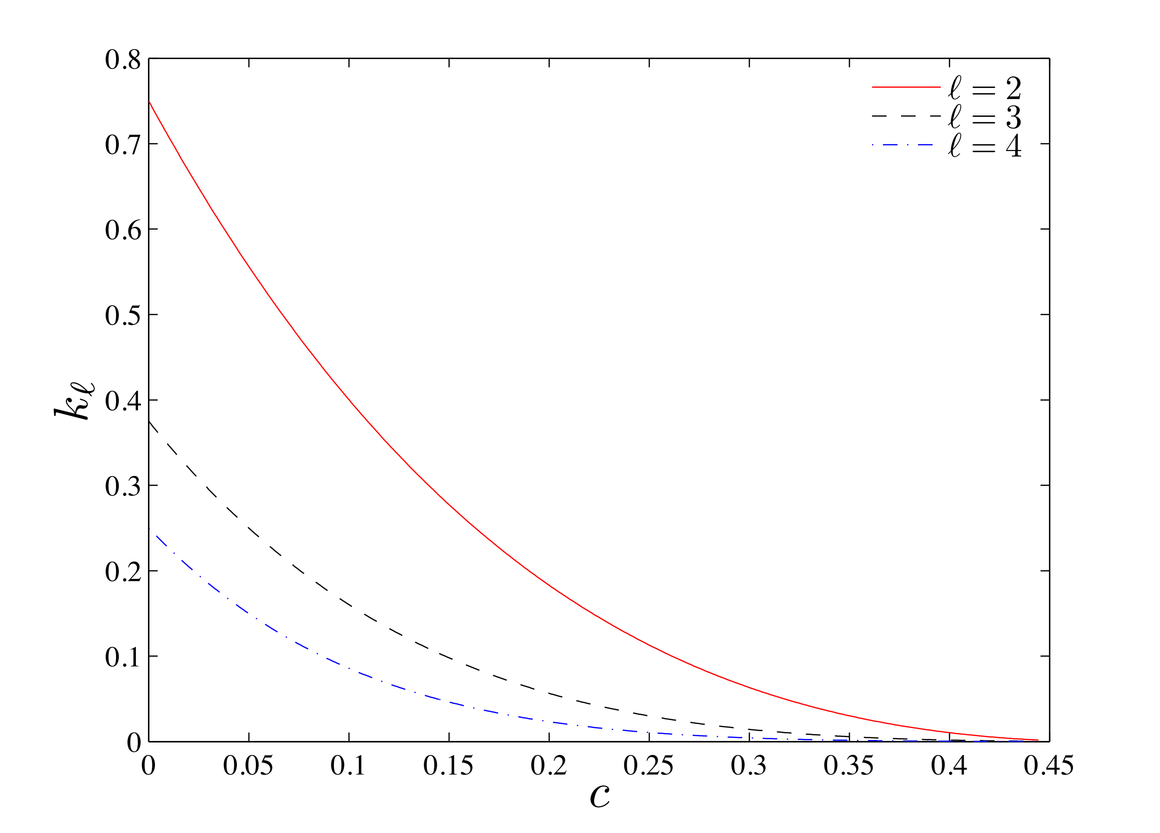
EoSs with discontinuity

-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

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

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



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delta-function singular term proportional to 3/R

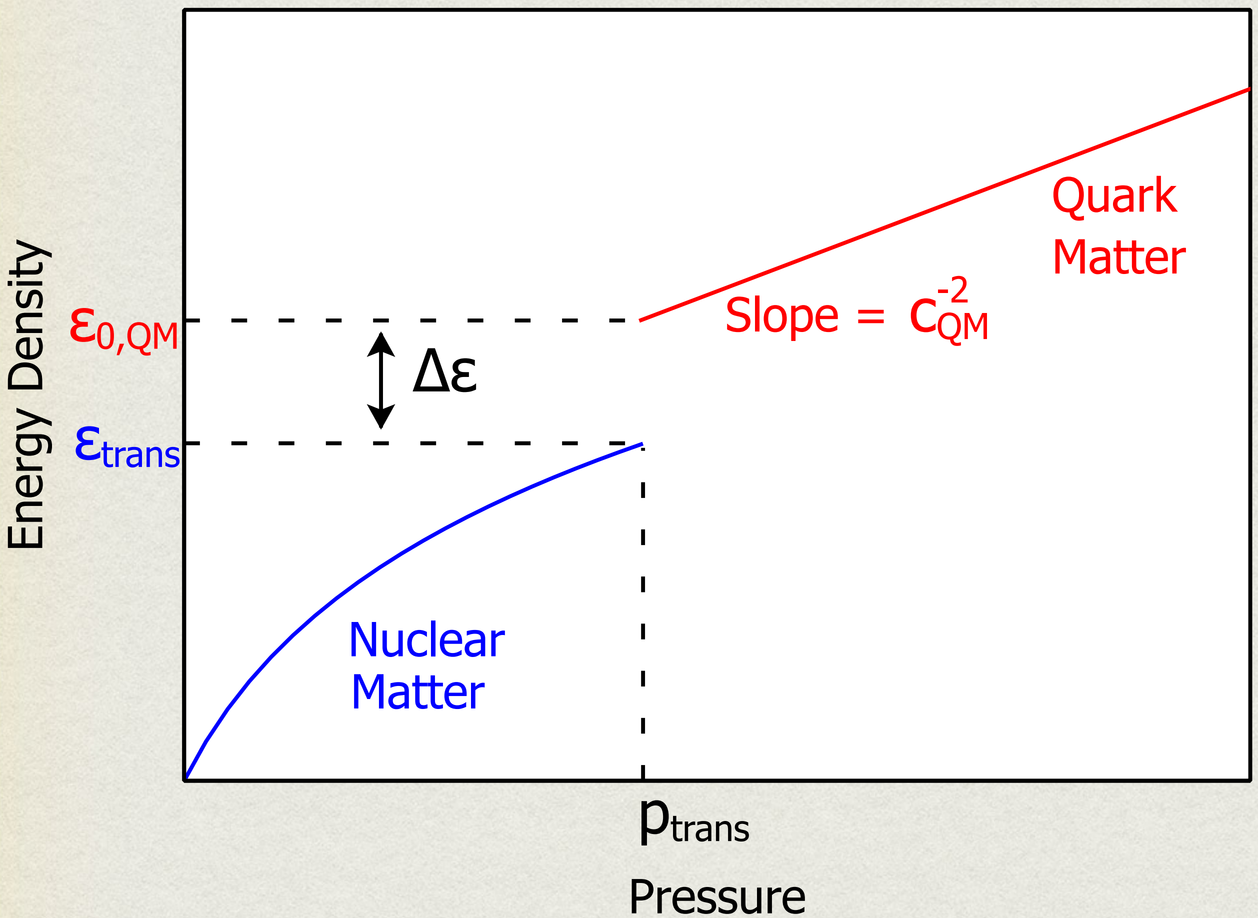
Damour & Nagar, arXiv:0906.0096

-Applicable to any sharp interface with abrupt density change

Generalize to PTs in hybrid stars

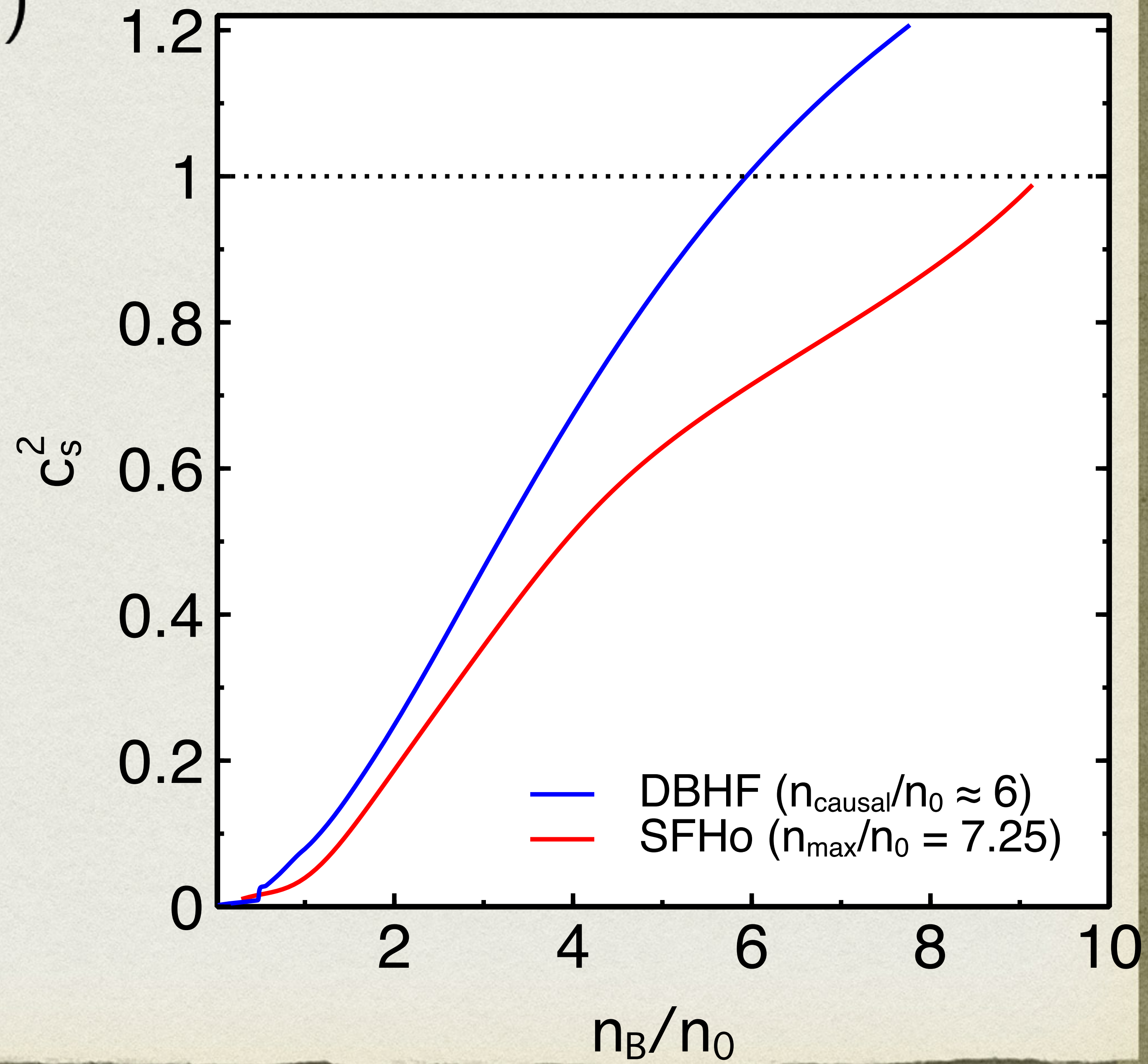
-Model-independent parametrization of high-density matter

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



Zdunik & Haensel, arXiv:1211.1231
Alford, SH & Prakash, arXiv:1302.4732

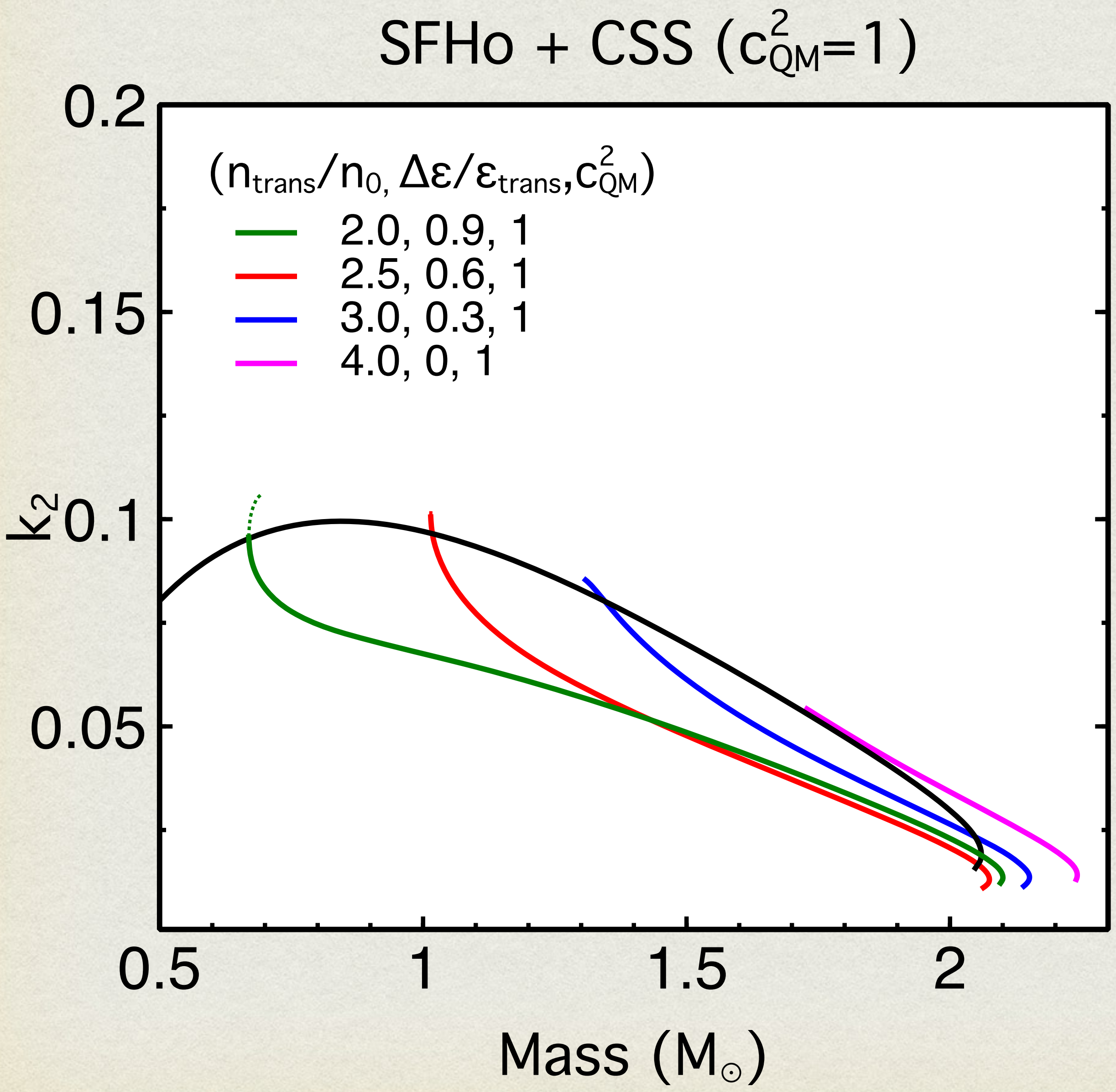
Hadronic EoSs

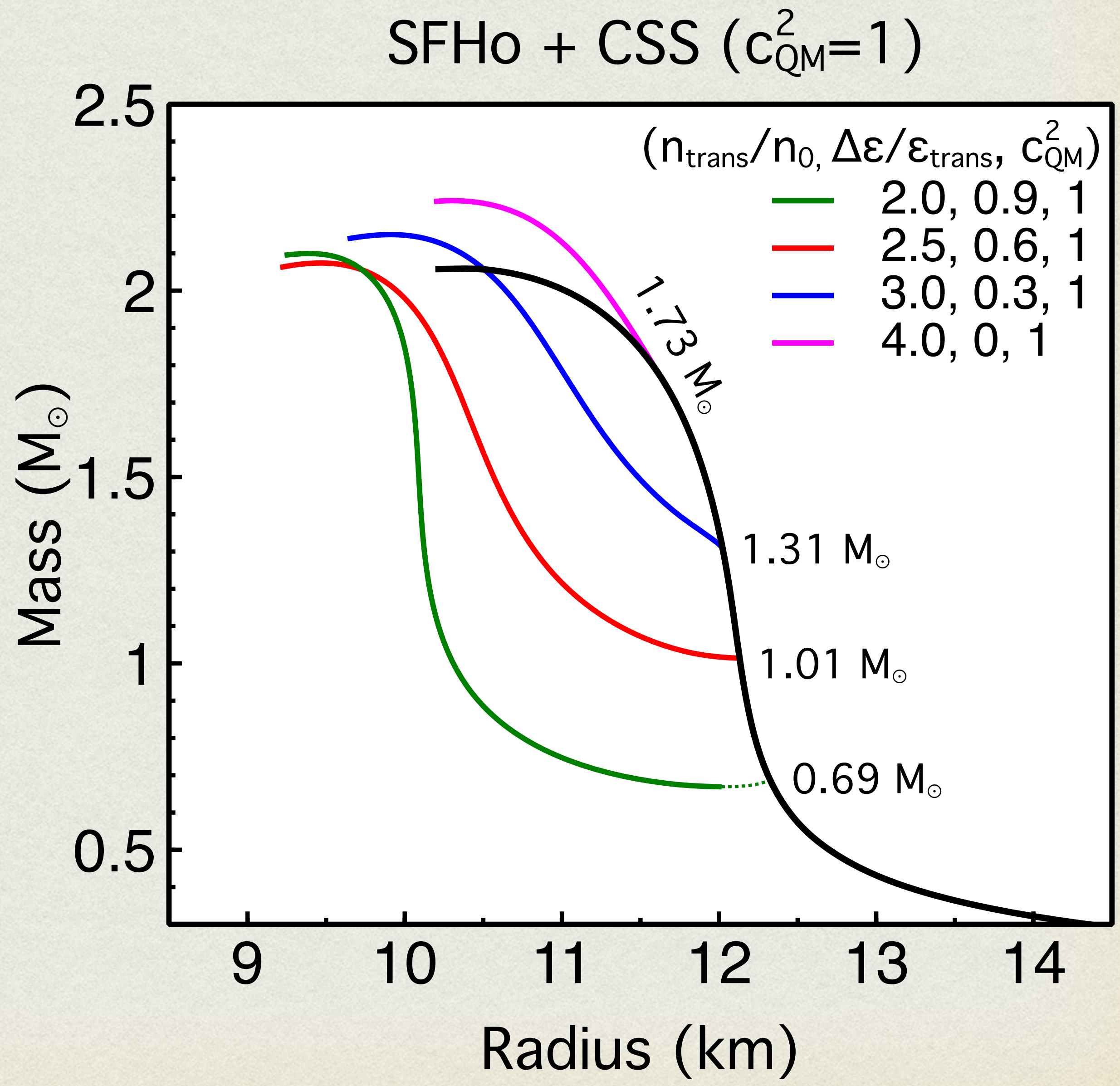


Generalize to PTs in hybrid stars

-Model-independent parametrization on high-density matter

-Sizable decrease in both k2 and R





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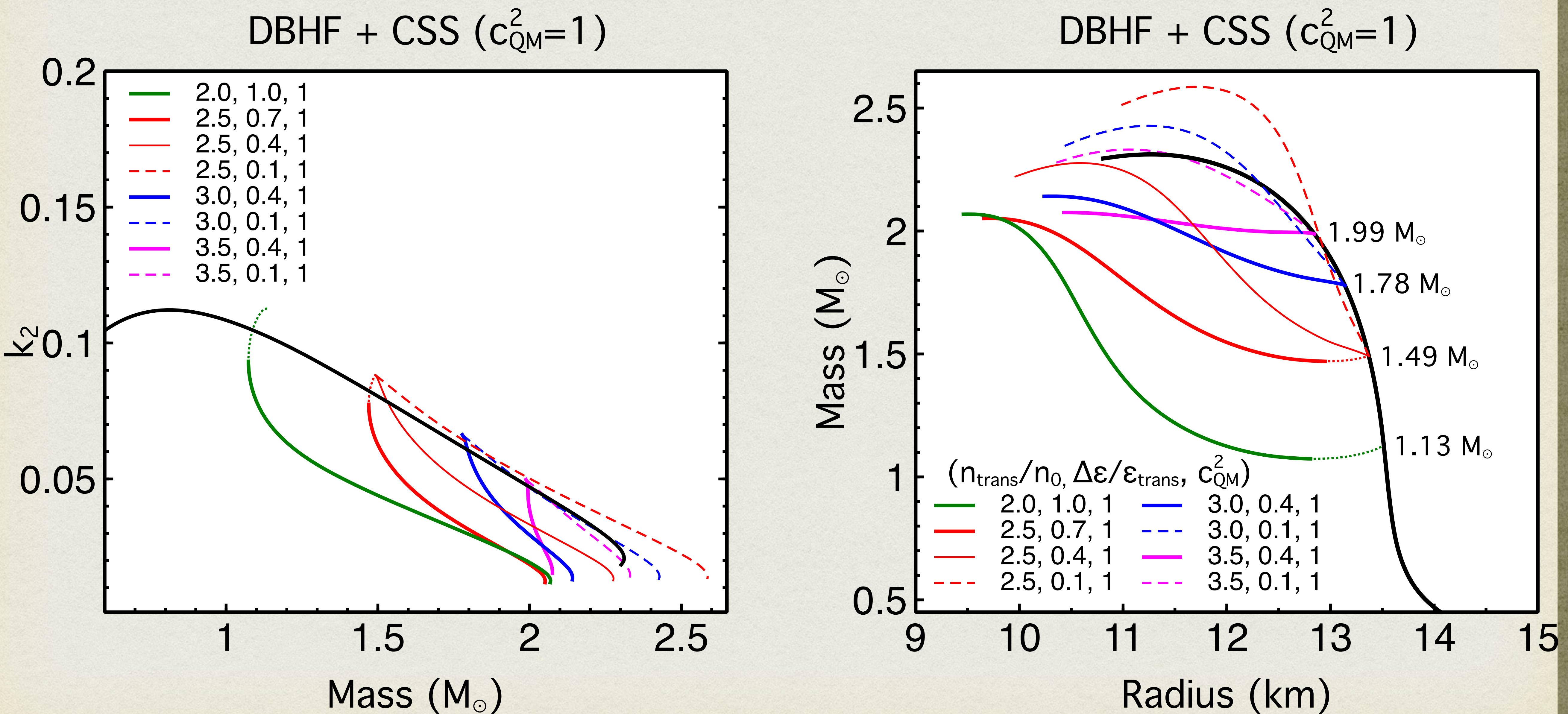
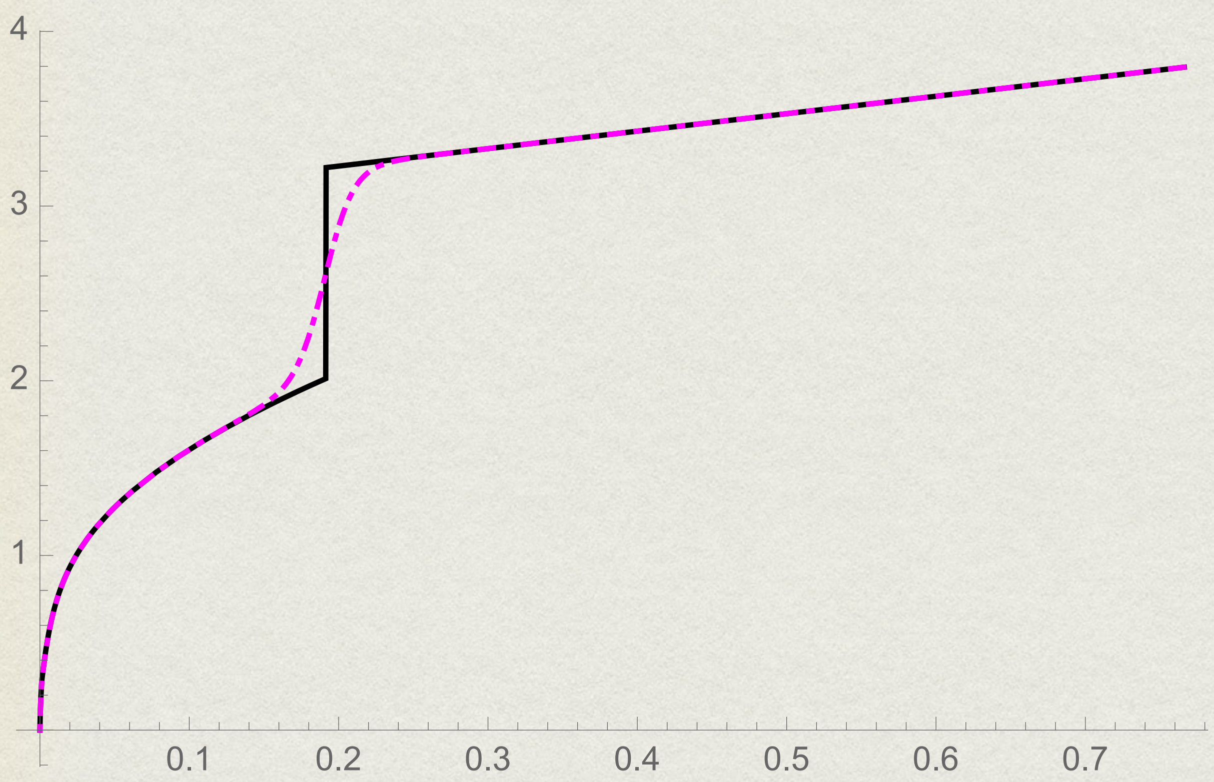


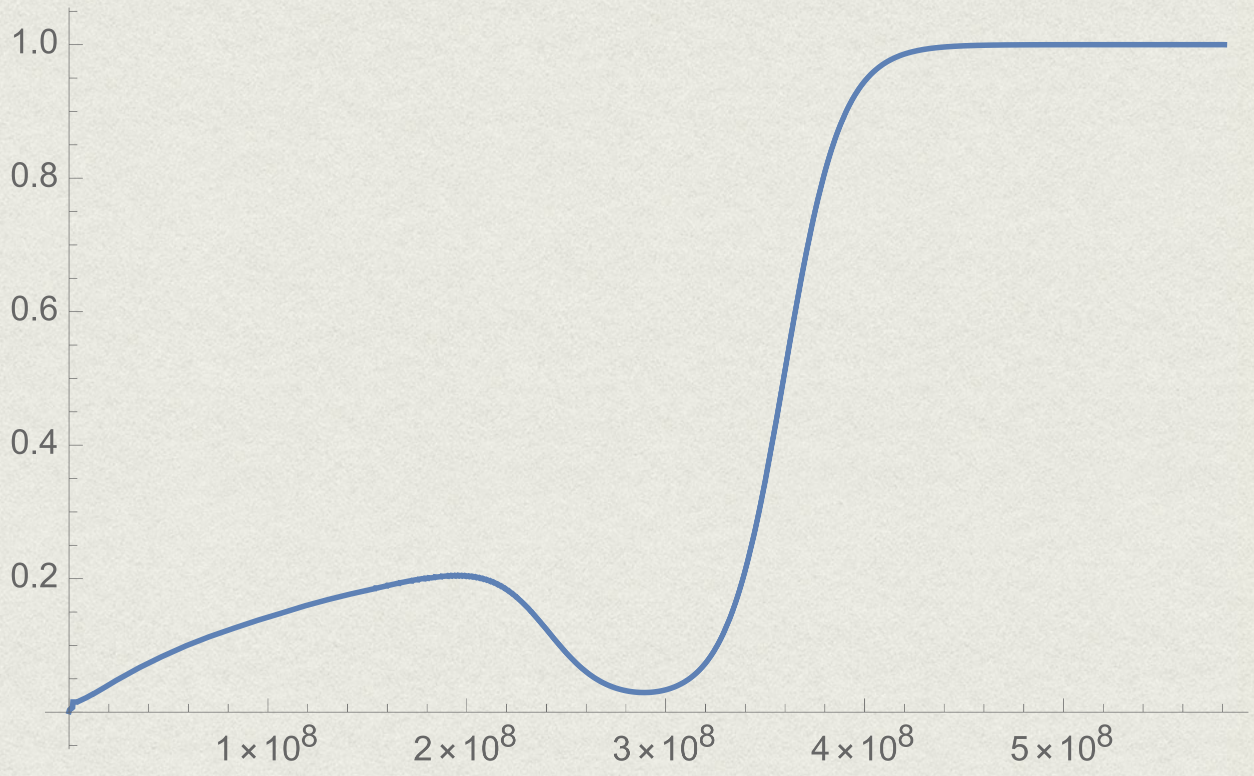
Smoothing to a crossover

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

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

Alford, Harris & Sachdeva, arXiv:1705.09880





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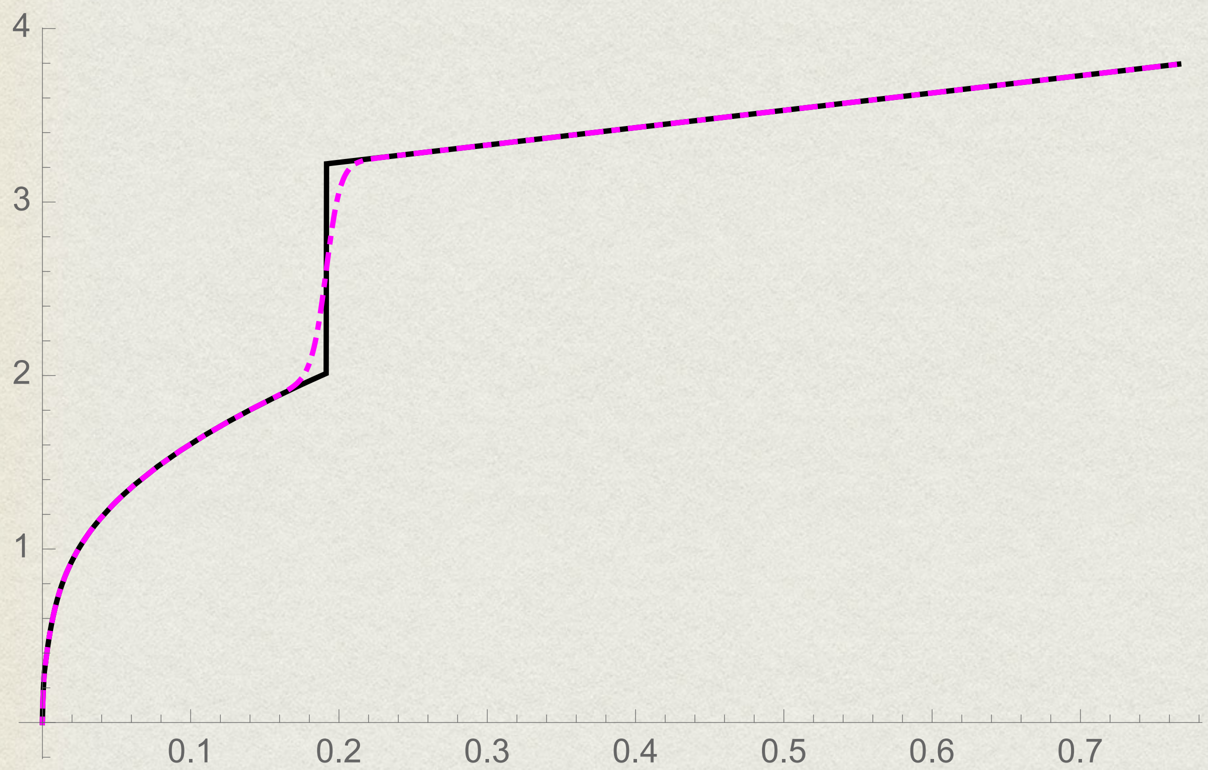
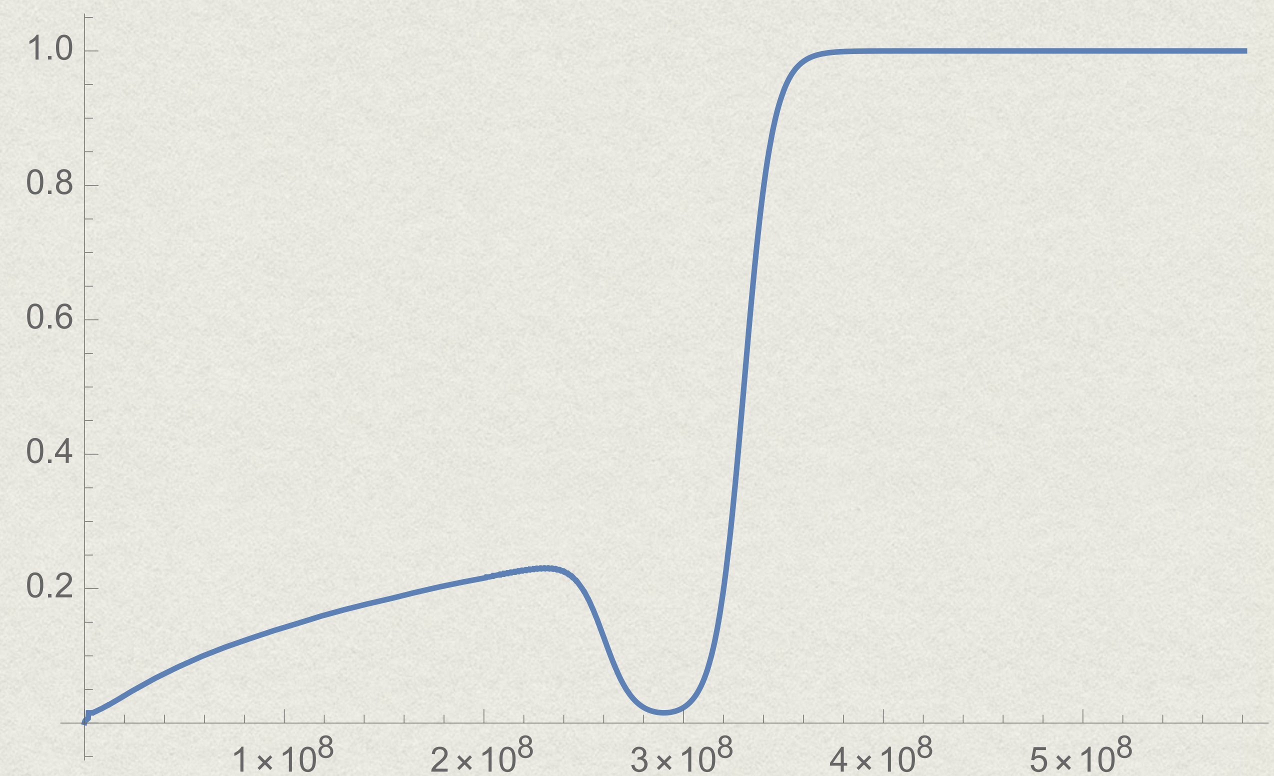
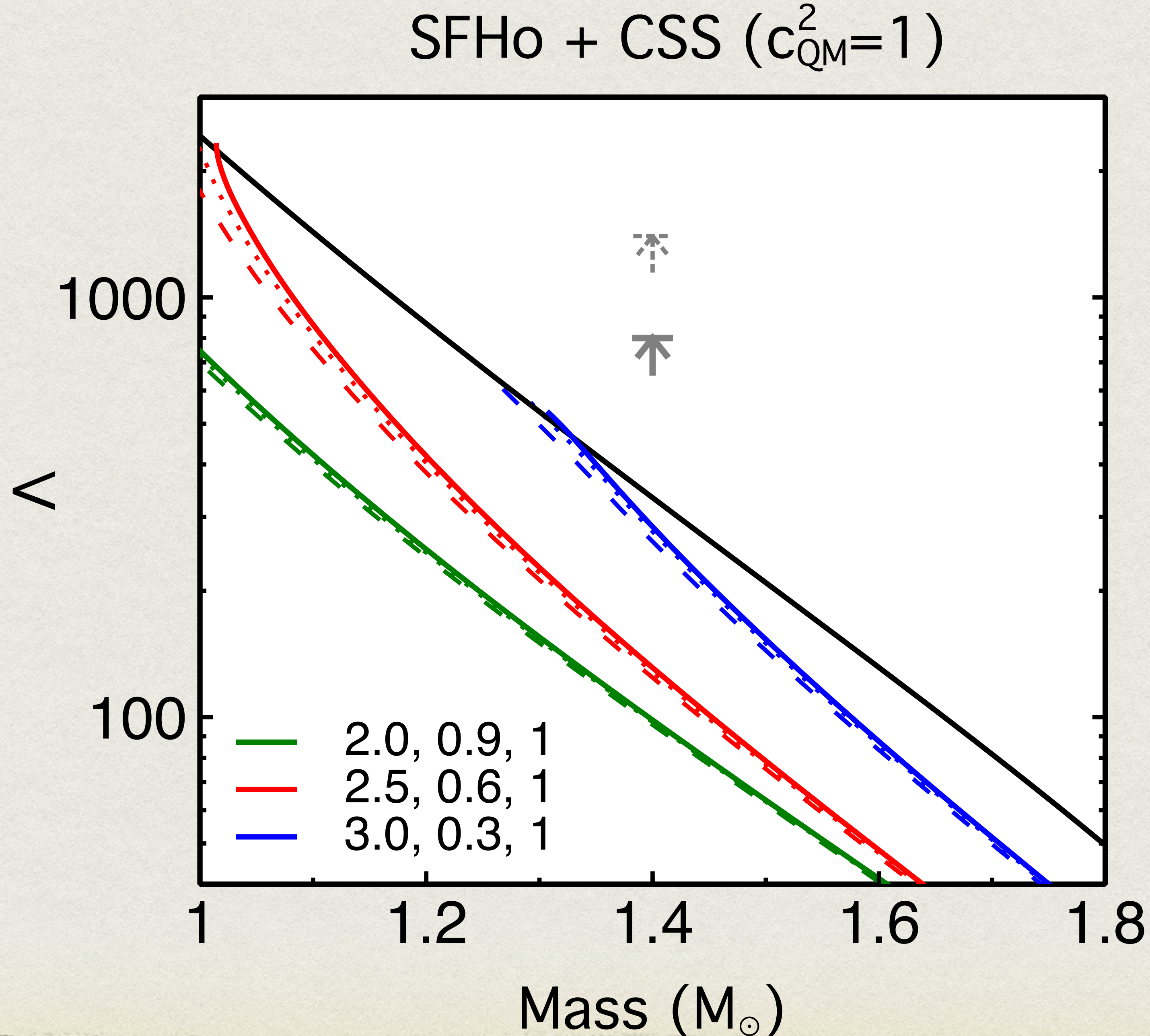




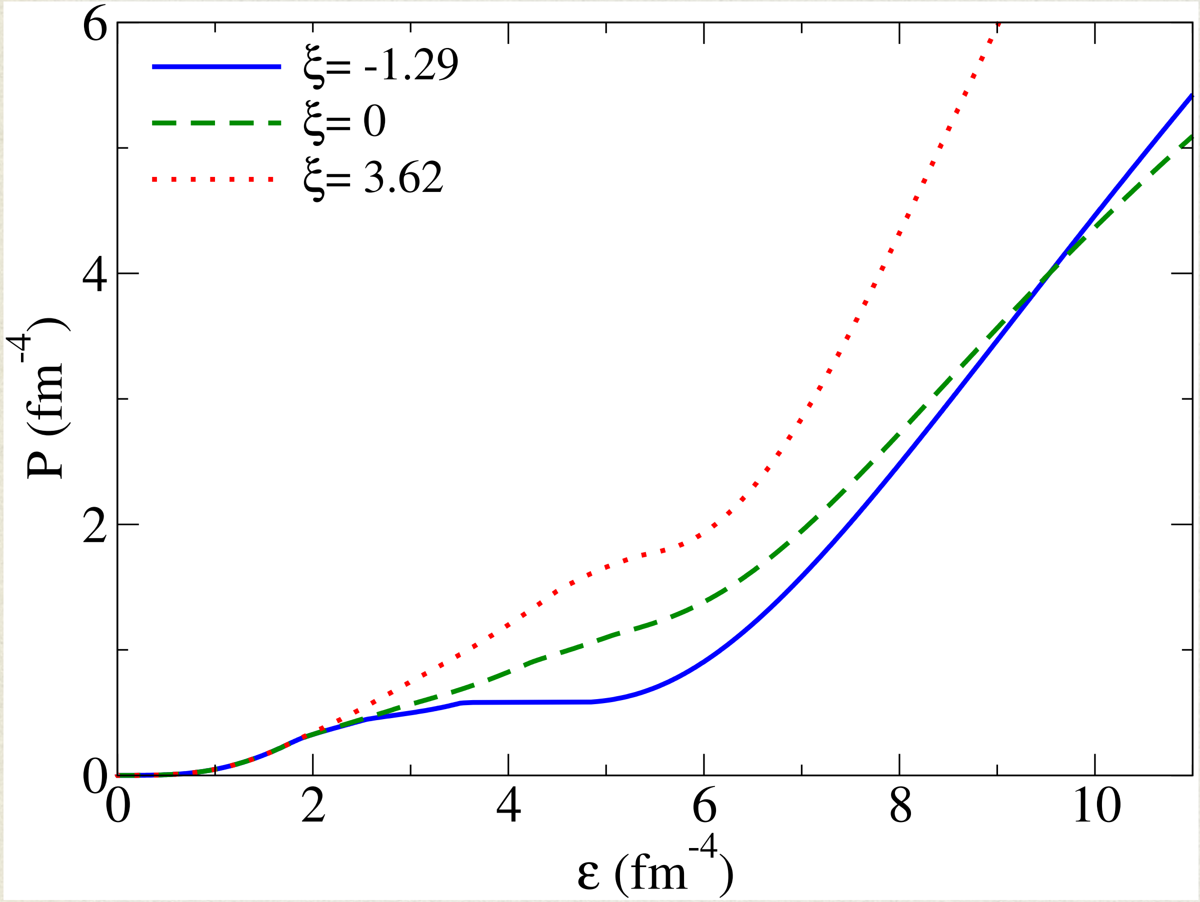
Smoothing to a crossover

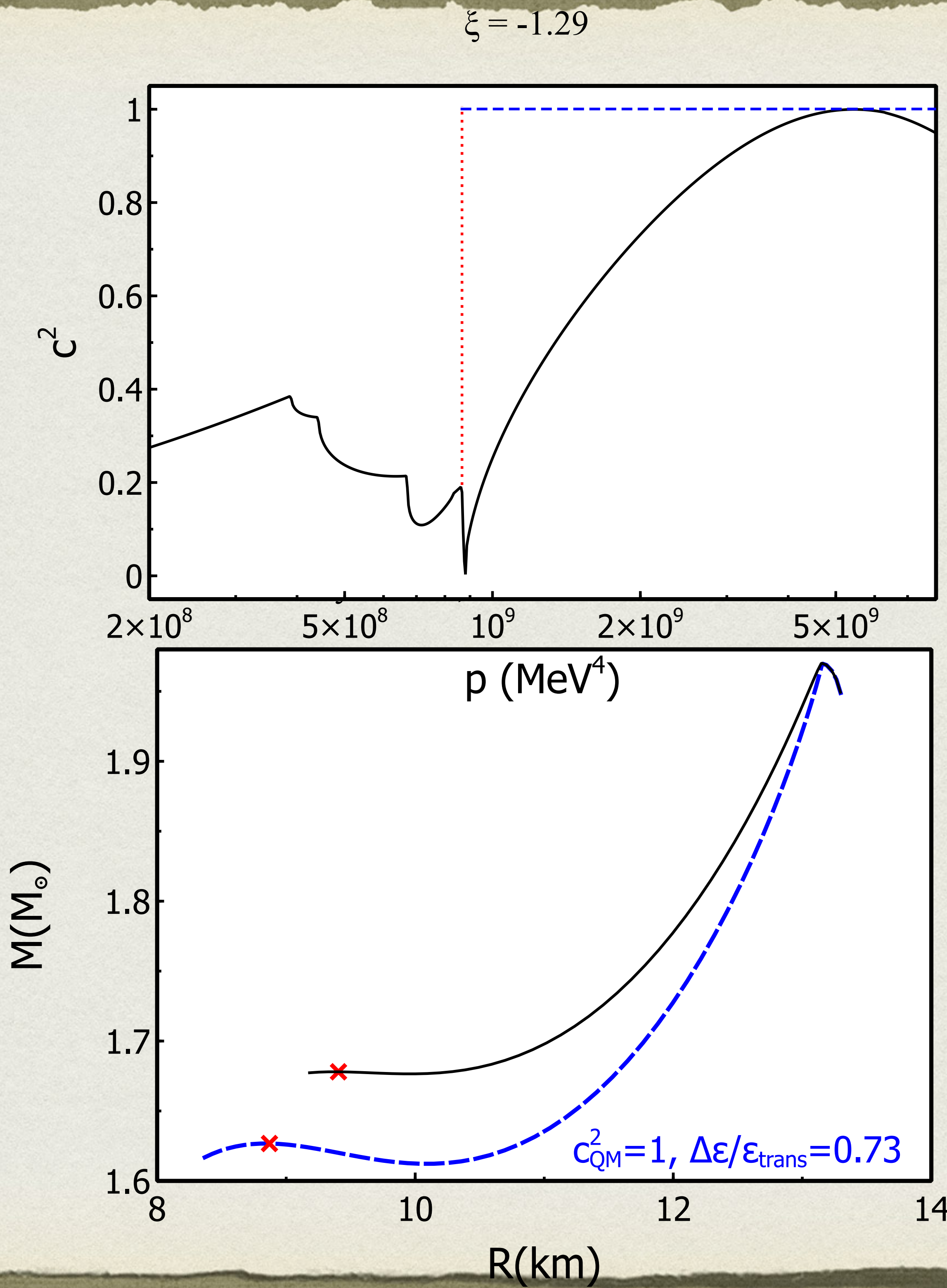
- Λ values slightly lower compared to sharp 1st-order transition
-Agrees with the discontinuous limit as $\delta p \to 0$



SH & Steiner, in prep.

Mimic quark models with PTs

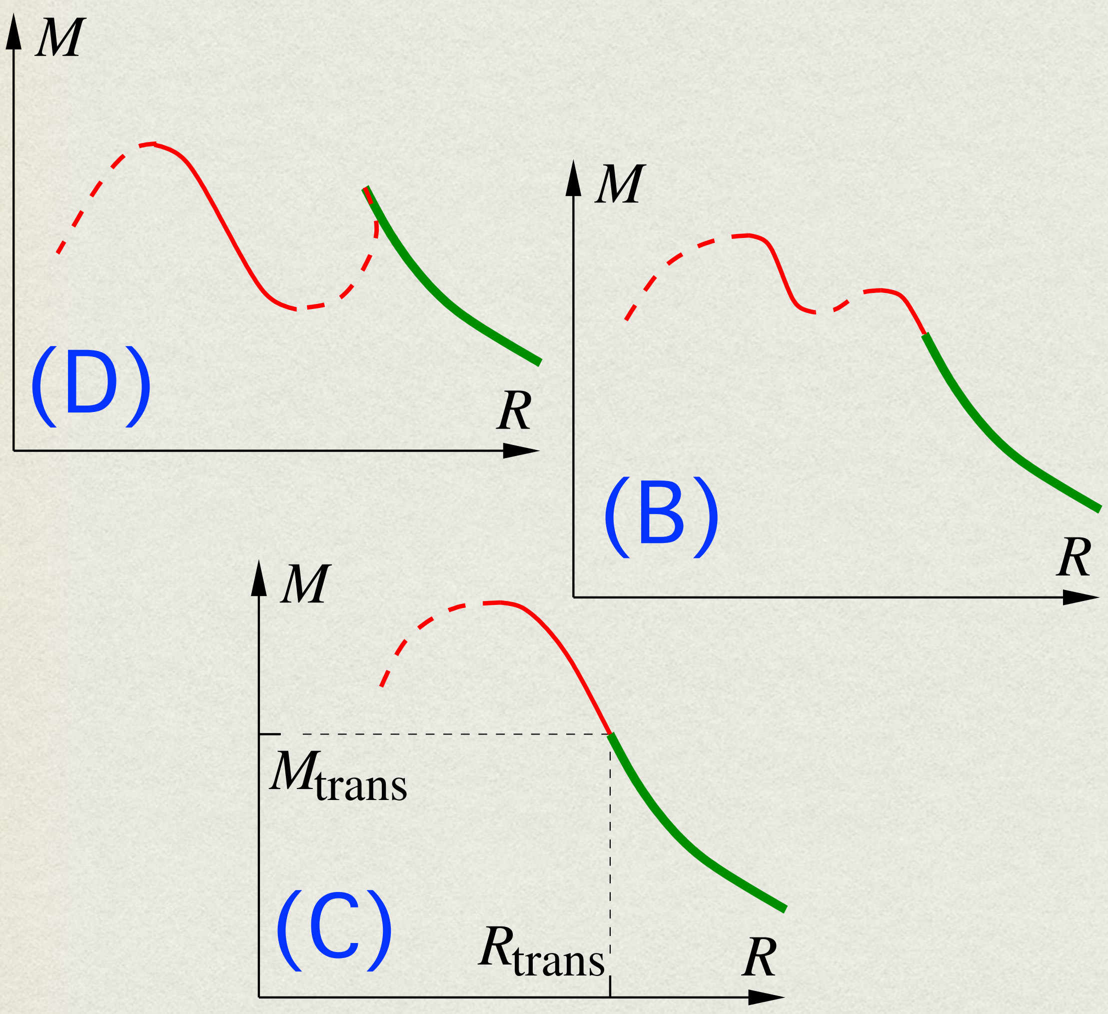


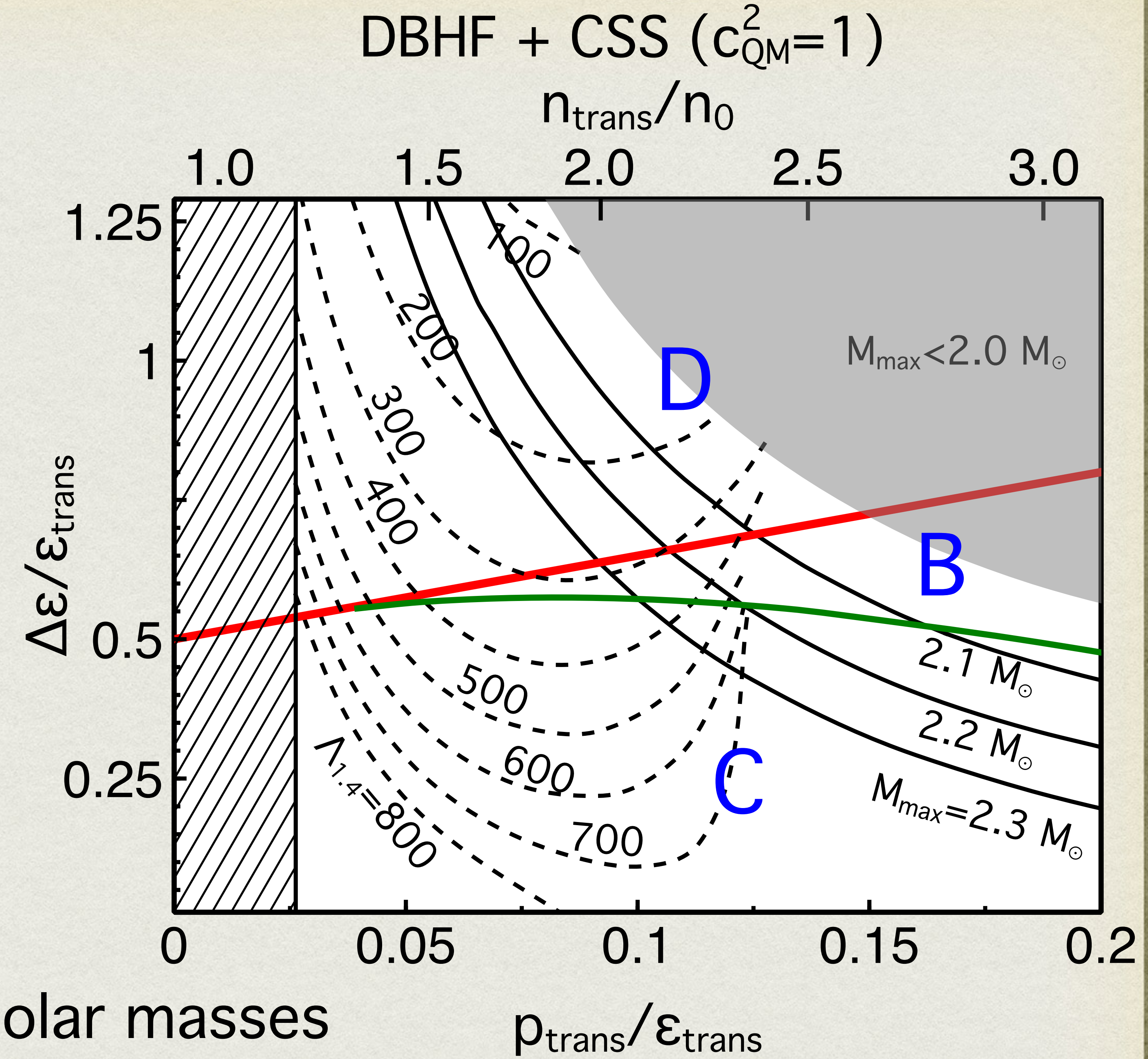


Dexheimer, Negreiros & Schramm,
arXiv:1411.4623

Constraints on PT-like EoSs

Better knowledge of nuclear matter helps





-Massive pulsars observed ~2 solar masses

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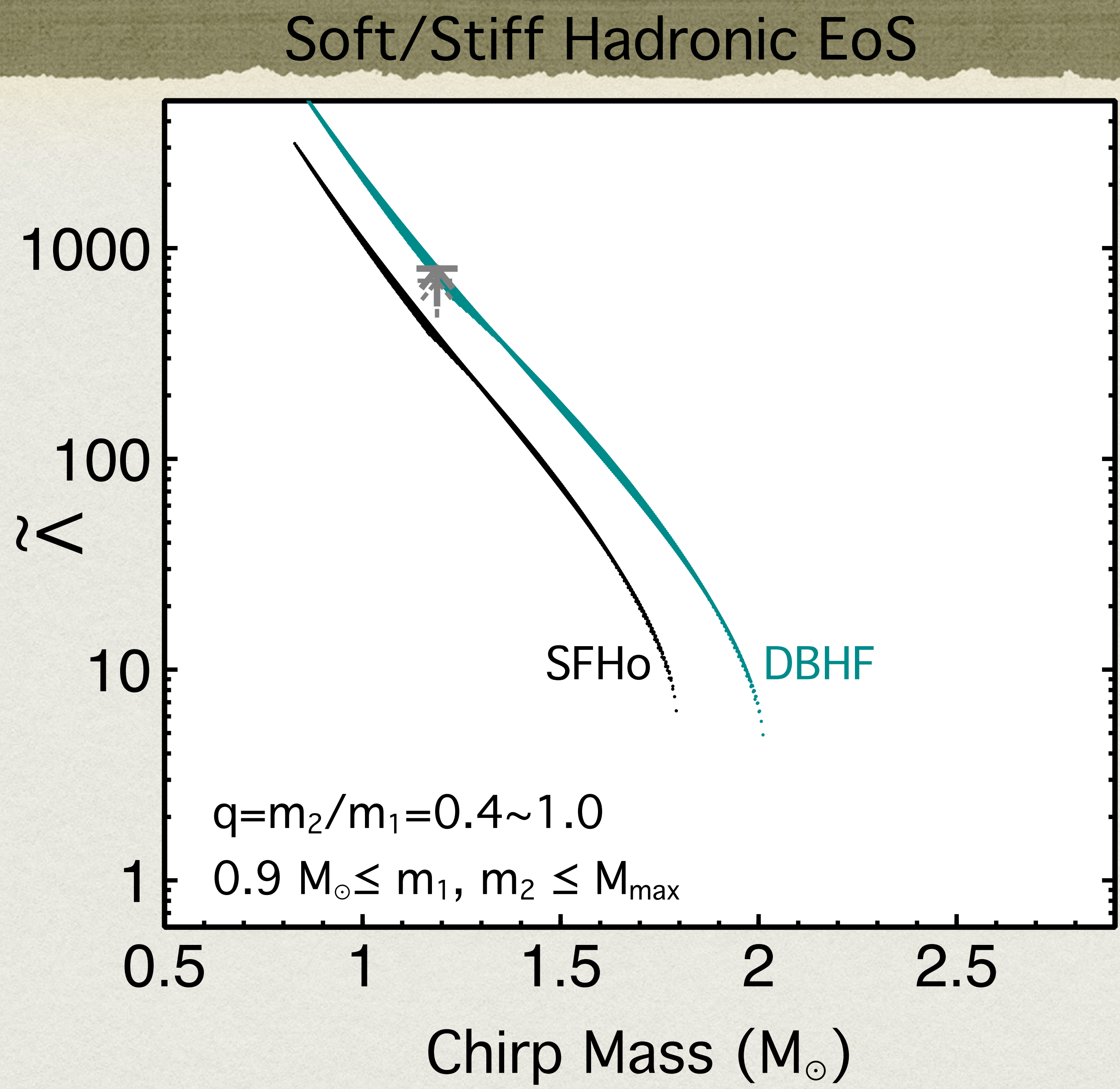
Combined tidal deformability

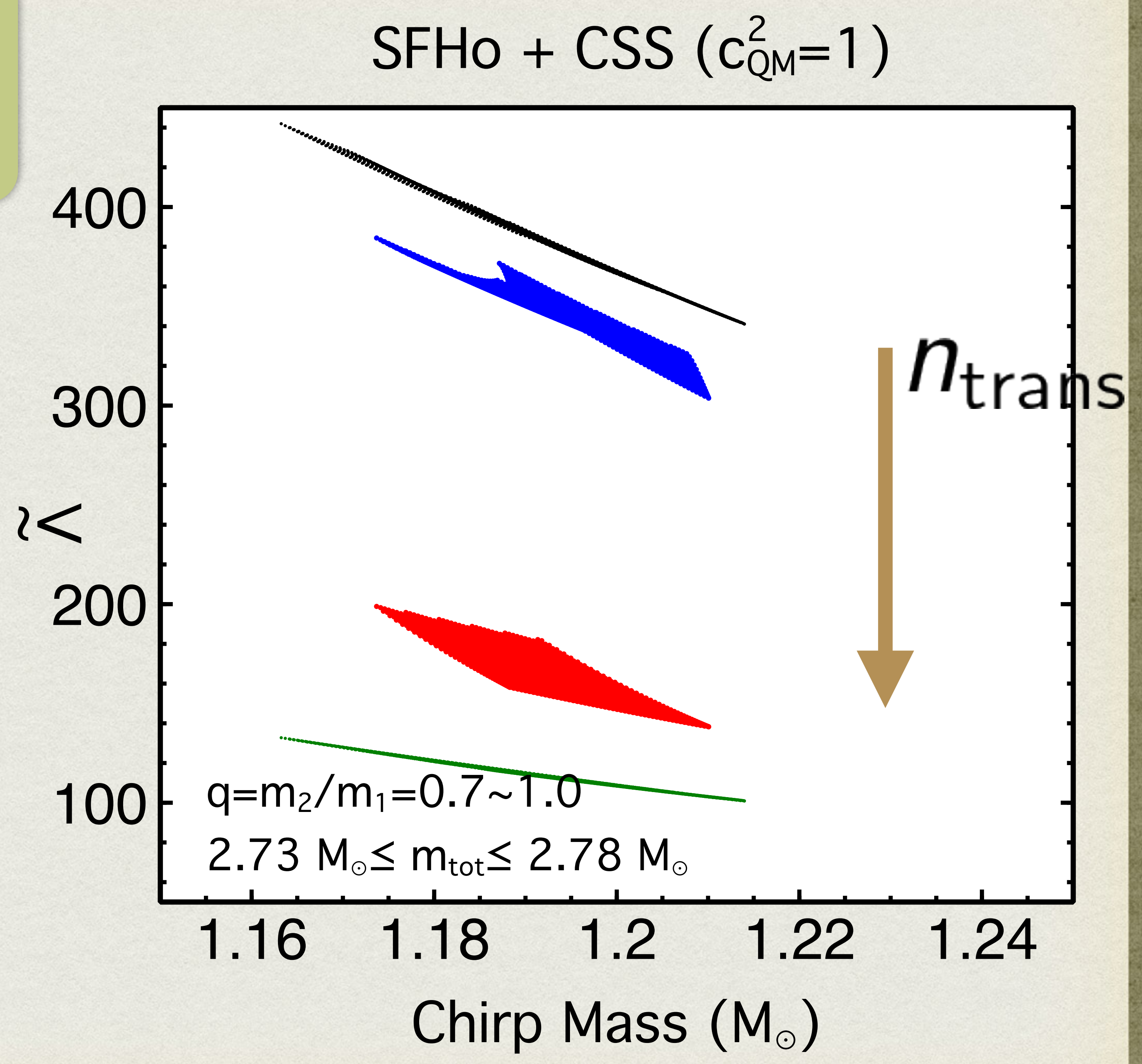


-Strikingly insensitive to the mass ratio $q = m_2/m_1$ for nuclear matter

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

Theoretical lower bound

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



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?

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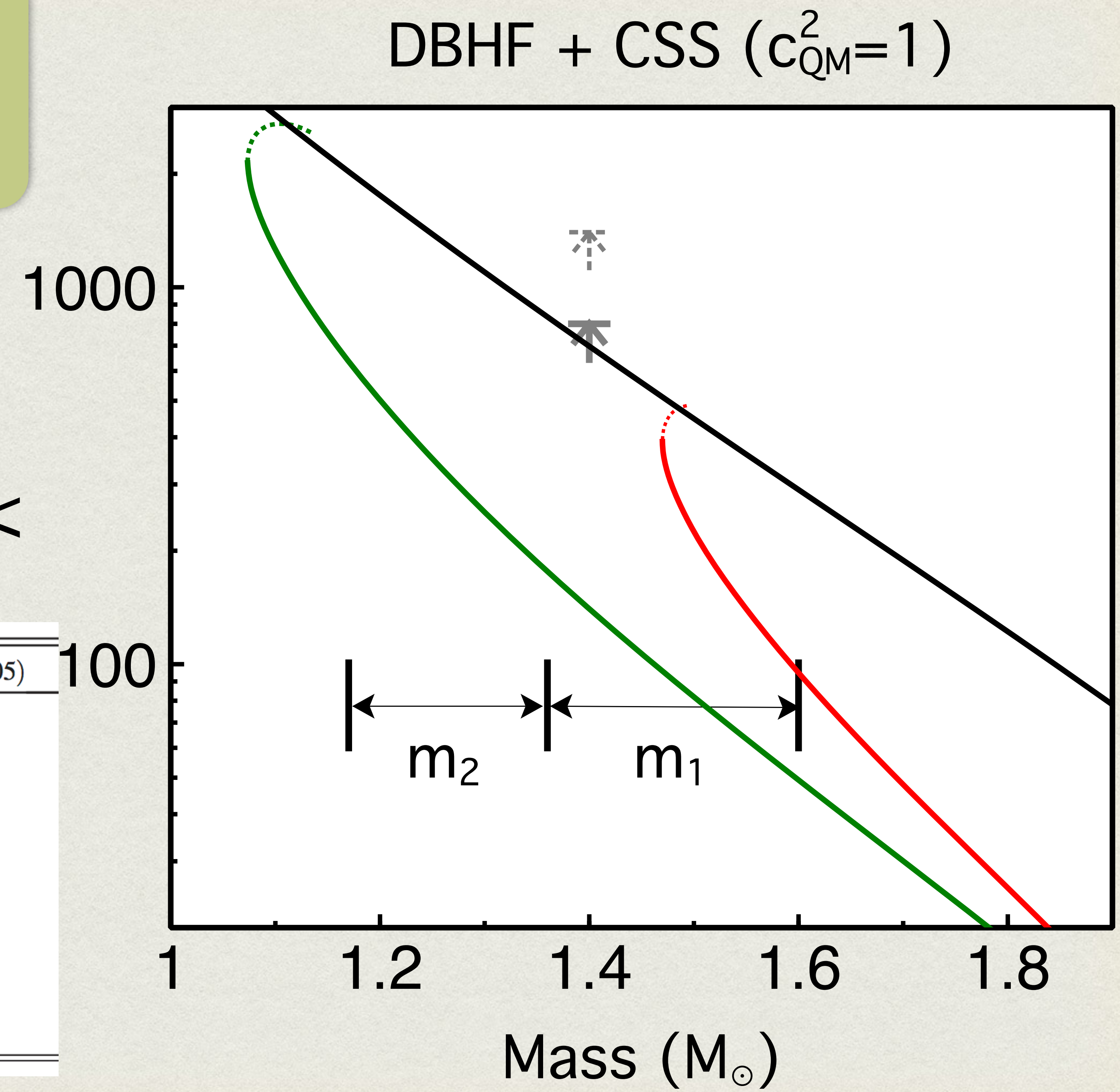

	Low-spin priors ($|\chi| \leq 0.05$)
Primary mass m_1	1.36–1.60 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$
Luminosity 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

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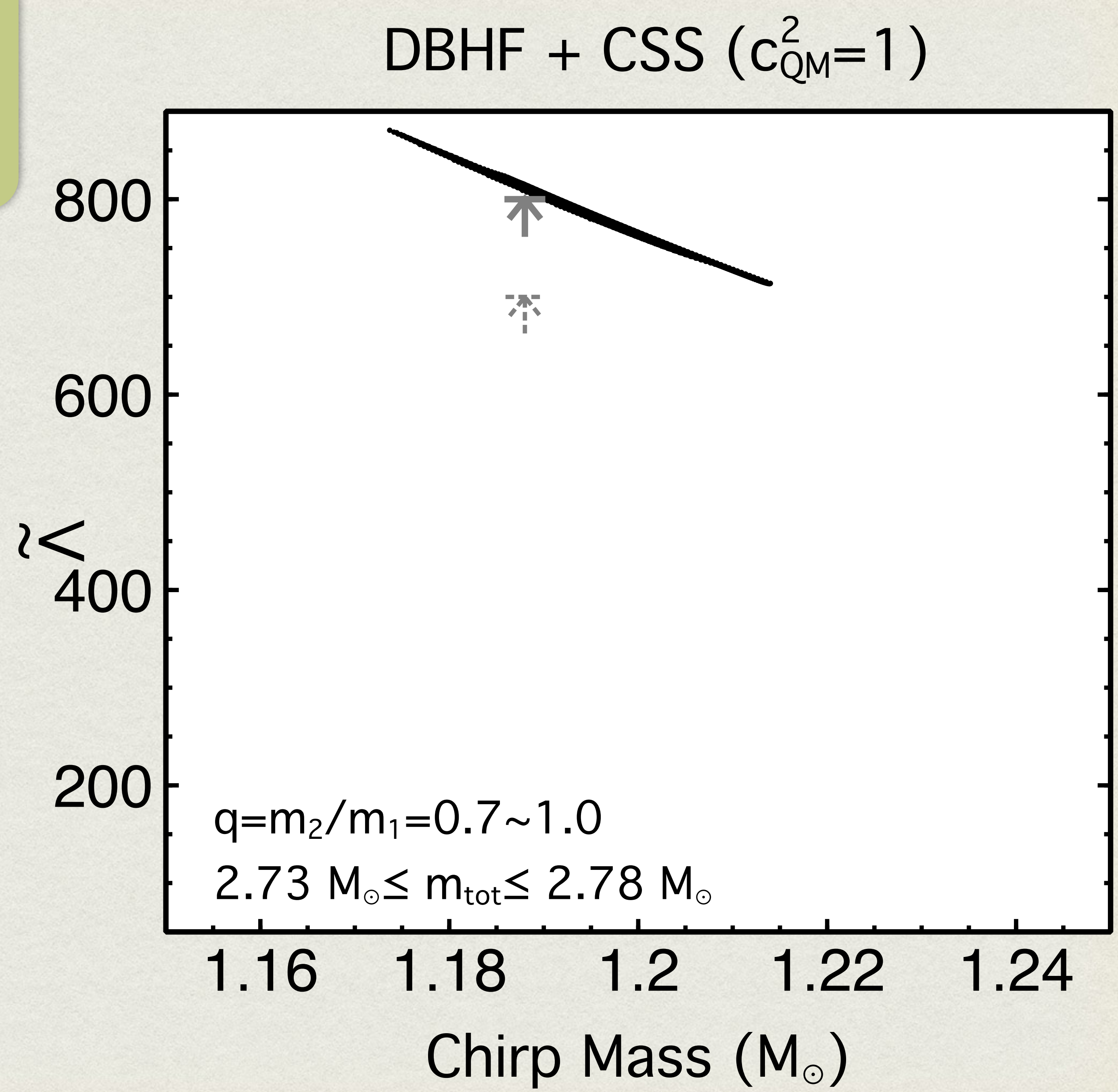

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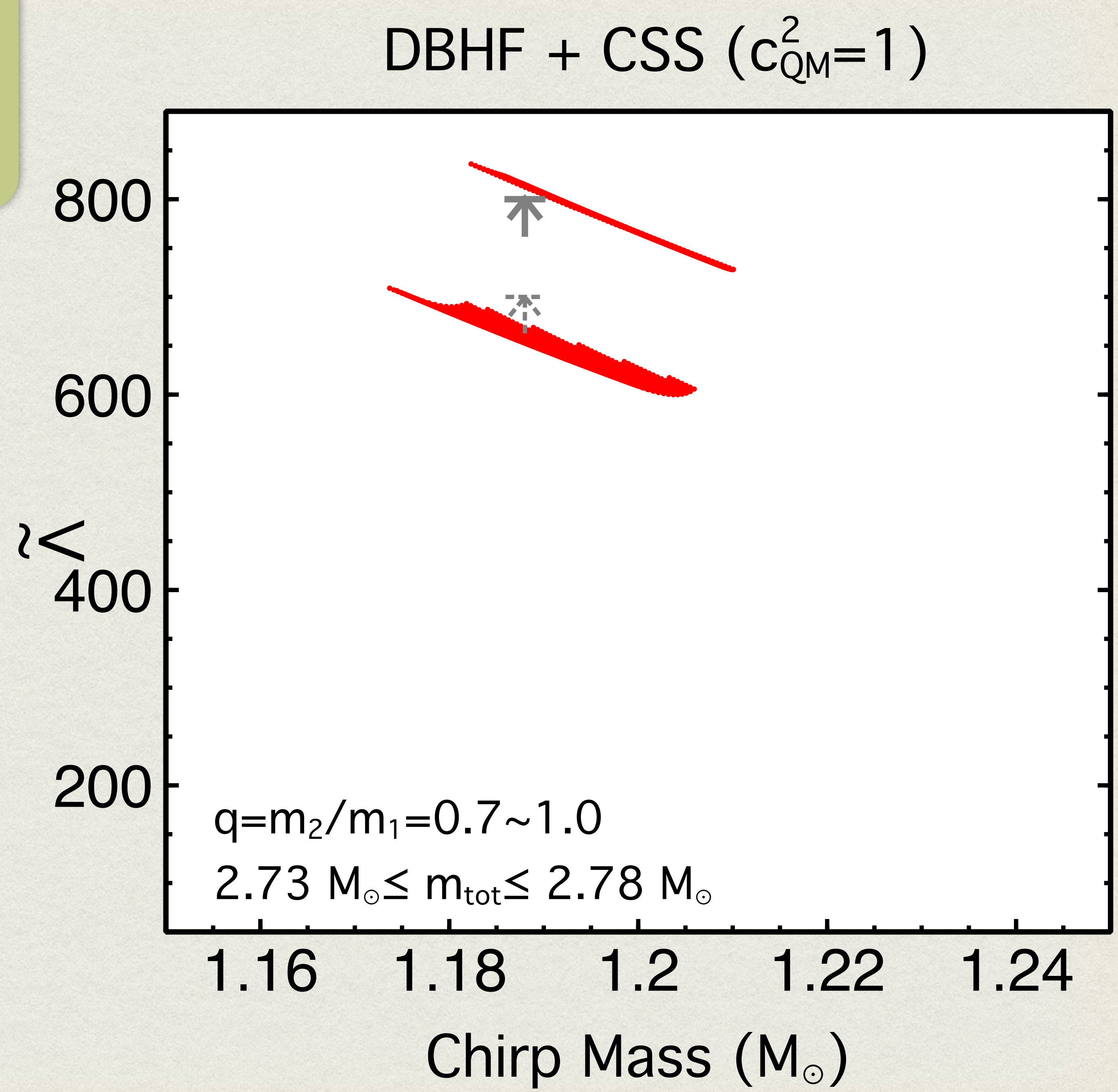

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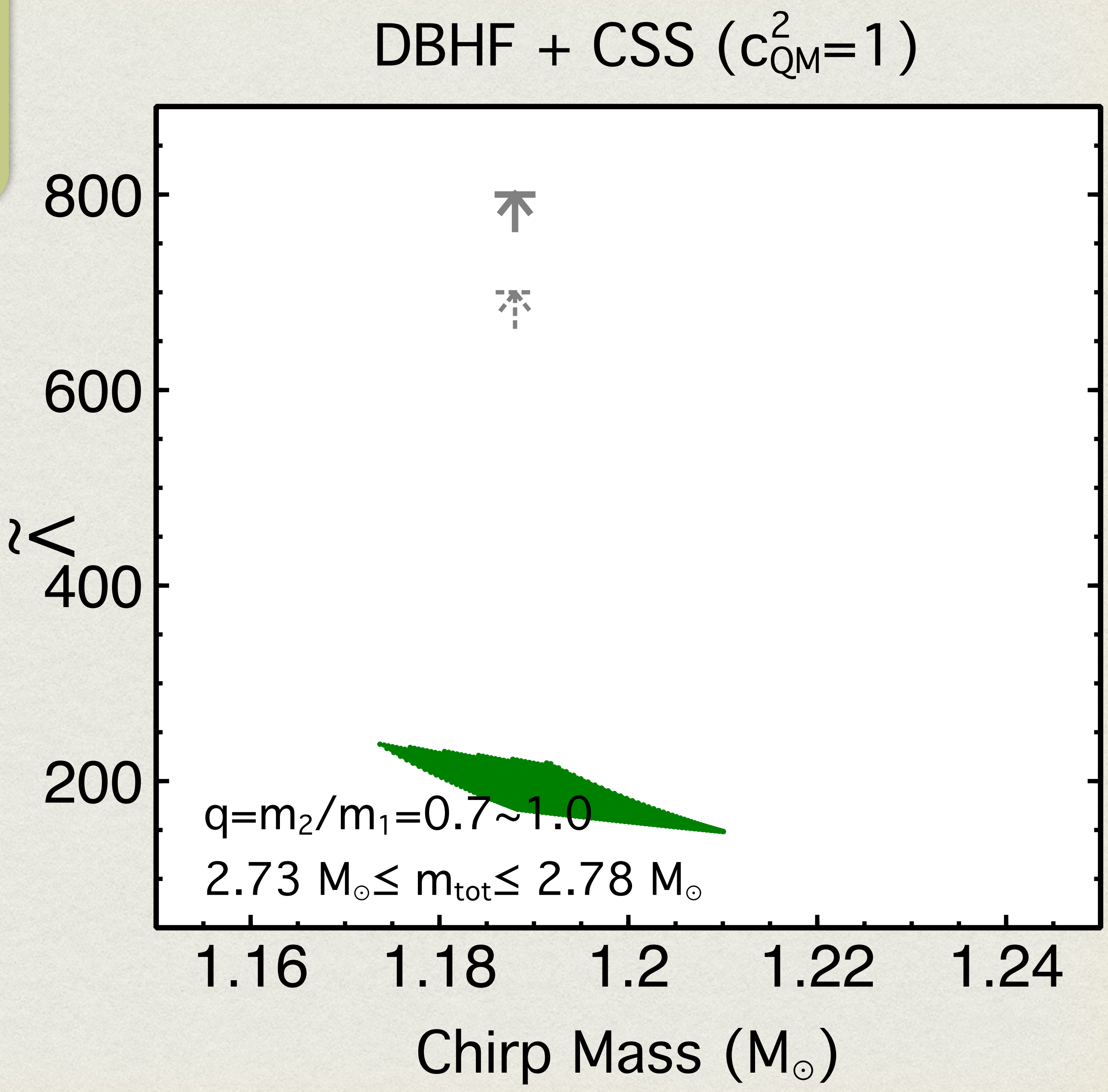

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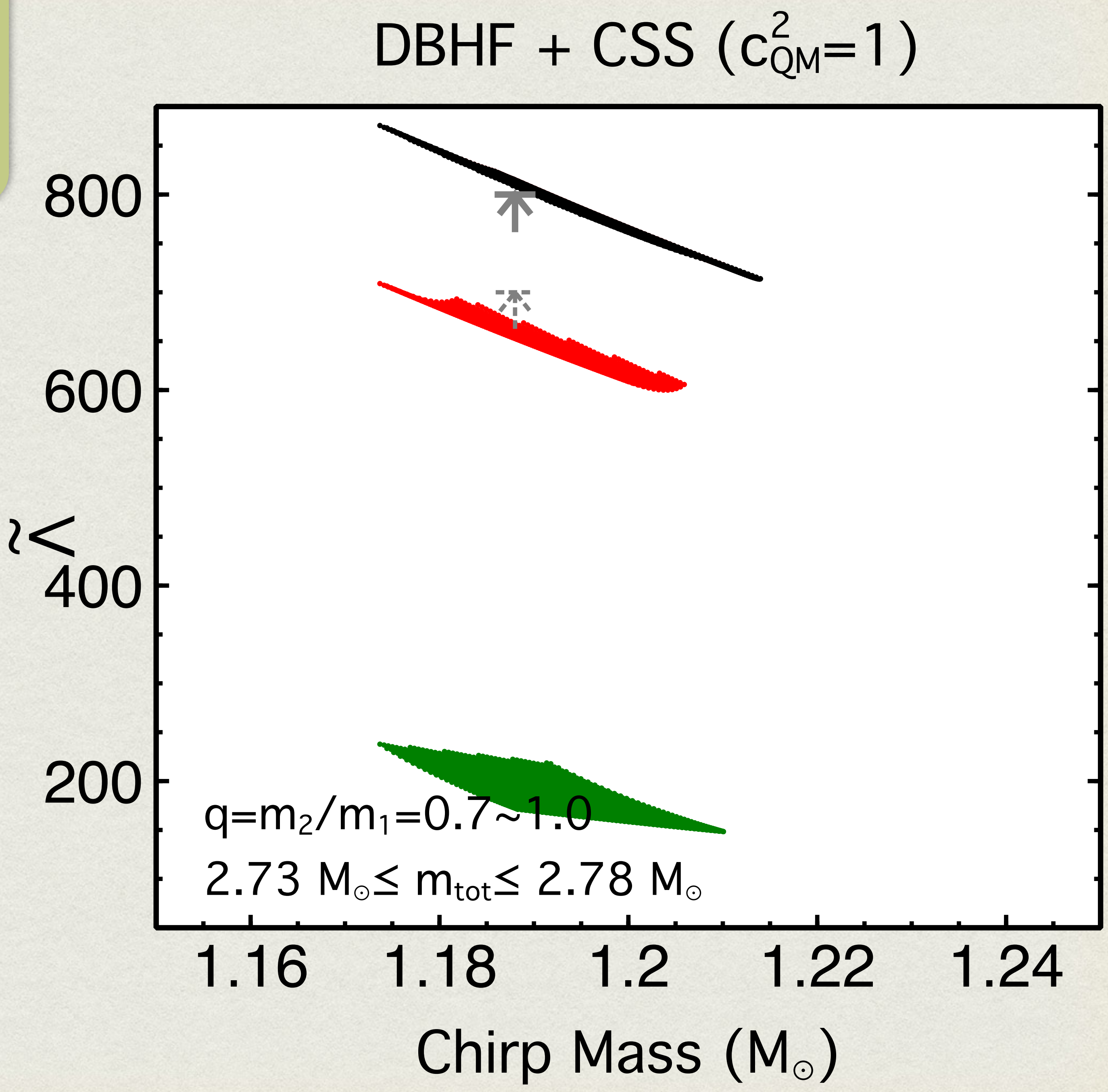
-Could we identify phase transition through future detections?



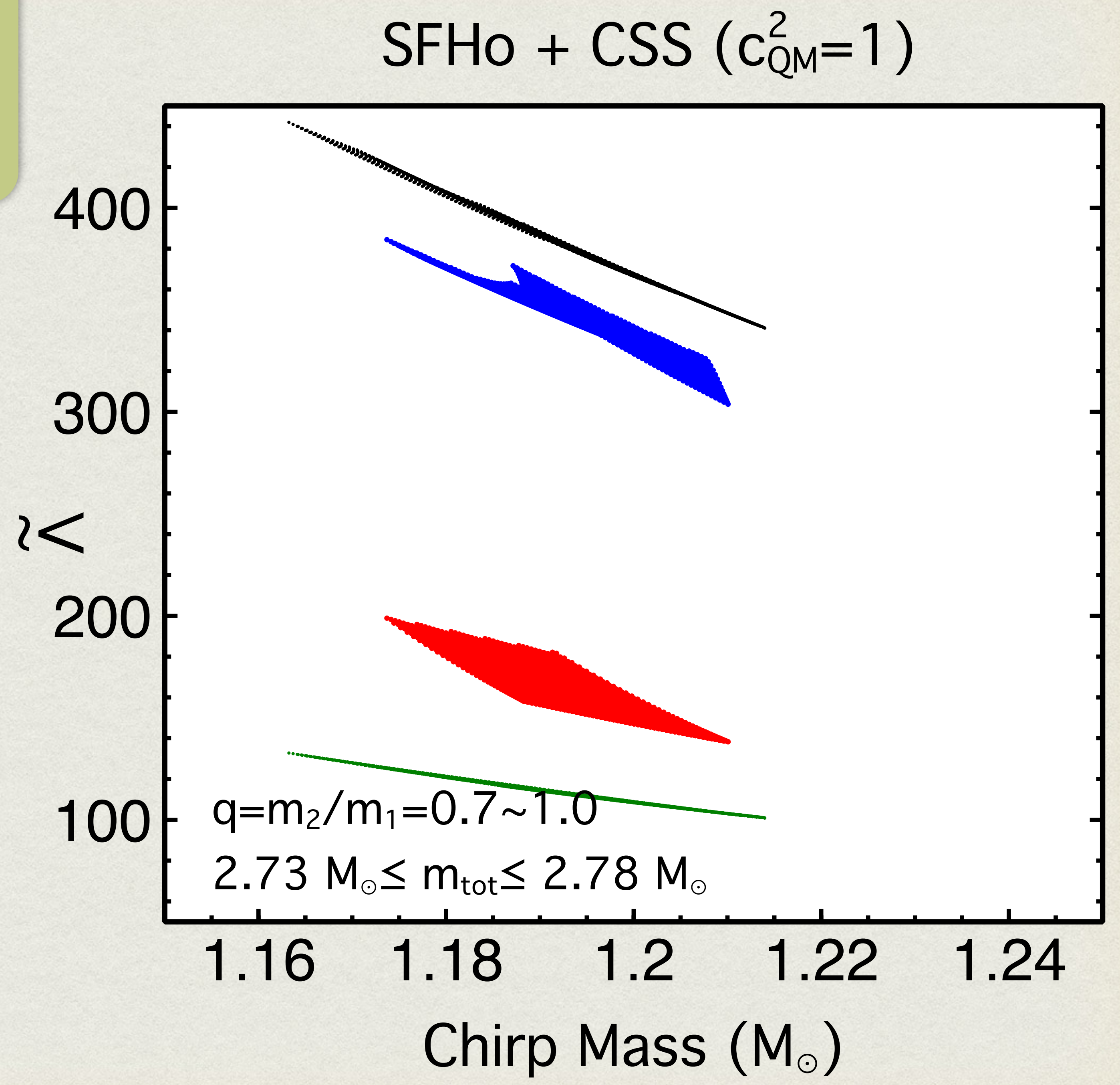
Theoretical lower bound

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?

-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

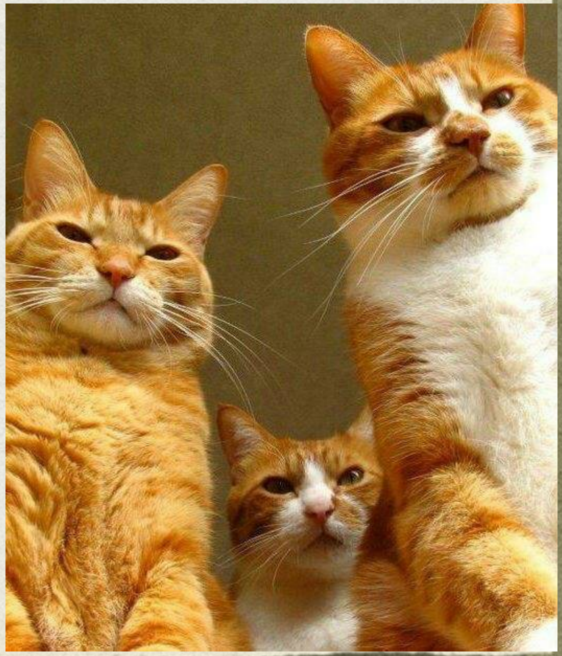
- Better constraints to expect

  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 EoS



THANK YOU!

Q & A