Searching for Quark Matter in Neutron Stars and Neutron Star Mergers: Challenges and Prospects

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Nuclear Physics in Mergers - Going Beyond the Equation of State

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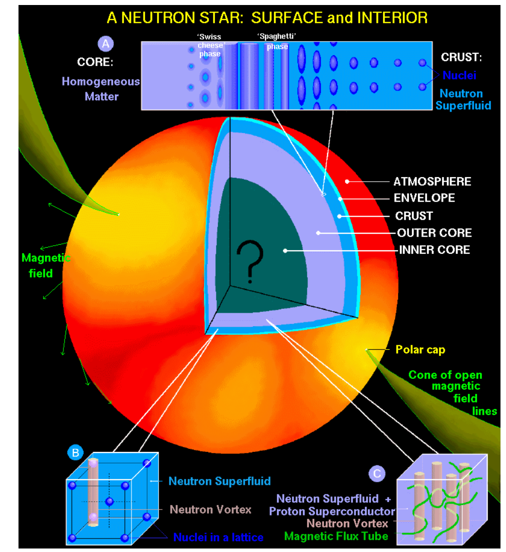
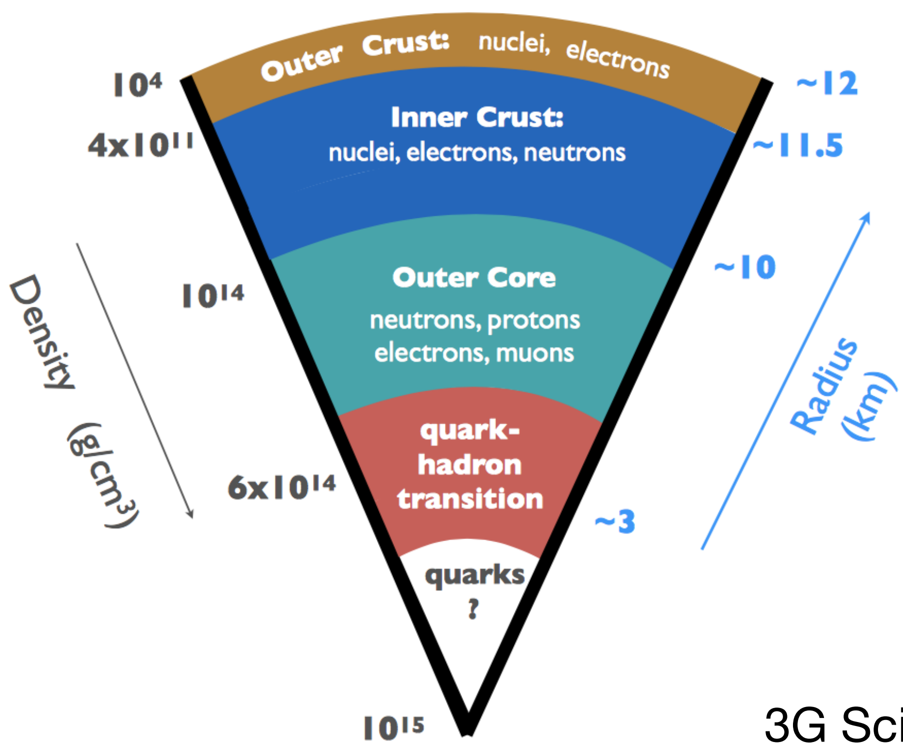
Summary

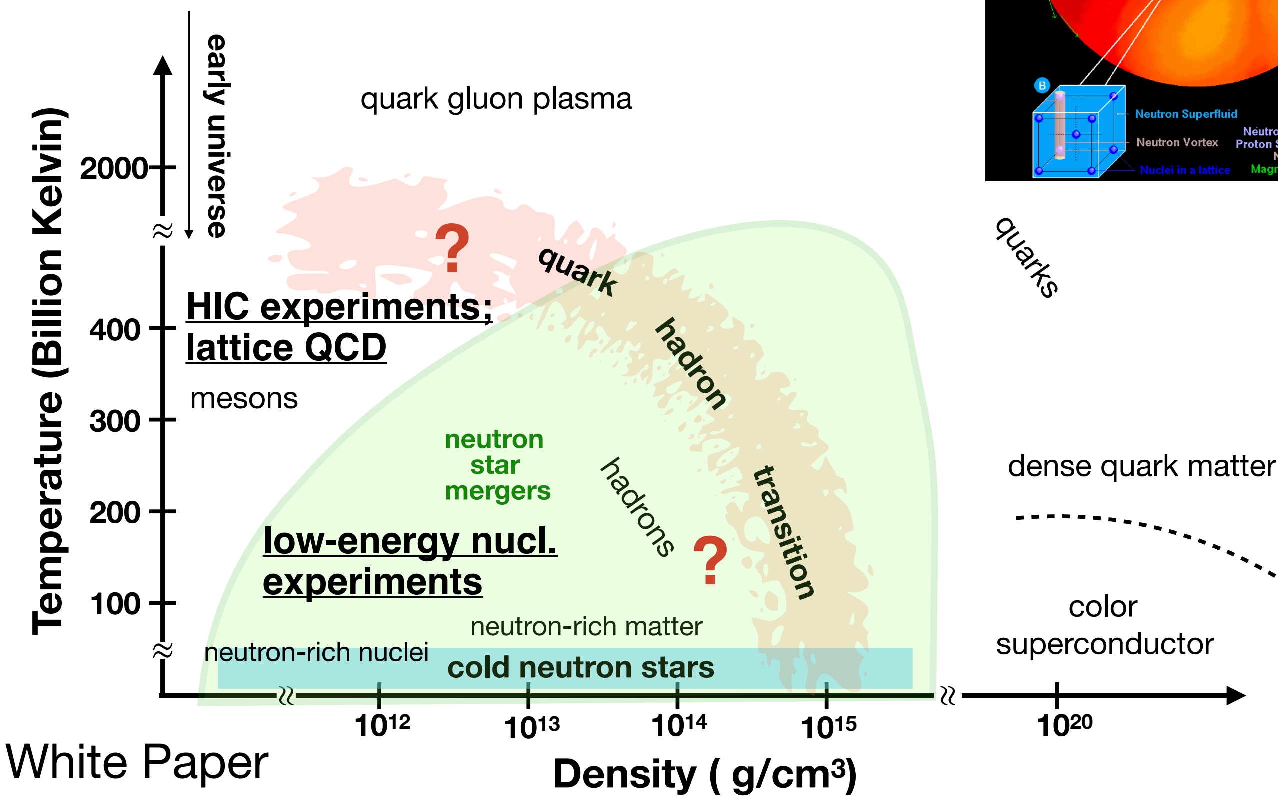
Quark matter in neutron stars - current status

1) no evidence to either rule out or confirm QM; better understanding of nuclear matter improves constraints on QM
2) massless weakly-interacting quarks strongly disfavored
3) some hints that neutrons & protons are insufficient; QM might help

credit: Dany Page







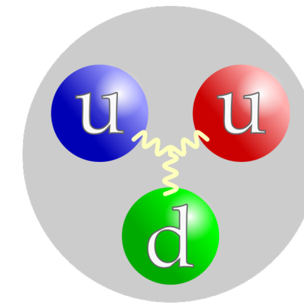
3G Science White Paper

Paths towards the high density regime

maximally distinguishable

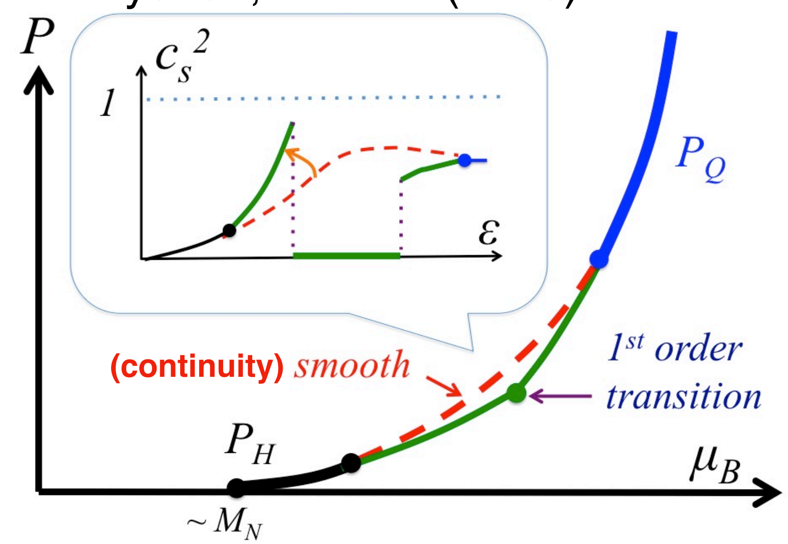
known up to ~saturation

- → purely hadronic/nucleonic matter (standard)
- → 1st-order PT? -> quarks
  - → sharp boundary - Maxwell
    - → strong PT
    - → weak PT
  - → mixed phase - Gibbs (geometrically separated)
- → smooth crossover (quarkyonic)?



"golden window" in the vicinity of ~2*nsat; hints from exp.?

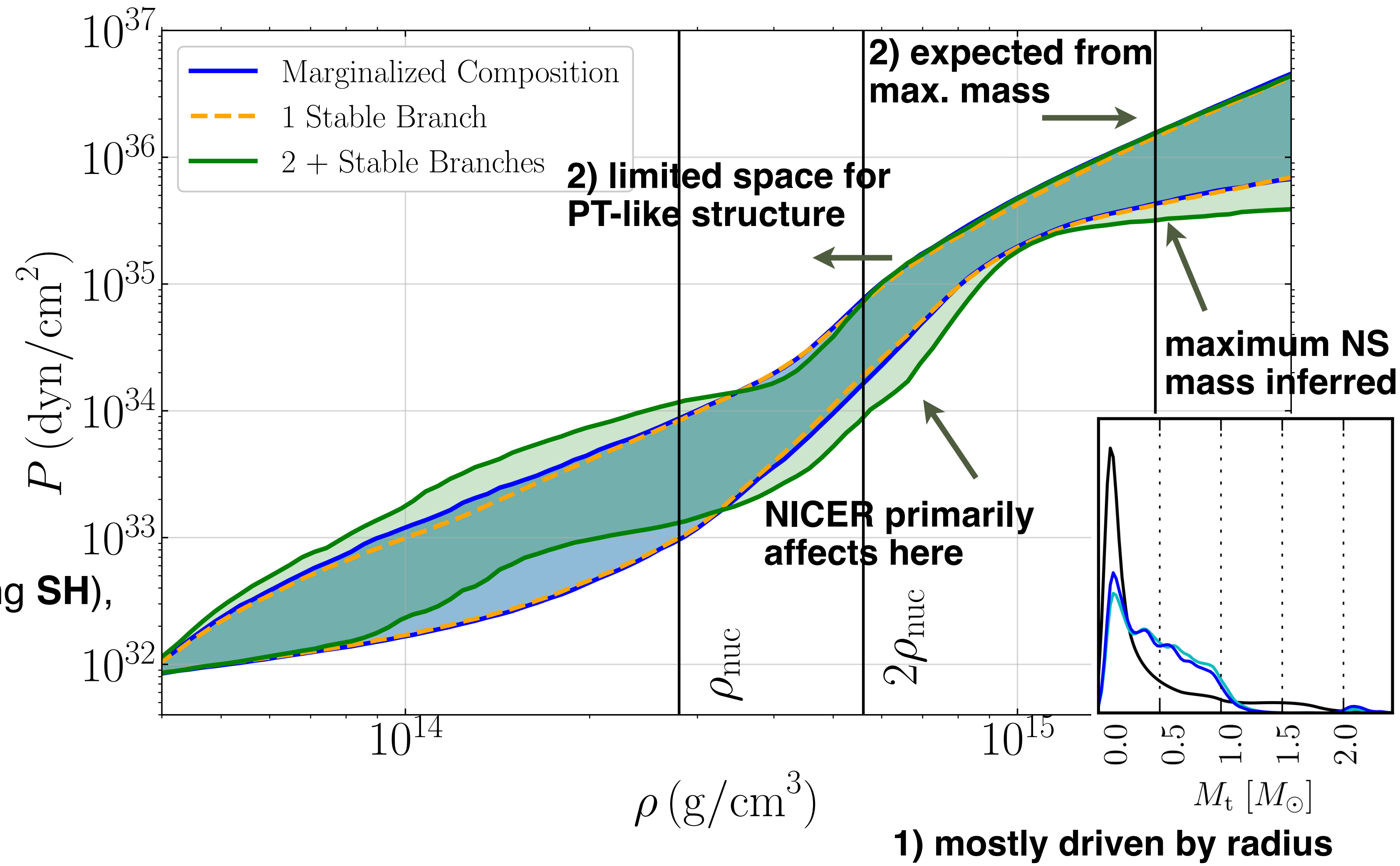
Baym et al. Rept. Prog. Phys. 81, 056902 (2018)



masquerade problem - EoSs with or without PTs may hardly be distinguishable via observations that constrain *M-R* only

- crossover models motivated by e.g. lattice calc.
- 1st-OPT: mixed phase (Gibbs) favored if the hadron/quark **surface tension** is small

e.g. single branch (minimal) vs. multiple branches



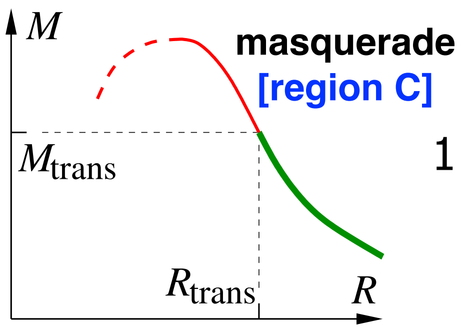
$\sim 2.2^{+0.3}_{-0.2}\,M_\odot$

$5.4^{+1.1}_{-1.2}\,\rho_{nuc}$

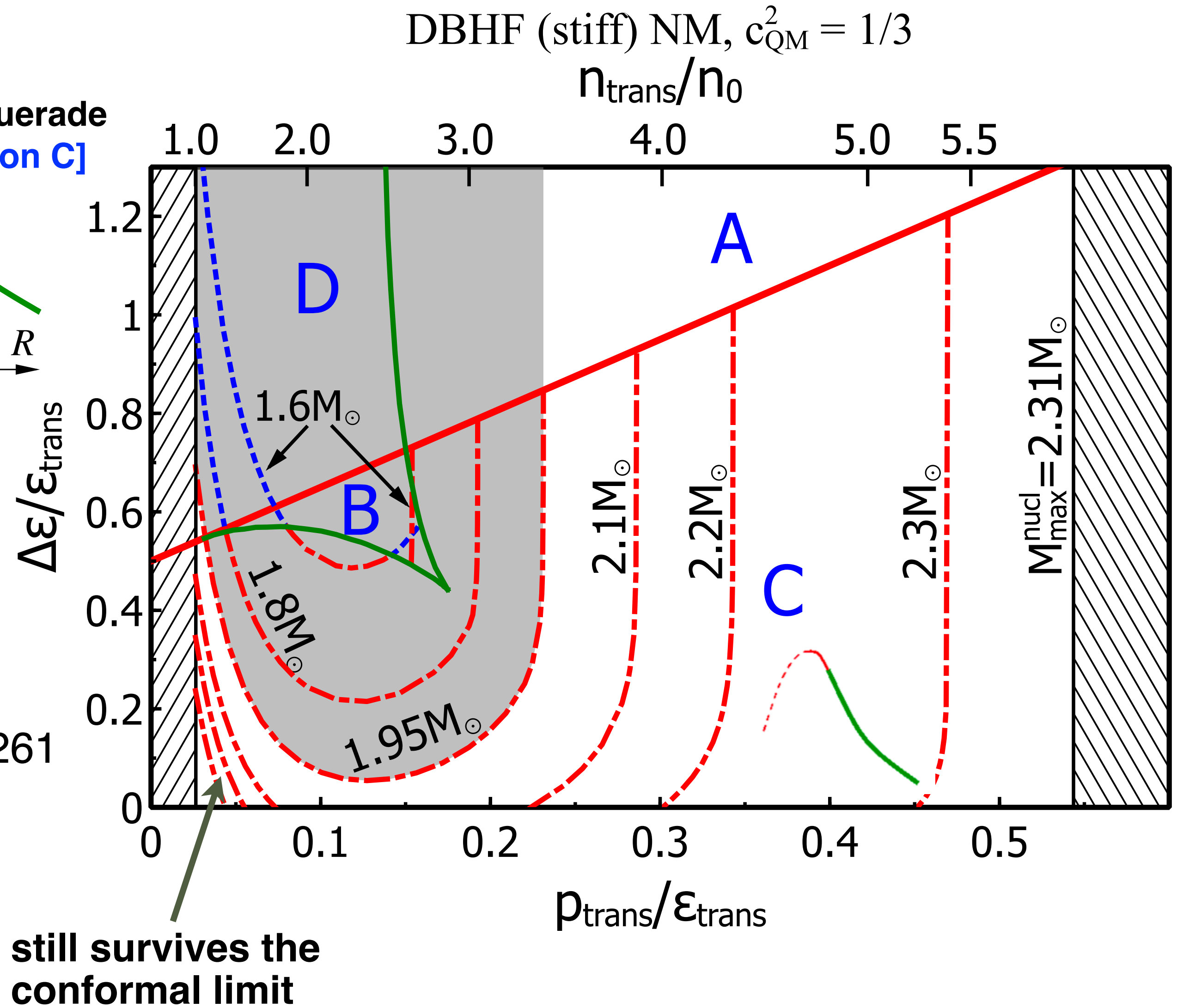
Legred et al. (including **SH**), arXiv:2106.05313

1) current data: full posterior is dominated by EoSs with a single stable branch
2) **onset** for the unstable branch **i.e. extra softening** pushed to two ends

Generic constraints on 1st-OPT from heavy pulsars



Alford & **SH**
arXiv:1508.01261

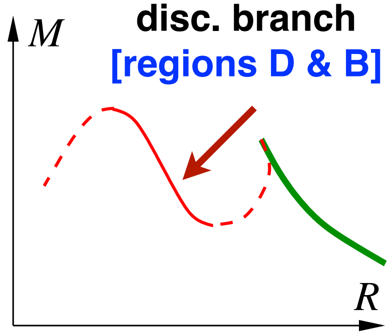


- with weakly interacting quarks (**nearly conformal, pQCD-like** matter), very limited para. space to reach two solar masses
- **high transition density** scenario
  - resembles no PT; short extension
- **low transition density** scenario
  - no twin / third-family stars

Generic ansartz

$$\varepsilon(p) = \varepsilon_{\text{trans}} + \Delta\varepsilon + c_{\text{QM}}^{-2}(p - p_{\text{trans}})$$

Generic constraints on 1st-OPT from heavy pulsars



Alford & **SH**
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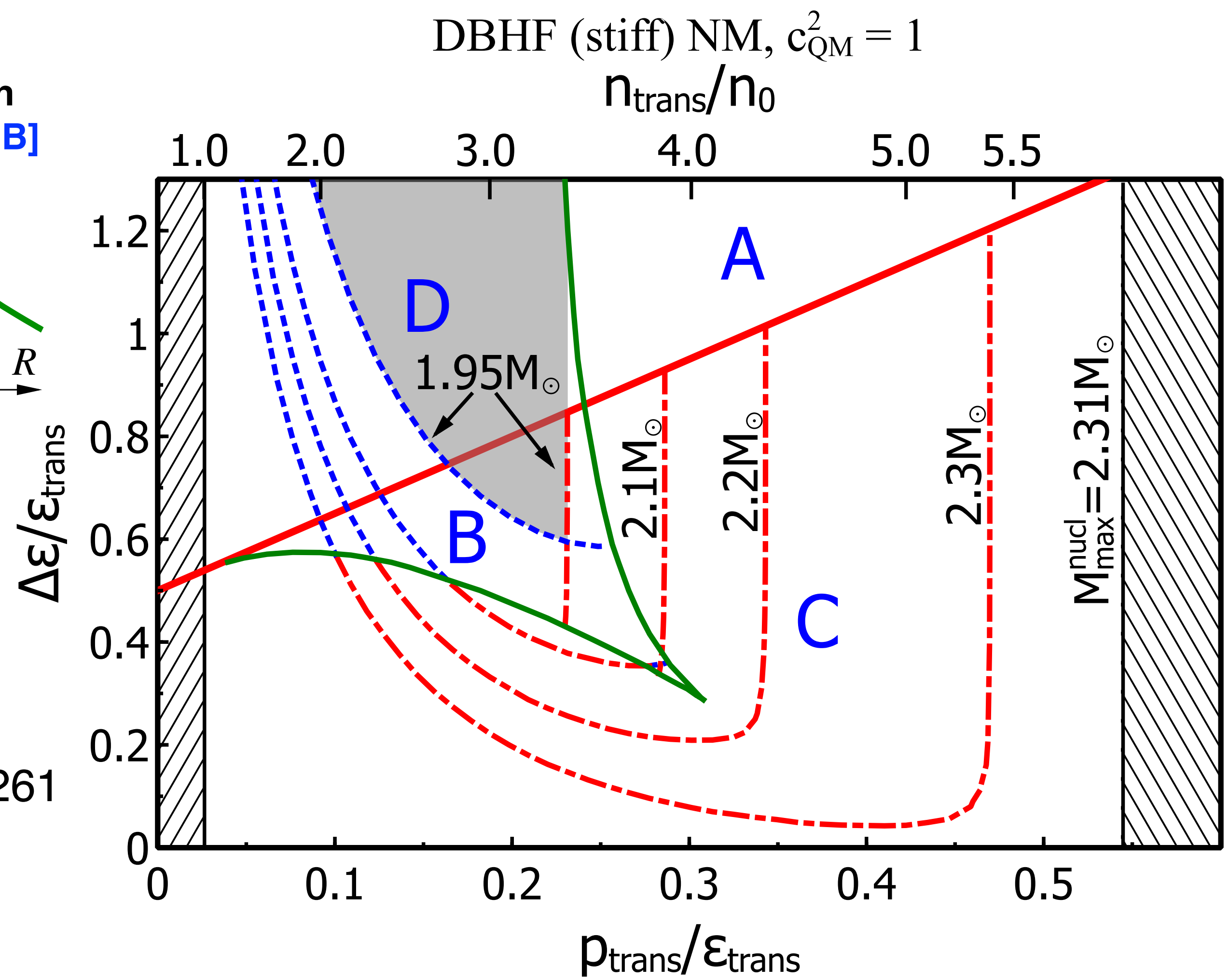
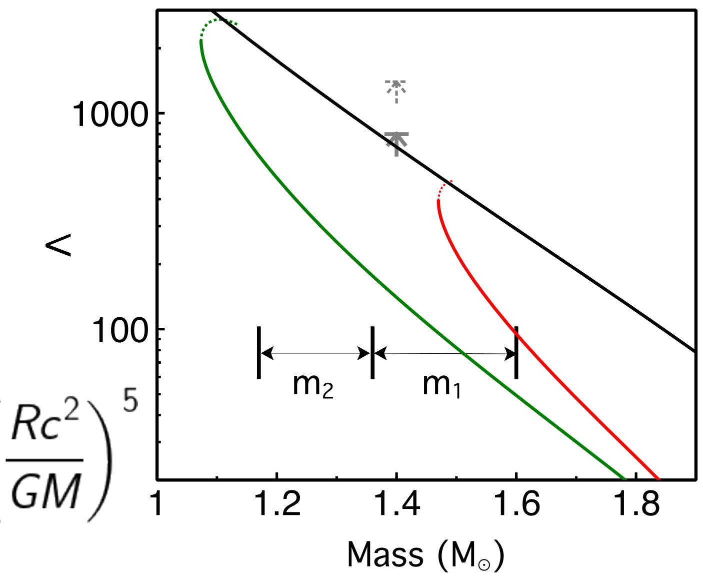


- with **maximally stiff** QM, a much broader range of the transition density is allowed
- distinct feature of the (twin) **disconnected** branch
- observability via e.g. future measurements of inspiral GWs from a **population** of events

Generic ansartz

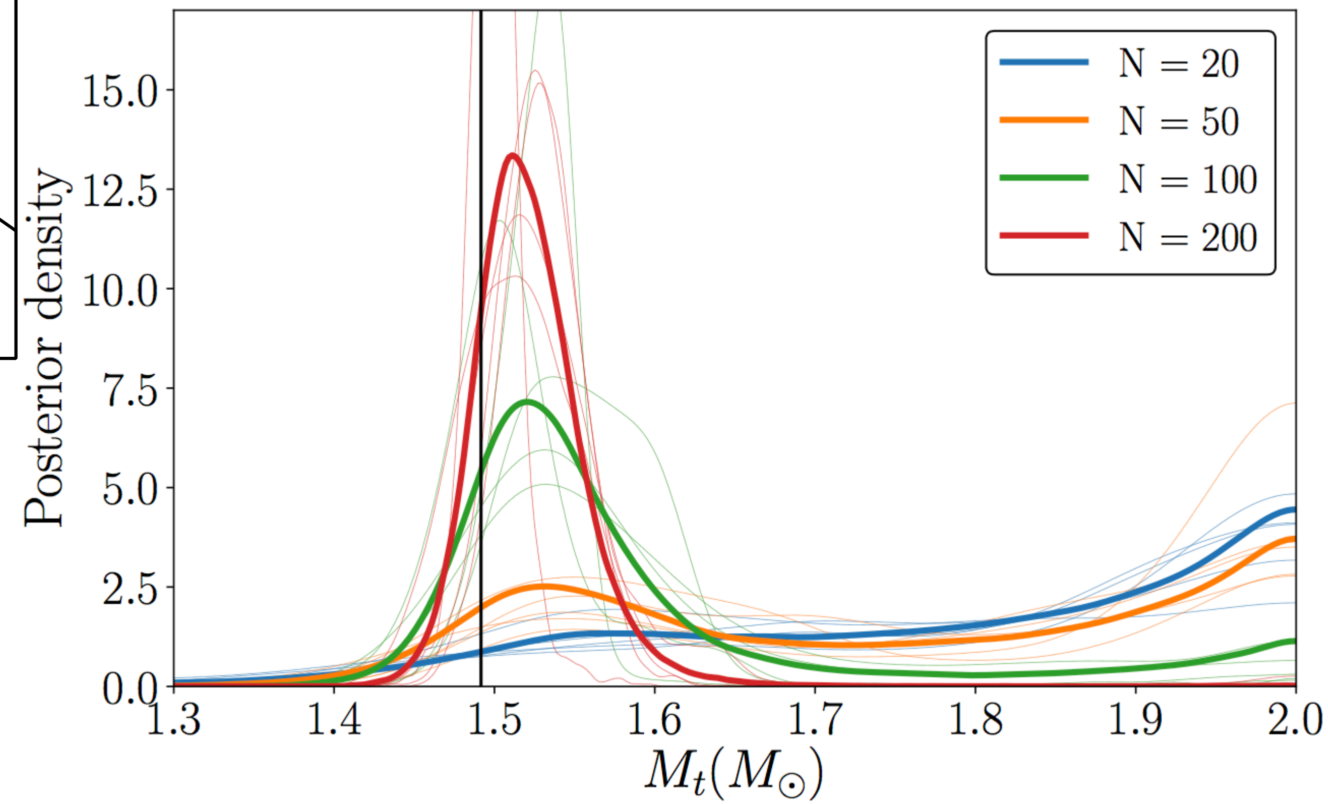
$$\varepsilon(p) = \varepsilon_{\text{trans}} + \Delta\varepsilon + c_{\text{QM}}^{-2}(p - p_{\text{trans}})$$

Best scenario with multiple BNS detections



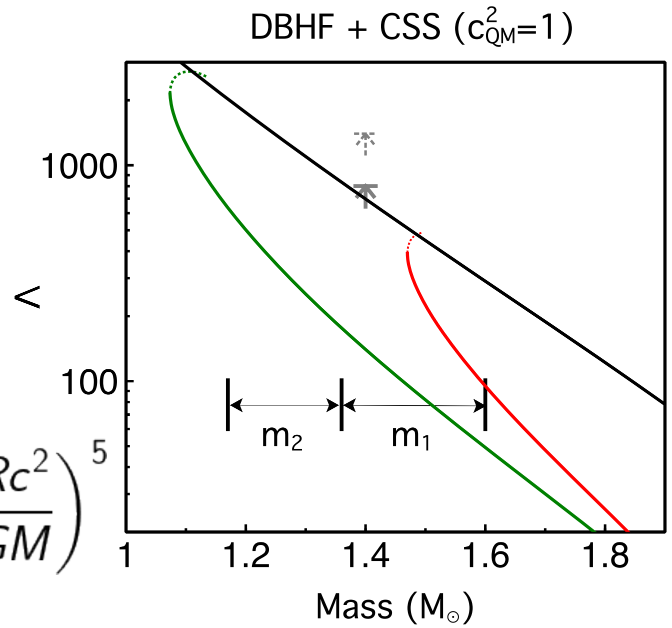
$$\Lambda \equiv \frac{\lambda}{M^5} \equiv \frac{2}{3} k_2 \left(\frac{Rc^2}{GM}\right)^5$$

Chatziioannou & **SH**, arXiv:1911.07091
SH & Steiner, arXiv:1810.10967



- most populated if the normal branch **> 13.5 km**
- **…**and the high density matter is still **strongly interacting** $c_s^2 \gtrsim 0.4$
  - might identify third-family stars (strong 1st-OPT) with **inspiral** GWs
  - requires multiple **[N~50-100]** future detections to separate different families: NS-NS, NS-HS, HS-HS mergers

Best scenario with multiple BNS detections



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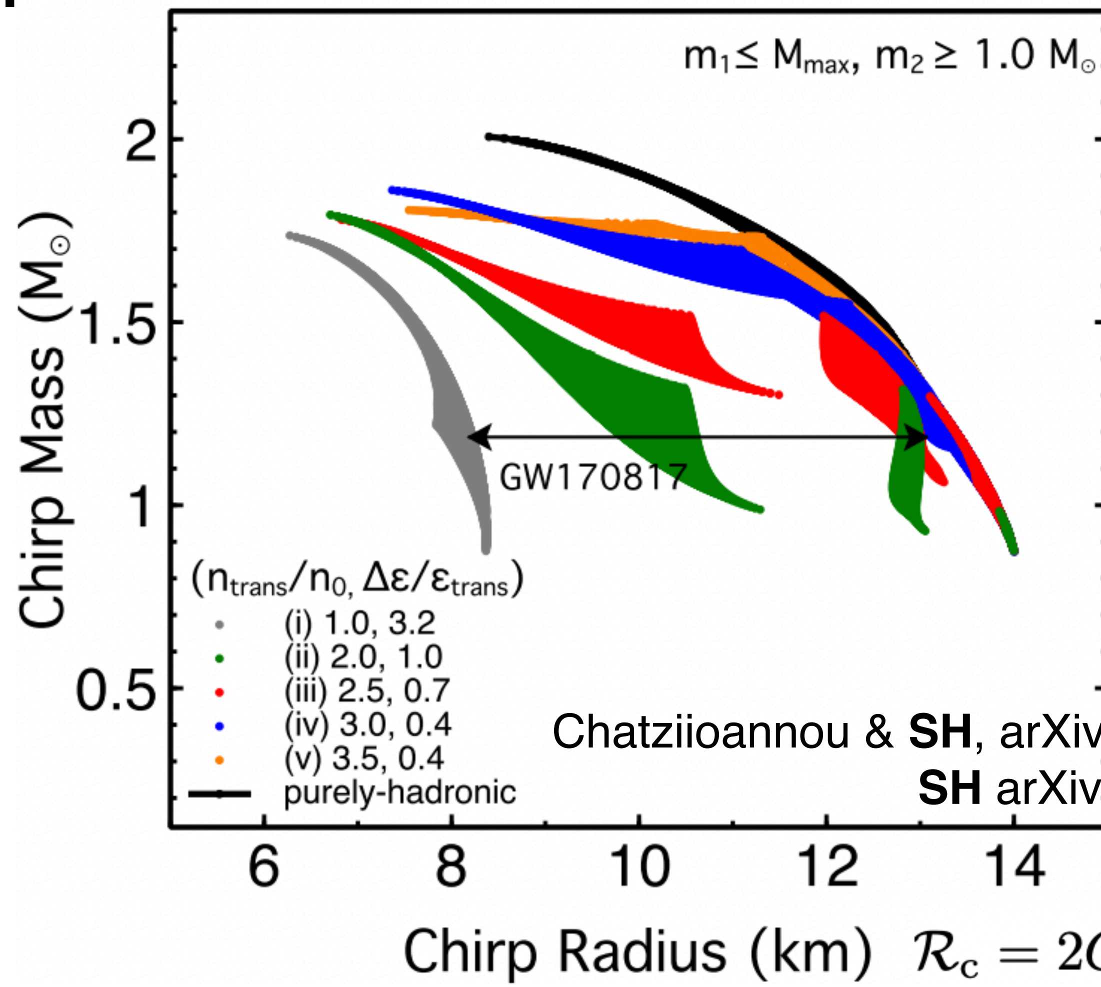

Chatziioannou & **SH**, arXiv:1911.07091
SH arXiv:1904.09918

$\mathcal{R}_c = 2G\mathcal{M}_c\tilde{\Lambda}^{1/5}/c^2$

- most populated if the normal branch **> 13.5 km**
- **…**and the high density matter is still **strongly interacting** $c_s^2 \gtrsim 0.4$
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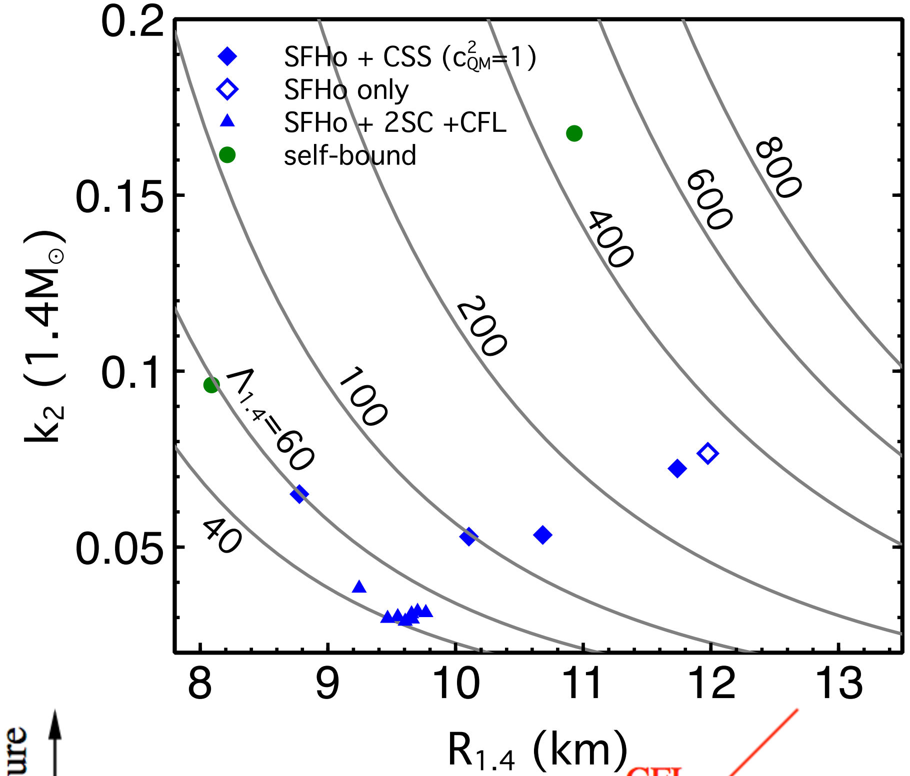
Other static observables?

SH & Steiner, arXiv:1810.10967



EoS-insensitive universal relations

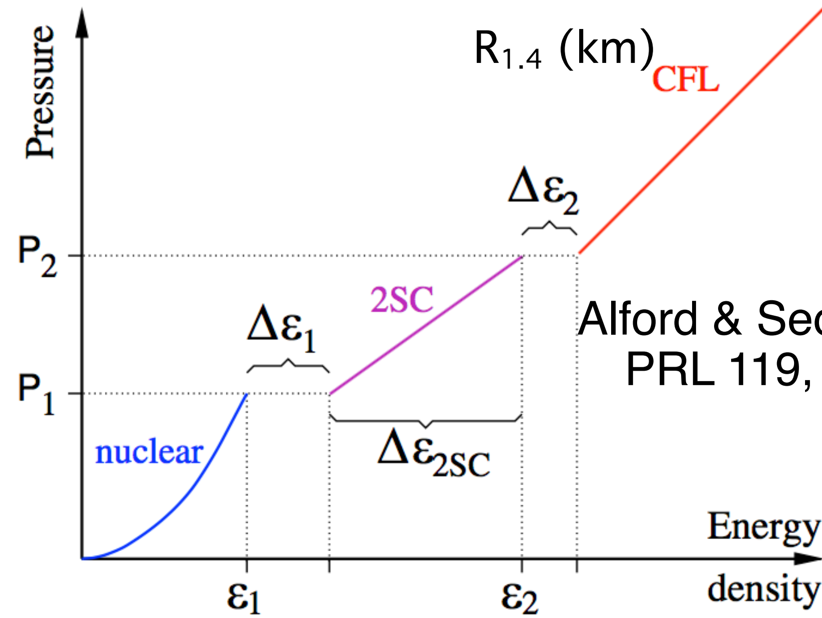
- moment of inertia vs. tidal deformability
- moment of inertia vs. compactness

Possible exceptions

- sequential first-order phase transitions
- (bare) self-bound strange quark stars (SQSs)
- novel solid phases e.g. crystalline color-superconducting (CCSC) matter

Even more exotic

- dark halos, vacuum energy etc. can modify tidal properties

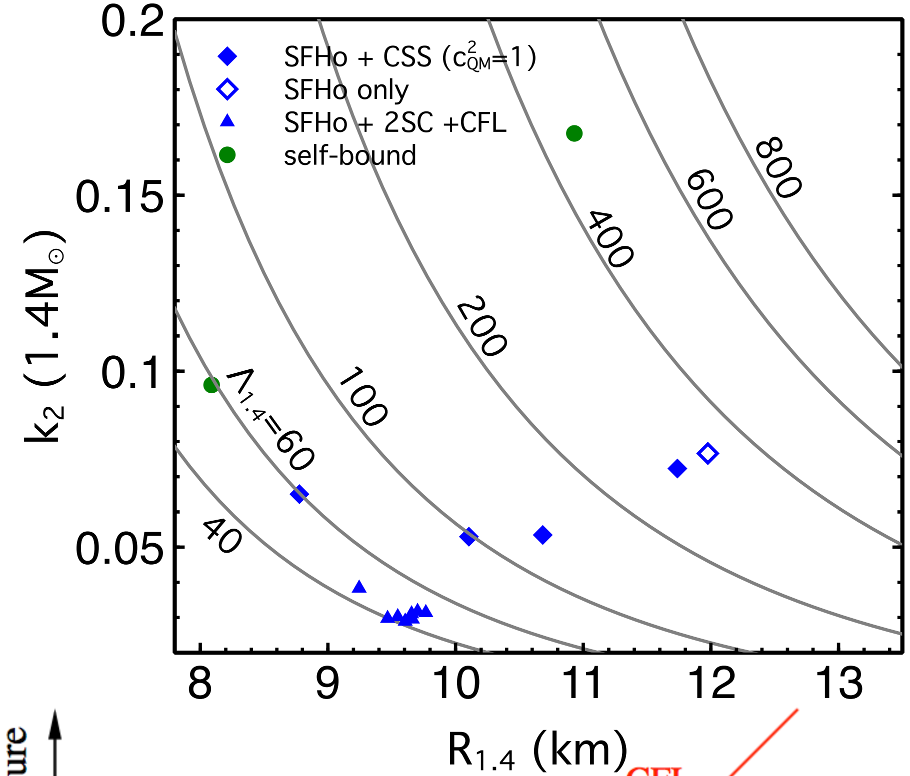


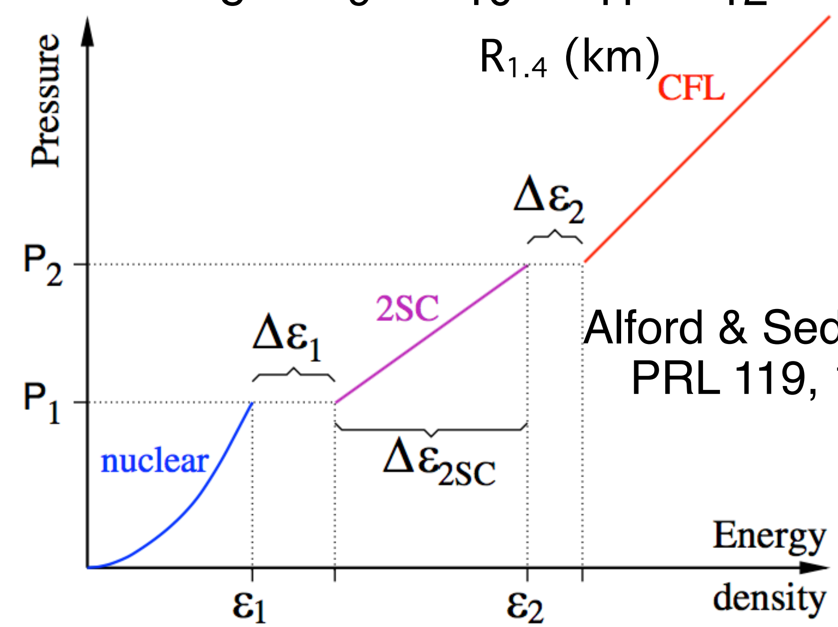
Alford & Sedrakian, PRL 119, 161104 (2017)

Some extreme values predicted

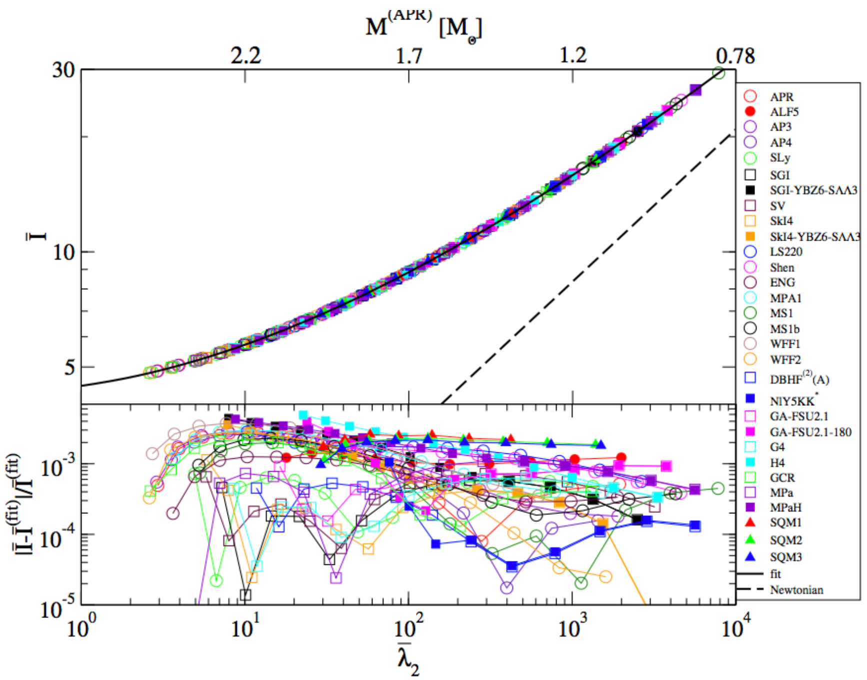
- smallest radius: self-bound SQS
- smallest tidal deformability & tidal Love number: sequential phase transitions (new!)
- largest tidal Love number: self-bound SQS
- largest moment of inertia: self-bound SQS
- largest deviation from quasi-universal relations: sequential phase transitions (new!)

SH & Steiner, arXiv:1810.10967

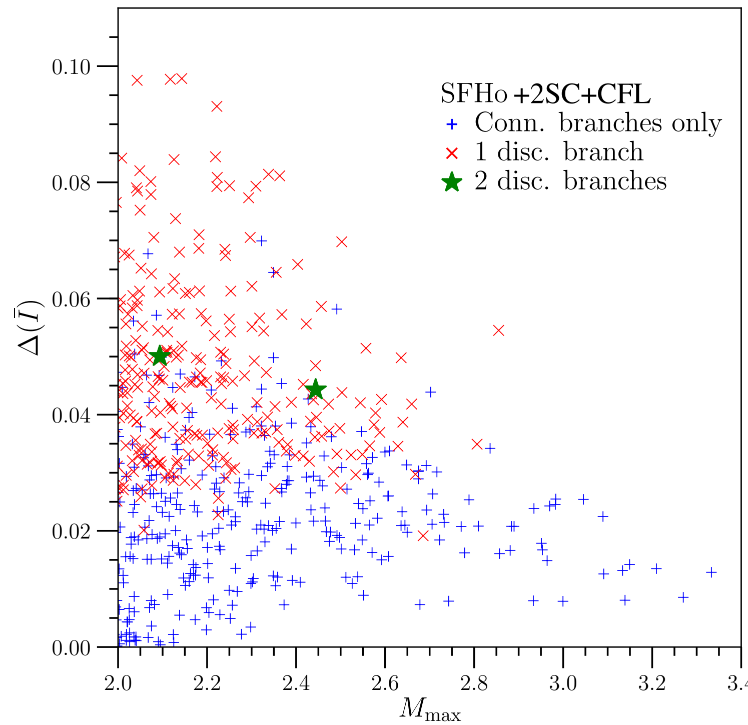




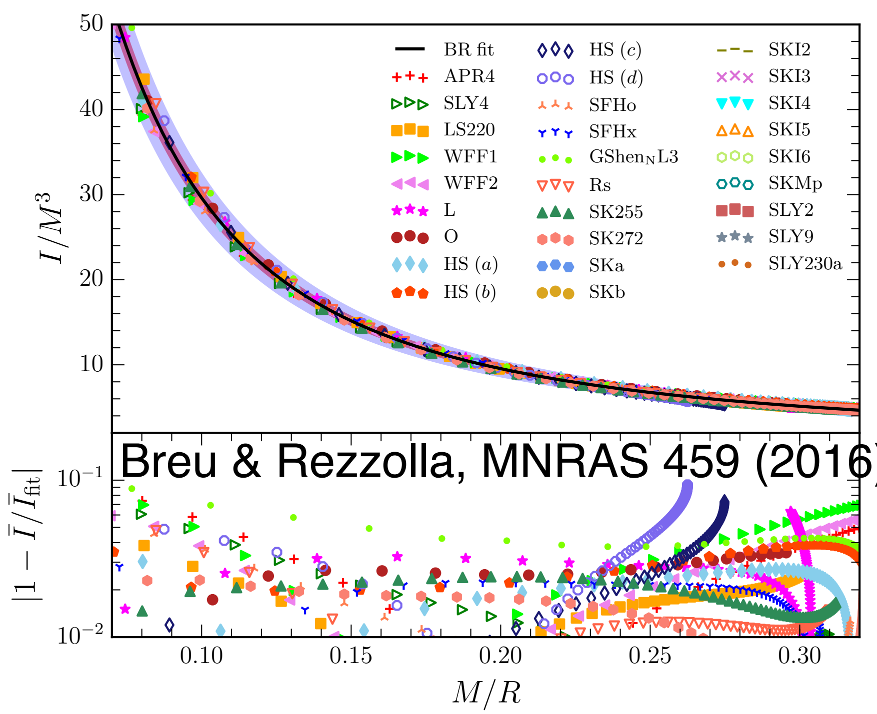
Alford & Sedrakian, PRL 119, 161104 (2017)



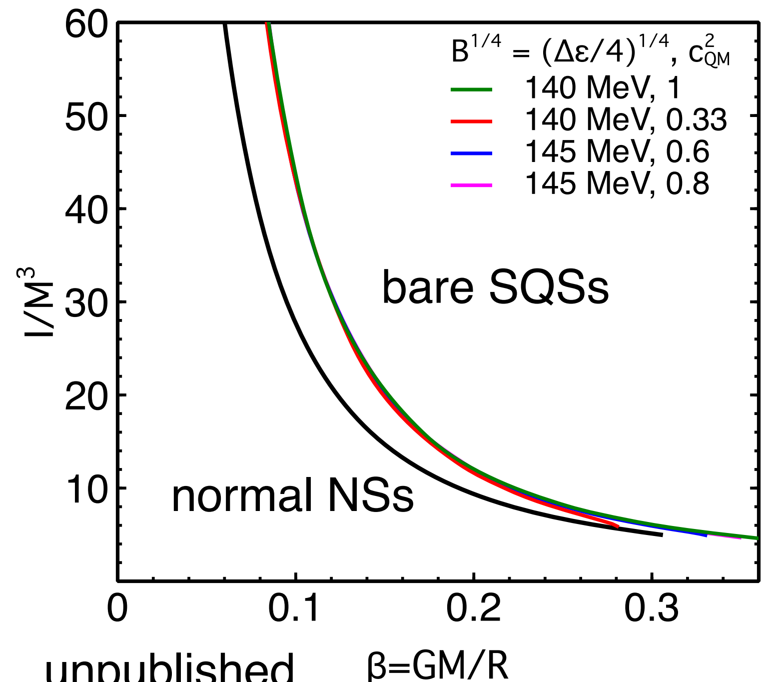
Yagi & Yunes, Phys. Rept. 681 (2017)



arXiv:1810.10967

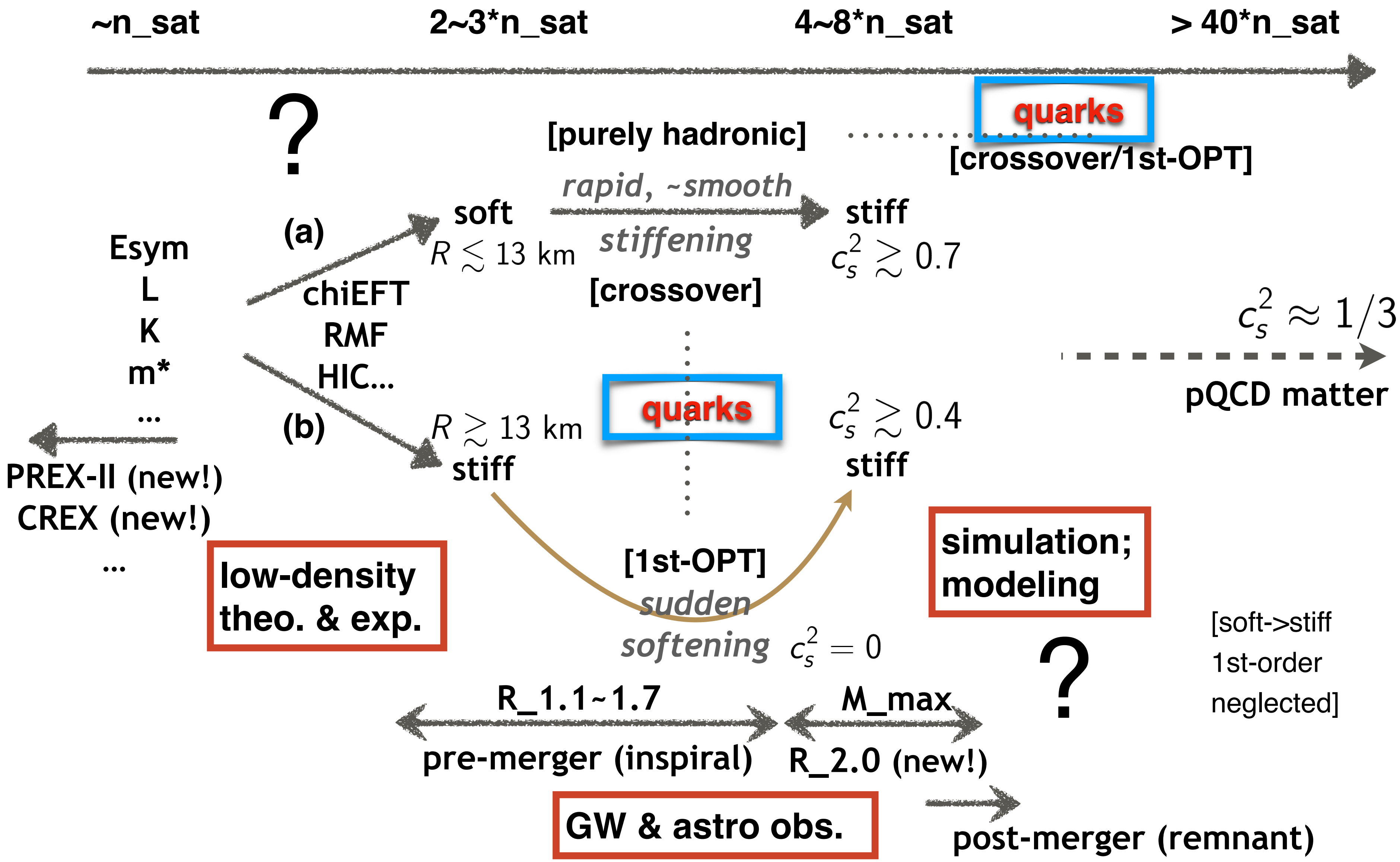


Breu & Rezzolla, MNRAS 459 (2016)



unpublished

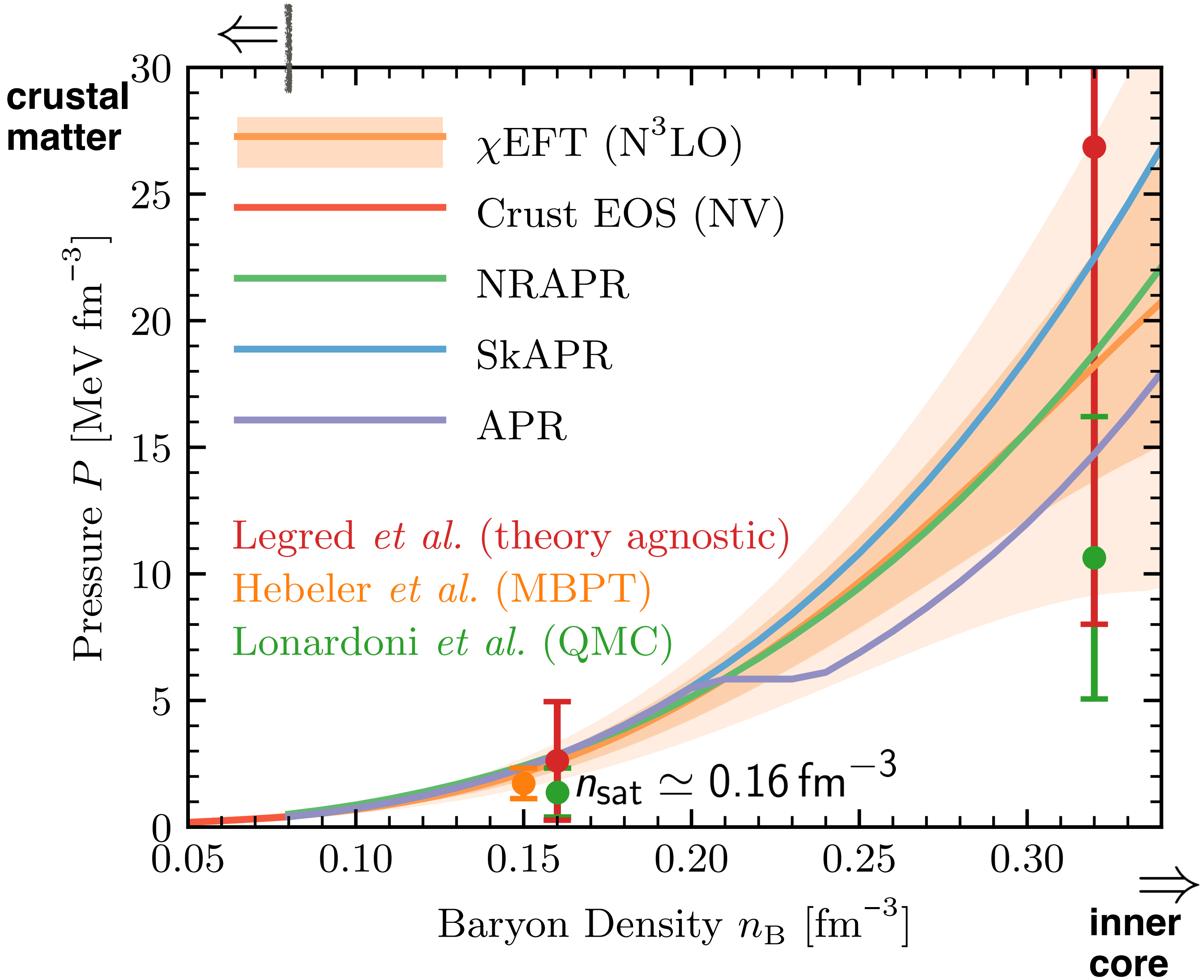
Limiting ground state EoS for dense matter



Challenges and prospects of finding quark matter - part A

1) 1st-order PT: stiff nuclear matter preferred for typical quark models; possible onset of deconfined quarks in the pre-merger components
2) crossover: soft nuclear matter required (limited by GW170817 & NS radius @~1.4 Msolar)
3) weakly interacting quarks are almost ruled out for canonical NSs, except maybe in the innermost region of most-massive ones, and/or temporarily in hot explosive environments
4) distinguishability via M-R only possible for strongest 1st-OPT that leads to separate branches
5) generic bound on the sound speed in dense QCD highly sensitive to M_max and/or large (?) radii @ 2 Msolar~J0740

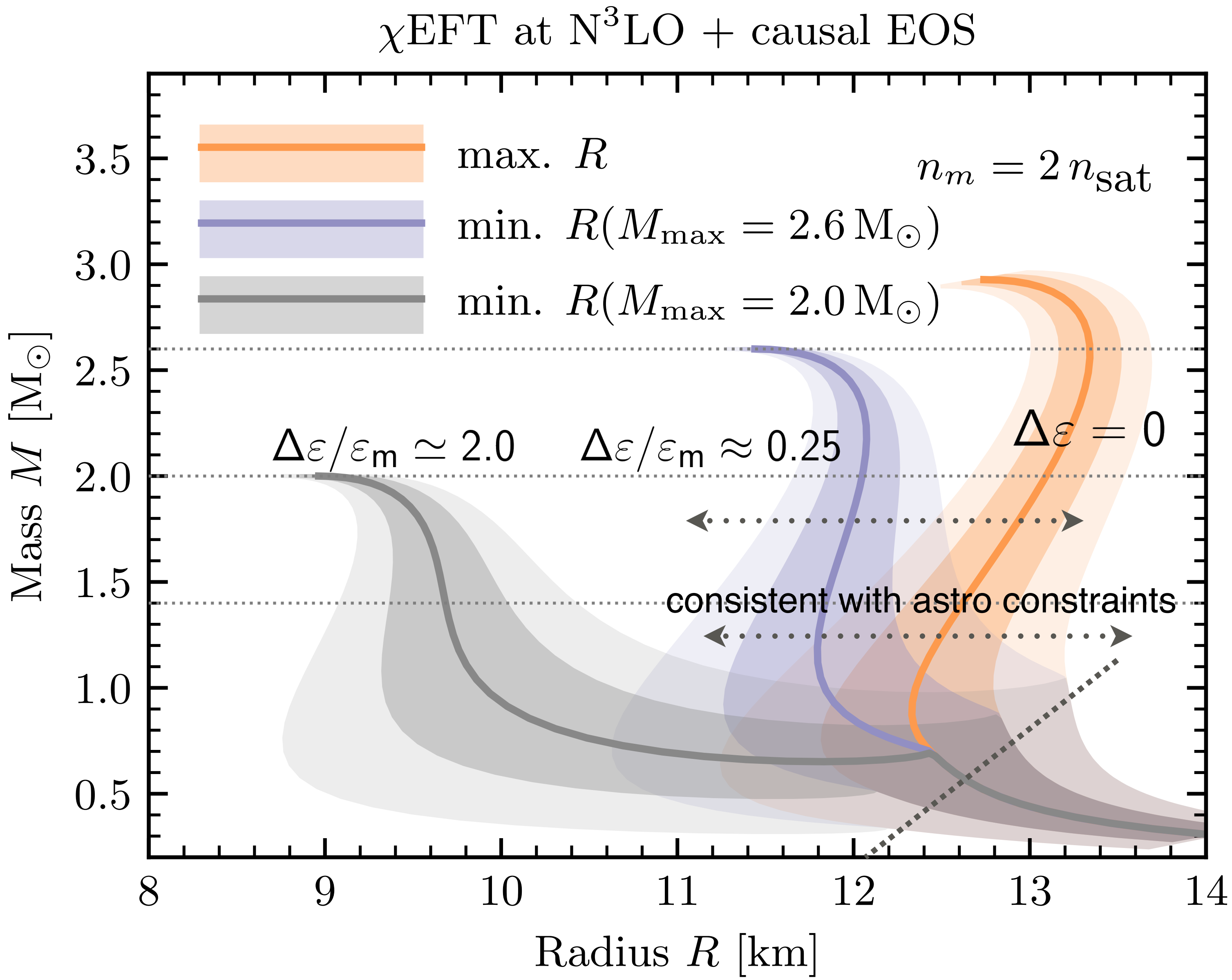
The “golden window” of nuclear matter



Drischler, **SH** & Reddy
arXiv:2110.14896

- pressure at low densities **[outer core]** controls typical NS radii: stiff or soft?
- reliably **quantified** uncertainties from chiEFT for beta-equilibrated NSM
- less than **~5%** deviation from PNM pressures
- to **extrapolate** or match at higher densities in the **inner core**

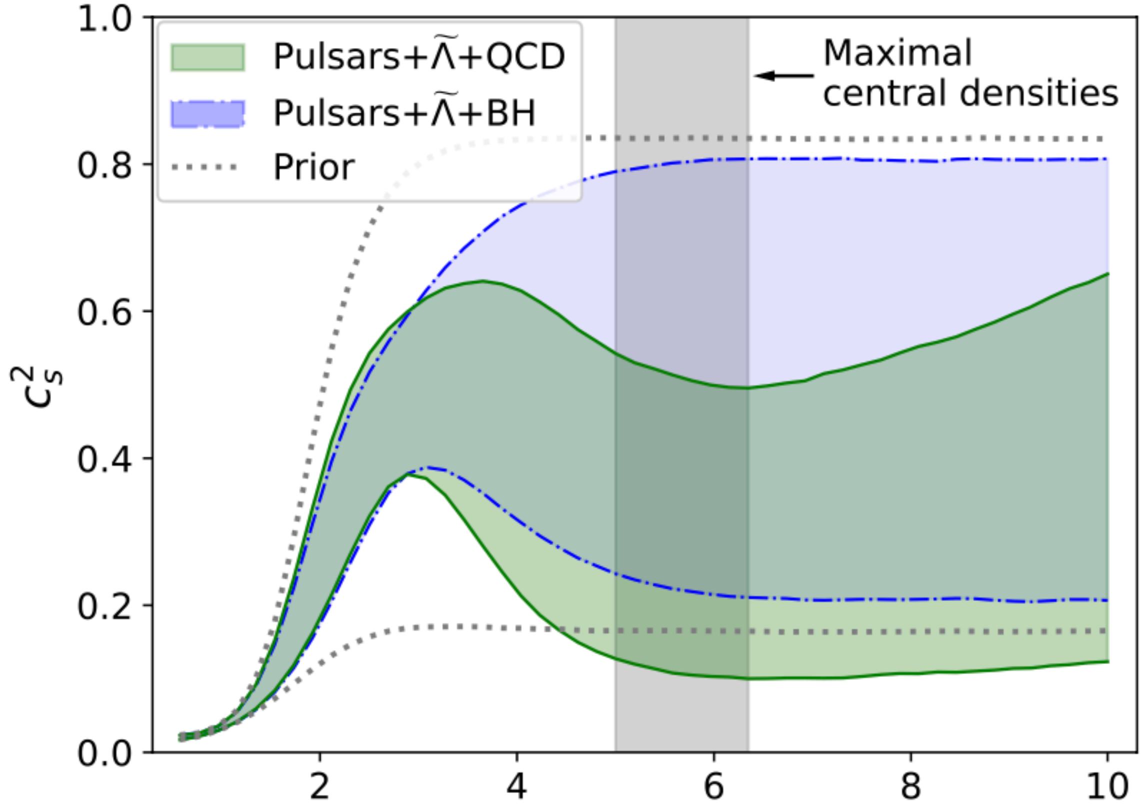
Generic bounds from causality



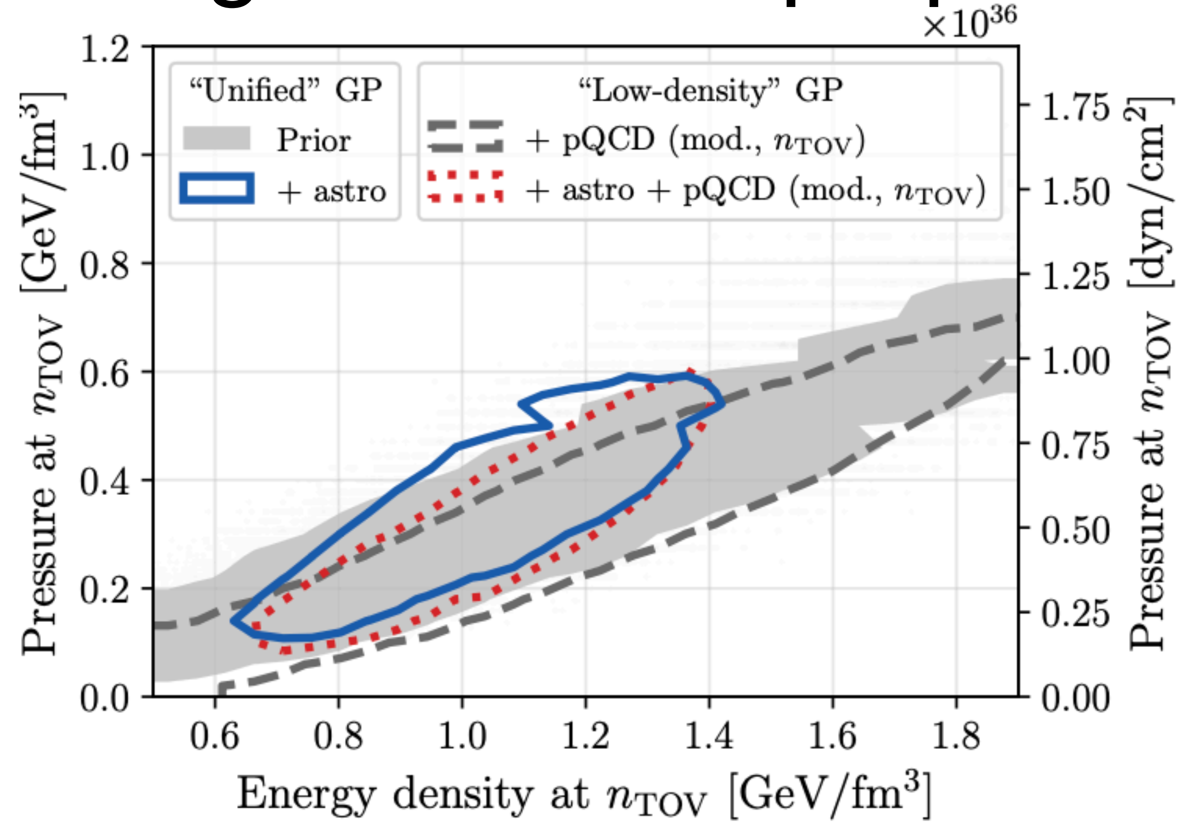
Drischler, **SH**, Lattimer, Prakash, Reddy and Zhao, arXiv:2009.06441

- pressure at low densities **[outer core]** controls typical NS radii: stiff or soft?
- reliably **quantified** uncertainties from chiEFT for beta-equilibrated NSM
- absolute **causal** limits imposed at high densities
- confronted with data: **interplay** between M_max and NS radii

Ultra-high density regime: affecting TOV-mass prop.?



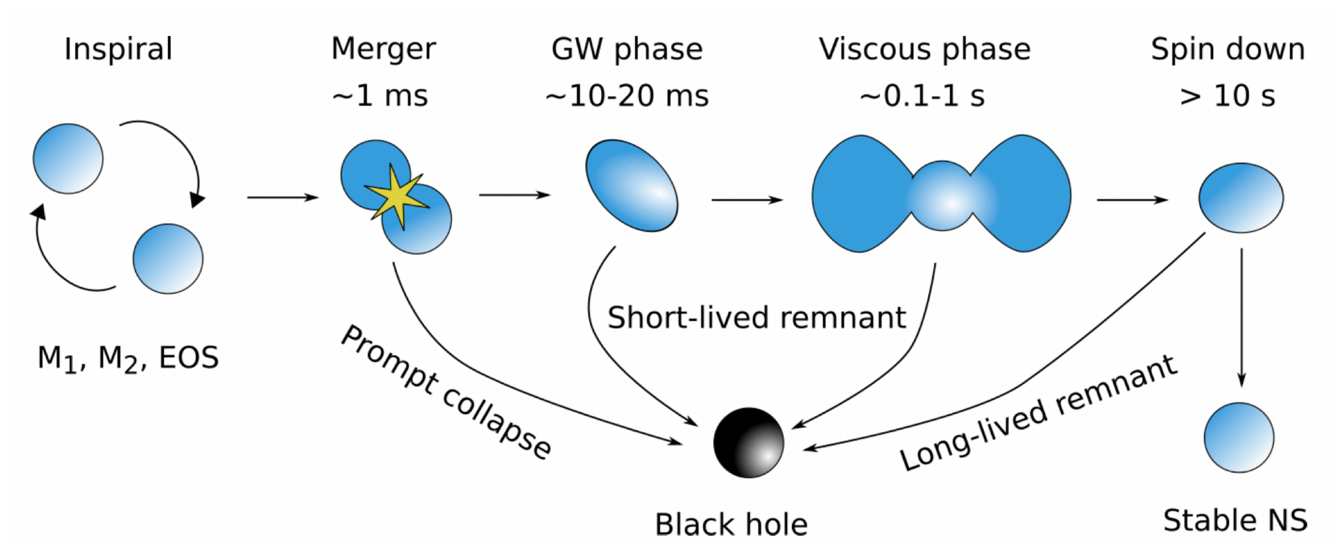
Gorda et al. arXiv:2204.11877



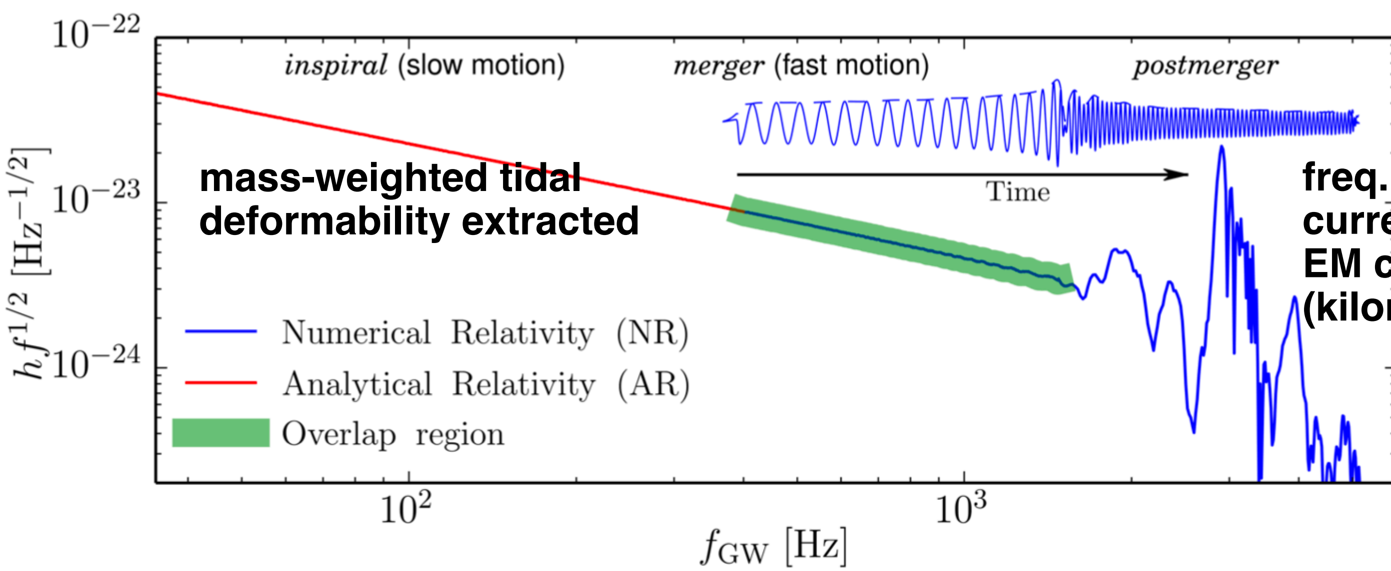
Finch et al. (including **SH**) arXiv:2505.13691

- employing uncertainty band from pQCD EoS calculations at nonzero \mu (need to specify choice of renormalization scale)
- pQCD input seems to favor sound speed already decreasing around maximal NS densities, but little to no impact on macroscopic observables

Finding QM in BNS mergers?



Radice et al. (2020)



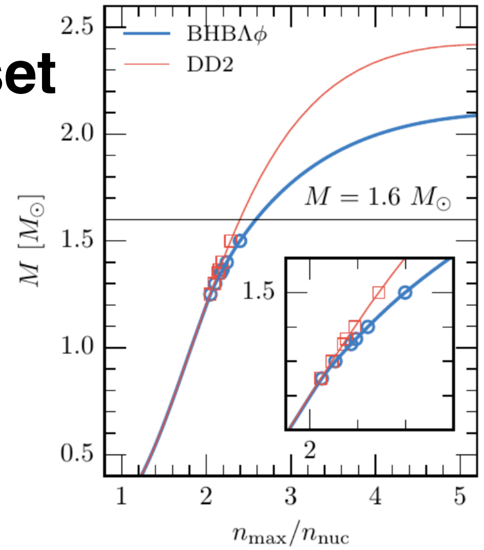
mass-weighted tidal deformability extracted

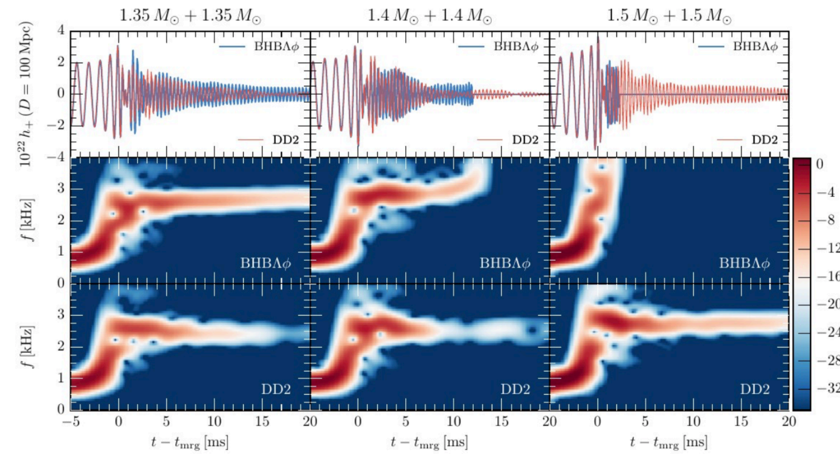
freq. too high wrt current sensitivity; EM counterparts (kilonovae) seen

Uncertainty wrt (degenerate) softening effects

hyperon onset

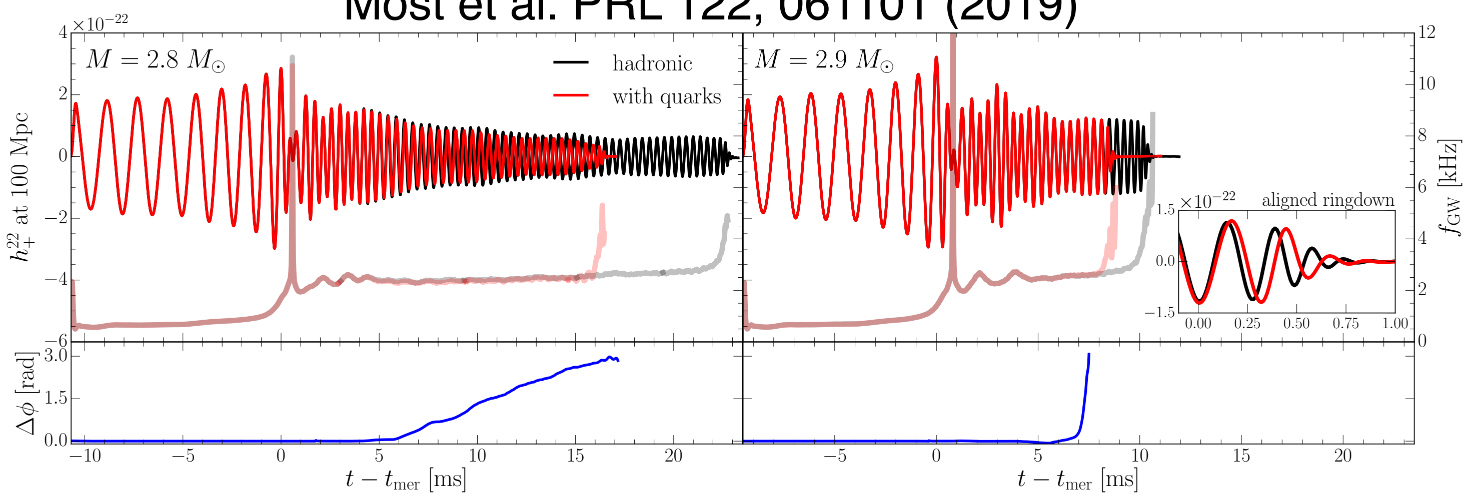
- more compact remnant (higher central density)
- earlier collapse; higher frequency





Radice et al. ApJL 842, L10 (2017)

Most et al. PRL 122, 061101 (2019)

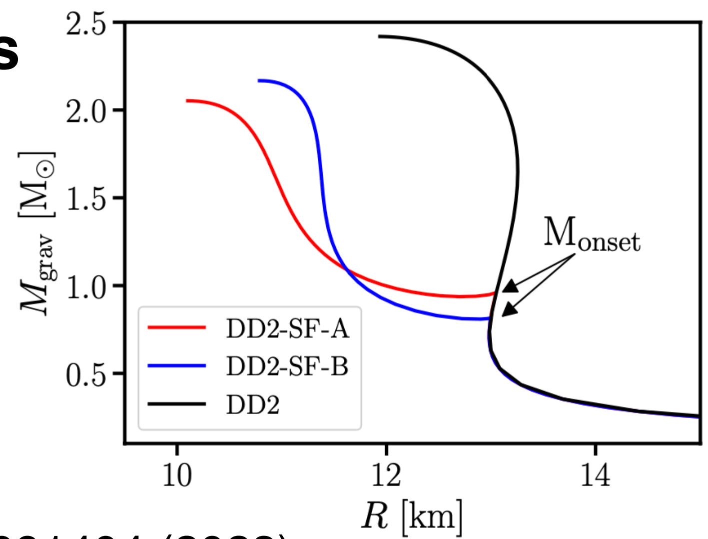


1st-OPT to soft quark matter after merger

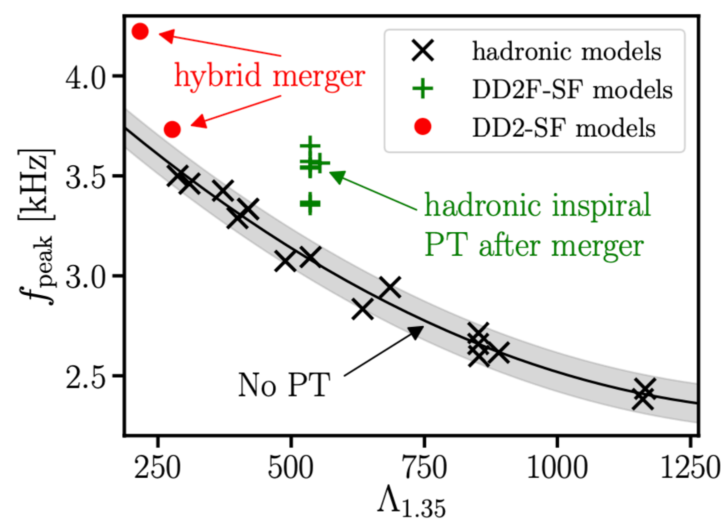
Uncertainty wrt (degenerate) softening effects

third-family “twin” stars

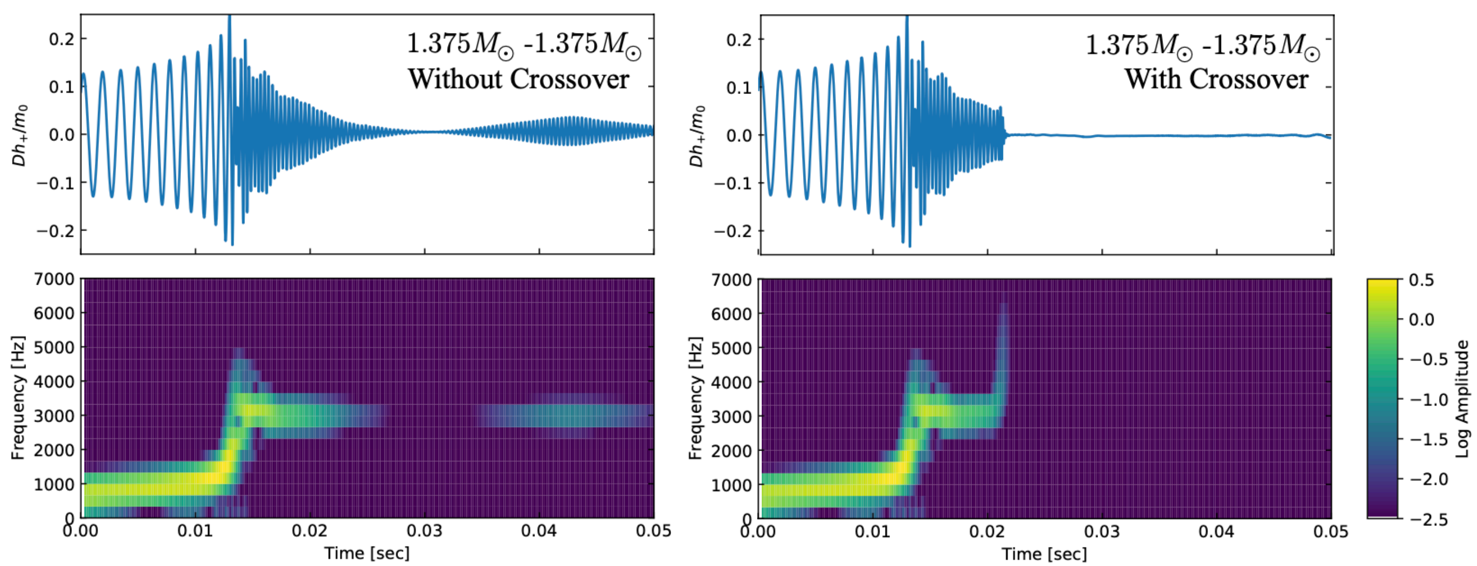
- ***stiff*** EoS at low density - DD2
- strong **1st-OPT** to ***stiff*** quark matter **before merger**



Bauswein & Blacker (2020)



Fujimoto et al. PRL 130, 091404 (2023)

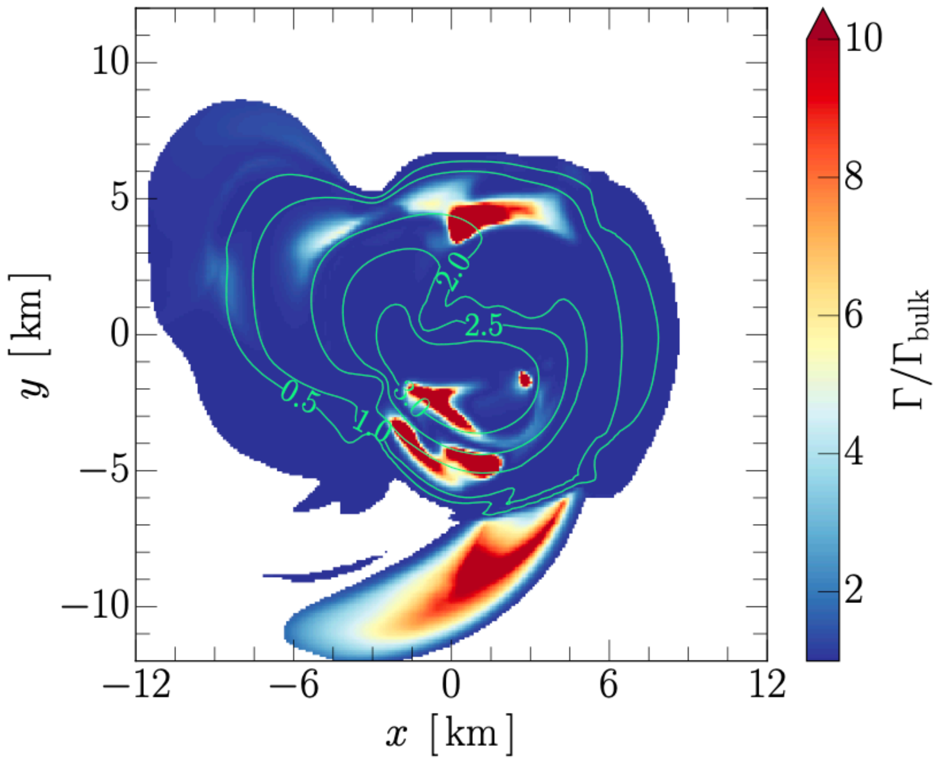


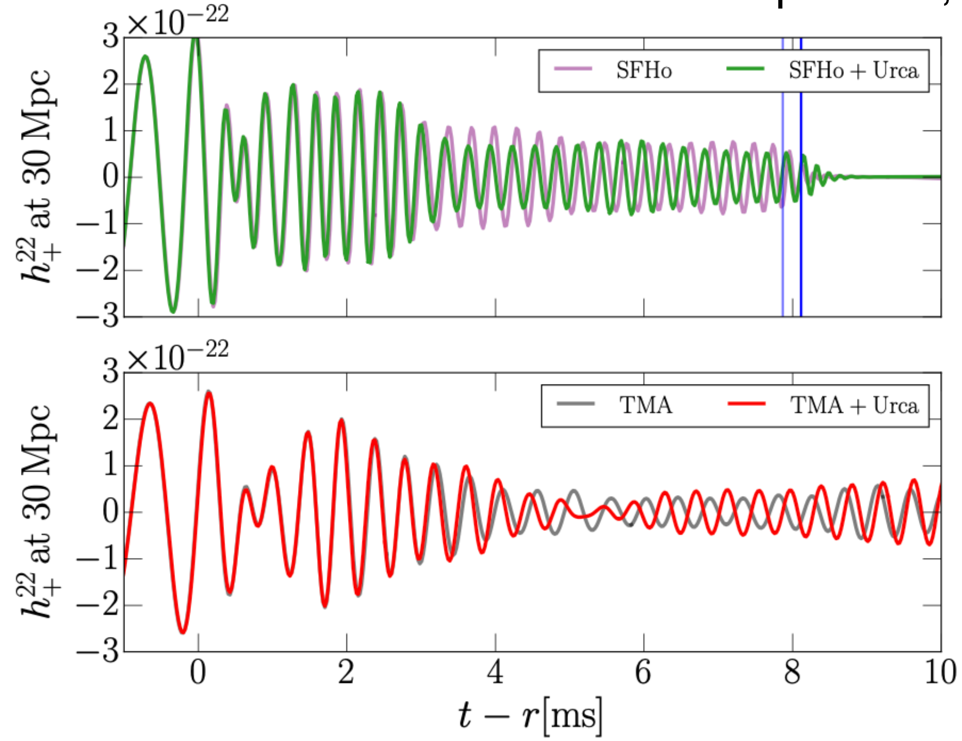
- ***soft*** EoS at low density ~N3LO chiEFT
- rapid ***stiffening*** within the crossover regime

crossover into *soft* quark matter after merger

Bulk viscous phase in merger

Most et al. ApJL 967, L14 (2024)





- remnant evolution: impact of weak-interaction driven out-of-equilibrium dynamics; potential **phase shift** of the gravitational-wave spectrum
- dissipation via **nucleonic** Urca processes on a millisecond timescale
- different channels of chemical equilibration for **hyperons, quarks etc.** -> bulk viscosities with different dependencies on temperature and density

Finite-temperature extension of EoS tables with PT

Hot Gibbs vs Maxwell

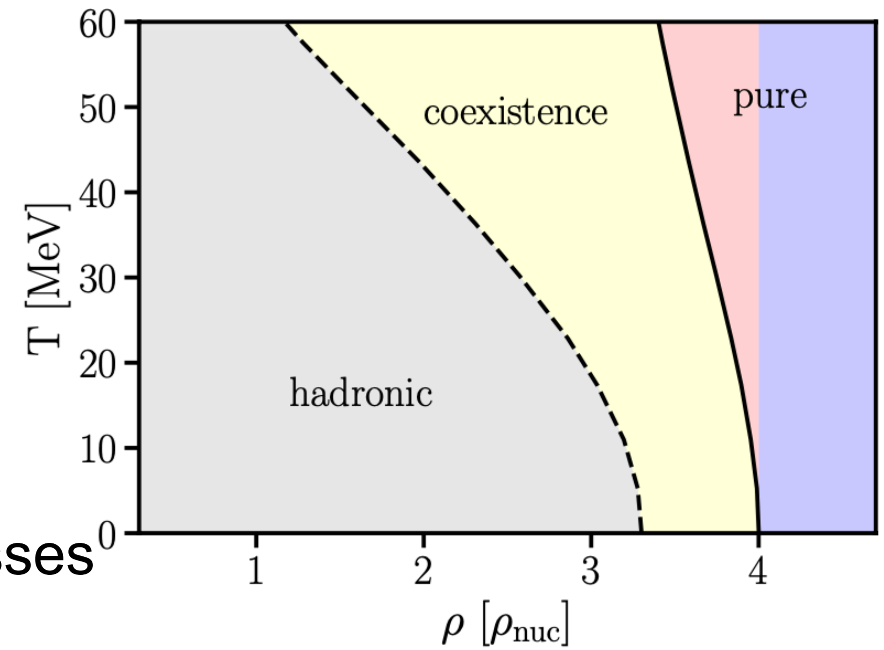
corr. to thermal gamma law

quarkyonic phase?

polytropic parametrizations

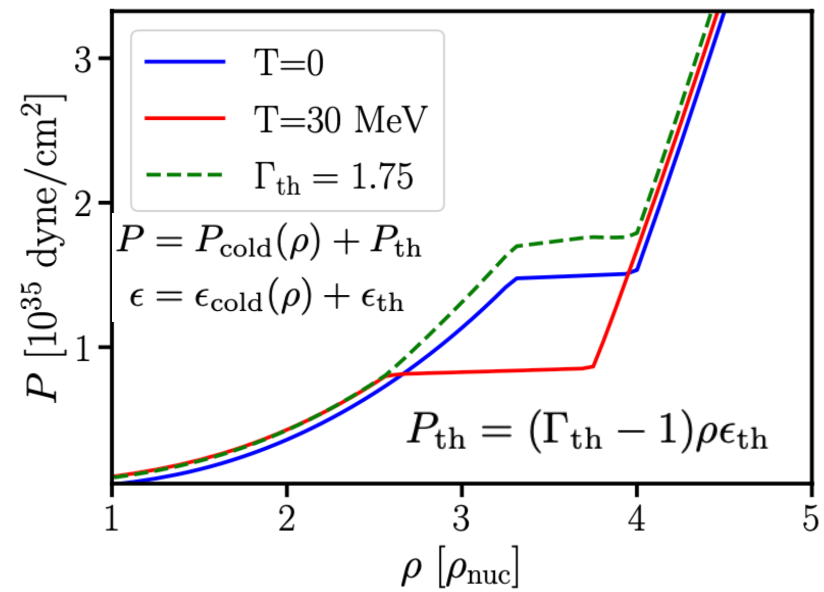
(derivatives of) effective masses

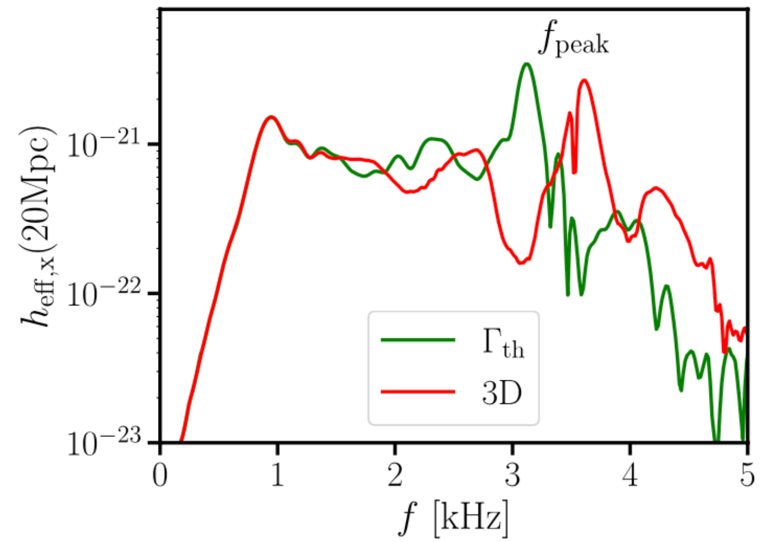
…



Blacker et al. arXiv:2304.01971

DD2F-SF-1 EoS





- traditional approach for thermal pressures (ideal-gas gamma law) fails for Maxwell construction substantially
- impact on NS merger dynamics and observables - GW freq. and spectrum, remnant lifetime, threshold mass

Finite-temperature extension of EoS tables with PT

Hot Gibbs vs Maxwell

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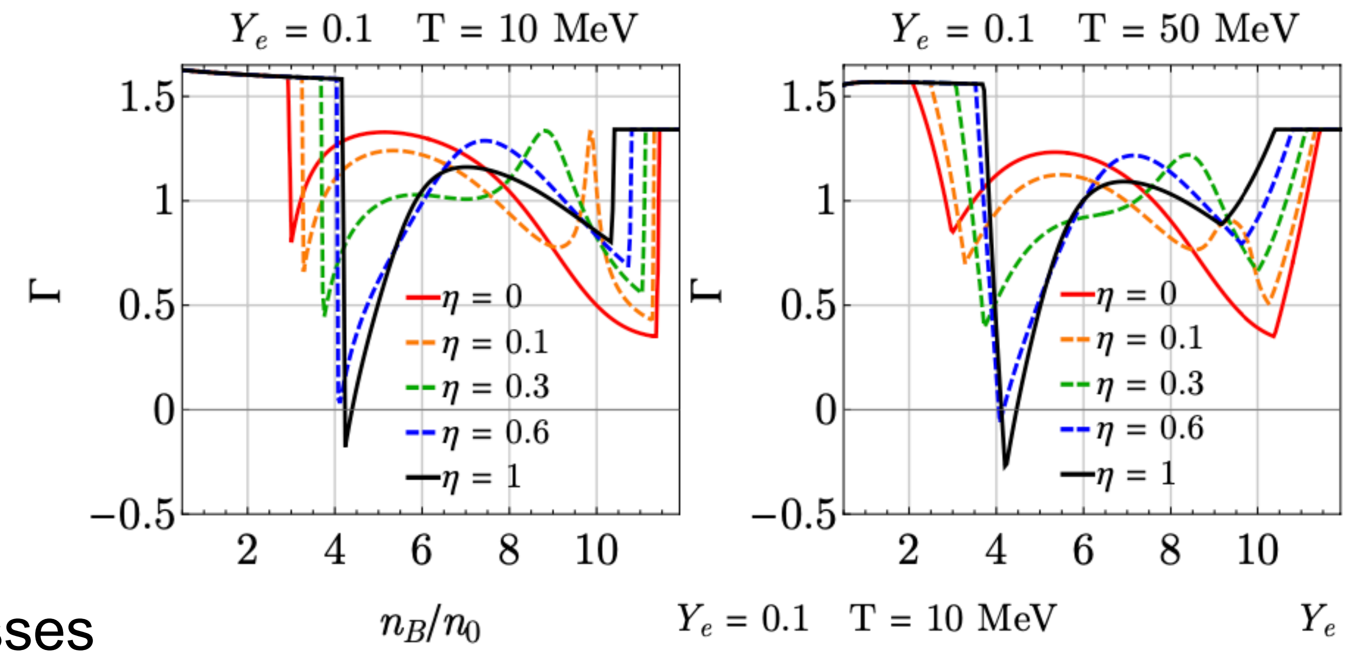
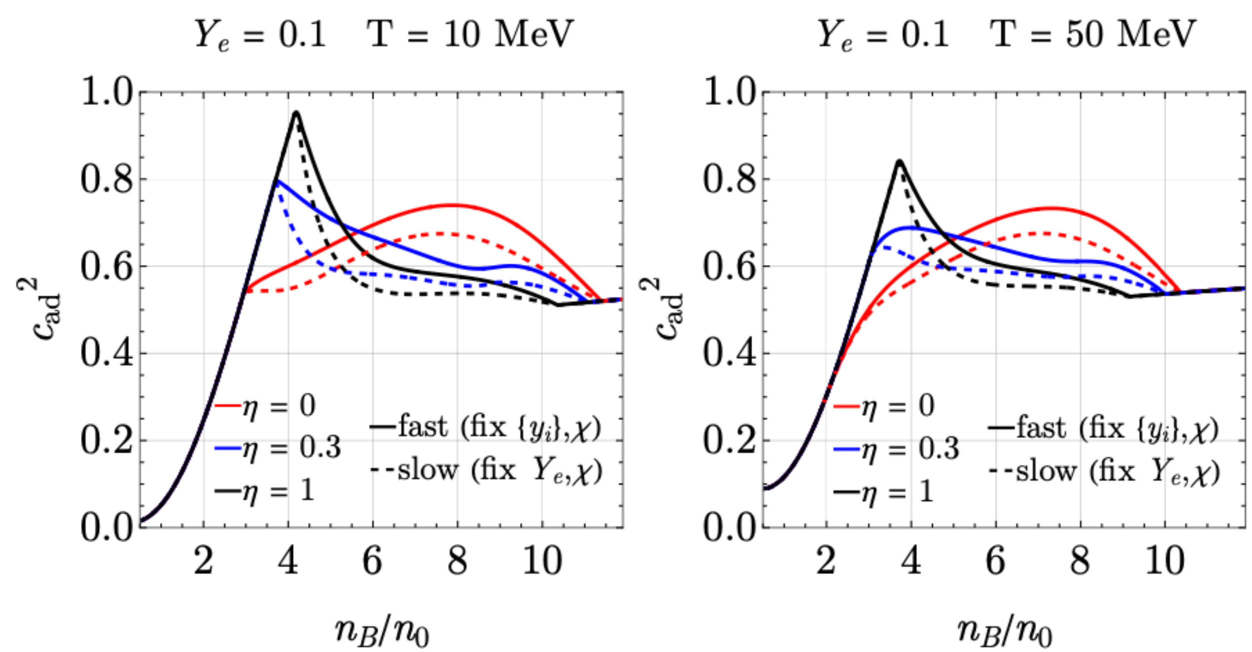


Constantinou, Guerrini, Zhao, **SH** and Prakash, arXiv:2506.20418



- more complicated for the Gibbs mixed phase scenario: both ends of the phase boundaries shifted to different densities at different temps with detailed structure in between

Stellar vibrations

matter imprints in **transient** GWs

- tidal effects on pre-merger (inspiral) waveform of BNS mergers
- tidal disruptions in NS-BH mergers
- oscillations of merger remnant
- oscillations in supernova post-collapse phase

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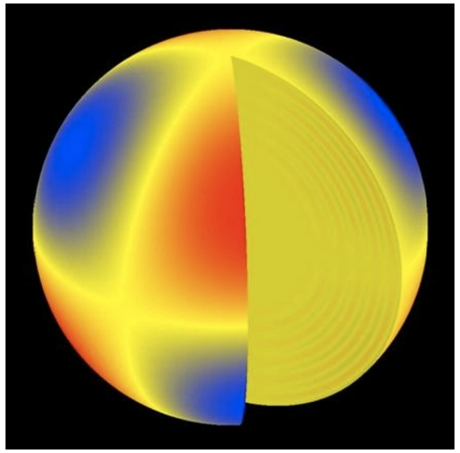
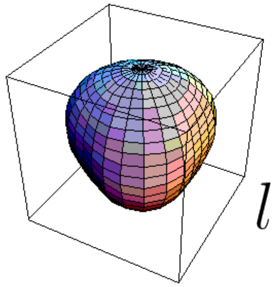
promising sources for XG detectors



stable oscillation modes (“ringing”) -> **continuous** GWs

- ***f*-mode (fundamental mode)** scales with average density
- *p*-mode (pressure mode) probes the sound speed
- ***g*-mode (gravity mode)** sensitive to **composition**/thermal gradients
- *w*-mode, *s*-mode, *i*-mode/*r*-mode..



$l = 3, \ m = 3$

small amplitude oscillations -> weak (continuous) emission of GWs

..unless they become unstable

Restoring forces and typical frequencies

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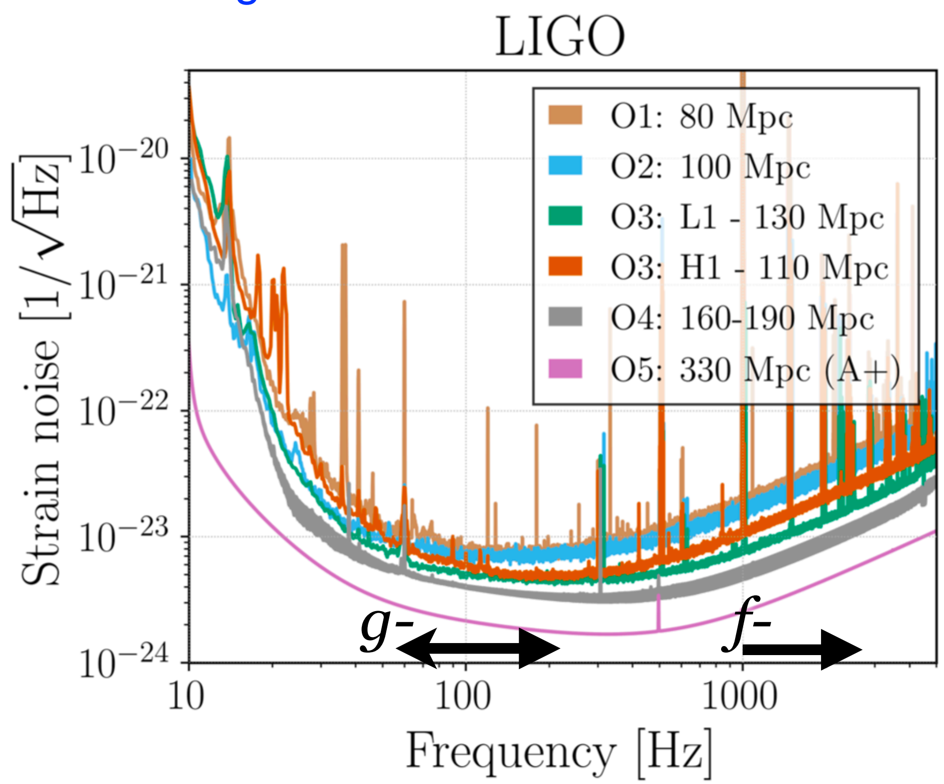


promising sources for XG detectors

oscillation modes ("ringing") -> **continuous** GWs

- *p*-mode/*f*-mode: main restoring force is the pressure (>1.5 kHz)

$$\nu \approx \sqrt{\frac{GM}{R^3}}$$

- inertial modes (*r*-modes): main restoring force is the Coriolis force

$$\nu \approx \Omega$$

- *w*-modes: pure space-time modes i.e. only in GR (>5 kHz)

$$\nu \approx \frac{1}{R}\left(\frac{GM}{Rc^2}\right)$$

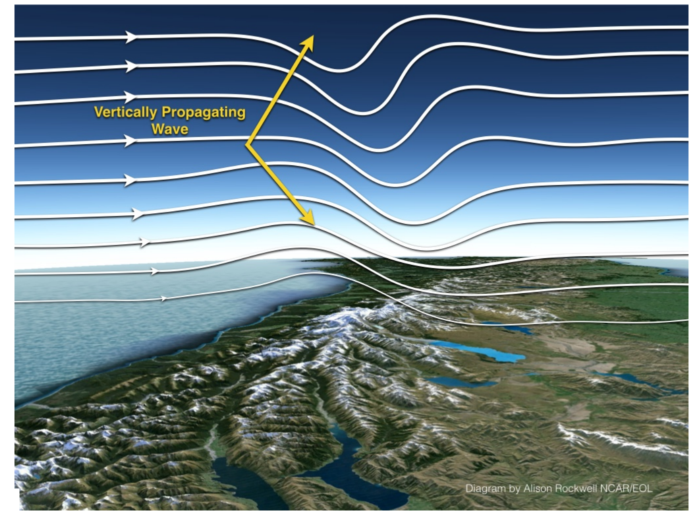
- shear-/torsional-; many other more

g-modes (gravity modes)

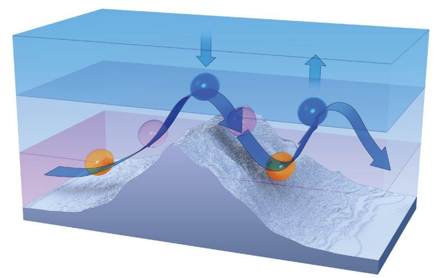
restoring forces from buoyancy/gravity

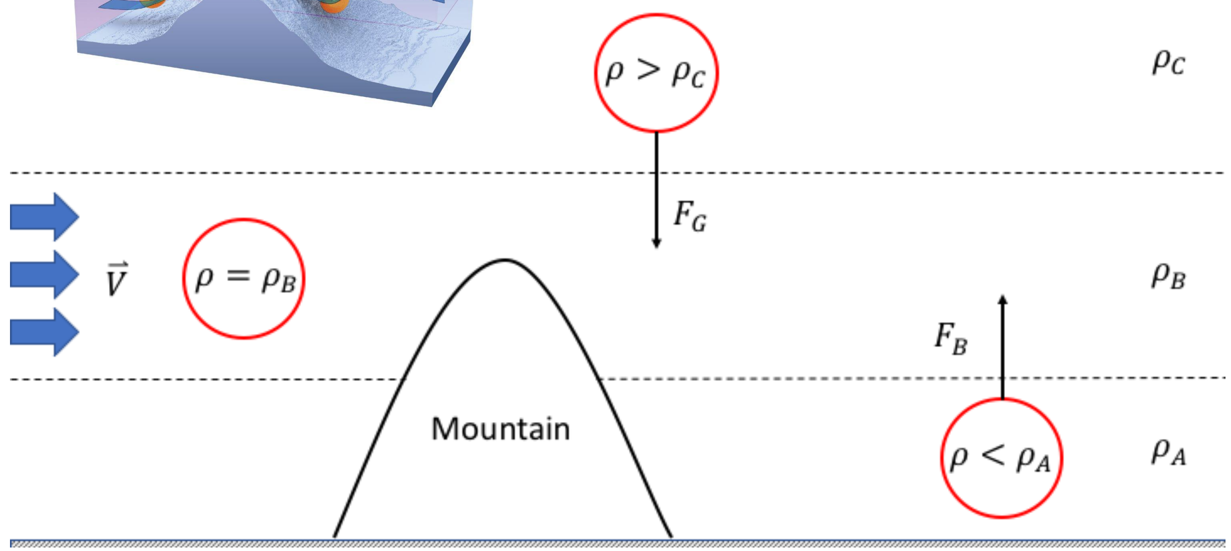
e.g. atmospheric/ocean waves

- hydrostatic equilibrium: gravitational force balanced by pressure gradient force
- perturbed from equilibrium -> gravity or buoyancy pulls/pushes it back -> oscillation



AUSTRALIAN ANTARCTIC PROGRAM





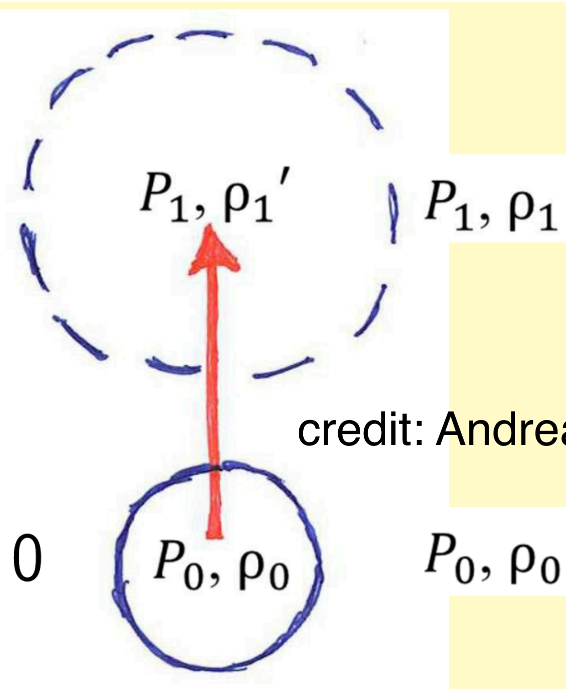
Brunt–Väisälä (buoyancy) frequency

- pressure instantaneously equilibrated, but not for composition and density
- continuity equation & the equation of motion
- “adiabatic” (composition frozen) sound speed vs. “equilibrium” sound speed

$$\Delta\rho = -\rho\frac{\partial^2\xi}{\partial t^2}$$

$$\downarrow \vec{g}$$

$$\frac{\partial^2\xi}{\partial t^2} + N^2\xi = 0$$



credit: Andreas Reisenegger

$$dp/dr = -\rho g$$

[hydrostatic equilibrium]

$$N^2 \equiv g^2\left(\frac{1}{c_{eq}^2} - \frac{1}{c_{ad}^2}\right)e^{\nu-\lambda}$$

← local metric coefficients

$$c_{eq}^2 = \left(\frac{dp/dr}{d\varepsilon/dr}\right) \qquad c_{ad}^2 = \left(\frac{\partial p}{\partial\varepsilon}\right)_{y_i}$$

NS core g-modes

local Brunt–Väisälä (buoyancy) frequency

$$N^2 \equiv g^2 \left(\frac{1}{c_{eq}^2} - \frac{1}{c_{ad}^2} \right) e^{\nu - \lambda}$$

- stability criterion: $N^2 > 0 \leftrightarrow$ stable stratification
- assuming cold NS (zero temperature/ entropy); no convection or turbulence

$$\text{osc. amplitude} \sim e^{i\omega t},\ \omega \propto \sqrt{N^2}$$

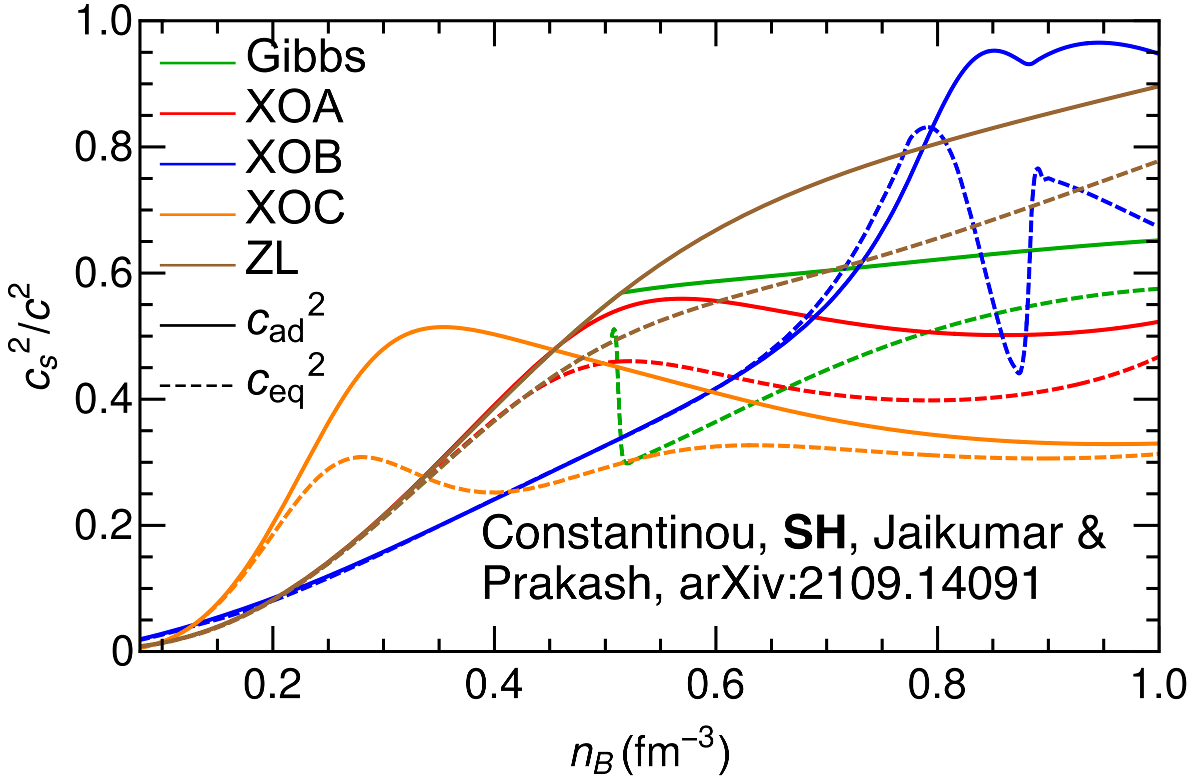
$$c_{ad}^2 \geqslant c_{eq}^2 \Rightarrow \text{mode stablized}$$

- in bulk region of the NS liquid core: restored by buoyancy due to the chemical composition gradient e.g. proton fraction
- crustal modes behave differently and are expected to be quite small

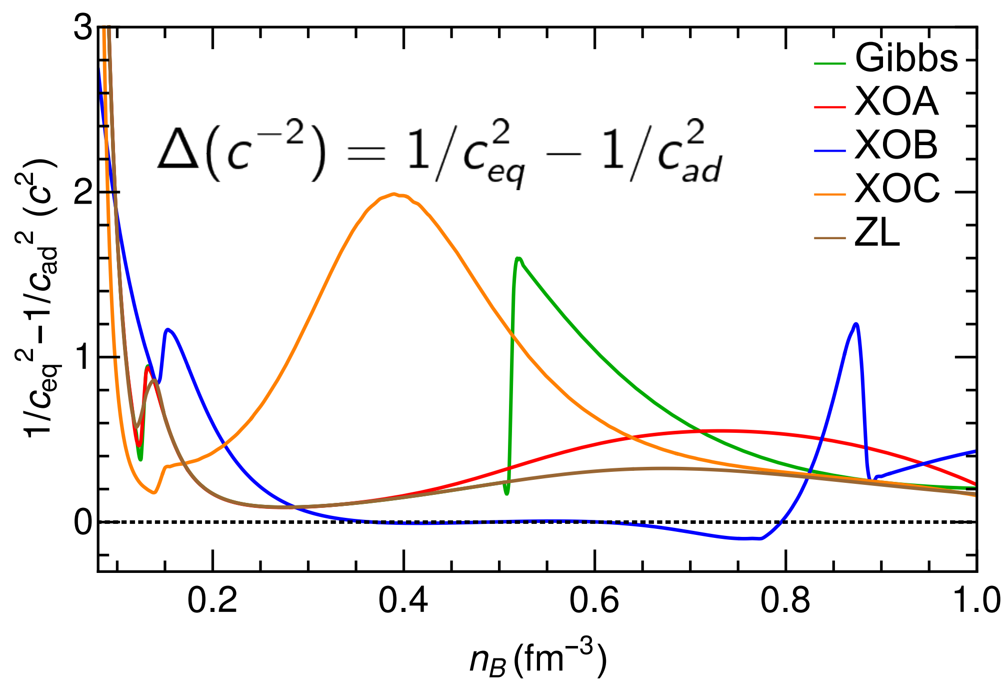
e.g. in *n*-*p*-*e* matter

$$\tilde{\mu} = \mu_e + \mu_p - \mu_n \quad c_{ad}^2 - c_{eq}^2 = - \left(\frac{\partial p}{\partial Y_e} \right)_{\varepsilon} \left(\frac{dY_e}{d\varepsilon} \right)$$

Sound speed profiles - adiabatic vs. equilibrium



- nucleonic only models: both speeds increase monotonically
- **admixtures** of nucleons and quarks (Gibbs or crossover) induce non-monotonic behavior
- $c_{ad}^2 > c_{eq}^2$ for all densities except XOB



- the **difference** $\Delta(c^{-2}) = 1/c_{eq}^2 - 1/c_{ad}^2$ drives the restoring force for *g*-mode oscillations
- smooth variations in composition are unlikely observable; requires radical changes in (new) particle species

Sound speed profiles - adiabatic vs. equilibrium

- adiabatic sound speed: start with the unconstrained system -> compute partial derivatives -> evaluate quantities at beta-equilibrium

$$(i = n, p, u, d, s, e, \mu)$$

$$c_{ad}^2(n_B, y_i) = \left(\frac{\partial p}{\partial n_B}\right)_{y_i} \left(\frac{\partial \varepsilon}{\partial n_B}\right)_{y_i}^{-1}$$

enforce beta-equilibrium

↓

$$y_i \to y_{i,\beta}(n_B)$$

$$c_{ad,\beta}^2(n_B) = c_{ad}^2\left[n_B, y_{i,\beta}(n_B)\right]$$

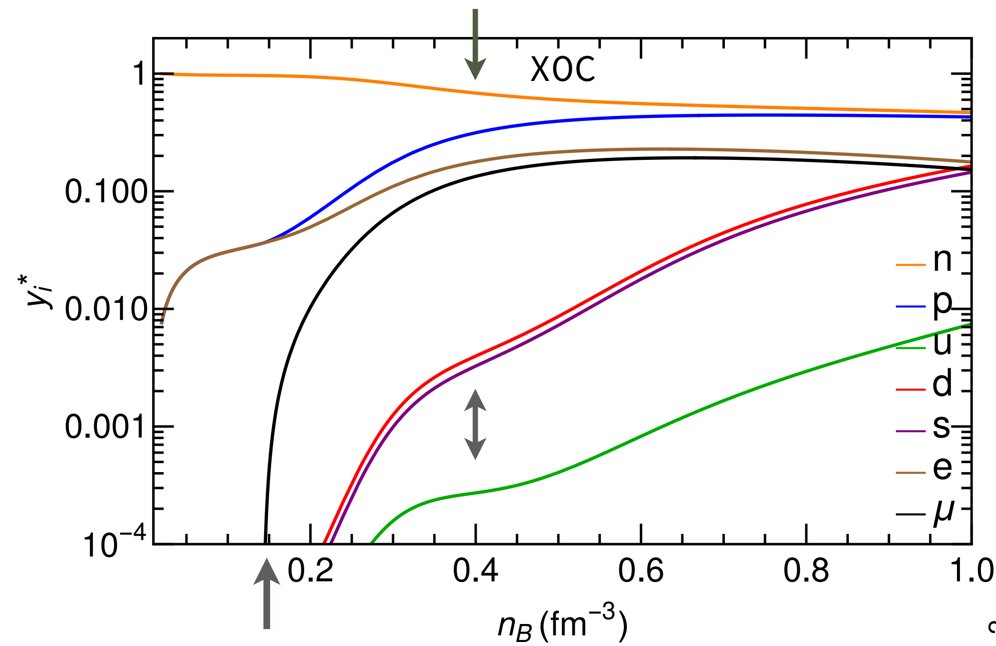
$$\mu_n = \mu_p + \mu_e; \; \mu_e = \mu_\mu; \; \mu_d = \mu_s$$

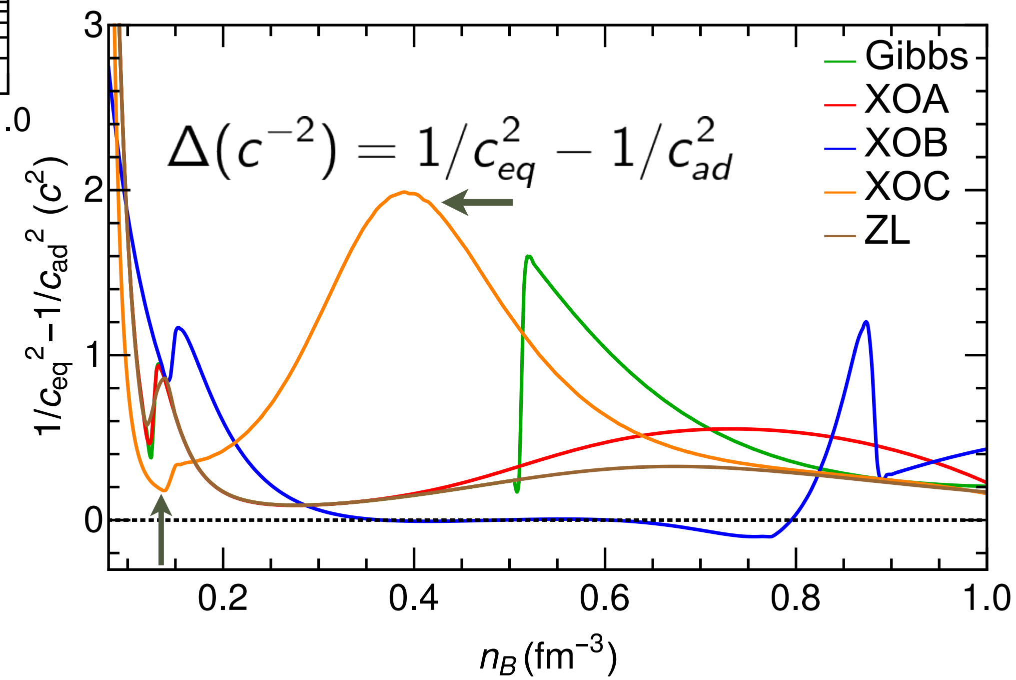
$$\mu_n = \mu_u + 2\mu_d; \; \mu_p = 2\mu_u + \mu_d$$

- equilibrium sound speed

$$c_{eq}^2(n_B) \equiv \left(\frac{dp}{d\varepsilon}\right)_\beta = \left(\frac{dp}{dn_B}\right)_\beta \left(\frac{d\varepsilon}{dn_B}\right)_\beta^{-1}$$

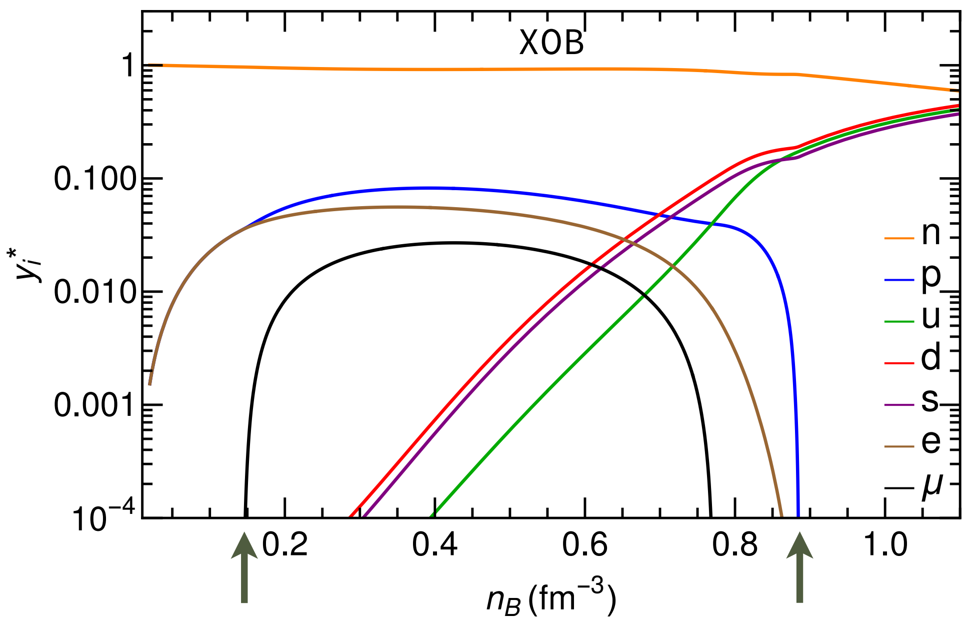
Sound speed difference and composition

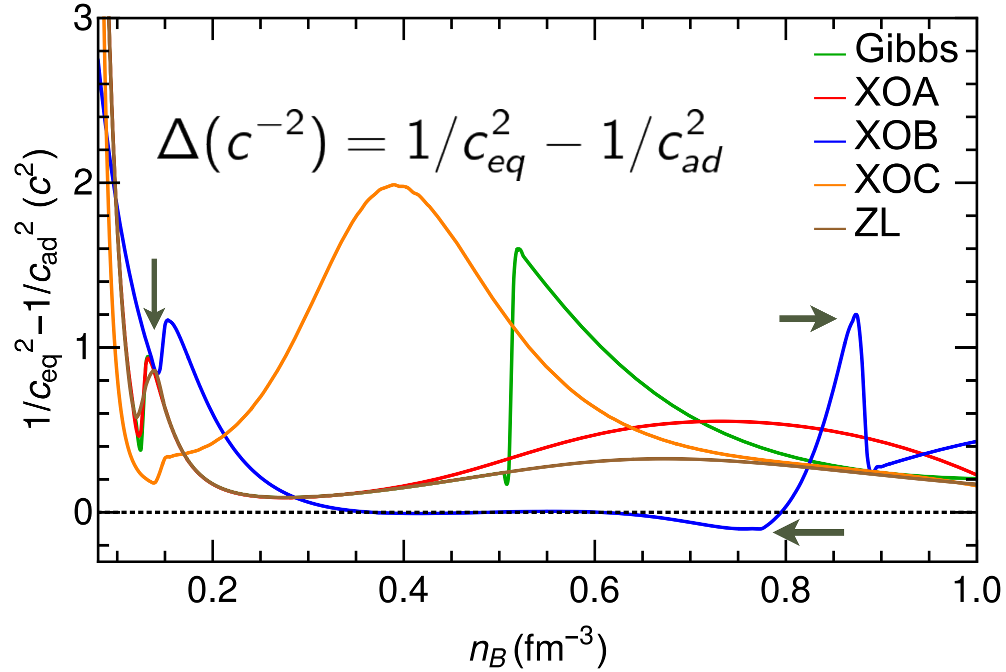




- muons set in ~nsat
- peak ~2.5 nsat: **inflection points** in quark and neutron fractions
- too stiff at low densities; predicted too large radii **incompatible** with e.g. GW170817

Sound speed difference and composition





- muons set in ~nsat
- peak ~5.5 nsat: muons and protons suddenly **disappear**
- **instability** to convection - (local) unphysical region

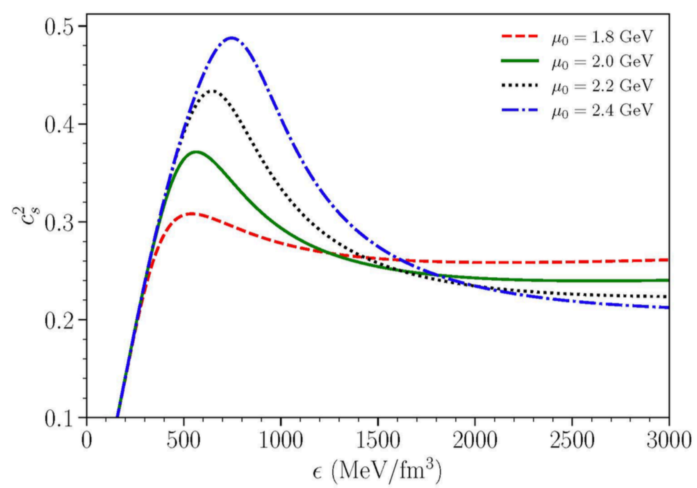
Aside: example of crossover matter EoS

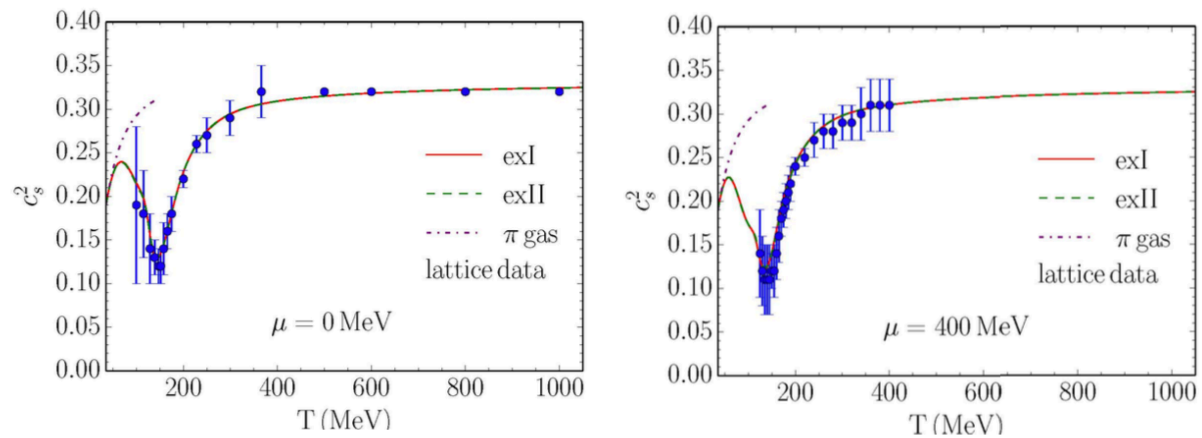
- Kapusta-Welle approach: **switching function** of baryon chemical potential

[arXiv:2103.16633]

$$P_B = (1 - S)P_H + SP_Q$$

$$S = \exp\left[-(\mu_0/\mu)^4\right]$$





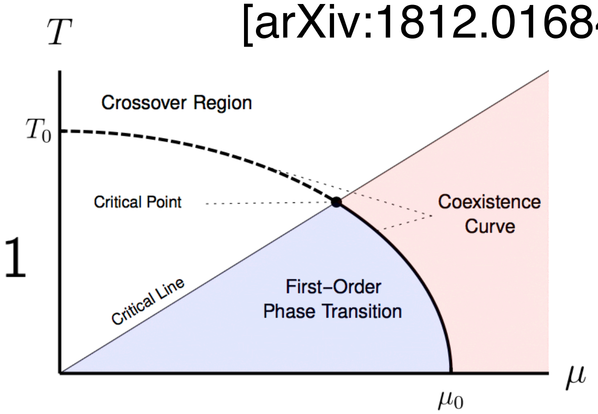
$$P(T,\mu) = SP_{\rm pQCD} + (1-S)P_{\rm hadron} \qquad S = \exp\left[-\frac{1}{(T/T_0)^n + (\mu/3\pi T_0)^n}\right]$$

Albright, Kapusta & Young 2015.

[arXiv:1812.01684]

$$S = 1/2$$

$$\left(\frac{T}{T_0}\right)^2 + \left(\frac{\mu}{\mu_0}\right)^2 = 1$$



- analogy: lattice QCD shows a crossover at finite temperature

Aside: Gibbs vs. crossover

- Kapusta-Welle approach: **switching function** of baryon chemical potential

[arXiv:2103.16633]

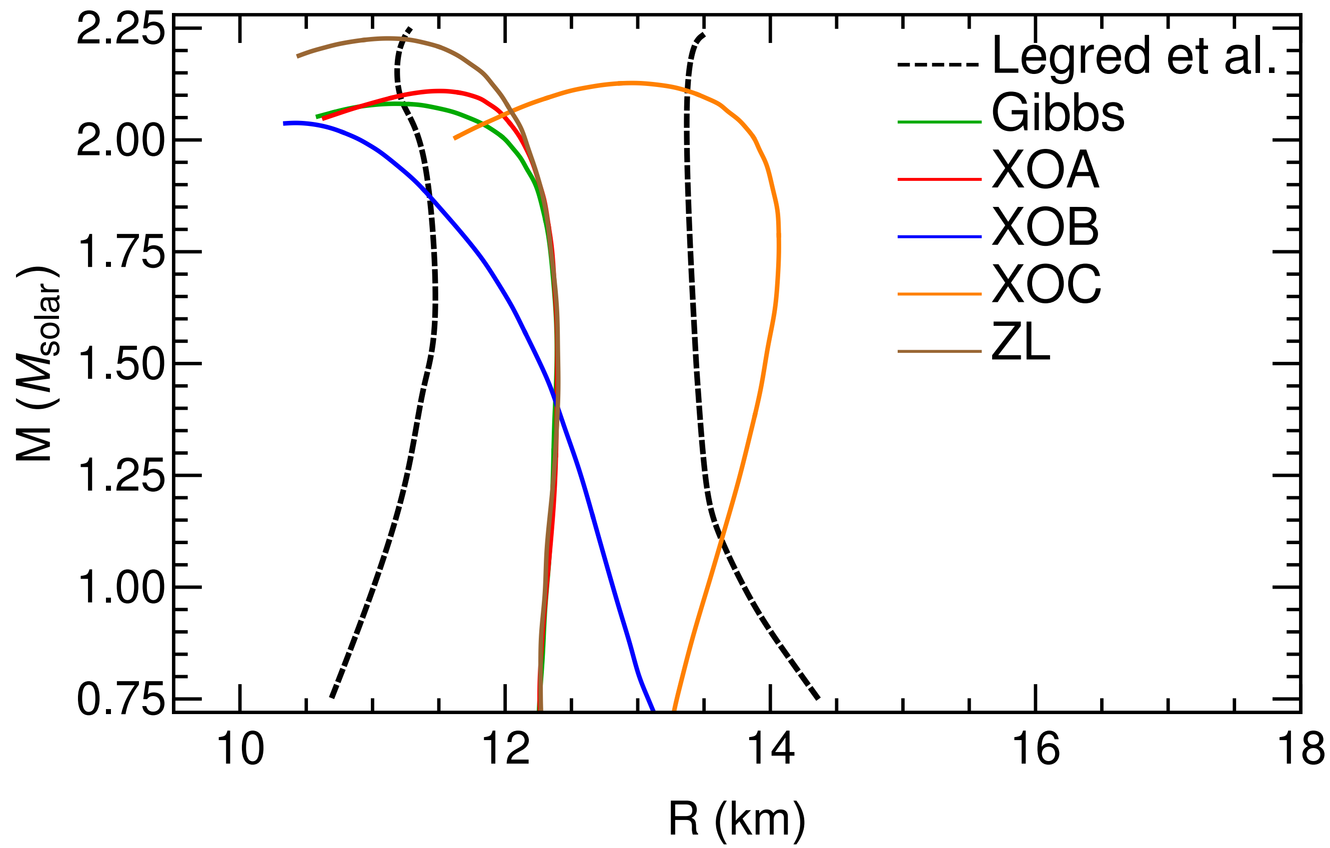
$$P_B = (1-S)P_H + SP_Q$$

$$S = \exp\left[-(\mu_0/\mu)^4\right]$$

$$\mu_0 \sim 2.0\,\mathrm{GeV}$$

$$\mu = \frac{n_n\mu_n + n_p\mu_p}{n_n + n_p}$$

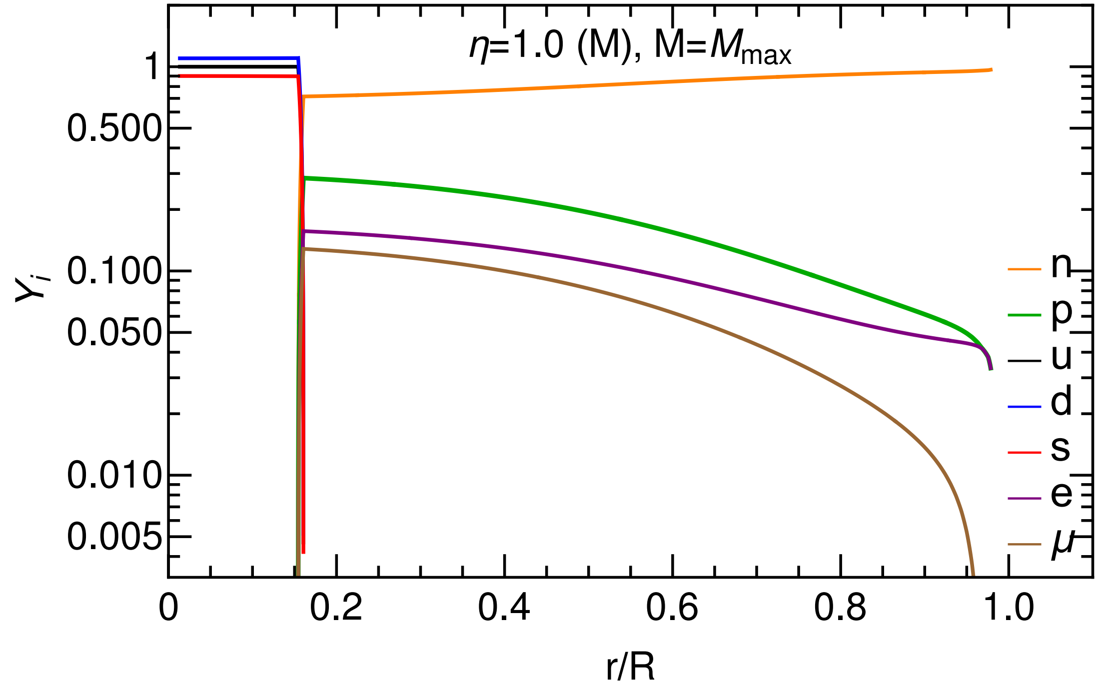
$$n_i = \left.\frac{\partial P}{\partial \mu_i}\right|_{\mu_j}$$

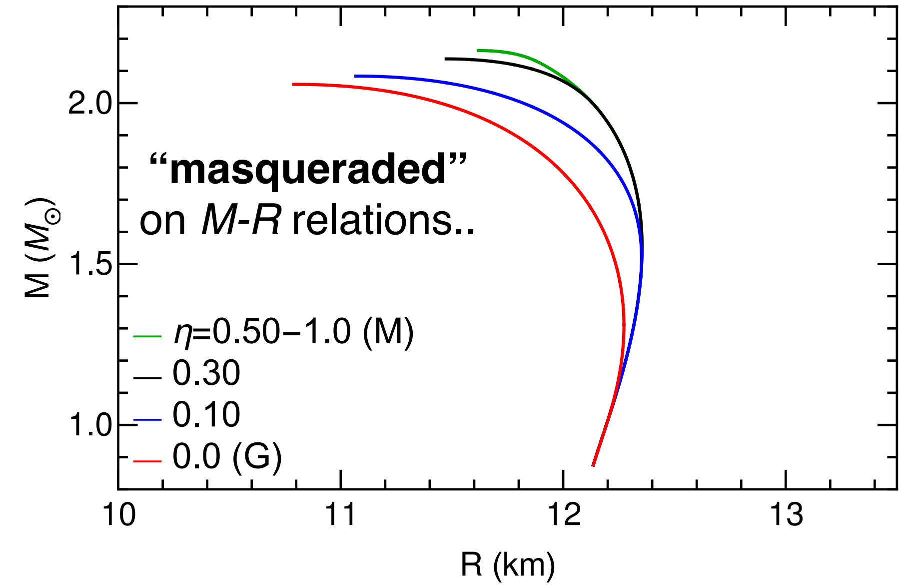


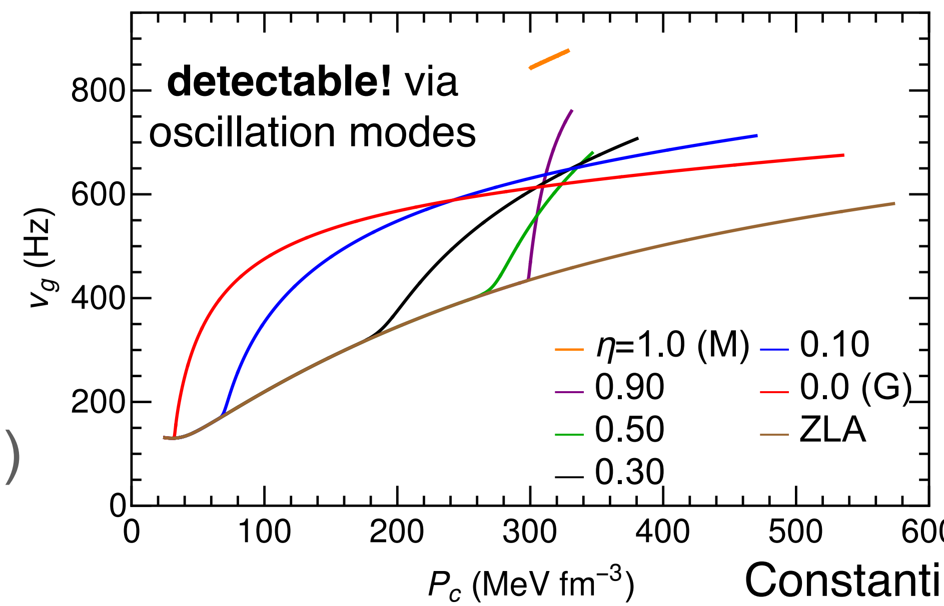
- our unified framework: construct Gibbs mixed phase and crossover using ZL (nucleonic) + vMIT (quark) + KW model parameters

Global *g*-mode frequency for NSs with PT

hybrid system under **local vs. global charge neutrality** in Maxwell (M) vs. Gibbs (G) construction for a 1st-OPT







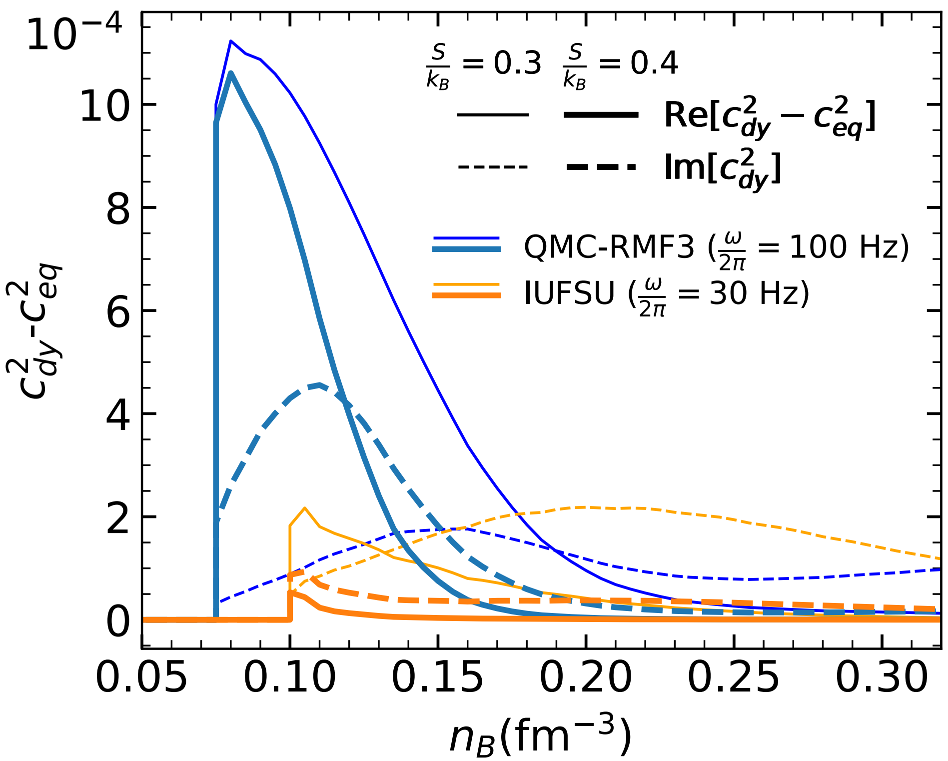
- "discontinuity" *g*-mode observed when there exists a **sharp** boundary (+ slow-conversion)
- **distinct signature** of exotic phases: higher frequency implies larger fraction of quarks

Constantinou, Zhao, **SH** & Prakash, arXiv:2302.04289

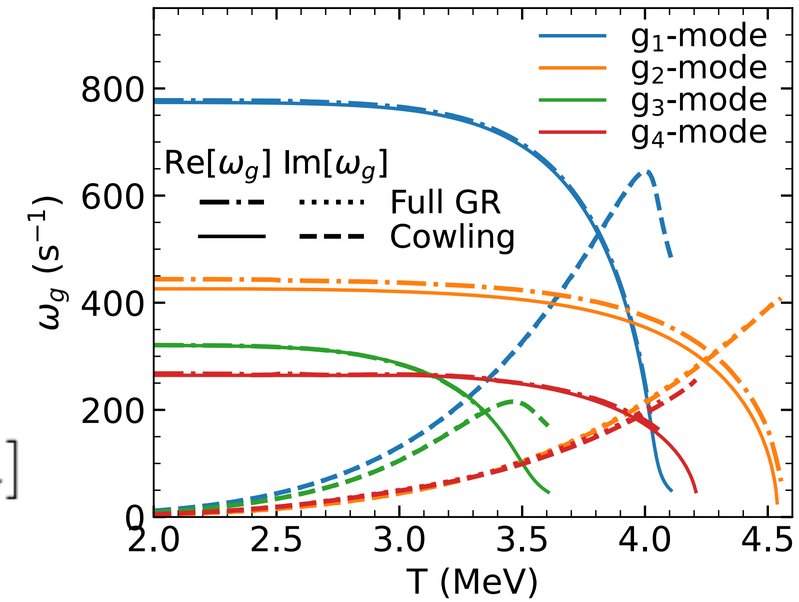
Bulk viscous damping of *g*-modes

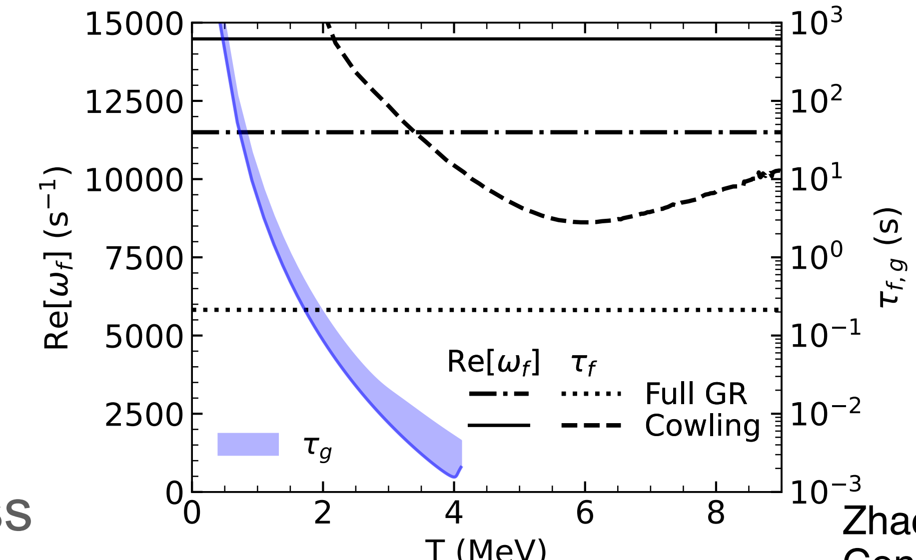
$$c_{\rm dy}^2 = \frac{p}{\varepsilon + p}\Gamma = c_{\rm eq}^2 + \frac{c_{\rm ad}^2 - c_{\rm eq}^2}{1 + \dfrac{\gamma}{i\omega}}$$

complex, frequency-dependent generalization of the adiabatic sound speed - **“dynamical”** sound speed



$$\zeta = \frac{\varepsilon + p}{\omega}\mathrm{Im}\left[c_{\rm dy}^2\right]$$





- little impact on *f*-mode (semi-divergent free)
- **dissipative effects** can completely suppress composition *g*-modes in **warm** NSs

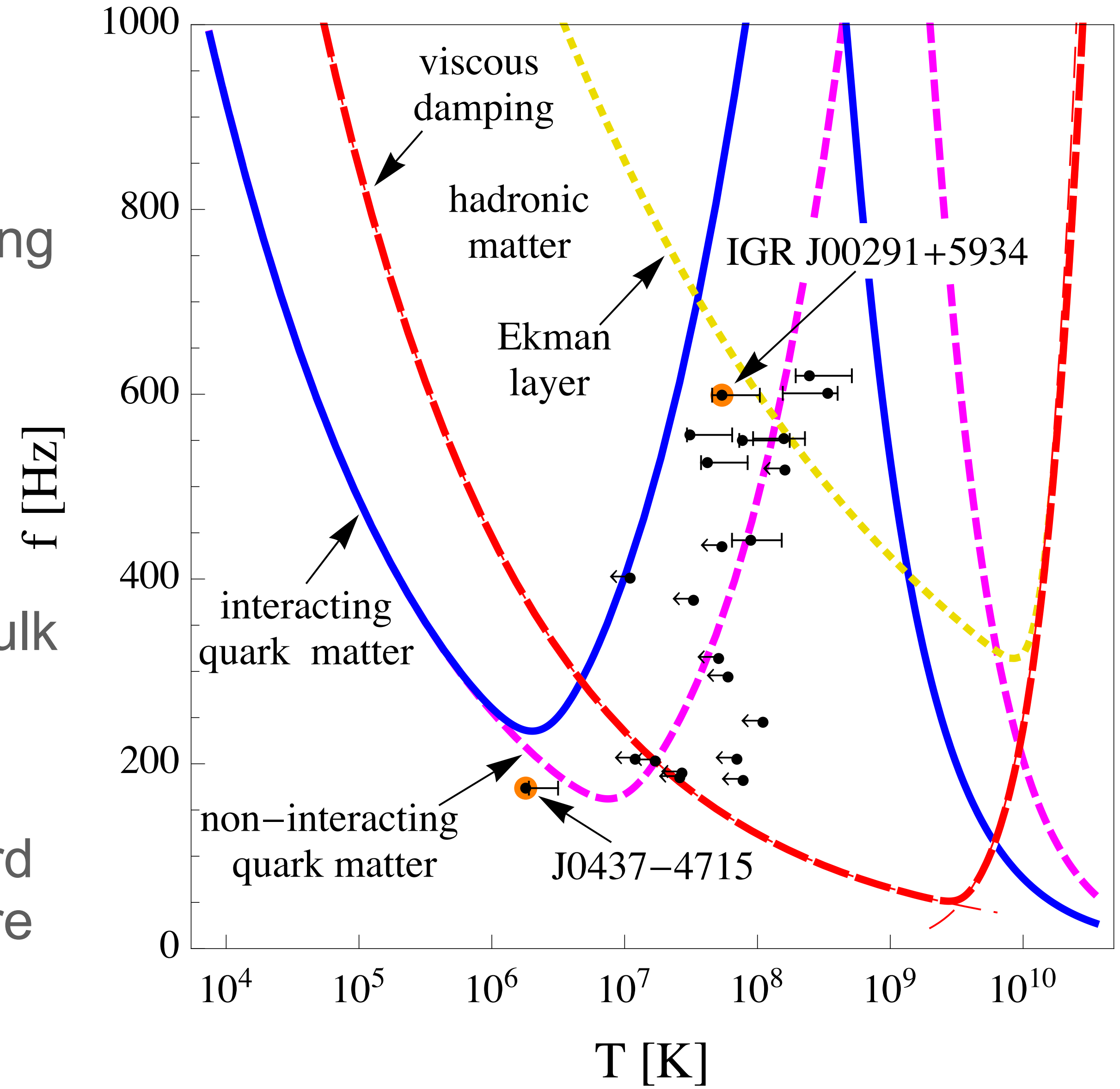
Zhao, Rau, Haber, Harris, Constantinou & **SH**
arXiv:2504.12230

Spin evolution

- many unresolved puzzles: long periods of young NSs; fast-rotating NSs in *r*-mode instability window of hadronic matter; glitches..

e.g. *r*-modes

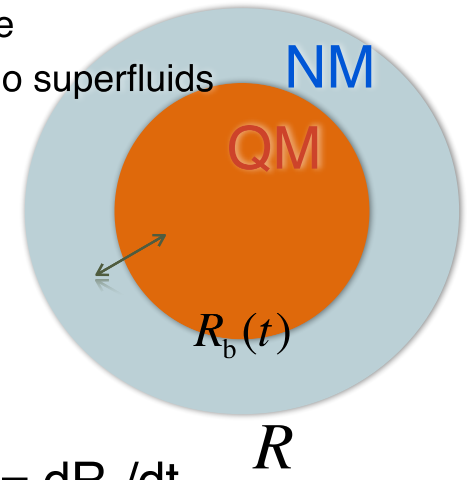
- transport properties of dense matter: shear [particle scattering; strong/EM interaction] & bulk [particle transformation; weak interaction] viscosities
- *r*-modes both heat and spin-down NS: standard (minimal) model **inconsistent** with temperature and frequency data of LMXBs
- promising **saturation** mechanisms: superfluid mutual friction? crust resonance? phase-conversion at hadron/quark interface?



Alford & Schwenzer, PRL 113, 251102 (2014)

e.g. dissipation at an interface

- toy model: steady-state transport
- no acceleration/deceleration effects
- no turbulence
- no leptons; no superfluids



- Ekman layer damping from shear rubbing of a fluid core along a solid crust

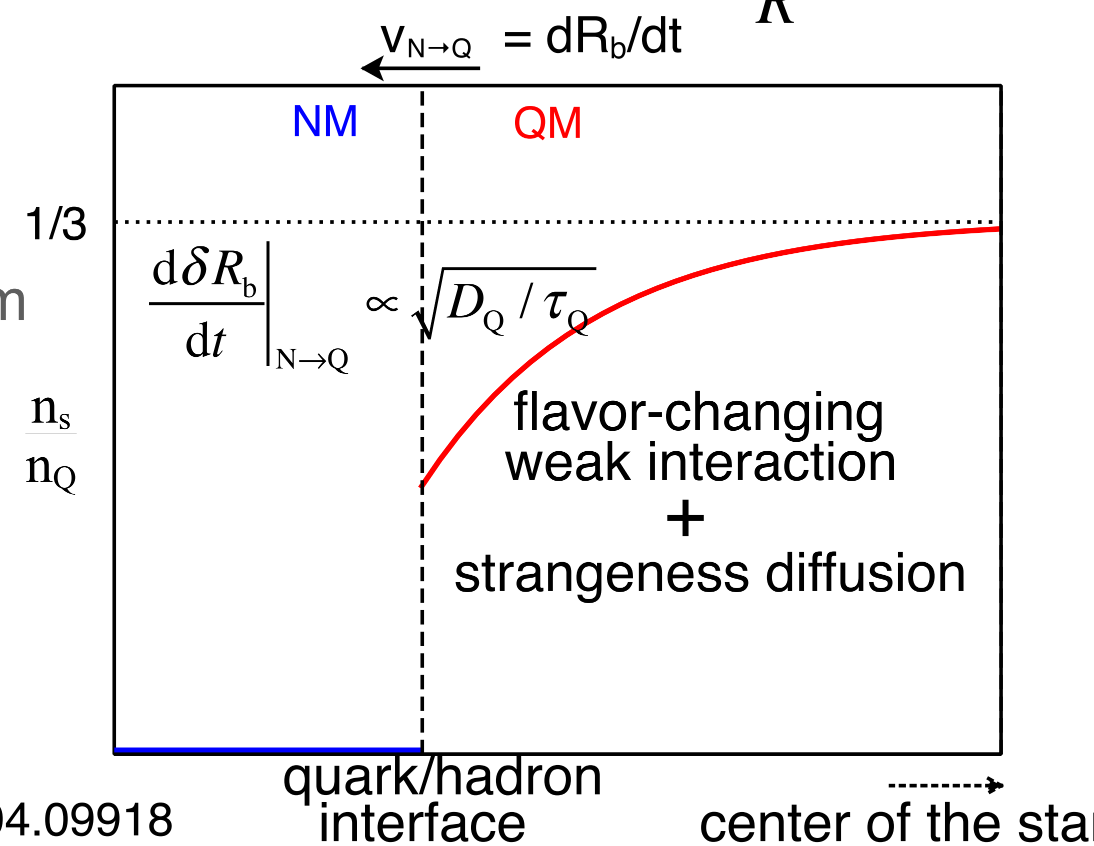
Phase-conversion dissipation (PCD)

- between fluids in different phases with first-order transition separated by a **sharp** interface
- quark/hadron conversion

1) **flavor-changing** process $d \leftrightarrow s$ out of equilibrium due to global oscillations

2) instantaneous restoration $\Leftrightarrow$ phase boundary moves arbitrarily fast (no diss.)

3) finite rate of weak interaction and flavor diffusion
   $\rightarrow$ a **phase lag** in system response
   $\rightarrow$ dissipates energy



SH arXiv:1904.09918

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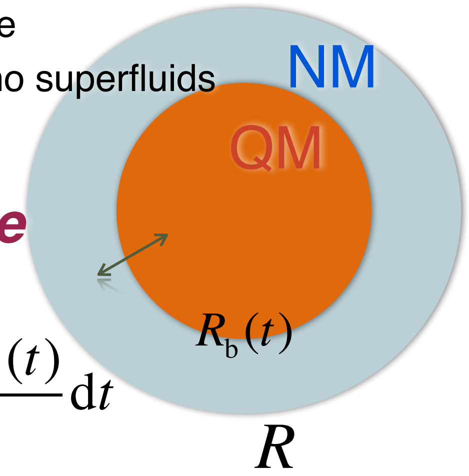

- Ekman layer damping from shear rubbing of a fluid core along a solid crust

Phase-conversion dissipation (PCD)

out of phase

$$dW = -dS\left(\frac{n_N}{n_Q}-1\right)\int_0^\tau \delta p_b(t)\,\frac{d\delta R_b(t)}{dt}\,dt$$

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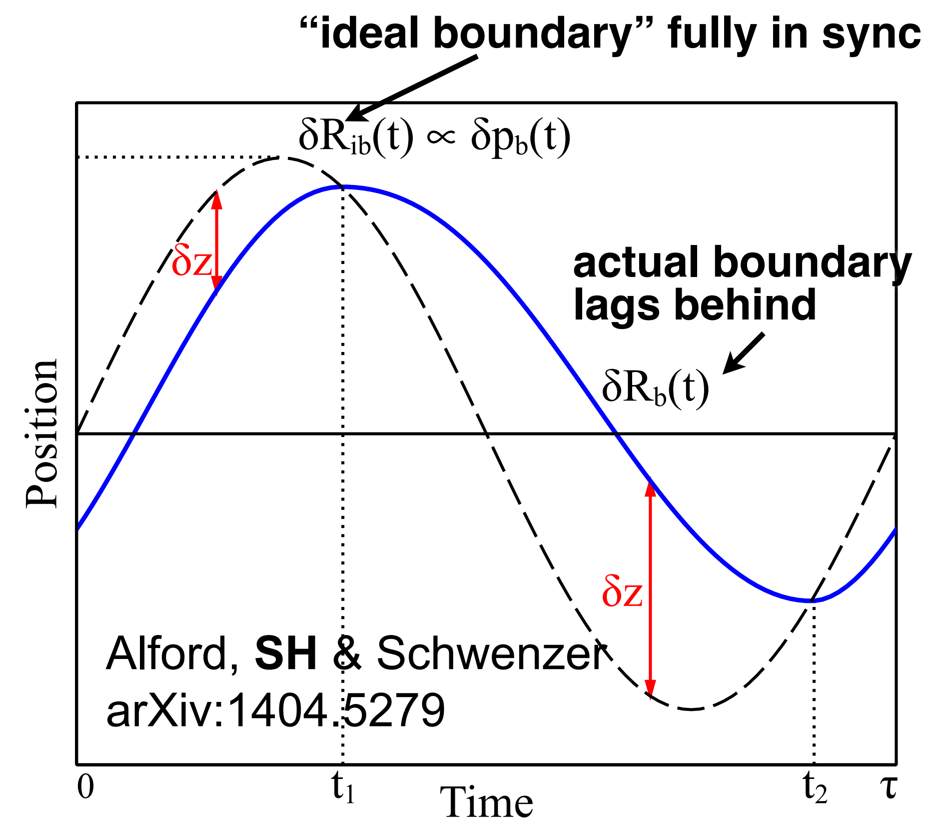

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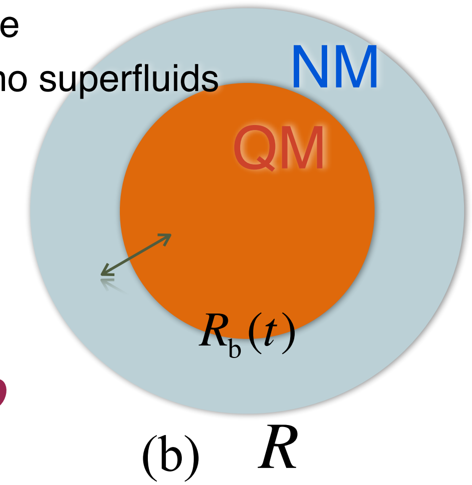

amp. most sensitive to core size

- Ekman layer damping from shear rubbing of a fluid core along a solid crust

Phase-conversion dissipation (PCD)

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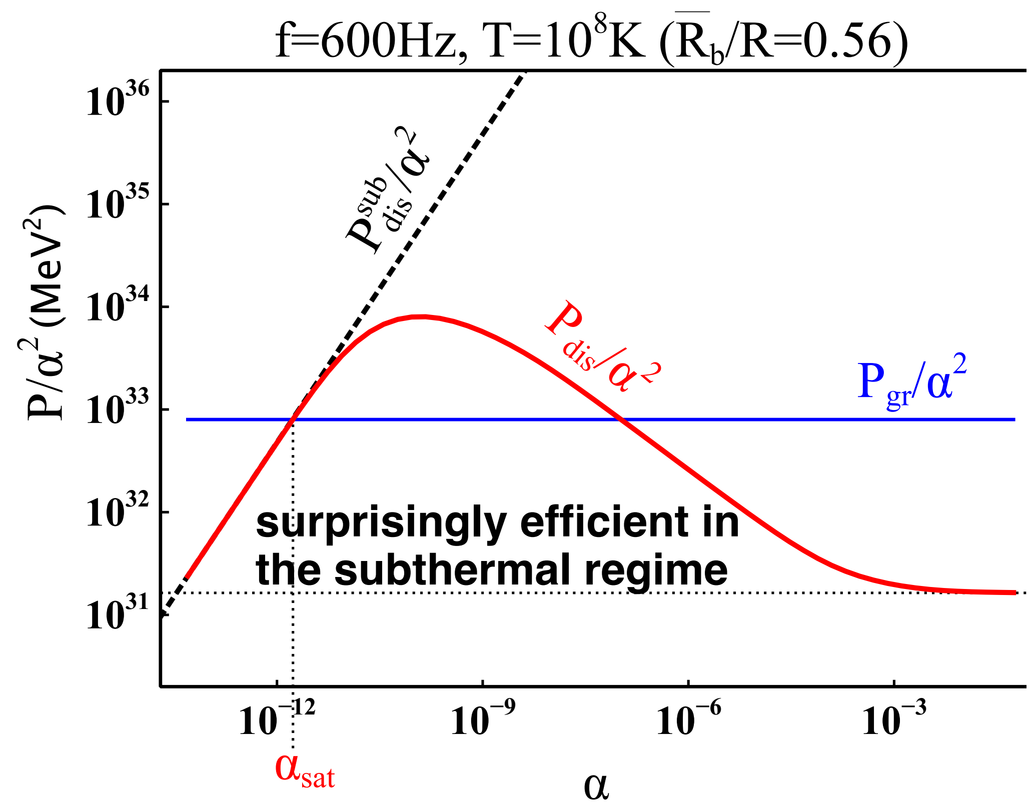
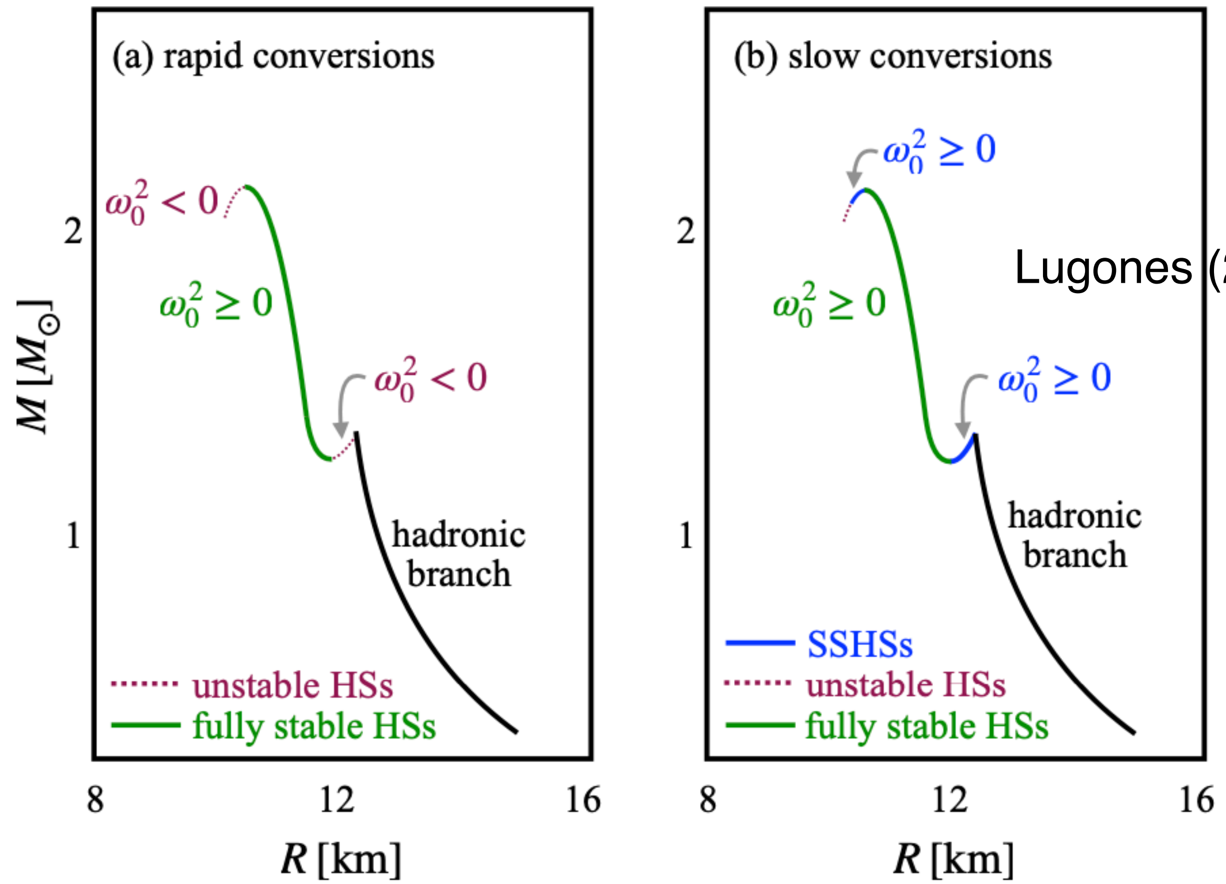


Rapid vs. slow conversions: reacting interfaces

discontinuity *g*-modes can be excited in SSHSs (shorter damping time & higher frequencies ~1-2 kHz)

but not in hybrid stars with rapid conversion interfaces as buoyancy force is absent

- viable mechanisms for populating both branches ?



Lugones (2023)

- green branch remains stable against radial perturbation for **any** conversion speed
- blue branches only stable for **slow** conversions (dynamically stable)
- **critical density** of transition between hadronic and quark phases may vary - low vs. high; affects the mass-distribution of hybrid stars

Thermal evolution

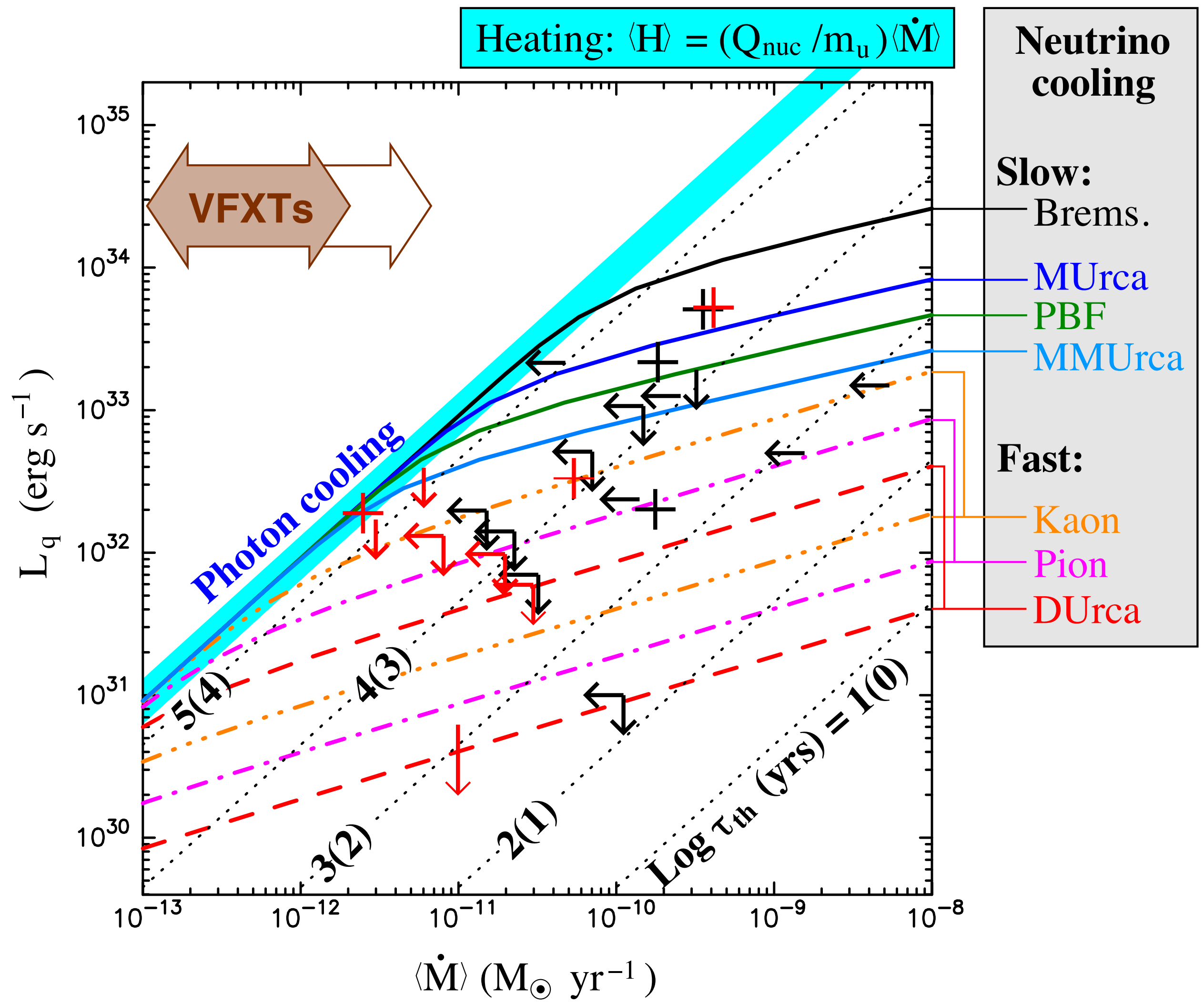
observables: surface luminosity of isolated NSs (long-term) and accreting NSs (transient); age estimation; mass accretion rate

Dense matter input

- dominant channel of neutrino emission: standard or enhanced cooling?
- heat capacity, thermal conductivity
- superfluidity
- modeling of crust and envelope

Candidate DM particles ?

- constraints on axion-cooling, annihilation heating etc.



Wijnands et al. MNRAS, 432, 2366 (2013)

Long-term cooling of isolated NSs

Core: neutrino losses; isothermal

Crust & envelope: dominates early evolution of young NSs <~100 yrs

- heat flow (inwards & outwards): conduction
- heavy vs. light elements
- crust thickness

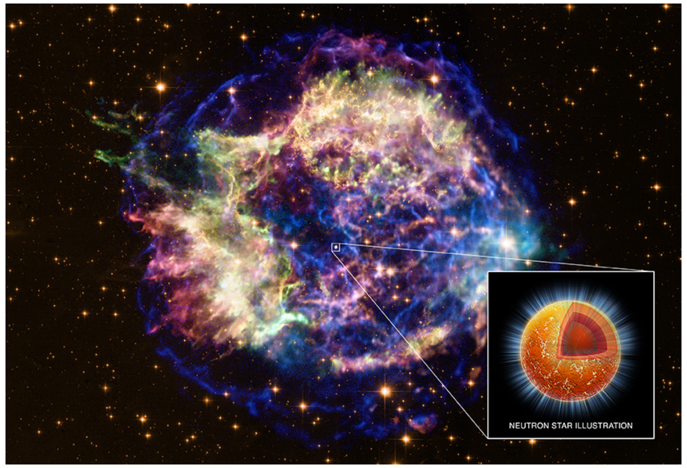
$$\frac{dT(r)}{dr} = -\frac{1}{K}\frac{L_\gamma(r)}{4\pi r^2}$$

$$\tau_{\rm th} \sim \frac{C_v l^2}{K}$$

Surface: photon emissions; observable

Neutrino reactions

$$\frac{dE_{th}}{dt} = C_v \frac{dT}{dt} = -L_\nu - L_\gamma$$



- **enhanced** (core dUrca)
- slow: mUrca, brems.
- medium: pair-breaking-formation

} **standard**

Soft x-ray transients (SXRTs)

in LMXBs with low magnetic fields

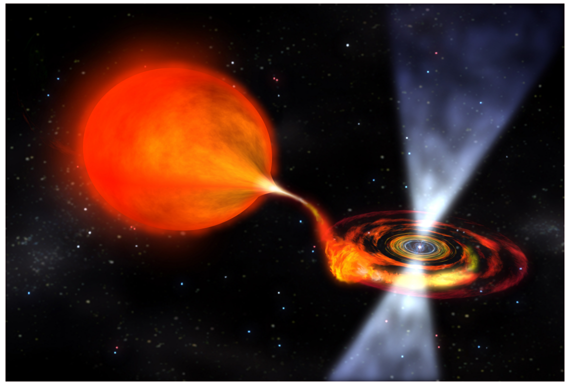
Surface, ocean & envelope

- thermonuclear bursts; shallow heating (?)

Deep-crustal heating   Brown et al. (1998); Haensel & Zdunik (1990, 2003)

- electron capture; pycnonuclear rexns; neutron emission, transfer & absorption
- time-averaged accretion rate

$$L_{\rm dh} = Q \times \frac{\dot{M}}{m_{\rm N}} \approx 6.03 \times 10^{33} \left(\frac{\dot{M}}{10^{-10}\,{\rm M}_\odot\,{\rm yr}^{-1}} \right) \frac{Q}{\rm MeV}\ erg\ s^{-1}$$



- accreted crust replaces original (catalyzed) crust

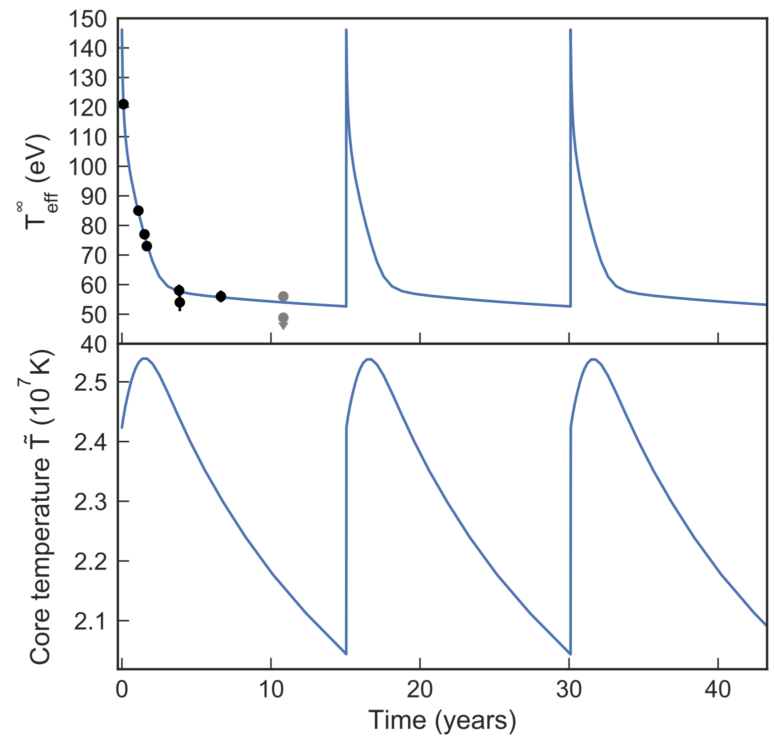
observables

Quiescent NSs: thermal equilibrium

- quasi-stationary state

$$L^{\infty}_{\rm dh}(\dot{M}) = L^{\infty}_{\gamma}(T_s) + L^{\infty}_{\nu}(T_i),\ T_s = T_s(T_i)$$

e.g. evidence for enhanced cooling from transients



Brown et al. PRL 120, 182701 (2018)

- MXB 1659-29: during accretion interior heated out of thermal equilibrium
- significant late-time crust cooling observed after outburst requires fast neutrino emission; yet the origin remains **unknown**: i) nucleonic dUrca (large **Esym** at high density) or ii) emergence of **exotica**
- able to derive constraints on the core heat capacity: limiting **superfluid phases**

Cooling of isolated vs. accreting NSs

Minimal scenario (Page et al. 2004)

- *npemu*-matter, **no dUrca**, mild neutron/proton superfluidity
- weak dependence on NS mass: assumed below dUrca

Alternative scenario (Gusakov et al. 2004)

- *npemu*-matter, dUrca + **strong proton superconductivity**
- varying EoS models shifts dUrca onset

Both agree fairly well with INSs data, but extremely cold, transiently accreting NSs infer

- fast cooling **~dUrca operating** at some level
- **vanishing superfluid gaps** in the core region
- little/zero light-element (hydrogen or helium) residue in the heat-blanketing envelope

Challenges and prospects of finding quark matter - part B

1) (large portion of) phases with too small specific heat ~CFL probably ruled out by the late-time crust cooling of transiently accreting NSs
2) unpaired quark matter unlikely to dominate - highly efficient neutrino emissions that tend to cool INSs much faster than needed
3) normal hadrons insufficient to explain the *r*-mode puzzle; shifted bulk viscosity resonance in bulk quark matter (unpaired) could help; PCD at sharp boundary might effectively work as a saturation mechanism
4) GW and neutrino signals in mergers/ CCSNe/ proto-NSs: beyond current detector sensitivity; largely model-dependent (& diverging..) results from different numerical simulations
5) composition *g*-modes are particularly sensitive to prominent changes in particle species - promising for XG detectors!

Takeaways: astrophysical signatures of quark matter

1) Static observables based on the EoS - mass, radius, moment of inertia, tidal deformability and density profile etc. not in general particularly sensitive to the phase of the material, although 1st-OPT between phases of very different density could verifiably affect the mass–radius relation
2) Neutron star mergers - dynamic material properties varying greatly between hadronic and quark phases greatly influence the evolution of the highly excited merger product and the future GW signal of the actual merger phase; could be degenerate with thermal/OoE/DM effects..
3) Oscillation modes, spin-down, **glitches** - particularly promising method to distinguish phases and/or their mixtures; next-gen detectors
4) **Astro solids** - high ellipticity of very rigid crystalline phase like CCSC at high density can be relevant for continuous GWs; shattering of strange(let) crust ? EM band signatures ?
5) Thermal evolution - tends to be dominated by the fastest neutrino emission channel; phase space of Urca reactions can be arbitrarily reduced by momentum restrictions due to the Fermi seas of the involved particles or by pairing; hard to distinguish hadrons vs. quarks confidently
6) **Neutrinos** from CCSNe? PT-induced explosion mechanism

- That said, **low-density nucl-th/exp, intermediate-energy HICs** can play an instrumental role in constraining high-density QM

THANK YOU!

Q & A