Detectability of Phase Transitions from Binary Neutron Star Mergers

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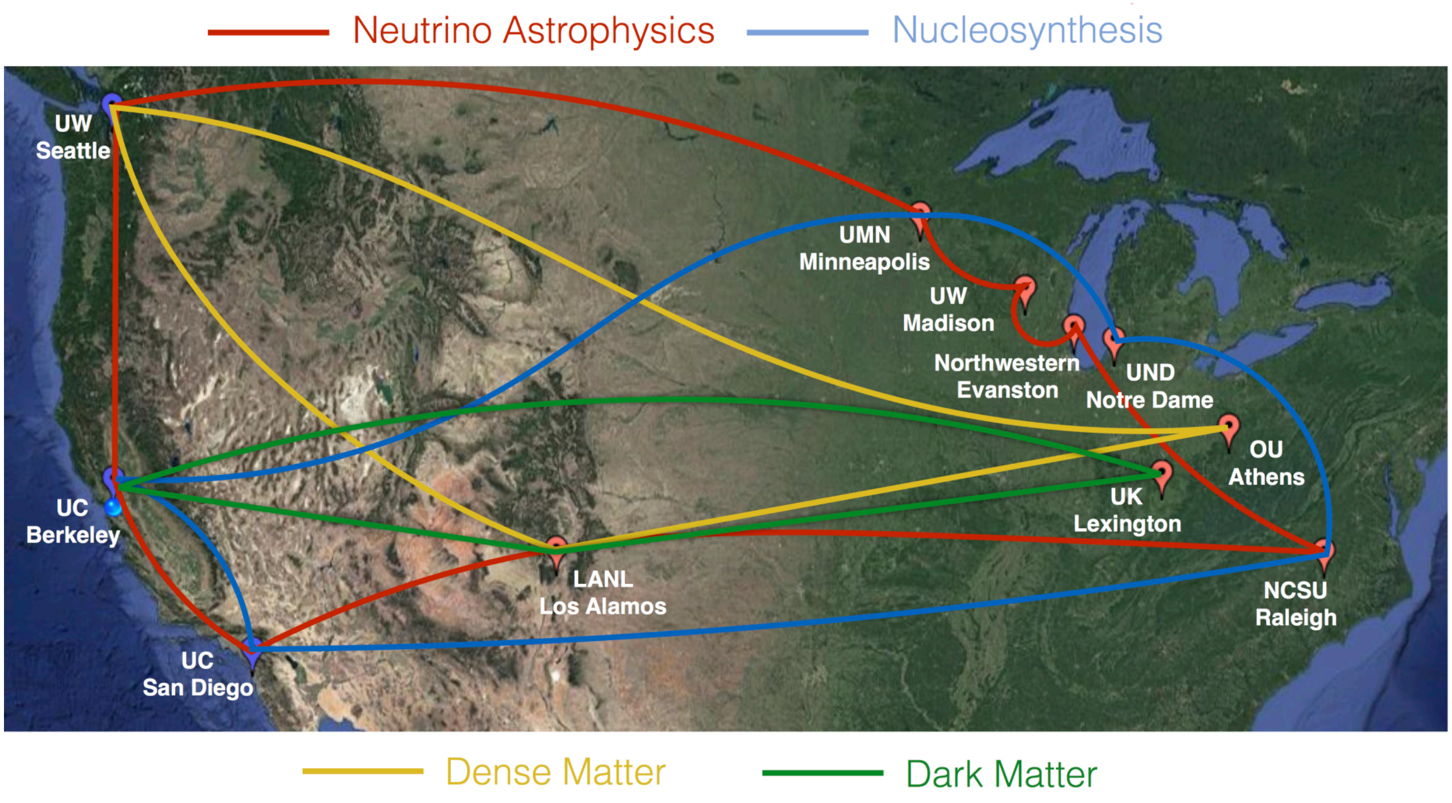
arXiv:1906.04095

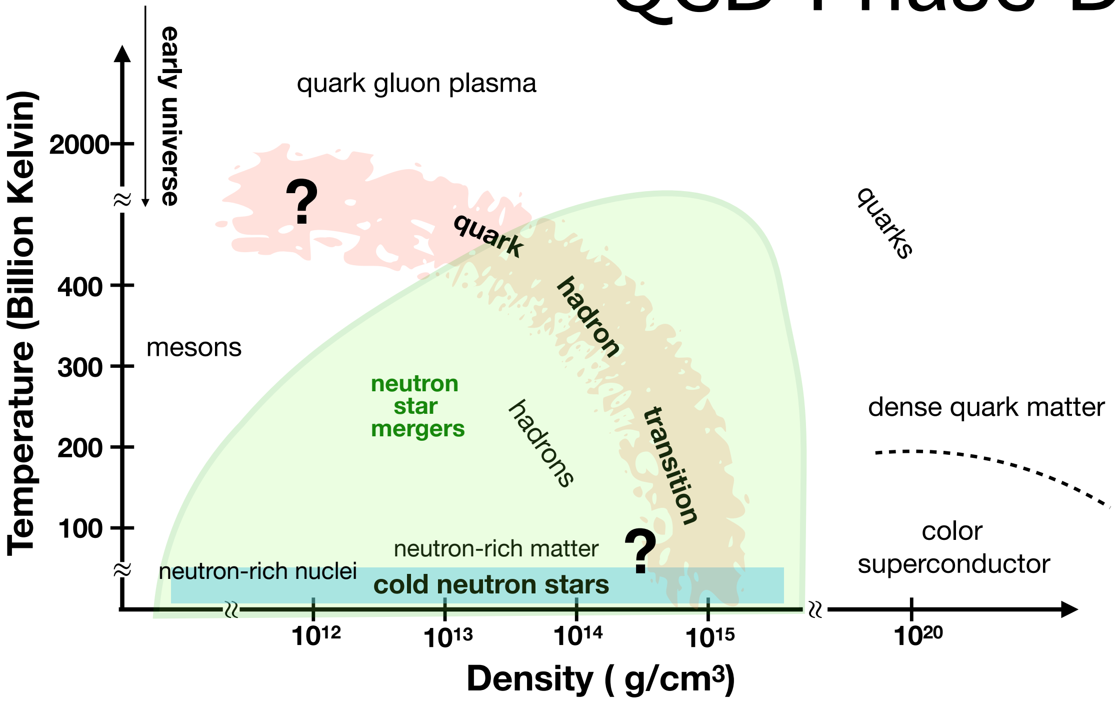
arXiv:1904.05471

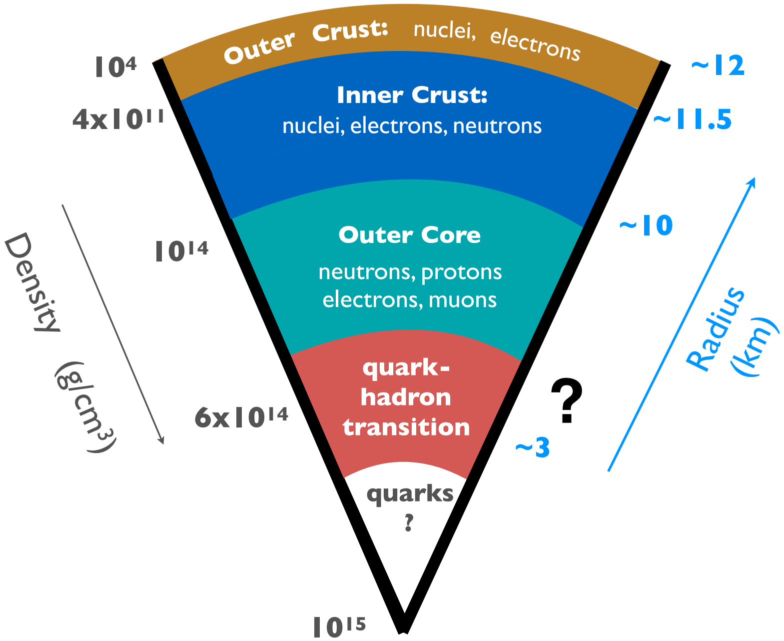
arXiv:1810.10967

YITP MMGW2019
Sep. 24, 2019 @Kyoto



QCD Phase Diagram





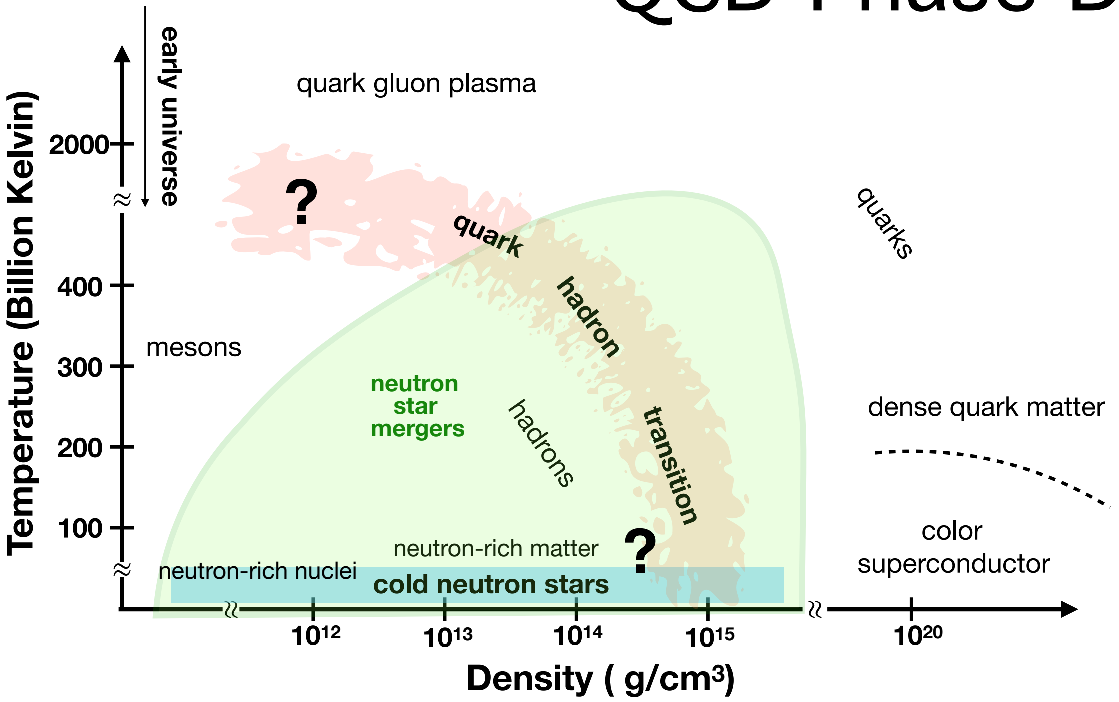
3G Science white paper

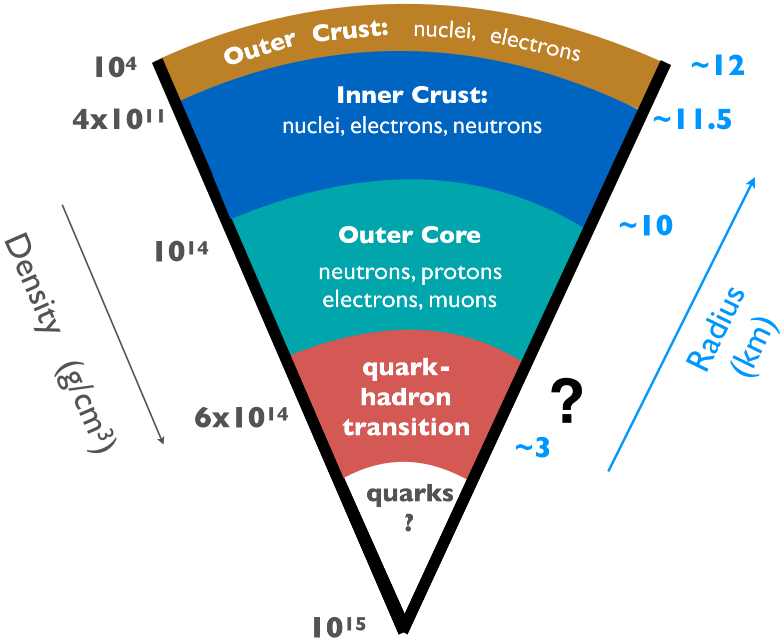
motivation

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**!

QCD Phase Diagram





3G Science white paper

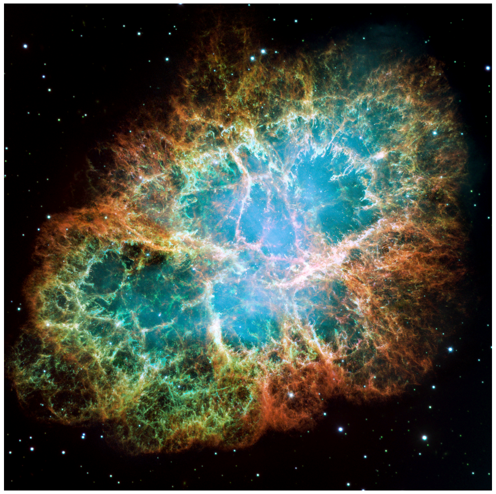
summary

Current status: quark matter in neutron stars

- no evidence to rule out QM
- no evidence to confirm QM
- massless weakly-interacting quarks strongly disfavored
- some hints that neutrons and protons are not enough
- better understanding of **nuclear matter** improves constraints on QM

Neutron Stars

Messengers: photons, neutrinos and gravitational waves



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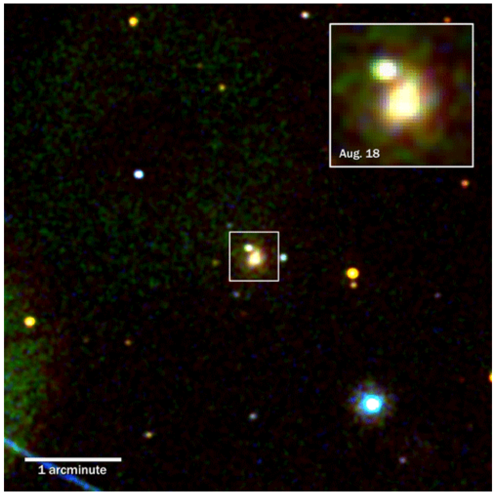
Facilities

- Hubble, Chandra, Fermi, NICER, Parkes, NRAO, SKA..
- Super-K (Hyper-K), SNO+, IceCube..
- LIGO, Virgo, KAGRA, GEO600, LISA..

Sources

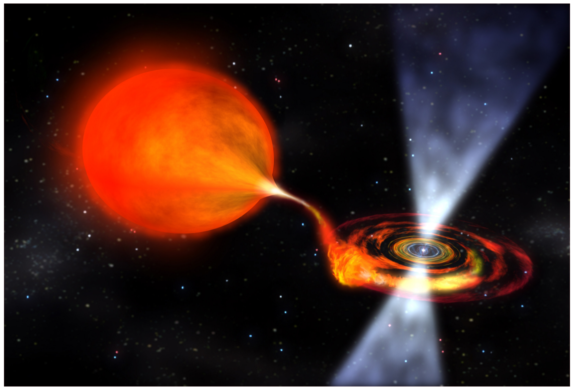
- core-collapse supernovae, accreting & isolated NSs
- mergers of NS/NS, NS/BH
- MSRPs, magnetars, gamma-ray bursters
- double pulsar system



Recent Advances

Massive pulsars ~2 solar masses observed

(Shapiro delay) **new**! PSR J0740+6620 with $2.14^{+0.20}_{-0.18} M_\odot$



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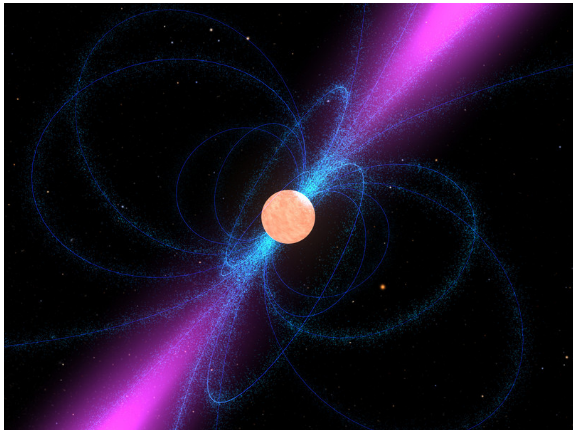
BNS mergers

- pre-merger GW170817 signal favors “small” stars
- sGRBs, kilonova lightcurves, afterglow



Accreting & isolated NSs

- crust cooling of accreting NSs to quiescence
- X-ray bursts, super-bursts, QPOs
- long-term cooling in e.g. Cassiopeia A
- glitches; pulsar timing

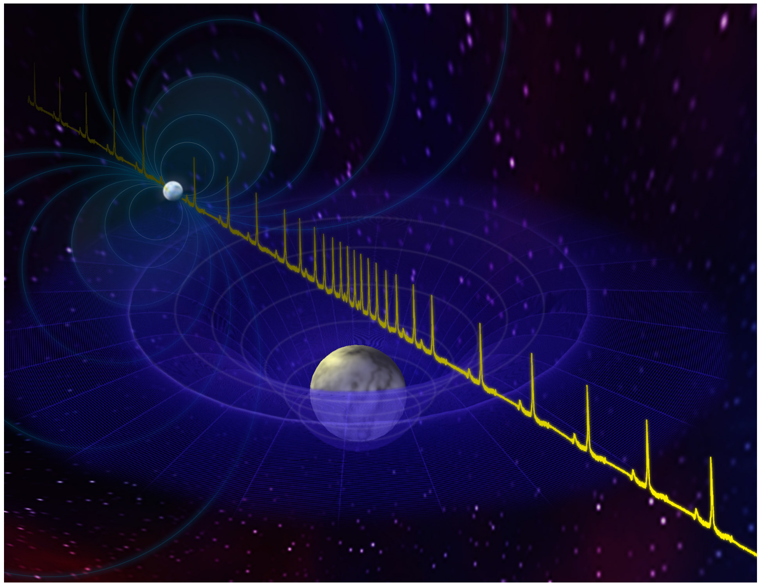
Dense Matter in Neutron Stars

Properties	Observables
Static: dense matter equation of state (EoS)	global structure: mass, radius, tidal deformation, binding energy, moment of inertia
Dynamic: thermal, elastic & transport properties	evolution: surface temperature/luminosity, rotational frequency, neutrinos, magnetic field, gravitational waves

Connections

- nuclear & particle physics
- atomic, condensed matter physics
- computational astrophysics, gravitational physics

I. Global Structure



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Microphysics input

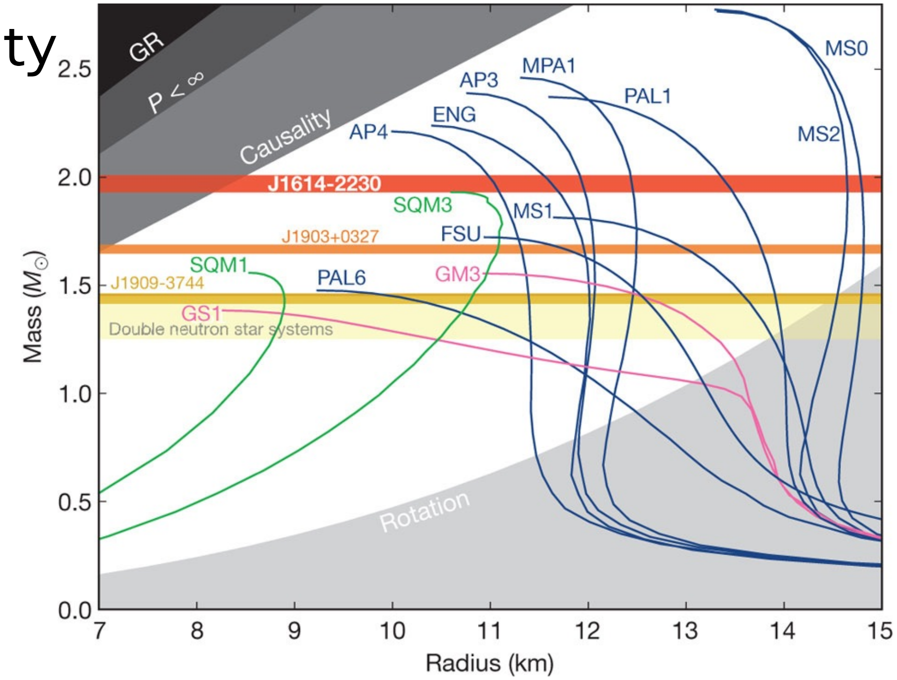
- equations of state (EoS); pressure vs. density

Context

- cold, beta-stable, non-magnetars
- hydrostatic equilibrium in General Relativity

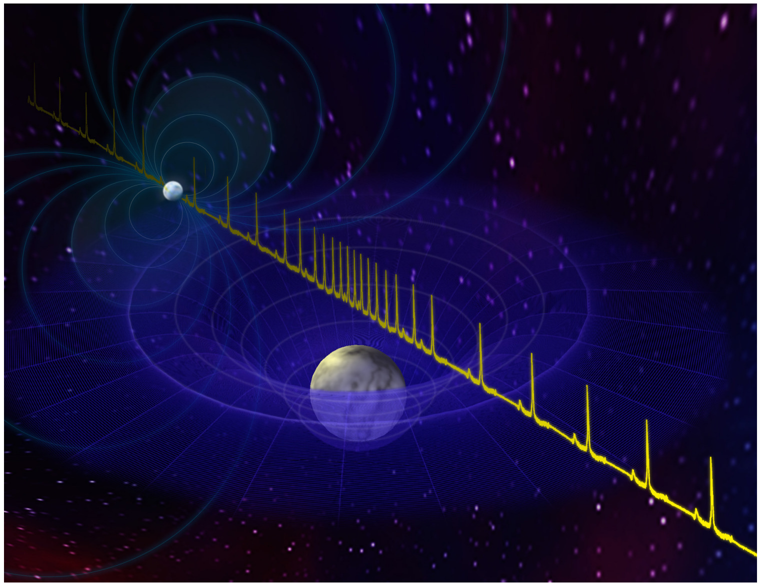
Output

- masses and radii; compactness M/R
- binding energy
- tidal Love number & tidal deformability
- moment of inertia



Demorest et al., Nature 467, 1081 (2010)

I. Global Structure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Microphysics input

- equations of state (EoS); pressure vs. density

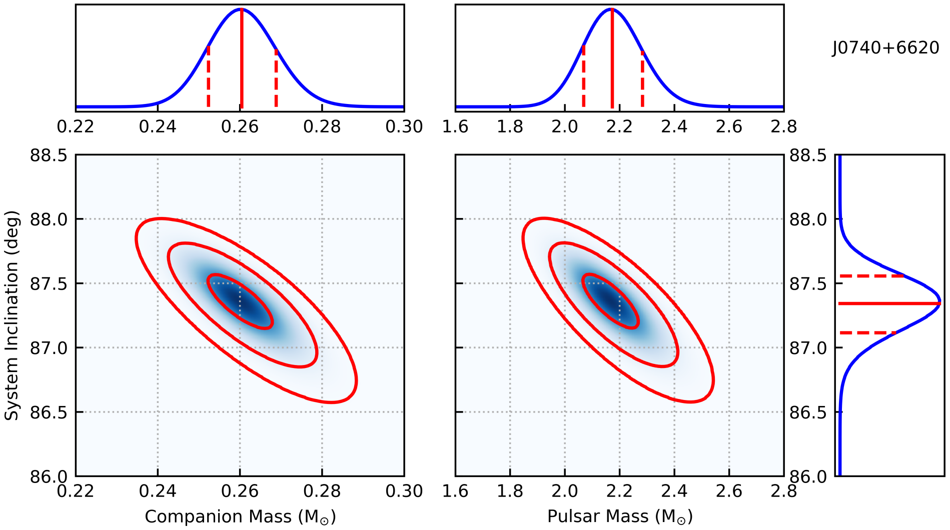
Context

- cold, slowly-rotating, non-magnetars
- hydrostatic equilibrium in GR

Output

- masses and radii; compactness M/R
- binding energy
- tidal Love number & tidal deformability
- moment of inertia

new! PSR J0740+6620 with $2.14^{+0.20}_{-0.18} M_\odot$



Cromartie et al., arXiv:1904.06759

Equation of State (EoS)

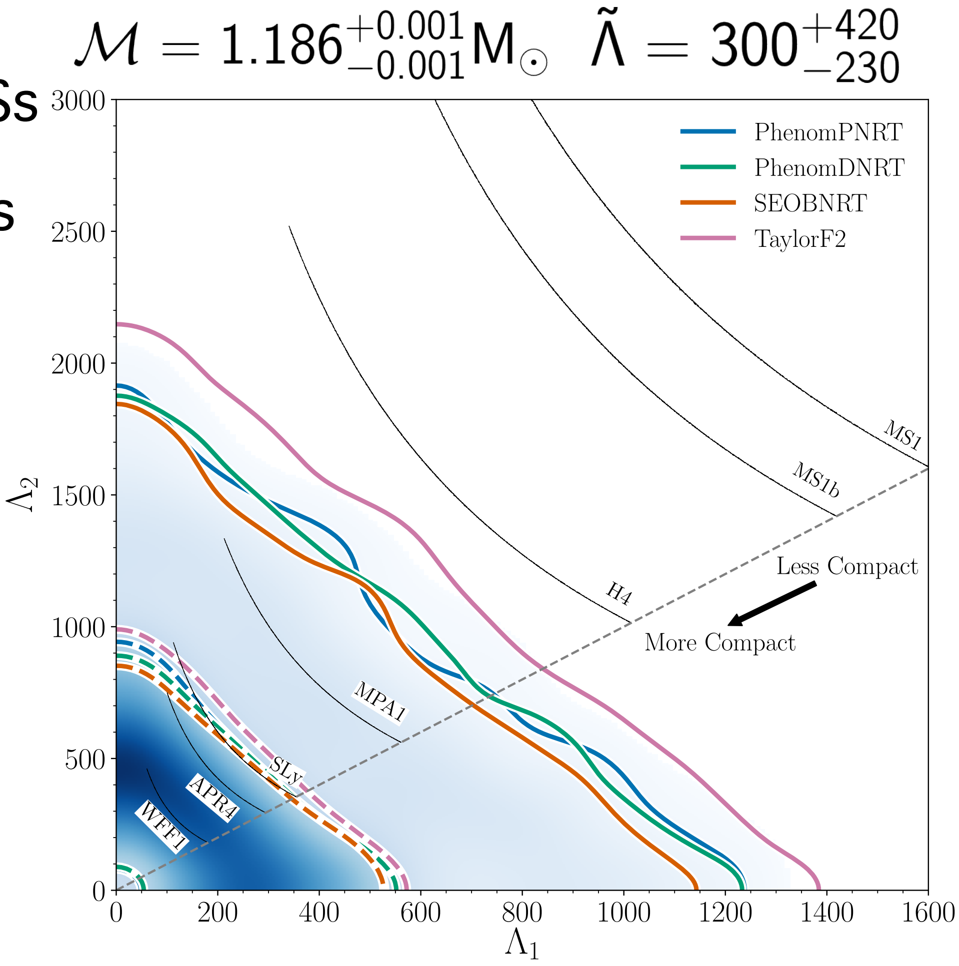
Best constraints so far

- massive pulsars: rule out too “soft” EoSs
- small tidal deformation in mergers: rules out too “stiff” EoSs

Theoretical models

- minimal scenario: dense nuclear matter EoS
- hybrid EoS: phase transition to e.g. hyperonic matter, kaon/pion condensates, quark matter..
- strange matter hypothesis

Laboratory experiments: near nuclear density



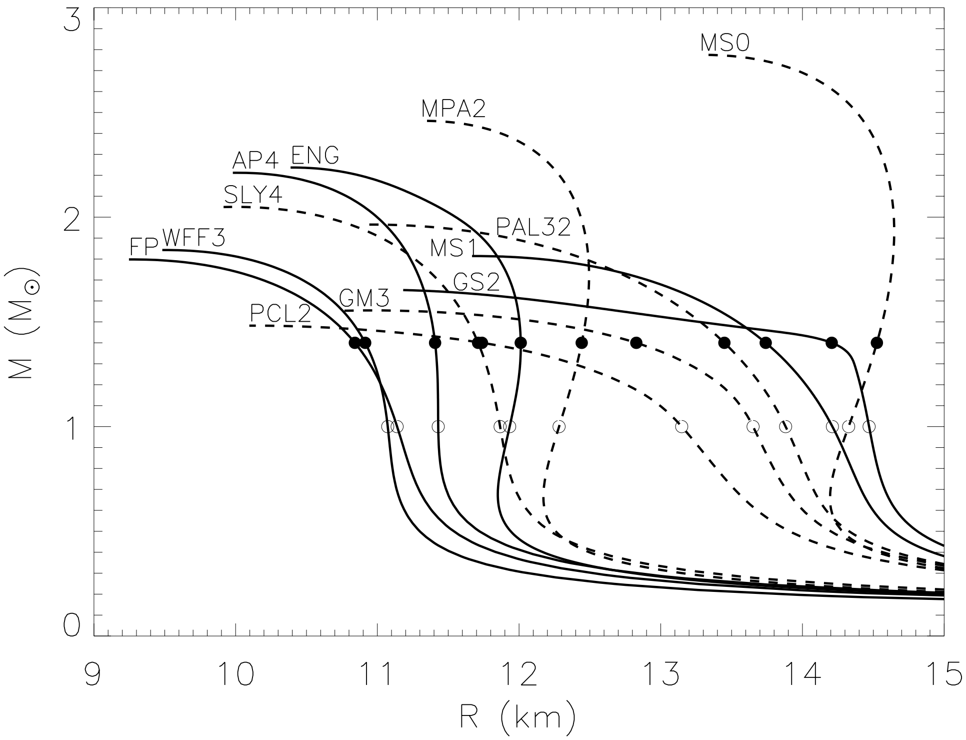
LVC collaboration, arXiv:1805.11579

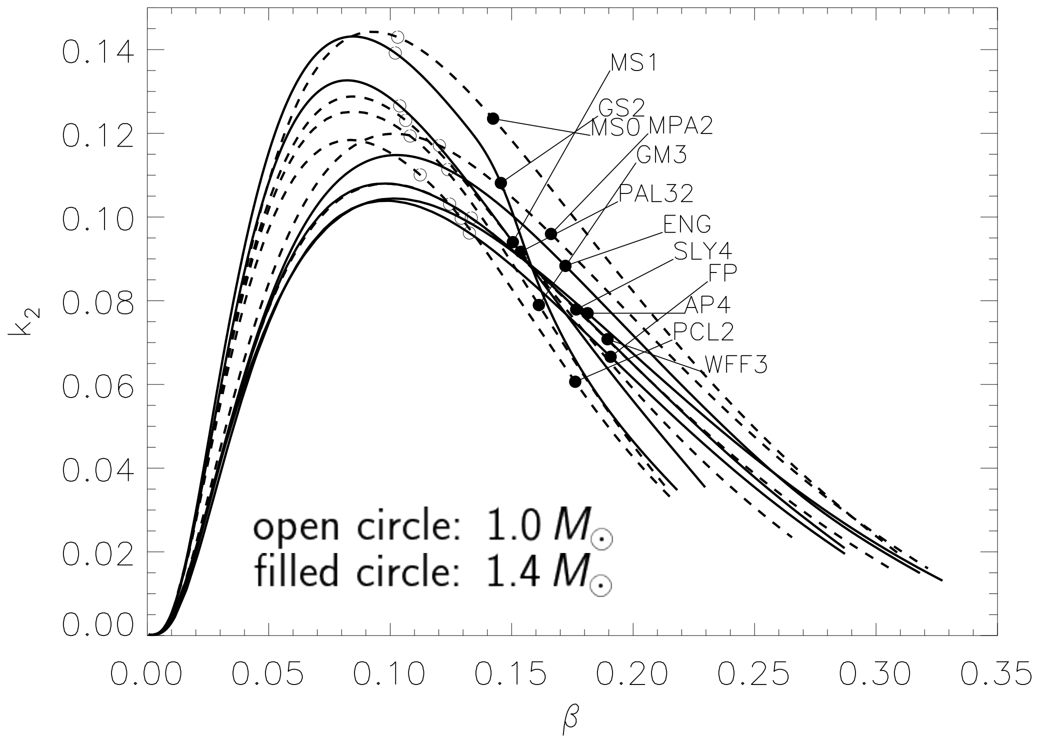
Normal Hadronic EoSs

- 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





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

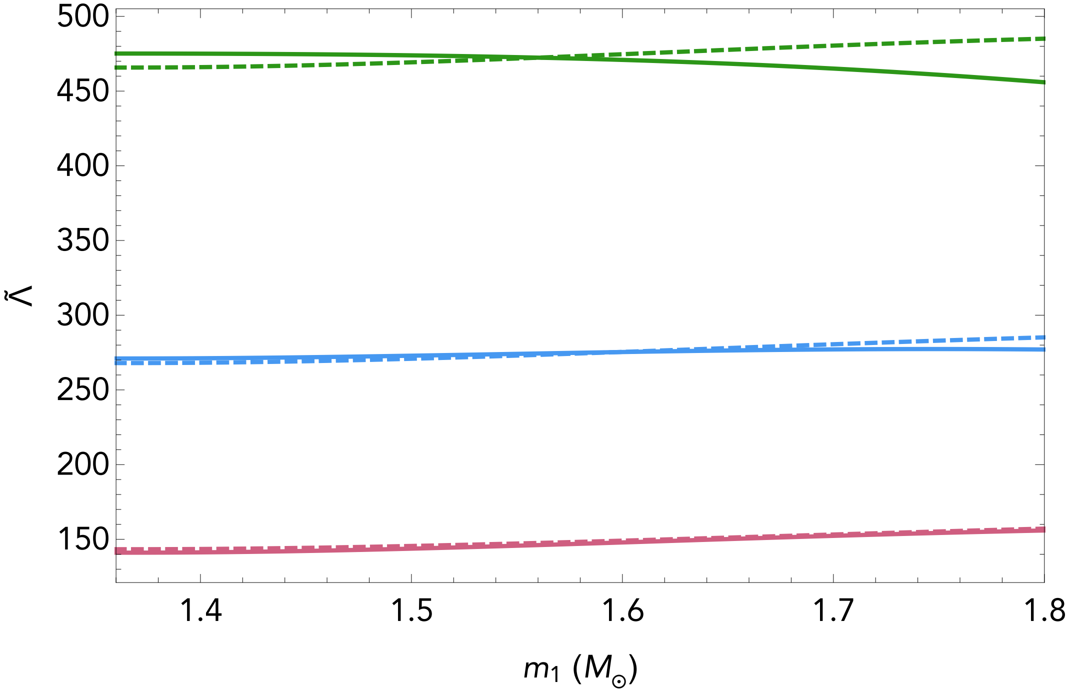
Postnikov, Prakash & Lattimer,
Phys. Rev. D 82, 024016 (2010)
arXiv:1004.5098

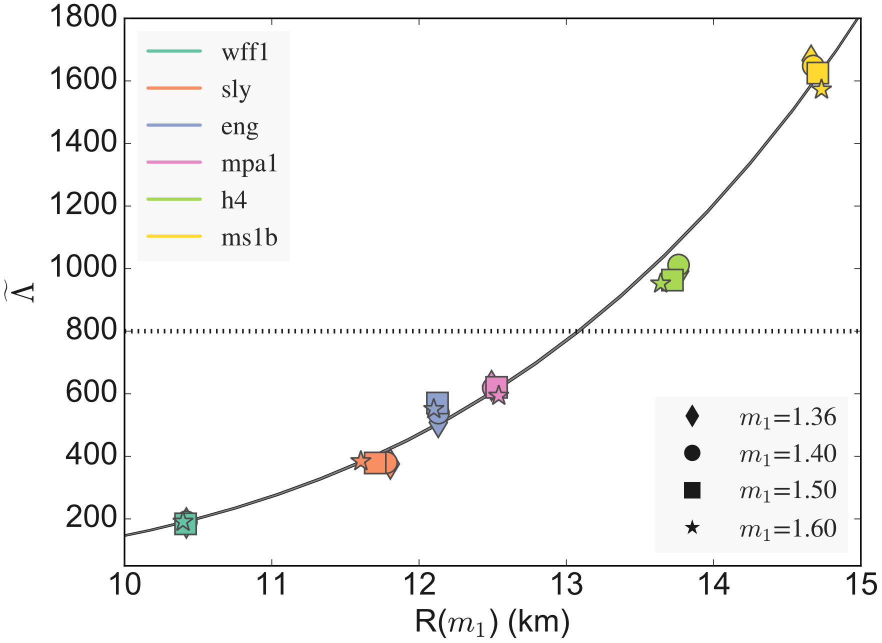
Binary Tidal Deformability

$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$$

$$\mathcal{M} = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$$

Raithel, Özel & Psaltis,
ApJ. Lett. 857, L23 (2018)
arXiv:1803.07687





- strikingly insensitive to the mass ratio for **nuclear matter** EoS
- chirp mass measured to high accuracy -> estimate range of $\tilde{\Lambda}(\mathcal{M})$
- allows for direct probe of the neutron star radius

Minimal Scenario

Nuclear matter models

- “stiffness” parameters: symmetry energy S and its slope L around nuclear saturation density

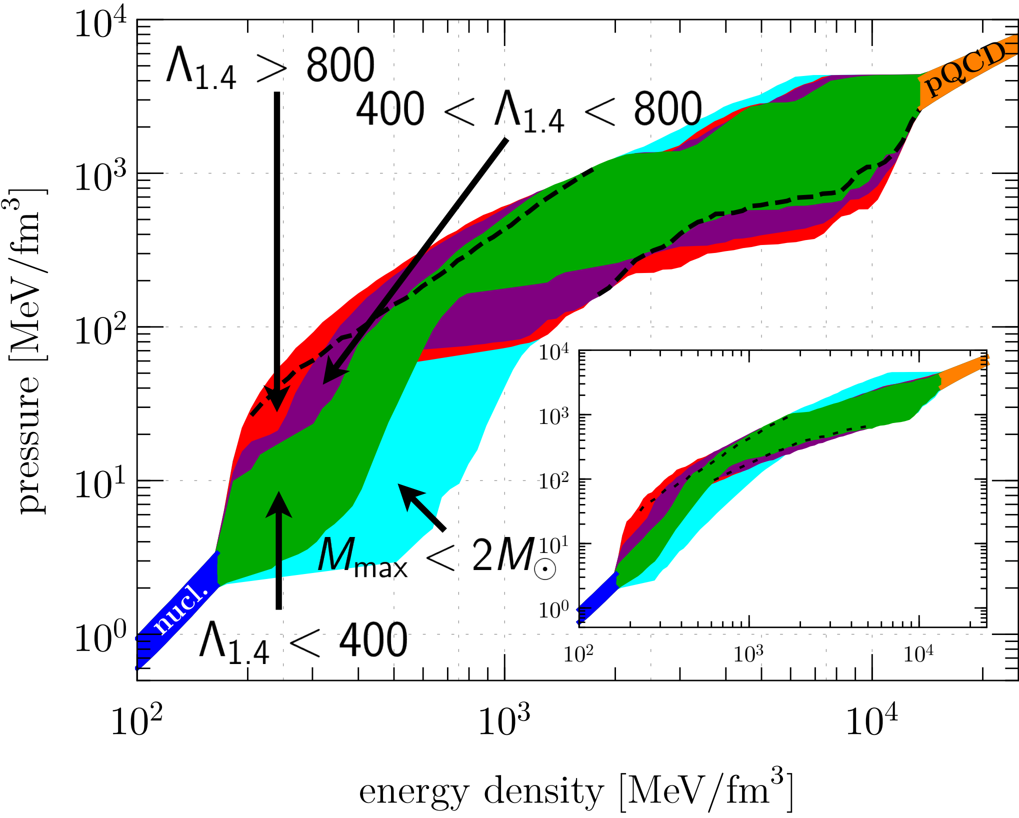
Theory

- requires strong repulsive interactions to support massive NSs; caution: causality limit
- likely tension implies a rapid switch from “soft” to “stiff” EoS around twice saturation density; QMC, chEFT

Experiment

- neutron skin, nuclei masses, dipole polarizability, heavy-ion collisions..

- chEFT + piece-wise polytrope extrapolation



Annala et al., PRL 120, 172703 (2018)

Speed of Sound

$$c_s^2(r) \equiv dp(r)/d\varepsilon(r)$$

how fast pressure rises with energy density

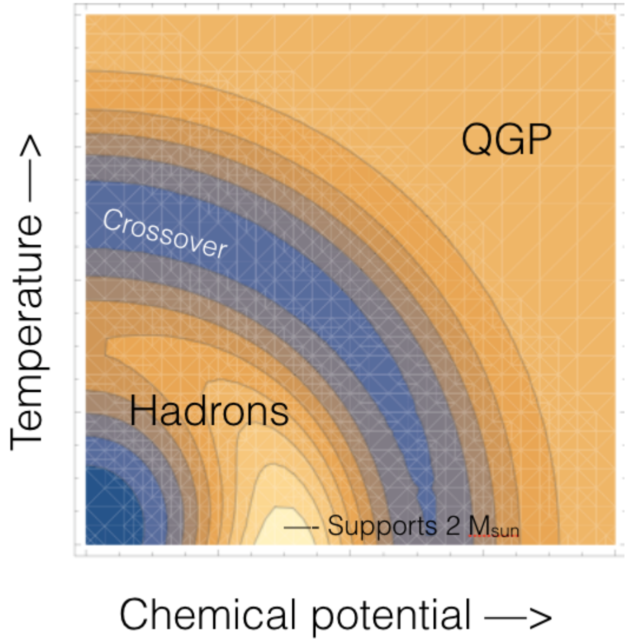
Behavior in neutron stars

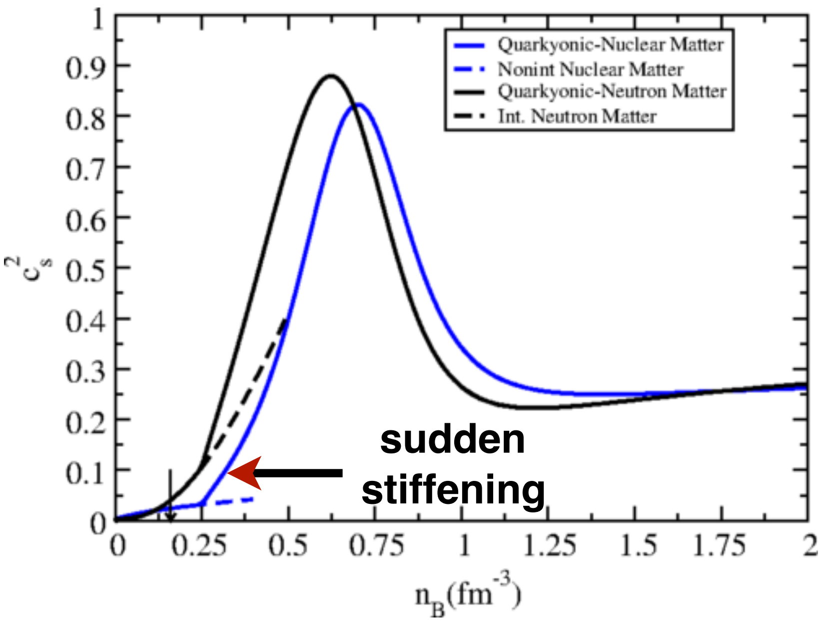
- minimal scenario of nuclear matter: smooth, monotonically increasing function of pressure
- first-order phase transition scenario: finite energy density **discontinuity** induces sudden softening near the phase boundary
- crossover scenario (quark-hadron continuity)

Limits

- asymptotically high density: ~1/3
- intermediate: need to support massive NSs
- high-T: matches lattice calc./heavy-ion data

The Phases of Dense Matter
(INT-16-2b)





McLerran & Reddy,
PRL 122. 122701 (2019)

Modeling Quark Cores

1st-order transition

- infinite surface tension: Maxwell construction
- zero surface tension: Gibbs construction

Crossover transition

- quarkyonic model (second order)
- interpolation scheme

Key questions

- what is the minimum NS mass that is likely to contain quarks?
- what is the minimum density where a hadron-quark transition of any kind can occur?
- which astronomical observations have the best potential to attest to the presence of quarks?

1st-order Transition

Hybrid EoS models

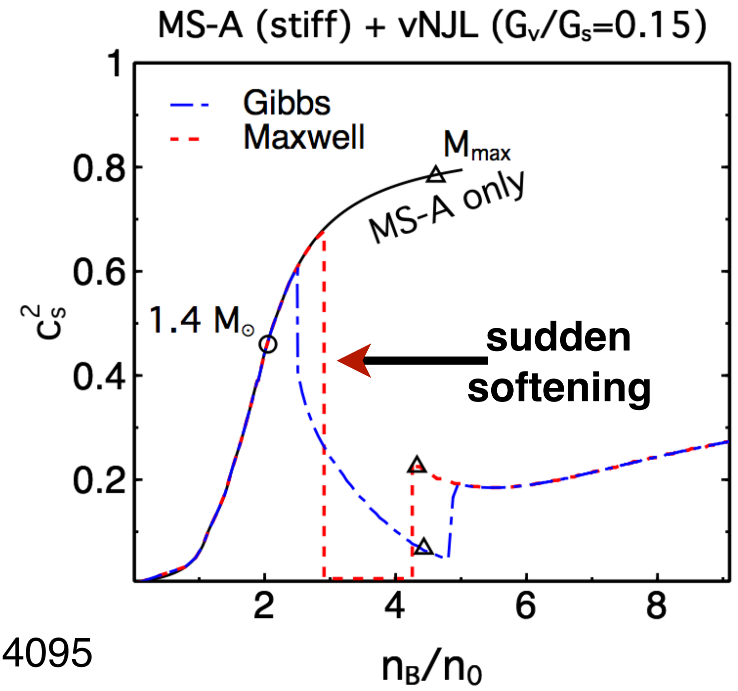
- phase transition parameters: threshold density, weak or strong PT, stiffness (speed of sound) above PT
- input: nuclear matter EoS below PT

Theory

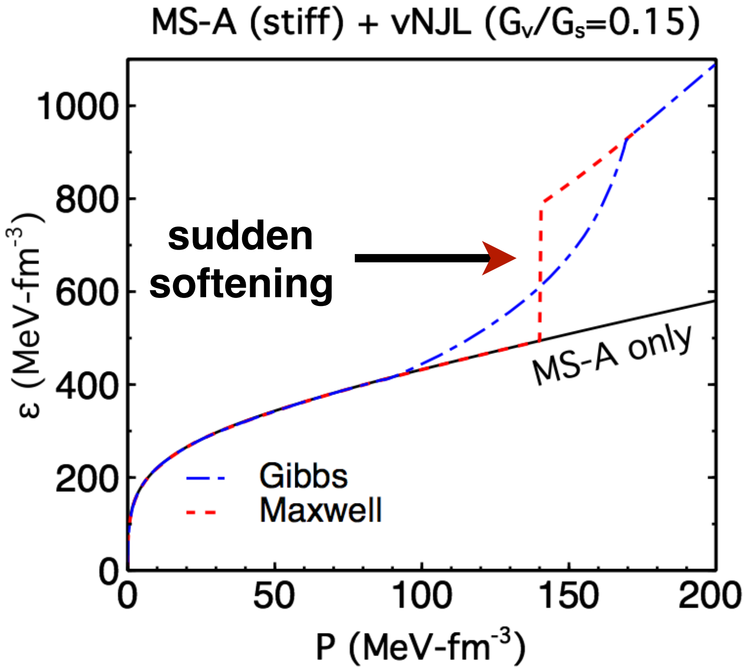
- high-density quark models: pQCD, **NJL models**, chiral sigma model, **MIT bag..**
- surface tension at the hadron/quark interface: sharp transition or mixed phase?

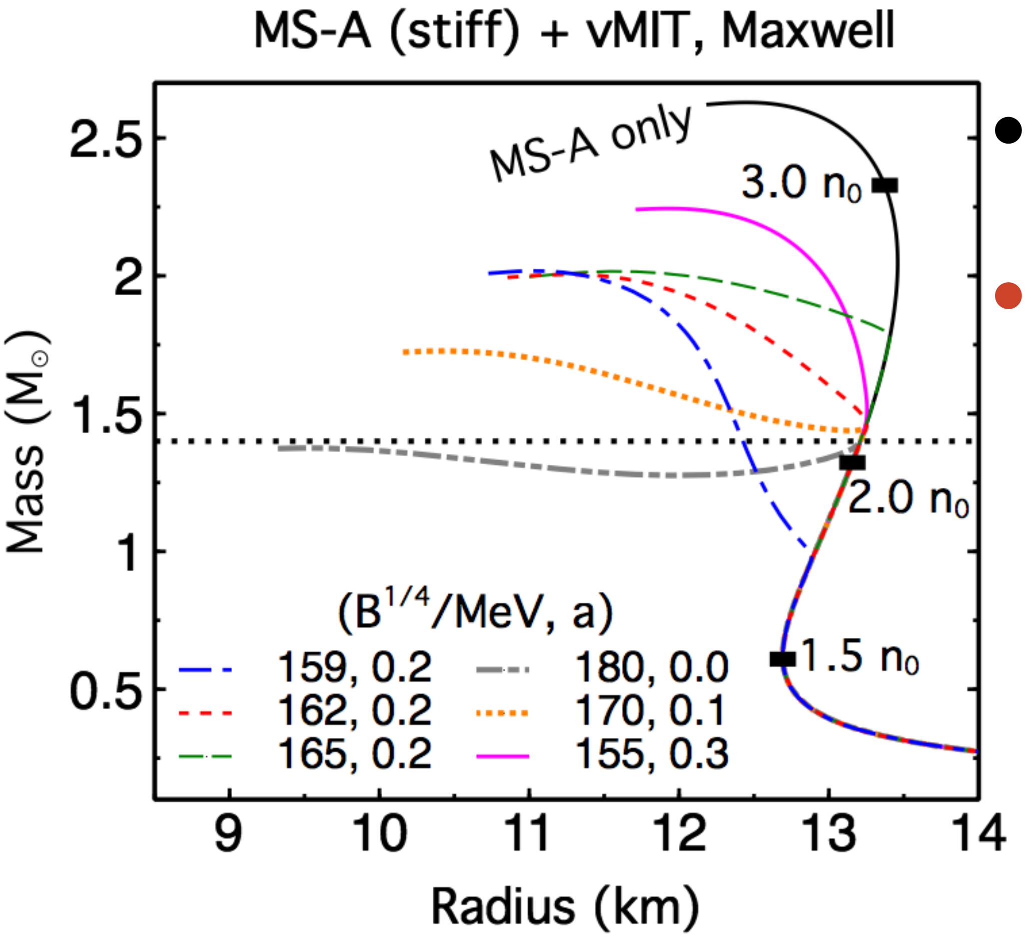
Evident signatures

- **disc.** M-R; **multivalued** tidal parameters

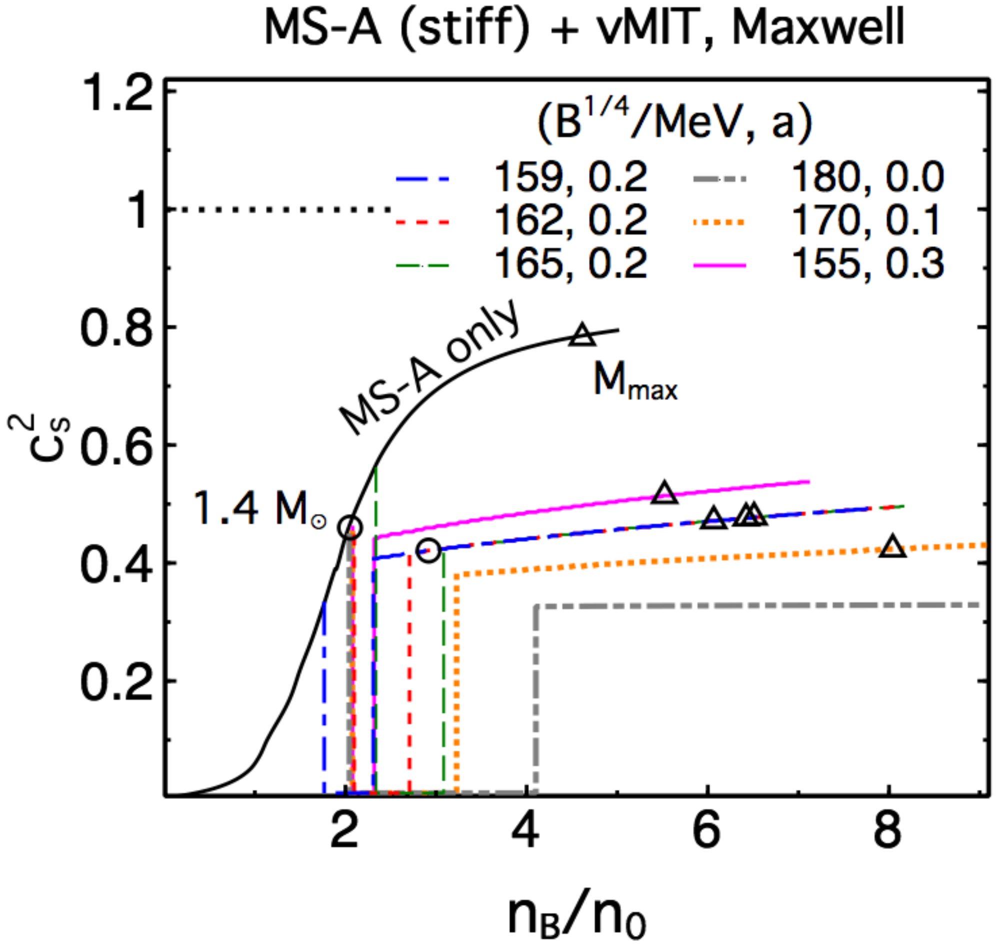


arXiv:1906.04095

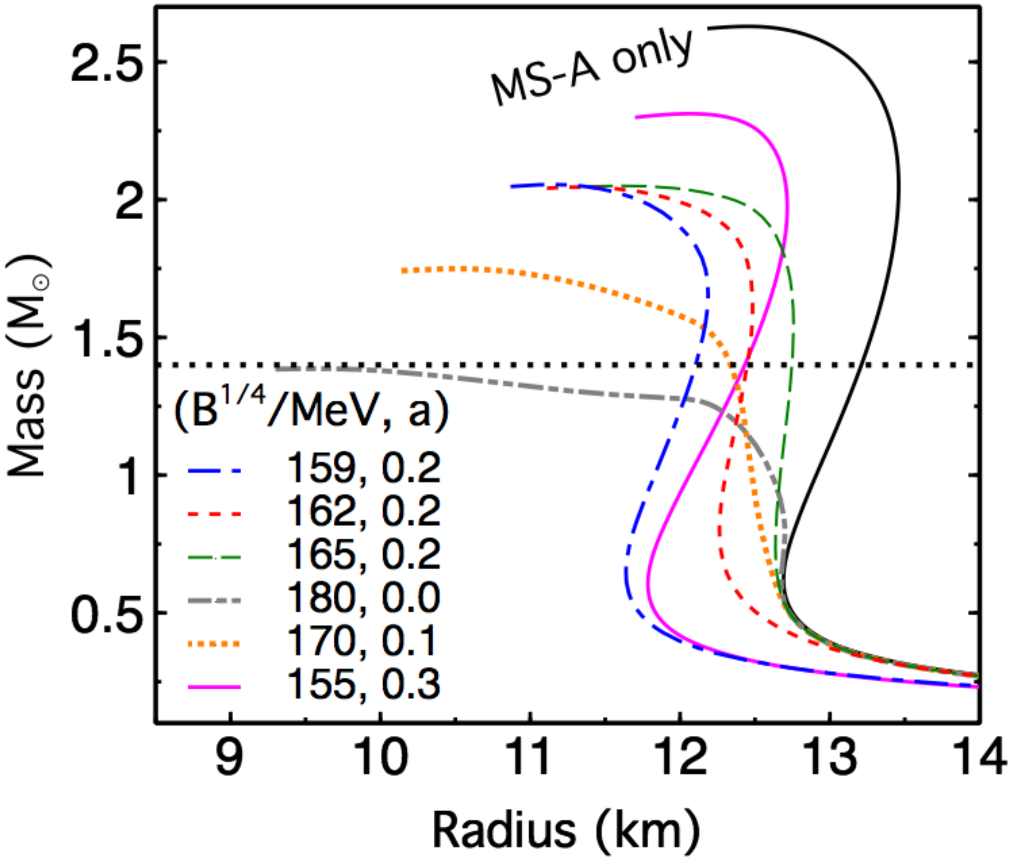


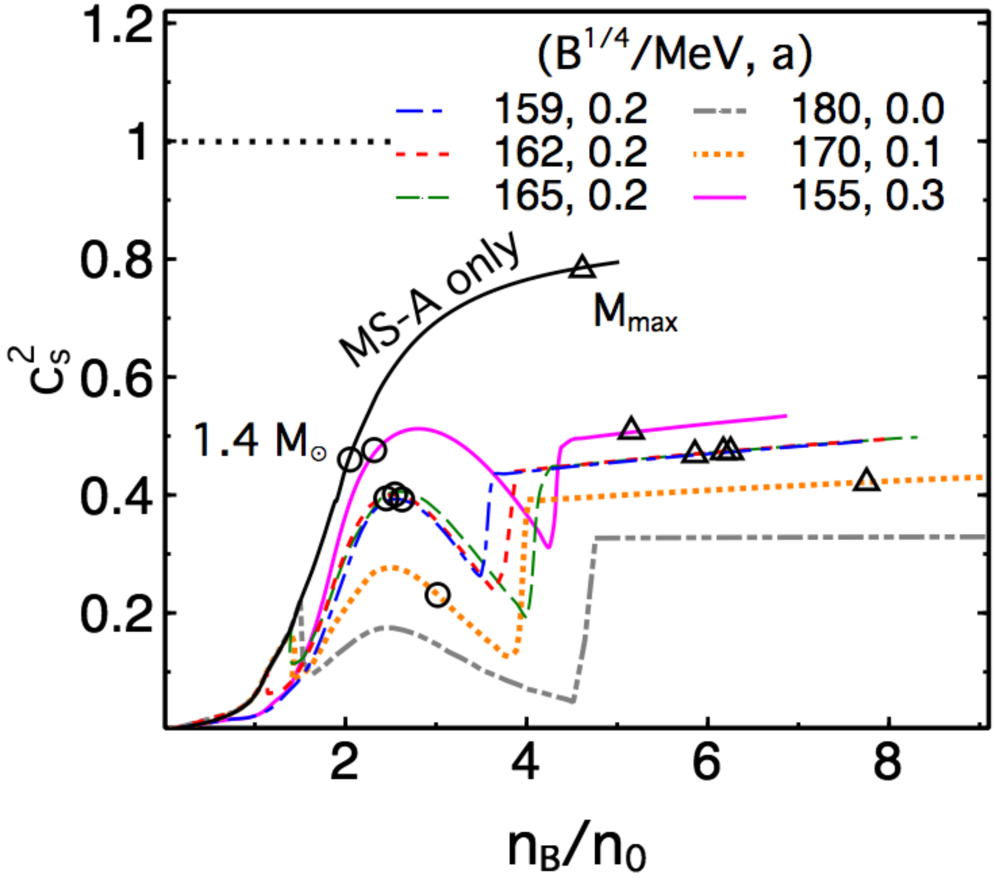


- if quarks appear **too late:** i) immediate collapse; ii) violates tidal deformability
- only **stiff NM to stiff QM @** $\lesssim 3n_0$ survives!

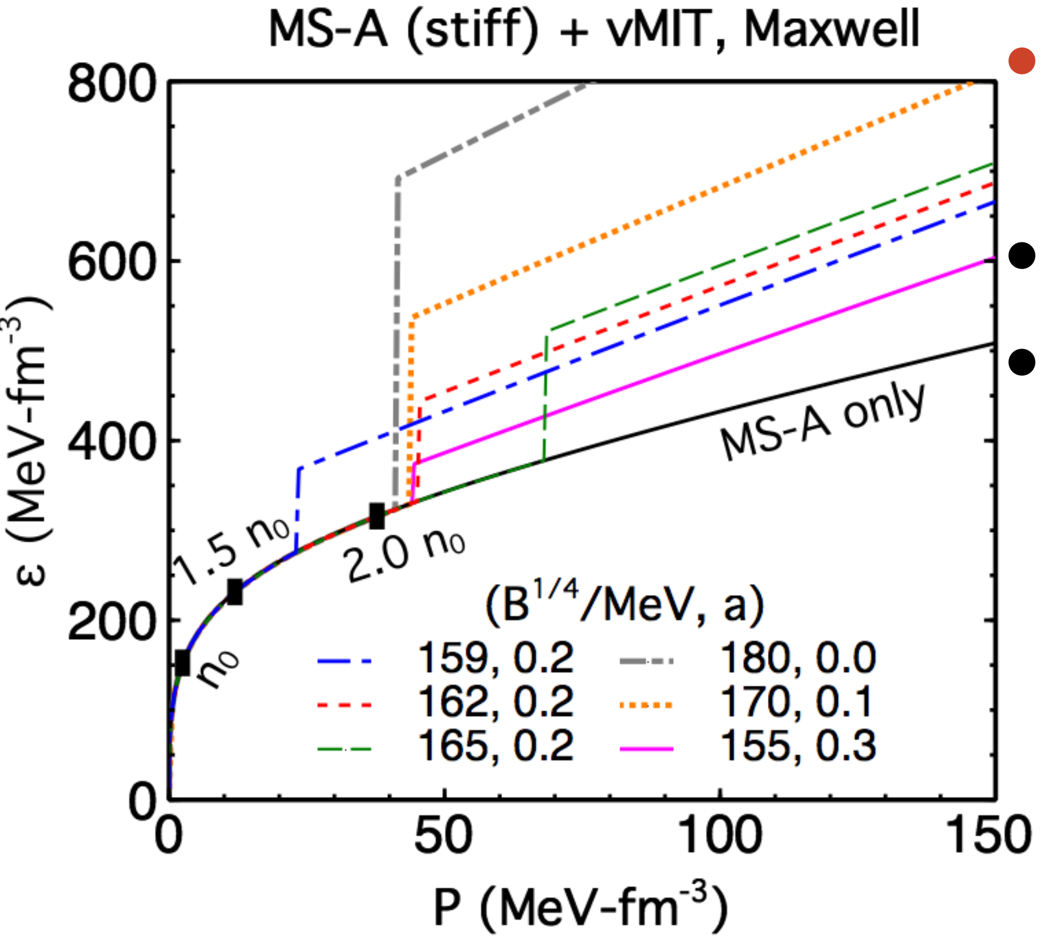


- 1st-order: reduces both R and Mmax
- soft q-EoS: **cannot** support 2 solar masses
- soft n-EoS: **no** valid PT (pressure & chemical potential equality)


MS-A (stiff) + vMIT, Gibbs

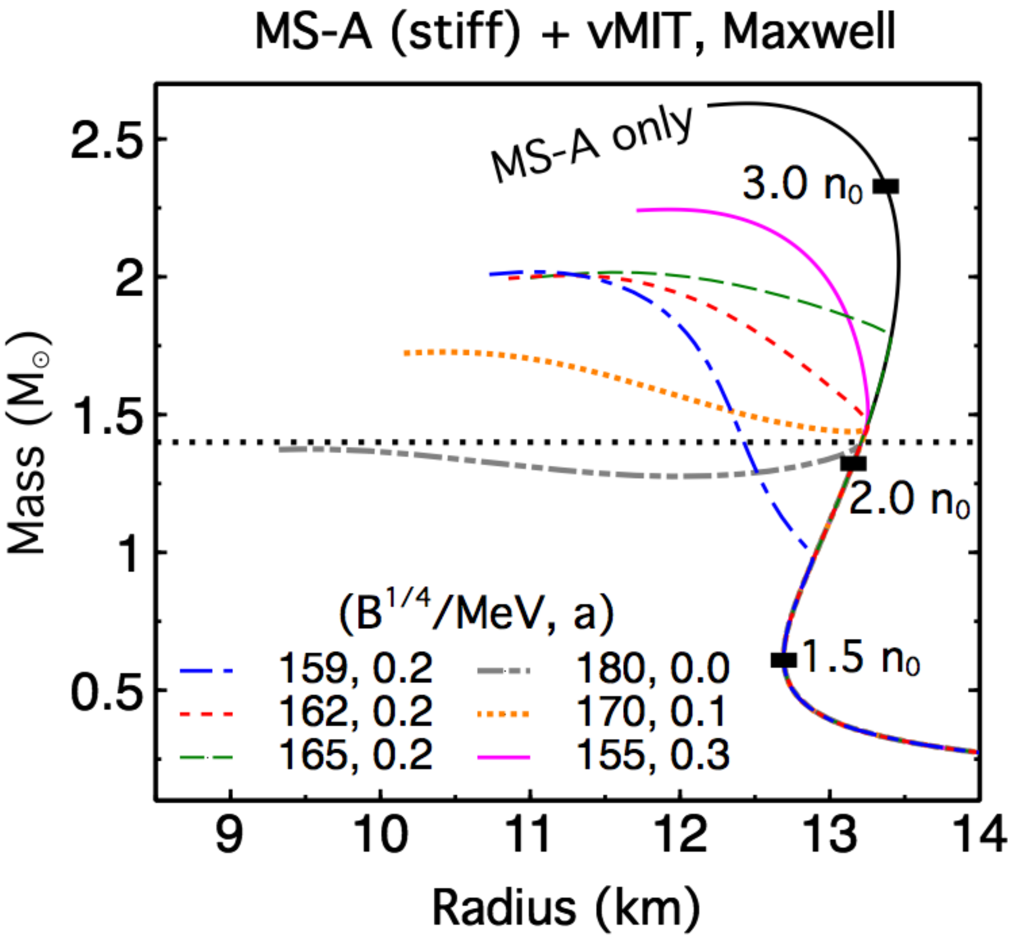

MS-A (stiff) + vMIT, Gibbs

- Gibbs: smoothes out mass-radius
- even lower threshold
- indistinguishable



- if **stiff NM to stiff QM** is true: quarks probably exist in **pre-merger** NSs
- can it be manifest in observations?
- Maxwell: **yes** if PT is strong; Gibbs: **no**

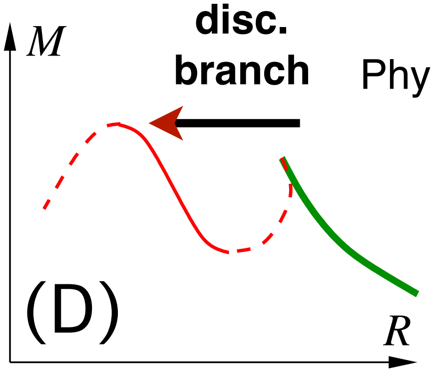
- if n-EoS @ $\sim 2n_0$ proved **soft:** no 1st-order PT; resort to crossover, or
- quark models applied **fail** to capture **soft to stiff** 1st-order PT
- model-independent parametrization

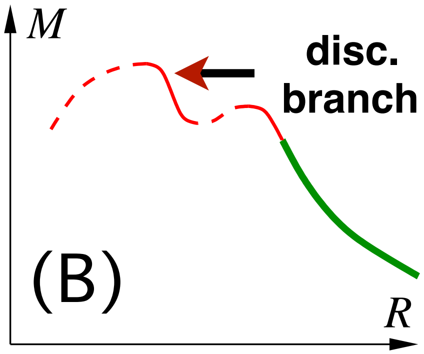


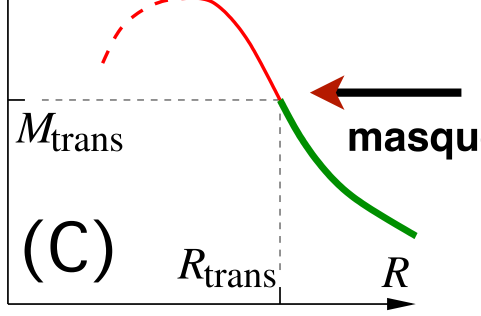
Constraints on 1st-order PT

Better knowledge of nuclear EoS helps

Alford, **SH** & Prakash
Phys. Rev. D88, 083013 (2013)

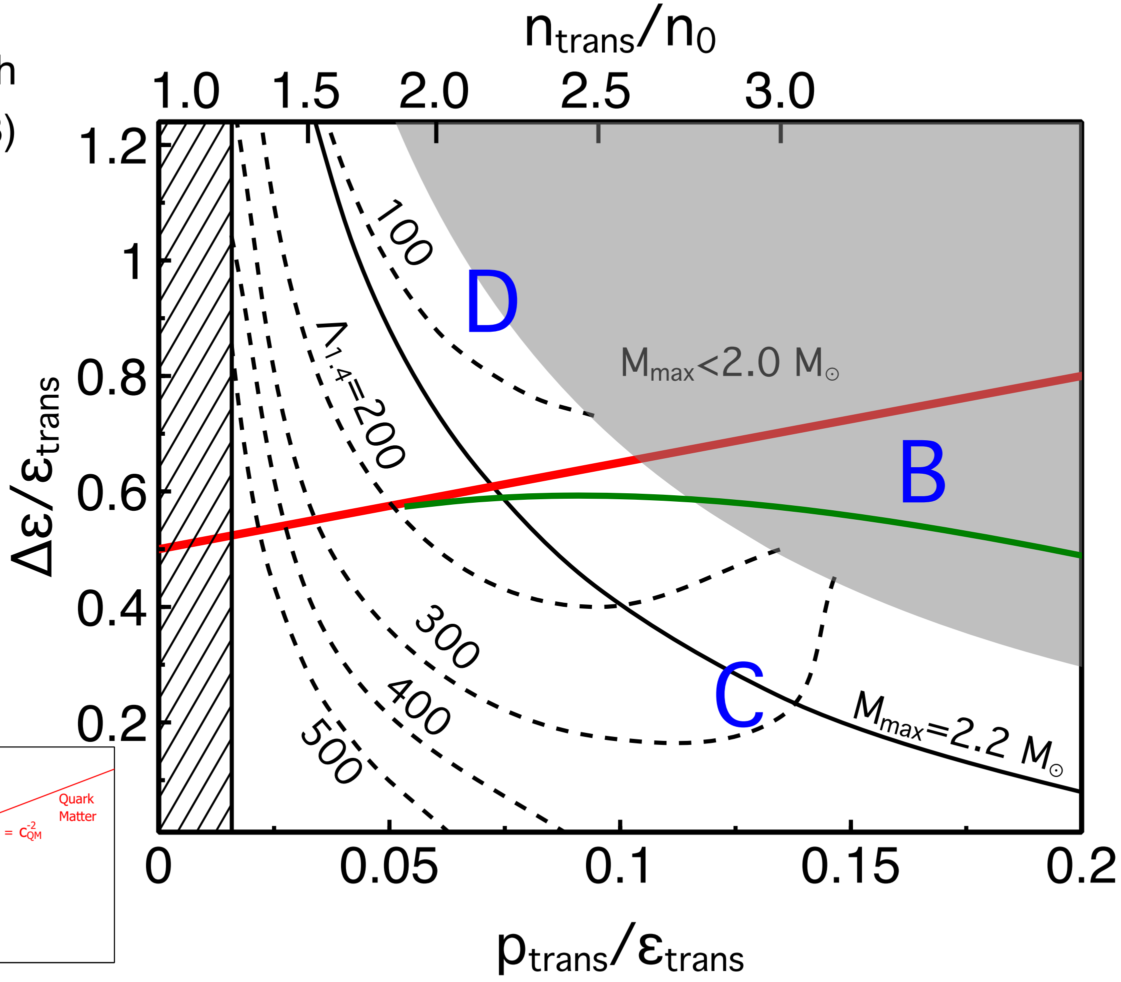


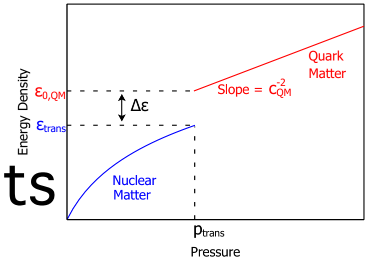




SH & Steiner, arXiv:1810.10967

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





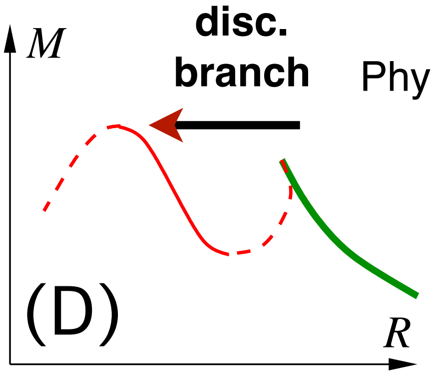
Observational constraints

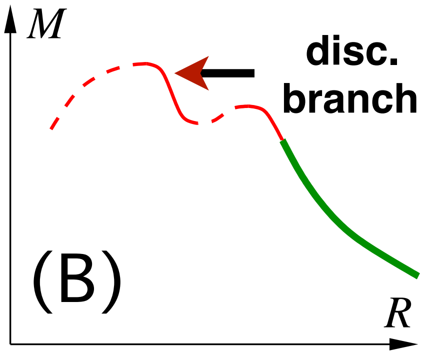
- massive pulsars observed ~2 solar masses
- pre-merger GW signals detected limit tidal deformability

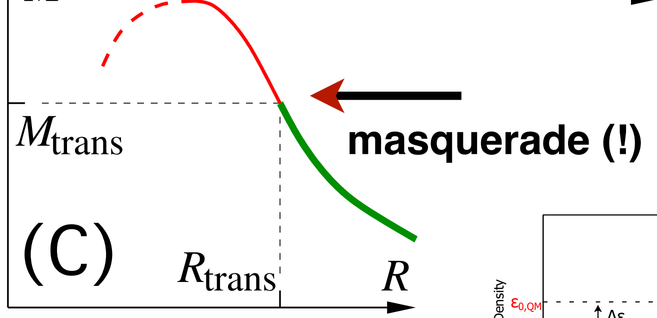
Constraints on 1st-order PT

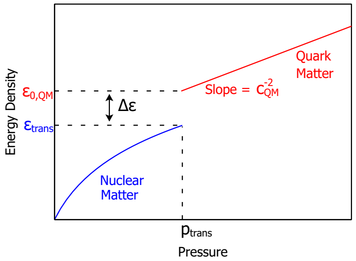
Better knowledge of nuclear EoS helps

Alford, **SH** & Prakash
Phys. Rev. D88, 083013 (2013)



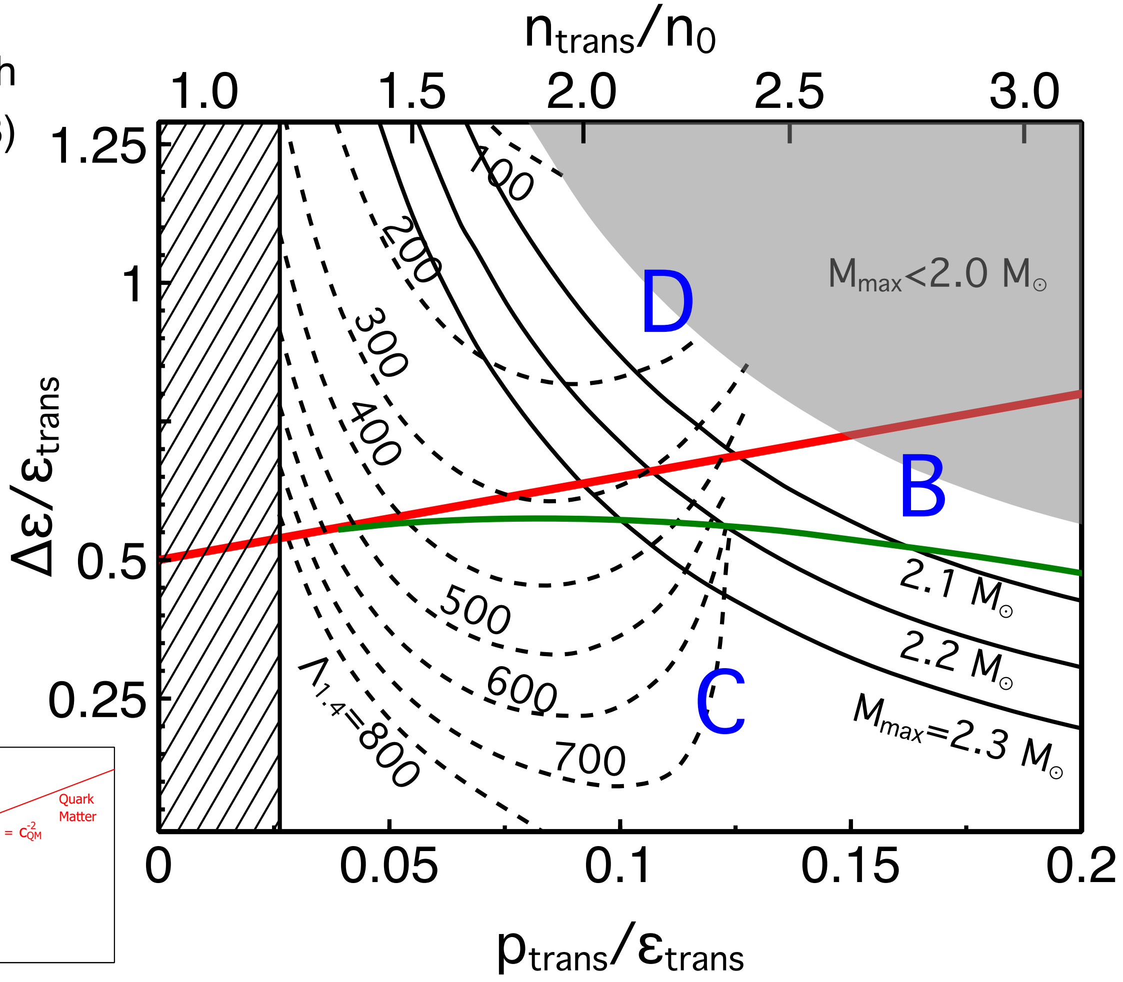






SH & Steiner, arXiv:1810.10967

stiff DBHF + CSS (c_{QM}^2=1)

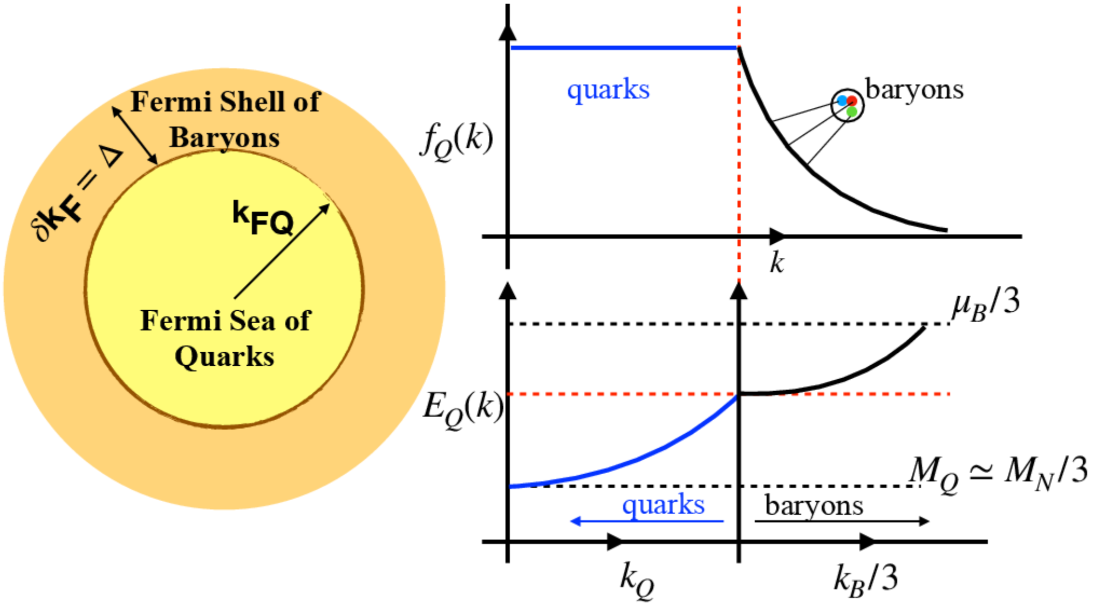


Implications

- **stiff** nuclear matter preferred; too-high transition density ruled out
- **distinguishability** (“D/B” vs. “C”) depends on the **strength** of PT: $\Delta\varepsilon/\varepsilon_{\rm trans}$

Quarkyonic Matter

McLerran & Reddy,
PRL 122, 122701 (2019)



- both quarks and hadrons exist in the system simultaneously
- choose a QCD inspired cutoff and obtain the “shell” in Fermi sphere

$$\Delta = \frac{\Lambda_Q^3}{k_F^2} + \kappa \frac{\Lambda_Q}{N_c^2}$$

- quark momenta

$$k_{Fq} = \frac{(k_{FB} - \Delta)}{N_c} \Theta(k_{FB} - \Delta)$$

- quarks appear after when $k_{FB} > \Delta$

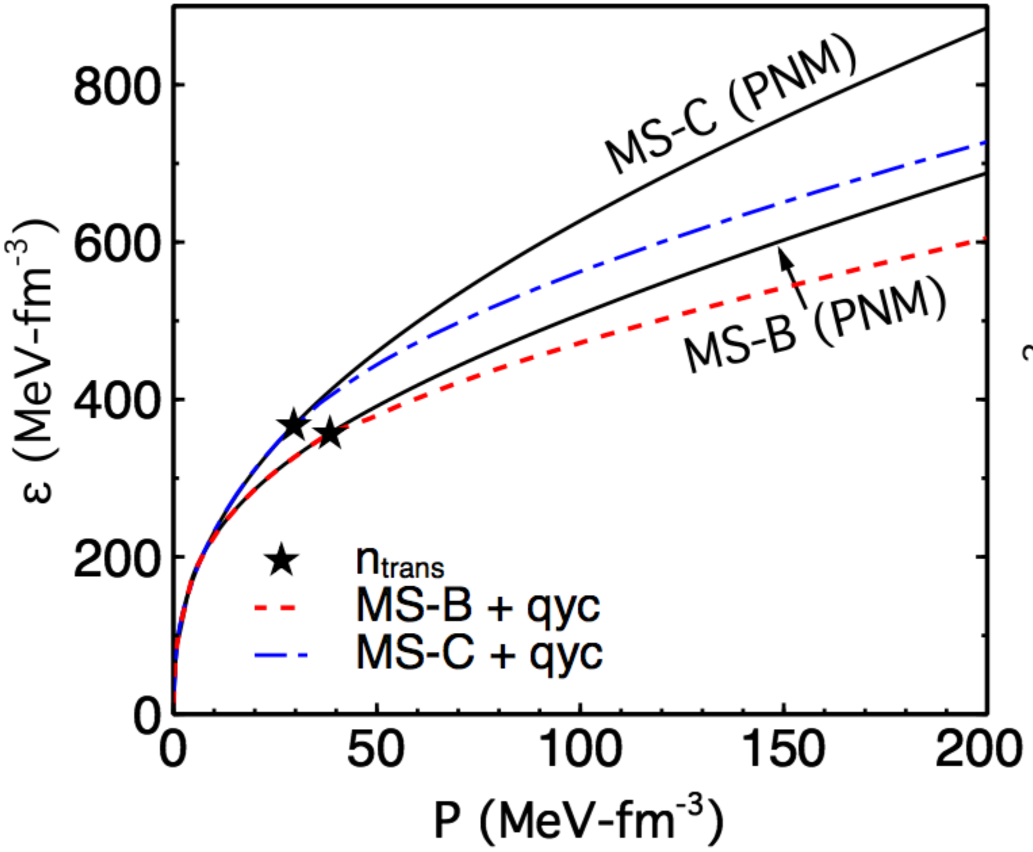
- smooth crossover; both pressure and energy density continuously increase
- peak of sound velocity supports massive star

- Λ_Q and κ determine the onset (below which n-EoS is suitably chosen)

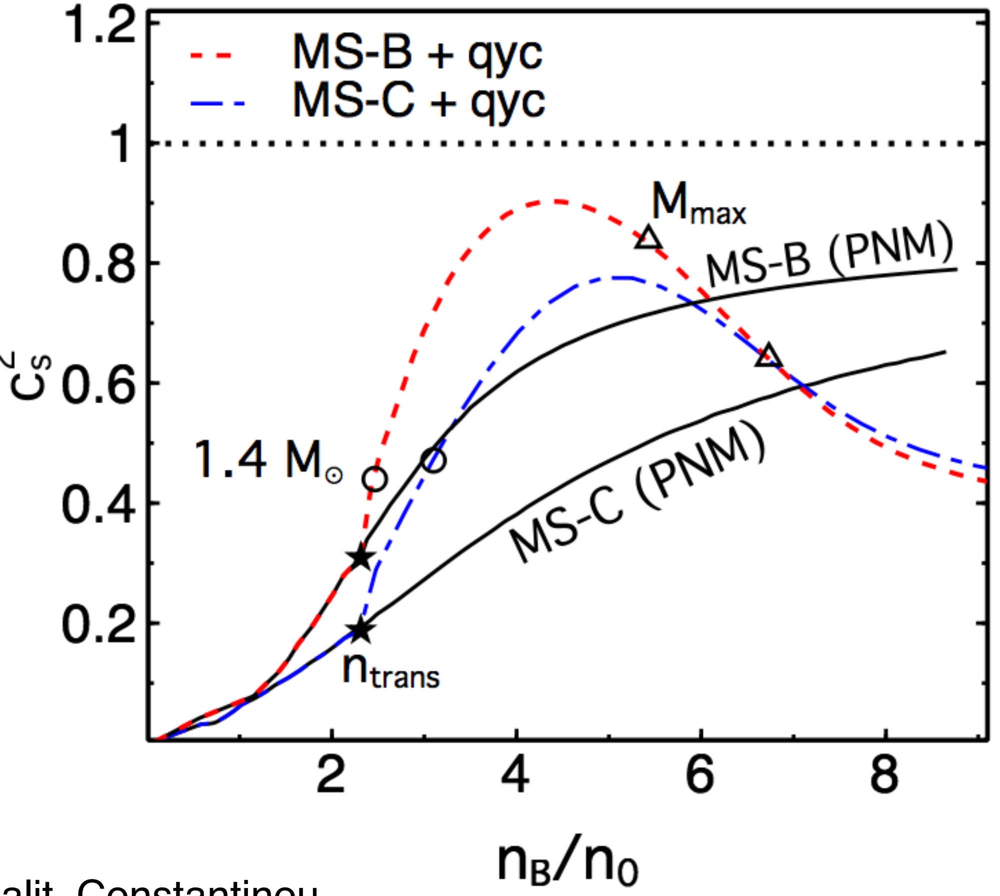
Crossover Transition

- example: pure neutron matter (PNM) + quarkyonic
- boosts both tidal deformability & maximum mass

MS-B/C (PNM) + Quarkyonic (u, d)



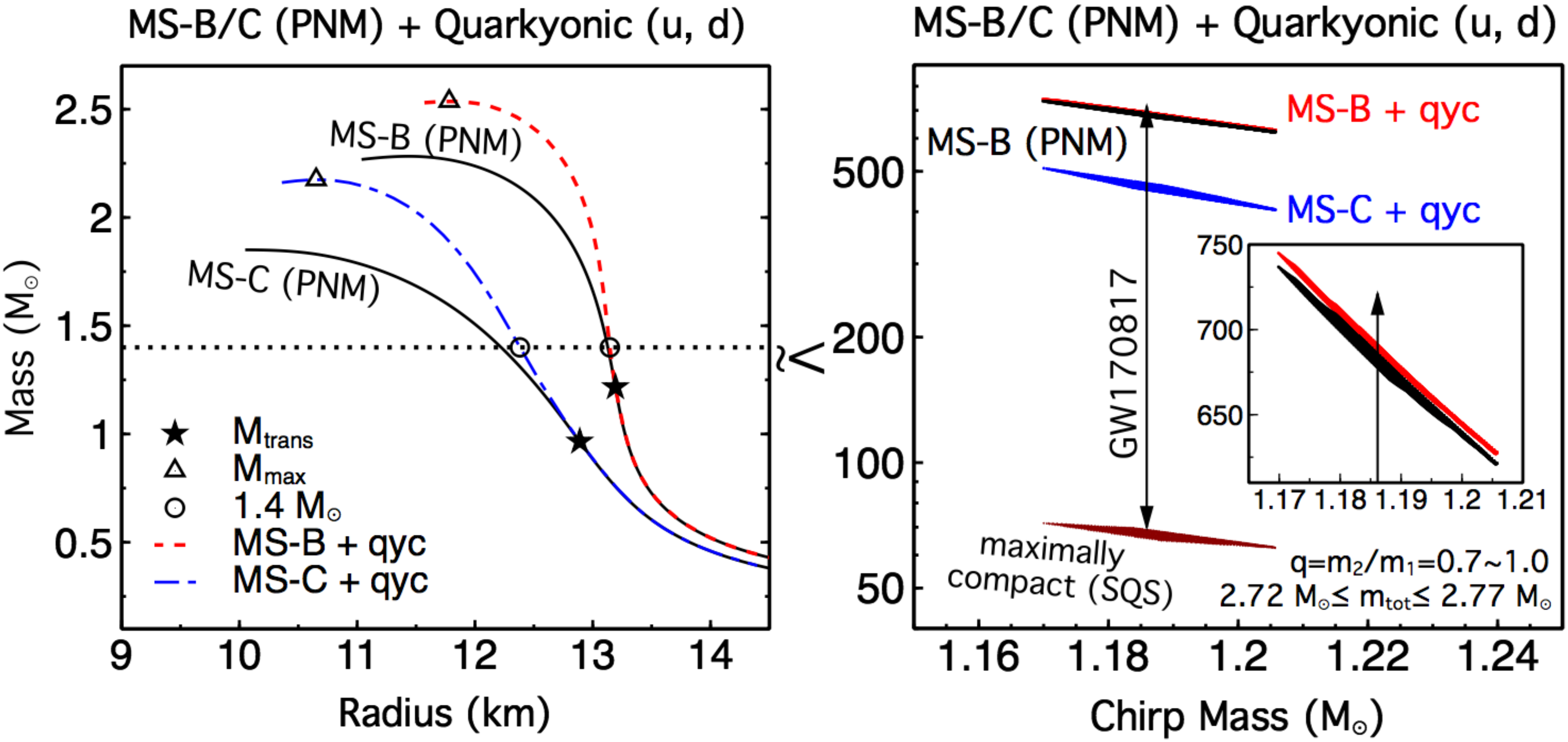
MS-B/C (PNM) + Quarkyonic (u, d)



SH, Al Mamun, Lalit, Constantinou
& Prakash, arXiv:1906.04095

Crossover Transition

- relies on **soft** nuclear matter to ensure small R & deformability
- **indistinguishable (!)** from purely hadronic stars

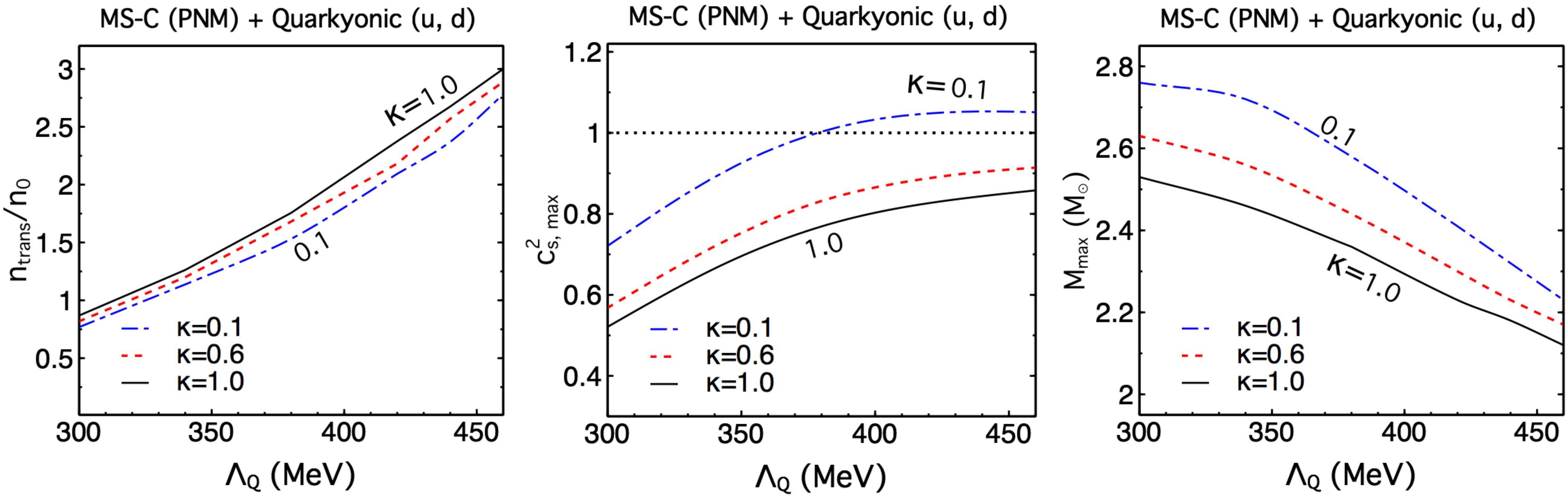

MS-B/C (PNM) + Quarkyonic (u, d)

MS-B/C (PNM) + Quarkyonic (u, d)

SH, Al Mamun, Lalit, Constantinou & Prakash, arXiv:1906.04095

Crossover Transition

- relies on **soft** nuclear matter to ensure small R & deformability
- exploring the limits of **threshold density**

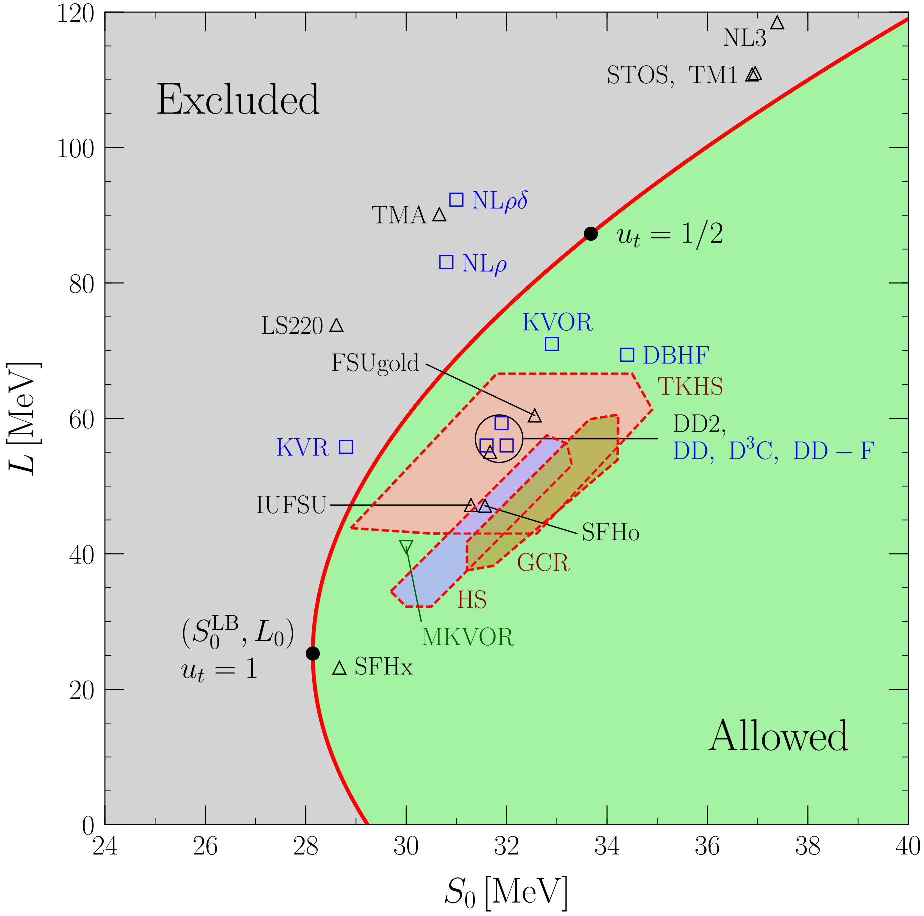


SH, Al Mamun, Lalit, Constantinou & Prakash, arXiv:1906.04095

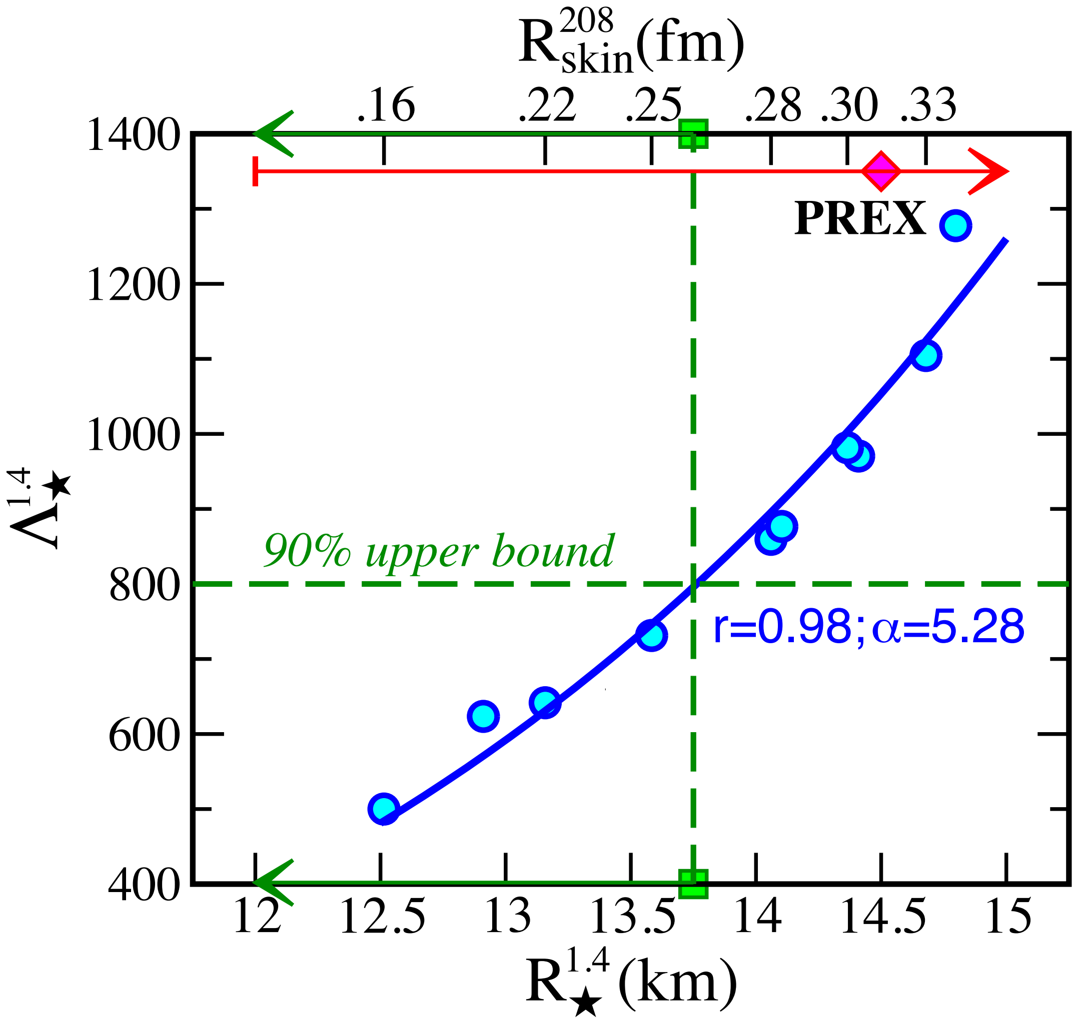
Low-energy Theory/Experiment

- example: unitary gas constraints
- neutron-skin thickness of neutron-rich nuclei

Fattoyev, Piekarewicz & Horowitz,
PRL 120, 172702 (2018)

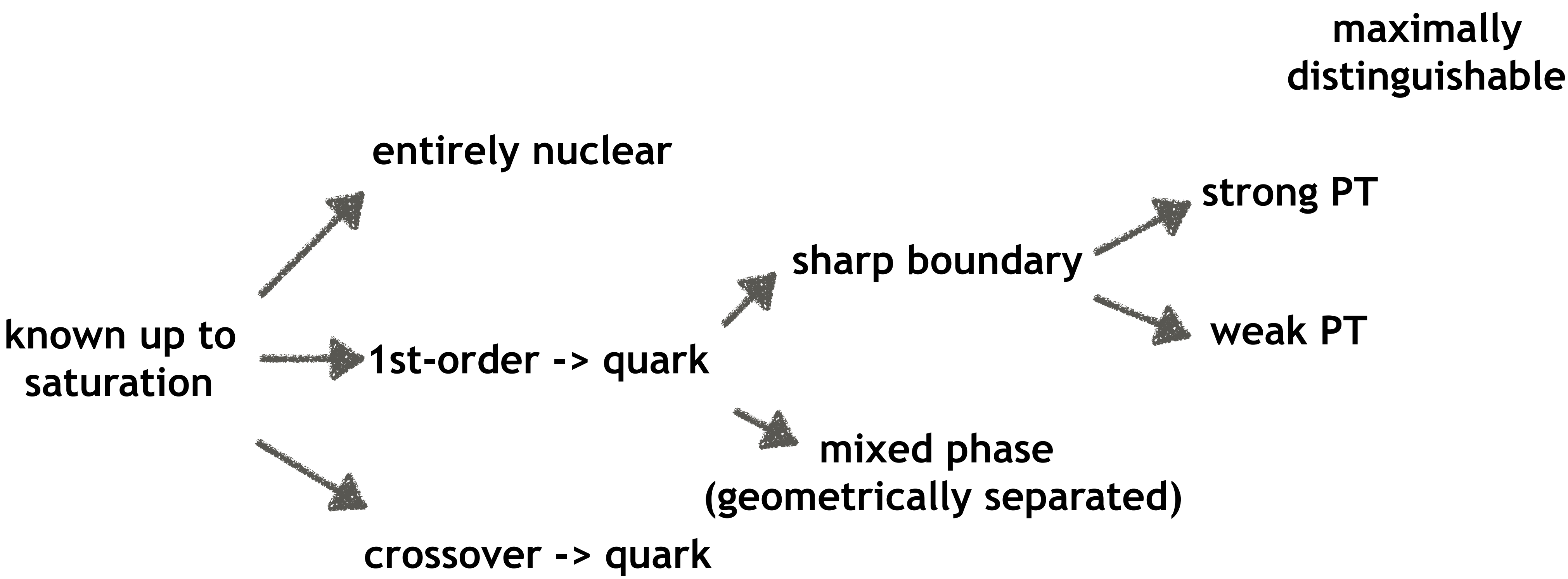


Tews, Lattimer, Ohnish & Kolomeitsev,
Astrophys. J. 848, 105 (2017)



- **paths to go beyond saturation?**

Summary: Crossroads



maximally distinguishable

known up to saturation

entirely nuclear

1st-order -> quark

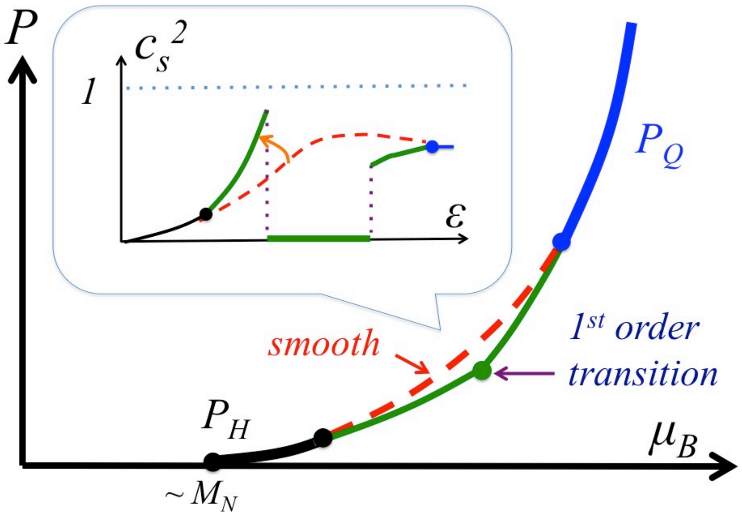
crossover -> quark

sharp boundary

mixed phase (geometrically separated)

strong PT

weak PT

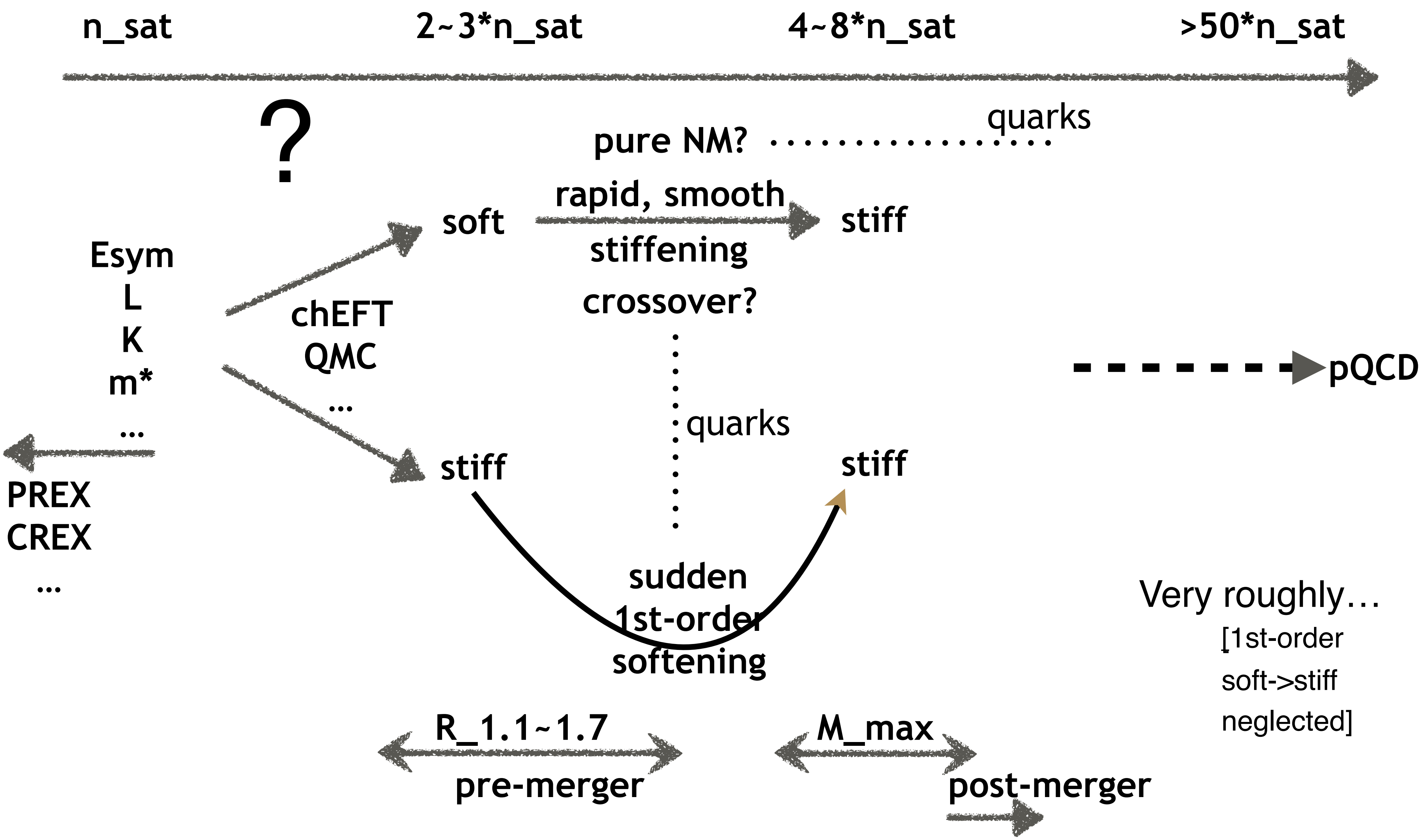


interpolation scheme - crossover

Baym et al., arXiv:1707.04966
Rept. Prog. Phys. 81, 056902 (2018)

see also Kojo et al. (2015); Fukushima & Kojo (2016); Masuda et al. (2013).

Summary: Crossroads



n_sat

2~3*n_sat

4~8*n_sat

>50*n_sat

?

quarks

pure NM? ………………

Esym
L
K
m*
…

PREX
CREX
…

chEFT
QMC
…

soft

rapid, smooth
stiffening
crossover?

stiff

quarks

stiff

stiff

sudden
1st-order
softening

pQCD

R_1.1~1.7

pre-merger

M_max

post-merger

Very roughly…
[1st-order
soft->stiff
neglected]

Highlights: Global Structure

arXiv:1906.04095

arXiv:1904.05471

arXiv:1810.10967

Limits on PT within neutron stars

- weakly interacting quarks are nearly ruled out
- 1st-order: **stiff** nuclear matter preferred (for typical quark models)
- crossover: **soft** nuclear matter required
- possible onset of deconfined quarks in the **pre-merger** components $1.1 \sim 1.7\mathrm{M}_\odot$

Distinguishability of QM

- sharp transition: ✓separate branches with different radii
- smooth transition: $\times$simple topology that resembles purely hadronic phase

Looking forward

- **dynamic** observables important: sensitive to transport properties
- cooling, spin-down, osc. modes, gravitational-wave radiation..

Highlights: Dynamics

arXiv:1906.04095

arXiv:1904.05471

arXiv:1810.10967

Thermal evolution

- isolated stars: compatible with “minimal cooling”
- evidence for enhanced nu-emission in accreting stars, yet origin unknown
- phases with too small specific heat ruled out by late-time crust cooling
- unpaired quark matter: unlikely to dominate

Spin evolution

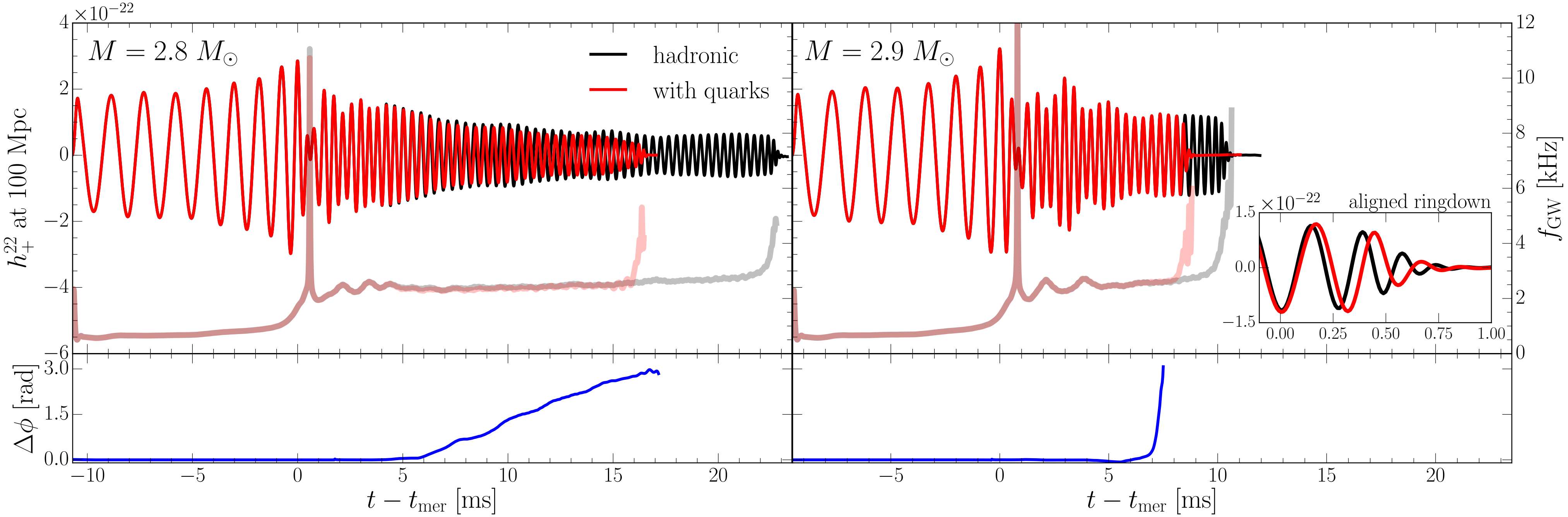
- pulsar glitch: suggests superfluidity
- r-mode puzzle: hadrons insufficient; shifted bulk viscosity resonance in quark matter (unpaired); phase-conversion dissipation

Gravitational waves

- ellipticity of solid phases: continuous GWs from “mountains”
- neutron star mergers: frequency and spectra

e.g. merger simulation with quarks

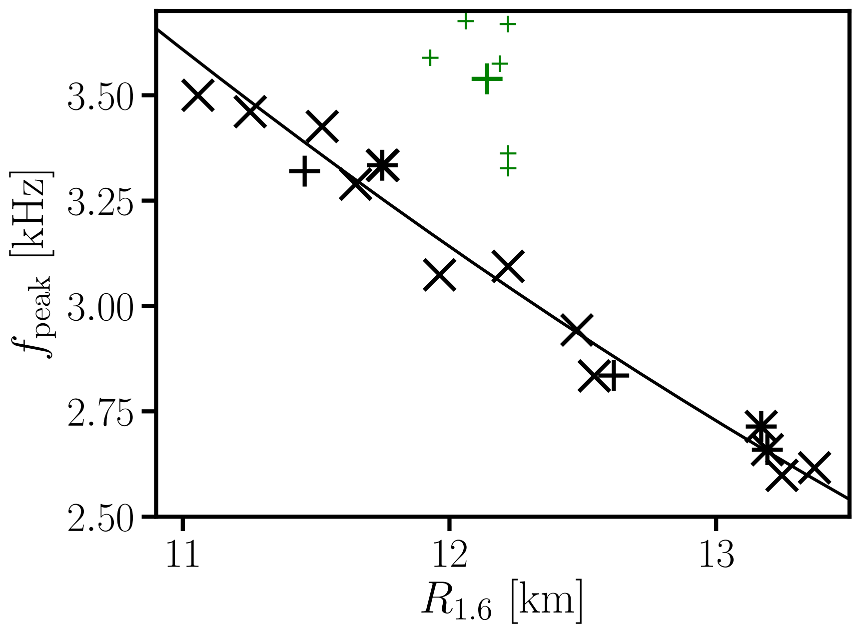
Most et al., arXiv:1807.03684
PRL 122, 061101 (2019)

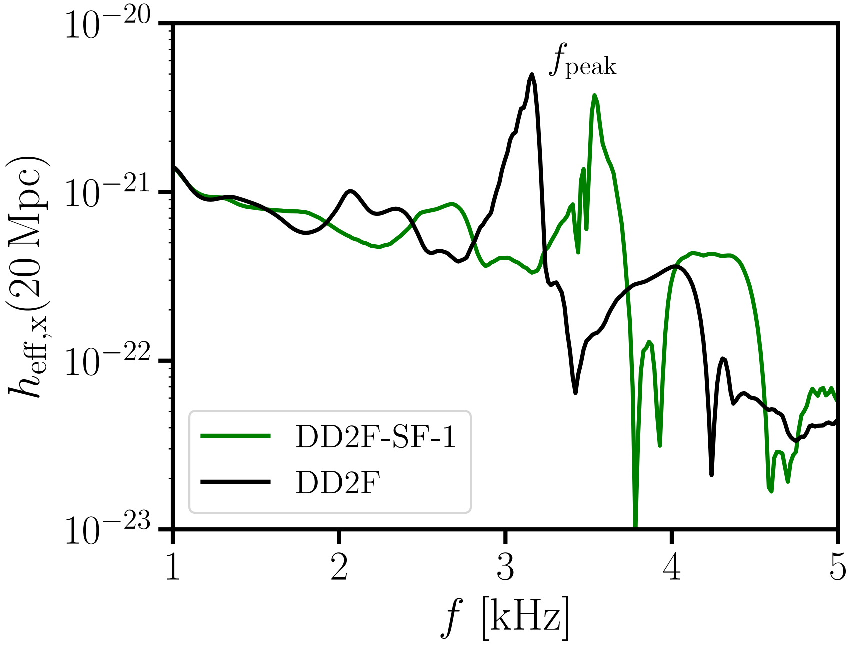


- evolution of temperature and density of merger remnant
- different post-merger GW collapse time, ringdown; full GR

e.g. merger simulation with quarks

Bauswein et al., arXiv:1809.01116
PRL 122, 061102 (2019)





- correlation with R_1.6 breaks down
- shifted peak frequency in power spectra density

Near Future

Observation

- refined ranges of binary tidal deformability from more merger data; 3G detectors
- better determination of radii
- capability of measuring moment of inertia in the next decade
- upper bound on maximum mass

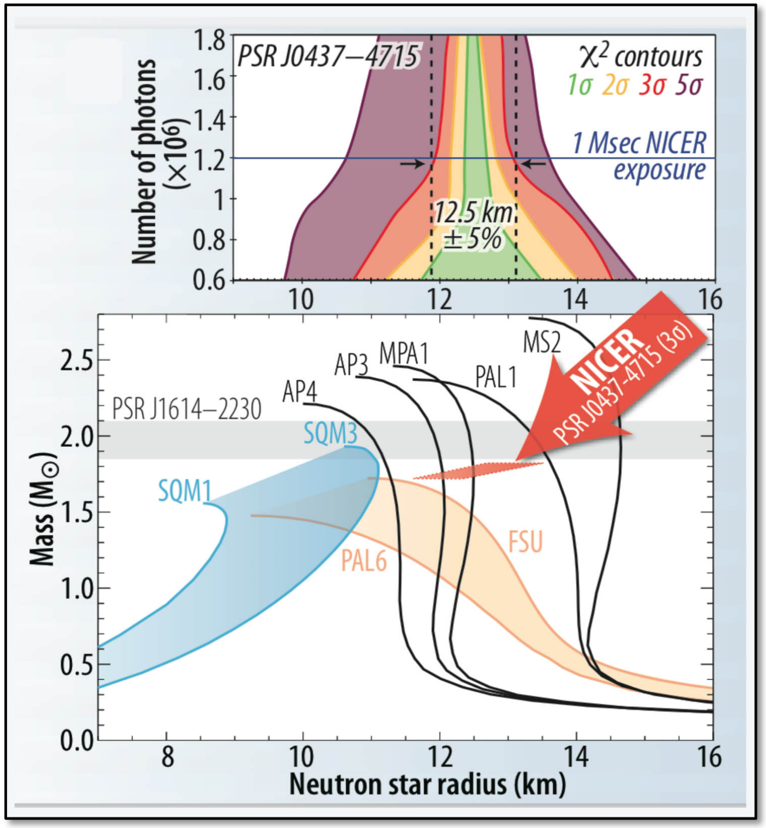
Simulations/Modeling of data

- expand EoS templates to include phase transitions (thermal effects important)

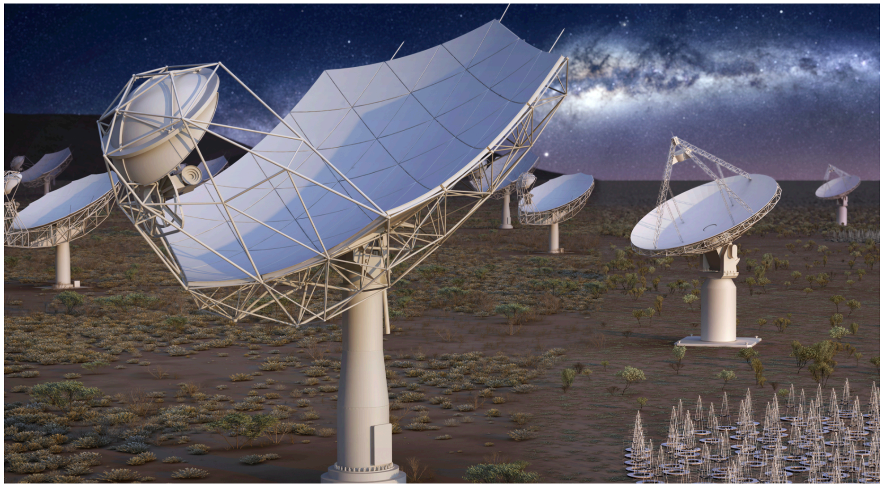
Nuclear theory & experiment

- quantifying EoS uncertainties near twice saturation density

NICER mission



https://www.skatelescope.org



THANK YOU!

Q & A

BACKUP

SLIDES

II. Dynamics

Thermal evolution

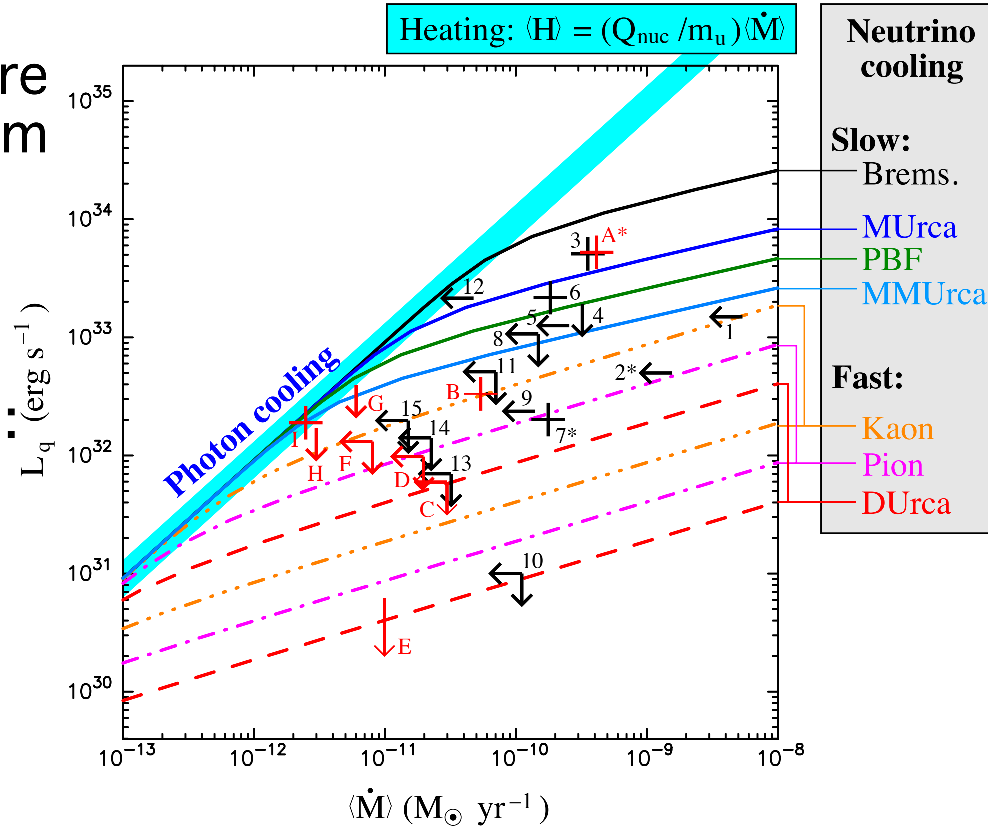
- observe surface luminosity/temperature of isolated and accreting NSs: long-term or transient

Dense matter

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

Candidate DM particles

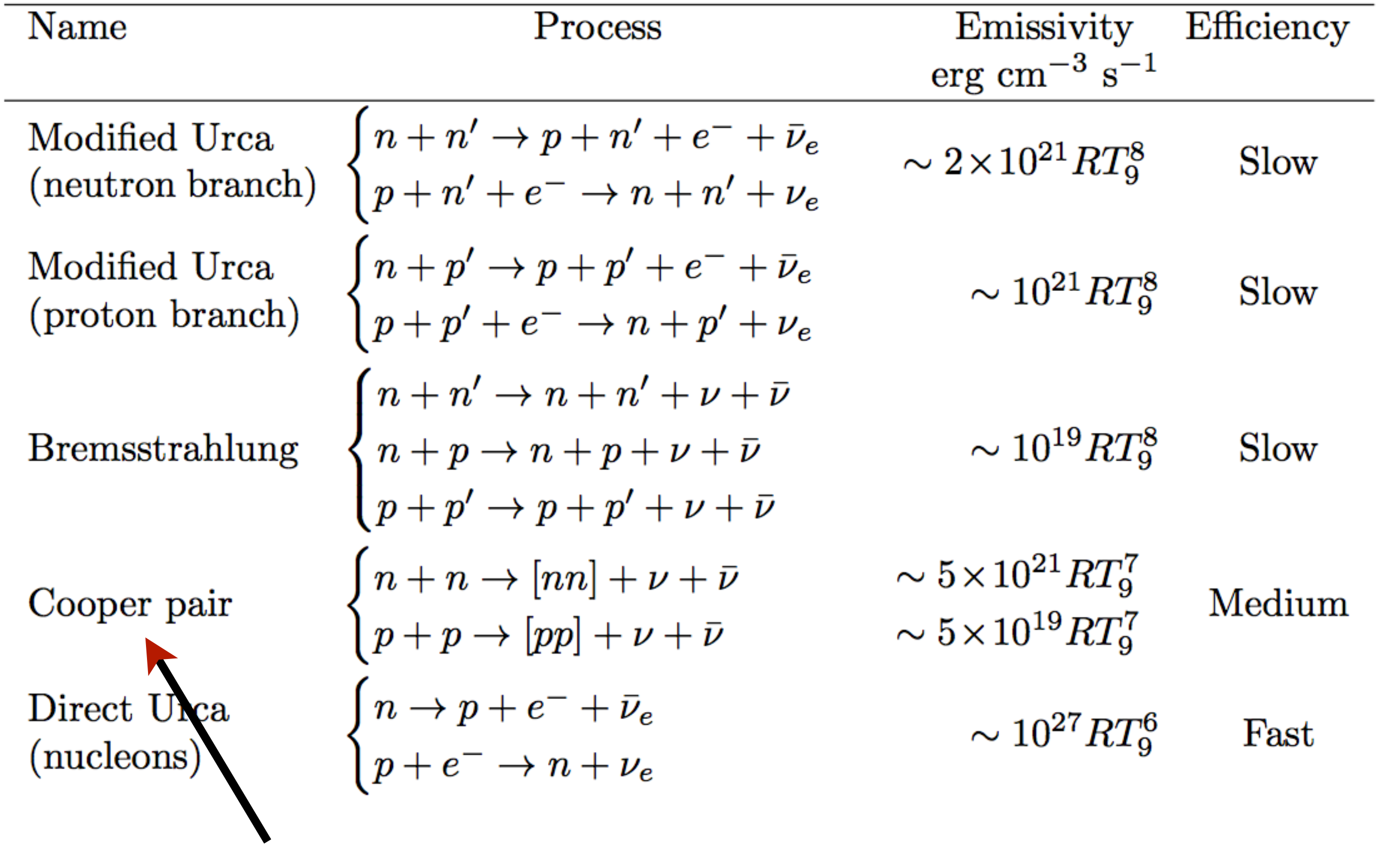
- constraints on axion-cooling etc.



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

Neutrino Emission Mechanism

Nuclear matter



Name	Process	Emissivity erg cm^{-3} s^{-1}	Efficiency
Modified Urca (neutron branch)	$n + n' \to p + n' + e^- + \bar{\nu}_e$ $p + n' + e^- \to n + n' + \nu_e$	$\sim 2\times 10^{21} R T_9^8$	Slow
Modified Urca (proton branch)	$n + p' \to p + p' + e^- + \bar{\nu}_e$ $p + p' + e^- \to n + p' + \nu_e$	$\sim 10^{21} R T_9^8$	Slow
Bremsstrahlung	$n + n' \to n + n' + \nu + \bar{\nu}$ $n + p \to n + p + \nu + \bar{\nu}$ $p + p' \to p + p' + \nu + \bar{\nu}$	$\sim 10^{19} R T_9^8$	Slow
Cooper pair	$n + n \to [nn] + \nu + \bar{\nu}$ $p + p \to [pp] + \nu + \bar{\nu}$	$\sim 5\times 10^{21} R T_9^7$ $\sim 5\times 10^{19} R T_9^7$	Medium
Direct Urca (nucleons)	$n \to p + e^- + \bar{\nu}_e$ $p + e^- \to n + \nu_e$	$\sim 10^{27} R T_9^6$	Fast

- standard cooling (slow processes)

$$L_\nu^{\text{slow}} \approx \frac{3}{4}\pi R^3 \cdot Q^{\text{slow}}\, T_9^8$$

- enhanced cooling (fast processes)

$$L_\nu^{\text{fast}} = \frac{3}{4}\pi R_p^3 \cdot Q^{\text{fast}}\, T_9^6$$

Pairing in nucleonic SF: suppresses Urca processes but triggers PBF neutrino emission

Neutrino Emission Mechanism

Exotic matter

Direct Urca (Λ hyperons)	$\begin{cases} \Lambda \to p + e^- + \bar{\nu}_e \\ p + e^- \to \Lambda + \nu_e \end{cases}$	$\sim 10^{27} R T_9^6$	Fast
Direct Urca (Σ^- hyperons)	$\begin{cases} \Sigma^- \to n + e^- + \bar{\nu}_e \\ n + e^- \to \Sigma^- + \nu_e \end{cases}$	$\sim 10^{27} R T_9^6$	Fast
Direct Urca (no-nucleon)	$\begin{cases} \Lambda + e^- \to \Sigma^- + \nu_e \\ \Sigma^- \to \Lambda + e^- + \bar{\nu}_e \end{cases}$	$\sim 2 \times 10^{27} R T_9^6$	Fast
Direct Urca (π^- condensate)	$\begin{cases} n + < \pi^- > \to n + e^- + \bar{\nu}_e \\ n + e^- \to n + < \pi^- > + \nu_e \end{cases}$	$\sim 10^{26} R T_9^6$	Fast
Direct Urca (K^- condensate)	$\begin{cases} n + < K^- > \to n + e^- + \bar{\nu}_e \\ n + e^- \to n + < K^- > + \nu_e \end{cases}$	$\sim 10^{25} R T_9^6$	Fast
Direct Urca cycle ($u - d$ quarks)	$\begin{cases} d \to u + e^- + \bar{\nu}_e \\ u + e^- \to d + \nu_e \end{cases}$	$\sim 10^{27} R T_9^6$	Fast
Direct Urca cycle ($u - s$ quarks)	$\begin{cases} s \to u + e^- + \bar{\nu}_e \\ u + e^- \to s + \nu_e \end{cases}$	$\sim 10^{27} R T_9^6$	Fast

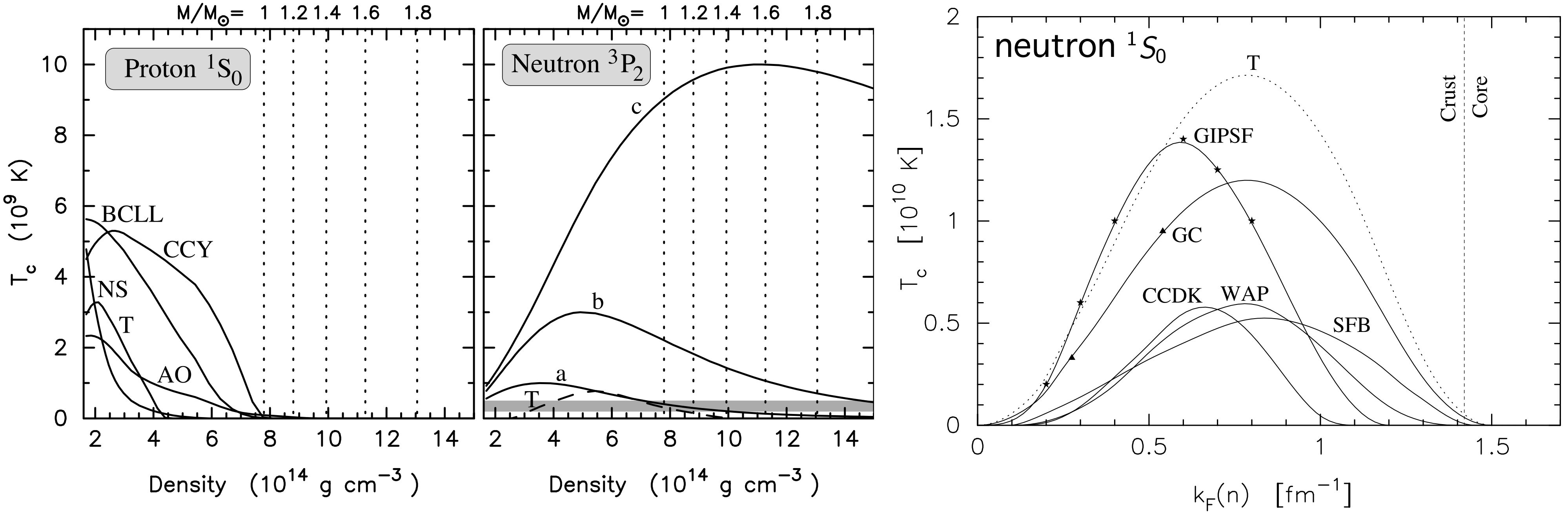
- hyperons, deconfined quarks, meson condensates...

Stellar Superfluids

outer core

inner core

Page et al. (2013)



- density/radial profiles of the nucleonic superfluid critical temperatures remain highly uncertain
- suppresses Urca neutrinos and induce pair-breaking-formation neutrinos: presence of superfluid alters the **dominant** cooling channel
- older stars (>10-100 yrs) observed are cold: crust fully paired; cooling data only probe **core** superfluids

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

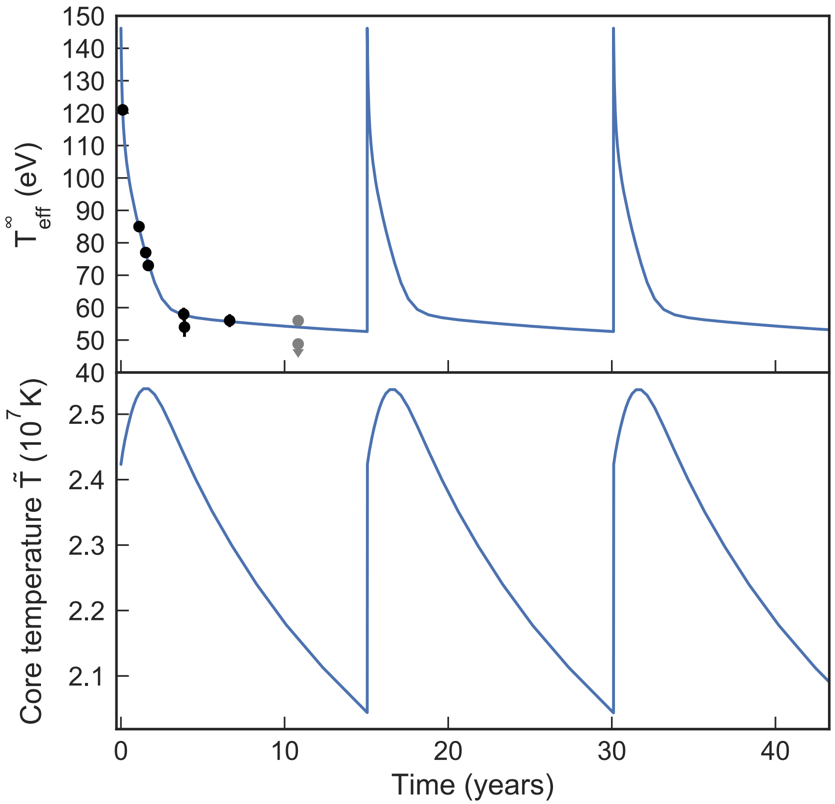
Alternative scenario (Gusakov et al. 2004)

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

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

- fast cooling ~**dUrca operating**
- **vanishing superfluid gaps** in the core
- little/zero light-element (hydrogen or helium) residue

Evidence for Enhanced Cooling

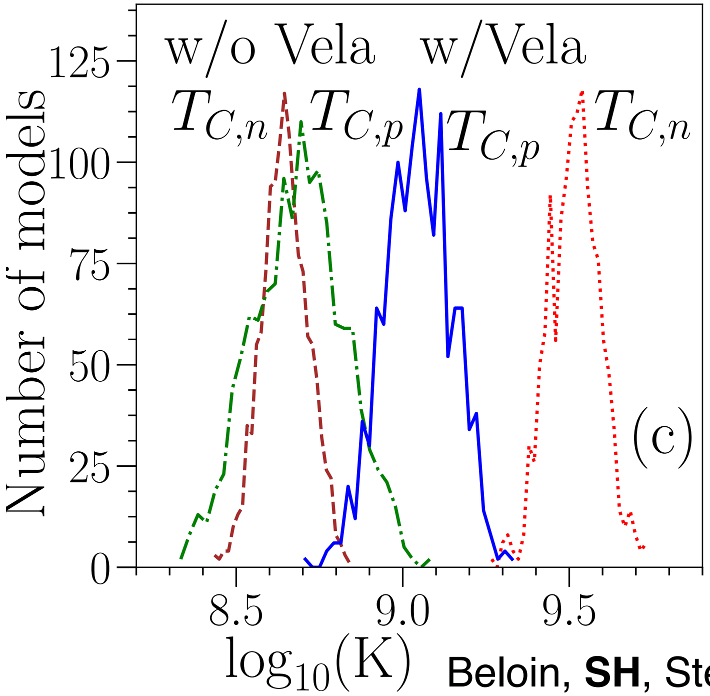


Brown et al., arXiv:1801.00041
PRL 120, 182701 (2018)

- 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 Constraints on T_c

- npemu-matter (**excluding** exotica for now)
- Gaussian parametrization $n\,^3P_2 : [T^{\text{max}}_{\text{cnt}}, k^{\text{peak}}_{Fn}, \Delta k_{Fn}]$ $p\,^1S_0 : [T^{\text{max}}_{\text{cps}}, k^{\text{peak}}_{Fp}, \Delta k_{Fp}]$
- results sensitive to cold sources
- **inconsistency!** between fitting X-ray data from isolated neutron stars & accreting neutron stars

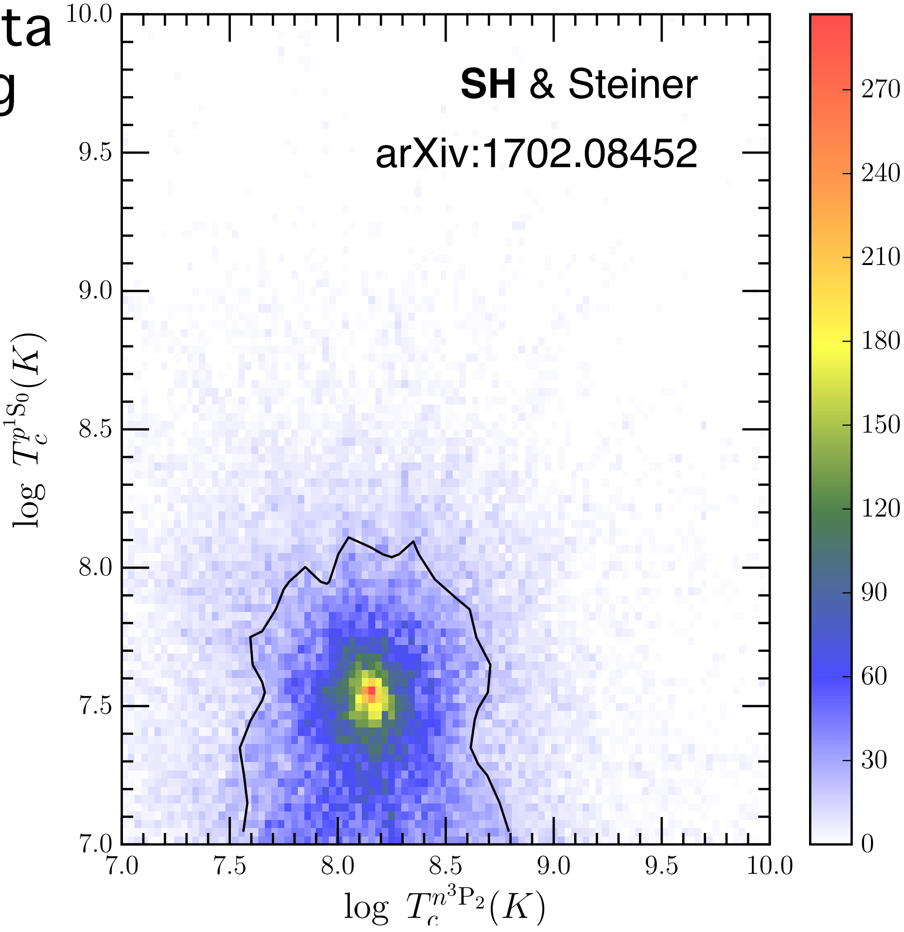


isolated NSs (see also arXiv:1612.04289)

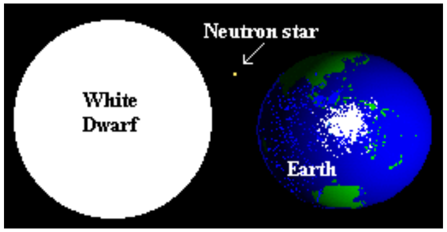
arXiv:1812.00494

Beloin, **SH**, Steiner & Odbadrakh

quiescent transients



Cooling: Questions & Tasks



Questions

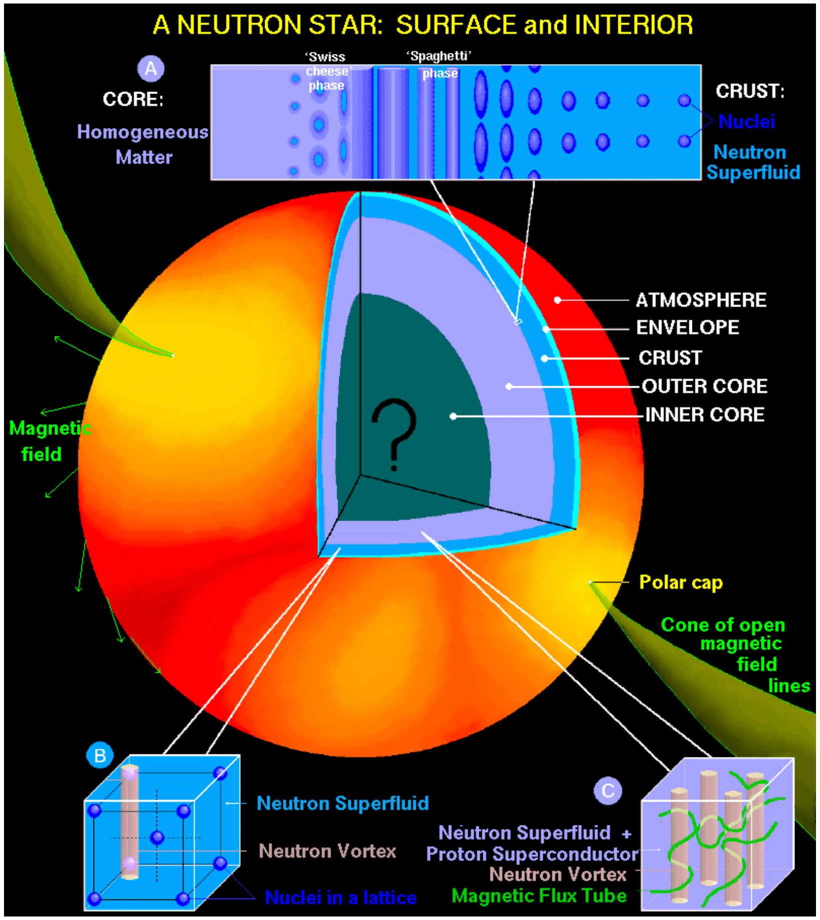
- amount of dUrca cooling?
- fraction of normal/superfluid baryons?
- (non-)existence of exotic particles?

Theory/Modeling

- EoS constraints; crust & envelope properties
- better understanding of pairing and its extent in NS

Observation

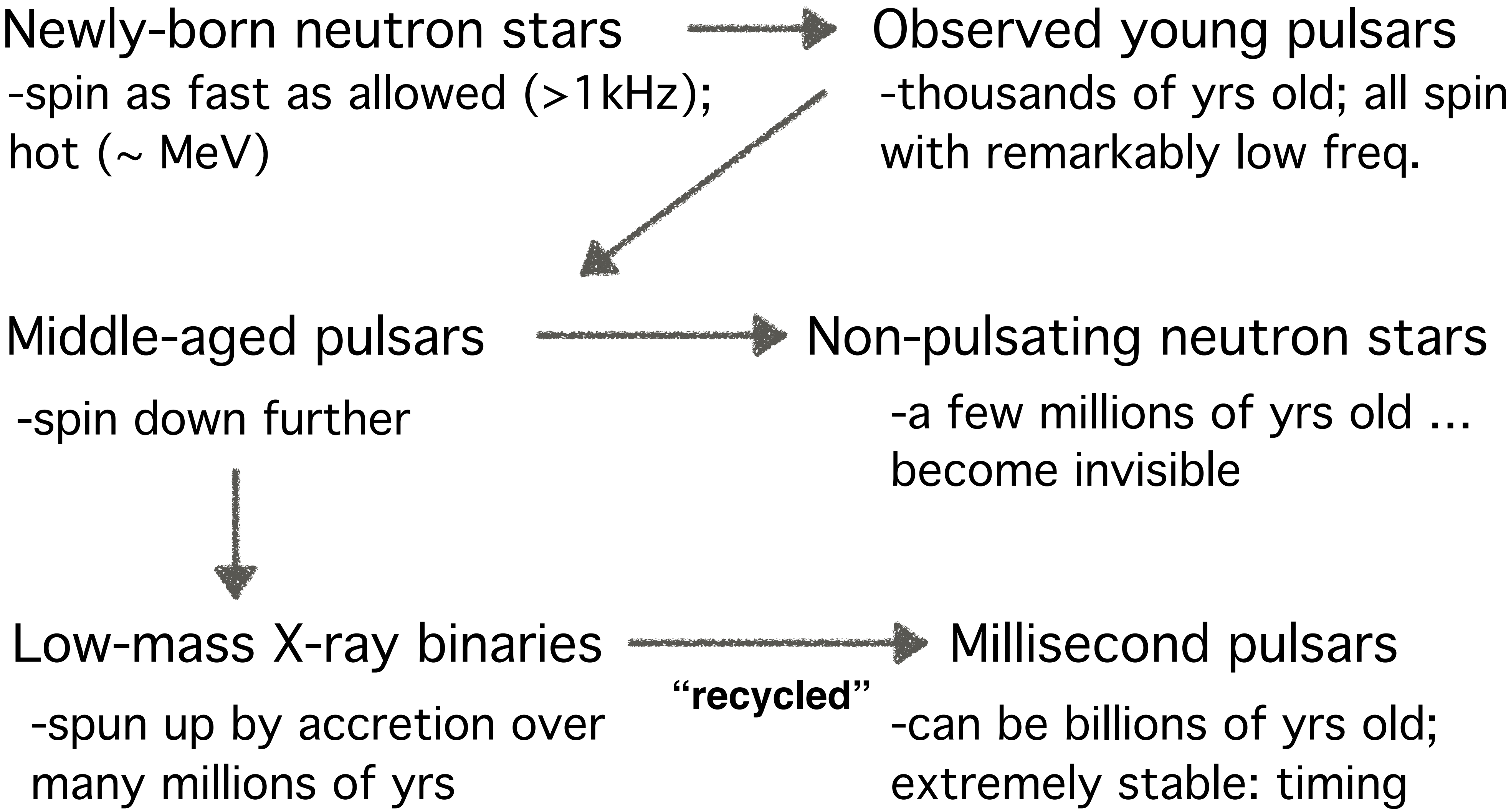
- enlarge data sample
- improve estimates on T, accretion, etc.
- incorporate statistical analysis



Neutron stars: unique laboratory for extreme physics

credit: D. Page

Generic Evolution of Pulsars



Newly-born neutron stars

-spin as fast as allowed (>1kHz); hot (~ MeV)

Observed young pulsars

-thousands of yrs old; all spin with remarkably low freq.

Middle-aged pulsars

-spin down further

Non-pulsating neutron stars

-a few millions of yrs old ... become invisible

Low-mass X-ray binaries

-spun up by accretion over many millions of yrs

“recycled”

Millisecond pulsars

-can be billions of yrs old; extremely stable: timing

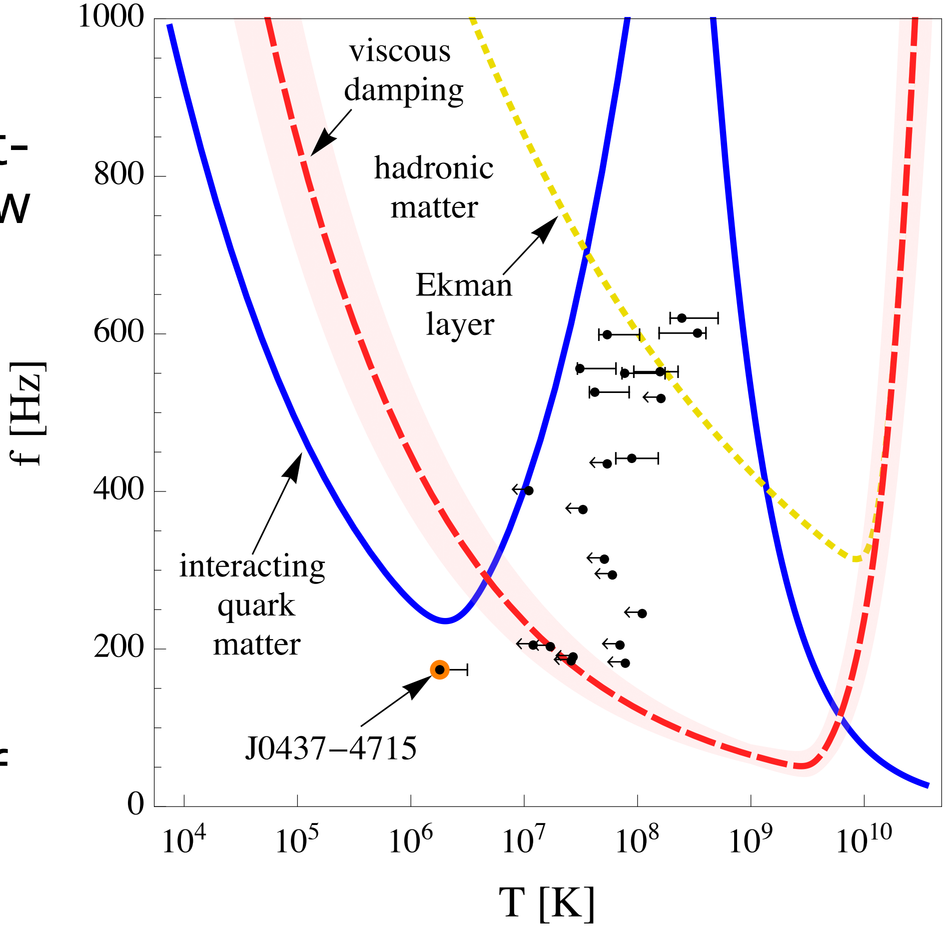
II. Dynamics (cont.)

Spin evolution

- 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 & bulk **viscosity**
- 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; phase-conversion at hadron/quark interface



Alford & Schwenzer, arXiv:1310.3524

Haskell, Degenaar & Ho, arXiv:1201.2101

II. Dynamics (cont.)

Spin evolution

- 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 & bulk **viscosity**
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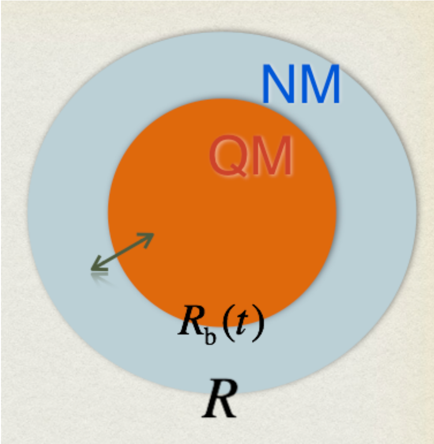
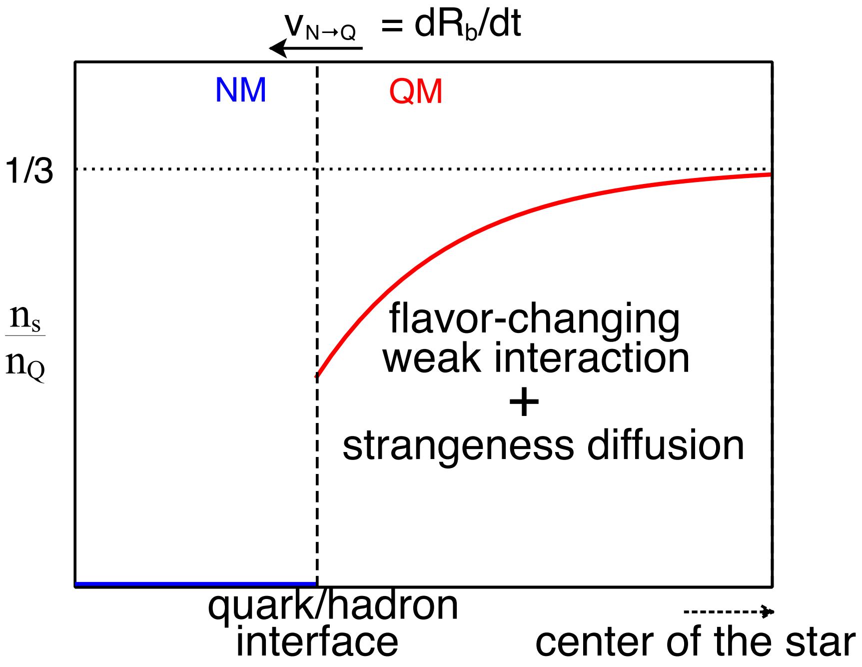


-steady-state transport

-no acceleration/deceleration effects; no turbulence

-no leptons; no superfluids

$(udd) \leftrightarrow (uds)$

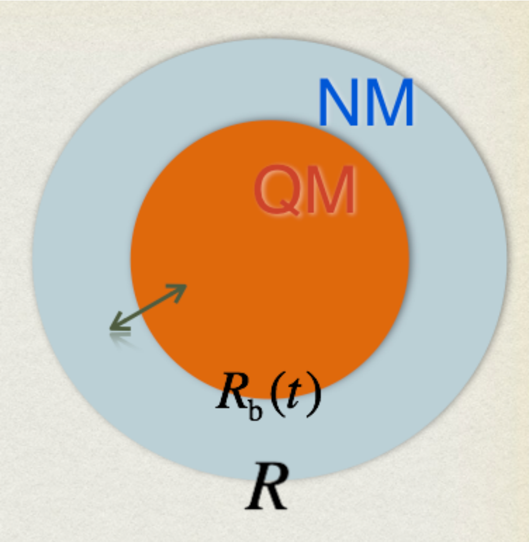


Dissipation at an Interface

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

Phase-conversion dissipation (PCD)

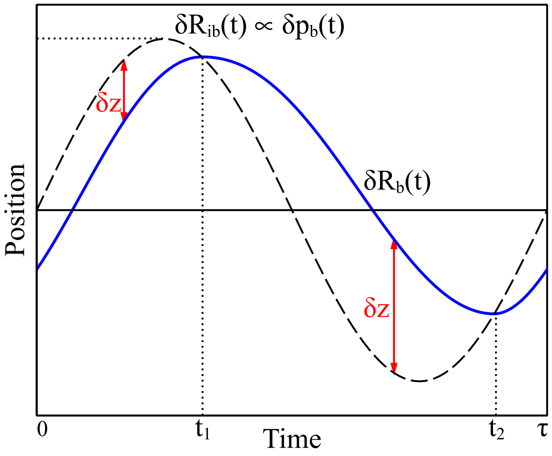
- between fluids in different phases with first-order transition separated by a **sharp** interface
- quark/hadron conversion



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
$\longrightarrow$ a **phase lag** in system response
$\longrightarrow$ dissipates energy



Alford, **SH** & Schwenzer
arXiv:1404.5279

II. Dynamics (cont.)

Supernovae and BNS mergers

- explosive environment: high entropy, short expansion, neutron-rich matter
- high-performance computing (HPC)
- observatories for GW & electromagnetic counterparts

Theory & simulation

- neutrino scattering & absorption in a dense medium: dynamic response
- sensitivity to finite-temperature EoSs: electron fraction Ye; heat transport (diffusion, convection) by neutrinos
- neutrino oscillation: luminosity in different flavors
- nucleosynthesis: predict amount & composition of ejecta
- hydrodynamics, numerical relativity, magnetic field..

II. Dynamics (cont.)

GW detection in mergers

- pre-merger (inspiral): dense matter EoS and tidal effects are important; mass, radius and tidal deformability affect GW spectra -> distinguish EoSs!
- merger: complicated evolution of temperature and density; viscosity & oscillation modes; ejecta, r-process and jets..
- post-merger: remnant GW signals (NS or BH? evolution of rotation?); attendant gamma-ray, x-ray, optical and infrared signals: multi-messenger tools

Future

- more data from merger events enable systematic analysis: prospects for future detections to discern possible phase transition at supra nuclear densities
- continuous GW sources, e.g. mountains on a NS or CFS-unstable modes