Neutron stars and stellar mergers as a laboratory of dense QCD matter

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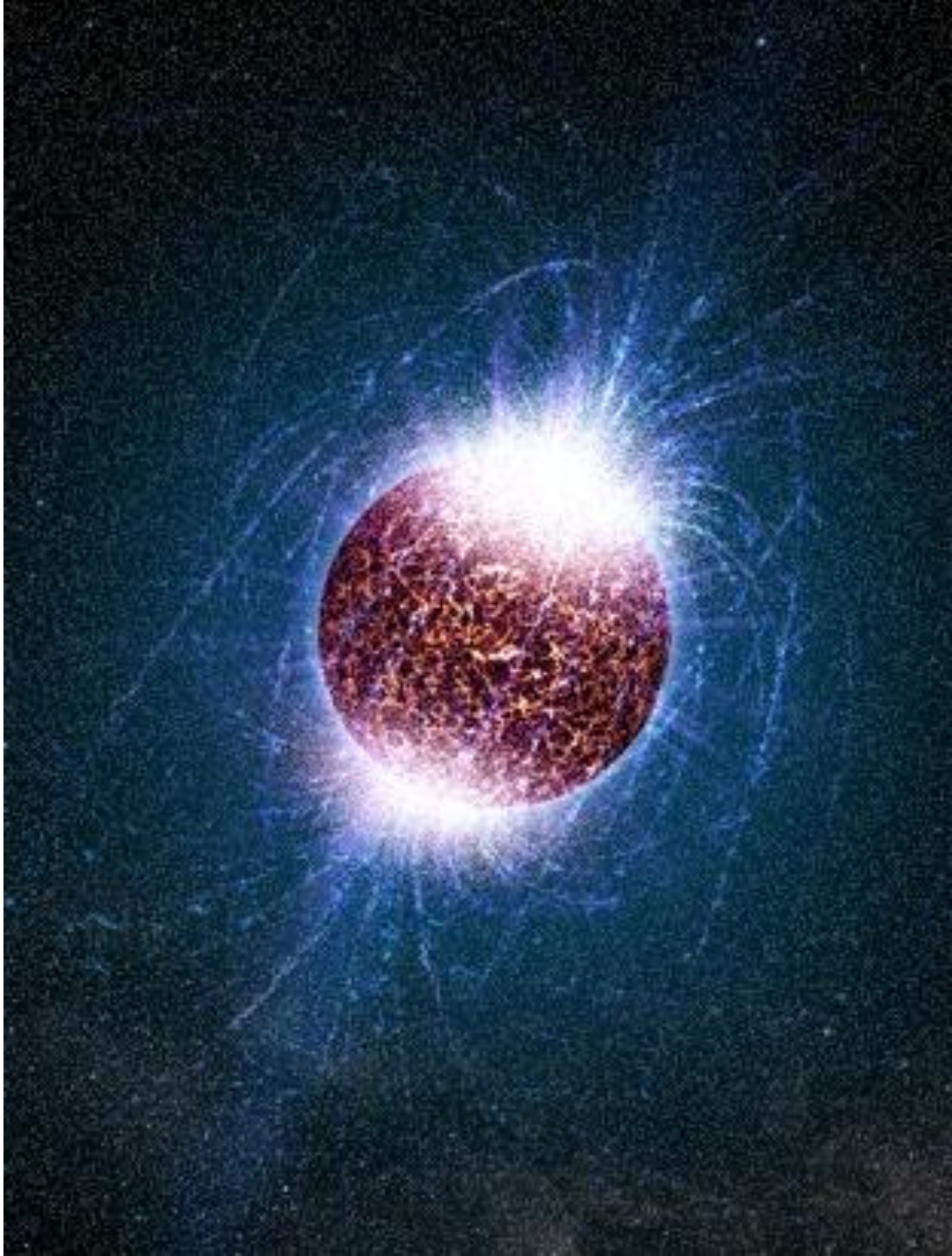
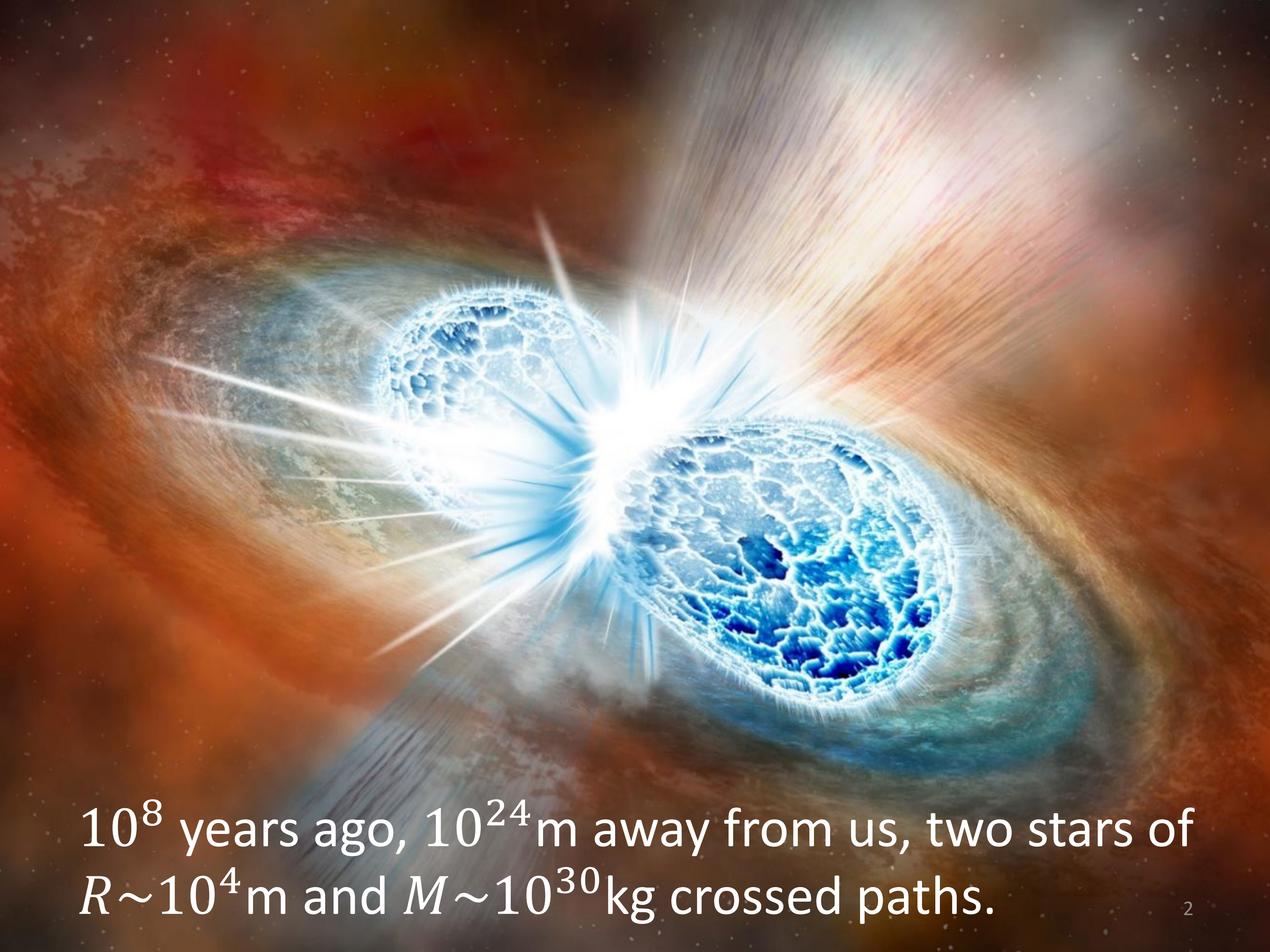
Quark Matter, Lido Island

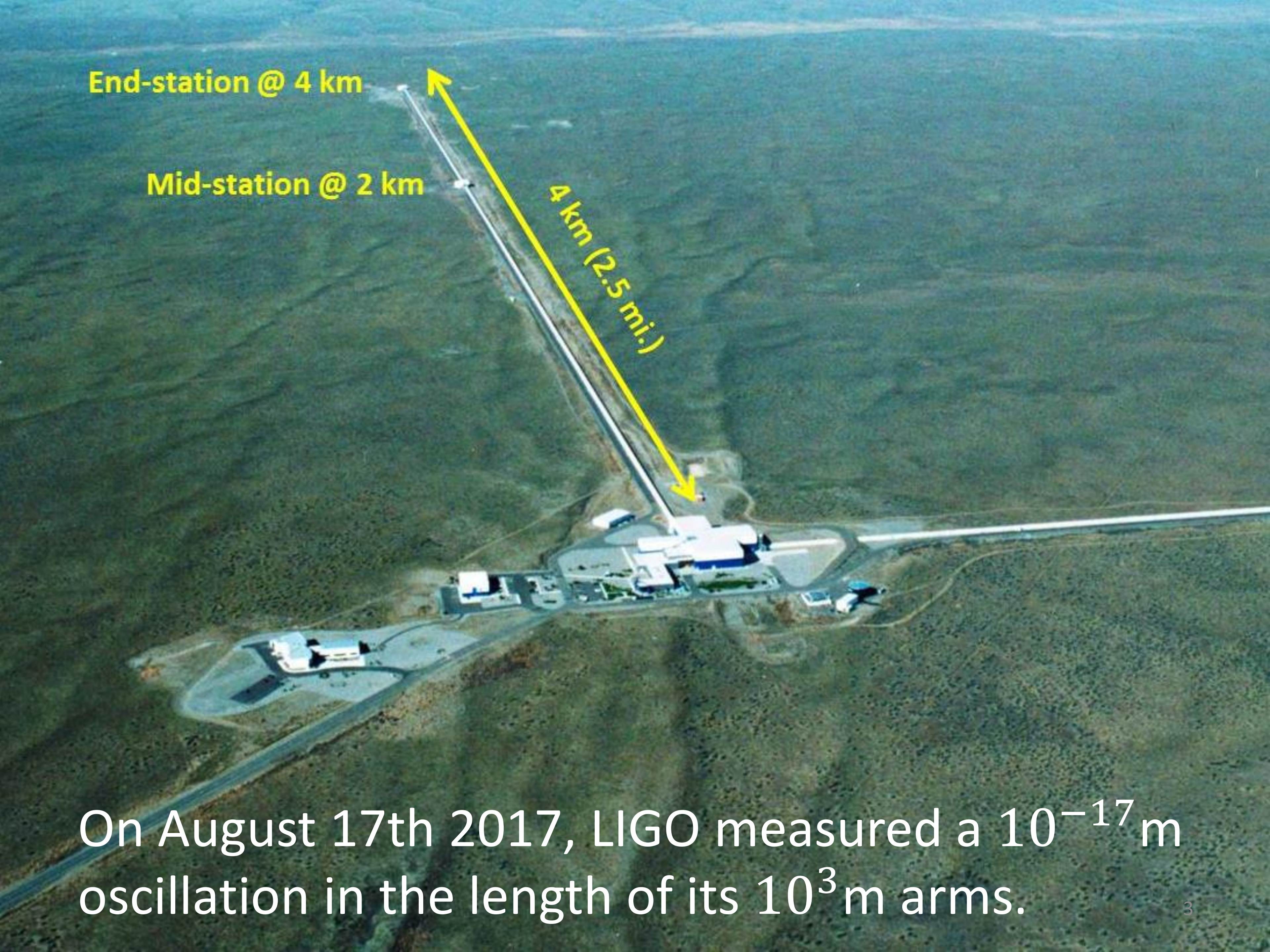
14 May 2018

Main reference: Annala, Gorda, Kurkela, Vuorinen, PRL 120 (2018), 1711.02644

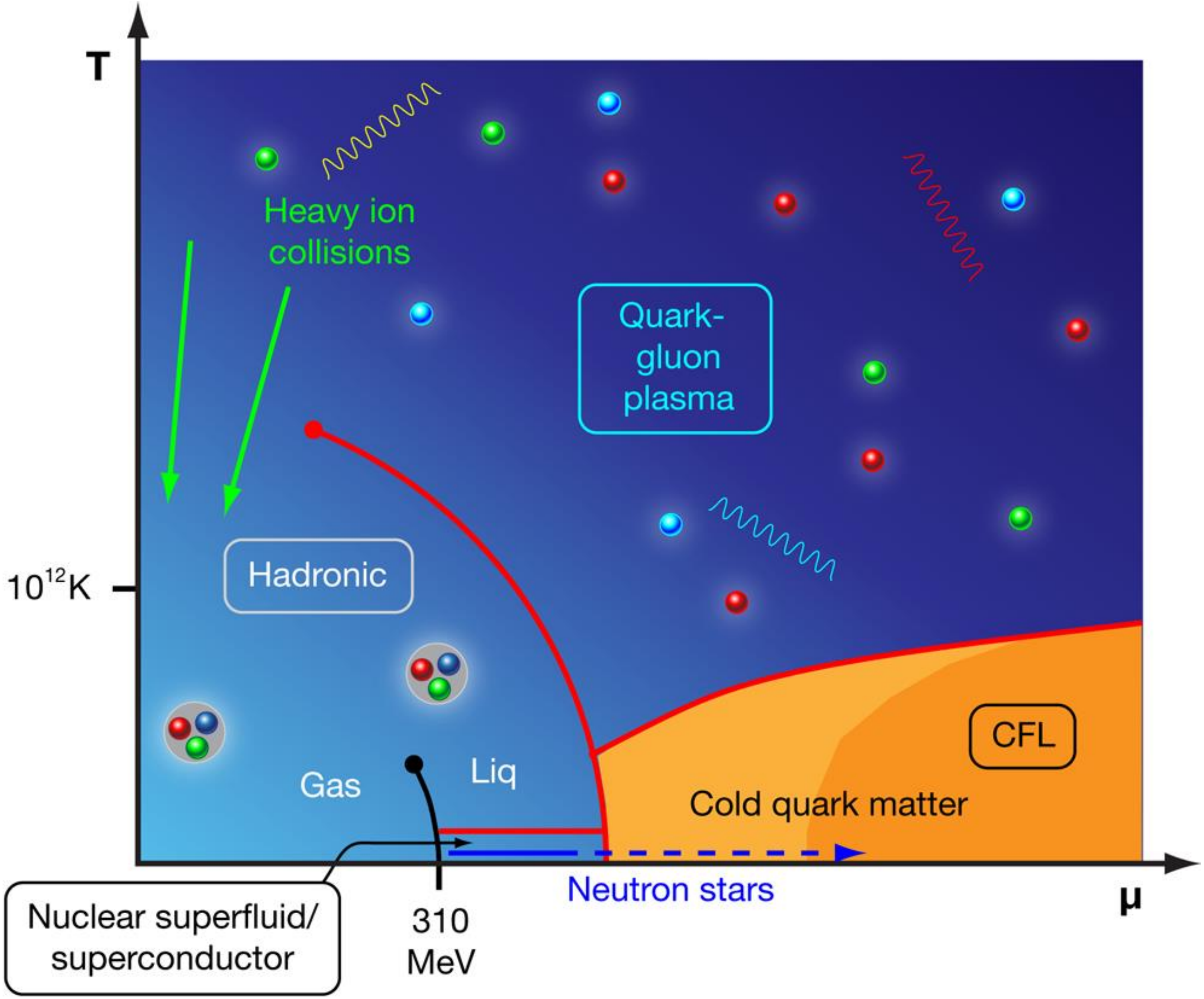




10^8 years ago, 10^{24}m away from us, two stars of $R \sim 10^4$m and $M \sim 10^{30}$kg crossed paths.

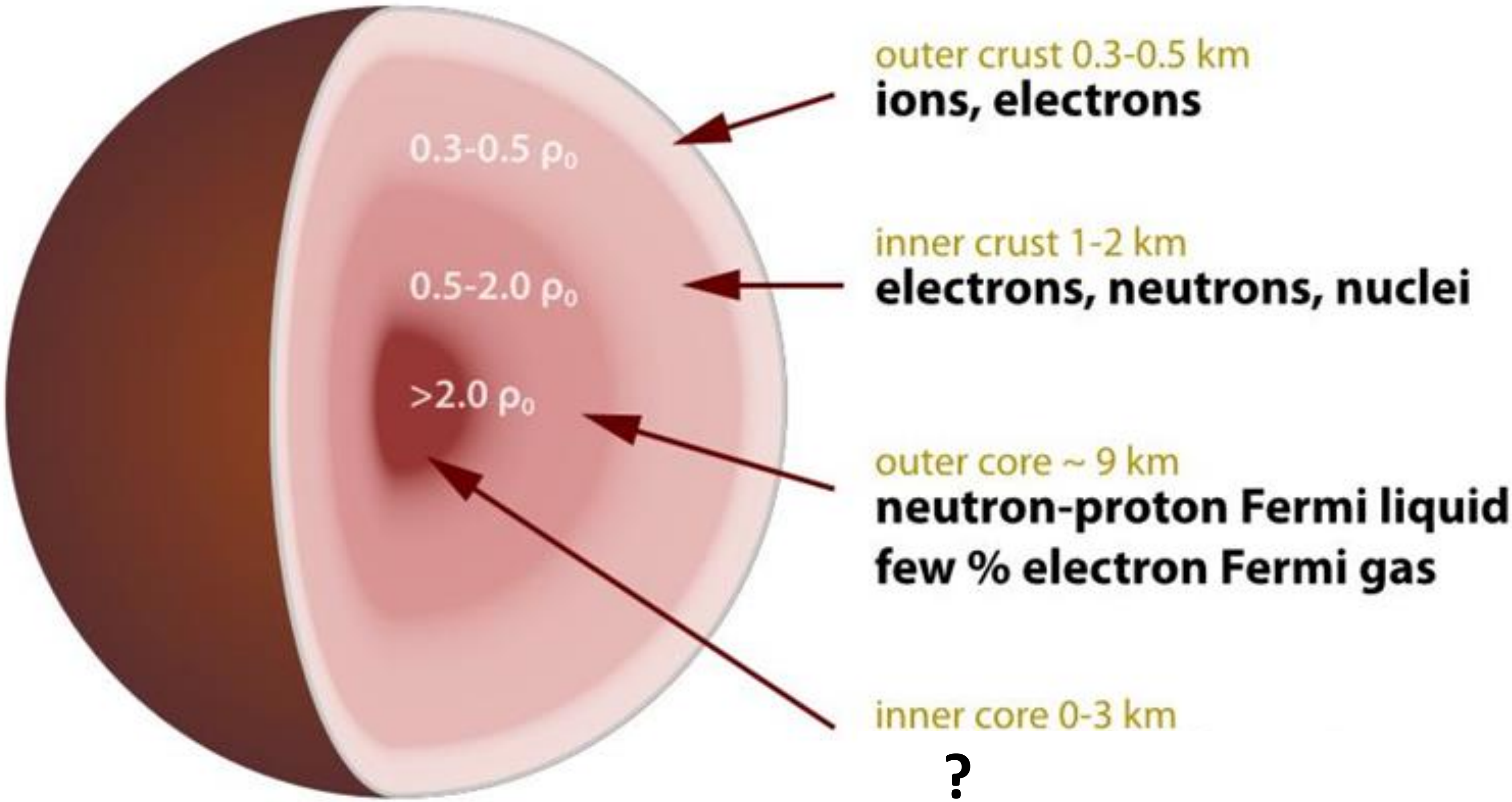


On August 17th 2017, LIGO measured a 10^{-17}m oscillation in the length of its 10^{3}m arms.



Today: Implications on physics of scale 10^{-15}m.

Neutron star basics

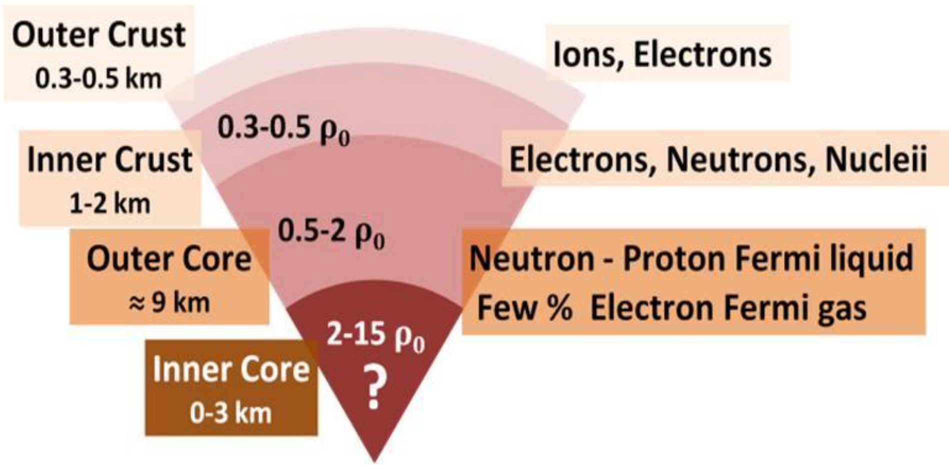

0.3-0.5 ρ_0
0.5-2.0 ρ_0
>2.0 ρ_0
outer crust 0.3-0.5 km
ions, electrons
inner crust 1-2 km
electrons, neutrons, nuclei
outer core ~ 9 km
neutron-proton Fermi liquid
few % electron Fermi gas
inner core 0-3 km

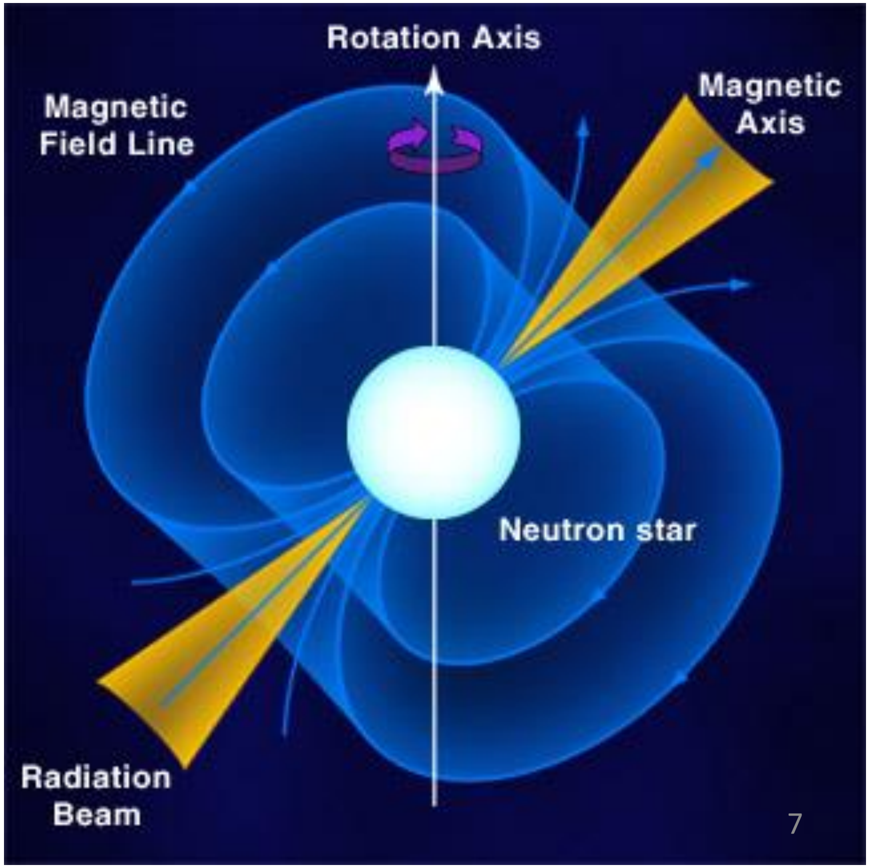
?

NS characteristics:

- Masses $\lesssim 2M_{\odot}$
- Radii $\approx 12-13$ km
- Spin frequencies $\lesssim$ kHz
- Temperatures $\lesssim$ keV
- Strong magnetic fields up to 10^{15}G

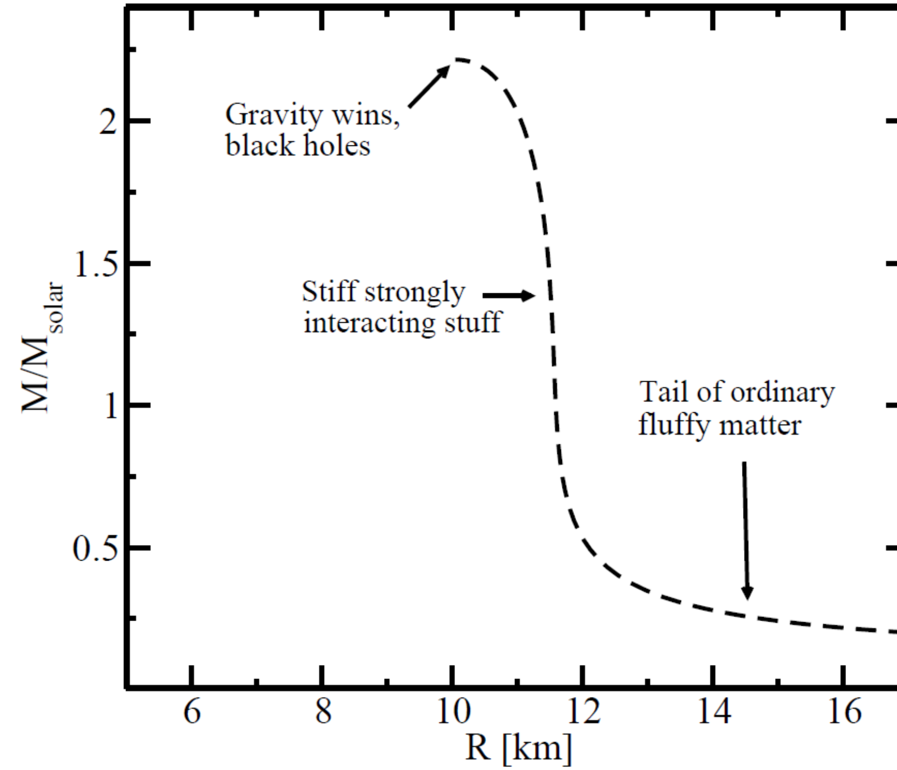
Unique laboratory for strong interaction physics: Density in NS cores high enough to probe nuclear matter well beyond saturation density





Physics picture: Hydrostatic equilibrium resulting from fierce competition between gravity and the pressure of QCD matter

GR description via Tolman-Oppenheimer-Volkov eqs:



Ozel et al., ApJ 820 (2016)

$$\begin{aligned} \frac{dM(r)}{dr} &= 4\pi r^2 \varepsilon(r), \\ \frac{dp(r)}{dr} &= -\frac{G\varepsilon(r)M(r)}{r^2}\frac{(1+p(r)/\varepsilon(r))\left(1+4\pi r^3 p(r)/M(r)\right)}{1-2GM(r)/r} \end{aligned}$$

$$\varepsilon(p) \Rightarrow M(R)$$

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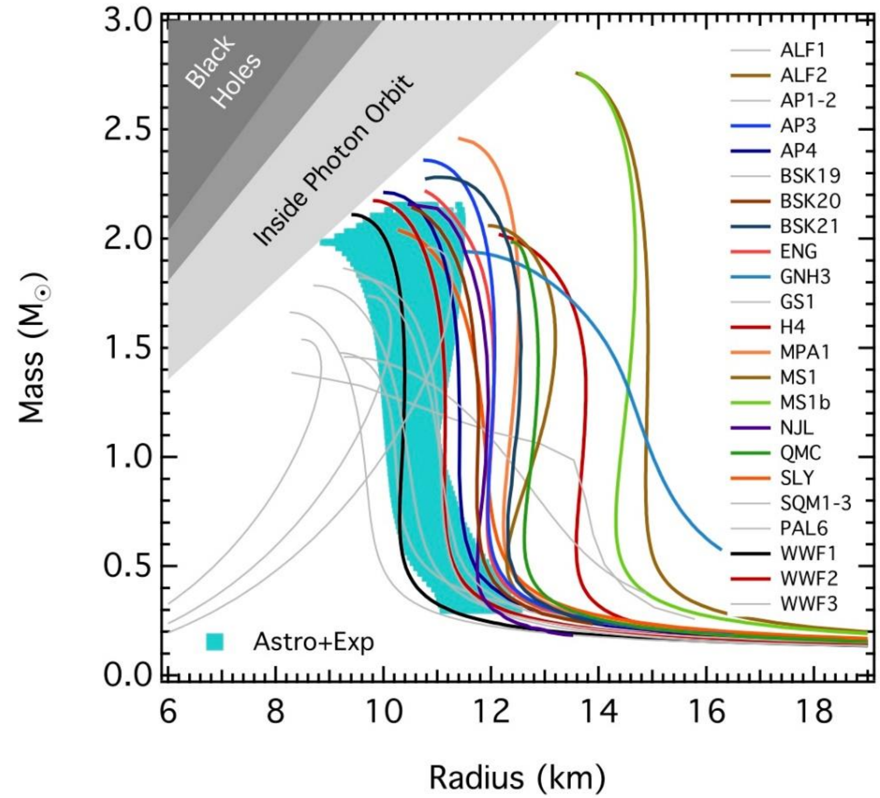

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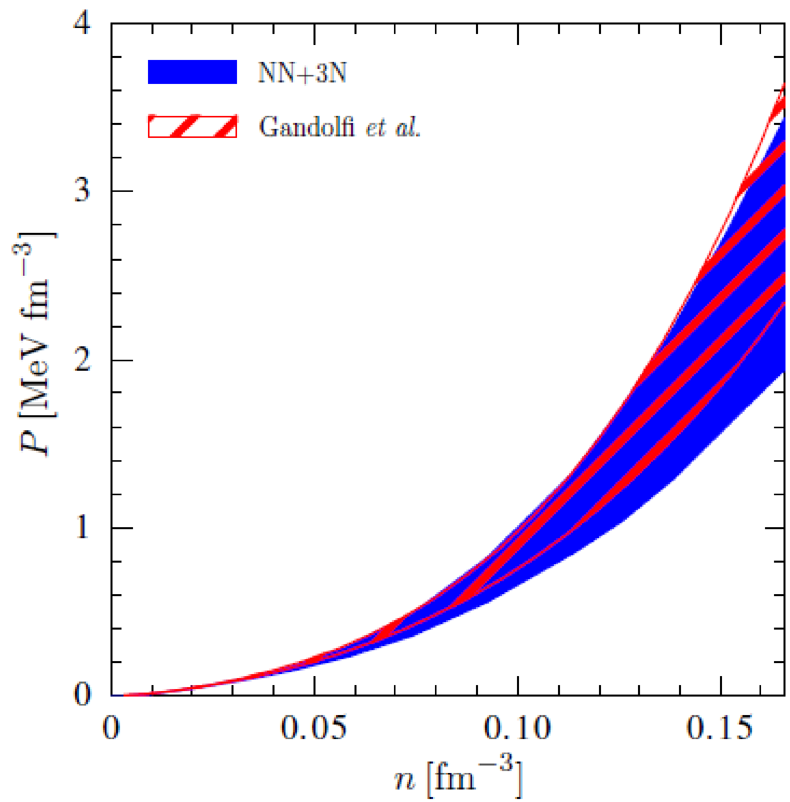
$$\varepsilon(p) \Rightarrow M(R)$$

Particle/nuclear theory challenge: Find Equation of State of strongly interacting matter that is

- Cold and dense
- Electrically neutral:
  $$2/3n_u - n_d/3 - n_s/3 + n_e = 0$$
- In beta equilibrium:
  $$\mu_B/3 = \mu_d = \mu_s = \mu_u + \mu_e$$



Hebeler et al., ApJ 773 (2013)

Big open questions:

- Can QCD theorists predict neutron star measurements?
- Can we infer the QCD matter EoS from observations?
- **Can deconfined matter be found inside the stars?**

What do we know from observations?

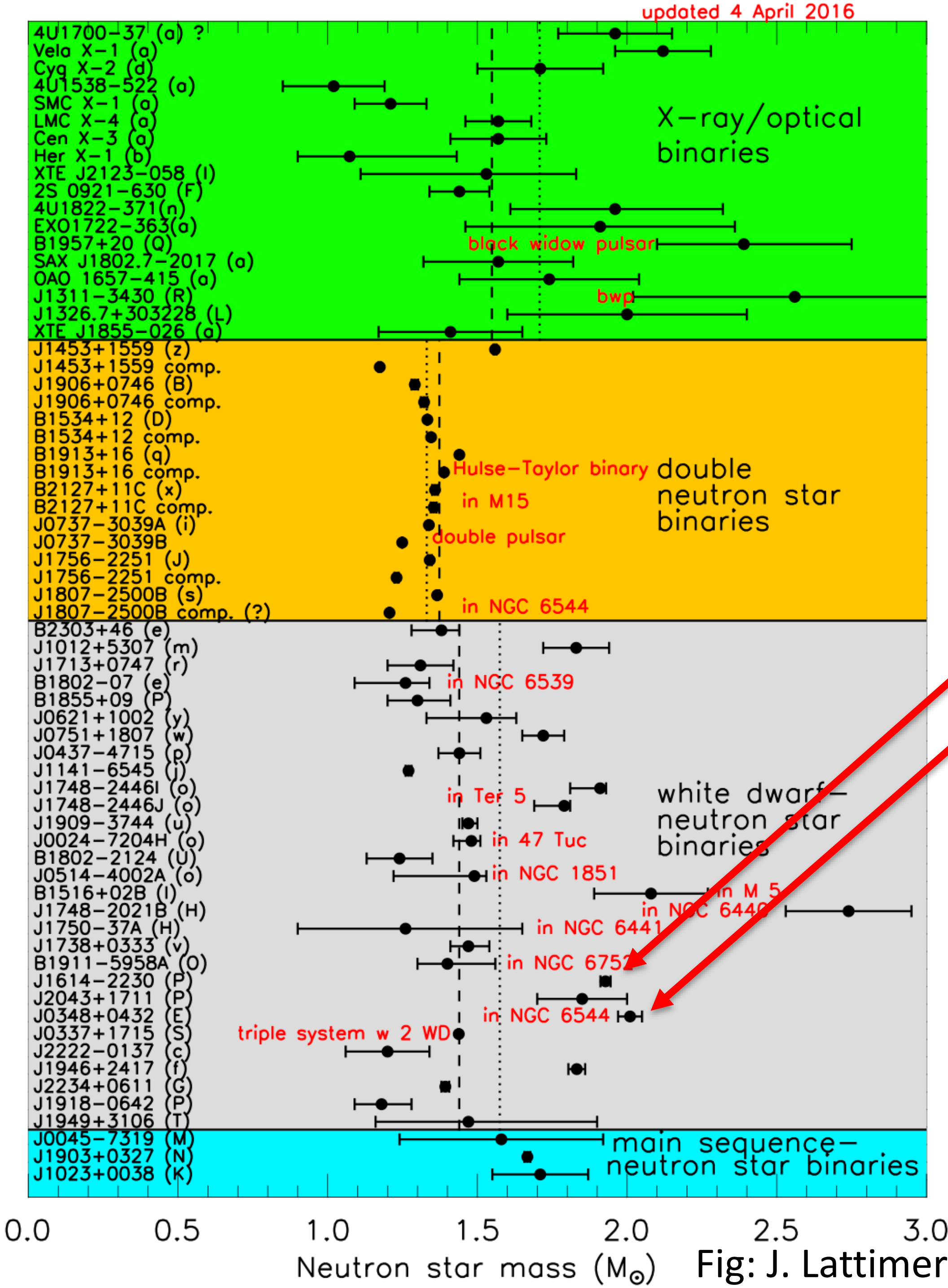


Fig: J. Lattimer

By now, two accurate Shapiro delay measurements of two-solar-mass stars:

Demorest et al., Nature 467 (2010)

Antoniadis et al., Science 340 (2013)

$$\therefore \quad M_{\max} > 2M_\odot$$

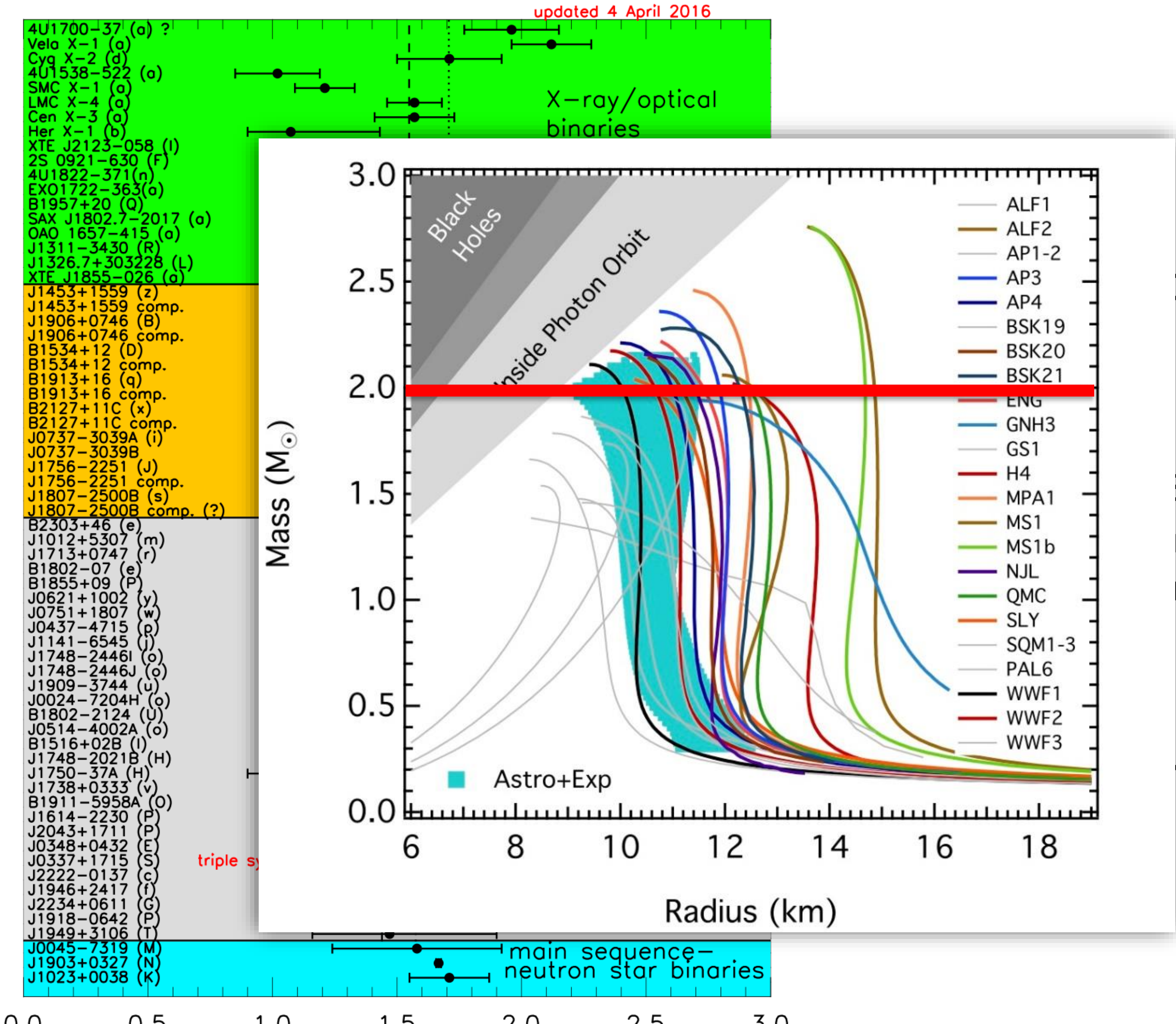


Fig: J. Lattimer

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s:

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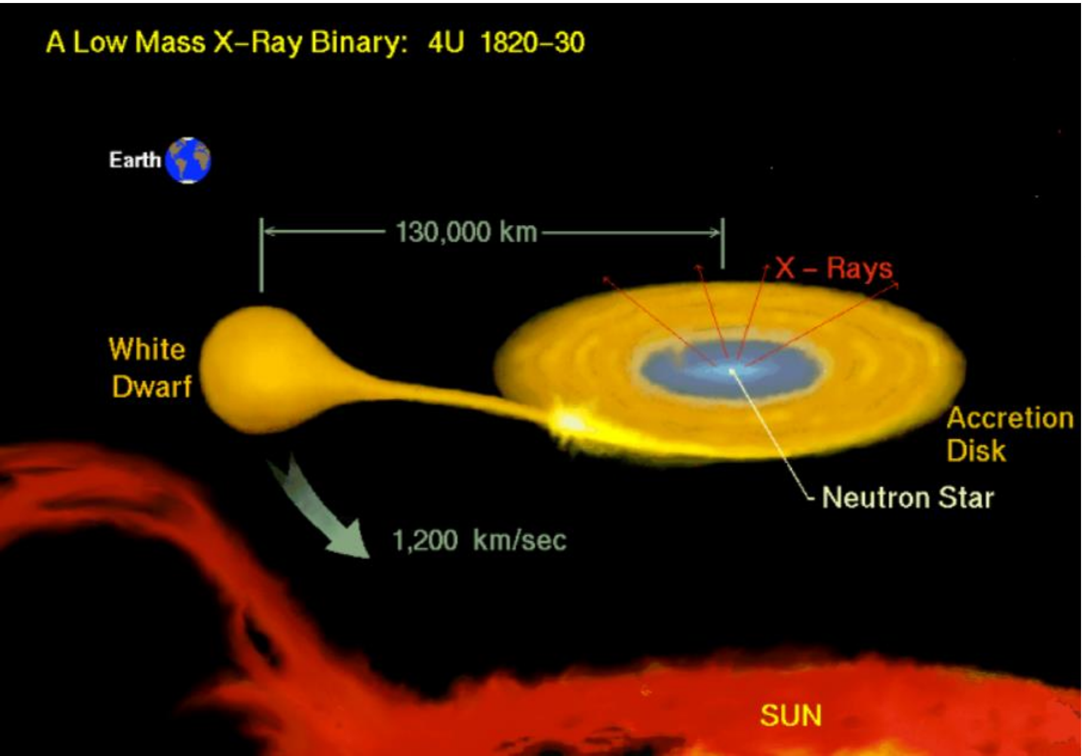
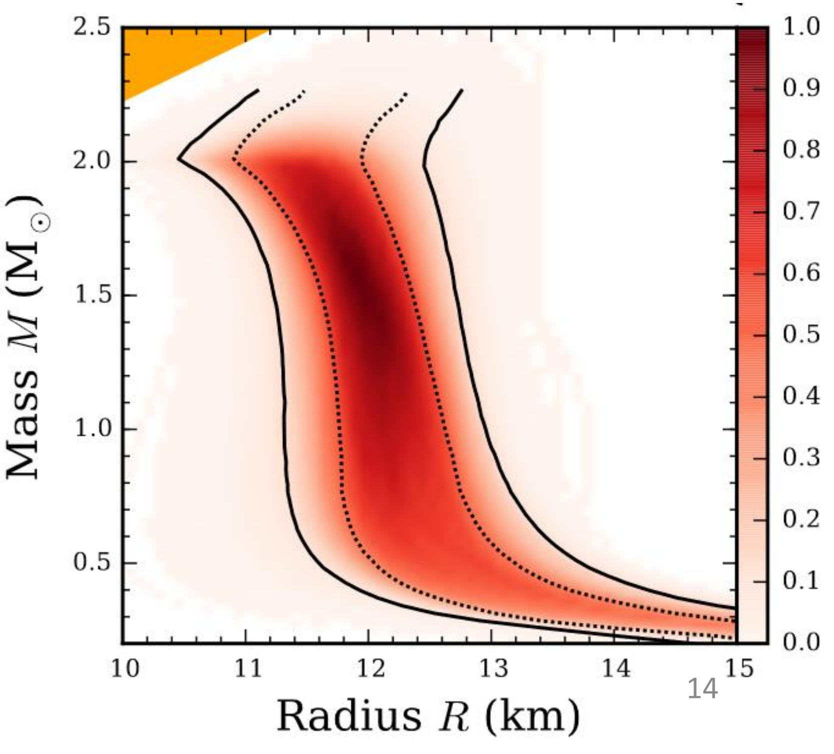
$2M_\odot$

Radius measurements more problematic, but progress through observation of X-ray emission:

- Cooling of thermonuclear X-ray bursts provide radii to ~500m [Nättilä et al., Astronomy & Astrophysics 591 (2016), …]
- With NICER mission, launched 3 June 2017, X-ray pulse profiling → Radius of a single star (perhaps) to ~200m





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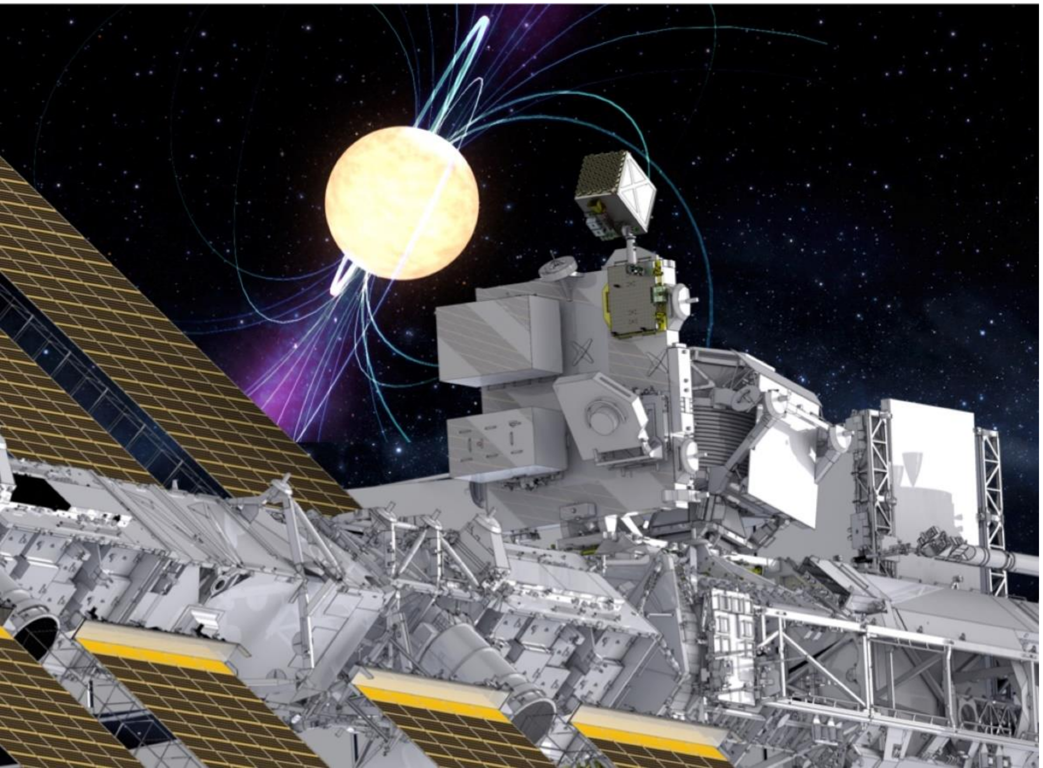
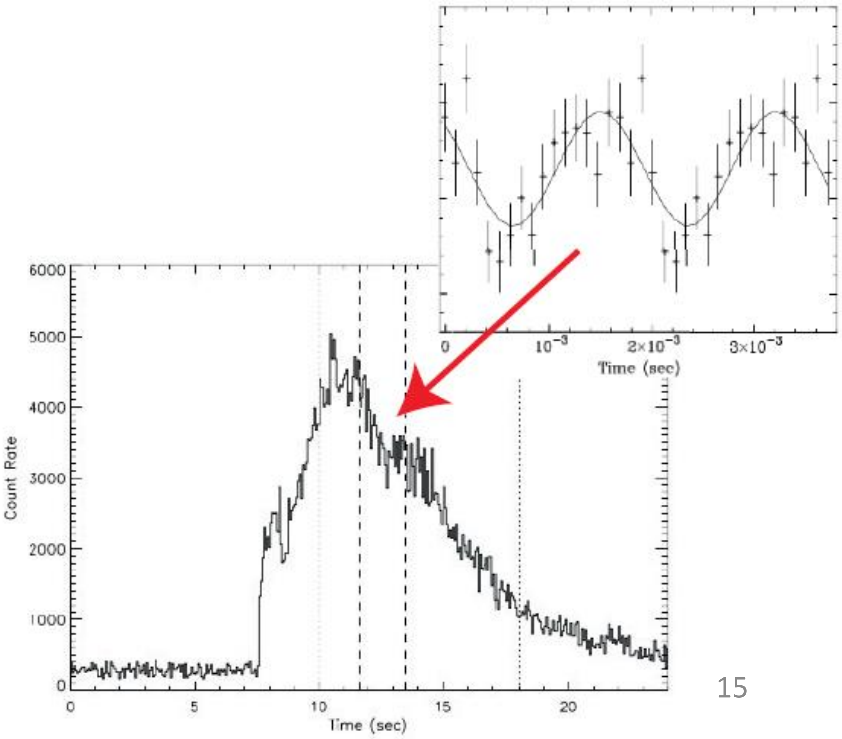
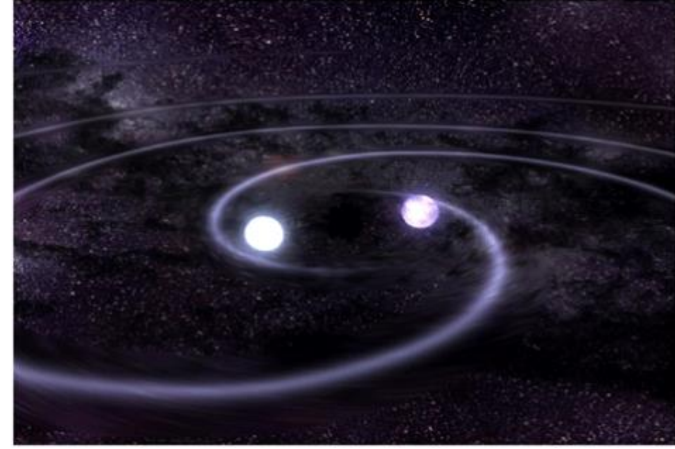


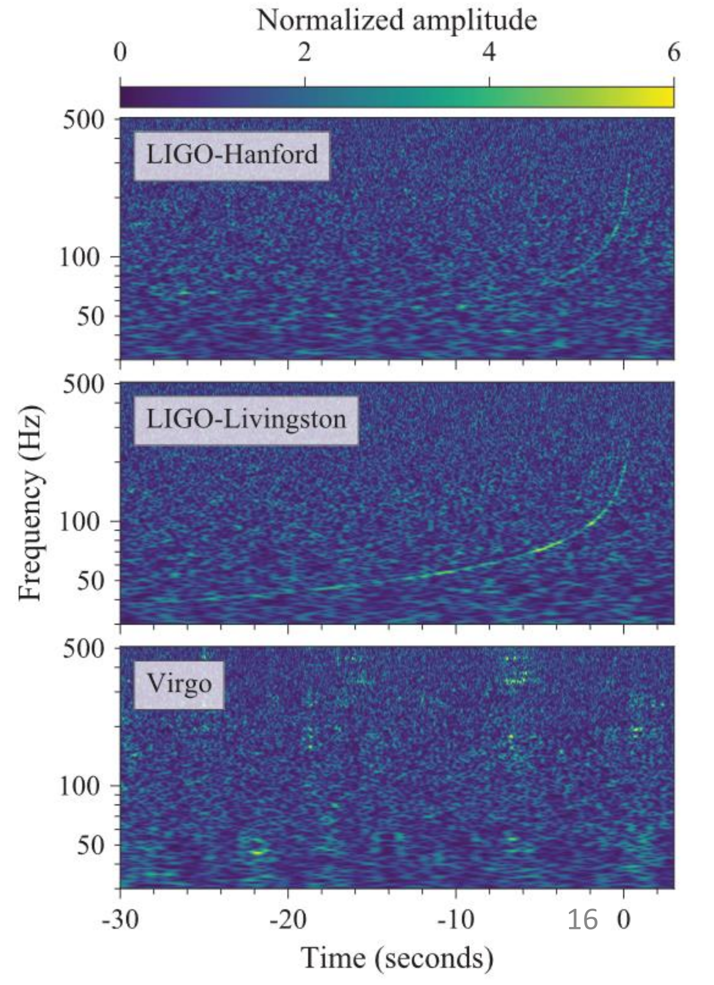


Gravitational wave breakthrough: LIGO and Virgo observation of NS merger 130 million ly away!



Three types of potential inputs:

1) Tidal deformabilities of the NSs during inspiral – good measure of stellar compactness
2) EM signatures – present if no immediate collapse to a BH
3) Ringdown pattern – sensitive to EoS (also at $T \neq 0$), but freq. too high for LIGO

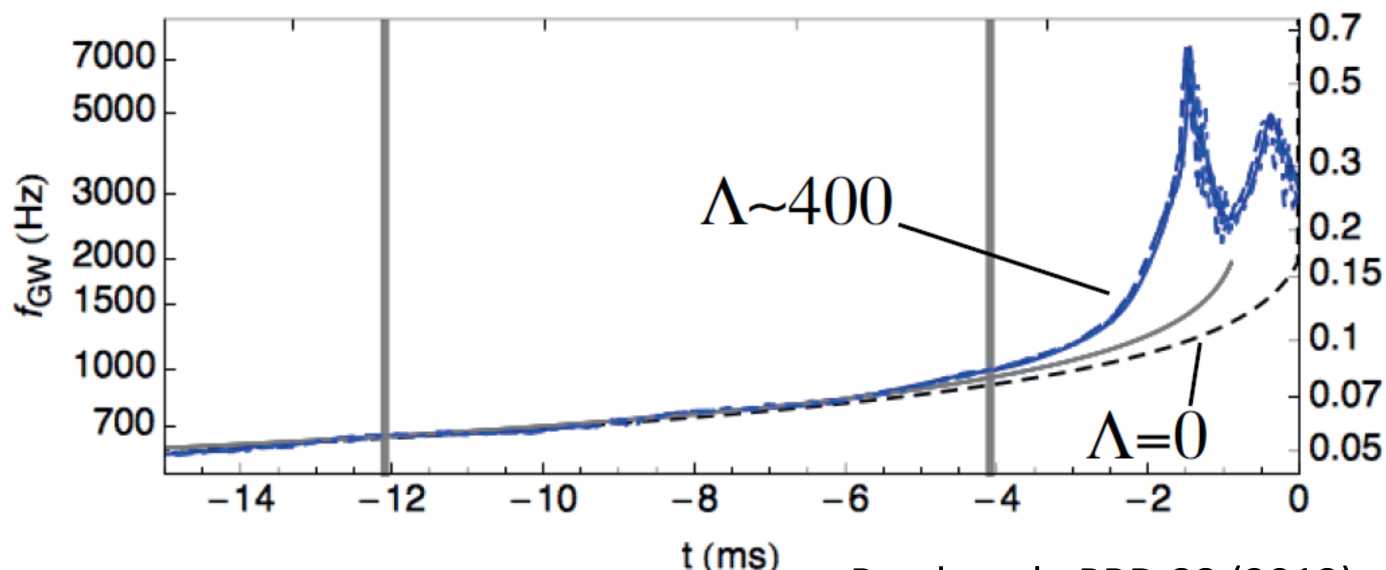


LIGO and Virgo collaborations, PRL 119 (2017)

Tidal deformability: How large a quadrupolar moment a star's gravitational field develops due to an external quadrupolar field

$$Q_{ij} = -\Lambda \mathcal{E}_{ij}$$

Substantial effect on observed GW waveform during inspiral phase

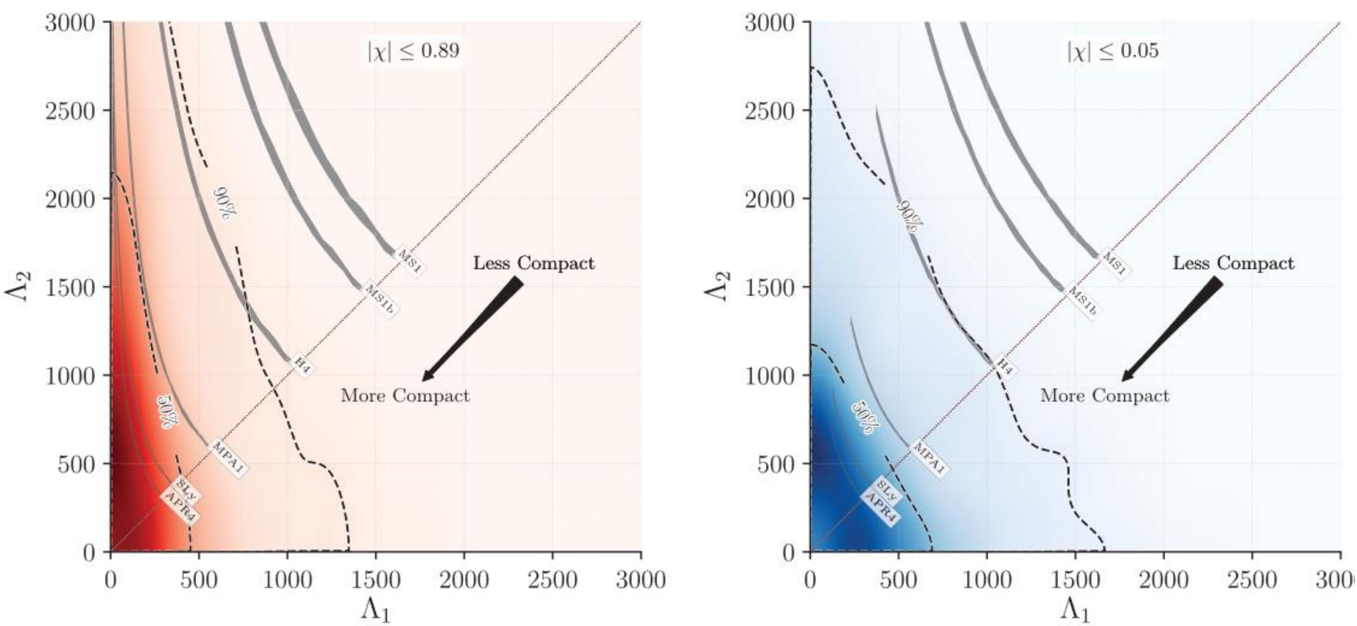


Read et al., PRD 88 (2013)

Tidal deformability: How large a quadrupolar moment a star's gravitational field develops due to an external quadrupolar field

$$Q_{ij} = -\Lambda \mathcal{E}_{ij}$$

However, no detection by LIGO → Upper limit $\Lambda(1.4M_{\odot}) < 800$ at 90% credence (low spin prior)



Gravitational wave breakthrough: LIGO and VIRGO observation of NS merger 130 million ly away!

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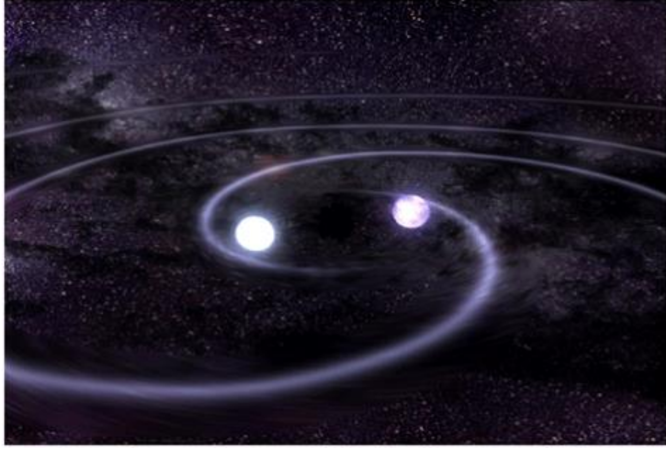
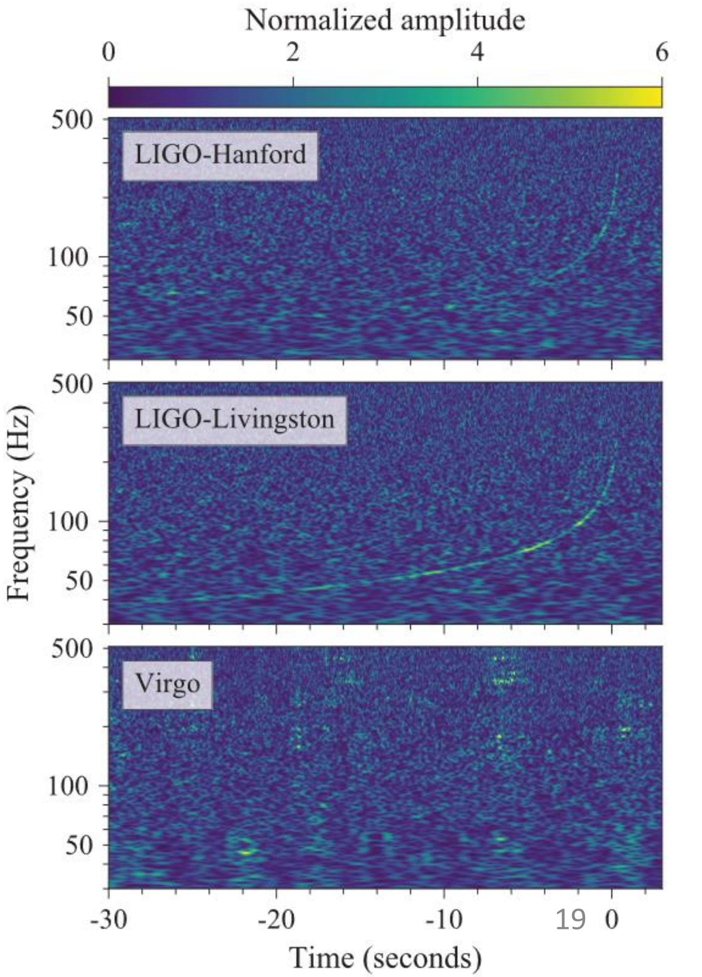
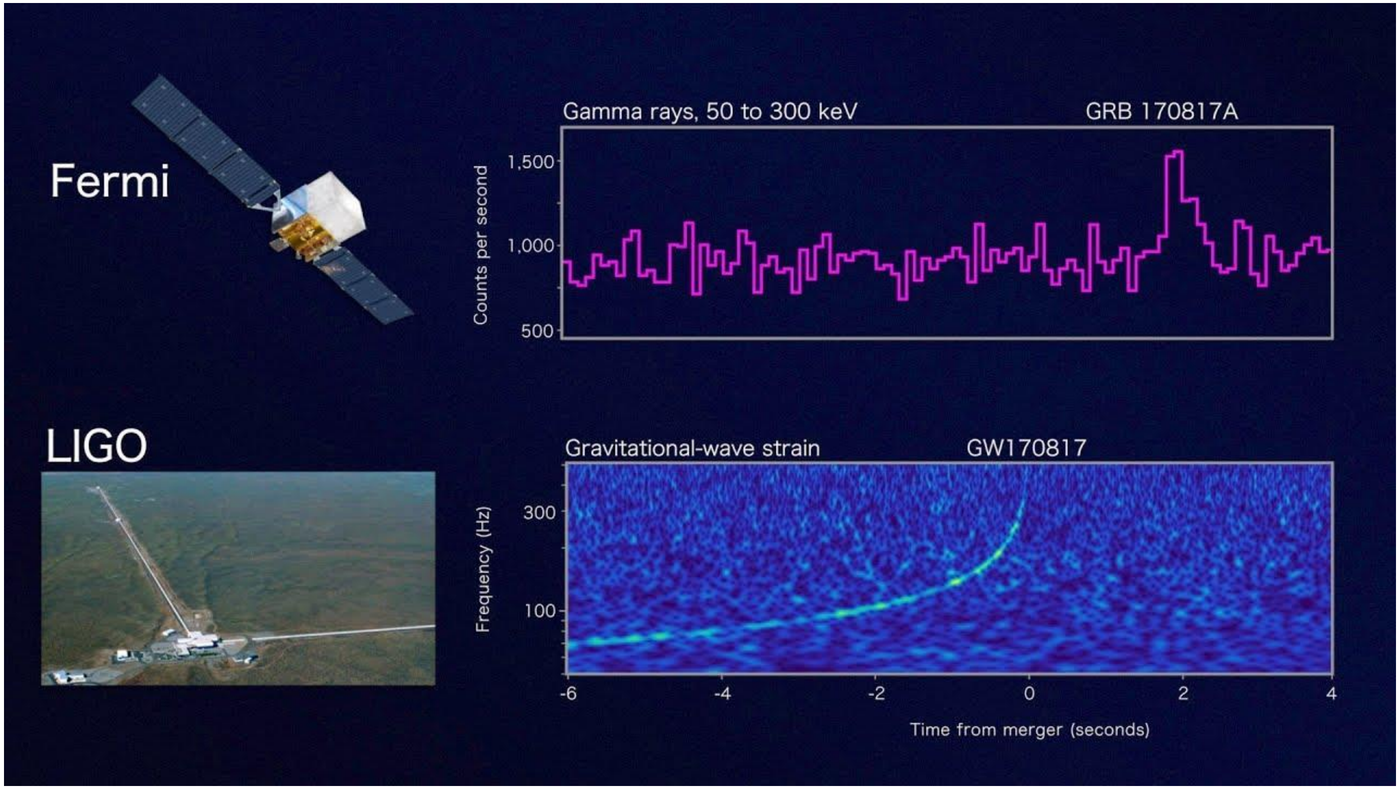


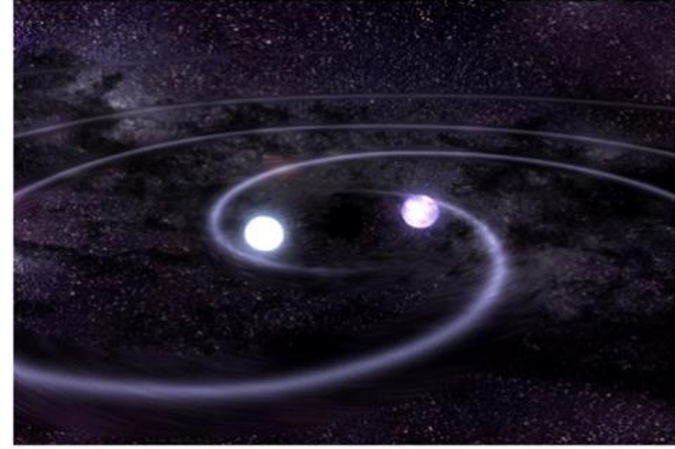




EM counterpart: short gamma ray burst detected 1.7s after GW measurement, followed by an optical signal

- Kilonova: Decay of heavy r-process elements
- GRB → Proposed upper limit for the maximal mass of NSs: $M_{\max} \leq 2.16^{+0.17}_{-0.15} M_{\odot}$ [Rezzolla, Most, Weih, ApJ 852 (2018)]

Gravitational wave breakthrough: LIGO and VIRGO observation of NS merger 130 million ly away!



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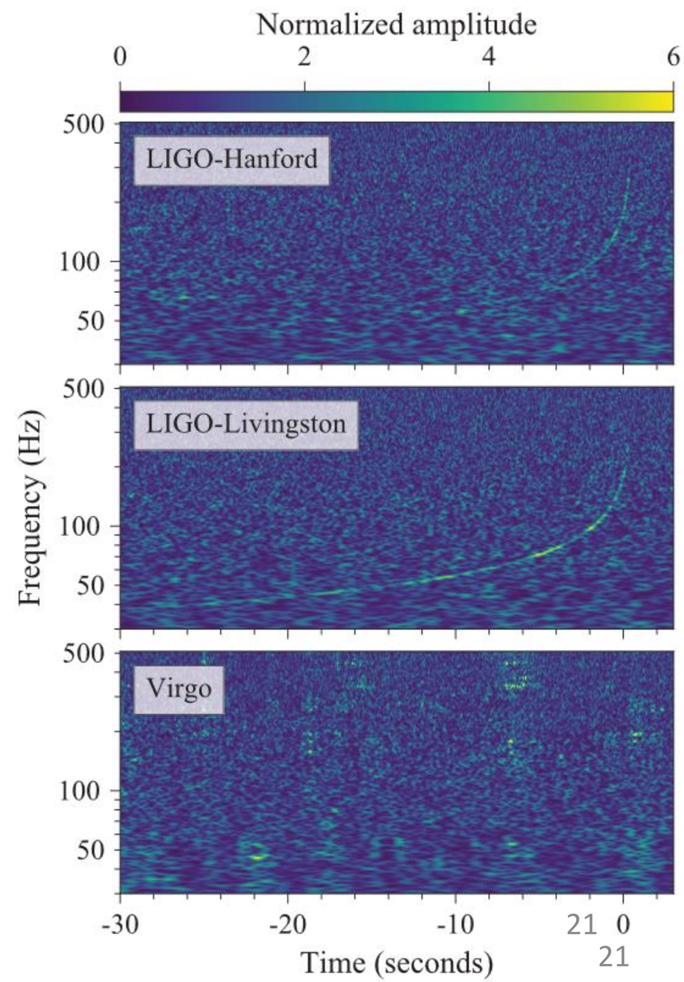
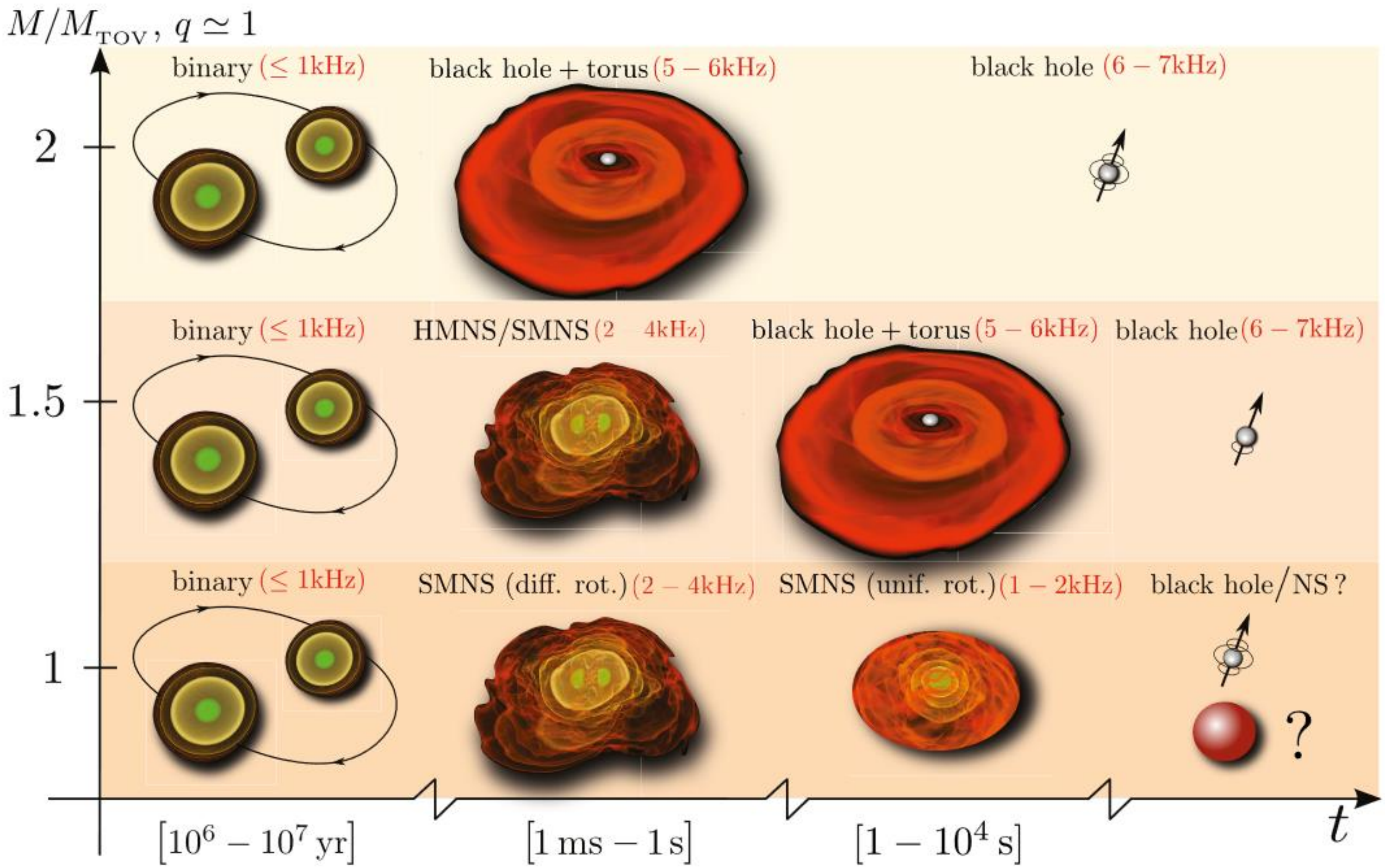
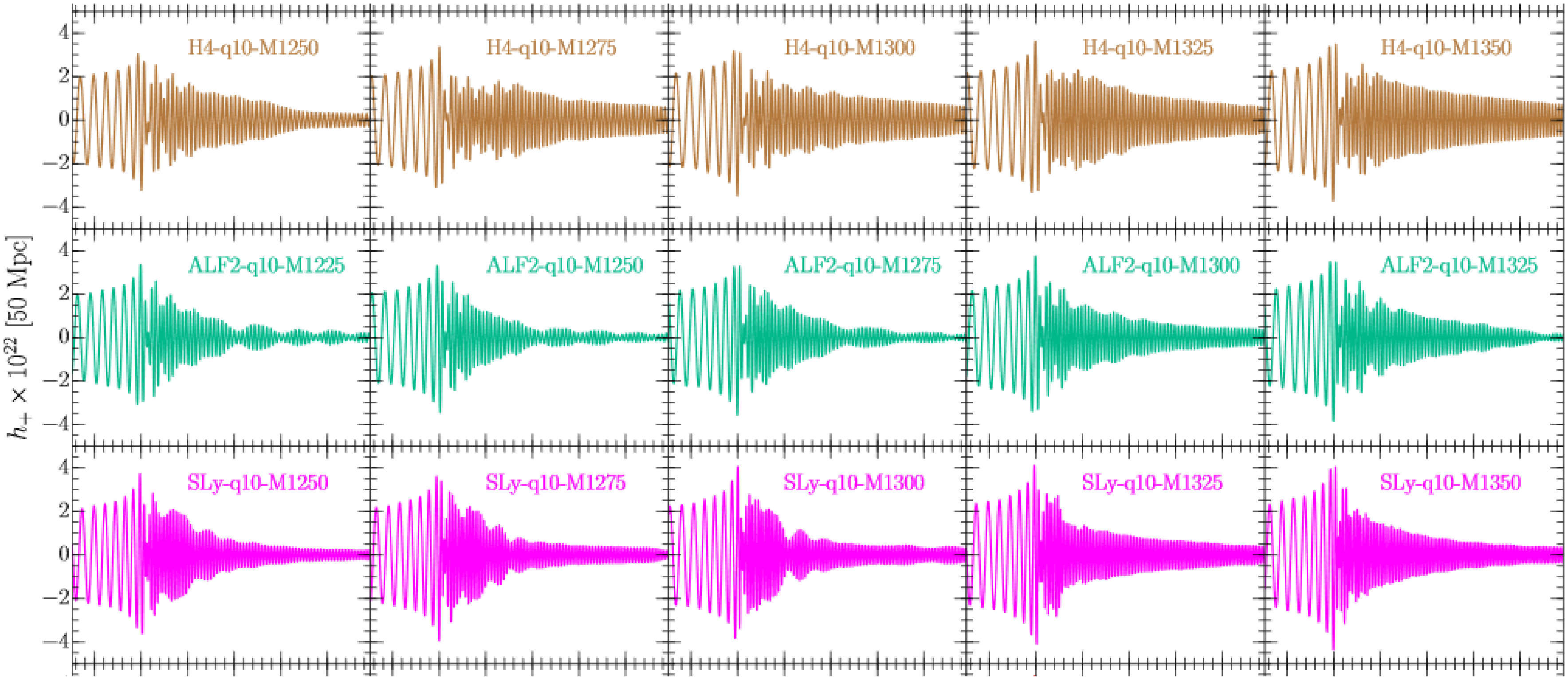


Ringdown pattern: Unlike in BH mergers, expect a complex period of relaxation characterized by GW spectrum sensitive to both initial NS masses and the EoS



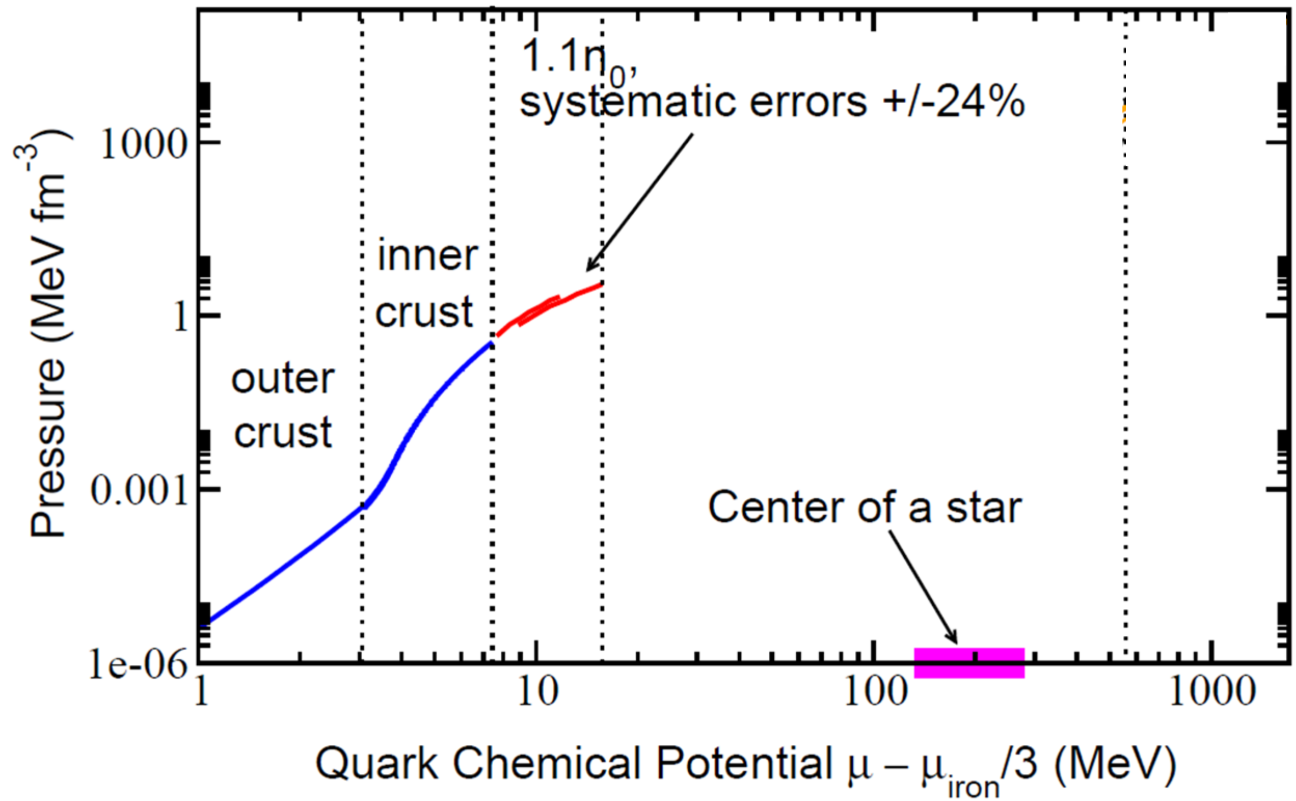
Baiotti, Rezzolla, Rept.Prog.Phys. 80 (2017)

Post-merger dynamics can be studied with relativistic hydrodynamics, showing marked sensitivity to EoS, but frequency range (currently) too high for LIGO and Virgo



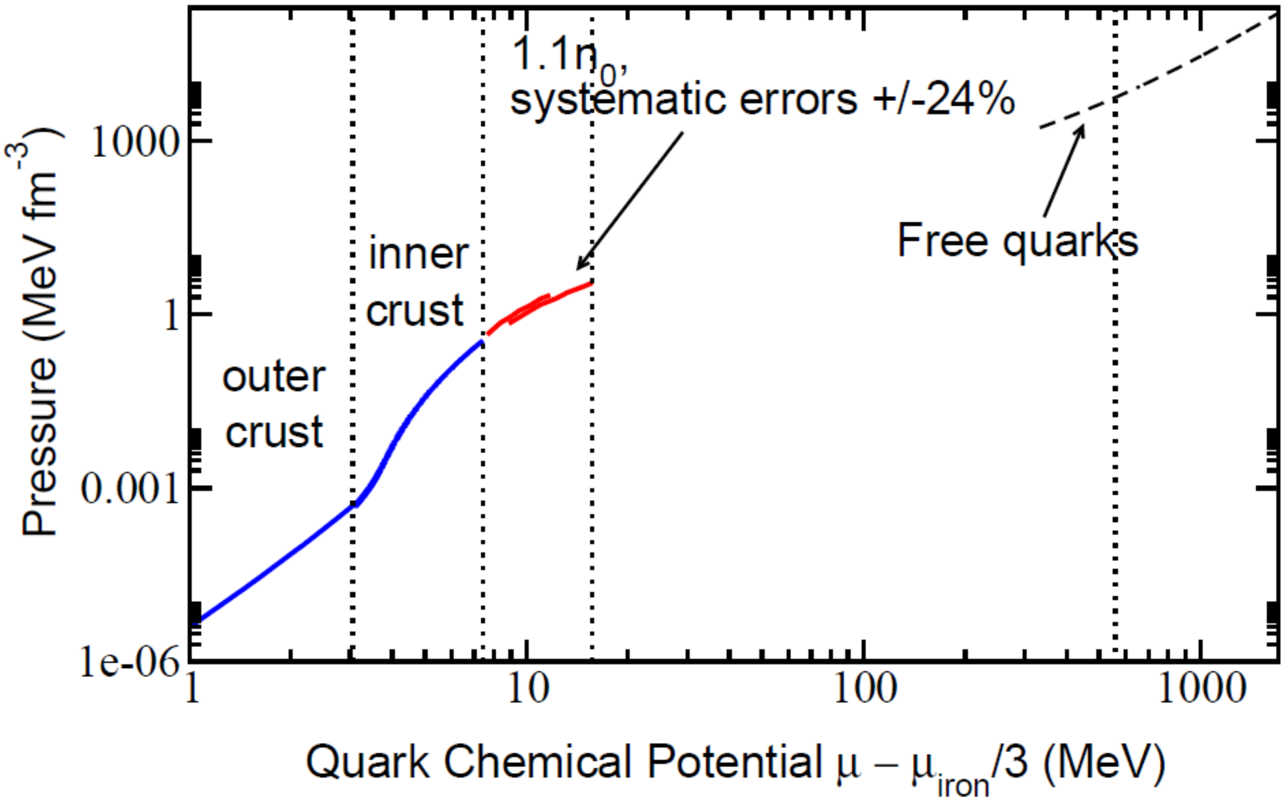
Takami, Rezzolla, Baiotti, PRD 91 (2015)

EoS – theoretical limits



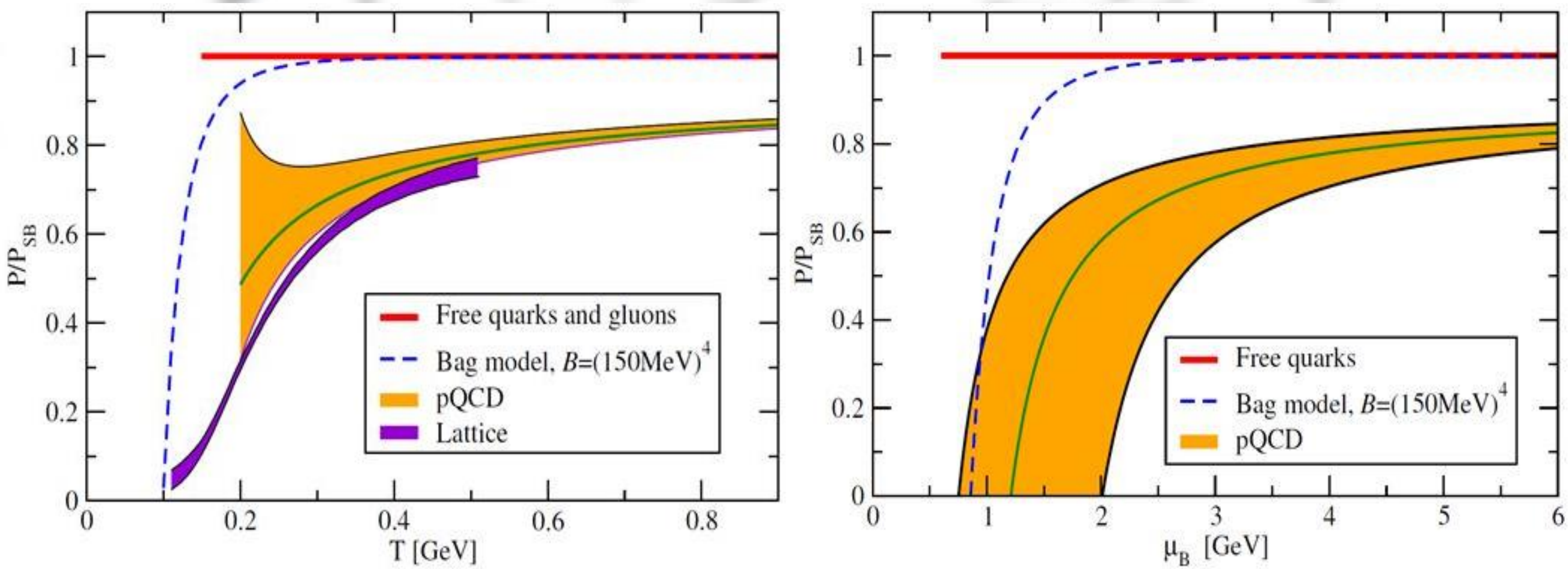
Low-density behavior of EoS well known from nuclear theory side. Challenges begin close to saturation density:

- At $1.1n_s$, current errors in Chiral Effective Theory EoS $\pm 24\%$ - mostly due to uncertainties in effective theory parameters
- State-of-the-art EoS NNNLO in chiral perturbation theory power counting [Tews et al., PRL 110 (2013), Hebeler et al., ApJ 772 (2013)]

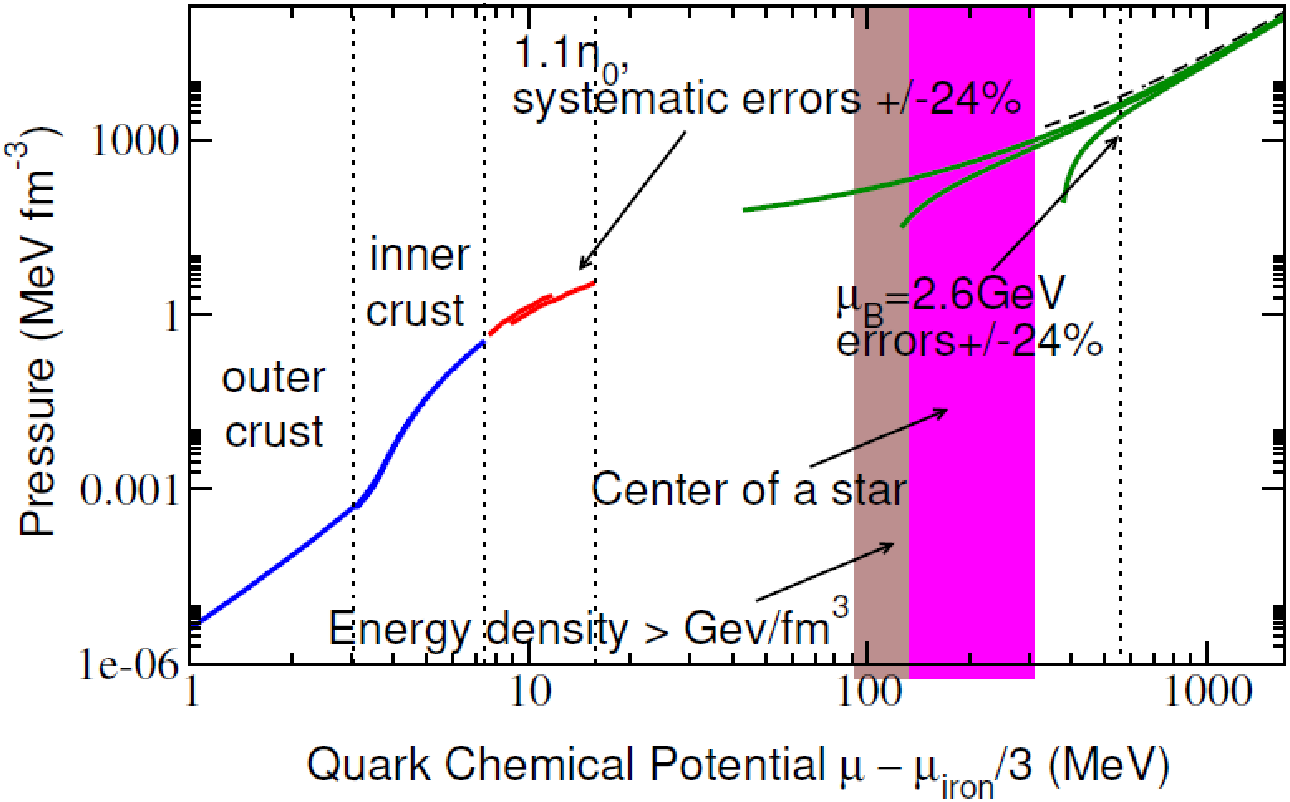


Asymptotic freedom of QCD ⇒ High-density limit from a non-interacting theory. However,…

- At interesting densities $(1-10)n_s$ system strongly interacting but no nonperturbative methods available
- Naïve expectation: Weak coupling methods only useful at very high densities

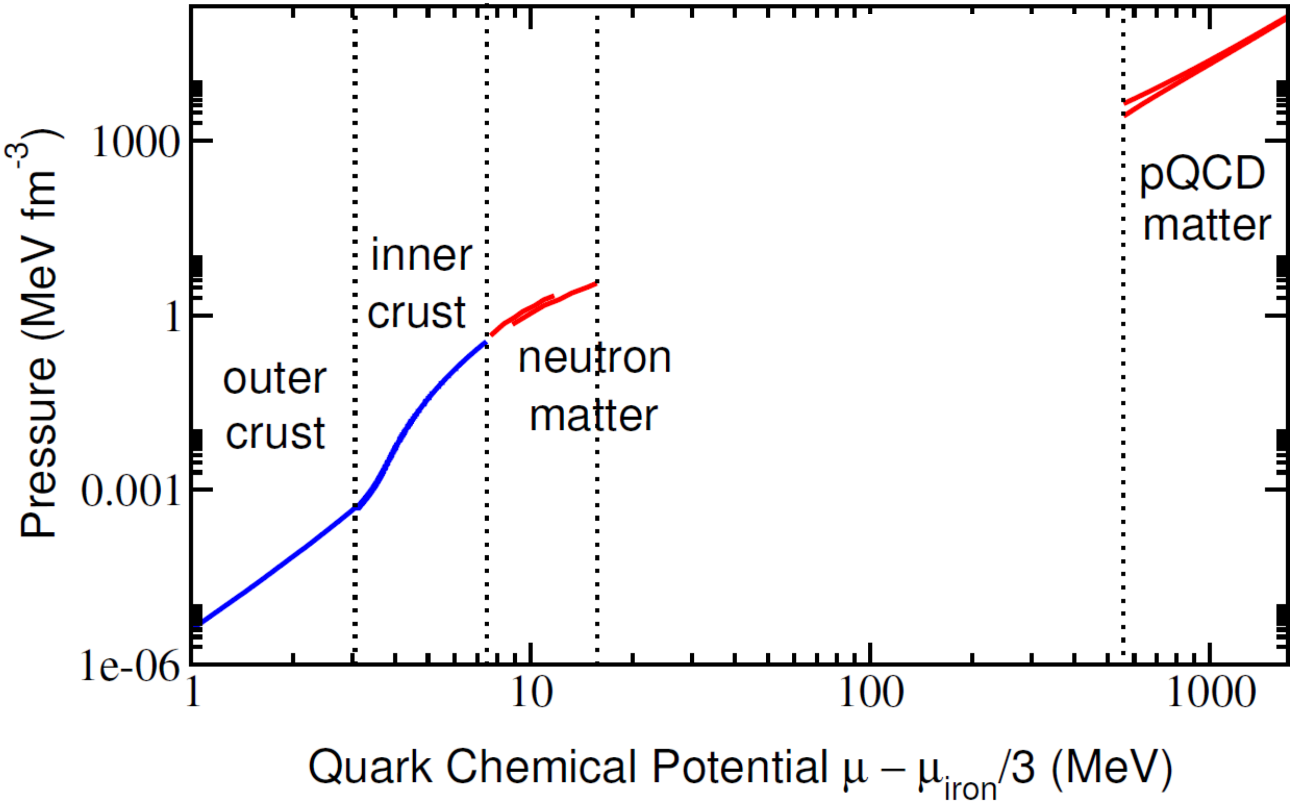


Recent improvement: First part of four-loop pressure at $T = 0$ derived: $p_{4-\mathrm{loop}} \ni -\frac{11}{12}\frac{N_c d_A}{(2\pi)^3}\alpha_s m_\infty^4 \ln^2 \alpha_s$ [Gorda, Kurkela, Romatschke, Säppi, Vuorinen, arXiv:1806.xxxxx]



Three-loop result with nonzero quark masses [Kurkela, Romatschke, Vuorinen, PRD 81 (2009)]

- Uncertainty of result at $\pm 24\%$ level around $40n_s$
- Main uncertainty from renormalization scale dependence
- Pairing contributions to EoS subdominant at relevant densities



Conclusion: Sizable no man's land extending from outer core to densities not realized inside physical neutron stars

Options: Use models, deform theory, or interpolate EoS between known limits and use astrophysical constraints

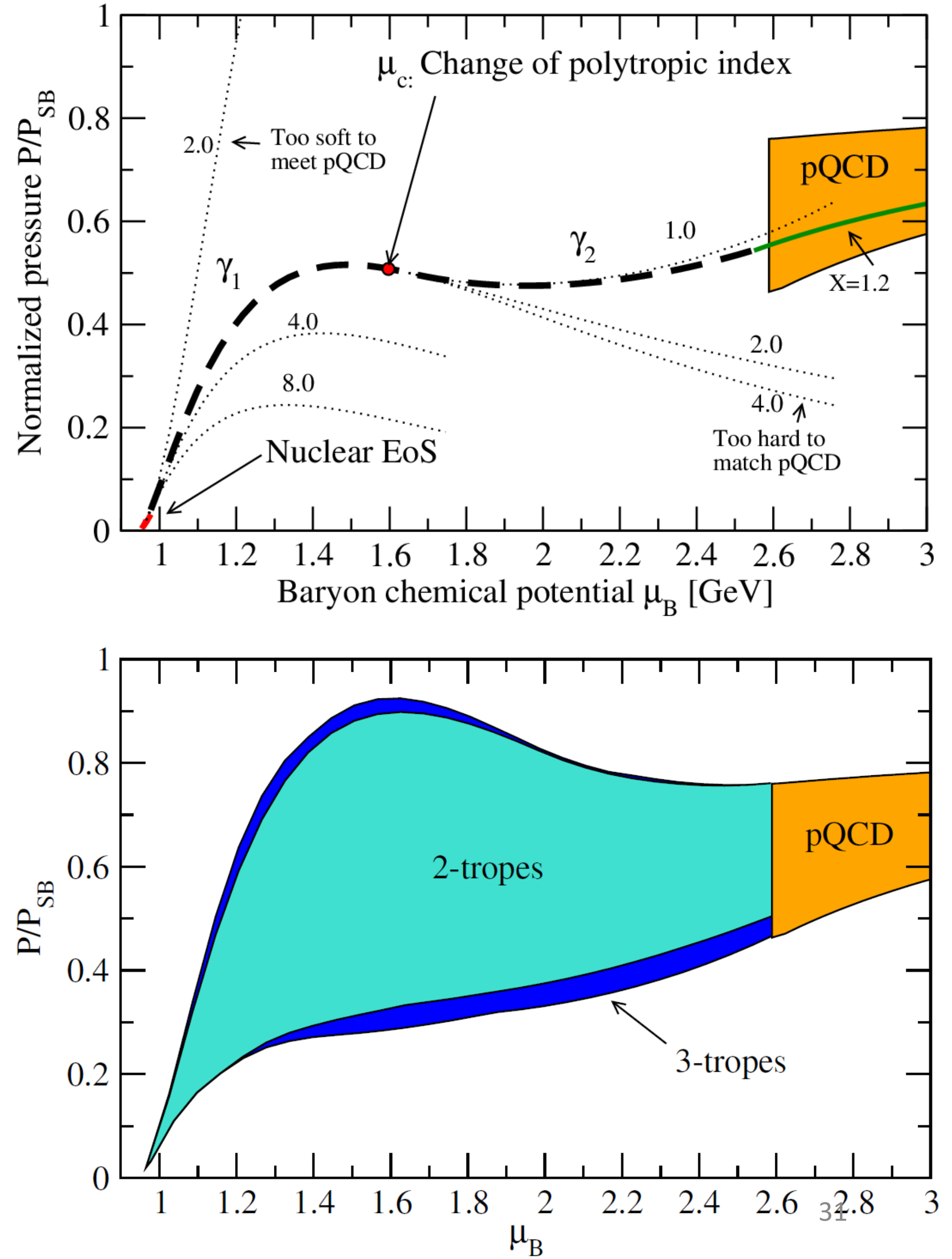
Interpolation – with and without observational constraints

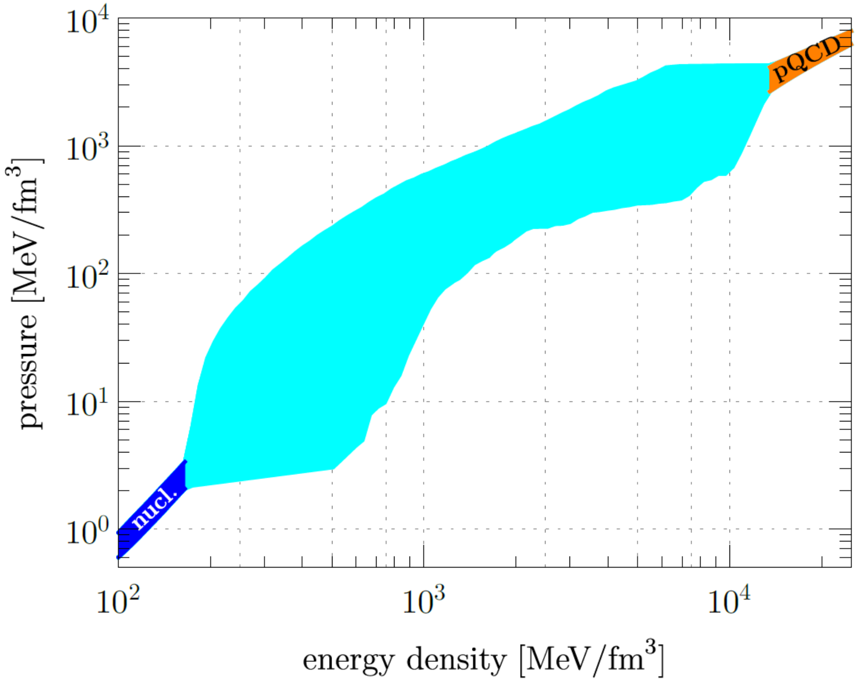
Interpolate EoS using piecewise polytropic form, $p_i(n) = \kappa_i n^{\gamma_i}$, varying all parameters (γ_i, μ_i^{match})

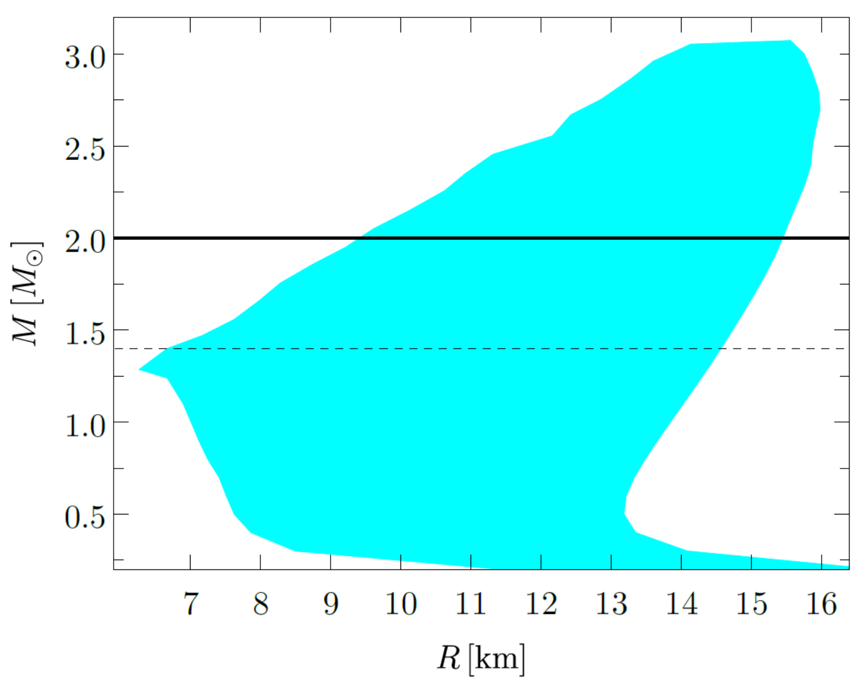
Require:

1) Smooth matching to nuclear and quark matter EoSs
2) Continuity of p and n – with at most one exception (1st order transition)
3) Subluminality
4) Optional: astrophysical constraints

[Kurkela et al., ApJ 789 (2014)]

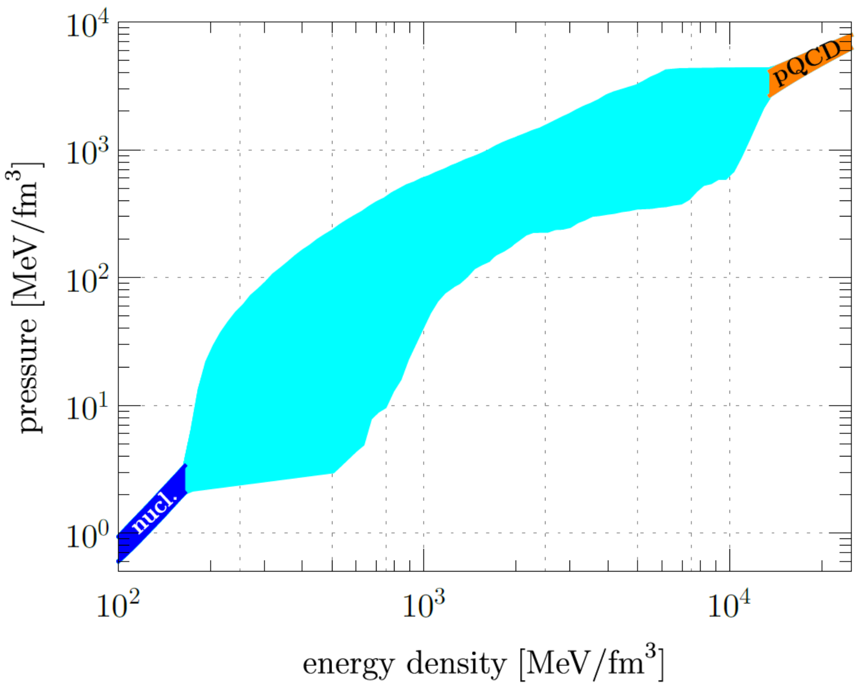


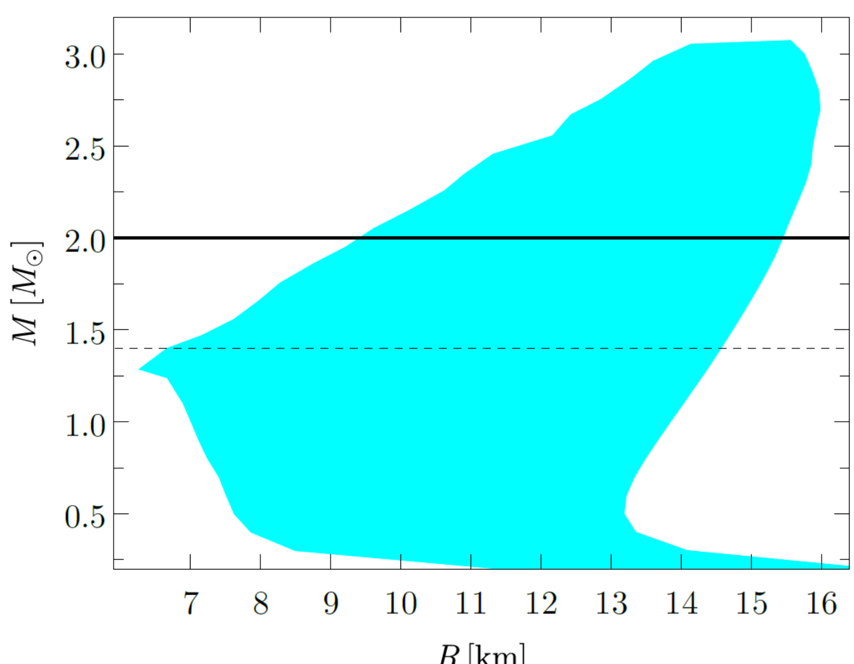




Quadrutropic interpolation, using close to 200.000 randomly generated EoSs

Figures from [Annala, Gorda, Kurkela, Vuorinen, PRL 120 (2018)]

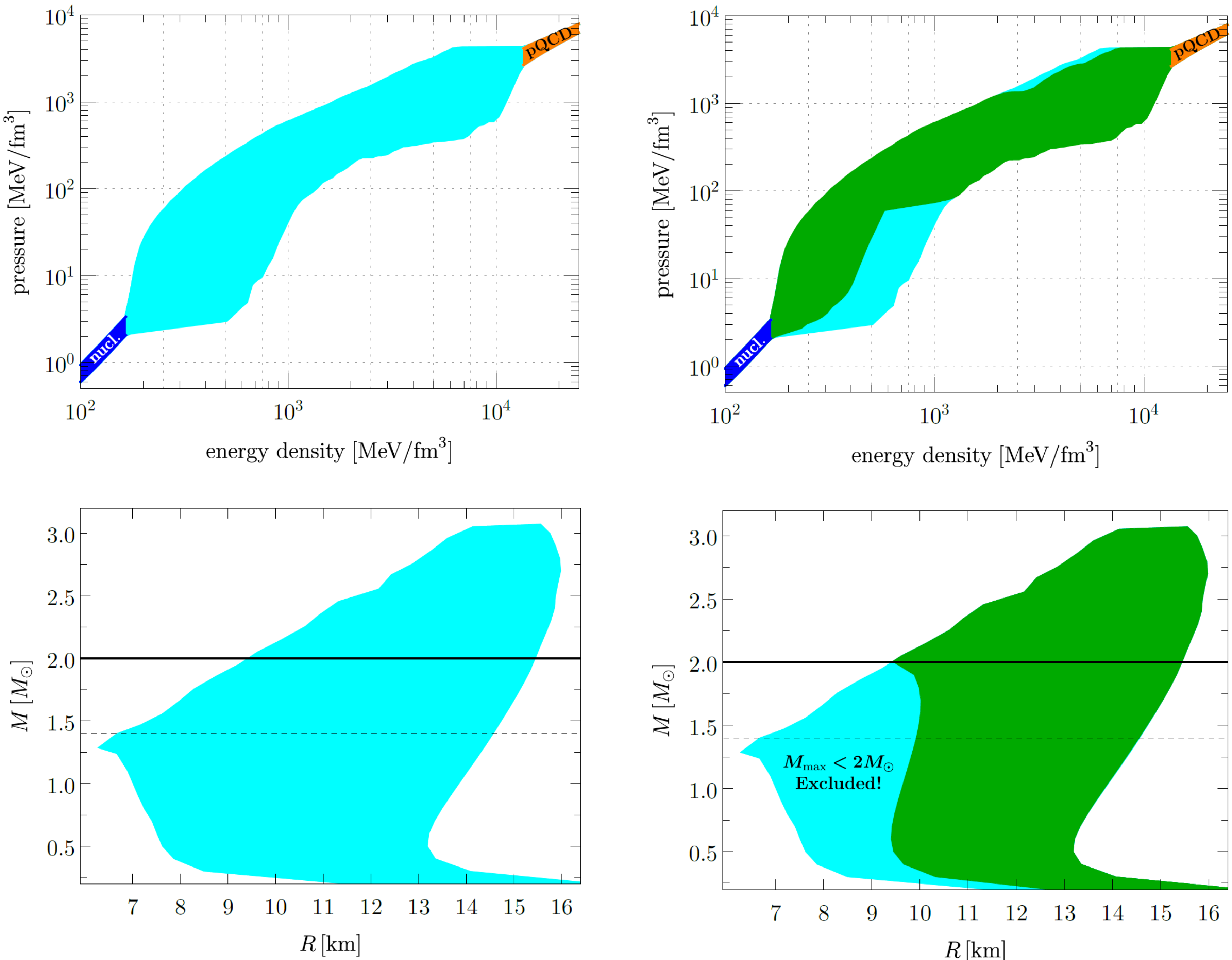


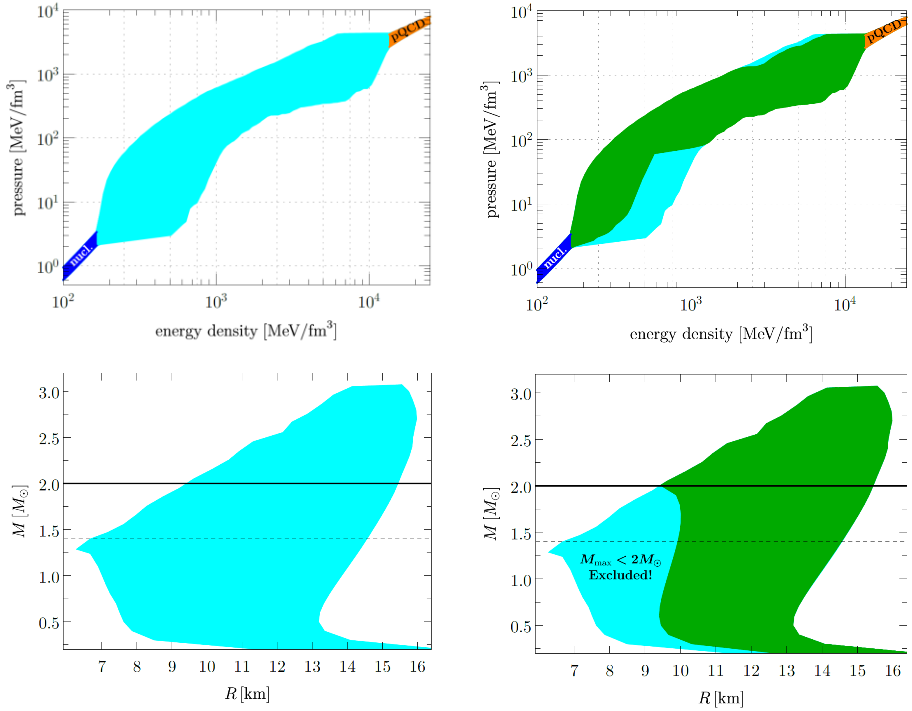


Implement then two-solar-mass constraint: Accept only EoSs that fulfill $M_{\max} > 2M_{\odot}$

Assumption here and in the following: All stars considered main seq. NSs

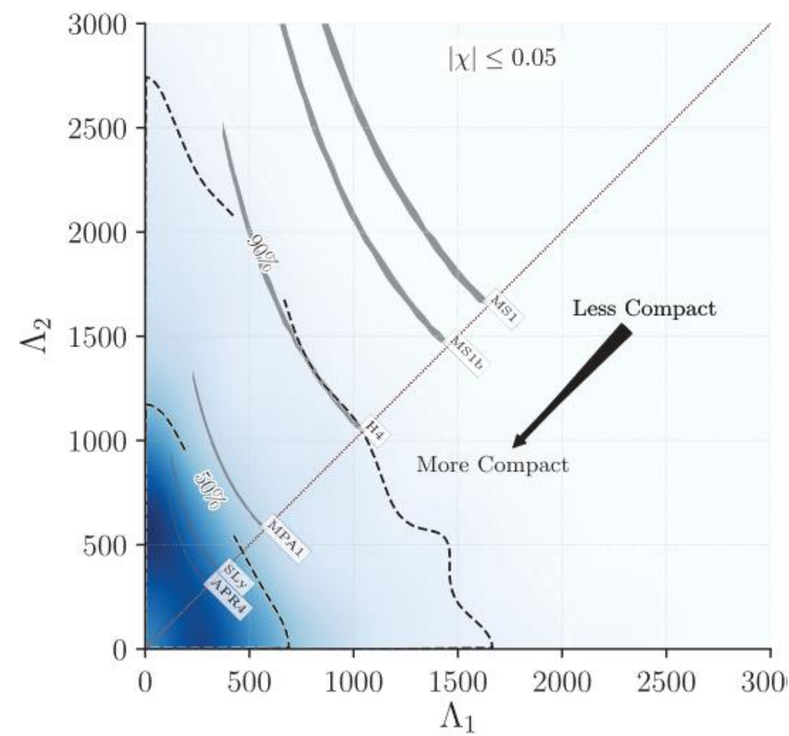
- Excluded: twin stars [e.g. Alvarez-Castillo, Blaschke, PRC96 (2017)], strange quark stars [Weber et al., IAU 291 (2013)]

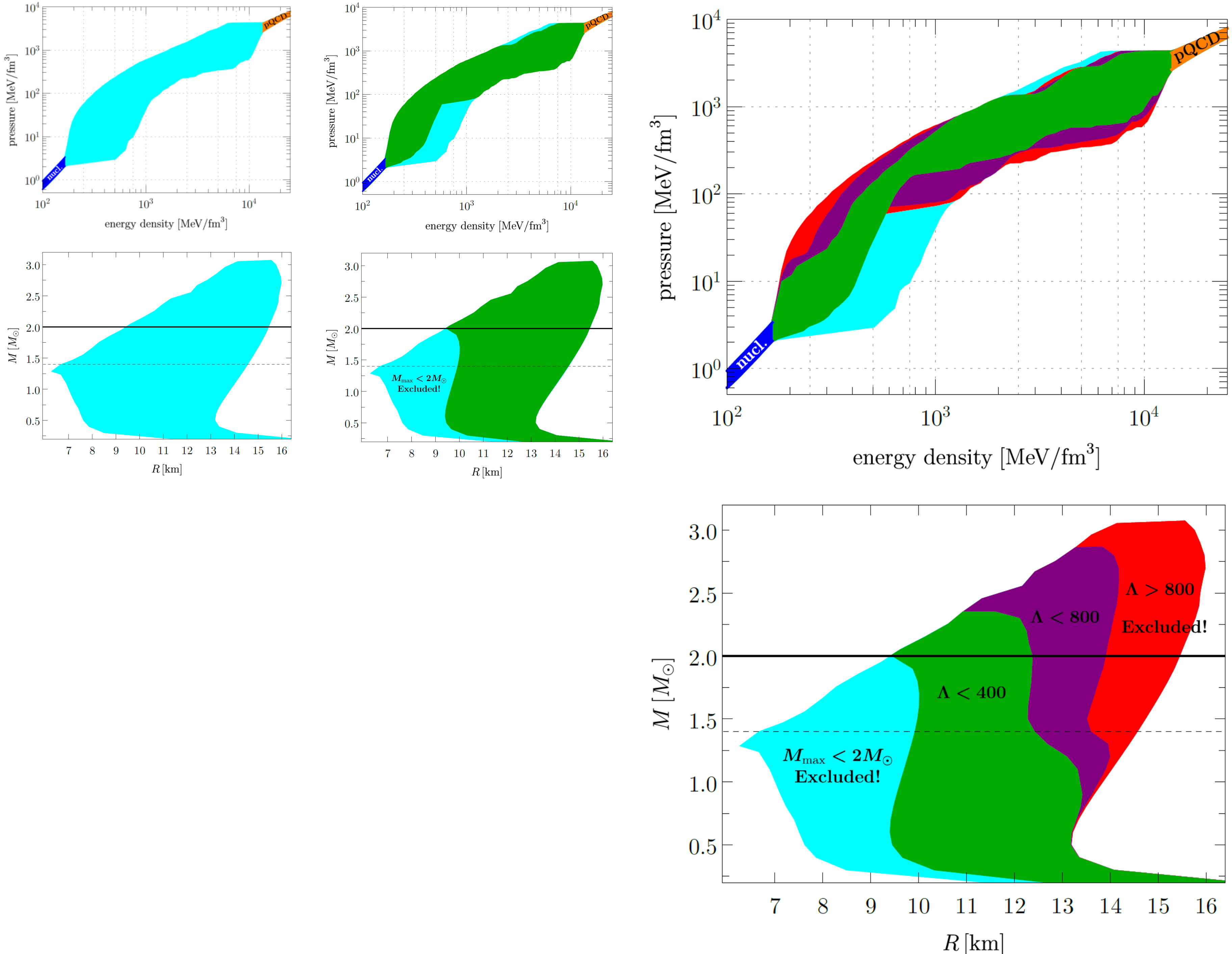

pQCD
nucl.
pressure [MeV/fm³]
energy density [MeV/fm³]
M [M☉]
R [km]
$M_{\rm max} < 2M_\odot$
Excluded!



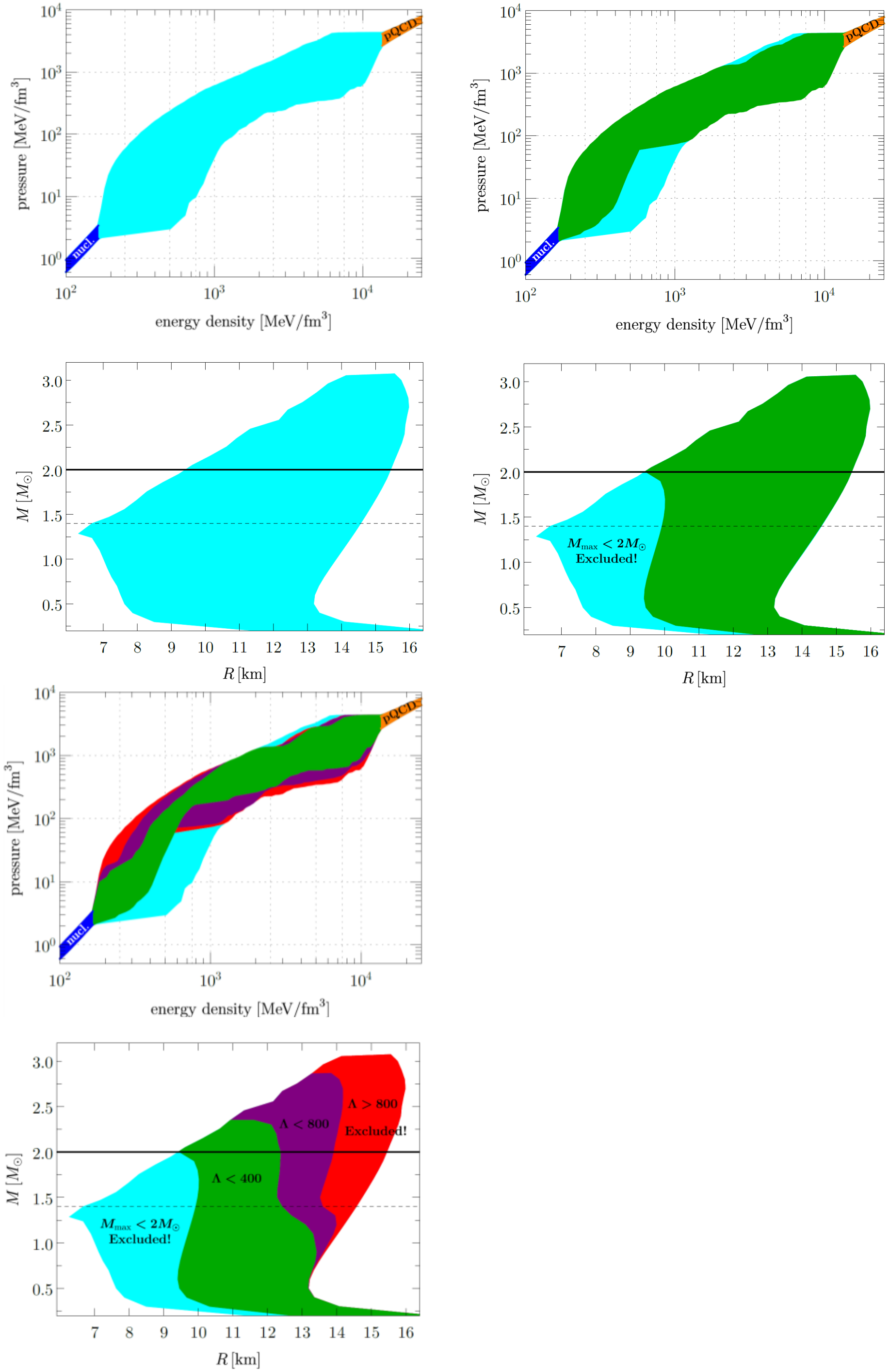
Next, determine tidal deformabilities from each EoS and compare to LIGO results for $1.4M_\odot$ stars:

- $\Lambda(1.4M_\odot) < 800$ at 90%
- $\Lambda(1.4M_\odot) < 400$ at 50%



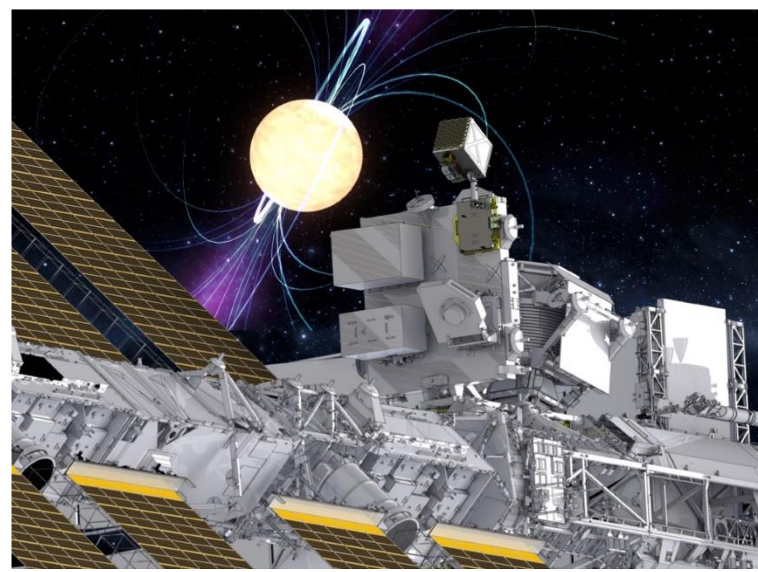


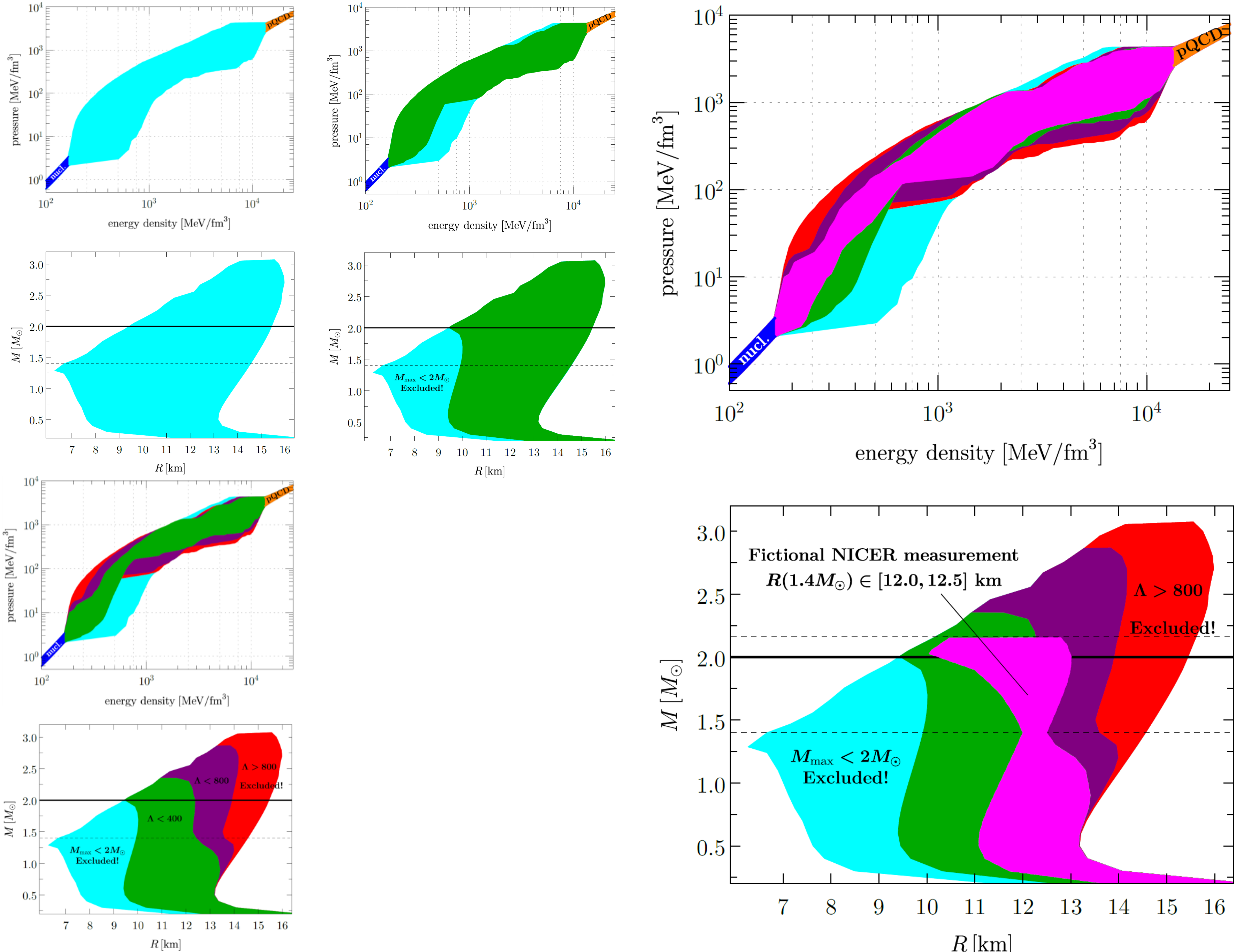
pressure [MeV/fm^3]
energy density [MeV/fm^3]
nucl.
pQCD
$M\,[M_\odot]$
$R\,[\mathrm{km}]$
$M_{\max} < 2M_\odot$
Excluded!
$\Lambda < 400$
$\Lambda < 800$
$\Lambda > 800$
Excluded!



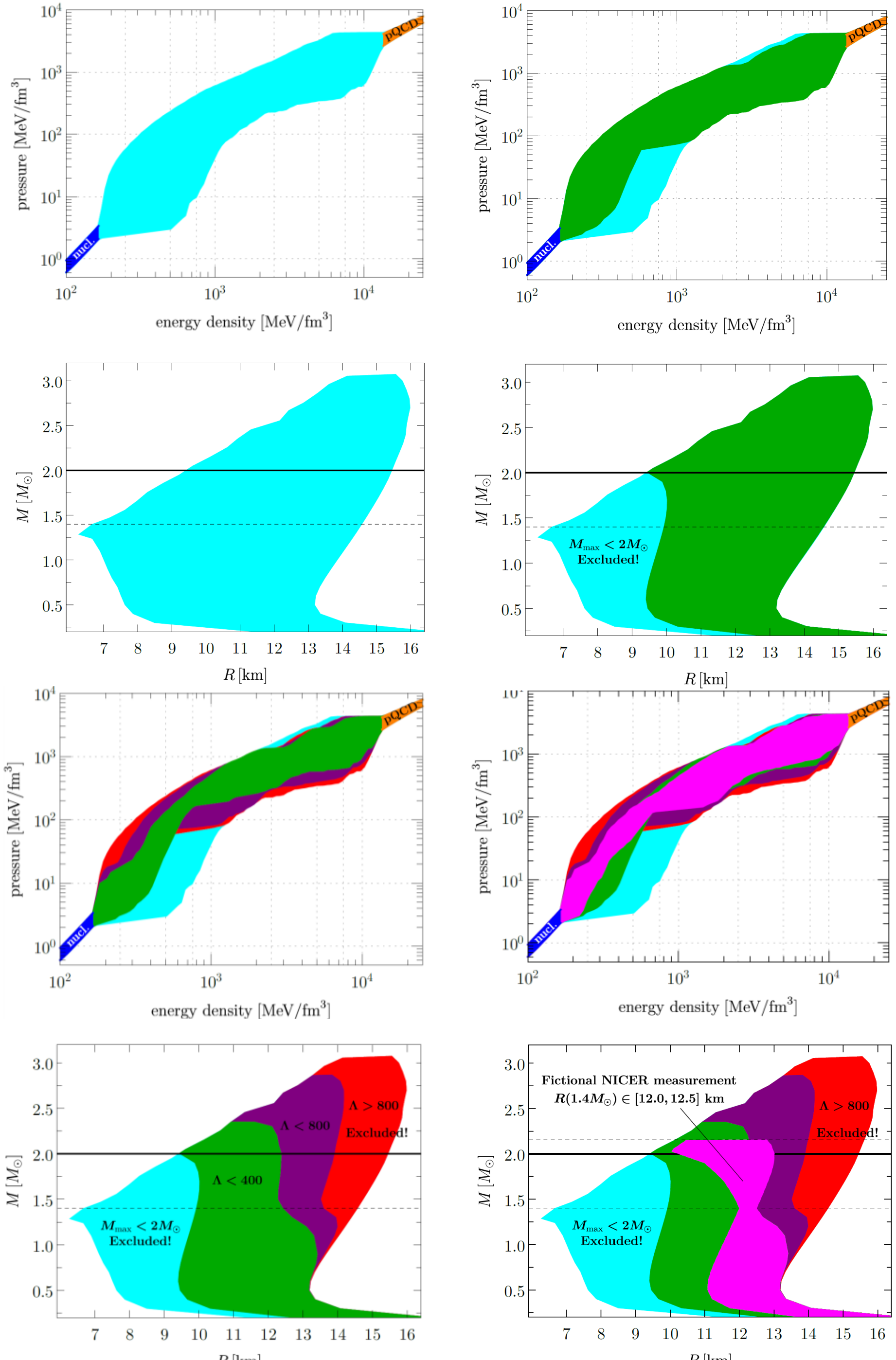
How would this look with future improved radius measurements, e.g. NICER $R(1.4M_\odot) = 12.25 \pm 0.25$ km?

Or with proposed limit $M_{\max} \leq 2.16M_\odot$ [Rezzolla, Most, Weih, ApJ 852 (2018)]?

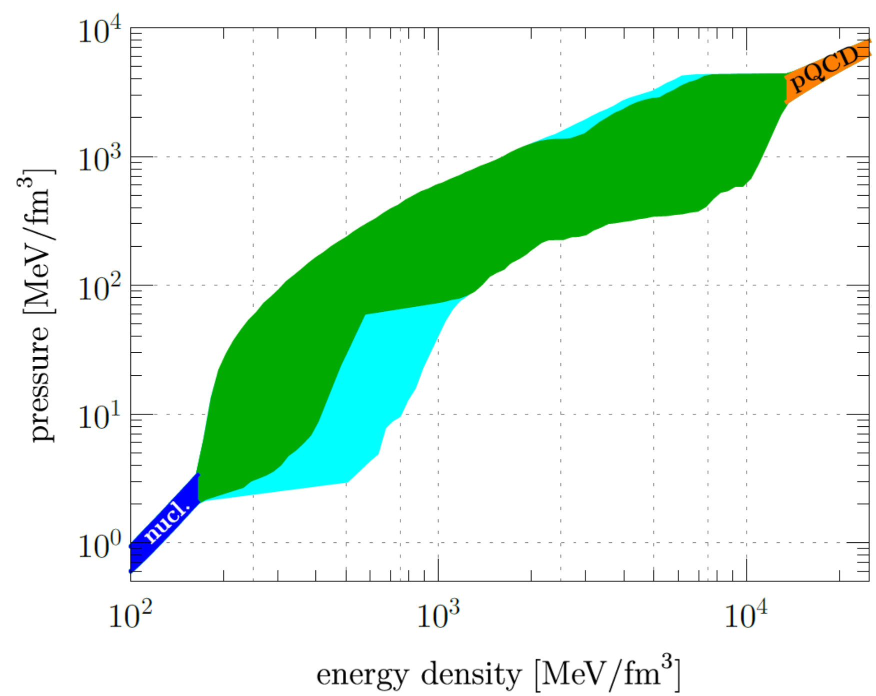


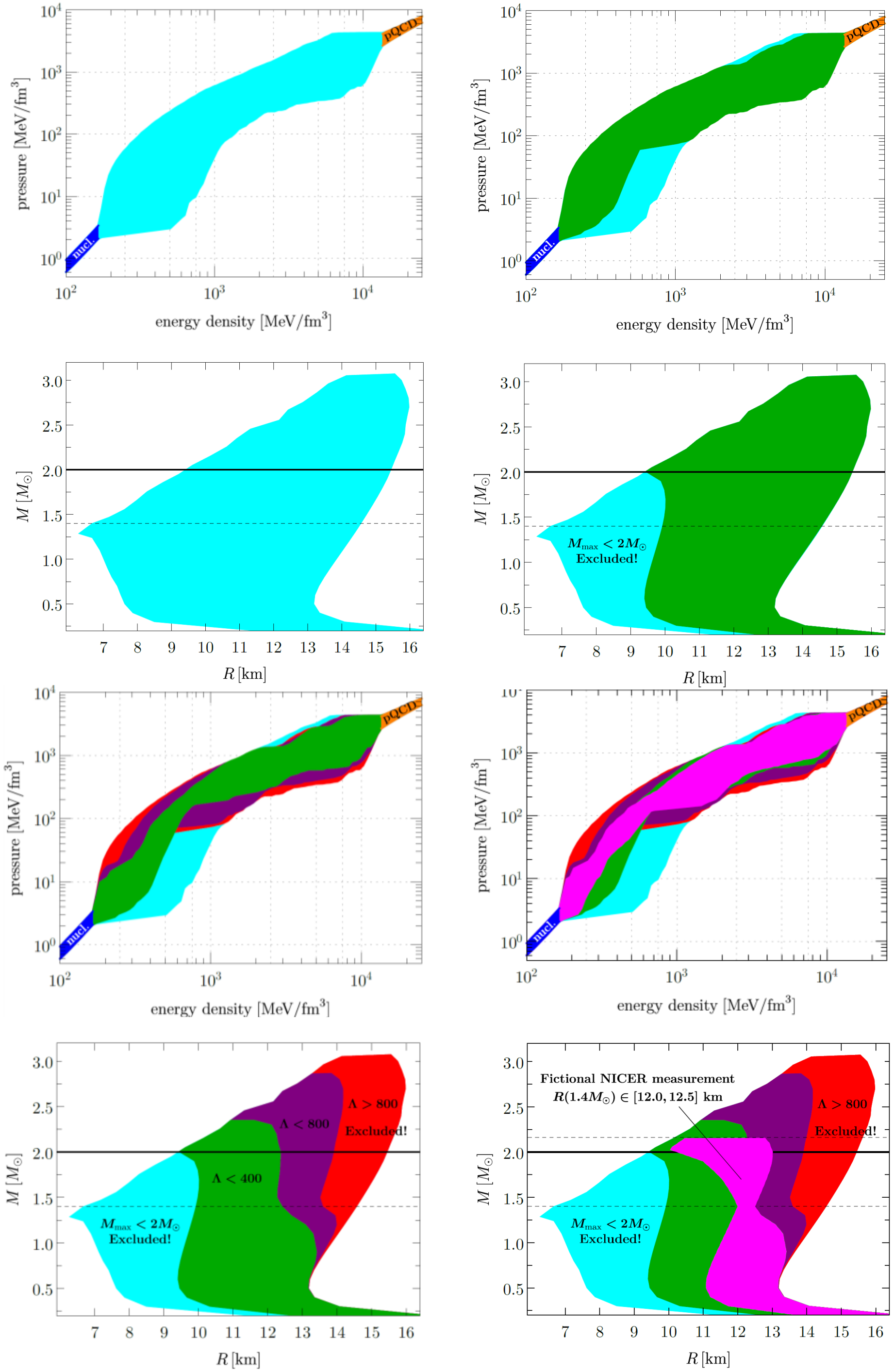


pressure [MeV/fm^3]
energy density [MeV/fm^3]
nucl.
pQCD
M [$M_\odot$]
R [km]
$M_{\max} < 2M_\odot$
Excluded!
$\Lambda < 400$
$\Lambda < 800$
$\Lambda > 800$
Excluded!
Fictional NICER measurement
$R(1.4M_\odot) \in [12.0, 12.5]$ km

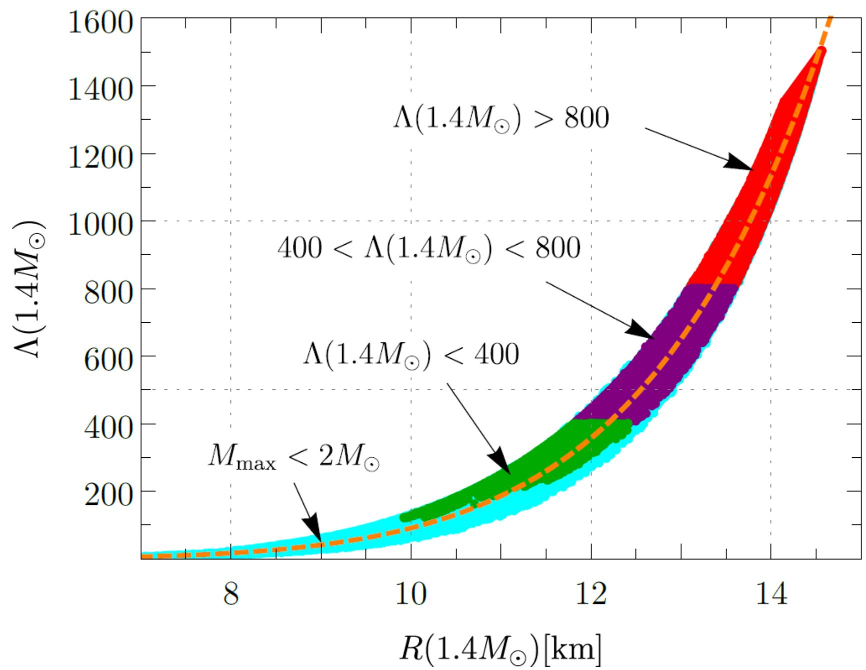


Lesson 1: $2M_\odot$ and pQCD constraints force EoS to be hard at low density and soft at high density → Efficient bracketing of $p(\epsilon)$, $R(1.4M_\odot) \geq 10$km





Lesson 2: Stringent limits from only one tidal deformab. measurement: EoS cannot be overly stiff at low density, $R(1.4M_\odot) \leq 13.6\text{km}$



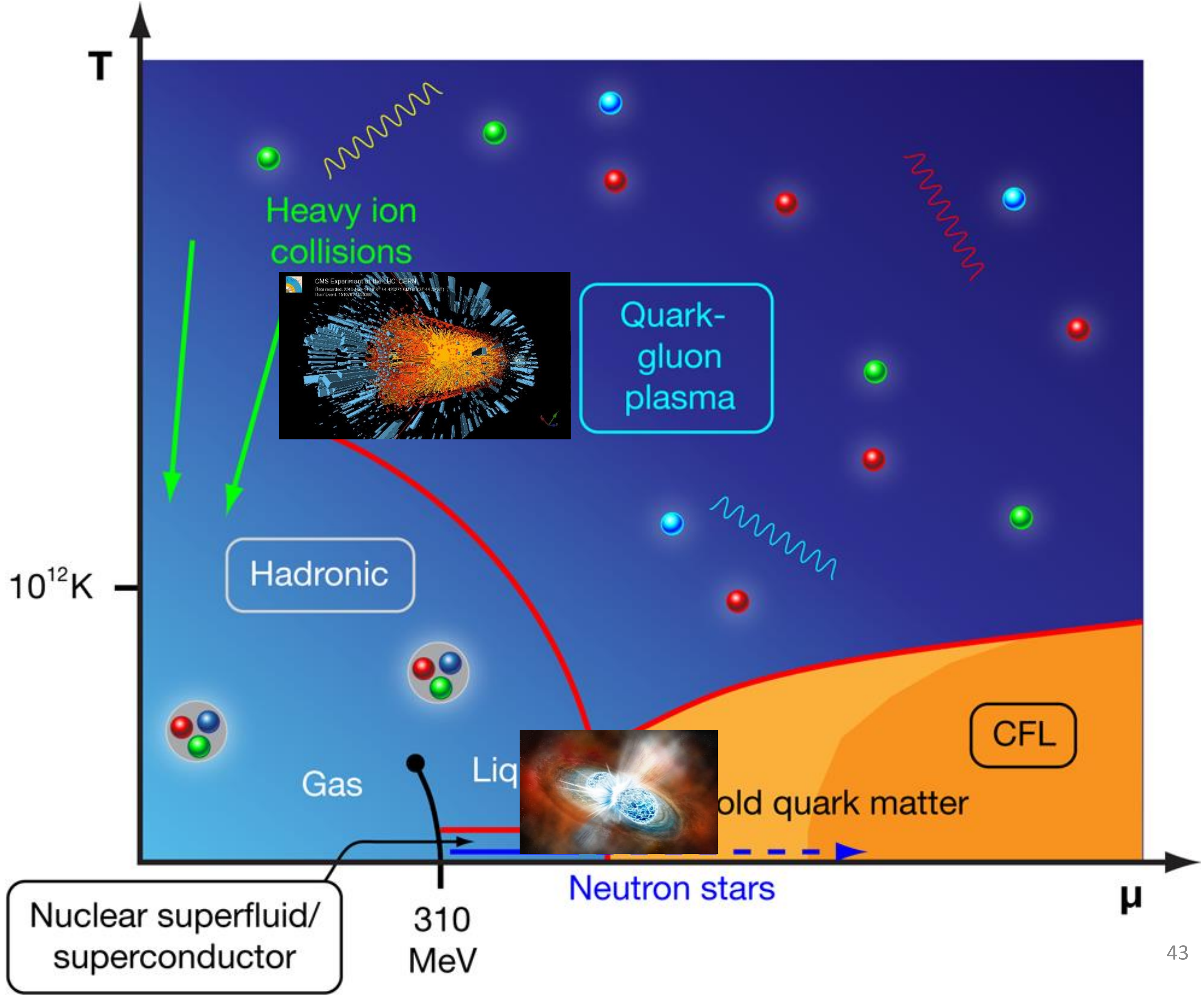
One stellar merger later – where are we?

Big open questions:

- Can QCD theorists predict neutron star measurements?
  - ➢ Not there yet – need fundamentally new machinery

- Can we infer the QCD matter EoS from observations?
  - ➢ Looks very promising, fast progress with GWs

- **Can deconfined matter be found inside the stars?**
  - ➢ **Tough question, but we’re on the right path!**


T
Heavy ion
collisions
Quark-
gluon
plasma
10^{12}K
Hadronic
Gas
Liq
old quark matter
CFL
Neutron stars
μ
Nuclear superfluid/
superconductor
310
MeV