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

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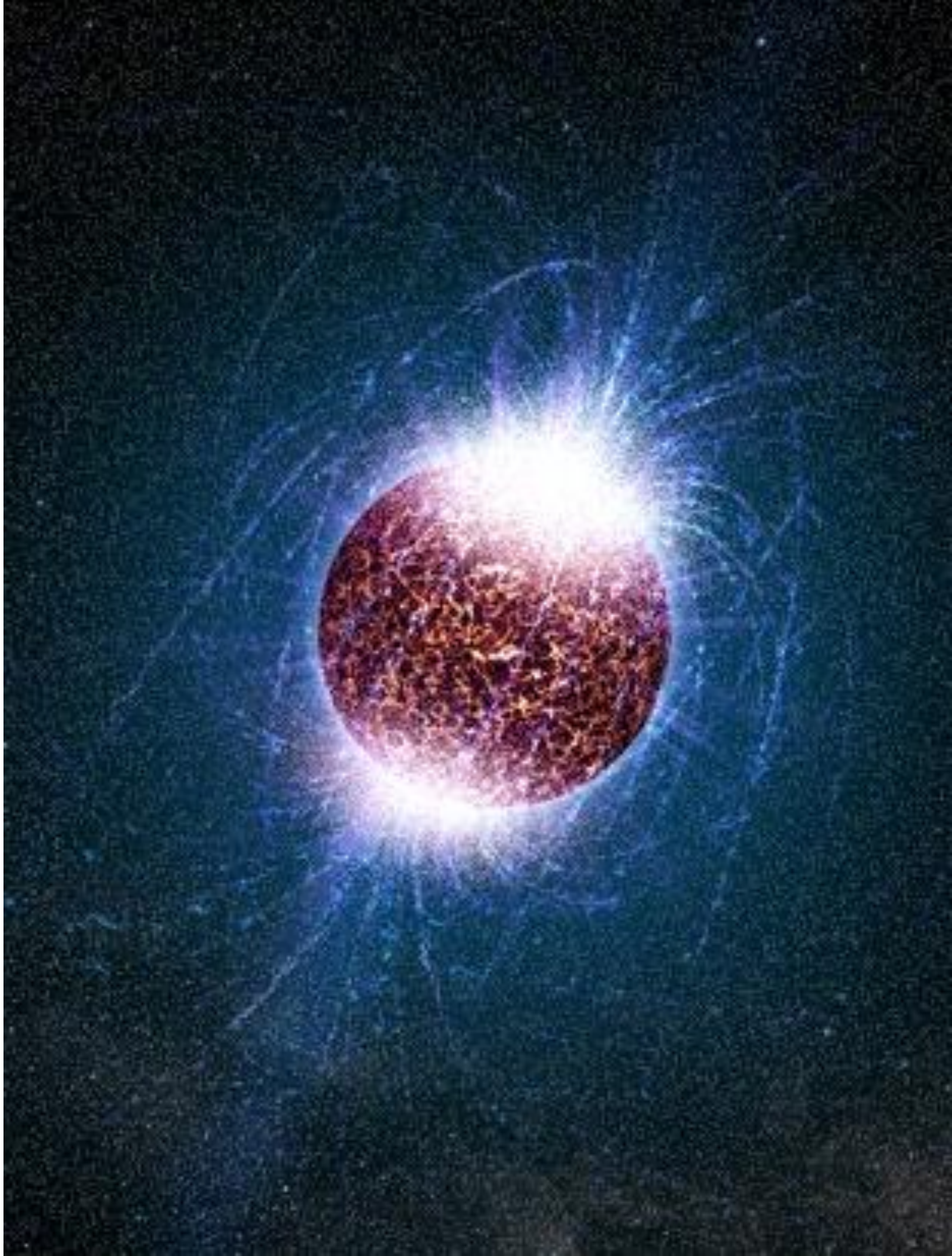
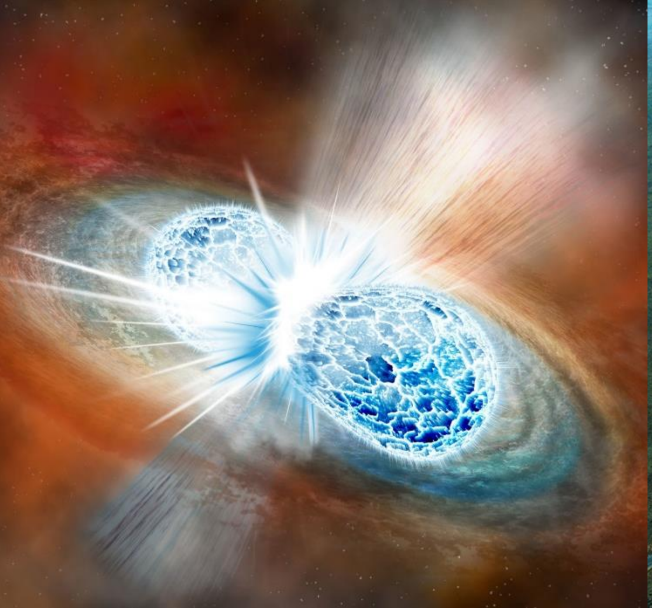
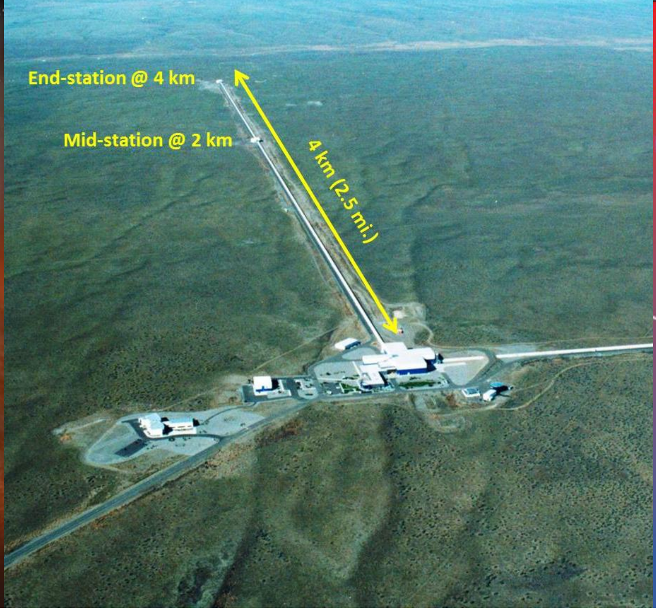
YKIS2018b

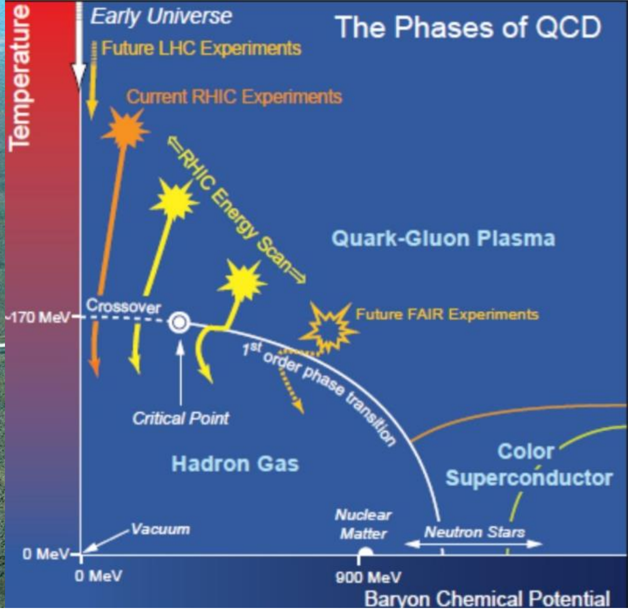
Kyoto, 13 June 2018

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









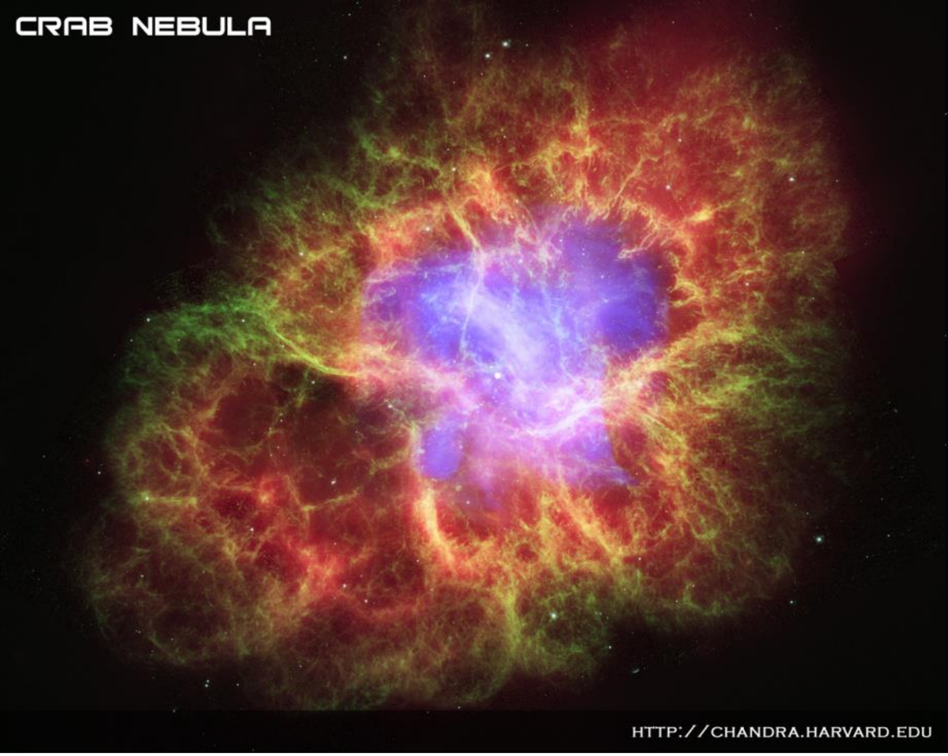
10^8 years ago, 10^{24}m away from us, two stars of $R \sim 10^4$m and $M \sim 10^{30}$kg crossed paths.

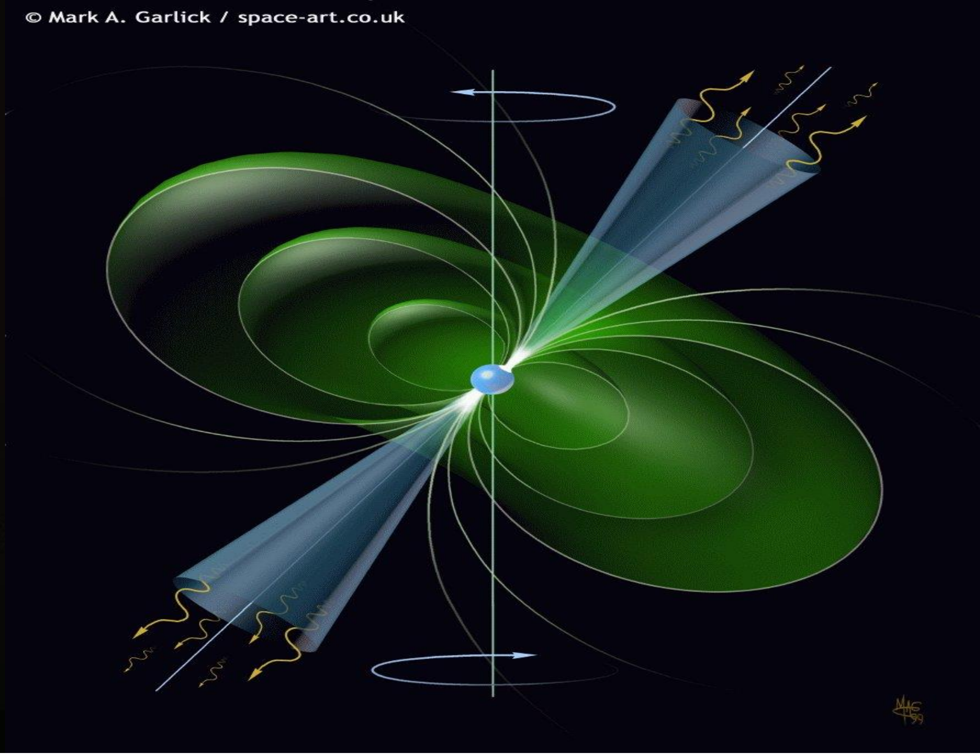
On August 17 2017, LIGO measured a 10^{-17}m oscillation in the length of its 10^3m arms.

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

I. Neutron star basics
II. Observational information
III. Theoretical limits for the neutron star matter Equation of State
IV. Interpolating the EoS from low to high densities
V. Final thoughts

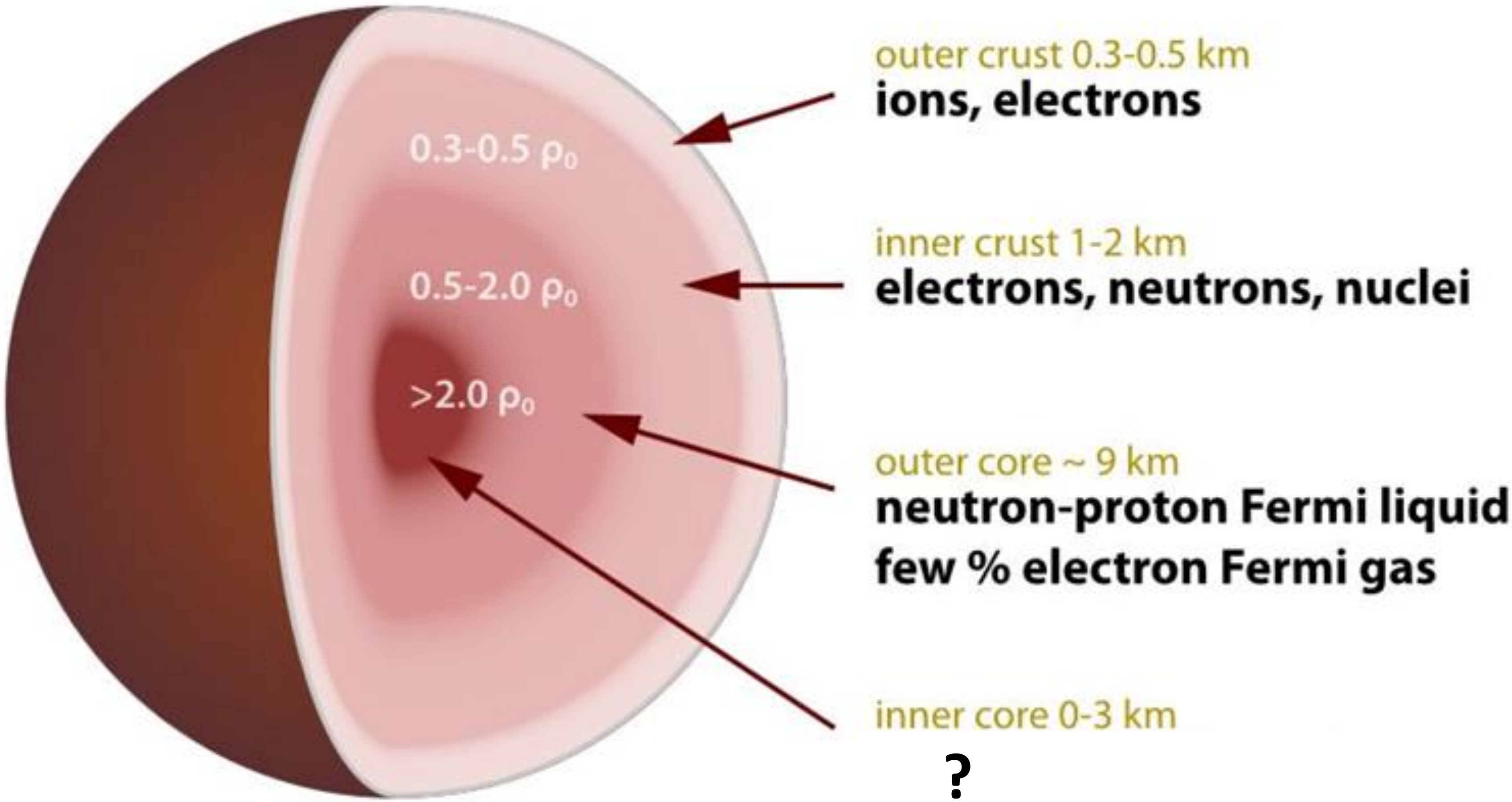
What are neutron stars?





When a hydrogen burning star runs out of fuel:

- $\mathrm{M} \lesssim 9M_{\mathrm{sun}}$ ⇒ White dwarf
- $\mathrm{M} \gtrsim 9M_{\mathrm{sun}}$ ⇒ Supernova explosion
    - $\mathrm{M} \gtrsim 20M_{\mathrm{sun}}$ ⇒ Gravitational collapse into BH
    - $\mathrm{M} \lesssim 20M_{\mathrm{sun}}$ ⇒ Gravitational collapse into…

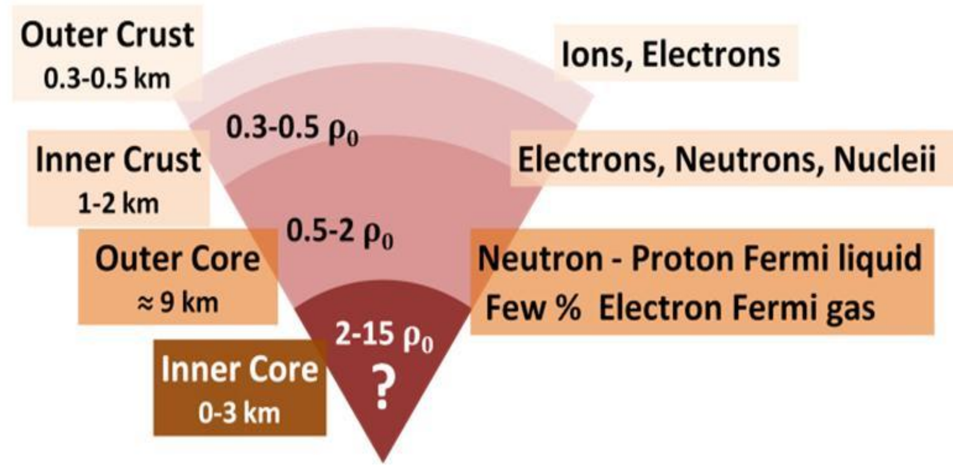


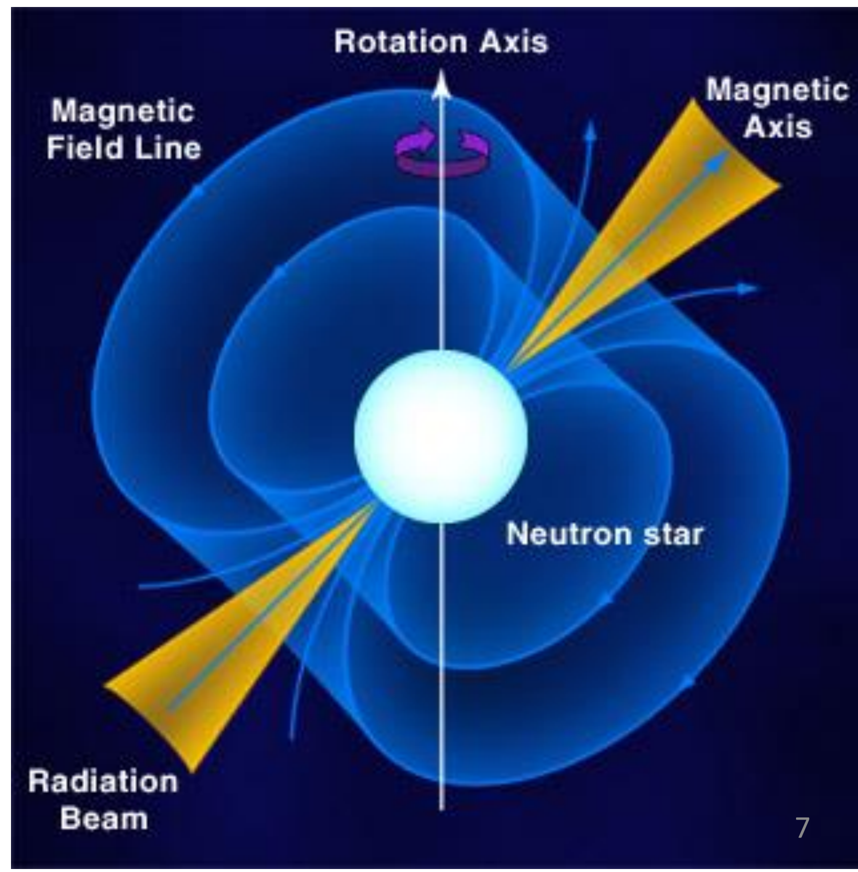
outer crust 0.3-0.5 km
ions, electrons
$0.3\text{-}0.5\ \rho_0$
inner crust 1-2 km
electrons, neutrons, nuclei
$0.5\text{-}2.0\ \rho_0$
$>2.0\ \rho_0$
outer core ~ 9 km
neutron-proton Fermi liquid
few % electron Fermi gas
inner core 0-3 km
?

NS characteristics:

- Masses $\lesssim 2M_\odot$
- Radii $\approx 11 - 13$ km
- Spin frequencies $\lesssim$ kHz
- Temperatures $\lesssim$ keV
- Strong magnetic fields up to 10^{15}G

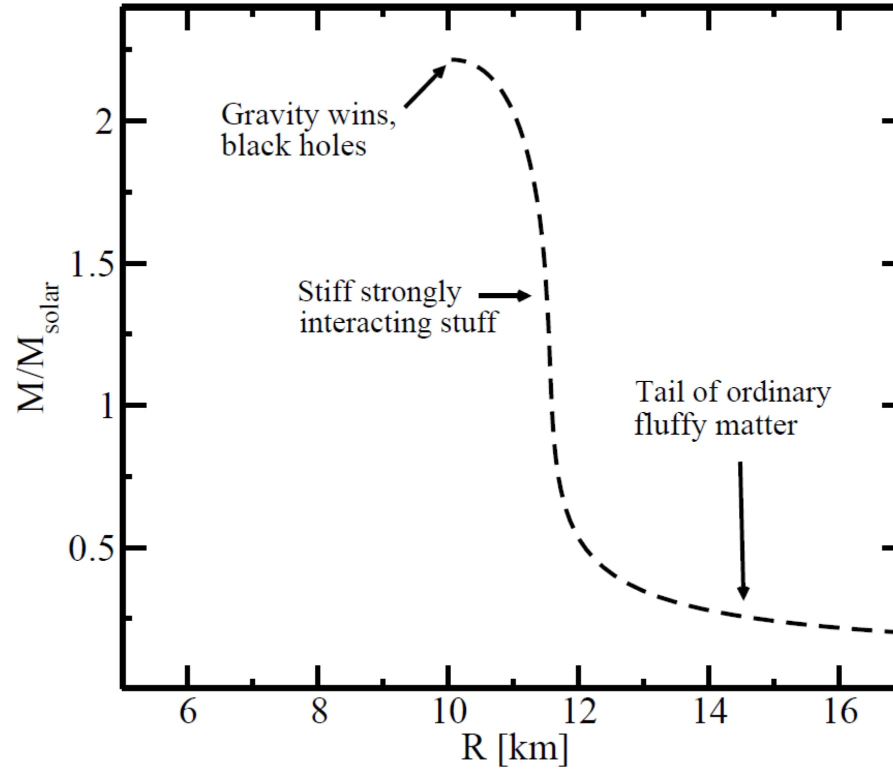
Unique laboratory for strong interaction physics: Density in NS cores high enough to probe nuclear matter well beyond saturation density





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)

$$\frac{dM(r)}{dr} = 4\pi r^2 \varepsilon(r),$$

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

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

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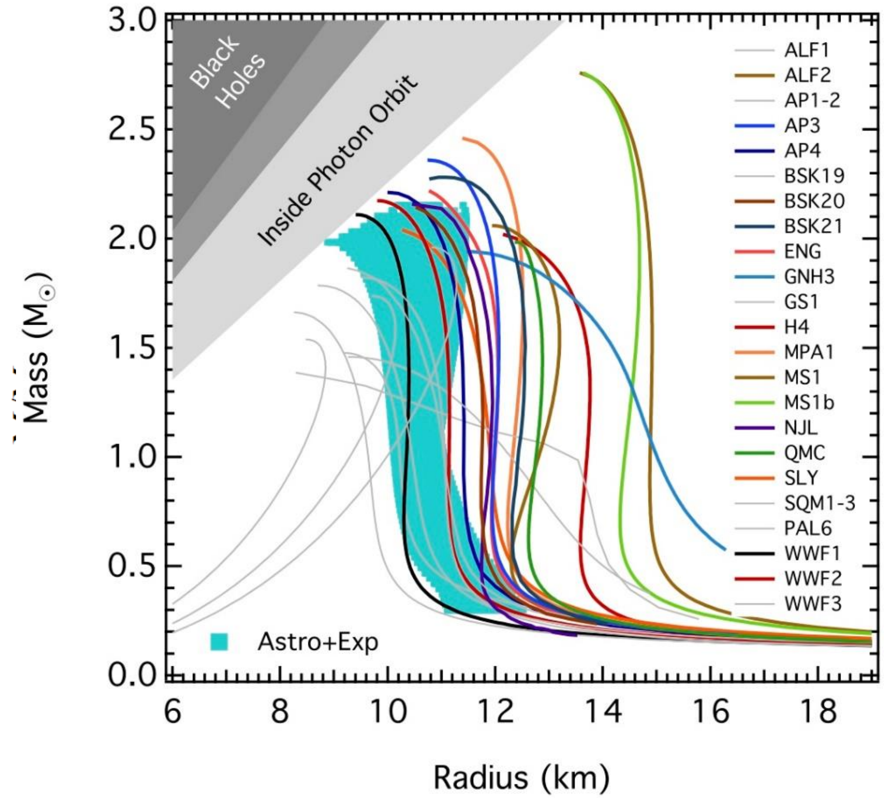

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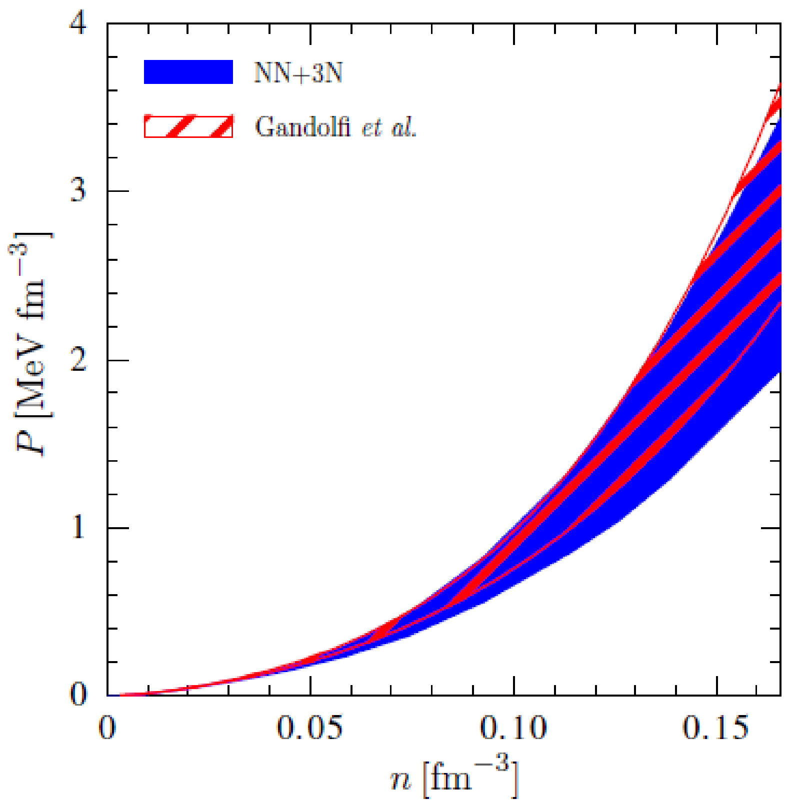
$$\varepsilon(p) \Rightarrow M(R)$$

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?

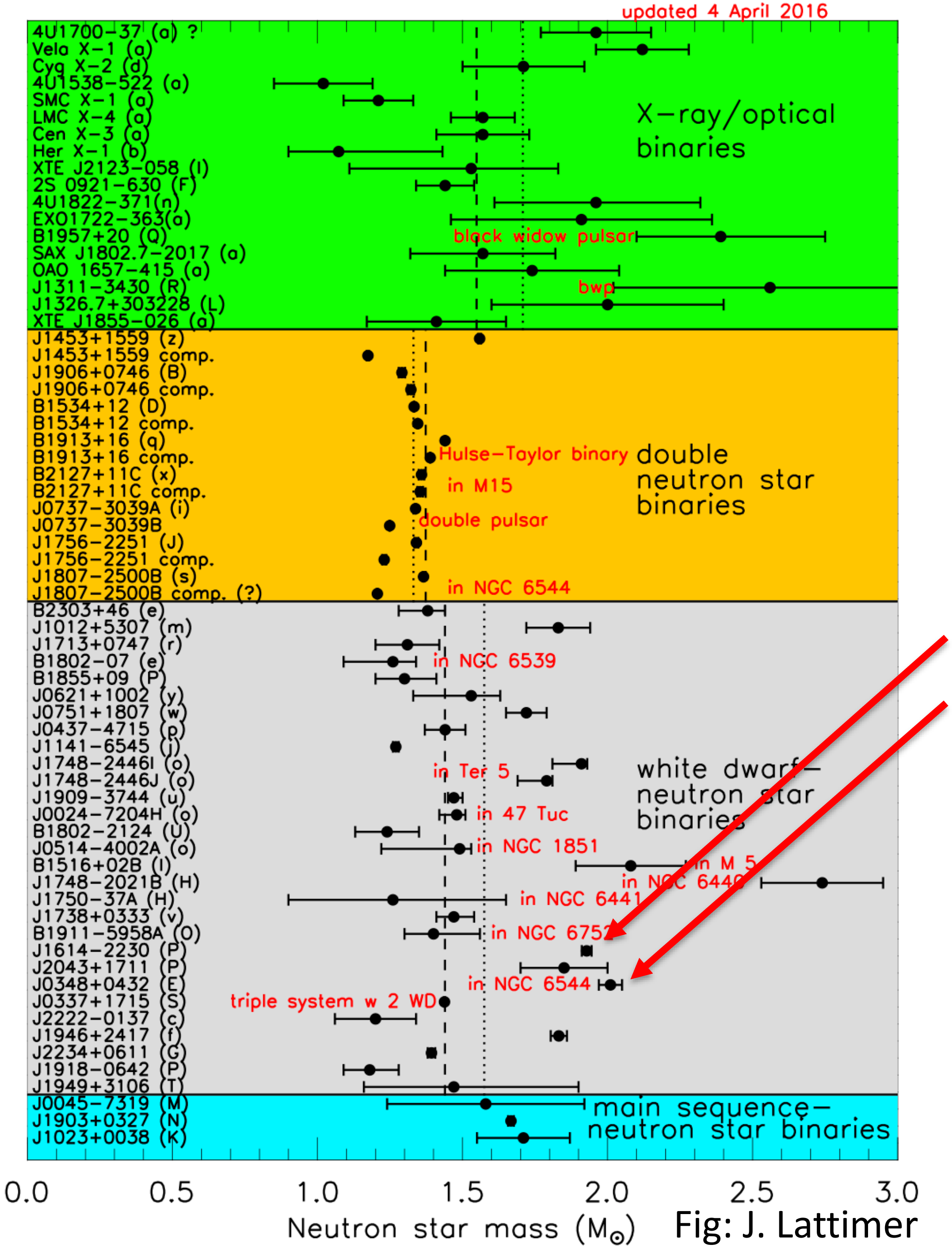


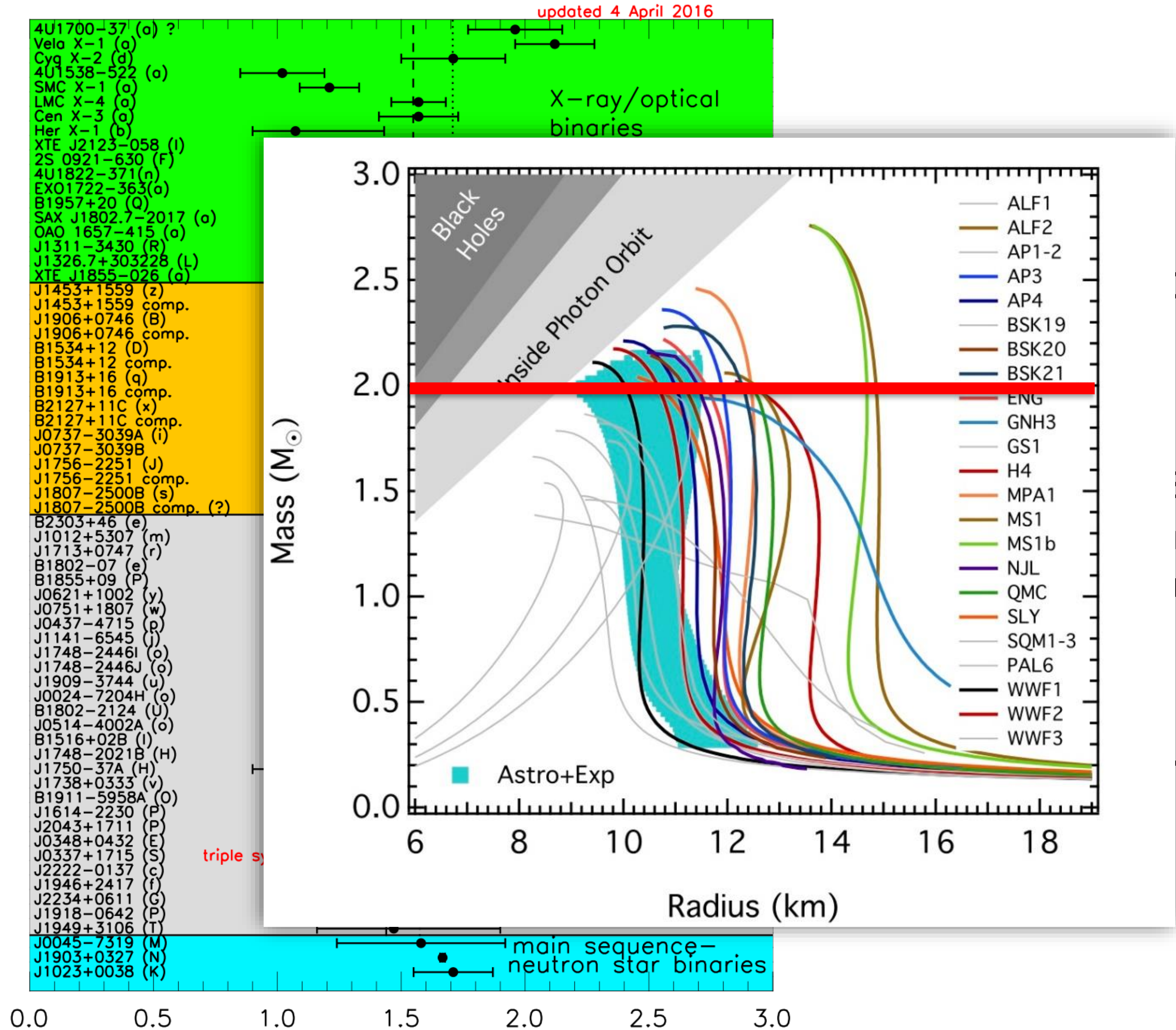
Fig: J. Lattimer

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

Demorest et al., Nature 467 (2010)

Antoniadis et al., Science 340 (2013)

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



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of two-

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re 467 (2010)

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$2M_\odot$

Fig: J. Lattimer

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

- Cooling of thermonuclear X-ray bursts provide radii to ~ 400m [Nättilä et al., Astronomy & Astrophysics 608 (2017), …]
- With NICER mission, launched 3 June 2017, X-ray pulse profiling → Radius of a single star (perhaps) to ~ 200m

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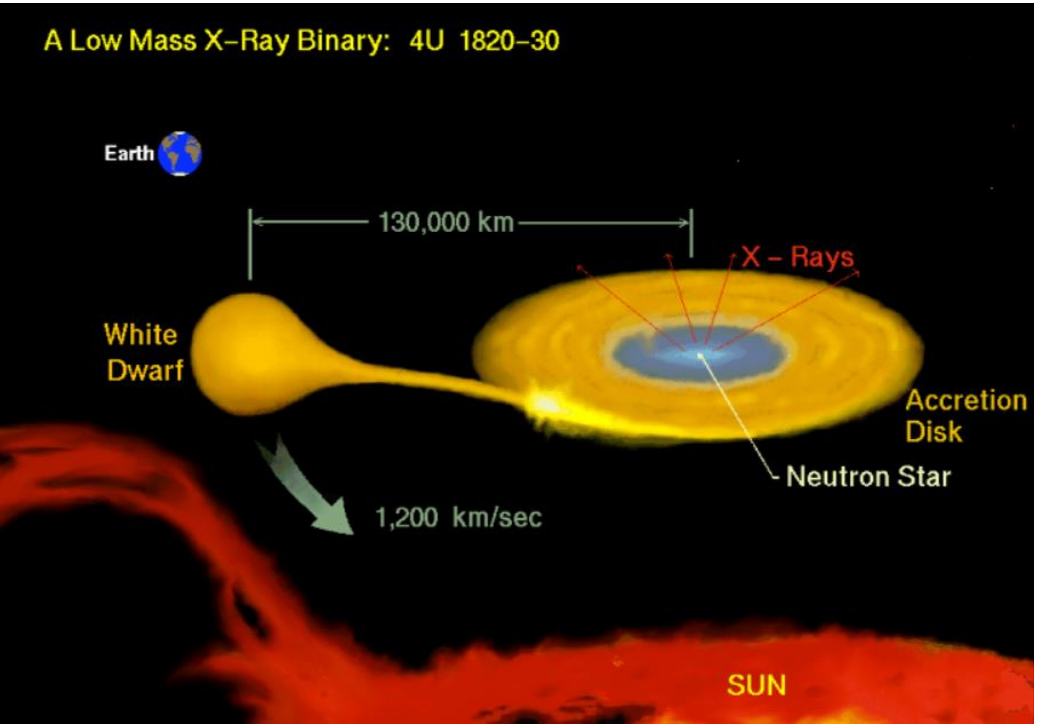
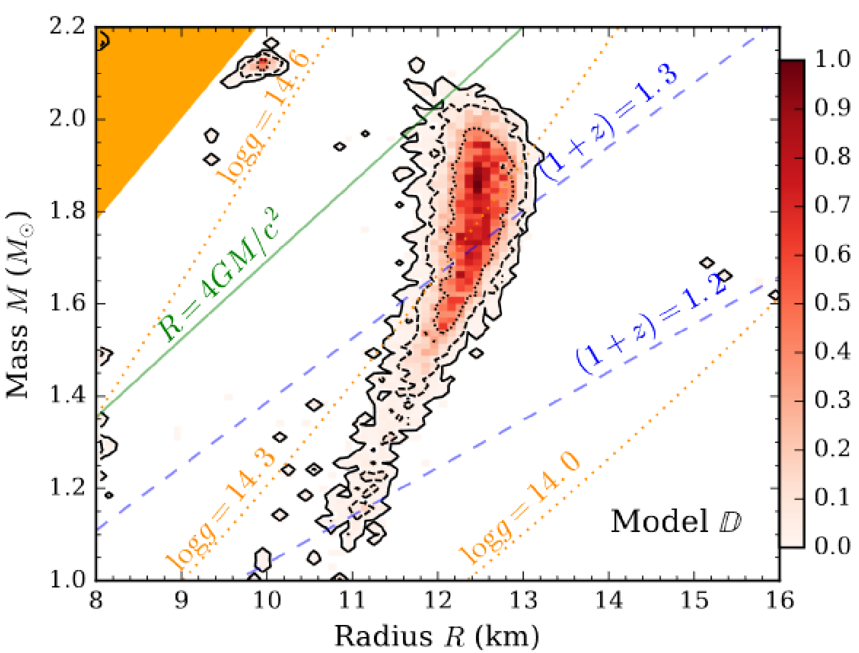
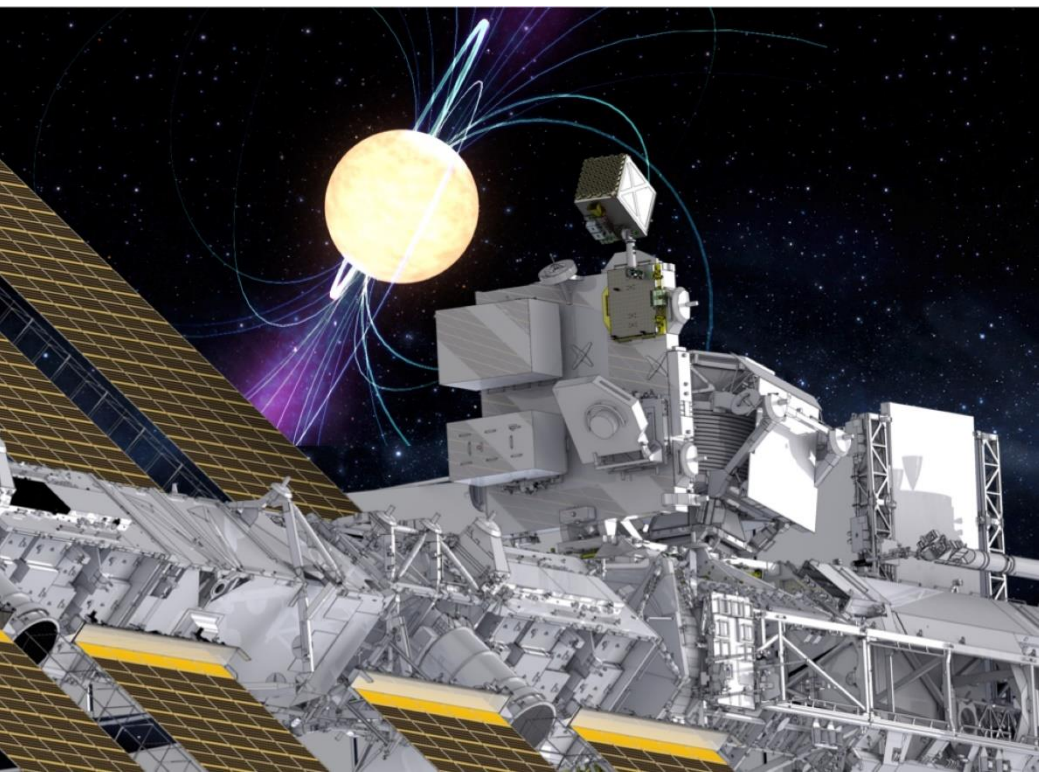
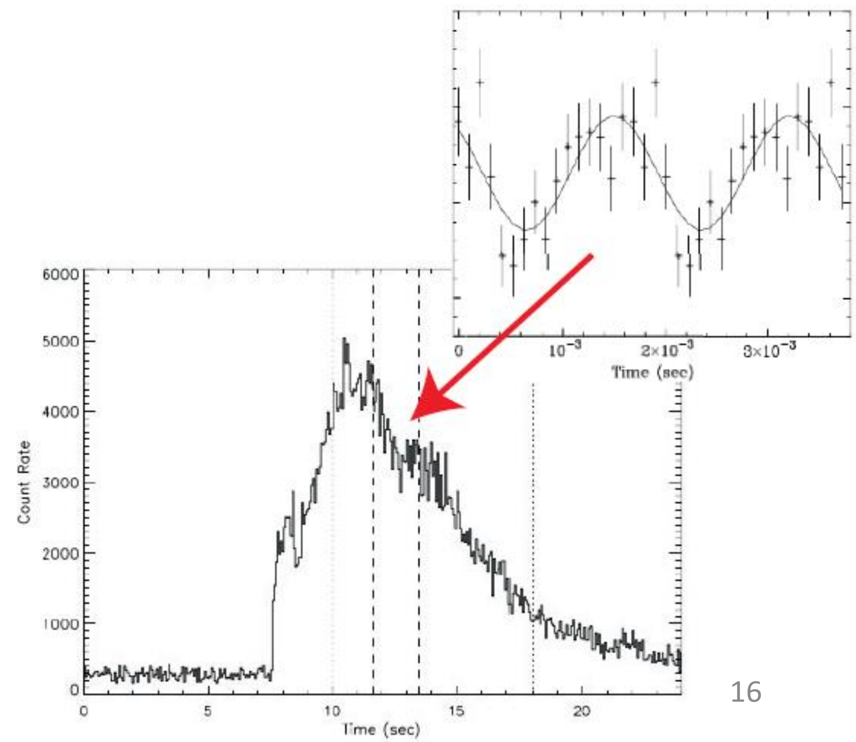




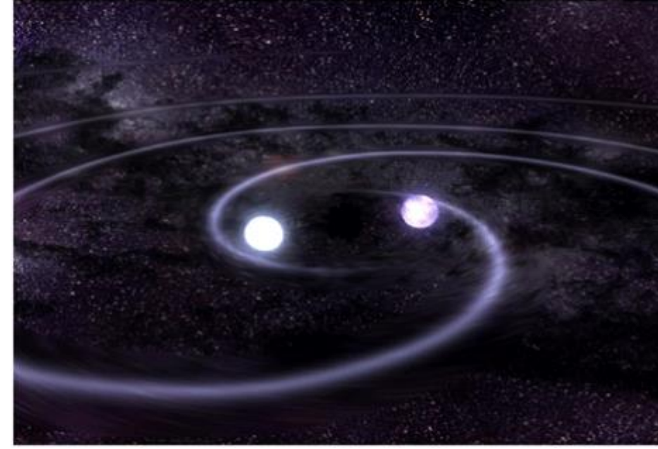
Radius measurements more problematic, but progress through observation of X-ray emission:

- Cooling of thermonuclear X-ray bursts provide radii to $\sim 400\text{m}$ [Nättilä et al., Astronomy & Astrophysics 608 (2017), …]
- With NICER mission, launched 3 June 2017, X-ray pulse profiling → Radius of a single star (perhaps) to $\sim 200\text{m}$



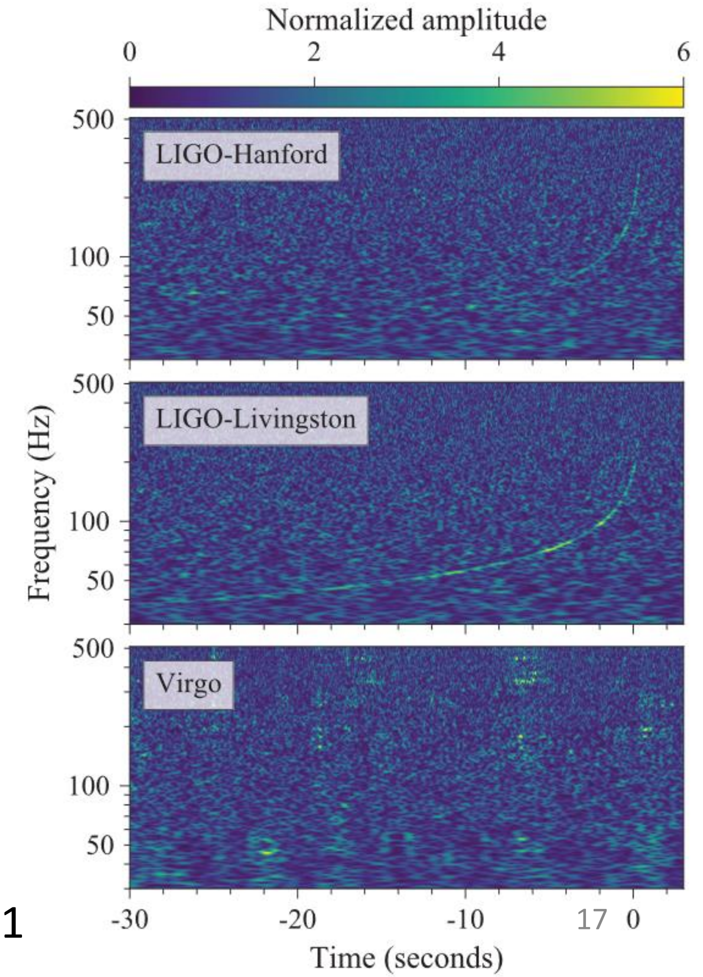


Gravitational wave breakthrough: LIGO and Virgo observation of NS merger 130 million ly away!



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); 1805.11581

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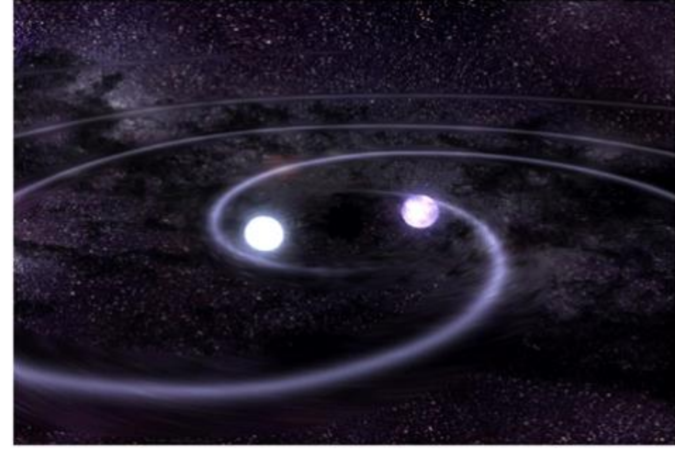

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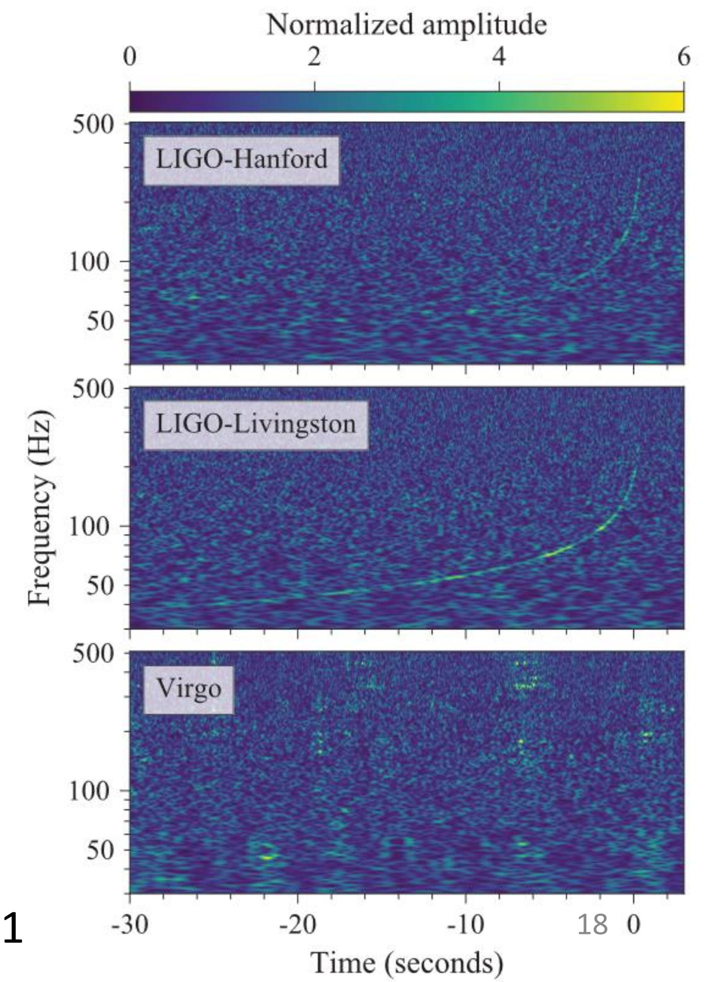
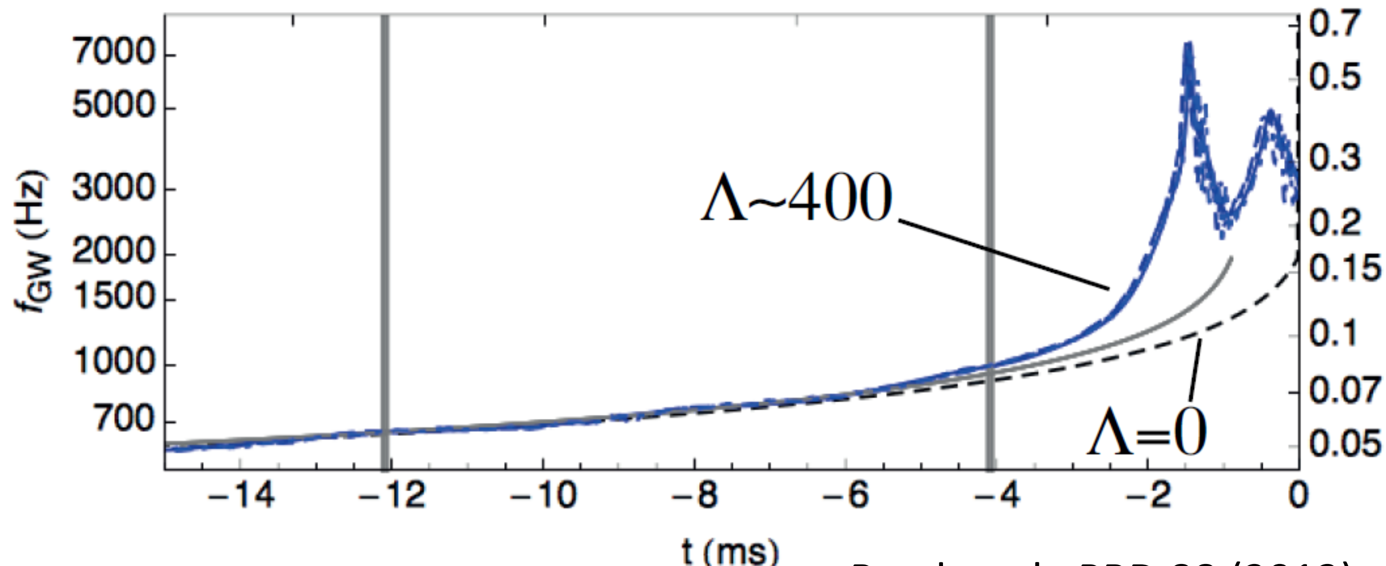


LIGO and Virgo collaborations, PRL 119 (2017); 1805.11581

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

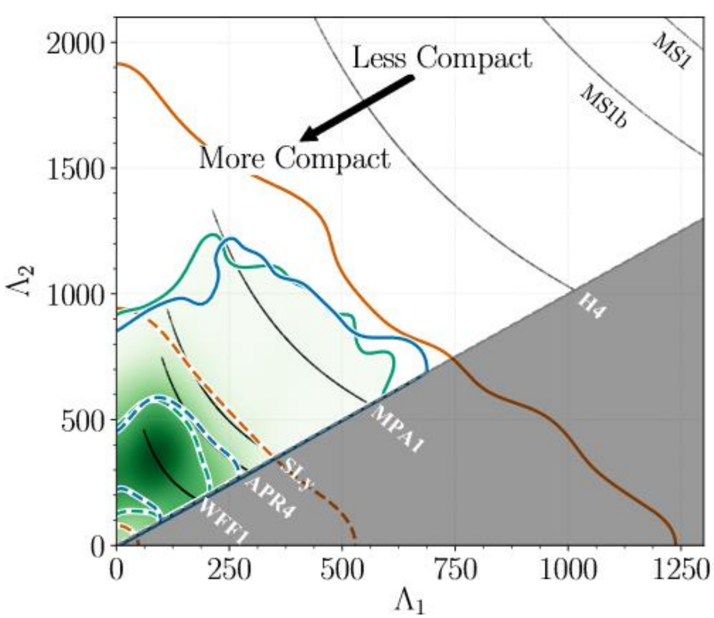


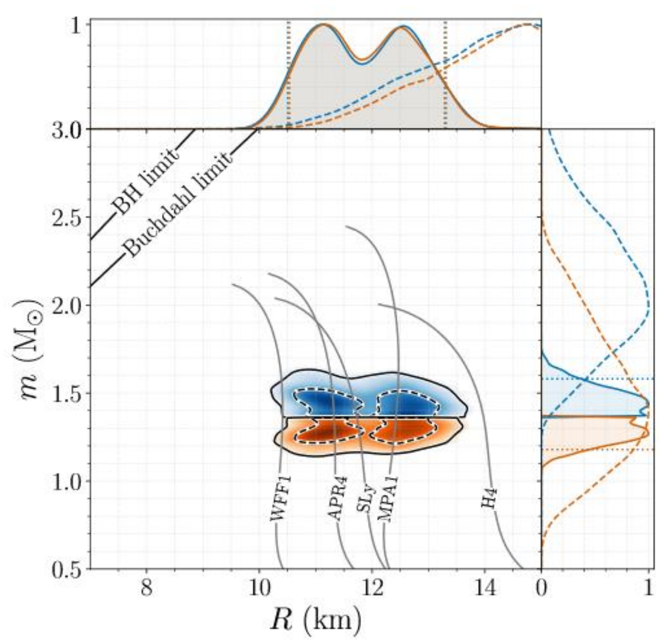
Read et al., PRD 88 (2013)

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

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

Recent LIGO bound $70 < \Lambda(1.4 M_{\odot}) < 580$ at 90% credence using low spin prior [LIGO and Virgo, arXiv:1805.11581]





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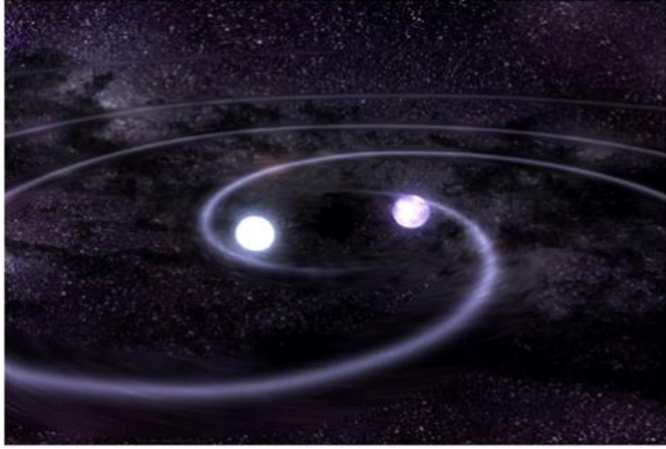

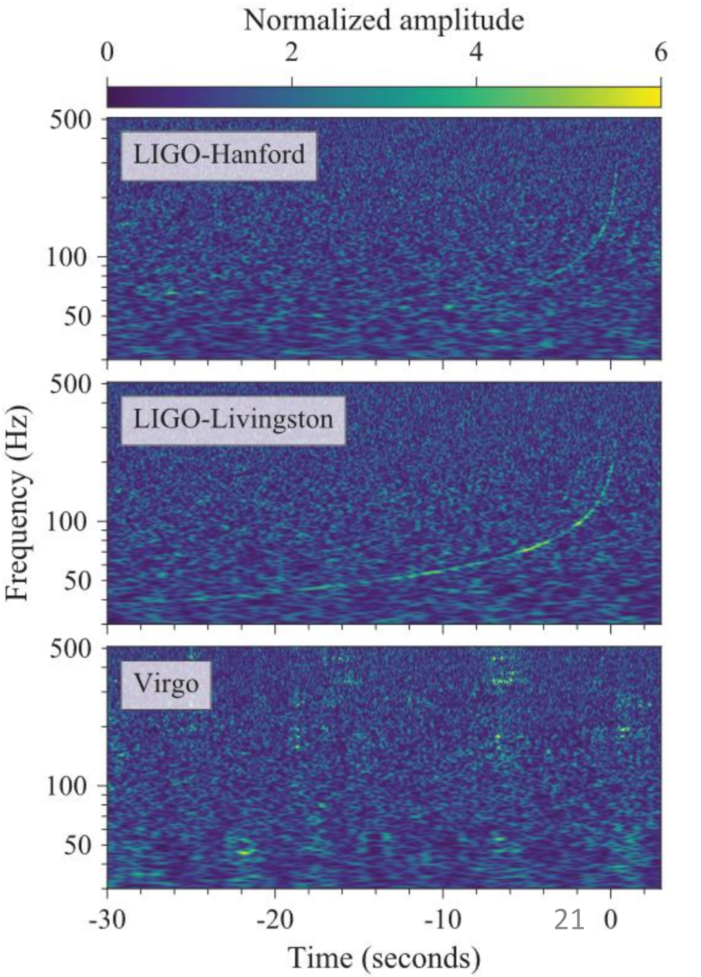

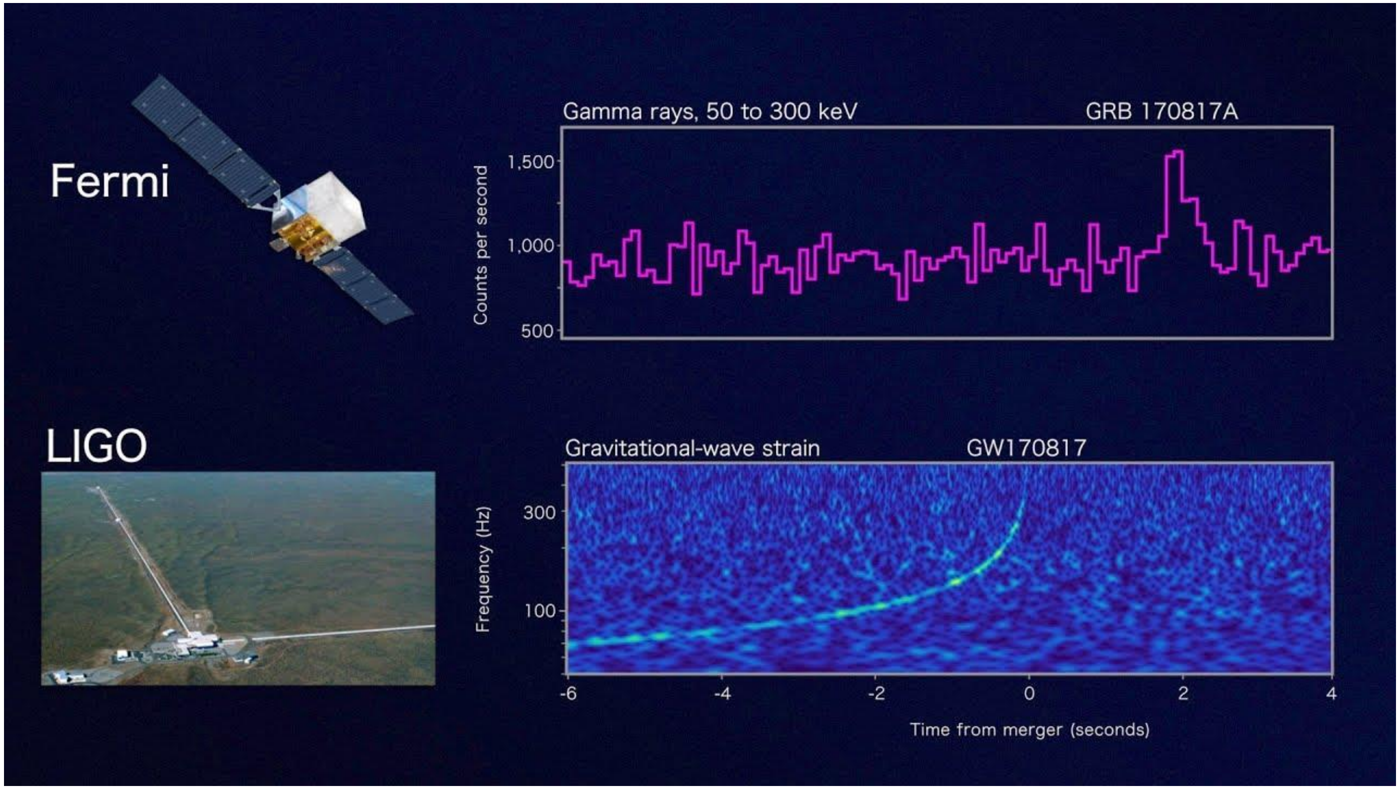

EM counterpart: short gamma ray burst detected 1.7s after GW measurement, followed by an optical signal

- 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)]

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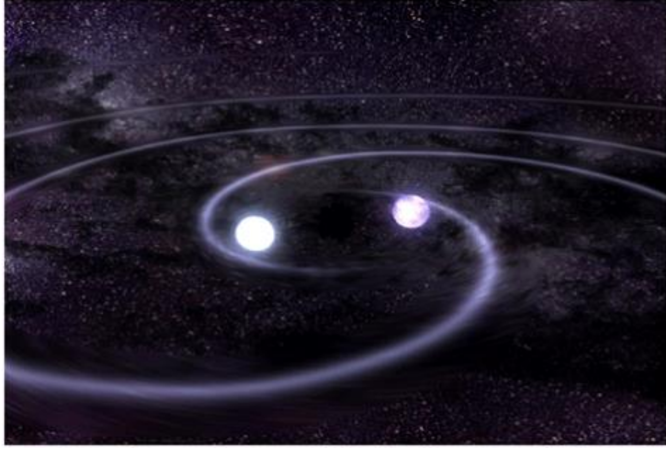

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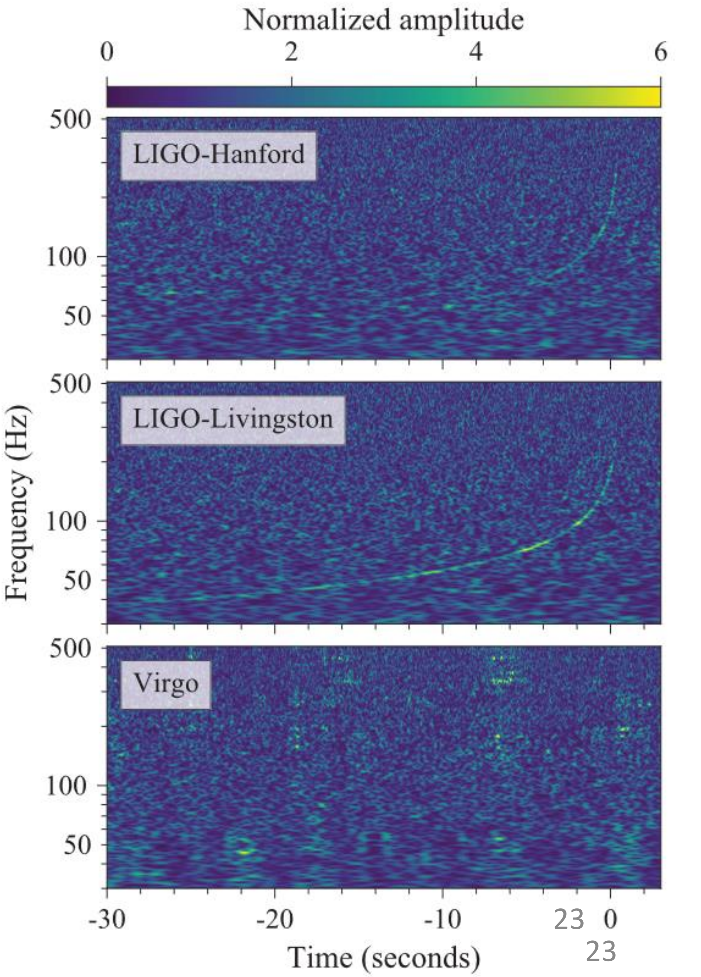
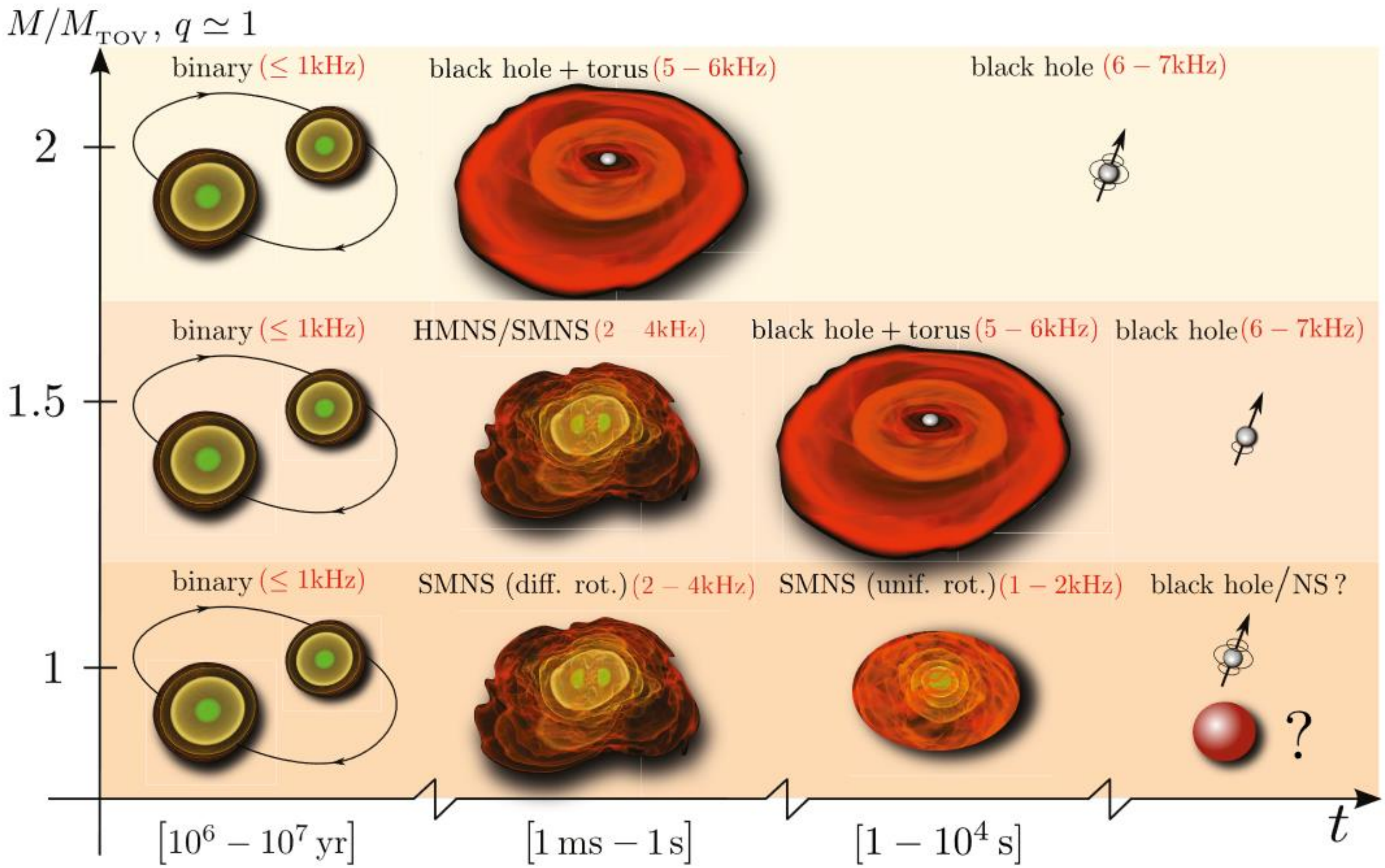
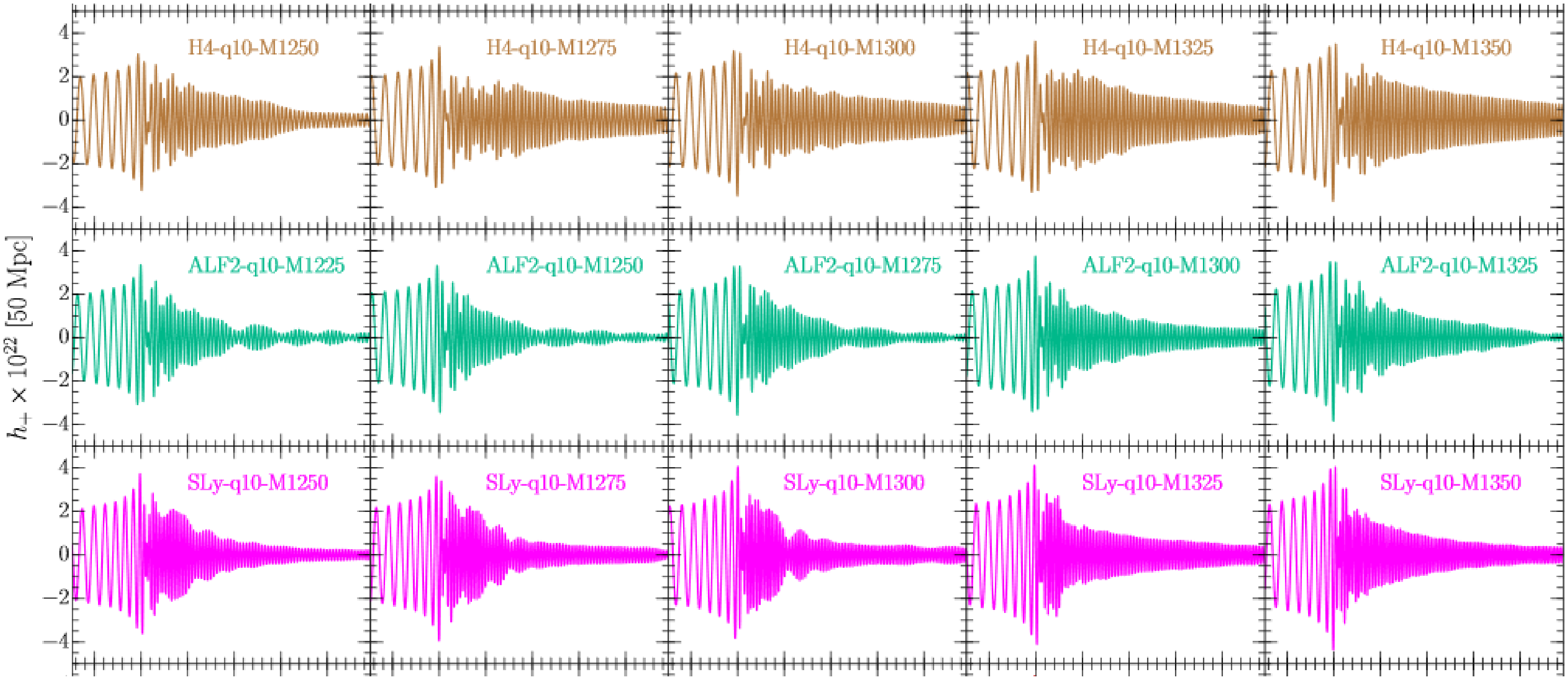


Ringdown pattern: Unlike in BH mergers, expect a complex period of relaxation characterized by GW spectrum sensitive to both initial NS masses and the EoS



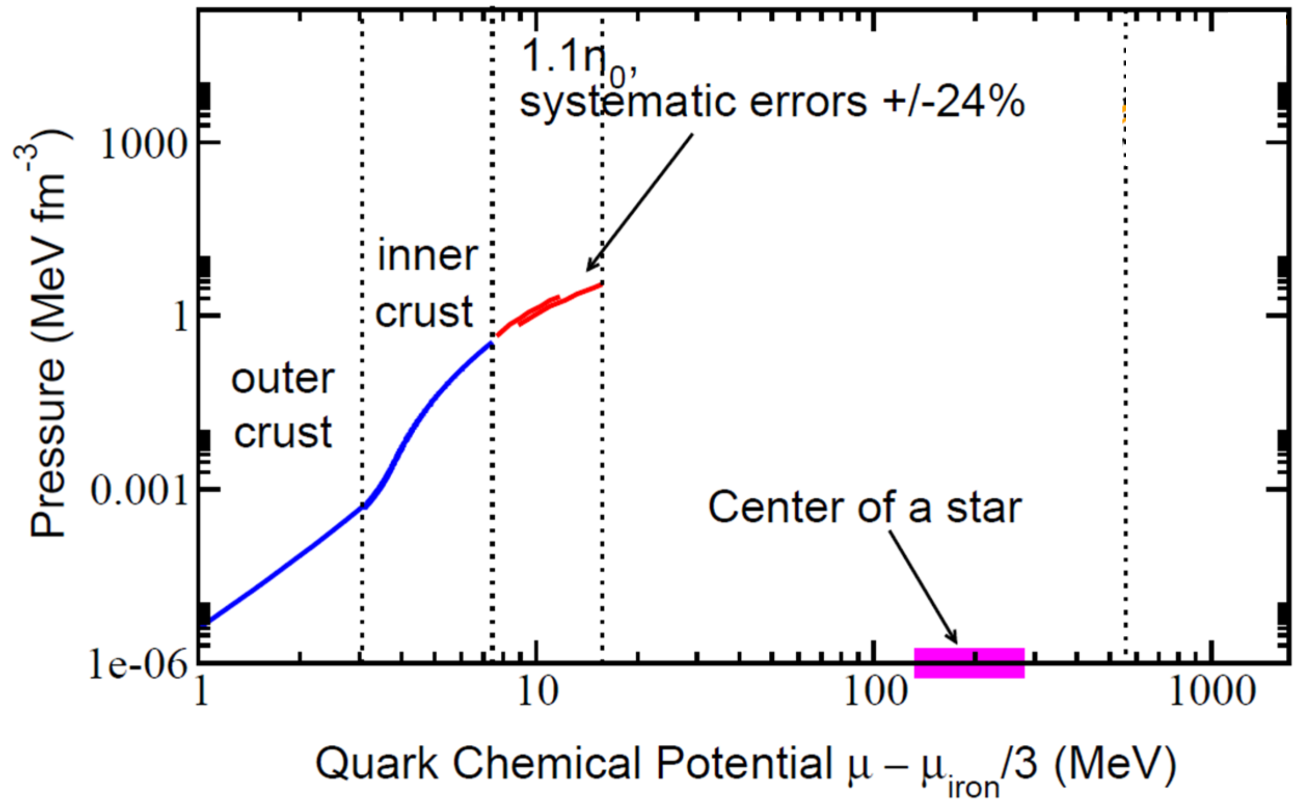
Baiotti, Rezzolla, Rept.Prog.Phys. 80 (2017)

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



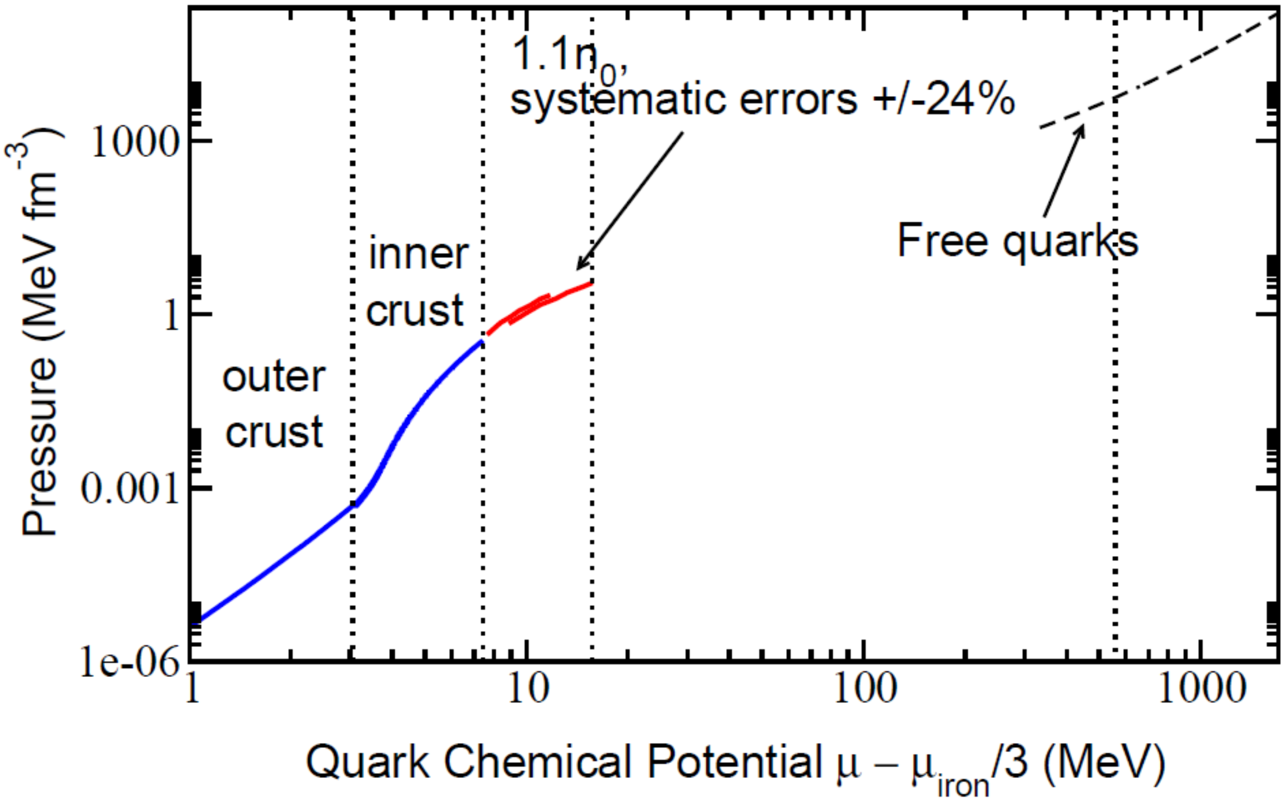
Takami, Rezzolla, Baiotti, PRD 91 (2015)

EoS – theoretical limits



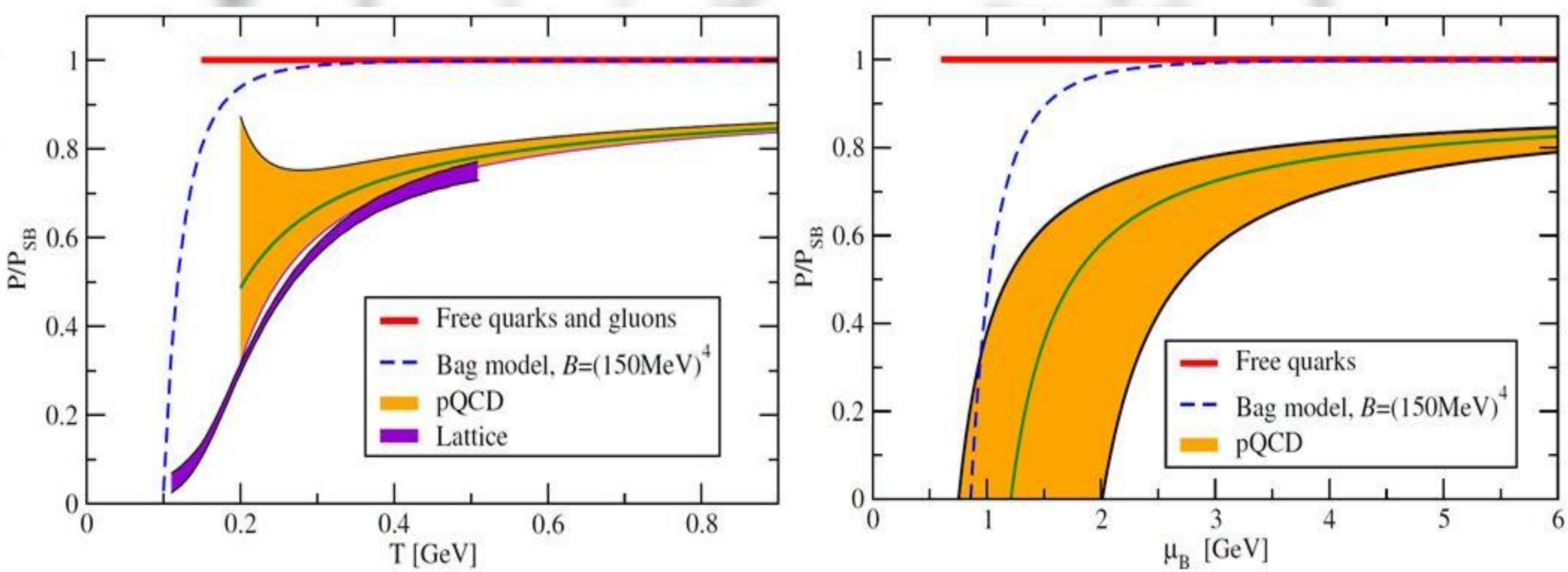
Low-density behavior of EoS well known from nuclear theory side. Challenges begin close to saturation density:

- 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)]

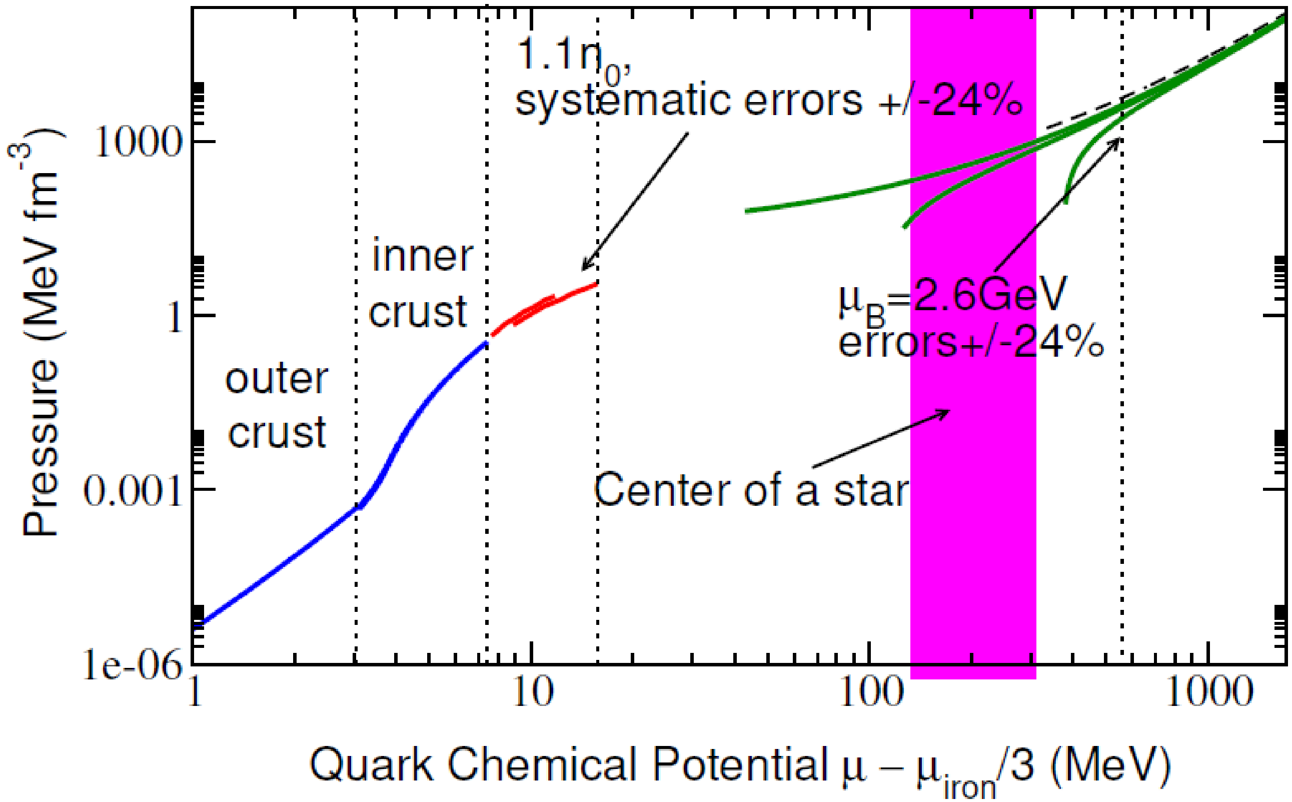


Asymptotic freedom of QCD ⇒ High-density limit from a non-interacting theory. However,…

- 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

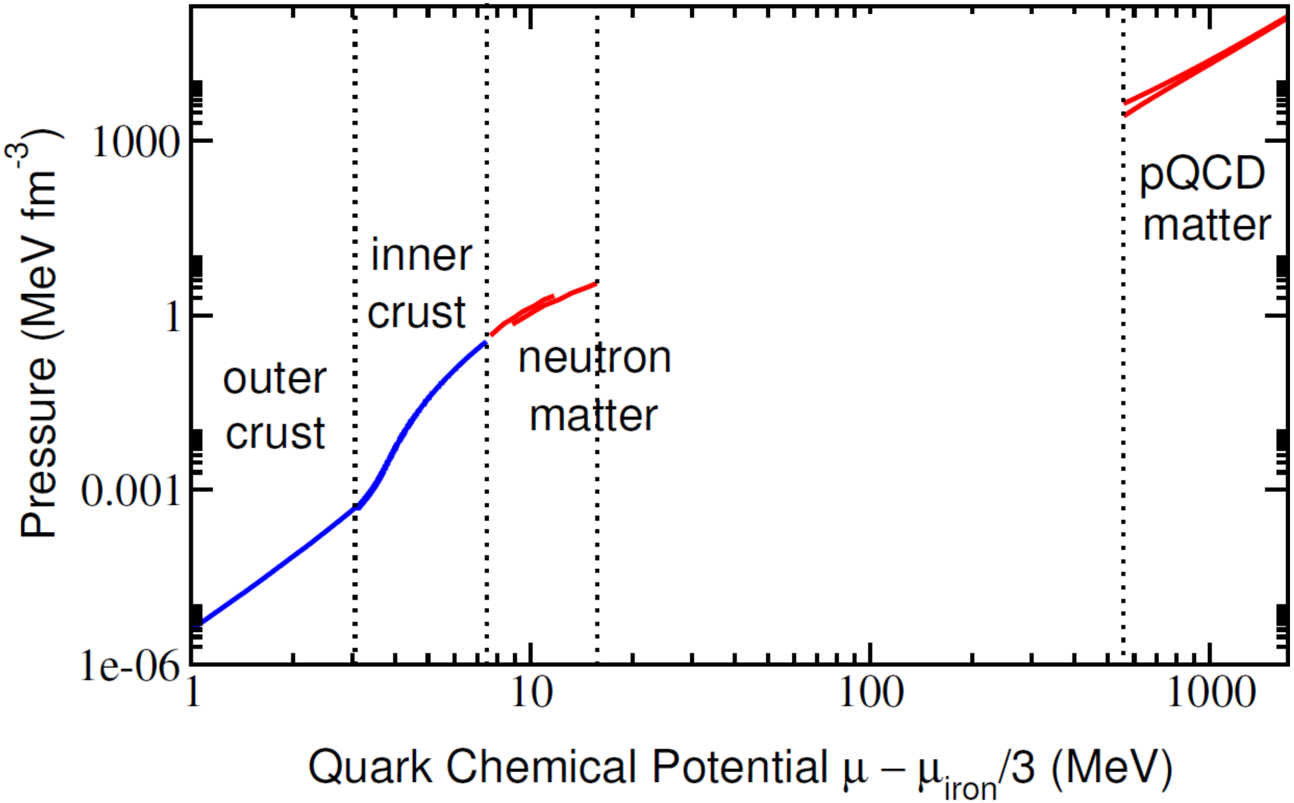


Recent improvement: First part of four-loop pressure at $T = 0$ derived: $p_{4-\mathrm{loop}} \ni -\frac{11}{12}\frac{N_c d_A}{(2\pi)^3}\alpha_s m_\infty^4 \ln^2 \alpha_s$ [Gorda, Kurkela, Romatschke, Säppi, Vuorinen, arXiv:1806.xxxxx] – cf. talk by Matias Säppi



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

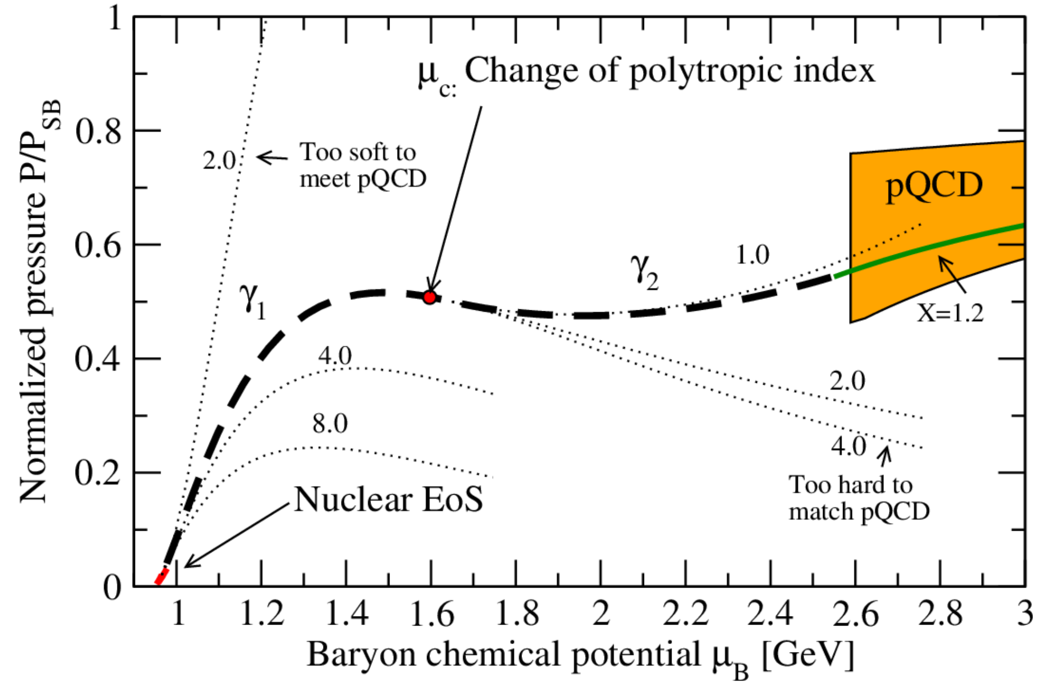
Interpolation – with and without observational constraints

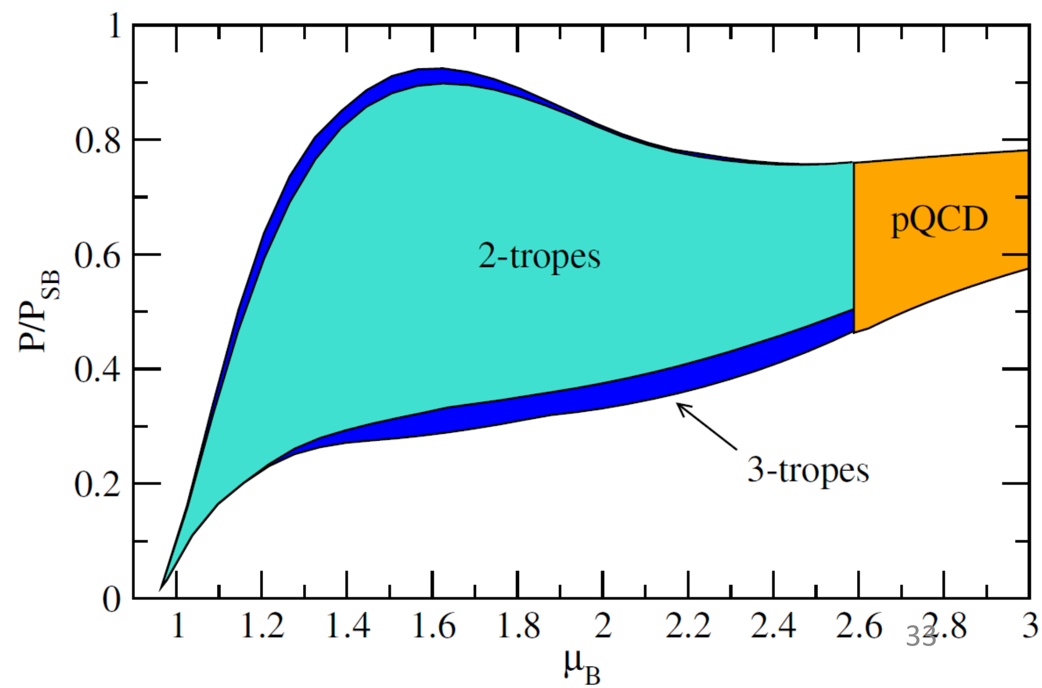
Interpolate EoS using piecewise polytropic form, $p_i(n) = \kappa_i n^{\gamma_i}$, varying all parameters (γ_i, μ_i^{match})

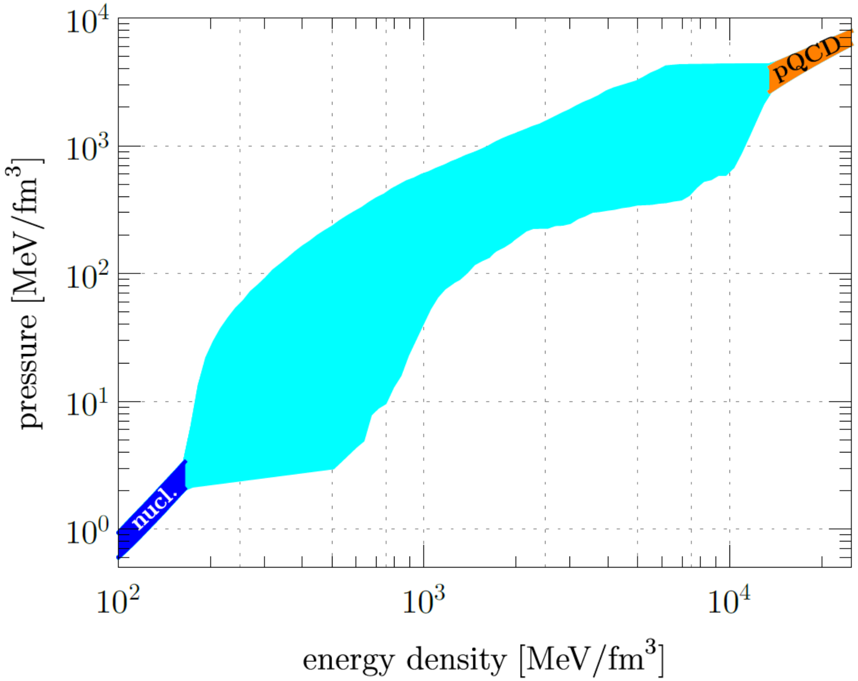
Require:

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

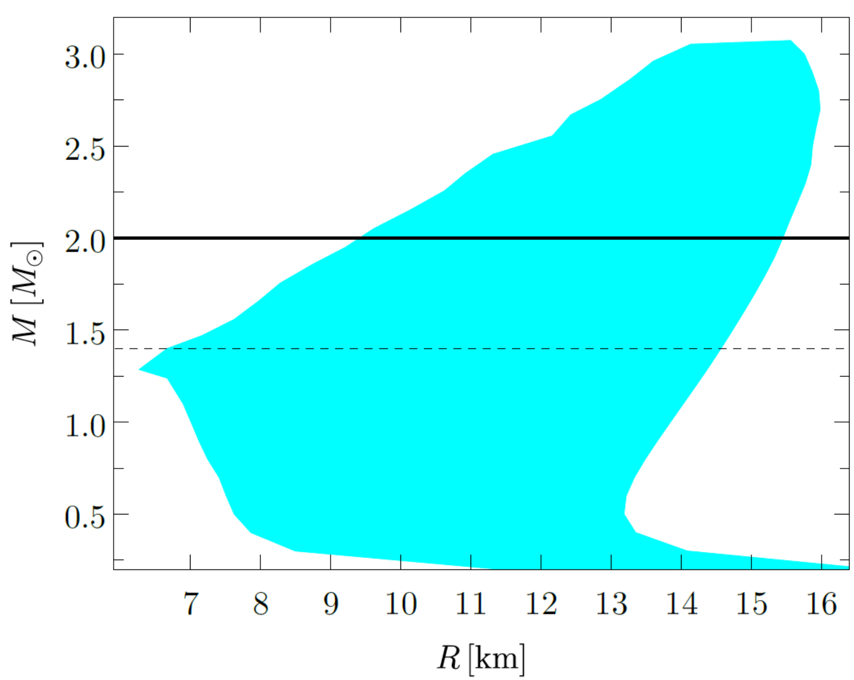
[Kurkela et al., ApJ 789 (2014)]



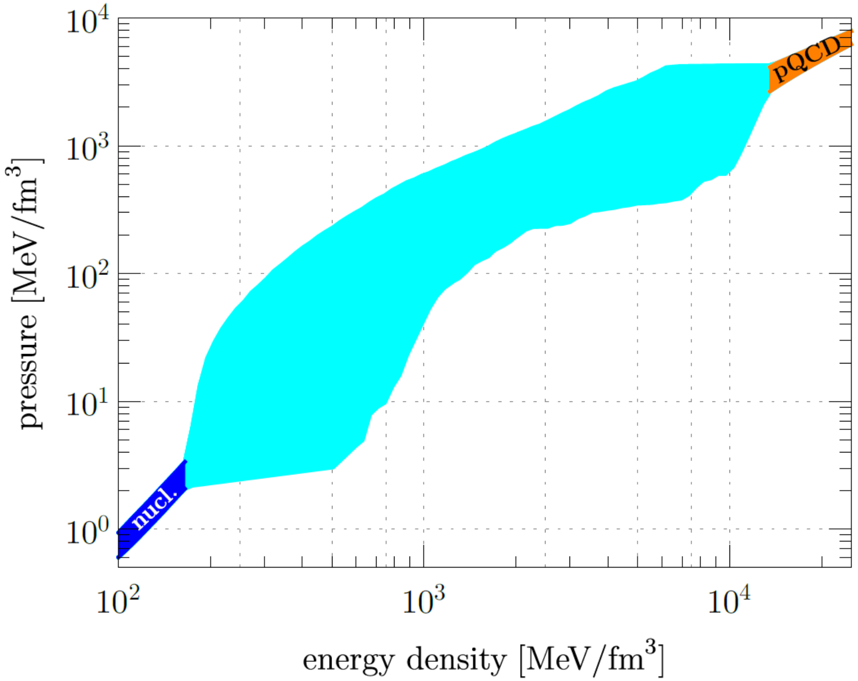


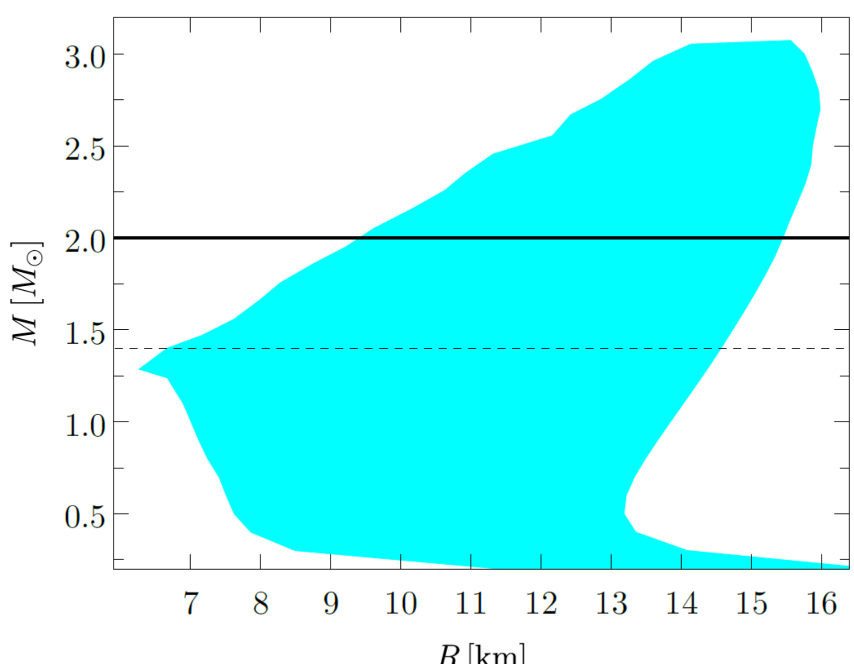


Quadrutropic interpolation, using close to 200.000 randomly generated EoSs



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

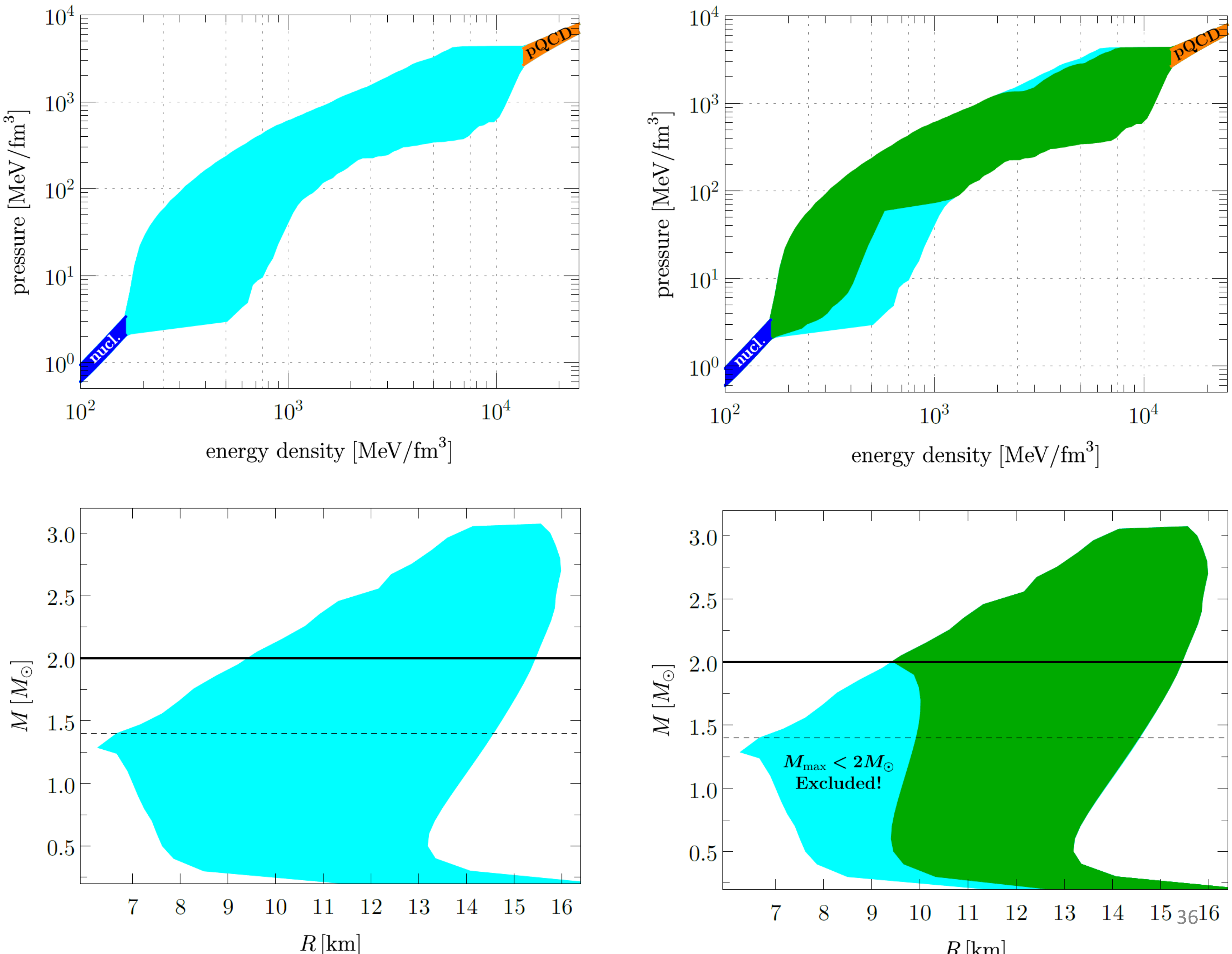


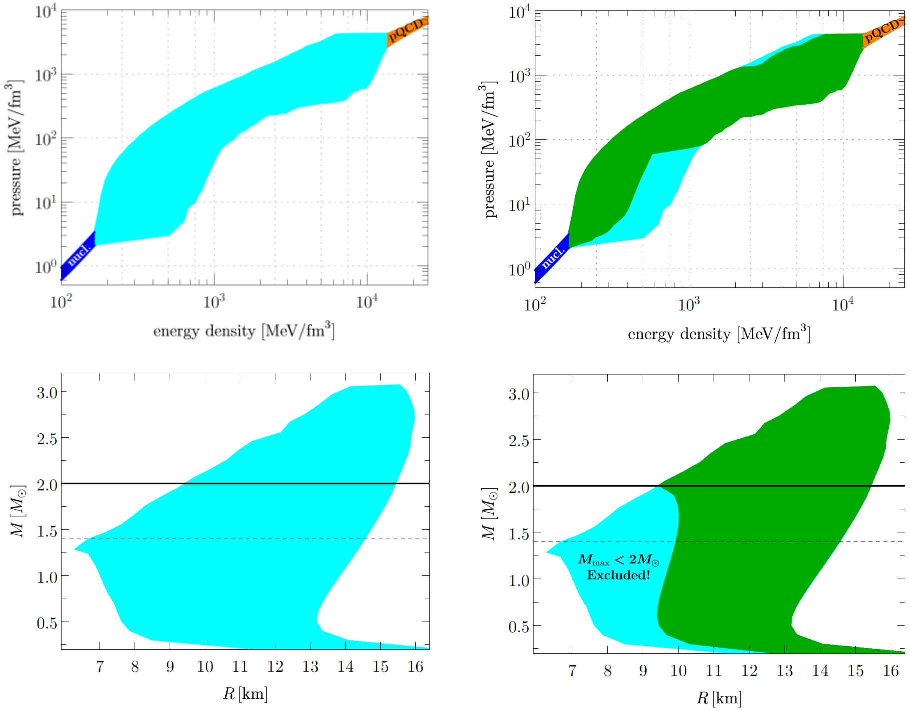


Implement then two-solar-mass constraint: Accept only EoSs that fulfill $M_{\max} > 2M_\odot$

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

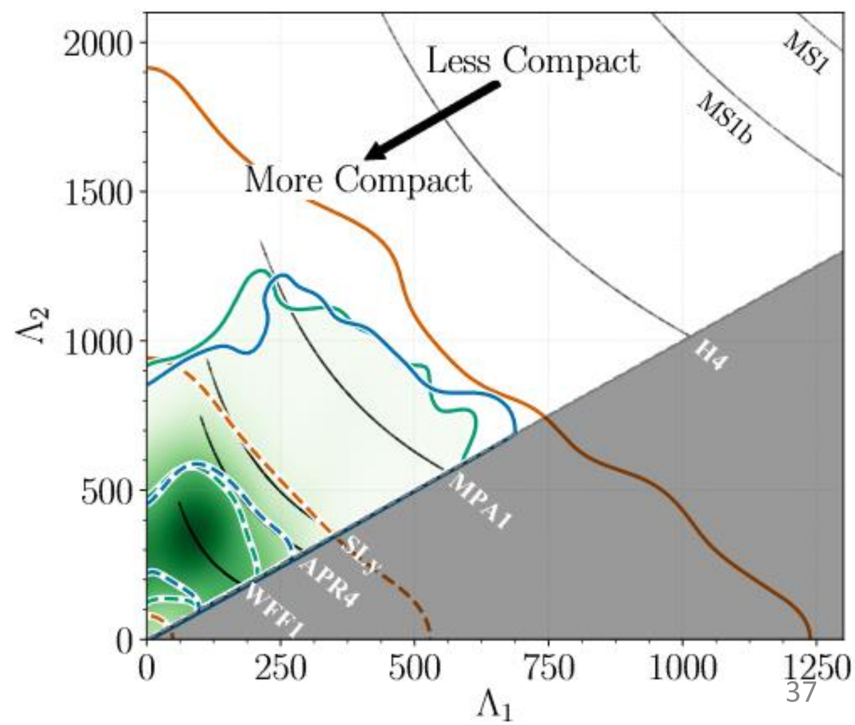
- Excluded: twin stars [e.g. Alvarez-Castillo, Blaschke, PRC96 (2017)], strange quark stars [e.g. Weber et al., IAU 291 (2013)]

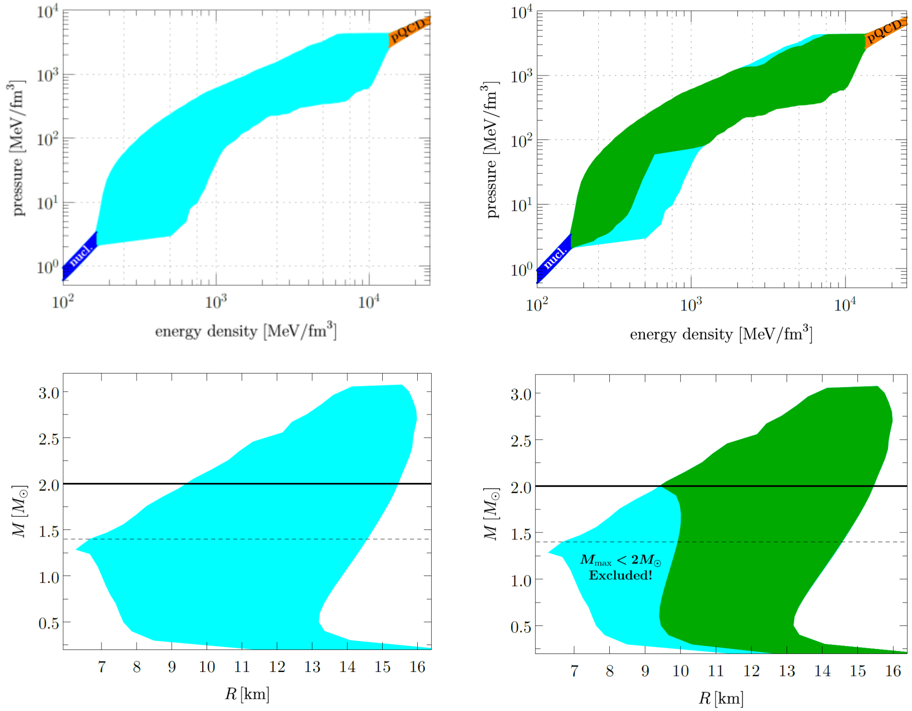

pressure [MeV/fm^3]
energy density [MeV/fm^3]
nucl.
pQCD
$M\,[M_\odot]$
R [km]
$M_{max} < 2M_\odot$
Excluded!



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

- $70 < \Lambda(1.4M_\odot) < 580$ at 90% credence

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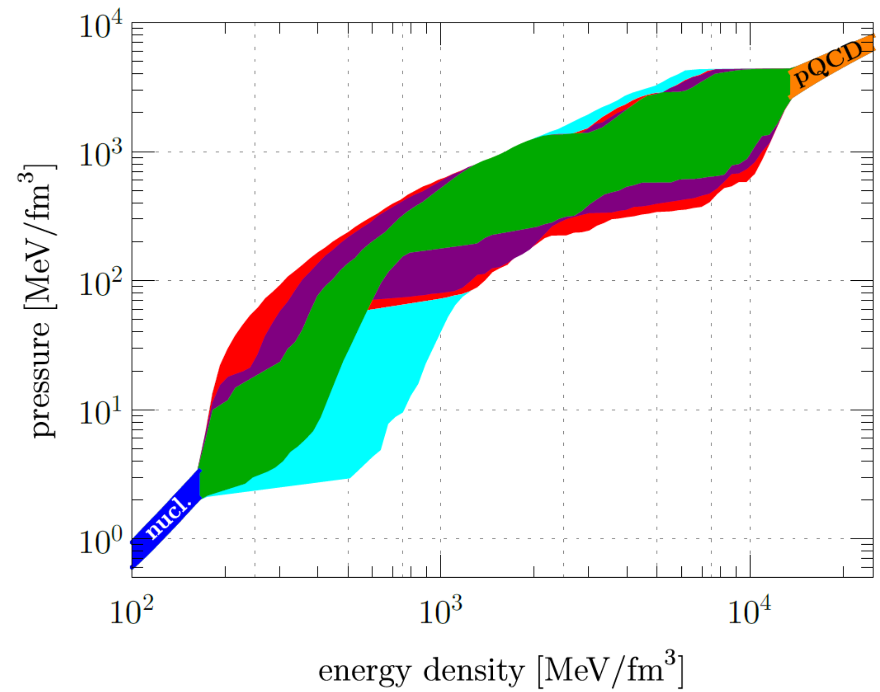
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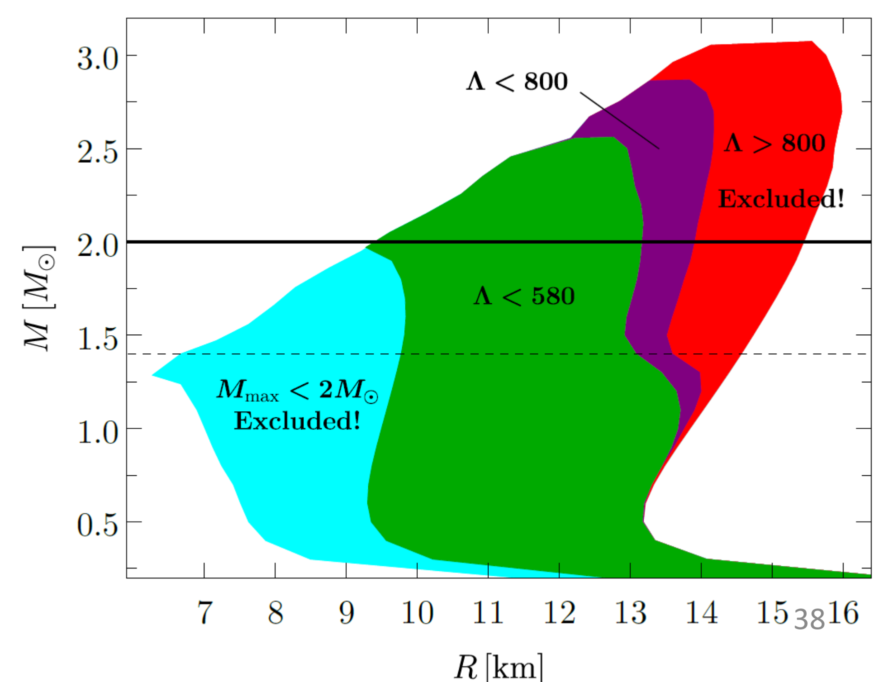
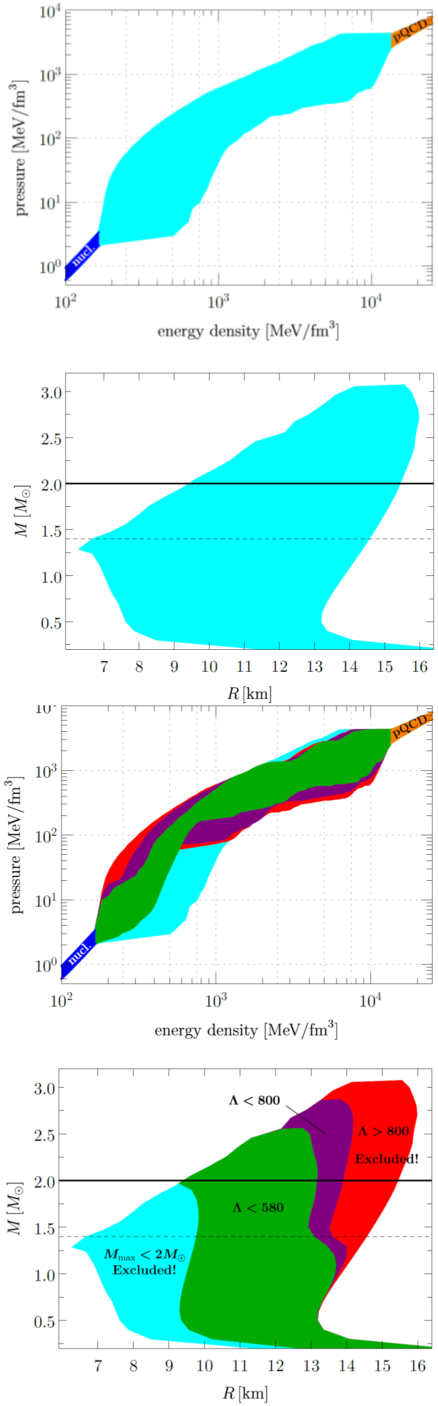
nucl.
pQCD

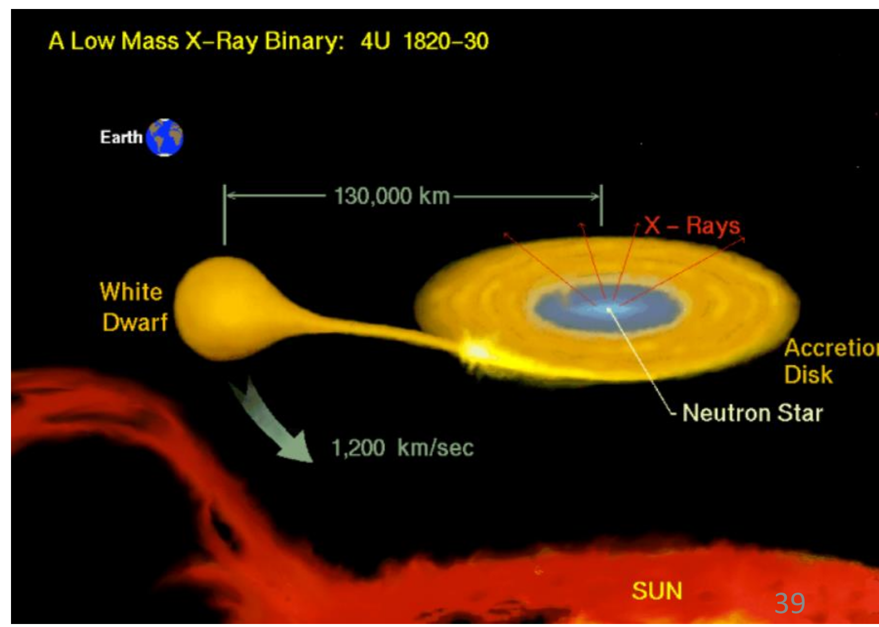

M [$M_\odot$]
R [km]
$\Lambda < 800$
$\Lambda > 800$
Excluded!
$\Lambda < 580$
$M_{max} < 2M_\odot$
Excluded!

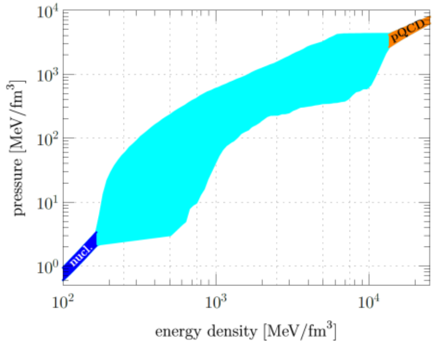


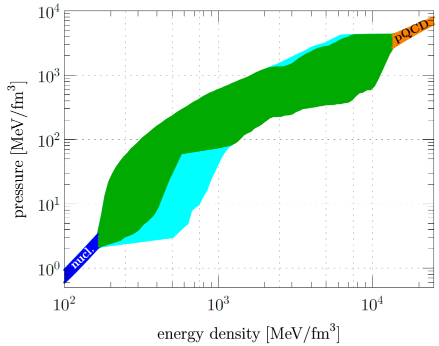
Recent result of Nättilä et al., Astronomy & Astrophysics 608 (2017):

$R(1.9M_\odot) = 12.4 \pm 0.4$ km with 1σ credence

Caveat: mass measurement of the star in question still rather uncertain




pressure [MeV/fm^3]
energy density [MeV/fm^3]
nucl.
pQCD


pressure [MeV/fm^3]
energy density [MeV/fm^3]
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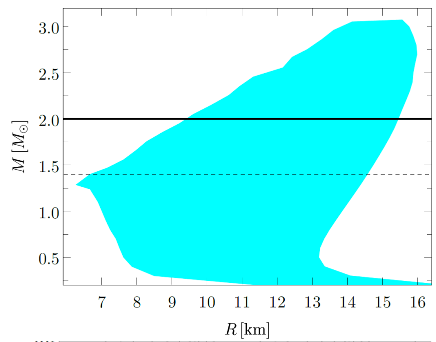
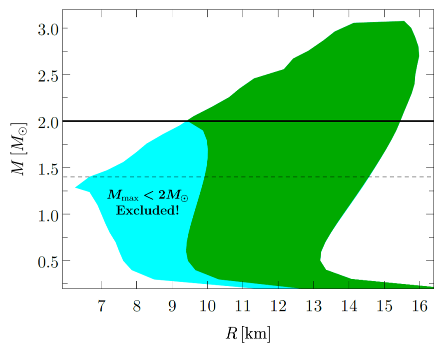
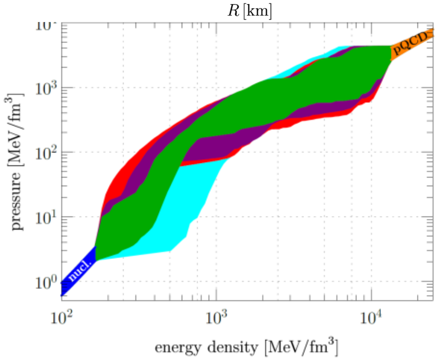
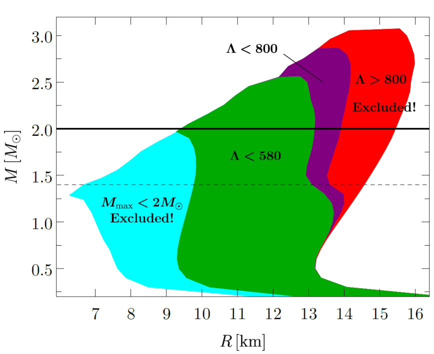
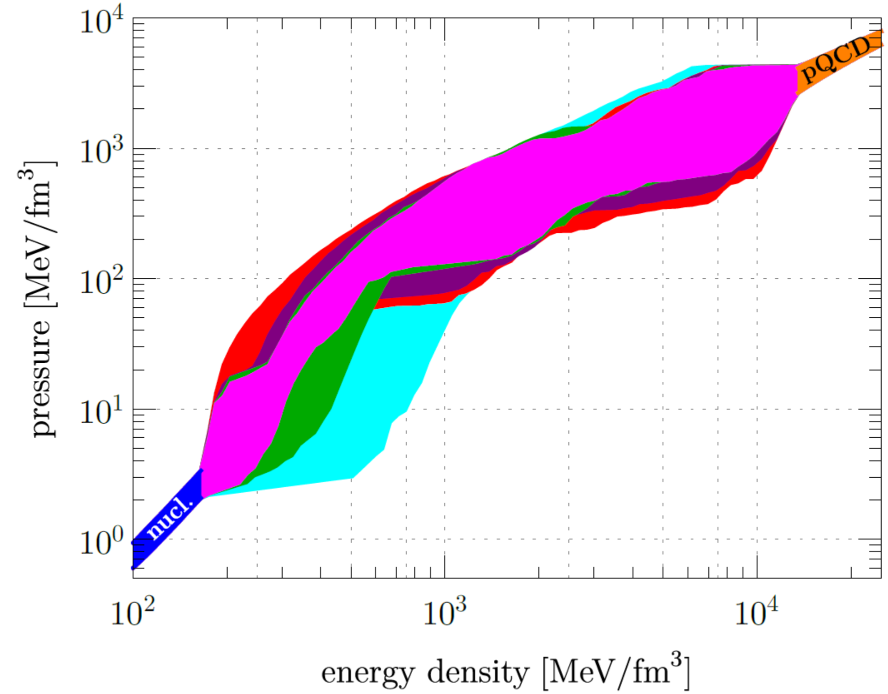
pQCD

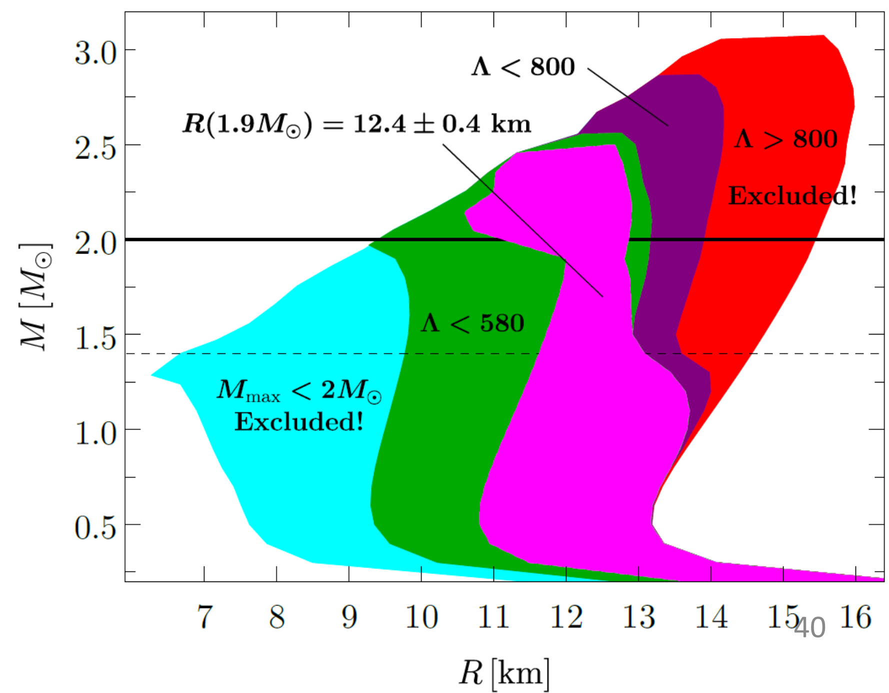

M [$M_\odot$]
R [km]


M [$M_\odot$]
R [km]
$M_{max} < 2M_\odot$ Excluded!

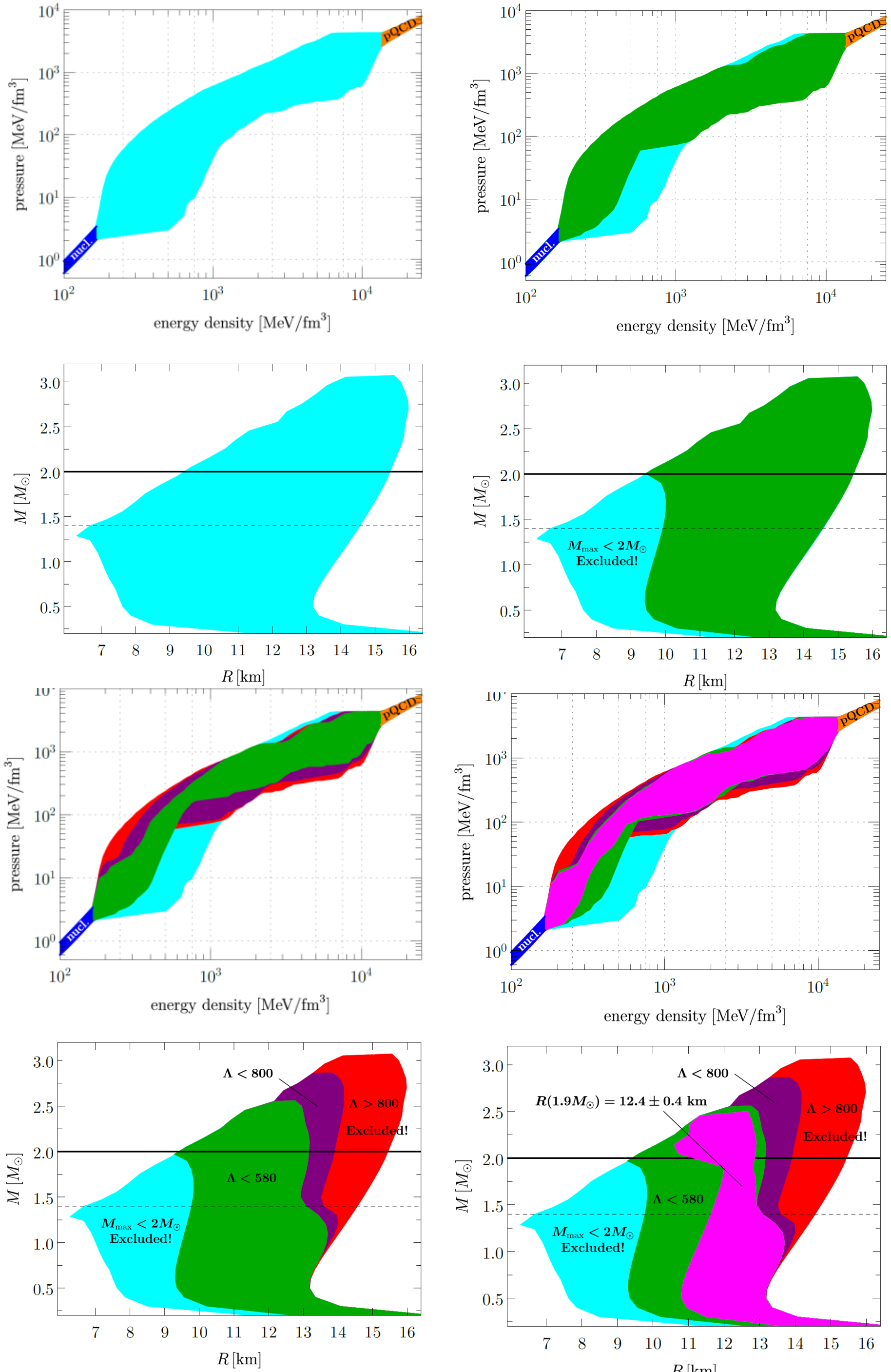

pressure [MeV/fm^3]
energy density [MeV/fm^3]
nucl.
pQCD

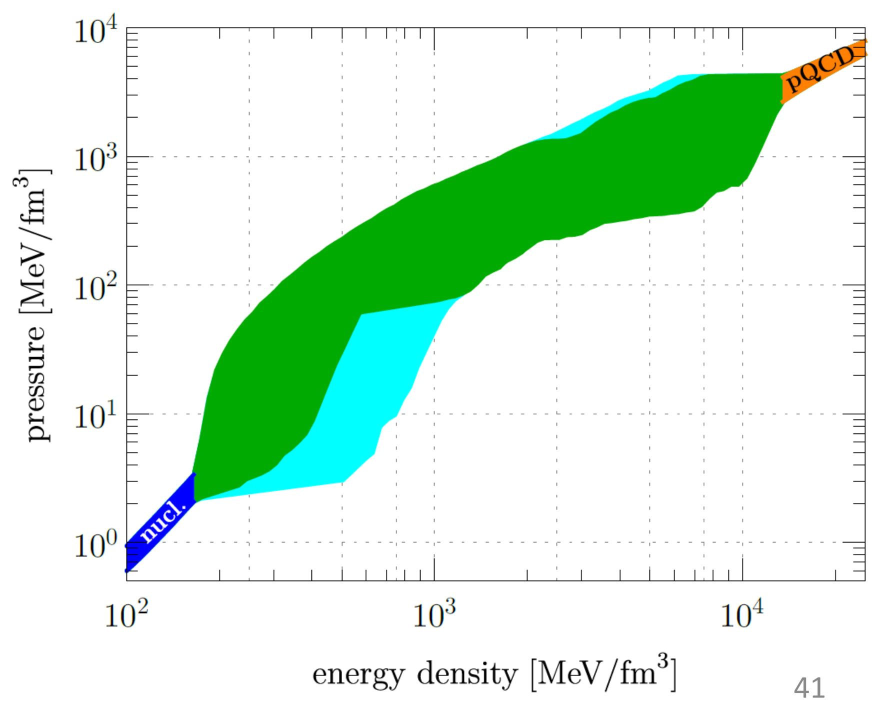

M [$M_\odot$]
R [km]
$\Lambda < 800$
$\Lambda > 800$ Excluded!
$\Lambda < 580$
$M_{max} < 2M_\odot$ Excluded!


pressure [MeV/fm^3]
energy density [MeV/fm^3]
nucl.
pQCD

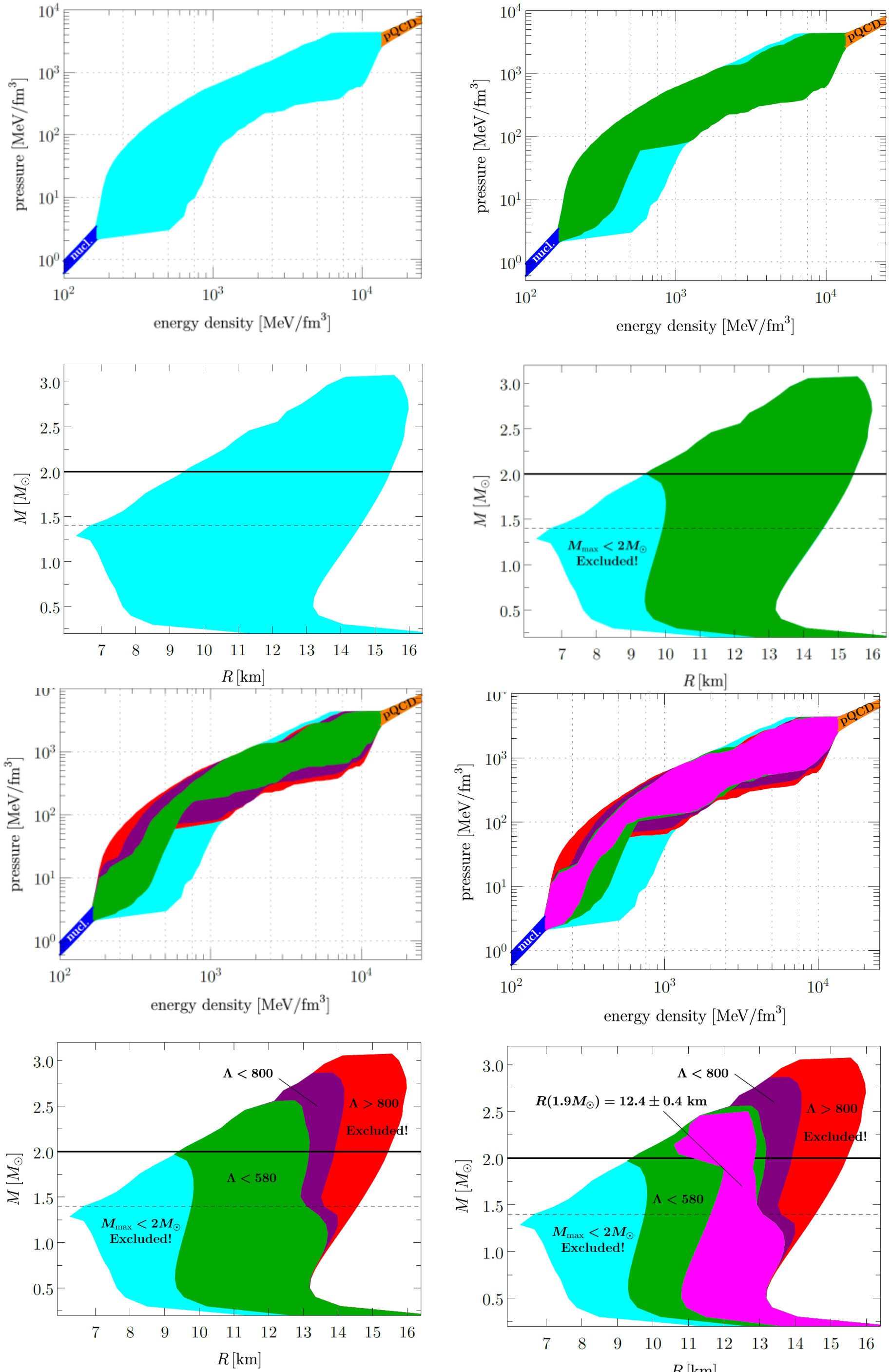

M [$M_\odot$]
R [km]
$\Lambda < 800$
$R(1.9M_\odot) = 12.4 \pm 0.4$ km
$\Lambda > 800$
Excluded!
$\Lambda < 580$
$M_{max} < 2M_\odot$
Excluded!

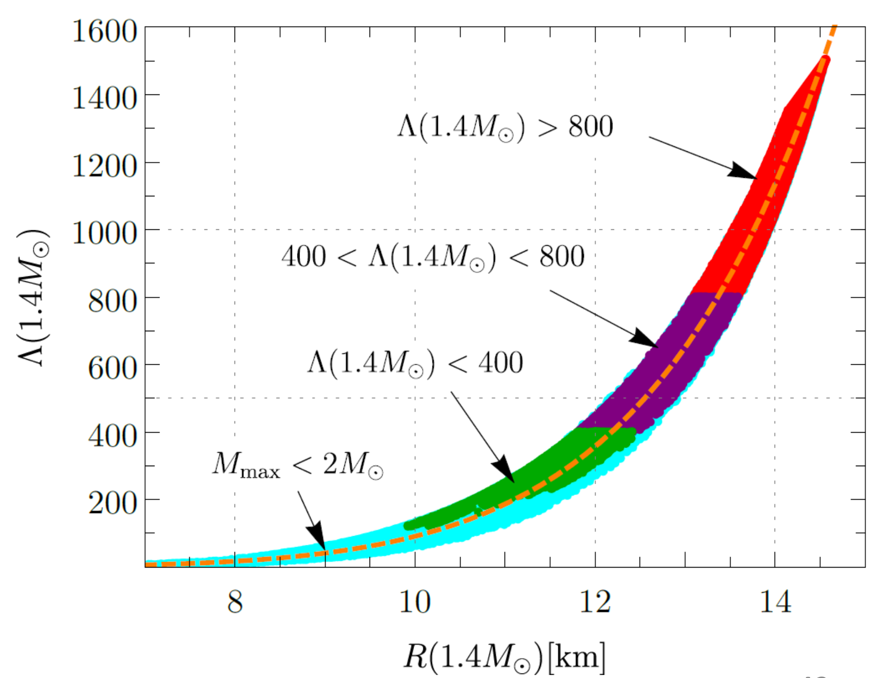
Lesson 1: $2M_{\odot}$ and pQCD constraints force EoS to be hard at low density and soft at high density → Efficient bracketing of $p(\epsilon)$, $R(1.4M_{\odot}) \geq 10\text{km}$

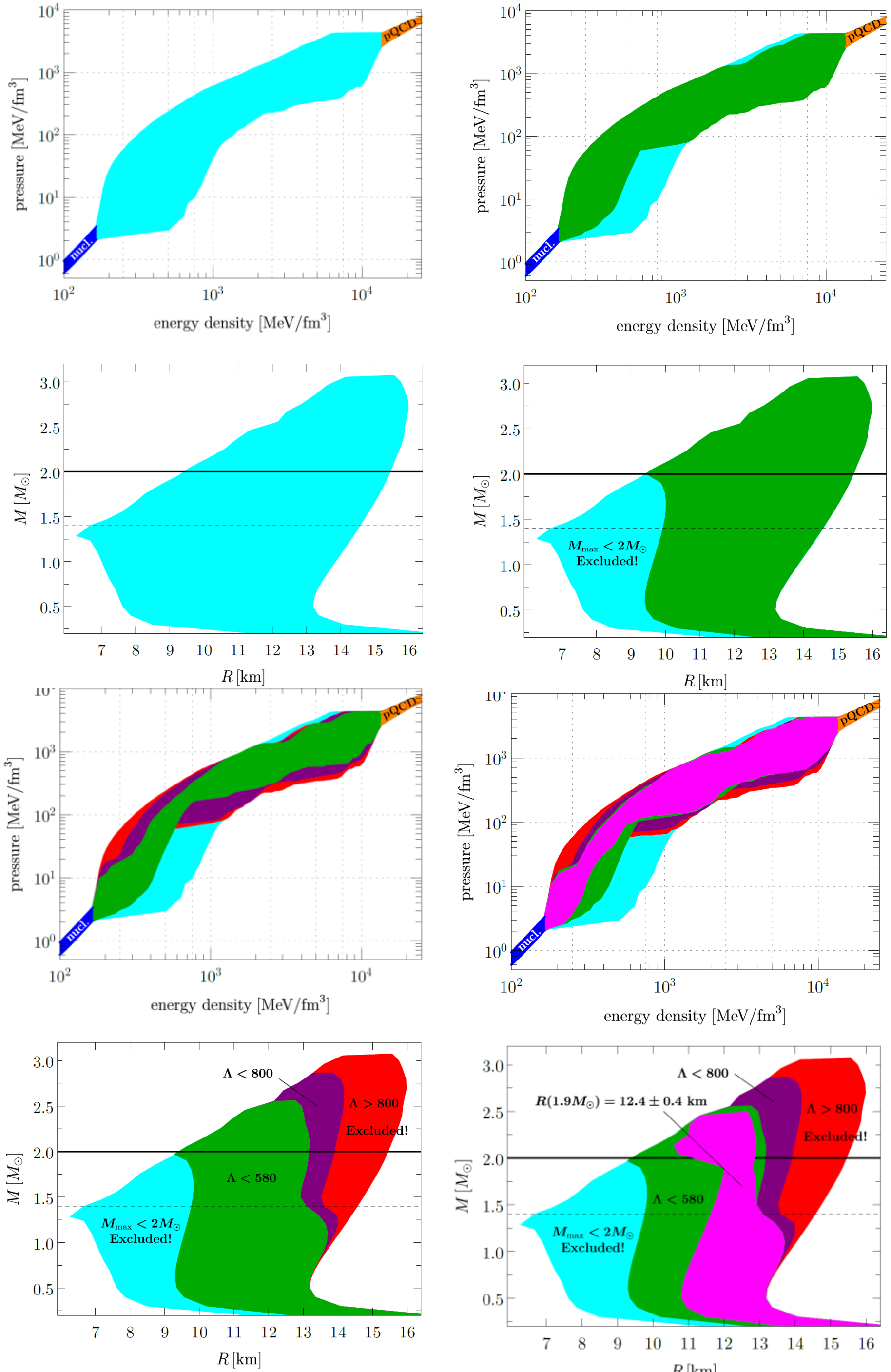




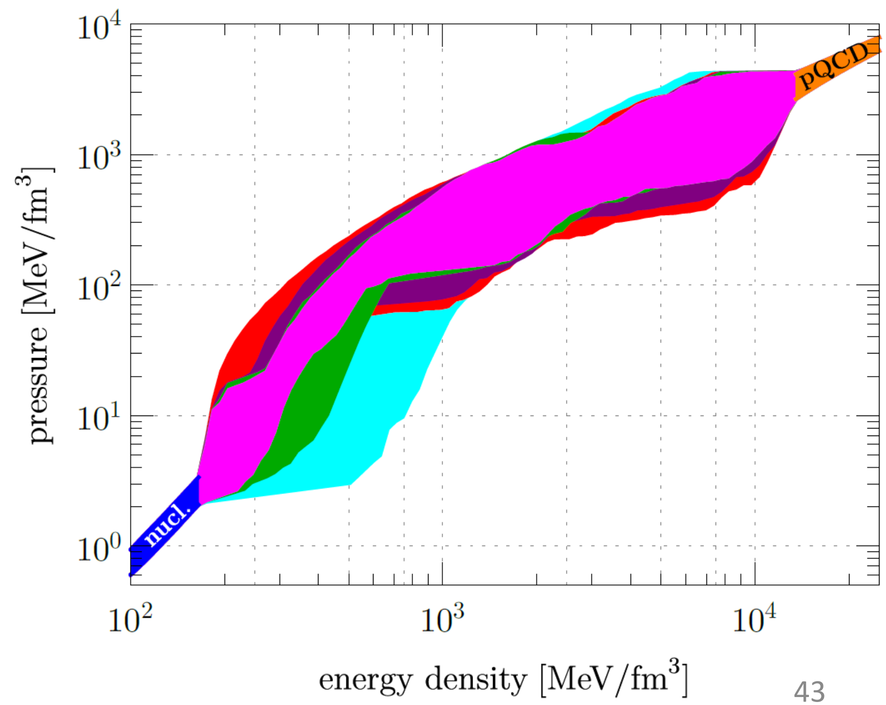
Lesson 2: Stringent limits from only one tidal deformab. measurement: EoS cannot be overly stiff at low density, $R(1.4M_\odot) \leq 13\text{km}$







Lesson 3: Accurate radius measurements of stars with well-known (large) masses very valuable for EoS determination especially at low densities



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!**