« 1st MaNiTou Summer School on Gravitational Waves », 4-8 juillet 2022, Marseille

GW and nuclear physics:
The search for the dense matter equation of state

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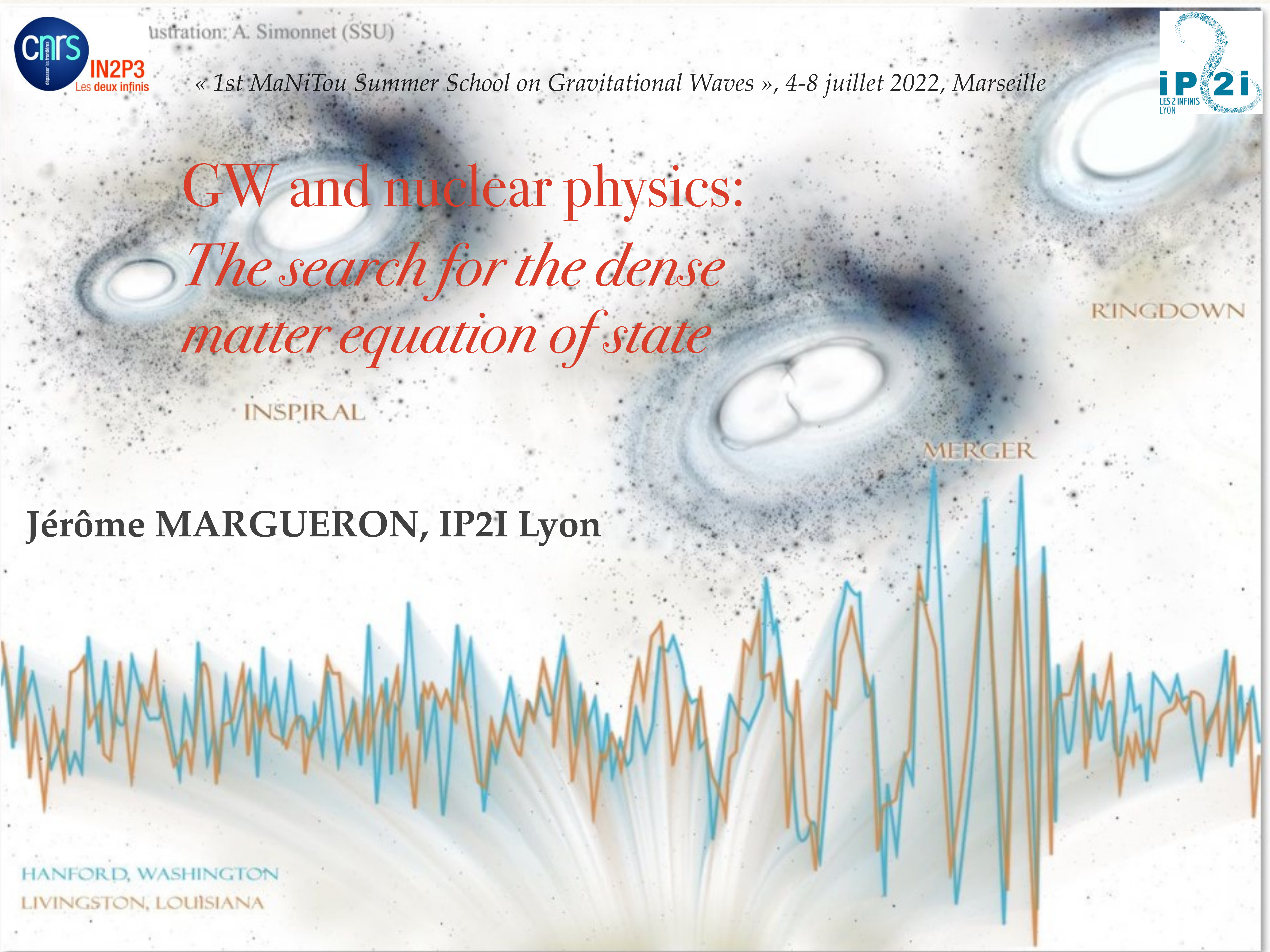
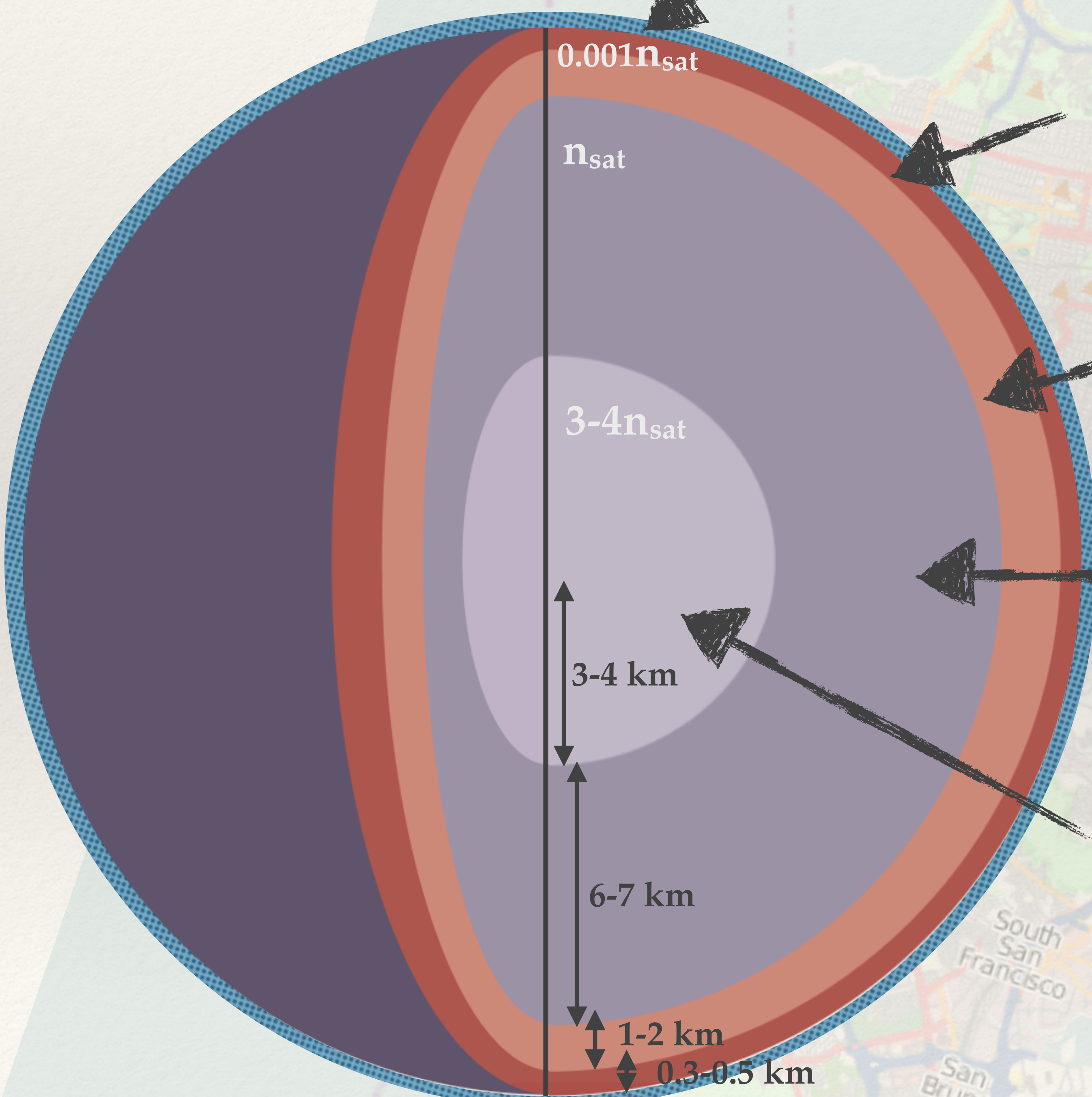


Anatomy of a neutron star (NS)



Atmosphere: H, He

NS are largely investigated thanks to our knowledge in nuclear and hadron physics.

Outer crust: nuclear clusters+electons

Radius $\approx 11 - 14$km

Mass $\approx 1.2 - 2.2 M_\odot$

Inner crust: nuclear clusters+electrons+neutron gas

Outer core: uniform nuclear matter (n, p, e, μ)

Inner core: unknown composition

NS **radius** provides information about the **core** mostly, but there is also a contribution from the crust (10%).

EoS [nuclear] <=> NS (M,R) [astro]

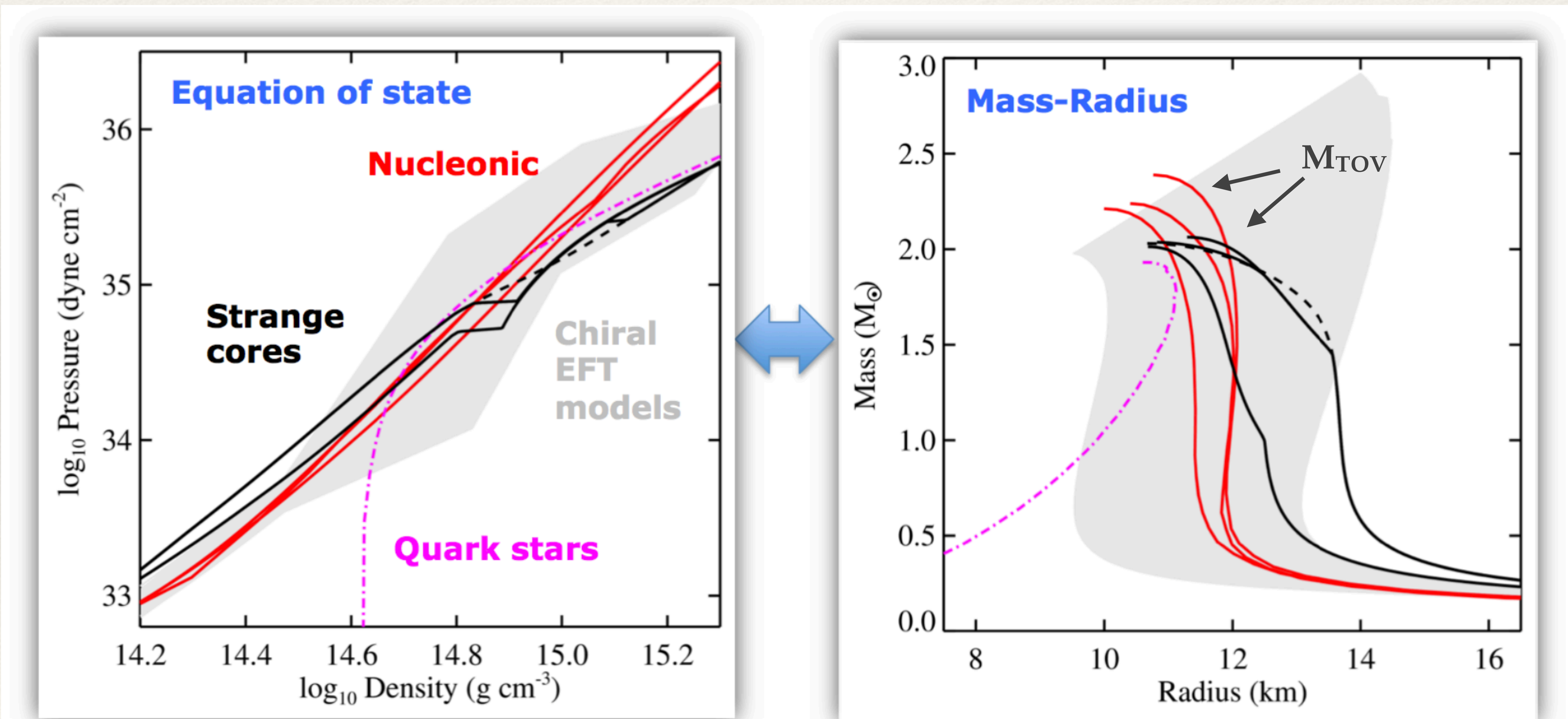
Properties of extreme matter

P(n)

Tolmann-Oppenheimer-Volkov (TOV) GR equations

(M,R)(n_c)

Astrophysical observations

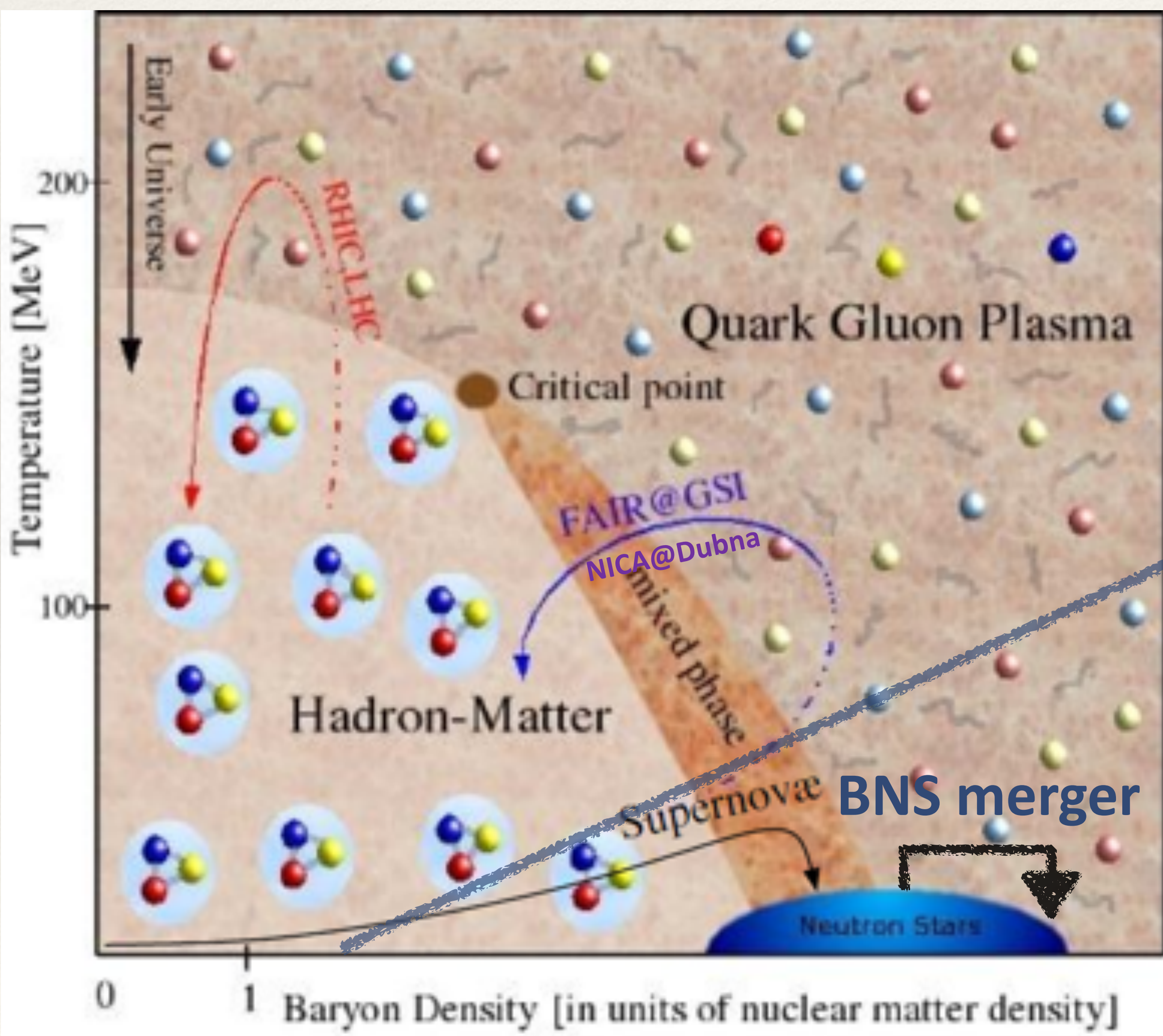


[A. Watts et al., PoD (AASKA 14) 043]

Reverse engineering,
Bayesian statistics

Probing extreme matter

Main questions: How changes the **nuclear interaction** with density, isospin asymmetry, temperature?
Which **new particles** appear at supra-saturation densities (phase transition)?
Links between **deconfinement** and **chiral symmetry** restoration?

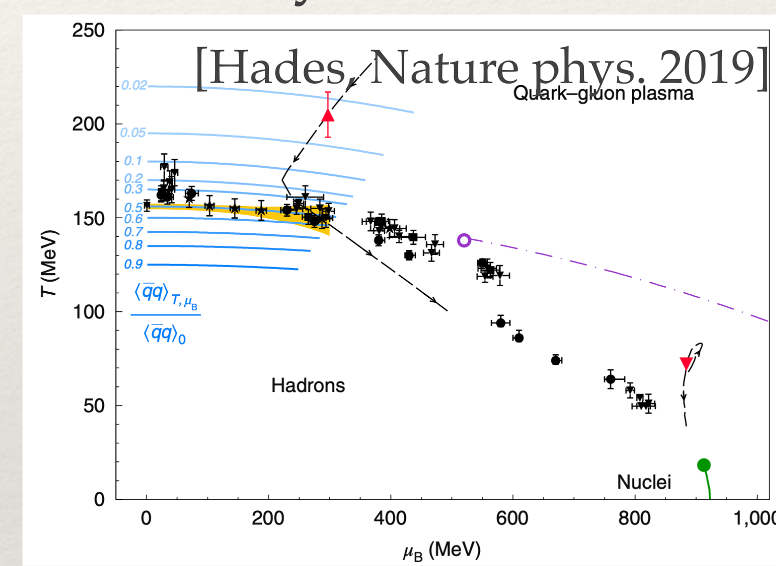


Particle and nuclear accelerators

Astrophysical observations

Neutron stars, supernovae, kilonovae…

Heavy Ion collision



Probe limits of extreme matter

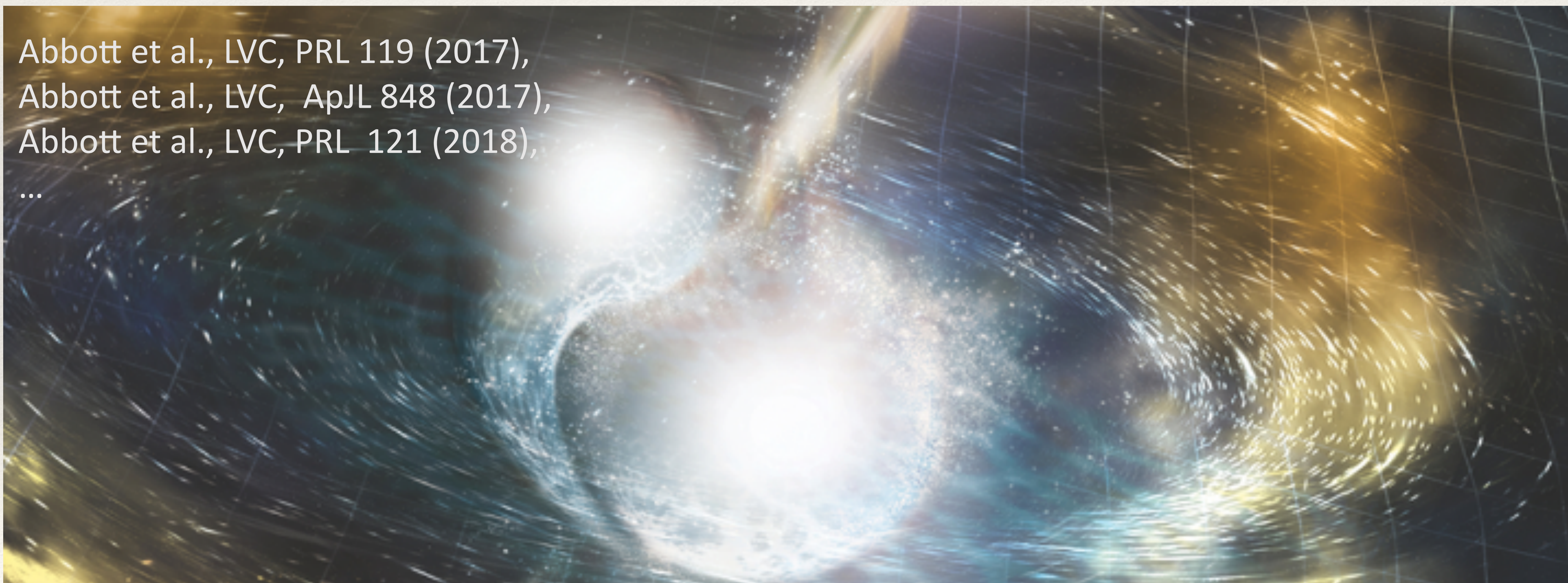
Directly related questions: How **neutrinos** propagate? What are the **transport properties** of extreme matter?
Are BNS the main astrophysical site for the **r-process**?

LIGO-Virgo GW observatory

2015: first detection of GW from BBH (O1).

2017: first detection of GW from BNS (O2). → gravity and cosmology, dark matter and dark energy, **dense matter.**

2019: first detection of GW from BHNS (O3).



Cataclysmic Collision Artist's illustration of two merging neutron stars. The rippling space-time grid represents gravitational waves that travel out from the collision, while the narrow beams show the bursts of gamma rays that are shot out just seconds after the gravitational waves. Swirling clouds of material ejected from the merging stars are also depicted. The clouds glow with visible and other wavelengths of light. Image credit: NSF/LIGO/Sonoma State University/A. Simonnet

EoS [nuclear] <=> BNS GW [astro]

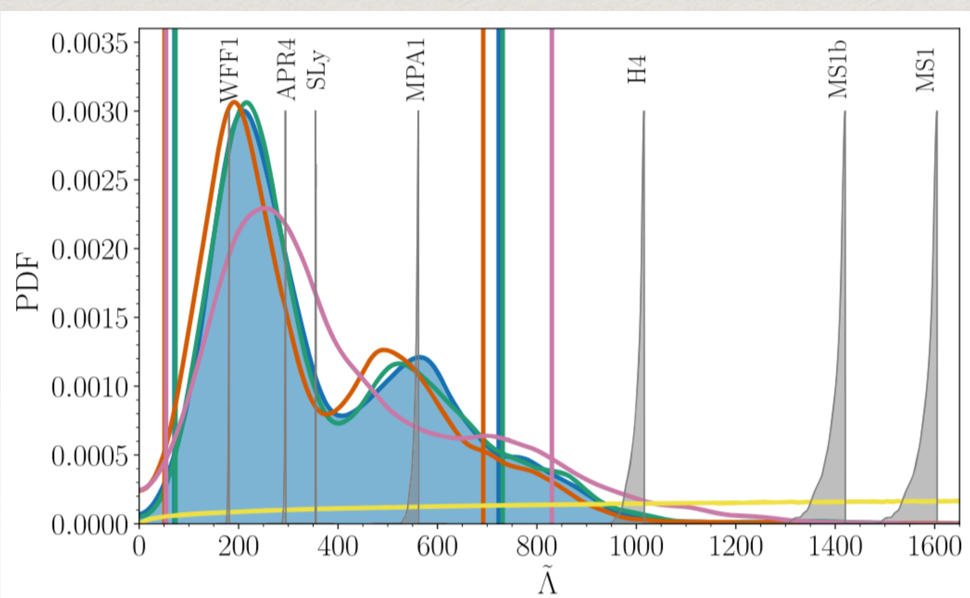
- Tidal field E_{ij} from companion star induces a quadrupole moment Q_{ij} in the NS
- Amount of deformation depends on the stiffness of EOS via the tidal deformability Λ.

$$Q_{ij} = -\Lambda(\mathrm{EOS}, m) m^5 \mathcal{E}_{ij}$$

Post-Newtonian expansion of the waveform: Tidal effect enters at 5th order.

Hinderer+ 2008, Blanchet, Damour

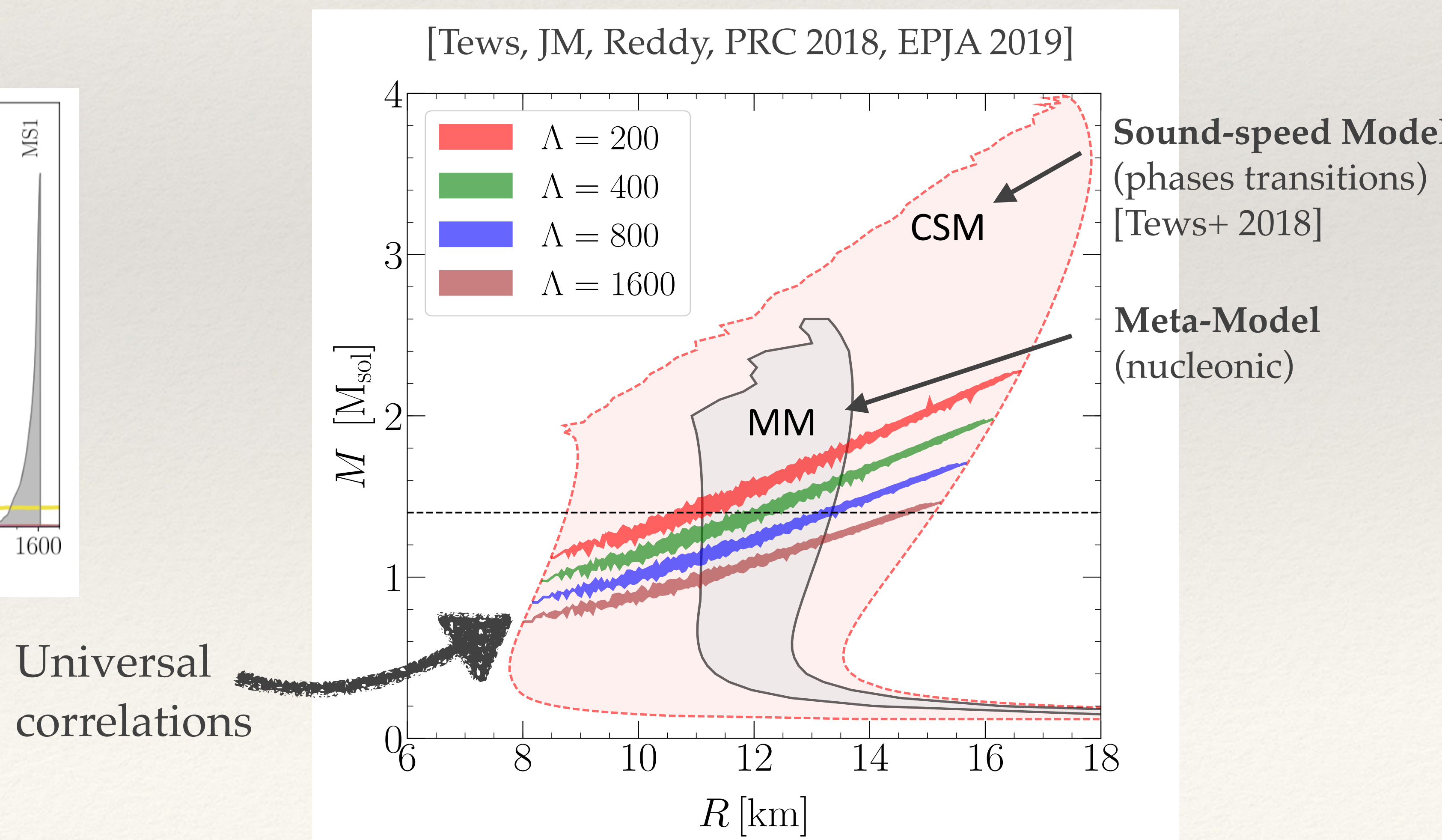
LVC, Phys. Rev. X 9, 011001 (2019)



GW170817

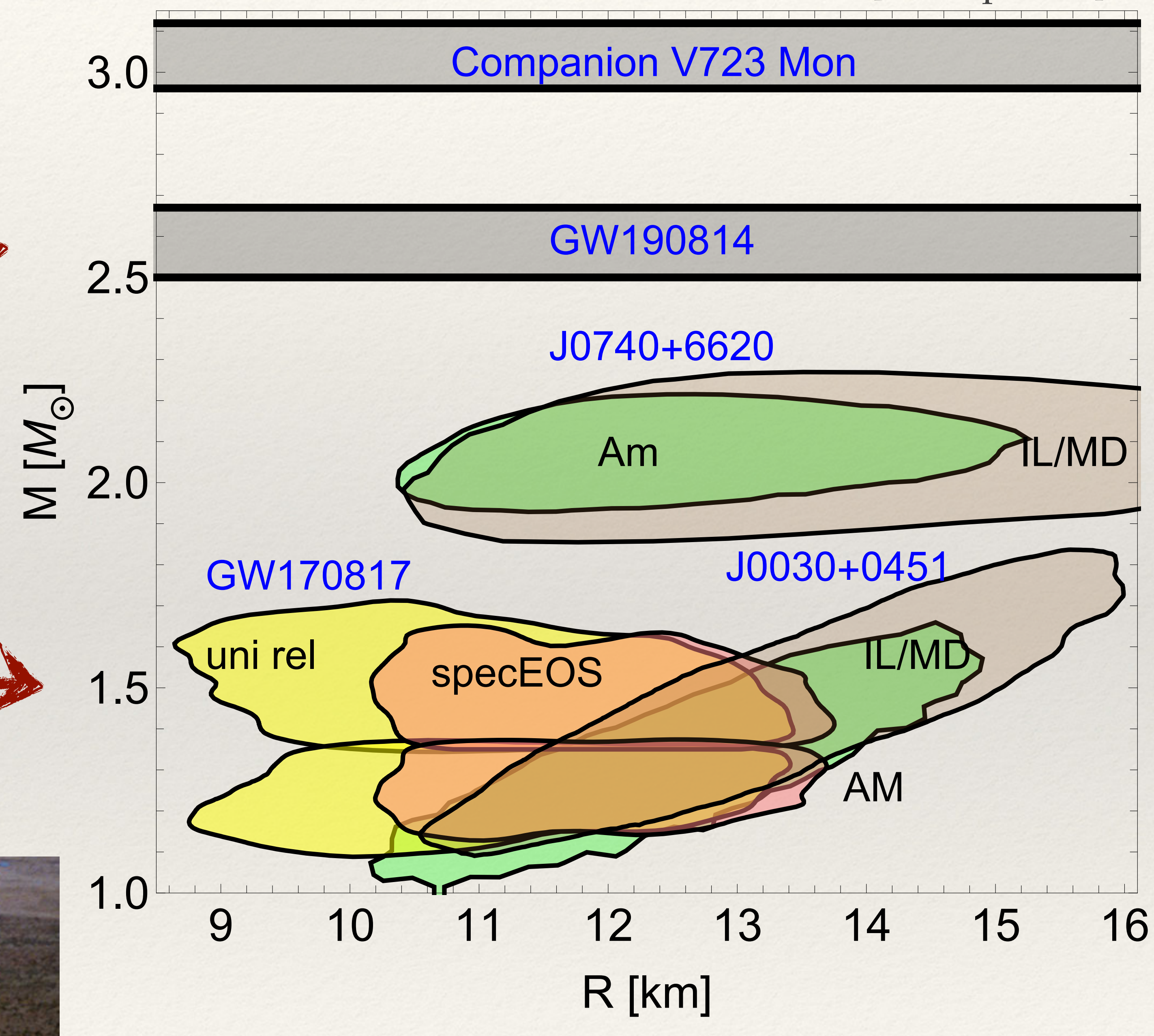
→ 70 ≤ Λ ≤ 720 (90% CL)

→ +E-M 300 ≤ Λ ≤ 800



GW+NICER X-ray observatory

Tan, Dore, Dexheimer+ arXiv:2106.03890[astro-ph.HE]



Description of dense matter

Microscopic approach

Hamiltonian or Lagrangian

Many-body treatment (Hartree-Fock, quantum Monte-Carlo, …)

Phase(s) transition(s)

Matter at beta-equilibrium

Lepton contribution

EoS in extreme matter

Microscopic description of dense matter

There is no microscopic theory for dense matter, only models. *Why?*

QCD is the theory for **strong force**.
It describes the interaction between quarks and it has a special property: **asymptotic freedom**.
-> it is perturbative at high density, non-perturbative at **low energy**.

Nuclear physics is low-energy
-> it is then in the **non-perturbative** regime of QCD.

At low energy, QCD has another property: **color confinement**.

Quarks prefer to be color white, then to combine together 3 complementary colors.
-> quarks form neutrons and protons.

The nuclear interaction between neutrons and protons is the **residual of the strong force** (like Van der Waals force in atomic physics).

Bridging from QCD (fundamental theory) to nuclear interaction is difficult.
It is necessary to consider an effective or phenomenological approach.

-> There are **several approaches in nuclear physics** with various links to QCD. No theory, but several models.

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Agnostic approach

Construct the relation p <-> ρ mathematically.

Ignore the interaction.

Ignore the many-body treatment.

May include phase(s) transition(s).

But ignoring the composition of matter.

EoS in extreme matter

Exemple of an agnostic approach

Polytropic EoS: $P(\rho) = K\rho^{\Gamma}$ ← Adiabatic index

Pression (dyn cm-2) — Density (g cm-3)

We deduce the energy as

$$e(\rho) = 1 + a + \frac{1}{\Gamma - 1} K\rho^{\Gamma-1}$$

constant

using

$$P(\rho) = \rho^2 \frac{de}{d\rho}$$

Piecewise polytropes:

Above ρ_0, a set of densities is considered: $\rho_0 < \rho_1 < \rho_2 < \ldots$

$$P(\rho) = K_i \rho^{\Gamma_i}$$

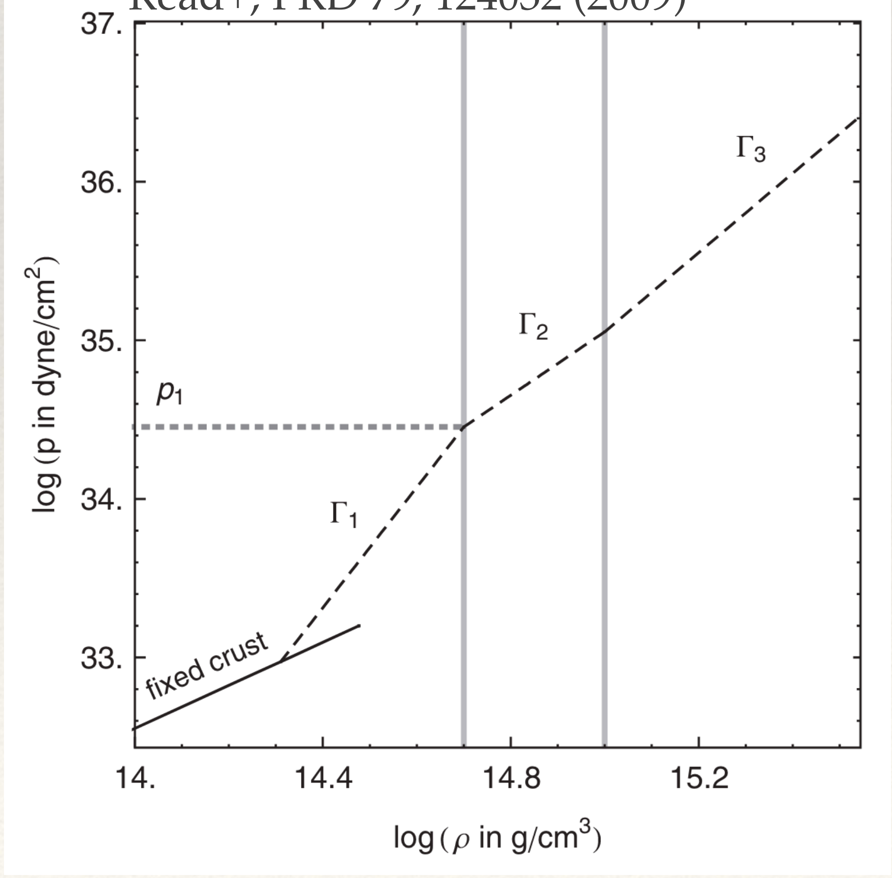
$$e(\rho) = 1 + a_i + \frac{1}{\Gamma_i - 1} K_i \rho^{\Gamma_i - 1}$$

The continuity of P and e at ρ_i is imposed -> fix a_i and K_i.

ρ_i and Γ_i are free parameters:

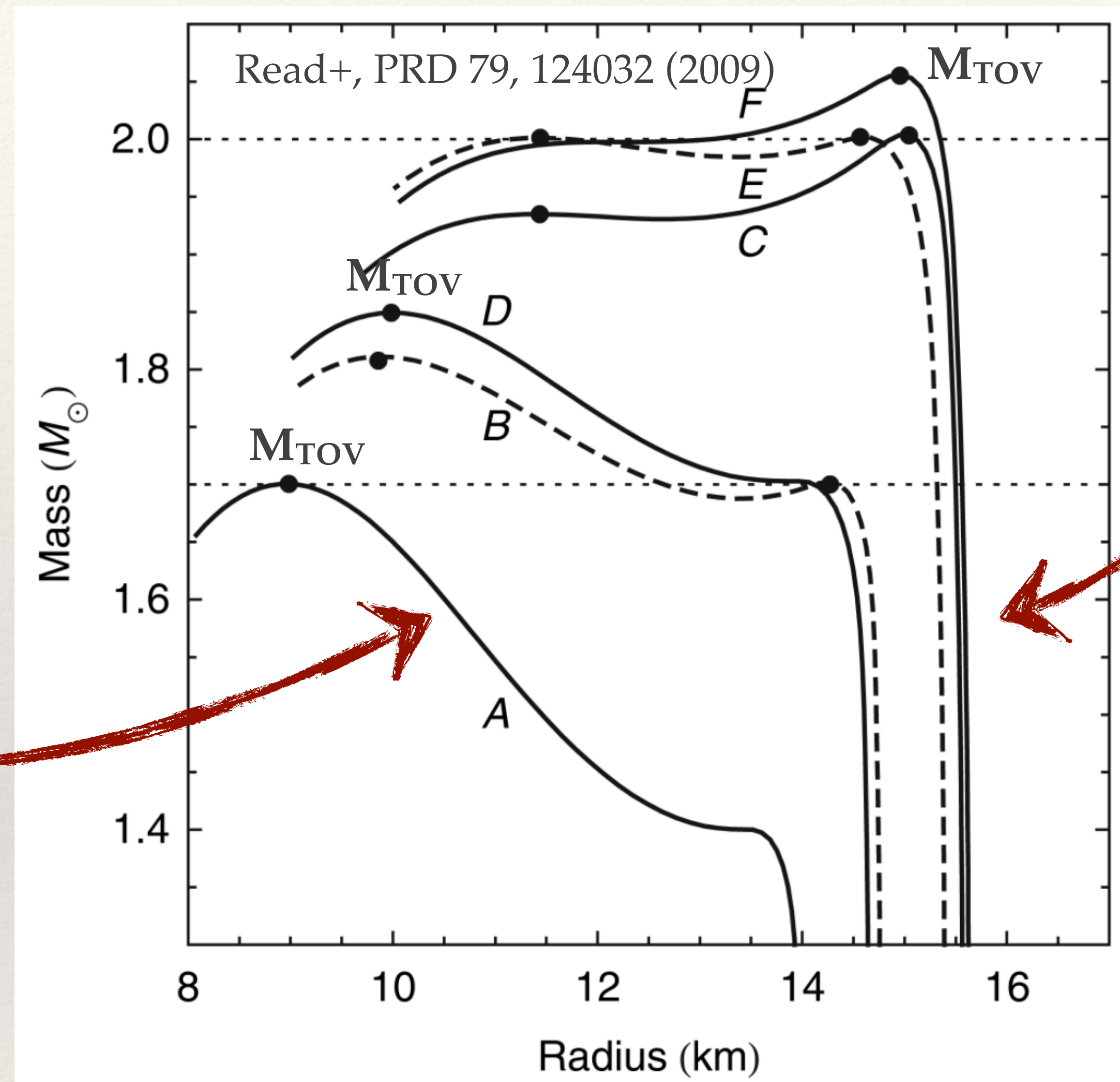
- They can be adjusted to reproduce existing EoS,
- Or they can be tossed randomly in a MCMC exploration.

Read+, PRD 79, 124032 (2009)



MR relations from piecewise polytropes

Second branch



First branch

-> There are maybe 2 branches of neutron stars:
First branch explaining large radii,
Second branch explaining small radii.

This is not specific from piecewise polytopes.
From microscopic understanding, this comes from the onset of a **phase transition** between **nuclear matter** towards an **exotic matter**.

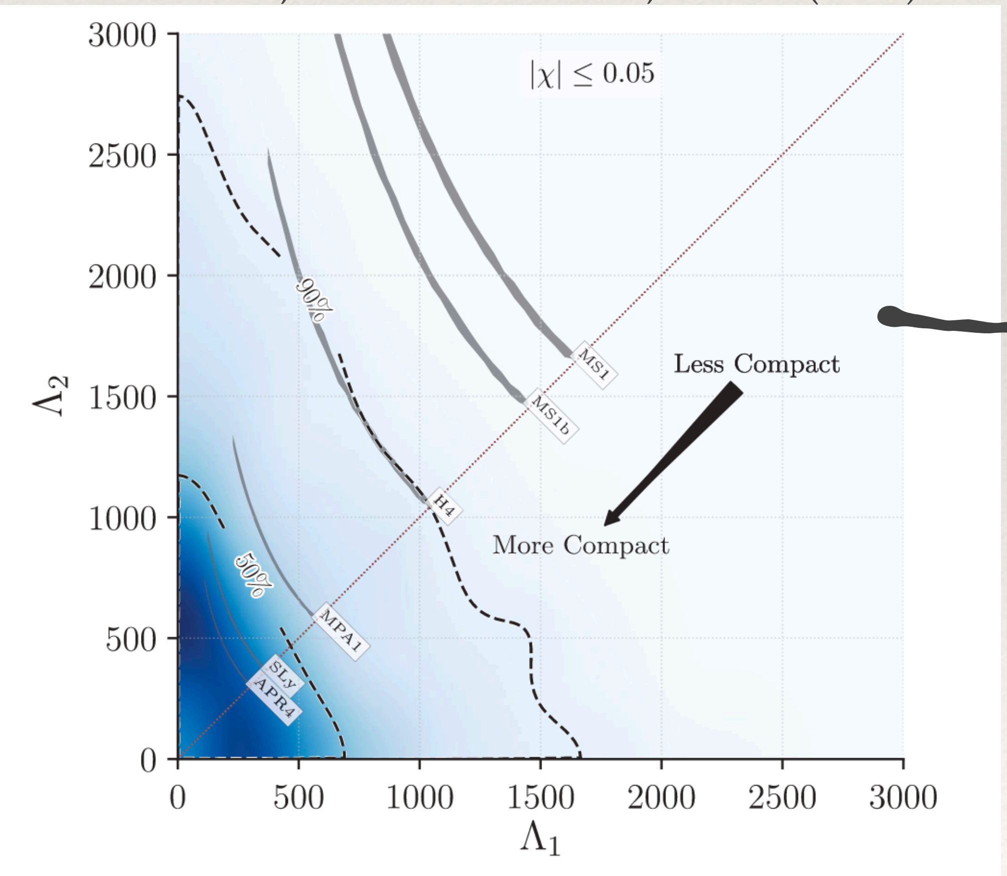
Quark matter, or hyperon matter, or …

Agnostic analysis of GW170817

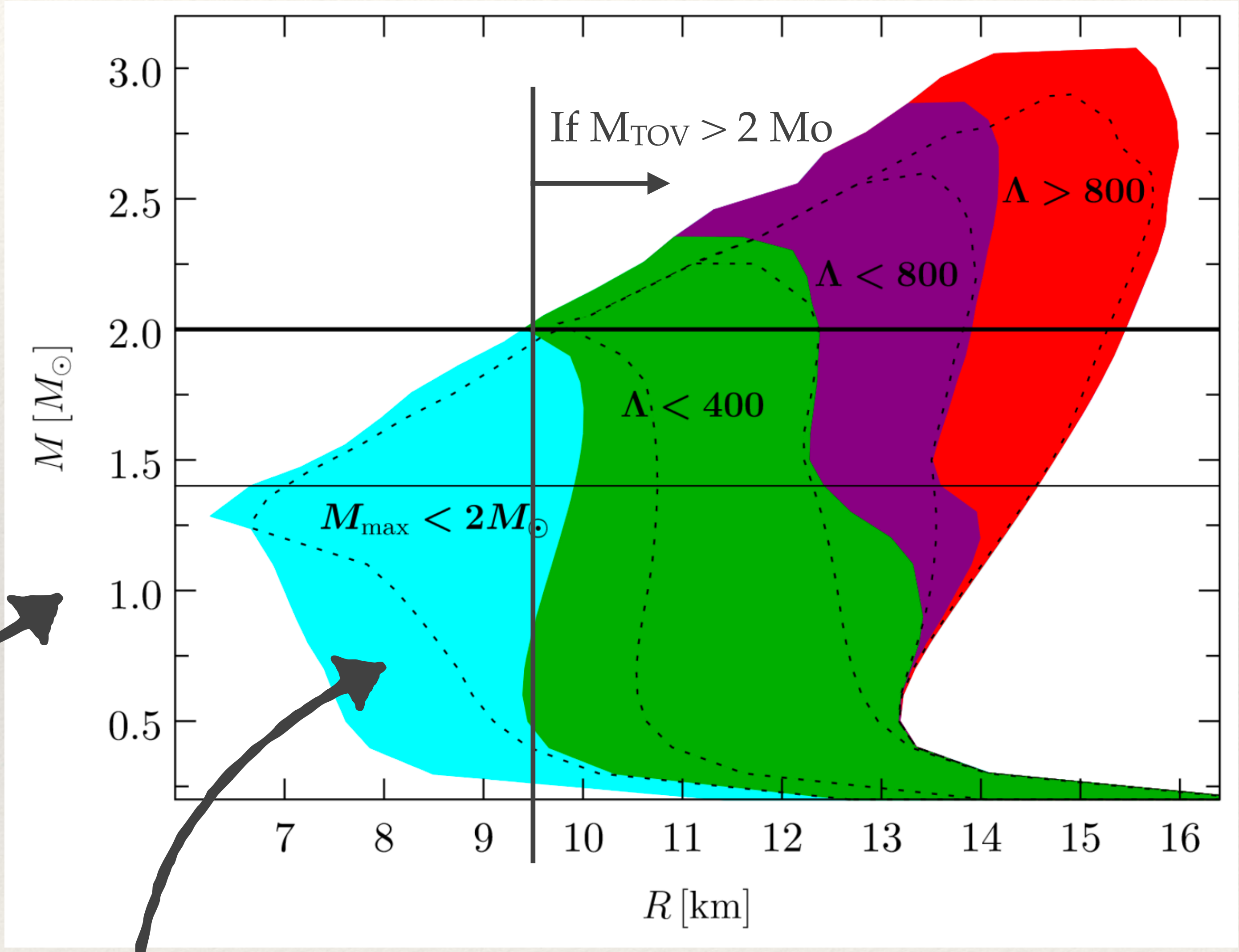
GW170817 detection and analysis in terms of the tidal deformability:

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

Abbott, LVC Coll. PRL 119, 161101 (2017)



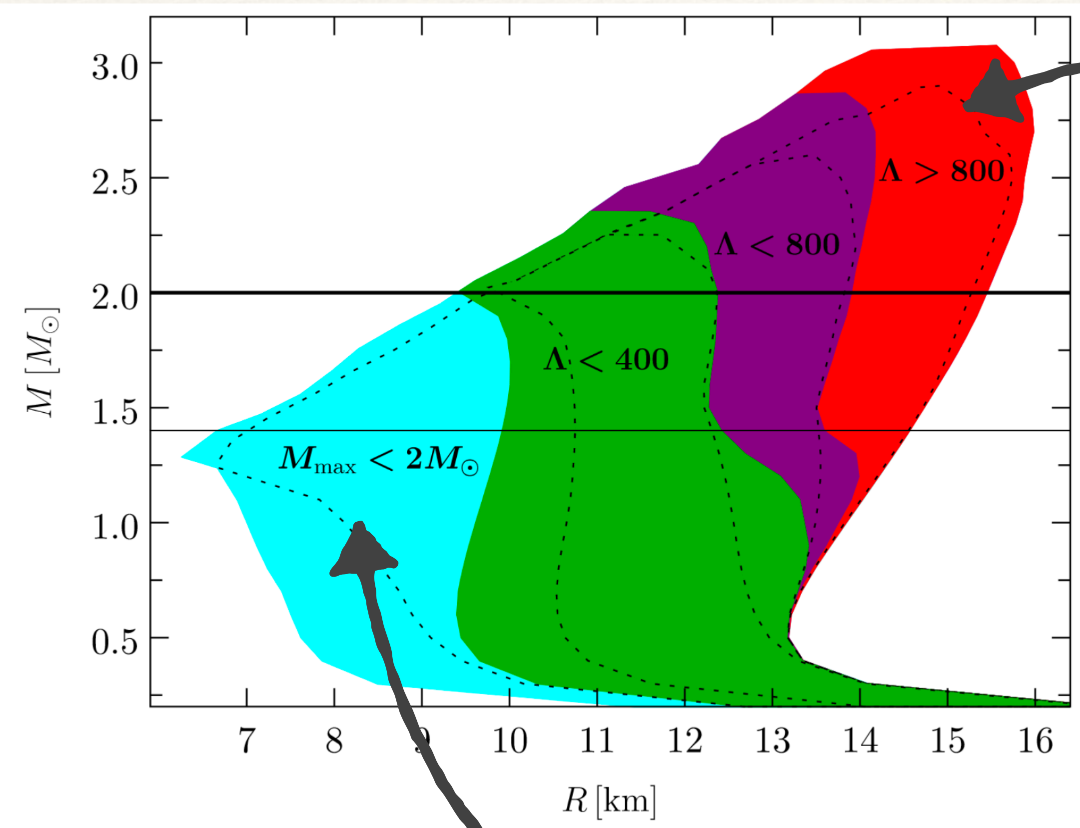
Annala+, PRL 120, 172703 (2018)

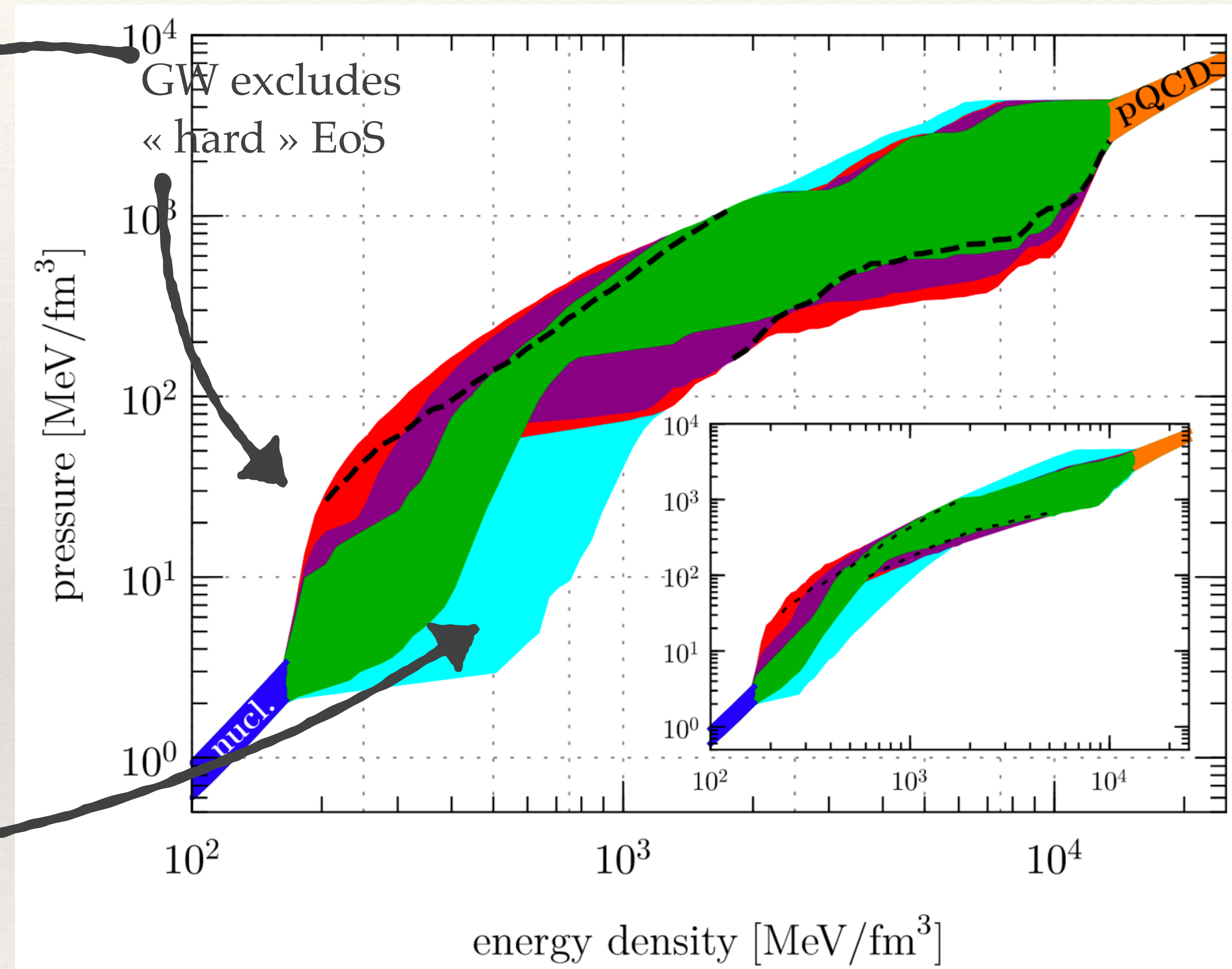


NS with M>2Mo has recently been observed (radio astronomy): -> M_{TOV} > 2 Mo

Consequences for extreme matter EoS

Annala+, PRL 120, 172703 (2018)





Excluded by M_{TOV} limit

« soft » EoS

Radio and GW astronomy bound the EoS.

- More accurate measurement of $\tilde{\Lambda}$ -> further reduction of EoS band.
- Simple illustration of a multi-messenger analysis (see talk of S. Antier for more evolved analyses).

Sound speed model (CSM)

The sound speed is defined as: $c_s^2 = \frac{dp}{d\rho}$ (At zero temperature and for a single component)

Introducing the energy density (MeV fm-3): $\epsilon = \rho c^2$ and the number density (fm-3): $n = \rho / m_{nuc}$

From thermodynamic: Chemical potential: $\mu = \frac{d\epsilon}{dn}$ and number density: $n = \frac{dp}{d\mu}$

We deduce: $(c_s/c)^2 = \frac{n}{\mu}\frac{d\mu}{dn}$

Similarly to the piecewise polytopes, one can consider a set of densities where the sound speed is given.

Given $n_0 < n_1 < n_2 < \ldots$ with $c_{s,0}^2, c_{s,1}^2, c_{s,2}^2$ well chosen (to reproduce existing model or to explore uncertainties), one can obtain:

$$\mu(n) = \mu_i \left(\frac{n}{n_i}\right)^{c_{s,i}^2} \qquad \epsilon(n) = \epsilon_i + \int \frac{d\epsilon}{dn'}dn' = \epsilon_i + \int \mu(n')dn'$$

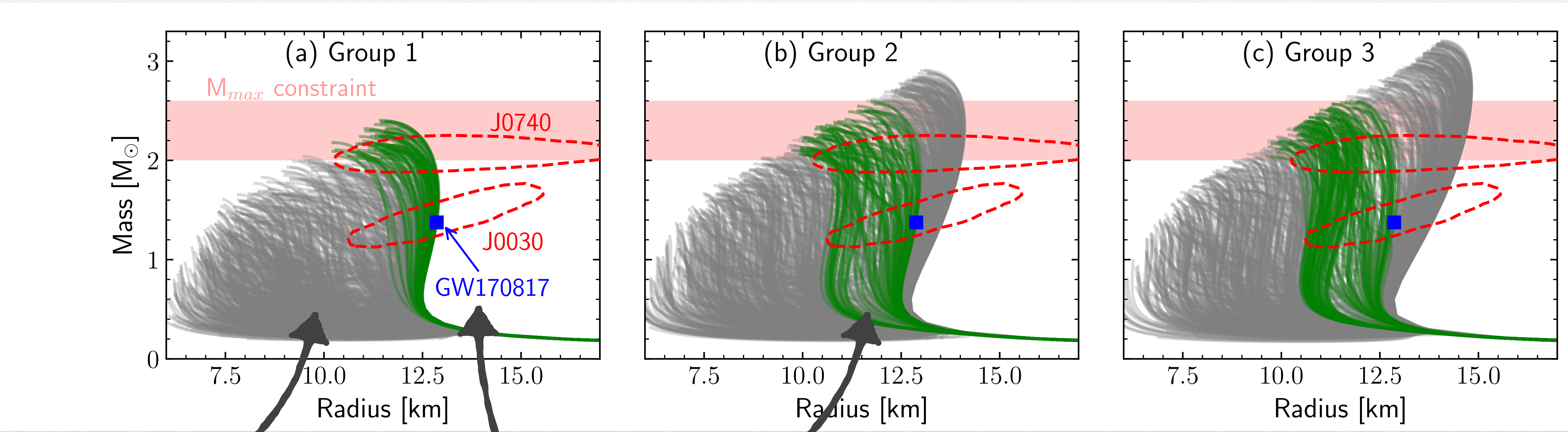
$$p(n) = p_i + \int \frac{dp}{dn'}dn' = p_i + \int \frac{dp}{d\epsilon}\frac{d\epsilon}{dn'}dn' = p_i + c_{s,i}^2 \int \mu(n')dn'$$

Tews+, ApJ 860, 149 (2018)

Sound speed structure from NS observations

[Somasundaram+, arXiv 2022]

Agnostic approach based on the sound speed approach.



Prior

Posterior

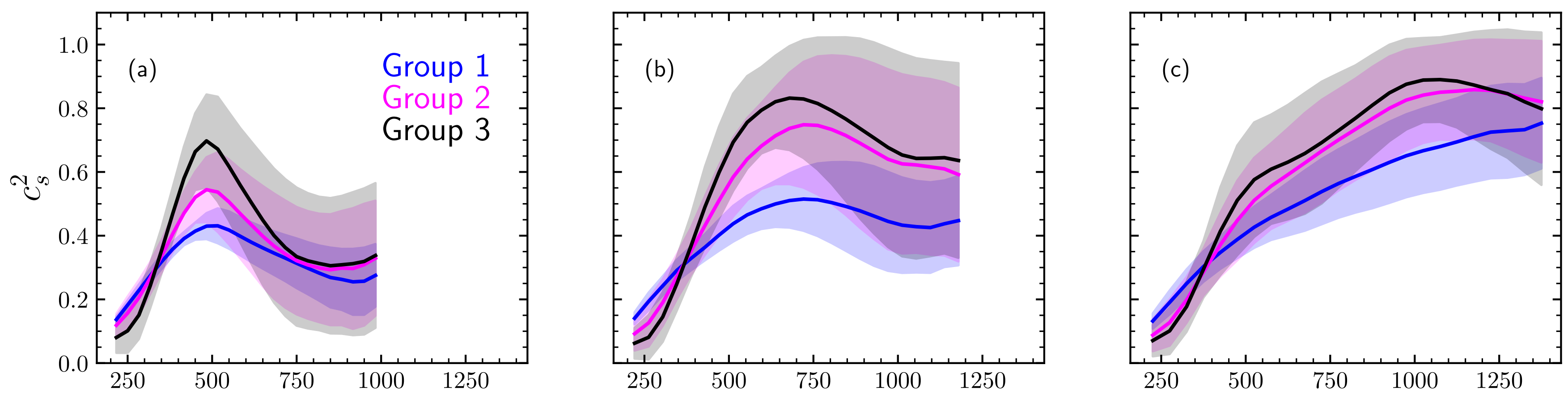
NS observations

The groups reflect the slope of the sound speed:

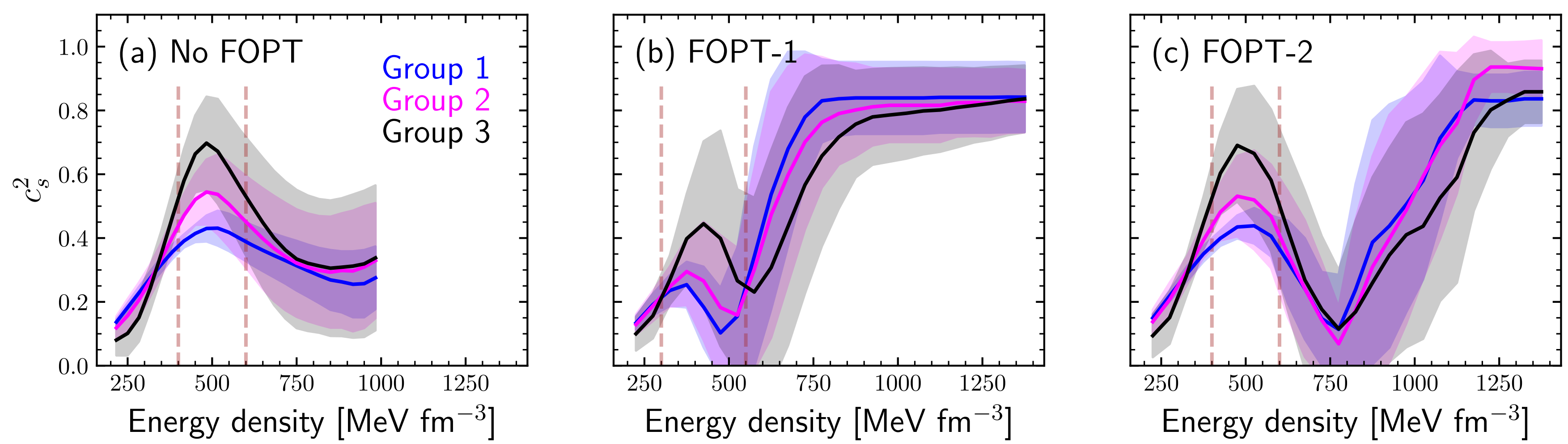
Increasing slope of c_s

Sound speed structure from NS observations

Increasing slope of c_s

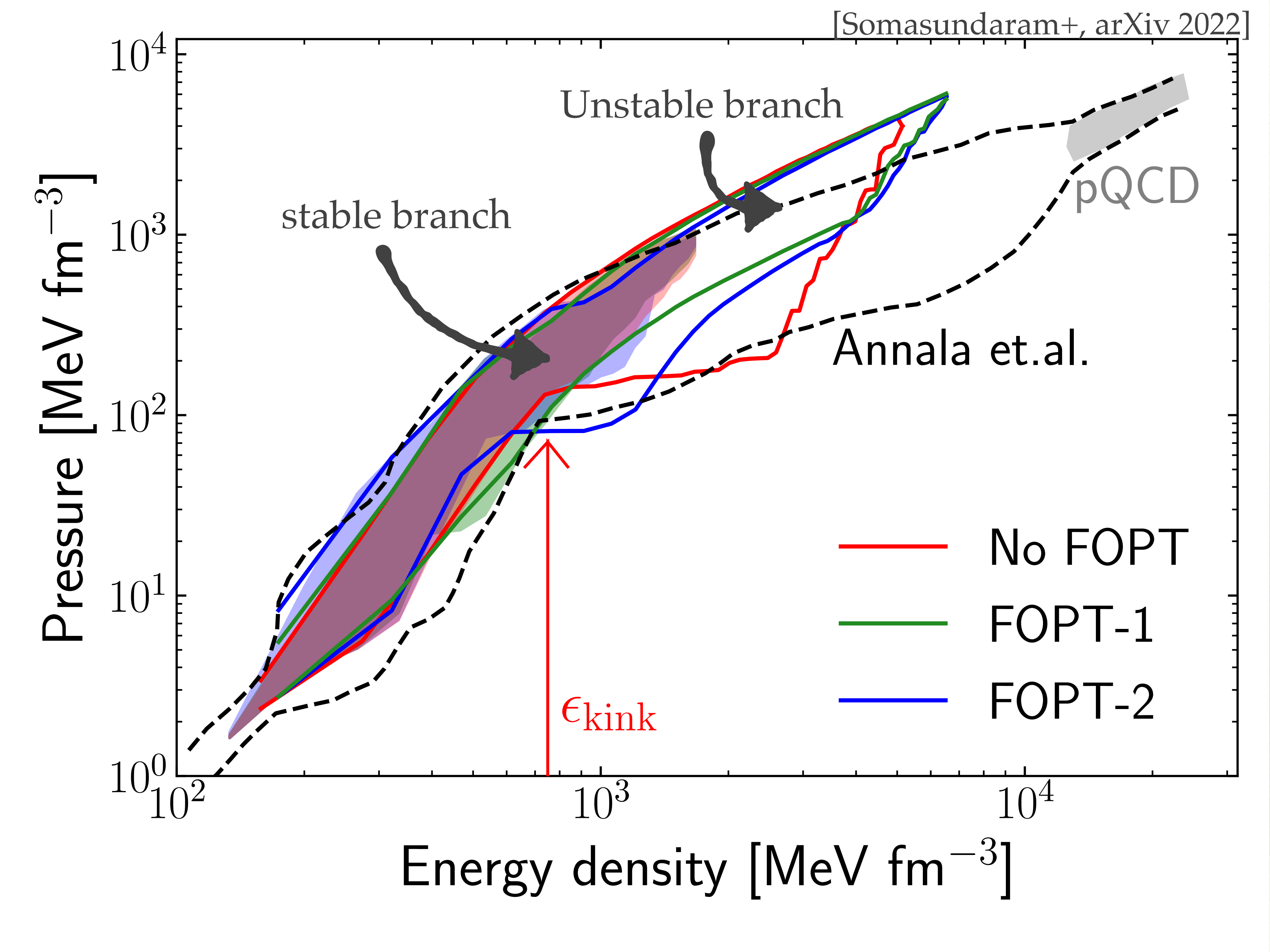


First order phase transition (FOPT) explicitly considered



[Somasundaram+, arXiv 2022]

Impact on the EoS



—> astrophysical information to date do not necessarily require a phase transition to exotic (quark) matter.

Conclusions

Using agnostic approaches, we have shown how raw data can be transformed into **constraints for dense matter** (mainly on the EoS and on the existence of phase transition).

Combining radio + GW data: we illustrated that the **EoS can be bounded.**
-> soft EoS removed by radio.
-> stiff EoS removed by GW.

An agnostic approach based on the **sound speed model** was used to analyze in more details the properties of dense matter. **No evidence for phase transition** could be obtained from this analysis, but the accumulation of data will lead to more clear conclusions in the future.

Agnostic approaches are great, but, the **matter composition** remains **unknown**.

-> we do not know what we describe! Is it a paradox?

-> Microscopic and agnostic approaches are complementary: the understanding of matter composition requires **microscopic description** of dense matter (for instance the nucleonic meta-model).