Bayesian Inference of Neutron Star Properties: When Astro and Nuclear physics go hand in hand

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05/09/2025

The QCD Phase Diagram & Neutron Star Matter

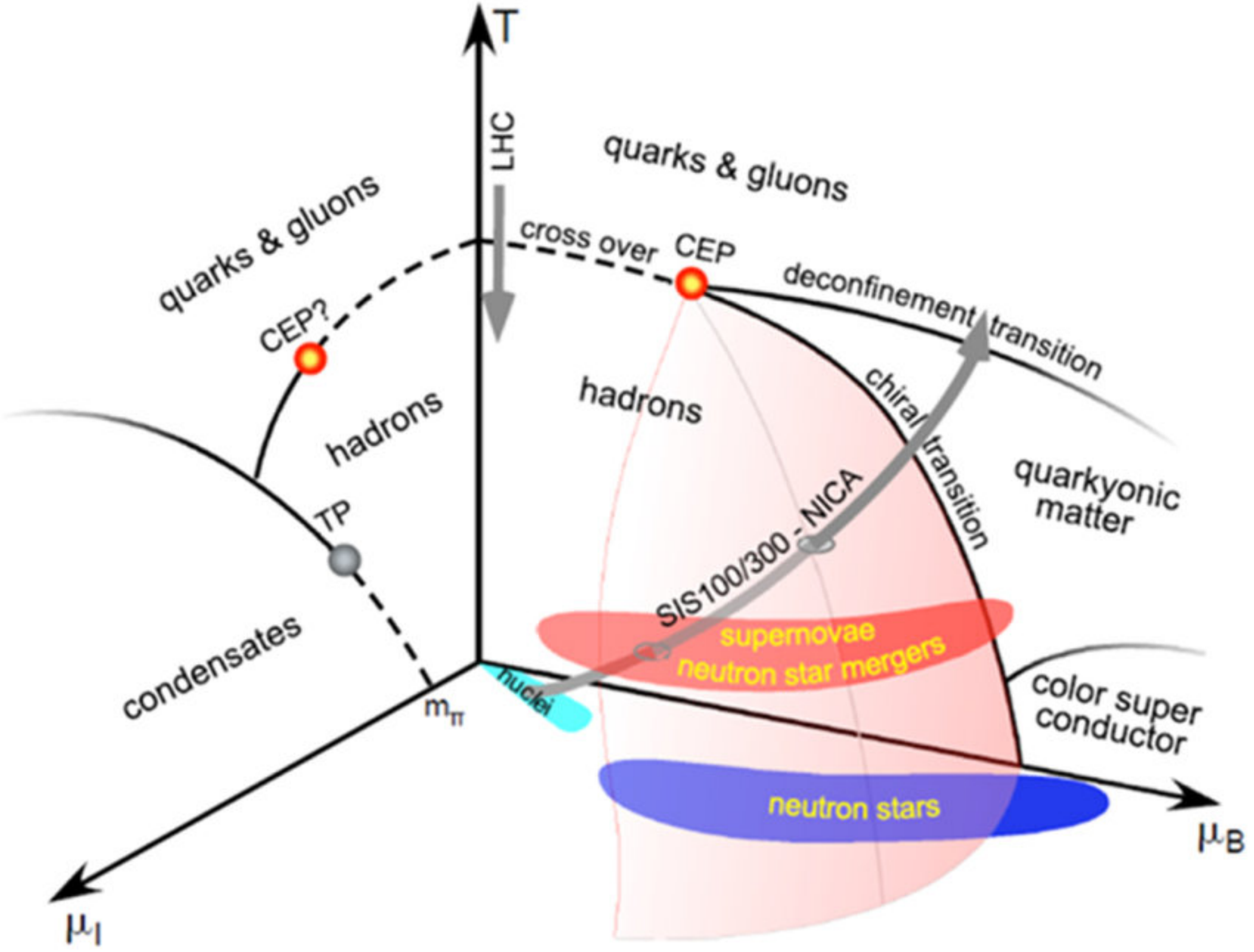
Neutron stars probe high-density, low-temperature QCD

n_b up to $\sim 10\, n_0$

Ultradense

$T \lesssim MeV$ and $\epsilon_f \gtrsim 10\, MeV$

Cold



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Ultradense

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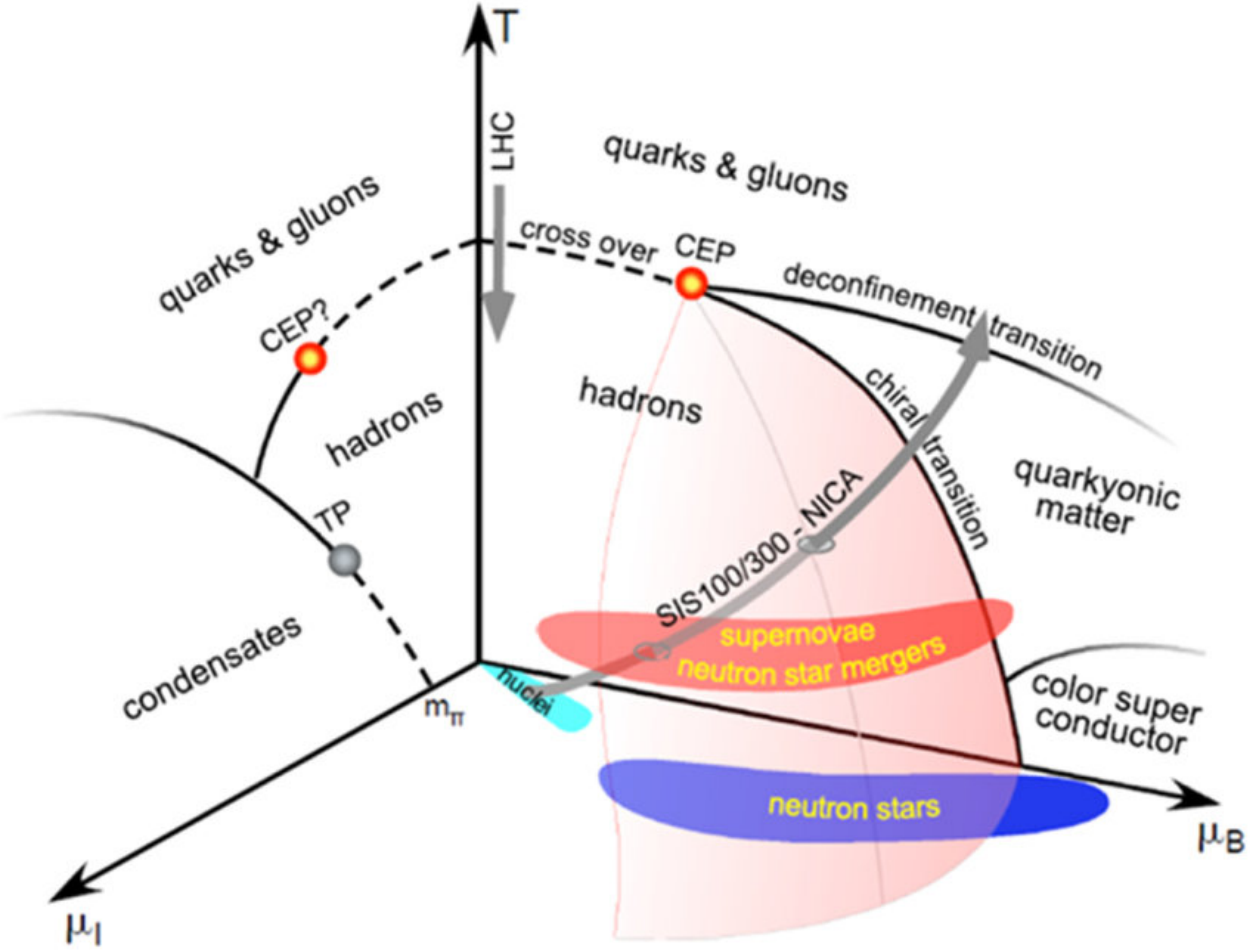
Cold

No direct experiments

No theoretical derivation

Nucleonic ⟶ Hyperonic ⟶ Quark matter?

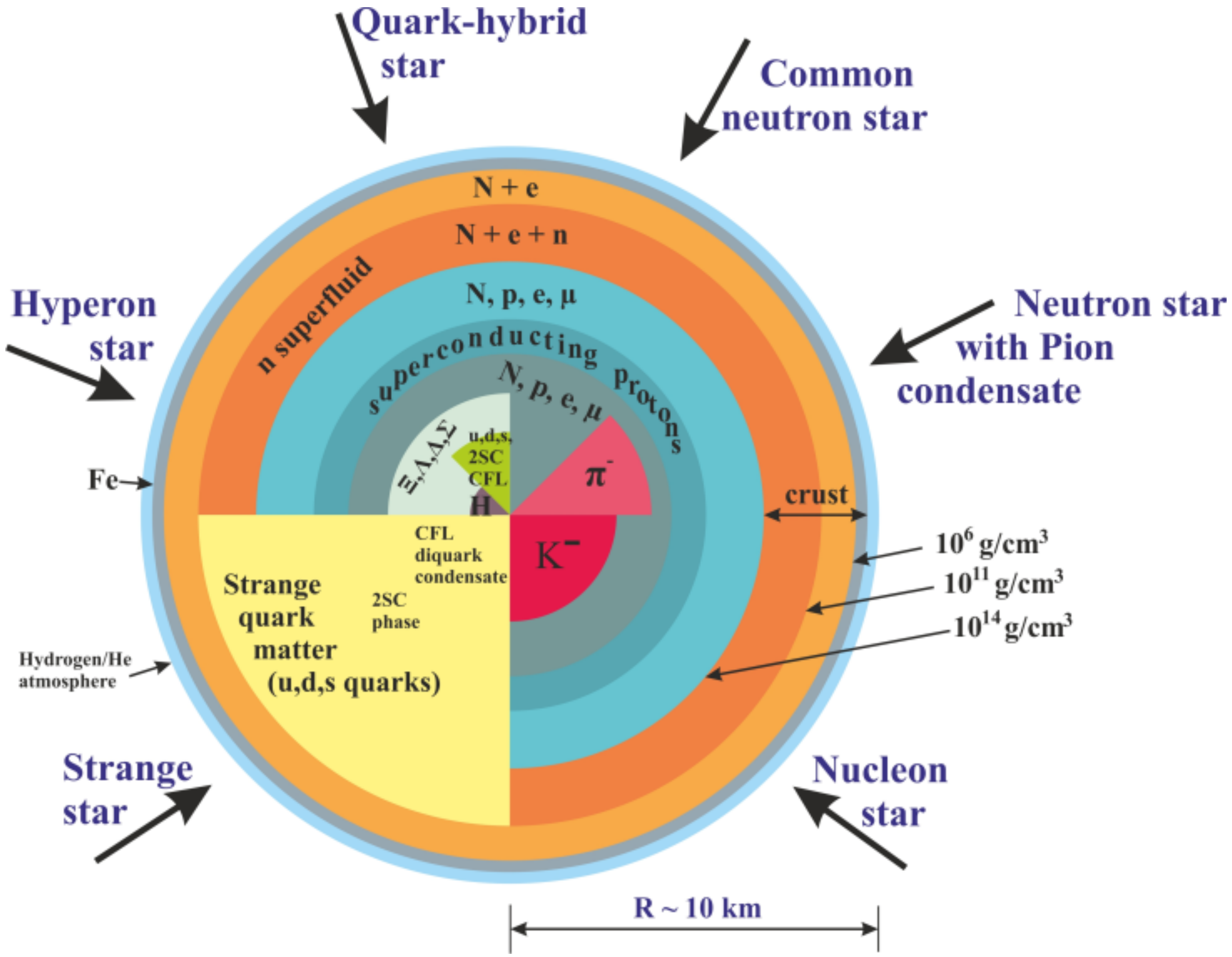


Uncertain Composition of Neutron Star Interiors

We can't observe the **internal structure**

Compressing matter liberates degrees of freedom

We need **astro-observables** to disentangle the different possibilities



Neutron star static observables: Mass - Radius

The TOV impose an **univocal relation**

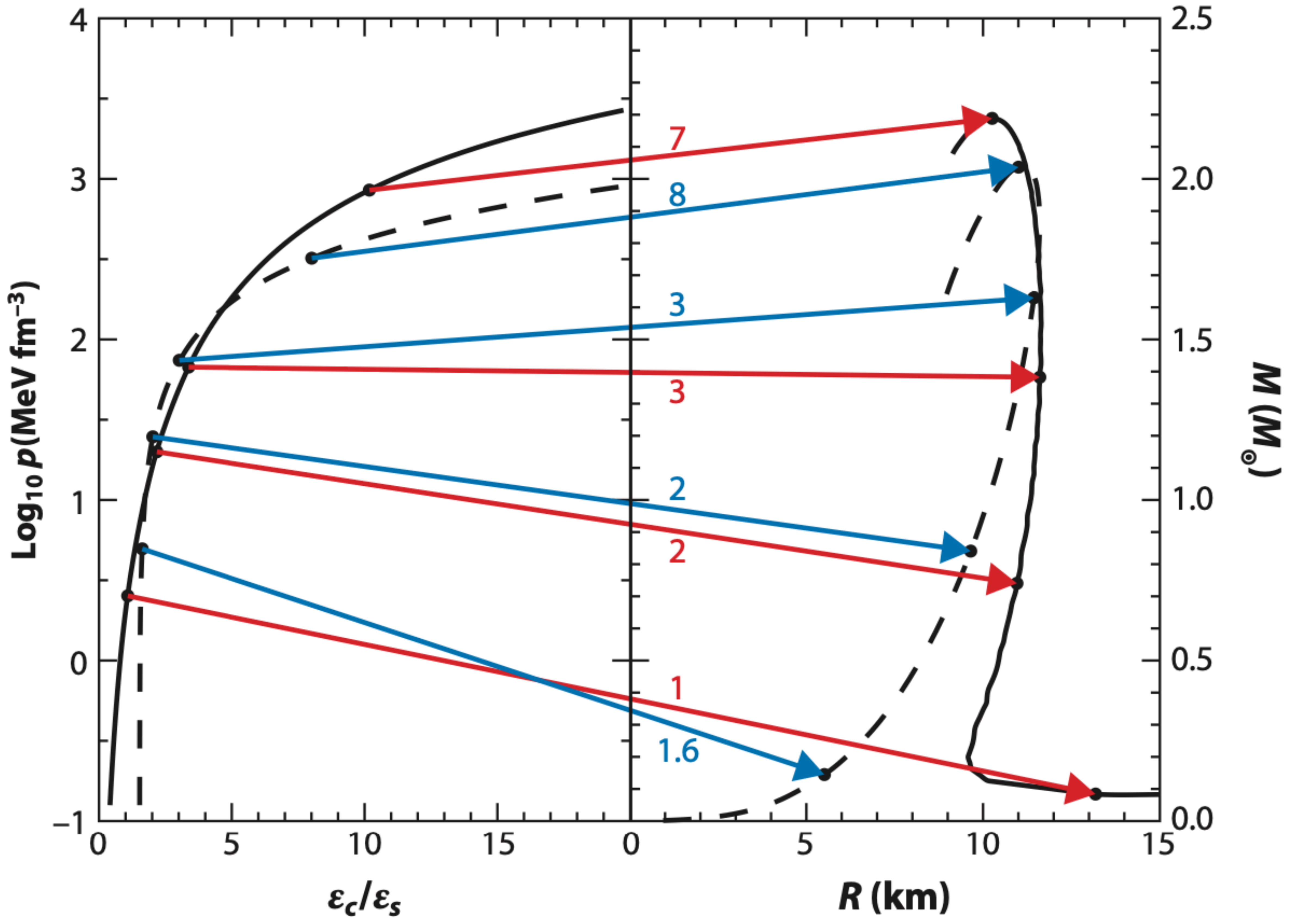
$$P(\rho) \Longleftrightarrow M(R)$$

By solving them for different central pressure (or densities) we obtain the $M(R)$

$$\frac{dP}{dr} = -\frac{(\rho + P)(M + 4\pi r^3 P)}{r(r - 2M)}$$

$$\frac{dM}{dr} = 4\pi r^2 \rho$$

J.Lattimer Ann.Rev.Nucl.Part.Sci 2012



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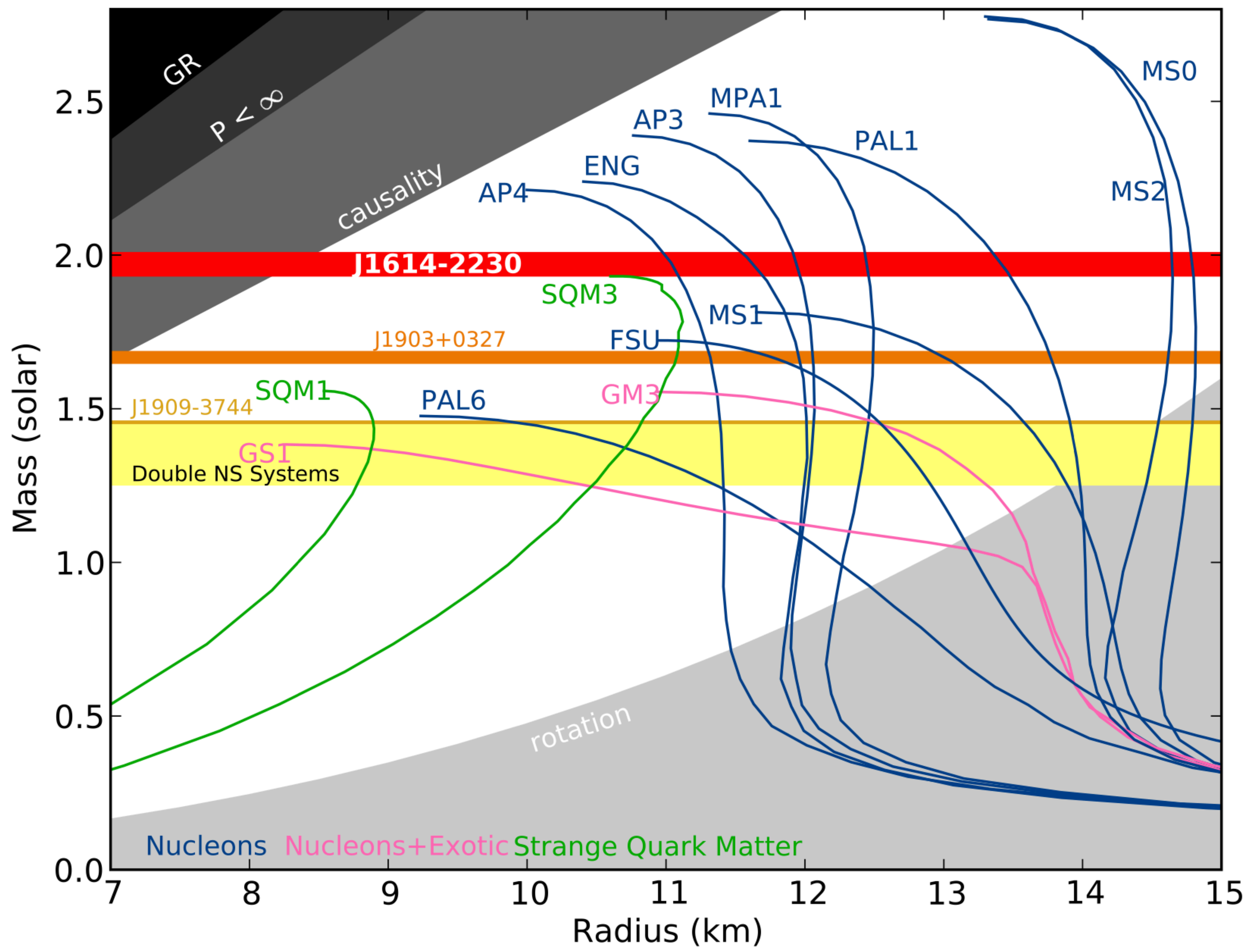
Direct probe of the equation of state

Stiffer EoS ⟶ Larger radius

Softer EoS ⟶ Smaller radius

Demorest et al, Nature 467 (2010)



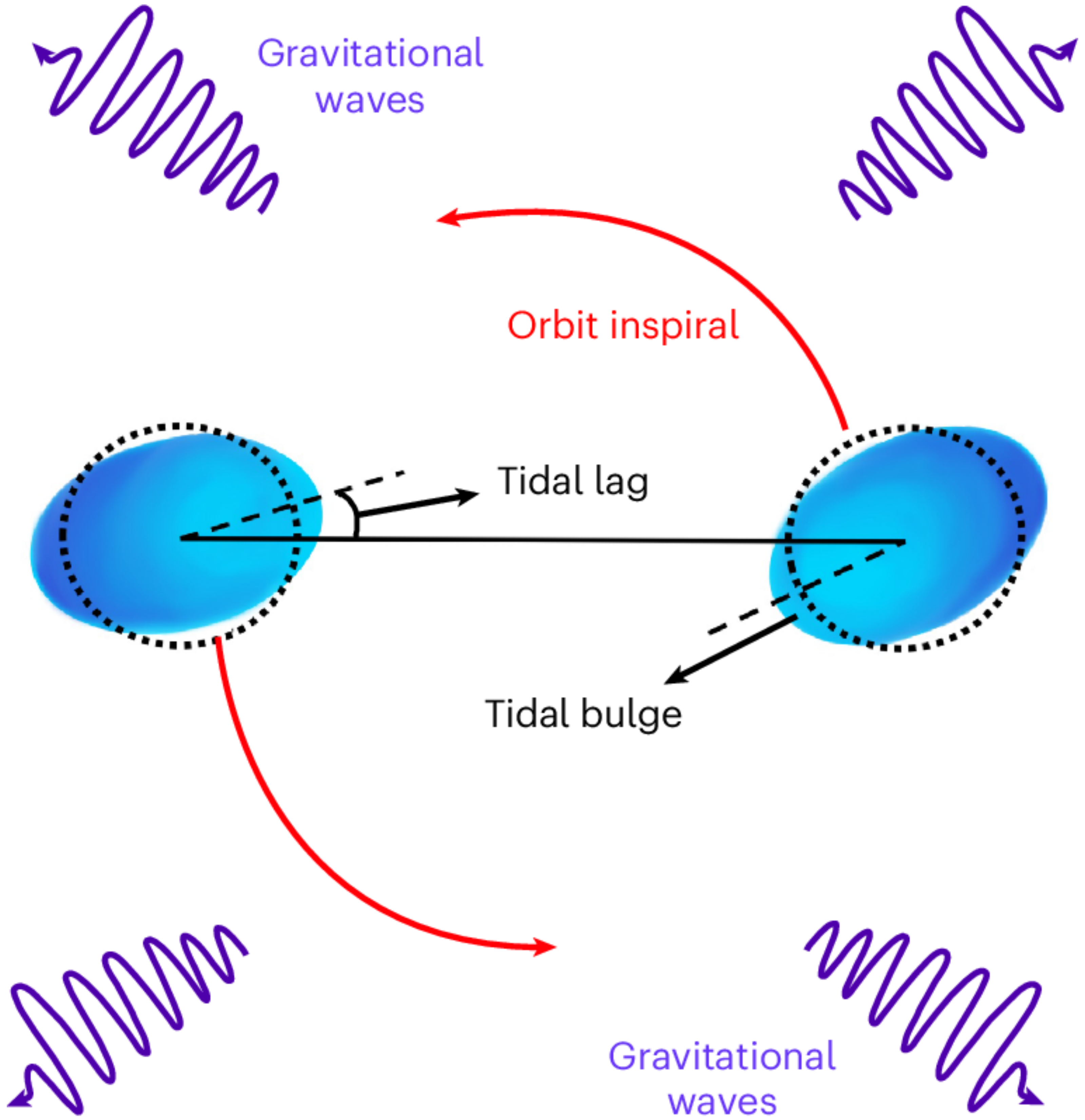
Neutron star static observables: Tidal deformability

Response of a neutron star's to its companion's tidal field in the static limit

Ripley, Hegade, Chandramouli, Nature Astronomy (2024)

Quantified by the **dimensionless tidal deformability**

$$\Lambda = \frac{2}{3}\frac{k_2(P(\rho))}{C^5} = \frac{2}{3}k_2(P(\rho))\left(\frac{R}{M}\right)^5$$



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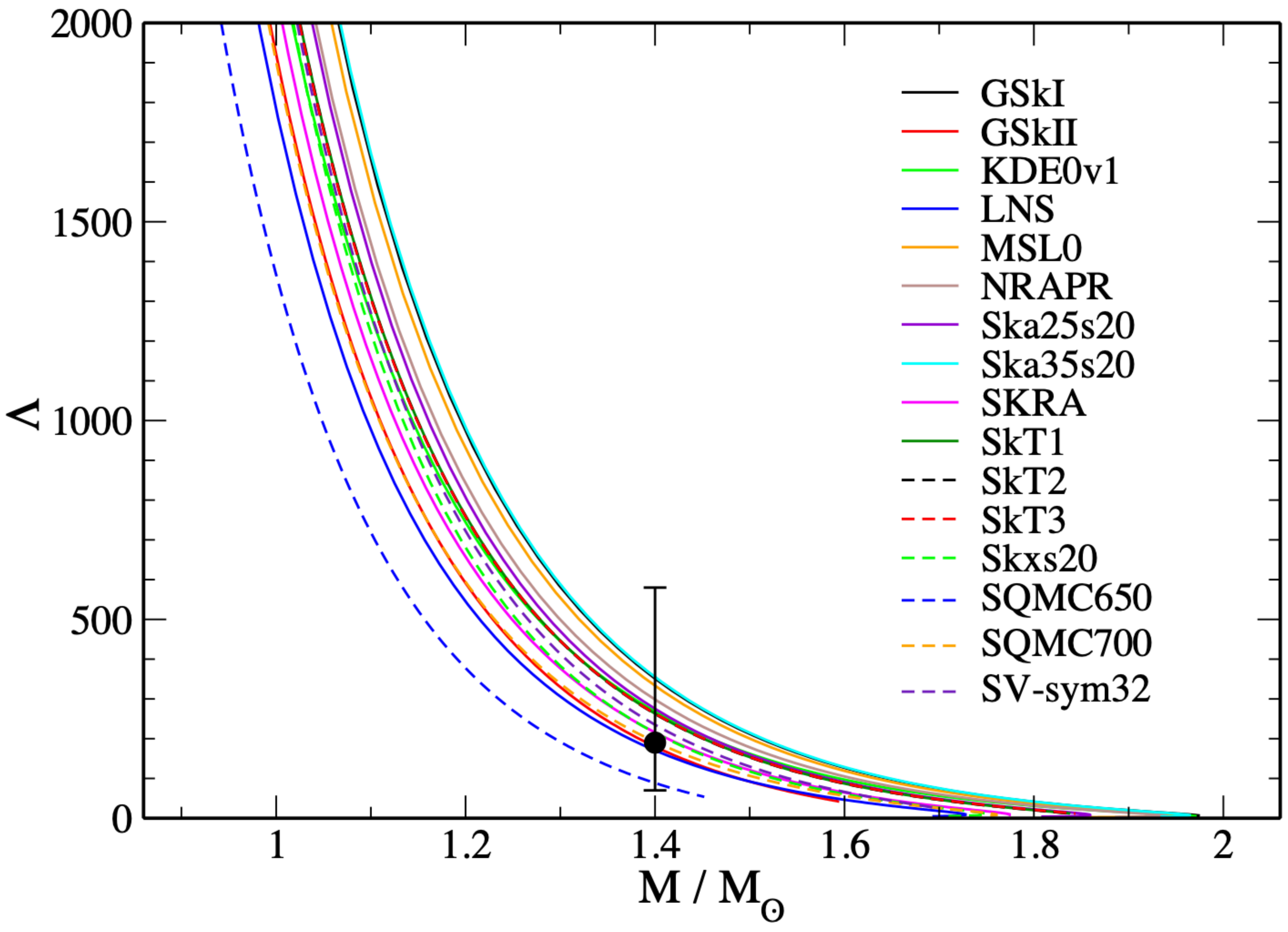
Encodes information about the **EoS**

Stiffer EoS → Larger radius → Larger Λ

Softer EoS → Smaller radius → Smaller Λ

Leaves imprints in gravitational wave signals during inspiral



The quest for the Nuclear EoS: Information across scales

Nuclear experiment

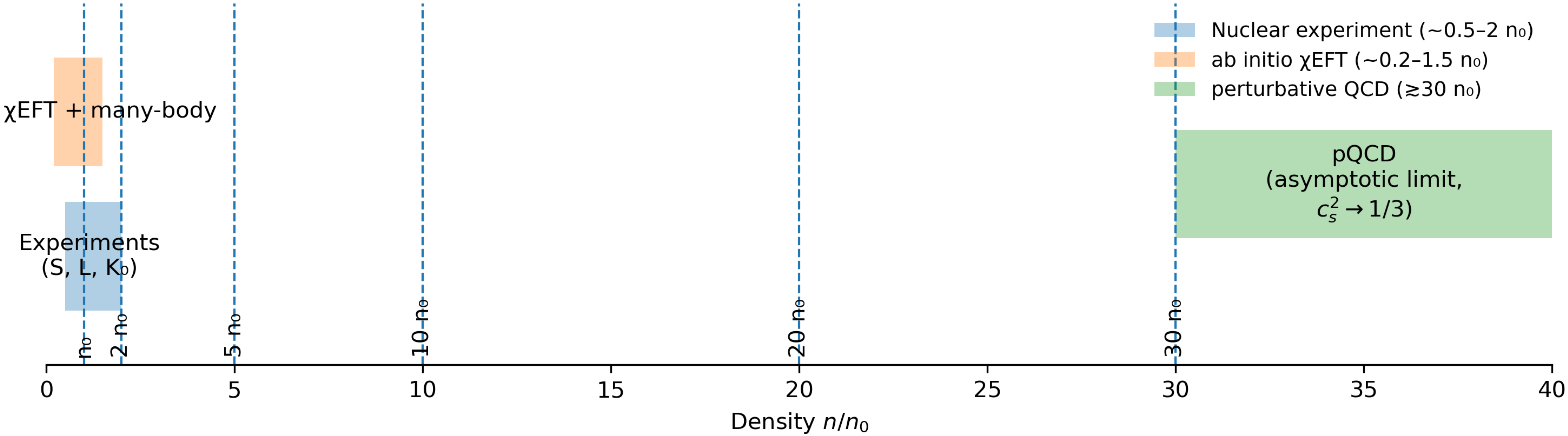
$0.5 - 2\ n_0$

χ_{EFT}

$0.2 - 1.5\ n_0$

pQCD

$> 30\ n_0$



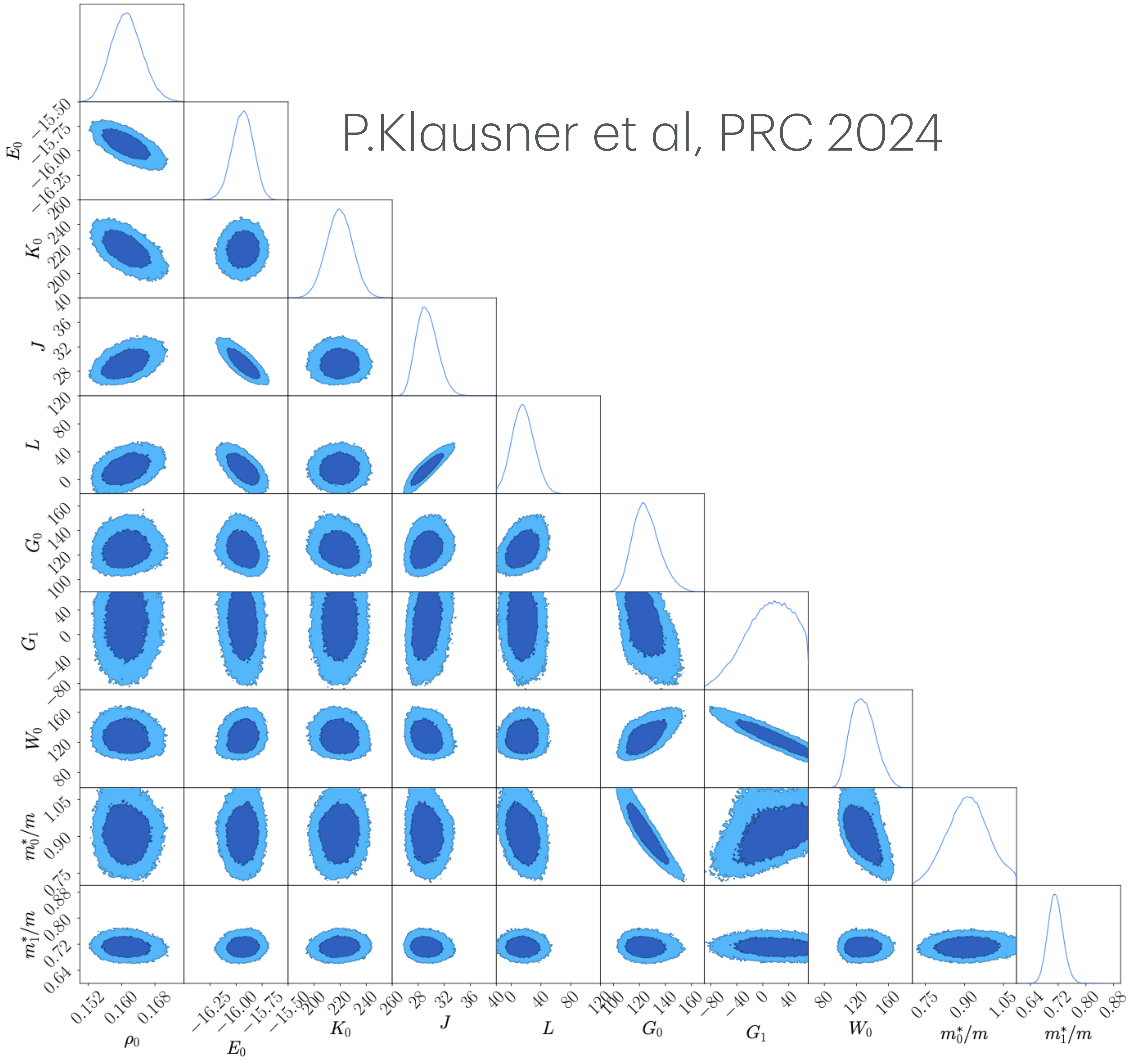
The quest for the Nuclear EoS: Nuclear experiment

Nuclear structure constrain the EOS near saturation

Ground-state properties			
	$B.E.$ [MeV]	R_{ch} [fm]	ΔE_{SO} [MeV]
^{208}Pb	1636 ± 1.8	5.49 ± 0.03	2.34 ± 0.16
^{48}Ca	417 ± 1.2	3.51 ± 0.02	1.92 ± 0.20
^{40}Ca	342 ± 1.6	3.50 ± 0.02	-
^{56}Ni	482 ± 1.4	-	-
^{68}Ni	590 ± 1.0	-	-
^{100}Sn	826 ± 1.6	-	-
^{132}Sn	1103 ± 1.7	4.71 ± 0.03	-
^{90}Zr	784 ± 1.3	4.27 ± 0.02	-

Isoscalar resonances		
	E^{IS}_{GMR} [MeV]	E^{IS}_{GQR} [MeV]
^{208}Pb	13.5 ± 0.3	10.8 ± 0.4
^{90}Zr	17.8 ± 0.4	-

Isovector properties			
	α_D [fm^3]	$m(1)$ [MeV fm^2]	A_{PV} [p.p.b.]
^{208}Pb	19.5 ± 0.5	958 ± 22	589 ± 5
^{48}Ca	2.30 ± 0.08	-	2591 ± 54



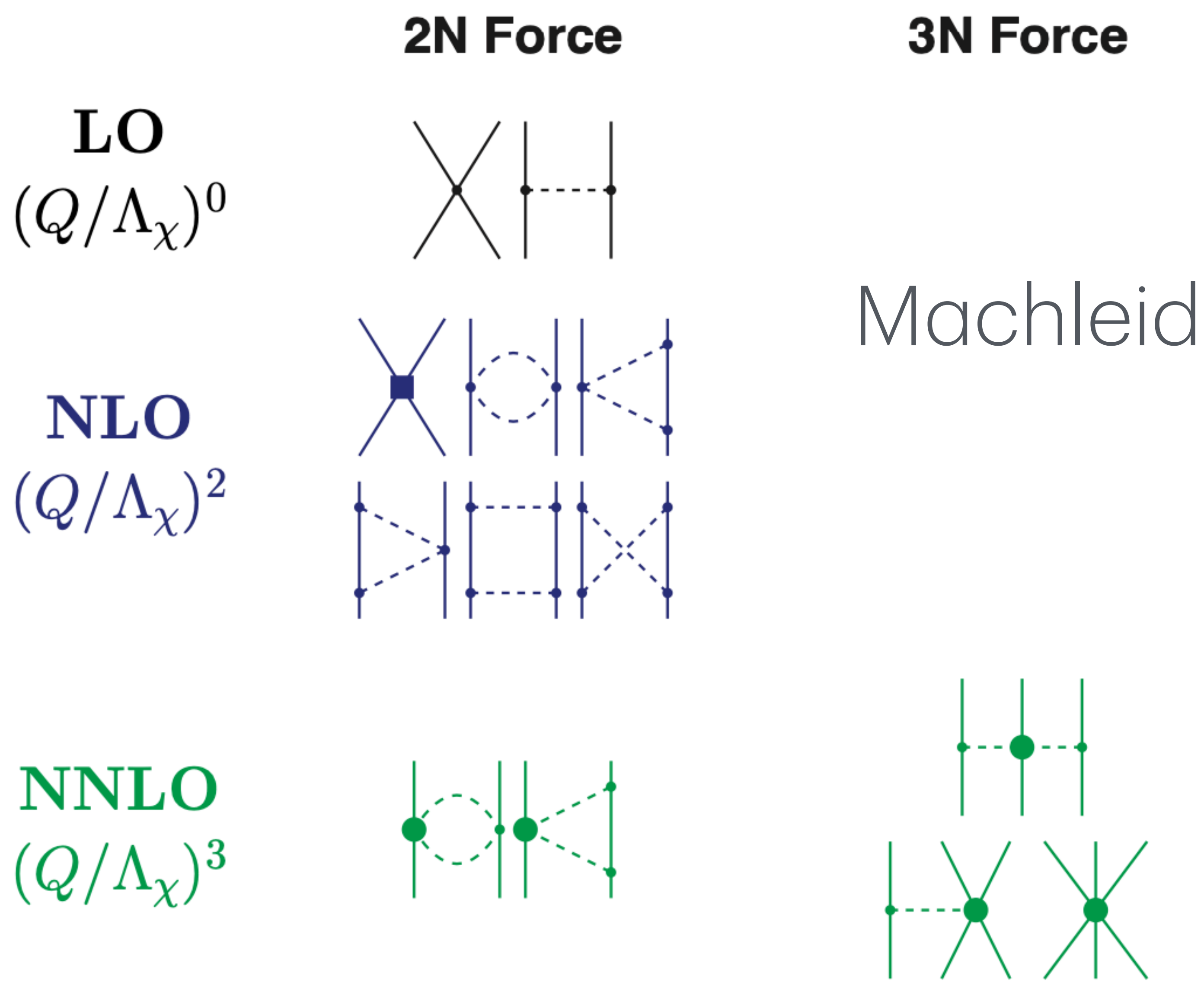
P.Klausner et al, PRC 2024

The quest for the Nuclear EoS: Ab initio Nuclear theory

Interaction from chiral effective field theory χ_{EFT}

Diagrammatic expansion → Controlled truncation errors

Momentum expansion → Only valid at low density



Machleidt R., Int J Mod Phys. (2017)

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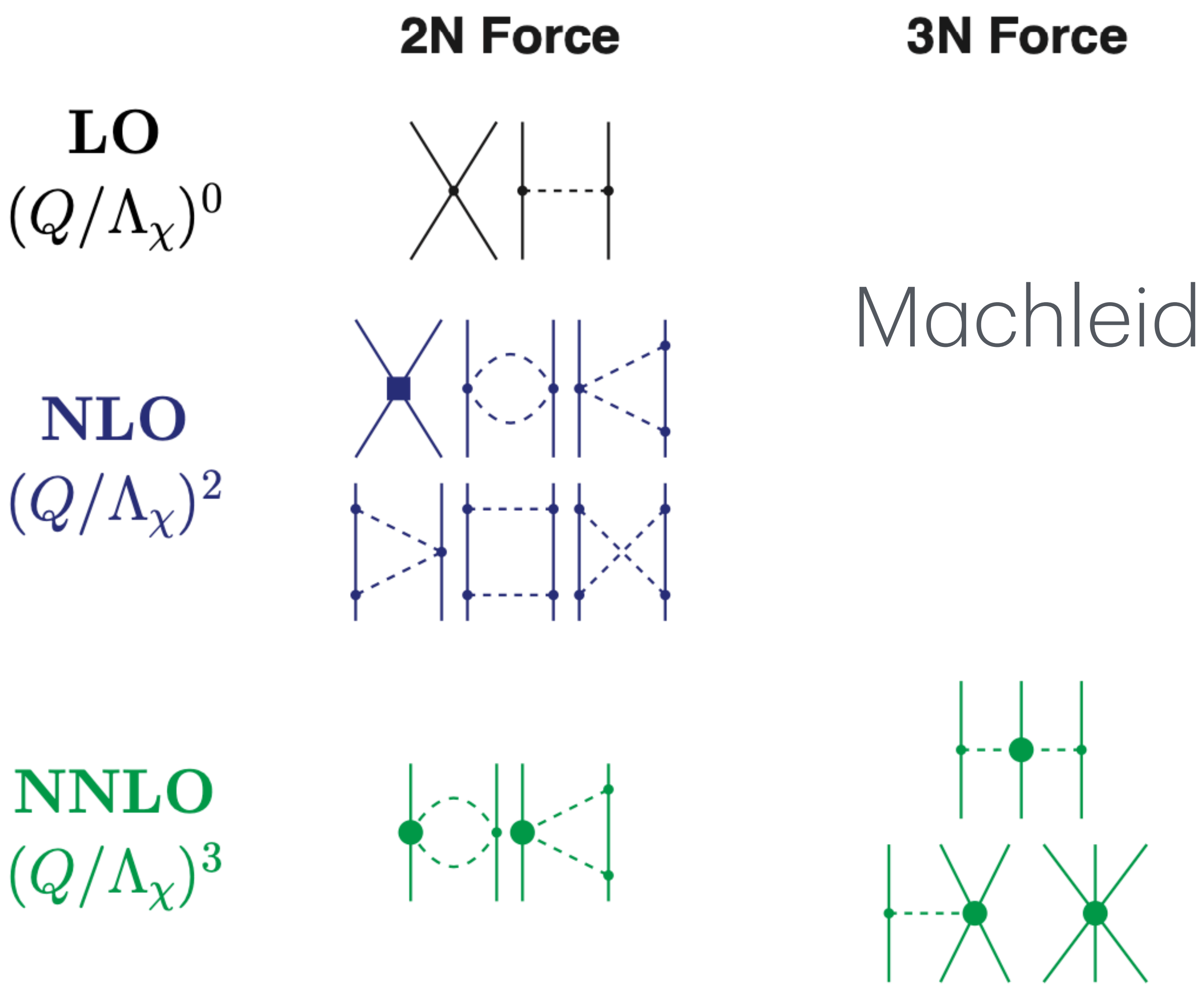
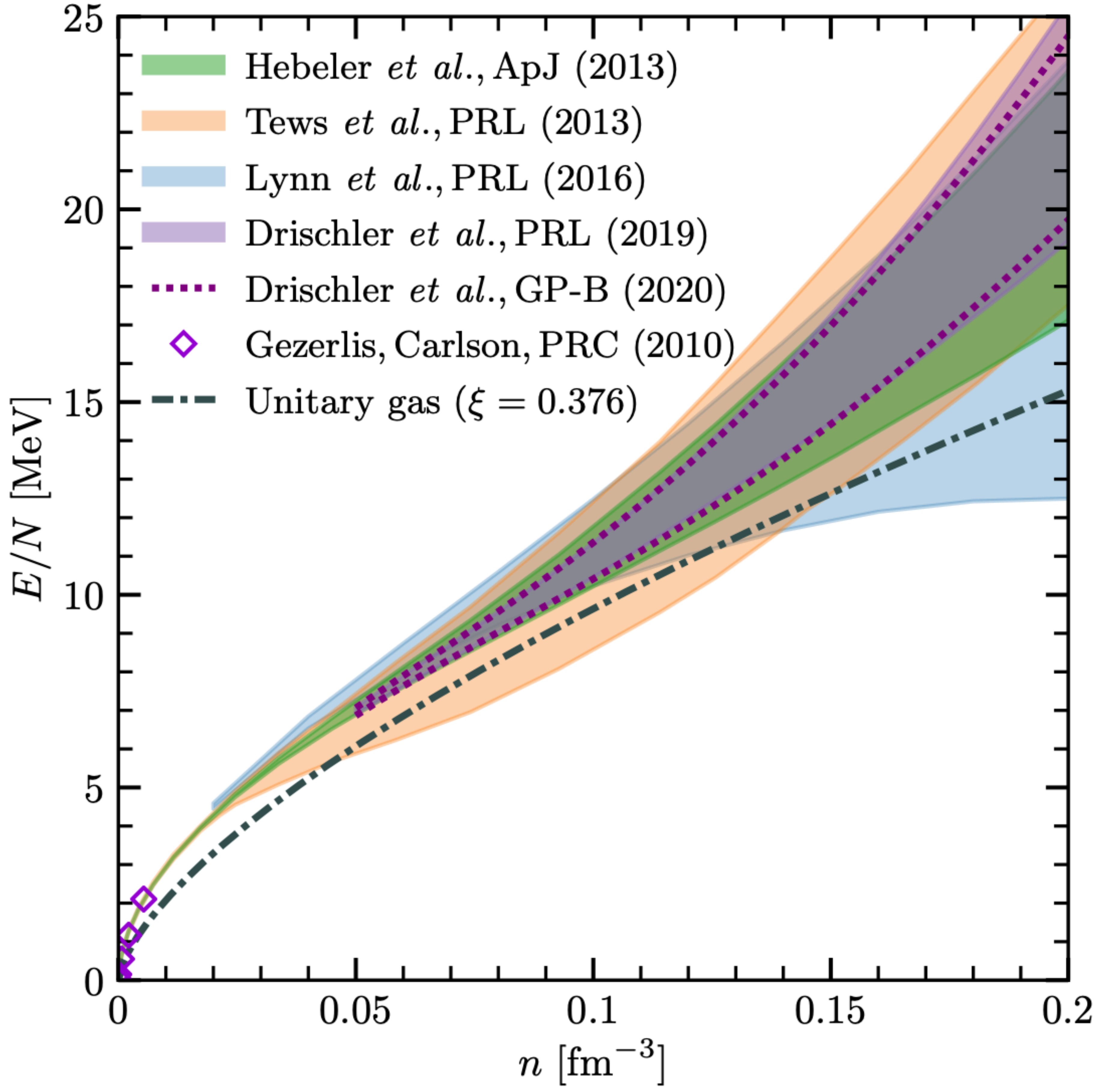


Machleidt R., Int J Mod Phys. (2017)

S. Huth et al, Phys. Rev. C 103, 025803 (2021).



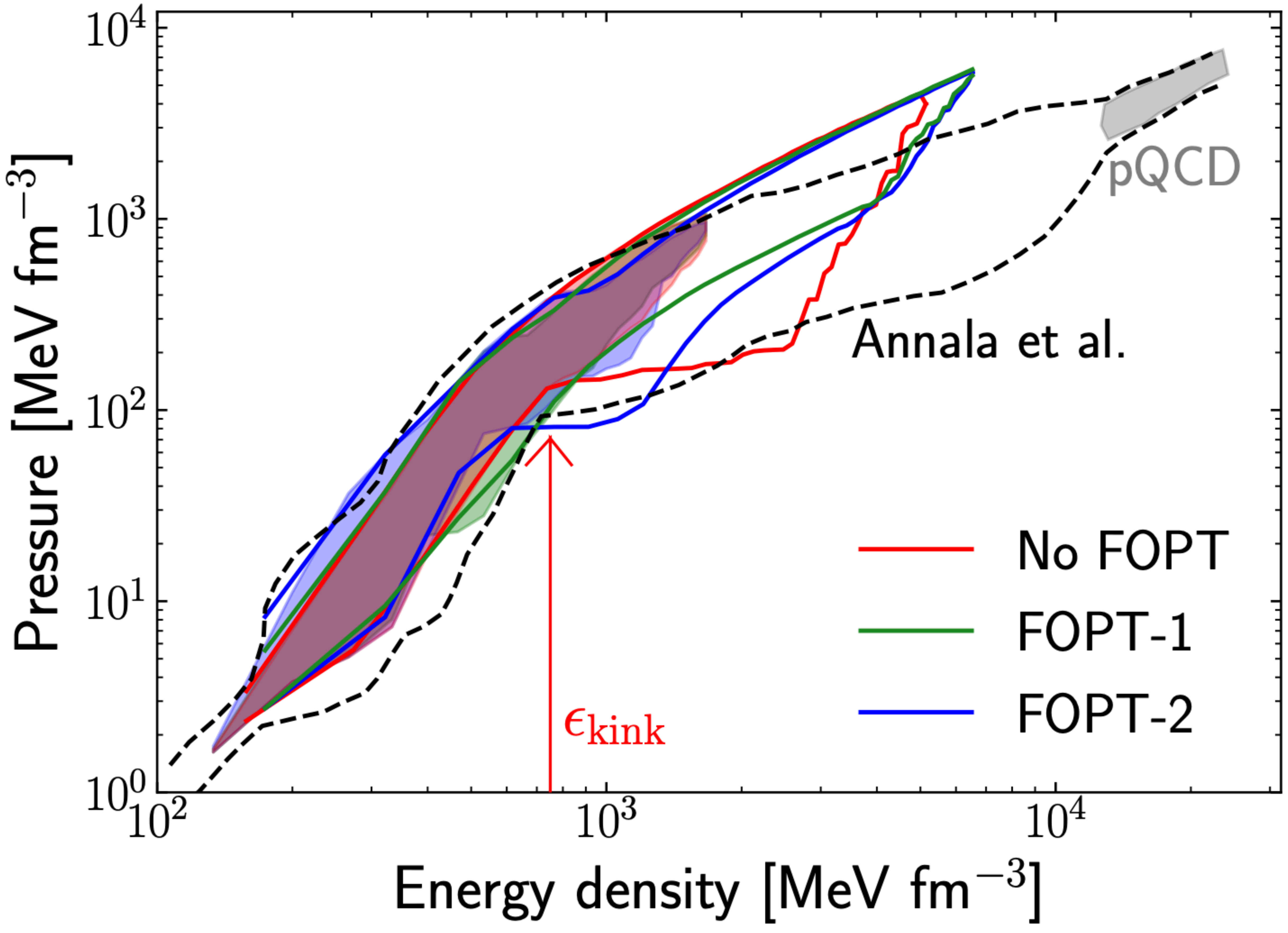
The quest for the Nuclear EoS: Perturbative QCD

At very high μ_b QCD is tractable

↓

EoS must be able to approach it consistently with thermodynamic and causality

Somasundaram et al PRC 107 (2023)



The quest for the Nuclear EoS: Perturbative QCD

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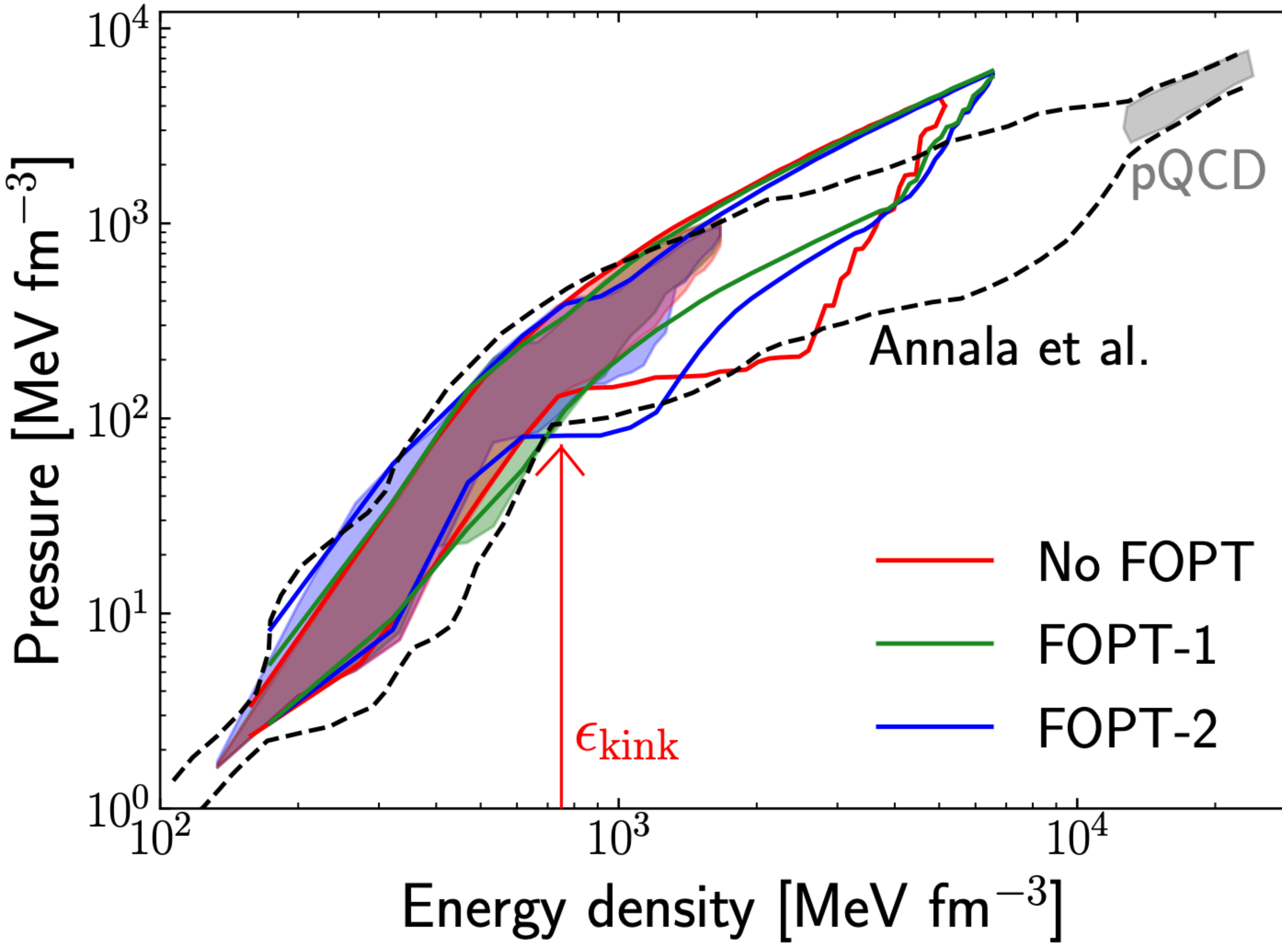
EoS must be able to approach it consistently with thermodynamic and causality

It has a softening effect

Somasundaram et al PRC 107 (2023)



The quest for Nuclear EoS: Complementing with astro-observables

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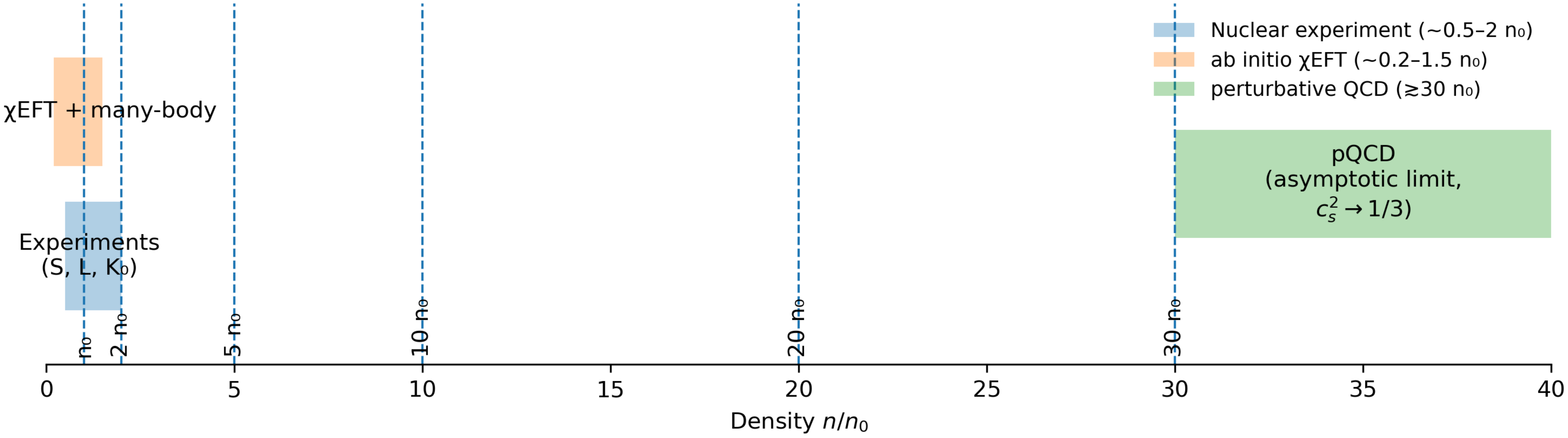

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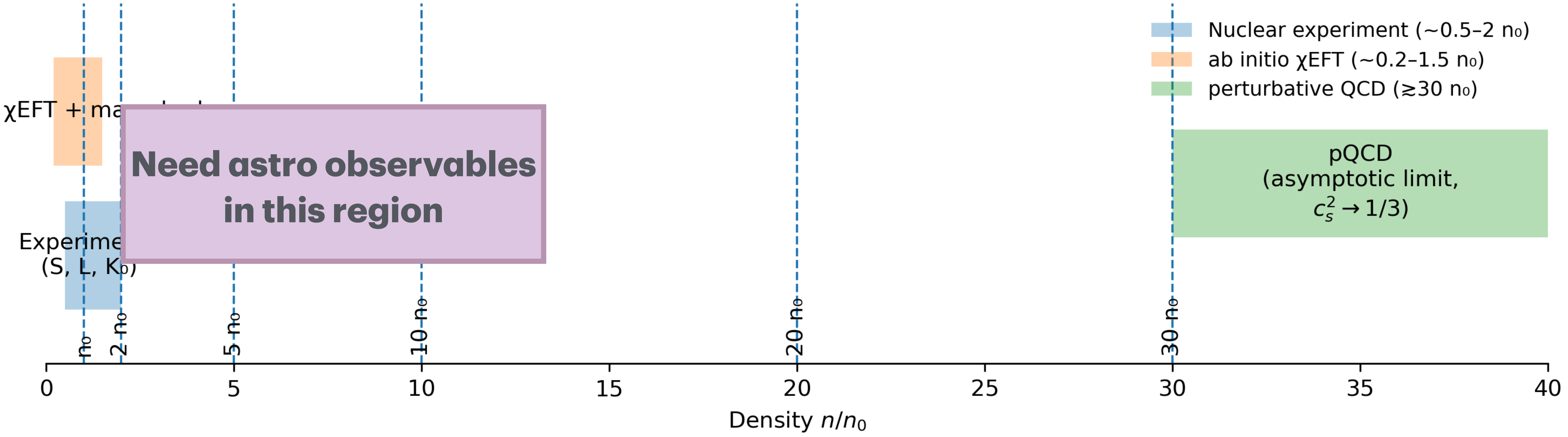


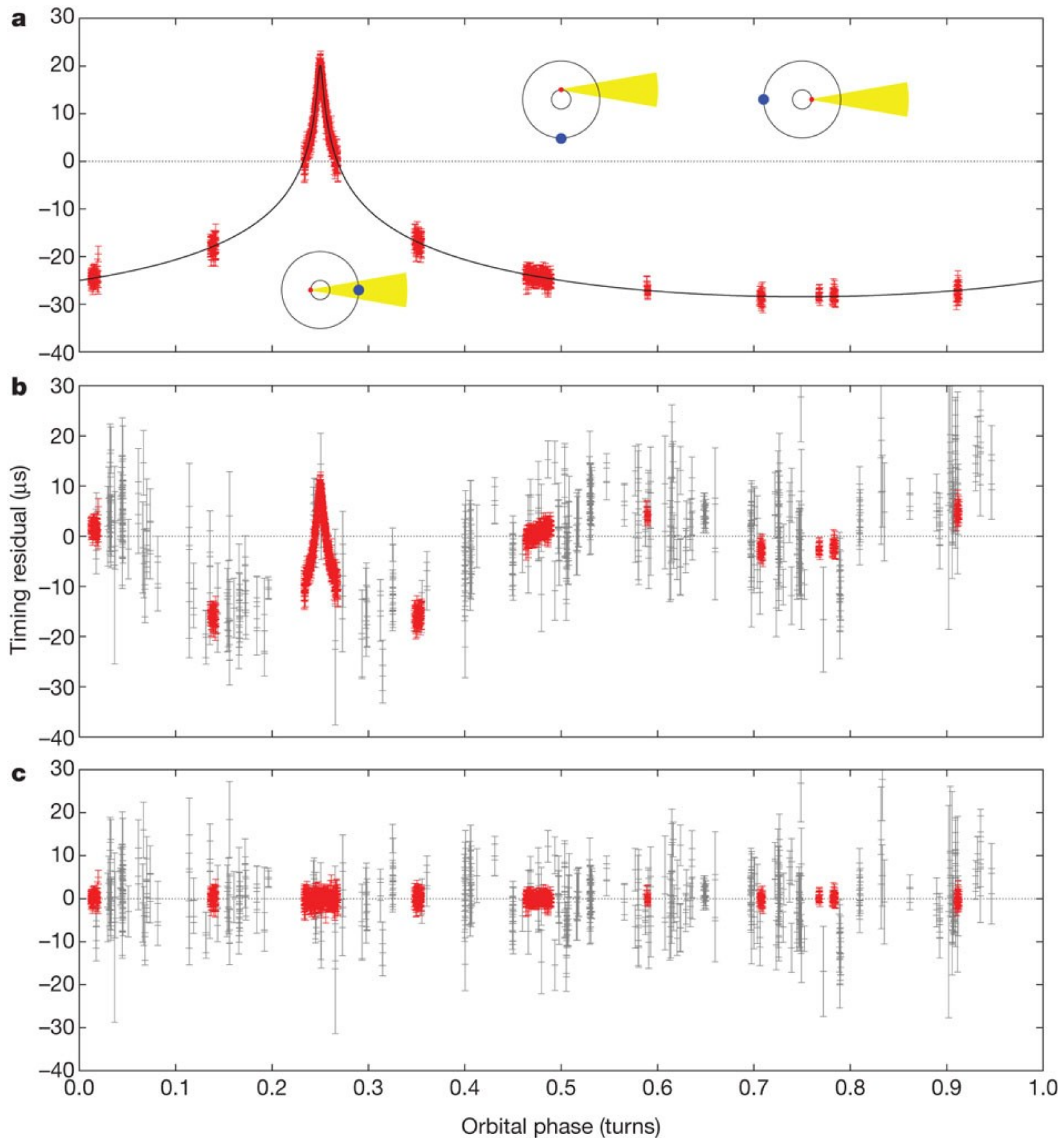
Measuring Neutron Star Masses with the Shapiro Delay

Signal delay caused when **pulsar radio waves** pass near a massive companion's

$$\Delta t \propto -2\frac{GM_c}{c^3}\ln\left(1-\sin i\,\sin\phi\right)$$

M_c and i **fitted on the measured curve**

Demorest et al, Nature 467 (2010)



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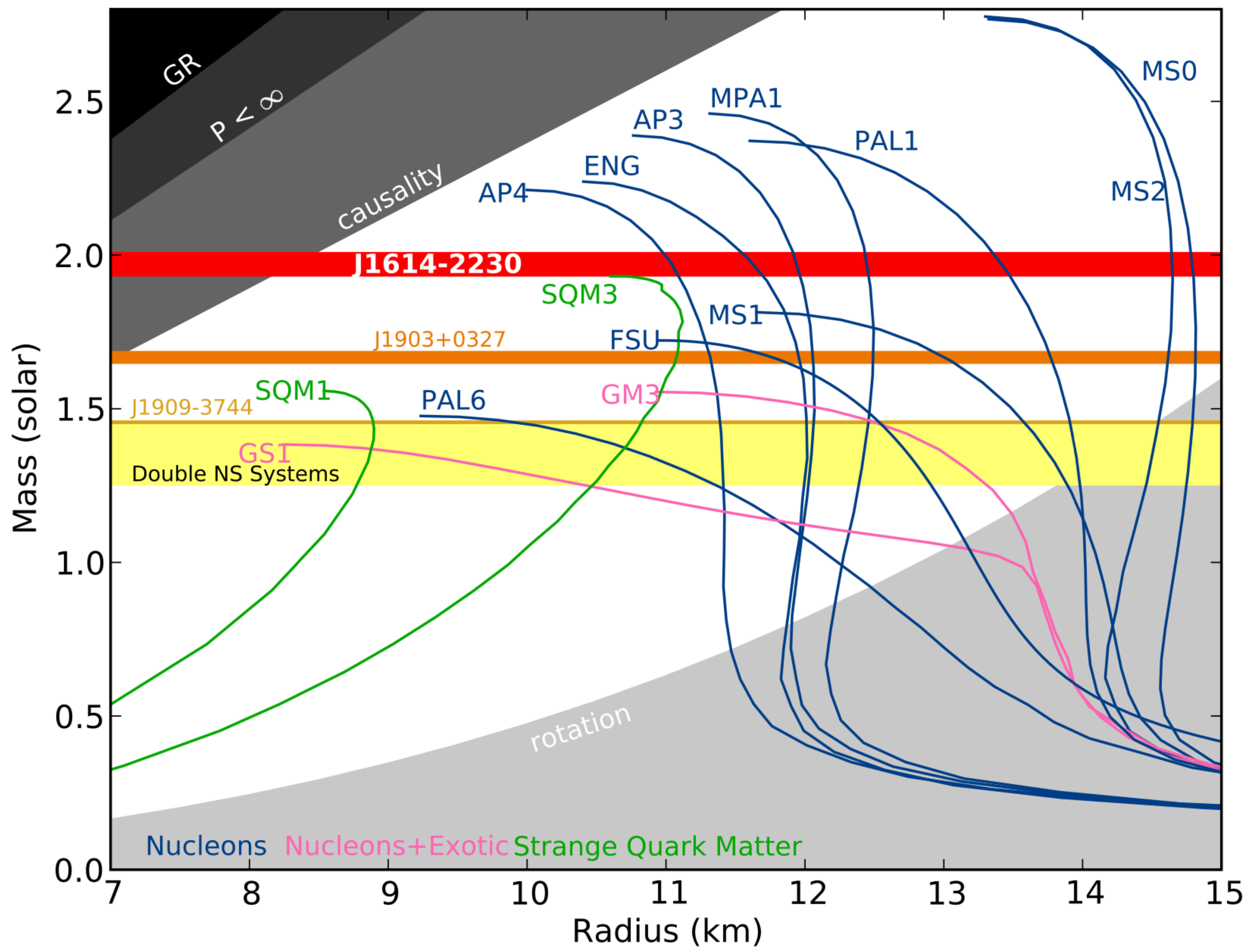
M_c and i **fitted on the measured curve**

Pulsar mass M_p **extracted from the period** once the rest is known

Demorest et al, Nature 467 (2010)



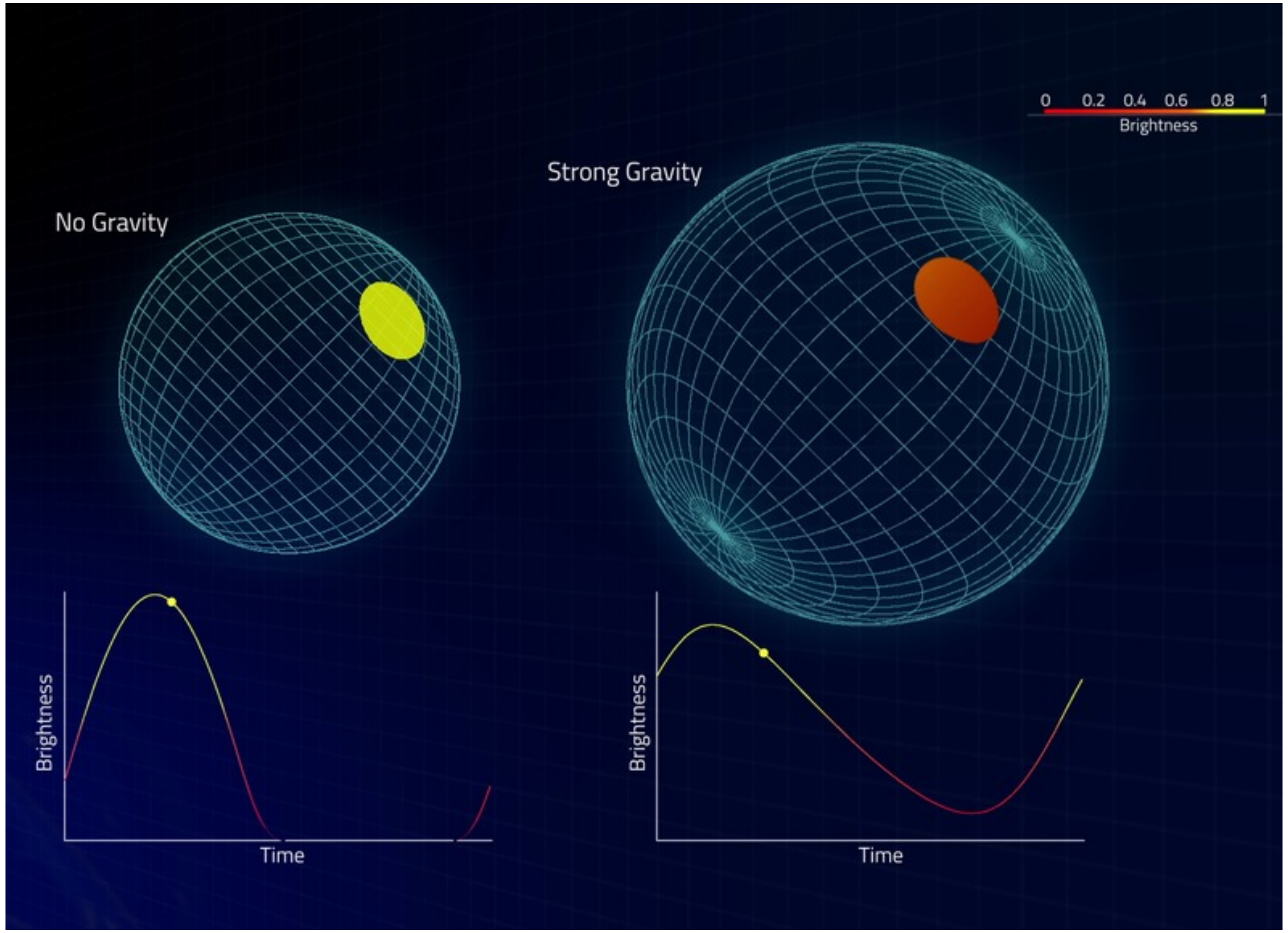
NICER Constraints on the Dense Matter Equation of State

NICER (Neutron Star Interior Composition ExploreR)

Records X-rays from **rotating hot spots** with high time and energy resolution

The shape encodes **light bending** and other effects

Stronger bending → Higher compactness M/R



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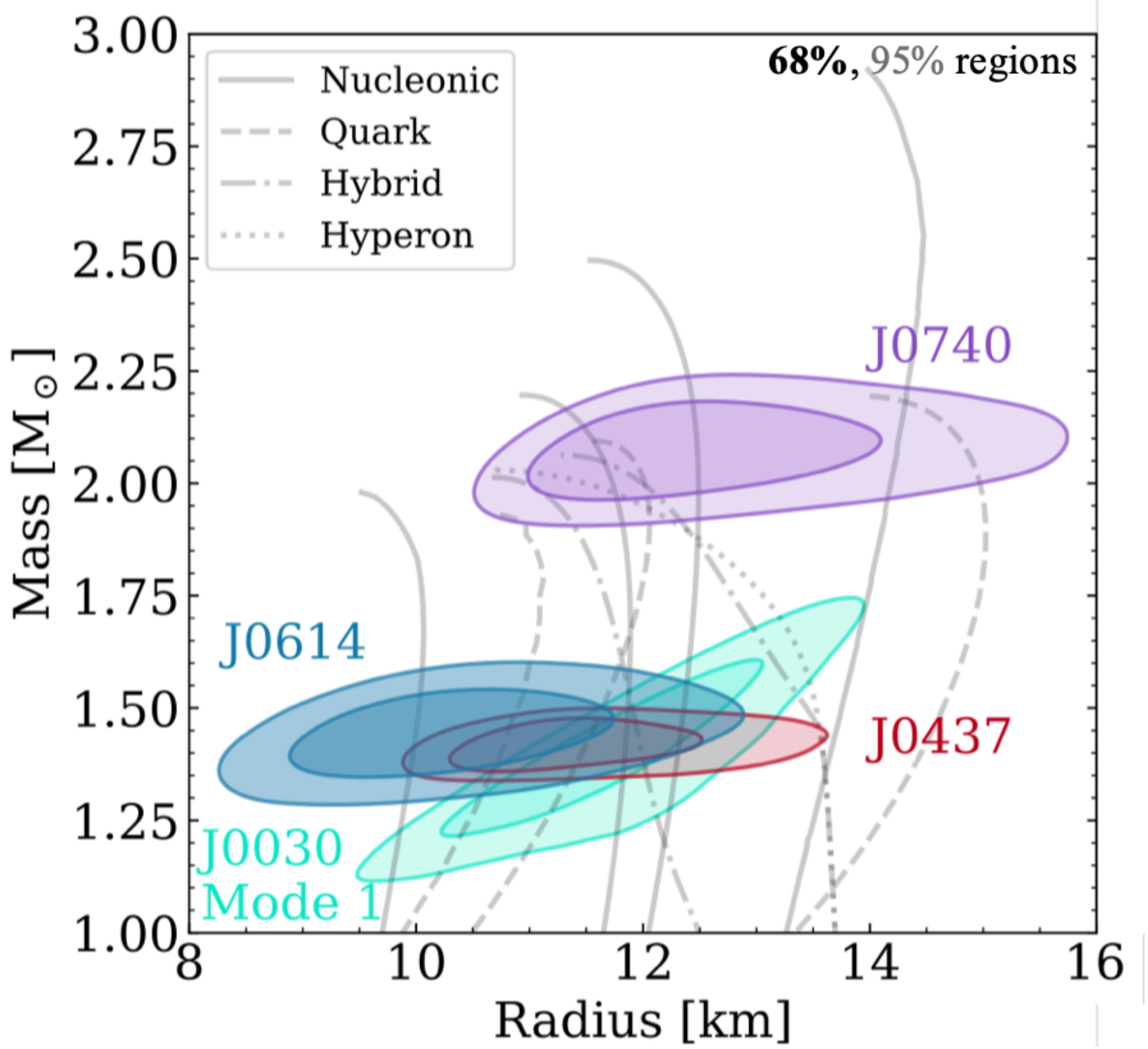
Combine with **mass estimates from other sources** to break degeneracy

Joint M-R probability



Neutron Star Mergers & Gravitational Waves

Late inspiral

Static properties:

⟶ TOV + tidal

⟶ NSs still cold

Merger

Expensive NR simulations

⟶ Big limitation

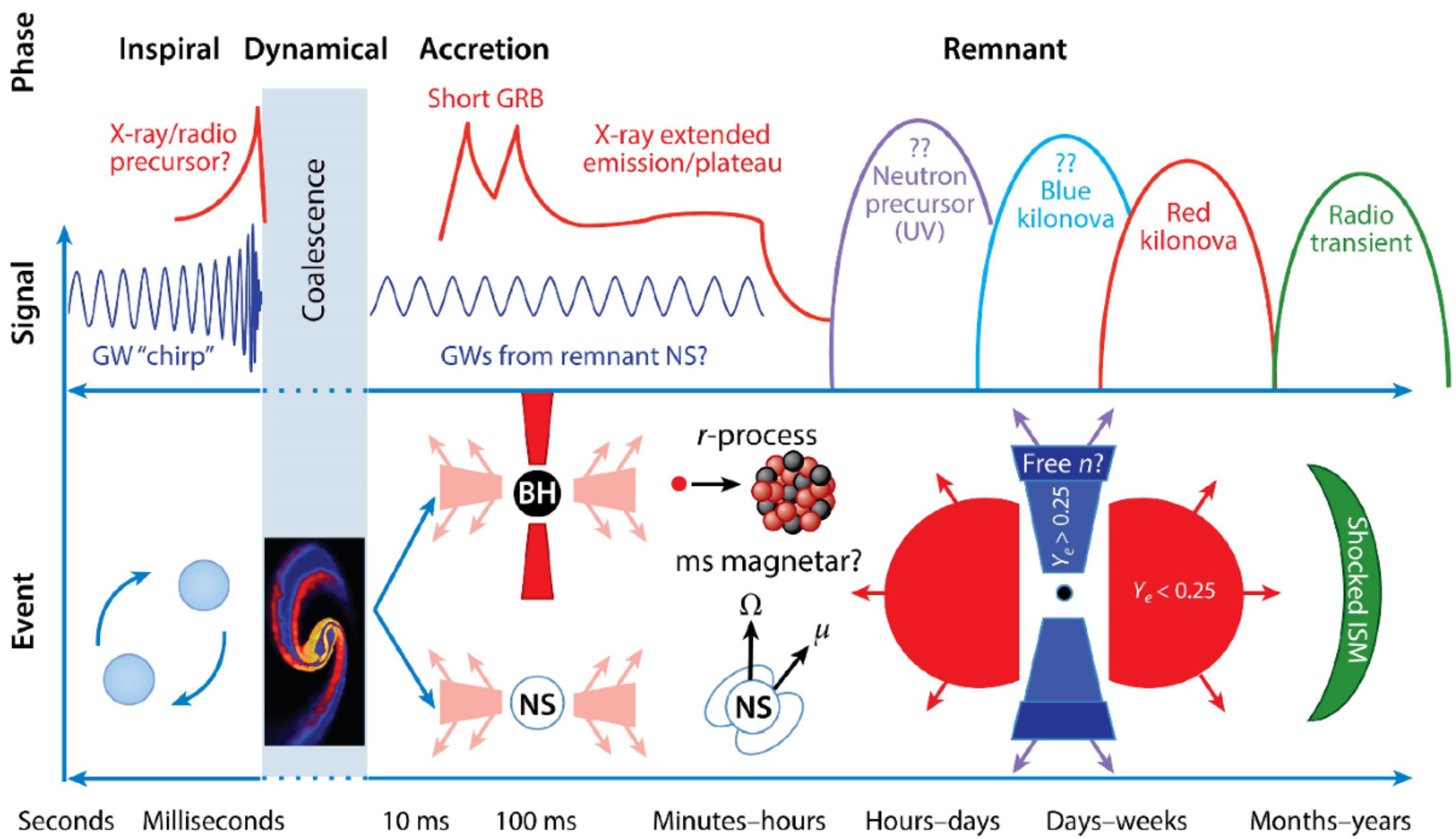
Post-merger

Hot and dense

⟶ Harder to detect

⟶ Carries a lot of EoSs information

E. Burns, Living Reviews in Relativity (2020)



Extraction of the tidal effects

Information from the inspiral:

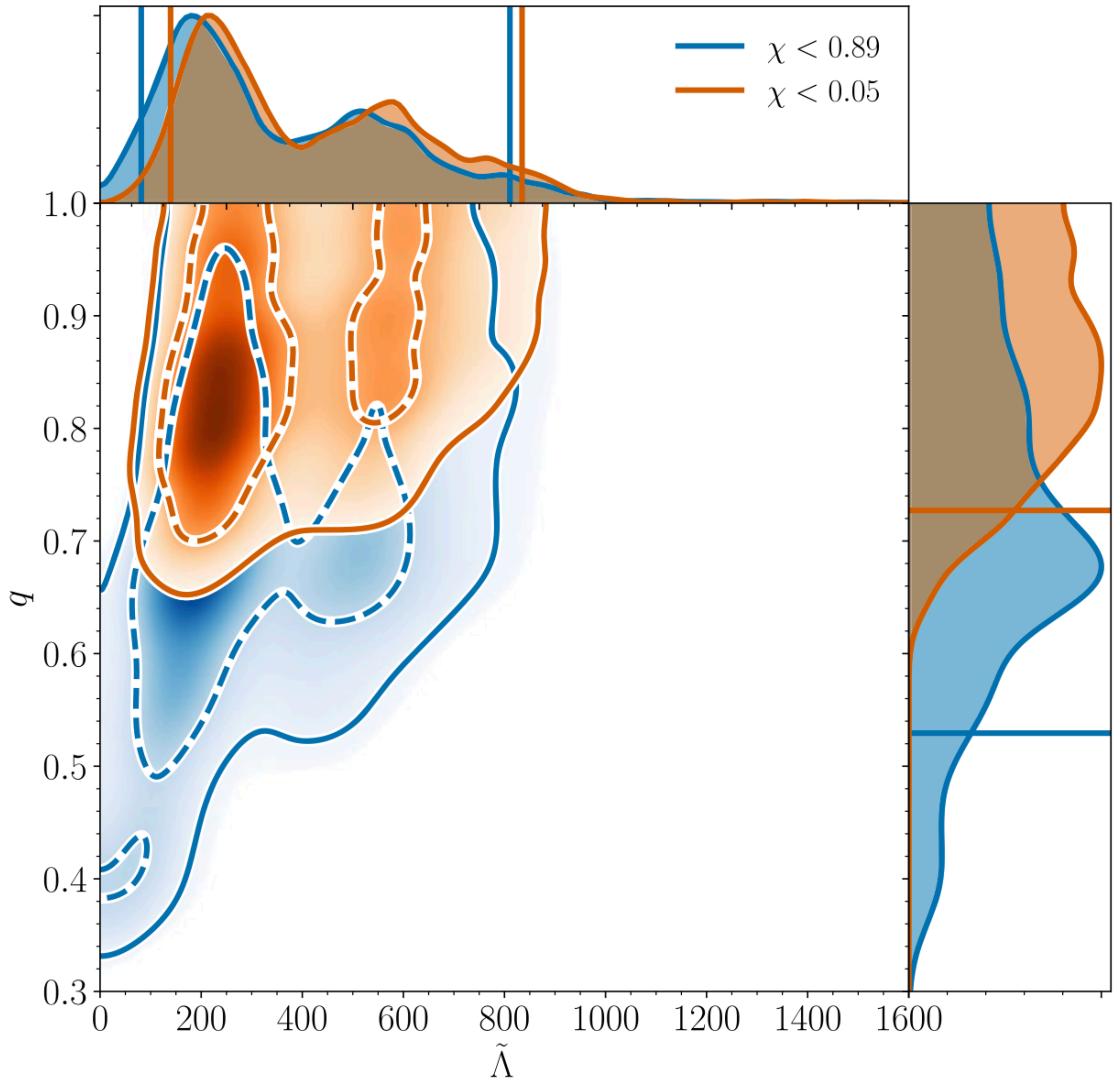
→ The joint lambda $\tilde{\Lambda}$ not Λ_1, Λ_2

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

→ The chirp mass M_c and q not m_1,m_2

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} \qquad q = \frac{m_2}{m_1}$$

LVC, PRX 9 (2019), 011001



Modelling of the EoS: Agnostic frameworks

Agnostic models aim to describe the behavior of matter at extremely high densities, as found in NS, **without specific microphysics assumptions** (e.g., baryonic composition or phases like quark matter)

Microphysics at supranuclear densities is uncertain → Avoids bias from specific nuclear or particle physics models

Certain physical condition must be fulfilled, e.g. causality $v_s < c$ and thermodynamic stability $dP/d\epsilon > 0$ → Designed to automatically enforce those

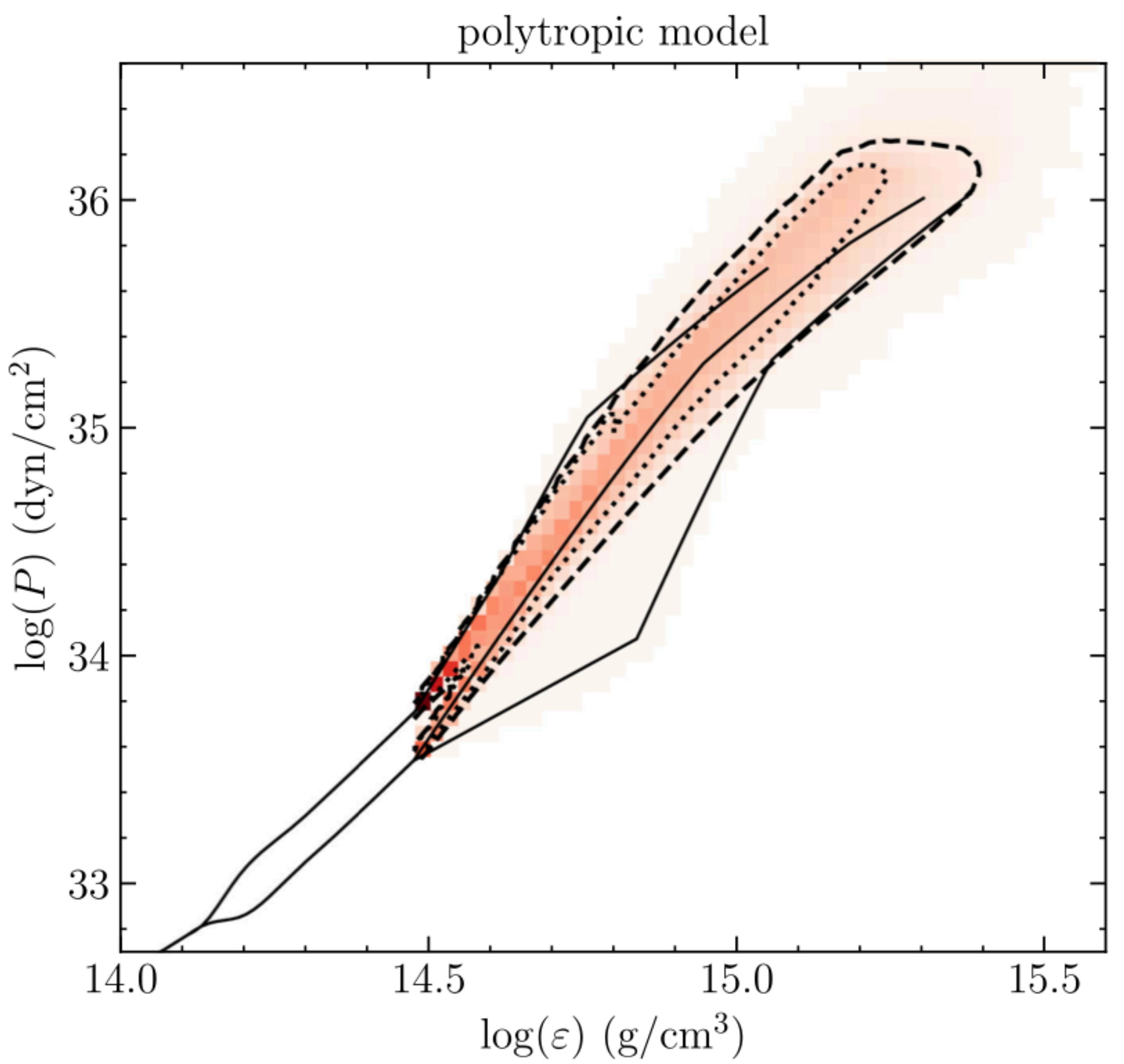
Can accommodate a wide variety of behaviors → Bayesian frameworks provide natural ways to estimate uncertainties and posterior distributions.

Modelling of the EoS: Agnostic frameworks example

Piecewise polytrope

Divide density range into segments, apply simple polytropic relation $P = k\rho^\gamma$

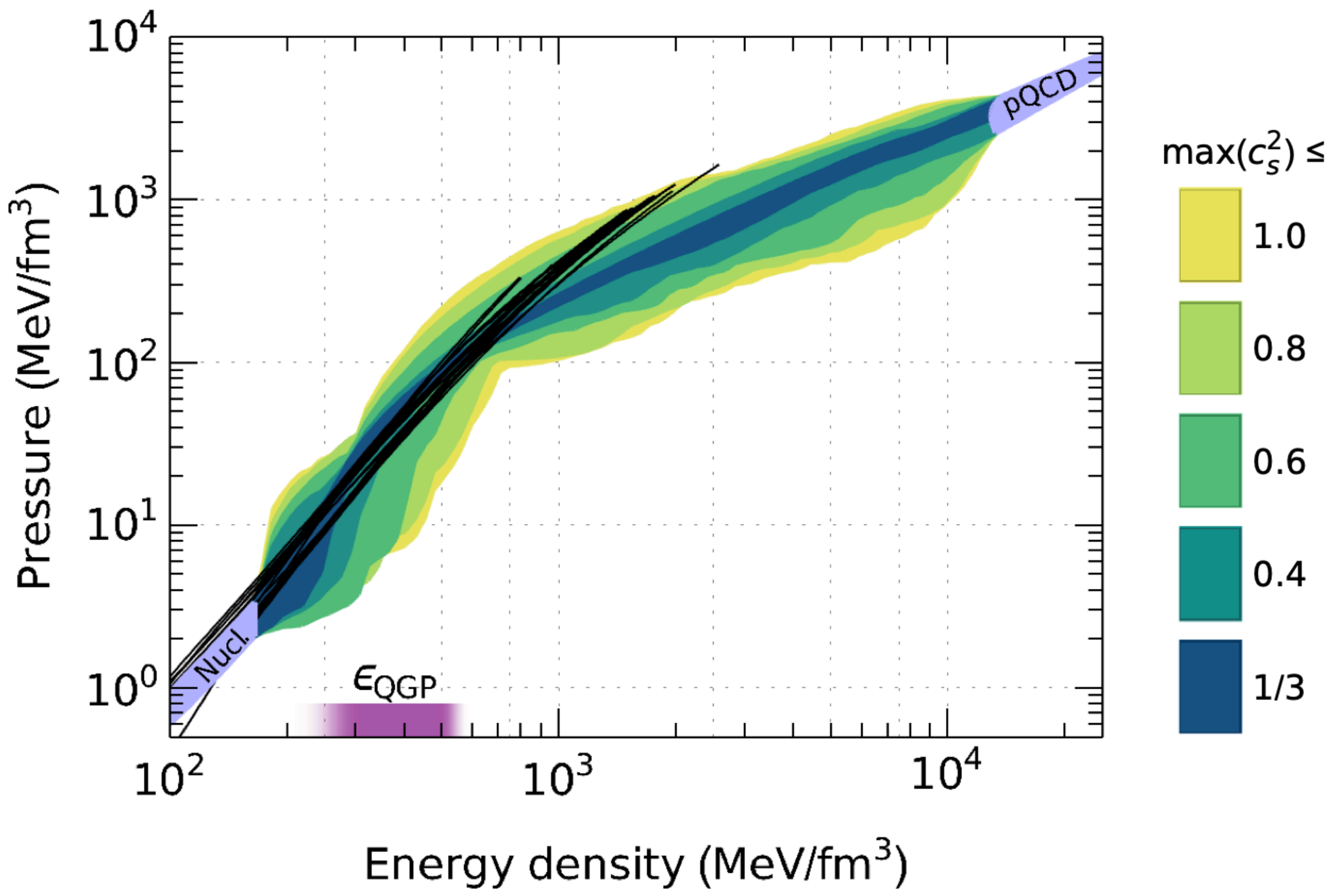
Greif et al 2019 MNRAS.485.5363G



Speed of sound models

Parametrize directly the speed of sound

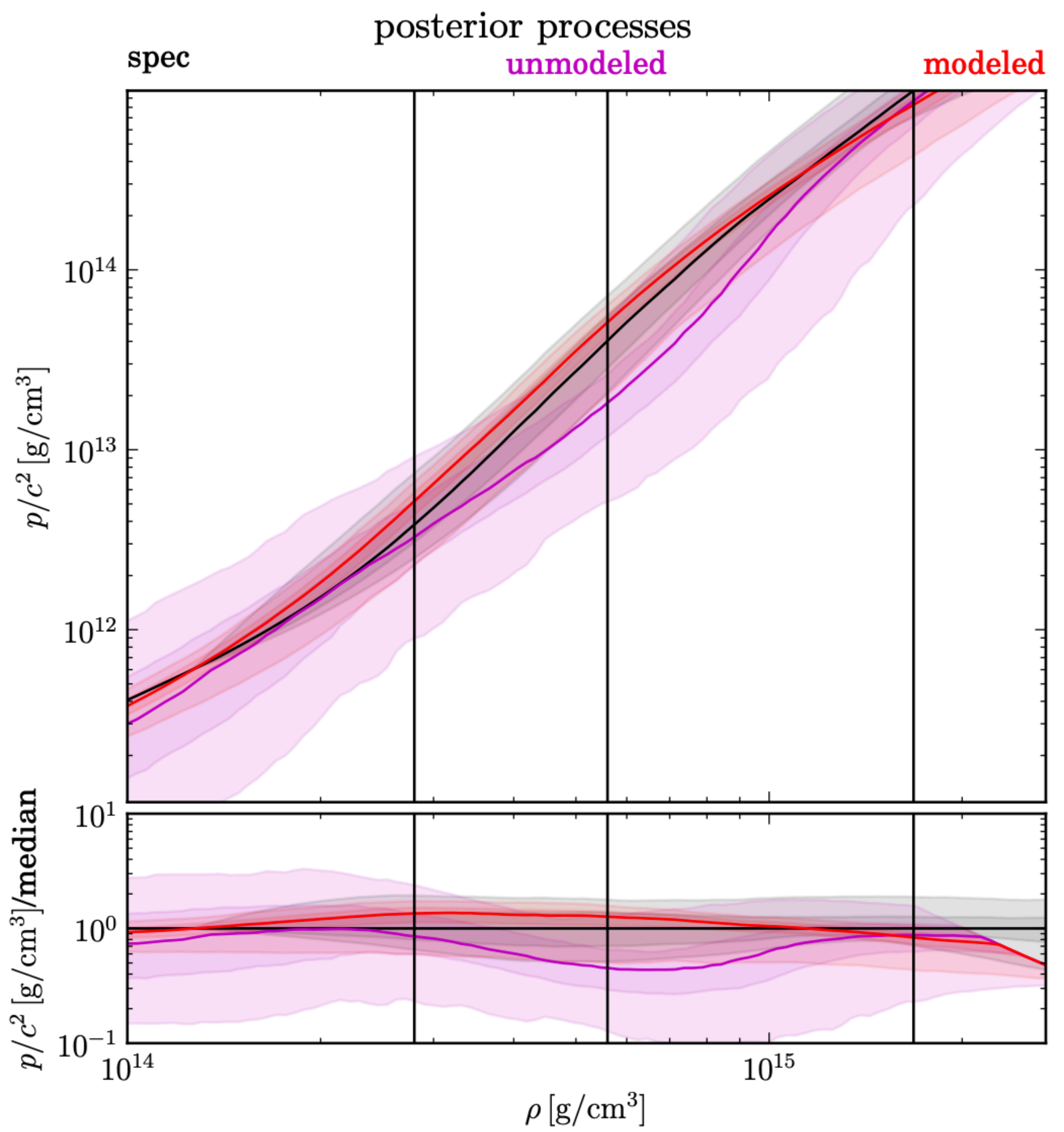
Annala et al Nature Physics (2020)



Gaussian processes

Models EoS as a random function constrained by data

Landry et al PhysRevD.99.084049



Modelling of the EoS: Density functional approach

An **Energy Density Functional** is a tool from nuclear many-body theory used to describe the energy of a nuclear system as a functional of the local densities

Experimental data above nuclear saturation density are limited	→	Computationally tractable way to model such systems
$e(\rho_b, \rho_l, \rho_s)$ directly modeled, giving access to the composition	→	Cooling, nucleosynthesis, out-of-β-equilibrium effect and transport properties
They are mostly tuned on finite nuclei and low density ab-initio	→	Natural extension to non-homogeneous phase in NS, such as crustal lattice

Modelling of the EoS: Density functional approach

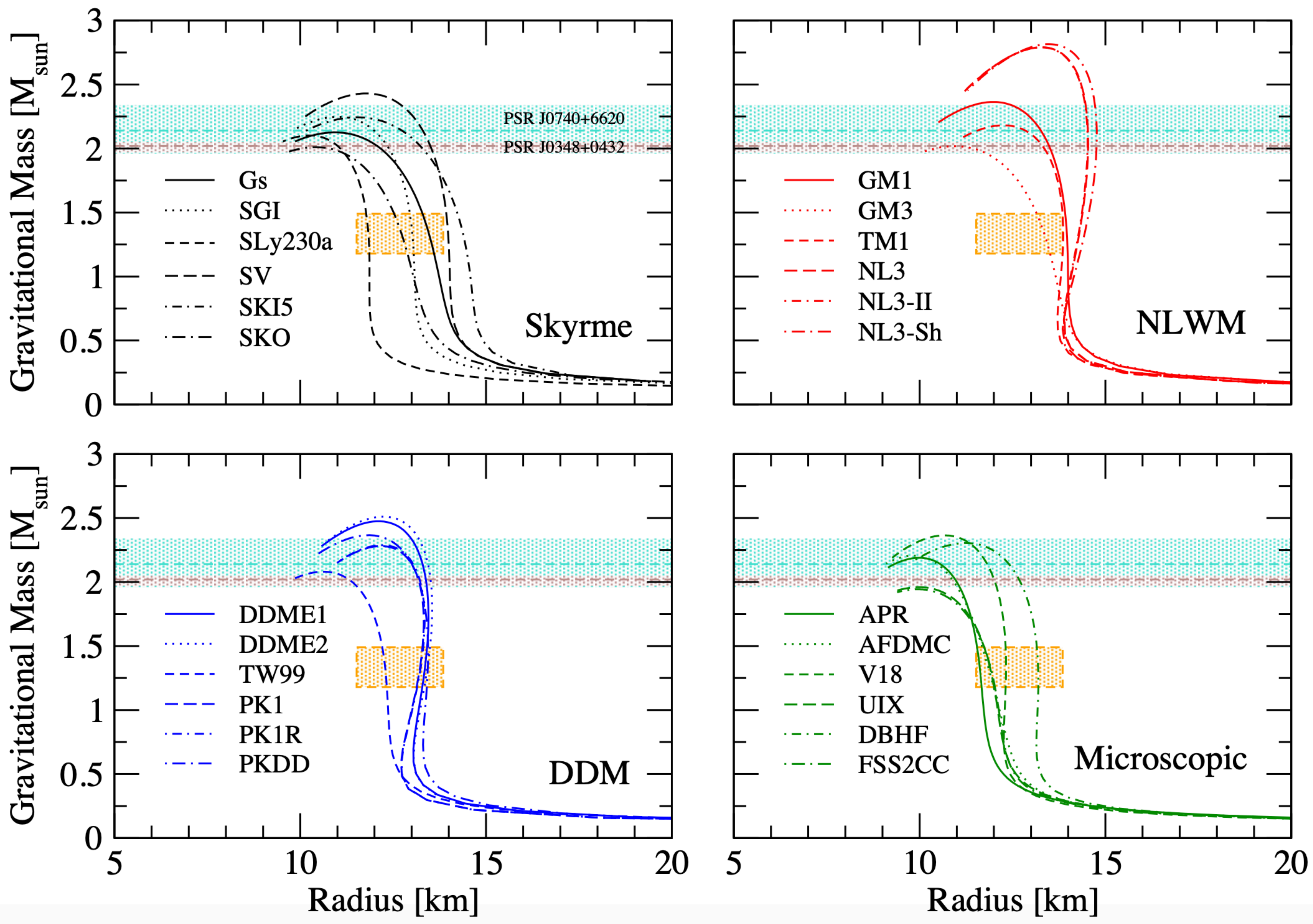
Choice of functional form

Model dependent phenomenological approach with limited connection to fundamental theory

Extrapolation Uncertainty at High Densities

Typically fitted to data at or below nuclear saturation density n_0 but NS exceed it by several times

Uncertainty grows rapidly with density, predictions diverge among different EDF



F.Burgio, I.Vidana, Universe 2020, 6, 119

Modelling of the EoS: Summary of the strategies

Two possible directions

From nuclear to astro

$$\epsilon(n_p, n_n) \Rightarrow P(\rho) \Rightarrow M, R, \Lambda$$

Controlled dof, hypotheses and approximations, exp info included

The predictive power for astro observables is limited, lack of description for exotic phases

From astro to "nuclear"

$$M, R, \Lambda \Rightarrow P(\rho) \nRightarrow \epsilon(n_p, n_n)$$

Agnostic and parametric modeling of the equation of state

Not enough constraints for the EoS, some observables not accessible (e.g. cooling or g-modes)

A point in between: Meta-modelling of the EoS

Originally presented in [PRC 97, 025805 (2018)]

Parametric representation of the energy density $\epsilon_X(n_n, n_p, ...)$ as a function of the different species

The variation of the parameters set X makes possible to explore the EoS space compatible with the hypothesis of a matter with the chosen species

Both nuclear and Astro observables are accessible

r_i, BE_i ⟹ $e_X(n_n, n_p, ...)$ ⟸ M, R, Λ

Nuclear observables

Astro observables

Almost causal meta-model: A possible choice of the energy density

Montefusco et al [in prep]

Causality asymptotically implemented

Starting ansatz:

Nuclear asymmetry

$\delta = 1 - 2(x_e + x_\mu)$

Quartic correction

$$e_4(n) = A\frac{n/n_0}{1 + \left(n/n_0\right)^B}$$

$$\epsilon(n, x_e, x_\mu) = \epsilon_k(n, x_e, x_\mu) + n\left[e_0(n) + \delta^2 e_2(n) + \delta^4 e_4(n)\right]$$

free fermi gas energy density for $npe\mu$ matter

Nucleonic Potential (per baryon)

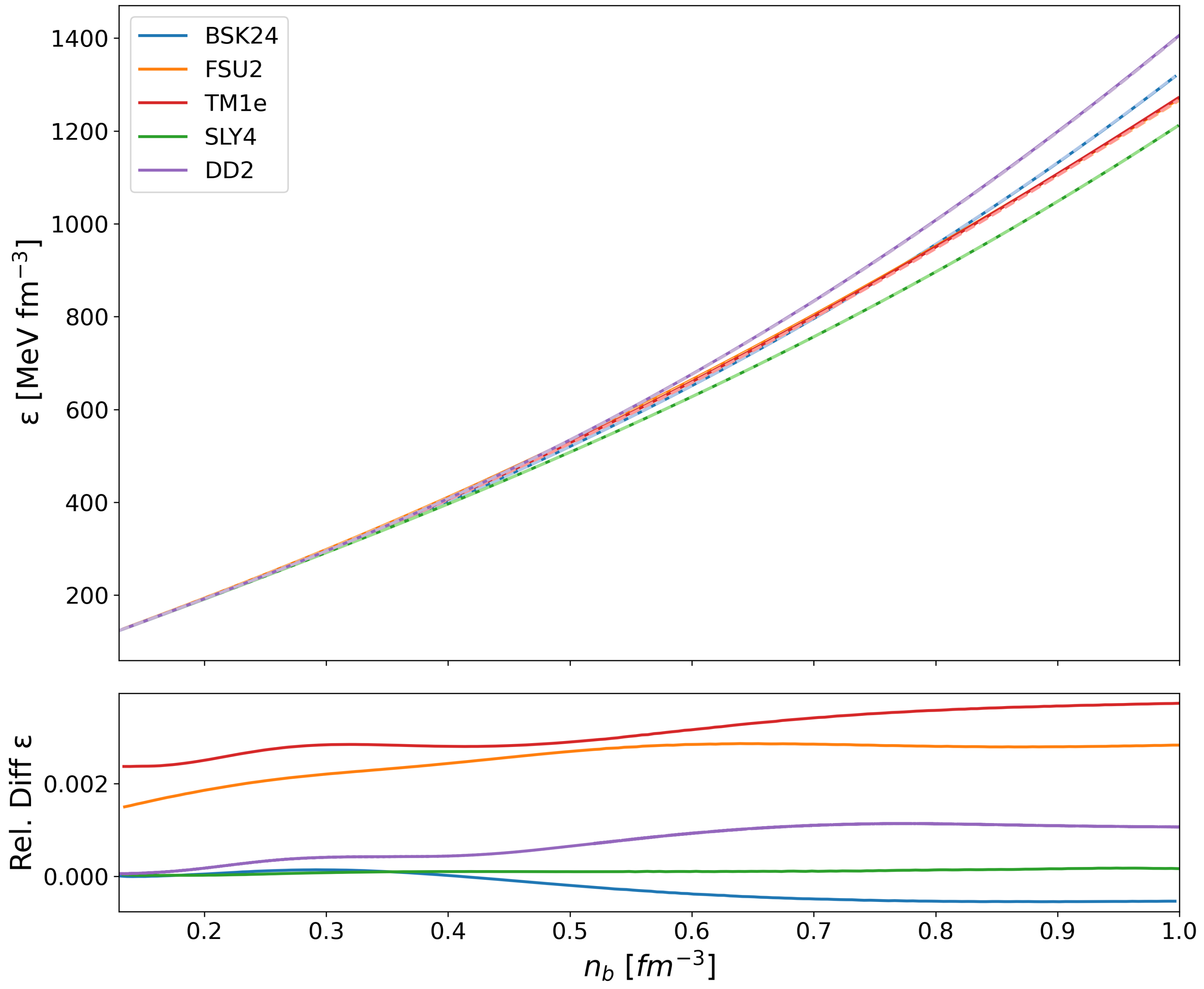
$$e_0(x) = V_0(x) + \frac{h_0 + h_1 x + h_2 x^2 + h_3 x^3}{(1 + a_0 x)(1 + b_0 x)(1 + c_0 x)}$$

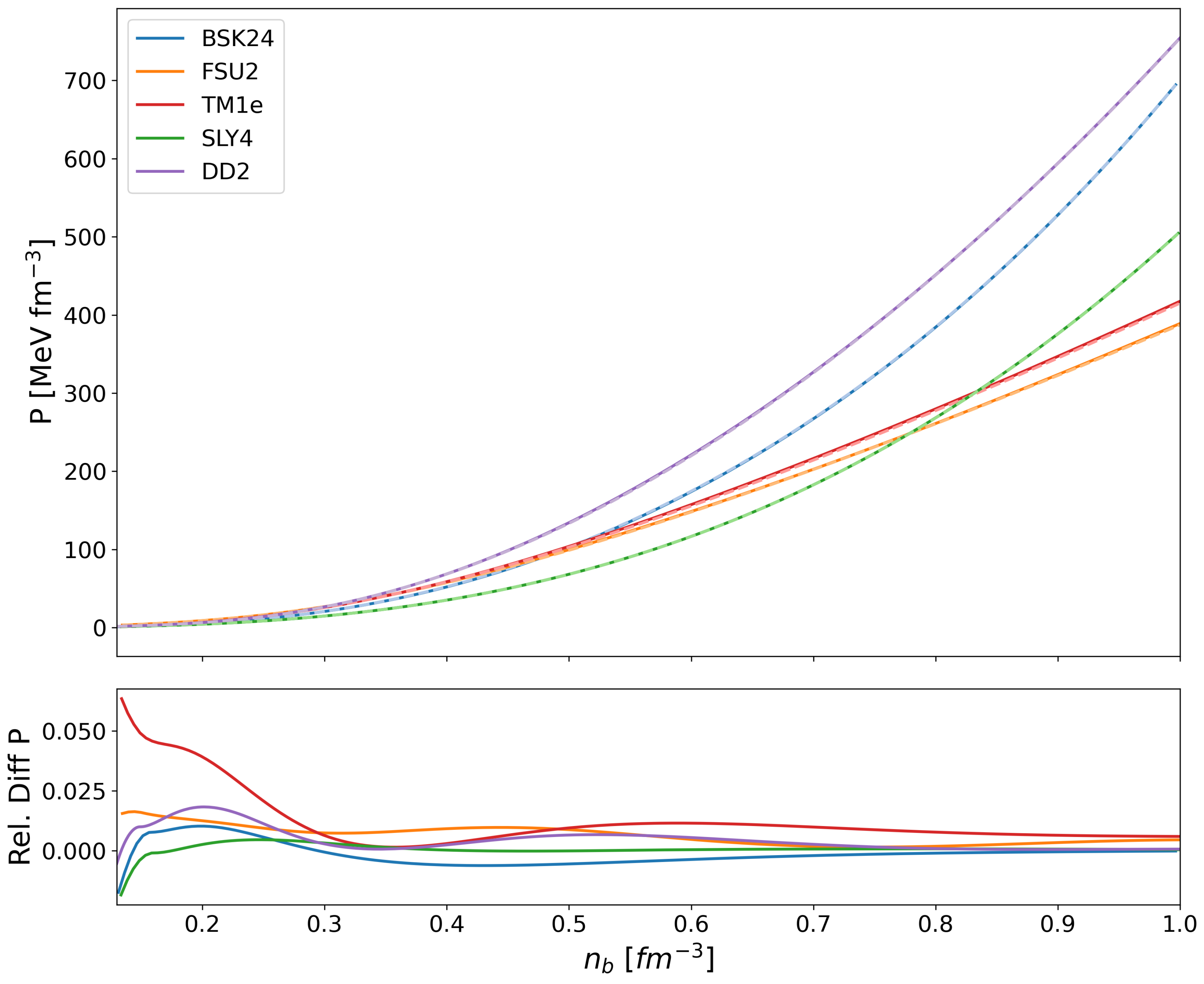
Almost causal meta-model: EoS reconstruction

Test the flexibility of the model to reproduce β-equilibrated EoS

Constrain the space of the unphysical parameters

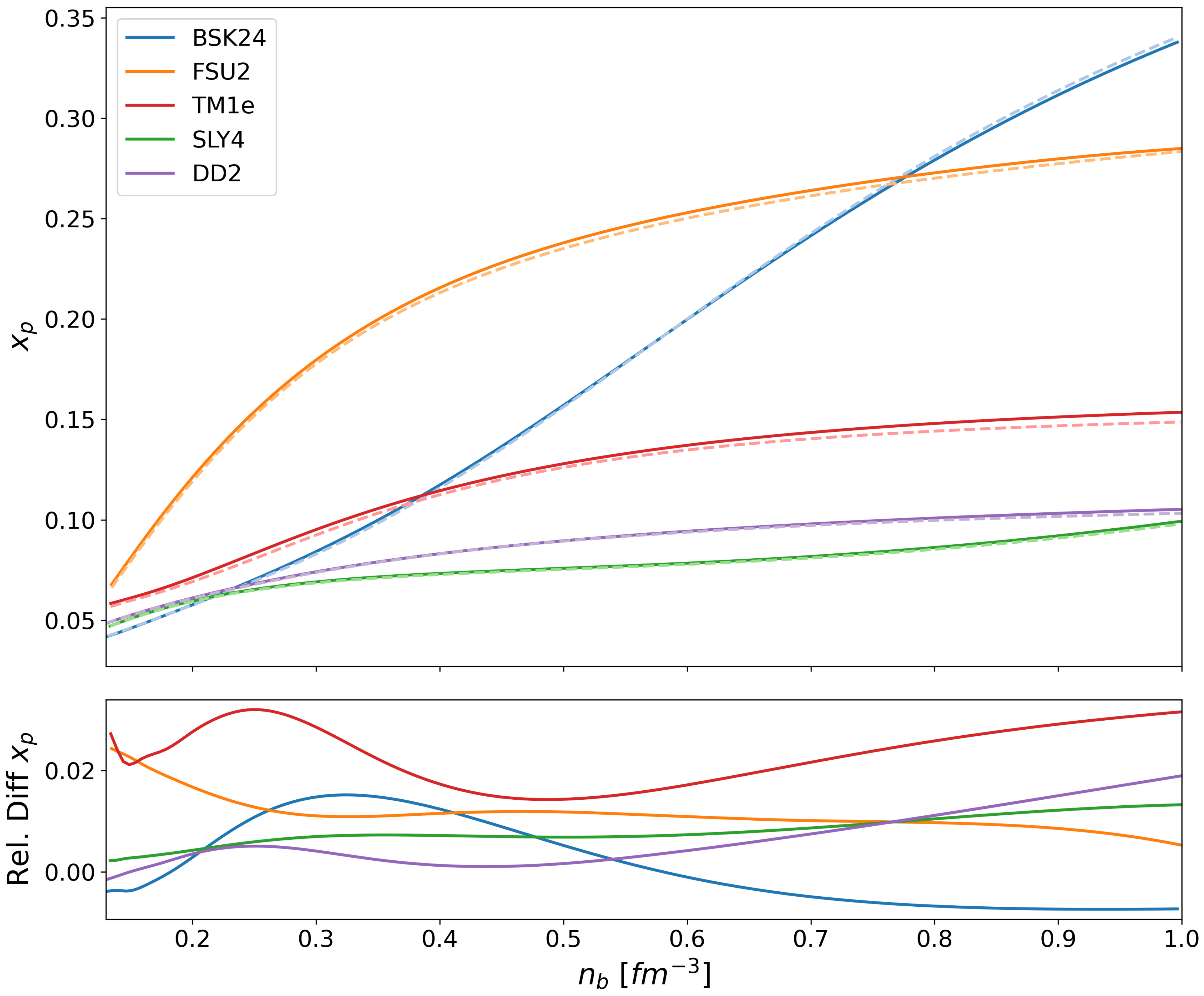
We have chosen: Sly4, BSK24, DD2, FSU2 and TM1e



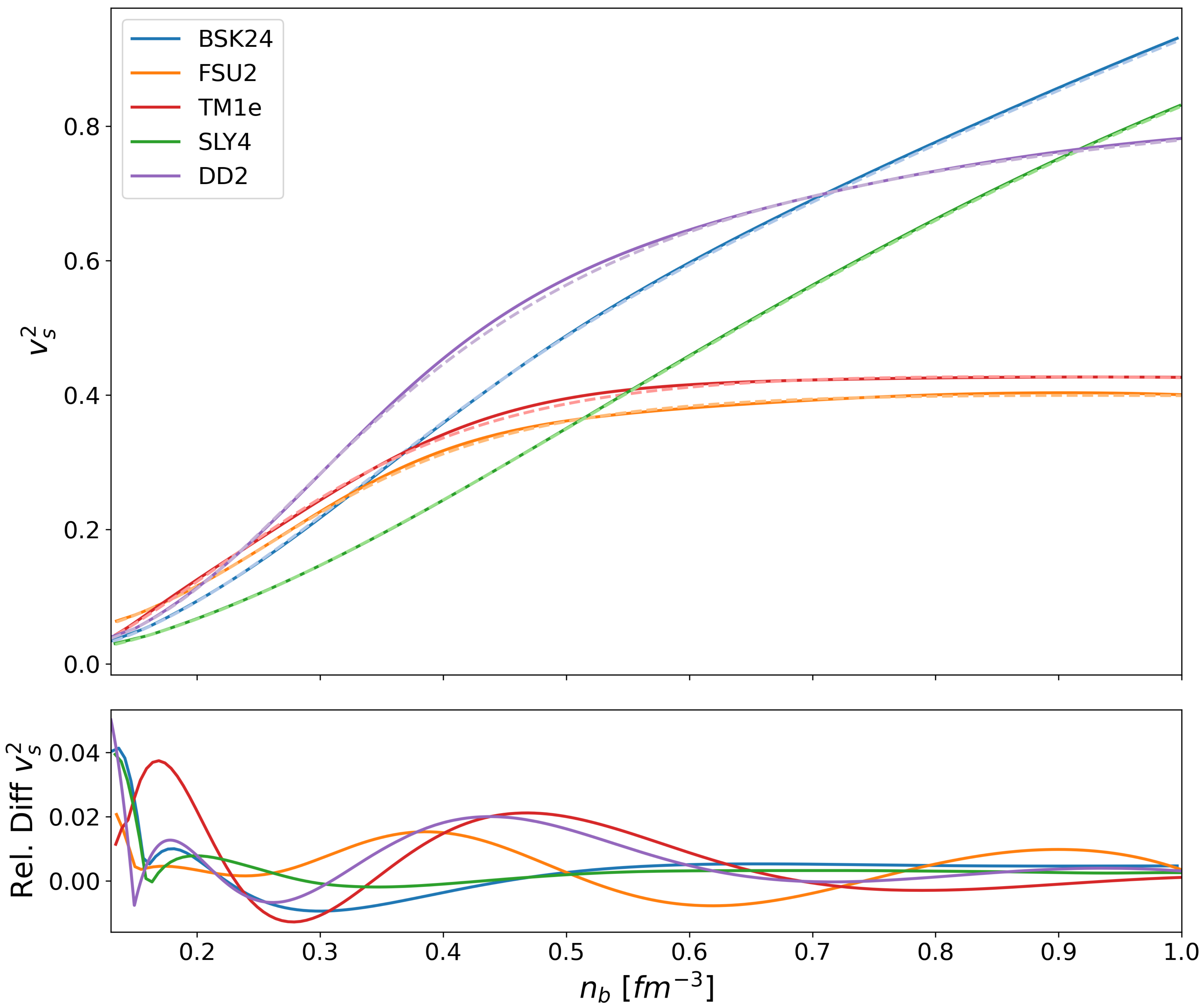


Almost causal meta-model: EoS reconstruction

Proton fraction



Speed of sound



Almost causal meta-model: Bayes Inference

$$\mathscr{M} : \mathbf{X} \to \{\epsilon(n_B), P(n_B), \delta(n_B), v_\beta(n_B), v_{FR}(n_B), \ldots\}$$

$$\mathscr{L}(\mathbf{X}) = \prod_j \mathscr{L}_j(\mathbf{X}) = \prod_j p\left(D_j \,|\, \mathscr{M}(\mathbf{X})\right)$$

Almost causal meta-model: Bayes Inference

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$$\mathscr{L}(\mathbf{X}) = \prod_j \mathscr{L}_j(\mathbf{X}) = \prod_j p\left(D_j \,|\, \mathscr{M}(\mathbf{X})\right)$$

Informed prior sampling the χ_{EFT} band[1] of PNM energy with a metropolis MCMC

At this stage we have 10^9 models

→

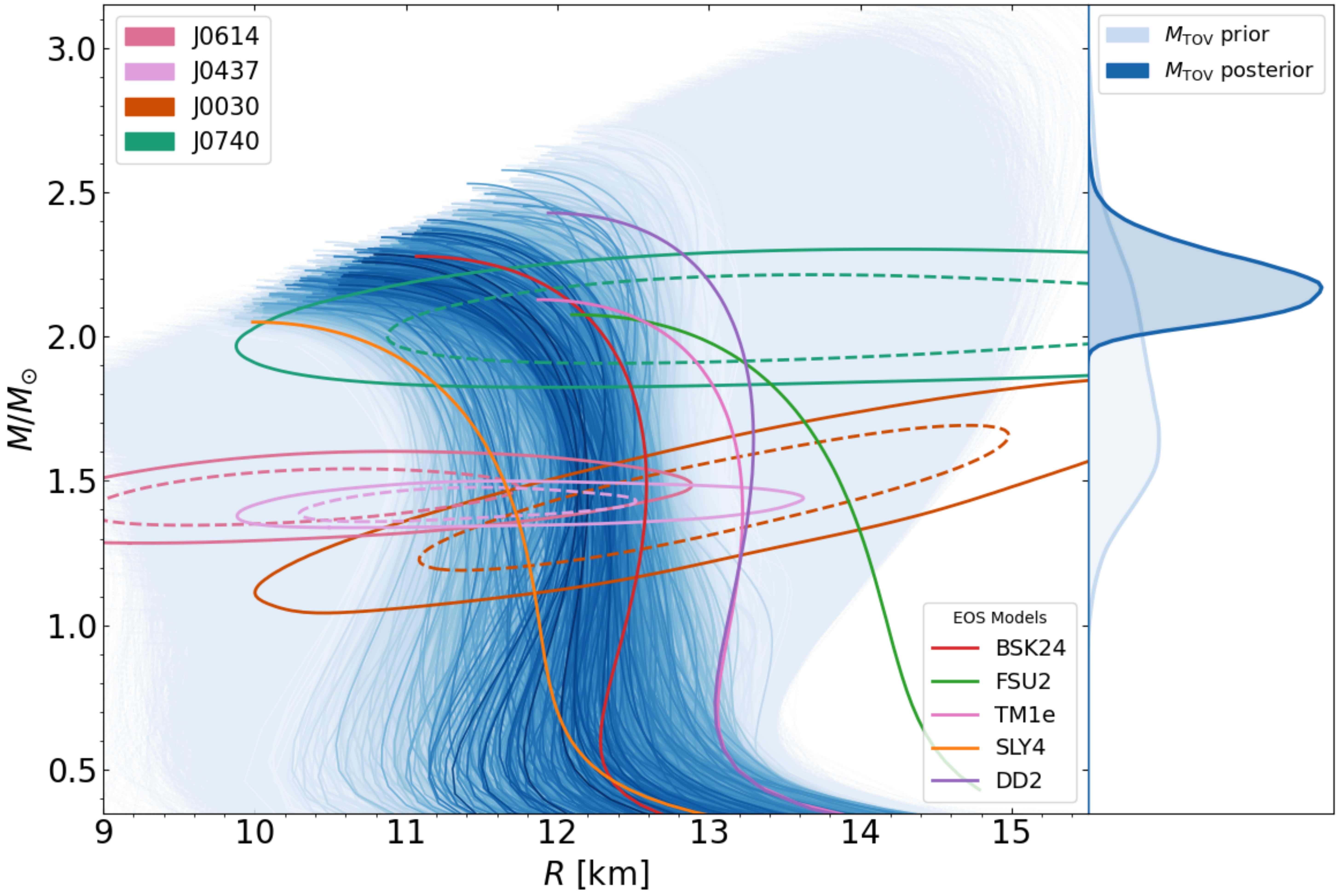
We extract 5×10^5 models that pass through the remaining filter:

- AME2020 nuclear masses table
- Maximum observed NS mass from radio-timing of PSRJ0348 and PSRJ0740
- Tidal deformability from GW170817 event detected by Ligo/Virgo collaboration
- NICER+XMN M-R measurements of PSRJ0030, PSRJ0347, PSRJ0614 and PSRJ0740

[1] Huth et al, 2021, Phys. Rev. C, 103, 025803

Almost causal meta-model: Mass - Radius

We cover a wide range of masses, radii and tidal

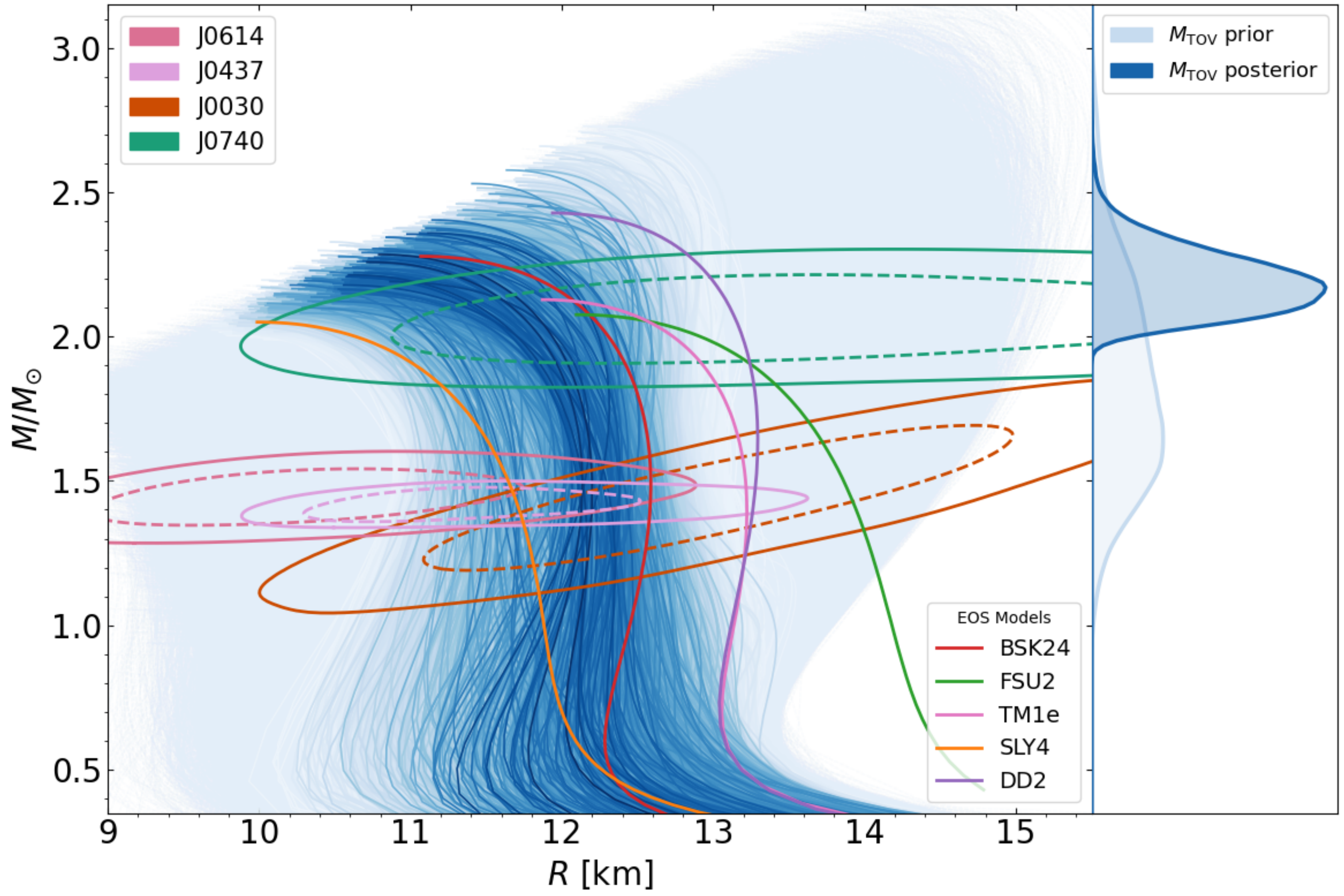


Almost causal meta-model: Mass - Radius

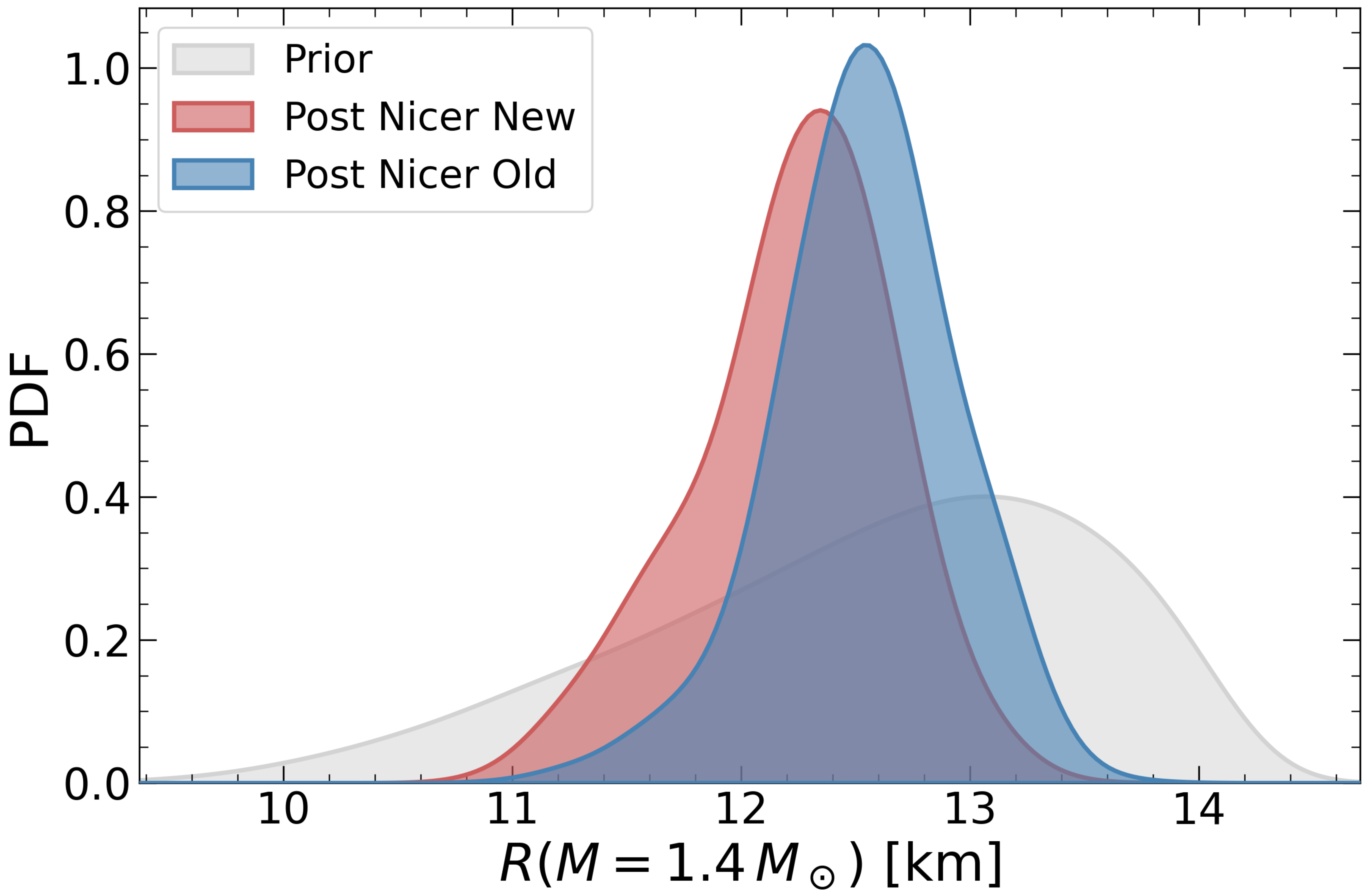
We cover a wide range of masses, radii and tidal

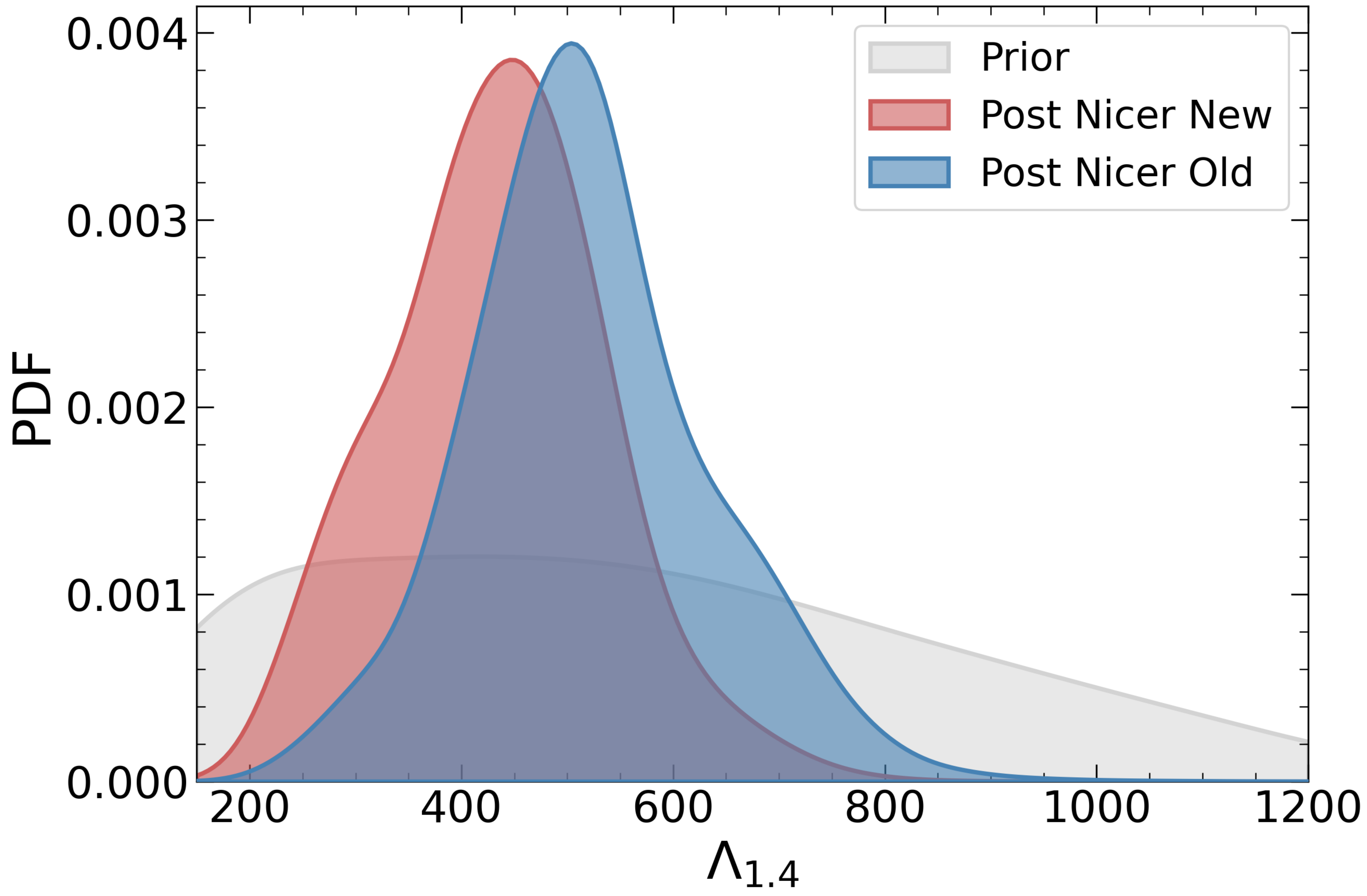
The two newest NICER data suggest a soft EoS

$M_{TOV} > 2.5 M_\odot$ is disfavored



Almost causal meta-model: NICER softening

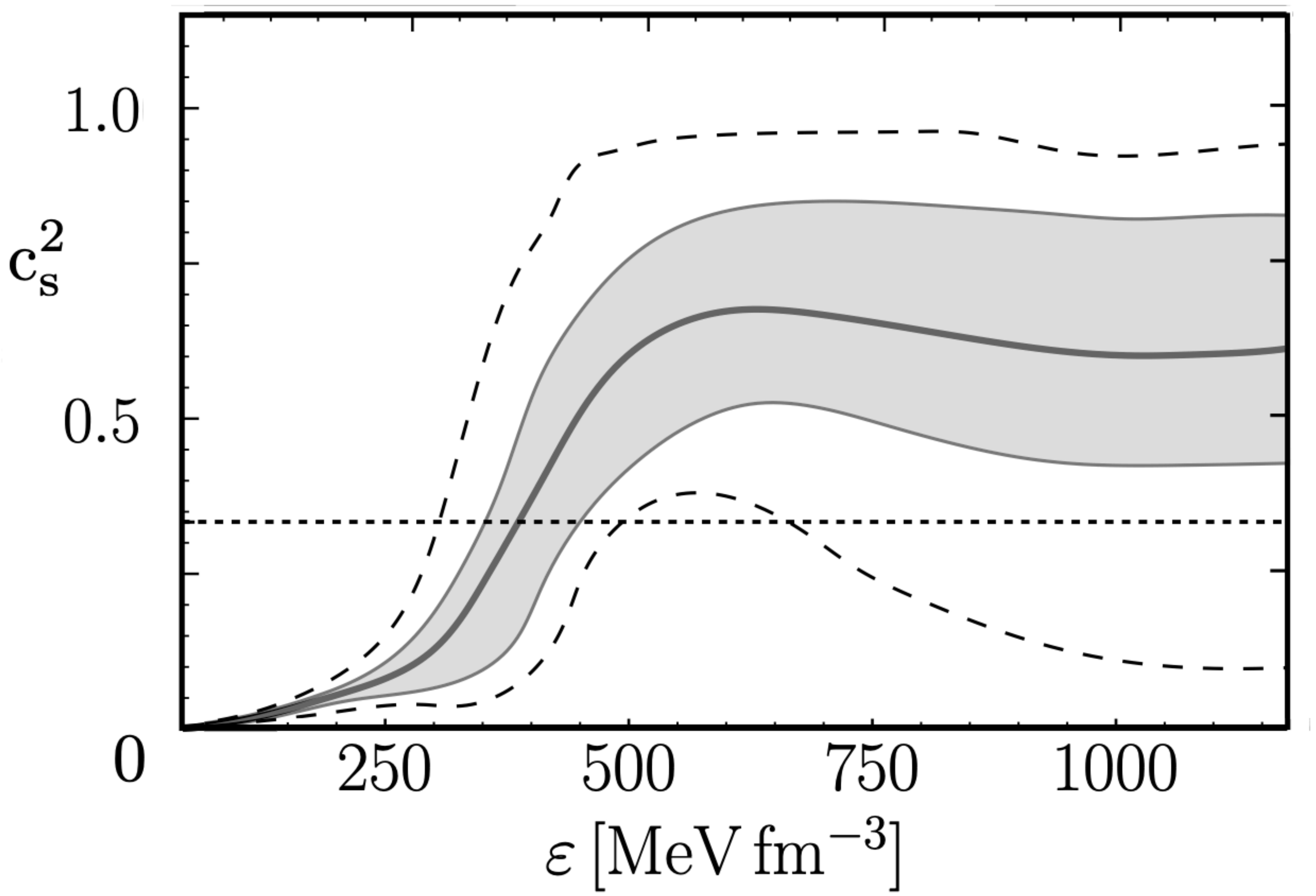




Almost causal meta-model: Speed of sound

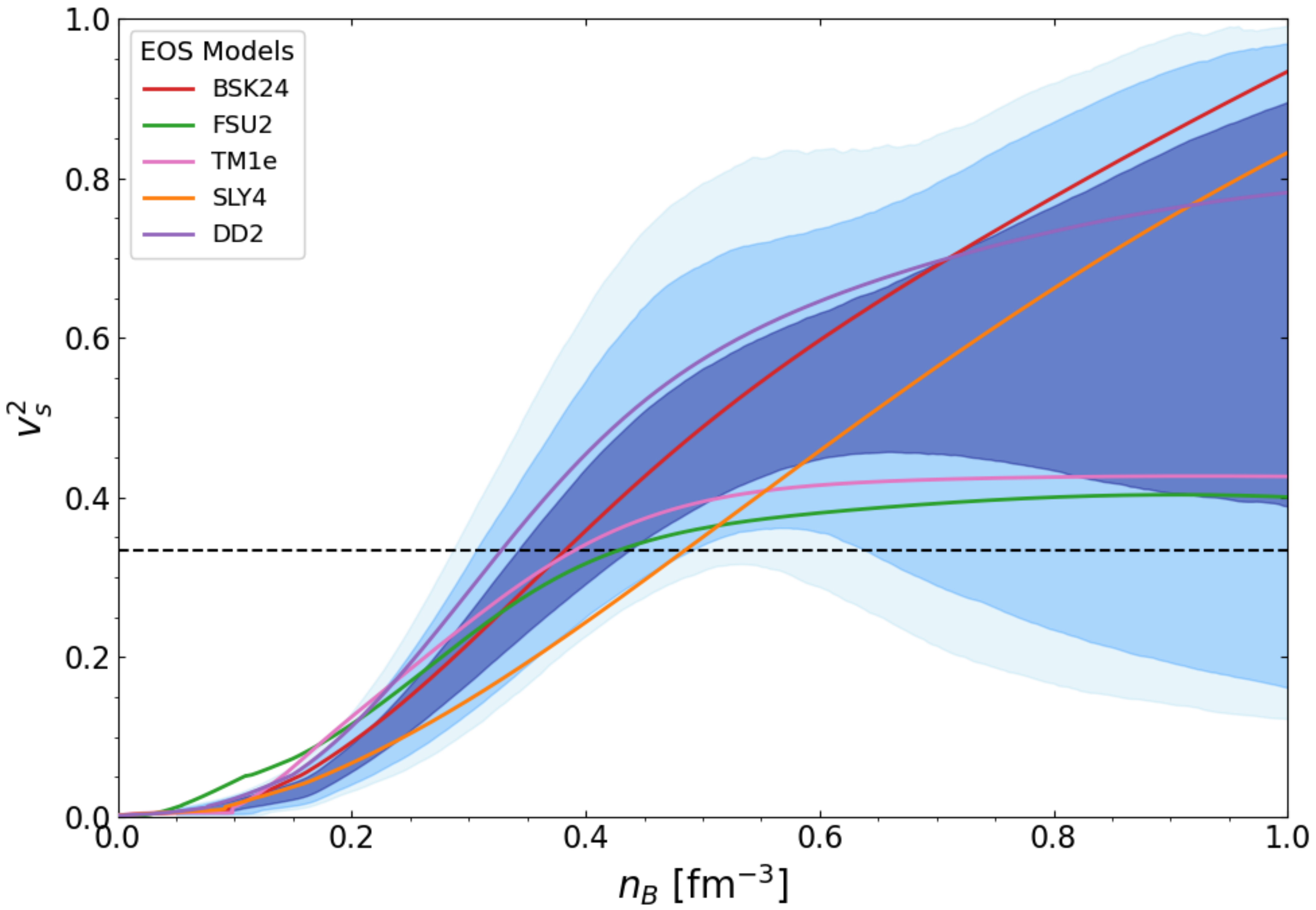
Brandes et Weise
PhysRevD.111.034005 (2025)

c_s parametrization



Montefusco et al [in prep]

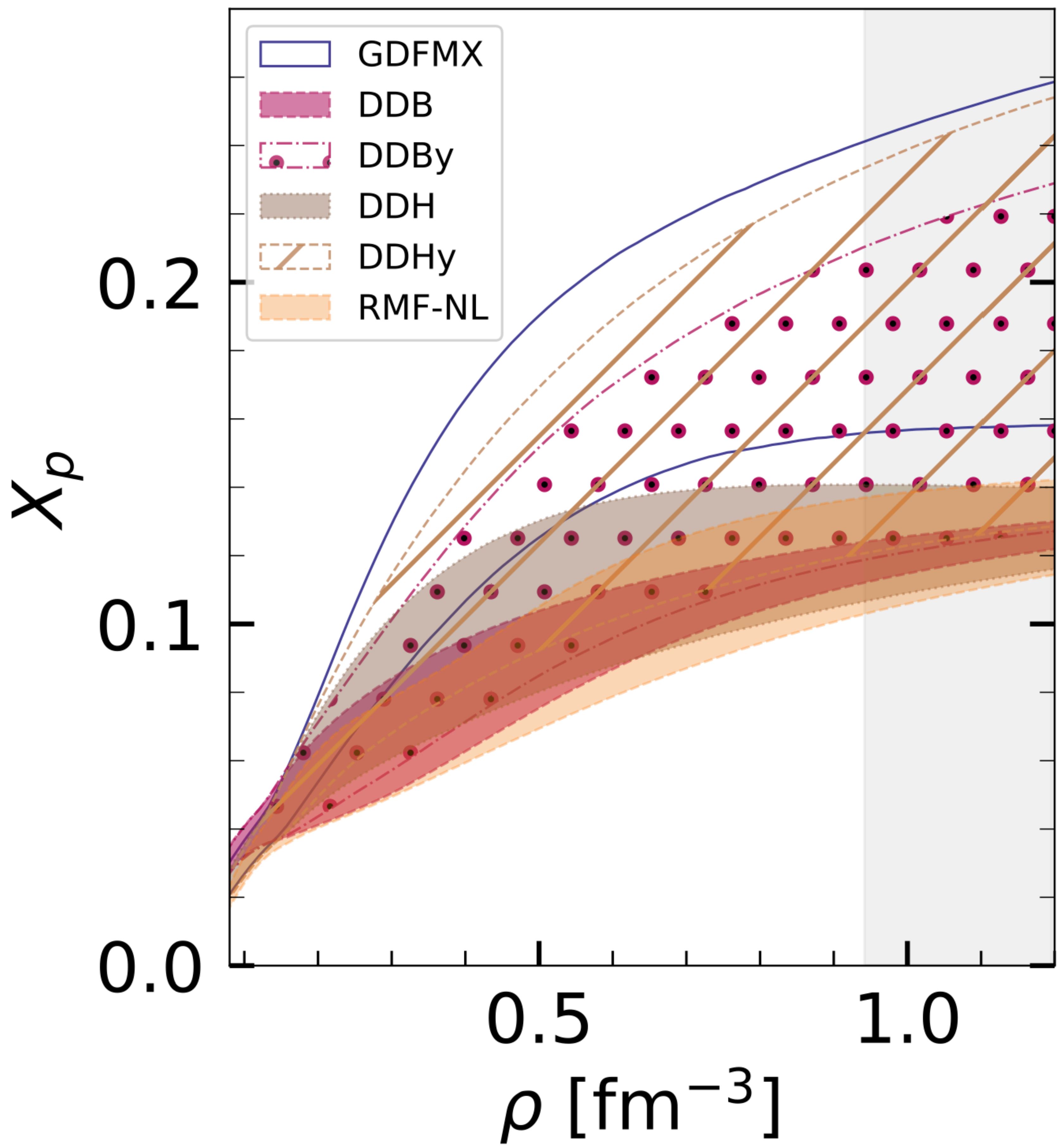
Almost causal MM



Almost causal meta-model: Composition

Cartaxo et al arXiv:2506.03112 (2025)

Density functional approach



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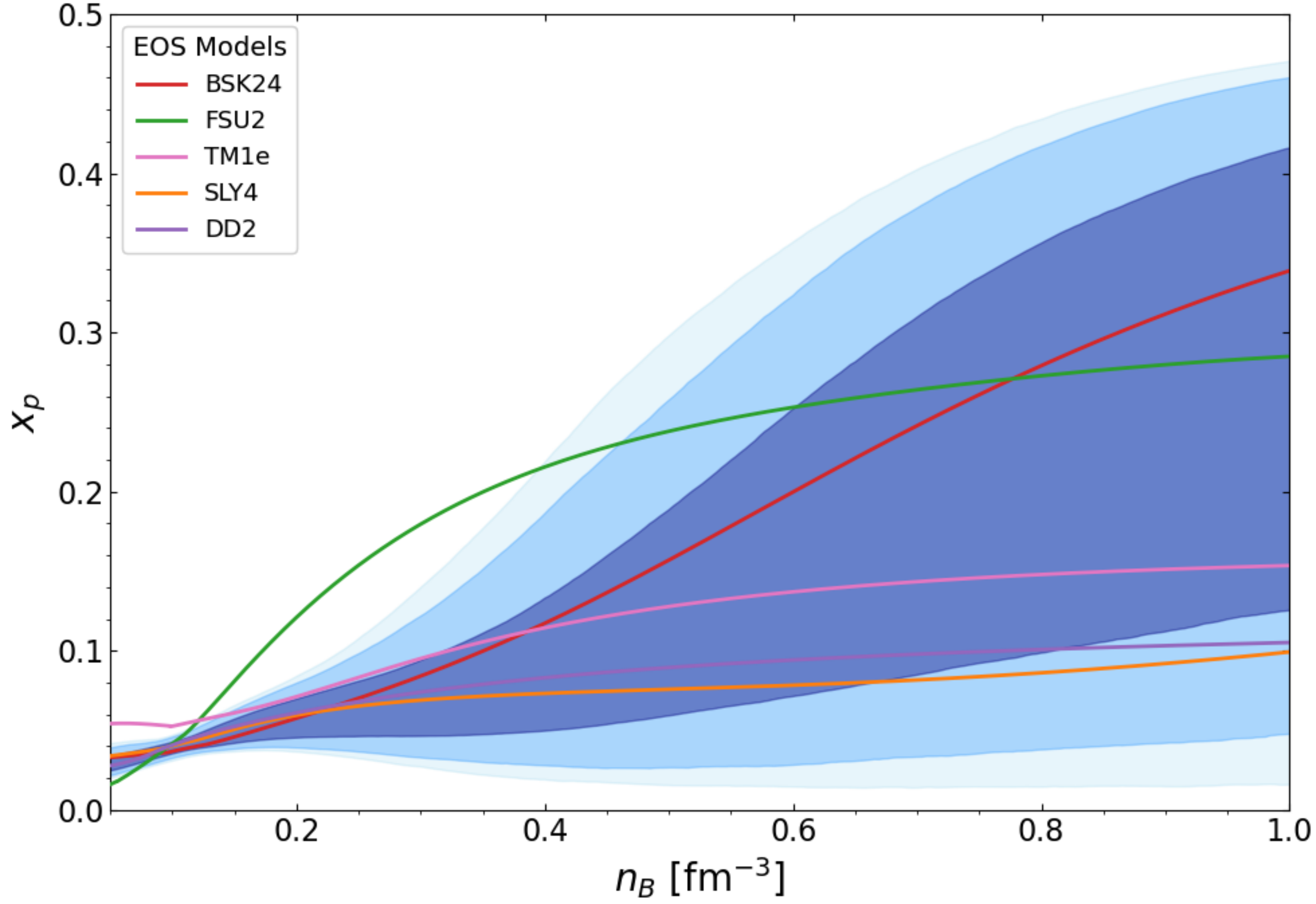


Quasi-normal modes: Introduction

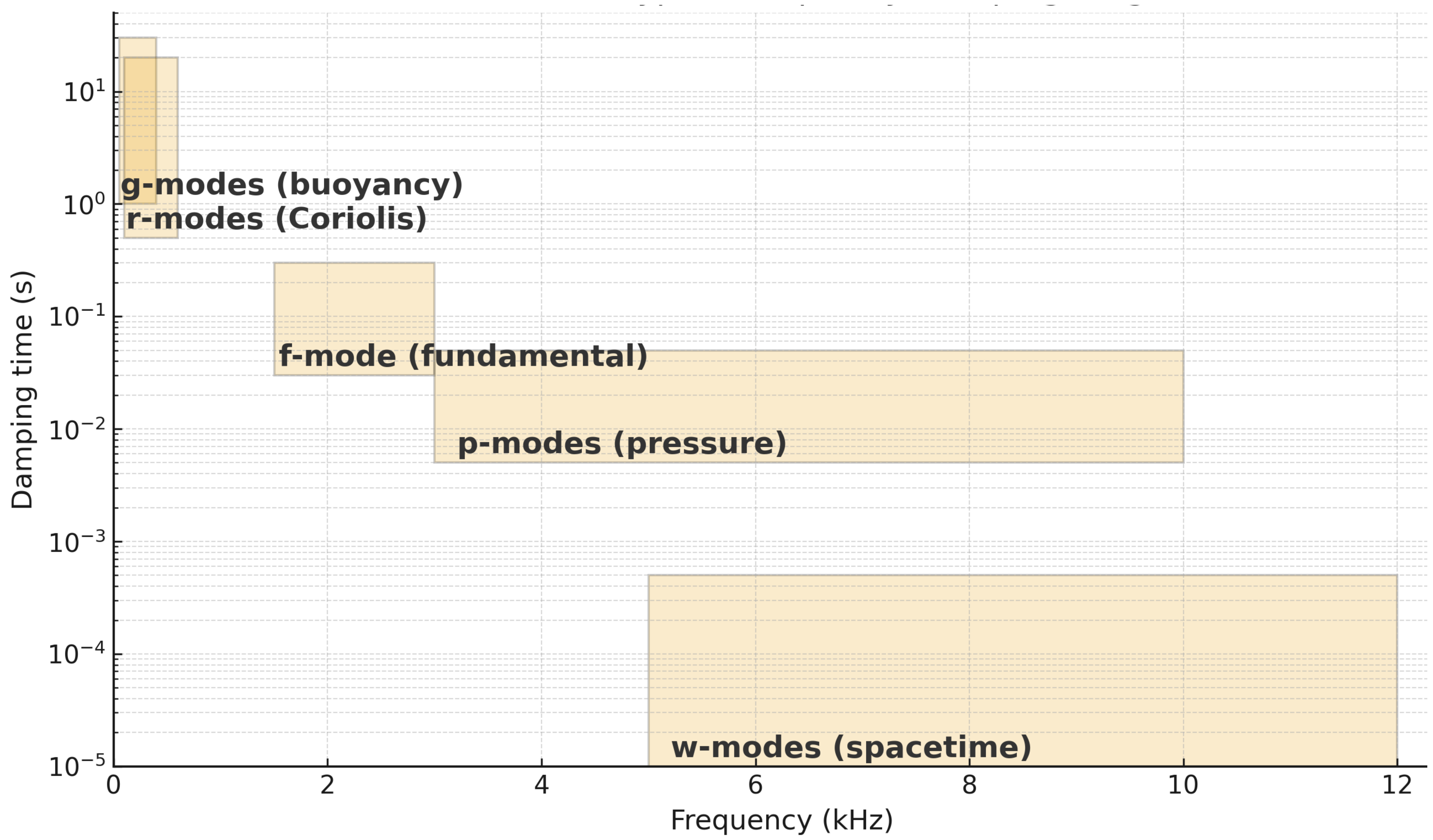
Quasi-normal modes are the **characteristic damped oscillations**, excited by perturbations of the star–spacetime system

Classified by the restoring force

Discrete complex frequencies

Real part → Oscillation

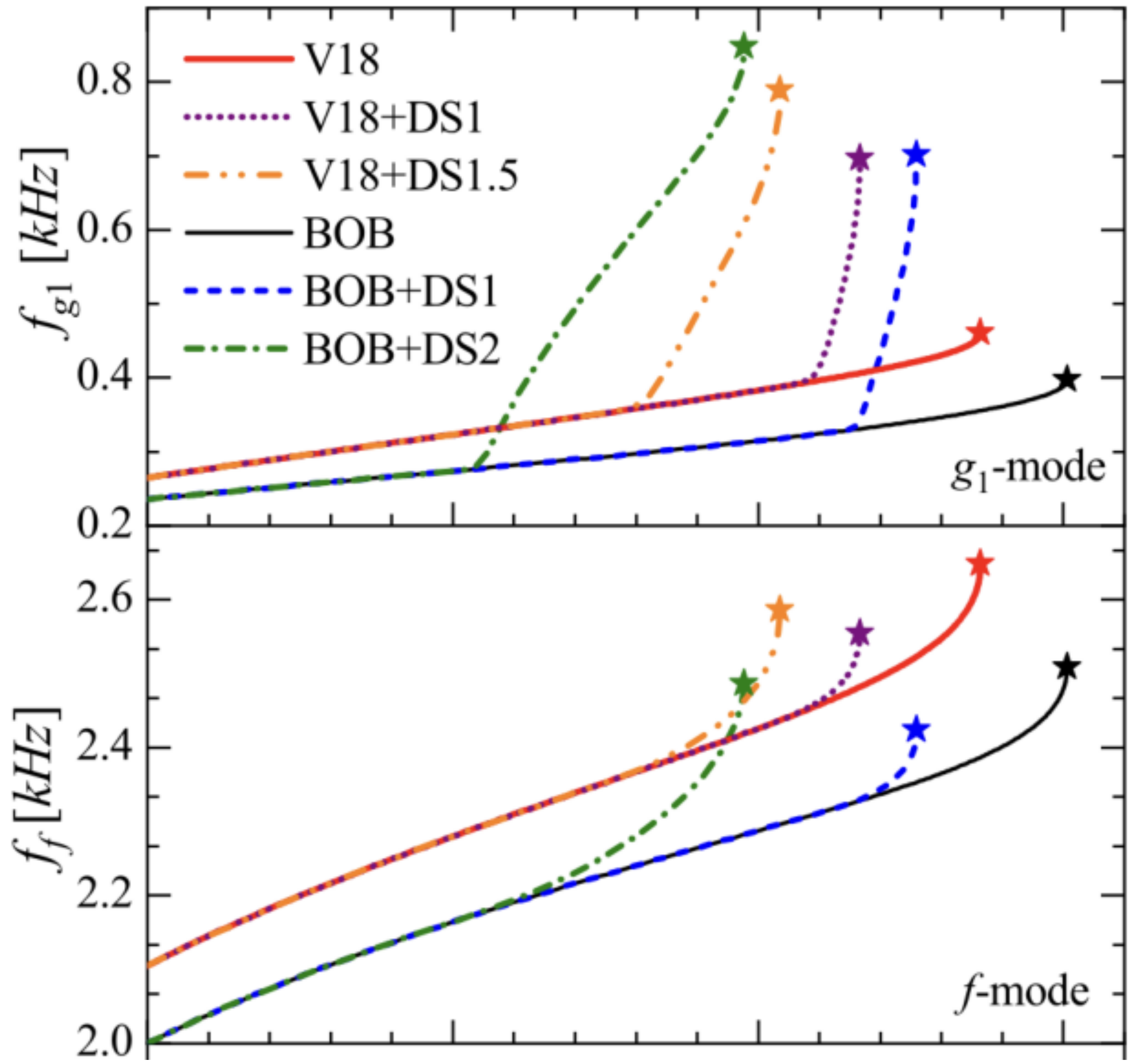
Imaginary part → Damping



Quasi-normal modes: Introduction

Quasi-normal modes are the **characteristic damped oscillations**, excited by perturbations of the star–spacetime system

Zheng et al (2023)
PhysRevD.107.103048



Classified by the restoring force

Discrete complex frequencies

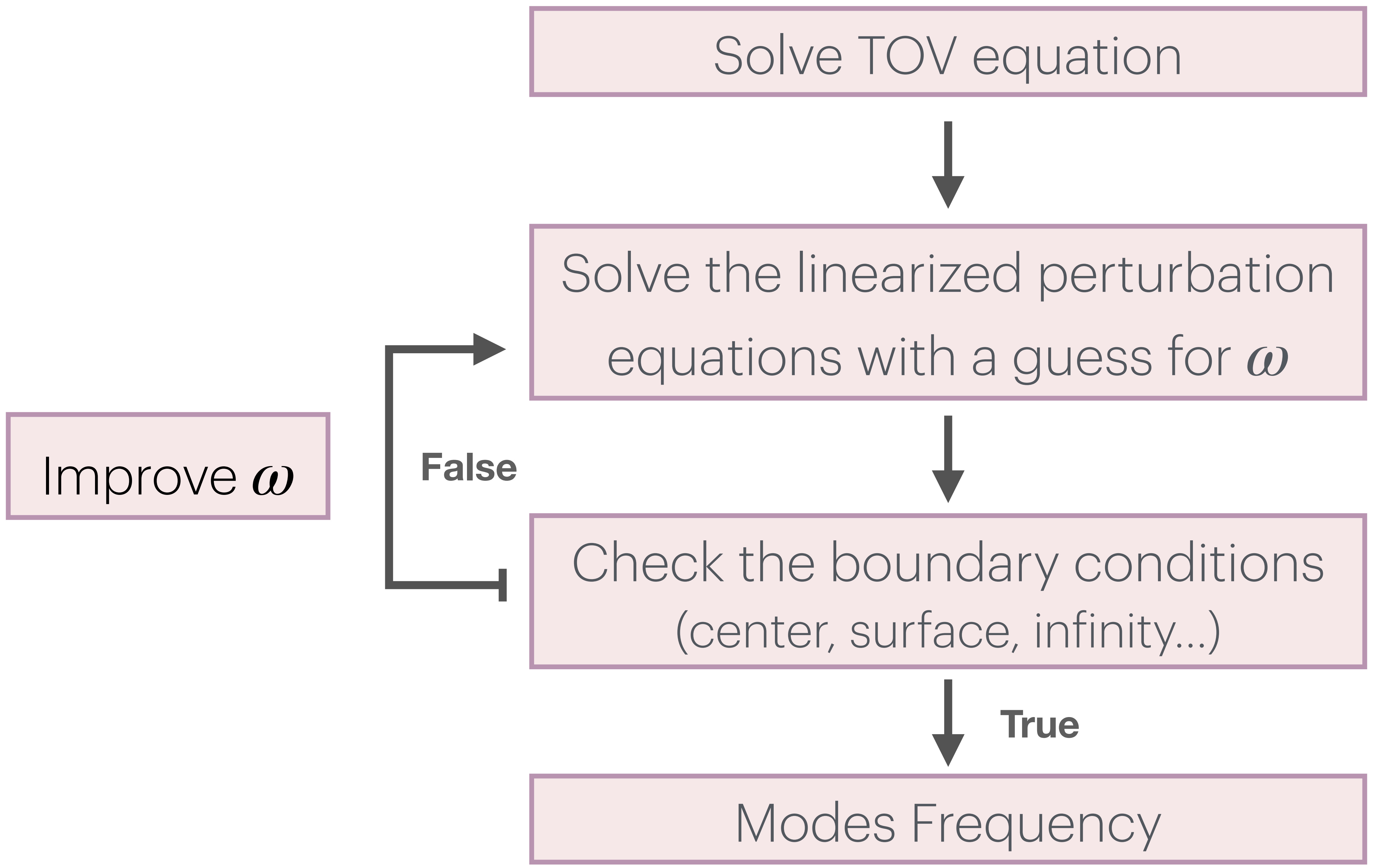
Real part → Oscillation

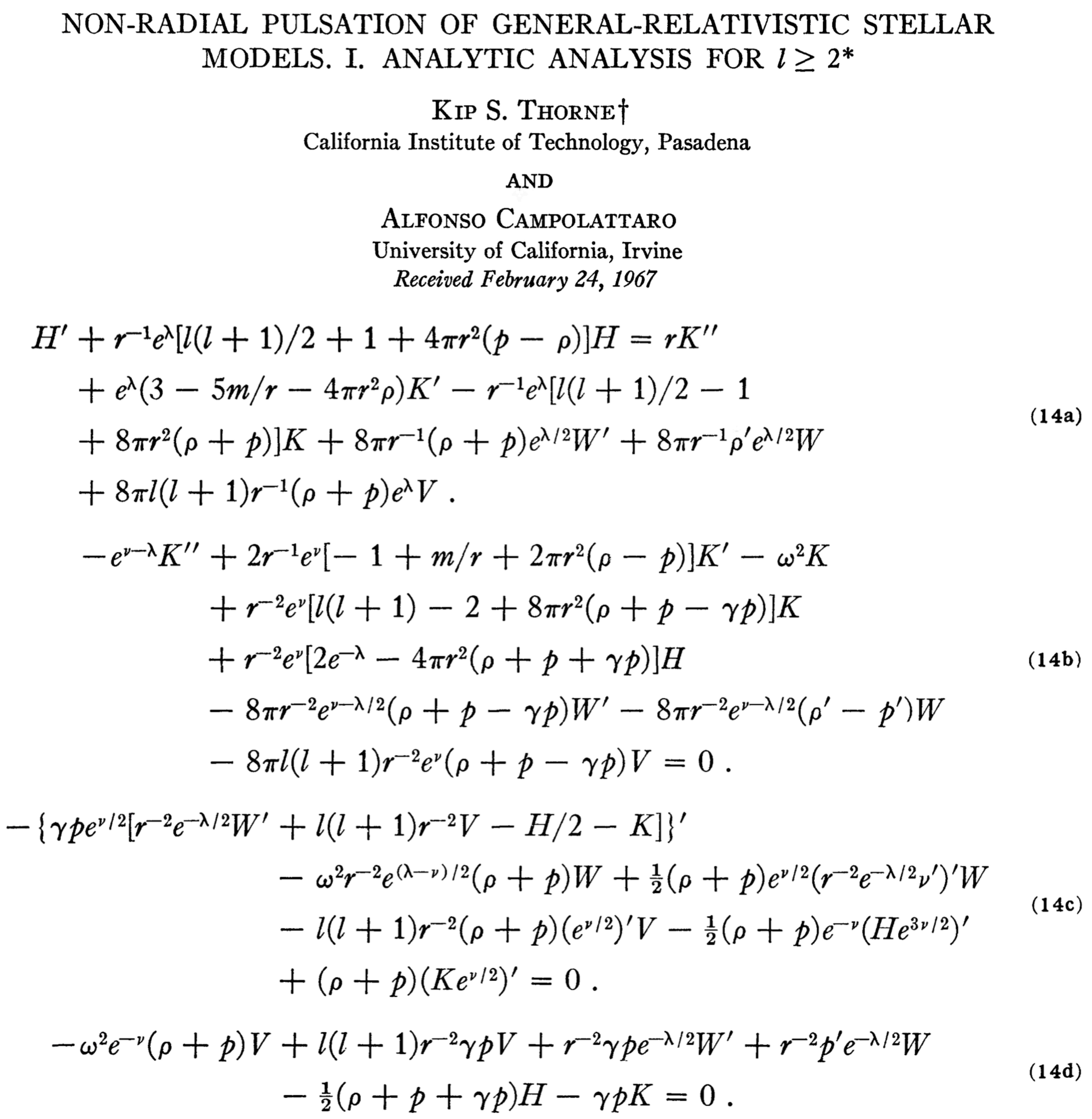
Imaginary part → Damping

May be sensitive not only to the EoS but also to the internal composition

Quasi-normal modes: A difficult eigenvalue problem

Eigenvalue problem





NON-RADIAL PULSATION OF GENERAL-RELATIVISTIC STELLAR MODELS. I. ANALYTIC ANALYSIS FOR $l \geq 2$*

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California Institute of Technology, Pasadena
AND
Alfonso Campolattaro
University of California, Irvine

Received February 24, 1967

$$H' + r^{-1}e^{\lambda}[l(l+1)/2 + 1 + 4\pi r^2(p-\rho)]H = rK'' + e^{\lambda}(3 - 5m/r - 4\pi r^2\rho)K' - r^{-1}e^{\lambda}[l(l+1)/2 - 1 + 8\pi r^2(\rho+p)]K + 8\pi r^{-1}(\rho+p)e^{\lambda/2}W' + 8\pi r^{-1}\rho' e^{\lambda/2}W + 8\pi l(l+1)r^{-1}(\rho+p)e^{\lambda}V\,. \tag{14a}$$

$$-e^{\nu-\lambda}K'' + 2r^{-1}e^{\nu}[-1 + m/r + 2\pi r^2(\rho-p)]K' - \omega^2 K + r^{-2}e^{\nu}[l(l+1) - 2 + 8\pi r^2(\rho+p-\gamma p)]K + r^{-2}e^{\nu}[2e^{-\lambda} - 4\pi r^2(\rho+p+\gamma p)]H - 8\pi r^{-2}e^{\nu-\lambda/2}(\rho+p-\gamma p)W' - 8\pi r^{-2}e^{\nu-\lambda/2}(\rho'-p')W - 8\pi l(l+1)r^{-2}e^{\nu}(\rho+p-\gamma p)V = 0\,. \tag{14b}$$

$$-\{\gamma p e^{\nu/2}[r^{-2}e^{-\lambda/2}W' + l(l+1)r^{-2}V - H/2 - K]\}' - \omega^2 r^{-2}e^{(\lambda-\nu)/2}(\rho+p)W + \tfrac{1}{2}(\rho+p)e^{\nu/2}(r^{-2}e^{-\lambda/2}\nu')'W - l(l+1)r^{-2}(\rho+p)(e^{\nu/2})'V - \tfrac{1}{2}(\rho+p)e^{-\nu}(He^{3\nu/2})' + (\rho+p)(Ke^{\nu/2})' = 0\,. \tag{14c}$$

$$-\omega^2 e^{-\nu}(\rho+p)V + l(l+1)r^{-2}\gamma p V + r^{-2}\gamma p e^{-\lambda/2}W' + r^{-2}p' e^{-\lambda/2}W - \tfrac{1}{2}(\rho+p+\gamma p)H - \gamma p K = 0\,. \tag{14d}$$

Quasi-normal modes: Cowling Approximation

Cowling approximation

Neglect perturbation of the metric

↓

No dissipation due to GW emissions

↓

Only real part of the frequency

Quasi-normal modes: Cowling Approximation

Cowling approximation

Neglect perturbation of the metric

↓

No dissipation due to GW emissions

↓

Only real part of the frequency

The equations become:

$$W' = \left(\frac{dP}{d\epsilon}\right)^{-1}\left[\omega^2 r^2 V + \Phi' W\right] - l(l+1)e^{\Lambda}V$$

$$V' = 2\Phi' V - e^{\Lambda}\frac{W}{r^2} - A\left[\frac{\Phi'}{\omega^2 r^2}e^{2\Phi-\Lambda}W + V\right]$$

Where V, W are the fluid displacement vectors and A is the Schwarzschild discriminant

By imposing the **boundary condition** $\Delta P = 0$ at the stellar surface it is obtained

$$\omega^2 R^2 e^{\Lambda - 2\Phi}V + \Phi' W = 0$$

This let us obtain the frequency as the omega for which this BC is satisfied

Quasi-normal modes: Frozen vs β-equilibrated regime

We tested the impact on mode frequencies of assuming two opposite limits for the reaction rates

Equilibrium regime

Each perturbed fluid element has time to re-equilibrate the composition

$$v_\beta^2 = \frac{dP}{d\epsilon} = \frac{dP(n, x_e(n), x_\mu(n))/dn}{d\epsilon(n, x_e(n), x_\mu(n))/dn}$$

Used in the studies that assumes agnostic barotropic or β-equilibrated EoS

Frozen regime

Each perturbed fluid element remain at fixed composition

$$v_{FR}^2 = \left.\frac{\partial P}{\partial \epsilon}\right|_{x_e, x_\mu} = \frac{\partial P(n, x_e(n), x_\mu(n))/\partial n}{\partial \epsilon(n, x_e(n), x_\mu(n))/\partial n}$$

This is the maximal speed of information in a reacting mixture[1]:
For stable and causal matter

$$0 < v_\beta < v_{FR} < 1$$

[1] Camelio G. et al Phys. Rev. D, 107, 103031

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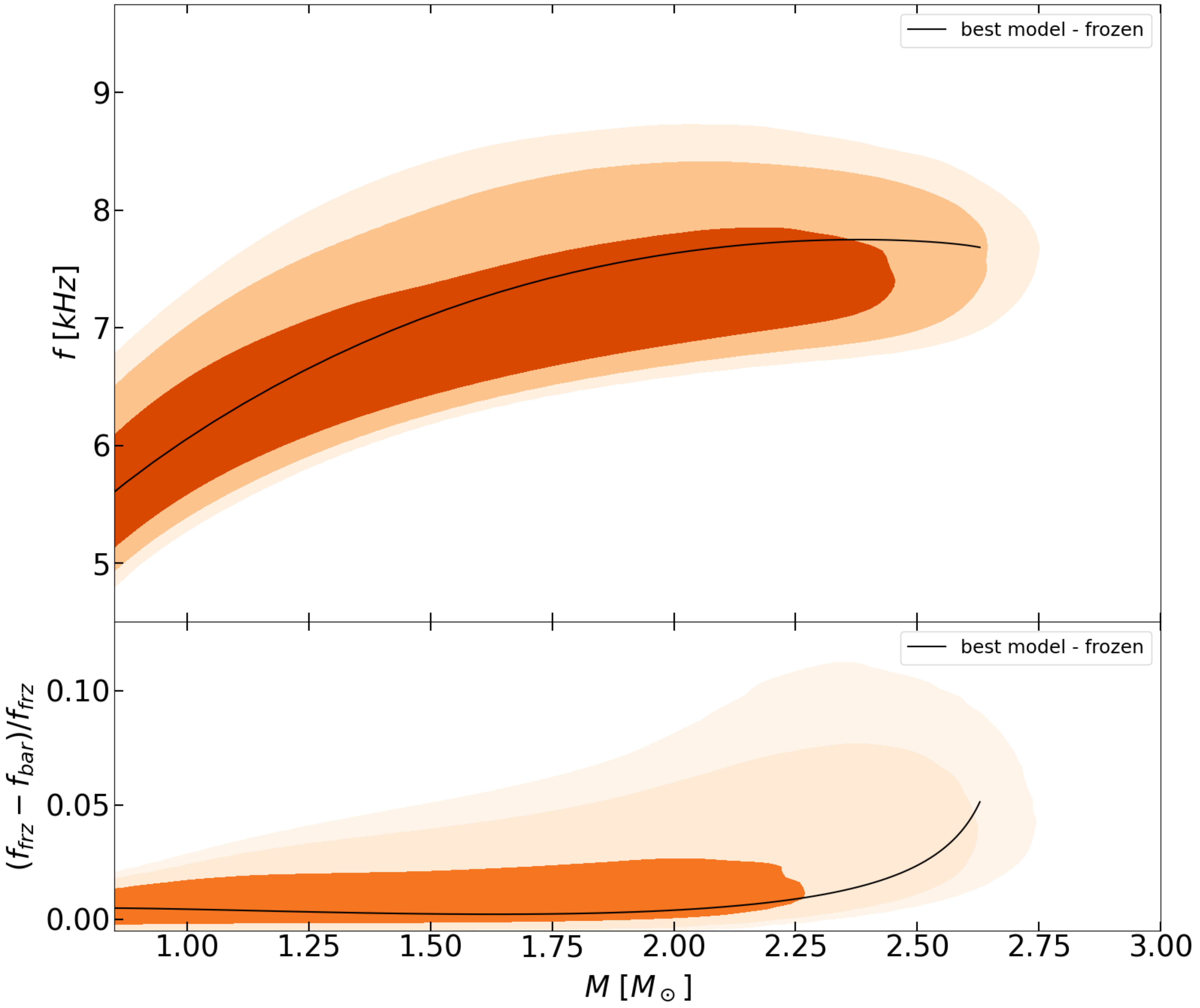
$$V' = 2\Phi' V - e^{\Lambda}\frac{W}{r^2} - A\left[\frac{\Phi'}{\omega^2 r^2} e^{2\Phi - \Lambda} W + V\right]$$

Quasi-normal modes:
Frozen vs β-equilibrated regime

f-**mode** differences smaller than 0.5%

p_1-**mode**: difference < 5% except for $M \rightarrow M_{max}$ where they reach up to 10%

Since the differences are small, if v_{FR} is not available, it is possible to use the barotropic frequencies with very little errors.



Quasi-normal modes: Quasi universal relation

$$\omega M = a_0 + a_1 \frac{M}{R} + a_2 \left(\frac{M}{R}\right)^2 + a_3 \left(\frac{M}{R}\right)^3$$

[Phys. Rev. C 103, 035810] [Phys. Rev. D 103, 123015]

f-mode

accuracy > 95%

p_1-mode

accuracy > 90%

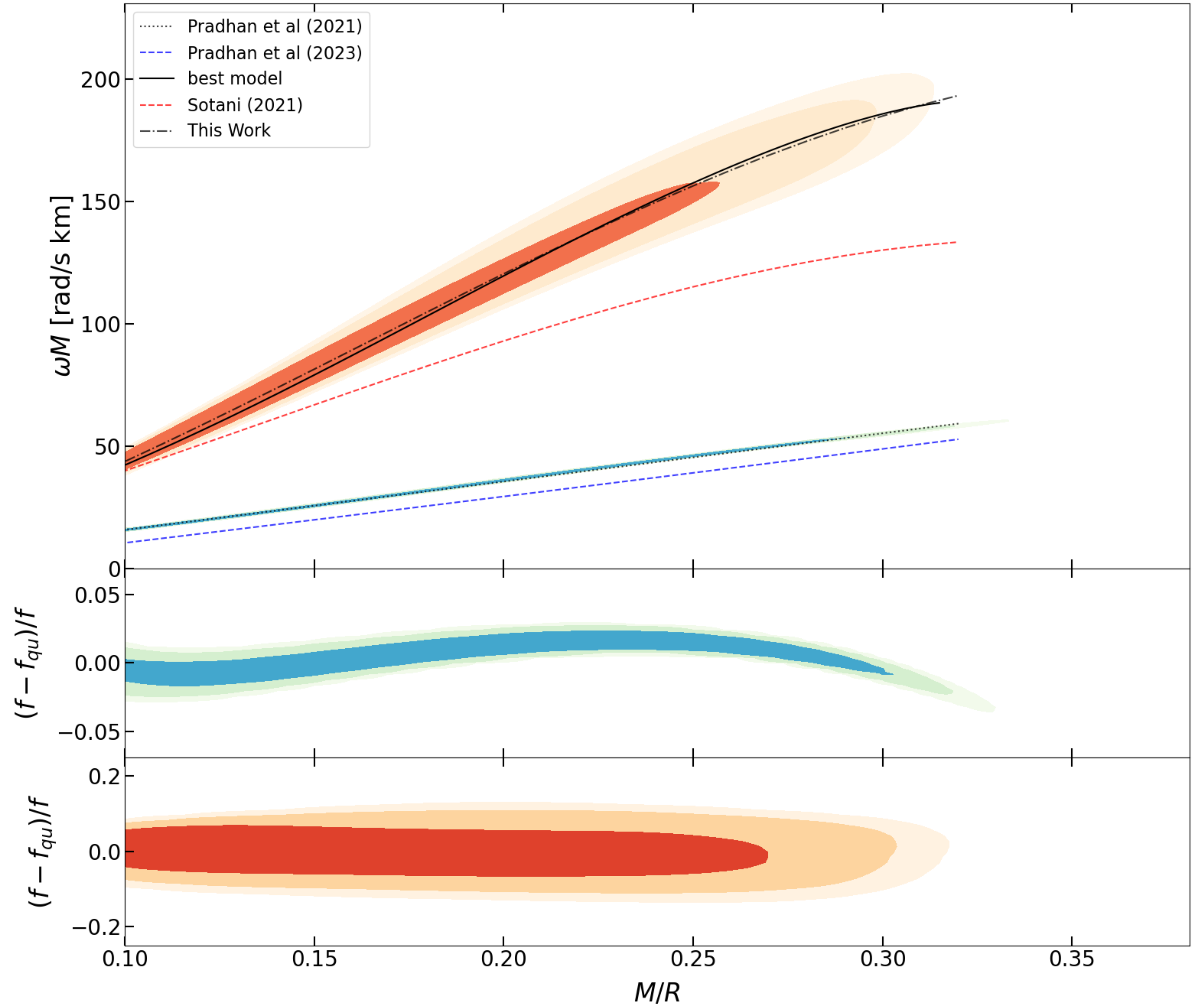
Every different set of EoS gave compatible fit

↓

It is a **Quasi-universal** relation

It is possible to obtain the frequencies by evaluating only the M-R relation

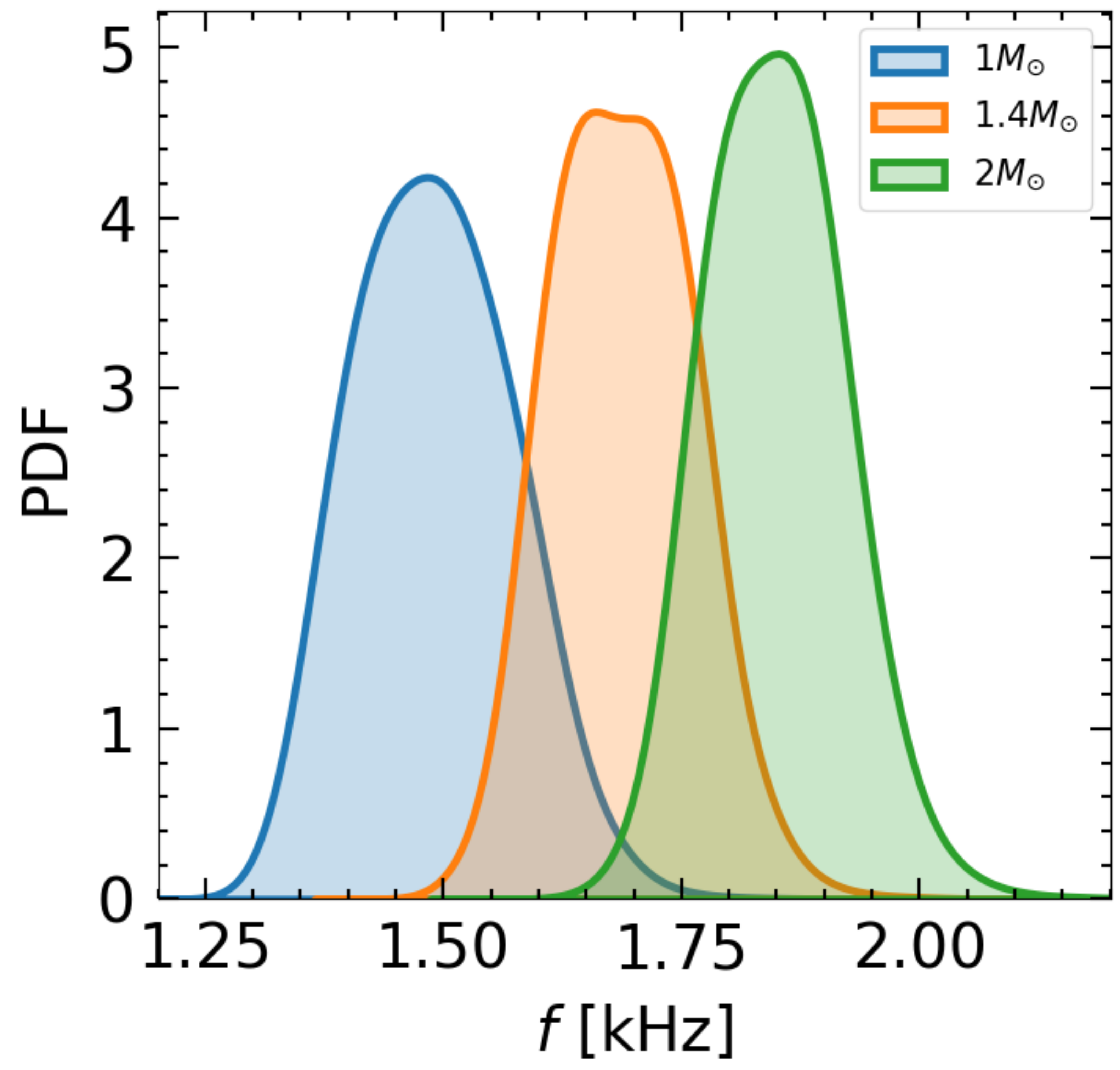
[A&A, 694, A150 (2025)]



Quasi-normal modes: Synthetich full-GR frequency

[A&A, 694, A150 (2025)]

$f - mode$

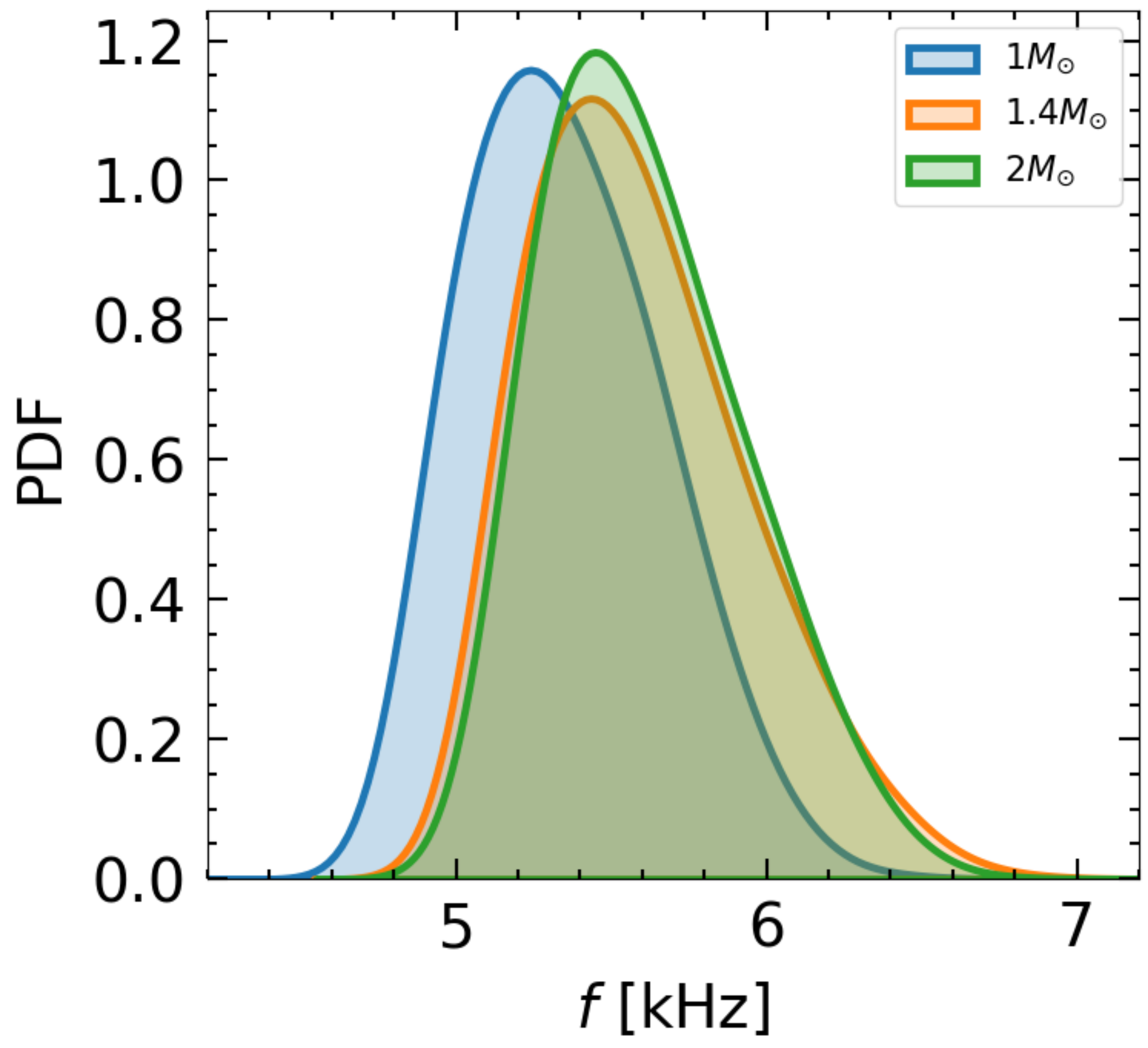


The split is larger for the f**-mode** than the p_1**-mode**

It is possible to constrain the mass from an f-mode observation

This information is lost for the p_1-mode

$p_1 - mode$



Summary

– NS probe extreme densities and EoS can be univocally mapped to their static properties → This is the only way to complement experiment and pQCD

– No ab-initio model of nuclear matter for all densities → Bayesian techniques allow controlled extrapolations of low density constraints from nuclear theory and experiments

– The meta-modeling framework gives access to the composition without sacrificing the flexibility of agnostic model → It opens new channels to probe the EoS in a systematic way, e.g. modes, cooling, glitches

– The quasi-normal modes offers a deeper insight into the internal composition → With the next generation GW detectors may be possible to observe them and constrain the EoS

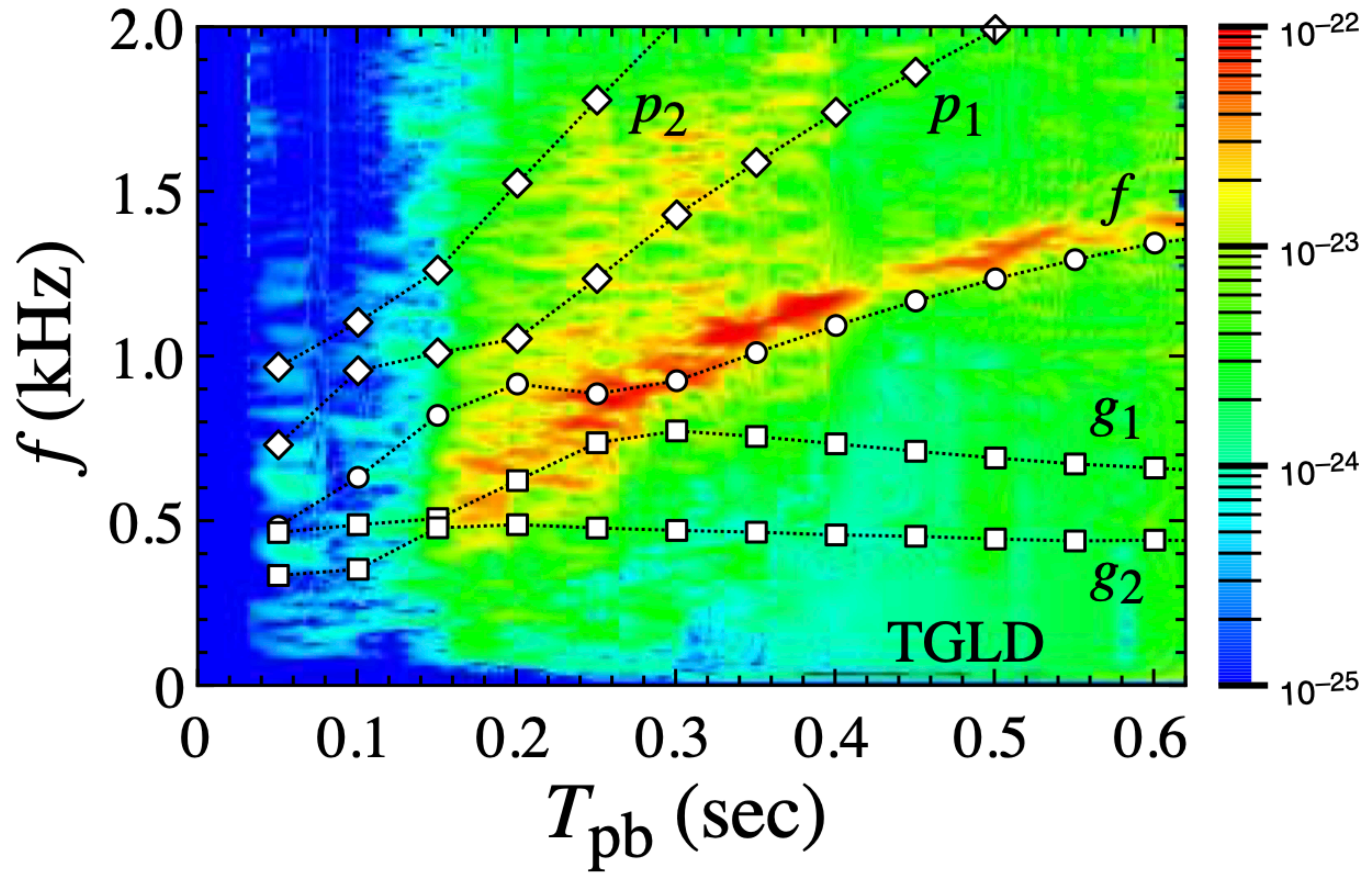
Next frontier: better understanding of finite temperature effects and magnetization for mergers and supernovae

BACKUP SLIDES

Quasi-normal modes: Astrophysical scenario

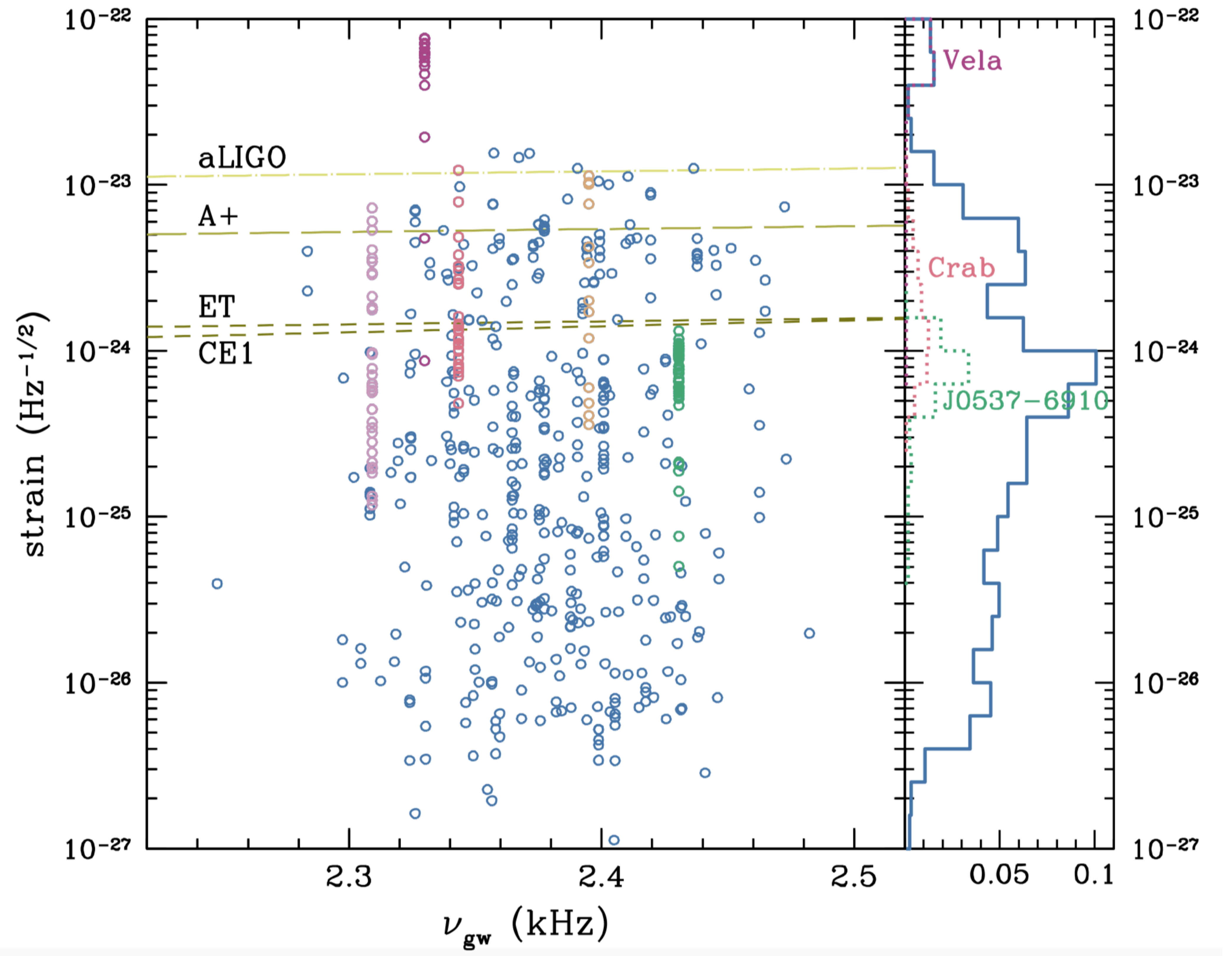
Comparison between **numerical simulations** and **eigenvalue obtained** frequencies for PNS

[Phys. Rev. D 104, 123009]

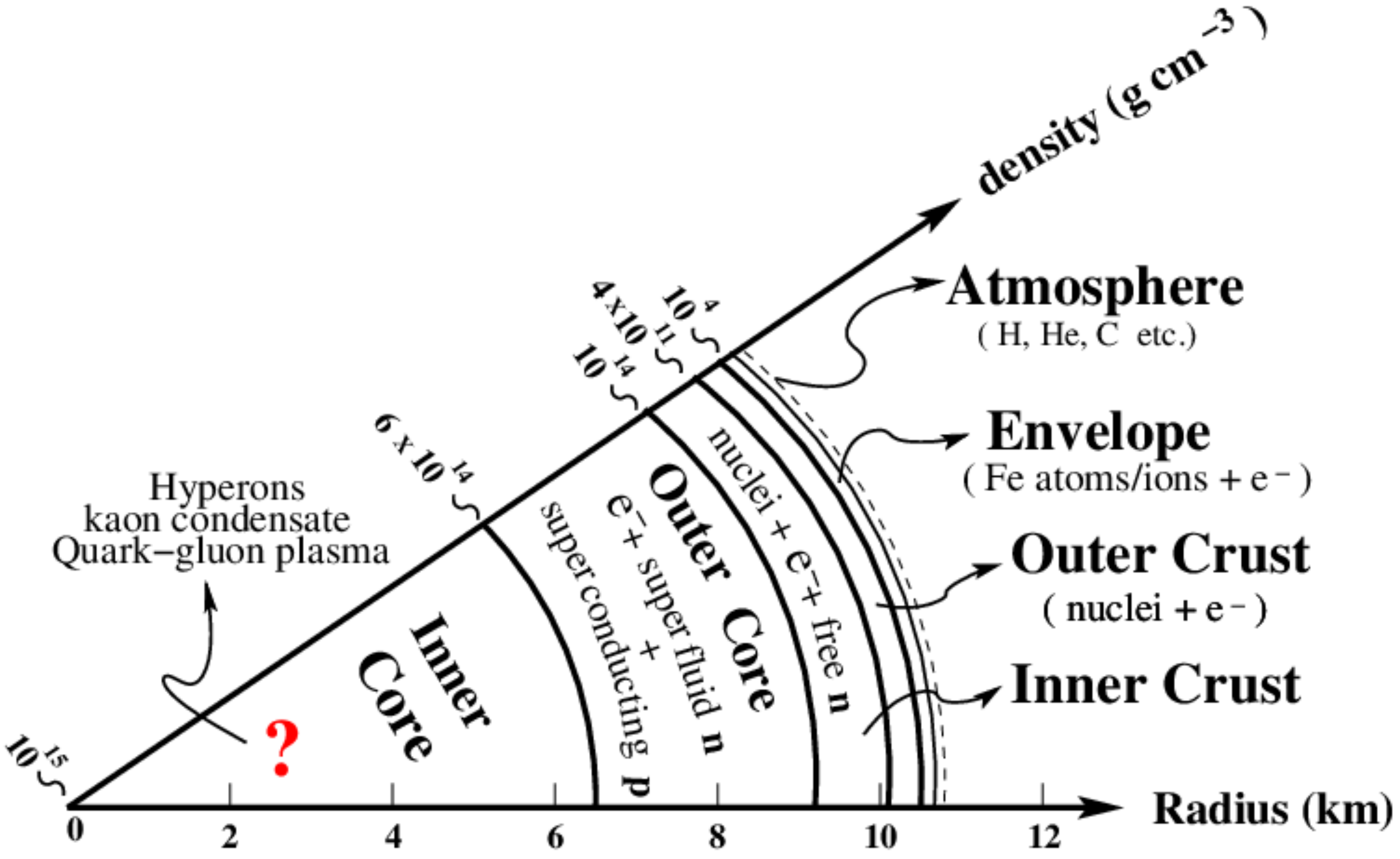


Strain prediction for the **f-mode excited by glitches**

[Phys. Rev. D 101, 103009]



Radial profile of Neutron stars



Metamodel representation of the nucleonic EoS

Which are the best uses for a metamodel?

EoS reconstruction

Bayesian inference

Numerical relativity simulation

Assessing uncertainty from astro observations

Can we decipher the composition?

Bayes inference: filters and likelihood zoo

[Phys. Rev. X 15, 021014]

$$\mathcal{M} : \mathbf{X} \to \{\epsilon(n_B), P(n_B), \delta(n_B), v_\beta(n_B), v_{FR}(n_B), \ldots\}$$

$$\mathcal{L}(\mathbf{X}) = \prod_j \mathcal{L}_j(\mathbf{X}) = \prod_j p\left(D_j \,|\, \mathcal{M}(\mathbf{X})\right)$$

Nuclear

pQCD

χ_{EFT}

Nuclei information: NMP, AME masses, more?

Heavy Ion collision

Radio and X-Ray

Heavy pulsar radio timing

Black widow pulsar

NICER M-R

Kilonovae and gamma ray bursts

Gravitational wave

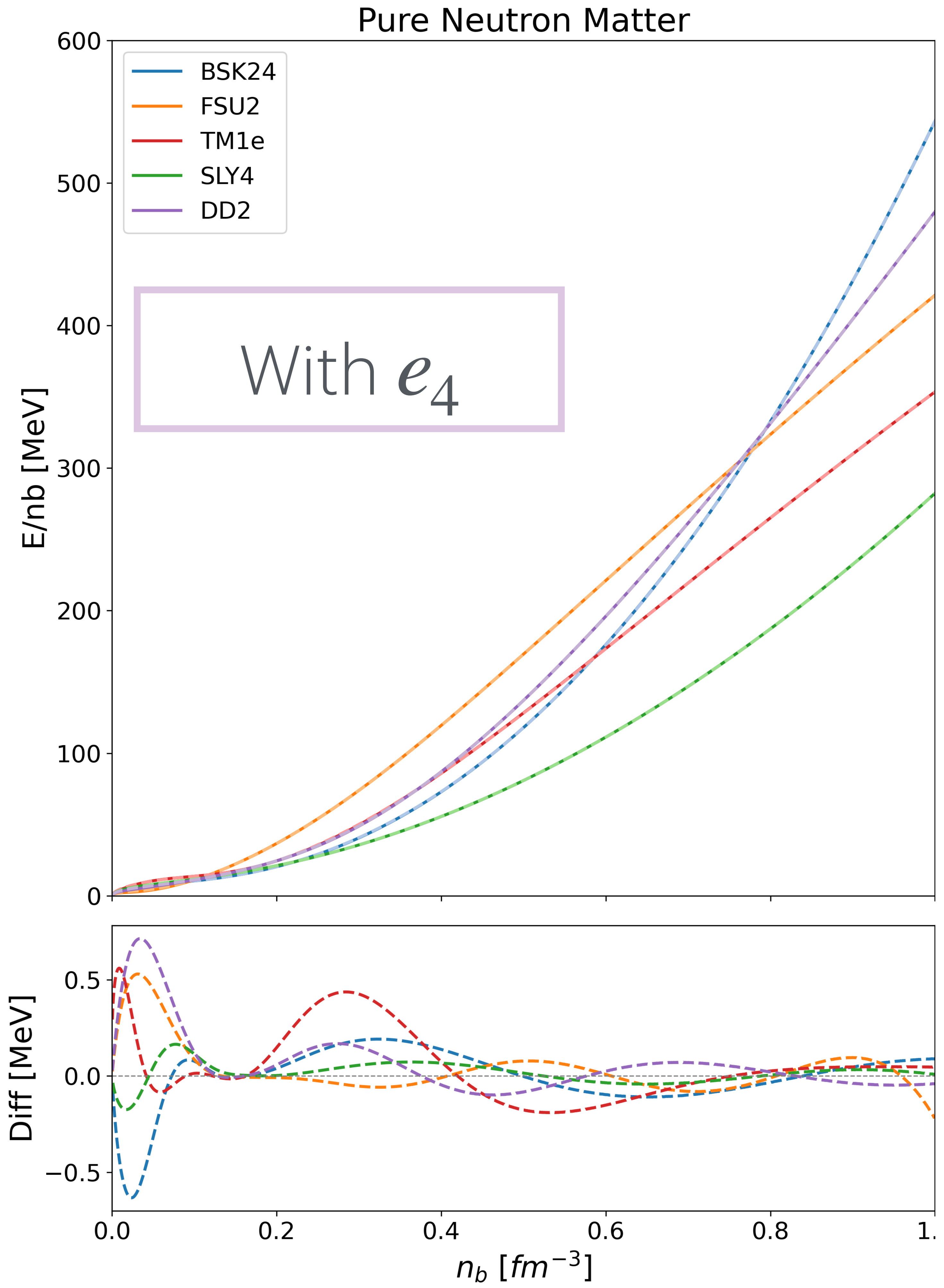
GW170817

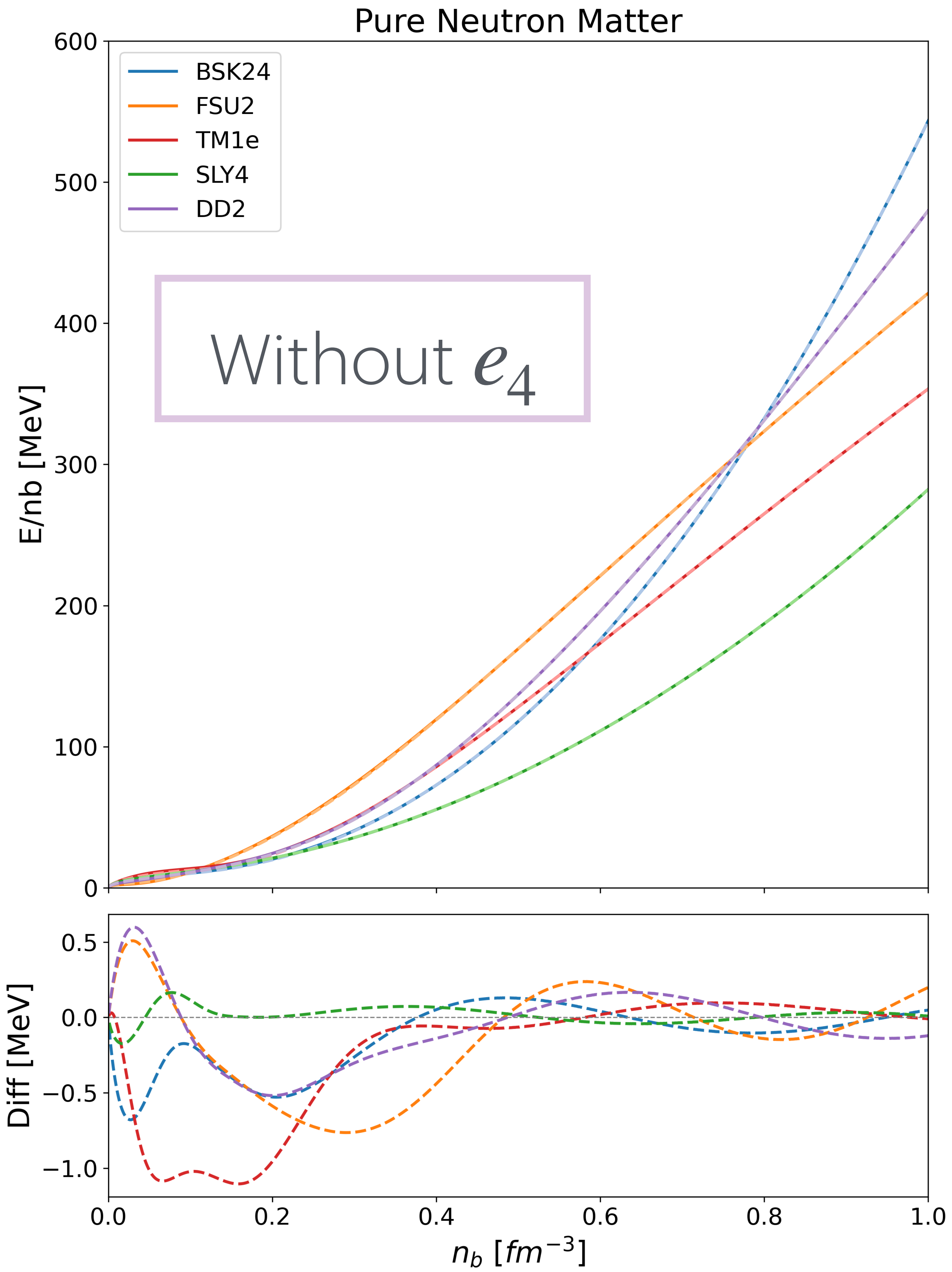
GW190425

Fit without the quartic δ correction

Without the correction around saturation the PNM fit exhibit a $\sim 0.5/1$ MeV of difference

The overall accuracy doesn't change





FIT: results for SNM and PNM

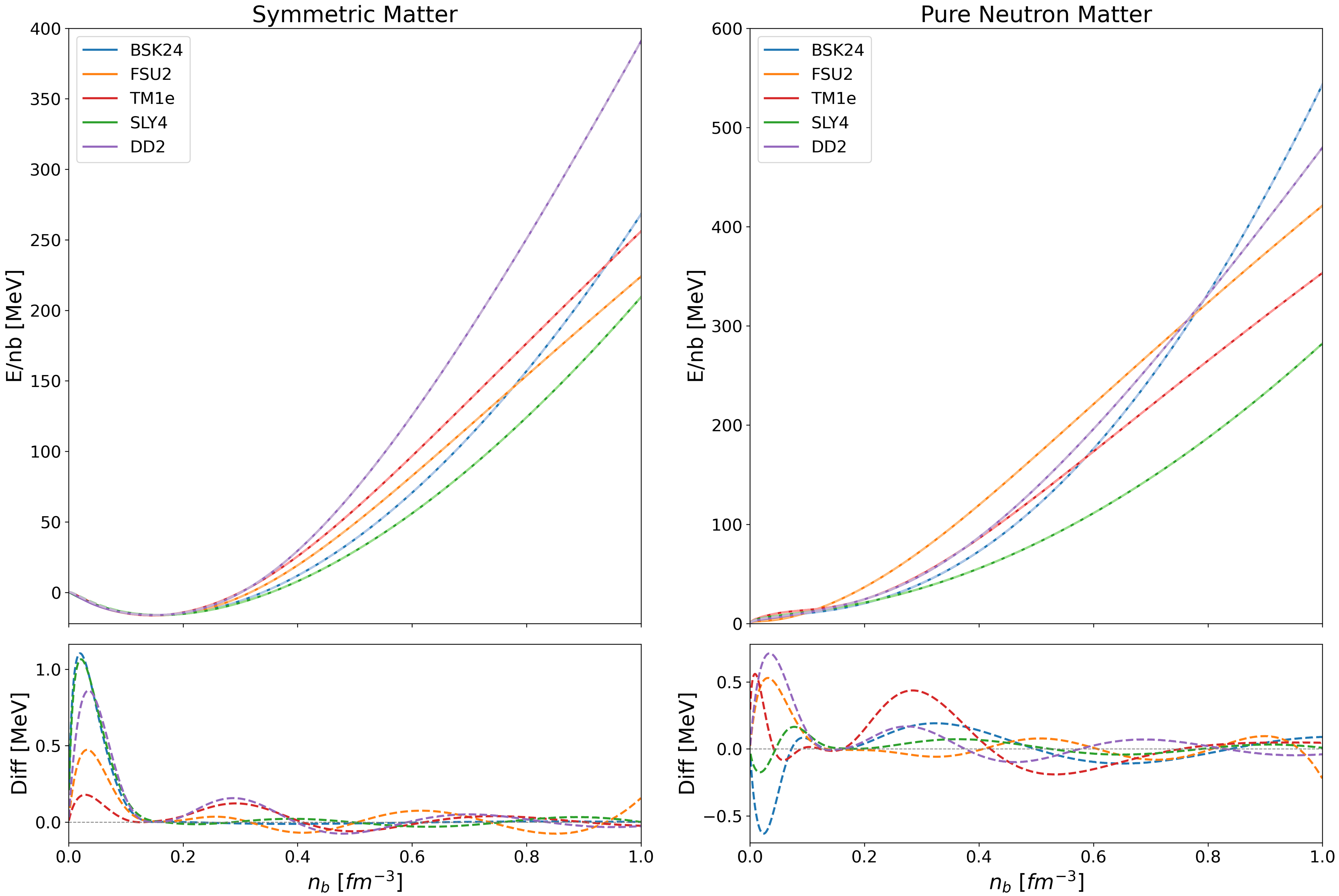
We found satisfying results with

$a_{0,2} = b_{0,2}$ and $g_{0,2} = 0$

Less Paramaters!

Before saturation the accuracy is limited

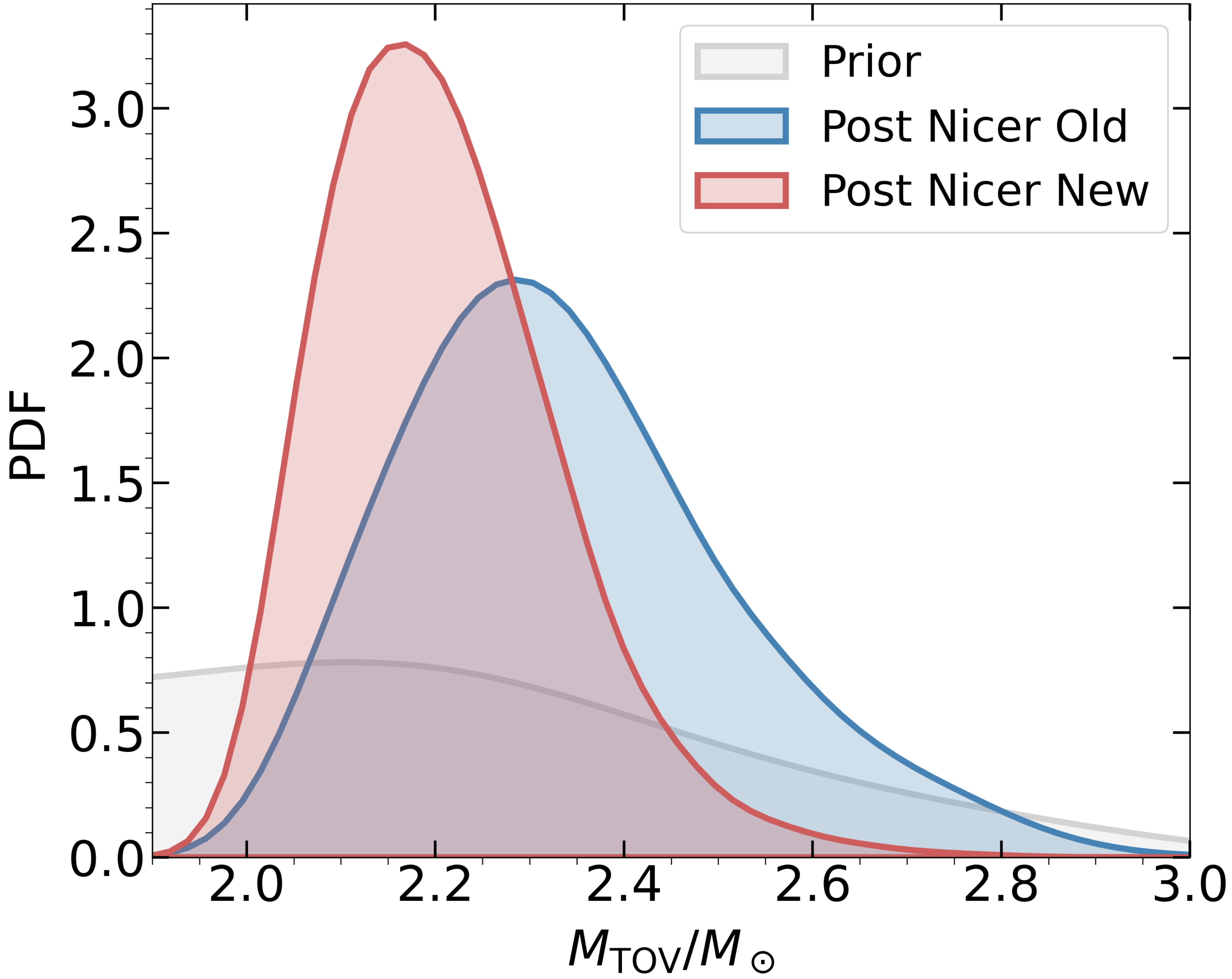
Focus on astrophysics

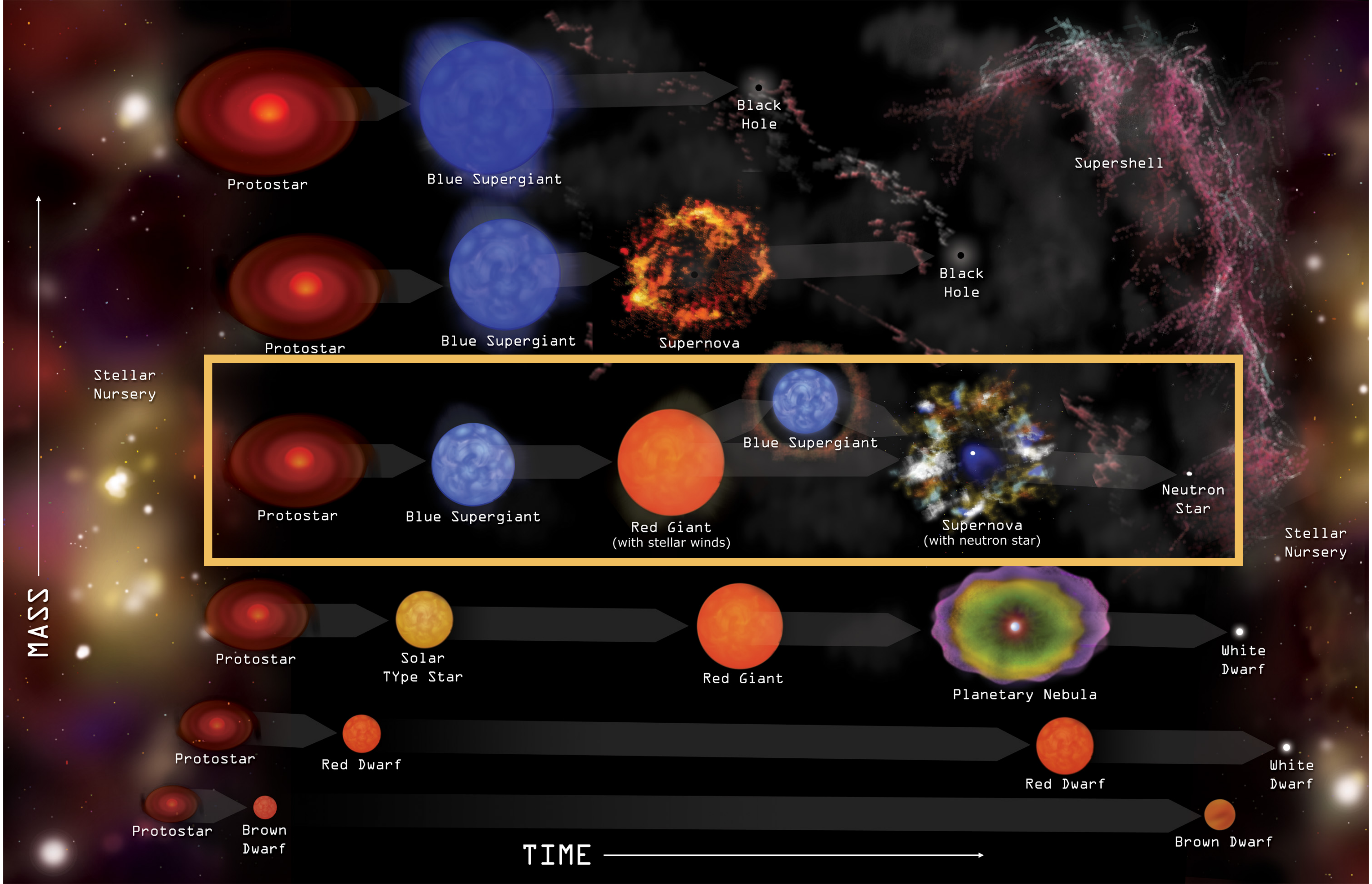


Nicer old vs nicer new: M_{tov}

The two latest Nicer measures prefer soft EoS

We can see the effects on the PDF of M_{TOV} which is peaked on lower masses





Protostar
Blue Supergiant
Black Hole
Supershell
Protostar
Blue Supergiant
Supernova
Black Hole
Stellar Nursery
Protostar
Blue Supergiant
Red Giant
(with stellar winds)
Blue Supergiant
Supernova
(with neutron star)
Neutron Star
Stellar Nursery
MASS
Protostar
Solar Type Star
Red Giant
Planetary Nebula
White Dwarf
Protostar
Red Dwarf
Red Dwarf
White Dwarf
Protostar
Brown Dwarf
Brown Dwarf
TIME