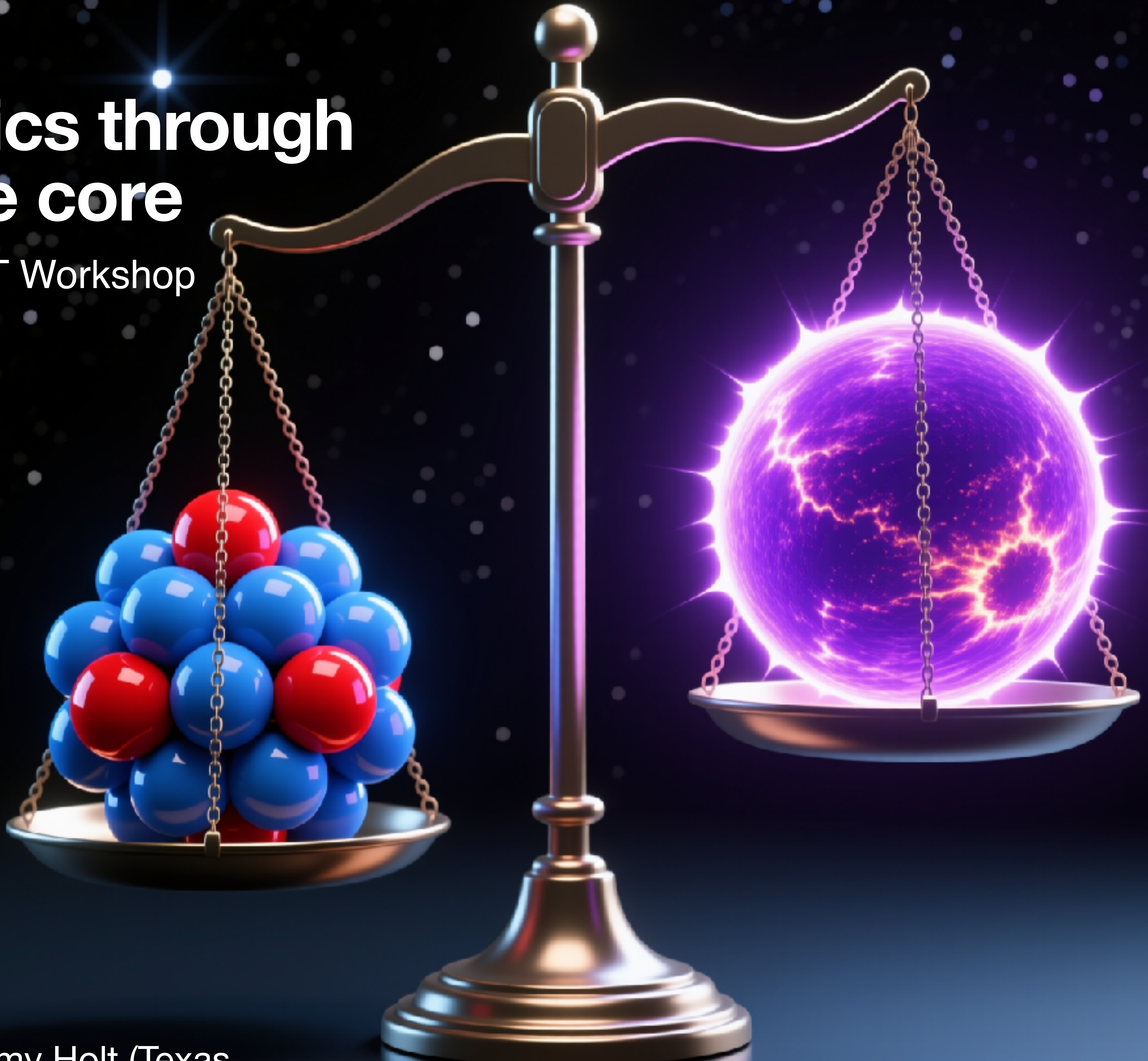
Geometric radius measurement during NS mergers

Leveraging low-density nuclear physics through dynamical resonance to constrain the core

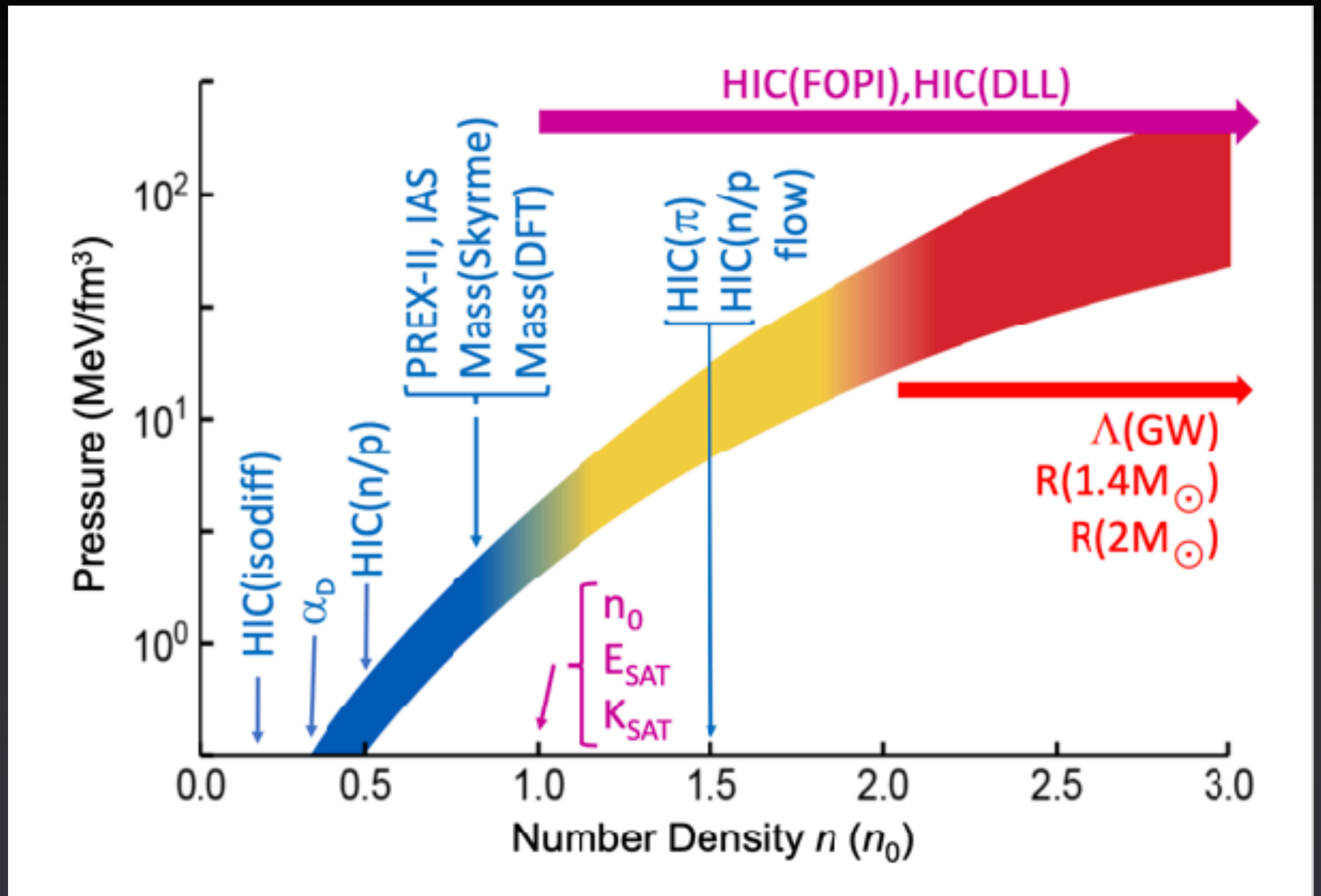
Nuclear Physics in Mergers - Going Beyond the Equation of State INT Workshop
25-94W, University of Washington,
Wednesday 10 September 2025



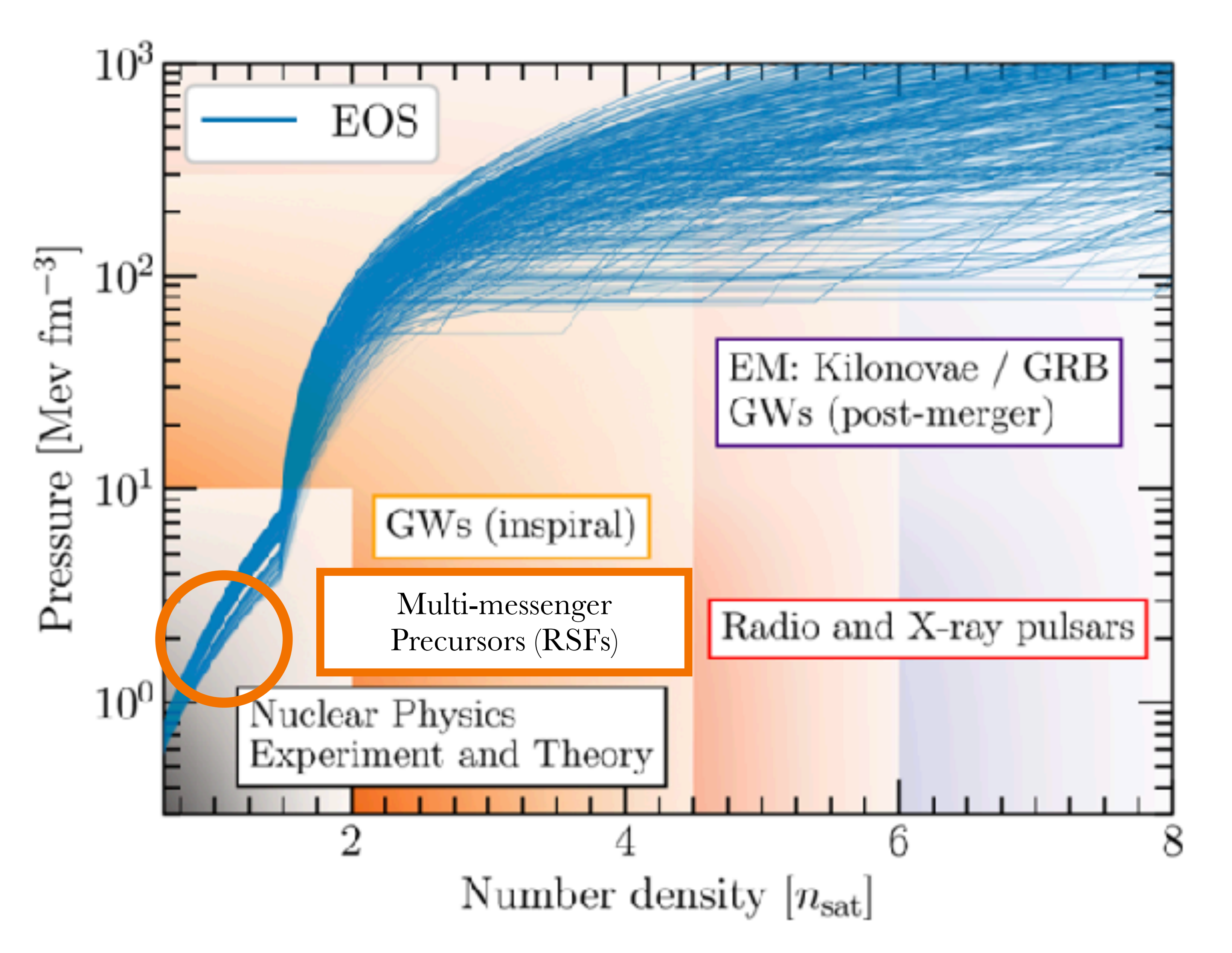
David Tsang, University of Bath

With **Duncan Neill** (University of Bath), Will Newton (East Texas A&M), Jeremy Holt (Texas A&M), Christian Drischler (Ohio University/FRIB) & Jérôme Margueron (CNRS/FRIB)

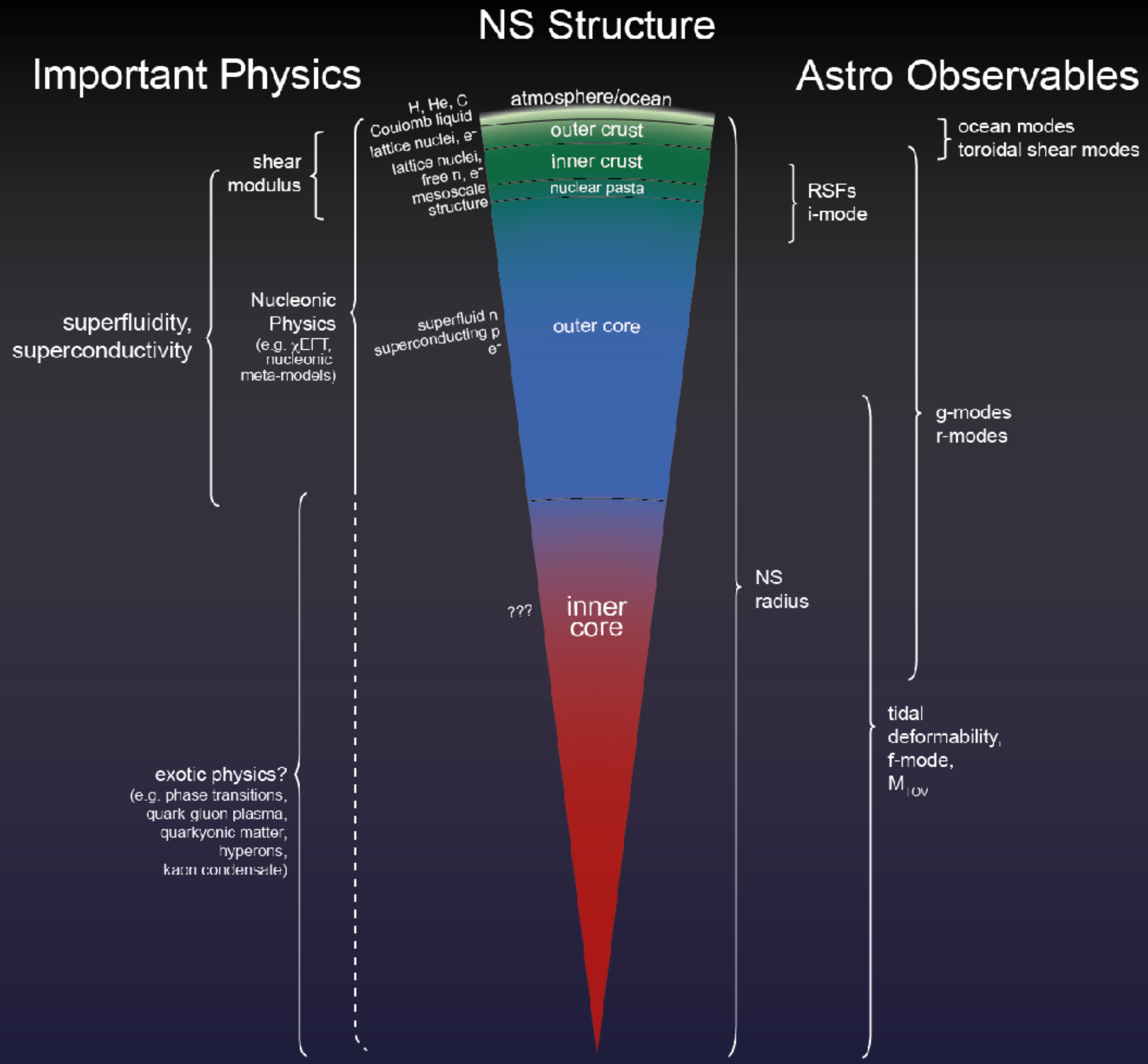
Title slide generated by Qwen-image (arXiv:2508.02324)

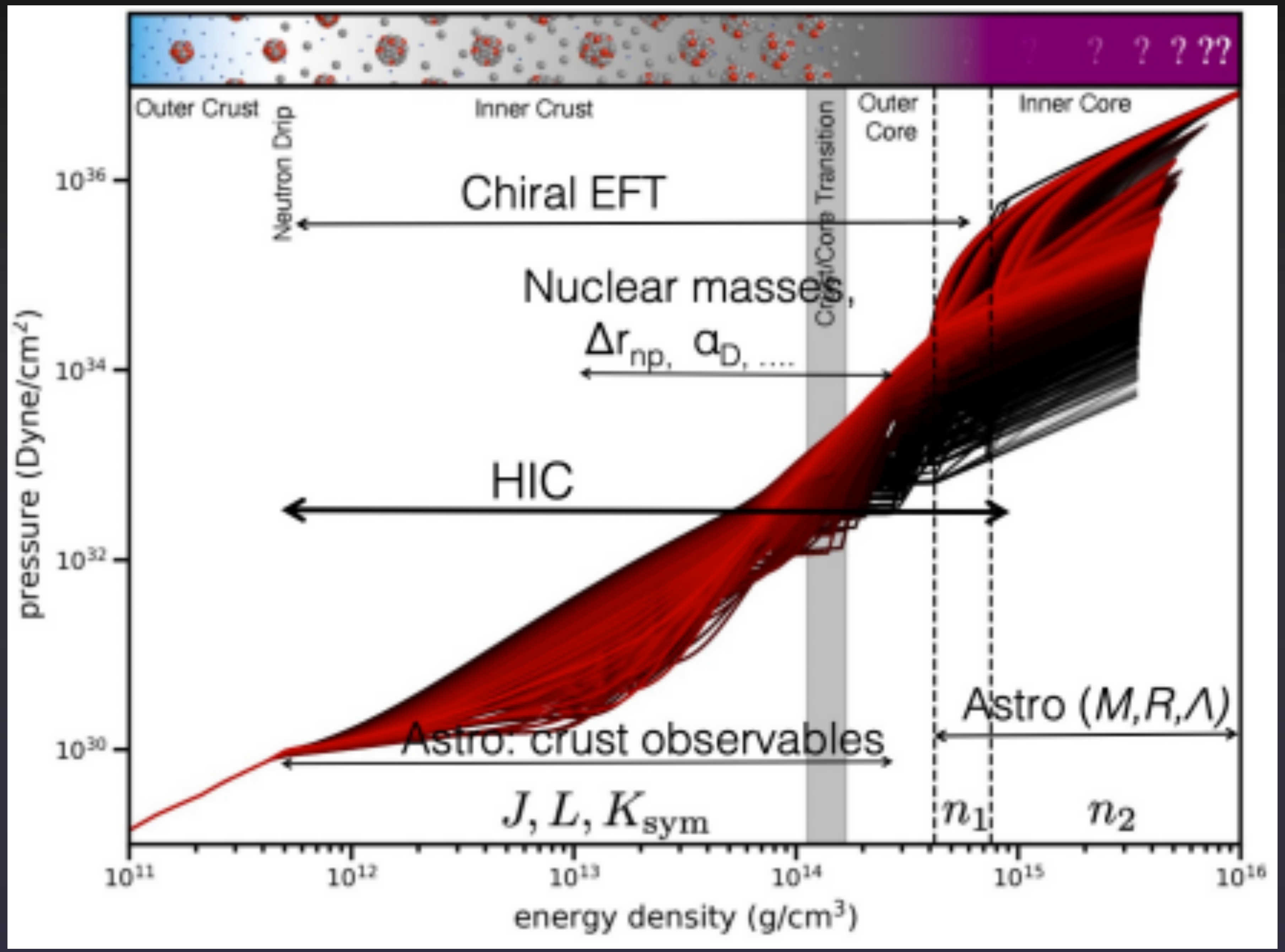


C.Y. Tsang et al., 2023 arXiv:231011588



Adapted from Pang et al., (2023) Nature Comm, 14:8352



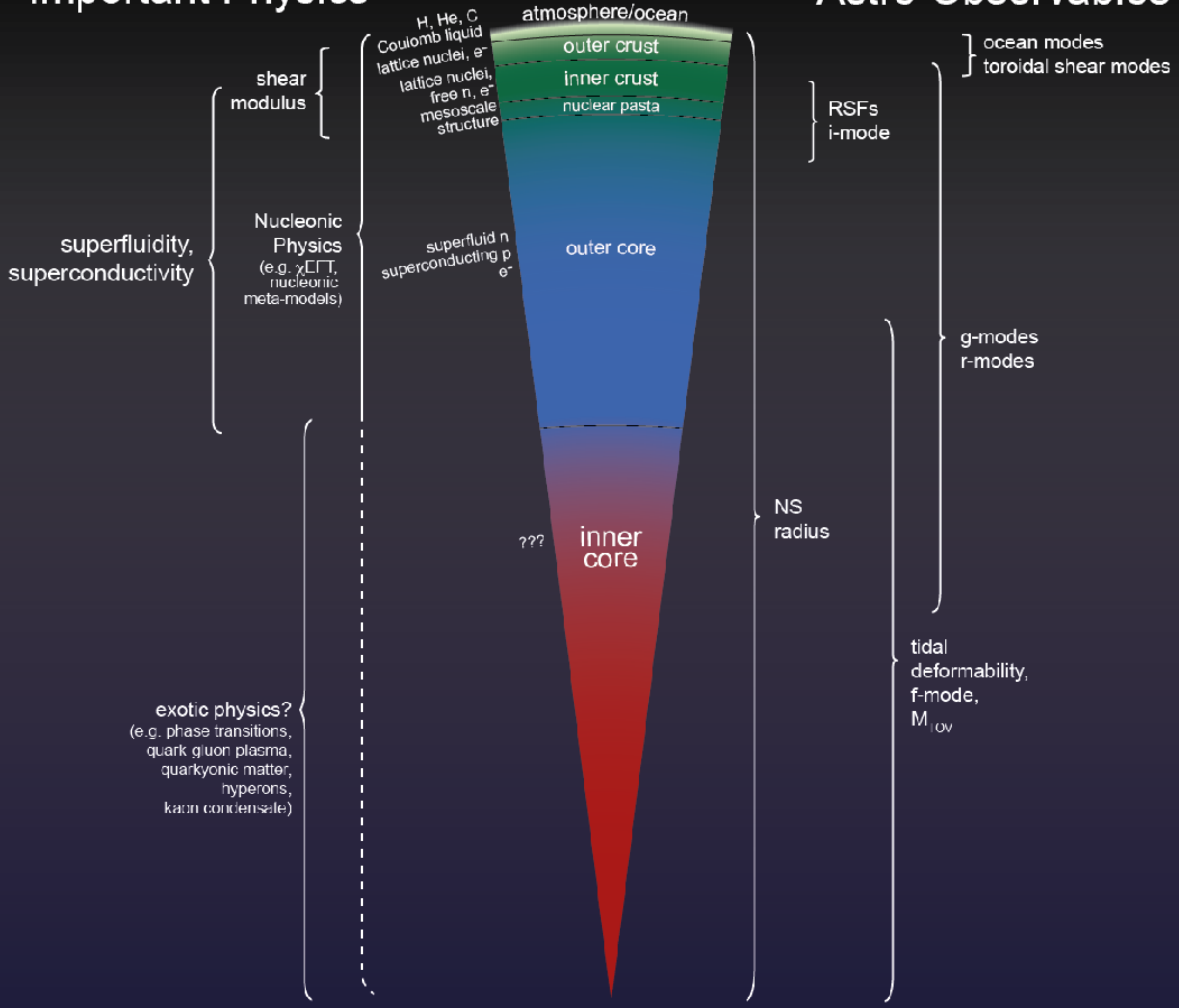


Adapted from Neill et al, 2022

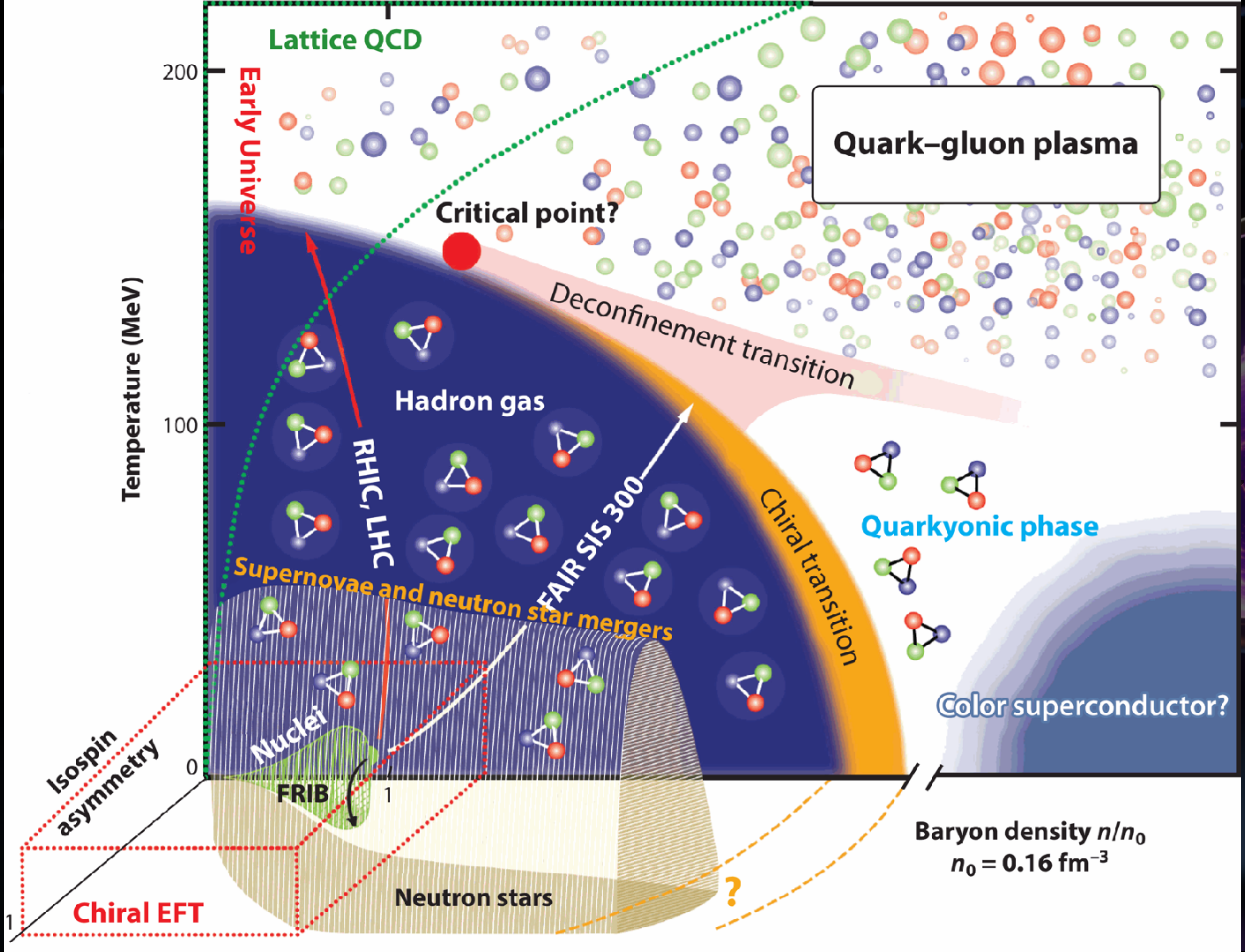
NS Structure

Important Physics

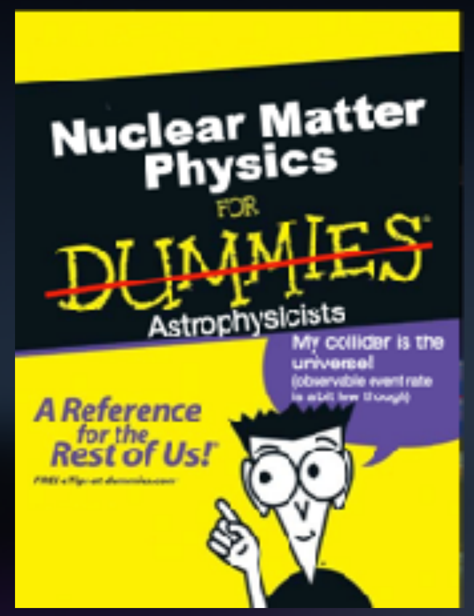
Astro Observables




Nuclear Matter Physics
FOR
~~DUMMIES~~
Astrophysicists
My collider is the universe!
(observable event rate is a bit low though)
A Reference for the Rest of Us!
FREE eTips at dummies.com

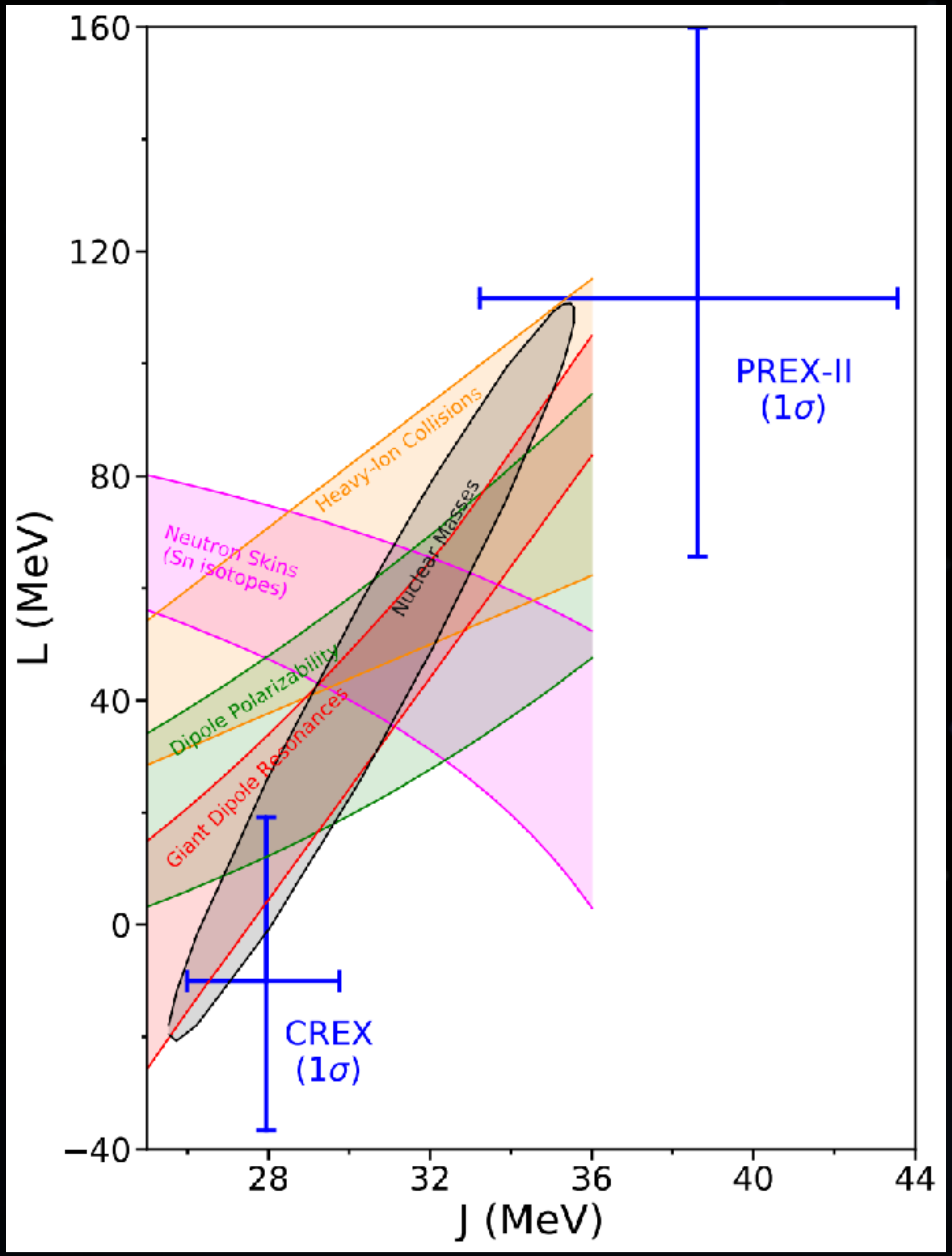


Drischler, Holt, & Wellenhofer (2021), Ann. Rev. of Nucl., 71, 403




(Cold) Infinite Nuclear Matter Equation of State
Energy per baryon
Pure Neutron Matter (PNM)
Symmetric Nuclear Matter (SNM)
(Equal Protons and Neutrons)
"isoscalar"
"isovector"
Nuclear Symmetry Energy:
$E_{\rm sym}(n)$
$K \propto \left.\frac{\partial^2 E_{\rm sym}}{\partial n^2}\right|_{n=n_o}$
$L \propto \left.\frac{\partial E_{\rm sym}}{\partial n}\right|_{n=n_o}$
$J = E_{\rm sym}(n_o)$
Saturation Density
$n_o \simeq 0.16\ \mathrm{fm}^{-3}$
n
Baryon Density
Nuclear Matter Physics
FOR
~~DUMMIES~~
Astrophysicists
A Reference for the Rest of Us!

Experimental Constraints on J-L

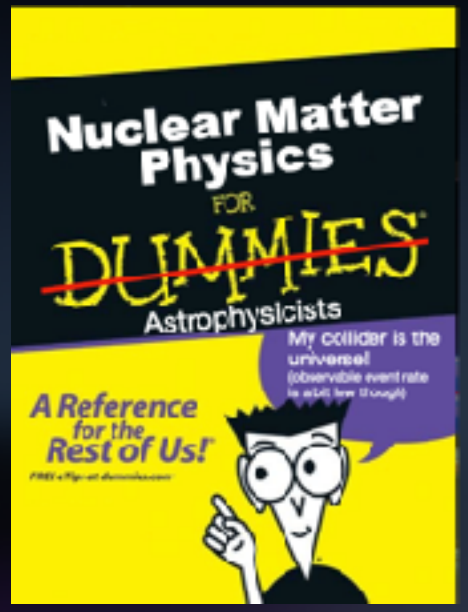


Adapted by D. Neill (2023 Thesis) from Lattimer & Lim 2013 including (Skryme dependent) J-L constraints on PREX and CREX from Zhang & Chen (2023) Phys Rev C, 108, 2, 024317

^{208}Pb/^{48}Ca Neutron "Skin" thickness

https://www.stonybrook.edu/commcms/physics/research/archive/2022/0217_neutronskin

Experimental constraints of symmetry energy and nucleonic physics



Nuclear Effective Field Theories

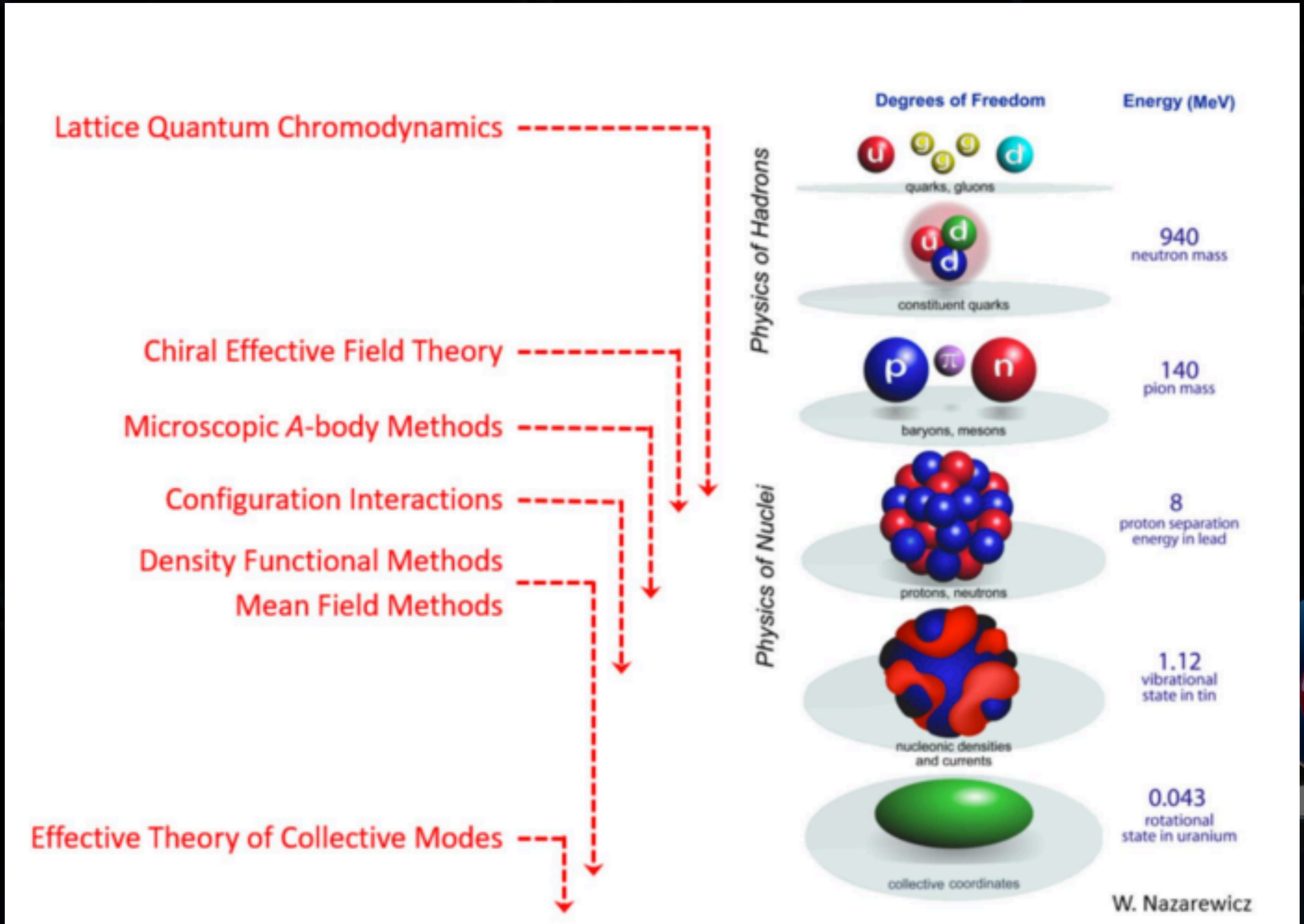
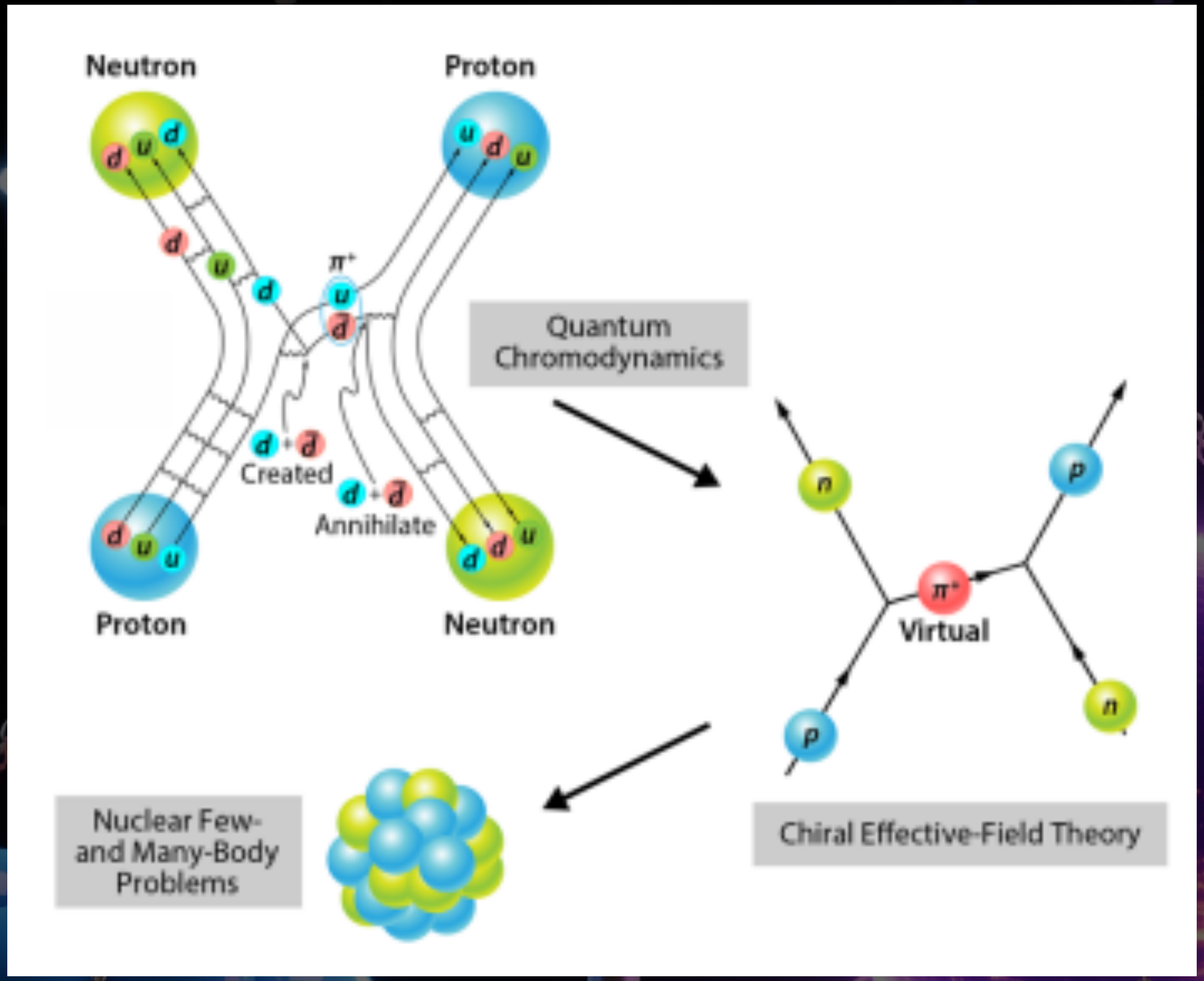
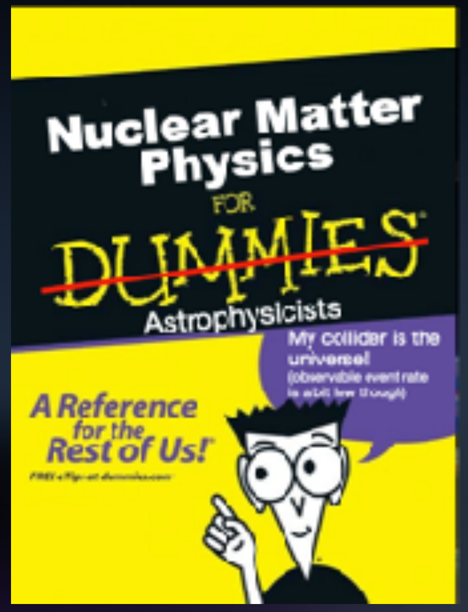


Illustration from https://indico-tdli.sjtu.edu.cn/event/2821/attachments/5277/8738/20241210_SJTU_bnlu.pdf

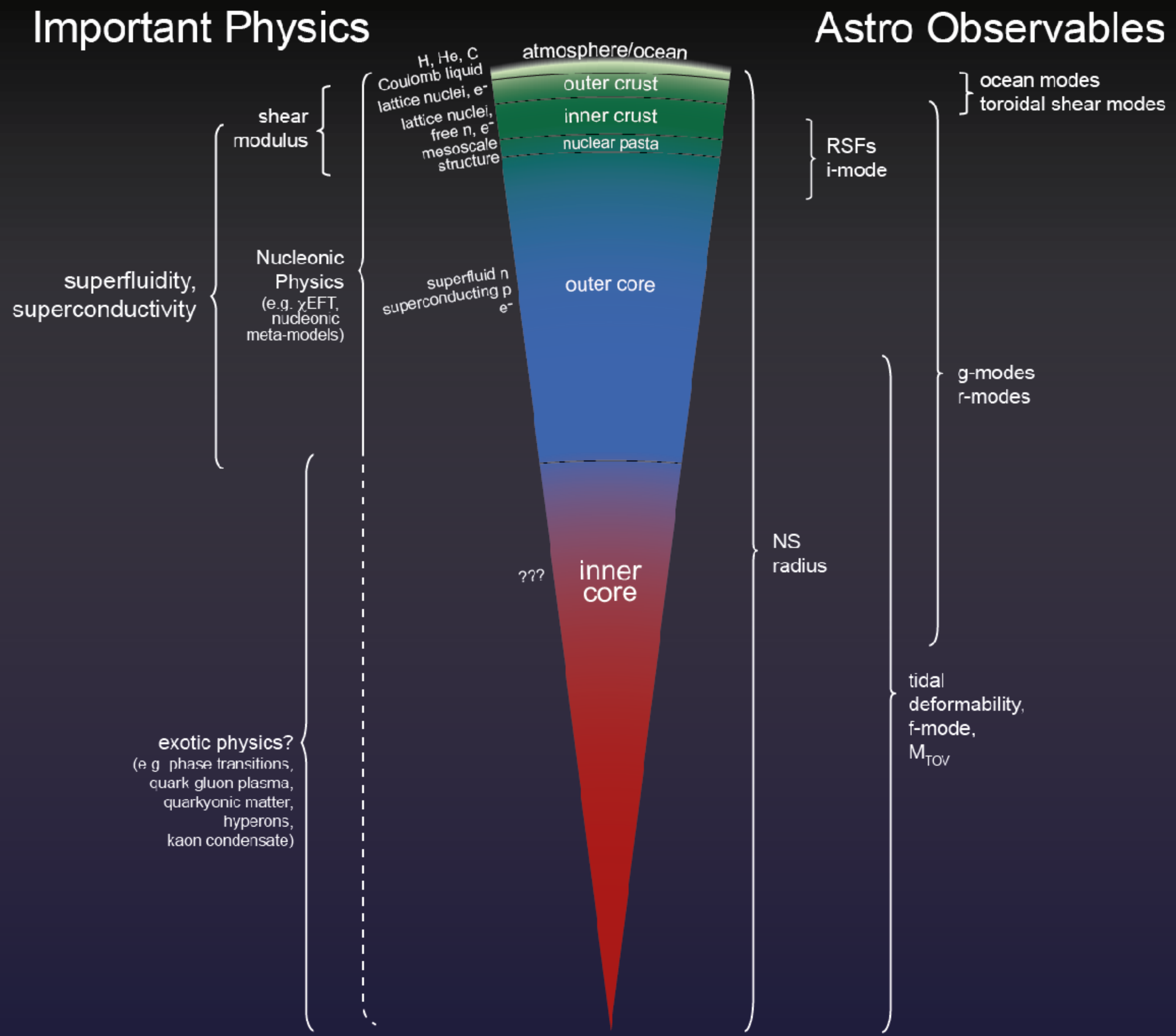


Hjorth-Jensen, Physics 10, 72, 2017 (APS/Alan Stonebraker)

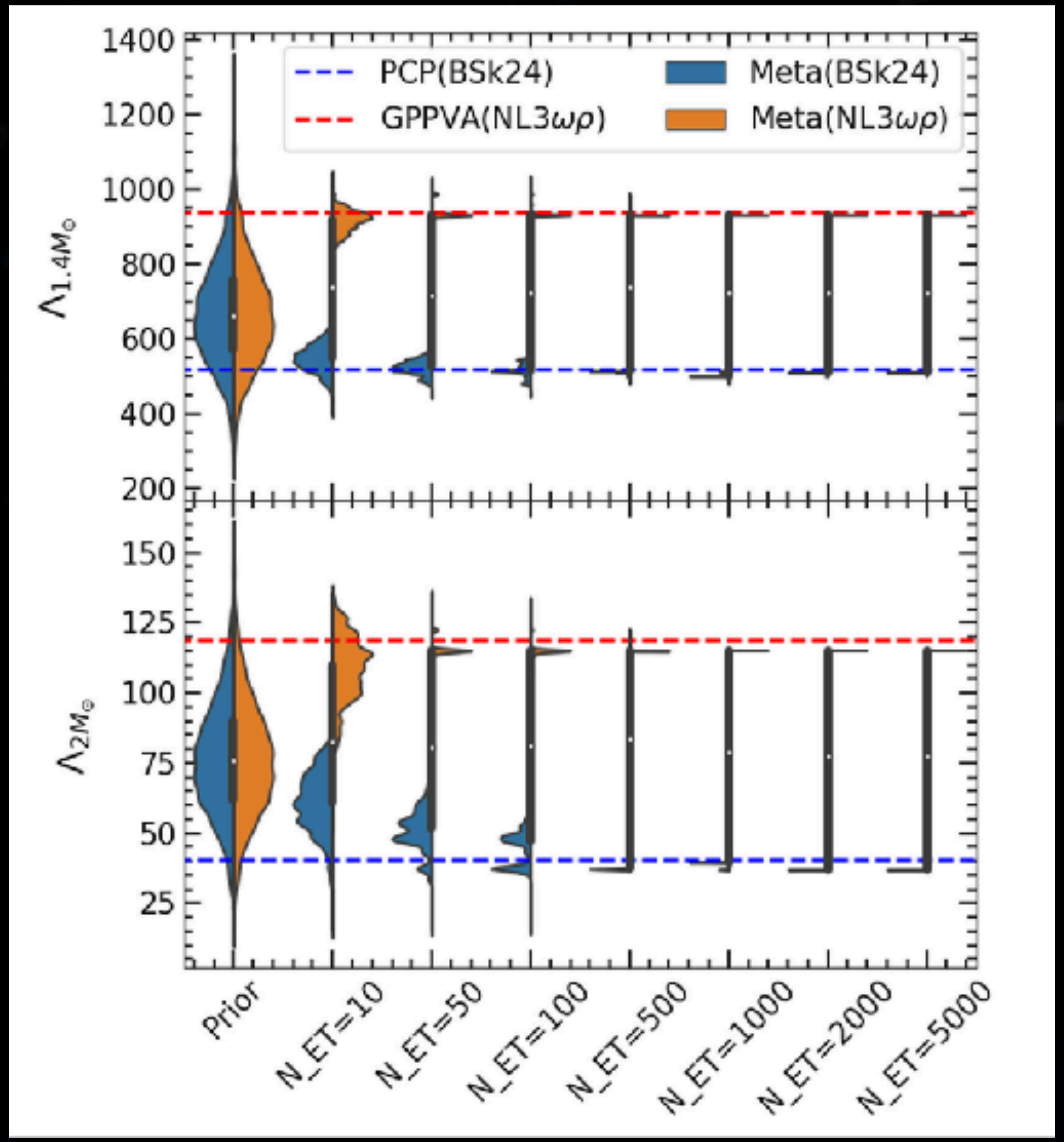
Theoretical models of nuclear matter

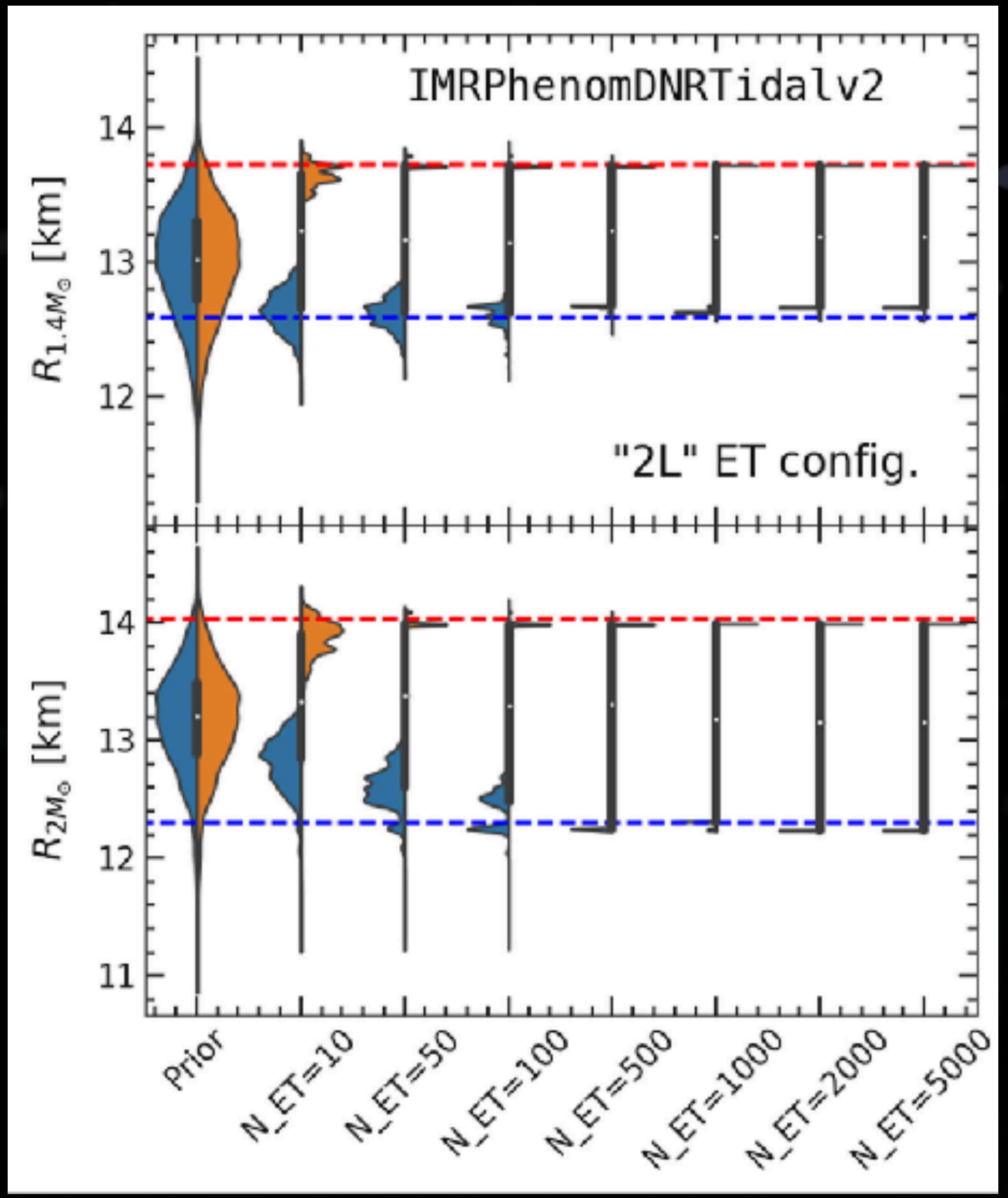


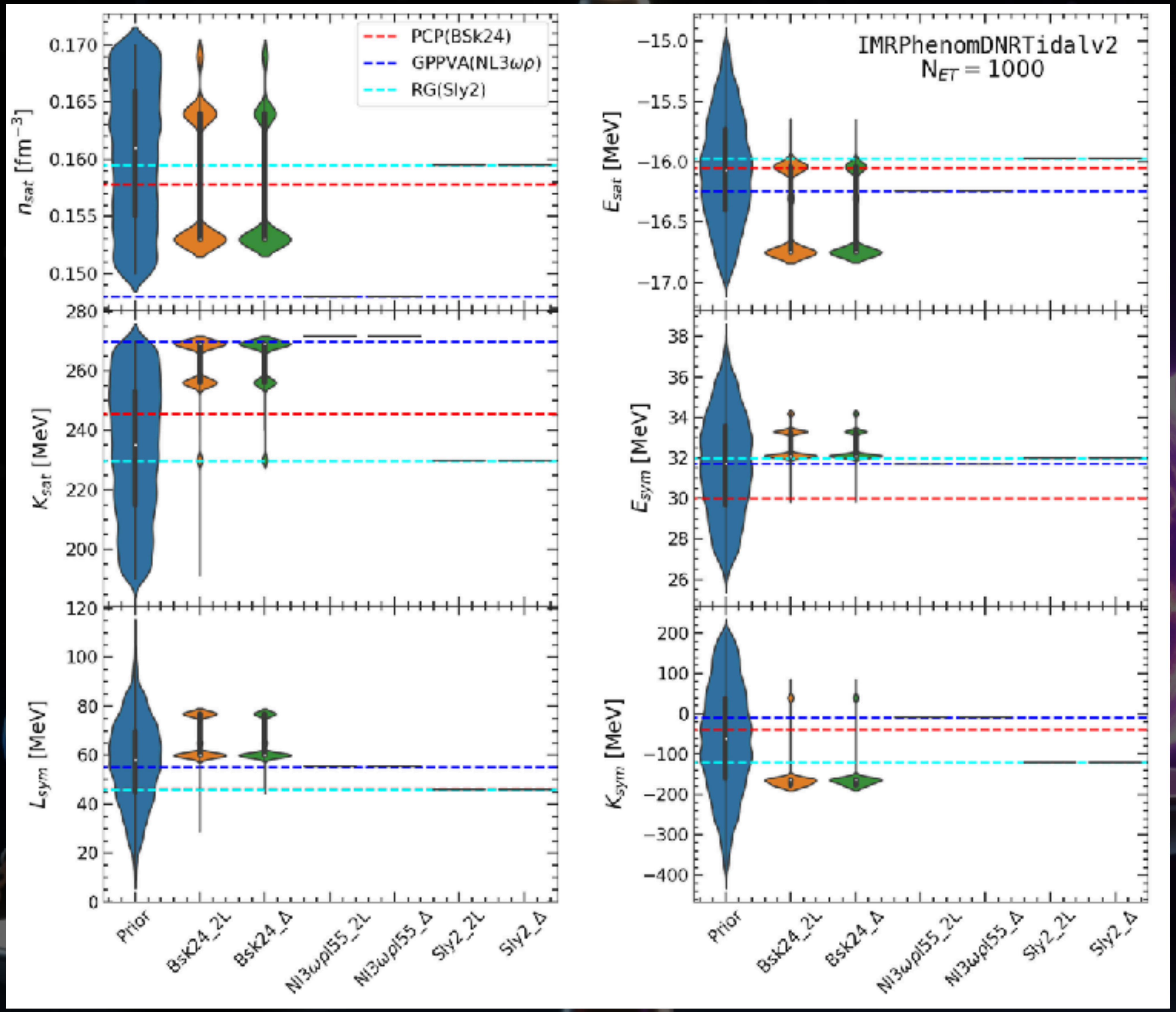
NS Structure



GW Bulk Observables





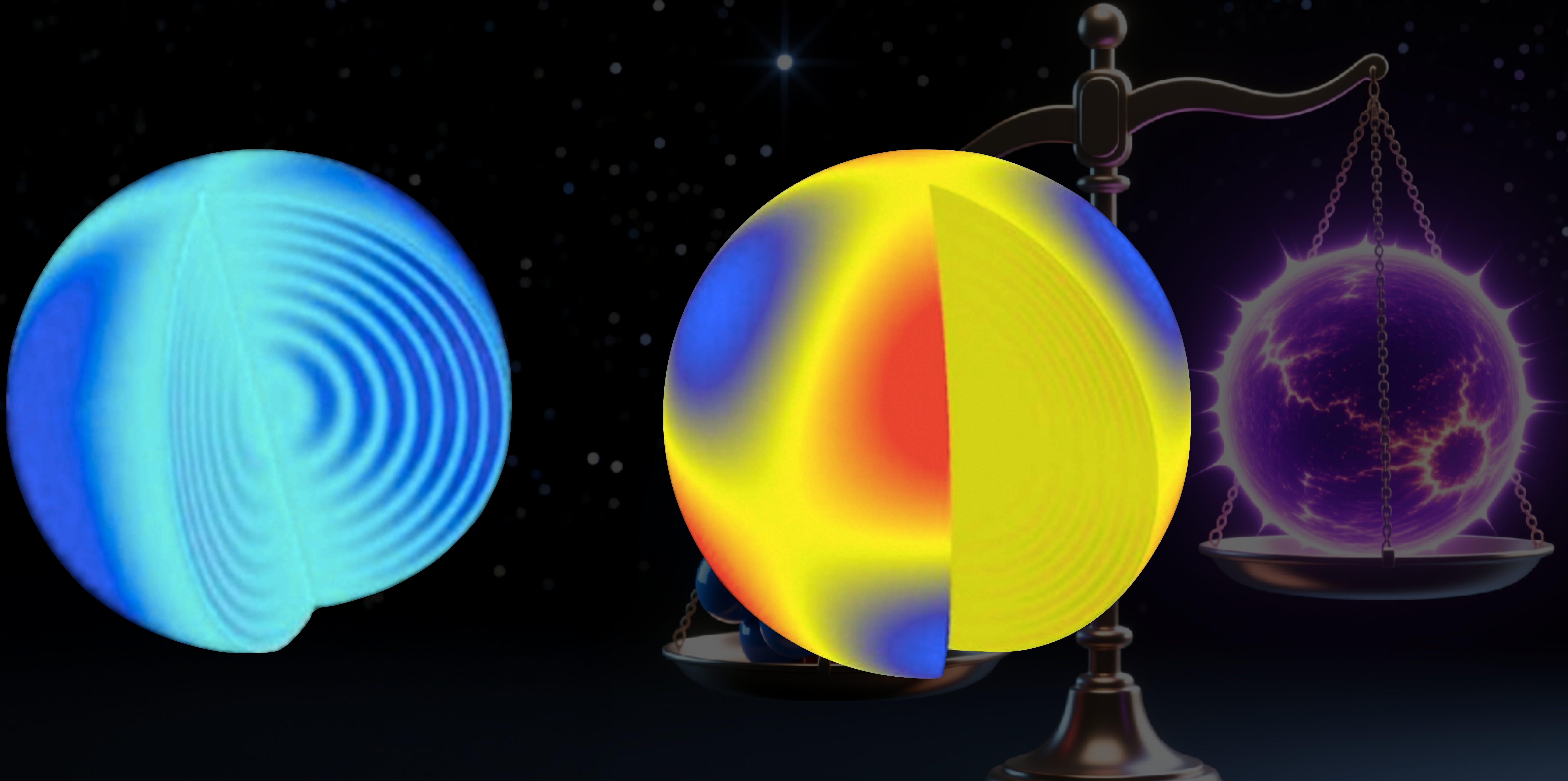


Iacovelli et al. (2023) PRD, 108, 122006

If you assume the entire star is nucleonic then constraints can be placed on the radius and isovector/isoscalar parameters from the GW tidal deformability, particularly with the next gen observatories. However, this isn't necessarily a good assumption.

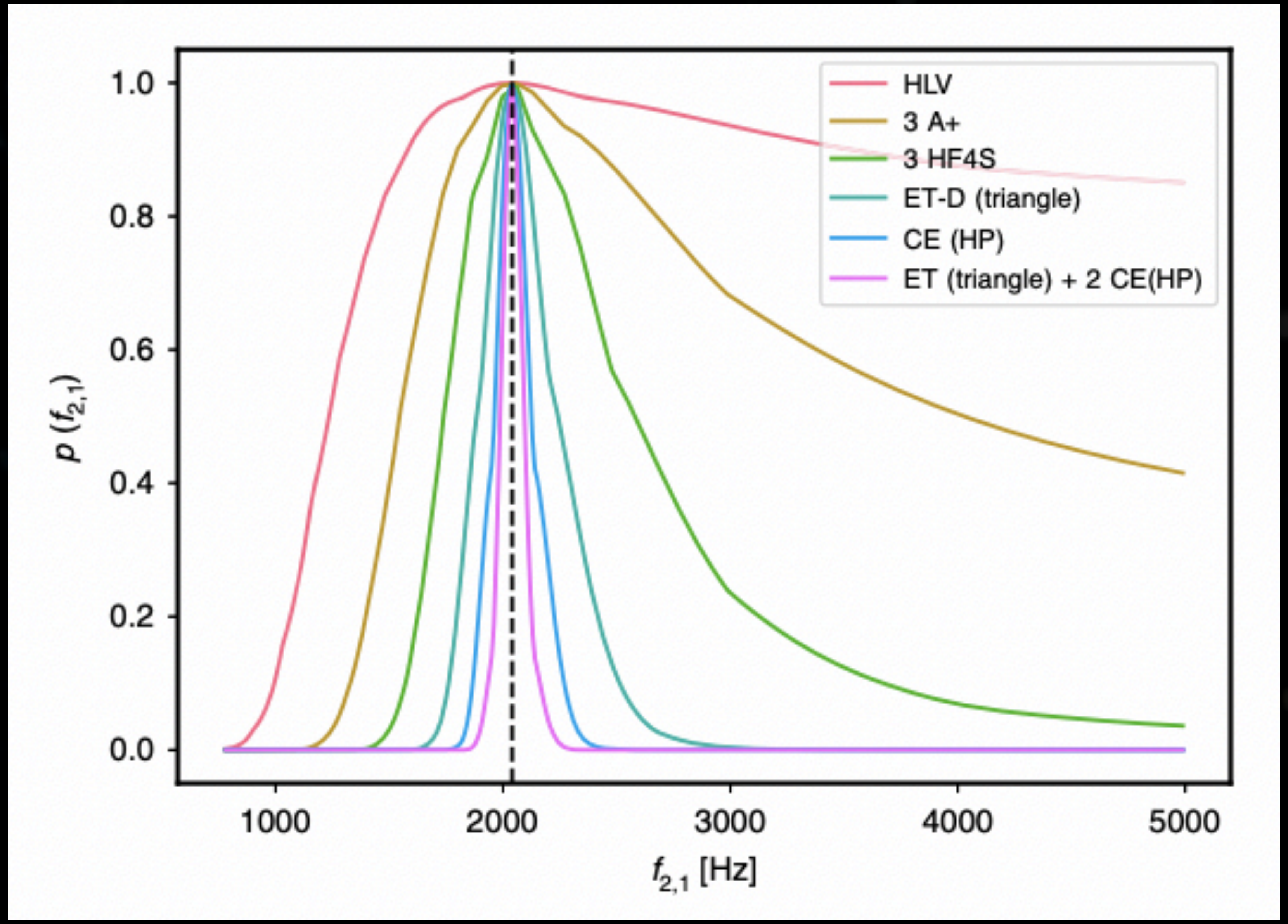
See Legred et al (2025) arXiv:2505.07677, or Isaac's entire talk on Monday

Asteroseismology!

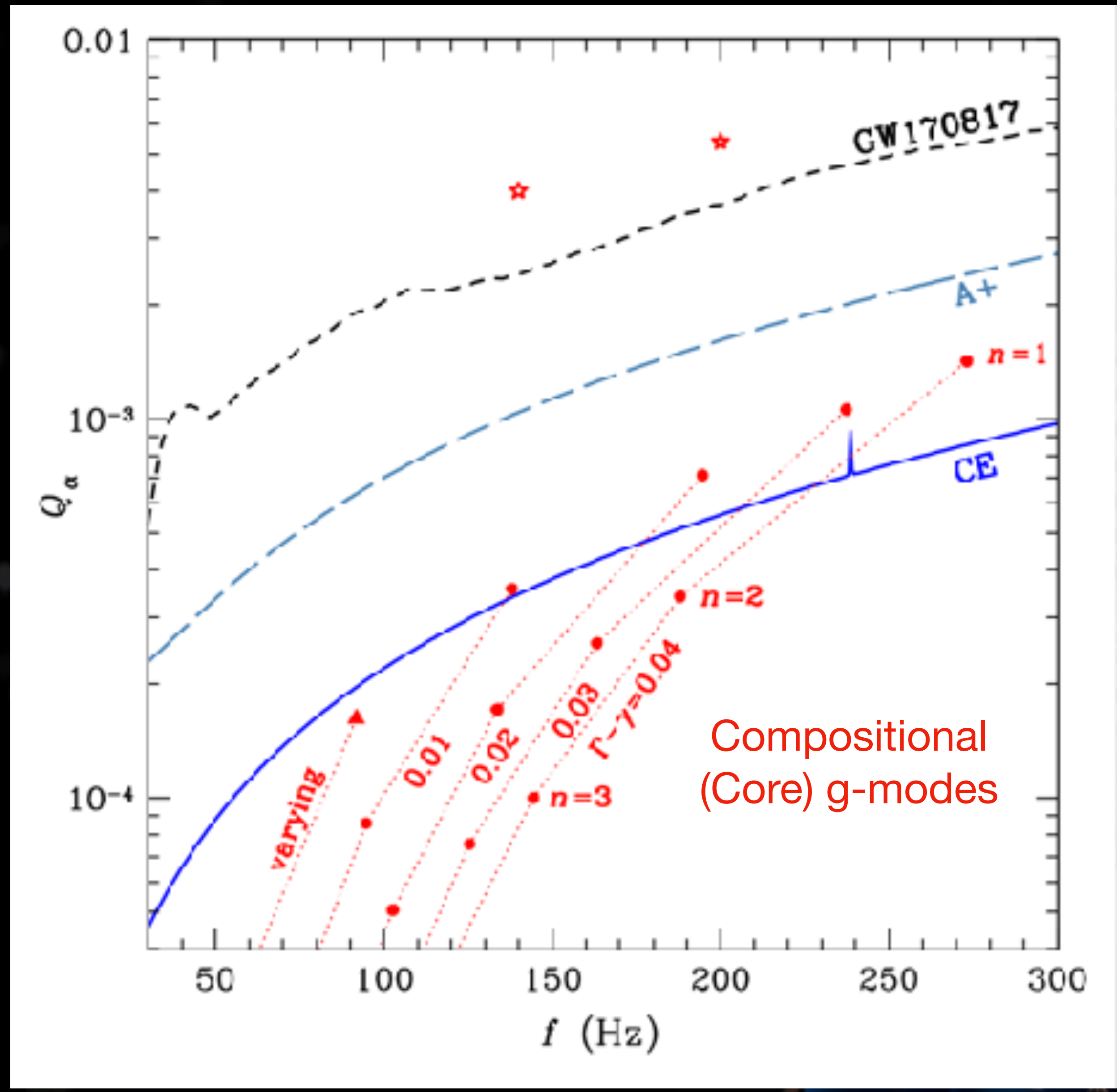


Modes probe the dynamics where their eigenfunctions are concentrated

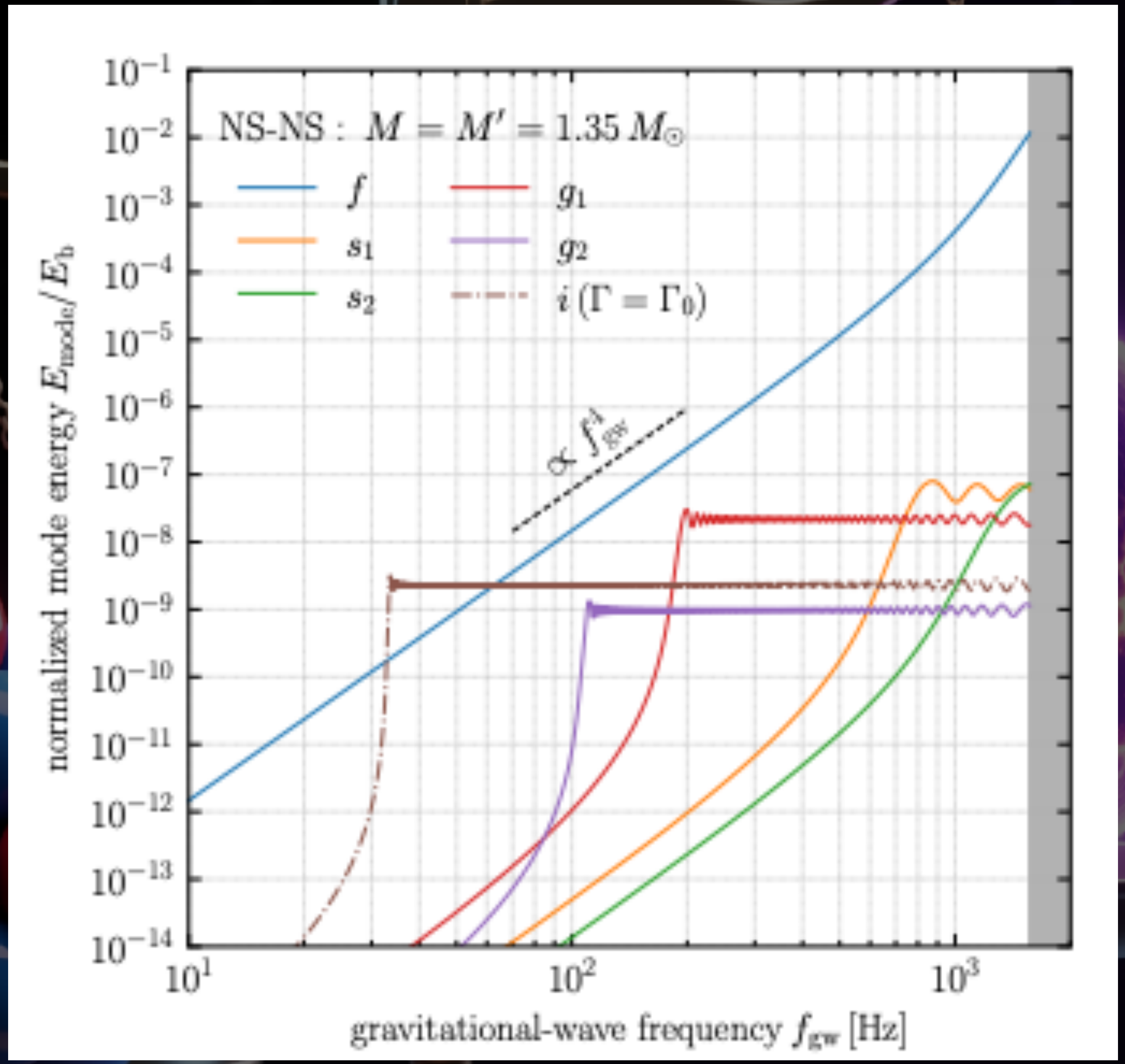
Asteroseismology!



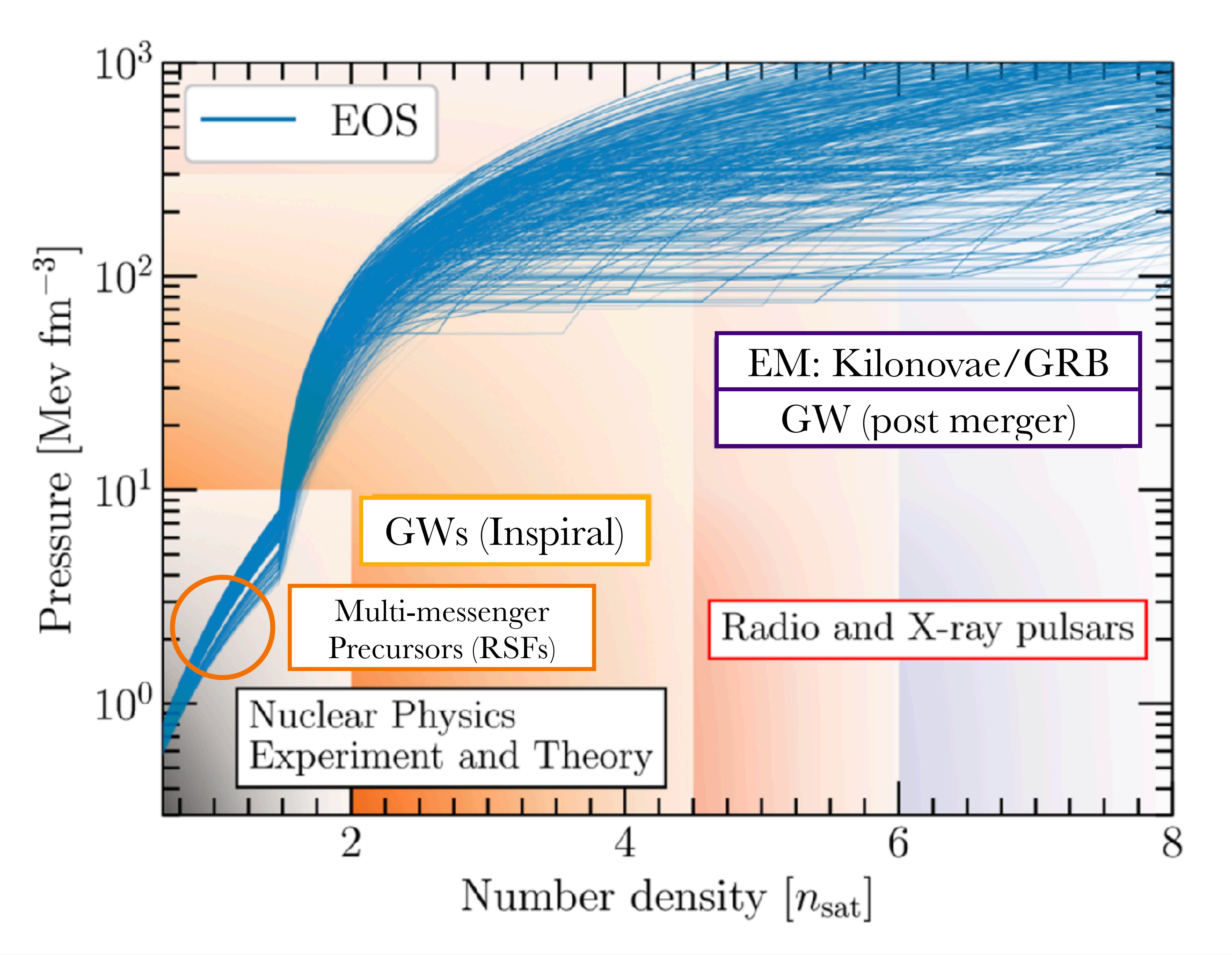
Fundamental modes (same EOS info as Λ)
(non-resonant during inspiral)
Pratten, Schmidt, & Hinderer (2020) Nature Comm., 11, 2553



Other asteroseismic modes
(resonant during inspiral)
Ho & Andersson (2023), PRD 108, 043003

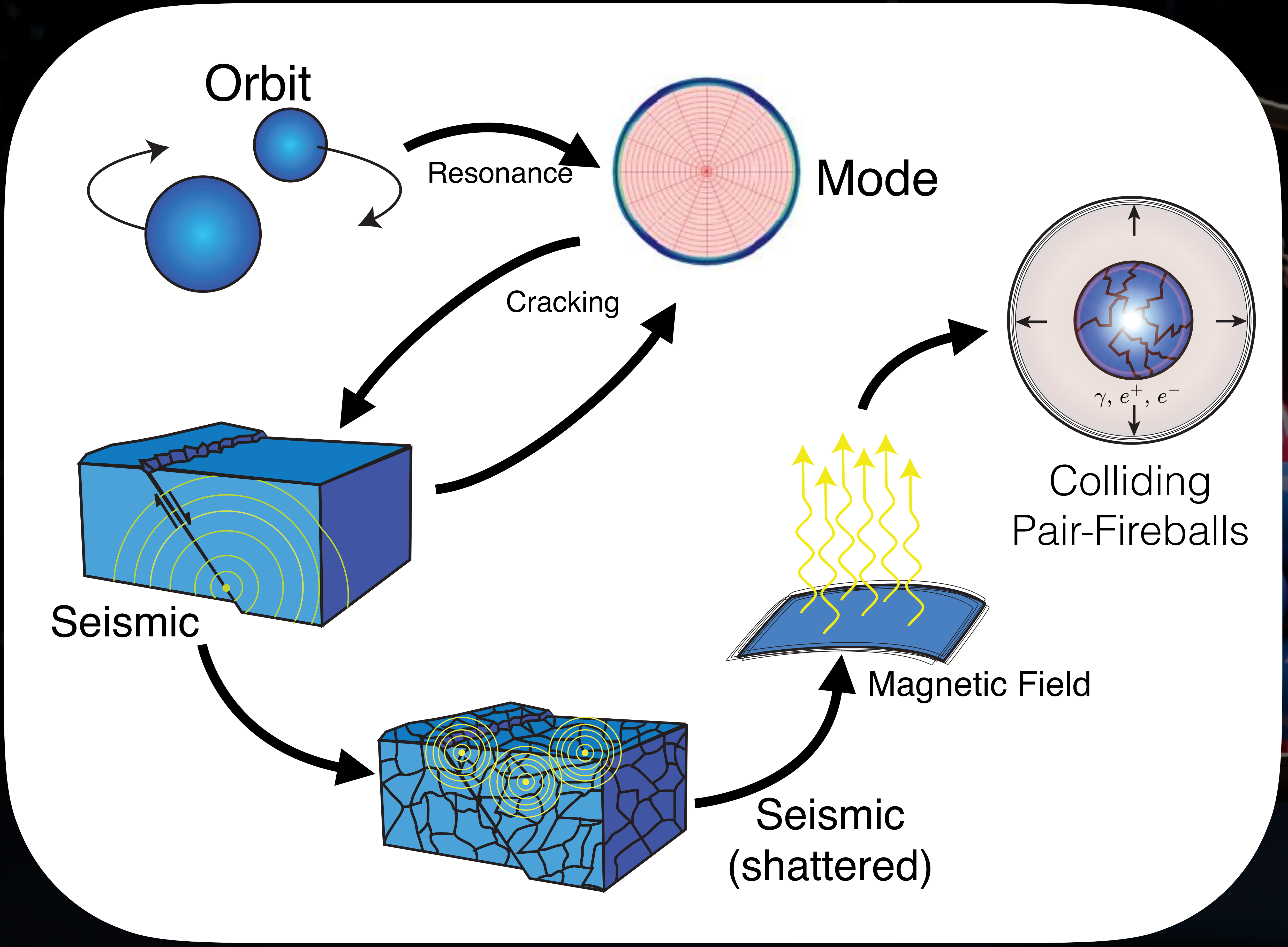


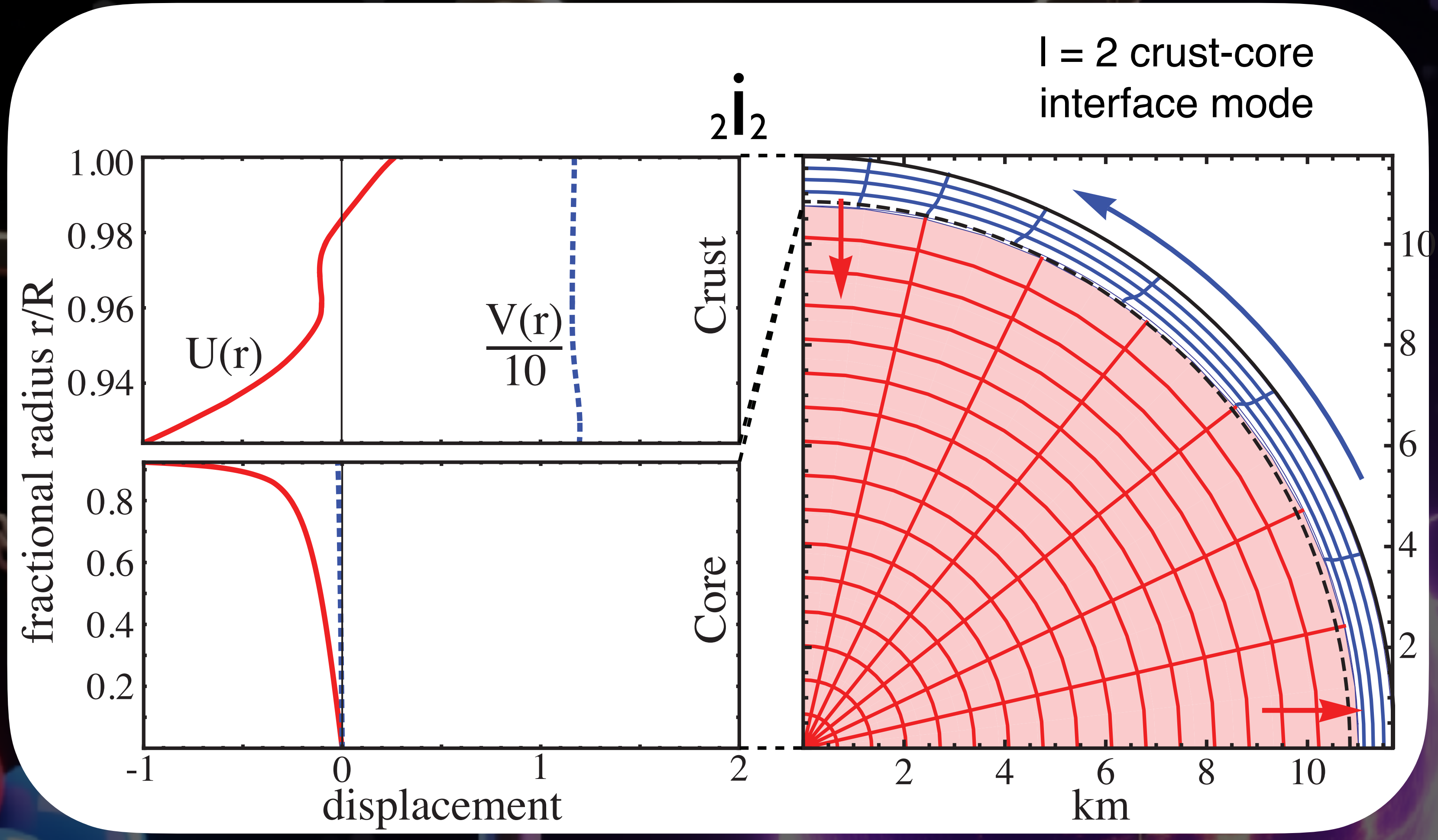
Gao et al (2025) arXiv:2509.00257v1

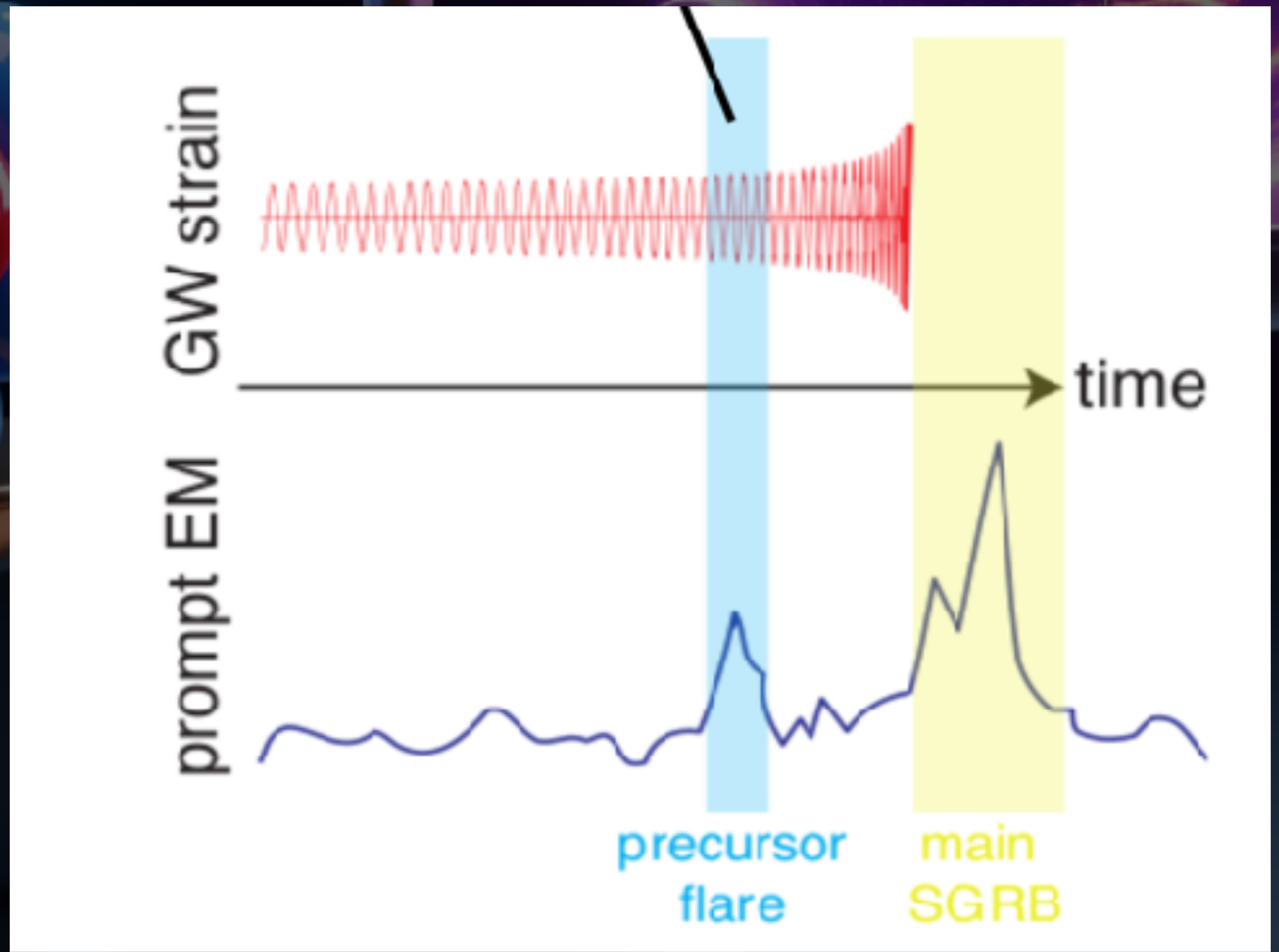


Adapted from Pang et al., (2023) Nature Comm, 14:8352

Multi-messenger Precursors (RSFs)



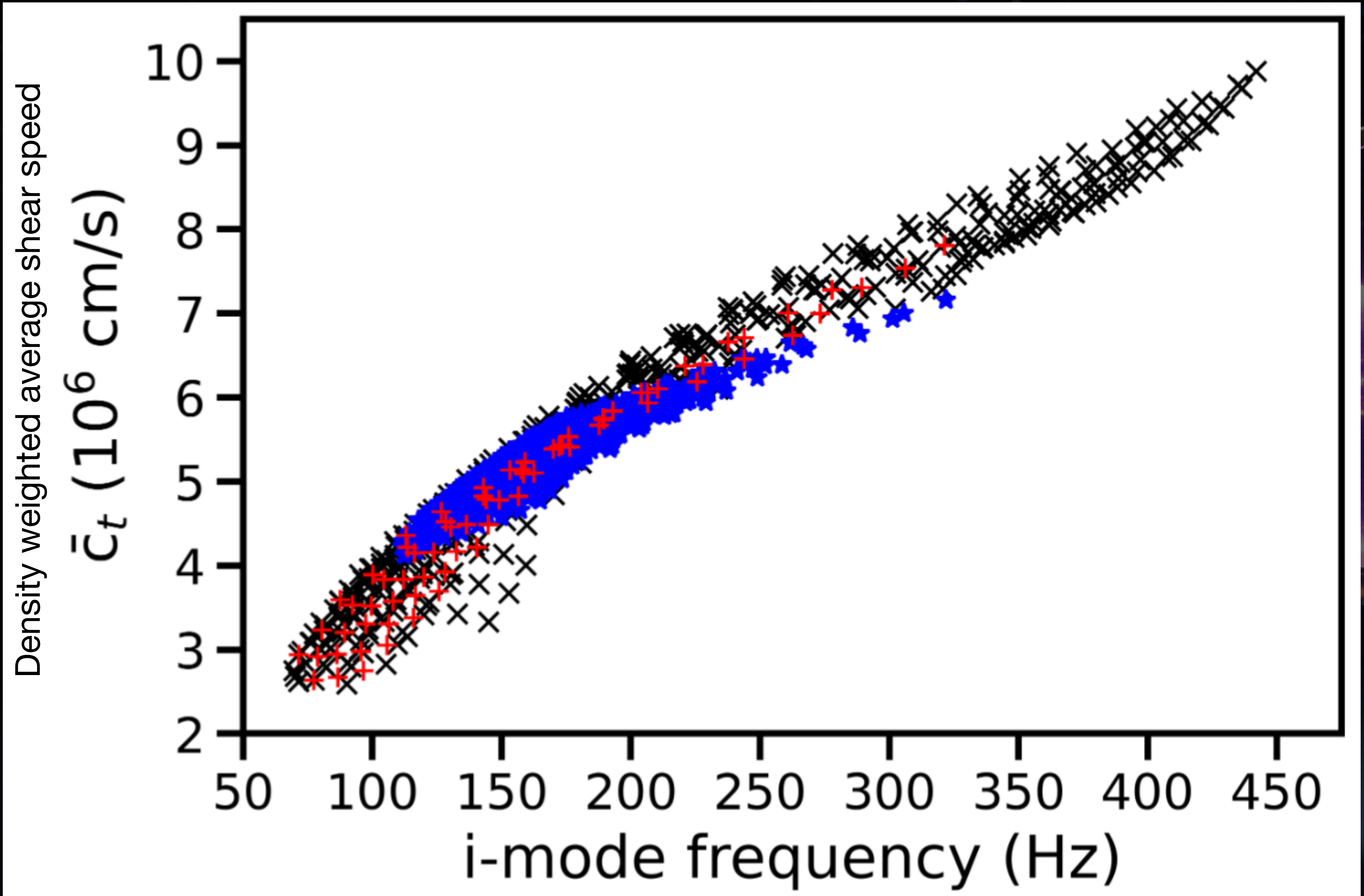




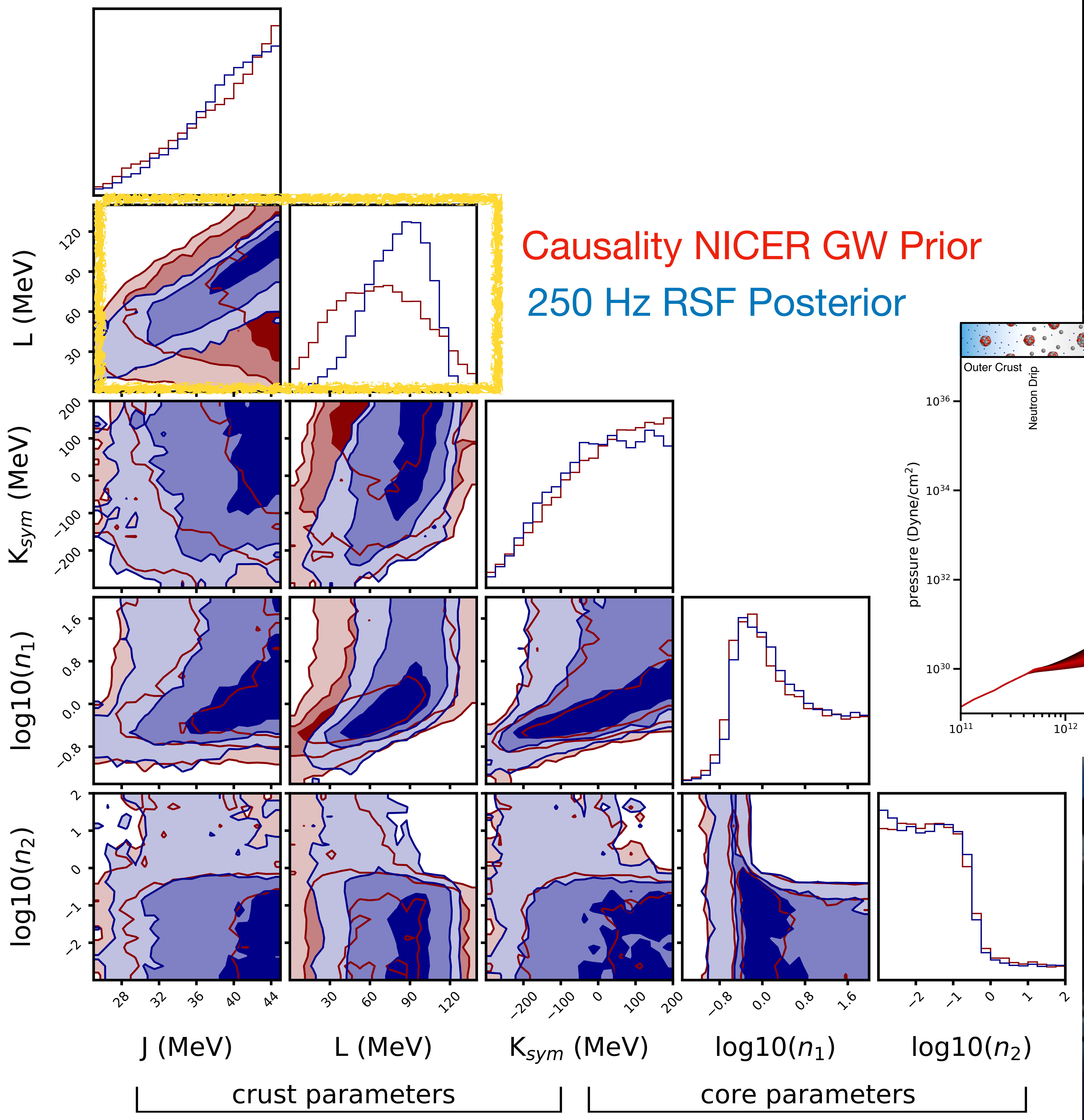
See also Kuan, Suvorov, & Kokkatos (2021),
Suvorov, Kuan, & Kokkatos (2024)
Gao, Kuan, Xia, Silva, & Shibata (2025)

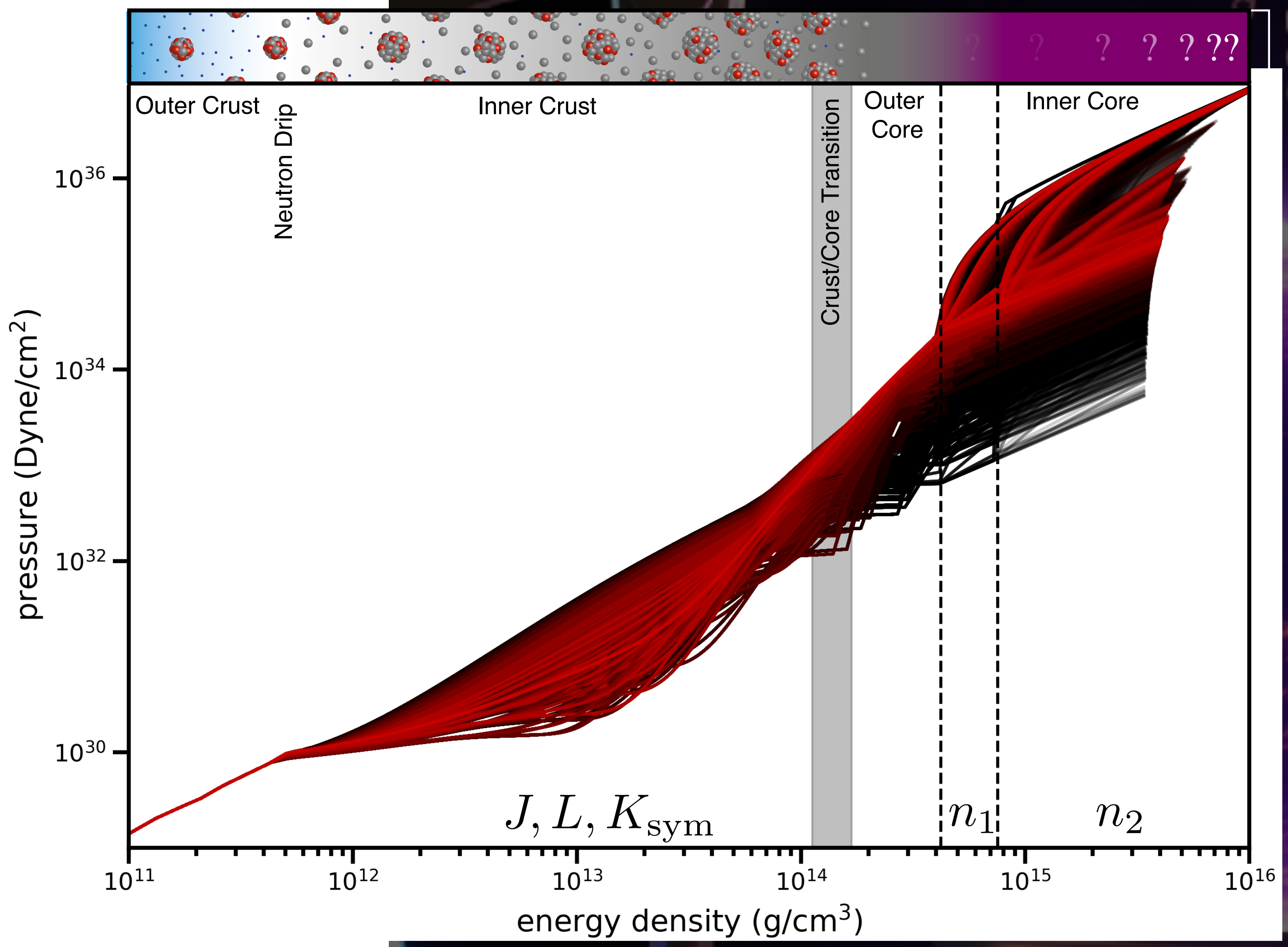
DT, et al. (2012) PRL 108, 011102
DT (2013) ApJ 777, 103
Neill, DT, Van Eerten, Ryan, & Newton (2022) MNRAS, 514, 4

Multi-messenger Precursors (RSFs)



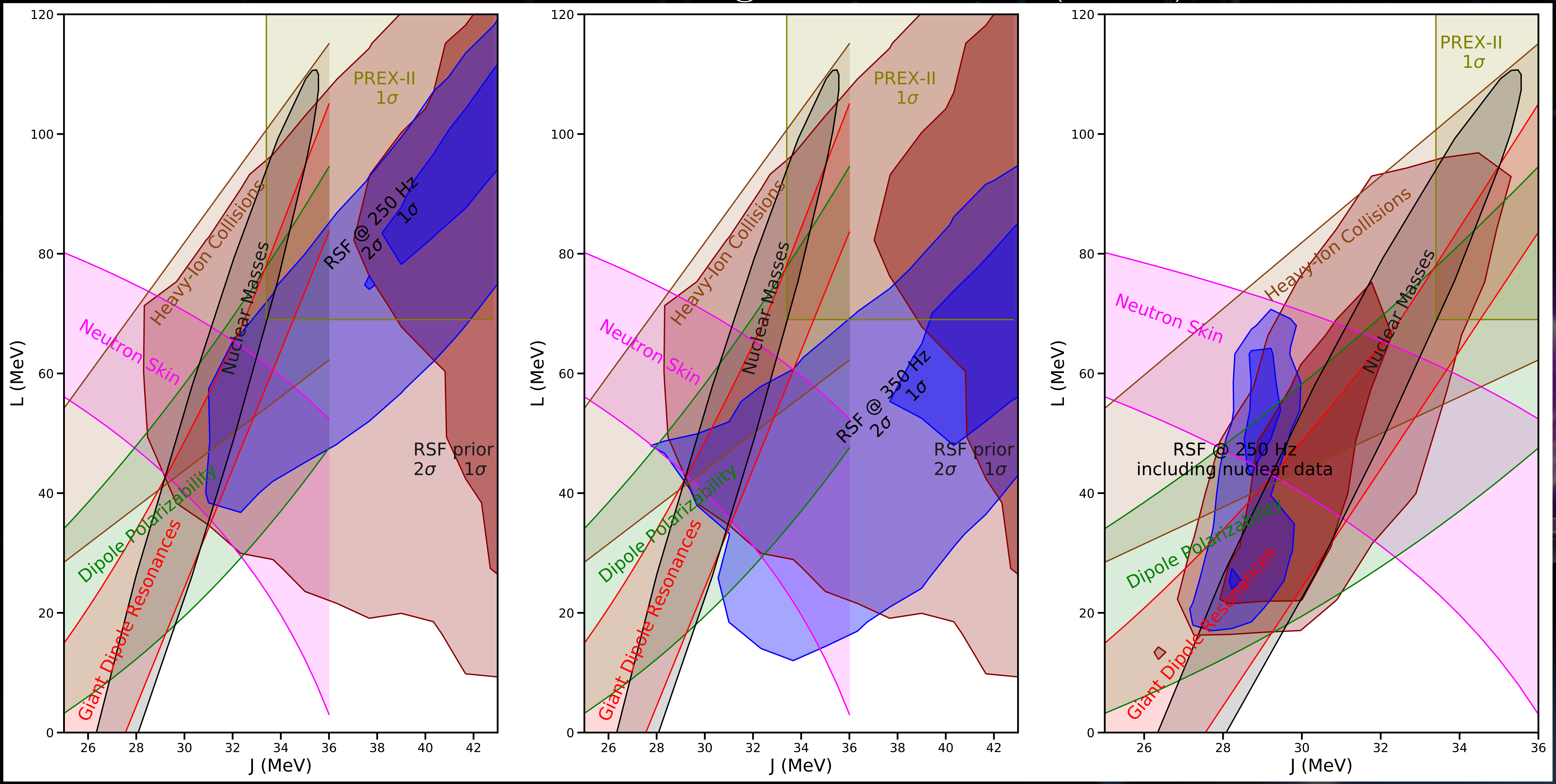
Neill, Newton, & DT (2021), MNRAS 504, 1, 1129





Neill, Preston, Newton & DT (2023), PRL, 130, 112701

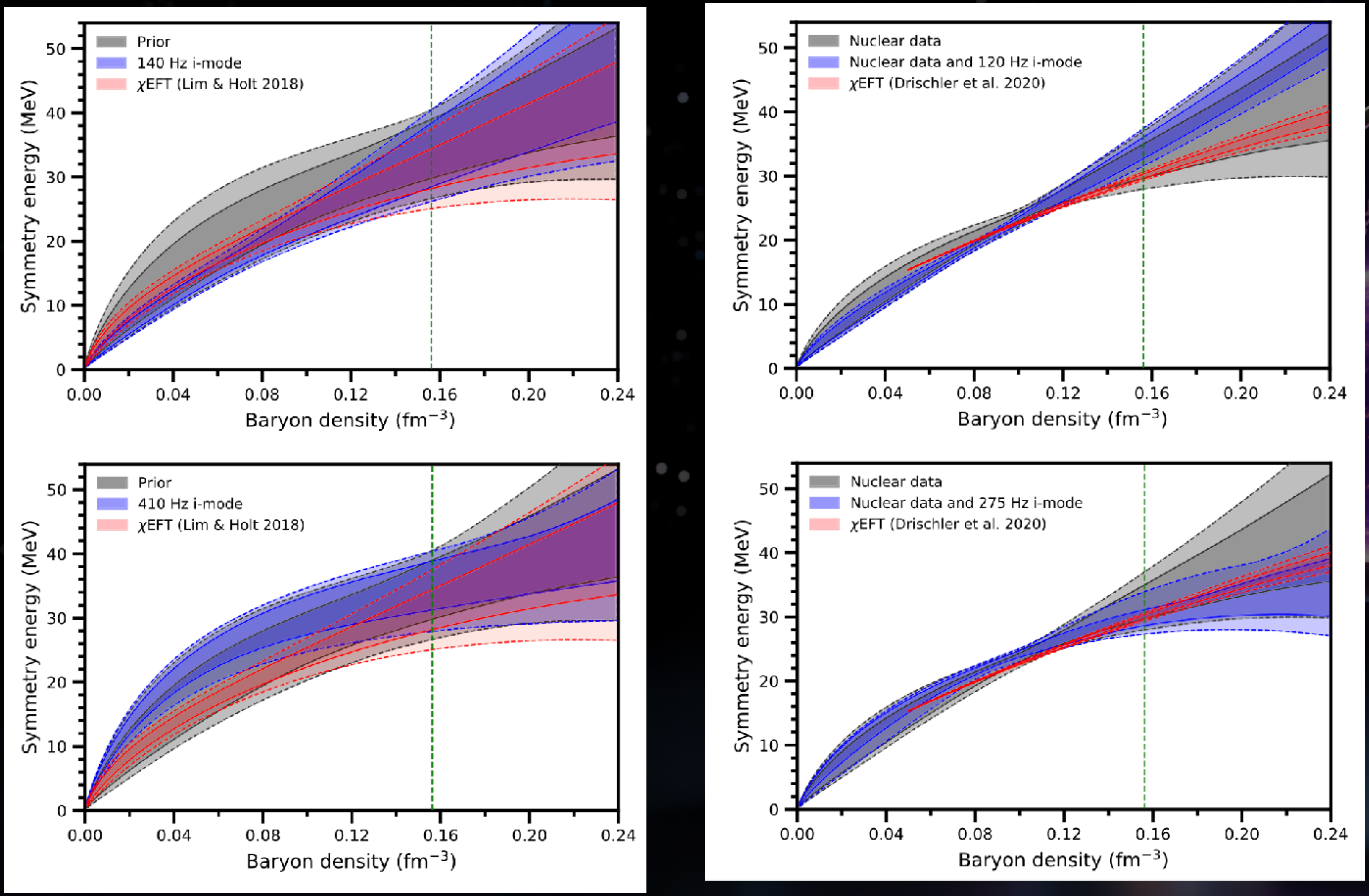
Multi-messenger Precursors (RSFs)



Neill, Preston, Newton & DT (2023), PRL, 130, 112701

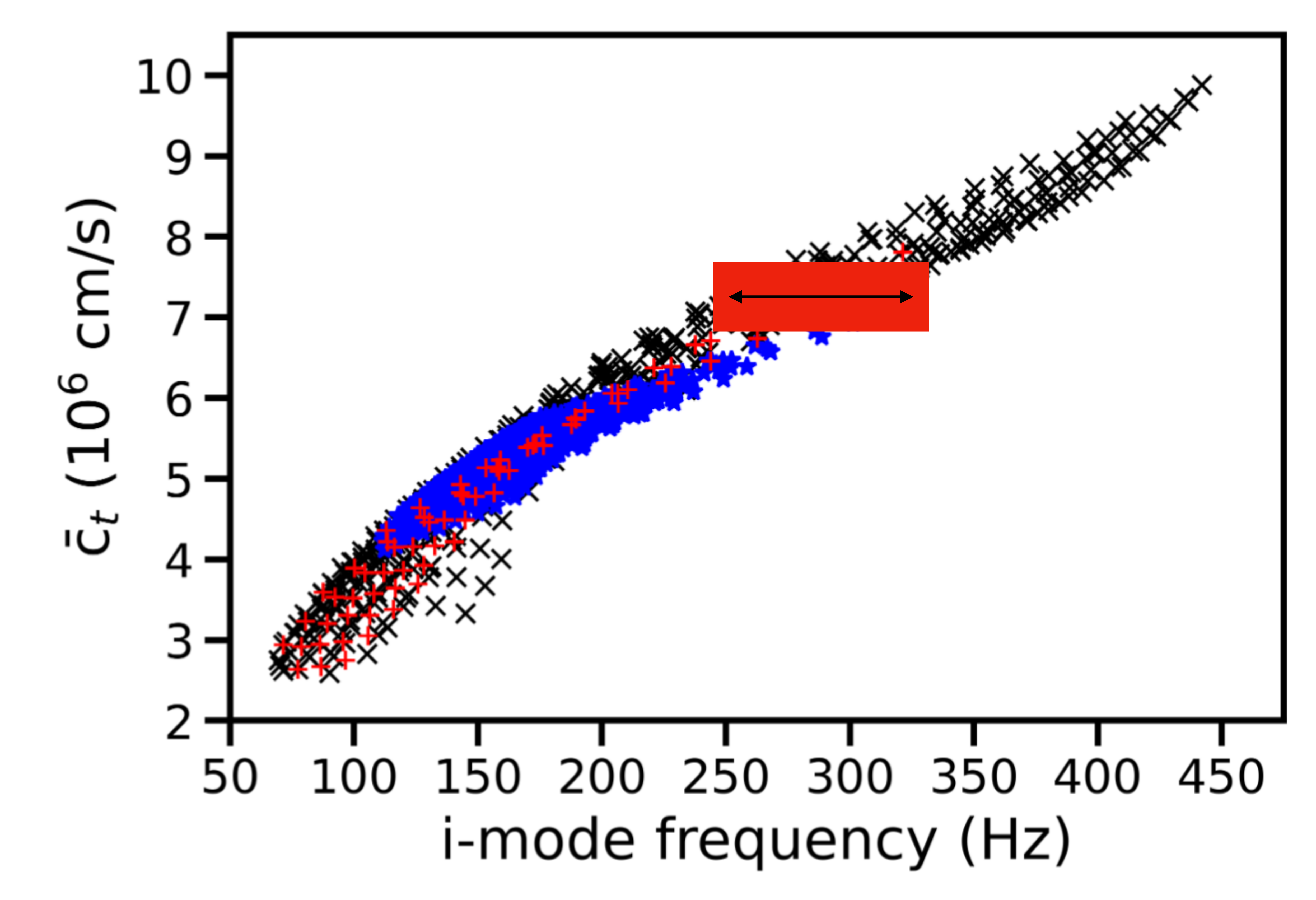
See also Neill, DT, & Newton(2024) MNRAS 532, 1, 82

Testing Chiral Effective Field Theory with RSFs



Neill, DT, Drischler, Holt, & Newton (2025) Phys Rev C, 111, 1, 015809

But wait!



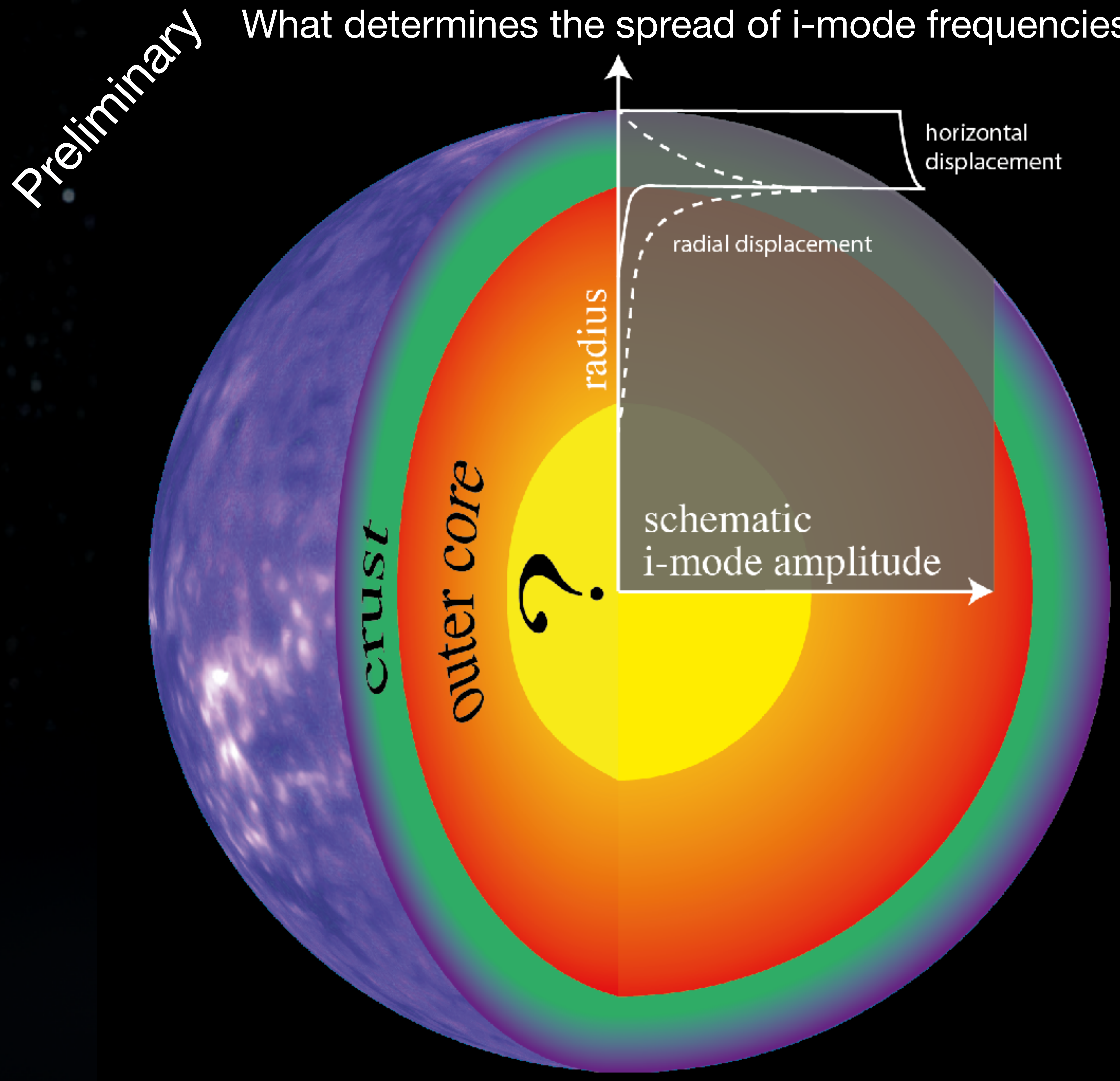
Neill, Newton, & DT (2021), MNRAS 504, 1, 1129

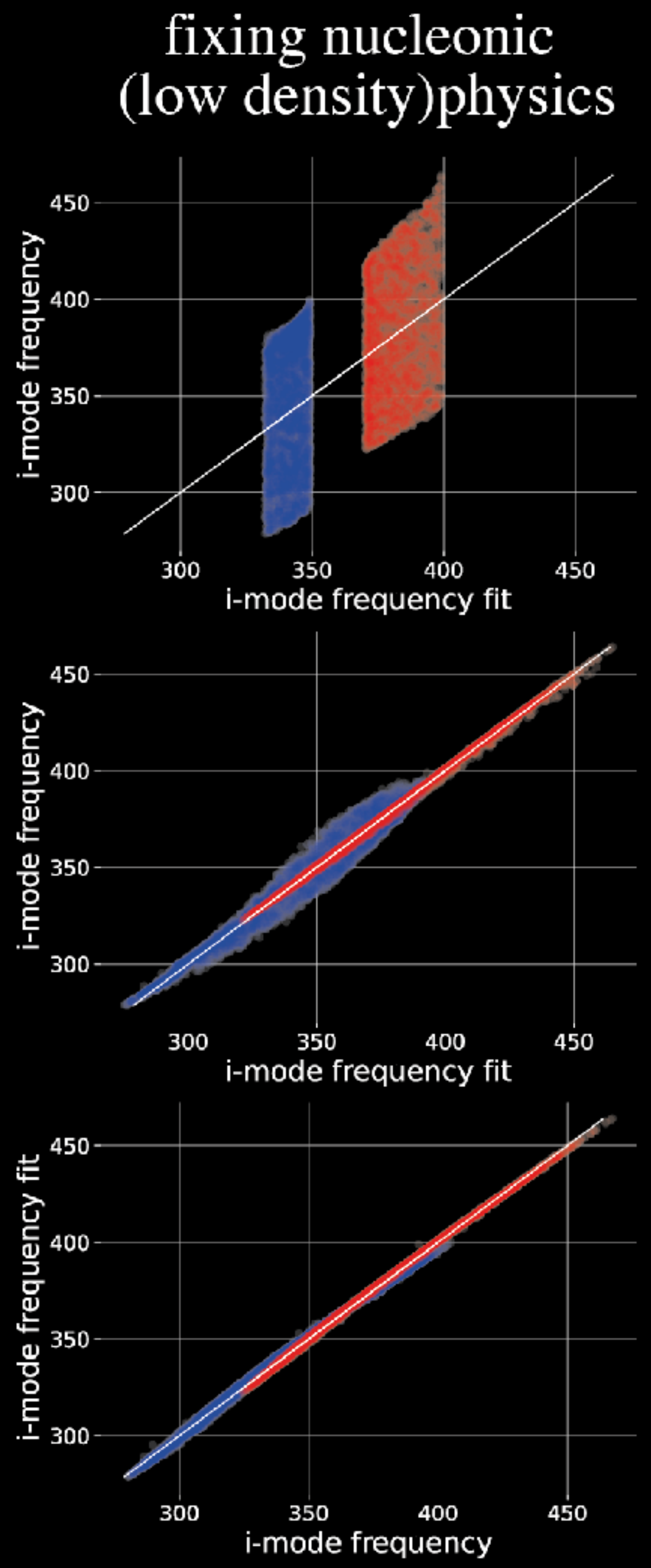
If we fix the crust/outer core physics…

What determines the spread of i-mode frequencies?

Neill, Newton, Holt, Drischler, Margueron, & DT in prep

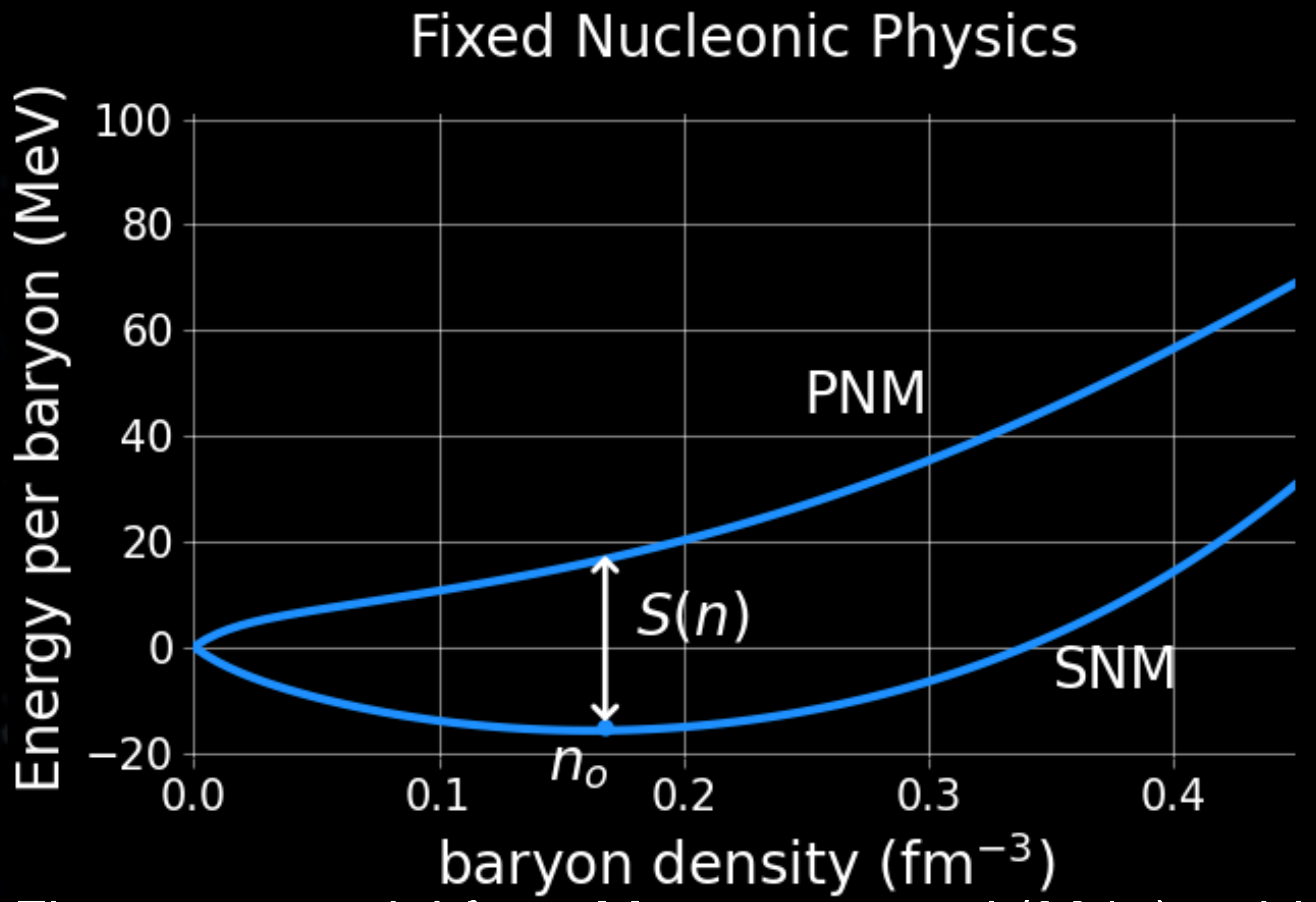
What determines the spread of i-mode frequencies?



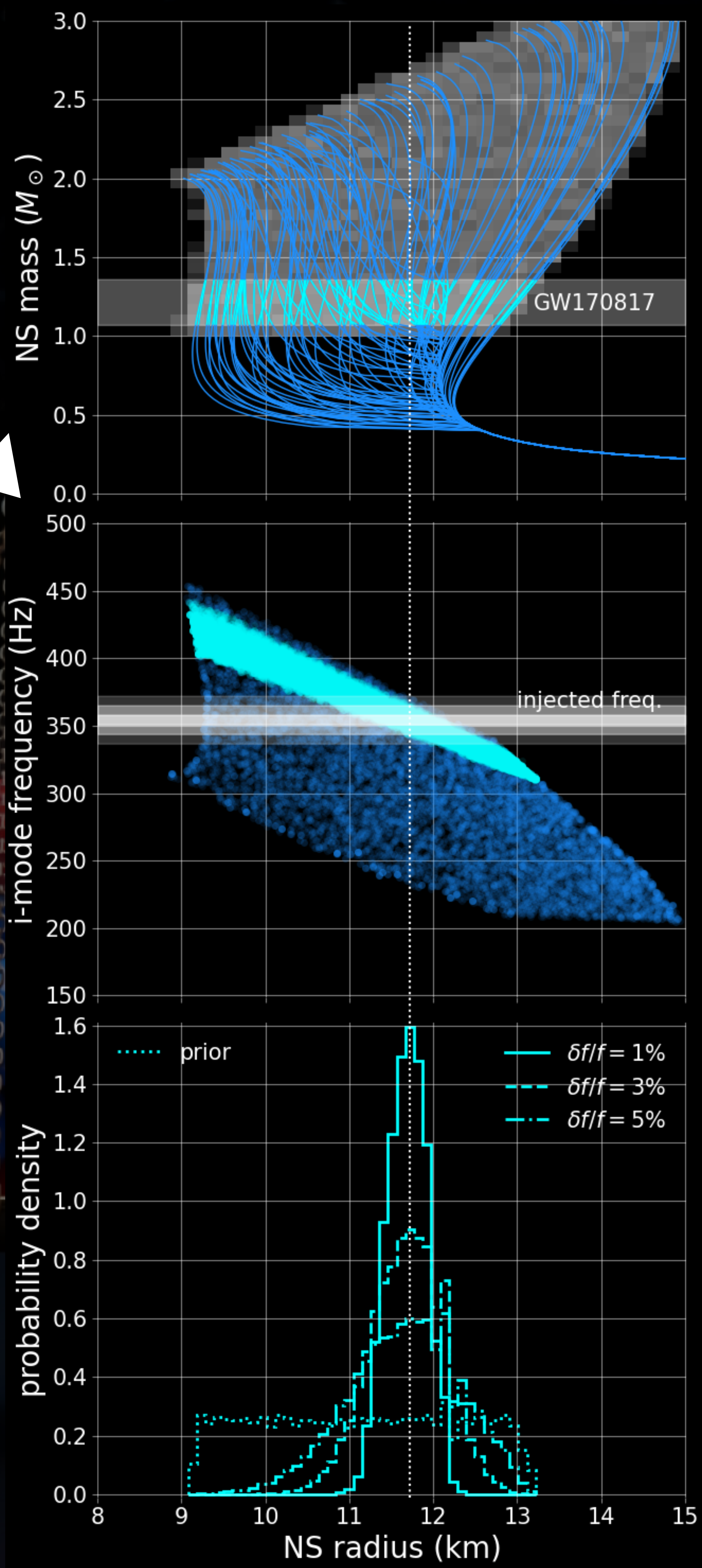


Neill, Newton, Holt, Drischler, Margueron, & DT in prep

Preliminary



Fix a metamodel from Margueron et al (2017), add arbitrary phase transition to linear sound speed to vary the bulk core properties. Generate random samples of (n_{PT}, Δn_{PT}, c_s^2, dc_s^2/dn) for spread in M-R plane.



Sampled with uniform prior in M-R within masses between 1-3M_{sun}

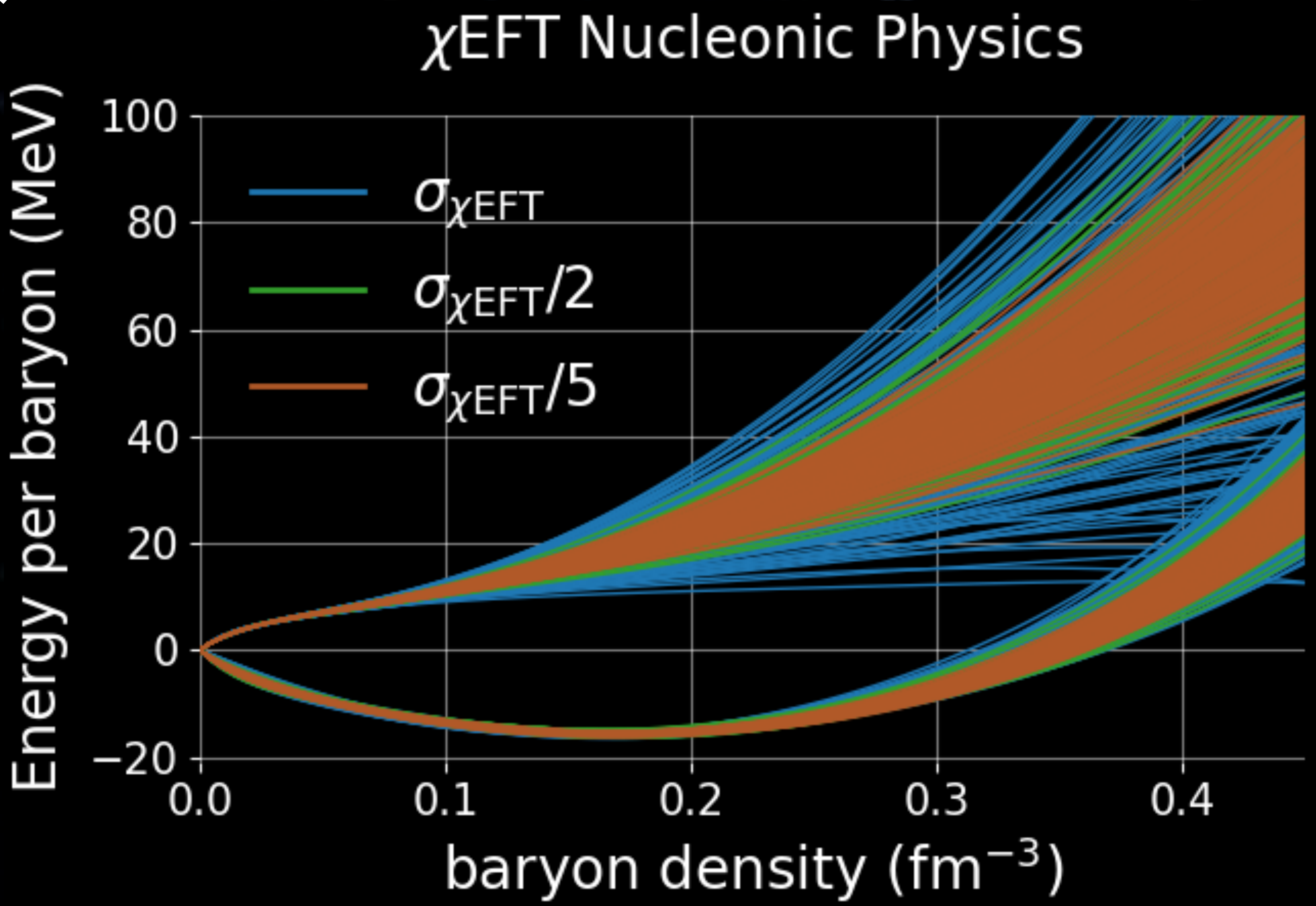
Inject mass data taken to be consistent with GW170817

Injected i-mode frequency with different uncertainties

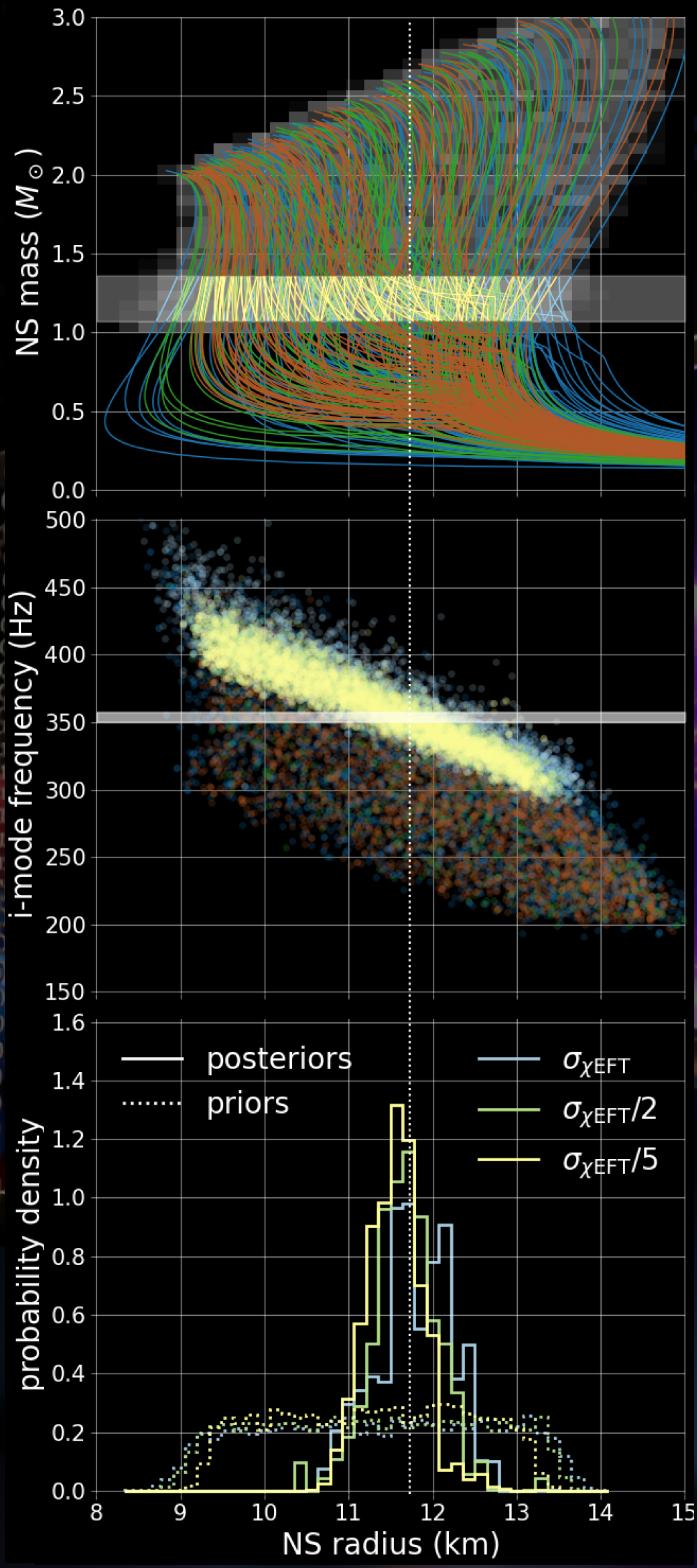
Geometric radius measurement with precision down to ~ ± 0.5km

Neill, Newton, Holt, Drischler, Margueron, & DT in prep

Preliminary



Same as before, but allowing nucleonic model to vary with uncertainty range consistent with χEFT from Lim & Holt (2018), with with covariance matrix scaled by constant factor to get estimates for "improved" constraints.



Sampled with uniform prior in M-R within masses between 1-3M_{sun}

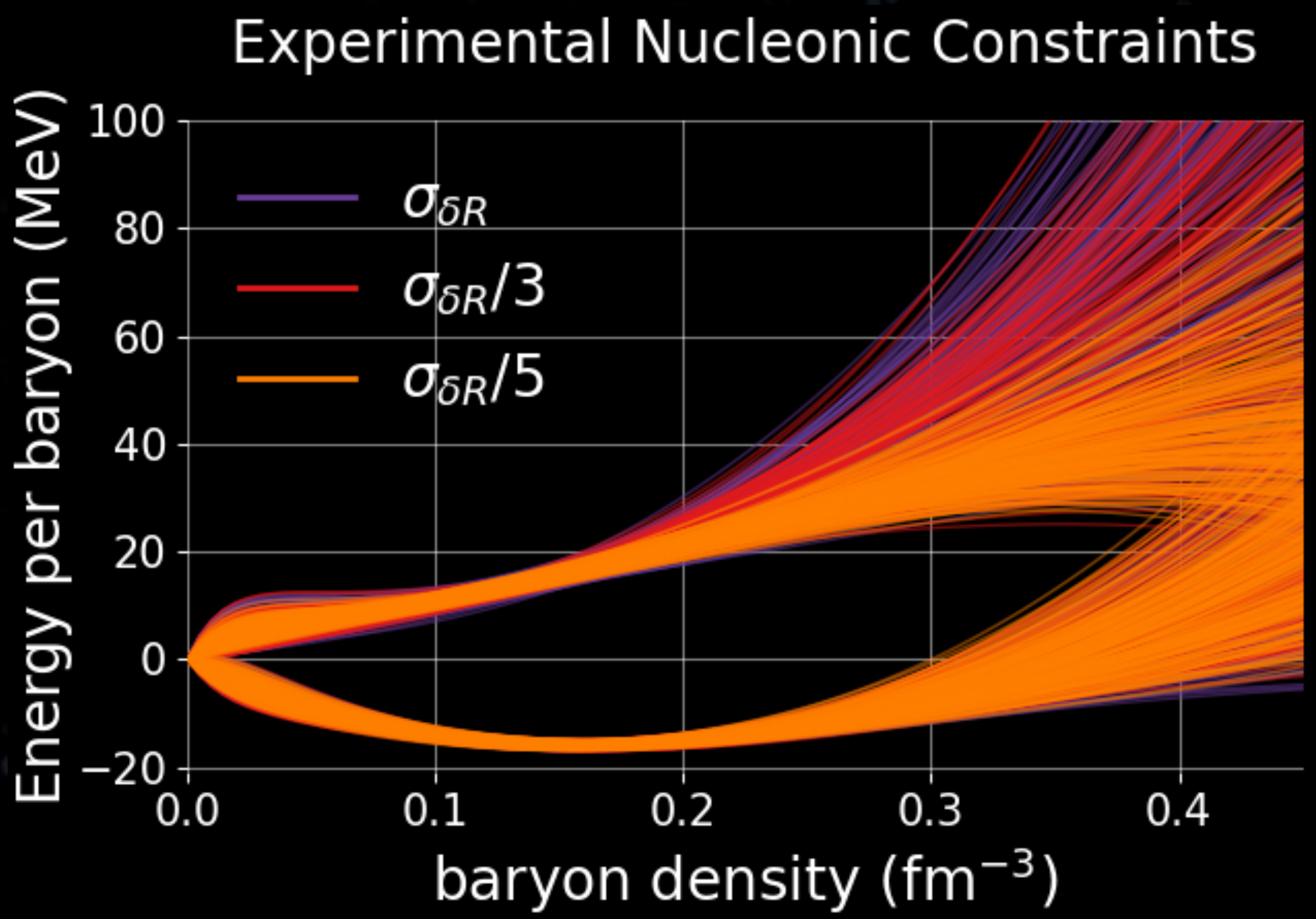
Inject mass data taken to be consistent with GW170817

Injected i-mode frequency with 1% uncertainty (mostly mass uncertainty dominated)

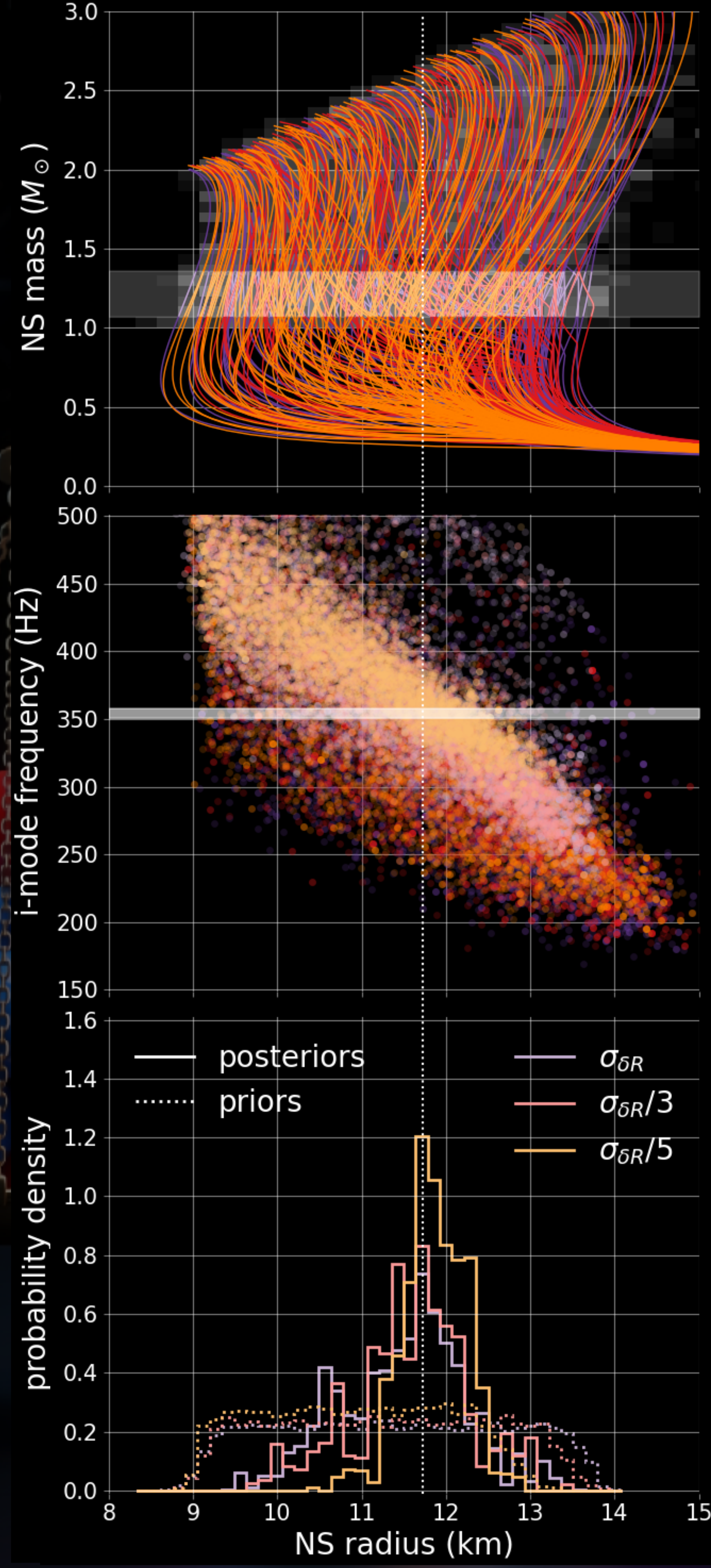
Radius precision improves with better theoretical constraints

Neill, Newton, Holt, Drischler, Margueron, & DT in prep

Preliminary



Using Newton & Crocombe (2021) isoscalar/isovector parameters, into meta-model. Varying only δR neutron skin depth from experimental results (effected through Skyrme EDF).



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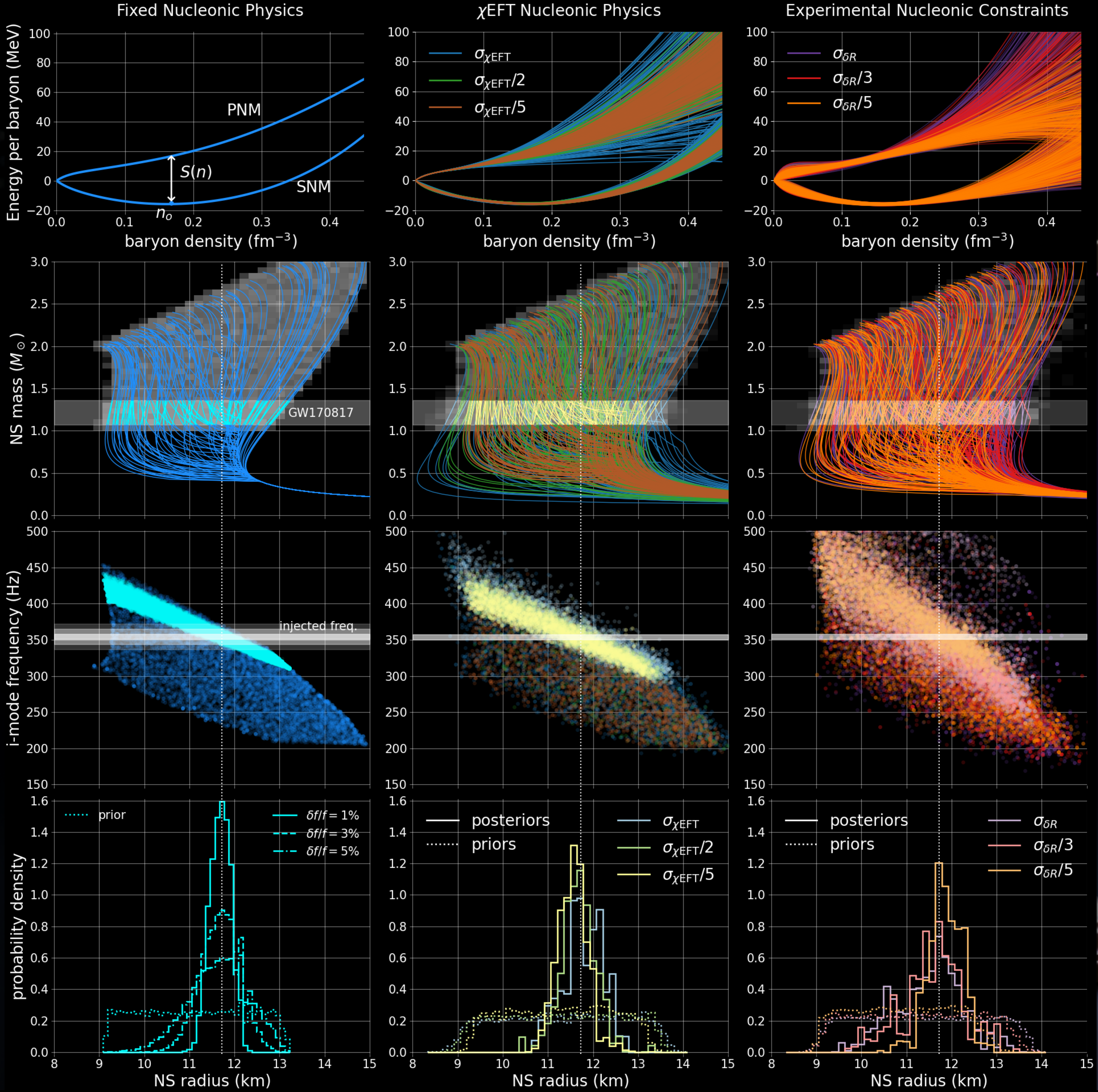

Neill, Newton, Holt, Drischler, Margueron, & DT in prep

Summary:

- Different observables probe different regions, inner core is uncertain physics
- i-mode probes crust-core transition region, nuclear physics ~ 0.5 n_{sat}
- Geometric measure of R_{NS} **that does not depend on details of inner core!**
- Improving uncertainties for low-density nucleonic physics will improve δR_{NS}
- **Uses asteroseismology to leverage low-density physics to constraint high-density physics**
- i-mode detectable with RSFs (this gen) or with next-gen dynamical tides

Caveats:

- Post phase-transition buoyancy is assumed to be zero (fast reactions compared to mode freq)
- Pasta effects not fully included (just CLDM in these calculations)
- Mass uncertainty will definitely improve with next gen GW observatories
- Our estimate of "experimental" uncertainty is not really properly modelled
    - key take-away is to see improvement in R_{NS} constraint from better $\delta R_{n\text{-}skin}$ constraint
- Mixing of i and first g-mode when compositional stratification becomes stronger
    - Included in the calculation, but can weaken geometric R dependence if it is very large

Acknowledgements:

Duncan Neill (University of Bath)
(Currently applying for jobs/fellowships)

Will Newton (East Texas A&M)

Jeremy Holt (Texas A&M)

Christian Drischler (Ohio University/FRIB)

Jérôme Margueron (CNRS/MSU)

UNIVERSITY OF BATH

Generated from discussions during:

XMXS 2024

eXtreme Matter in eXtreme Stars

Lorentz Center, Netherlands

Sept 23-27, 2024

NASA

NSF

UKRI

Science and Technology Facilities Council