

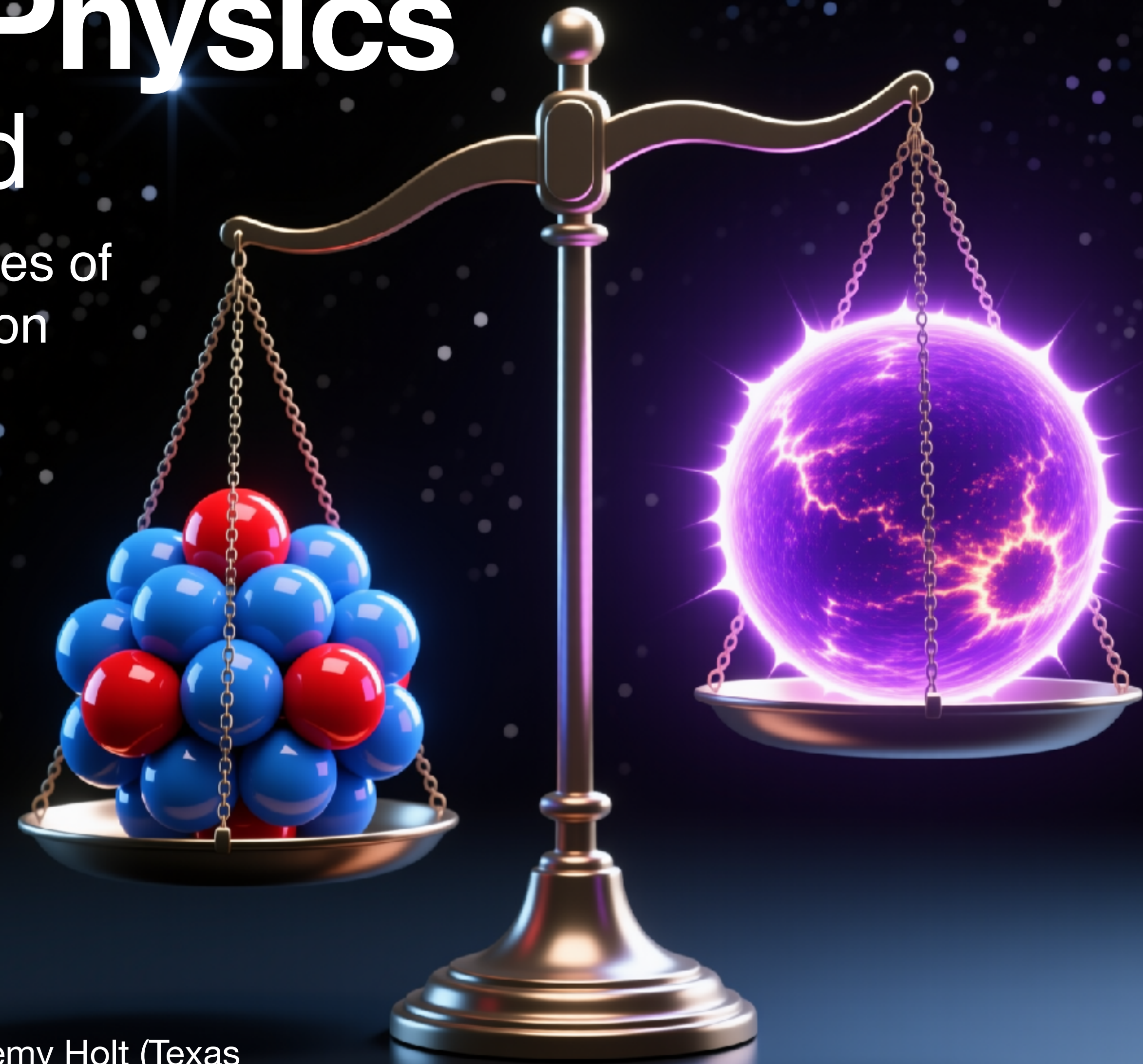
Neutron Star Asteroseismology and Dense Matter Physics

In the LVK era and beyond

From Colliders to the Cosmos: Exploring the Extremes of
Matter with Experiment and Astrophysical Observation

INT Program 25-2b, Seattle, USA

25 September, 2025



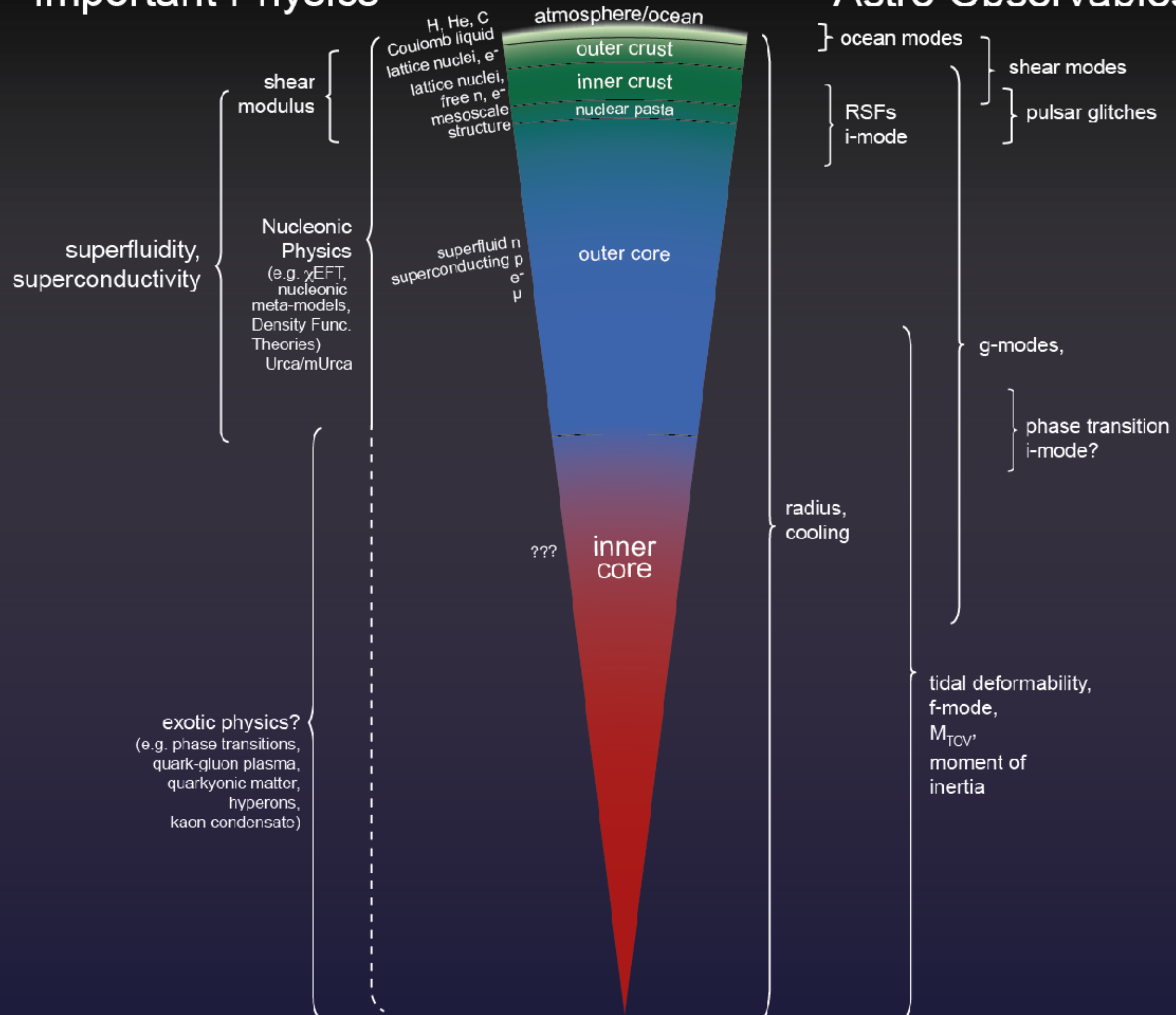
David Tsang, University of Bath

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)

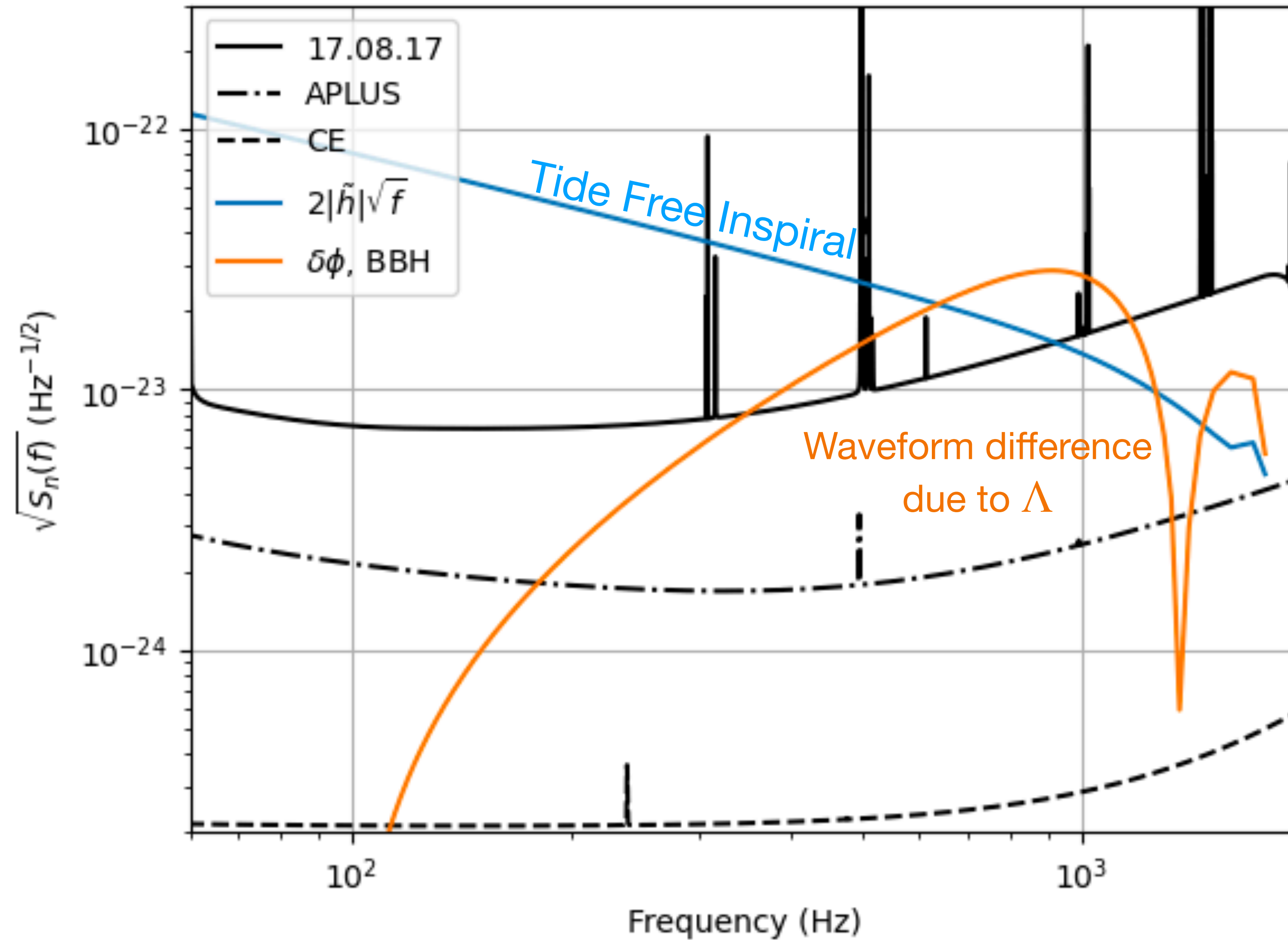
NS Structure

Important Physics

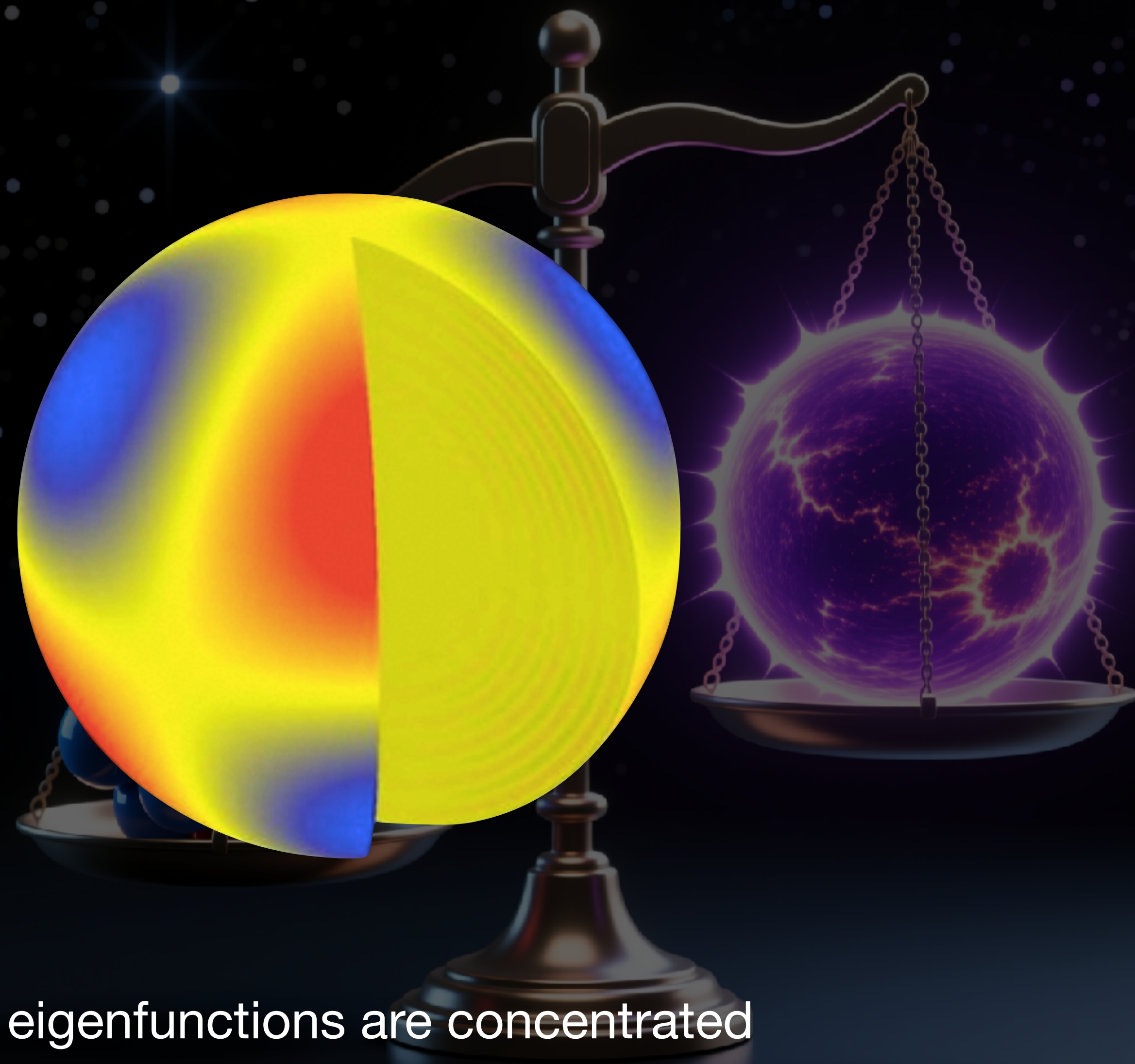
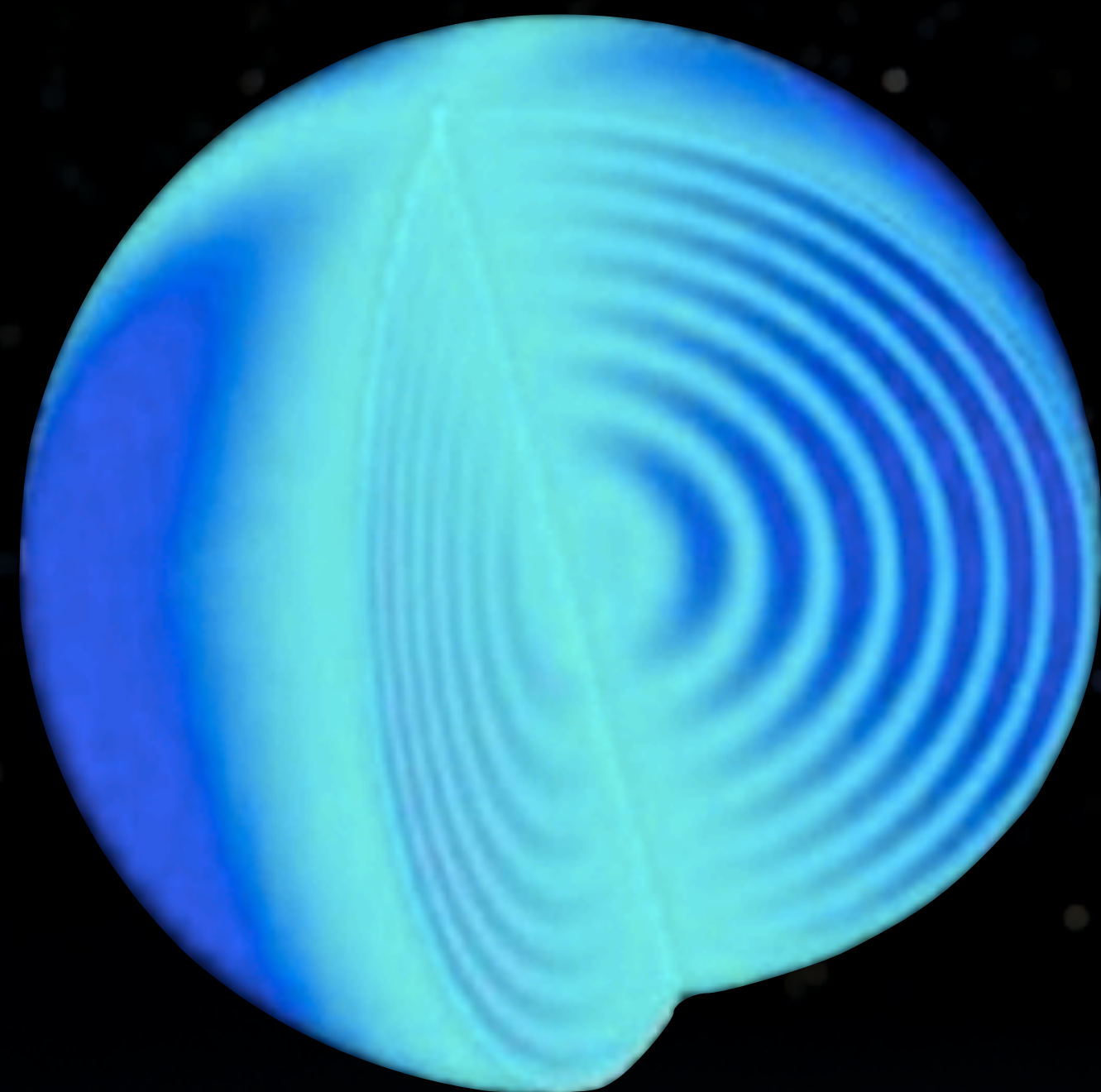
Astro Observables



GWs (Inspiral)



Asteroseismology!

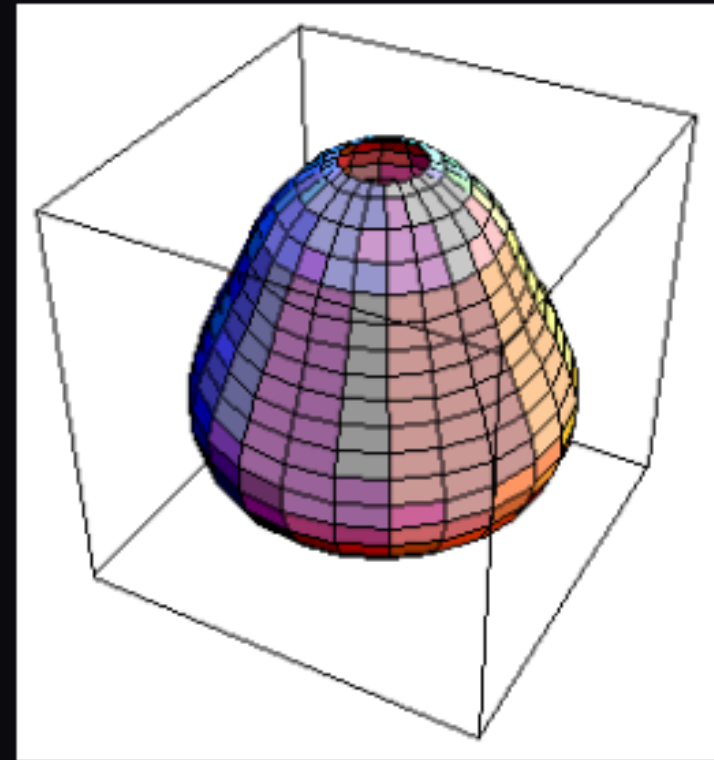


Modes probe the dynamics where their eigenfunctions are concentrated

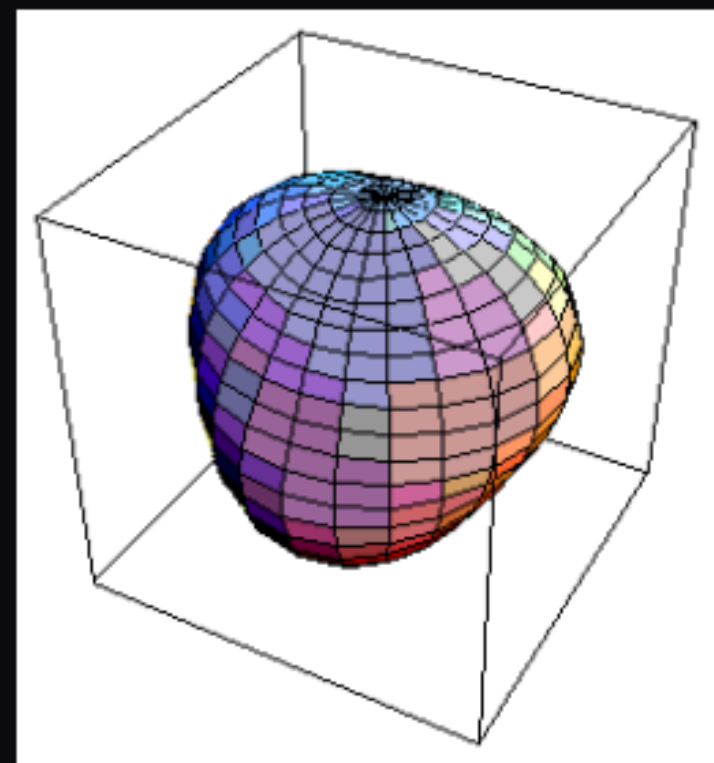
Neutron-Star Mode Spectrum

- *f*-mode: scales with average density
- *p*-modes: sound waves in the star (overtone of the *f*-mode)
- *g*-modes: buoyancy waves from thermal/composition gradients
- inertial modes (including *r*-modes): associated with rotation
- *i*-modes: arise from phase transitions
- Also:
 - *w*-modes, *s*-modes, Alfvén modes, ...

➔ Modes provide *unprecedented* access to neutron-star physics

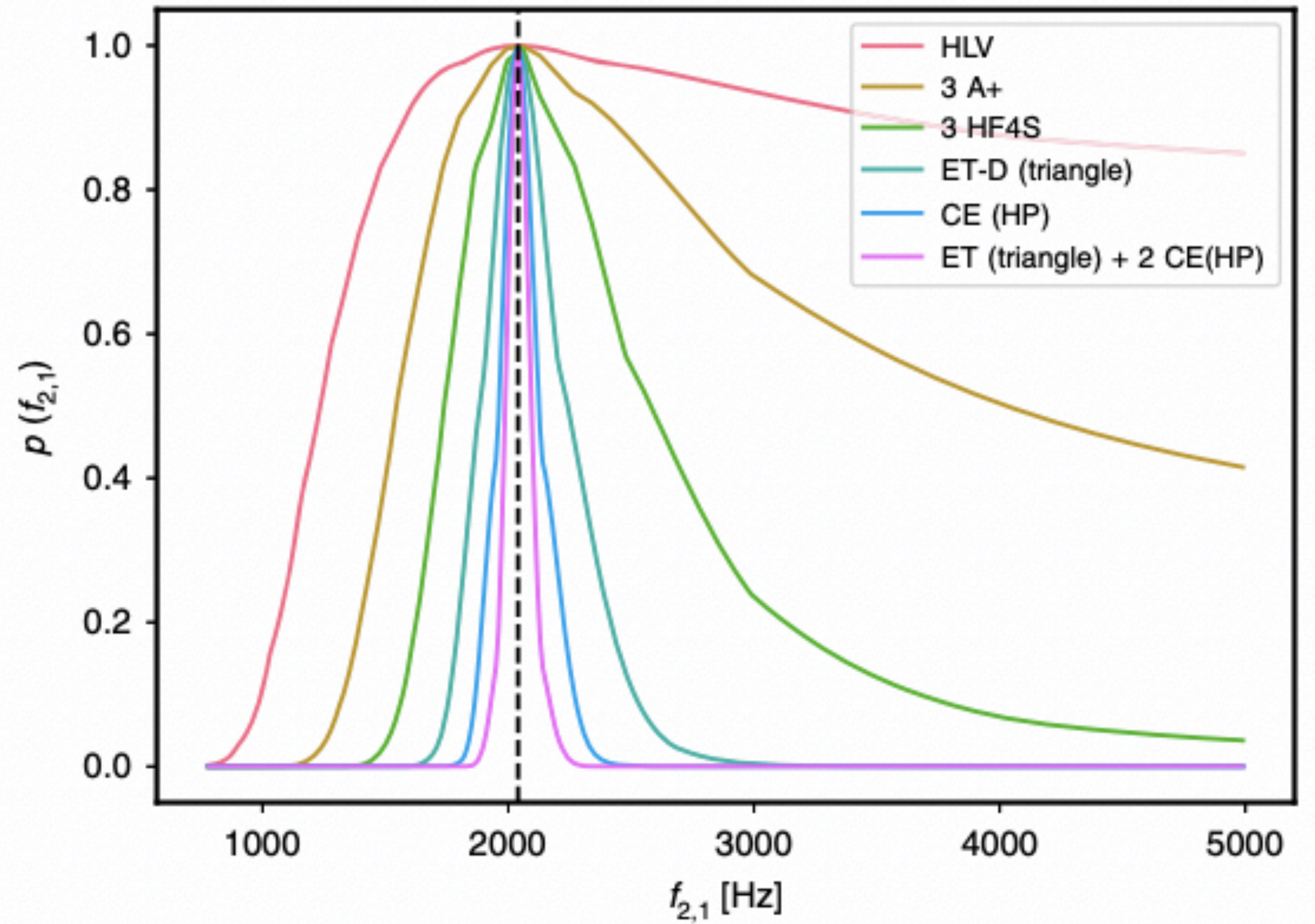


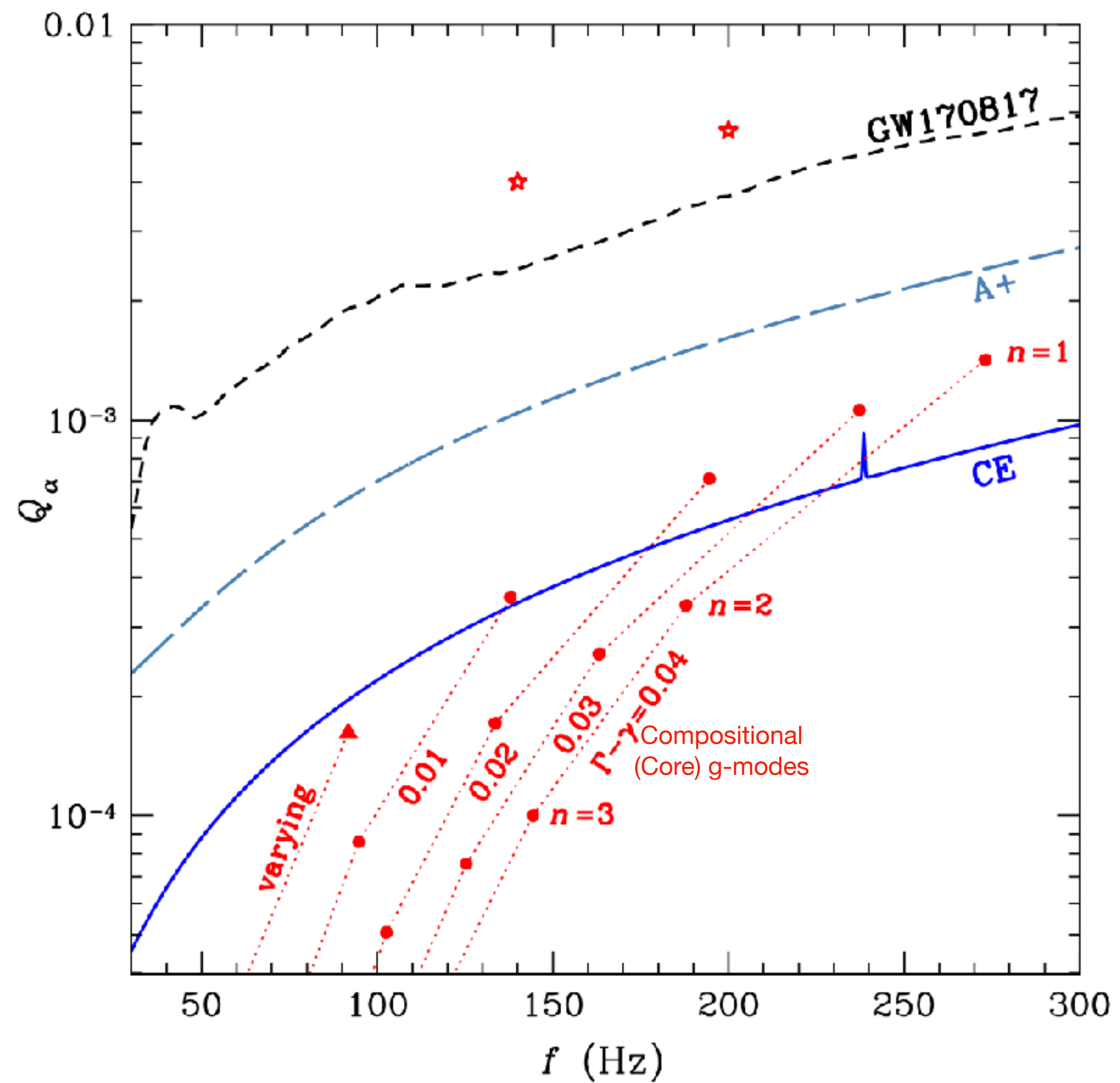
$(l, m) = (3, 0)$



$(l, m) = (3, 2)$

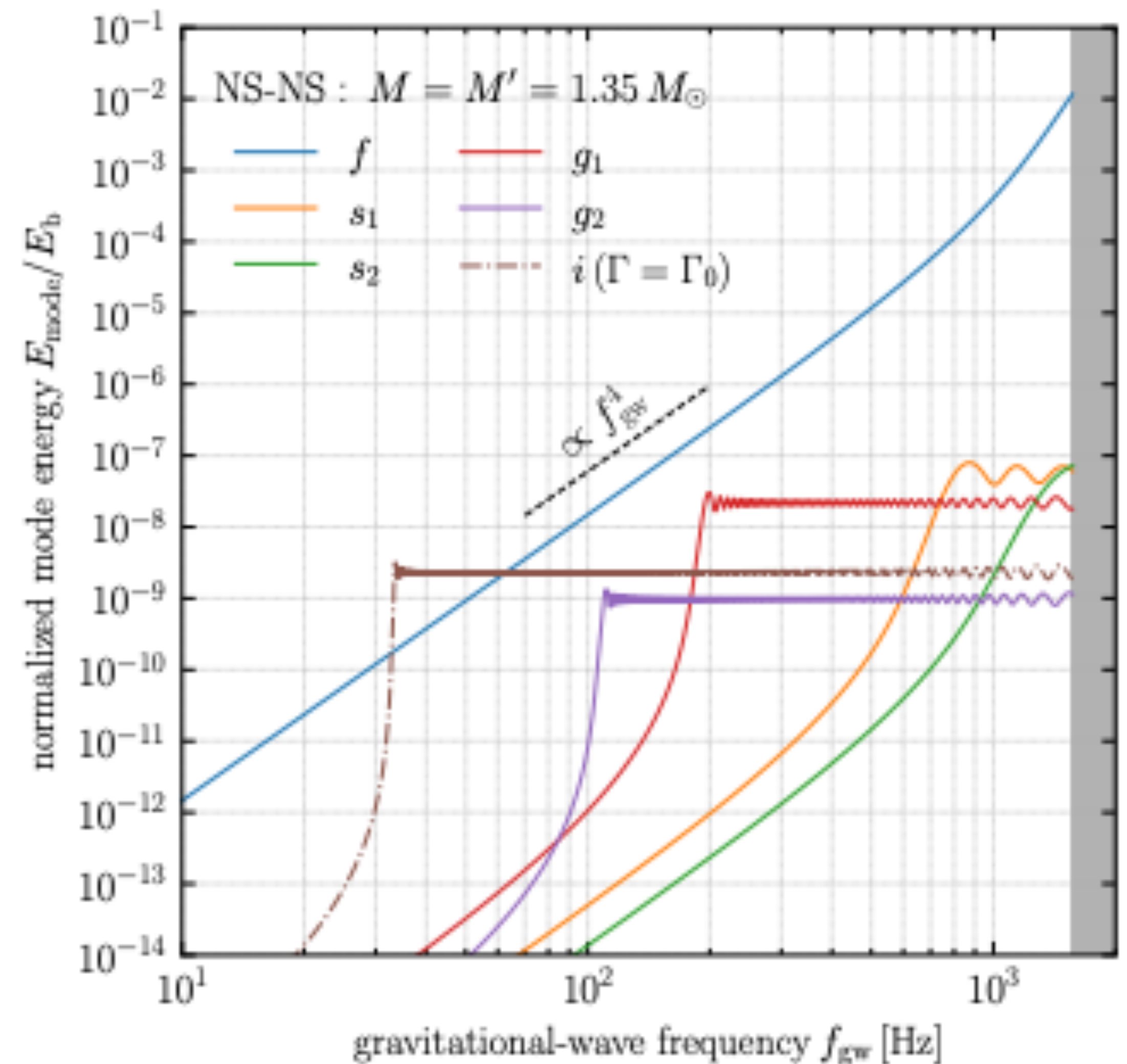
Fundamental modes (same EOS info as Λ)
(non-resonant during inspiral)



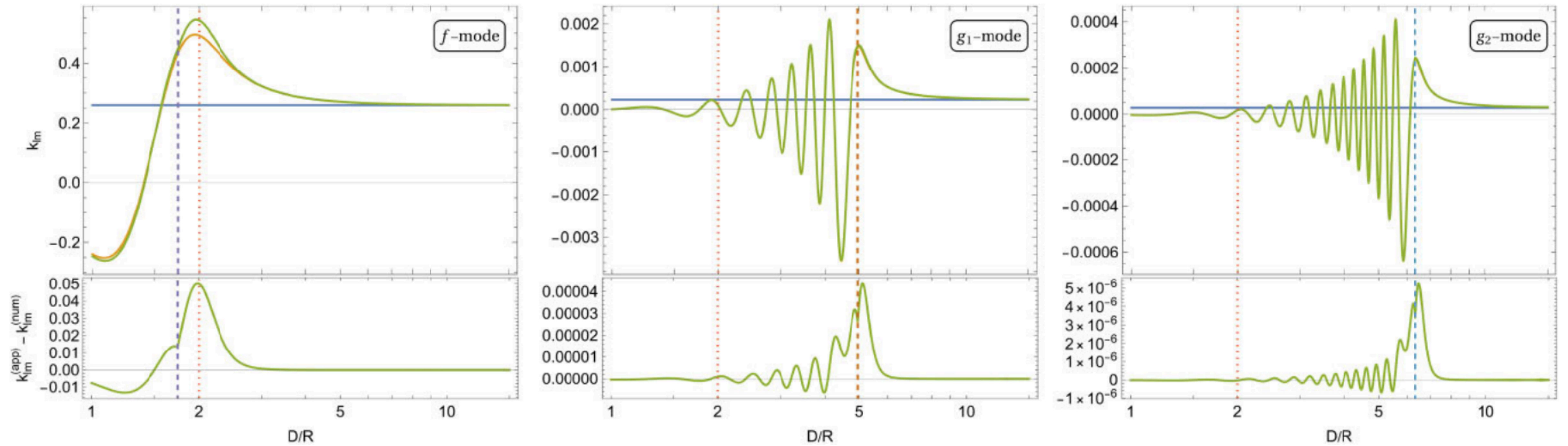


Other asteroseismic modes
(resonant during inspiral)

Ho & Andersson (2023), PRD 108, 043003



Gao et al (2025) arXiv:2509.00257v1

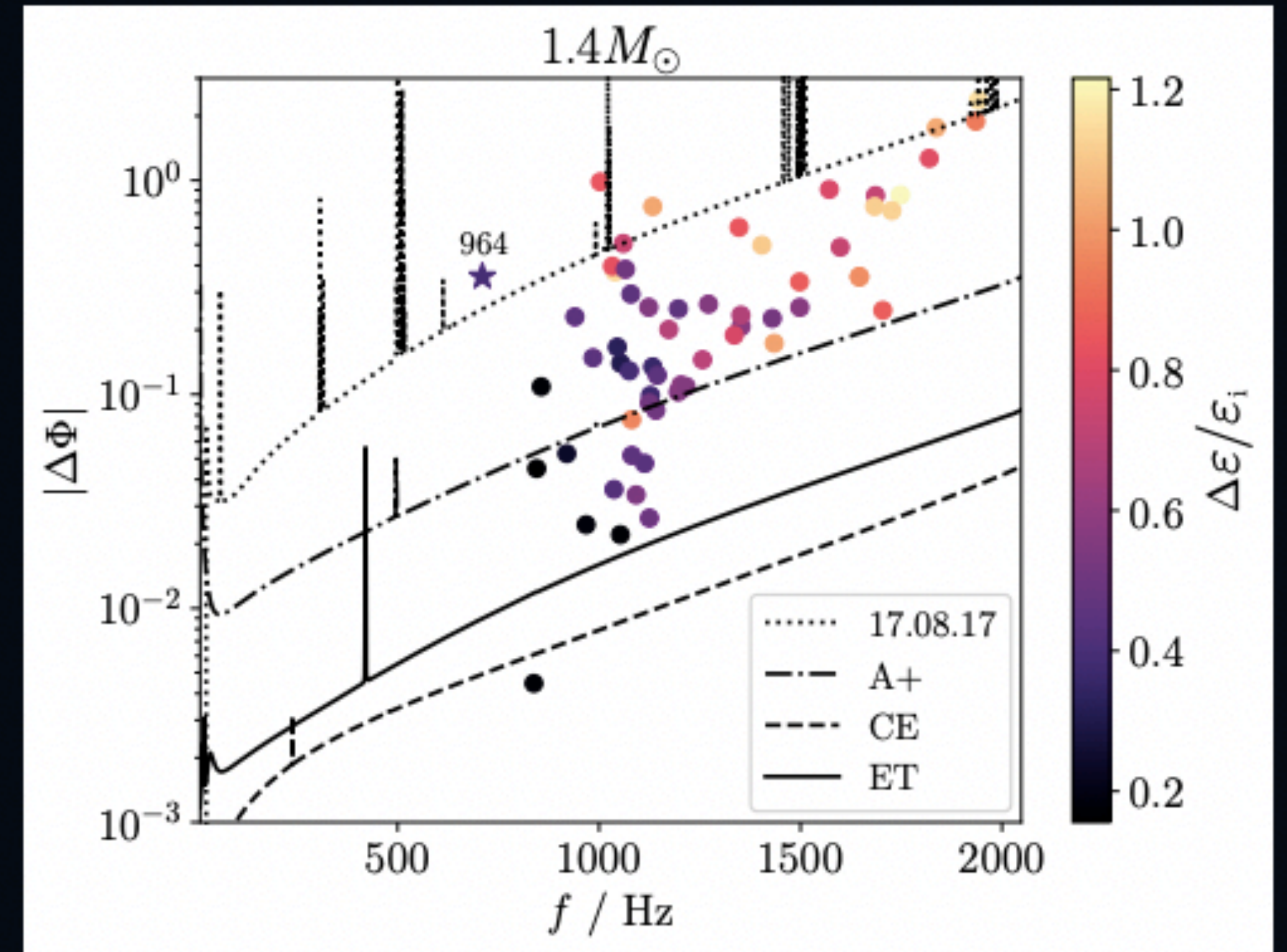
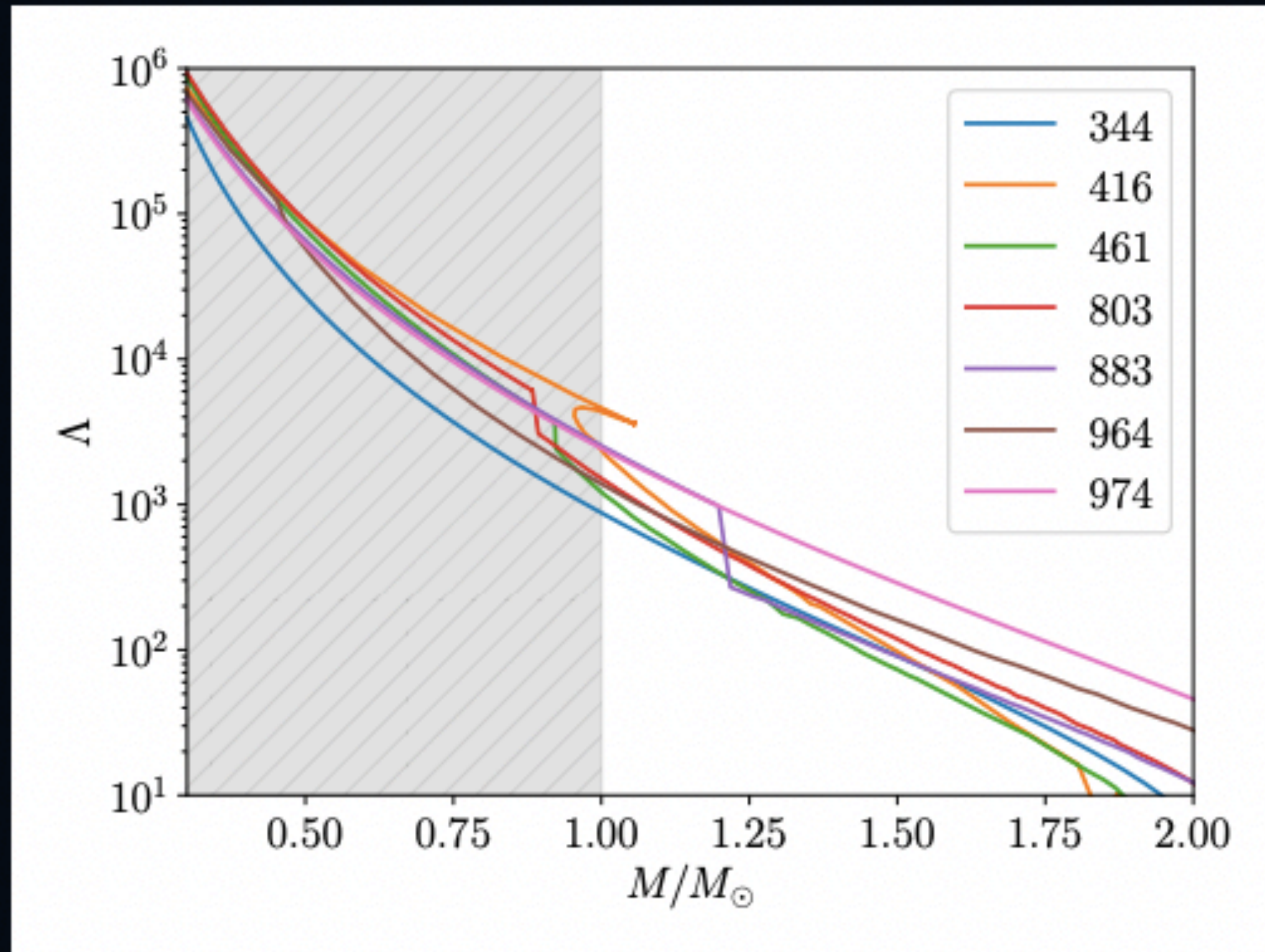


Pnigouras, Andersson, Gittins, & Counsell (2025), MNRAS, 542, 1375

- Contribution to effective love number changes with frequency!
- Static response includes zero frequency response of all dynamical modes!
- At frequencies much greater than their resonances, modes stop contributing to dynamical tide
- Effect on detectability quantitatively uncertain until waveform models can be developed (Nils says soon)
- Almost all direct effects (besides f-mode) below LVK detectability) except maybe....?

i-mode Resonances

Interface-mode from phase transition in inner core



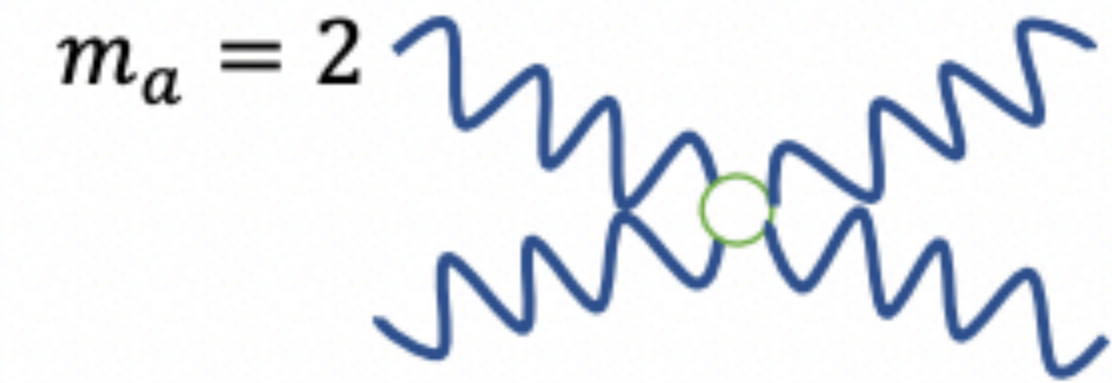
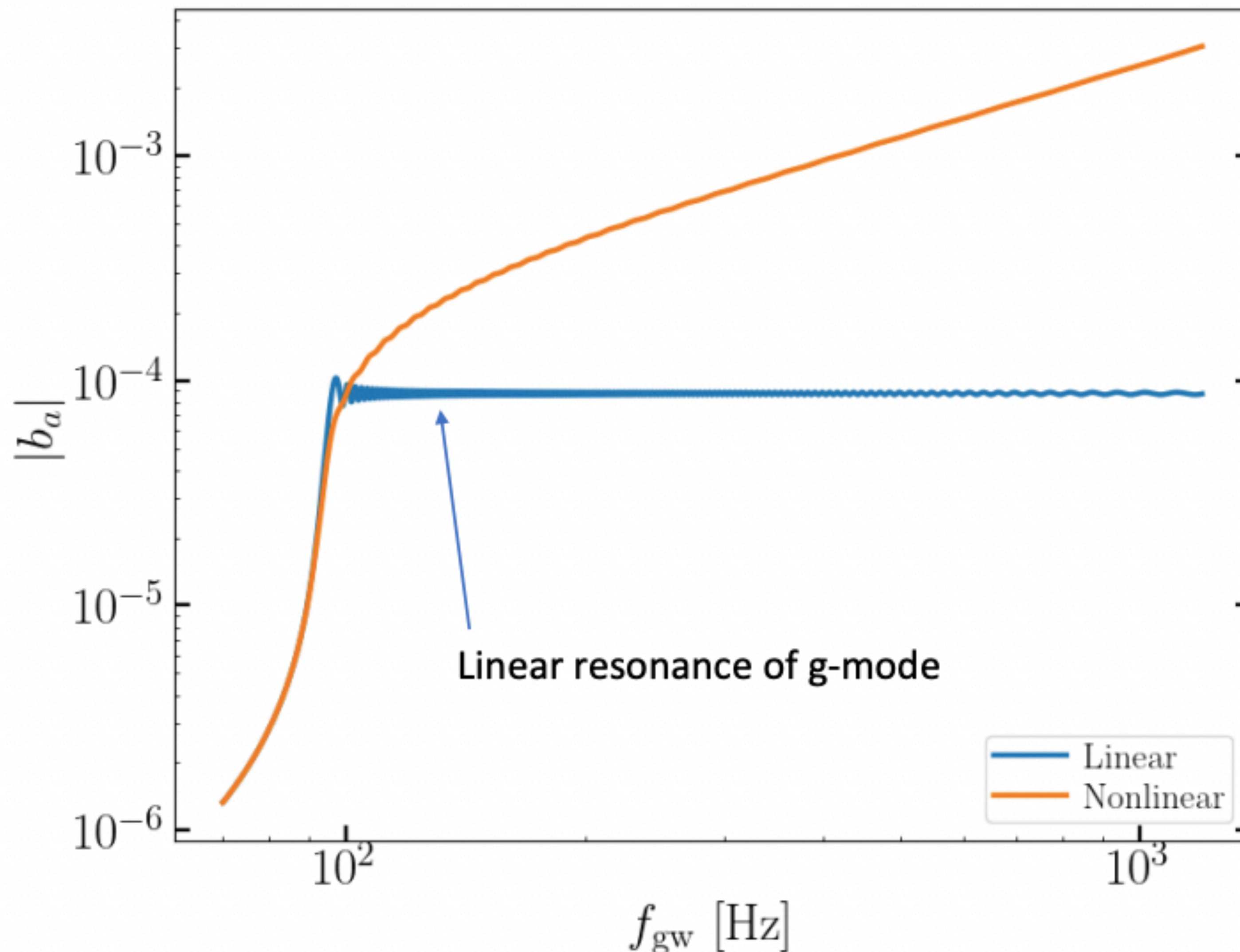
[Counsell+, Phys. Rev. Lett. **135**, 081402 (2025)]

- **Challenge:** Can we develop models of this resonant behaviour?

From Fabian Gittins' talk last week



Resonance locking of g-modes



Linear case:

Decoupled with the orbit afterward.

Small phase shift < 0.01 rad (Lai 94; HY & Weinberg 17a, b)

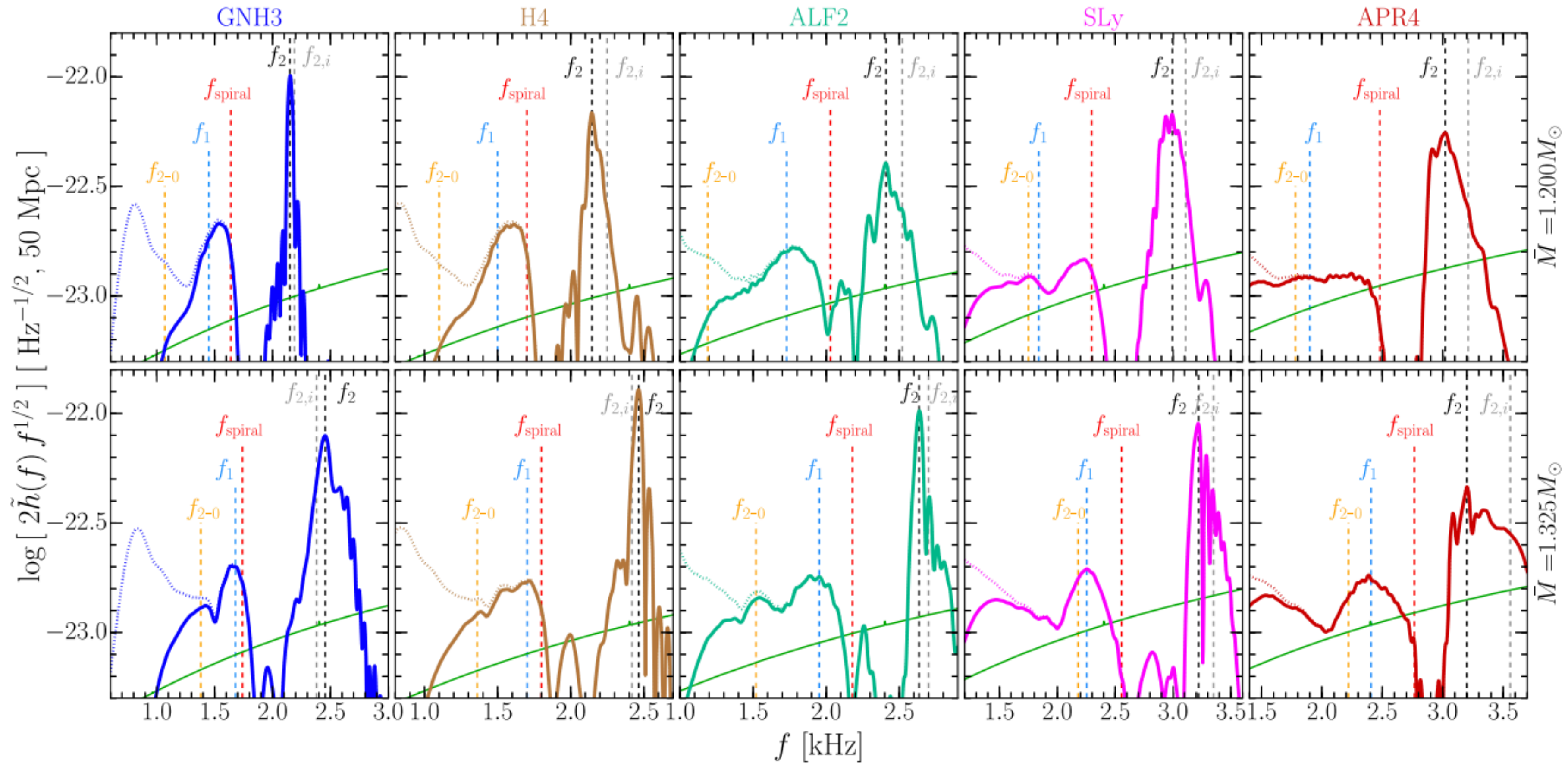
Nonlinear case:

Continuously amplified by resonance and coupled with the orbit.

Significant phase correction ~ 3 rad!

From Hang Yu's Talk last week

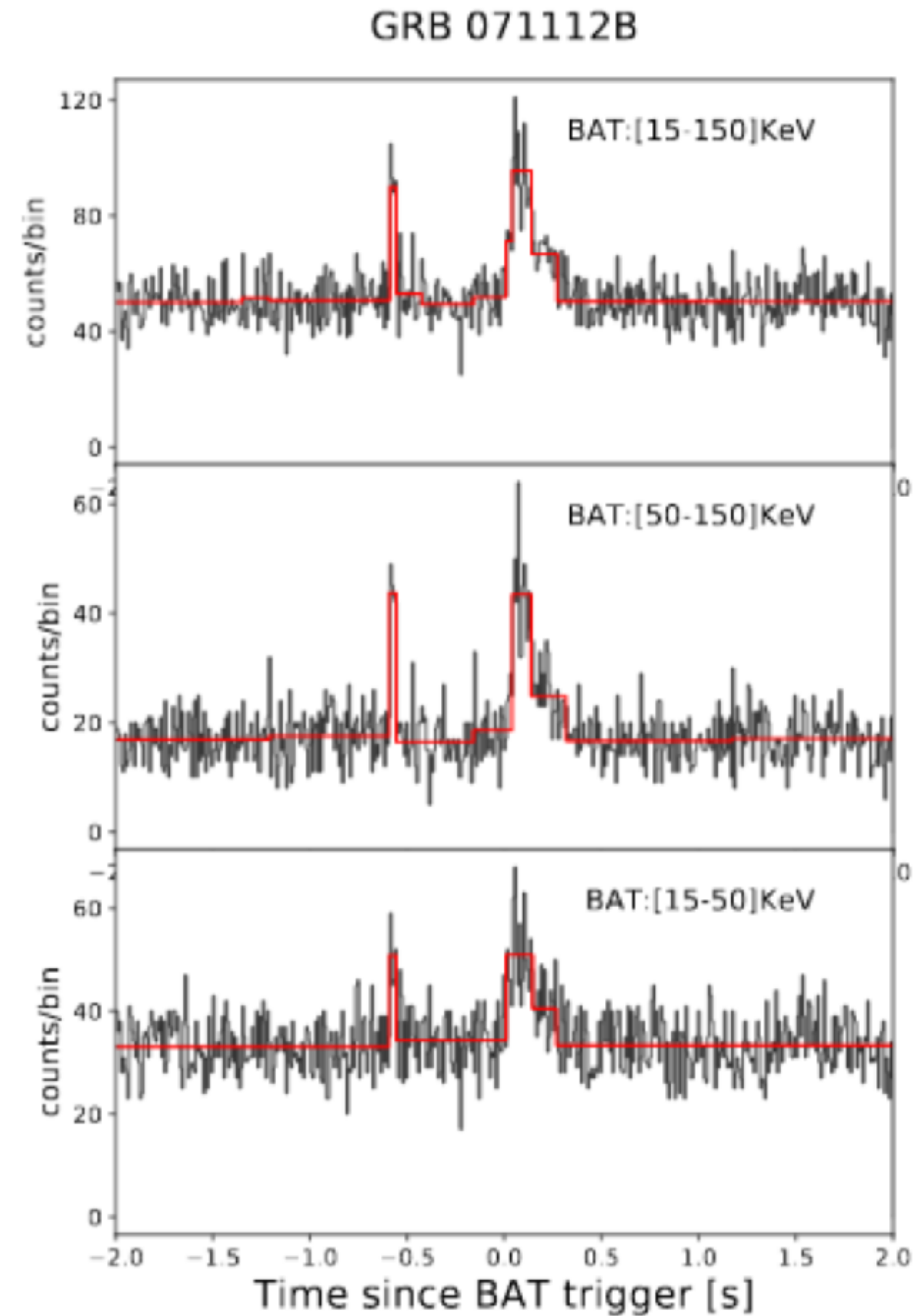
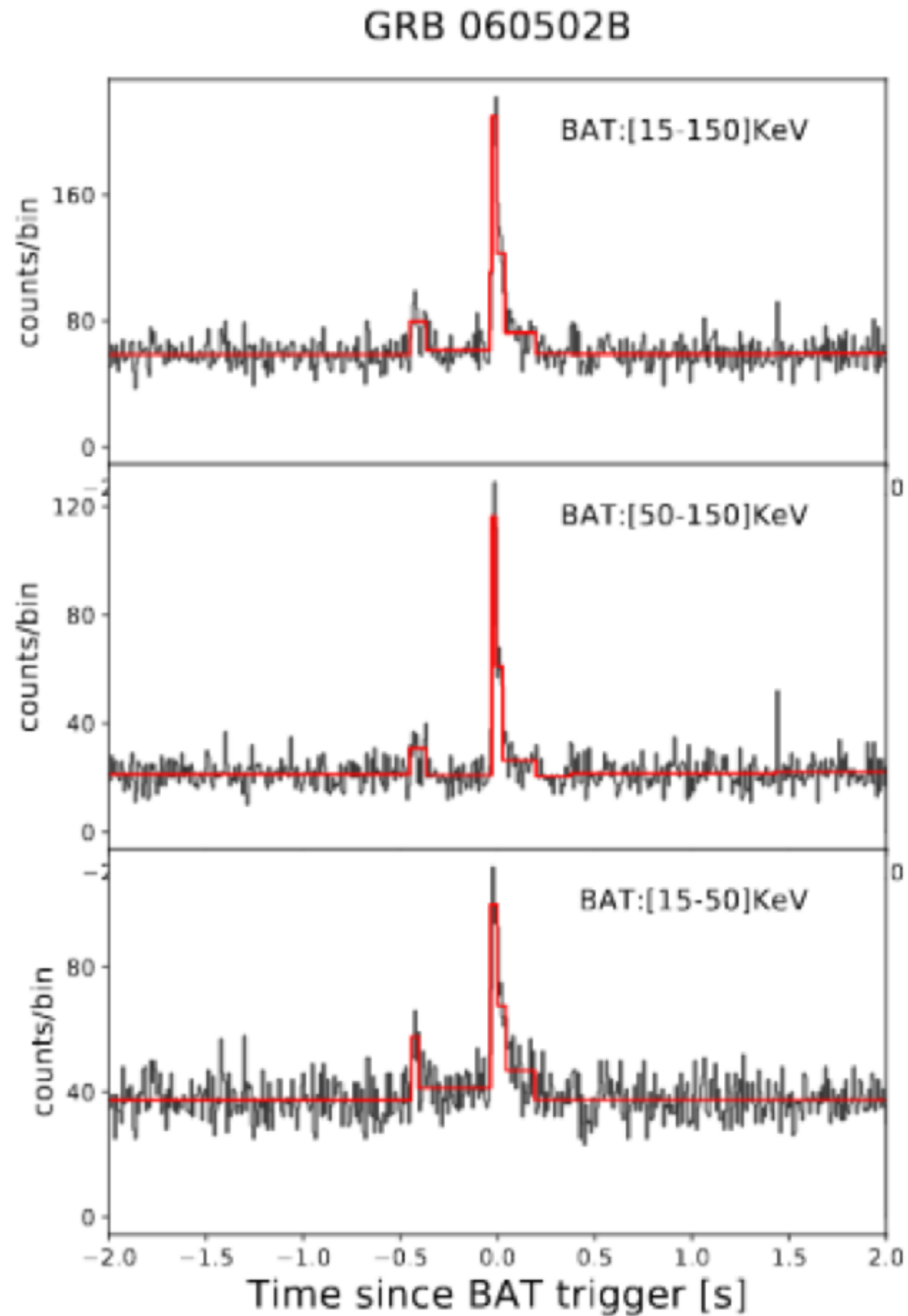
GW “Spectroscopy” of a HMNS Remnant



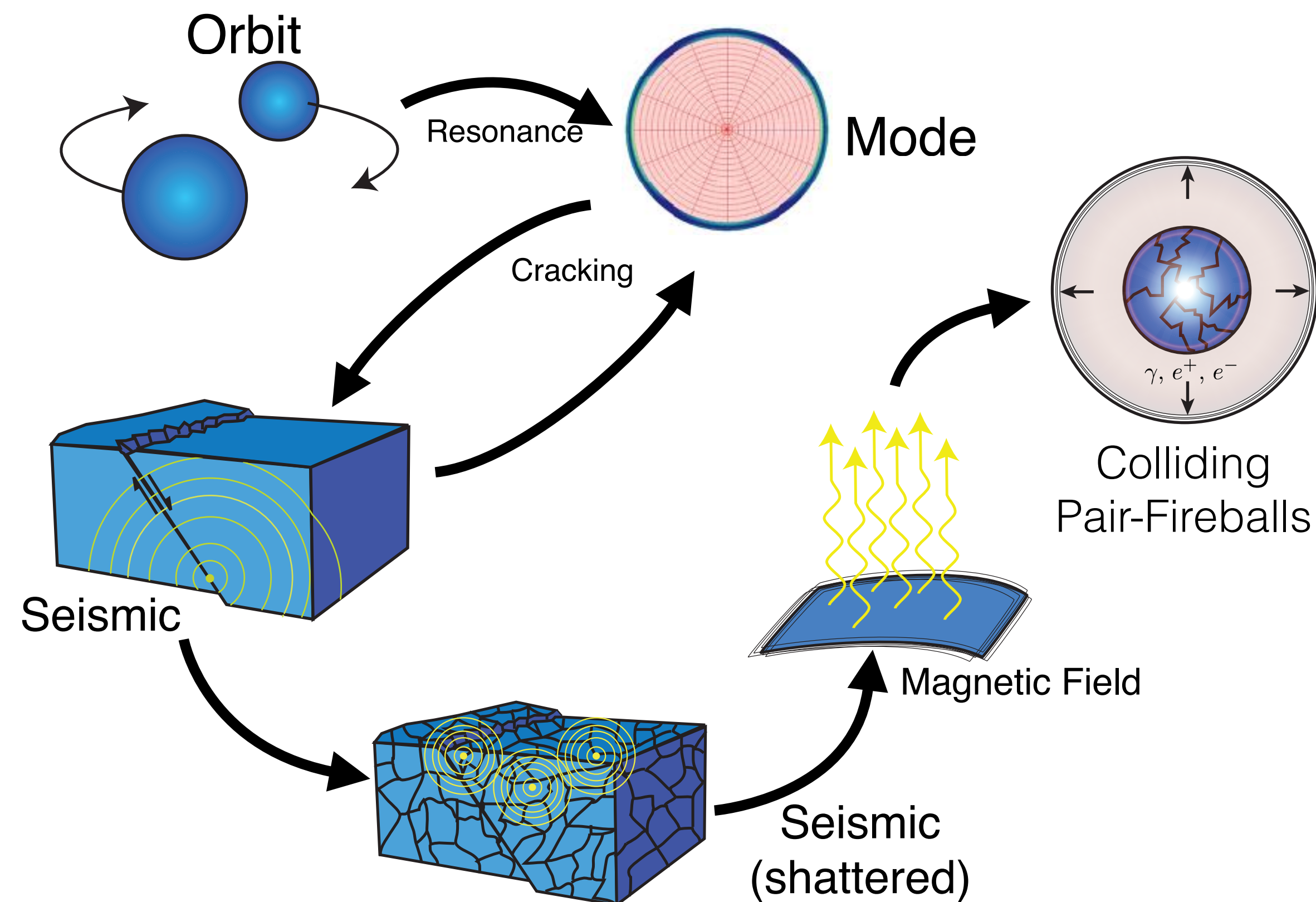
Can we get early access (during the LVK era) to
asteroseismology without needing direct detection of
dynamical tides?

Perhaps...

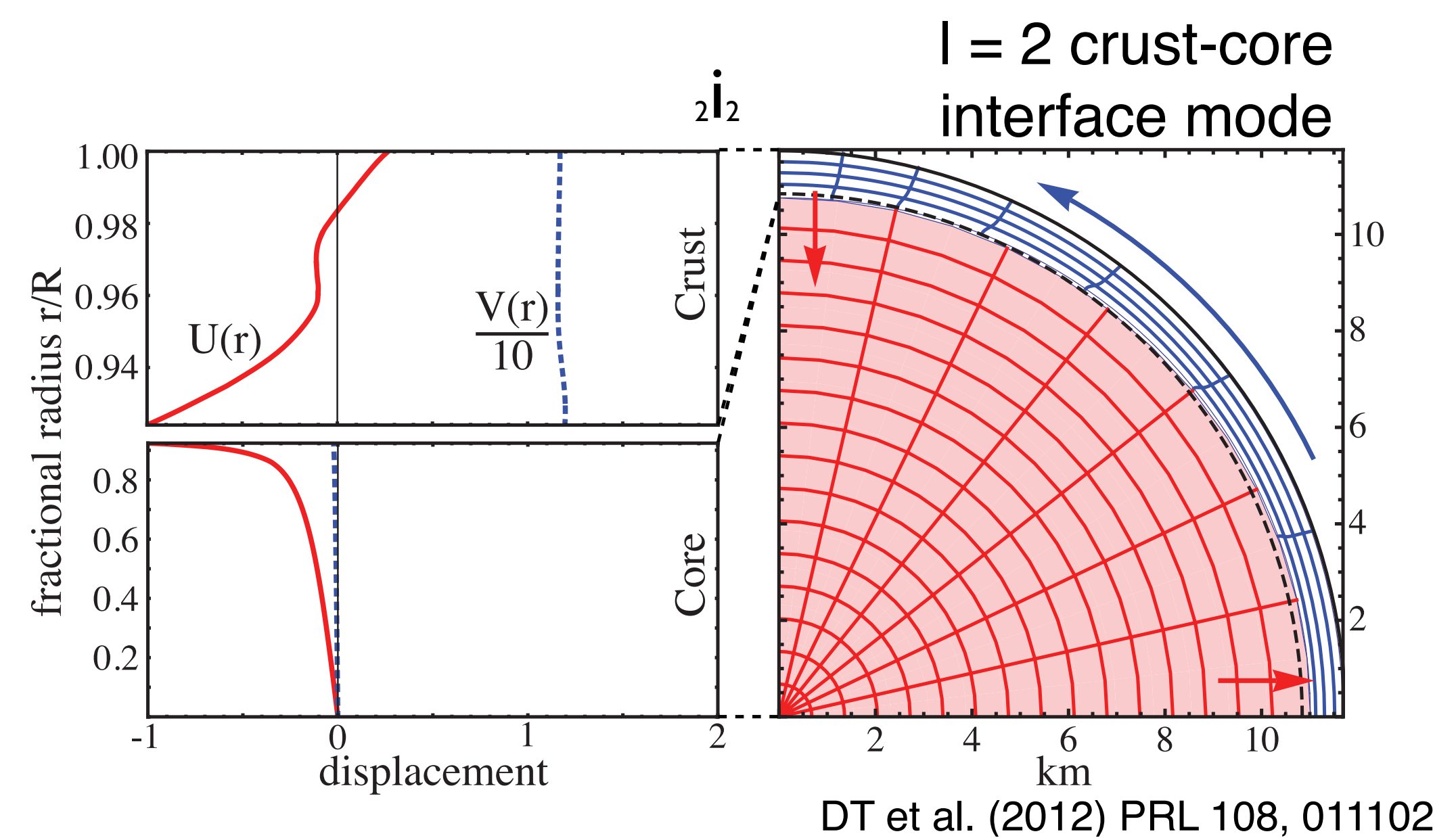
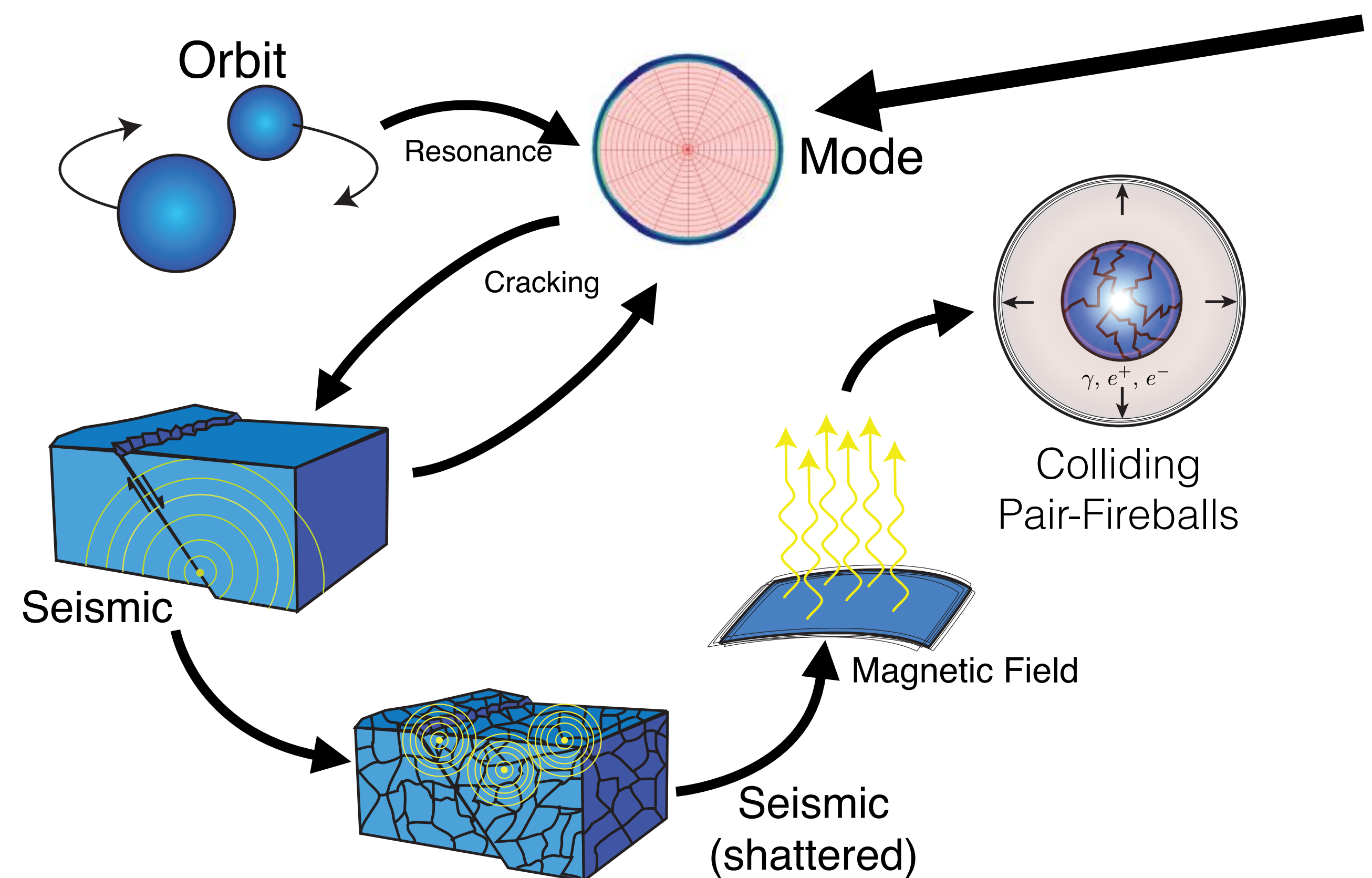
Some SGRBs have precursors...



Resonant Shattering Flares



Resonant Shattering Flares



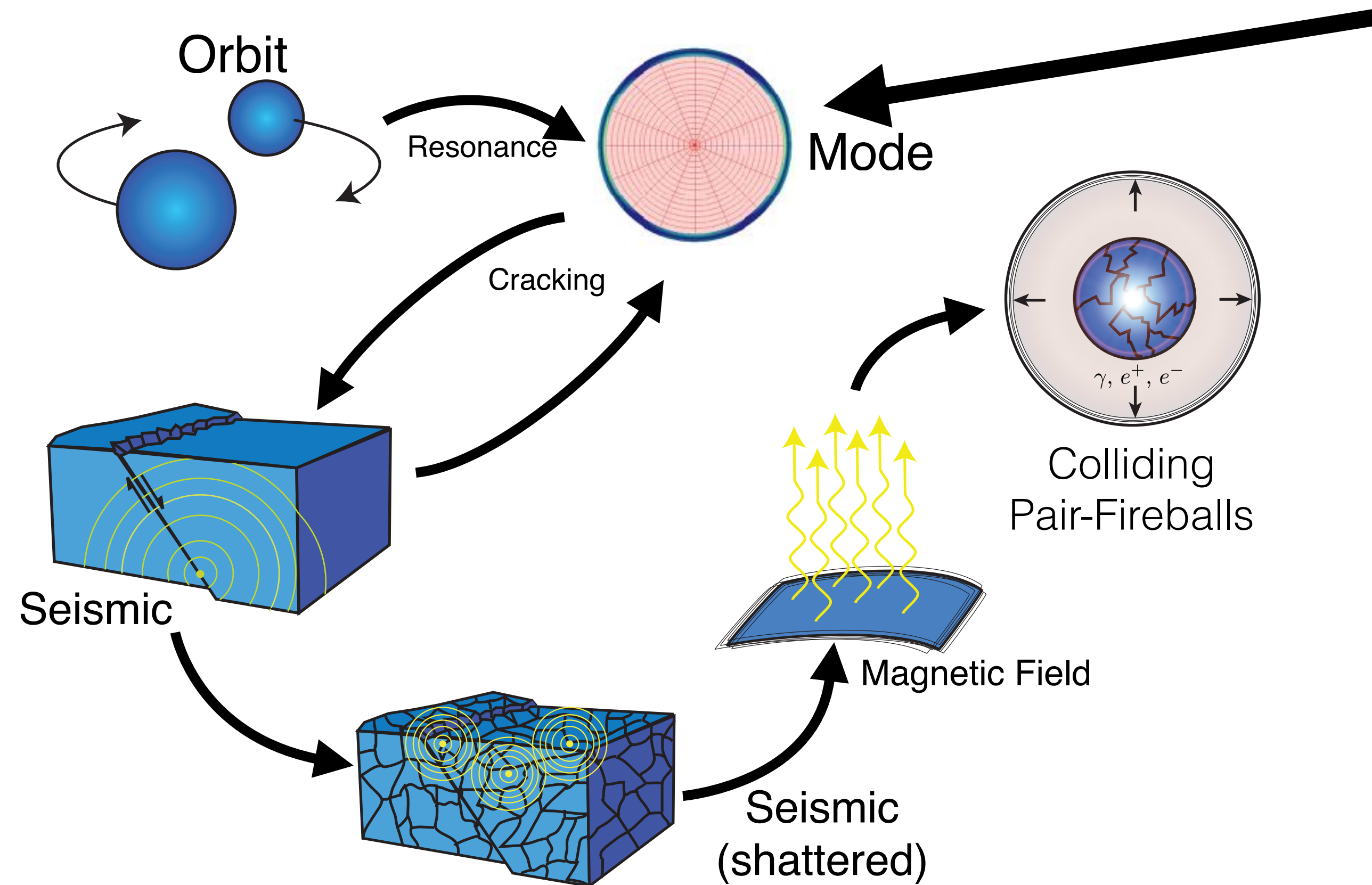
DT, et al. (2012) PRL 108, 011102

DT (2013) ApJ 777, 103

Neill, DT, Van Eerten, Ryan, & Newton (2022) MNRAS in press



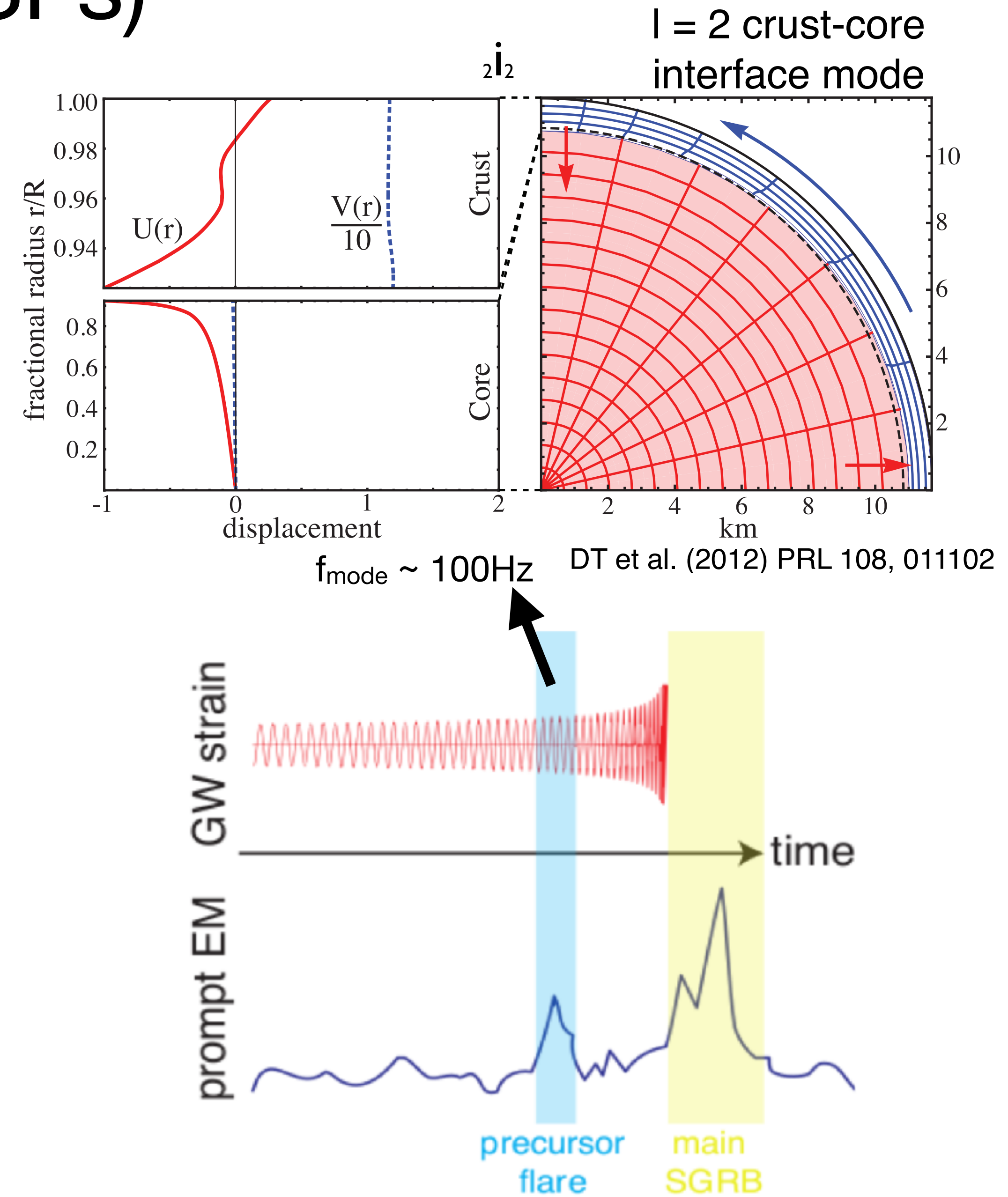
Resonant Shattering Flares (RSFs)

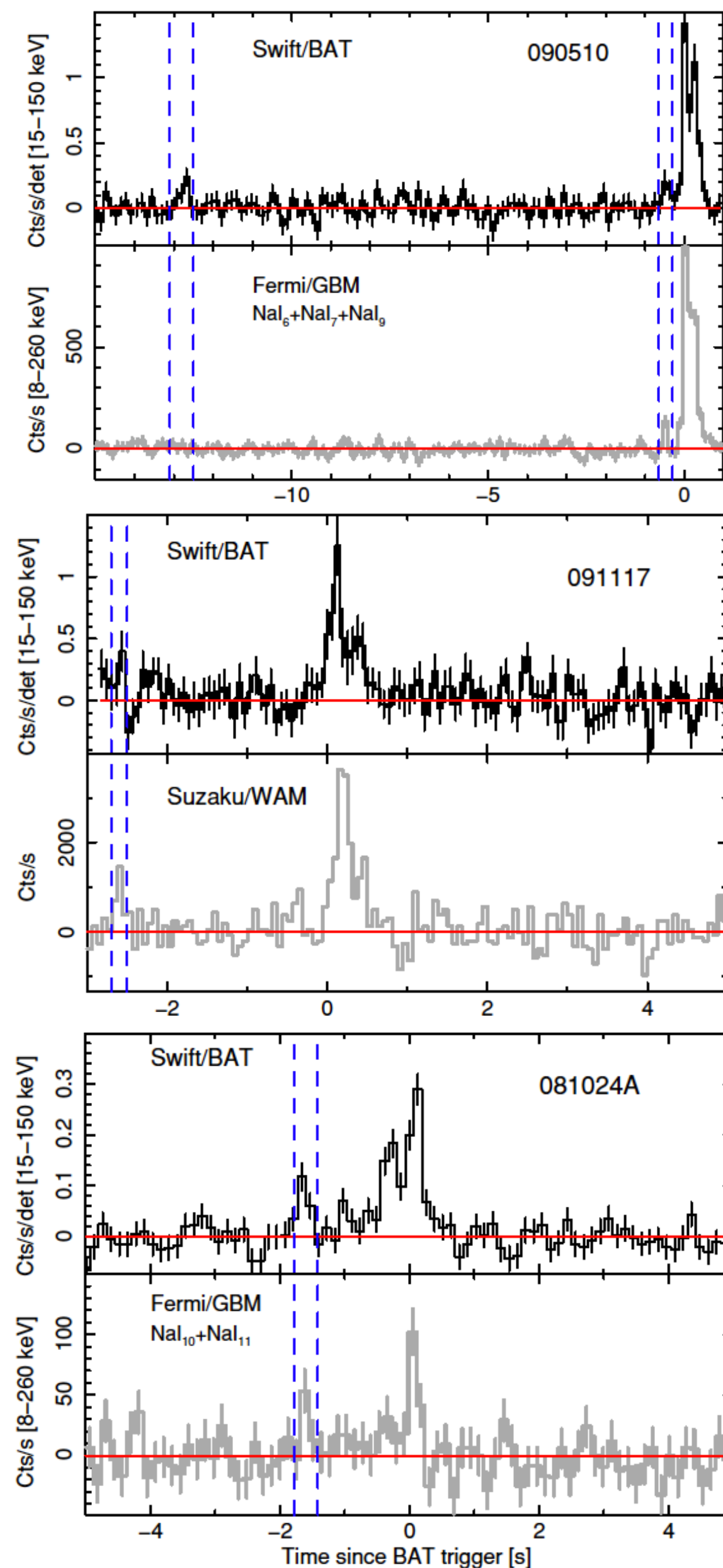


DT, et al. (2012) PRL 108, 011102

DT (2013) ApJ 777, 103

Neill, DT, Van Eerten, Ryan, & Newton (2022) MNRAS





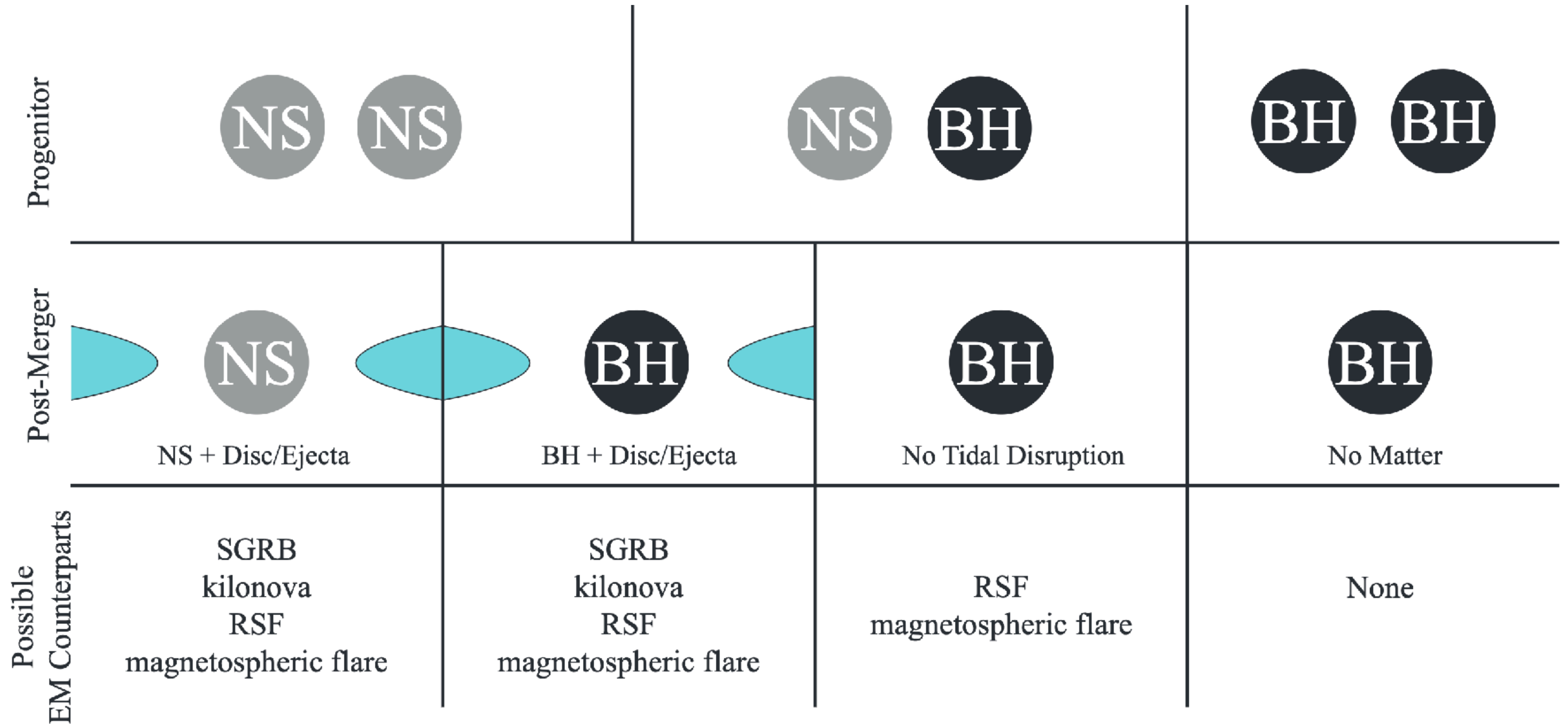
Potential Orphan RSFs?

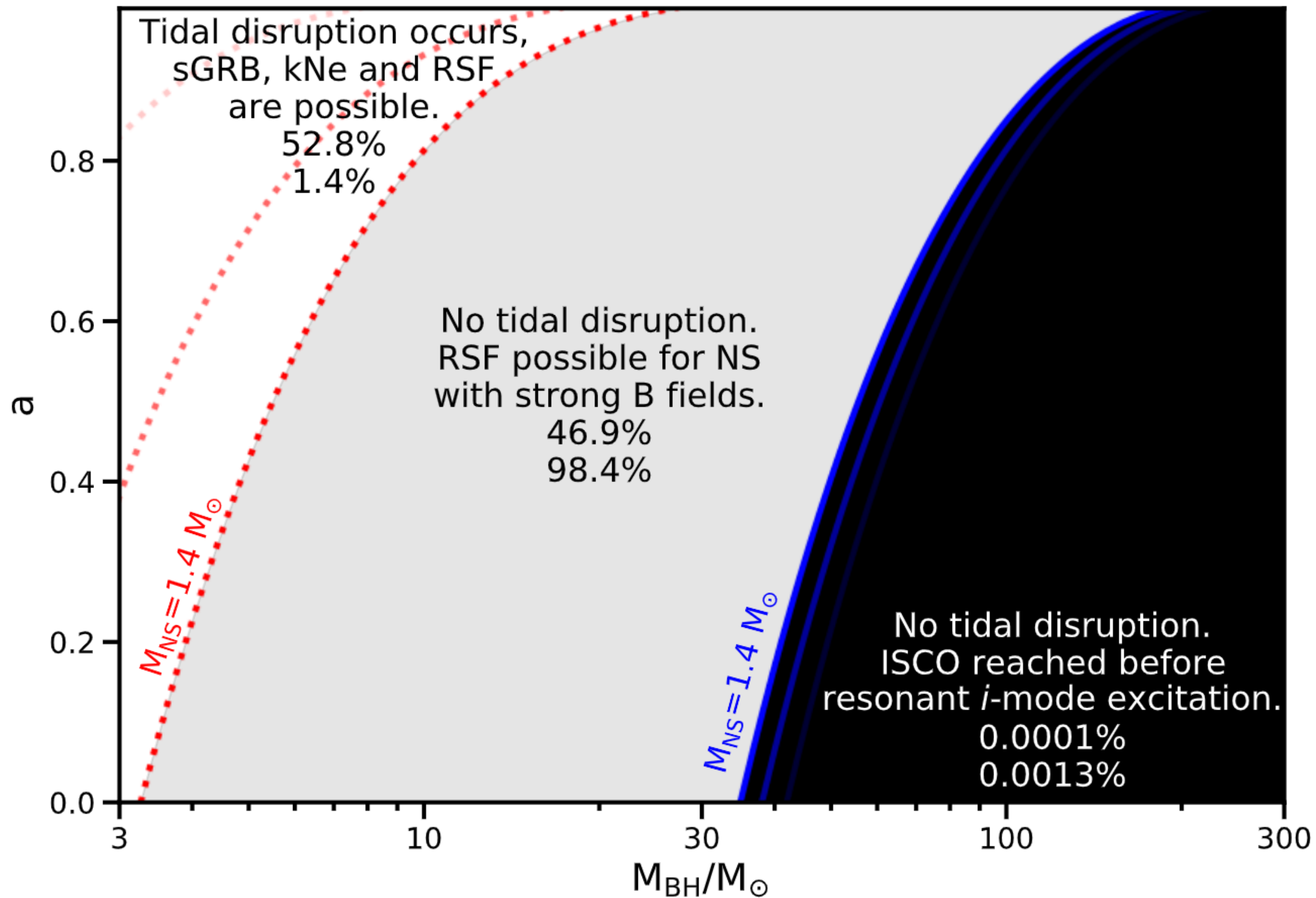
$$E_{\text{RSF}} \sim 10^{46} - 10^{49} \text{ erg}, t_{\text{RSF}} \sim 0.1 \text{ s}$$

GRB	$T_{90}(\text{s})$	z	BAT Fluence ($10^{-7} \text{ erg cm}^{-2}$)	$E_{\text{BAT ISO}}$ (erg)	Notes
150101B	0.018	0.13	0.23	2.6×10^{48}	High E_{kin} ; Fong+(2016)
050509B	0.073	0.225	0.09	1.1×10^{48}	Gehrels+(2005)
060502B	0.131	0.287	0.4	7.9×10^{48}	Bloom+ (2006)
050906	0.128	0.031*	0.07	1.5×10^{46}	Levan & Tanvir (2008)
090417A	0.07	0.088*	0.19	2.5×10^{47}	Mandhai+(2018)
130515A	0.29	0.023*	1.5	2.8×10^{47}	Mandhai+(2018)
111020A	0.40	0.018*	0.65	9.4×10^{46}	Mandhai+(2018)

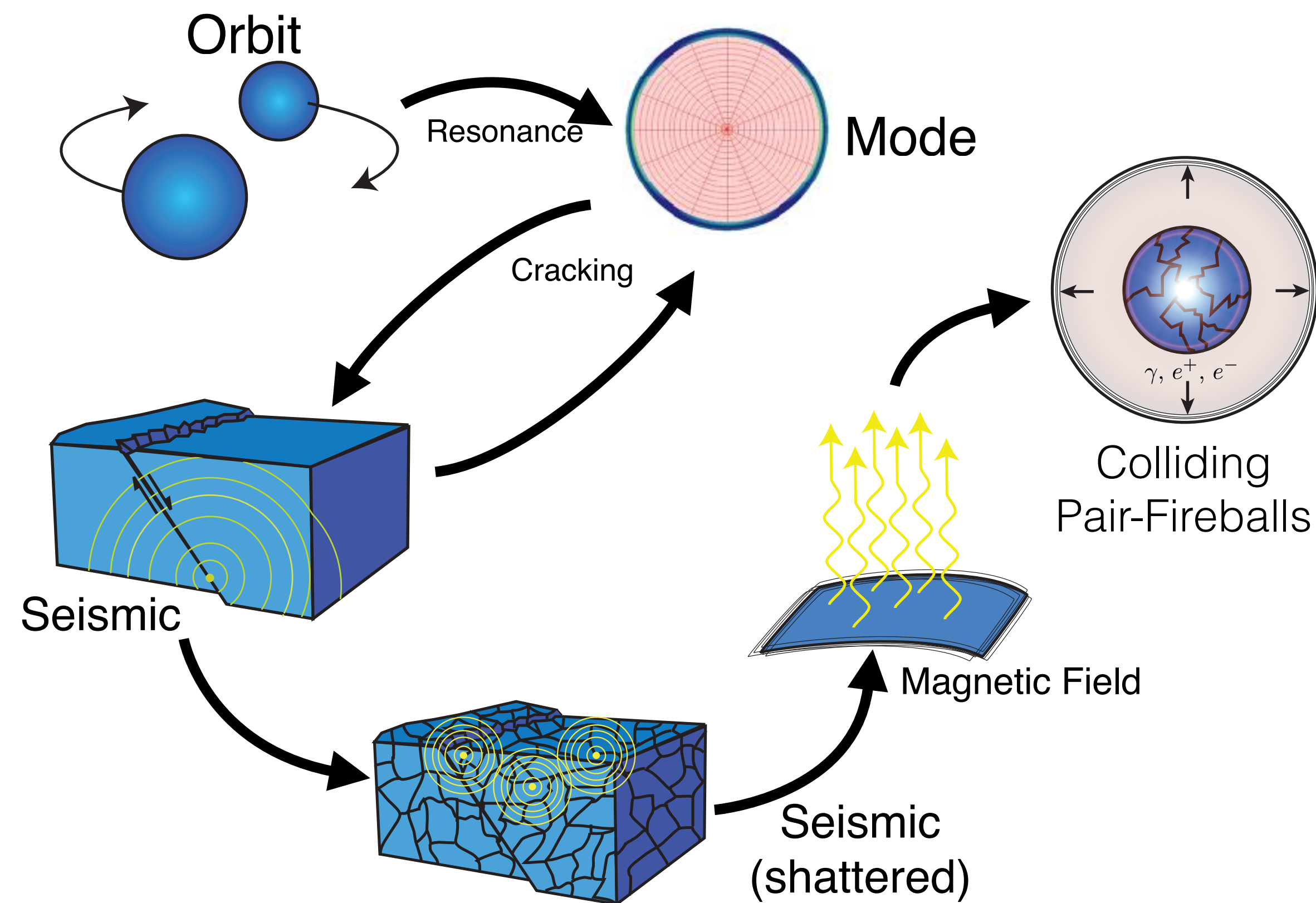
*no afterglow; host galaxy within BAT error box

Q: Is there a local orphan RSF component in SGRBs population?





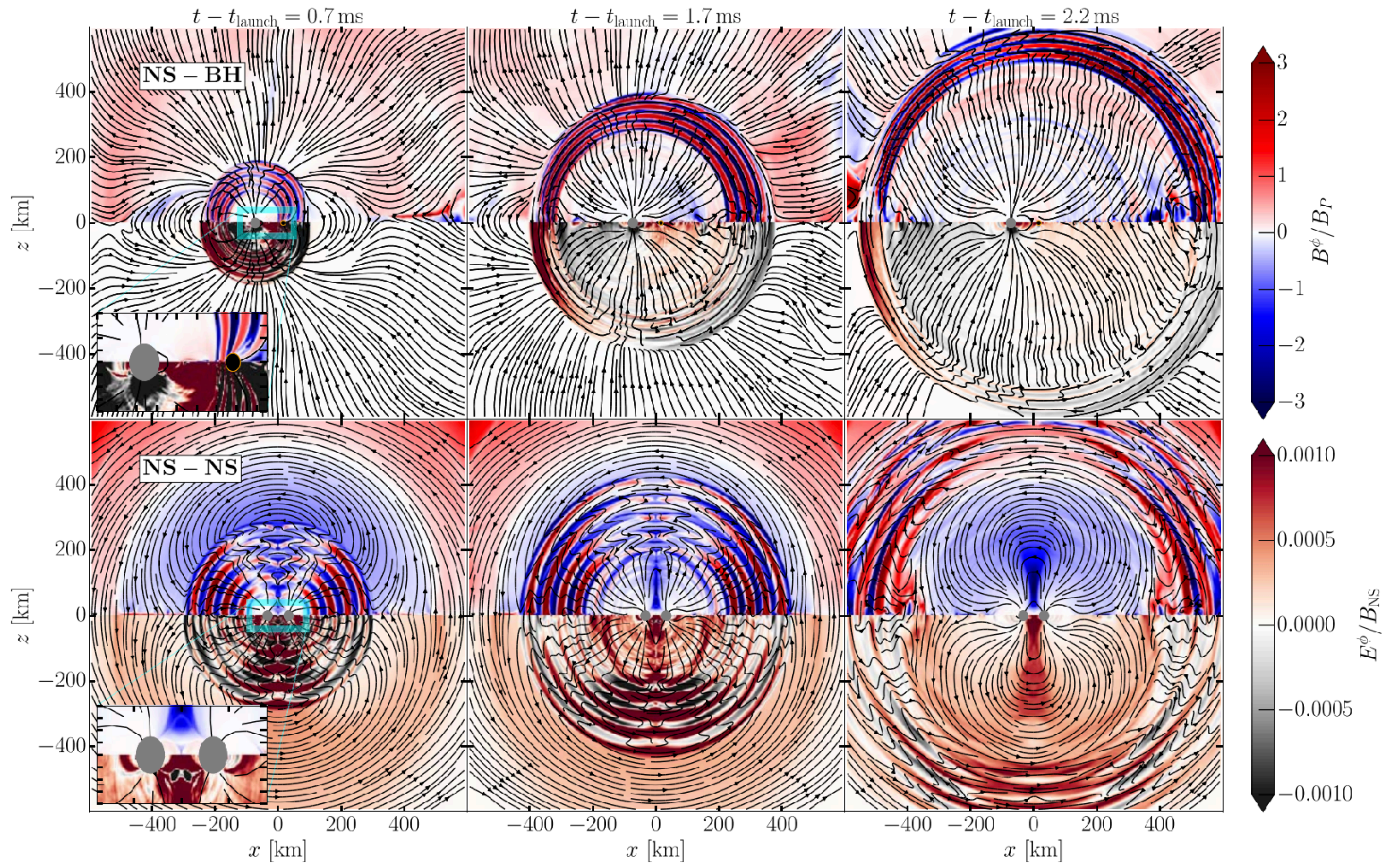
Resonant Shattering Flares



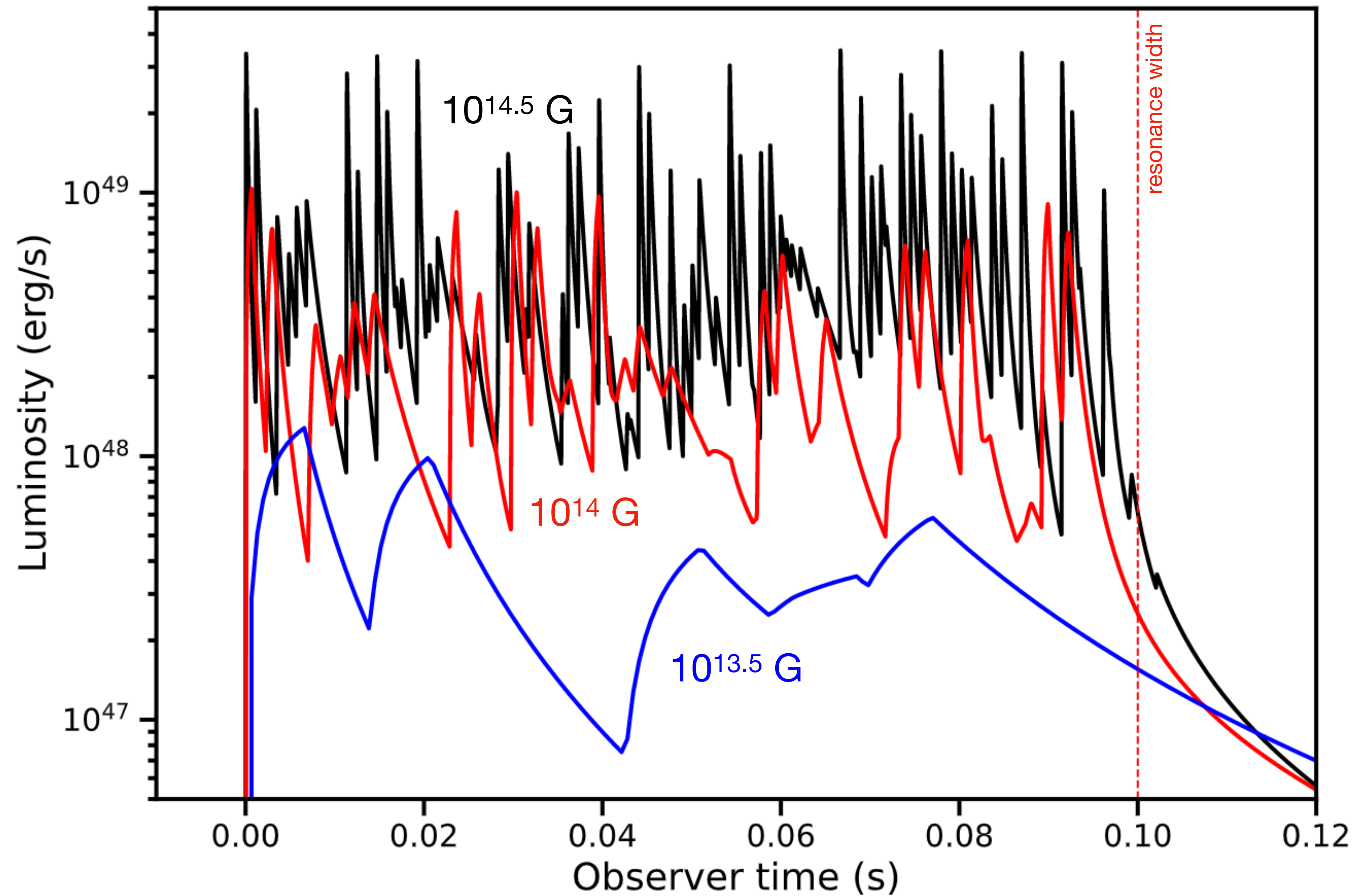
DT, et al. (2012) PRL 108, 011102

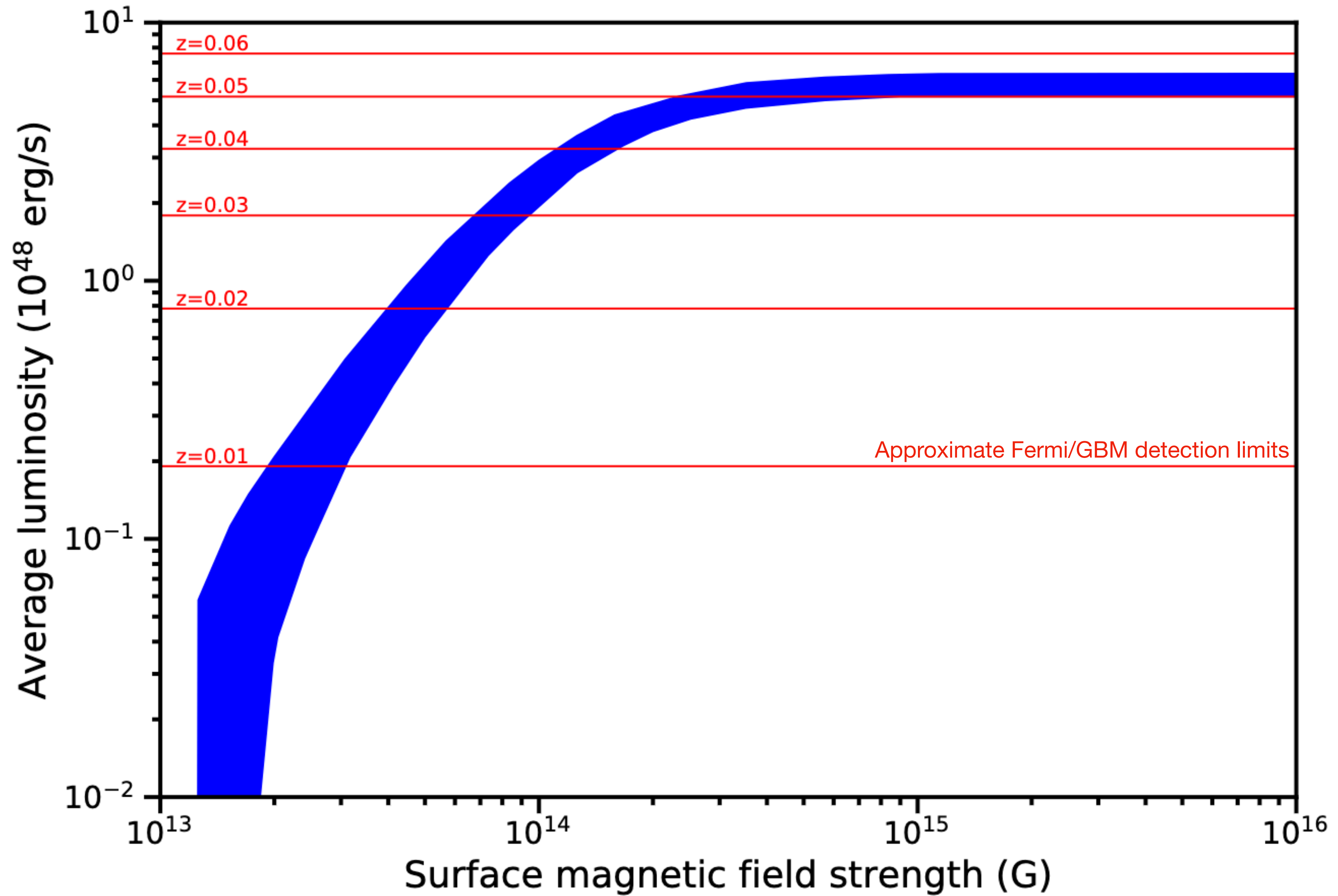
DT (2013) ApJ 777, 103

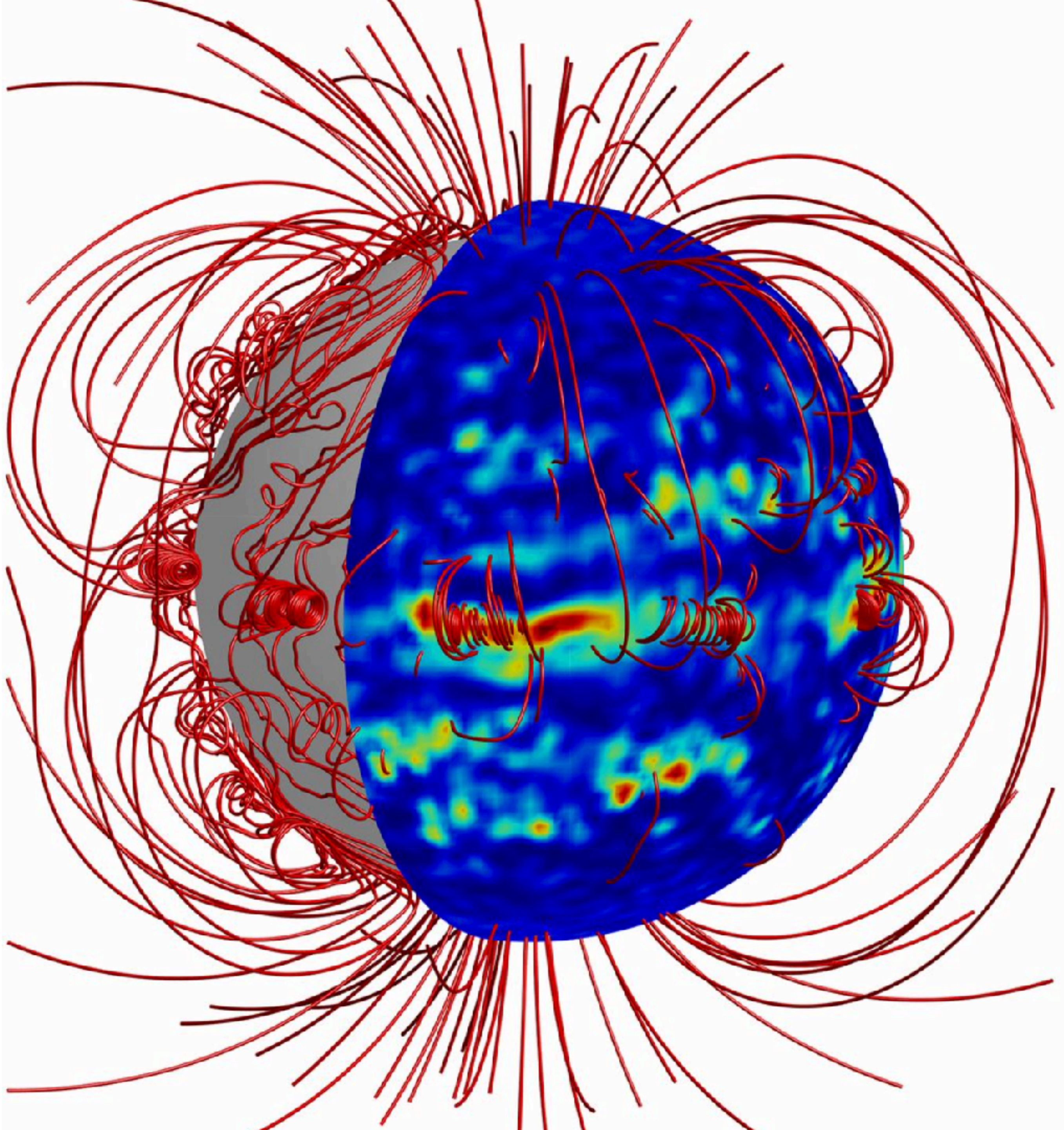
Neill, DT, Van Eerten, Ryan, & Newton (2022) MNRAS, 514, 4

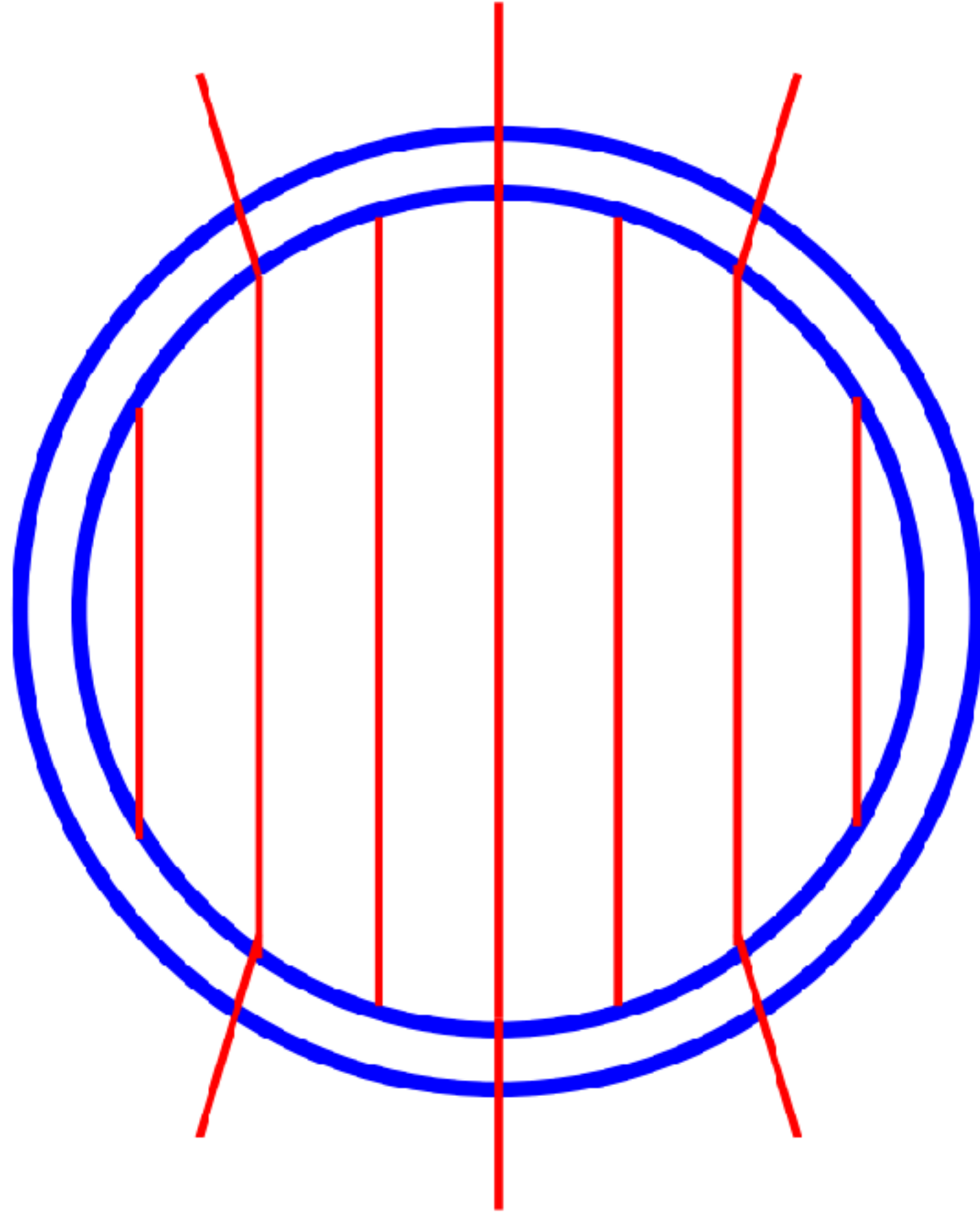


Non-thermal emission from shell collisions

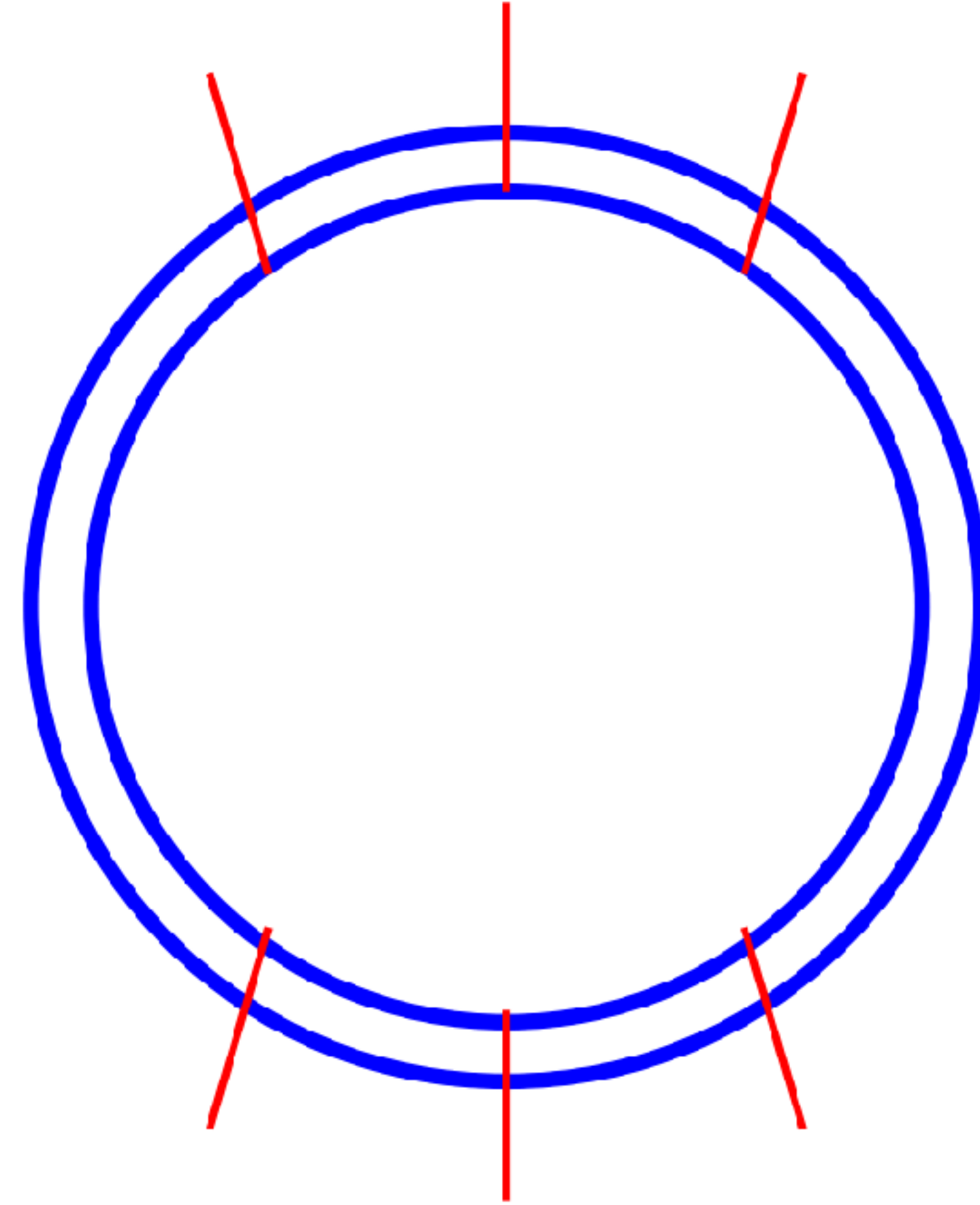




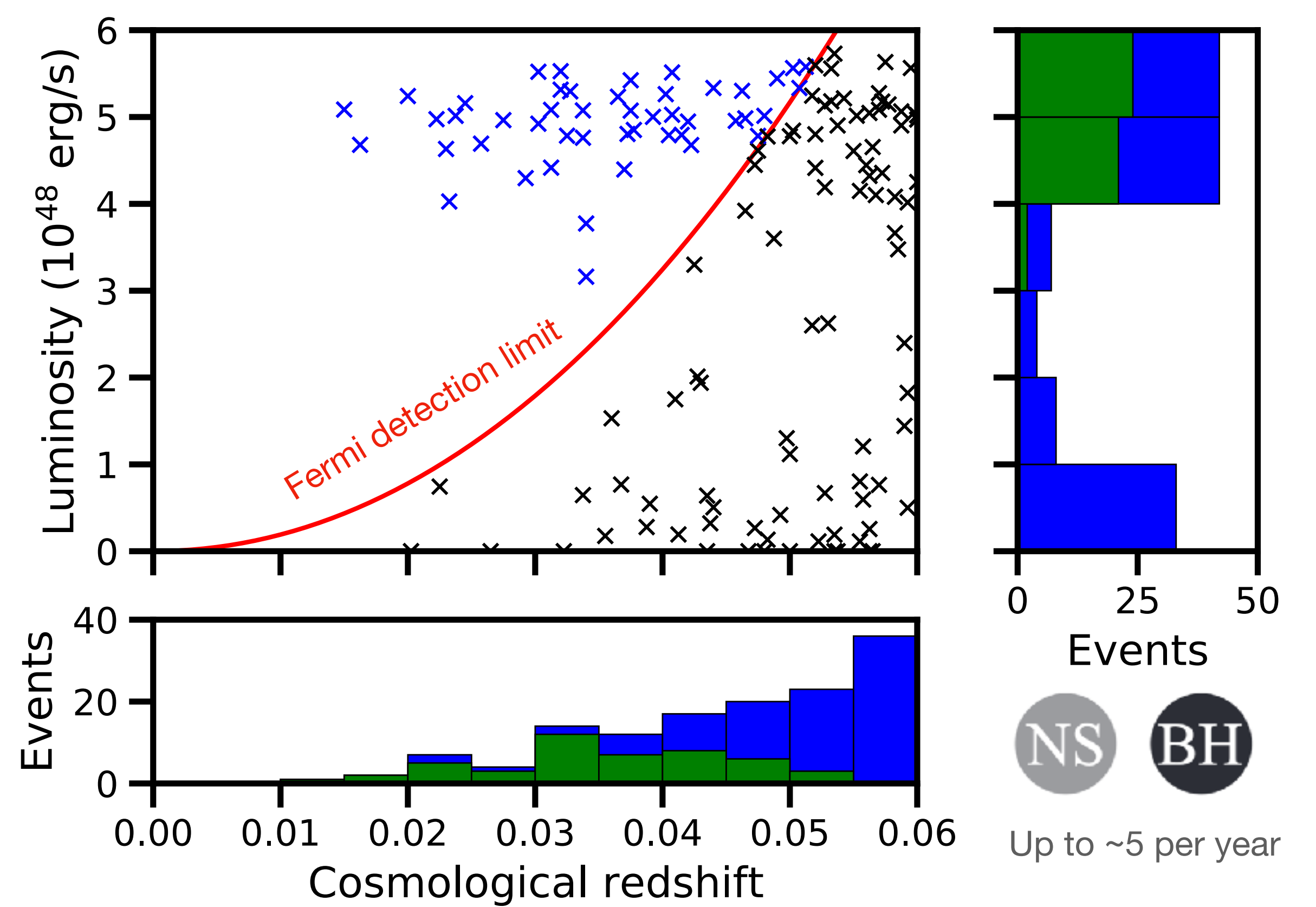
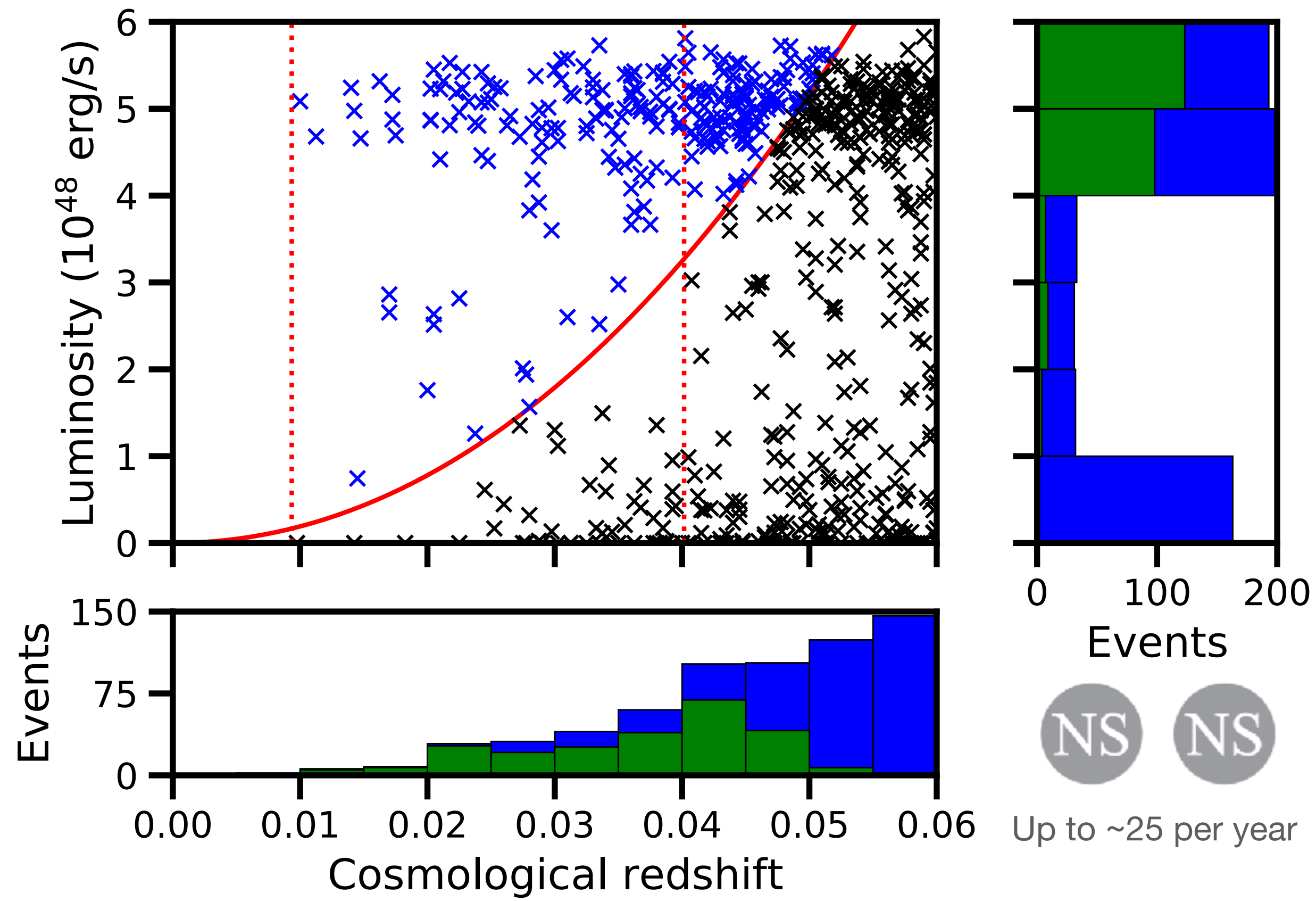




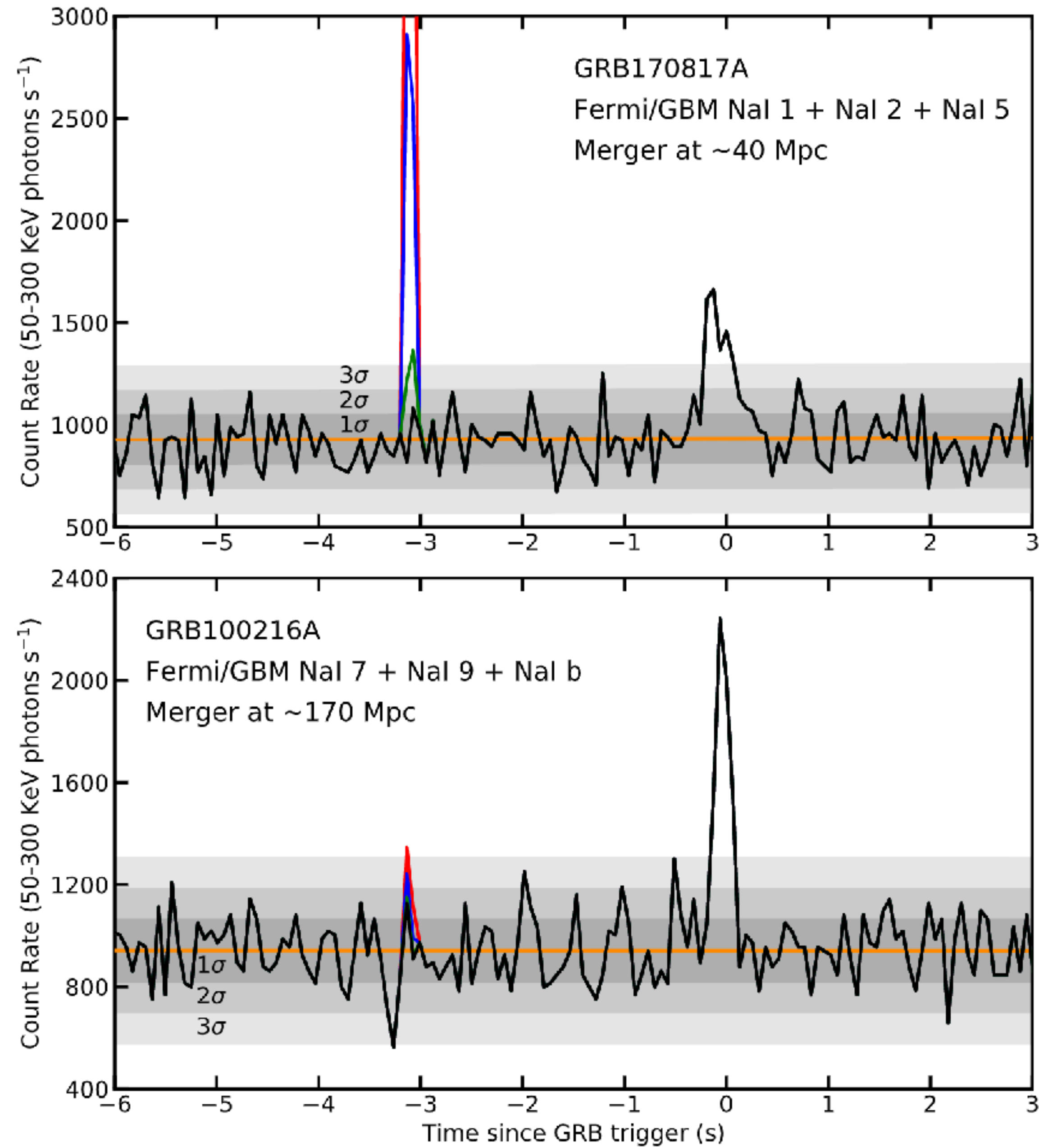
Fields are long lived if
they thread the core

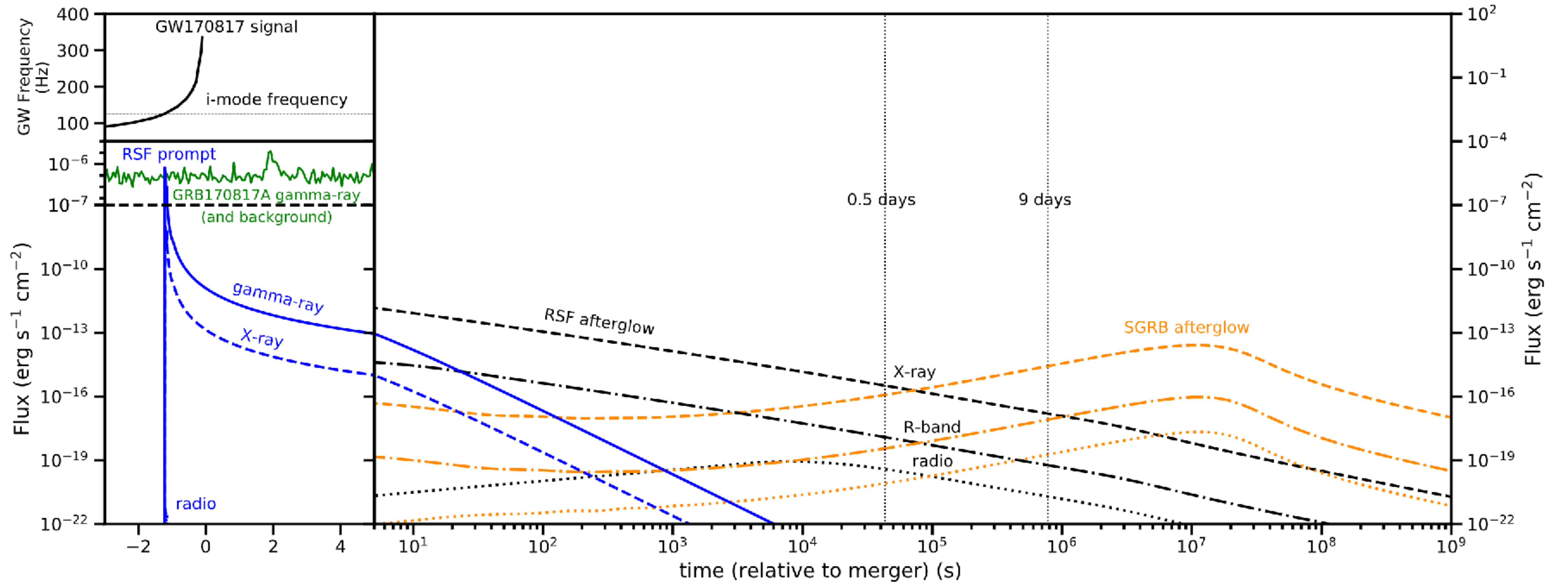


Fields decay in $< 10^6$ years if
anchored only in the crust

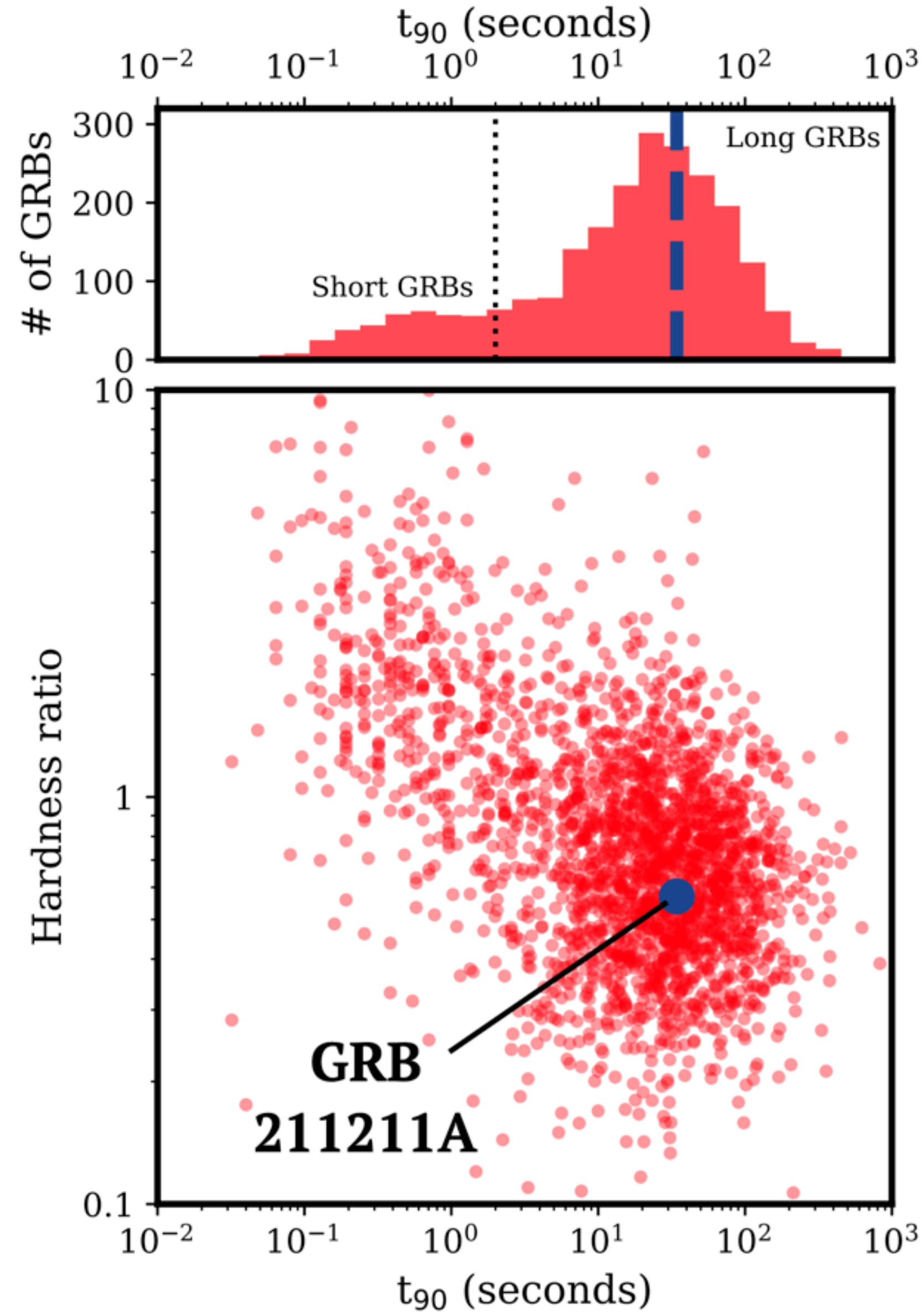
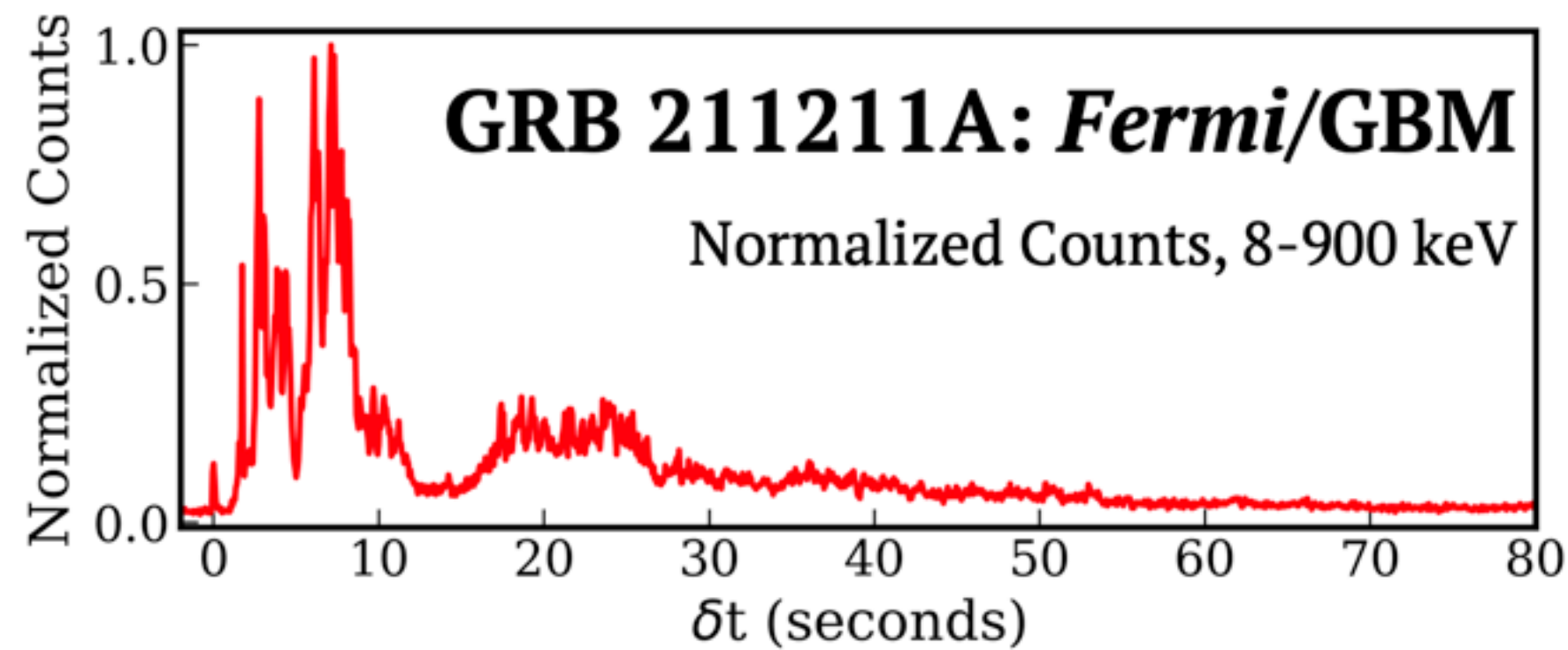
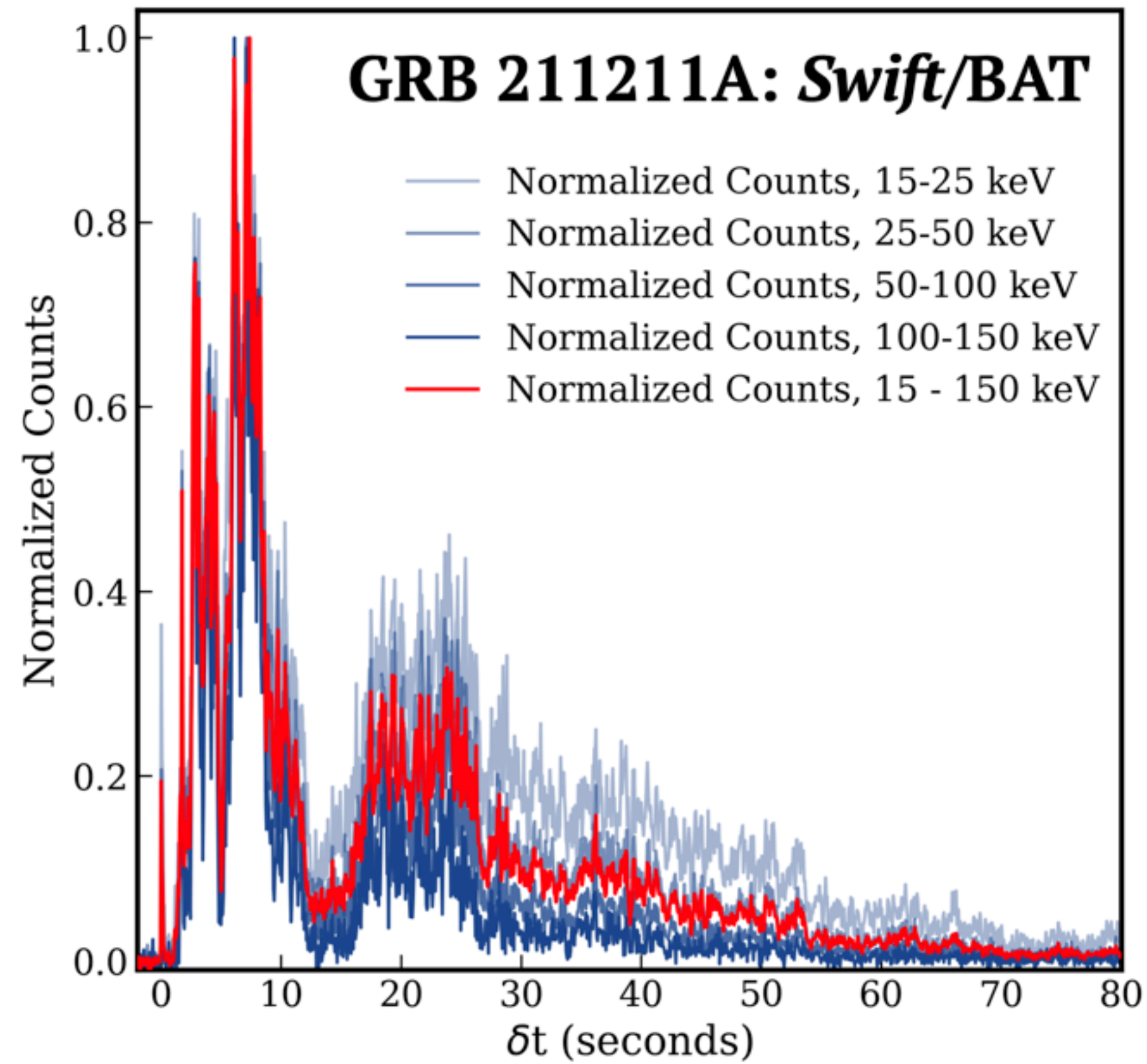


$10^{14.5}$ G
 10^{14} G
 $10^{13.5}$ G

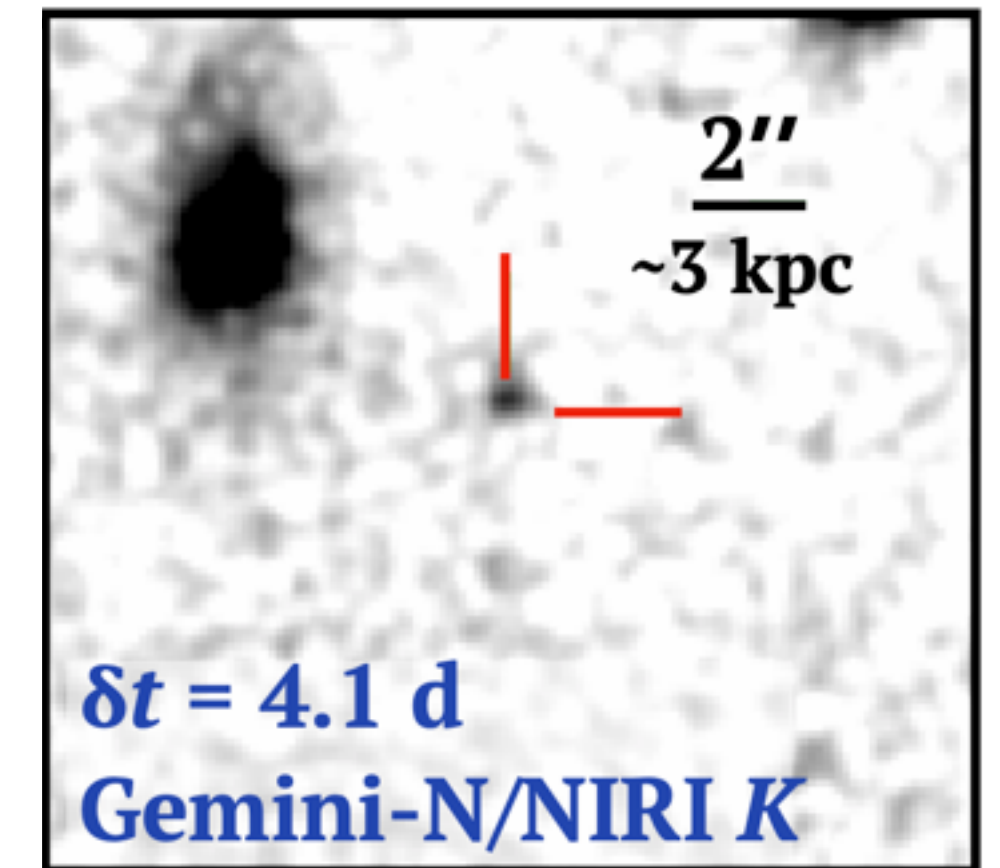




No detectable precursor implies $B_{\text{surf}} \lesssim 10^{13.5} \text{ G}$

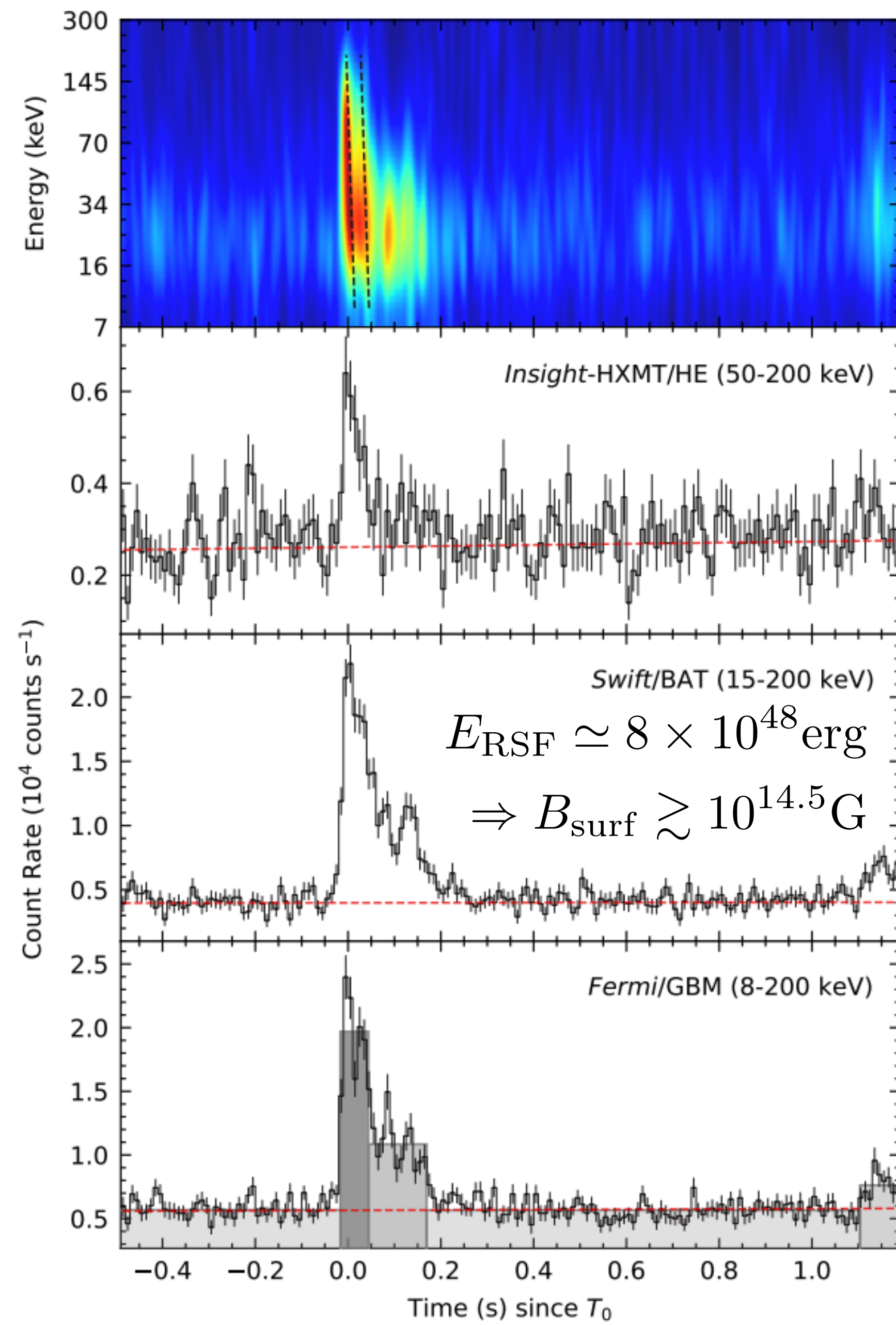
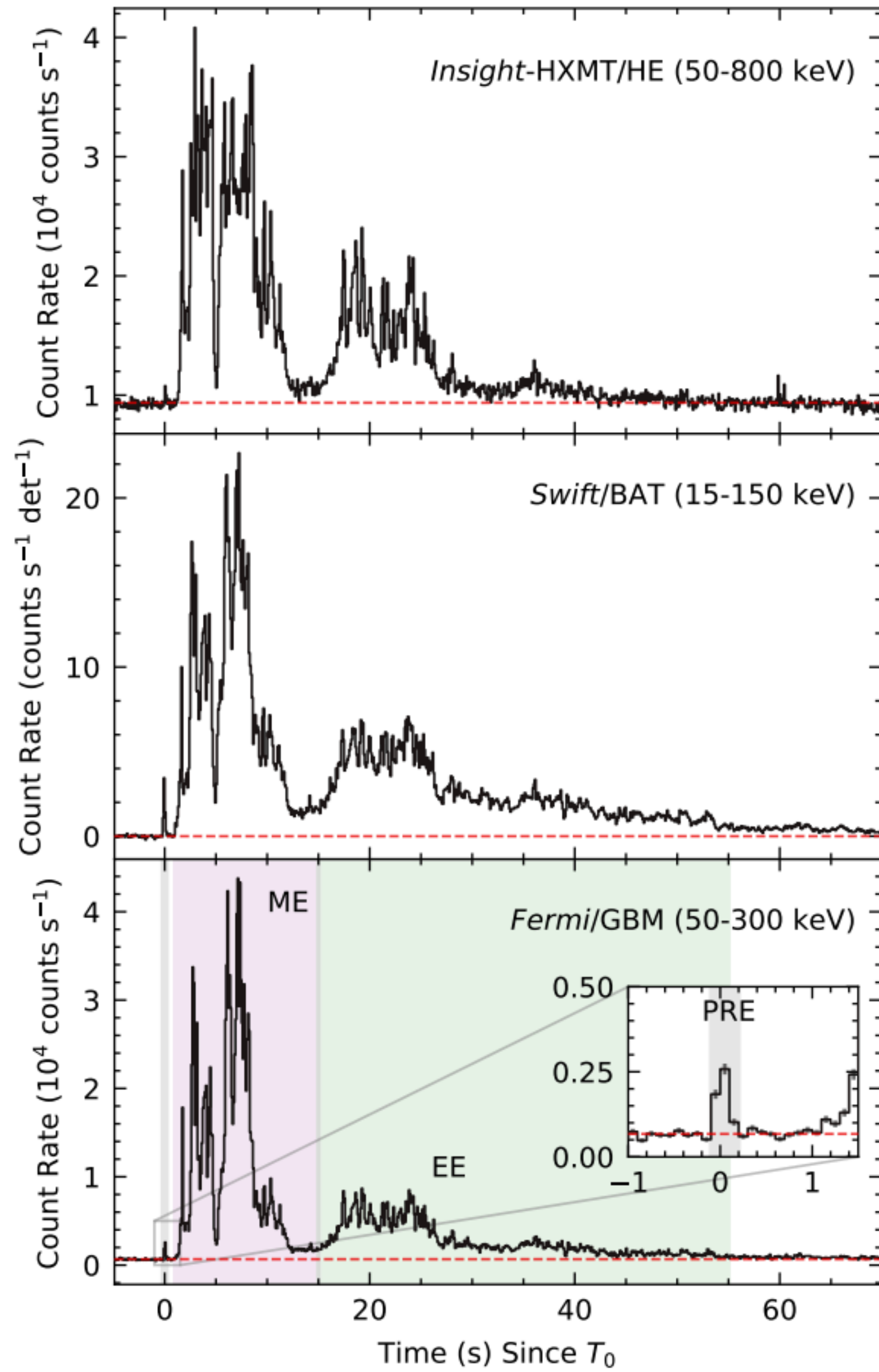


Associated Kilonova!

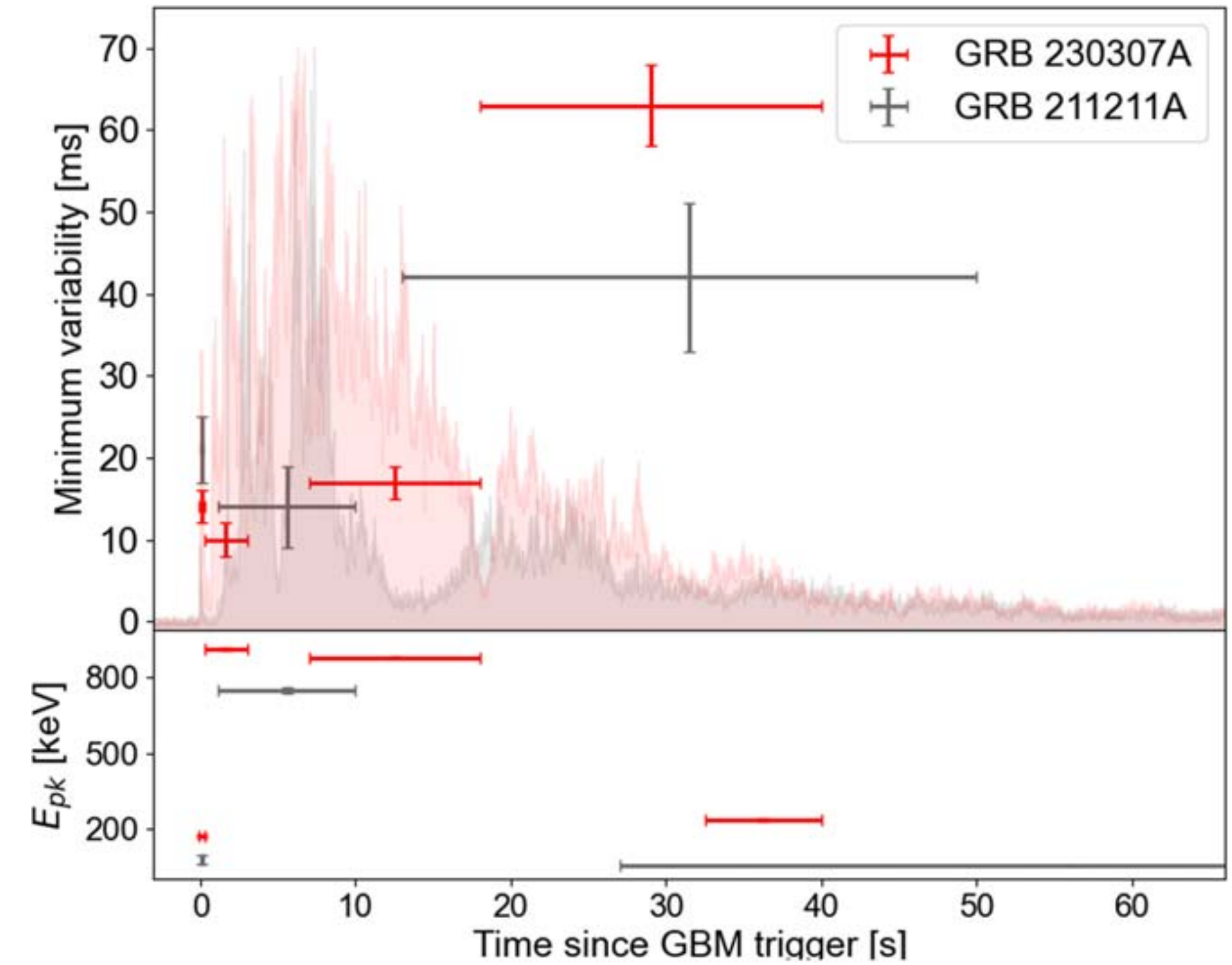
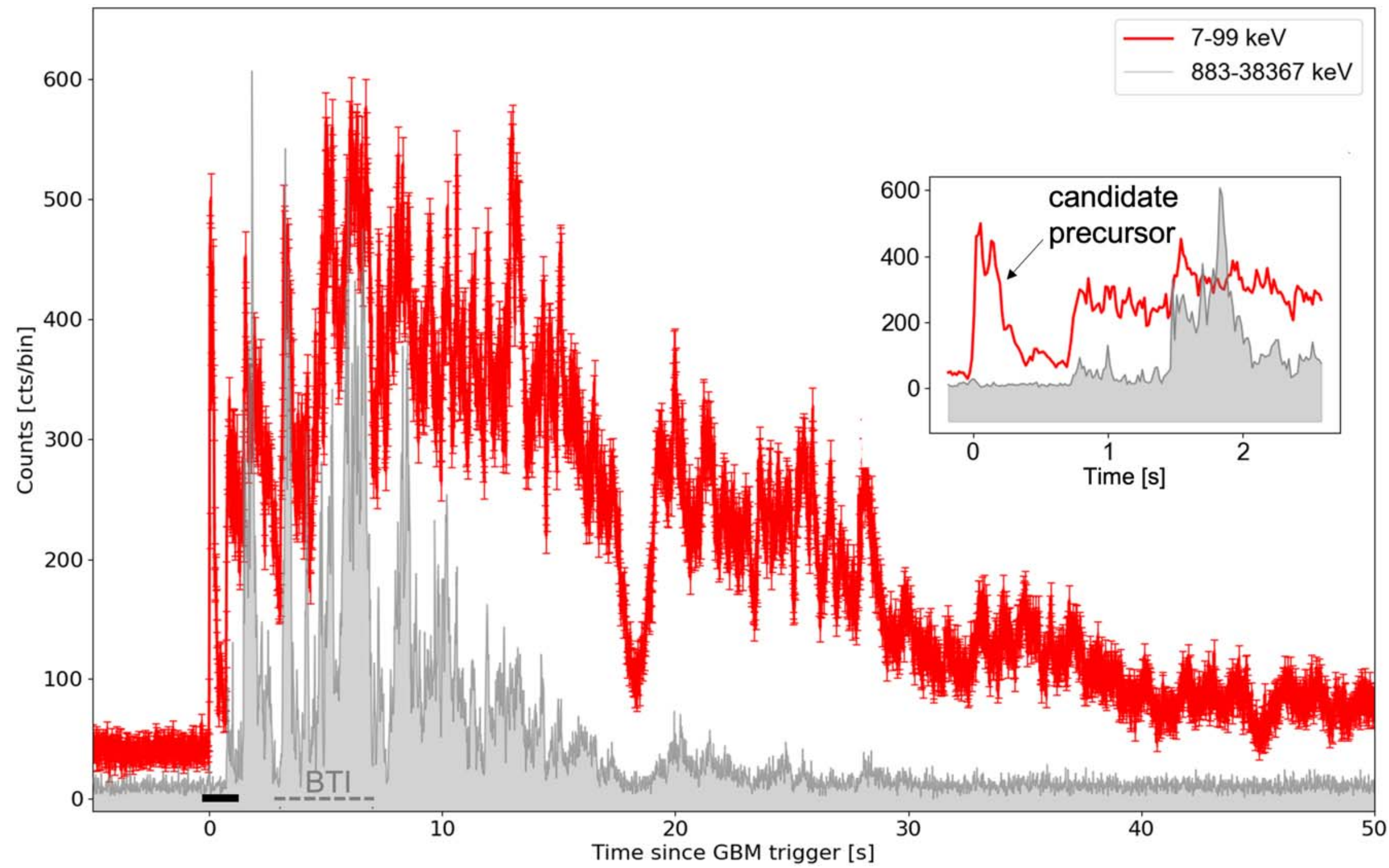


$$z = 0.0763 \pm 0.0002$$

$$d \simeq 350 \text{ Mpc}$$

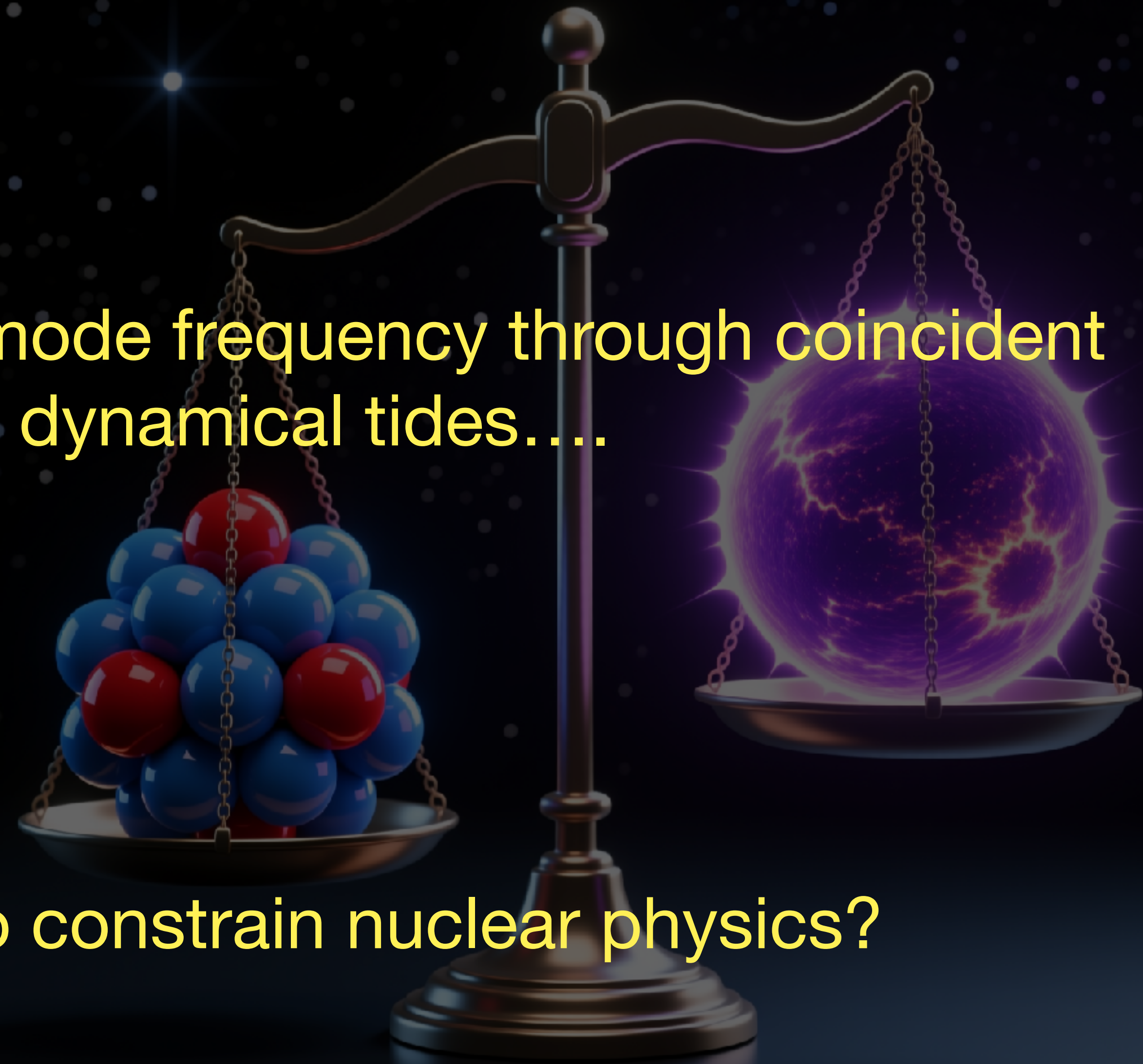


Another: GRB 230307A



If we can determine the crust-core i-mode frequency through coincident timing of RSFs or GW dynamical tides....

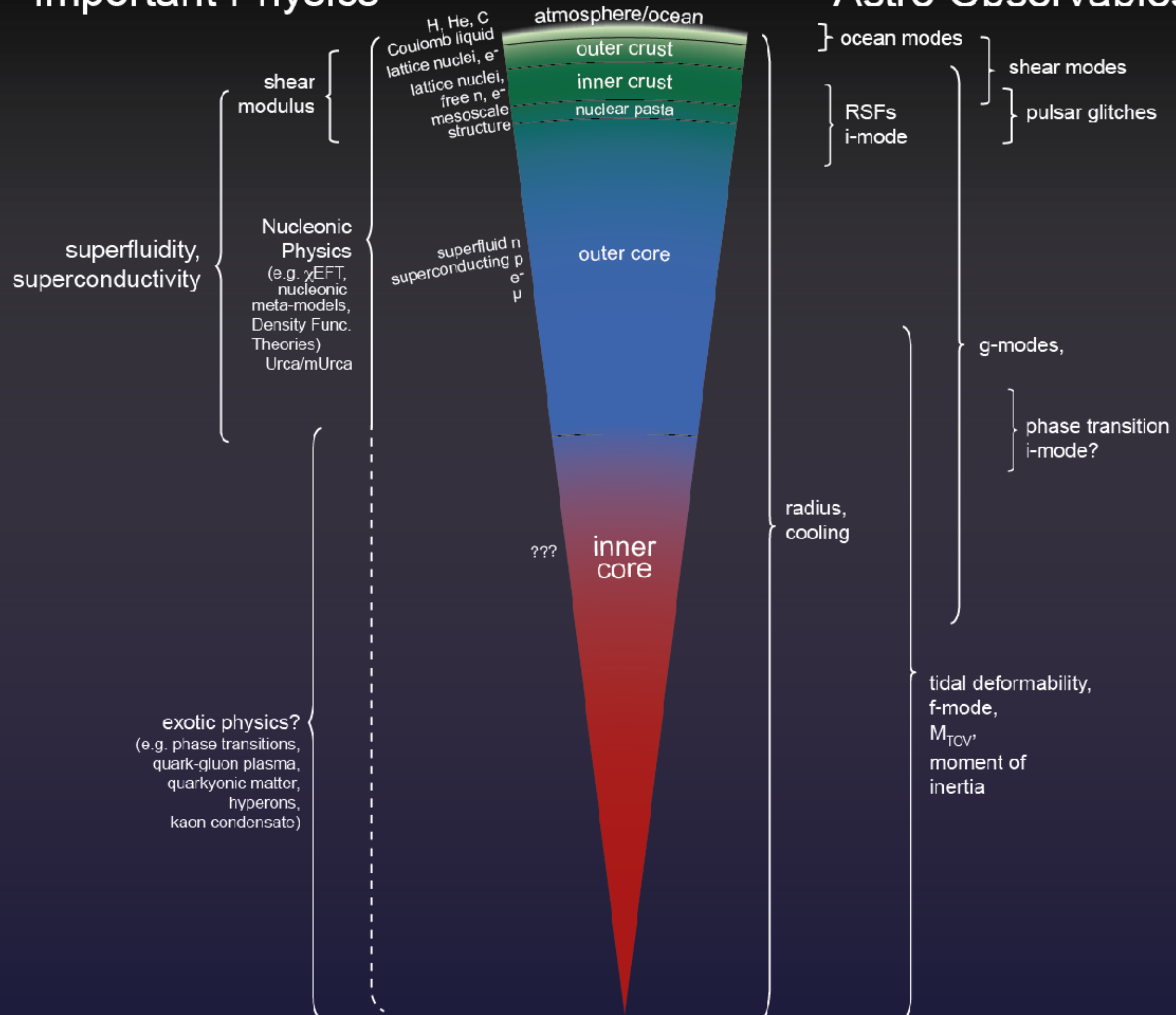
How can we use the i-mode to constrain nuclear physics?



NS Structure

Important Physics

Astro Observables



Nuclear Matter Physics

FOR
~~DUMMIES~~

Astrophysicists

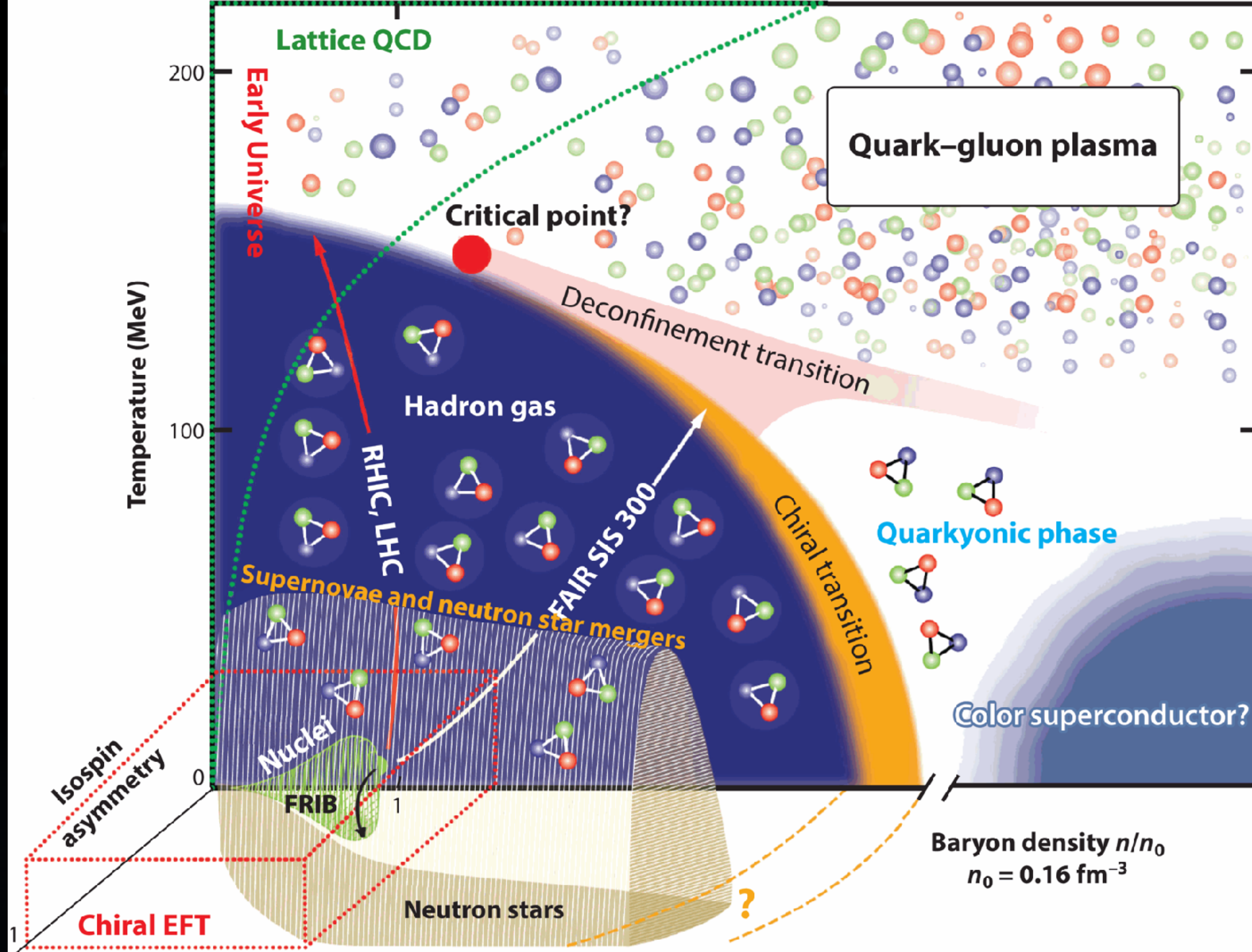
*A Reference
for the
Rest of Us!*

FREE eTips at dummies.com

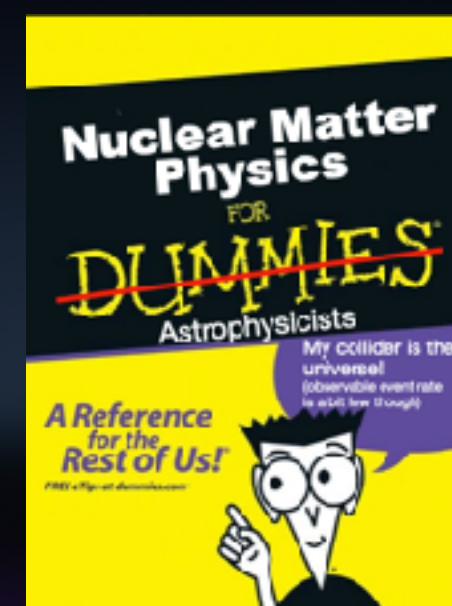


My collider is the
universe!
(observable event rate
is a bit low though)





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



(Cold) Infinite Nuclear Matter Equation of State

Energy per baryon

$$K \propto \left. \frac{\partial^2 E_{\text{sym}}}{\partial n^2} \right|_{n=n_o}$$

$$L \propto \left. \frac{\partial E_{\text{sym}}}{\partial n} \right|_{n=n_o}$$

$$J = E_{\text{sym}}(n_o)$$

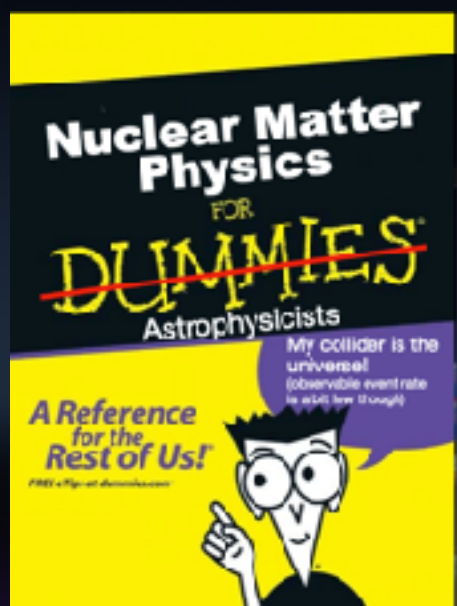
Saturation Density
 $n_o \simeq 0.16 \text{ fm}^{-3}$

n
Baryon Density

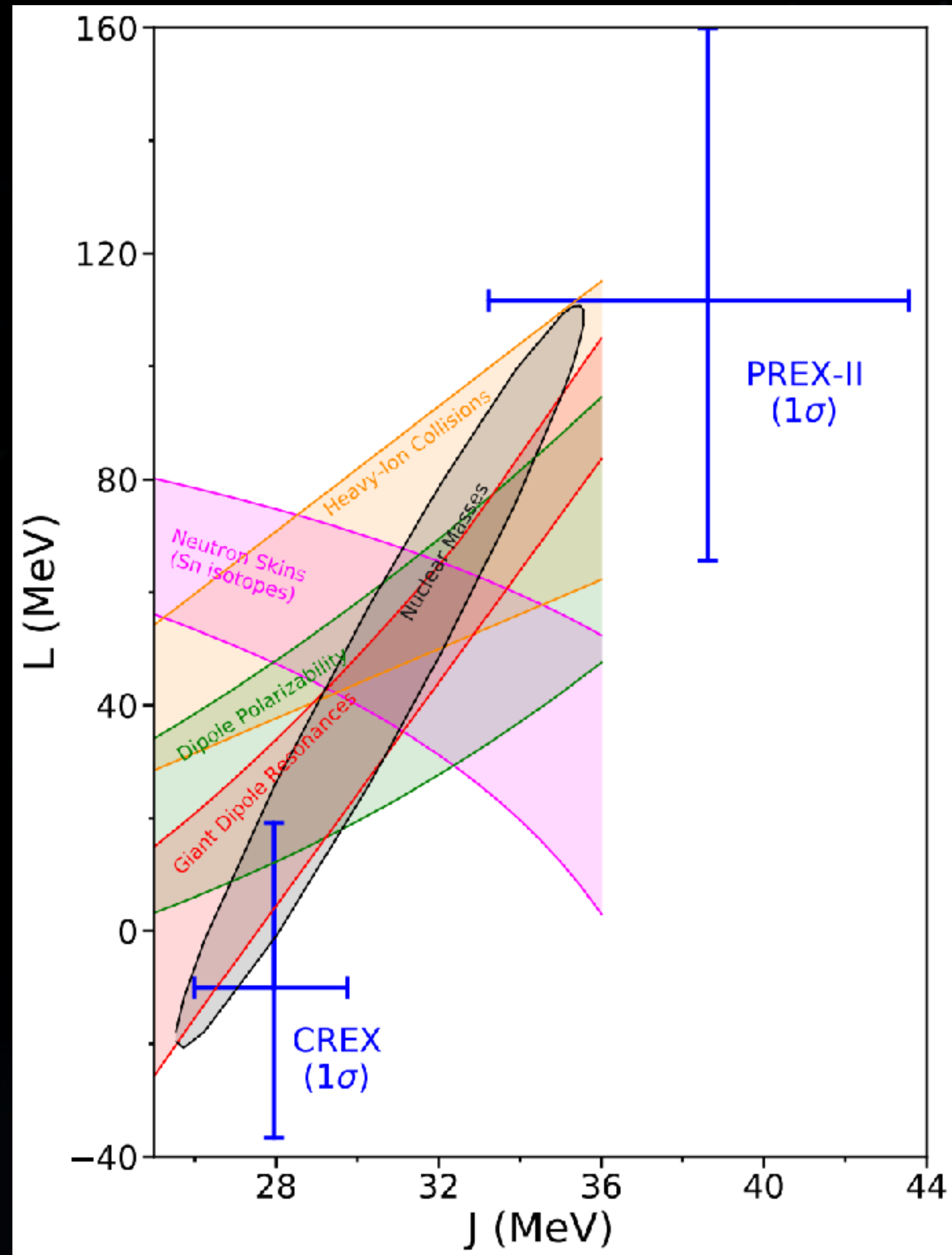
Pure Neutron Matter (PNM)

“isovector”
Nuclear Symmetry
Energy:
 $E_{\text{sym}}(n)$

Symmetric Nuclear Matter (SNM)
(Equal Protons and Neutrons)
“isoscalar”

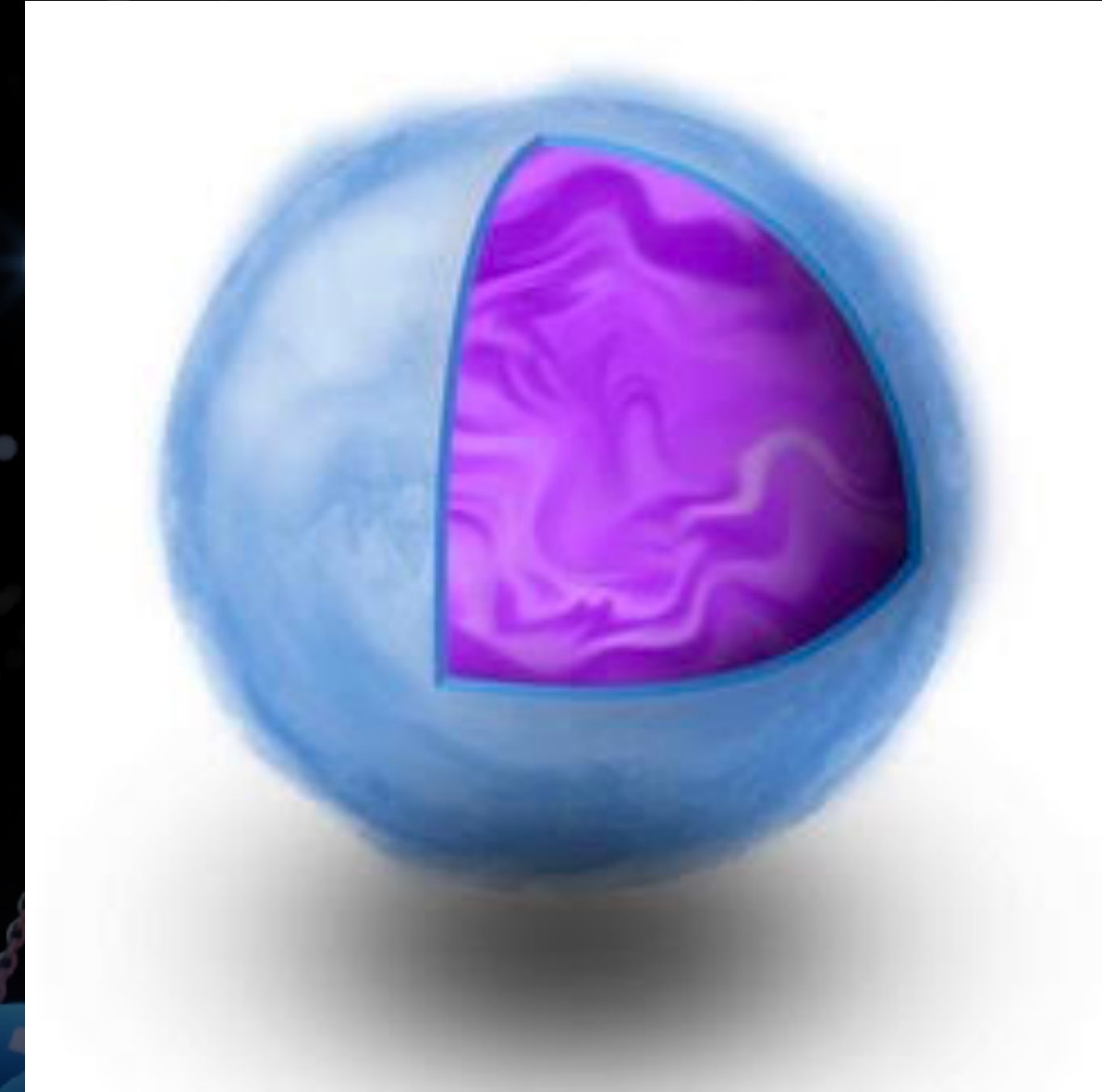


Experimental Constraints on J-L



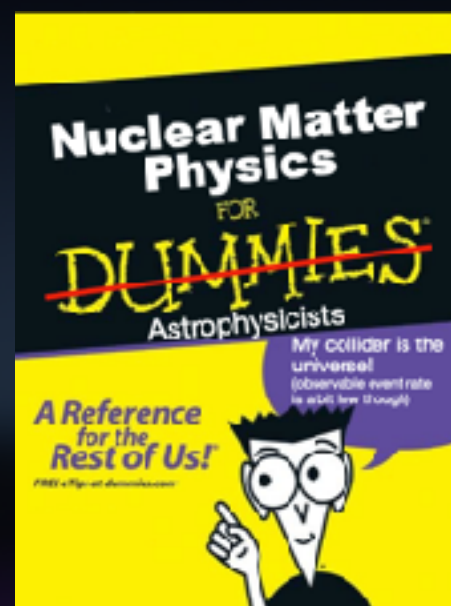
Adapted by D. Neill (2023 Thesis) from Lattimer & Lim 2013 including (Skryme dependent) J-L constraints on PREX and CREX from Zhang & Chen (2023) Phys Rev C, 108, 2, 024317

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

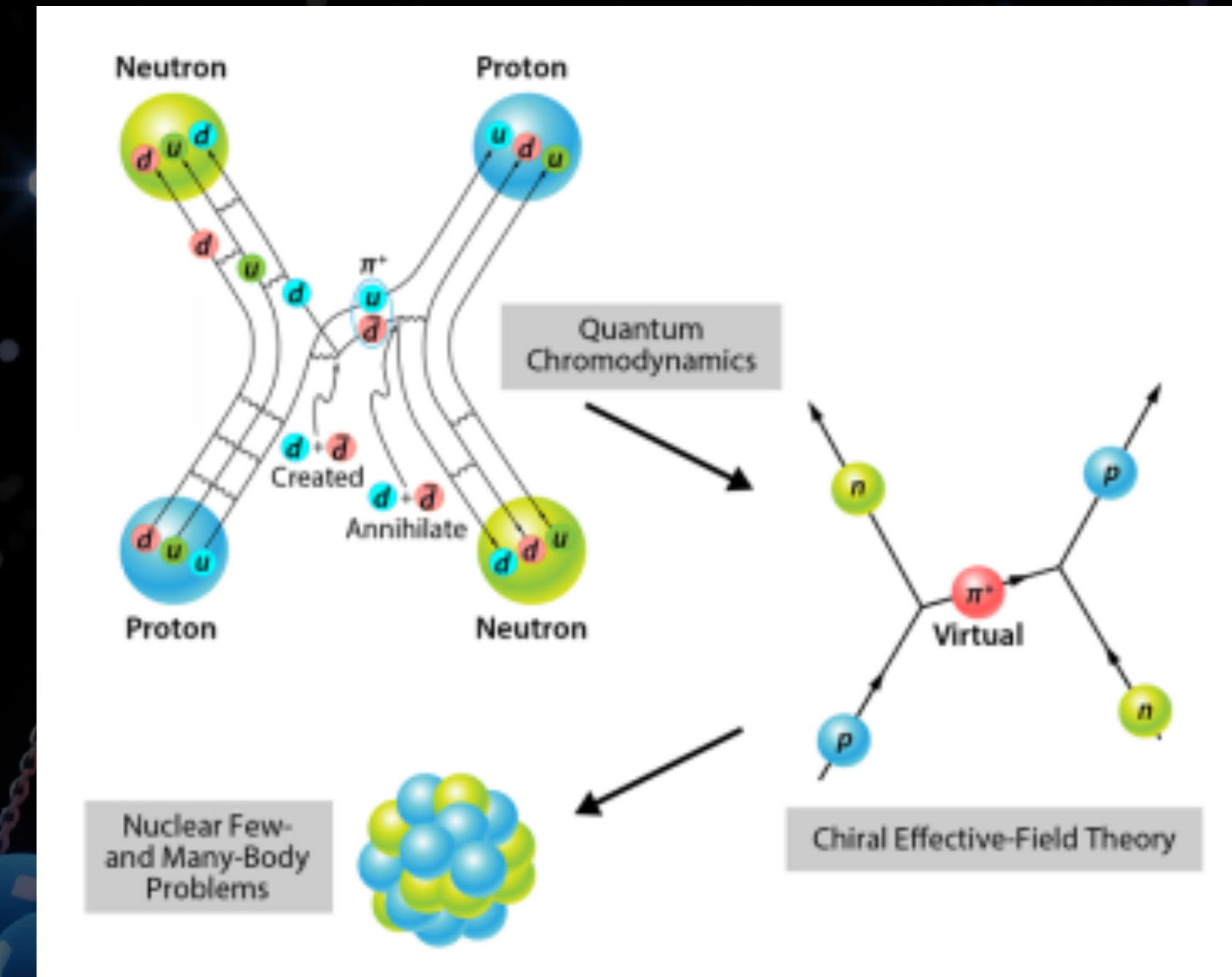
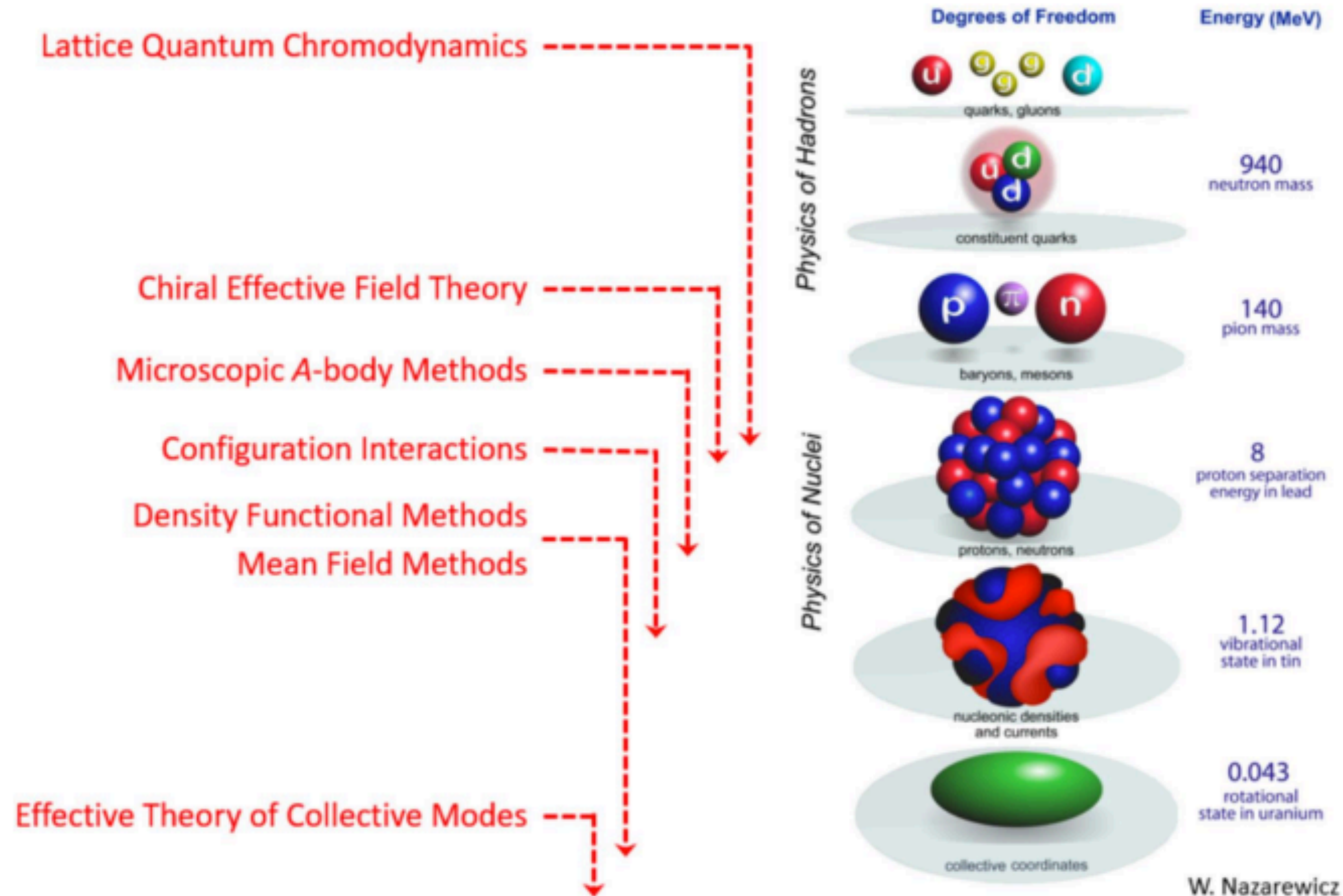


https://www.stonybrook.edu/commcms/physics/research/archive/2022/0217_neutronskin

Experimental constraints
of symmetry energy
and nucleonic physics



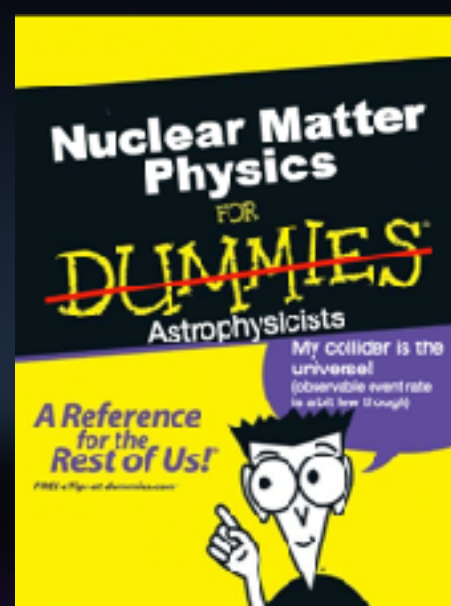
Nuclear Effective Field Theories



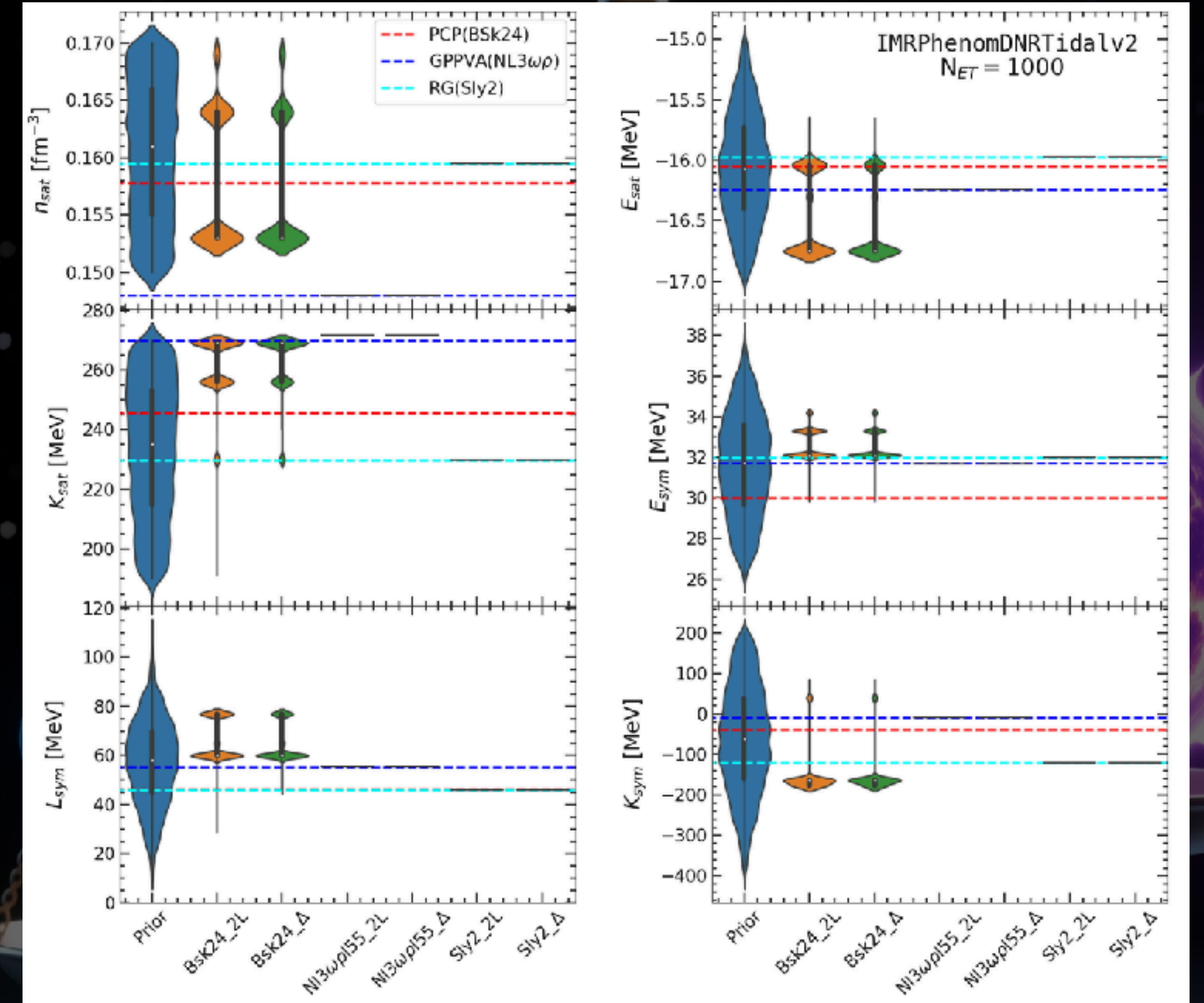
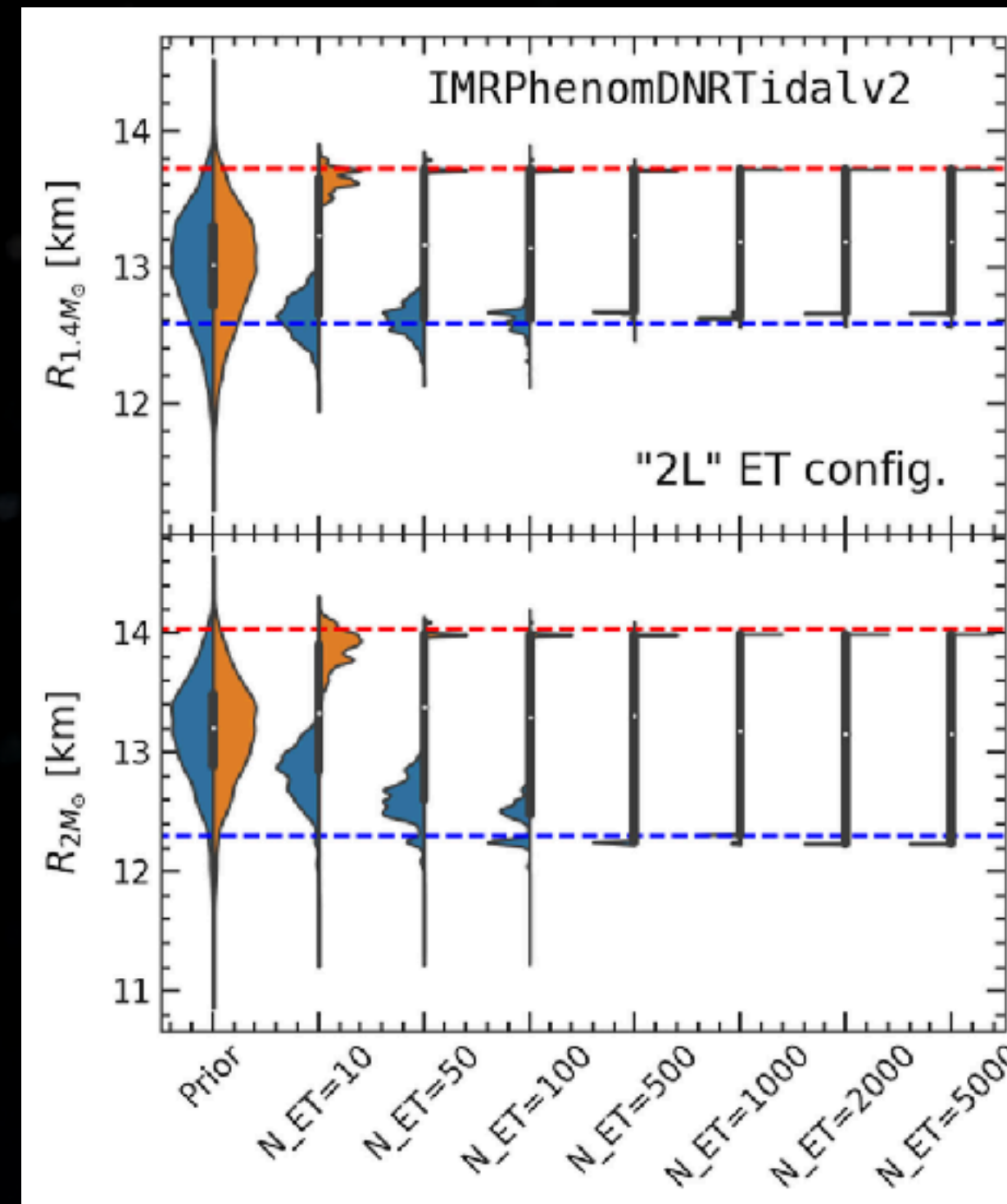
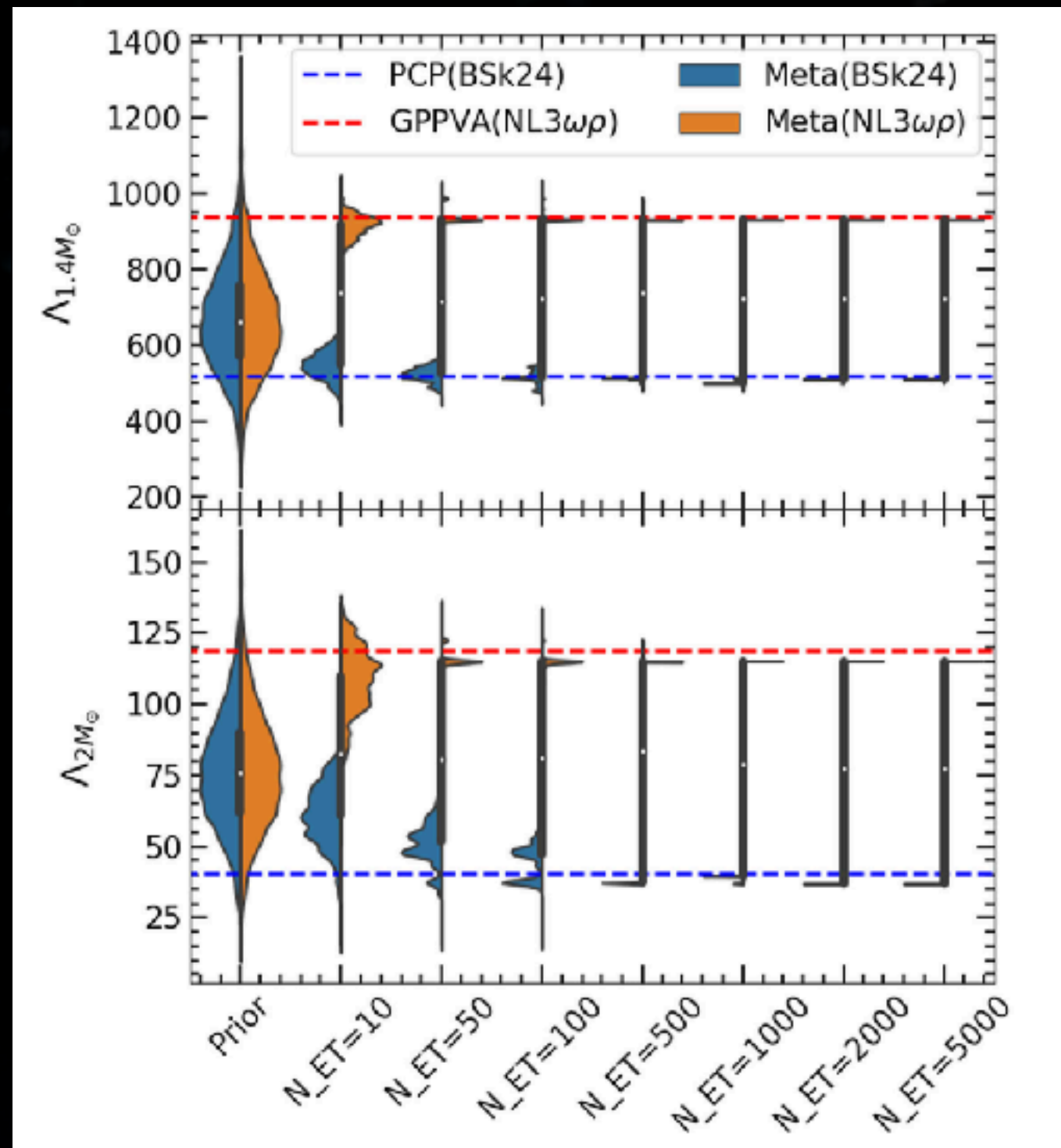
Hjorth-Jensen, Physics 10, 72, 2017 (APS/Alan Stonebraker)

Theoretical models of nuclear matter

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

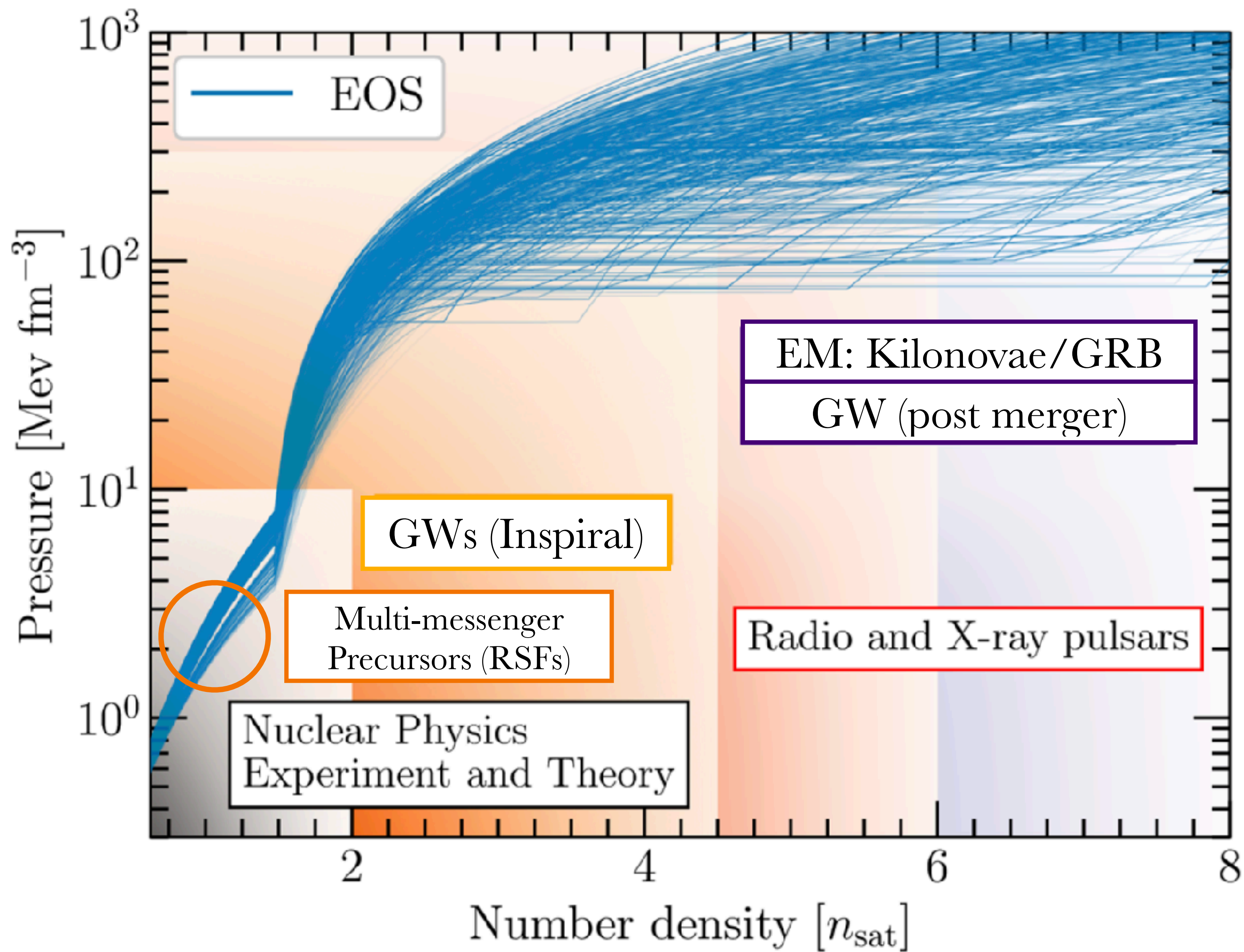


GW Bulk Observables

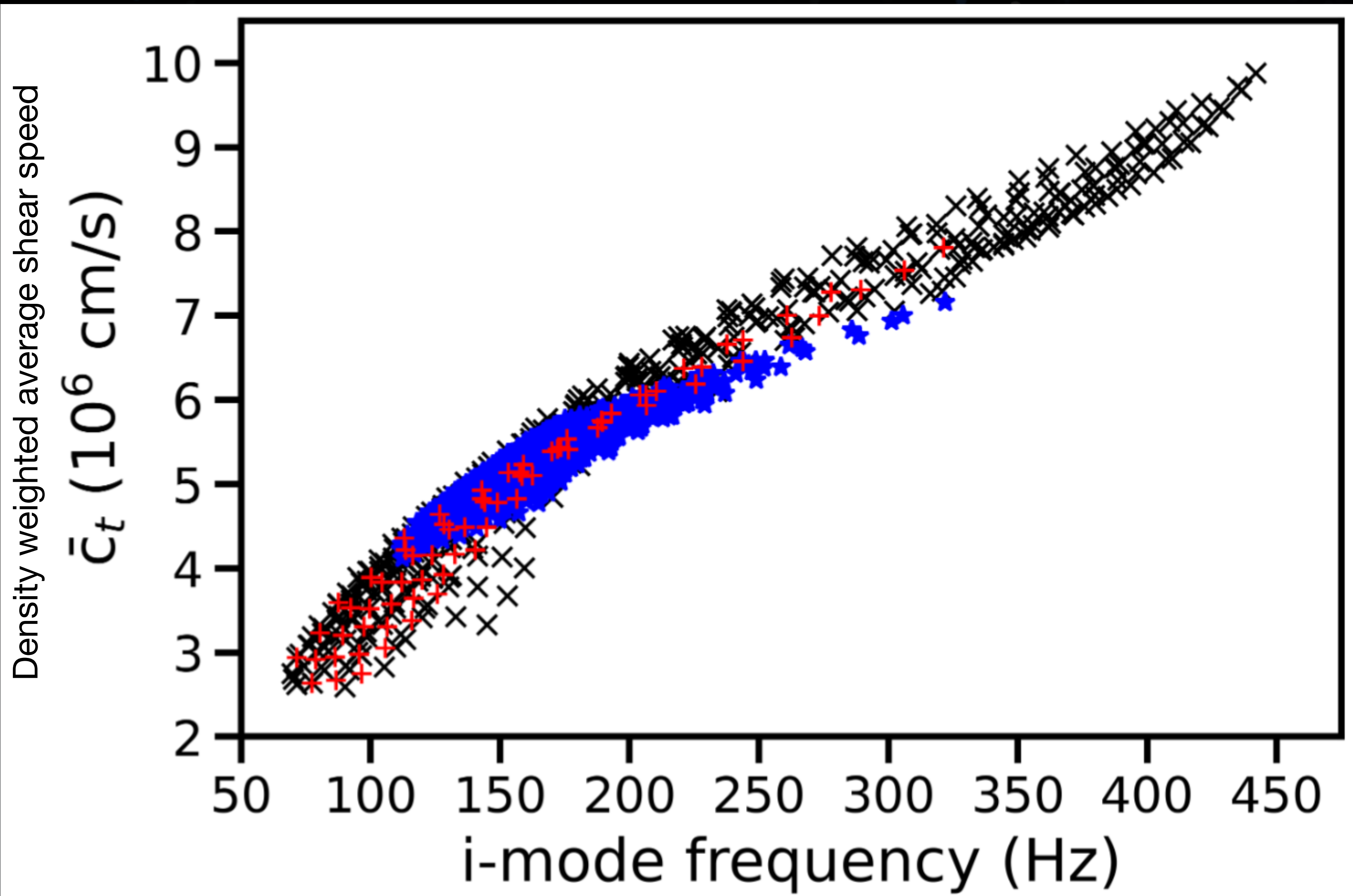


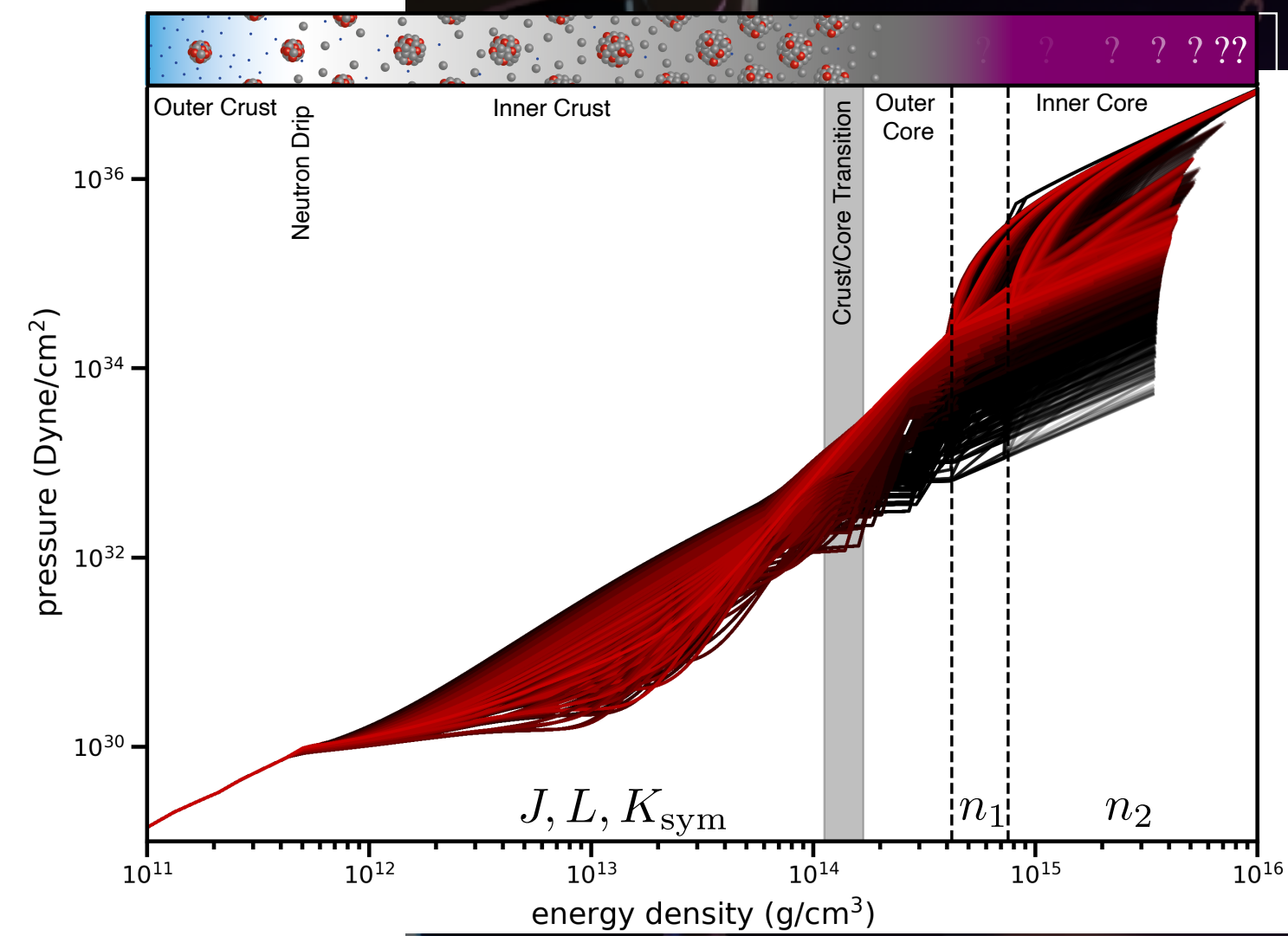
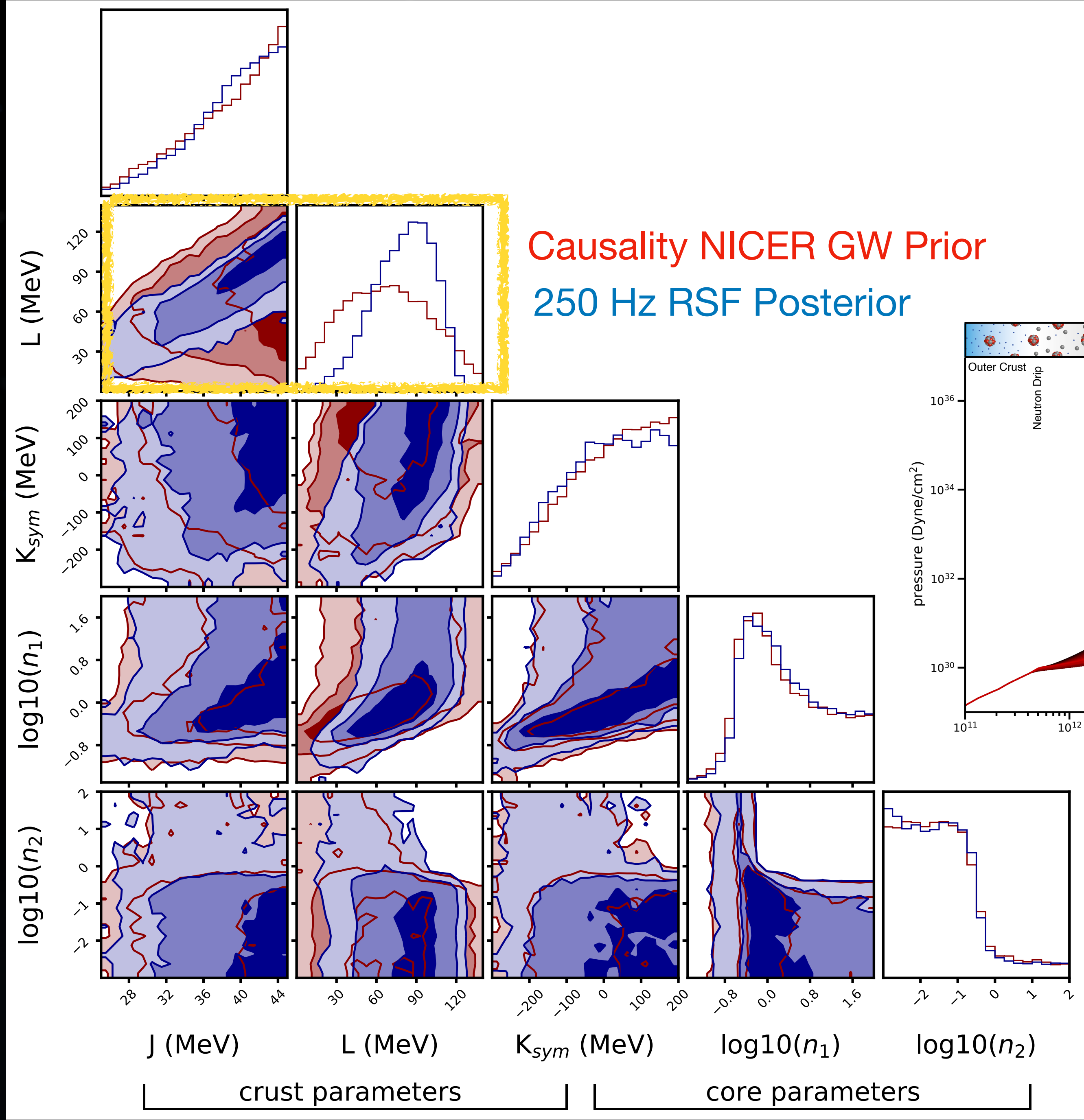
If you assume the entire star is nucleonic then constraints can be placed on the radius and isovector/isoscalar parameters from the GW tidal deformability, particularly with the next gen observatories. However, this isn't necessarily a good assumption.

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

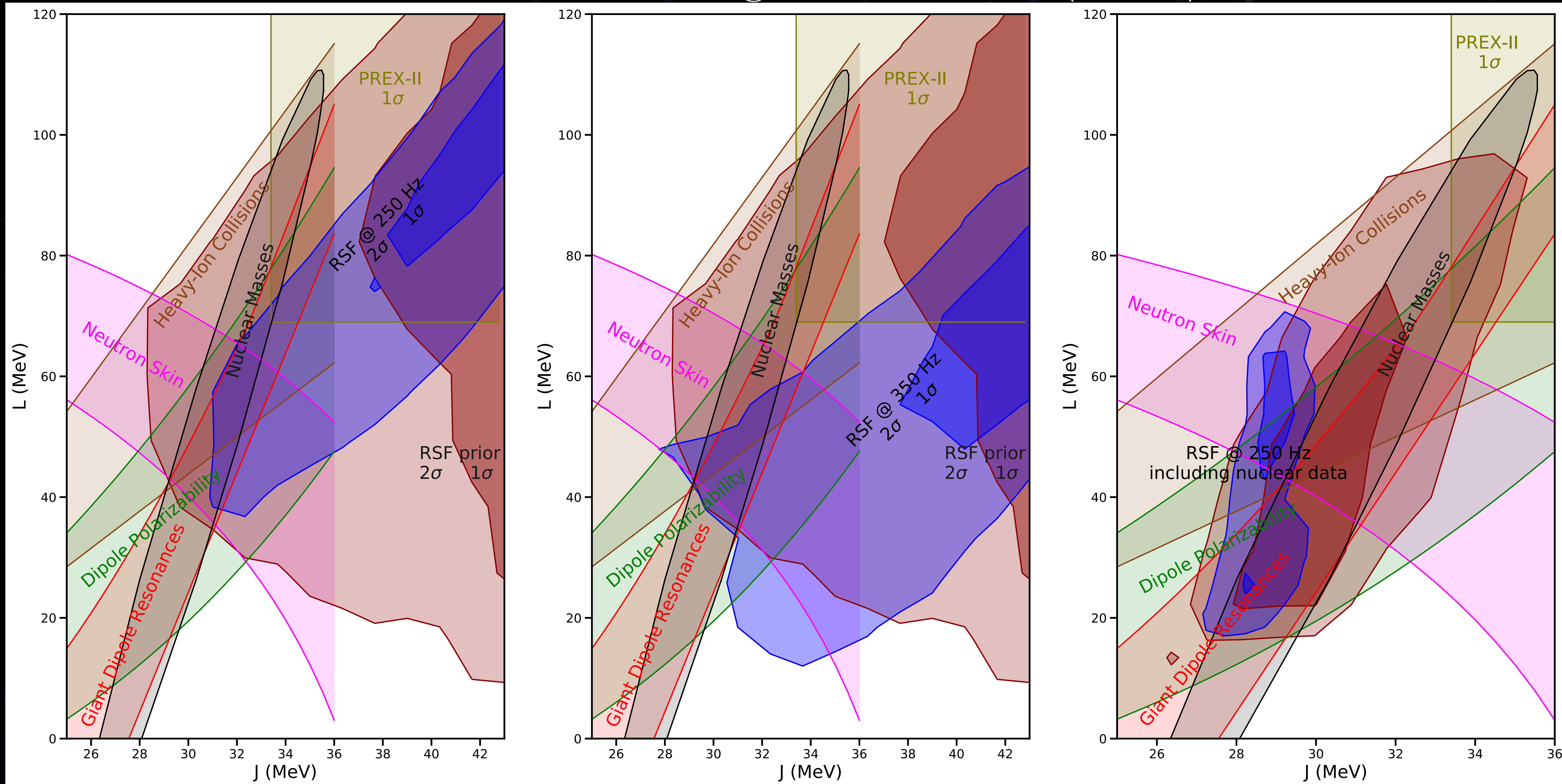


Multi-messenger Precursors (RSFs)





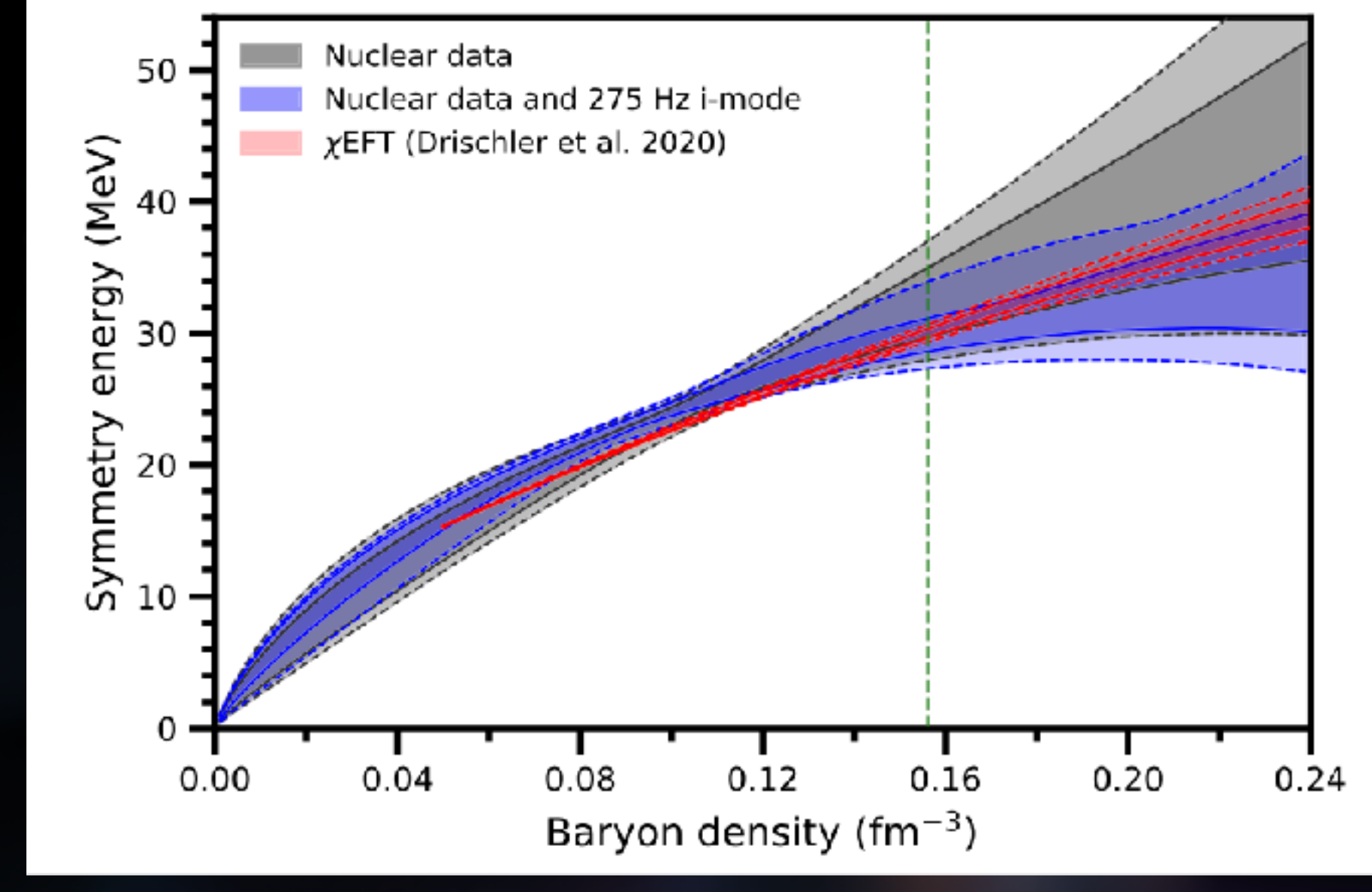
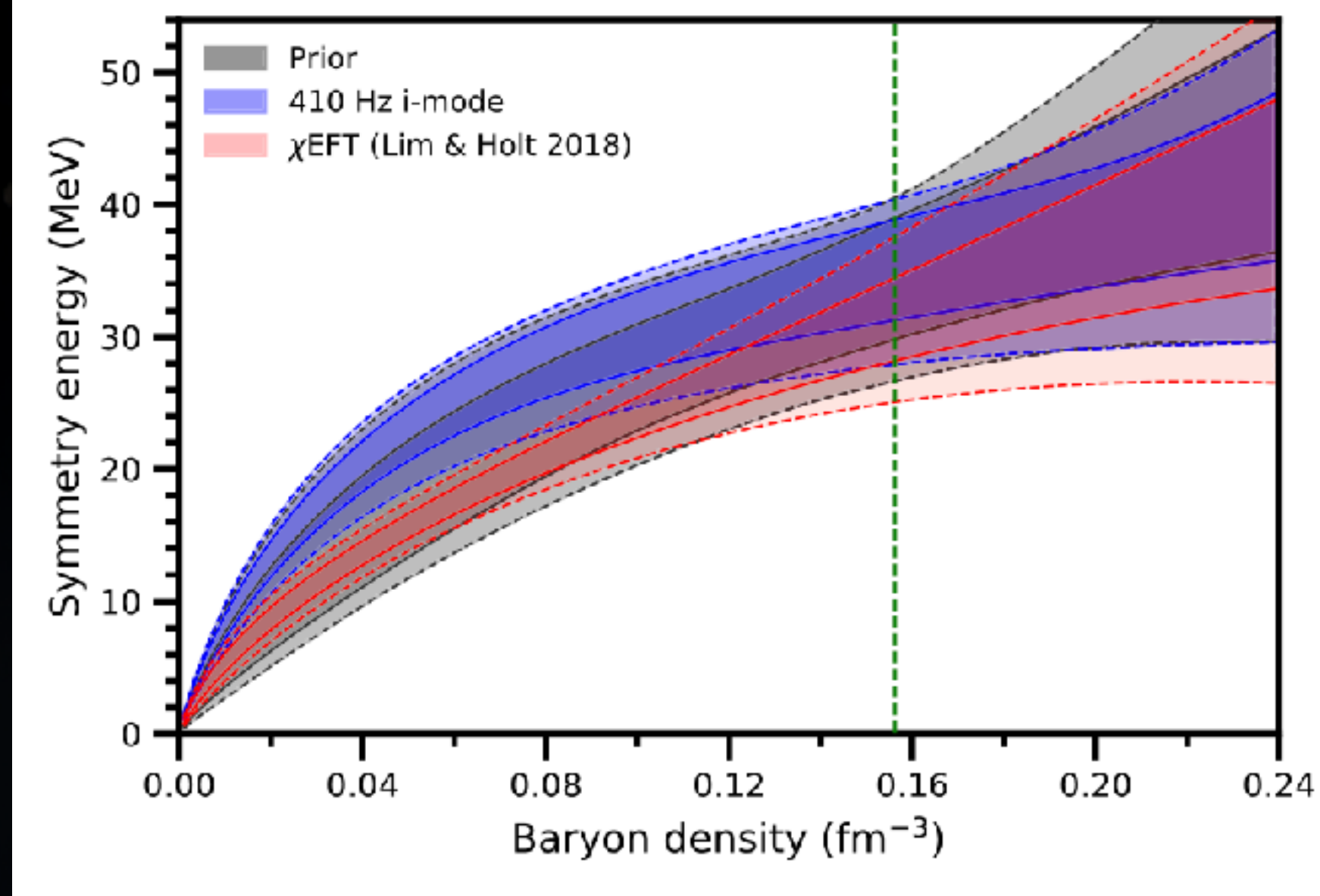
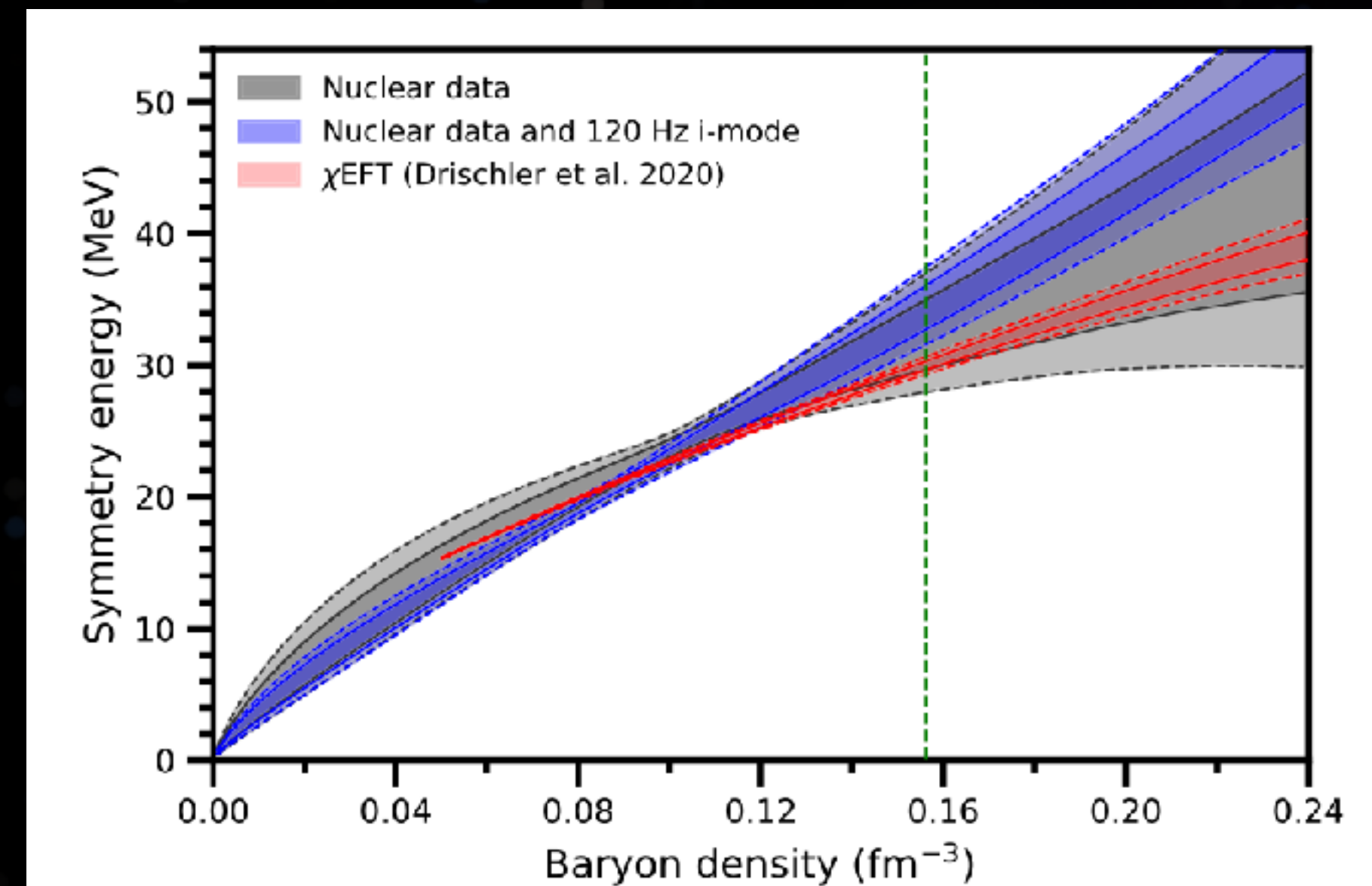
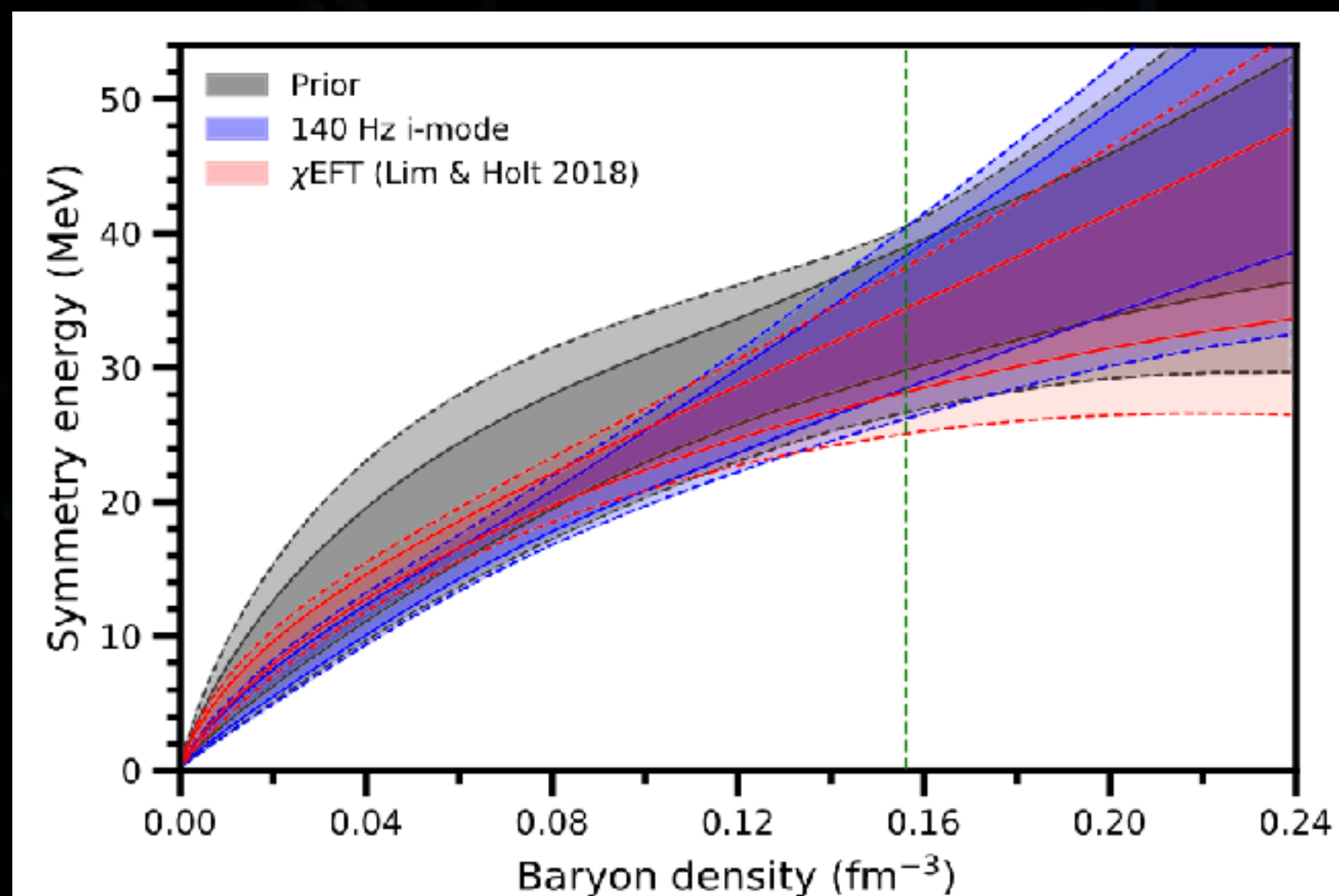
Multi-messenger Precursors (RSFs)



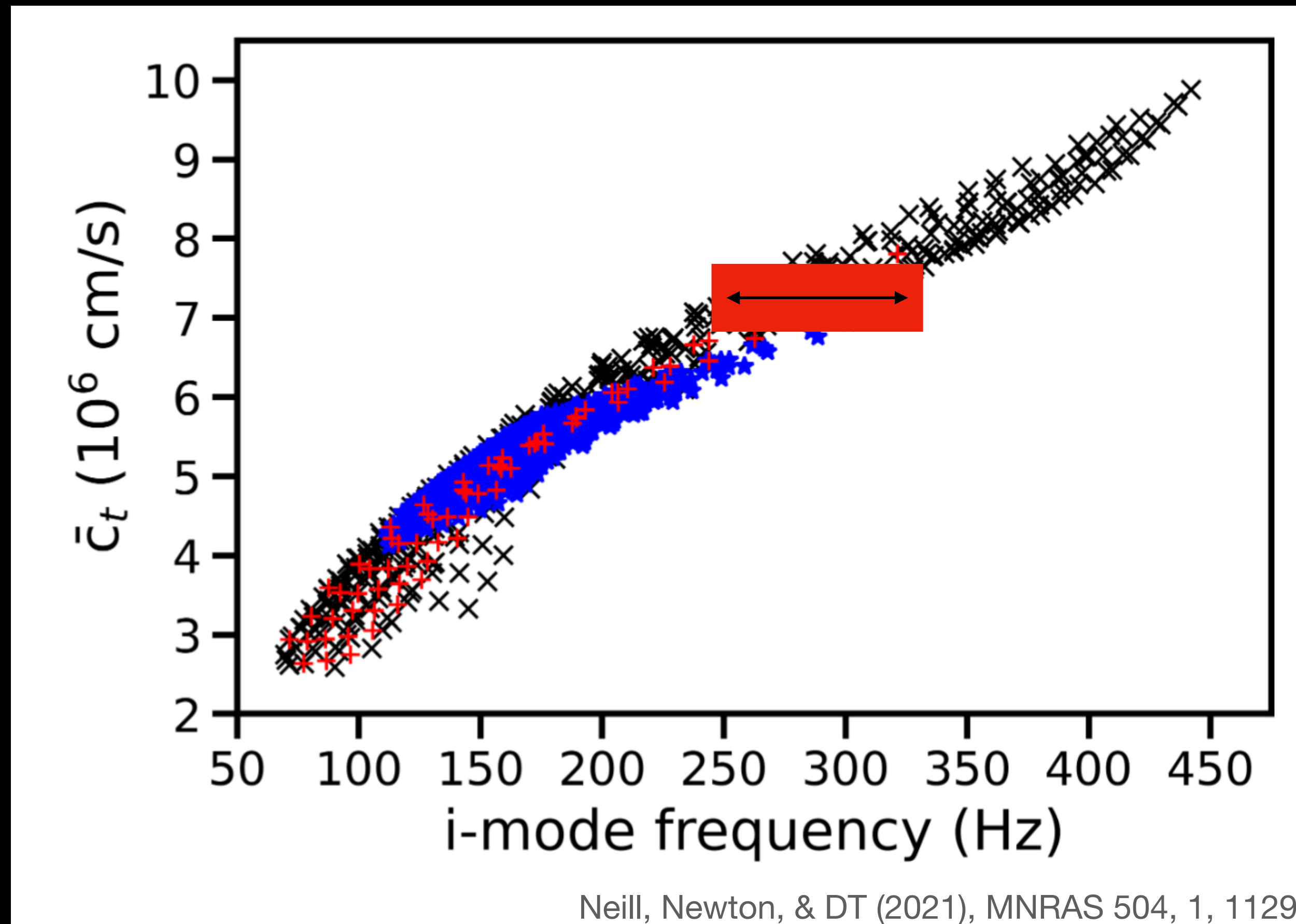
Neill, Preston, Newton & DT (2023), PRL, 130, 112701

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

Testing Chiral Effective Field Theory with RSFs



But wait!

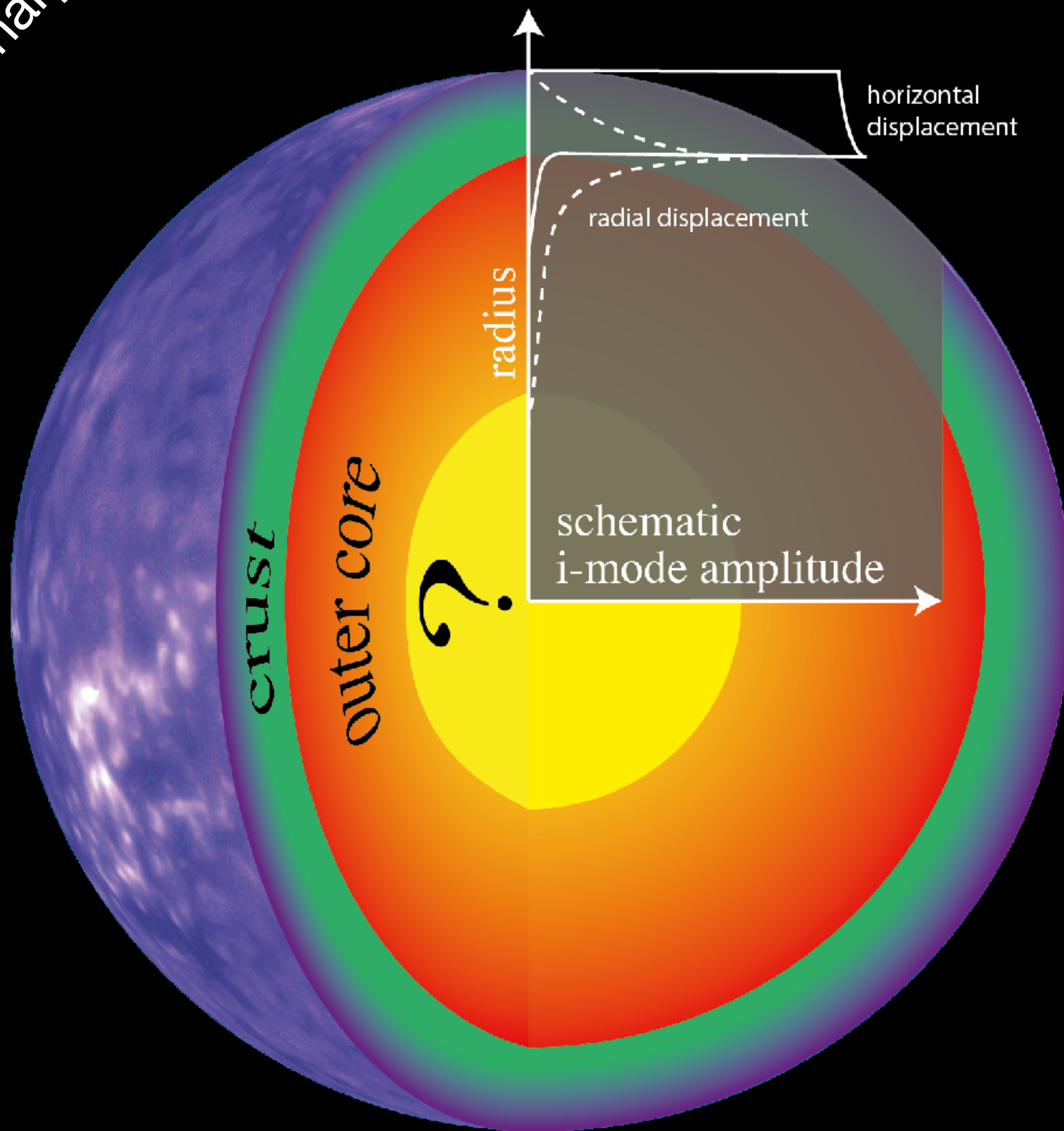


If we fix the crust/outer core physics...

What determines the spread of i-mode frequencies?

Preliminary

What determines the spread of i-mode frequencies?



frequency
fit
including

NS mass

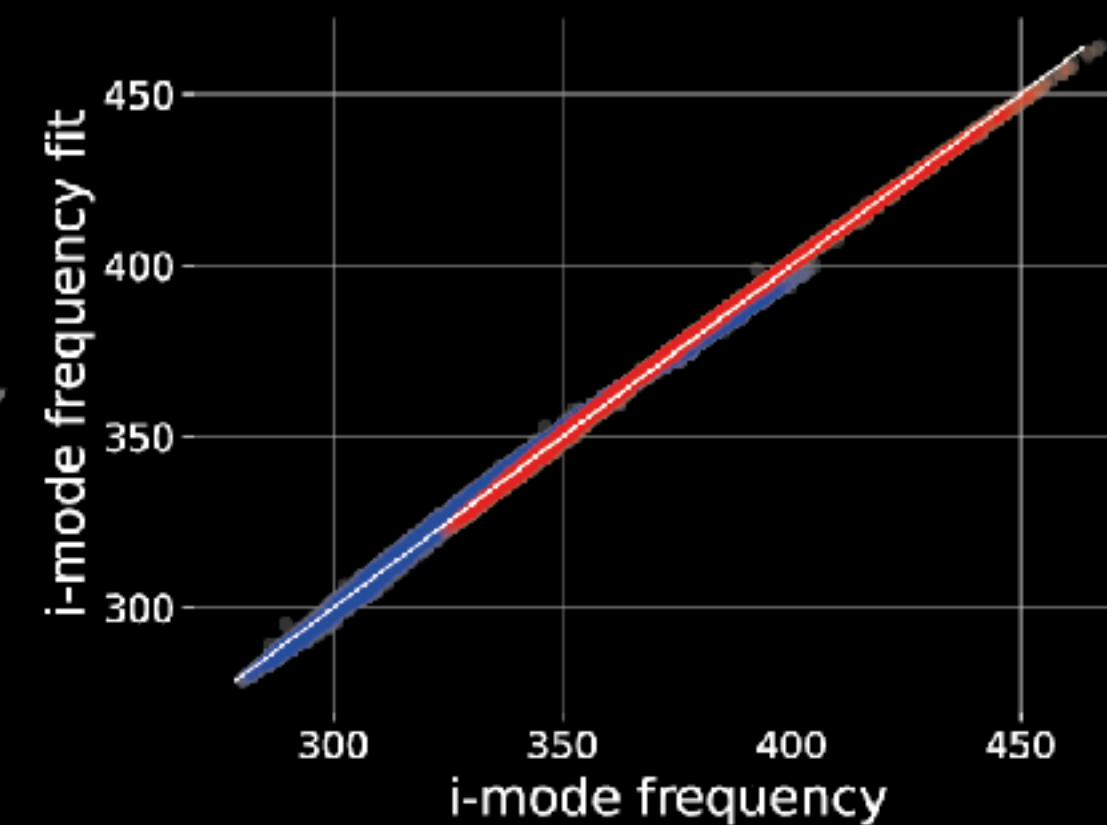
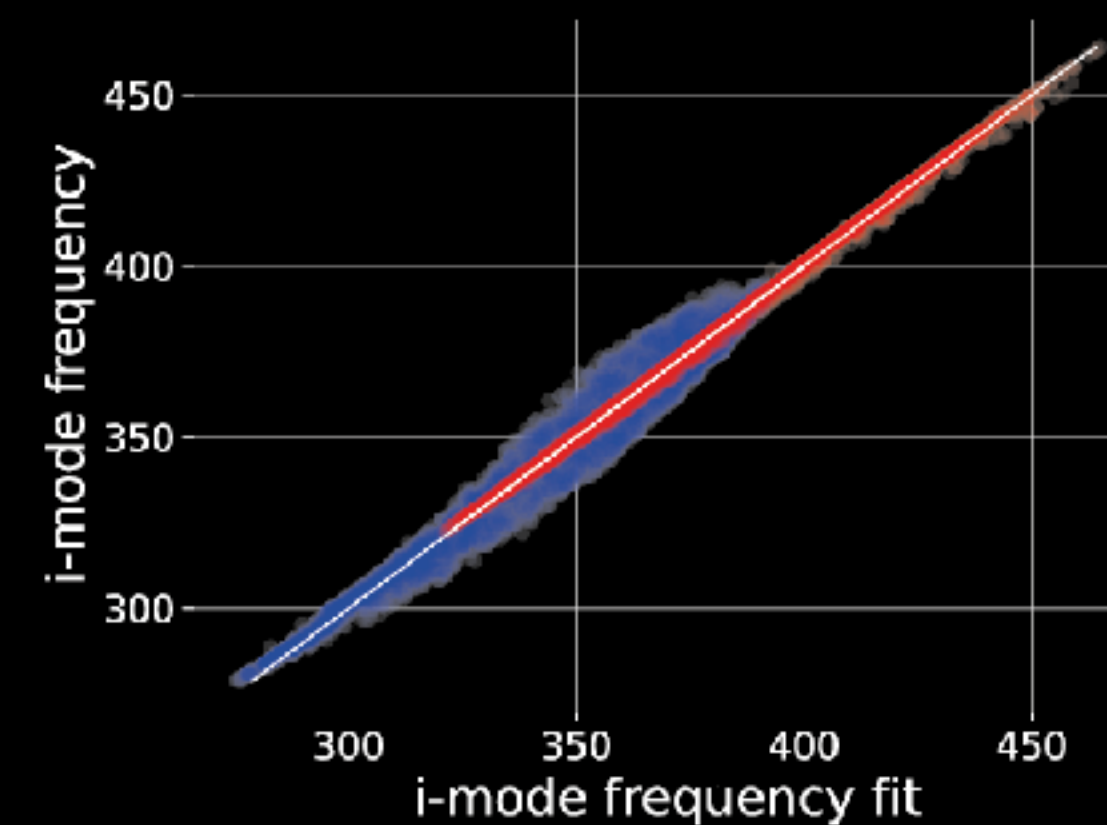
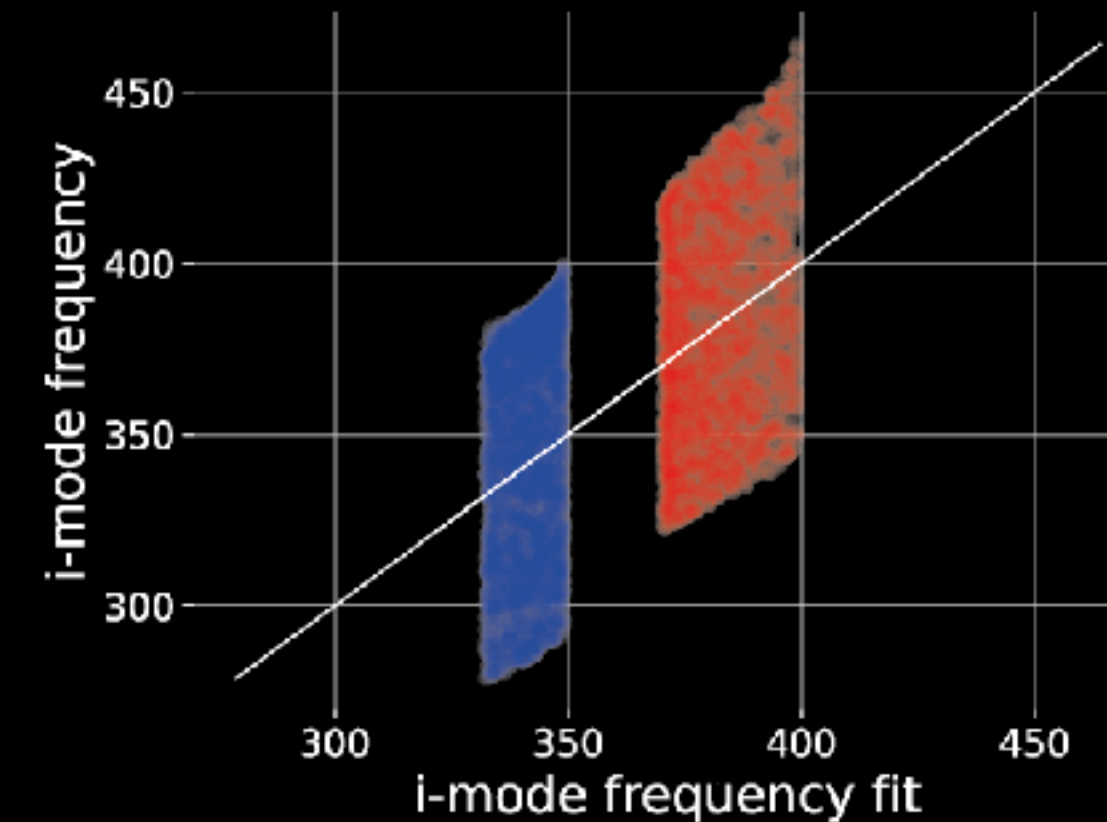
+

NS radius

+

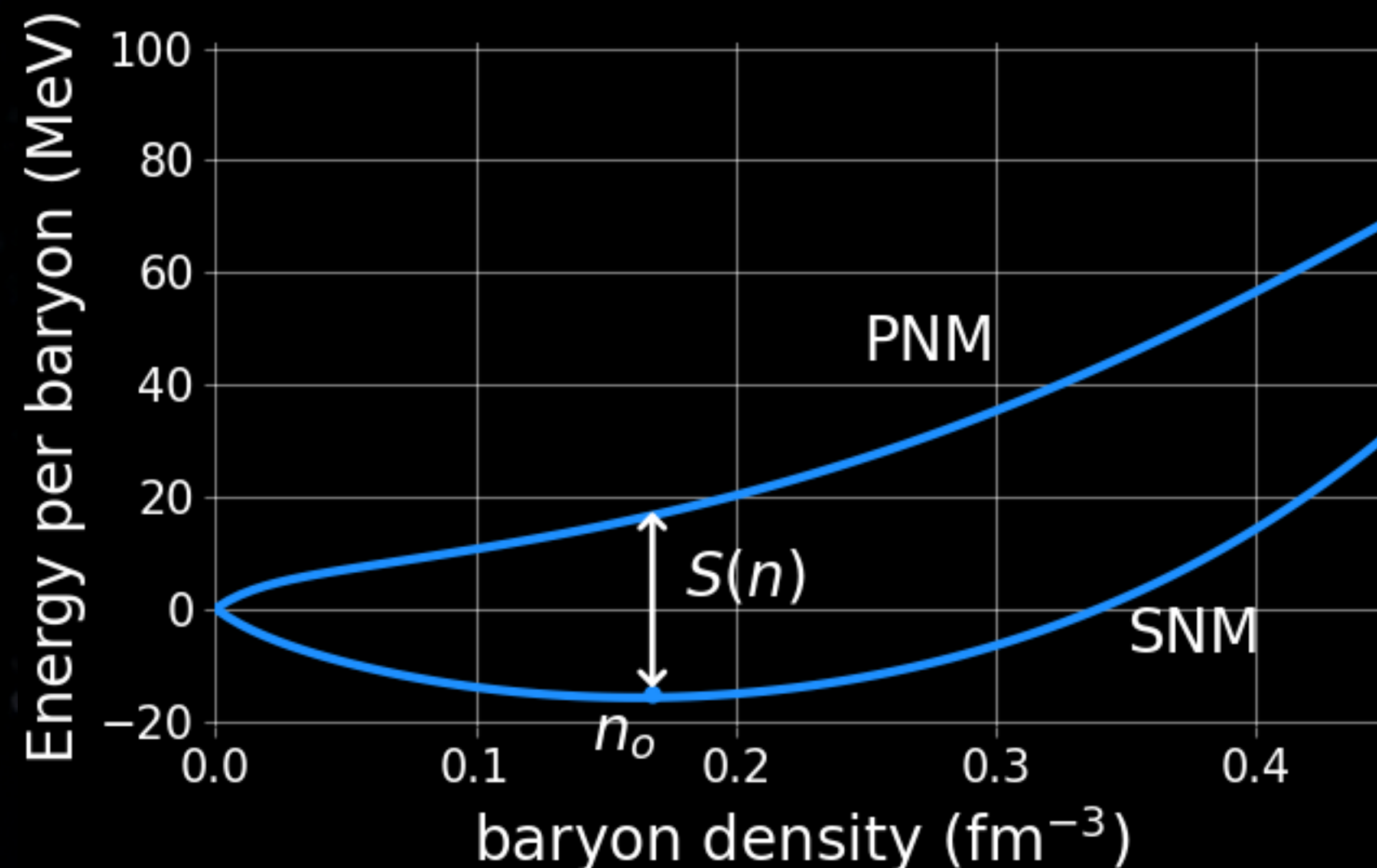
average
bouyancy

fixing nucleonic
(low density) physics

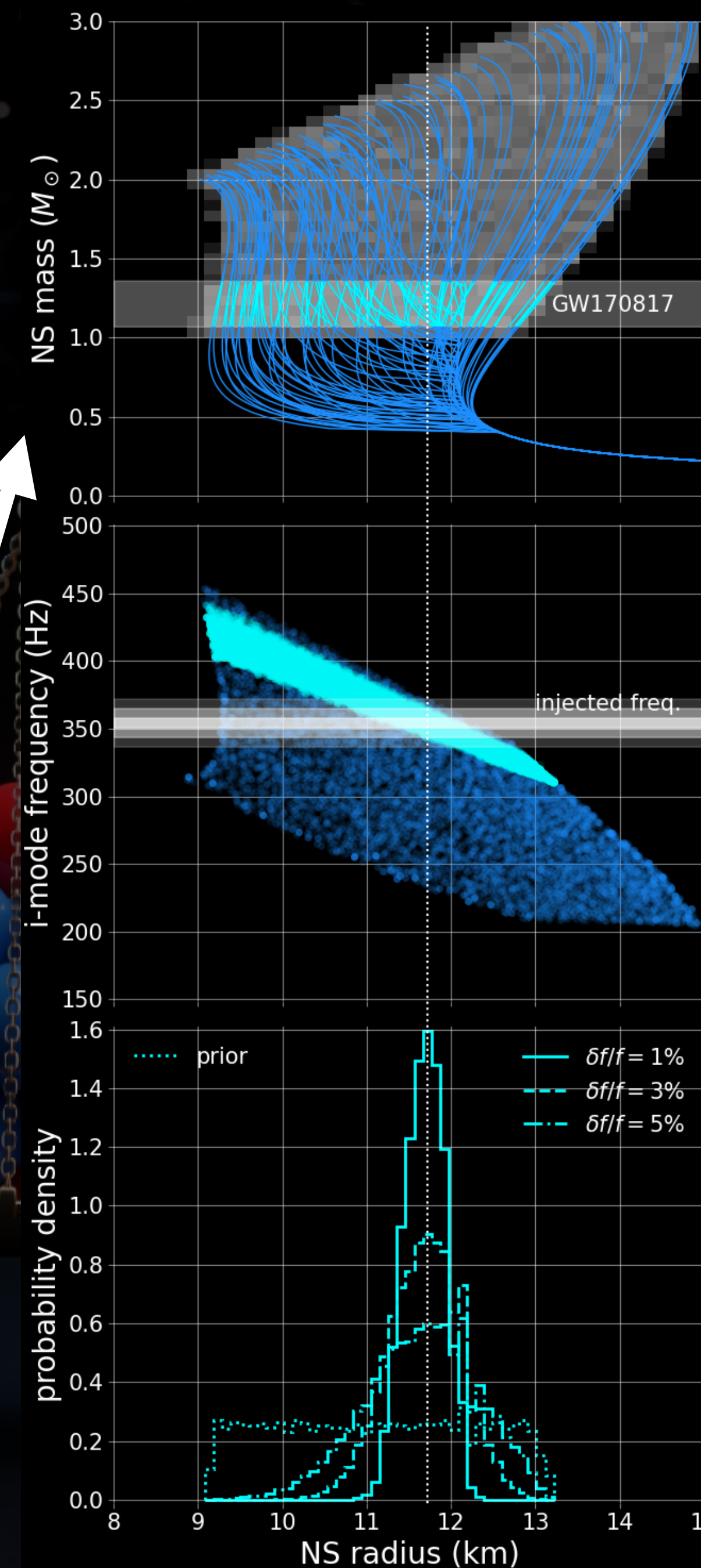


Preliminary

Fixed Nucleonic Physics



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 $(n_{\text{PT}}, \Delta n_{\text{PT}}, c_s^2, dc_s^2/dn)$ for spread in M-R plane.



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

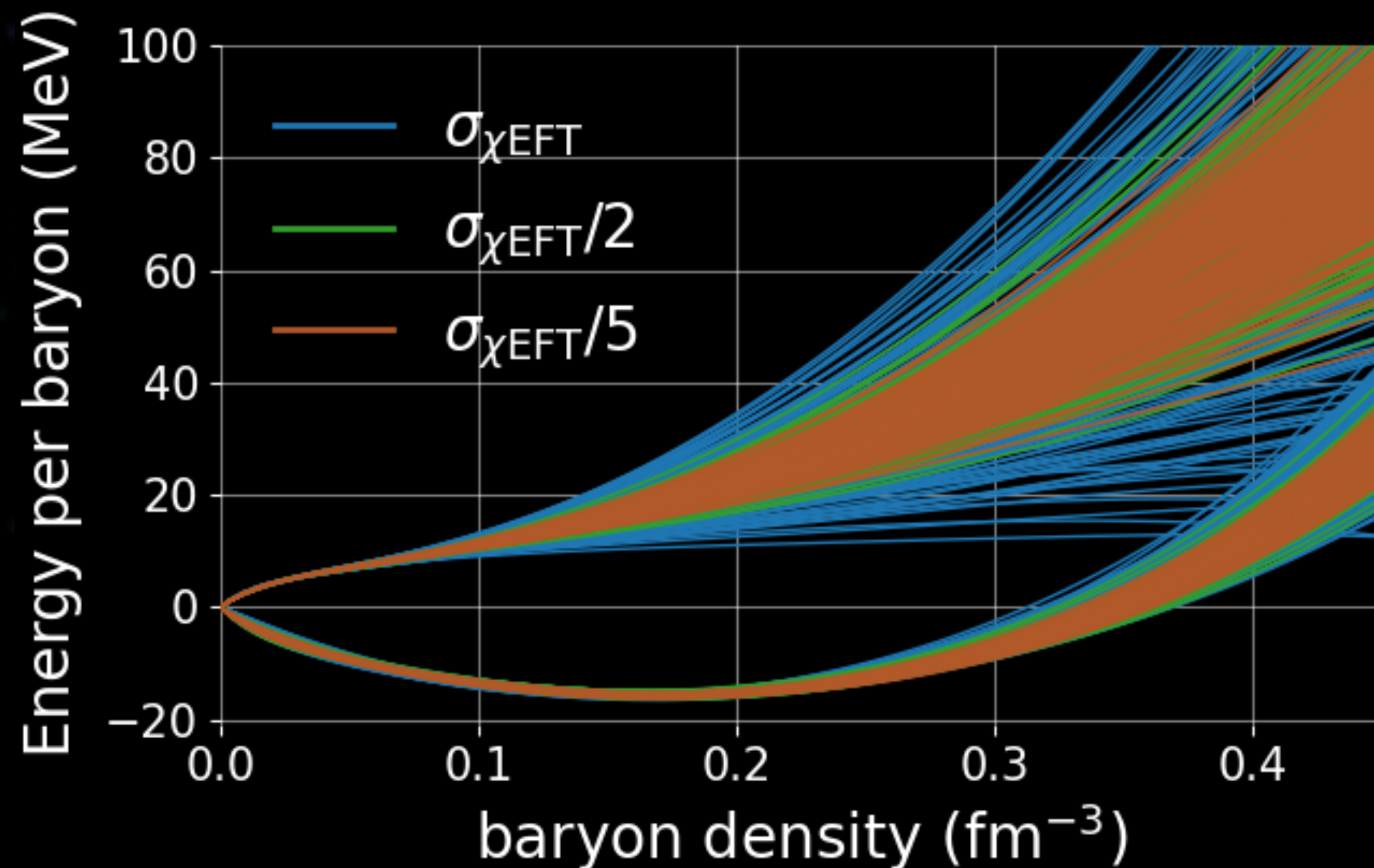
Inject mass data taken to be consistent with GW170817

Injected i-mode frequency with different uncertainties

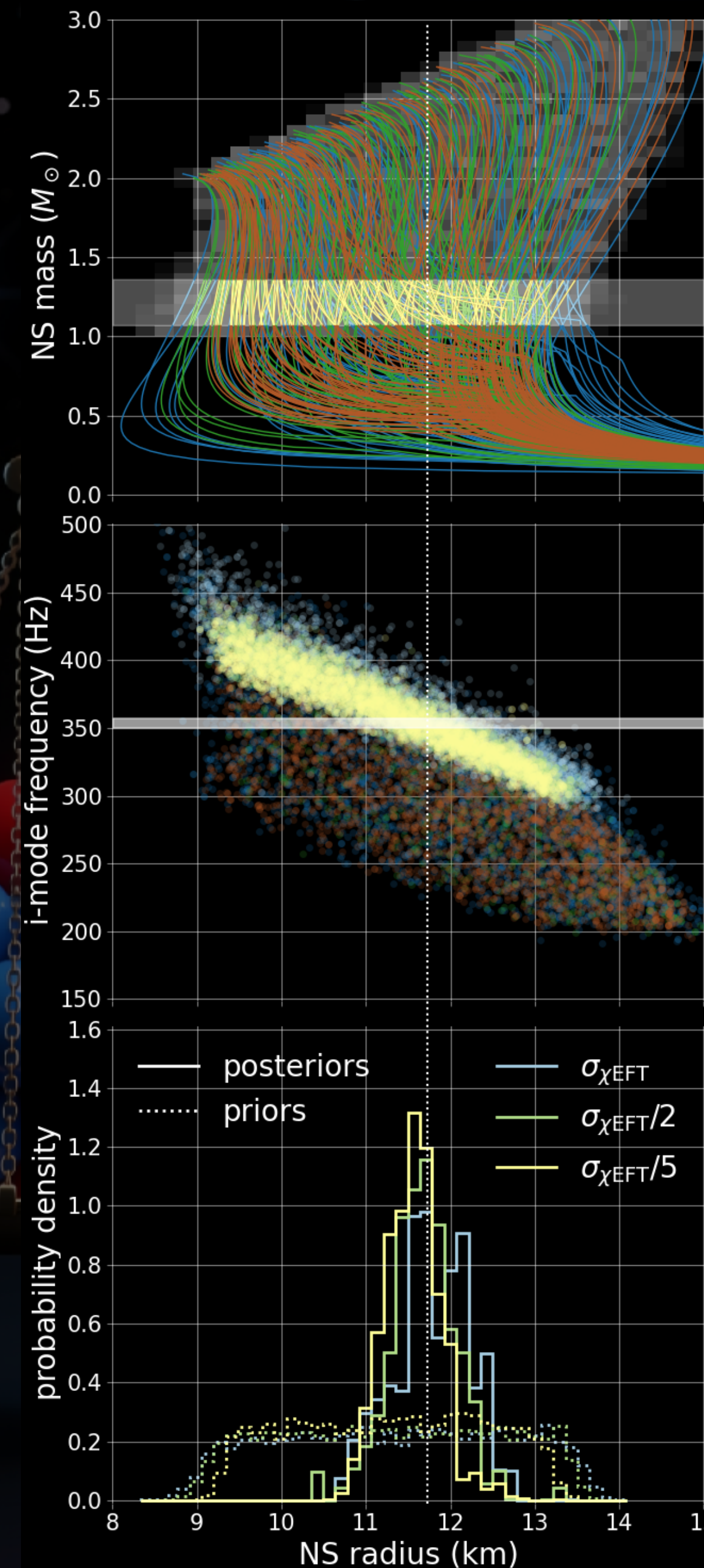
Geometric radius measurement with precision down to $\sim \pm 0.5 \text{ km}$

Preliminary

χ EFT Nucleonic Physics



Same as before, but allowing nucleonic model to vary with uncertainty range consistent with χ EFT 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 1-3 M_{sun}

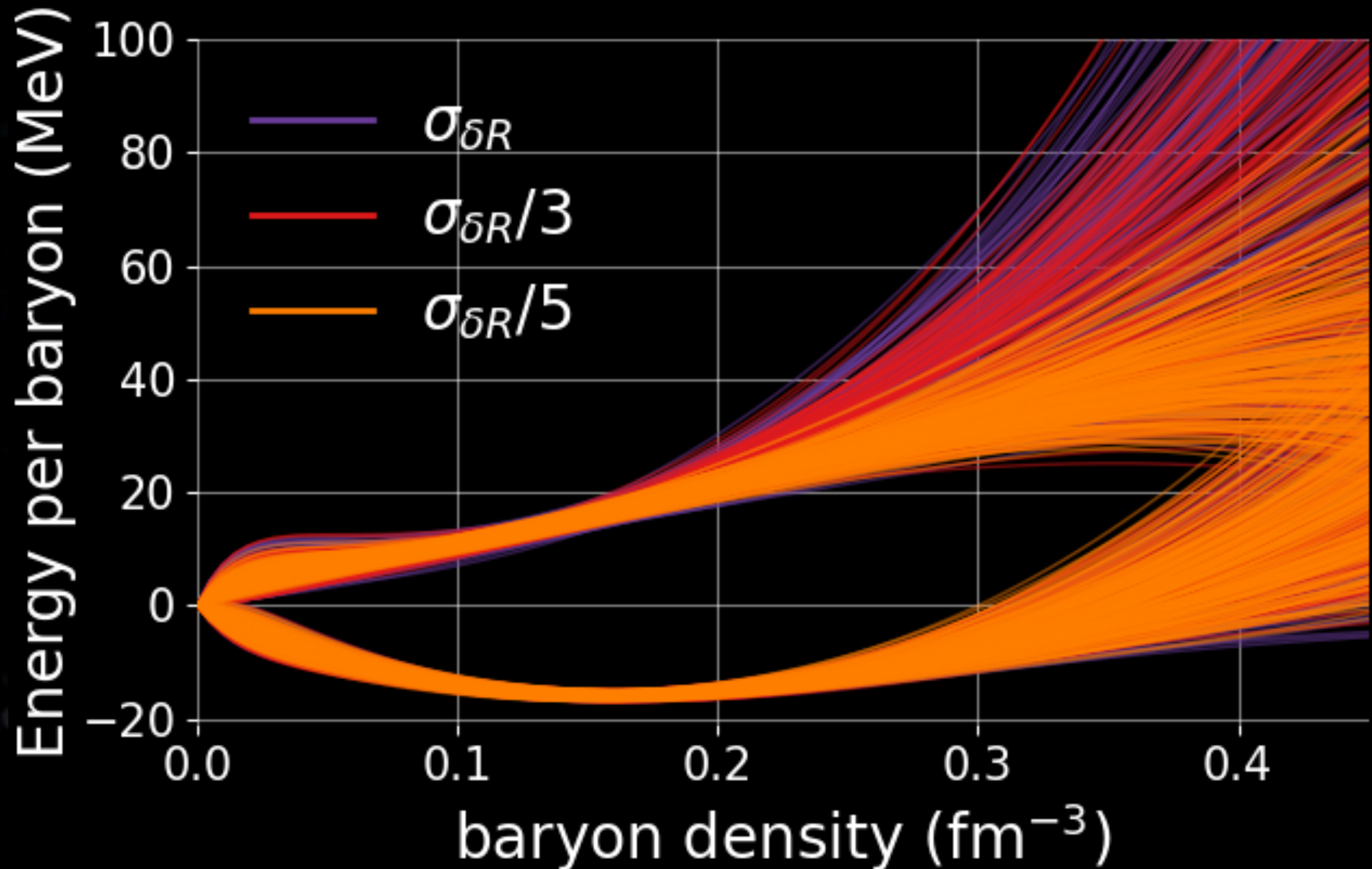
Inject mass data taken to be consistent with GW170817

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

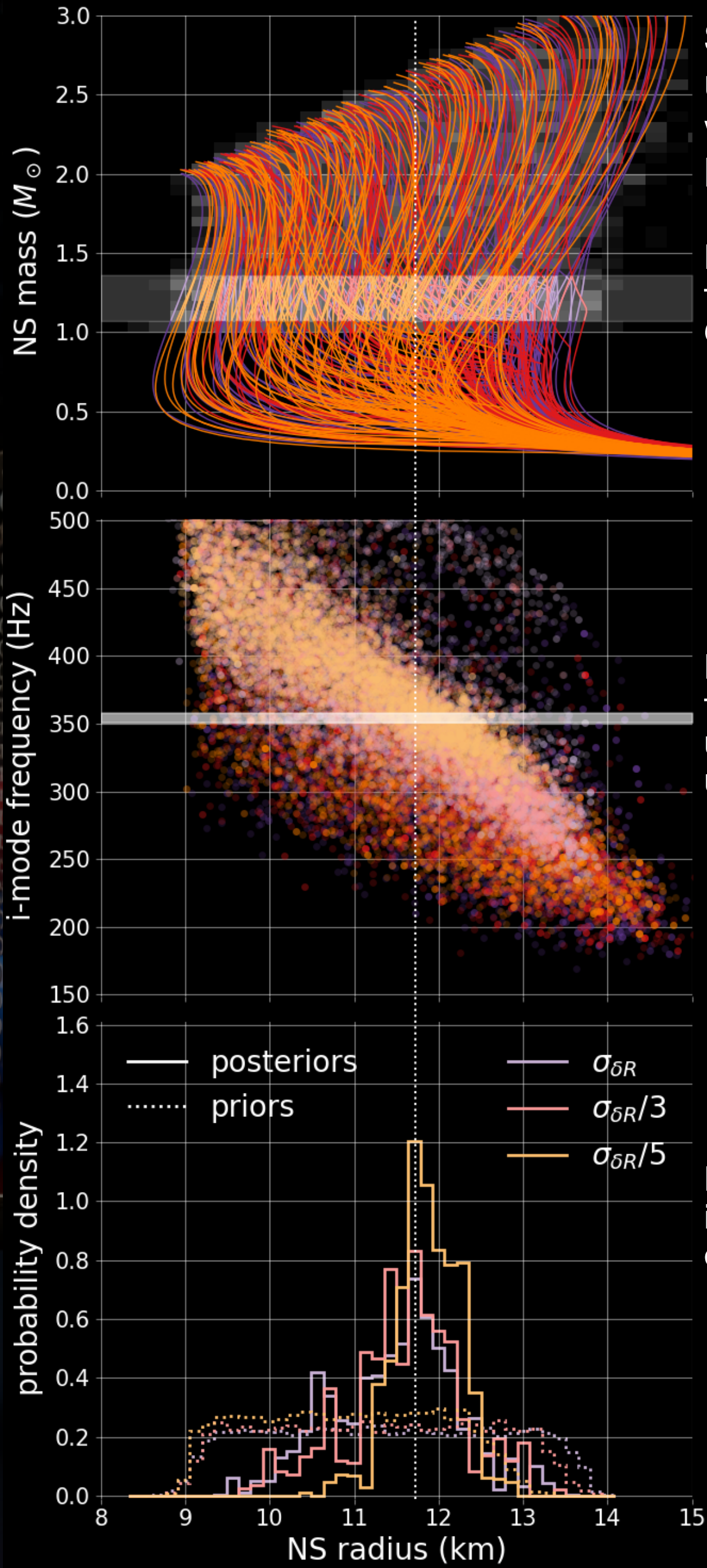
Radius precision improves with better theoretical constraints

Preliminary

Experimental Nucleonic Constraints



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



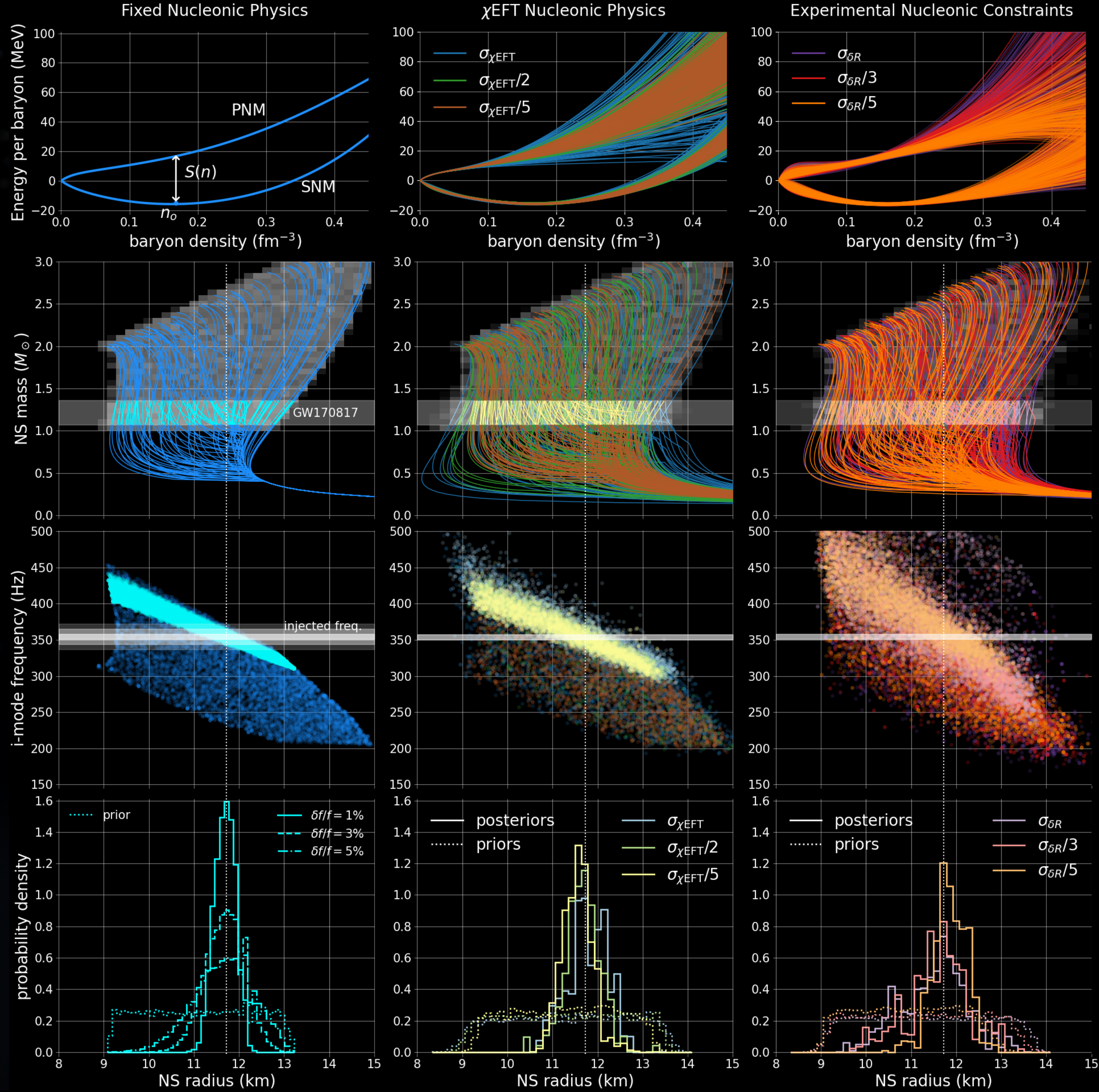
Sampled with uniform prior in M-R within masses between 1-3 M_{sun}

Inject mass data taken to be consistent with GW170817

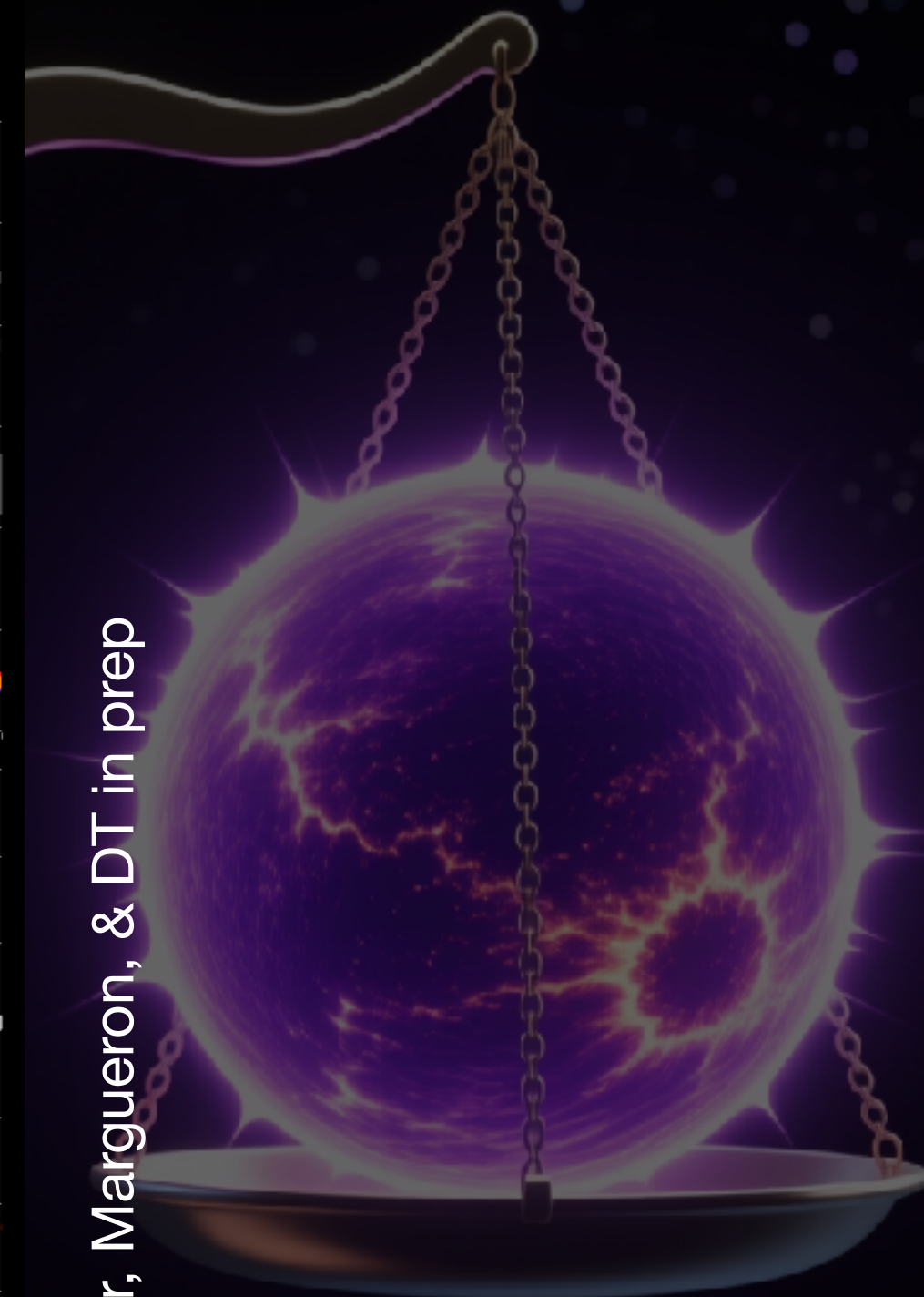
Injected i-mode frequency with 1% uncertainty (mostly mass uncertainty dominated)

Radius precision improves with better experimental constraints

Preliminary



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

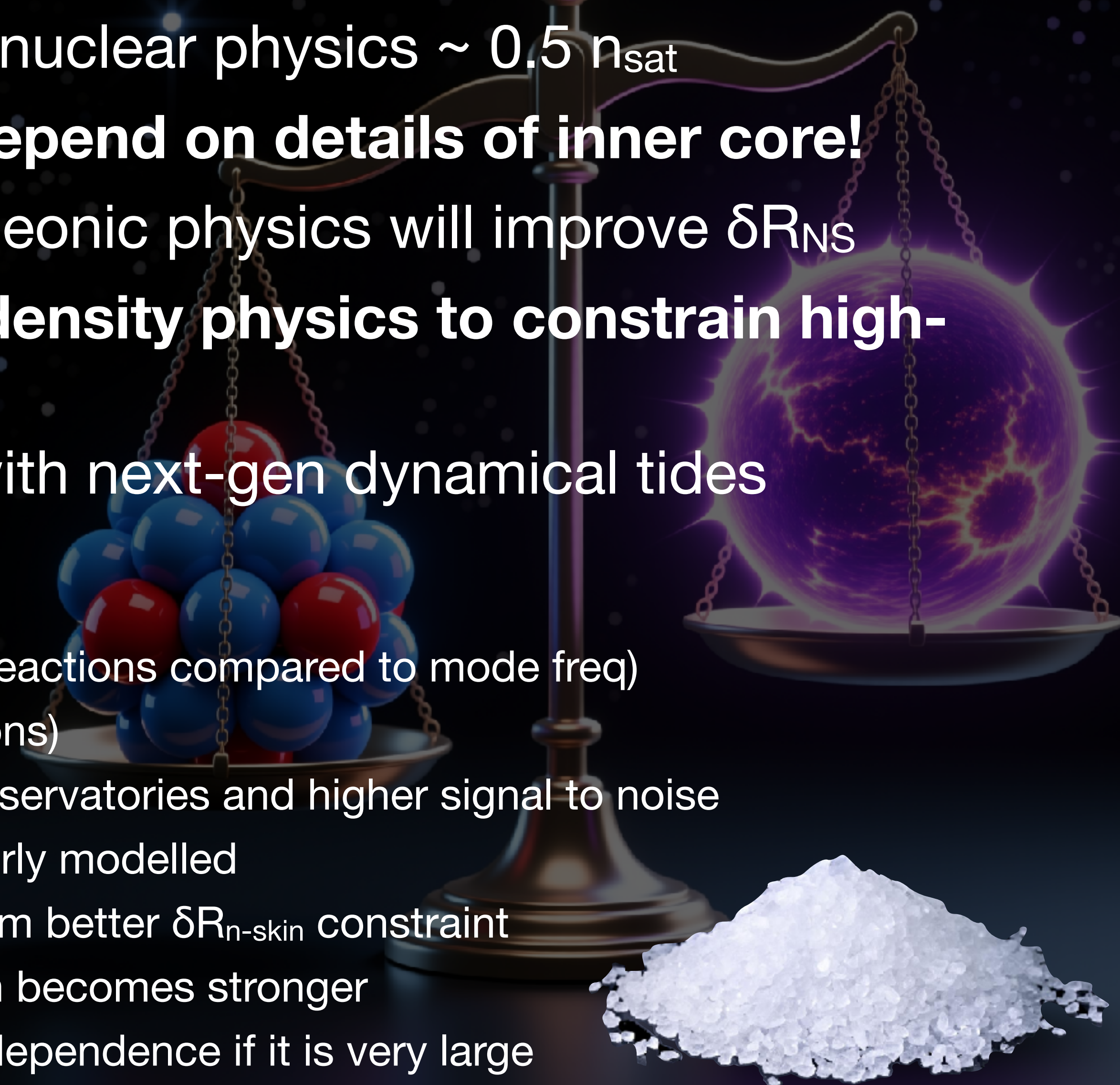


Geometric Radius from the i-mode

- Different observables probe different regions, inner core is uncertain physics
- i-mode probes crust-core transition region, nuclear physics $\sim 0.5 n_{\text{sat}}$
- 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 constrain high-density physics**
- i-mode detectable with RSFs (this gen) or with next-gen dynamical tides

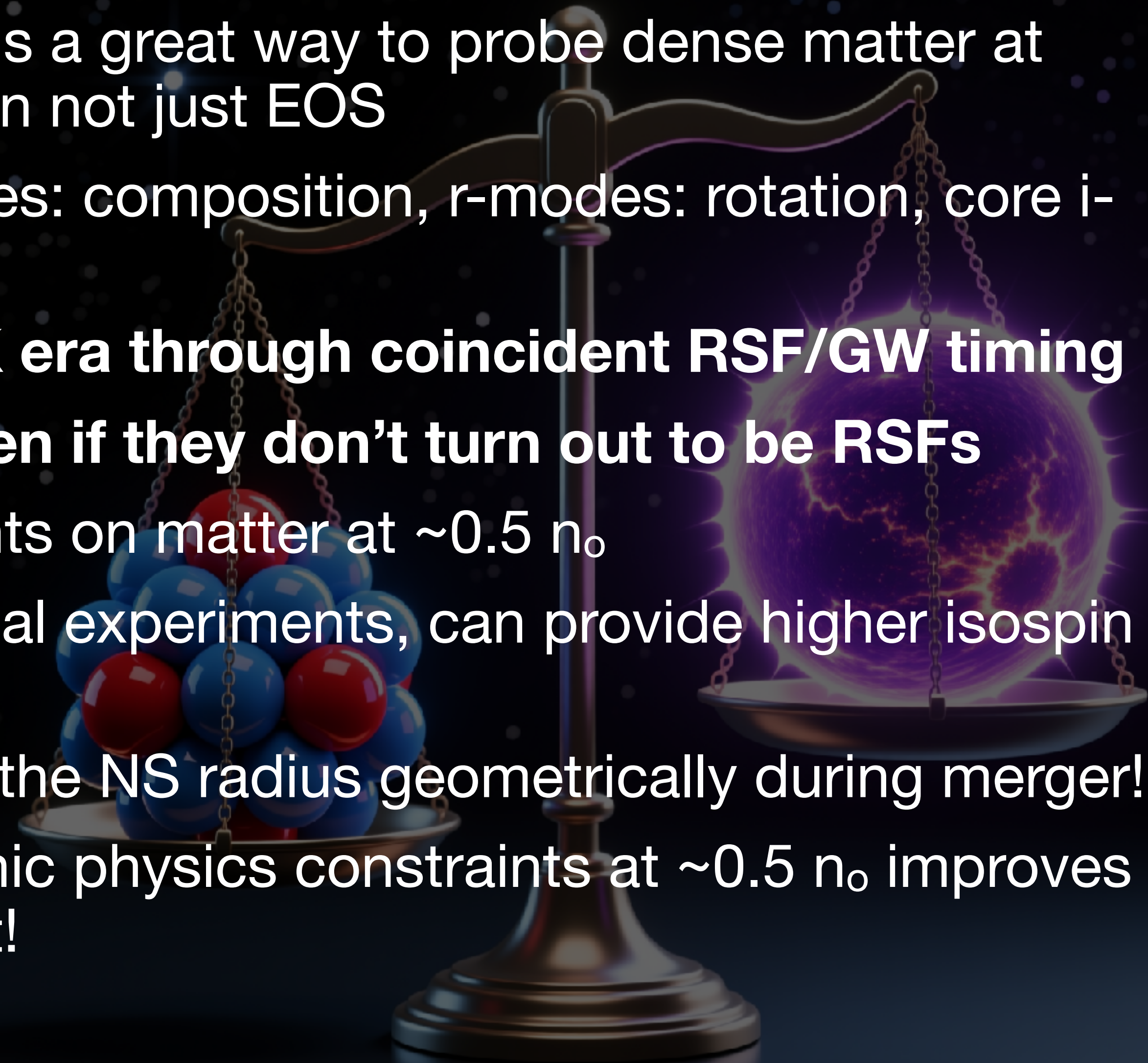
Caveats:

- 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 and higher signal to noise
- Our estimate of “experimental” uncertainty is not really properly modelled
 - key take-away is to see improvement in R_{NS} constraint from better $\delta R_{\text{n-skin}}$ 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



Key Takeaways:

- Astero-seismology particularly in the inspiral is a great way to probe dense matter at specific densities, dynamics and composition not just EOS
- f-mode: similar to tidal deformability, g-modes: composition, r-modes: rotation, core i-modes: phase transition
- **core-crust i-mode can be obtained in LVK era through coincident RSF/GW timing**
- **EM merger precursors are interesting, even if they don't turn out to be RSFs**
- Core-crust i-mode provides strong constraints on matter at $\sim 0.5 n_0$
 - J-L constraints complementary to terrestrial experiments, can provide higher isospin asymmetry test of χ EFT
- Can use the i-mode frequency to determine the NS radius geometrically during merger!
 - Astero-seismic leverage: Improved nucleonic physics constraints at $\sim 0.5 n_0$ improves radius and high density physics constraint!



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Jeremy Holt (Texas A&M)



Christian Drischler (Ohio University/FRIB)



Jérôme Margueron (CNRS/MSU)

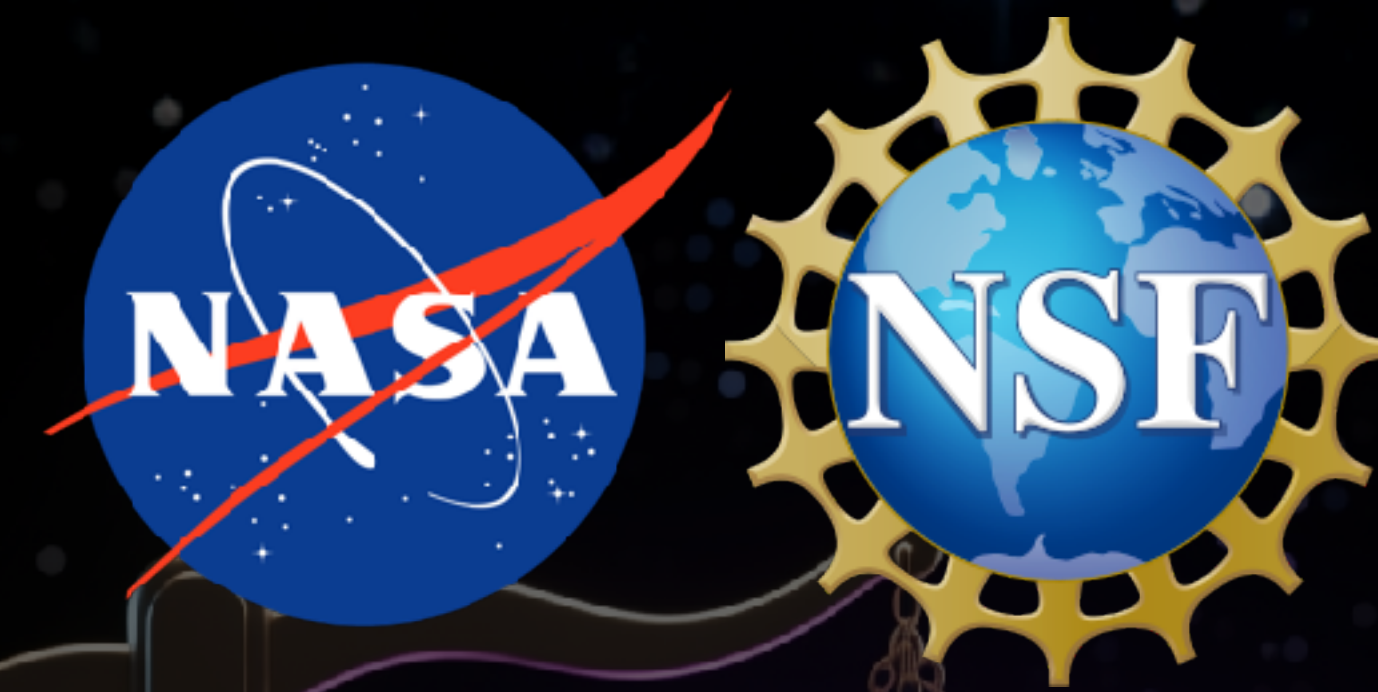


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