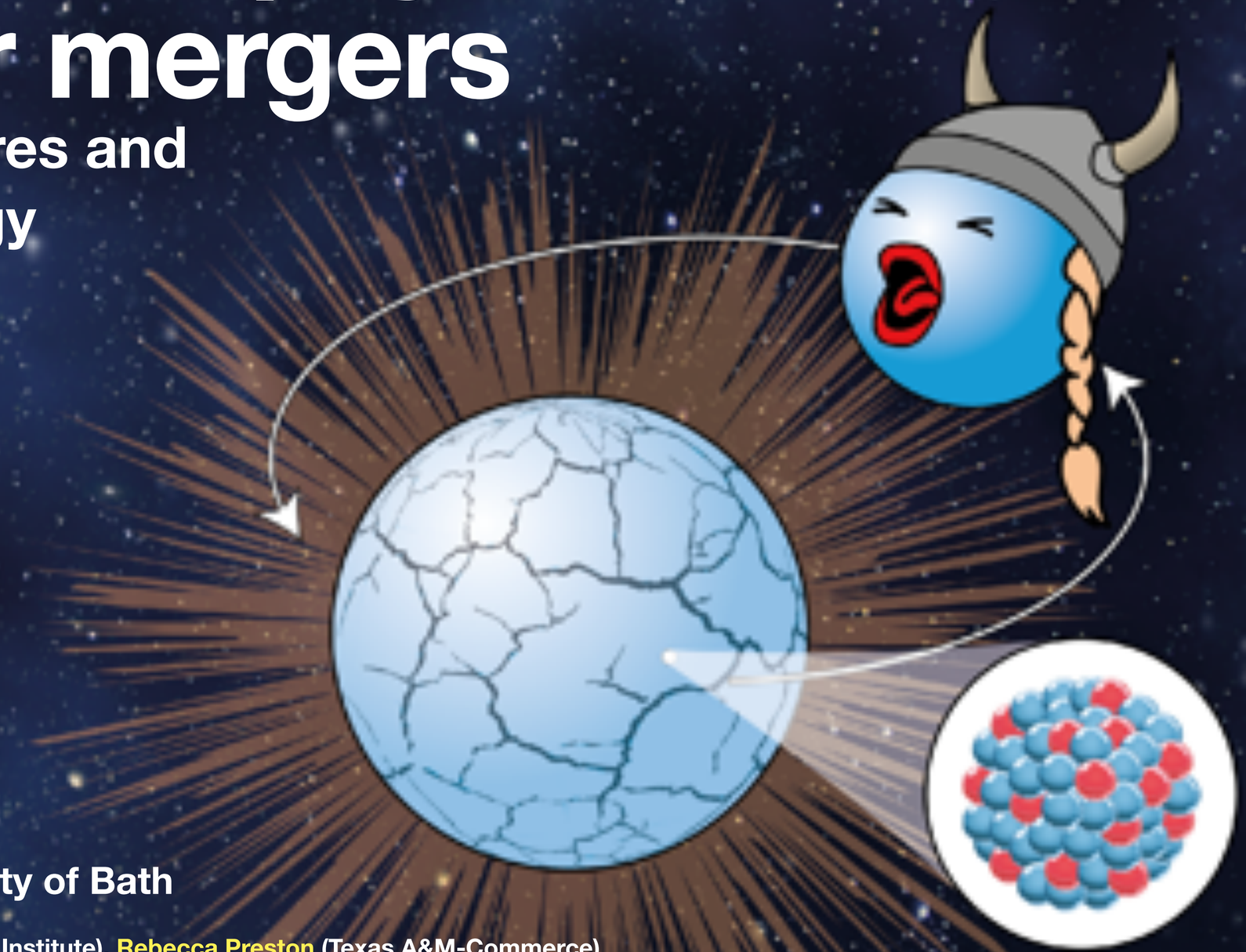
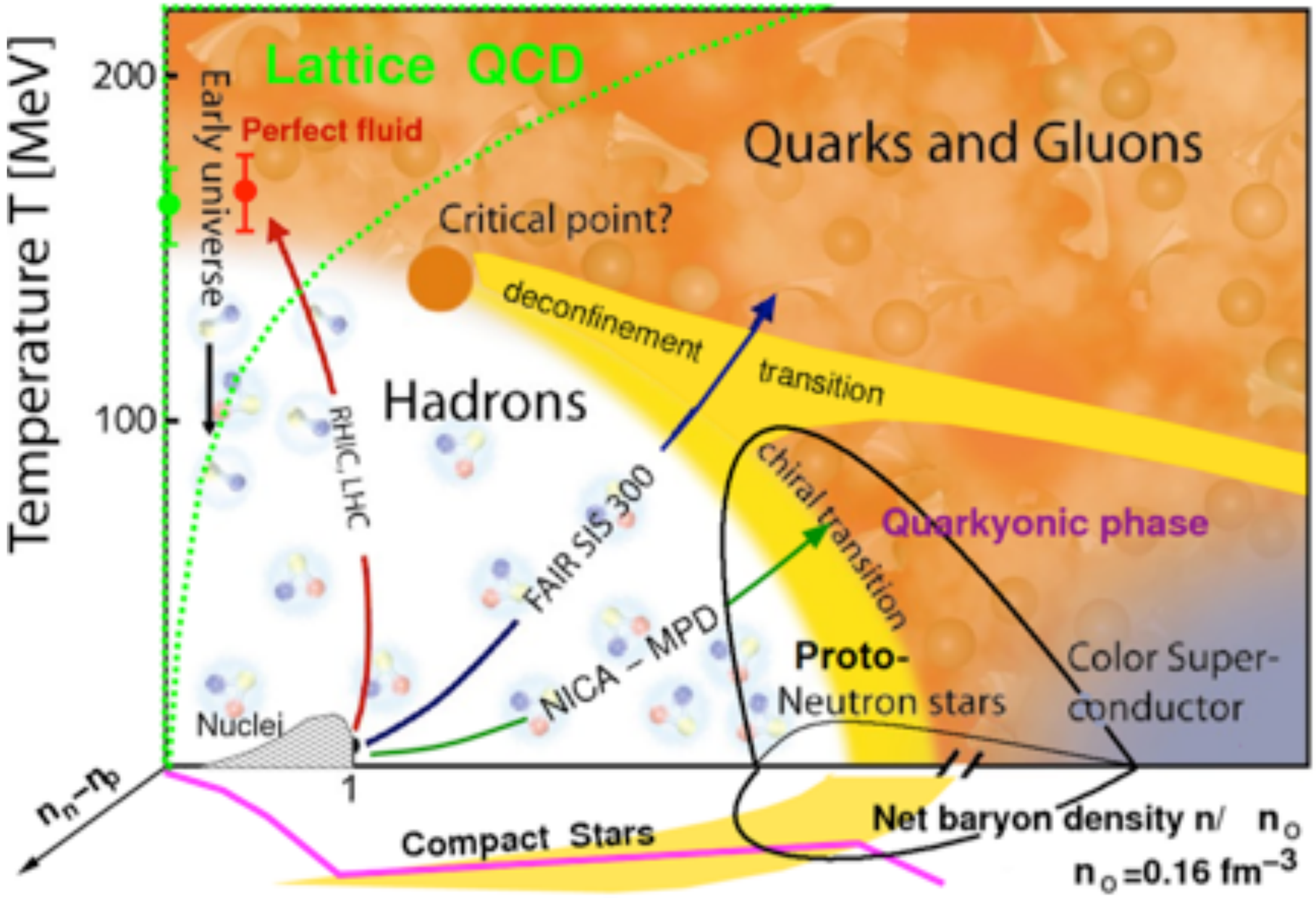
Probing nuclear physics with neutron star mergers

Resonant shattering flares and nuclear symmetry energy

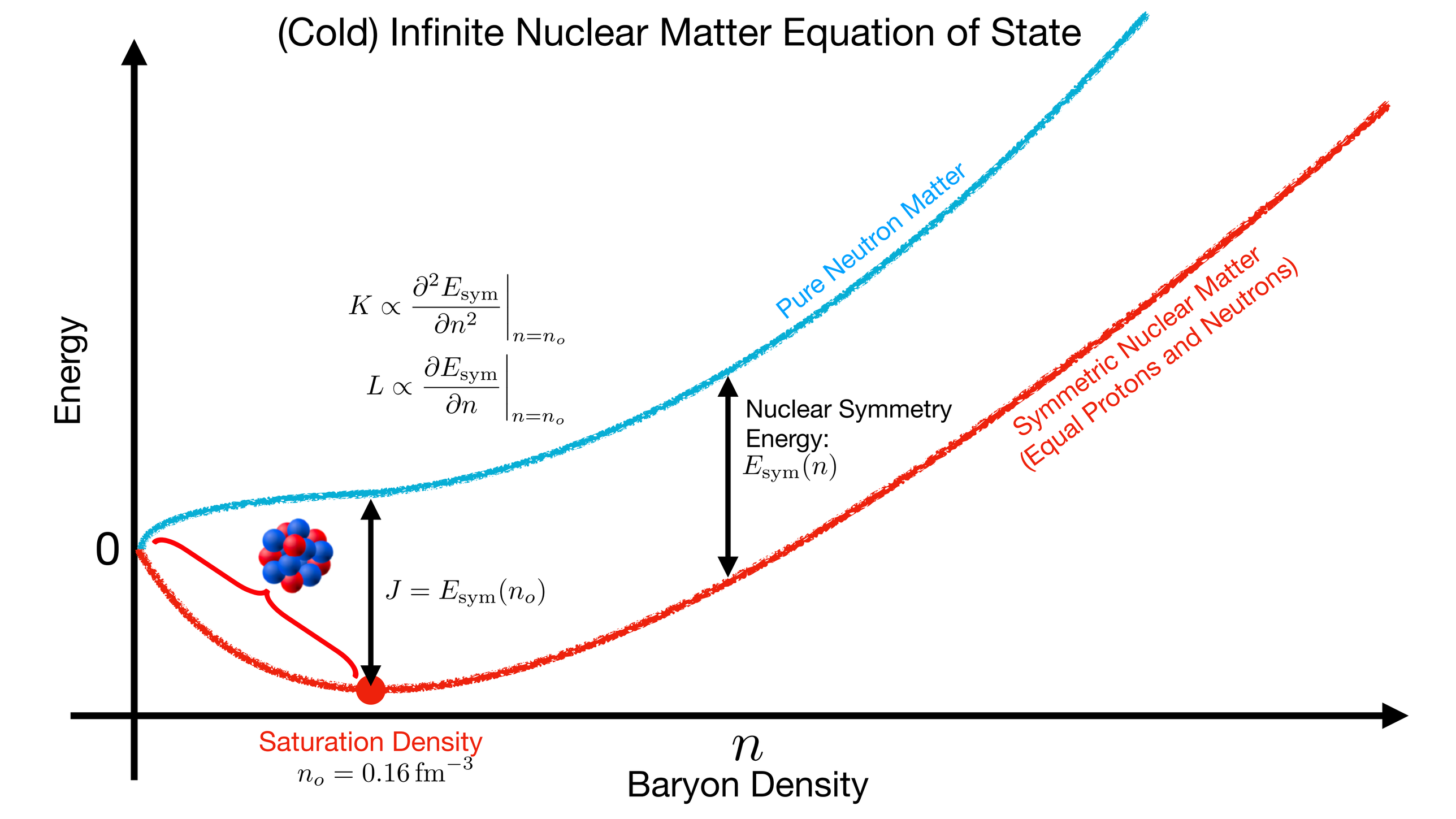
INT Neutrons ↑ and ↓ Workshop
June 28, 2023



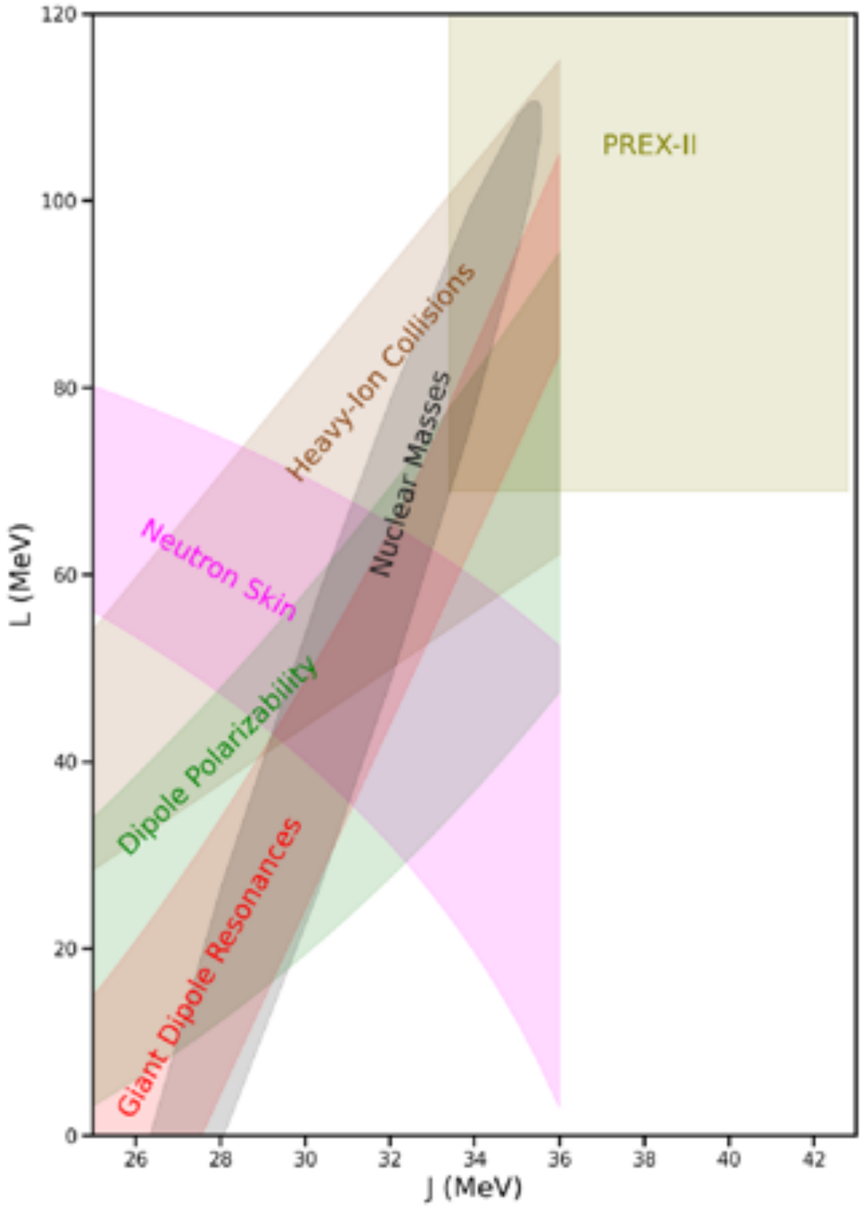
David Tsang, Duncan Neill, University of Bath
With Will Newton (Texas A&M-Commerce),
Hendrik Van Eerten (U. Bath), Geoffery Ryan (Perimeter Institute), Rebecca Preston (Texas A&M-Commerce)



https://web.infn.it/CSN4/IS/Linea3/STRENGTH/


(Cold) Infinite Nuclear Matter Equation of State
Energy
0
$K \propto \left.\frac{\partial^2 E_{\rm sym}}{\partial n^2}\right|_{n=n_o}$
$L \propto \left.\frac{\partial E_{\rm sym}}{\partial n}\right|_{n=n_o}$
Pure Neutron Matter
Symmetric Nuclear Matter
(Equal Protons and Neutrons)
Nuclear Symmetry
Energy:
$E_{\rm sym}(n)$
$J = E_{\rm sym}(n_o)$
Saturation Density
$n_o = 0.16\,{\rm fm}^{-3}$
n
Baryon Density

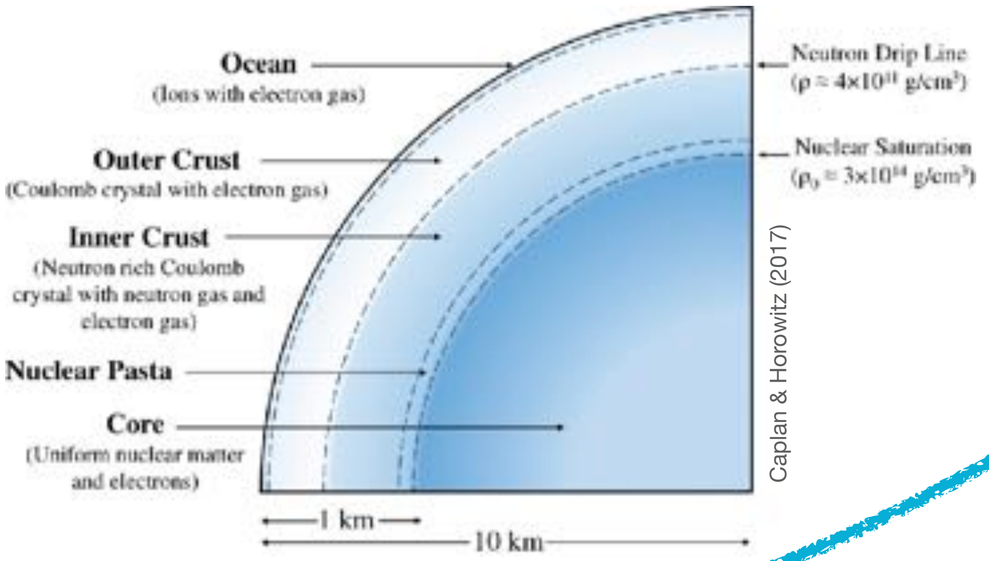
Symmetry energy constraints from terrestrial experiments



How can we measure Symmetry Energy with astrophysics?

Which regions of a neutron star tell us about which physics?

(Cold) Infinite Nuclear Matter Equation of State



Energy

0

Pure Neutron Matter

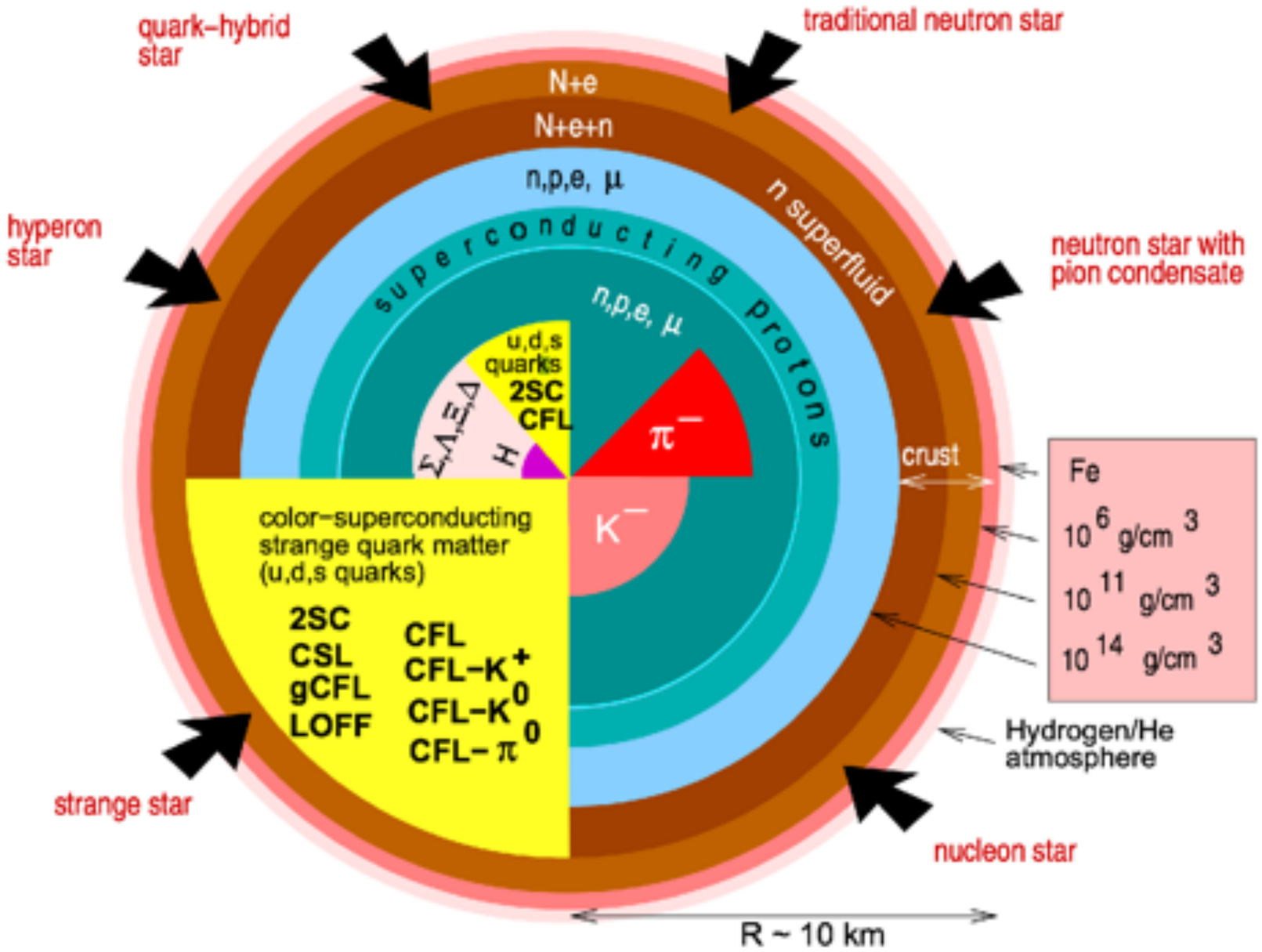
Symmetric Nuclear Matter
(Equal Protons and Neutrons)

Nuclear Symmetry Energy:
$E_{\rm sym}(n)$

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

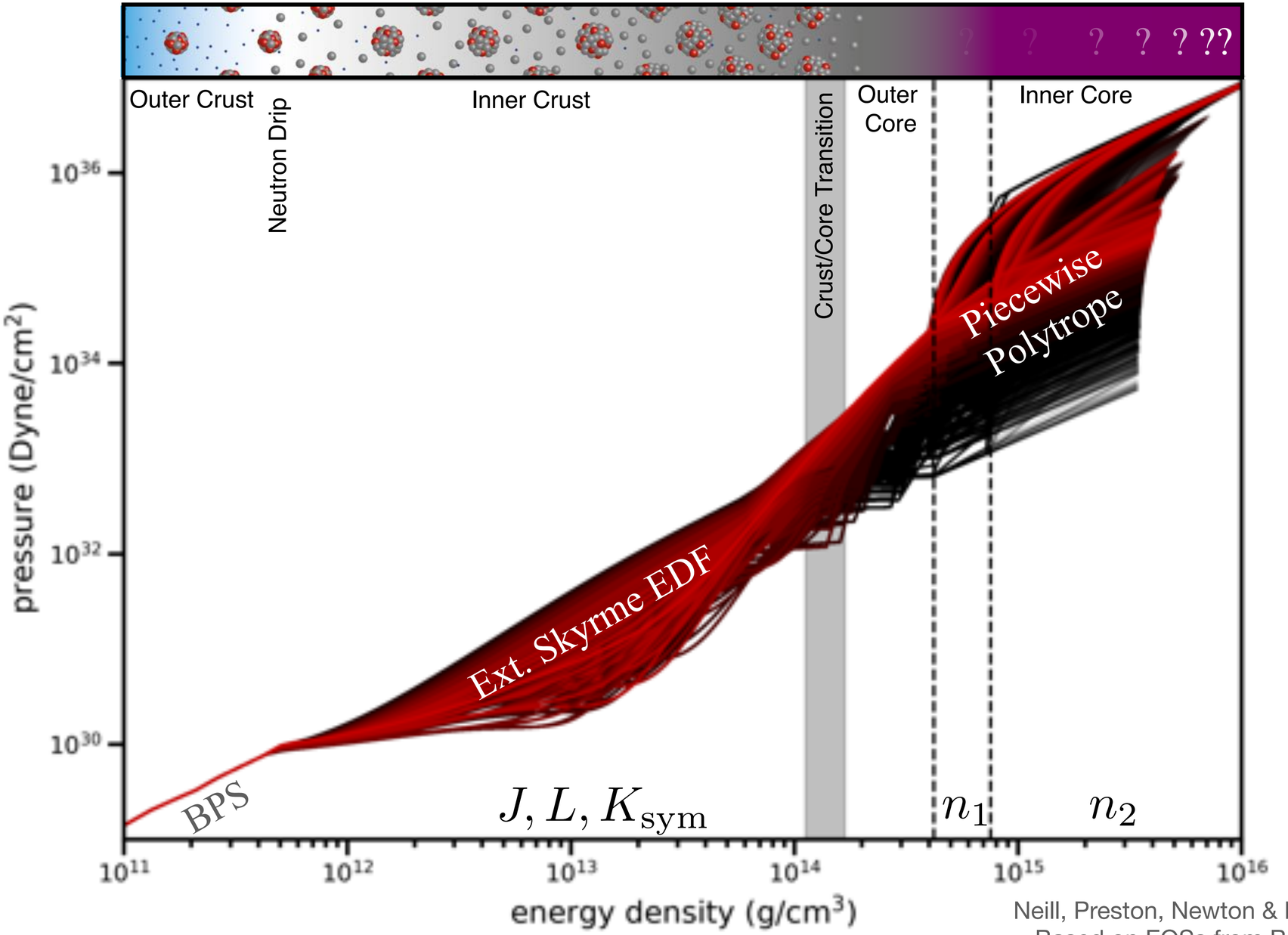
Saturation Density
$n_o = 0.16\,{\rm fm}^{-3}$

n
Baryon Density



Weber 2004, arXiv:astro.ph/0407155

Parameterised Crust and Core EOS

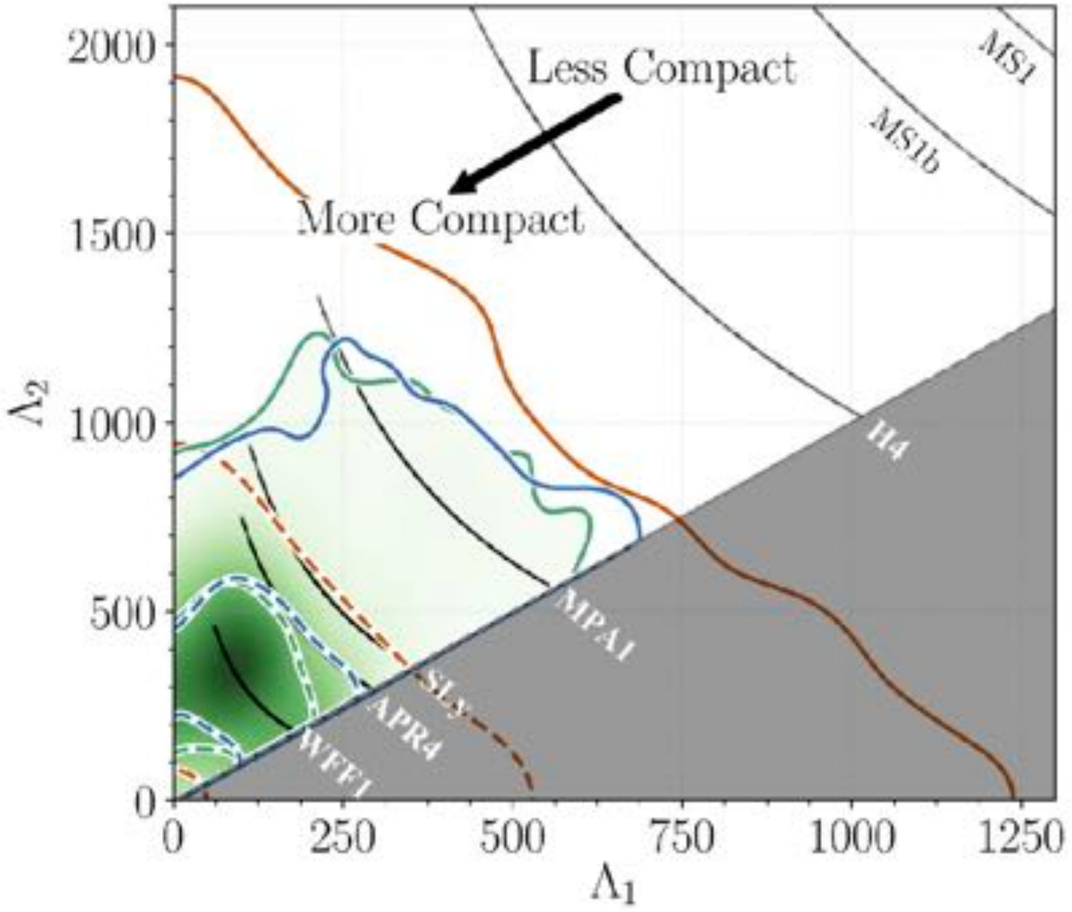


Neill, Preston, Newton & DT (2023), PRL, 130, 112701
Based on EOSs from Balliet et al, 2021, ApJ 918:79

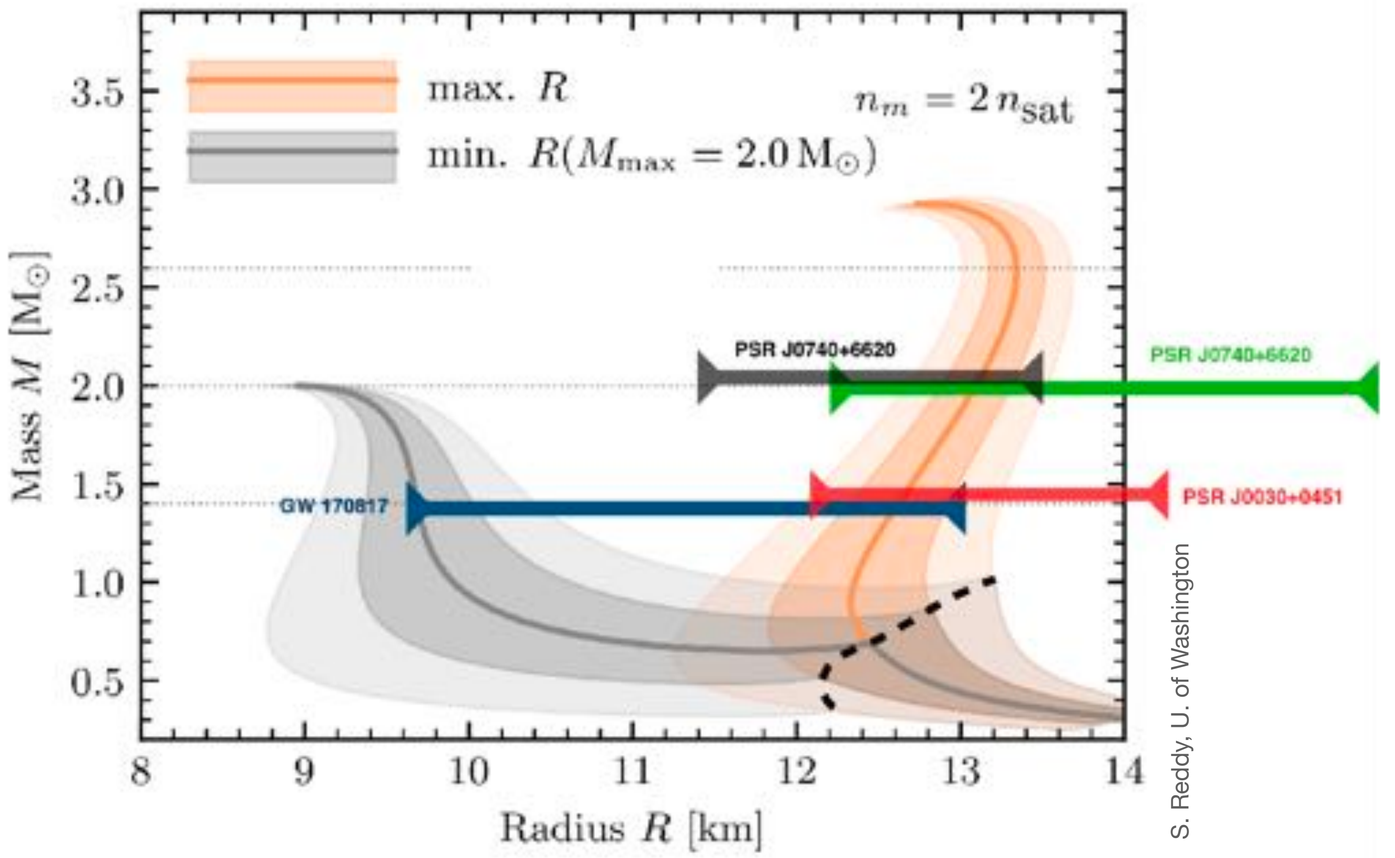
What multi-messenger observables can we use?

Kilonovae and Short Gamma Ray Bursts tell us a lot about the messy post-merger physics!
But it’s difficult to extract info about the neutron star progenitors themselves…

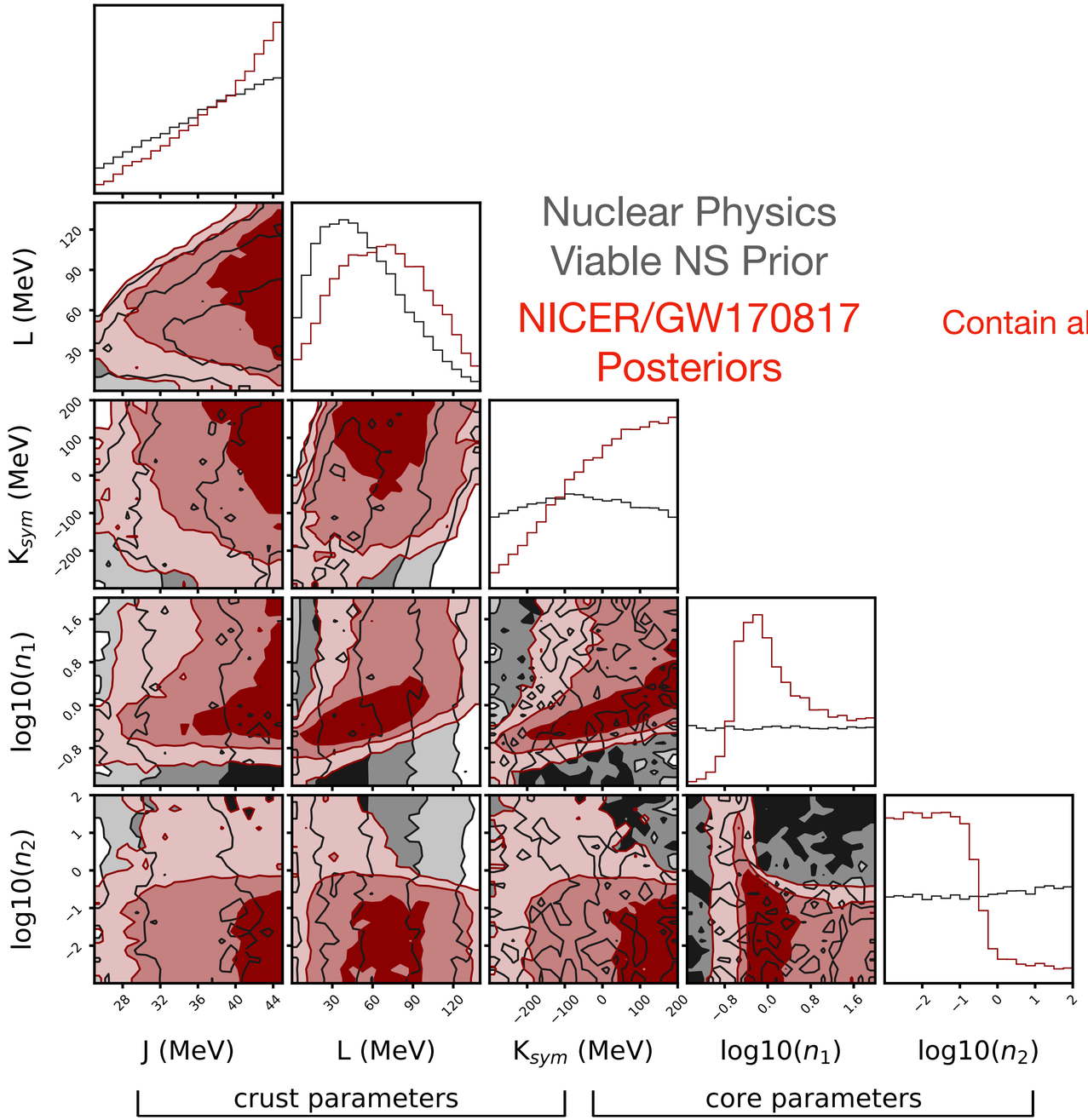
Tidal deformability, M-R, M_{max}, f-mode mostly functions of core properties



LIGO/Virgo (2018) PRL 121, 161101



S. Reddy, U. of Washington



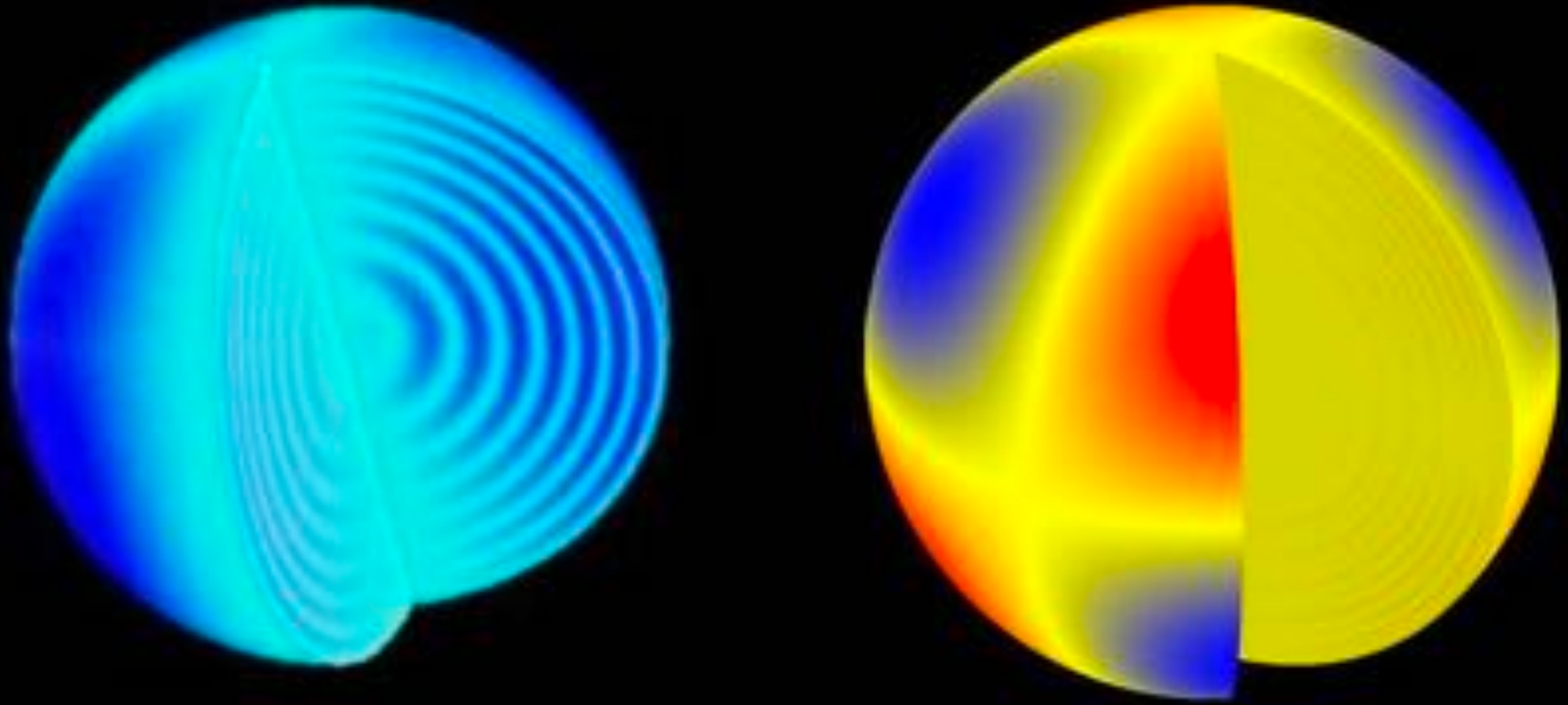
Nuclear Physics
Viable NS Prior

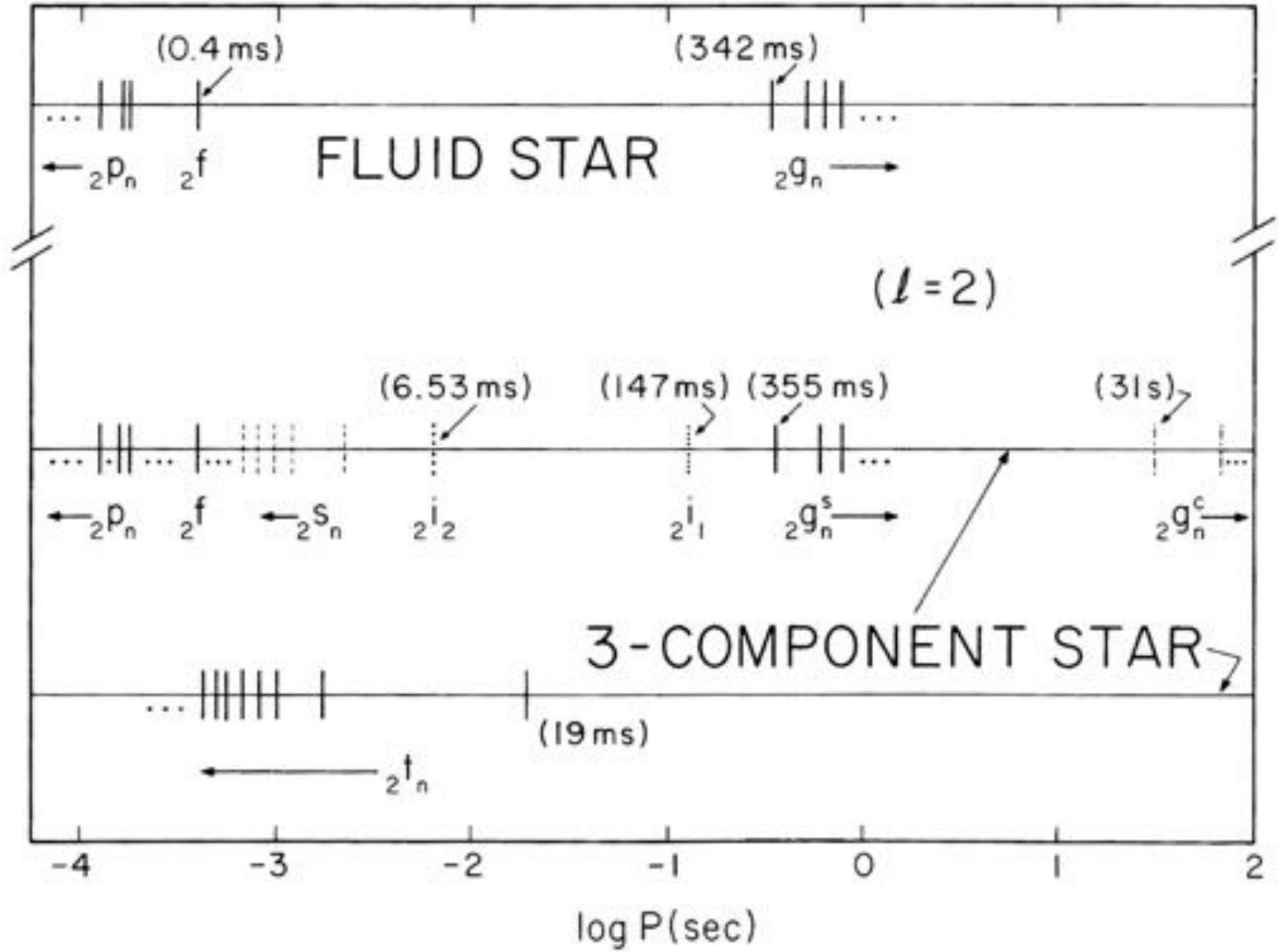
NICER/GW170817
Posteriors

Contain almost no information about
inner/outer crust

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

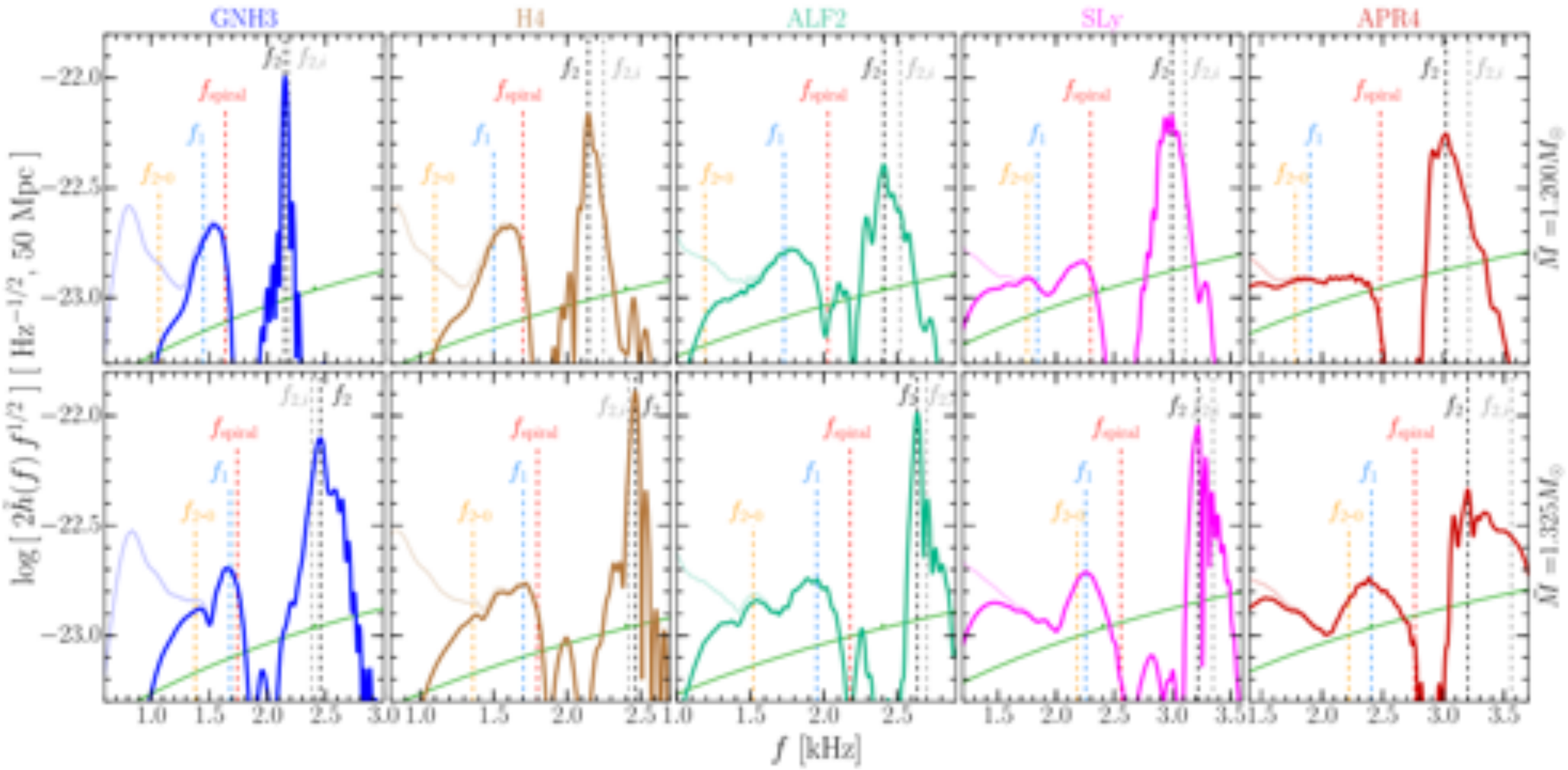
Stellar Vibrations





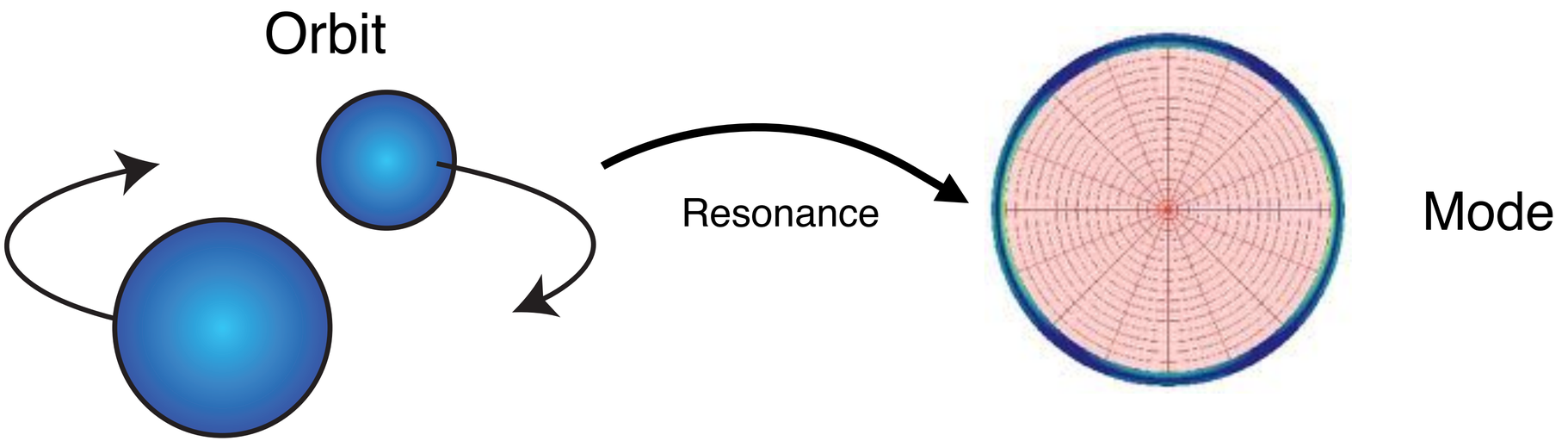
McDermott et al 1988

GW “Spectroscopy” of a HMNS Remnant

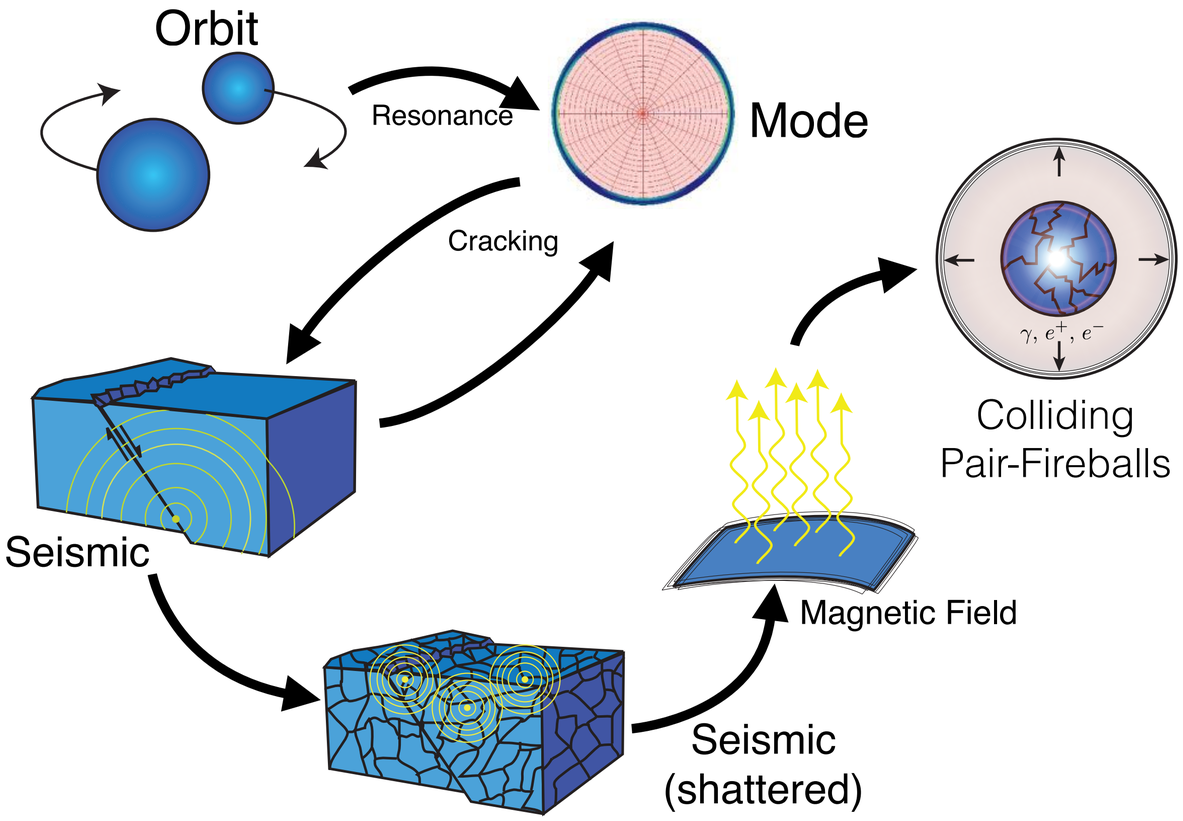


Rezzolla & Takami (2016)

Tidal Resonance

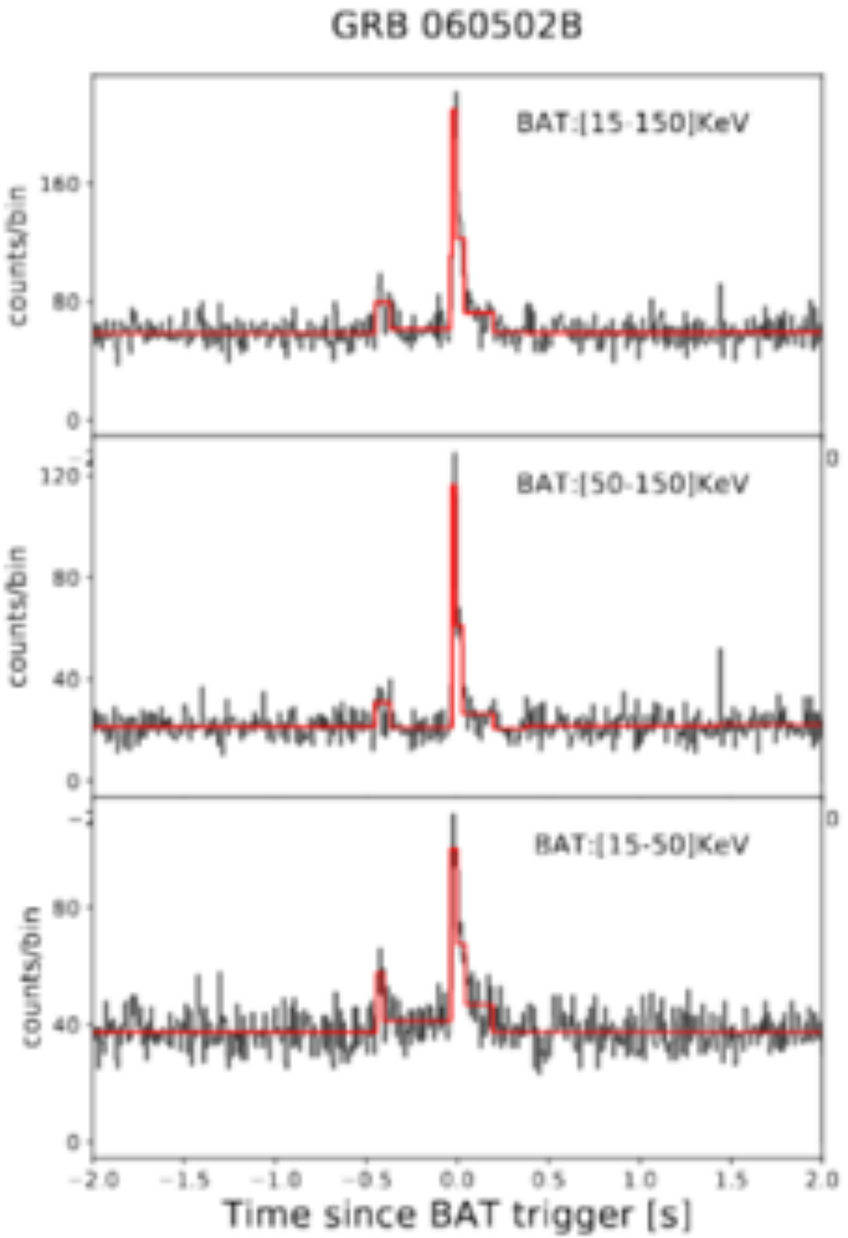


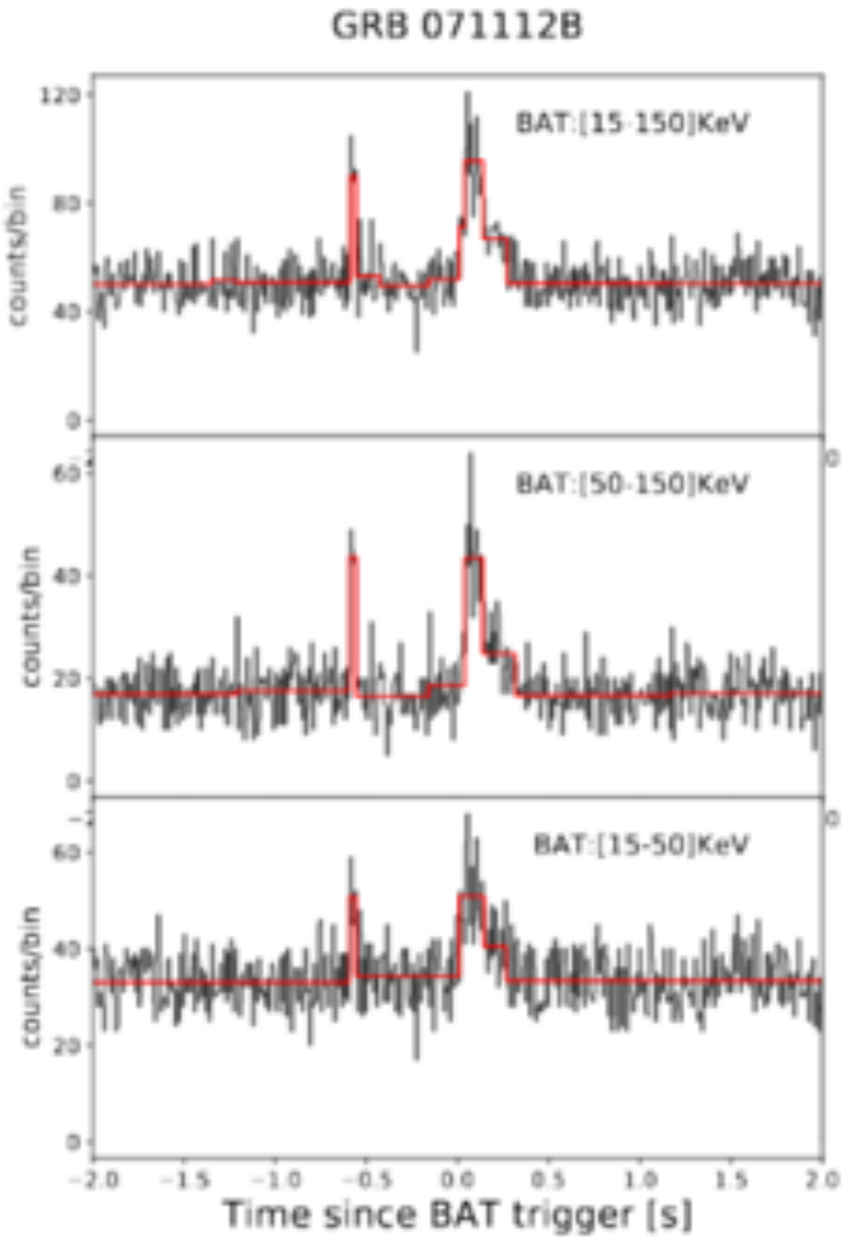
Resonant Shattering Flares



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

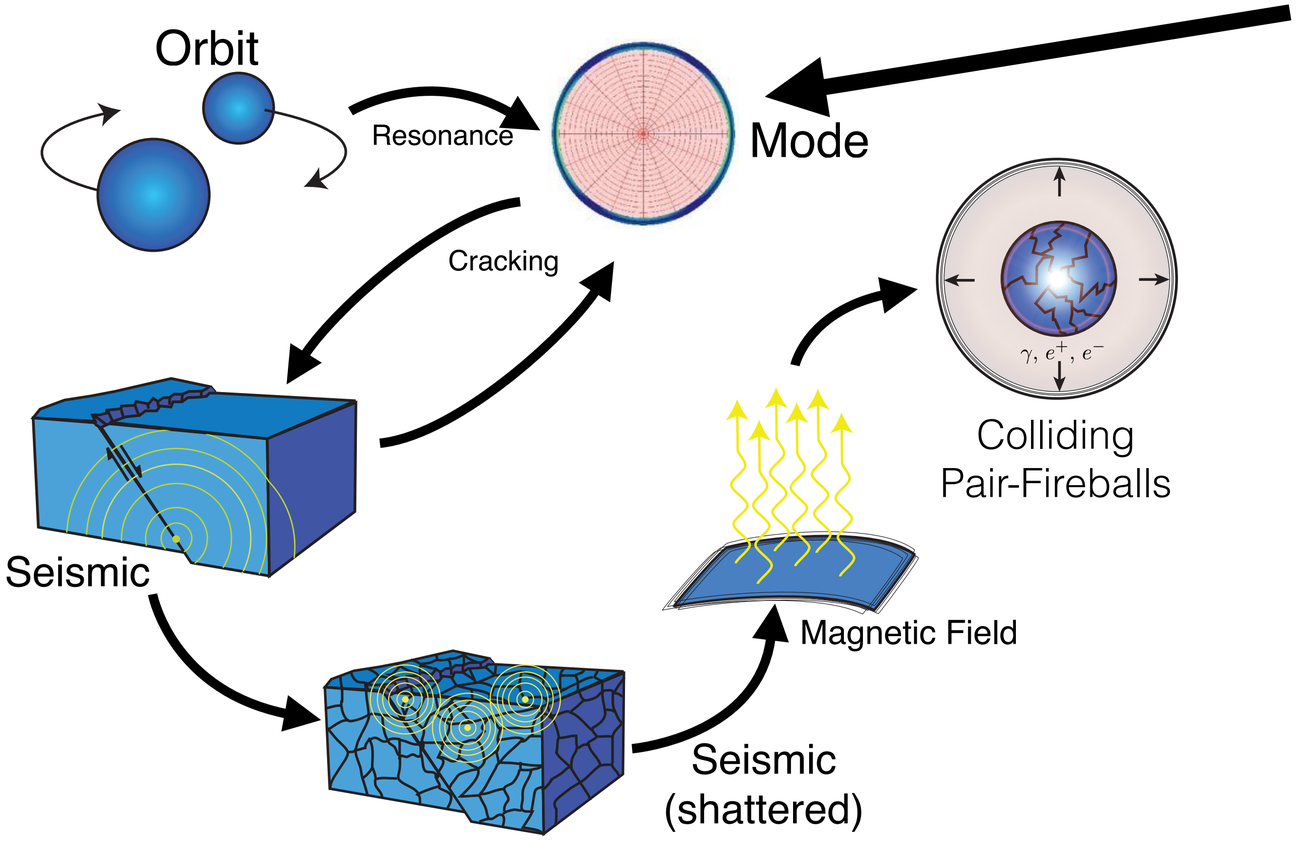
Some SGRBs have precursors…





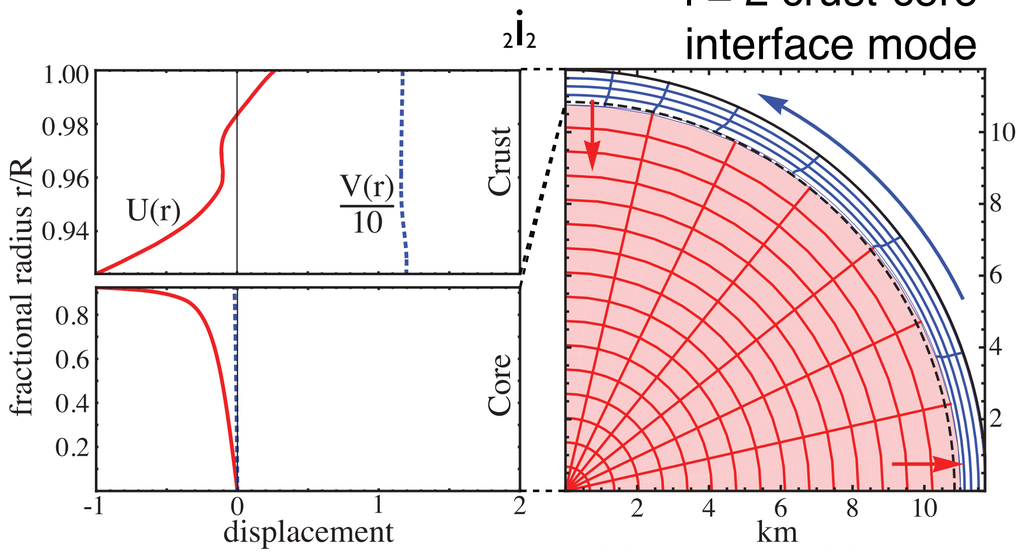
Zhong et al. (2019) ApJ 884, 25

Resonant Shattering Flares



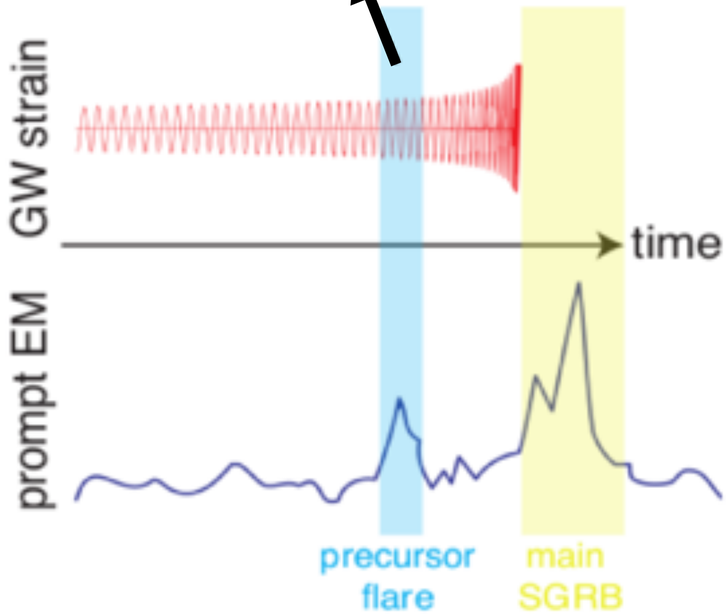
DT, et al. (2012) PRL 108, 011102
DT (2013) ApJ 777, 103
Neill, DT, Van Eerten, Ryan, & Newton (2022) MNRAS

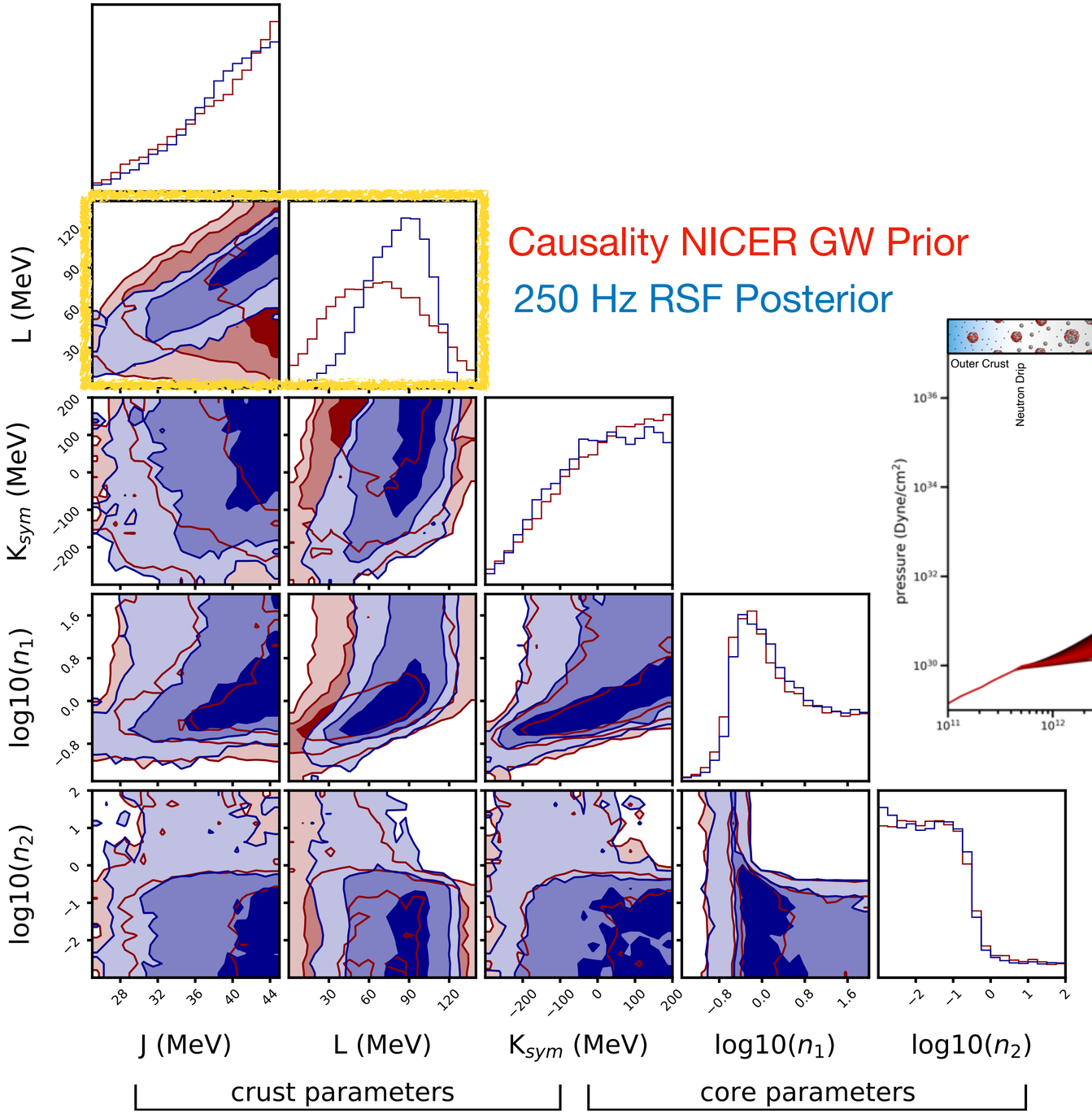
l = 2 crust-core interface mode



DT et al. (2012) PRL 108, 011102

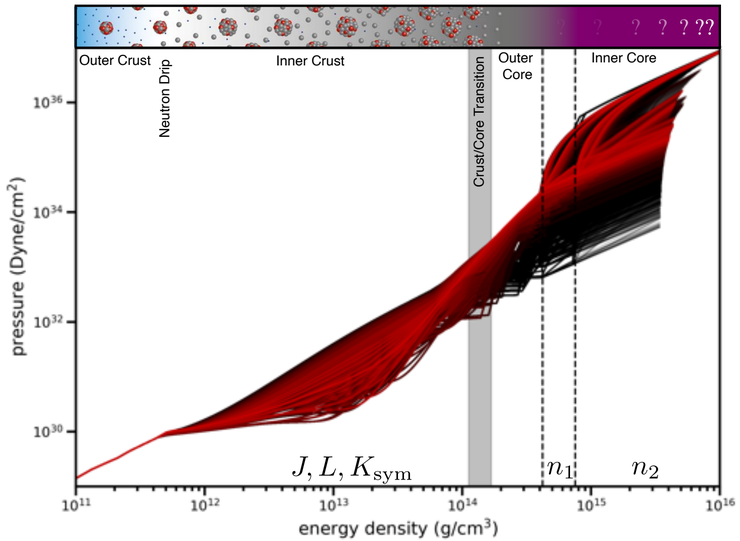
f_{mode} ~ 100Hz



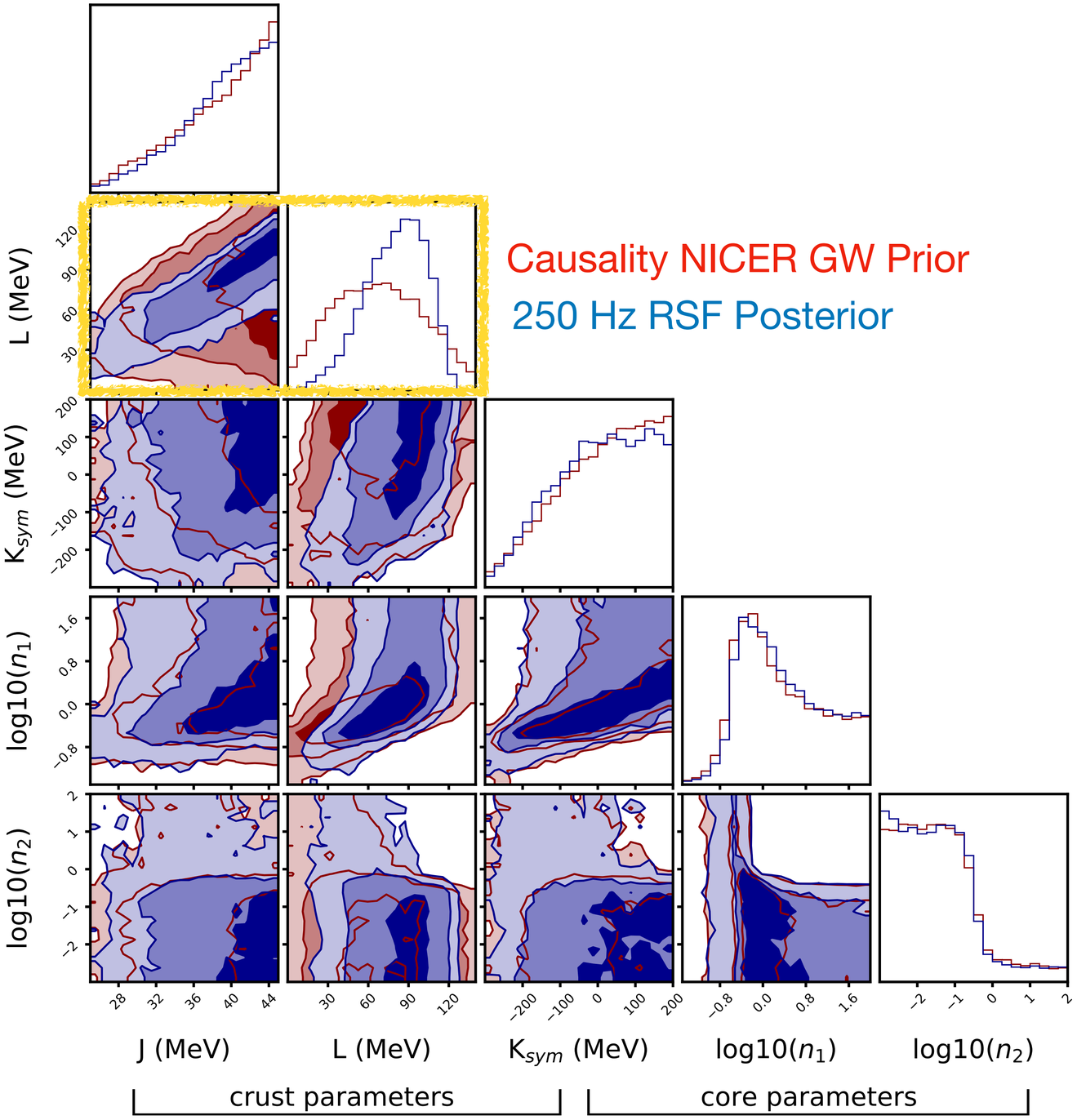


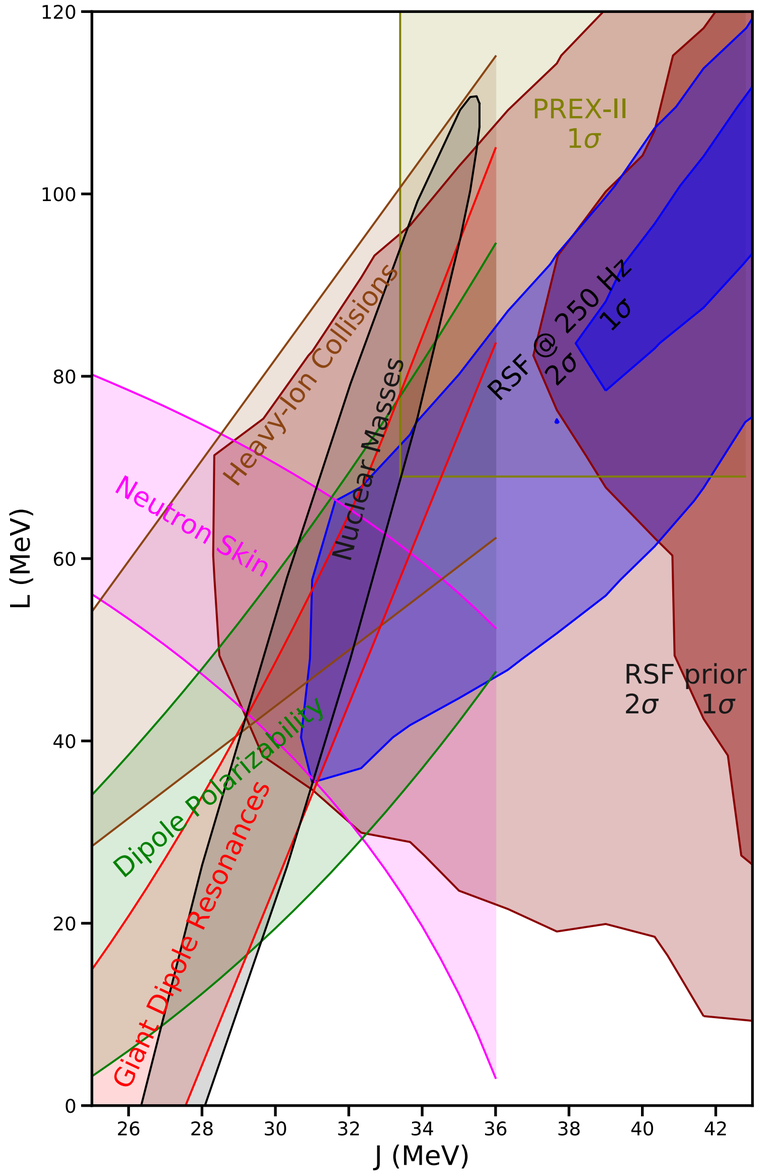
Causality NICER GW Prior

250 Hz RSF Posterior

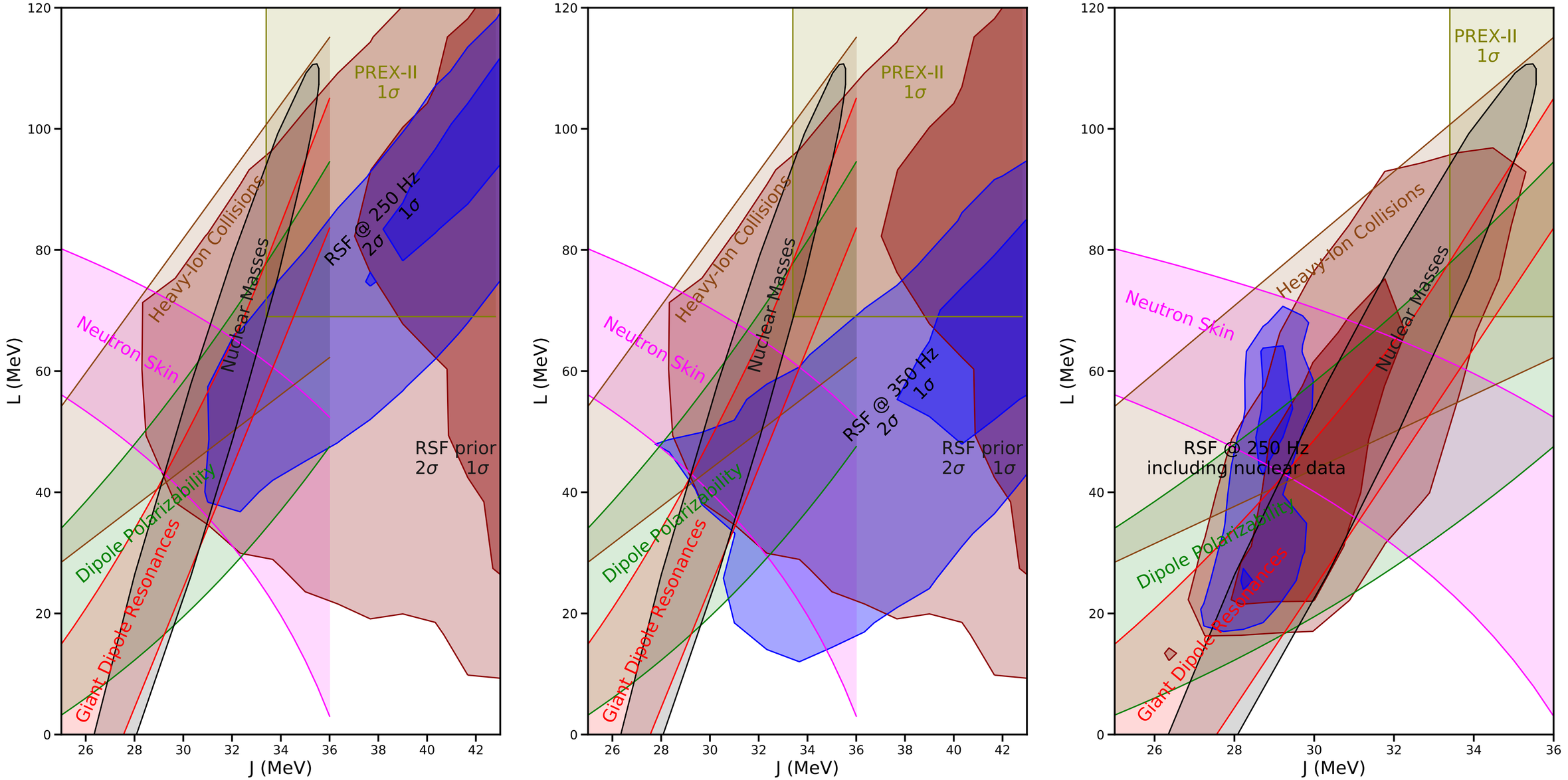


Neill, Preston, Newton & DT (2023), PRL, 130, 112701

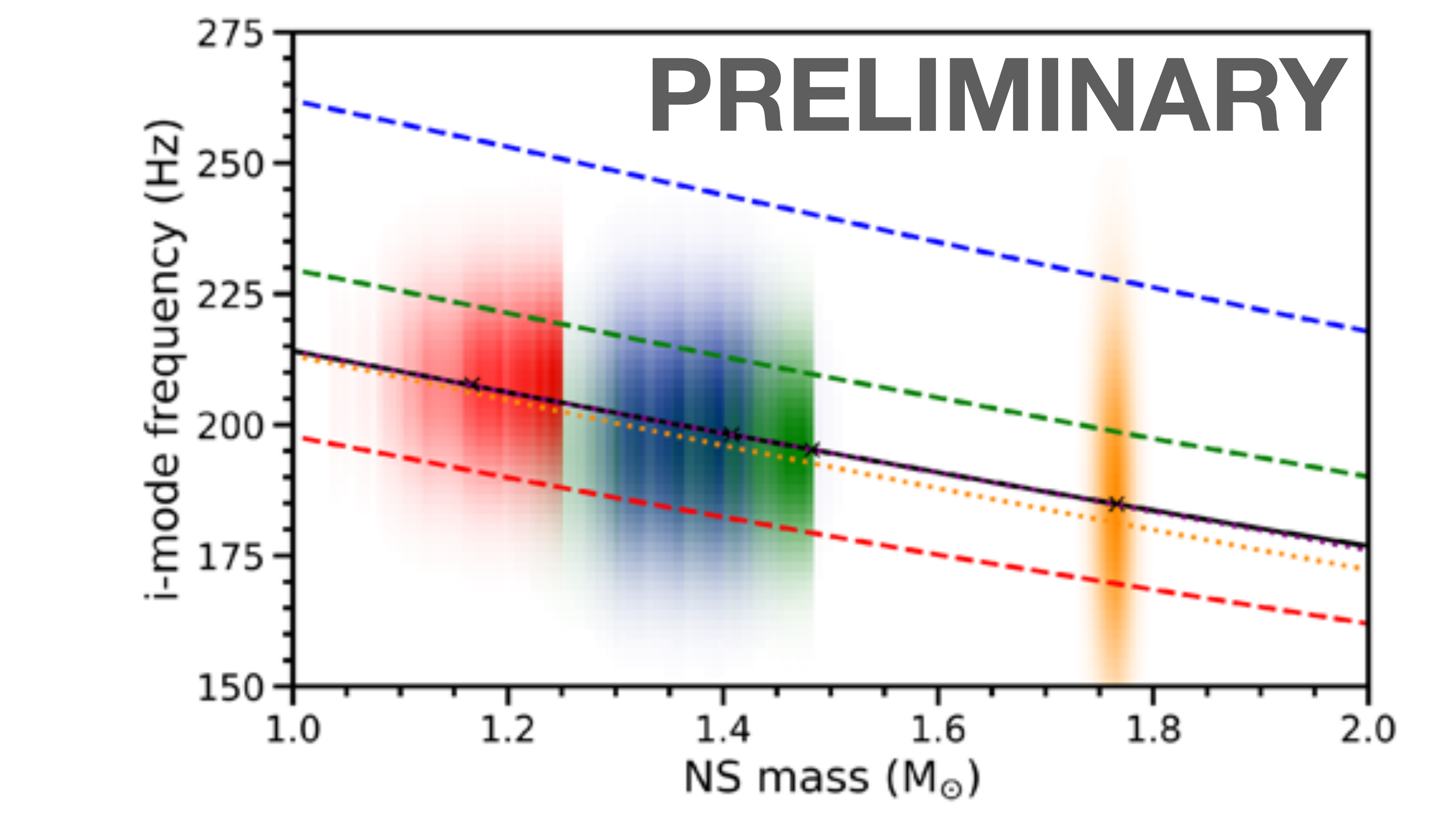


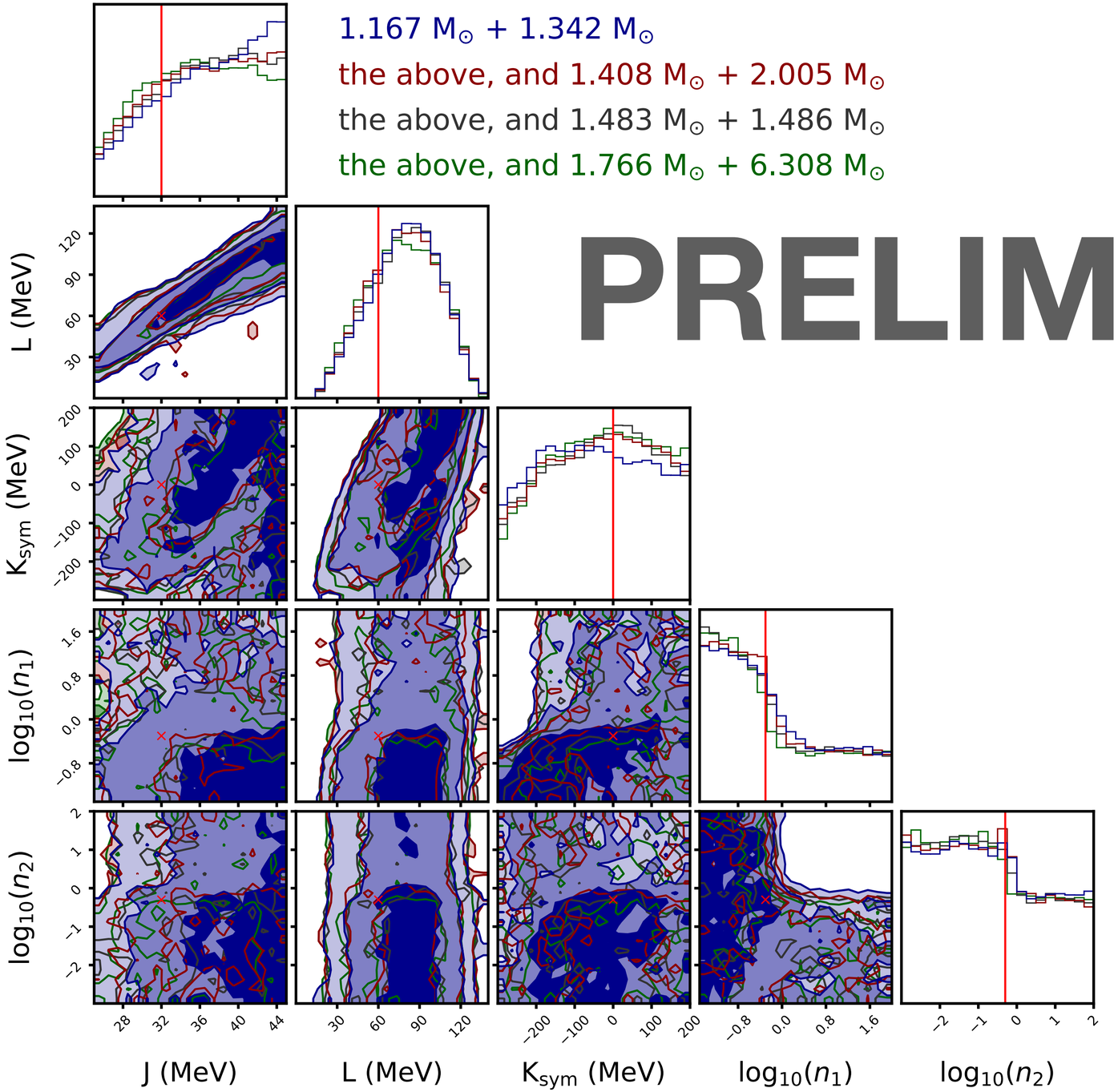


Neill, Preston, Newton & DT (2023), PRL, 130, 112701

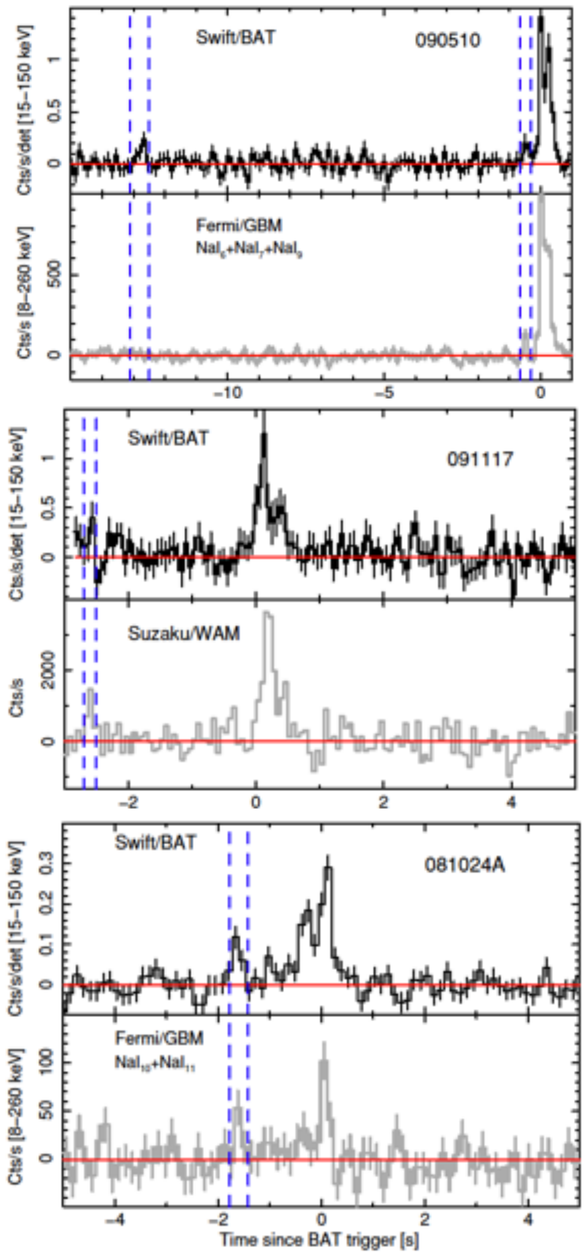


Neill, Preston, Newton & DT (2023), PRL, 130, 112701


PRELIMINARY
i-mode frequency (Hz)
275
250
225
200
175
150
1.0
1.2
1.4
1.6
1.8
2.0
NS mass ($M_\odot$)


1.167 M⊙ + 1.342 M⊙
the above, and 1.408 M⊙ + 2.005 M⊙
the above, and 1.483 M⊙ + 1.486 M⊙
the above, and 1.766 M⊙ + 6.308 M⊙
PRELIMINARY
J (MeV)
L (MeV)
Ksym (MeV)
log10(n1)
log10(n2)

What are the prospects for detecting RSFs?



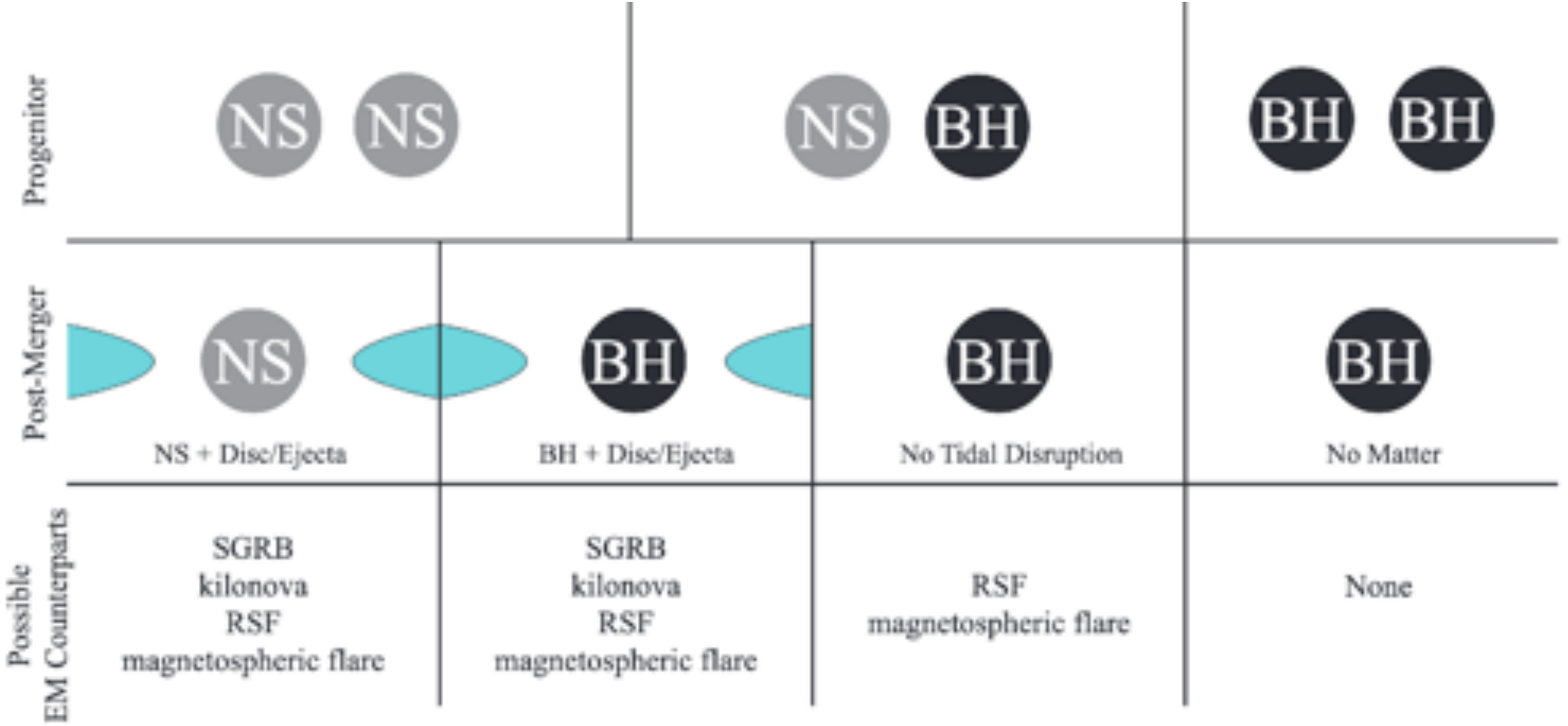
Potential Orphan RSFs?

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

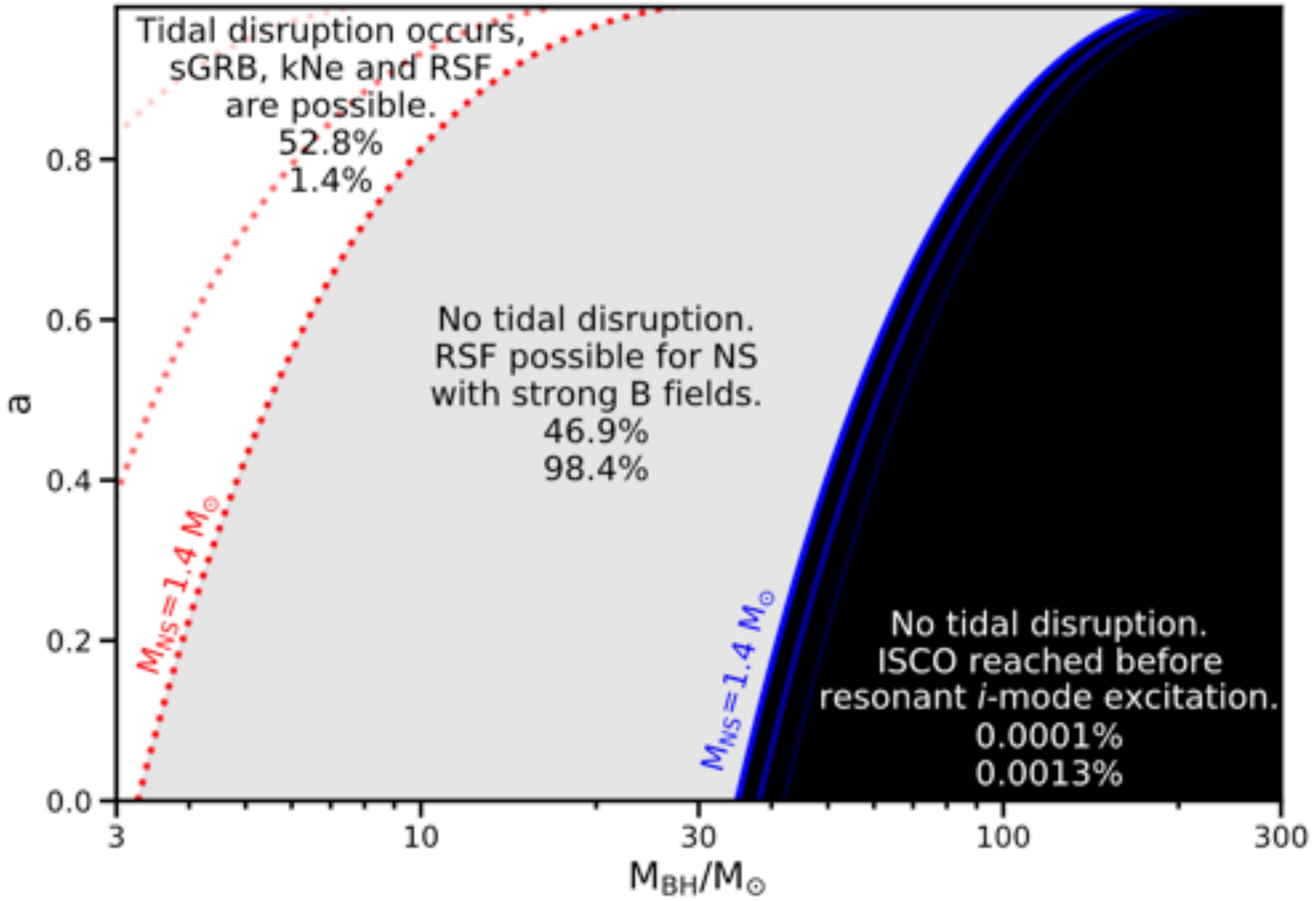
GRB	T_{90}(s)	z	BAT Fluence (10^{-7} erg cm^{-2})	$E_{BAT\ ISO}$ (erg)	Notes
150101B	0.018	0.13	0.23	2.6×10^{48}	High E_{kin}; Fong+(2016)
050509B	0.073	0.225	0.09	1.1×10^{48}	Gehrels+(2005)
060502B	0.131	0.287	0.4	7.9×10^{48}	Bloom+ (2006)
050906	0.128	0.031*	0.07	1.5×10^{46}	Levan & Tanvir (2008)
090417A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



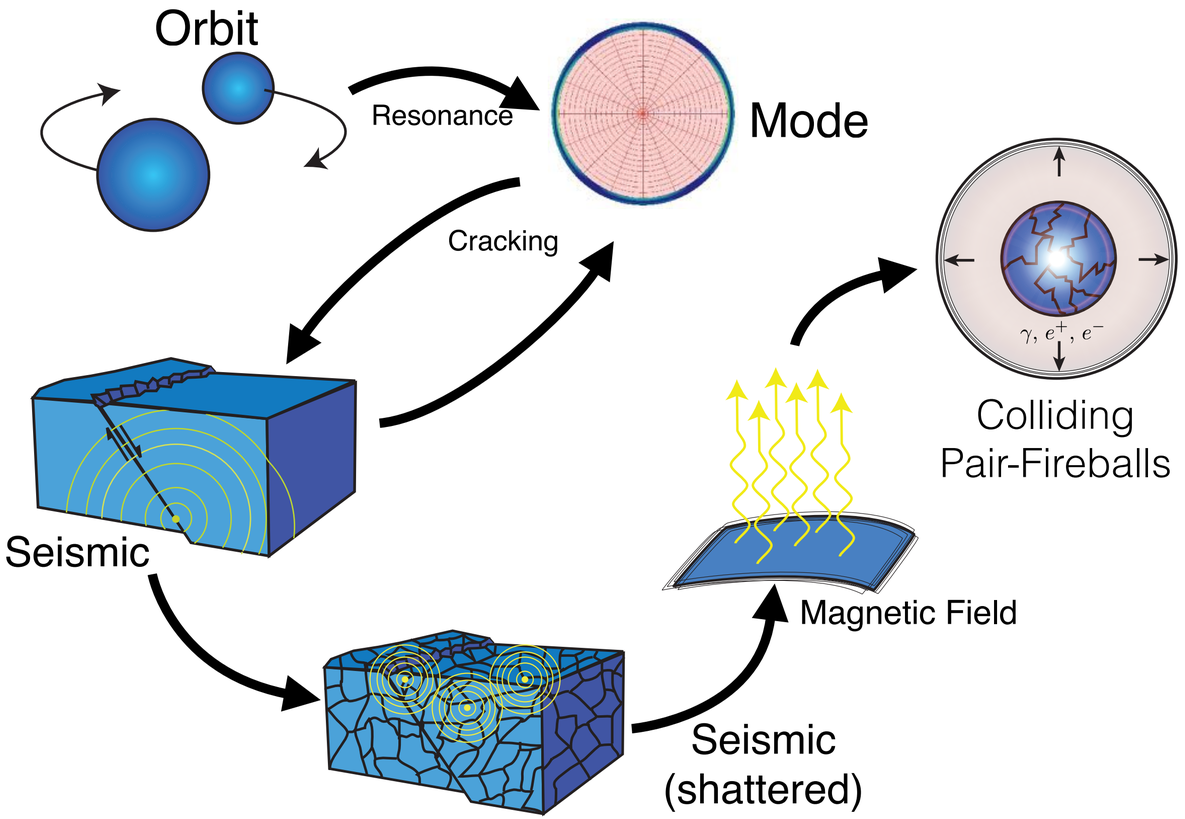
Neill, DT, Van Eerten, Ryan, & Newton (2022) MNRAS, 514, 4



NS BH

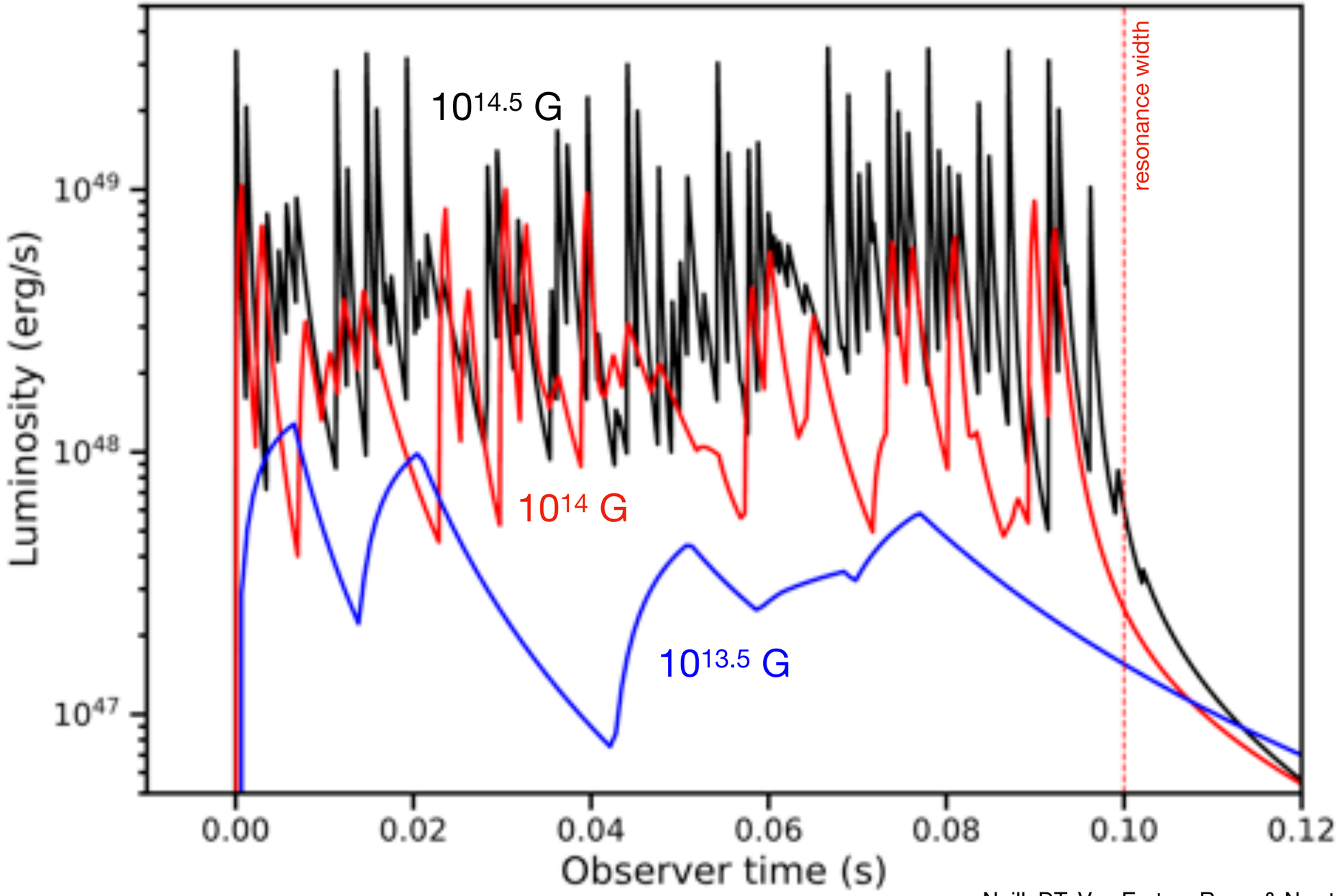
Neill, DT, Van Eerten, Ryan, & Newton (2022) MNRAS, 514, 4

Resonant Shattering Flares

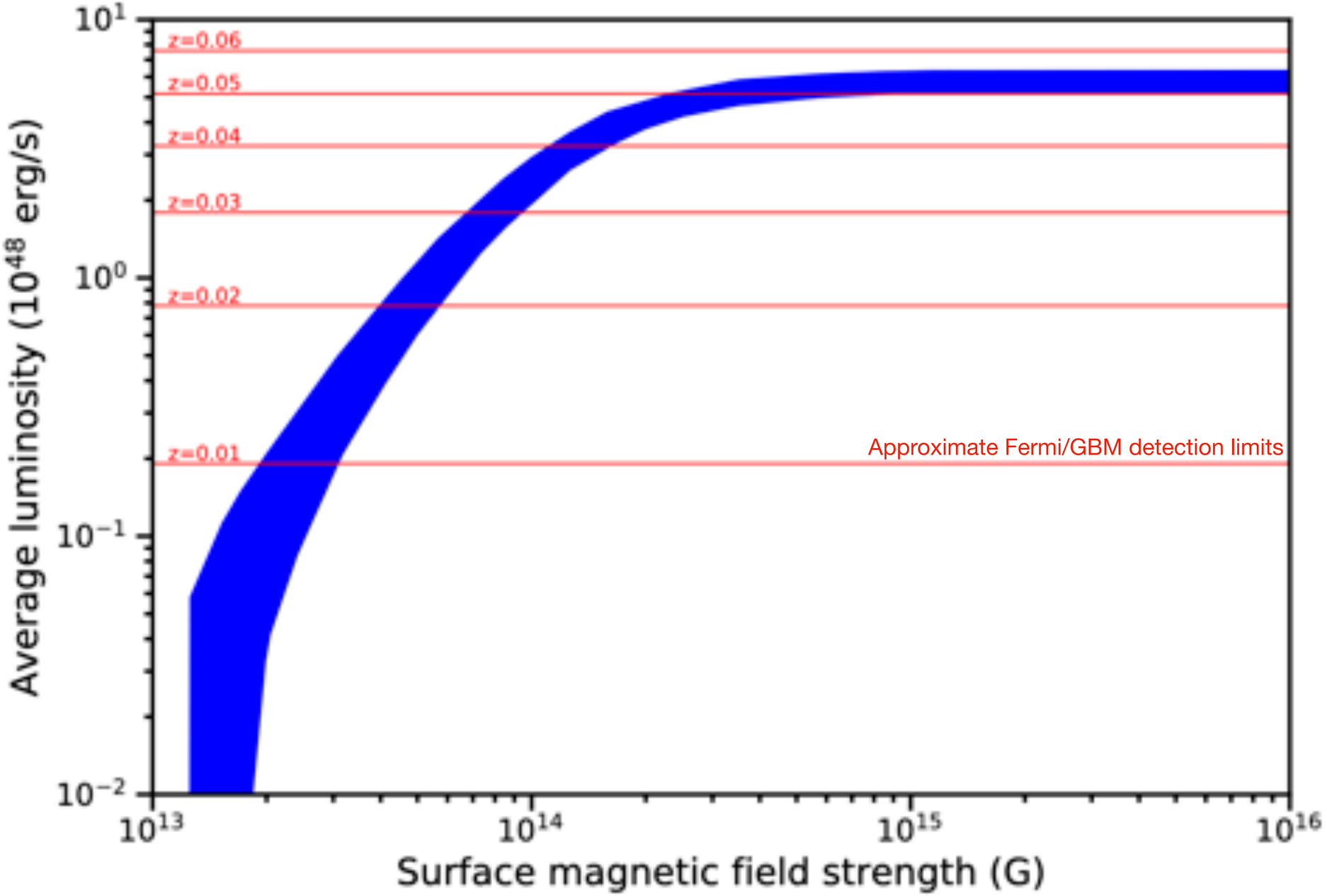


DT, et al. (2012) PRL 108, 011102
DT (2013) ApJ 777, 103
Neill, DT, Van Eerten, Ryan, & Newton (2022) MNRAS, 514, 4

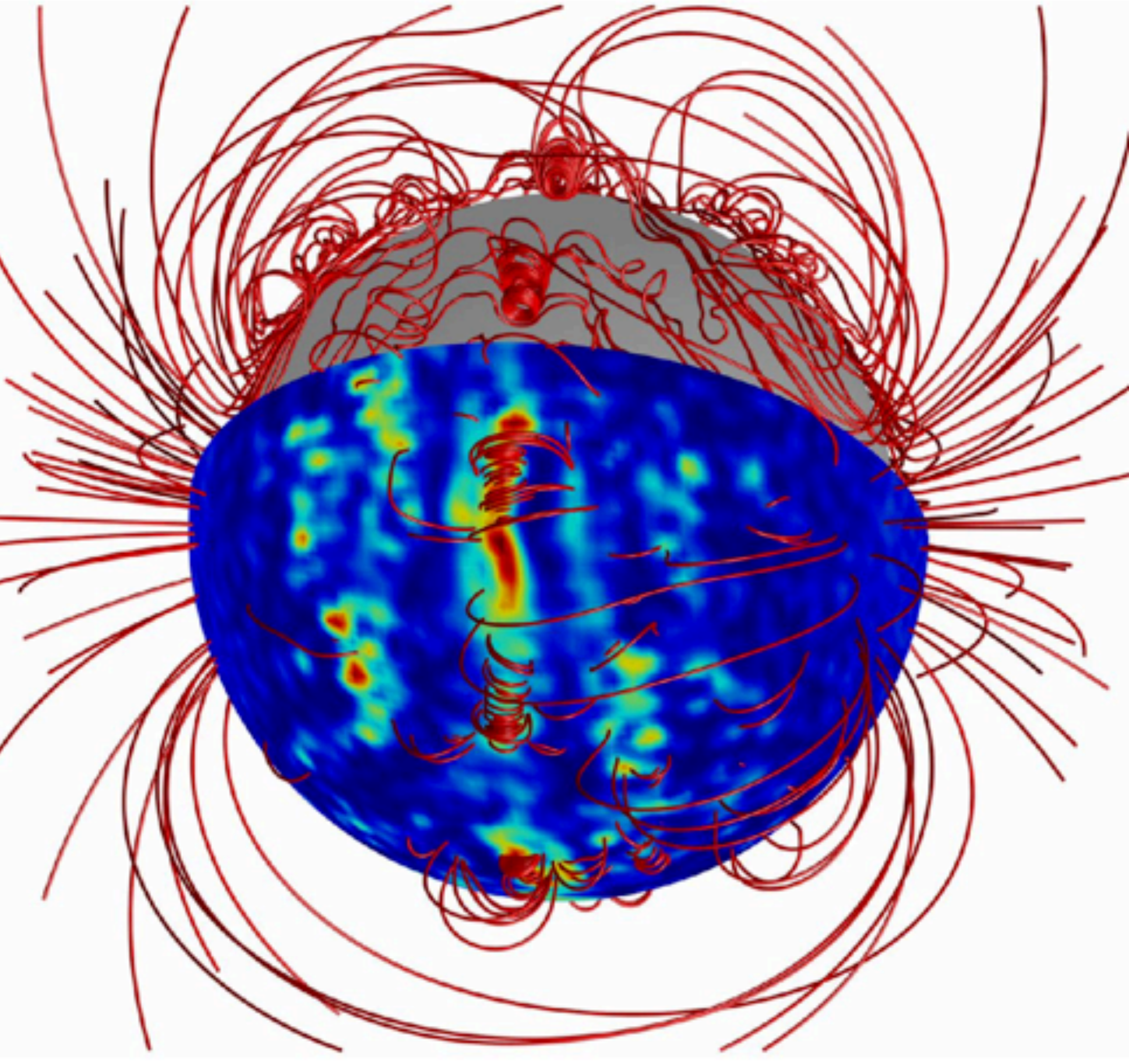
Non-thermal emission from shell collisions



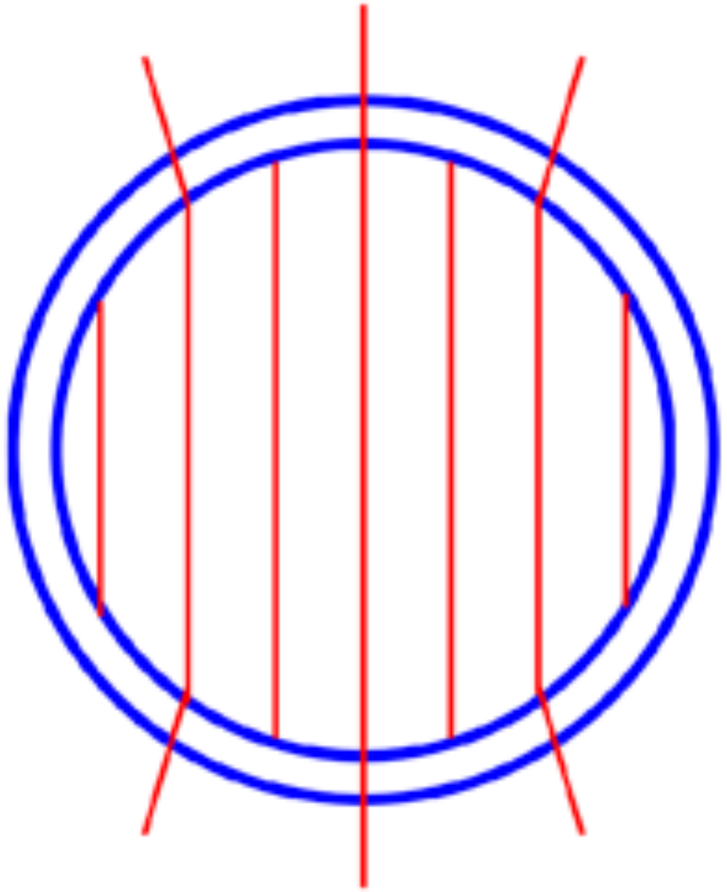
Neill, DT, Van Eerten, Ryan, & Newton (2022) MNRAS, 514, 4



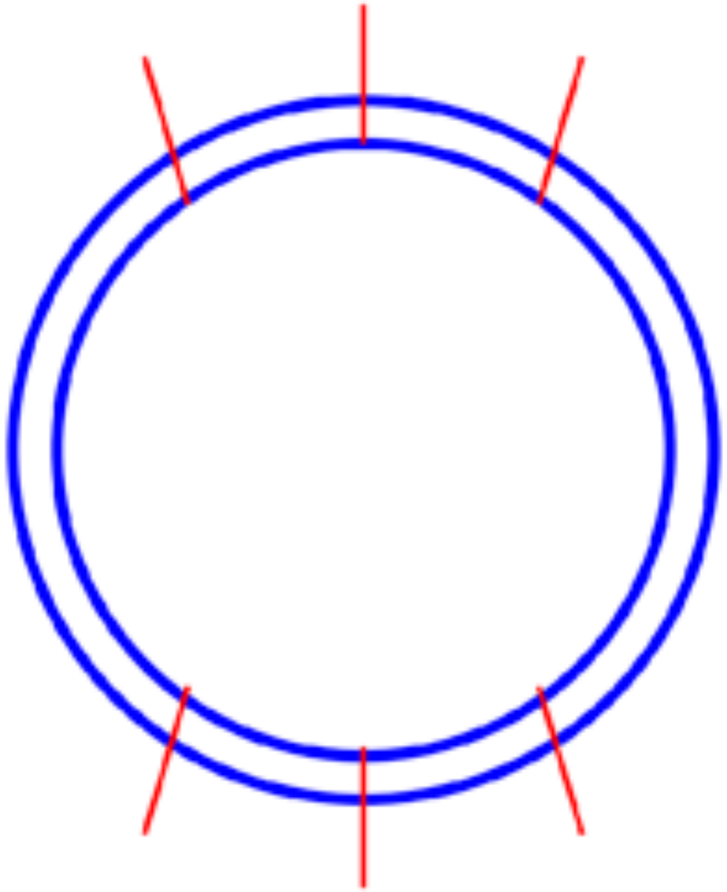
Neill, DT, Van Eerten, Ryan, & Newton (2022) MNRAS, 514, 4



Gourgouliatos, Wood, & Hollerbach (2016) PNAS, 113, 15, 3944

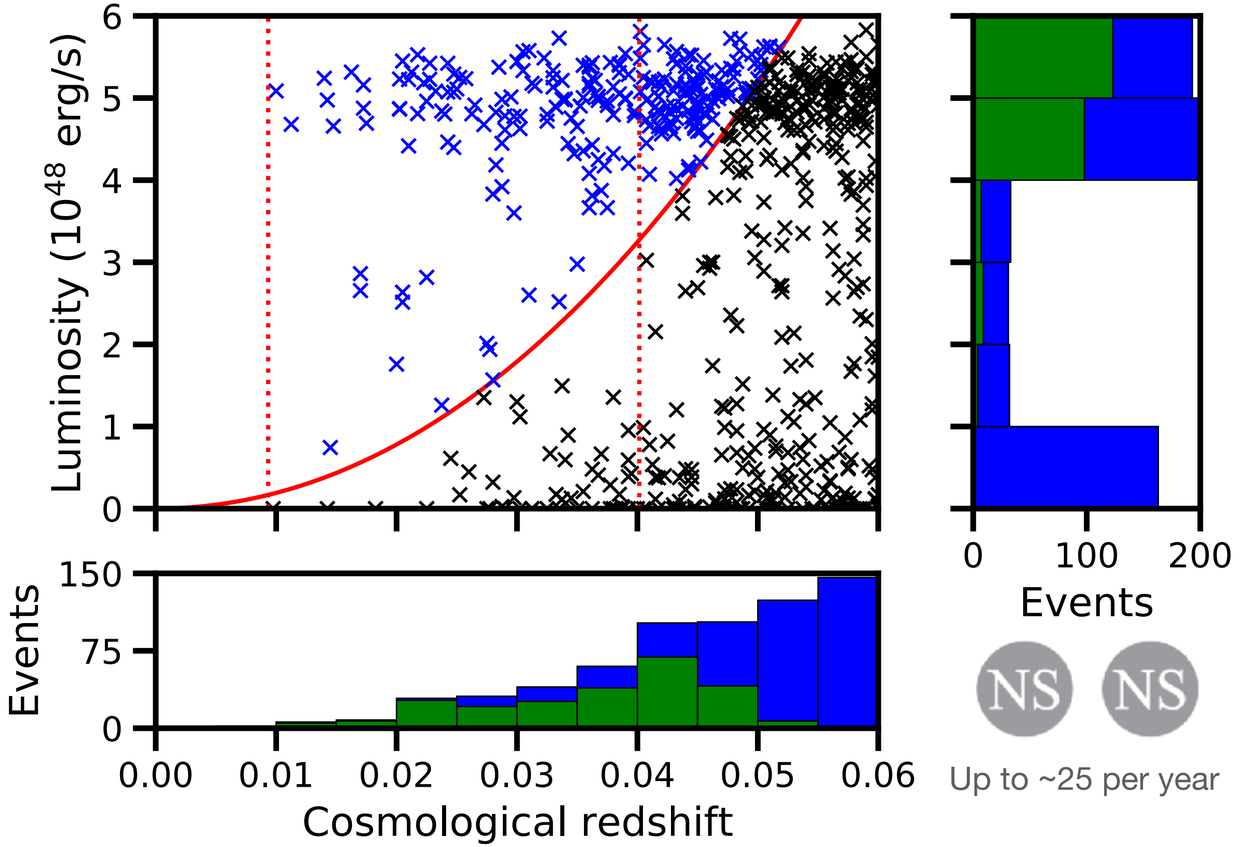


Fields are long lived if they thread the core

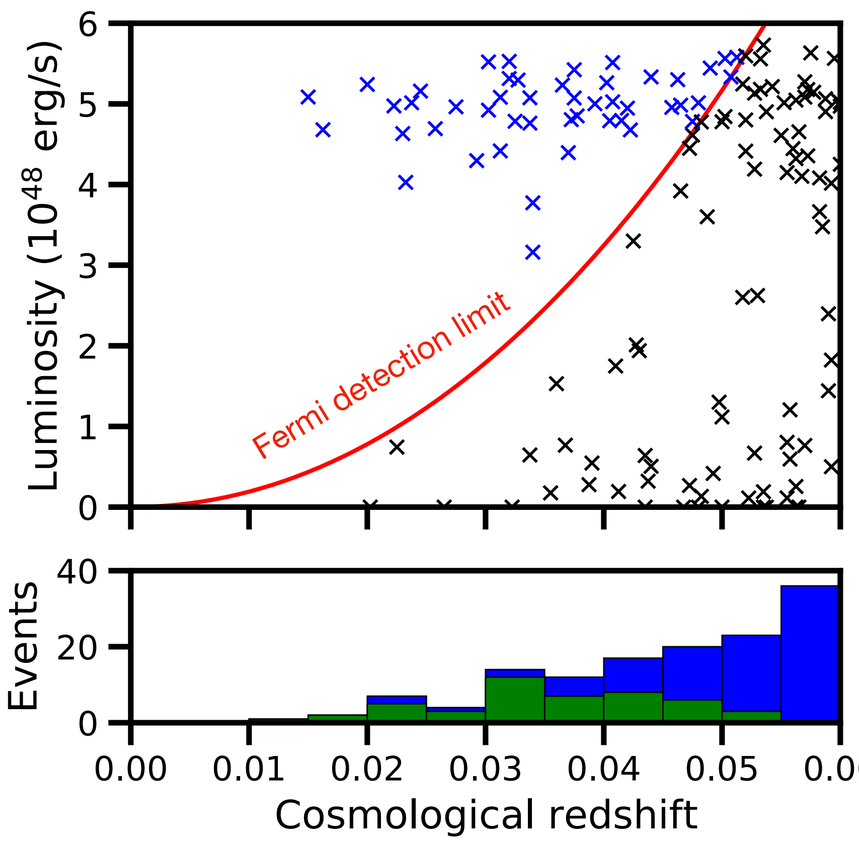


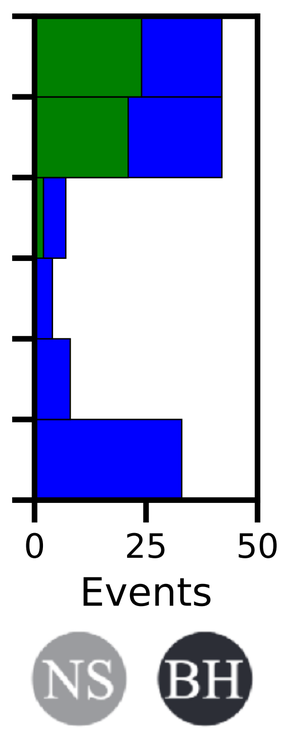
Fields decay in < 10^6 years if anchored only in the crust

Ho, Andersson & Graber (2017) PRC, 96, 065801
Konenkov & Geppert (2000) MNRAS, 313, 1, 66



Up to ~25 per year





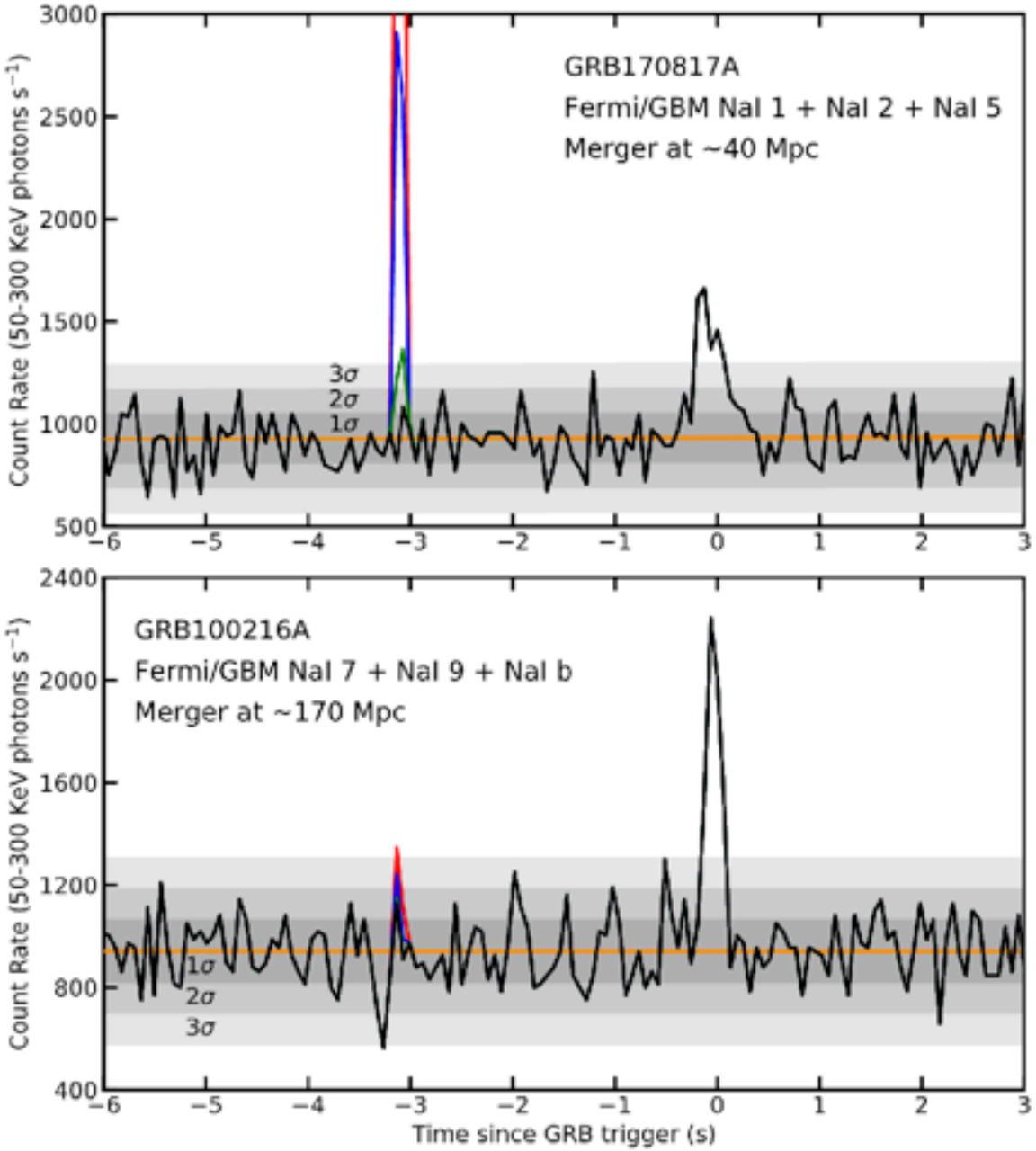
Up to ~5 per year

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

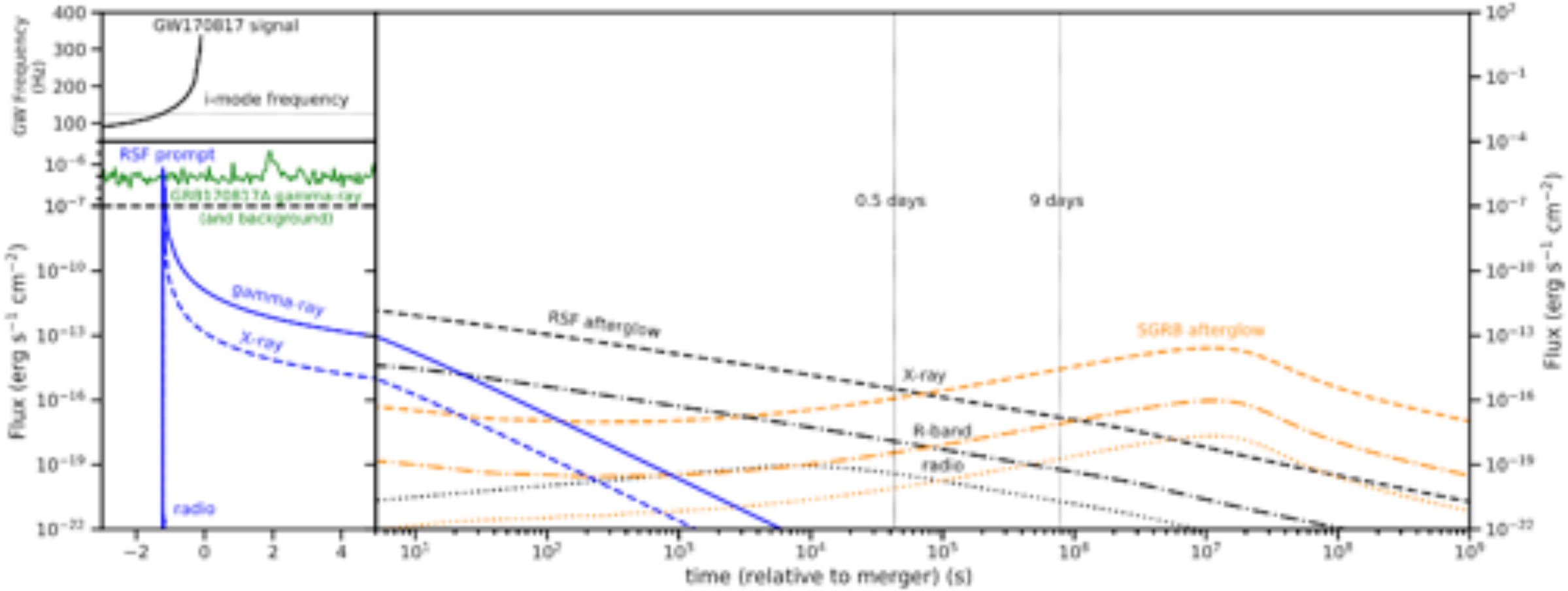
$10^{14.5}$ G

10^{14} G

$10^{13.5}$ G

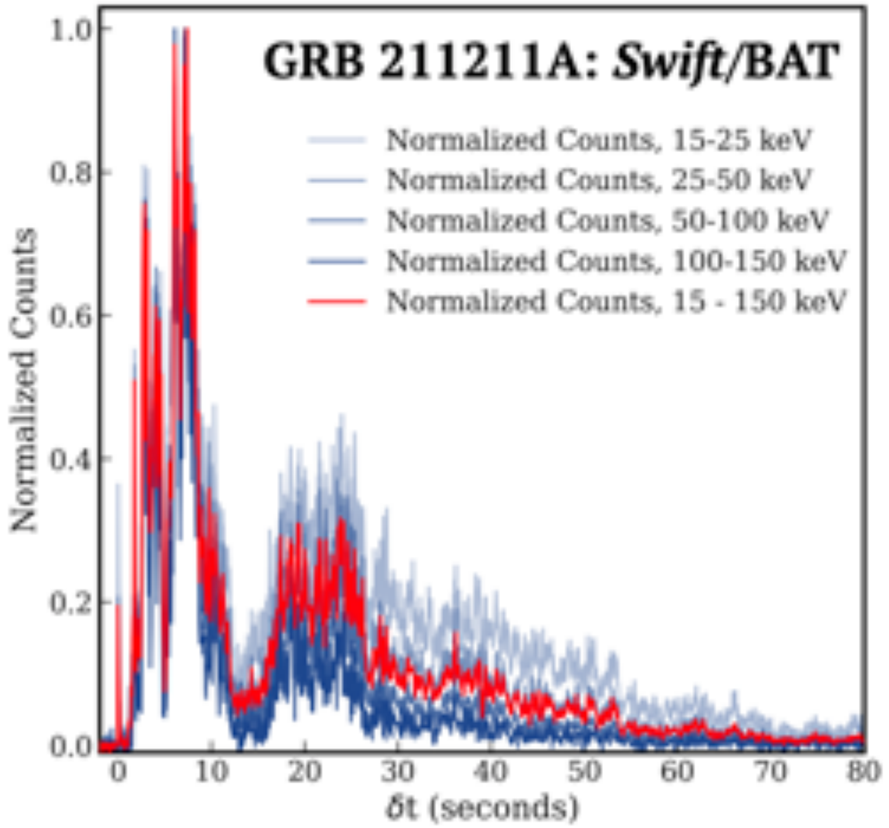


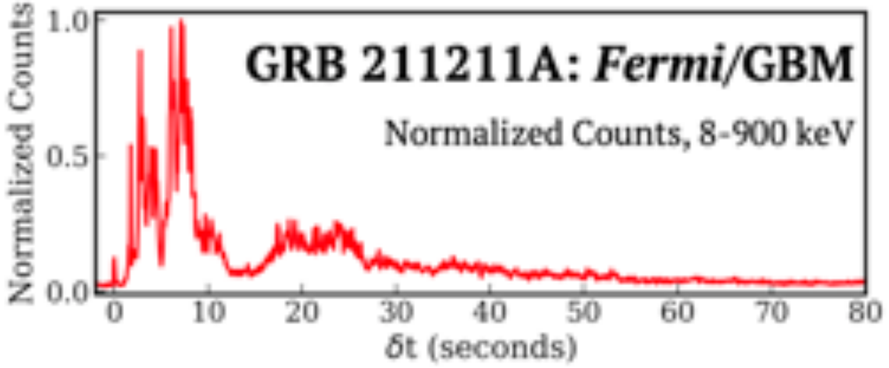
Neill, DT, Van Eerten, Ryan, & Newton (2022) MNRAS, 514, 4

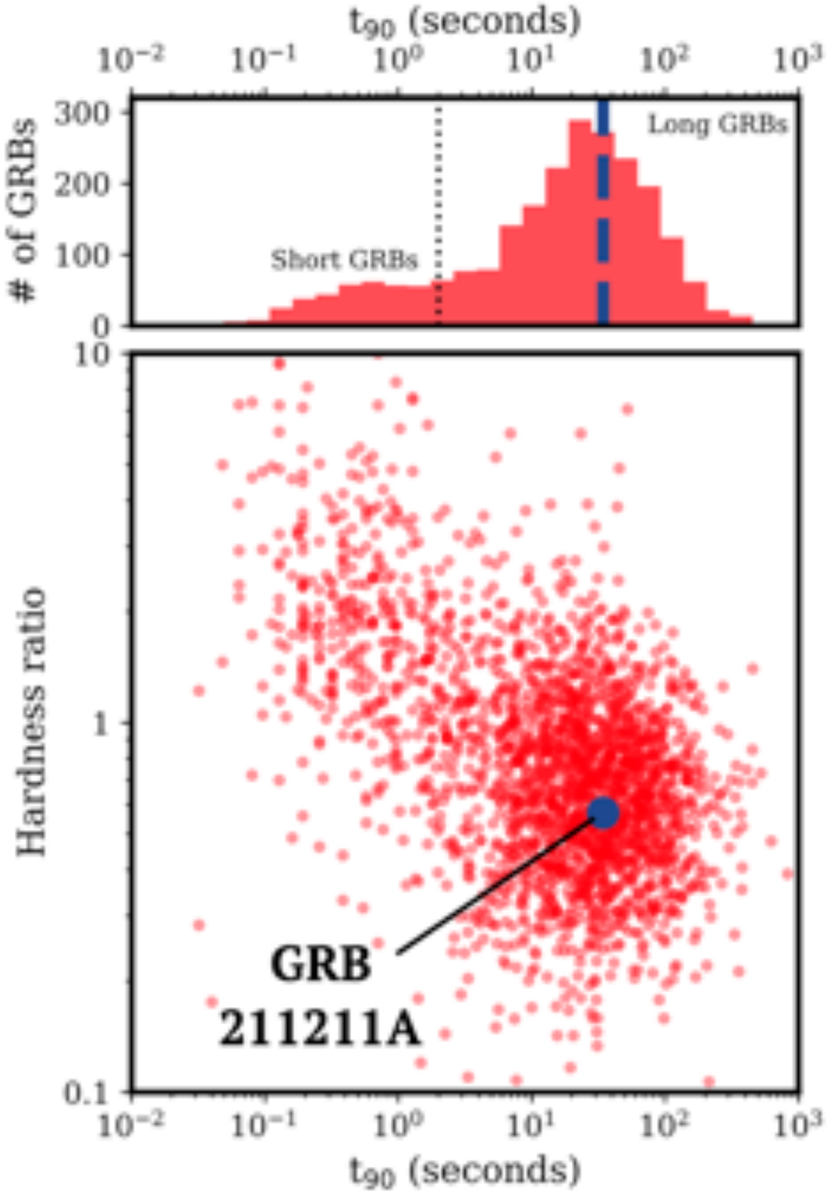


No detectable precursor implies $B_{\rm surf} \lesssim 10^{13.5}{\rm G}$

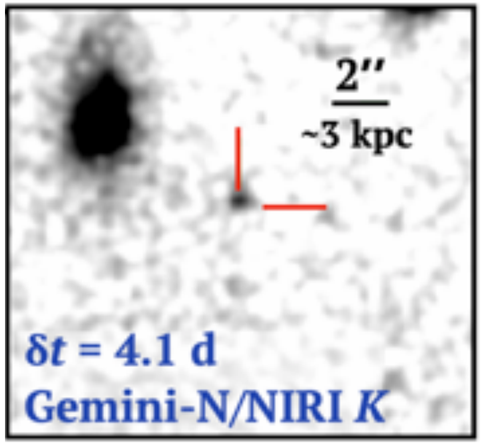
Neill, DT, Van Eerten, Ryan, & Newton (2022) MNRAS, 514, 4







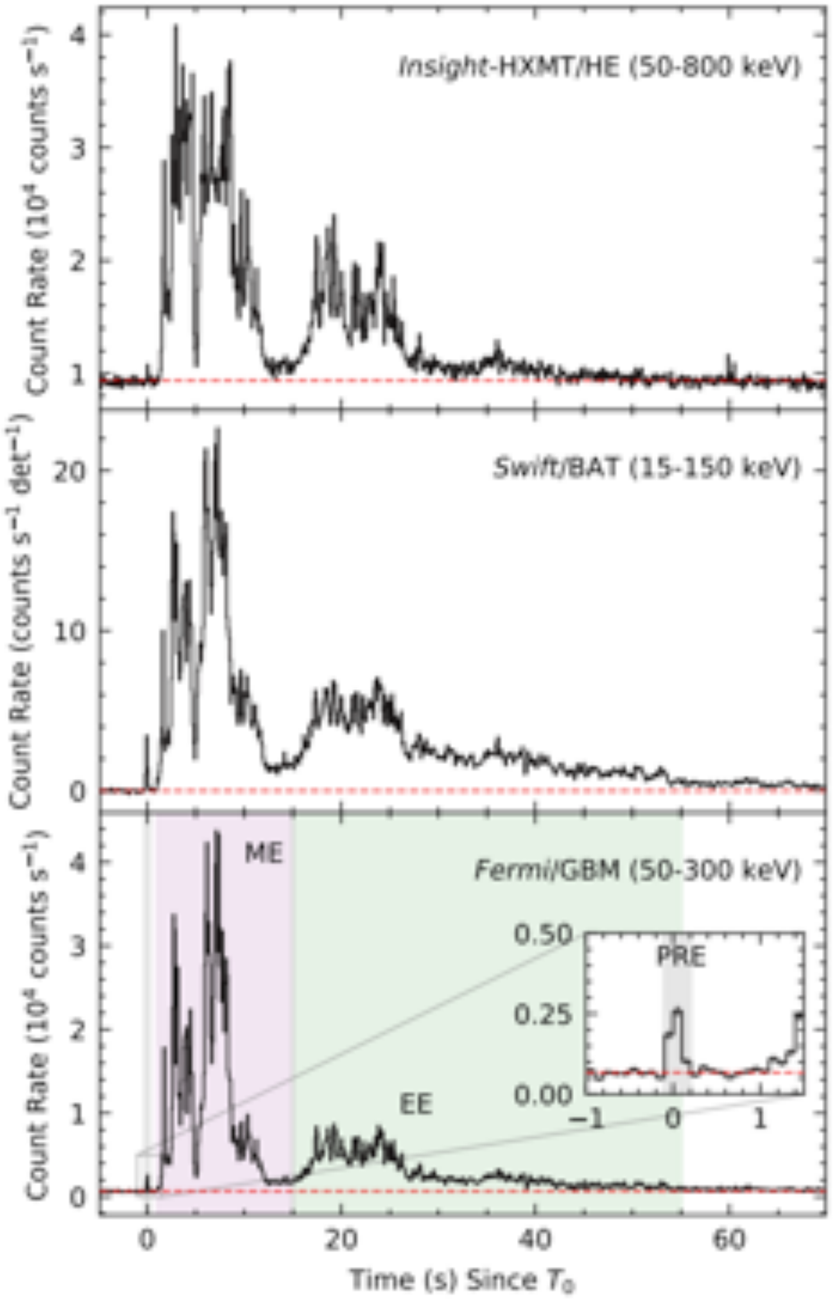
Associated Kilonova!

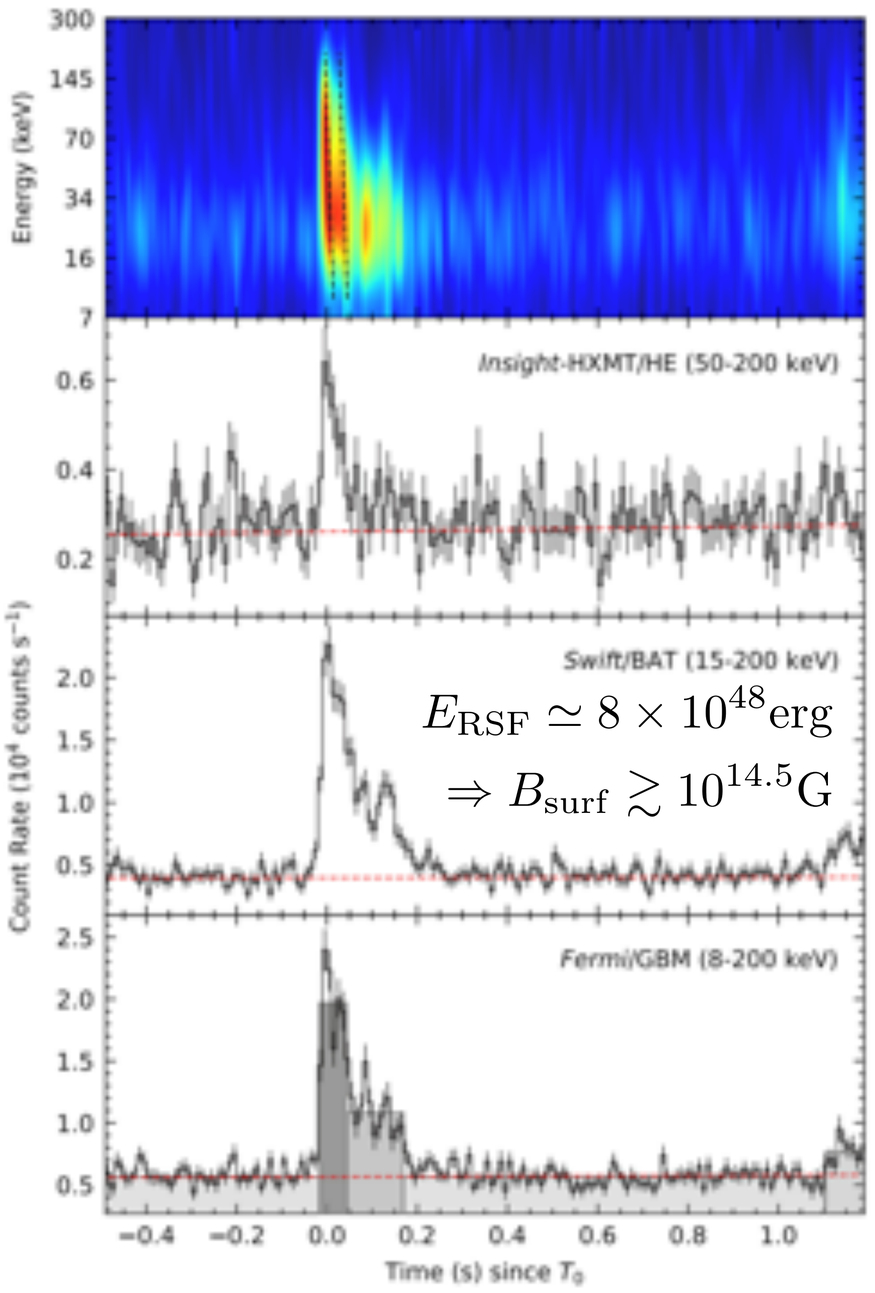


$z = 0.0763 \pm 0.0002$

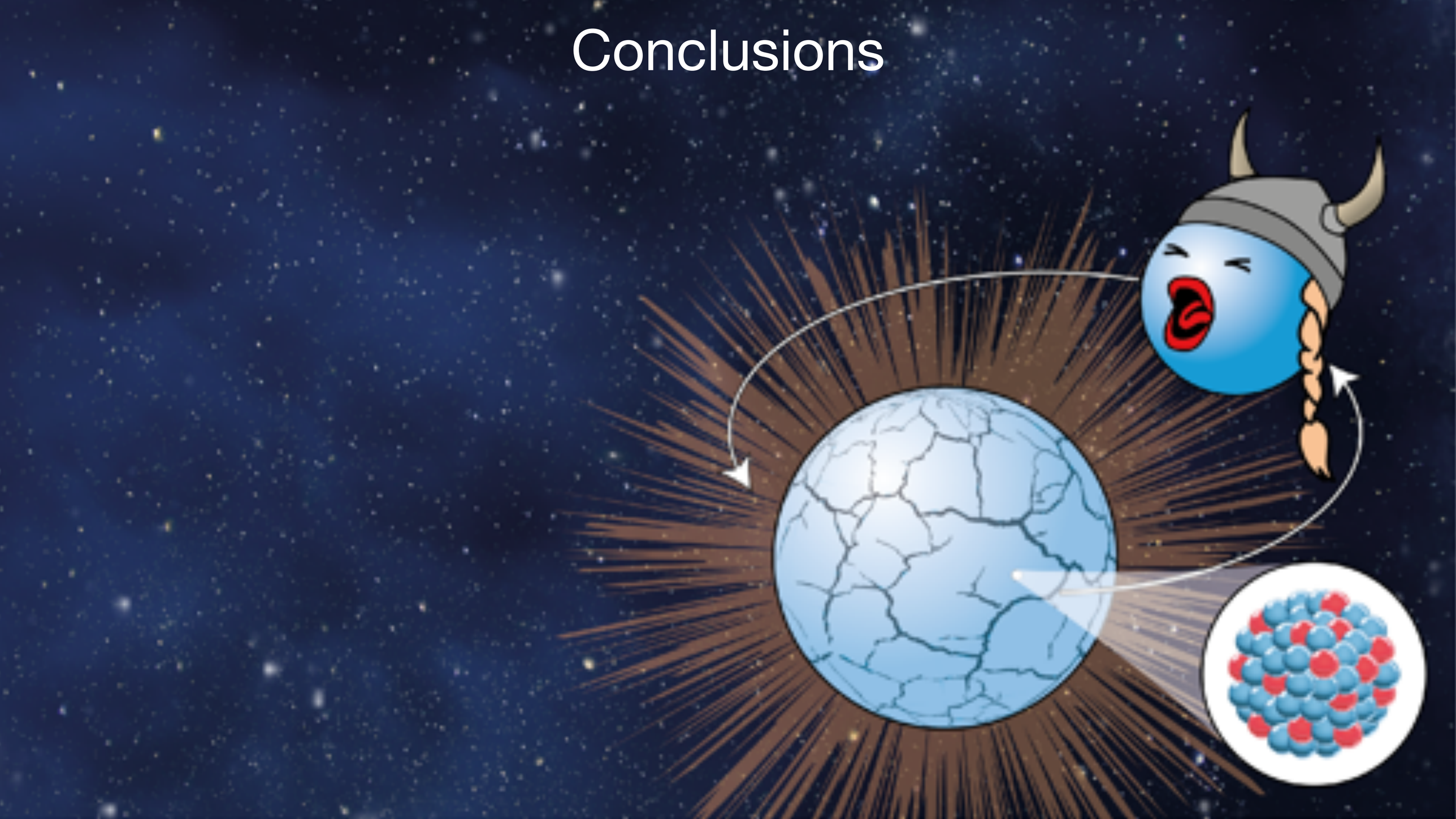
$d \simeq 350\,\mathrm{Mpc}$

Rastinejad+ (2022) arXiv:2204.10864





Conclusions



Conclusions

- Nuclear physicists want to understand many-body interactions of bulk nuclear matter
- Symmetry Energy is diff in binding energy between symmetric nuclear matter and pure neutron matter
- The inner core of a neutron star is very uncertain: may or may not be nucleonic
- Symmetry Energy is important, but most core-dominated observables do not probe Symmetry Energy!
- It is best probed near the core/crust boundary.
- RSFs are tidally induced resonances that cause Gamma-Ray flares
- RSFs naturally probe the crust-core boundary (~ 1/2 saturation)
- Let's build collaboration to probe the different regions of neutron stars and the different physics
- Asteroseismology is great for probing different regions