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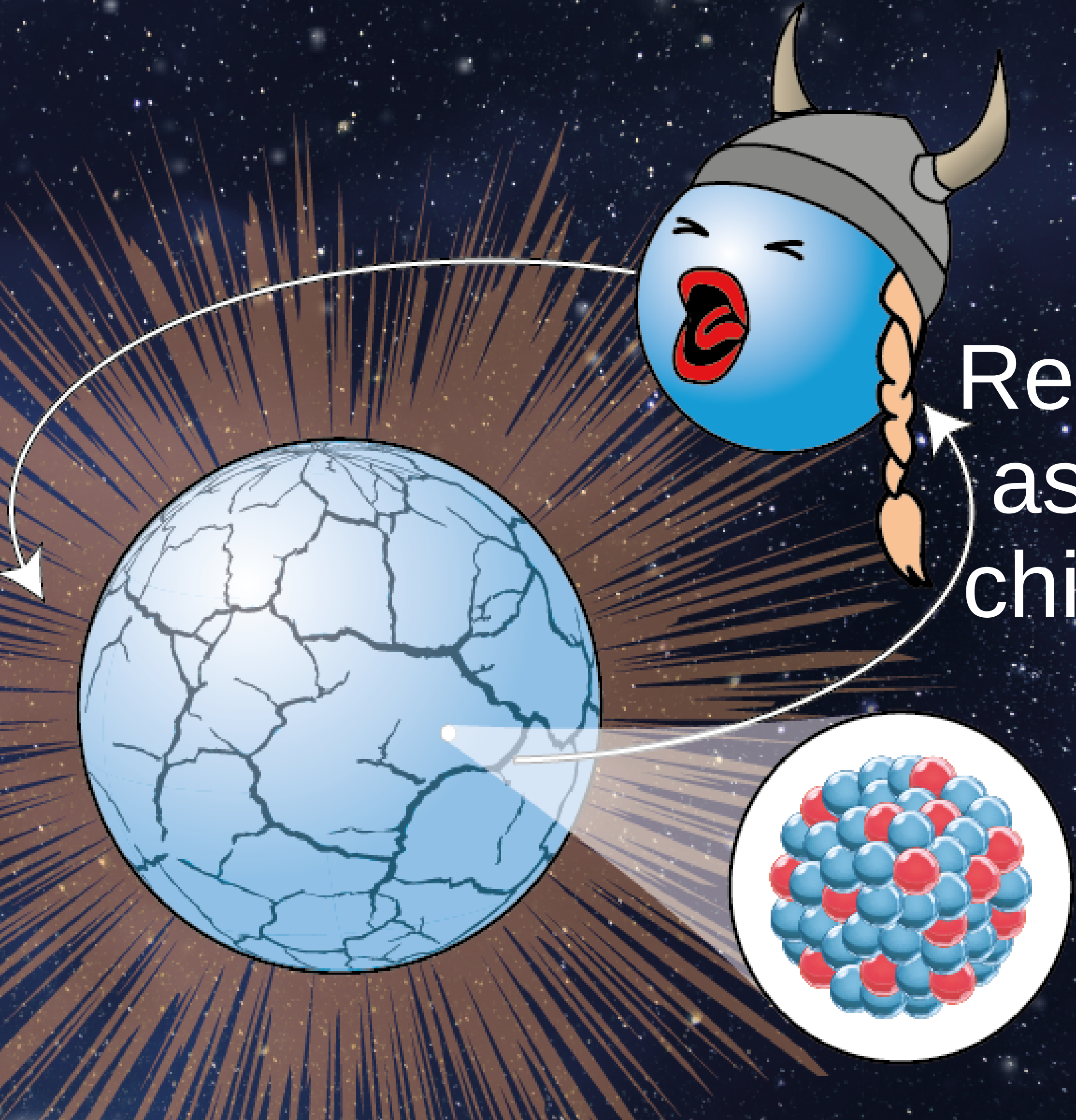

Resonant shattering flares as astrophysical tests of chiral effective field theory

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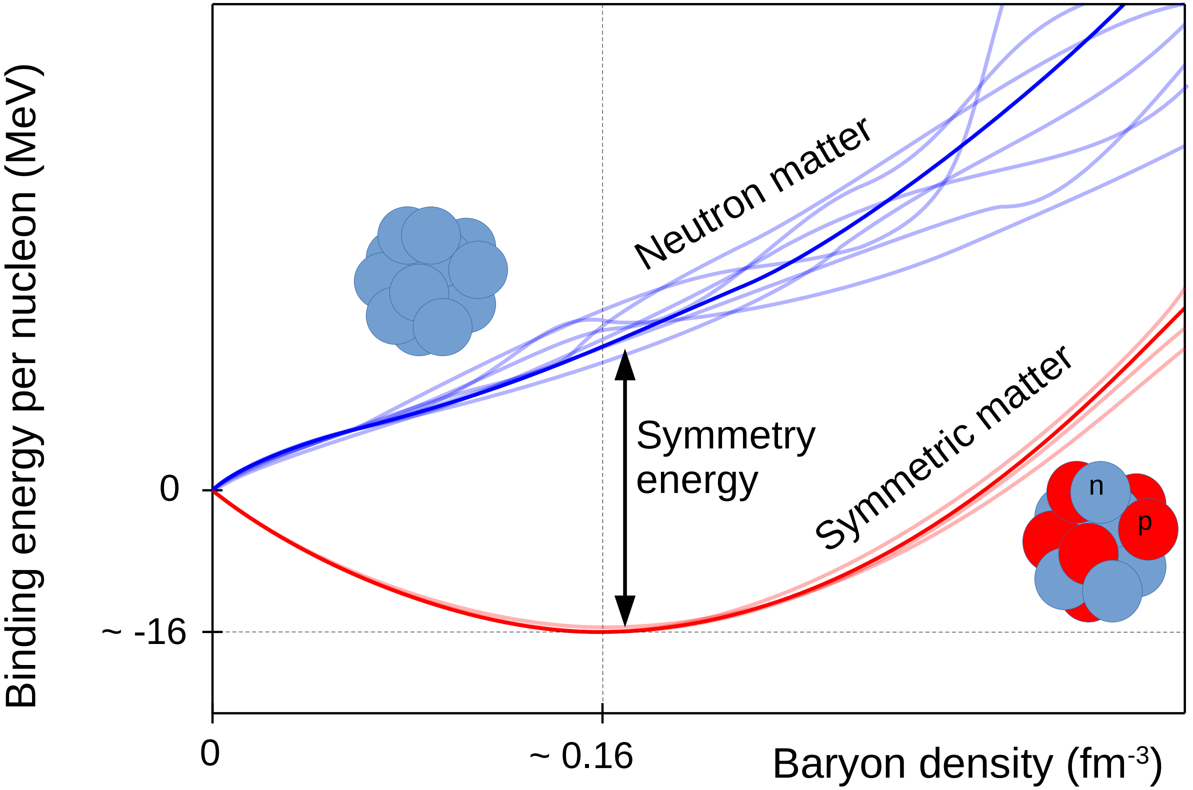
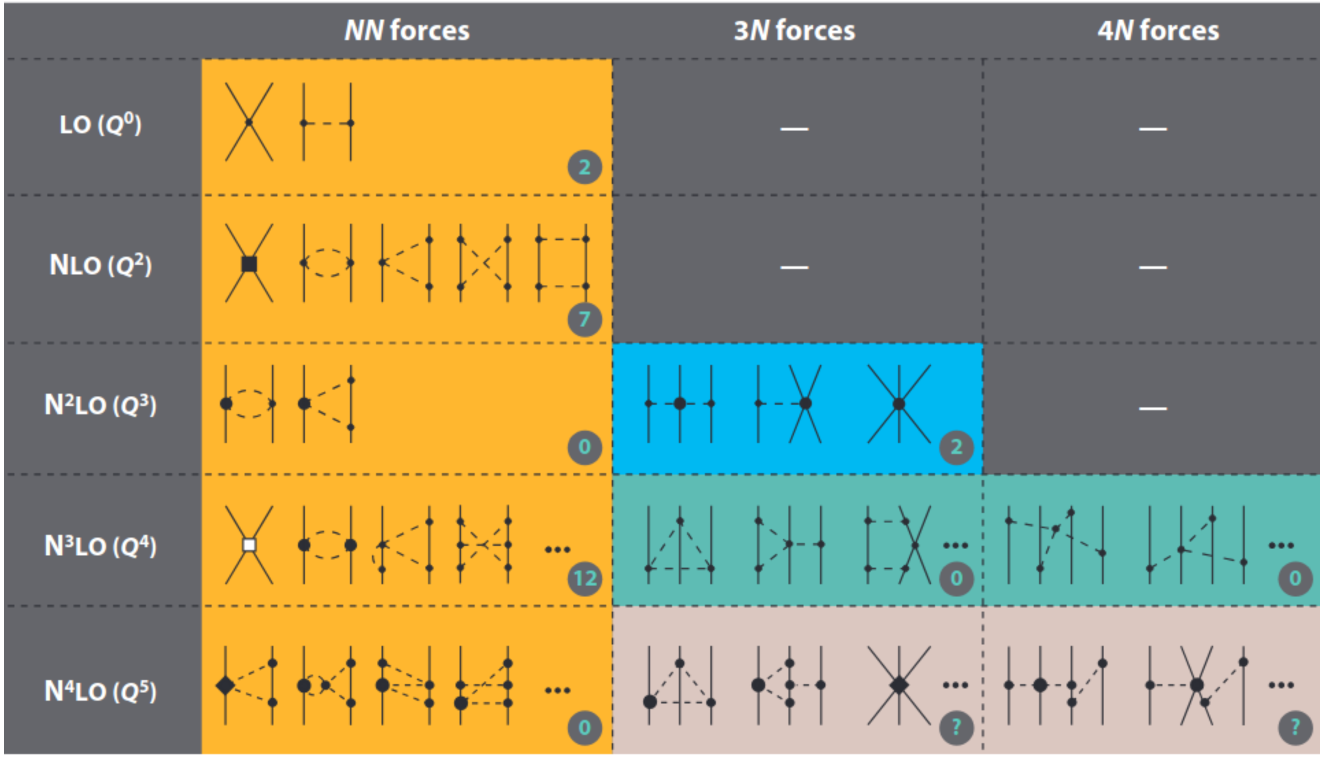
Nuclear matter EOS

- A key component in modelling nuclei and neutron stars
- Various approaches have been developed to calculate properties of nuclear matter.



Chiral effective field theory

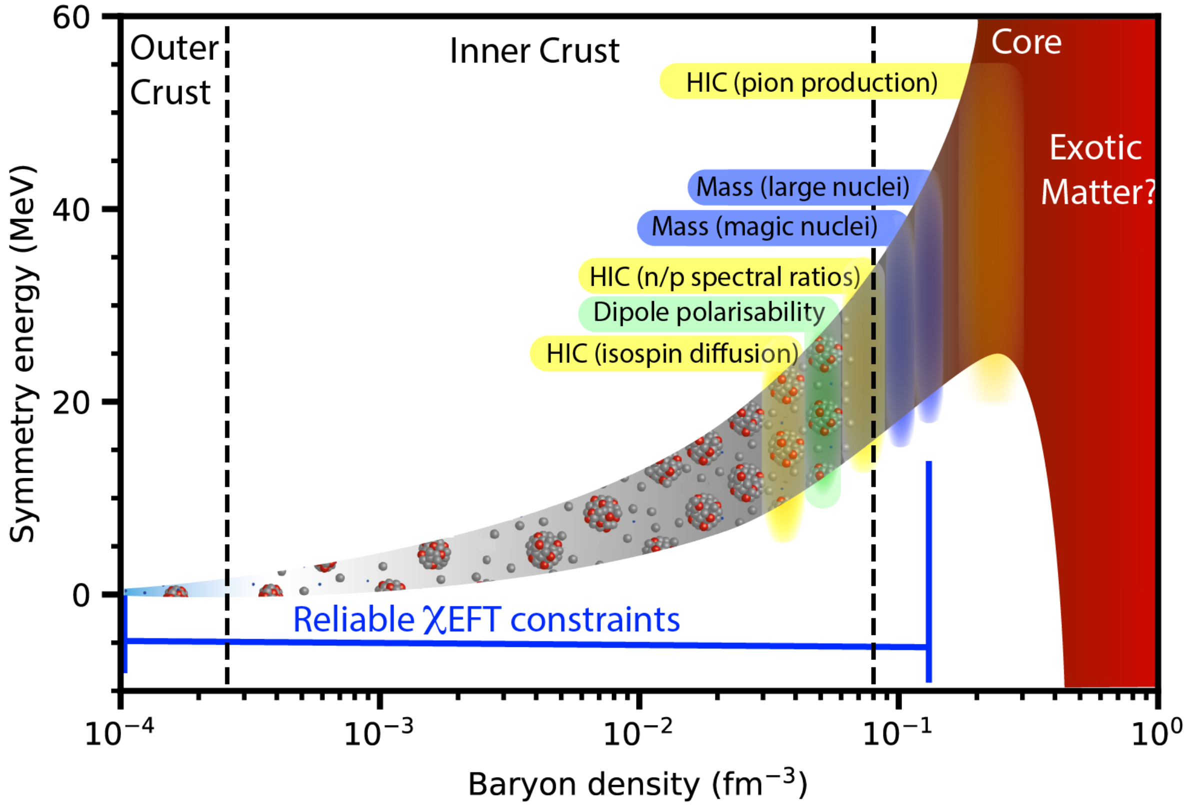
- Consistent with the symmetries of QCD, but using nucleon and pion degrees of freedom.
- Uncertainties can be meaningfully quantified
- How can we test its predictions for nuclear matter?



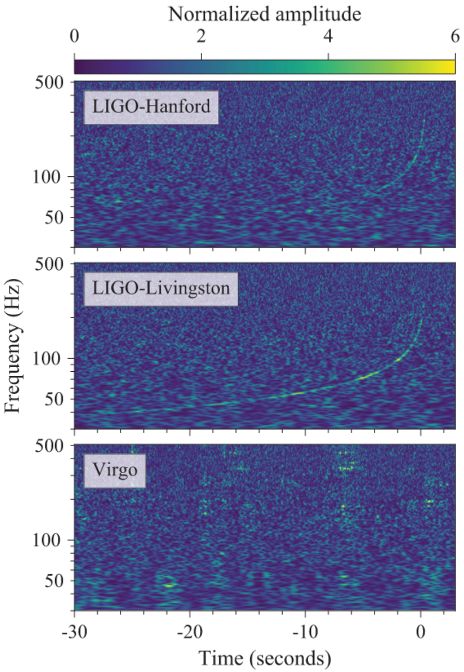
Drischler C., Holt J., Wellenhofer C., 2021, ARNPS, 71, 403

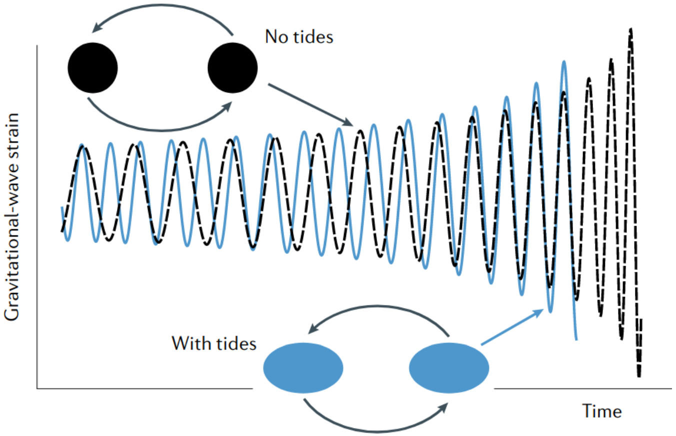
Nuclear symmetry energy

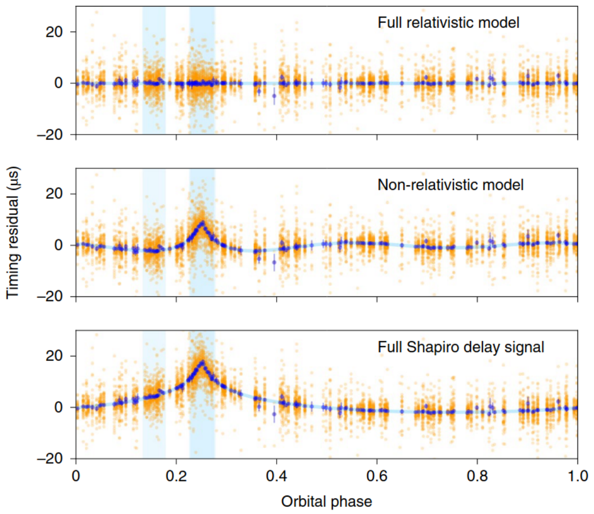
- Probed at low density in experiment
- What can we learn from neutron stars?

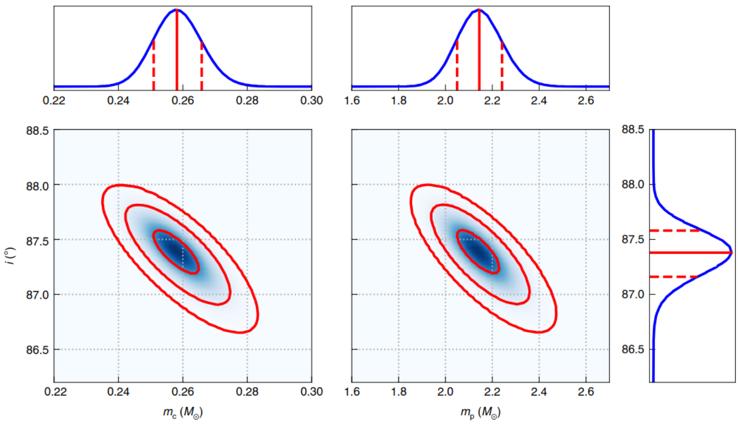


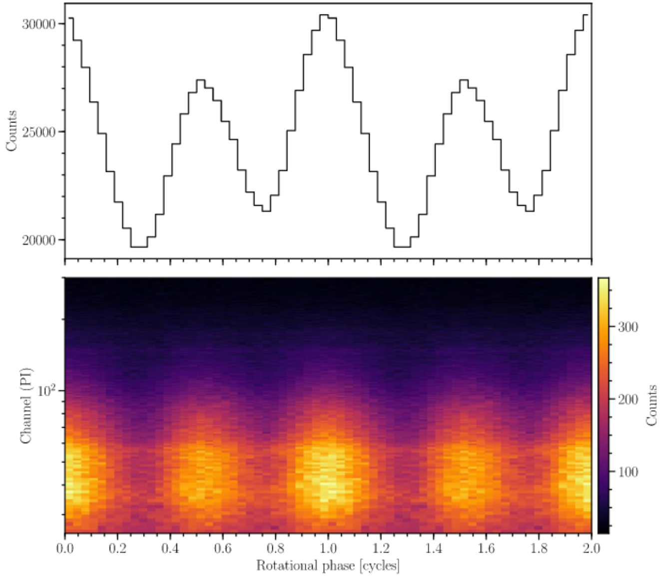
Neutron star observables

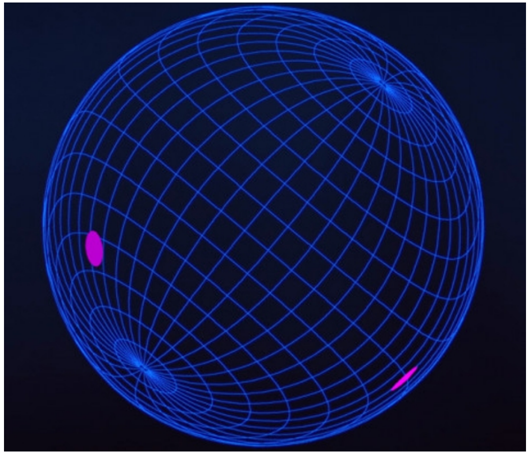








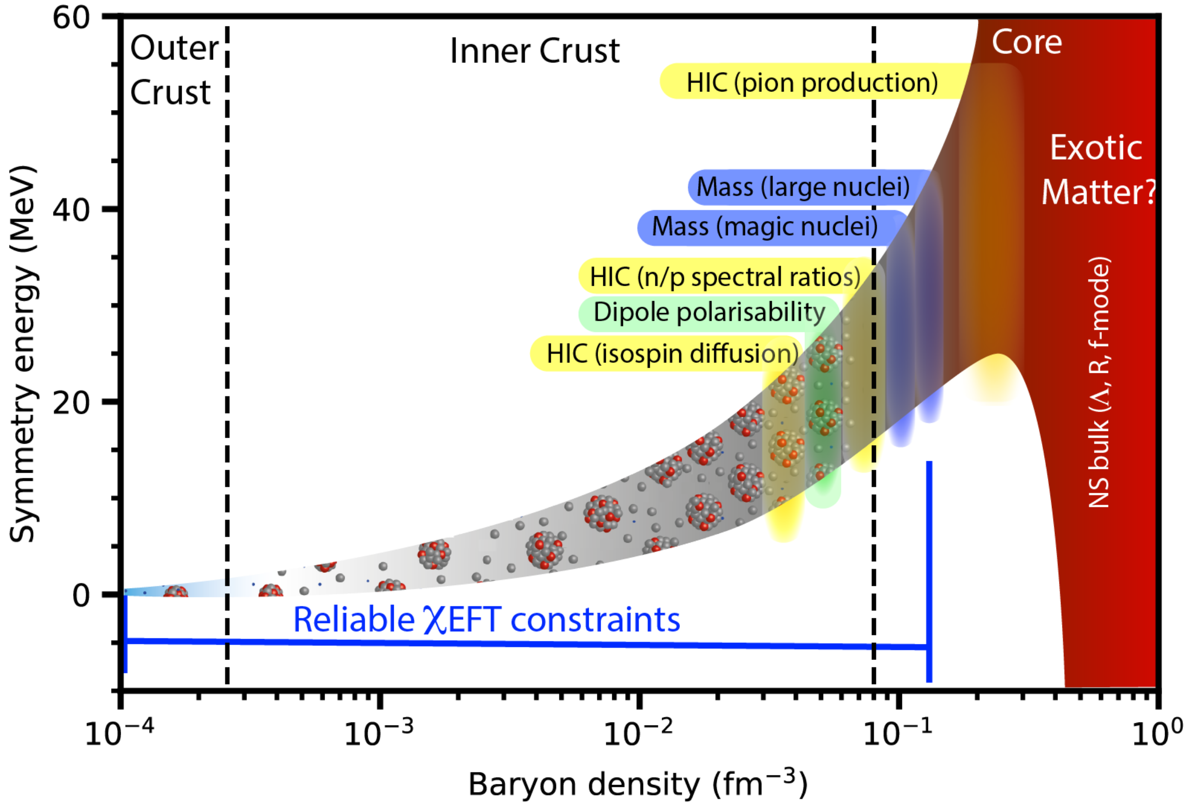




Abbott B.~P. et al., 2017, PhRvL, 119, 161101
Cromartie H.~T. et al., 2020, NatAs, 4, 72
Riley T.~E. et al., 2021, ApJL, 918, L27

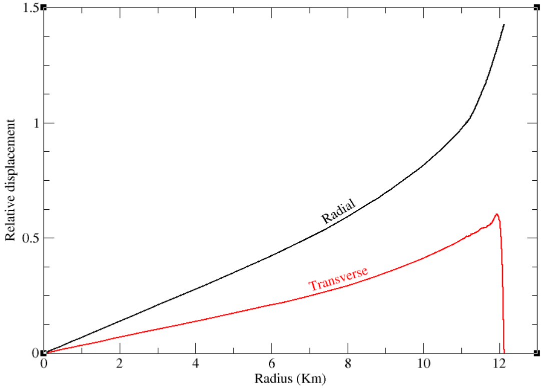
Nuclear symmetry energy

- Probed at low density in experiment
- Probed at high density in neutron stars
- Can we also look at low densities in neutron stars?

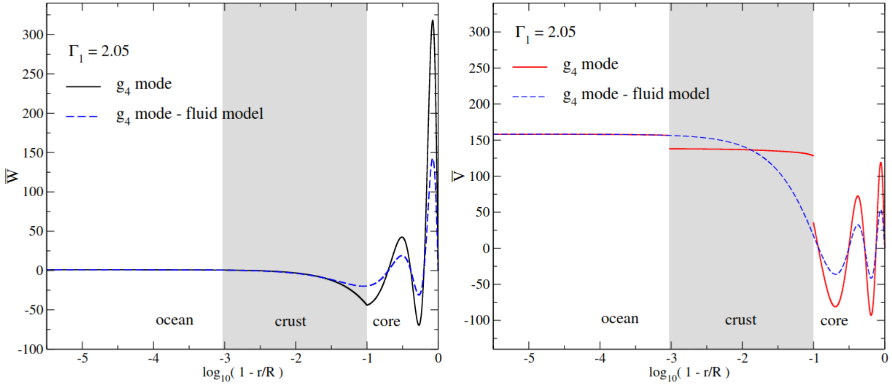


Asteroseismic (quasi-)normal modes

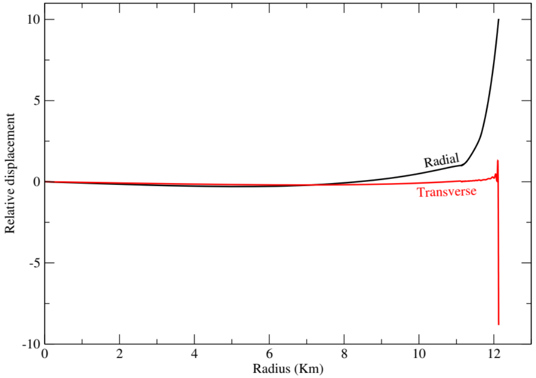
Fundamental (f) mode



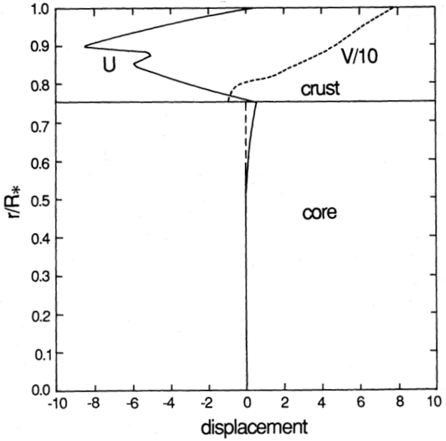
Gravitational (g) modes



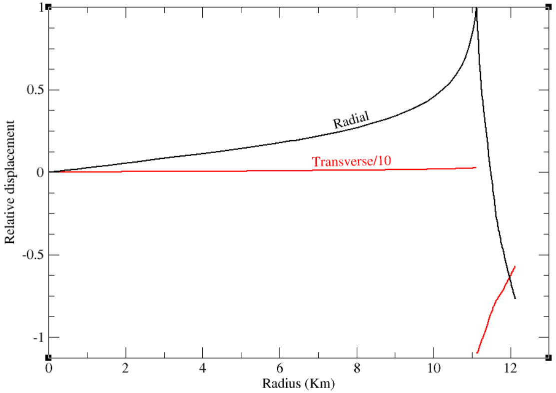
Pressure (p) modes



shear (s) modes



Interface (i) modes



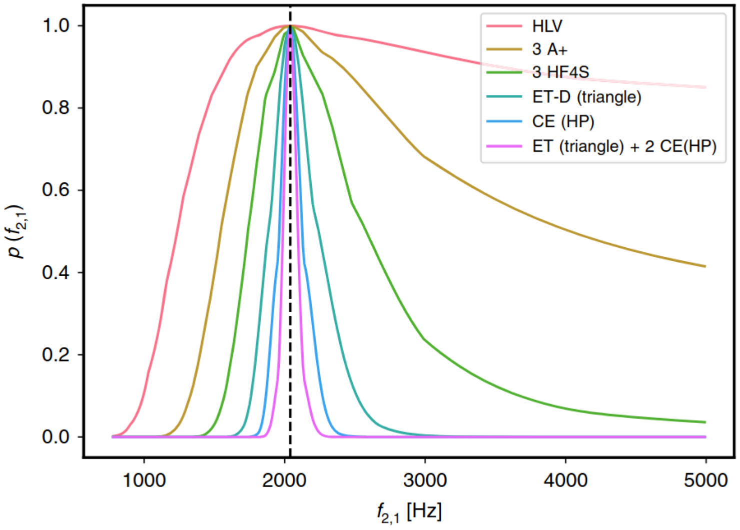
McDermott P.~N. et al, 1988, ApJ, 325, 725
Passamonti A. et al, 2021, MNRAS, 504, 1273

Signatures of modes

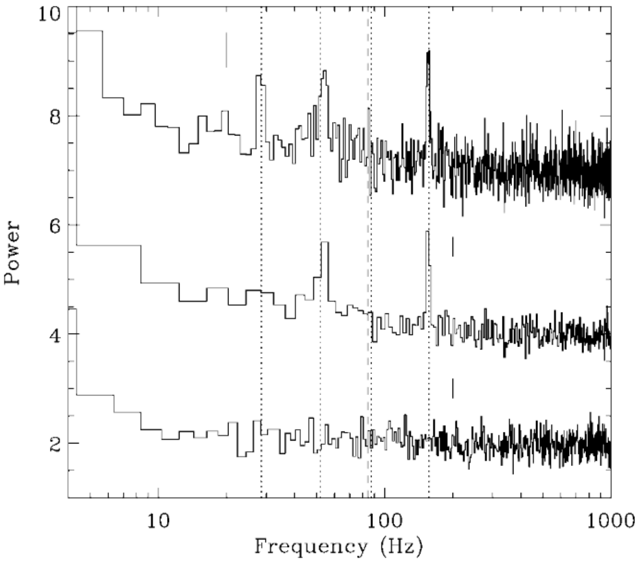
Tidal signature in GWs

QPOs in SGR giant flares

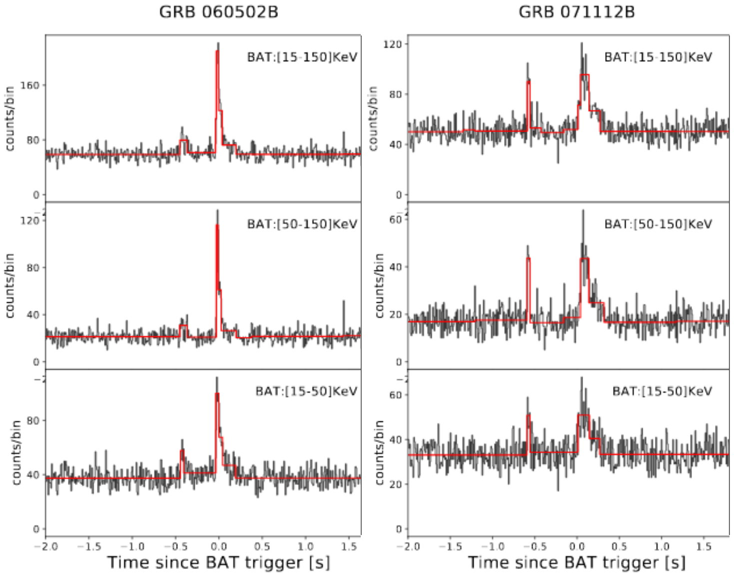
SGRB precursor flares?



Fundamental mode



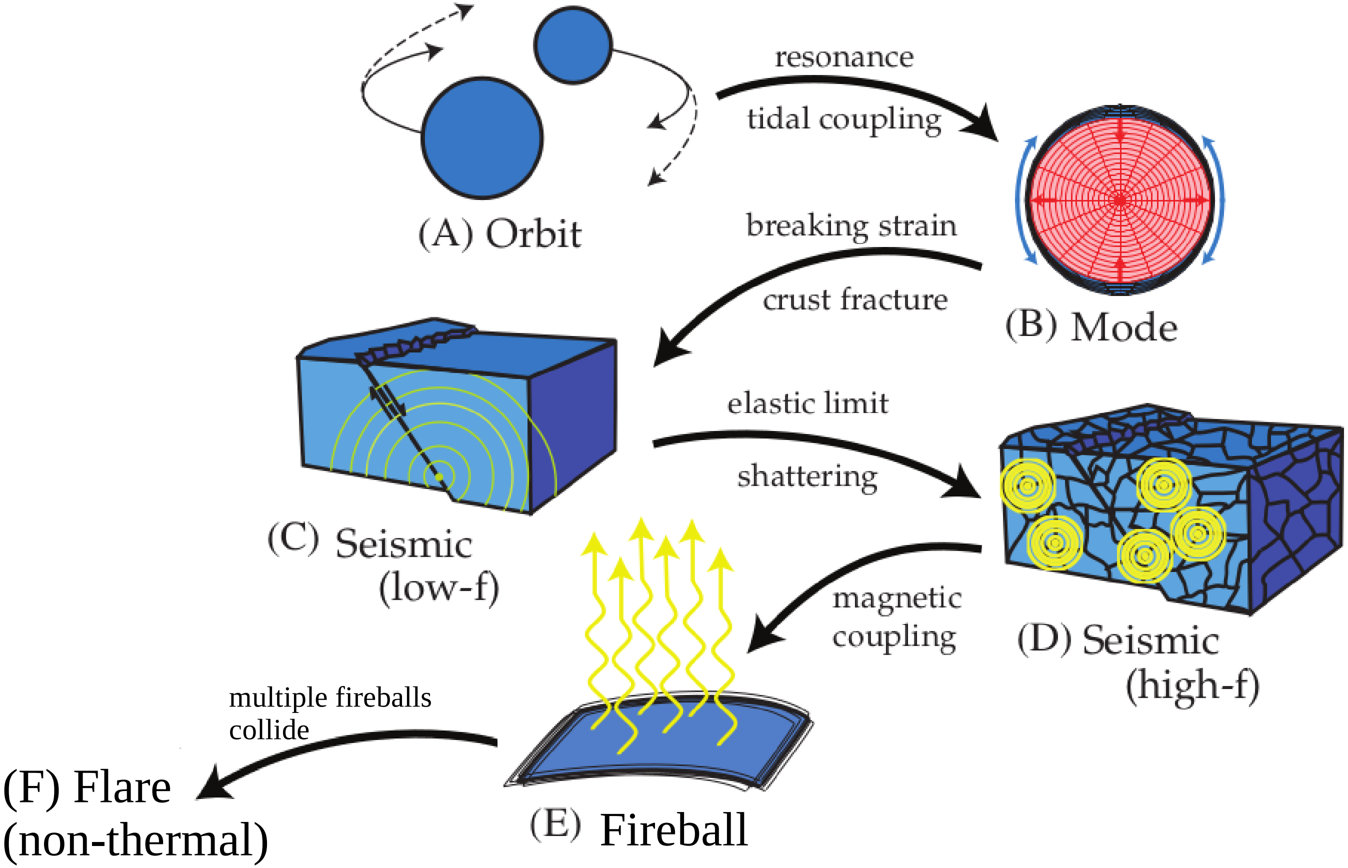
Toroidal shear modes?



Crust-core interface mode?

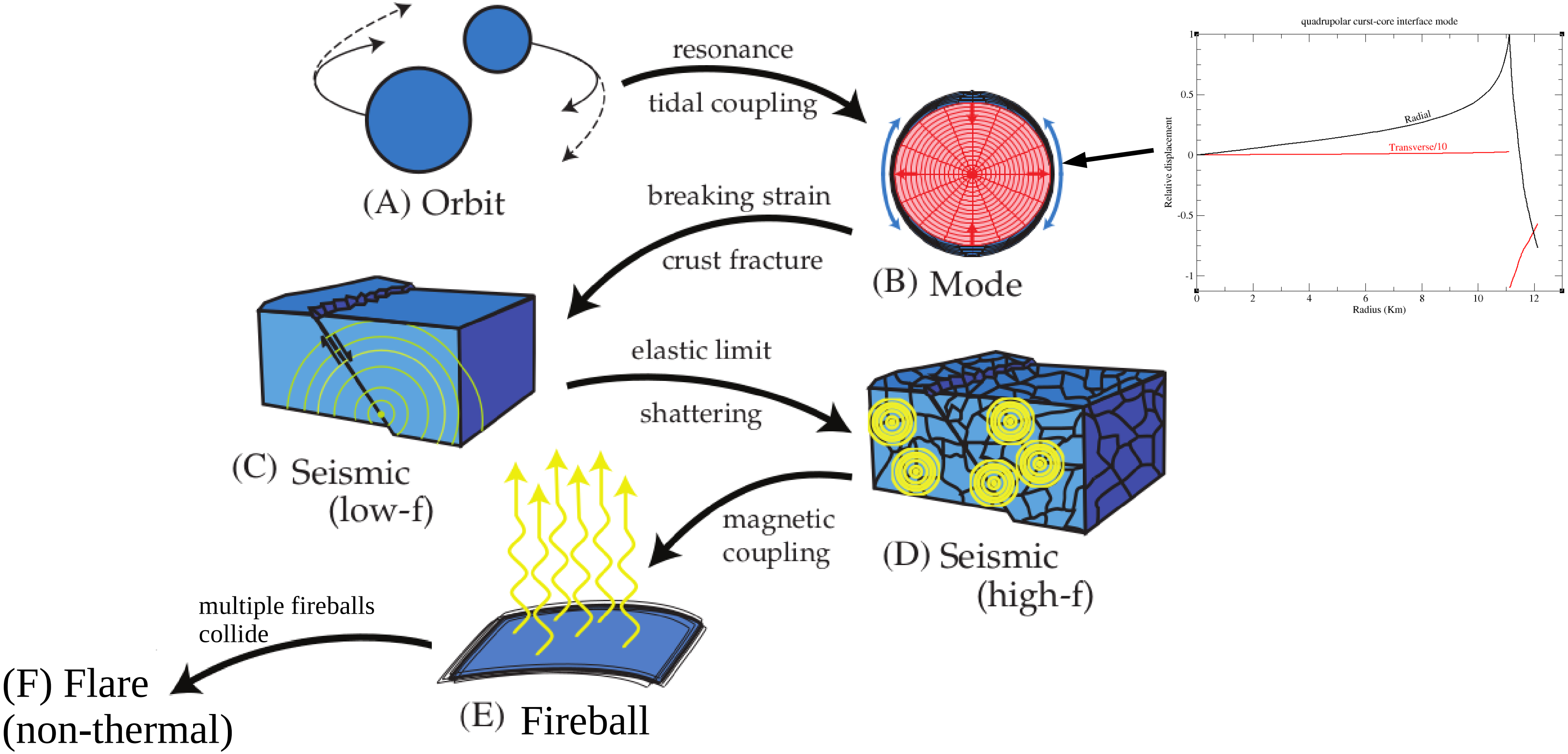
Pratten G. et al., 2020, NatCo, 11, 2553
Strohmayer & Watts, 2005, ApJL, 632, L111
Zhong S.-Q. et al., 2019, ApJ, 884,25

Resonant Shattering Flares (RSFs)



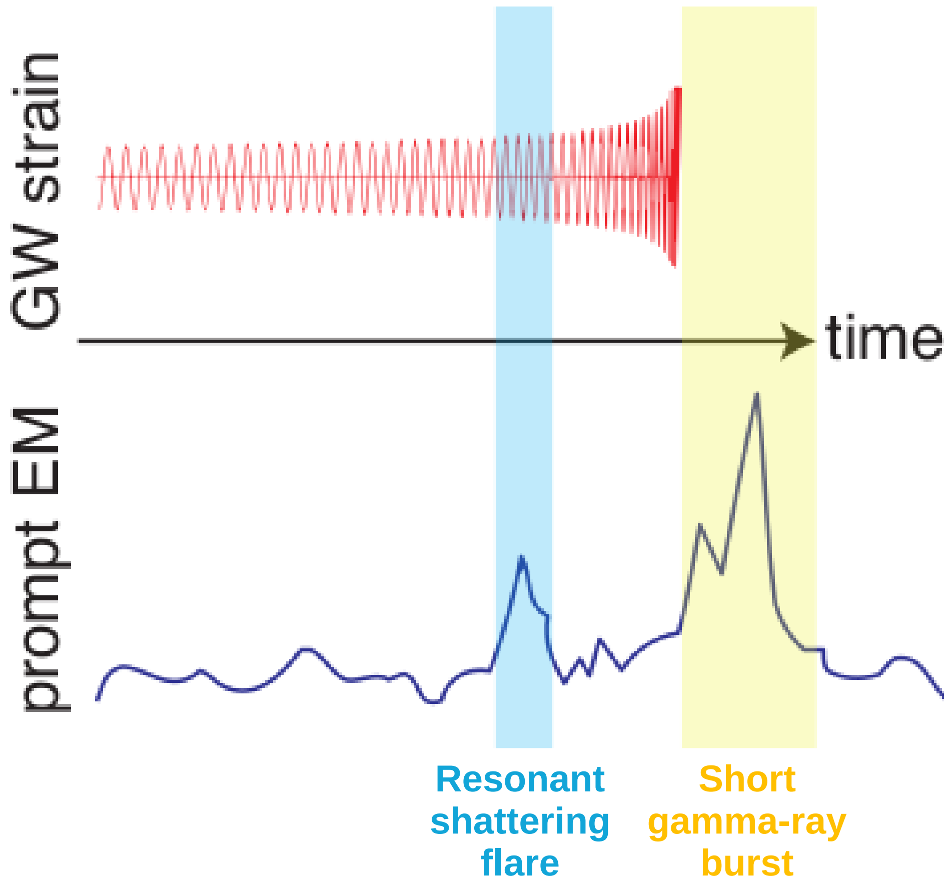
Tsang D., 2013, ApJ, 777, 103
Tsang D. et al., 2012, Phys. Rev. Lett., 108, 011102

Resonant Shattering Flares (RSFs)



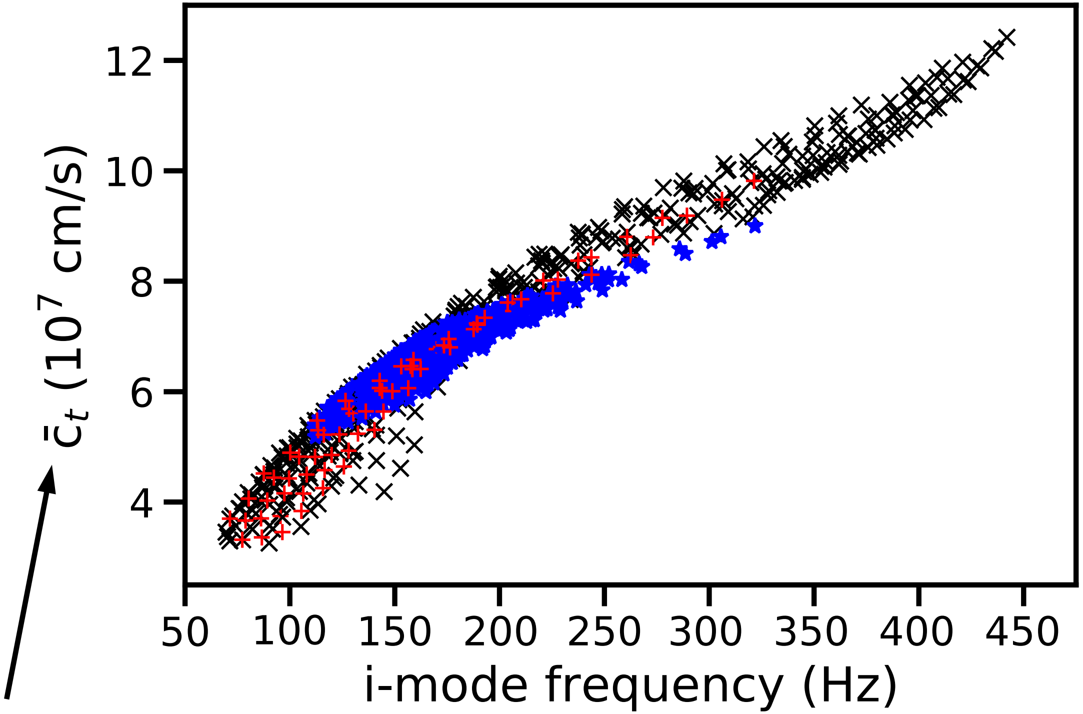
Tsang D., 2013, ApJ, 777, 103
Tsang D. et al., 2012, Phys. Rev. Lett., 108, 011102

Multimessenger observation



- A RSF occurs when the i-mode is resonant with the binary orbit
- The GW frequency is simply twice the orbital frequency
- Measuring the GW frequency at the time of an RSF gives us the i-mode frequency

Probing NS crust composition



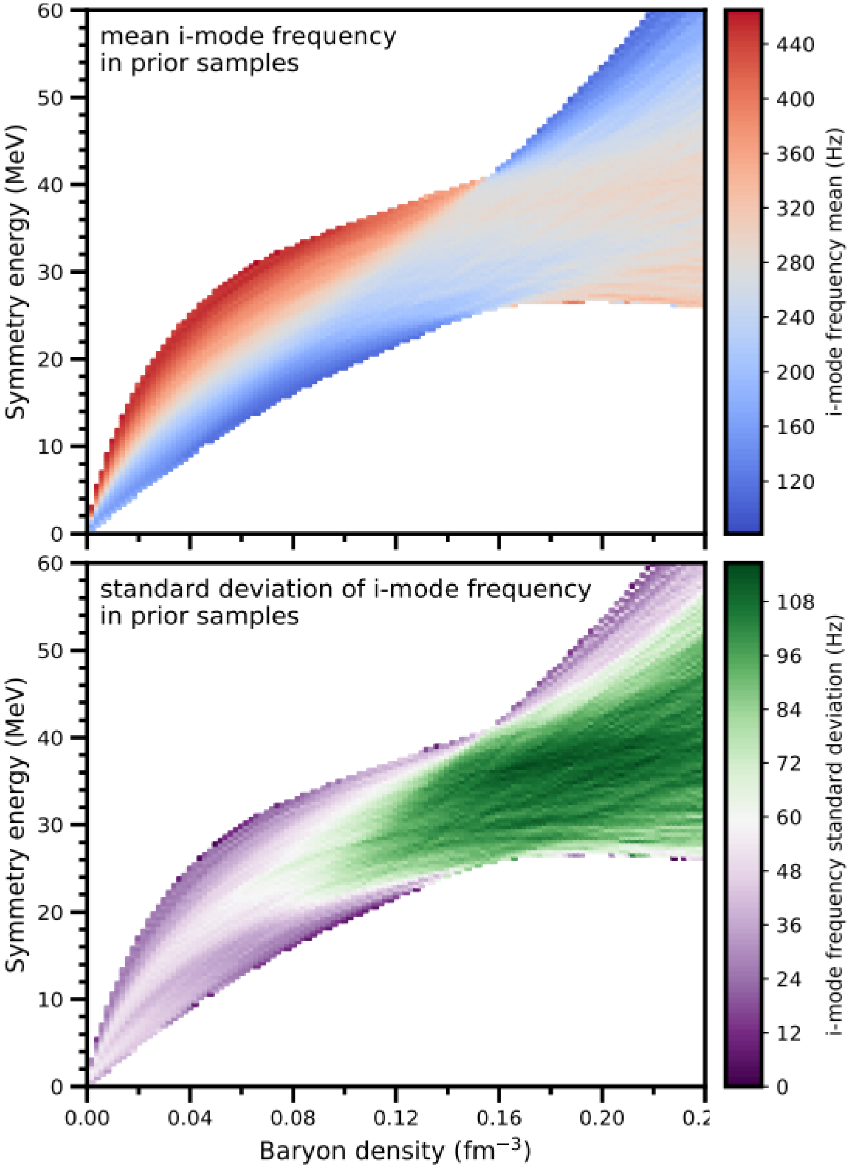
Density-weighted average shear speed in the crust

- The i-mode is restored by shear forces, so its frequency depends on shear speed in the crust

- Shear speed in turn depends on the crust's composition, so the frequency and shear speed are strongly correlated

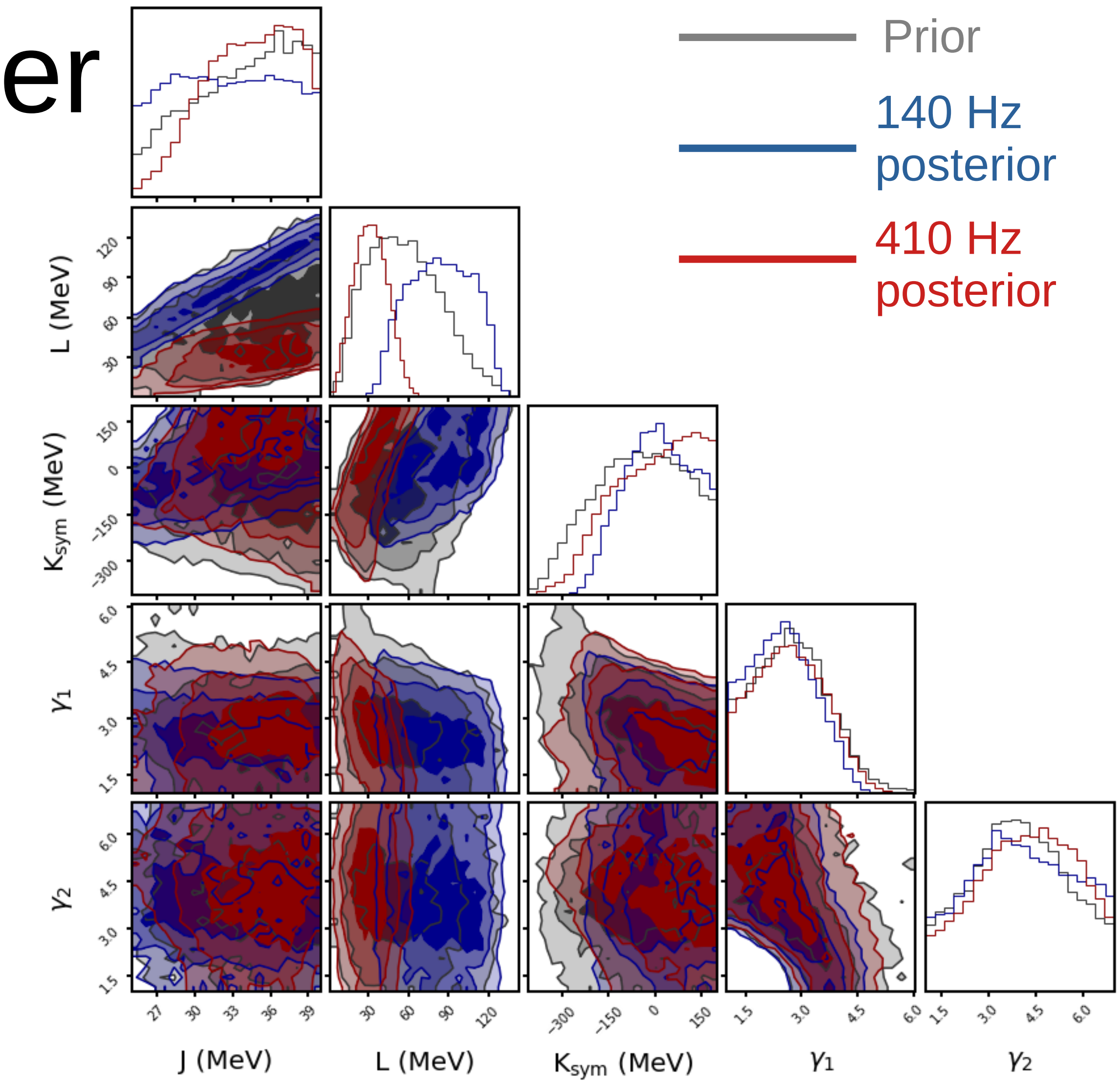
The i-mode's relationship to the symmetry energy

- Sample the nuclear matter EOS via an extended Skyrme model
- Bin samples by their symmetry energies at various densities
- Construct NS models using the sampled EOSs, and calculate their i-mode frequencies
- Find the mean and standard deviation of the i-mode frequencies of samples in each bin

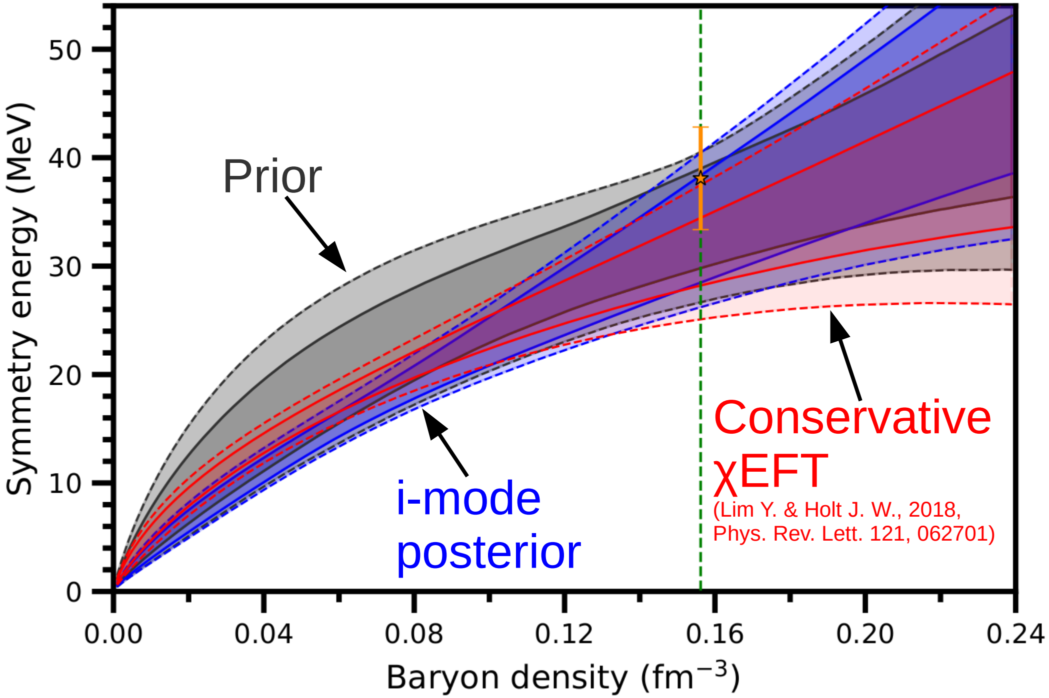


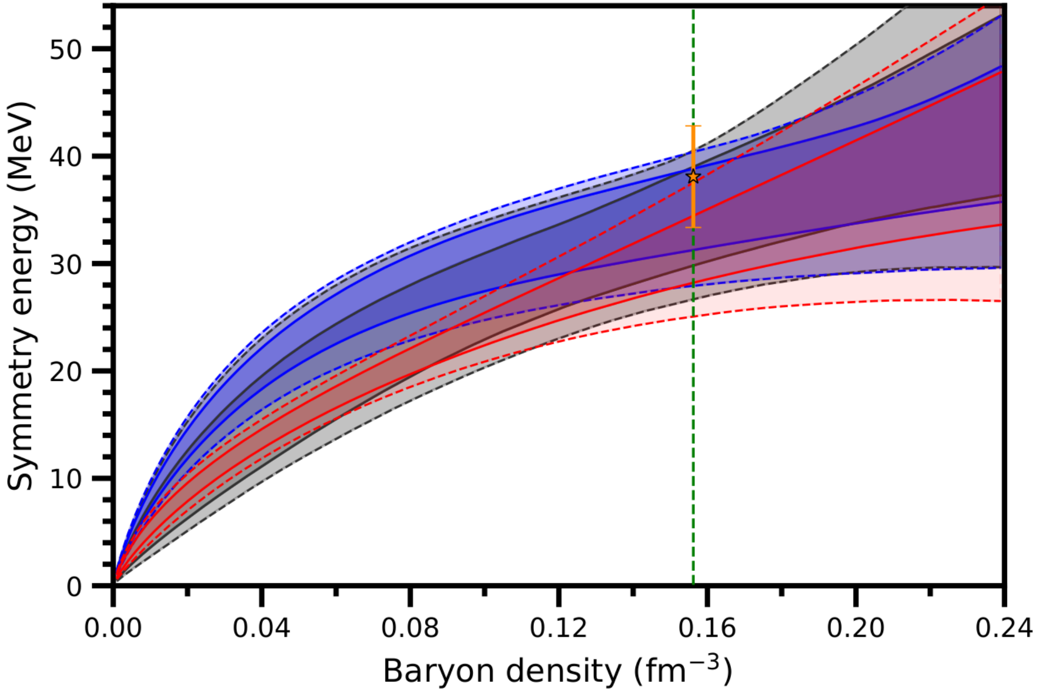
Bayesian parameter inference

- Inject precursor flares (RSFs) measurements
- Infer the parameters of a NS meta-model based on an extended Skyrme interaction
- Infer the indices of polytropes in the core to deviate from nucleonic degrees of freedom



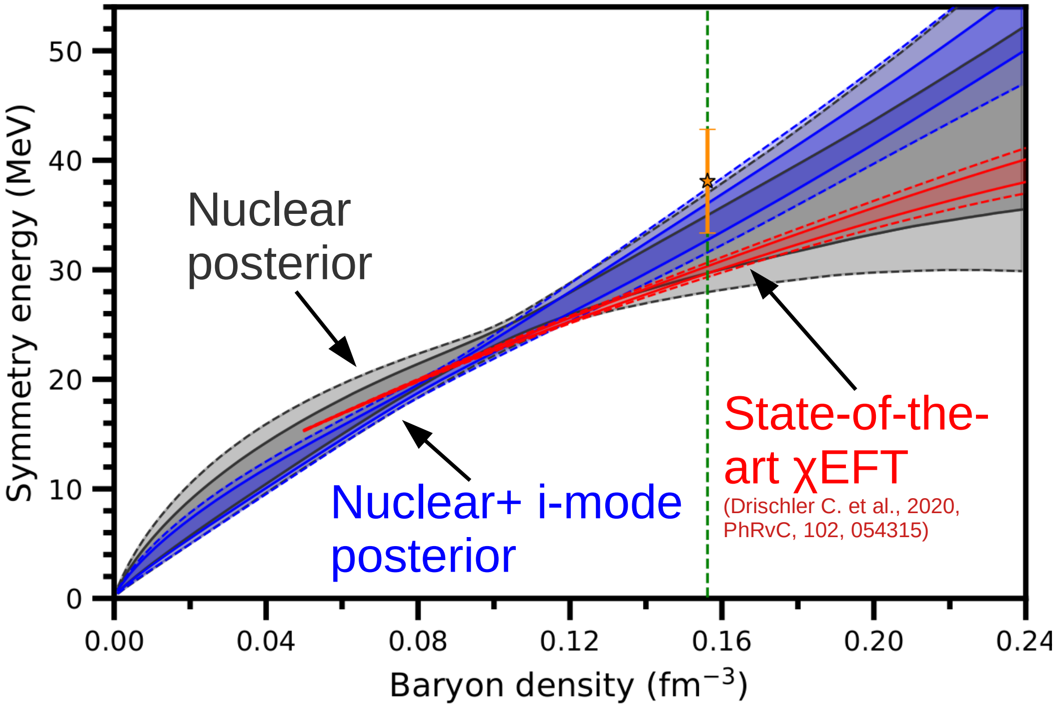
Inferences with an uninformed prior


Injection at 140 Hz


Injection at 410 Hz

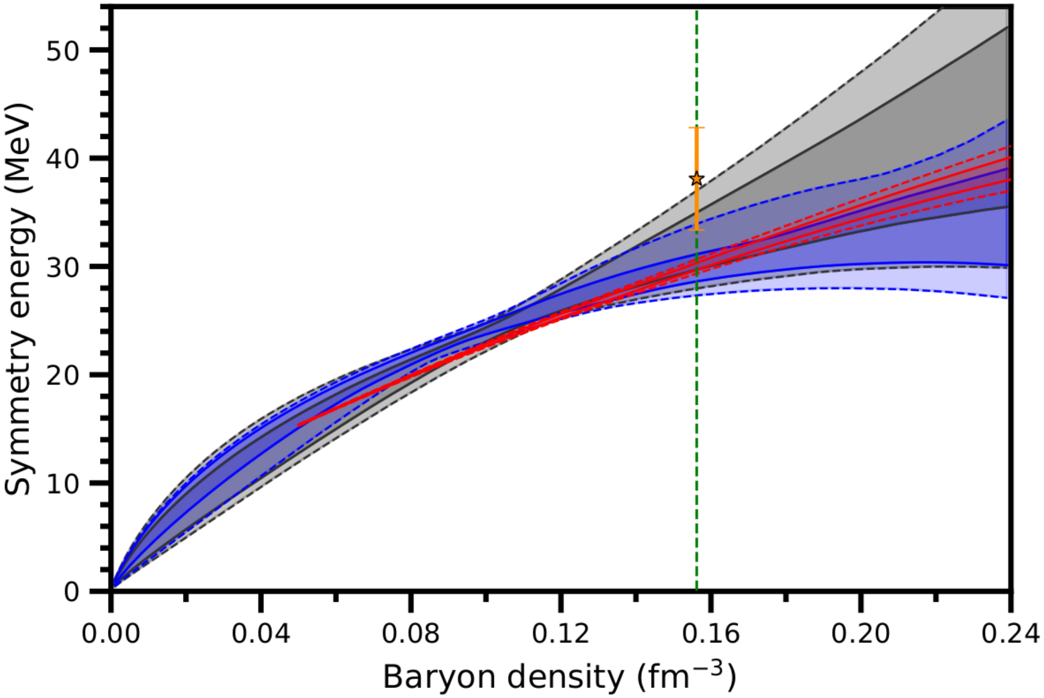
- Good for constraining the symmetry energy below saturation
- Different frequencies can have qualitatively different agreement with χEFT

Inferences including nuclear data



Injection at 120 Hz

(Drischler C. et al., 2020, PhRvC, 102, 054315)

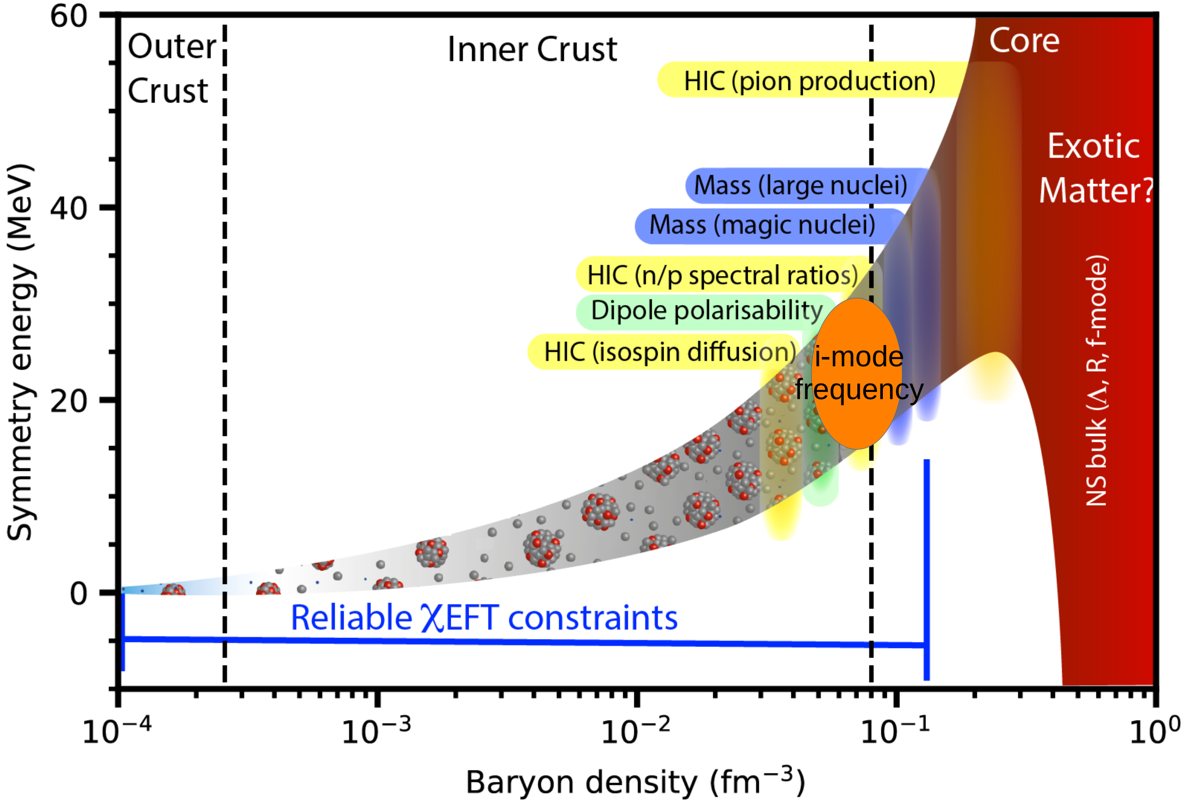


Injection at 275 Hz

- Nuclear binding energies and charge radii complement the i-mode nicely
- Constrained enough to meaningfully test state-of-the-art χEFT predictions

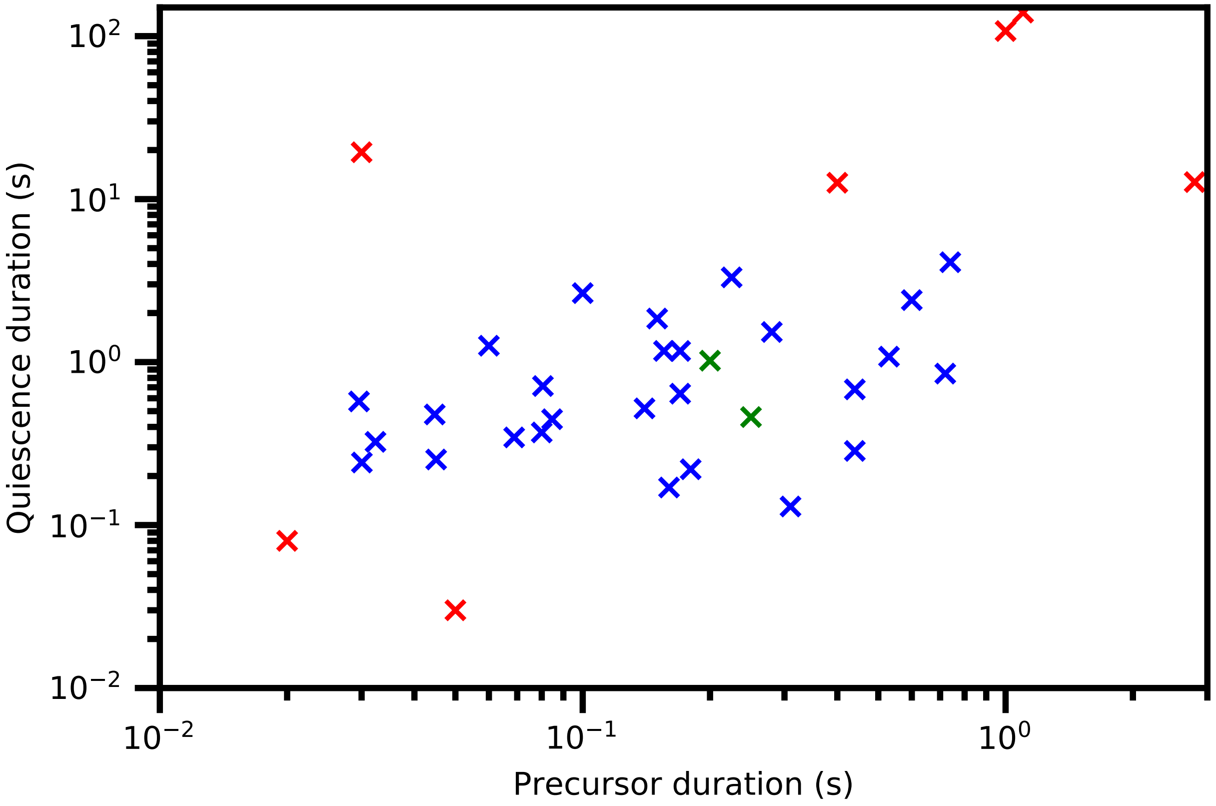
Nuclear symmetry energy

- Probed at low density in experiment
- Probed at high density in neutron stars
- Asteroseismology allows us to probe it at low density in neutron stars

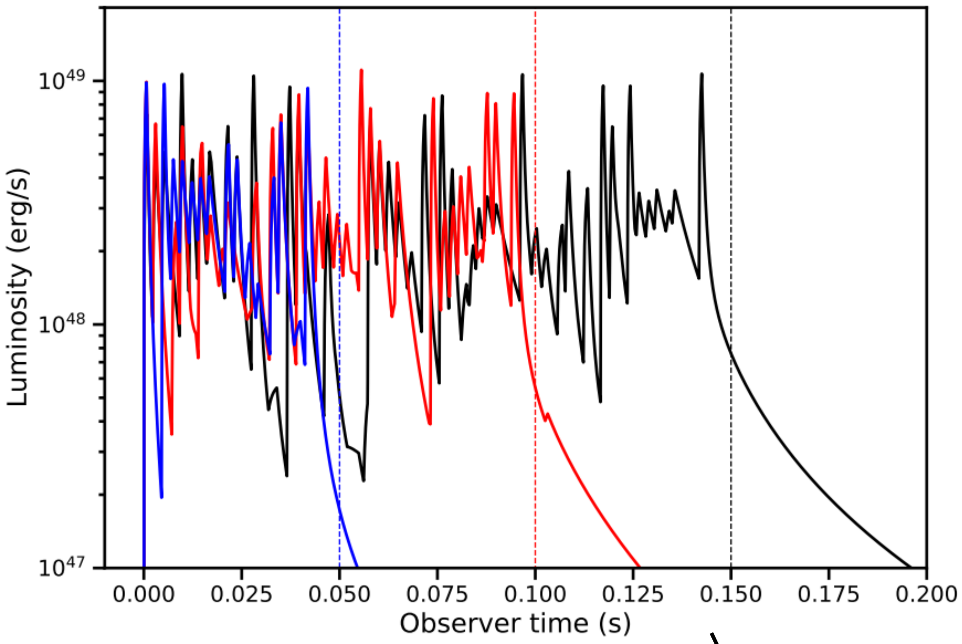


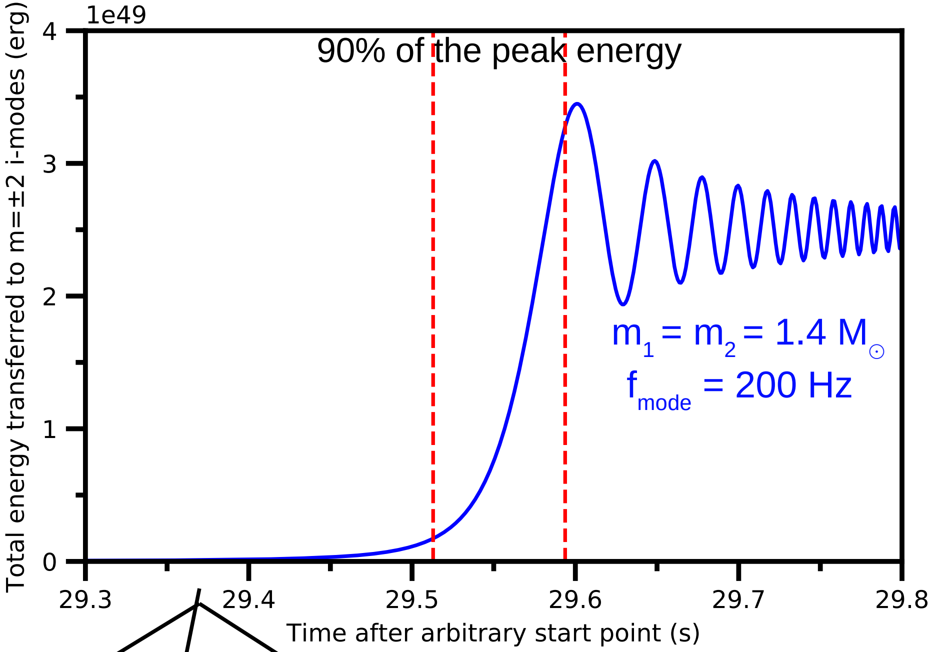
Precursor timings

- SGRB precursors collated from 5 different works
- Red: outliers that we discard (difficult to explain as RSFs)
- From timings alone, the rest could be RSFs (but could also be other things, we need coincident GWs to be certain!)



Precursor timings: flare duration





Fitting t_{res} for various $\mathcal{M}$ and $f_{\rm mode}$:

$$t_{\rm flare} \approx t_{\rm res} \approx 0.296{\rm s} \left(\frac{\mathcal{M}}{1.2\ {\rm M}_\odot}\right)^{-0.854} \left(\frac{f_{\rm mode}}{100\ {\rm Hz}}\right)^{-1.856}$$

Using the stationary phase approximation:

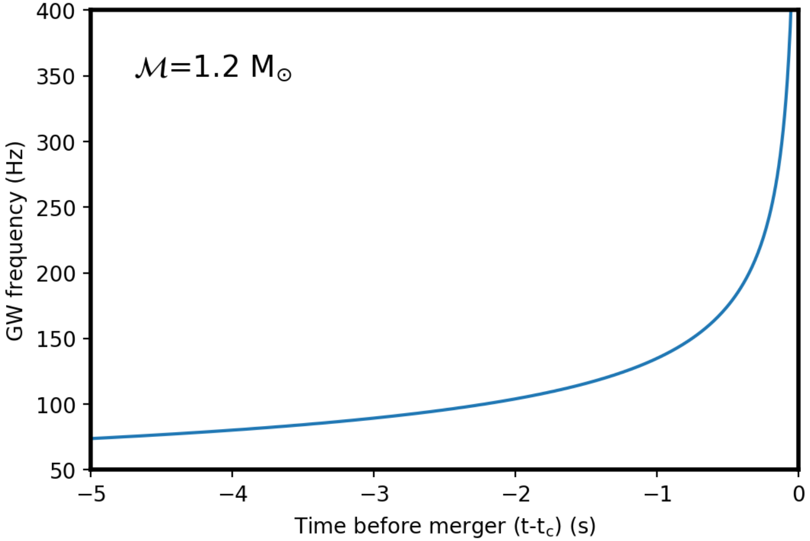
$$t_{\rm flare} \approx t_{\rm res} \approx 0.08{\rm s} \left(\frac{\mathcal{M}}{1.2\ {\rm M}_\odot}\right)^{-5/6} \left(\frac{f_{\rm mode}}{100\ {\rm Hz}}\right)^{-11/6}$$

We use these as upper and lower bounds

Precursor timings: quiescence

- From the zeroth-order evolution of the orbital frequency due to GW evolution:

$$f_{GW}(t) \approx \frac{5^{3/8}}{8\pi}\left(\frac{c^3}{G\mathcal{M}}\right)^{5/8}(t_c - t)^{-3/8}$$



- SGRB delay means that $t_c - t \neq t_q$, but it is the best we have until we see a multimessenger GW and RSF event

Conclusions

- Testing chiral effective field theory's predictions of nuclear matter properties is important at high and low densities

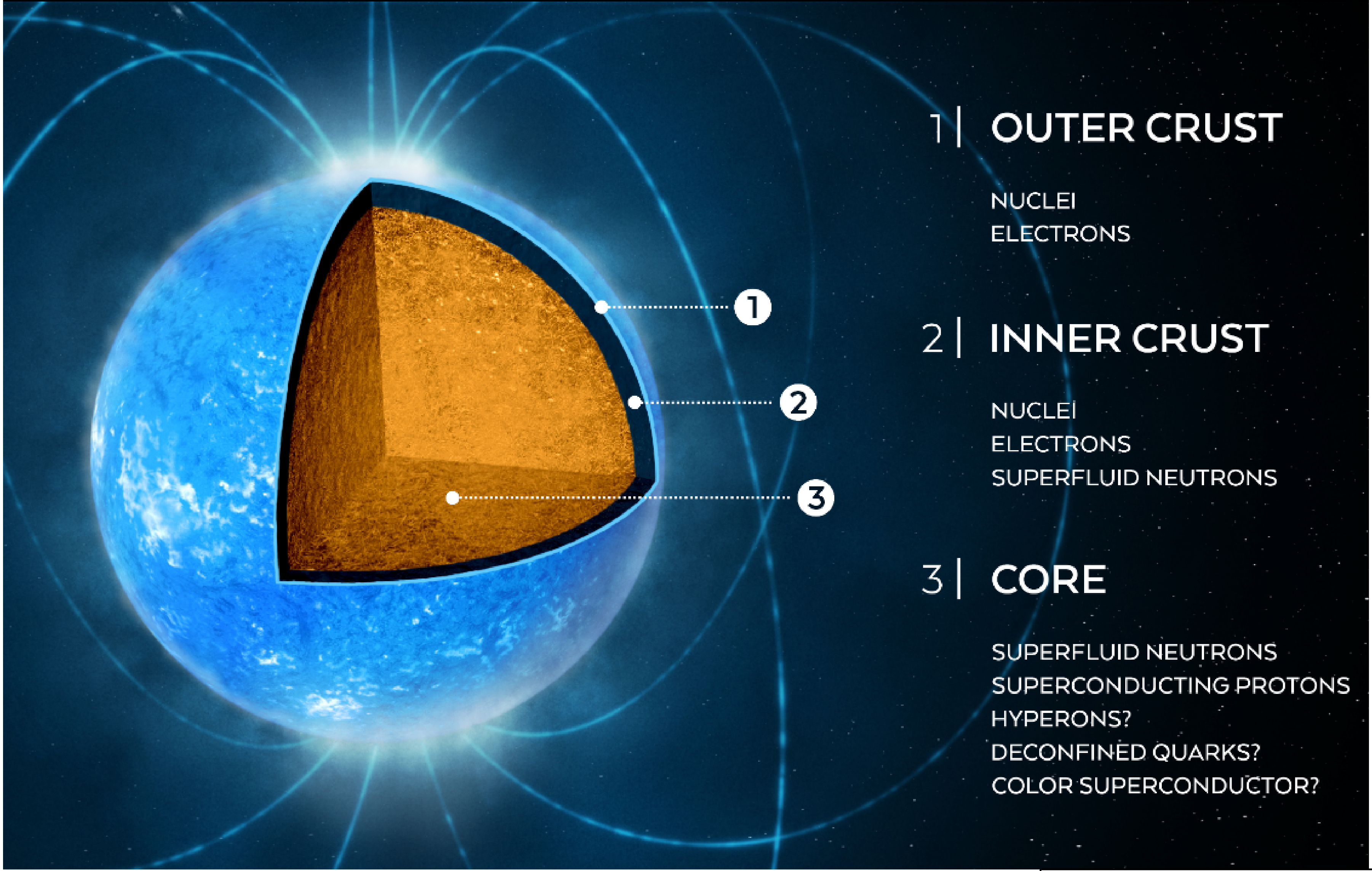
- The low density nuclear matter EOS is probed with nuclear experiment, while NSs are typically only considered as places to probe the high density EOS

- However, asteroseismology may allow for low density matter to be studied in NSs too

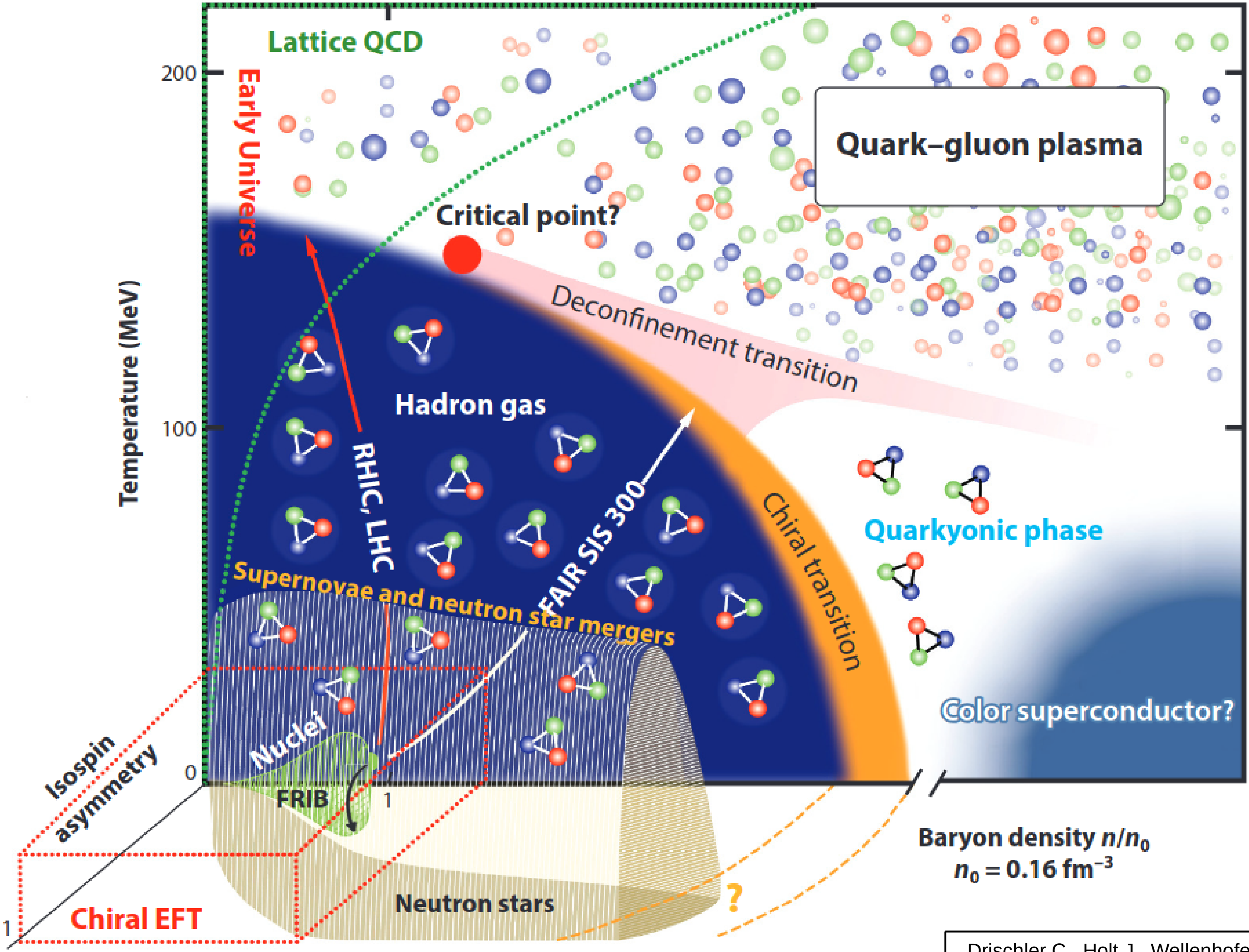
- The i-mode frequency as measured with RSFs would provide a useful probe of the low density EOS and thus could be used to test the predictions of chiral effective field theory

Duncan Neill, David Tsang, Christian Drischler, Jeremy Holt & William Newton, in-prep.

Tsang D. et al., 2012, Phys. Rev. Lett., 108, 011102 | **Neill D.**, Newton W. G., Tsang D., 2021, MNRAS, 504, 1129 | **Neill D.**, Newton W. G., Preston R., Tsang D., 2023, Phys. Rev. Lett., 130, 112701

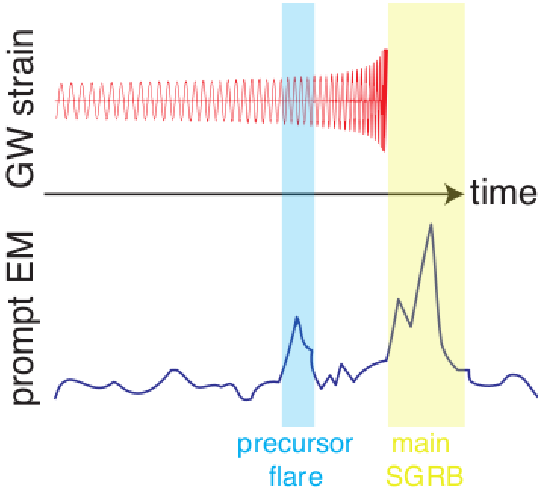


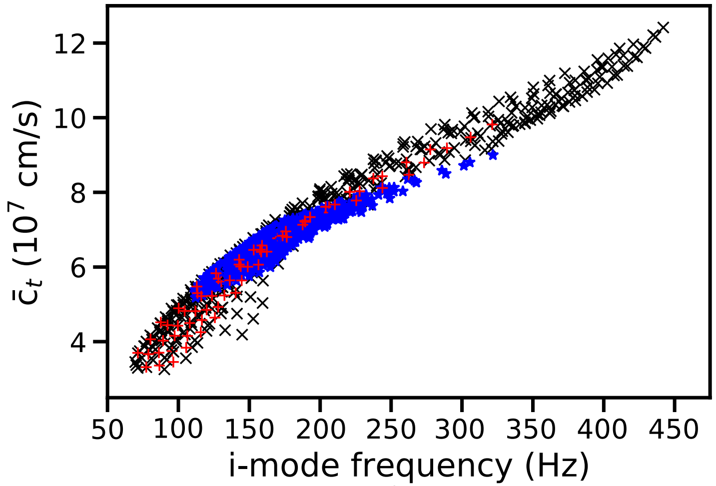
Watts A. et al., 2016, Rev. Mod. Phys., 88, 021001

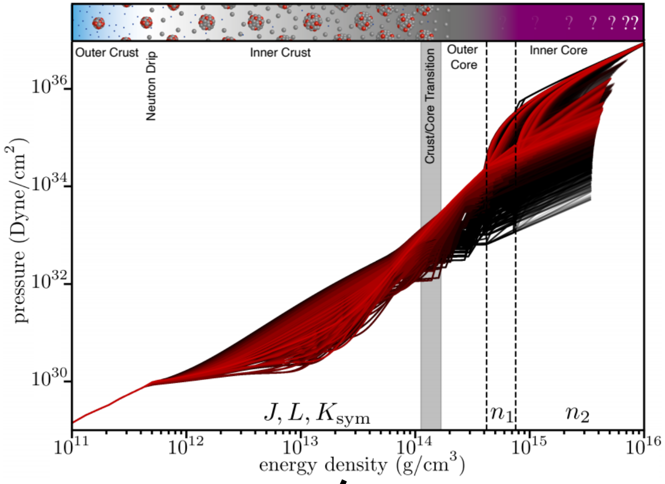


Drischler C., Holt J., Wellenhofer C., 2021, ARNPS, 71, 403

Constraining nuclear physics with multimessenger astrophysics







Multimessenger RSF + GW observation → i-mode frequency → Composition of the NS crust → Fundamental nuclear physics