Resonant shattering flares as multimessenger probes of nuclear symmetry

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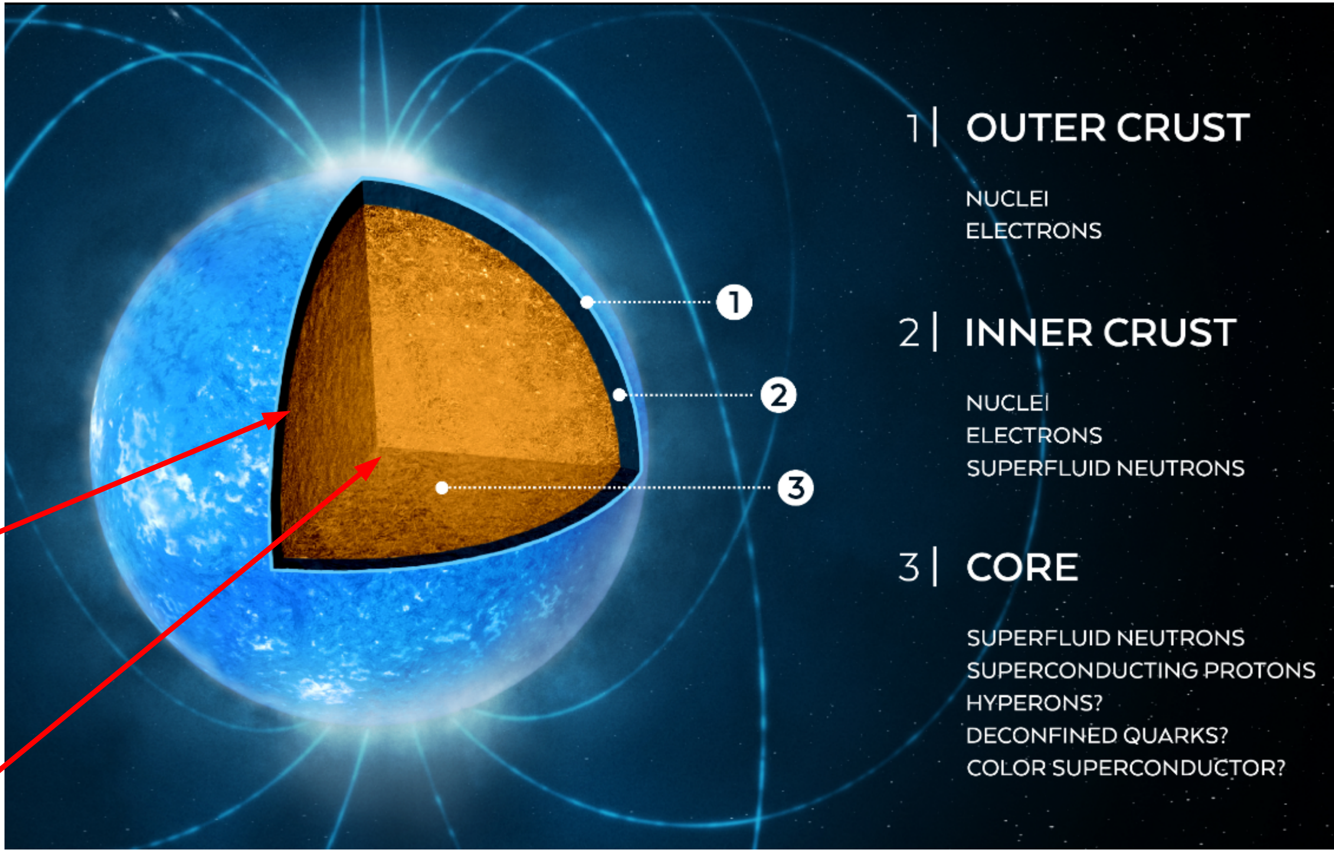
Neutron stars

- Neutron stars are very dense and neutron rich, ideal for the study of the symmetry energy
- We need to identify observables that let us probe their structure

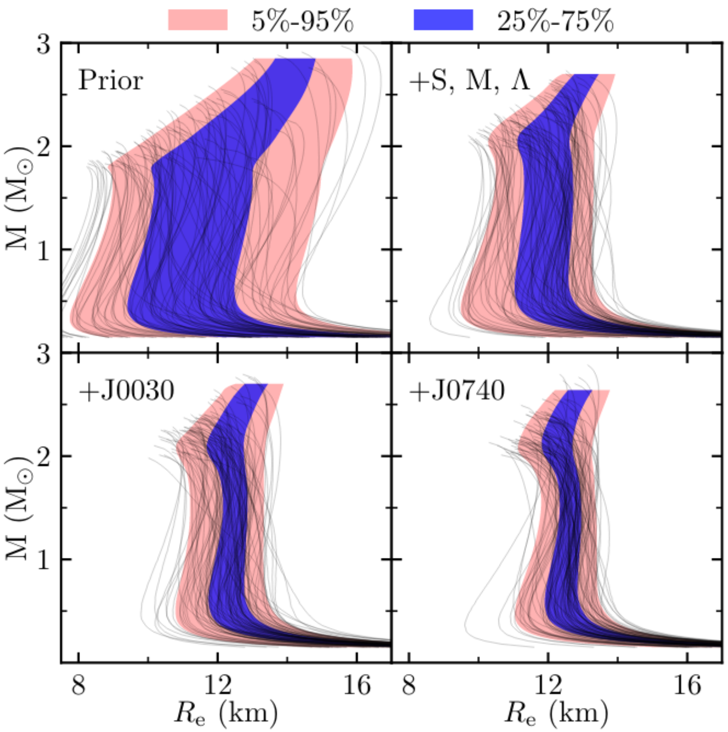
The crust-core transition occurs around half nuclear saturation density

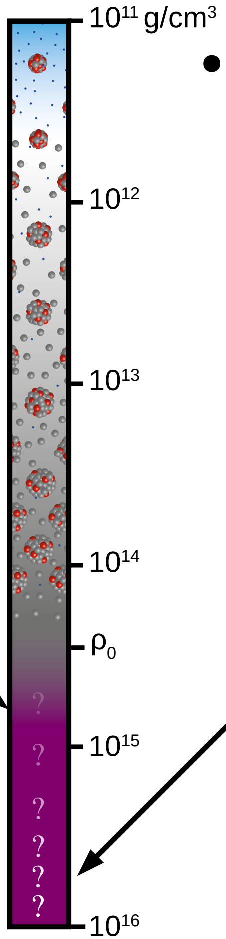
The nature of matter in the inner core is unknown (quarks, hyperons, …?)



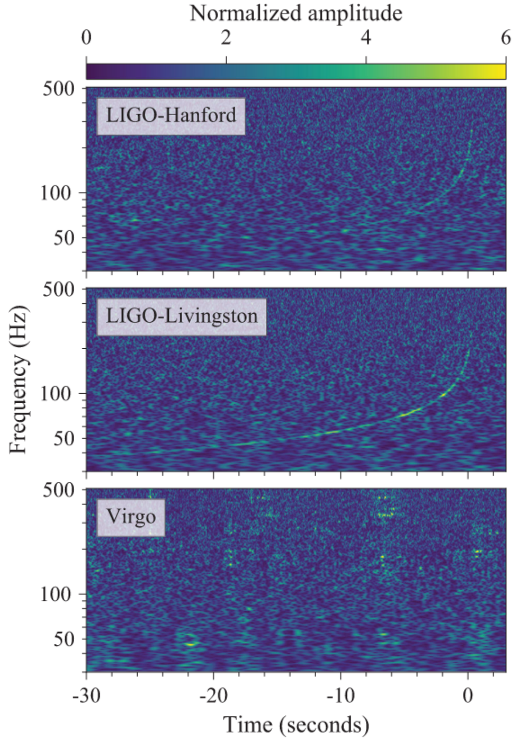
Core-dependent NS properties

- Pulsar timing, etc. → mass-radius relationship

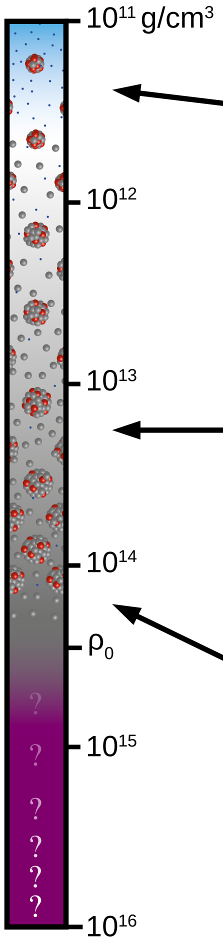




- Gravitational waves → mass and tidal deformability

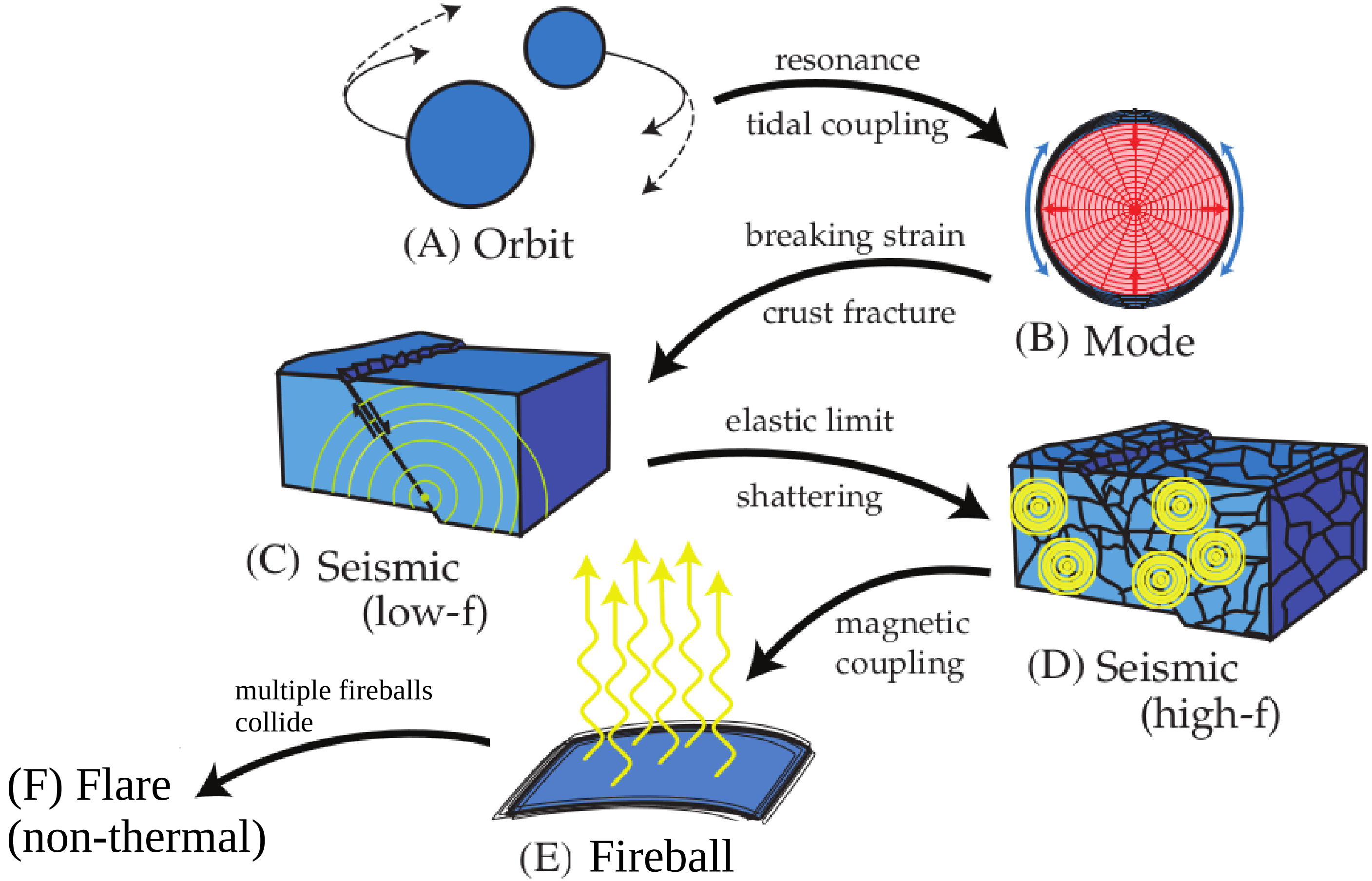


Asteroseismic modes

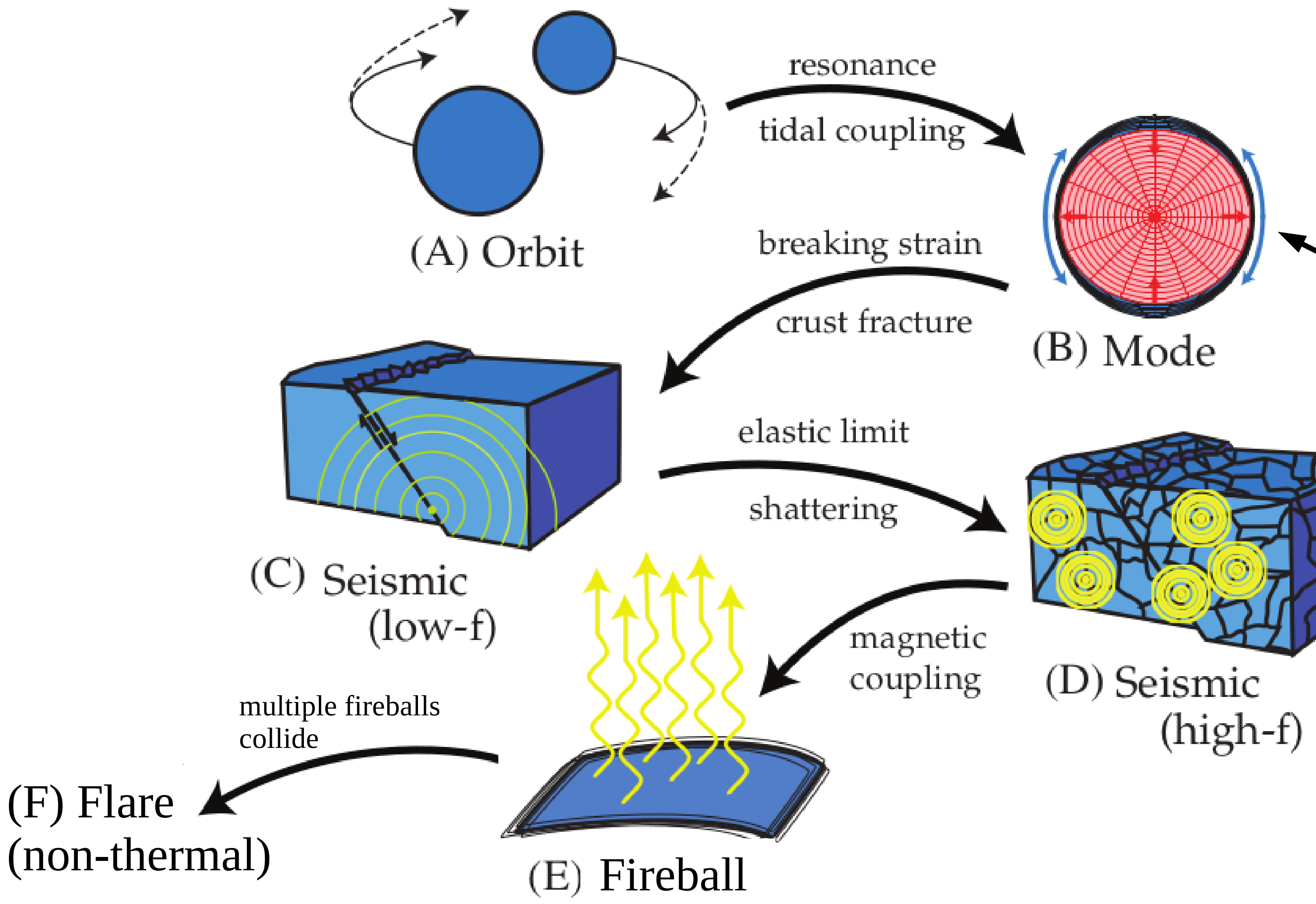


- Fundamental (f) mode
- Gravitational (g) modes
- Pressure (p) modes
- Shear (s) modes
- Interface (i) modes

Resonant Shattering Flares (RSFs)



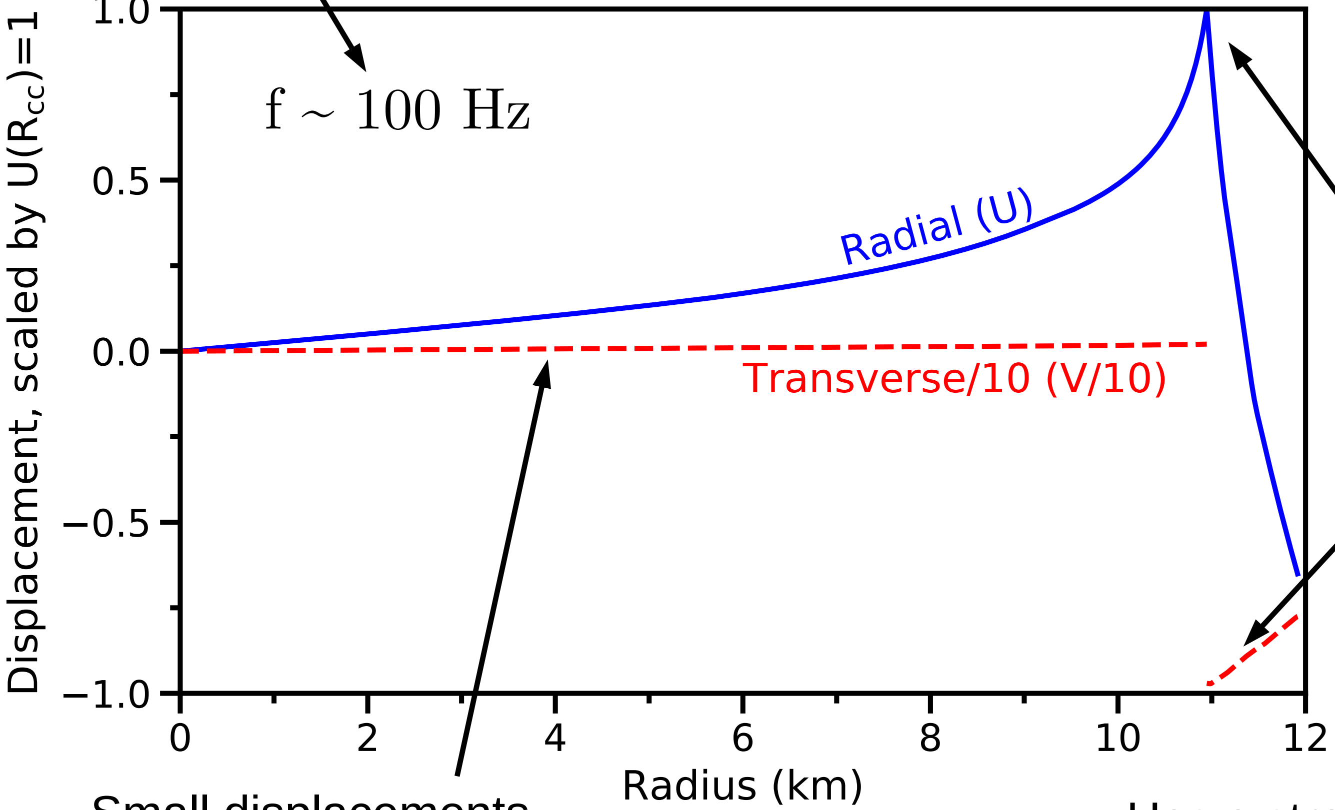
Resonant Shattering Flares (RSFs)



Which mode could trigger these flares?

Crust-core interface mode

Resonant ($2f_{orbit} \approx f_{mode}$)
shortly before merger

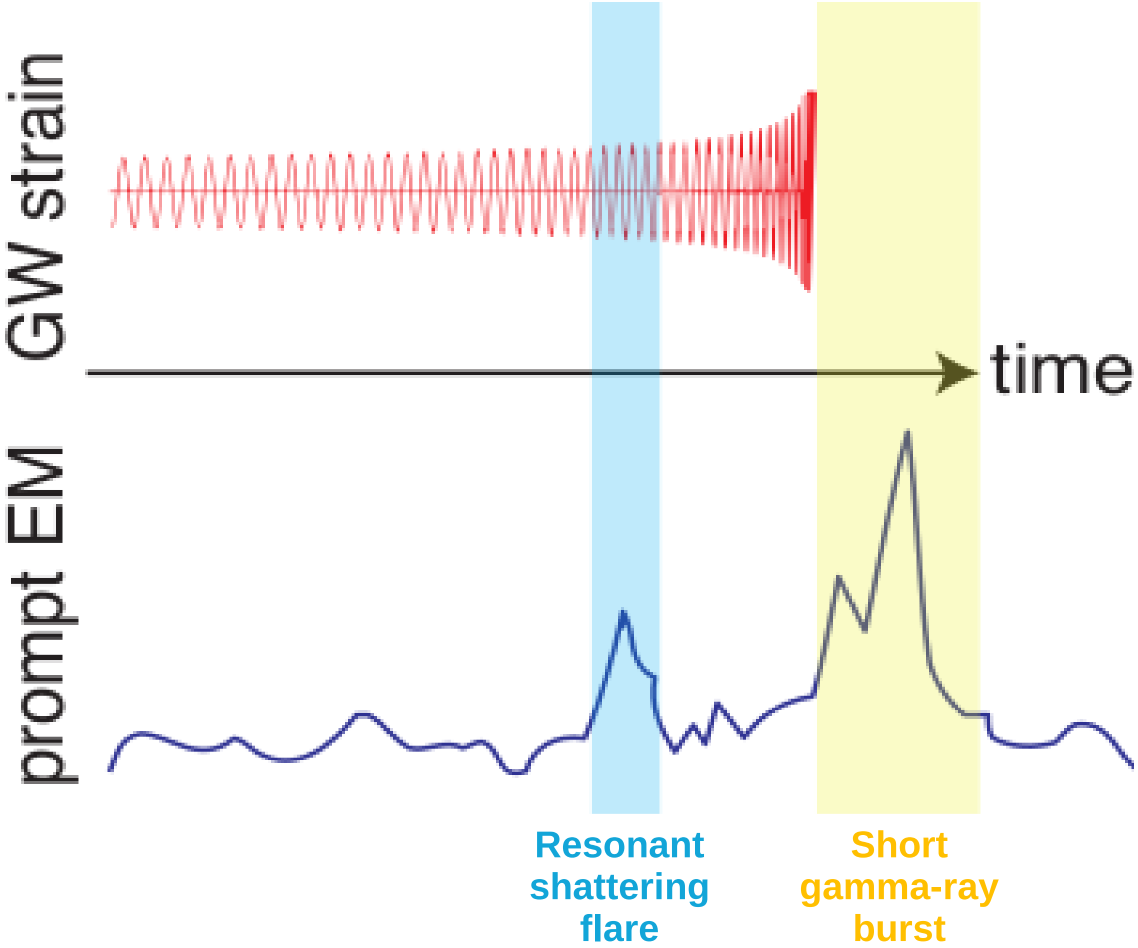


Peaks are at the
crust-core boundary

Small displacements
in the core

Has a strong overlap with the tidal
field compared to most modes.

Multimessenger observation



EM observation of a RSF tells us when to look at the GW signal to get the orbital frequency which resonantly excited the i-mode

$f_{GW}(t_{RSF})$

↓

f_{mode}

↓

NS structure/composition

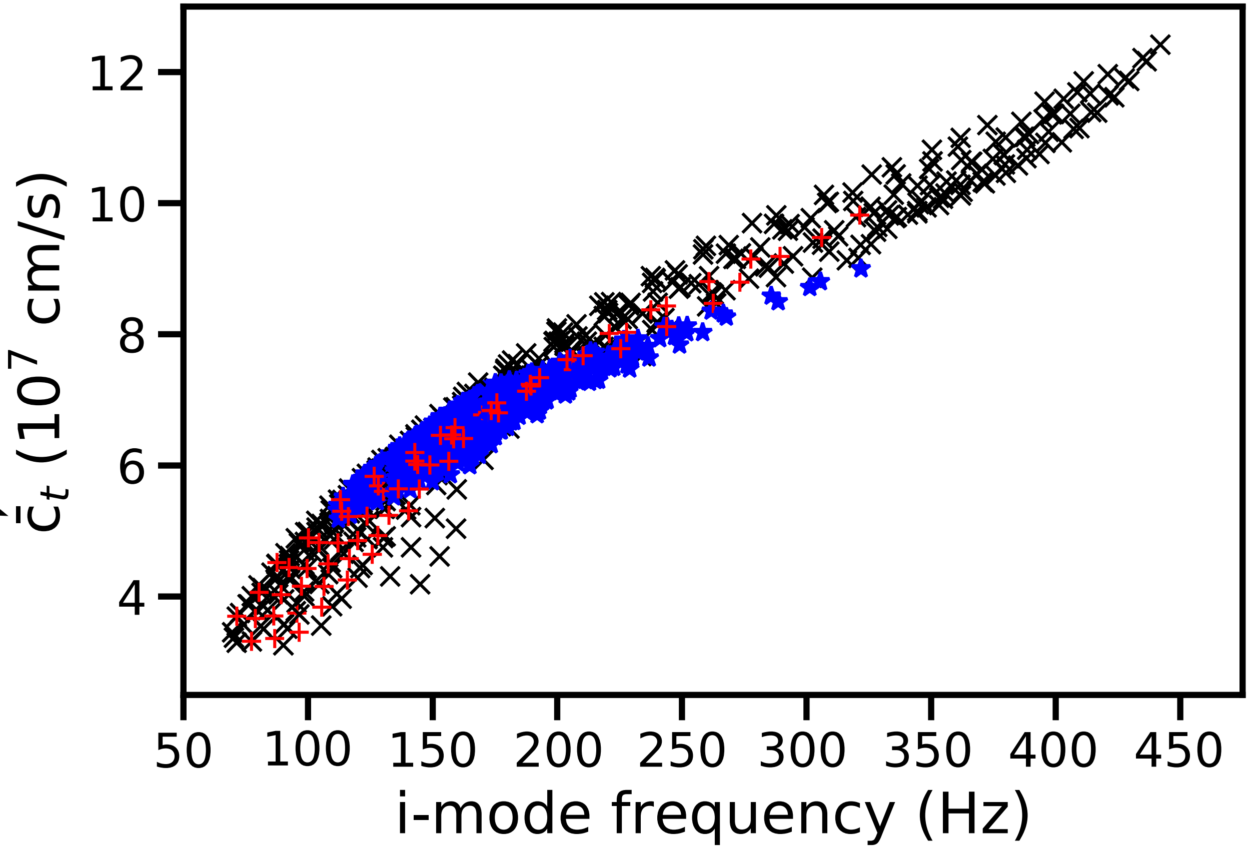
↓

Fundamental nuclear physics

Probing crust composition

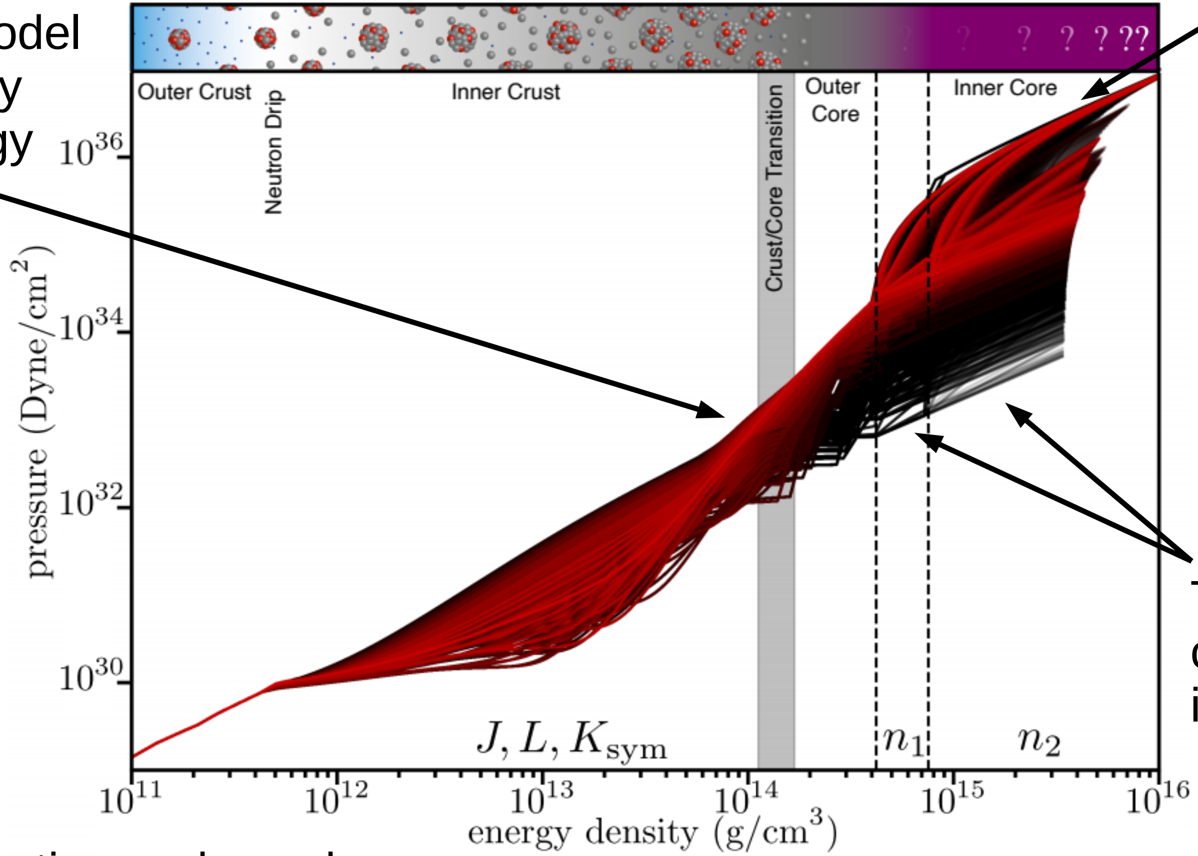
i-mode frequency is sensitive to the density-weighted average shear speed in the crust

(a material property that is dependent on the crust's composition and thus on its underlying nuclear physics)



NS meta-model

Consistent crust and outer core, constructed from the Skyrme model and parametrised by the symmetry energy



Causality enforced ($c_s < c$)

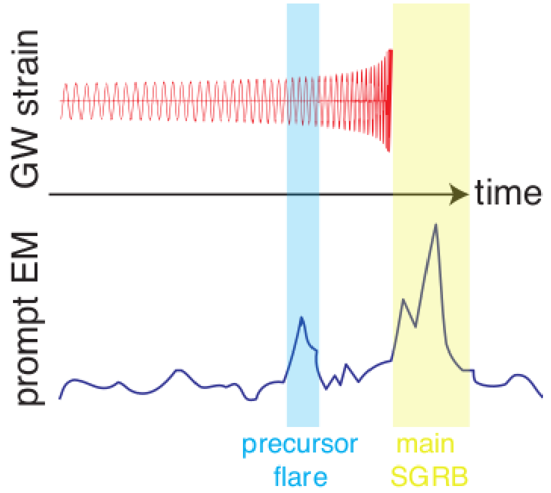
Two polytropes in the core, to accommodate its unknown nature

Compositional properties such as shear modulus and adiabatic index can also be calculated

Constraining nuclear physics with multimessenger astrophysics

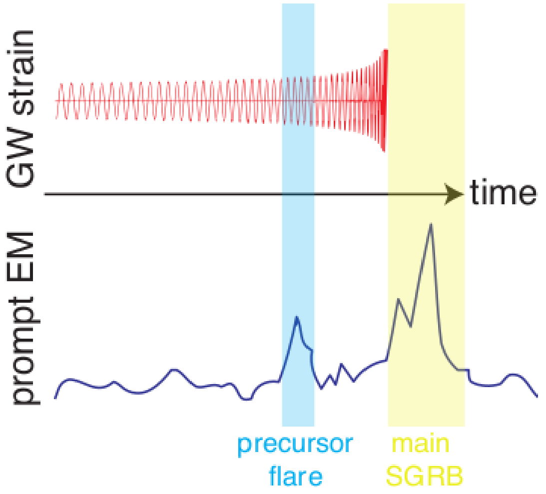
Multimessenger RSF
+ GW observation

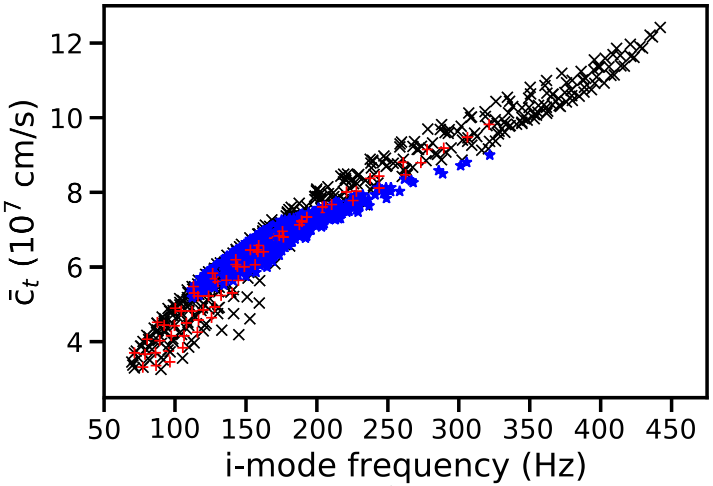
Constraining nuclear physics with multimessenger astrophysics



Multimessenger RSF + GW observation → i-mode frequency

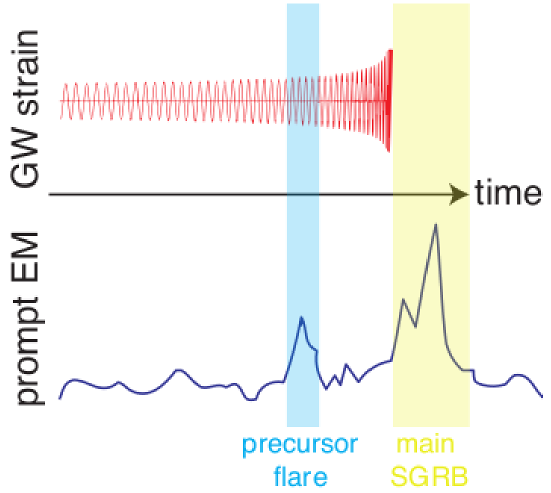
Constraining nuclear physics with multimessenger astrophysics

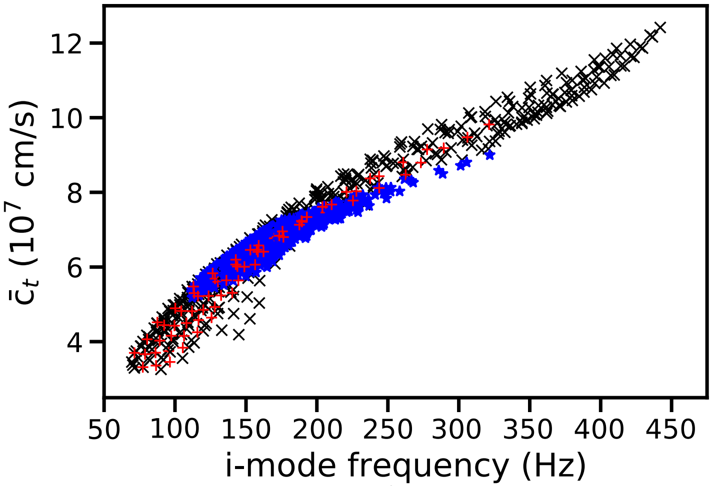


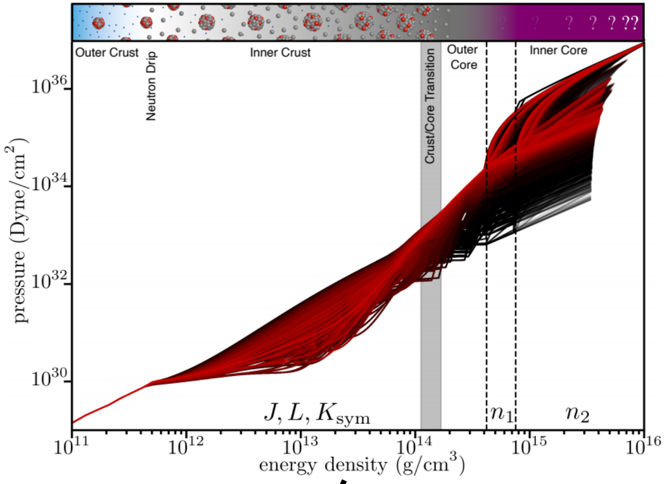


Multimessenger RSF + GW observation → i-mode frequency → Composition of the NS crust

Constraining nuclear physics with multimessenger astrophysics

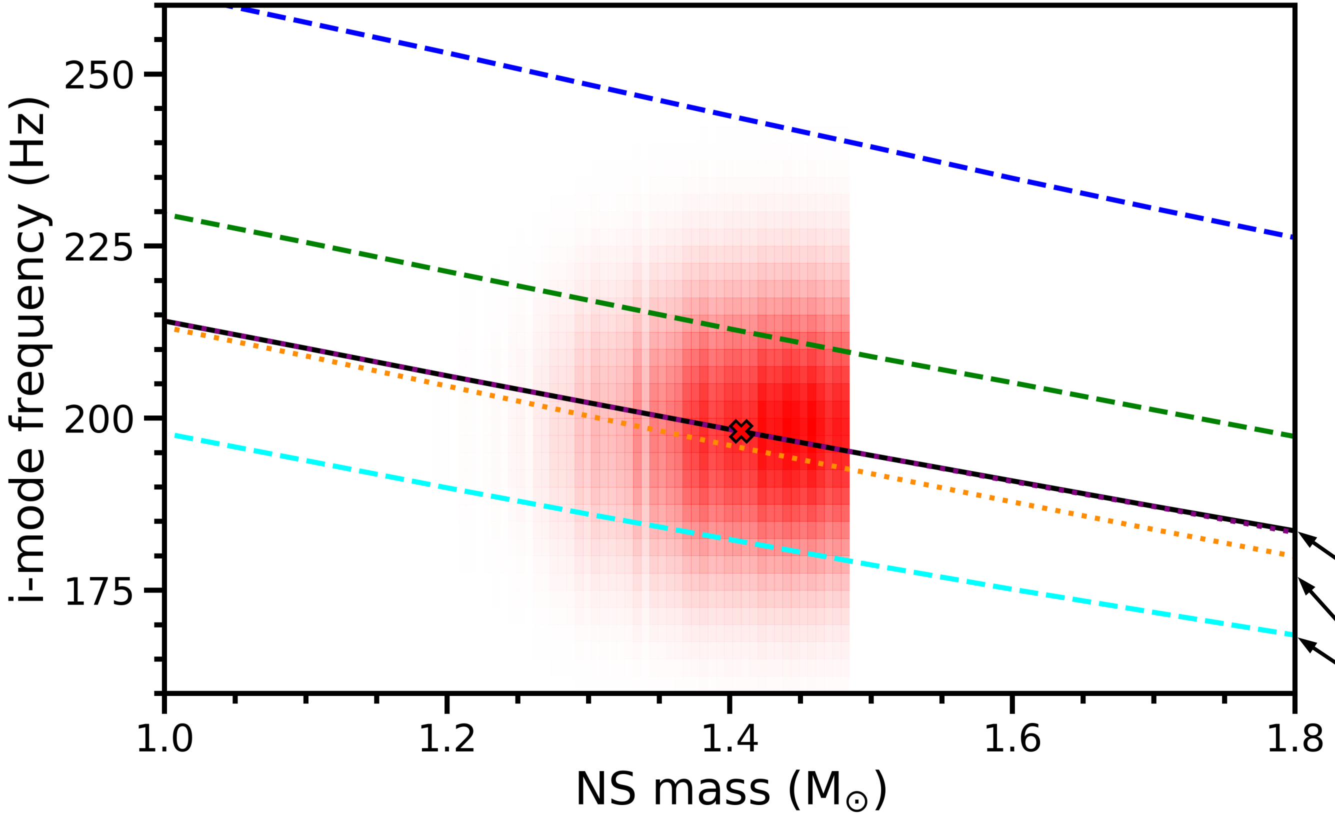






Multimessenger RSF + GW observation → i-mode frequency → Composition of the NS crust → Fundamental nuclear physics

Injecting a measurement



- Frequency uncertainty from RSF duration
- Mass uncertainty from GW analysis (using BILBY)

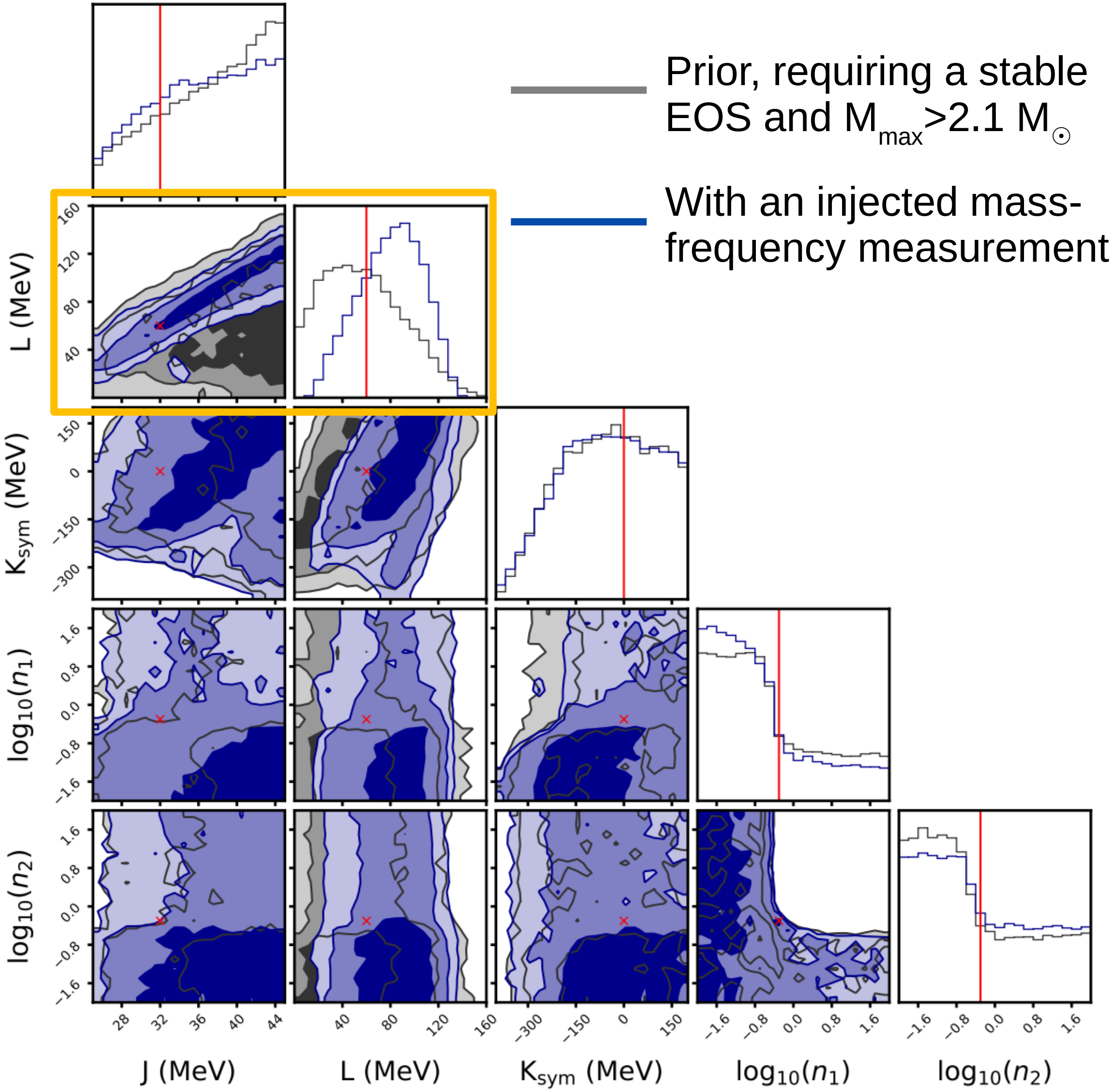
Injected NS model

Small variations of meta-model parameters around their injected values

Neill D. et al., in prep.

Parameter inference

- The i-mode frequency informs us about the first two symmetry energy parameters
- Very little improvement in the core parameters (the opposite of mass-radius constraints)



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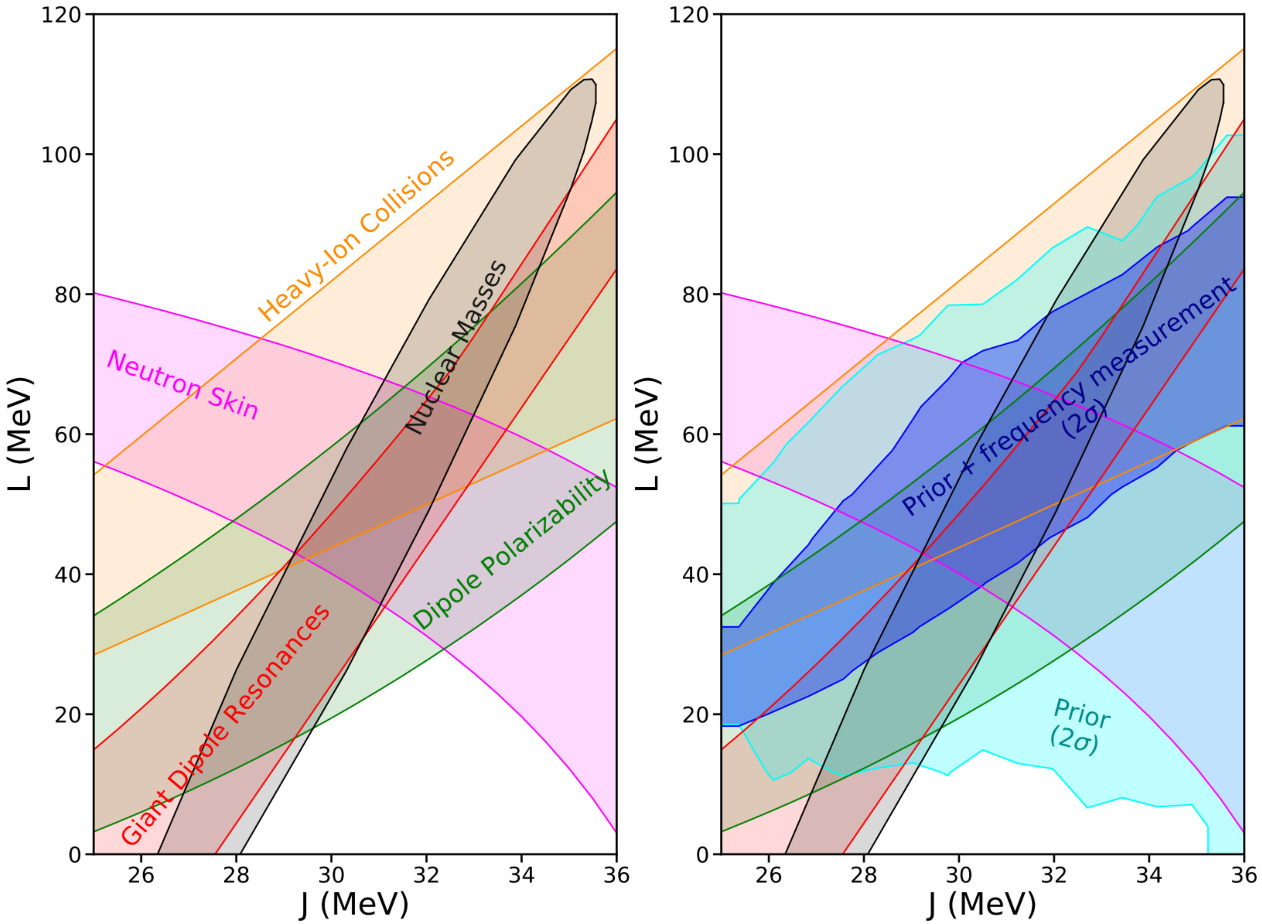
Parameter inference

At 2σ, the symmetry energy constraints inferred from a measurement of the i-mode frequency are competitive with those from nuclear experiment, even when using highly conservative injected data

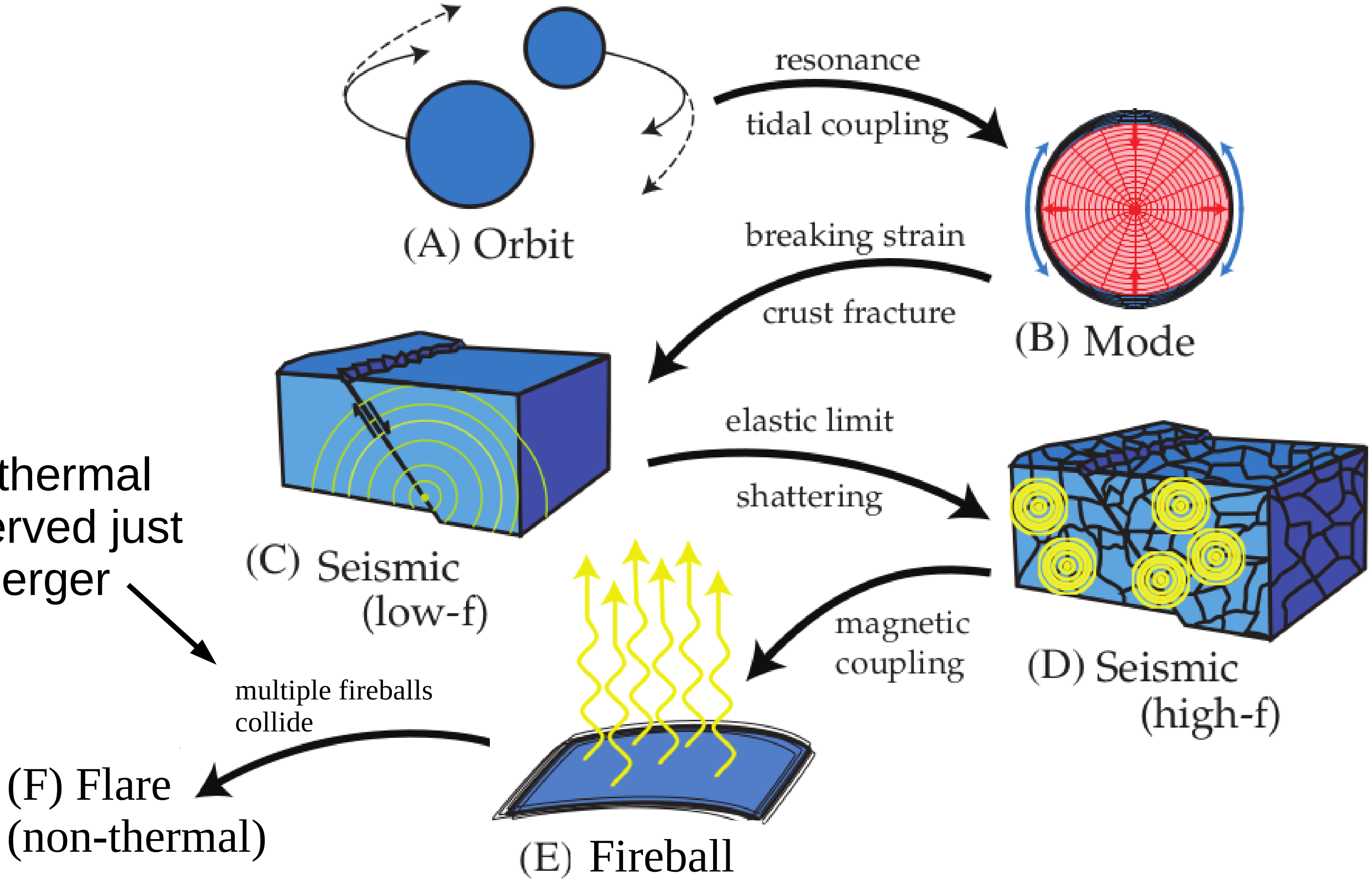


The experimental nuclear constraints are taken from:
Lattimer J. M. & Steiner A. W. (2014), EPJA, 50, 40

Neill D., Newton W. G., Preston R., Tsang D., 2023, Phys. Rev. Lett., 130, 112701

Multimessenger RSF and GW events may be useful, but are we going to observe any of them?

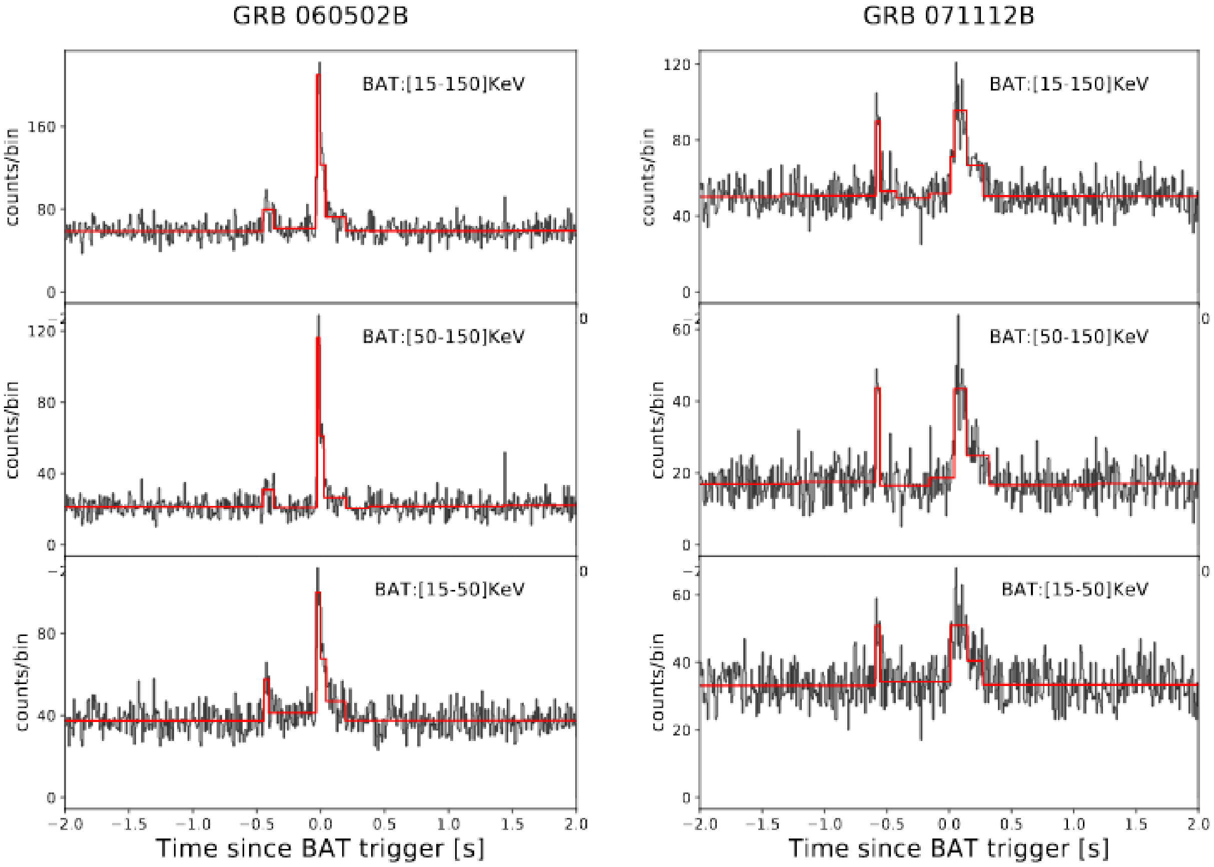
Resonant Shattering Flares (RSFs)



Short non-thermal flares observed just before a merger

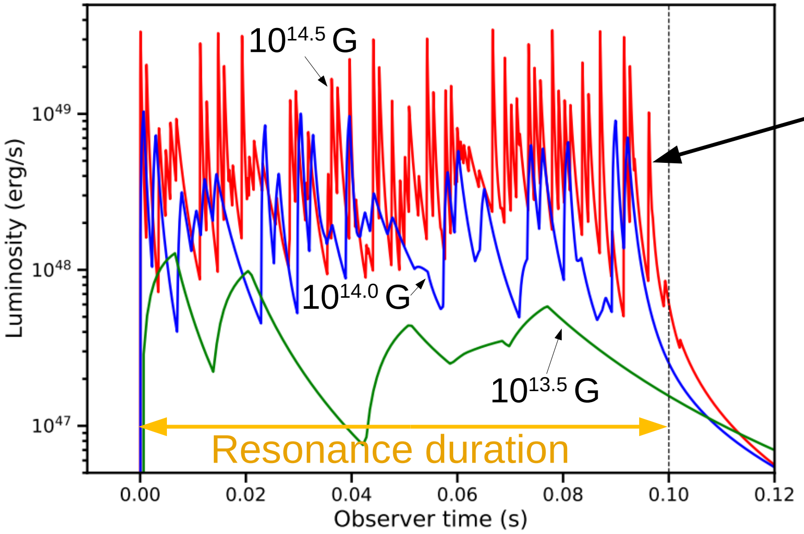
SGRB precursor flares

- A few percent of SGRBs are preceded by precursor flares
- The cause of these flares is unclear



Non-thermal emission: colliding shells

- Resonance duration ≈ Flare duration
- Luminosity strongly dependent on surface magnetic field strength



Total non-thermal luminosity (mostly gamma-rays)

Non-thermal emission: colliding shells

- Resonance duration ≈ Flare duration
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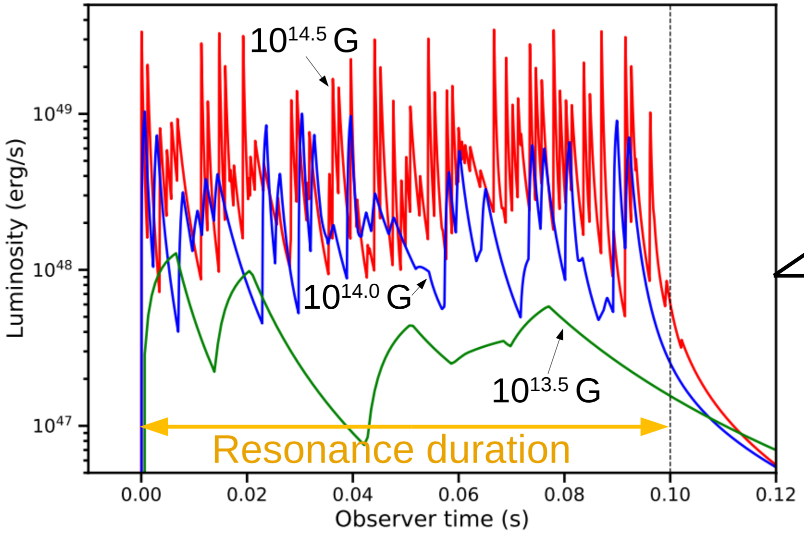
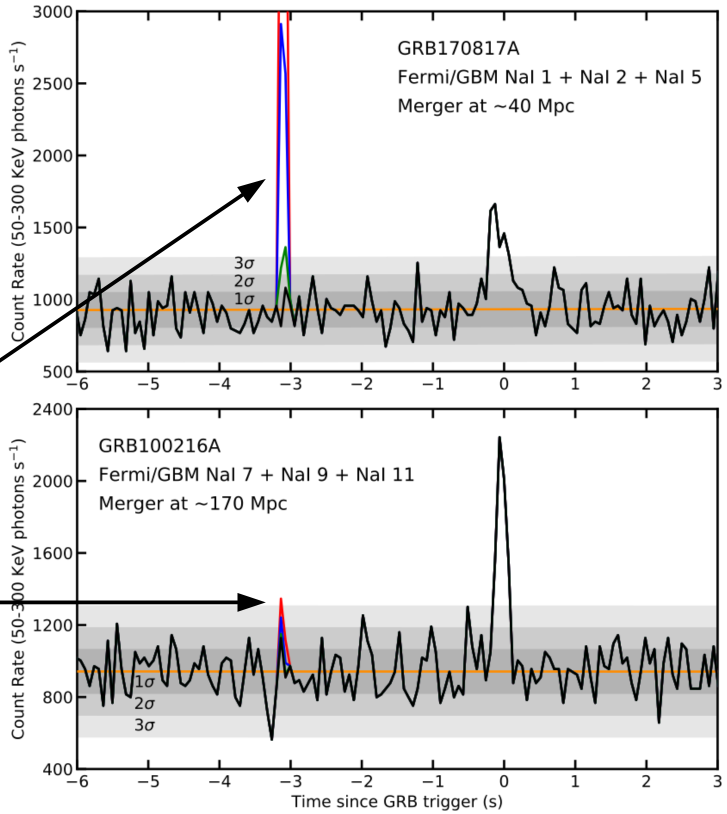


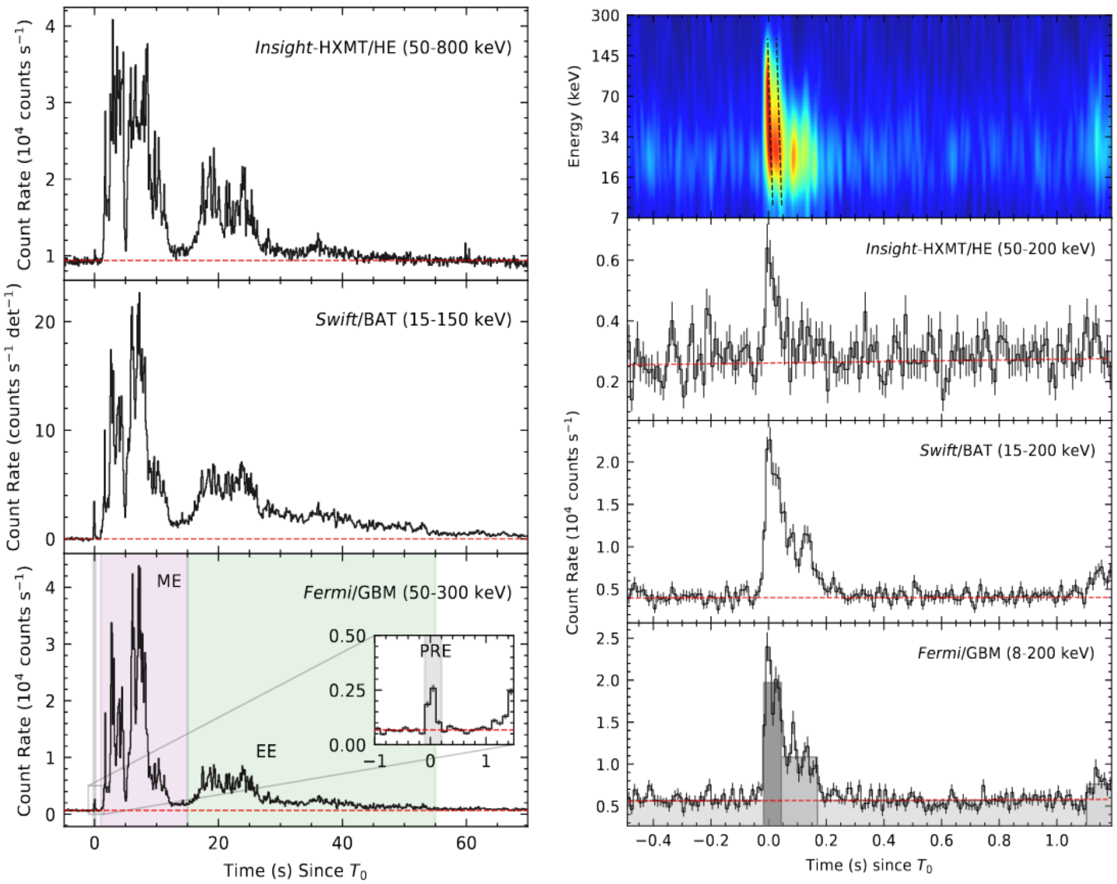


(These events are just used as examples of SGRBs, there is no evidence that either had a RSF)

Precursor flares could be RSFs → RSFs may be detected reasonably often, so we are just waiting for multimessenger RSF and GW events!

GRB211211A

- Has a precursor
  → properties are consistent with our RSF calculations
- Evidence for a kilonova
  → SGRB from a nearby merger
- Has extended emission
  → post-merger magnetar?

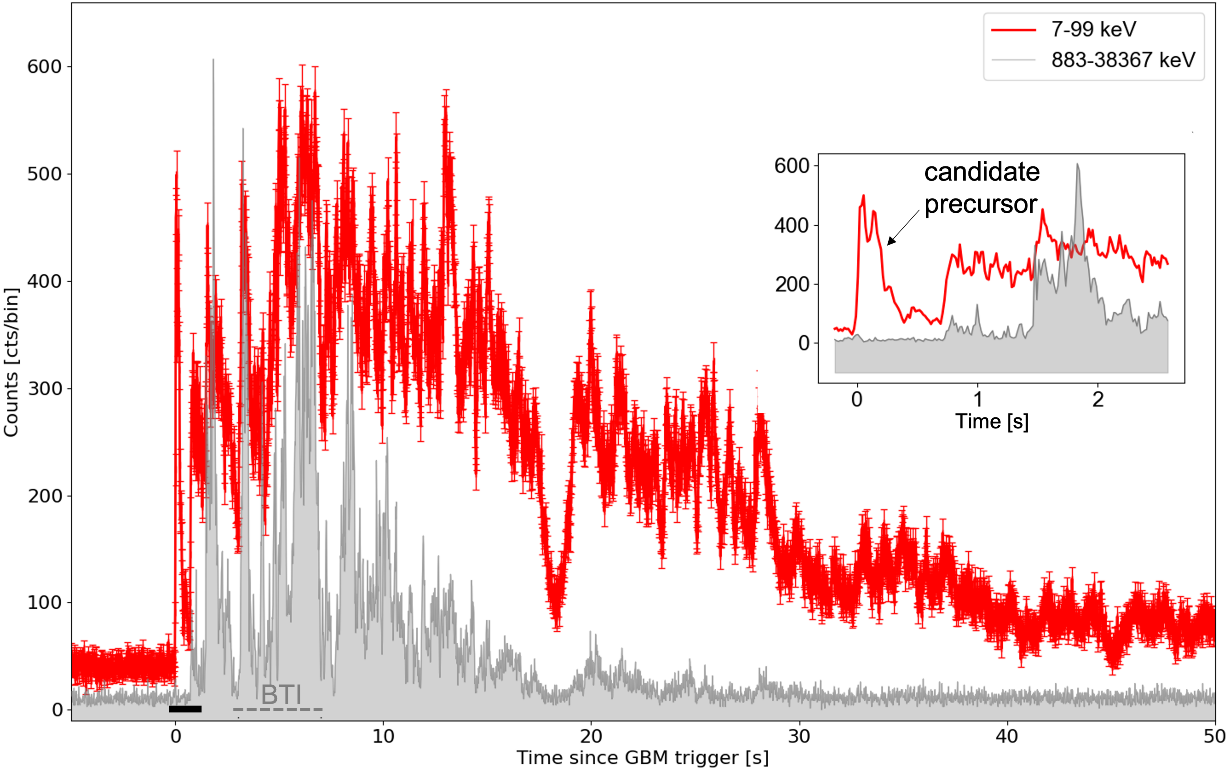


GRB230307A

- Qualitatively similar to GRB211211A
- The precursor is spectrally different to the main SGRB

↓

These precursors may be RSFs, so we are optimistic about multimessenger events in LIGO/Virgo’s O4



Dichiara S. et al., 2023, APJL. 954, L29

Conclusions

- Multimessenger RSF and GW events allow us to measure the crust-core interface mode's frequency, which provides symmetry energy constraints as strong as those from nuclear experiments
- Such events could be common, if SGRB precursor flares are RSFs

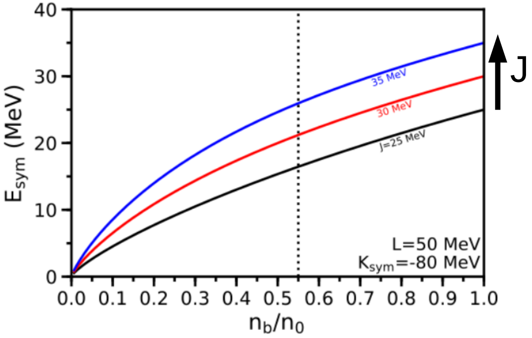
Astrophysical constraints on nuclear physics are becoming comparable to those from terrestrial experiments. What do we need to work on in order to compare and combine astrophysical and terrestrial data in statistically consistent ways?

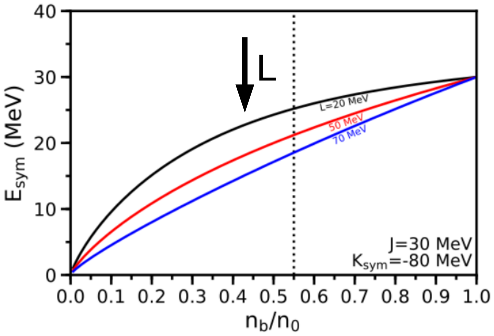
- **Neill D.**, Newton W. G., Preston R., Tsang D., 2023, Phys. Rev. Lett., 130, 112701
- Dichiara S., Tsang D. et al., 2023, APJL. 954, L29
- **Neill D.** et al., in prep.

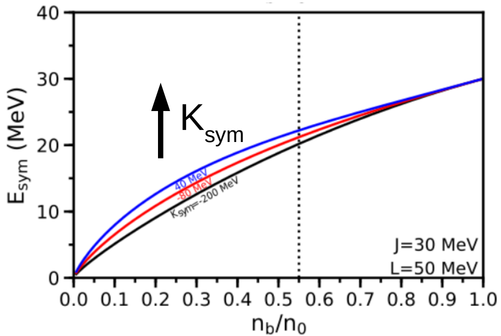
Why do J, L and K_{sym} affect the shear speed?

Increase in J/K_{sym}
or decrease in L

Increase in E_{sym}
in the crust



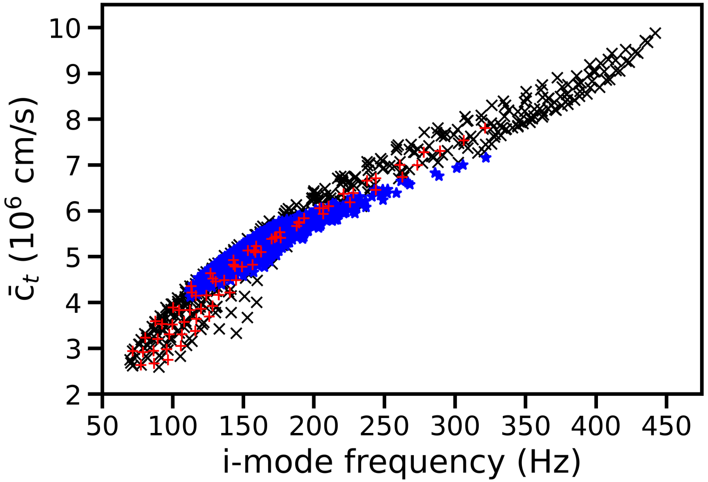




Higher proton
fraction

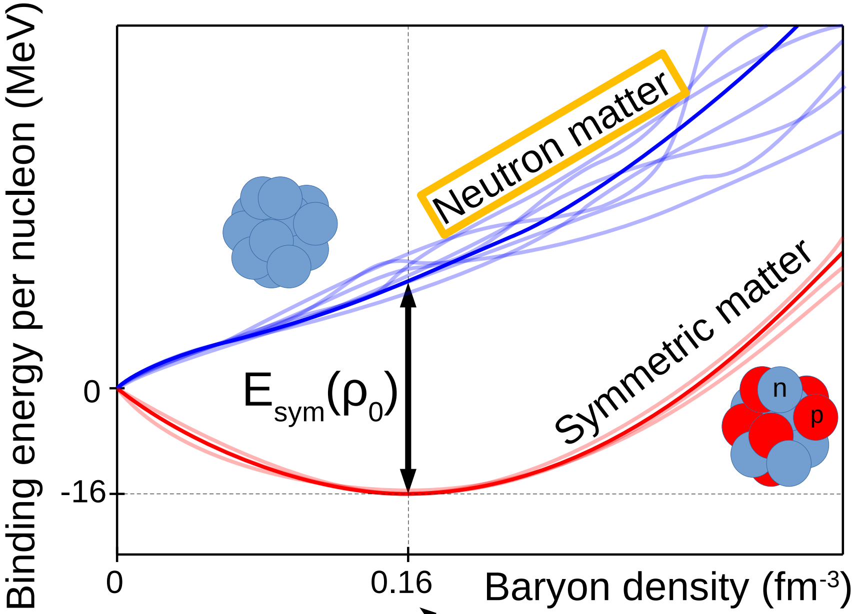
Increased fraction of
nucleons contained in nuclei

Increased shear modulus
(and therefore shear speed)



Nuclear matter equation of state

- Describes the binding energy of nuclear matter
- For symmetric nuclear matter it is well known
- How does it change with proton fraction and density?



Nuclear saturation density (ρ_0)

$$E(\rho,\delta) = E(\rho,0) + E_{\text{sym}}(\rho)\delta^2 + \mathcal{O}[\delta^4]$$

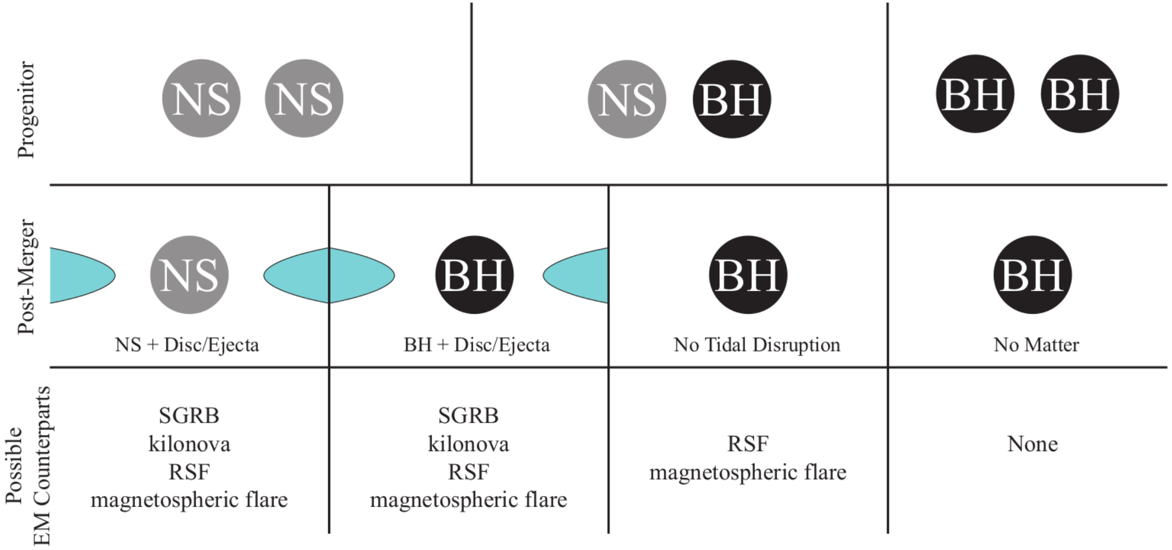
$$E(\rho,0) = E_0 + \frac{1}{2}K_0 x^2 + \mathcal{O}[\rho^3]$$

$$\boxed{E_{\text{sym}}(\rho) = J + Lx + \frac{1}{2}K_{\text{sym}}x^2 + \mathcal{O}[\rho^3]}$$

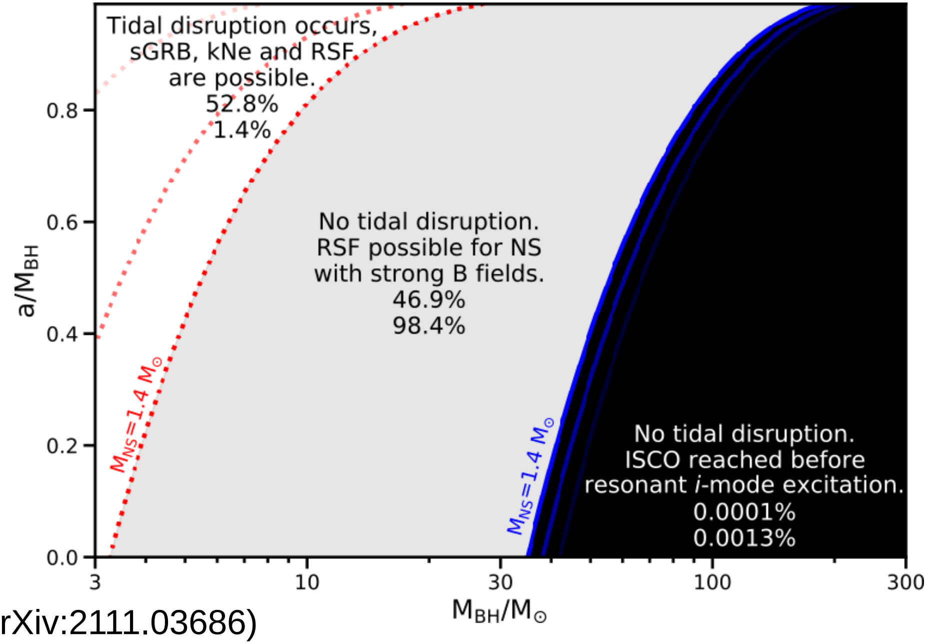
$$\left(x = \frac{\rho - \rho_0}{3\rho_0}\right)$$

Tidal disruption or resonance?

- Tidal disruption is not required for RSFs
- A significantly higher fraction of BHNS binaries may produce RSFs than SGRBs/Kilonovae



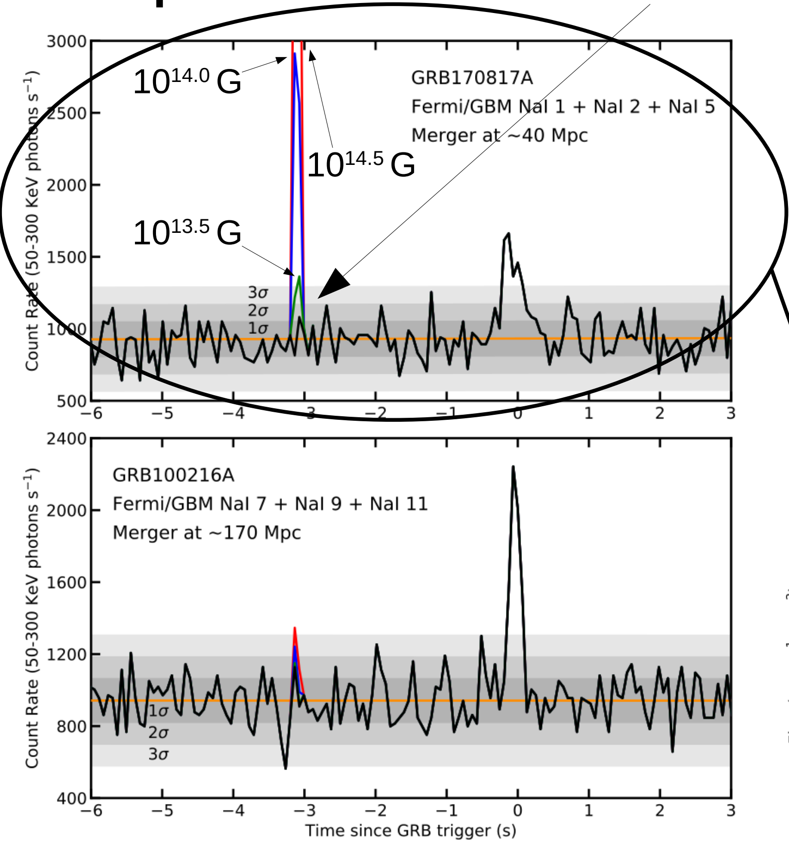
Progenitor	NS NS	NS BH		BH BH
Post-Merger	NS NS + Disc/Ejecta	BH BH + Disc/Ejecta	BH No Tidal Disruption	BH No Matter
Possible EM Counterparts	SGRB kilonova RSF magnetospheric flare	SGRB kilonova RSF magnetospheric flare	RSF magnetospheric flare	None



Neill D. et al., 2021, preprint (arXiv:2111.03686)

EM signals

The NS involved in GW170817 likely had dipole fields below ~10^{12}G



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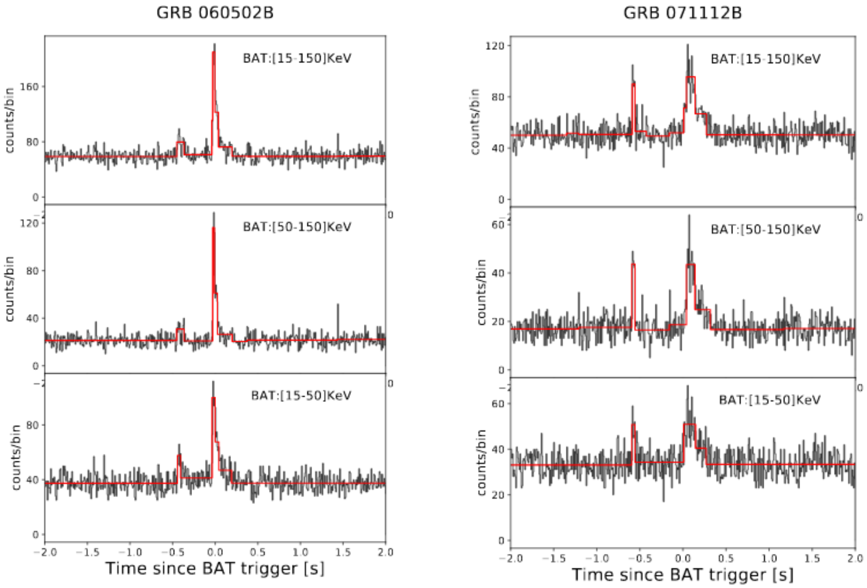
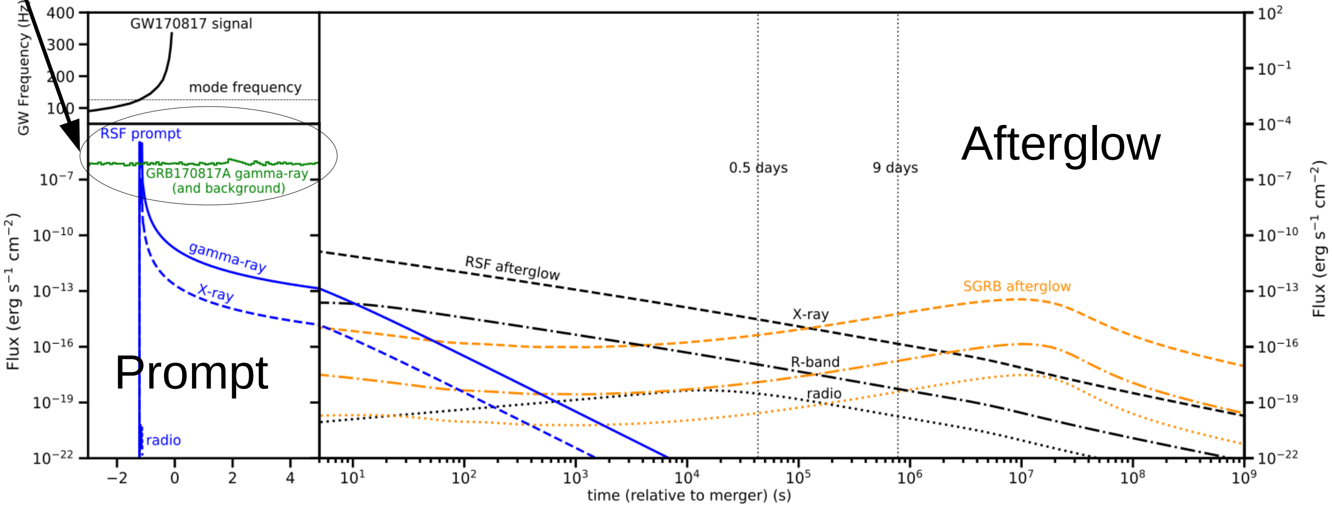
Zhong S.-Q. et al., Precursors in Short Gamma-Ray Bursts as a Possible Probe of Progenitors, 2019, ApJ, 884,25





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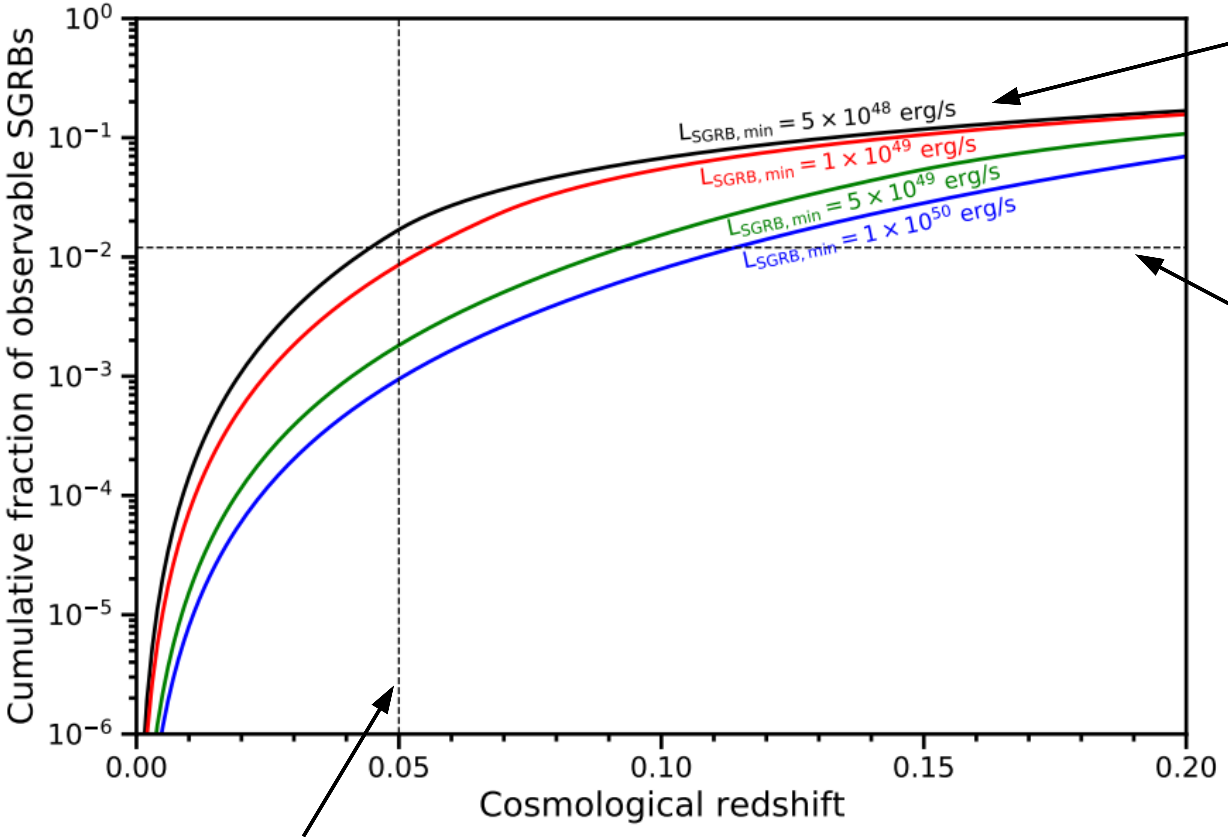
Precursor (RSF) fraction



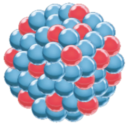
The dimmer SGRBs can be, the more of them will be nearby (and thus close enough for RSFs to be detectable)

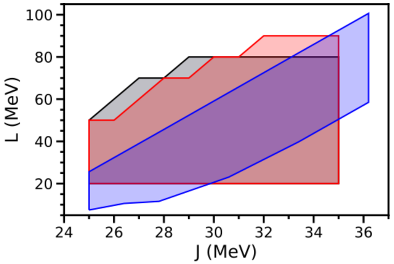
~ fraction of SGRBs with known precursor flares

RSFs can be bright enough to be seen up to z ≈ 0.05

Neill D., Newton W. G., Tsang D.,
2021, MNRAS, 504, 1129

Initial nuclear symmetry energy parameters (J, L, K_{sym}) ranges





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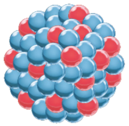
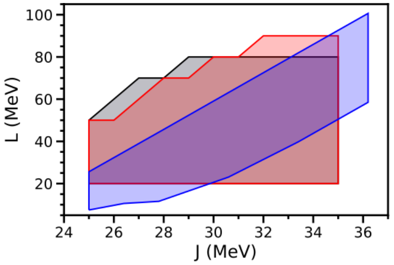
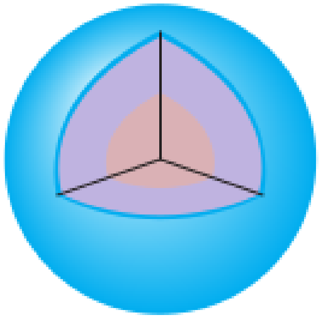




Skyrme EOS, with parameters set to produce chosen J,L,K_{sym}

Calculate NS structure and composition



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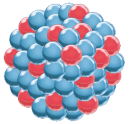

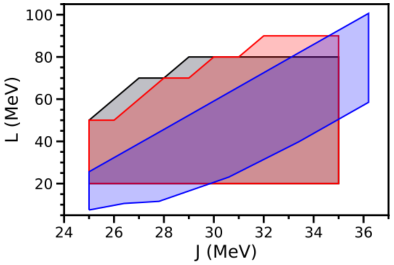

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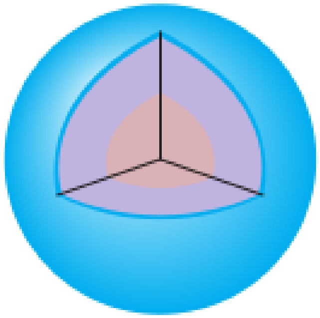
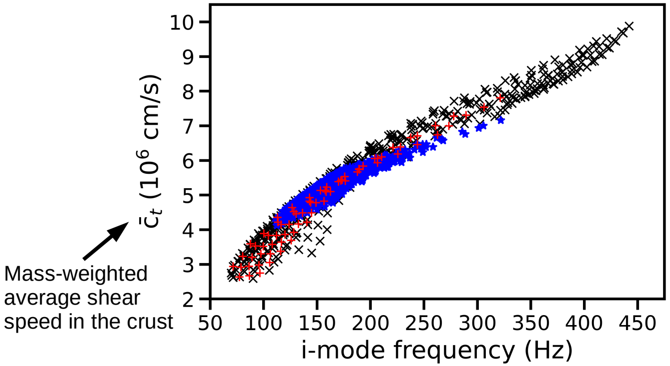


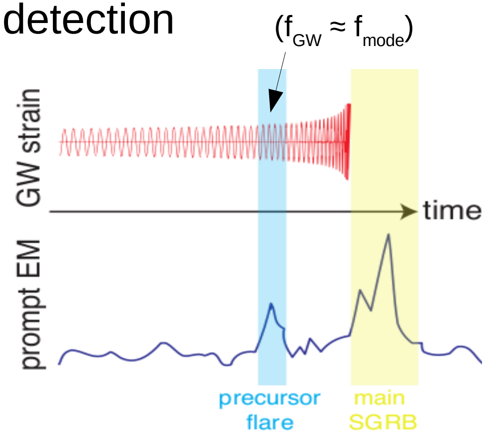
Calculate i-mode frequency.
Calculate material properties ($\bar{c}_t$).

Strongly correlated with shear speed ($\bar{c}_t$), which is dependent on J,L,K_{sym}



Mass-weighted average shear speed in the crust

Measure frequency from multi-messenger GW+RSF detection



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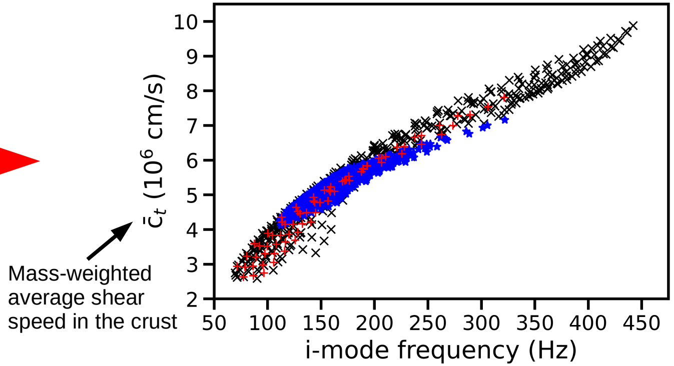

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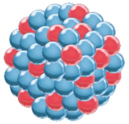

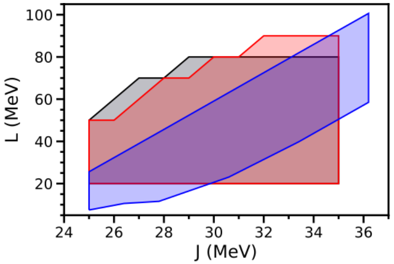

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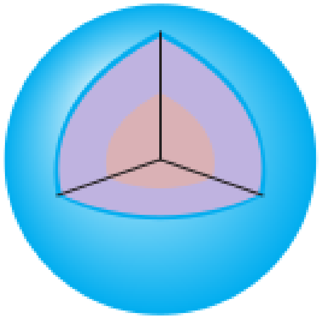

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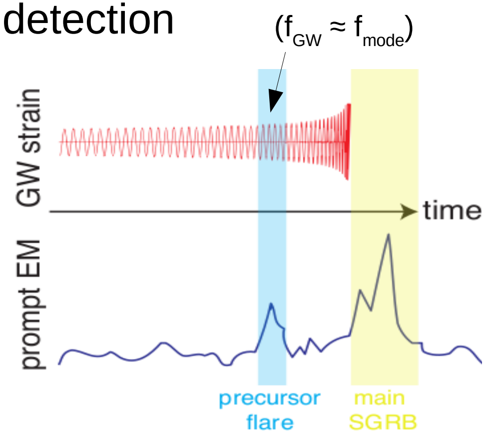
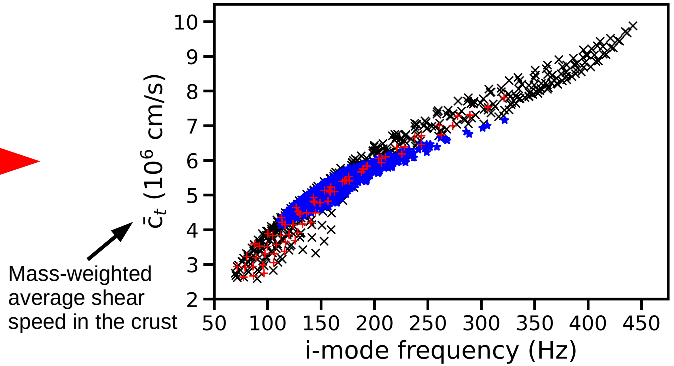
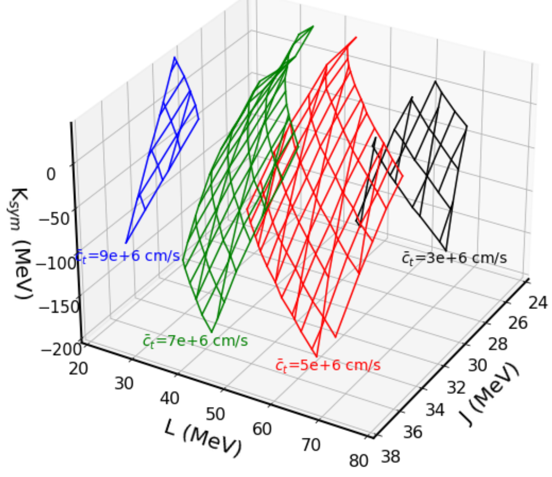


Strongly correlated with shear speed ($\bar{c}_t$), which is dependent on J,L,K_{sym}



Mass-weighted average shear speed in the crust

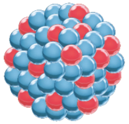
Constrain J,L,K_{sym}

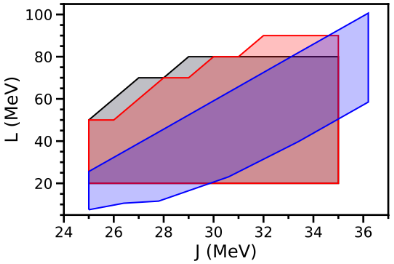


Neill D., Newton W. G., Tsang D., 2021, MNRAS, 504, 1129

Calculate i-mode frequency.
Calculate material properties ($\bar{c}_t$).

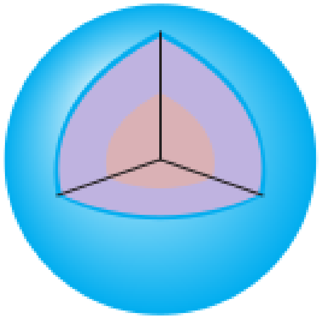
Initial nuclear symmetry energy parameters (J, L, K_{sym}) ranges



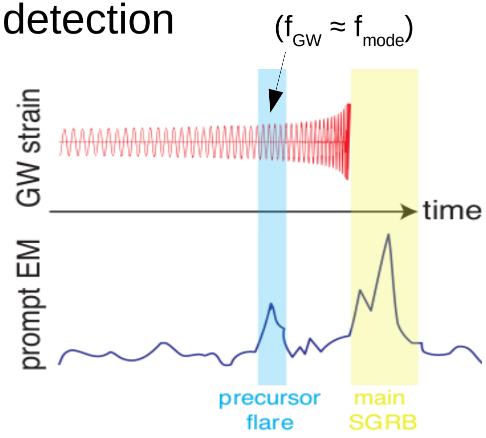


Skyrme EOS, with parameters set to produce chosen J,L,K_{sym}

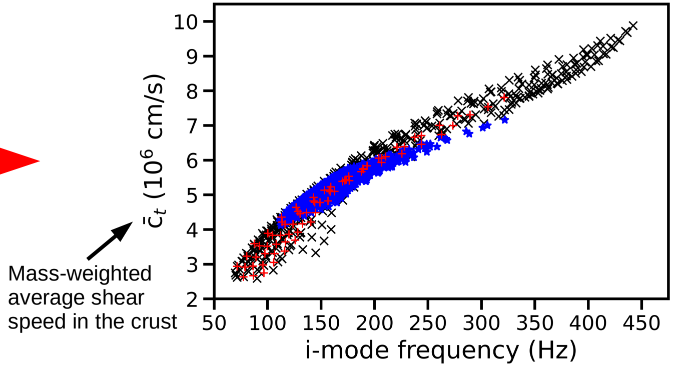
Calculate NS structure and composition



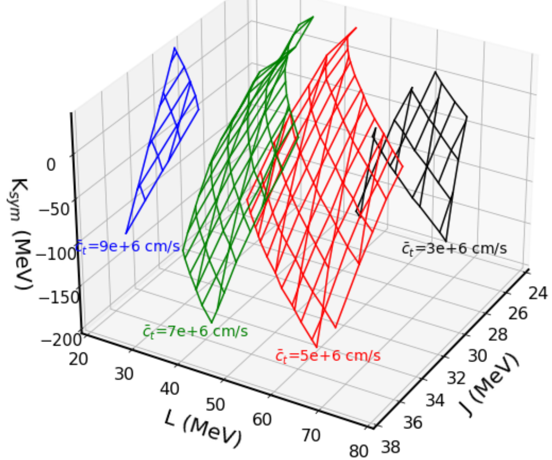
Measure frequency from multi-messenger GW+RSF detection



Strongly correlated with shear speed ($\bar{c}_t$), which is dependent on J,L,K_{sym}



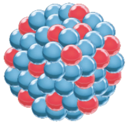
Constrain J,L,K_{sym}

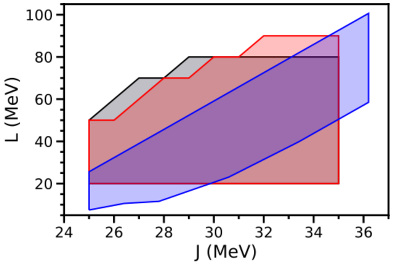


Neill D., Newton W. G., Tsang D., 2021, MNRAS, 504, 1129

Calculate i-mode frequency.
Calculate material properties ($\bar{c}_t$).

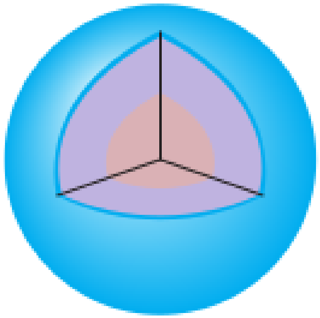
Initial nuclear symmetry energy parameters (J, L, K_{sym}) ranges





Skyrme EOS, with parameters set to produce chosen J,L,K_{sym}

Calculate NS structure and composition



Constrain NS EOS