3G Neutron Star Working Group

Neutron star science with 3G detectors

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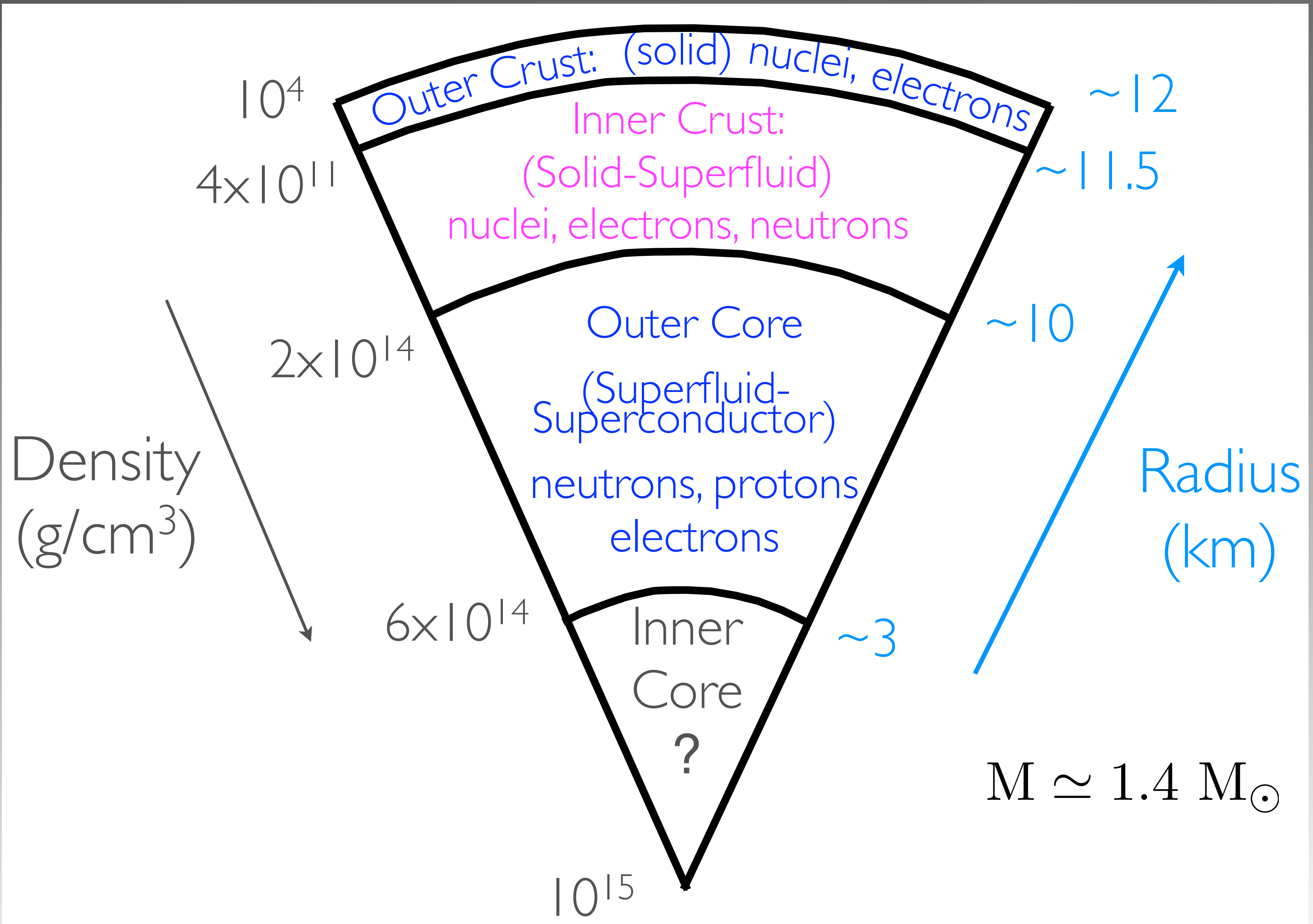
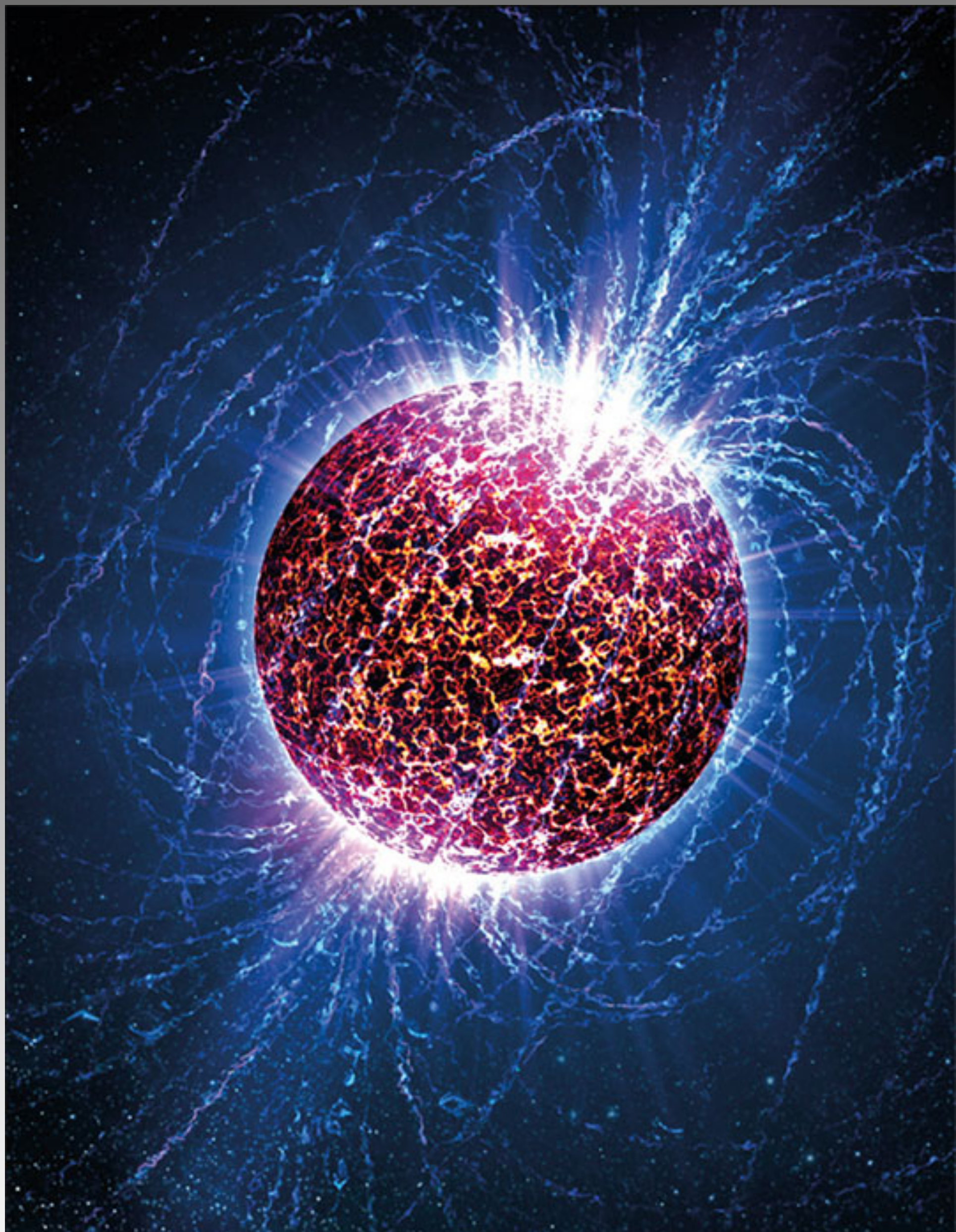




Questions at the Forefront

1. Does matter in neutron stars and neutron star mergers contain novel phases not realized inside nuclei and heavy-ion collisions?
2. Can neutron star observations guide and validate theories of nuclei and nuclear matter?
3. Is there a diversity in the neutron star population and what are its implications?
4. How do nuclear and neutrino reactions shape NS merger dynamics and nucleosynthesis?
5. How do the properties of nuclei far from stability impact on the electromagnetic emission from neutron star merger ejecta ?
6. Can neutron stars sustain long-lived large quadrupolar deformations?
7. Do large scale (magneto)hydrodynamic instabilities influence spinning and merging neutron stars?
8. Can we combine GW and EM signatures to validate multi-physics simulations of NS-NS and NS-BH mergers to predict ejecta, nucleosynthesis, and the gamma-ray burst mechanism?
9. Can we model and observe post-merger oscillations to reliably constrain dense matter and merger dynamics.
10. Does dark matter and physics beyond the standard model play a role in neutron stars and neutron star mergers?

Sources that need 3G detectors

I. Merging BNSs and NS-BHs

- Inspiral: Masses and tidal deformability
- Post-merger dynamics: Oscillations, ejecta, connection to EM.

II. Spinning Neutron Stars (Continuous GWs)

- Elastic and magnetic deformations: properties of dense matter.
- Instabilities (eg. r-modes): Transport and dissipation in dense matter.

III. Bursting, Flaring or Glitching Neutron Stars

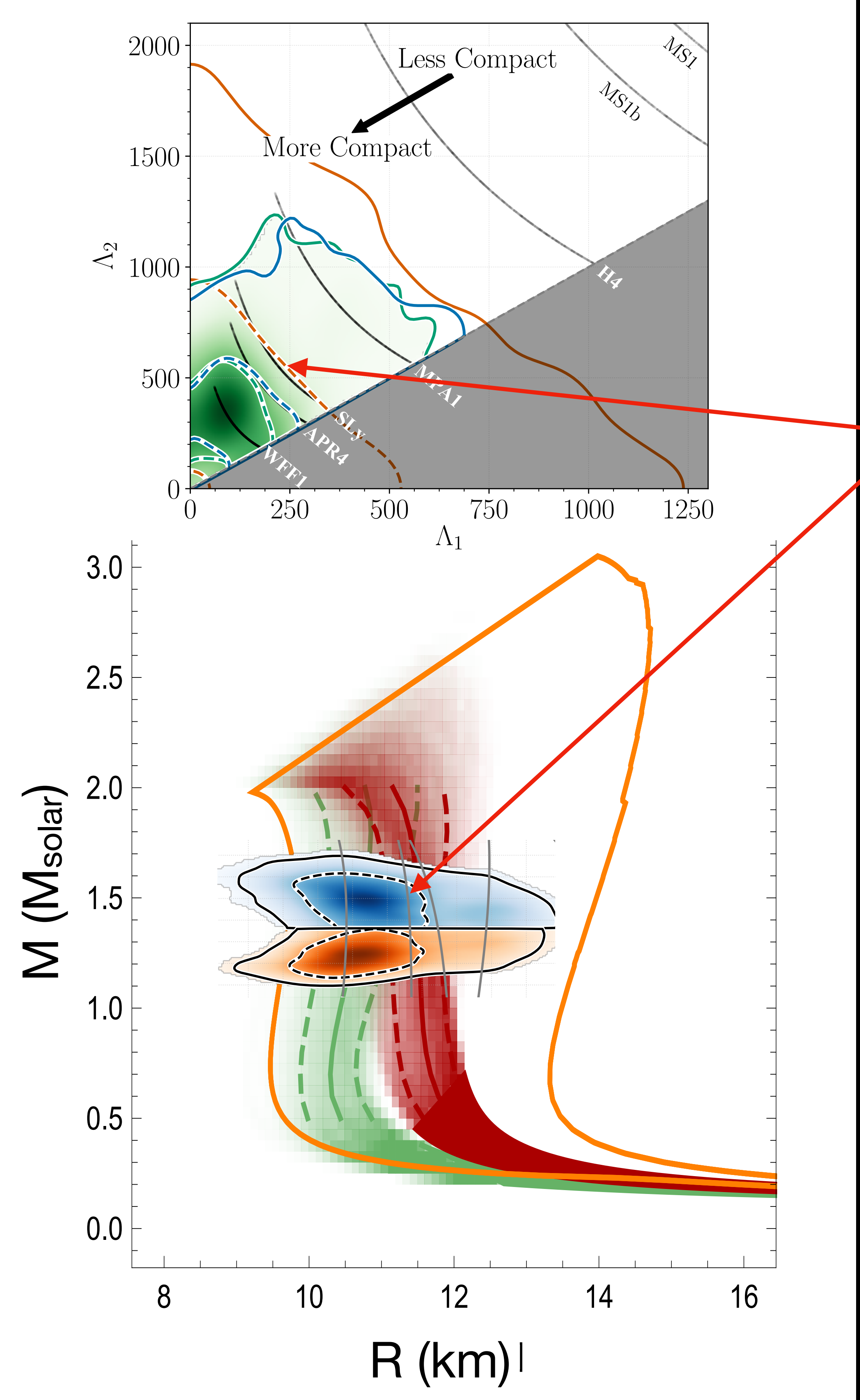
- Evolution of internal magnetic fields
- Superfluid and solid phases and their dynamics

Inspiral: NS Mass and Radius

GW170817 demonstrated that it is possible to constrain the neutron star mass-radius relation using GW data. This is a watershed moment in neutron star science.

However, these constraints are not stringent enough to provide new insights. Realistic nuclear EOSs predict a smaller range of radii (and tidal deformability) compatible with GW170817 constraints.

To have an impact the tidal deformability needs to be measured to better than 10%. And we will need several measurements across the accessible mass range. Both can be achieved with third-generation detectors.



LIGO-Virgo Collab. arXiv:1805.11581.
See also De et al. PRL (2018)

Tews, Margueron, Reddy (2018)

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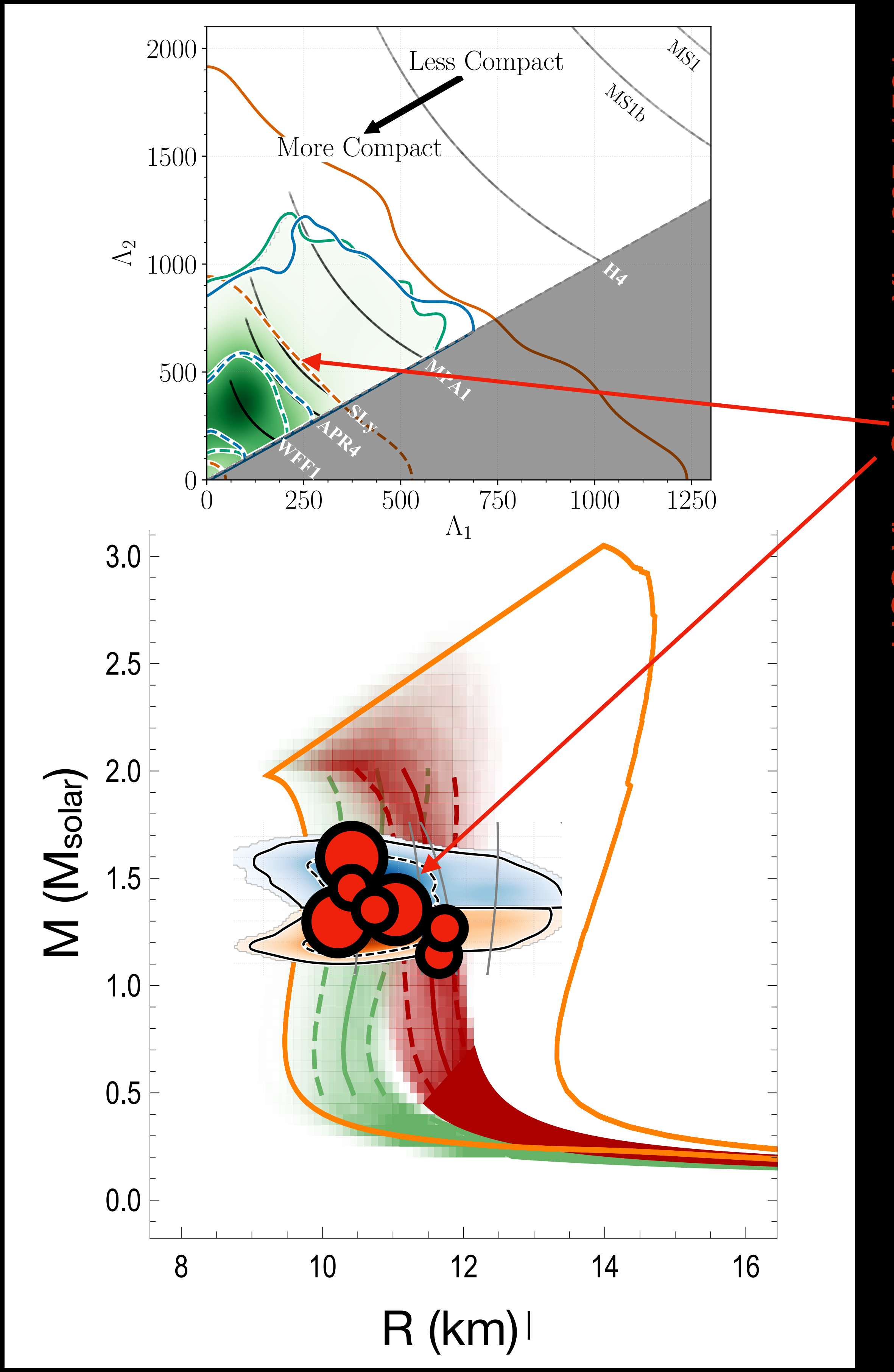

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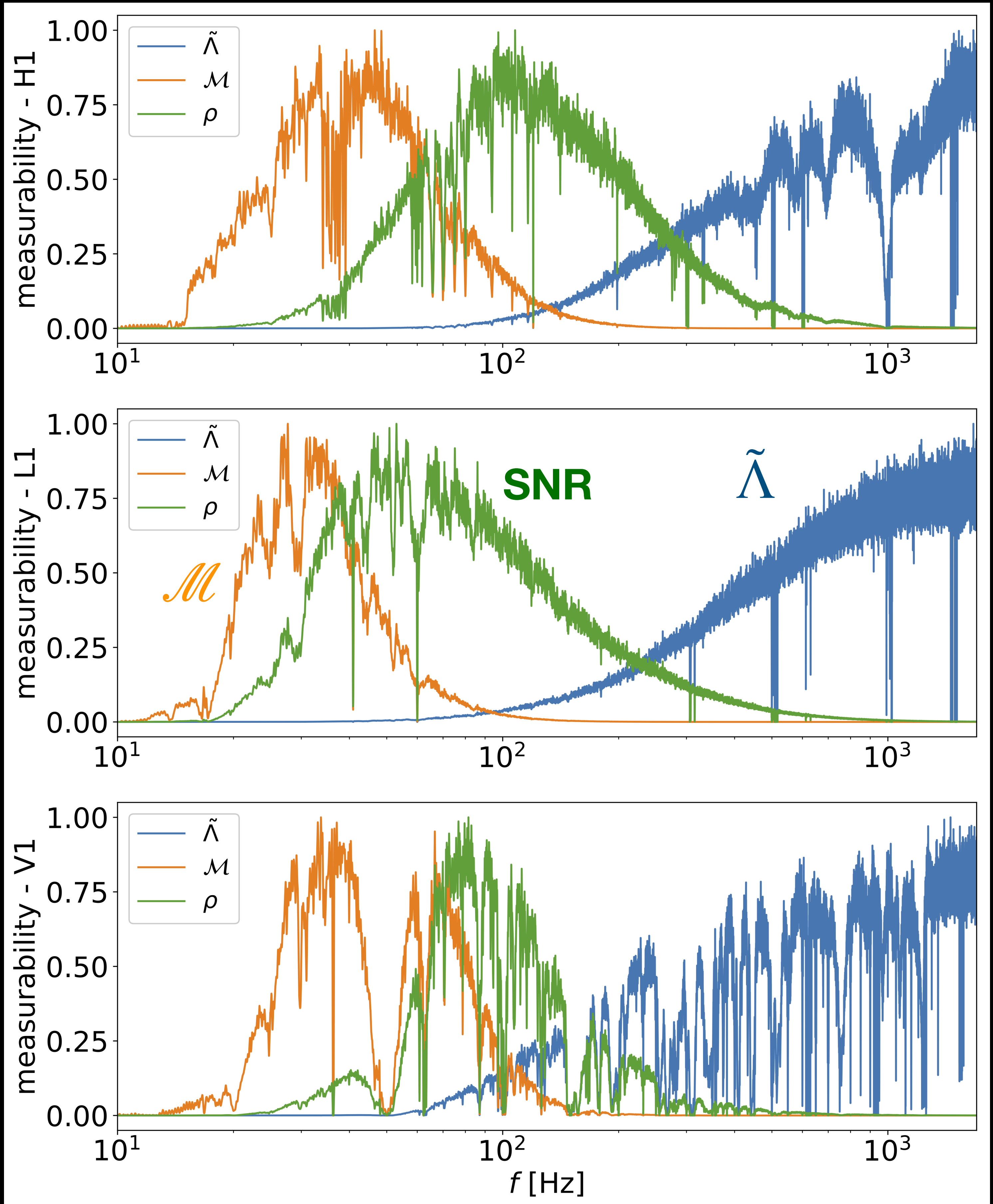
Tidal Deformability & High Frequency Sensitivity

Current detectors are not optimized to measure neutron star parameters.

(figure from De et al. (2018))

The chirp mass is determined at low frequency and the tidal polarizability is determined at high frequency.

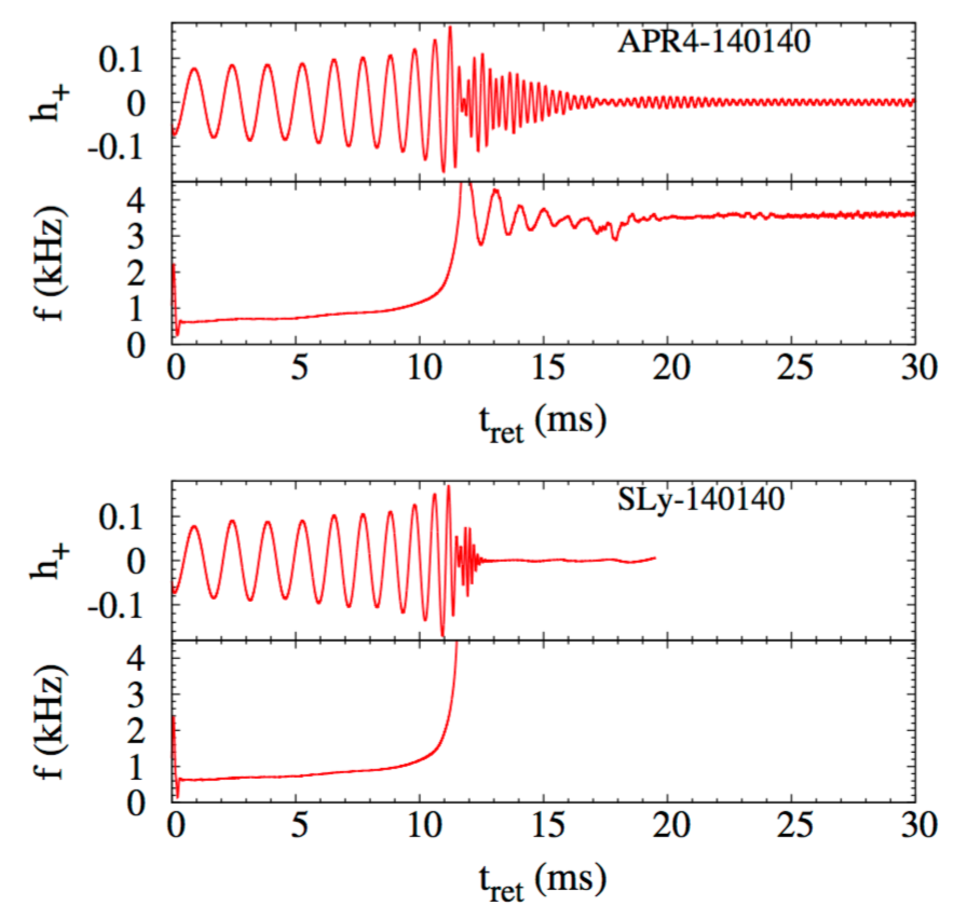
Improved high frequency sensitivity is key to extracting constraints on the compactness of neutrons stars.

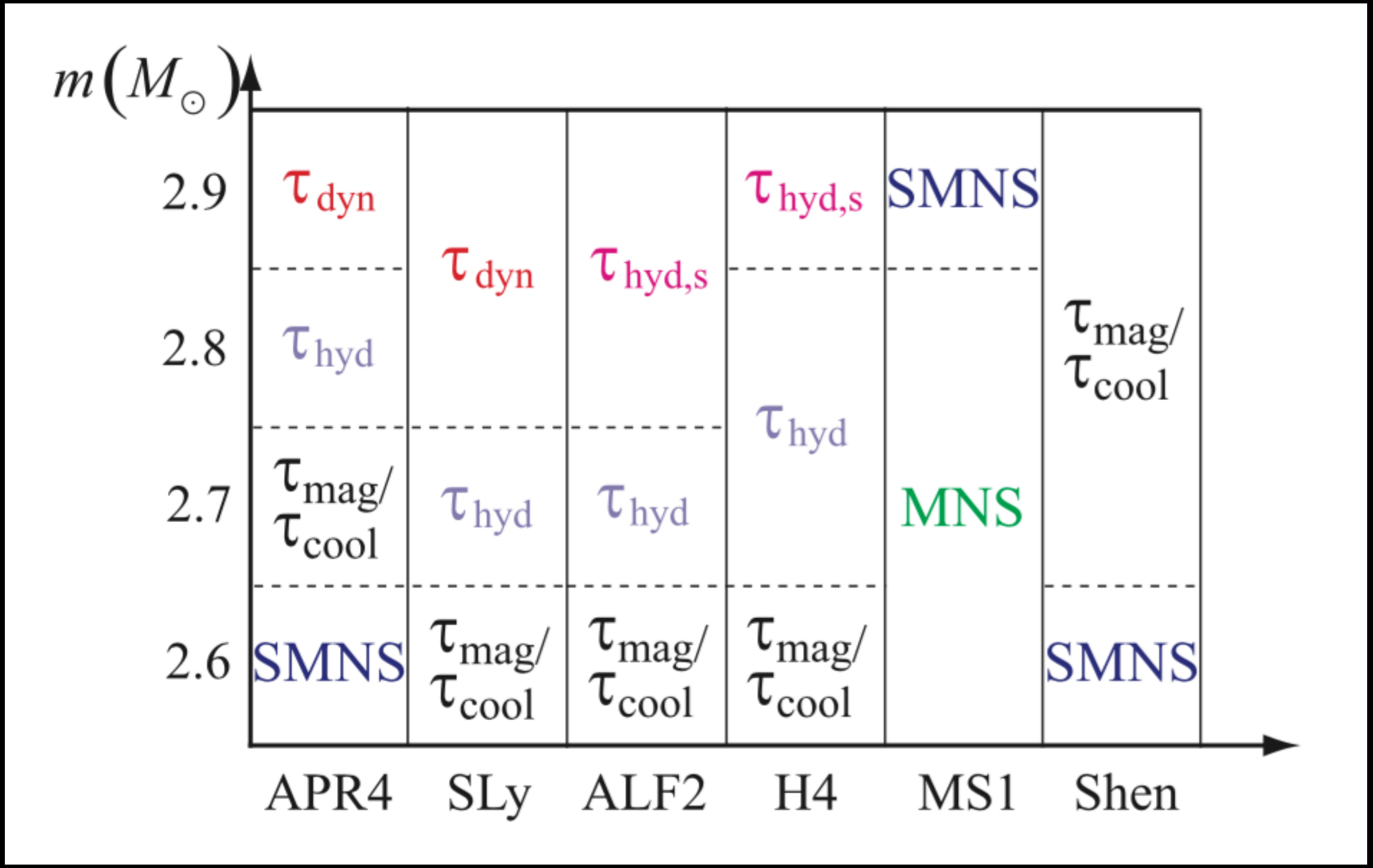


Impact of EOS Post-merger

EOS determines:

- Remnant fate & lifetime
- Ejecta & Composition.
- Post-Merger oscillations





$m(M_\odot)$	APR4	SLy	ALF2	H4	MS1	Shen
2.9	τ_{dyn}	τ_{dyn}	$\tau_{hyd,s}$	$\tau_{hyd,s}$	SMNS	τ_{mag}/τ_{cool}
2.8	τ_{hyd}			τ_{hyd}	MNS	
2.7	τ_{mag}/τ_{cool}	τ_{hyd}	τ_{hyd}			
2.6	SMNS	τ_{mag}/τ_{cool}	τ_{mag}/τ_{cool}	τ_{mag}/τ_{cool}		SMNS

τ_{dyn}: BH formed on dyn. time scale

τ_{hyd}: HMNS lifetime determined by hydrodynamic effects

$\tau_{hyd,s}$: like τ_{hyd}, but < 10 ms

$\tau_{mag/cool}$: HMNS lifetime determined by MHD-effects/ν-cooling

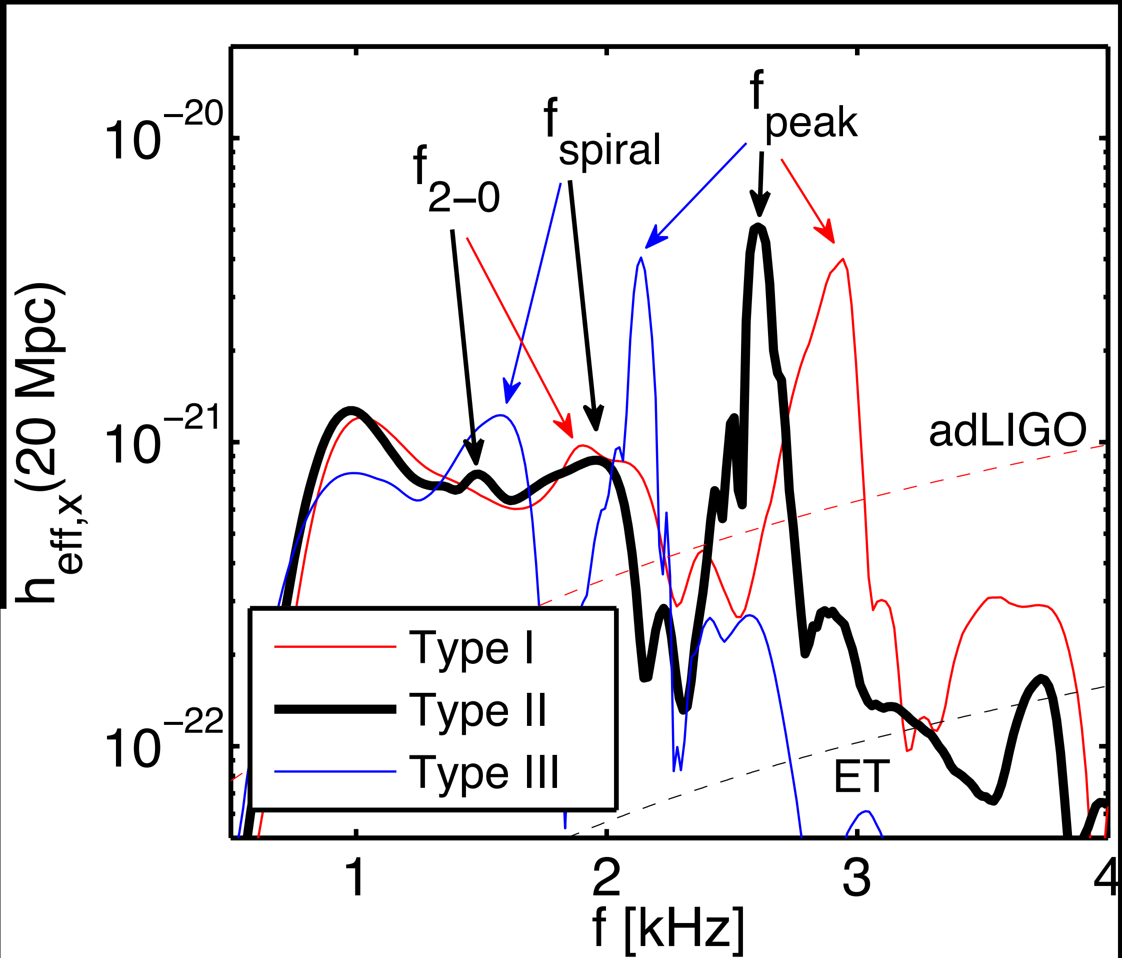
from Hotokezaka+ 2013

(Hypermassive) Neutron Star Seismology

Merger excites high frequency quasi-normal modes. The spectrum is sensitive to the compactness of the hypermassive neutron star.

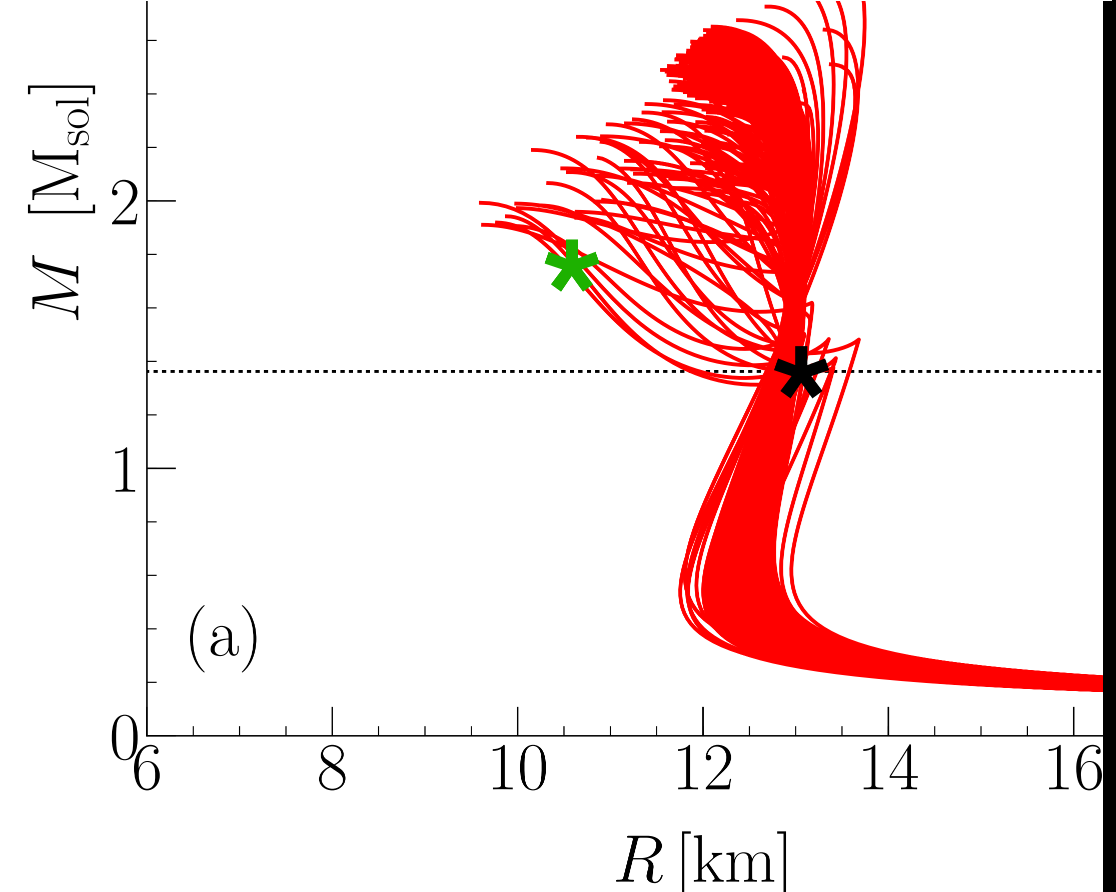
$$\begin{aligned}
f_{\mathrm{peak}}[\mathrm{kHz}] &= 199(M/R)^2 - 28.1(M/R) + 2.33 \\
f_{\mathrm{spiral}}[\mathrm{kHz}] &= 358(M/R)^2 - 82.1(M/R) + 6.16 \\
f_{2-0}[\mathrm{kHz}] &= 392(M/R)^2 - 88.3(M/R) + 5.95
\end{aligned}$$

Bauswein & Stergioulas (2015)



Phase transitions in the the hypermassive neutron star can alter the correlation between compactness measured from the tidal deformability and post-merger oscillations.

Bauswein et al. (2018)



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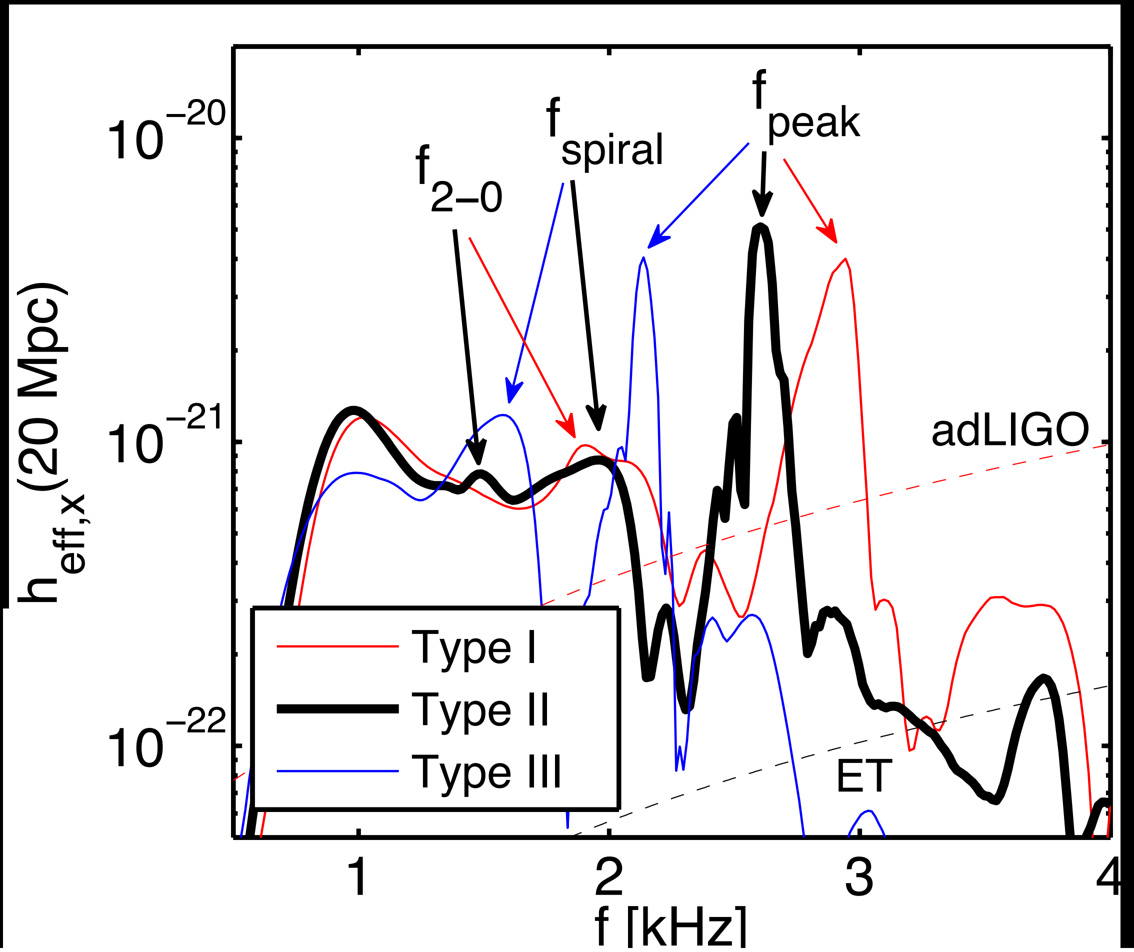

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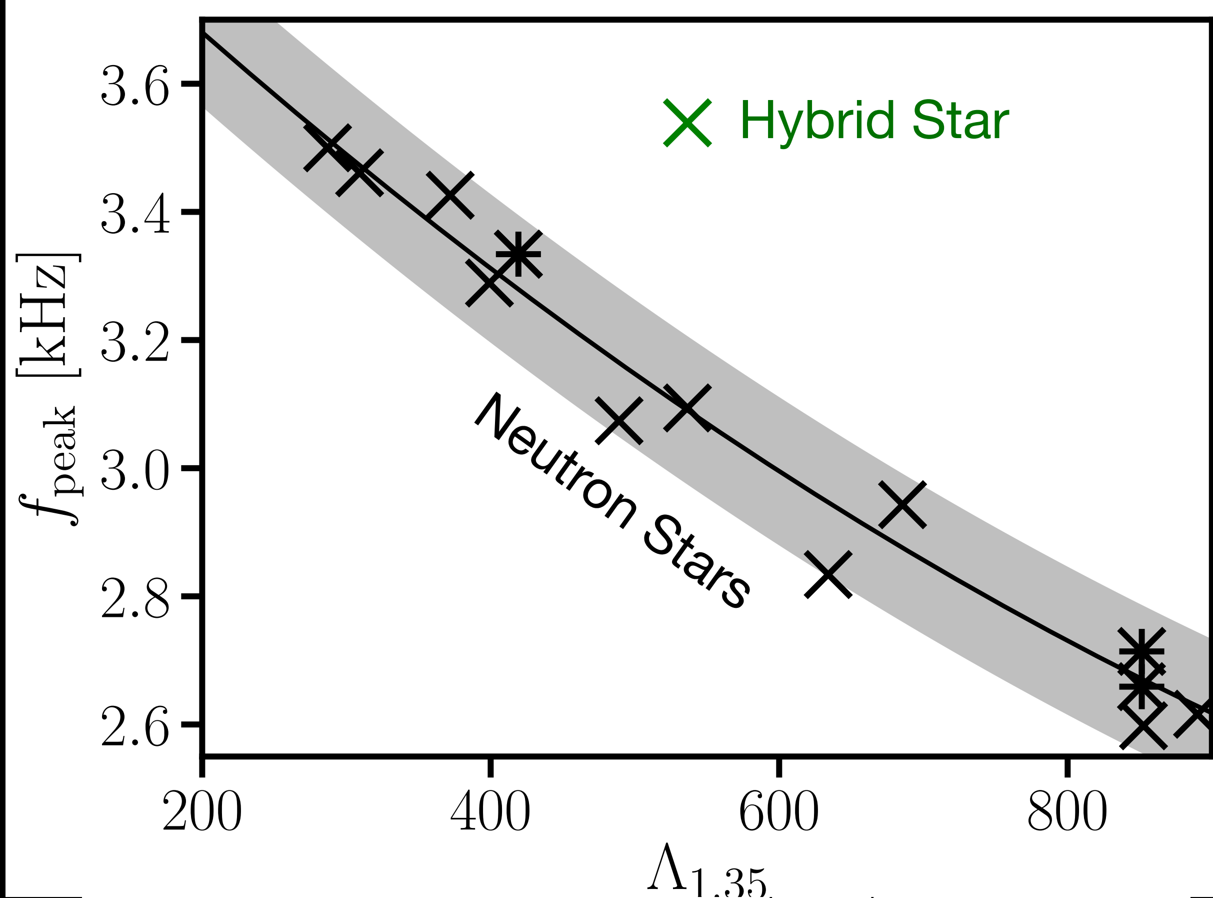


EOS & merger dynamics

SFHo: $M_{\rm max}$= 2.06 $M_\odot$ DD2: $M_{\rm max}$= 2.42 $M_\odot$

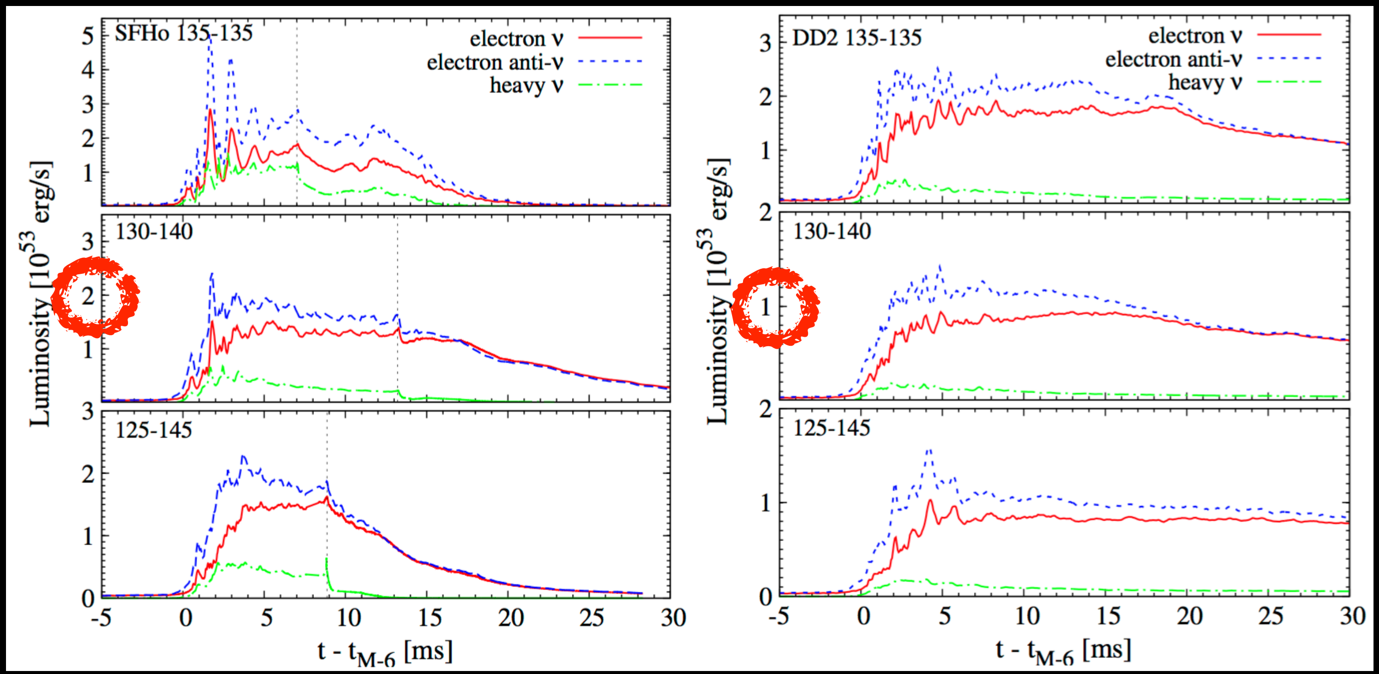
Softer EOS leads to:

- merger at shorter separation
- larger velocities
- higher temperatures
- higher neutrino luminosities
- easier to shock-heat matter ($v > c_s$)
- more positron captures:

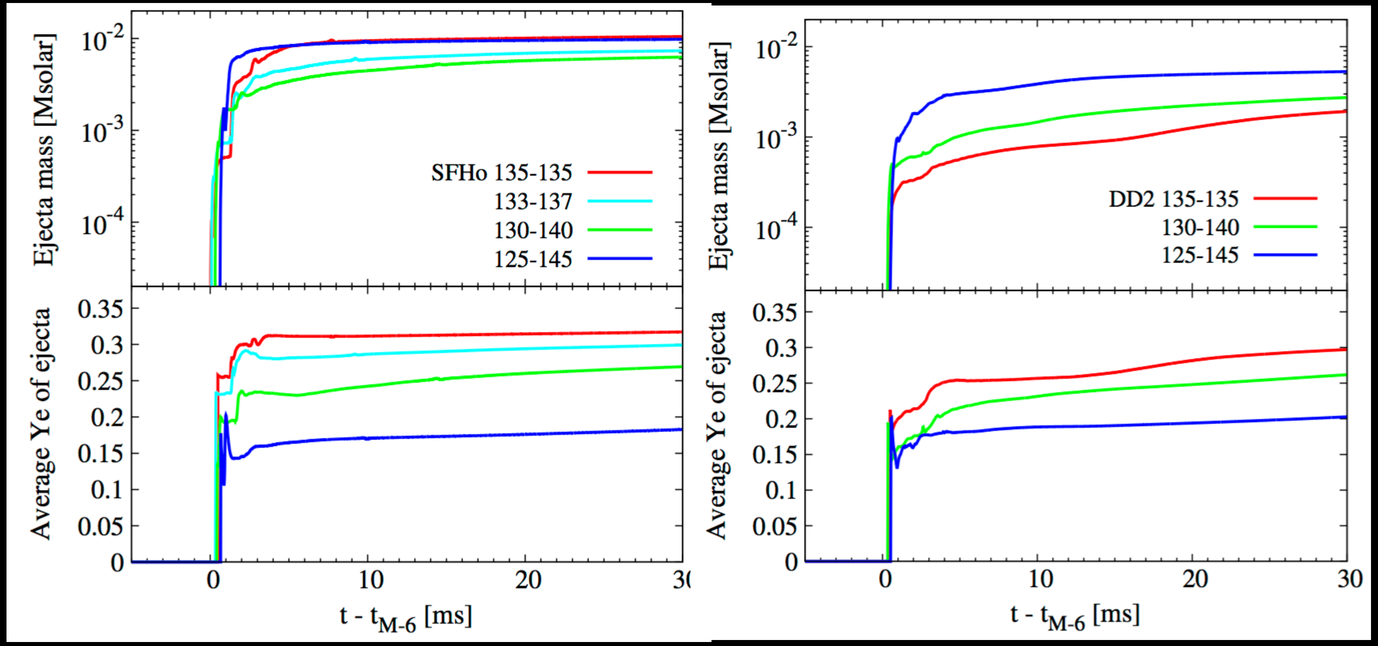
$$e^+ + n \rightarrow p + \bar{\nu}$$

- higher electron fraction Y_e in ejecta
- bluer macronova

neutrino emission



ejecta

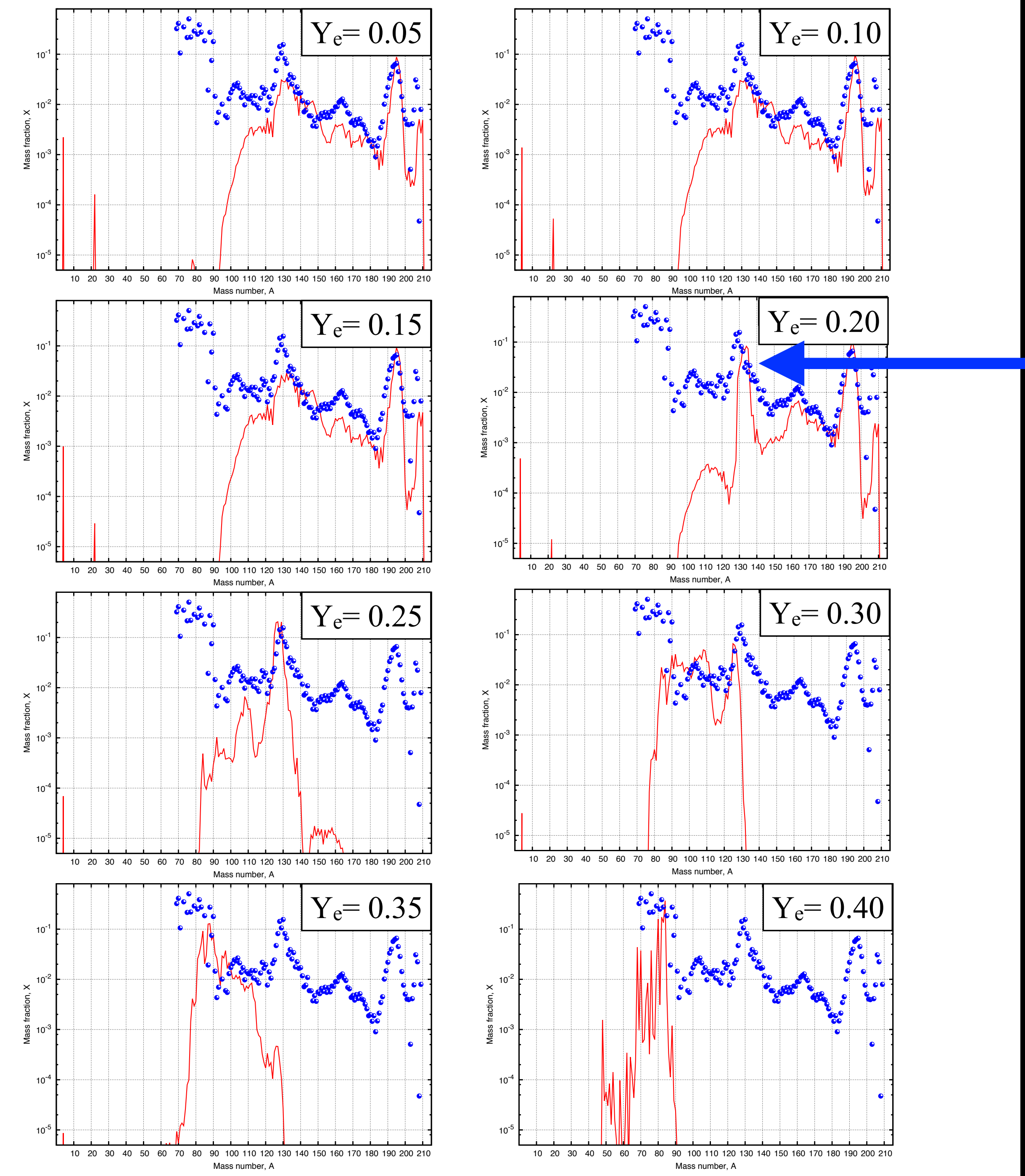


Sekiguchi+ 2016

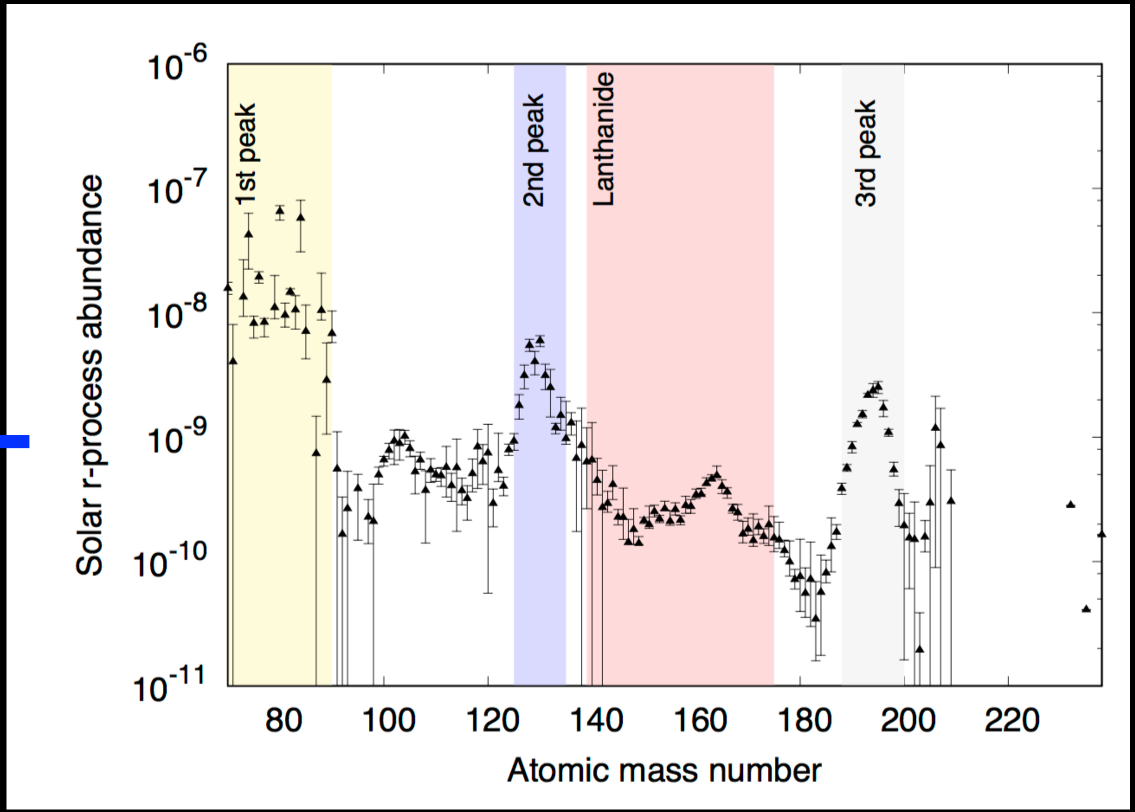
Nucleosynthesis and Y_e of Ejecta

Electron fraction (Y_e) of the ejecta determines the nucleosynthetic outcomes.

(vej= 0.25c, WinNet 5831 isotopes, FRDM mass formula)



Rosswog+ 2018

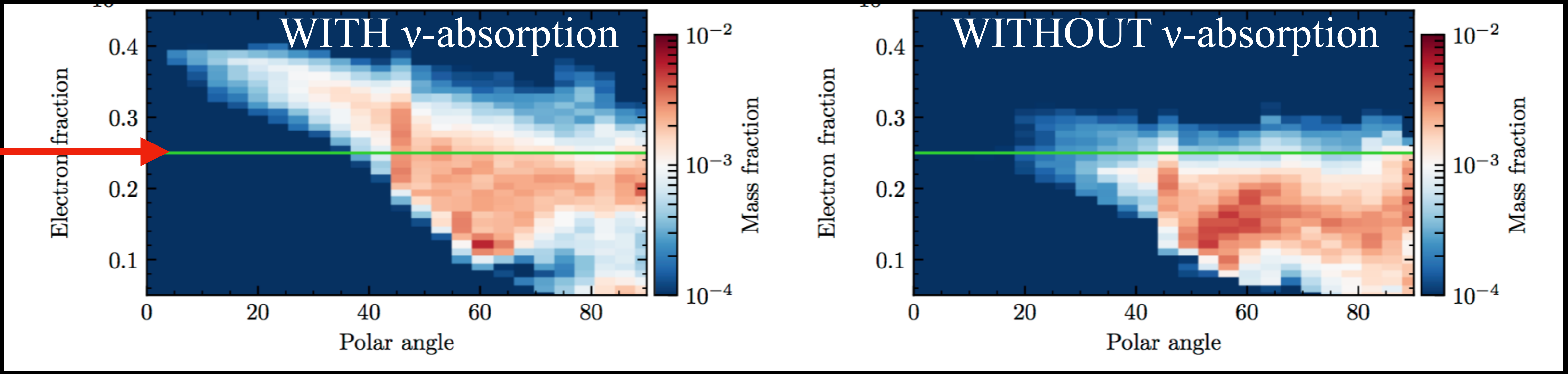


- Threshold value: $Y_e^{crit} \approx 0.25$
  - $Y_e < Y_e^{crit}$:
    - "strong/heavy" r-process A ≳ 130
    - insensitive to details of trajectory
  - $Y_e > Y_e^{crit}$:
    - A ≲ 130
    - sensitive to details of trajectory

Neutrinos and EM Signal

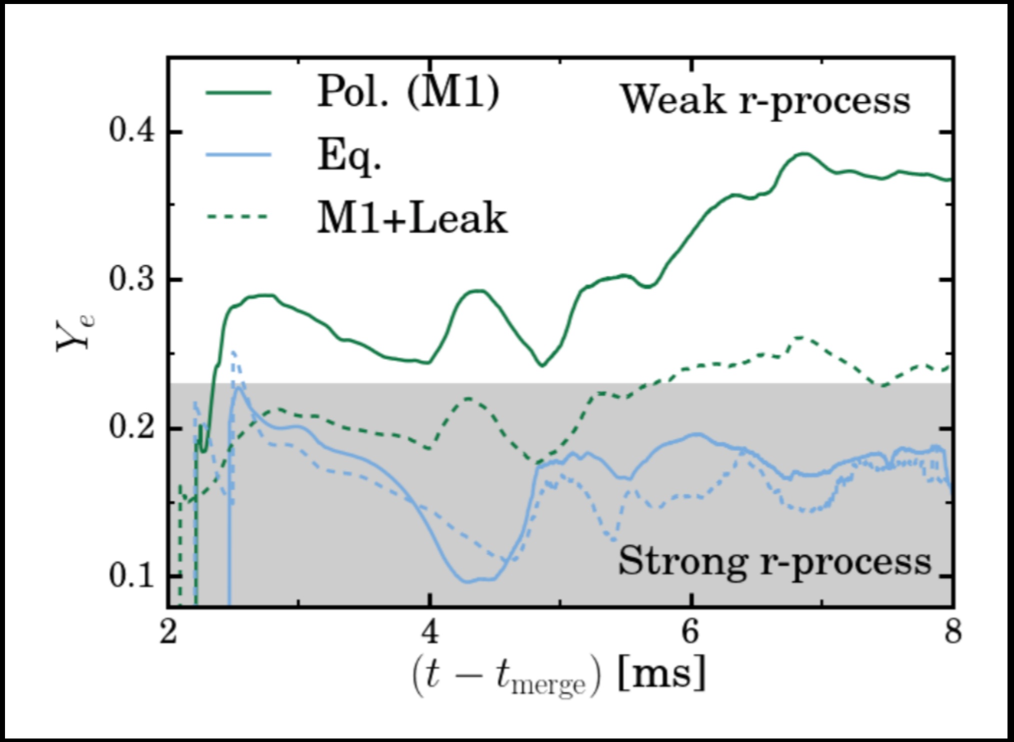
- neutrino heating: ejecta from 1.35 + 1.35 M$_\odot$; SFHO-EOS (Perego+ 2017)

Y_e^{crit}



⇒ determines color of macronova!

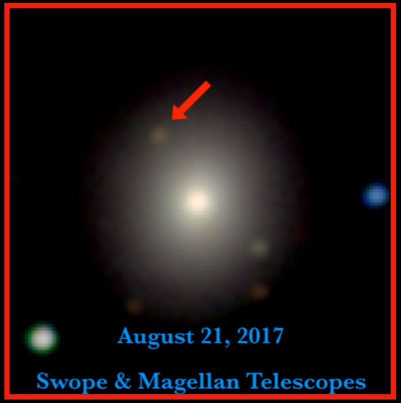
- accurate treatment of neutrino transport needed to predict EM-transient



Foucart+ 2016

⇒ “blue transient”

⇒ “red transient”



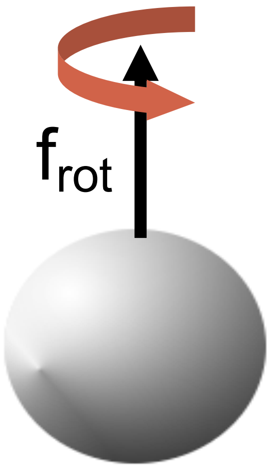
Continuous Gravitational Waves

Non axisymmetric shape:

Crustal deformations, Internal deformations

- geological history, magnetic field, re-adjustments, if in binary: accretion-powered hot-spot

$$h_0 = \frac{4\pi^2 G}{c^4 D} I_{zz} \epsilon f_{\mathrm{GW}}^2 = 3 \times 10^{-25} \left(\frac{\mathrm{kpc}}{D}\right) \left(\frac{\epsilon}{10^{-6}}\right) \left(\frac{f_{\mathrm{GW}}}{\mathrm{kHz}}\right)$$



Bumpy Neutron Star

$$\varepsilon = \frac{|I_{xx} - I_{yy}|}{I_{zz}}$$

Predictions of max values range between 10^{-3} and 10^{-7}

Non axisymmetric motion:

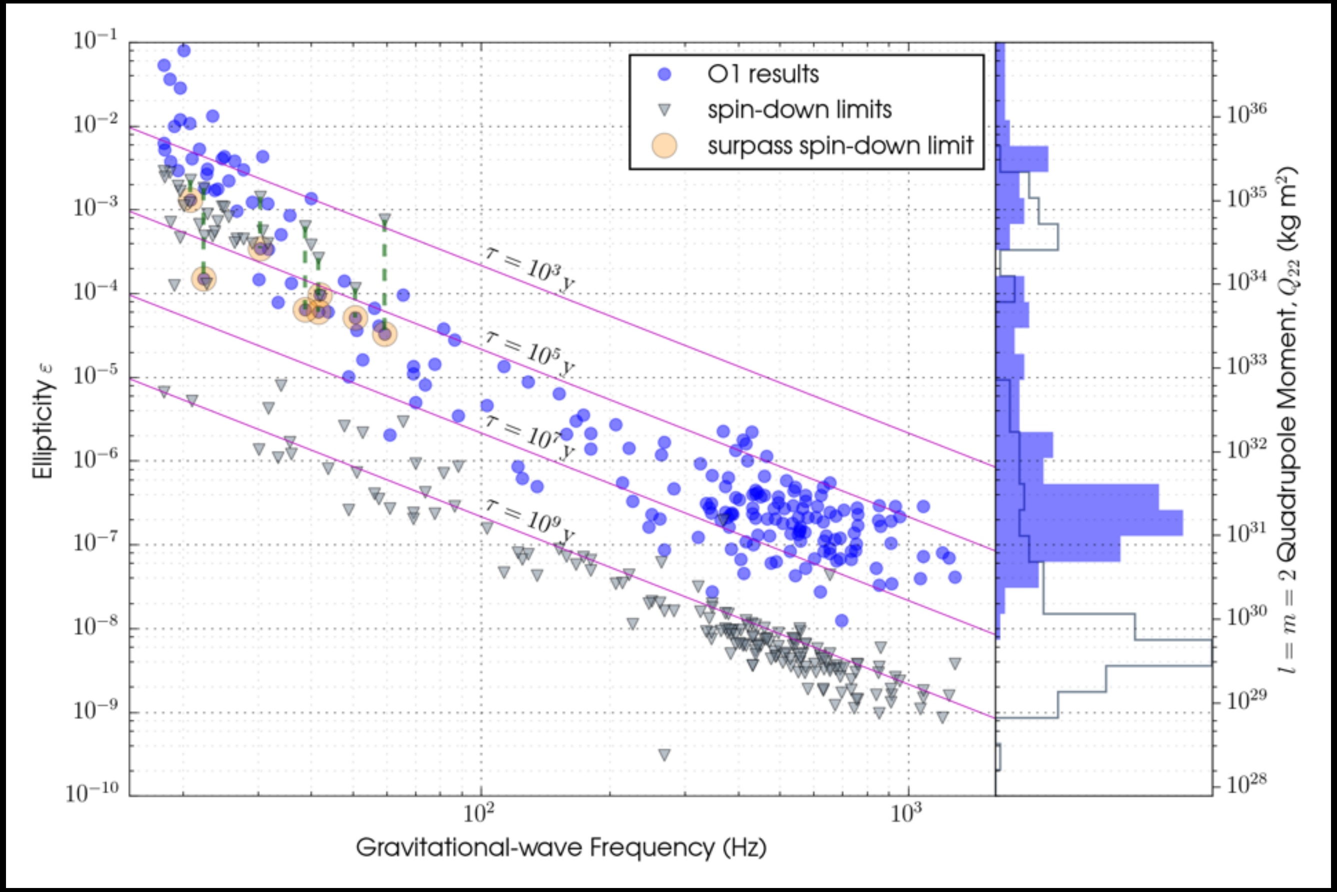
- Free-precession
- R-modes
- Ekman flows

Predictions on GW amplitude span orders of magnitude.

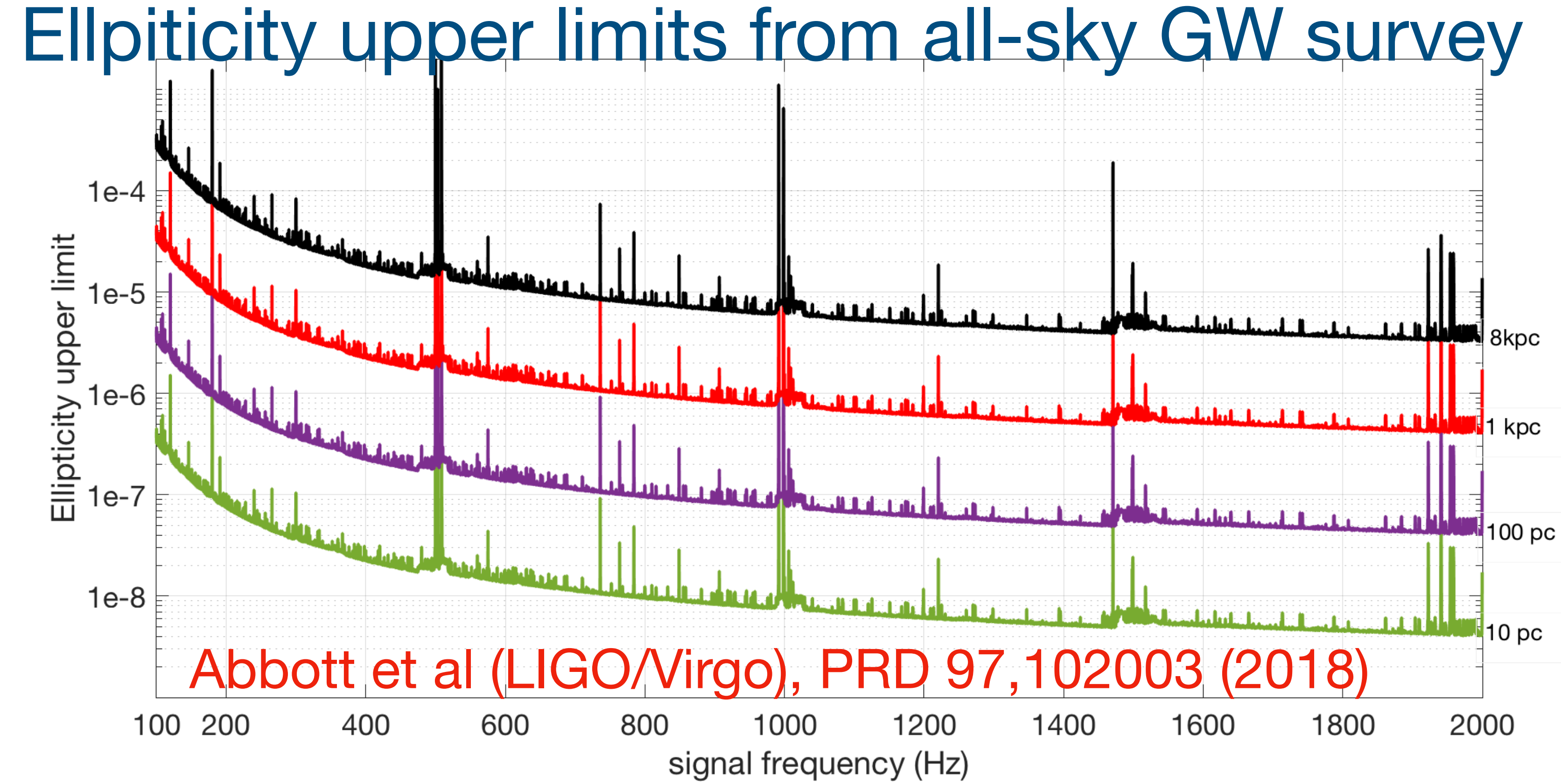
Joint EM and GW observation of a CW signal could shed light on: emission mechanism, NS interiors, NS evolution and NS populations.

Bounds on the ellipticity of NSs

With 3 detectors at Ad. LIGO sensitivity bound improves by factor of 4 in one year. To access 100 times smaller bounds will require new detectors with improved low frequency sensitivity.



All sky survey can exclude objects with ellipticities ≥ 10^{-7} within a distance of 100 pc of Earth at frequencies ≥ 1000 Hz.


Ellpiticity upper limits from all-sky GW survey

Abbott et al (LIGO/Virgo), PRD 97,102003 (2018)

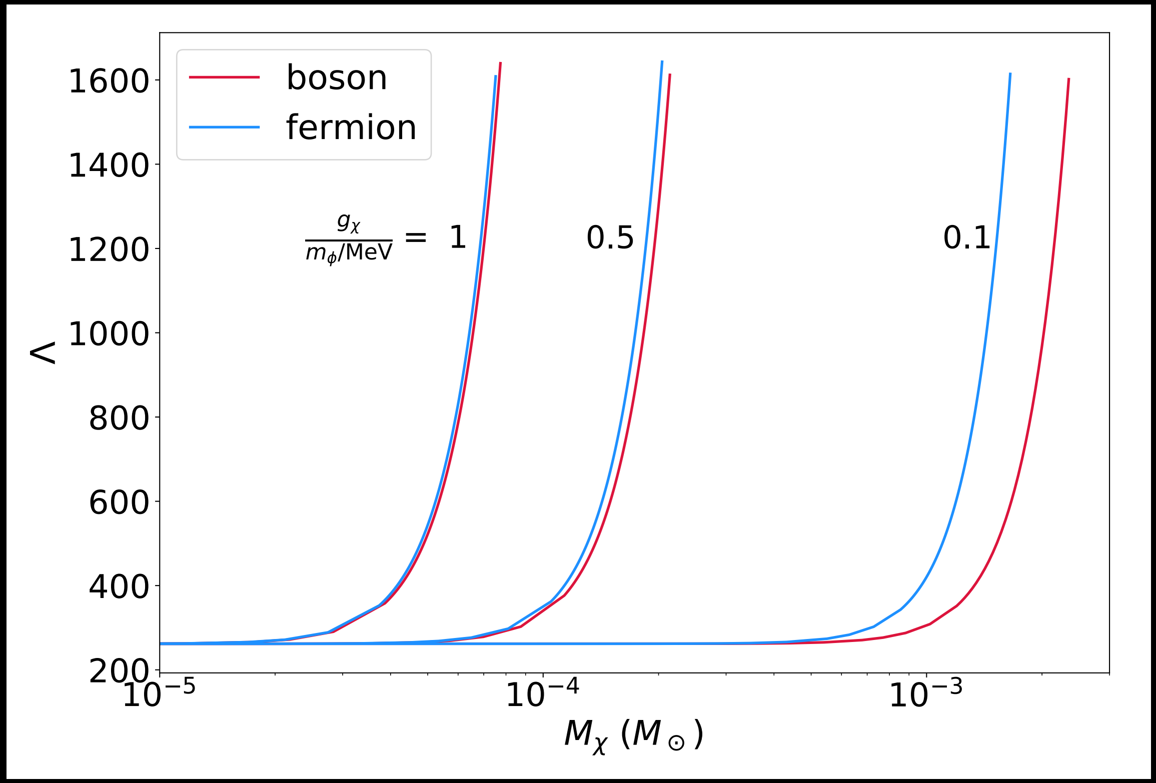
Physics Beyond the Standard Model & Neutron Stars

Speculative ideas about neutron stars containing an admixture of dark matter have explored recently.

These include:

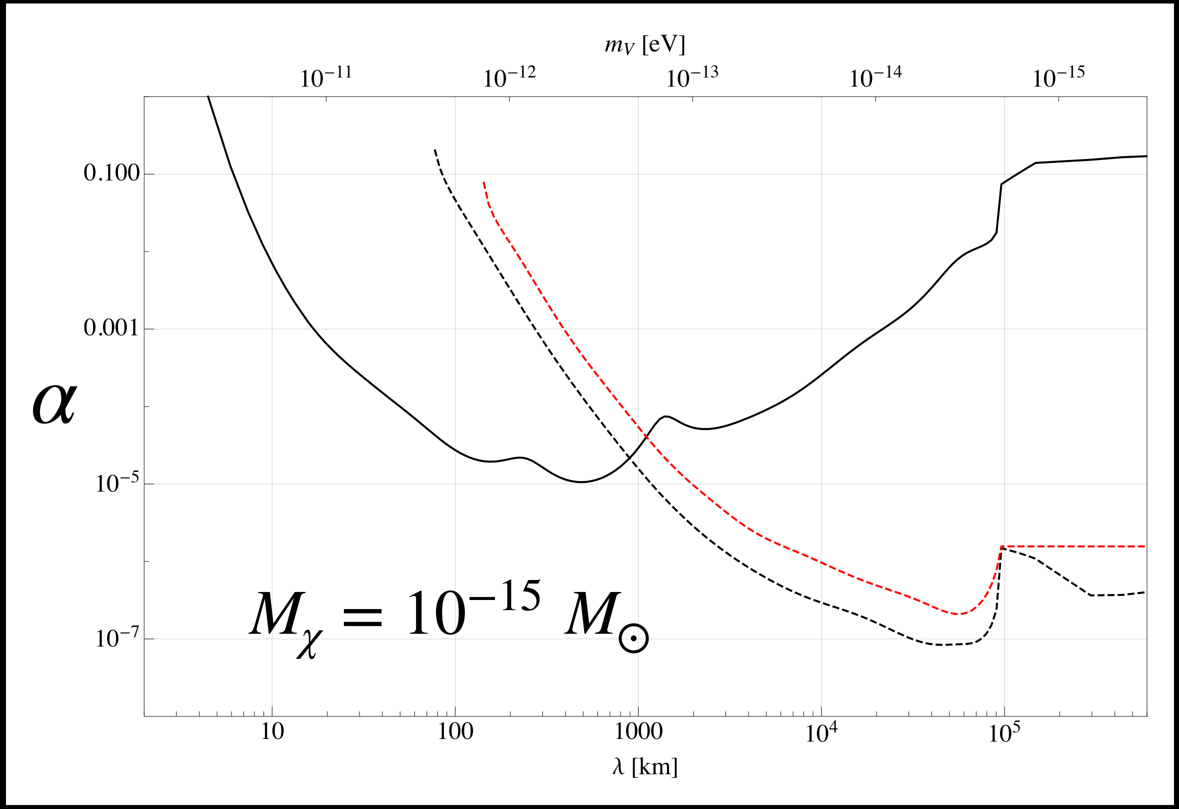
Dark halos around neutron stars generated by trace amounts of strongly interacting dark matter and its ability to enhance the neutron stars tidal deformability.

Nelson, Reddy, Zhou (2018).



Constraints on very long range forces between neutron stars (containing dark matter) in a binary.

Alexander et al. (2018), Croon et al. (2018).



Conclusions

- To constrain the equation of state of dense matter the tidal deformability of a tens of neutron stars needs to be measured with few percent accuracy. Next generation GW detectors could be the **ONLY** way to do it.

- Correlations between the inspiral tidal deformability and post-merger neutron star dynamics (seismology and the lifetime) can reveal phase transitions in massive neutron stars - need to observe the high frequency (1-5 kHz) GW signal.

- Validating multi-physics simulations needed to connect merger dynamics to EM and nucleosynthetic signatures will rely on our ability to detect and interpret the post-merger GW signal.

- Next generation detectors with improved wide-band sensitivity will enhance searches for continuous GWs. Bounds on the neutron star ellipticity can be improved by a factor of 100.

- Detection of GWs from bursting, flaring and/or glitching neutron stars would be fascinating and provide valuable clues about internal dynamics.