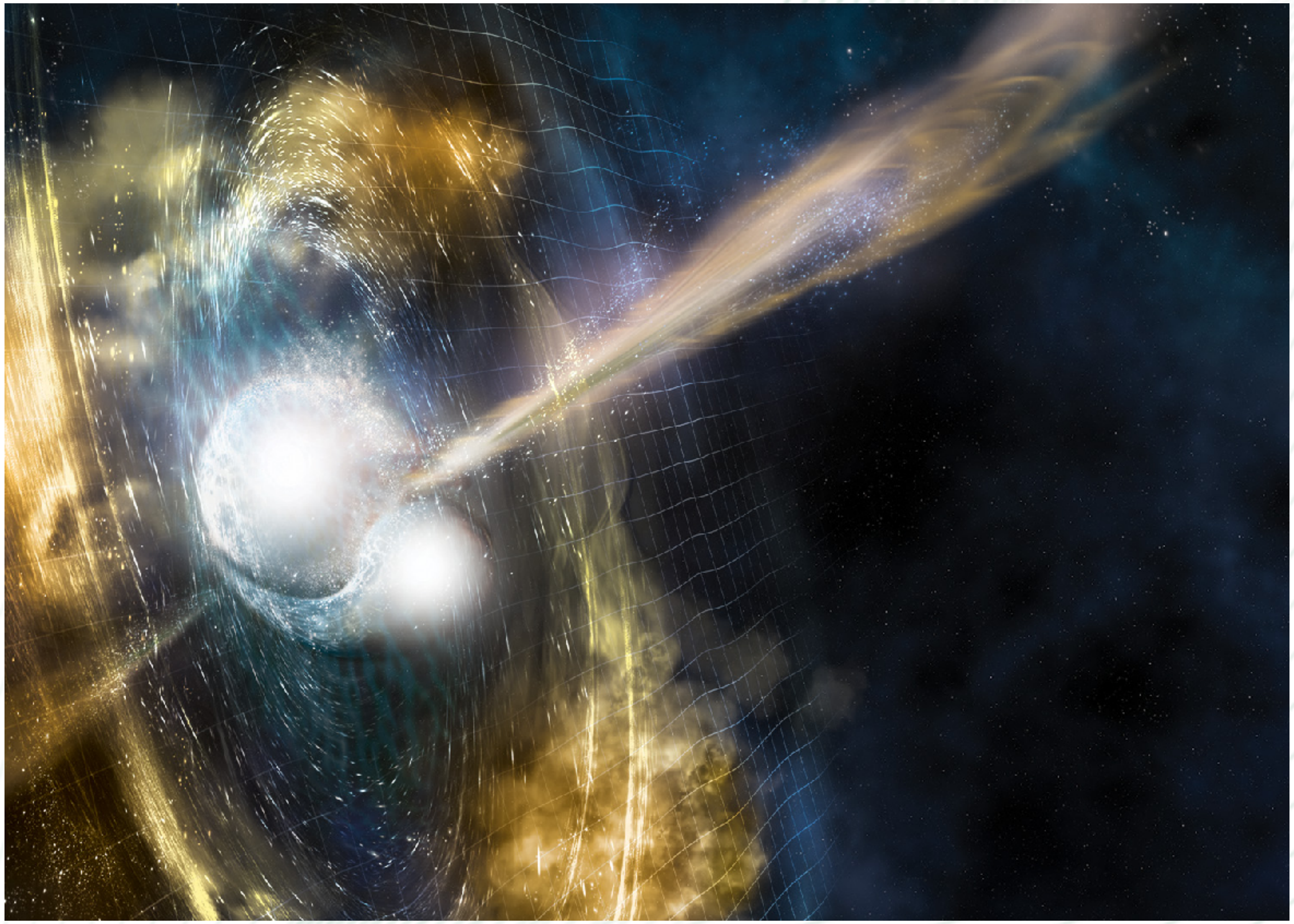
Neutron Stars and Gravitational Waves - Part 2



Cecilia Chirenti

Fermi Summer School - Lewes DE - June 2 2022

Neutron star binaries and gravitational waves

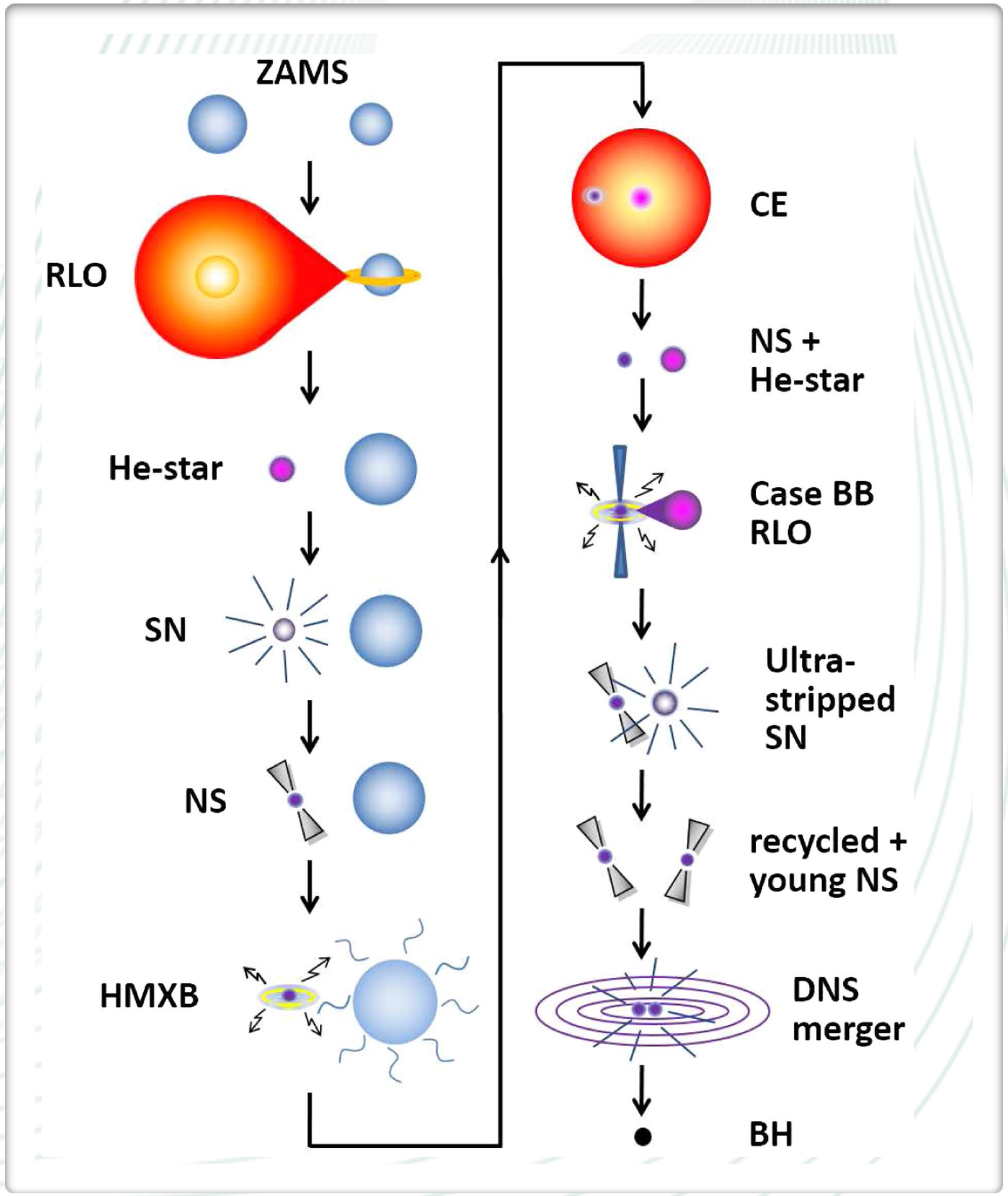
How do neutron stars form binary systems*?

*that collide in a time less than the age of the universe?

Note: we already know 10 such systems in our galaxy!

Question:

What could go wrong in this scenario?

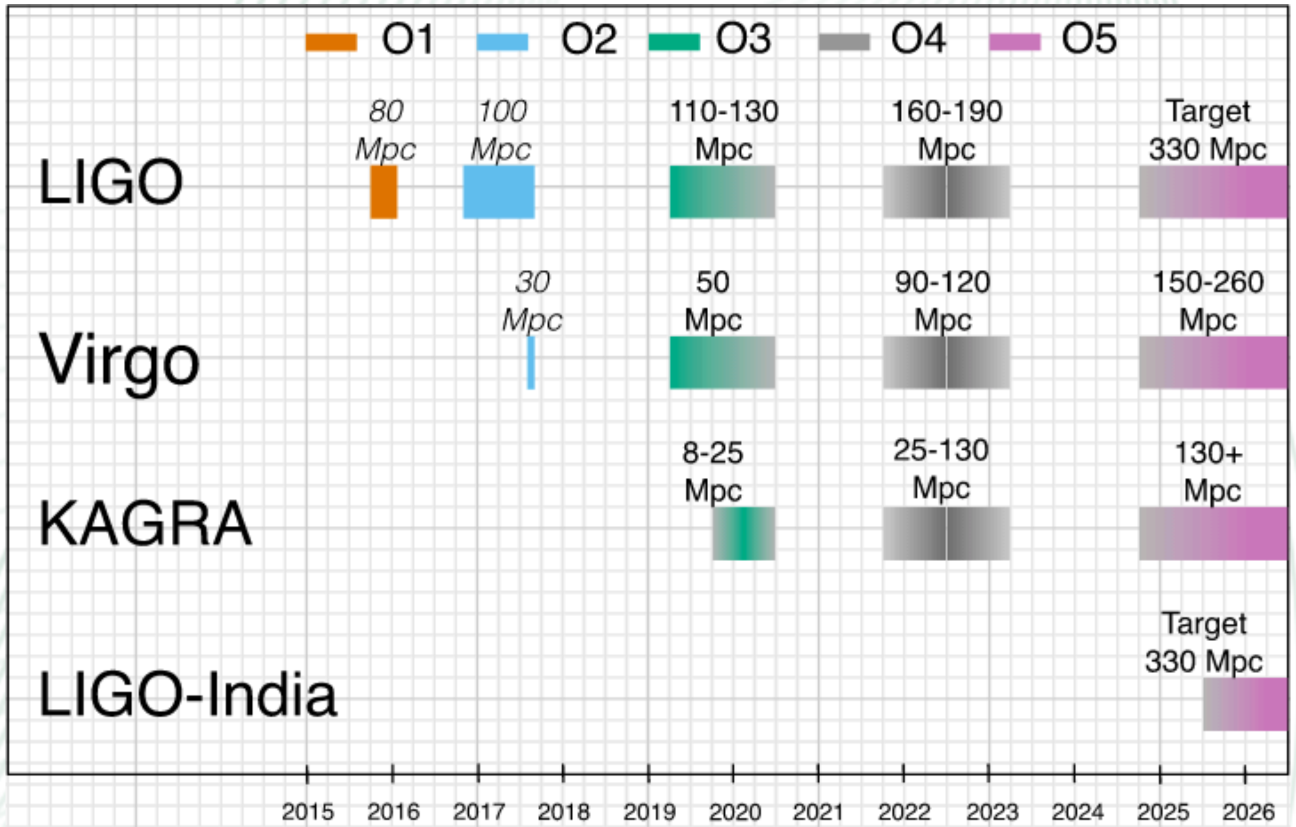


[Tauris et al., 2017]

UFABC

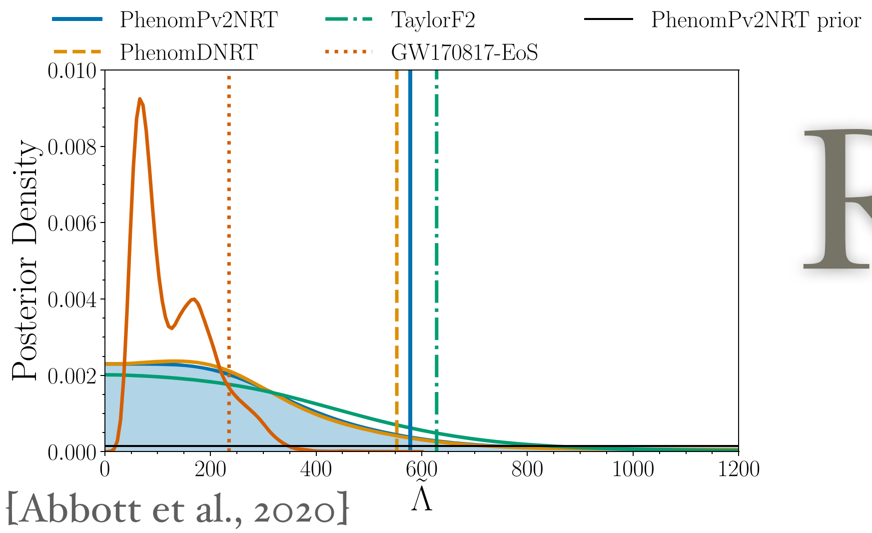
Rates of binary NS mergers

* before O1 ???
* after O1
  $110 - 3840\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
* after O2
  $80 - 180\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
* after O3:
  $13 - 1900\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$



trend?

UFABC



[Abbott et al., 2020]

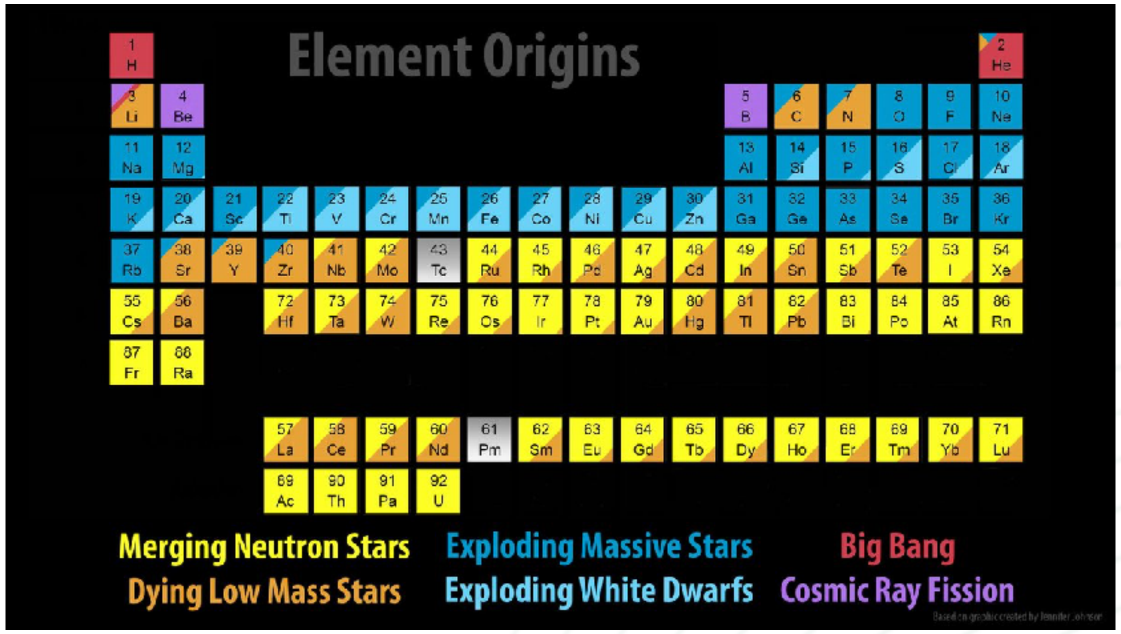
Recap: 2 events so far

* GW170817
* masses
  $m_1 = 1.36 - 2.26\,M_\odot$
  $m_2 = 0.86 - 1.36\,M_\odot$
* distance 40 Mpc
* observed by H, L, V
  with EM counterpart

* GW190425
* masses
  $m_1 = 1.61 - 2.52\,M_\odot$
  $m_2 = 1.12 - 1.61\,M_\odot$
* distance 88 – 230 Mpc
* observed by L, V
  without EM counterpart

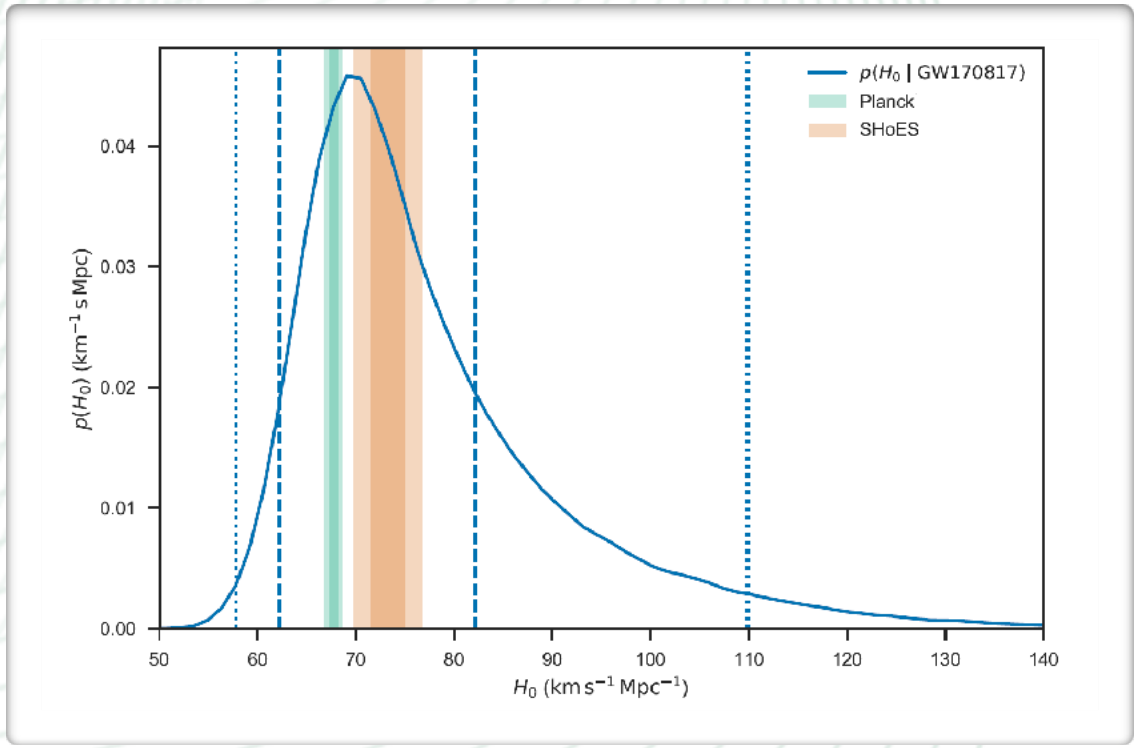
UFABC

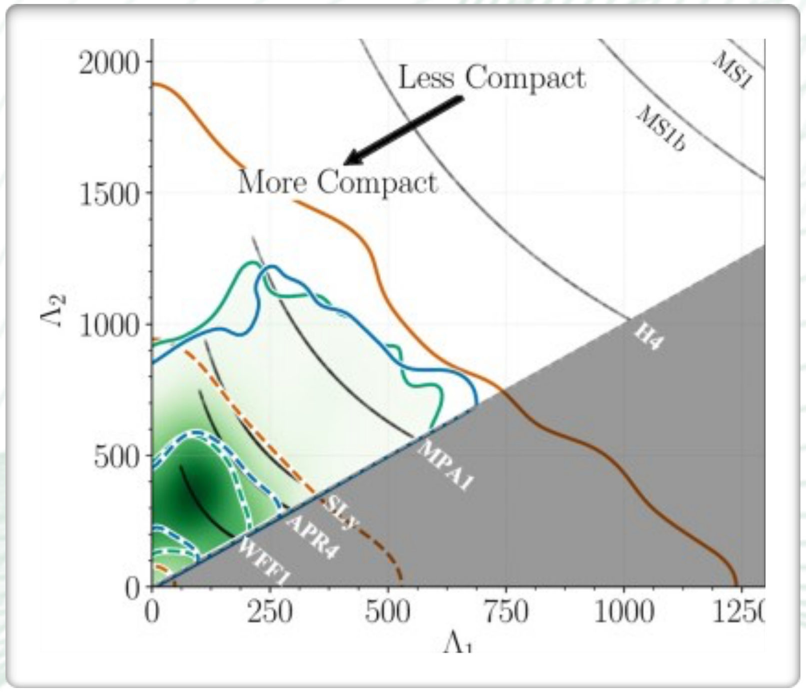
What can we learn from binary neutron star mergers



Formation of heavy elements

Determination of the Hubble constant



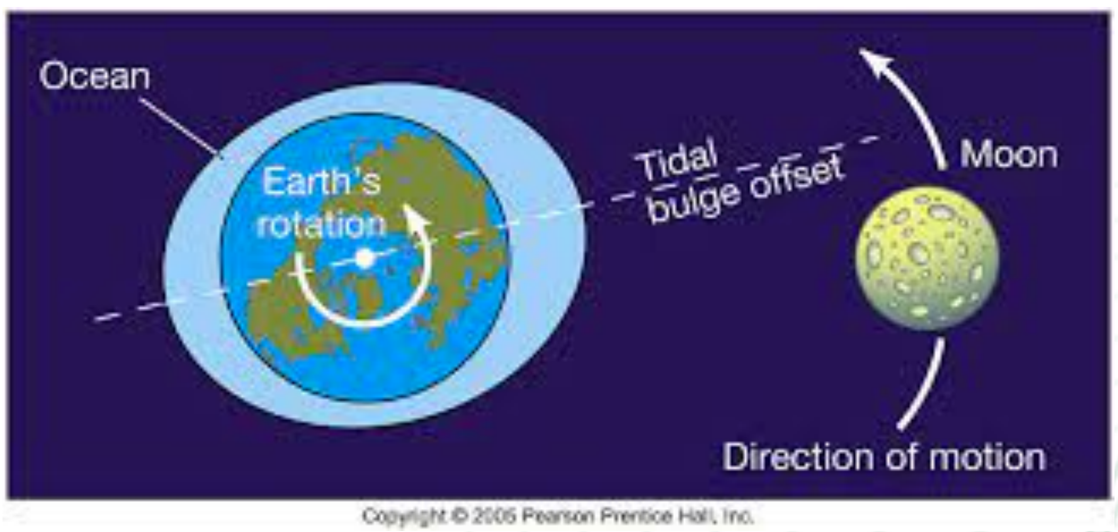


Neutron star equation of state

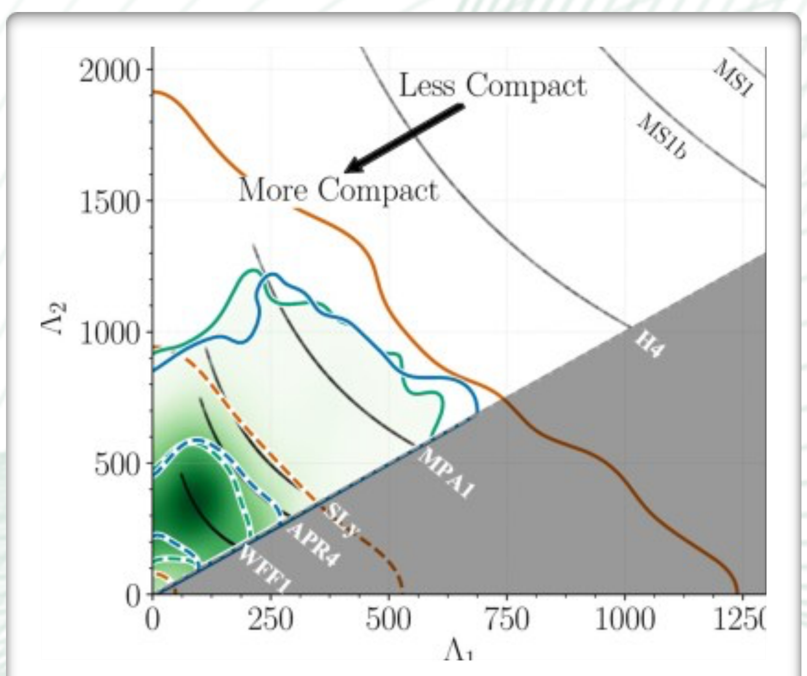
UFABC

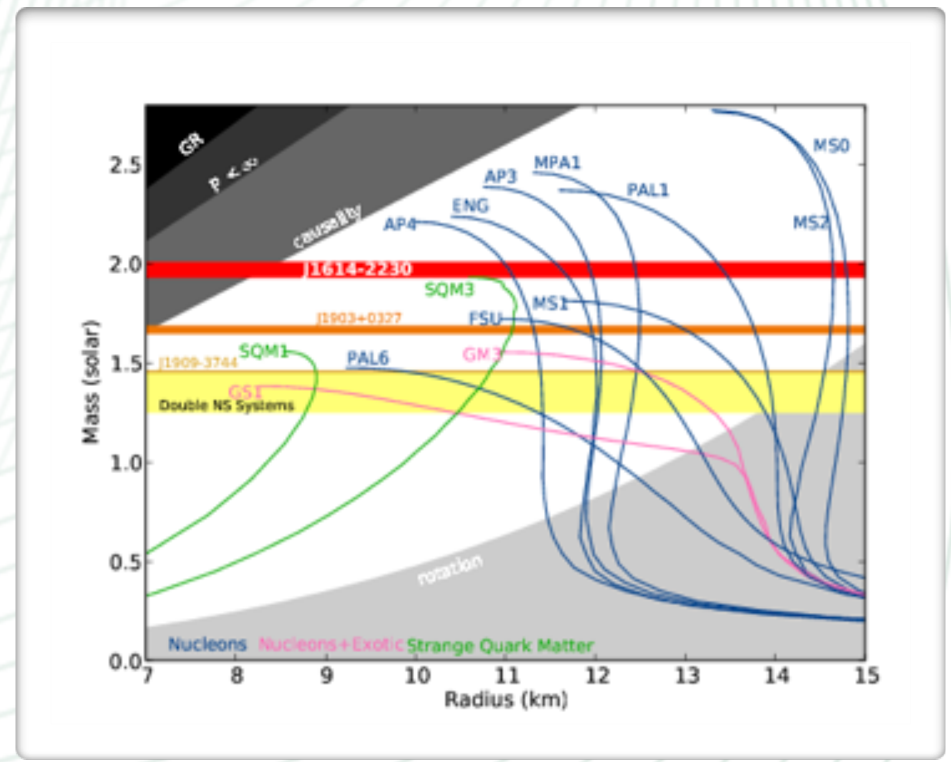
Neutron star equation of state

tidal forces



Tidal deformability causes the neutron stars to merge sooner



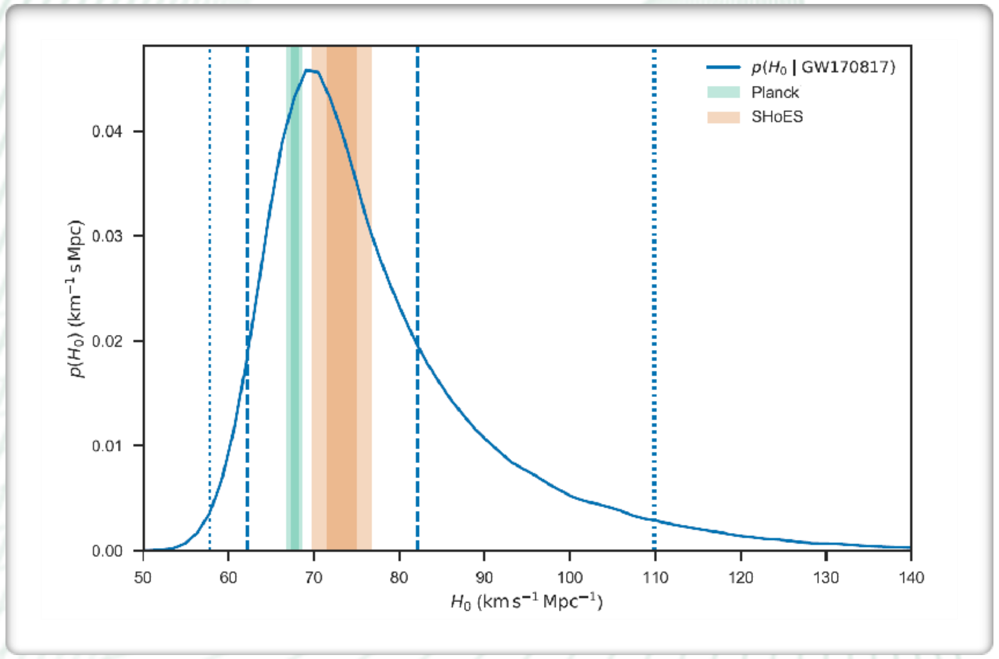


Less compact stars have larger radii and are easier to deform

UFABC

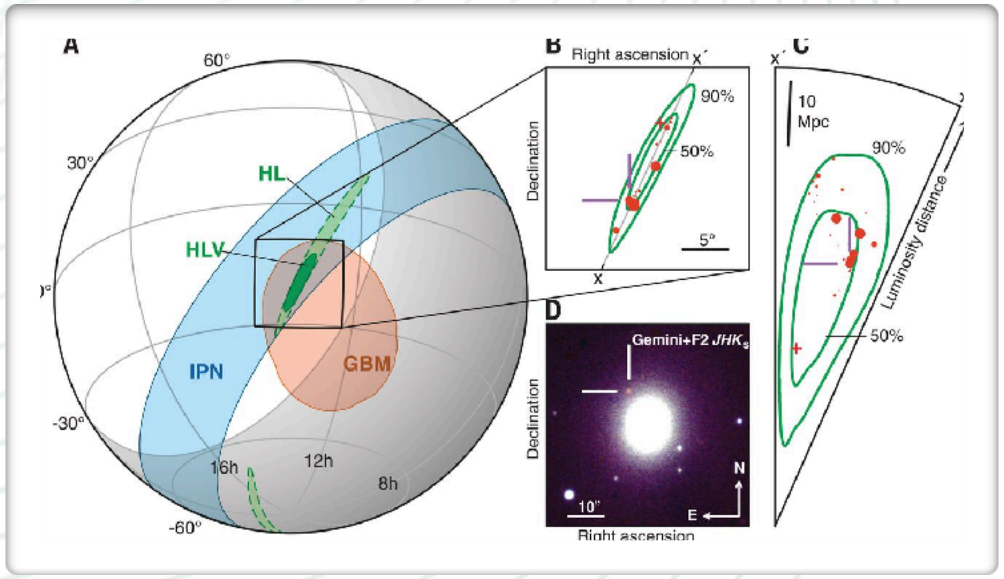
Determining the Hubble constant

measured
unknown



* Chirp mass $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$

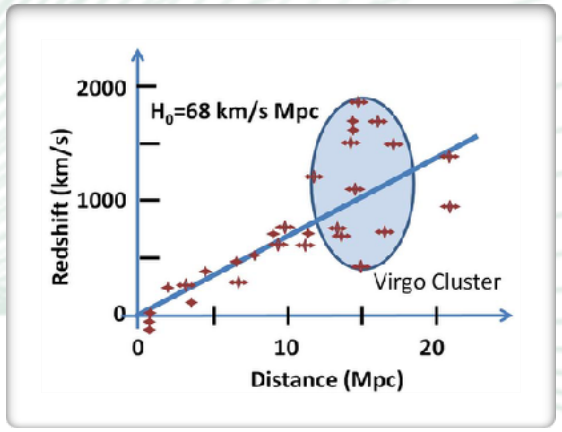
* Amplitude $A \propto \frac{\mathcal{M}^{5/3}}{D_L} F(\cos(\iota))$ inclination angle



* Frequency $\dot{f} \propto \mathcal{M}^{5/3} f^{11/3}$

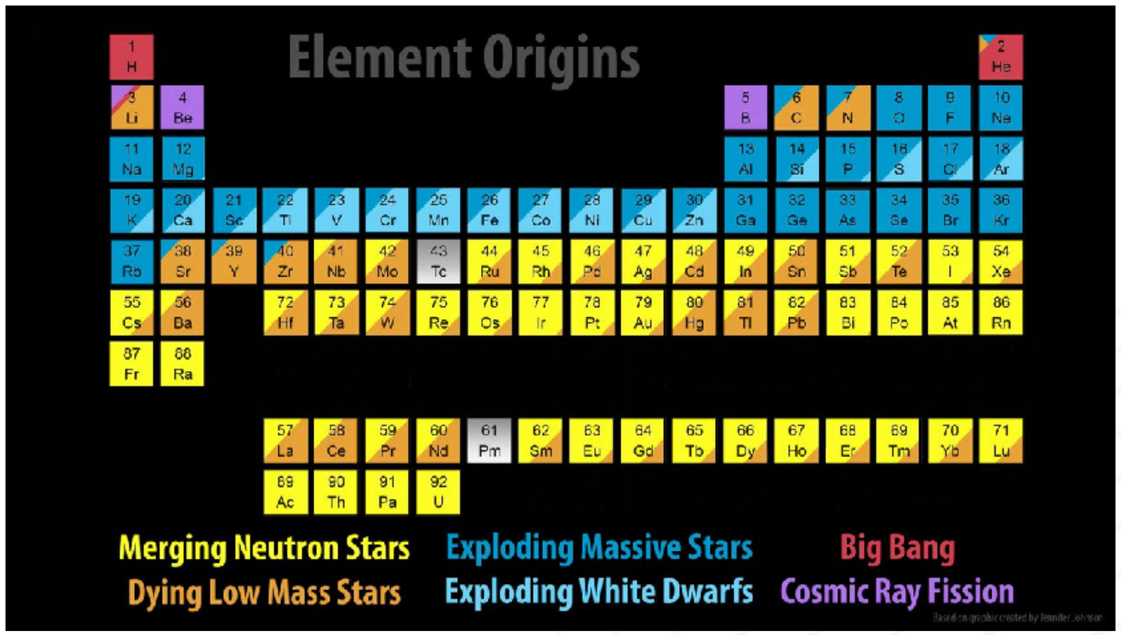
* Luminosity distance D_L + sky localization allow us to obtain the redshift z

Hubble's law: $z \simeq \frac{H_0 D_L}{c}$



UFABC

Formation of heavy elements



Where do the r-process elements come from?

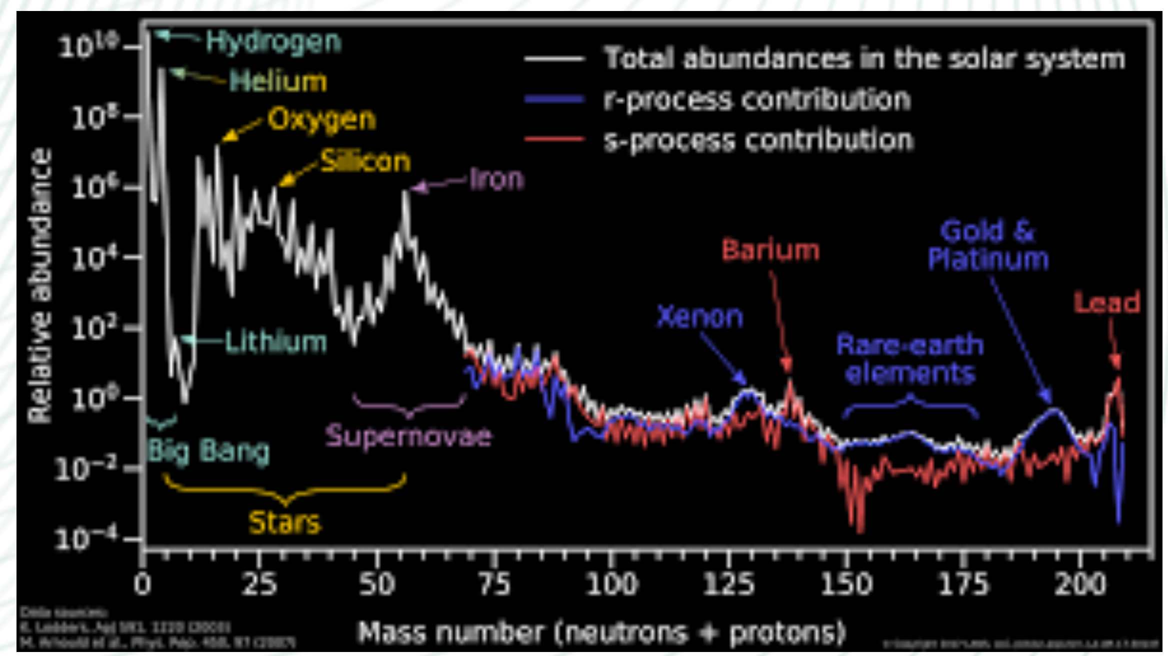
Supernovae

More frequent
Less mass

Neutron star mergers

Less frequent
More mass

GW170817 produced 200* times the mass of the Earth in gold!



* according to models

UFABC

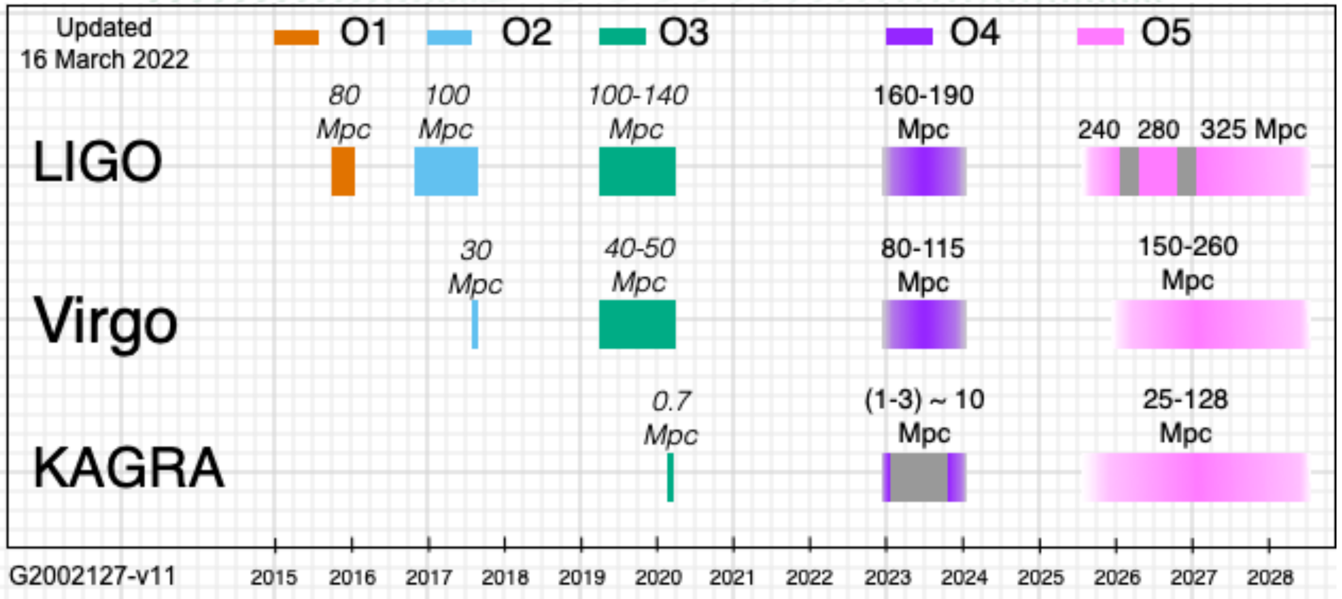
Future Timeline for Gravitational Wave Detectors

* LIGO: O4 (planned start in mid-December 2022) and beyond

* 3G ground detectors: estimated operation in mid-2030's

* Space detector LISA: estimated launch 2037

[https://sci.esa.int/web/lisa/-/61367-mission-summary]

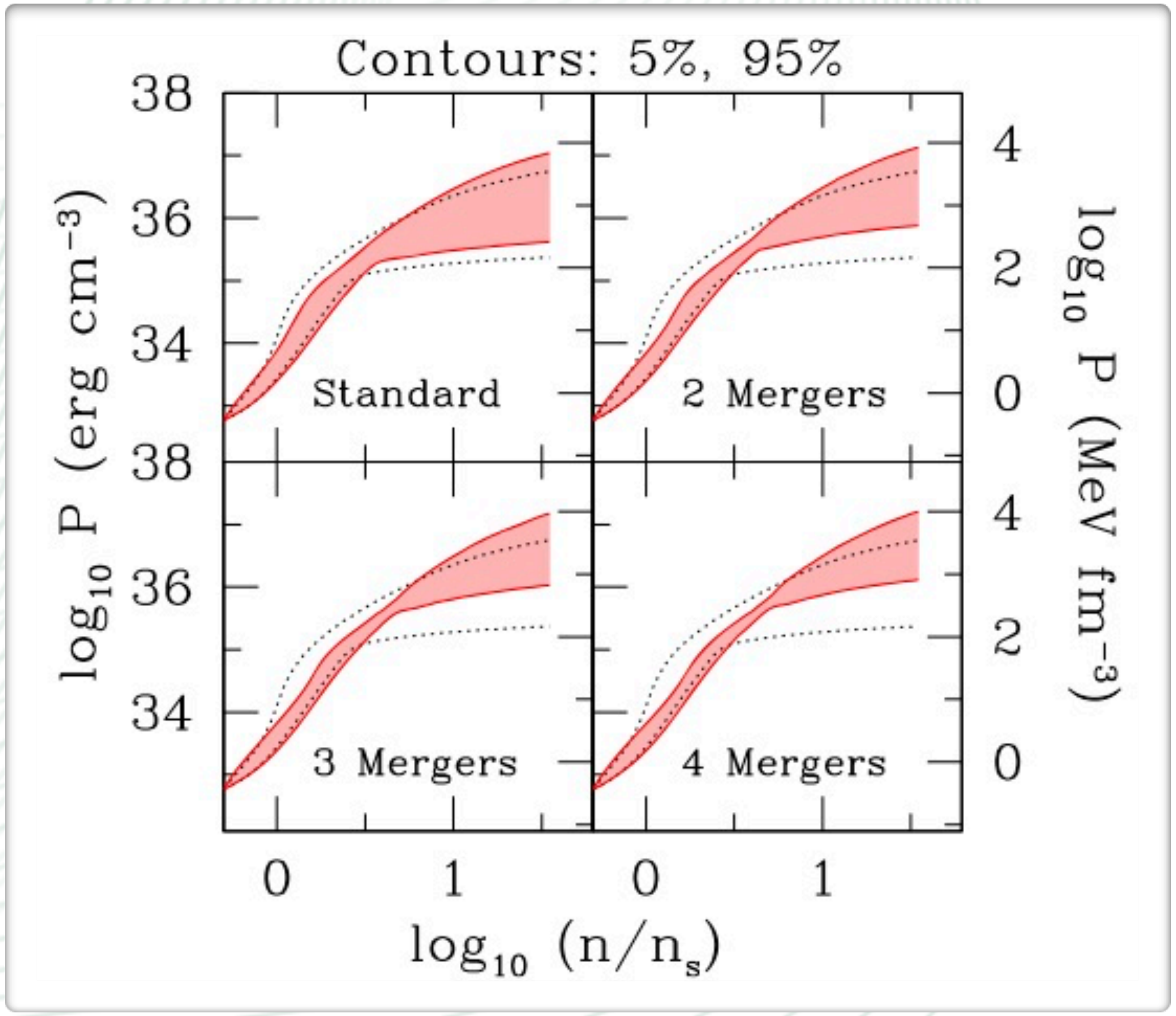


pandemic starts
delays ensue

UFABC

LIGO: O4 and beyond

* What can we gain from more detections: e.g. improvements on tidal deformability constraints
* More stringent upper limits
  * continuous waves
  * stochastic background
* If really lucky:
  * galactic magnetar/supernova



[Miller, Chirenti & Lamb, 2020]

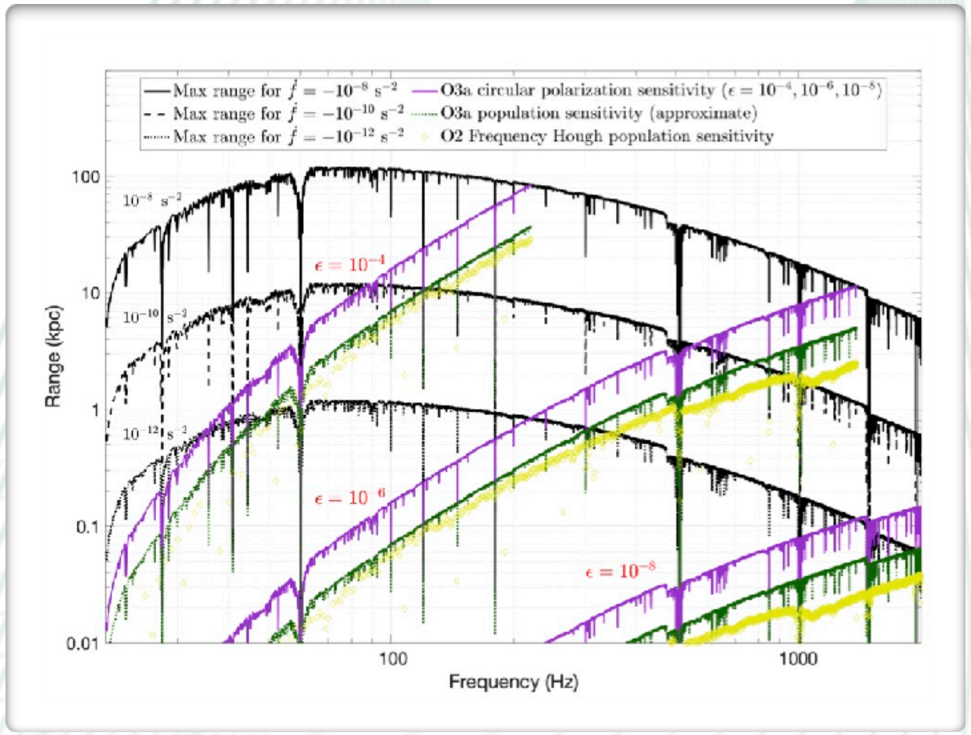
UFABC

LIGO: O4 and beyond

Continuous Waves

NS with a "mountain"

[Saint-Exupéry, 1943]

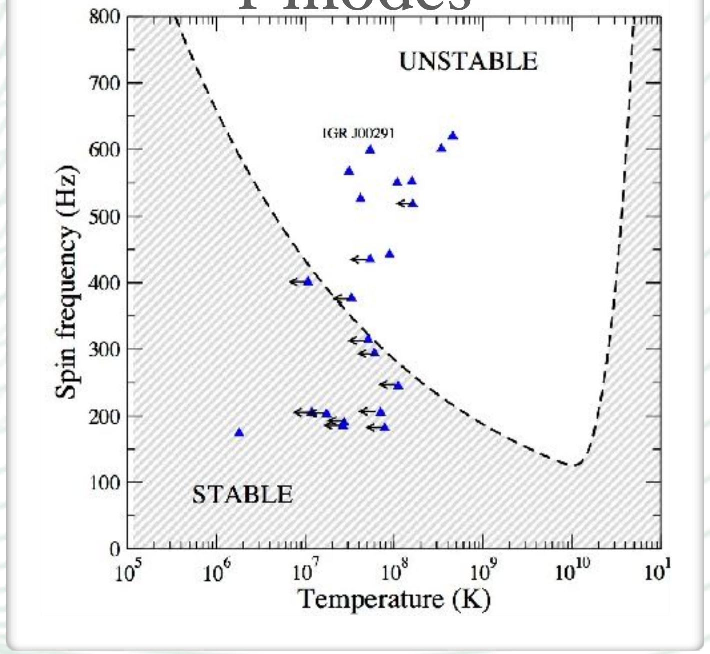


[LIGO, Virgo, KAGRA, 2021]

* upper limits on the gravitational wave emission limit the ellipticity of the NS
* the stronger the crust, the higher the mountain it can support
* the highest height of the NS "mountain" could be < 1 mm!

[Horowitz & Kadau, 2009; Gittins & Andersson, 2021]

r-modes

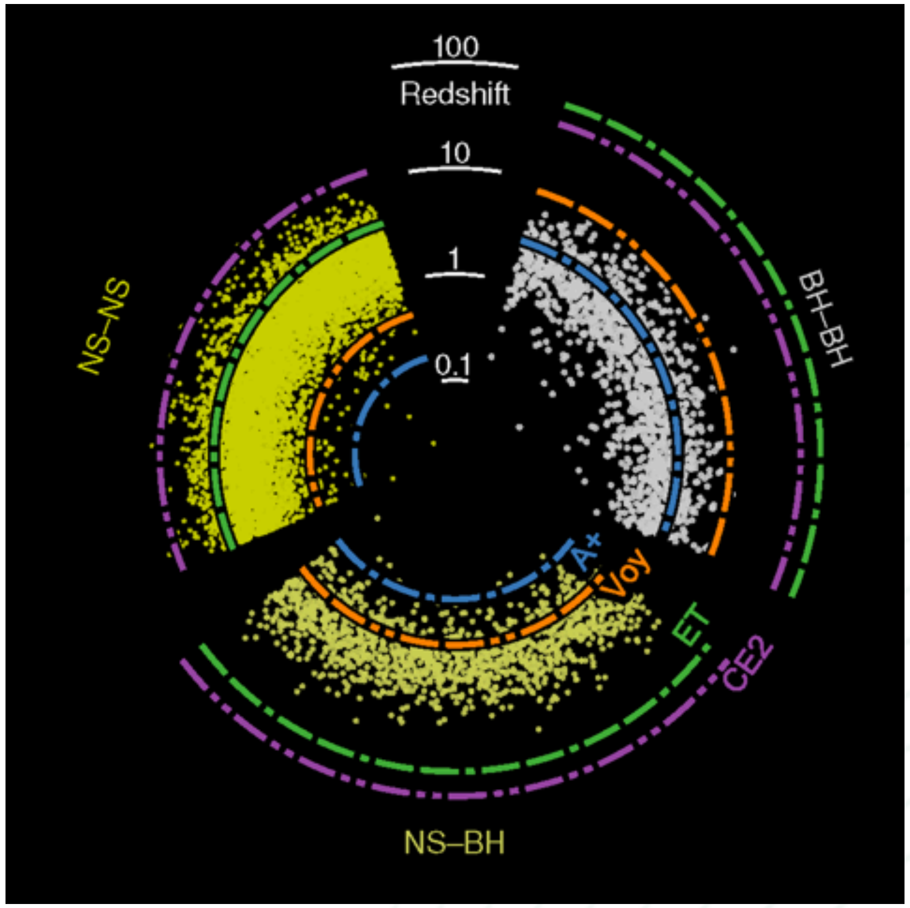


[Haskell, Degenaar & Ho, 2012]

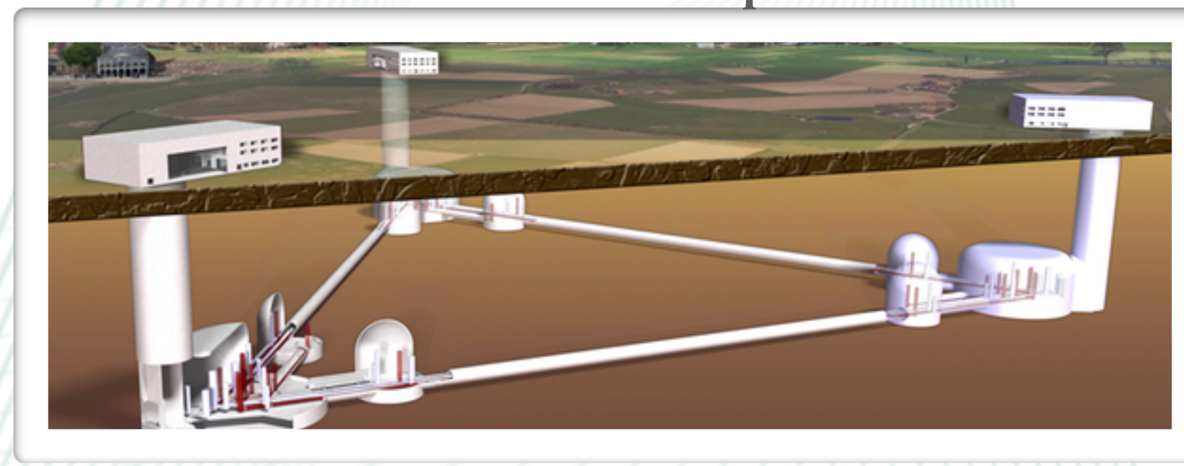
Shape of the instability window depends on NS bulk and shear viscosities

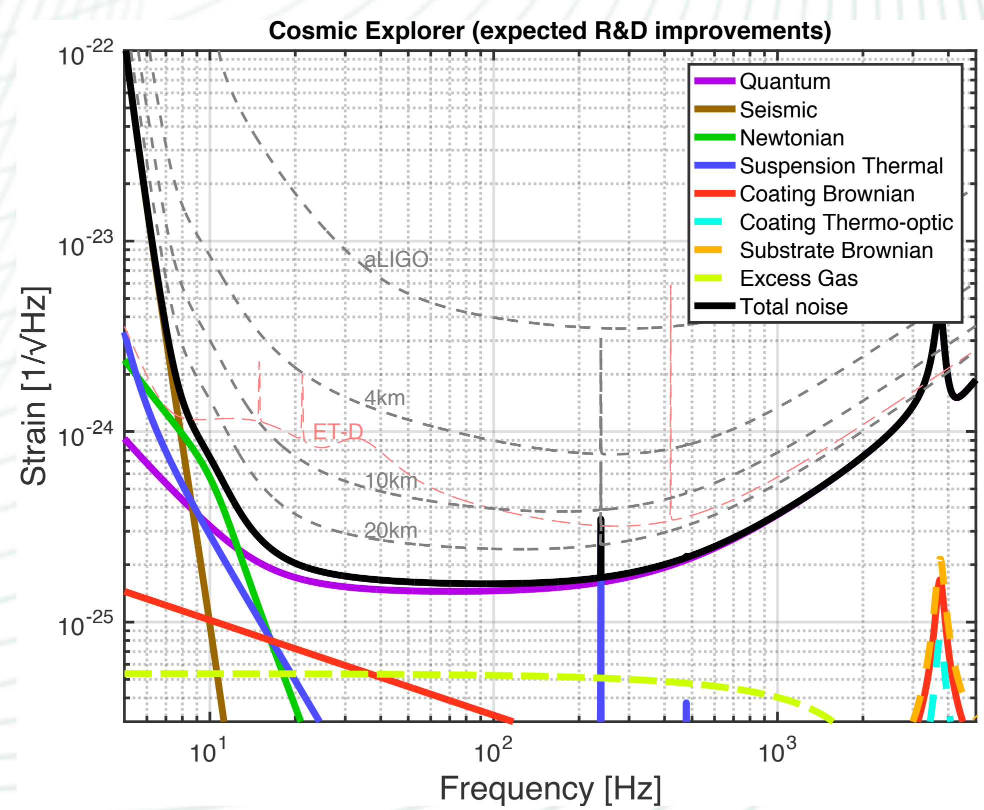
UFABC

3G: Einstein Telescope/Cosmic Explorer



Einstein Telescope





[Abbott et al., 2017]

- ET: 10 km (underground), could detect NS-NS mergers up to $z \sim 2-3$
- CE: 40 km, could detect **all** NS-NS mergers (up to $z \sim 6$)

3G Detectors: ET/CE

* Low frequency sensitivity
  * Advance warning for EM counterparts

better kilonova observations

* High frequency sensitivity
  * pre-merger: tidal deformability and dynamical tides
  * post-merger: HMNS oscillations

Neutron star asteroseismology!

* Overall improved sensitivity
  * better upper limits (maybe detections?)

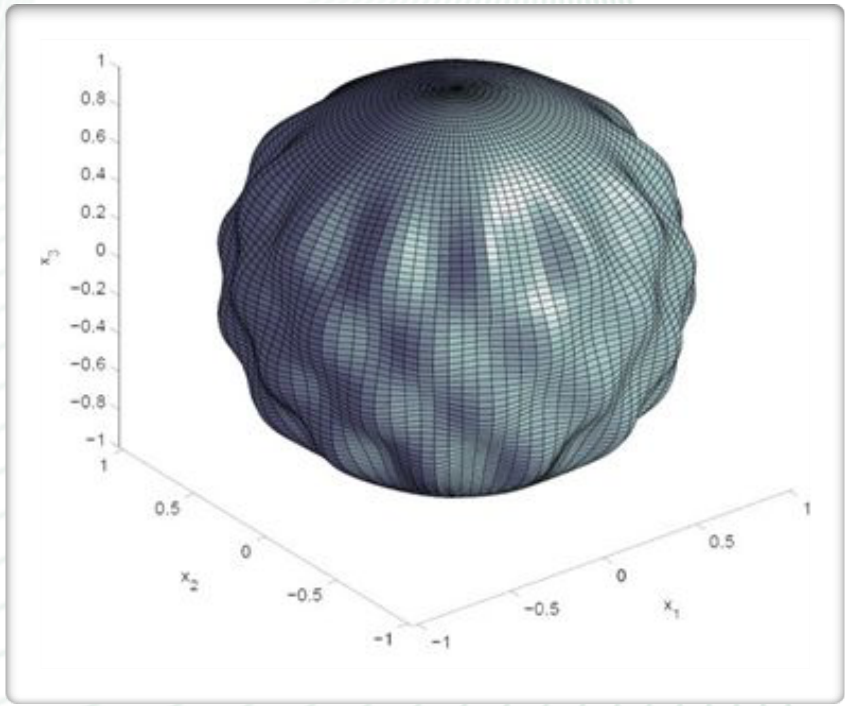
* If really lucky:
  * galactic magnetar/supernova

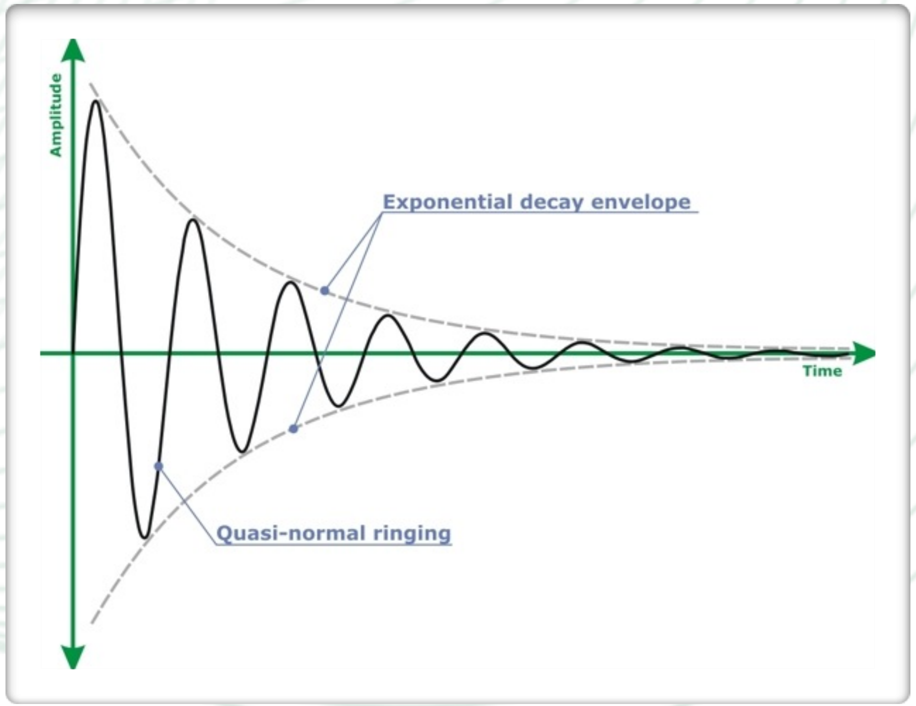
more multimessenger observations!

UFABC

Neutron Star Asteroseismology (Quasinormal mode frequencies)

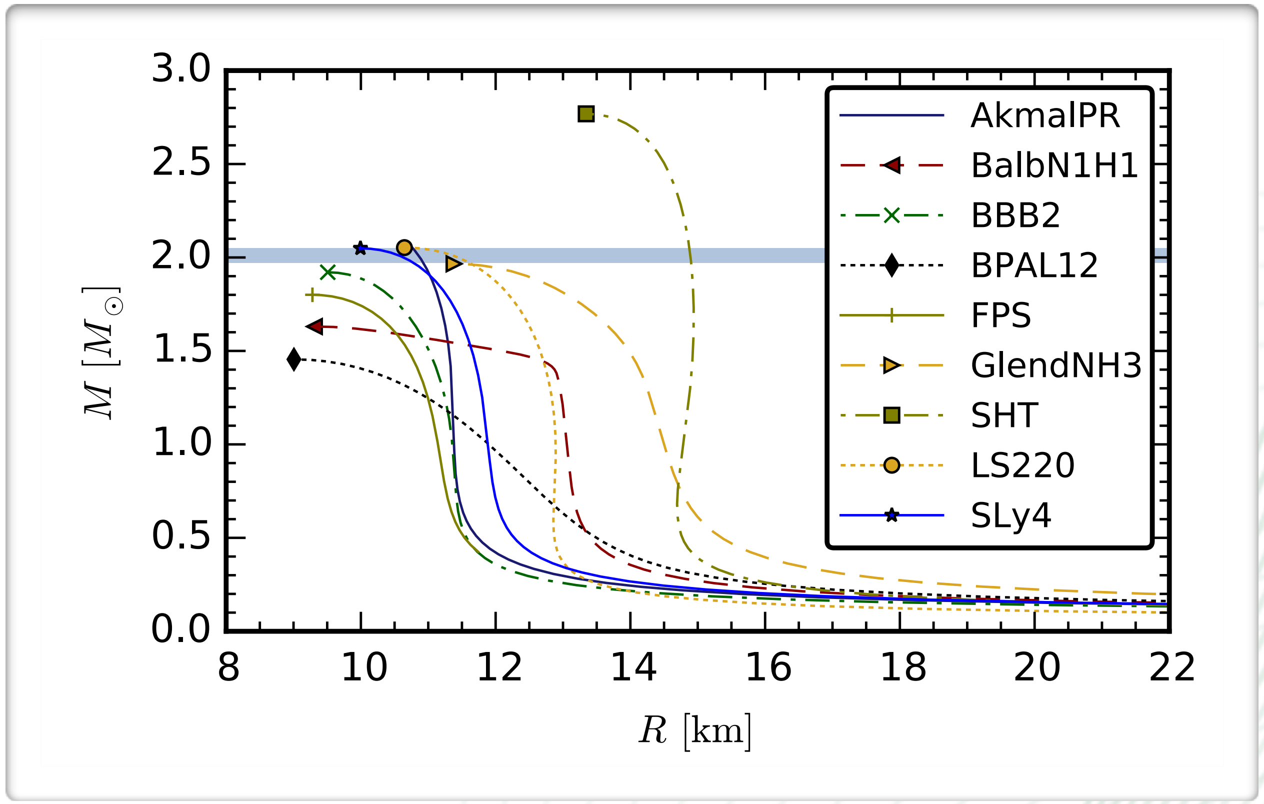
* Oscillation modes of the fluid coupled to the emission of gravitational waves
* Different families of modes ↔ different restoring forces
* For non-rotating (and non-magnetized) stars
    * f-modes (fundamental)
    * p-modes (pressure)
    * g-modes (gravity)
    * w-modes (spacetime modes), etc



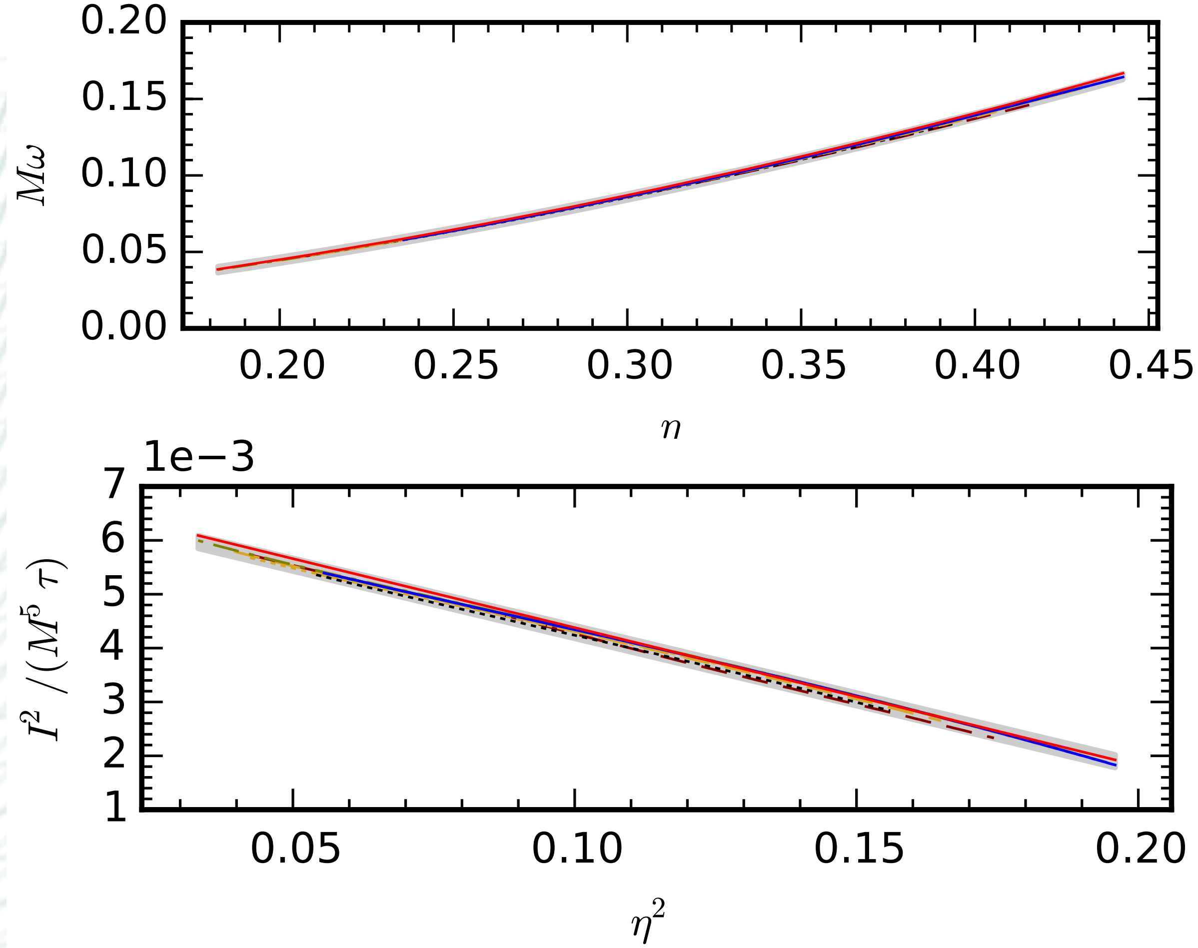


UFABC

What can we learn from QNMs? Example: Universal relations and the inverse problem



f-modes



We can use EOS-independent information to learn about the EOS

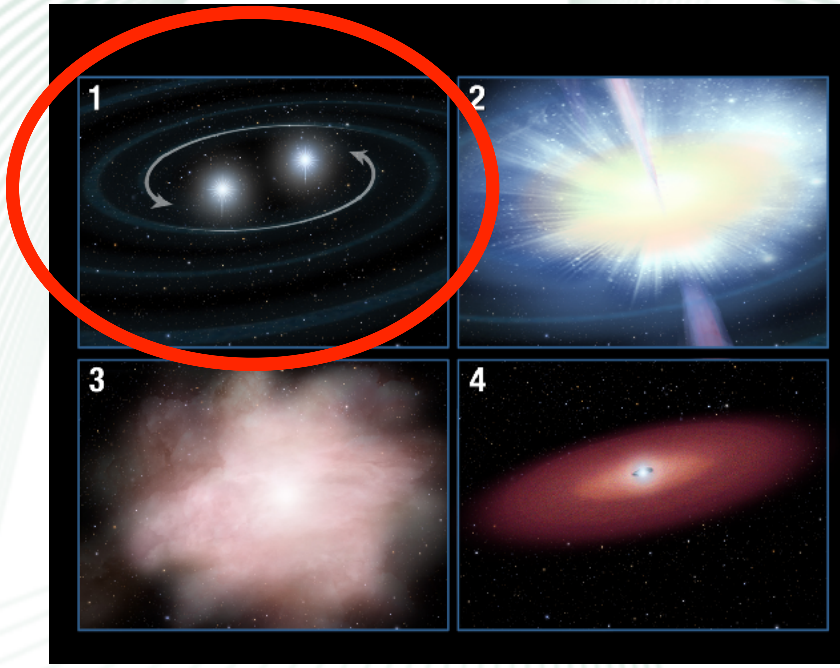
Effective compactness: $\eta \equiv \sqrt{M^3/I}$

[Chirenti, de Sousa & Kastaun, 2015]

See also: [Andersson & Kokkotas, 1998; Benhar, Ferrari & Gualtieri, 2004; Lau, Leung & Lin, 2010; Maselli et al. 2013; Sotani & Kumar, 2021, ...]

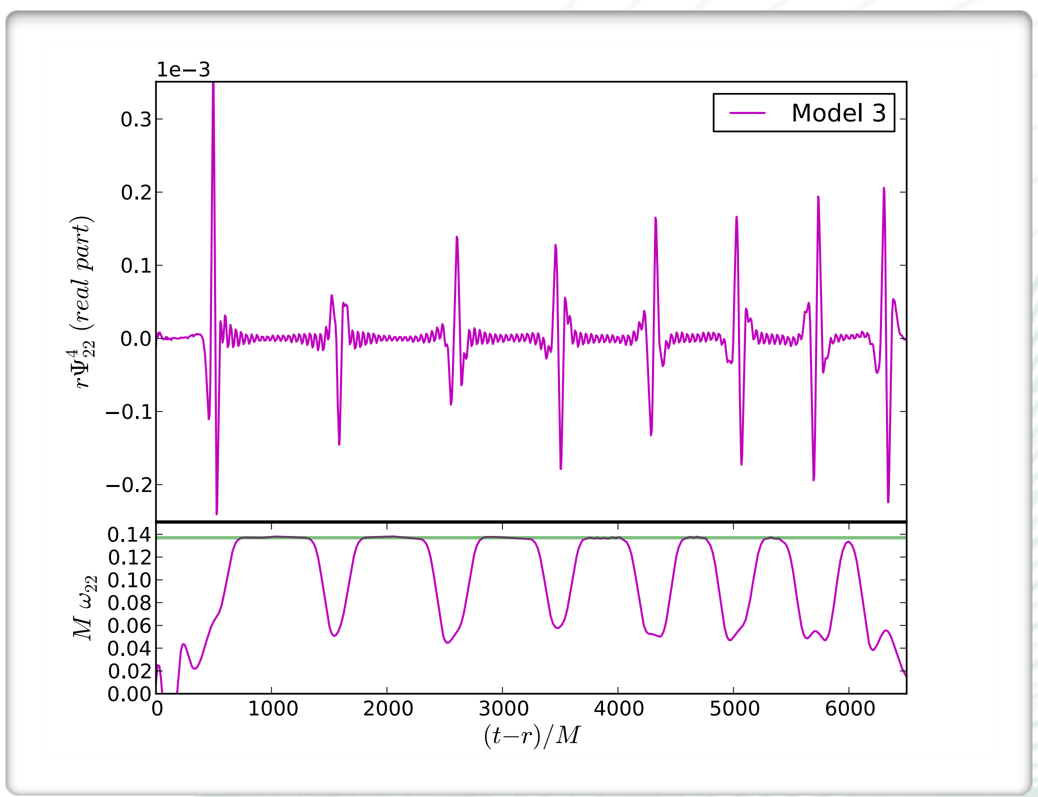
UFABC

Pre-merger: Oscillations in the inspiral

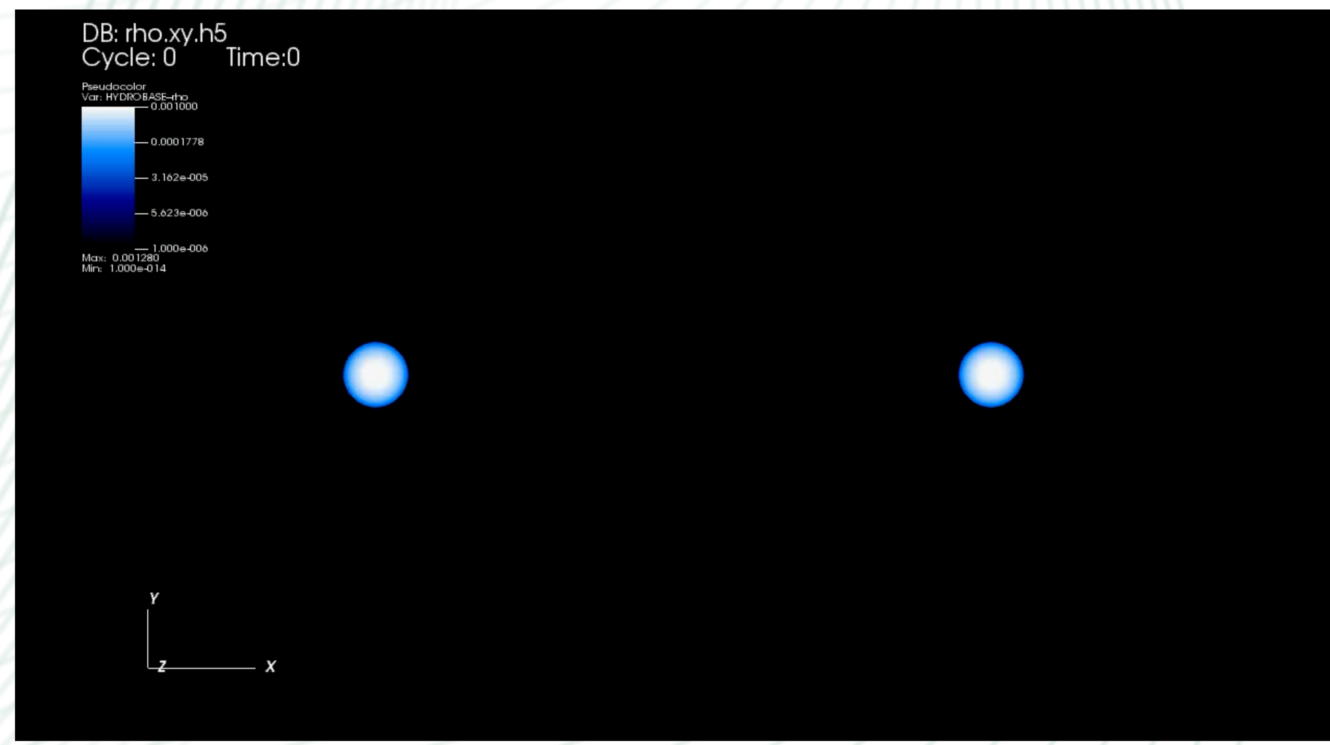


Tidal excitation of f-modes in eccentric binaries could be detectable with 3G!

[Chirenti, Gold & Miller, 2017]



[Gold et al., 2012]



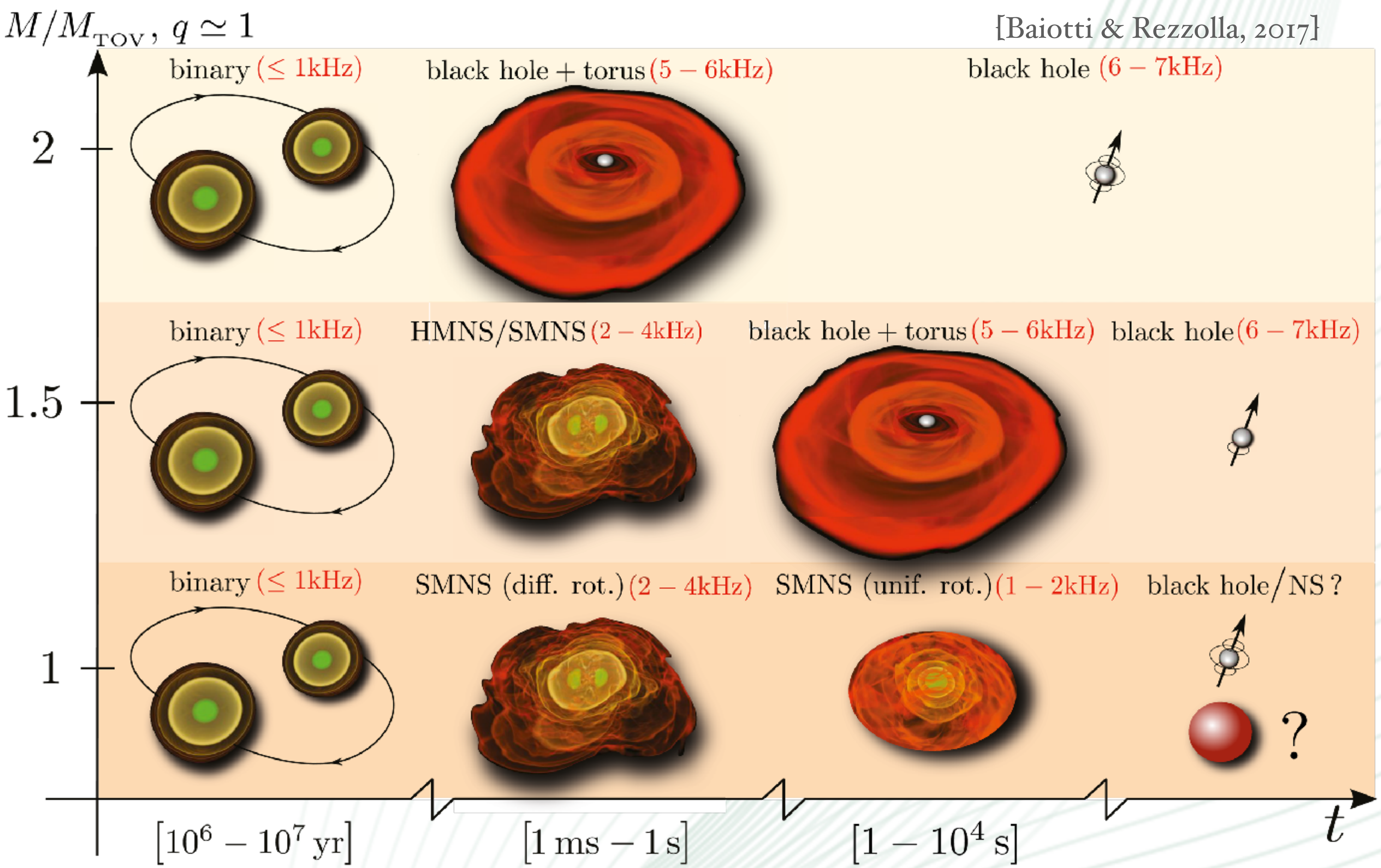
[Simulation by Shawn Rosofsky]

f-modes could also be detectable in the very late stages of circular binaries

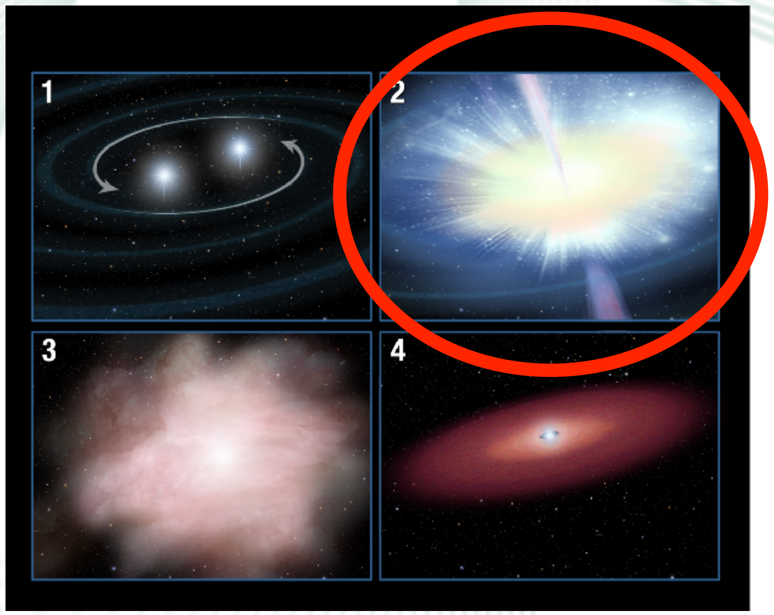
[Schmidt & Hinderer, 2019]

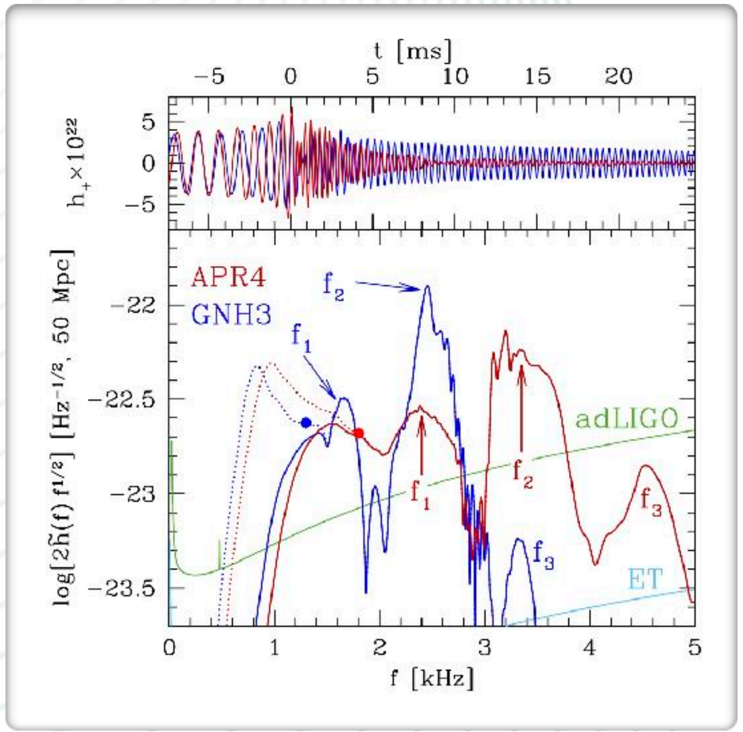
UFABC

Post-merger: HMNS oscillations



[Baiotti & Rezzolla, 2017]





[Takami, Rezzolla & Baiotti, 2014]

Frequencies carry information on the hot EOS.
Oscillations may modulate the SGRB signal.

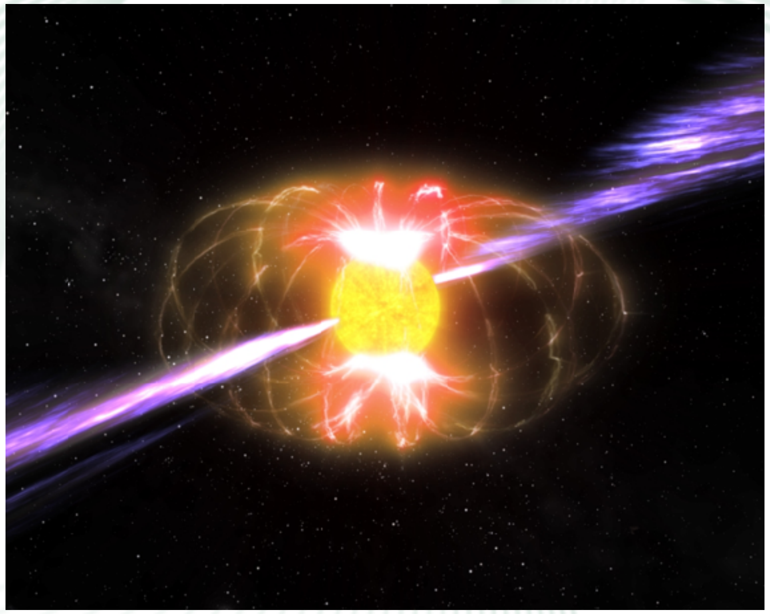
[Chirenti et al., 2019]

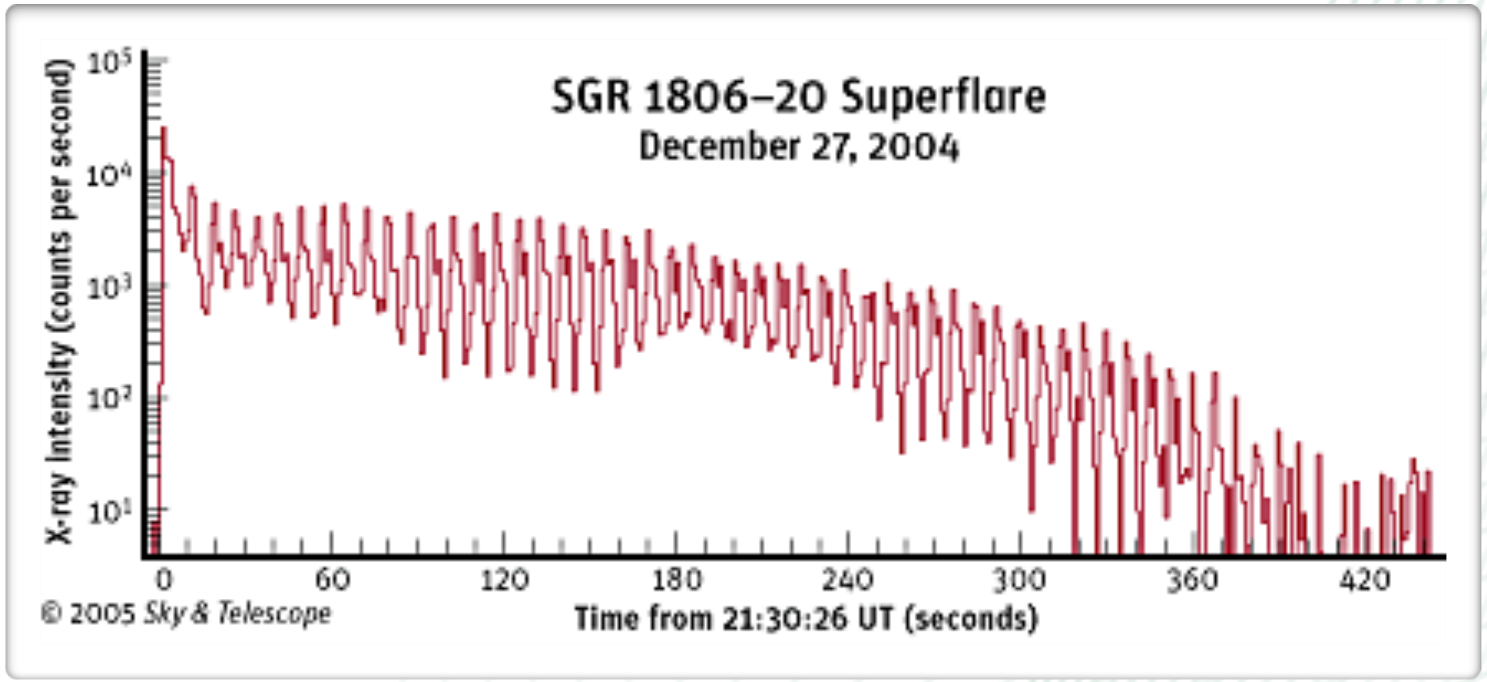
Universal relations for HMNSs?

[Bauswein et al., 2012; Lioutas, Bauswein & Stergioulas, 2021]

UFABC

Galactic observations: Magnetar giant flares





* 18, 26, 29, 92.5, 150, 625.5 and 1837 Hz

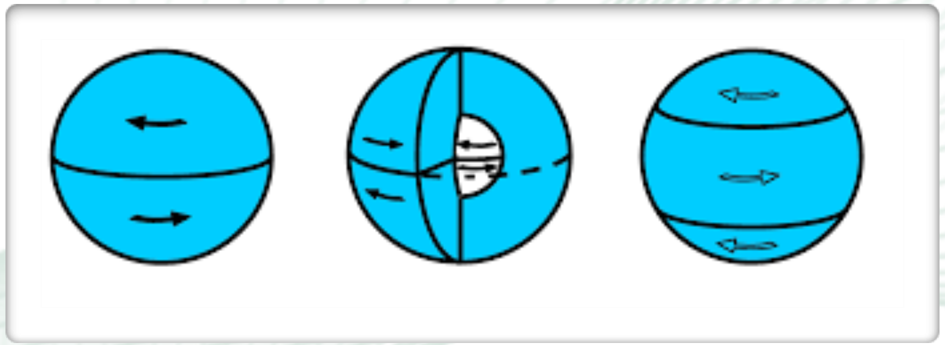
[Israel et al, 2005; Watts & Strohmayer, 2006; Strohmayer & Watts, 2006, Miller et al, 2019]

Gravitational waves from galactic magnetar giant flares may be detectable.

[Zink, Lasky & Kokkotas, 2012]

Rare events - or not?

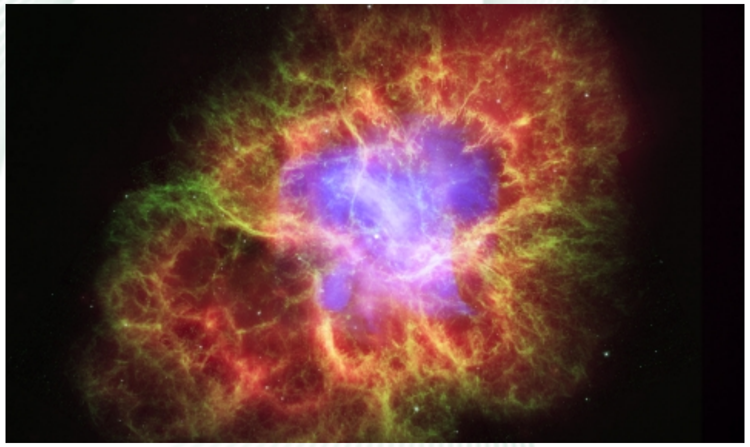
[Burns et al, 2021]

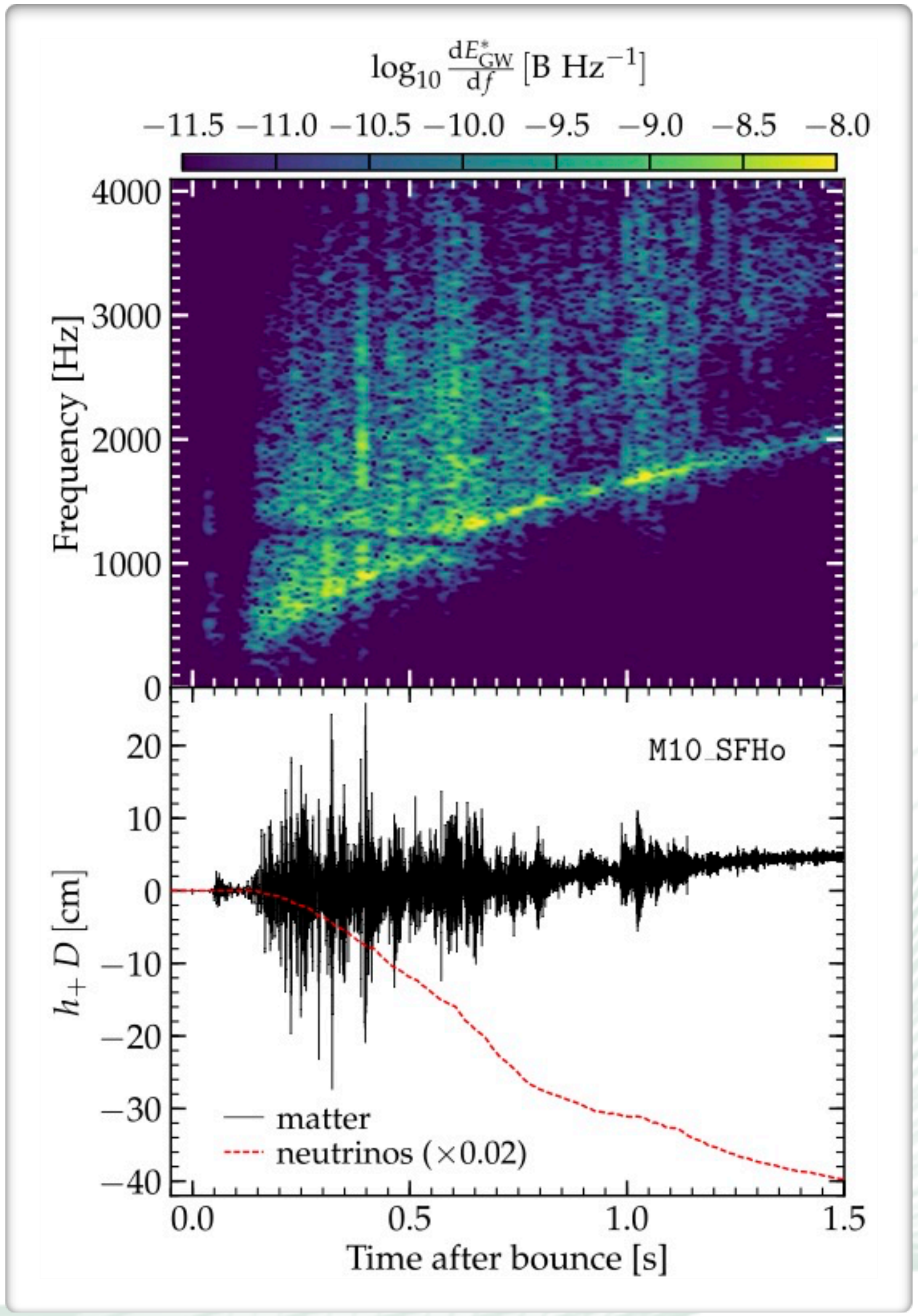


Torsional crustal modes?

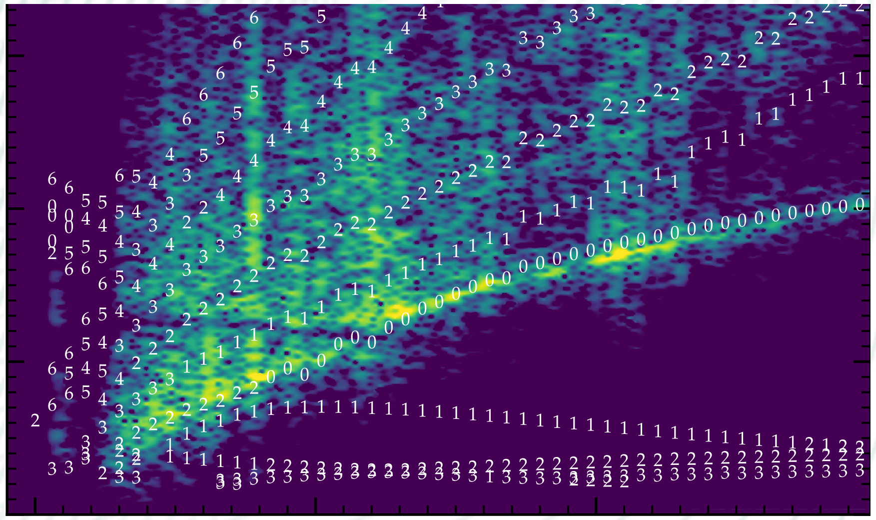
UFABC

Galactic observations: Core Collapse Supernovae





[Morozova et al, 2018]



Signal is templatable and can be described by the quasinormal modes of the proto neutron star!

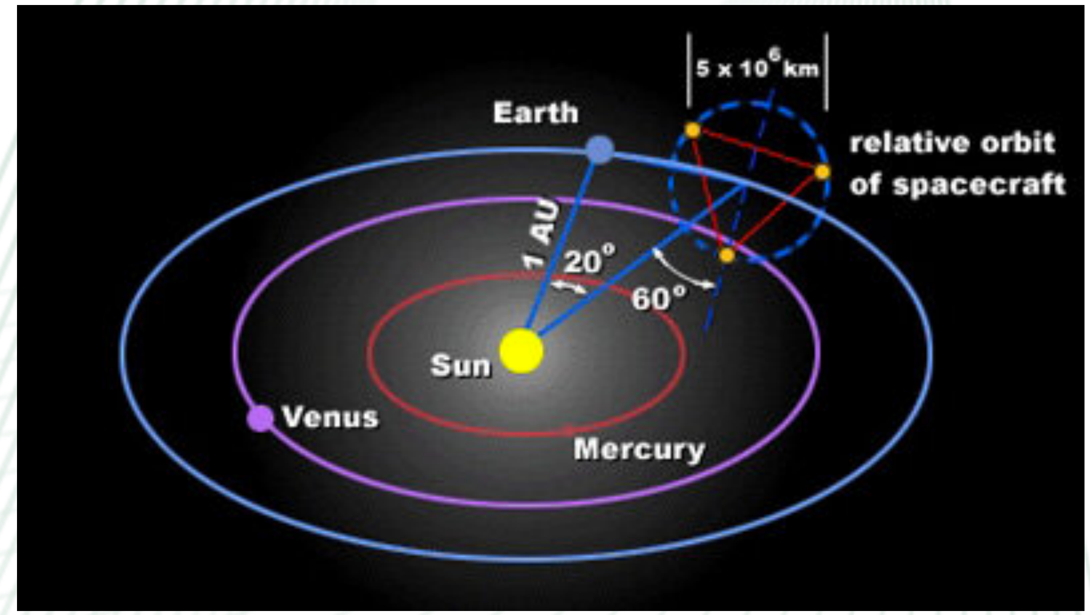
Universal relations for PNSs?

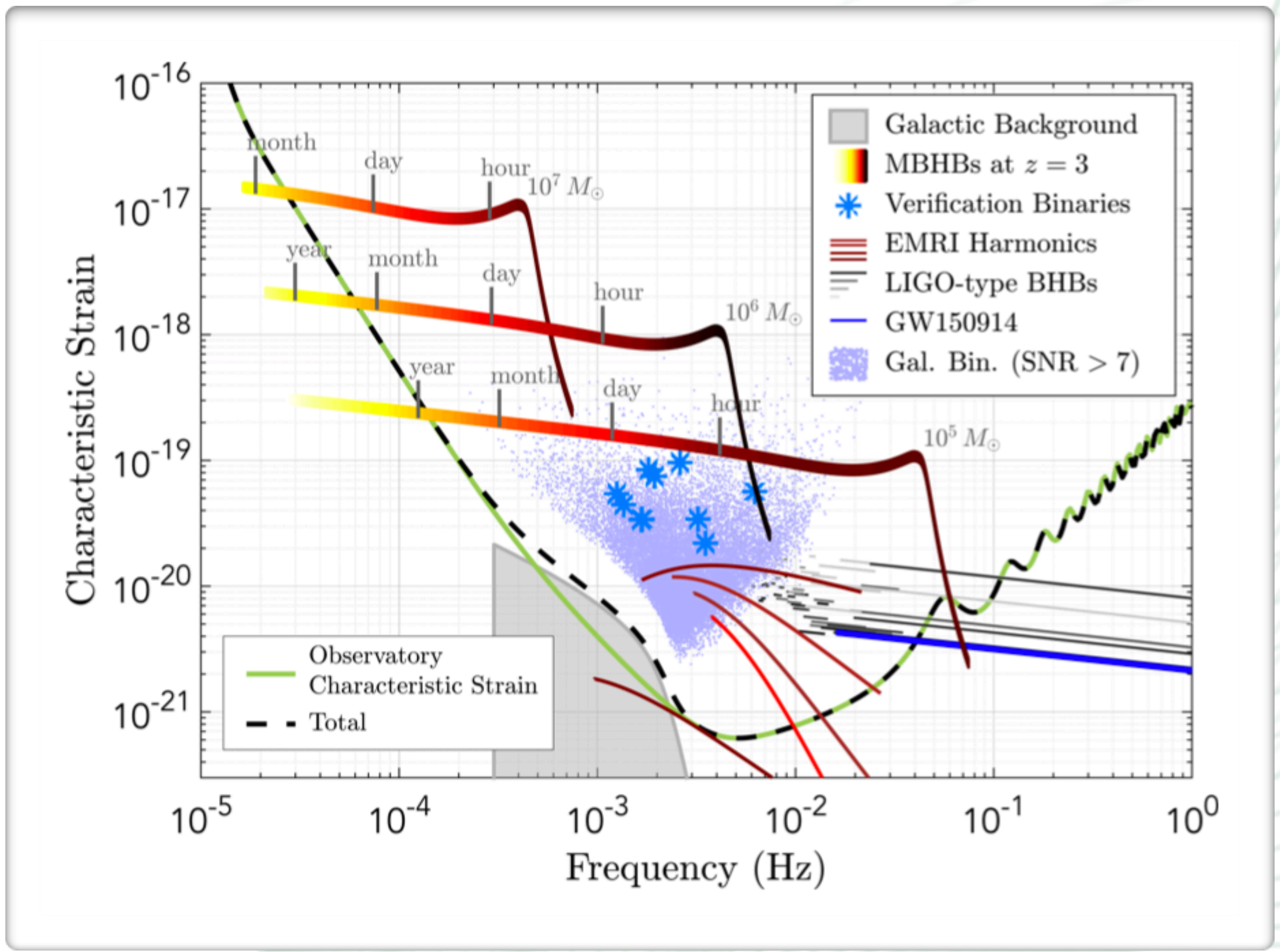
[Torres-Forné et al, 2019]

UFABC

LISA

LISA will be able to see supermassive black hole binaries, and early stages (larger separations) of stellar mass black hole binaries





[Amaro-Seoane et al., 2017]

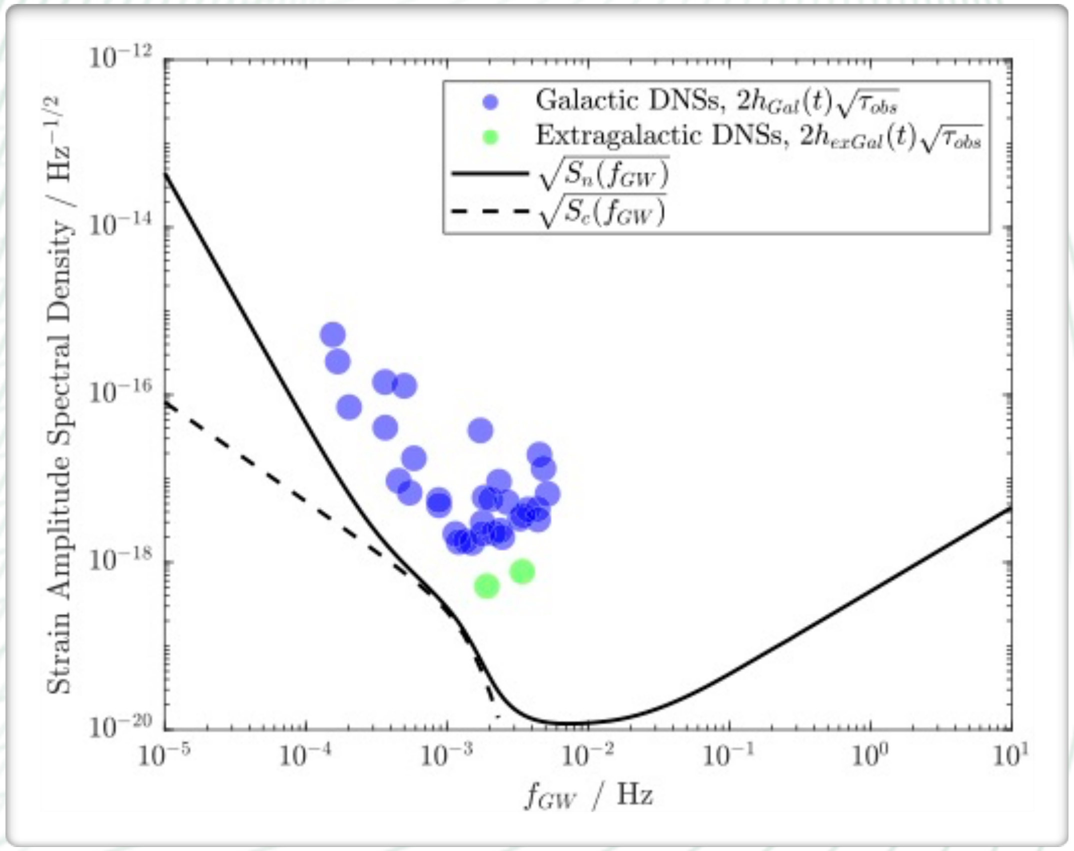
Sounds great!
And what about neutron stars?
Not obvious.

UFABC

LISA and Neutron Stars

~ 35 binary neutron stars should accumulate SNR > 8 during the 4 year LISA mission

At LISA frequencies, many of the binaries will be eccentric (expected median eccentricity 0.11)



[Lau et al., 2020]

Determination of orbital properties could provide information on progenitors, formation channels and natal kicks

UFABC

Conclusions and Outlook

* Future gravitational wave observations can provide important information on the EOS of cold catalyzed matter.
* In particular, neutron star oscillations can be particularly helpful. But they aren't easy to observe! There are already indications of observations in X-ray data, and maybe also in radio.
* Gravitational wave observation of neutron star oscillations will require 3G detectors. Oscillations from hypermassive neutron stars can provide information on the hot EOS.
* LISA observations can help probing formation channels of binary neutron star systems.

References, further reading and videos

* Jocelyn Bell: The Discovery of Pulsars:
https://www.youtube.com/watch?v=-335gUOvdhA

* What is a pulsar?
https://www.youtube.com/watch?v=gjLk_72V9Bw&t=2s

* Neutron stars for undergraduates, R. Silbar & S. Reddy
https://arxiv.org/abs/nucl-th/0309041

* Gravity from the Ground Up, B. Schutz
http://www.gravityfromthegroundup.org

* Black Holes, White Dwarfs and Neutron Stars, S. L. Shapiro & S. A. Teukolsky

* Gravity: an Introduction to Einstein's General Relativity, J. B. Hartle

* Gravitational Waves, vols. 1 & 2, M. Maggiore

UFABC

Questions?