Microscopic matter models for GW physics (ongoing activity @USAL)

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October 20, 2020

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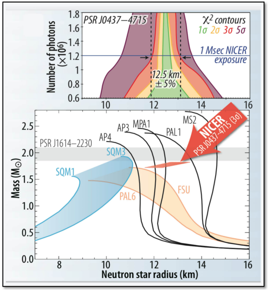
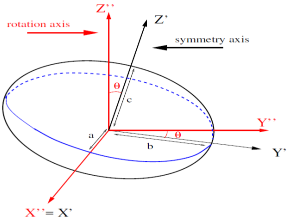
GWs from asymmetric NSs





- A rotating neutron star generates GWs if it has some long-living axial asymmetry.
- This can be obtained in different ways: mountains, glitches, osc. modes, precession, magnetic deformations..
- Matter **microscopic** properties, i.e. EoS is the key ingredient.

Continuous GW emission

A deformed compact object will emit a monochromatic signal at $f_{GW} = 2\nu$, with amplitude h_0 at distance d given an ellipticity

$$\epsilon = \frac{I_{xx} - I_{yy}}{I_{zz}} \tag{1}$$

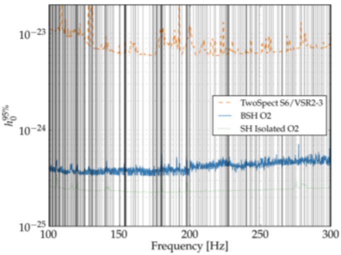
Then the strain amplitude is given by

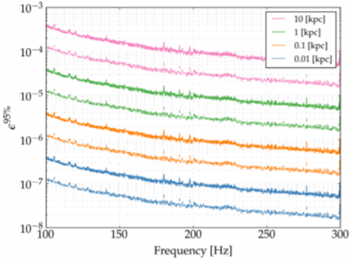
$$h_0 = \left(\frac{16\pi^2 G}{c^4} \right) \frac{\epsilon I_{zz} \nu^2}{d} \tag{2}$$

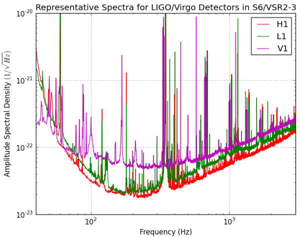
For a closeby fast-spinning neutron star

$$h_0 = 10^{-25} \left(\frac{\epsilon}{10^{-6}} \right) \left(\frac{I_{zz}}{10^{38} \mathrm{kg\,m}^2} \right) \left(\frac{\nu}{50\,\mathrm{Hz}} \right)^2 \left(\frac{100\,\mathrm{pc}}{d} \right) \tag{3}$$

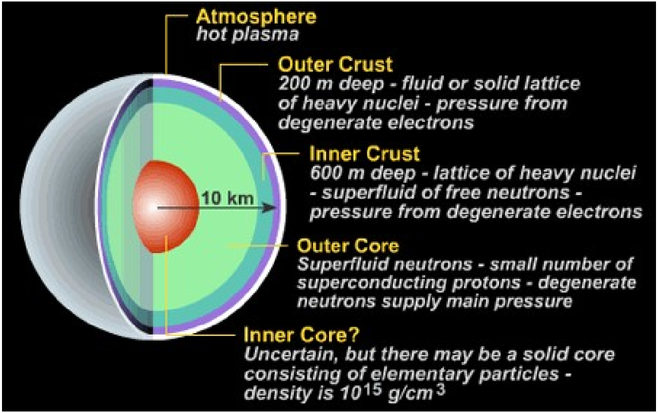
GW from Neutron Stars in binaries yield weak signal [aLIGO Covas & Sintes PRL 124(2020)]





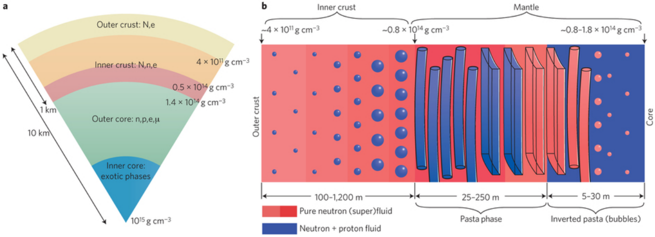


NS deformation



- Deformation can be supported by stress in the crust (or core) on long timescales
- *Pasta phases* appear in the inner NS crust (~ 0.5 km) with densities $10^{13\div14}$ g/cm^3

Pasta phases in the crust

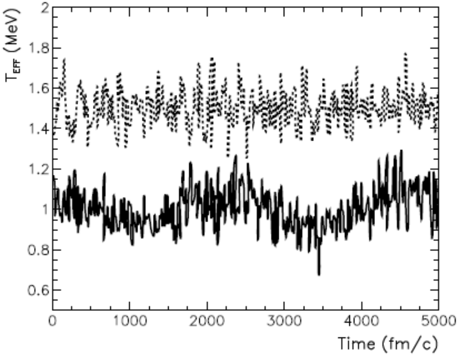


Source: COMPSTAR outreach

- charges conserved

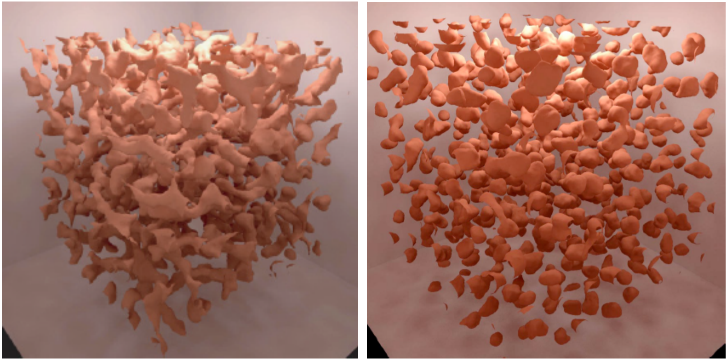
conditions	In-medium equilibrium
weak decay $n \to p + e + \bar{\nu_e}$	$\mu_n = \mu_p + \mu_e$
elec.charge neutrality $n_p = n_e + n_\mu$	$\mu_p = \mu_e + \mu_\mu$
conservation baryon number	$\rho_B = \rho_n + \rho_p$

- Microscopic models must reflect long-range correlations (defects or impurities) $\to$ extract elastic properties $\to$ GW amplitude.



Better T control in the NVT system than rescaling

$n_b = 0.016\,\mathrm{fm}^{-3}$, $Y_e = 0.2$ for $Q = 10^6\mathrm{MeV(fm/c)}^2$ (upper) and $Q = 10^8\mathrm{MeV(fm/c)}^2$ (lower) [Pérez-García et al 2018]



Neutron rich pasta

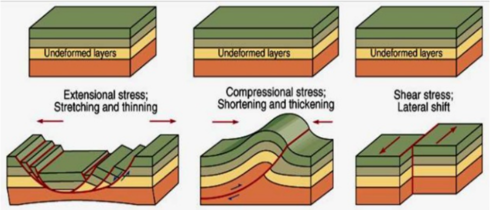
$0.03 fm^{-3}$ proton density isosurface, $n_b = 0.05\ fm^{-3}$ (left) and $n_b = 0.025\ fm^{-3}$ (right).[Horowitz, Pérez-García et al. PRC 70 (2004), PRC72 (2005)]

Elasticity of Pasta

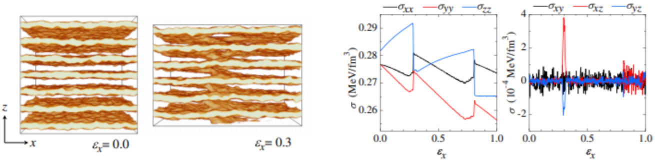
- In order to determine the elastic properties of Pasta one must obtain stress

$$\sigma_{a\beta} = \frac{1}{V}\sum_i \left[m u_a^{(i)} u_\beta^{(i)} + \frac{1}{2}\sum_{i\neq j}\left(x_a^{(i)} - x_a^{(j)}\right) f_\beta^{(ij)} \right] \quad (4)$$

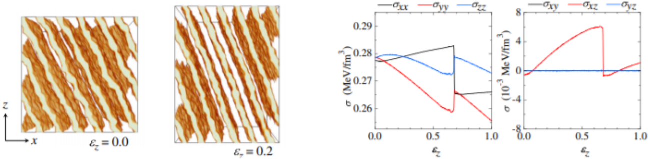
with x, u, f position, velocities and forces mixing tensile and shear stresses.



Lasagna plates show max. breaking strains of order 0.1 MeV/fm^3. $n_b = 0.05\ fm^{-3}$, $Y_p = 0.4$.[Caplan,Schneider et al., PRL121 (2018)]



(b) Tensile deformation pulling lasagna sheets laterally while compressing them



(c) Lasagna sheets experiencing both tensile and shear strains

- This max. breaking strain determines the max. quadrupole moment, source of GWs

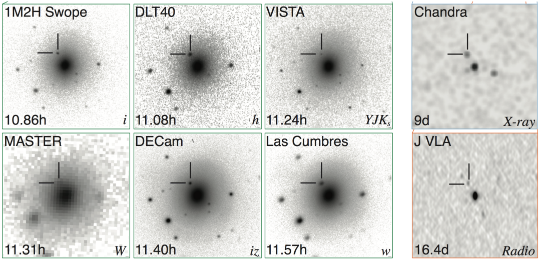
$$\epsilon = \sqrt{\frac{8\pi}{15}} \frac{\Phi_{22}}{I_{zz}}$$

where for slowly rotating neutron stars Φ_{22} can be written as

$$\Phi_{22,\max} = 2.4 \times 10^{39} g \, \mathrm{cm}^2 \left(\frac{\sigma_{\max}}{10^{-1}} \right) \left(\frac{R}{10 \, \mathrm{km}} \right)^{6.26} \left(\frac{1.4 M_{\odot}}{M} \right)^{1.2}$$

- However allowed range $10^{-5} < \sigma_{\max} < 10^{-1}$. [Ushomirsky, Cutler et al, MNRAS 319 (2000), Caplan et al. 2018]

More about NSs: multimessenger signal in BNS

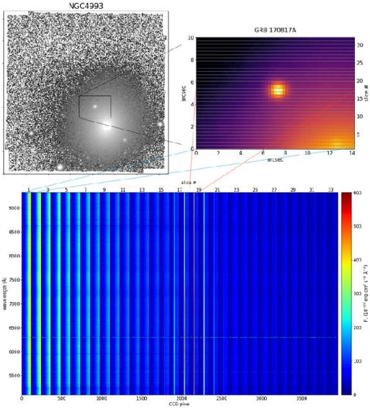


- Hours to days from GW170817 broadband EM radiation was detected in AT2017gfo. Optical images (left) taken between 10 and 12 hours after the merger whilst days after those in X-rays (right). `Source: LIGO website.`
- Microscopic matter properties also determines the ejected mass in the BNS$\rightarrow$ UV/visible/IR transient emission and more energetic channels perhaps interesting as a complementary standard candle in cosmology.

MAAT @GTC

MAAT visitor instrument @GTC

A new Integral-Field Spectroscopy mode for OSIRIS on the 10.4-m Gran Telescopio CANARIAS



Parameter	Value
Spectrograph	OSIRIS
Module	Integral Field Unit
Field-of-View	$14.20'' \times 10.00''$
Field aspect ratio	1.42
Slicer width	$0.303''$
Spatial sampling	$0.303'' \times 0.127''$
Wavelength range	360 to 1000 nm
Spectral resolution	600 to 4100
Detector	$4k \times 4k$ (15 μm pixel)
CCD plate scale	$0.127''$ per pixel

MAAT simulated CCD frame of MAAT of kilonova AT2017gfo in NGC 4993.

(The simulations are based on a MUSE archival spectral cube of NGC 4993)

“First Light” early 2023

White Paper on MAAT@GTC: *https://arxiv.org/pdf/2007.01603.pdf*

Conclusions

- NSs are complex objects where matter properties determine the deformations capable of generating GWs
- Microscopic simulations of neutron rich matter must consider interplay of short-range potentials and EM interaction, besides additional quantum effects.
- Richer description will provide more accurate answers, however this is computationally challenging.
- Deformations of NSs provided by current crust elasticity models could yield breaking strains up to $\sim 10^{-1}$ (MeV/fm^3).

THANK YOU