Gravitational waves from hot neutron stars and how to find out more about matter under extreme conditions with them

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Online Physikerinnentagung

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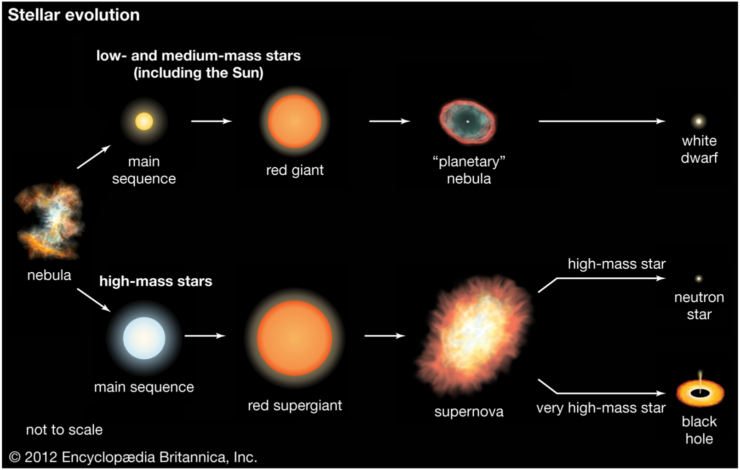
Overview

1. Neutron stars
   - Final stages of stellar evolution
   - Characteristics
2. Gravitational waves
   - Theory and observation
   - Binary neutron star merger
3. Research project: gravitational waves from hot neutron stars
   - Asteroseismology
   - Current state of research
   - Outlook

Outline


Stellar evolution
low- and medium-mass stars
(including the Sun)
main
sequence
red giant
“planetary”
nebula
white
dwarf
nebula
high-mass stars
main sequence
red supergiant
supernova
high-mass star
neutron
star
very high-mass star
black
hole
not to scale
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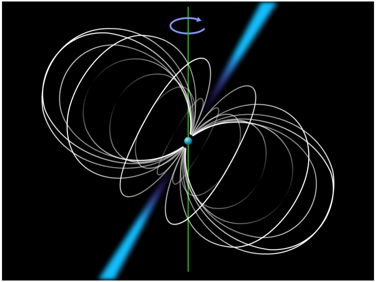
- Mass $1.4 - 2\ M_\odot$
- Radius $8 - 15$ km
- High central densities $\sim 10^{15}\mathrm{g/cm}^3$ (sun "only´´ $10^2\mathrm{g/cm}^3$)
- approx. 2000 discovered out of estimated 100 million in the Milky Way
- Very high magnetic fields, 10^{16} times stronger than on Earth
- Rapid rotationa
- Extreme gravitational forces: 2 billion times as strong as on Earth!



Pulsar emitting gamma and x-rays. Figure taken from
https://de.wikipedia.org/wiki/Pulsar

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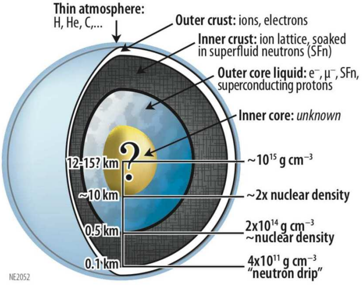

Figure taken from `https://heasarc.gsfc.nasa.gov/`

⇒ Holy grail of neutron star research: *Equation of state of nuclear matter under extreme conditions*

- Simplest case: modelled as an adiabatic perfect fluid, **polytropic** relation

$$p = K\rho^\Gamma, \qquad \epsilon = \rho + Np, \tag{1}$$

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Einstein's theory of general relativity

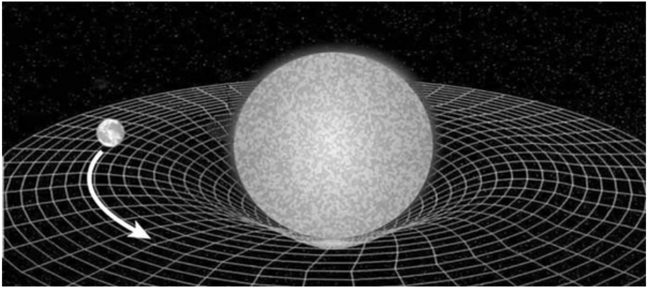


Figure taken from http://einstein.stanford.edu/

Field equations relate spacetime curvature to matter properties:

$$G_{\mu\nu} + \lambda g_{\mu\nu} = \kappa T_{\mu\nu} \tag{2}$$

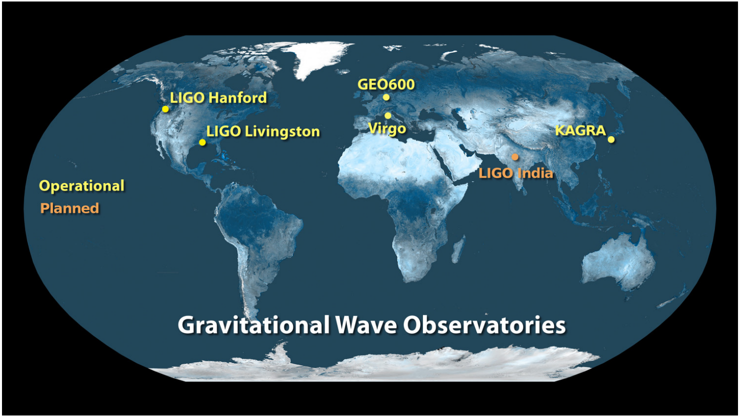
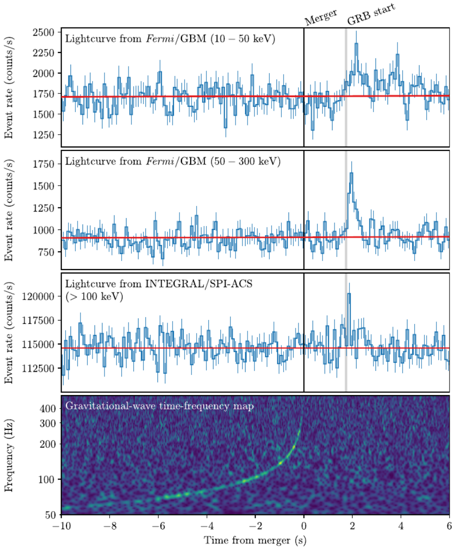


Figure taken from LIGO Lab Caltech

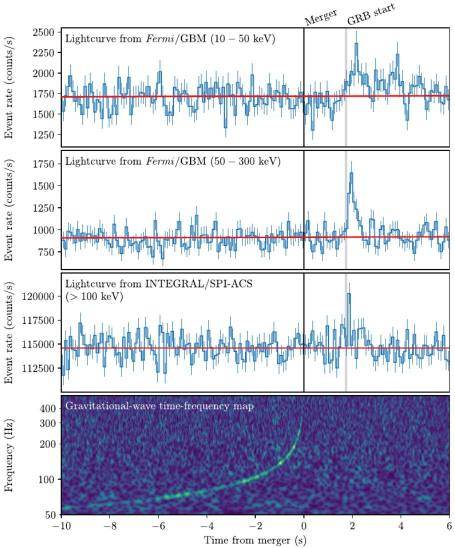
→ See YouTube video

Gravitational waves

Binary neutron star merger - GW170817



LIGO and Virgo Collaboration (2017)



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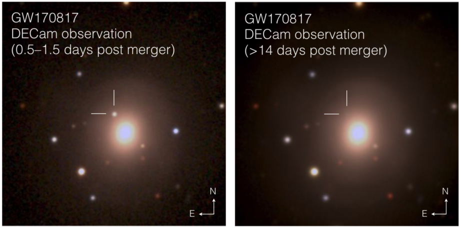


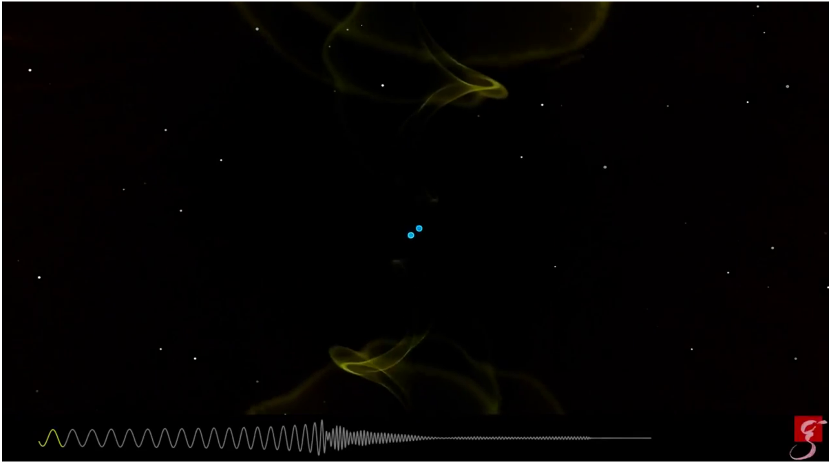
Figure from Dark Energy Camera, Fermilab

Gravitational & electromagnetic waves

$\Rightarrow$ *Multimessenger astronomy*

Gravitational waves

Binary neutron star merger - simulation



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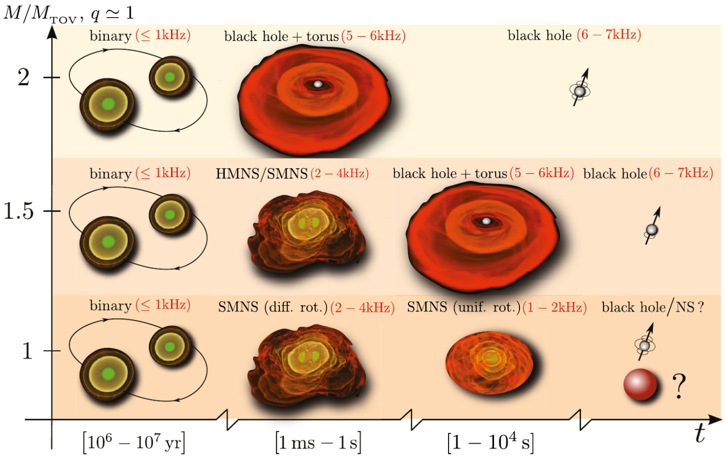
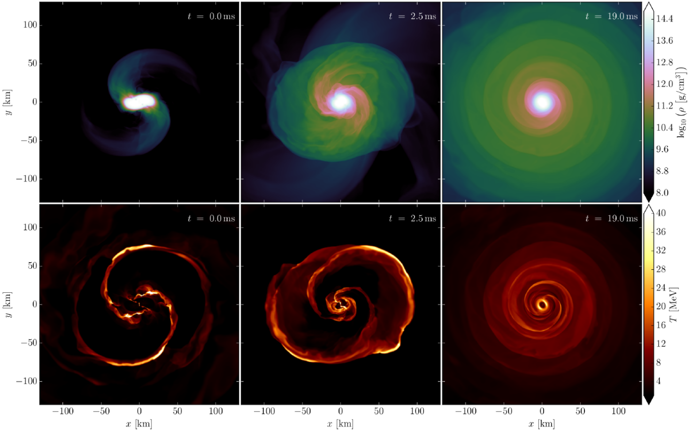


Baiotti and Rezzolla (2017)

- Very massive: $M \sim 2.5 - 3\,\mathrm{M}_\odot$ $\rightarrow$ unstable
- Rapid rotation $f \sim \mathrm{kHz}$ $\Rightarrow$ *Oscillations*
- High temperature $T \sim 10^{12}\,\mathrm{K}$

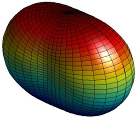


Endrizzi et al. (2018)

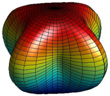
Outline

Model: mass, equation of state

$\Downarrow$



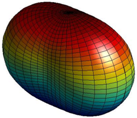
(a) ${}^{2}f$-mode



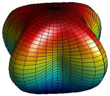
(b) ${}^{4}f$-mode

Model: mass, equation of state

⇓

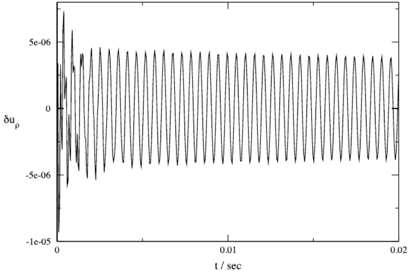


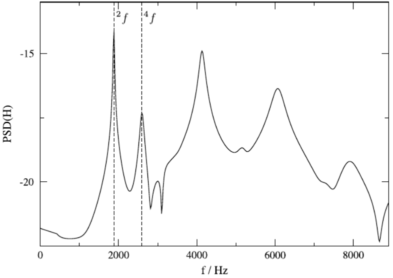
(c) ^{2}f-mode



(d) ^{4}f-mode

⇒





Gaertig and Kokkotas (2008)

Model: mass, equation of state

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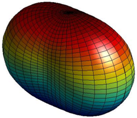
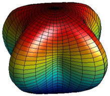
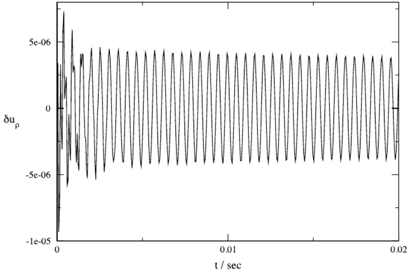


(e) $^2 f$-mode

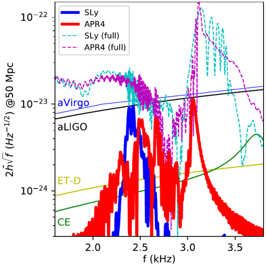


(f) $^4 f$-mode

$\Rightarrow$

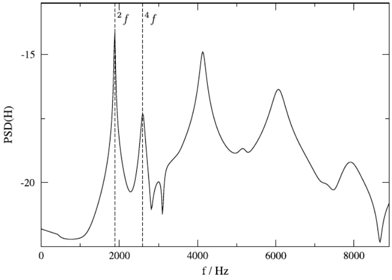


$\Uparrow$



De Pietri et al. (2018)

$\Leftarrow$



Gaertig and Kokkotas (2008)

Methods:

- Calculation of the **equilibrium background models**
  - Using the `rns` code developed by Stergioulas and Friedman (Stergioulas, 1995; Stergioulas and Friedman, 1995)
  - Solve the hydrostatic equilibrium using *Einstein's field equations* for a given equation of state, rotation rate and density

  → Gain equilibrium star with mass M and radius R

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- Evolution and calculation of the **oscillations**
  - Apply *linear perturbation theory* $x = x_0 + \delta x$ with small perturbations δx for the fluid variables around the equilibrium x_0
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- **Asteroseismology**
  - Compare the oscillation spectrum with actual *observations*
  - Make adjustments to the equilibrium models

  → *Constrain the equation of state*

g**(ravity)-oscillation modes:**

- Driven by buoyancy
- Occur due to temperature gradients or stratification of composition

→ Strongly dependent on the description of the inner structure ⇒ *equation of state*

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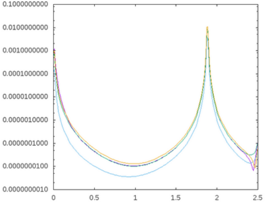
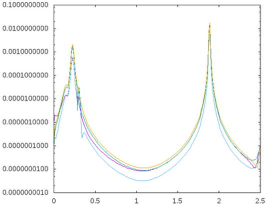
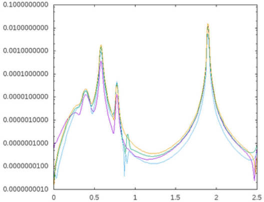
Oscillation spectrum:



(j) no gradients



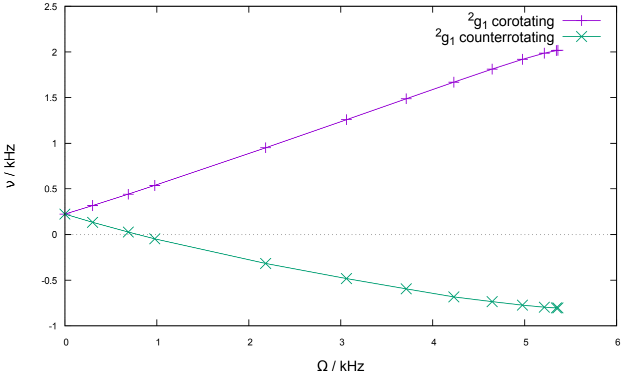
(k) mild gradients



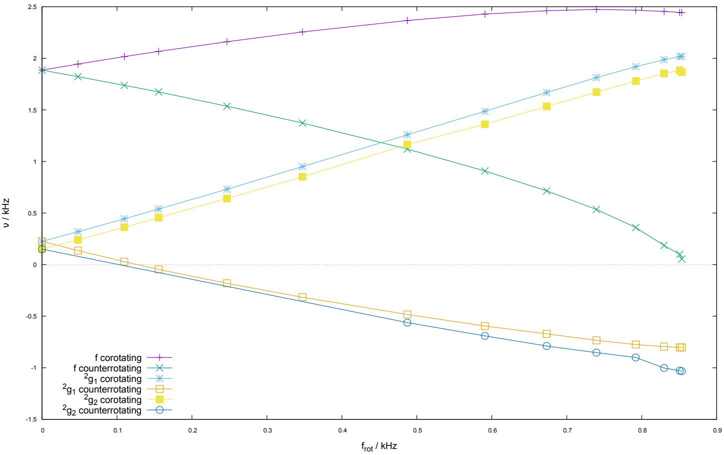
(l) steep gradients

- Typical neutron star with $M = 1.4\,\mathrm{M}_\odot$ and $R = 14.16\,\mathrm{km}$.

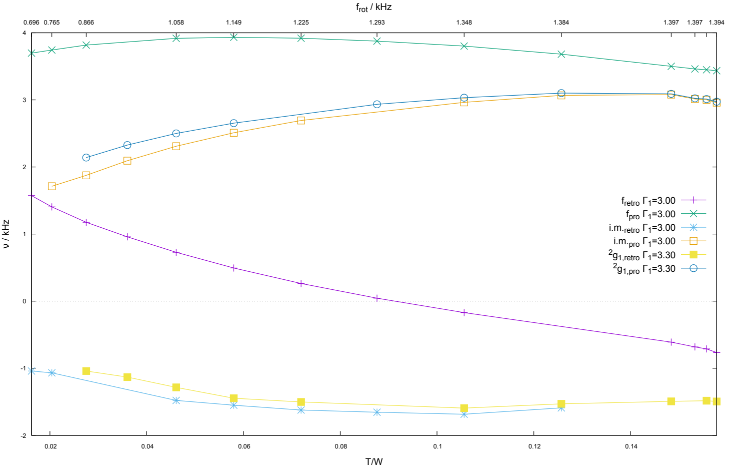
Rotation splits the modes:



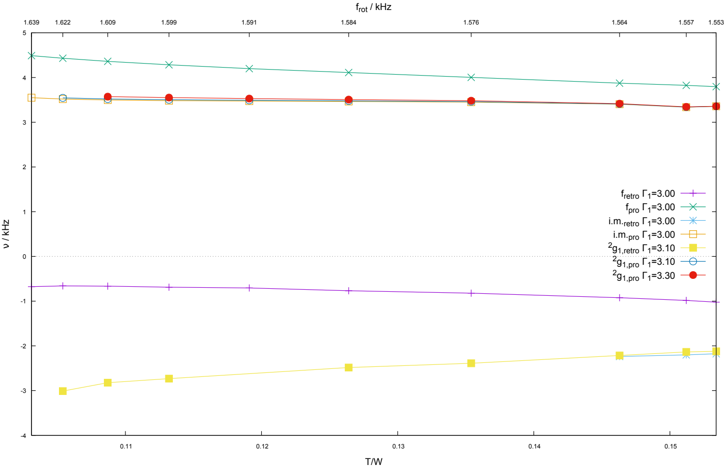
Fundamental g-mode for a mild gradient and a neutron star of mass $1.4\,\mathrm{M}_\odot$.



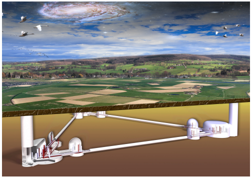
All modes, neutron star with $1.4\,\mathrm{M}_{\odot}$.



All modes, neutron star with $2.6\,\mathrm{M}_{\odot}$.

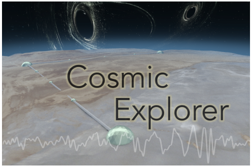


All modes, neutron star with $2.9\,\mathrm{M}_{\odot}$.



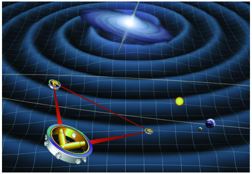
(m) Einstein Telescope, 10 km

Credit: Einstein Telescope Mediakit



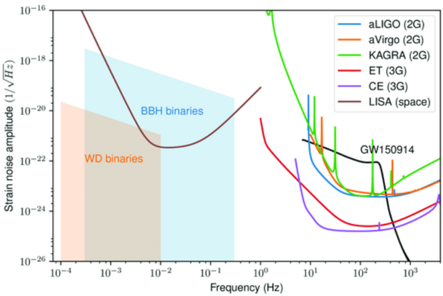
(n) Cosmic Explorer, 40 km

Credit: Cosmic Explorer Project

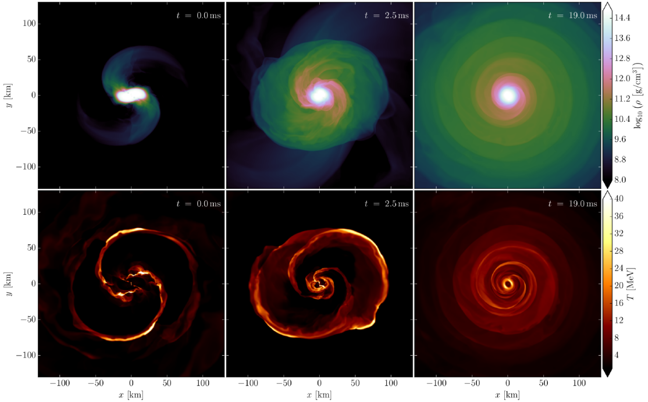


(o) LISA, 2.5 Mio km

Credit: NASA/ESA

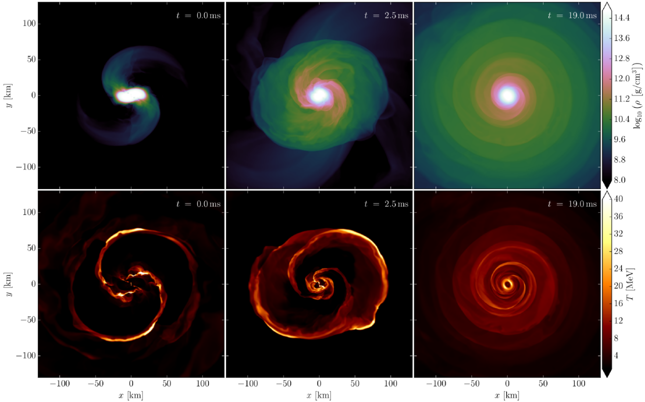


(p) Sensitivities, Credit: Ezquiaga et al. (2018)



More realistic. . .

- Equations of state
- Rotational profiles
- Temperature profiles



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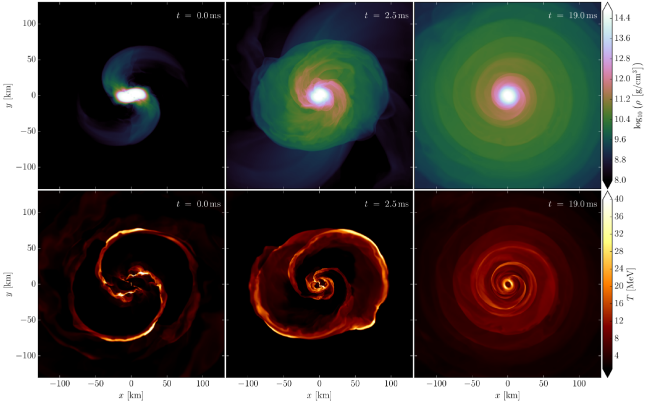
→ Analysis of the oscillation modes

→ Comparison with simulations and observations

→ *Asteroseismology*



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⇒ Information about the *equation of state of nuclear matter under extreme conditions*

Thank you for your attention!

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Studienstiftung des deutschen Volkes

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