Astrophysics of compact objects

Part III: Observational signatures

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Lecture LAPTH, Annecy, November 20-25, 2025

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Outline

Plan

1. Mature neutron stars
   - Pulsar timing : mass and radius
   - Cooling
2. Neutron stars as sources of gravitational waves
3. Core-collapse supernovae

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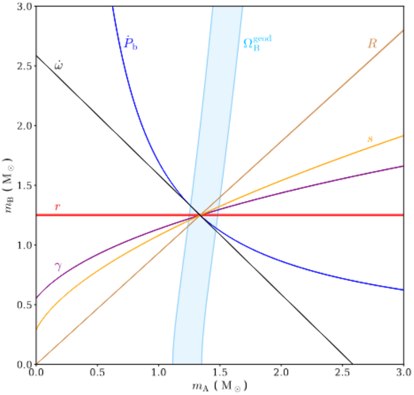
Pulsar mass measurements

Mass function equation

$$\frac{(M_c \sin i)^3}{(M_P + M_c)^2} \propto \frac{x^3}{P_b^2}$$

x, P_b measured from binary motion

- Degenerate in M_c, M_p, i
- Additional information needed (compagnon model, optical spectroscopy on compagnon, post-keplerian parameters)
- Observed masses in binary systems (NS-NS, NS-WD, X-ray binaries) with most precise measurements from double neutron star systems.



[Wex& Freire 2025]

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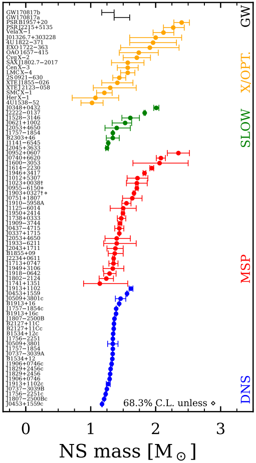
Observed pulsar masses

- Precise mass measurements in NS-WD binaries
  - $M = 1.908 \pm 0.016 M_\odot$ (PSR J1614-2230) [Demorest+ 2010, Fonesca+ 2016, Shamohammadi+ 2023]
  - $M = 2.08 \pm 0.07 M_\odot$ (PSR J0740+6620) [Cromartie+ 2021]
- Indications for massive pulsars in other systems (black widows), but analysis model dependent and resulting uncertainties very large

Given EoS ⇔ maximum mass

Additional particles add d.o.f.
→ softening of the EoS
→ lower maximum mass
→ constraint on core composition



[CompOSE, courtesy L. Suleiman]

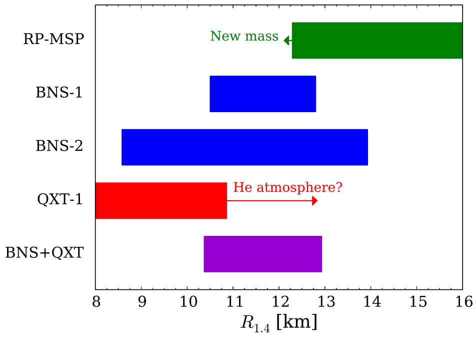
Radius estimates from X-ray observations

- Radii from different types of objects, but model dependent :
  - Atmosphere modelling (much recent progress)
  - Interstellar absorption (X-ray observations)
  - Distance, magnetic fields, rotation, ...

Many discussions

Consensus : radius of a fiducial $M = 1.4 M_\odot$ star 10-15 km

2σ error bars, radii at $M = 1.4 M_\odot$

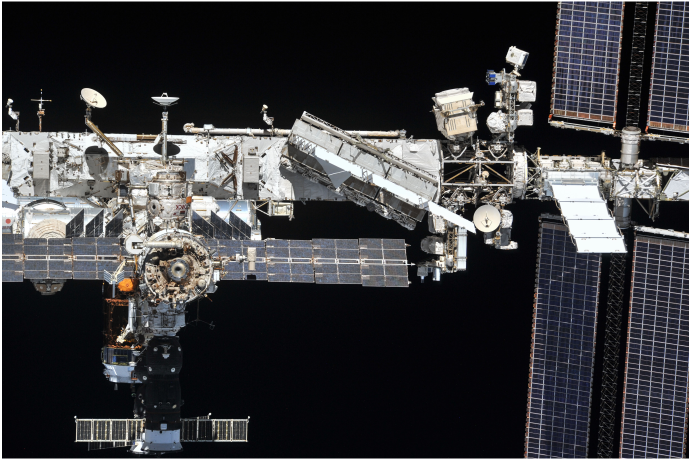


[courtesy M. Fortin, CAMK]

NICER

Pulsars timing in x-rays

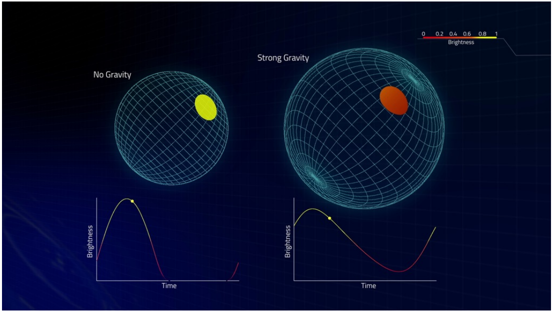
Mission on the International Space Station (ISS)



Neutron star Interior Composition ExploreR, launched in 2017

Gravitational lensing

Following General relativity, gravity deviates light rays :
$\Rightarrow$ important for compact objects, such as black holes and neutron stars



$\Rightarrow$ Possible to have an image behind the star
$\Rightarrow$ The effect depends on the compacity of the star $\propto M/R$

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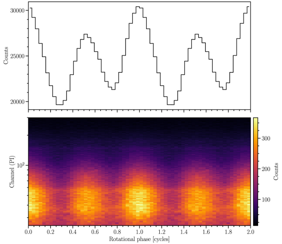
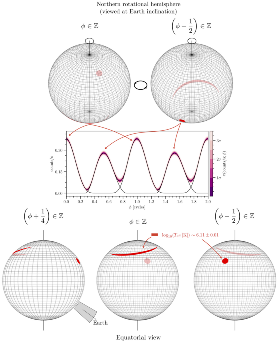
NICER

Results



Observation of PSR J0030+0451 [Riley+ 2019]

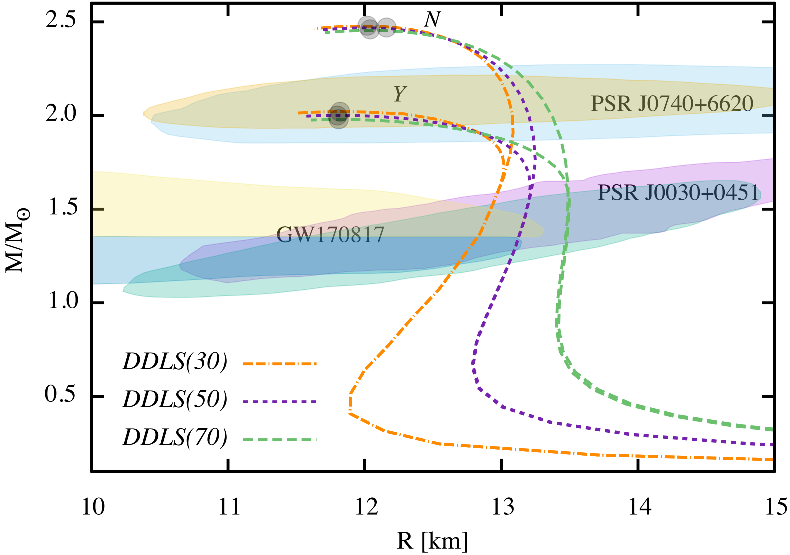
Measurement of compactness (M/R) with NICER and mass from radio observations
$\Rightarrow$ masss and radius of same object
Direct constraint on NS EoS via mass-radius relation



Models for PSR J0030+0451 [Riley+2019]

$\Rightarrow$ Different objects observed by NICER
$\Rightarrow$But difficulties in determining the geometry of hot spots on the NS surface
$\rightarrow$ still large uncertainties

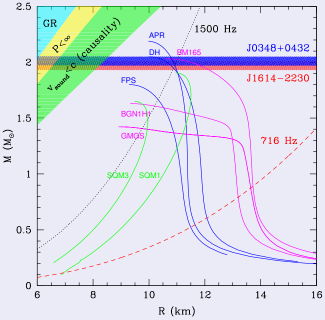
Mass-radius relations



[Tsiopelas+2024]

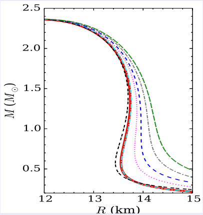
Pulsar timing

- Measurements of rotational frequency
  - $f = 716$ Hz (PSR J1748-2446ad) [Hessels+ 2006]
- Theory : Kepler frequency [Haensel+ 2009]
  $f_K = 1008\,\mathrm{Hz}\,(M/M_\odot)^{1/2}\,(R/10\mathrm{km})^{-3/2}$



[Courtesy M. Fortin]

NS radii, dependence on crust-core transition



[Fortin+ 2016]

→ A measured frequency of 1.4 kHz would constrain $R_{1.4} < 9.5$ km !

Remark of caution

Predicted radii are sensitive to surface definition and to treatment of crust-core transition !

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Plan

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Cooling observations

To obtain observational constraints on theoretical cooling curves, the surface temperature T_s and the age of the neutron star has to be known.

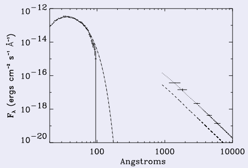
1. Age

- Some neutron stars are related to known historical supernova events, e.g. crab $\leftrightarrow$ SN 1054
- For some neutrons stars the age can be estimated from the expansion rate and extension of the associated supernova remnant
- The age can be estimated from the spin-down rate

2. Surface temperature

- A distant observer detects the apparent temperature $T_s^\infty = T_s\sqrt{1 - 2GM/(Rc^2)}$
- Only accessible for isolated neutron stars
- For most neutron stars, the thermal radiation should be in X-rays or UV
- Obtained from the observed spectrum assuming either a black-body spectrum or a model for the atmosphere (generally magnetised or non-magnetised hydrogen atmosphere)

RXJ 1856-3754



Theoretical description

- Description of energy balance and heat transport inside a neutron star governed by (with general relativistic corrections)

$$\frac{dLe^{2\Phi}}{dr} = -\frac{4\pi r^2 e^{\Phi}}{\sqrt{1-2GM/(Rc^2)}}\left(C_V \frac{dT}{dt} + e^{\Phi} Q_\nu\right)$$

and

$$\frac{d(Te^{\Phi})}{dr} = -\frac{1}{\kappa}\frac{Le^{\Phi}}{4\pi r^2\sqrt{1-2GM/(Rc^2)}}$$

.

- Energy loss by surface photon emission and neutrino emission
- Microscopic input from specific heat C_V, neutrino emissivity Q_ν and thermal conductivity κ.
- Theory predicts essentially three cooling stages
  1. Crust thermalisation ($\sim$ 10-50 yr) : the crust stays hotter than the core which evacuates heat by strong neutrino cooling
  2. Neutrino cooling ($\sim 10^5 - 10^6$ yr) : stellar interior isothermal, cooling by neutrino emission from the core
  3. Photon cooling ($t \gtrsim 10^6$ yr) : neutrino cooling dies out and cooling is governed by surface photon emission

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The specific heat of a BCS superconductor

The specific heat enters the heat transport equations and has a very specific behavior in a superconductor/superfluid. It is defined as

$$C_V = \frac{T}{V} \left. \frac{\partial S}{\partial T} \right|_{V,N} \approx -T \frac{\partial^2 \omega}{\partial T^2} \ .$$

In the BCS case, for small temperatures $\Delta \to \Delta_0$ and we can evaluate the grand canonical potential and the derivative, too, obtaining for the specific heat

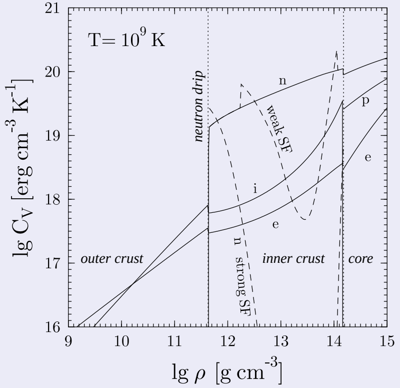
$$C_V = 2N(0)\Delta_0 (2\pi)^{1/2} \left(\frac{\Delta_0}{T} \right)^{3/2} e^{-\Delta_0/T} \ .$$

This shows the important result that the contribution to the specific heat of fermion paired in a scalar condensate is exponentially suppressed at low temperatures.

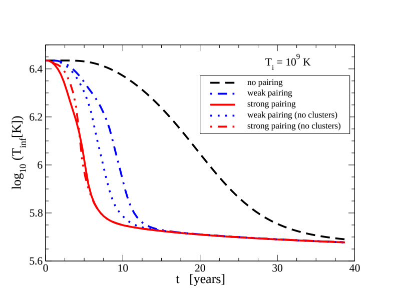
Note that this is not necessarily true for pairing in other channels.

Crust thermalisation and the specific heat

Neutron superfluidity plays a very important role . . .



[Gedin et al. 2001]



[Fortin et al. 2009]

The main neutrino emission mechanisms

1. Nonsuperfluid core

- The modified URCA process $n + N \to p + N + e^- + \bar{\nu}$ and $p + N + e^- \to n + N + \nu$.
  The direct URCA process $n \to p + e^- + \bar{\nu}$ and $p + e^- \to n + \nu$, a very efficient cooling process, is suppressed in the cold neutron star due to energy and momentum conservation. It can reappear in the very dense core if the proton fraction exceeds $\sim$ 11-14%.

Why is direct URCA suppressed?

Consider the reaction $n \to P + e^- + \bar{\nu}$.

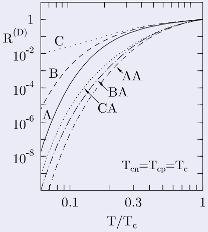
- Energy conservation $E_n = E_p + E_{e^-} + E_\nu$, where n, p, e^- have $E_i \sim E_{F_i} \pm T$, thus the neutrino has $E_\nu \sim T$.
- β equilibrium $\mu_n = \mu_p + \mu_e$ and charge neutrality give $p_{F,e} = p_{F,p} \sim p_{F,n}^2/(2m_n) \ll p_{F,n}$
- Momentum conservation $\vec{p}_n = \vec{p}_p + \vec{p}_{e^-} + \vec{p}_\nu$ with $|\vec{p}_\nu| \sim T$ can then no longer be fulfilled, since $p_{F,n} \lesssim p_{F,p} + p_{F,e}$.

- Nucleon-Nucleon Bremsstrahlung $N + N \to N + N + \nu + \bar{\nu}$.
- In the dense core, several other processes depending on the composition (nucleons, hyperons, pions, kaons, quarks, etc) can contribute to neutrino cooling

The main neutrino emission mechanisms

2. Superfluid core

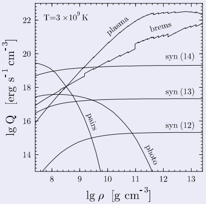
- Due to the energy gap in the particle spectra, neutron and/or proton superfluidity suppresses the direct URCA process (of any kind)
- Cooling can be enhanced due to additional Cooper pair breaking processes
$$B \to B + \nu + \bar{\nu}\ .$$
(B can be any paired baryon)



[Yakovlev et al. 2000]

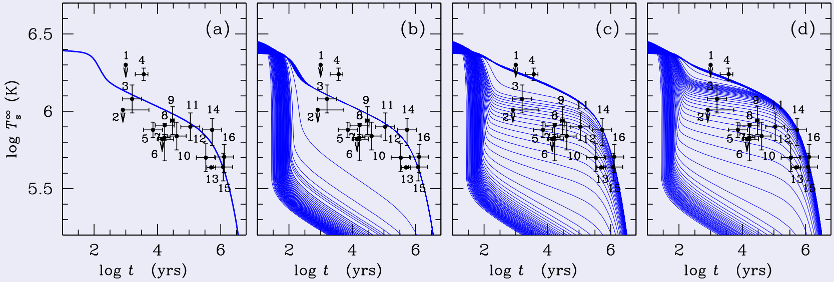
3. Crust

- In the crust, many additional processes contribute, i.e. $e^- + e^+ \to \nu + \bar{\nu}, e \to + \nu + \bar{\nu}, e + \gamma \to e + \nu + \bar{\nu}$ and processes on nuclei, e.g. neutron-nucleus bremsstrahlung



[Yakovlev et al. 2000]

Some cooling curves



[Yakovlev et al. 2007]

(A) Nonsuperfluid $1.3 M_\odot$ star

(B) Stars with $1.1 M_\odot < M < 1.97 M_\odot$, sharp direct URCA threshold

(C) Two different types of proton superfluidity → broadening of the URCA threshold

Many other cooling scenarios have been considered including different compositions of dense matter (pion/kaon condensation, hyperons, quarks etc.).

Plan

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What is a gravitational wave ?

- Analogy :
  electromagnetic waves from accelerated charges
  $\leftrightarrow$ gravitational waves from accelerated masses
- Gravitational waves are oscillations of space-time
- Modification of the distance between two points (measured as light going forth and back) as $\Delta L \sim hl$.

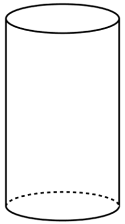
  h corresponds to the amplitude of the GW
- Gravitational waves exist for at least quadrupolar mass deformations

A neutron star coalescence

Some orders of magnitude

- Estimation of gravitational luminosity (total radiated energy per second by gravitational waves) :
  - It is proportional to the square of third time derivative of the quadrupole moment $Q_{ij} = \int \rho(\vec{x})(x_i x_j - \frac{1}{3}\boldsymbol{x}^2) d^3x$ which is $\dddot{Q} \sim s\omega^3 M R^2$ (s being a factor related to non-sphericity of the matter distribution).
  - The prefactor is (dimensional reasoning) G/c^5.

- We obtain $L \sim \frac{G}{c^5} s^2 \omega^6 M^2 R^4$
- Plug in numbers : $c^5/G = 3.6 \times 10^{52} W$!
- What is the gravitational luminosity of a steel cylinder with $M = 490$ tons, $L = 20$m, $r = 1m$, rotating at $\omega = 28$rad/s (close to the rupture limit) ?



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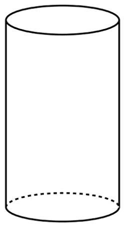

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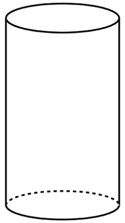

$\rightarrow$ $L \approx 10^{-28} W$ no hope for detection

Neutron stars as sources of gravitational waves

Let us rearrange the gravitational luminosity is $L \sim \frac{G}{c^5} s^2 \omega^6 M^2 R^4$ introducing $M = c^2 R_s/(2G)$, and $\omega \sim v/R = v/cc/R$. We then obtain

$$L \sim \frac{c^5}{G} s^2 \left(\frac{R_s}{R}\right)^2 \left(\frac{v}{c}\right)^6$$

. (Remind that R_s/R is the compacity Ξ defined earlier.)

This allows to see that good sources are

- Non-spherical (and dynamically changing)
- Compact ($\Xi \sim 1$)
- In relativistic motion

$\rightarrow$ with the exception of the first point, neutron stars are good potential sources.

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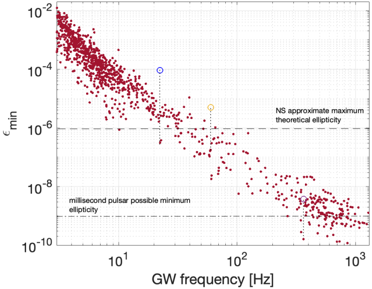
Asterosismology

To be efficient emitters, it is not enough to be flattened by rotation : they must have a variation in time of their quadrupole moment : *e.g.* deformation not symmetric / rotation axis.



[Abac+ 2025]

Off-axis deformations can come from

- Magnetic field
- Crust (1 mm high mountains)
- Oscillations (vibrations) of the fluid : many different modes . . .

Limits on deformation (ellipticity) obtained from GW observations of known pulsars

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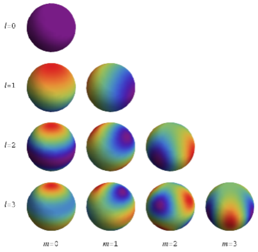
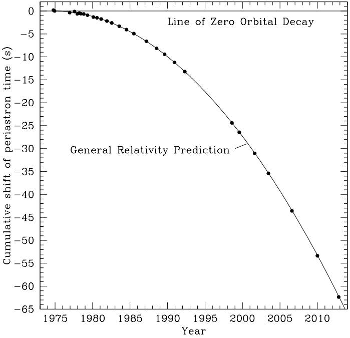
Neutron star mode spectrum

- Mode family classification depending on restoring force
  - f-modes : scale with average density
  - p-modes : sound waves in the star (overtones of the f-modes)
  - g-modes : buoyancy waves from thermal/composition gradients
  - inertial modes (including r-modes which are driven unstable by gravitational wave emission)
  - i-modes : arise at phase transition interfaces
  - Not a complete list !



[Pnigouras & Kokkotas]

Binary pulsars in general relativity



Binary pulsars have been timed in an extreme accurate way, starting with PSR 1913+16, by Russel Hulse and Joseph Taylor.

This precise timing allowed for a comparison with General Relativity prediction of

- The periastron shift
- The angular momentum loss due to emission of gravitational waves.

Excellent agreement and indirect proof of gravitational wave emission → Nobel Price in 1993 (cf lecture 1)

First direct detection in 2015 (merger of a binary black hole)

Detectors

Virgo and LIGO

Laser Interferometer Gravitational-Wave Observatory (USA) first version constructed in 2002

LIGO : USA, Louisiana

LIGO : USA, Washington

VIRGO : France/Italy (Pisa)

3 km arms (VIRGO) et 4 km (LIGO)
Virgo : european instrument (France, Italy, Netherlands, Hungary and Poland), first version in 2004.

In contrast to optical telescopes, it is not sufficient to observe to see something
$\longrightarrow$ enormous data analysis work

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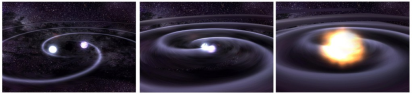
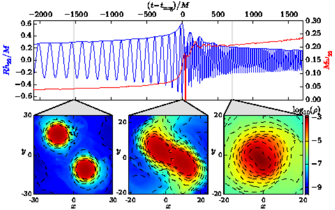
Neutron star binaries ?



(Credit : NASA/CXC/GSFC/T.Strohmayer)

Binary neutron stars very good sources of gravitational waves



(S. Bernuzzi)

Different phases

- inspiral
- merger
- potential post-merger formation of super/hyper-massive neutron star
- collapse to a black hole

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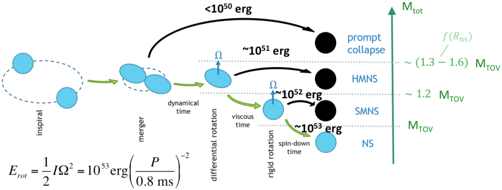
GWs from binary neutron star mergers

- GW170817 : first detection of a NS-NS merger with LIGO/Virgo detectors

- Information from the different phases
  - Inspiral → masses of objects
  - Late inspiral → tidal deformability $\tilde{\Lambda}$



$$E_{rot} = \frac{1}{2} I\Omega^2 = 10^{53}\,\mathrm{erg}\left(\frac{P}{0.8\ \mathrm{ms}}\right)^{-2}$$

[Metzger 2019]

  - Post merger GW emission not yet detected but in reach for 3rd generation detectors
  - Electromagnetic counterpart with information about ejecta properties, kilonova (site for r-process nucleosynthesis in the ejecta), ...

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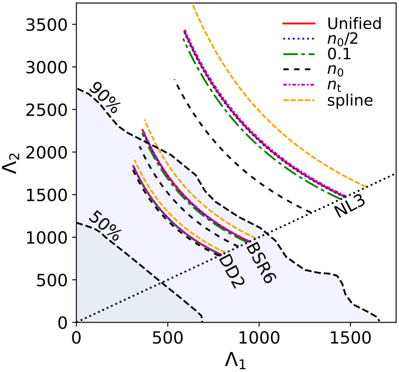
Tidal deformability and NS EoS

- Tidal effects influence the late inspiral, measurement of $\tilde{\Lambda}$ from GW170817
- Recall $\tilde{\Lambda}$ is a combination of the masses and tidal deformabilities (related to k_2 Love number) of both stars



[Suleiman+2021]

- Current data mildly constrain NS EoS
- No other informative event for the moment
- 3rd generation detectors expected to measure many events with precisely constrained NS EoS

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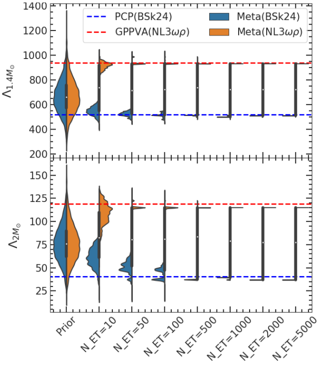

[Iacovelli+2023]

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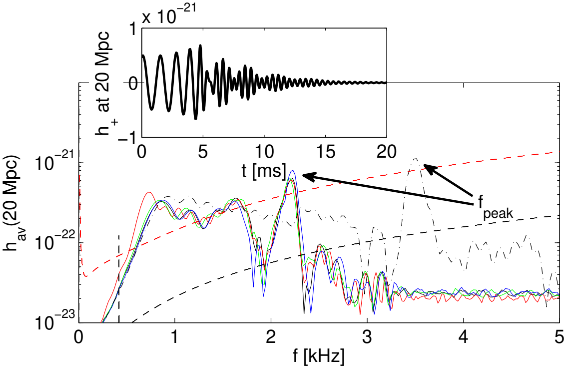
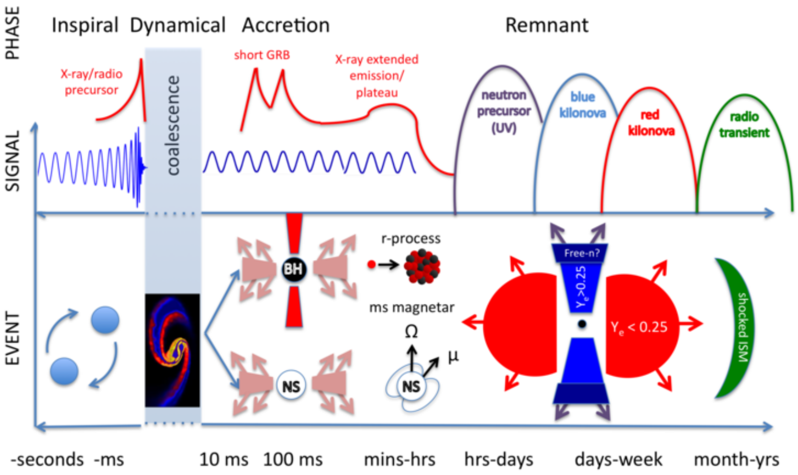
Post-merger spectrum



[Bauswein+ 2011]

- Prominent post-merger oscillations
- Dominant modes are quadrupolar f-modes
- Much richer than the inspiral phase, but complicated numerical models

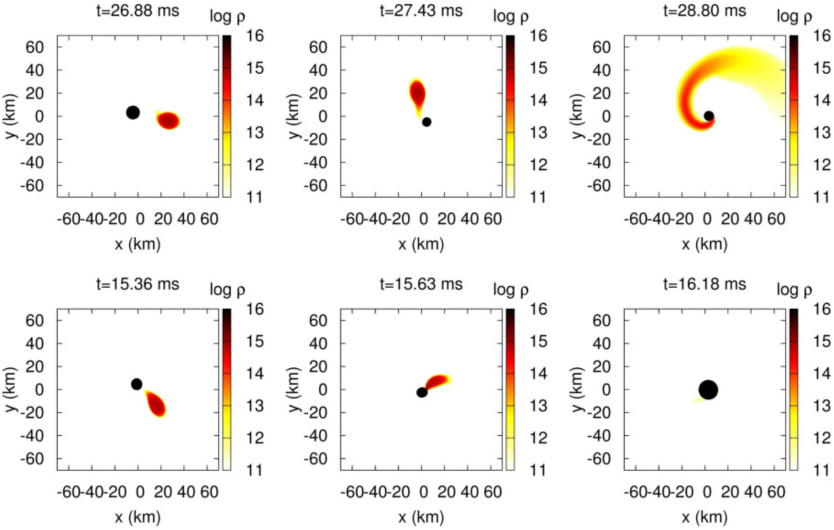
Further evolution



[R. Fernandez]

BH-NS BINARIES

Different scenarios : tidal disruption / plunge of the neutron star



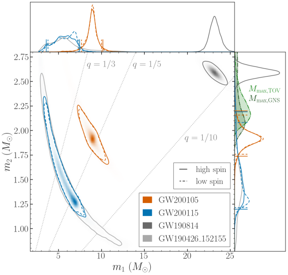
[Kyutoku+ 2011]

Depends on many parameters, including the equation of state

BH-NS BINARIES

- GW200105 and GW200115 : first detection of two BH-NS merger events with LIGO/Virgo detectors

- Information from different phases depends on scenario : tidal disruption / plunge of the neutron star
  - Inspiral $\longrightarrow$ masses of objects
  - Late inspiral $\longrightarrow$ tidal deformability $\tilde{\Lambda}$, but very small for $M_{\rm BH} \gg M_{\rm NS}$ $\longrightarrow$ only detectable for low BH mass close by events
  - Plunge of the neutron star $\longrightarrow$ no further information about NS



[LVC : Abbott+2021]

- Tidal disruption (low-mass BH with high spin) $\longrightarrow$ cut in GW signal upon disruption, ejected material very different from BNS mergers, no information about NS from post-merger oscillations

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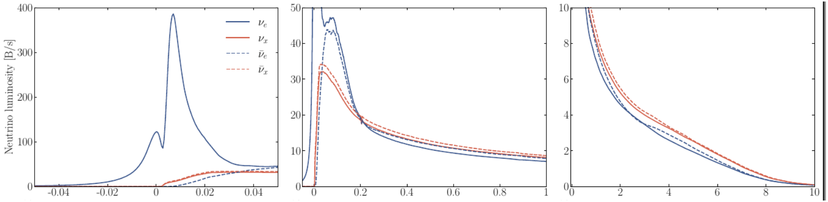
Plan

1. Mature neutron stars
   - Pulsar timing : mass and radius
   - Cooling
2. Neutron stars as sources of gravitational waves
3. Core-collapse supernovae

Neutrinos



[Fiorello+ 2023]

- SN1987A : detection of 30 neutrinos in Kamiokande, Baksan, IMB
- Compatible with numerical CCSN models, main question on PNS convection and late events
- Future galactic event with information on large-scale hydrodynamic phenomena, neutrino flavor oscillations

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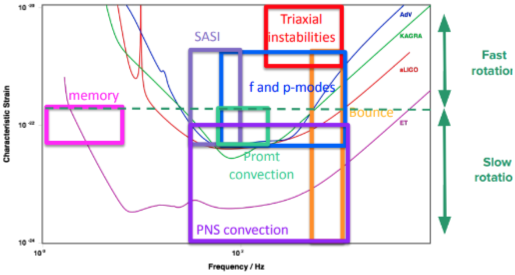
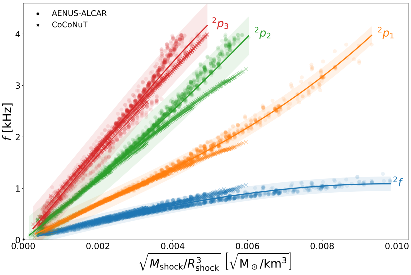
Gravitational waves



Credit: Pablo Cerdà-Duràn



[Torres-Forné+ 2019]

- Different features potentially detectable for a galactic event
- Information in explosion mechanism and PNS properties, among others PNS mass and radius

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Some useful links

- Paolo Freire's collection of pulsar mass measurements, https://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html
- The Gravitational Wave Open Science Center, https://gwosc.org/
- The Garching group's core collapse supernova page with simulation data and movies, https://wwwmpa.mpa-garching.mpg.de/ccsnarchive/
- The GREAT code : General Relativistic Eigenmode analysis tool, https://www.uv.es/cerdupa/codes/GREAT