Using gravitational waves to understand neutron stars

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Plan of the talk

- Our present understanding of merging binary NSs
- Anatomy of GW signal: characteristic frequencies
- Role of B-fields and EM counterparts

Will not discuss:
- ejecta and nucleosynthesis
- black hole-torus system and magnetic fields
Why study binary neutron stars?

• We know they exist (as opposed to binary BHs) and are among the strongest sources of GWs.

• GWs have the potential of providing accurate information on the EOS.

• We expect them related to short gamma-ray bursts; energies released are huge: \(10^{48-50}\) erg.

• No self-consistent model has yet been produced to explain them.
The equations we solve

**Bottom-top** approach: we solve the Einstein equations and those of relativistic hydrodynamics/MHD to model, *ab-initio*, BNSs. Not always realistic but at least physically consistent...

\[ R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu} , \]  
(field equations)

\[ \nabla_{\mu} T^{\mu\nu} = 0 , \]  
(cons. energy/momentum)

\[ \nabla_{\mu} (\rho u^{\mu}) = 0 , \]  
(cons. rest mass)

\[ p = p(\rho, \epsilon, Y_e, \ldots) , \]  
(equation of state)

\[ \nabla_{\nu} F^{\mu\nu} = I^{\mu} , \quad \nabla^* F^{\mu\nu} = 0 , \]  
(Maxwell equations)

\[ T_{\mu\nu} = T^{\text{fluid}}_{\mu\nu} + T^{\text{EM}}_{\mu\nu} + \ldots \]  
(energy – momentum tensor)
The two-body problem in GR

- For BHs we know what to **expect**:  
  \[ \text{BH + BH} \rightarrow \text{BH + gravitational waves (GWs)} \]

- For NSs the question is more **subtle**: the merger leads to an hyper-massive neutron star (HMNS), ie a metastable equilibrium:  
  \[ \text{NS + NS} \rightarrow \text{HMNS + ... ?} \rightarrow \text{BH + torus + ... ?} \rightarrow \text{BH} \]
Broadbrush picture

\[ M/M_{\text{max}}, q \approx 1 \]

- Binary (\( \leq 1\text{kHz} \))
- Black hole + torus (5 – 6kHz)
- Black hole (6 – 7kHz)

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- HMNS (2 – 4kHz)
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- Binary (\( \leq 1\text{kHz} \))
- HMNS (2 – 4kHz)
- Supramassive NS (1 – 2kHz)
- NS (2 – 4kHz)

\[ t \]

- \([10^6 – 10^7 \text{yr}]\)
- \([1 \text{ms} – 1 \text{s}]\)
- \([1 – 10^4 \text{s}]\)
Broadbrush picture
The two-body problem in GR

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  \[ NS + NS \rightarrow \text{HMNS + ...?} \rightarrow \text{BH + torus + ...?} \rightarrow \text{BH} \]

All complications are in the intermediate stages; the rewards high:
• studying the HMNS will show strong and precise imprint on the EOS
• studying the BH+torus will tell us on the central engine of GRBs

NOTE: with advanced detectors we expect to have a realistic rate of \( \sim 40 \text{ BNSs} \) inspirals a year, ie \( \sim 1 \) a week (Abadie+ 2010)
Quantitative differences are produced by:

- differences induced by the gravitational MASS:
  a binary with smaller mass will produce a HMNS further away from the stability threshold and will collapse at a later time.
Hot EOS: **high-mass** binary

\[ M = 1.6 \, M_\odot \]
Anatomy of the GW signal

GNH3, $\bar{M} = 1.350M_\odot$
Anatomy of the GW signal

Inspiral: well approximated by PN/EOB; tidal effects important
Anatomy of the GW signal

Merger: highly nonlinear but analytic description possible
Anatomy of the GW signal

**Post-merger**: quasi-periodic emission of bar-deformed HMNS
Anatomy of the GW signal

Collapse-ringdown: signal essentially shuts off.

$GNH3, \ M = 1.350M_\odot$
Anatomy of the GW signal

Chirp signal (track from low to high frequencies)

Cut off (very high frequents)

clean peak at high frequents

???
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- **differences induced by MASS ASYMMETRIES:**
  tidal disruption before merger; may lead to prompt BH
the torii are generically more massive
the torii are generically more extended
the torii tend to stable quasi-Keplerian configurations
overall unequal-mass systems have all the ingredients needed to create a GRB
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- **differences induced by the EOS:**
  stiff/soft OESs will have different compressibility and deformability, imprinting on the GW signal

- **differences induced by MAGNETIC FIELDS:**
  the angular momentum redistribution via magnetic braking or MRI can increase/decrease time to collapse; EM counterparts!

- **differences induced by RADIATIVE PROCESSES:**
  radiative losses will alter the equilibrium of the HMNS
How to constrain the EOS
Anatomy of the GW signal

Inspiral
Hints of quasi-universality

Read+, 2013, found “surprising” result: quasi-universal behaviour of GW frequency at amplitude peak

Bernuzzi+, 2014 and Takami+, 2015 confirmed with new simulations.

Quasi-universal behaviour in the inspiral of BNSs: once $f_{\text{max}}$ is measured, so is tidal deformability, hence $I, Q, M/R$

$$\Lambda = \frac{\lambda}{M^5} = \frac{16}{3} \kappa_2$$

tidal deformability or Love number
Anatomy of the GW signal

merger/post-merger

GNH3, $\bar{M} = 1.350 M_{\odot}$
Extracting information from the EOS

Takami, LR, Baiotti (2015)
There are lines! Logically not different from emission lines from stellar atmospheres
A new approach to constrain the EOS

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A new approach to constrain the EOS

It is possible to correlate the values of the peaks with the properties of the progenitor stars, i.e. M, R, and combinations thereof.

Each cross refers to a given mass and crosses of the same color refer to the same EOS.

The high-freq. peak $f_2$ has been shown to correlate with stellar properties, e.g., $R_{\text{max}}$, $R_{1.6}$, etc (Bauswein+ 2011, 2012, Hotokezaka+ 2013).

The correlation depends on mass.

The low-freq. peak $f_1$ shows a much tighter correlation; most importantly, it does not depend on the EOS.
Quasi-universal or not?

Identification of mode in PSD is delicate, especially for $f_1$ which is created in short time window.

Bernuzzi+ (2015) seem to confirm the quasi-universality.

Universality not lost at very low masses (1.2 M); more validation in progress.
Takami et al. 2015 have considered correlations of $f_{\text{max}}$, $f_1$ and $f_2$ with a number of different physical quantities.

Particularly interesting is the correlation between $f_2$ and the tidal deformability.

Hence tidal deformability is a good telltale both for inspiral and post-merger.
An example: start from equilibria

Assume that the GW signal from a binary NS is detected and with a SNR high enough that the two peaks are clearly measurable.

Consider your best choices as candidate EOSs
An example: use the $M(R,f_1)$ relation

The measure of the $f_1$ peak will fix a $M(R,f_1)$ relation and hence a single line in the $(M, R)$ plane.

All EOSs will have one constraint (crossing)
An example: use the \( M(R,f_2) \) relations

The measure of the \( f_2 \) peak will fix a relation \( M(R,f_2,EOS) \) for each EOS and hence a number of lines in the \( (M, R) \) plane.

The right EOS will have **three** different constraints (APR, GNH3, SLy excluded)
An example: use measure of the mass

If the mass of the binary is measured from the inspiral, an additional constraint can be imposed.

The right EOS will have **four** different constraints. Ideally, a single detection would be sufficient.
This works for all EOSs considered

In reality things will be more complicated. The **lines will be stripes**; Bayesian probability to get precision on $M, R$.

Some numbers:
- at 50 Mpc, freq. uncertainty from Fisher matrix is 100 Hz
- at SNR=2, the event rate is 0.2-2 yr$^{-1}$ for different EOSs.
The role of magnetic fields
**Ideal Magnetohydrodynamics**

Most simulations to date make use of ideal MHD: conductivity is infinite and magnetic field simply advected.

- **can B-fields be detected during the inspiral?**
  - **NO**: present and future GW detectors will not be sensitive enough to measure the small differences
    
    Giacomazzo+ (2009)

- **can B-fields be detected in the HMNS?**
  - **YES** (in principle): different B-fields change the survival of the HMNS and can grow via MRI; very difficult problem
    

- **can B-fields grow after BH formation?**
  - **YES**: B-fields are subject to instabilities and rotation of the BH introduces preferred direction for field geometry
    
MHD instabilities and B-field amplifications

• at the merger, the NS create a strong shear layer which could lead to a Kelvin-Helmholtz instability; magnetic field can be amplified

(Baiotti+2008)
MHD instabilities and B-field amplifications

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- direct simulations don’t show significant exponential growth (Giacomazzo+2011, Kiuchi+2014). Timescale too short? Resolution too poor?
- sub-grid models suggest B-field grows to $10^{16}$ G (Giacomazzo+2014)
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- sub-grid models suggest B-field grows to $10^{16}$ G (Giacomazzo+2014)
- differentially rotating magnetized fluids develop the MRI (magnetorotational instability; Velikhov 1959, Chandrasekhar 1960)
- the MRI leads to exponential growth of B-field and to an outward transfer of angular momentum: responsible for accretion in discs
- overall, consensus MRI can develop in HMNS (Siegel+2013, Kiuchi+2014)
- degree of amplification is unknown: 2-3 or 5-6 orders of magnitude? What about resistivity? (Kiuchi+2015, Obergaulinger+2015)
Do we understand X-ray afterglows?

- X-ray afterglows have been observed by Swift lasting as long as $10^2$–$10^4$ s (Rowlinson+ 13; Gompertz+13).

- The X-ray afterglow could also be produced by a “magnetically-driven” wind generated by differential rotation (Siegel+ 14).

- The X-ray afterglow could be produced by “proto-magnetar”: dipolar emission with $L_x \sim 10^{49}$ erg s$^{-1}$ (Zhang & Mezsaros 01, Metzger+ 11, Zhang 13).
How long can the BMP survive?

PDF of the collapse time for three EOSs. The vertical lines refer to values as deduced from the observations of 4 SGRB remnants Rowlinson+ (2013).
The elephant in the room...

Magnetars are appealing for their simplicity but hardly a solution

- differential rotation lost over Alfven timescale: $\sim 10$ s; magnetically driven wind can’t explain sustained emission for $10^3$-$10^4$ s
- X-ray plateaus follow the gamma emission, yet magnetar must come before the BH-torus.
- simulations do not show any sign of jet, which emerges only when BH-torus is produced.

If the standard picture requires that:

- X-rays produced by metastable magnetar
- gamma-rays produced by jet and BH-torus system

How can the gammas arrive before the X-rays? Riddle!
A solution to the riddle?

LR, Kumar (2014) (also Ciolfi, Siegel 2014)
A novel paradigm for GRBs?

LR, Kumar (2014)

Isotropic equivalent of luminosity of cocoon in host-galaxy frame as a function of observer time (\(z\) is galaxy redshift)

Cocoon temperature

\[
\dot{M}_{sw} = 10^{-3} M_\odot \text{s}^{-1}
\]

\[
V_{sw} = c/2
\]

\[
t_{sw} = 10 \text{ s}
\]
A novel paradigm for GRBs?

LR, Kumar (2014)

- **solves the timescale riddle**: X-ray luminosity is produced by BMP and can last up to $10^4$ s
- **solves the timing riddle**: X-ray emission is produced before gamma emission but propagates more slowly.
- **consistent with simulations**: slow wind is produced by a number of effects.
- proposes **unifying view with long GRBS**: a jet has to propagate in confining medium
- **predictions**: X-ray emission possible before gamma; IC of thermal photons at break out.
- GW signal peak **earlier** than thought before.
- **potential problem**: need to produce a disk at collapse and could be difficult (Margalit+15).
Conclusions

- Modelling of binary NSs in full GR is mature: GWs from the inspiral can be computed with precision of binary BHs.
- Spectra of post-merger shows clear peaks: cf lines for stellar atmospheres. Some peaks are "quasi-universal".
- If observed, post-merger signal will set tight constraints on EOS.
- Magnetic fields unlikely to be detected during the inspiral but important after the merger: instabilities and EM counterparts.
- Extended X-ray emission is a riddle. A way out is possible in terms of a two-wind scenario.

Overall, binary neutron stars via GWs and EM waves are likely to soon provide important input in nuclear physics.