Title: Looking for hypermassive neutron stars

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Series: Colloquium

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Abstract: Hypermassive neutron stars (HMNS) can be briefly formed after a binary neutron star merger and are likely to be highly deformed and strongly oscillating. These oscillations may be seen as modulation of the associated short gamma-ray burst and could provide observational evidence for the HMNS phase. I will discuss the prospects for their detection and the important physical information that can be gained by their observation.

Looking for Hypermassive Neutron Stars

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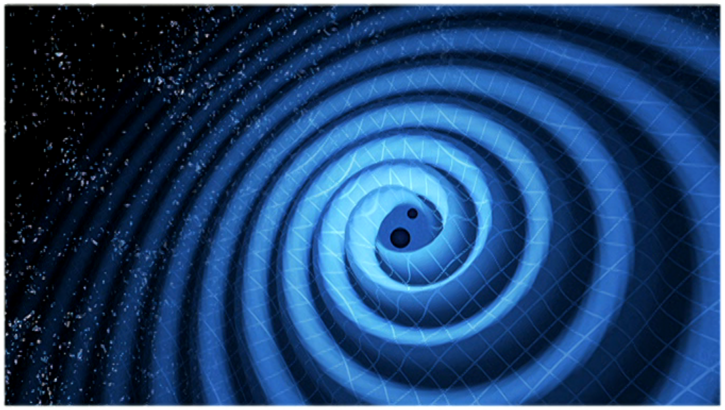
Work done in collaboration with Cole Miller (UMD), Tod Strohmayer (GSFC) and Jordan Camp (GSFC)
arXiv: 1906.09647, accepted in ApJL

Colloquium, Perimeter Institute, October 2 2019

Gravitational waves - the minimum



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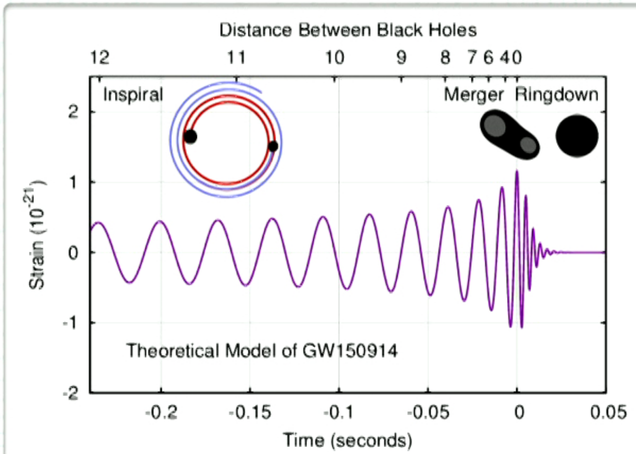
Compact binary coalescences

3 stages of the GW signal:



http://ccrg.rit.edu/GW150914

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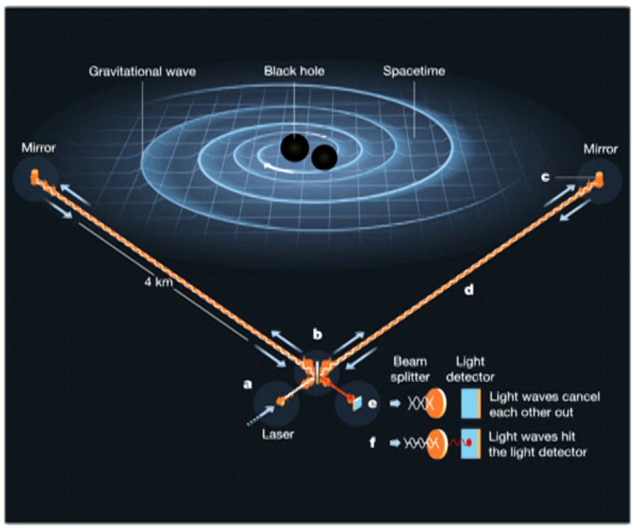
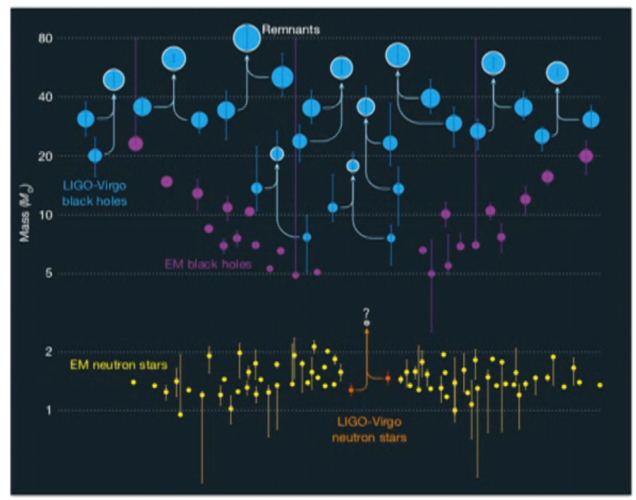
Gravitational waves - and data!

* I know this is the Perimeter Institute for **Theoretical Physics**, but… we finally have **lots** of GW data!





[Miller & Yunes, 2019]

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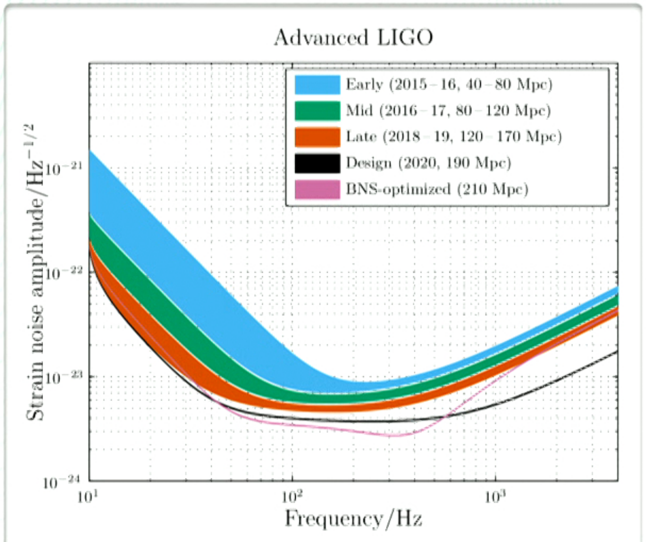
Gravitational wave detectors - and frequencies

Virgo site, 2006



[Abbott et al., 2018]

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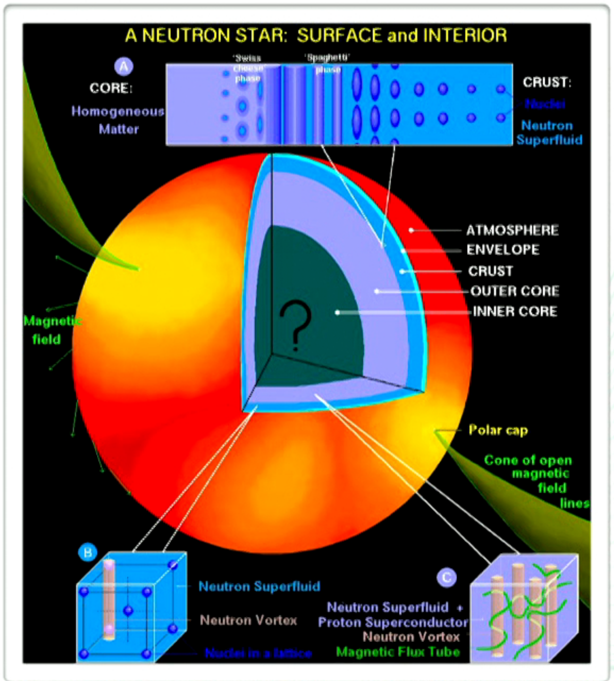
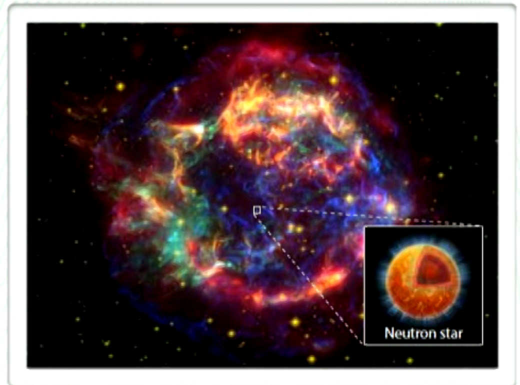
Neutron stars - the minimum

Equation of state (EOS)?



http://www.astroscu.unam.mx/neutrones/NS-picture/NStar/NStar-I.gif



Possible end state of a massive star

Hint: black holes are much simpler than neutron stars!

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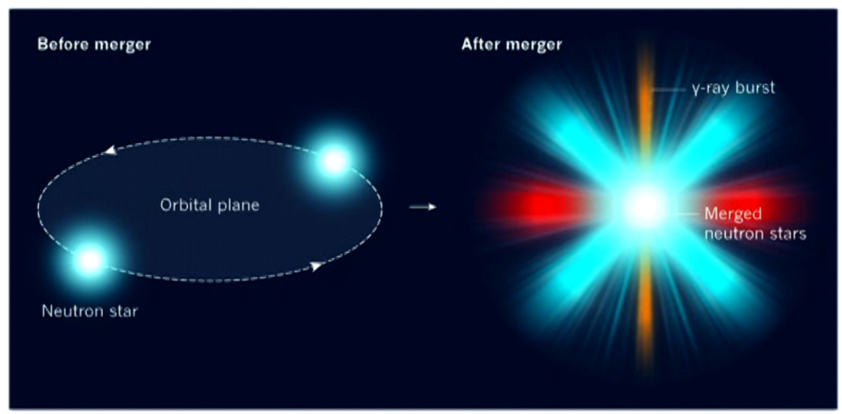
Binary neutron star mergers and Multimessenger Astronomy

* GW170817 and the birth of multi messenger astronomy!
* Just how lucky were we with GW170817?
* Reasons to expect more and even better data in O3
* What else can we aim to learn in the future?



[Miller, 2017]

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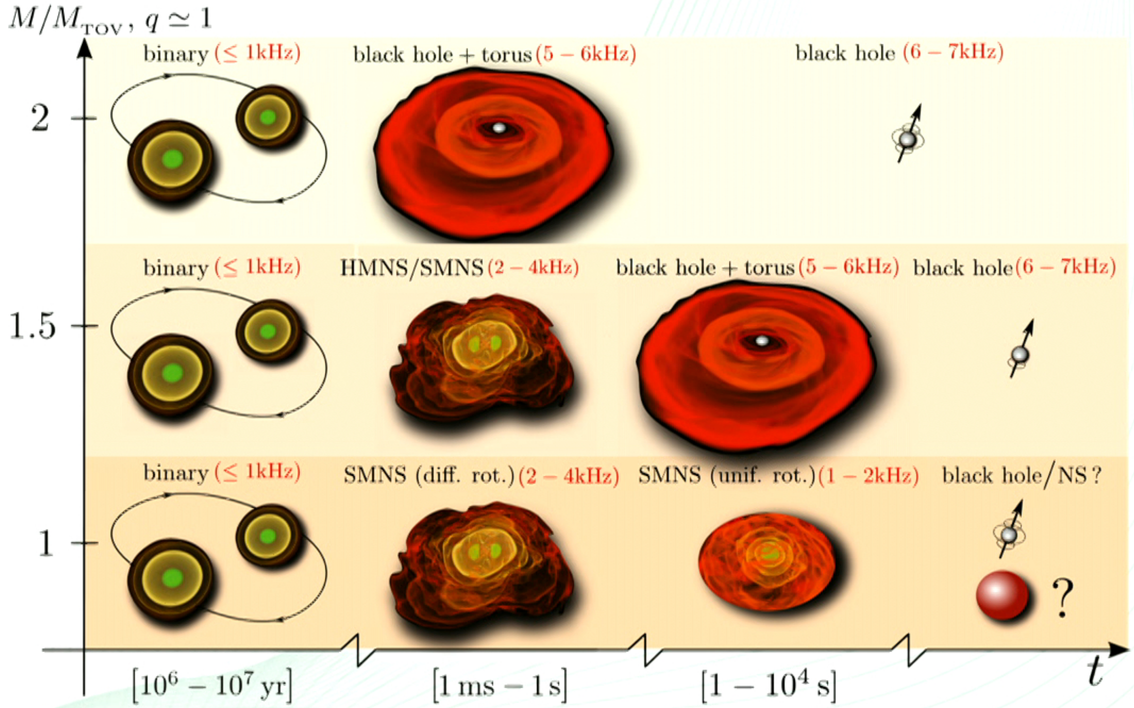
Numerical relativity simulations: Hyper Massive Neutron Star (HMNS)



[Baiotti & Rezzolla, 2017]

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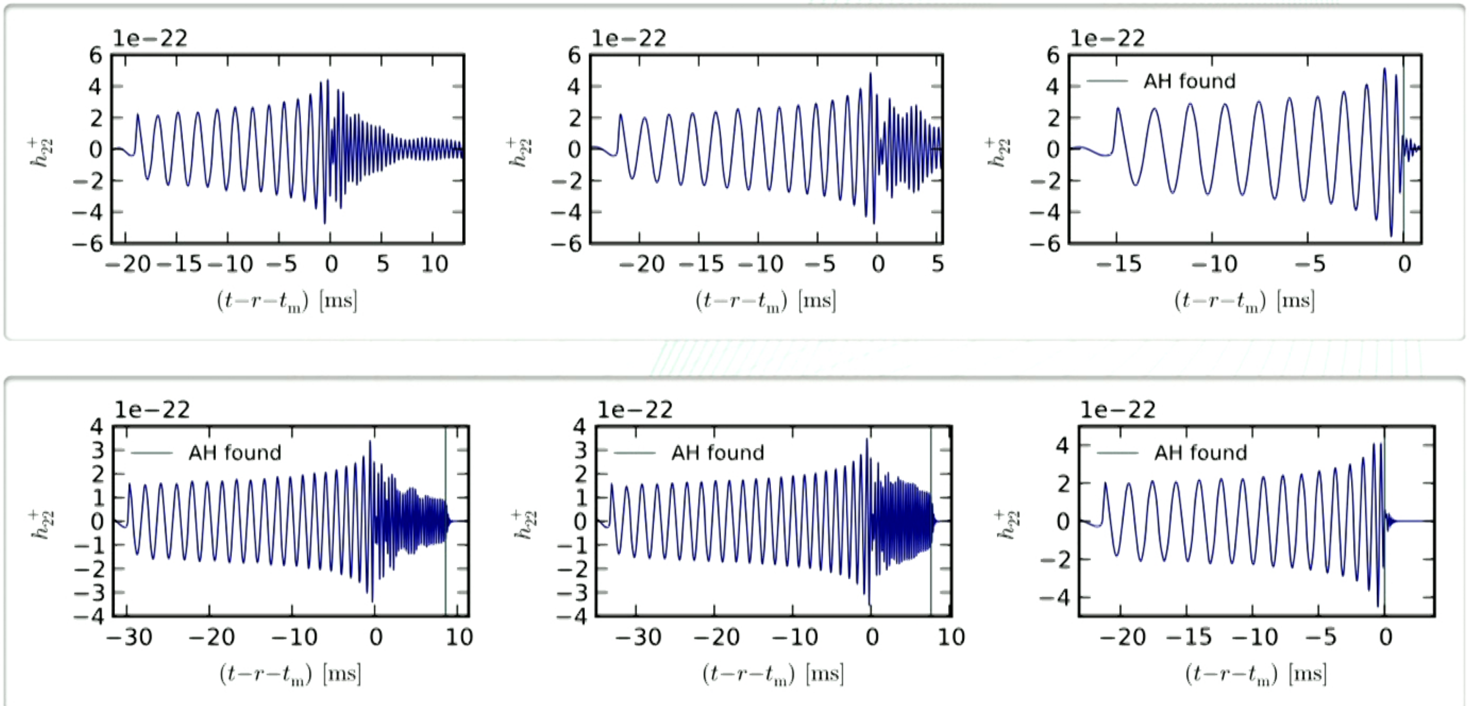
Gravitational wave signature of a HMNS (ringdown)



[W. Kastaun & F. Galeazzi, 2015]

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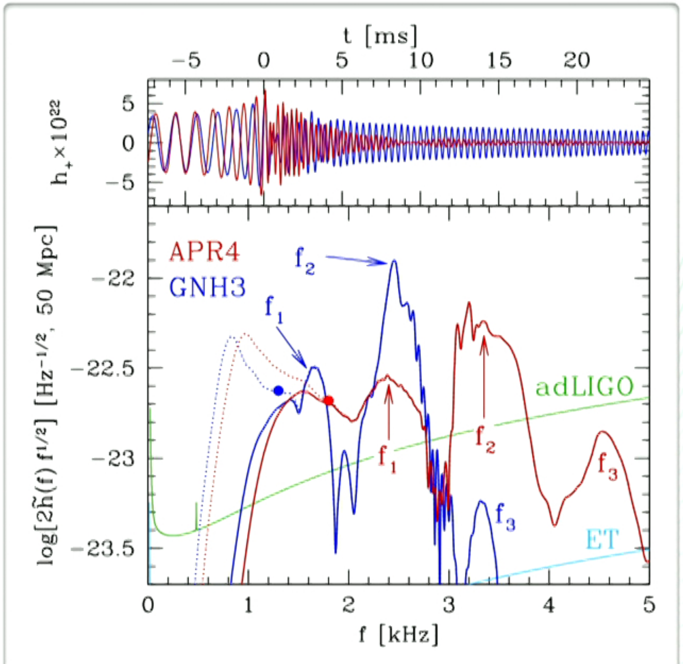
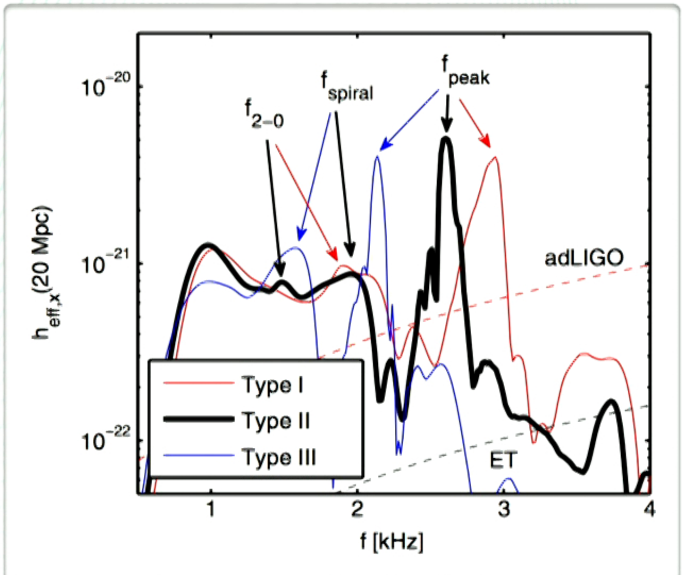
HMNS spectroscopy?



[Takami, Rezzolla & Baiotti, 2014]



[Bauswein & Stergioulas, 2015]

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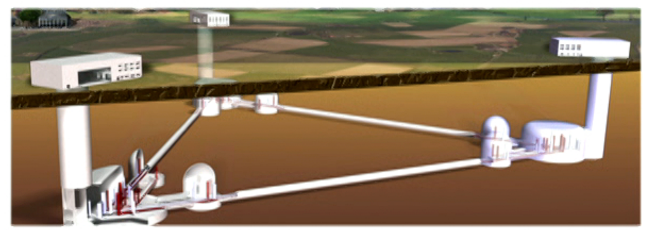
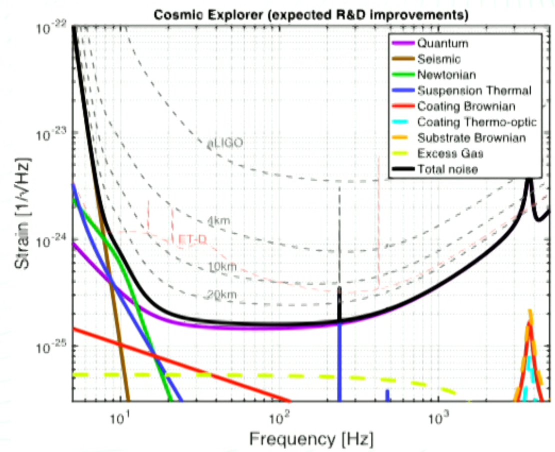
How can we see the HMNS?

* In gravitational waves:
    * with LIGO, only if we are very, very lucky
    * probably with ET/CE, but that will take some time
* What about the EM signal...?





[Abbott et al., 2017]

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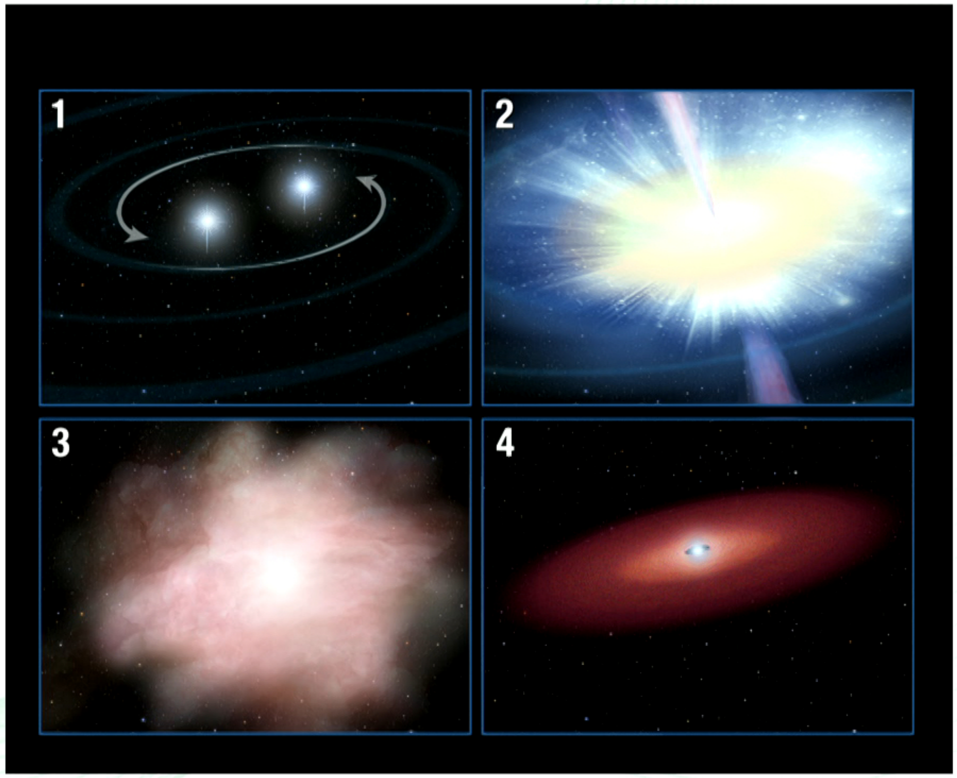
Electromagnetic counterpart of a BNS merger

Inspiral

Short gamma-ray burst



Kilonova

Remnant + disk

[NASA, ESA, and A. Feild (STScI)]

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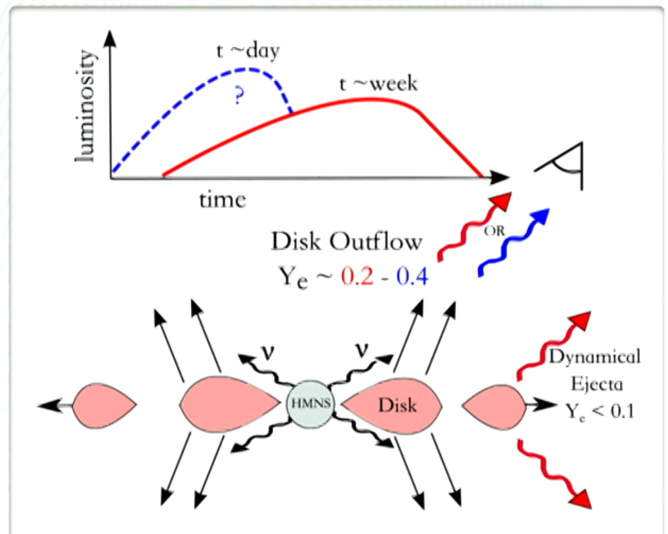
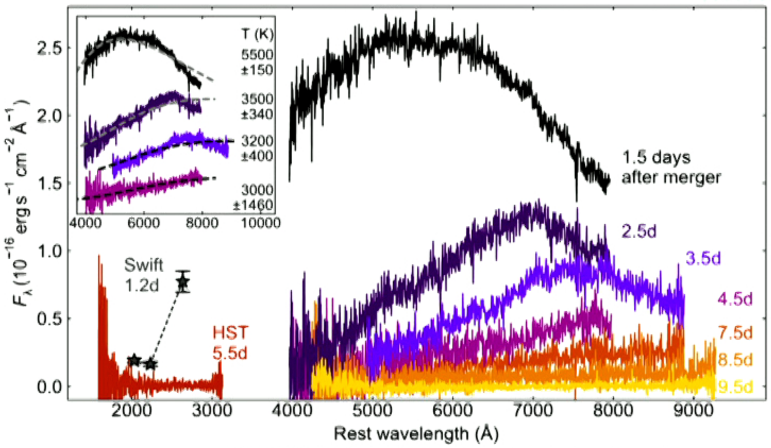
Kilonova models and observational evidence for a HMNS phase

Kilonova model



[Metzger & Fernández, 2014]

Real data from GW170817



[Nicholl et al., 2017]

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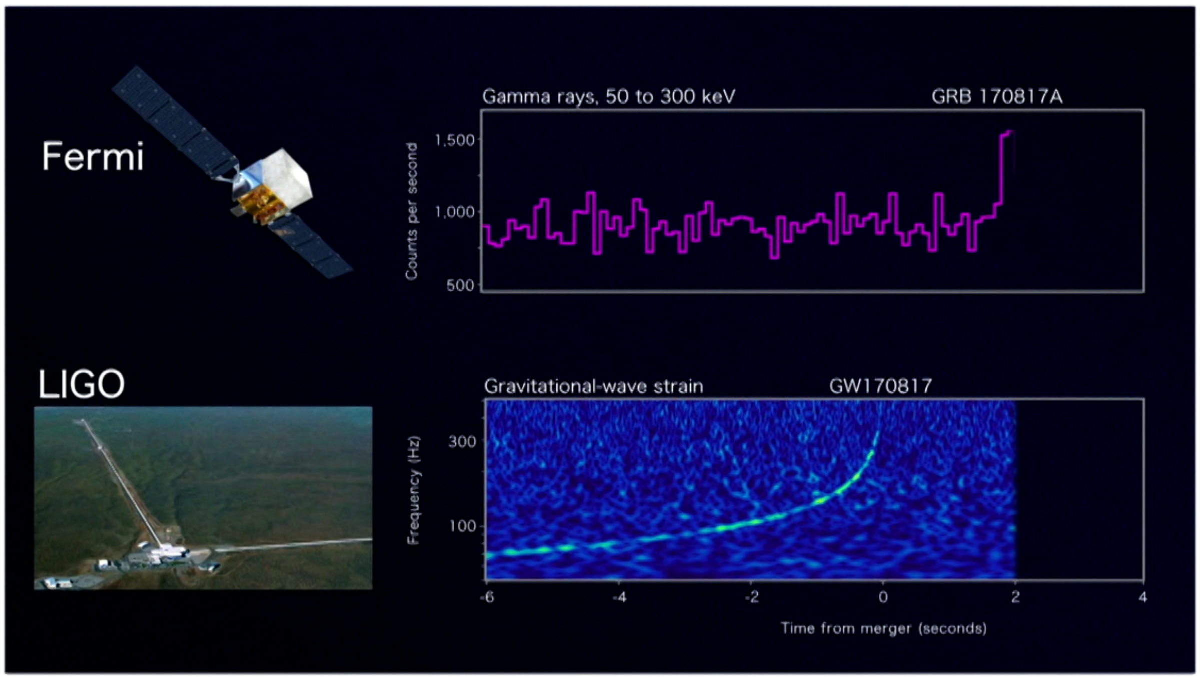
(Very) early EM counterpart: GRB 170817A



LIGO

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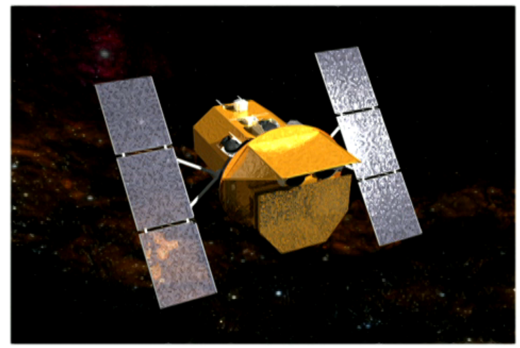
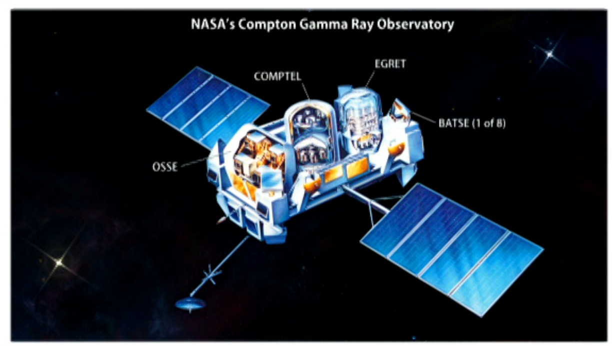
Gamma-ray observatories: past and current

Swift



Fermi

BATSE



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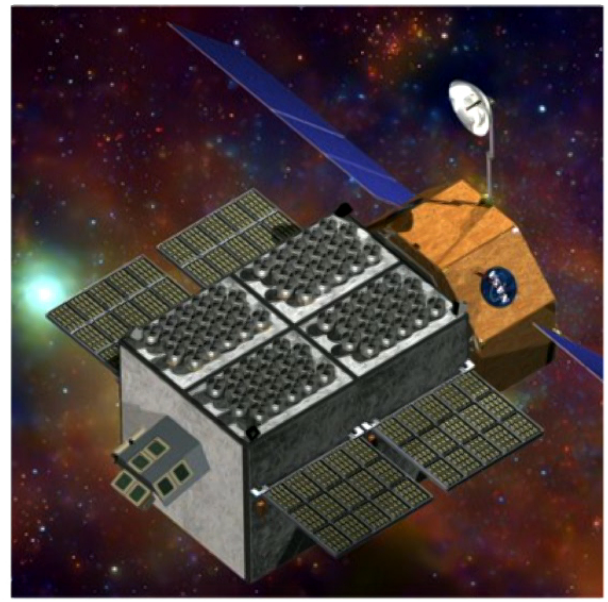
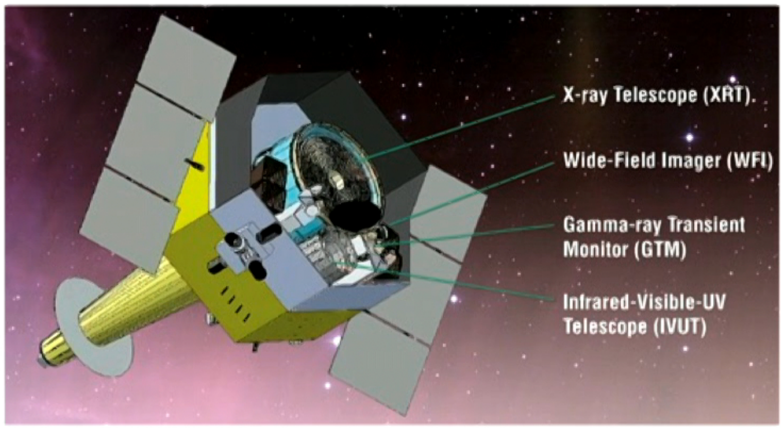
Gamma-ray observatories: future

STROBE-X





TAP

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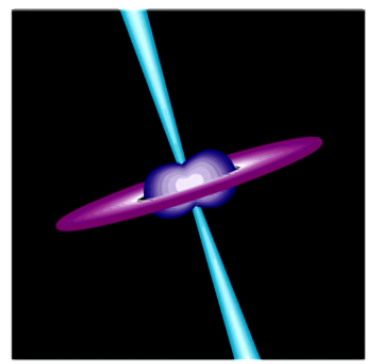
Two possible models for the SGRB engine

* The merger remnant collapsed to a rotating black hole with a surrounding disk that powered the SGRB [Shibata et al., 2006]

* The merger formed a rapidly rotating, strongly magnetized NS (millisecond magnetar) with an accretion disk [Metzger et al., 2008]

* Can we see the HMNS as modulation of the short GRB?



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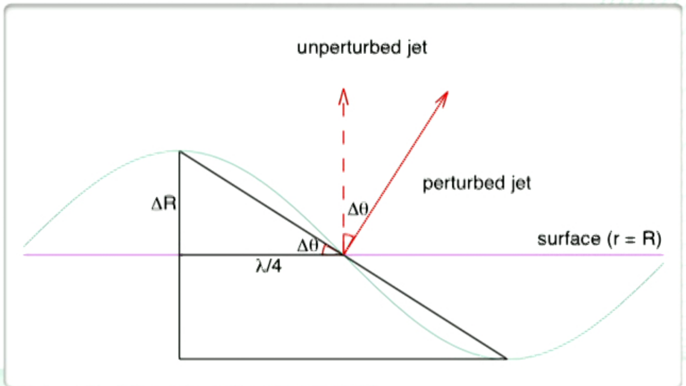
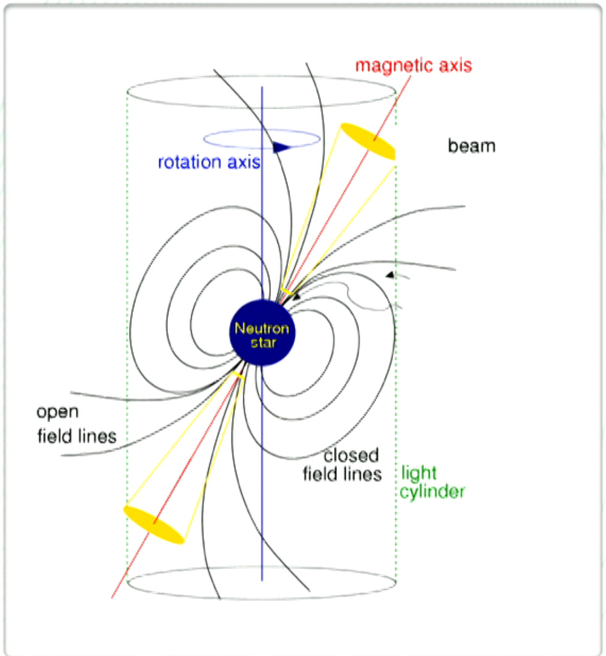
Model for the modulation of the SGRB: How does it work?

* surface oscillations can produce a deviation of the beam direction [Strohmayer, 1992]

* Question: is it detectable?





adapted from Lorimer & Kramer, 2004

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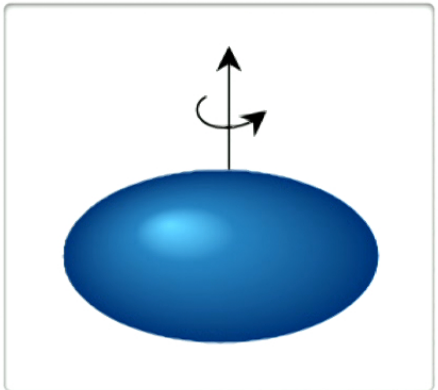
Understanding the GW signal of the HMNS

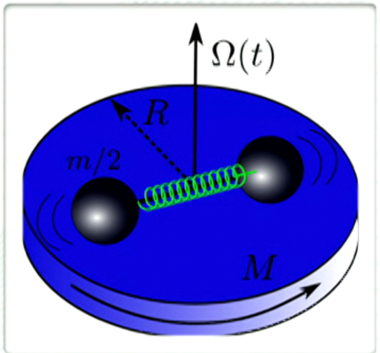
Spinning, highly deformed HMNS



COMPSTAR

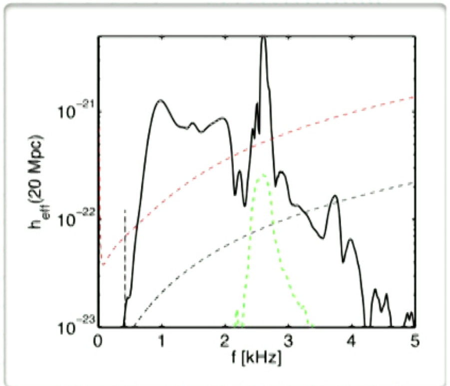
?

A toy model



[Takami, Rezzolla & Baiotti, 2015]

Characteristic oscillations of the HMNS



[Bauswein, Stergioulas & Janka, 2016]

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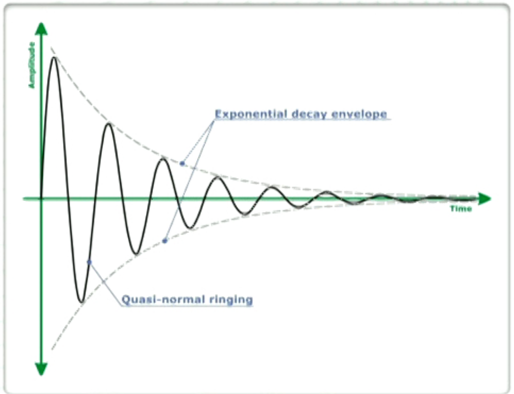
Neutron Star Asteroseismology (Quasinormal mode frequencies)

* 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



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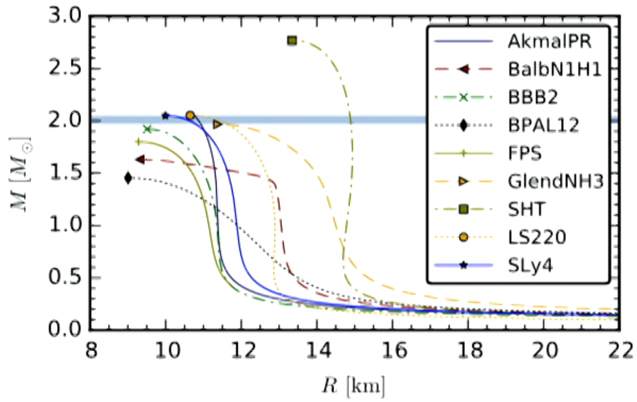
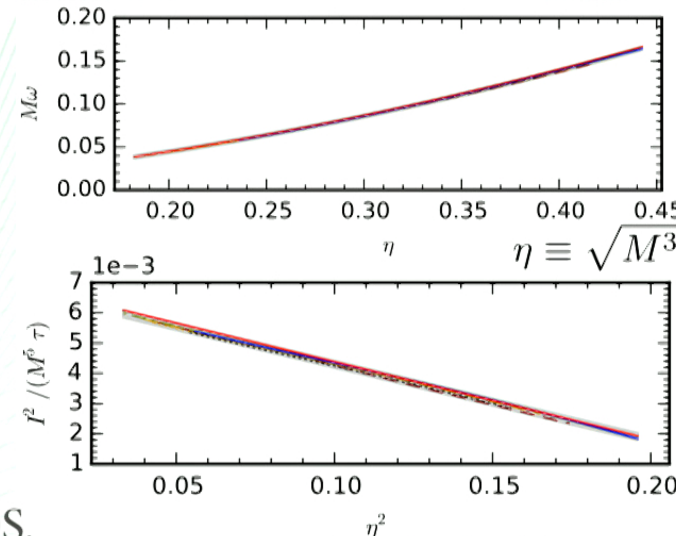
What can we learn? Example:
Universal relations and the inverse problem



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

For cold isolated neutron stars:



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

[Chirenti, de Sousa & Kastaun, 2015]

For HMNS: information on the hot EOS, complementary to constraints from tidal deformability!

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Order of magnitude estimate of the detectability of the modulation

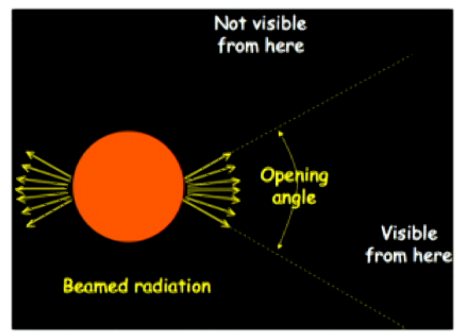
* HMNS surface displacement:

$$h \approx 4 \times 10^{-23} \epsilon (P/1\,\mathrm{ms})^{-2} (100\,\mathrm{Mpc}/r) \Rightarrow \epsilon \approx 8.5 \times 10^{-3} \Rightarrow \Delta R \approx 120\,\mathrm{m}$$

* SGRB beam deviation

$$\Delta\theta \approx \Delta R/(\lambda/4) \Rightarrow \Delta\theta \approx 7 \times 10^{-3}$$

* SGRB jet width



adapted from http://astronomy.swin.edu.au/cosmos/

Jet opening angle $\theta_j \approx 0.02 - 0.14$

Relativistic beaming $\theta_b \approx 1/\gamma \approx 10^{-3} - 10^{-2}$

[Jin et al. 2018]

Resulting estimated flux variation up to $\approx \Delta\theta/\theta_j \sim 0.4$

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Order of magnitude estimate of the detectability of the modulation

* Fluctuation in the photon counts

$$n = F_{\mathrm{SGRB}} \times \Delta T_{\mathrm{HMNS}} \times A_{\mathrm{det}} / E_{\mathrm{peak}}^{\mathrm{obs}} \approx 1230$$

statistical variation: $\sqrt{n}/n \approx 3\%$

* Statistical significance for a fractional variation $a_{\mathrm{osc}} = 0.25$

$$n_\sigma = \frac{1}{2} I a_{\mathrm{osc}}^2 \sqrt{\frac{\Delta T}{\Delta f}} \approx 7$$

(values estimated for Swift)

$F_{\mathrm{SGRB}} \approx 5 \times 10^6\,\mathrm{erg\,cm^{-2}\,s^{-1}}$

$E_{\mathrm{peak}}^{\mathrm{obs}} \approx 350\,\mathrm{keV}$

$\Delta T_{\mathrm{HMNS}} \approx 0.1\,\mathrm{s}$

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Prospects for (past?) detection in the EM counterpart signal

* Coincident detections with GW events are obvious candidates!

* Future instruments like TAP and Strobe-X will help even more

* But existing data from Fermi GBM, Swift BAT and BATSE can also be used to look for this signal

* Then why haven't we seen it yet? [Dichiara, Guidorzi & Frontera, 2013]

Because it's not easy! And we'll need at least a model for the frequencies and their evolution...

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What are the difficulties for the detection and what to do about them

* More than one mode present
* Quasi-periodic oscillations, not periodic oscillations
* Need (close to) EOS-independent relations for the frequencies and their dependence on the spin-down
* Exploring the parameter space with NR is expensive!
* One solution: work with a semi-analytical model in the linear perturbation regime (work in progress!)

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Conclusions and Outlook

* Possibility of looking for the signal in existing data; could reinforce (or not) NS-NS mergers as progenitors of most SGRBs
* Information on the structure and composition of the HMNS (hot EOS) and on the initial masses of the binary
* Detailed calculation of the frequencies and their evolution is needed
* Future work: linear calculations are inexpensive and allow a thorough exploration of the parameter space

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