Neutron stars as sources for third generation gravitational wave detectors

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Based on Andersson, Ferrari, DIJ, Kokkotas, Krishnan, Read, Rezzolla & Zink, arXiv:0912.0384

Compact objects & ET

Two sorts of justification for ET:

1. To see source at all
2. To see source better (i.e. see detailed emission and/or build statistics)

Will examine these issues for three sorts of source:

- Binary inspiral
- Supernova core collapse
- Rotating neutron stars

The rich physics of compact objects

Compact objects are sensitive to all aspects of the equation of state, including:

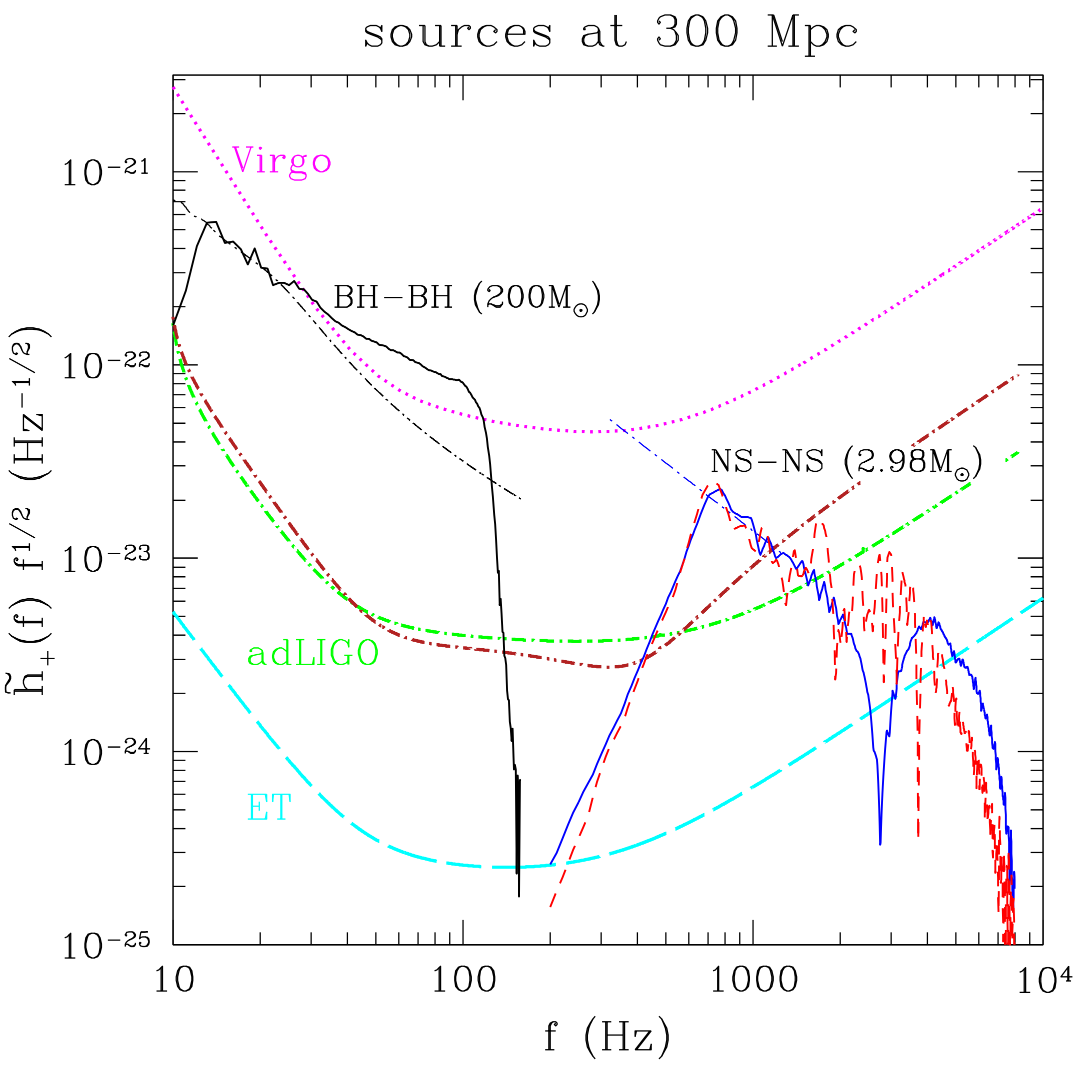
- Crustal compressibility, shear modulus, and breaking strain
- Thermal and electrical conductivities
- Fluid bulk and shear viscosity
- Presence of condensates, including neutron superfluidity and proton superconductivity
- Strength and geometry of magnetic field
- Presence of exotic phases at high density

Binary inspiral: rate estimates

- NS-NS event rate estimated to lie in range 10^{-4} to 10^{-5} events per typical galaxy per year.
- Correspond estimated detection rates (Kopparapu et al 2008, Papa 2008):

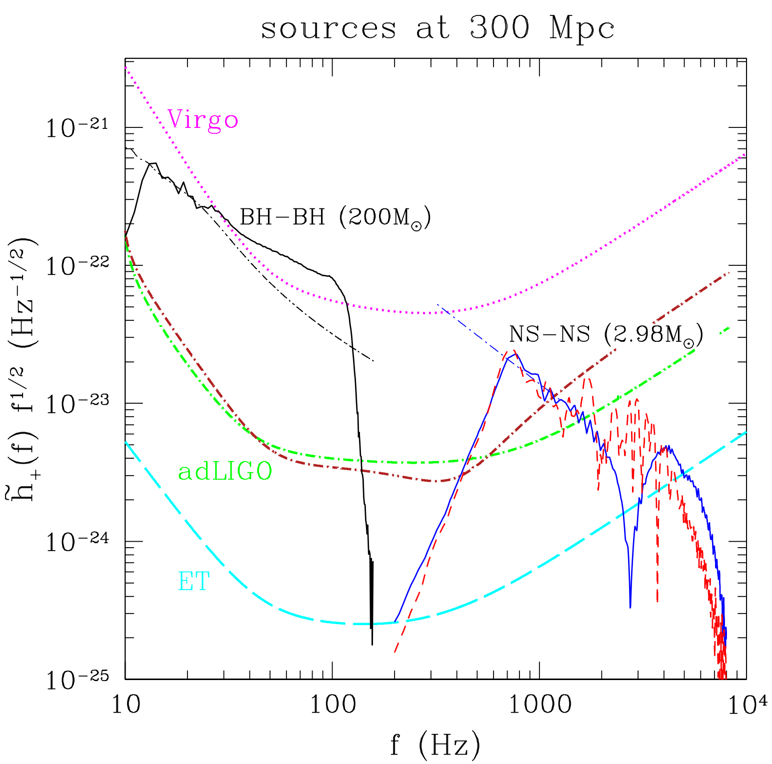
detector	d_h	event rate
LIGO S5	30 Mpc	1 event per 25-400 yrs
Advanced LIGO/Virgo	300 Mpc	Several to hundreds of events per year
ET	3 Gpc	Tens to thousands of events per year

Binary inspiral: importance of equation of state

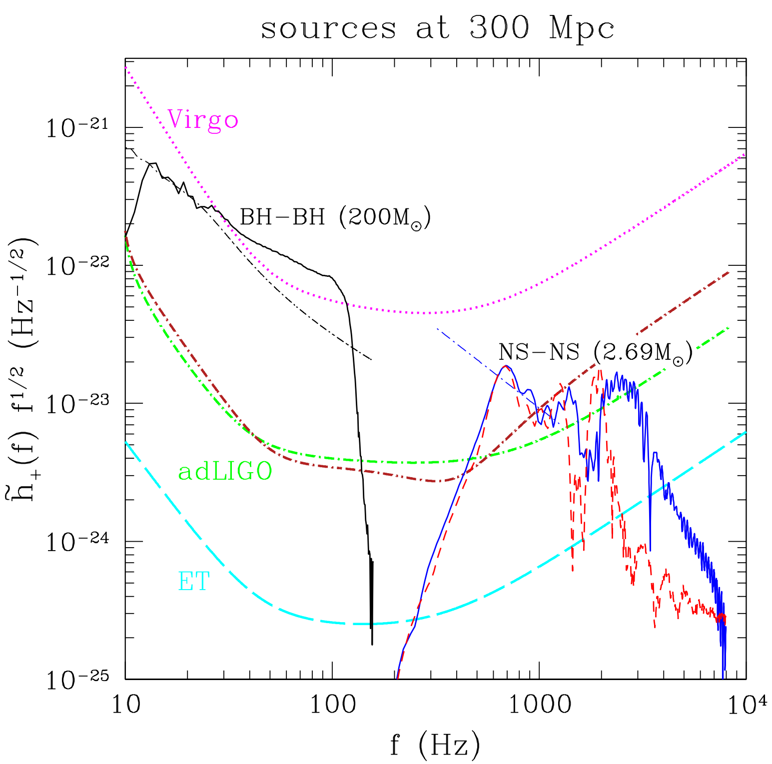


Blue = ‘cold’ EoS, Red = ‘hot’ EoS

Binary inspiral: importance of total mass



High mass binary



Low mass binary

Blue = ‘cold’ EoS, Red = ‘hot’ EoS

Supernovae: important issues

- Event rate of order few per century per typical galaxy
- Detection rate less clear
- Key issues include:
  - Angular momentum profile in pre-collapse star
  - Numerical difficulties:
    - Large ranges in density and length scales
    - Need for radiation/neutrino transport

Supernovae: explosion mechanisms & GWs

Despite these difficulties, several distinct explosion mechanisms identified:

- Neutrino mechanism
- Magneto-rotational mechanism
- Acoustic mechanism

The different mechanisms may have different GW signatures (Ott 2009)

Supernovae: detection

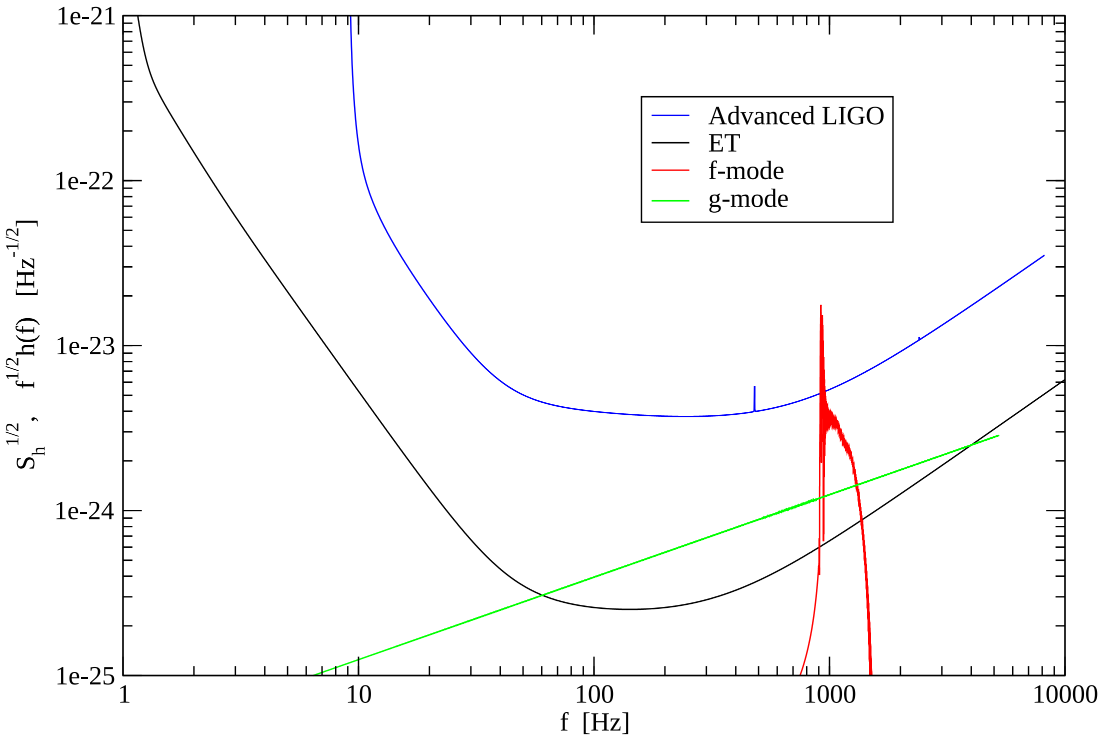
- Galactic supernova detectable by Advanced LIGO/Virgo.
- But event rate low; need to look beyond Galaxy.
- Detection rate of few per year would require sensitivity over 3-5 Mpc distance.
- Numerical simulations suggest this may be too far for Advanced LIGO/Virgo; ET may be required.

Supernovae: proto-neutron stars

- Proto-neutron star is hot puffed-up (20-30 km) object
- Exists for few tens of seconds before cooling & shrinking to regular NS
- Too long-lived for full 3-d numerical treatment.
- Perturbaive methods needed instead
- Modelling shows that f- and g-modes could be important...

Supernovae: proto-neutron stars

- e.g. for star at 10 kpc, a signal-to-noise ratio of 8 requires $\Delta E_f = 2 \times 10^{-12} M_\odot$ or $\Delta E_g = 3 \times 10^{-11} M_\odot$:



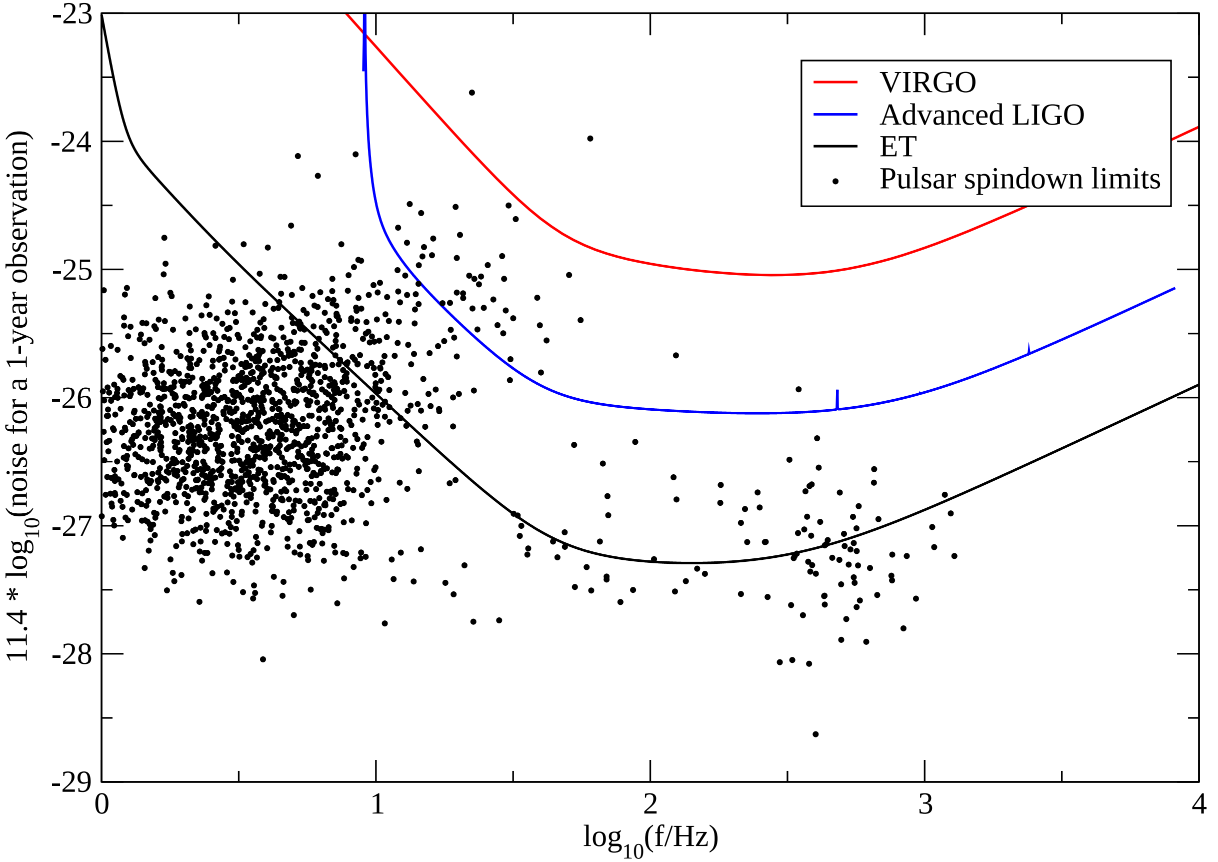
Rotating stars: GW mechanisms

Two main GW mechanisms:

1. ‘Mountains’; deformations supported by elastic and/or magnetic stresses
2. Modes; may be excited in pulsar glitches or magnetar flares, or may be driven unstable in rapidly rotating stars

Rotating stars: mountains

Can derive upper bound on GW emission from known pulsars assuming 100% conversion of kinetic energy into GWs:

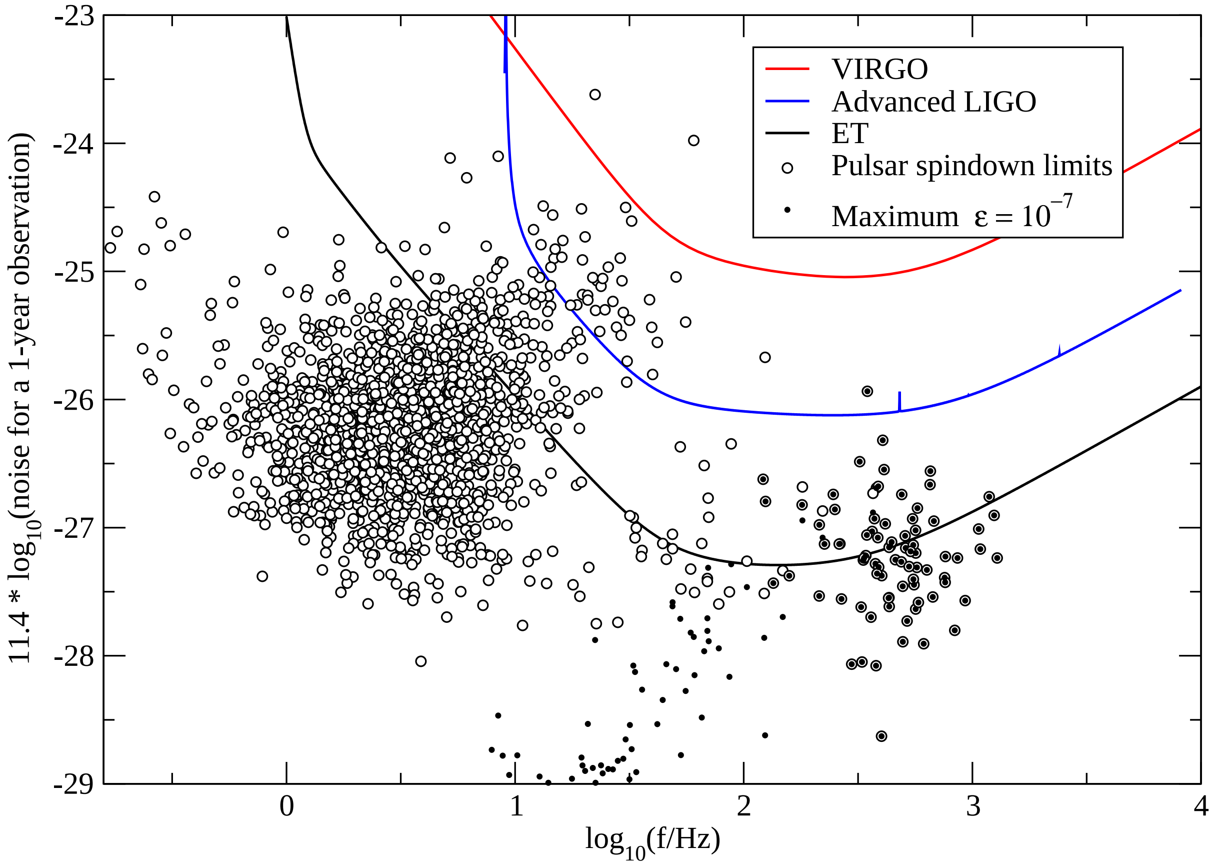


Rotating stars: mountains

- This makes dangerous assumption: assumes stars capable of supporting necessary asymmetries
- In practice, finite crustal shear modulus, breaking strain, and magentic field srength limit mountain size
- In any case, direct observation has limited Crab emission to less than 1/7 of spin-down limit (Abbott et al 2009)

Rotating stars: mountains

More sensible plot limits maximum deformation, e.g. for $\epsilon_{\max} = 10^{-7}$:



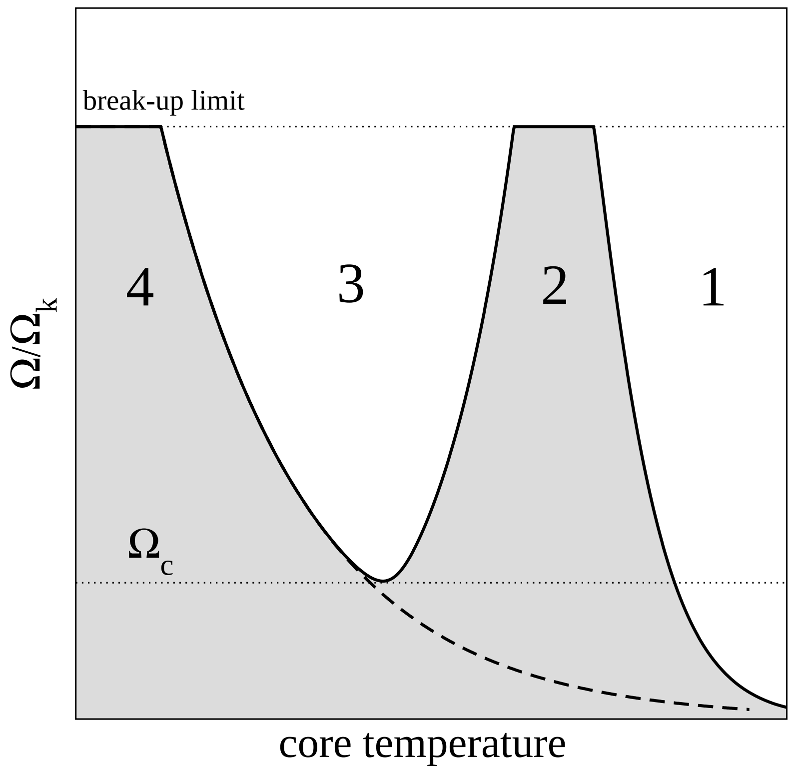
Also, pinned superfluid may add harmonic structure (DIJ 2010)

Rotating stars: modes

- Compact objects have a rich zoo of modes:
- Can go unstable to gravitational radiation reaction in sufficiently rotating stars
- Depends upon competition with stabilising dissipative processes, e.g. shear and bulk viscosity

Rotating stars: modes

Can draw stability curves in Ω–T plane. Schematically:



Rotating stars: modes

Outstanding theoretical issues include:

- Role of superfluidity/superconductivity
- Development of instability in non-linear regime
- Role of exotic phases in core on bulk viscosity
- How to make the data analysis tractable

Summary

- Binary inspiral
  - 2G likely fine for detection, but unique EoS information buried in high frequency merger phase which may require 3G
- Supernovae
  - 2G fine for Galaxy, but low event rate means 3G may be needed for detection
  - High quality GW observation may reveal explosion mechanism
  - Galactic ET observations of a proto-neutron star could give very clean EoS information
- Rotating stars:
  - Mountains: upper limits reasonably well understood (but EoS dependent), but realistic sizes not
  - Modes: key ingredients identified, but more modelling required to assess detectability

Conclusion

Main point for ET:

In many cases, high quality observation can reveal important signal structure not necessarily visible in initial detection.

$\Rightarrow$ role for ET regardless of findings of 2G detectors.