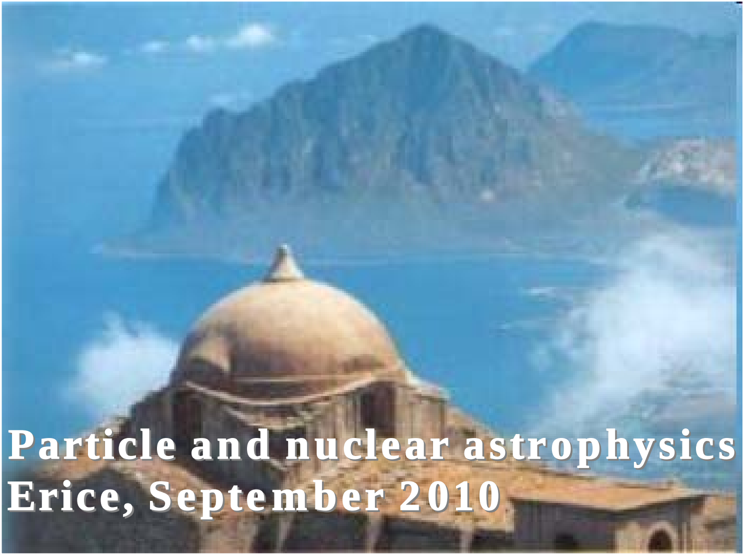
Gravitational-wave Astronomy

Promises and challenges



Particle and nuclear astrophysics
Erice, September 2010

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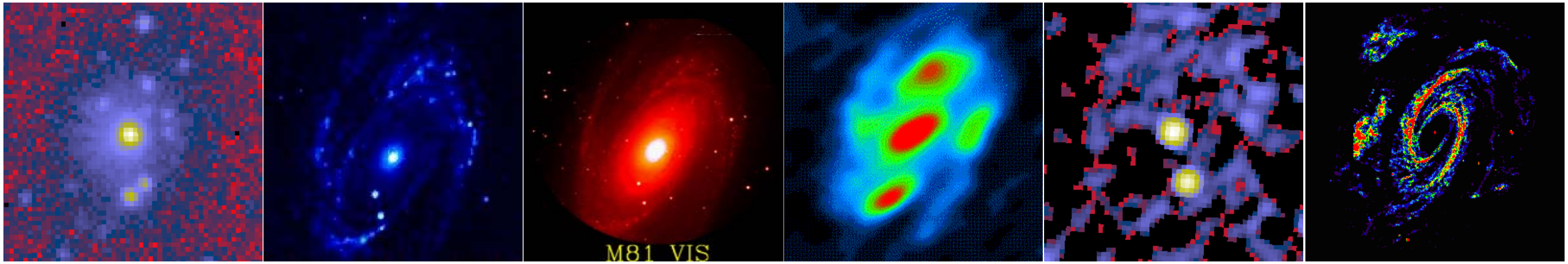
the dark side

There are many different ways to view the Universe (here the galaxy M81):

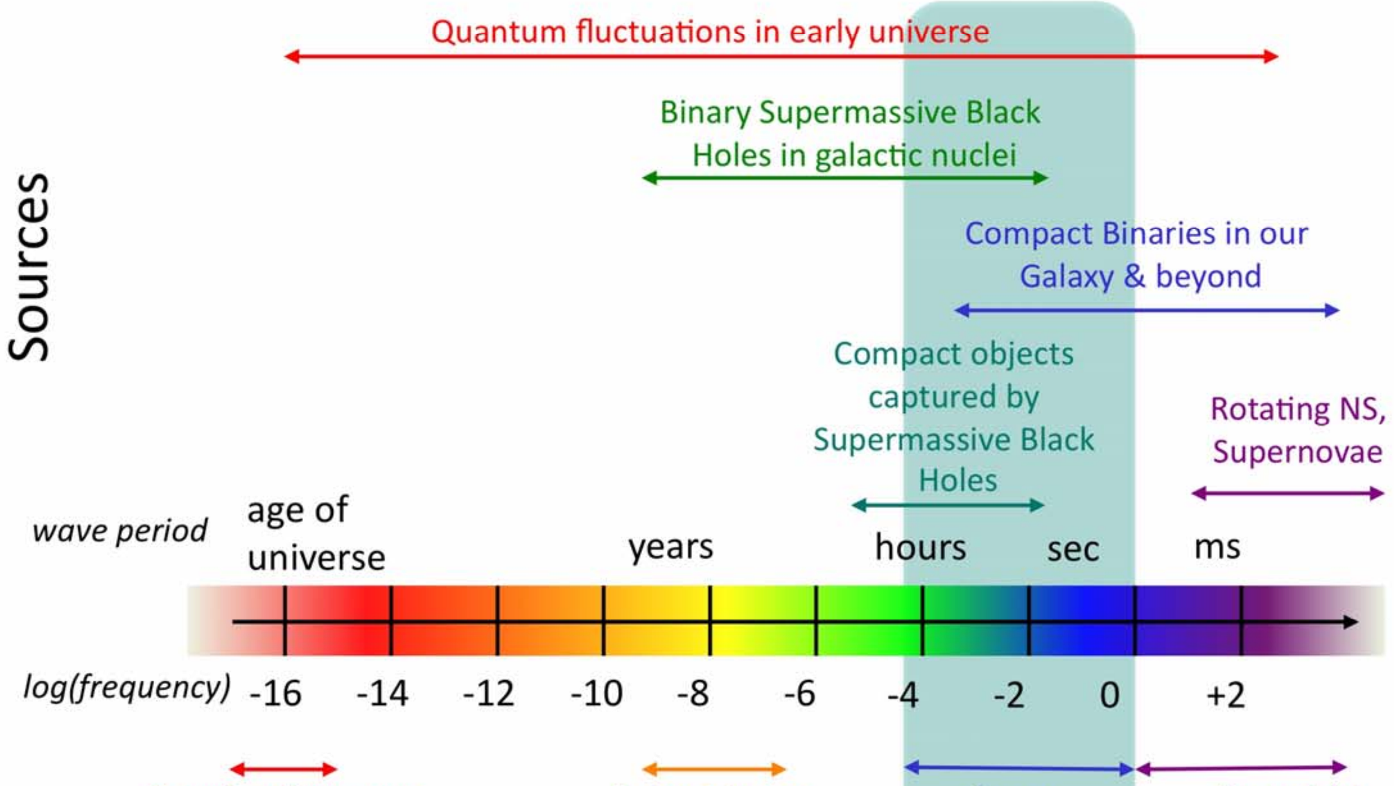


X-ray: 10 nm | UV: 200 nm | Optical: 600 nm | Infrared: 100 mm | Radio: 21cm | Radio – HI filter

So far our information is based on electromagnetic waves at different wavelengths. GWs provide **complementary** information.

Electromagnetic waves	**Gravitational waves**
From individual particles	From bulk motion of matter
Scattered many times since generation	Couple weakly to matter, arrive in pristine condition
Imaging small fields of view	Detectors cover the entire sky
Wavelength smaller than source	Wavelength larger than source (no “imaging”)

The Gravitational Wave Spectrum



Sources

Quantum fluctuations in early universe

Binary Supermassive Black Holes in galactic nuclei

Compact Binaries in our Galaxy & beyond

Compact objects captured by Supermassive Black Holes

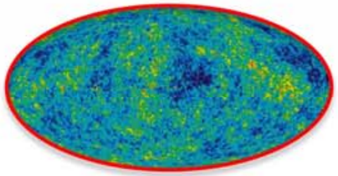
Rotating NS, Supernovae

wave period age of universe | years | hours | sec | ms

log(frequency) -16 | -14 | -12 | -10 | -8 | -6 | -4 | -2 | 0 | +2

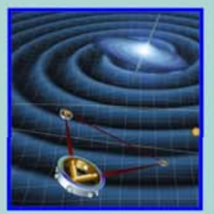
Detectors

Cosmic microwave background polarization



Pulsar Timing

Space Interferometers



Terrestrial interferometers

promises

GW astronomy has the potential to revolutionize our understanding of the Universe.

– Observations should prove the existence of black holes (verifying Einstein's theory?), providing insight into the endpoint of stellar evolution.

– GWs from supernovae and gamma-ray bursts provide a unique view of the dynamics of gravitational collapse (complementary to neutrino and gamma-ray signals).

– NS signals provide information about poorly understood fundamental physics like the state of matter at extreme densities (complementary to that gleaned from X-ray and radio observations).

– Cosmological sources shed light on galaxy formation, the nature of dark matter and dark energy.

– A stochastic cosmological background would improve our understanding of the very early Universe.

– …

challenges

However… to achieve this we need to overcome a range of challenges, regarding **technology**, **data handling** and **theory modelling**. We need;

– to develop the technology required for the 2nd and 3rd generation of ground-based interferometers and LISA.

– quality signal templates and data analysis strategies for binary inspiral and merger (numerical relativity).

– to develop accurate models for the gravitational radiation reaction for extreme-mass-ratio binaries (spacetime mapping) .

– reliable simulations of supernova core collapse events (more “physics”).

– a quantitative understanding of neutron star dynamics and the different ways that these systems may radiate (mountains/oscillations/instabilities).

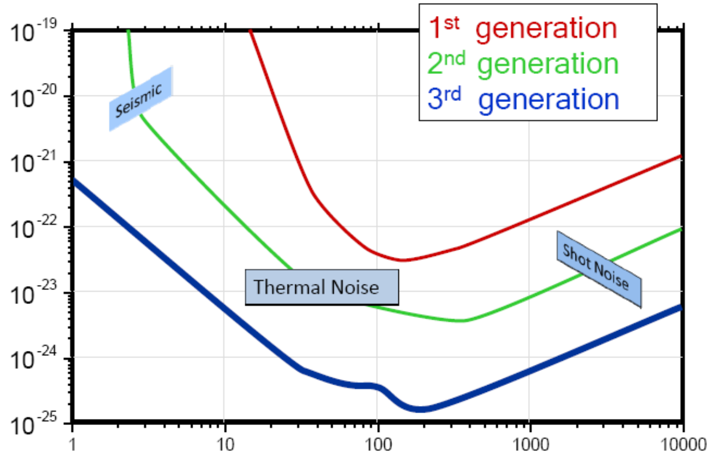
– improved models for cosmological signals (lensing)

– …

the detectors

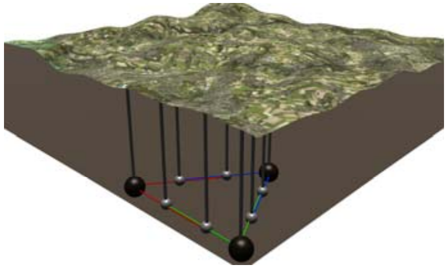
The first generation of large interferometers (LIGO, Virgo, GEO600) have reached design sensitivity.

LIGO collected 1 yr of data in the S5 science run, and is now running in an "enhanced" configuration.



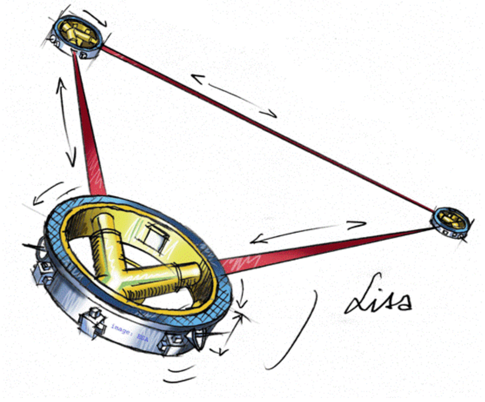
No detections yet!

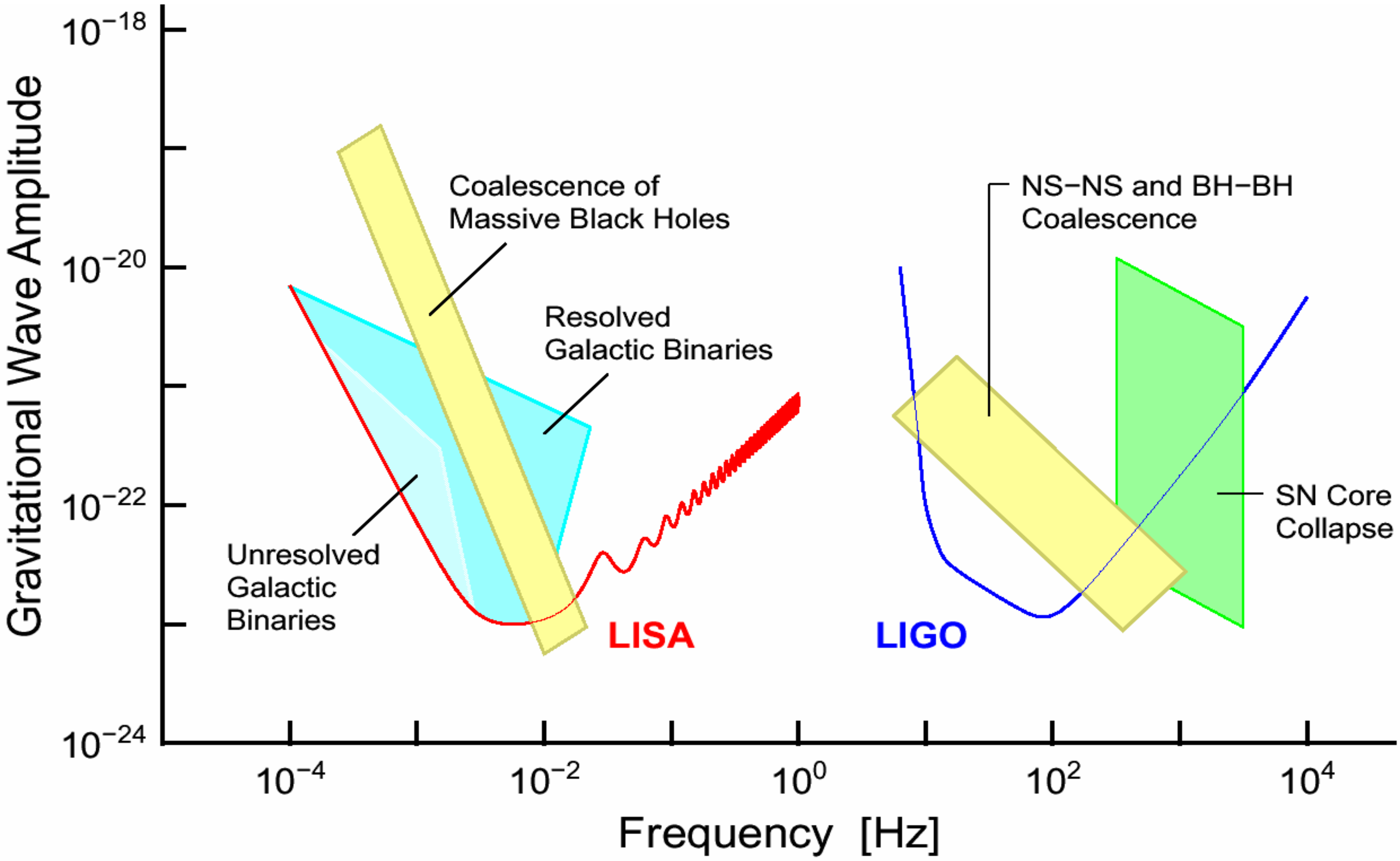
The upgrade to advanced LIGO (around 2015) will improve the sensitivity by a factor of 10.



3rd generation detectors, like the 10 km, cryogenic, Einstein Telescope (ET), should improve the sensitivity by another factor of 10 or so.

The space detector LISA (strongly supported by the US decadal survey) is guaranteed to see galactic binaries, and will study massive BHs throughout the Universe.




Gravitational Wave Amplitude
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
Frequency [Hz]
Coalescence of Massive Black Holes
Resolved Galactic Binaries
Unresolved Galactic Binaries
LISA
LIGO
NS–NS and BH–BH Coalescence
SN Core Collapse

binaries

Binary signals have the advantage that the inspiral chirp is well modelled by post-Newtonian methods. The amplitude is “calibrated” by the two masses and does not depend (much) on “finite size” effects.

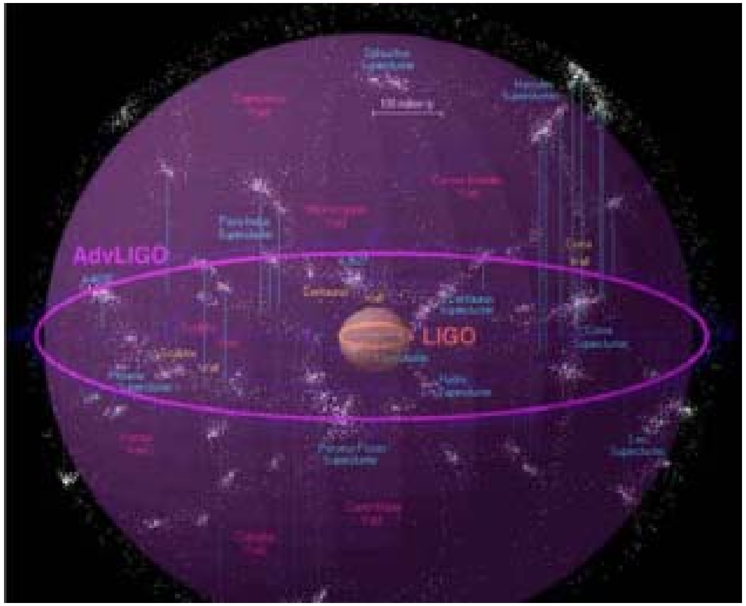
BH binaries may be the most promising, but rates are uncertain (metallicities).

Consider horizon distance d_h;
How far you can see a **neutron star binary** with S/N of 8?

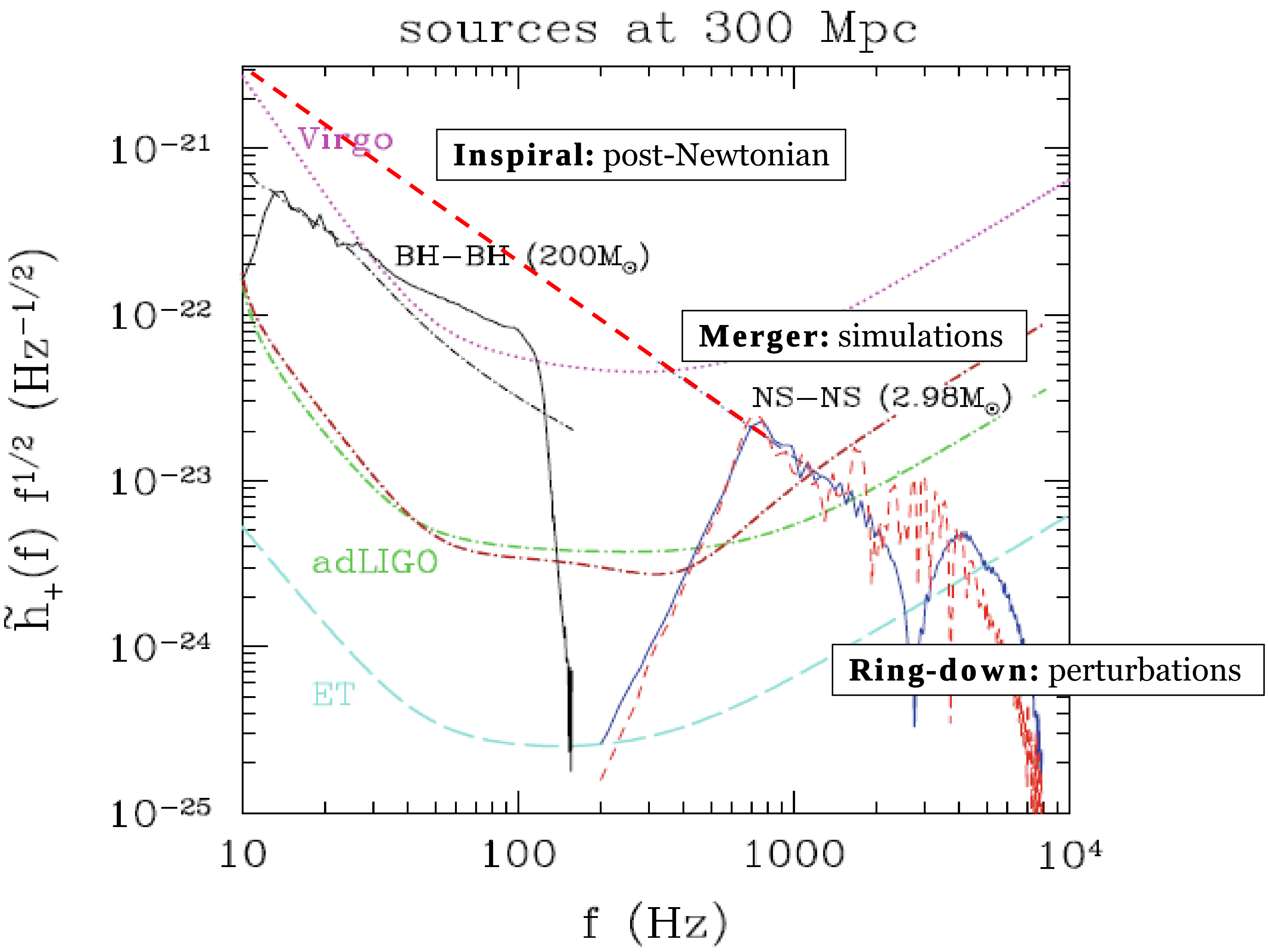
LIGO S5 science run:
d_h=30 Mpc
expect 1 event per 25-400 yrs

AdLIGO: factor of 10 better sensitivity
d_h=300 Mpc
2-40 events per year

ET: another factor of 10 improvement
d_h=3 Gpc
thousands of events per year



AdLigo should see binaries, but we may need ET to study populations.



Inspiral: post-Newtonian

Merger: simulations

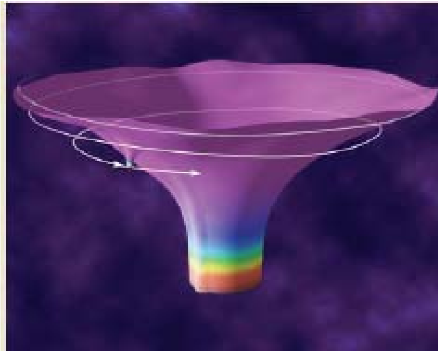
Ring-down: perturbations

supermassive BHs

Gravitational waves from merging massive BH binaries “throughout cosmic time” will be visible with LISA.

Measure masses and spins directly (unprecedented precision).

Probe early Universe, structure formation scenarios and the growth of supermassive BHs.



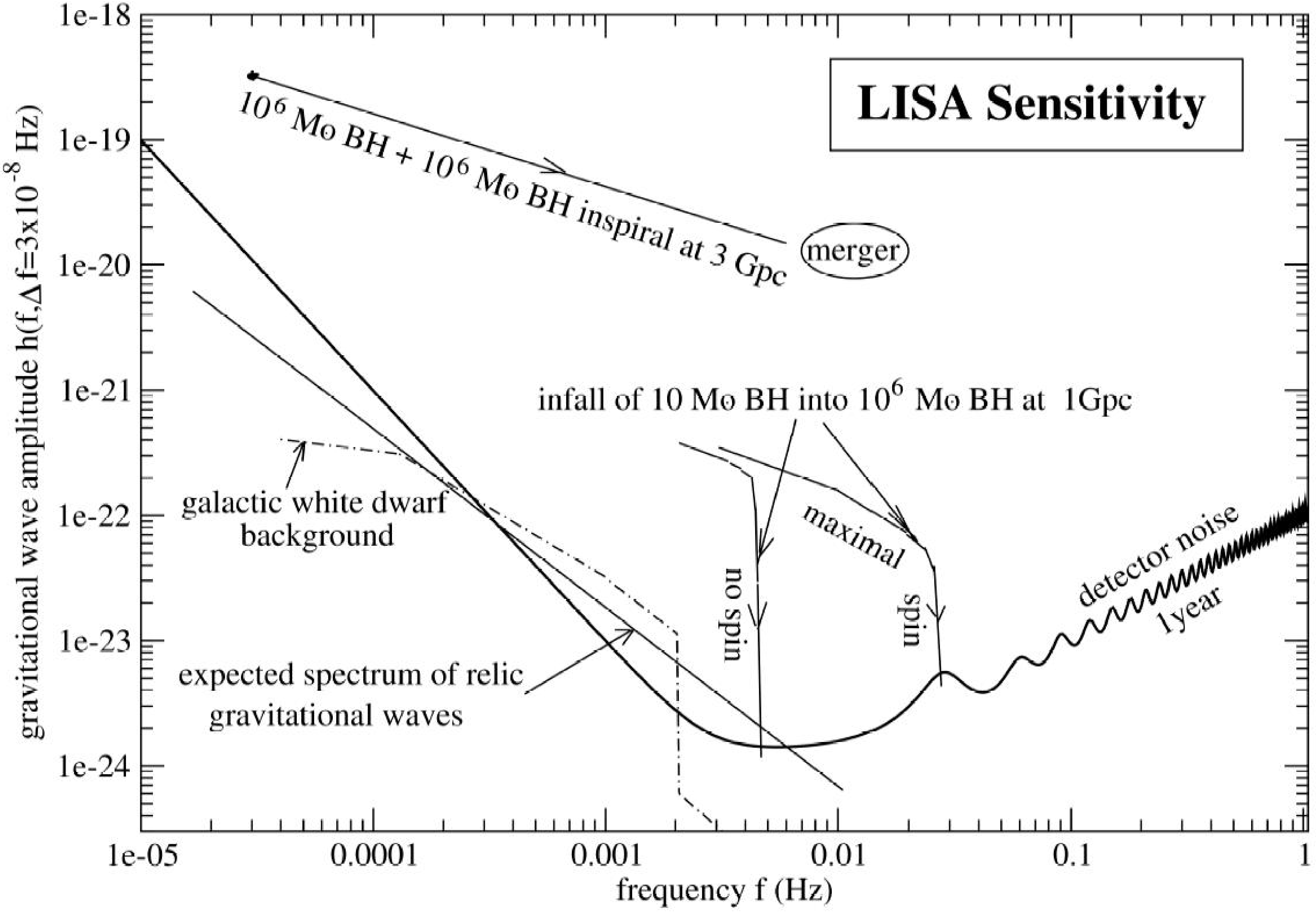
LISA will also detect captures of compact objects by BHs in galaxy cores.

– “Plunge” orbits take 10,000 or more cycles before capture.

– Signal encodes the geometry of spacetime near the large BH. LISA can map this with excellent precision.

– Allows tests of many predictions of General Relativity, including the “no hair” theorem.

– Numerous sources, possible confusion.


LISA Sensitivity
10^6 Mʘ BH + 10^6 Mʘ BH inspiral at 3 Gpc
merger
infall of 10 Mʘ BH into 10^6 Mʘ BH at 1Gpc
maximal
spin
no spin
galactic white dwarf background
expected spectrum of relic gravitational waves
detector noise
1year
gravitational wave amplitude h(f,Δ f=3x10^{-8} Hz)
frequency f (Hz)
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
1e-05
0.0001
0.001
0.01
0.1
1

cosmography

LISA will be able to infer distances to coalescing binary systems (standard "sirens"), providing a **distance scale** of the Universe in a precise, calibration free measurement.

Will be exploited by AdLIGO first (out to 300 Mpc). NS binaries associated with gamma-ray bursts/afterglows may shed light on whether we live in a local void.

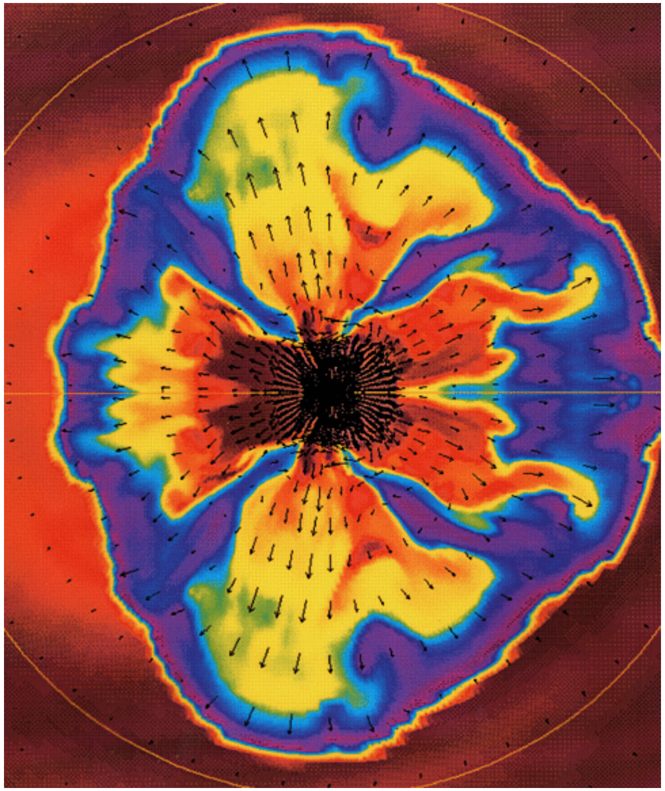
LISA has fantastic sensitivity to massive BH mergers at z=1 and would be able to detect 10^4 M_o systems out to z=20.

If these mergers have an observable electromagnetic counterpart, then we will have redshifts and LISA will measure w and (perhaps) dw/dt.

This makes LISA relevant as a dark energy mission.

neutron star scenarios

Neutron stars are cosmic laboratories of exotic/exciting physics. They are interesting GW sources, and can radiate via a number of mechanisms:



binary inspiral and merger:
the inspiral chirp provides a clean signal carrying information about the system, while the merger phase probes strong field gravity

supernova core collapse:
the birth of a neutron star may lead to a GW burst

“mountains”:
crustal or magnetic field asymmetries lead to GW emission at twice the spin frequency

oscillations/instabilities:
fast spinning neutron stars may suffer both dynamical bar-mode and secular instabilities (r-modes?)

Modelling these mechanisms is far from easy…

“real” neutron stars

A minimal neutron star model requires:

— supranuclear equation of state
(hyperons, quarks etc.)

— superfluids/superconductors
(vortices, fluxtubes)

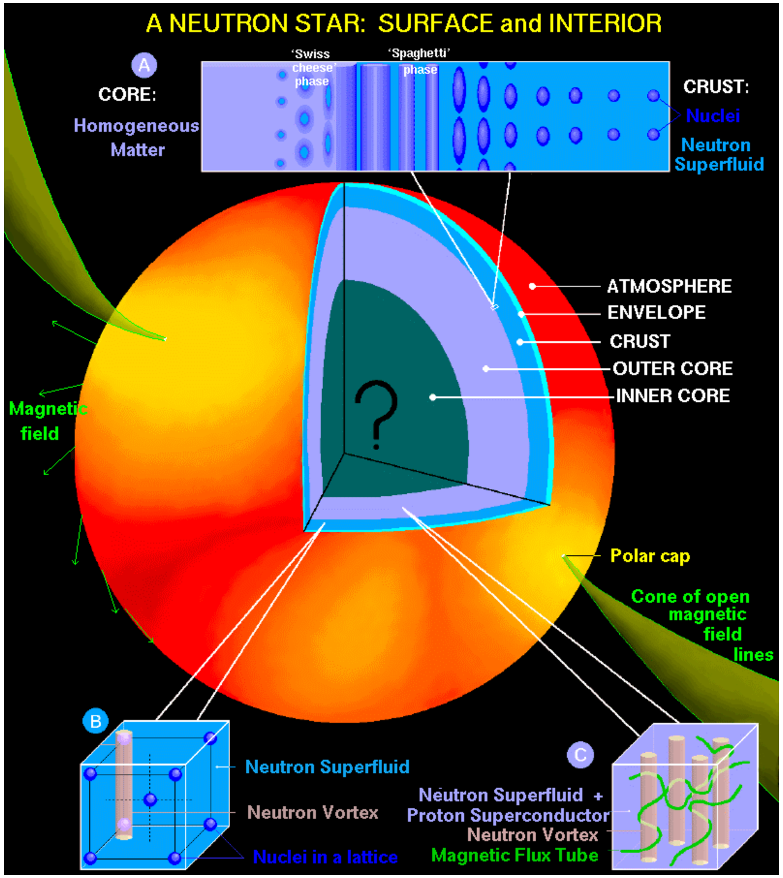
— elastic crust

— temperature profiles
(cooling mechanisms)

— magnetic field
(configuration, currents?)

— rotation (various instabilities)

— general relativity (!)



Much of this physics is “unknown”.

Can we use GW observations to test theoretical models?

core collapse

Simulations suggest that the energy radiated from core collapse supernovae is low.

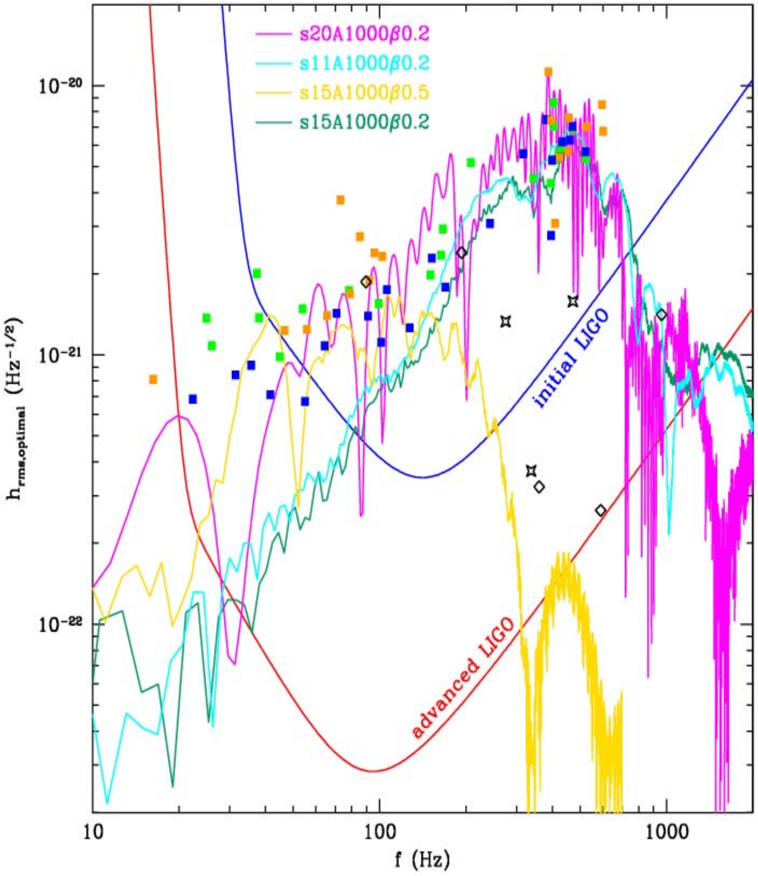
Signal possibly only detectable from within near neighbourhood of the galaxy, making observable events rare…

However… detection would provide unique insight into SN physics:

- optical signal hours after collapse
- neutrinos after several seconds
- GWs emitted during collapse

A number of neutrino related mechanisms may lead to detectable signals.

Different scenarios lead to qualitatively different GW signals, so detection should help distinguish between proposed SN explosion mechanisms.



Need to get explosions in simulations!

pulsar “mountains”

NS with “mountains”, e.g. with a strained crust or a misaligned magnetic field, radiate continuous low amplitude GWs.

Require long observation time, but many objects with known frequency and position. Targeted search for <u>known radio pulsars</u>.

Key question: What level of asymmetry can the NS crust sustain?

Theory suggests that;

$$\varepsilon < 2\times10^{-5}\left(\frac{u_{\text{break}}}{10^{-1}}\right)$$

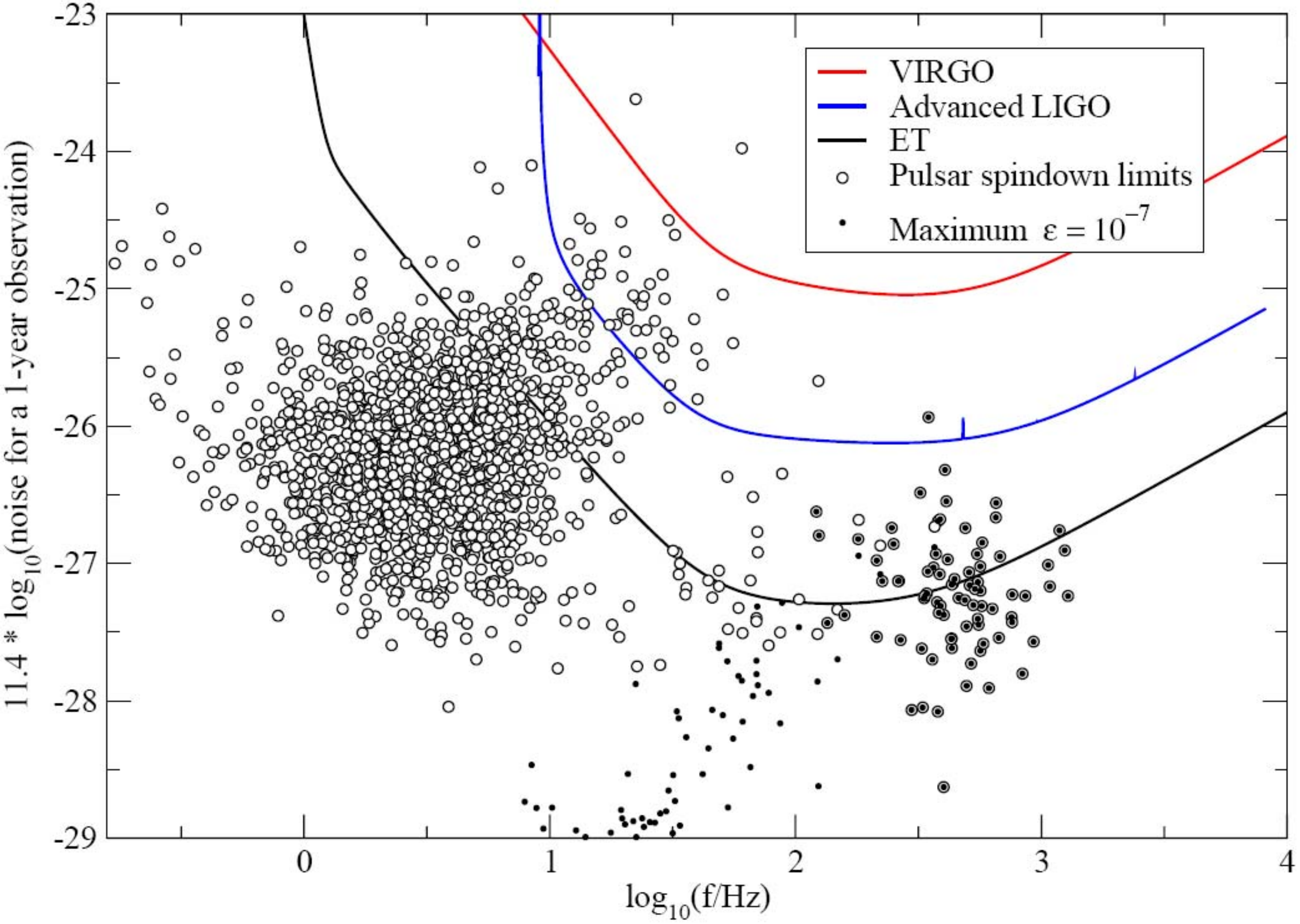
Breaking strain u_{break} recently found to be surprisingly large, around 0.1 (although...).

LIGO upper limits:

— strongest constraint $\varepsilon<7\text{x}10^{-7}$ for J2124-3358 (1 month of S3/4 data)

— S5 data used to beat Crab “spin-down limit” (less than 2% emitted in GWs!)

<u>Effective amplitude</u> of signal increases as square root of observation time...


VIRGO
Advanced LIGO
ET
Pulsar spindown limits
Maximum ε = 10^-7
11.4 * log10(noise for a 1-year observation)
log10(f/Hz)
-23
-24
-25
-26
-27
-28
-29
0
1
2
3
4

future prospects

LIGO S5: improve factor 2 in sensitivity, and a full year of data. Constraint for J2124-3358 at $\varepsilon<10^{-7}$

AdLIGO: factor of 10 better sensitivity, but still 1 year integration should reach $\varepsilon<10^{-8}$

ET: another factor of 10 improvement, push the limit to $\varepsilon<10^{-9}$?

Need a generation mechanism: Why is the star deformed in the first place?

Is there a smallest allowed mountain?

In principle, the magnetic field deformation sets a lower limit.

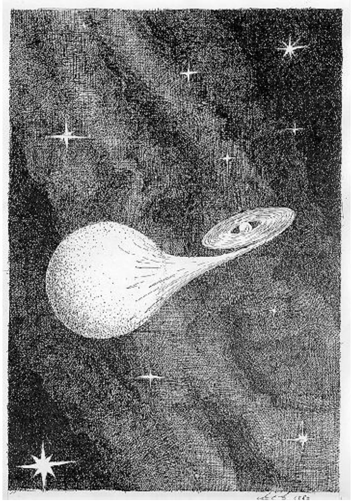
$$\varepsilon \approx 10^{-12}\left(B/10^{12}\,\mathrm{G}\right)^{2}$$

Unlikely to be detectable (superconductivity?)...

Accreting systems (LMXBs) could be promising. Need

$$\varepsilon = 4.5\times10^{-8}\left(\frac{dM/dt}{10^{-9}\,M_{\mathrm{o}}/yr}\right)^{1/2}\left(\frac{300\ \mathrm{Hz}}{\nu_{s}}\right)^{5/2}$$

to balance the accretion torque and halt spin-up. However, these are really messy systems and detection will be difficult.

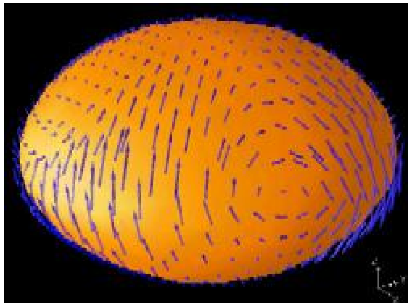


asteroseismology

Neutron stars have rich oscillation spectra, with families of modes more or less directly associated with different core physics (cf. Helioseismology).

f-mode:	scales with average density, and is the most effective GW emitter.
p-modes:	acoustic modes, depend on sound speed.
g-modes:	depend on thermal/composition gradients. Instability in hot star may trigger convection.
w-modes:	pure spacetime oscillations.
r-modes:	inertial mode restored by the Coriolis force. Radiates mainly through current multipoles. Driven unstable by GW emission!

Observations would constrain the theoretical models.



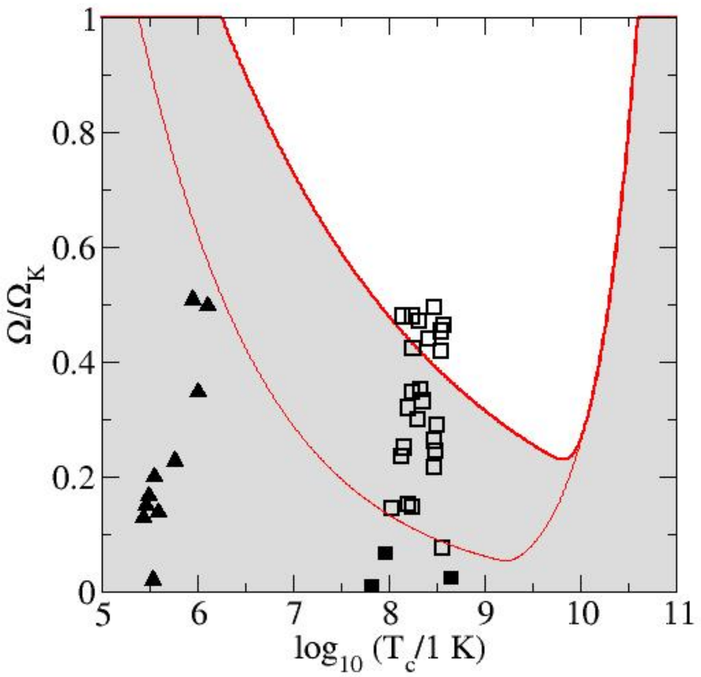
Key issue: How are the modes excited?

Need instability to reach significant amplitude?

the r-modes

The r-modes may be driven unstable by the emission of gravitational waves in a rotating neutron star.

Sensitive probe of the core physics.



What are the key damping mechanisms?

— superfluid mutual friction

— crust-core boundary layer

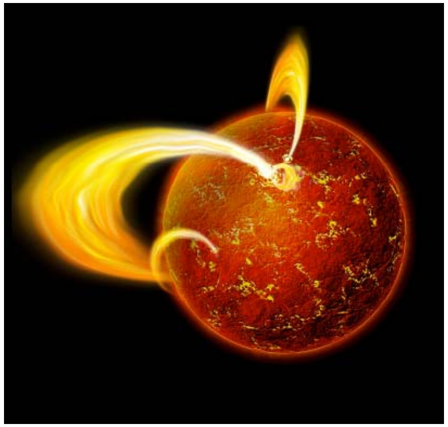
— exotic bulk viscosity (hyperons/quarks)

In principle, we should not observe any "usual" pulsar in the **instability window**. Use this to "rule out" theoretical models?

<u>Difficult to model</u> the GW signal. The r-mode growth phase is adequately described by perturbation theory, but nonlinear effects soon become important.

Instability saturates at low amplitude due to coupling to other inertial modes. Subsequent evolution very complex.

bursts/flares/glitches



Gamma-ray bursts:

Should have a GW component (mergers/collapsars).

LIGO null result for GRB070201 rules out neutron star merger in M31 as source.

SGR flares:

May already be doing asteroseismology!

QPOs observed in the tails of magnetar flares have been interpreted as torsional oscillations of the crust. Provides a constraint on mass and radius?

LIGO found no signal from 27/12 2004 event in SGR 1806-20.

However, crust oscillations should not be relevant for GWs…

Does the core take part in the oscillation?

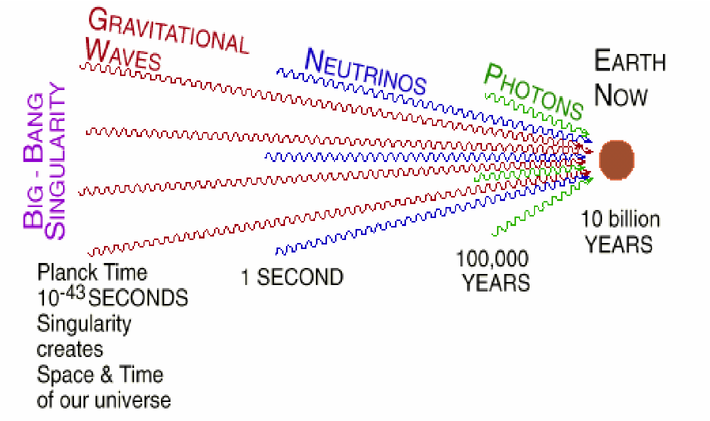
Pulsar glitches:

Set a "reasonable" energy level for recurring events in the Milky Way, but the glitch mechanism is not understood.

In order to be relevant GW events, glitches need to excite global asymmetries.

May well be too optimistic…

“fundamental” physics



The most fundamental GW observation may be a cosmological background from the Big Bang.

Slope of spectrum and peaks give masses of particles, energies of transitions, or sizes of key dimensions.

Detection requires cross-correlation of detectors.

Standard inflation is out of reach for AdLIGO/Virgo/ET and LISA.

LISA’s frequency band (mHz) represents GWs that had the horizon size at the electroweak phase-transition. If this transition were first order, then there could be a detectable background (baryon-antibaryon symmetry breaking?)

Cosmic strings emit GWs with a characteristic signature. These may be detectable even if they are not a significant component of the mass budget of the Universe.

Best window, free of “local” GW sources, is around 0.1-1 Hz. Need LISA follow-on mission?

towards astronomy

The next decade will see the opening of the GW window to the Universe.

The first signal is likely to come from an inpiralling (BH?) binary.

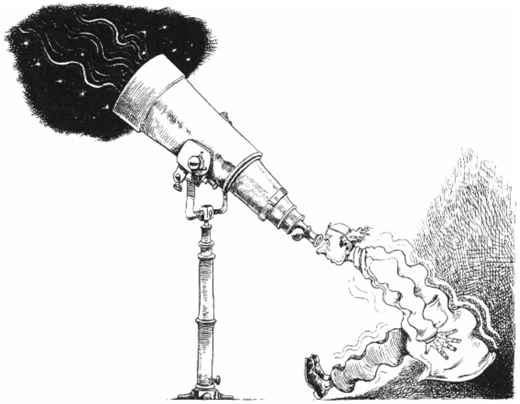
For decades we have been making predictions;

2nd generation interferometers will enable gravitational-wave phenomenology (real astronomy?)

LISA will "see" supermassive black holes

3rd generation interferometers should probe NS physics, and provide constraints on the state of matter at extreme densities.

Can hope to learn much fundamental physics…



Compare current "ignorance" to radio in 1930s or X-ray in 1960s:

Expect the unexpected!