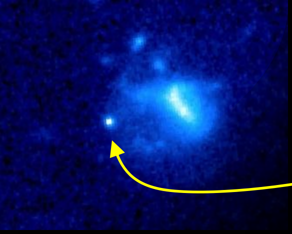


Optical afterglow of GRB 050709

Hubble image 5.6 days after initial gamma-ray burst

(Credit: Derek Fox / Penn State University)

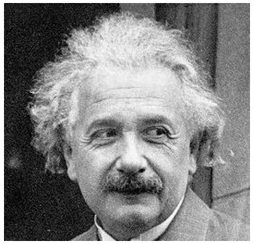
Sources of Gravitational Waves

Peter Shawhan

SLAC Summer Institute — August 2, 2011

LIGO-G1100861

General Relativity with *Nearly* Flat Spacetime



Start with the Einstein field equations:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

The spacetime metric

where $$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R$$

Consider a small perturbation from the flat (Minkowski) metric $\eta_{\mu\nu}$:

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

To linear order, get a wave equation for $h_{\mu\nu}$.

In transverse-traceless gauge, assuming wave is traveling in +*z* direction, solutions have the form

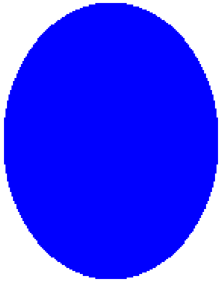
$$h_{\mu\nu} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} e^{i\omega\left(\frac{z}{c}-t\right)}$$

What Gravitational Waves Do

Once produced, gravitational waves:

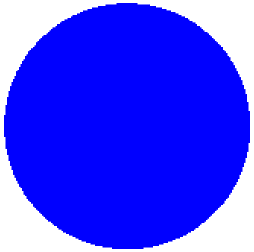
- Travel away from the source at the speed of light
- Change the effective distance between inertial points — i.e. the spacetime metric — transverse to the direction of travel

Looking at a fixed place in space while time moves forward, the waves alternately *stretch* and *shrink* the space



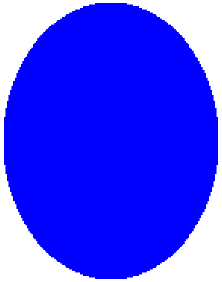
“Plus” polarization

✛



“Cross” polarization

✕



Circular polarization

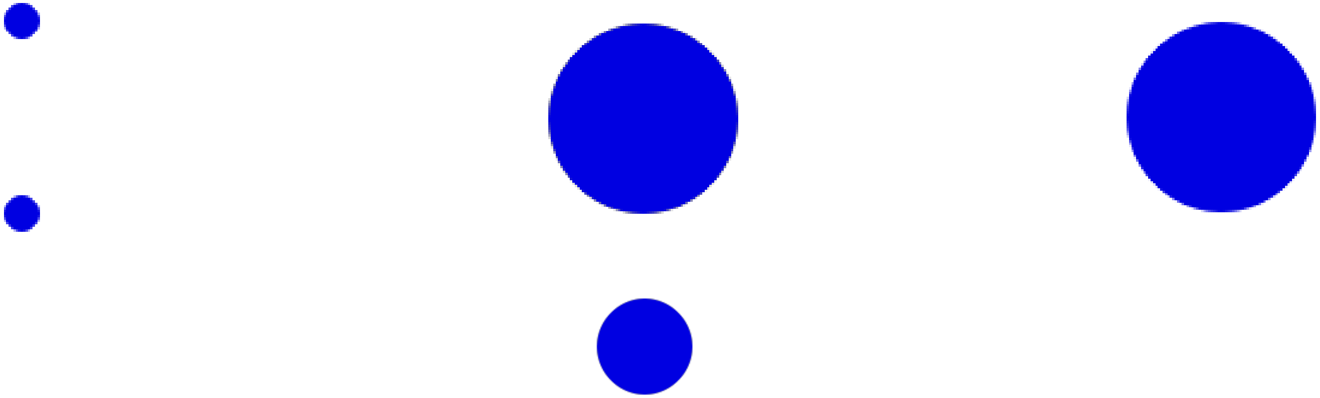
↻

…

Gravitational Wave Scaling

Two massive, compact objects in a tight orbit

deform space (and any object in it) with a frequency which is twice the orbital frequency



The stretching is described by a dimensionless strain, $h(t) = \Delta L(t)/L$ (here, h_+ since this is plus polarization)

$h(t)$ is inversely proportional to the distance from the source

GW Emission in General

Plus and cross polarizations are transverse tensor modes

***Any* system with a time-varying mass quadrupole moment will couple to those modes**

Or a time-varying mass *current* quadrupole

Higher multipoles too – but no monopole or dipole emission in GR

Gravitational radiation is a unique messenger

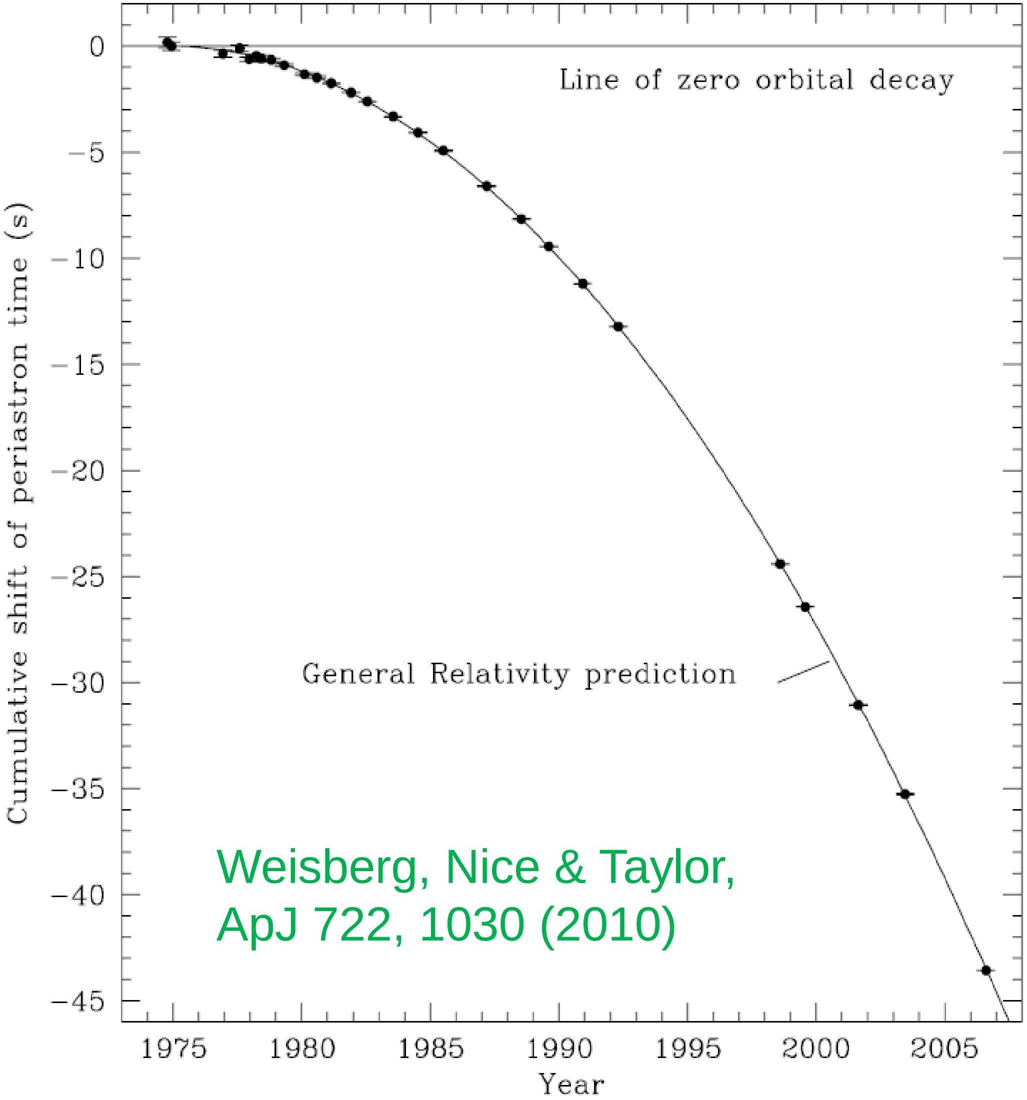
- Emission is only weakly anisotropic
- Not scattered or attenuated by matter
- Carries information about the core engine of astrophysical events
- Details of waveform reflect the fundamental theory of gravity
- May accompany detectable EM / particle radiation, or may not

However, GWs have not been directly detected yet …

Do Gravitational Waves *Really* Exist?

Long-term radio observations of the Hulse-Taylor binary pulsar B1913+16 have yielded neutron star masses (1.44 and 1.39 $M_\odot$) and orbital parameters

System shows very gradual orbital decay – just as general relativity predicts!
⇒ Very strong indirect evidence for gravitational radiation

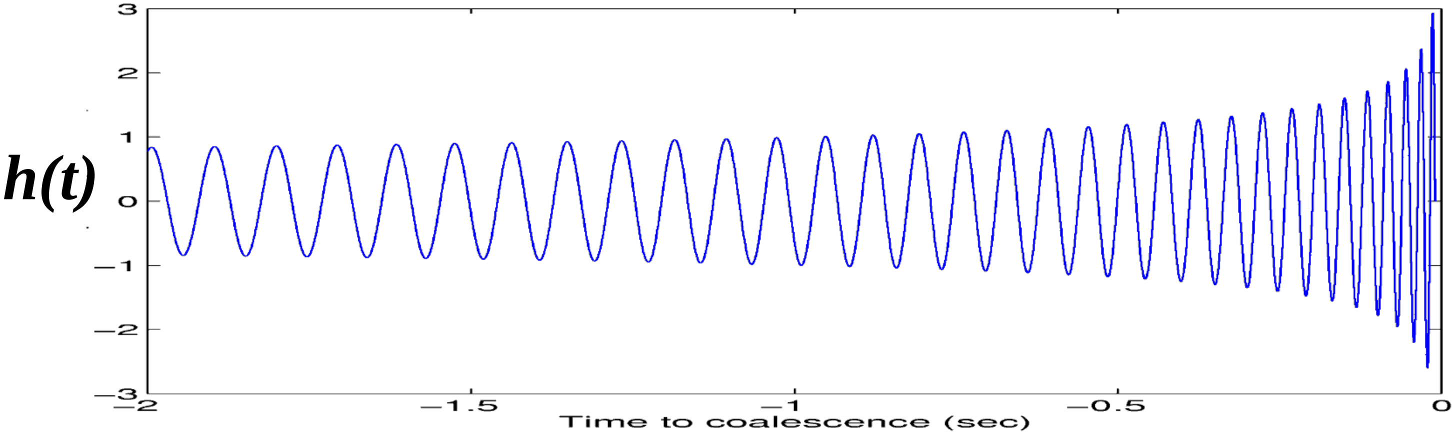


Weisberg, Nice & Taylor, ApJ 722, 1030 (2010)

The Fate of B1913+16

Gravitational waves carry away energy and angular momentum

Orbit will continue to decay (inspiral) over the next ~300 million years, until…



The neutron stars will merge !

- And possibly collapse to form a black hole
- Final few minutes will be in audio frequency band

Gravitational wave detectors can listen for signals like these

Information from the Inspiral

Time evolution of GW amplitude and frequency depend on the masses, spins and orbit orientation of the binary system

Compact objects: white dwarfs, neutron stars, black holes

First-order effect: “chirp rate” when not too close to merger

Characteristic time scale: $\tau \propto \frac{(m_1+m_2)^{1/3}}{m_1 m_2}$

So higher mass → chirps more quickly

Inspiral ends at innermost stable circular orbit (ISCO)

Depends on masses and spins; $f_{\mathrm{ISCO}} \propto \frac{1}{(m_1+m_2)}$

So higher mass → signal cuts off at a lower frequency

Relative amplitude and phase of polarization components (h_+, $h_\times$) indicate the orientation of the orbit

Relativistic Corrections

Orbital phase vs. time → orbital phase vs. frequency during chirp

“Post-Newtonian expansion” if spins are negligible:

$$\begin{aligned}
\Psi(f) &= 2\pi f t_c + \frac{3}{128\eta}(\pi m f)^{-5/3} && \text{Newtonian} \\
&+ \frac{5}{96\eta}\left(\frac{743}{336} + \frac{11}{4}\eta\right)(\pi m f)^{-1} && \text{1PN} \\
&- \frac{3\pi}{8\eta}(\pi m f)^{-2/3} && \text{1.5PN} \\
&+ \frac{15}{64\eta}\left(\frac{3058673}{1016064} + \frac{5429}{1008}\eta + \frac{617}{144}\eta^2\right)(\pi m f)^{-1/3} && \text{2PN} \\
&+ \cdots
\end{aligned}$$

Relativistic effects

where $m = (m_1 + m_2)\,, \quad \eta = \dfrac{m_1\, m_2}{m^2}$

So phase evolution near merger gives individual masses

Into the Merger

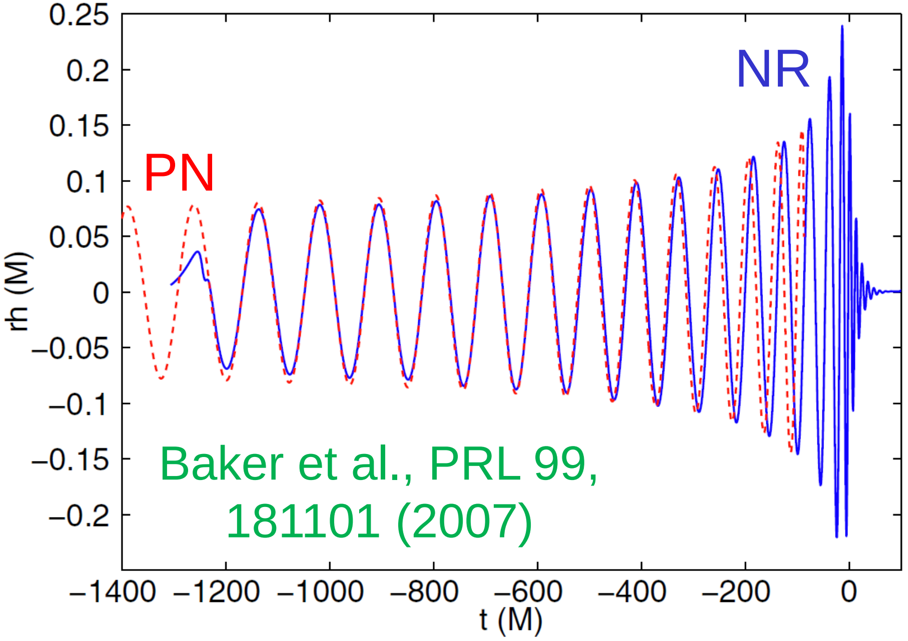
Merger dynamics are driven by strong-field gravity

Post-Newtonian expansion loses accuracy

Neutron star tidal deformation can affect final part of inspiral

Black hole spins can cause orbital plane to precess and strongly influence final “plunge”

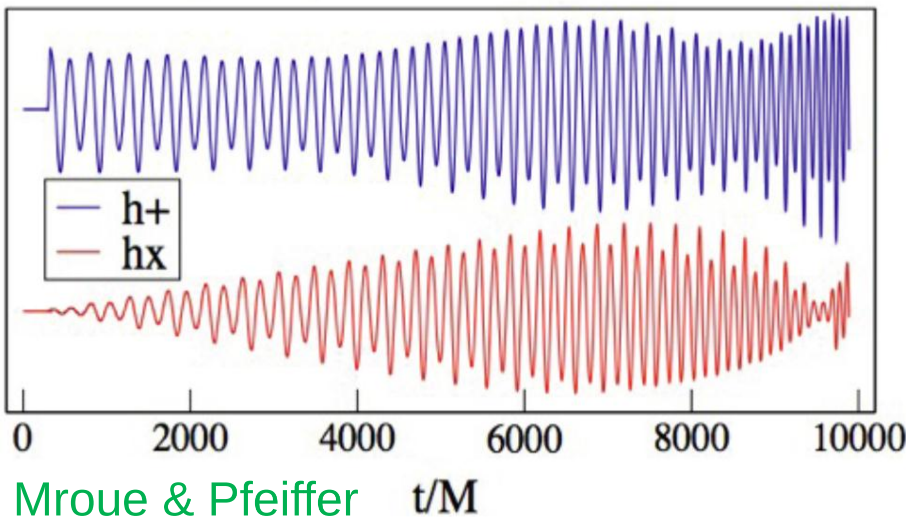
Numerical relativity to the rescue !



Baker et al., PRL 99, 181101 (2007)

Precessing binary:

$m_1/m_2=3, \ \chi_1=(0.5,0,0), \ \chi_2=(0,0,0)$



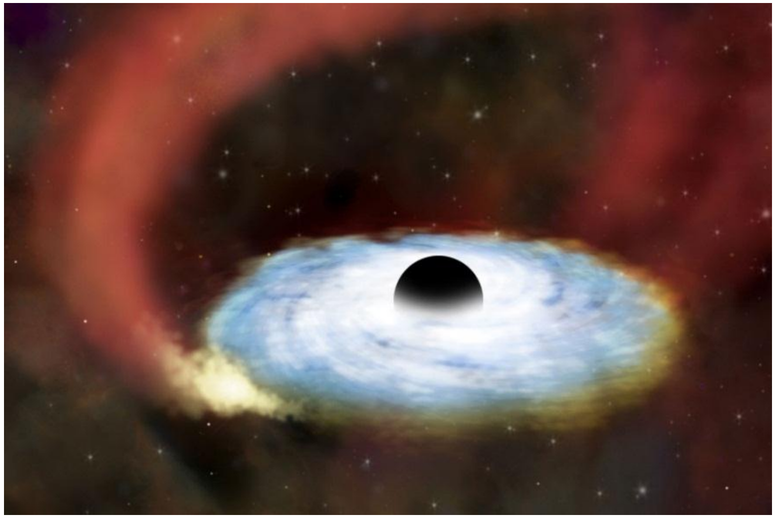
Mroue & Pfeiffer

History of Binary Mergers in the Universe

GW observations can determine merger rate, masses, spins, host galaxy types, position in or near host galaxies for the population(s) of compact binaries

Key question: How did supermassive black holes grow ?

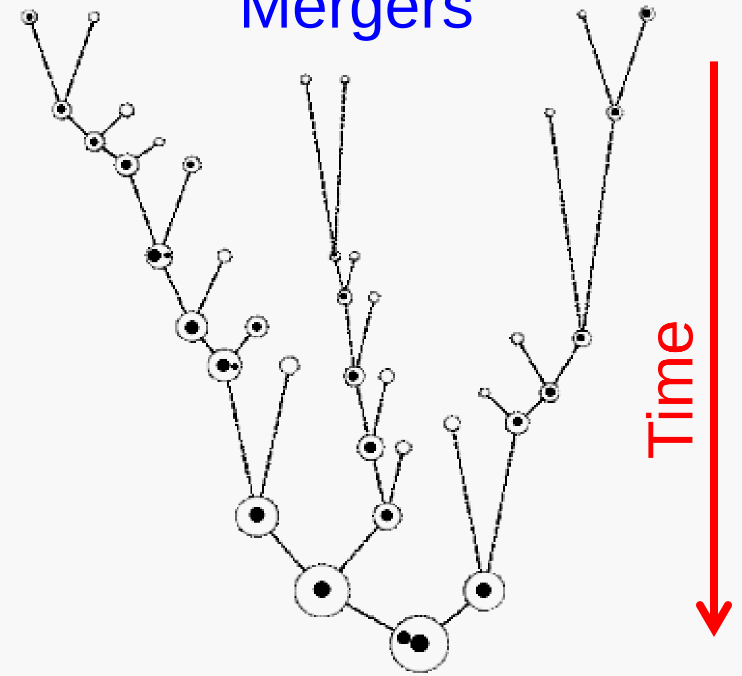
Gas accretion



NASA/CXC/SAO

vs.

Mergers

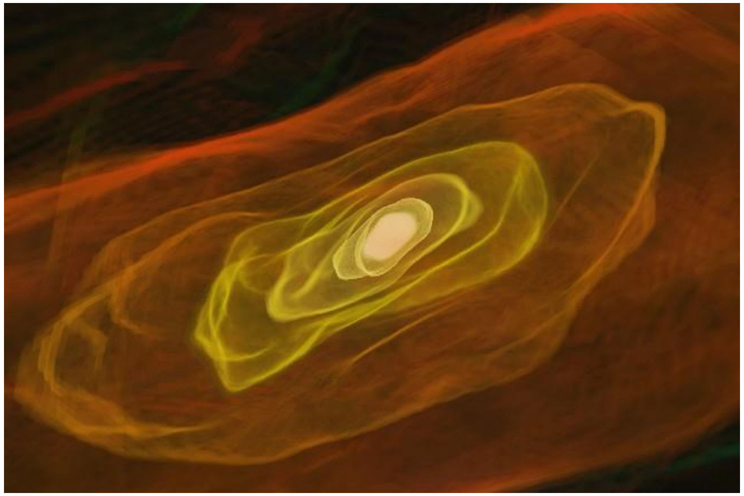


M. Volonteri

History of Binary Mergers in the Universe

Key question: **How were the *first* black holes formed ?**

Population III stars

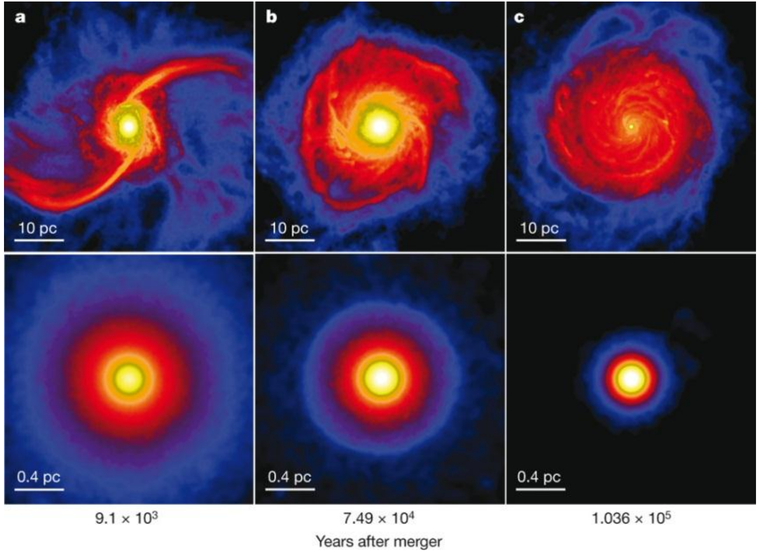


Visualization: Ralf Kaehler (ZIB) & Tom Abel (Penn State); Simulation: Tom Abel (Penn State), Greg Bryan (Oxford) & Mike Norman (UCSD)

Star mass > ~ 300 $M_\odot$
→ Black hole mass > ~ 100 $M_\odot$

vs.

Direct collapse of gas clouds



Mayer *et al. Nature* **466**, 1082 (2010)

Black hole mass ≈ 10^3–10^5 $M_\odot$
or even more (“massive seeds”)

vs. runaway collapse of dense stellar clusters, vs. dark stars…

Expansion History of the Universe

GR predicts the *absolute* luminosity of a binary inspiral+merger → detection of a signal measures the luminosity distance directly

“Standard siren” – neutron star binaries out to z~1, BH binaries anywhere

Precision depends on SNR, ability to disentangle orbit orientation

GW signal alone does not determine redshift *

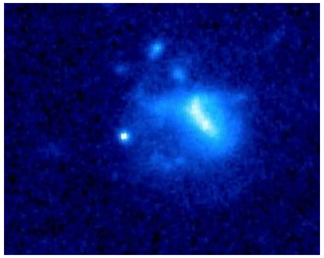
GW signal is redshifted, but that looks just like a change in masses

* Neutron stars could in principle break this degeneracy

Identifying an optical counterpart provides redshift

Host galaxy redshift can be measured

Knowing exact sky position of the source helps analysis



With a sample of events, can trace out distance-redshift relation

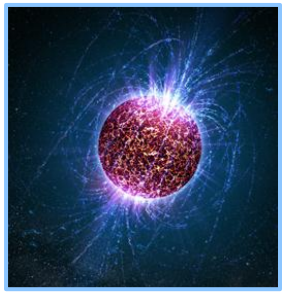
e.g. measure cosmological *w* parameter to within a few percent

One systematic: weak lensing

Another GW Source: Spinning Neutron Star

Relic of past collapse of a moderately massive star

- Remnant spin from progenitor, or from having been spun up by accretion
- Generally magnetized, sometimes very strongly
- A small fraction of neutron stars are seen as **pulsars**

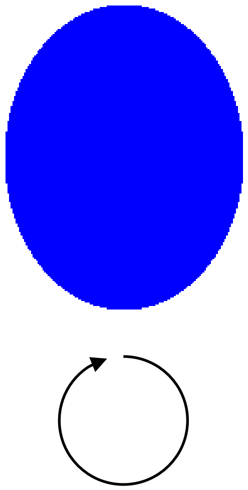


Casey Reed/PSU

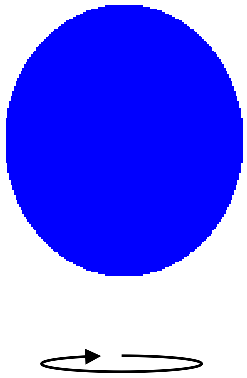
If not axisymmetric, will emit gravitational waves

Example: ellipsoid with distinct transverse axes

Along spin axis:



From side:



→ Continuous GW signal

Can integrate over months
to detect a weak signal

Modulated by source & detector motion

Some searches have to handle very large parameter space—technically challenging

History of Neutron Star Formation

Key question: **How asymmetric are the neutron stars out there?**

Depends on maximum ellipticity / bumpiness the star can support

- Equation of state, and other properties of neutron star material
- Asymmetry may be supported by magnetic fields
- Or by thermal anisotropy from accretion

But might not actually explore that maximum –
Depends on the formation and cooling of the neutron star

- Initial asymmetry could get frozen in
- Accreted material could produce permanent asymmetry

Lots of theoretical activity, no clear picture yet

Stellar Core Collapse

Core-Collapse Supernovae (type Ib/c and type II) occur frequently and liberate up to

Bill Saxton, NRAO/AUI/NSF

$\sim 10^{53}$ erg

~1% as EM radiation

- Optical
- Radio
- X-ray
- Gamma ray

~99% as neutrinos

- Low-energy
- High-energy

??? as gravitational waves

- Depends on mass flows

CCSN GW Emission Mechanisms

Reviews: Ott CQG 26, 063001 (2009),
Fryer & New Living Reviews in Relativity 2011-1

Collapse and bounce

Shape & strength depend on rotation, equation of state of nuclear matter

Rotational instabilities

e.g. *r*-modes

Convection

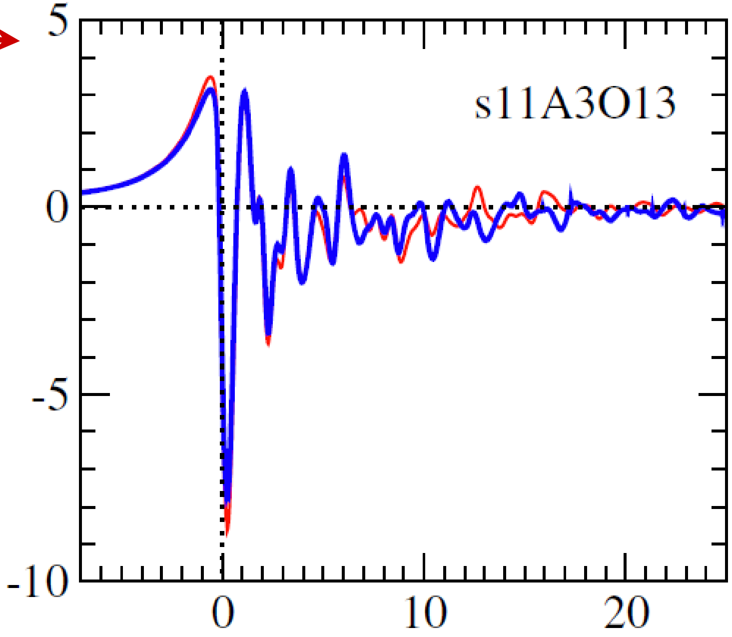
Standing accretion shock instability (SASI)

Proto-neutron star oscillations (*g*-modes)

Anisotropic outflows

Black hole formation

Fallback onto black hole



Dimmelmeier et al., PRD 78, 064056 (2008)

Core Collapse Supernova Modeling

Is very challenging !

Trying to infer mechanism that drives the explosion

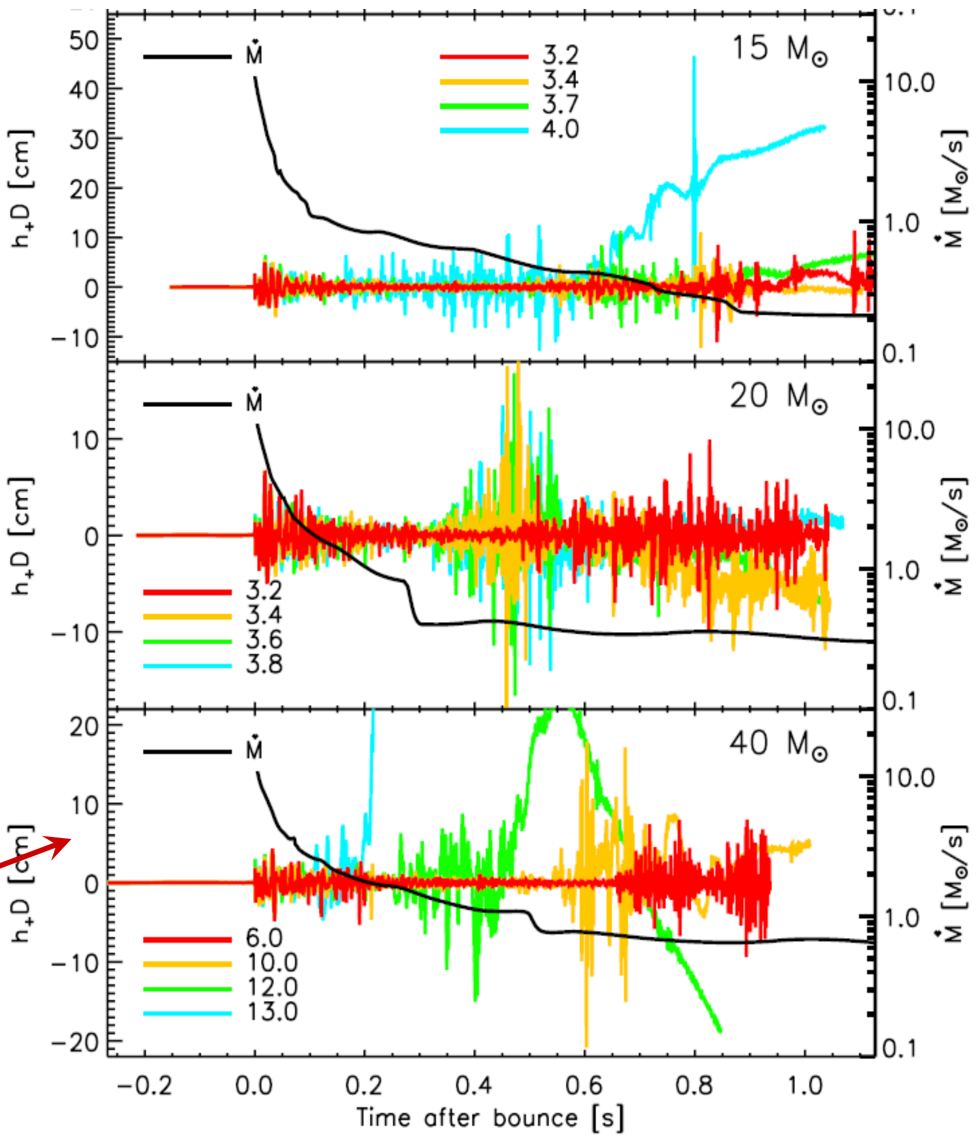
Lots of astrophysics

Relativistic flows
MHD
Rotation, buoyancy
Equation of state
Neutrino transport

2D simulations may miss some effects; 3D more computationally demanding

Example simulations:

Murphy, Ott & Burrows, ApJ 707, 1173 (2009)



What Waveforms Can We Expect?

Mechanism	Waveform	Polarization
Collapse and bounce	spike	linear
Rotational instabilities	quasiperiodic	circular
Convection	broadband	mixed
SASI	broadband	mixed
Proto-neutron star *g*-modes	quasiperiodic	linear
Anisotropic matter outflow or neutrino emission	slow growth with memory	linear
Black hole formation	QNM ringing	lin/circ
Fallback onto black hole	driven QNMs	”

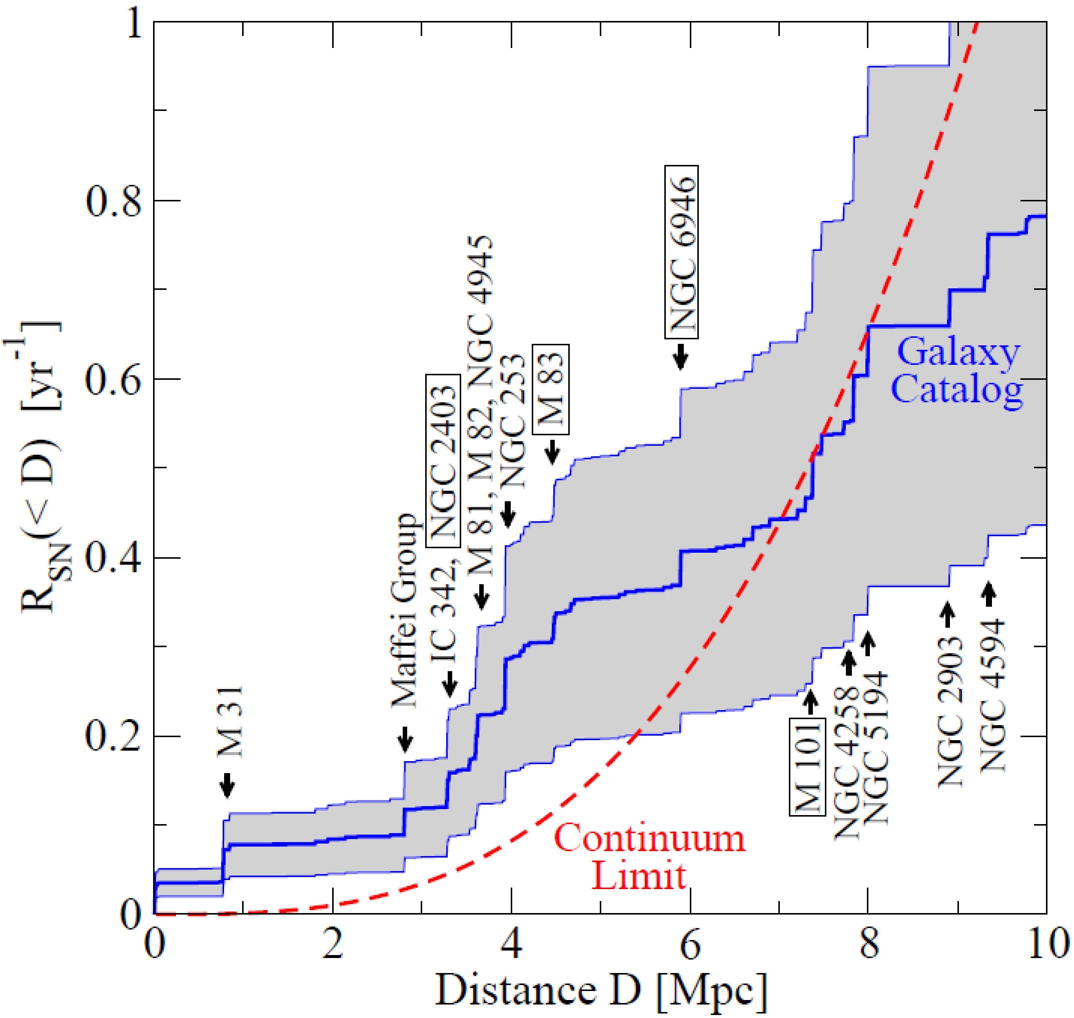
→ Detecting (or not detecting) a GW signal can tell us what is driving supernova explosions

How Far Do We Need to Reach?

Milky Way rate
~1 per 30–100 years

Expect one
core-collapse SN
within 5 Mpc
every 2–5 years

Relatively weak GW emssion expected in most modeled mechanisms – probably limited to Milky Way and nearby galaxies (similar to neutrino detectors)



Ando et al., PRL 95, 171101 (2005)

What if GR is Wrong?

Alternative theories of gravity permit additional modes

besides the tensor modes of GR

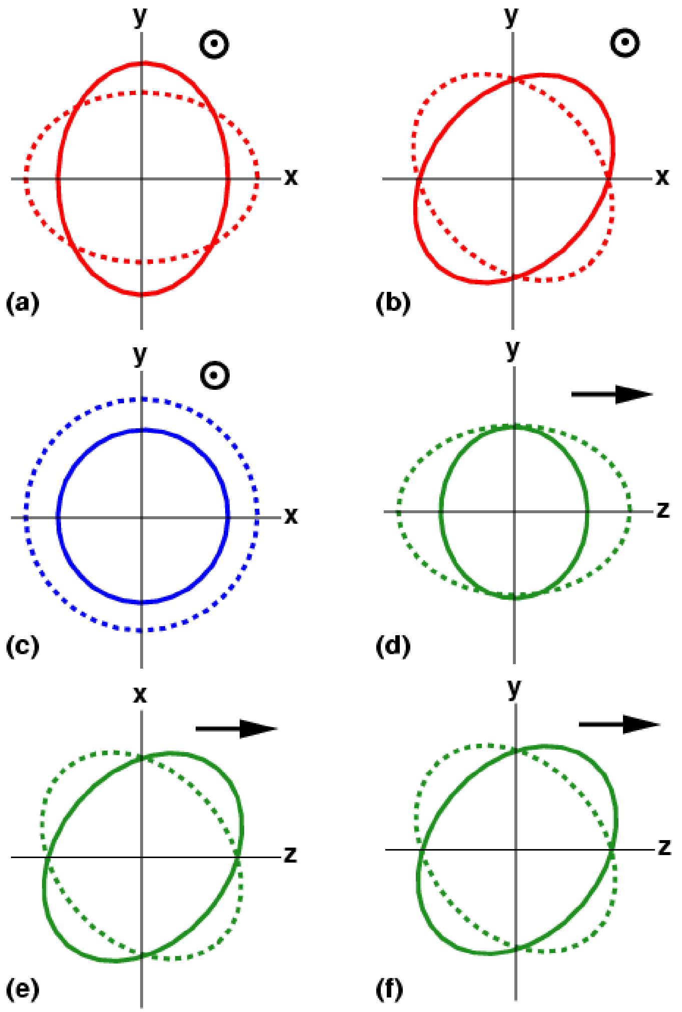
e.g. scalar-tensor theories

Brans-Dicke is one

Actual coupling depends on the specific theory

Could allow core-collapse supernova to be detected from farther away?

Gravitational–Wave Polarization



Stochastic Gravitational Waves

Random signal from sum of unresolved sources

From the early universe, or from astrophysical sources since then

Usual assumptions about the signal:

Stationary

Gaussian

Unpolarized

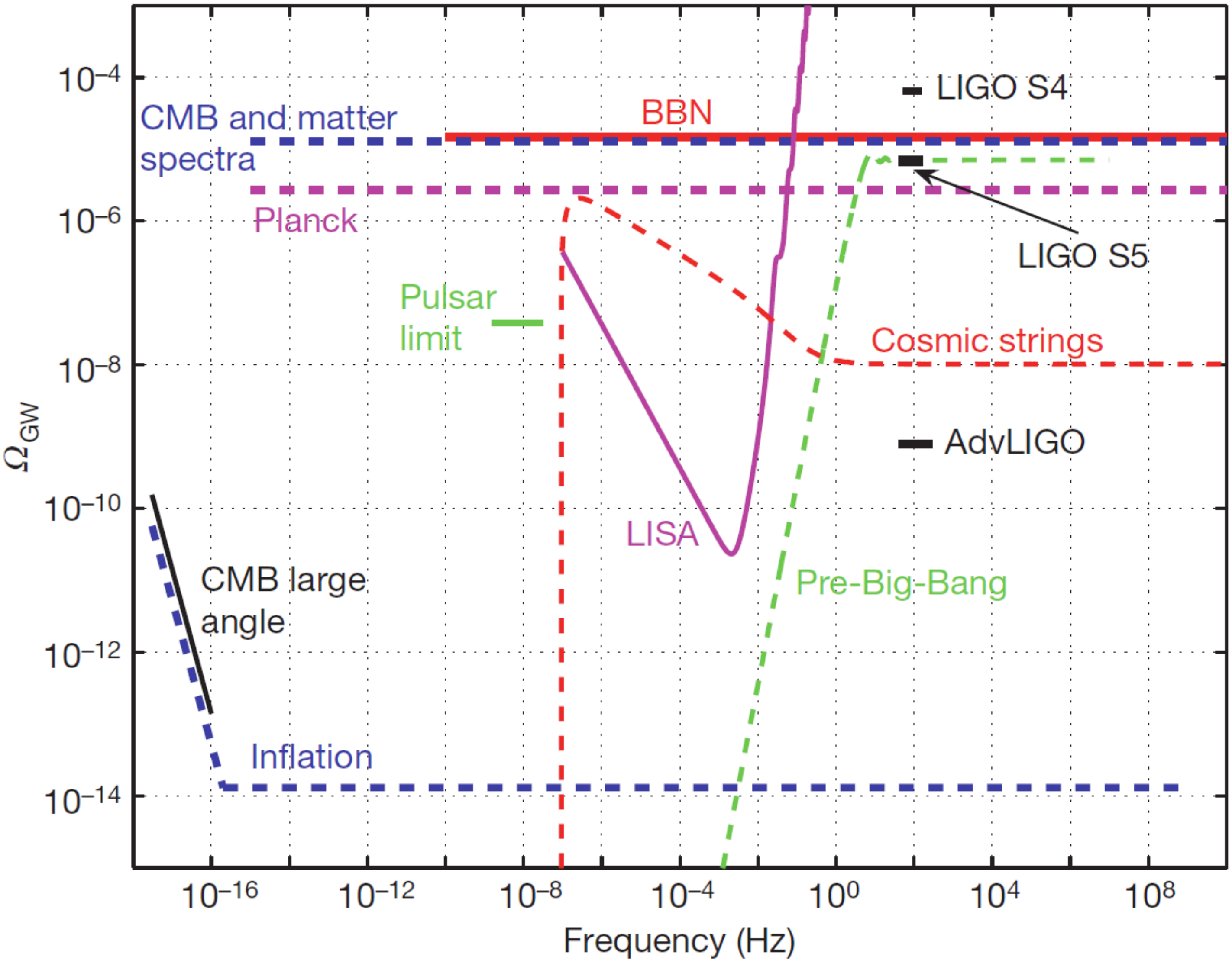
Power-law frequency dependence, probably (e.g. f^{-3})

May be isotropic, or not

Looks basically like extra noise in each detector !

To detect stochastic signal, cross-correlate data from different detectors

Isotropic Stochastic Models and Limits



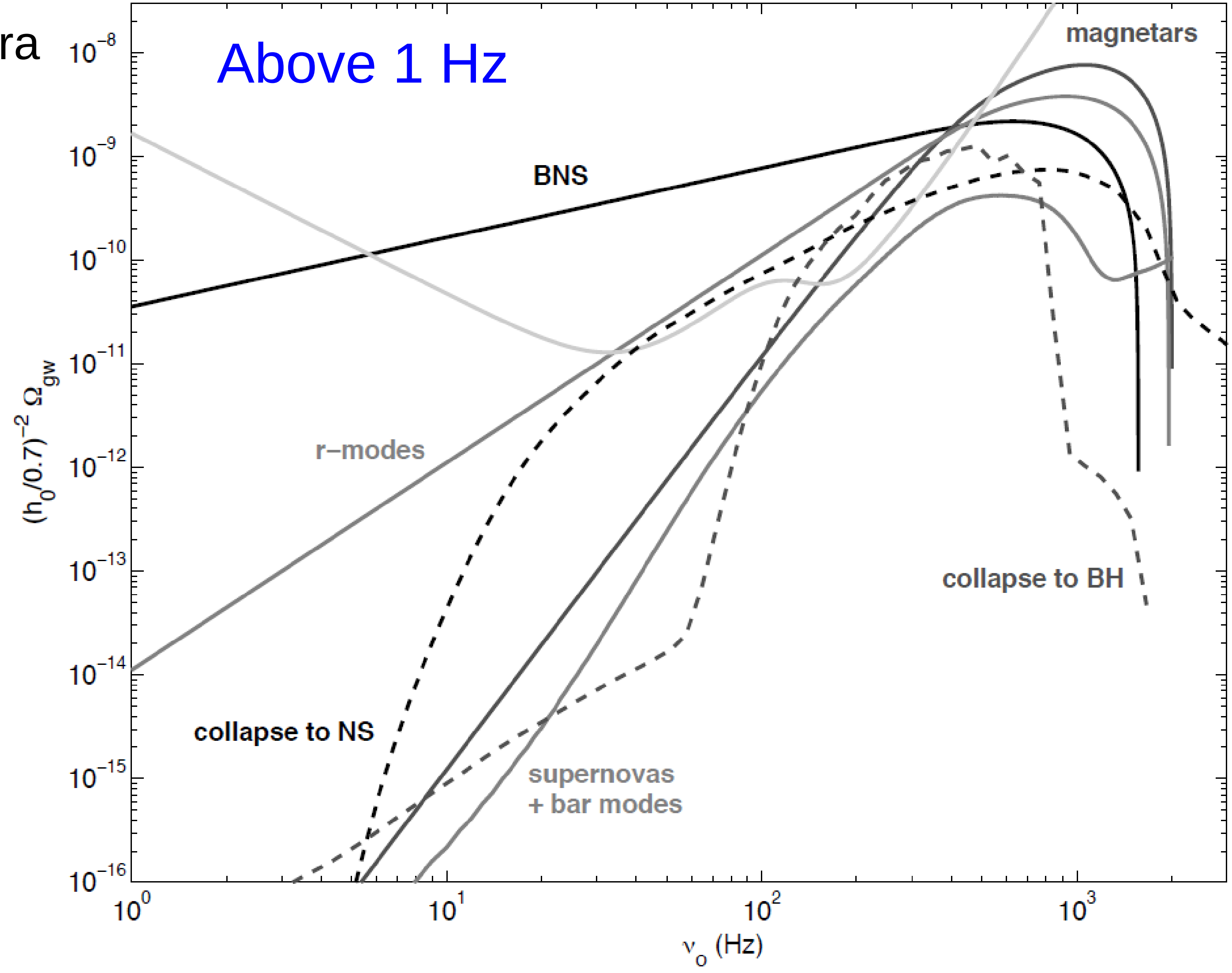
LSC+Virgo, Nature **460**, 990 (2009)

Wide range of possible frequencies

Can probe some models of the early history of the universe

Stochastic GWs from Astrophysical Sources

Different spectra expected from astrophysical sources



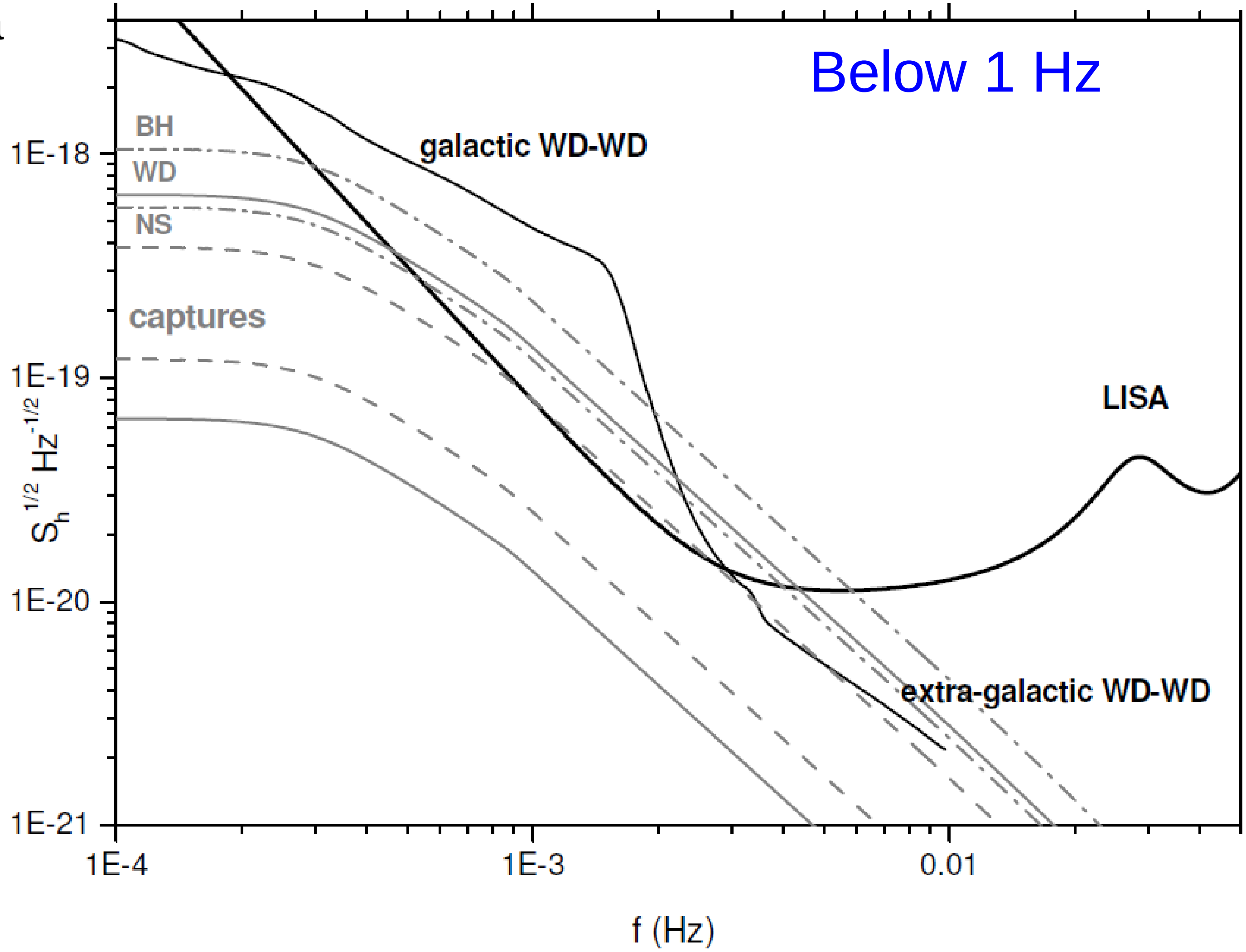
Regimbau, arXiv:1101.2762

Stochastic GWs from Astrophysical Sources

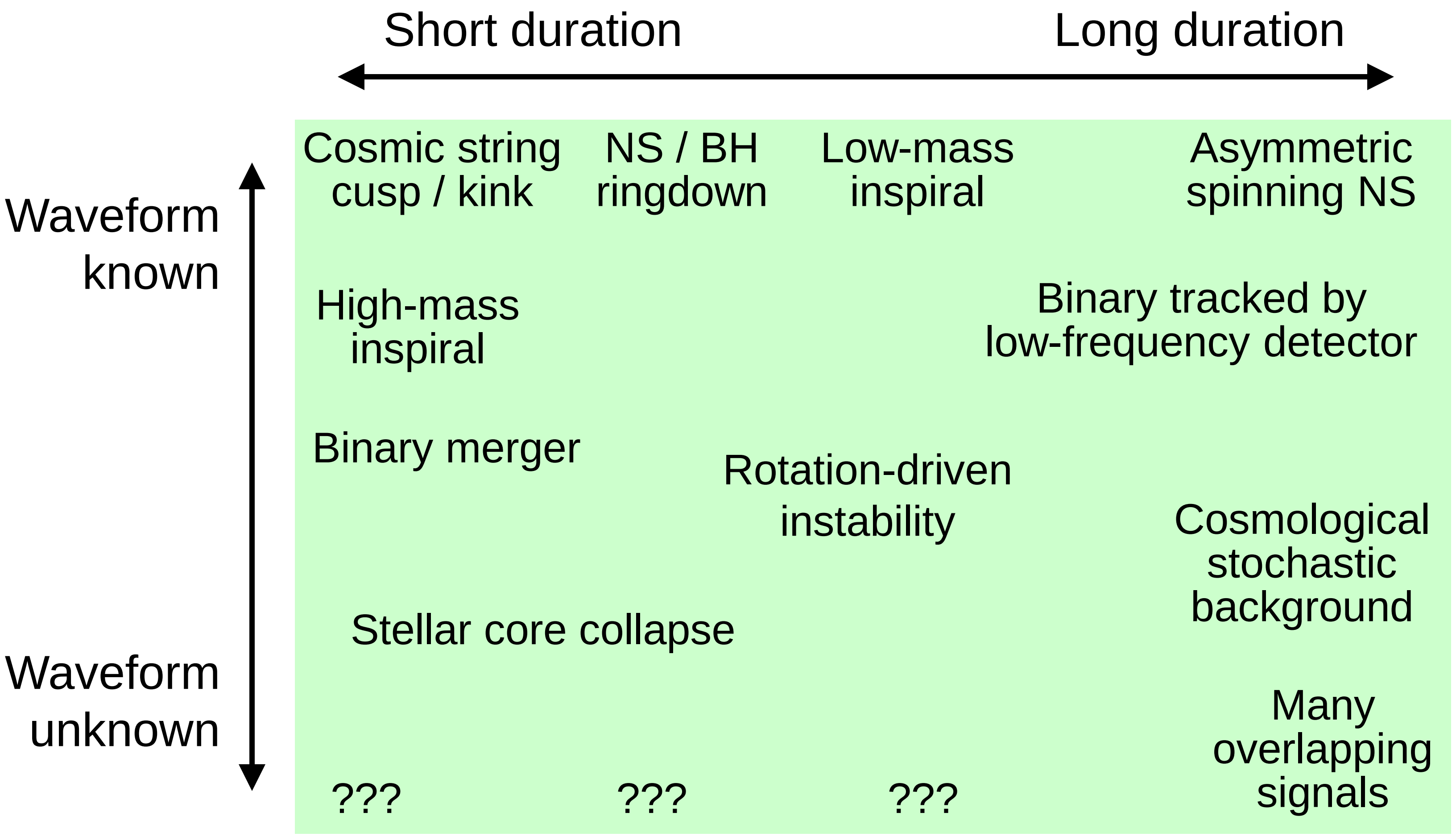
Different spectra expected from astrophysical sources

Not necessarily istotropic

Regimbau, arXiv:1101.2762



The Gravitational Wave Signal Tableau



Short duration

Long duration

Waveform known

Waveform unknown

Cosmic string cusp / kink

NS / BH ringdown

Low-mass inspiral

Asymmetric spinning NS

High-mass inspiral

Binary tracked by low-frequency detector

Binary merger

Rotation-driven instability

Cosmological stochastic background

Stellar core collapse

Many overlapping signals

???

???

???