Gravitational waves from binary mergers

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10/3/2012

Workshop on Massive Stars, MN

Personal opinions
Not speaking on behalf of LIGO or Virgo

Why gravitational waves & binaries?

- Context and provocations : binary evolution
- New window on universe
- Applications
  - Electromagnetic counterparts
  - Measuring the merging binary
  - Nuclear matter and the “cosmological collider”
- What to expect

Context

Detections likely soon

[Abadie et al 2010, arXiv:1003.2480]

Galactic NS-NS : ~ few mergers/Myr

[ROS & Kim 2010,ApJ 715 230]

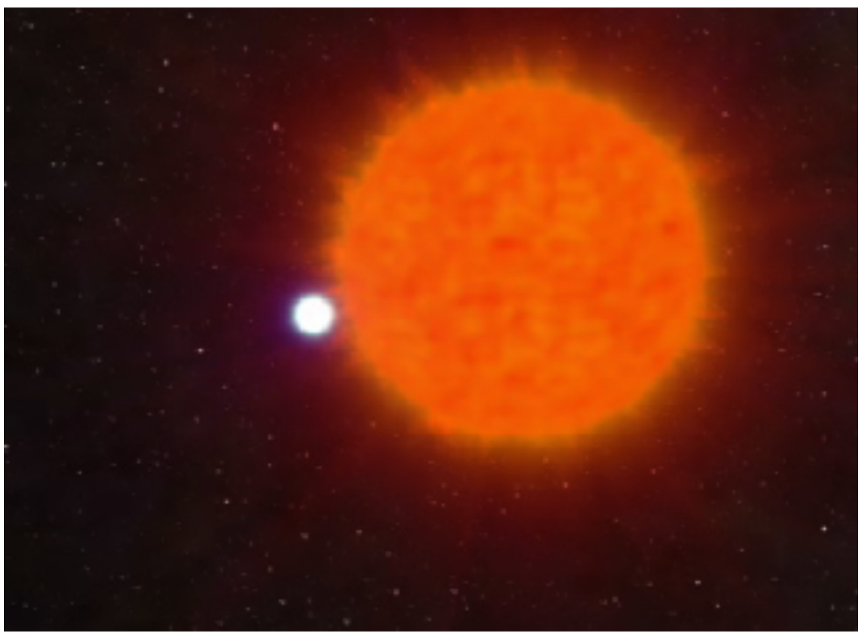
LIGO range : ~200 Mpc (conservative 1-ifo)

→ 10-ish /yr NS-NS mergers

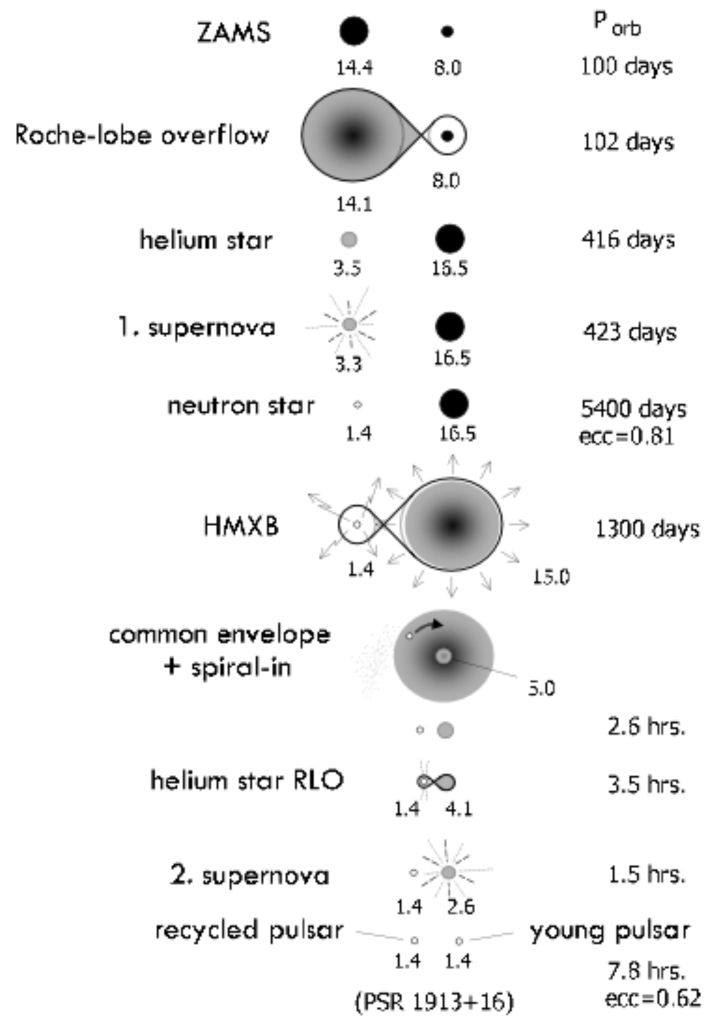
Context

Population synthesis

- <u>Outline of (typical) evolution</u>:
  - Evolve and **expand**
  - Mass transfer (perhaps)
  - Supernovae #1
  - Mass transfer (perhaps)
  - Supernovae #2



Movie: [John Rowe]



Formation of Hulse-Taylor (B1913+16)
Voss and Tauris 2003

Interaction needed

- **Mass transfer**:

  Small orbit-> MT essential

  GW radiation "fast" (< 10 Gyr) only for tight orbits

  Example: Hulse-Taylor PSR

$$\tau_{gw} \simeq 0.3\text{Gyr}$$

$$a \simeq 2.7 R_\odot \ll O(10^3 R_\odot) \simeq R_{\text{giant}}$$

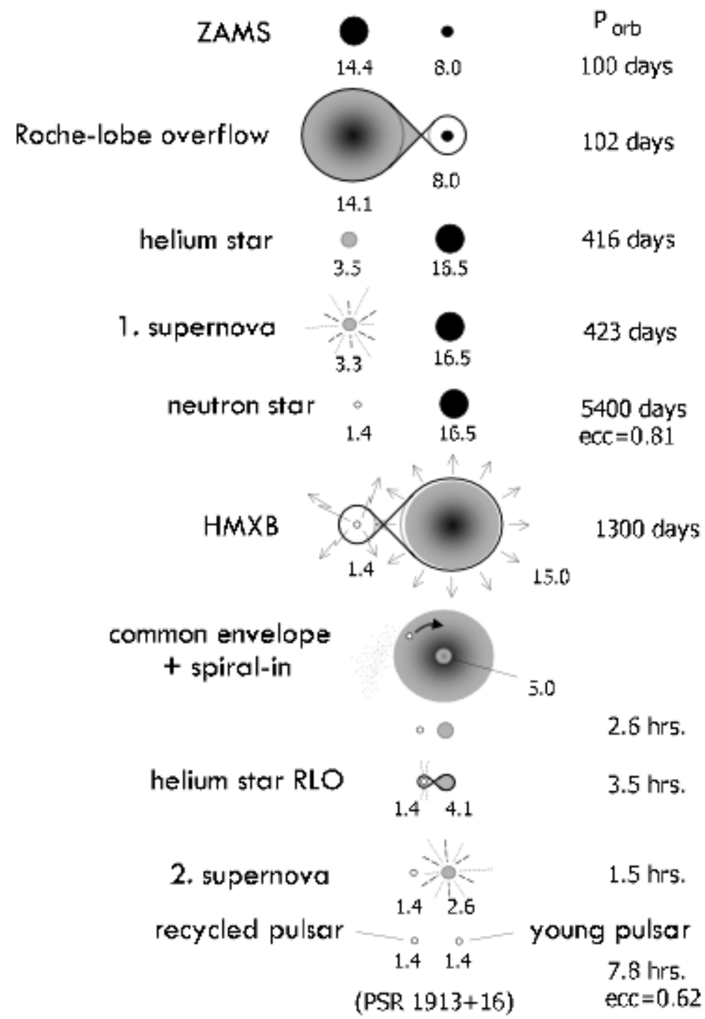
Kicks on BHs: **(assumed)** **Weak/suppressed**

[fallback]

Common envelope ~ needed

… + **avoid merger as stars**

BH-BH binaries **barely merge** – long delays



Formation of Hulse-Taylor (B1913+16)
Voss and Tauris 2003

First estimate

Synthetic galactic population

TABLE 1
GALACTIC MERGER RATES [Myr^{-1}][a]

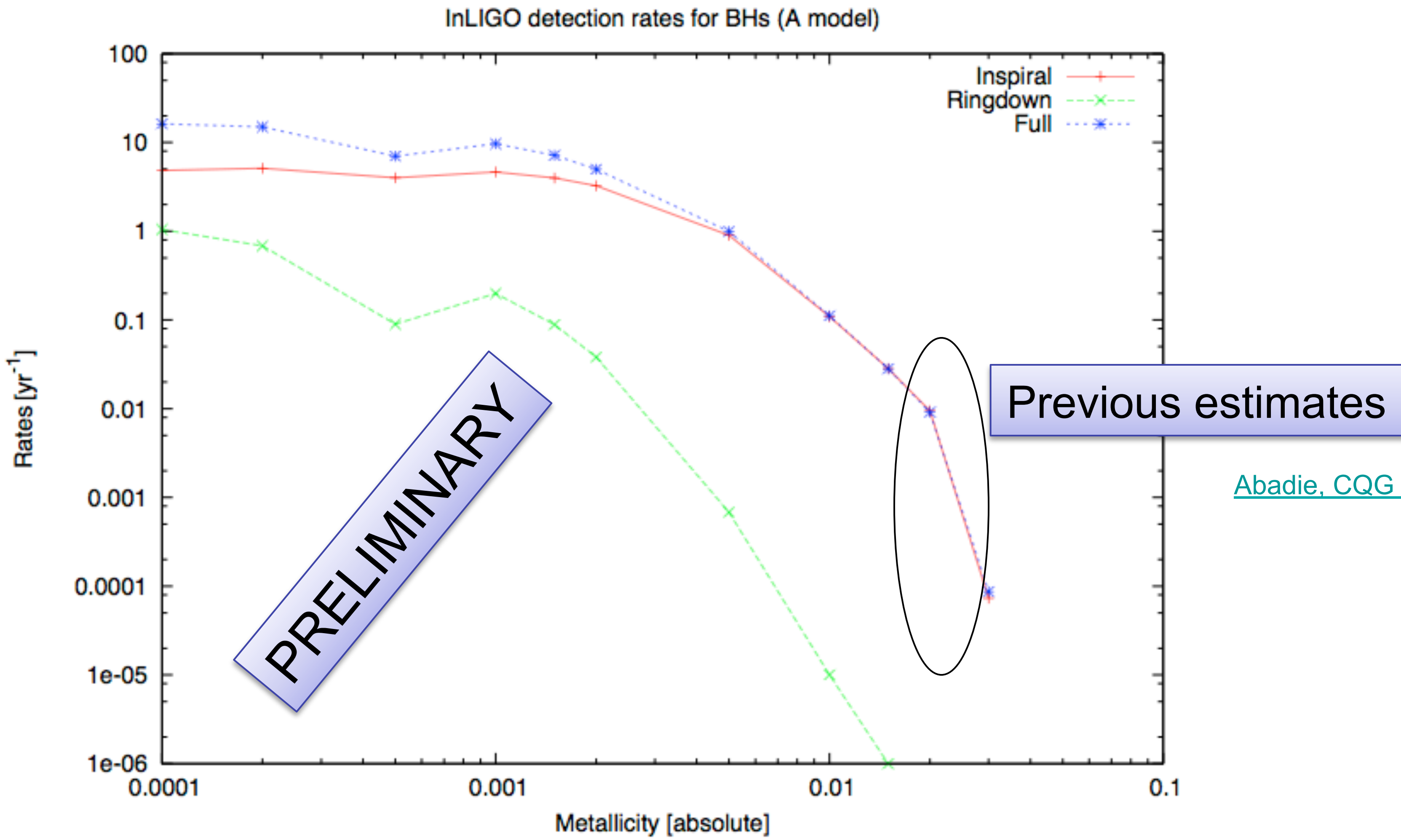
Type	$Z_\odot$ (100%)	$0.1\ Z_\odot$ (100%)	$Z_\odot + 0.1\ Z_\odot$ (50% + 50%)
NS-NS	40.8 (14.4)	41.3 (3.3)	41.1 (8.9)
BH-NS	3.2 (0.01)	12.1 (7.0)	7.7 (3.5)
BH-BH	1.5 (0.002)	84.2 (6.1)	42.9 (3.1)
TOTAL	45.5 (14.4)	138 (16.4)	91.7 (15.4)

Belczynski et al 2010 [arxiv:1004.0386]
Dominik et al 2012 [arXiv:1202.4901]

Low metallicity contribution

Event rate versus metallicity

All low Z star formation (ever) important?



[Abadie, CQG 27 3001]()

Dominik et al in prep

Really? Let nature decide…

Table 1
Advanced LIGO/VIRGO Detection Rates [yr^{-1}] [a]

Model	NS-NS	BH-NS	BH-BH
S	3.9 (1.3)	9.7 (5.1)	7993.4 (518.7)
V5	3.9 (1.3)	9.4 (4.8)	8057.8 (533.7)
V6	3.9 (1.3)	9.3 (4.7)	8041.7 (523.6)
V7	5.0 (1.5)	14.8 (8.3)	8130.1 (574.2)
V8	3.9 (1.3)	1.2 (0.3)	172.2 (14.0)
V9	3.9 (1.3)	11.8 (6.7)	8363.6 (654.9)
V10	5.2 (1.7)	5.7 (4.9)	7762.7 (487.0)
V11	3.9 (1.1)	10.5 (6.3)	12434.4 (888.1)
V12	11.7 (0.8)	7.6 (5.8)	8754.6 (275.3)
V13	3.7 (0.9)	76.9 (62.1)	1709.6 (966.1)

Belczynski and Dominik 2012 (1208.0358)
mixture: 50% solar, 50% 0.1 solar

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- Applications
  - Electromagnetic counterparts
  - Measuring the merging binary
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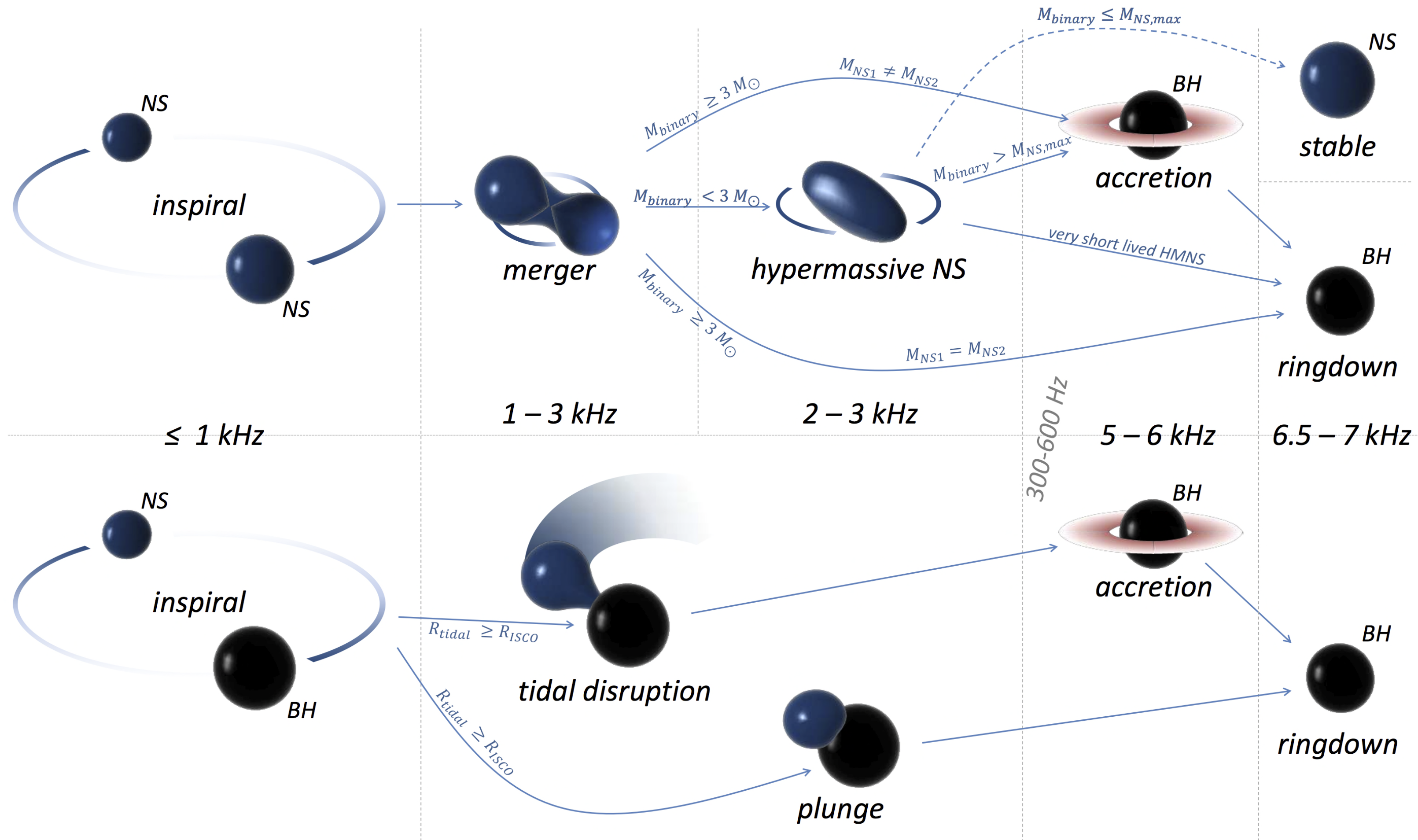
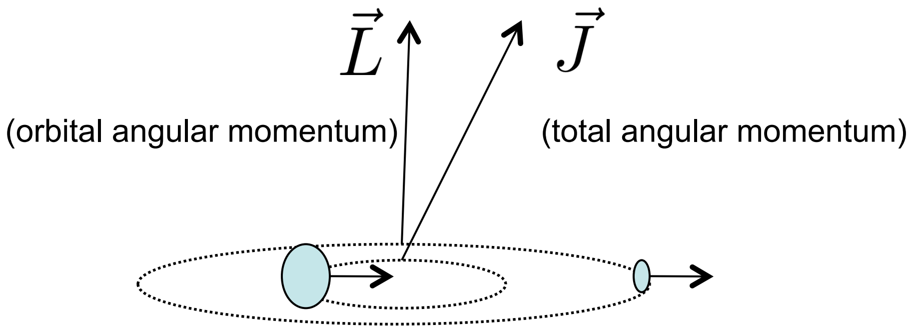
- What to expect

Binary merger dynamics



Merger dynamics

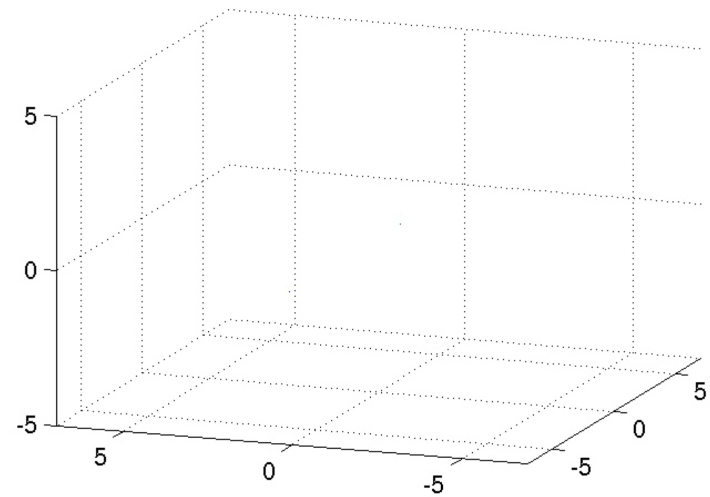
Merger dynamics



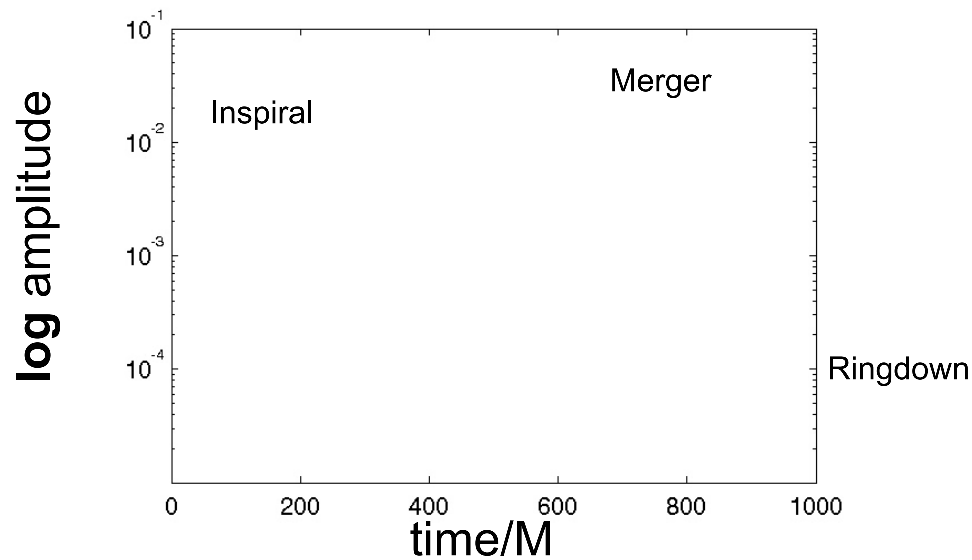
$$m_1/m_2 = 4$$
$$a_1 = a_2 = 0.6$$

ROS et al 1209.3712

Locations

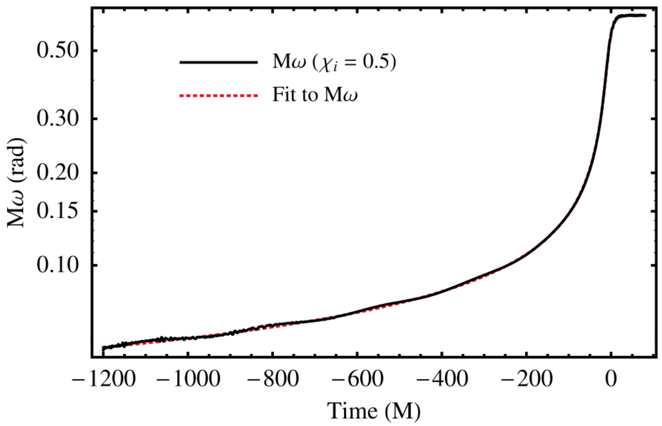


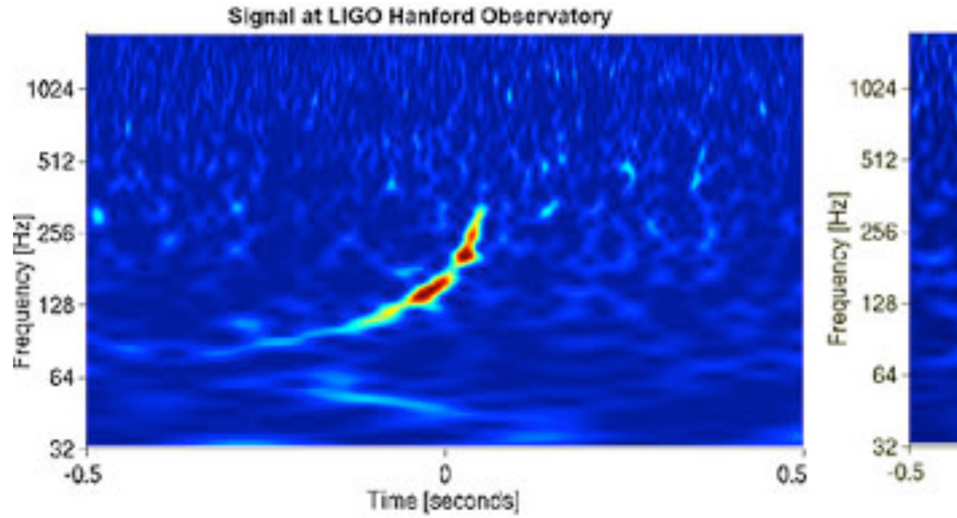
Waveform (one direction)



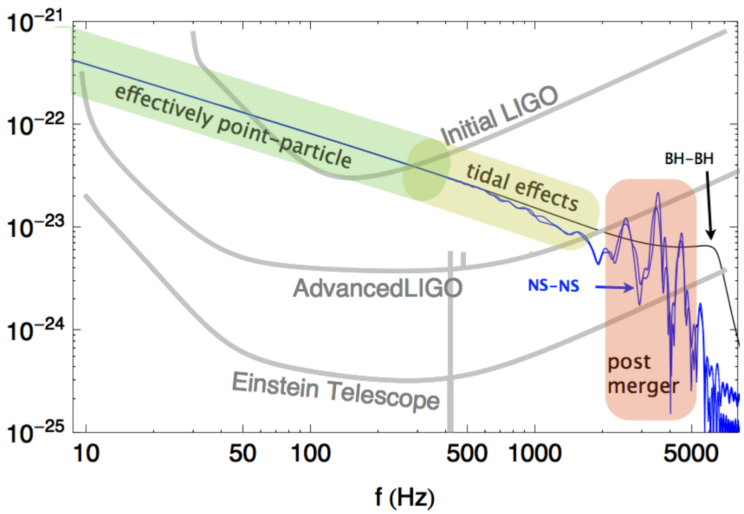
Merger signal

Time-frequency





Strain vs frequency



Strain vs time

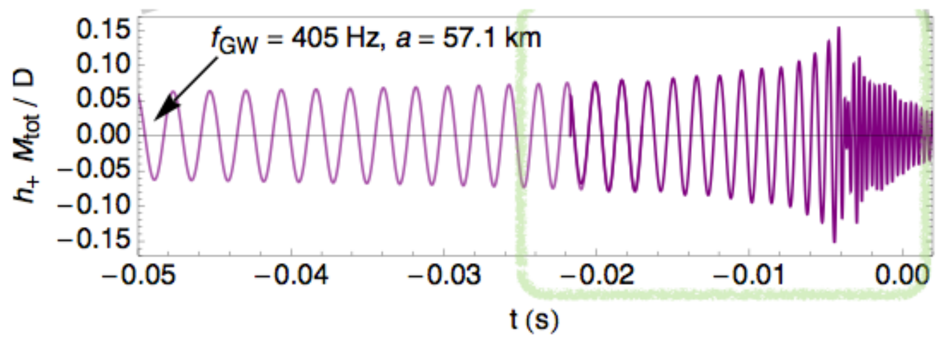
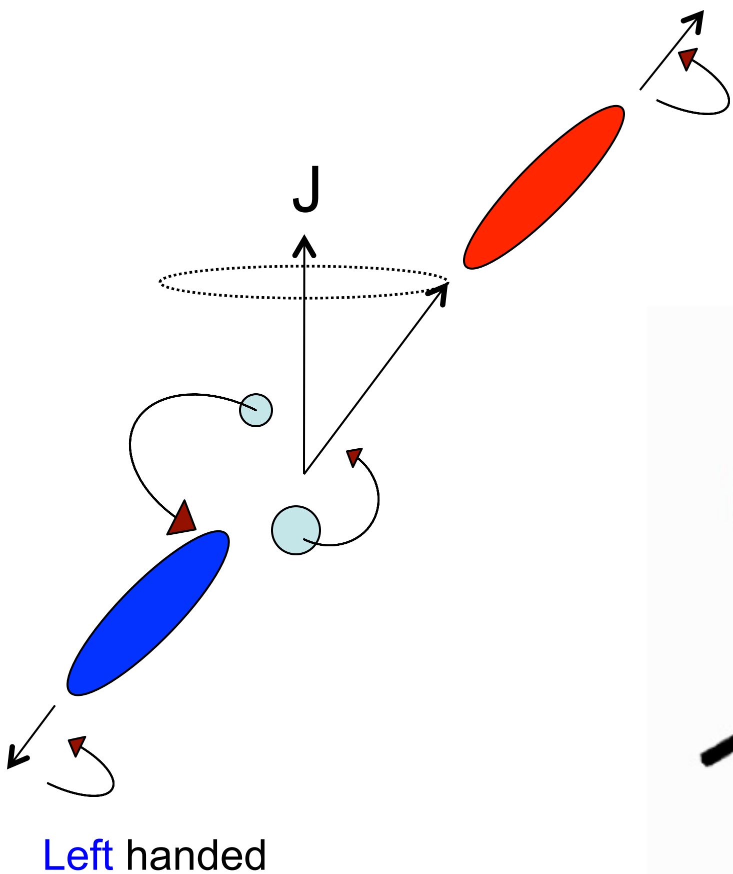
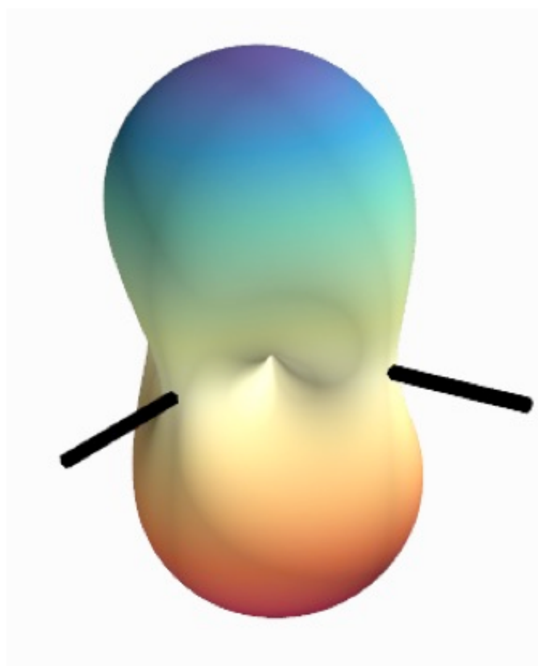


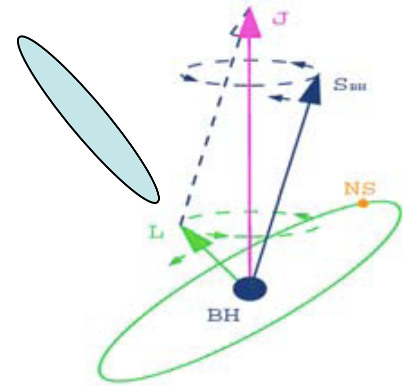
Image credits: J. Read, KITP conference 2012; Hannam et al 2010; LIGO blind injection

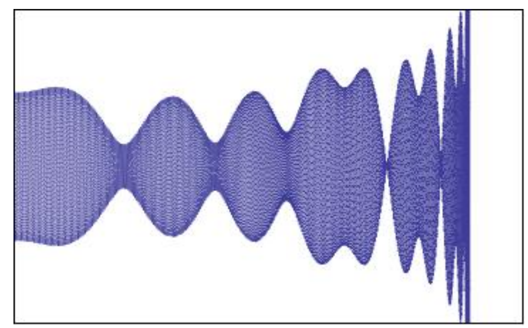
Beaming and modulation

Right handed







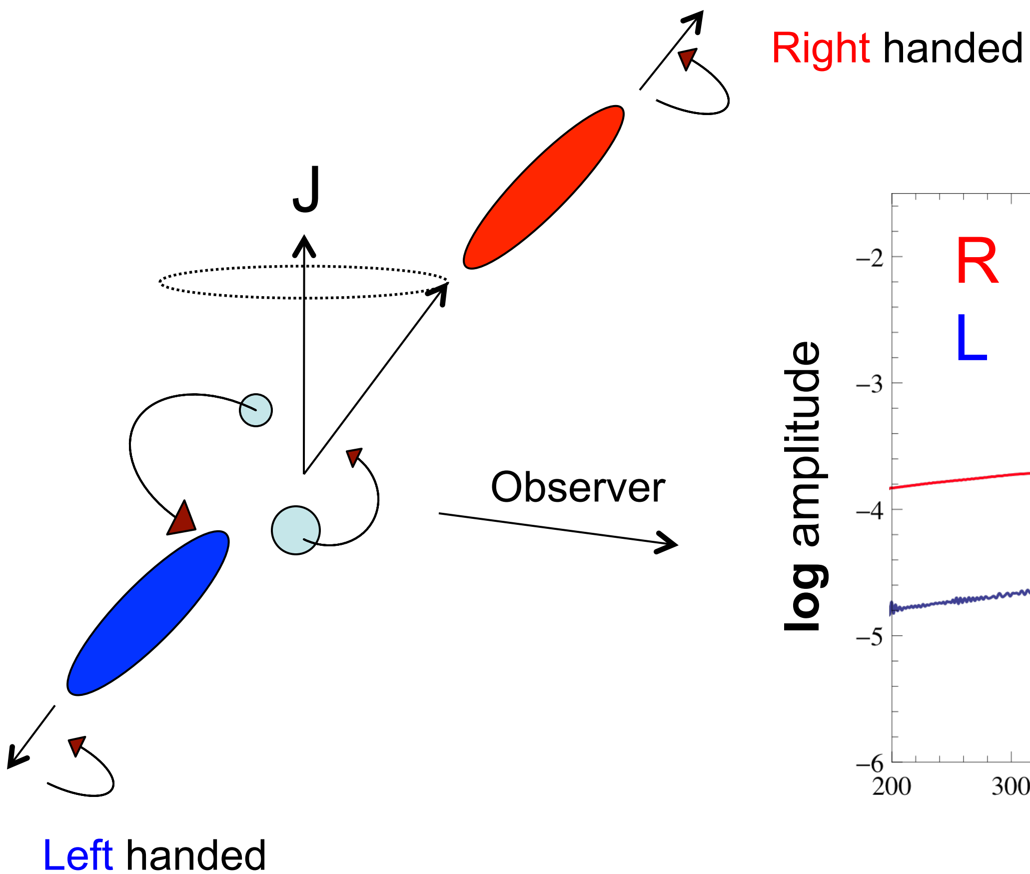


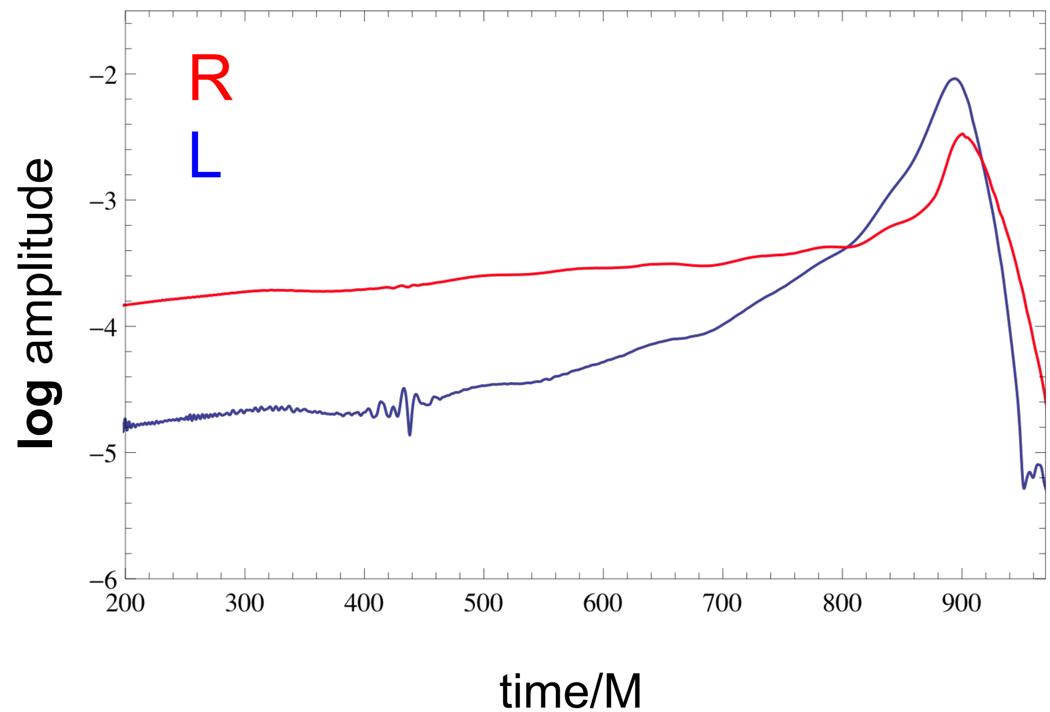
Polarization changes

- Experiments see one line of sight

  Measure R,L

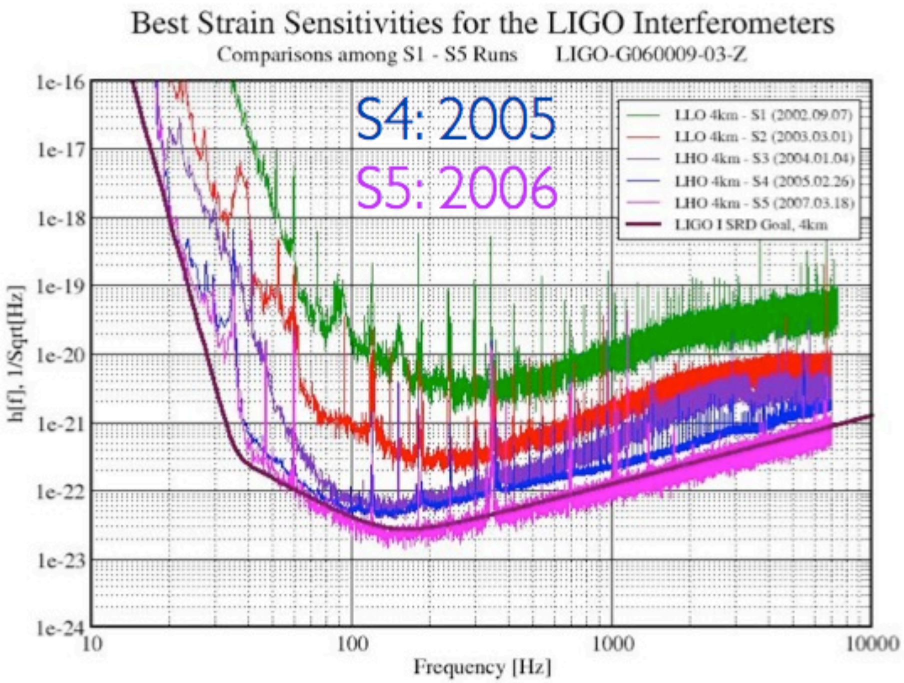
  …if sensitive to both linear polarizations
- Polarization changes over time

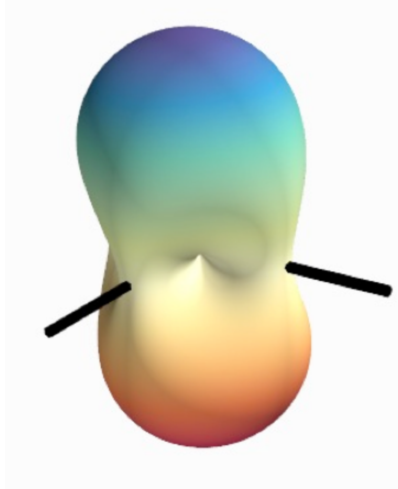


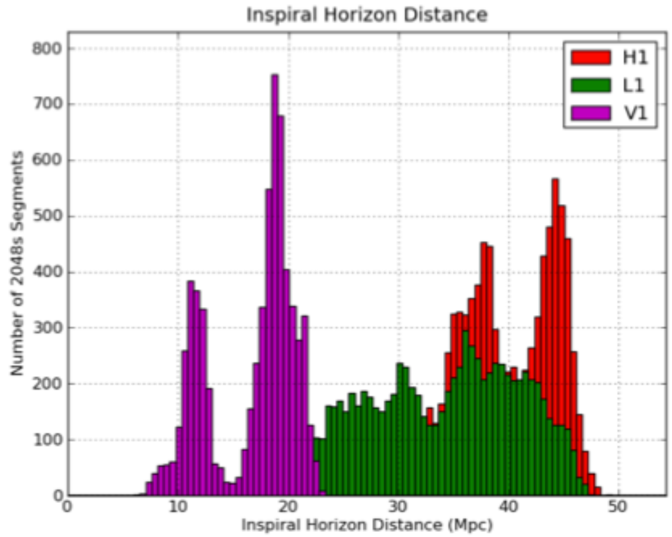


Detectors

Prior experience



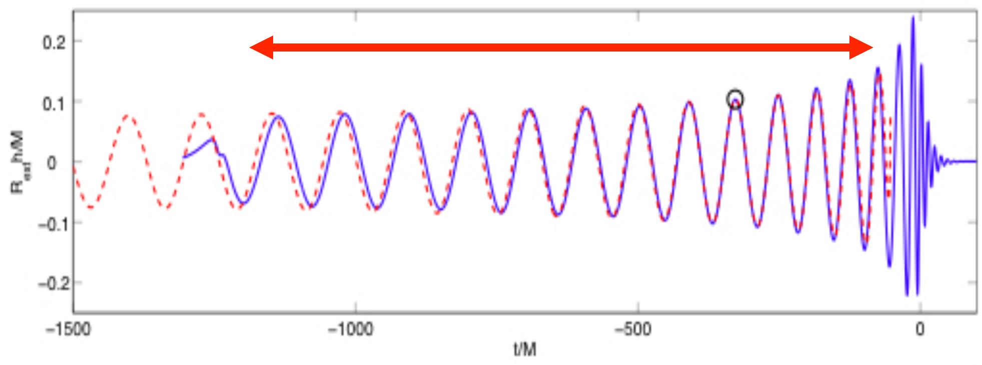




1203.2674
Initial LIGO, inspiral

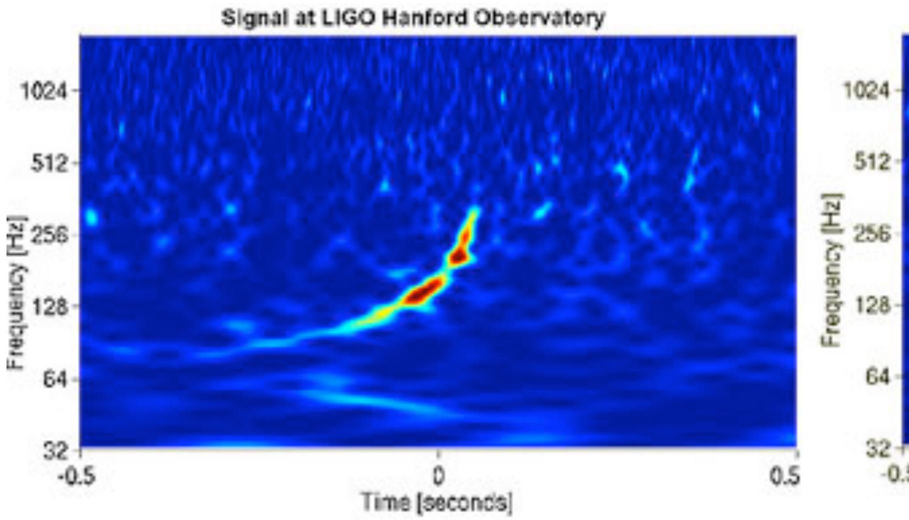
Detection and range

Search for model



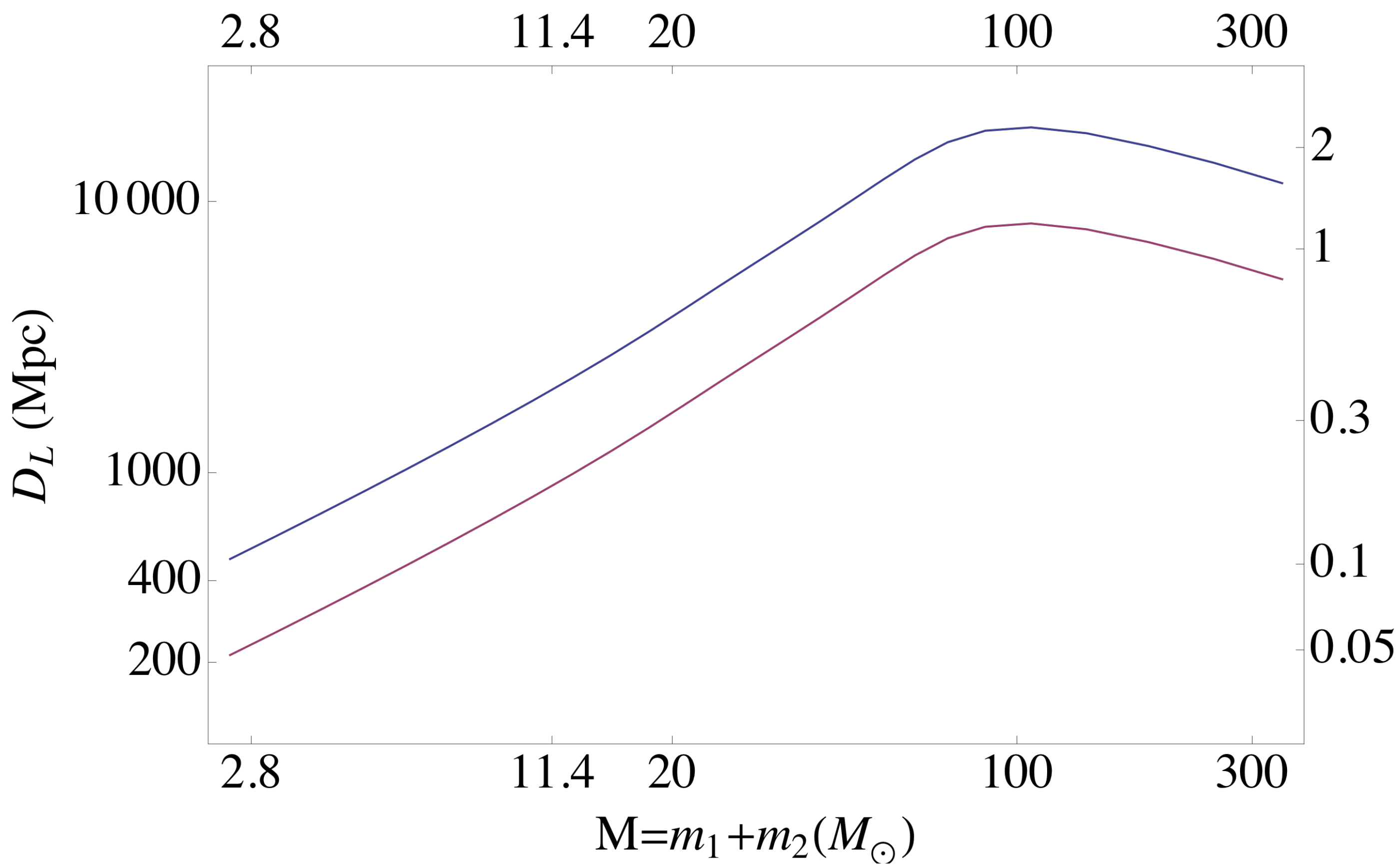
Unmodeled

Smaller, algorithm dependent range



Detection and range

Search for model



Equal mass

Why gravitational waves & binaries?

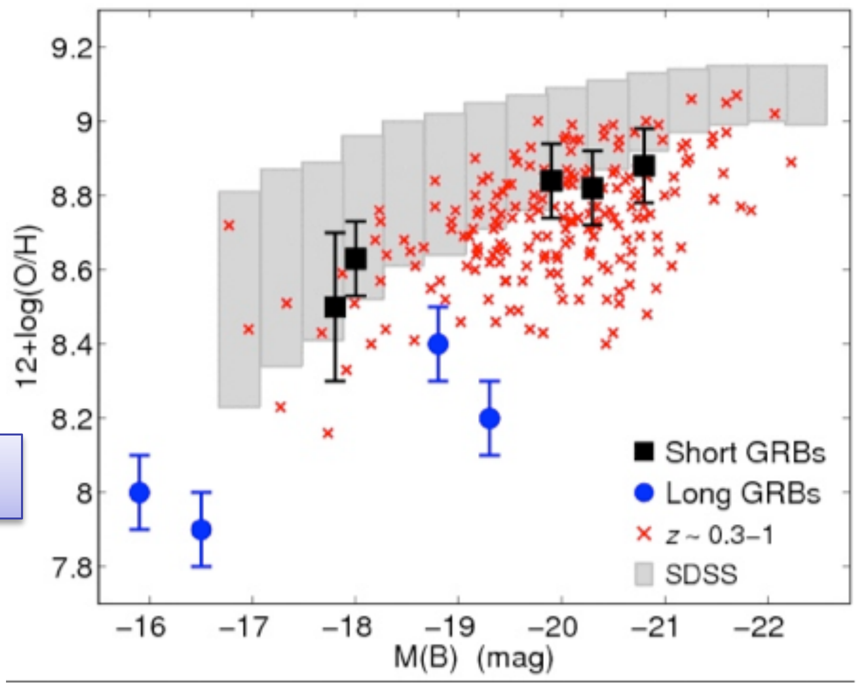
- New window on universe
- Applications
  - Electromagnetic counterparts
  - Measuring the merging binary
  - Nuclear matter
- What to expect

Electromagnetic counterparts

Berger 2009

Goals:

- Host galaxy/progenitors?
  - Typical host?
  - Age, Z of population?
  - Position vs host?



Common for SN, GRBs (Fruchter talk)

- Engine energetics
  - GRB = "collider"
    - GW : input
    - EM : output

Electromagnetic counterparts

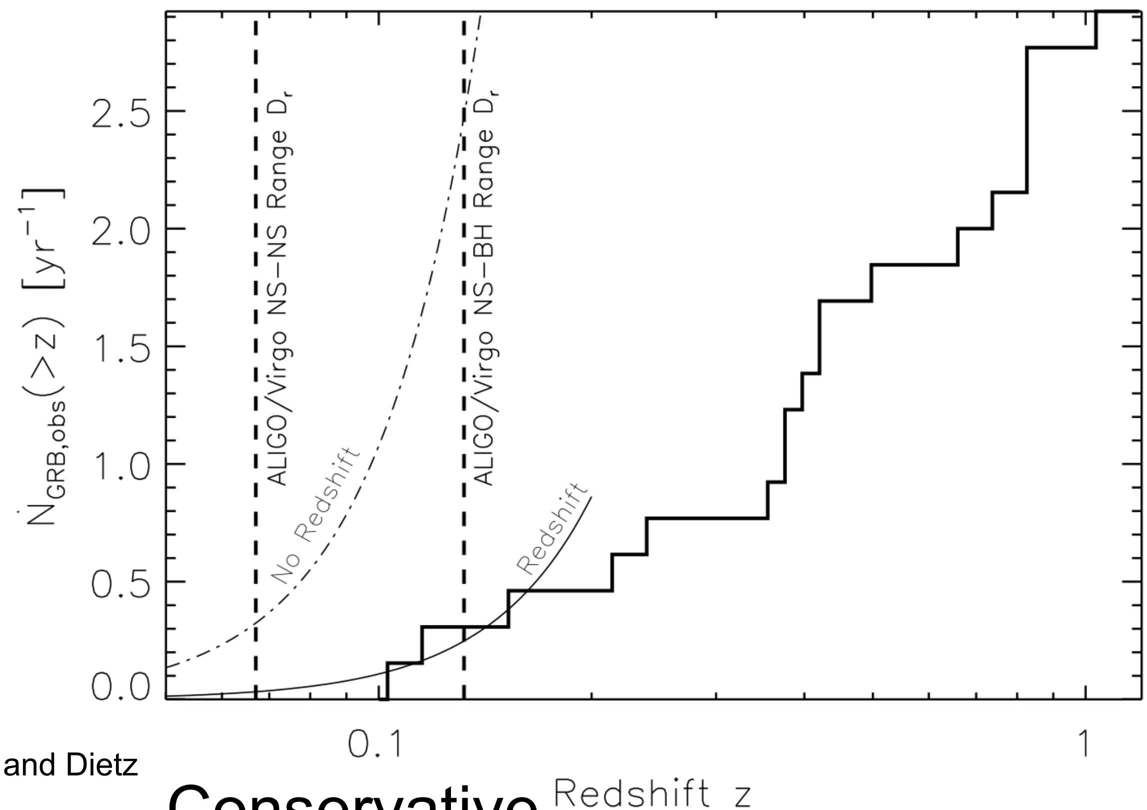
Strong EM source (short GRBs)

Rate of events: **debated**   [GW detection threshold & noise statistics; beaming; GRB distributions; source mass]

Here's one way:

- Fraction of EM GRB rate
  [simplifies beaming,L,…]

- BH-NS: possible >~ 1/yr
- NS-NS:
  Sensitive to prior (# faint?)
  Estimate ~ few % of blind rate



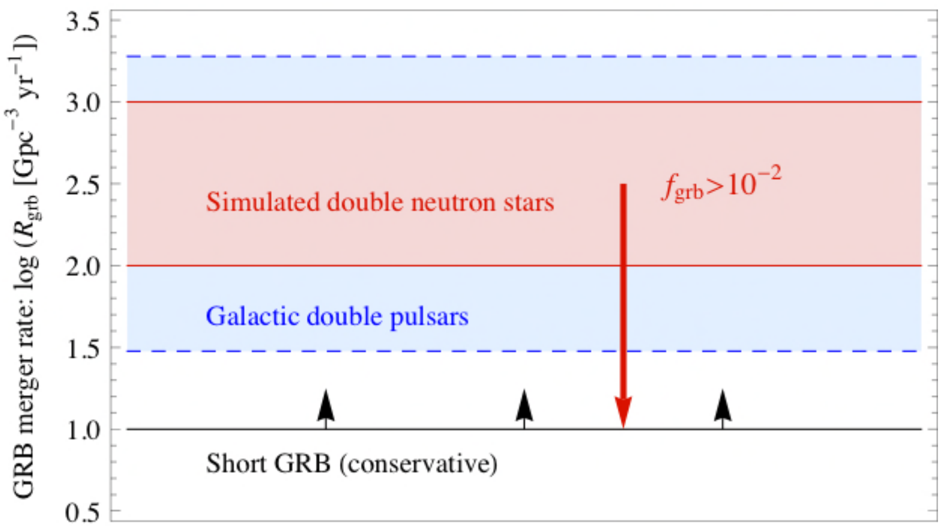
Conservative

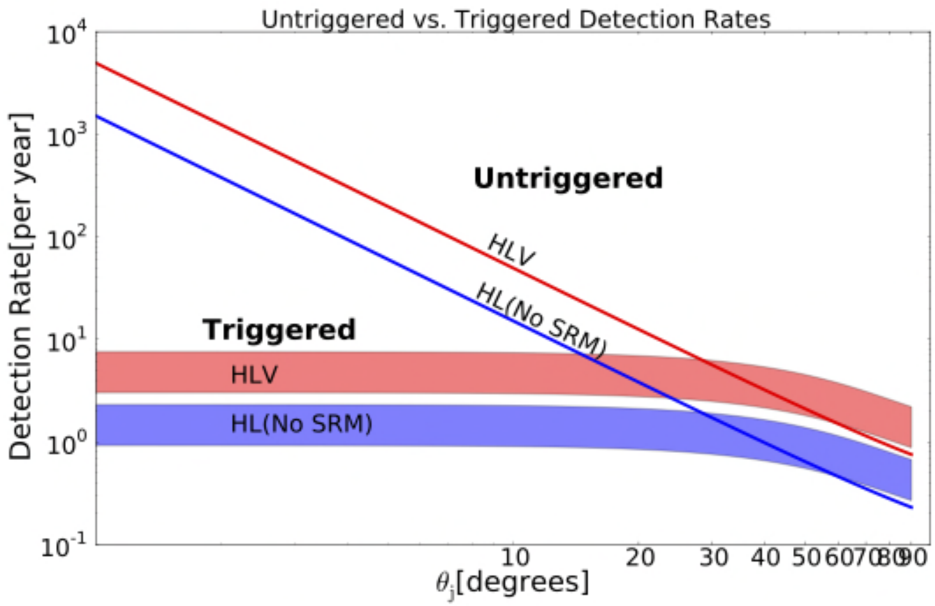
Metzger and Berger 2012
Yunes, ROS et al 2010
Chen and Holz 2012; Kelly et al 2012; Petrillo and Dietz
Abadie et al 2012 [1205.2216]
In prep: Dietz et al; Nissanke et al

Electromagnetic counterparts

Here's another

- Start with (beamed) GRB event rate/volume
- Correct for beaming





Belczynski, ROS et al 2007

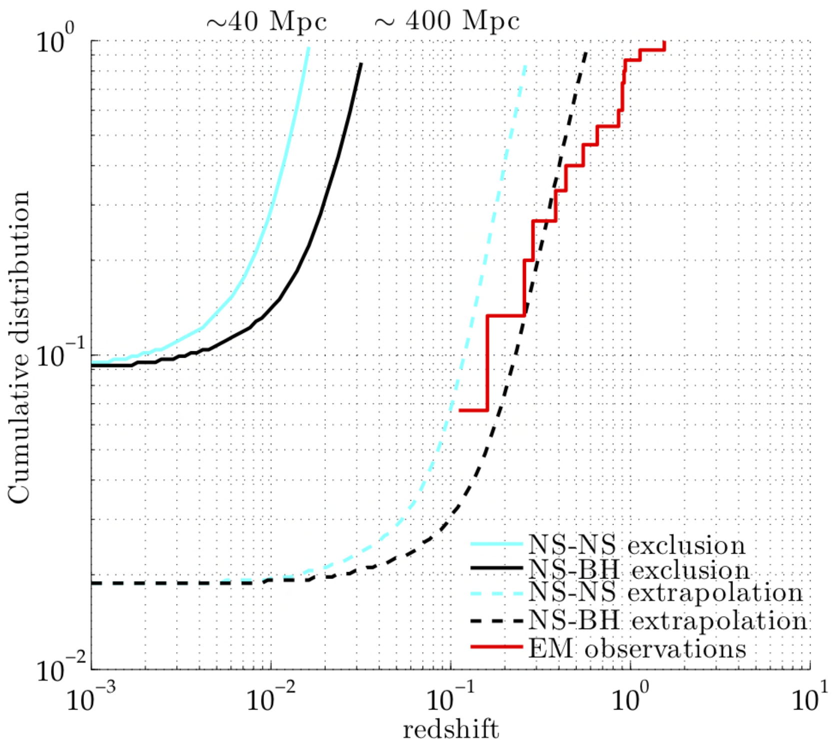
Chen and Holz 2012

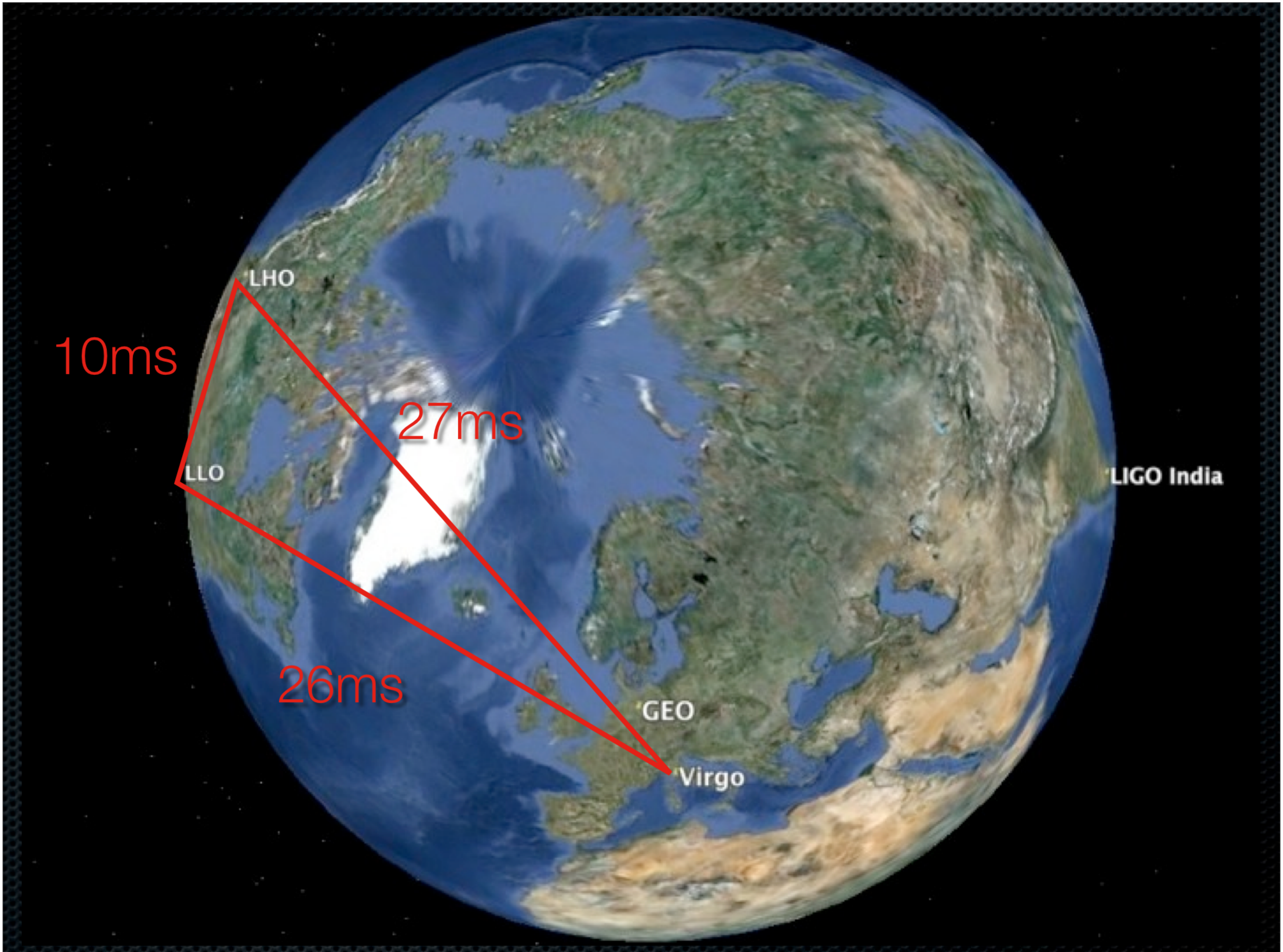
Also: Coward et al 2011; Petrillo and Dietz 2012 (102.0804)

Electromagnetic counterparts

Here's another

- Extrapolate existing LIGO search (S6 short GRB: 1206.2216)
  90% **upper limits** on population




LHO
10ms
27ms
LLO
LIGO India
26ms
GEO
Virgo

Electromagnetic counterparts

GW-triggered EM followup

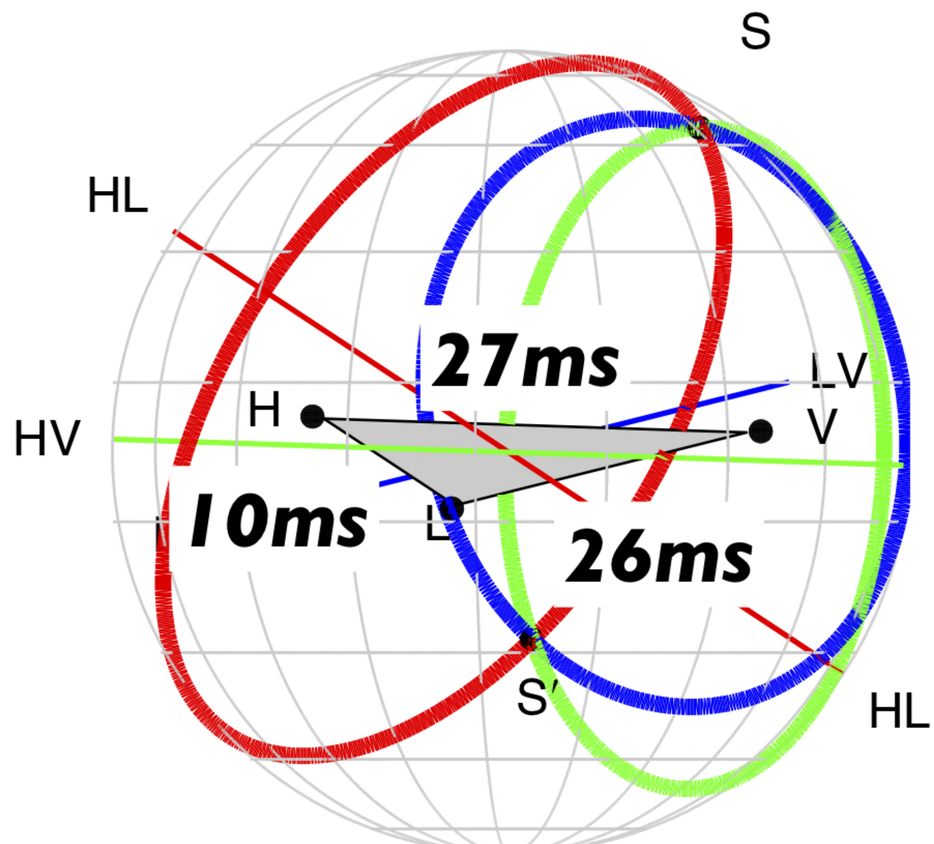
Faint, isotropic event?

GW localize poorly

10s-100s deg^2

Cover out to 200 Mpc ?

Mansi = ok



Fairhurst, KITP 2012
Fairhurst 2009

Why gravitational waves & binaries?

- New window on universe

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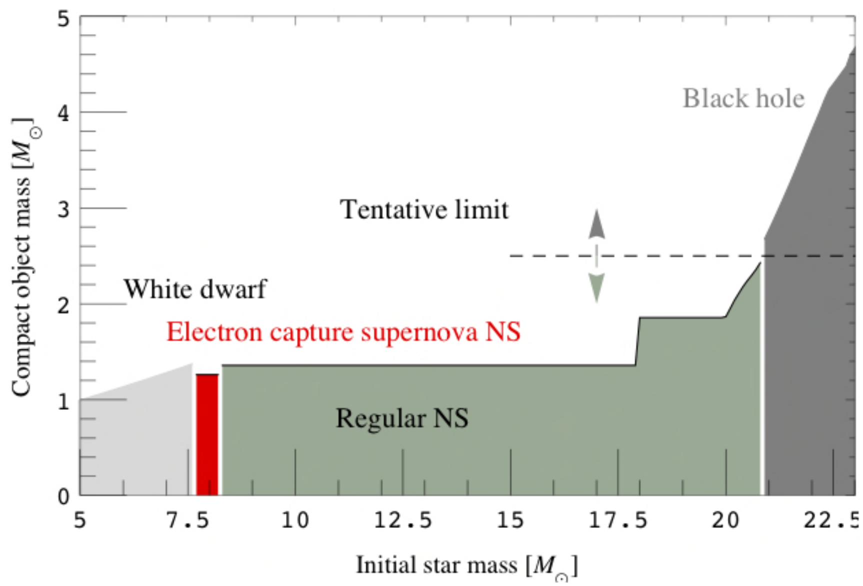
- What to expect

Properties of the binary at merger

Why?

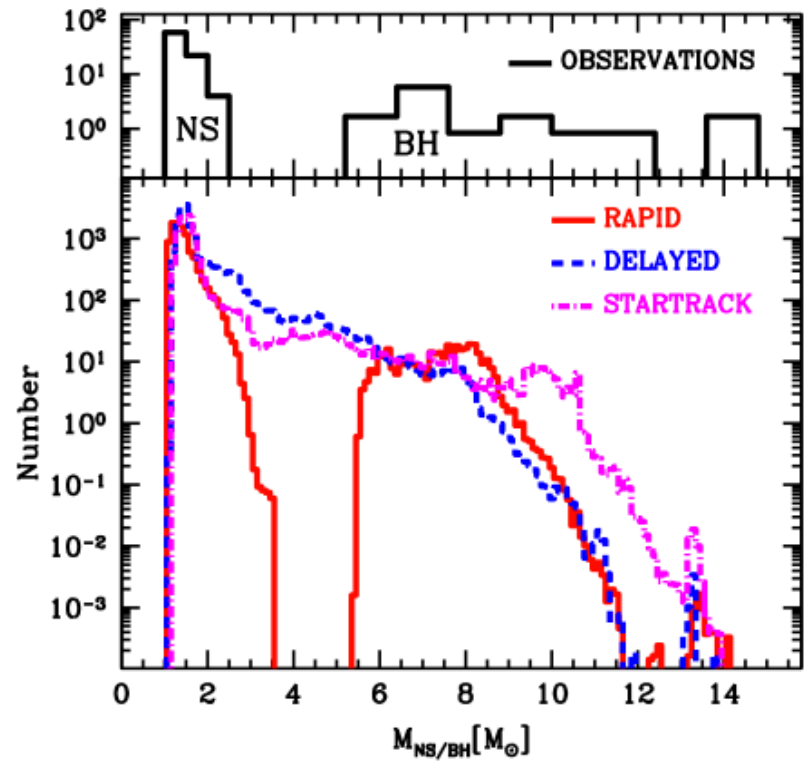
Mass distributions probe supernova physics

One initial-final relation (with fallback)



Belczynski, ROS, et al ApJ 680 129

X-ray binaries



Belczynski et al 2012, ApJ 757 91

Properties of the binary at merger

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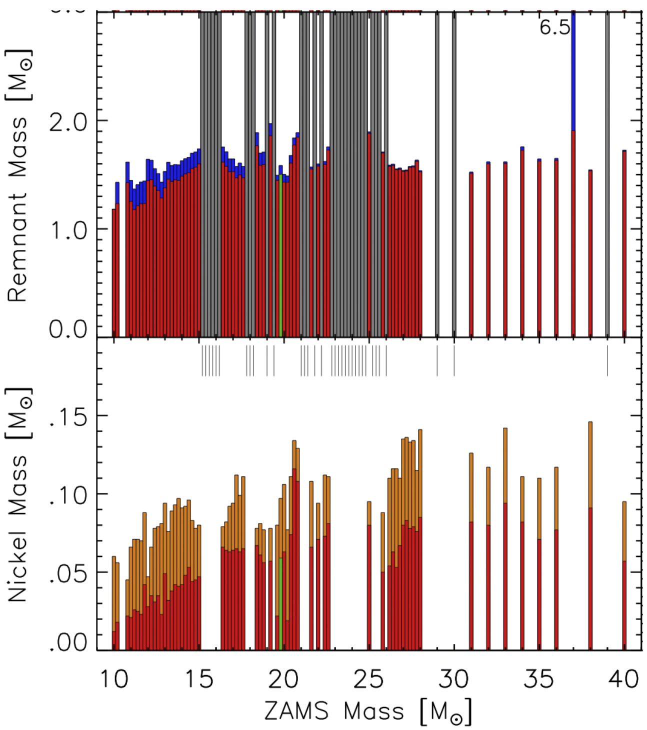
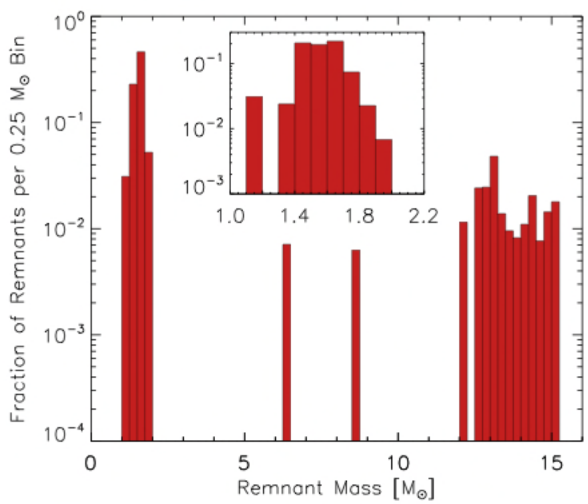
Mass distributions probe supernova physics

Another initial-final relation
(with fallback)



Ugliano et al 2012



Properties of the binary at merger

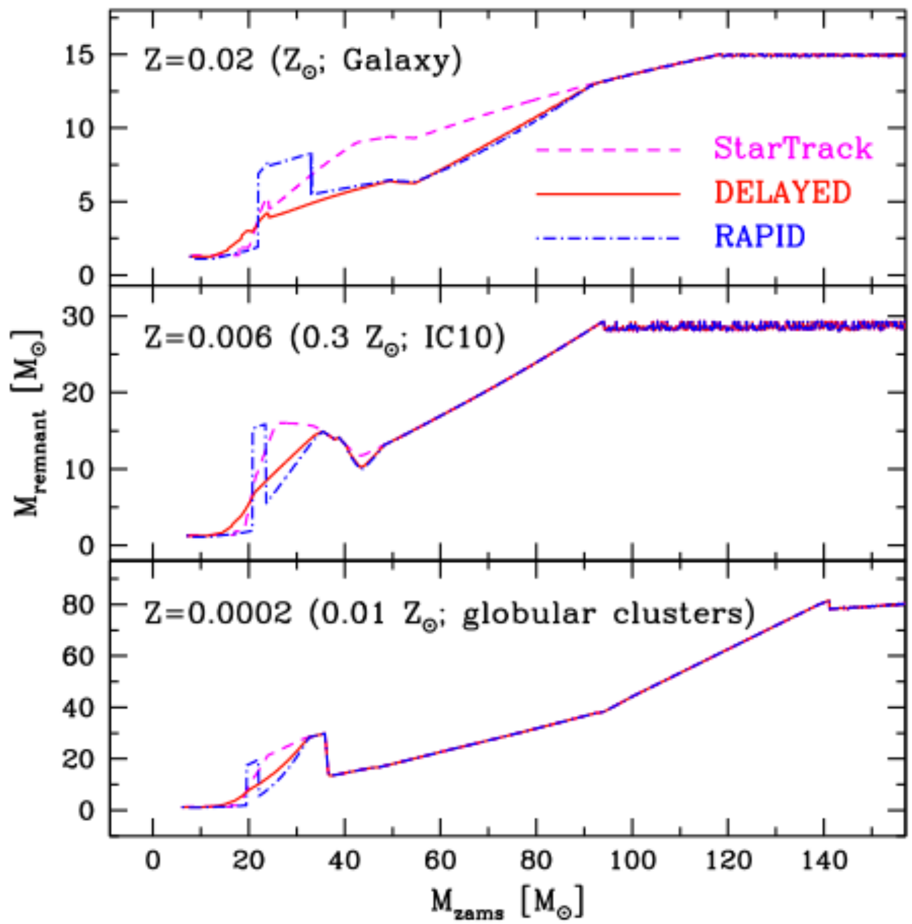
Why?

BH mass distributions probe

mass loss rate

binary interactions

Z distribution



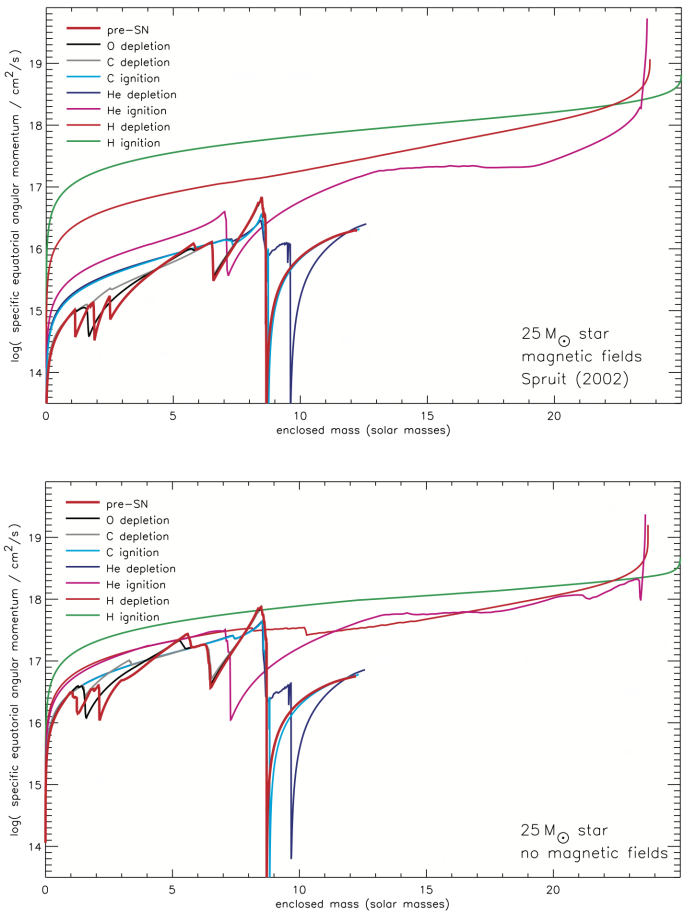
Properties of the binary at merger

Why?

BH spin distributions probe

J transport in rotating stars

Binarity (spinup, stripping)



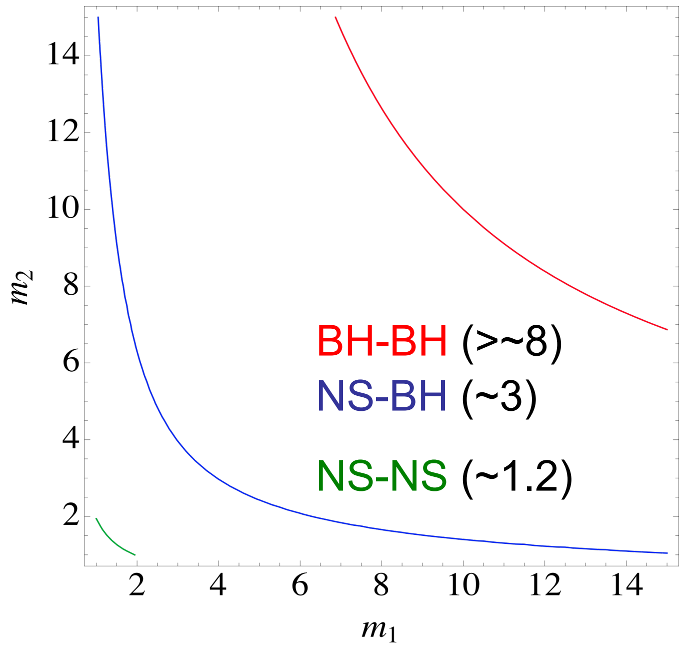
NS progenitor, Heger et al 2005 ApJ 626 350

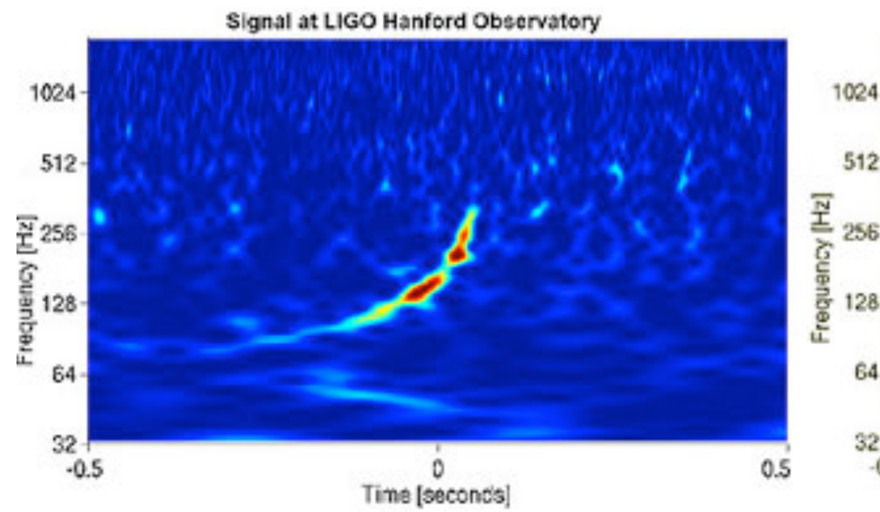
Properties of the binary at merger

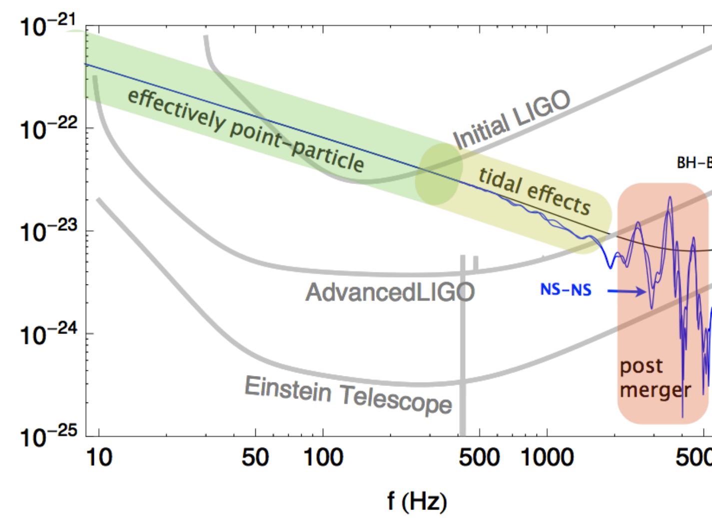
How

- "Chirp" -> "chirp" mass

$$\mathcal{M}_c = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$







- "Exact" at low mass $m_1 + m_2 \ll 30 M_\odot$

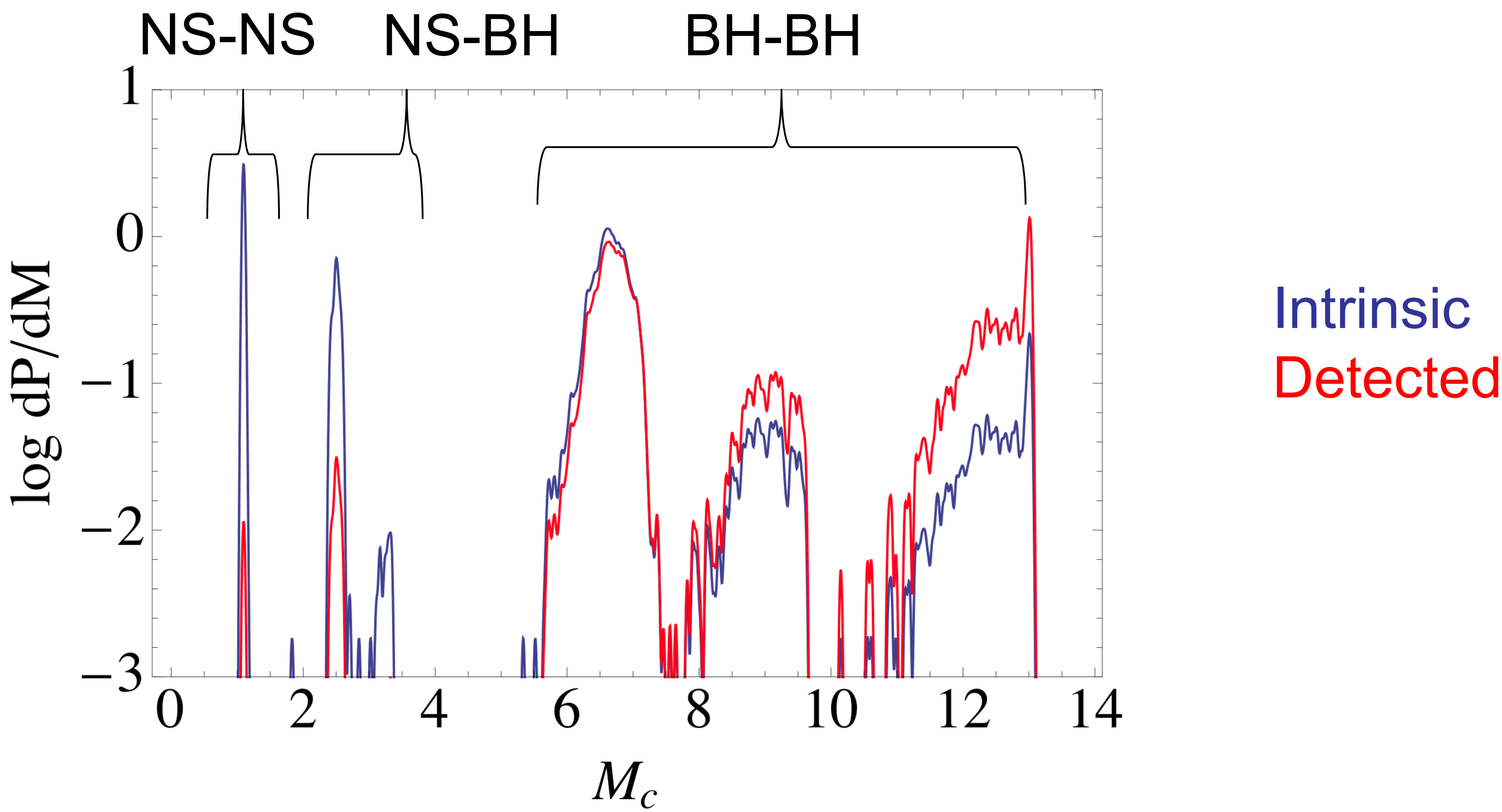
$$\Delta\mathcal{M}_{c,90\%} \lesssim 0.1 M_\odot (\mathcal{M}_c/3)^{8/3}$$

iLIGO

Cho et al 2012 1209.4494 + in prep

Properties of the binary at merger

Distribution predictions



Data from Dominik et al 2012 (V1A)

Constraint methods: ROS (1209.3712); Mandel (0912.5531); Bulik et al 2003; Farr et al 2011 (1011.1495); Pejcha et al 2012

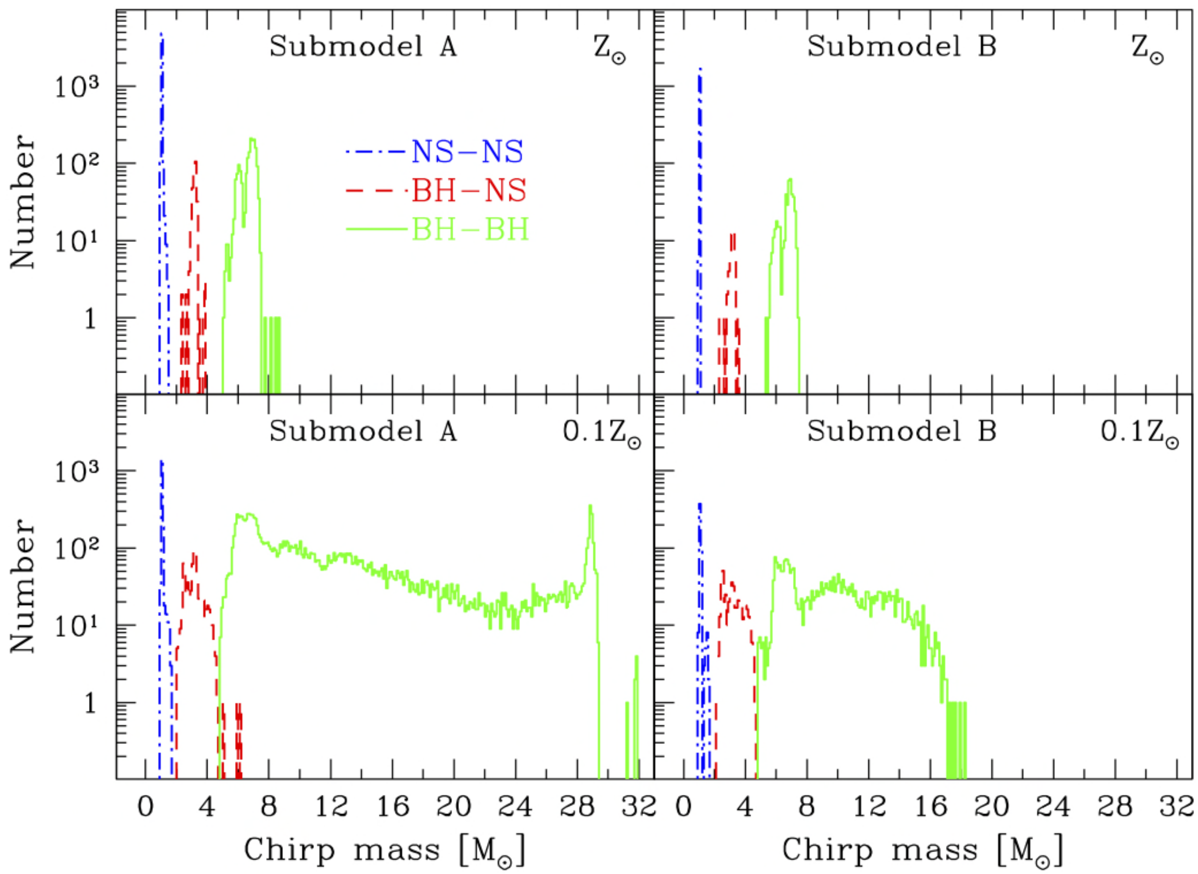
Properties of the binary at merger

Distribution predictions

Significant variability

Easy to distinguish…

if enough events



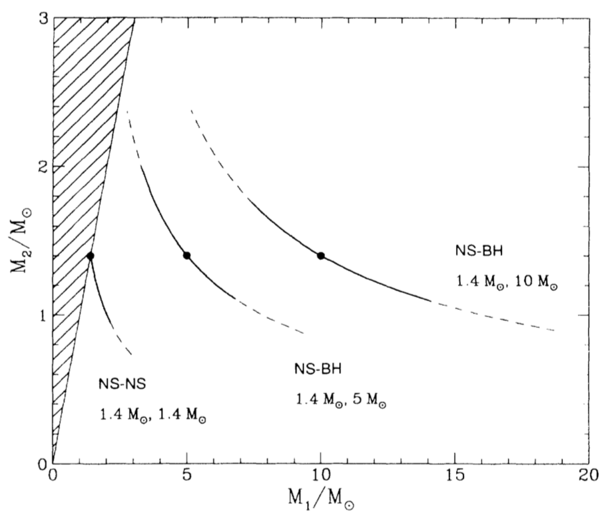
Dominik et al 2012 (arXiv:1202.4901)

Properties of the binary at merger

Bad news: Mass ratio

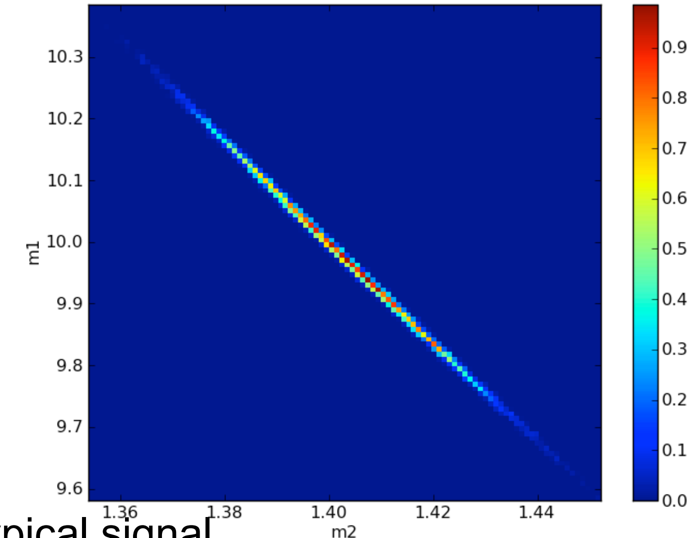
$$\eta = \frac{m_1 m_2}{(m_1+m_2)^2}$$

$$\begin{aligned} \eta &= 1/4 && \text{Equal} \\ &\simeq 0.1 && \text{BH-NS} \\ &\simeq 0.22 && \text{2:1} \\ \Delta\eta_{90\%} &\simeq (0.02 - 0.1) && \text{BH-NS} \end{aligned}$$

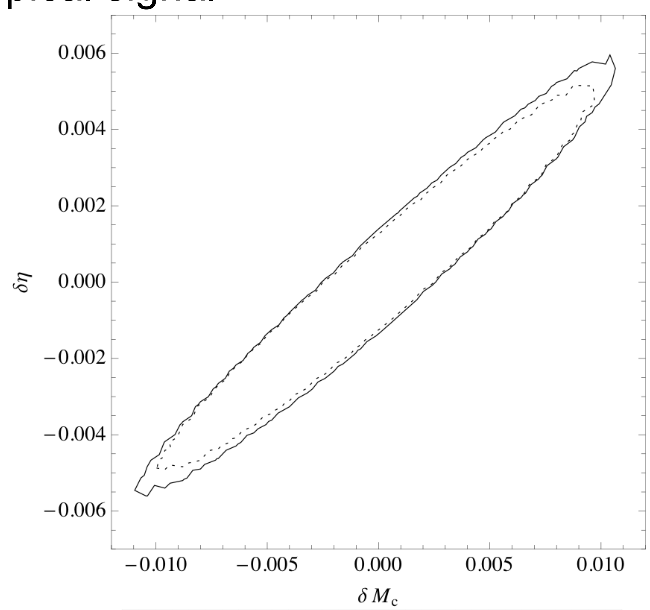


Cutler and Flanagan 1994

Very strong signal



Typical signal



Cho et al 2012 1209.4494 + in prep

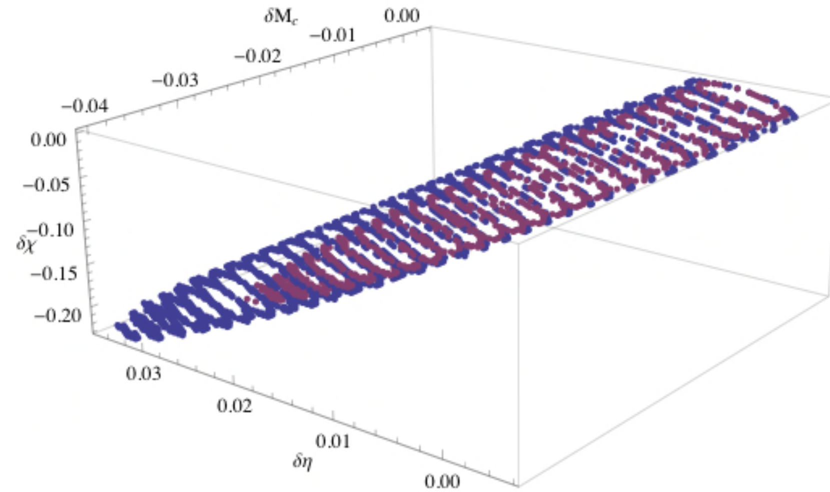
Properties of the binary at merger

Spin : spin-orbit

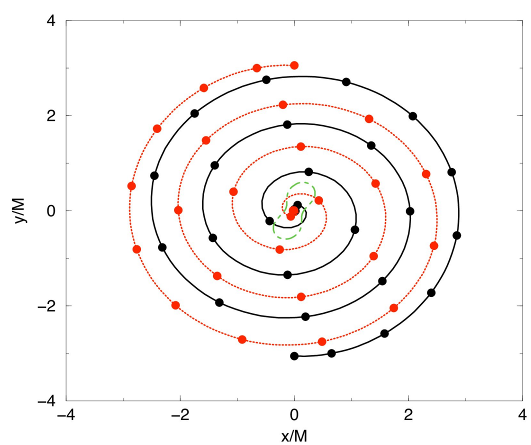
Bad

Orbit duration: many factors

= spin↑or mass↓



↑↑



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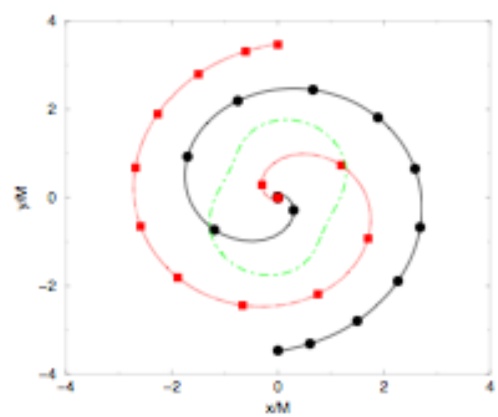


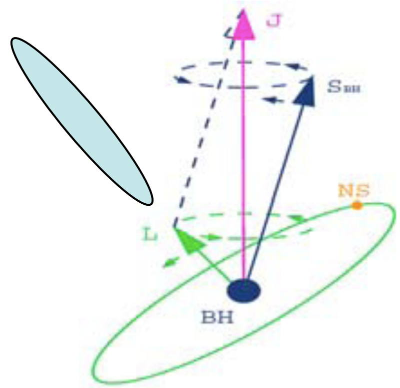
Properties of the binary at merger

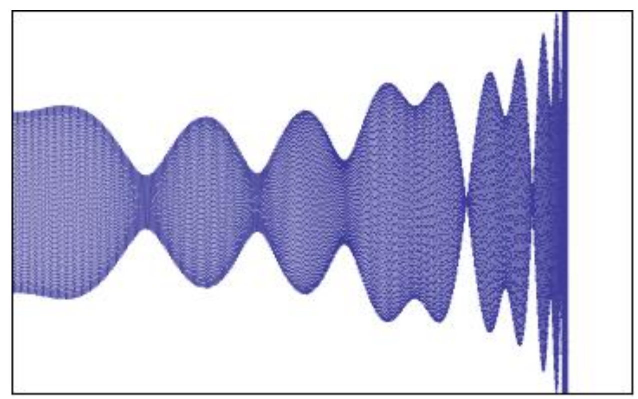
Spin

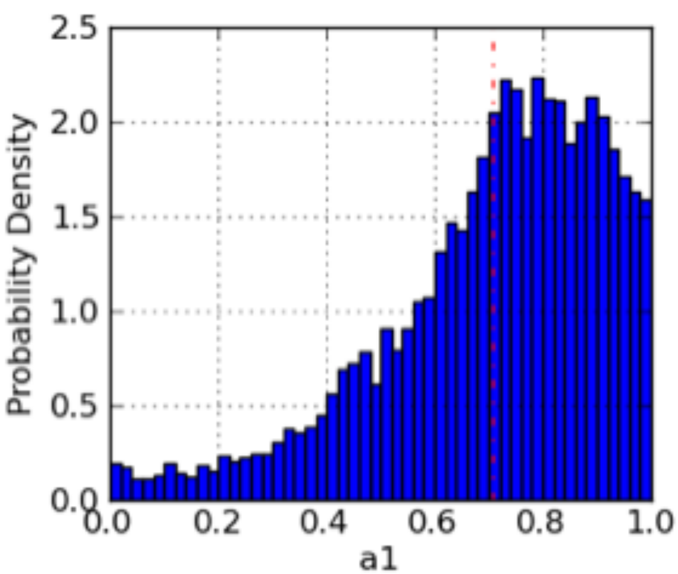
Bad: Orbit duration degeneracy

Good: **Precession** modulates

Spin encoded **geometrically**







Veitch, KITP Conference 2012

$\Delta\chi_{90\%} \simeq 0.1$ BH-NS

Brown,Lundgren, ROS (1209.3712)
Cho et al 2012 1209.4494 + in prep

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- What to expect

Nuclear matter

How do GW constrain?

Pre-merger tidal distortion

Tidal disruption

Post-merger remnant

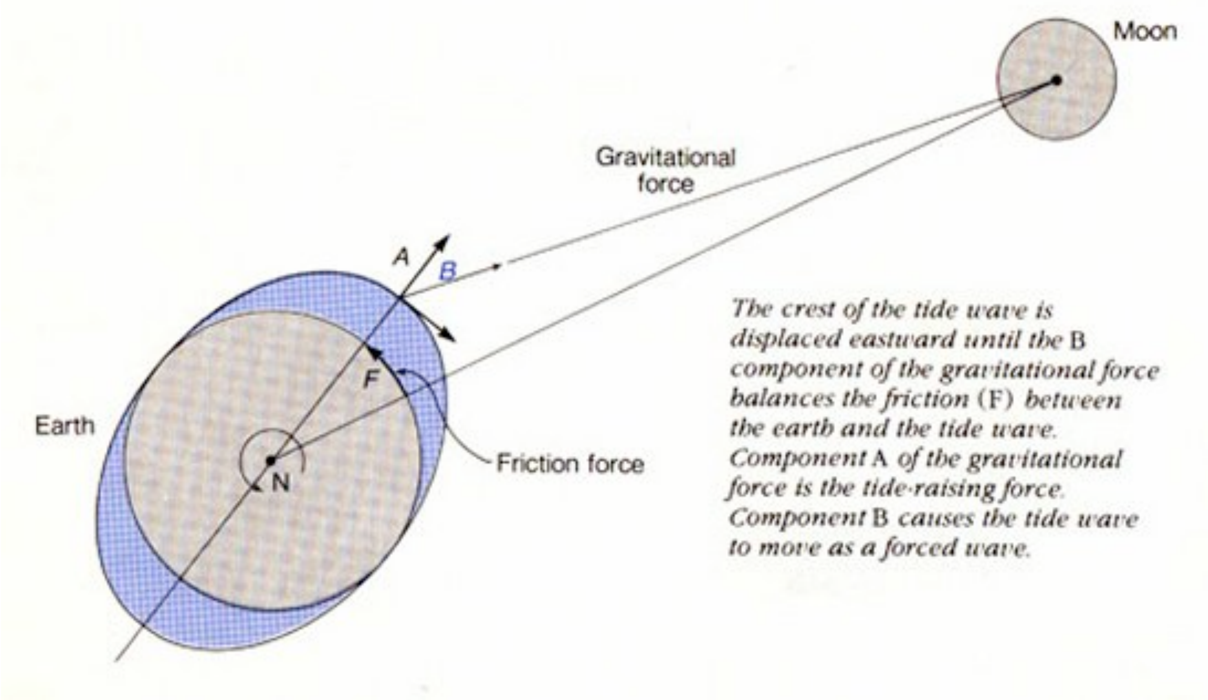
Hypermassive NS modes, lifetime

Disk modes [weak]

Stack events? [Many faint >> one strong? : Markakis et al 2010 1008.1822]

Nuclear Matter

Pre-merger tidal distortion



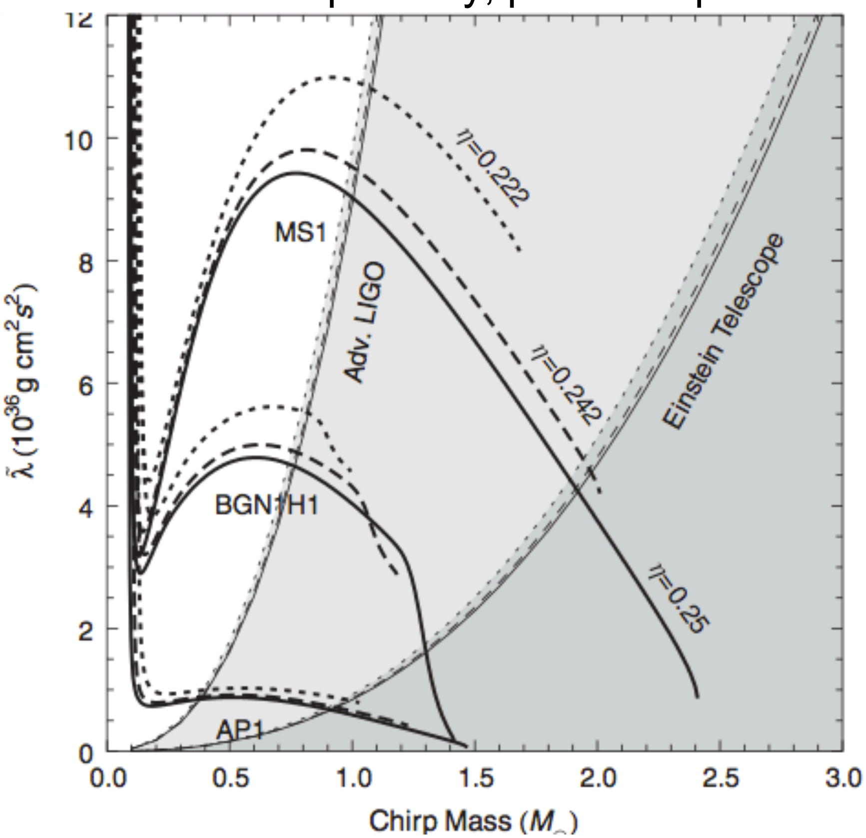
$$\lambda = \frac{Q}{\mathcal{E}} = \frac{\text{size of quadrupole deformation}}{\text{strength of external tidal field}}$$

Nuclear Matter

NS-NS

Conservative

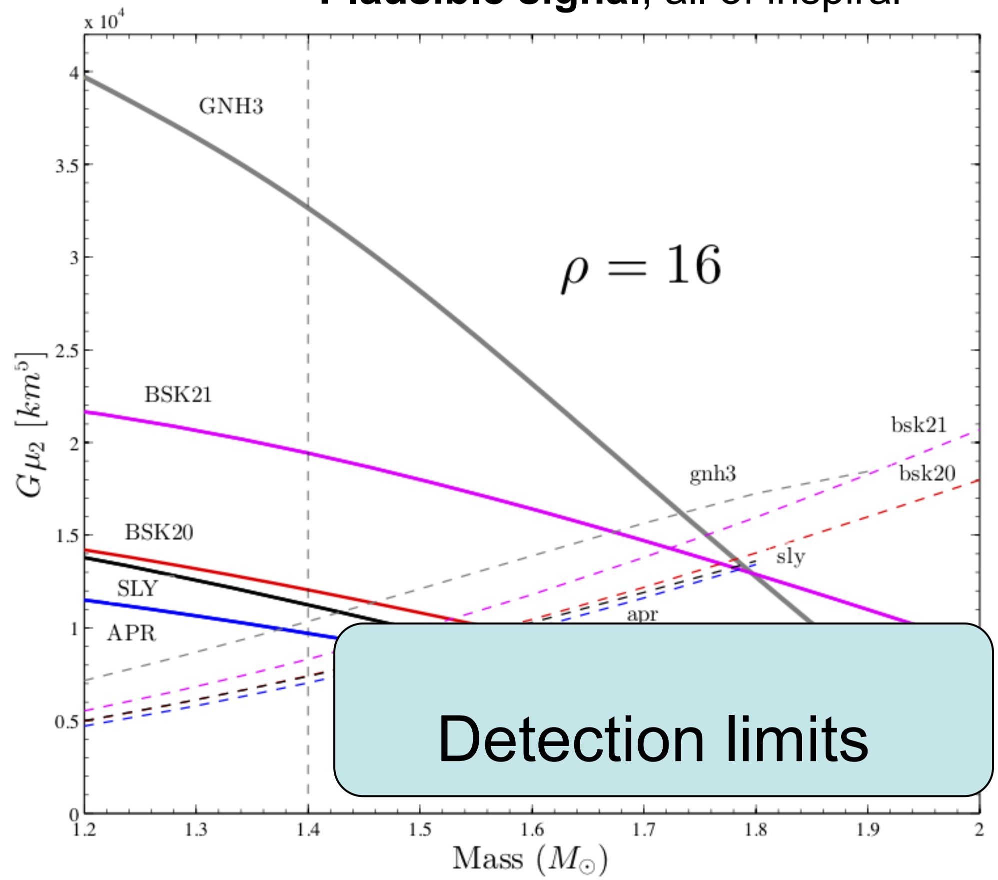
100 Mpc away; part of inspiral



Hinderer et al 2010, PRD

Aggressive

Plausible signal; all of inspiral



Damour, Nagar, Villian 2012,PRD

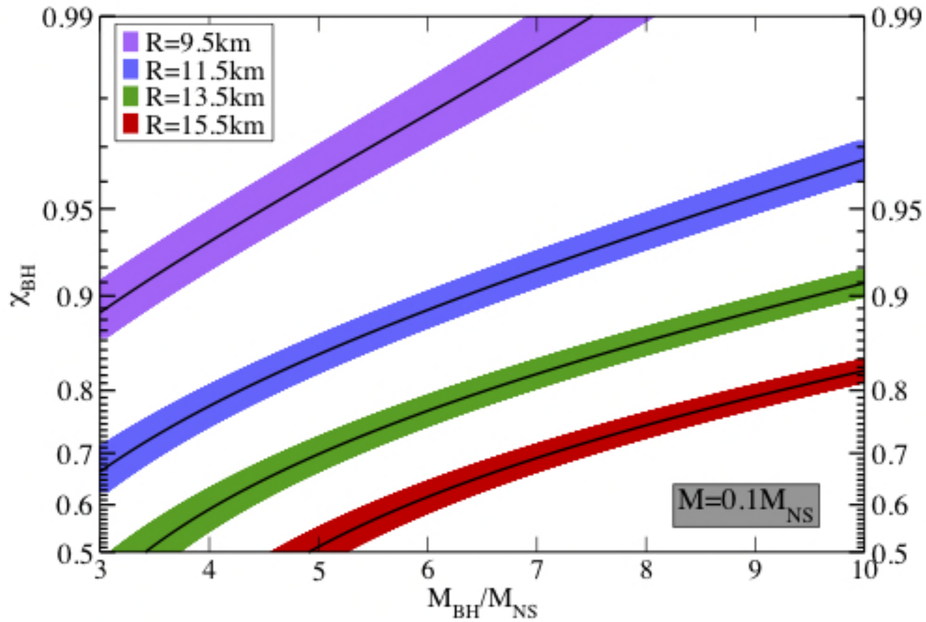
Nuclear Matter

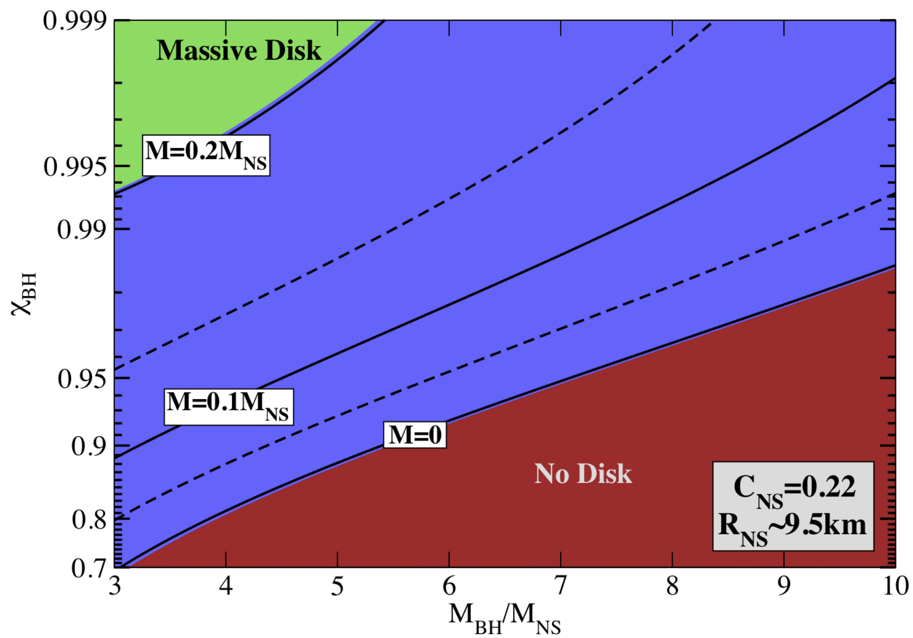
Tidal disruption

Small BH horizon

(low M, high a)

Larger NS





Foucart 1207.6304

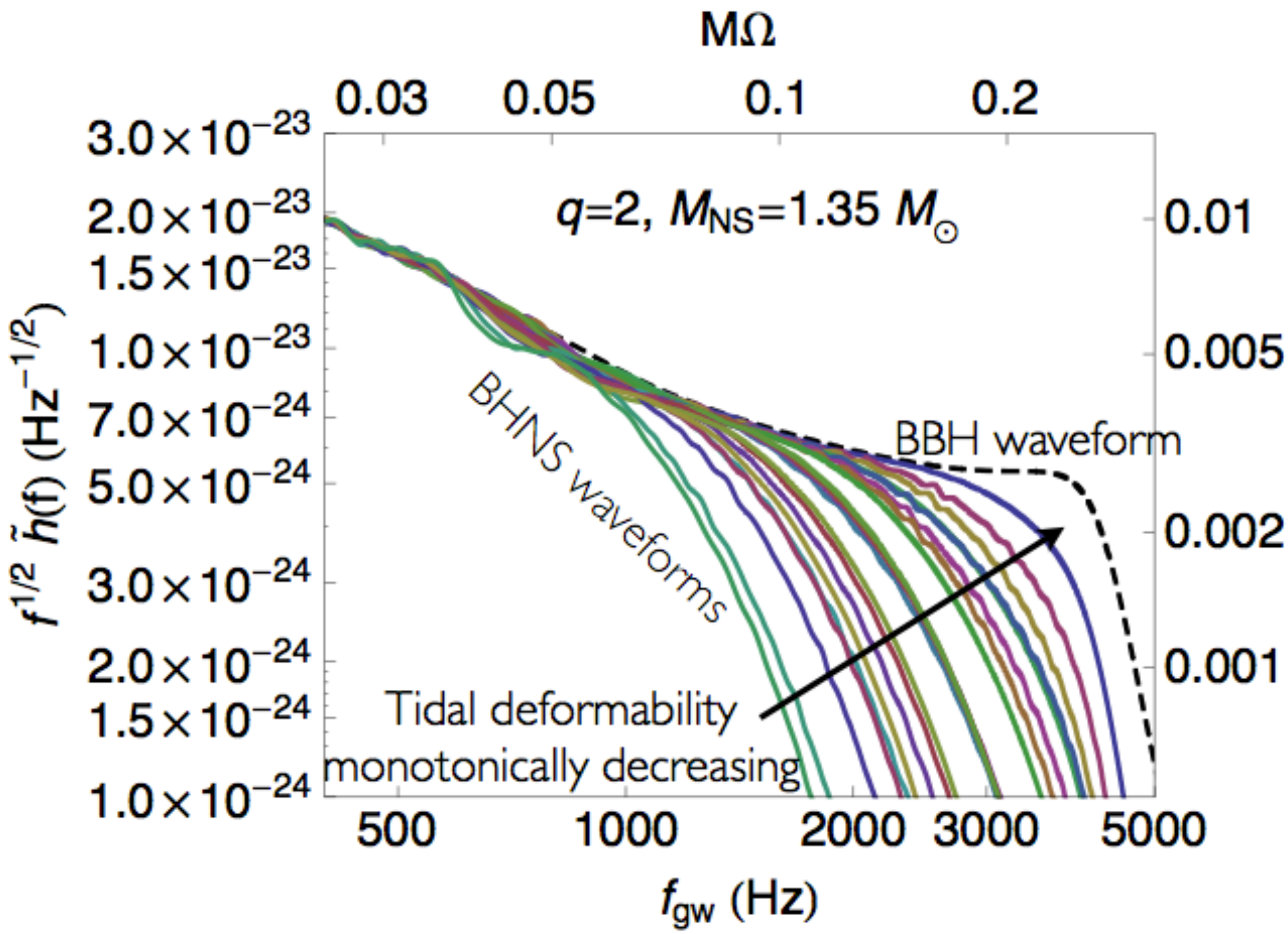
Nuclear Matter

BH-NS

Just λ

R : 10-40%

at 100 Mpc

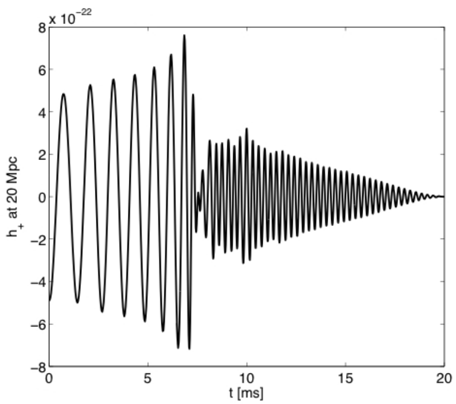


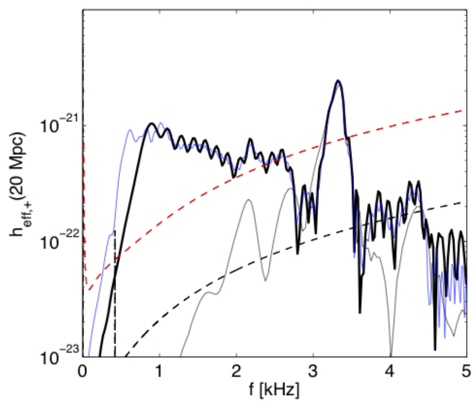
Lackey et al, PRD 2012

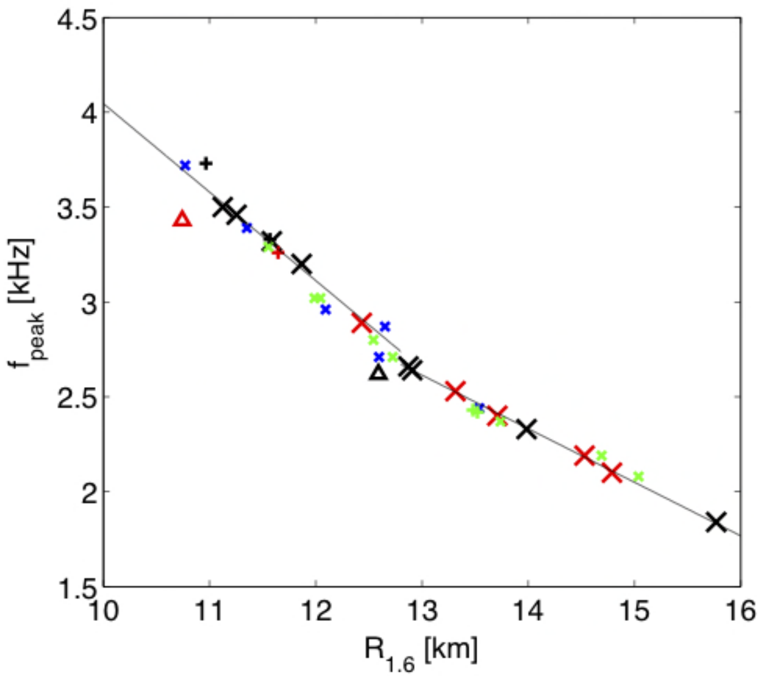
Nuclear Matter

Post-merger remnant

Hypermassive NS modes, lifetime







Bauswein et al 2012

Method: Frequencies of remnant

Systematics:

MRI, neutrino cooling/P support;

EOS?

Examples:

Janka, Stergoulias,

Japan: Shibata et al group

SXS: Duez et al

Illinois: Shapiro et al group

Lehner; +….

Disk modes

What to expect

- Timeline
  - Gradual increase in sensitivity [Abadie et al in prep; Mandic talk]
- Science
  - EM counterparts : engine, host (+nucleosynthesis?)
  - Compact object mass, spin distributions
    - But can we interpret them? Scenarios with robust predictions (fallback-dominated)?
  - Nuclear matter?
    - Possible (stacking weak; high rate; alt noise curve; …)
    - Systematics? Work in progress (MCMC)