Title: Exploring (astro)physics with gravitational waves

Date: Jun 05, 2013 11:00 AM

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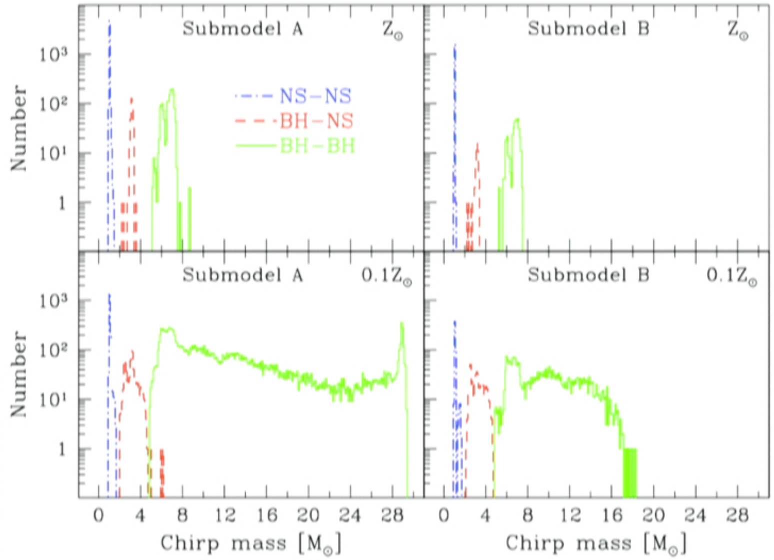
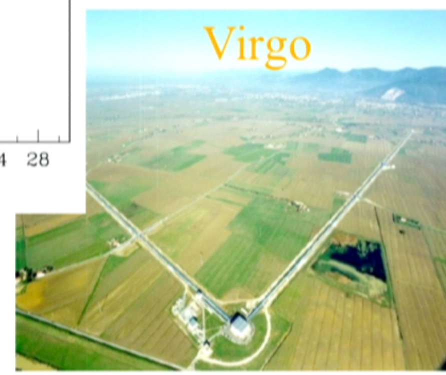
Abstract: The ground-based gravitational-wave telescopes LIGO and Virgo approach the era of first detections. Gravitational-wave observations will provide a unique probe for exploring strong-field general relativity and compact-binary astrophysics. In this talk, I describe recent predictions regarding the distributions of black-hole and neutron-star binary mergers, and progress on solving the inverse problem of turning gravitational-wave observations into astrophysical information. I highlight some exciting recent investigations into the use of gravitational waves as tests of general relativity.

Exploring (astro)physics with gravitational waves



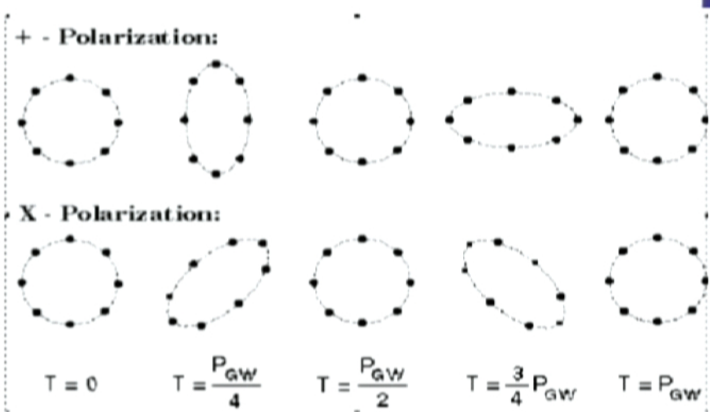


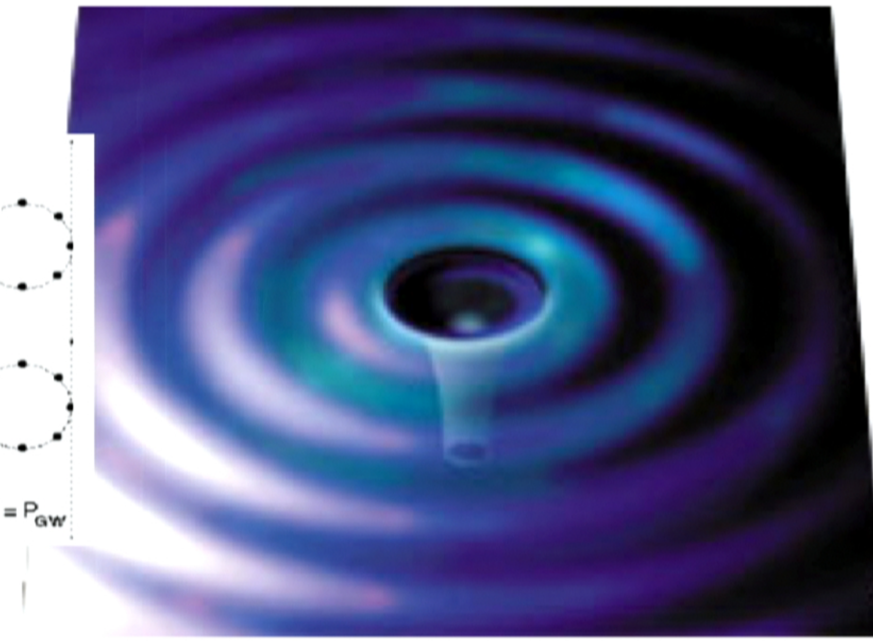
Ilya Mandel
(University of Birmingham)

June 5, 2013
Perimeter Institute

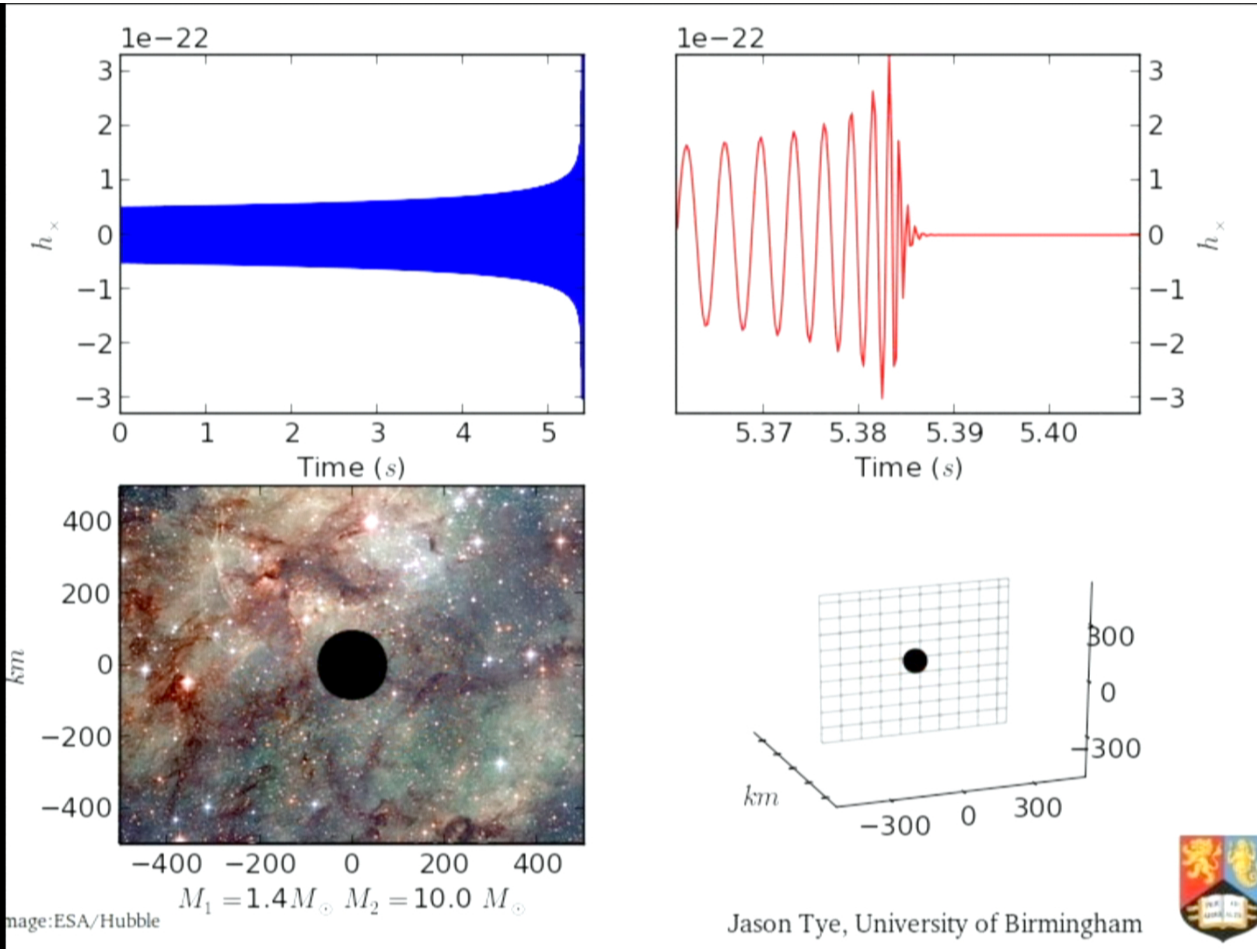
Gravitational Waves

- Ripples in spacetime:





- Caused by time-varying mass quadrupole moment; GW frequency is twice the orbital frequency for a circular, non-spinning binary
- Huge amounts of energy released: GW energy output of SMBH binary greater than EM radiation from entire galaxy over a Hubble time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Time (s)
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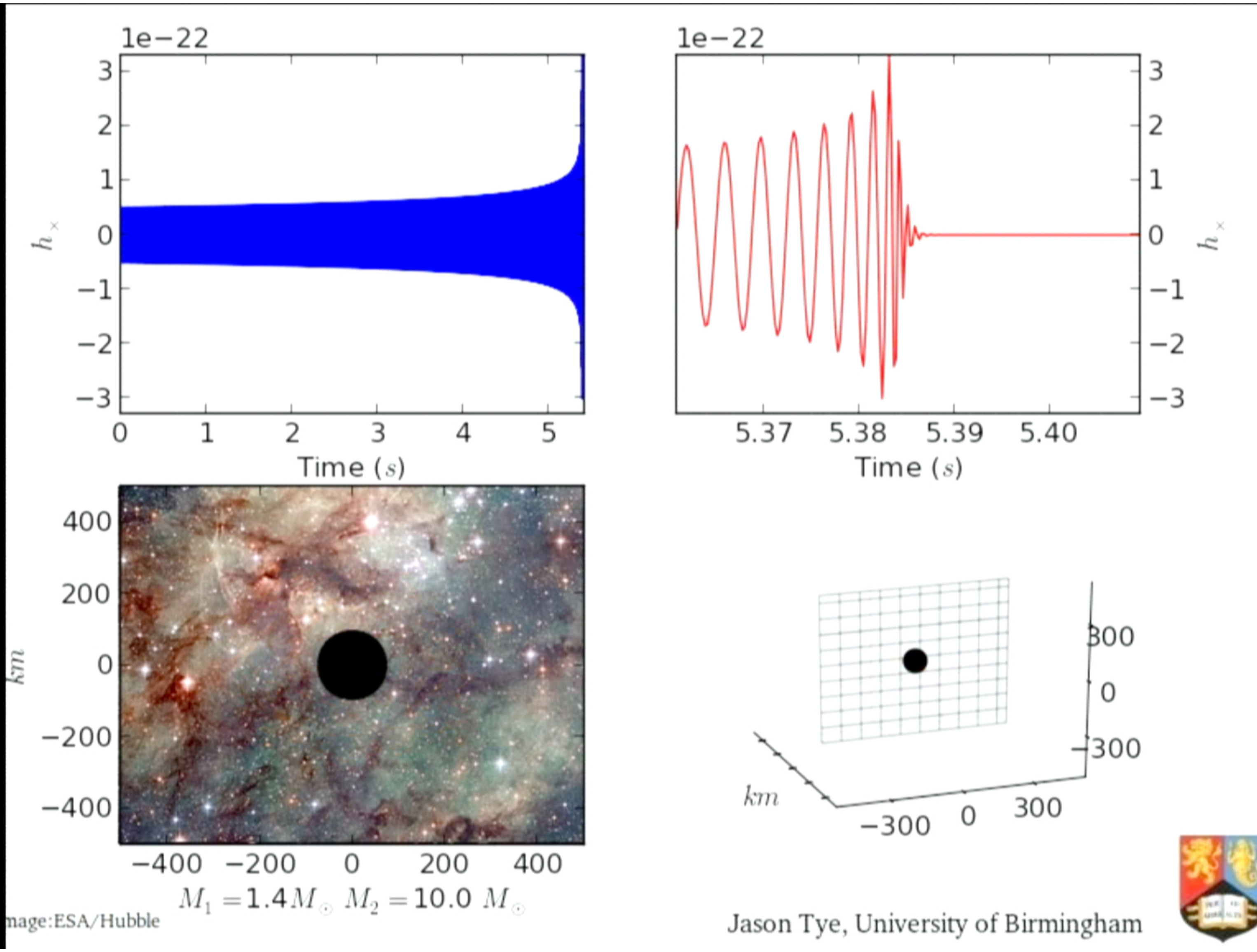
$M_1 = 1.4 M_\odot$ $M_2 = 10.0\ M_\odot$
mage:ESA/Hubble
Jason Tye, University of Birmingham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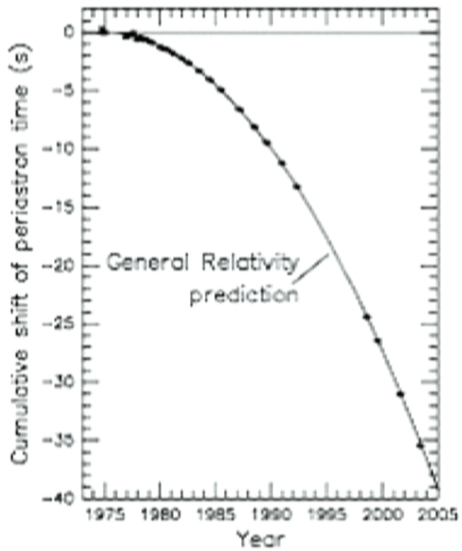
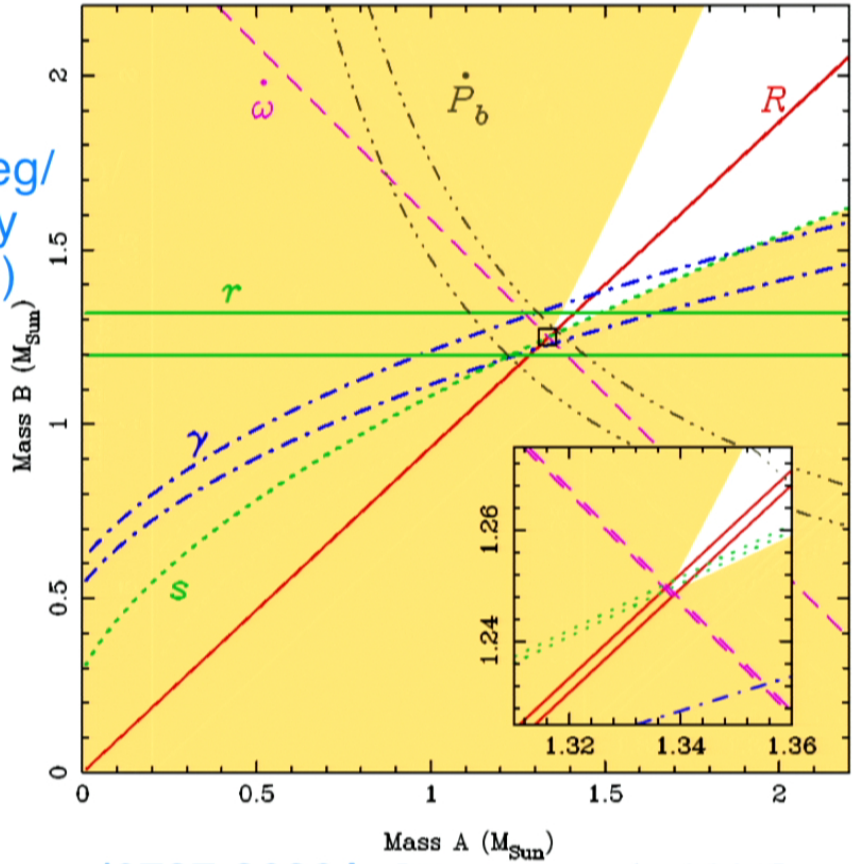
Indirect observations of GWs

- PSR 1913+16
- Discovered in 1974
- GR precession of 4.2 deg/yr (vs. 43 arcsec/century for Mercury, out of 5600)

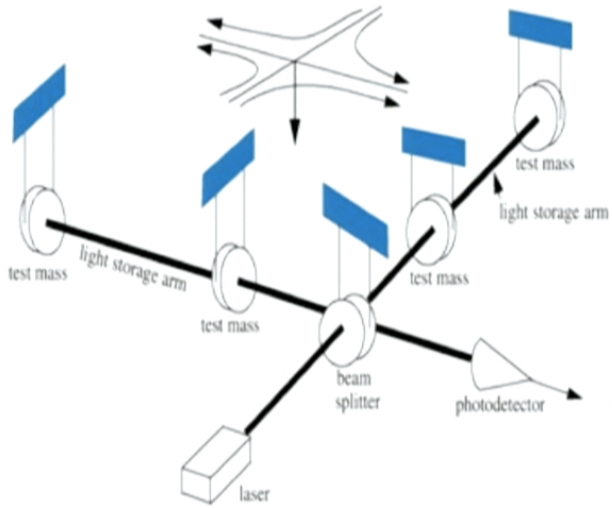


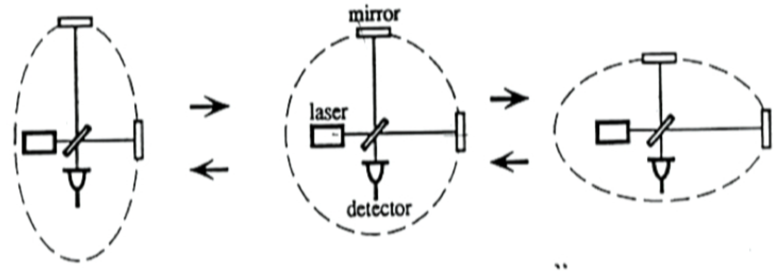


J0737-3039A: [Kramer et al., 2005]

Opportunity and Challenge

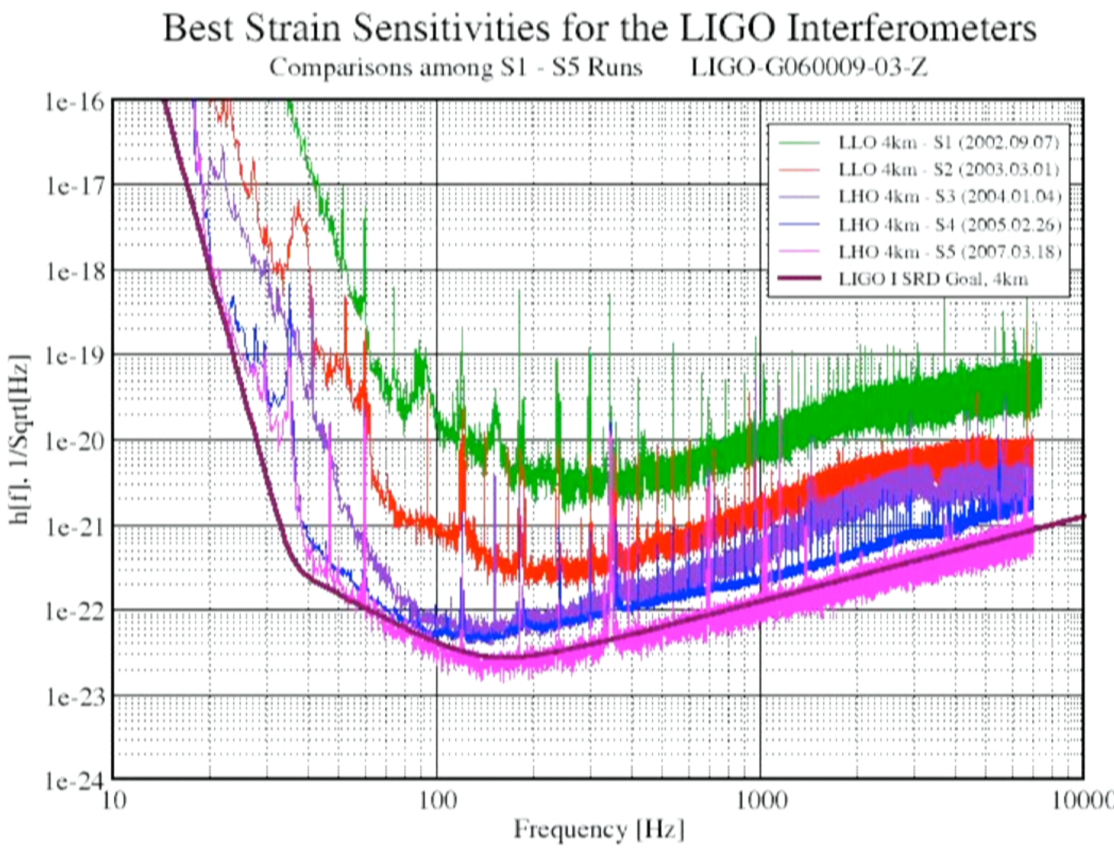
GWs carry a lot of energy, but interact weakly: can pass through everything. including detectors!





Michelson-type interferometers

LIGO Noise Spectrum



Outline

1. Compact-binary-coalescence rate predictions for ground-based observatories

2. Constraining astrophysics with observed event rates, upper limits, and population parameter distributions

3. Testing general relativity with intermediate- and extreme-mass-ratio inspirals

Predicting merger rates

Method	Strength	Weakness
Direct extrapolation from observed Galactic binaries	Most direct available probe; ~10 known (~5 merging) Galactic binary pulsars	Low statistics, poorly known selection effects, only relevant for BNS systems

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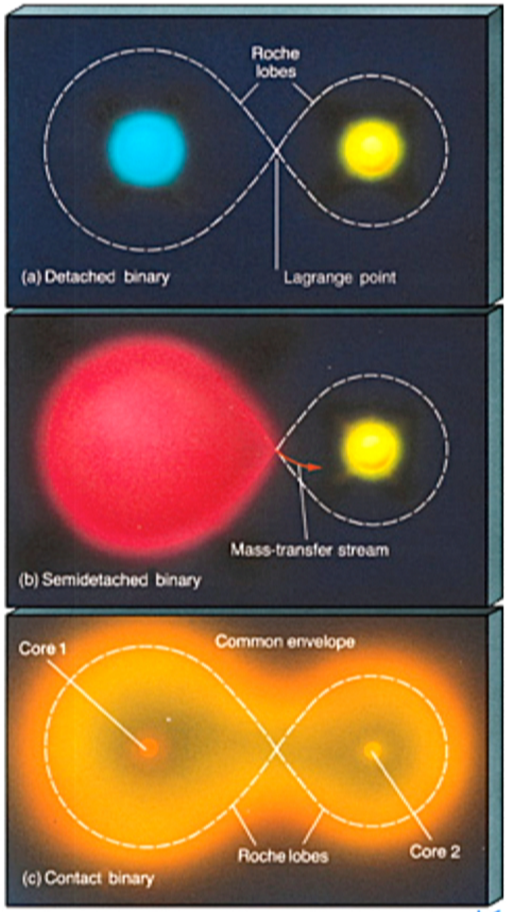
Population synthesis models

- No observed NS-BH or BH-BH binaries
- Predictions based on population-synthesis models for isolated binary evolution with StarTrack [Belczynski et al., 2005, astro-ph/0511811] or similar codes
- Many poorly constrained parameters: SN kicks, stellar winds, mass transfer efficiency, common envelope physics [O'Shaughnessy et al., 2005 ApJ 633 1076; 2008 ApJ 672 479]
- Also: metallicity variations, SN mechanism/fallback, fate of Hertzsprung gap donor in common envelope... [Dominik et al., 2012 ApJ, 759, 52]



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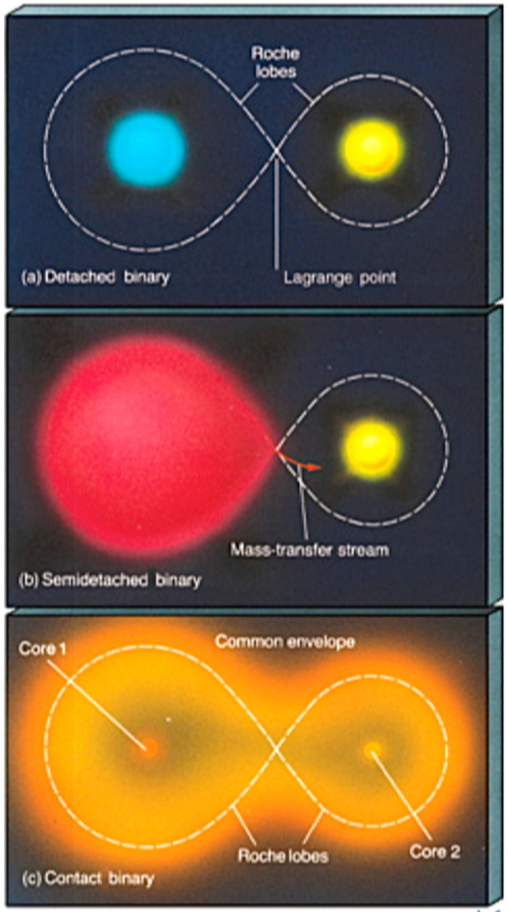

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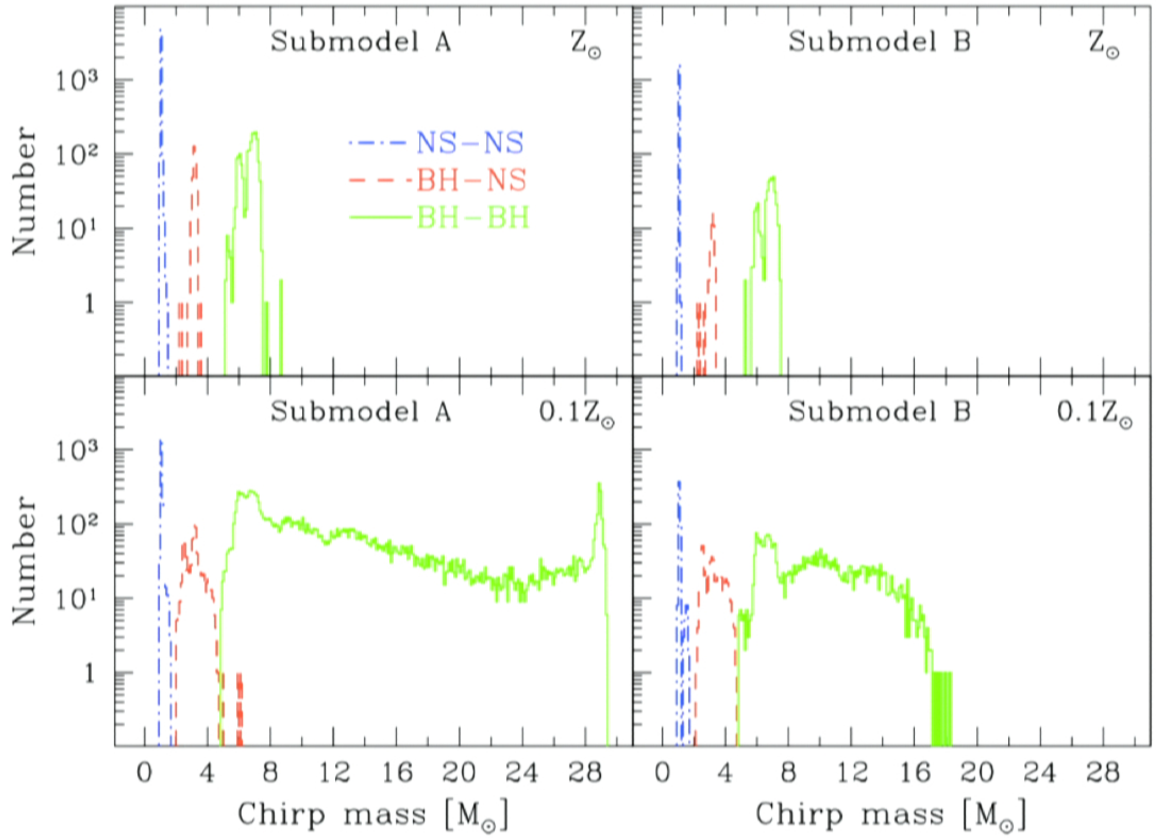
Population synthesis predictions

Galactic Merger Rates, $Z_{\odot}$ [Myr^{-1}] [a]

Model	NS-NS	BH-NS	BH-BH
S	23.5 (7.6)	1.6 (0.2)	8.2 (1.9)
V1	0.4 (0.4)	0.002 (0.002)	1.1 (1.1)
V2	11.8 (1.1)	2.4 (0.08)	15.3 (0.4)
V3	48.8 (14.3)	4.6 (0.03)	5.0 (0.03)
V4	20.8 (0.3)	0.9 (0.0)	0.3 (0.0)
V5	24.1 (8.1)	1.4 (0.2)	8.3 (2.0)
V6	24.1 (8.3)	1.4 (0.2)	8.0 (1.9)
V7	32.4 (9.5)	1.9 (0.3)	10.4 (2.1)
V8	23.3 (7.7)	0.03 (0.004)	0.05 (0.005)
V9	23.4 (8.0)	1.4 (0.2)	16.9 (4.2)
V10	25.6 (8.9)	0.07 (0.03)	0.6 (0.08)
V11	24.2 (6.5)	1.2 (0.2)	29.7 (3.6)
Range	0.4–48.8 (0.4–9.5)	0.002–4.6 (0.0–0.3)	0.05–29.7 (0.0–4.2)

[Dominik et al., 2012 ApJ, 759, 52]

Predictions of component mass distributions



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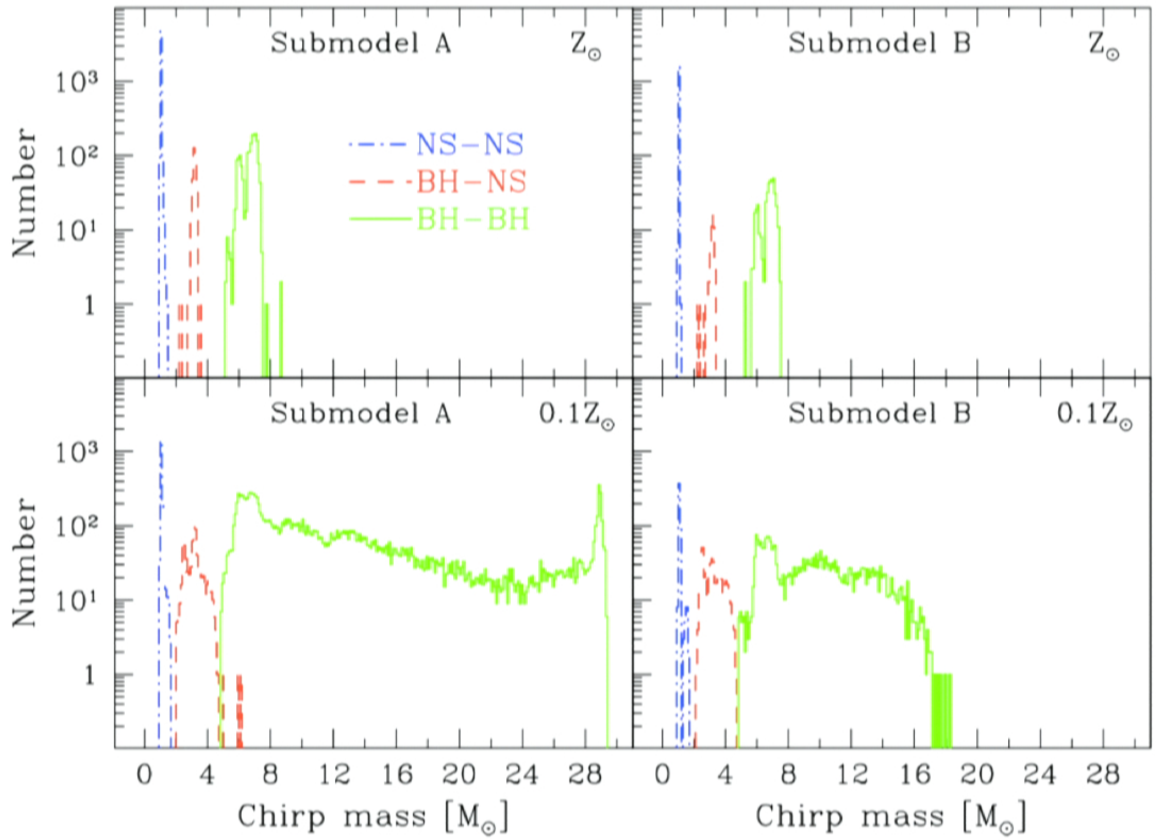

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Population synthesis of isolated binaries	Applies to all binary types, creates models for future astrophysical inference	A number of poorly known input parameters (SNe kicks, winds, common envelope)

Merger Rate Predictions

Source	$R_{\rm low}$	$R_{\rm re}$	$R_{\rm high}$
NS-NS ($\mathrm{MWEG}^{-1}\ \mathrm{Myr}^{-1}$)	1	100	1000
NS-BH ($\mathrm{MWEG}^{-1}\ \mathrm{Myr}^{-1}$)	0.05	3	100
BH-BH ($\mathrm{MWEG}^{-1}\ \mathrm{Myr}^{-1}$)	0.01	0.4	30

S6 / VSR2,3 Upper Limits

[Abadie et al., PRD D 85, 082002, 2012]

System	BNS	NSBH	BBH
Component masses ($M_\odot$)	1.35 / 1.35	1.35 / 5.0	5.0 / 5.0
$D_{\rm horizon}$ (Mpc)	40	80	90
Non-spinning upper limit ($\mathrm{Mpc}^{-3}\mathrm{yr}^{-1}$)	1.3×10^{-4}	3.1×10^{-5}	6.4×10^{-6}
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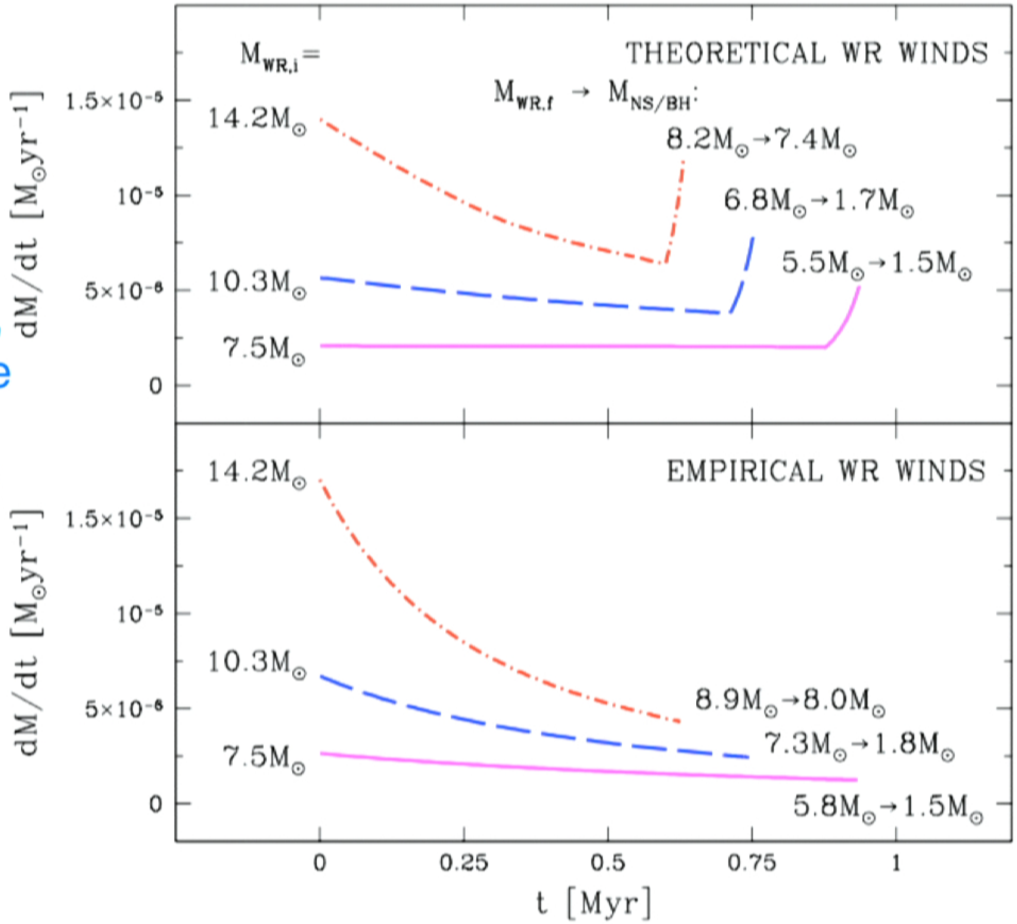
Forward evolution of observed X-ray binaries		

Forward Evolution

- Predict future evolution of known NS or BH binaries
- Uncertainties in velocity and mass measurements (e.g., just how massive are the WR-BH binaries IC10 X-1 & NGC300 X-1 [Bulik+, 2011, ApJ, 730, 140]), SN mechanism and fallback (e.g., Cygnus X-3 [Belczynski+, arXiv: 1209.2658])



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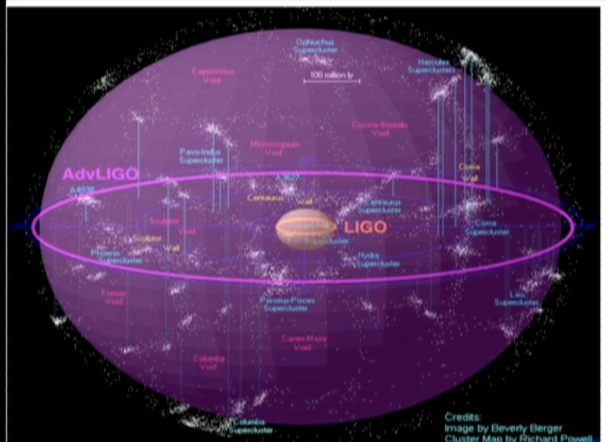
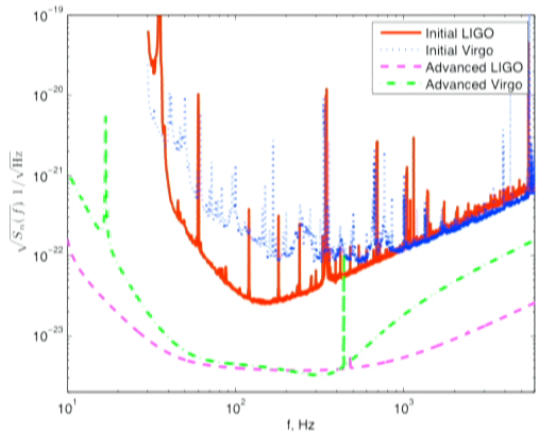
Merger and Detection Rates





[IM & O'Shaughnessy, 2010, CQG 27 114007; Abadie et al., 2010, arXiv:1003.2480]

IFO	Source	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm high}$ yr^{-1}
	NS-NS	2×10^{-4}	0.02	0.2
Initial	NS-BH	7×10^{-5}	0.004	0.1
	BH-BH	2×10^{-4}	0.007	0.5
	NS-NS	0.4	40	400
Advanced	NS-BH	0.2	10	300
	BH-BH	0.4	20	1000

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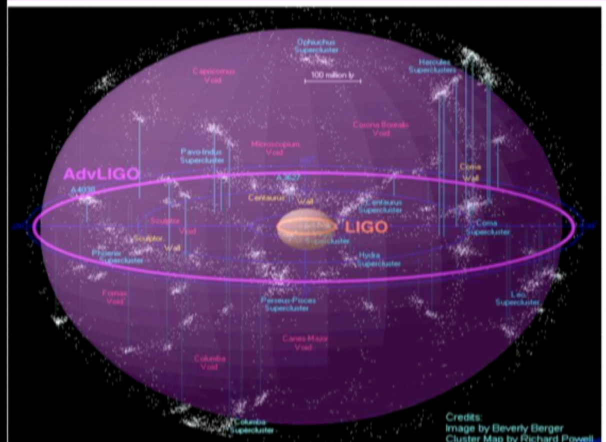

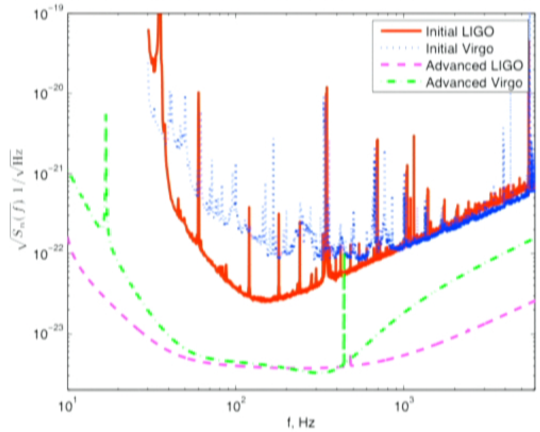

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	NS-BH	0.2	10	300
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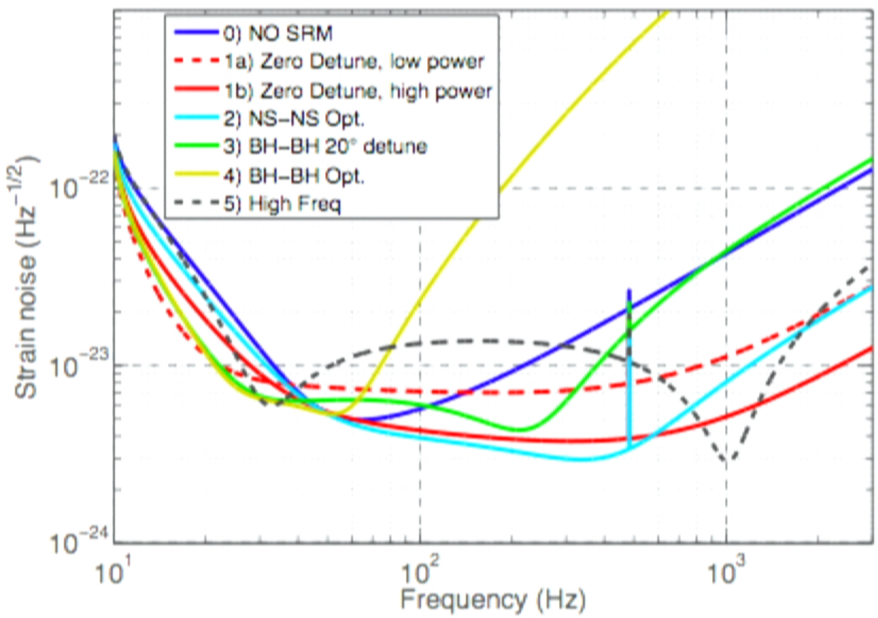
Dynamical Formation

- BH-BH mergers in dense black-hole subclusters of globular clusters
  - » [O'Leary, O'Shaughnessy, Rasio, 2007 PRD 76 061504]
  - » Predicted rates 10^{-4} to 1 per Mpc^3 per Myr
  - » Plausible optimistic values could yield 0.5 events/year for Initial LIGO
- BH-BH scattering in galactic nuclei with a density cusp caused by a massive black hole (MBH)
  - » [O'Leary, Kocsis, Loeb, 2009 arXiv:0807.2638]
  - » Based on a number of optimistic assumptions
  - » Predicted detection rates of 1 to 1000 per year for Advanced LIGO
- BH-BH mergers in nuclei of small galaxies without an MBH
  - » [Miller and Lauburg, 2009 ApJ 692 917]
  - » Predicted rates of a few X 0.1 per Myr per galaxy
  - » Tens of detections per year with Advanced LIGO

Informing GW searches with Astro

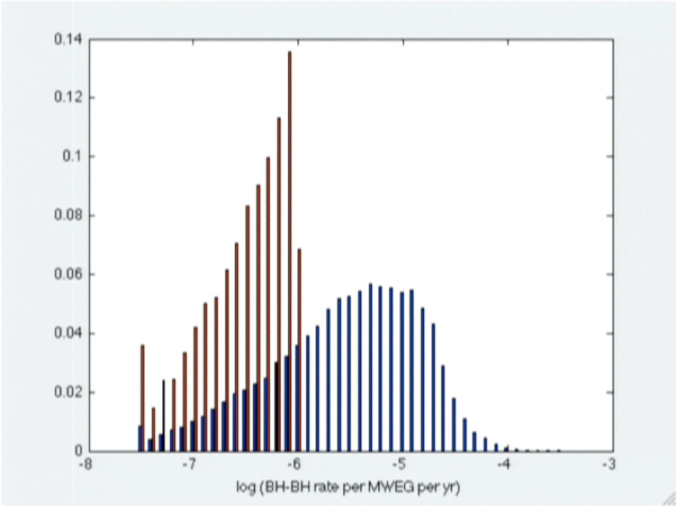
- Informing instrument design decisions. Where do we get the most benefits? Should different IFOs have different tuning?
- Informing search decisions. Which searches should we focus resources on? Which waveforms should we focus on?



Public LIGO document T-070247

Astrophysics: the Inverse Problem

- Comparing predicted rates of binary mergers with model predictions can allow us to constrain the input (astro)physics
  - » Even non-trivial upper limits can do the trick:



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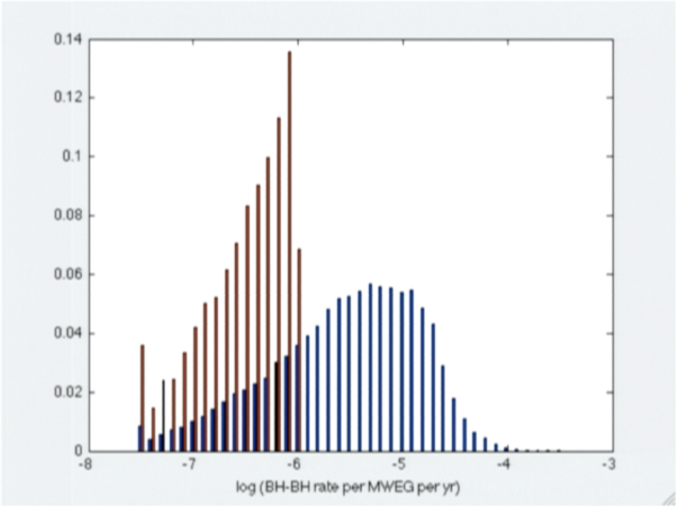

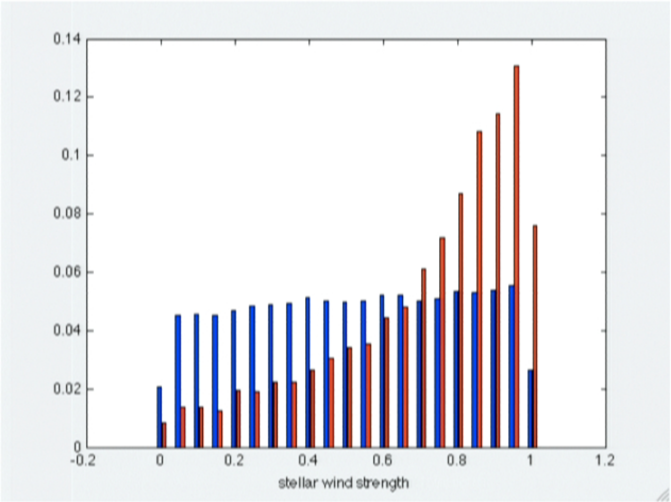

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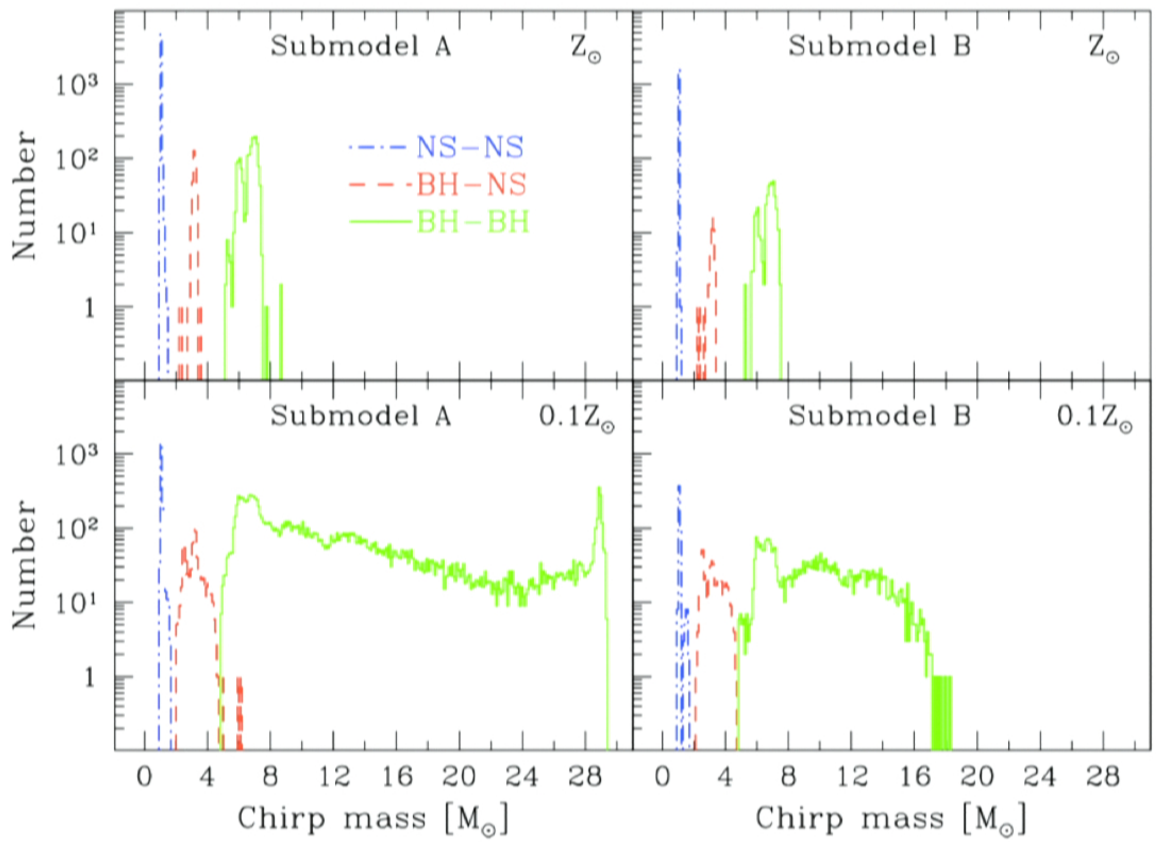
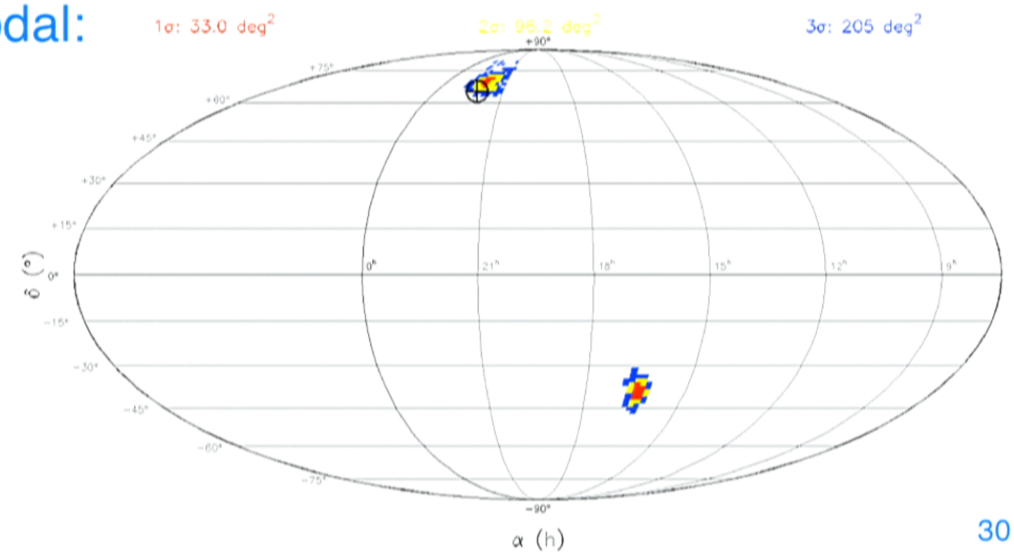
Predictions of component mass distributions



[Dominik et al., 2012 ApJ, 759, 52]

Parameter estimation: challenges

- Explore a large physical parameter space: 9 to 15 dimensions
- Analyze data streams coherently
- Make use of a priori information
- Infer posterior distribution on signal parameters
- Could be multi-modal:



Solution: Bayesian inference & stochastic sampling

Compute the full posterior probability density function on the parameter space $\boldsymbol{\theta}$ of the signal model $\boldsymbol{H}$, given data $\{d\}$.

Posterior ↘ Prior ↘ Likelihood ↙

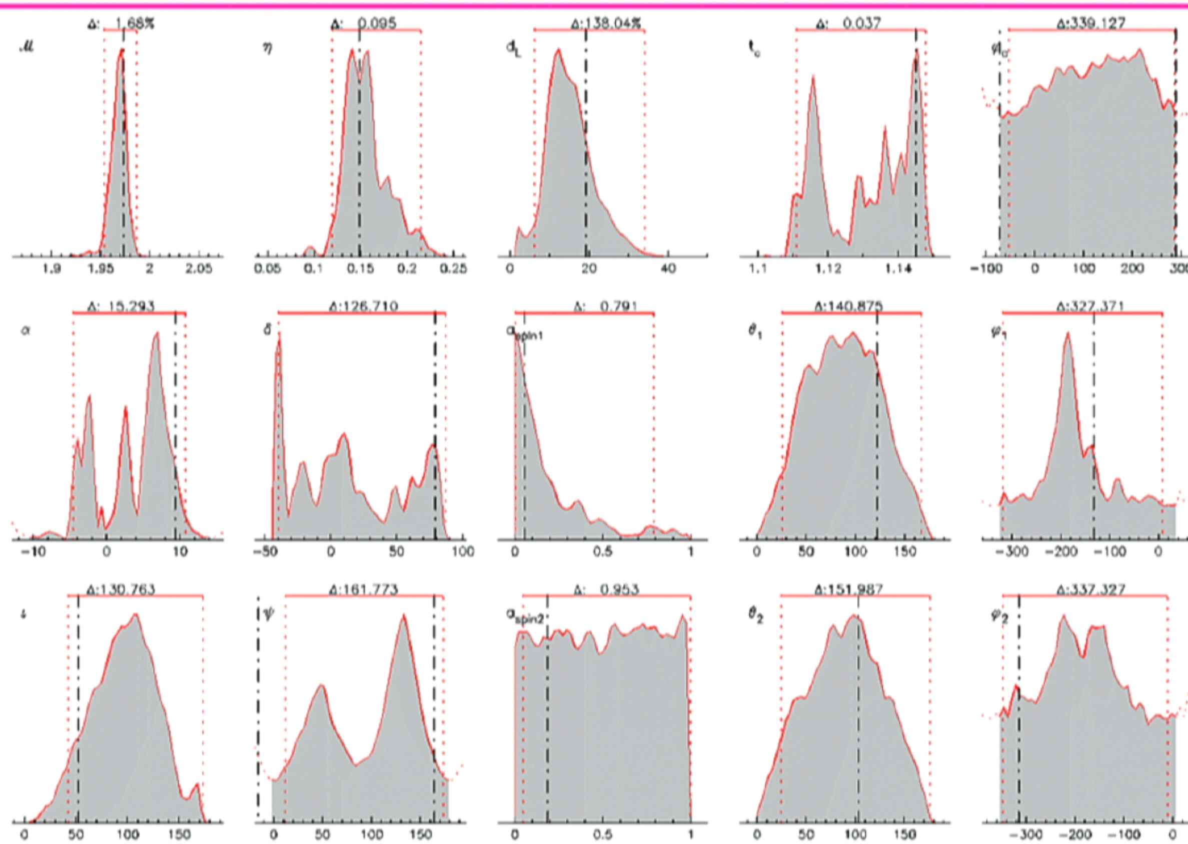
$$p(\vec{\theta}|\{d\},H) = \frac{p(\theta|H)p(\{d\}|\theta,H)}{p(\{d\}|H)} \longleftarrow \text{Evidence}$$

Likelihood: $p(\{d\}|\theta,H) \propto e^{-<d-h(\theta)|d-h(\theta)>/2}$

Evidence: $p(\{d\}|H) = \int p(\theta|H)p(\{d\}|\theta,H)d\theta$

[van der Sluys et al., 2008, 2008, 2009; Raymond et al., 2009,2010; Farr and IM, 2011; Vitale et al., 2011; Veitch et al., 2012...]

Accurate Parameter Estimation



van der Sluys, IM, Raymond, et al., 2009, CQG 26, 204010

Astrophysics: the Inverse Problem

- Comparing predicted rates of binary mergers with model predictions can allow us to constrain the input (astro)physics
- Can learn a lot more by comparing distributions of observed parameters (masses, spins) with model predictions
  - Requires accurate parameter estimation on individual sources
  - Requires combining information from multiple detection while accounting for selection effects

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  - » Requires accurate parameter estimation on individual sources
  - » Requires combining information from multiple events to construct a statement about population distribution (accounting for selection bias, etc.)
  - » Requires a library of catalogs of simulations based on different assumed astrophysical parameters
  - » Requires a pipeline for comparing observations and catalogs
  - » We need to be able to test population synthesis models themselves: need to over-determine the parameters... how many detections will this require? what will be the correlations/degeneracies in the astrophysical parameter space?

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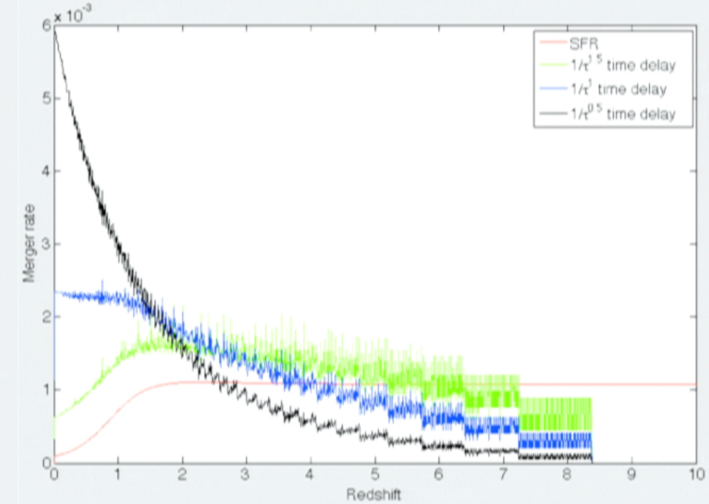
- Comparing predicted rates of binary mergers with model predictions can allow us to constrain the input (astro)physics
- Can learn a lot more by comparing distributions of observed parameters (masses, spins) with model predictions
- More model-independent inference
  - » Search for subpopulations (e.g., distinguish isolated and dynamically formed BH-BH binaries based on spin-orbit alignment)
  - » Directly measure time delays by observing dependence of merger rate on redshift [IM+, in prep.]



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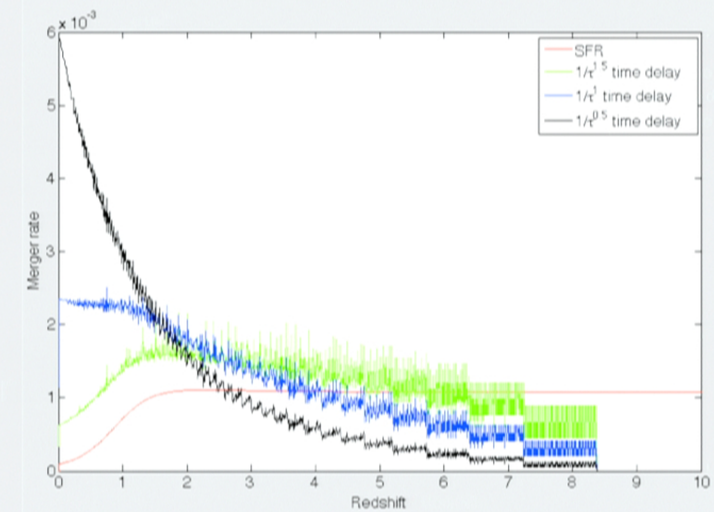

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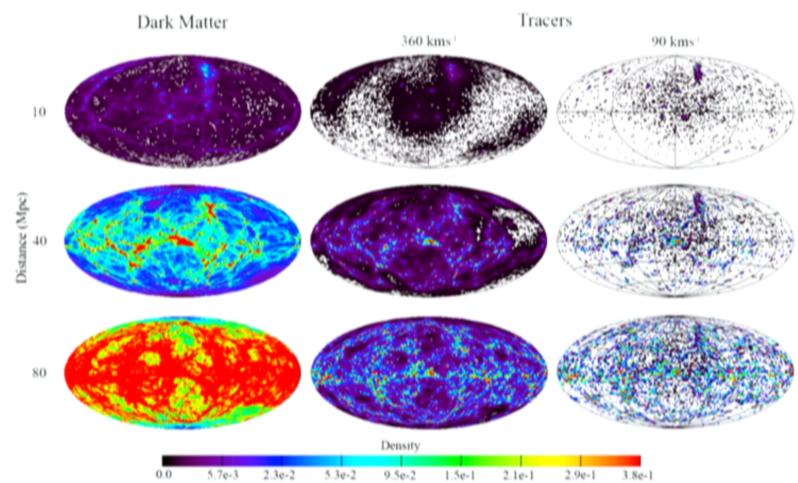
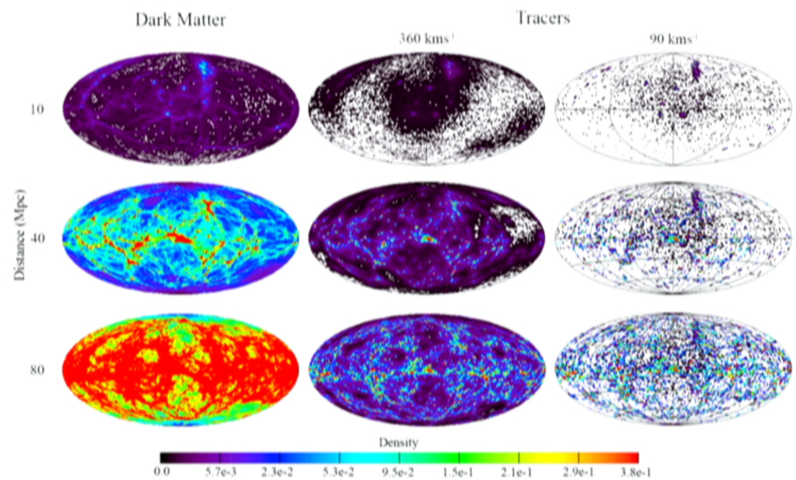
- Can learn a lot more by comparing distributions of observed parameters (masses, spins) with model predictions
- Still more model-independent inference
  - » Measure binary kick velocities from GWs without EM counterparts [L. Kelley et al., 2010, ApJL 725 L91]
  - » Probes of cosmology with and without electro-magnetic counterparts, [e.g., Taylor, Gair, IM, 2012, PRD 85 023535]



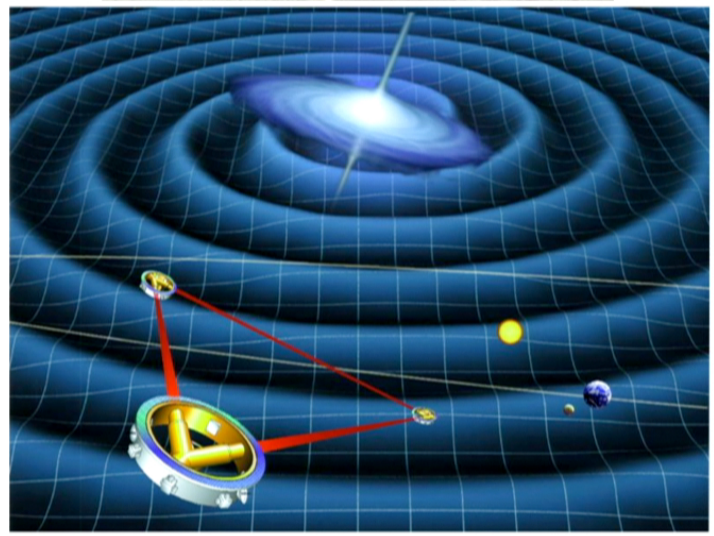
Astrophysics: the Inverse Problem

- Comparing predicted rates of binary mergers with model predictions can allow us to constrain the input (astro)physics
- Can learn a lot more by comparing distributions of observed parameters (masses, spins) with model predictions
- Still more model-independent inference
  - » Measure binary kick velocities from GWs without EM counterparts [L. Kelley et al., 2010, ApJL 725 L91]
  - » Probes of cosmology with and without electro-magnetic counterparts, [e.g., Taylor, Gair, IM, 2012, PRD 85 023535]

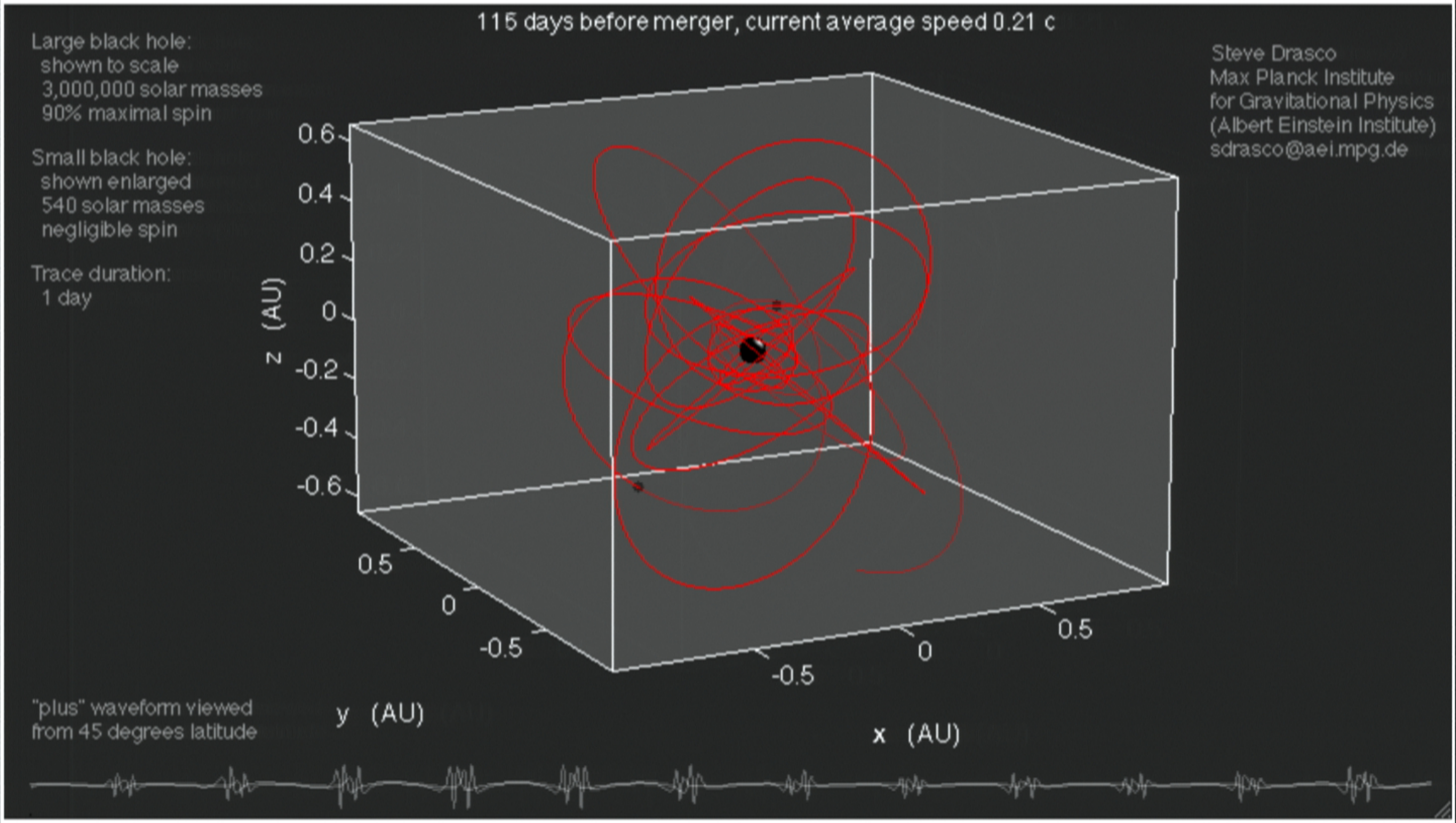


Testing GR with extreme-mass-ratio inspirals

- LIGO sensitive @ a few hundred Hz
  - » NS-NS, NS-BH, BH-BH binaries
  - » and intermediate-mass-ratio inspirals of NSs or BHs into IMBHs
    - – could observe up to tens per year [IM+, 2008, ApJ 681 1431]
- LISA sensitive @ a few mHz
  - » massive black-hole binaries
  - » galactic white dwarf (and compact object) binaries
  - » extreme-mass-ratio inspirals of WDs/NSs/BHs into SMBHs
    - – could observe tens to hundreds to z~1 [e.g., Amaro-Seoane et al., 2007, CQG 24 R113]



Extreme Mass Ratio Inspirals



Exploring the spacetime...

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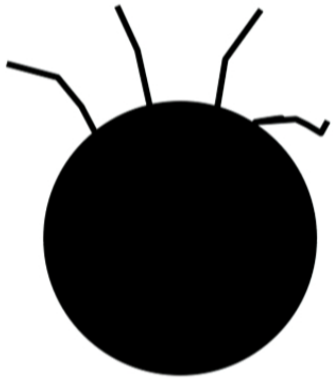
Testing the “no-hair” theorem

Testing the no-hair theorem?

Stationary, vacuum, asymptotically flat spacetimes in which the singularity is fully enclosed by a horizon with no closed timelike curves outside the horizon are described by the Kerr metric

Do black holes have hair?



$$M_n + iS_n \neq M(ia)^n$$

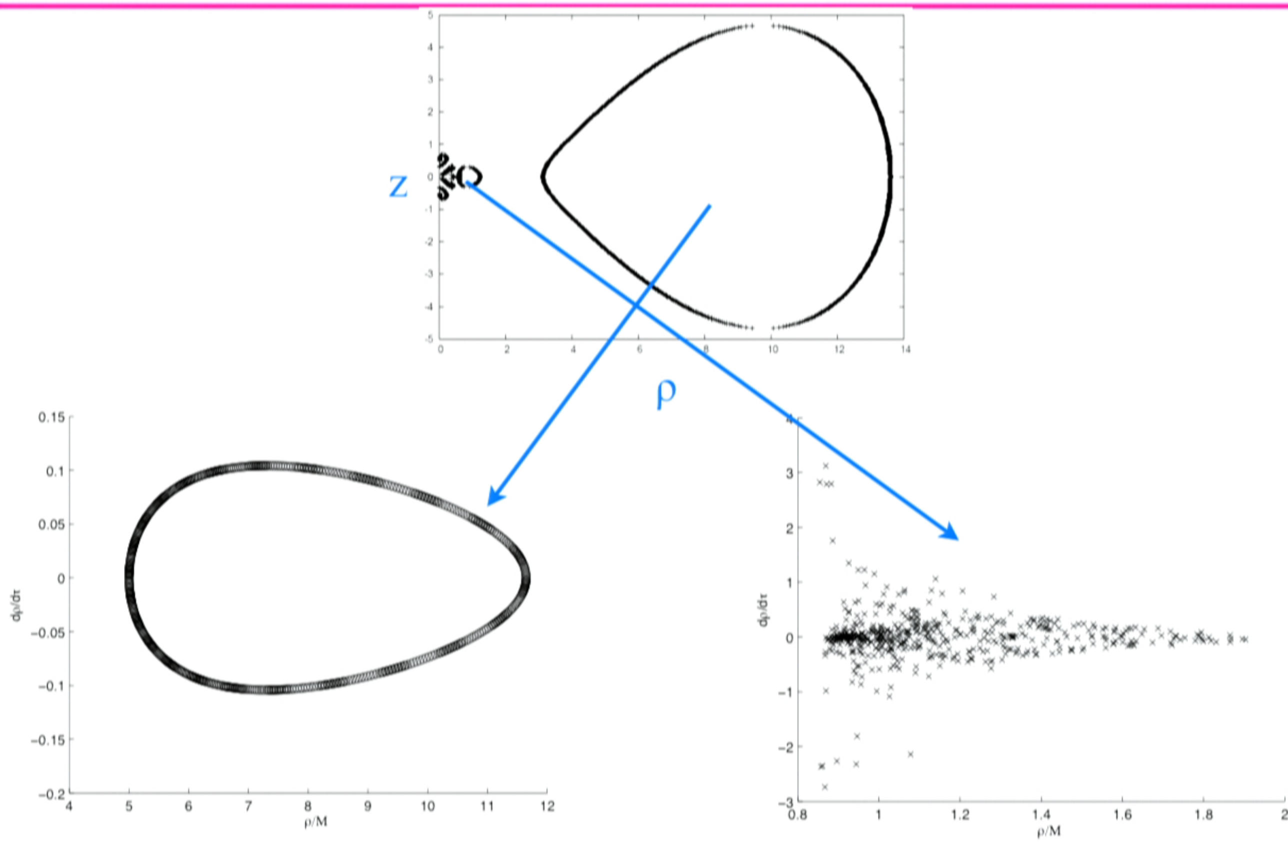
Ryan's theorem [1995]: GWs from nearly circular, nearly equatorial orbits in stationary, axisymmetric spacetimes encode all of the spacetime multipole moments... *in principle*

Manko-Novikov spacetime, an exact solution of Einstein's equations:

$$\mathrm{d}s^2 = -f(\rho,z)\,(\mathrm{d}t - \omega(\rho,z)\,\mathrm{d}\phi)^2 + \frac{1}{f(\rho,z)}\left[\mathrm{e}^{2\gamma(\rho,z)}\,(\mathrm{d}\rho^2 + \mathrm{d}z^2) + \rho^2\,\mathrm{d}\phi^2\right]$$

Search for observable imprints of a "bumpy" spacetime, such as deviations from the full set of isolating integrals (energy, angular momentum, Carter constant) in Kerr [Gair, Li, IM, 2009, PRD 77:024035]

It's a mad, mad, mad, mad geodesic



$E=0.95$, $L_Z=-3$, $a/M=0.9$, $q=0.95$

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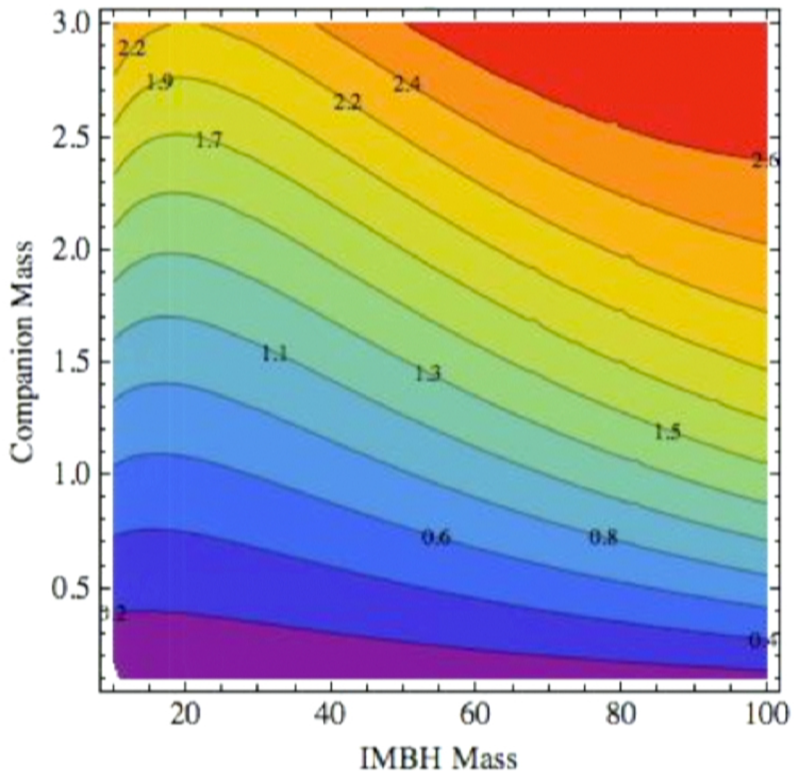
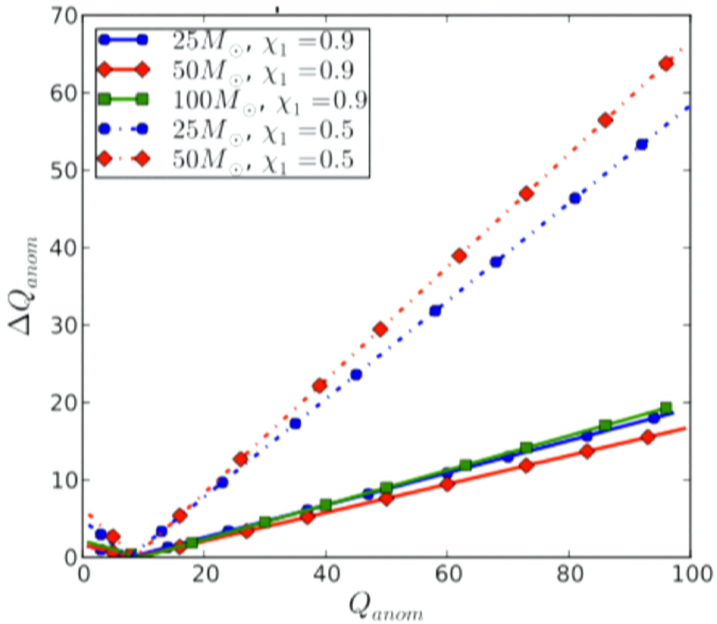
IMRI: null-hypothesis test of Kerrness





[Rodriguez, IM, Gair, PRD 85, 062002]

Summary

- Advanced LIGO is likely to observe GWs from NS-NS, NS-BH, BH-BH coalescences; tens or more coalescences may be observed according to some models, including signatures of dynamical formation
- GW detections and upper limits for compact-object coalescences will allow us to constrain astrophysical parameters through comparisons with model predictions
- Extreme- or intermediate- mass-ratio inspirals can serve as precise tests of General Relativity
- There's lots of work to be done in order to make true GWastrophysics a reality!

Astrophysics: the Inverse Problem

- Comparing predicted rates of binary mergers with model predictions can allow us to constrain the input (astro)physics
- Can learn a lot more by comparing distributions of observed parameters (masses, spins) with model predictions
- (Almost) Model-independent inference
  - Evidence for a mass gap? [Dominik, IM, Belczynski, in prep.]