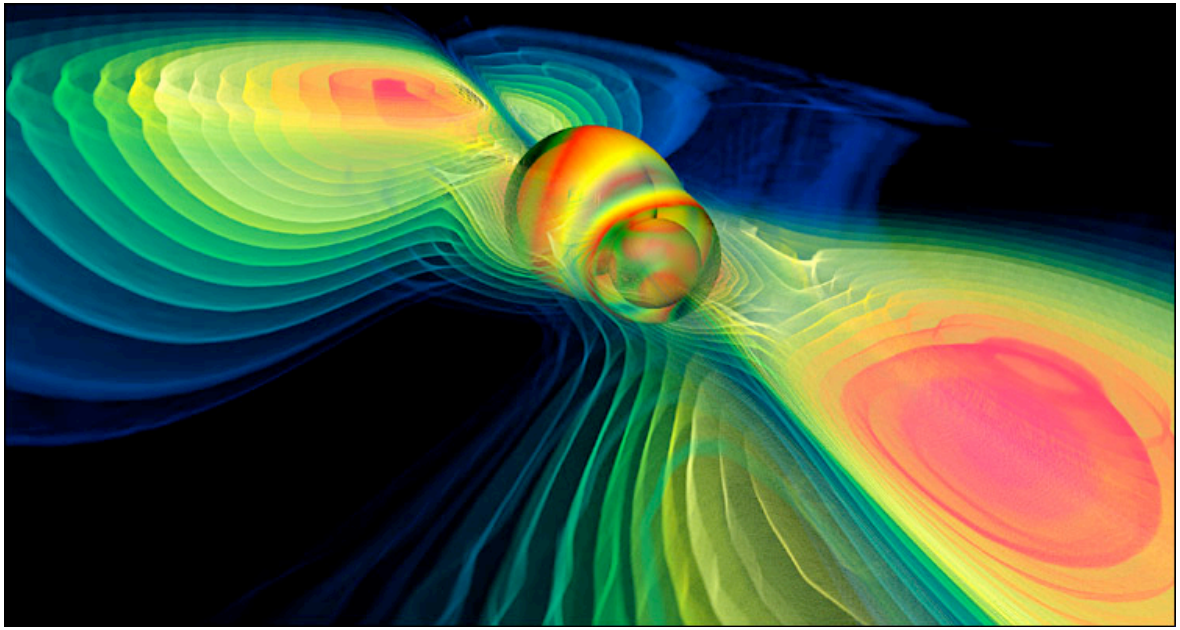
Gravitational Waves from Binaries



(Image: MPI for Gravitational Physics / W.Benger-ZIB)

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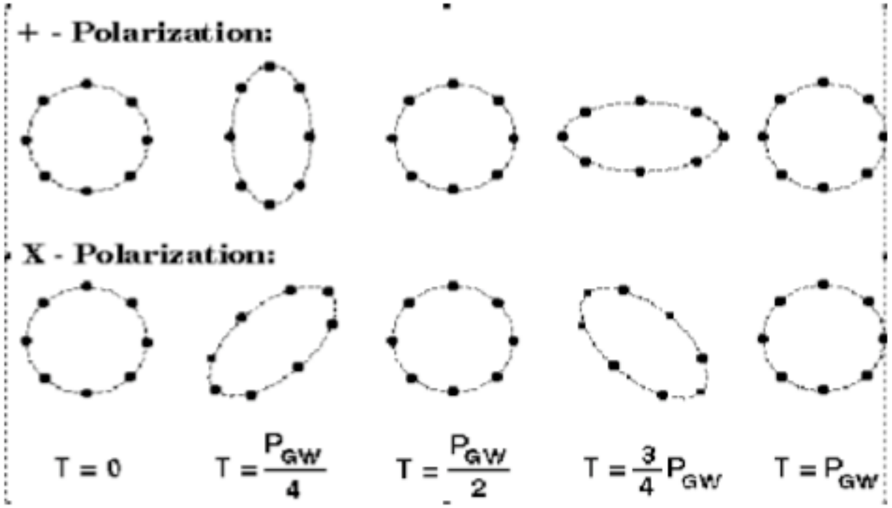
(NSF AAPF, CIERA @Northwestern University)
October 19, 2009
Harvard-Smithsonian CfA

Gravitational Waves

- Ripples in spacetime:

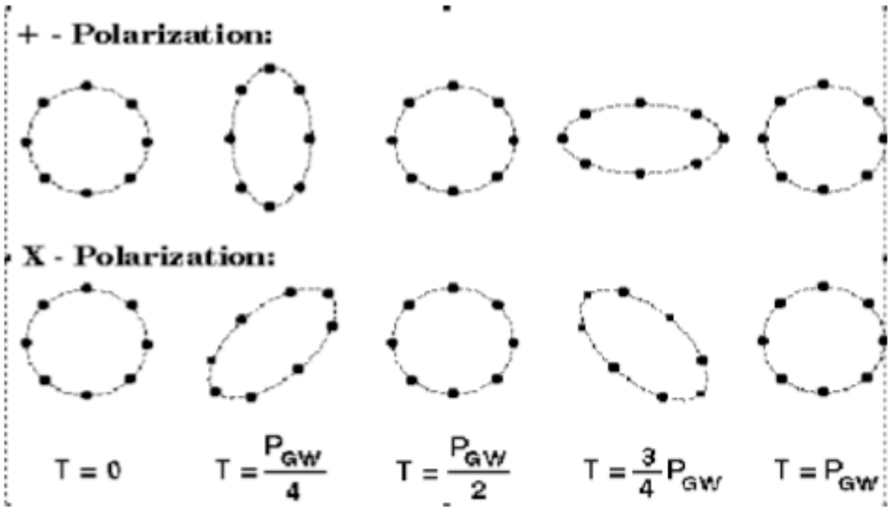


- Caused by time-varying mass quadrupole moment; GW frequency is twice the orbital frequency for a circular, non-spinning binary
- Indirectly detected by Hulse & Taylor [binary pulsar]
- Huge amounts of energy released: 5% of mass-energy of a supermassive black hole binary is comparable to the electromagnetic radiation emitted from an entire galaxy over the age of the universe!

Gravitational Waves

- Ripples in spacetime:

Inspiral sound borrowed from Scott Hughes



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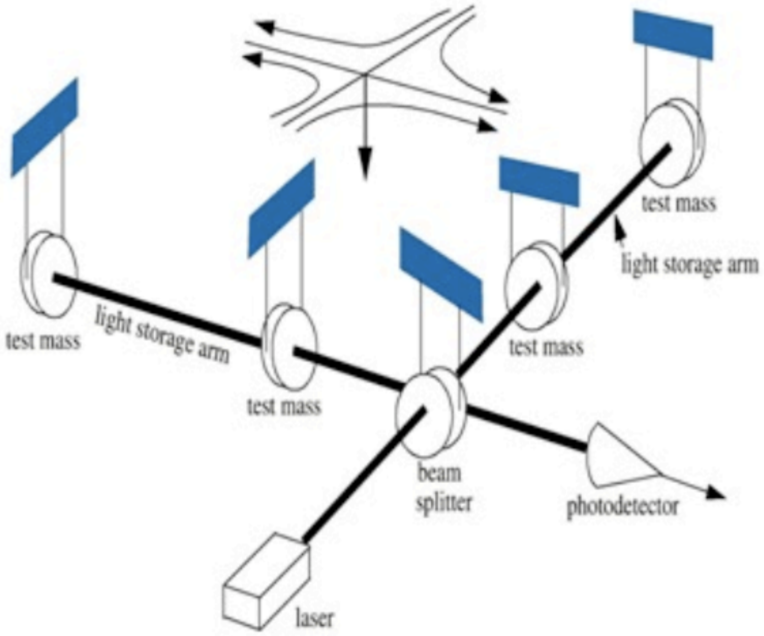
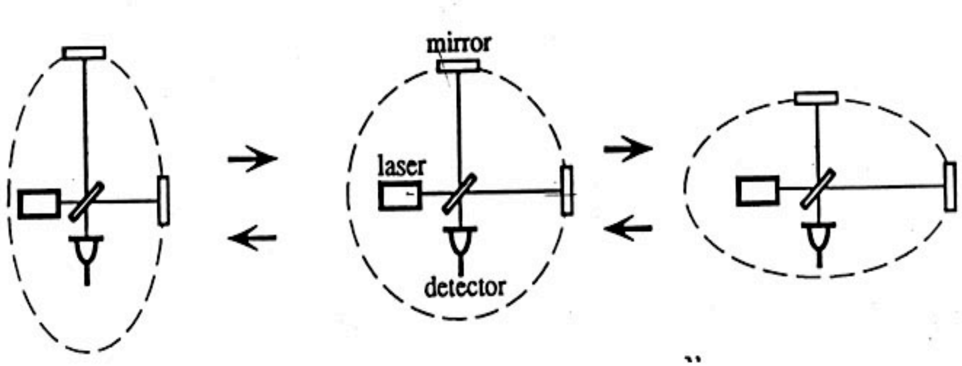
Opportunity and Challenge

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



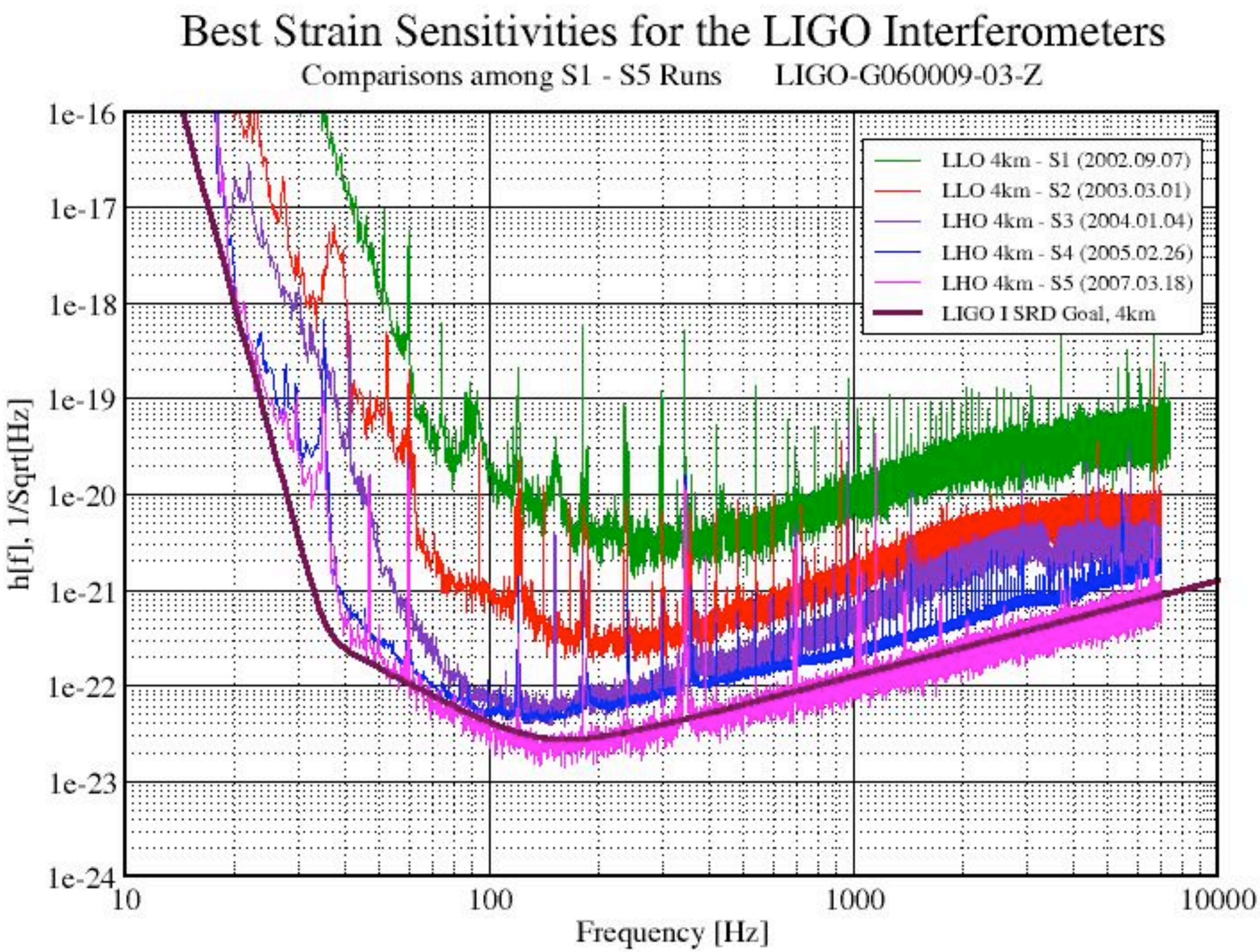


Michelson-type interferometers

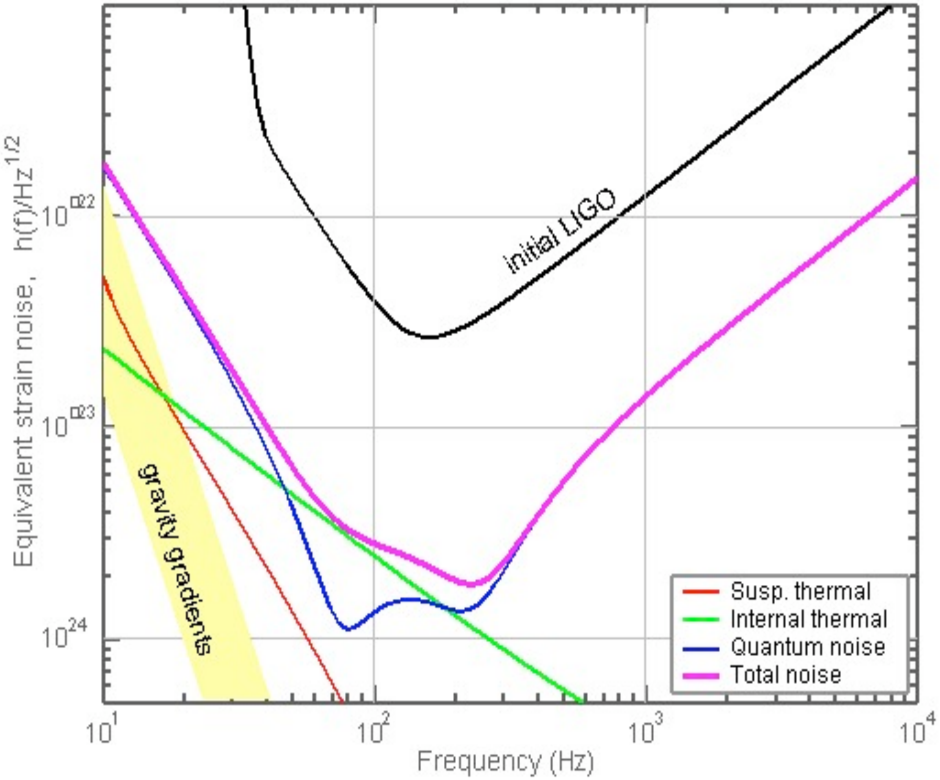
LIGO (Laser Interferometer Gravitational-Wave Observatory)

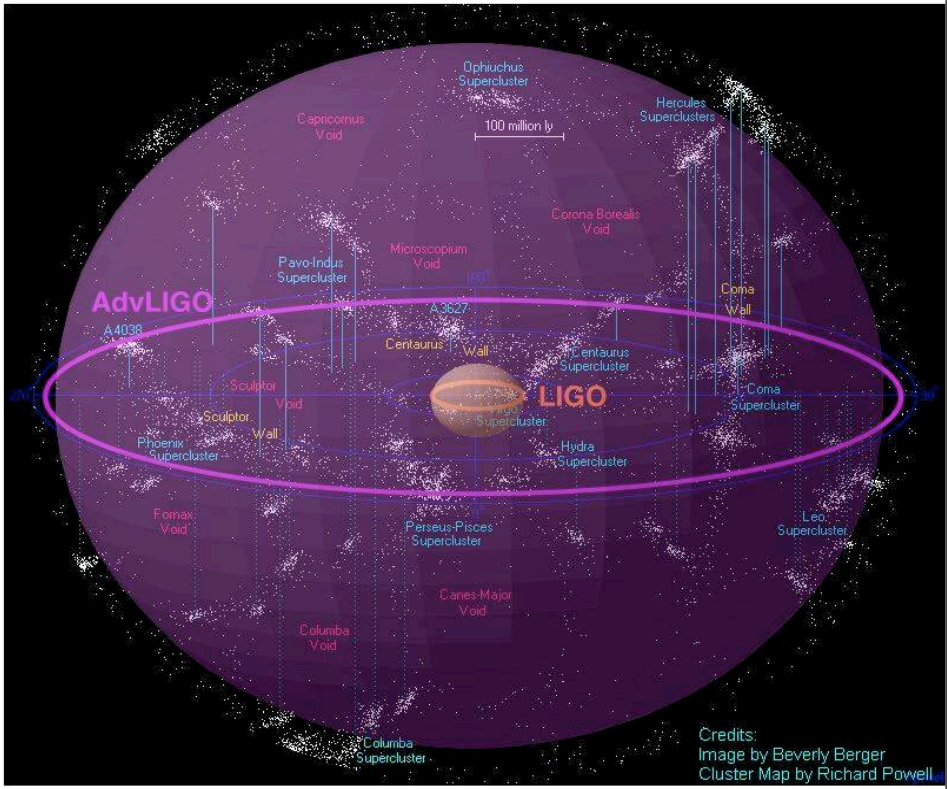
- 4 km long arms
- Typical strains $h = \Delta L / L \sim 10^{-21}$ (NS-NS in Virgo cluster)
- Needs to measure $\Delta L = hL \sim 10^{-18}$ m
- 2 LIGO detectors in US + Virgo, GEO in Europe
- Virgo has 3 km baseline; data-sharing agreement with LIGO

LIGO Noise Spectrum



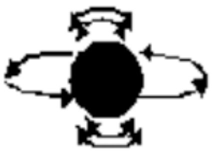
Advanced LIGO



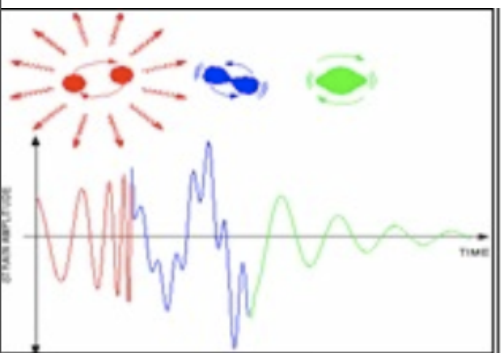


- ~ x10 in range -> ~ x1000 in event rate
- 10 Hz low frequency cutoff

Types of GW sources

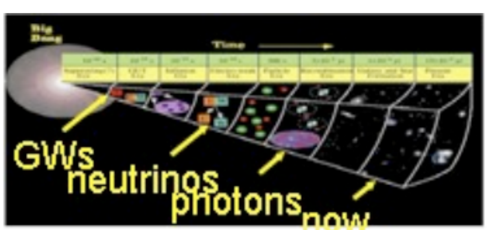


- Continuous sources [sources with a slowly evolving frequency]: e.g., non-axisymmetric neutron stars, slowly evolving binaries



- Coalescence sources: compact object binaries

- Burst events [unmodeled waveforms]: e.g., asymmetric SN collapse, cosmic string cusps



- Stochastic GW background [early universe]
- ??? [expect the unexpected]

Why do we want to see GWs?

- Probing stellar dynamics and evolution via stellar-mass compact-object binary measurements (NS-NS, NS-BH, BH-BH)
- Studying galactic structure formation by measuring mass and spin distributions of massive black holes (MBHs); measuring high-redshift mergers of MBH progenitors; understanding galactic mergers (e.g., kicks) and history of structure formation
- Direct probes of early-universe cosmology by measuring GWs emitted soon after the Big Bang
- Mapping cosmology with GW events as standard candles (especially with electromagnetic counterparts to binary mergers)
- Studying structure of neutron stars and white dwarfs
- Studying compact objects falling into massive black holes in galactic nuclei
- Probing gravity in the strong field, testing general relativity

Rates predictions

- Ground-based interferometric detectors (LIGO, Virgo, GEO 600, AIGO, LCGT) are sensitive @ tens/hundreds Hz: ideal for detecting NS-NS, NS-BH, BH-BH binaries
- Coalescence rate predictions from:
  - extrapolation from observed binary pulsars
  - simulations of isolated binary evolution
  - dynamical-formation models
  - intermediate-mass-black holes ?
- Instrument sensitivity and conversion to detection rates
- All astrophysical rates estimates depend on limited observations and/or models with many ill-understood parameters, and are still significantly uncertain at present

Prognostication

10-Day Business Travel Forecast for
Cambridge, MA

[English | Metric] Printable Forecast

Weather for your lif

Flights & Business Trav

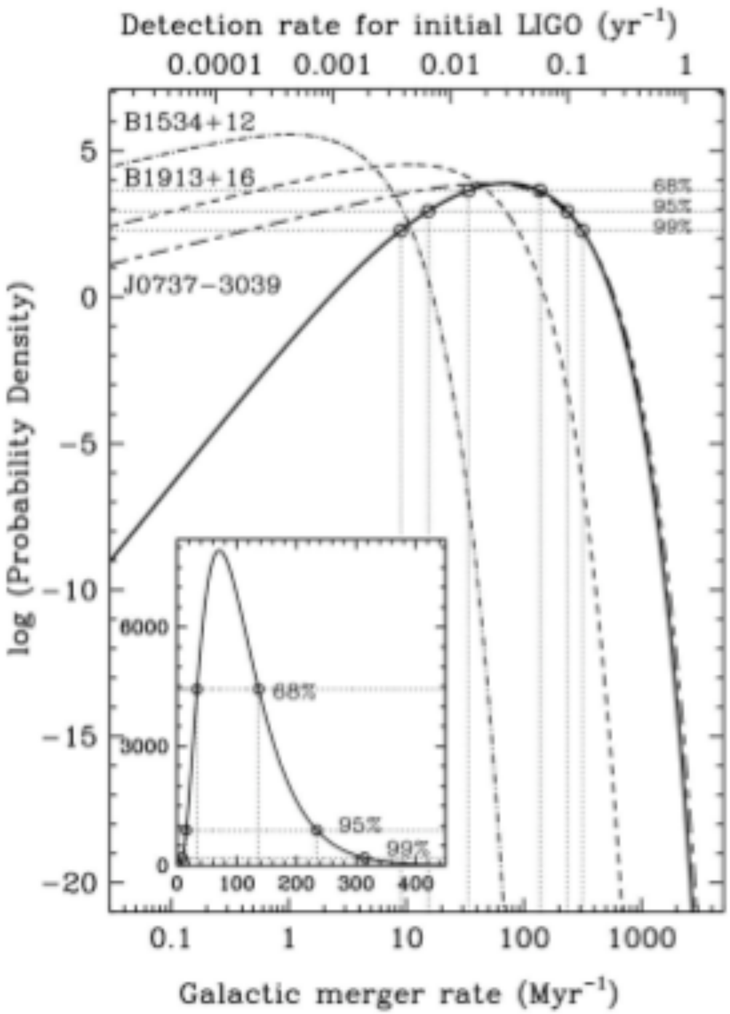
Forecast Conditions		High °C Low °C	Precip. Chance	High Temperatures
Mon Oct 19	Partly Cloudy	8° 3°	10%	8°C

Records and Averages for October °F | °C

Month	Average low	Average high	Average precip	Record low	Record high
Oct 1	11°	19°	0.3 cm	2° (1992)	32° (1927)
Oct 2	11°	19°	0.3 cm	1° (1997)	31° (1954)
Oct 3	11°	19°	0.3 cm	3° (1945)	29° (1922)
Oct 4	10°	19°	0.3 cm	2° (1945)	30° (2007)
Oct 5	10°	18°	0.3 cm	1° (1965)	31° (1922)
Oct 6	9°	18°	0.3 cm	1° (1984)	30° (1990)
Oct 7	9°	18°	0.3 cm	2° (1984)	32° (1963)
Oct 8	9°	18°	0.3 cm	2° (1964)	27° (1931)
Oct 9	9°	18°	0.3 cm	2° (1937)	28° (1942)
Oct 10	9°	17°	0.3 cm	0° (1979)	31° (1939)
Oct 11	9°	17°	0.3 cm	0° (1979)	28° (1955)
Oct 12	8°	17°	0.3 cm	2° (1956)	32° (1954)
Oct 13	8°	17°	0.3 cm	0° (1934)	31° (1930)
Oct 14	8°	17°	0.3 cm	1° (1958)	27° (1923)
Oct 15	8°	17°	0.3 cm	1° (1979)	27° (1947)
Oct 16	8°	16°	0.3 cm	1° (1978)	31° (1956)
Oct 17	8°	16°	0.3 cm	0° (1937)	32° (1947)
Oct 18	7°	16°	0.3 cm	-1° (1939)	28° (1947)
Oct 19	7°	16°	0.3 cm	-2° (1922)	29° (1945)
Oct 20	7°	16°	0.3 cm	0° (1974)	26° (1969)

Extrapolation from BNS observations

- Best NS-NS merger-rate estimates come from observed Galactic binary pulsars
- Small-number statistics (~10 total, ~5 merging in 15 Gyr)
- Selection effects (pulsar luminosity distribution)
- [Kim et al., 2003 ApJ 584 985, 2006 astro-ph/0608280; Kalogera et al., 2004, ApJ 601 L179]



Population synthesis models

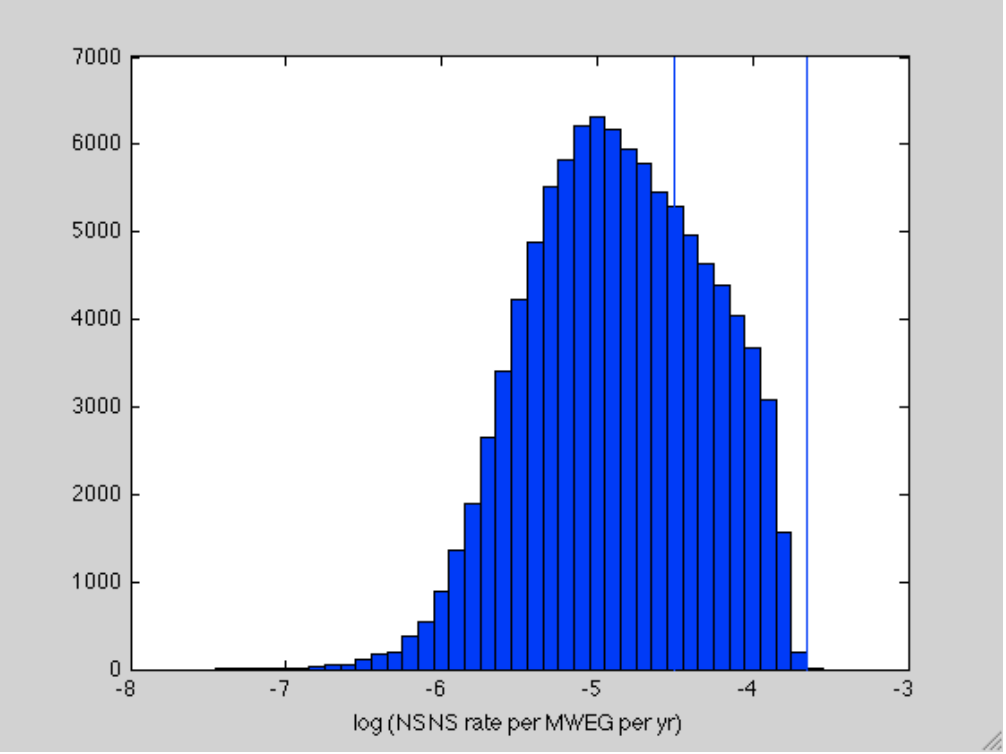
- No observed NS-BH or BH-BH binaries
- Predictions based on population-synthesis models for isolated binary evolution with StarTrack [Belczynski et al., 2005, astro-ph/0511811] or similar codes
- Thirty poorly constrained parameters
- [O'Shaughnessy et al., 2005 ApJ 633 1076, 2008 ApJ 672 479] vary seven most important parameters:

1. power-law index in binary mass ratio

2, 3, 4. supernovae kicks described by two independent Maxwellians and their relative contribution

5. strength of massive stellar wind
6. common-envelope efficiency
7. fractional mass retention during nonconservative mass transfer

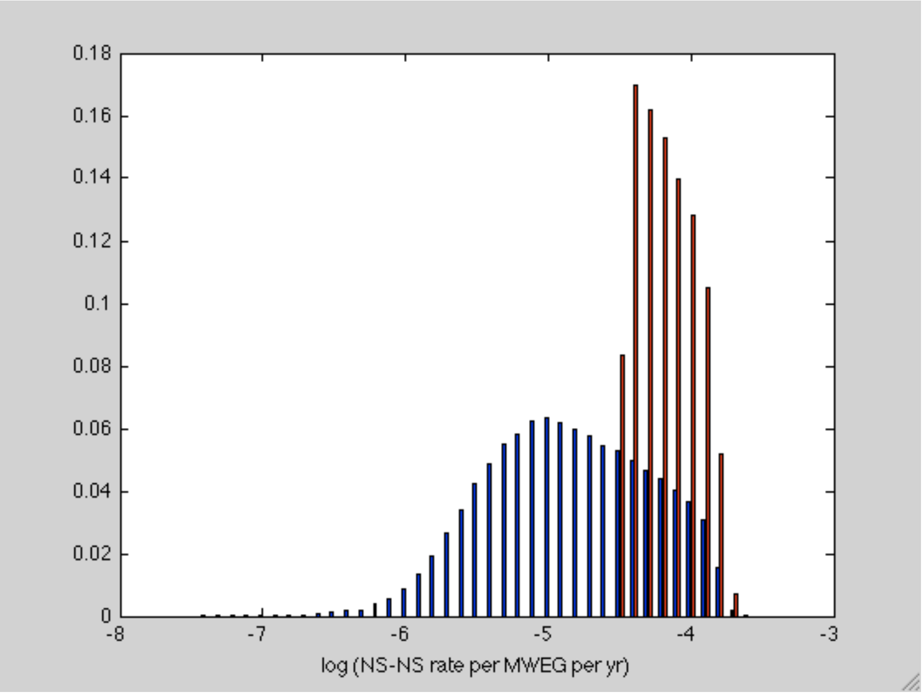
Constraining models



- Add constraints from observations; binary pulsars: NS-NS, NS-WD, supernovae, etc.
- Average over models that satisfy constraints

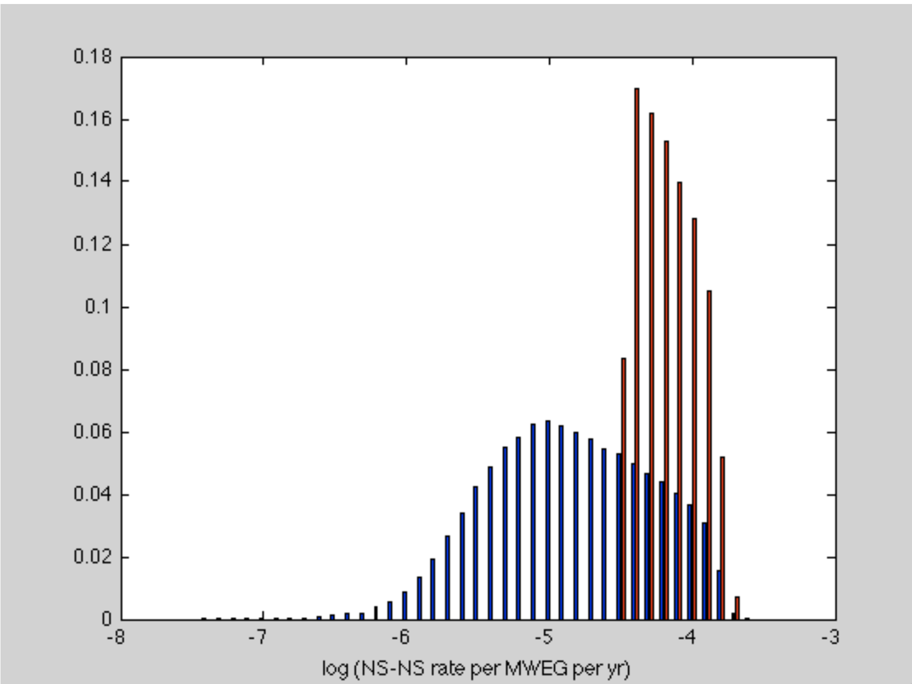
CIERA

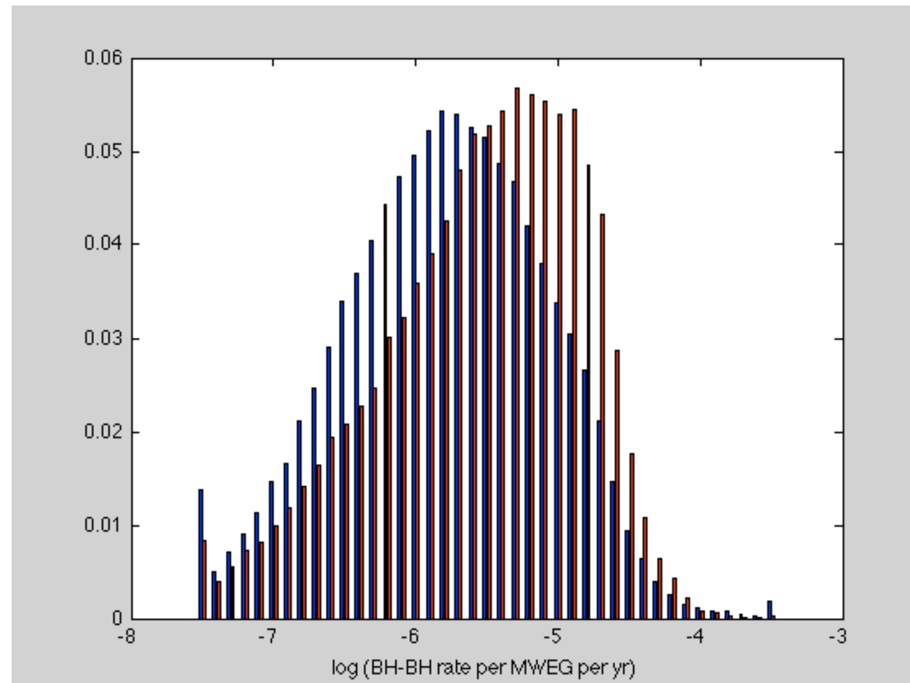
Effect of adding constraints, 1



Single constraint satisfaction - no accounting for sampling uncertainties or model fitting errors

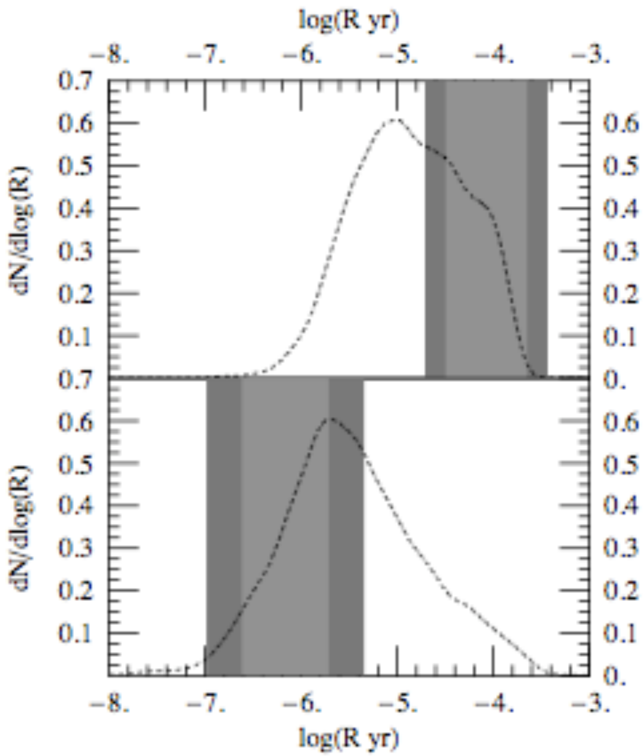
Effect of adding constraints, 1

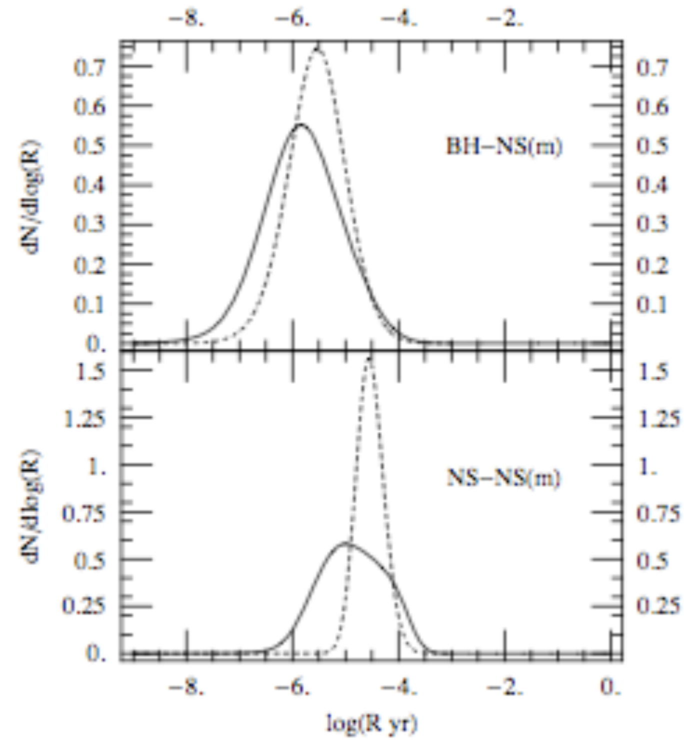




Single constraint satisfaction - no accounting for sampling uncertainties or model fitting errors

Effect of adding constraints, 2





Constraints from observed binary pulsars

BH-NS and NS-NS rate/MWEG predictions

[O'Shaughnessy et al., 2008, ApJ 672 479]

Rates per Galaxy

Source	$R_{\rm low}$	$R_{\rm re}$	$R_{\rm pl}$
NS-NS (L_{10}^{-1} Myr^{-1})	0.6	50	500
NS-BH (L_{10}^{-1} Myr^{-1})	0.03	2	60
BH-BH (L_{10}^{-1} Myr^{-1})	0.006	0.2	20

- In simplest models, coalescence rates are proportional to stellar-birth rates in nearby spiral galaxies, so we quote rates in units of L_{10} (blue-light luminosity of 10^{10} Suns)
- However, this does not properly account for delay of coalescence relative to star formation (esp. elliptical galaxies)

LIGO sensitivity

[Kopparapu et al., 2008 ApJ 675 1459]

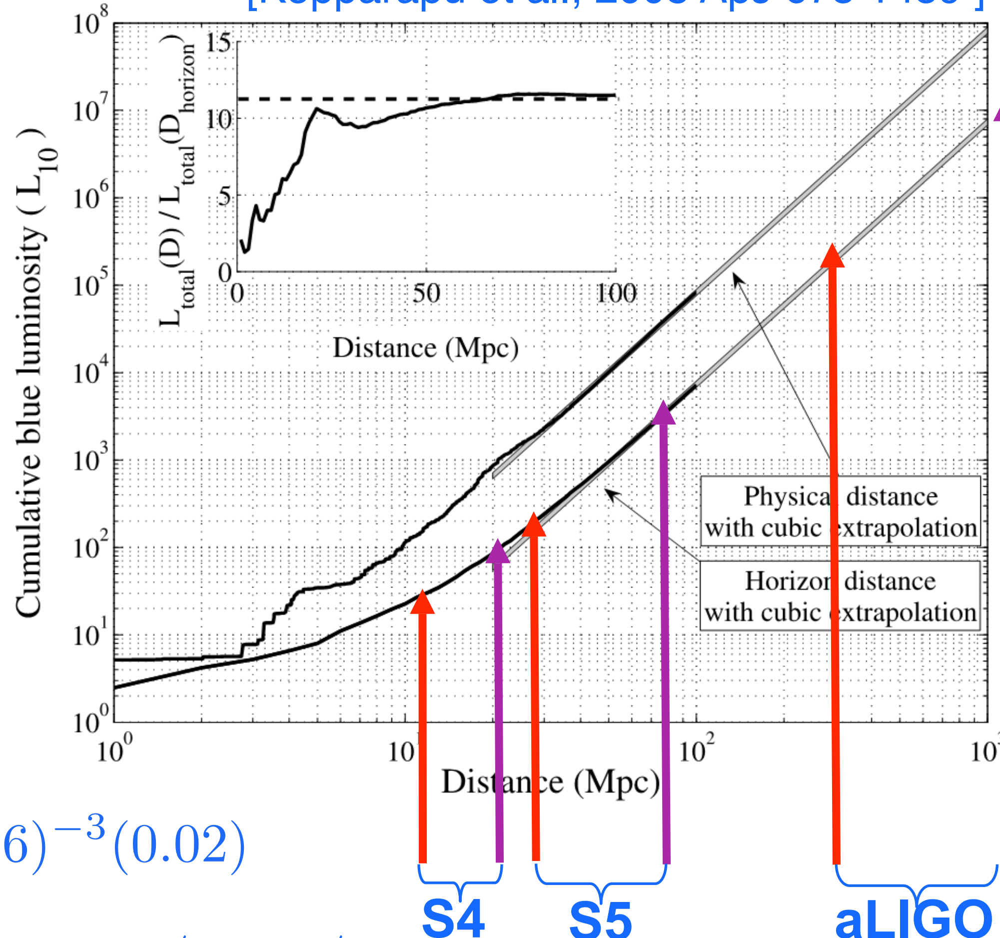
$$\dot{N} = R \times N_G$$

(merger rate) =
(merger rate per L10) *
(Ng in L10's)

$$\rho \equiv \sqrt{4 \int_0^{f_{\rm ISCO}} \frac{|\tilde{h}(f)|^2}{S_n(f)} df}$$

$$\rho(D_{\rm horizon}) \equiv 8$$

1/2.26 -- sky and orientation averaging; 0.02 L_{10} per Mpc^3



$$N_G\ (\mathrm{L}_{10}) = \frac{4}{3}\pi \left(\frac{D_{\rm horizon}}{\rm Mpc}\right)^3 (2.26)^{-3}(0.02)$$

$$|\tilde{h}(f)| = 2/D * (5\mu/96)^{1/2}(M/\pi^2)^{1/3} f^{-7/6}$$

Detection Rates

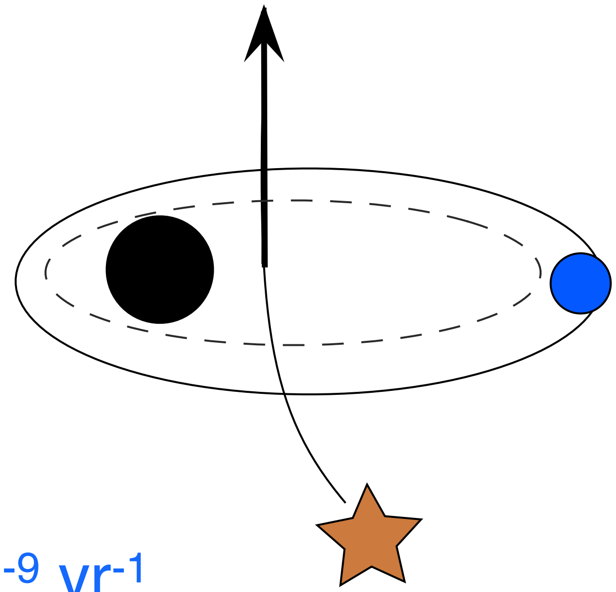
IFO	Source	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm pl}$ yr^{-1}
Initial	NS-NS	2×10^{-4}	0.02	0.2
	NS-BH	9×10^{-5}	0.006	0.2
	BH-BH	2×10^{-4}	0.009	0.7
Advanced	NS-NS	0.4	40	400
	NS-BH	0.2	10	300
	BH-BH	0.5	20	1000

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

Inspirals into IMBHs

- Intermediate-mass-ratio inspirals of compact objects (1.4 solar-mass NSs or 10 solar-mass BHs) into intermediate-mass black holes in globular clusters
- Dominant mechanism:
IMBH swaps into binaries,
3-body interactions tighten
IMBH-CO binary, merger
via GW radiation reaction
[IM et al., 2008 ApJ 681 1431]

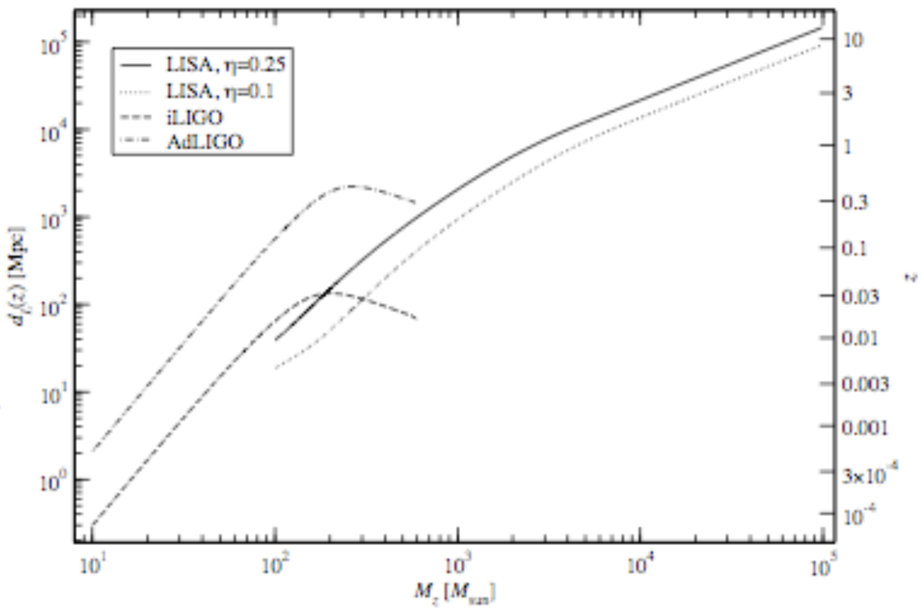


- Rate per globular cluster: few x 10^{-9} yr^{-1}
- Predicted Advanced LIGO event rates between 1/few years and ~30/year

Inspirals of two IMBHs

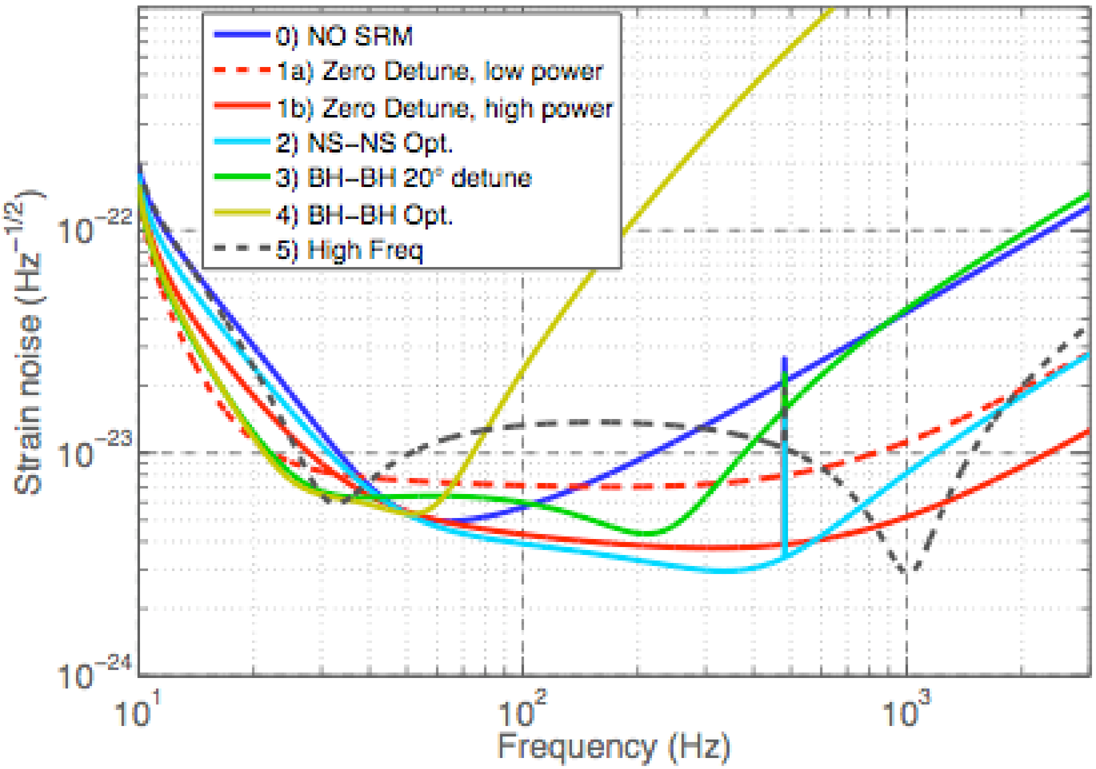
- Two very massive stars could form in globular clusters with sufficient binary fraction, then grow through run-away collision to form two IMBHs in same GC

- Rates of order 1/year are possible for Advanced LIGO [Fregeau et al., 2006 ApJ 646 L135]
- IMBH binaries could also form when two GCs merge [Amaro-Seoane and Freitag, 2006, ApJ 653 L53]



Informing GW searches with Astro, 1

- Selecting IFO configuration based on astro predictions

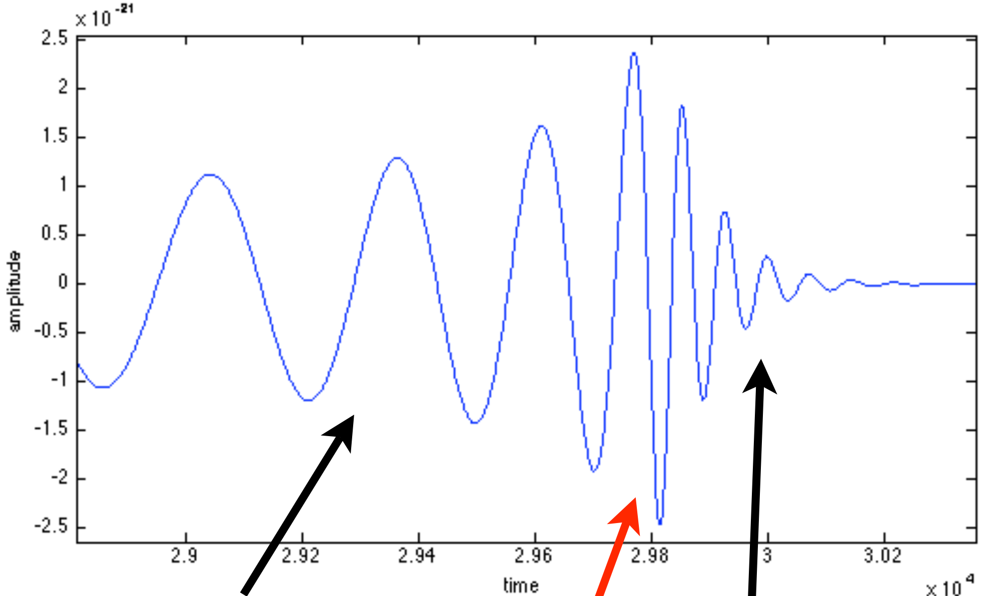


Public LIGO document T-070247

Informing GW searches with Astro, 2

- Rates predictions can help to determine which searches we should focus resources on
- Choice of waveform templates for detection

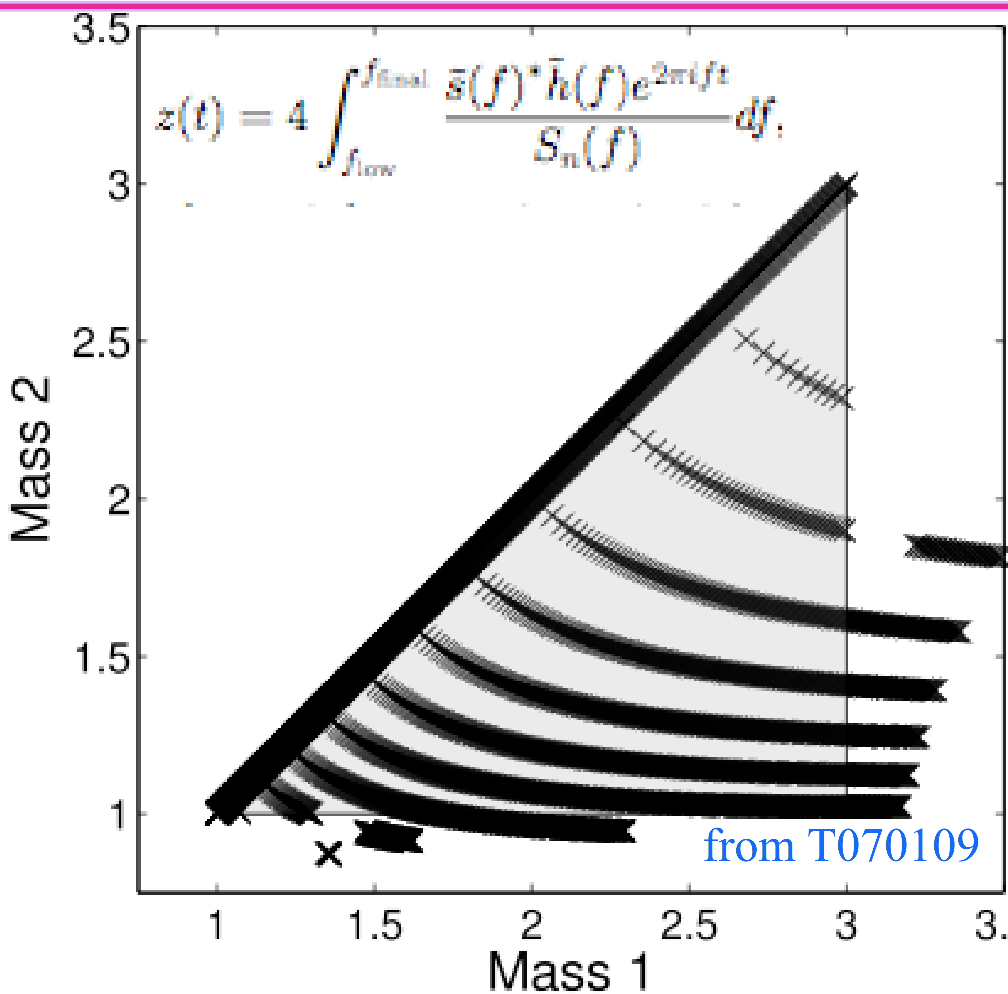
Waveform families

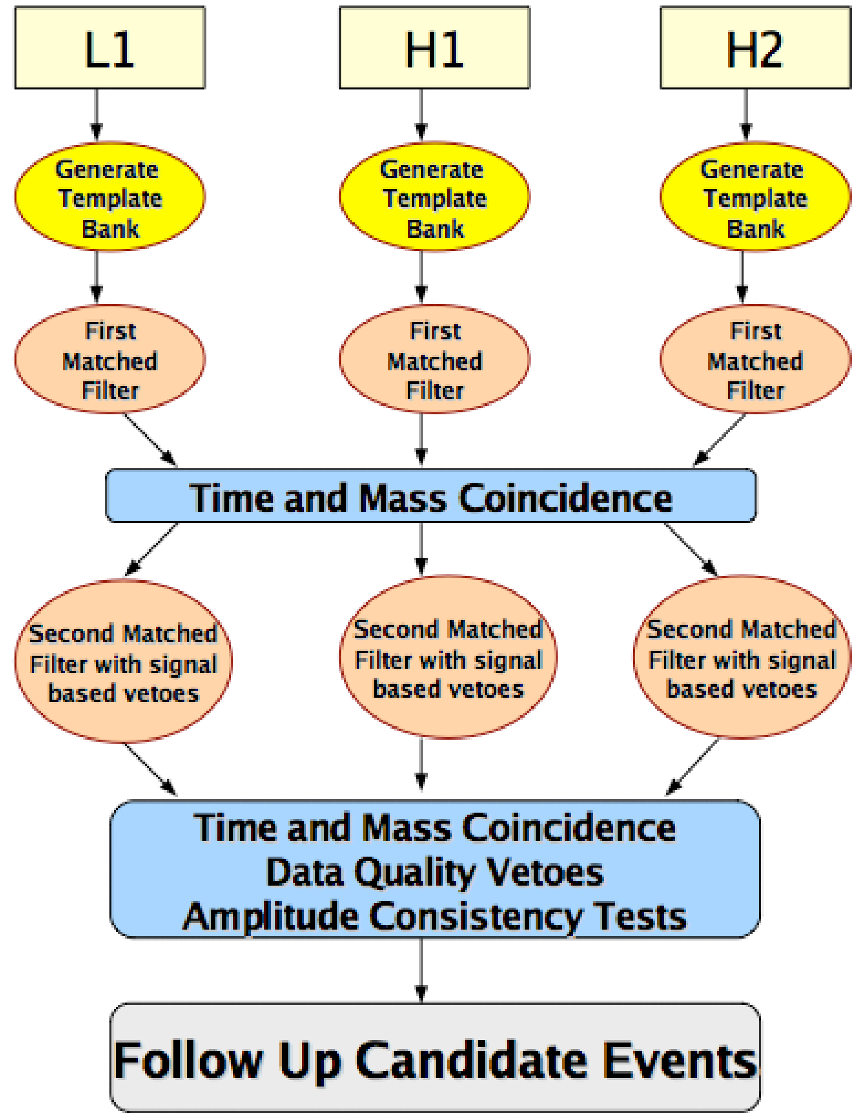


- Typical frequency scales as 1/Mass
- For massive systems ($M \gtrsim 50 M_\odot$ for LIGO), merger and ringdown contribute significantly to signal-to-noise ratio (SNR)
- Inspiral alone can be below detector's frequency band, pN waveforms are inadequate
- Spins add complications

Detection: Matched Filtering

$$z(t) = 4\int_{f_{\rm low}}^{f_{\rm final}} \frac{\tilde{s}(f)^*\tilde{h}(f)e^{2\pi i f t}}{S_n(f)}\,df,$$





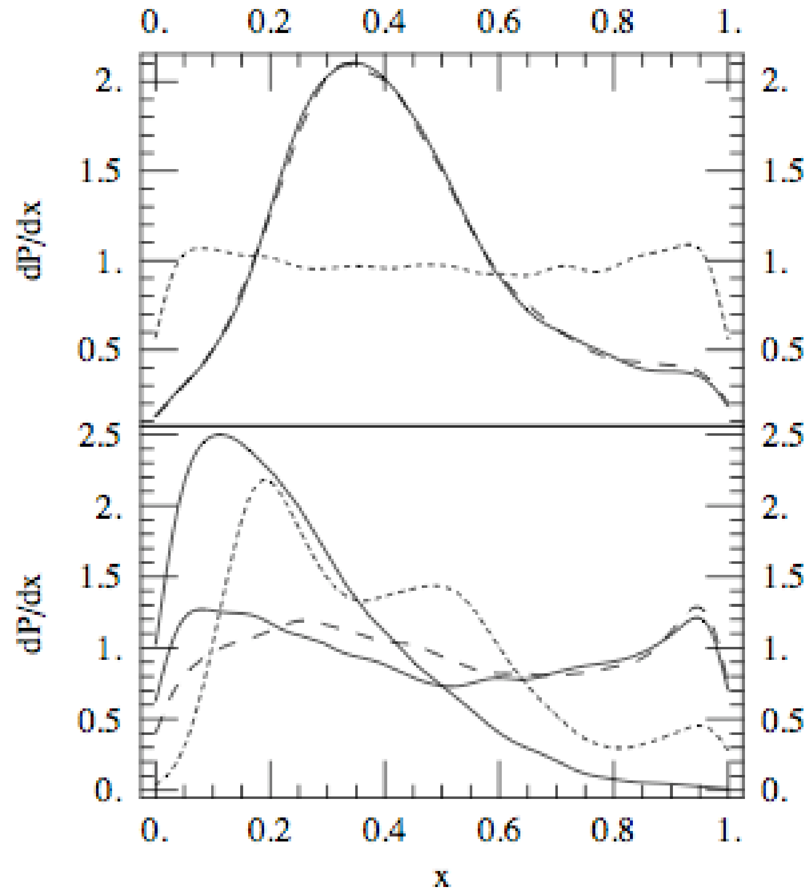
Use time slides to measure efficiency

Informing GW searches with Astro, 2

- Rates predictions can help to determine which searches we should focus resources on
- Choice of waveform templates for detection:
  - » Example 1: Low chirp masses may make merger/ringdown waveforms unnecessary for most stellar-mass BH-BH mergers; however, searches with the full inspiral-merger-ringdown waveforms informed by numerical relativity will be necessary for GWs from IMBH sources
  - » Example 2: Spin is important for accurate parameter estimation of BH-NS and BH-BH binaries
  - » Example 3: Could cut down on template number (and reduce FAR) for spinning BH-NS template banks since very massive BHs will be hard to spin up [Pan et al., 2004, PRD 69 104017]

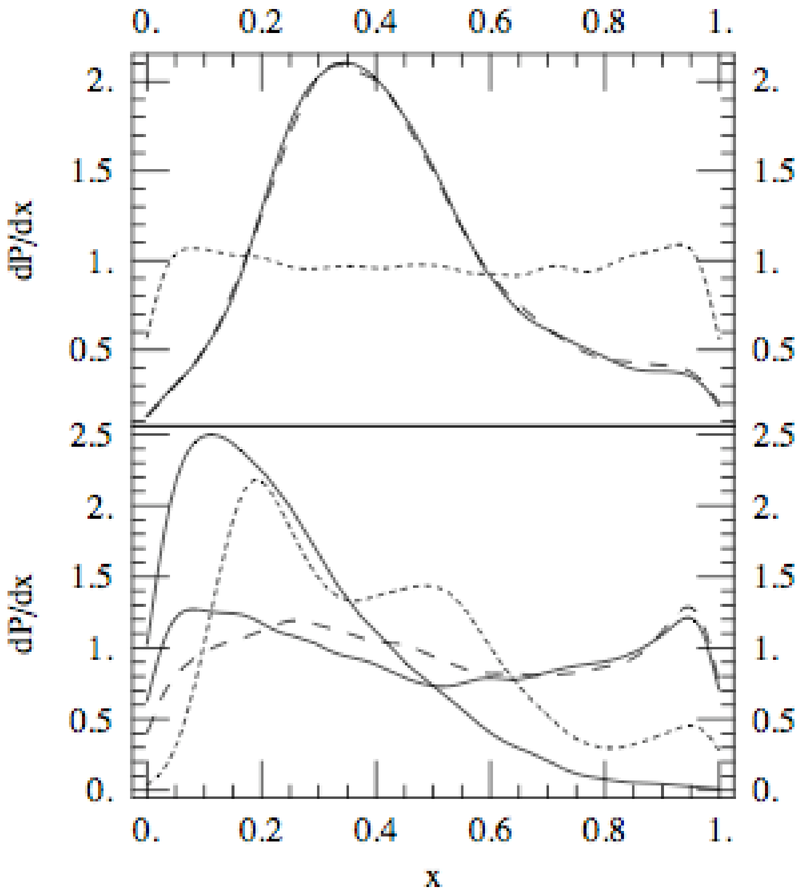
Astrophysics with GW searches

- Constraints on astrophysical parameters from existing electromagnetic observations
  [O'Shaughnessy et al., 2008 ApJ 672 479]:



Astrophysics with GW searches

- Constraints on astrophysical parameters from existing electromagnetic observations [O'Shaughnessy et al., 2008 ApJ 672 479]:
- Observed GW event rates can be compared with models to determine important astrophysical parameters;

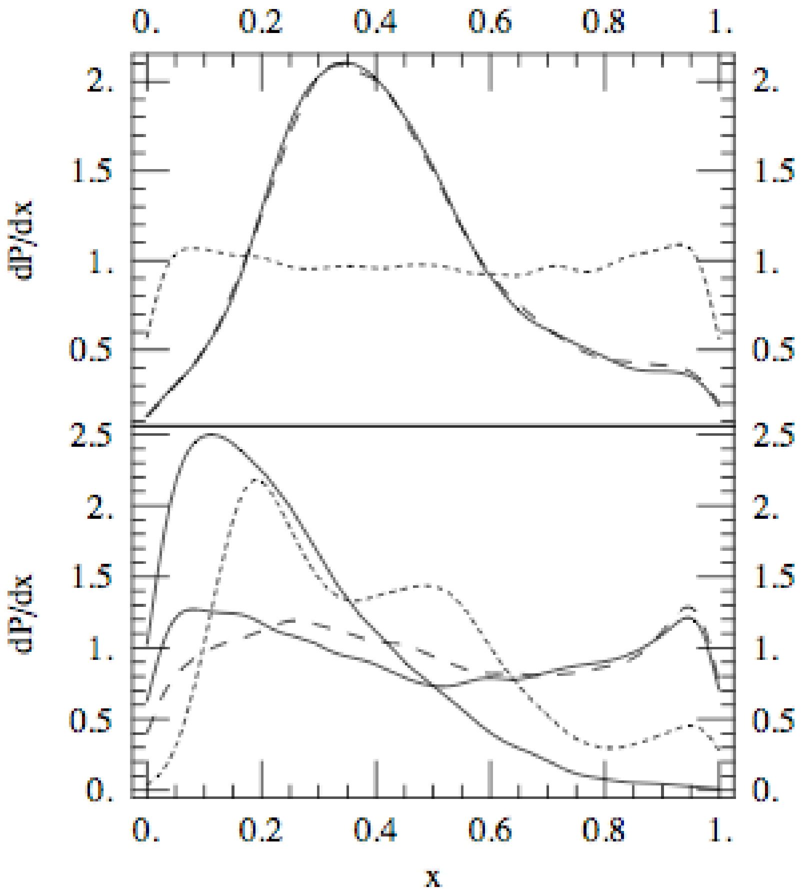


Rates to parameter constraints - theory

- Let f(R) be the measured rates distribution
- The constrained distribution of astrophysical parameters is given by Bayes Rule: $$p(\vec{\Theta}|f(R)) = \frac{p(f(R)|\vec{\Theta})p(\vec{\Theta})}{p(f(R))}$$
- For a given choice of model parameters, population synthesis codes coupled to information about galaxy distributions and detector sensitivity provide a distribution of the detectable event rate, $p(\hat{R}|\vec{\Theta})$
- If an actual rate R is measured, then the likelihood that the model with a given choice of parameters fits the measurement is $$\mathcal{L}(R|\vec{\Theta}) = e^{-\frac{|R-\hat{R}|^2}{2\sigma_R^2}}$$
- Then $$p(f(R)|\vec{\Theta}) = \int d\hat{R}\mathcal{L}(R|\vec{\Theta})p(\hat{R}|\vec{\Theta})$$

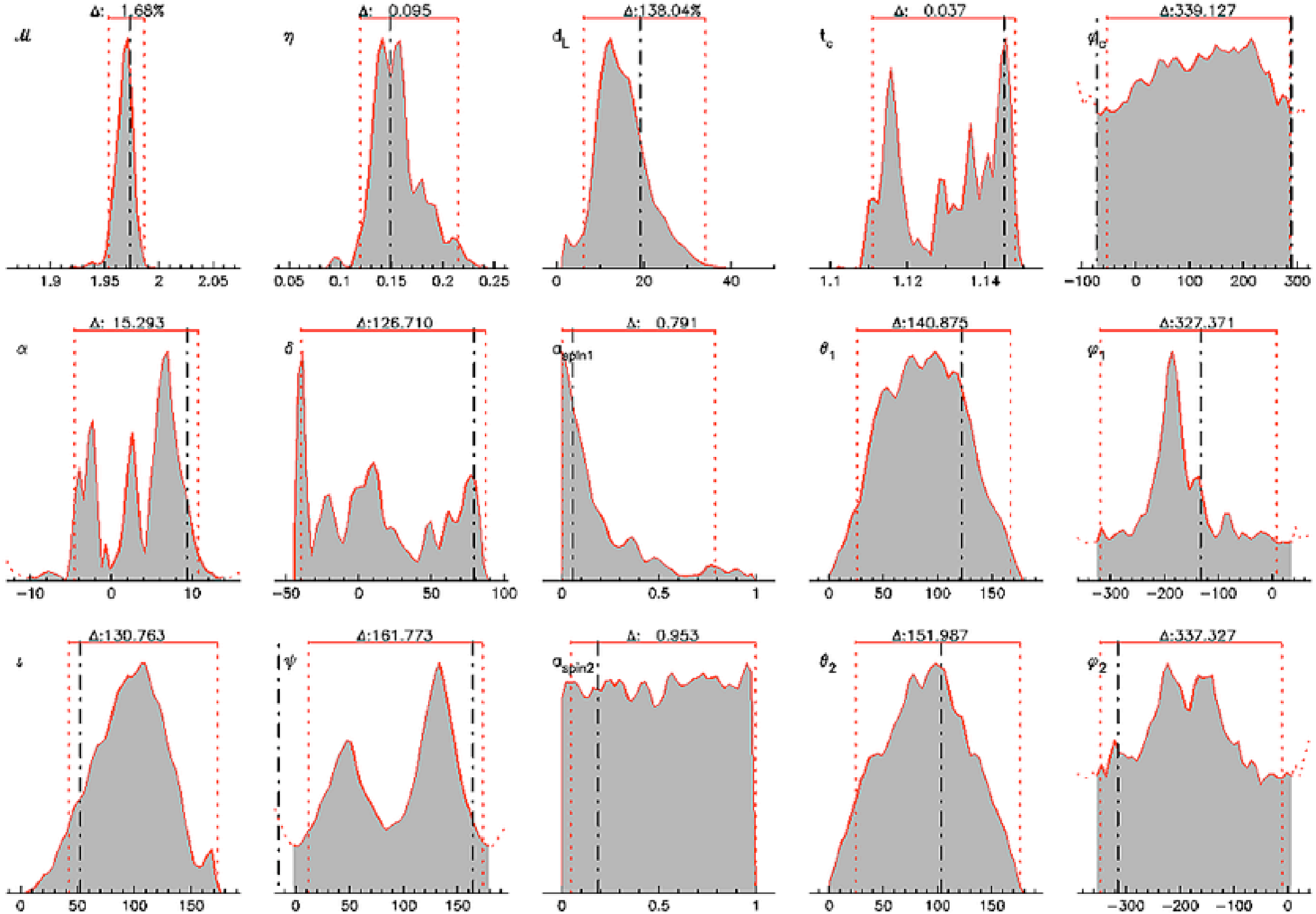
Astrophysics with GW searches

- Constraints on astrophysical parameters from existing electromagnetic observations [O'Shaughnessy et al., 2008 ApJ 672 479]:
- Observed GW event rates can be compared with models to determine important astrophysical parameters;
- Could match measured mass distributions, etc. to models (requires accurate parameter determination)



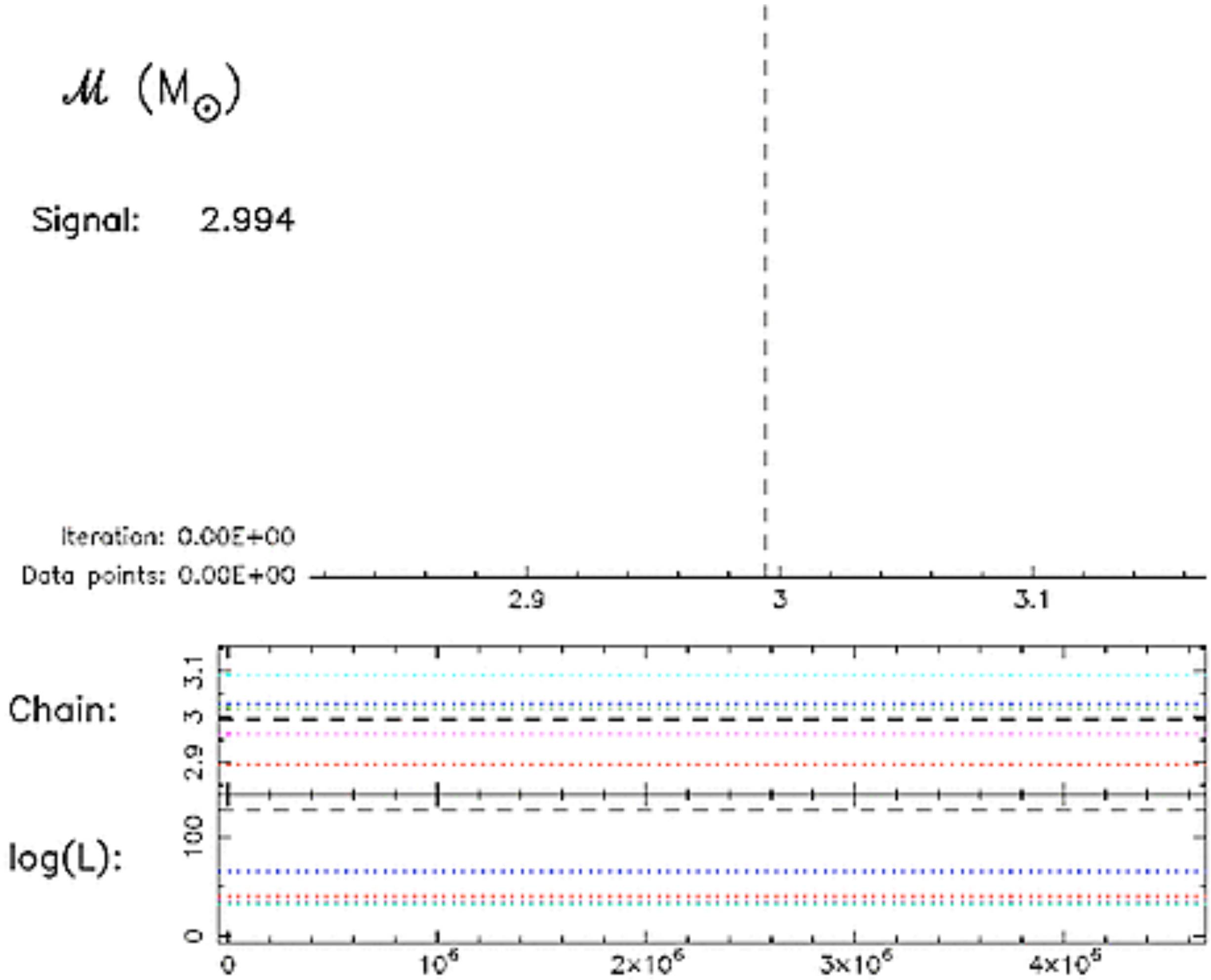
C I E R A

Accurate Parameter Estimation



van der Sluys, IM, Raymond, et al., 0905.1323

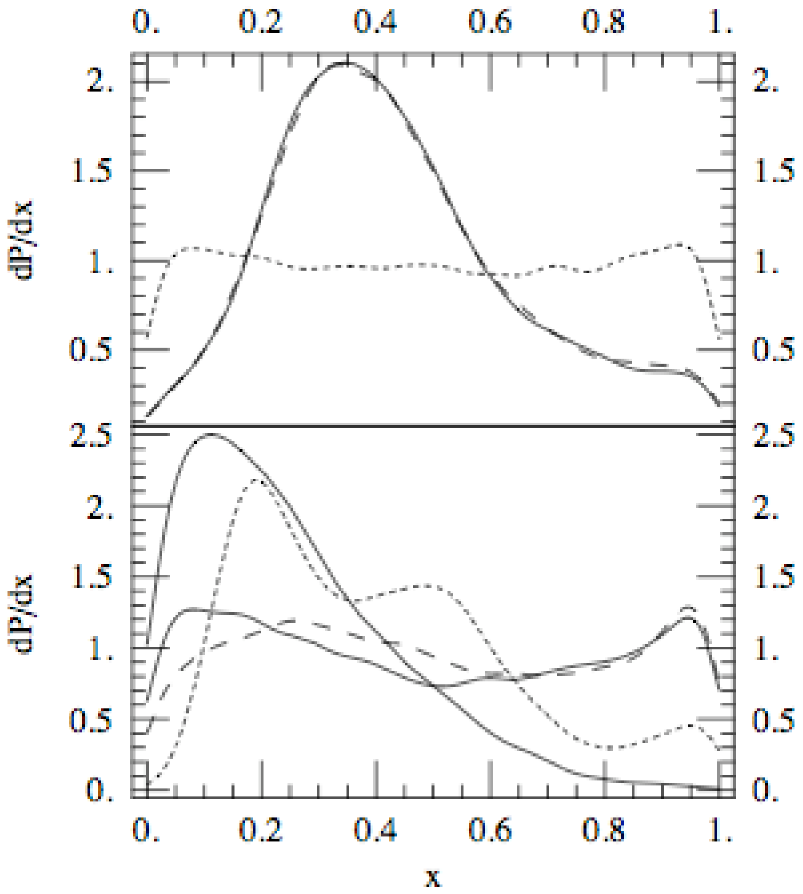
Markov Chain Monte Carlo



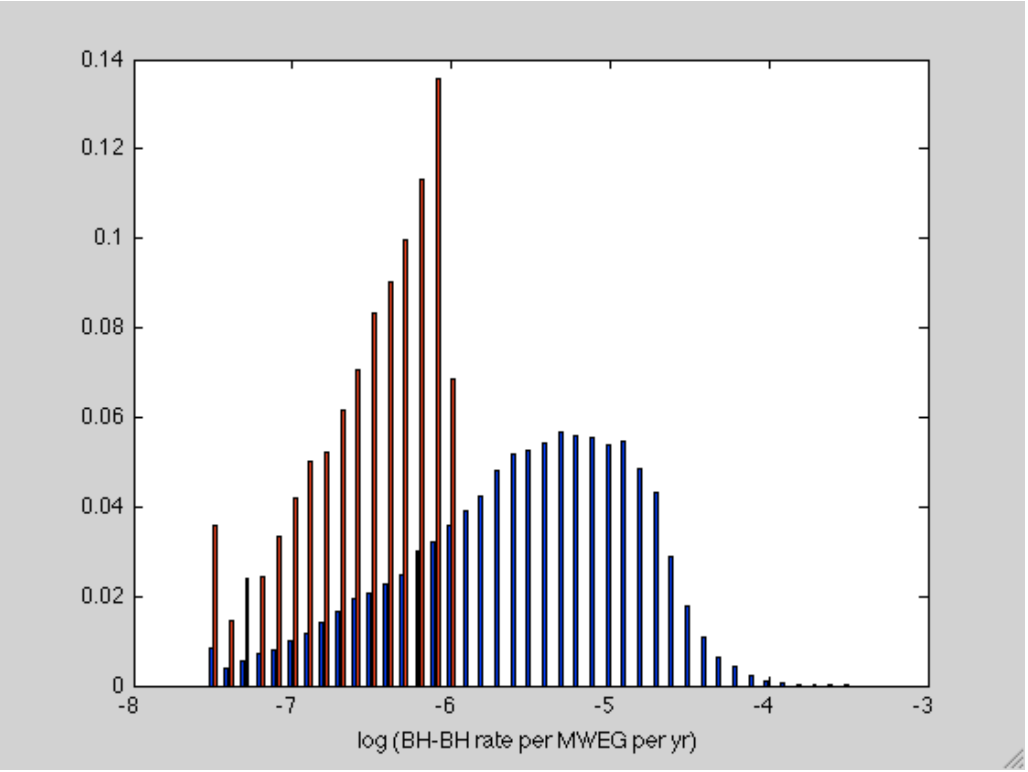
Animation by Marc van der Sluys

Astrophysics with GW searches

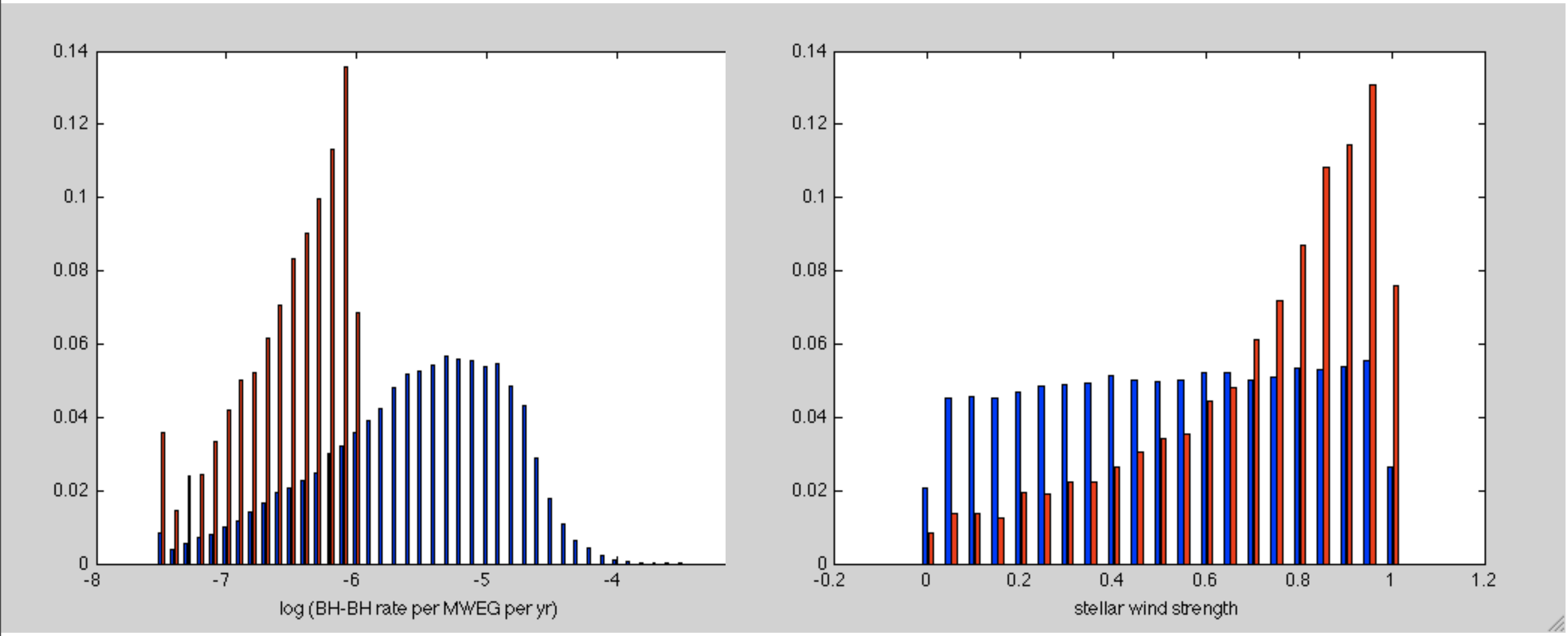
- Constraints on astrophysical parameters from existing electromagnetic observations [O'Shaughnessy et al., 2008 ApJ 672 479]:
- Observed GW event rates can be compared with models to determine important astrophysical parameters;
- Could match measured mass distributions, etc. to models (requires accurate parameter determination)
- As detector sensitivity improves, even upper limits can be useful in constraining parameter space for birth kicks, common-envelope efficiency, winds, etc.



Constraints from upper limits - example



Constraints from upper limits - example

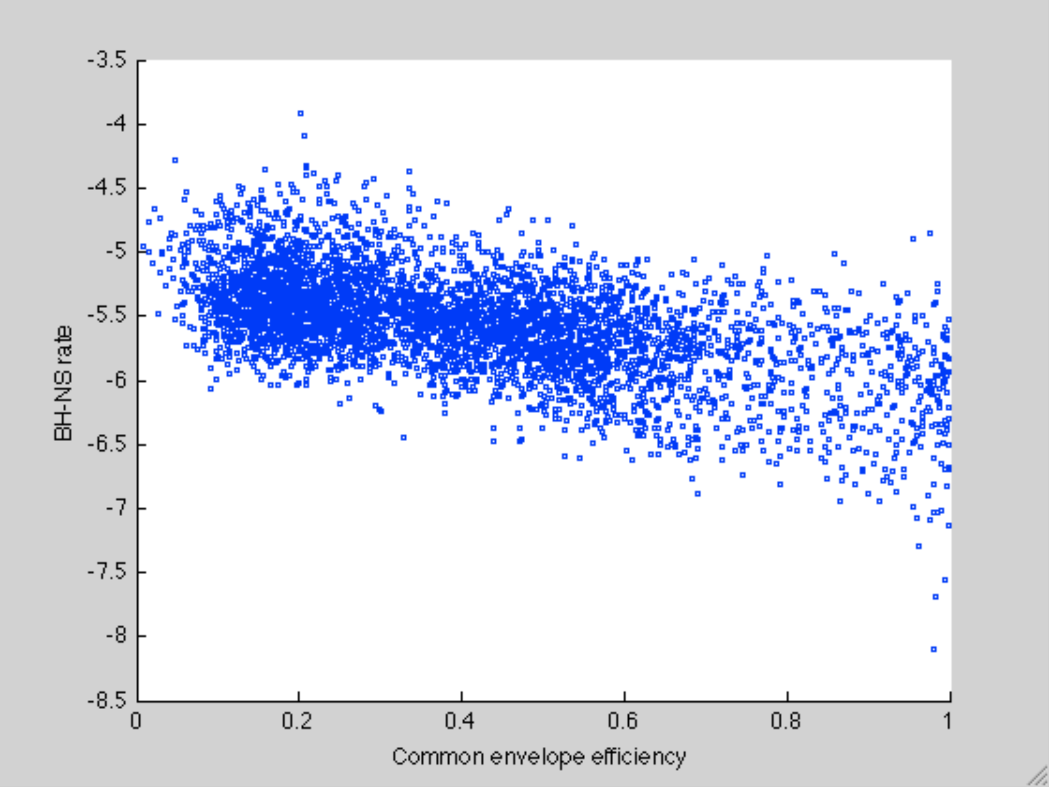


Common Envelope Efficiency

Double Compact Object Formation Channels

Formation Channel	Relative Efficiency[α]	Evolutionary History[β]
NSNS:01	20.3 %	NC:a→b, SN:a, HCE:b→a, HCE:b→a, SN:b
NSNS:02	10.8 %	NC:a→b, SCE:b→a, NC:a→b, SN:a, HCE:b→a, SN:b
NSNS:03	5.5 %	SCE:a→b, SN:a, HCE:b→a, HCE:b→a, SN:b
NSNS:04	4.0 %	NC:a→b, SCE:b→a, SCE:b→a, SN:b, HCE:a→b, SN:a
NSNS:05	3.2 %	DCE:a→b, SCE:a→b, SN:a, HCE:b→a, SN:b
NSNS:06	2.5 %	SCE:a→b, SCE:b→a, NC:a→b, SN:a, HCE:b→a, SN:b
NSNS:07	2.2 %	NC:a→b, NC:a→b, SN:a, HCE:b→a, HCE:b→a, SN:b
NSNS:08	2.0 %	NC:a→b, DCE:b→a, SN:a, HCE:b→a, SN:b
NSNS:09	2.0 %	DCE:a→b, DCE:a→b, SN:a, SN:b
NSNS:10	1.6 %	NC:a→b, SCE:b→a, SN:b, HCE:a→b, SN:a
NSNS:11	1.5 %	NC:a→b, SCE:b→a, DCE:b→a, SN:a, SN:b
NSNS:12	1.5 %	NC:a→b, SCE:b→a, DCE:a→b, SN:a, SN:b
NSNS:13	1.0 %	DCE:a→b, SN:a, HCE:b→a, SN:b
NSNS:14	3.0 %	all other
BHNS:01	4.5 %	NC:a→b, SN:a, HCE:b→a, SN:b
BHNS:02	1.6 %	NC:a→b, SCE:b→a, SN:a, SN:b
BHNS:03	1.3 %	SCE:a→b, SN:a, HCE:b→a, NC:b→a, SN:b
BHNS:04	2.0 %	all other
BHBH:01	17.7 %	NC:a→b, SN:a, HCE:b→a, SN:b
BHBH:02	10.5 %	NC:a→b, SCE:b→a, SN:a, SN:b
BHBH:03	1.4 %	all other

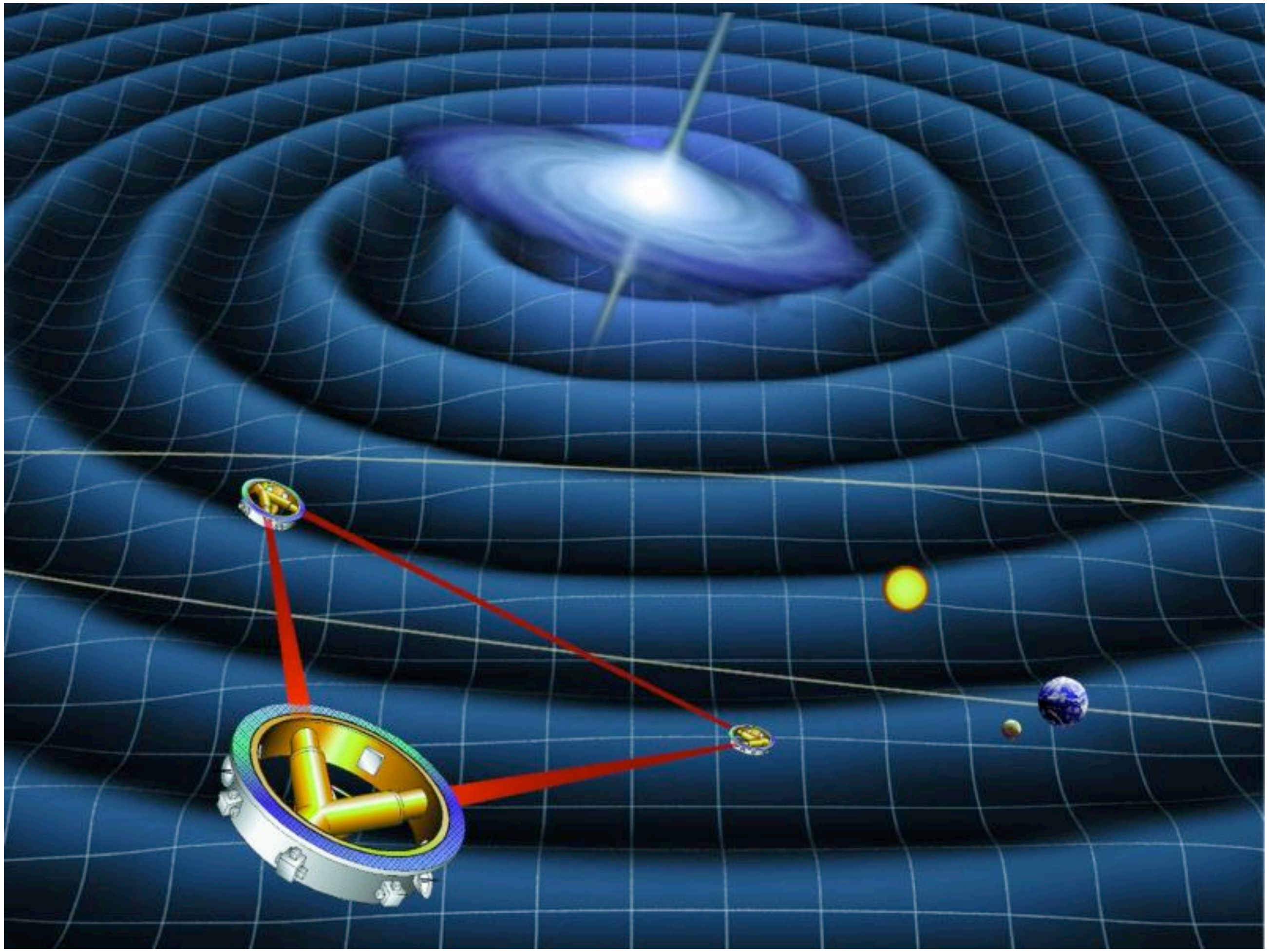
[Kalogera et al., 2007, Physics Reports 442, 75]



Also possible to constrain common-envelope model with LISA observations:

[Belzcynski, Benacquista, Bulik, 2008, arXiv:0811.1602]

LISA:
Laser Interferometer Space Antenna

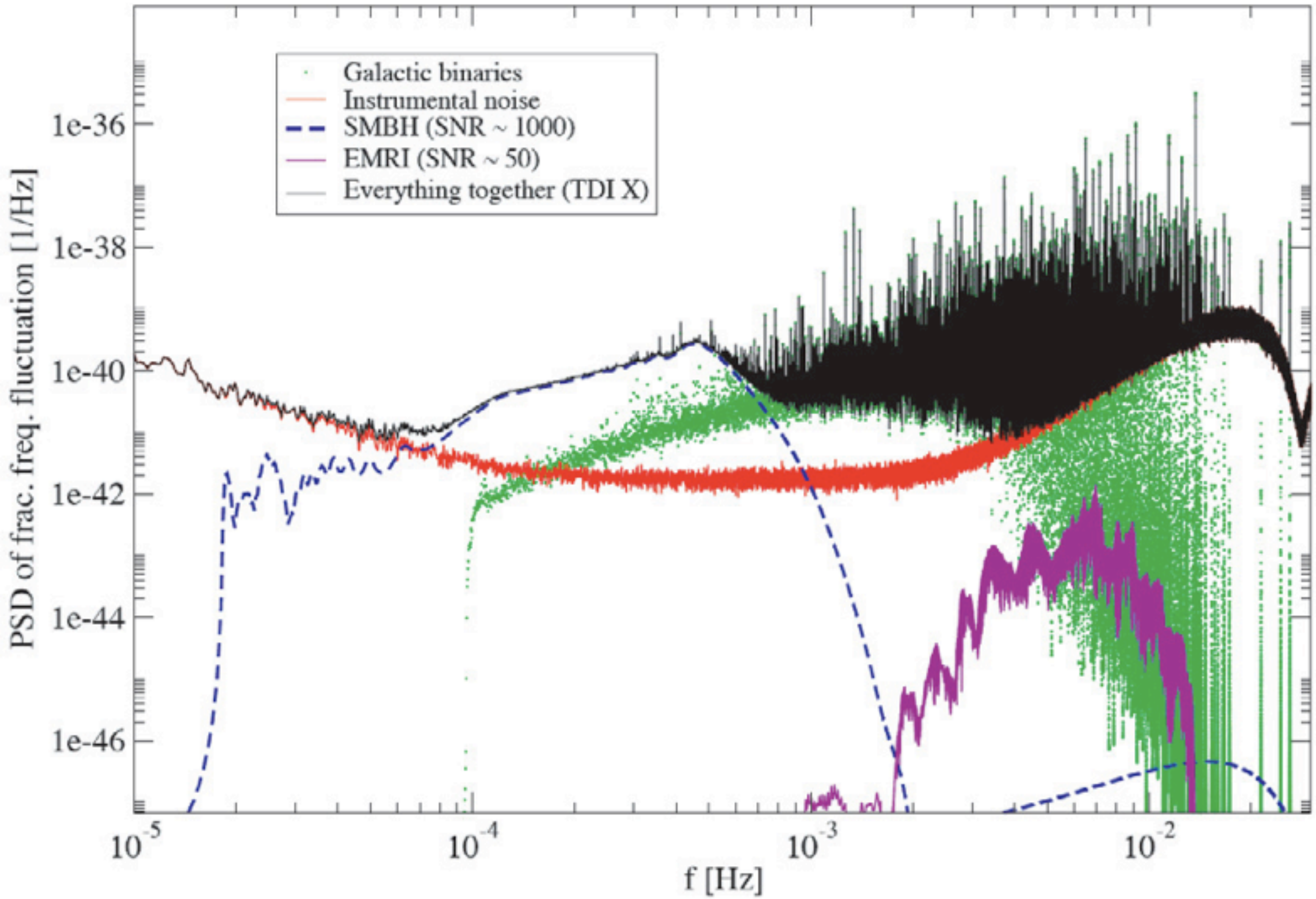


3 spacecraft following Earth around Sun,
5 million km apart

LISA Binary Sources

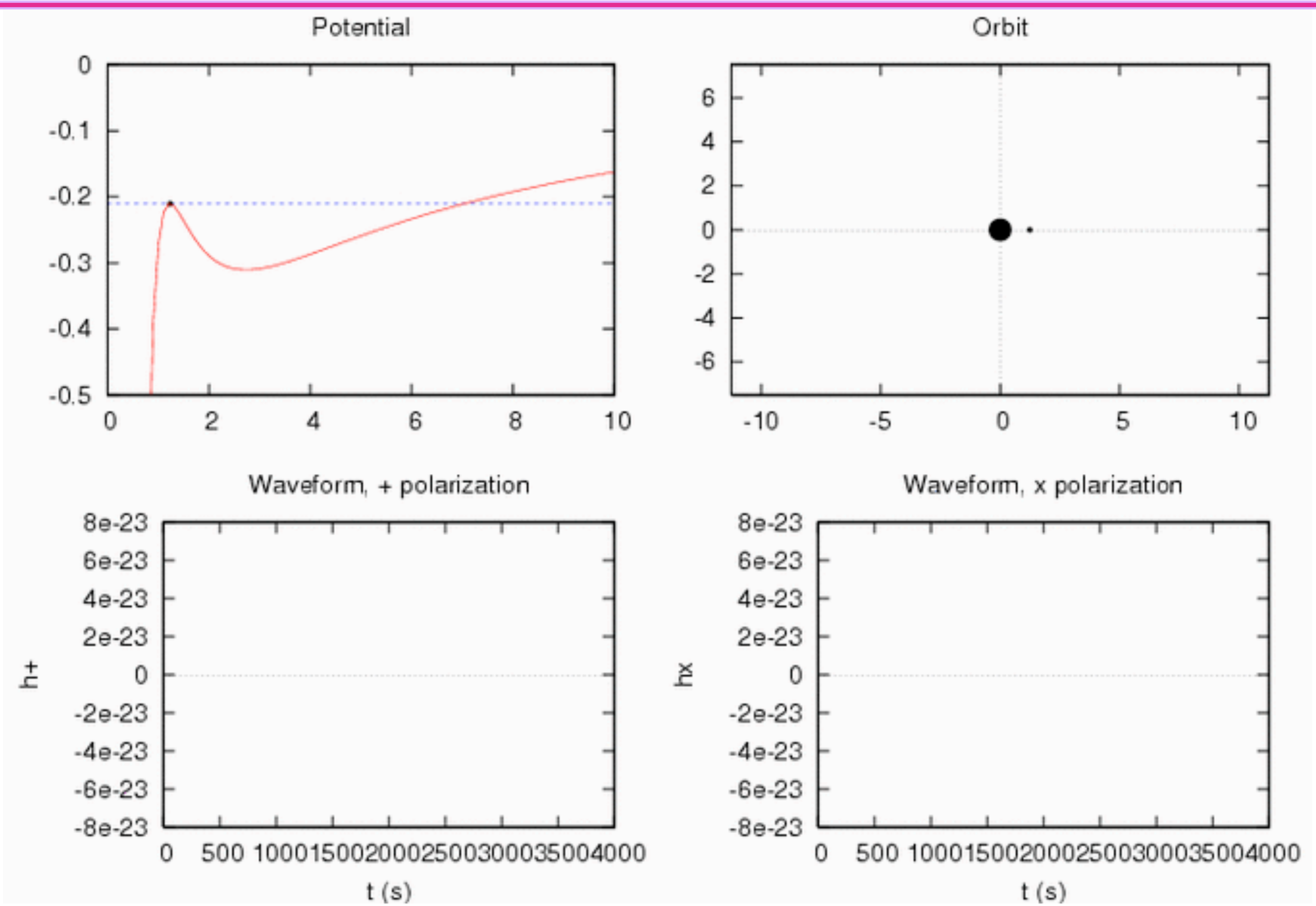
- LIGO sensitive @ a few hundred Hz
  - NS-NS, NS-BH, BH-BH binaries
- LISA sensitive @ a few mHz

Embarrassment of riches



from Amaro-Seoane et al., 2007

EMRI: Extreme Mass Ratio Inspiral



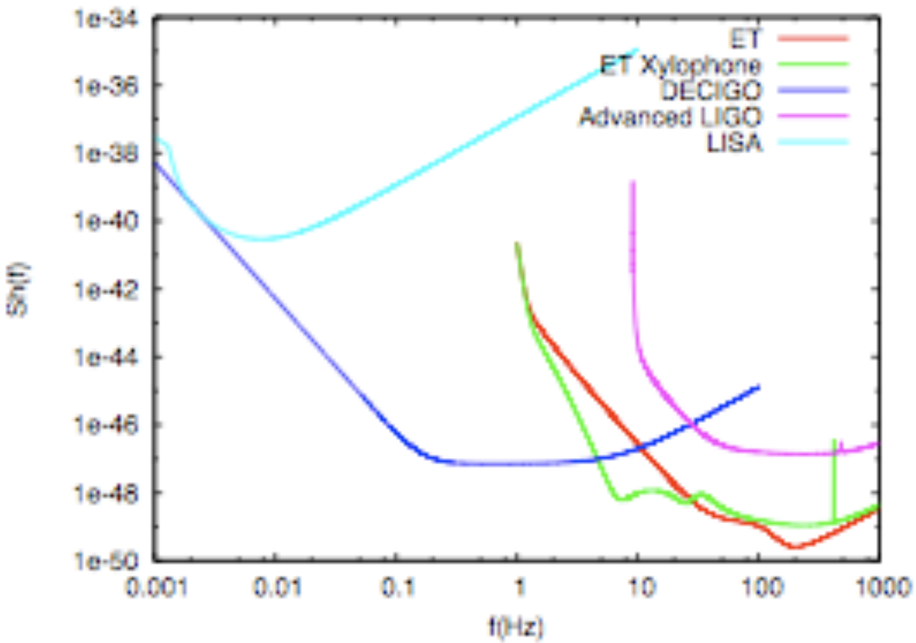
Animation from Jon Gair

LISA Binary Sources

- LIGO sensitive @ a few hundred Hz
  - NS-NS, NS-BH, BH-BH binaries
- LISA sensitive @ a few mHz
  - massive black-hole binaries
    - merger tree models to describe history of Galactic mergers
    - could be detected anywhere in Universe, SNR up to thousands
    - a few to tens of detections [e.g., Sesana et al., 2005]
  - galactic white dwarf (and compact object) binaries
    - 30 million in Galaxy, create noise foreground [Farmer & Phinney, 2003]
    - 20,000 resolvable
  - extreme-mass-ratio inspirals of WDs/NSs/BHs into SMBHs
    - complicated modeling of dynamics in Galactic centers: loss cone problem, resonant scattering, etc.
    - can see tens to hundreds to z~1 [e.g., Gair et al., 2004]

Third-generation detectors

- The Einstein Telescope:
  - Underground, sensitive to 1 Hz
  - Exciting science example: mergers of light seeds of massive black holes at high redshifts [Sesana, Gair, IM, Vecchio, 2009]
- ALIA/DECIGO/BBO
  - Space-based LISAs on steroids
  - Exciting science example: using 300,000 merging binaries as standard candles for precision cosmology: Hubble constant to 0.1%, w to 0.01 [Cutler & Holz, 2009]
- Pulsar timing
  - Sensitive to SMBHBs @ 10^{-8} Hz



from Gair, IM, Sesana, Vecchio, 2009

Conclusion

- Current understanding of coalescence rates and properties of compact binaries is imperfect
- Advanced LIGO is likely to see NS-NS, NS-BH, BH-BH coalescences; tens or more coalescences may be seen according to some models, including dynamical formation
- Improved understanding of astrophysics can help GW search by informing detector configuration, template family
- GW detections and upper limits for compact-object coalescences will allow us to constrain the astrophysical parameters
- Future GW detectors (LISA and beyond) will allow precise probes of a wide range of astrophysical environments