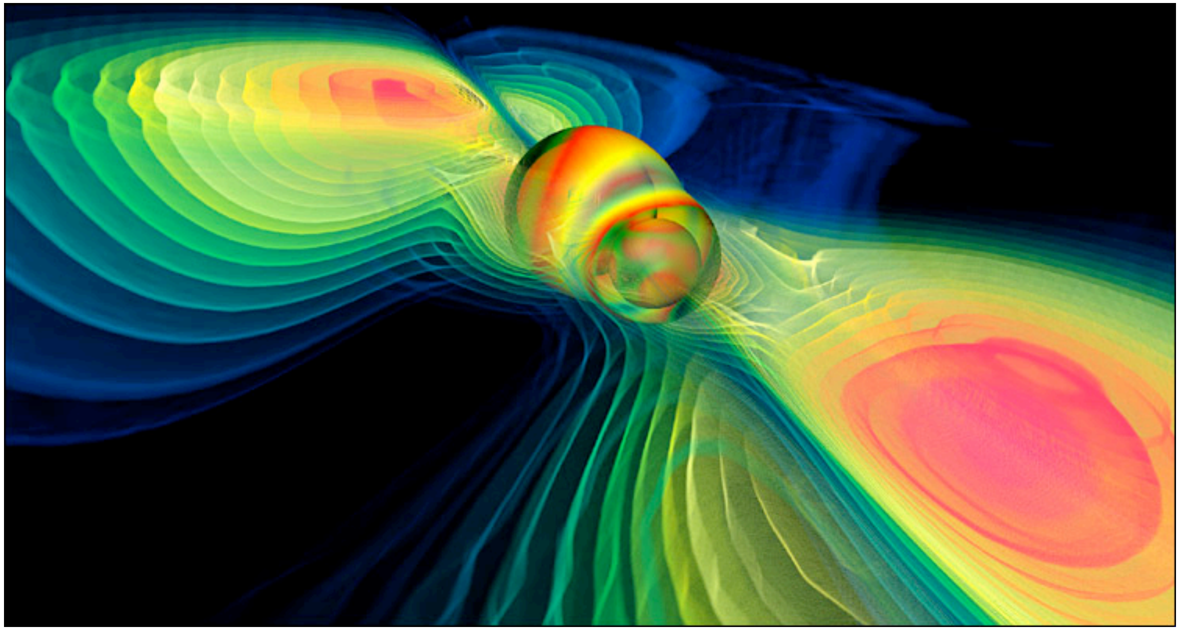
Prospects in Gravitational-Wave Astronomy



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

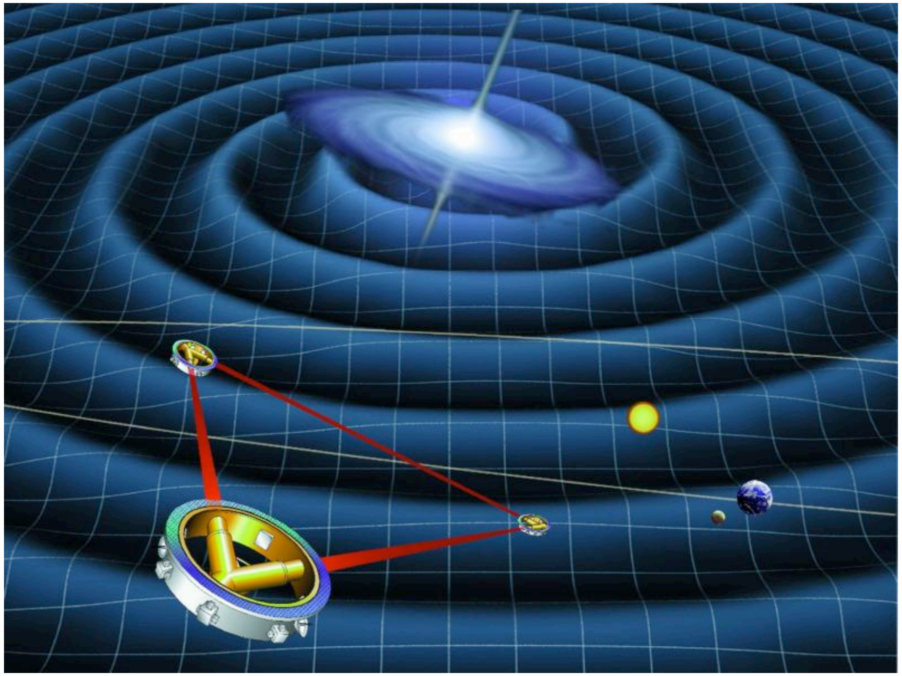
Ilya Mandel
(NSF AAPF, CIERA @Northwestern University)

May 14, 2010

RIT Seminar

Gravitational-wave observatories

LIGO:
Laser
Interferometer
Gravitational-wave
Observatory

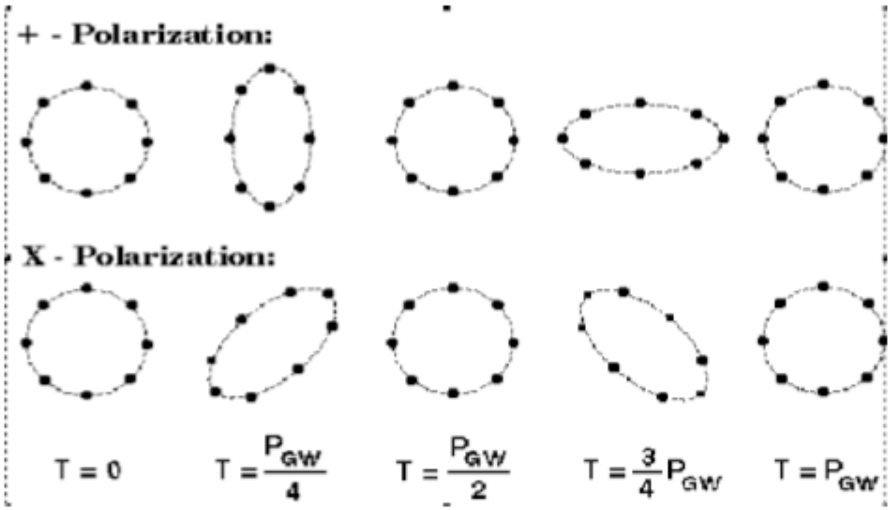


LISA:
Laser
Interferometer
Space
Antenna

Gravitational Waves

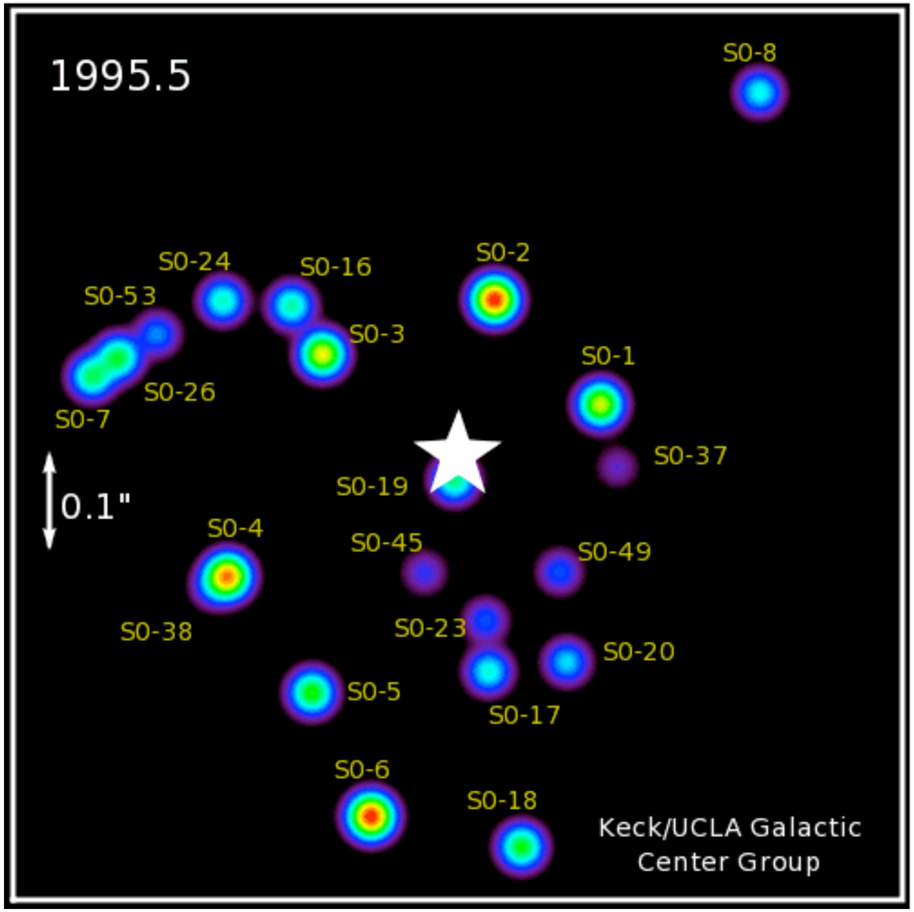
- Ripples in spacetime:

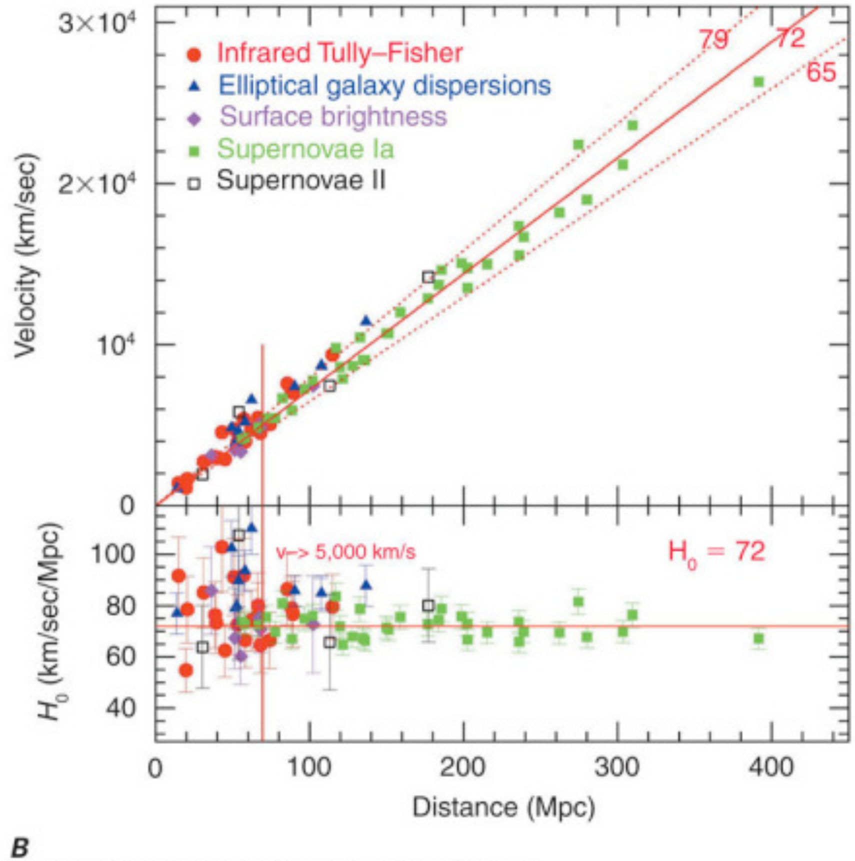
Inspiral sound borrowed from Scott Hughes



- 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!

Why do we want to see GWs?





(Wendy L. Freedman, Observatories of the Carnegie Institution of Washington, and NASA)

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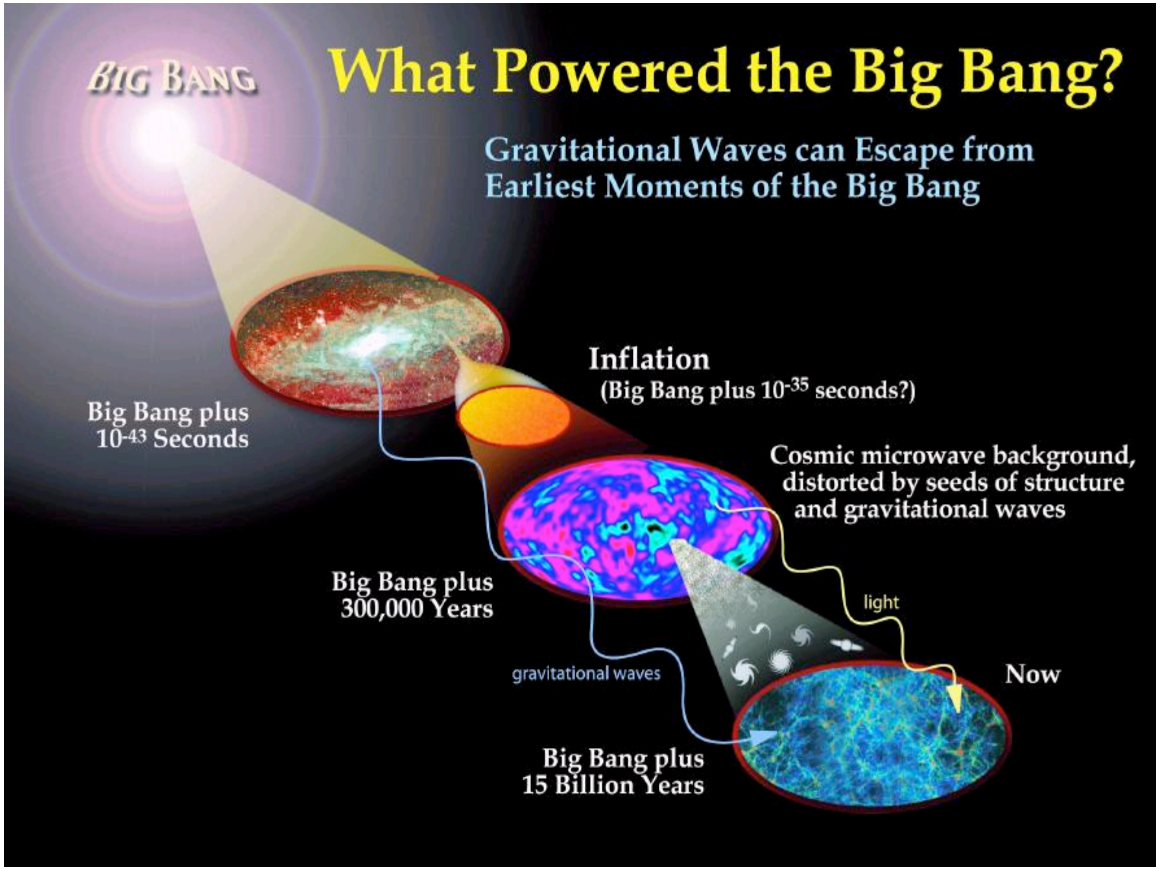

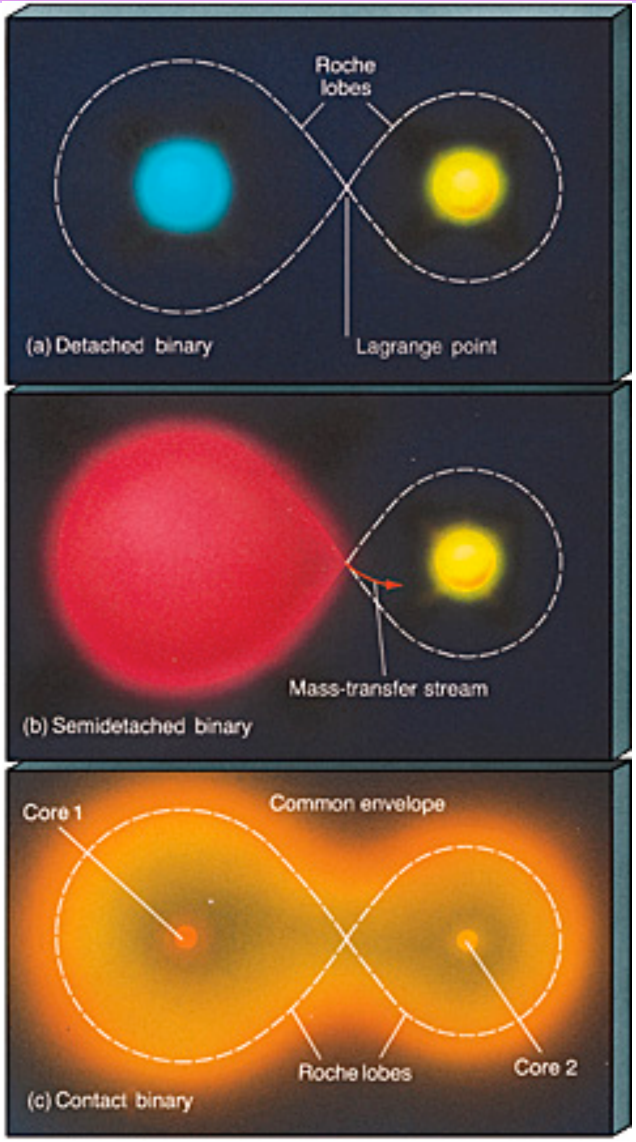

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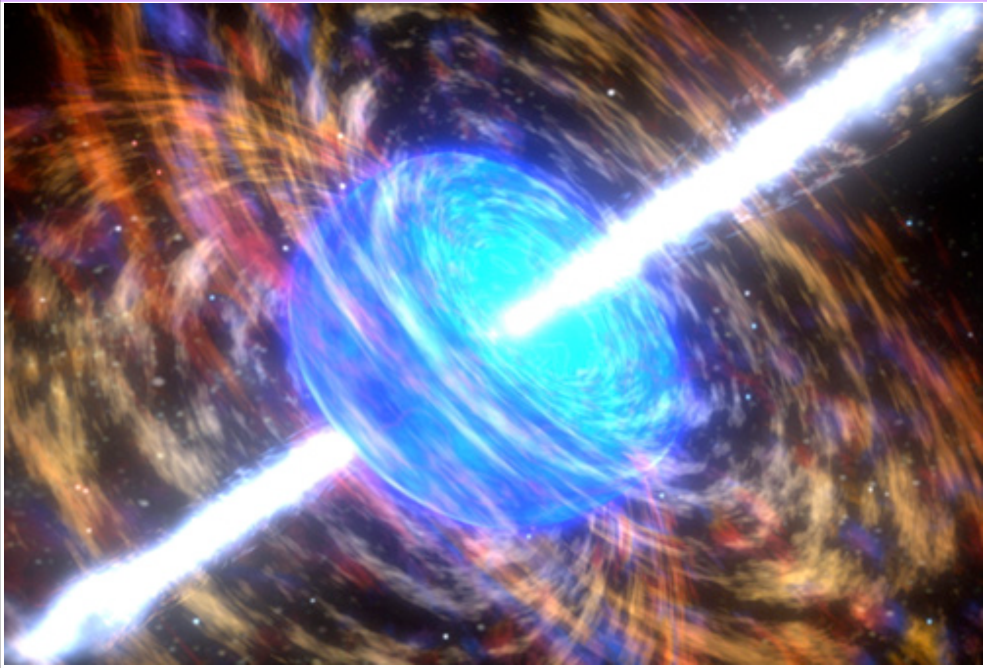
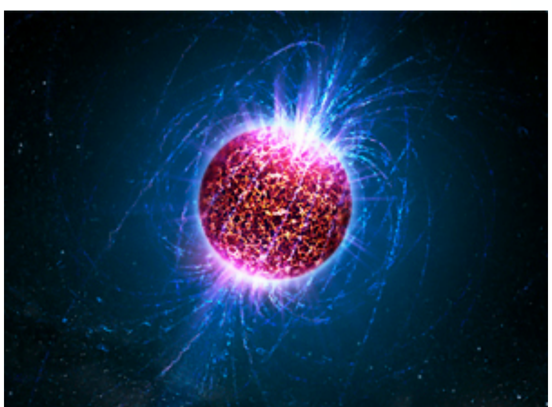
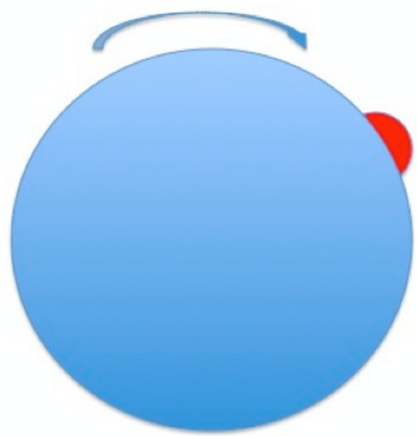
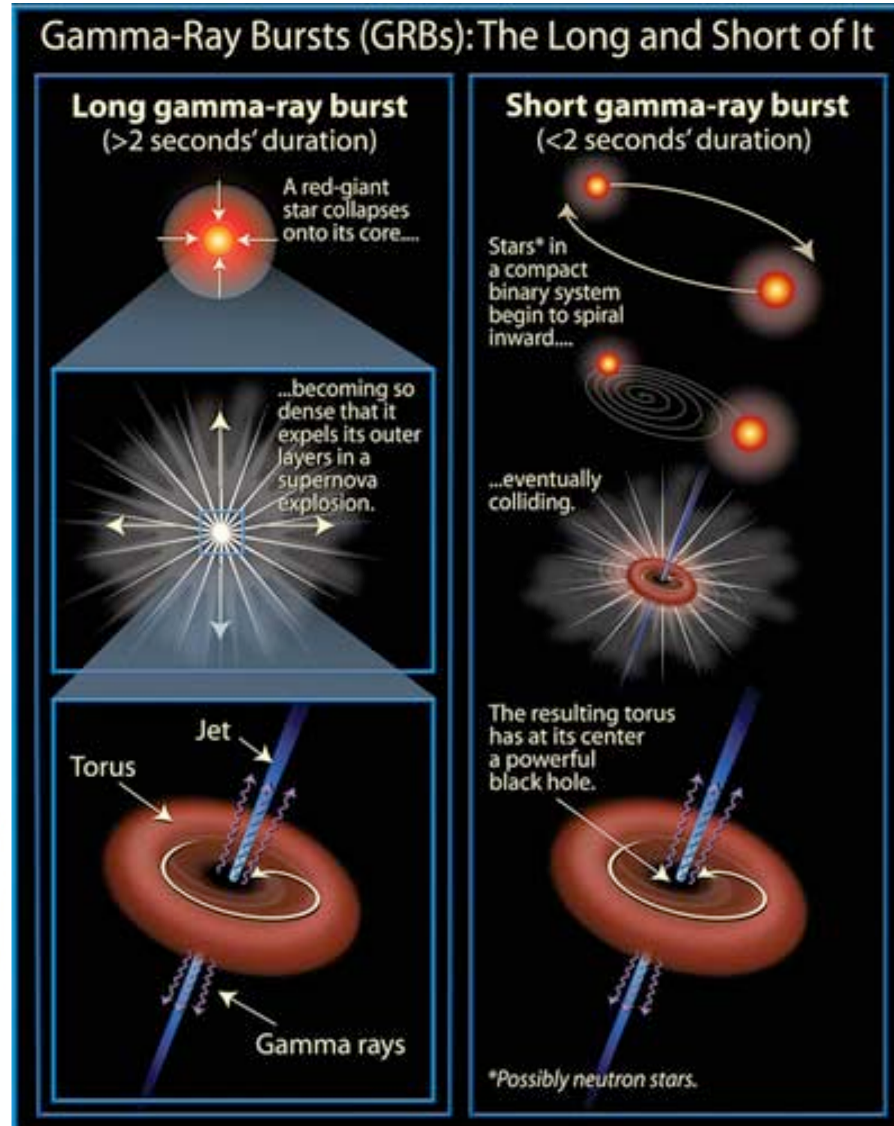
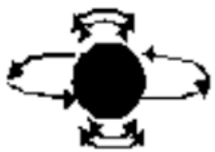


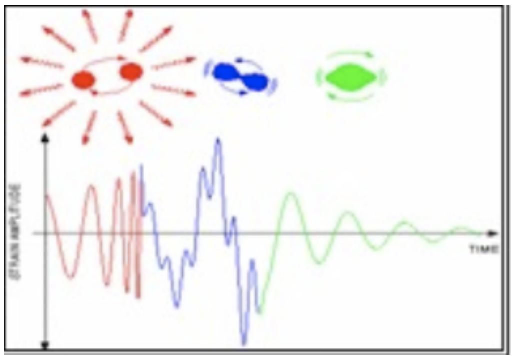






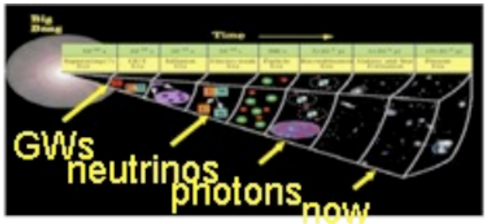
Types of GW sources





- Continuous sources [sources with a slowly evolving frequency]: e.g., non-axisymmetric neutron stars, slowly evolving binaries
- Coalescence sources [known waveforms, matched filtering]: compact object binaries

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



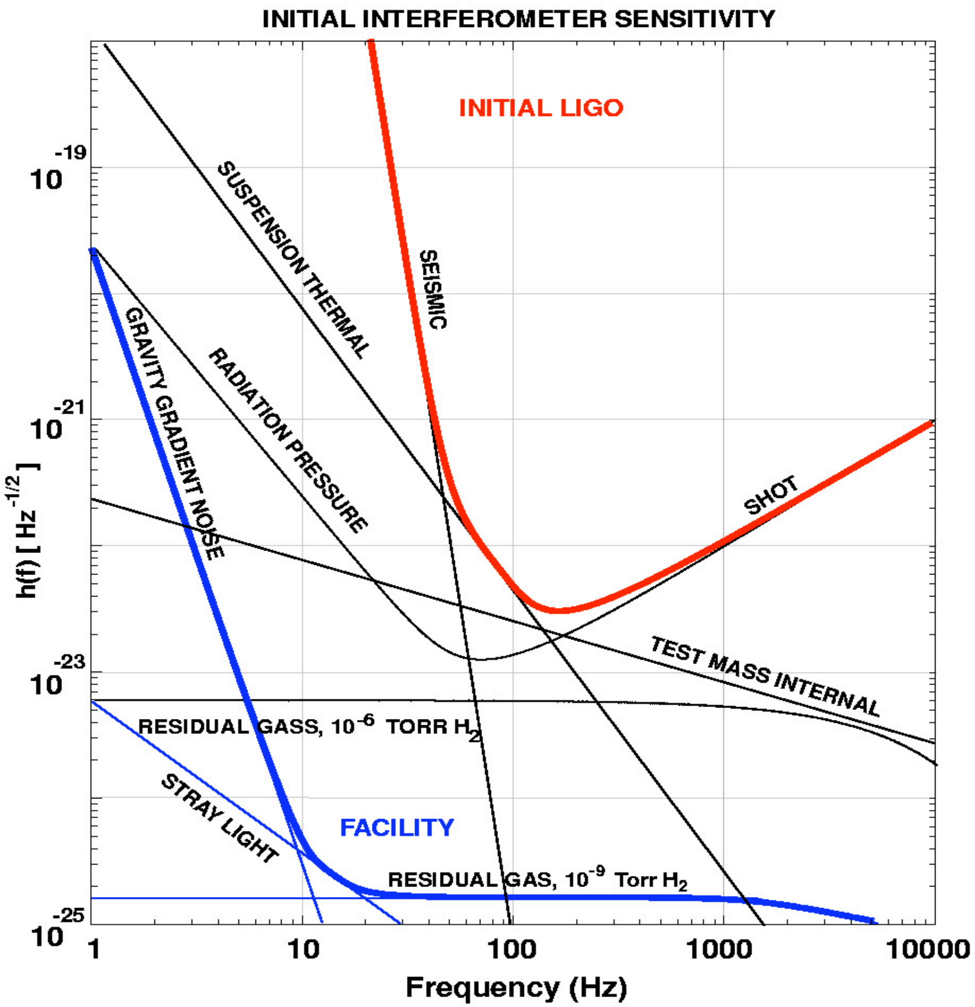
- Stochastic GW background [early universe]
- ??? [expect the unexpected]

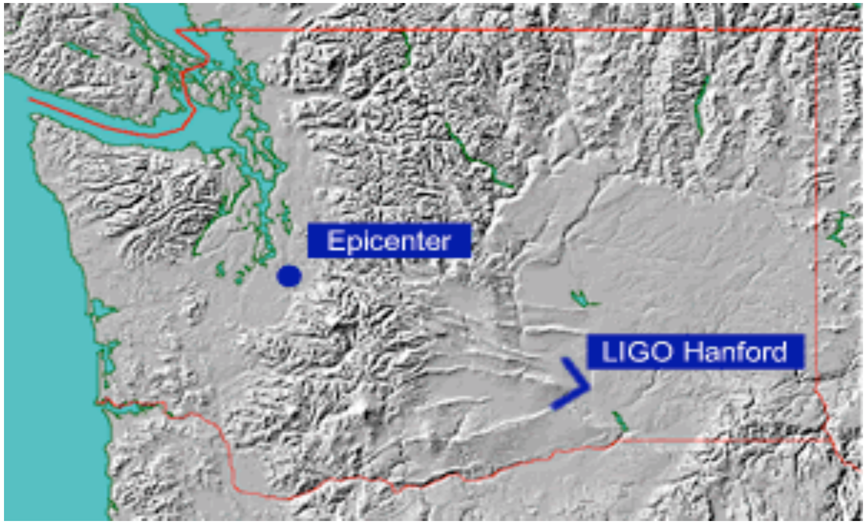
LIGO (Laser Interferometer Gravitational-Wave Observatory)

$$h \sim \frac{\ddot{Q}}{d} \sim \frac{mr^2\omega^2}{d} \sim \frac{m}{d}\frac{M}{r}$$

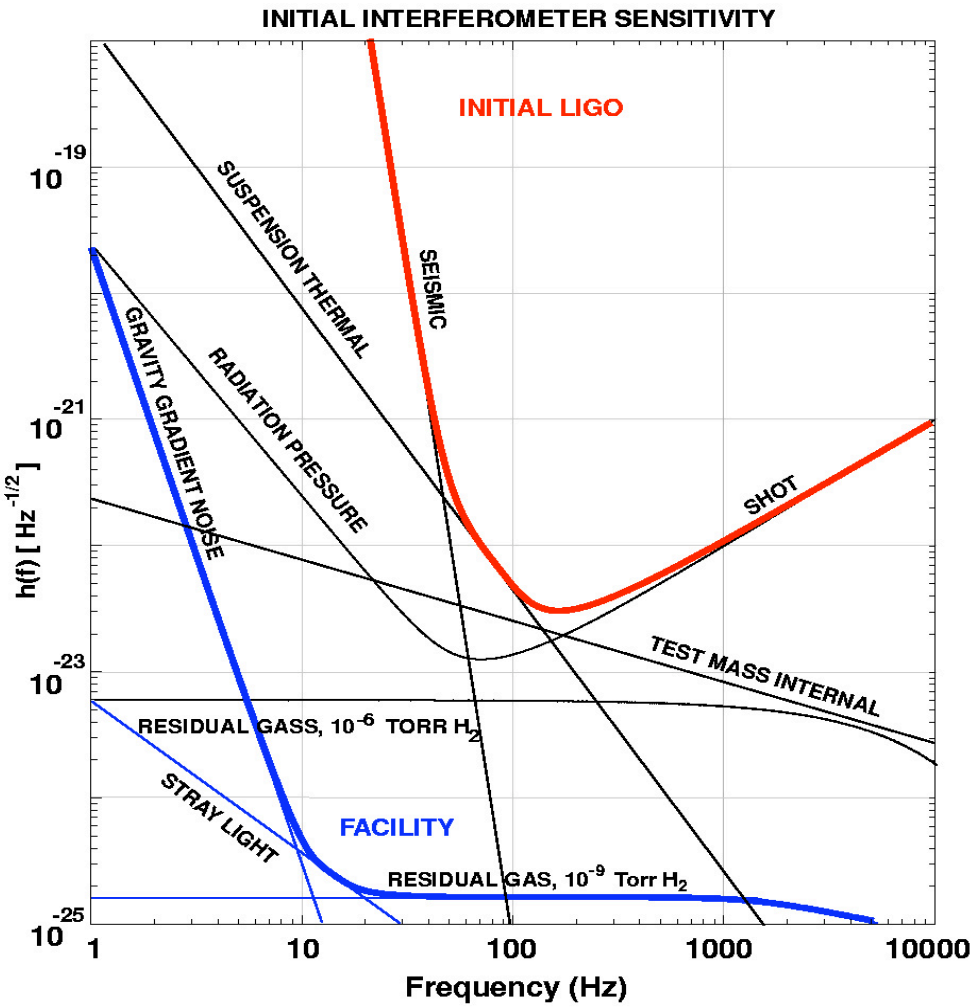
- 4 km long arms
- Typical strains $h = \Delta L / L \sim 10^{-21}$ (NS-NS in Virgo cluster)
- Needs to measure $\Delta L = hL \sim 10^{-18}$ m
- 2 LIGO detectors in US + Virgo, GEO in Europe
- Virgo has 3 km baseline; data-sharing agreement with LIGO

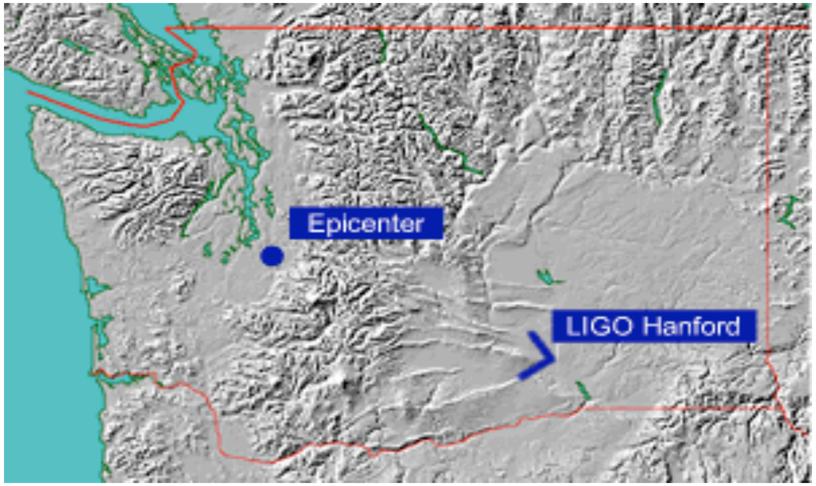
Detection Challenges



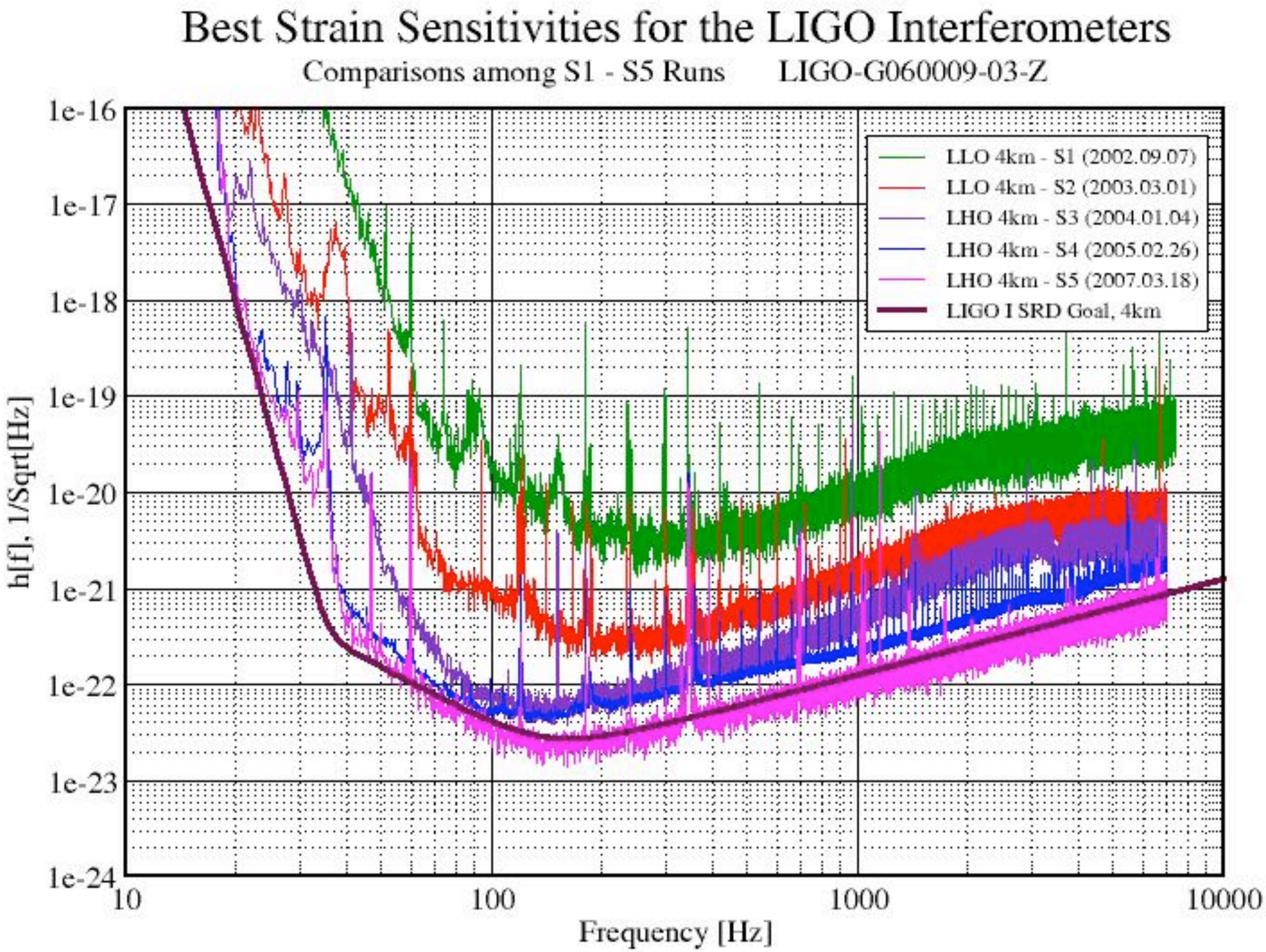


Detection Challenges

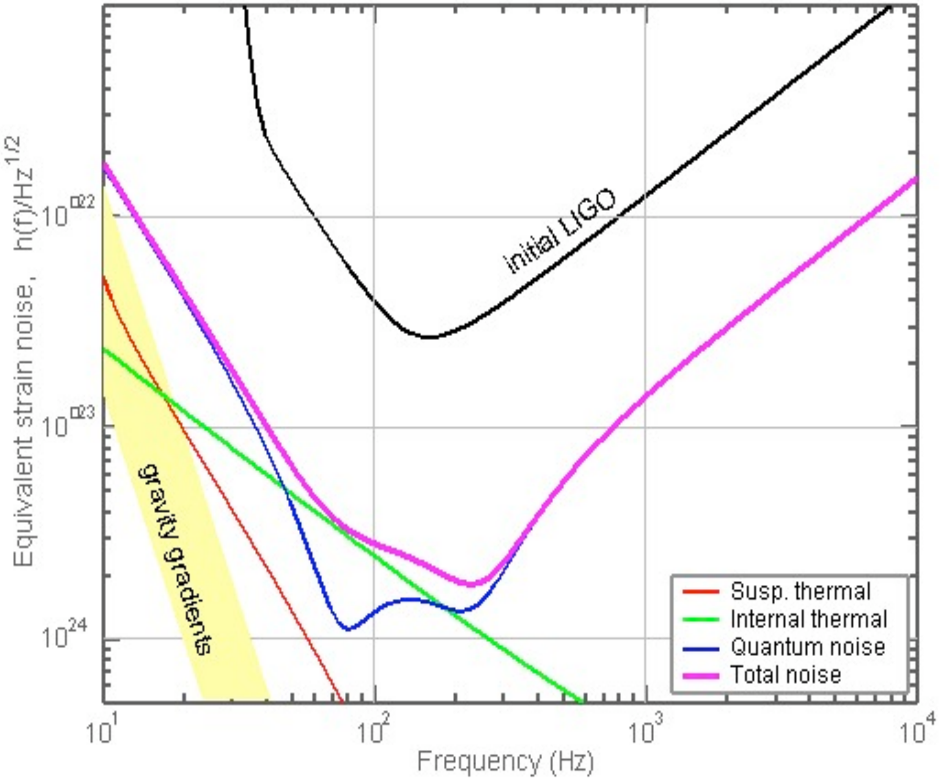


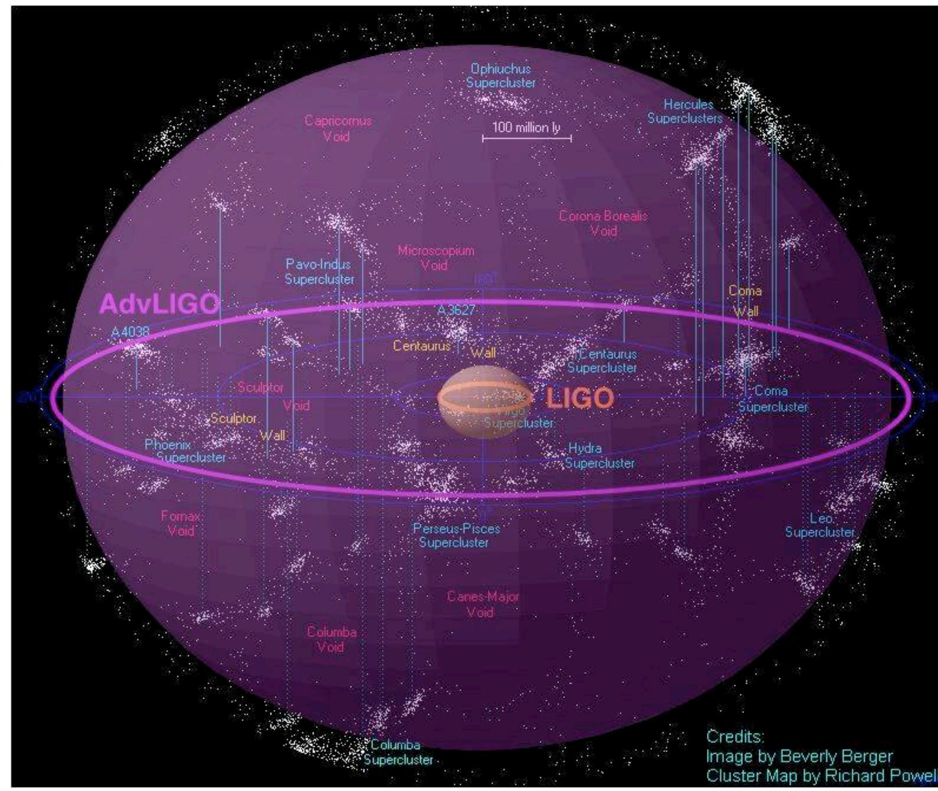


LIGO Noise Spectrum



Advanced LIGO





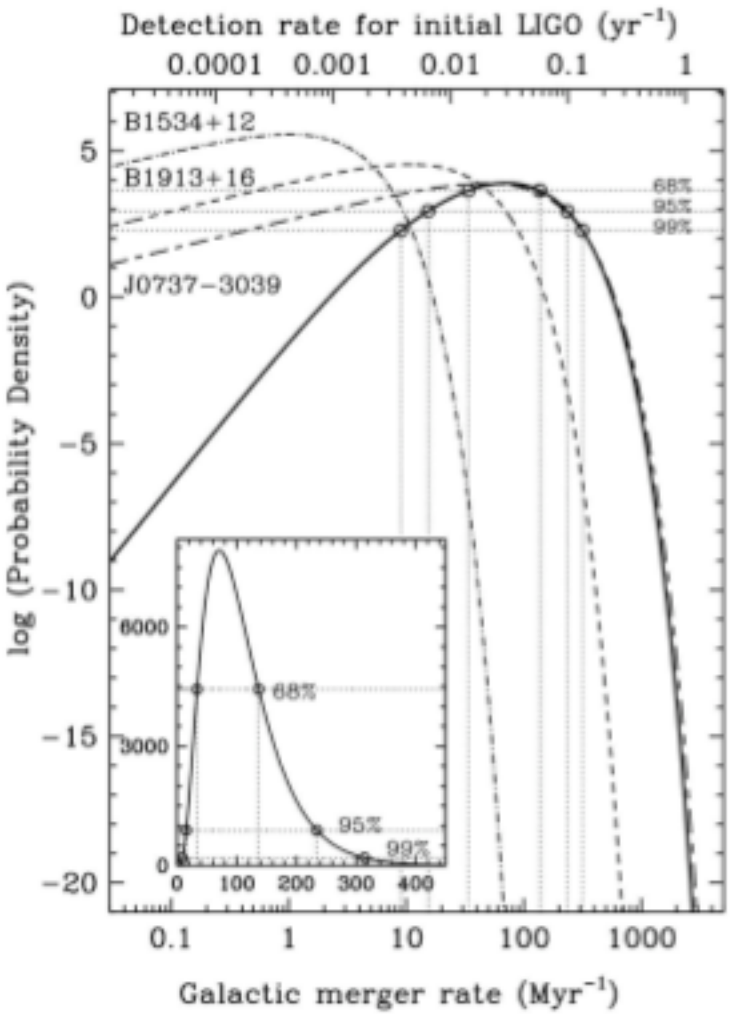
- ~ x10 in range -> ~ x1000 in event rate
- 10 Hz low frequency cutoff

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

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

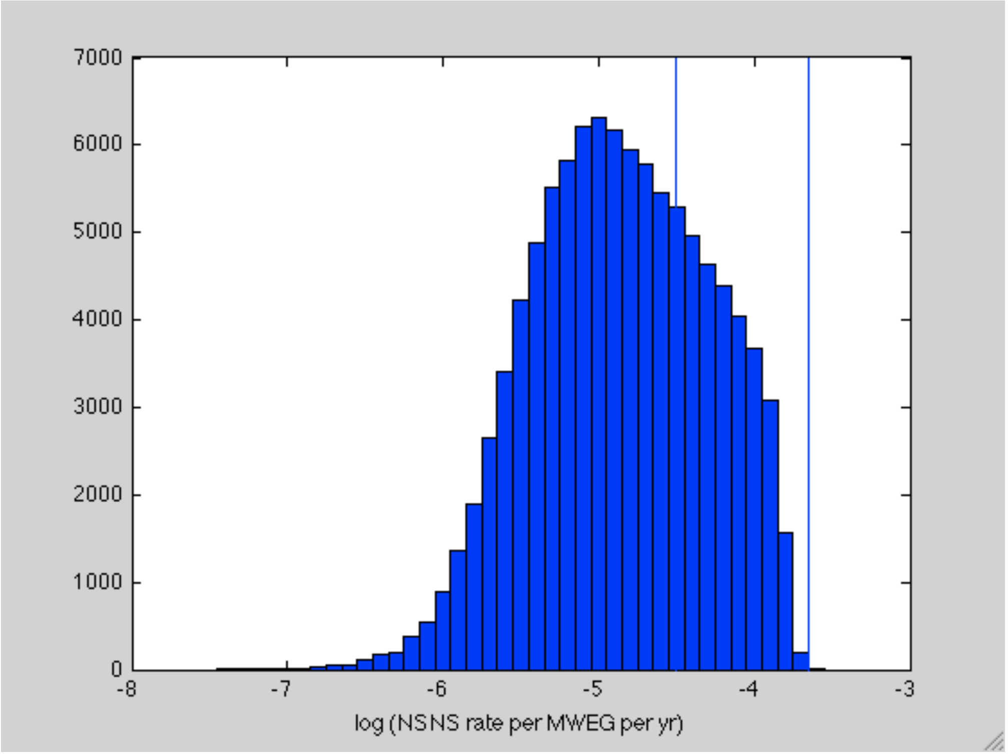
- No observed NS-BH or BH-BH binaries
- Predictions based on population-synthesis models for isolated binary evolution with StarTrack [Belczynski et al., 2005, astro-ph/0511811] or similar codes
- Thirty poorly constrained parameters
- [O'Shaughnessy et al., 2005 ApJ 633 1076, 2008 ApJ 672 479] vary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

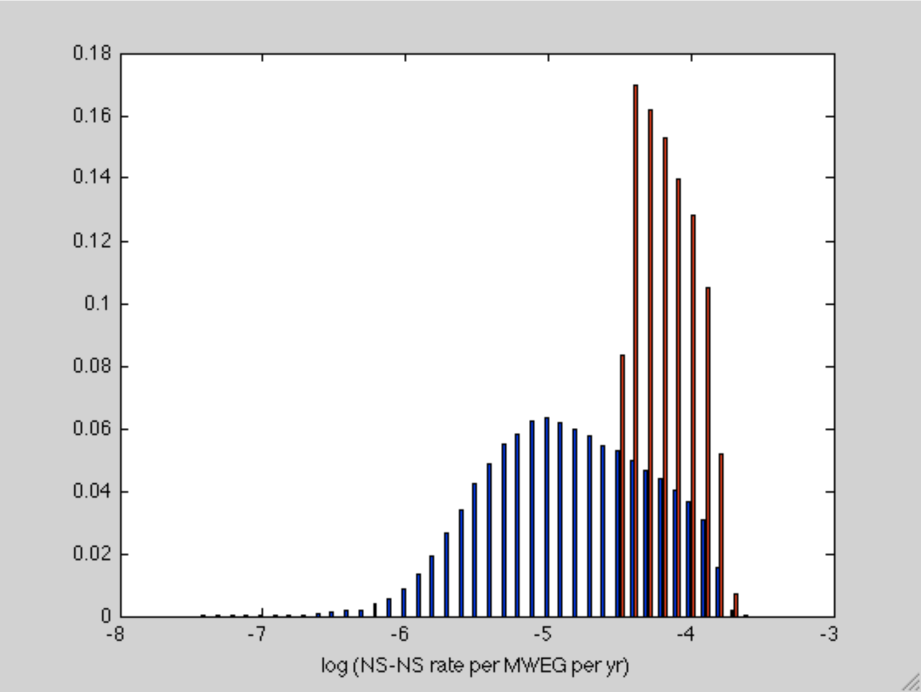
5. strength of massive stellar wind
6. common-envelope efficiency
7. fractional mass retention during nonconservative mass transfer

Constraining models



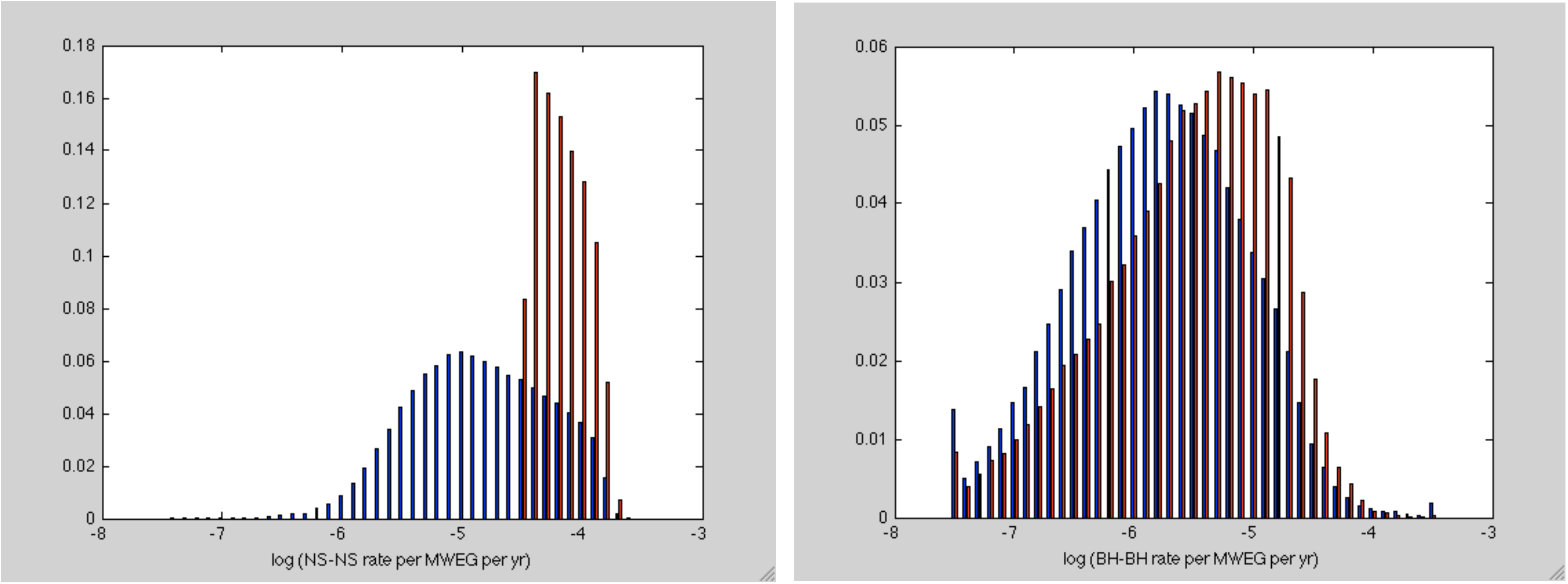
- Add constraints from observations; binary pulsars: NS-NS, NS-WD, supernovae, etc.
- Average over models that satisfy constraints

Effect of adding constraints, 1



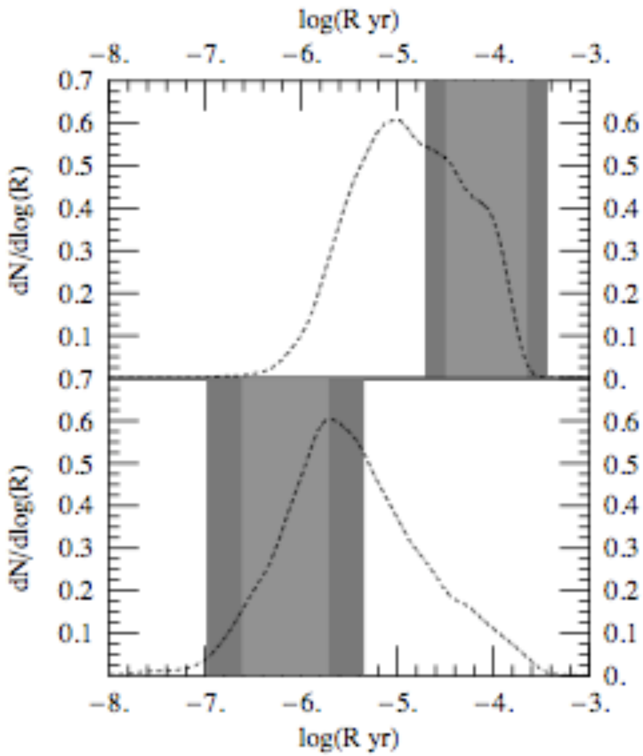
Single constraint satisfaction - no accounting for sampling uncertainties or model fitting errors

Effect of adding constraints, 1

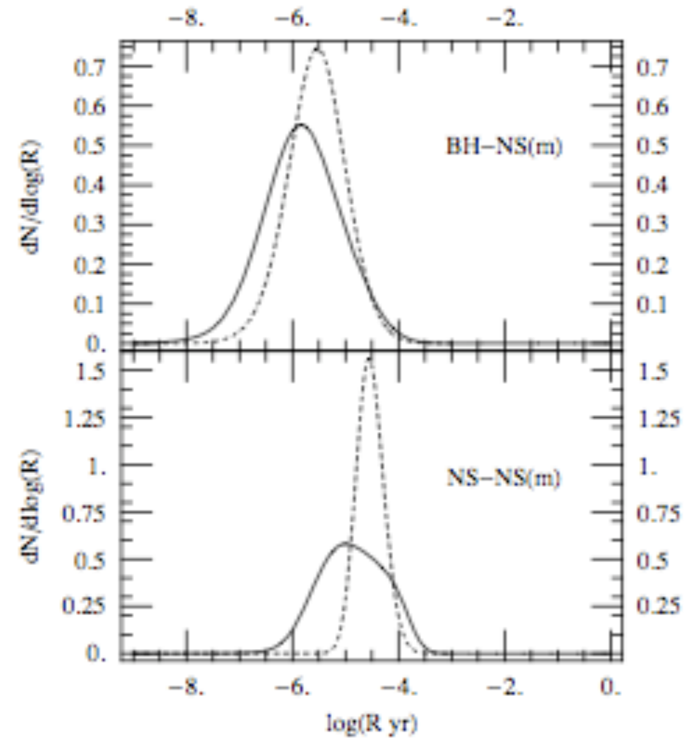


Single constraint satisfaction - no accounting for sampling uncertainties or model fitting errors

Effect of adding constraints, 2



Constraints from observed binary pulsars

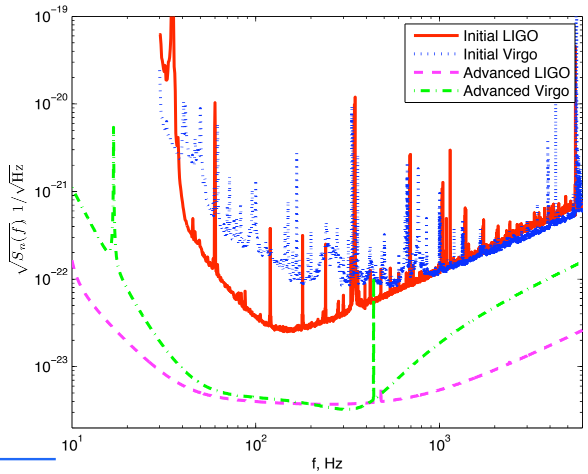


BH-NS and NS-NS rate/MWEG predictions

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

Merger and Detection Rates

Source	$R_{\rm low}$	$R_{\rm re}$	$R_{\rm pl}$
NS-NS (L_{10}^{-1} Myr^{-1})	0.6	60	600
NS-BH (L_{10}^{-1} Myr^{-1})	0.03	2	60
BH-BH (L_{10}^{-1} Myr^{-1})	0.006	0.2	20



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

[IM & O'Shaughnessy, 2009, arXiv:0912.1074; Abadie et al., 2010, arXiv:1003.2480]

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)

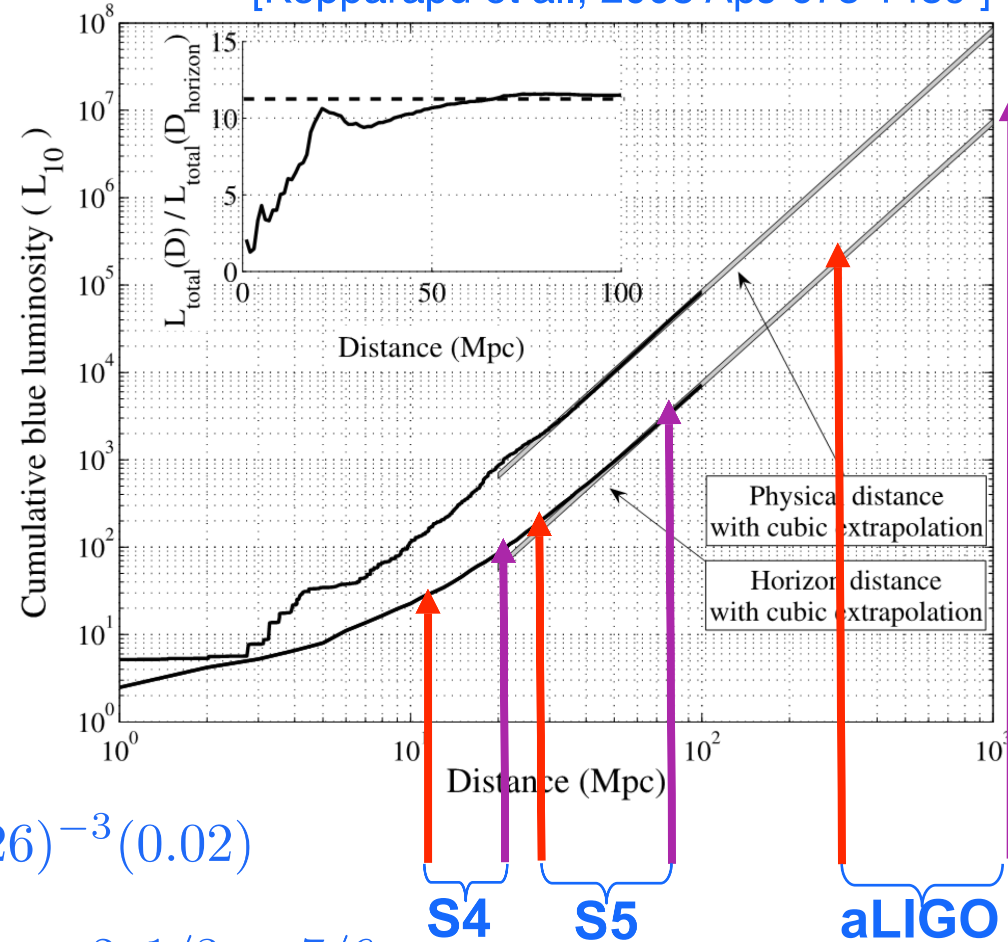
$$\rho \equiv \sqrt{4 \int_0^{f_{\rm ISCO}} \frac{|\tilde{h}(f)|^2}{S_n(f)} df}$$

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

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

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

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

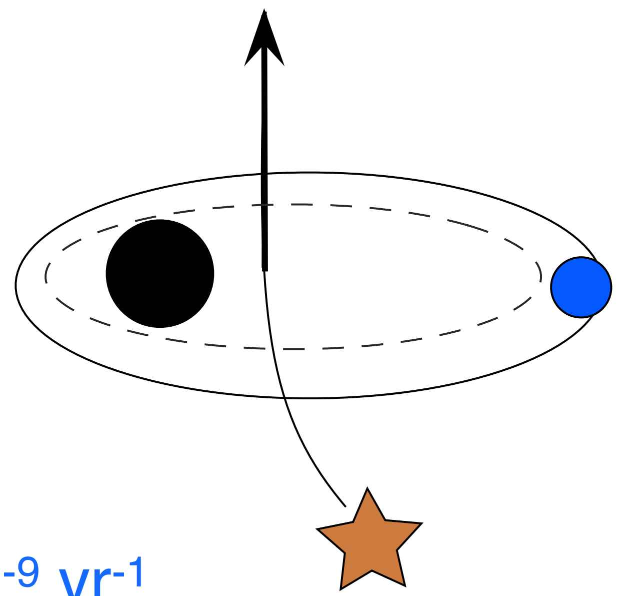


Dynamical Formation

- 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

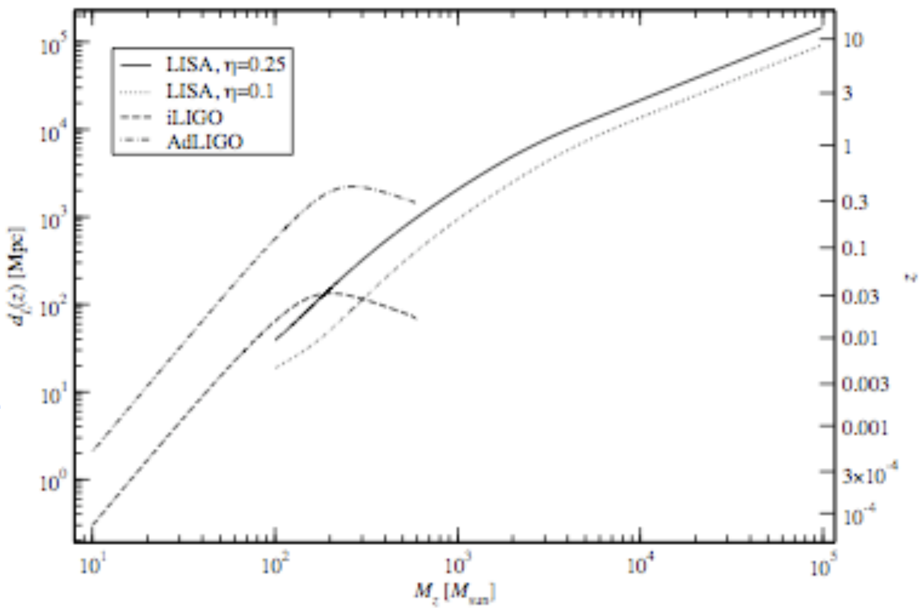
- Intermediate-mass-ratio inspirals of compact objects (1.4 solar-mass NSs or 10 solar-mass BHs) into intermediate-mass black holes in globular clusters
- Dominant mechanism:
  IMBH swaps into binaries,
  3-body interactions tighten
  IMBH-CO binary, merger
  via GW radiation reaction
  [IM et al., 2008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

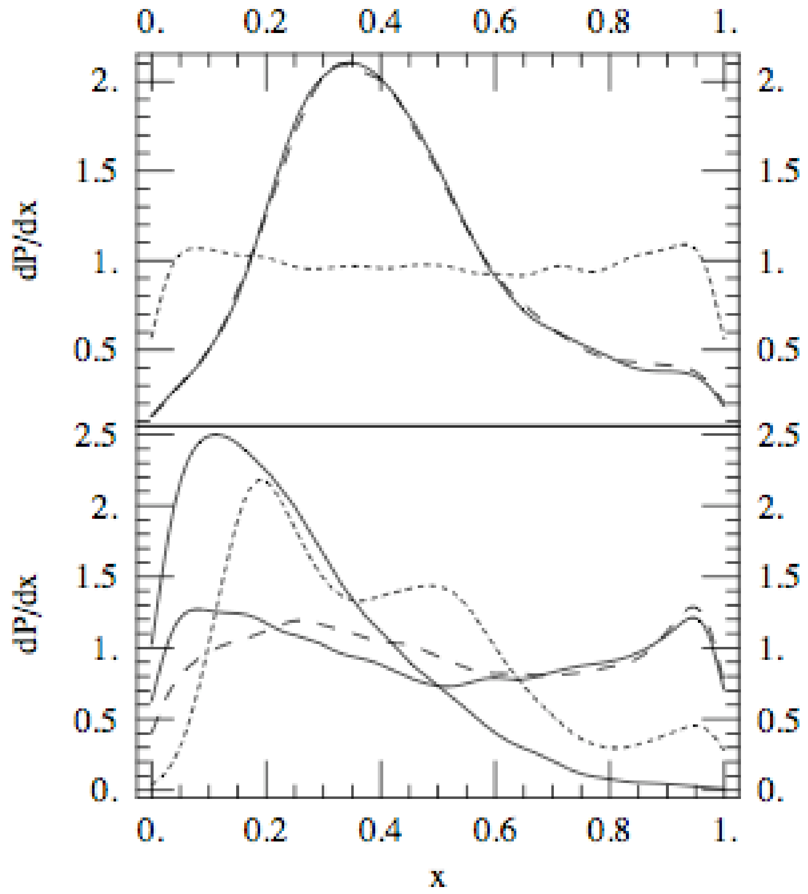
Inspirals of two IMBHs

- 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]



Astrophysics with GW searches

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



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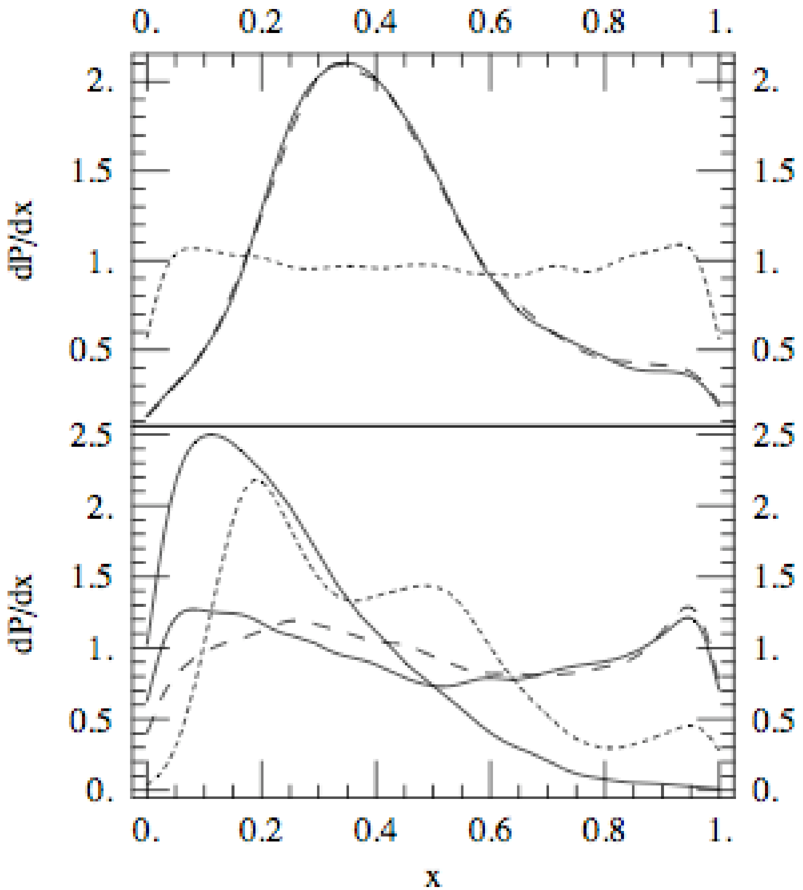
- Observed GW event rates can be compared with models to determine important astrophysical parameters;



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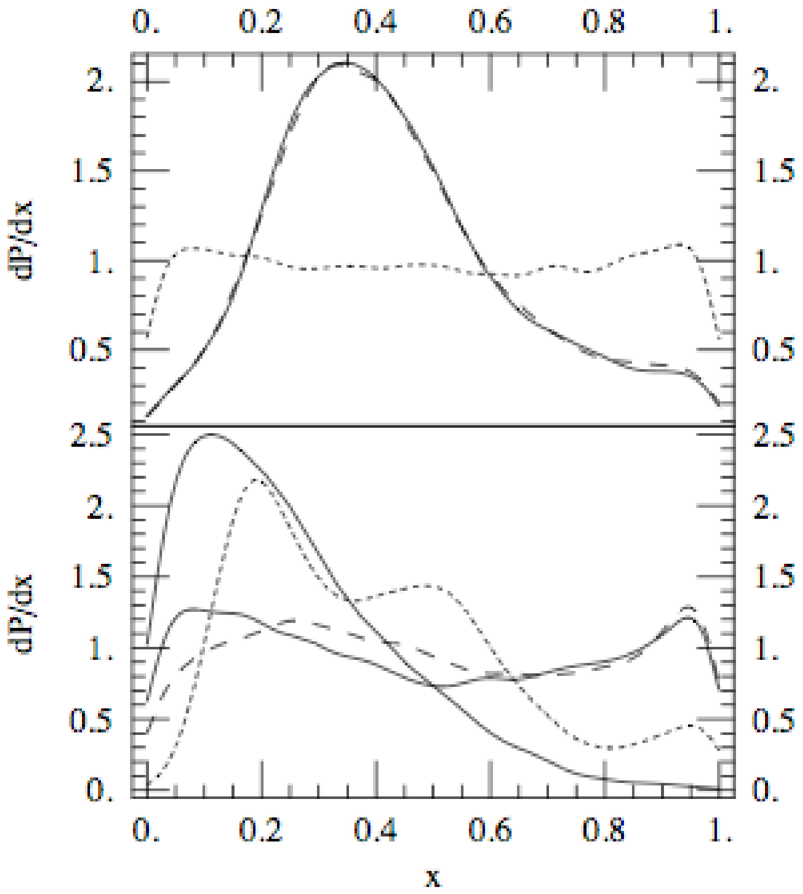
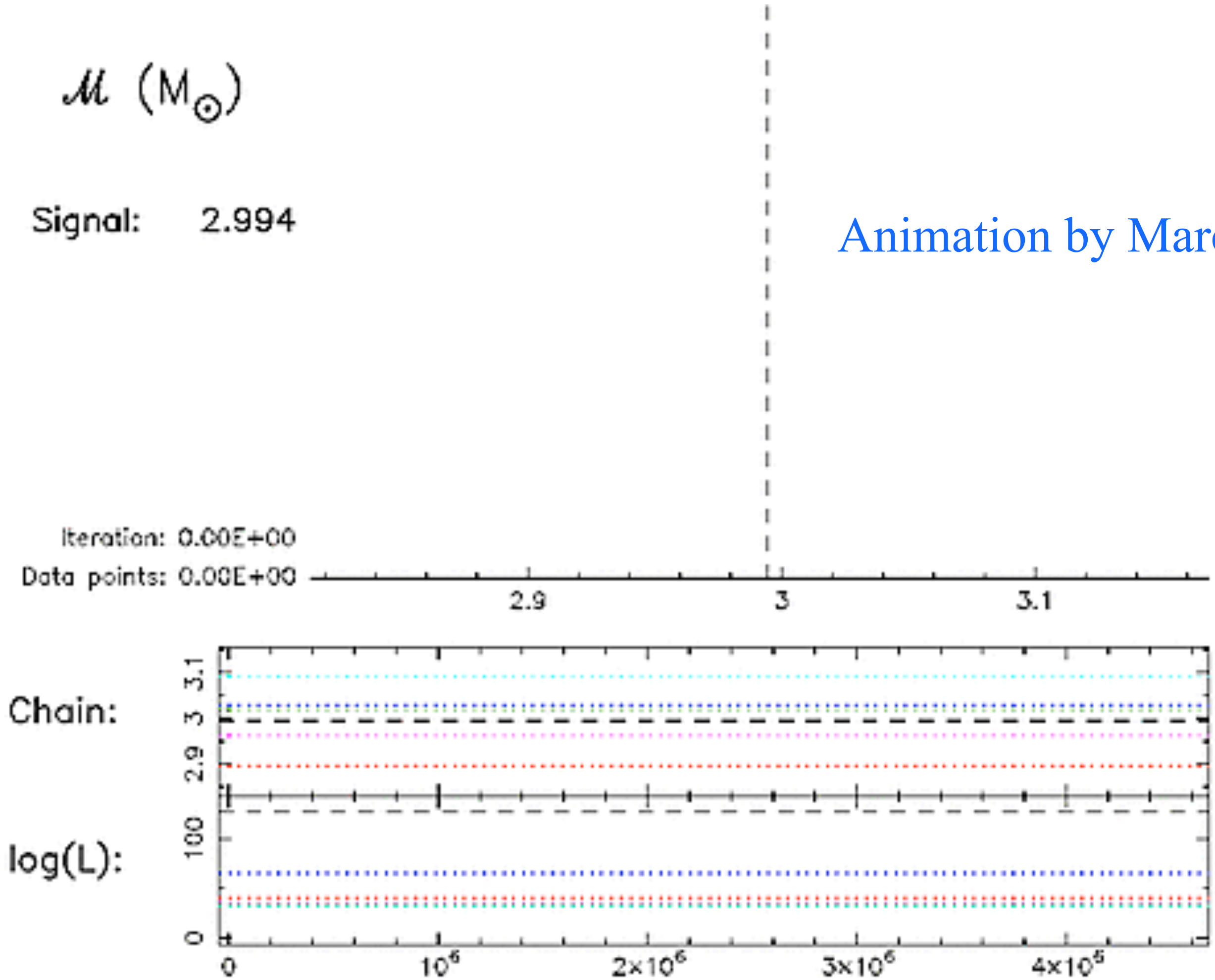


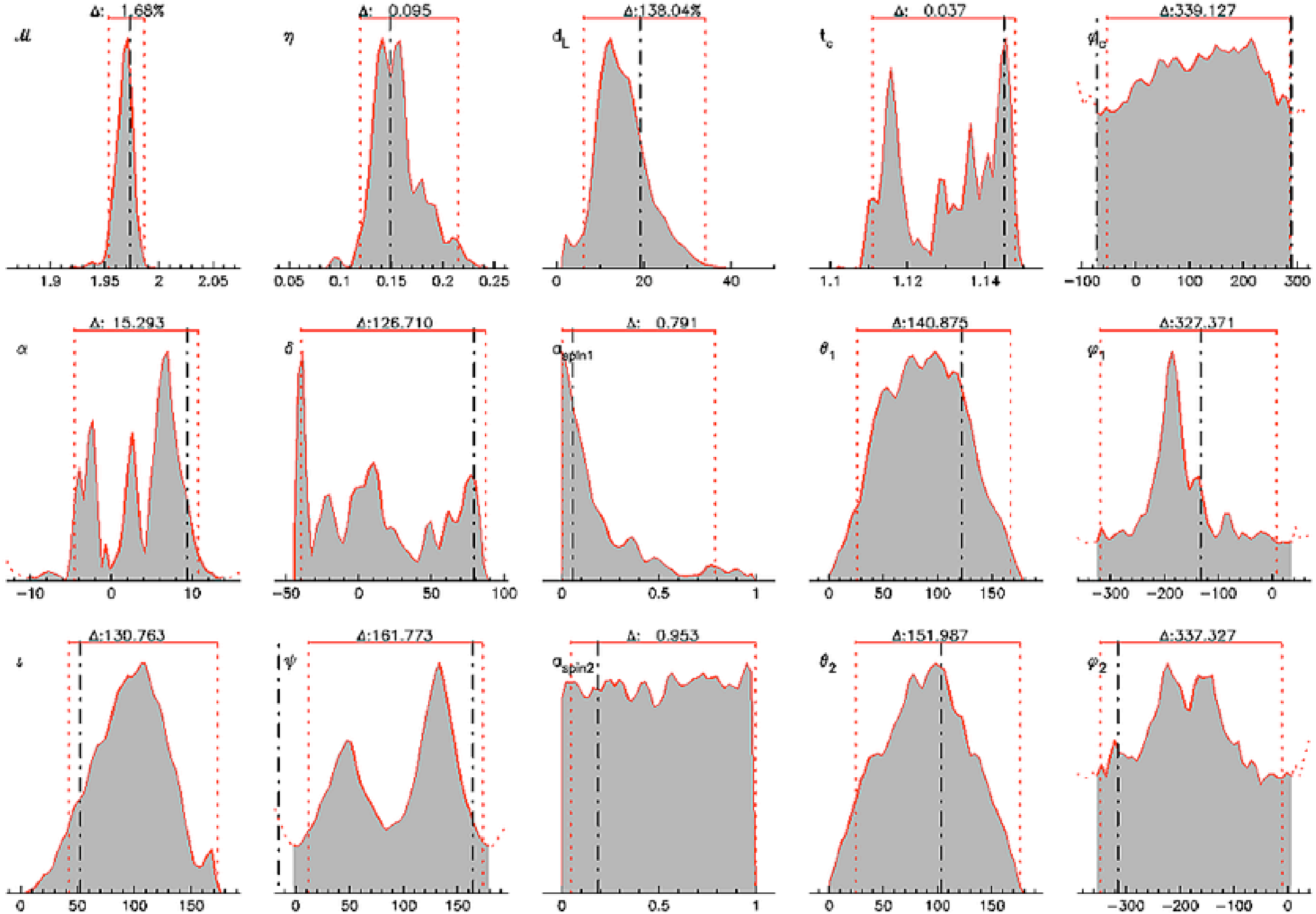
Markov Chain Monte Carlo



Animation by Marc van der Sluys

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

Accurate Parameter Estimation



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

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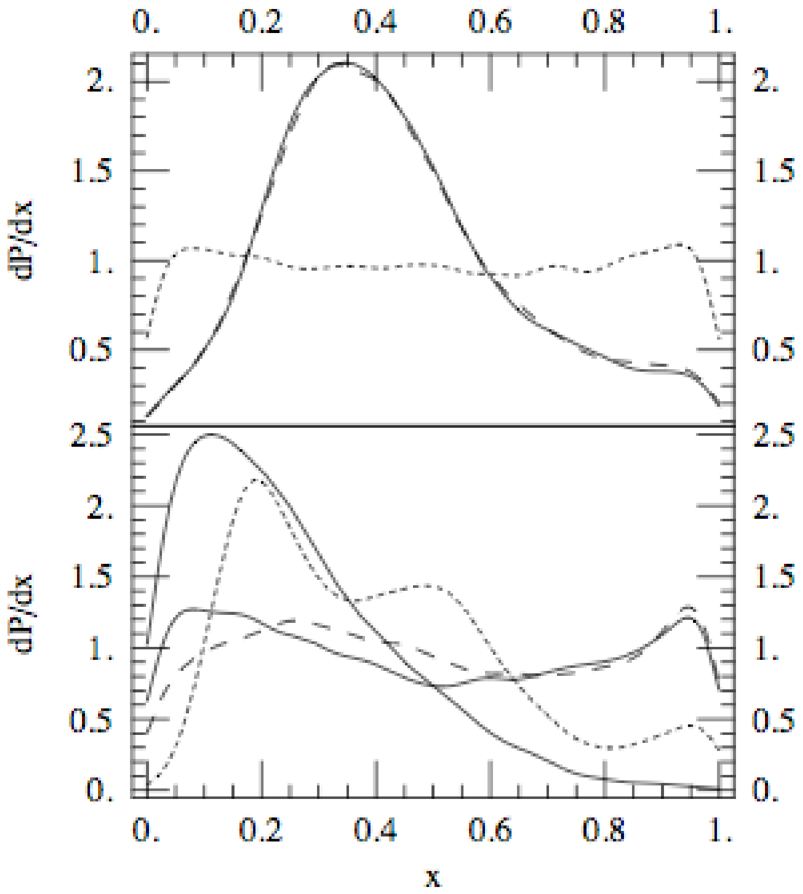
- Observed GW event rates can be compared with models to determine important astrophysical parameters;
- Could match measured mass distributions, etc. to models (requires accurate parameter determination)
- As detector sensitivity improves, even upper limits can be useful in constraining parameter space for birth kicks, common-envelope efficiency, winds, etc.



Astrophysics with GW searches

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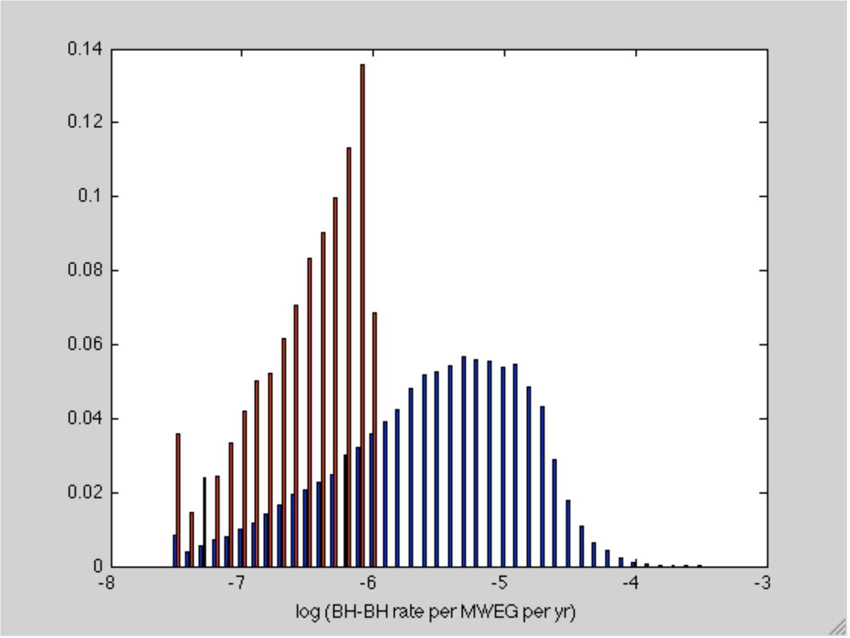
Constraints from upper limits - example



[IM & O'Shaughnessy, 2009]

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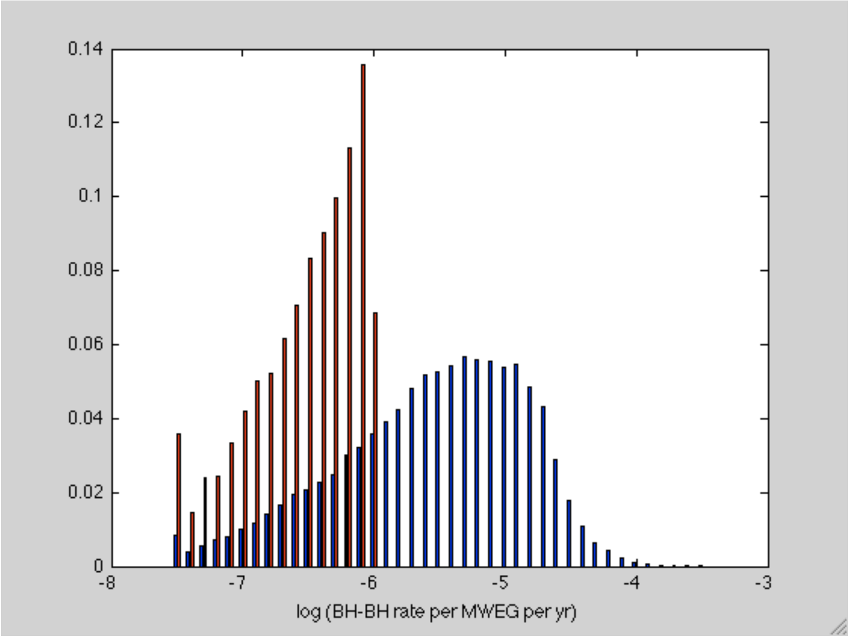
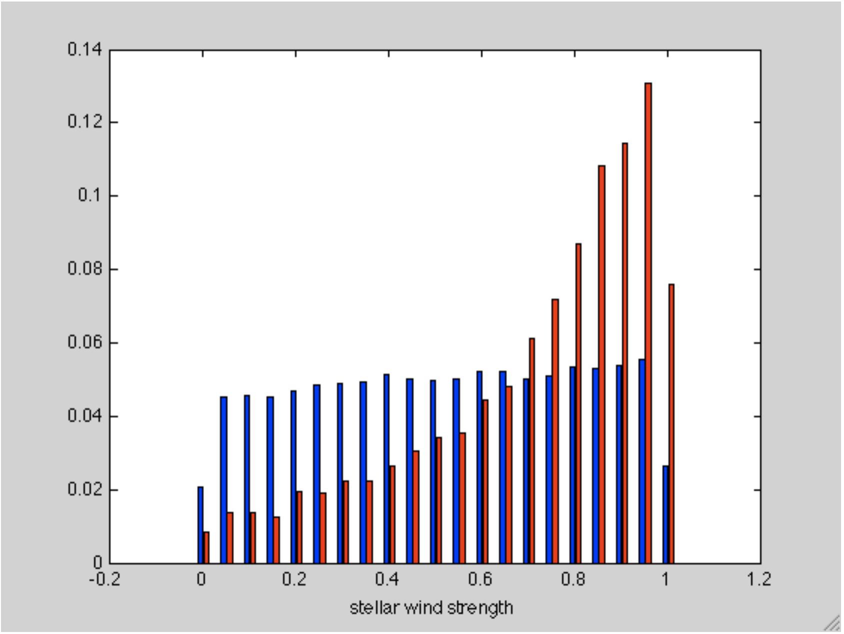
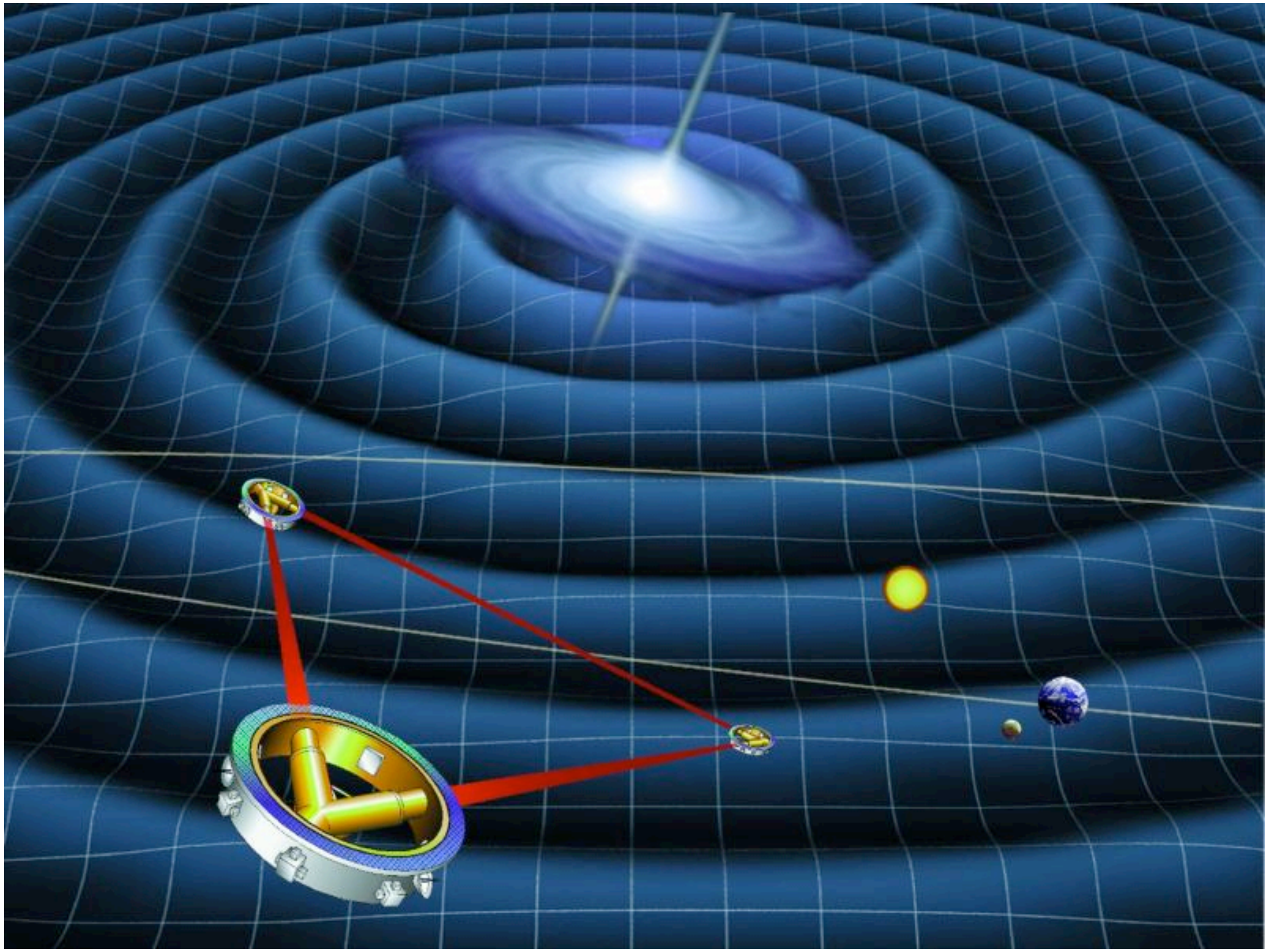




[IM & O'Shaughnessy, 2009]

LISA: Laser Interferometer Space Antenna

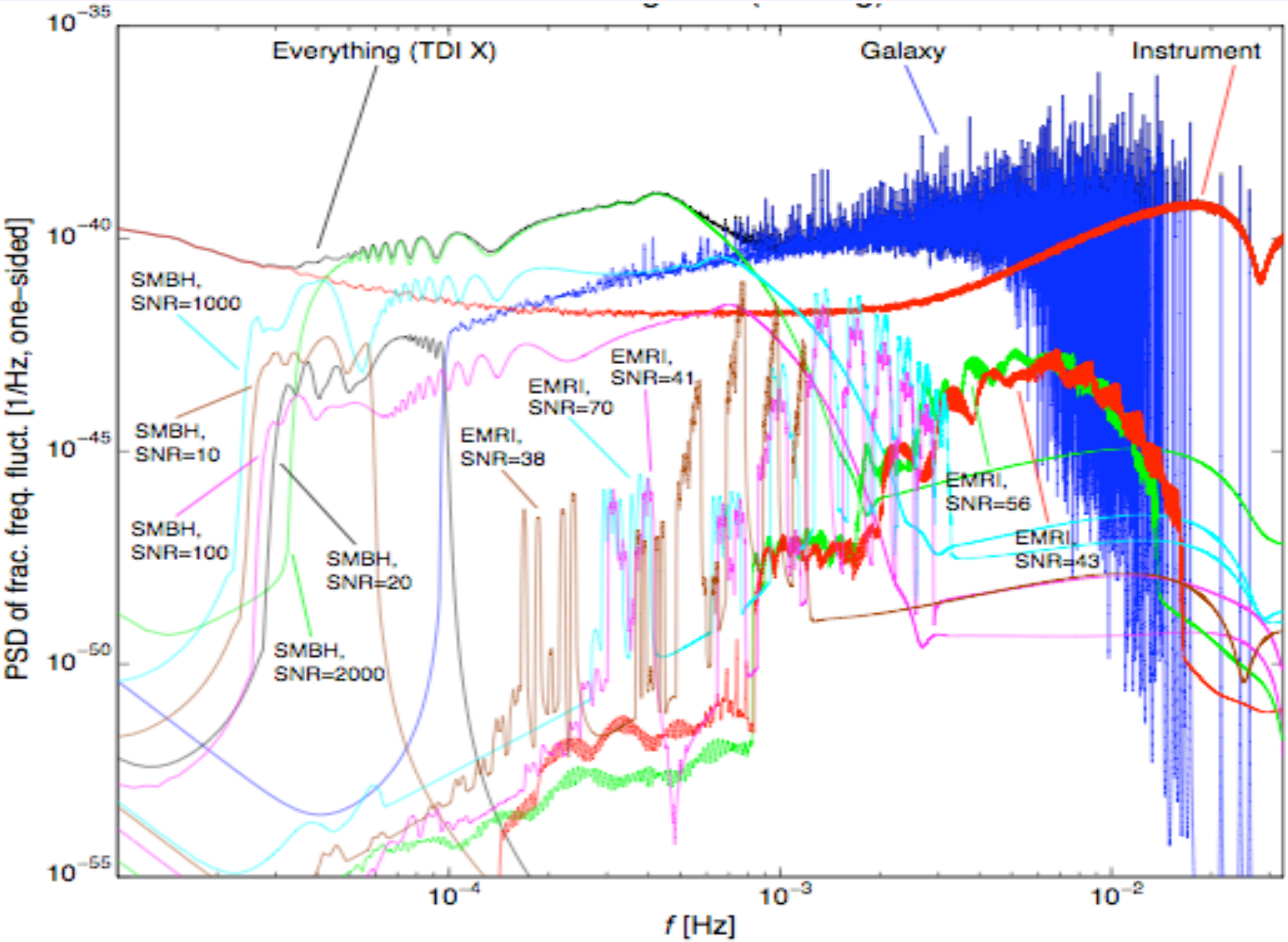


3 spacecraft around the Sun,
5 million km apart

LISA Binary Sources

- LIGO sensitive @ a few hundred Hz
  - » NS-NS, NS-BH, BH-BH binaries
- LISA sensitive @ a few mHz
  - » 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.
    - – could see tens to hundreds to z~1 [e.g., Gair et al., 2004]

Embarrassment of riches



[Arnaud et al., 2007, CQG 24 S551]

LISA Data Analysis

$$h(t) = h(M_1, M_2, \vec{S}_1, \vec{S}_2, \theta, \phi, D_L, e, ...; t)$$

17 parameters

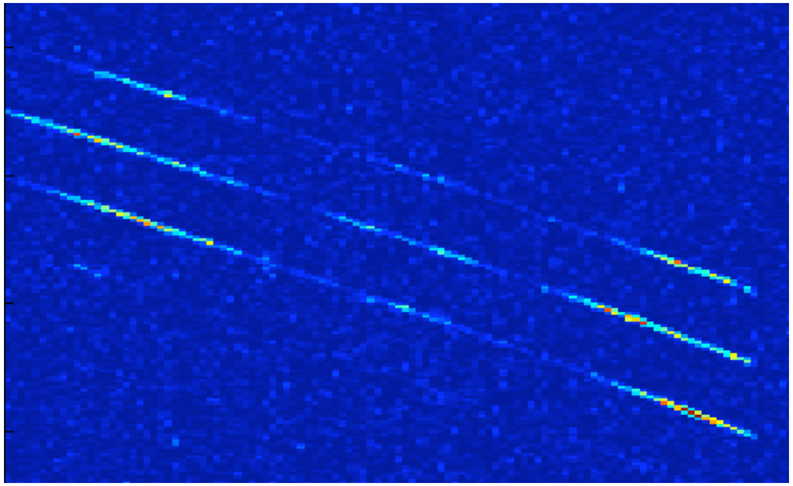
What has already been accomplished?

	MLDC 1	MLDC 2	MLCD 1B	MLDC 3
GB	• Verification ✓ • Unknown, isolated ✓ • Unknown, interfering ✓	• Galaxy of 3×10^6 ✓	• Verification ✓ • Unknown, isolated ✓ • Unknown, confused ✓	• Galaxy of 6×10^7 chirping ✓
MBH	• Isolated ✓	• 4–6x, over Galaxy and EMRIs ✓	• Isolated ✓	• Over Galaxy spinning, precessing ✓
EMRI		• Isolated ✓ • 4–6x, over Galaxy and SMBHs	• Isolated ✓	• 5 together, weaker ✓
New				• Cosmic string cusp bursts ✓ • Cosmological background ✓

Table by M. Vallisneri

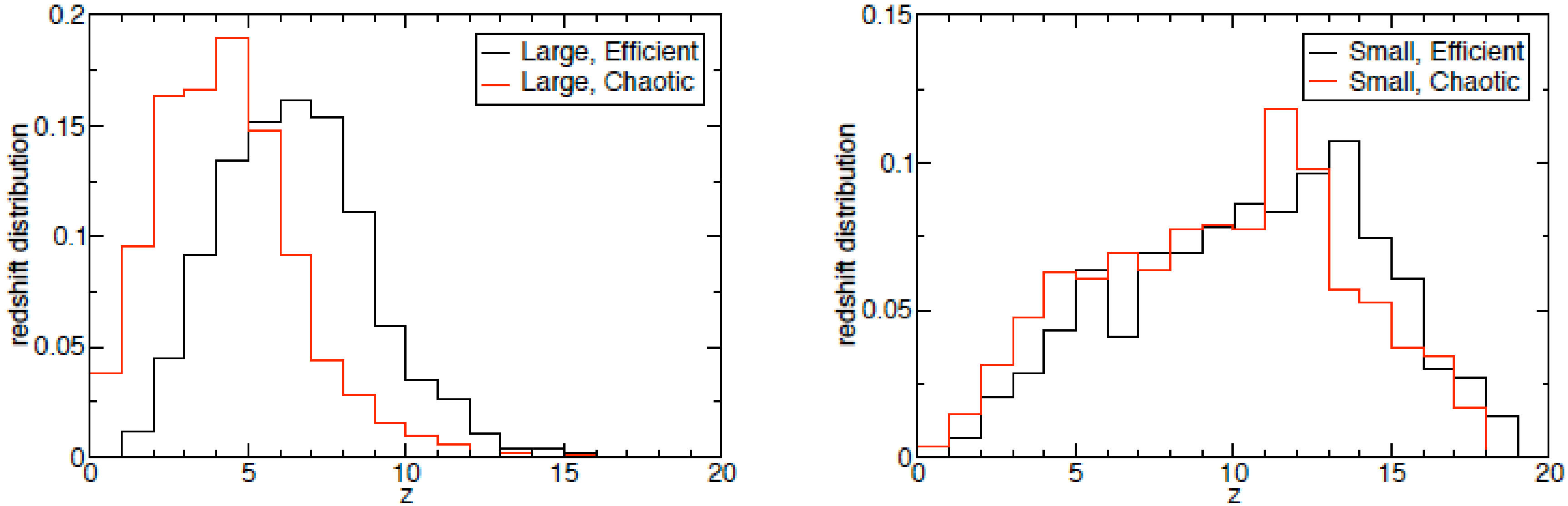
Mock LISA Data Challenges

Need innovative search techniques to separate many overlapping signals: Markov-Chain Monte Carlo, MultiNest, genetic algorithms



[Gair, IM, Wen, 2008, CQG 25 184031]

SMBH binaries

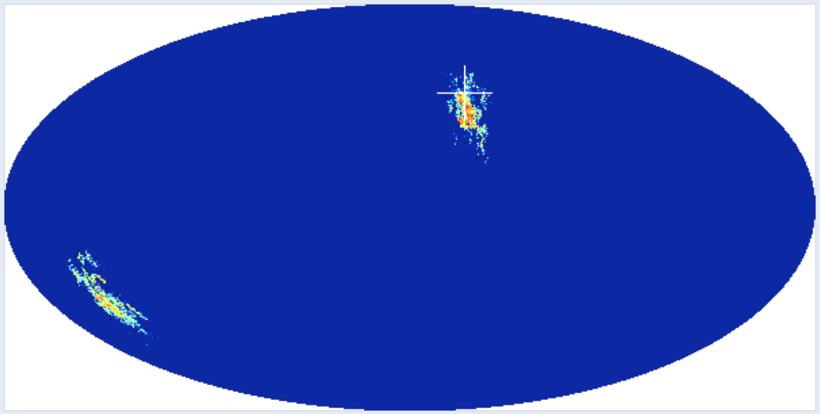


Model	N	$N_{\rm det}$	$N_{10\% D_L}$	$N_{10\,\rm deg^2}$	$N_{10\,\rm deg^2,\,10\% D_L}$	$N_{1\,\rm deg^2}$	$N_{1\,\rm deg^2,\,1\% D_L}$
SE	80	33 (25)	21 (8.0)	8.2 (1.5)	7.9 (1.1)	2.2 (0.6)	1.7 (0.1)
SC	75	34 (27)	17 (4.4)	6.1 (0.4)	5.5 (0.4)	1.3 (0.1)	1.3 (0.1)
LE	24	23 (22)	21 (7.7)	10 (0.8)	10 (0.7)	2.2 (0.1)	1.2 (0.05)
LC	22	21 (19)	14 (4.3)	6.5 (0.5)	5.4 (0.5)	1.8 (0.04)	1.0 (0.1)

from [Arun et al. (LISA Parameter Estimation Taskforce), 2008, CQG 26, 094027]

Mock LISA Data Challenge Results

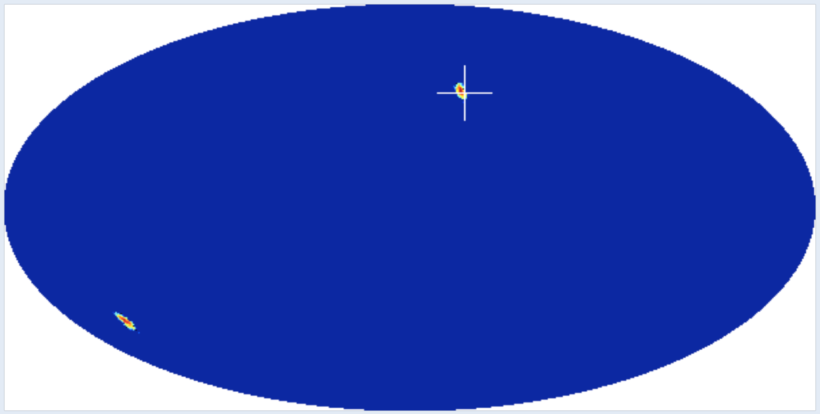
Challenge 3.2 : Massive Black Holes



30 days before merger

Monte Carlo by Neil Cornish

Challenge 3.2 : Massive Black Holes

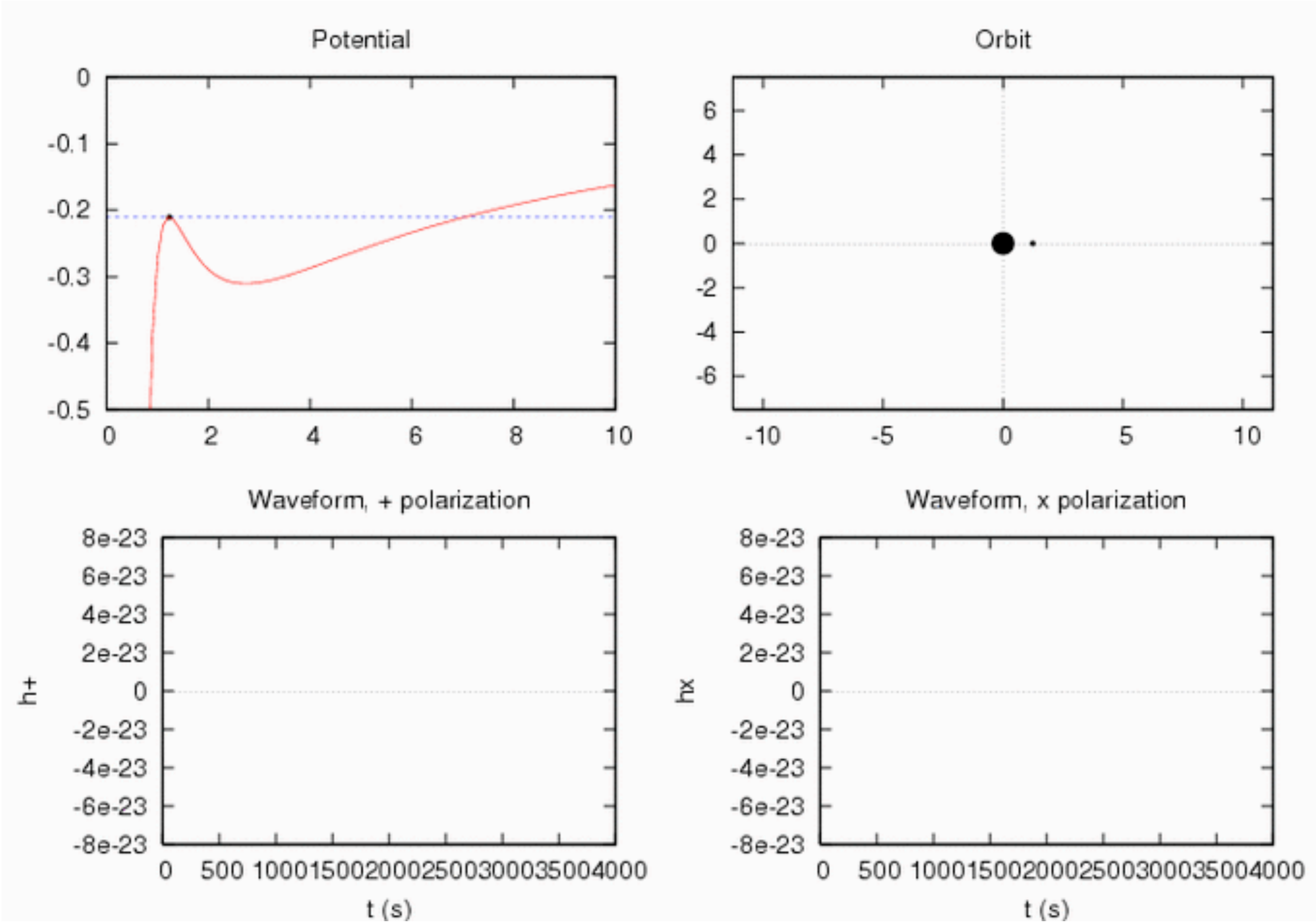


1 day before merger

Monte Carlo by Neil Cornish

source (SNR_{true})	group	$\Delta M_c/M_c$ $\times 10^{-5}$	$\Delta\eta/\eta$ $\times 10^{-4}$	Δt_c (sec)	Δsky (deg)	Δa_1 $\times 10^{-3}$	Δa_2 $\times 10^{-3}$	$\Delta D/D$ $\times 10^{-2}$	SNR	FF_A	FF_E
MBH-1	AEI	2.4	6.1	62.9	11.6	7.6	47.4	8.0	1657.71	0.9936	0.9914
(1670.58)	CambAEI	3.4	40.7	24.8	2.0	8.5	79.6	0.7	1657.19	0.9925	0.9917
	MTAPC	24.8	41.2	619.2	171.0	13.3	28.7	4.0	1669.97	0.9996	0.9997
	JPL	40.5	186.6	23.0	26.9	39.4	66.1	6.9	1664.87	0.9972	0.9981
	GSFC	1904.0	593.2	183.9	82.5	5.7	124.3	94.9	267.04	0.1827	0.1426

Extreme Mass Ratio Inspirals

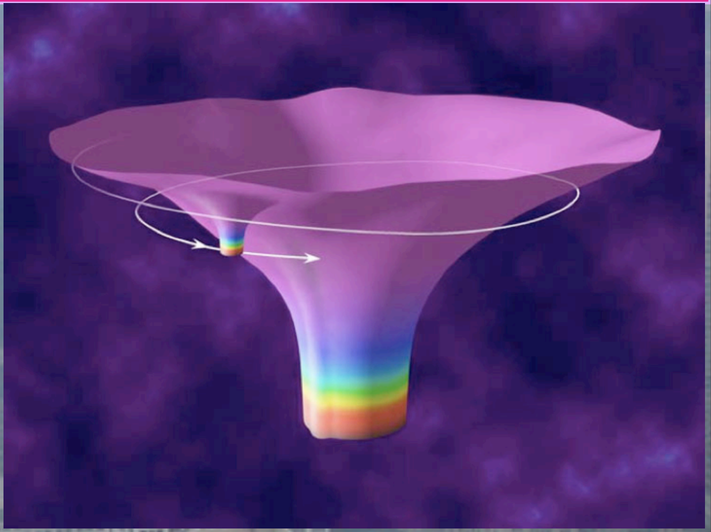


Sound from Scott Hughes

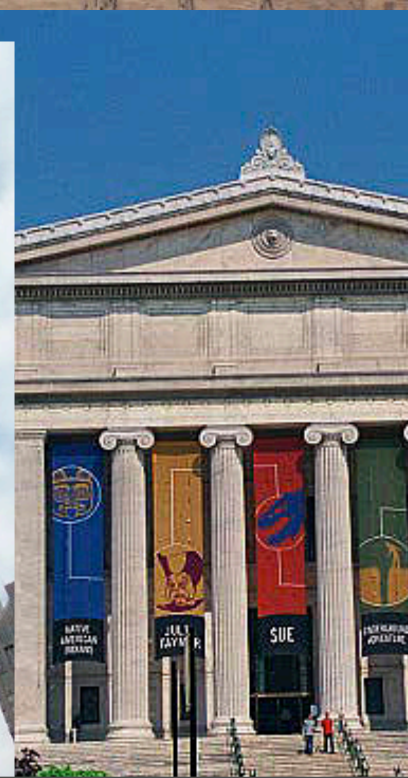
Animation from Jon Gair

CIERA

Exploring the spacetime...

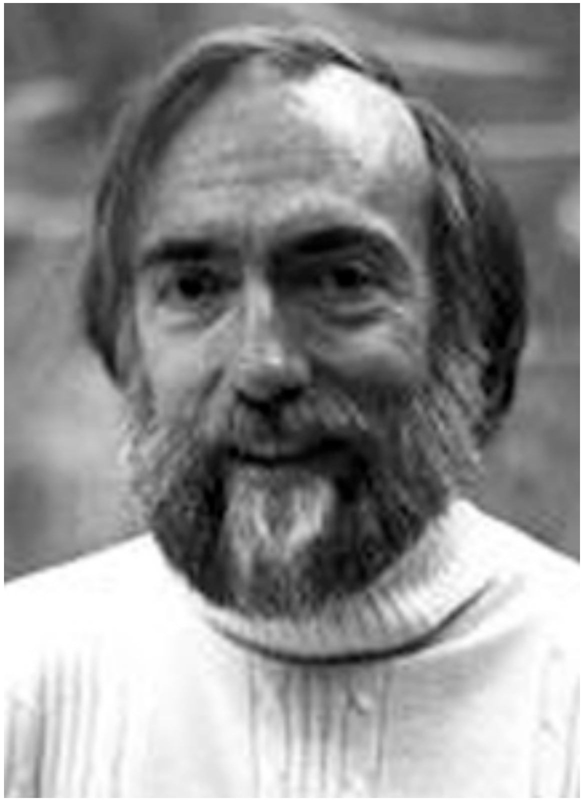


... taking lots of pictures



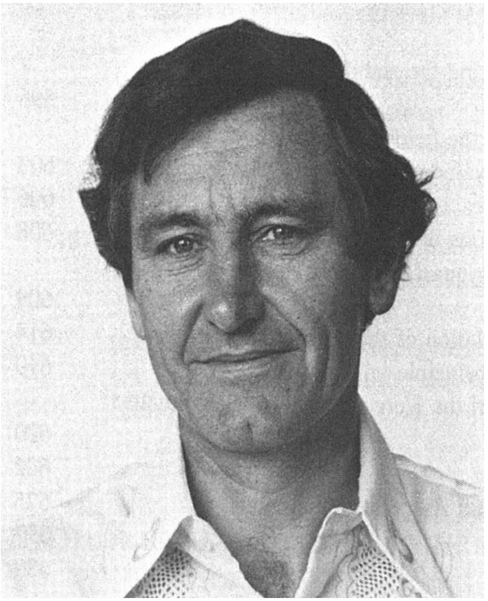
Testing the “no-hair” theorem

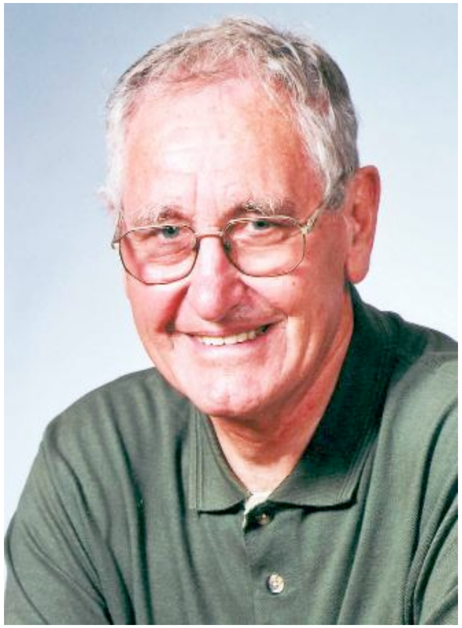
Testing the no-hair theorem



C I E R A

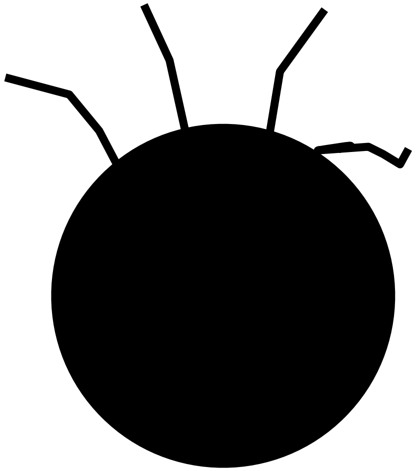
Testing the no-hair theorem?



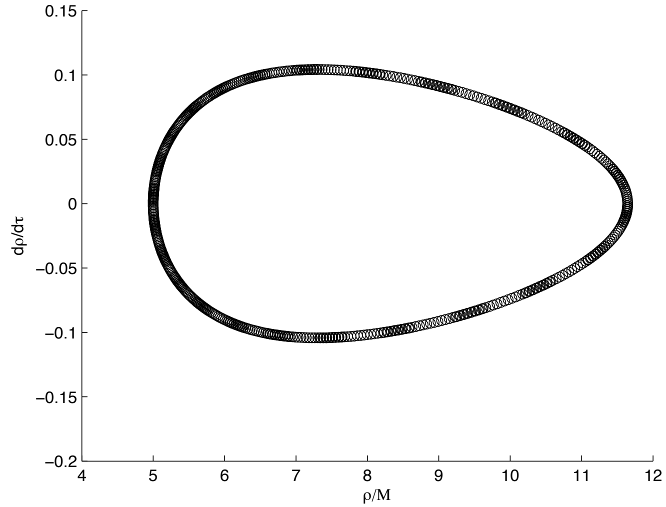


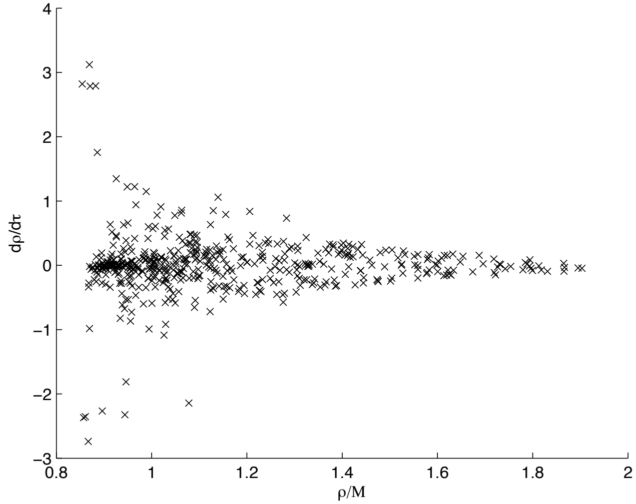
Stationary, vacuum, asymptotically flat spacetimes in which the singularity is fully enclosed by a horizon with no closed timelike curves outside the horizon are described by the Kerr metric

Do black holes have hair?



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

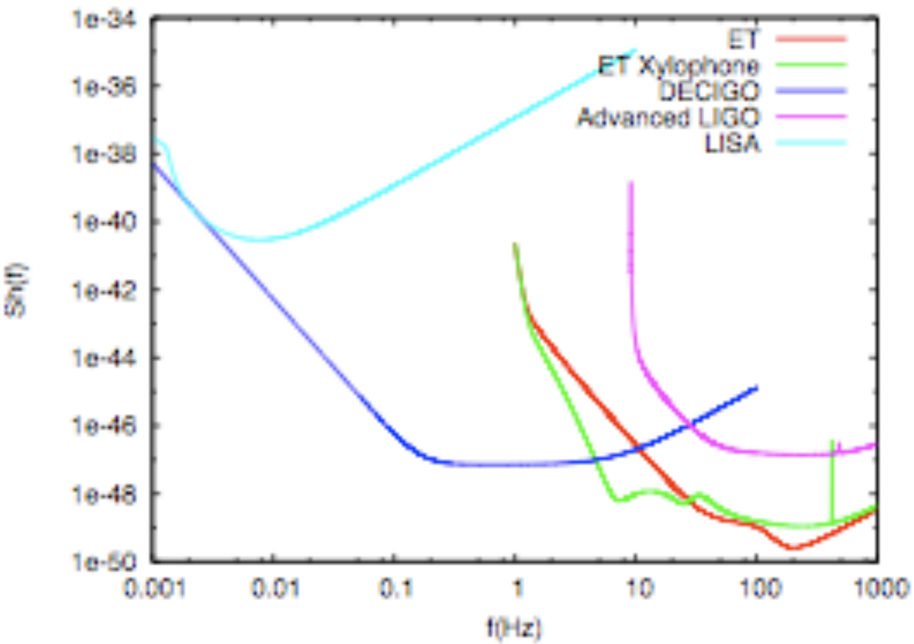




[Gair, Li, IM, 2009, PRD 77:024035]

The future: 3rd-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]

Summary

- 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