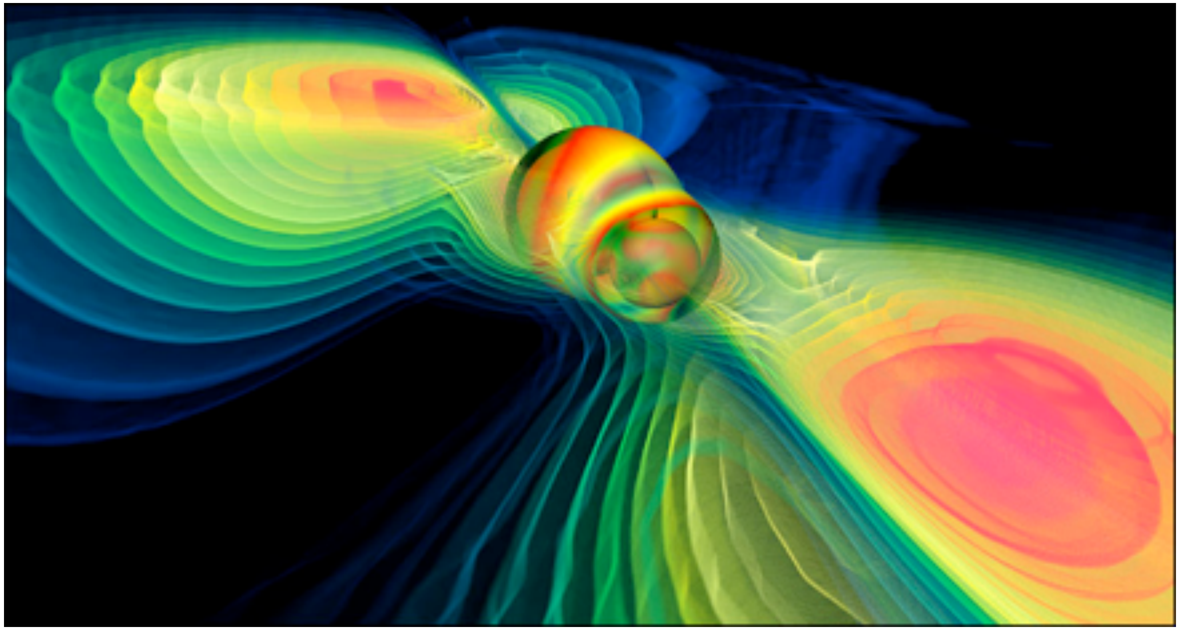
GWastrophysics



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

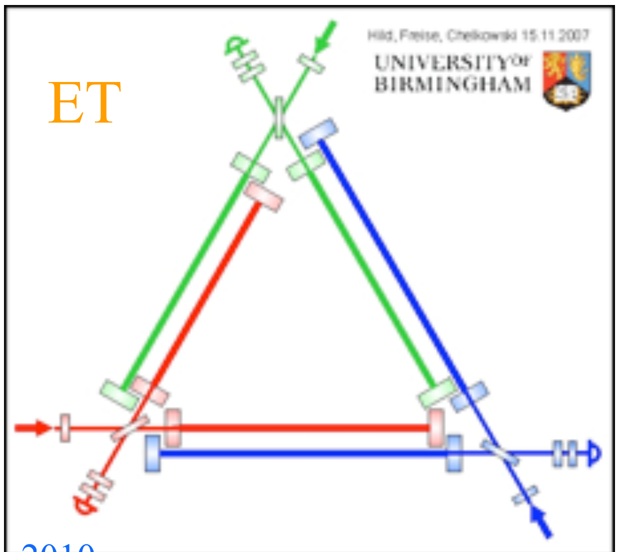
Ilya Mandel

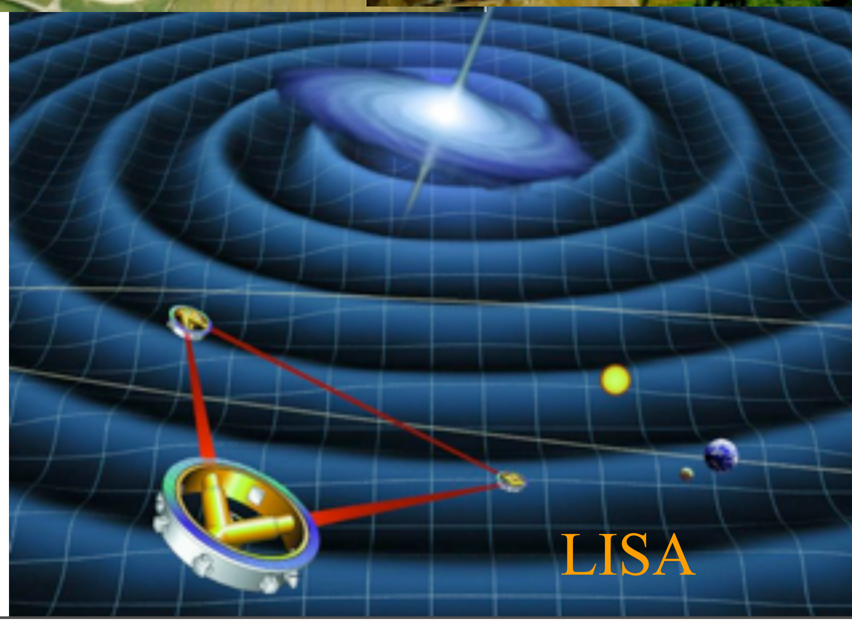
(NSF Astronomy and Astrophysics Postdoc Fellow,
Northwestern University / MIT)

July 14, 2010

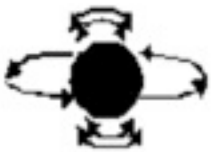
University of Birmingham

Gravitational-wave observatories

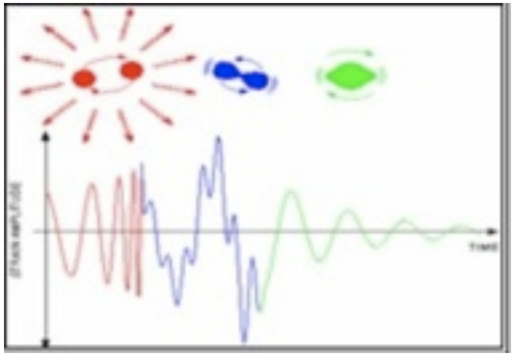




Types of GW sources

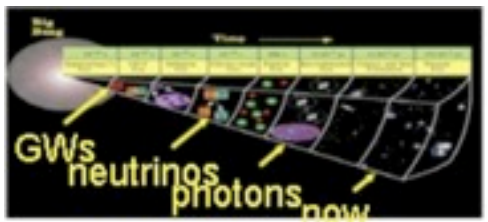


- Continuous sources [sources with a slowly evolving frequency]: e.g., non-axisymmetric neutron stars, slowly evolving binaries



- 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]

Outline

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

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

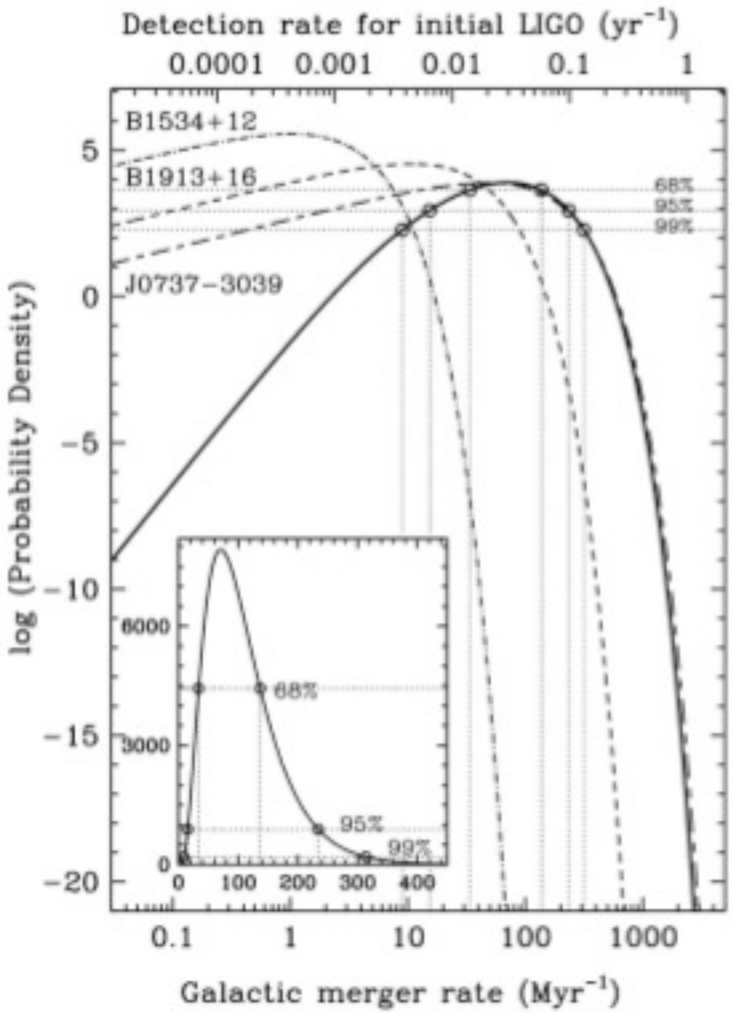
3. Testing general relativity with intermediate- and extreme-mass-ratio inspirals

Coalescence rate predictions

- Based on [IM and O'Shaughnessy, 2010; Abadie et al., 2010]
- 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 ?
- These estimates are still significantly uncertain at present
- "There are known knowns. There are things we know that we know. There are known unknowns. That is to say, there are things that we now know we don't know. But there are also unknown unknowns. There are things we do not know we don't know." [Donald Rumsfeld]

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

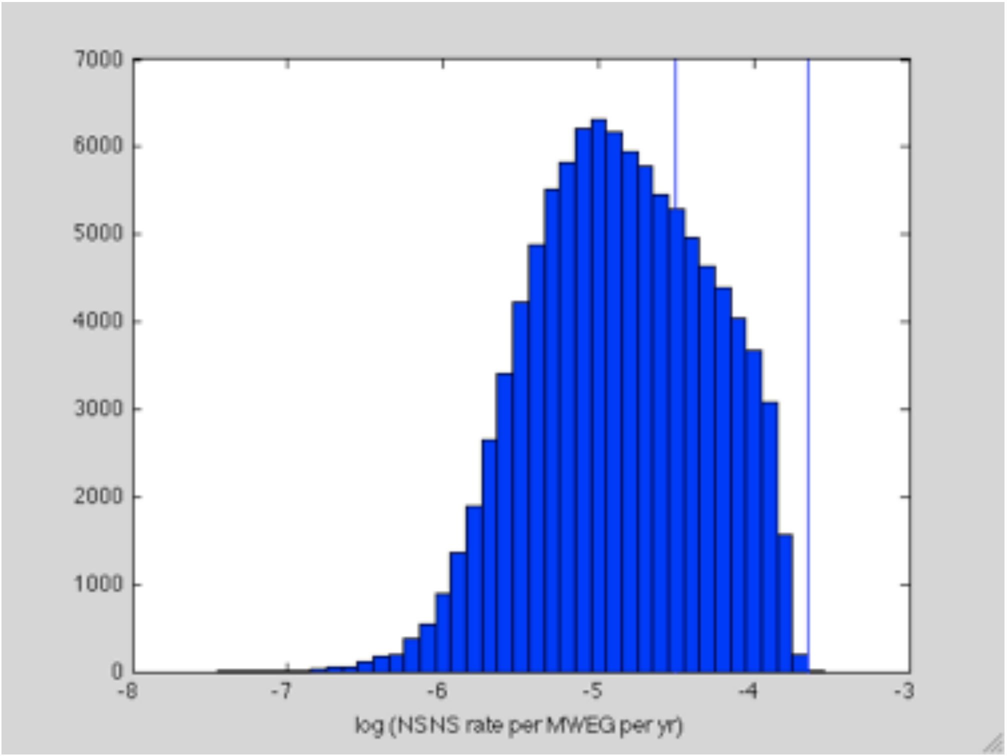
2, 3, 4. supernovae kicks described by two independent Maxwellians and their relative contribution

5. strength of massive stellar wind

6. common-envelope efficiency

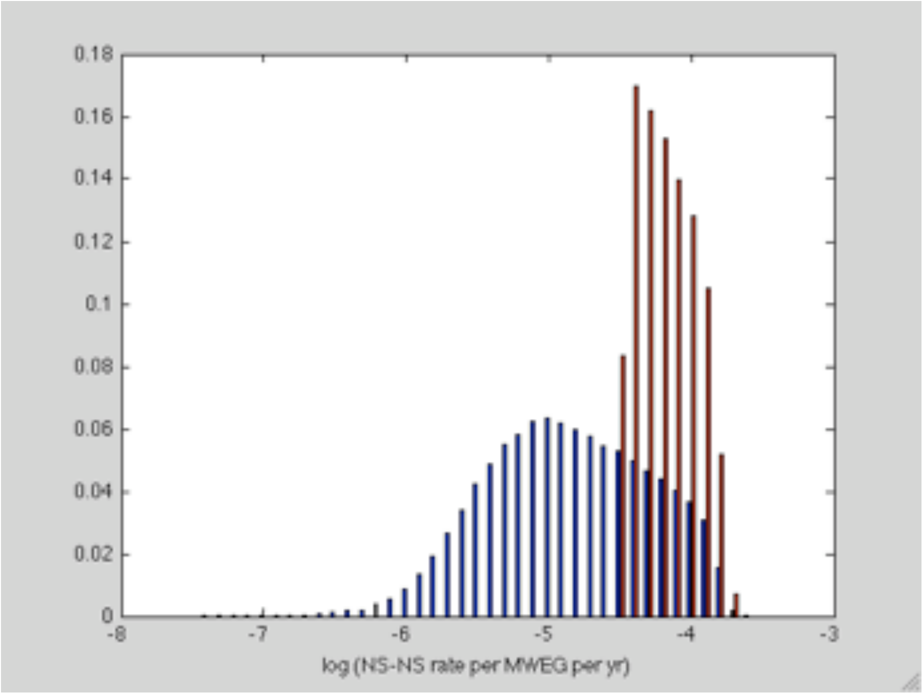
7. fractional mass retention during nonconservative mass transfer

Constraining models



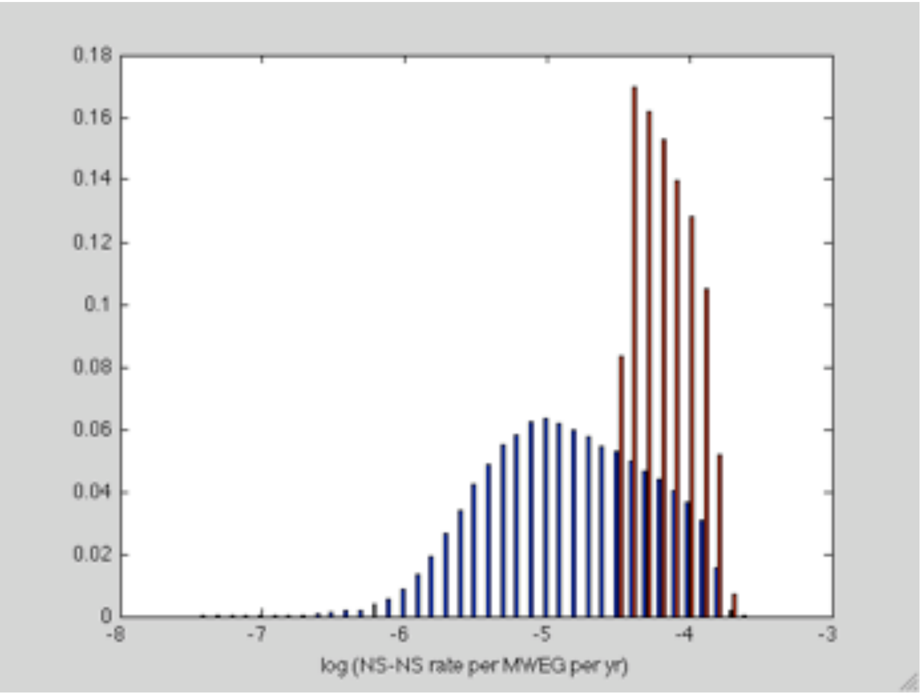
- Add constraints from observations; binary pulsars: NS-NS, NS-WD, supernovae, etc.
- Average over models that satisfy constraints

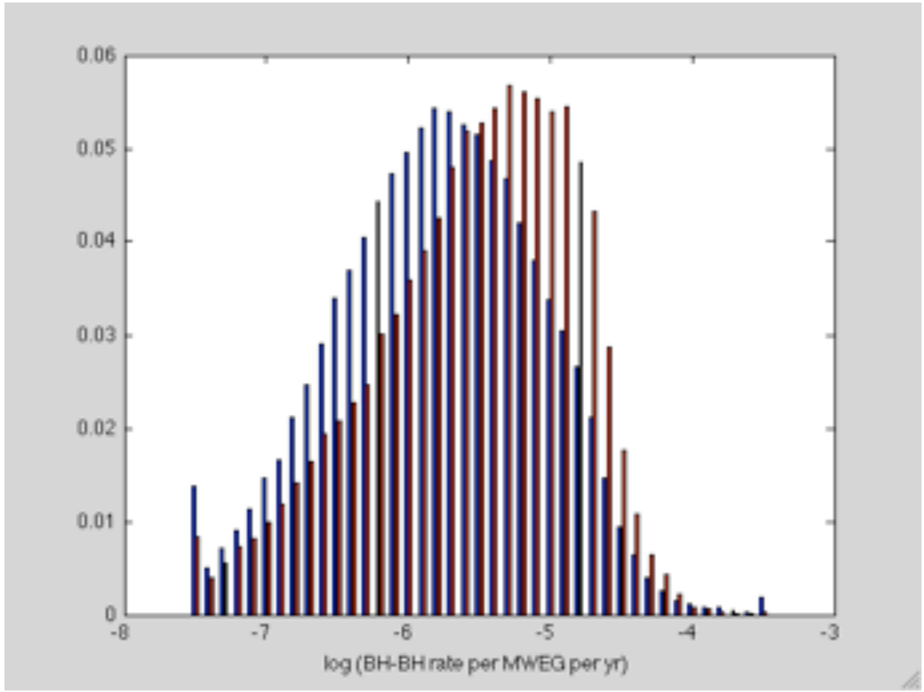
Effect of adding constraints, 1



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

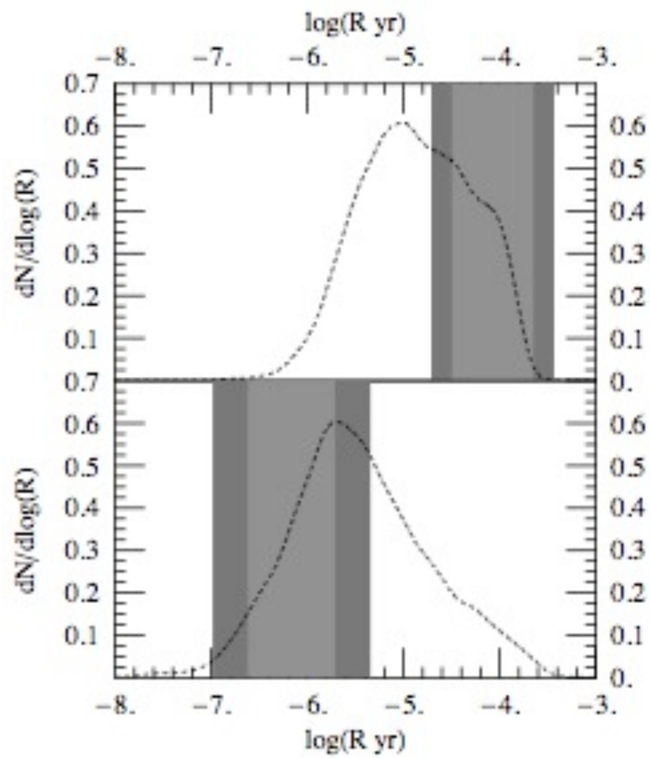
Effect of adding constraints, 1



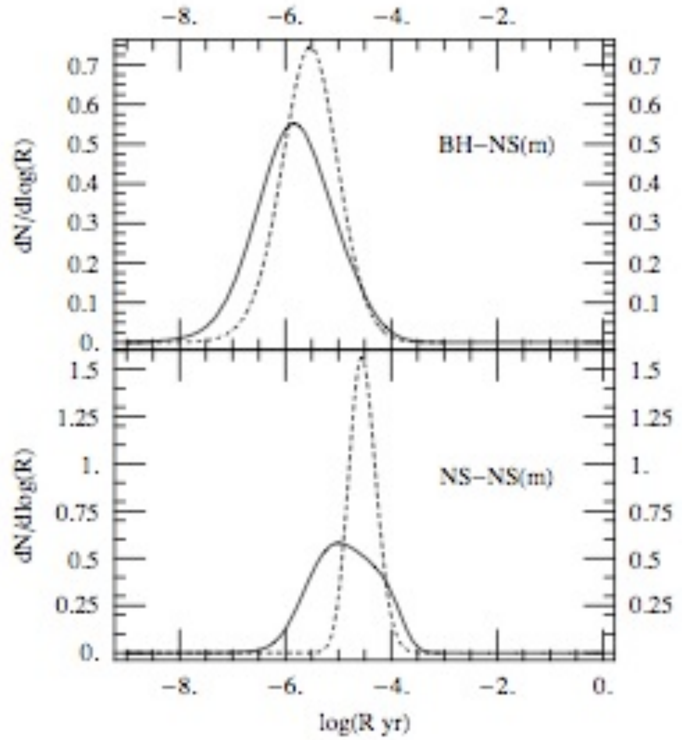


Single constraint satisfaction - no accounting for sampling uncertainties or model fitting errors

Effect of adding constraints, 2



Constraints from
observed binary pulsars



BH-NS and NS-NS
rate/MWEG predictions

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

LIGO sensitivity

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

(merger rate) =

(merger rate per L_{10}) *

(N_G in L_{10}'s)

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

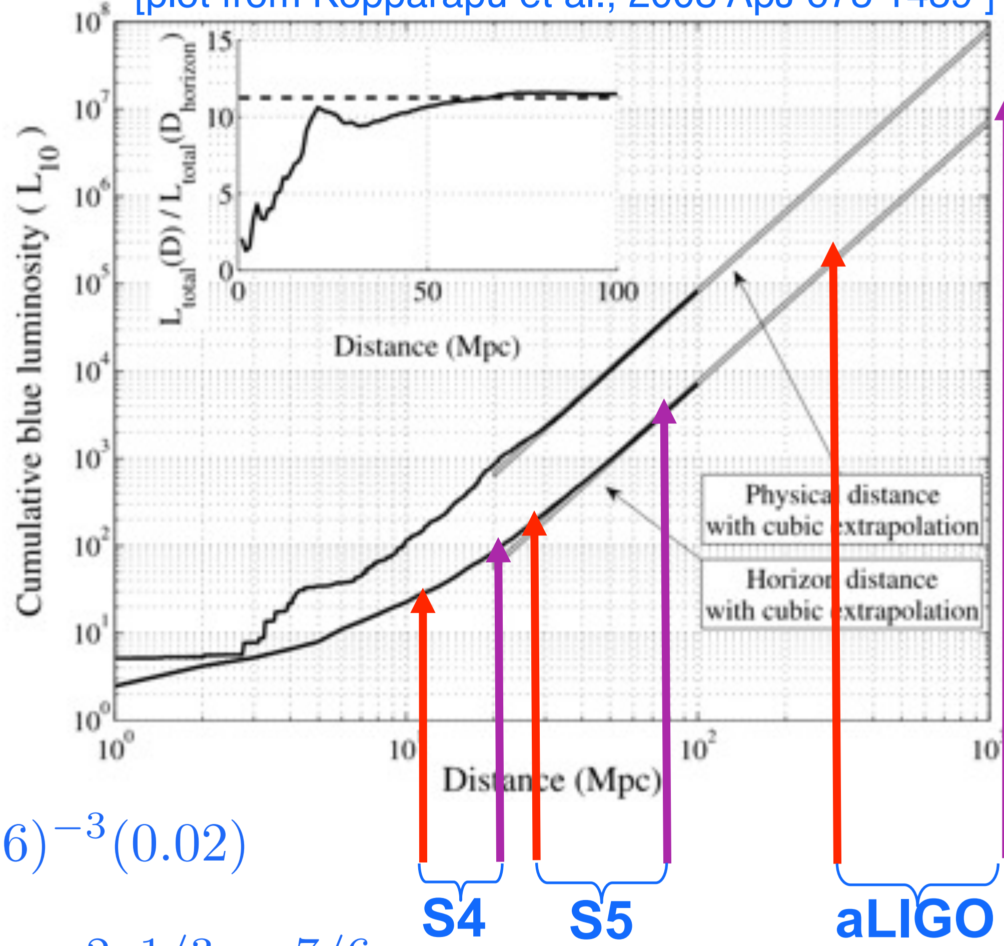
$$\rho(D_{\rm horizon}) \equiv 8$$

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

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

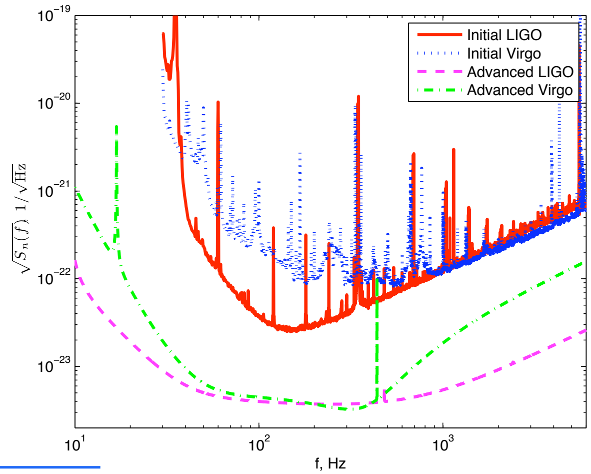
$$|\tilde{h}(f)| = 2/D * (5\mu/96)^{1/2}(M/\pi^2)^{1/3} f^{-7/6}$$

[plot from Kopparapu et al., 2008 ApJ 675 1459]



Merger and Detection Rates

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



IFO	Source	$\dot{N}_{\rm low}$ $\rm yr^{-1}$	$\dot{N}_{\rm re}$ $\rm yr^{-1}$	$\dot{N}_{\rm high}$ $\rm yr^{-1}$
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

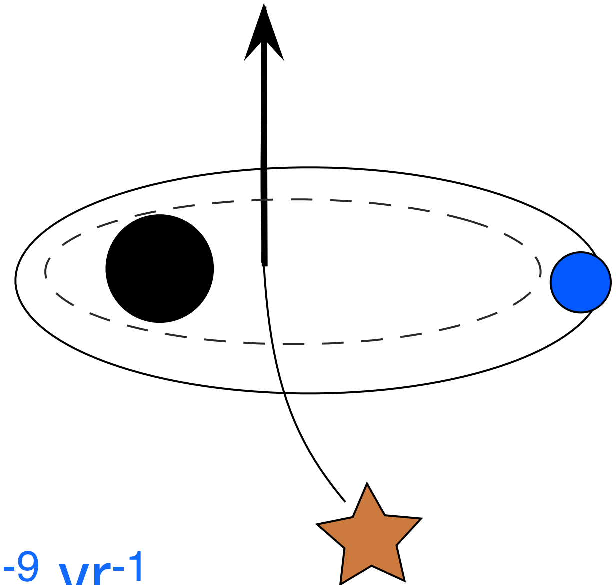
[IM & O'Shaughnessy, 2010, CQG 27 114007; Abadie et al., 2010, arXiv:1003.2480]

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]

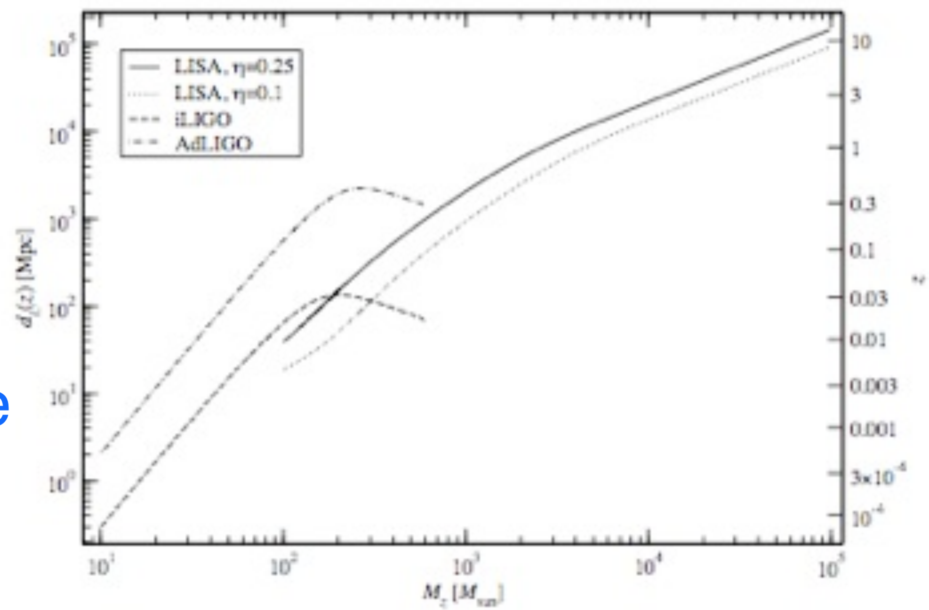


- Rate per globular cluster: few x 10^{-9} yr^{-1}
- Predicted Advanced LIGO event rates between 1/few years and ~30/year

Inspirals of two IMBHs

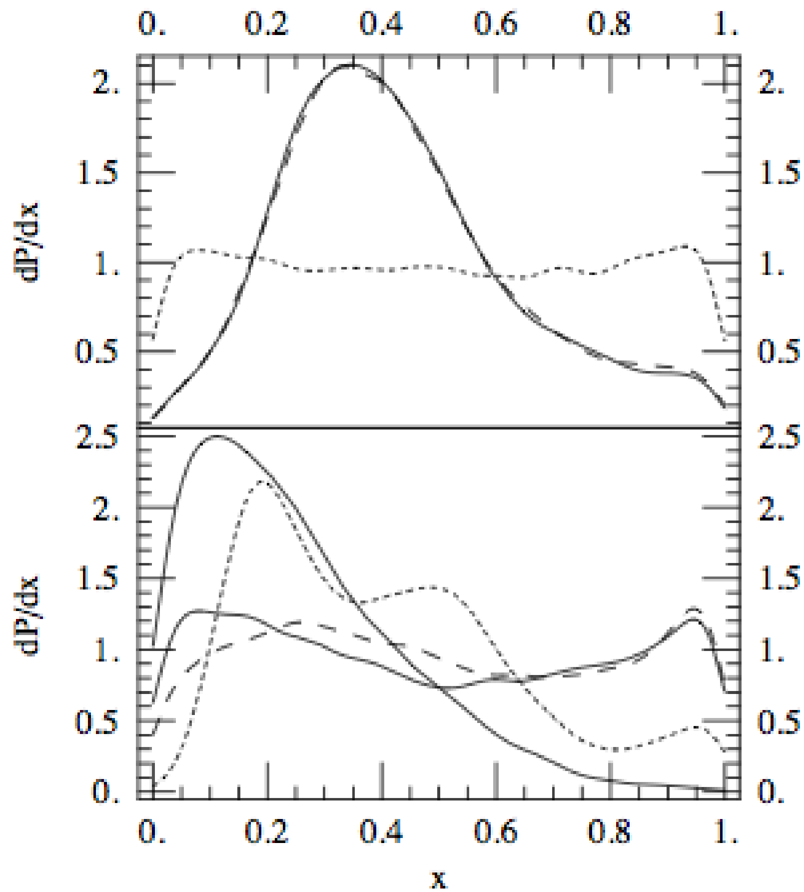
- Two very massive stars could form in globular clusters with sufficient binary fraction, then grow through run-away collision to form two IMBHs in same GC

- 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]:



Astrophysics with GW searches

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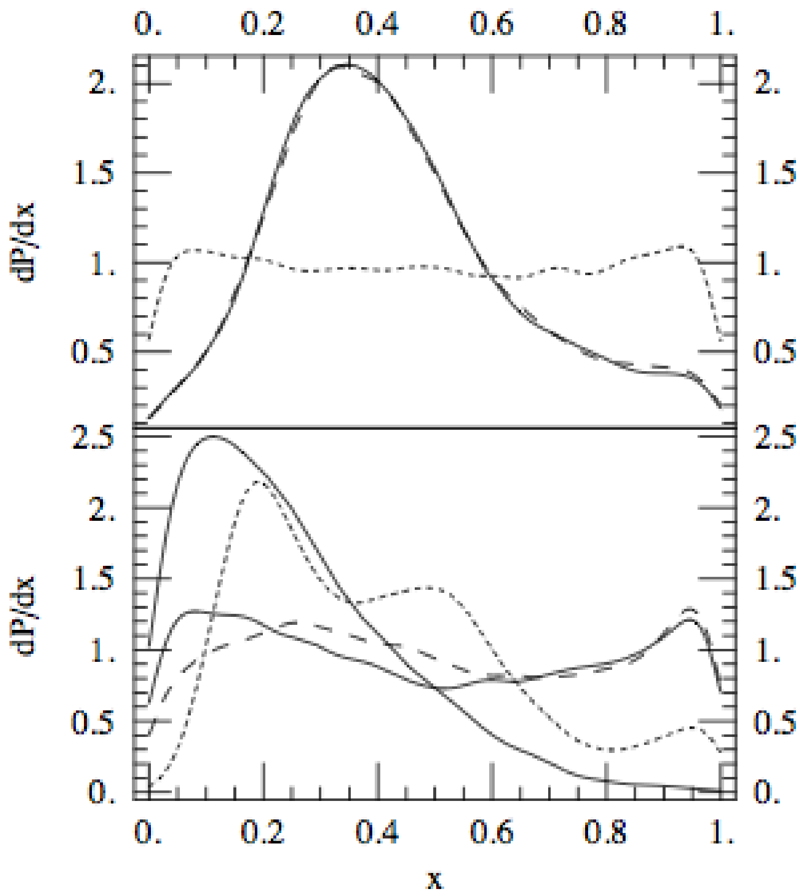

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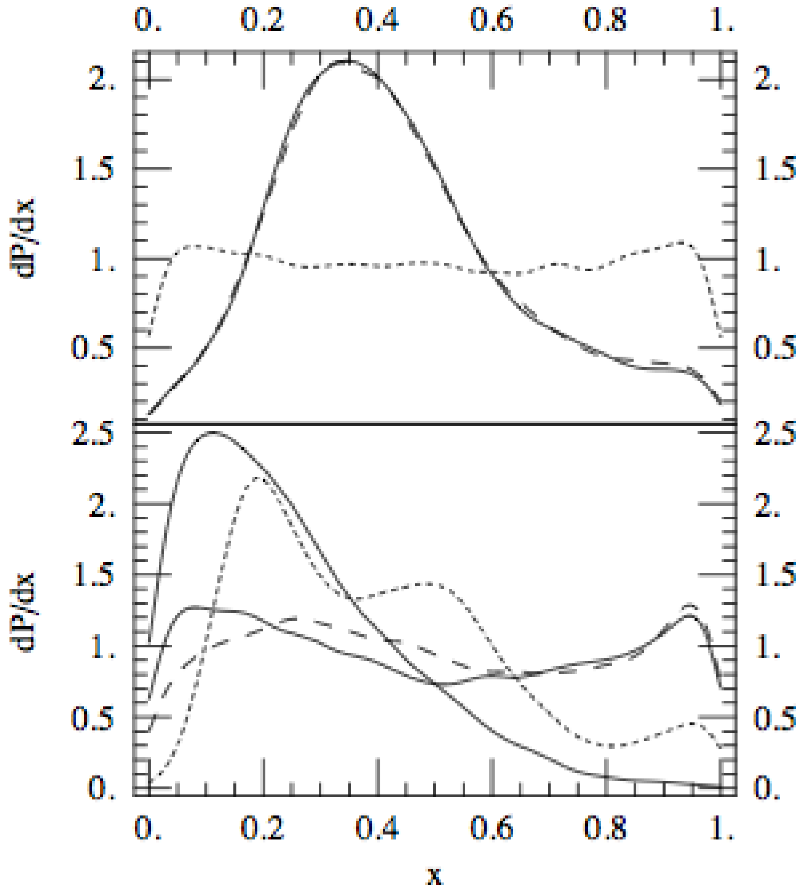
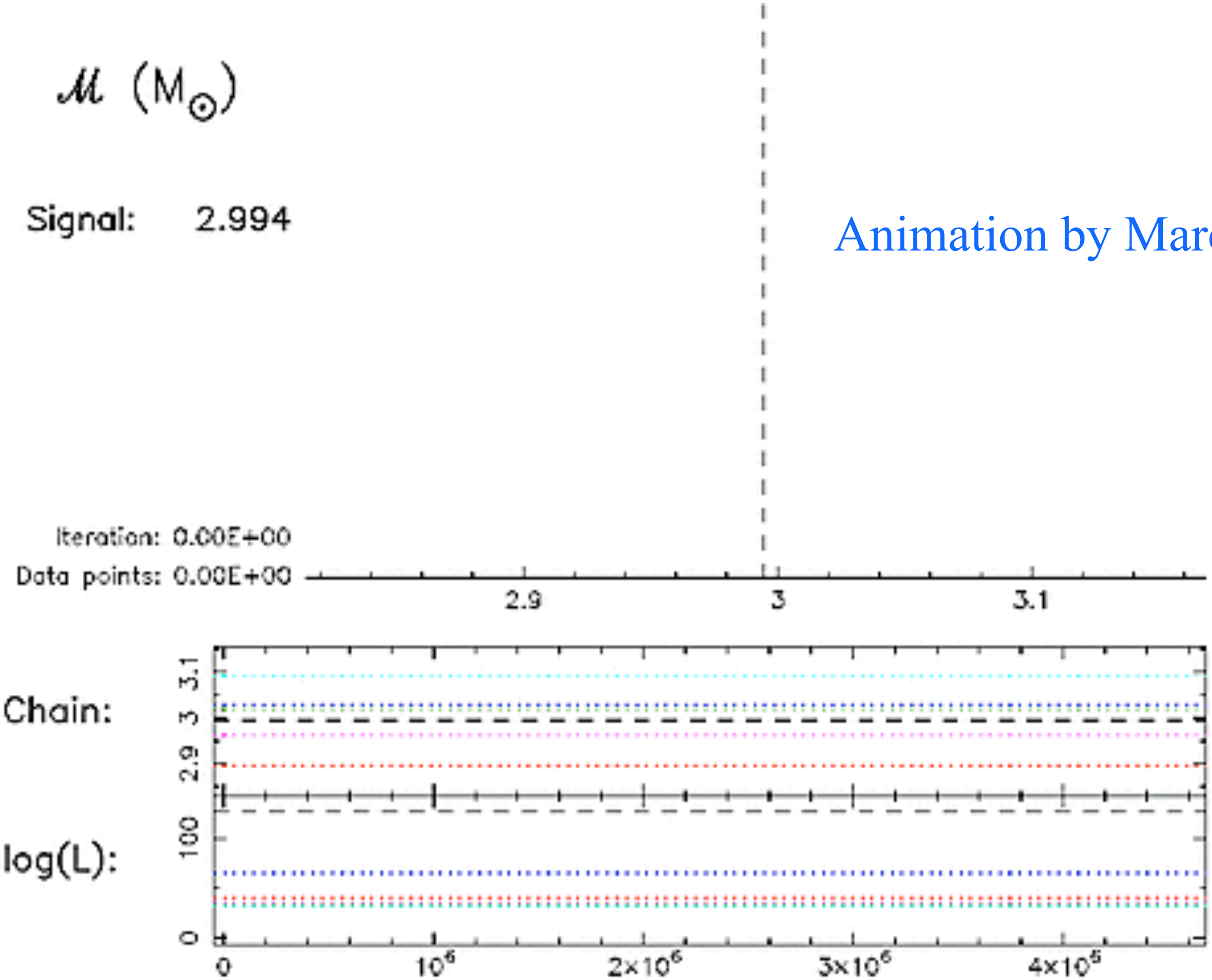


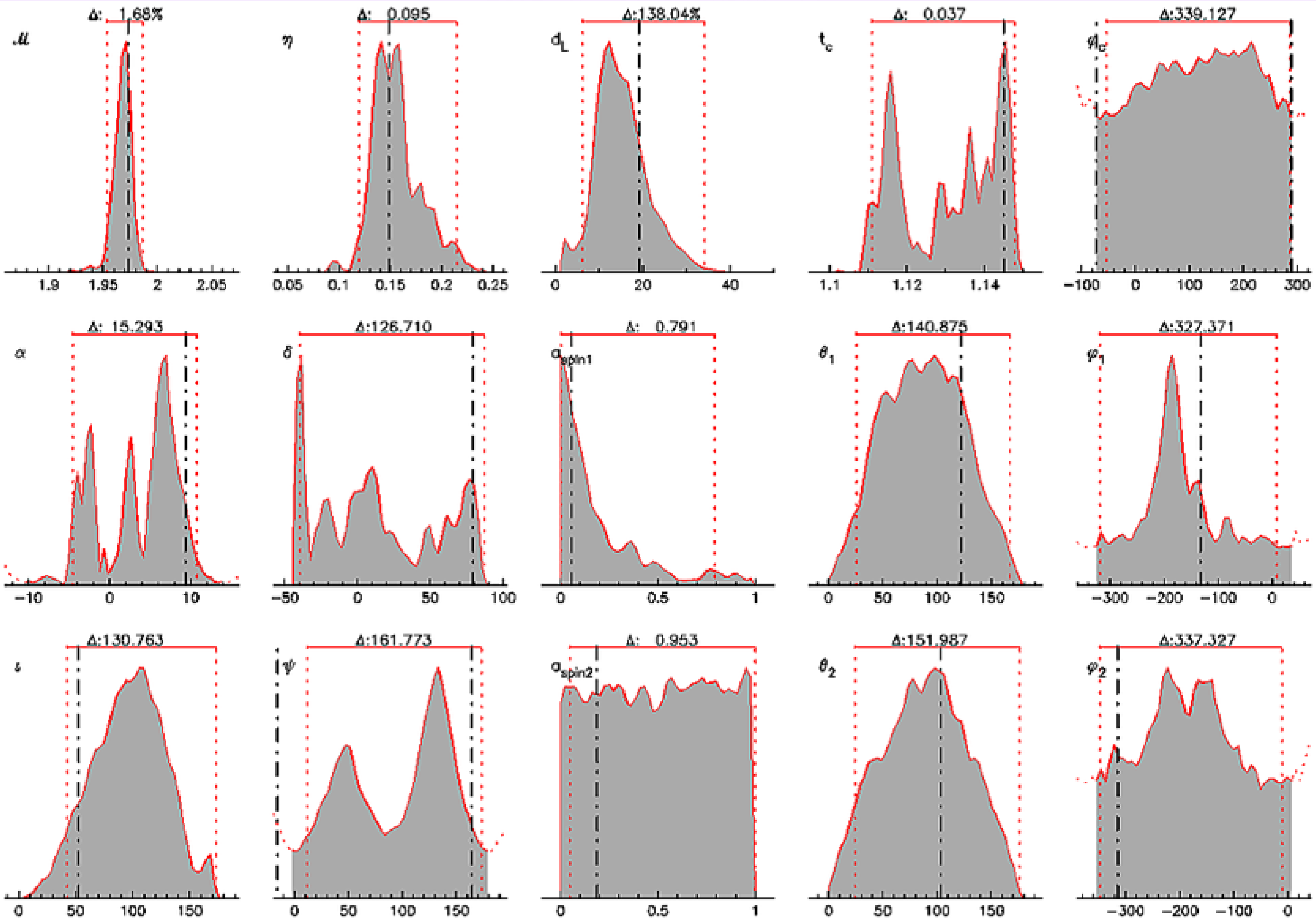
Markov Chain Monte Carlo



Animation by Marc van der Sluys

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

Accurate Parameter Estimation

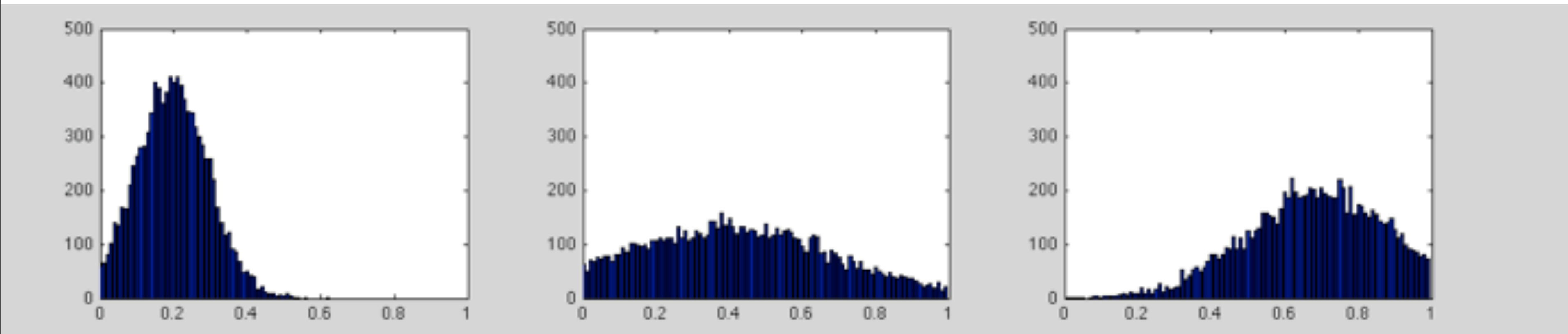


van der Sluys, IM, Raymond, et al., 0905.1323

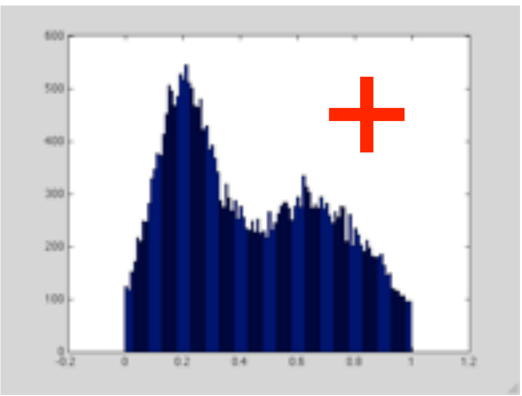
Combining events into populations

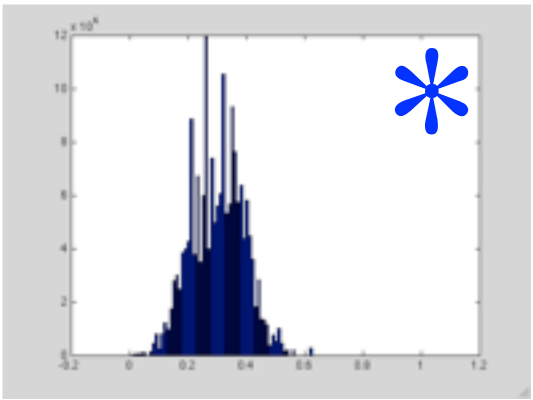
Parameter estimation on multiple GW detections:

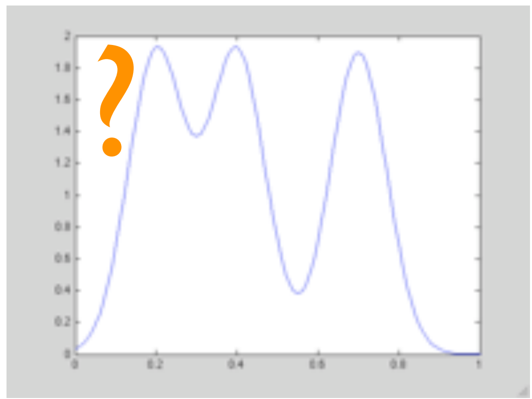
yield a set of individual marginalized posterior probability density functions



How do we combine these to make a statement about parameter distribution of the population being sampled?



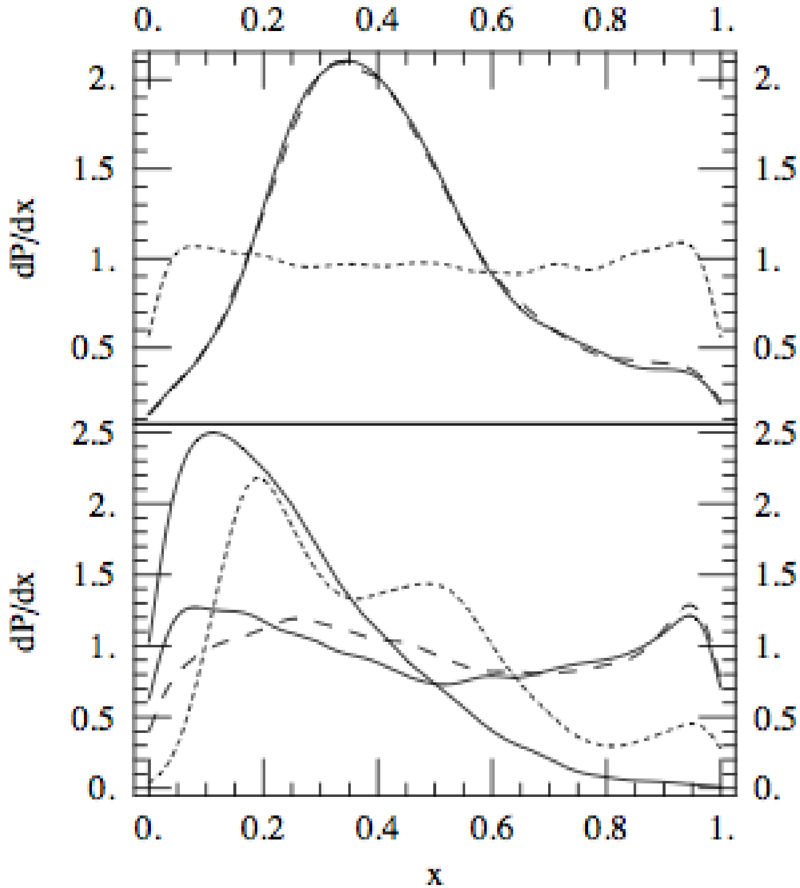




[IM, 2010, PRD 81, 084029]

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.



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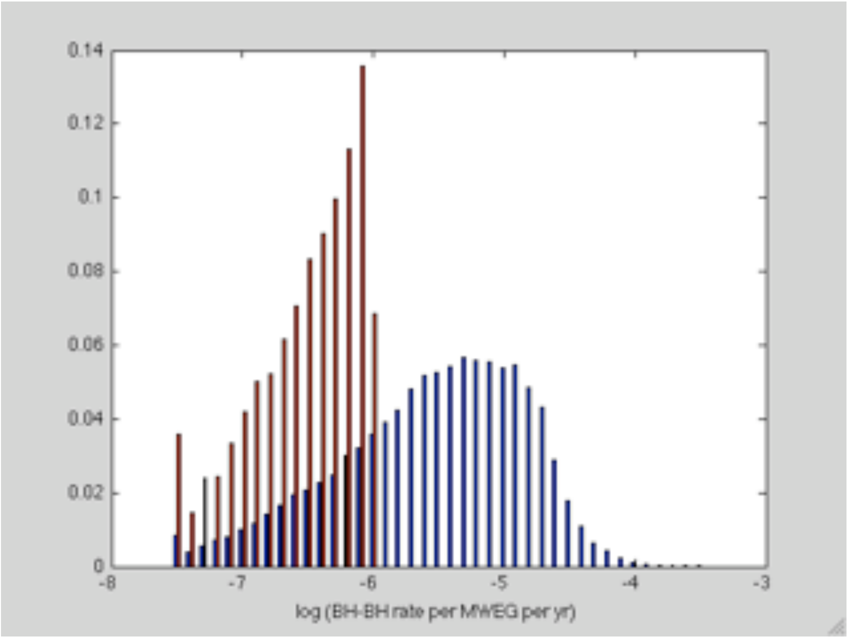
Constraints from upper limits - example



[IM & O'Shaughnessy, 2010, CQG 27 114007]

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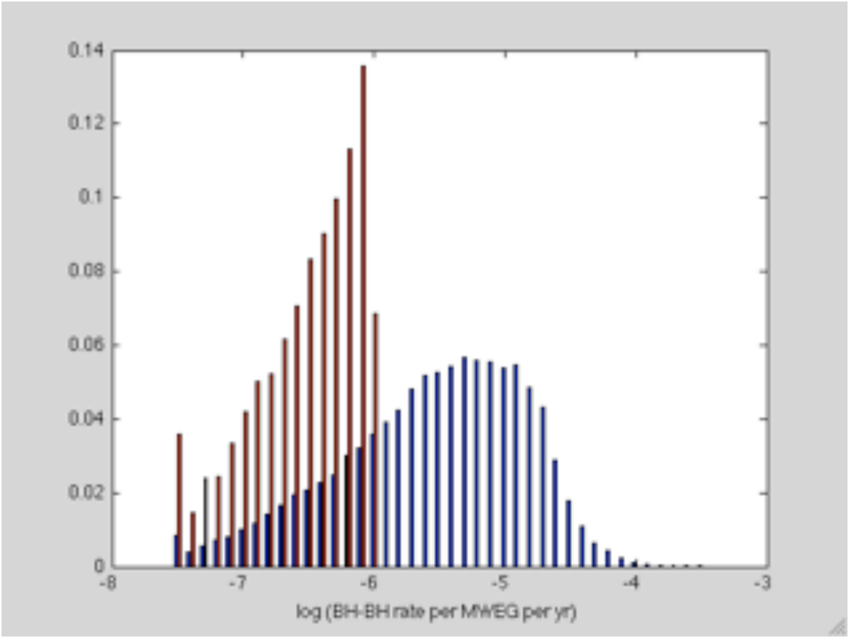
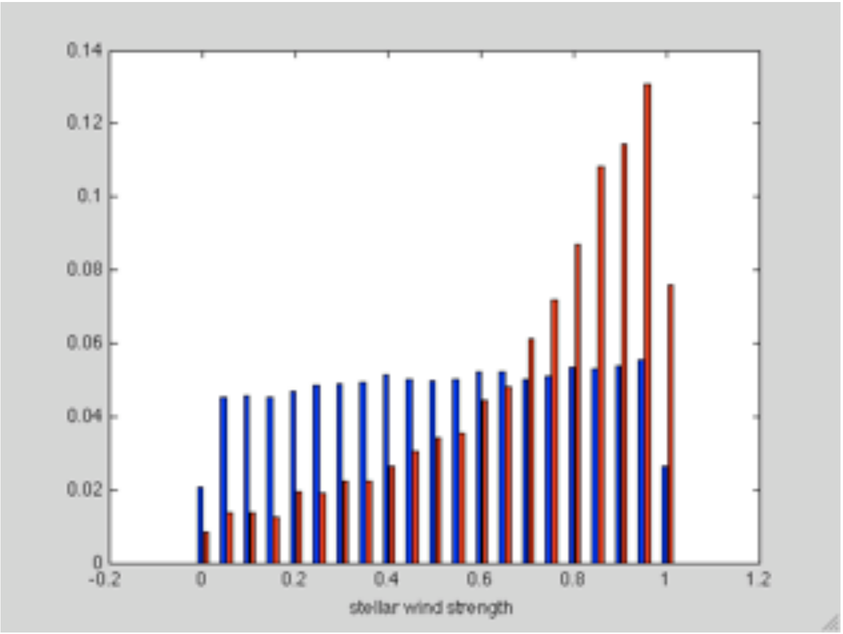
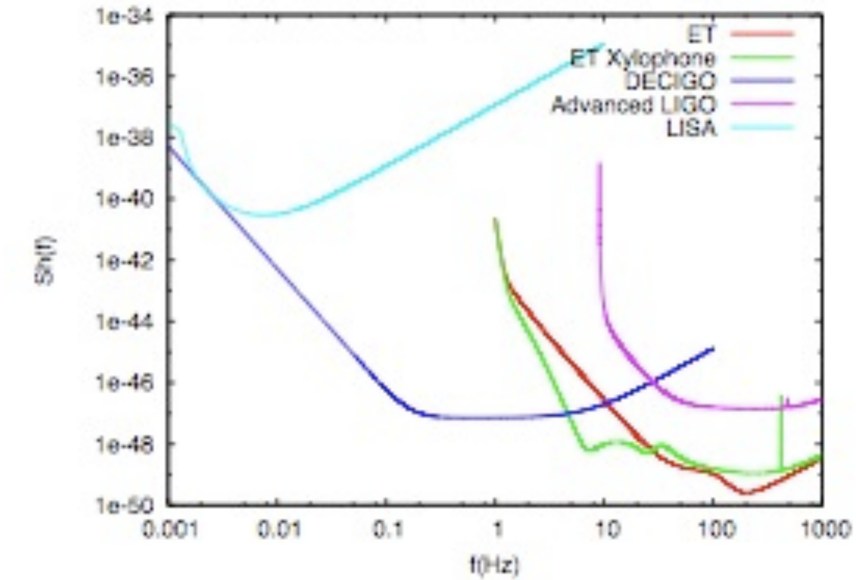




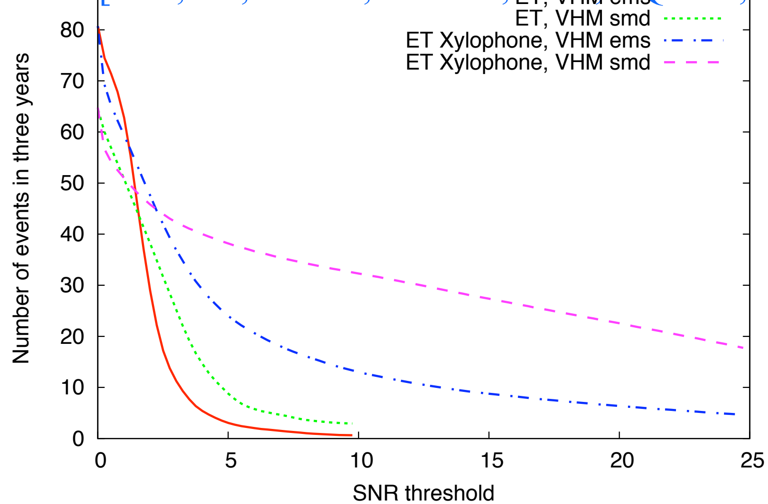
[IM & O'Shaughnessy, 2010, CQG 27 114007]

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, ApJL 698 121]
  - May detect thousands of IMBH-IMBH mergers and hundreds of IMRIs into IMBHs in globular clusters (see review [Gair, IM, Miller, Volonteri, 2010, arXiv:0907.5450])



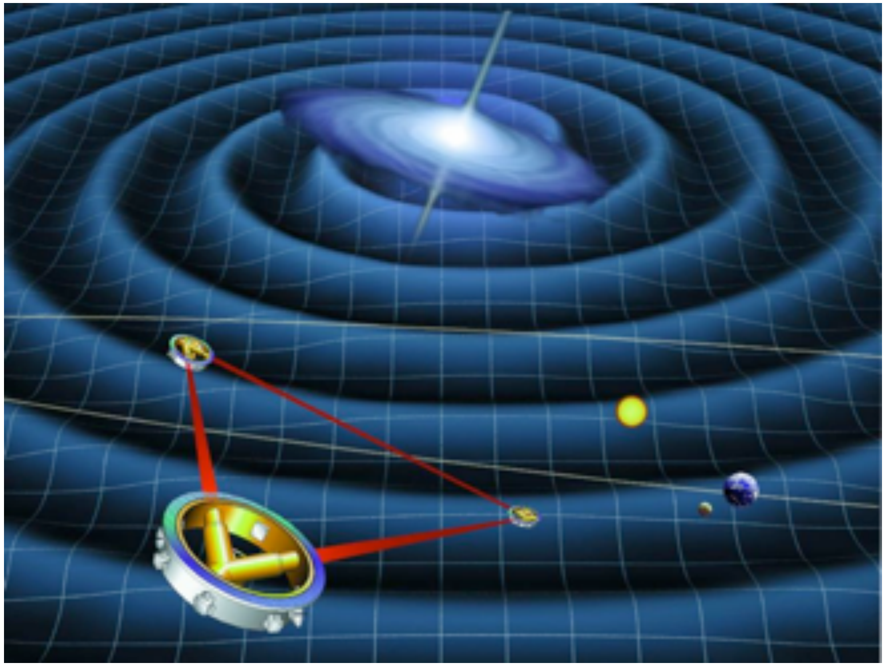
[Gair, IM, Sesana, Vecchio, 2009, CQG 26, 204009]



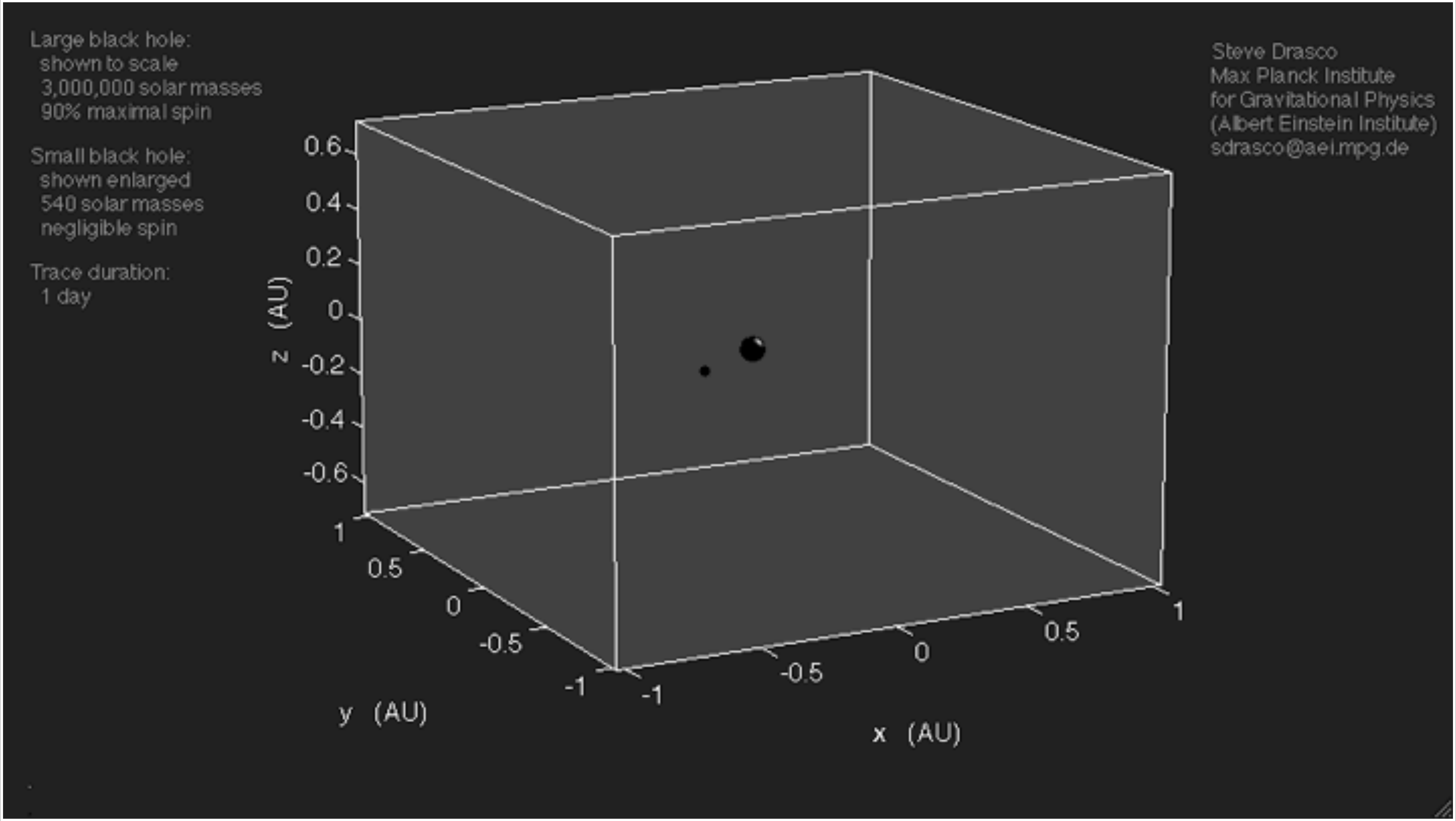
Tuesday, November 9, 2010

LISA Binary Sources: EMRIs

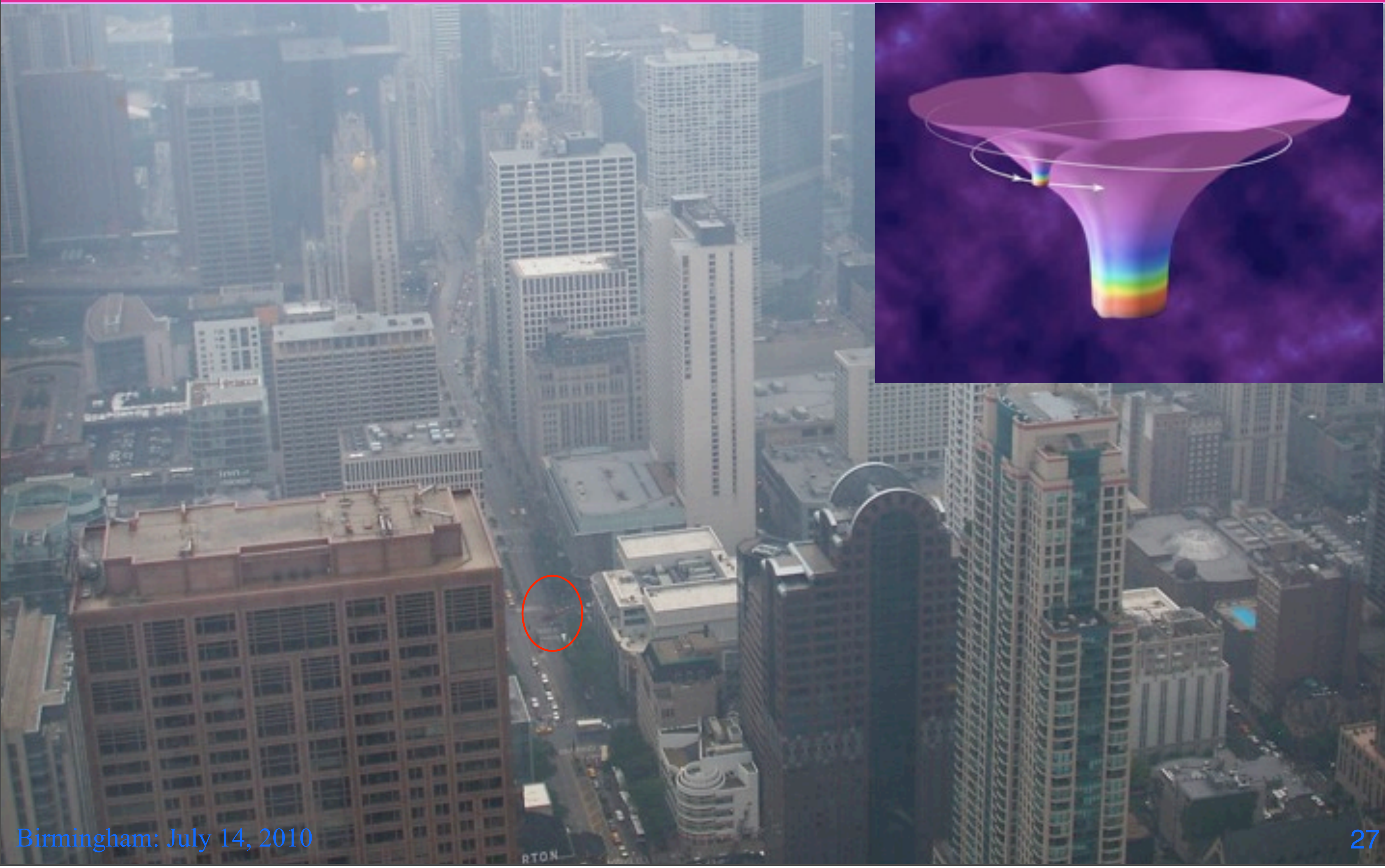
- LIGO sensitive @ a few hundred Hz
  - » NS-NS, NS-BH, BH-BH binaries
- LISA sensitive @ a few mHz
  - » massive black-hole binaries
  - » galactic white dwarf (and compact object) binaries
  - » extreme-mass-ratio inspirals of WDs/NSs/BHs into SMBHs
    - – could see tens to hundreds to z~1 [e.g.,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



Extreme Mass Ratio Inspirals



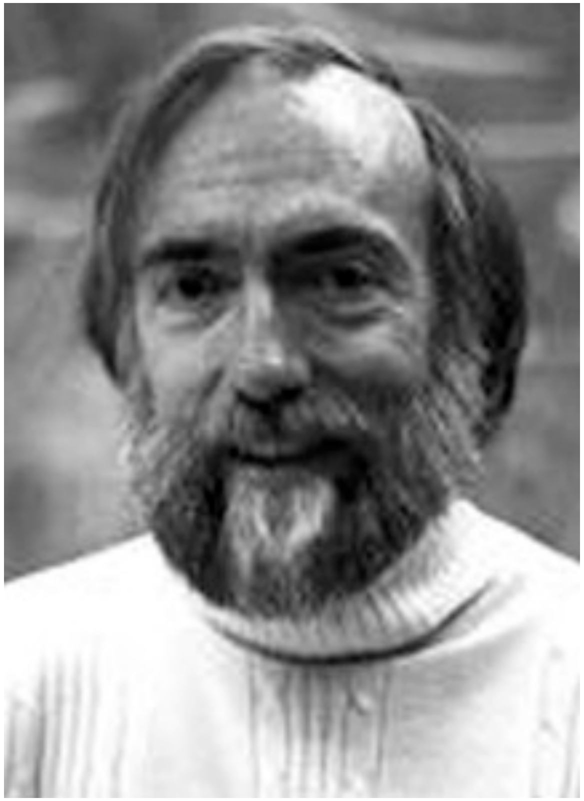
Exploring the spacetime...



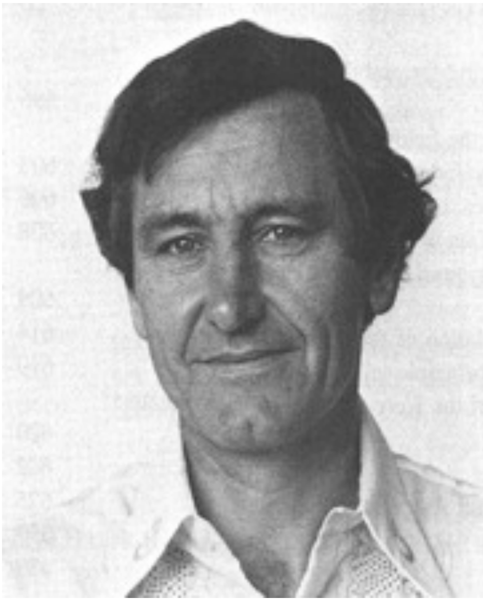
... taking lots of pictures

Testing the “no-hair” theorem

Testing the no-hair theorem

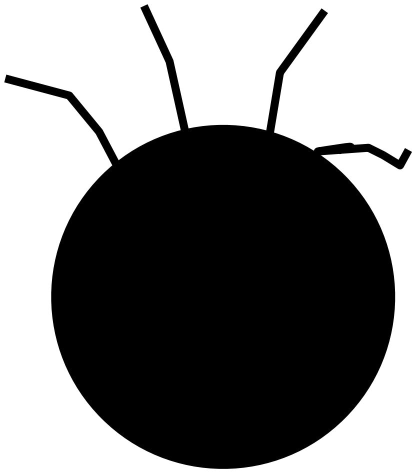


Testing the no-hair theorem?



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:

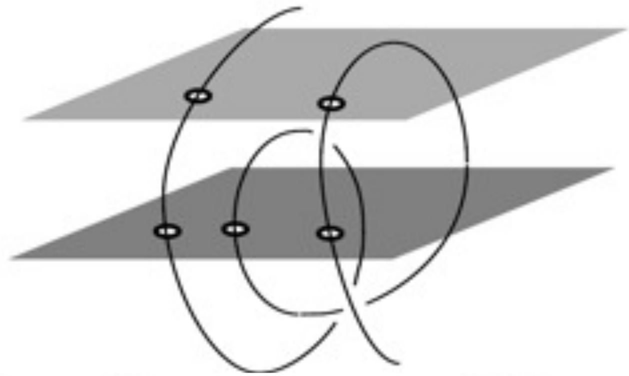
$$\mathrm{d}s^2 = -f(\rho,z)\,\left(\mathrm{d}t - \omega(\rho,z)\,\mathrm{d}\phi\right)^2 + \frac{1}{f(\rho,z)}\left[\mathrm{e}^{2\gamma(\rho,z)}\,\left(\mathrm{d}\rho^2 + \mathrm{d}z^2\right) + \rho^2\,\mathrm{d}\phi^2\right]$$

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]

The emergence of chaos

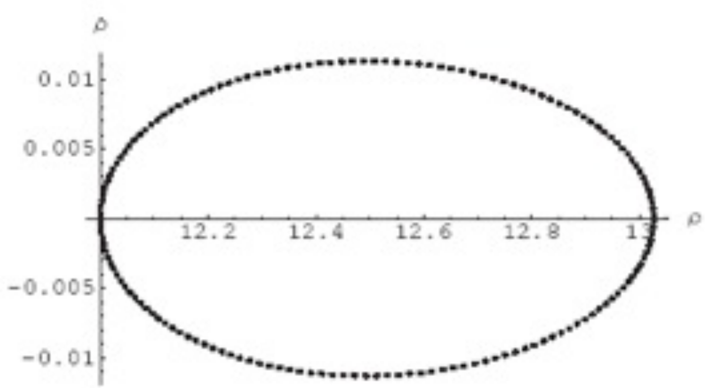
Solve the geodesic equation
and study Poincare maps:

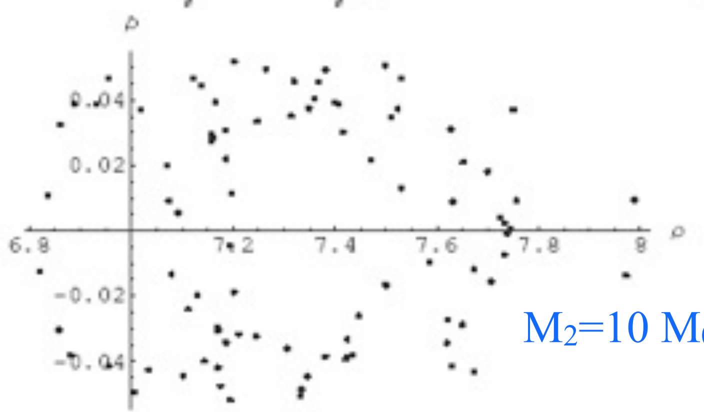
$$\frac{\partial^2 x^\alpha}{\partial \tau^2} = -\Gamma^\alpha_{\beta\gamma}\frac{\partial x^\beta}{\partial \tau}\frac{\partial x^\gamma}{\partial \tau}$$



- Plot dρ/dt vs. ρ for $z=z_0$ crossings
- Phase space plots should be closed curves for all z_0 iff there is a third isolating integral [Carter constant]

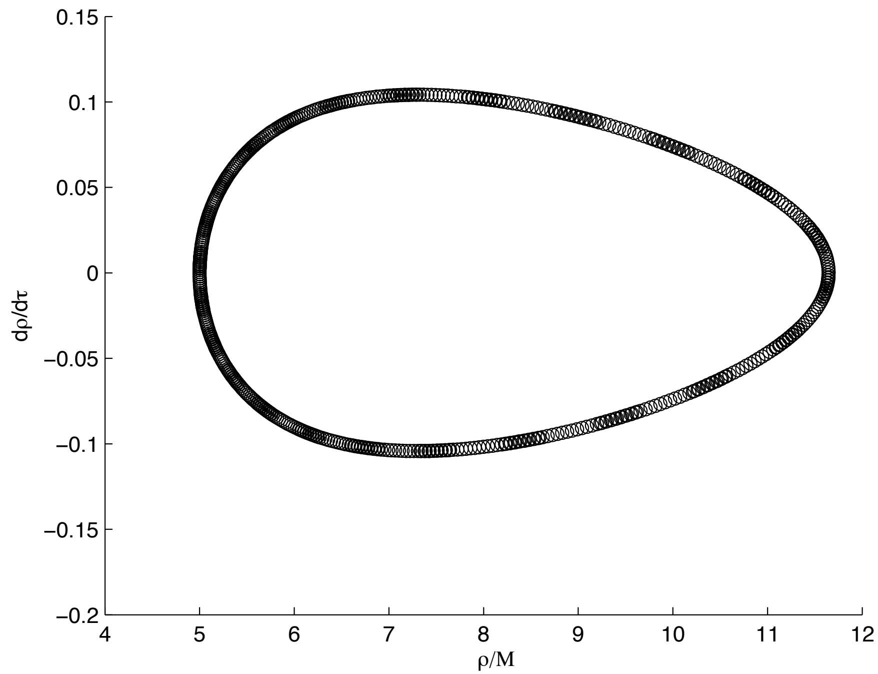
Newtonian+hexadecapole: $V(r,\theta) = -\frac{M_0}{r} + \frac{M_2}{r^3}P_2(\cos\theta) + \frac{M_4}{r^5}P_4(\cos\theta)$





$M_2=10\ M_0$; $M_4=400\ M_0$

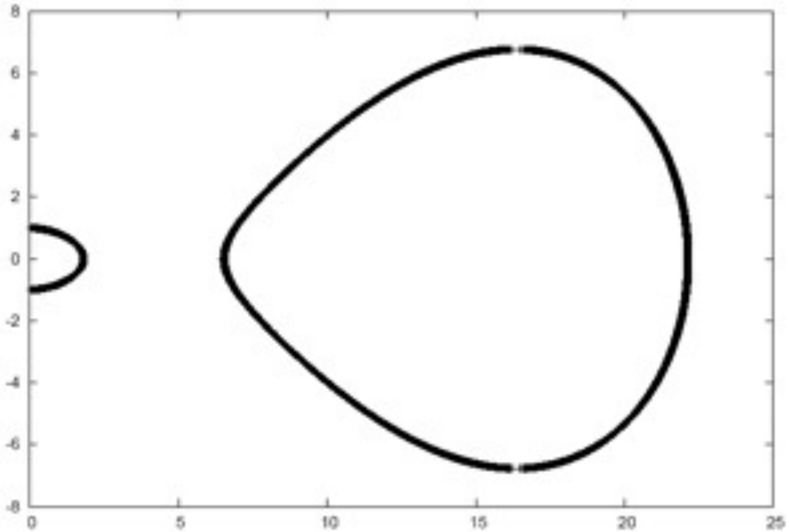
All is regular in “bumpy” spacetimes



Poincare map for E=0.95, L_Z=-3, a/M=0.9, q=0.95

Or is it?...

Effective potential $(\dot{\rho}^2 + \dot{z}^2) = V(E, L_z, \rho, z)$ defines allowed bound orbits



z

ρ

E=0.95, L_z=-3, a/M=0.9, q=0

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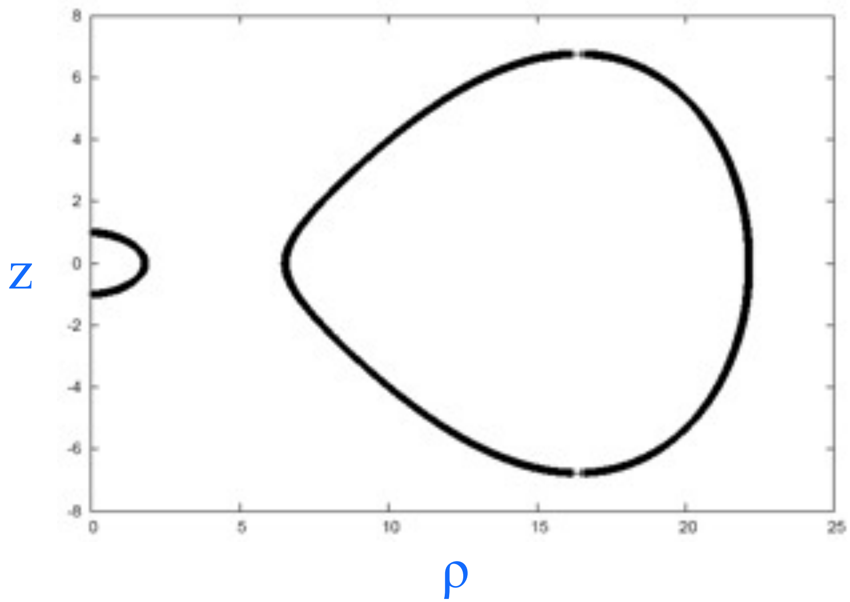
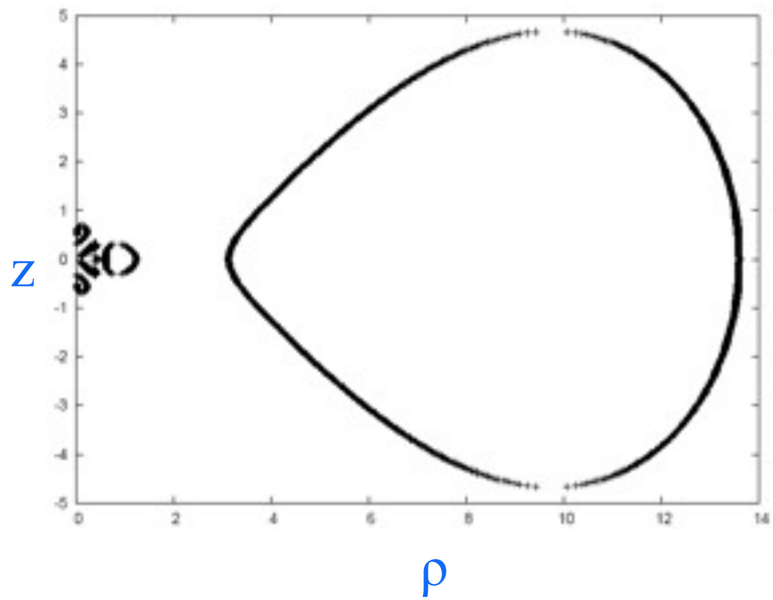


$E=0.95$, $L_z=-3$, $a/M=0.9$, $q=0$

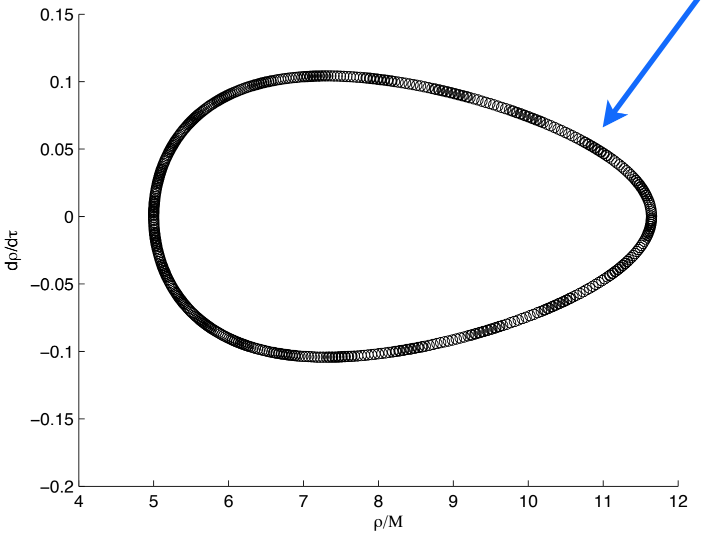


$E=0.95$, $L_z=-3$, $a/M=0.9$, $q=0.95$

It’s a mad, mad, mad, mad geodesic

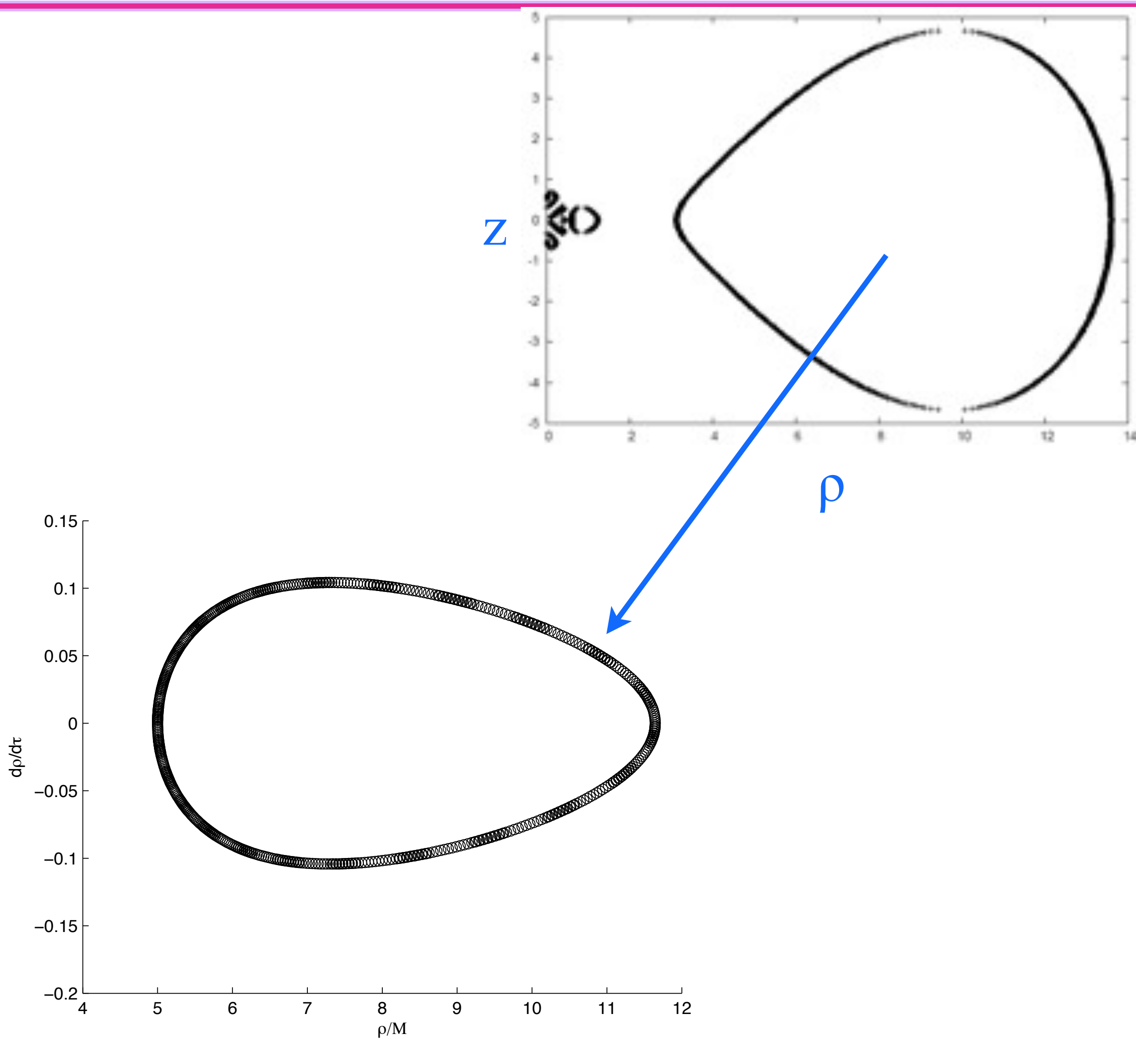
z

ρ



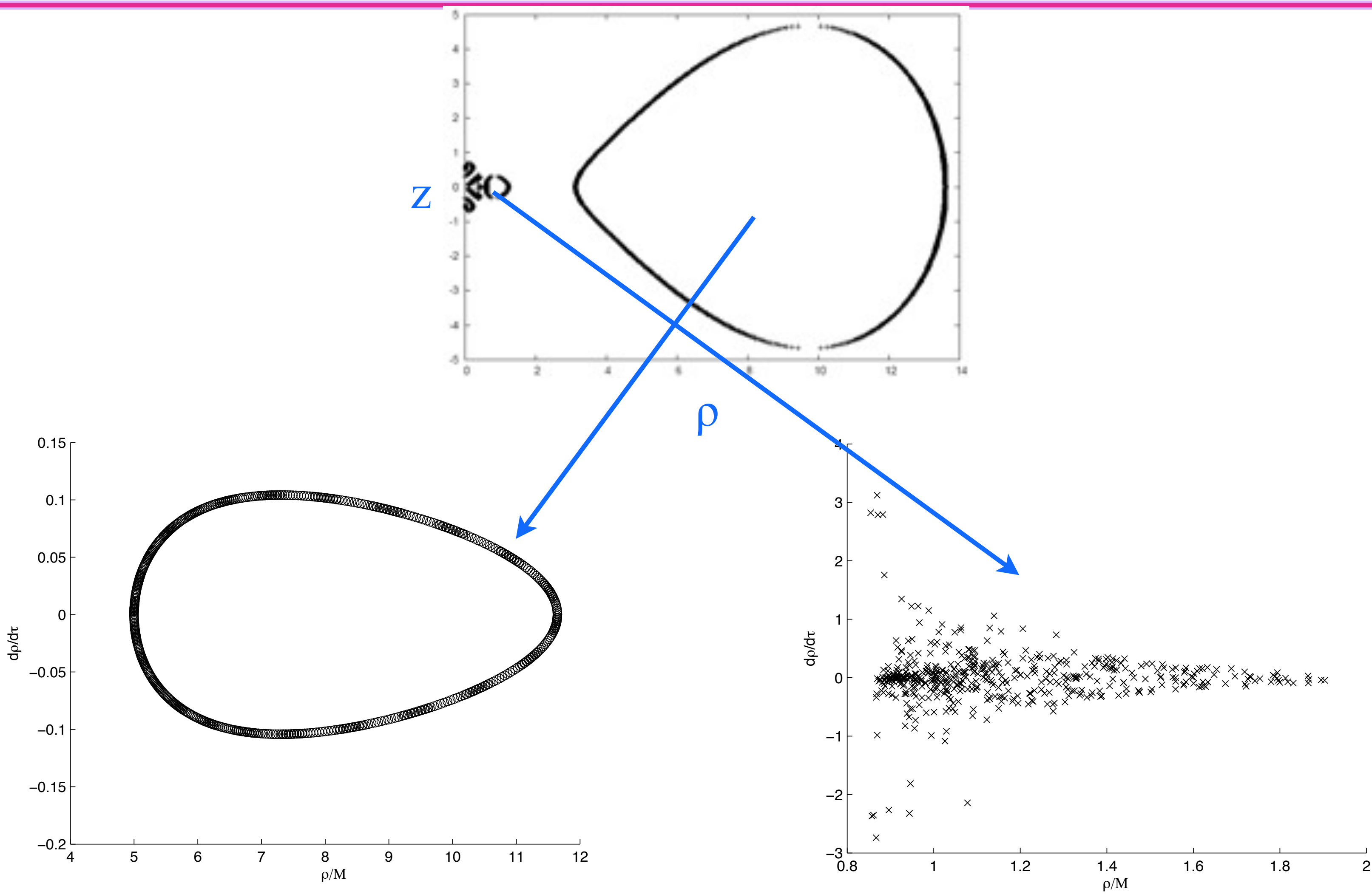
$E=0.95$, $L_z=-3$, $a/M=0.9$, $q=0.95$

It’s a mad, mad, mad, mad geodesic



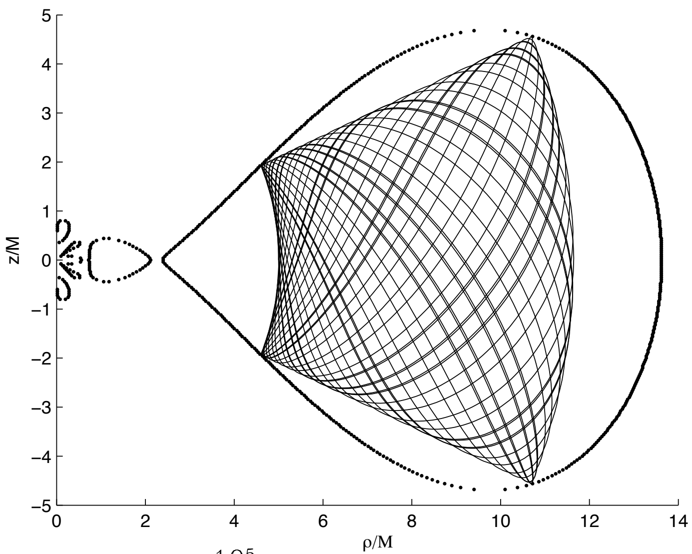
$E=0.95,\ L_z=-3,\ a/M=0.9,\ q=0.95$

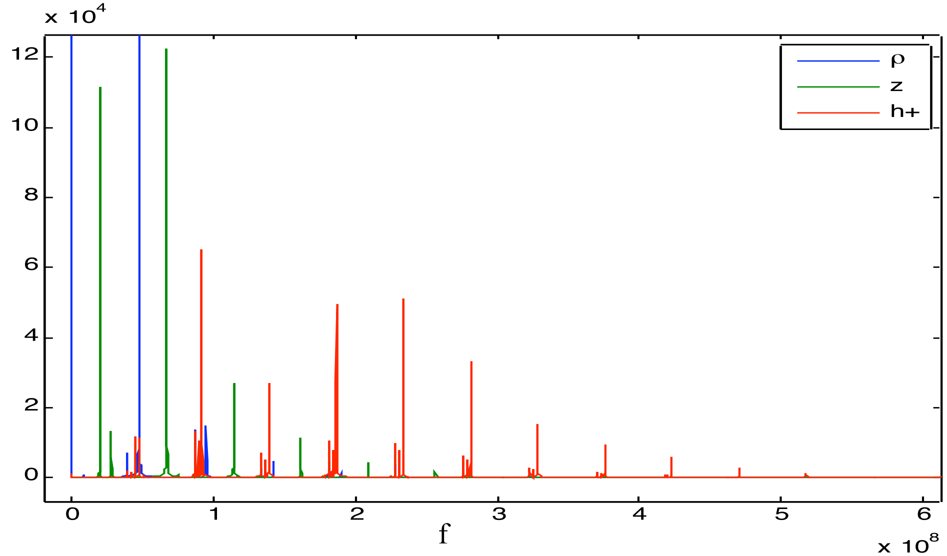
It's a mad, mad, mad, mad geodesic

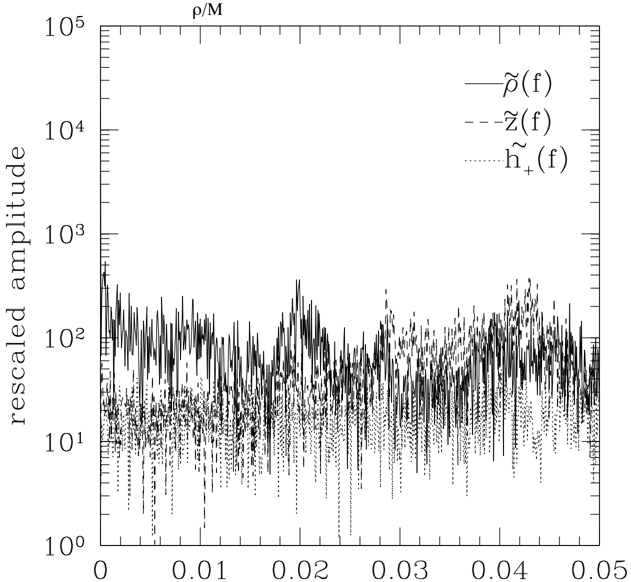


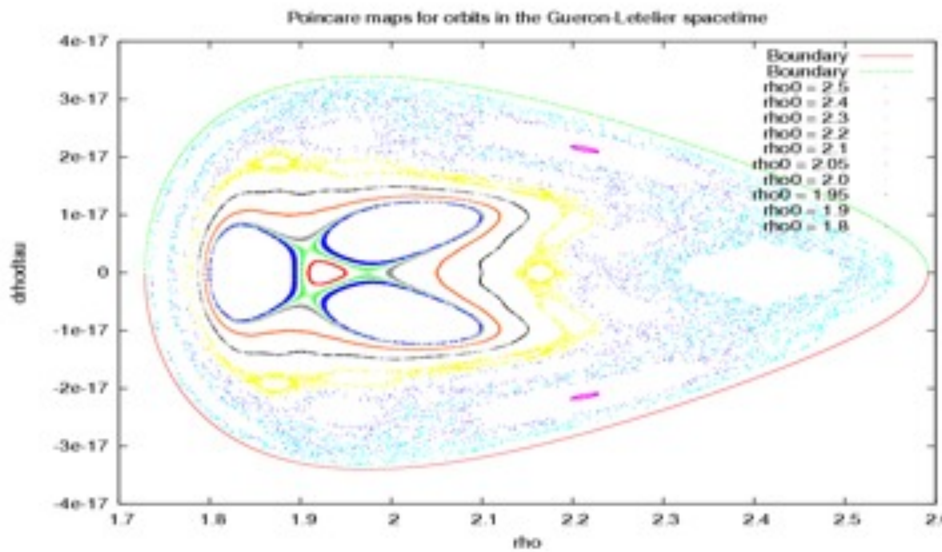
$E=0.95$, $L_z=-3$, $a/M=0.9$, $q=0.95$

Order and Chaos, side by side



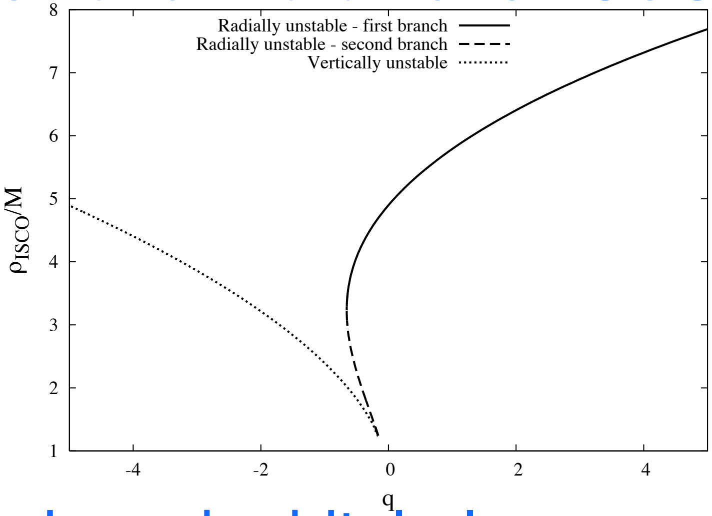


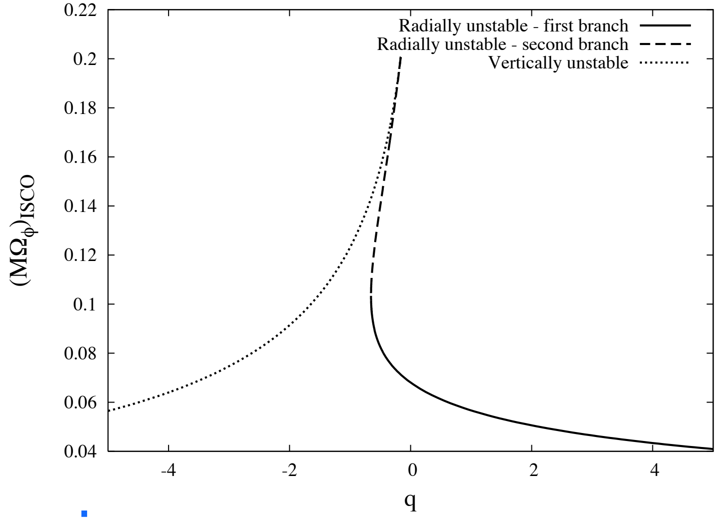




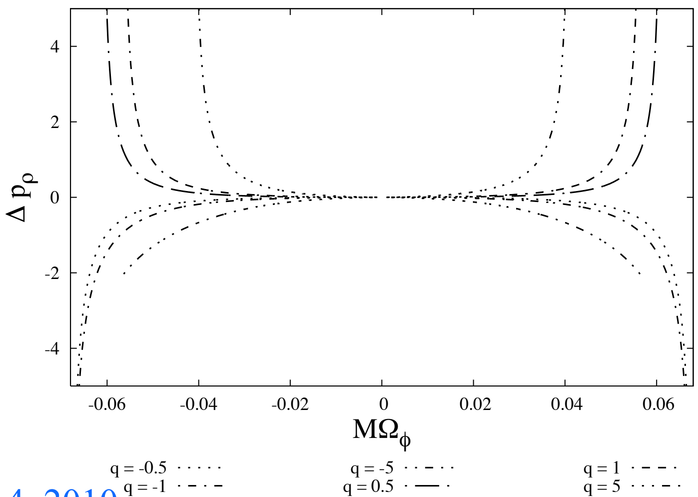
Other signs of non-Kerr spacetimes

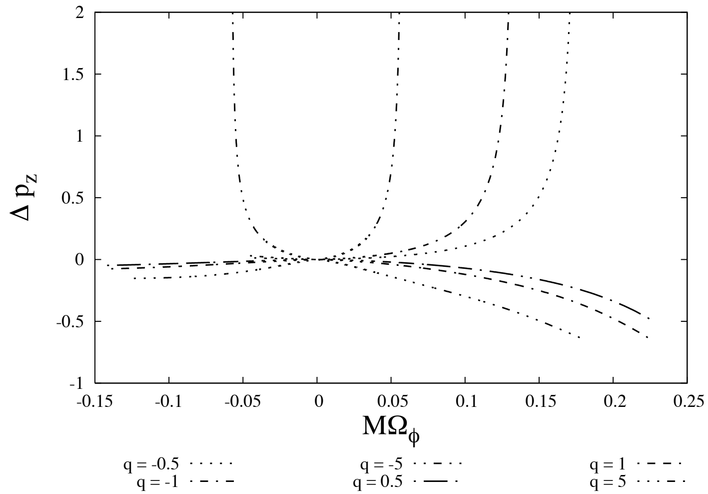
- Location and character of ISCO



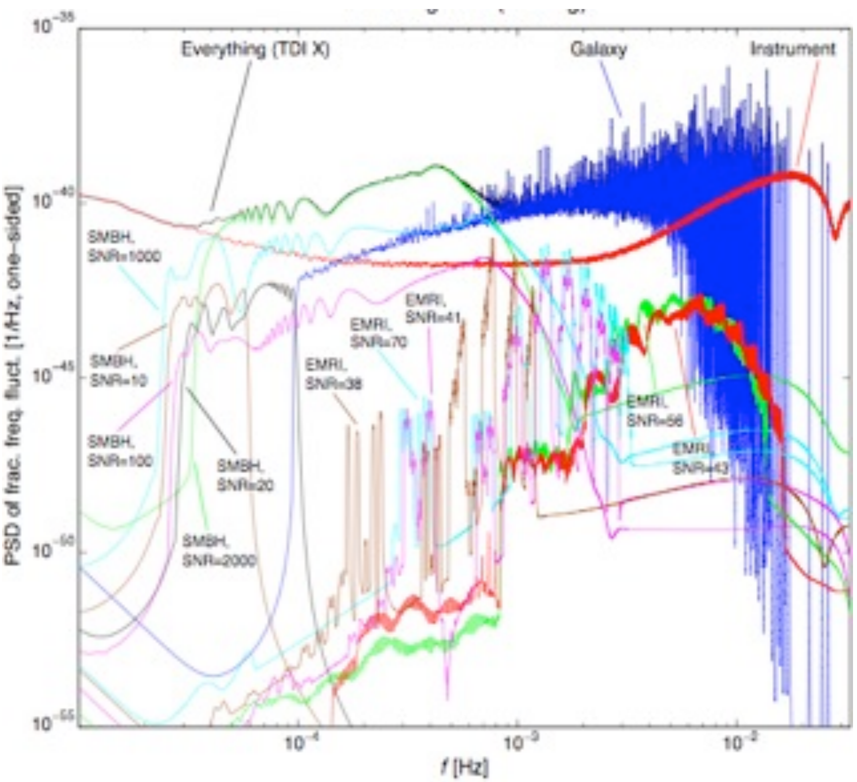


- Periapsis and orbital-plane precession





LISA Data: An embarrassment of riches



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

What has already been accomplished?

	MLDC 1	MLDC 2	MLCD 1B	MLDC 3
GB	• Verification ✓ • Unknown, isolated ✓ • Unknown, interfering ✓	• Galaxy of $3x10^6$ ✓	• Verification ✓ • Unknown, isolated ✓ • Unknown, confused ✓	• Galaxy of $6x10^7$ 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 ✓

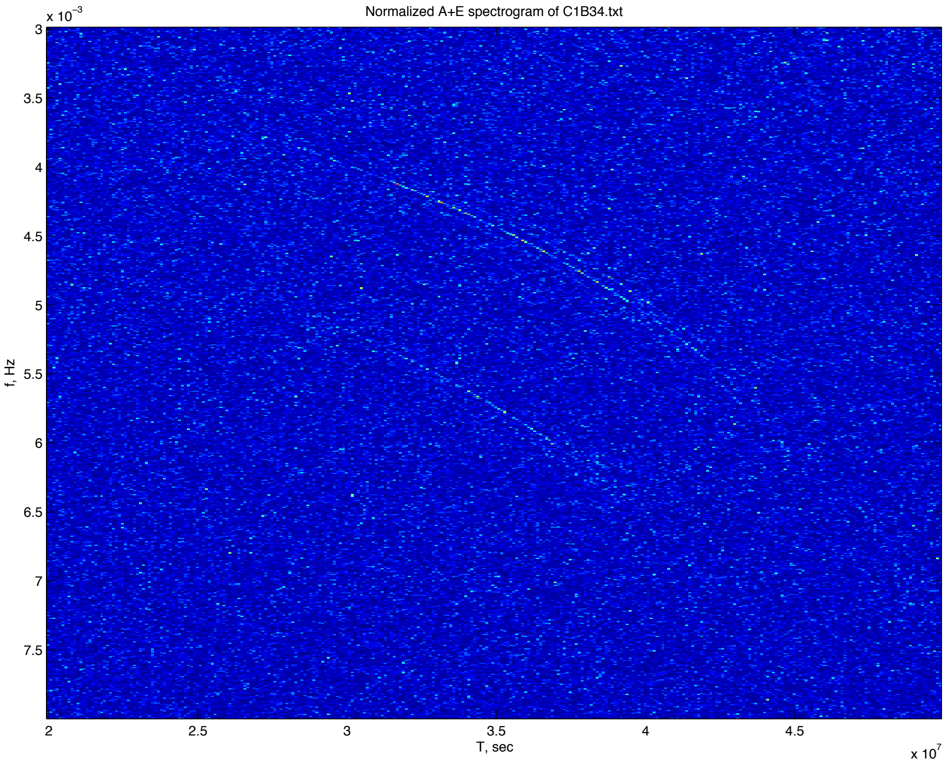
Table by M. Vallisneri

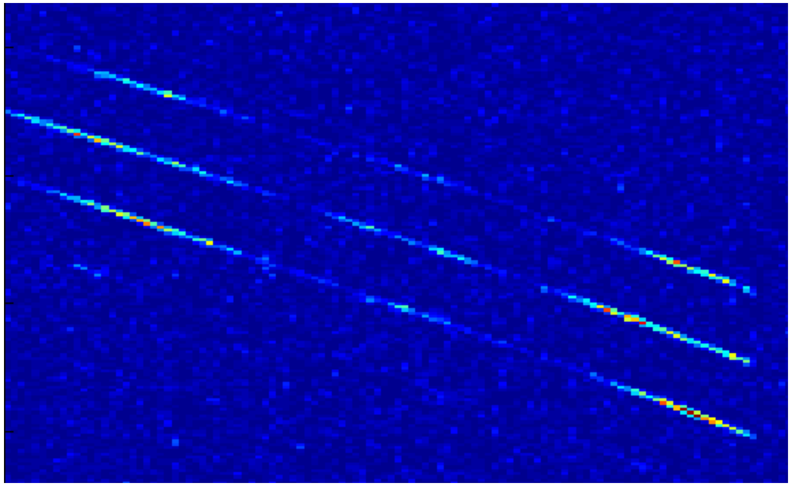
Mock LISA Data Challenges;
LISA Parameter-Estimation task force

EMRI detection and analysis

$$h(t) = h(M_1, M_2, \vec{S}_1, \vec{S}_2, \theta, \phi, D_L, e, ...; t)$$ 17 parameters

Need innovative search techniques to separate many overlapping signals: Markov-Chain Monte Carlo, MultiNest, time-frequency searches



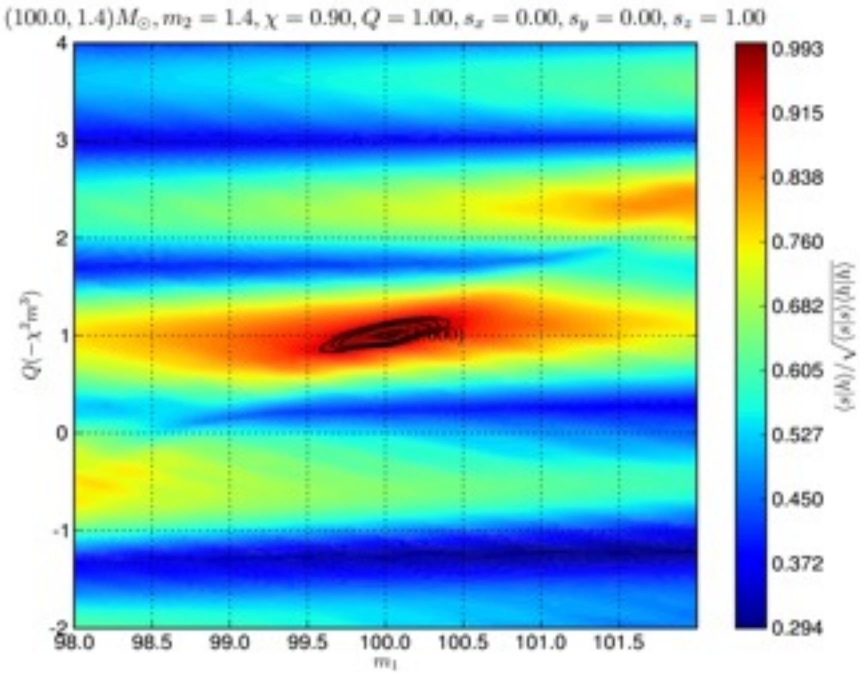


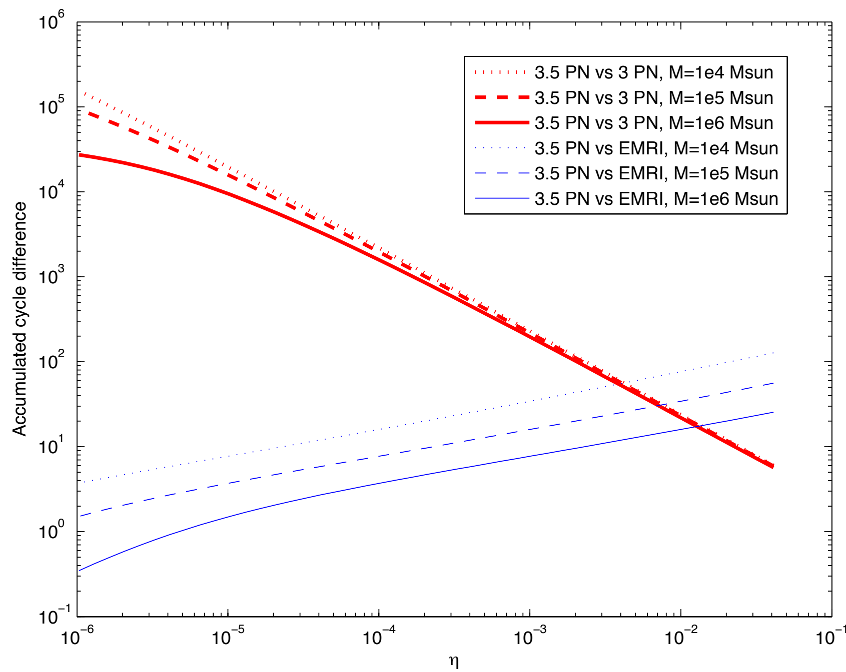
[Gair, IM, Wen, 2008, CQG 25 184031]

Intermediate-mass-ratio Inspirals

Can measure mass quadrupole moment to around 20% of Kerr value with Advanced LIGO [Brown et al., PRL 99, 201102]

Waveforms are a problem: both post-Newtonian and self-force waveforms currently fail in the intermediate regime [IM and Gair, 2005, PRD 72 084025]





Summary

- 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
- 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