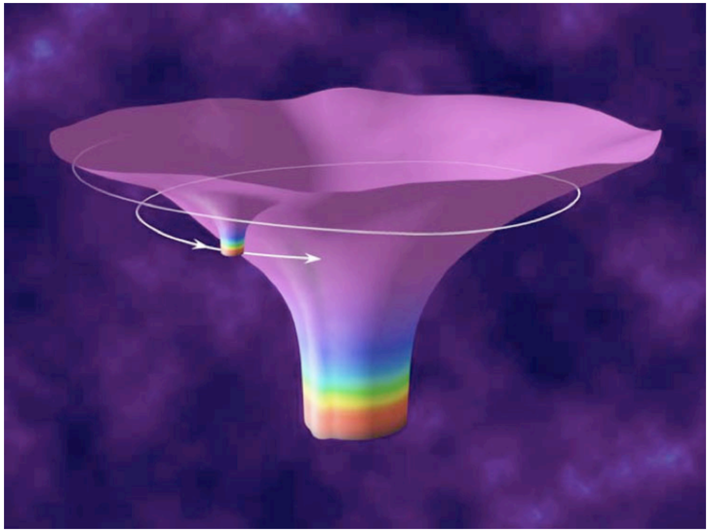
Testing General Relativity with Gravitational Waves from Extreme Mass Ratio Inspirals



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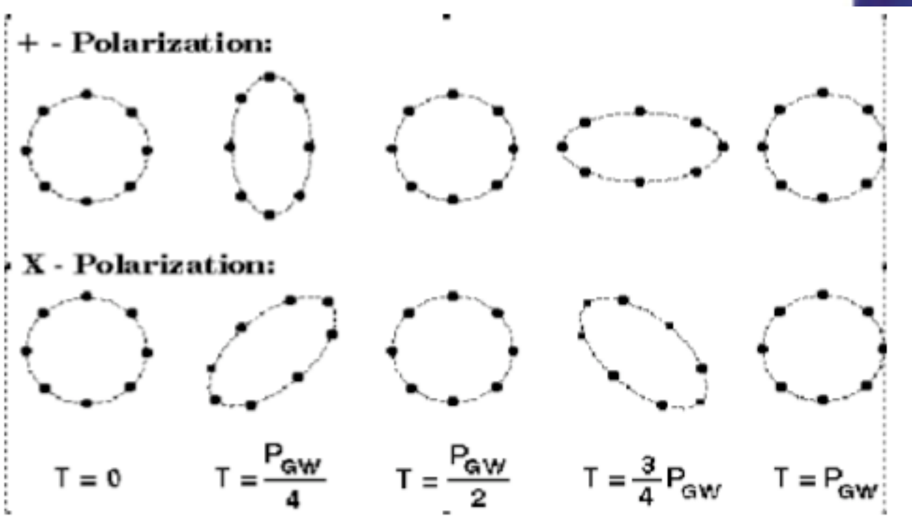
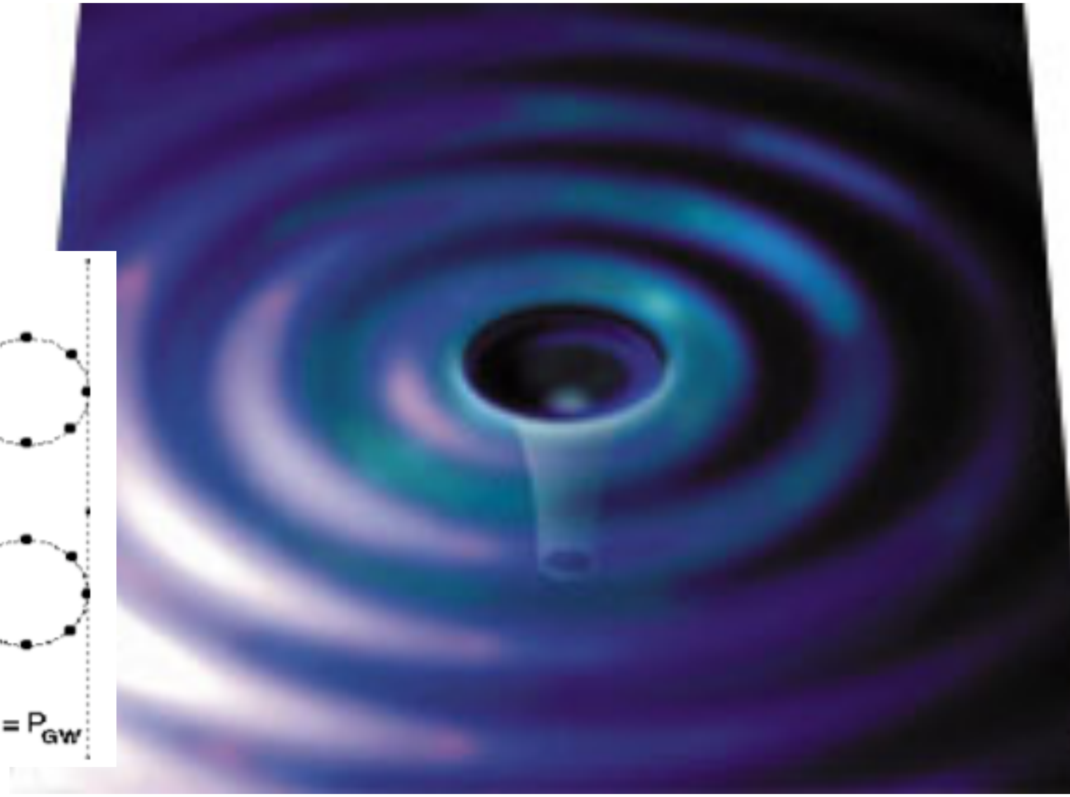
July 20, 2010
COSPAR-10, Bremen

Gravitational Waves

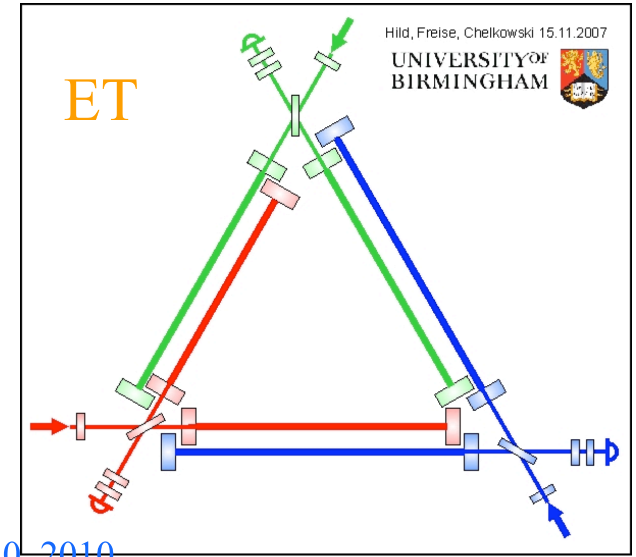
- Ripples in spacetime:

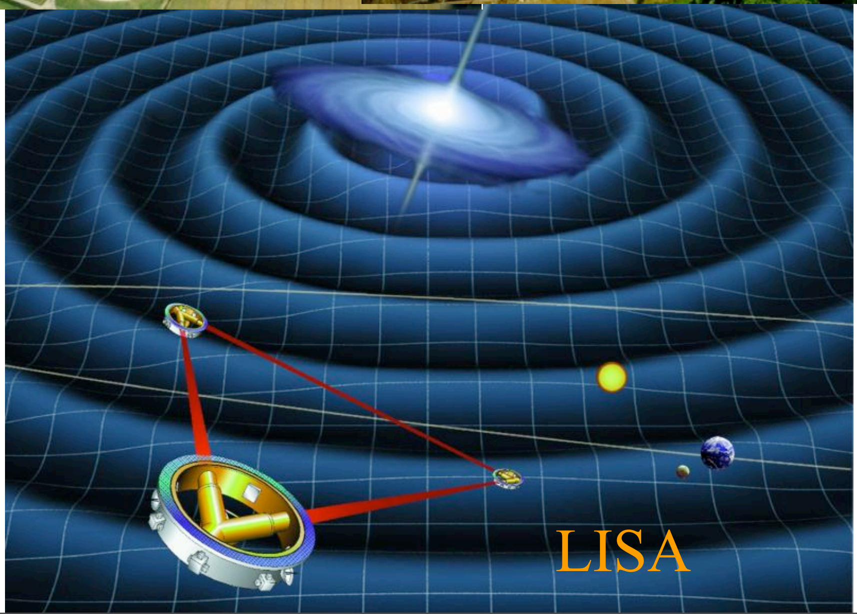




- Caused by time-varying mass quadrupole moment; GW frequency is twice the orbital frequency for a circular, non-spinning binary
- Indirectly detected by Hulse & Taylor: binary pulsar

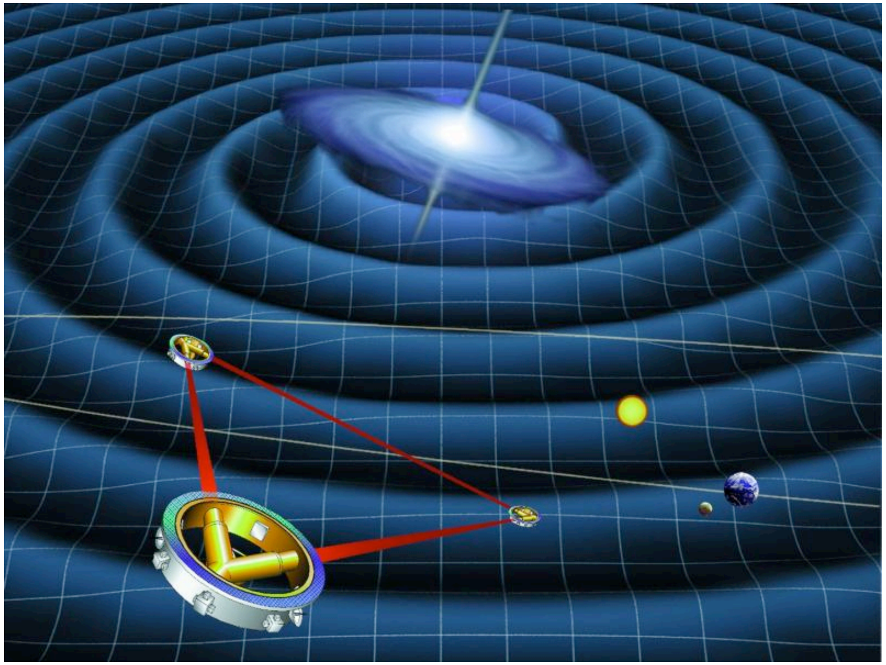
Gravitational-wave observatories



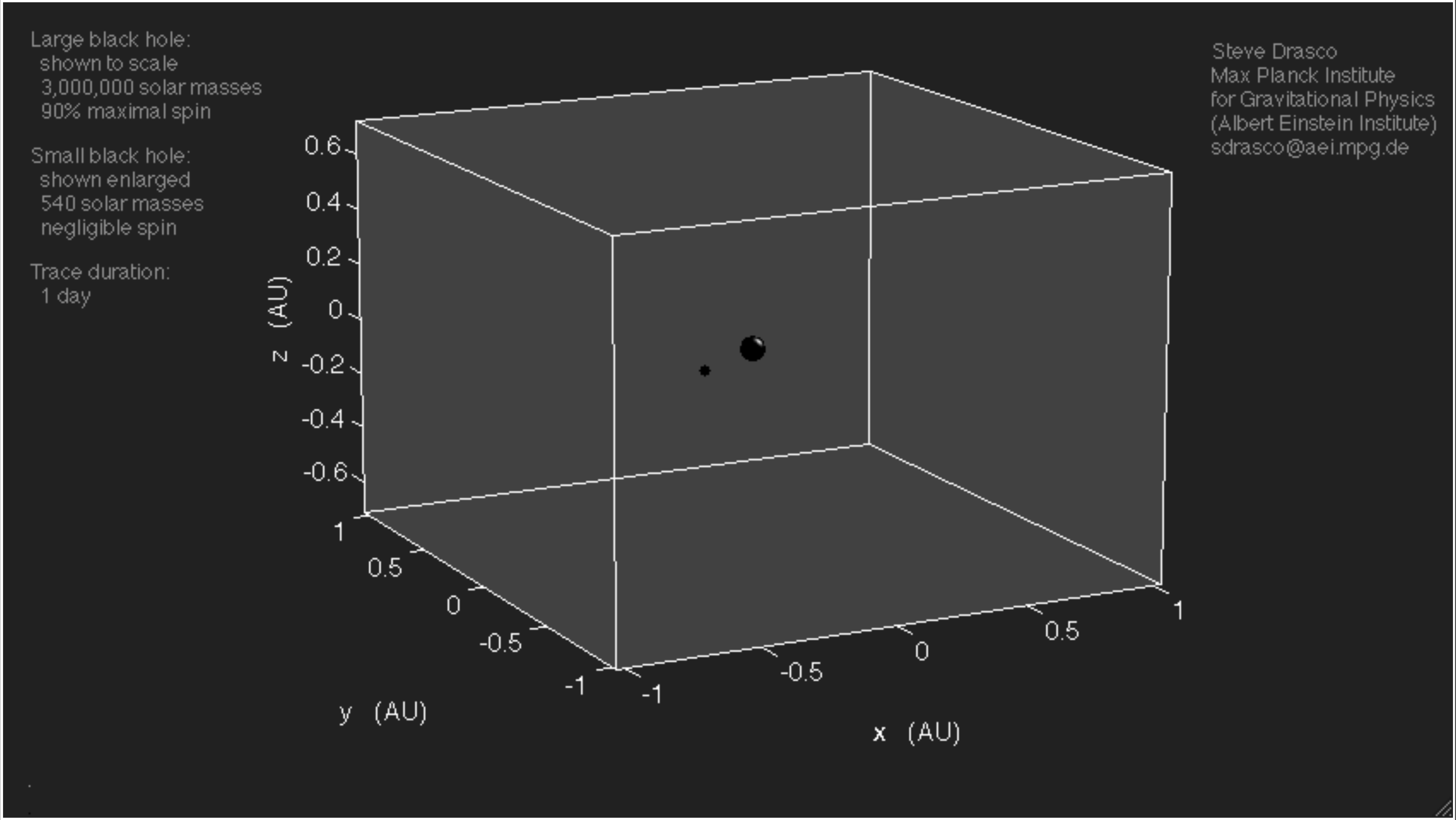


LISA Binary Sources: EMRIs

- 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., Gair et al. 2004; Amaro-Seoane et al., 2007]

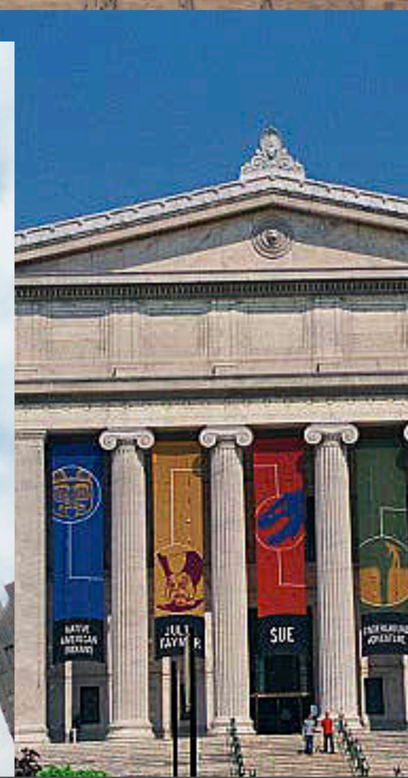


Extreme Mass Ratio Inspirals



Exploring the spacetime...

... taking lots of pictures

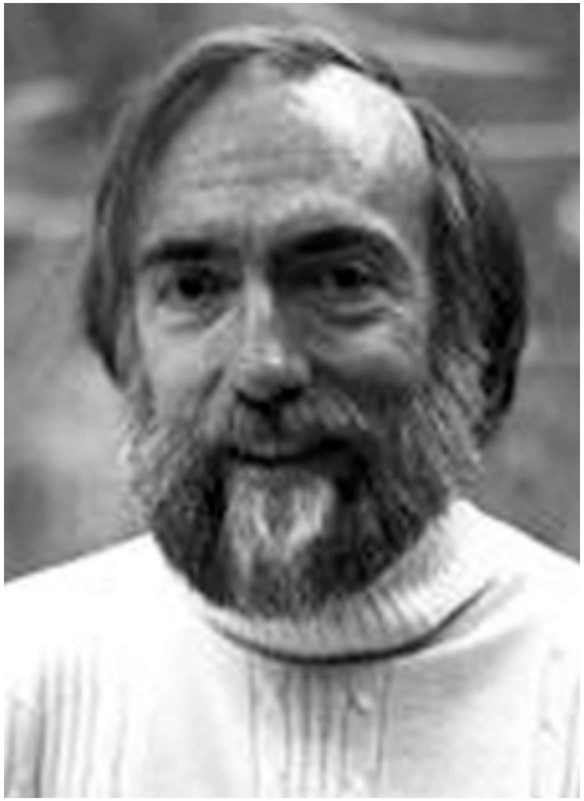


Deviations from Expectations

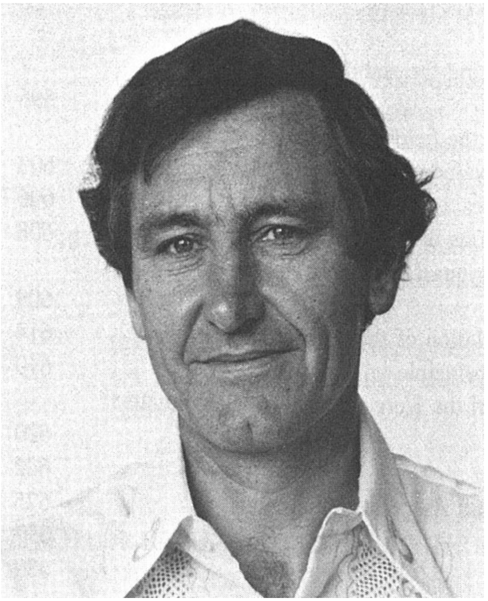
- Dirty EMRIs: Matter (disks, other compact objects) as an astrophysical perturber
  - » Gravitational influence of matter [Barausse et al., 2007]
  - » Hydrodynamic drag [Barausse & Rezolla, 2008]
- GR breaks down
  - » Test specific alternative theories of gravity [e.g., Sopuerta and Yunes, 2009]
  - » Parametrized or phenomenological deviations [e.g., Yunes and Pretorius, 2009; IM et al., in prep.]
  - » Massive gravitons [e.g., Will 1997, Babak & Grishchuk 2003, Berti et al. 2005]
- GR is correct, but the central objects are not black holes
  - » Non-vacuum solutions of Einstein's equations (boson stars, gravistars)
  - » Vacuum solutions that violate some cherished assumptions (e.g., naked singularities)

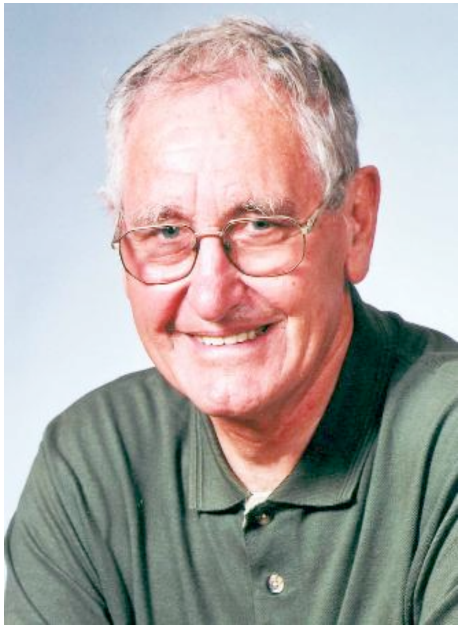
Testing the “no-hair” theorem

Testing the no-hair theorem



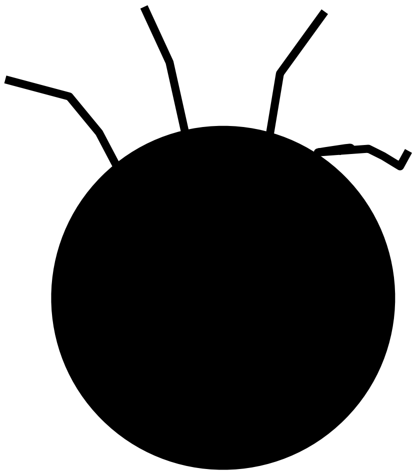
Testing the no-hair theorem?





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?

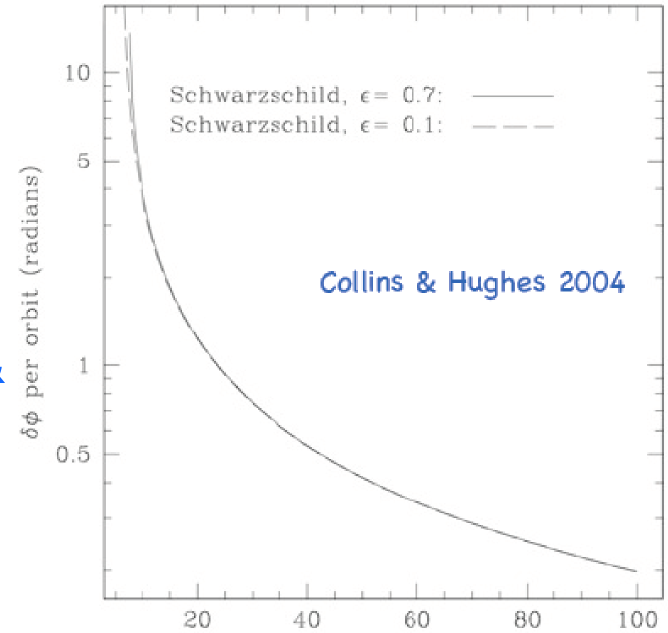


$$M_n + iS_n \neq M(ia)^n$$

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

Bumpy black holes

- Perturbed black holes
  - Perturbed Schwarzschild [Collins & Hughes, 2004]
  - Perturbed Kerr [Vigeland & Hughes, 2009]
  - Quasi-Kerr with slow spins [Glampedakis & Babak, 2006]
  - Kludge pN term due to mass quadrupole [Barack & Cutler, 2007]
  - Ringdown modes [Berti, Cardoso, Will, 2006]
- Exact solution of Einstein's equations



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

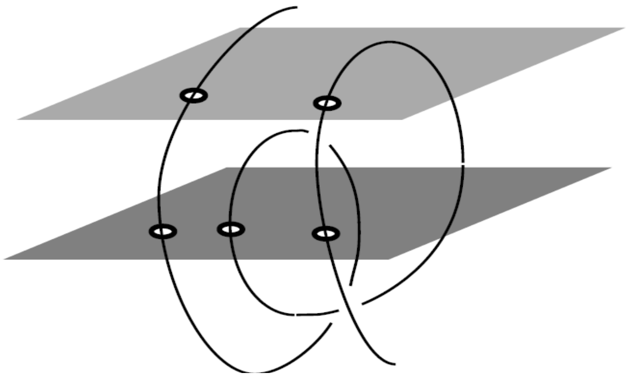
$$ds^2 = -f(\rho,z)\,(dt - \omega(\rho,z)\,d\phi)^2 + \frac{1}{f(\rho,z)}\left[e^{2\gamma(\rho,z)}\,(d\rho^2 + dz^2) + \rho^2\,d\phi^2\right]$$

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

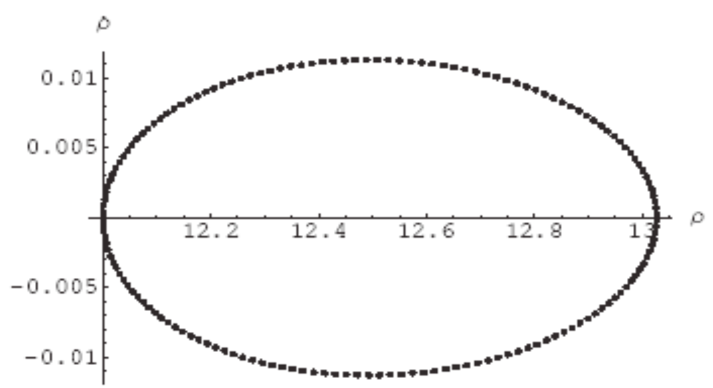
Solve the geodesic equation
and study Poincare maps:

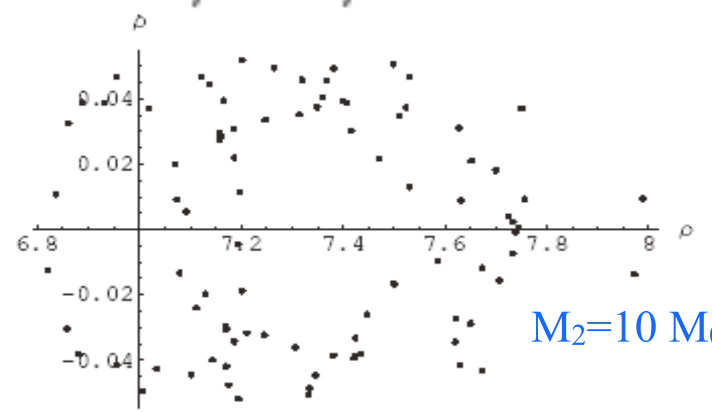
$$\frac{\partial^2 x^\alpha}{\partial \tau^2} = -\Gamma^\alpha_{\beta\gamma} \frac{\partial x^\beta}{\partial \tau} \frac{\partial x^\gamma}{\partial \tau}$$



- 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]

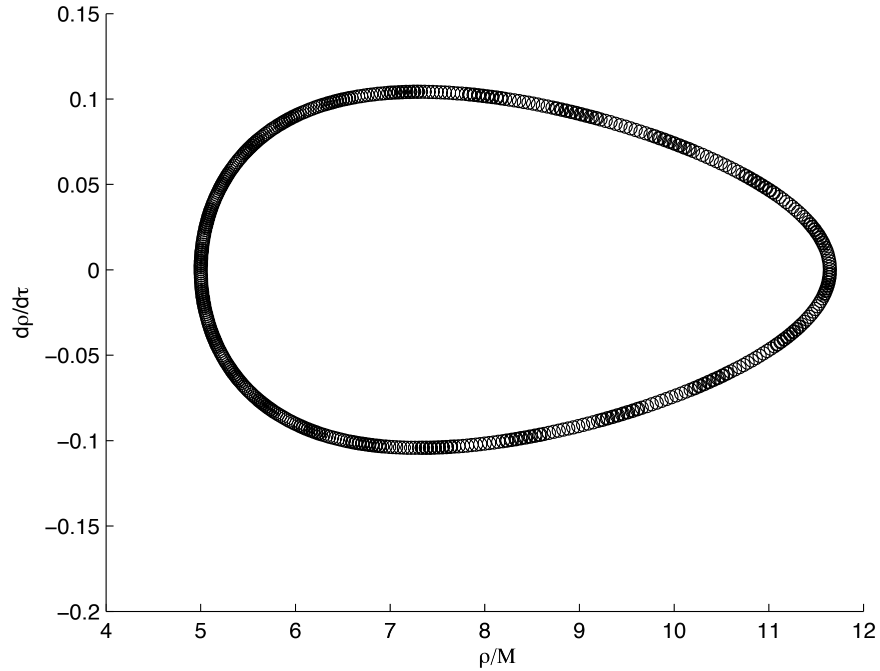
Newtonian+hexadecapole: $V(r,\theta) = -\frac{M_0}{r} + \frac{M_2}{r^3} P_2(\cos\theta) + \frac{M_4}{r^5} P_4(\cos\theta)$





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

All is regular in "bumpy" spacetimes

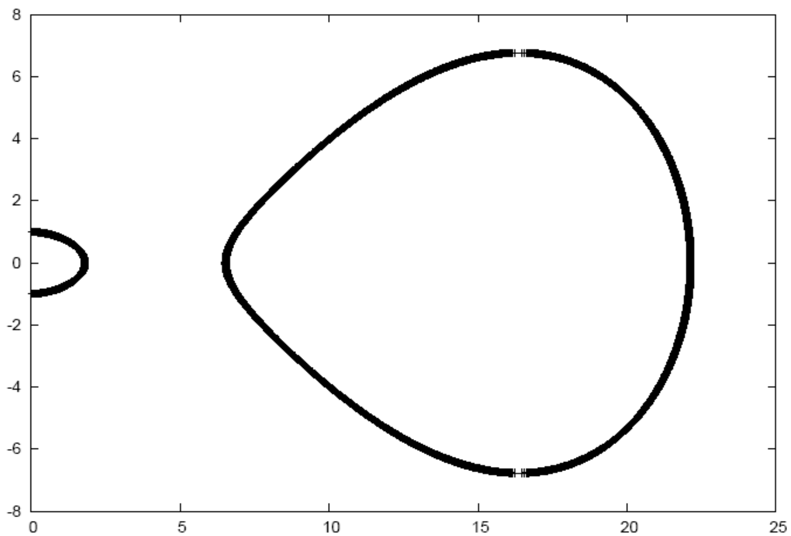


Poincare map for E=0.95, L_z=-3, a/M=0.9, q=0.95

Or is it?...

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

z



ρ

z

ρ

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

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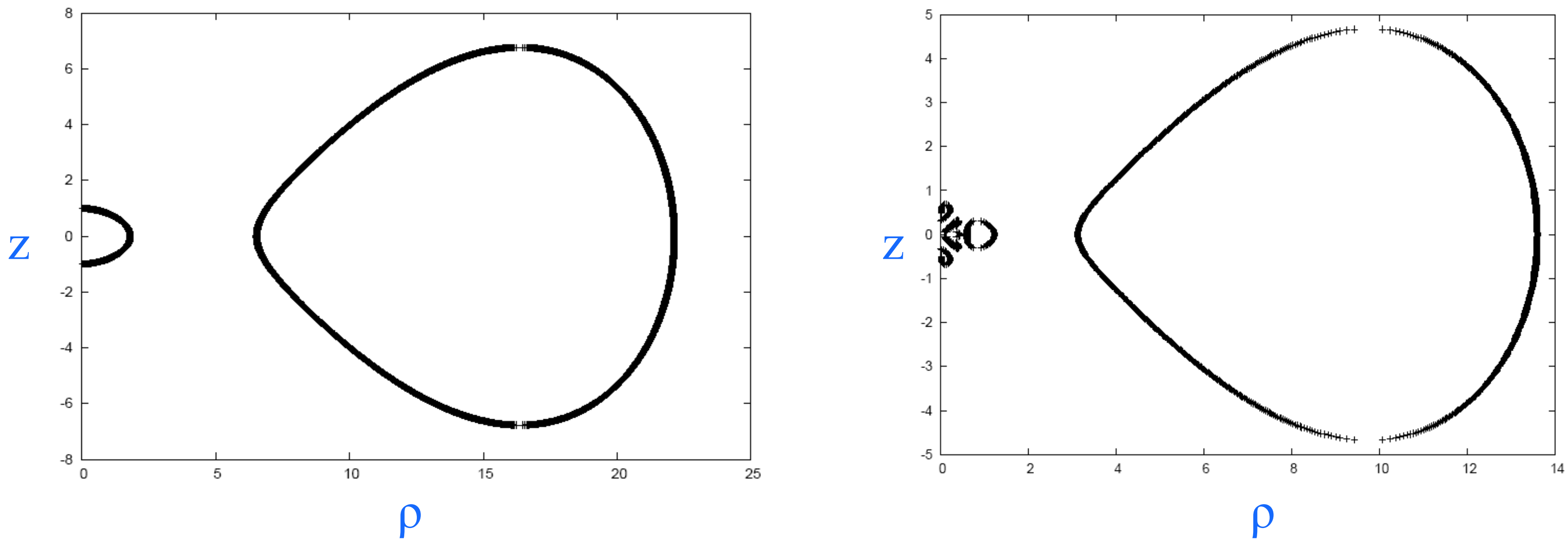


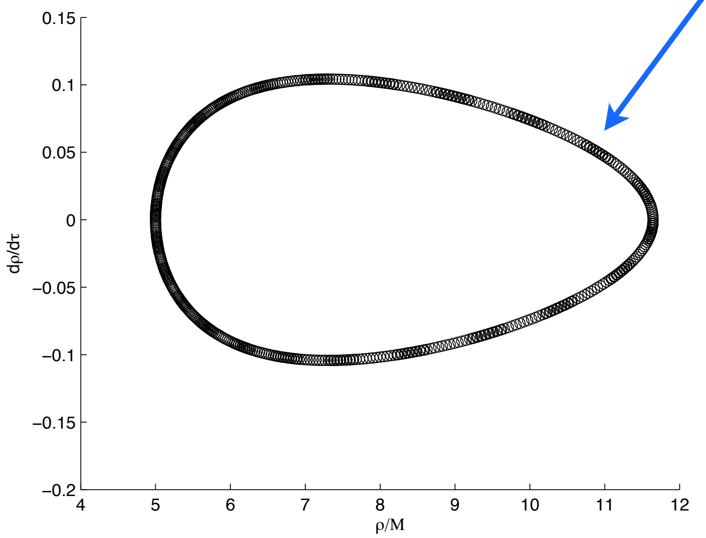
E=0.95, L_z=-3, a/M=0.9, q=0

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

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

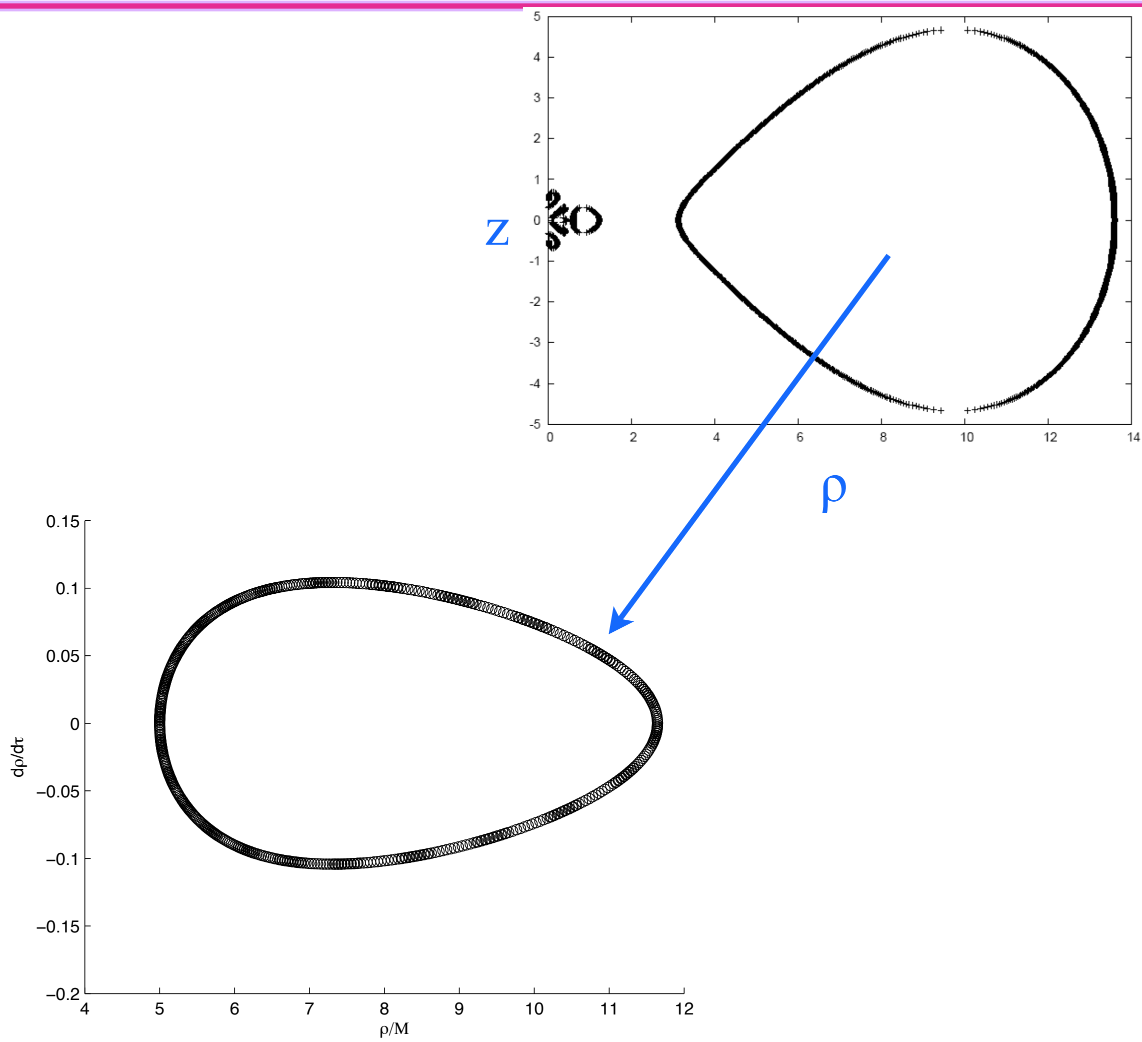
z

ρ



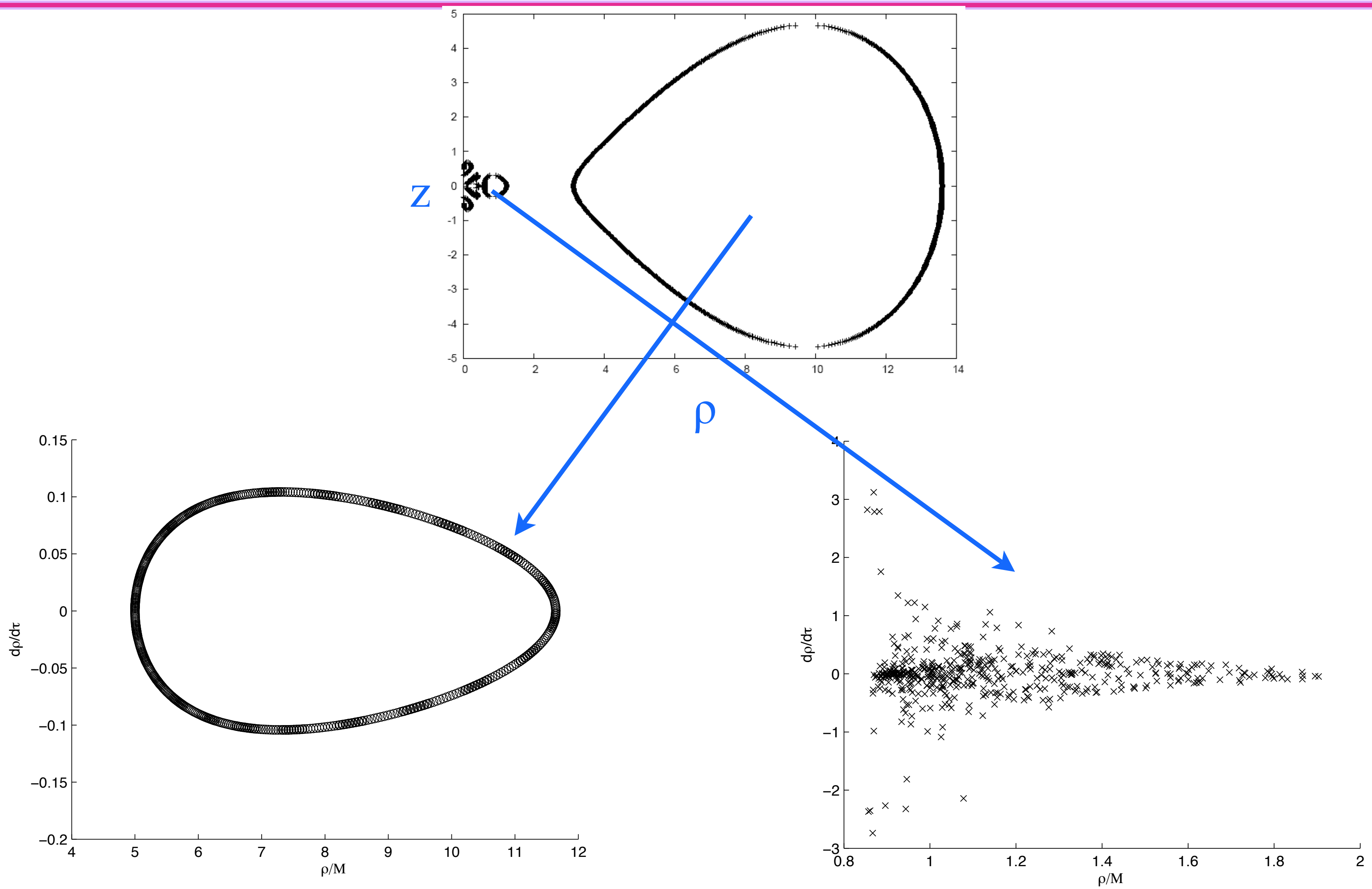
$E=0.95$, $L_z=-3$, $a/M=0.9$, $q=0.95$

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



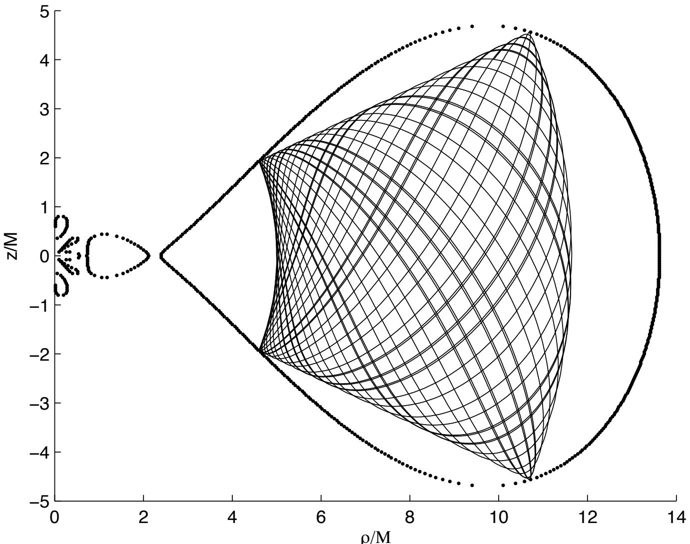
$E=0.95$, $L_z=-3$, $a/M=0.9$, $q=0.95$

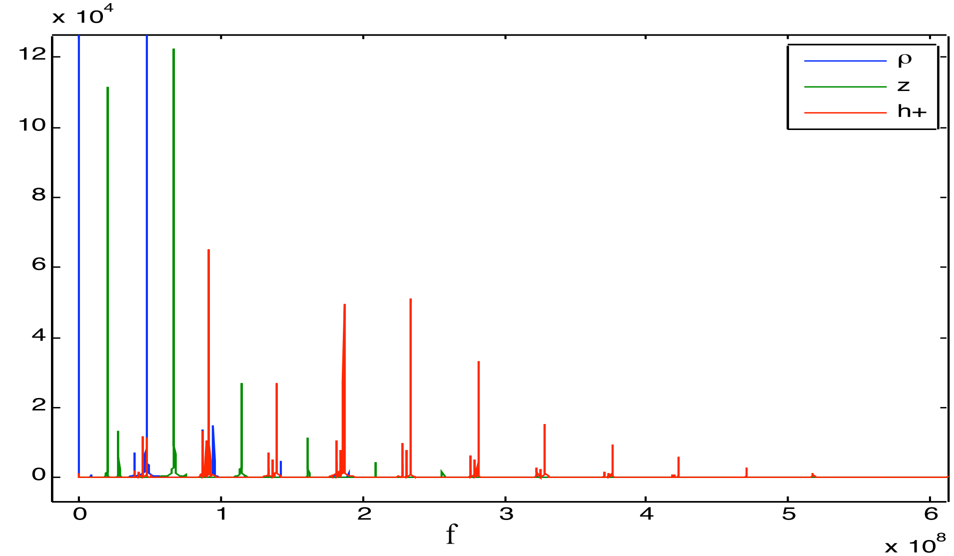
It's a mad, mad, mad, mad geodesic

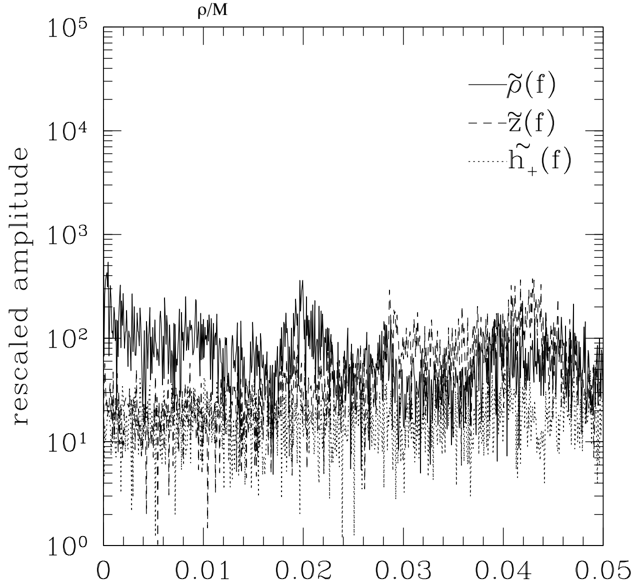


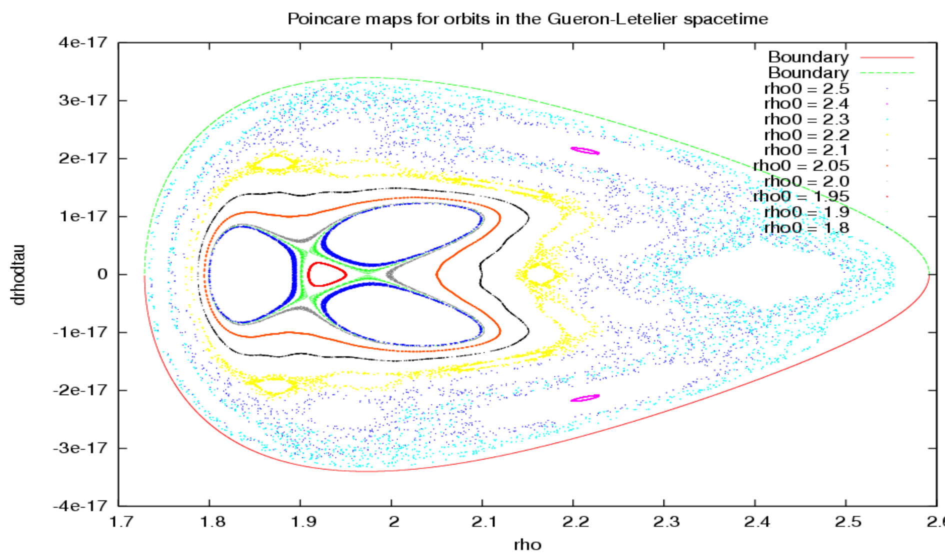
$E=0.95,\ L_z=-3,\ a/M=0.9,\ q=0.95$

Order and Chaos, side by side



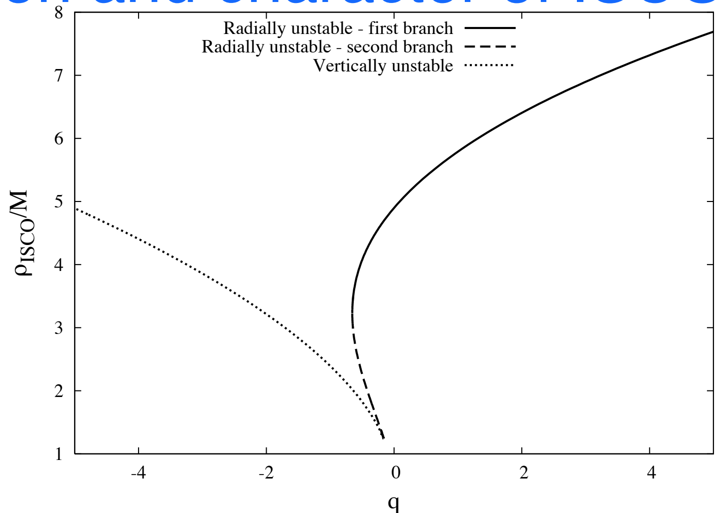


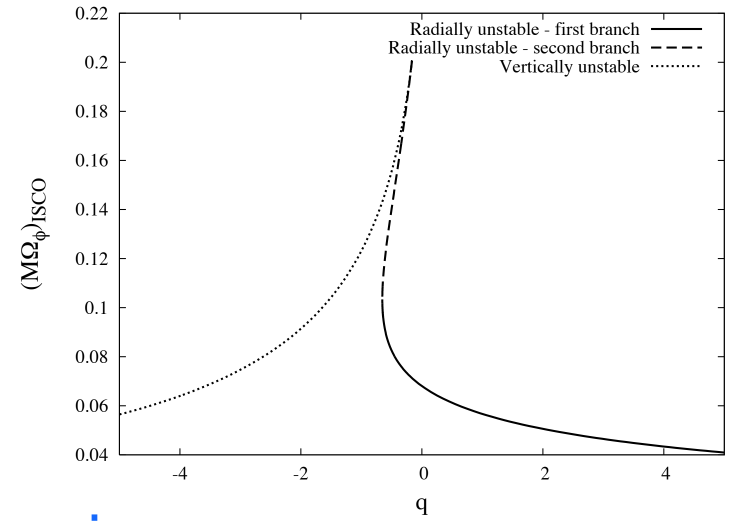




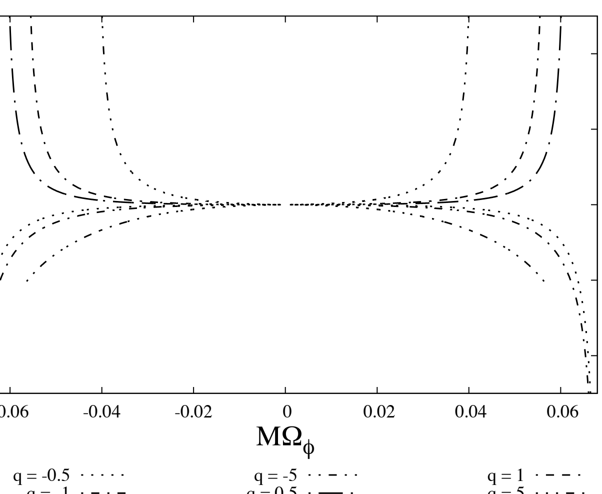
Other signs of non-Kerr spacetimes

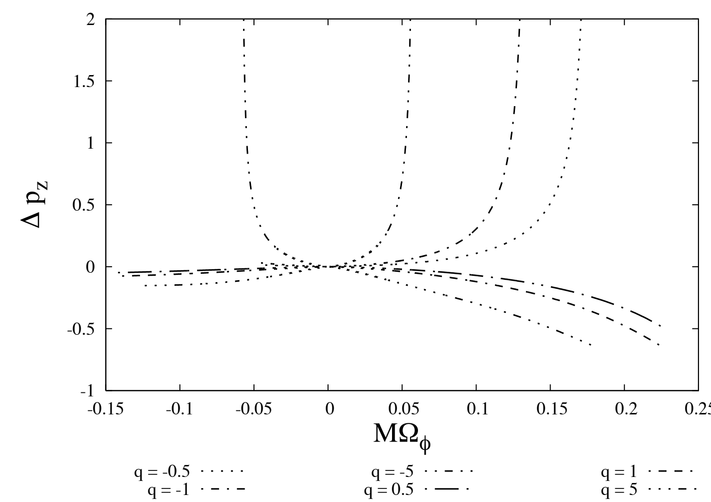
- Location and character of ISCO



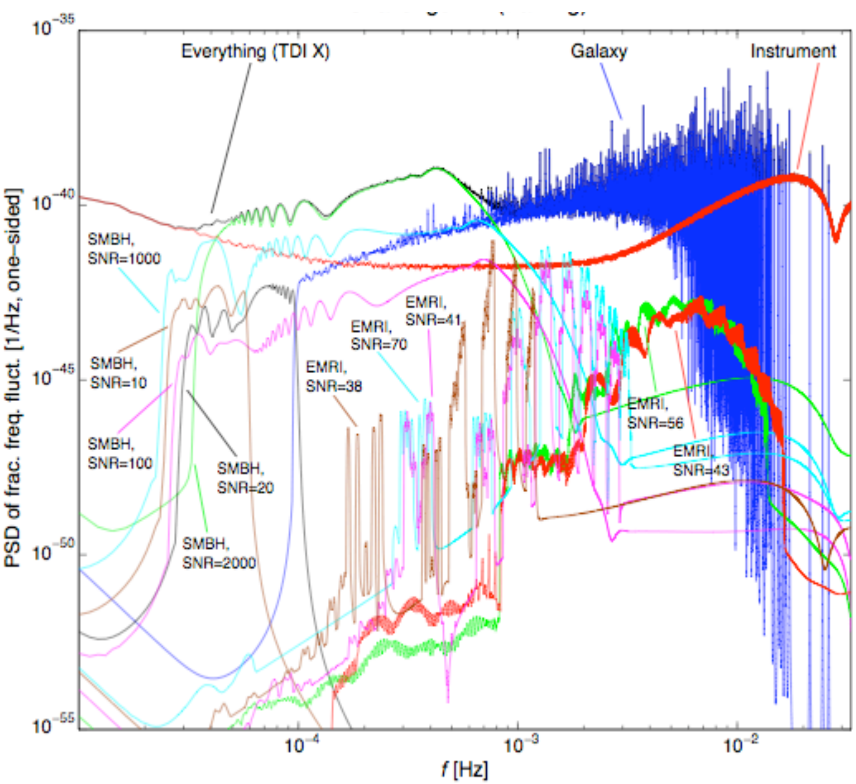


- Periapsis and orbital-plane precession





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 ✓

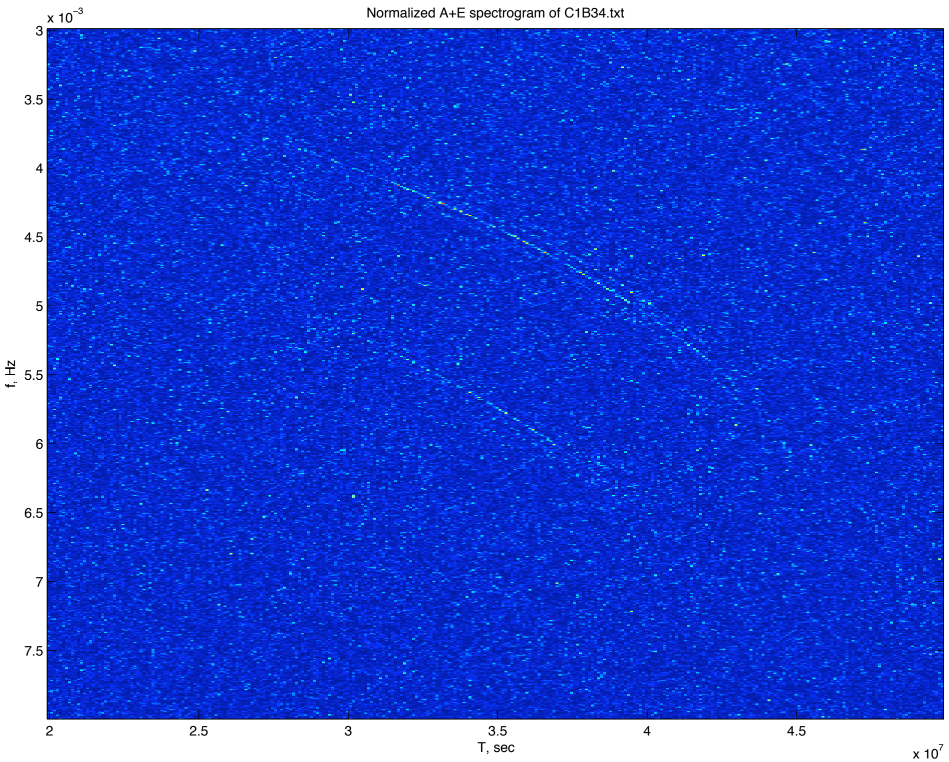
Table by M. Vallisneri

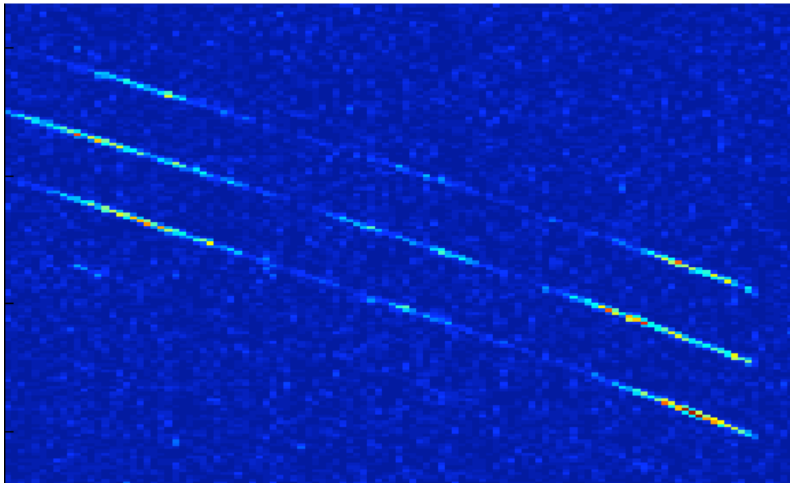
Mock LISA Data Challenges;
LISA Parameter-Estimation task force

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



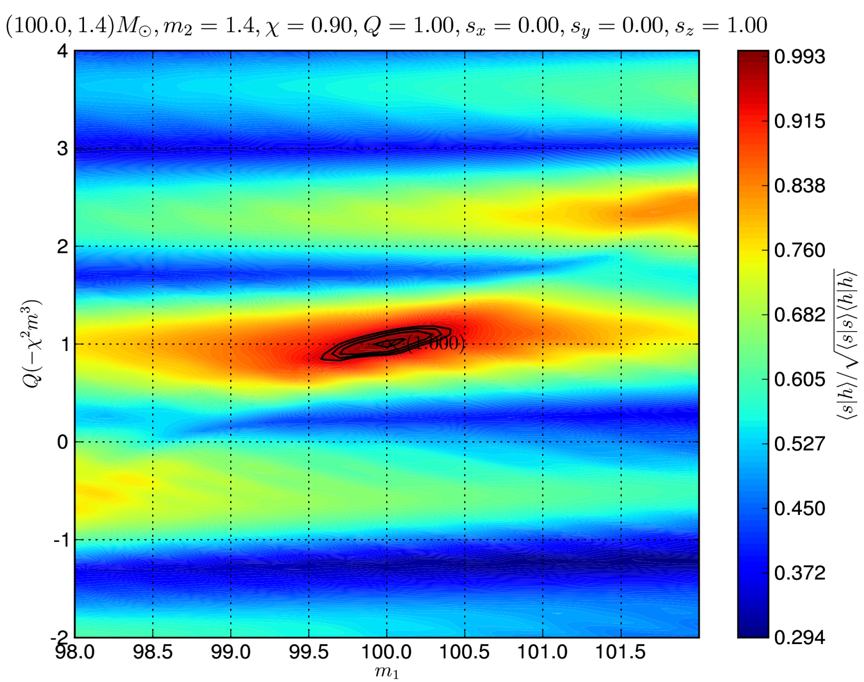


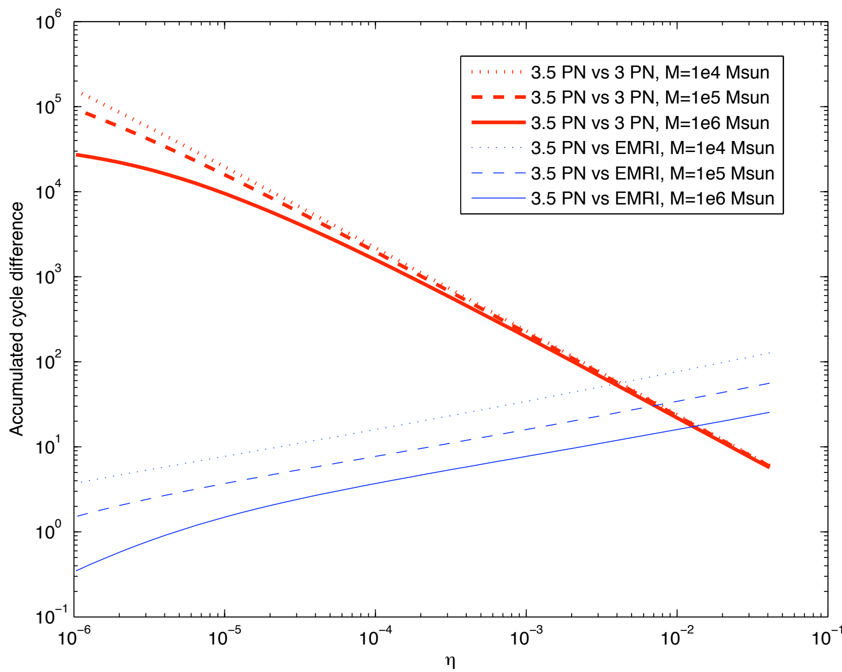
[Gair, IM, Wen, 2008, CQG 25 184031]

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

- Extreme- or intermediate- mass-ratio inspirals are great probes of strong gravity
- They give us an opportunity to test General Relativity
- Focus on null-hypothesis tests: are the massive, compact objects consistent with being Kerr black holes?
- Several smoking guns are possible, from the emergence of chaos to changes in the frequencies and characteristics of the ISCO and precessions