Science applications of gravitational wave observations of EMRIs

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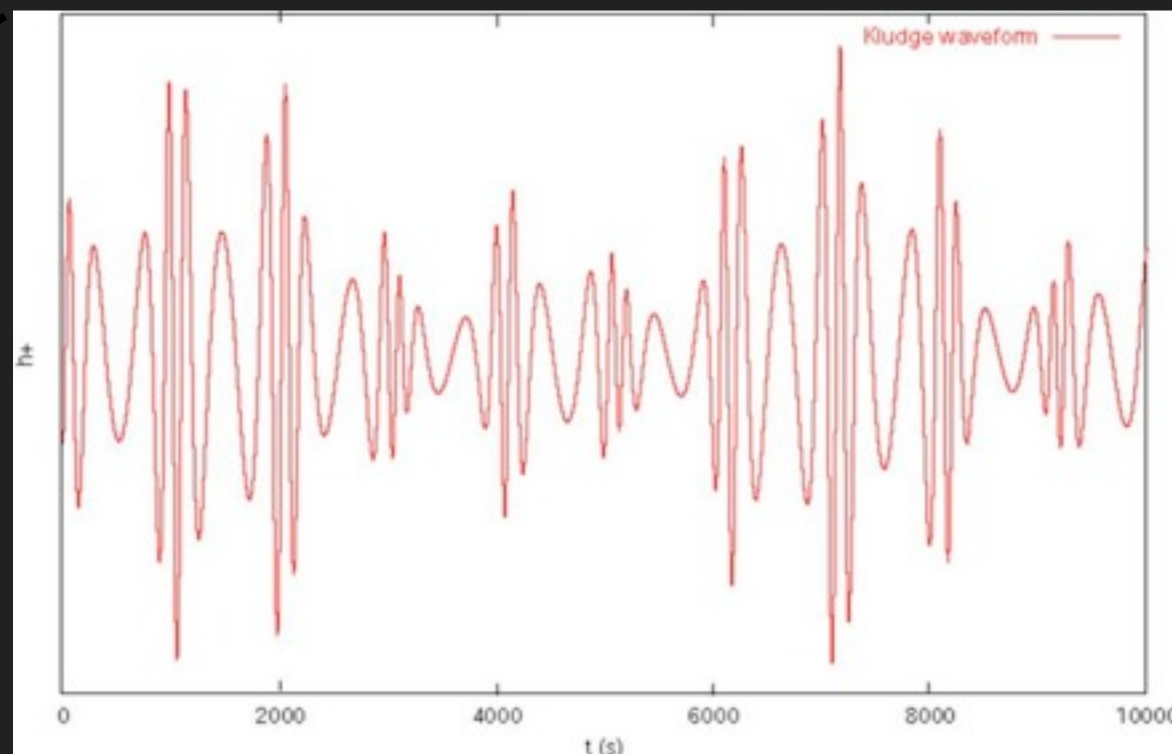
Weizmann Institute, December 10th 2009



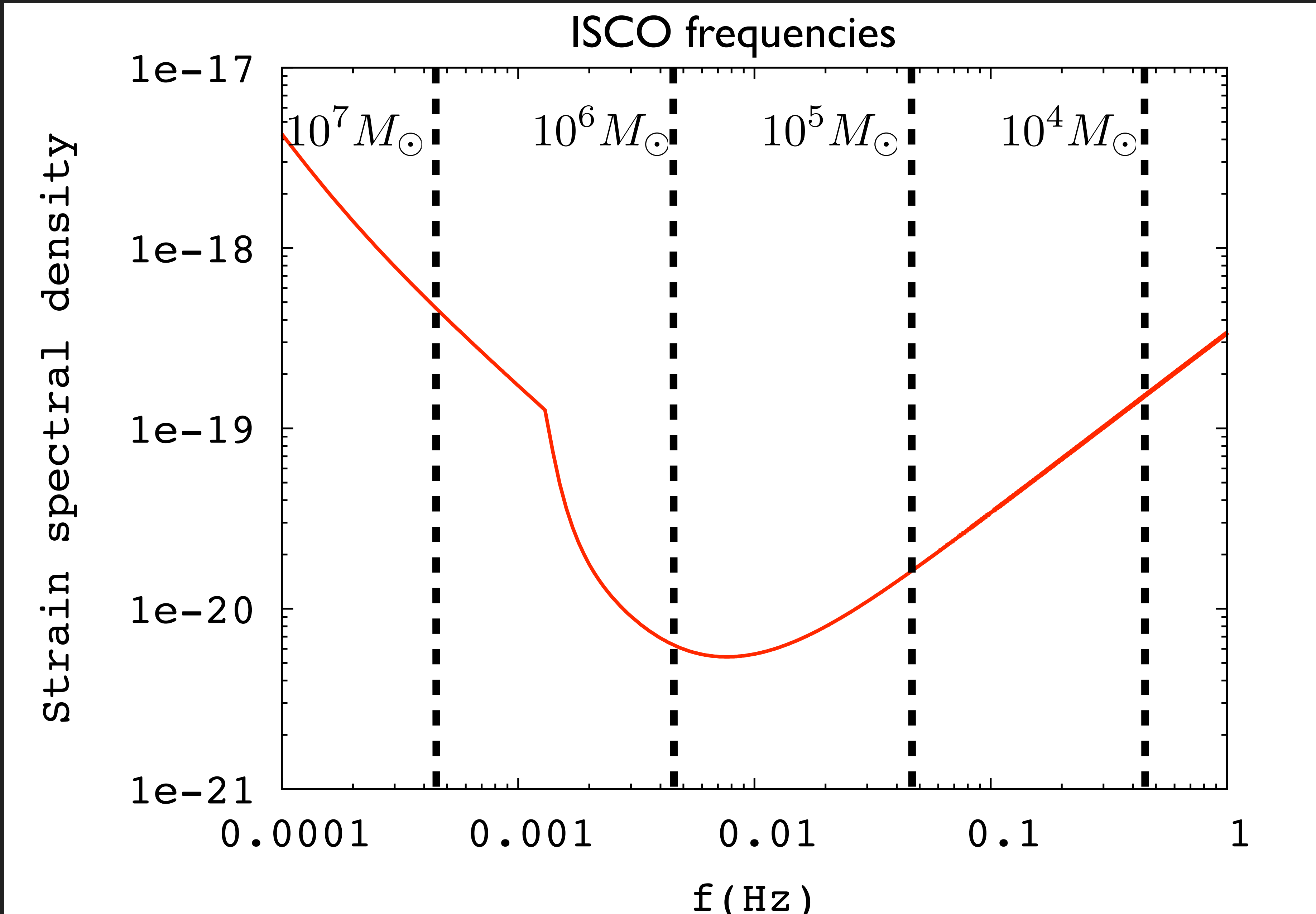
Talk Outline

- Extreme mass ratio inspirals (EMRIs) - waveform properties etc.
- Scientific applications of EMRI detections to
  - **Astrophysics**
  - **Cosmology**
  - **Fundamental Physics**
- Data analysis
- Source modelling
- Summary

Extreme mass ratio inspirals

- An extreme mass ratio inspiral (EMRI) is the inspiral of a compact object (a white dwarf, neutron star or black hole) into a SMBH. Main sequence stars tidally disrupted before gravitational radiation becomes significant.
- Focus on last few years of inspiral when evolution dominated by gravitational wave emission.
- Originate in dense stellar clusters through direct capture, binary splitting, star formation in a disc etc. (see Miller talk).
- For black holes with mass in the range $10^4 M_\odot - 10^7 M_\odot$, EMRIs generate gravitational waves detectable by LISA. Mass range set by sensitivity of the detector.

Extreme mass ratio inspirals



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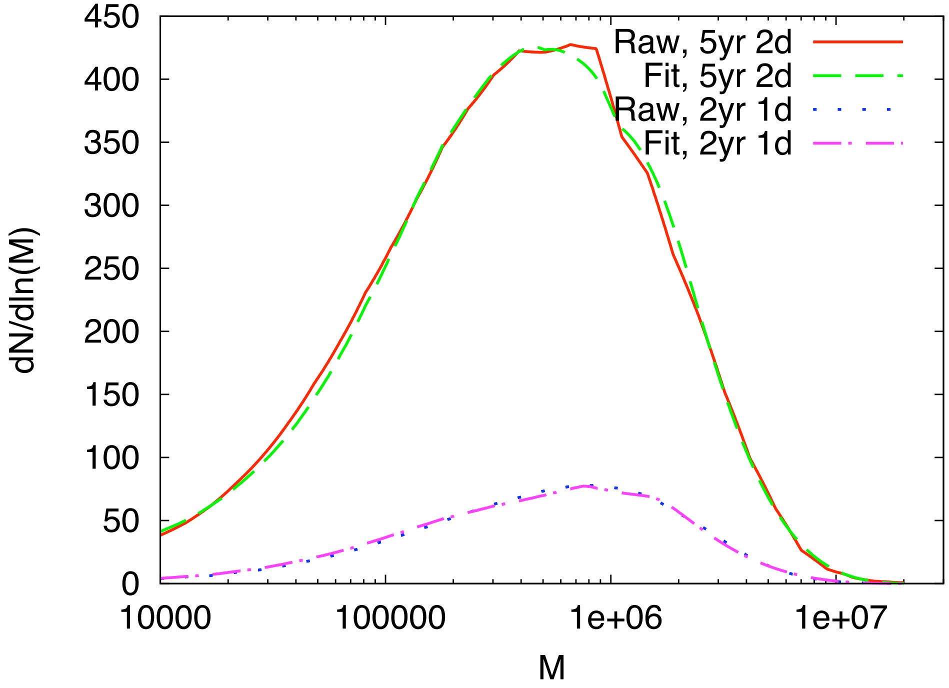
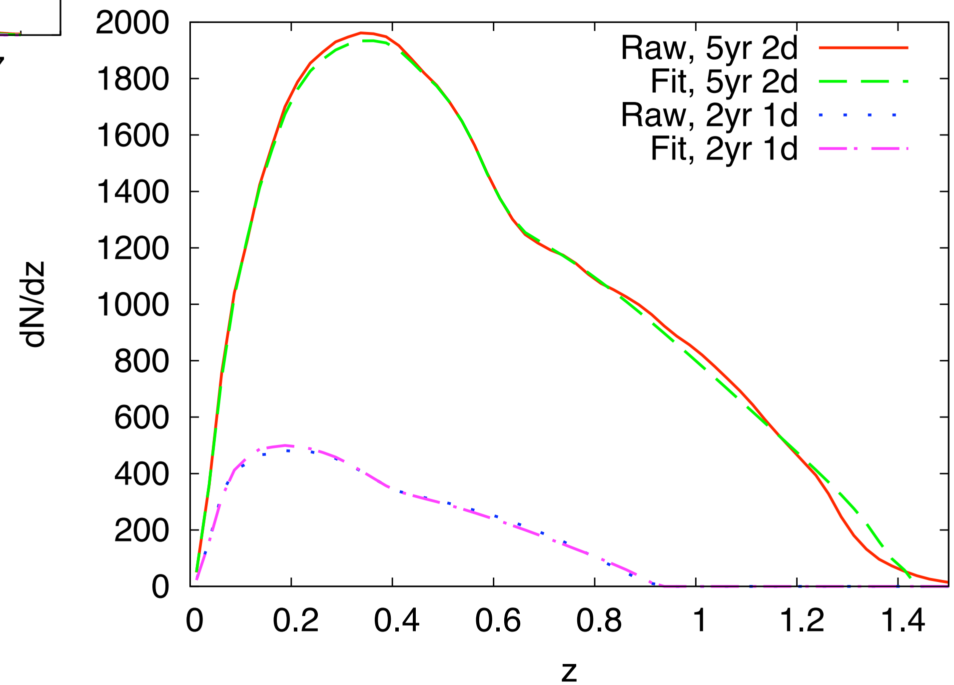
- For black holes with mass in the range $10^4 M_\odot - 10^7 M_\odot$, EMRIs generate gravitational waves detectable by LISA. Mass range set by sensitivity of the detector.
- LISA will see between a few tens and a few thousand events, at redshift $z \lesssim 1.5$. Overwhelming majority will be BH inspirals.

Extreme mass ratio inspirals





Extreme mass ratio inspirals

- Gravitational wave radiation is emitted when the object is in the strong field region of the spacetime close to the black hole.
- Inspiral is relatively slow - expect ~100,000 waveform cycles over last year before plunge.
- Expect orbits to be both eccentric and inclined to the equatorial plane of the central black hole - object explores much of the spacetime as it inspirals.
- Complex gravitational waveforms include three fundamental frequencies - orbital frequency, perihelion precession frequency and orbital plane precession frequency.
- This reflects the "zoom and whirl" nature of the source orbits.

Science applications of EMRIs - astrophysics

- EMRI detections allow accurate parameter measurement (Barack & Cutler 04, Huerta & JG 09)

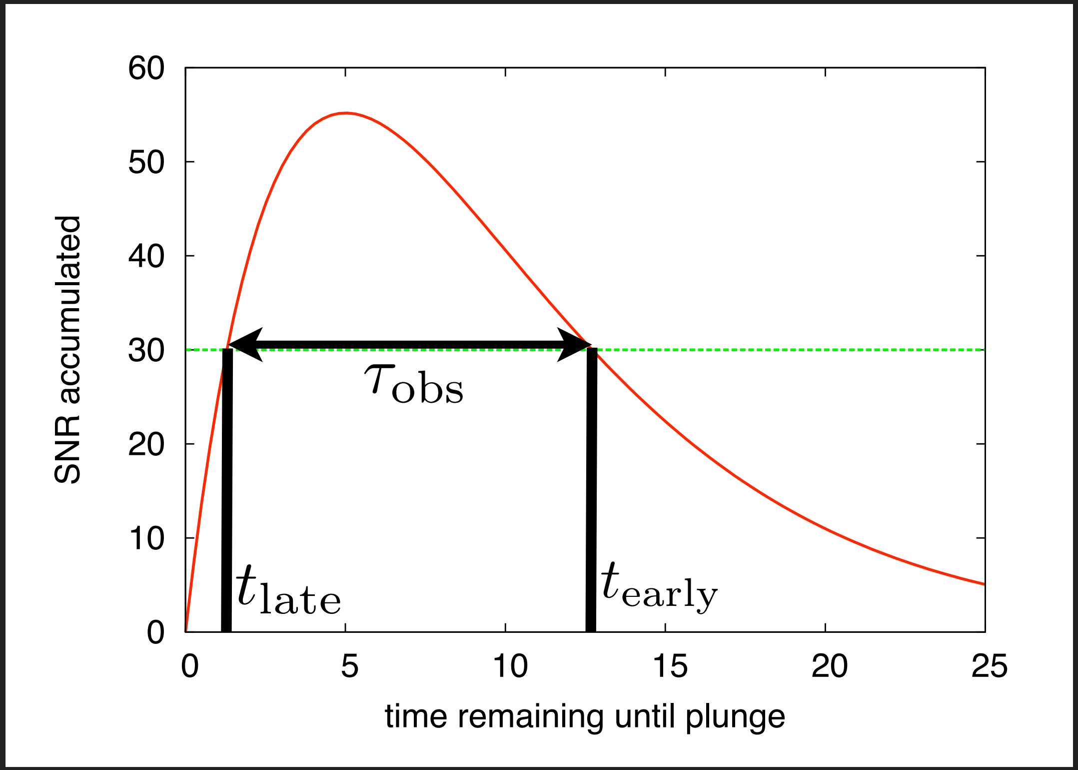
$$\Delta M, \Delta(S/M^2), \Delta(\ln m) \sim 10^{-4}$$

$$\Delta(\ln D) \sim 0.05, \Delta\Omega_S \sim 10^{-3}, \Delta e \sim 10^{-4}$$

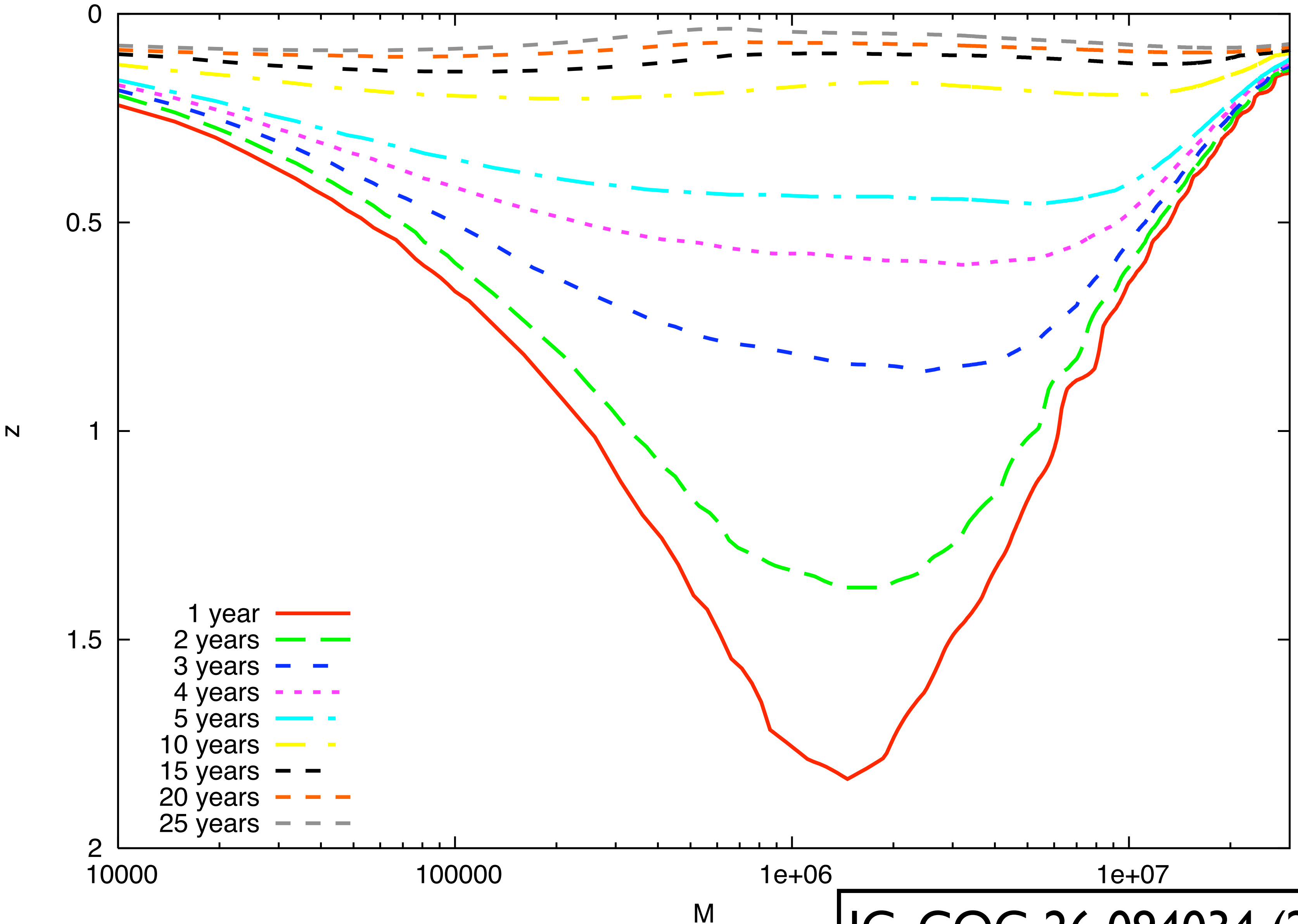
- What can the set of observed EMRI events tell us?
  - Properties of SMBHs at low redshift.
  - Properties of dense stellar cluster.
- EMRIs start stochastically in a given galaxy - particular model predicts intrinsic rate at which events occur.
- *Observed* rate is product of intrinsic rate and LISA selection function.

Selection Effects

- Need certain signal-to-noise to detect an event. Not detectable if LISA turns on *too early* or *too late* in an inspiral.
- Define *observable lifetime*, $\tau_{\rm obs}$, as length of time during which LISA could start taking data and event be observed.
- Rate of observed events is then $\tau_{\rm obs}/T$, where T is average time between plunges.

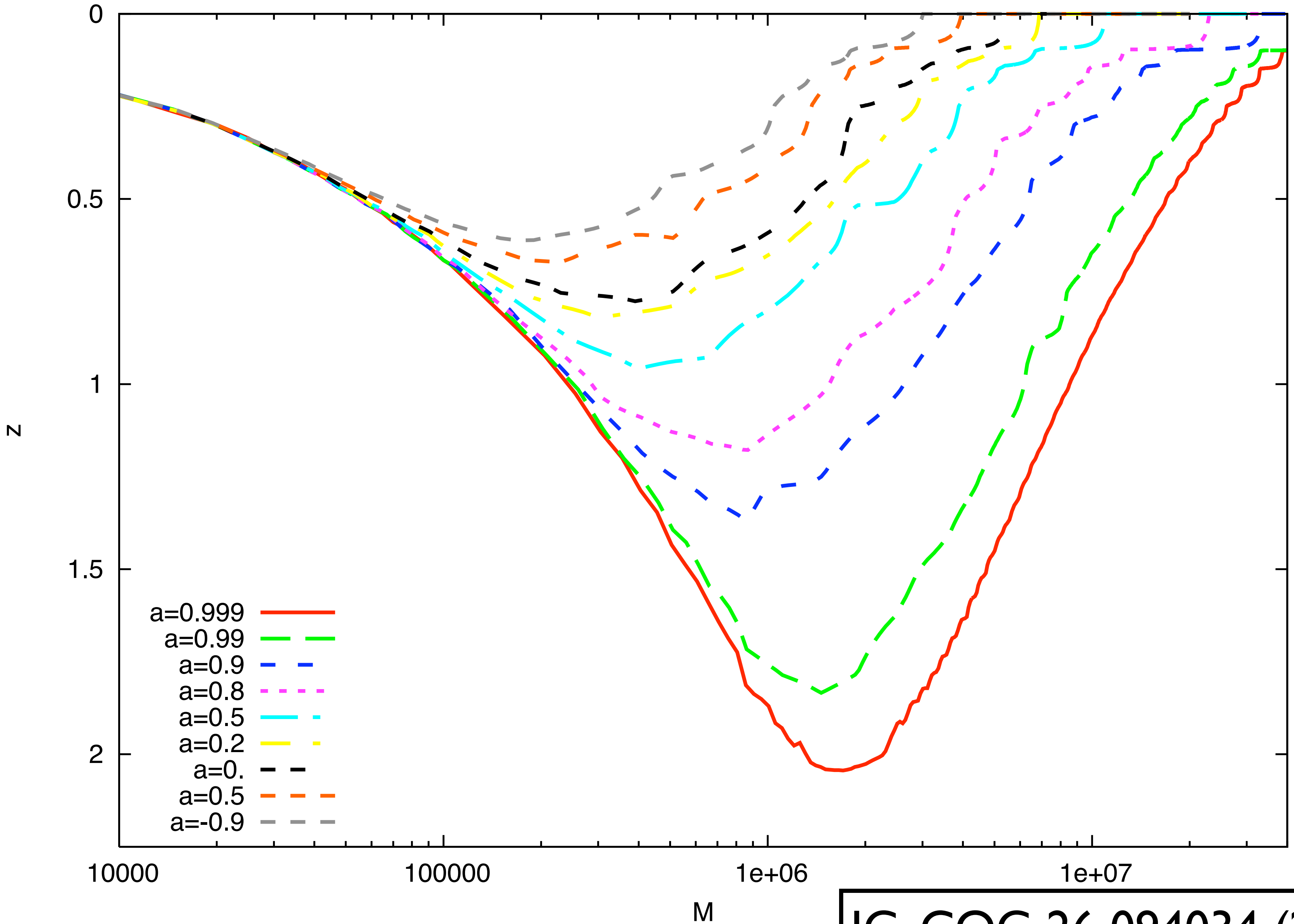


Selection Effects



JG, CQG 26 094034 (2009)

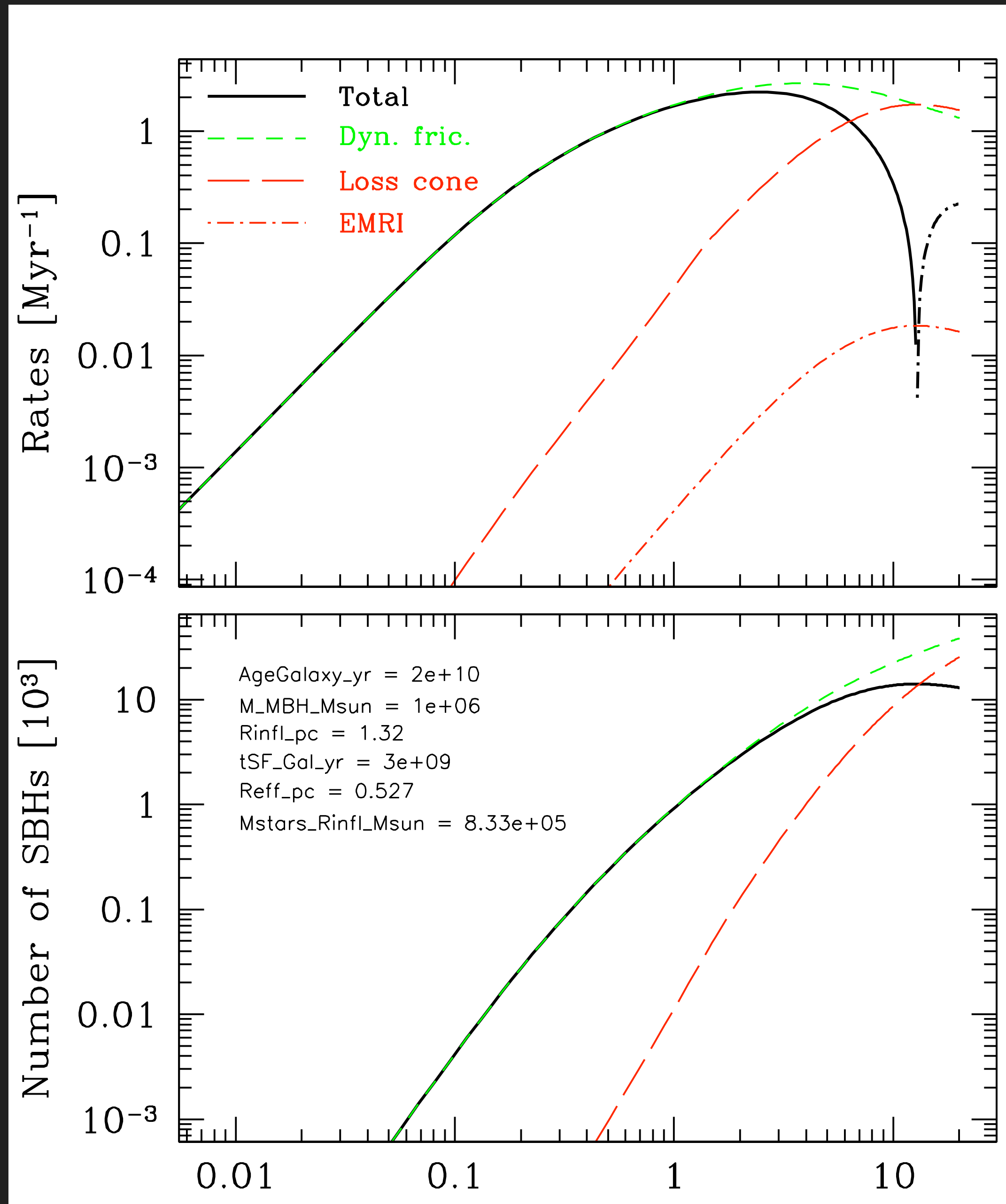
Selection Effects



JG, CQG 26 094034 (2009)

Intrinsic EMRI rate

- Astrophysical rate of events depends on two quantities
  - Number of black holes with particular mass, spin etc.
  - Rate at which EMRIs start in given black hole system
- The latter is poorly known at present, but we can try to model it via
  - Fokker-Planck integration (Hopman 2009).
  - Analytic approximation (Amaro-Seoane, Freitag & JG in prep.; see PAS talk).



Black Hole Mass Function

- Assuming scaling with BH mass is known, can use LISA events to probe BH mass function, which is well fit by

$$dn/d\log M = AM^{\alpha}/(B+M^{\beta})$$

- Not well constrained in LISA range - use simple power law

$$dn/d\log M = AM^{\alpha}$$

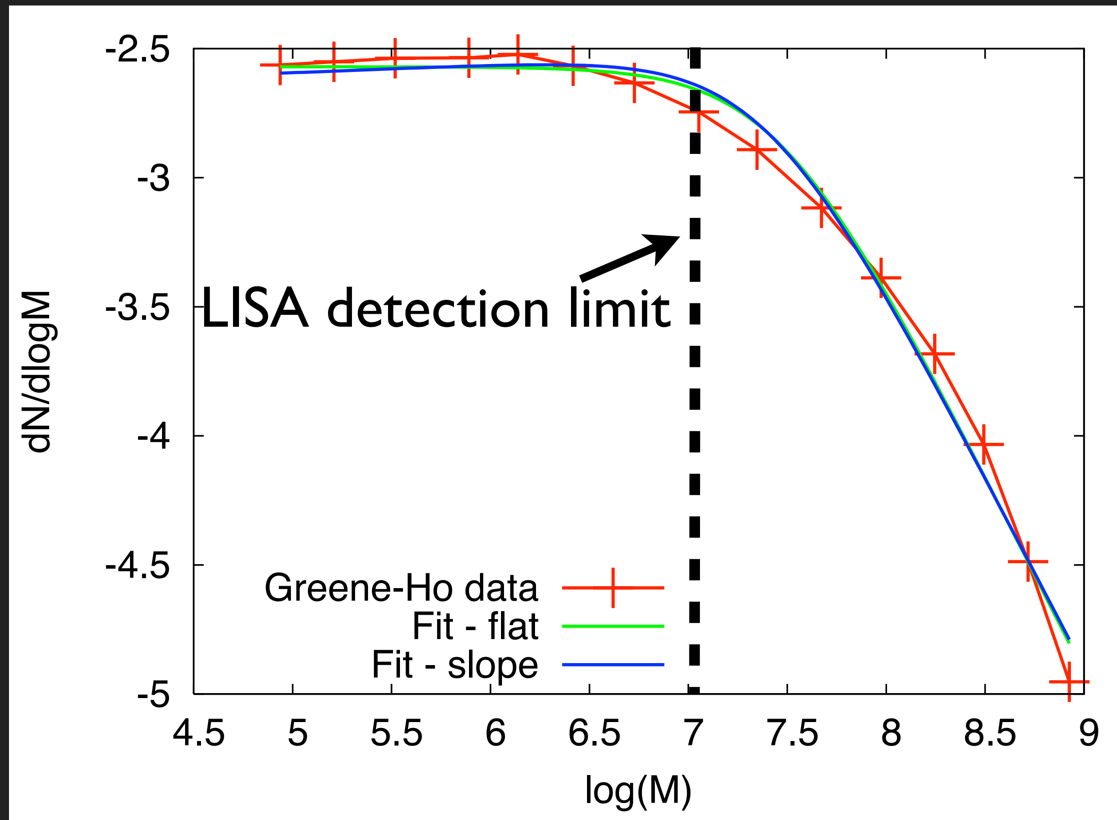
- Consider both redshift independent case

$$A = A_0,\ \alpha = \alpha_0$$

- and redshift dependent

$$A = A_0 - A_1 z,\ \alpha = \alpha_0 - \alpha_1 z$$

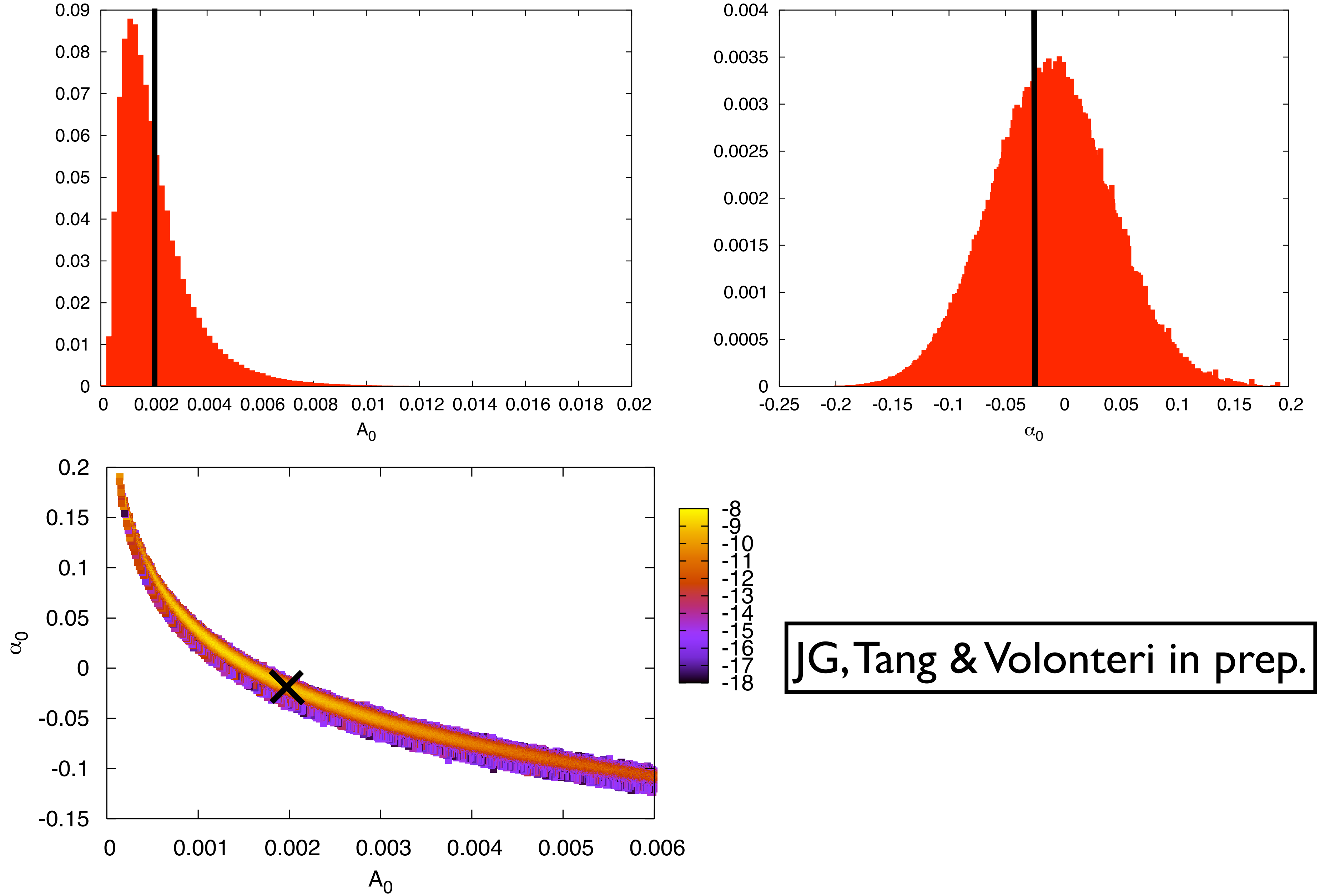
- Explore posterior using Bayesian methods - MCMC.



JG, Tang & Volonteri in prep.

Data from Greene & Ho (2007)

Astrophysical Inference using EMRIs



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Wednesday, 23 December 2009

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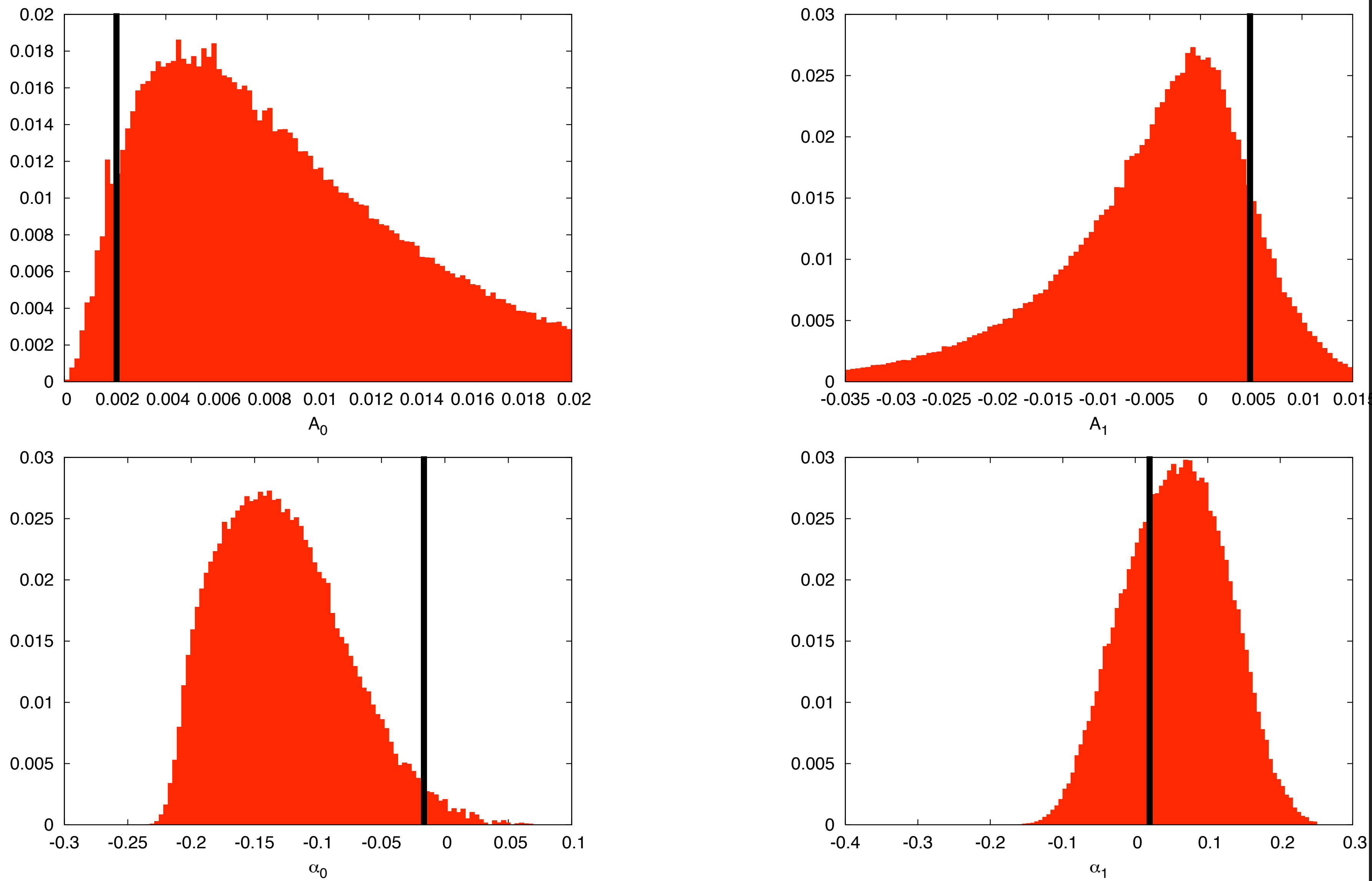

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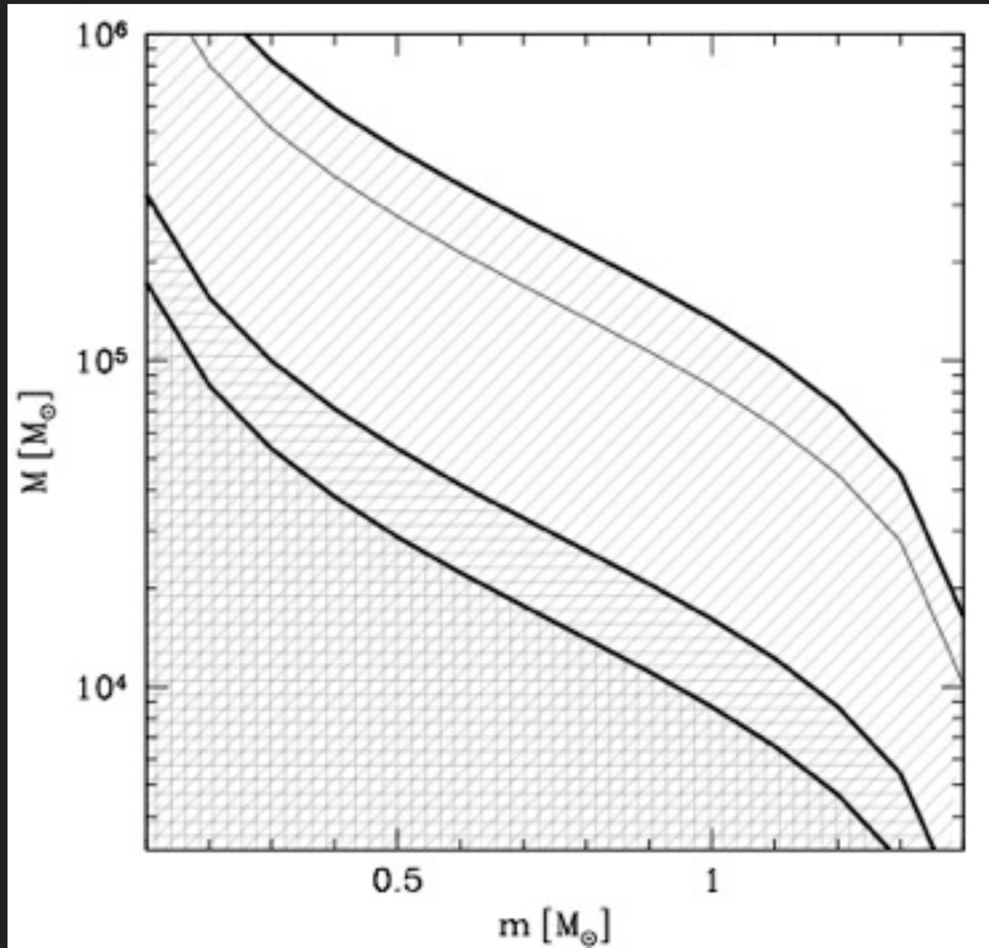
Astrophysical Inference using EMRIs

- Extreme-mass-ratio inspirals can also tell us about
  - **Black hole spins**
  - **EMRI formation mechanisms**: eccentricity and inclination of events tell us about formation channels
  - **Dense stellar clusters**: IMF, mass segregation etc.
- More powerful constraints can be derived from combined observations
  - **LISA SMBH mergers**: SMBH mergers probe BHs at high redshift cf. EMRIsat low redshift.
  - **Electromagnetic observations**: population statistics or simultaneous observations.

EMRI science - probe of white dwarfs

- A white dwarf EMRI into a low mass black hole could end in tidal disruption (Sesana et al. 2008).
- Simultaneous GW and EM observations probe white dwarf structure
  - Tidal interaction perturbs orbit.
  - Disruption frequency.
- GW pre-localisation to a few sq. degrees possible but there may be a lag in analysis.
- Event rate is likely to be low. Even a single event allows interesting science.



Sesana et al. (2008)

More details in Menou talk.

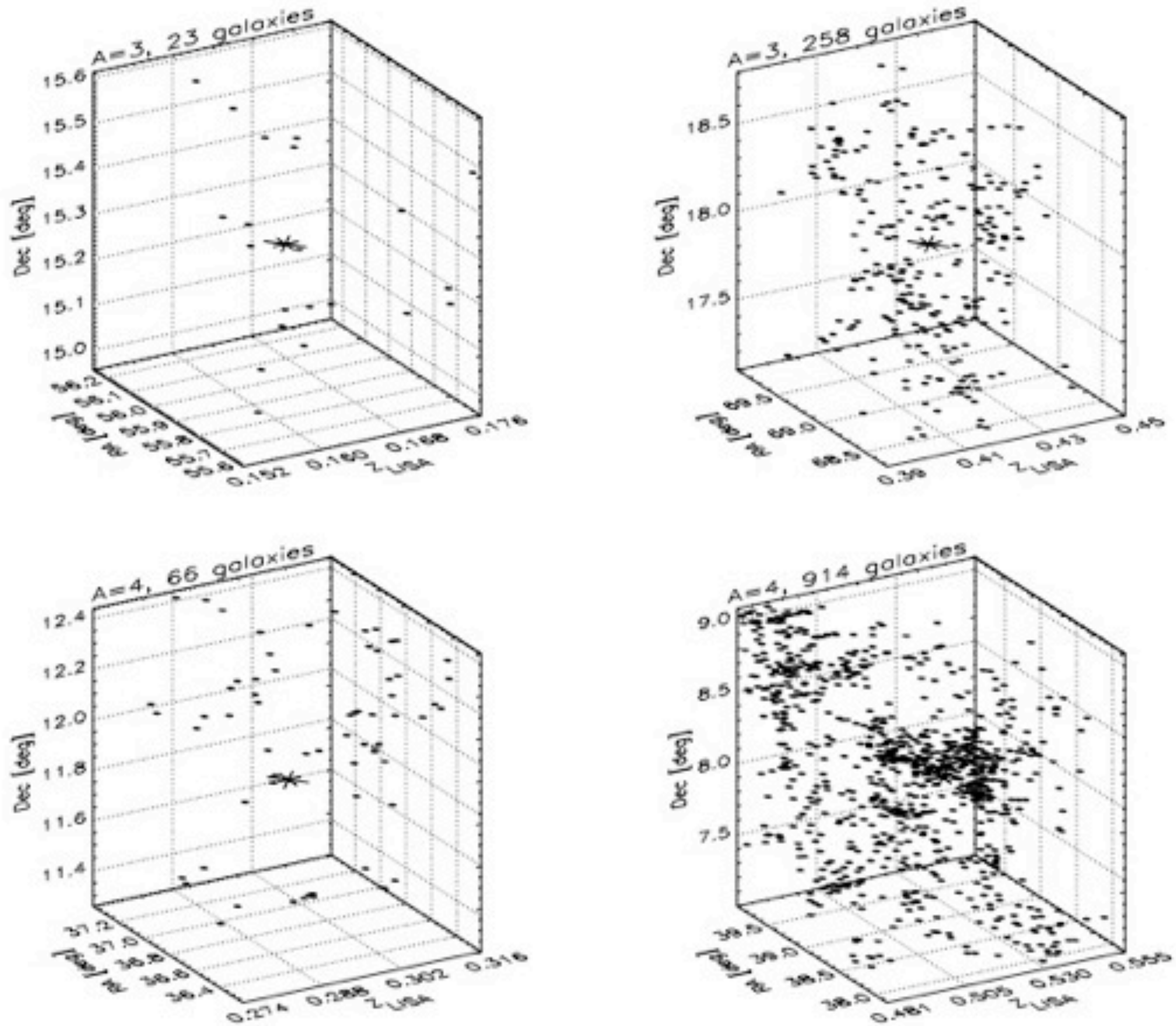
Cosmology with EMRIs

- GW sources give distances not tied to local scale (Schutz 86) - measure $D_L(z)$ and $M(1+z)$.
- Need an electromagnetic counterpart for redshift.
- Counterpart to EMRI only by WD tidal disruption (Sesana et al. 2008).
- Central black hole must have mass at the low end of the LISA range, $\sim 10^4 - 10^5 M_\odot$. Rate of events likely to be low, but not entirely astrophysically uninteresting (JG 2009).
- A single EMRI event for which an electromagnetic counterpart is observed will give the Hubble constant to an accuracy of ~3%. N such events give accuracy of $\sim 3/\sqrt{N}$ %.

Cosmology with EMRIs

- Even without a counterpart, can estimate Hubble constant statistically (McLeod & Hogan 08)
  - Let every galaxy in the LISA error box "vote" on the Hubble constant.
  - If ~20 EMRI events are detected at $z < 0.5$, will determine the Hubble constant to ~1%.

Cosmology with EMRIs



McLeod & Hogan (2008)

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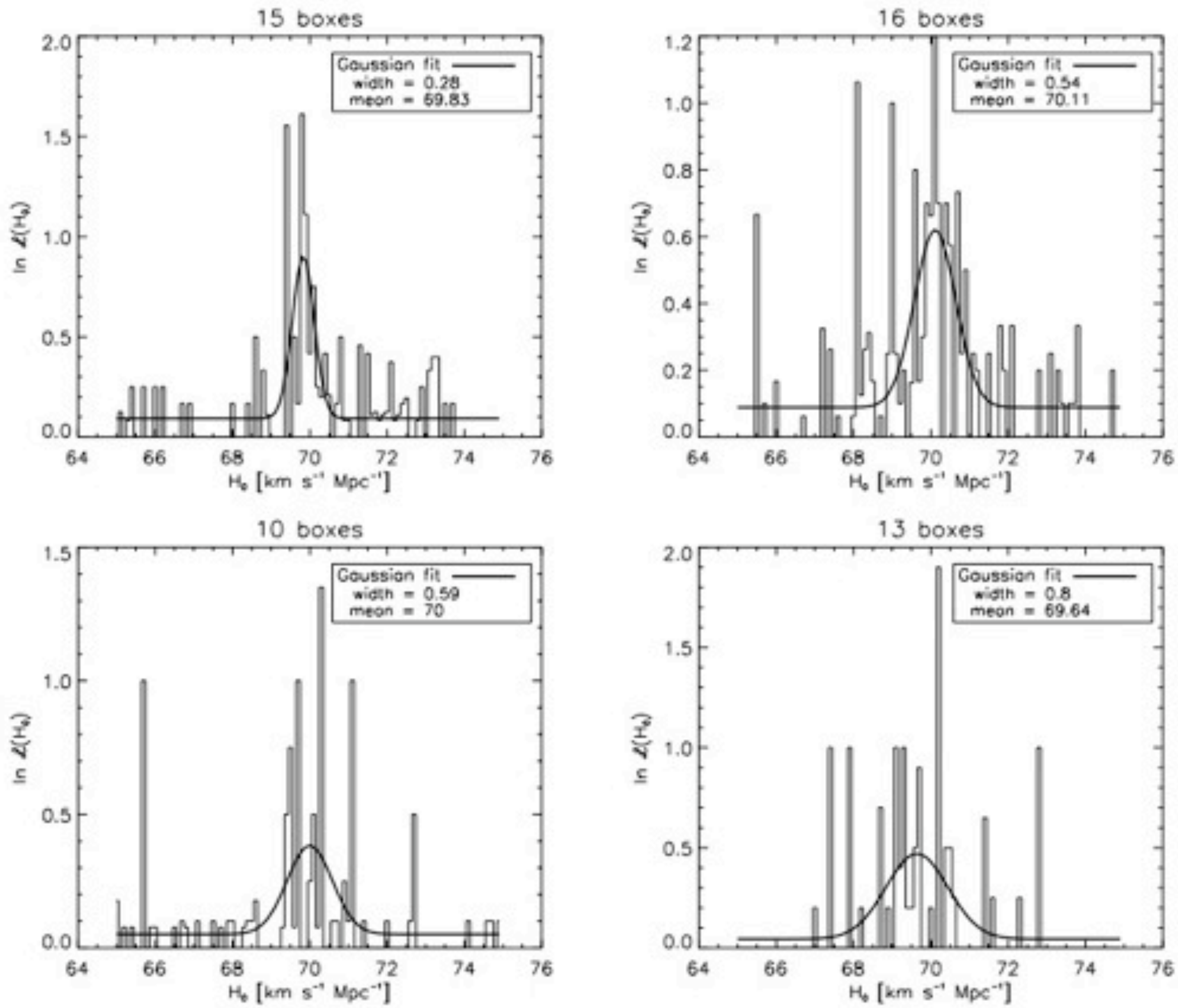

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Cosmology with EMRIs

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  - Let every galaxy in the LISA error box "vote" on the Hubble constant.
  - If ~20 EMRI events are detected at $z < 0.5$, will determine the Hubble constant to ~1%.
  - Determining redshifts of all galaxies in the error box at $z < 0.5$ is already possible technologically.
- Even pessimistically, an EMRI rate of 80/Gyr per galaxy will provide 20 events at $z < 0.5$ (JG 2009). Current rate prediction is 400/Gyr.
- With many events, can test Copernican principle by comparing Hubble constant inferred from different directions on the sky, e.g., measure dipole anisotropy and constrain higher moments.

Fundamental Physics - nature of black holes

- Black Hole Hypothesis - massive compact objects observed in the centres of galaxies are spinning black holes described by the Kerr metric of Relativity.
- Extreme mass ratio ensures that the inspiralling object acts like a test particle. Use emitted gravitational waves to map spacetime - 'bothrodesy' or 'holiodesy'.
- Deviations could arise for several reasons
  - Astrophysical perturbations, i.e., matter exterior to the black hole.
  - Existence of an exotic central object, consistent with Relativity, e.g., a Boson Star.
  - One of the assumptions of the uniqueness theorem is violated, e.g., axisymmetry, presence of a horizon, no closed-timelike-curves.
  - Breakdown of the theory of Relativity in the strong field.

Signatures of Deviations in the Metric

- Can characterize a vacuum, axisymmetric spacetime in GR by its multipole moments. For a Kerr black hole, these satisfy the 'no-hair' theorem:

$$M_l + \mathrm{i} S_l = M (\mathrm{i} a)^l$$

- Multipole moments are encoded in gravitational wave observables - precession frequencies & number of cycles spent near a given frequency (Ryan 95).

$$\Delta \mathcal{N}(f) = \frac{f^2}{\mathrm{d}f/\mathrm{d}t} = f^2 \frac{\mathrm{d}E/\mathrm{d}f}{\mathrm{d}E/\mathrm{d}t}$$

- Multipole moments enter at different orders in $M\Omega$

$$\frac{\Omega_p}{\Omega} = 3(M\Omega)^{\frac{2}{3}} - 4\frac{S_1}{M^2}(M\Omega) + \left(\frac{9}{2} - \frac{3}{2}\frac{M_2}{M^3}\right)(M\Omega)^{\frac{4}{3}} + \cdots$$

Signatures of Deviations in the Metric

- Multipole expansion impractical for analysis - consider 'quasi-Kerr' spacetimes that deviate a small amount.

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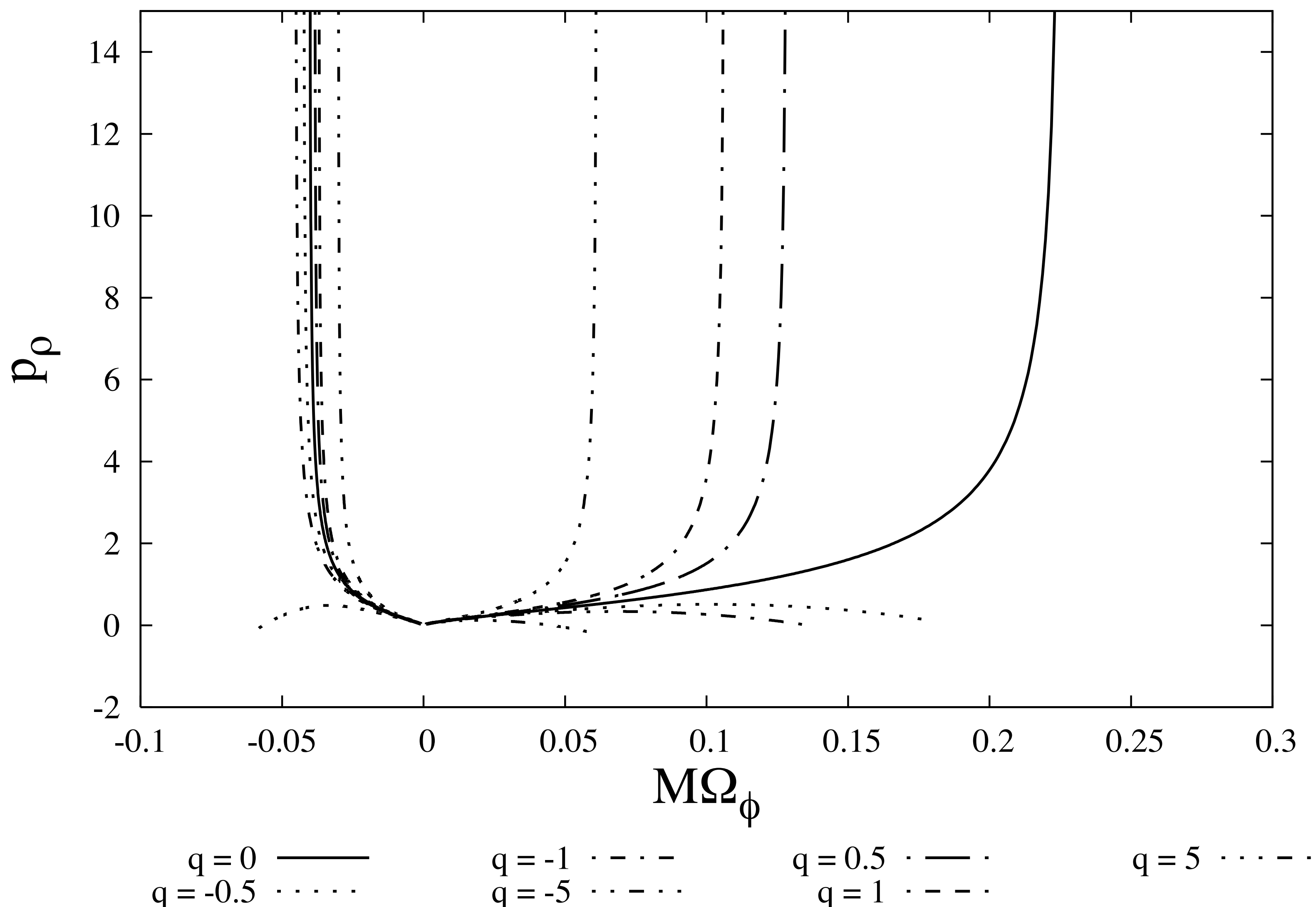

JG, Li and Mandel (2007)

Signatures of Deviations in the Metric

- Multipole expansion impractical for analysis - consider 'quasi-Kerr' spacetimes that deviate a small amount.
- Fisher Matrix analysis indicates quadrupole moment can be measured to ~0.1% simultaneously with the mass and spin (Barack & Cutler 2007). A strong test of the 'no-hair' property.
- Strong field deviations can be more extreme
  - See loss of third-integral for some orbits (JG et al. 2007), although unlikely to be astrophysically relevant.

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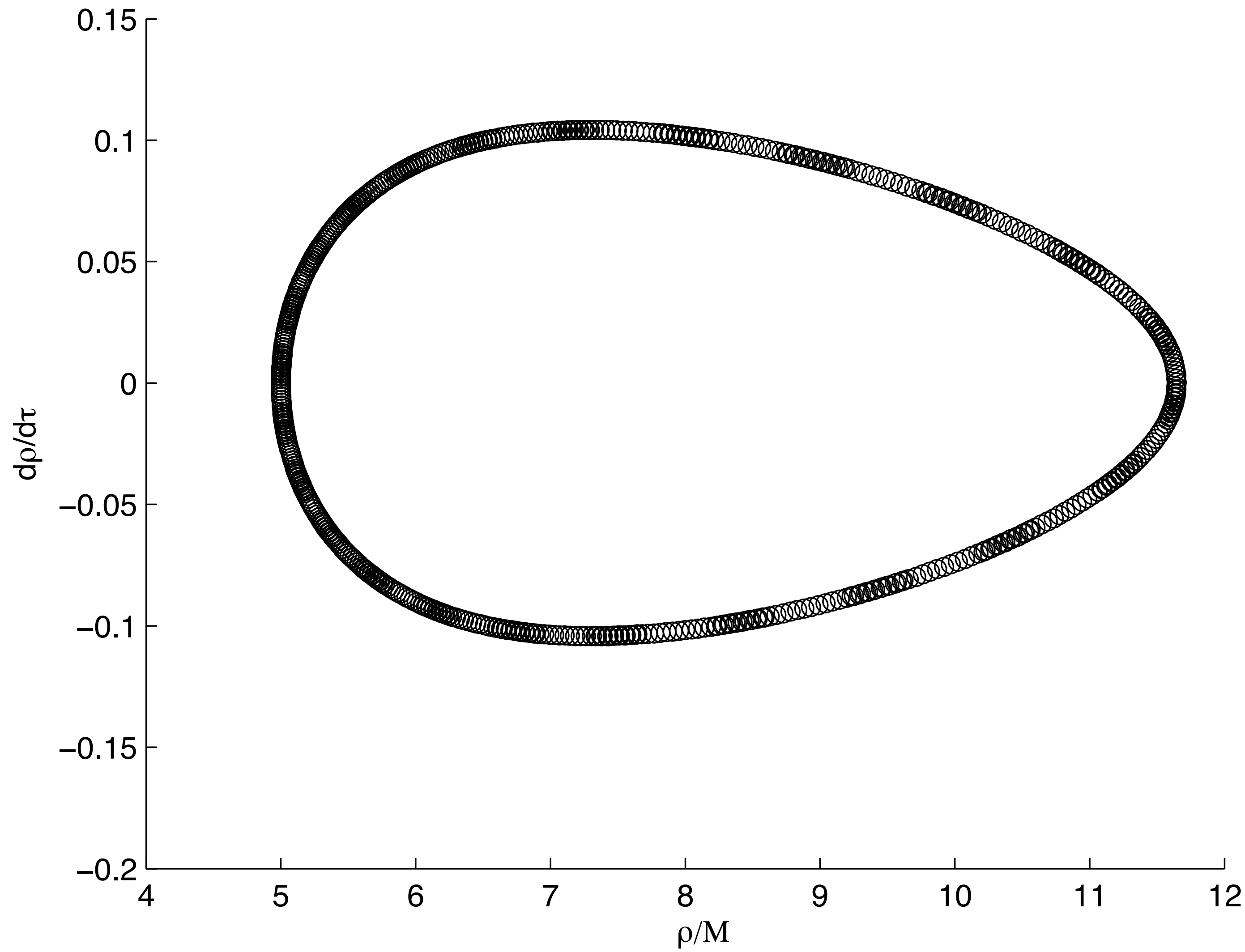

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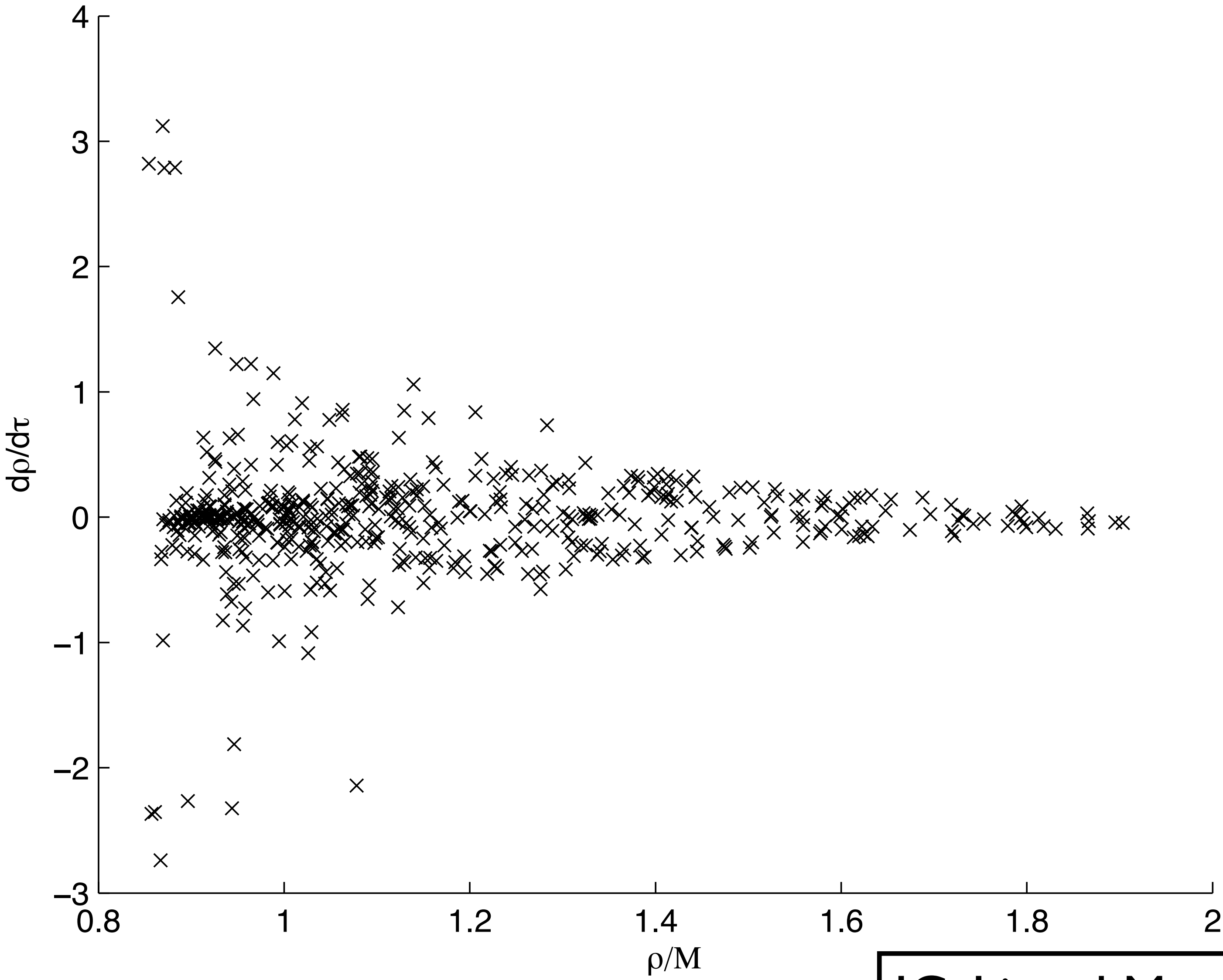

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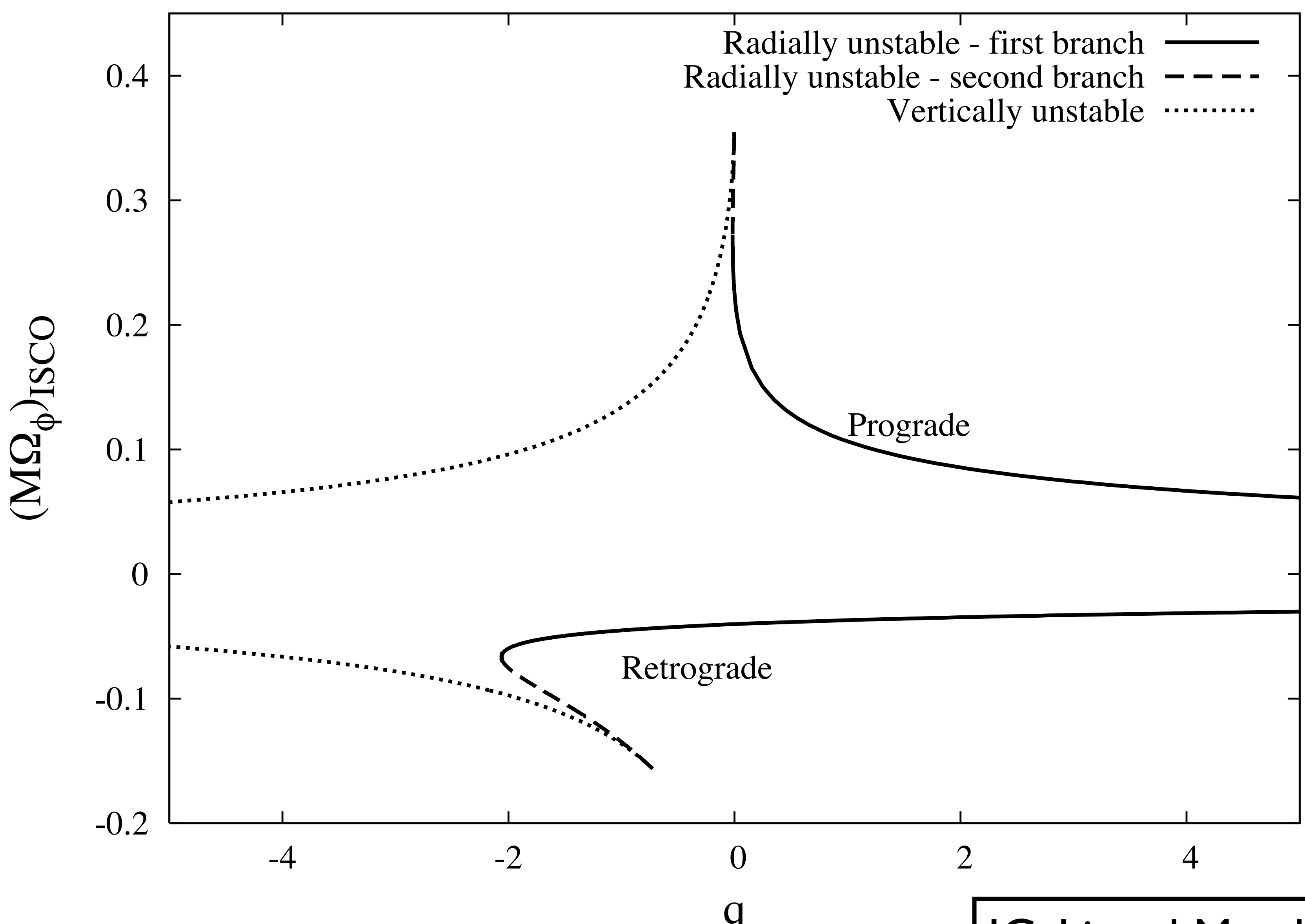

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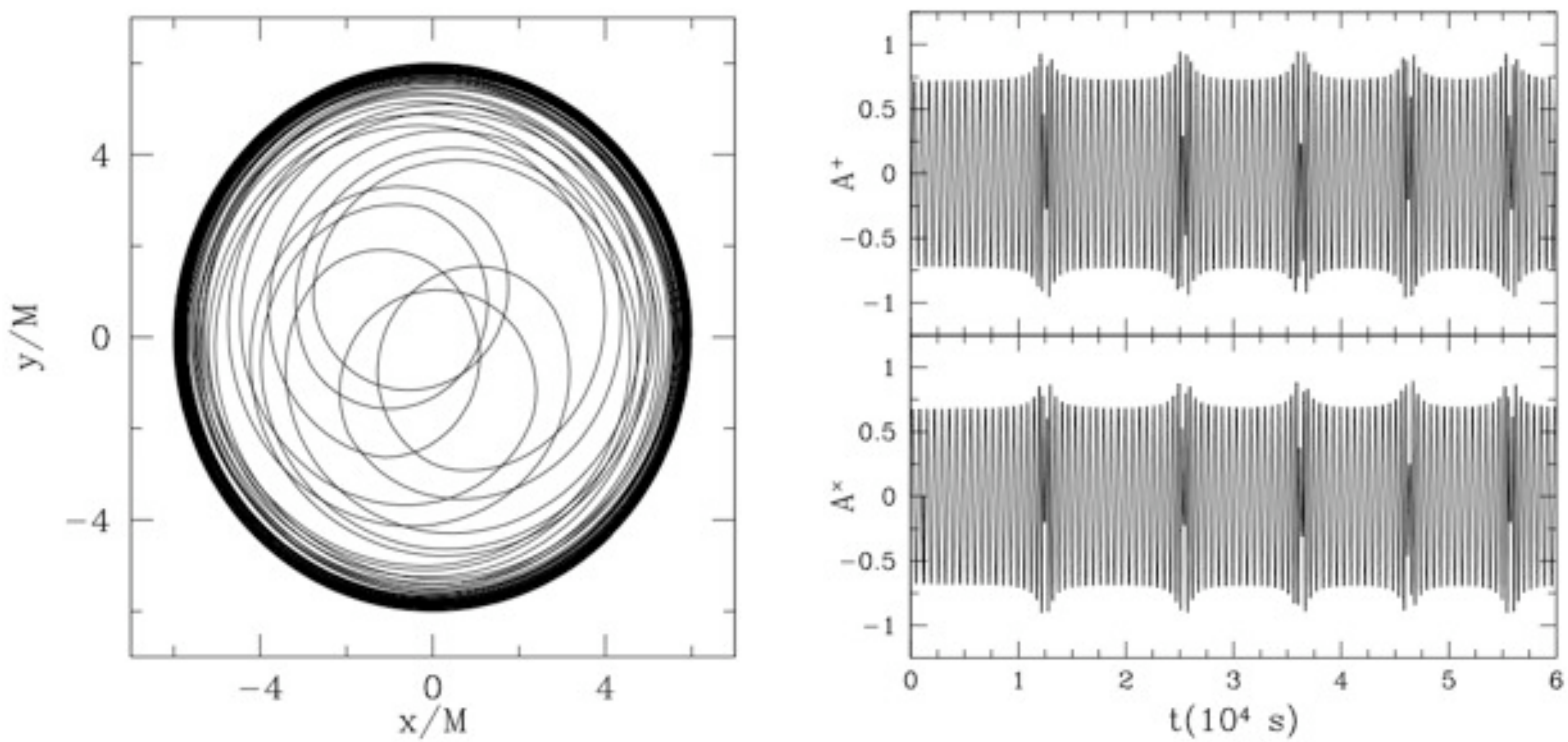

Kesden, JG & Kamionkowski (2004)

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- Information about the central object is also encoded in the tidal-coupling interaction (Li & Lovelace 07).

Influence of Matter

- The presence of matter in the spacetime could, in principle, leave a measurable imprint on an EMRI.
- The gravitational influence of material, e.g., an accretion torus, could perturb the orbit (Barausse et al. 2007)
  - Orbits in the same spacetime with and without a torus generate significantly different GW signals.

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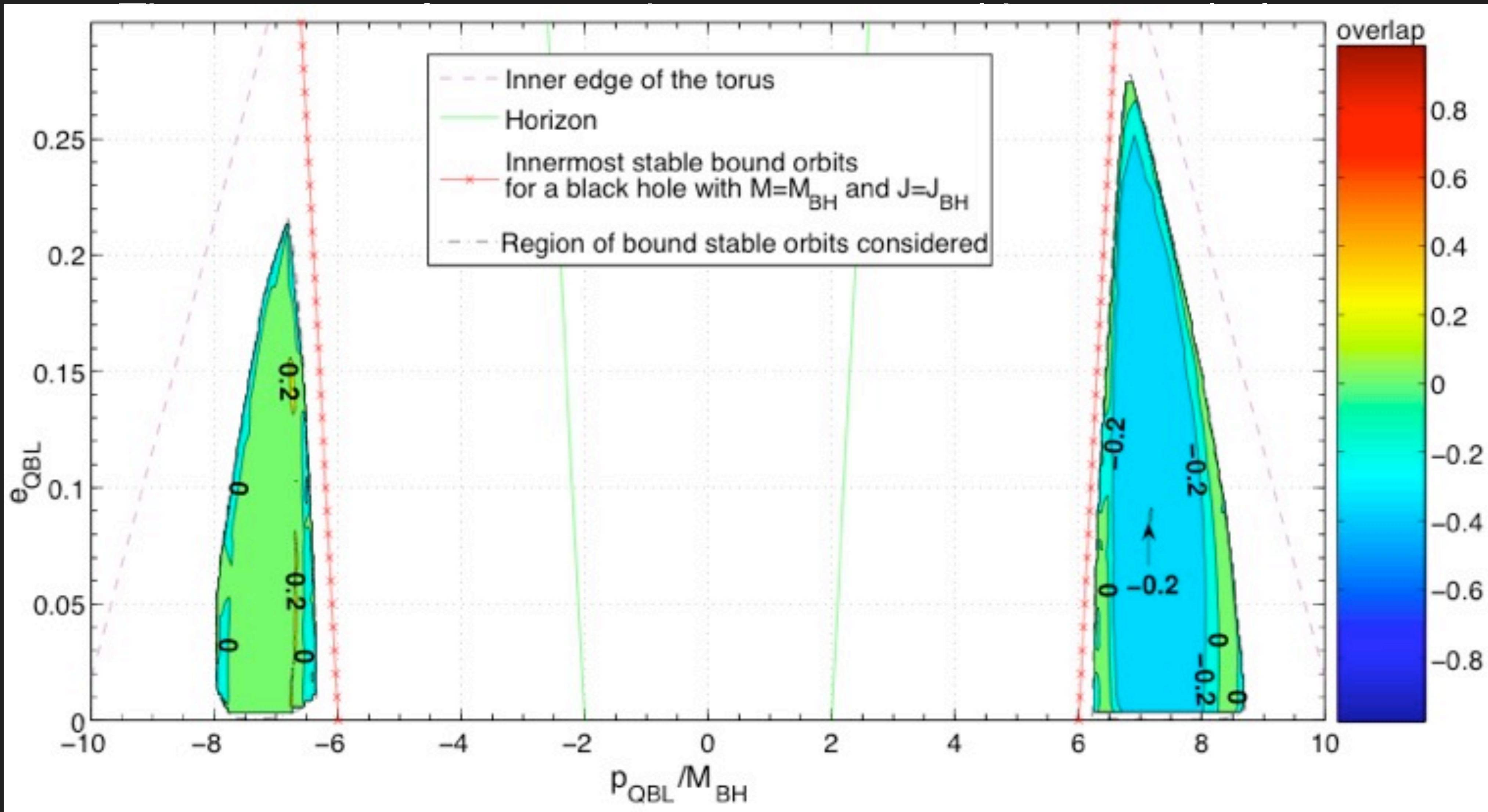

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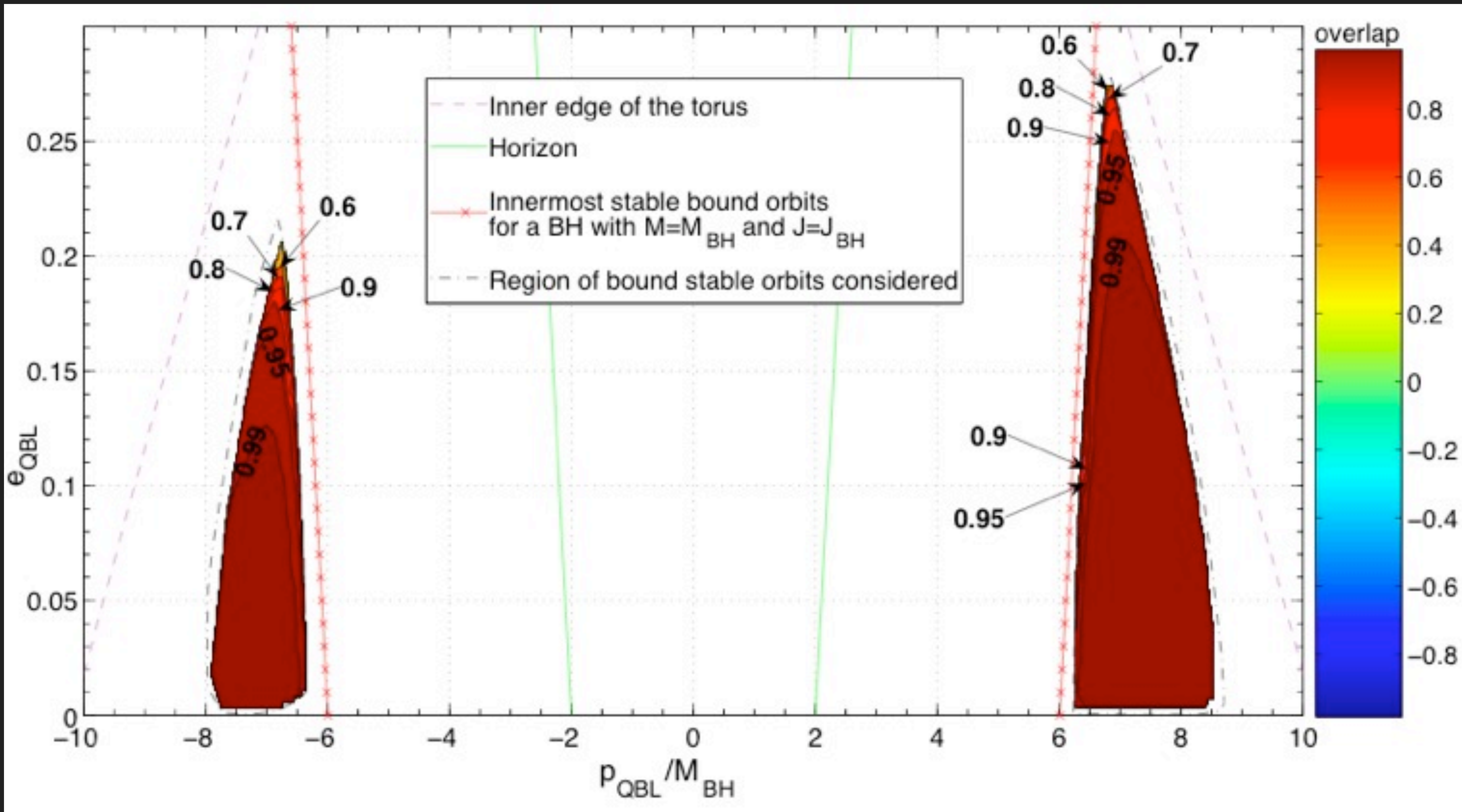

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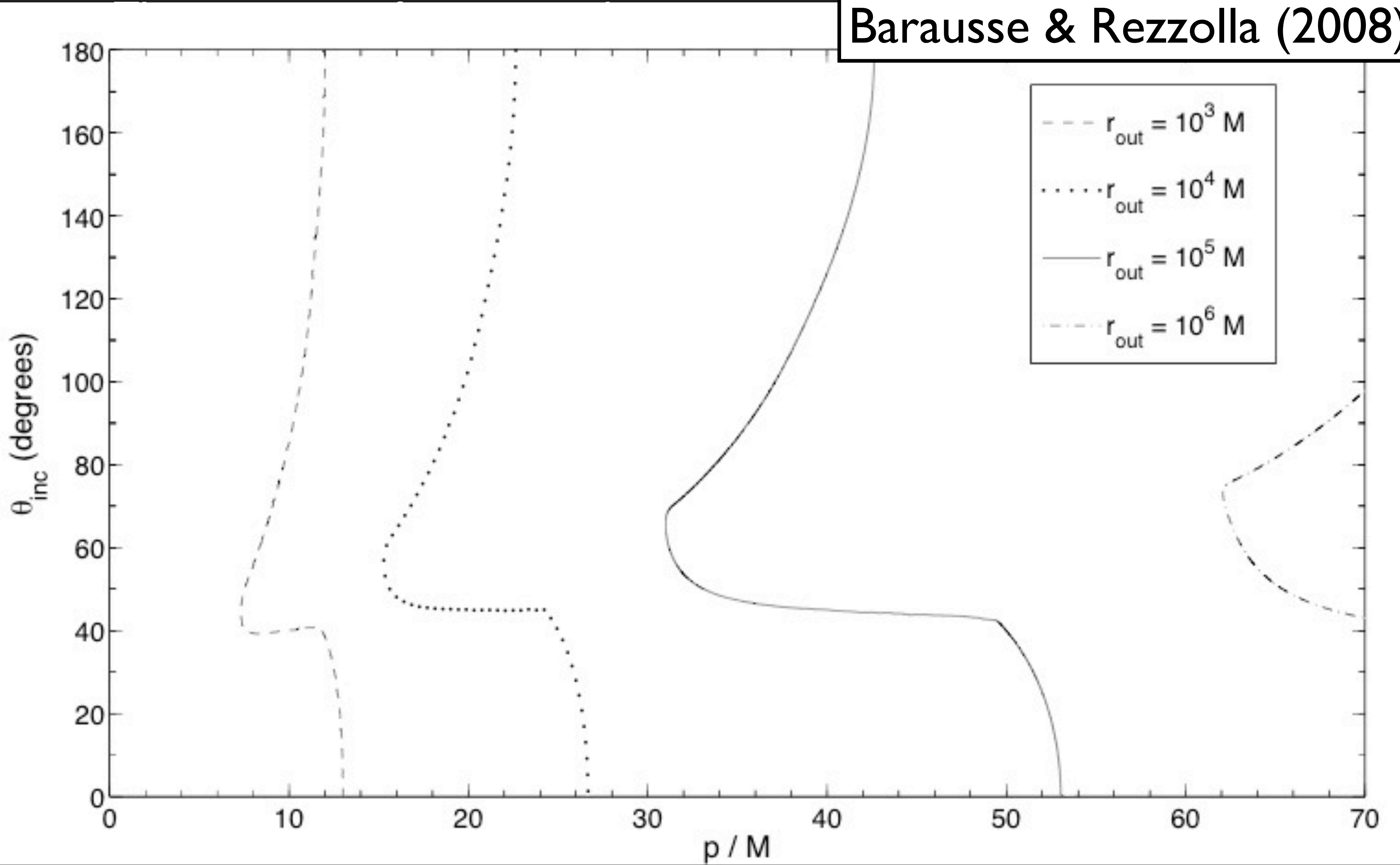
  - Orbits in the same spacetime with and without a torus generate significantly different GW signals.
  - If the mass and spin of the black hole are modified as well, the signals are not distinguishable.
  - Inspiral may break this degeneracy. However, these results were for an unphysically massive torus. So, this is unlikely to be observed.
- An inspiraling object could also suffer hydrodynamic drag if the orbit intersects matter in the spacetime (Barausse & Rezzolla 2008). Signature is a decrease in orbital inclination during inspiral. Could be detected for systems containing low mass SMBHs or very compact accretion tori.

Influence of Matter

Barausse & Rezzolla (2008)



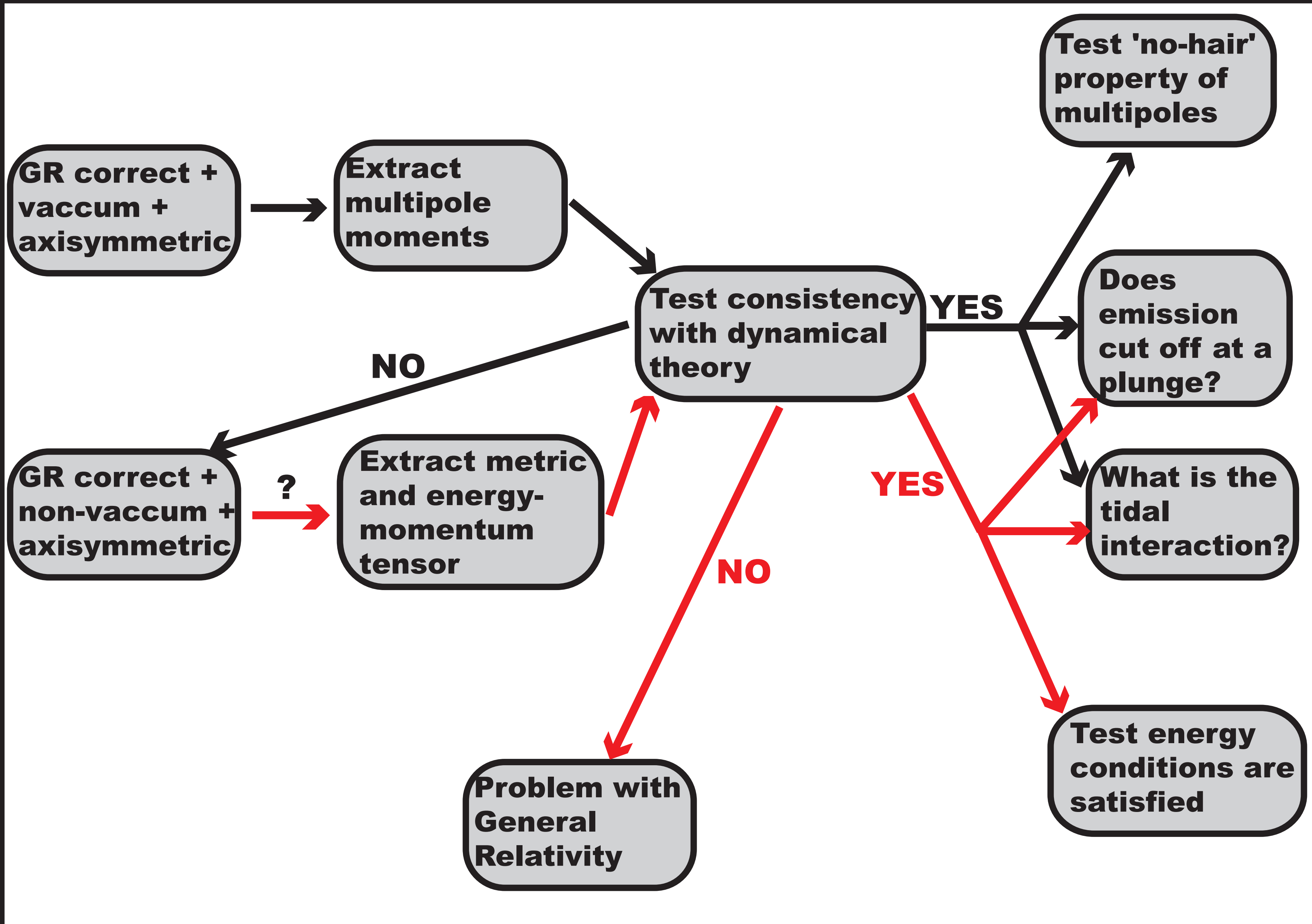
Testing Dynamical Relativity

- Research to date has focused on spacetime mapping, i.e., testing that the metric outside the object is Kerr. This is not a test of GR as several alternative theories also admit the Kerr metric as a solution.
- Psaltis et al. (2007) considered several theories for which this was true, e.g., *General Quadratic Gravity*

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \alpha' K_{\mu\nu} + \beta' L_{\mu\nu} + \Lambda g_{\mu\nu} = 0$$

- If the vacuum field equations depend only on $R_{\mu\nu}$ and R, then the Kerr metric (with $R_{\mu\nu} = 0$) is a solution.
- Dynamical theory *is different*. Deviations from GR shows up in inspiral rates and waveform multipole structure.
- In Chern-Simons modified gravity, correction is second order (Sopuerta & Yunes 09), but black holes are different.

Spacetime Mapping



Data analysis for EMRIs

- EMRI detection is hard due to large parameter space of possible signals. Several algorithms are under development
  - semi-coherent hierarchical search with a template bank; time-frequency search; Markov Chain Monte Carlo and nested sampling.
- Detection of isolated EMRI sources demonstrated in MLDC.

type[1]	ν (mHz)	$\mu/M_\odot$	$M/M_\odot$	e_0	θ_S	φ_S	λ	a/M^2	SNR
True	0.1920421	10.296	9517952	0.21438	1.018	4.910	0.4394	0.69816	120.5
Found	0.1920437	10.288	9520796	0.21411	1.027	4.932	0.4384	0.69823	118.1
True	0.34227777	9.771	5215577	0.20791	1.211	4.6826	1.4358	0.63796	132.9
Found	0.34227742	9.769	5214091	0.20818	1.172	4.6822	1.4364	0.63804	132.8
True	0.3425731	9.697	5219668	0.19927	0.589	0.710	0.9282	0.53326	79.5
Found	0.3425712	9.694	5216925	0.19979	0.573	0.713	0.9298	0.53337	79.7
True	0.8514396	10.105	955795	0.45058	2.551	0.979	1.6707	0.62514	101.6
Found	0.8514390	10.106	955544	0.45053	2.565	1.012	1.6719	0.62534	96.0
True	0.8321840	9.790	1033413	0.42691	2.680	1.088	2.3196	0.65829	55.3
Found	0.8321846	9.787	1034208	0.42701	2.687	1.053	2.3153	0.65770	55.6
Blind									
True	0.1674472	10.131	10397935	0.25240	2.985	4.894	1.2056	0.65101	52.0
Found	0.1674462	10.111	10375301	0.25419	3.023	4.857	1.2097	0.65148	51.7
True	0.9997627	9.7478	975650	0.360970	1.453	4.95326	0.5110	0.65005	122.9
Found	0.9997626	9.7479	975610	0.360966	1.422	4.95339	0.5113	0.65007	116.0

Babak, JG & Porter (2009)

Data analysis for EMRIs

- EMRI detection is hard due to large parameter space of possible signals. Several algorithms are under development
  - semi-coherent hierarchical search with a template bank; time-frequency search; Markov Chain Monte Carlo and nested sampling.
- Detection of isolated EMRI sources demonstrated in MLDC.
- Significant challenges remain
  - **'Whole enchilada' for LISA**: simultaneous recovery of several SMBH mergers, thousands of white dwarf binaries and perhaps hundreds of EMRIs. Sources strongly overlap in time and frequency.
  - **Spacetime mapping**: lots of ideas, but no practical scheme has yet been developed to put these ideas into practice. How well will we be able to constrain deviations from the Kerr metric in practice?
  - **Online analysis**: how fast can we process the data? Can we detect and localise sources in advance to warn electromagnetic telescopes?

Source modelling - status and future directions

- Extreme-mass-ratio waveforms still not fully known, but various techniques are in hand
  - **Self-force**: accurate perturbative solution. Known for Schwarzschild orbits but computationally expensive. Extension to Kerr ongoing. Radiative part known for Kerr (Drasco et al. 2008).
  - **Approximations**: analytic kludge (Barack and Cutler 2003), semi-relativistic approximation (JG et al. 2004) and EOB (Yunes et al. 2009).
  - **Numerical kludge**: close to self-force and accurate. Possible to include most physics, e.g., conservative effects (Huerta & JG 2009).
  - Need to understand range of validity of various approximations. Data analysis will use cheaper approximations at first stage.

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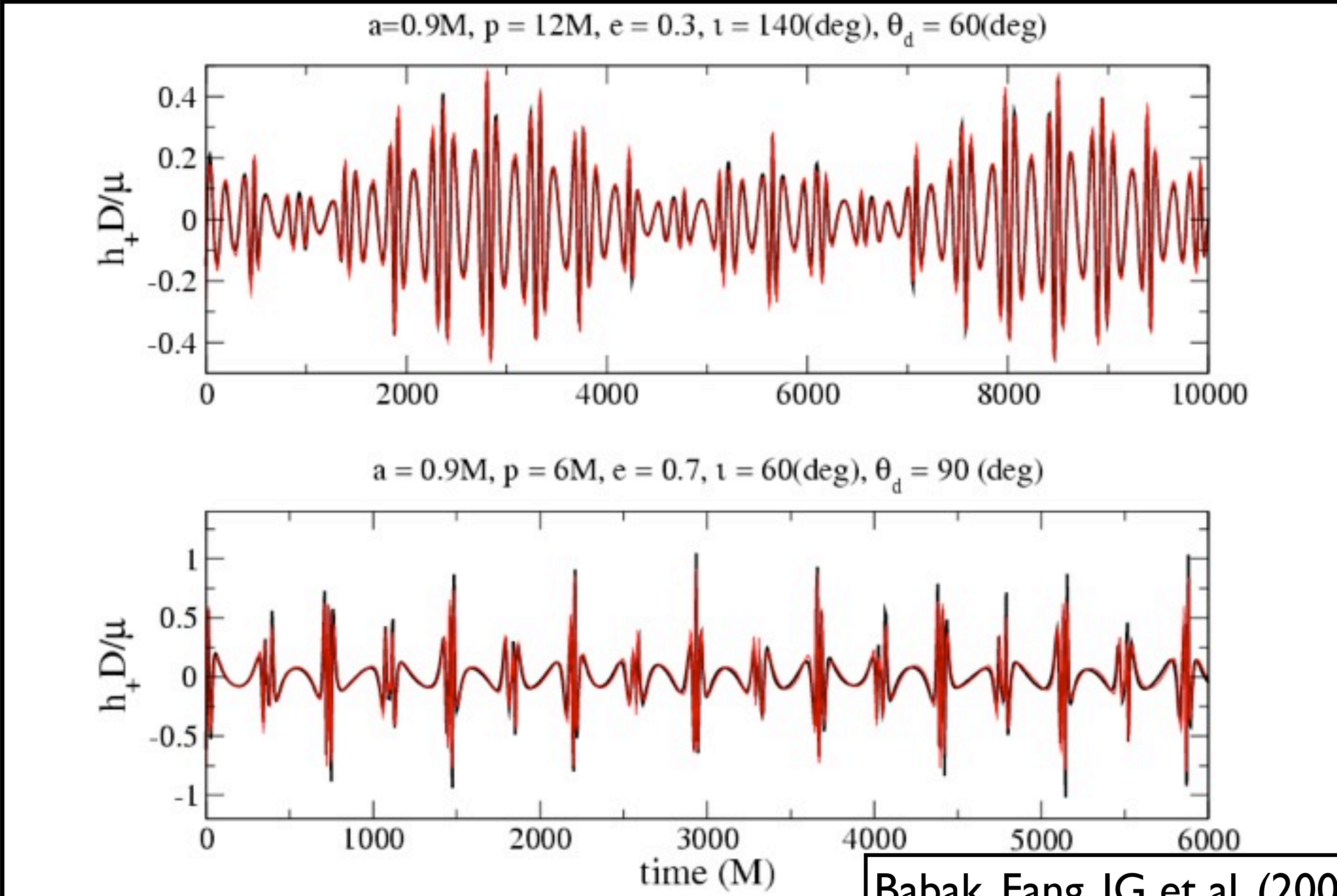

Babak, Fang, JG et al. (2007)

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  - Need to understand range of validity of various approximations. Data analysis will use cheaper approximations at first stage.
- A significant challenge for the future is to model intermediate-mass-ratio inspirals. Neither perturbative nor pN approximations will be good enough (Mandel & JG 2009).

Summary

- Gravitational waves from EMRIs are expected to have a very rich structure which encodes detailed information about the source.
- EMRI detections will increase our understanding of the Universe in many ways
  - **Astrophysics**: properties of supermassive black holes, dense stellar clusters and stellar evolution. Probe of white dwarfs.
  - **Cosmology**: independent measurement of distance scale.
  - **Fundamental physics**: nature of black holes, test theory of gravity in strong field and non-linear regimes.
- Much work must still be done to ensure we maximize the scientific payoff of GW detections.
- Significant challenges remain for data analysis and source modelling.