Fundamental Physics, Cosmology and Astrophysics with Advanced and 3G Detectors

B.S. Sathyaprakash

GW2010 - 14-16 October 2010, University of Minnesota, Minneapolis

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

Einstein Telescope Vision Document

- FP7-funded ET design study (Harald Lueck's talk)
  - Provided an opportunity to study the potential of a 3G detector
- 85-page document detailing the science case for 3rd generation gravitational wave detectors
  - Contributions made by some 30 authors from around the world - resulted in some 15 research papers so far
- Available from
  - https://workarea.et-gw.eu/et/WG4-Astrophysics/visdoc

Credits

Michele Punturo and Harald Lueck

Scientific Coordinators of ET

- Patrick Sutton
- Christian Ott
- Jonathan Gair
- Chris Van Den Broeck
- Sukanta Bose
- Richard O'Shaughnessy
- Tania Regimbau
- Thomas Dent
- James Clark
- Gareth Jones
- Alberto Vecchio
- John Veitch
- Craig Robinson
- Andrew Melatos
- Eric Chassande-Mottin
- Pau Amaro-Seoane
- Nils Andersson
- K.G. Arun
- Leone Bosi
- Tomasz Bulik
- Kostas Kokkotas
- Mark Hannam
- Sascha Husa
- Badri Krishan
- Joceylyn Read
- Luciano Rezzolla
- Tjonnie Li
- Eliu Huerta
- Lucia Santamaria
- Bala Iyer

Compact binaries for fundamental physics, cosmology and astrophysics

- Black holes and neutron stars are the most compact objects
  - The potential energy of a test particle is equal to its rest mass energy

$$\frac{GmM}{R} \sim mc^2$$

- Being the most compact objects, they are also the most luminous sources of gravitational radiation
  - The luminosity of a binary could increase a million times in the course of its evolution through a detector's sensitivity band
  - The GW luminosity of a binary black hole outshines, during merger, the EM luminosity of all stars in the Universe
- Compact binaries are standard sirens
  - GW observations measure both the apparent luminosity (strain) and absolute luminosity (chirp rate) of a source

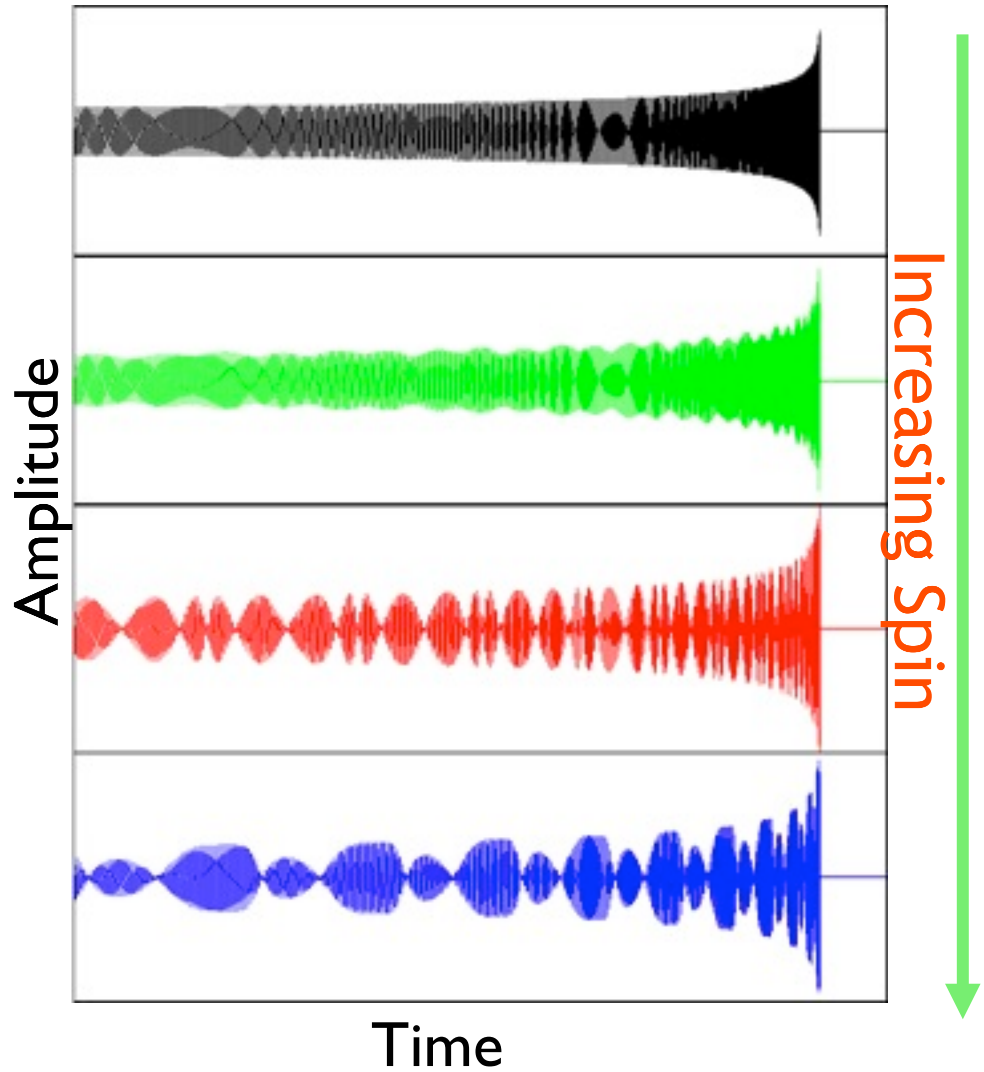
Compact binaries: theoretically the best studied sources

- In general relativity the two-body problem has no known exact analytic solution
- Approximate methods have been used to understand the dynamics: post-Newtonian (PN) approximation
  - The binary evolves by emitting gravitational-waves whose amplitude and frequency both grow with time - a chirp
  - Coalescence results in a single deformed black hole which emits "ringdown" signals with characteristic frequency and damping time
- Progress in analytical and numerical relativity over the last decade has led to a good understanding of the merger dynamics

Black hole binary waveforms

- Late-time dynamics of compact binaries is highly relativistic, dictated by non-linear general relativistic effects
- Post-Newtonian theory, which is used to model the evolution, is now known to $O(v^7)$
- The shape and strength of the emitted radiation depend on many parameters of the binary: masses, spins, distance, orientation, sky location, ...

$$h(t) = 4\eta \frac{M}{D} \frac{M}{r(t)} \cos 2\varphi(t)$$



Structure of the full post-Newtonian (PN) waveform

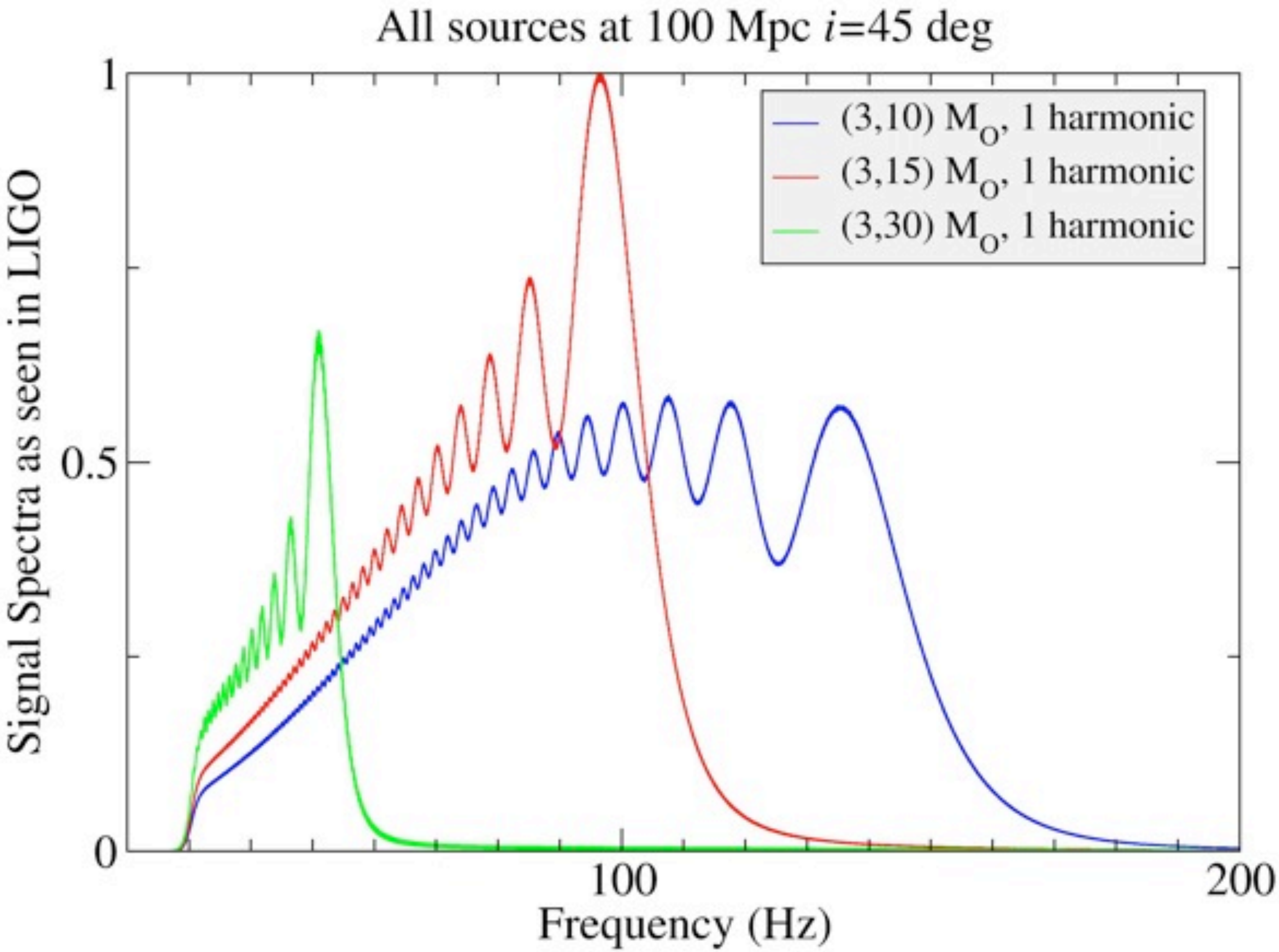
- Radiation is emitted not just at twice the orbital frequency but at all other harmonics too

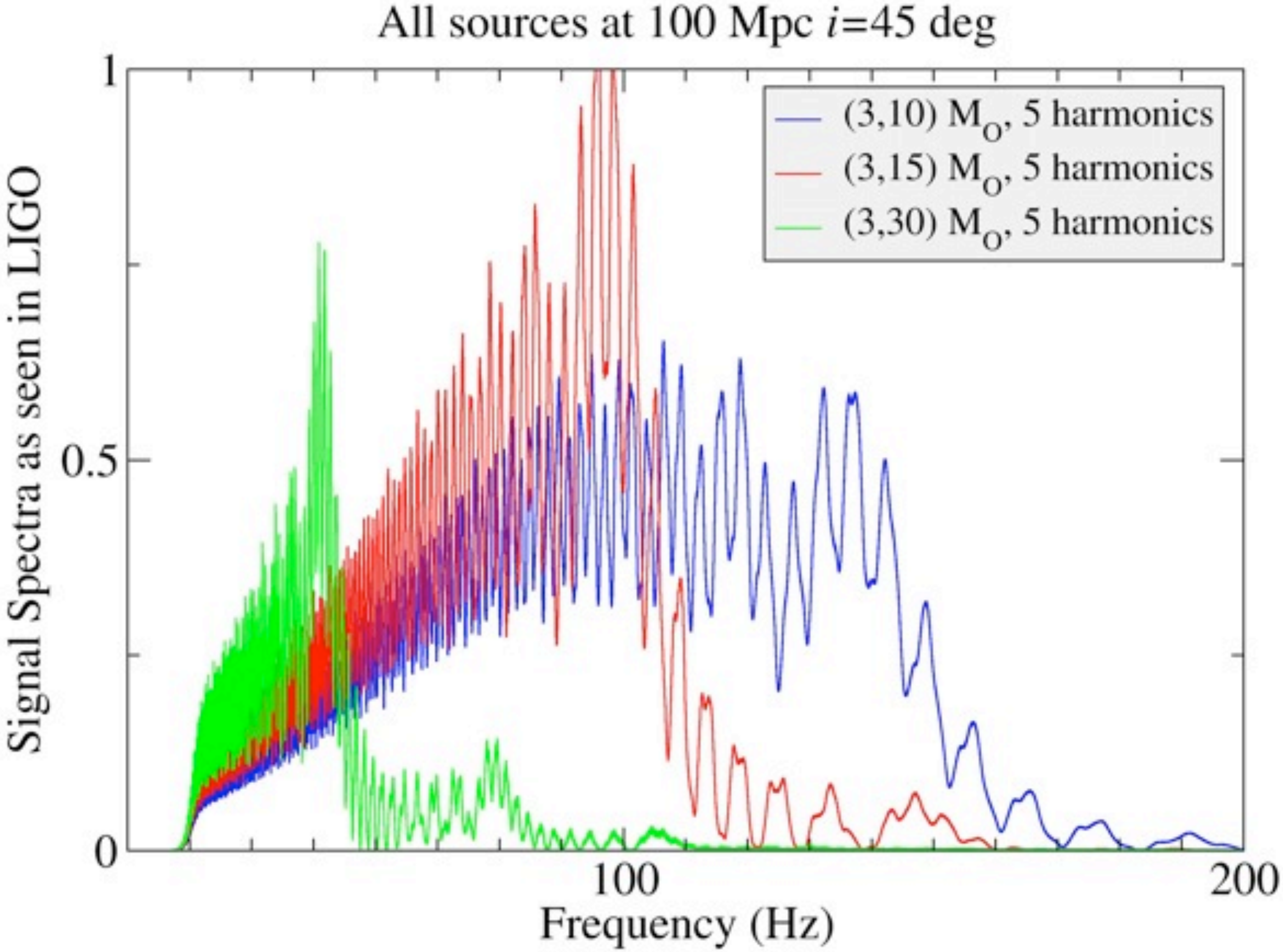
$$h(t) = \frac{2M\eta}{D_{\rm L}} \sum_{k=1}^{7} \sum_{n=0}^{5} A_{(k,n/2)} \cos\left[k\Psi(t) + \phi_{(k,\,n/2)}\right] x^{\frac{n}{2}+1}(t)$$

- This is the "full" waveform (FWF). The waveform corresponding to n=0 is called the restricted PN waveform (RFW)
- These amplitude corrections have a lot of additional structure
- Increased mass reach of detectors
- Greatly improved parameter estimation accuracies

Blanchet, Buonanno, Damour, Iyer, Jaranowski, Schaefer, Will, Wiseman

Andrade, Arun, Gopakumar, Joguet, Esposito-Farase, Faye, Kidder, Nissanke, Ohashi, Owen, Ponsot, Qusaillah, Tagoshi …


All sources at 100 Mpc i=45 deg
Signal Spectra as seen in LIGO
Frequency (Hz)
1
0.5
0
100
200
(3,10) M_O, 1 harmonic
(3,15) M_O, 1 harmonic
(3,30) M_O, 1 harmonic


All sources at 100 Mpc i=45 deg
Signal Spectra as seen in LIGO
Frequency (Hz)
(3,10) M_O, 5 harmonics
(3,15) M_O, 5 harmonics
(3,30) M_O, 5 harmonics
1
0.5
0
100
200

Fundamental Physics

- Properties of gravitational waves
  - Test wave generation formula beyond quadrupole approx.
  - Number of GW polarizations?
  - Do gravitational waves travel at the speed of light?
- Equation-of-State of supra-nuclear matter
  - Signature neutron star equation-of-state in gravitational waves from binary neutron star mergers, NS normal modes, etc.
- Black hole no-hair theorem and cosmic censorship
  - Are black hole candidates black holes of general relativity?
- Merger dynamics of spinning black hole binaries
  - Understanding the two-body problem in general relativity
- Measuring/limiting the mass of neutrino
  - Simultaneous obs. of neutrinos and GW from SN

Fundamental Physics: Testing GR with GW observations

BBH Signals as Testbeds for GR

- Gravity gets ultra-strong during a BBH merger compared to any observations in the solar system or in binary pulsars
  - In the solar system: $\varphi/c^2 \sim 10^{-6}$
  - In a binary pulsar it is still very small: $\varphi/c^2 \sim 10^{-4}$
  - Near a black hole $\varphi/c^2 \sim 1$
  - Merging binary black holes are the best systems for strong-field tests of GR
- Dissipative predictions of gravity are not even tested at the 1PN level
  - In binary black holes even $(v/c)^7$ PN terms might not be adequate for high-SNR (~100) events

Do gravitational waves travel at the speed of light?

- Coincident observation of a supermassive black hole binary and the associated gravitational radiation can be used to constrain the speed of gravitational waves:
- If Δt is the time difference in the arrival times of GW and EM radiation and D is the distance to the source then the fractional difference in the speeds is

$$\frac{\Delta v}{c} = \frac{\Delta t}{D/c} \simeq 10^{-14} \left(\frac{\Delta t}{1\mathrm{sec}}\right) \left(\frac{D}{1\mathrm{Mpc}}\right)$$

- It is important to study what the EM signatures of massive BBH mergers are
- Can be used to set limits on the mass of the graviton slightly better than the current limits.

Will (1994, 98)

Massive graviton causes dispersion

- A massive graviton induces dispersion in the waves

$$\frac{v_g^2}{c^2} = 1 - \frac{m_g^2 c^4}{E^2}, \quad v_g/c \approx 1 - \frac{1}{2}(c/\lambda_g f)^2, \text{ where } \lambda_g = h/m_g c$$

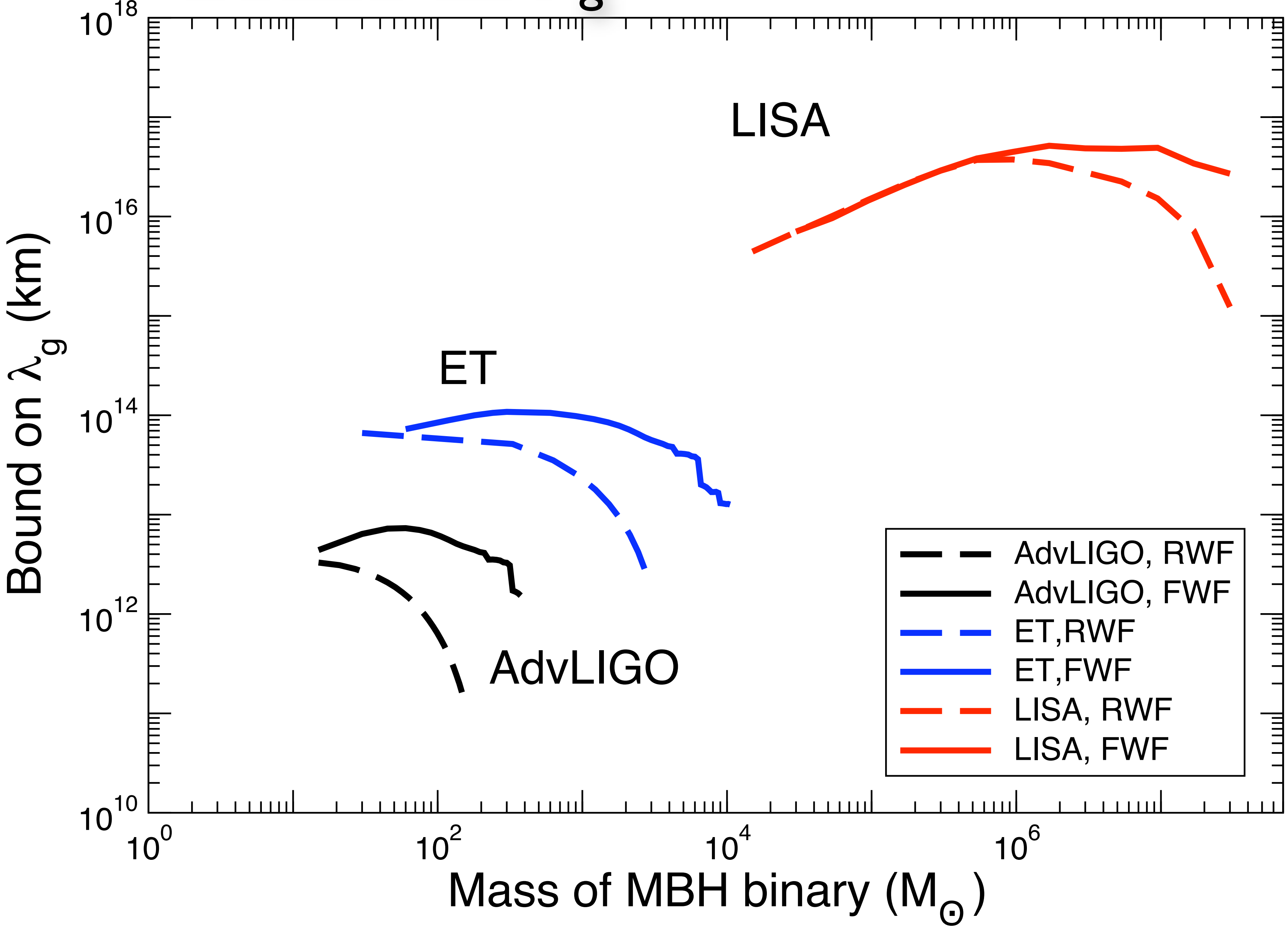
- Arrival times are altered due to a massive graviton - frequency-dependent effect
- One can test for the presence of this term by including an extra term in our templates

$$t_a = (1+Z)\left[t_e + \frac{D}{2\lambda_g^2 f_e^2}\right] \qquad \Delta\psi_k(f) = \frac{k}{2}\Delta\psi(2f/k) = -\frac{k^2}{4}\pi D/f_e\lambda_g^2$$

Will (1994, 98)

Bound on λ_g

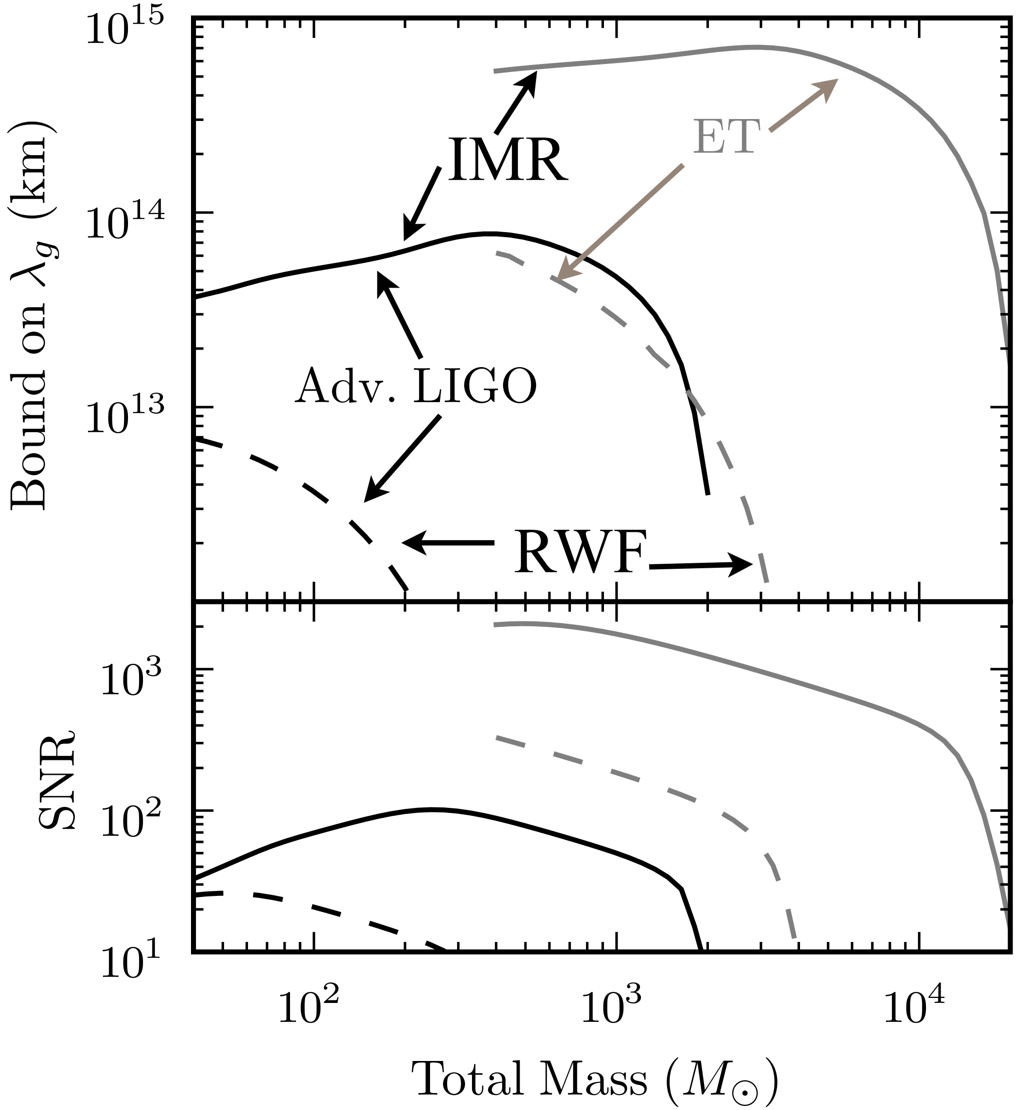
Arun and Will (2009)



Improving bounds with IMR Signals

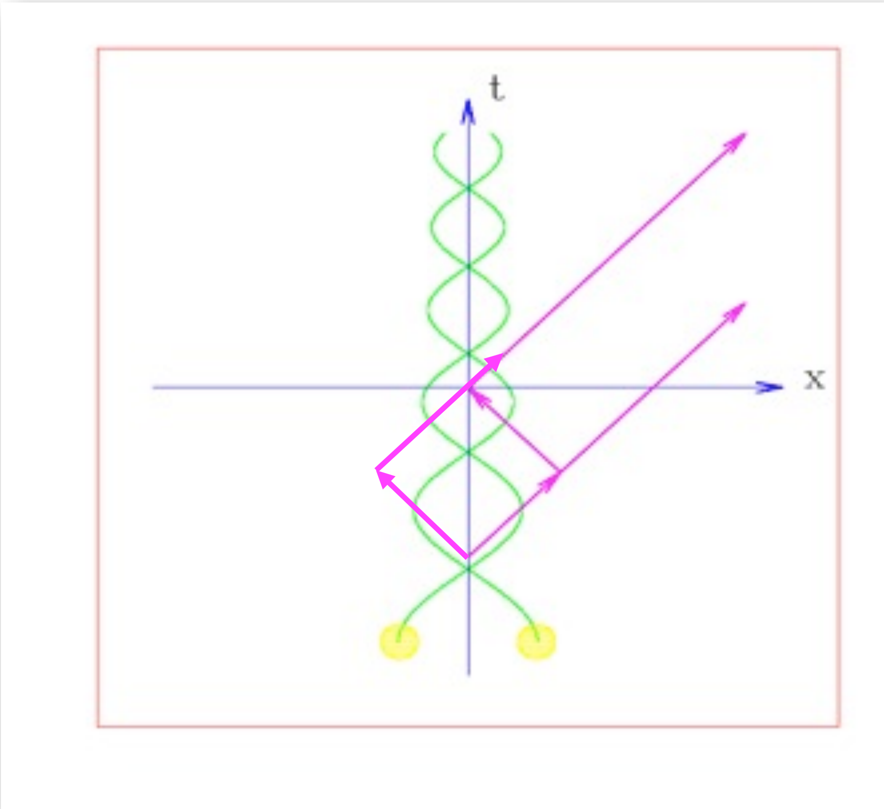
Keppel and Ajith (2010)

- By including the merger and ringdown part of the coalescence it is possible to improve the bound on graviton wavelength
- Equal mass compact binaries assumed to be at 1 Gpc
- ET can achieve 2 to 3 orders of magnitude better bound than the best possible model-independent bounds



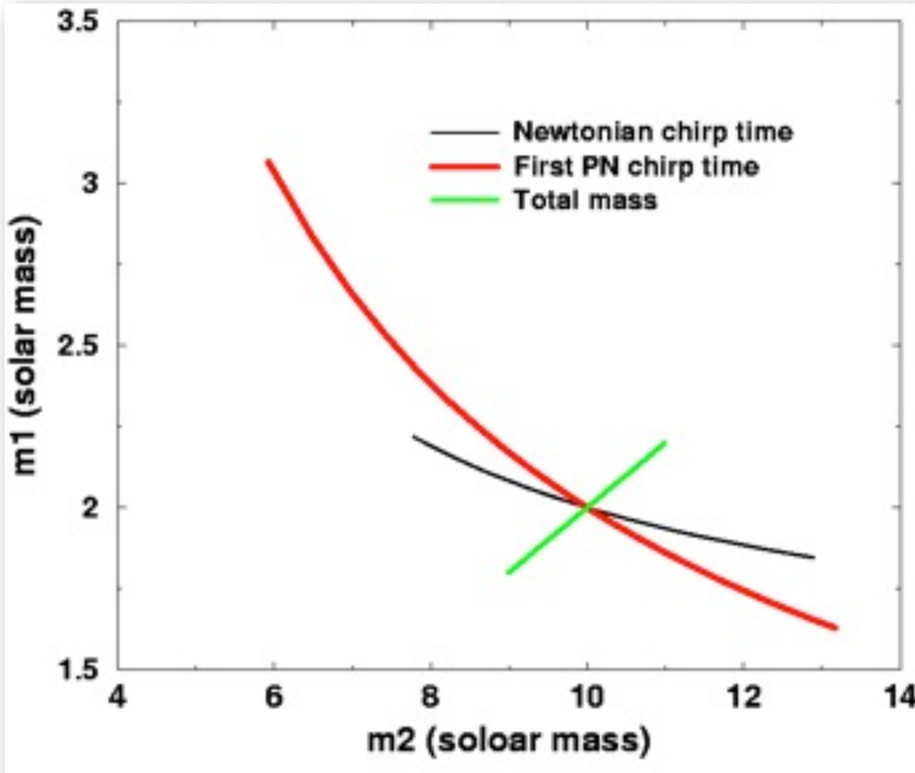
Testing the tail effect

Gravitational wave tails



Blanchet and Schaefer (1994)

Testing the presence of tails



Blanchet and Sathyaprakash (1995)

Testing general relativity with post-Newtonian theory

Post-Newtonian expansion of orbital phase of a binary contains terms which all depend on the two masses of the binary

$$H(f) = \frac{\mathcal{A}(M, \nu, \text{angles})}{D_L} f^{-7/6} \exp\left[-i\psi(f)\right]$$

$$\psi(f) = 2\pi f t_C + \varphi_C + \sum_k \psi_k f^{(k-5)/3}$$

$$\psi_k = \frac{3}{128} (\pi M)^{(k-5)/3} \alpha_k(\nu)$$

$$\alpha_0 = 1, \quad \alpha_1 = 0, \quad \alpha_2 = \frac{3715}{756} + \frac{55}{9}\nu, \ldots$$

Testing general relativity with post-Newtonian theory

- Post-Newtonian expansion of orbital phase of a binary contains terms which all depend on the two masses of the binary

$$\psi_k = \frac{3}{128}(\pi M)^{(k-5)/3}\alpha_k(\nu)$$

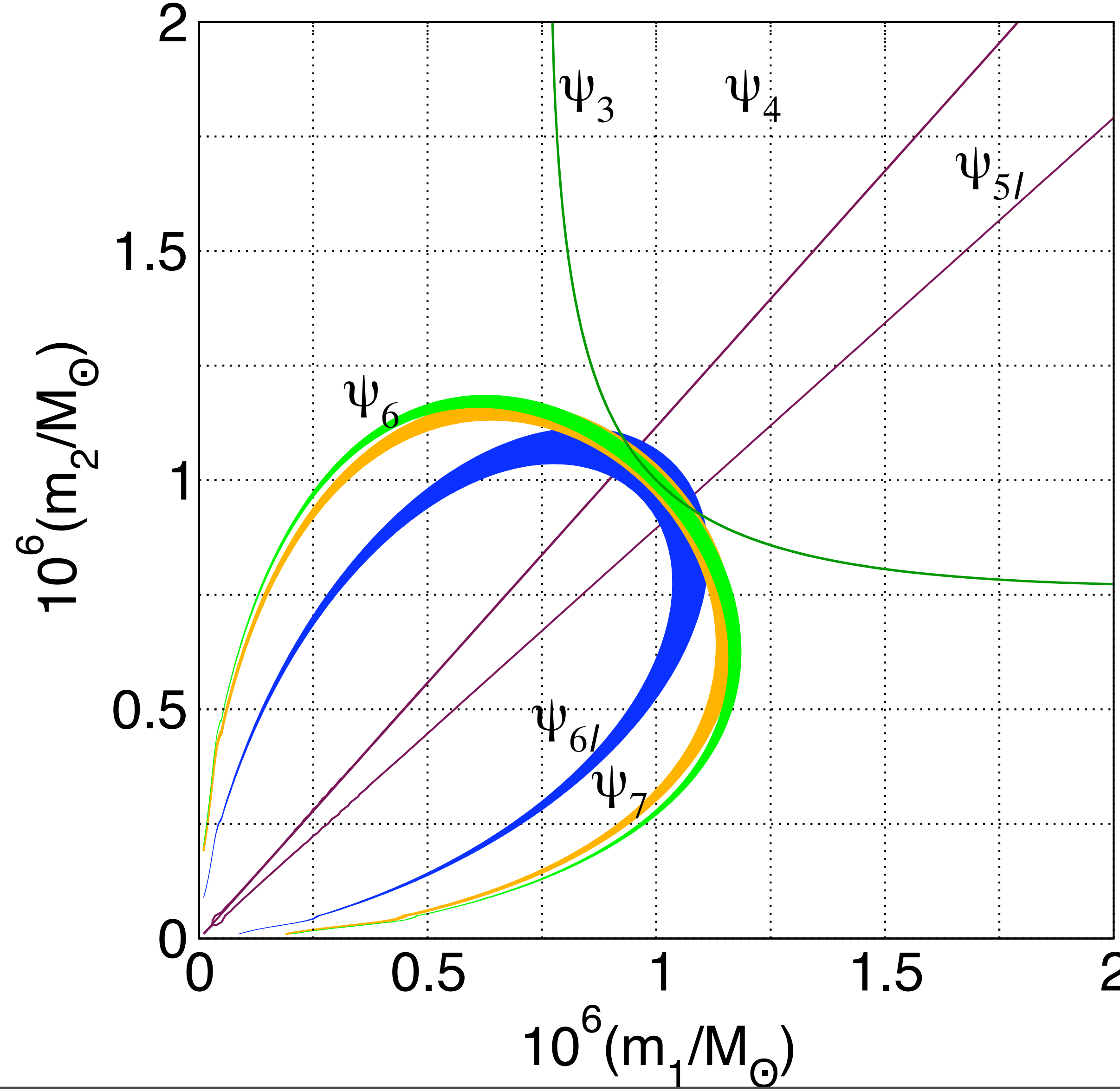
- Different terms arise because of different physical effects
- Measuring any two of these will fix the masses
- Other parameters will have to consistent with the first two

Arun, Iyer, Qusailah, Sathyaprakash (2006a, b)

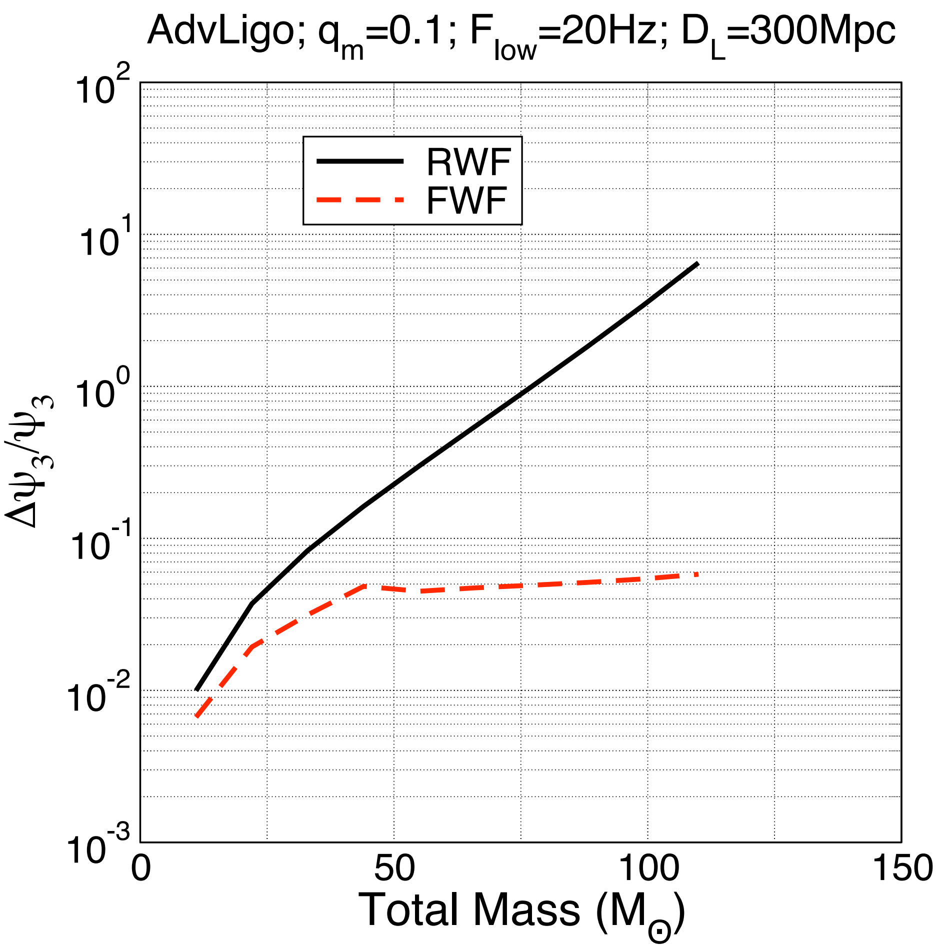
Testing post-Newtonian theory

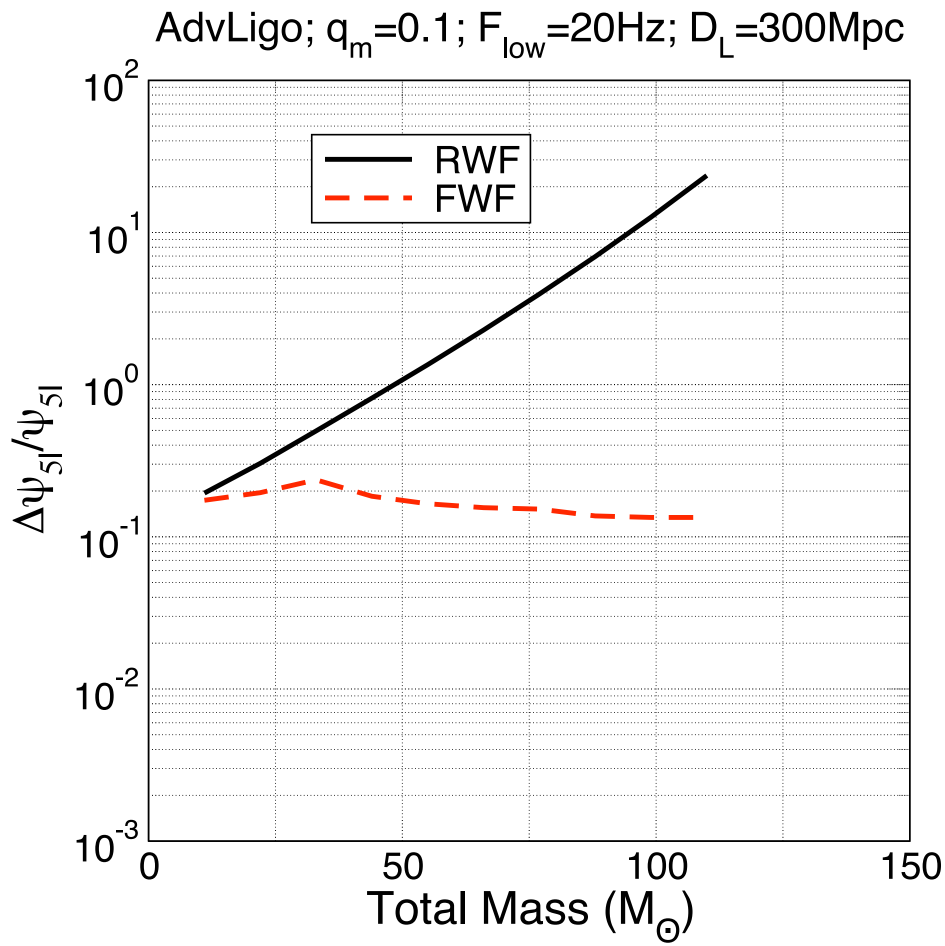
Arun, Iyer, Qusailah, Sathyaprakash (2006a, b)

LISA observation of a single super-massive black hole merger can test GR to a fantastic accuracy



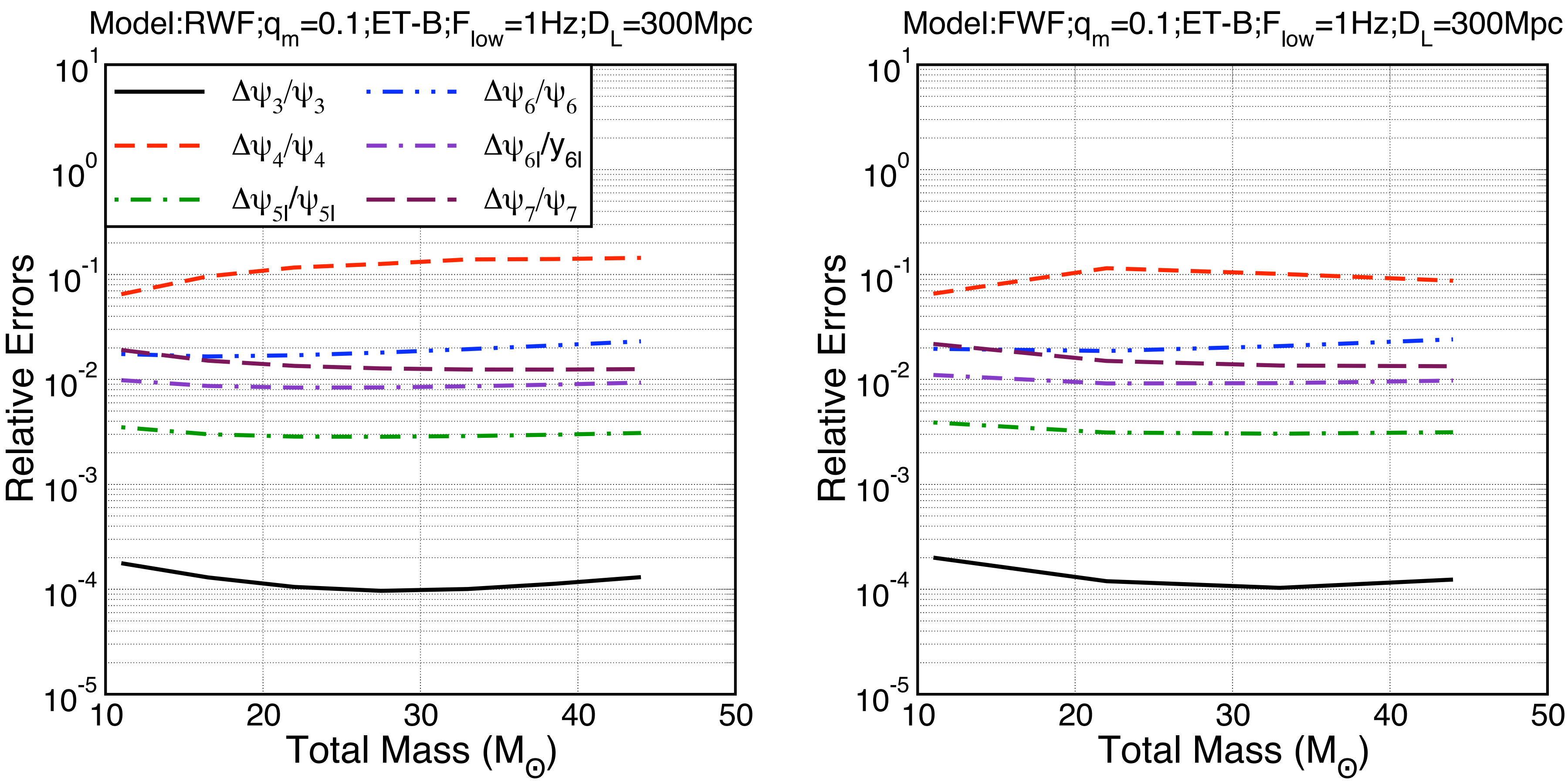
Confirming the presence of tail- and log-terms with Advanced LIGO





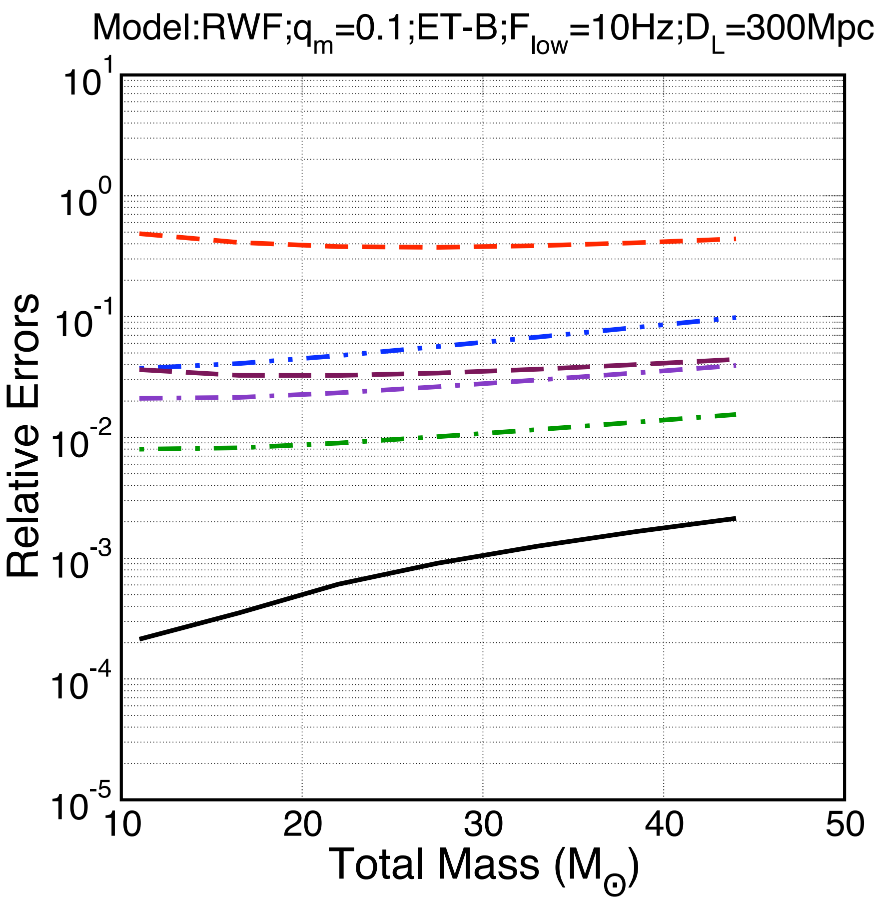
Arun, Mishra, Iyer, Sathyaprakash (2010)

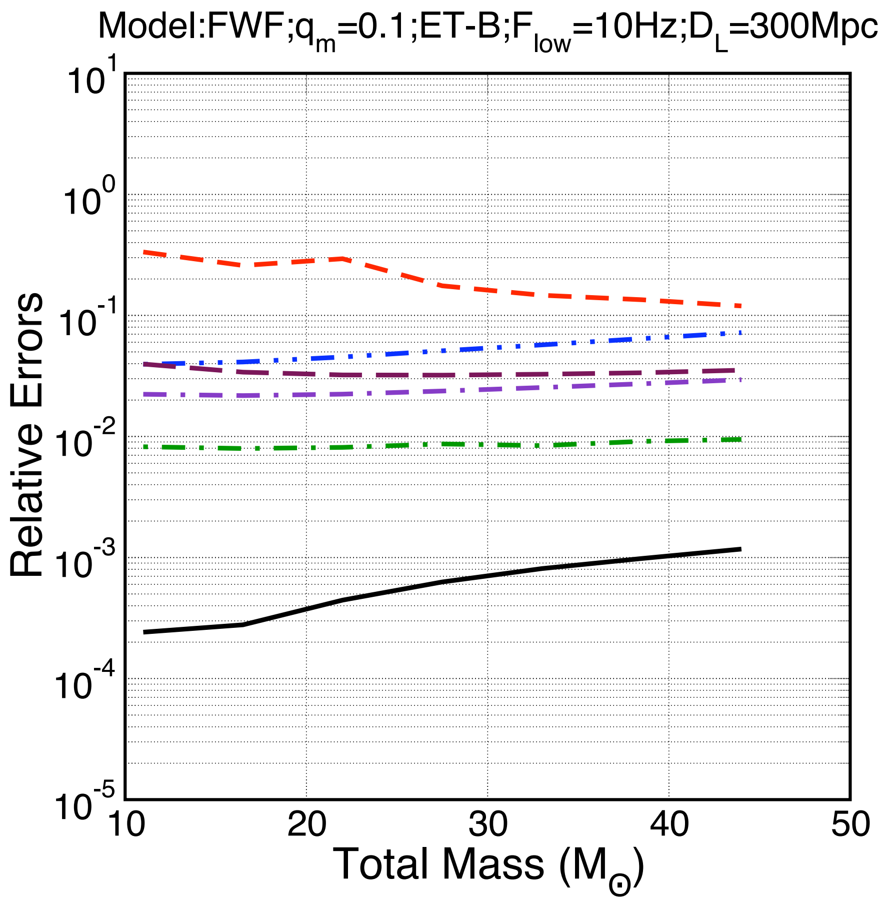
PN parameter accuracies with ET
1 Hz lower cutoff



Arun, Mishra, Iyer, Sathyaprakash (2010)

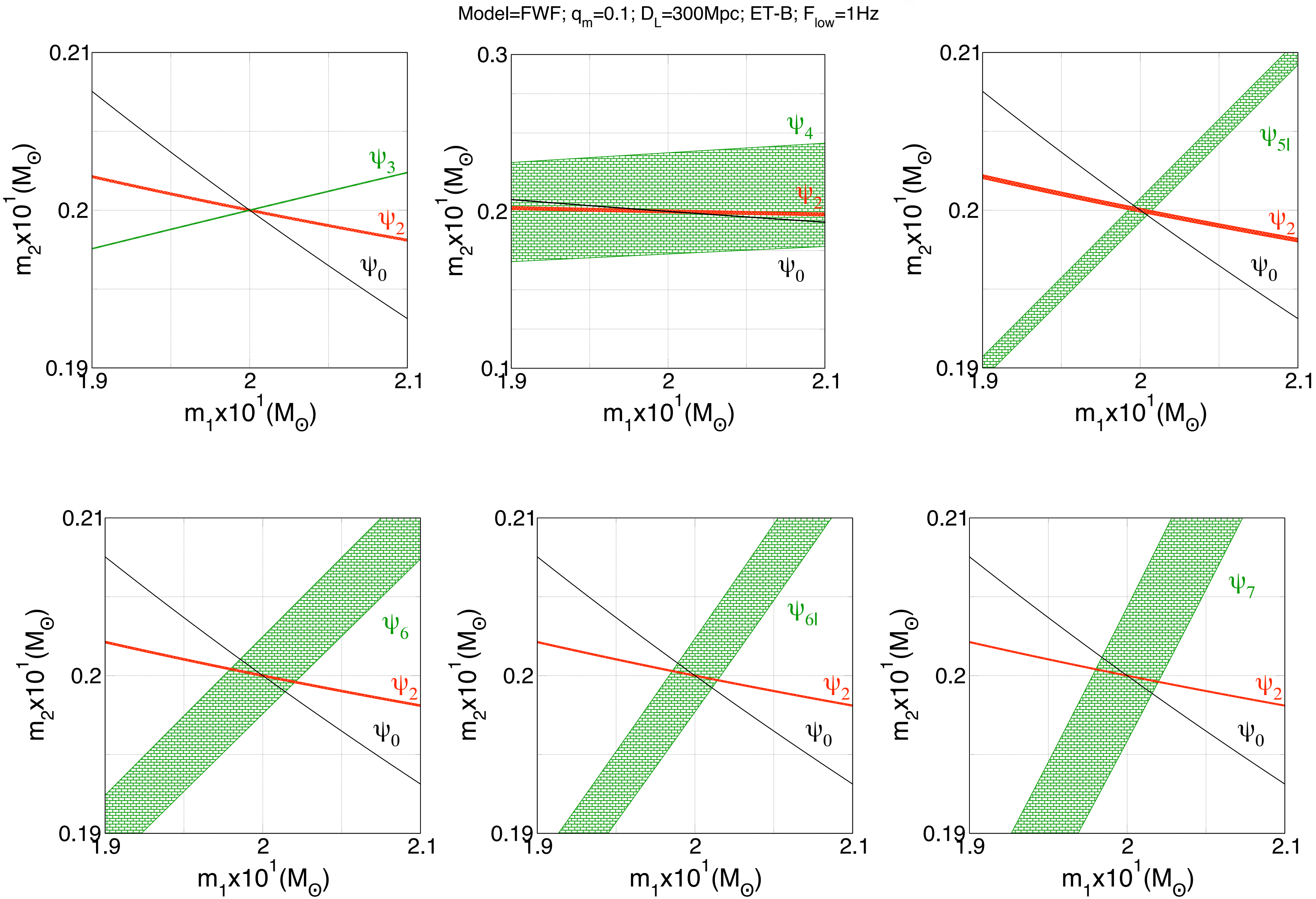
PN parameter accuracies with ET
10 Hz lower cutoff





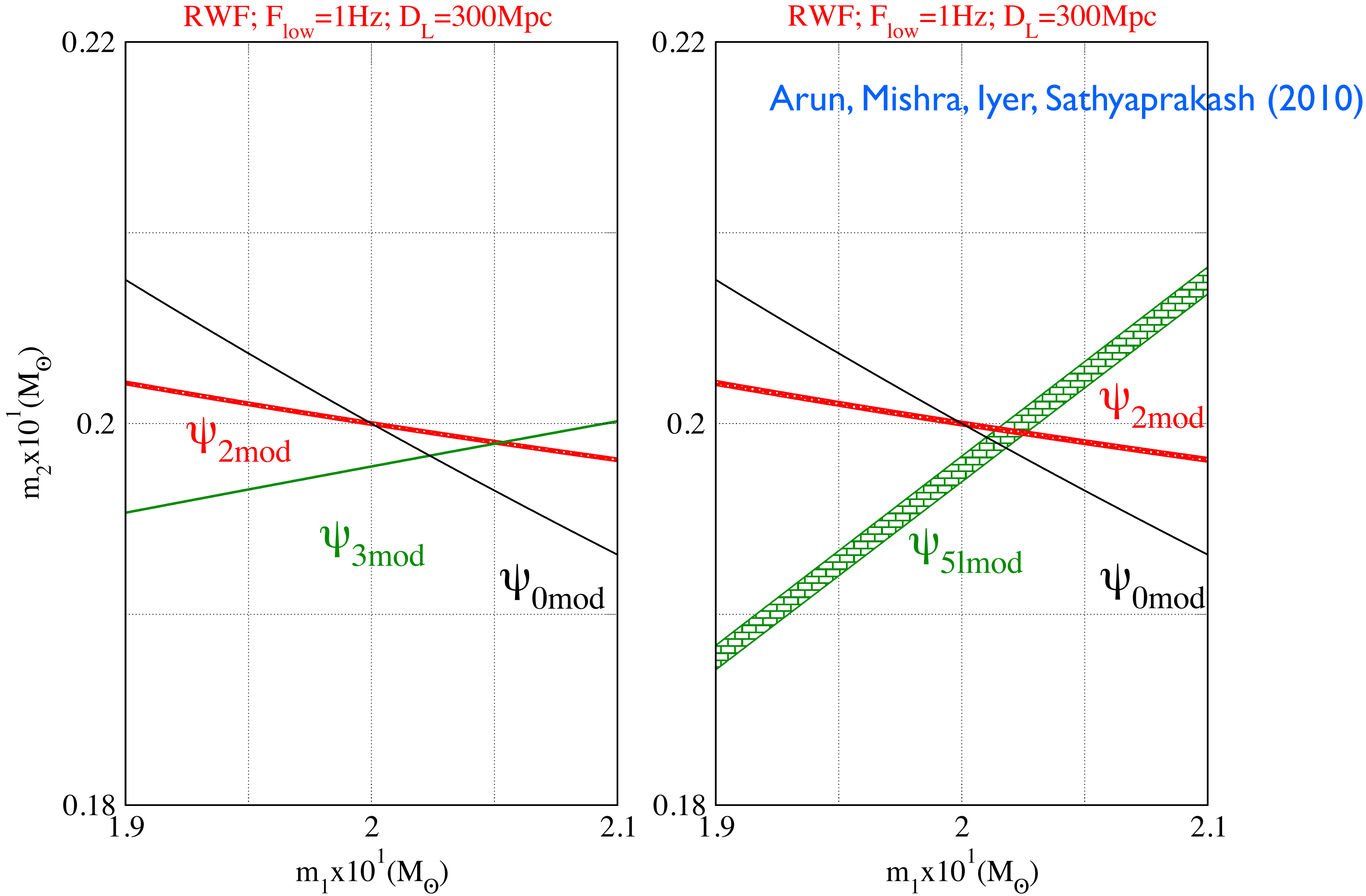
Arun, Mishra, Iyer, Sathyaprakash (2010)

Test as seen in the plane of component masses



Power of the PPN Test

Effect of changing the coefficients ψ_3 and ψ_{51} by 1% on the test.



NOTE: Reference System: (2-20) $(M_\odot)$

Cosmology: Measuring Dark Energy EoS with ET

Cosmology

- Cosmography
  - H_0, dark matter and dark energy densities, dark energy EoS w
- Black hole seeds
  - Black hole demographics and their hierarchical growth
- Anisotropic cosmologies
  - Is there a signature of anisotropy in cosmological parameters such as the Hubble constant?
- Primordial gravitational waves
  - Quantum fluctuations in the early Universe, stochastic BG
- Production of GW during early Universe phase transitions
  - Phase transitions, pre-heating, re-heating, etc.

Cosmological parameters

- Luminosity distance Vs. red shift depends on a number of cosmological parameters H_0, Ω_M, Ω_b, Ω_Λ, w, etc.

$$D_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz}{[\Omega_M (1+z)^3 + \Omega_\Lambda (1+z)^{3(1+w)}]^{1/2}}$$

- Advanced LIGO/Virgo/AIGO/LCGT network
  - Expected to detect many to 10's of BNS and NS-BH signals
- Einstein Telescope
  - Can detect 1000's of compact binary mergers for which the source can be identified (e.g. GRB) and red-shift measured.
- A fit to such observations can determine the cosmological parameters to good accuracy

Schutz 86

Compact Binaries are Standard Sirens

- Amplitude of gravitational waves depends on $h \propto \frac{\mathcal{M}^{5/6}}{D_\mathrm{L}}$
  - Chirp-mass=$\mu^{3/5}M^{2/5}$
- Gravitational wave observations can measure both
  - Amplitude (this is the strain caused in our detector)
  - Chirp-mass (because the chirp rate depends on the chirp mass)
- Therefore, binary black hole inspirals are standard sirens
  - From the apparent luminosity (the strain) we can conclude the luminosity distance
  - A new **model-independent** calibration for cosmic distance ladder
- However, GW observations alone cannot determine the red-shift to a source
- Joint gravitational-wave and optical observations can facilitate a new cosmological tool

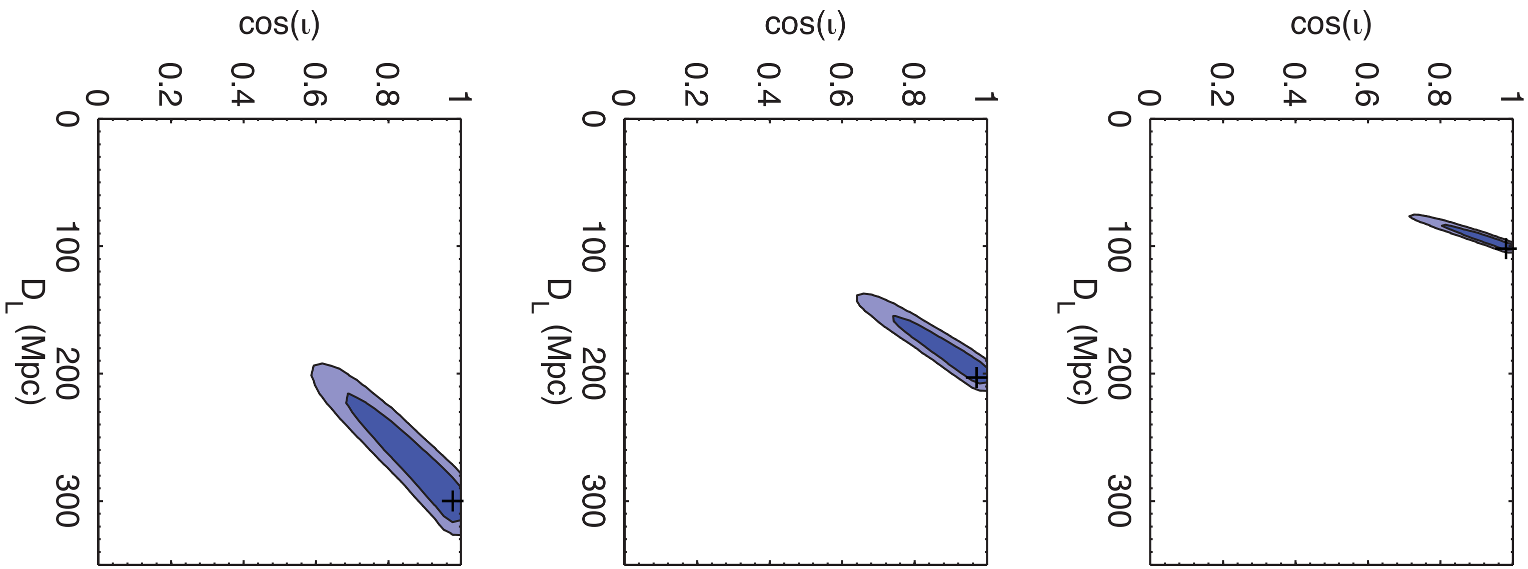
Hubble Constant from Advanced Detectors

EXPLORING SHORT GAMMA-RAY BURSTS AS GRAVITATIONAL-WAVE STANDARD SIRENS

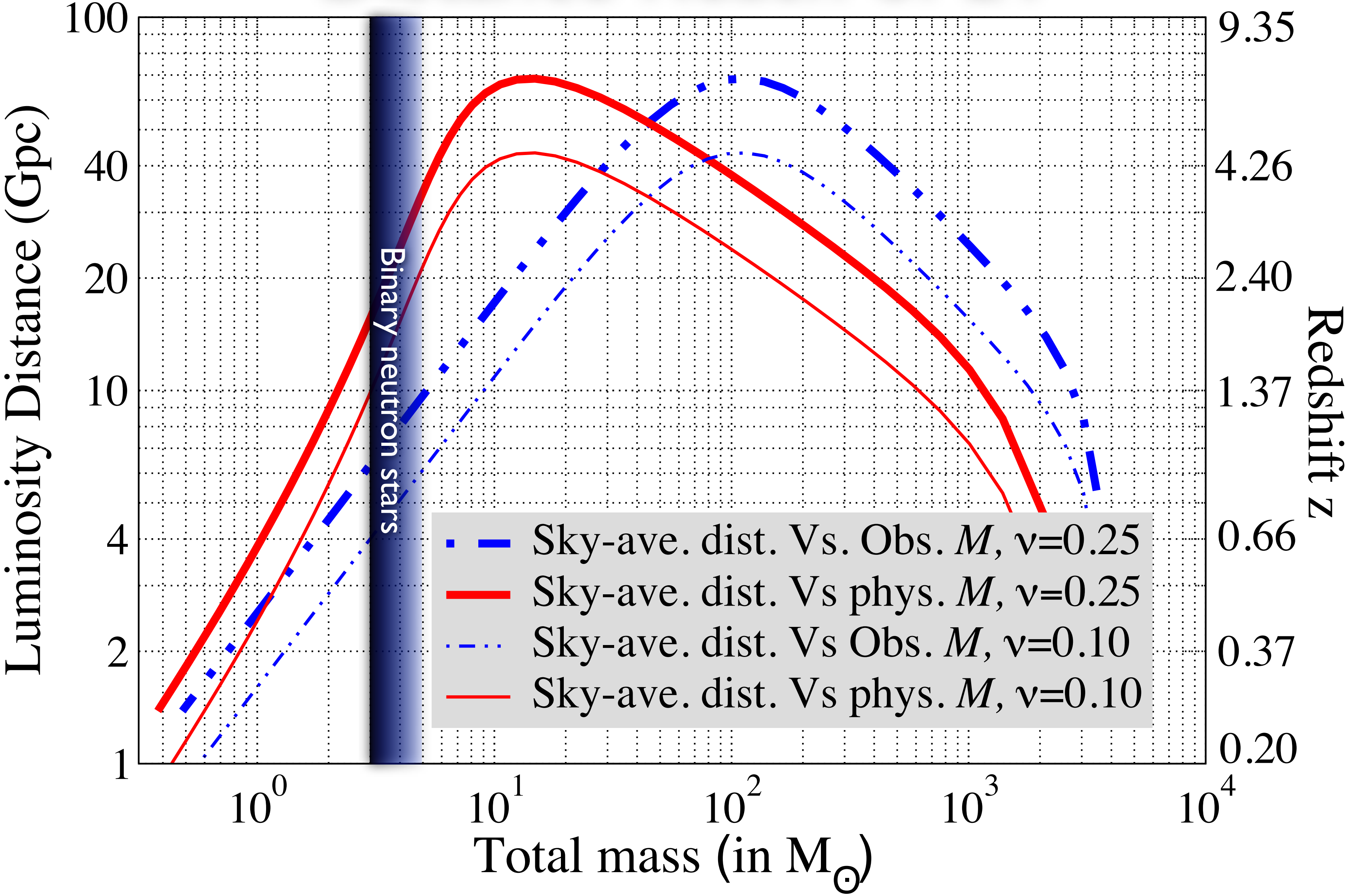
Samaya Nissanke[1,2], Scott A. Hughes[2], Daniel E. Holz[3], Neal Dalal[1], Jonathan L. Sievers[1]

Draft version April 7, 2009

we find that *one* year of observation should be enough to measure H_0 to an accuracy of $\sim 1\%$ if SHBs are dominated by beamed NS-BH binaries using the "full" network of LIGO, Virgo, AIGO, and LCGT—admittedly,

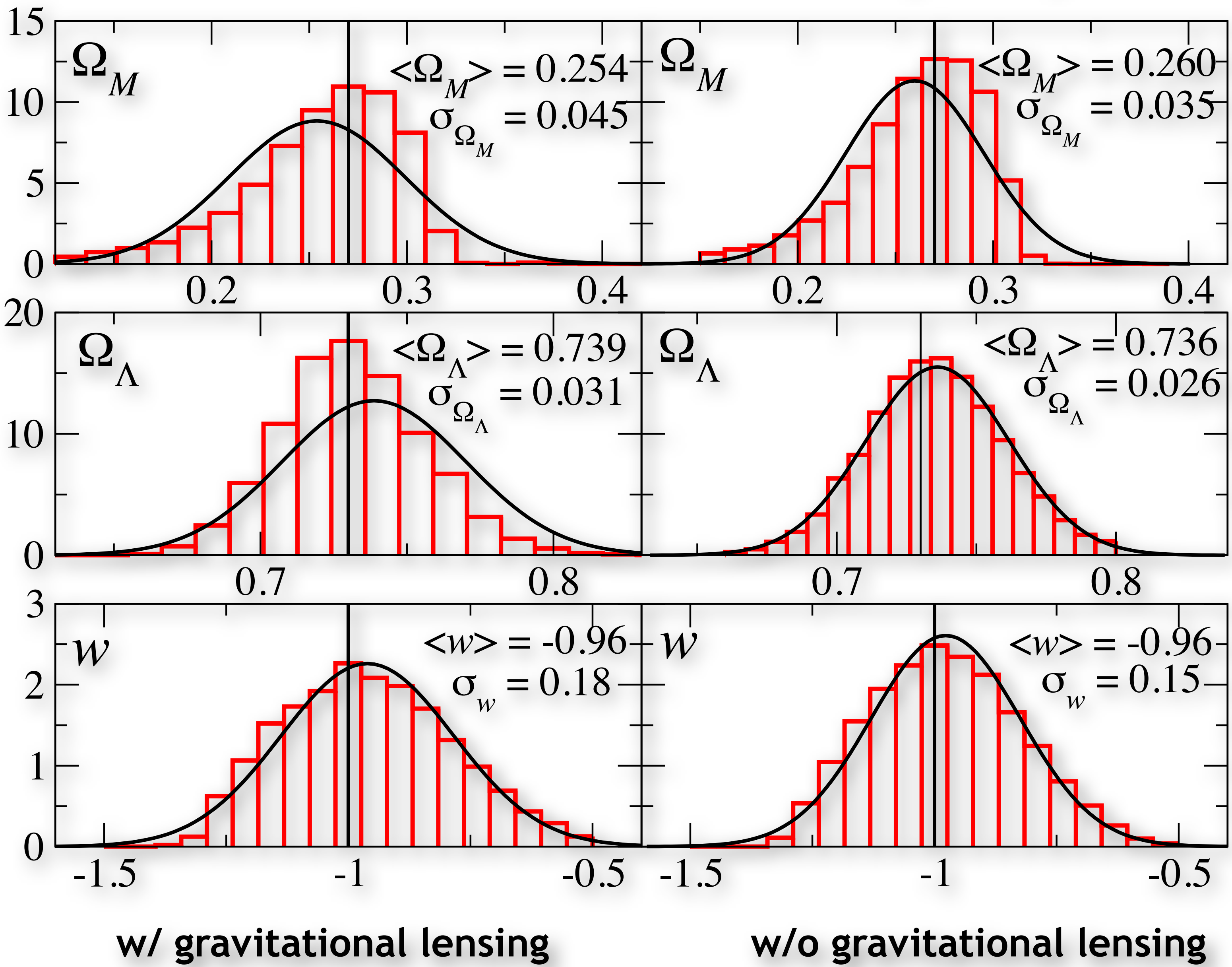


Distance Reach of ET

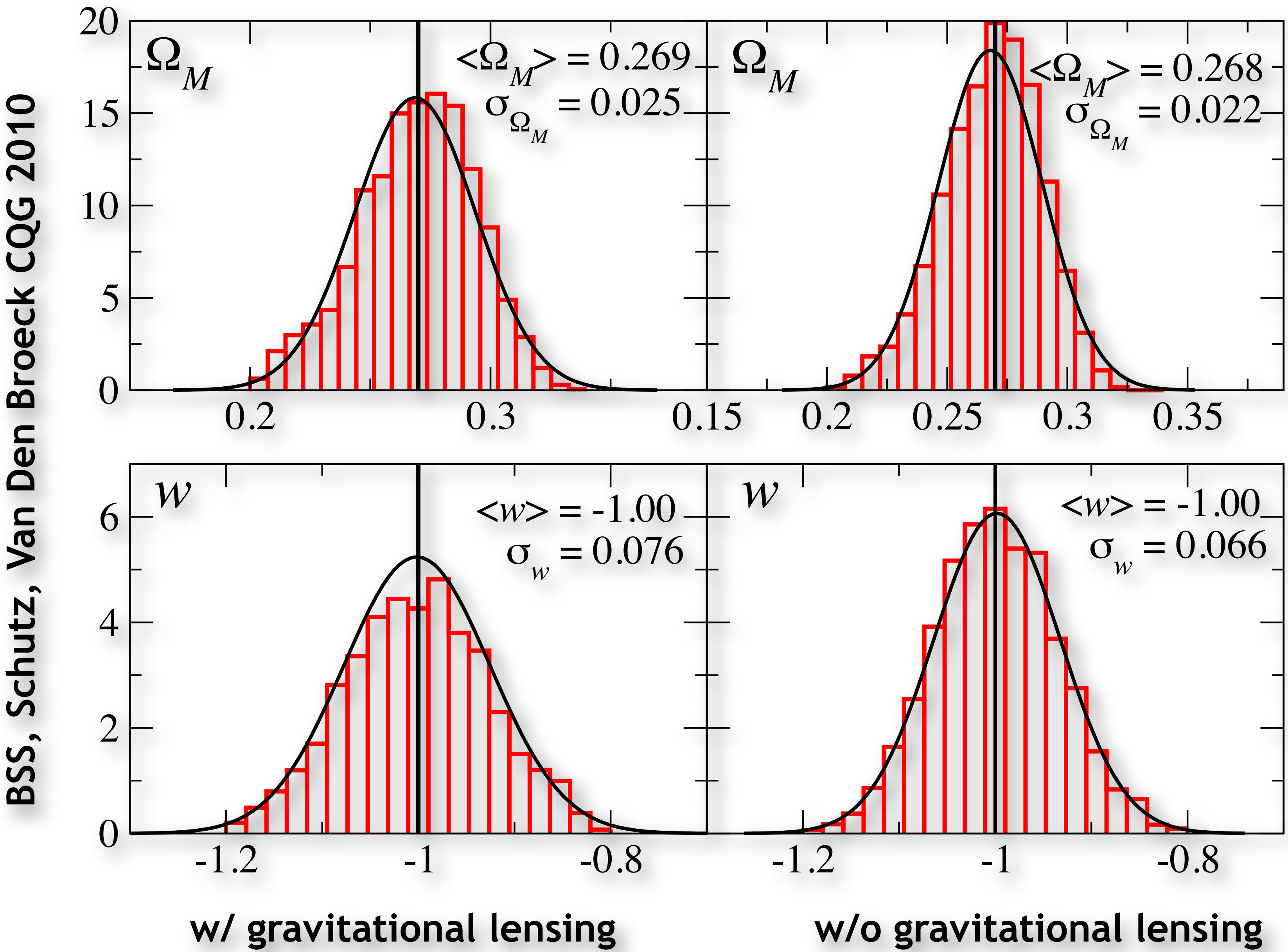


Measurement of *DM*, *DE*, *w*

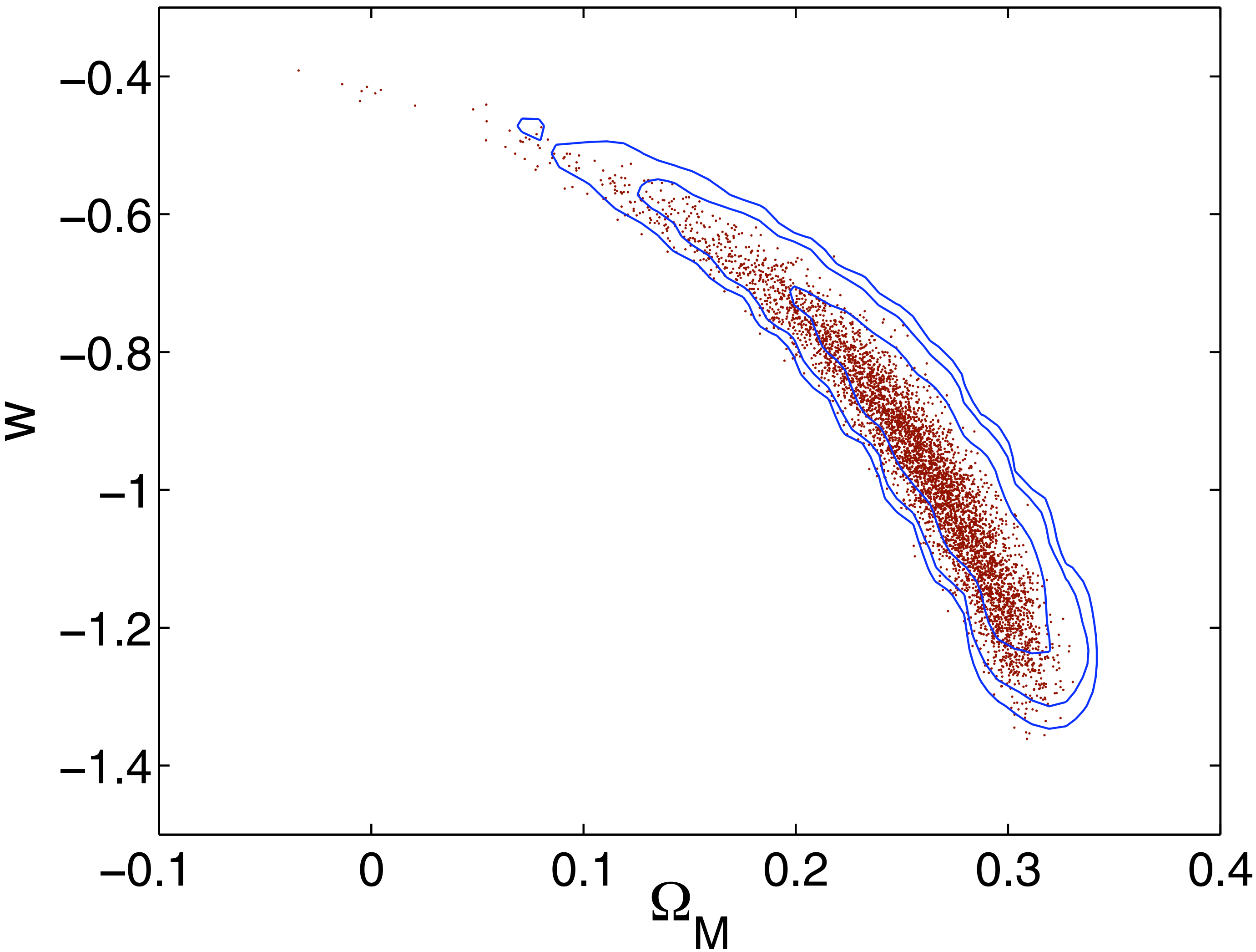
BSS, Schutz, Van Den Broeck, CQG 2010



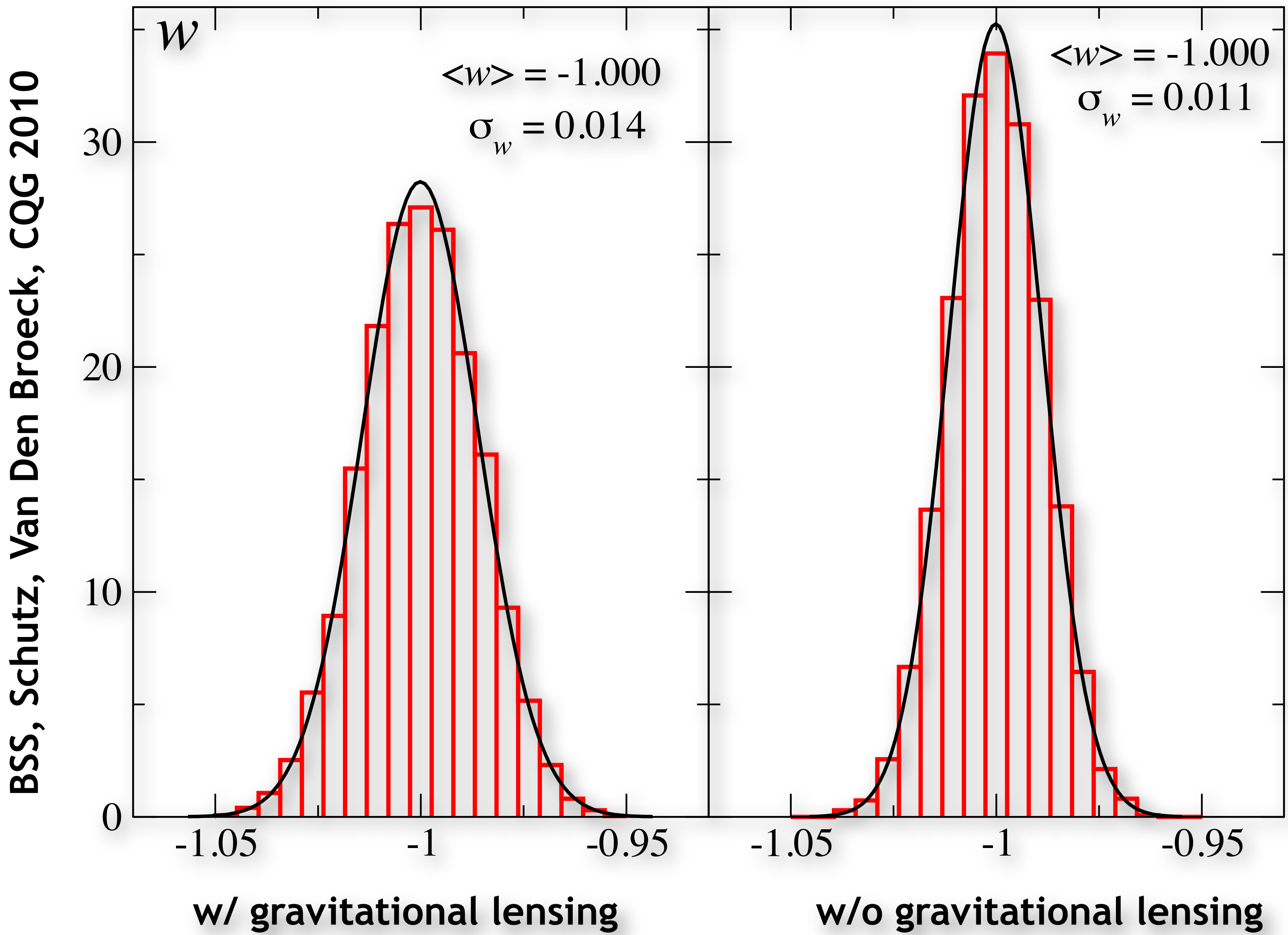
Measurement of *DM* and *w*



1- 2- and 3-Sigma Contours



Measurement of *w*



Astrophysics

- Unveiling progenitors of short-hard GRBs
  - Short-hard GRBs believed to be merging NS-NS or NS-BH
- Understanding Supernovae
  - Astrophysics of gravitational collapse and supernova?
- Evolutionary paths of compact binaries
  - Complex astrophysics drives the evolution
- Finding why pulsars glitch and magnetars flare
  - What causes sudden excursions in pulsar spin frequencies?
  - What is behind ultra high-energy transients in magnetars?
- Ellipticity of neutron stars
  - Mountains of what size can be supported on neutron stars?
- NS spin frequencies in LMXBs
  - Why are spin frequencies of neutron stars in low-mass X-ray binaries bounded, CFS instability and r-modes?
- Are massive objects at galactic nuclei really black holes?

Astrophysics: nature of central objects at galactic cores

Black Hole Spectroscopy: Test of GR and Test Black Hole Signature

O. Dreyer, B. Kelly, B. Krishnan, L. S. Finn, D. Garrison, and R. Lopez-Aleman, Class. Quantum Grav. **21**, 787 (2004), gr-qc/0309007.

- Black hole quasi-normal modes are damped sinusoids with characteristic frequencies and decay times
  - In general relativity frequencies f_{lmn} and decay times t_{lmn} all depend only on the mass M and spin q of the black hole
- Measuring two or modes unambiguously, would severely constrain general relativity
  - If modes depend on other parameters (e.g., the structure of the central object), then test of the consistency between different mode frequencies and damping times would fail

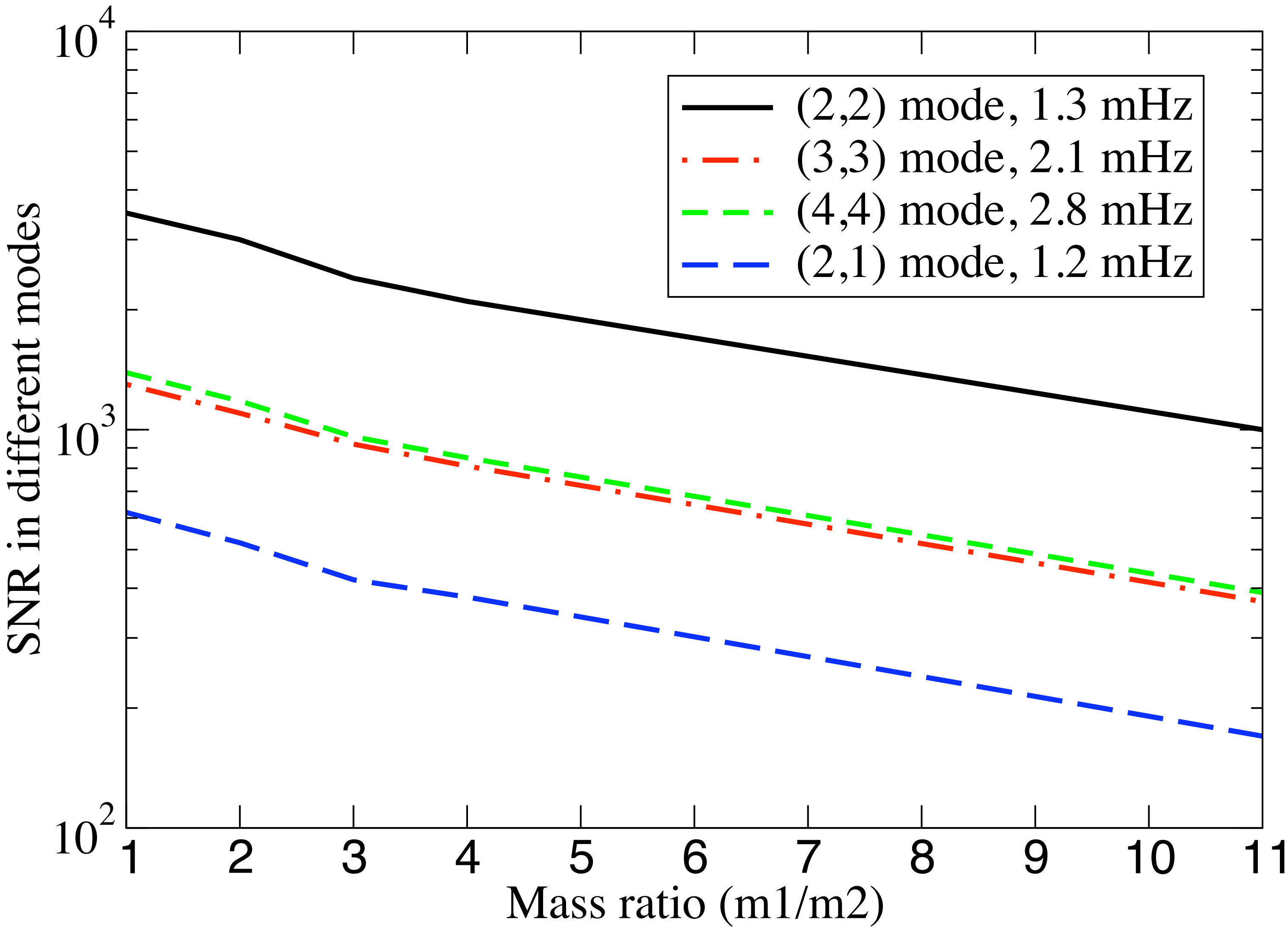
Emitted energy and relative amplitudes of different quasi-normal modes

Table 1: For different mass ratios (*q*=1, 2, 3, 4, 11), we show the final spin of the black hole, percent of energy in the radiation, amplitude of (2,1), (3,3), (4,4) modes relative to (2,2) mode.

q	j	% total energy	A_{21}/A_{22}	A_{33}/A_{22}	A_{44}/A_{22}
1	0.69	4.9	0.04	0.00	0.05
2	0.62	3.8	0.05	0.13	0.06
3	0.54	2.8	0.07	0.21	0.08
4	0.47	2.2	0.08	0.25	0.09
11	0.25	0.7	0.14	0.31	0.14

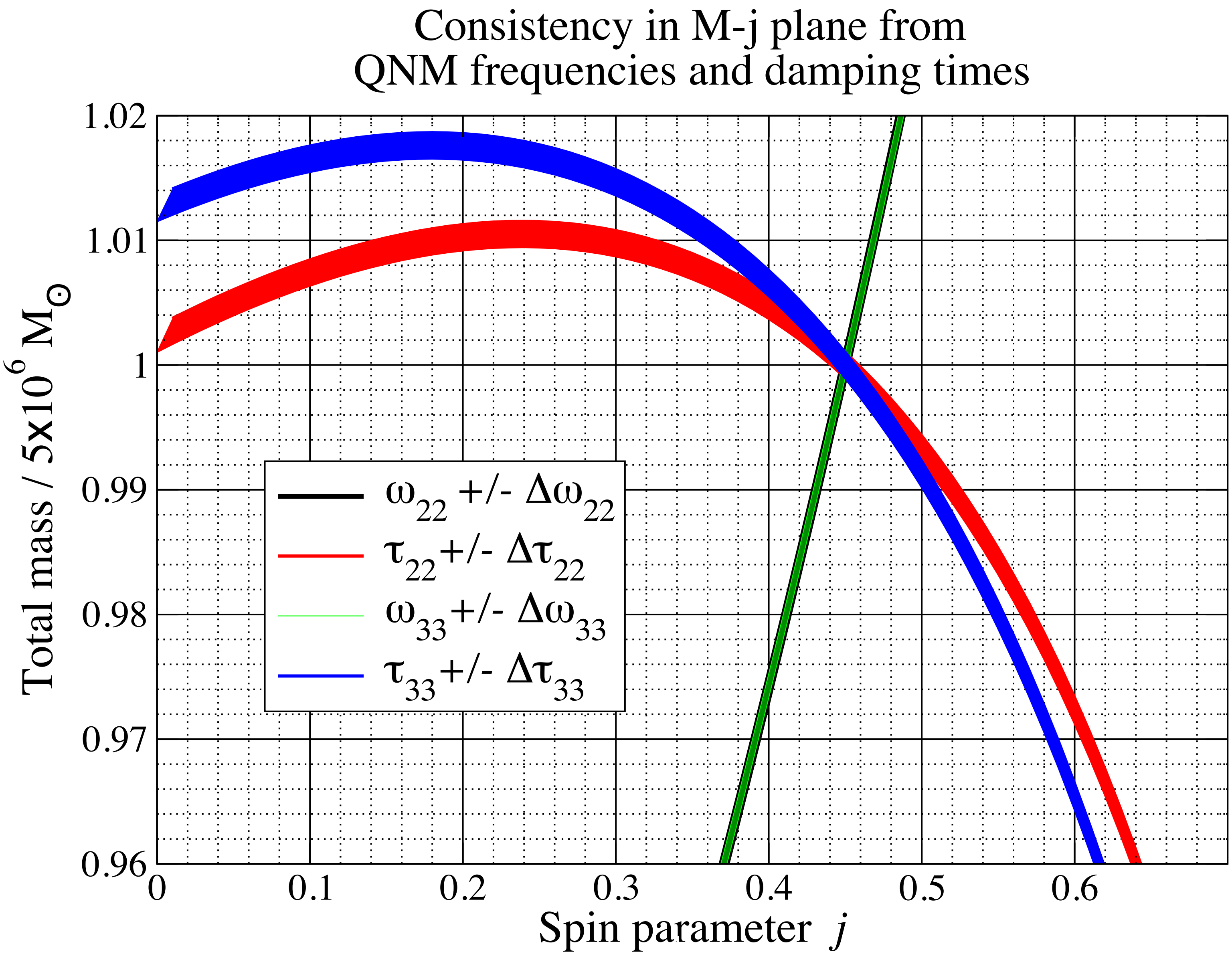
Kamaretsos, Hannam, Husa, Sathyaprakash, 2010

LISA SNRs for different QNMs

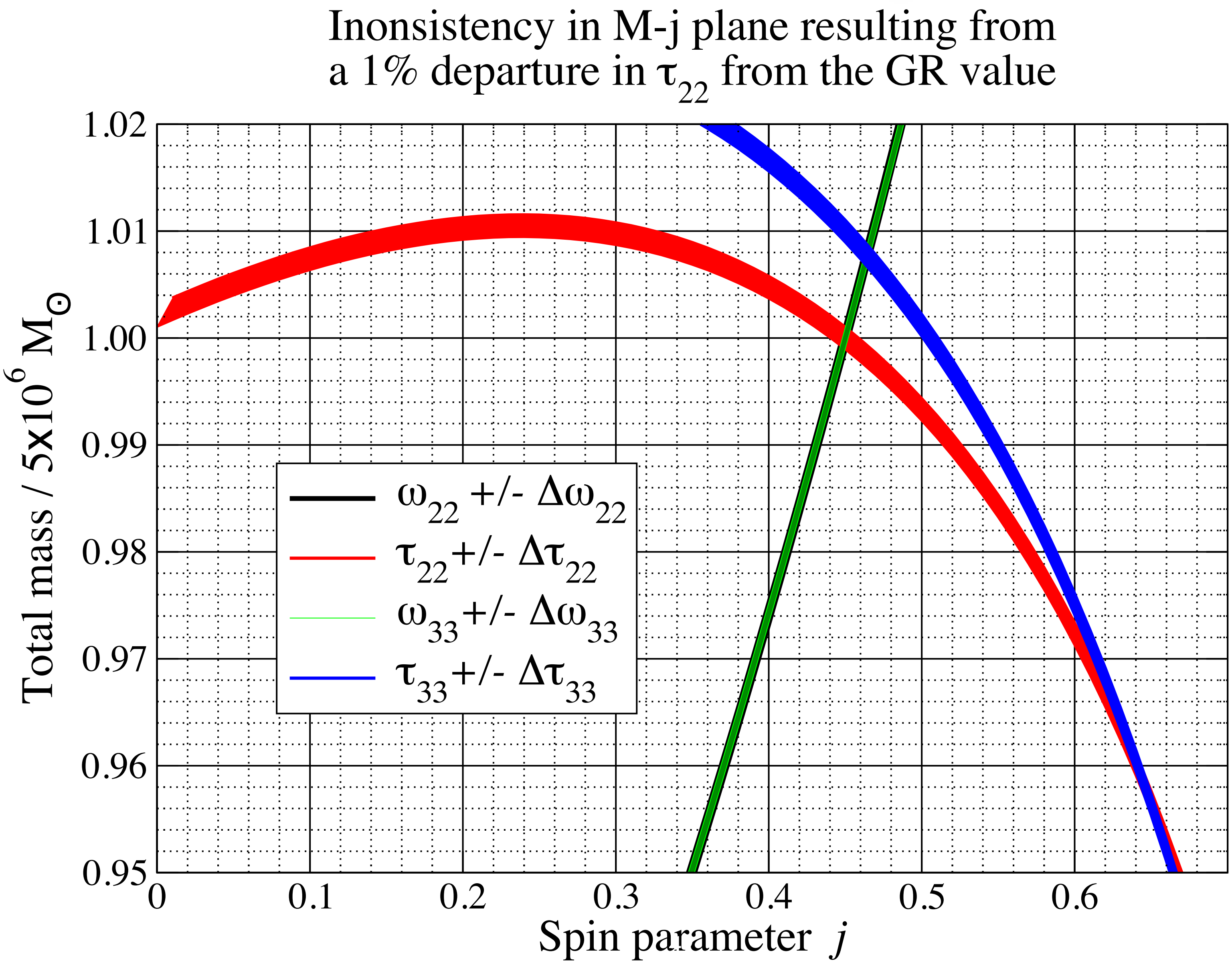


Kamaretsos, Hannam, Husa, Sathyaprakash, 2010

How can QNMs help test GR?



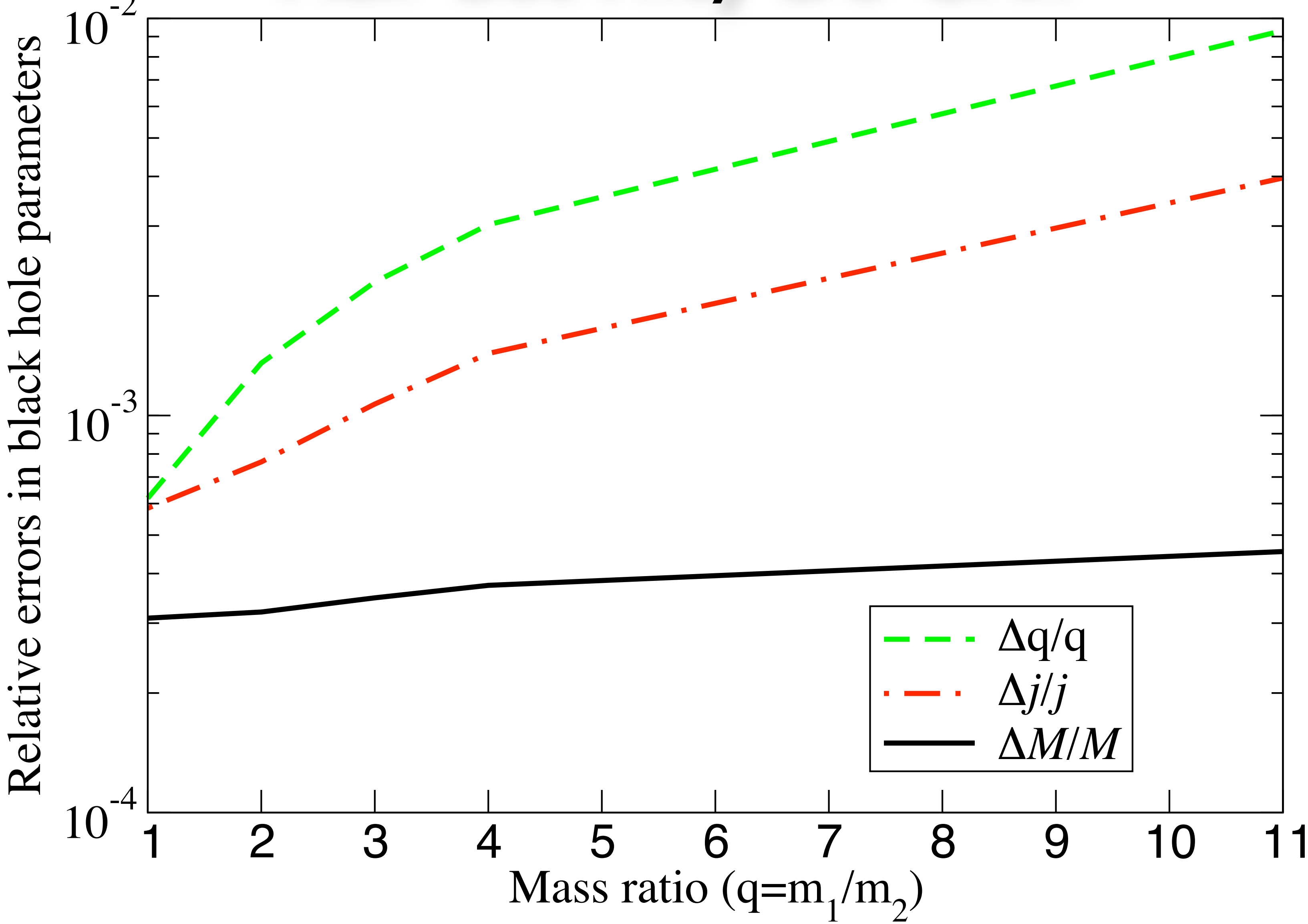
How can QNMs help test GR?



Black Holes Ain't Got No Hair But They Do Grin

- Black hole no hair theorems don't apply to deformed black holes
- From the ringdown signals it should in principle be possible to infer the nature of the perturber
- In the case of binary mergers it should be possible to measure the masses and spins of the progenitor binary from the quasi-normal modes of the final black hole

Black Holes Ain't Got No Hair But They Do Grin



Conclusions

- Gravitational-wave observations offer new tests of general relativity in the dissipative strongly non-linear regime
  - Advanced LIGO can already test tails of gravitational waves and the presence of the log-term in the PN expansion
  - Einstein Telescope will measure all known PN coefficients (except one at 2PN order) to a good accuracy
- A new "powerful" tool for cosmology
  - Measurement of cosmological parameters avoiding the cosmic distance ladder
- Black hole quasi-normal modes will be very useful in testing GR
  - Consistency between different mode frequencies and damping times can be used to constrain GR
  - Ringdown modes can be used to measure component masses of progenitor binary and test predictions of numerical relativity