Testing theories of gravity using upcoming gravitational-wave observations

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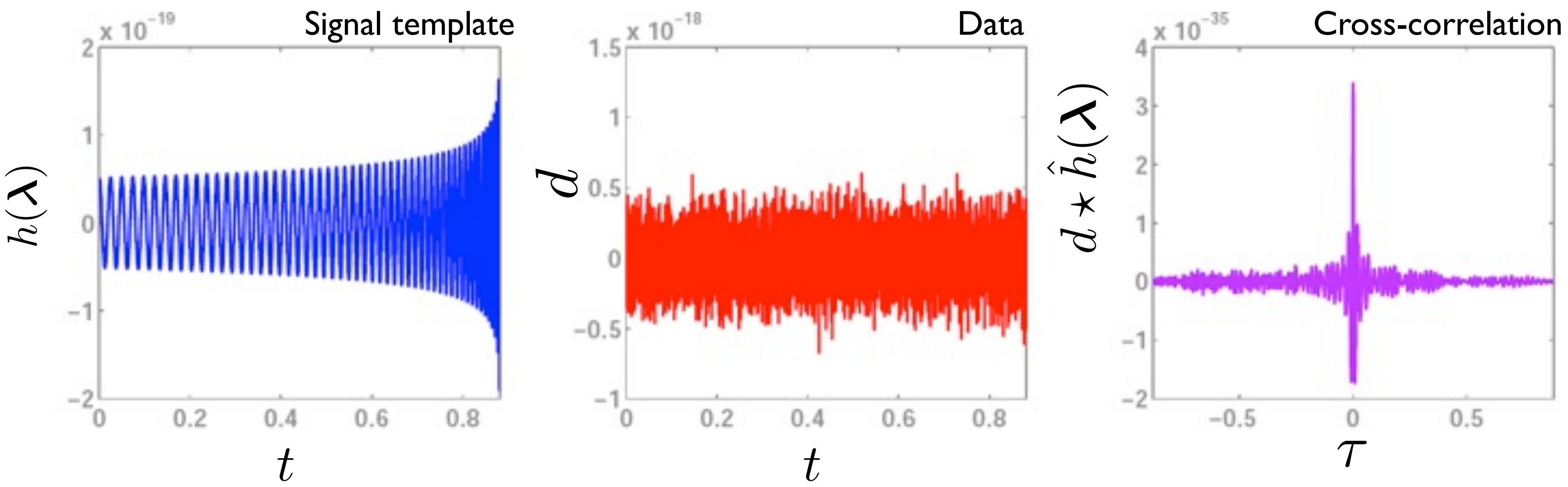
Extracting information from GW observations

- For sources such as CBCs, expected signals are well-modelled in GR. Weak signals buried in the noise can be detected by cross-correlating the data with "banks" of theoretical templates.

$$\underbrace{\rho}_{\text{SNR}} \equiv \max_{\boldsymbol{\lambda}} \left[\underbrace{d}_{\text{data}} \star \underbrace{\hat{h}}_{\text{signal template}}(\underbrace{\boldsymbol{\lambda}}_{\text{source parameters}}) \right]$$



Extracting information from GW observations

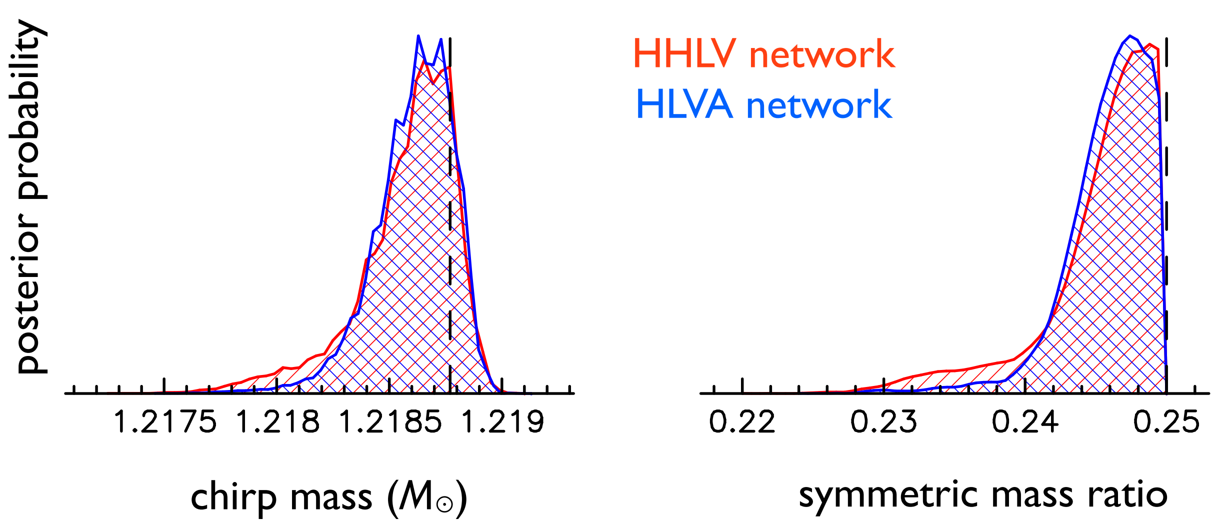
- Posterior distribution of the source parameters can be estimated by Bayesian inference.

prior distribution
of parameter λ

$$p(\boldsymbol{\lambda}|d) \propto p^0(\boldsymbol{\lambda})\, \mathcal{L}(d|\boldsymbol{\lambda})$$

posterior distribution
of λ, given data d

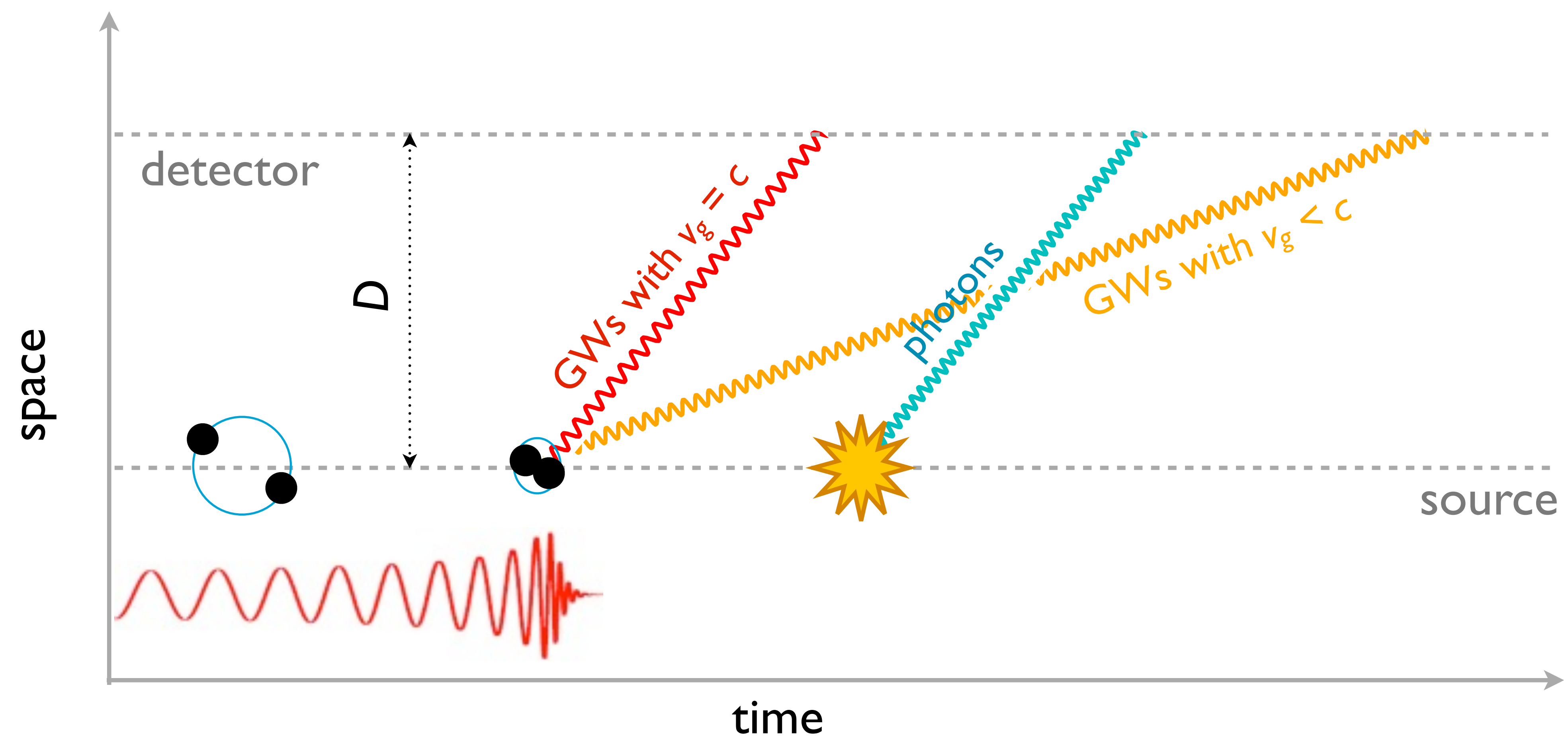
likelihood of d,
given λ



[Veitch et al (2012)]

Speed of GWs from joint GW-EM measurements

- Time-delay between GW and EM (γ-ray) signals from SGRBs can constrain the speed of GWs [Will 1998].



Tests of GR using GW observations

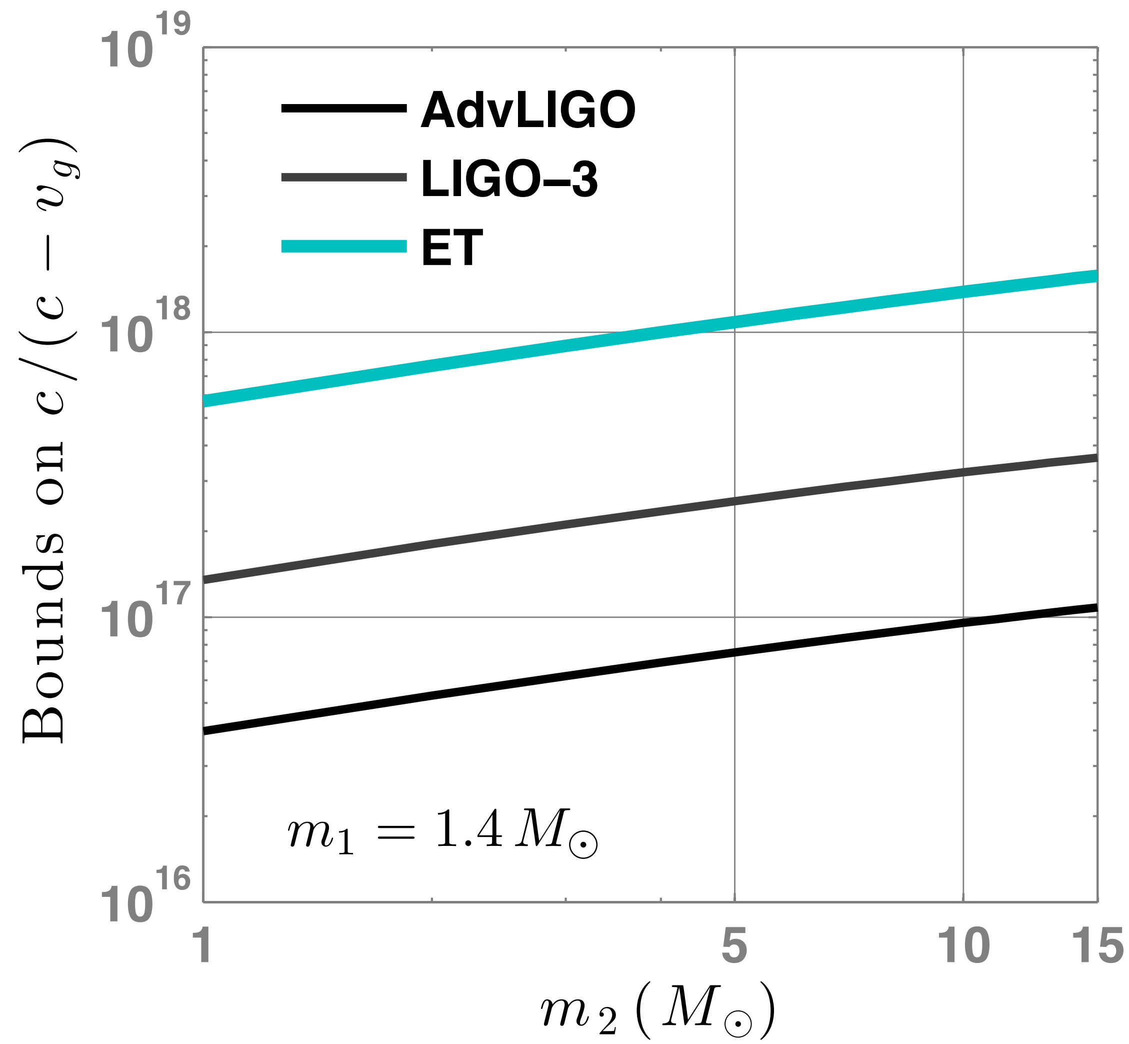
- Time-delay between GW and EM (γ-ray) signals from SGRBs can constrain the speed of GWs [Will 1998].

distance to the source

$$\frac{c}{c - v_g} = \frac{D}{c\,\Delta t}$$

speed of GWs (v_g= c in GR)

observed time-difference btwn the GW & EM signals



From the coincident GW+EM observation (Δt = 1sec) of one SGRB, powered by NSBH merger (located at the horizon distance).

Mass of the graviton from joint GW-EM measurements

- A bound on v_g implies a bound on the graviton-mass [Will 1998].

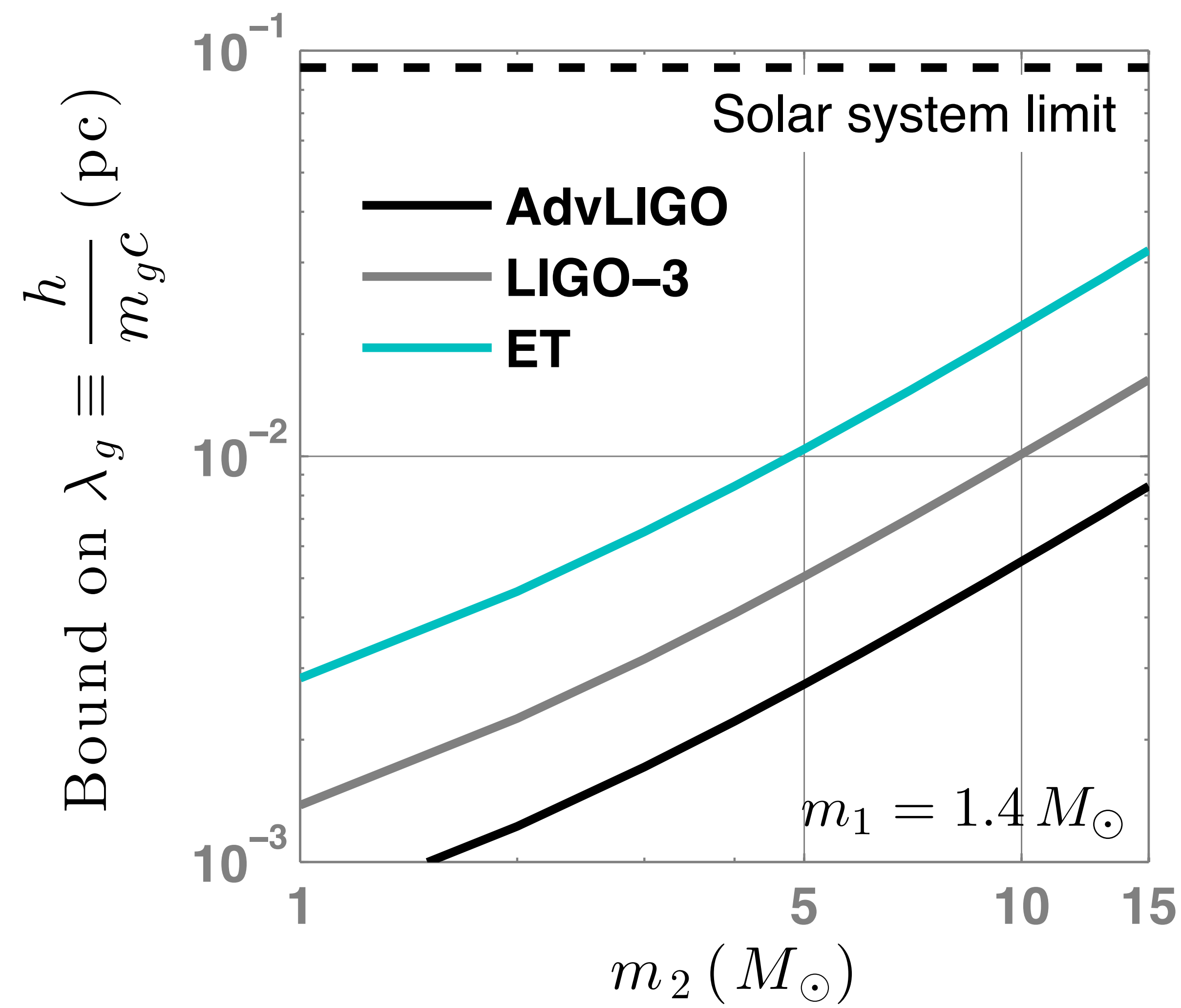
Dispersion relation

$$v_g^2/c^2 = 1 - m_g^2\, c^4/E_g^2$$

speed of GWs
(v_g= c in GR)

rest mass of
the graviton
(m_g= 0 in GR)

energy of
the graviton



From the coincident GW+EM observation (Δt = 1sec) of *one* SGRB, powered by NSBH merger (located at the horizon distance).

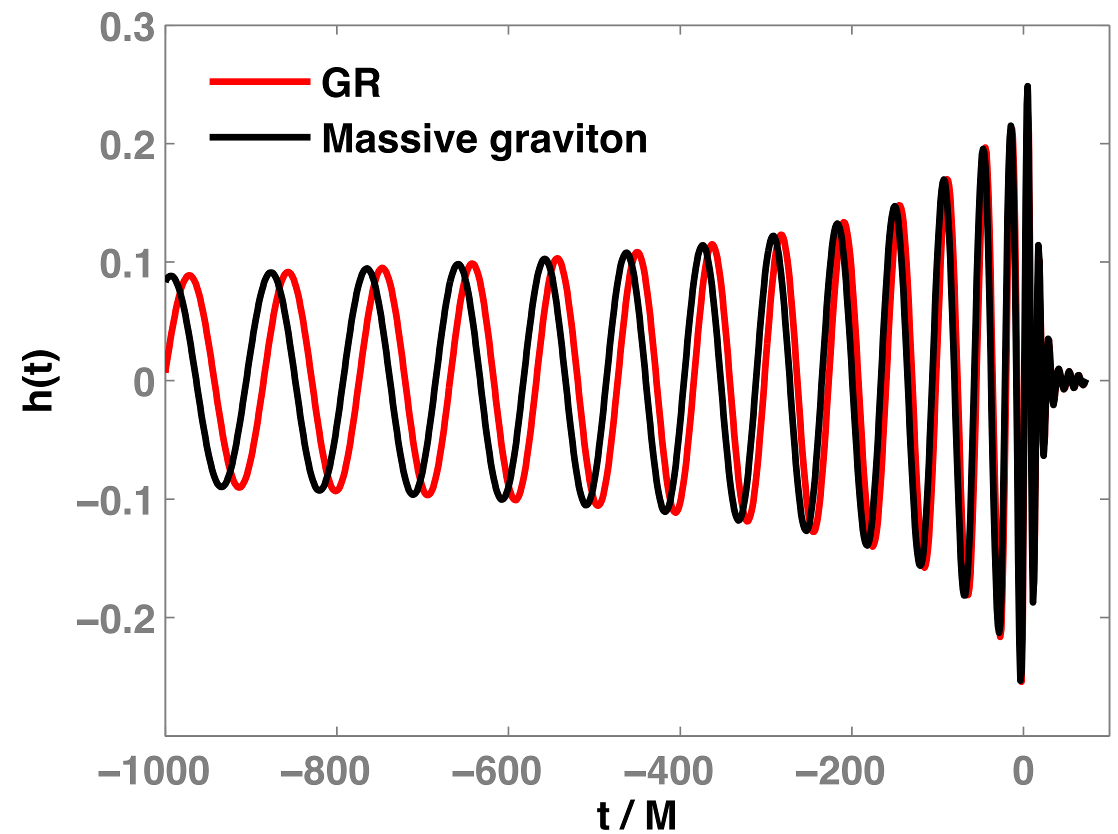
Parametrized deviations from GR: Mass of the graviton

- GW observations of CBCs can constrain the mass of graviton without relying on an EM counterpart. [Will 1998].

hf$_{GW}$

$$v_g^2/c^2 = 1 - m_g^2\, c^4/E_g^2$$

Different frequency components travel with different speeds → characteristic deformation in the observed signal!



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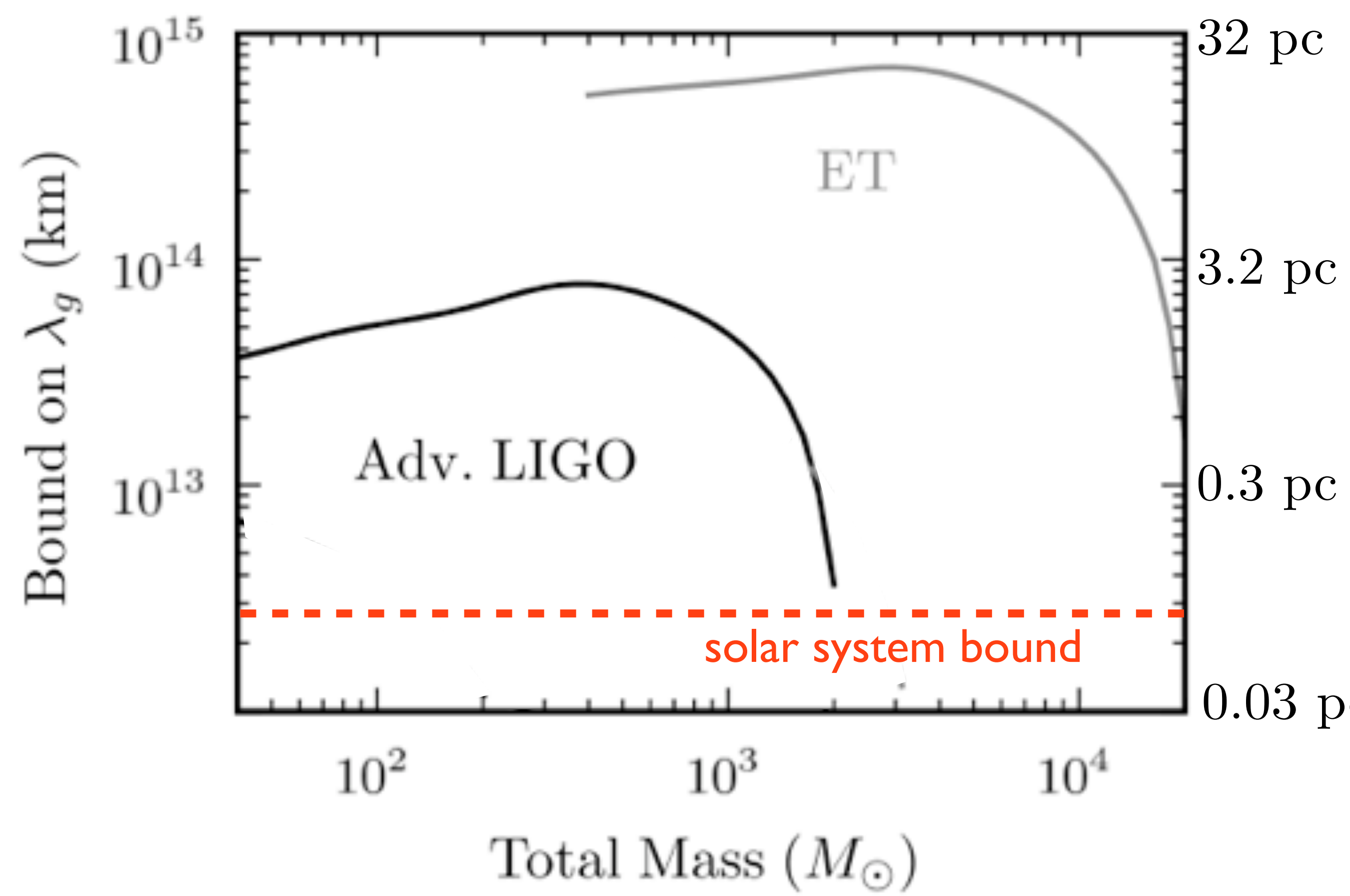
[Keppel & Ajith (2010)]



Expected bounds on the Compton wavelength of the graviton from BBH observations by future detectors. (d_L = 1 Gpc)

Parametrized deviations from GR: Mass of the graviton

- GW observations of CBCs can constrain the mass of graviton without relying on an EM counterpart. [Will 1998].

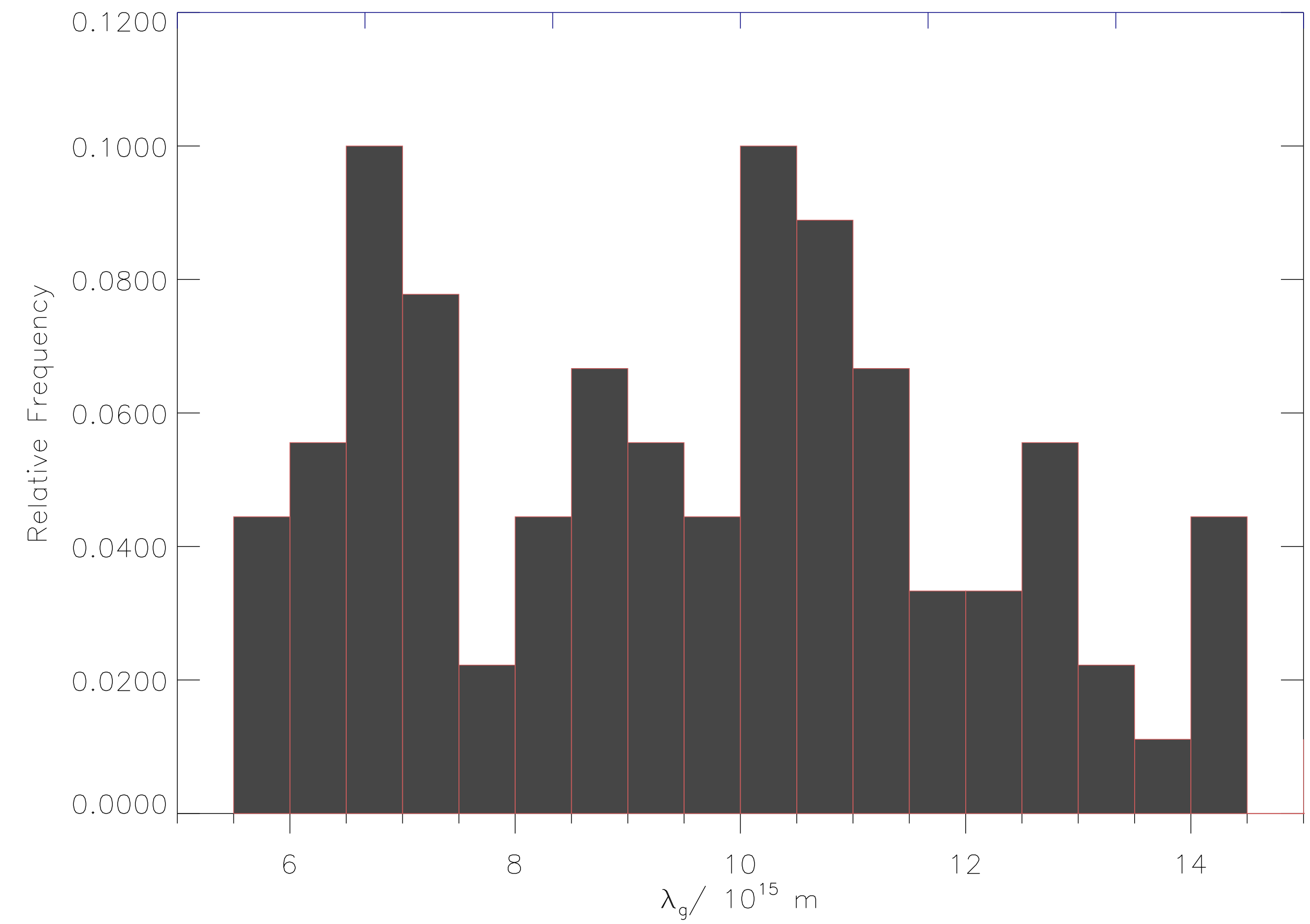
prior

$$p(\boldsymbol{\lambda}|d) \propto p^0(\boldsymbol{\lambda})\, \mathcal{L}(d|\boldsymbol{\lambda})$$

posterior distribution of $\boldsymbol{\lambda}$, given data d

likelihood of d, given $\boldsymbol{\lambda}$

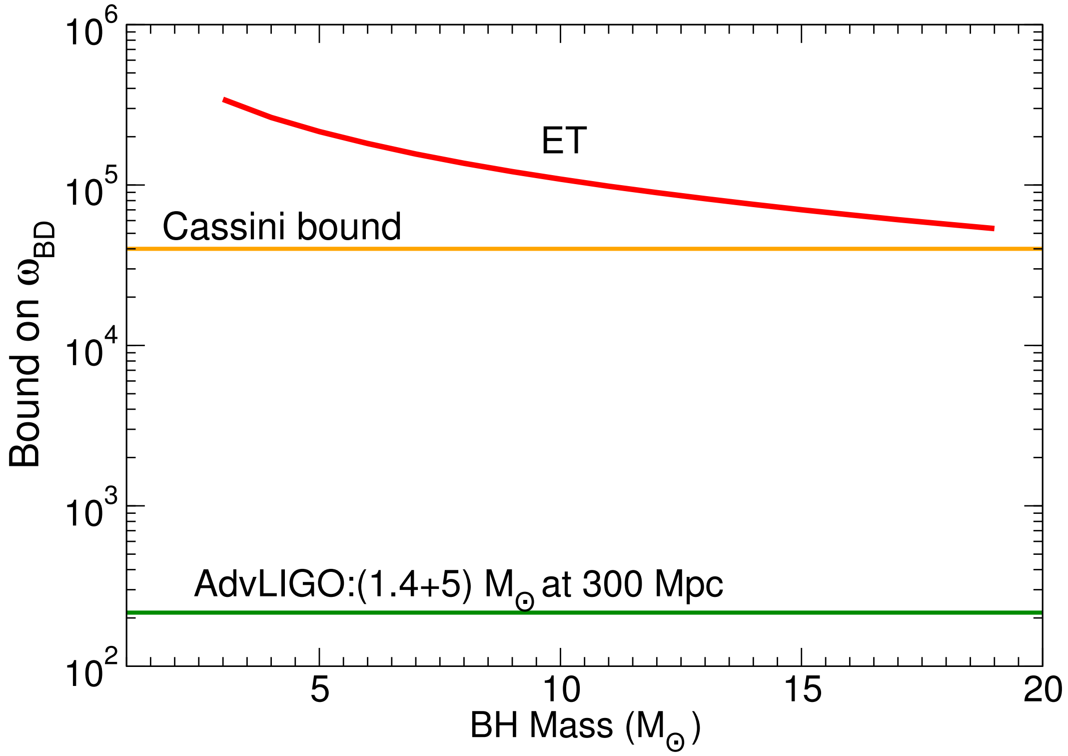
[Del Pozzo et al (2011)]



95% lower bound on the Compton wavelength of the graviton obtained from 100 simulated detections with 5 < SNR < 25.

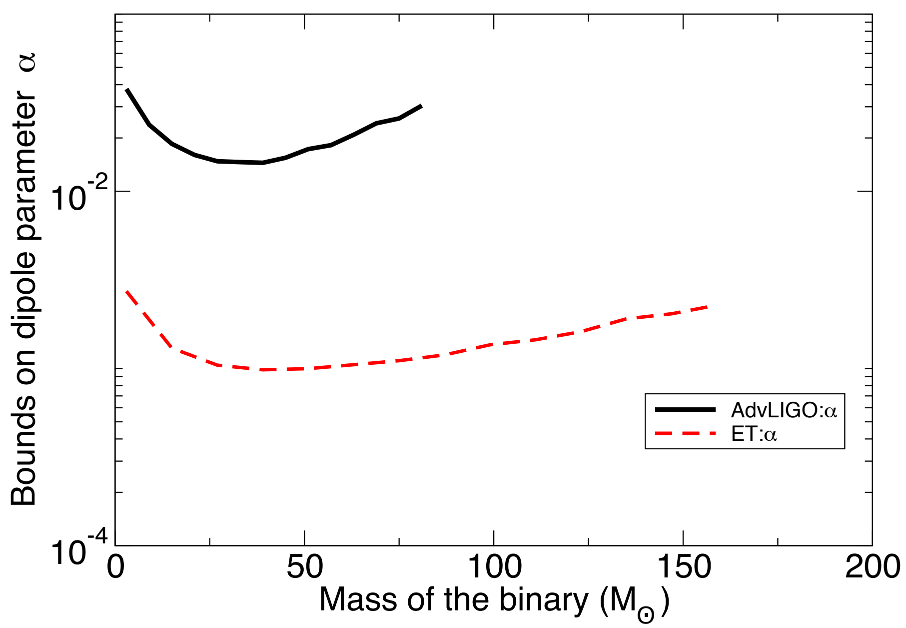
Parametrized deviations from GR: Scalar-tensor theories

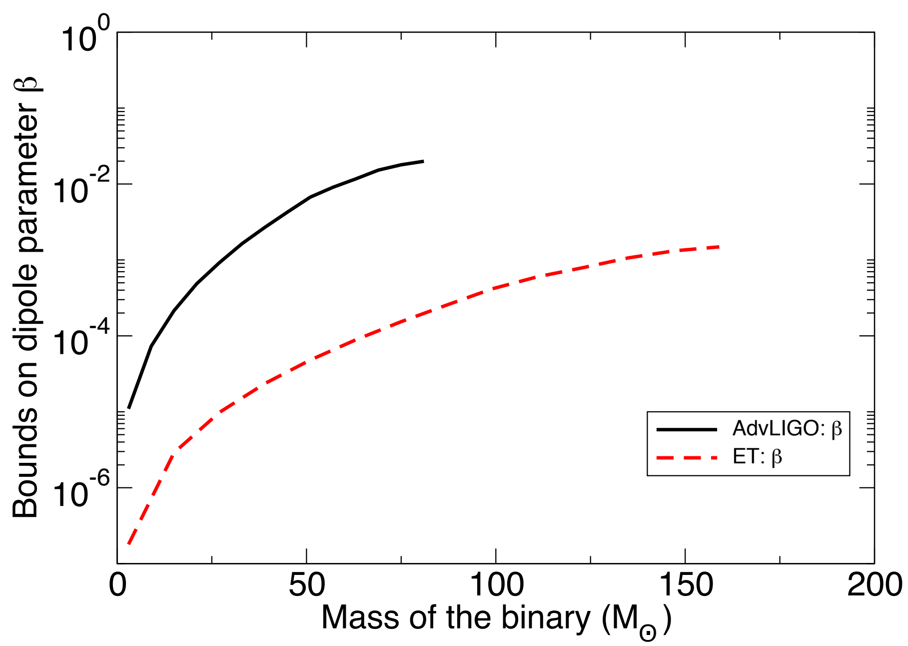
- Leading order radiation is dipolar. Possible to constrain the coupling parameter in known theories (e.g Brans-Dicke) & generic ST theories.



[Arun (2012)]

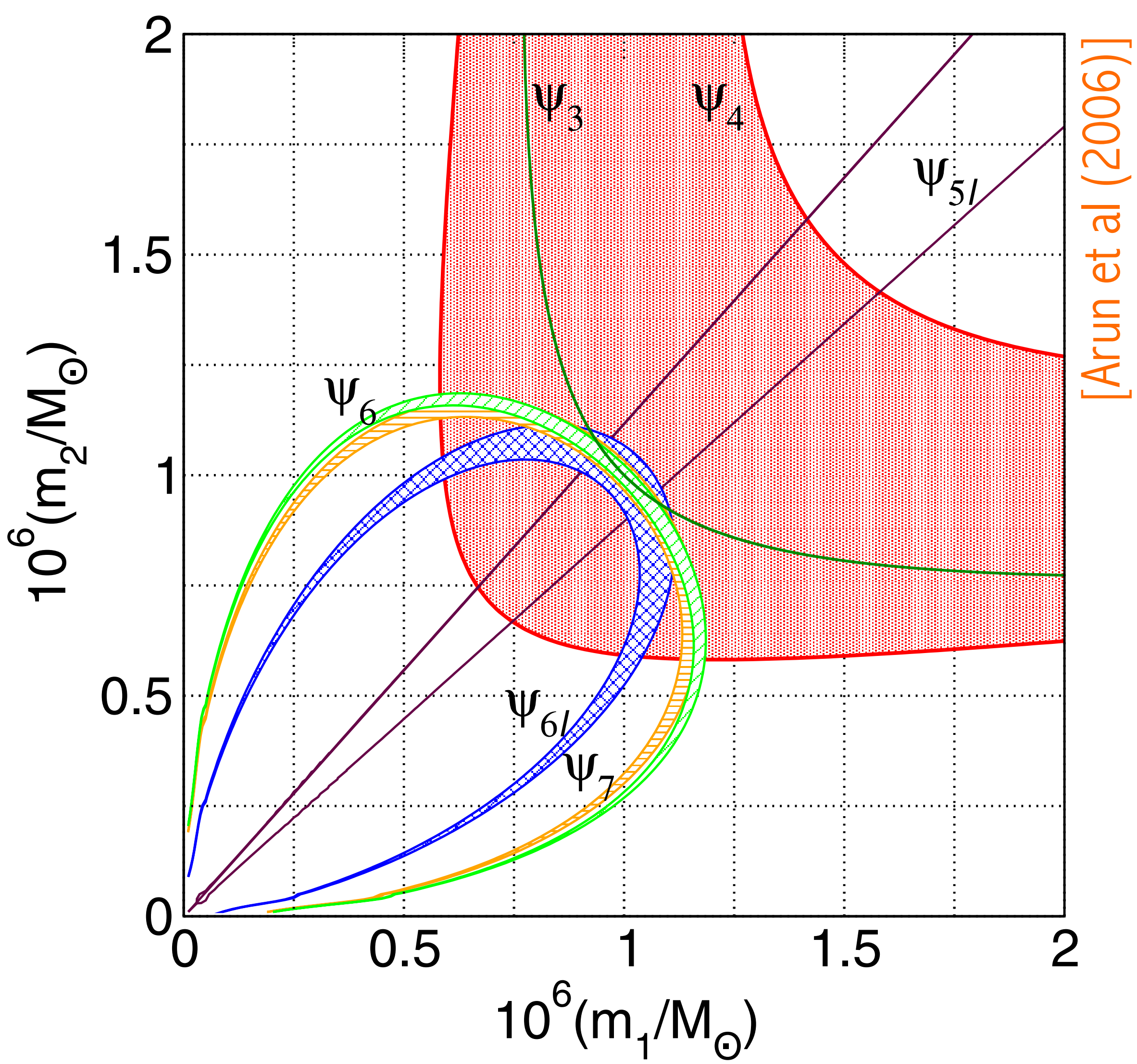
[Arun & Pai (2013)]



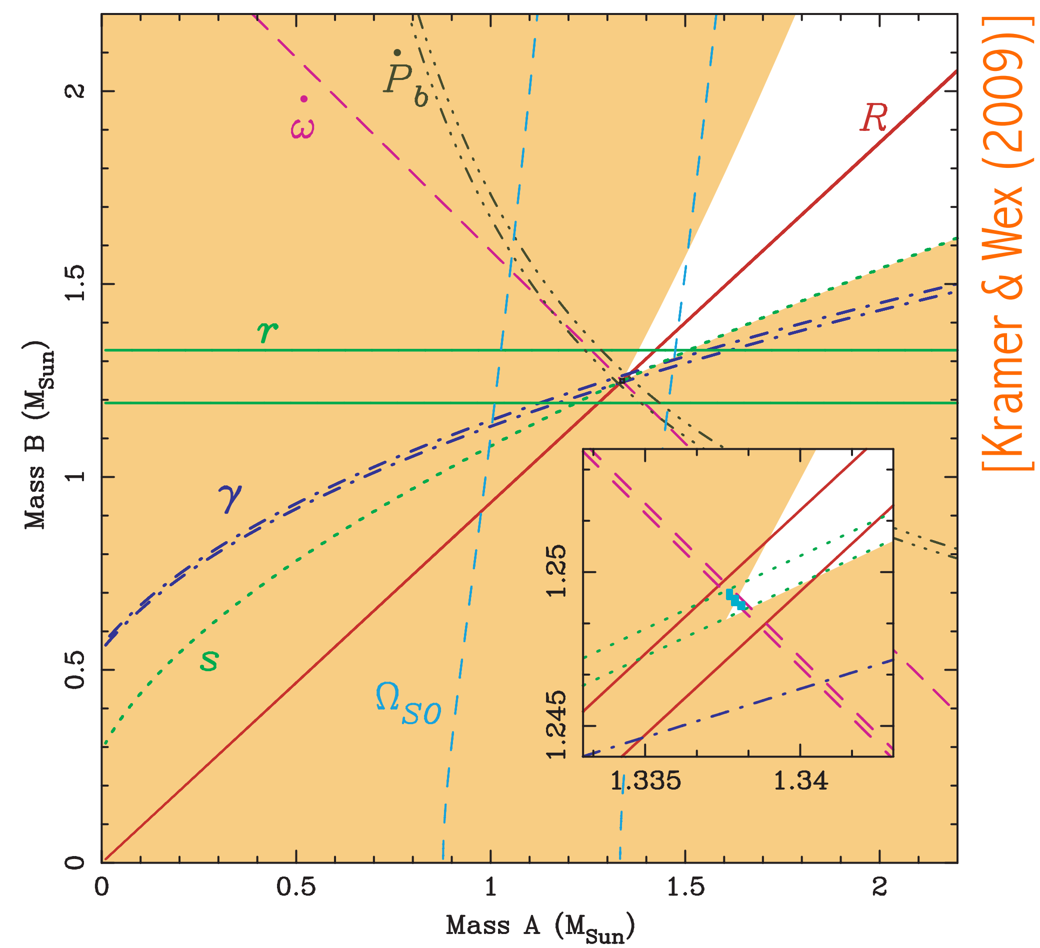


Parametrized (generic) deviations from GR

- Measure the deviations from the known PN coefficients of the GW phase by treating each coefficient as a free parameter



Analogous to the tests of GR using binary pulsars



Parametrized (generic) deviations from GR

[Mishra et al (2010)]

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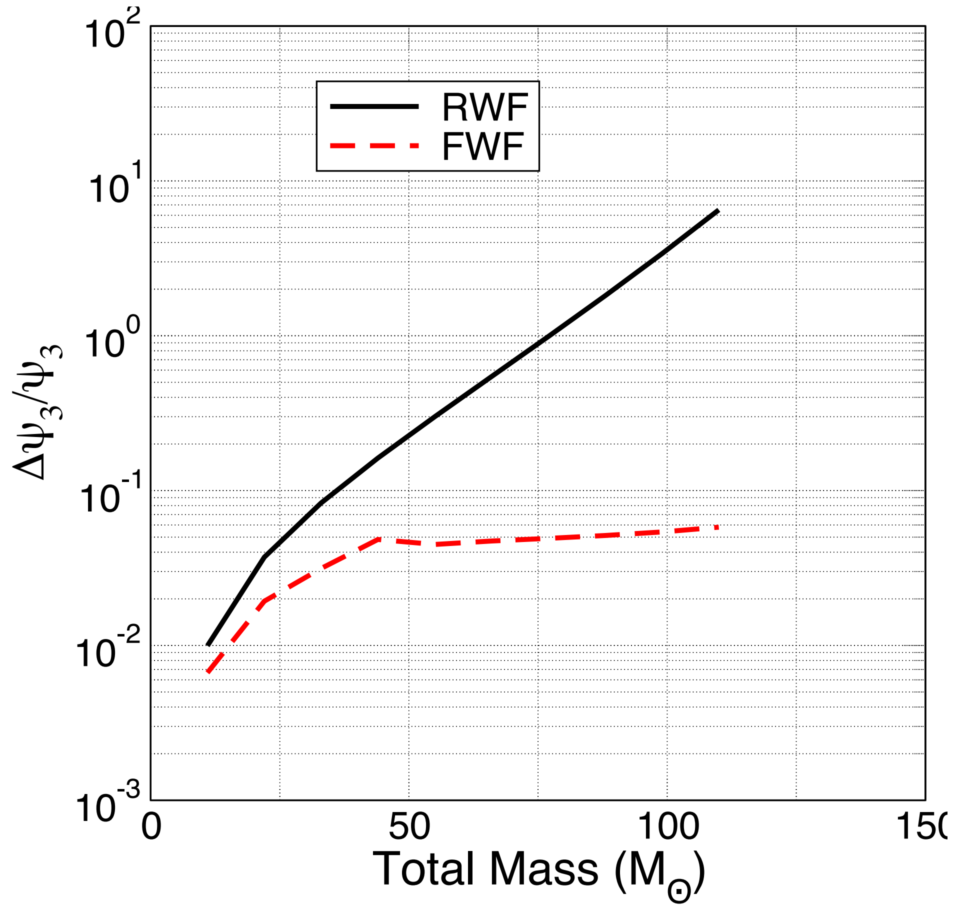
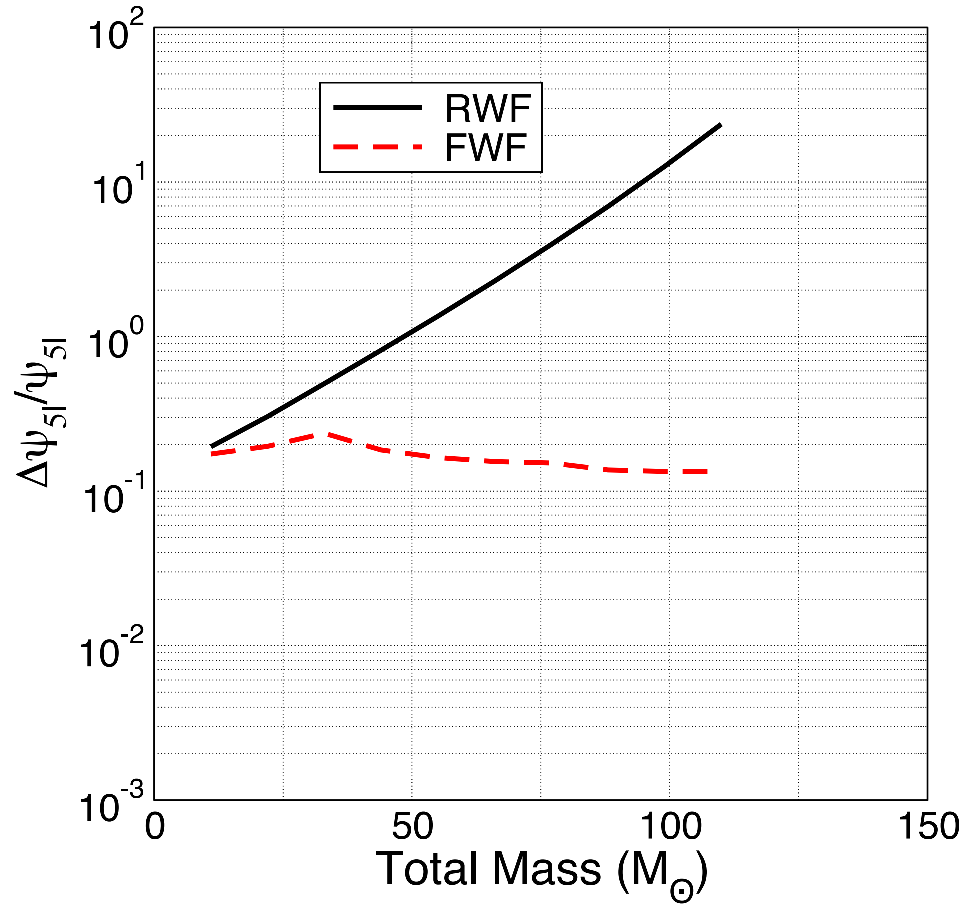


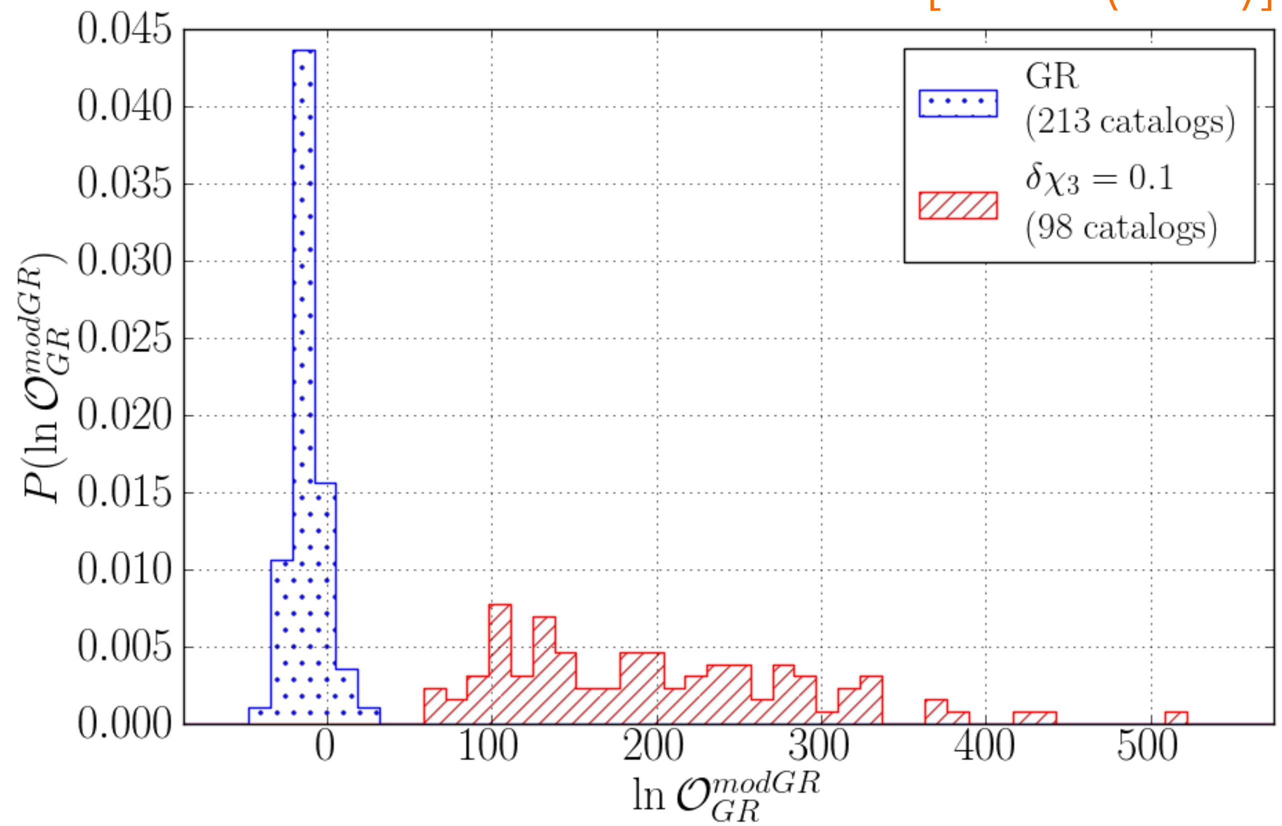


Expected constraints on the deviations from the PN coefficients in Adv LIGO (source located at 300 Mpc)

Parametrized (generic) deviations from GR

- Measure the deviations from the known PN coefficients of the GW phase by treating each coefficient as a free parameter

[Li et al (2012)]



Odds ratio of two hypotheses

modified gravity

$$\mathcal{O}^i_j = \frac{P(\mathcal{H}_i|d)}{P(\mathcal{H}_j|d)}$$

GR

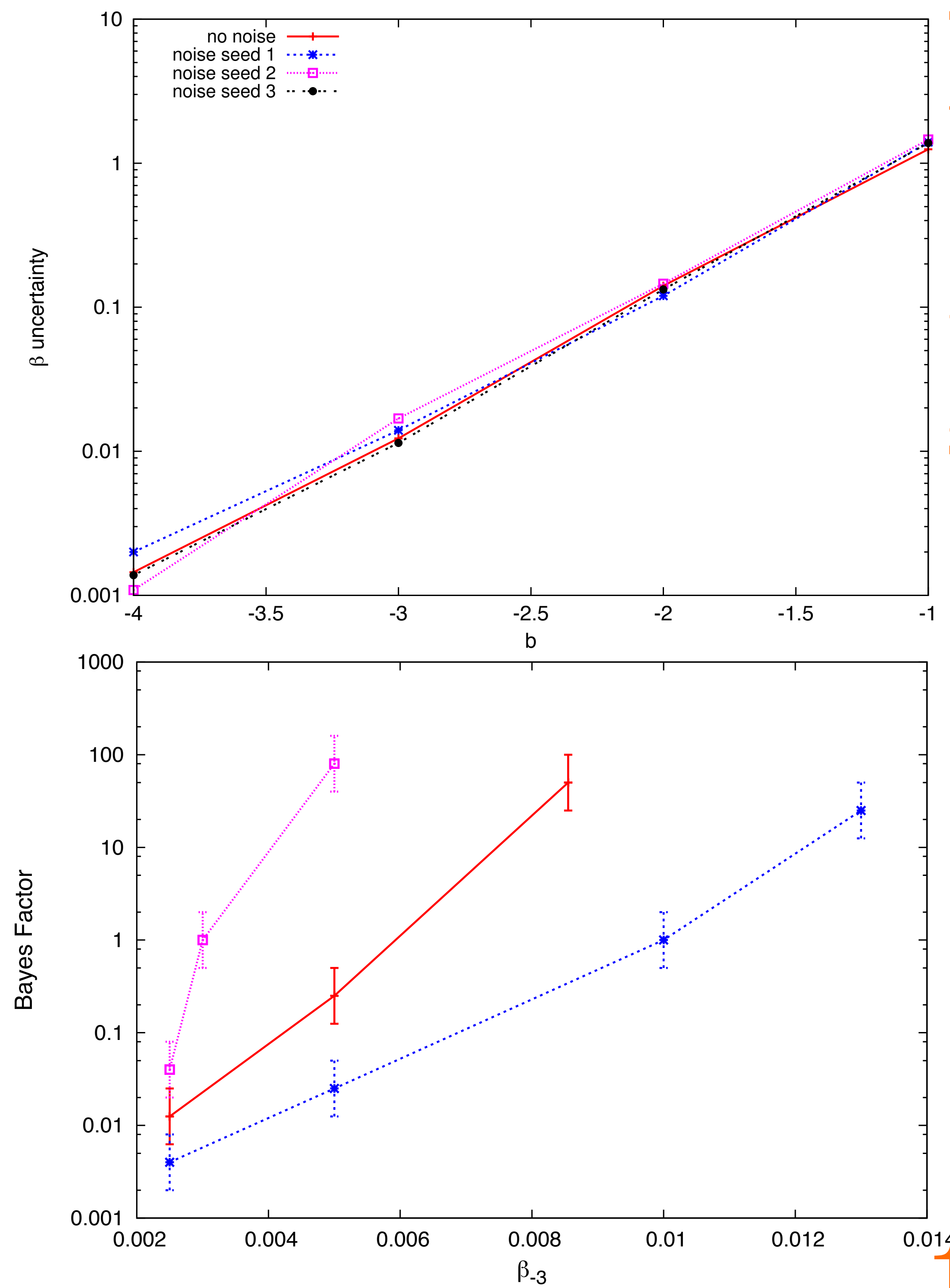
Parametrized (more generic!) deviations from GR

- **Parameterized Post-Einstein framework**
  Introduce deviations in the amplitude and phase of the GR signal, which are motivated by alternative theories. [Yunes & Pritorius]

$$\mathcal{A}(f) \to \left(1 + \sum_i \alpha_i u^{a_i}\right) A_{\rm GR}(f)\,,$$

$$\Psi(f) \to \left(\Psi_{\rm GR}(f) + \sum_i \beta_i u^{b_i}\right)\,,$$

Theory	a	α	b	β
Brans-Dicke [9, 10, 14–16]	–	0	-7/3	β
Parity-Violation [22, 34–37]	1	α	0	–
Variable $G(t)$ [38]	-8/3	α	-13/3	β
Massive Graviton [8–14]	–	0	-1	β
Quadratic Curvature [23, 44]	–	0	-1/3	β
Extra Dimensions [45]	–	0	-13/3	β
Dynamical Chern-Simons [46]	+3	α	+4/3	β

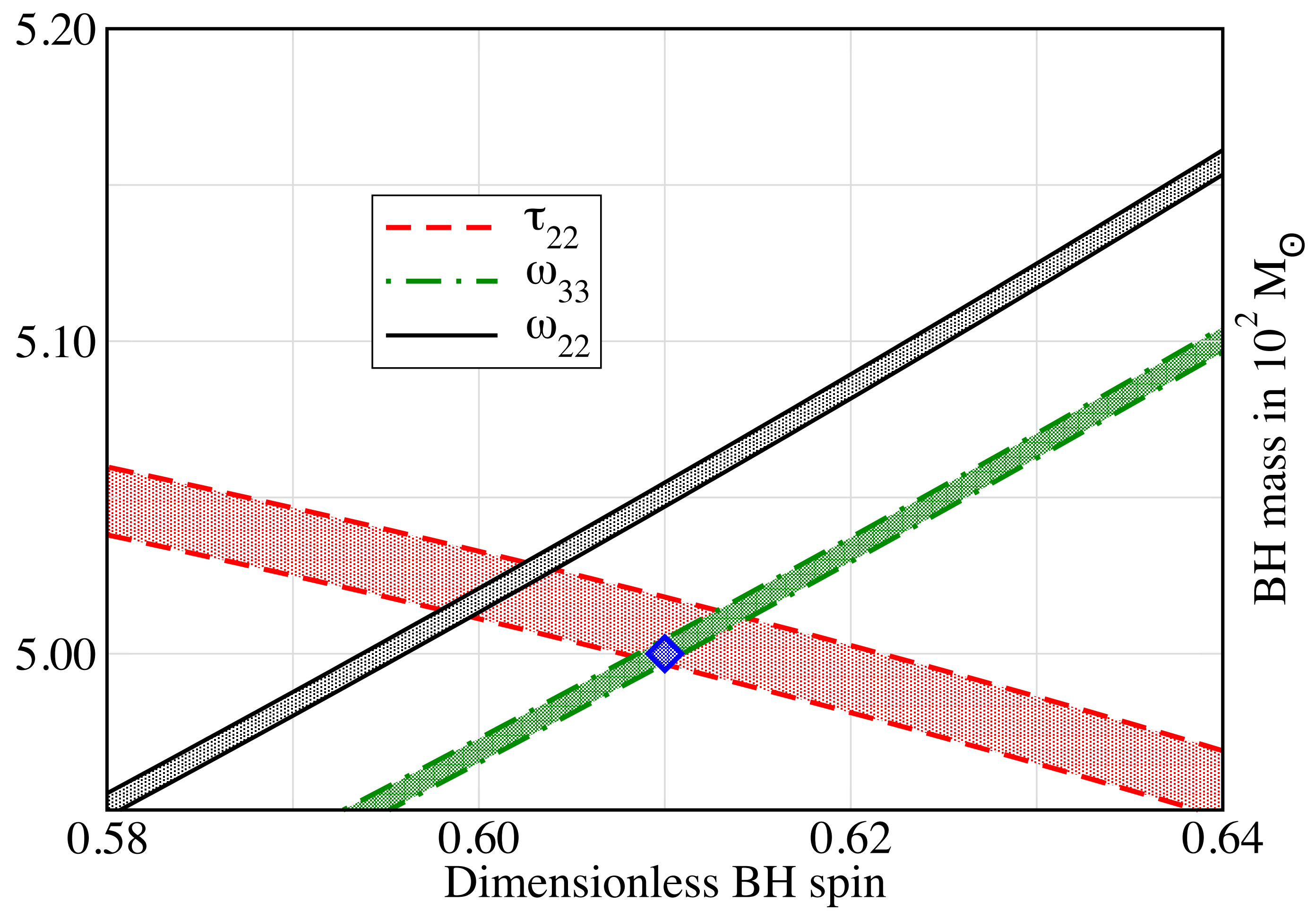


[Sampson et al (2013)]

Tests of no-hair theorem from black-hole ring downs

[Gossan et al (2012)]

- All QNM frequencies of a Kerr BH are unique functions of mass and spin. If we treat frequencies as free parameters, they all should intersect at one point in the mass-spin plane.



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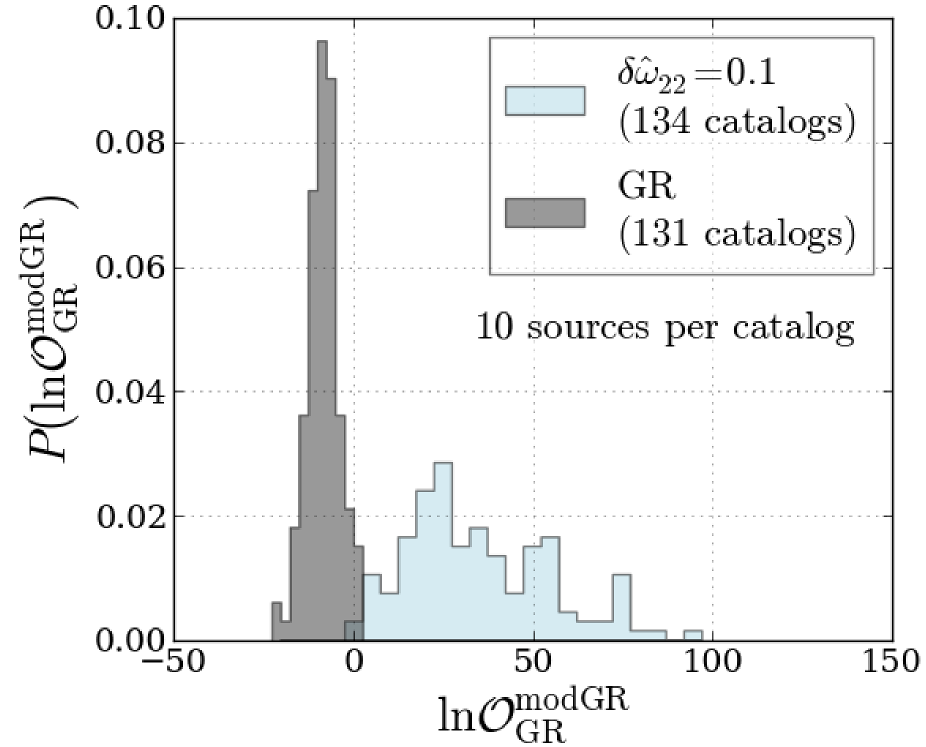
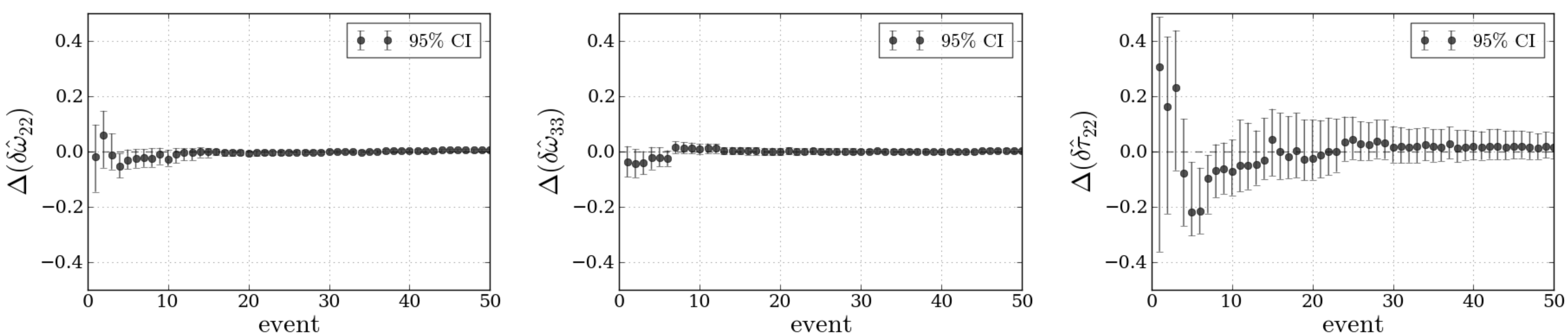


[Meidam et al (2014)]



Measuring the energy and ang momentum loss from BBHs

- Binary black-hole coalescences are the most energetic astrophysical processes after the Big Bang.

[Ongoing work with Abhirup Ghosh, Archisman Ghosh and Walter Del Pozzo]

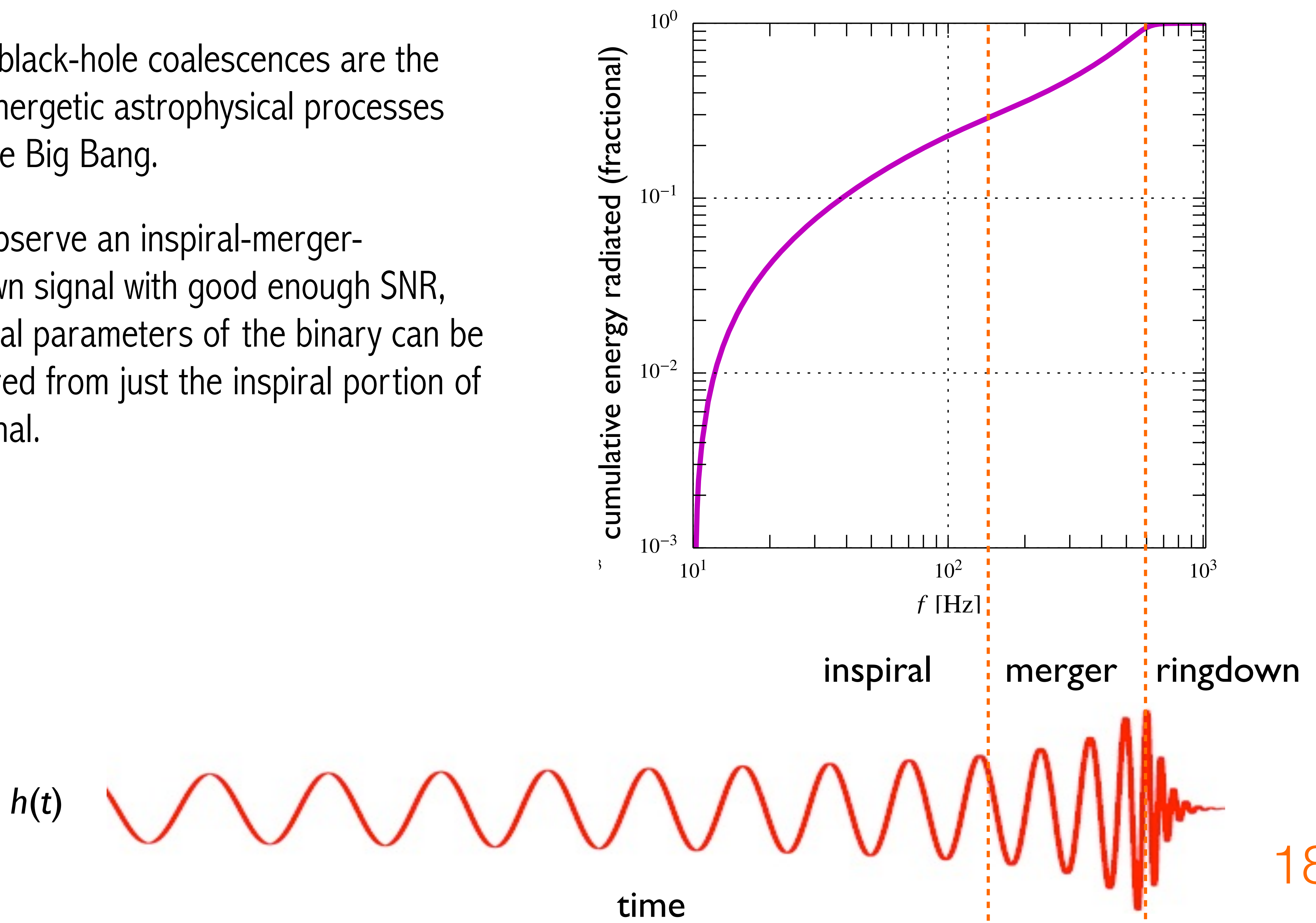
$$\mathcal{L}_{\mathrm{GW}} \sim \frac{0.1\, M c^2}{1000\, GM/c^3} \sim 10^{22} L_\odot$$

most of the energy is radiated over the late-inspiral & merger (time scale ~ 1000 M)

larger than the total luminosity of the observable EM universe!

Measuring the energy and ang momentum loss from BBHs

- Binary black-hole coalescences are the most energetic astrophysical processes after the Big Bang.
- If we observe an inspiral-merger-ringdown signal with good enough SNR, the initial parameters of the binary can be measured from just the inspiral portion of the signal.



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- From these estimates, the final state of the BBH can be predicted using NR simulations.

numerical relativity simulations

$$(m_1, m_2, \mathbf{S}_1, \mathbf{S}_2) \rightarrow (M_f, S_f)$$

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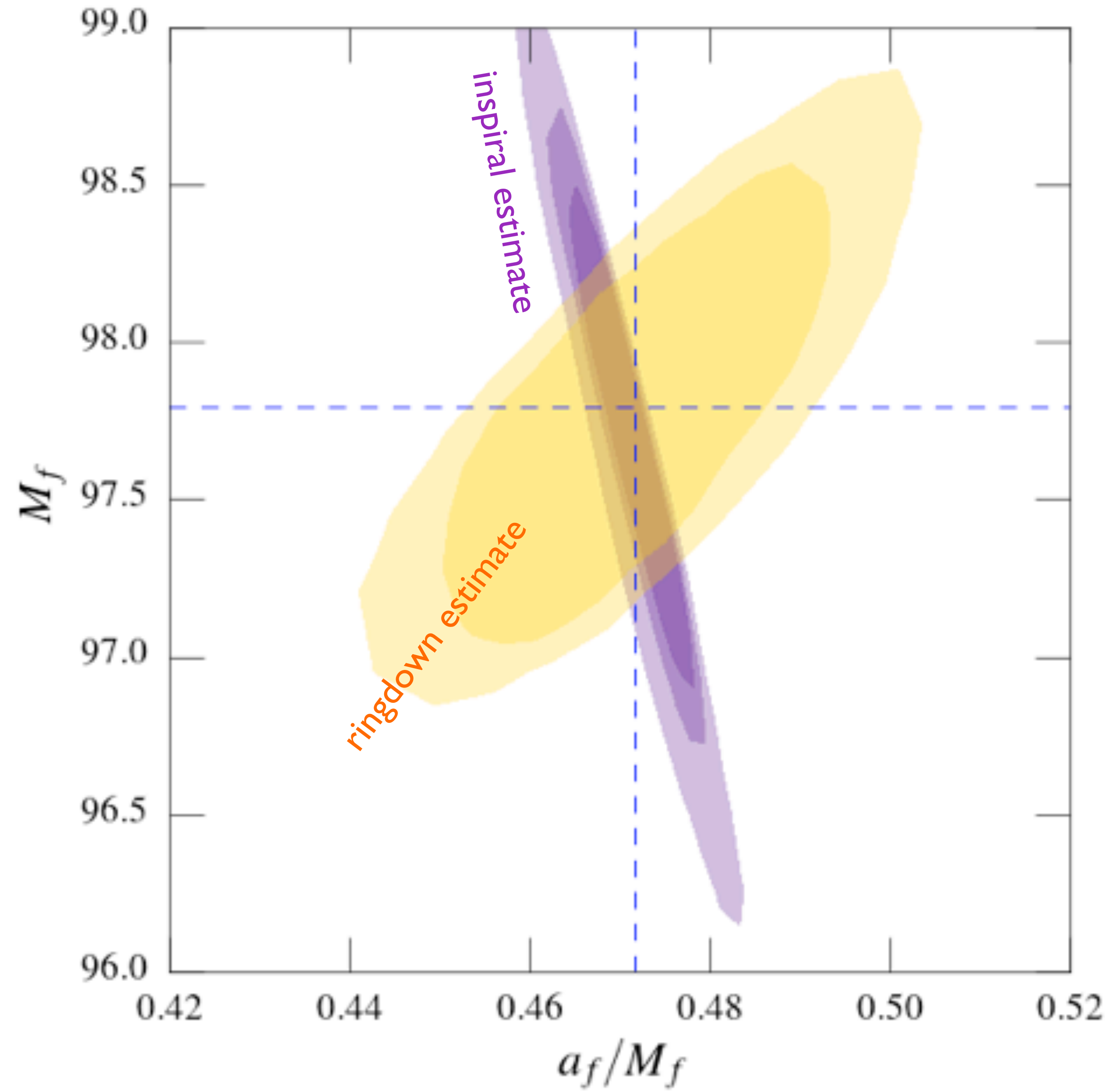
- If we observe an inspiral-merger-ringdown signal with good enough SNR, the initial parameters of the binary can be measured from just the inspiral portion of the signal.
- From these estimates, the final state of the BBH can be predicted using NR simulations.
- The mass and the spin of the final black hole can be measured independently from the ringdown part of the signal.

[Pic. Abhirup Ghosh]



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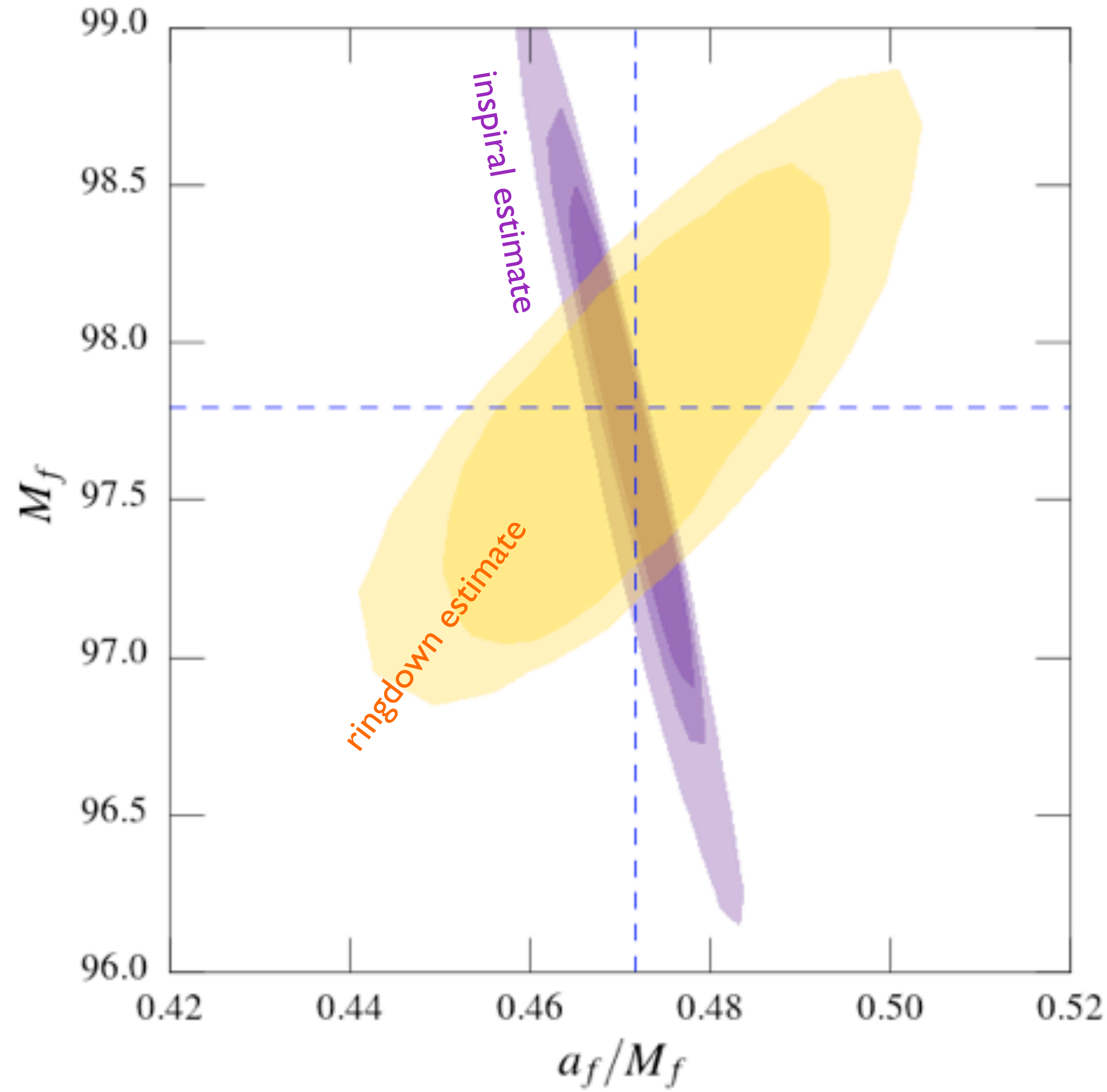

Inconsistency between these estimates point to unexplained loss of energy and angular momentum (extra dimensions?, dissipation?)

[PhD project of Abhirup Ghosh]

Other ideas of testing GR under exploration ...

- Constraints on non-GR polarizations [PhD project of Krishnendu]
- Bayesian parameter estimation of the ST coupling constant(s) from GW observations. [K. G. Arun, PA, A. Ghosh, ...]
- Testing cosmic censorship conjecture. Is $S \leq M^2$? [PA, A. Ghosh, ...]
- Completely model independent test. Subtract the best fit GR template from the data. Is the residual consistent with the noise?

What limits our measurements?

- **Calibration errors** GW detectors have calibration uncertainty ~few percents in amplitude and few degrees in phase.
- **Complexity in the source** spins, precession, eccentricity, non-quadrupole modes, matter effects, etc.
- **Waveform uncertainty** PN calculations are known only up to limited order, numerical and gauge issues in NR simulations, ...

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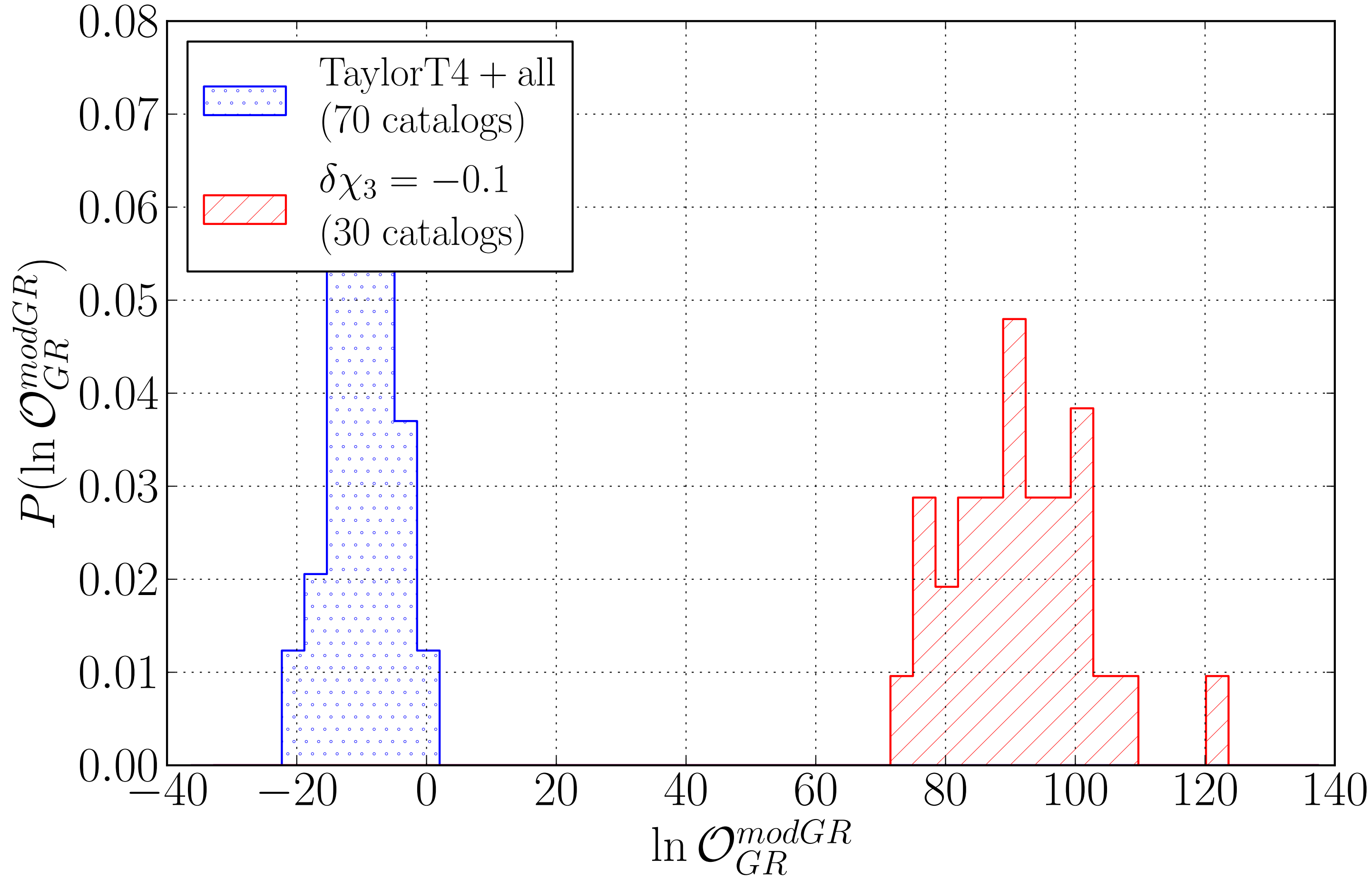
[Agathos et al (2014)]



"Known unknowns": Possible to model most of the errors and to account for them ...

[PhD projects of M. Saleem, Anuradha S]

Summary

[Quoted from Berti et al (2015)]

when asked what he would do if Eddington's expedition to the island of Principe failed to match his theory, Einstein famously replied: "I would feel sorry for the good Lord. The theory is correct." Chandrasekhar made a similar private remark to Clifford Will when Will was a postdoc in Chicago: "Why do you spend so much time and energy testing GR? We *know* that the theory is right."

... we will do it, any way.