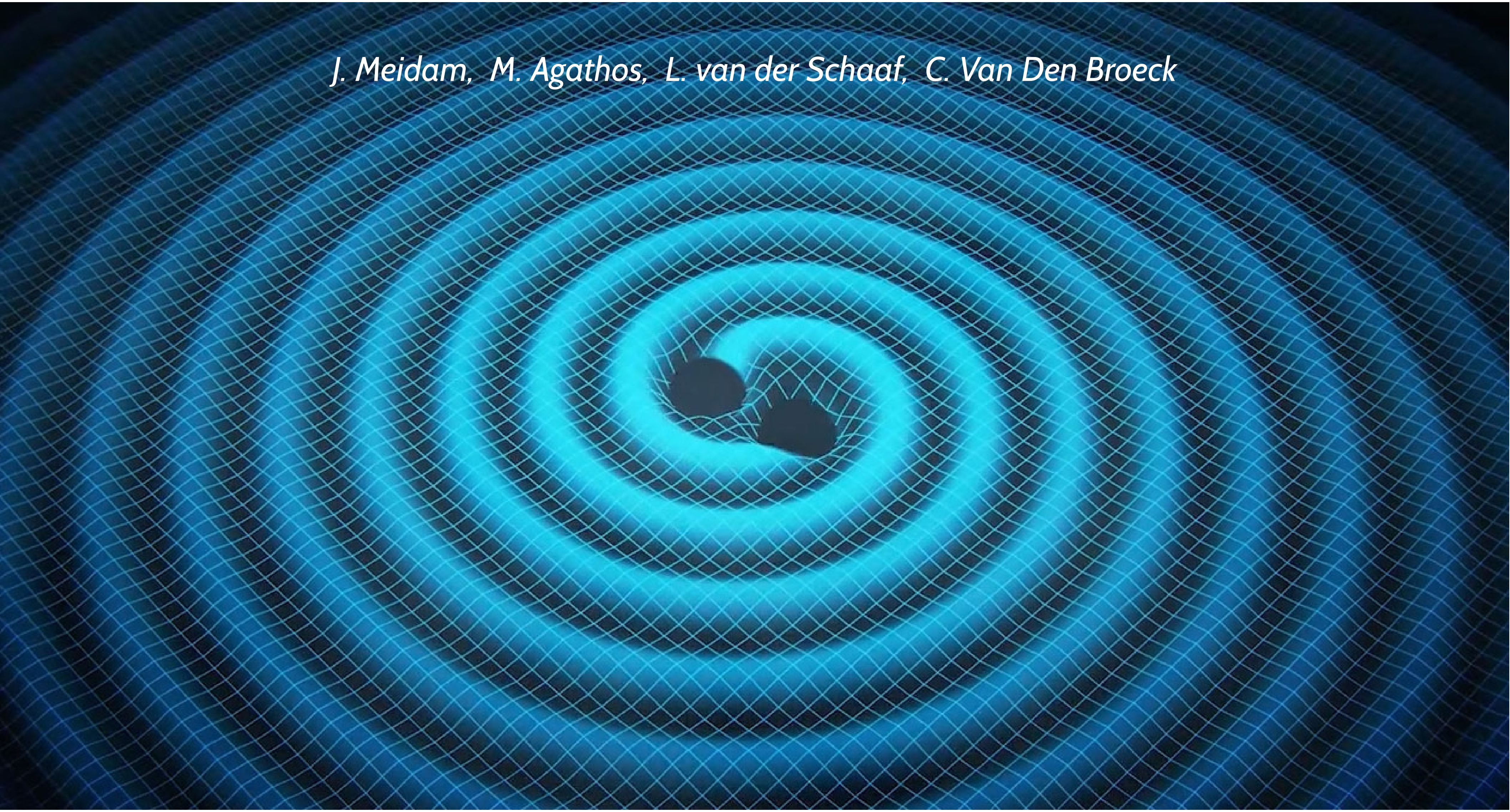
Testing the strong-field dynamics of general relativity with direct gravitational-wave observations of merging binary neutron stars and black holes

J. Meidam, M. Agathos, L. van der Schaaf, C. Van Den Broeck



Nikhef

December 15, Nikhef Annual Meeting, Amsterdam

General relativity at its 100th birthday

- Gravitational physics encompasses important questions:
  - Relation between gravitational physics and quantum physics?
  - What is the nature of black holes?
  - How did the universe come into being and how did it evolve?

- How is general relativity holding up in experiments and observations?
  - Solar system:
    Perihelium precession of Mercury, Shapiro time delay,
    bending of starlight by the Sun, frame dragging, equivalence principle, …
  - Cosmology
  - Radio observations of binary neutron stars

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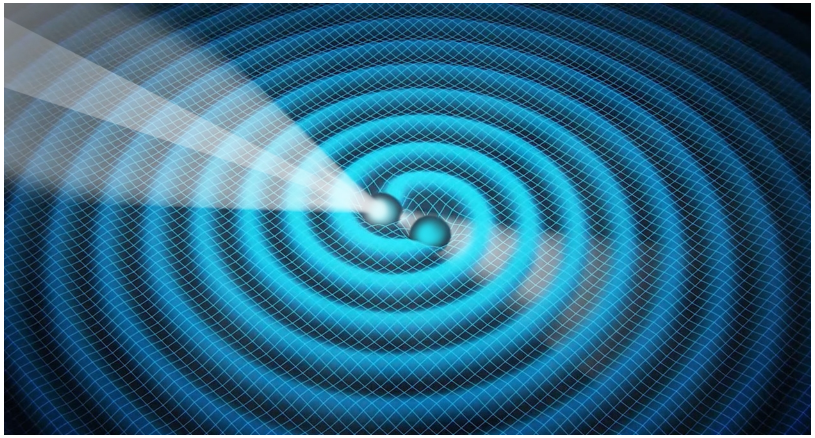
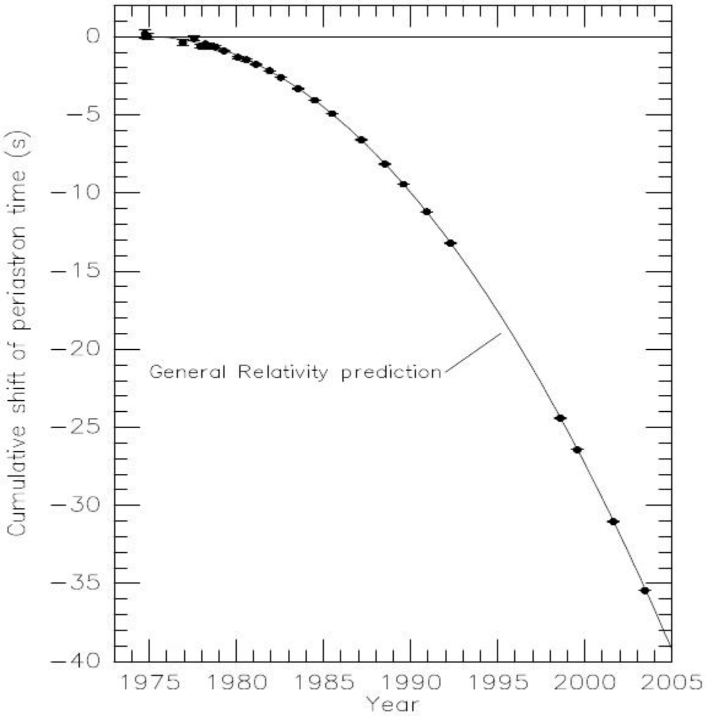
Existing tests only probe weak and/or stationary fields

No access to even the classical strong-field dynamics of spacetime

Gravitational Waves





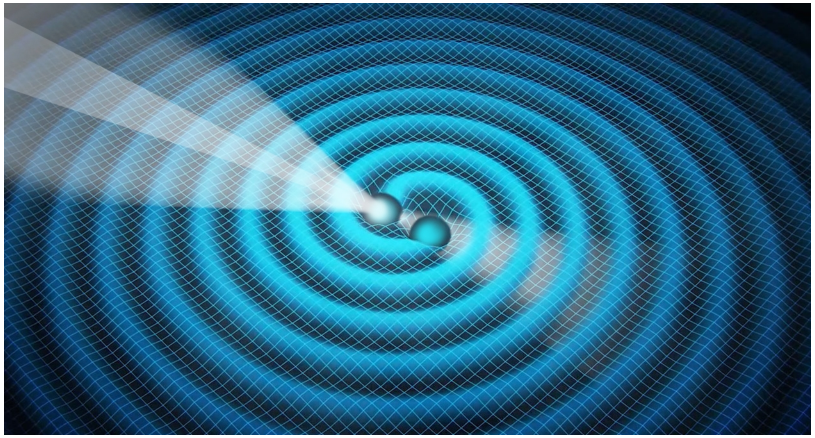
J. Weisberg and J. Taylor, ASP Conf.Ser. **328** (2005) 25

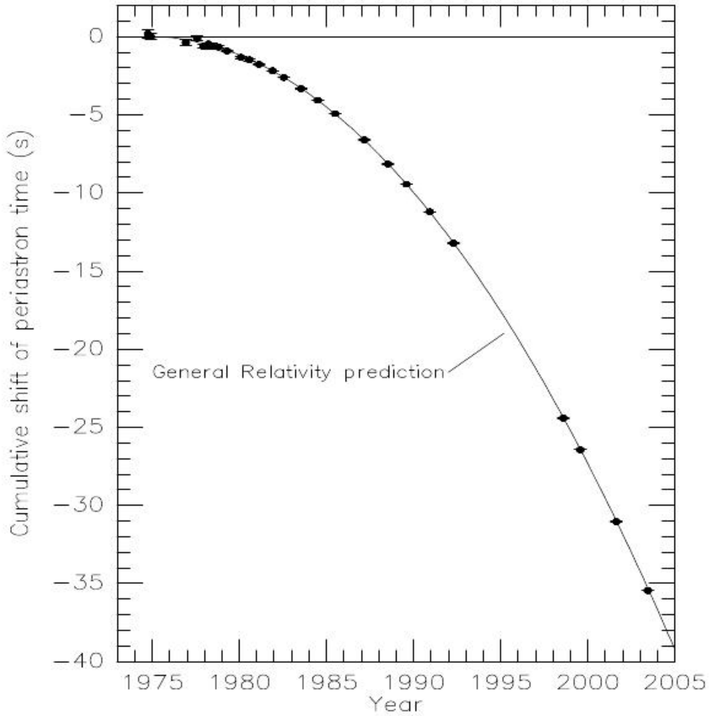
- Binary neutron stars in tight orbits lose orbital energy & angular momentum
  - Consistent with emission of gravitational waves
  - Hulse & Taylor Nobel Prize 1993

- Still weak-field dynamics from perspective of full general relativity
  - Typical velocity $v/c \sim 10^{-3}$
  - Typical field strength $\frac{GM}{c^2}R \sim 10^{-5}$

- Observe such objects as they merge?

Gravitational Waves





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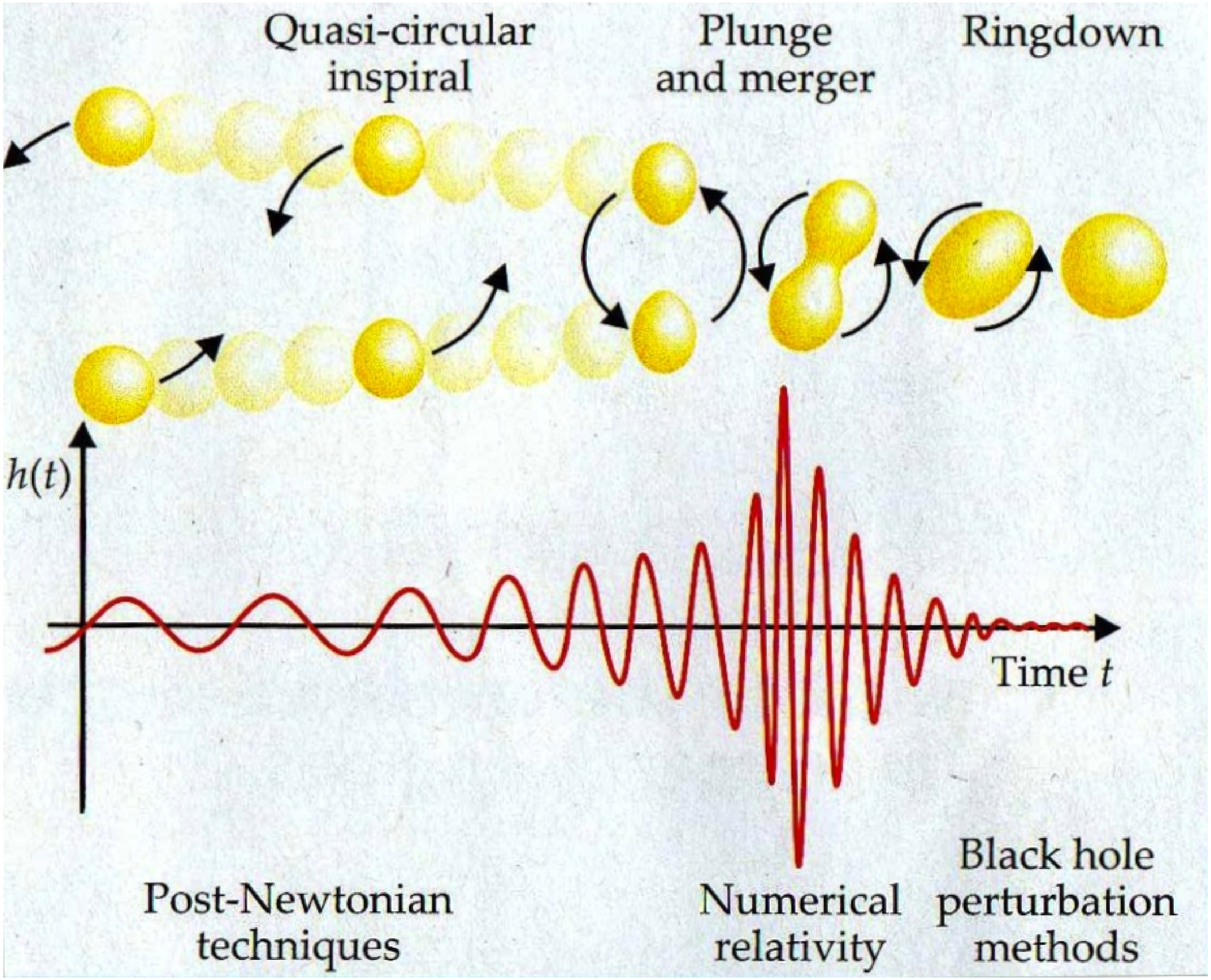
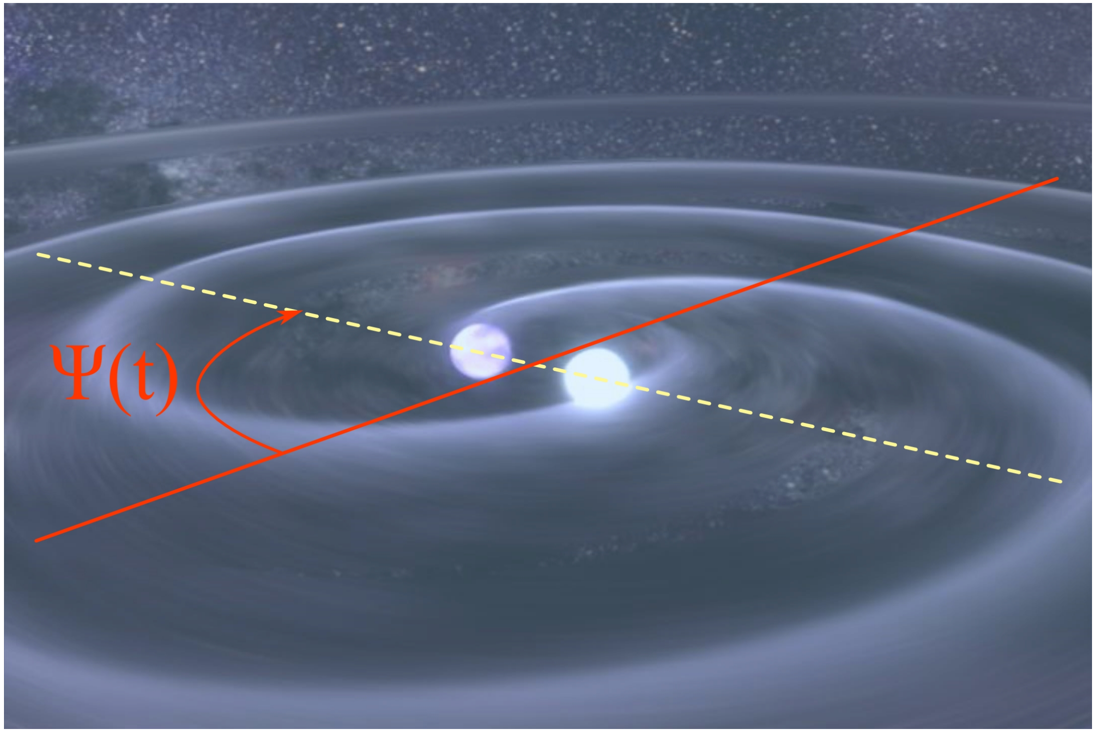
- Observe such objects as they merge?
  - Typical velocity $v/c > 0.5$
  - Typical field strength $\frac{GM}{c^2} > 0.2$

Need direct detection of gravitational waves

Coalescence of binary neutron stars and black holes



The inspiral of compact binaries



- Orbital motion during inspiral in terms of

$$\Psi(v) = \left(\frac{v}{c}\right)^{-5} \sum_{n=0}^{7} \left[\psi_n + \psi_n^{(l)} \ln \frac{v}{c}\right] \left(\frac{v}{c}\right)^n$$

- Up to factor 2, also the phase of GW signal
- In general relativity: ψ_n and ${\psi_n}^{(l)}$ are specific functions of component masses and spins

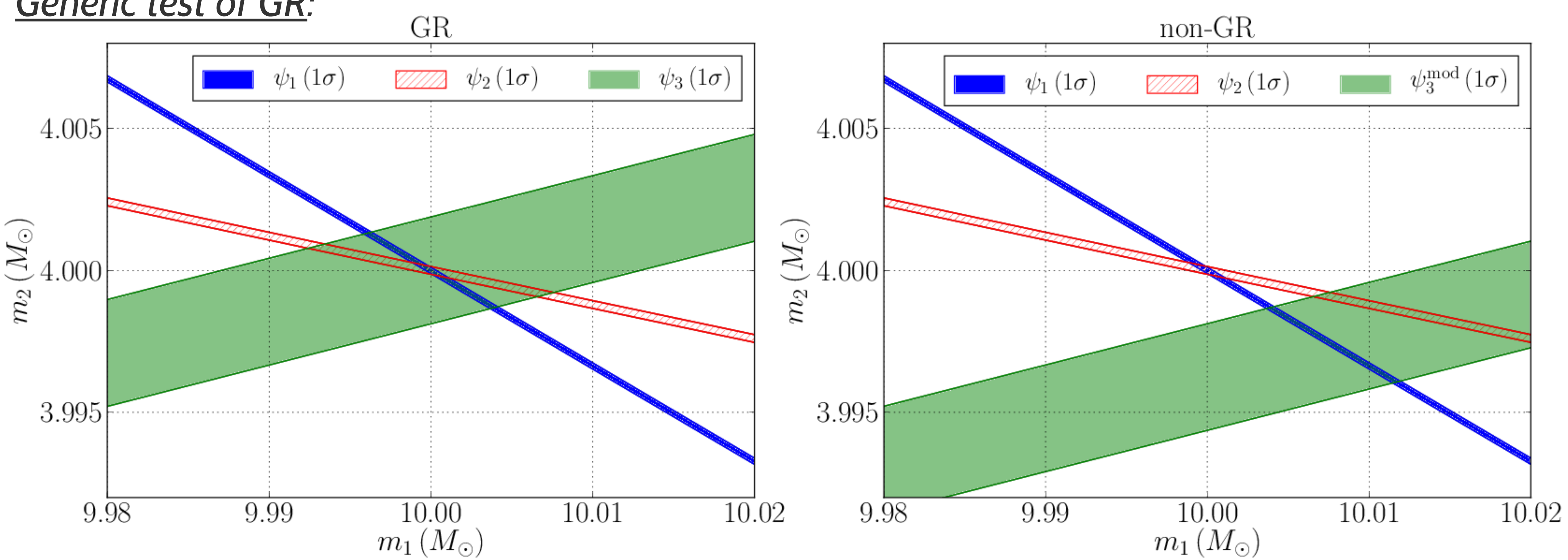
Probing the strong-field dynamics of spacetime

$$\Psi(v) = \left(\frac{v}{c}\right)^{-5} \sum_{n=0}^{7} \left[\psi_n + \psi_n^{(l)} \ln \frac{v}{c}\right] \left(\frac{v}{c}\right)^n$$

If no spins, then ψ_n and $\psi_n^{(l)}$ are only functions of masses

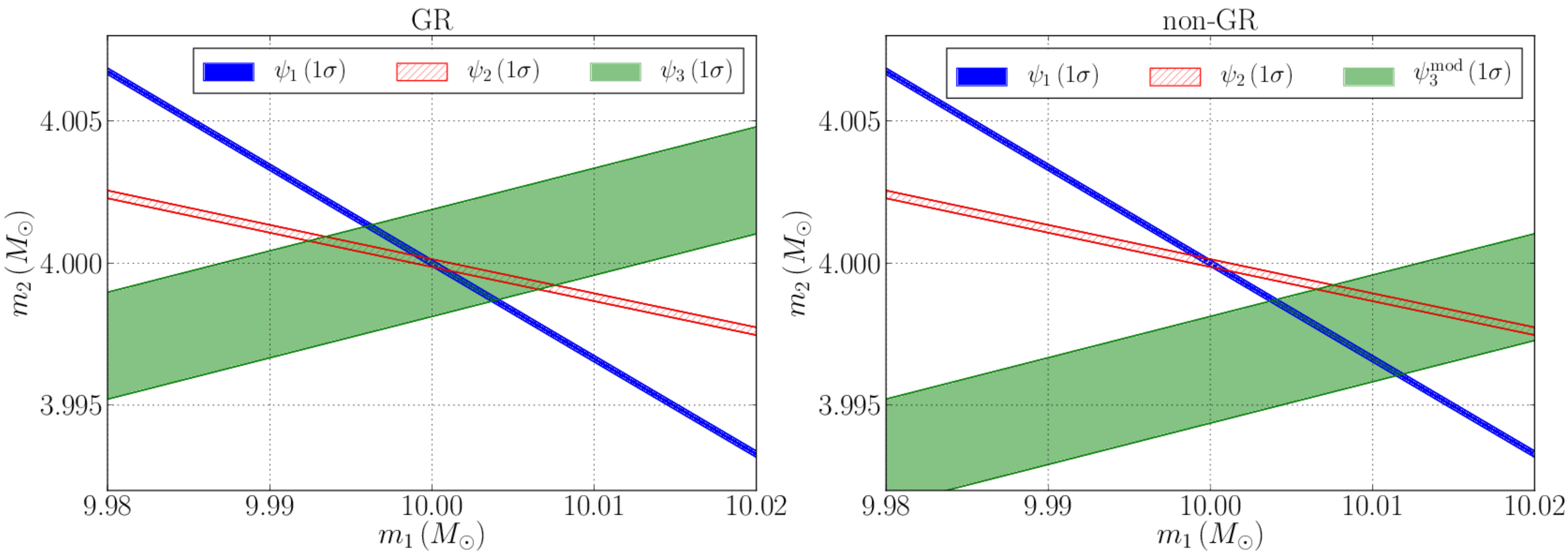
→ Only two of them are independent

Generic test of GR:



Arun et al., CQG **23**, L37 (2006); Arun et al., PRD **74**, 024006 (2006); Mishra et al., PRD **82**, 064010 (2010)

Probing the strong-field dynamics of spacetime



Want to combine information from all the sources we will detect

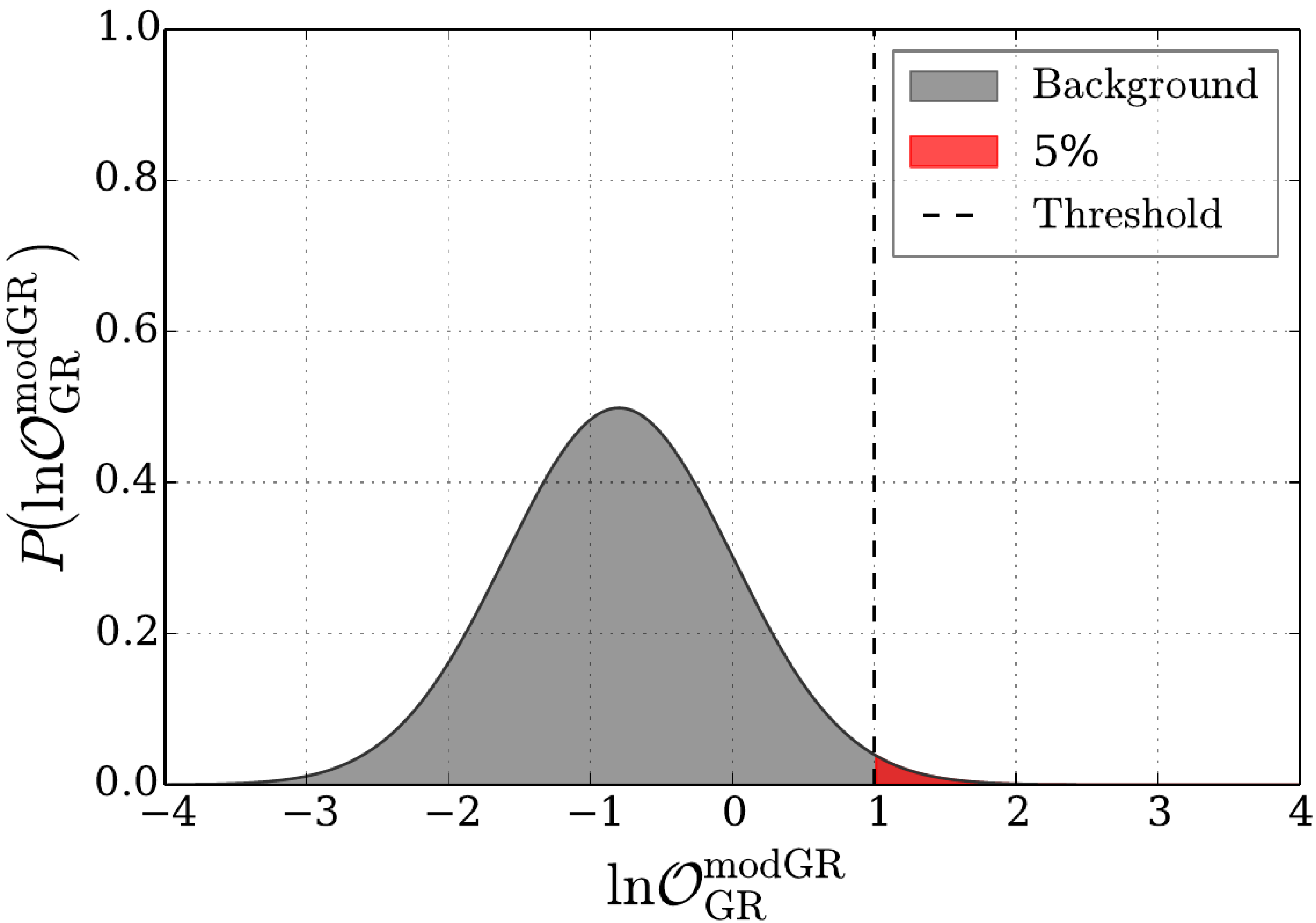
In practice: measuring parameters not convenient

Instead do *model selection* by computing an "odds ratio":

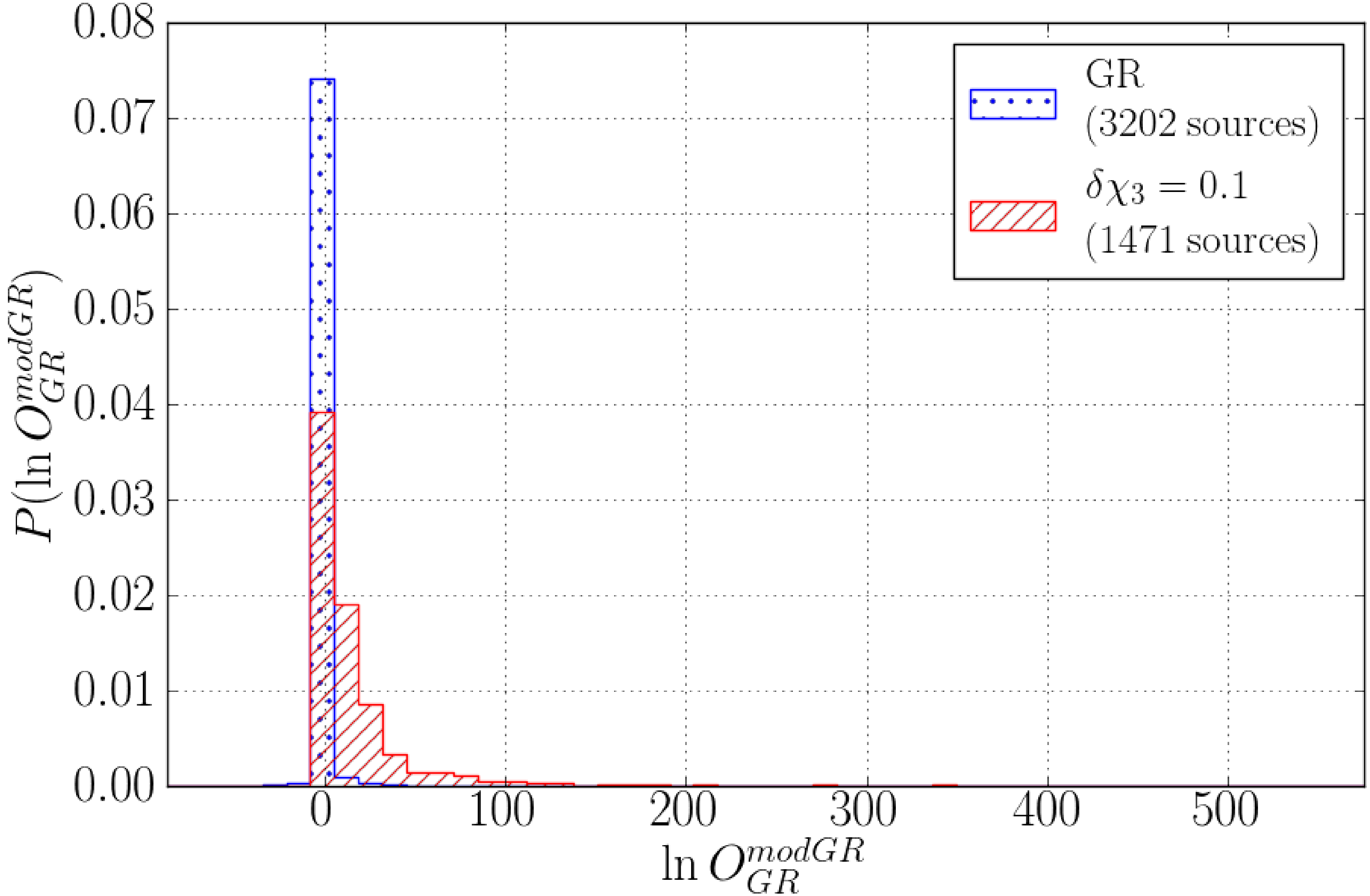
$$\mathcal{O}_{\rm GR}^{\rm modGR} = \frac{P(\mathcal{H}_{\rm modGR}|d, I)}{P(\mathcal{H}_{\rm GR}|d, I)}$$

Li et al., PRD **85**, 083003 (2012); Agathos et al. PRD **89** 082001 (2014)

Background distribution



Model selection examples



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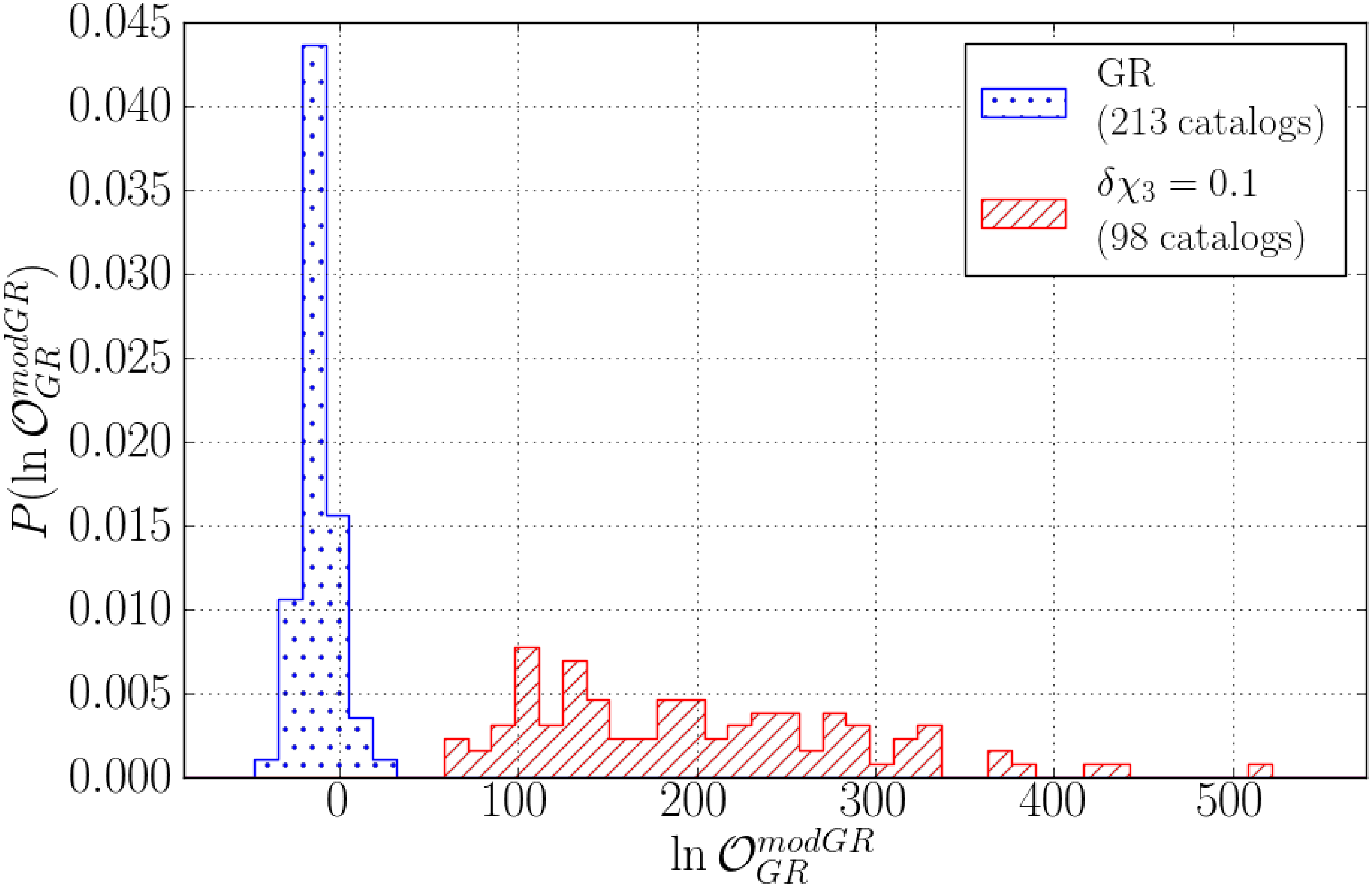
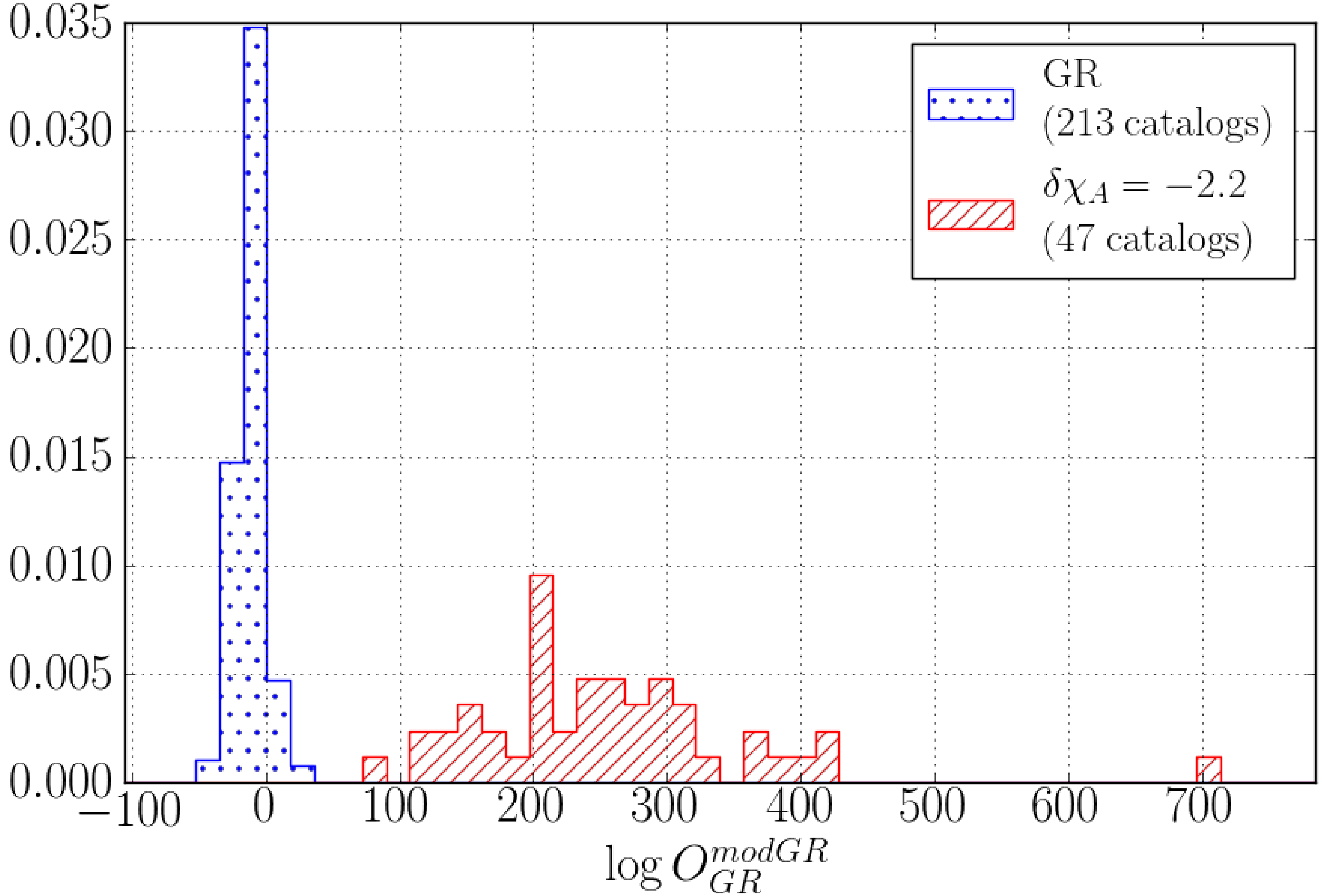
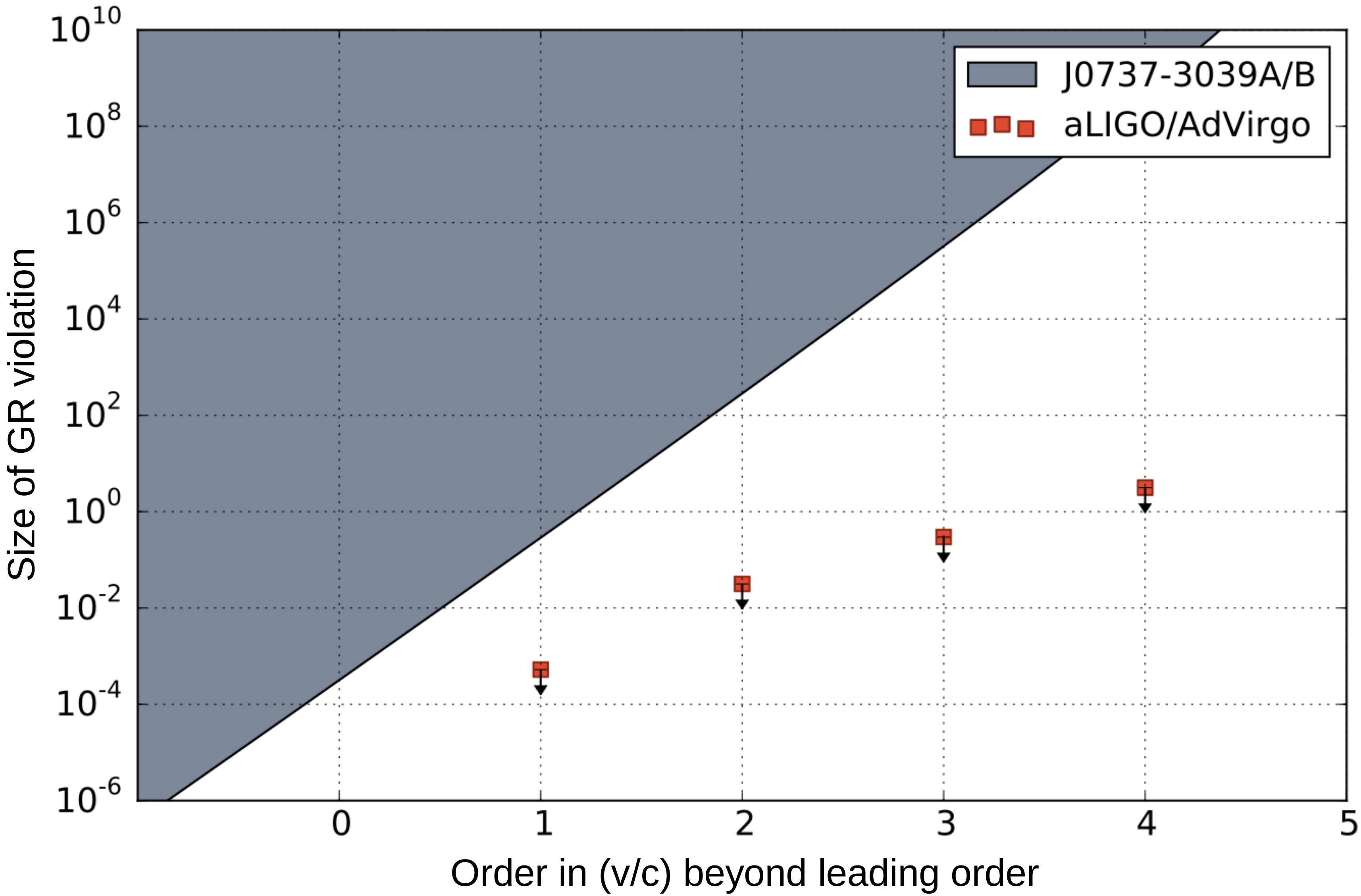


Model selection examples

- Deviation need not be a particular shift in one of the phasing terms
- Example: Anomalous frequency term



Bounds on phasing parameters



Yunes & Hughes, PRD **82**, 082002 (2010), Li et al., PRD **85**, 082003 (2012), Li et al., JPCS **363**, 012028 (2012), Agathos et al., PRD **89**, 082001 (2014)

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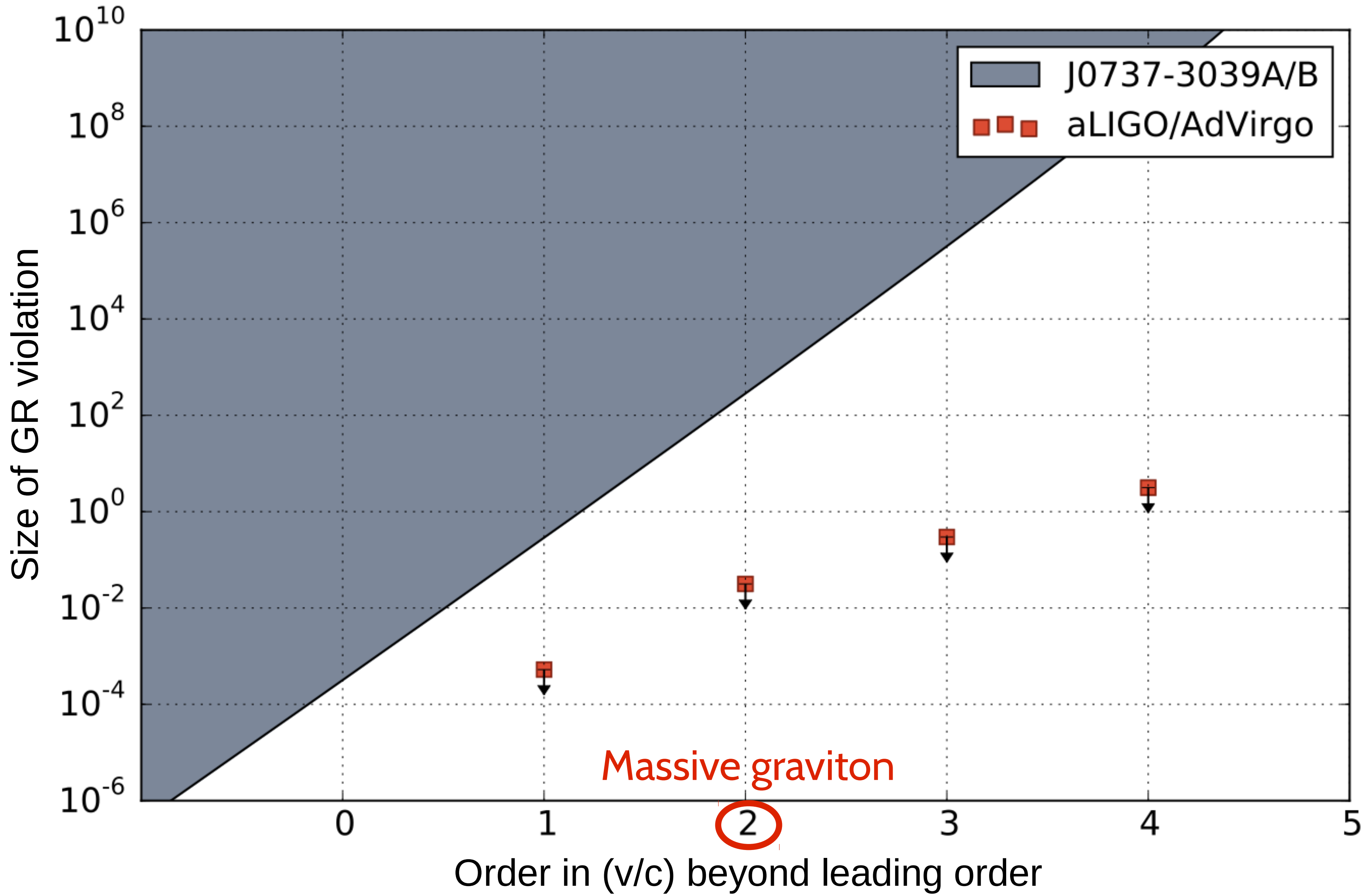

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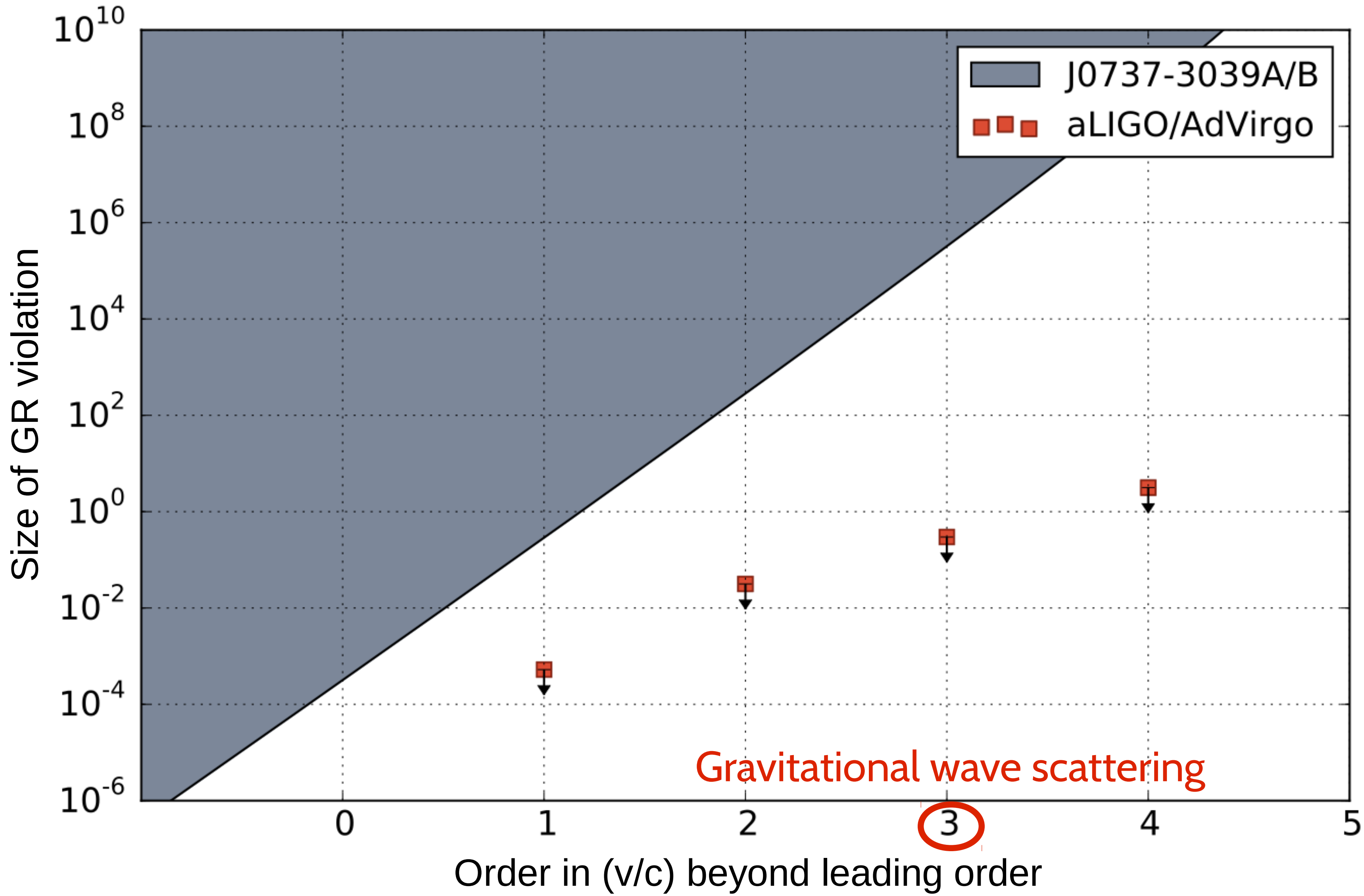

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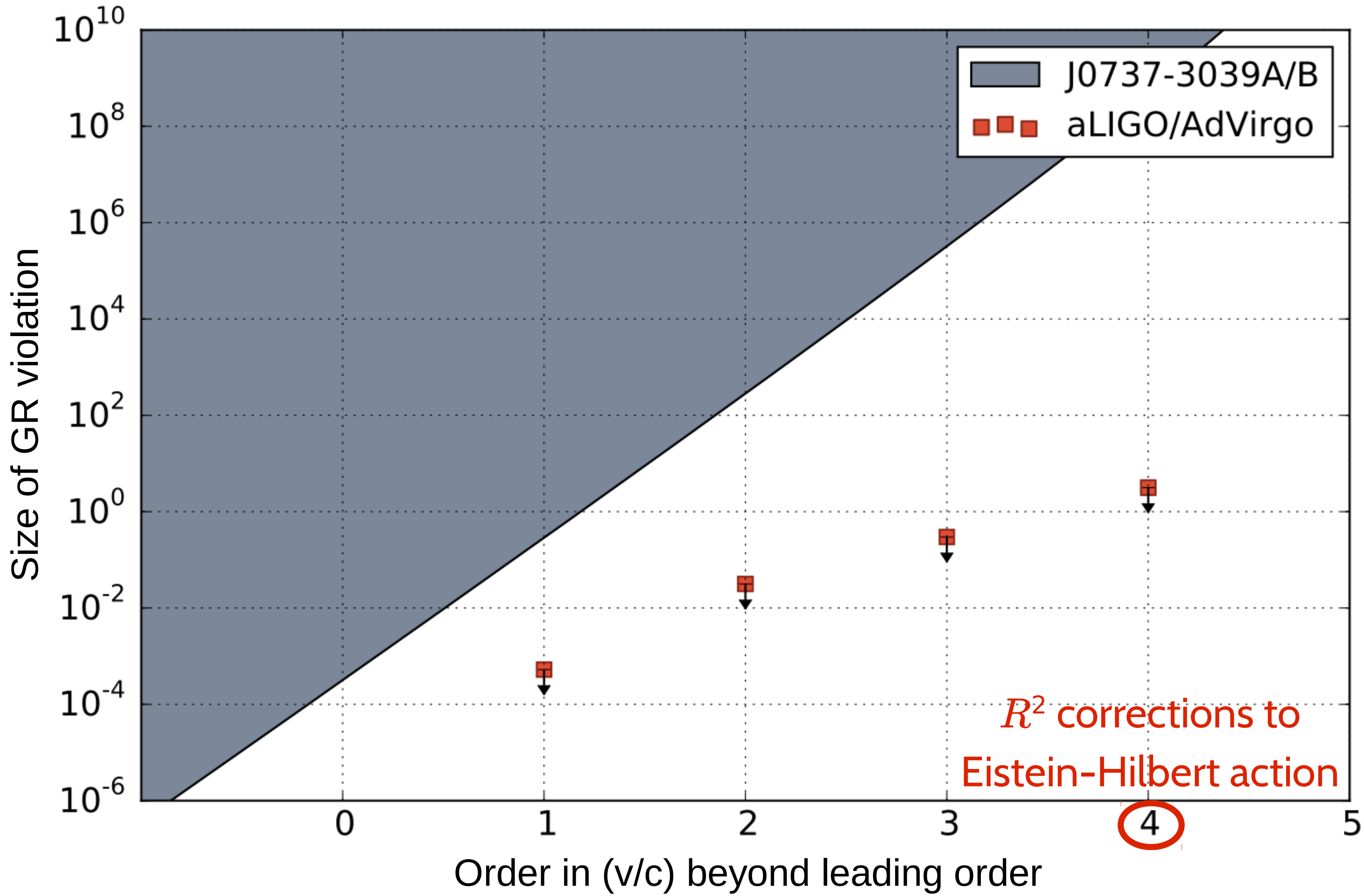

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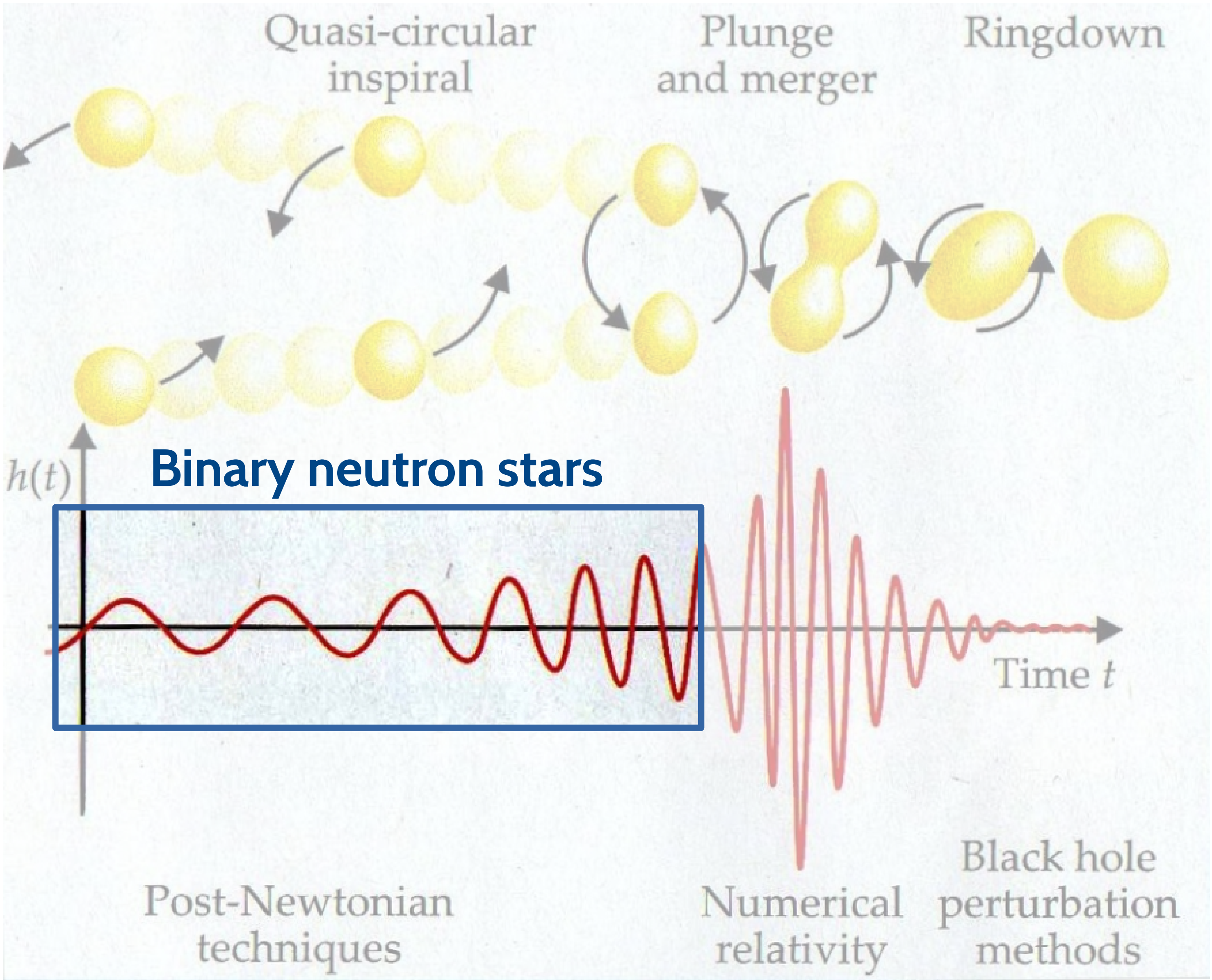
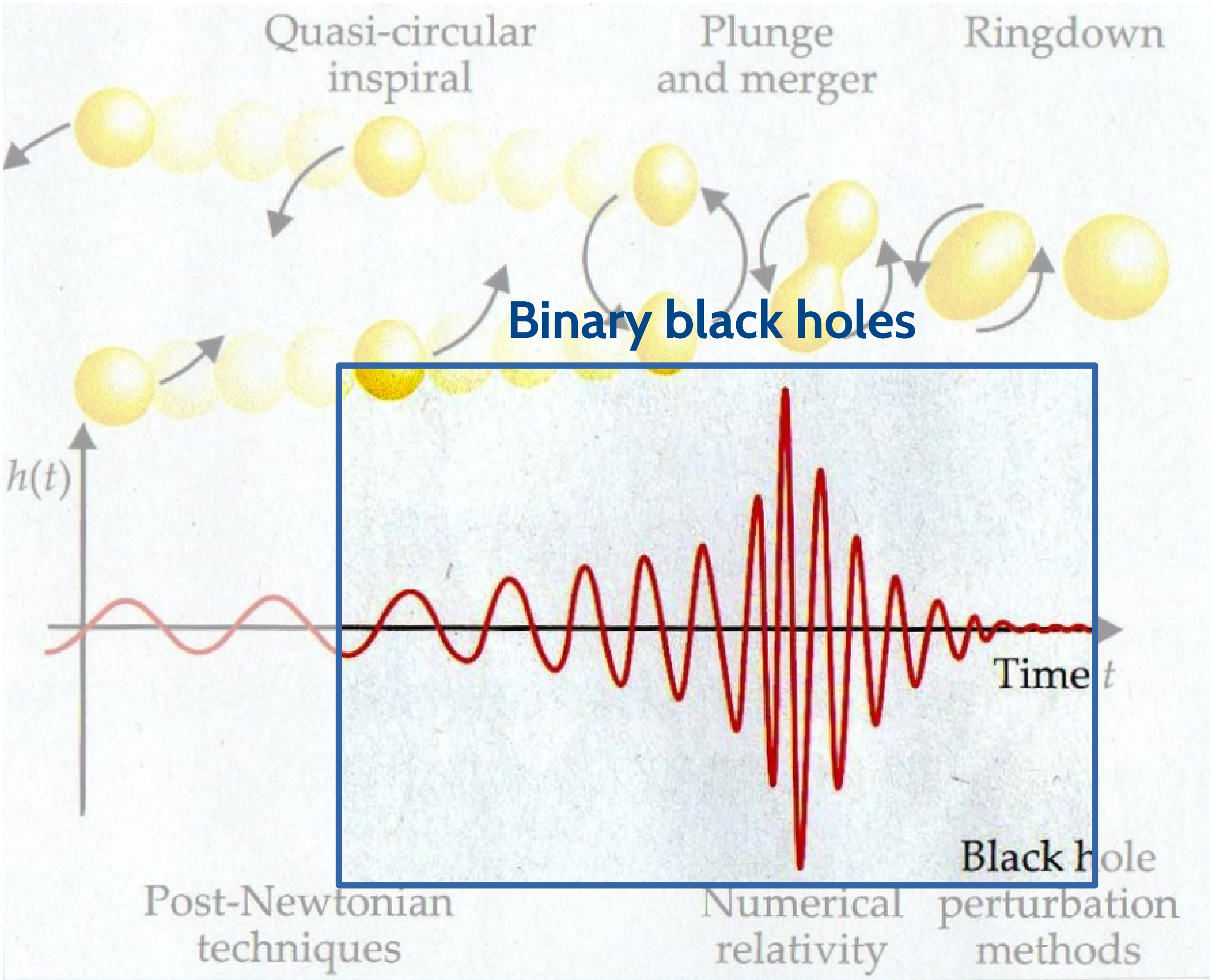
Visibility



Quasi-circular inspiral
Plunge and merger
Ringdown
h(t)
Binary neutron stars
Time t
Post-Newtonian techniques
Numerical relativity
Black hole perturbation methods

Visibility



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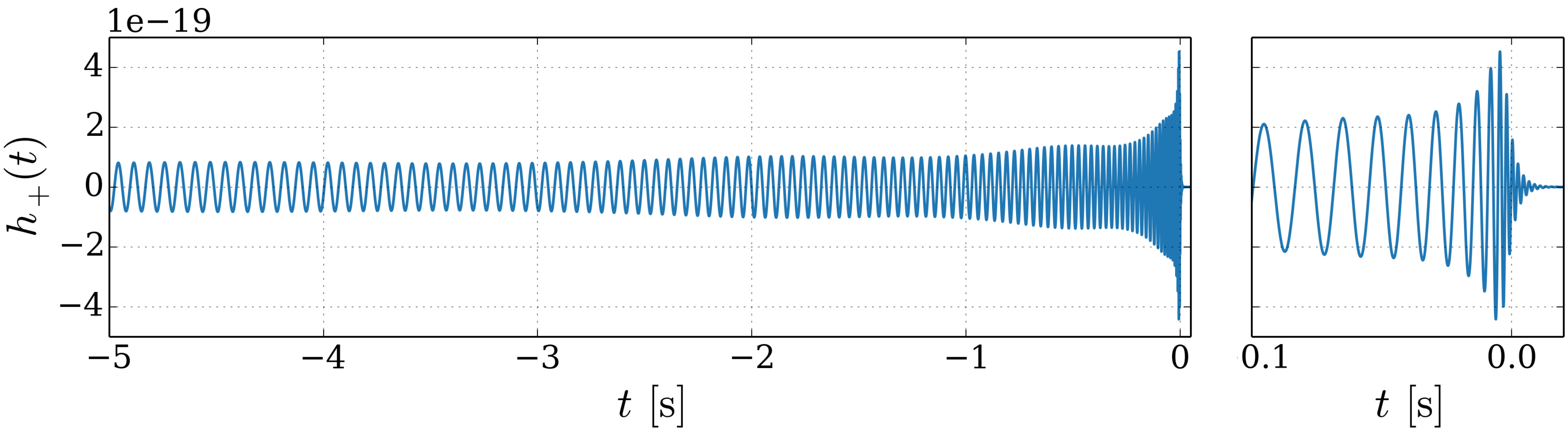
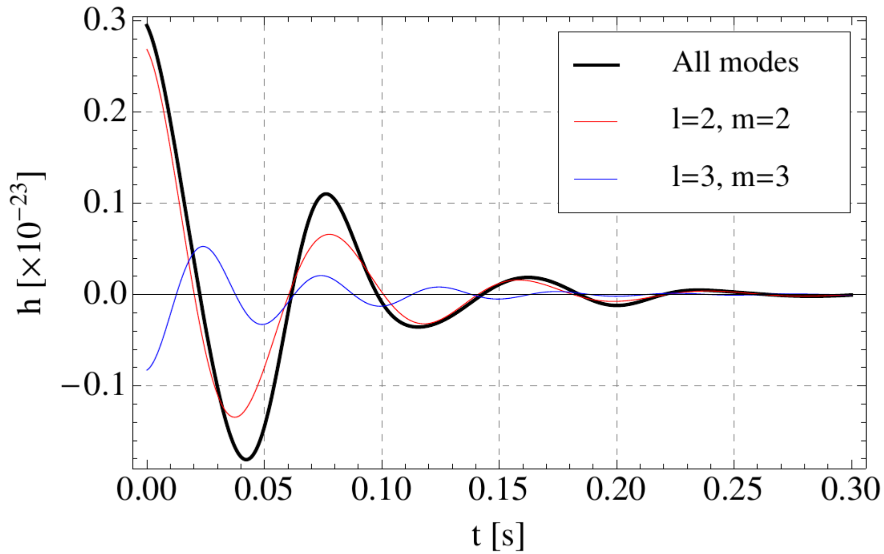
Binary Black Holes



- Very rich sources
- Modulation of orbit due to large spin-spin and spin-orbit interaction
- Merger within sensitivity band of detectors
  - Unveils genuinely strong field dynamics
- Ringdown also within band
  - First direct evidence for existence of black holes

Black hole ringdown



- Superposition of modes, characterized by mode frequencies and damping times:
  $\omega_{lm}(M,J)$ and $\tau_{lm}(M,J)$
- *No-hair theorem*: Final Black hole only depends on mass M and spin J
- Deviations from this prediction can be generically written as:

$$\omega_{lm} = \omega_{lm}^{\mathrm{GR}}(M, J)(1 + \delta\hat{\omega}_{lm})$$

$$\tau_{lm} = \tau_{lm}^{\mathrm{GR}}(M, J)(1 + \delta\hat{\tau}_{lm})$$

Test of No-hair theorem

Scenario: Measurements of odds ratio show no signs of violation

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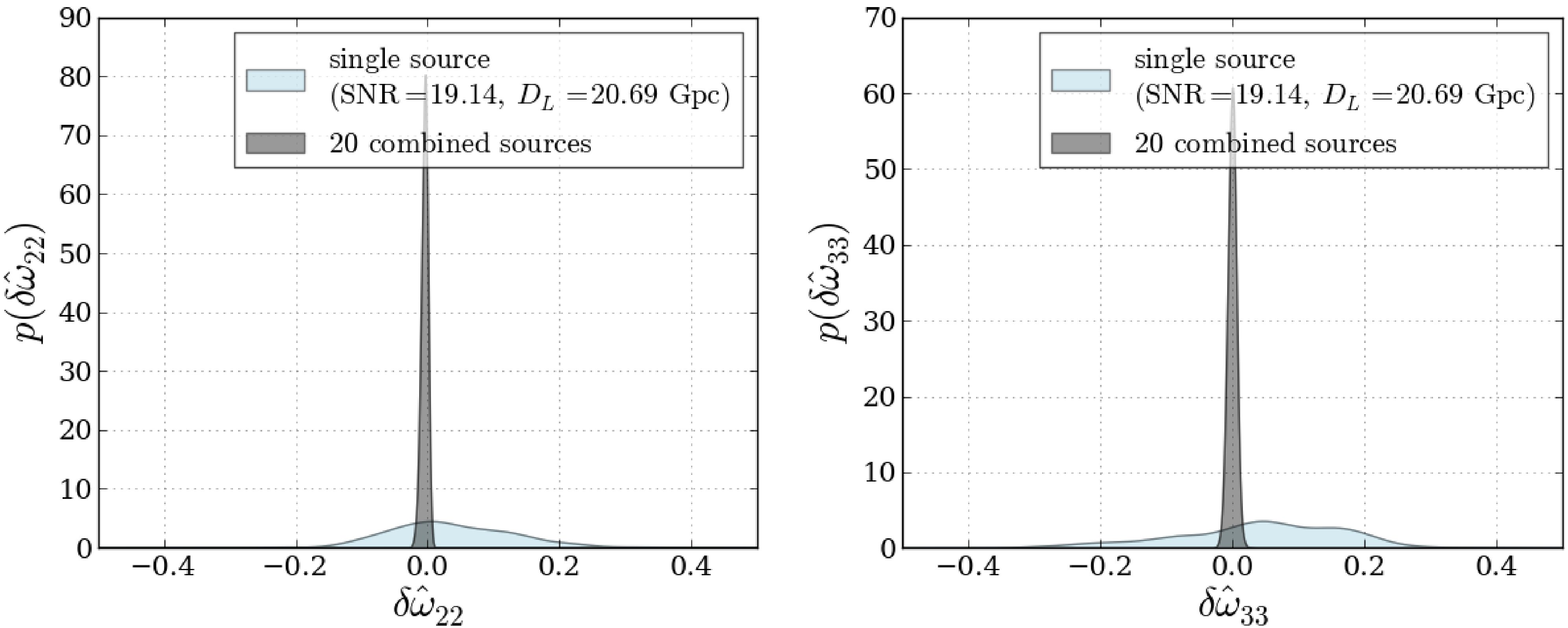

- Very stringent constraints on ringdown parameters possible
- Quadratic curvature corrections introduce relative shift of a factor of 2

Meidam et al., PRD **90**, 064009 (2014)

Summary

- Gravitational waves will allow us to probe the genuinely strong-field dynamics of general relativity

- We have a model independent test of general relativity
  - Using inspiral coefficients
  - Using ringdown mode frequencies and damping times to test no-hair theorem

- Until 2014 pipeline only for binary neutron stars
- This year successfully extended to binary black hole regime