Testing the strong-field dynamics of general relativity with gravitional waves

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Statement of the problem

General Relativity has enjoyed important successes:

- Perihelium precession of Mercury
- Deflection of star light by the Sun
- Shapiro time delay
- Gravity Probe B
  - Geodetic effect
  - Frame dragging
- Binary pulsars

Statement of the problem

General Relativity has enjoyed important successes:

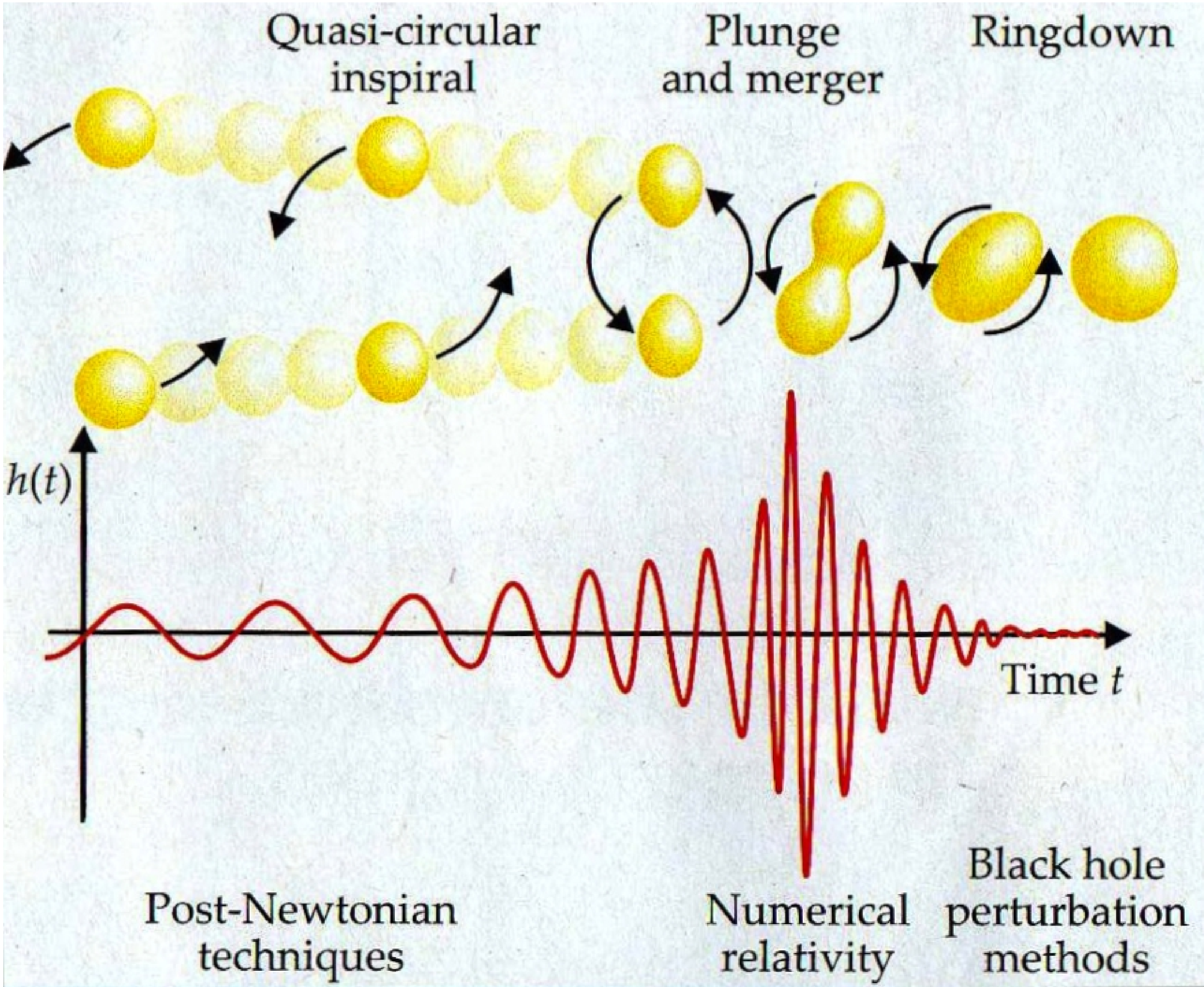
- Perihelium precession of Mercury [weak, static field]
- Deflection of star light by the Sun [weak, static field]
- Shapiro time delay [weak, static field]
- Gravity Probe B
  - Geodetic effect [weak, static field]
  - Frame dragging [weak, stationary field]
- Binary pulsars [dynamical but weak-field]

No tests of genuinely strong-field dynamics of spacetime

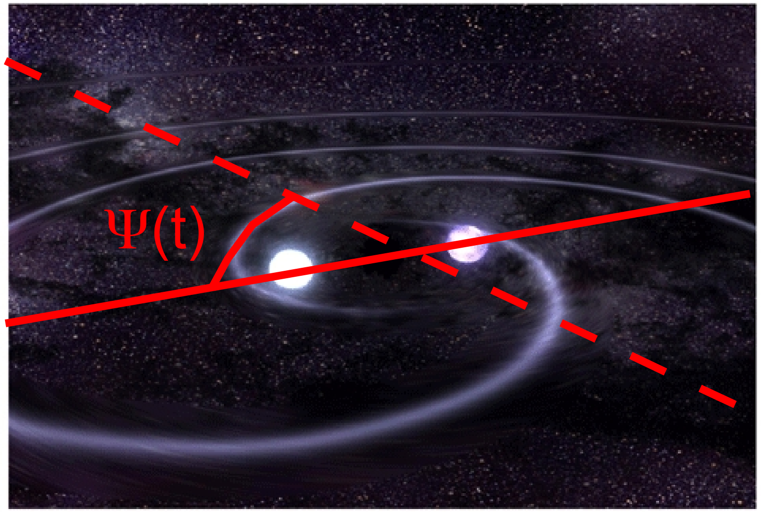
Ideal laboratories: coalescing binary neutron stars and black holes

→ *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 *v = v(t)*:

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

- Up to factor of 2, this is also the phase of the GW signal
- In general relativity:

ψ_n and $\psi_n^{(l)}$ are specific functions of component masses and spins

The inspiral of compact binaries

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

Physical content of coefficients:

- ψ_3 encodes lowest-order dynamical self-interaction of spacetime
- ψ_4 has lowest-order spin-spin effects
- $\psi_5^{(l)}$ is lowest-order logarithmic coefficient

Possible modifications to GR:

- Massive graviton modifies ψ_2
- “Dynamical scalarization” adds $\psi_{ST} v^{-2}$ inside the sum
- Quadratic curvature corrections add $\psi_{QC} v^4$
- Gravitational parity violations add $\psi_{CS} v^9$

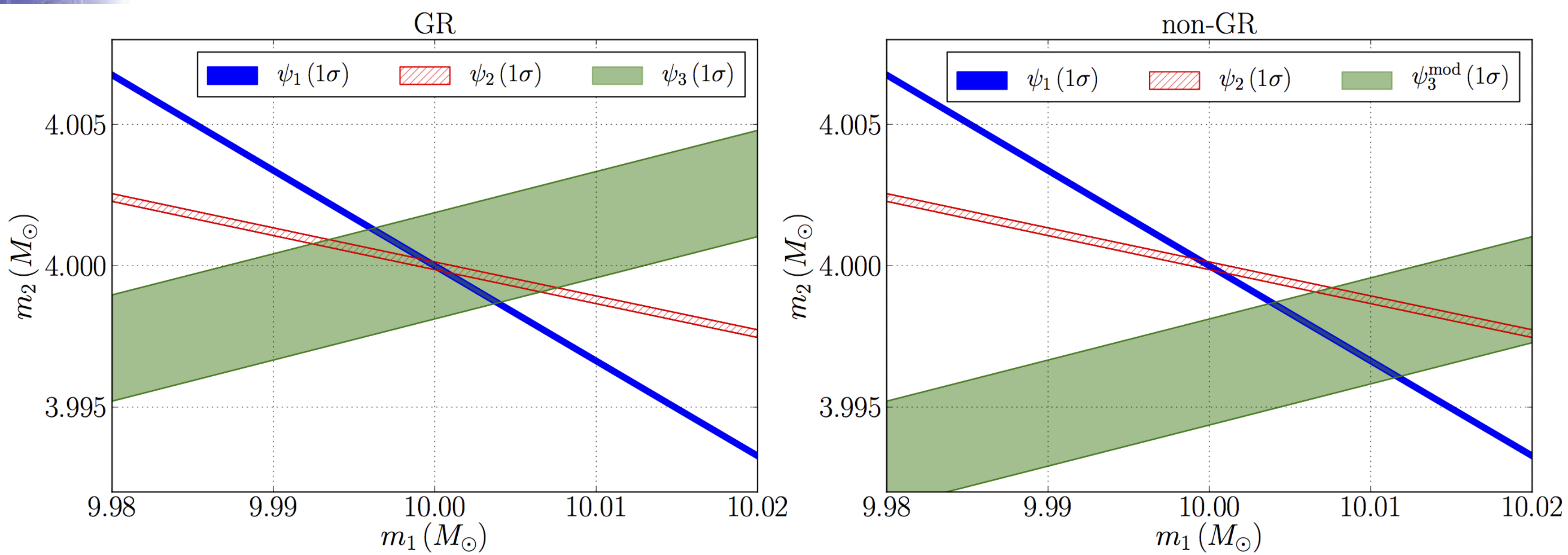
Probing the strong-field dynamics of spacetime

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

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

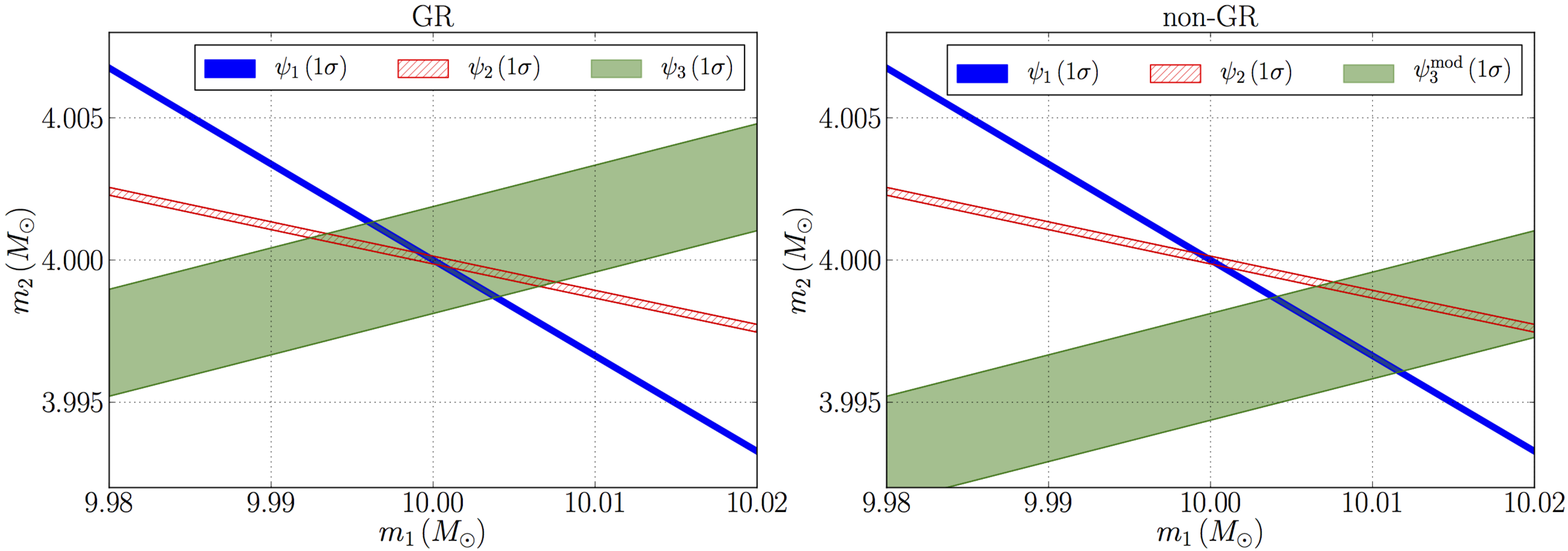
→ Only two of them are independent

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

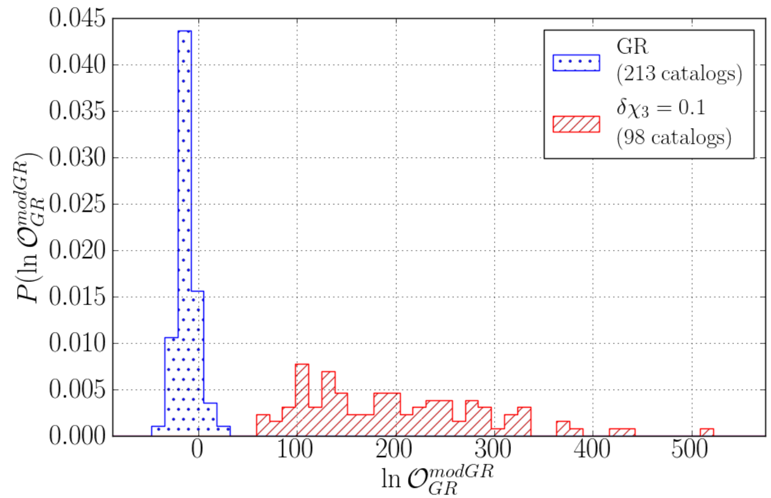
Instead do *model selection* by computing an “odds ratio”:

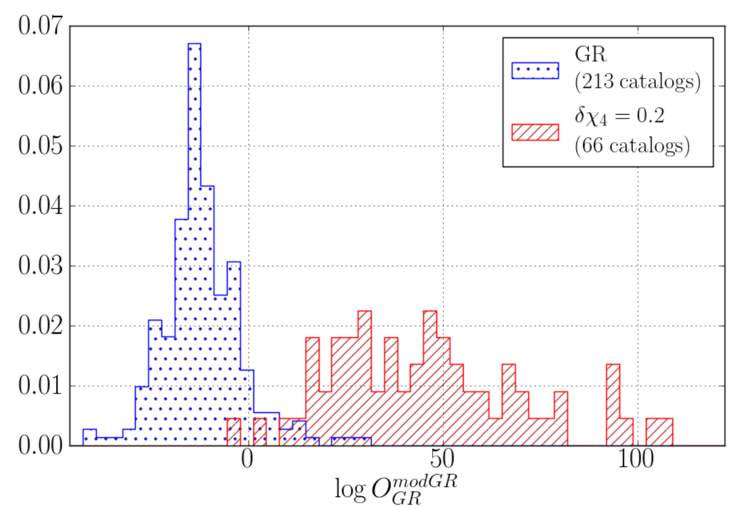
$$O_{\rm GR}^{\rm modGR} = \frac{P(\mathcal{H}_{\rm modGR}|d,\mathrm{I})}{P(\mathcal{H}_{\rm GR}|d,\mathrm{I})}$$

Li et al., PRD **85**, 082003 (2012); Li et al., J. Phys. Conf. Ser. **363**, 012028 (2012)

Examples: binary neutron stars, AdV/aLIGO/KAGRA/IndIGO

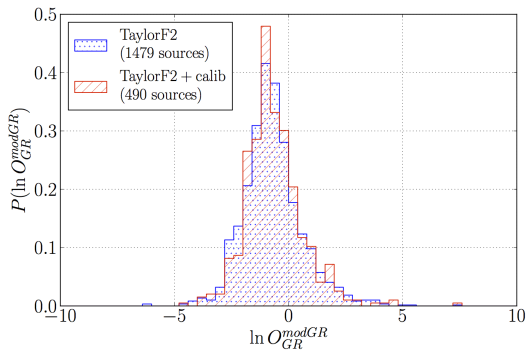
- Consider large number of simulated binary neutron star signals, combine into catalogs of 15 each
- How is (log) odds ratio distributed?
  - Example 1:
    - GR is right
    - 10% shift at $(v/c)^3$
      - Anomaly in dynamical self-interaction of spacetime
  - Example 2:
    - GR is right
    - 20% shift at $(v/c)^4$
      - Quadratic curvature corrections to Einstein-Hilbert action



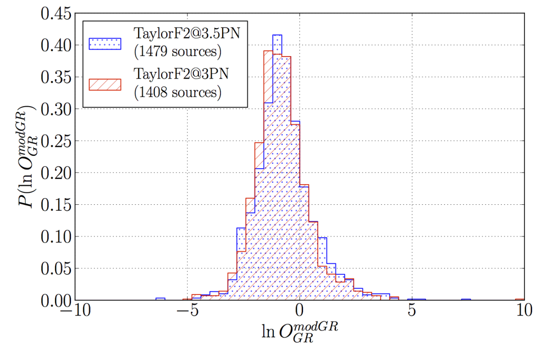


Binary neutron stars: robustness against unknown effects

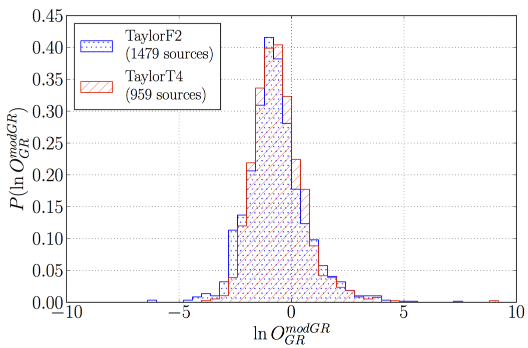
Instrumental calibration errors



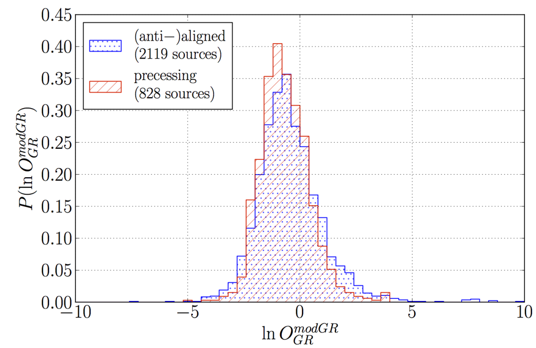
Finite number of known phase contributions



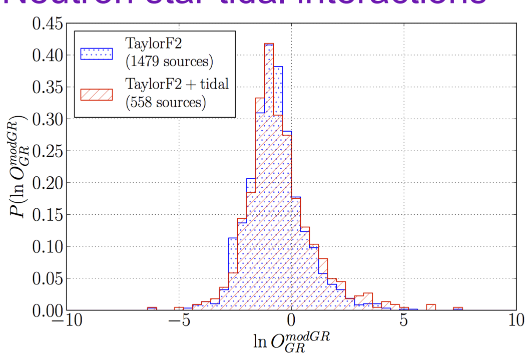
Different waveform approximations



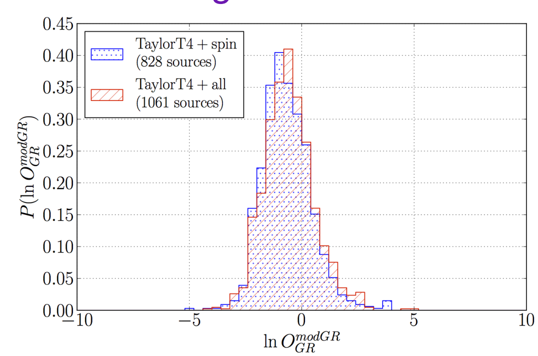
Neutron star spins



Neutron star tidal interactions



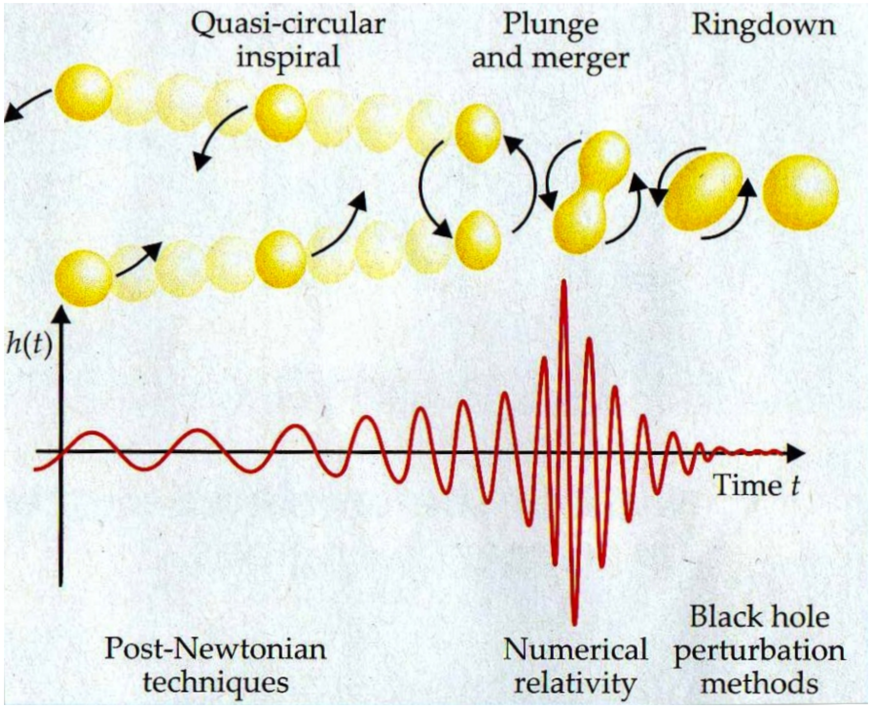
All effects together



Agathos et al., PRD **89**, 082001 (2014)

What about binary black holes?

- For binary neutron stars, things are under control
  - Only inspiral part of the waveform can be seen in detectors
  - Small spins



- Binary black holes:
  - Inspiral, merger, ringdown
  - Very large spins

Dynamically richer, but...

  - Good waveform models becoming available only now
  - Analysis problem much harder

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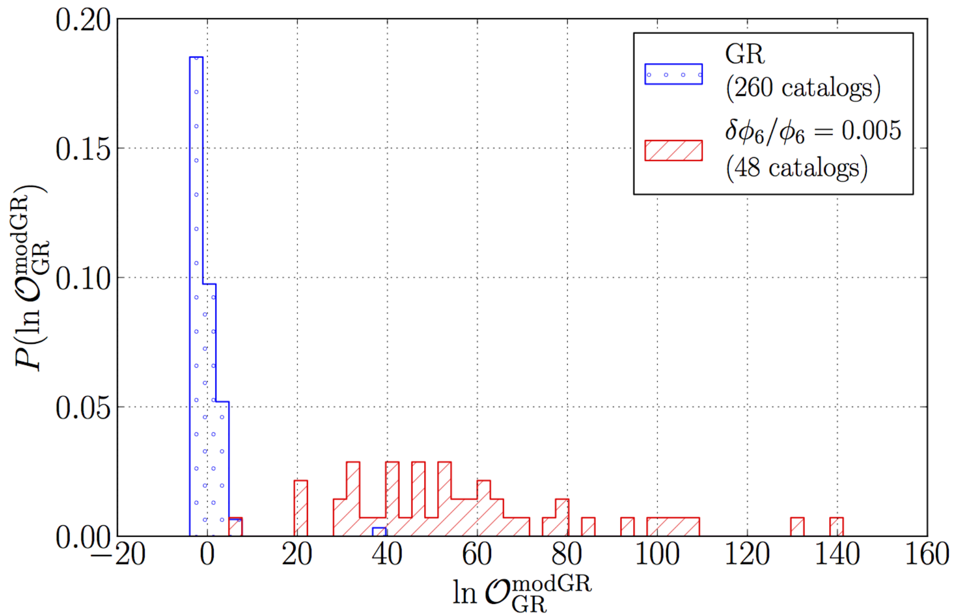
C. Van Den Broeck, to appear in Springer Handbook of Spacetime; arXiv:1301.7291 [gr-qc]



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Dynamically richer, but...

  - Good waveform models becoming available only now
  - Analysis problem much harder
  - From simulations that assume zero spins:
    0.5% deviation at $(v/c)^6$ beyond leading order can be seen (!)
  - Work in progress

Comparison with existing binary pulsar bounds?

- We will probe regime where (v/c) and GM/c^2R both $O(1)$

  Compare binary pulsar: $(v/c) \ll 1$ and $GM/c^2R \ll 1$

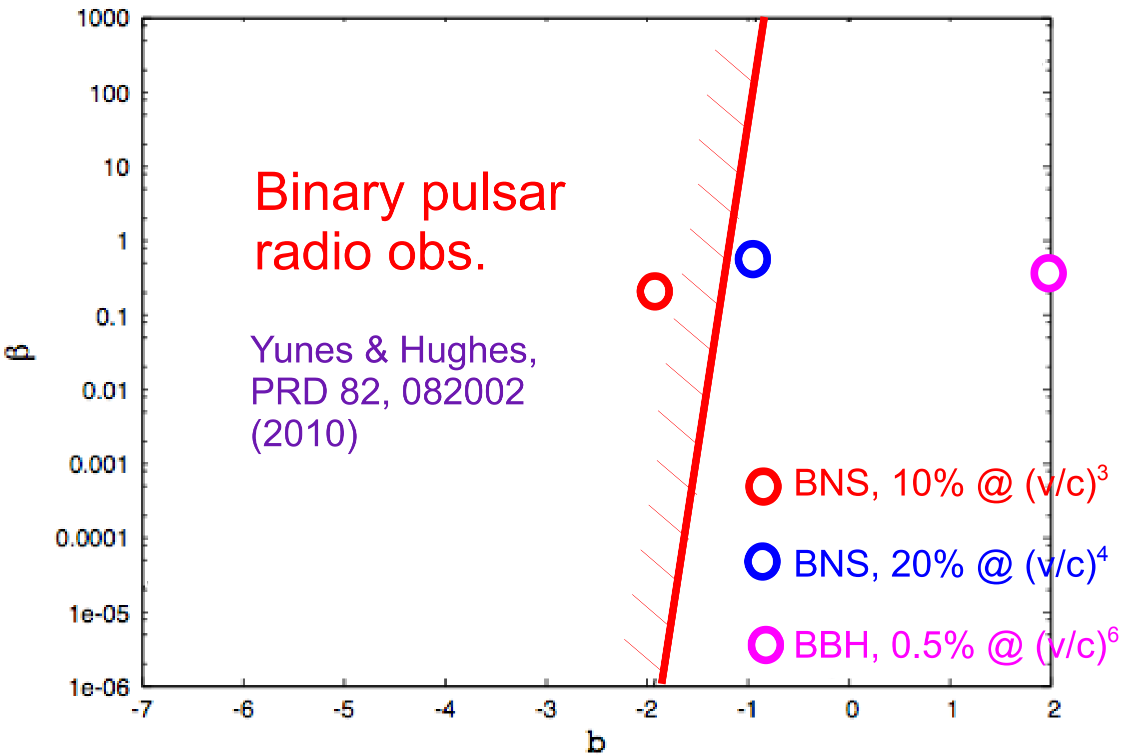
- GR violations may only appear at high v/c
  - Example: “dynamical scalarization”

- But, let's *assume* that any deviation at large v/c will also show up at small v/c, with “same size”

- Model deviations in phase as

$$\Psi(v) \longrightarrow \Psi(v) + \beta(v/c)^b$$

  - Results for binary neutron stars (BNS) already beat binary pulsar
  - Binary black holes (BBH): will get us in regime that is totally unconstrained



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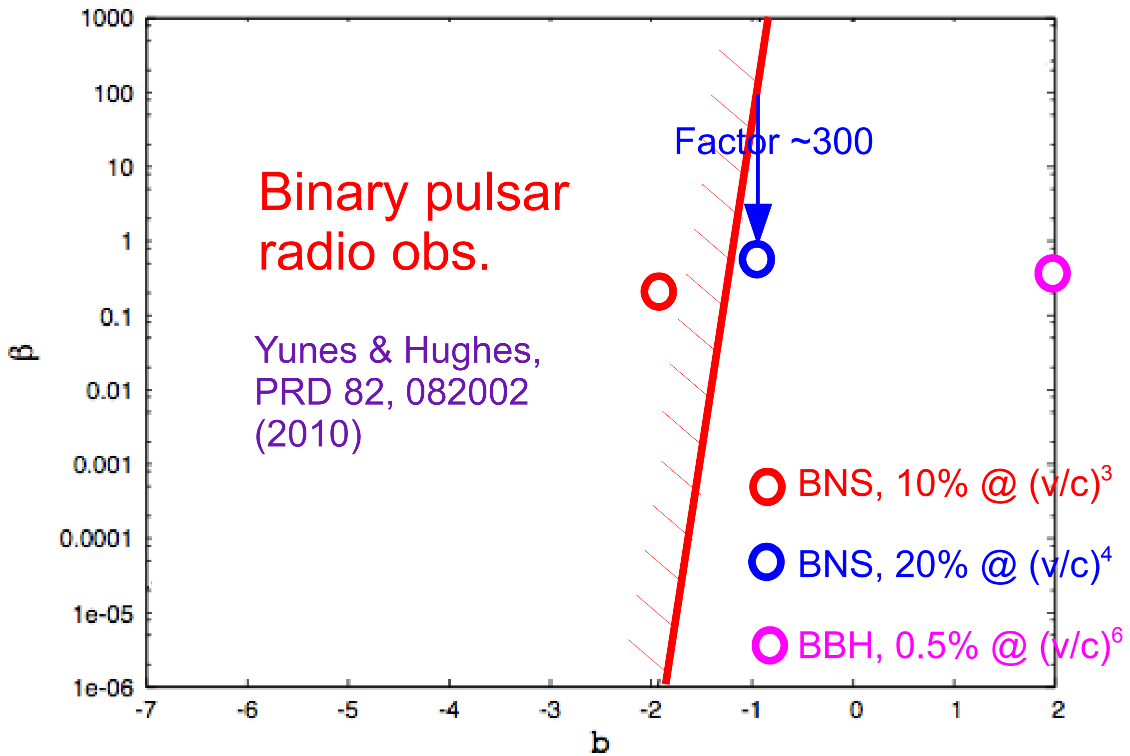

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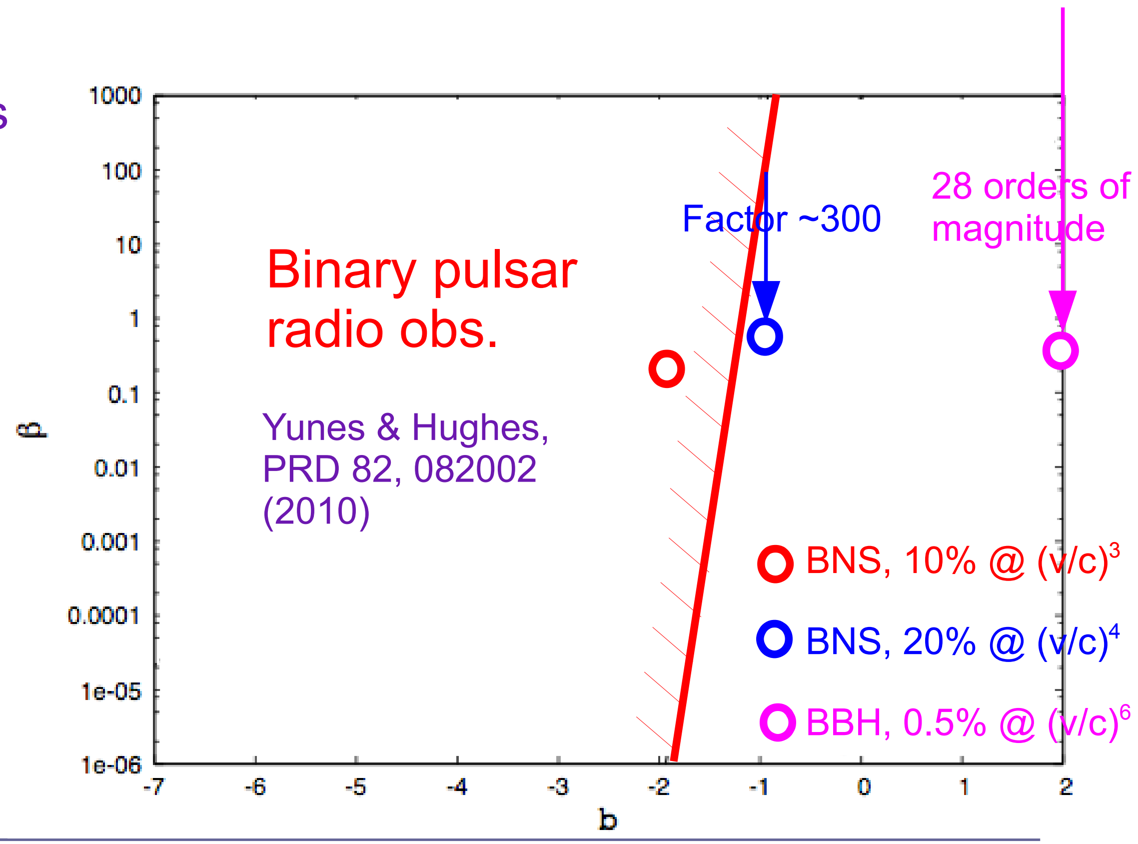
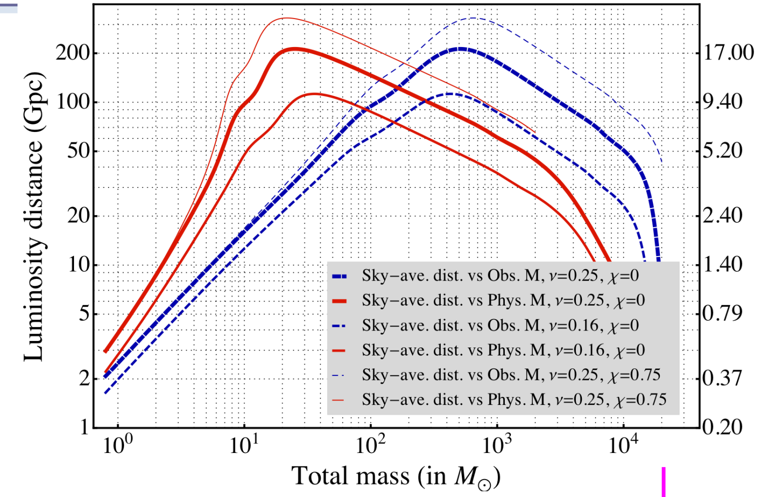
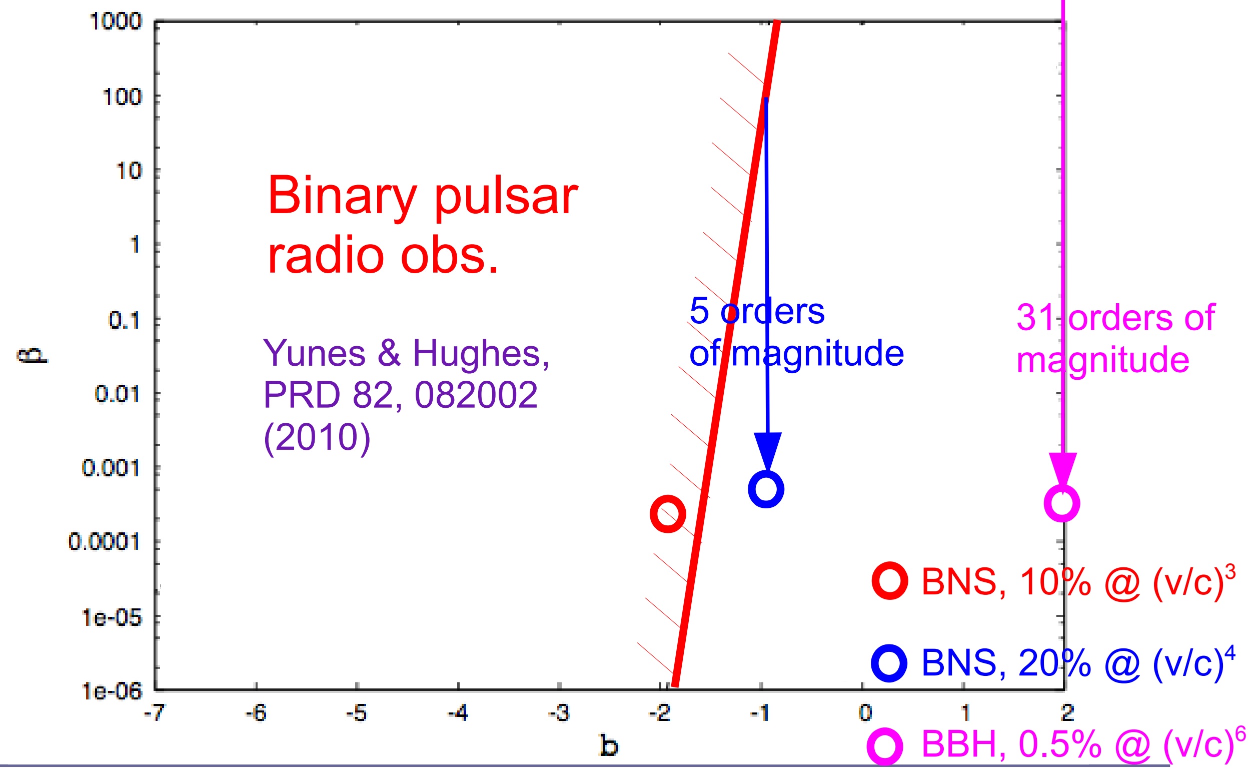


Einstein Telescope

- Signal-to-noise ratios ~10 times higher for sources at same distance
- May see > 10^4 sources out to redshifts > 5

→ Improvement of ~1000





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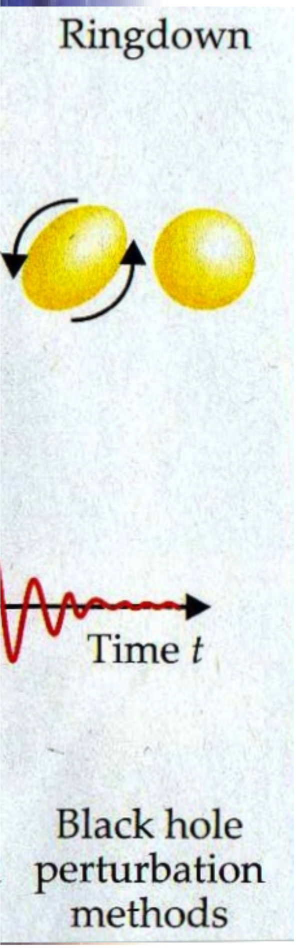
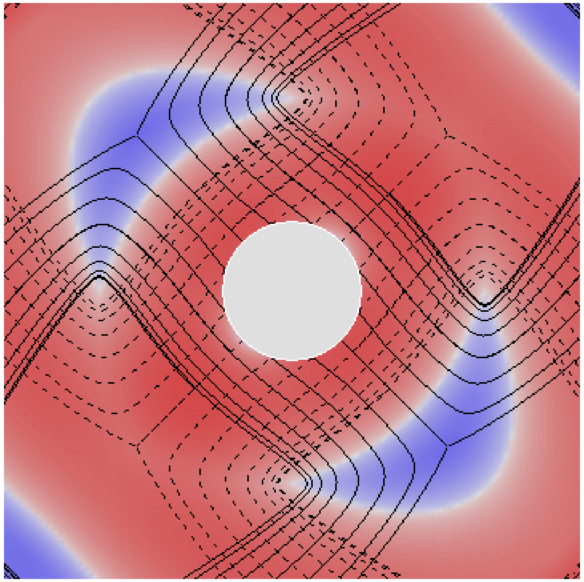




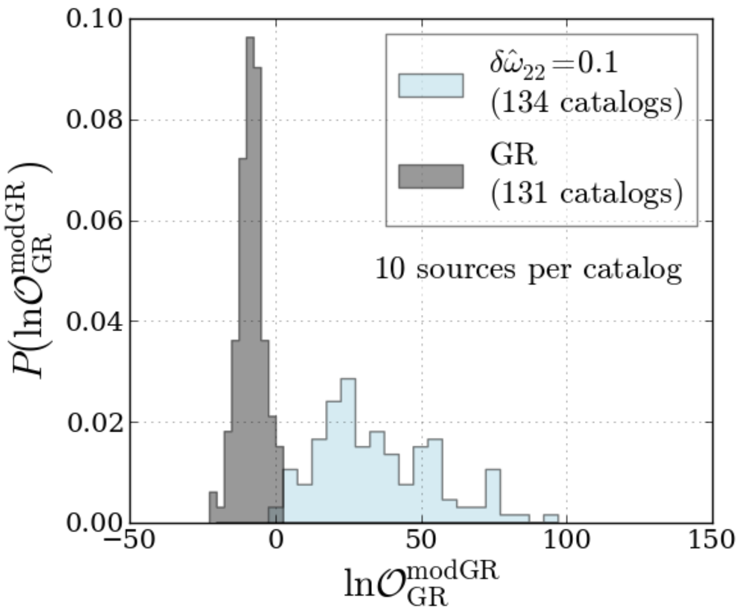
- Einstein Telescope will also allow us to clearly see ringdown signals
- Superposition of modes with
  - frequencies ω_{nlm}
  - damping times τ_{nlm}
- Einstein equations force all of these to depend on mass *M*, spin *J* of final black hole:

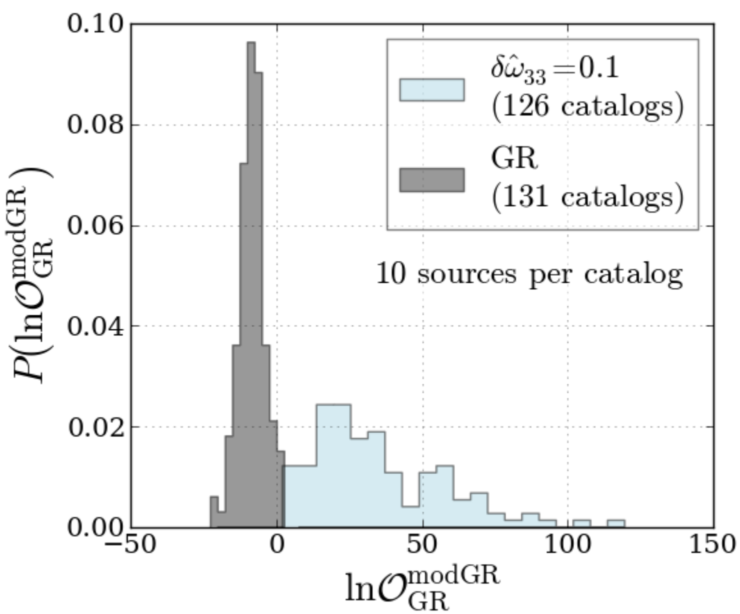
  $\omega_{nlm} = \omega_{nml}(M,J), \qquad \tau_{nml} = \tau_{nml}(M,J)$

  ... hence only two independent

→ *Test of the no-hair theorem*

Einstein Telescope





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→ *Test of the no-hair theorem*

J. Meidam et al., in preparation

Outlook

- Direct gravitational wave detection will gives us empirical access to the genuinely strong-field dynamics of spacetime
  - Rich physics
    - Observe dynamical self-interaction of spacetime itself
  - Variety of ways in which alternative theories of gravity can manifest themselves
- Already the 2nd generation detectors will take us well beyond the regime that we can access today
  - A robust data analysis pipeline for testing GR is already in place for the case of binary neutron star coalescence
  - Binary black holes much more challenging, but great rewards
- Einstein Telescope (and *e*LISA!) will herald precision gravitational physics
  - Additional tests, e.g. no-hair theorem