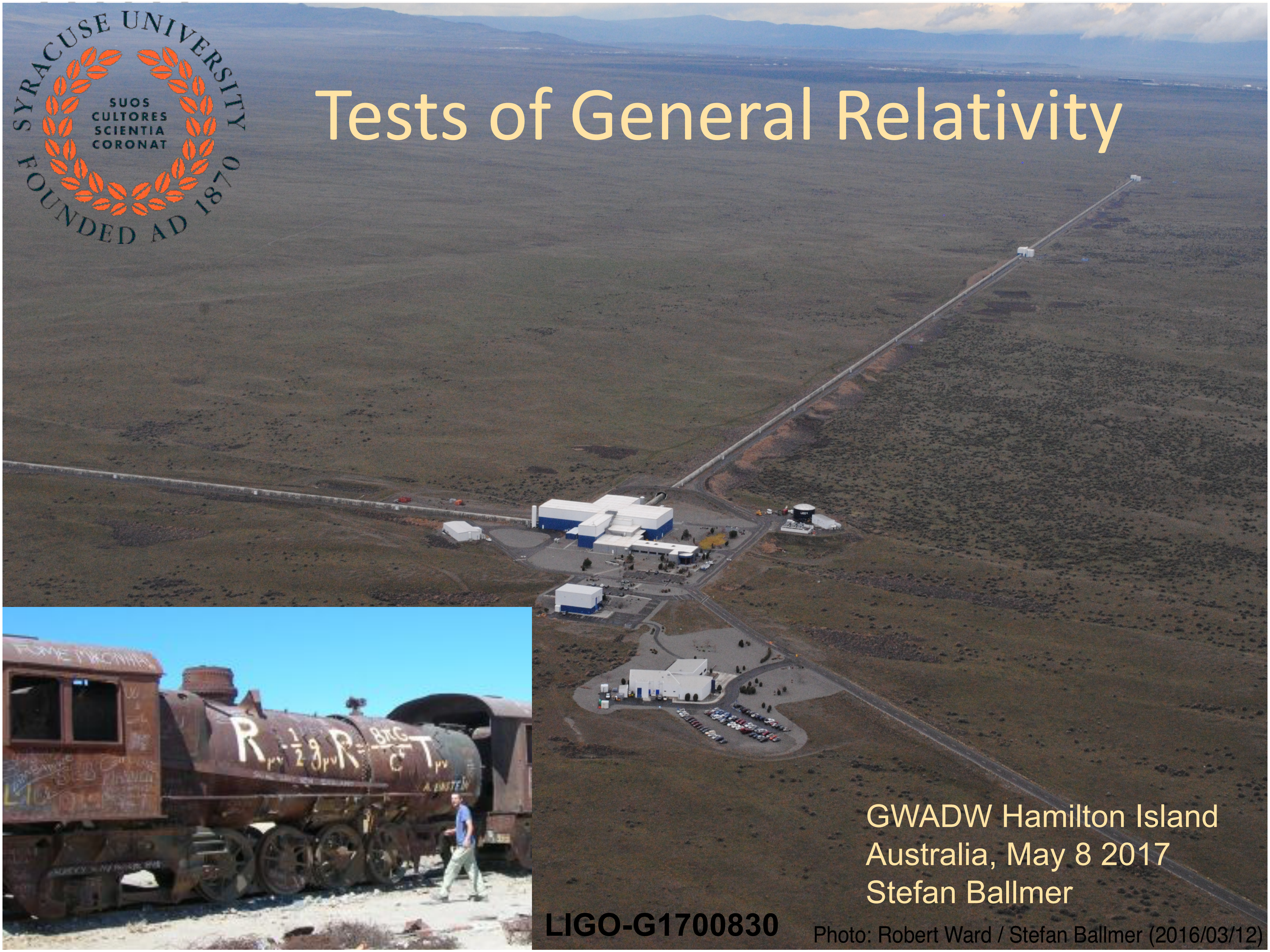
SYRACUSE UNIVERSITY
SUOS CULTORES SCIENTIA CORONAT
FOUNDED AD 1870

Tests of General Relativity



GWADW Hamilton Island
Australia, May 8 2017
Stefan Ballmer

LIGO-G1700830

Photo: Robert Ward / Stefan Ballmer (2016/03/12)

LIGO

This talk

- Attempt of an overview of what was done so far
- What is missing / interesting?
- What are the particular strengths of 3G detectors?

LIGO

What to test on GR?

(Nico Yunes's slide)

Classifying Deviations

Gravitational Wave Generation

Scalar/Vector Field Activation

Gravitational Parity Violation

Gravitational Lorentz Violation

Extra-Dimensional Leakage

Time-Variation of G

⋮

Spacetime Dimensionality

Parity Violation

Lorentz Violation

SEP Violation

Test Fundamental Pillars of GR

Gravitational Wave Propagation

Modified Dispersion Relations

Modified Kinematics

Gravitational Lorentz Violation

Cosmological Screening

Time-Variation of G

⋮

Speed of Gravity

Mass of Graviton

Lorentz Violation

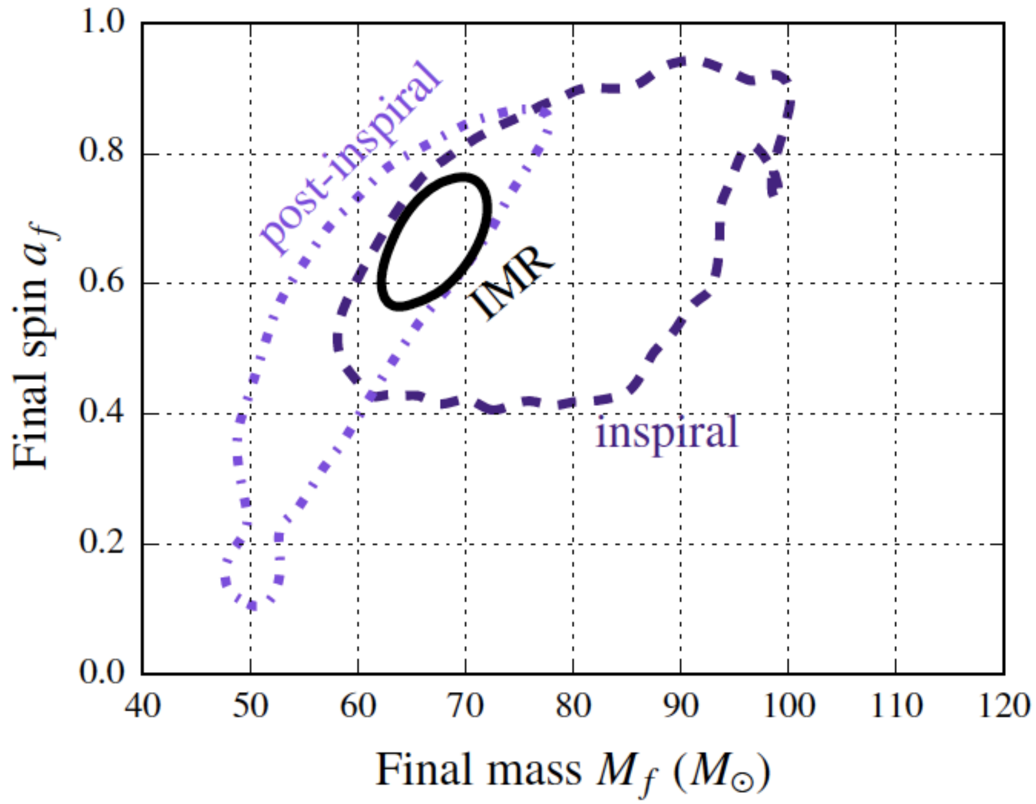
SEP Violation

LIGO Measurements types

- Generation:
  - Quadrupole and higher order emissions
  - Ring-down mode spectrum
  - PN coefficients / wave form
- Propagation:
  - Polarizations
    - By direct measurement (network)
    - Or by radiation back reaction
  - Dispersion / graviton mass

Tests done so far

- Early-late consistency checks
  - On mass / spin – so far crude agreement



- Better precision for 3G, but…
- …are there GR effects that produce disagreement? YES!

BH Kicks

- Required:
  - High spins and large spin misalignment
- Asymmetric emission of final chirp
- Linear momentum conservation
  → large kicks
- Up to 5000km/sec expected (v/c ~ 0.017)
  (Gonzales 2007, Campanelli 2007, Lousto Zlochower 2013)

Mass-redshift degeneracy

- In GW measurements, **total mass** and **redshift** are degenerate
- Kicks show up as a red/blueshift in the GW waveform!

Cosmology:

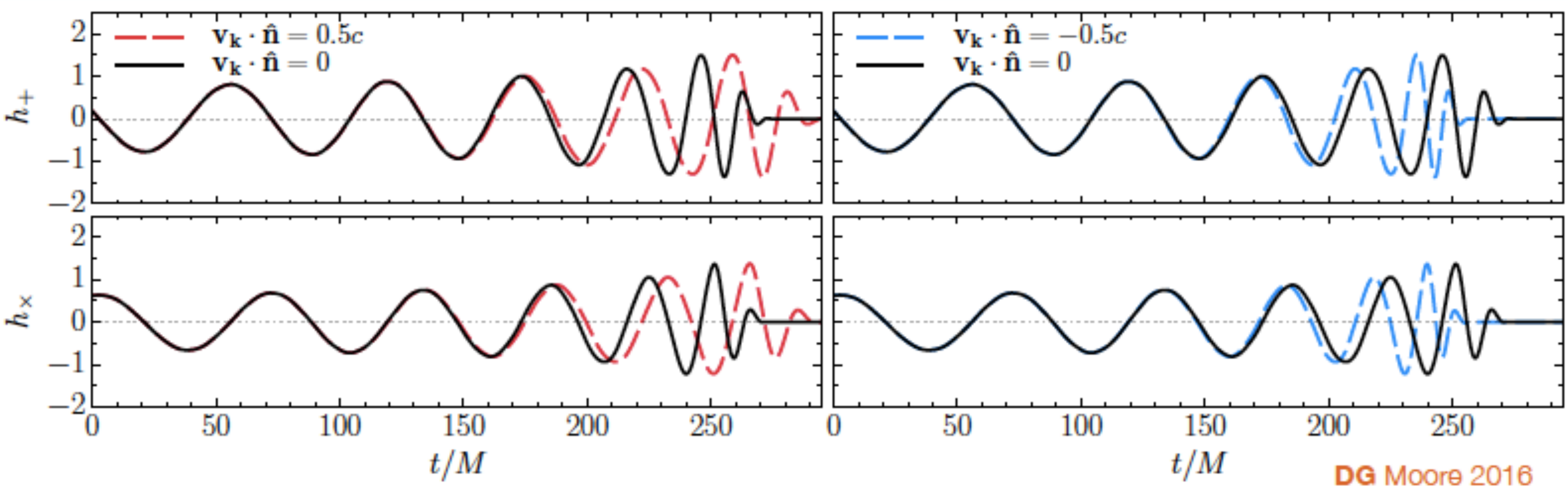
entire waveforms is shifted

$$M \to M(1+z)$$

Kicks:

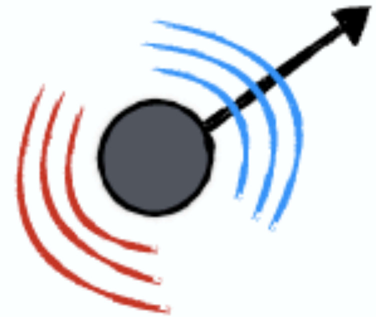
differential Doppler shift

$$M \to M\left(1 + \frac{\mathbf{v_k}(t)}{c} \cdot \hat{\mathbf{n}}\right)$$



Davide Gerosa, Aspen Winter Conf. 2/9/2017

Back of the envelope argument



$$h(t) = h_i(t) + h_r(t)$$

$$M_r = M_i(1 + \mathbf{v_k} \cdot \hat{\mathbf{n}})$$

- M_r: mass measured from the ringdown
- M_i: mass measured from the inspiral
- $\mathbf{v_k} \cdot \hat{\mathbf{n}}$: projection of the kick along the line of sight

To observe kicks $v_k = 0.01c \sim 3000\mathrm{km/s}$ we need to measure M_r at 1%

Ringdown SNR $\rho_r^2 = \frac{1}{S_n}\int_0^\infty h_r(t)^2\,\mathrm{d}t$

1d Fisher matrix $\left(\frac{1}{\Delta M_r}\right)^2 = \frac{1}{S_n}\int_0^\infty \left(\frac{\partial}{\partial M} h_r(t)\right)^2 \mathrm{d}t$

Schw. QNM $h_r(t) \propto \exp\left(\frac{-0.089}{M_r}\right)\sin\left(\frac{-0.37t}{M_r}\right)$

$$\frac{\Delta M_r}{M_r} \simeq \frac{0.322}{\rho_r}$$

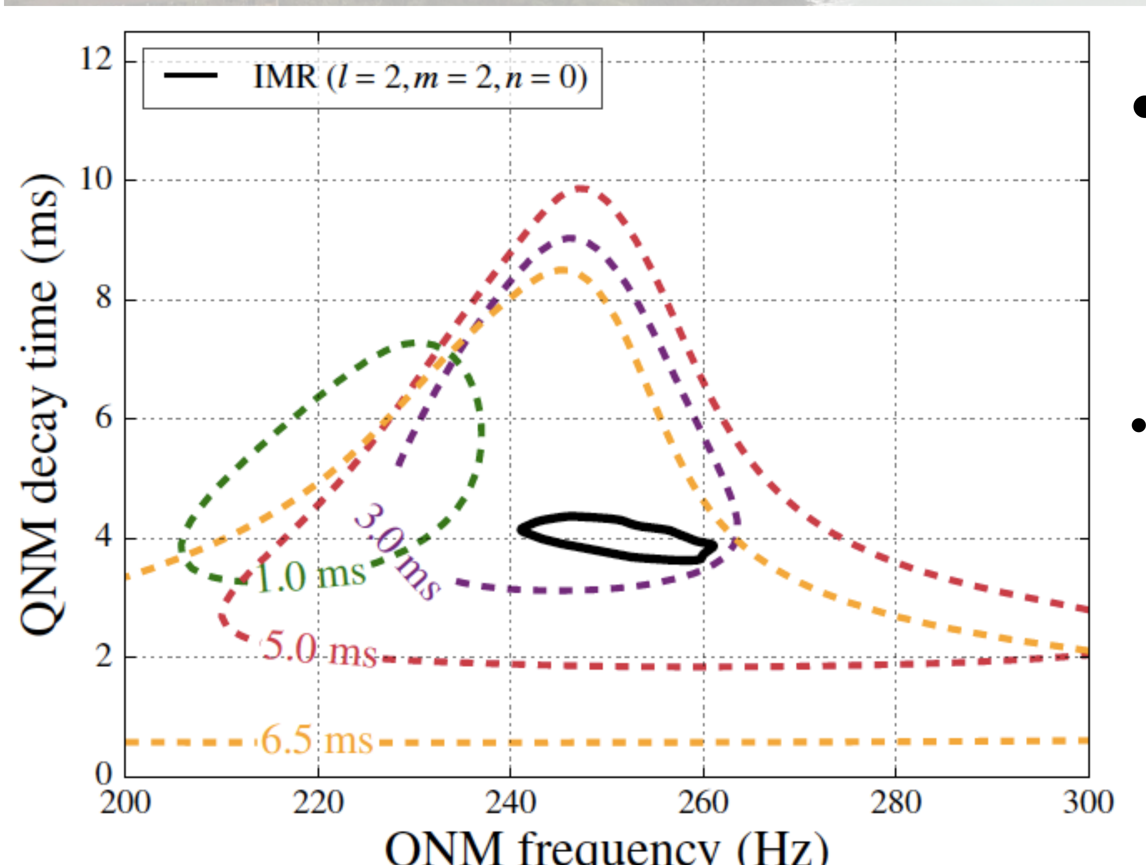
To measure $v_k \sim 900\mathrm{km/s}$ one needs $\rho_r \sim 100$

Tough for LIGO… but 3rd generation detectors and LISA will make it!

Davide Gerosa, Aspen Winter Conf. 2/9/2017

Tests done so far

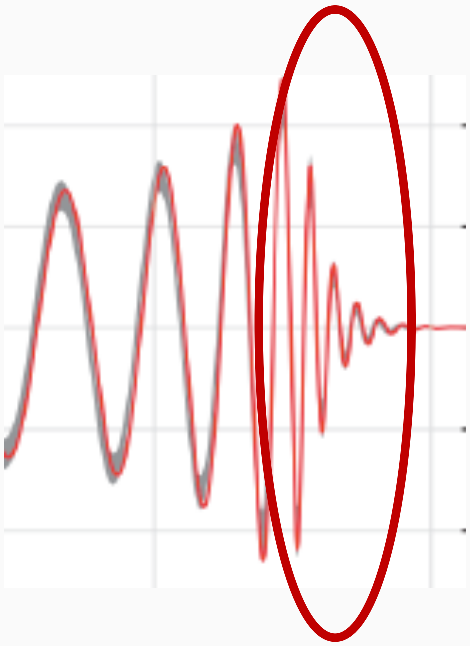
- Ring-down mode spectrum consistency
  - So far: only one mode resolved…

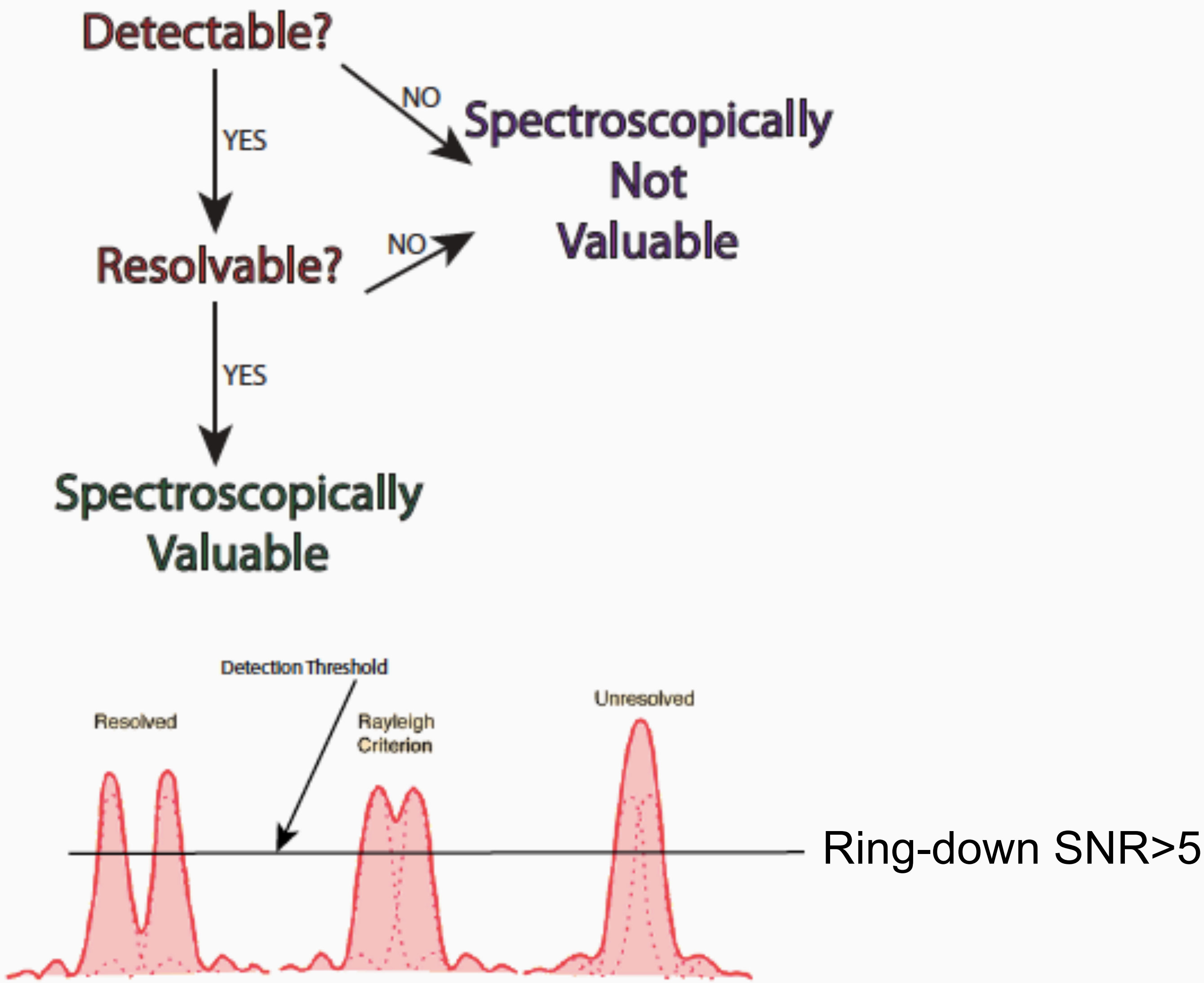


- But looks promising for the future:

- *"Spectroscopic analysis of BH mergers…" Swetha Bhagwat, Brown, Ballmer, PRD94,084024*

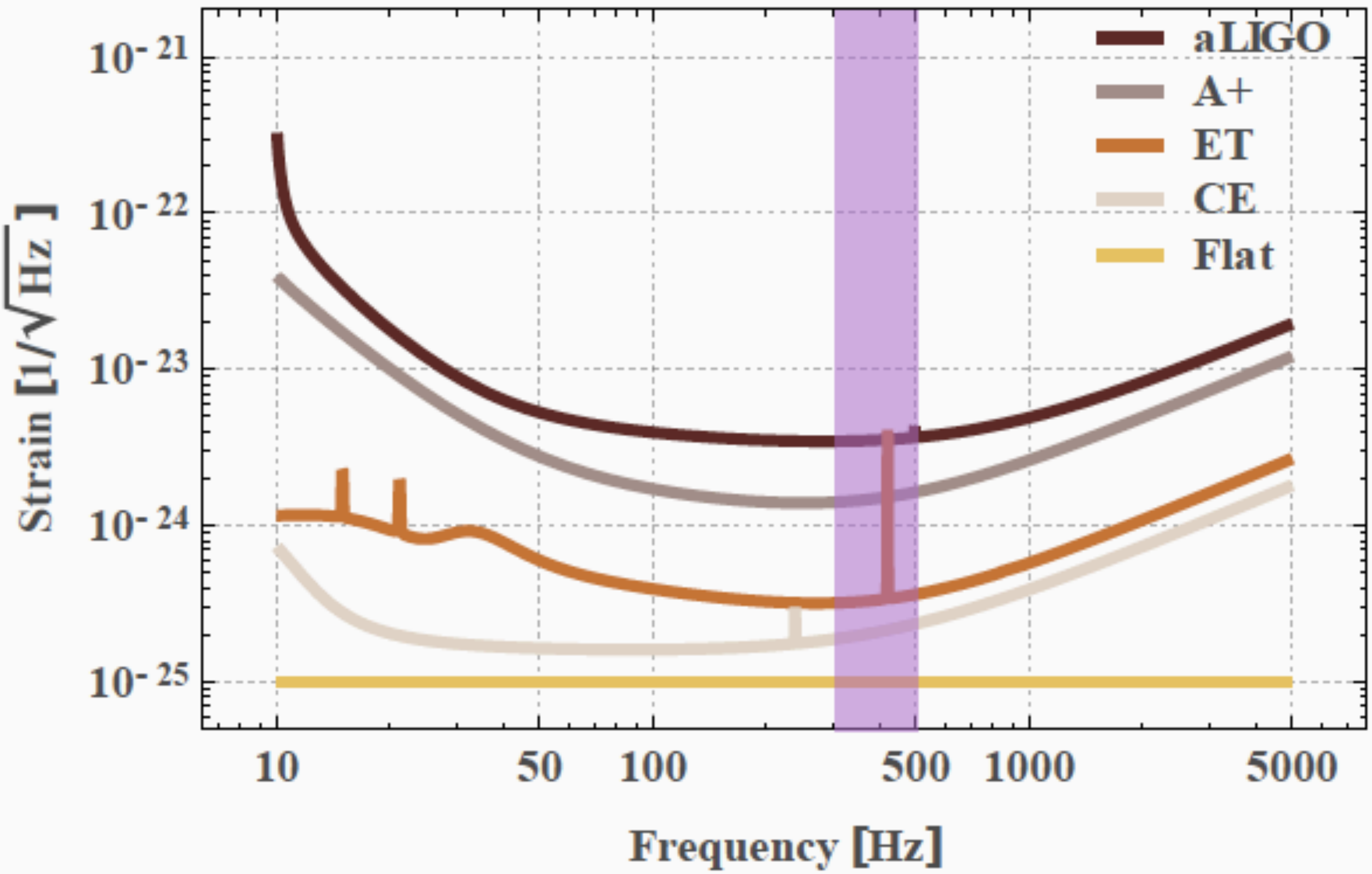
Analysis Framework





Bhagwat, Brown, Ballmer, PRD94,084024

Detector Models



Bhagwat, Brown, Ballmer, PRD94,084024

Results-1

- Sub-dominant mode has the most measurability: $(3, 3)$ and $(2, 1)$
- Limited by measurability and NOT by resolvability criterion.
- An increase in sensitivity $\approx$ 300 Hz and 500 Hz would enhance the measurability of both $l = m = 3$ and $l = m = 4$.

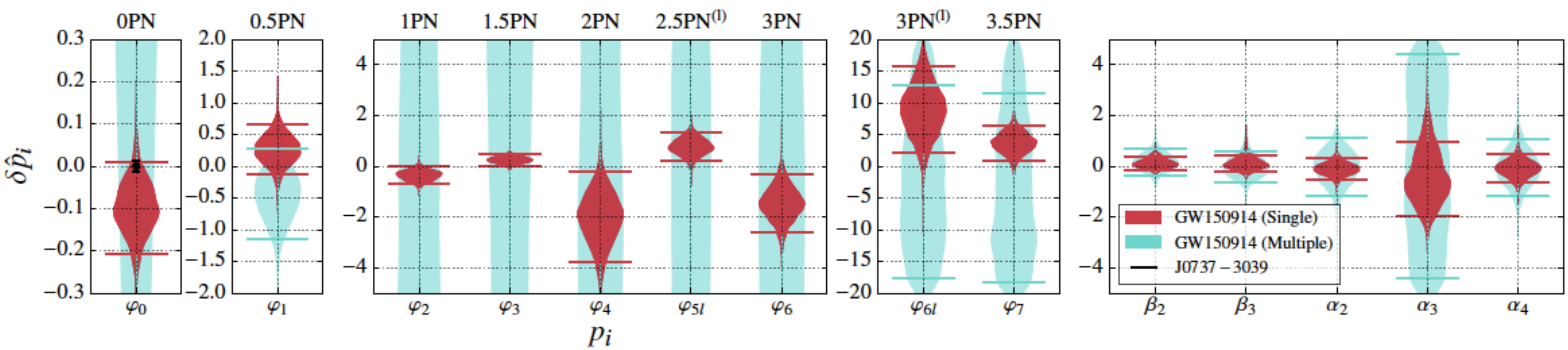
Bhagwat, Brown, Ballmer, PRD94,084024

Results-2

- Assuming an optimistic rate of 240 $Gpc^{-3}yr^{-1}$, about 3 events per year seem be spectroscopically valuable with Advanced LIGO.
- With detectors like CE and ET, approximately 20-30% of the total detected stellar mass BH mergers are spectroscopically valuable.
- Even a pessimistic rate of only 13 $Gpc^{-3}yr^{-1}$ binary BH mergers, about 4-60 events allow for multi-mode measurements using CE and ET.

The PN game

- Good 'single' value constraints
  - Can rule out theories predicting a deviation at a single order.
- But the various PN parameters are highly correlated.
- What matters is the mapping to a theory!



What to test on GR?

(Nico Yunes's slide)

What are we really learning with GWs?

Violations of the Strong Equivalence Principle

Lorentz Violations in Gravity

Gravitational Parity Violation

What matters the most is the *mapping* between ppE constraints and theoretical physics inferences

Graviton Mass and Propagation Effects

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.

(leaving out a lot of stuff here, e.g. no-hair tests with ringdown)

Nico Yunes's slide

Future Constraints on the Graviton Mass

Maximize Extraction:

Binary systems that are as far away as possible (SMBHs)

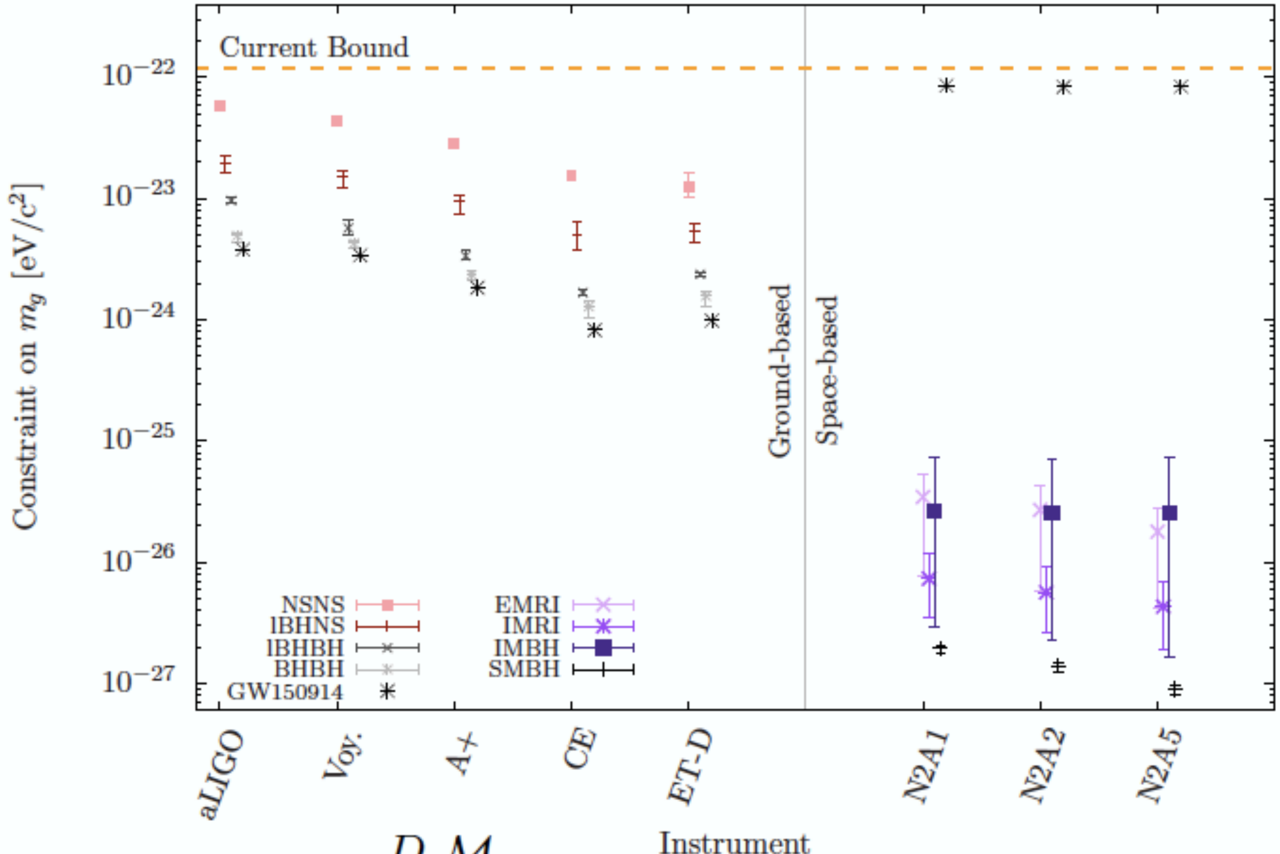
Binary with largest chirp mass

Open Questions:

Generation of GWs?

Merger? Hybrid IMR waveforms?

What is the Goal?



$$\beta = \pi^2 \frac{D\, \mathcal{M}_z}{1+z} m_g^2$$

[Chamberlain & Yunes, to appear soon]

Nico Yunes's slide

Future Constraints on Violations of SEP

Extractable Physics:

Non-Schw BHs (yes-hair theorem in EdGB)

NSs have scalar charge (scalar-tensor)

Compact Object binaries inspiral faster due to dipole radiation

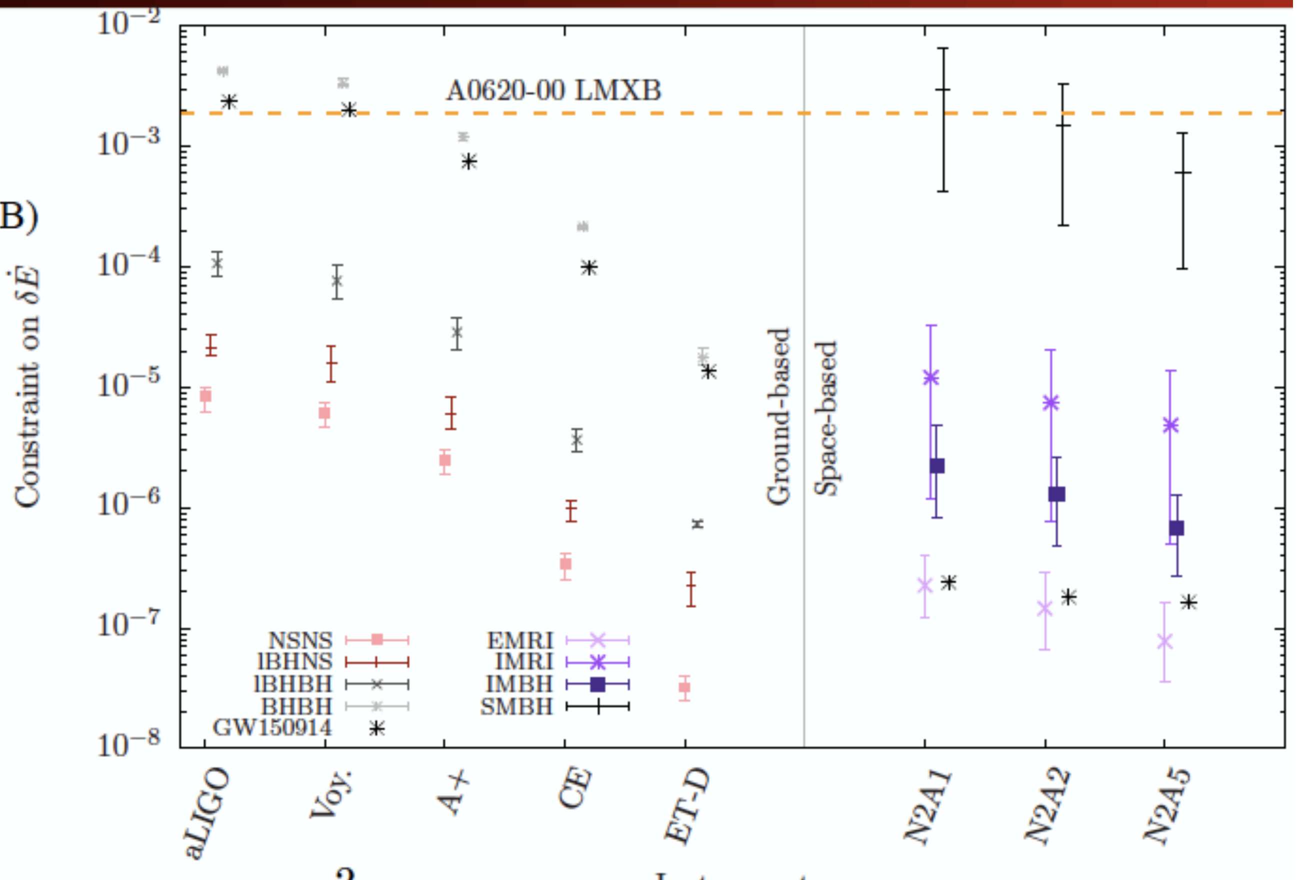
Maximize Extraction:

Low-mass BH or NS (long-inspiral) GWs

Binary with tiny mass ratio

Open Questions:

Merger?
Hybrid IMR waveforms?



$$\beta = -\frac{3}{224}\eta^{2/5}\delta\dot{E}$$

[Chamberlain & Yunes, to appear soon]

Nico Yunes, StronG Bad Workshop 3/2/2017

LIGO

3G strength

- Ground-based 3G detectors
  - Observe the merger!
  - Thus are esp. sensitive to higher order effects
    - Radiation from octopolar and higher moments
    - Higher order ring-down modes
    - Higher order PN corrections
- Win with sqrt(N) & sqrt(SNR)
- Challenged for long integration, but
  - “join” observation with LISA can change that

My questions for the workshop

- Are we tacking interesting fundamental physics?
- What other effects (from regular GR + matter) are there, complicating conclusions about GR?
  - Example: BH kicks, tidal resonances?
- "Integrated" tests of alternative theories?
  - Full alternative wave forms?


Thank you!