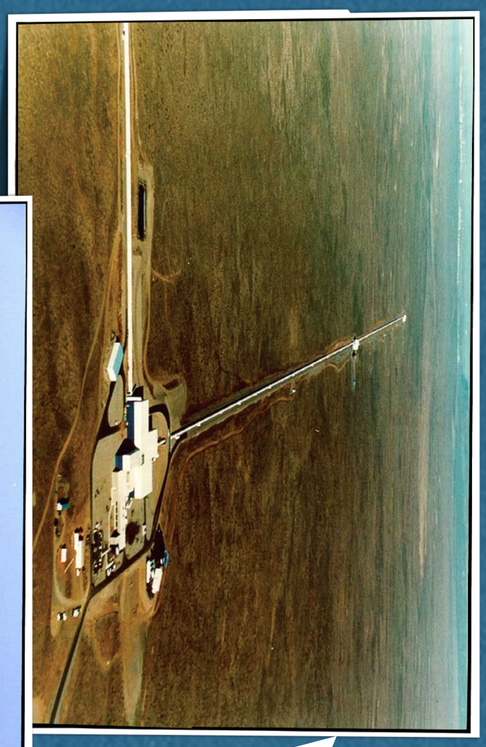
Tests of General Relativity

Chairs: A. Samajdar, L. Lehner
Panel: M. Agathos, G. Carullo, A. Tolley, H. Witek

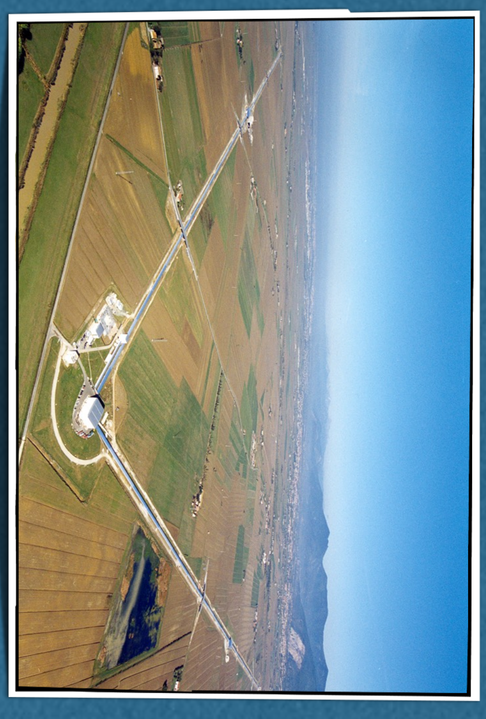
PAX VIII - MIT
01 Aug 2022

LIGO Hanford

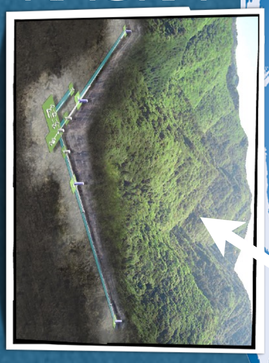


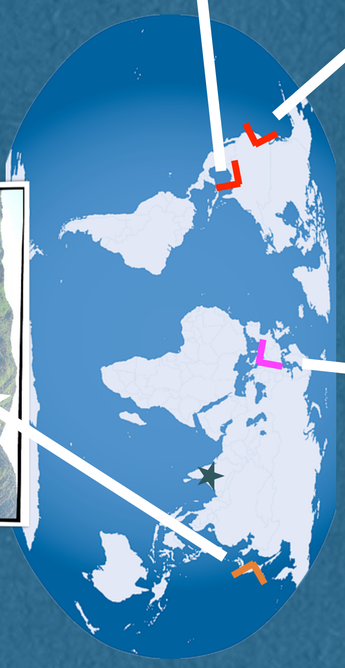
LIGO Livingston

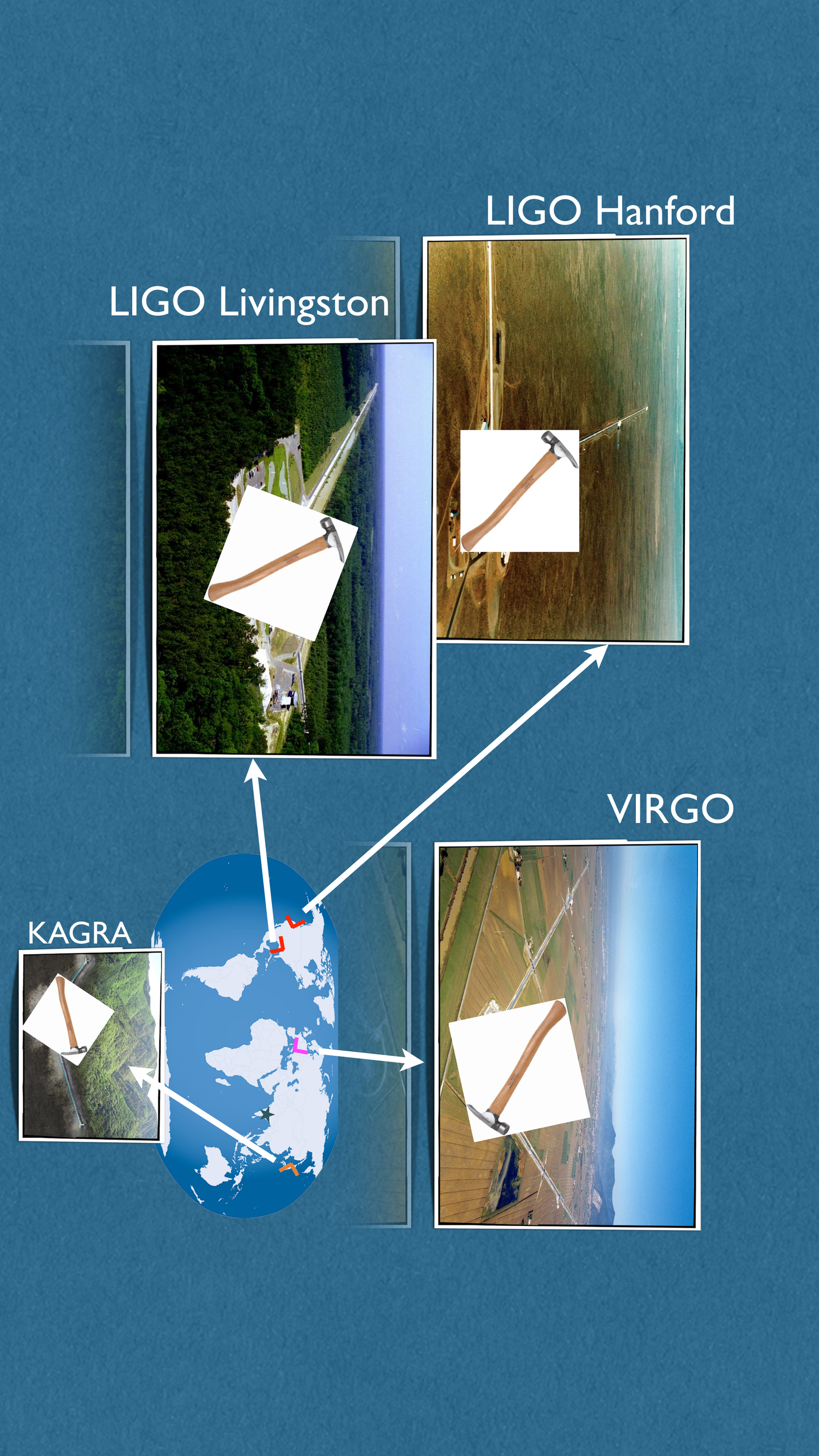
VIRGO



KAGRA






LIGO Hanford
LIGO Livingston
VIRGO
KAGRA

LIGO Hanford

LIGO Livingston

RGO

KAGR

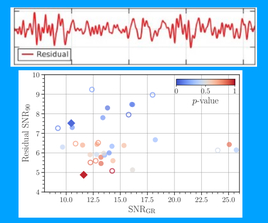
Outline

"The purpose of PAX-VIII is to better understand what can be done with NG observatories, and what are the factors that could limit their scientific potential. PAX is largely a discussion-based workshop with very strong involvement of participants."

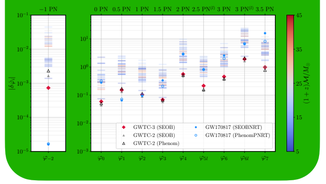
- Overview of where we stand and where we are headed
- Which directions **theory** points us to for modified gravity
- Setting out to explore and **model** this phenomenology
- Applying this knowledge to plan further **tests** on GR; what challenges lie ahead?
- Questions & Discussion

Where we are

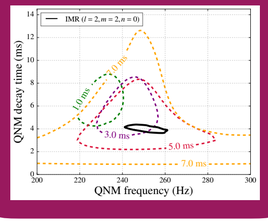
RESIDUALS



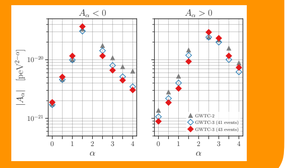
INSPIRAL PN PARAMS



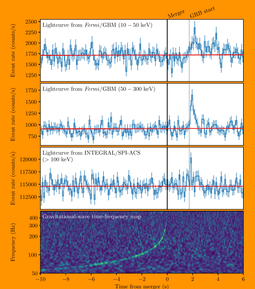
RINGDOWN



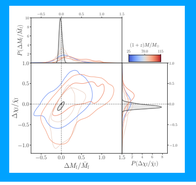
MODIFIED DISPERSION



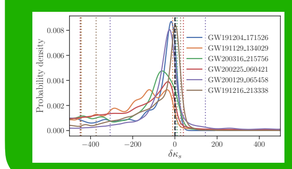
SPEED OF GRAVITY



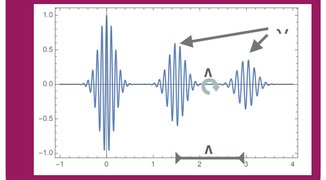
IMR CONSISTENCY



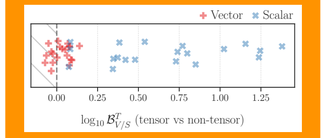
BH SPIN QUADRUPOLE



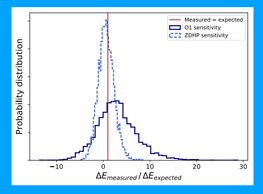
ECHOES



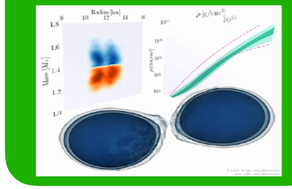
ALTERNATIVE POLARIZATIONS



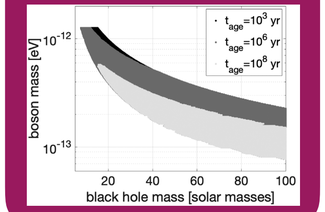
AREA THM



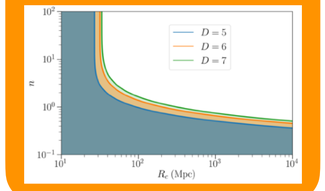
TIDES & RESONANCES



SUPERRADIANCE

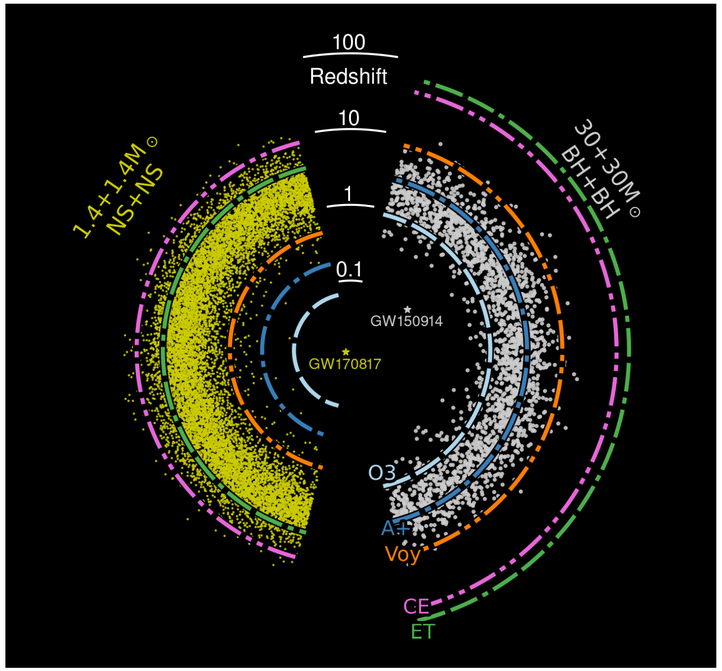


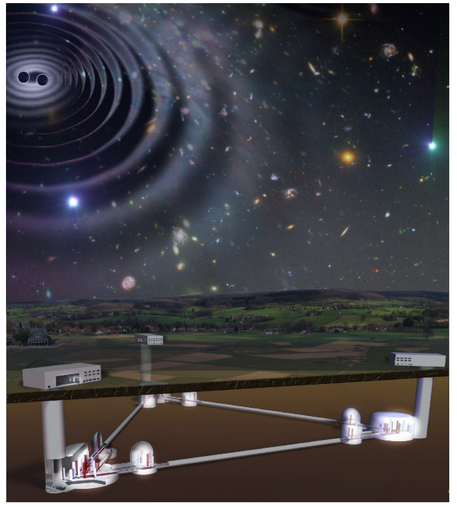
EXTRA DIMENSIONS

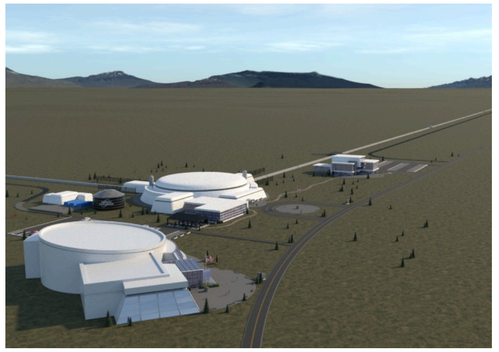


Where we are headed

- Much higher event **rates**
- High-**SNR** measurements
- Both in **inspiral** and **ringdown**/postmerger
- Larger **distances** (propagation, cosmology, astro-pop)
- Expand **frequency range** to lower and higher freqs
- Sensitivity to **non-compact-binary** observations







- ET Science Case
- CE Horizon Study

Modifications of Gravity

Andrew Tolley — Imperial College London

With standard physics assumptions - two essential types:

UV Modifications

No new degrees of freedom
at curvature scales/length scales probed by observed gravitational sources

Low energy gravity propagated by massless spin-2 gravity, minimally coupled to matter+ dark matter

IR Modifications

New light degrees of freedom
Masses of d.o.f. small compared to curvature scales/length scales probed by observed gravitational sources

With non-standard physics assumptions

Lorentz violating - e.g. Einsten-aether, Horava-Lifshitz, cuscaton, Lorentz violating massive gravity, ghost condensate, solid EFTs

Non-locality - e.g. firewalls? Modification of horizon, gravitational echoes

UV Modifications

$$+M_{\rm Pl}^2 M^2 \left(\frac{\phi}{M}\right)^a \left(\frac{\nabla}{M}\right)^b \left(\frac{Riemann}{M^2}\right)^c$$

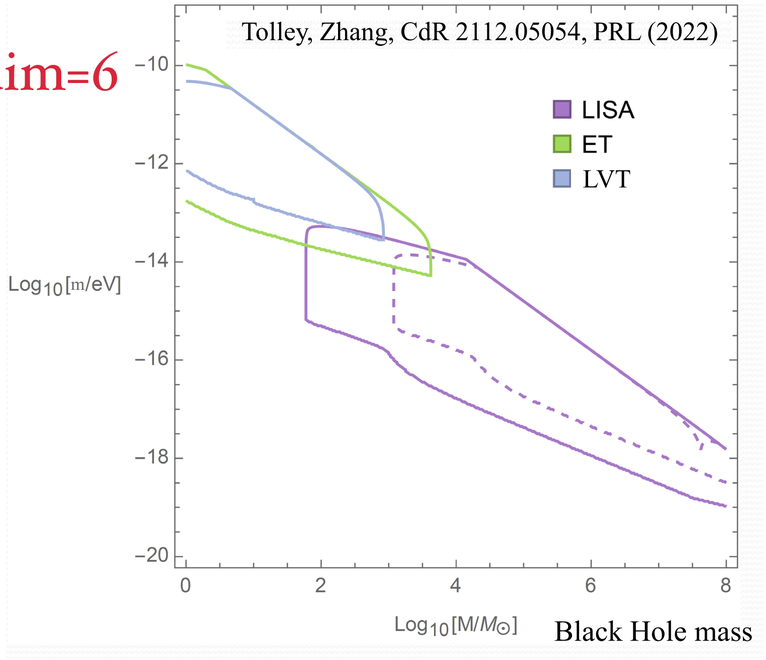
UV modifications well captured by EFT framework

$$\mathcal{L}_{EFT} = \frac{M_{\rm pl}^2}{2}\left[R + \frac{C_2}{M^2}(R^2 + R_{\mu\nu}^2) + \frac{C_3}{M^4}\mathrm{Riem}^3 + \frac{C_4}{M^6}\mathrm{Riem}^4 + \dots\right]$$

dim=4 (on C_2 term) dim=6 (on C_3 term) dim=8 (on C_4 term)

dim=4 Field redefinable but affects coupling to matter so still observable for e.g. neutron stars

dim=6



QNM frequencies $\delta = \frac{\omega_{EFT} - \omega_{GR}}{\omega_{GR}}$

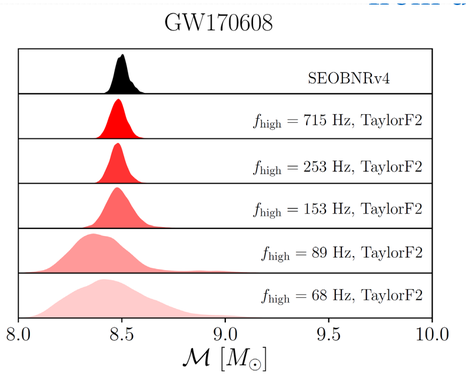
$$\delta_{dim=8} \sim (\Lambda r_S)^{-6} \ll \delta_{dim=6} \sim (\Lambda r_S)^{-4} \ll 1$$

dim=8

$$\delta\psi^{SPA}_{dim=6} \sim \frac{v^{10}}{(r_s M)^4}$$

$$\delta\psi^{SPA}_{dim=8} \sim \frac{v^{16}}{(r_s M)^6}$$

$$\Delta\psi^{SPA}_{dim=6} \sim \frac{1}{(r_s M)^4}\left((r_s f_f)^{5/3} - (r_s f_i)^{5/3}\right)$$



$$M = 10^{-13} eV$$

To be observable scale M (massess of UV d.o.f) needs to be dangerous low!!!!!!!! e.g. Sennett et al. 1912.09917

Implies existence of massive higher spins states s >=2, or strongly coupled physics

IR Modifications

New light gravitationally couples states - common motivation is cosmological new physics at Hubble + intermediate scales

$$E_{IR} \sim H \qquad \Lambda_N \sim \left(H^{N-1} M\right)^{\frac{1}{N}}$$

$$\Lambda_3 = (H^2 M)^{1/3} \sim 1000 km$$
$$\Lambda_2 = (HM)^{1/2} \sim 1 \text{ micron}$$

New light spin-0 states: Brans-Dicke/scalar-tensor, Galileon, Axion, Dilaton, String Moduli, D-branes, Horndeski, DHOST, Dynamical GB, Dynamical Chern-Simons, Symmetron, Chameleon, f(R) theories.
New spin-1 states: Generalized Proca, Proca-Nuevo (+ Beyond), Massive Gravity, Solid EFTs.
New spin-2 states: Large extra dimensions, KK modes, Braneworlds (DGP, warped gravity), Massive Gravity, Bi-gravity, String-states, strongly coupled CFTs

Example physical effects:

- Modification of dispersion relation (mass, Lorentz violating, environmental)
- Additional polarizations (6 or even more if multiple spin-2)
- Modified radiated gravitational power, differing multipole fall off
- Gravitational Birefringence + Graviton oscillations (e.g. multiple spin-2)
- Modification of horizon geometry, multiple effective horizons
- Fifth forces, modification of orbits, equivalence principle violations
- Gravitational Black Hole Hair, Superradiance
- Environment dependent modifications (e.g. chameleon and Vainshtein screening)

Many IR theories have a Rich phenomenology that has barely been worked theoretically or numerically!! HUGE PHYSICS POTENTIAL!!

Tests of general relativity

Source Modelling beyond GR

Luis/Anuradha: guiding principle for discussion:
"What can we do better with 3G?"

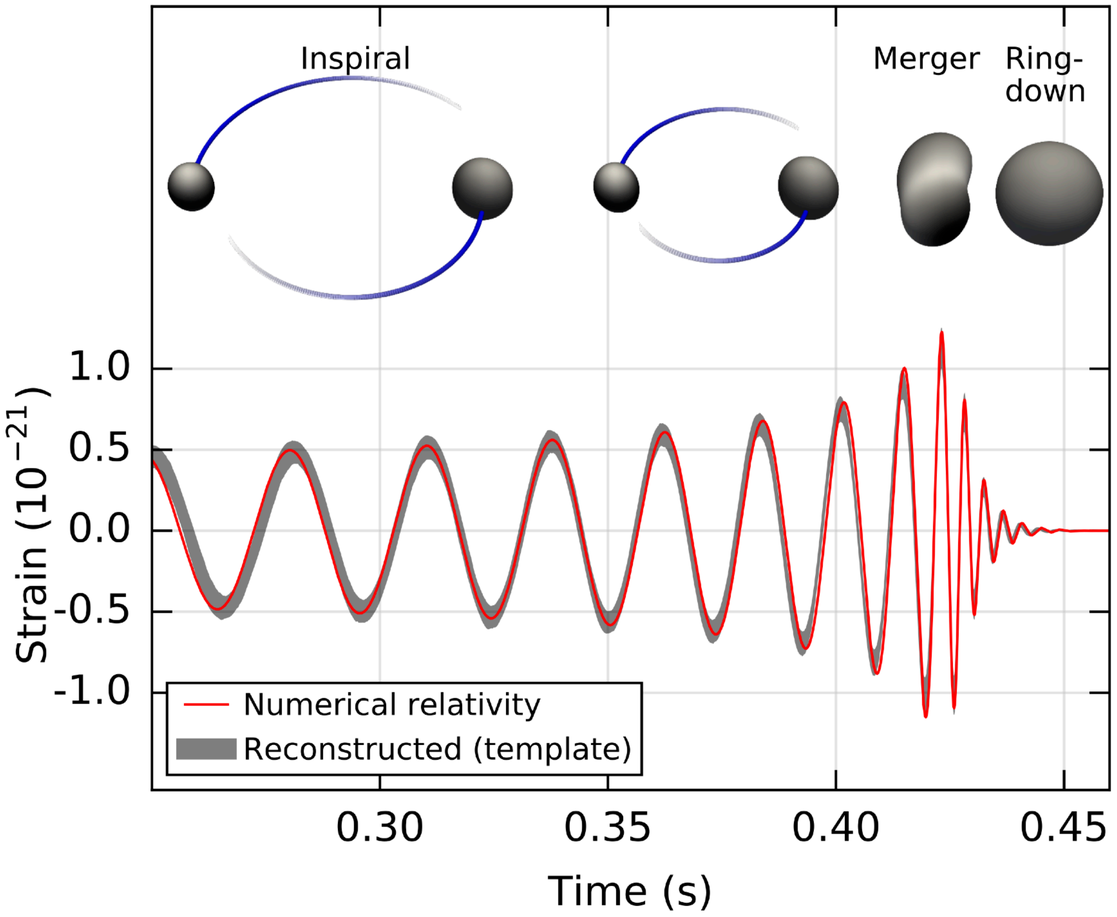
But: Waveform systematics ***in GR*** will become already become important in O5

My guiding principle: How do we need to improve our (beyond-GR) models to leverage precision GW measurements with 3G?

Helvi Witek – University of Illinois at Urbana-Champaign

See also Snowmass 2021 CF White Paper
[Foucart, Laguna, Lovelace, Radice, Witek '22]

Waveform modelling beyond GR – Techniques



Abbott+, PRL 116, 061102 (2016)

Theory-specific

(post-Newtonian, numerical relativity, perturbation)

- Tests against prediction in specific theories
- Informs theory-agnostic model building
- BUT: slow and resource-intensive

Theory-agnostic (parametrized post-Newtonian/-Einsteinian, …)

- Captures general features present in classes of beyond-GR theories
- More efficient to identify a non-GR feature
- BUT: No direct mapping to beyond-GR model

Waveform modelling beyond GR – Status

Extra fields

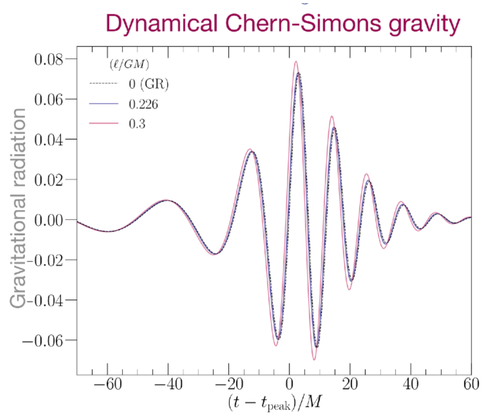
- scalar-tensor theory (Palenzuela & Liebling '15, Gerosa et al '16, Sperhake et al '17, Rosca-Mead et al '19, '20, Mendes '21; Barausse et al '12, Shibata et al '13, Healy et al '11, Berti et al '13, Sagunski et al '17, Bezares et al '21)
- Einstein-Maxwell-Dilaton (Hirschmann et al '17, Liebling '19)
- Horndeski gravity (Ripley & Pretorius '19, Bernard et al '19, Figueras & França '20, '21)
- boson stars (Liebling & Palenzuela '12, Palenzuela et al '17, Helfer et al '18, '19, '21, Bezares et al '18-'22, Alcubierre et al '19, Di Giovanni et al '21, Jaramillo et al '22...)
- axion stars and black holes or neutron stars (Clough, Dietrich et al '18)
- Black holes and light fields

Higher curvature

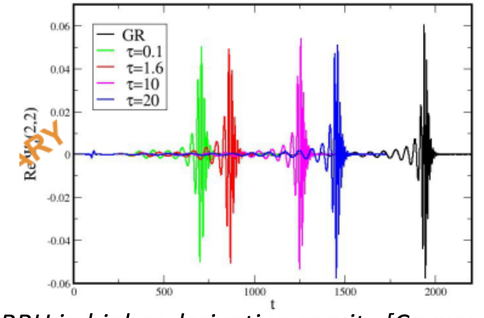
- Effective field theory of gravity (Held et al '21)
- Semi-classical loop quantum gravity (Benitez et al '20)
- black holes with near-horizon fluctuations (Liebling et al '17)
- Scalar Gauss–Bonnet gravity (Benkel et al '16; Doneva et al '17-'22; Ripley & Pretorius '19, '20; Ramazanoglu '19; Dima et al '20; Hegade et al '22; **HW** et al '18; Okounkova '20; East & Ripley '20; '21, Silva et al '21; Elley et al '22)
- dynamical Chern-Simons gravity (Okounkova et al '17 - '19, Doneva et al '20-'21)

Lorentz violations

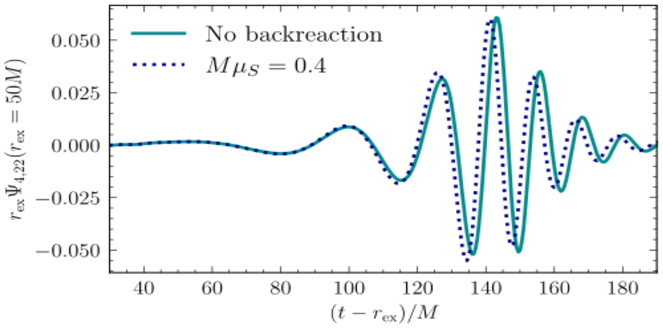
- Einstein-æther theory (Garfinkle et al '07; Barausse, Sarbach et al '19)
- bi-metric gravity (Torsello et al '19, Kocic et al '20)



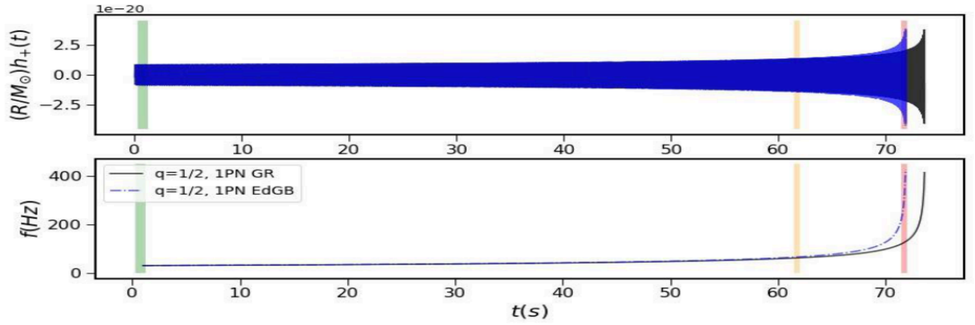
BBH in dynamical Chern-Simons [Okounkova et al '17]



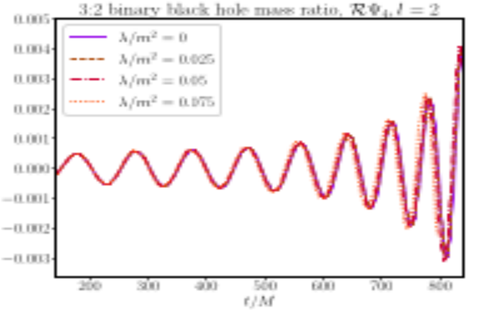
BBH in higher derivative gravity [Cayuso et al in prep]



BBH and massive scalars [Cheng, Ficarra, HW in prep]



BBH in Gauss-Bonnet [Shiralilou et al '21]



BBH in Gauss-Bonnet [Corman, East, Ripley in prep]

Discussion items: source modelling beyond GR

- Proof-of-principle (base) calculations in some beyond –GR models ☺
- Construct inspiral-merger-ringdown waveforms with Phenom/EoB/…

“We need the same accuracy as for GR to do meaningful tests”

<-> “This is not feasible”

- NR Waveform catalogs – parameter space coverage?
  Same as GR (1000s /theory)? Cornerstones for parametrized models (100 / theory)?
- How far beyond 2PN (in scalar-tensor and scalar Gauss-Bonnet)?

- What are we testing? How well do we understand our standard model GR?
  (eccentricity, precession, high-mass ratio environmental effects, …)
  See also afternoon discussion

TESTS POSSIBLE WITH 3G, BUT NOT WITH 2G (OR SPACE-BASED) DETECTORS?

NEW CHALLENGES ARISING?

Gregorio Carullo

European Research Council
Established by the European Commission

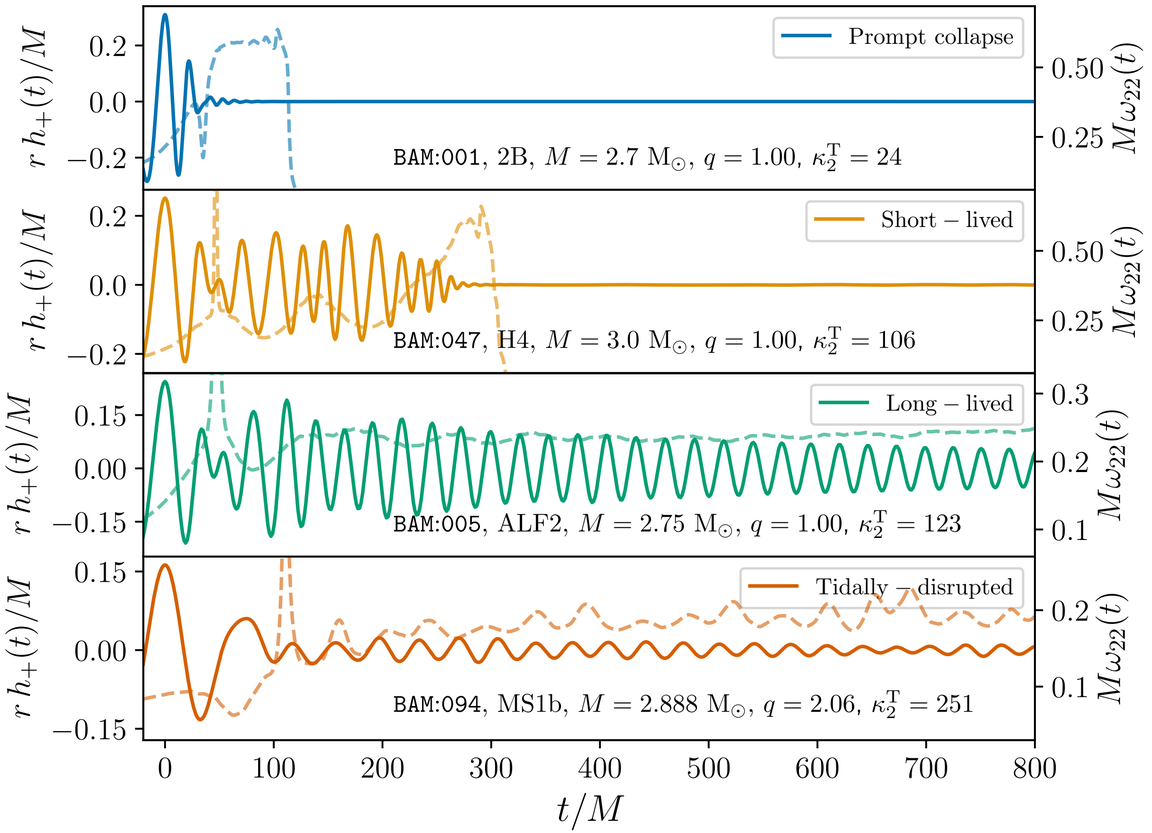
FRIEDRICH-SCHILLER-
UNIVERSITÄT
JENA

European
Commission

Horizon 2020
European Union funding
for Research & Innovation

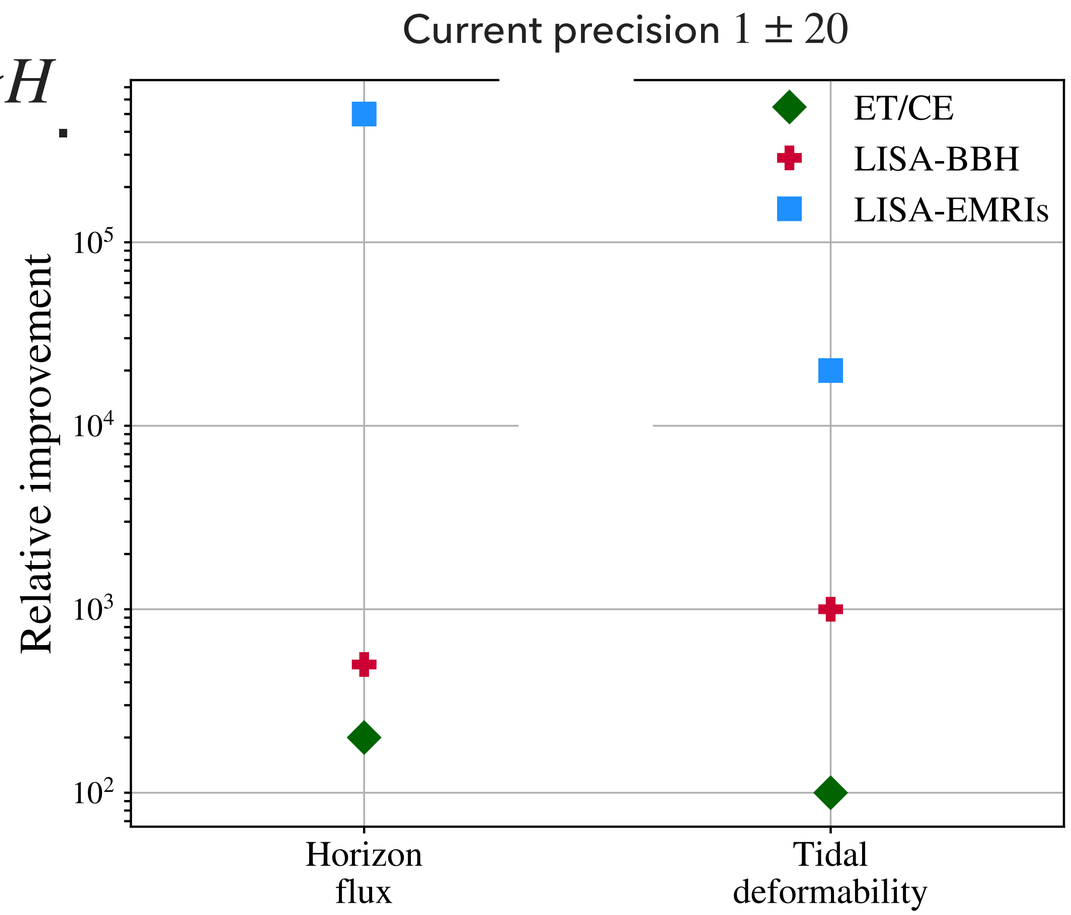
BNS POST-MERGER

- Only basic features understood. Phase transitions?
- Rewards: high curvature, ECOs more plausible at low M.
- Inspiral constrains par. space: known phenomenology per signal?
- **Smoking-gun signatures for GR/SM violations?**
  - Echoes, also possible for ultracompact stars.
  - t_{coll} exceeding upper bound?



HORIZON ABSORPTION

- Will start to be meaningfully **measurable** only by **3G** or **LISA**.
- Currently, using **slowly-varying perturbations**. EOB: resummed $\mathscr{F}^H$. Accuracy for comparable/ intermediate q?
- **Eccentricity** boost to this measurement?



Poisson-Chatziioannou-Yunes, 1211.1686
Cardoso+, 1701.01116 Maselli+, 1703.10612
Lai-Li, 1807.01840 Datta+, 1910.07841

MISC.

- Which effects may spoil **sub-population searches** (e.g. different tidal-deformabilities for different signals)? Probability of contamination?
  - **Lensing** distorsions, **overlapping** signals
  - "**Environmental**" effects: matter (baryonic, dark, charged), third companion… Causing *observable* ringdown spectral instabilities?
- Prospects for observing *~extremal* BHs? Rates?
  - **Light ring** closer to horizon —> ringdown probes **horizon physics**
  - "**Cold**" system: long-lived perturbations —> development of non-linearities?

Questions for Discussion

- How do we expect a discovery to appear?
  - null vs theory-agnostic vs theory-specific
  - golden binary vs cumulative effect
- How can we quantify the propagation of uncertainties from NR to models to inference?
- Vacuum vs Matter: should we focus on the simplicity of BHs or the richer potential of NS?
- What non-CBC types or sources are promising for tests of GR? How can we prepare for such a scenario?
- How much to invest in NR campaigns for modGR? How do we pick our targets?
- Will parameter dependence hinder or boost our ability to test GR vs alternatives?
- How do environmental factors affect our testingGR potential? Should we be worried?
- What extremely promising extremes are there, that are worth exploring?