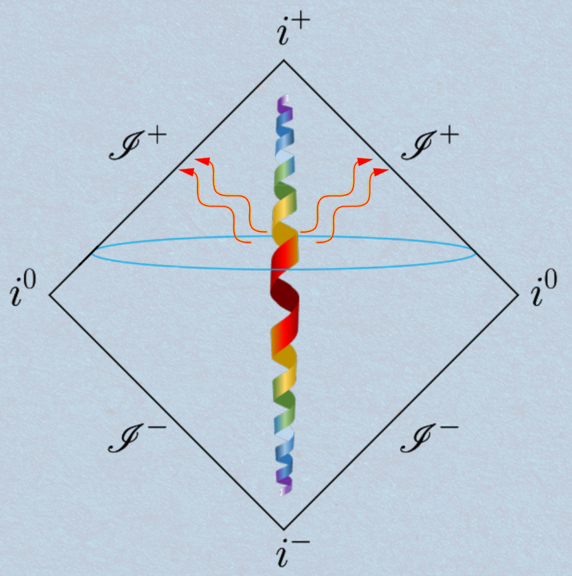


Quantum Gravity meets Cosmology:

Testing Quantum Gravity with gravitational waves

Speaker: David Maibach
Supervisor: Prof. Lavinia Heisenberg
Institute for Theoretical Physics, Heidelberg University/ETH Zürich

Quantum Gravity 2023, Radboud University

Scope and Objectives

Black Hole/Neutron Star Binary Merger: resolved gravitational events

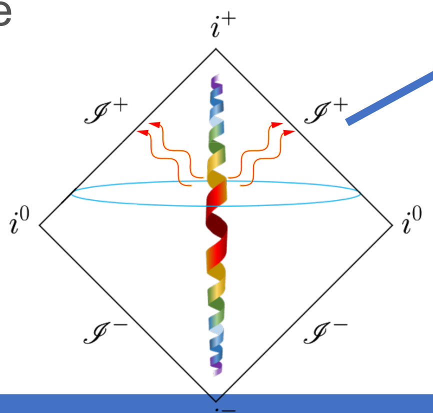
Stochastic Gravitational Wave Background: unresolved signals

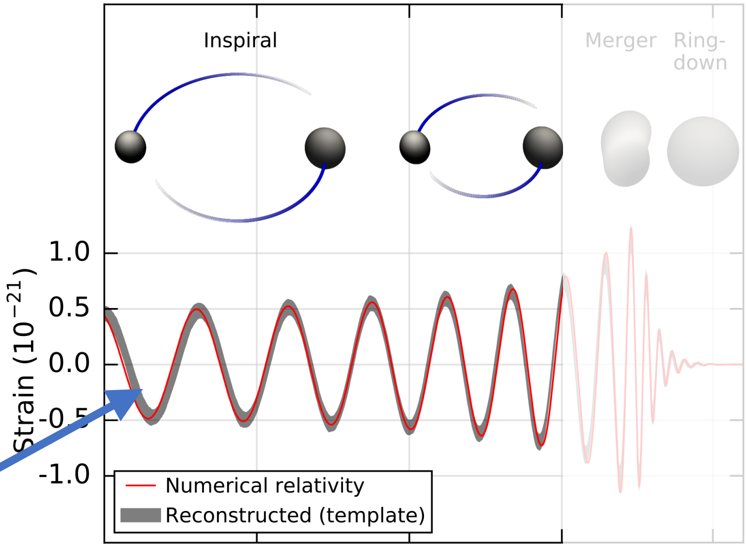
1. How does QG manifest in the SGWB and gravitational waveforms?
2. Why haven't we seen any signs of QG in waveforms or the SGWB yet?
3. What techniques can be applied to change that in the future?

⇒ Constraining your "favourite" theory of QG with the help of gravitational wave astronomy

Introduction - Gravitational Waveforms

- Resolved gravitational wave signals, i.e. waveform is "clearly" resolvable
- Dividable into **Inspiral**, Merger, Ringdown
- Inspiral:
    - Two massive objects orbiting
    - Dominant $l = 2, m = 2$ mode





[LIGO Scientific Collaboration, 2016]

Introduction - Gravitational Waveforms

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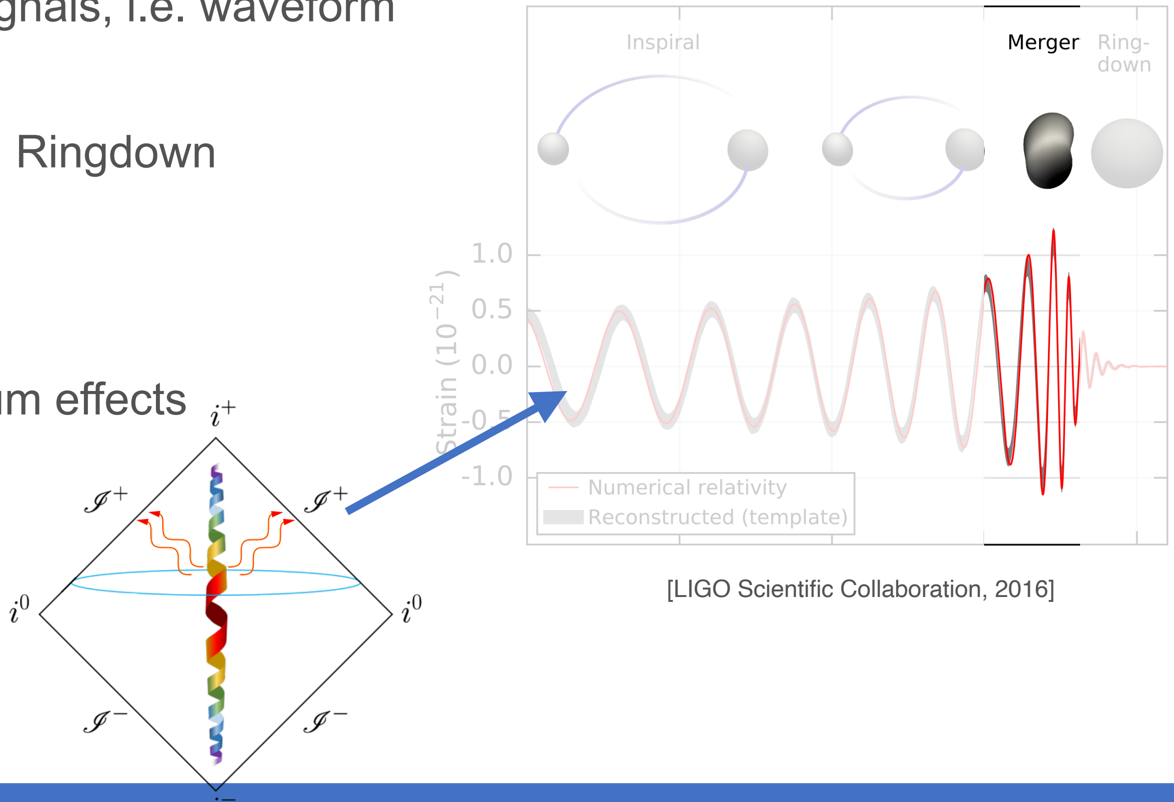
- Resolved gravitational wave signals, i.e. waveform is “clearly” resolvable
- Dividable into Inspiral, **Merger**, Ringdown
- Merger*:*
  - Strong field regime
  - Most susceptible by quantum effects
  - Not analytically solvable



[LIGO Scientific Collaboration, 2016]

Introduction - Gravitational Waveforms

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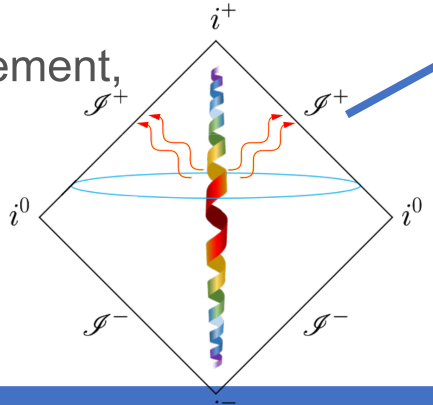
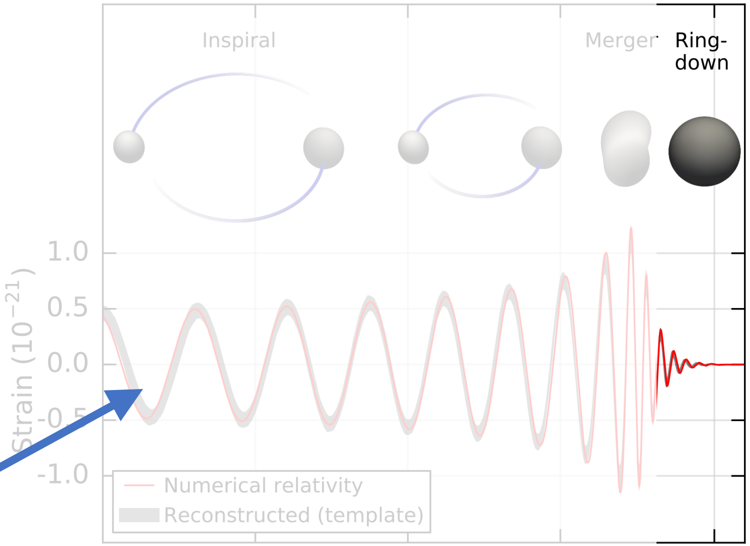
- Resolved gravitational wave signals, i.e. waveform is "clearly" resolvable
- Dividable into Inspiral, Merger, **Ringdown**
- Ringdown:
    - Exponential decay via quasi-normal modes (QNM)
    - Leaves permanent displacement, i.e. gravitational memory





[LIGO Scientific Collaboration, 2016]

QG in Gravitational Waveforms

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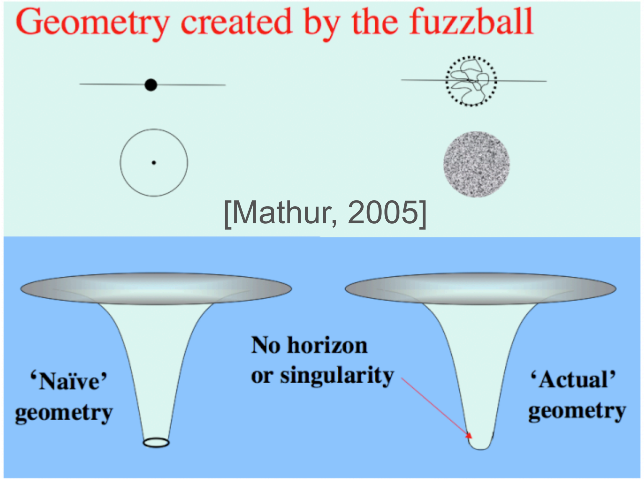
QG effects:

- Energy/Area quantisation [Ashtekar, '00; Agullo, '08/09], i.e. $A_N = \alpha l_p^2 N$, $N \in \mathbb{N},\ \alpha \in \mathbb{R}$
- Discrete absorption spectrum: $\omega = \frac{|\Delta M|}{\hbar} = \frac{\alpha \Delta N}{32\pi M}$ with $M_{N,j}^2 = \hbar \frac{\alpha N}{16\pi} + \hbar \frac{4\pi j^2}{N\alpha}$

$\Rightarrow$ **minimum absorption** frequency for GW of $(\omega,2,2)$ & width of **energy levels** $\alpha(J/M^2)$-**dependent** [Agullo et al., '21]

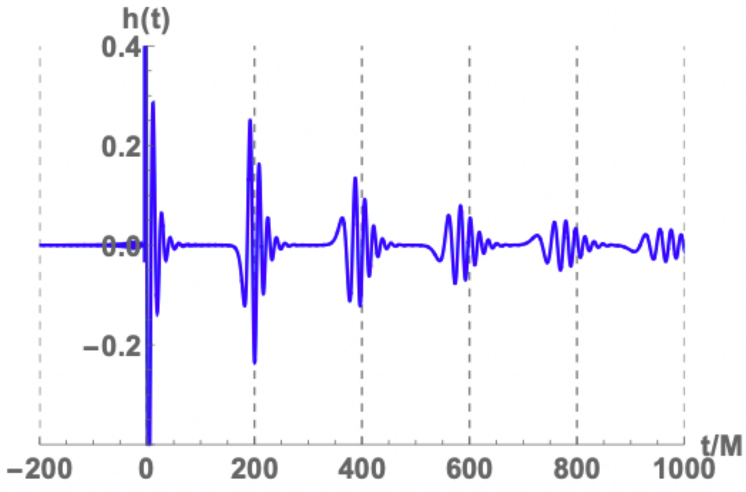
- Similar effect from membrane like horizons [Chakraborty et al., '22]



QG in Gravitational Waveforms

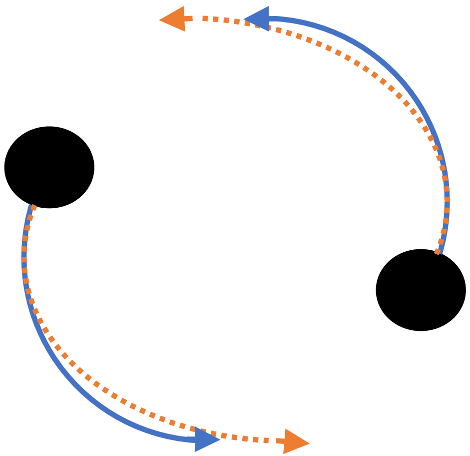
Consequence:

- QNM during ringdown can be reflected and **echo** back from the horizon [Cardoso et al., ’19]



[Mayerson, 2005]

- Absorption of GWs during inspiral: **Tidal Heating** [Hartle, ’73; Goswani et al., ’19]



QG in Gravitational Waveforms

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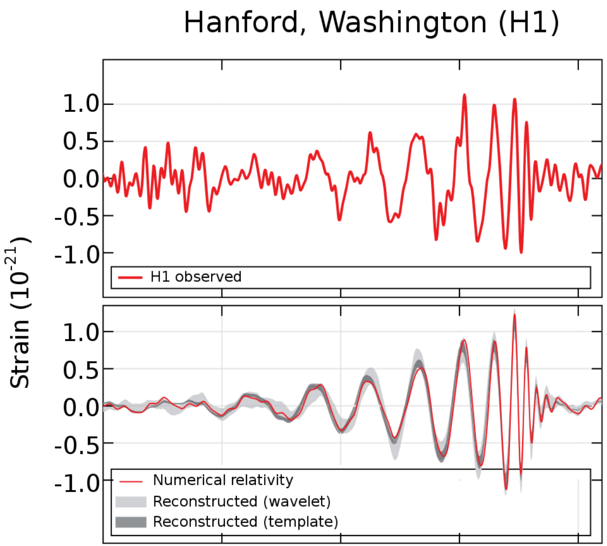
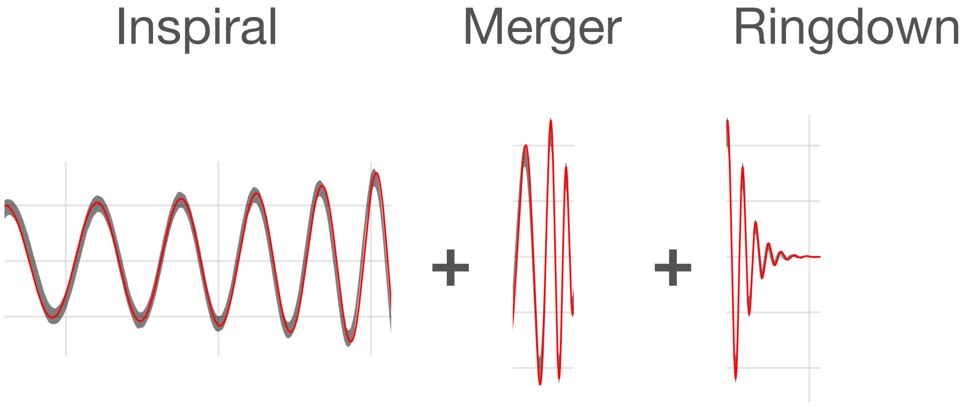
- **Problem:**





[LIGO and Virgo Scientific Collaboration, 2016]

Detection via matched filtering, generation of templates highly **non-trivial** and **very model-sensitive**

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Gravitational Waves in Full, Non-Linear General Relativity

Fabio D'Ambrosio*, [1], Shaun D. B. Fell†, [2], Lavinia Heisenberg‡, [2,1], David Maibach§, [2], Stefan Zentarra¶, [1], and Jann Zosso‖, [1]

[1] *Institute for Theoretical Physics, ETH Zurich, Wolfgang-Pauli-Strasse 27, 8093 Zurich, Switzerland*
[2] *Institut für Theoretische Physik, Philosophenweg 16, 69120 Heidelberg, Germany*

Abstract

These notes provide a student-friendly introduction to the theory of gravitational waves in full, non-linear general relativity (GR). We aim for a balance between physical intuition and mathematical rigor and cover topics such as the Newman-Penrose formalism, electromagnetic waves, asymptotically Minkowski spacetimes, the peeling theorem, the universal structure of null infinity, the Bondi-Metzner-Sachs group, and the definition of radiative modes in linear as well as in non-linear GR. Many exercises and some explicitly calculated examples complement the abstract theory and are designed to help students build up their intuition and see the mathematical machinery at work.

https://arxiv.org/abs/2201.11634

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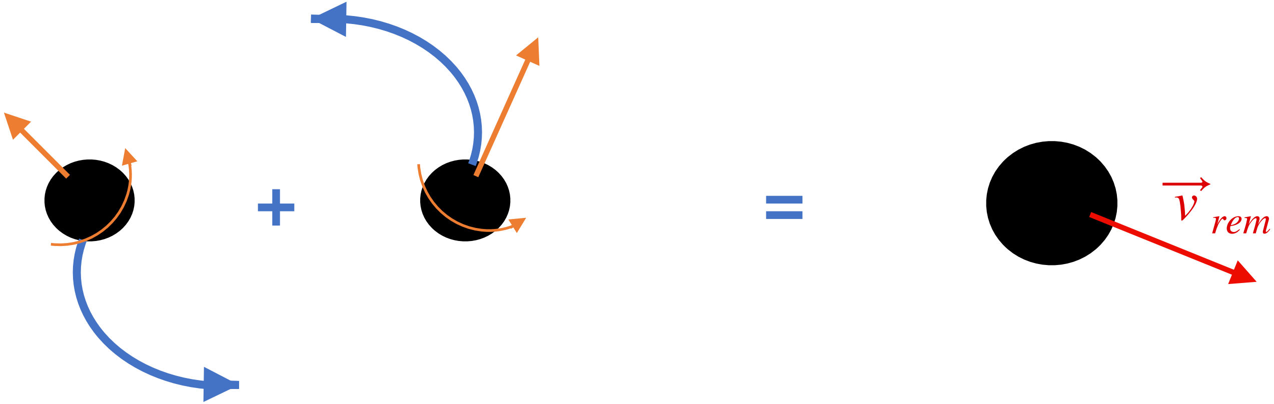
- Deriving and applying analytical constraints on gravitational waveforms
  - Linking **mass loss**,

$$\frac{G}{D_L c^2}\left(M_{i^\circ} - \frac{M_{i^+}}{\gamma^3\left(1-\frac{\vec{v}}{c}\hat{x}\right)^3}\right) = -\underbrace{\mathrm{Re}\{\eth^2\Delta\bar{\sigma}\}}_{=:\mathfrak{M}} + \frac{D_L}{4c}\int_{-\infty}^{\infty} \mathrm{d}t \left(\left(\dot{h}_+\right)^2 + \left(\dot{h}_+\right)^2\right)$$

[Ashtekar, Streubel, '81]



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STRUCTURES CLUSTER OF EXCELLENCE

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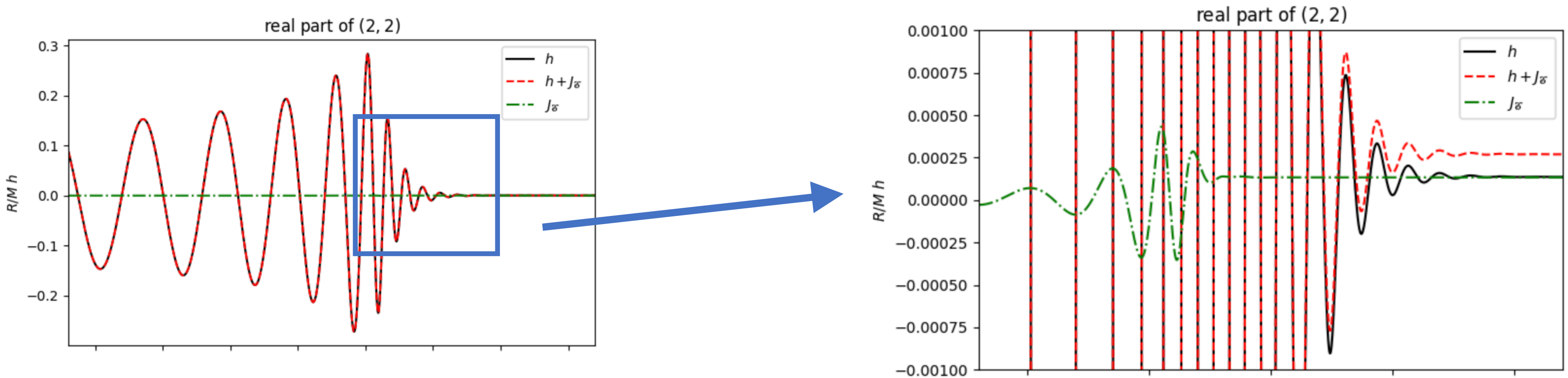
- Deriving and applying analytical constraints on gravitational waveforms
  - Linking mass loss, **gravitational memory**

$$\frac{G}{D_L c^2}\left(M_{i^\circ} - \frac{M_{i^+}}{\gamma^3\left(1-\frac{\vec{v}}{c}\hat{x}\right)^3}\right) = -\underbrace{\mathrm{Re}\{\eth^2\Delta\bar{\sigma}\}}_{=:\mathfrak{M}} + \frac{D_L}{4c}\int_{-\infty}^{\infty} \mathrm{d}t\left(\left(\dot{h}_+\right)^2 + \left(\dot{h}_+\right)^2\right)$$



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STRUCTURES CLUSTER OF EXCELLENCE

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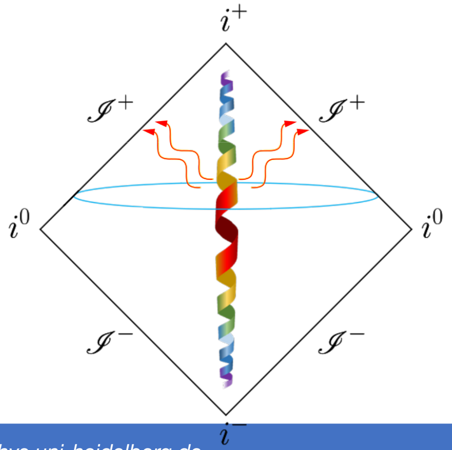
- Deriving and applying analytical constraints on gravitational waveforms
  - Linking mass loss, gravitational memory, **energy flux**

$$\frac{G}{D_L c^2}\left(M_{i^\circ} - \frac{M_{i^+}}{\gamma^3\left(1-\frac{\vec{v}}{c}\hat{x}\right)^3}\right) = -\underbrace{\mathrm{Re}\{\eth^2\Delta\bar{\sigma}\}}_{=:\mathfrak{M}} + \frac{D_L}{4c}\int_{-\infty}^{\infty}\mathrm{d}t\left(\left(\dot{h}_+\right)^2 + \left(\dot{h}_+\right)^2\right)$$



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- Deriving and applying analytical constraints on gravitational waveforms
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$$\frac{G}{D_L c^2}\left(M_{i^\circ} - \frac{M_{i+}}{\gamma^3\left(1-\frac{\vec{v}}{c}\hat{x}\right)^3}\right) = -\underbrace{\mathrm{Re}\{\eth^2\Delta\bar{\sigma}\}}_{=:\mathfrak{M}} + \frac{D_L}{4c}\int_{-\infty}^{\infty}\mathrm{d}t\left(\left(\dot{h}_+\right)^2+\left(\dot{h}_+\right)^2\right)$$

Soon to appear:

Testing Gravity using Gravitational Waves

Shaun D. B. Fell[*, 2], Francesco Gozzini[†, 2], Lavinia Heisenberg[‡, 2, 1], Henri Inchause[§, 2], David Maibach[¶, 2], and Jann Zosso[‖, 1]

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STRUCTURES CLUSTER OF EXCELLENCE

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QNM will be detectible with LISA, given the right template!

Soon to appear:

Testing Gravity using Gravitational Waves

Shaun D. B. Fell[*, 2], Francesco Gozzini[†, 2], Lavinia Heisenberg[‡, 2, 1], Henri Inchause[§, 2], David Maibach[¶, 2], and Jann Zosso[‖, 1]

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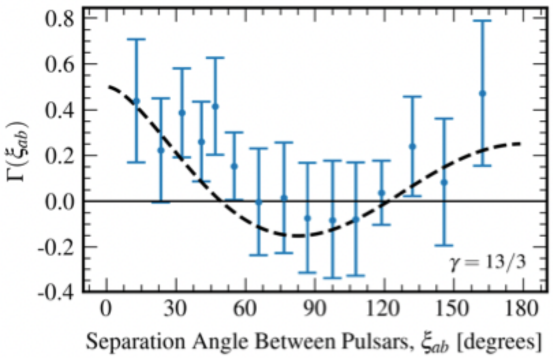
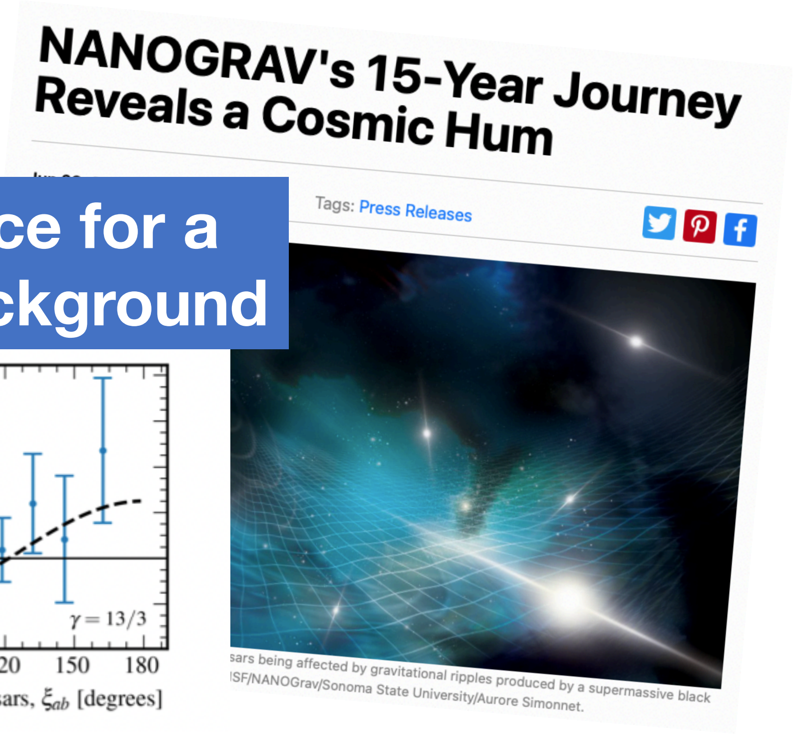
Introduction - SGWB

First evidence for a stochastic background





[Agazie et al., 2023]

Introduction - SGWB

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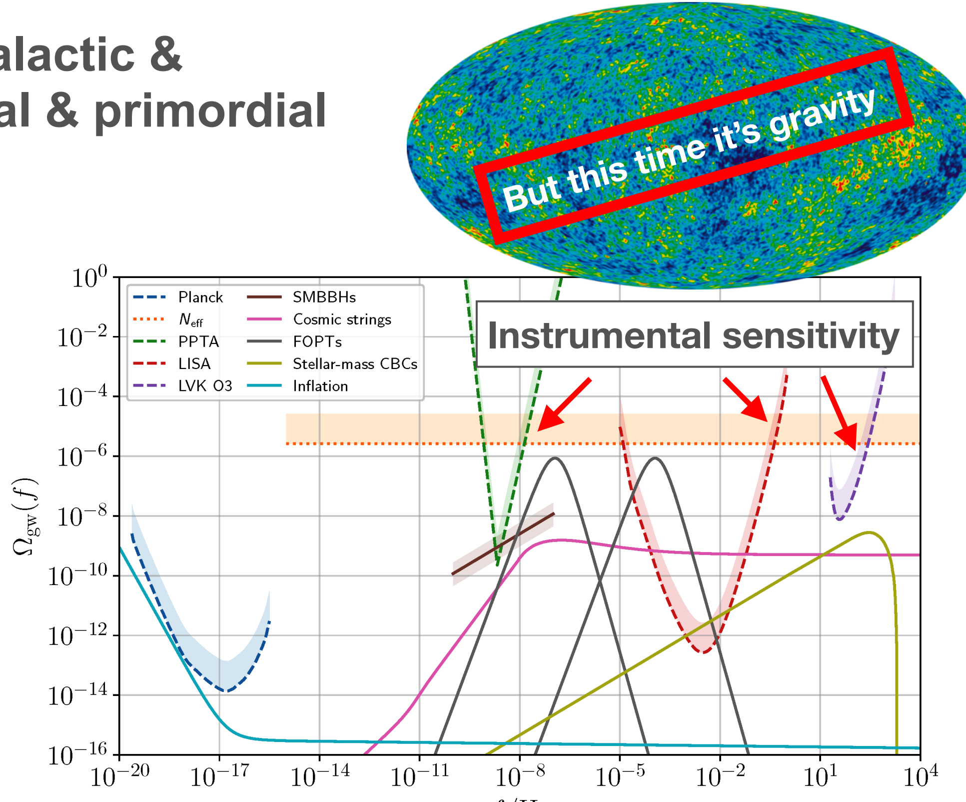
- Contributions include: **astrophysical, galactic & extragalactic sources** vs. **cosmological & primordial**



[Renzini et al., 2022]

QG in the SGWB

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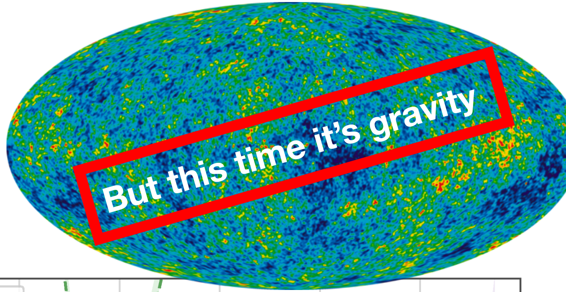
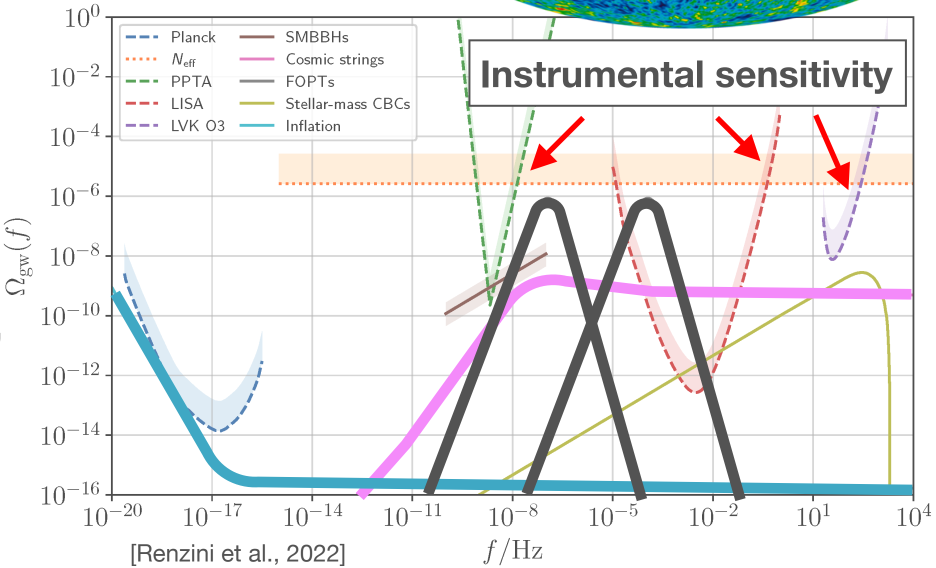


- Basis of cosmological contribution originates from **primordial tensor perturbation**

- QG manifests in: **alternative theories of inflation**, **new dof**, **new symmetries**, **cosmic defects**, …

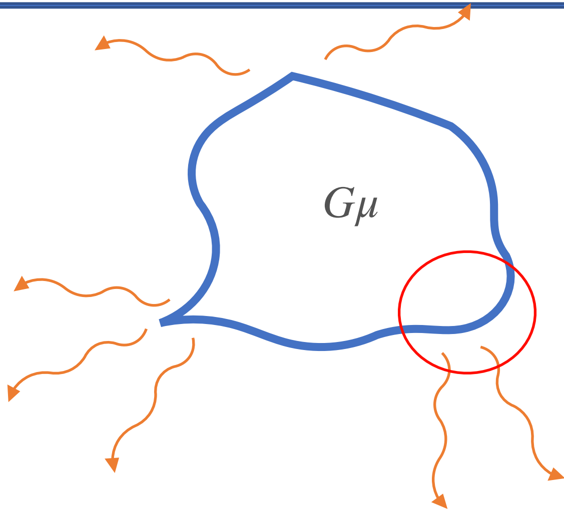


[Renzini et al., 2022]

QG in the SGWB

- **Cosmic strings** as stable topological defects [Kibble, ’73; Jeannerot et al., ’03] & **superstrings** from e.g. the end of brane inflation [Dvali, Vilenkin, ’03; Copeland et al., ’03]

- GW emission via **decay**, kinks, cusps



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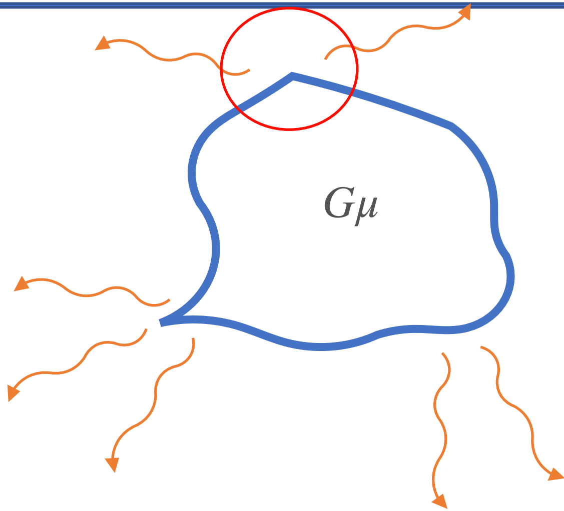

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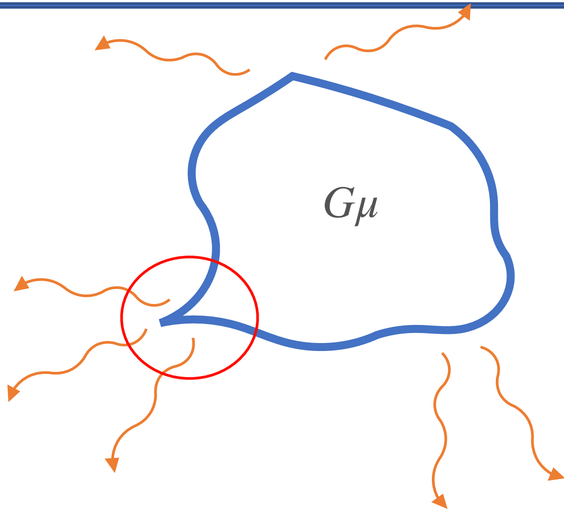

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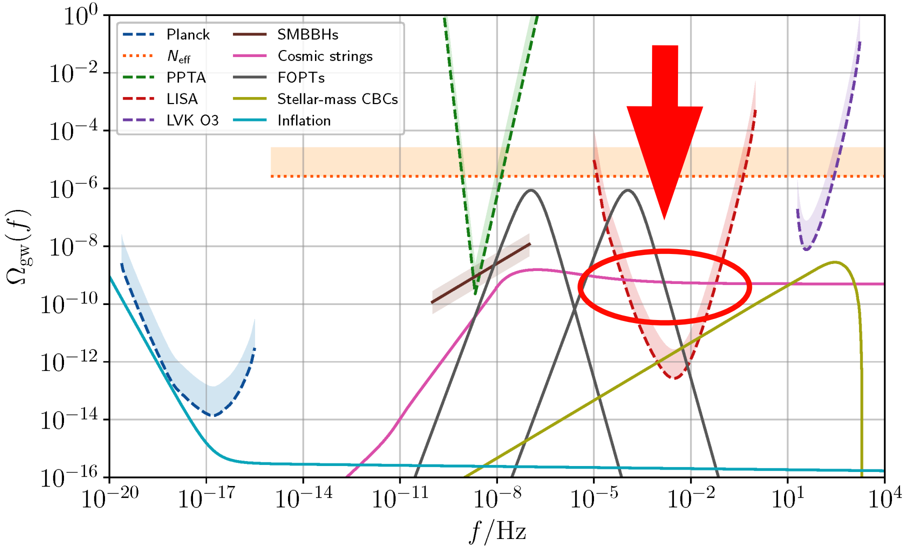
- GW emission via decay, kinks, cusps
- Distinction of origin requires additional probes [Brandenberger, ’14; DM et al., ’21]
- LISA will be sensitive to SGWB from CS of $G\mu \geq 10^{-17}$ [Auclair et al., ’19]



QG in the SGWB

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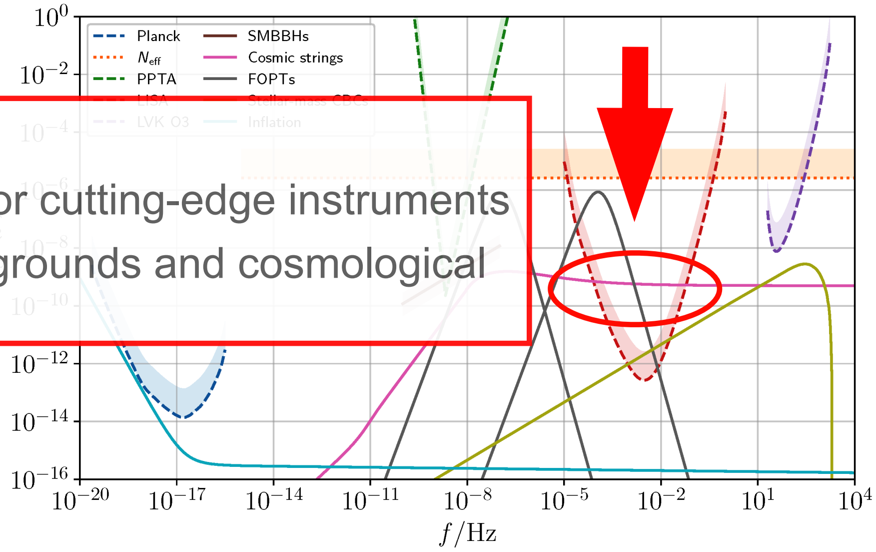
- LISA will be sensitive to SGWB from CS of $G\mu \geq 10^{-17}$ [Auclair et al., ’19]

- **Problem:**
  - Challenging to detect even for cutting-edge instruments
  - Discrimination between foregrounds and cosmological signal non-trivial



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- Use intrinsic motion (Doppler-boost) to **enhance features of the signal**

$$\Omega_{GW}(f, \hat{\mathbf{n}}) = \Omega'_{GW}(f)\left(1 + M(f) + \hat{\mathbf{n}}\hat{\mathbf{v}}D(f) + \left[\left(\hat{\mathbf{n}}\hat{\mathbf{v}}^2 - \frac{1}{3}\right)Q(f)\right]\right)$$

$$n_\Omega(f) = \frac{\mathrm{d}\log(\Omega'_{GW}(f))}{\mathrm{d}\log f}, \quad \alpha_\Omega(f) = \frac{\mathrm{d}n_\Omega(f)}{\mathrm{d}\log f}$$

and M, D, Q being functions of n_Ω, α_Ω

$\Rightarrow$ **Increasing likelihood of detection & resolving spectral shape**

Soon to appear:

Kinematic Gravitational Wave Background Anisotropies with LISA

Lavinia Heisenberg,[1,2,*] Henri Inchauspé,[1,†] and David Maibach[1,‡]

[1] *Institute for Theoretical Physics, University of Heidelberg, Philosophenweg 16 D-69120 Heidelberg Germany*
[2] *Institute for Theoretical Physics, ETH Zurich, Wolfgang-Pauli-Strasse 27, CH-8093 Zurich, Switzerland*
(Dated: July 9, 2023)

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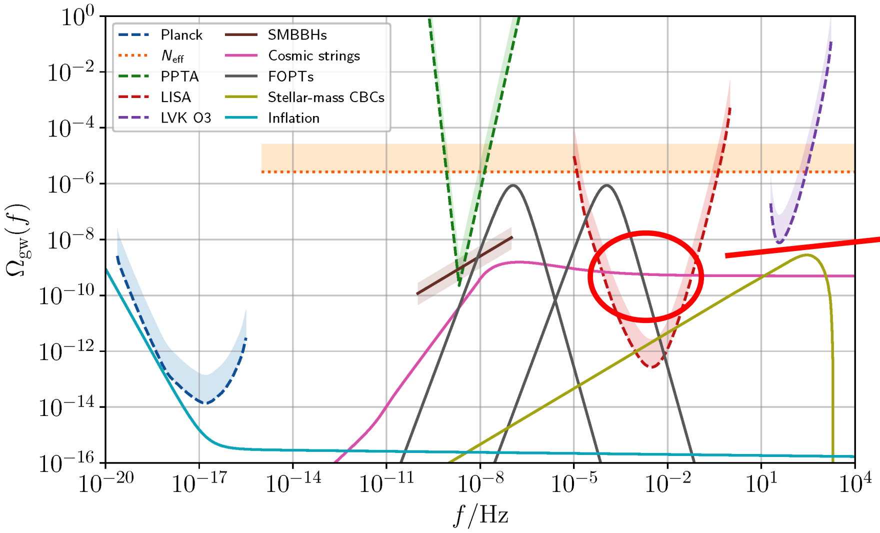
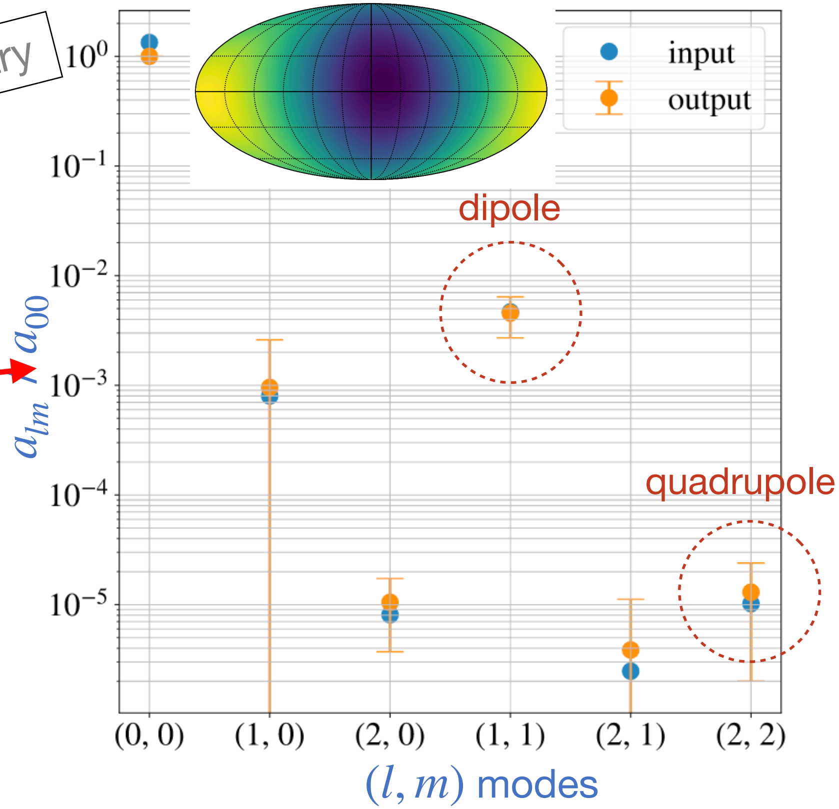
- **Results:**

Preliminary





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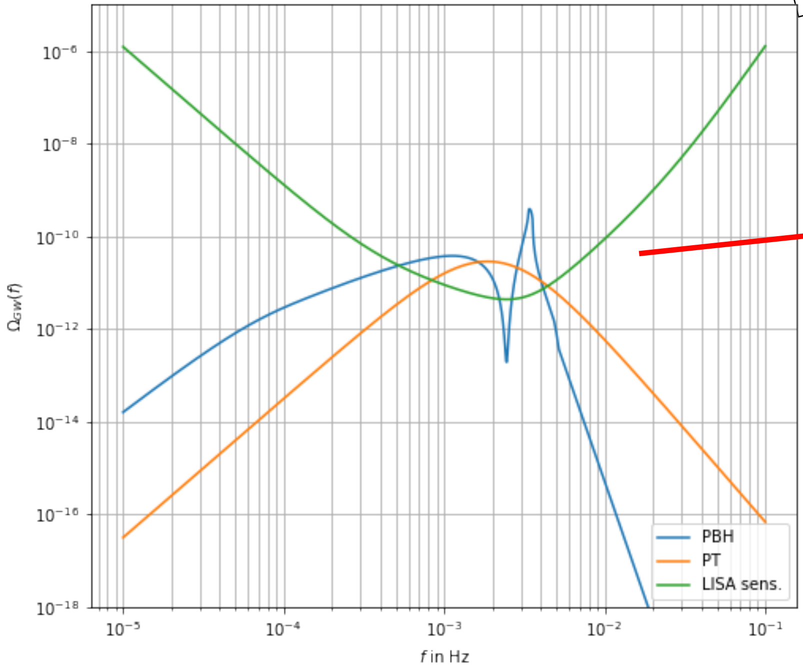

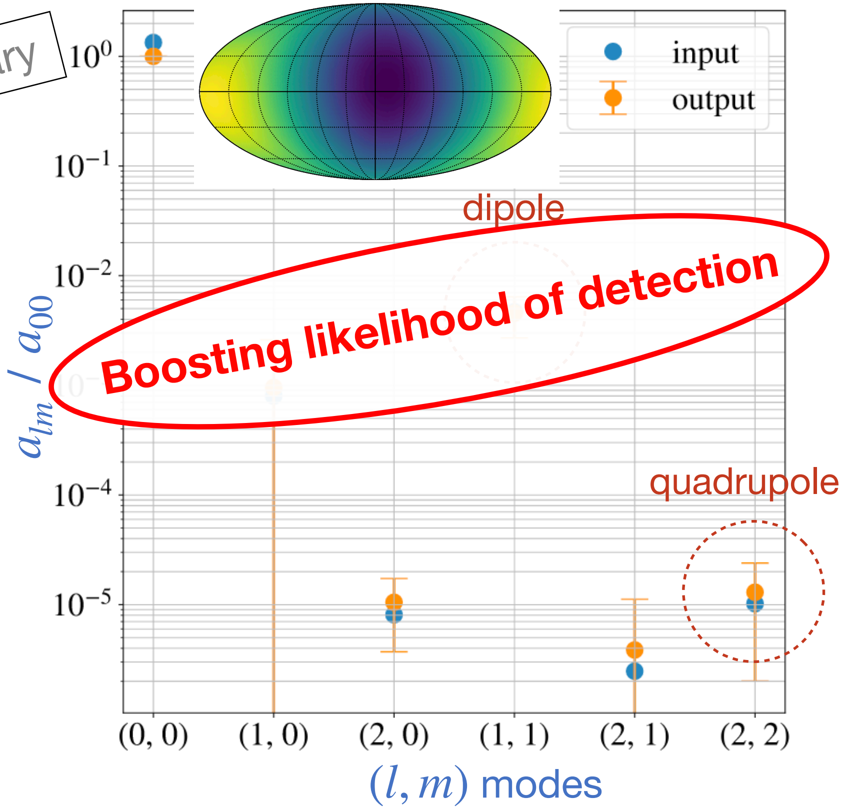

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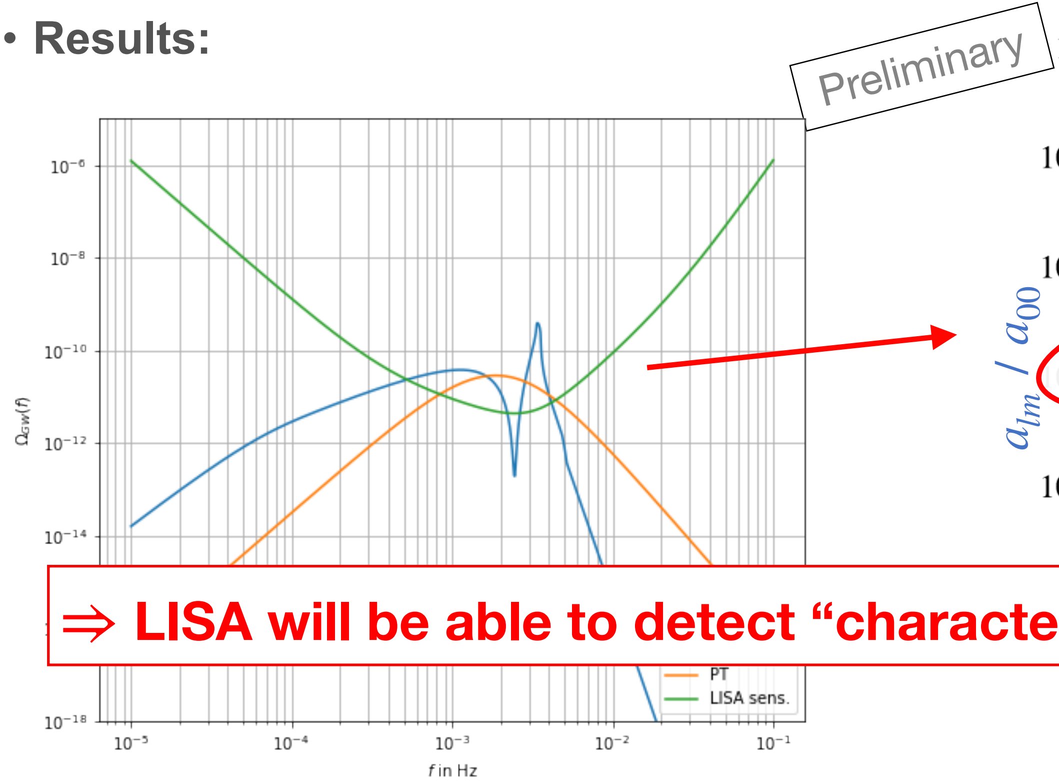
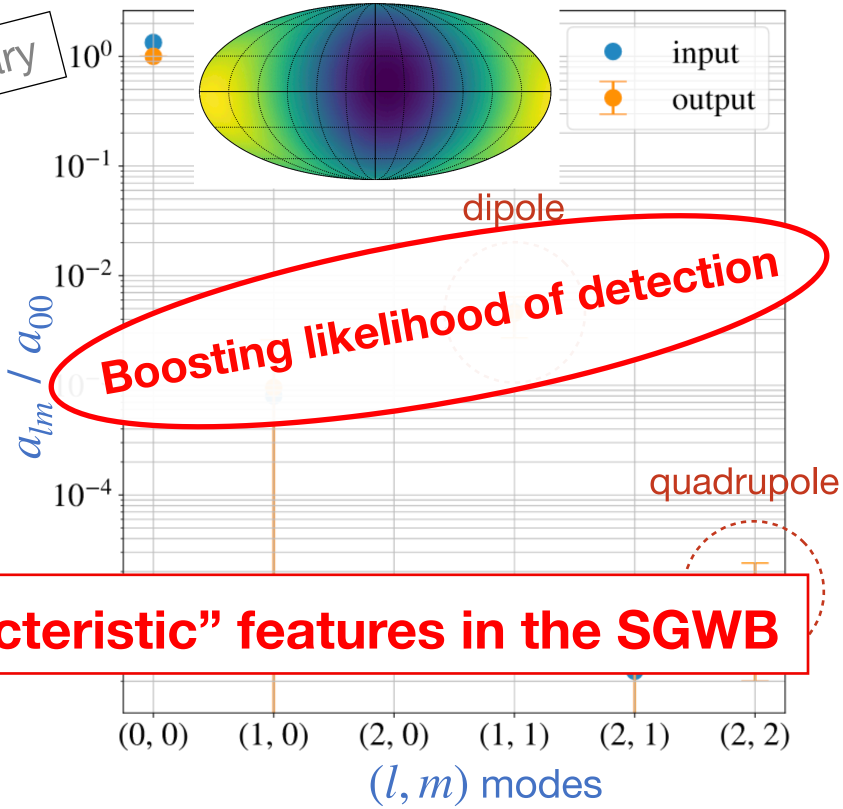
- **Results:**





⇒ LISA will be able to detect "characteristic" features in the SGWB

Summary

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- **What we know:**
  - Single waveforms gain **echos** and **discrete QNM spectra**
  - The full GW background gains **power** and **distinct features**

} QG detectible with LISA and others

- **What we need to do:**
  - Improve **constraints**, **add more features** to waveforms
  - **Single out** detectable features of the SGWB

} Theory gives us tools to factor out desired features

- **What the future will bring:**
  - Put tight **constraints on theories of QG**
  - **exploring quantum aspects** of BHs

} GW astronomy stands on the doormat of QG

Summary

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QG detectible with LISA and others

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GW astronomy stands on the doormat of QG

Back-up

Back-up

STRUCTURES CLUSTER OF EXCELLENCE
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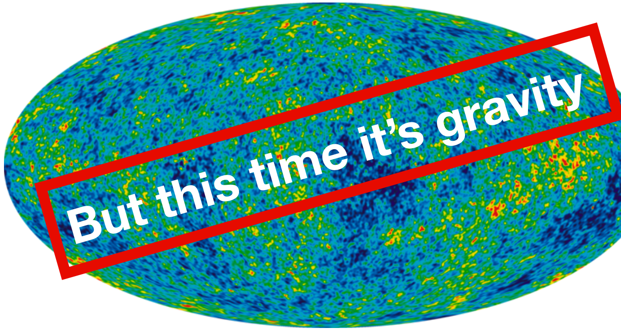
- *Irreducible* part from basic light-field inflation with $m^2 \ll H^2$, tensor modes turn into classical GW background upon reentry

$$P_h(k) \sim \left(\frac{k}{aH}\right)^{-2\epsilon}, \quad \epsilon \ll 1$$



- Time-dependence after reentering $\sim 1/a(\eta)$ allows for picking up non-trivial effects (e.g. supersymmetry [Watanabe & Komatsu, 2006])
- *Reducible* contributions can yield significant deviation from scale invariance, highly model dependent (produced during inflation)
- Further contributions include preheating, phase transitions, cosmic strings etc.

Todays focus: Contributions to the reducible sector and beyond

Back-up

STRUCTURES CLUSTER OF EXCELLENCE
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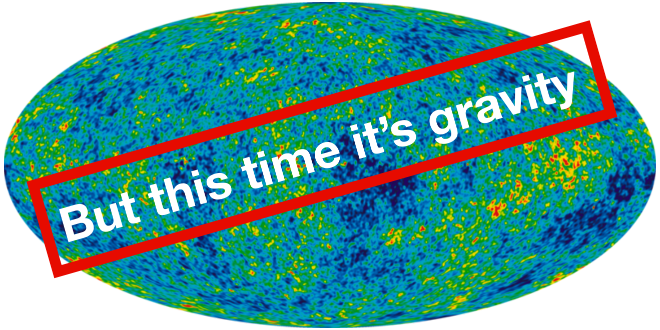
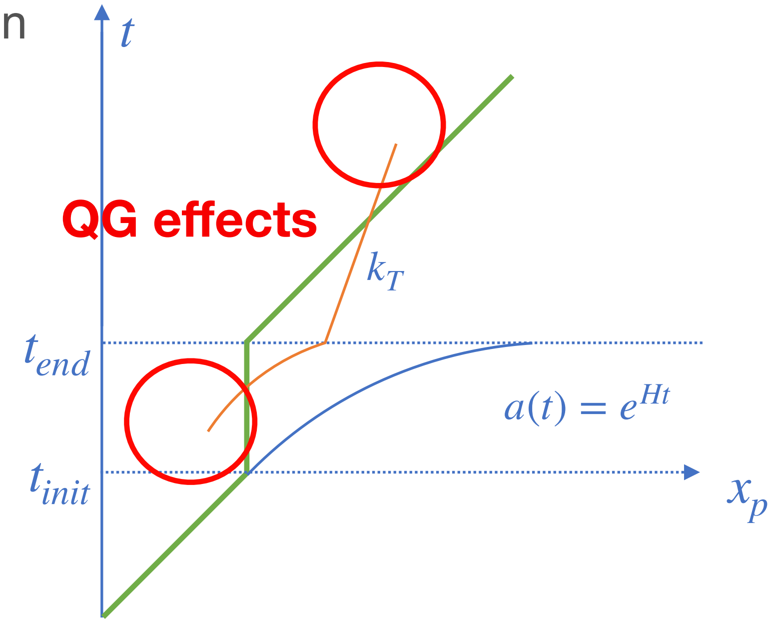
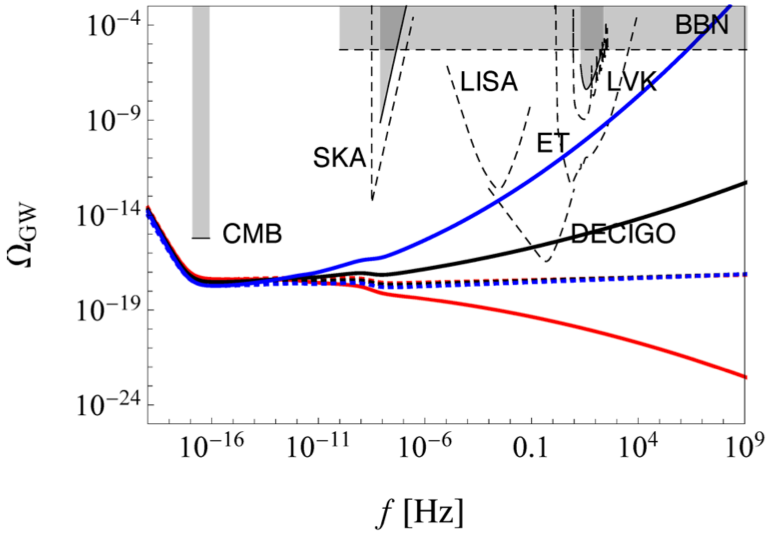




Back-up

- **Consequence:**
  - Reducible background gains scale dependence (blue-tilted) [Caprini, Figueroa, 2020]
  - Additional non-trivial features such as peaks and broken power-laws (e.g. PBH) [Pi, Sasaki, 2020]
  - (Some models yield exceptionally tiny corrections and/or red-tilted spectra)

- Potentially detectible [Calcagni, Kuroyanagi, 2021]:
  - String-Gas cosmology, new ekpyrotic scenarios, Brandenberger-Ho non-commutative inflation, multi-fractional inflation (beyond others)



[Calcagni, Kuroyanagi, 2021]

Back-up

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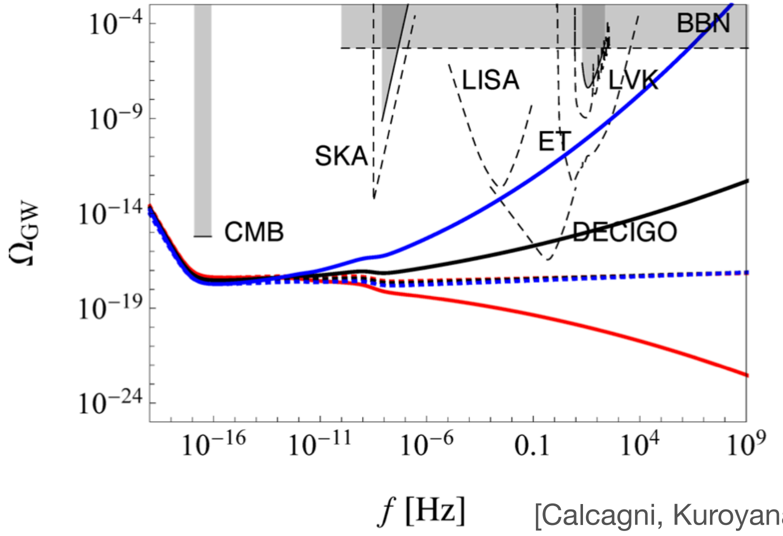
- Examples: additional fields present, new symmetry patterns, alternative theories of gravity, enhanced scalar perturbation at short scales (including primordial black holes)

- **QG effects**:
  - Modified initial (tensor) perturbation spectrum
  - New dynamics & interactions of perturbations
    e.g. thermal interactions
  - New phenomenological imprints

- **Consequences**:



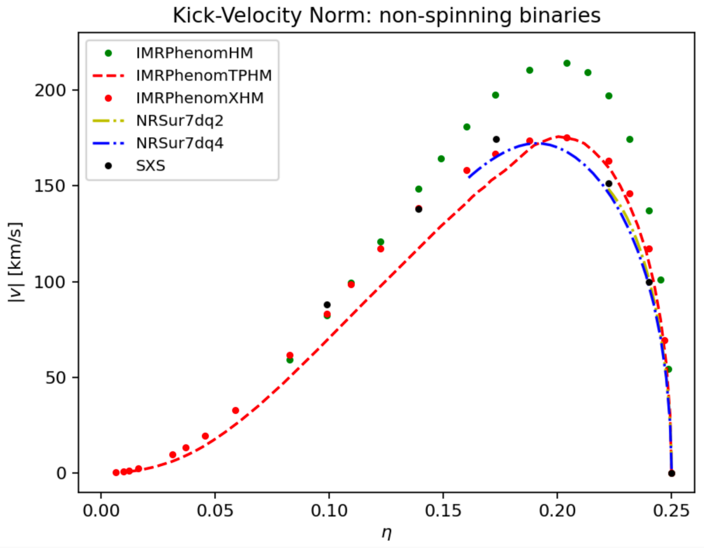
[Calcagni, Kuroyanagi, 2021]

Back-up

In Heidelberg:

- Large scale analysis of BBH events:
  - pin down shortcomings of EOB and phenomenological models
  - analyse correlations between dynamics of the remnant and memory (relevant for the merger phase)

Preliminary



- Reformulating/Adapting analytical constraints to general theories/new effects

Preliminary