Title: Grad Student Seminar: Maxence Corman and Amalia Madden

Speakers: Maxence Corman, Amalia Madden
Date: December 12, 2022 - 2:00 PM

URL: https://pirsa.org/22120067

Abstract: Maxence Corman, Perimeter Institute & University of Waterloo

Strong-gravity as a probe of new physics

The theory of general relativity captures most of what is known about the universe
on a large-scale, yet there are both theoretical and observational reasons to believe it is incomplete. This suggests that the strong-field regime could be described by some modification or extension of general relativity.

Advancement in our theoretical understanding of this
regime is key to complement both gravitational wave and astrophysical observations, and find signatures of new physics.

In this talk, I will discuss some recent developments in using the tools of numerical relativity to make detailed predictions in this regime.
This will include not only the mergers of black holes in modified theories of gravity,
but also the robustness of early universe cosmologies to large inhomogeneities.

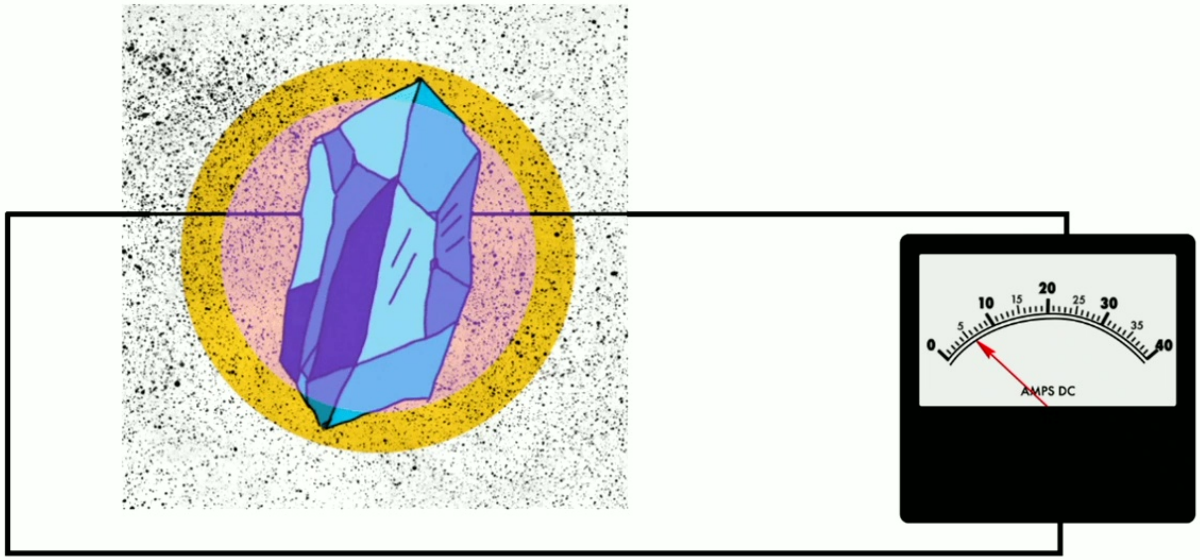
Amalia Madden, Perimeter Institute & University of Waterloo

New searches for the QCD axion with piezoelectric materials

The QCD axion is one of the best motivated extensions to the Standard Model, providing a solution to the strong CP problem as well as being an excellent dark matter candidate. In this talk I will describe two new observables, the "piezoaxionic" and "ferroaxionic" effects, that could be used to search for the QCD axion over many orders of magnitude of unexplored parameter space. Both of these observables rely on the interaction between the QCD axion and a class of materials known as piezoelectrics. I will then discuss our current progress in designing new experiments that could measure these observables. This talk will be based on 2112.11466 and unpublished work.

Zoom link: https://pitp.zoom.us/j/98585551152?pwd=aUF3SjlwQ1pPTG9CTUN4MWFqV1hZZz09

The Piezoaxionic Effect: New searches for the QCD axion



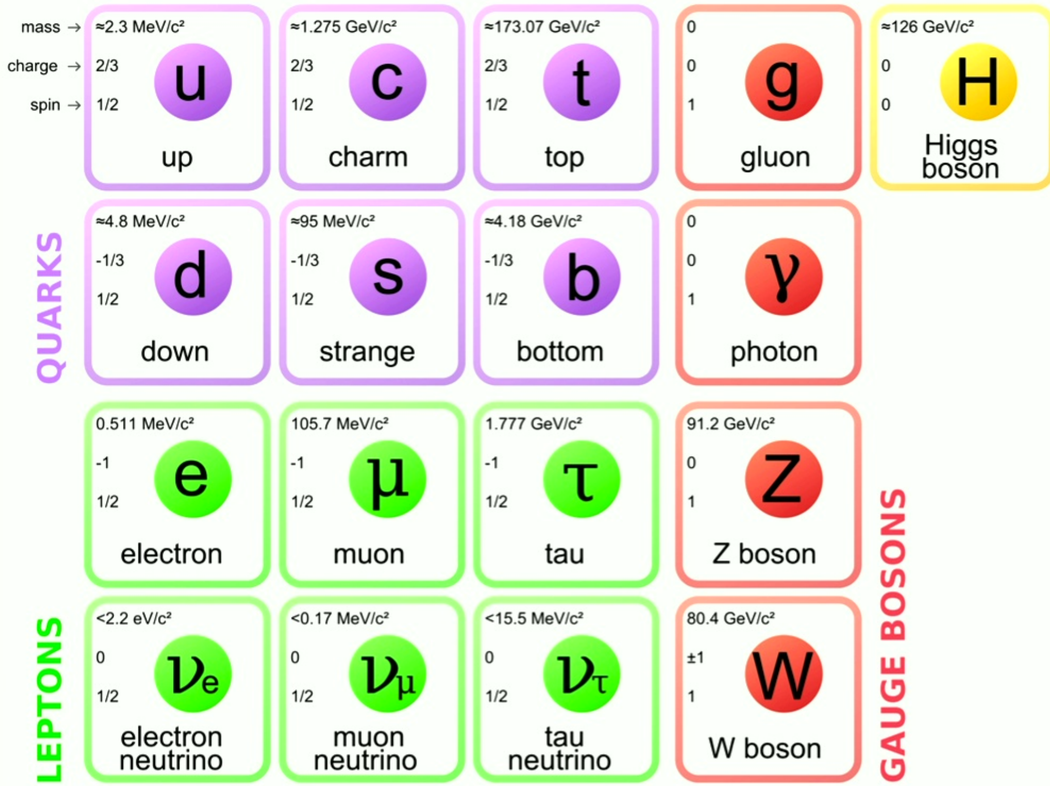
Amalia Madden - Perimeter Institute for Theoretical Physics

Based on 2112.11466 and upcoming work w/ Asimina Arvanitaki and Ken Van Tilburg

- What is the QCD axion?

- Where and how do we look for the QCD axion?

- How do axions interact with piezoelectric materials?


mass →
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≈2.3 MeV/c²
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photon
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electron
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μ
muon
1.777 GeV/c²
-1
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τ
tau
91.2 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
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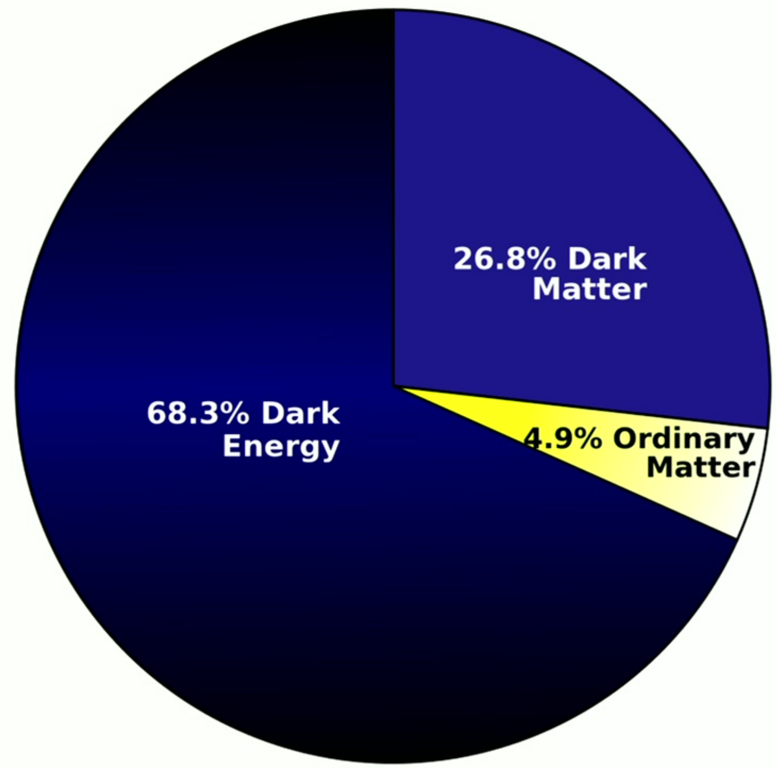
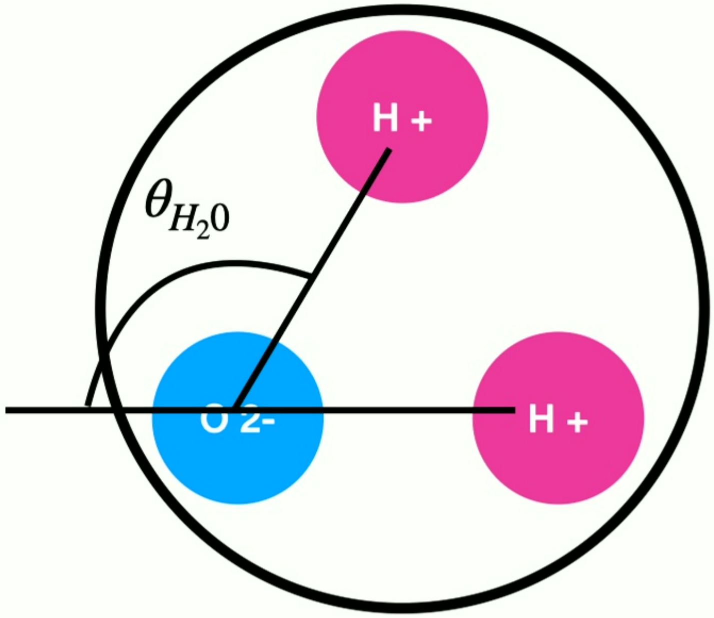
QUARKS
LEPTONS
GAUGE BOSONS


26.8% Dark Matter
68.3% Dark Energy
4.9% Ordinary Matter

The neutron electron dipole moment (EDM) puzzle*



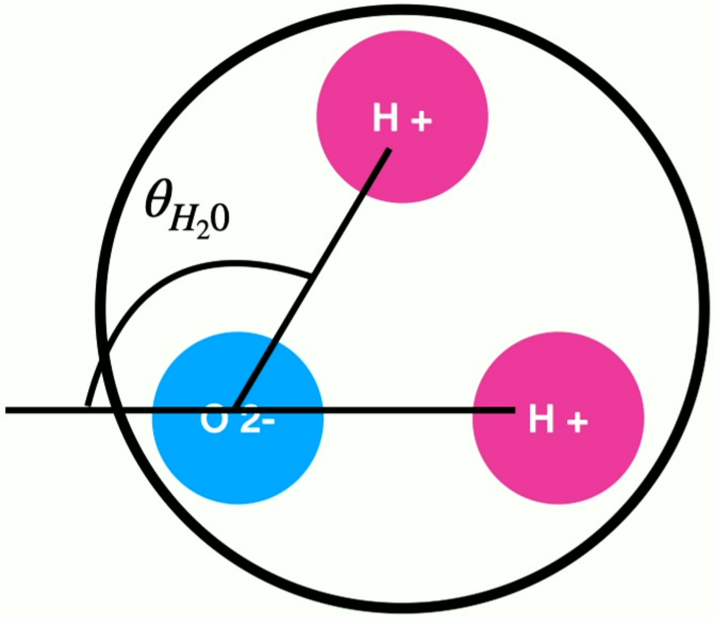
$$\vec{d} = \sum_i q_i \vec{r}_i$$

*** a.k.a the strong CP problem**

Questions a theorist should ask themselves:

- What is the DM made of?
- What problems does it solve in the Standard Model?
- How is it produced to match the density we observe in the Universe today?
- How do we detect it?

The neutron electron dipole moment (EDM) puzzle*



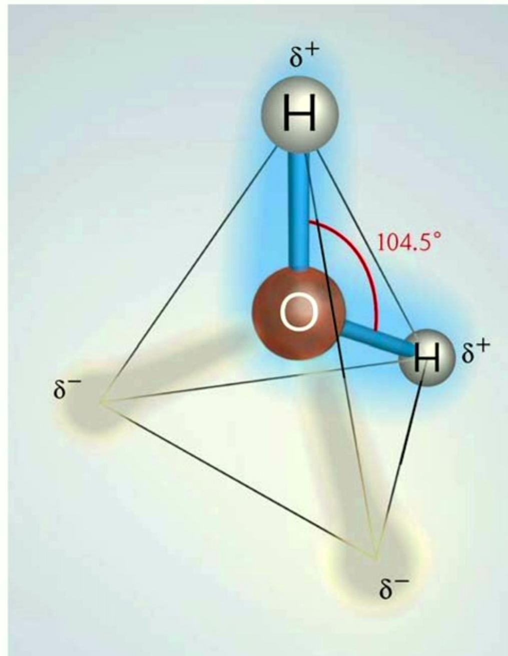
$$\vec{d} = \sum_i q_i \vec{r}_i$$

$$\theta_{H_20} = 104.5^\circ \qquad l_{O-H} \sim 1\text{Å}\,(10^{-8}\,cm)$$

$$|d_{H_2O}| \sim 3 \times 10^{-9}\, e \cdot cm$$

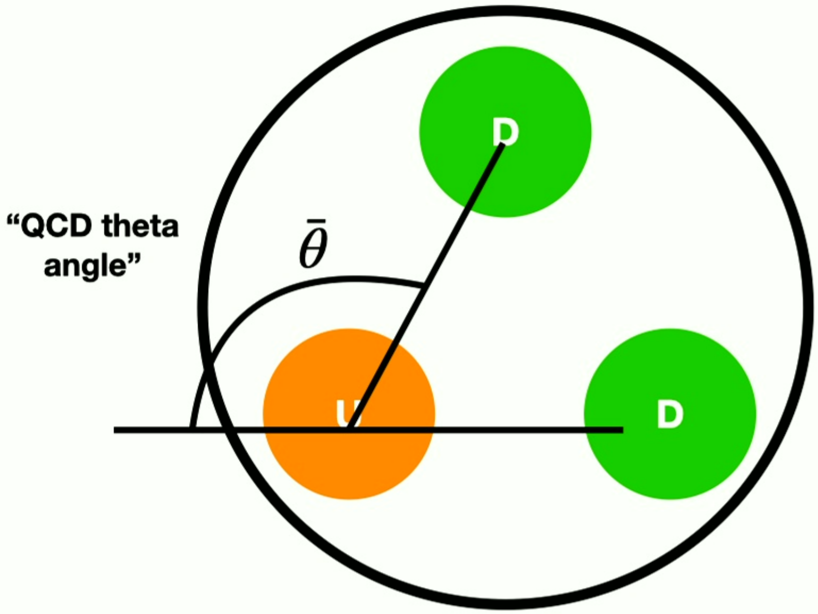
*** a.k.a the strong CP problem**

The neutron EDM puzzle



Tetrahedral structure

The neutron EDM puzzle



$$r_{neutron} \simeq 10^{-13} cm$$

$$|d_{n,SM}| \simeq 10^{-16}\,\bar{\theta} \cdot e \cdot cm$$

Experimentally, $|d_n| \lesssim 10^{-26} \cdot e \cdot cm$

The neutron EDM puzzle

$d = 0$ means that both P and T symmetries are preserved

The electroweak sector violates P and T, so why not QCD?

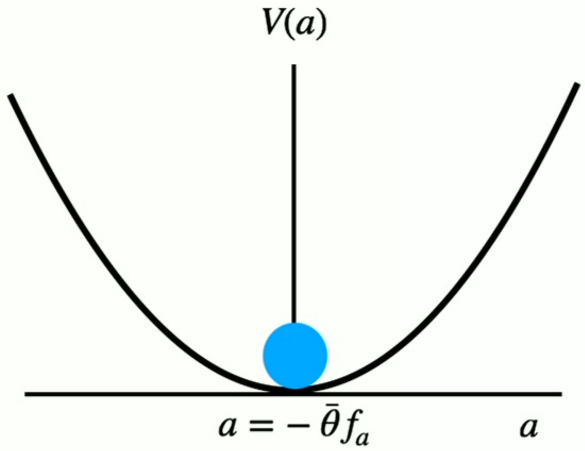
The QCD axion

- $\mathscr{L}_{SM} \supset \theta_0 \, \mathrm{tr}\, G\tilde{G}$

- Physical angle $\bar{\theta} = \theta_0 + \arg\det[M_q]$

- Introduce axion: $\mathscr{L} \supset \dfrac{a(x)}{f_a} \mathrm{tr}\, \tilde{G}G$

  (f_a = "axion decay constant")

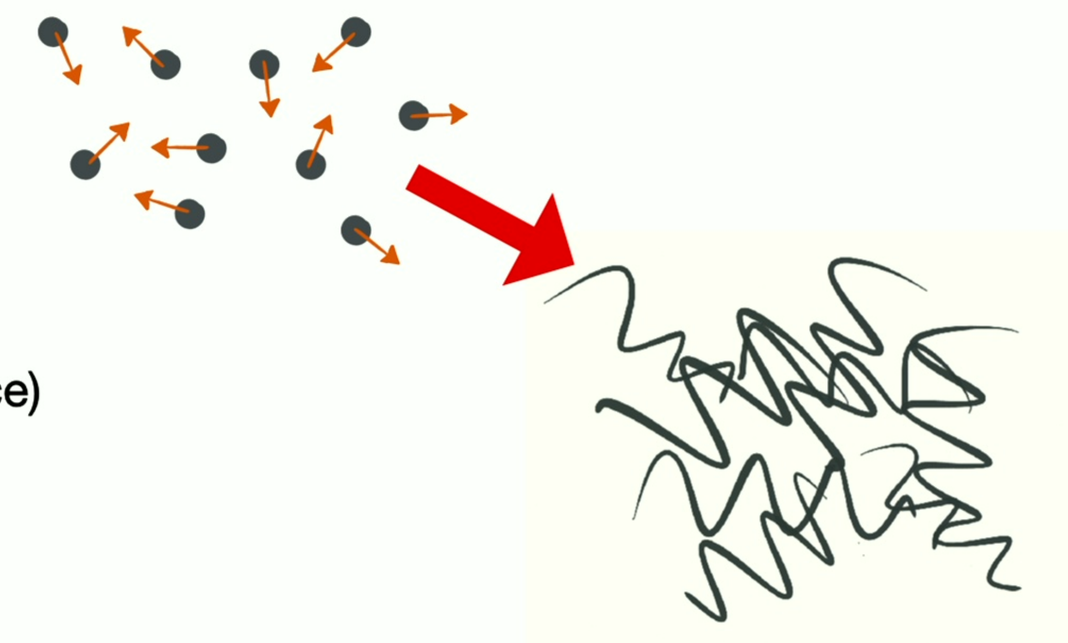


- Minimum of axion potential *dynamically* solves strong CP problem:
  $\theta_{eff} = \langle \dfrac{a(x)}{f_a} \rangle + \bar{\theta} = 0$

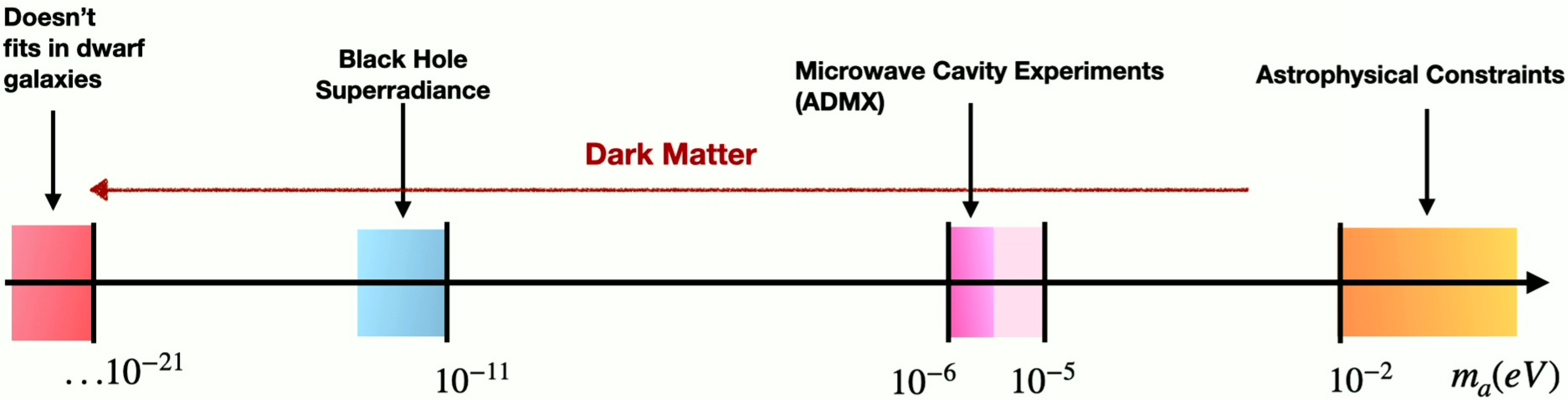
Wavy DM

Bosonic DM has wave-like properties when $n_{DM} > \frac{1}{\lambda_{DM}^3}$. In our galaxy: $m_{DM} < 1eV$.

- Locally, $a(t) \approx a_0 \cos \frac{m_a c^2}{\hbar} t$
- Amplitude $a_0 \propto \frac{\sqrt{\rho_{DM}}}{m_a}$
- Small frequency spread (coherence)
  $\delta\omega_a \approx \frac{v^2}{\hbar} \omega_a \approx 10^{-6} \omega_a$



$$m_a \sim 6 \times 10^{-11} eV \left(\frac{10^{17} GeV}{f_a} \right)$$



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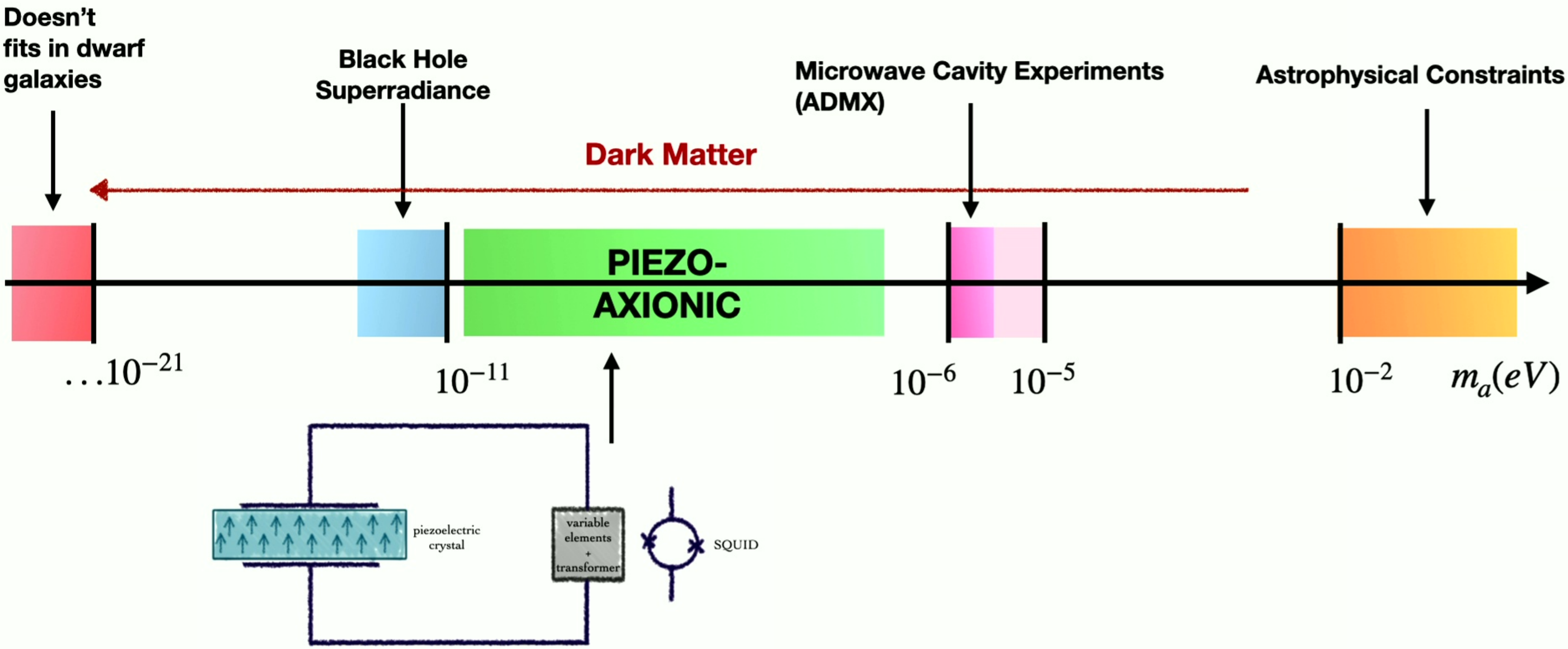
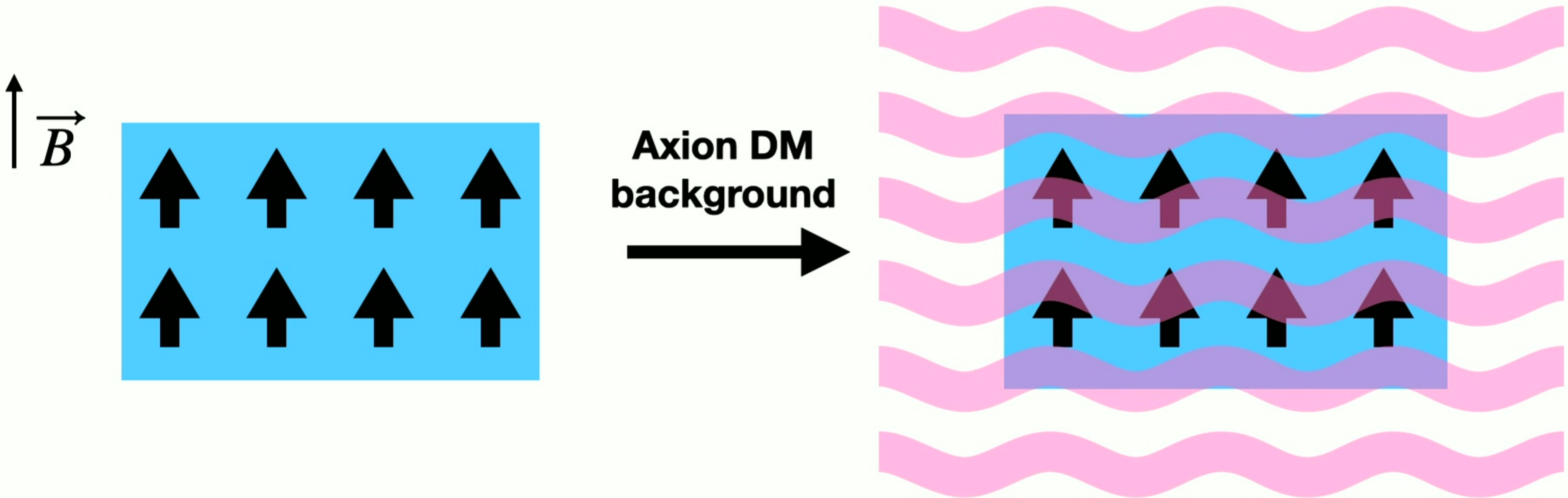


arxiv# 2112.11466

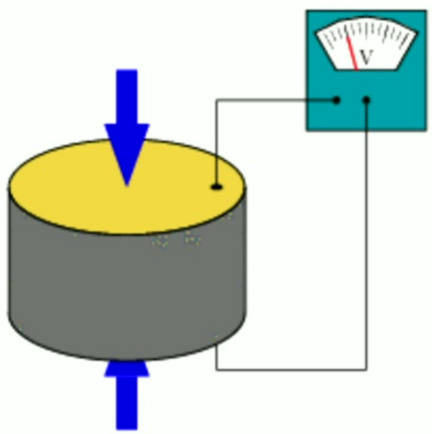
The Piezoaxionic Effect

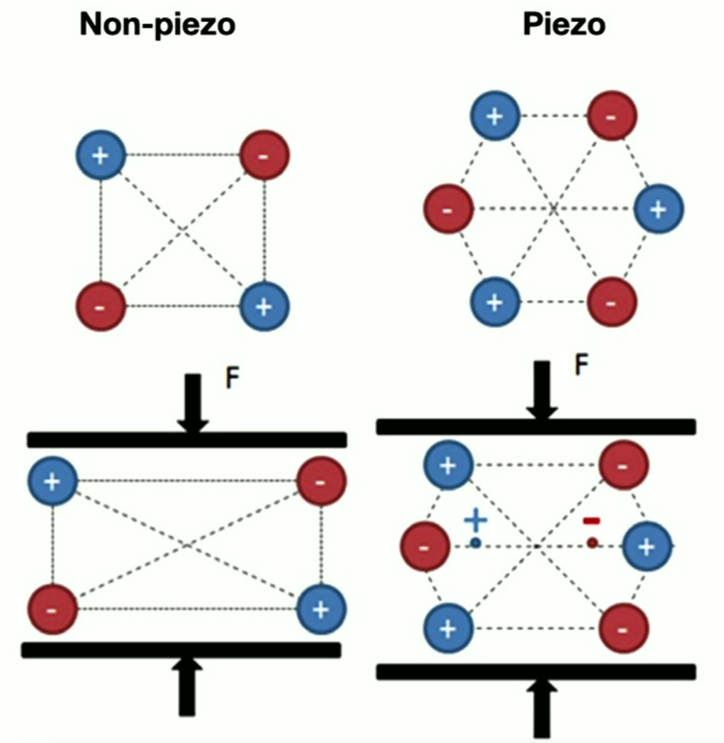


Piezoelectric Crystals

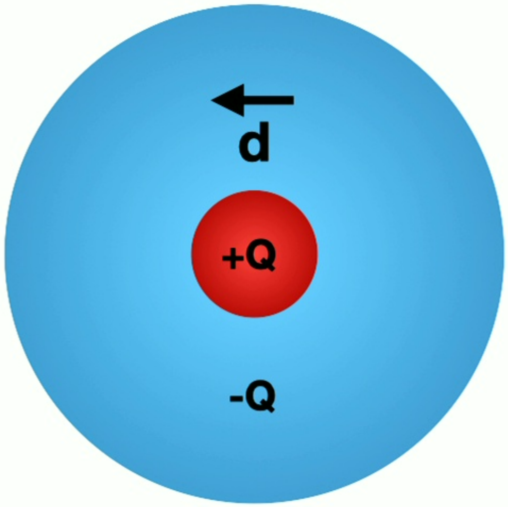
- Crystal structure breaks parity symmetry
  $(x, y, z) \neq (-x, -y, -z)$

- Deformation causes net charge across unit cell (and vice versa).



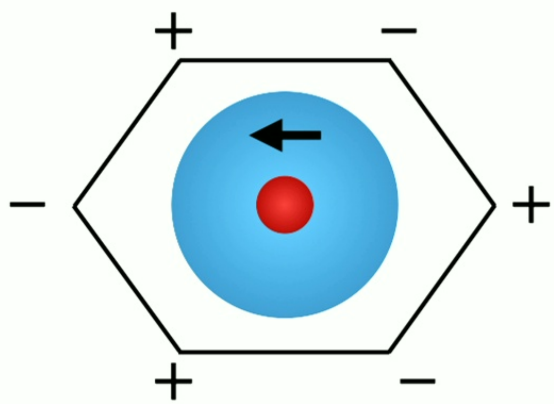


QCD axion dark matter induces an ***oscillating*** nuclear electric dipole moment (EDM):



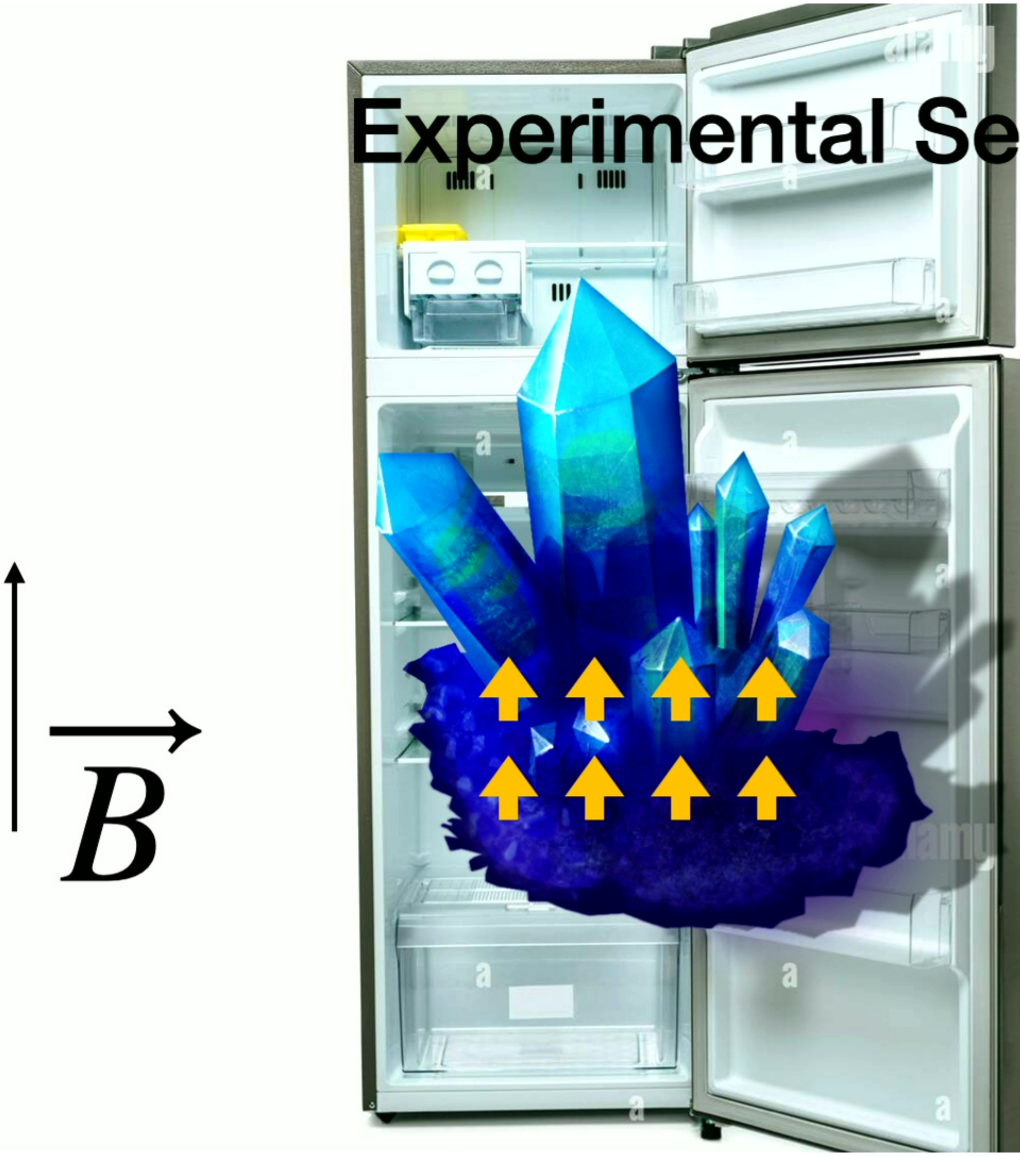
$$d_n \sim 10^{-16} \frac{\sqrt{\rho_{DM}}}{m_a f_a} \cos m_a t \cdot \mathrm{e} \cdot \mathrm{cm}$$

EDM generates an oscillating strain of unit cell in crystal:*

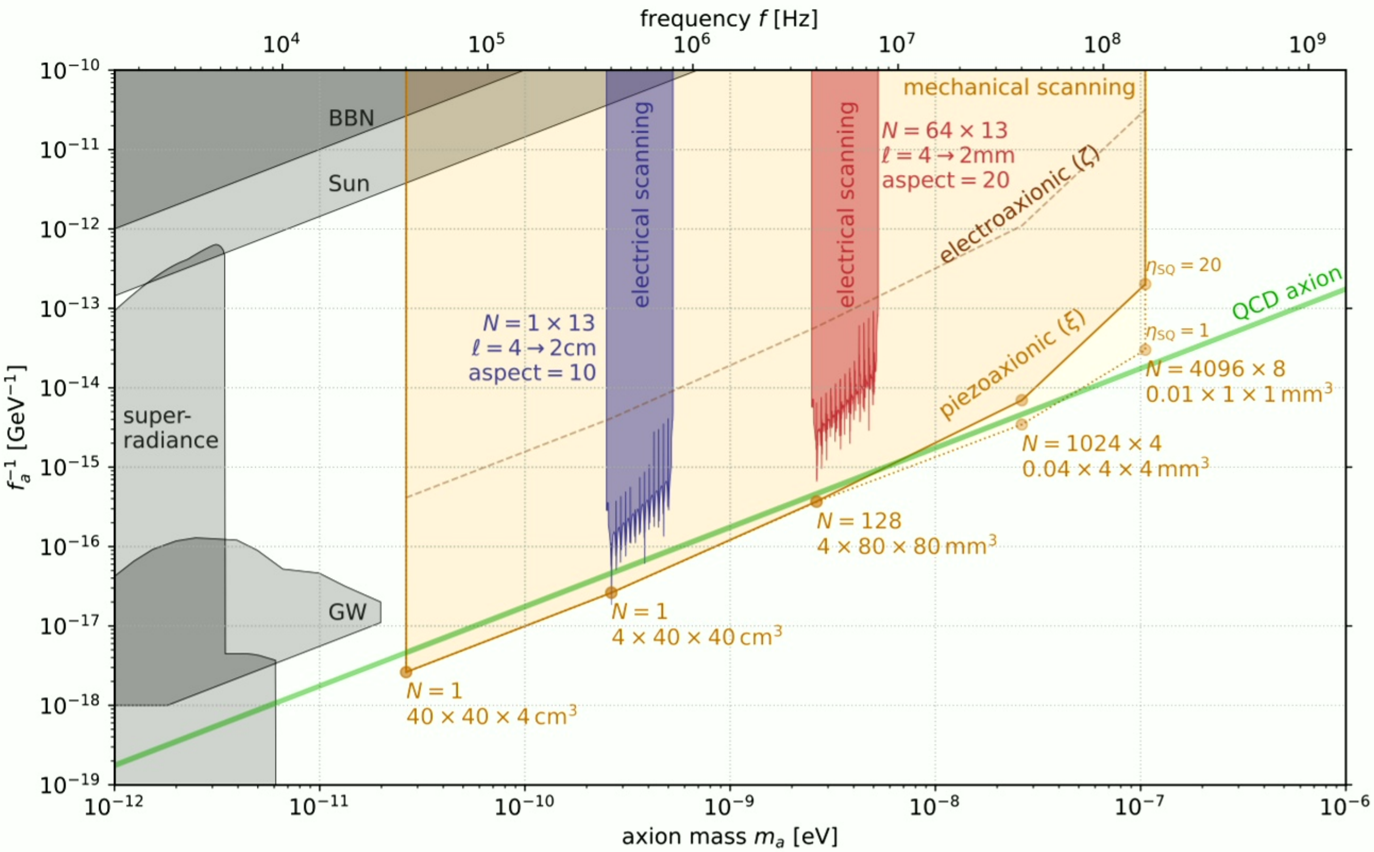


*this is super non-trivial

Experimental Setup



Idealized Forecast



https://github.com/kenvantilburg/piezoaxionic-effect

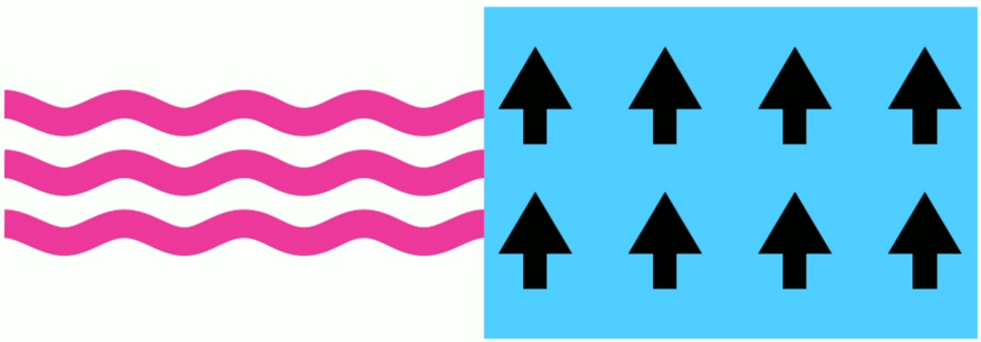
BBN: K. Blum, R. T. D'Agnolo, M. Lisanti, and B. R. Safdi (2014)

Sun: A. Hook and J. Huang (2018)

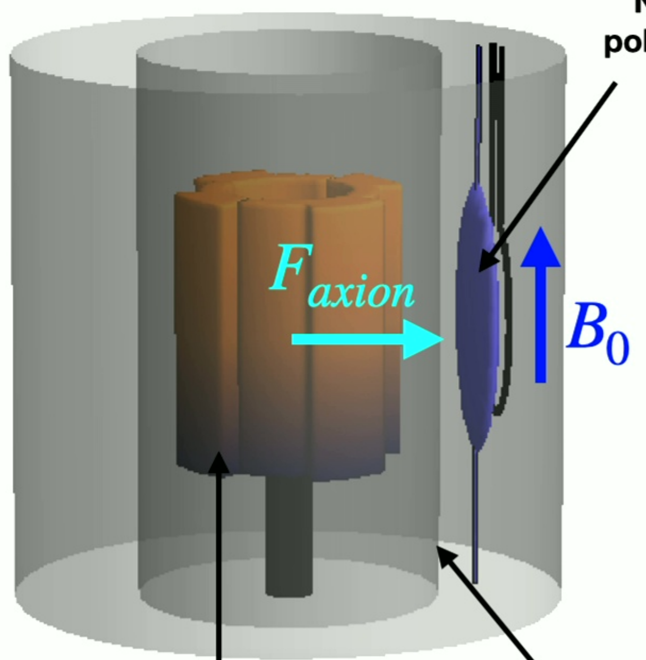
Superradiance: A. Arvanitaki and S. Dubovsky (2011)

GWs: J. Zhang, Z. Lyu, J. Huang, M. C. Johnson, L. Sagunski, M. Sakellariadou, and H. Yang (2021).

Ferroaxionic effect



$$\mathscr{L} \supset \frac{a}{f_a} G\tilde{G}$$



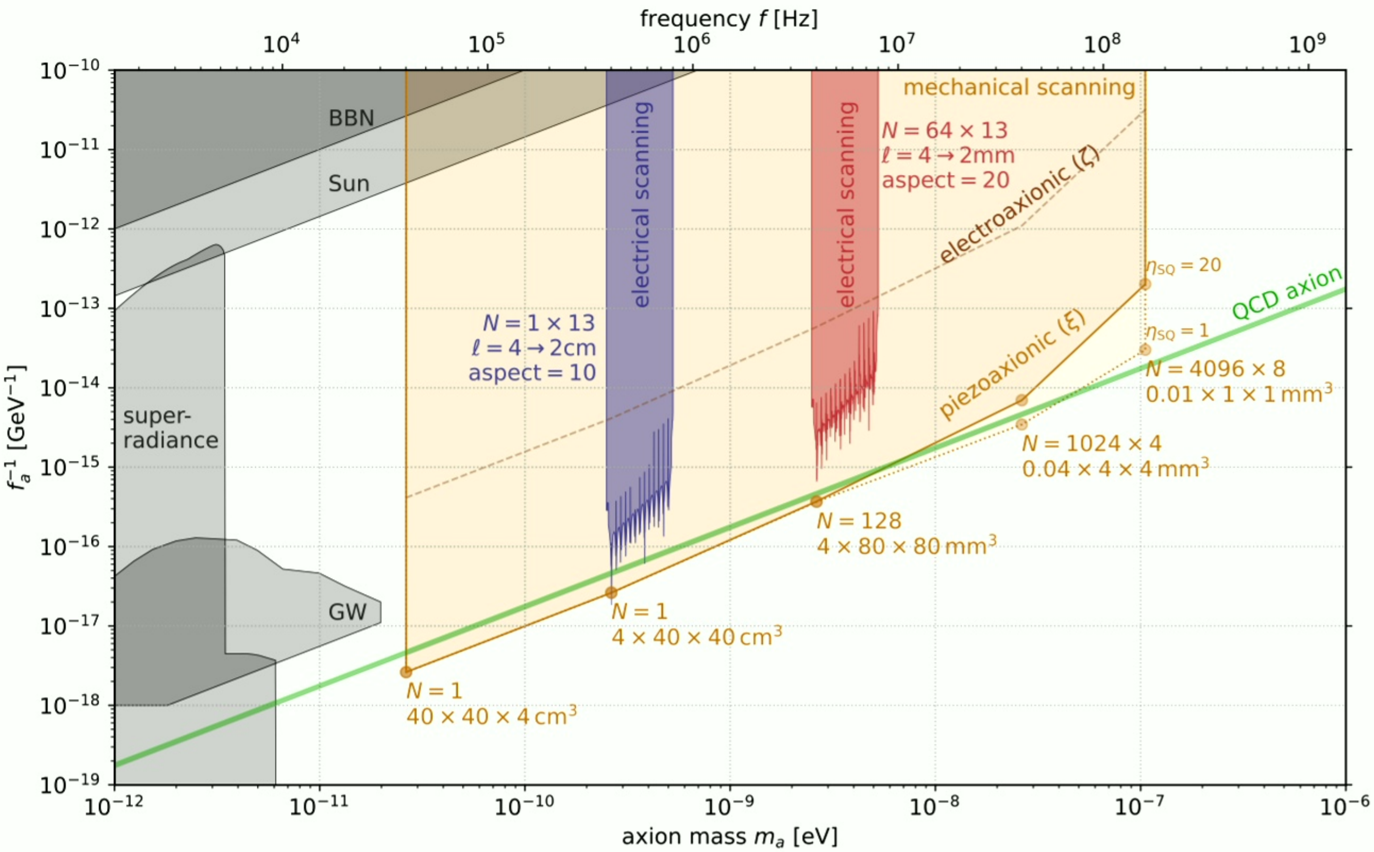
Sensitivity to $10^{-5} eV \lesssim m_a \lesssim 10^{-2} eV$

- The QCD axion is an excellent dark matter candidate that also explains the absence of CP violation in the strong force

- QCD axion DM could excite vibrational modes in piezoelectric crystals via their coupling to gluons. This could be used to probe axions in the mass range from $10^{-11}eV$ to $10^{-7}eV$.

- Ferroelectric crystals can also source axion-mediated forces. Through their interaction with an NMR sample, this could be used to axions in the mass range from $10^{-5}eV$ to $10^{-2}eV$.

Idealized Forecast



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Nonlinear dynamics of binary black hole mergers in Einstein-scalar-Gauss-Bonnet gravity

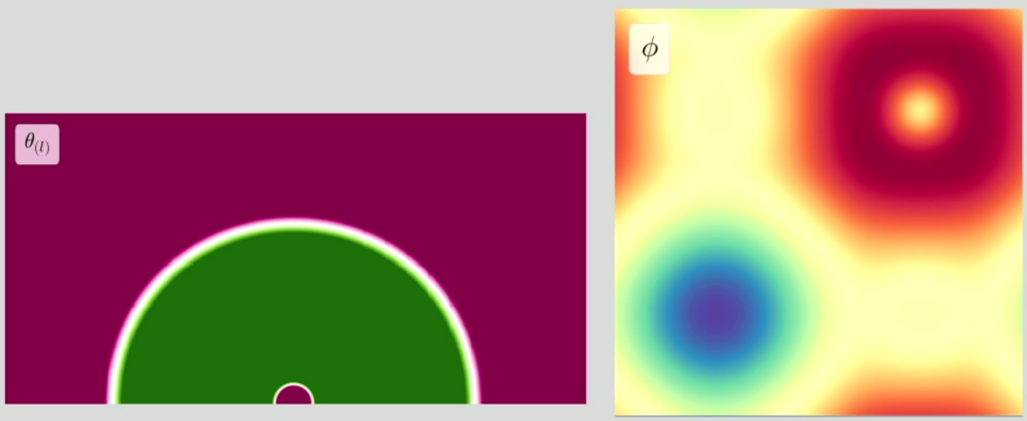
Maxence Corman
Perimeter Institute
with **William E. East** & **Justin Ripley**
Perimeter Institute, University of Cambridge & University of Illinois

December 12, 2022

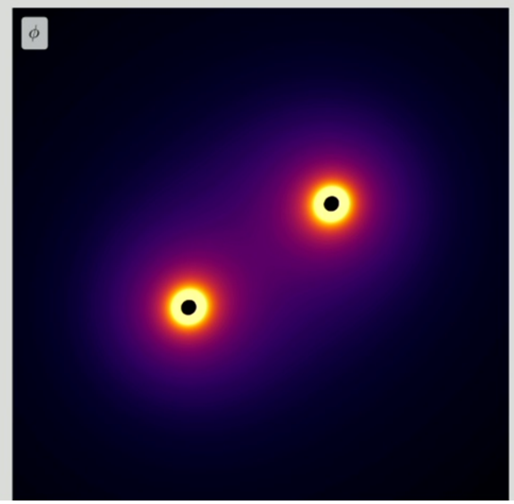
arXiv:2210.09235

Use the **strong-gravity** regime to discover **new physics**

Problem of initial conditions in the early universe



Binary black hole mergers in Horndeski theories



Use the **strong-gravity** regime to discover **new physics**

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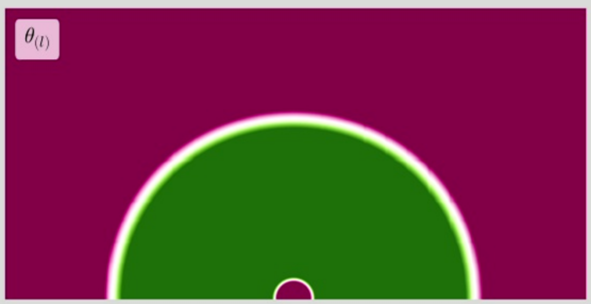

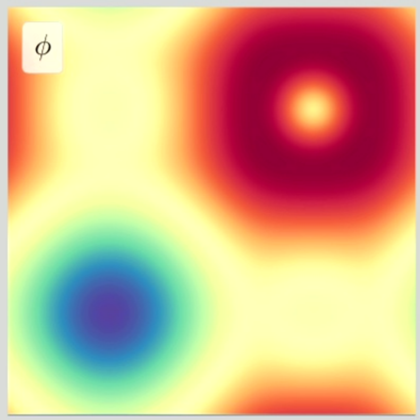

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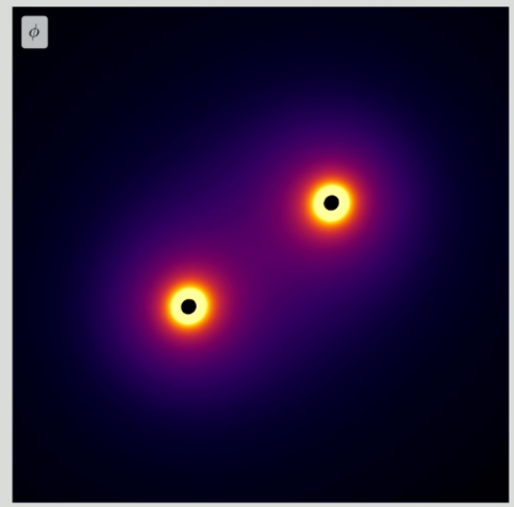
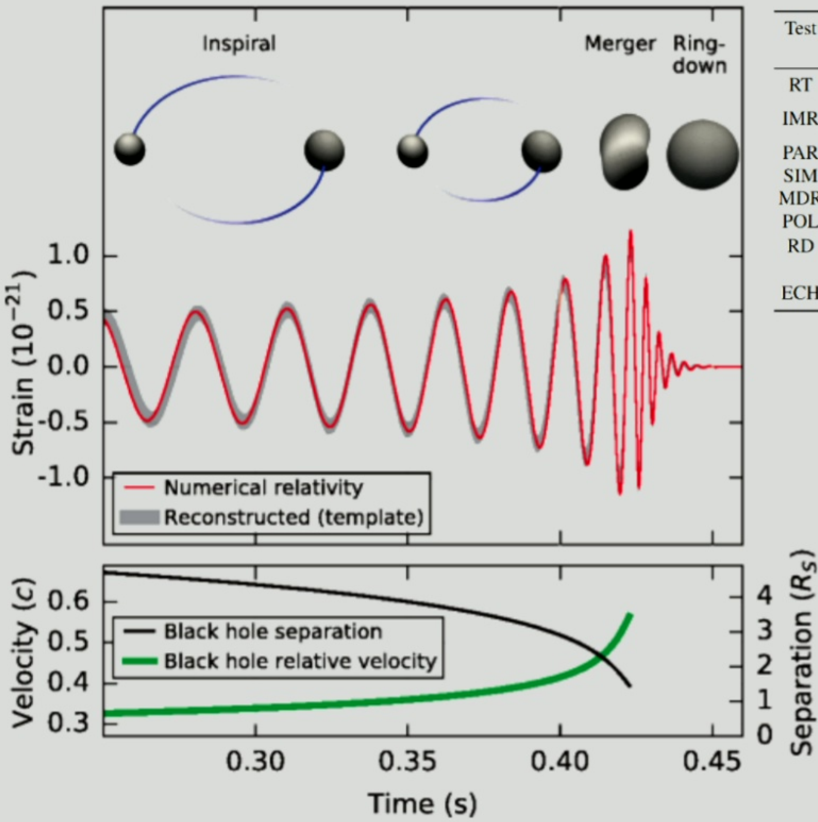
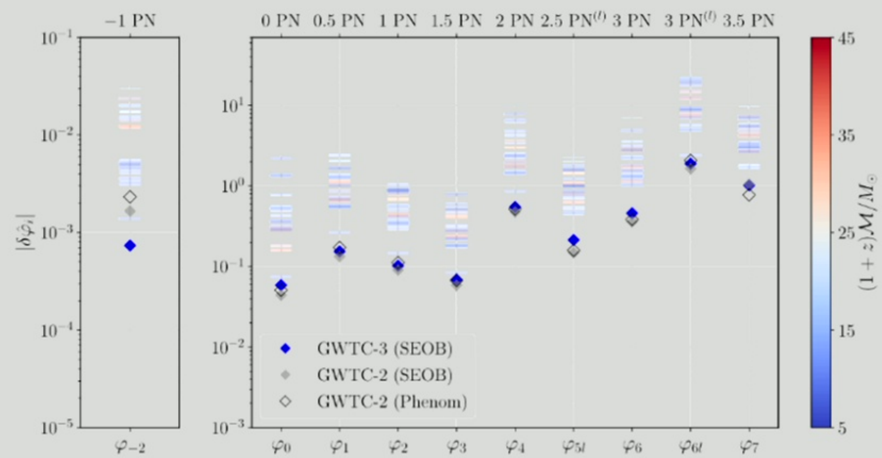


Testing modified theories of gravity



Test	Section	Quantity	Parameter	Improvement w.r.t. GWTC-2
RT	IV A	p-value	p-value	Not applicable
IMR	IV B	Fractional deviation in remnant mass and spin	$\left\{\frac{\Delta M_f}{\bar{M}_f}, \frac{\Delta \chi_f}{\bar{\chi}_f}\right\}$	1.1–1.8
PAR	V A	PN deformation parameter	$\delta\hat{\phi}_k$	1.2–3.1
SIM	V B	Deformation in spin-induced multipole parameter	$\delta\kappa_s$	1.1–1.2
MDR	VI	Magnitude of dispersion	$\lvert A_\alpha \rvert$	0.8–2.1
POL	VII	Bayes Factors between different polarization hypotheses	$\log_{10} \mathcal{B}_T^X$	New Test
RD	VIII A 1	Fractional deviations in frequency (pyRing)	$\delta \hat{f}_{221}$	1.1
	VIII A 2	Fractional deviations in frequency and damping time (pSEOB)	$\{\delta\hat{\tau}_{220}, \delta\hat{f}_{220}\}$	1.7–5.5
ECH	VIII B	Signal-to-noise Bayes Factor	$\log_{10} \mathcal{B}_{S/N}$	New Test

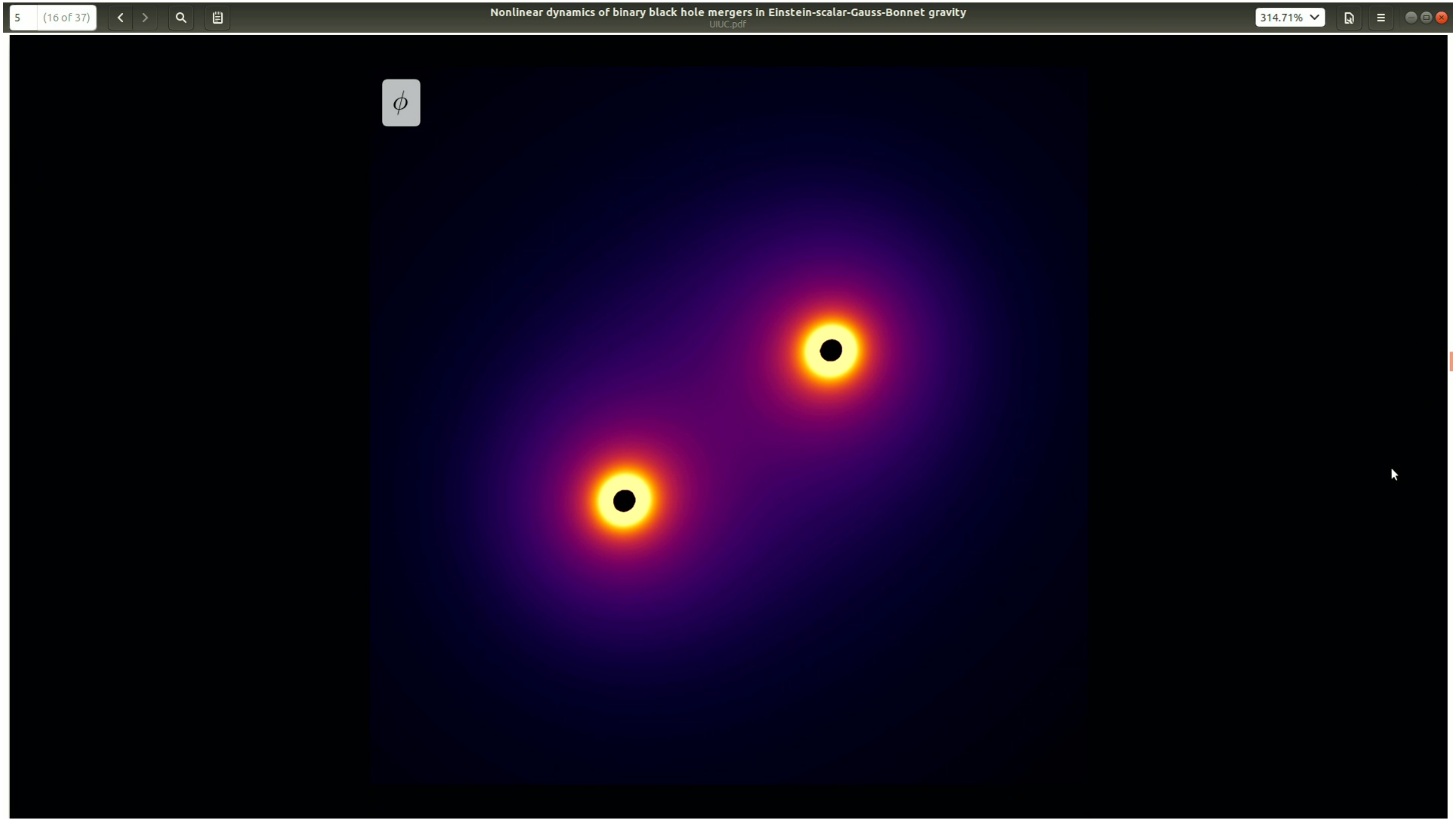


Einstein scalar Gauss Bonnet gravity

$$S = \frac{1}{16\pi} \int d^4x \sqrt{-g} \left(R - (\nabla\phi)^2 + \beta(\phi)\mathcal{G} \right)$$

with $\mathcal{G} \equiv R^2 - 4R_{ab}R^{ab} + R_{abcd}R^{abcd}$ and $\beta(\phi) = 2\lambda\phi$.

- Low-energy limit of many UV complete theories (Boulware+1985,Kanti+1995)
- Horndeski theory $\Rightarrow$ potentially well-posed (Papallo & Reall 2017, Kovacs & Reall 2020)
- Black hole solutions with scalar hair $\sim \zeta_1 \equiv \lambda/m^2$ (Sotiriou & Zhou 2014)
- Consistent with current observations: low-mass x-ray binaries (Yagi+2016), GW detections (Perkins+ 2021, Wang+2021, Lyu+2022) $\Rightarrow \sqrt{\lambda} \lesssim 5.9$ km (Lyu+ 2022)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Nonlinear dynamics of binary black hole mergers in Einstein-scalar-Gauss-Bonnet gravity
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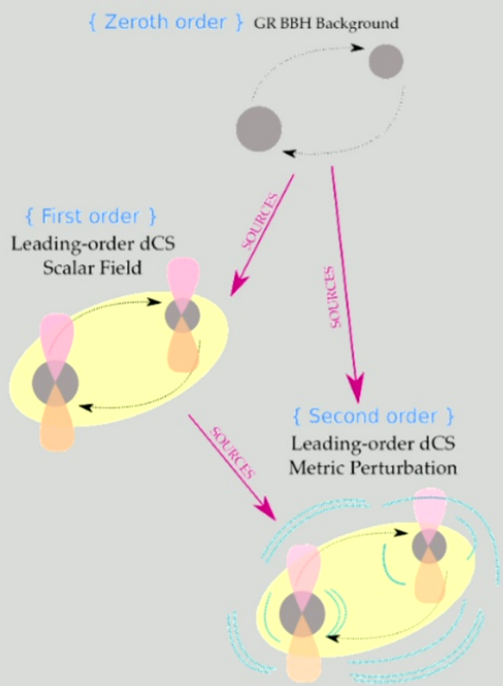
Evolving modified theories of gravity

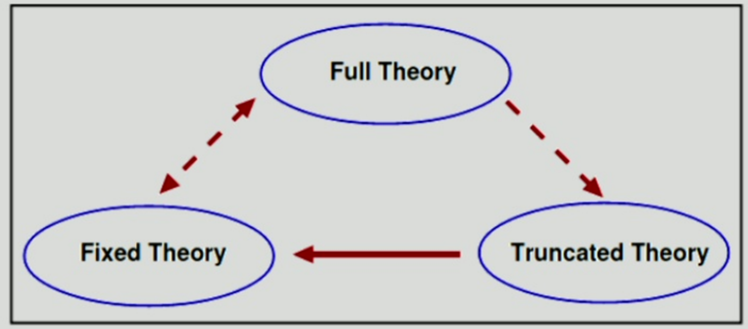
Order-reduction approach

(Okounkova+2019, Galvez Ghersi+ 2021, others)



Fixing the equations

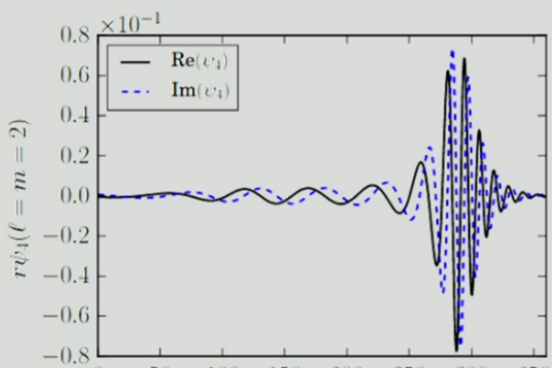
(Cayuso, Lehner+ 2017,2020; Bezares+ 2021,Lara+2021,Franchini+2022)



Solve full equations

Modified generalized harmonic

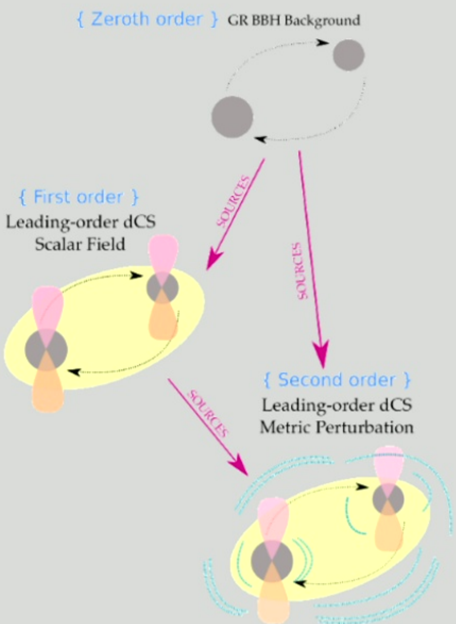
(Kovacs & Reall 2020, *East+ 2020,2021,2022; MC, Ripley & East 2022*)



Evolving modified theories of gravity

Order-reduction approach

(Okounkova+2019, Galvez Ghersi+ 2021, others)



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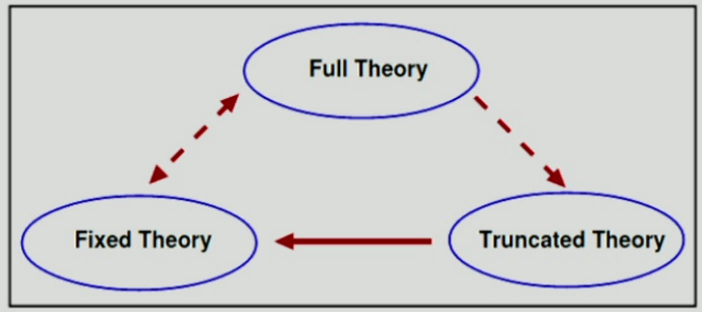

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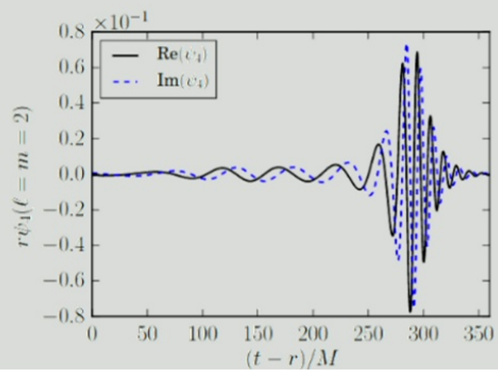
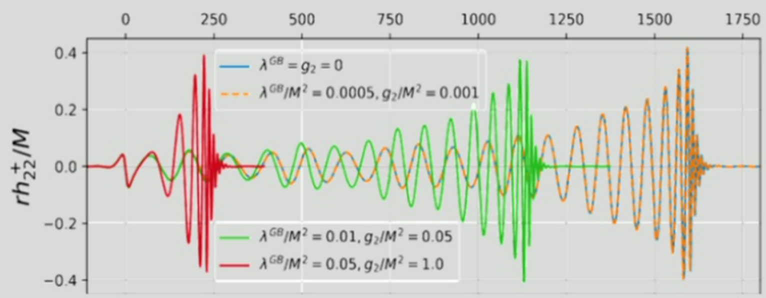
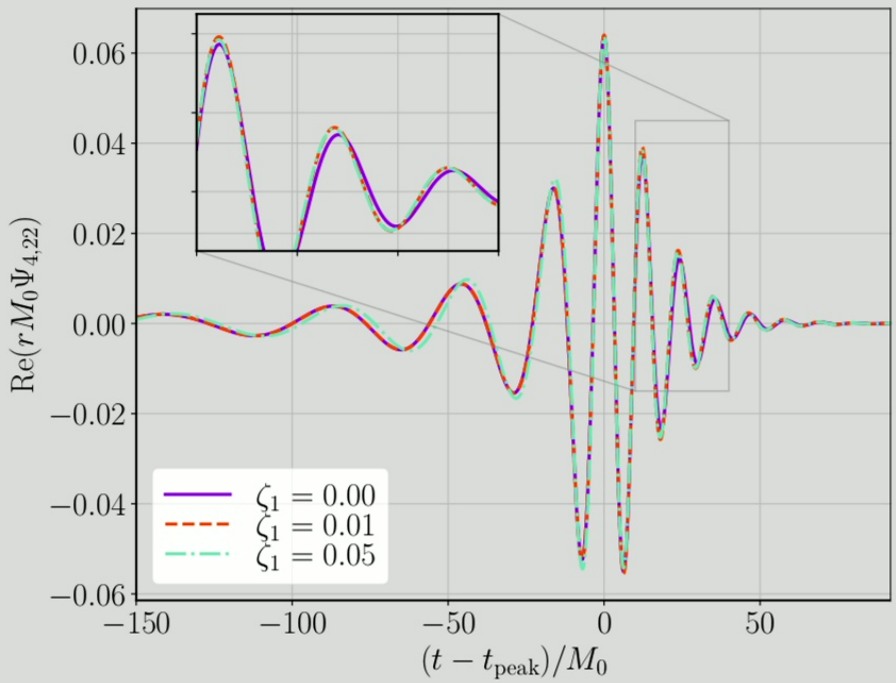


Modified CCZ4

(Figueras & Franca 2021; Saló +2022)



Merger dynamics in EsGB (MC,Ripley,East 2022)



Nonlinear dynamics of binary black hole mergers in Einstein-scalar-Gauss-Bonnet gravity

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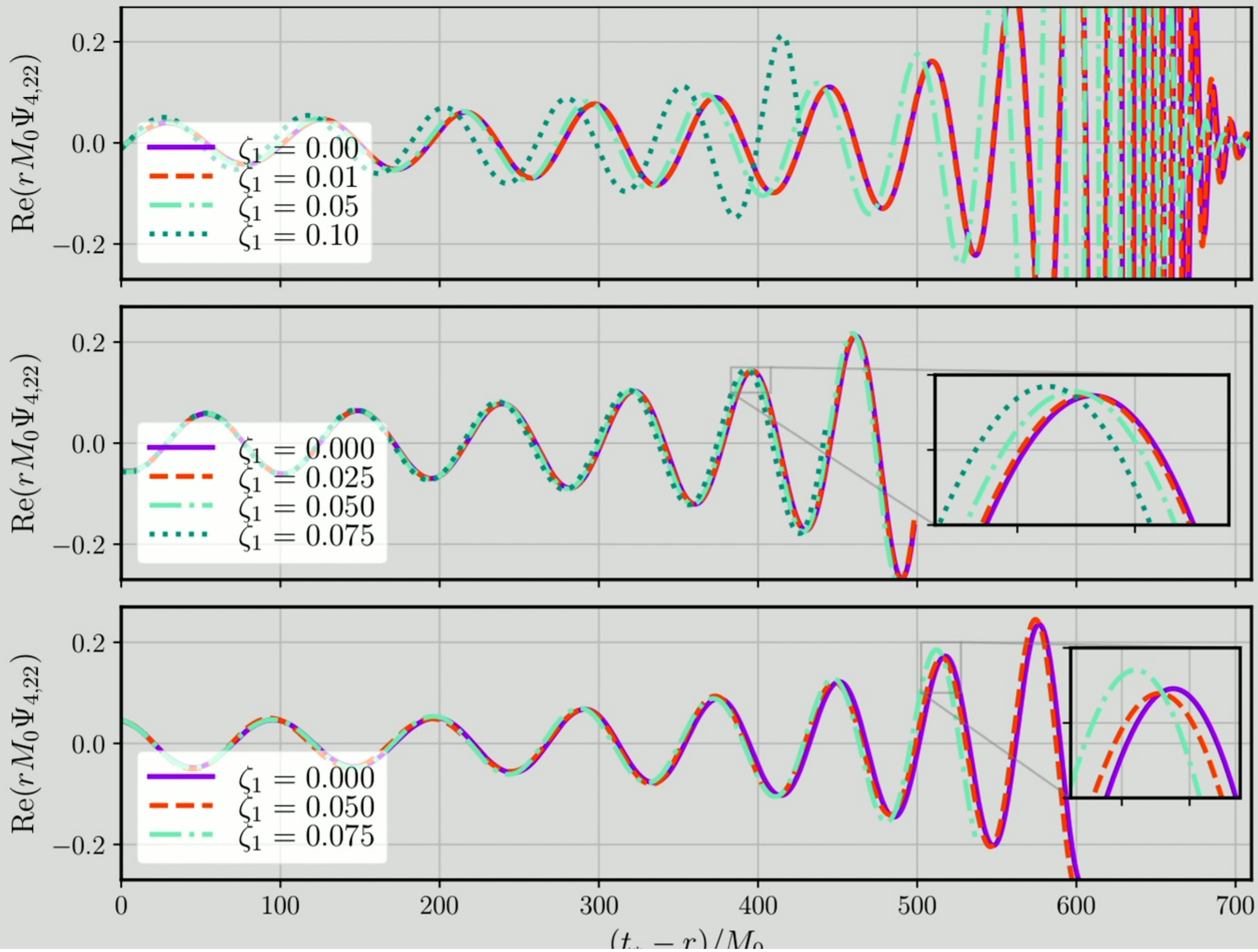
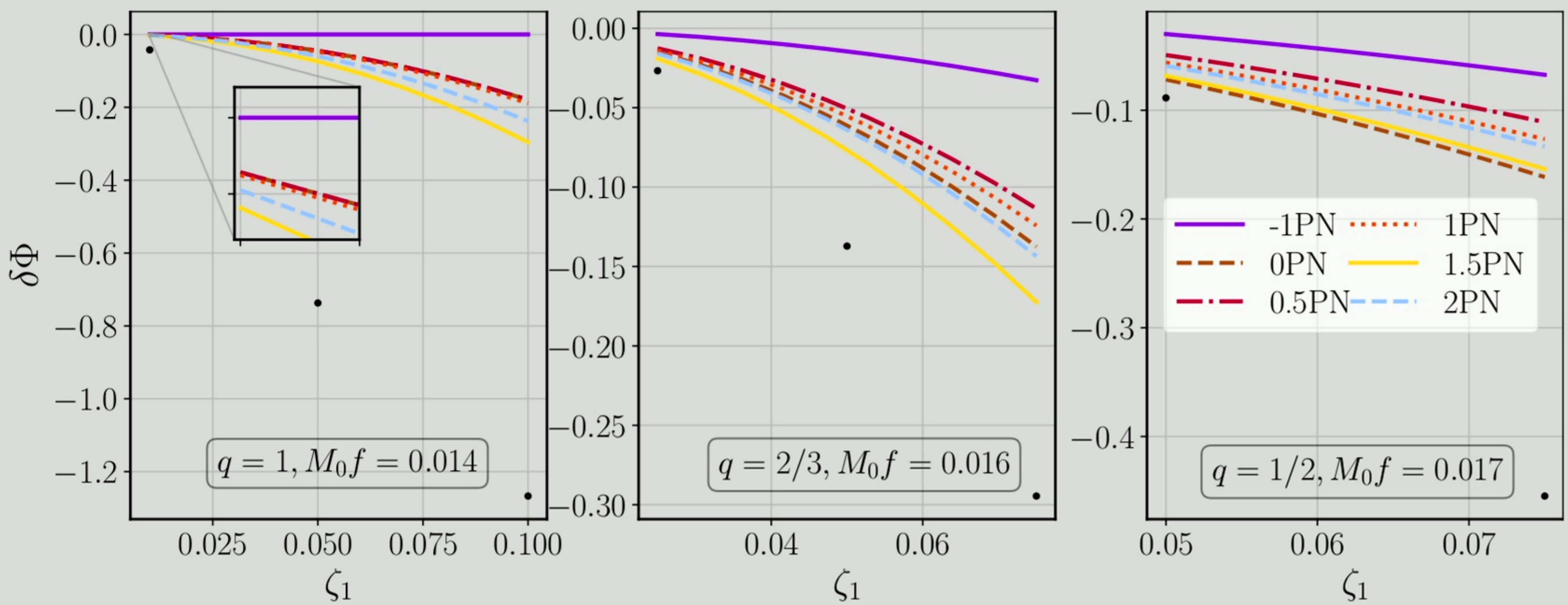


Comparison dephasing to PN theory (Sennet+2016,Lyu+2022)



Future directions

We now have the numerical tools to **non-perturbatively** evolve compact object mergers in Horndeski theories

- Solve the initial value problem in modified theories of gravity
- Further develop the modified generalized harmonic formulation
- Compare to order-reduction (Okounkova+2019), short-wavelength fixing approximations (Cayuso,Lehner+2017)
- Do data analysis, benchmark theory-agnostic tests
- Expand the parameter space

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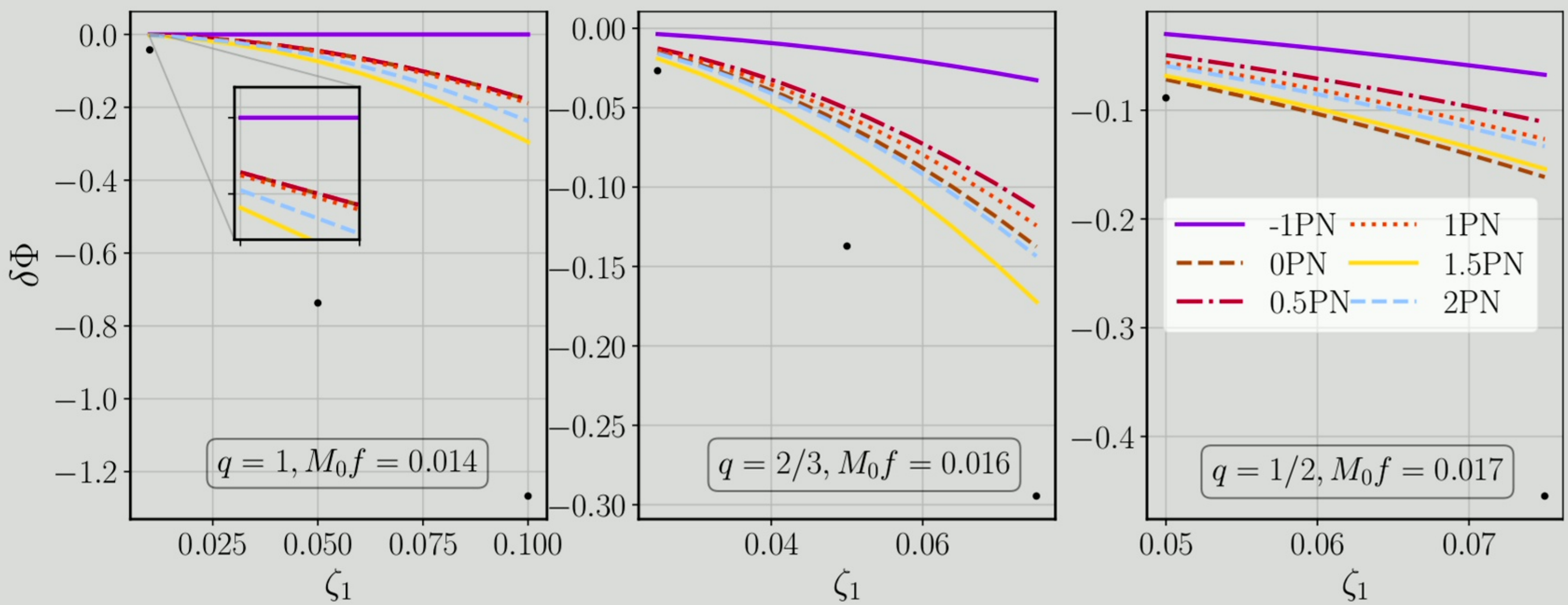
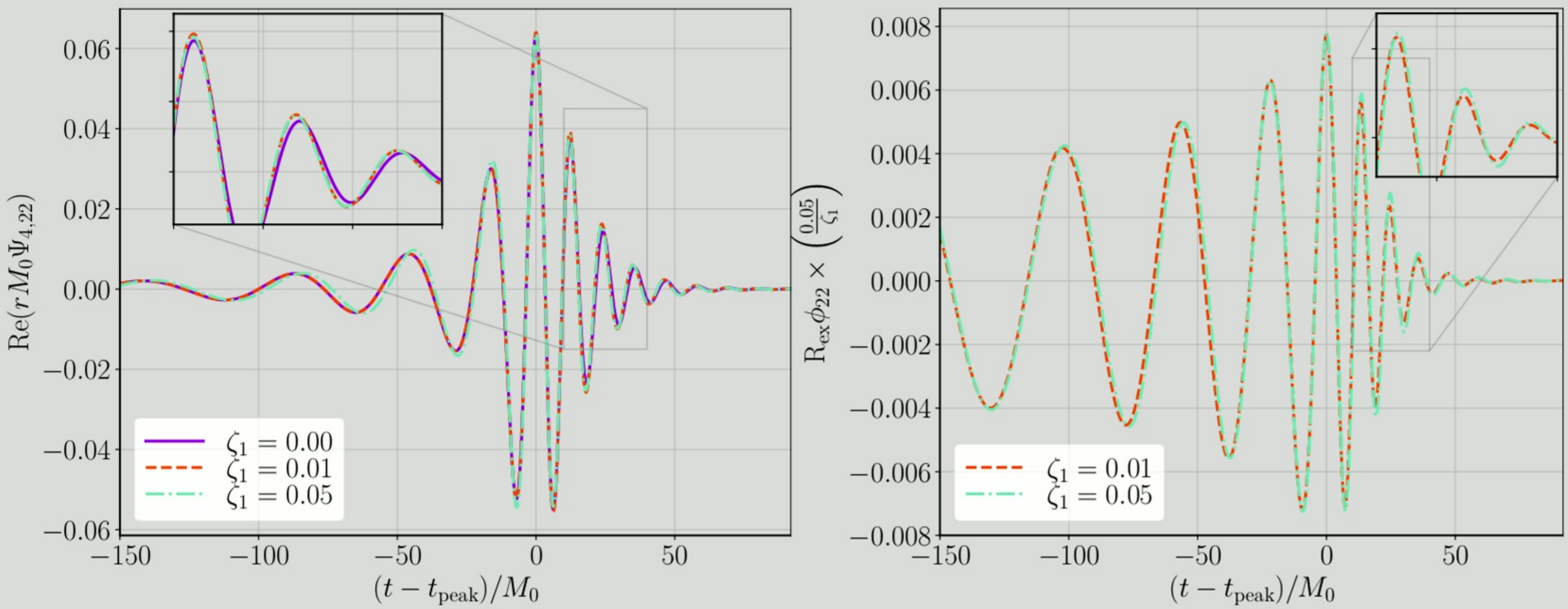
- Compare to order-reduction (Okounkova+2019), short-wavelength fixing approximations (Cayuso,Lehner+2017)
- Do data analysis, benchmark theory-agnostic tests
- Expand the parameter space
- Other phenomenologically interesting theories
- Neutron star binaries

Nonlinear dynamics of binary black hole mergers in Einstein-scalar-Gauss-Bonnet gravity

Comparison dephasing to PN theory (Sennet+2016,Lyu+2022)



Merger dynamics in EsGB (MC,Ripley,East 2022)



Comparison dephasing to PN theory (Sennet+2016,Lyu+2022)