

PASCOS 2026

25.06.2026

# Testing modified gravity with GW lensing

---

**Serena Giardino**  
**Imperial College London**  
In collaboration with  
Nicola Menadeo, Miguel Zumalacárregui

**IMPERIAL**   
Abdus Salam Centre for Theoretical Physics

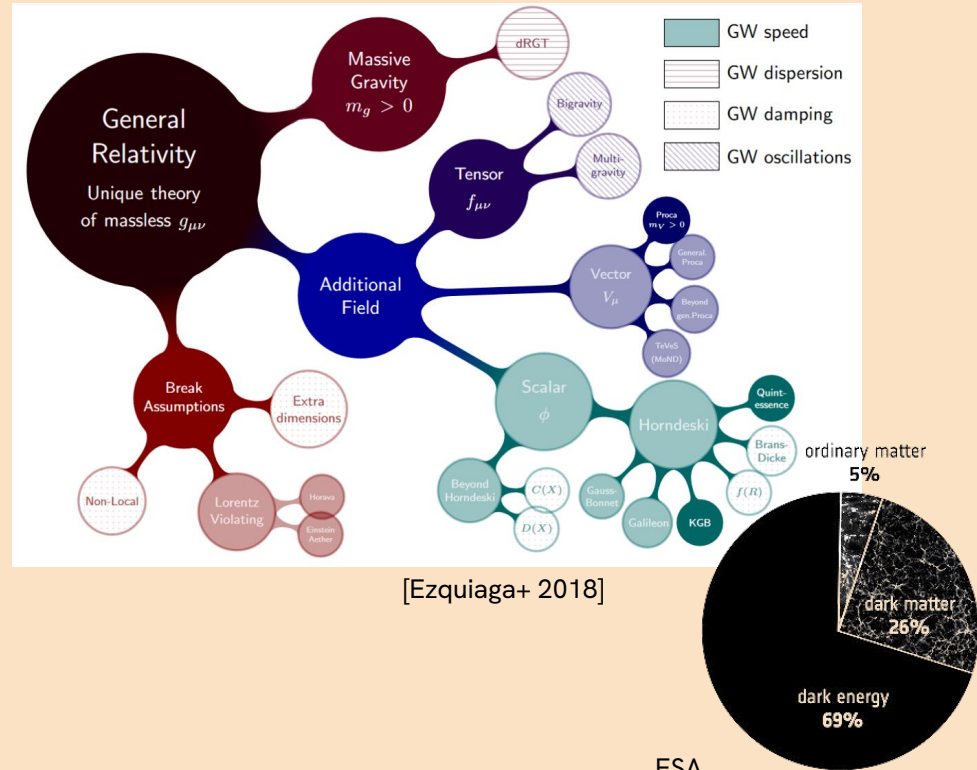


# Overture:

## Modified gravity and GW lensing

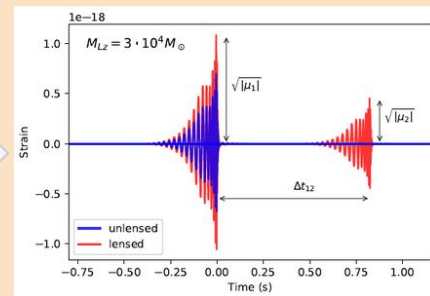
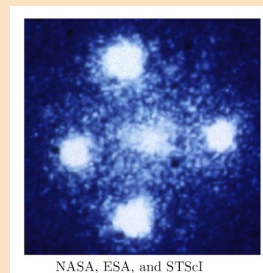
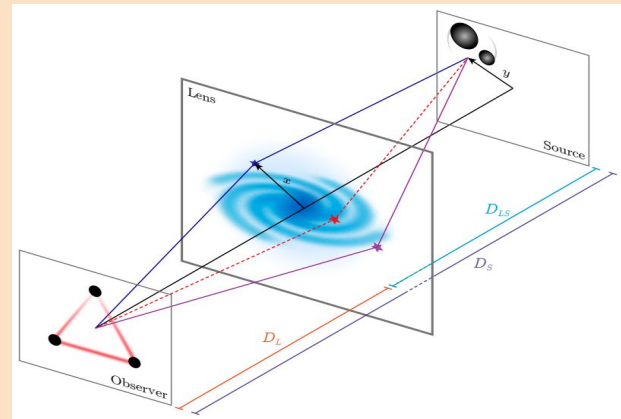
# Why even modify gravity?

- $\Lambda$ CDM successful, but
  - **Dark energy:**  $\Lambda$  fine-tuned  $\rightarrow$  dynamical DE? [DESI 25] - GR pushed to its limits
  - Dark matter
- **Knowledge of the dark sector is only as good as knowledge of gravity!**
- **Landscape** of gravity theories: GR + extensions
- Higher-order curvature terms, more degrees of freedom, breaking symmetries...
- All should respect basic principles (covariance, causality...) and observational constraints



# Gravitational wave lensing

- GW **inevitably lensed** during **cosmological propagation**
- Propagation is linear - small effects - large distances
- **Complementarity** of GWs & EM waves: GWs provide window at different frequencies, access to opaque regions, chance to study wave-optics effects
- **Wave-optics** regime relevant when  $\lambda_{GW} \sim R_S$
- GWs are **deflected & magnified**
- Strong lensing (by galaxies)  $\rightarrow$  **multiple images** (signals): precise timing, poor sky localization
- Main observables: **time delays** (Shapiro + geometric)
- First lensed GW discovery expected by LVK O5, routine with next-generation



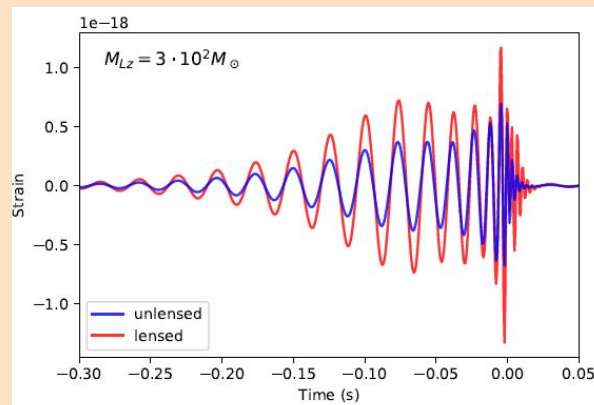
# GW lensing for fundamental physics

- **Lens properties leave distinctive signature:** small lens  $\rightarrow$  diffraction (microlensing)

- Amplification factor encodes lensing effect

$$F(f) \equiv \frac{\tilde{h}(f)}{\tilde{h}_0(f)} \quad \begin{array}{l} \text{lensed} \\ \text{unlensed} \end{array}$$

- Lensing can be **tested on any GW signal**
- Consequences for **fundamental physics and cosmology**
  - Magnify distant astrophysical sources (e.g. AGN binaries, SMBH binaries [Wang+ 2025])
  - Explore **dark matter** (sub-)structure (sub-halos) [Vujeva+ 2025]
  - Constrain **modified gravity** (as **dark energy** alternative)
- Not accounting for lensing  $\rightarrow$  **bias** in source parameter estimation!



Credit: Miguel Zumalacarregui

# GW constraints on modified gravity

- **GW170817** had tremendous impact
  - GW **speed** ruled out whole classes [Ezquiaga+ 2017, Baker+ 2017]
  - GW **dispersion** constrained Lorentz violation and massive gravity  $m_g < 7.7 \cdot 10^{-23} \text{ eV}$
  - GW **damping** constrained models with extra dimensions
- **Caveat:** LIGO frequencies very close to strong coupling scale of Horndeski, new terms could affect speed [de Rham+ 2018]
- Cosmological applications: i.e. standard sirens [Abbott+ 2017]
- All this assumes homogeneous + isotropic universe!

$$S_H = \int d^4x \sqrt{-g} \sum_{i=2}^5 \mathcal{L}_i \quad [\text{Horndeski 1974}]$$

$$\mathcal{L}_2 = G_2(\phi, X),$$

$$\mathcal{L}_3 = -G_3(\phi, X) \square \phi,$$

$$\mathcal{L}_4 = G_4(\phi, X) R + G_{4X} [(\square \phi)^2 - (\nabla_\mu \nabla_\nu \phi)(\nabla^\mu \nabla^\nu \phi)],$$

$$\mathcal{L}_5 = G_5(\phi, X) G_{\mu\nu} (\nabla^\mu \nabla^\nu \phi) - \frac{1}{6} G_{5X} [(\square \phi)^3 - 3(\square \phi)(\nabla_\mu \nabla_\nu \phi)(\nabla^\mu \nabla^\nu \phi) + 2(\nabla^\mu \nabla_\alpha \phi)(\nabla^\alpha \nabla_\beta \phi)(\nabla^\beta \nabla_\mu \phi)].$$

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [46] Brans-Dicke/ $f(R)$ [47, 48] Kinetic Gravity Braiding [50]	quartic/quintic Galileons [13, 14] Fab Four [15] de Sitter Horndeski [49] $G_{\mu\nu} \phi^\mu \phi^\nu$ [51], $f(\phi)$ -Gauss-Bonnet [52]
beyond H.	Derivative Conformal [19] [17] Disformal Tuning [21] quadratic DHOST with $A_1 = 0$	quartic/quintic GLPV [18] quadratic DHOST [20] with $A_1 \neq 0$ cubic DHOST [23]
	Viable after GW170817	Non-viable after GW170817

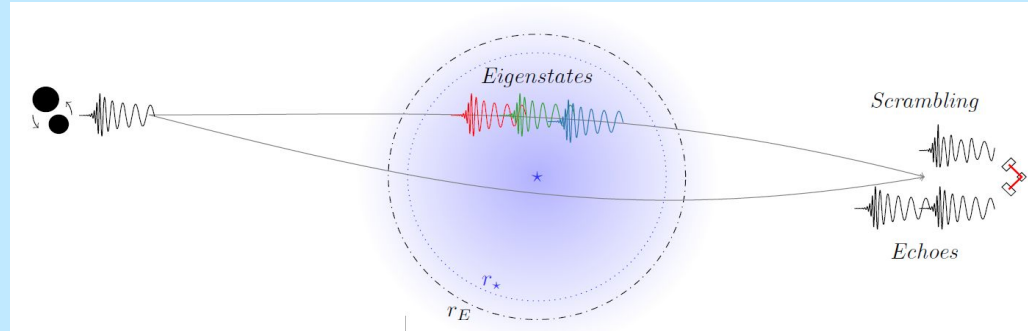


# Act I:

GW propagation beyond FLRW (and GR)

---

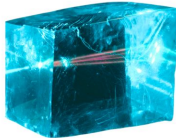
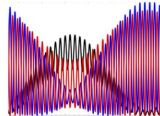
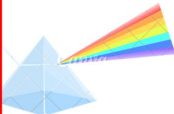
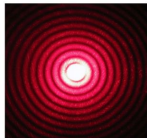
# GW propagation beyond FLRW



- Lenses break FLRW symmetries: SVT perturbations do not propagate independently
- **Different gravitational degrees of freedom can mix during propagation**
- Phenomenology includes [Ezquiaga & Zumalacarregui 2020]
  - birefringence
  - echoes (regime 1: delays larger than signal duration)
  - scrambling (regime 2: delays shorter than signal duration, interference)
  - “shadows” (induced non-propagating modes)
- Framework relies on short-wave (WKB) approximation and **geometric optics**

# GW propagation beyond GR (and geometric optics)

- Studying frequency-dependent effects requires **beyond geometric optics**
- Long-term goal: **full wave-optics** framework  $\lambda_{GW} \sim R_S$
- bGO corrections in GR [Cusin+ 2020, Dalang+ 2022]:
  - modifications to amplitude and phase
  - additional induced polarization mode (shadow, unclear interpretation)
- Lens-induced effects **discriminate between gravity theories** but **hard to disentangle** from lens/source properties
- Different interactions in Lagrangian produce different effects
- Dispersive and diffractive effects **generic** in any **beyond GR** theory

Modified GW lensing	Geometric optics		Wave optics
	$\mathcal{O}(f^2)$	$\mathcal{O}(f^0)$	Arbitrary $f$
Effect	speed	amplitude	phase
Observable	birefringence 	oscillations 	dispersion 
Interactions Tested	2 derivatives	1 derivatives	0 derivatives
			diffraction 
			all

$$\left[ \begin{pmatrix} \tilde{K}_{\mu\nu}^{\alpha\beta\gamma\rho} & 0 \\ 0 & \tilde{K}^{\gamma\rho} \end{pmatrix} \nabla_\gamma \nabla_\rho + \begin{pmatrix} \tilde{A}_{\mu\nu}^{\alpha\beta\gamma} & \tilde{A}_{\mu\nu}^\gamma \\ 0 & \tilde{A}^\gamma \end{pmatrix} \nabla_\gamma + \begin{pmatrix} \tilde{M}_{\mu\nu}^{\alpha\beta} & \tilde{M}_{\mu\nu}^h \\ \tilde{M}_\phi^{\alpha\beta} & \tilde{M} \end{pmatrix} \right] \begin{pmatrix} \tilde{h}_{\alpha\beta} \\ \delta\phi \end{pmatrix} = 0$$

Kinetic

Amplitude

Mass

Tensor+scalar wave propagation equation

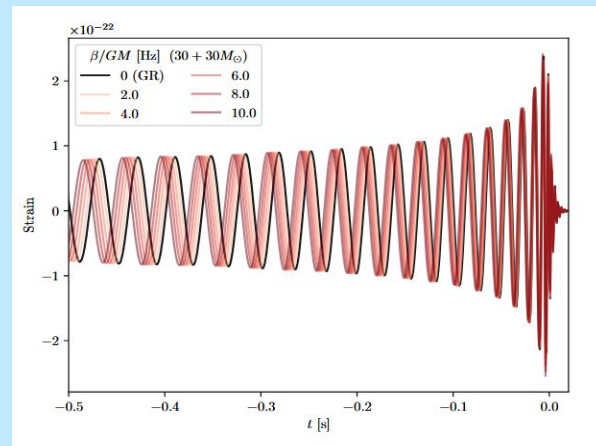
# Lens-induced dispersion

- Dispersive effects **generic beyond GR**, but weaker
- Dispersive correction to waveform  $\rightarrow$  **frequency-dependent phase shift**
- Similar to massive gravity (modified dispersion relation)
- For Brans-Dicke (fully luminal, point lens) [Menadeo+ 2024]
  - a. Breathing mode + dispersive correction
  - b. Apparent new polarization like in GR sourced by bGO corrections [Cusin+ 2020, Dalang+ 2022]
  - c. + and x receive novel frequency-dependent corrections - **clear signature**

$$e^{\frac{i\beta}{GMf}}$$

$$S_{\text{BD}} = \frac{1}{16\pi} \int d^4x \sqrt{-g} \left[ \phi R - \frac{\omega}{\phi} \nabla^c \phi \nabla_c \phi - V(\phi) \right] + S^{(m)}$$

$$E^2 - \mathbf{p}^2 = m_g^2.$$





# Act II:

Constraining gravity theories with GW  
lensing

---

# Screened scalar-tensor theories

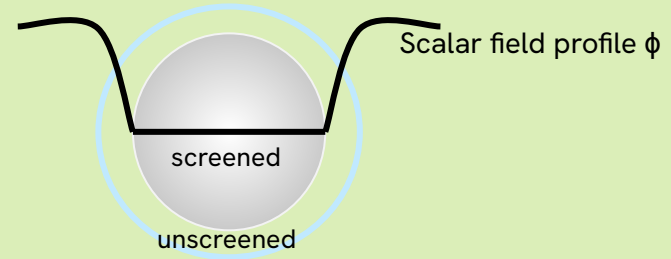
- No GR deviations in Solar System → **screening needed** for all viable theories
- Propagation in screened regions unexplored, scalar emission suppressed → we neglect scalar waves
- Mechanisms: chameleon (mass), **symmetron** (**coupling/symmetry**) [Hinterbichler+ 2010], Vainshtein (derivative self-interaction)
- Symmetry desirable: avoids fine-tuning
- **Thin-shell** screening - “broader” profile = more screening
- **Fully luminal** scalar-tensor theory (constraints + formalism limitations): canonical kinetic terms and conformal couplings
- Symmetrons not very constrained experimentally!

$$S = \int d^4x \sqrt{-g} \left[ \frac{M_{\text{Pl}}^2}{2} R - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right] + \int d^4x \sqrt{-\tilde{g}} \mathcal{L}_m(\psi, \tilde{g}_{\mu\nu})$$

Symmetry-breaking

Conformally coupled

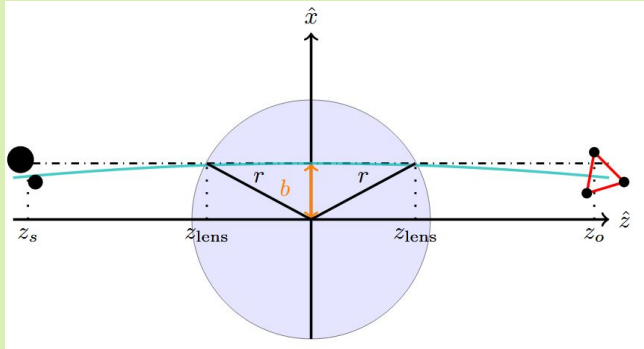
## Chameleon/symmetron screening mechanism



- **High density** region - symmetry unbroken - **screening** - GR effects (compact objects)
- **Low-density** region - symmetry broken - **no screening** - modified gravity effects

# Dispersion in screened theories

- **Extended lens** with uniform density, 3 regions
- Small  $M \rightarrow$  large  $A$ , large dispersion
- Non-trivial scalar field profile, matching required
- Lens-induced dispersion (LID) **significantly enhanced in symmetron** gravity for some lenses and params ( $\sim 7$  larger than for BD)



$$S = \int d^4x \sqrt{-g} \left[ \frac{M_{\text{Pl}}^2}{2} R - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right] + \int d^4x \sqrt{-\tilde{g}} \mathcal{L}_m(\psi, \tilde{g}_{\mu\nu})$$

Symmetry-breaking  $\uparrow$   
Conformally coupled

$$\tilde{g}_{\mu\nu} = A^2(\phi) g_{\mu\nu}$$

$$V(\phi) = -\frac{1}{2} \mu^2 \phi^2 + \frac{1}{4} \lambda \phi^4,$$

$$A(\phi) = 1 + \frac{\phi^2}{2M_s^2},$$

$$\phi_0 \equiv \mu / \sqrt{\lambda} \sim \frac{M_s^2}{M_{\text{Pl}}}.$$

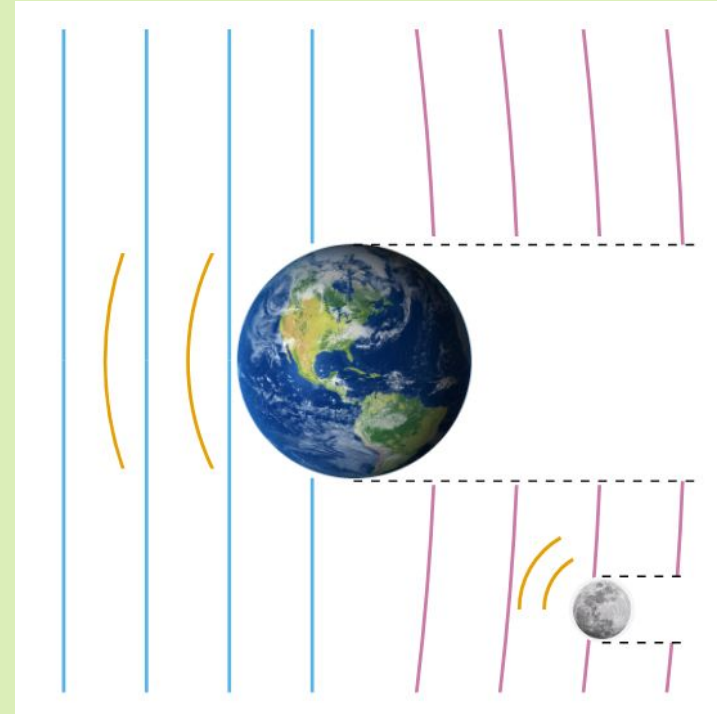
$$\frac{d^2}{dr^2} \phi + \frac{2}{r} \frac{d}{dr} \phi = V_{,\phi} + A_{,\phi} \rho$$

# Critical lens-induced dispersion frequency

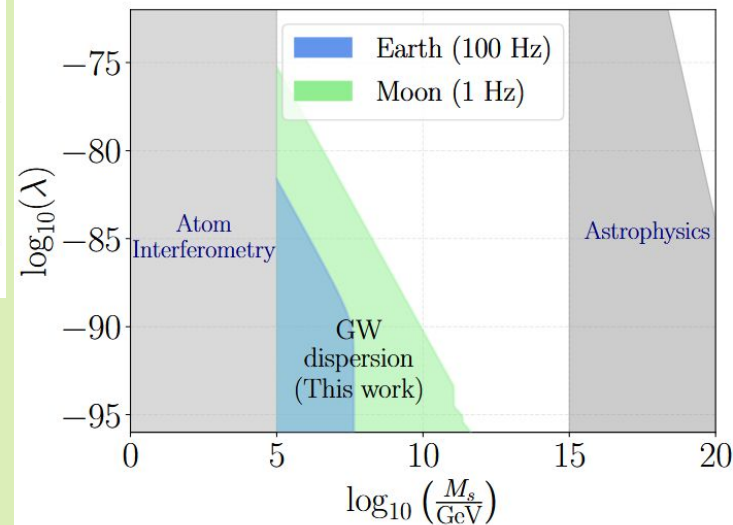
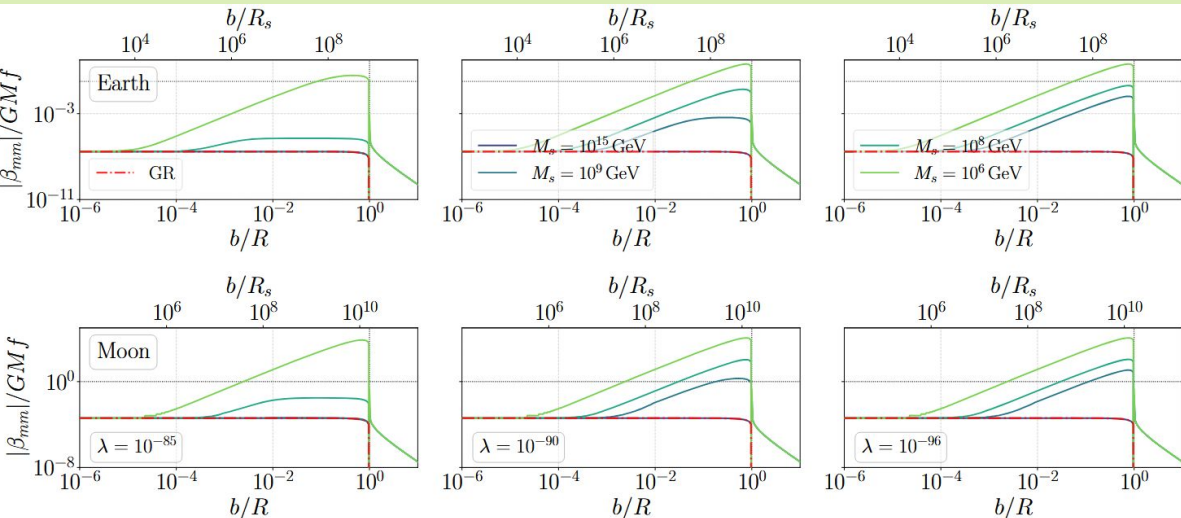
- Dispersion effects tiny for galaxies, clusters etc.
- Extreme consequences for Earth/Moon: **critical LID frequency** below which dispersion exponentially suppresses GW propagation
- Effective mass of  $h_+$ ,  $h_\times$  inside the lens  $\gg$  than signal frequency

$$f_c \approx \sqrt{\frac{\beta_0}{GM\Delta z}} \quad e^{\frac{i\beta}{GMf}}$$

- Analogous to **plasma frequency** for ionosphere
- **Competitive constraints** on symmetrons, precisely in the “desert”, using past GW events
- Caveats: basic assumptions in lensing formalism technically broken: thin lens, Born (deviations from flatness negligible) - 1D vs. 3D



# Constraints on symmetrons 2.0





# Finale:

## Summary & Outlook

---

## Summary

- **GWs inevitably lensed** in their propagation → not accounting for lensing leads to bias
- Developing framework for GW lensing beyond GR and **beyond geometric optics** (birefringence, dispersion, diffraction) → up to full wave-optics
- For simple (luminal) scalar-tensor theories, **frequency-dependent phase shift**
- Symmetron fields exhibit screening, whose effects on GW propagation neglected so far
- We find **enhanced dispersion in symmetron gravity** for near lenses (Earth/Moon) and critical LID frequency exponentially suppressing GWs
- This allows to **constrain symmetron gravity** in regime where unconstrained so far!
- GW lensing is promising avenue to constrain modified gravity, but plenty of more work needed

Thank you  
for listening!

---