New tests of gravity at large and small scales

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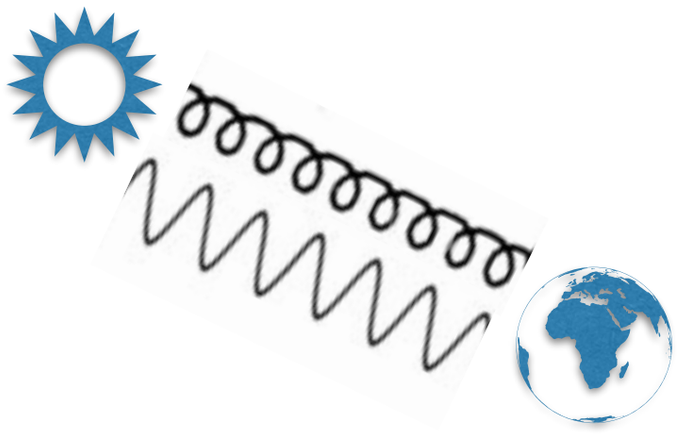
Measurement of GW's speed: GW170817 + GRB170817A



$$|c_T/c - 1| \leq 1 \cdot 10^{-15}$$

What does this imply for the phenomenology of generic extensions of GR?

New phenomenological tests at cosmological and local scales!

Virgo/Ligo collaborations, PRL19 no. 16 (2017)

The phenomenological impact of modified gravity

Effective Newton's G $G \rightarrow G_{\text{eff}}(t,k)$ (= 1 in GR)

Gravitational slip $\eta = \dfrac{G_{\text{eff}}^{(\text{light})}}{G_{\text{eff}}^{(\text{matter})}}$ (= 1 in GR)

Weak lensing $\Sigma = \dfrac{(1+\eta)G_{\text{eff}}}{2}$ (= 1 in GR)

Can be reconstructed in time and space from cosmological observations

Complementary information through reverse engineering

Gravitational waves $h_{ij}'' + (2 + \alpha_M)Hh_{ij}' + c_T^2 k^2 h_{ij} + a^2 \mu^2 h_{ij} = a^2 \Gamma \gamma_{ij}$

Modified friction — Modified speed — Massive interaction — Source term

Fifth force effects at stellar scales

Cosmological tests after GW170817

Viable Horndeski operators

Brans-Dicke K-essence Kinetic gravity braiding

$$\mathcal{L} = \frac{f(\phi)}{2}R + K(X,\phi)$$

$$\mathcal{L} = \frac{f(\phi)}{2}R + K(X,\phi) - G(X,\phi)\Box\phi$$

Einstein-Aether/Generalised Proca

slip	clustering*	lensing
$\eta \leq 1$	$G_{\rm eff} > 1$	$\Sigma \equiv \frac{(1+\eta)G_{\rm eff}}{2} = 1$
$\eta \leqslant 1$	$G_{\rm eff} > 1$	$\Sigma \equiv \frac{(1+\eta)G_{\rm eff}}{2} \neq 1$
$\eta = 1$	$G_{\rm eff} > 1$	$\Sigma \equiv \frac{(1+\eta)G_{\rm eff}}{2} = 1$

* **Possible exception:** Beyond Horndeski scalar-tensor theories (still viable!)

Consistency conditions

$\eta \leq 1$ & $\Sigma = 1$ Conformally coupled scalar field

$\eta > 1$ or $\Sigma \neq 1$ Presence of kinetic gravity braiding

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L. Amendola, M. Kunz, I.D.S, I. Sawicki, PRL 120 131101 (2018)
See also P. Creminelli, G. Tambalo, F. Vernizzi, V. Yingcharoenrat, arXiv:1910.14035 for further updated constraints.

A new prediction for stellar interiors

Post GW170817, scalar-tensor theories **beyond Horndeski** predict a fifth-force effect in **stellar interiors** through a partial breaking of the Vainshtein mechanism

$$\nabla^2\Phi = 4\pi G\rho + \boxed{G\frac{Y}{4}\nabla^2\left(\frac{dM}{dr}\right)}$$

Fifth-force effect
~ gradient of stellar density

Dimensionless fifth force coupling $Y > 0$ ($Y < 0$) weakens (enhances) gravity

Can we build precision tests for the fifth force strength at stellar scales?

M. Crisostomi & K. Koyama, PRD 97 (2018) no.2, 021301
J. Ben Achour, et al, JHEP 1612 (2016) 100

Probing fifth forces with helioseismology

Solar pulsations are predominantly acoustic (pressure) waves of period ~ few minutes

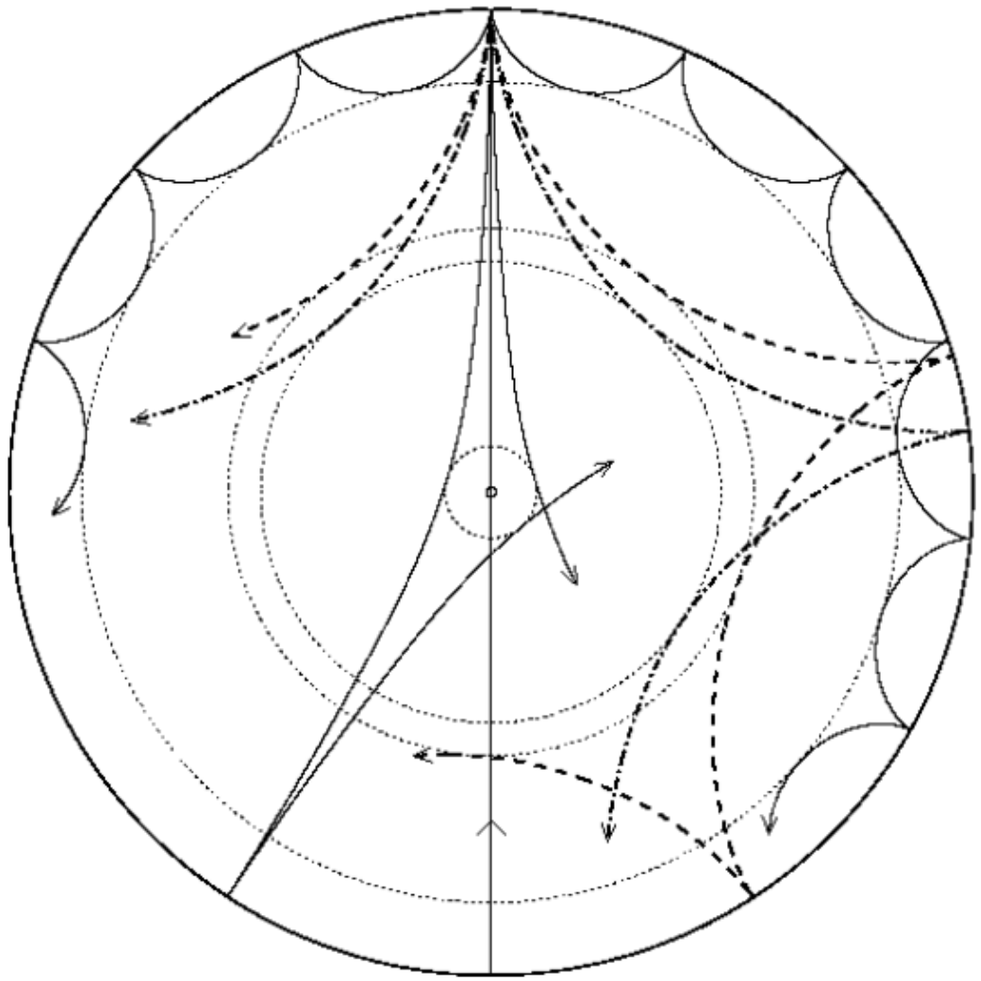
Frequencies of different degree probe distinct interior physics **from surface to the solar core**

$$\omega = \left(n + \frac{l}{2} + \frac{1}{4} + \alpha \right) \cdot \omega_0$$

Overtone — Degree — Surface reflection phase shift

$$\omega_0 \equiv \left(2 \int_0^{R_\odot} \frac{dr}{c_s} \right)^{-1}$$

Fundamental acoustic frequency

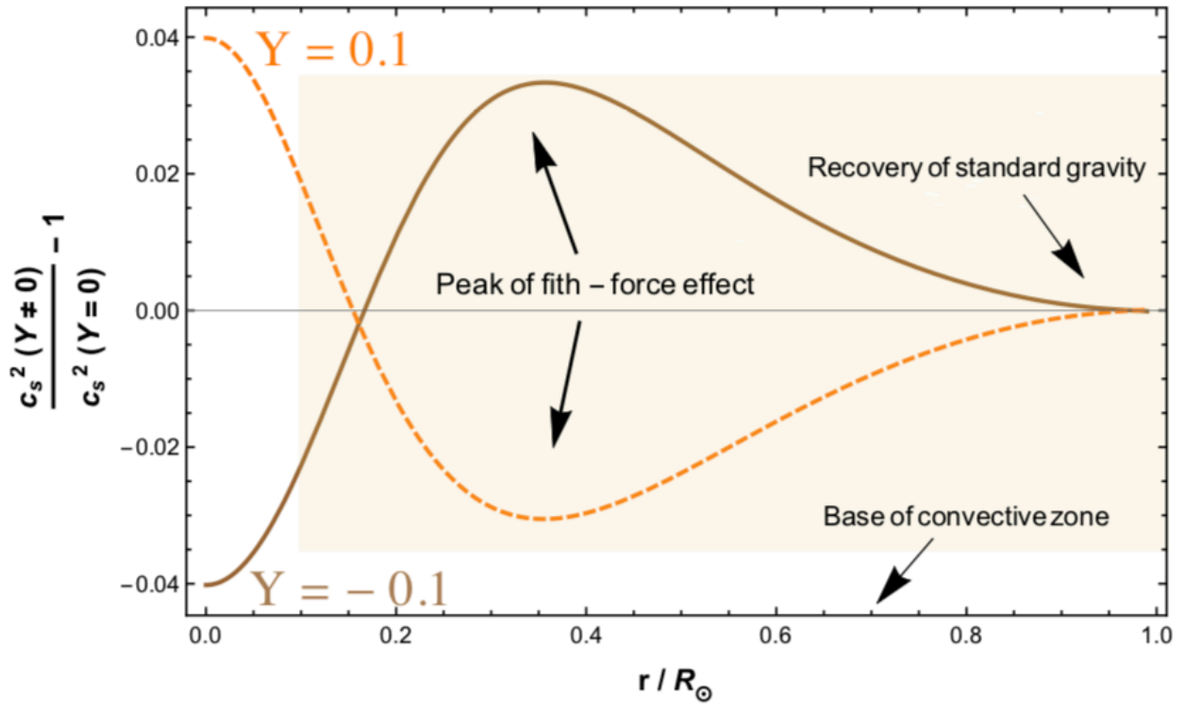


Thousands of acoustic modes observed at an extreme accuracy < 10^{-4}

A high precision test of fifth forces in stellar interiors

Picture from J. Christensen-Dalsgaard, arXiv: 0207403

The effect of the fifth force on the pulsation spectrum

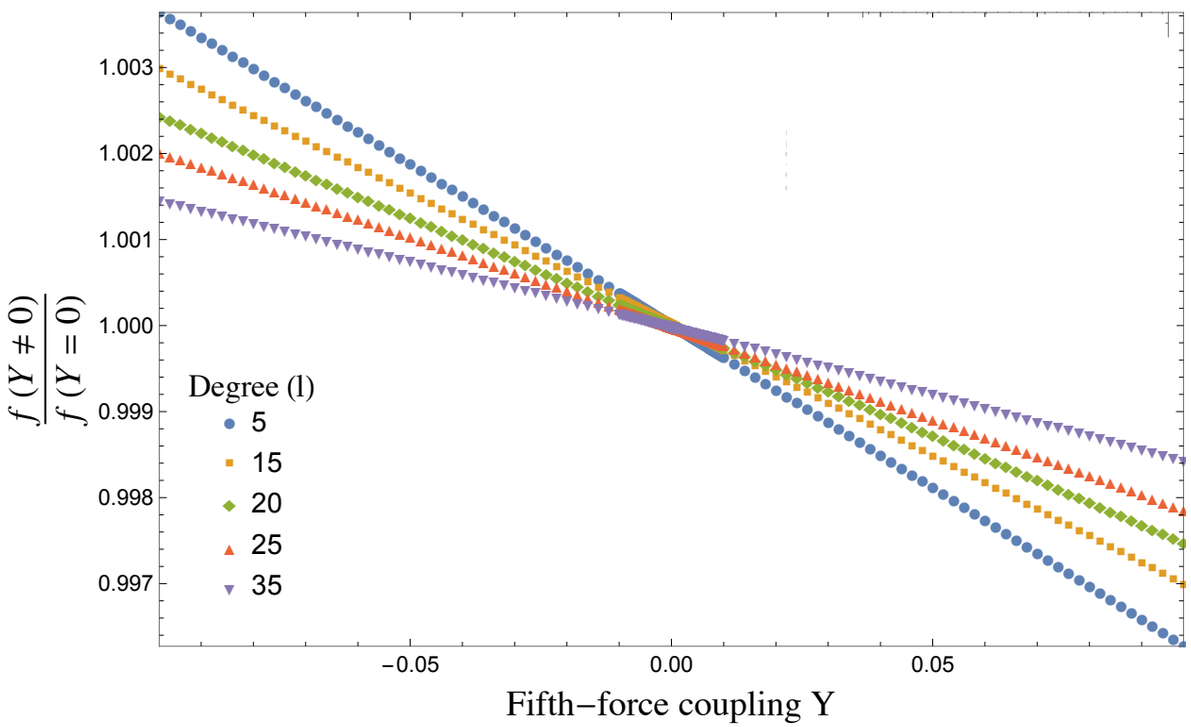


Fundamental mode $\omega_0 \equiv \left(2\int_0^{R_\odot} \frac{dr}{c_s}\right)^{-1}$

Effect of the fifth force on pulsation frequencies ~ 0.1 %

Promises stringent constraints on the fifth force at ~ 10^{-3} level

Confirmed through helioseismic simulations within the *Cowling approximation* and *neglecting solar evolutionary effects in modified gravity*



Weaker (stronger) gravity makes periods higher (smaller)

The strength of the effect is prolonged for low-degree modes

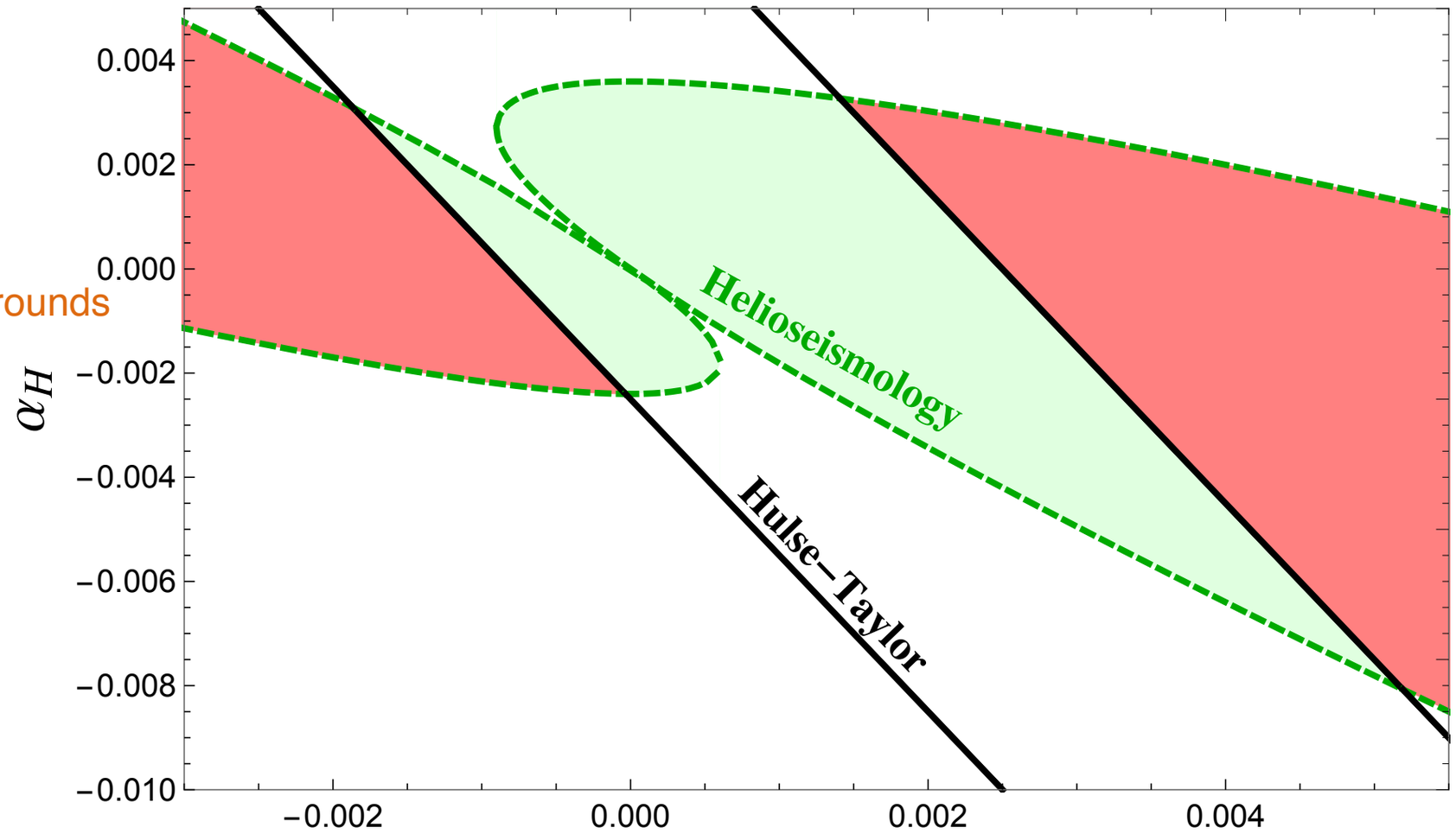
[***Simulations:*** *Pulsations assumed adiabatic and solved with d*ouble-shooting and a free-boundary surface condition. Calibrated reference solar model computed with “OPAL” opacities, “JINA REACLIB” nuclear reaction rates and a gray atmosphere.]

Role of systematics?
Going beyond the Cowling approximation?

I.D.S & I. Lopes PRL 123 (2019), 9 091103

Cosmological implications

Kinetic mixing between scalar and matter around cosmological backgrounds



Coupling strength of the higher-order operators around a cosmological backgrounded

$$Y = -\frac{(\alpha_H + \beta_1)^2}{\alpha_H + 2\beta_1}$$

$$-2.4 \cdot 10^{-3} \leq \alpha_H \leq 3.3 \cdot 10^{-3}$$

$$-1.9 \cdot 10^{-3} \leq \beta_1 \leq 5.2 \cdot 10^{-3}$$

Hulse-Taylor pulsar constraint from: A. Dima & F. Vernizzi, PRD 2018
See also P. Creminelli et al (2019) for recent stringent constraints on α_H arXiv:1910.14035

Final remarks

The measurement of the tensors' speed opened up exciting new phenomenological avenues at different scales

In cosmology, new consistency tests can reveal the nature of the coupling between the new fields (if any) and gravity

Important information can be extracted from stellar scales — Helioseismology can provide an exciting new window to the nature of gravity

Future & ongoing work: Solar evolution simulations and helioseismic inversions in modified gravity, prediction of solar acoustic spectrum beyond the Cowling approximation, … …

Thank you!