# Searching for dark energy with the Sun

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**Dark energy, Hubble tension:**
**Is GR modified at infrared scales?**

**New, precision cosmological and gravitational-wave surveys are under way.**

**Can we build new, precision tests of gravity and dark energy at stellar scales?**

# Extending General Relativity

New scalar-field interactions beyond GR

| | | |
|---|---|---|
| 1961 | Brans-Dicke | Newton's G promoted to a dynamical scalar |
| 1974 | Horndeski | Most general theory of a scalar field + metric, with second-order equations |
| 2016 | DHOST | Most general (higher-order) theory of a scalar field + metric without pathologies |

For reviews see: T. Clifton et al (2012) | D. Langlois et al (2017)

# Phenomenological imprints

Effective strength of gravity $G \cdot \rho_m \to G_{\rm eff}(t,k) \cdot \rho_m$

Gravitational slip $\eta \equiv \frac{G_{\rm eff}^{\rm (light)}}{G_{\rm eff}^{\rm (matter)}} \neq 1$

Weak lensing $\Sigma \equiv \frac{(1+\eta) G_{\rm eff}}{2} \neq 1$

↕ **Complementary information**

Gravitational wave propagation at any scale

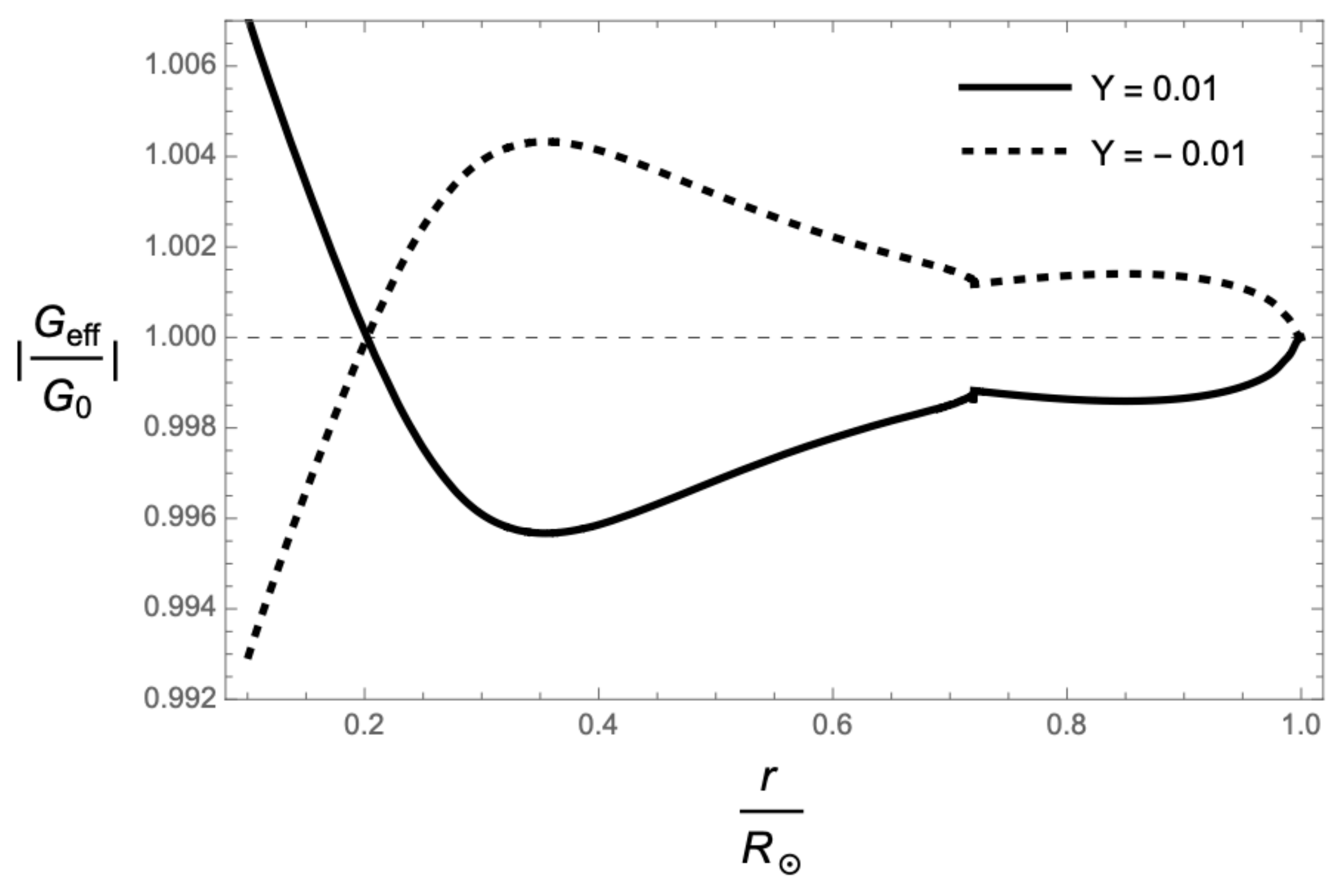
Fifth-force effects at local scales

# An intriguing prediction at local scales

The general scalar-tensor theories DHOST predict a new force inside matter sources:

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

Modified hydrostatic equilibrium: $$\frac{\mathrm{d}P(r)}{\mathrm{d}r} = -\rho(r)\frac{G_{\rm eff}(r)m(r)}{r^2}$$




$$G_{\rm eff} \equiv \left(1 + \frac{\mathcal{Y}}{4}r^2\frac{m''(r)}{m(r)}\right)G_0$$

**Y > 0 (Y< 0)** weakens (enhances) gravity

M. Crisostomi & K. Koyama (2018) I J. Ben Achour, et al (2016)

# Astrophysical probes

White dwarfs e.g. Jain (2016), Babichev et al (2016), Saltas et al (2018)

Red dwarfs e.g. Sakstein (2015)

Hulse-Taylor pulsar e.g. Dima & Vernizzi (2018)

Relativistic compact objects e.g. Babichev et al (2016)

Gravitational waves e.g. Creminelli et al (2018)

Solar system e.g. Crisostomi et al (2019)

Galaxy clusters e.g. Sakstein et al (2019), Pizzuti et al (2021)

Pre-main sequence stars Aguiar Gomes et al (2022)

Current stellar-scale constraints ~ O(0.1)

# Probing the theory with the Sun

The Sun offers a powerful laboratory for fundamental physics

Neutrino physics

Nuclear interactions

Dark matter

Axions

Primordial black holes

## Speed of sound in the solar interior

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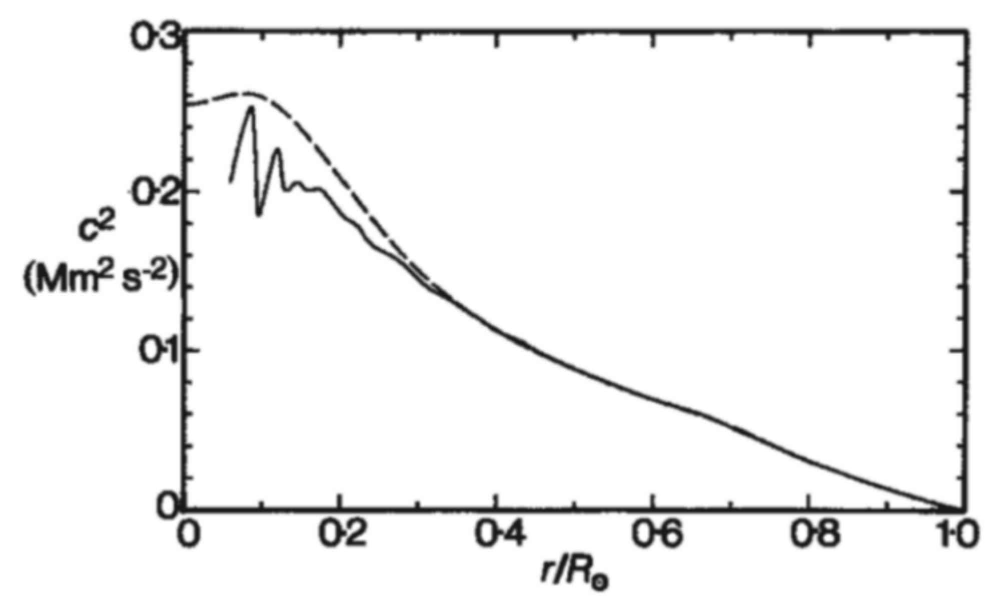
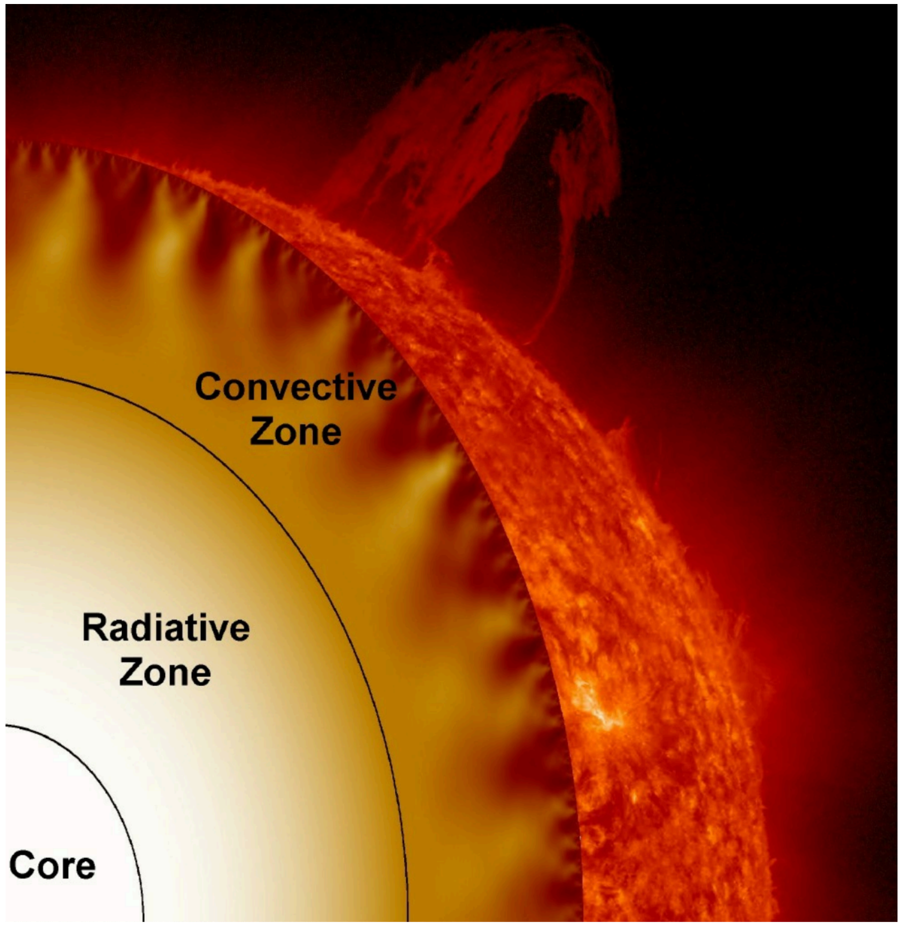
*Frequencies of solar 5-min oscillations can be used to determine directly the sound speed of the solar interior. The determination described here does not depend on a solar model, but relies only on a simple asymptotic description of the oscillations in terms of trapped acoustic waves.*




[Nature 315, 378–382 (1985)]

Helioseismic reconstructions of the solar sound speed profile offer a diagnostic observable of high precision

# The present Sun




$G \cdot M_\odot$ (from planetary motion)

Radius $\pm 0.01\ \%$ (from angular diameter distance)

Surface chemical composition $\pm 0.1\ \%$ (from spectroscopy + meteorites)

Effective temperature $\pm 1\ \%$ (from bolometric measurements )

Age $\pm 0.1\ \%$ (from radioactive dating of meteorites)

Base of the convective zone $\pm 1\ \%$ (from helioseismology)

Interior profiles as functions of radius (from helioseismology)

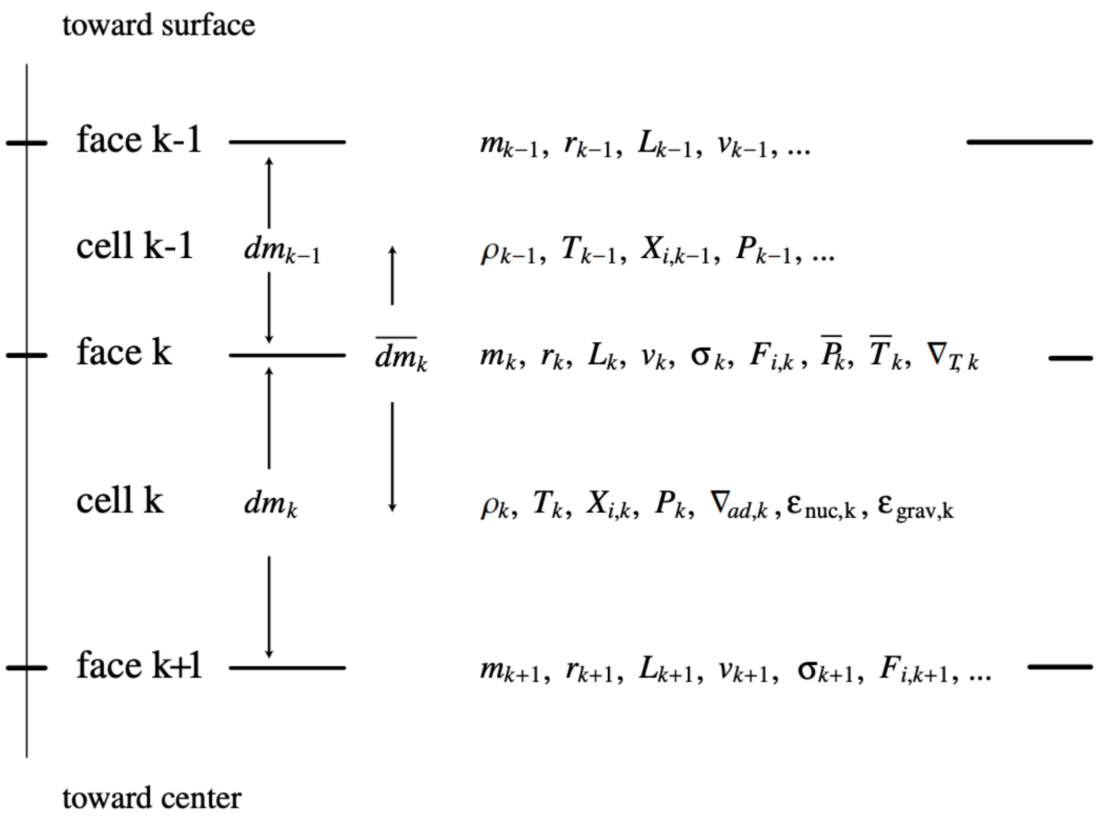
| Core | Radiative zone | Convective zone |
|---|---|---|
| Nuclear physics<br>Neutrinos<br>Relativistic effects | Radiative heat transfer<br>Opacity modelling is important<br>Most well understood solar region | Convective heat transfer<br>Convection modelling: **Mixing length theory** introducing 1 free parameter |

# Simulating a standard solar model

**Modules for Experiments in Stellar Astrophysics**

https://docs.mesastar.org

Solve the coupled stellar evolution equations on 1-D grid
subject to initial and boundary conditions in the presence of the fifth force.




Picture from: Paxton & Bildsten (2010), arXiv:1009.1622v1

$$\frac{\mathrm{d}p}{\mathrm{d}r} = -\frac{Gm\rho}{r^2}$$ hydrostatic equilibrium

$$\frac{\mathrm{d}m}{\mathrm{d}r} = 4\pi r^2 \rho\,.$$ mass conservation

$$\frac{\mathrm{d}T}{\mathrm{d}r} = \nabla \frac{T}{p}\frac{\mathrm{d}p}{\mathrm{d}r}$$ temperature gradient

$$\frac{\mathrm{d}L}{\mathrm{d}r} = 4\pi r^2 \left[\rho\epsilon - \rho\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{e}{\rho}\right) + \frac{p}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}t}\right]$$ energy equation

$$\frac{\partial X_i}{\partial t} = \mathcal{R}_i + \frac{1}{r^2\rho}\frac{\partial}{\partial r}\left[r^2\rho\left(D_i\frac{\partial X_i}{\partial r} + V_i X_i\right)\right]$$ element abundance

# Standard solar model in the presence of fifth force

| Equilibrium observables | Input physics | Initial conditions |
|---|---|---|
| Radius $\pm 0.01\ \%$ | Opacity $\pm 5\ \%\ (average)$ | Initial Helium abundance |
| Surface chemical composition $\pm 0.1\ \%$ | Diffusion $\pm 15\ \%$ | Initial metallicity |
| Effective temperature $\pm 1\ \%$ | Equation of state | Mixing length parameter (convection efficiency) |
| | Metallicity mixture | |
| | + more … | |

**Fix initial conditions at pre-main sequence and evolve models to present solar age**

→

**Produce *calibrated* models matching solar radius, surface abundance effective temperature**

↓

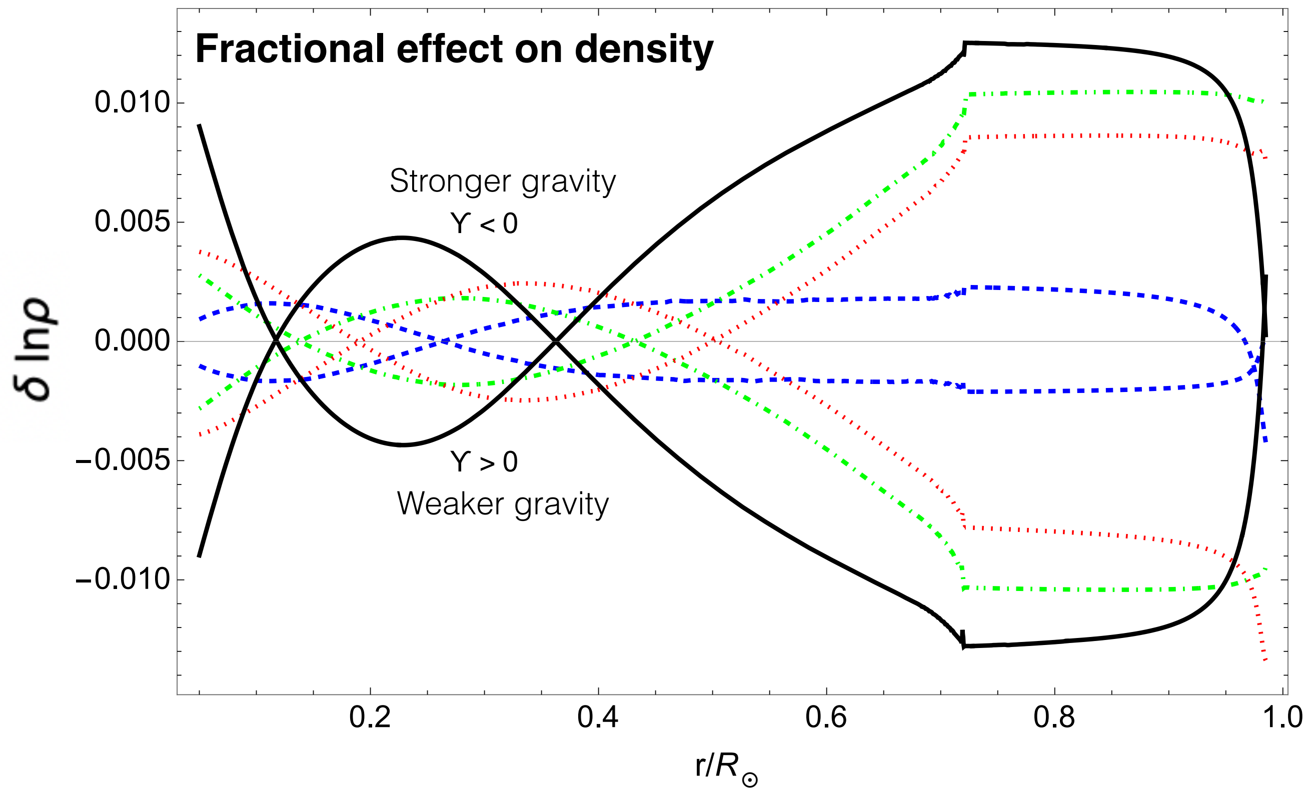
**Check systematics related to modelling of input physics**

←

**Study the effect of new physics on solar interior profiles**

# Fifth force effect on solar acoustic medium

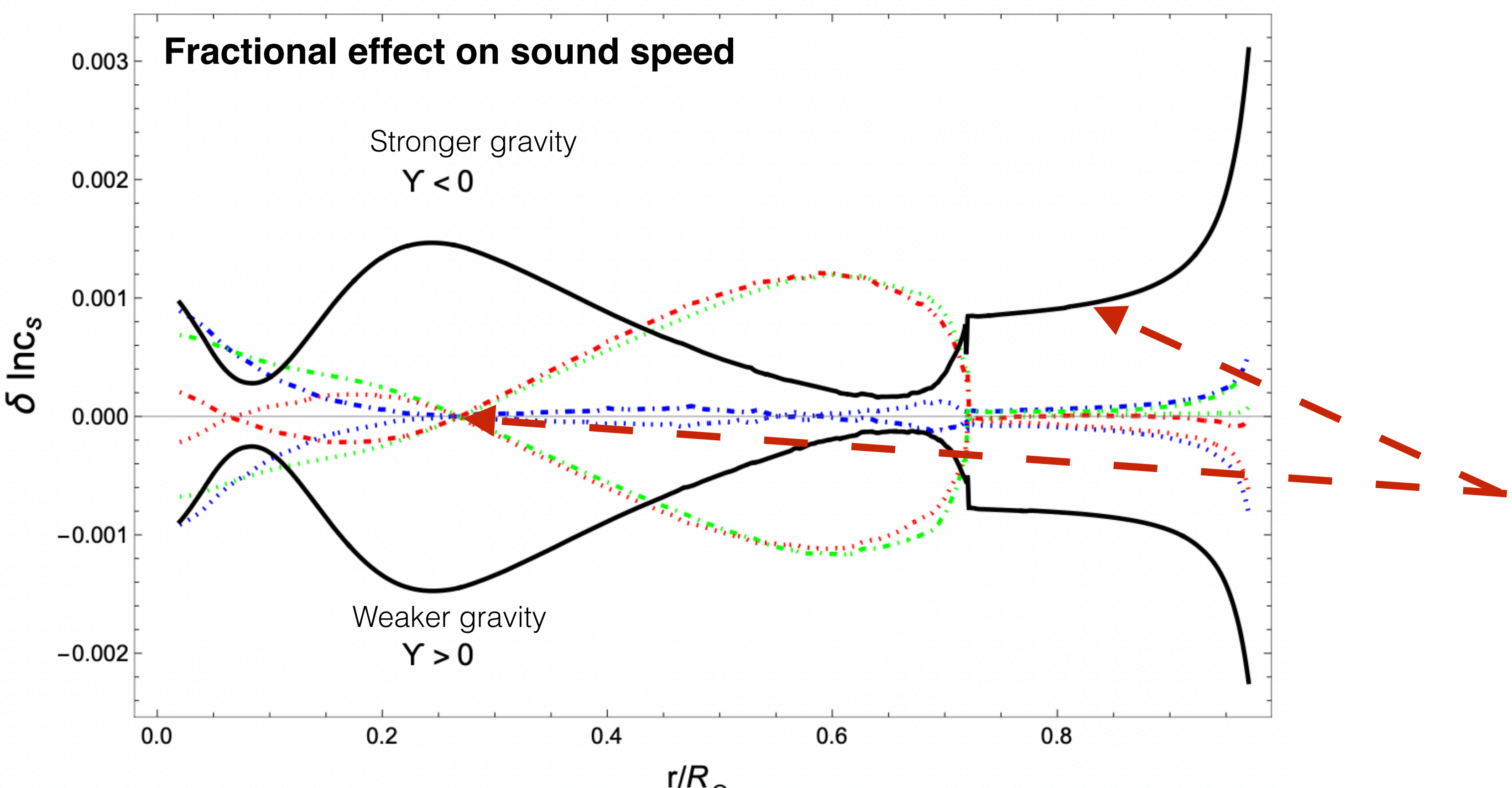
## (reference model) - (modified model)




- - - Opacity ±5%
-·-· Diffusion ±15%
······ Opacity ±5%, Diffusion ∓15%

**Systematics**

—— $\Upsilon = \pm 10^{-2}$ **Fifth force**




Fifth force wins against systematics

# Fifth-force effect on solar sound speed

**Peak of fifth force in the radiative zone:** Scaling of temperature and mean molecular weight force the systematics to a minimum, while amplifying the fifth force effect

A semi-analytic insight, assuming the ideal gas approximation:

$$p \simeq \frac{k_B \rho T}{\mu m_u}$$

pressure

$$\mu = \frac{4}{3 + 5X - Z}$$

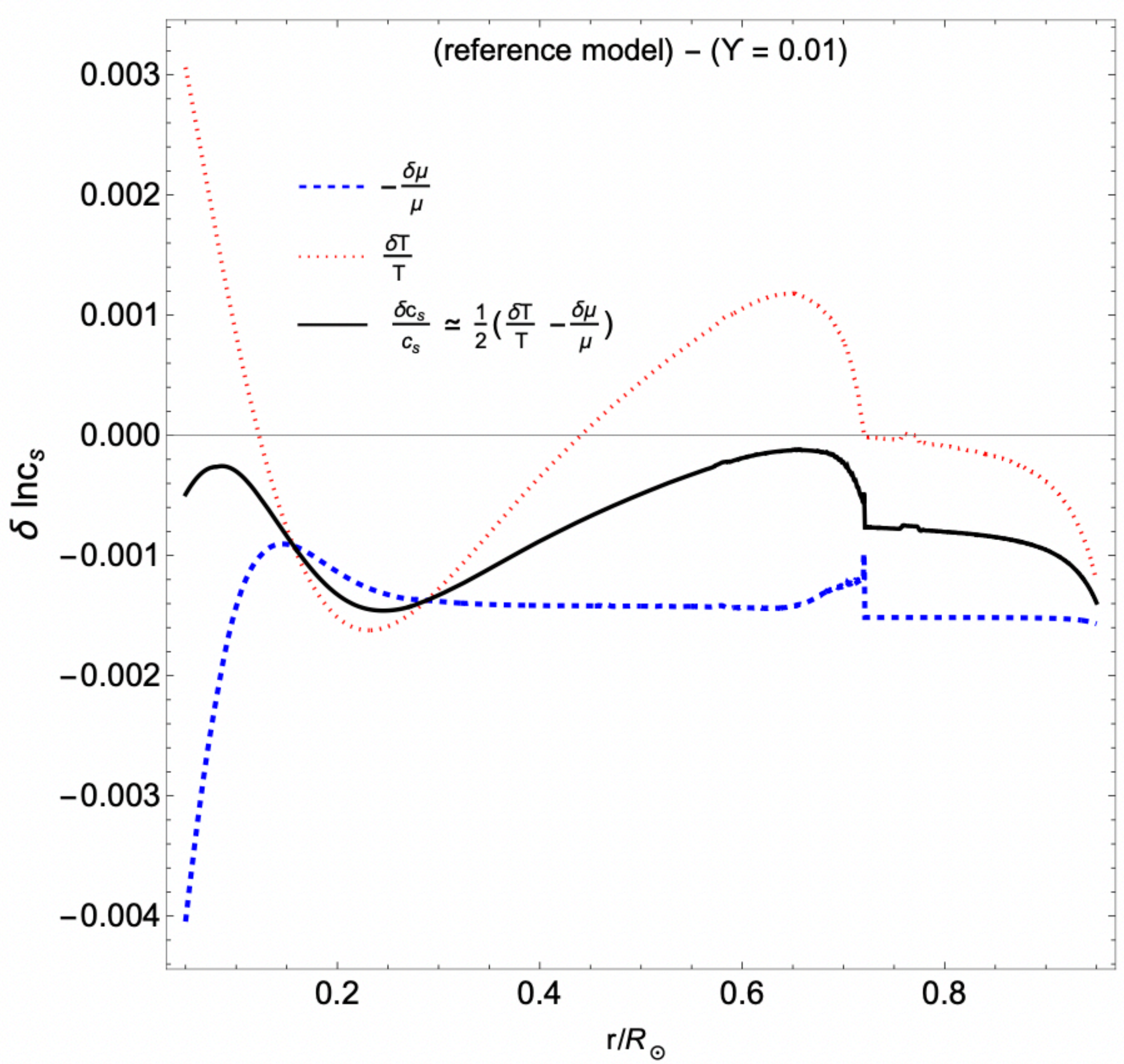
mean molecular weight

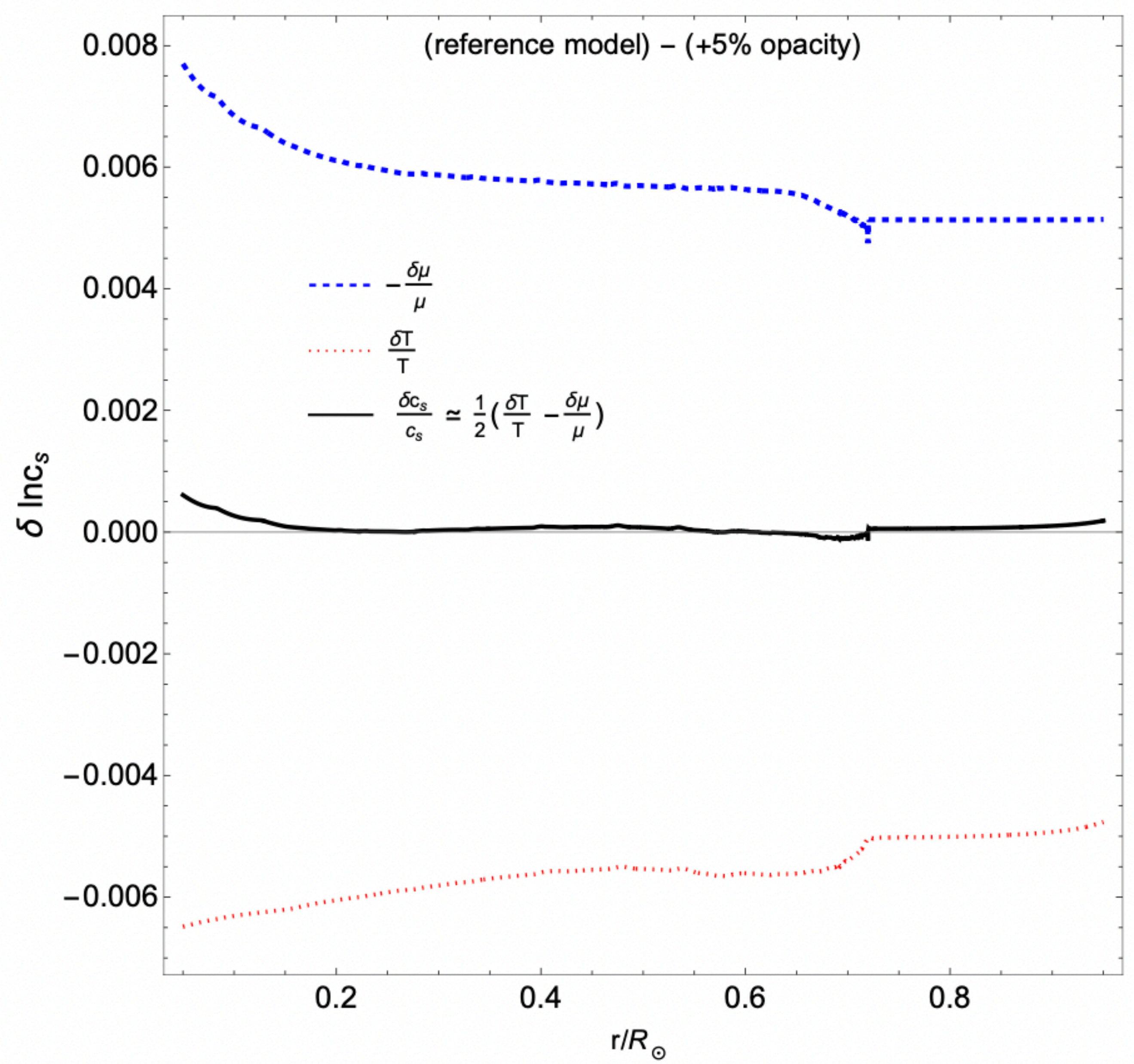
$$c_S^2 \propto \frac{\Gamma_1 \cdot T}{\mu}$$

sound speed

$$\Gamma_1 \simeq 5/3$$

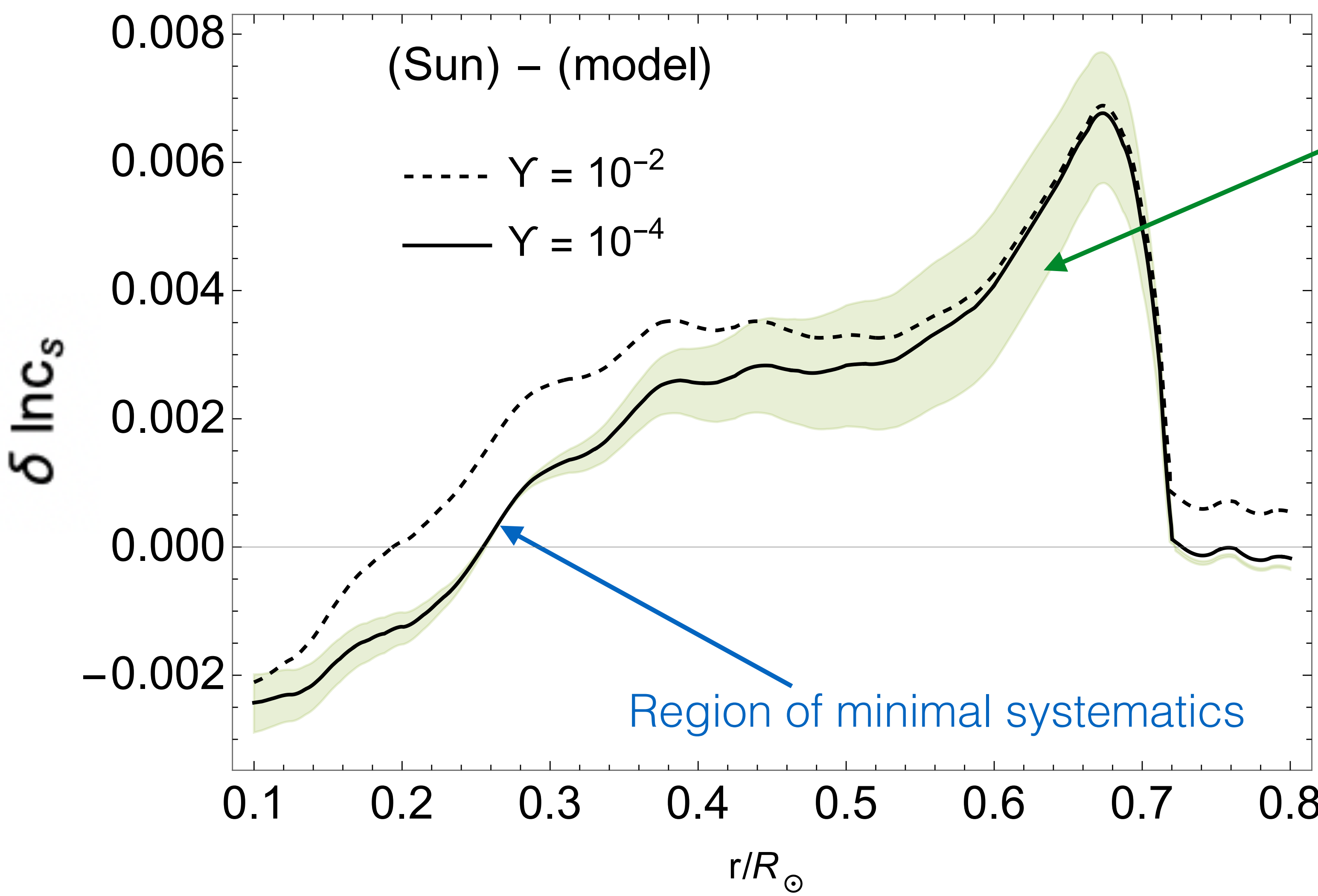
adiabatic index



# Fifth-force effect on solar sound speed

Predicted sound speed against helioseismic data for *calibrated* models.




Shading: Uncertainty from opacity and diffusion

Fifth force coupling relates to coupling functions governing cosmological dynamics

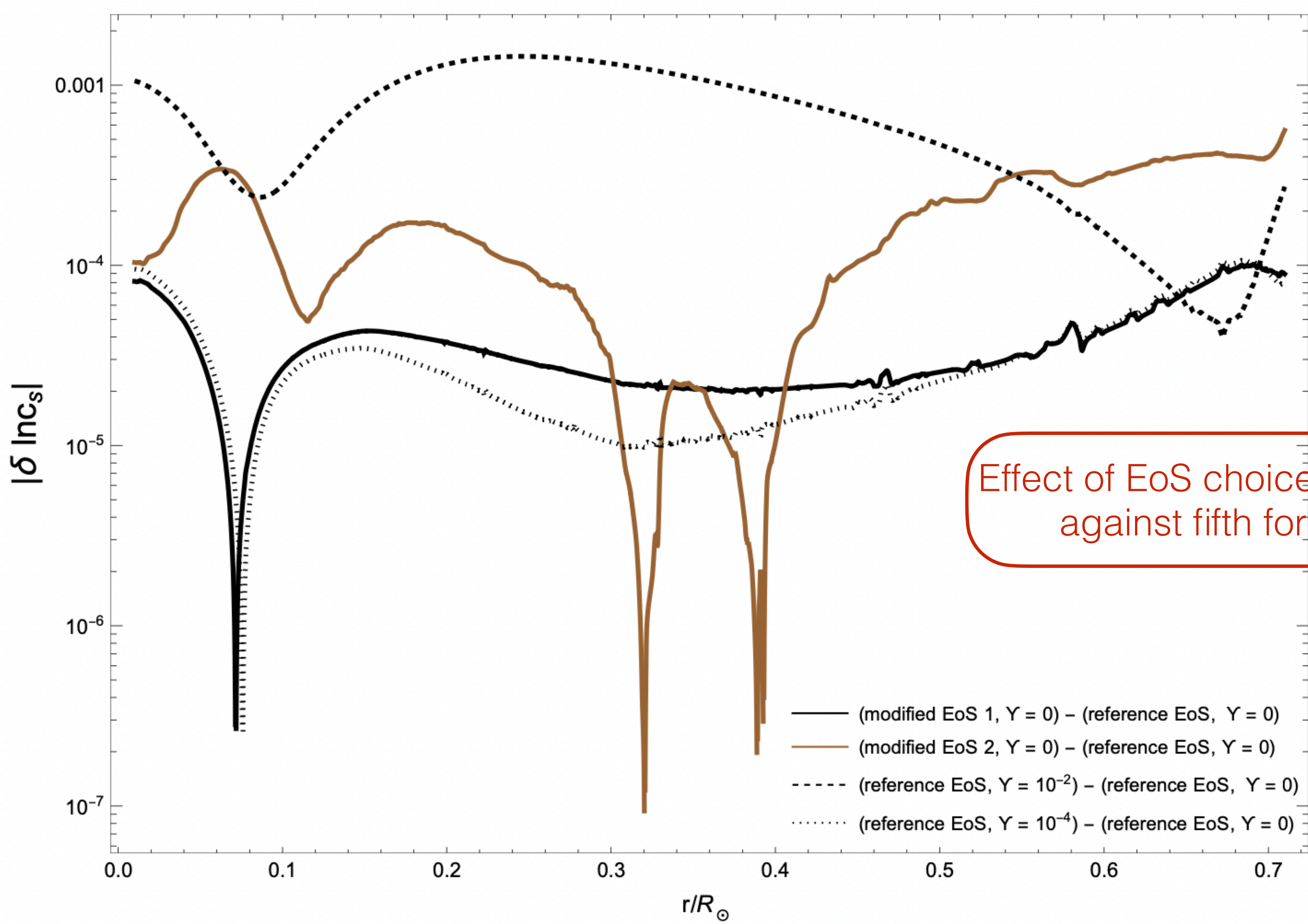
$$\mathcal{Y} = \frac{(\alpha_{\rm H} + \beta_1)^2}{\alpha_{\rm H} + 2\beta_1}$$

A new constraint on the fifth force coupling: $-10^{-3} \lesssim \mathcal{Y} \lesssim 5 \cdot 10^{-4}$

~ 3 orders of magnitude improvement of previous constraints

# Significance of the E.o.S choice

Could we be biased due to our choice of solar E.o.S ?




Effect of EoS choice at standard gravity against fifth force at fixed EoS

For sufficiently weak fifth force couplings, the choice of EoS can play a role.

# This is not the end!

A Monte-Carlo simulation over large sample of solar models to scan the full space of solar input physics + fifth force

Independent constraints on the fifth force from its effect on the solar convective zone

Helioseismic inversions provide an elegant diagnostic of the solar interior: Development of the machinery of helioseismic inversions for the reconstruction of solar interior profiles in the presence of the fifth force

# Summary

The Sun offers an exciting and precision laboratory
for gravity and dark energy

New constraints can significantly improve
our understanding of dark energy at
cosmological scales

Future analysis of solar oscillation frequencies
can provide further and more accurate constraints on dark
energy theories