

Hearing the strength of gravity (with the Sun)

Ippocratis Saltas
Czech Academy of Sciences, Prague

Based on:

I.D.S and I. Lopes, PRL 123 (2019), 9 091103 [arXiv:1909.02552]

I.D.S, I. Sawicki and I. Lopes, JCAP 1805 (2018) 028 [arXiv:1803.00541]



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MINISTRY OF EDUCATION,
YOUTH AND SPORTS

Our Universe is accelerating

One of the most puzzling issues of modern physics,
with no convincing solution yet.

Cosmological observations

A wealth of current and future surveys aims
at finding out: Euclid, SKA, ...

Local-scales tests

Can we build new and precision tests of gravity
at stellar scales?

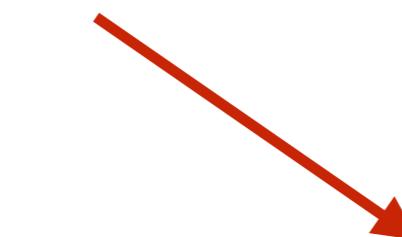
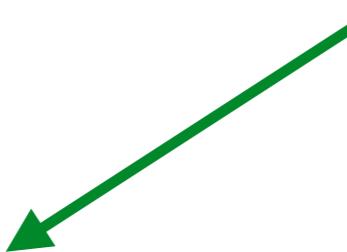
Our best (?) theory so far

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}^{\text{matter}}$$

But what is Λ ?

$$\Lambda = \Lambda_0 + \Lambda_{\text{matter}} \sim (\text{meV})^4$$

Bare piece
(free to tune)



Quantum contributions
from matter fields

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



Why cosmological probes are challenging

Geometry probes the **total** energy-momentum content in the Universe

$$G_{\mu\nu} = 8\pi G \boxed{T_{\mu\nu}^{\text{total}}} \quad \begin{array}{l} \xrightarrow{\hspace{1cm}} \text{Dark energy} \\ \xrightarrow{\hspace{1cm}} \text{Dark matter} \end{array}$$

Similarity with measurements of stellar mass:

$$\boxed{G \cdot M}$$

Phenomenological imprints

Effective strength of gravity

$$G \cdot \rho_m \rightarrow G_{\text{eff}}(t, k) \cdot \rho_m$$

Gravitational slip

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

Weak lensing

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



Complementary information

Gravitational wave propagation at any scale

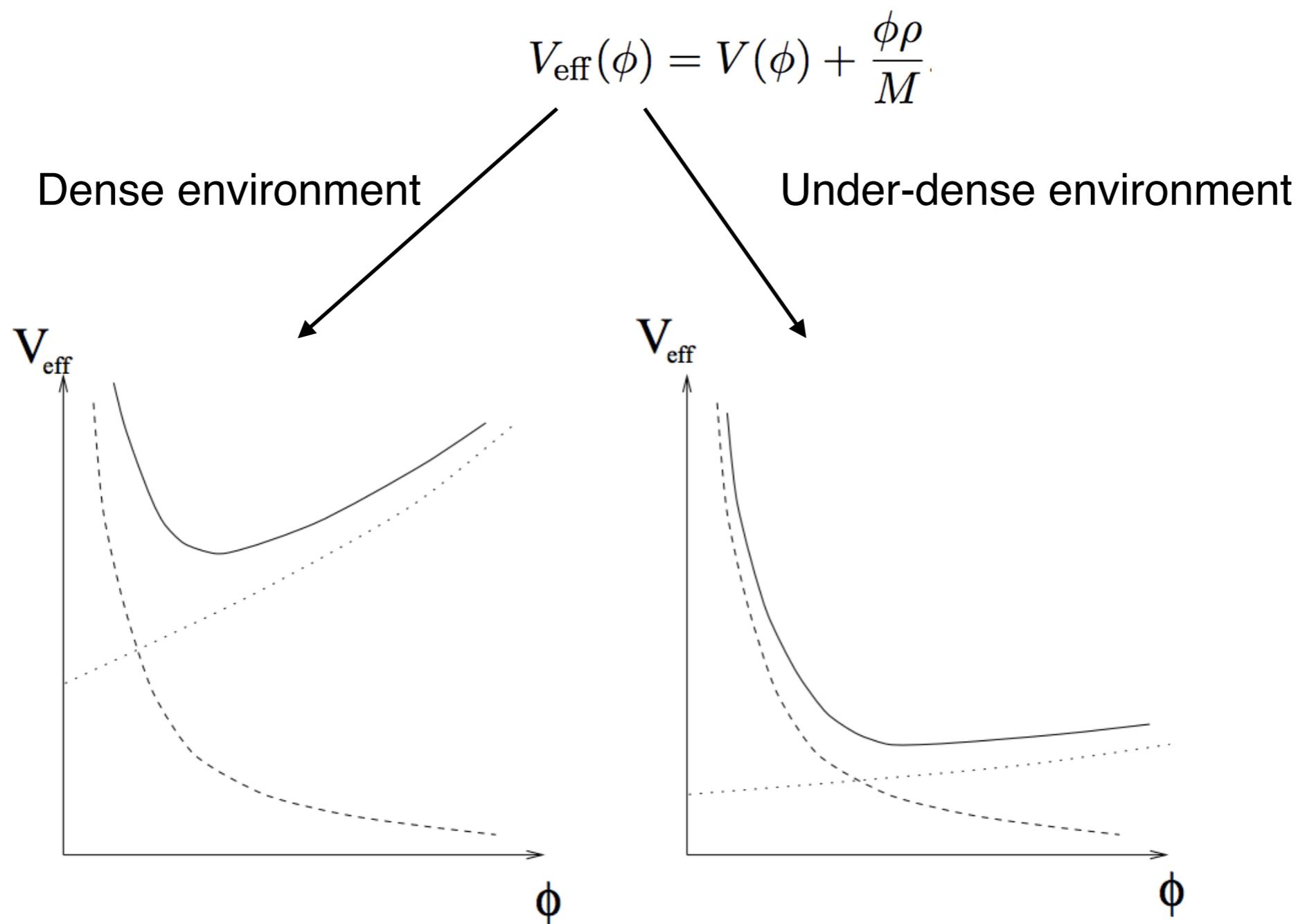
Fifth-force effects at local scales

New gravitational forces

New fields need to operate at cosmological scales, but “hide” at local scales

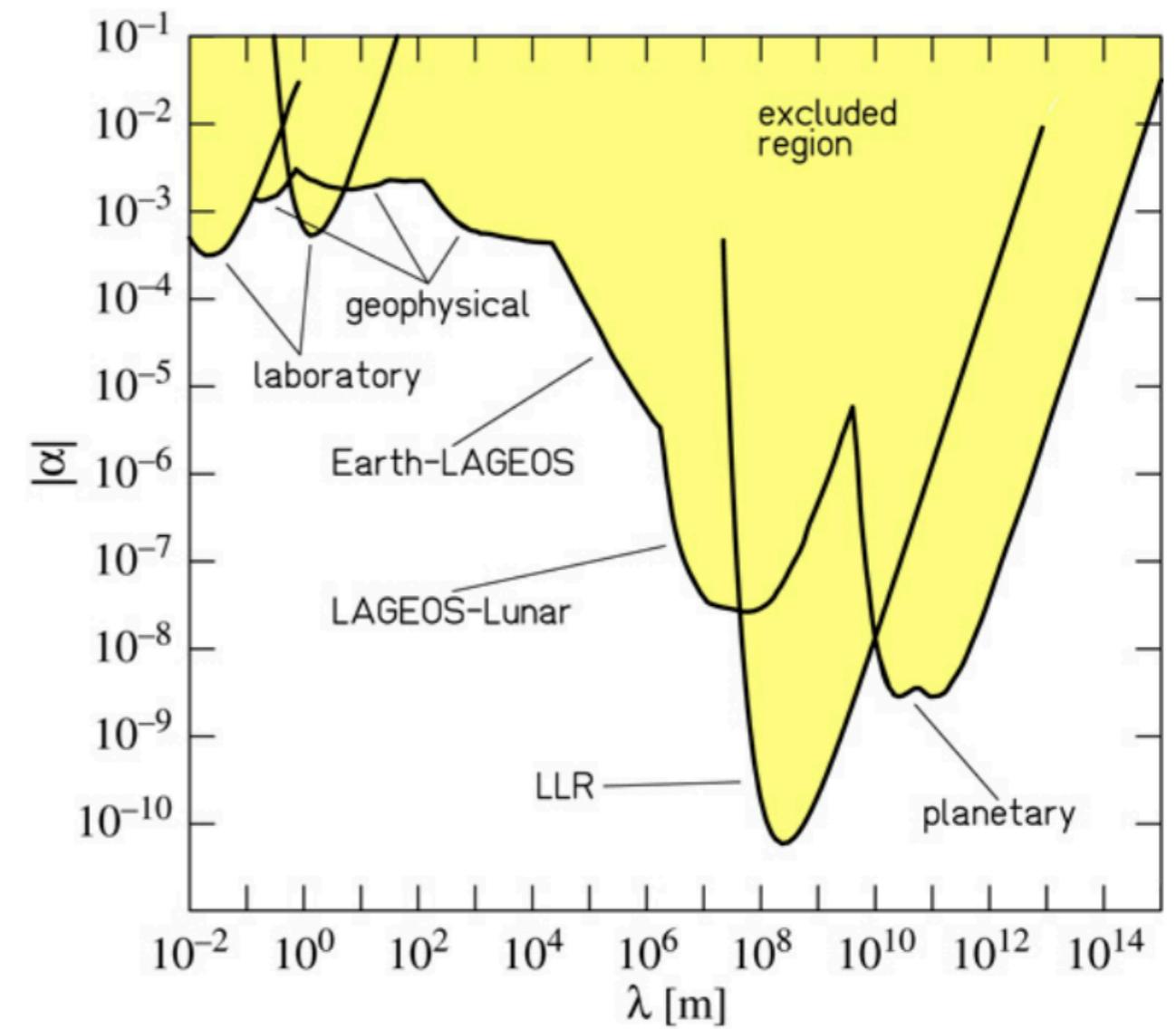
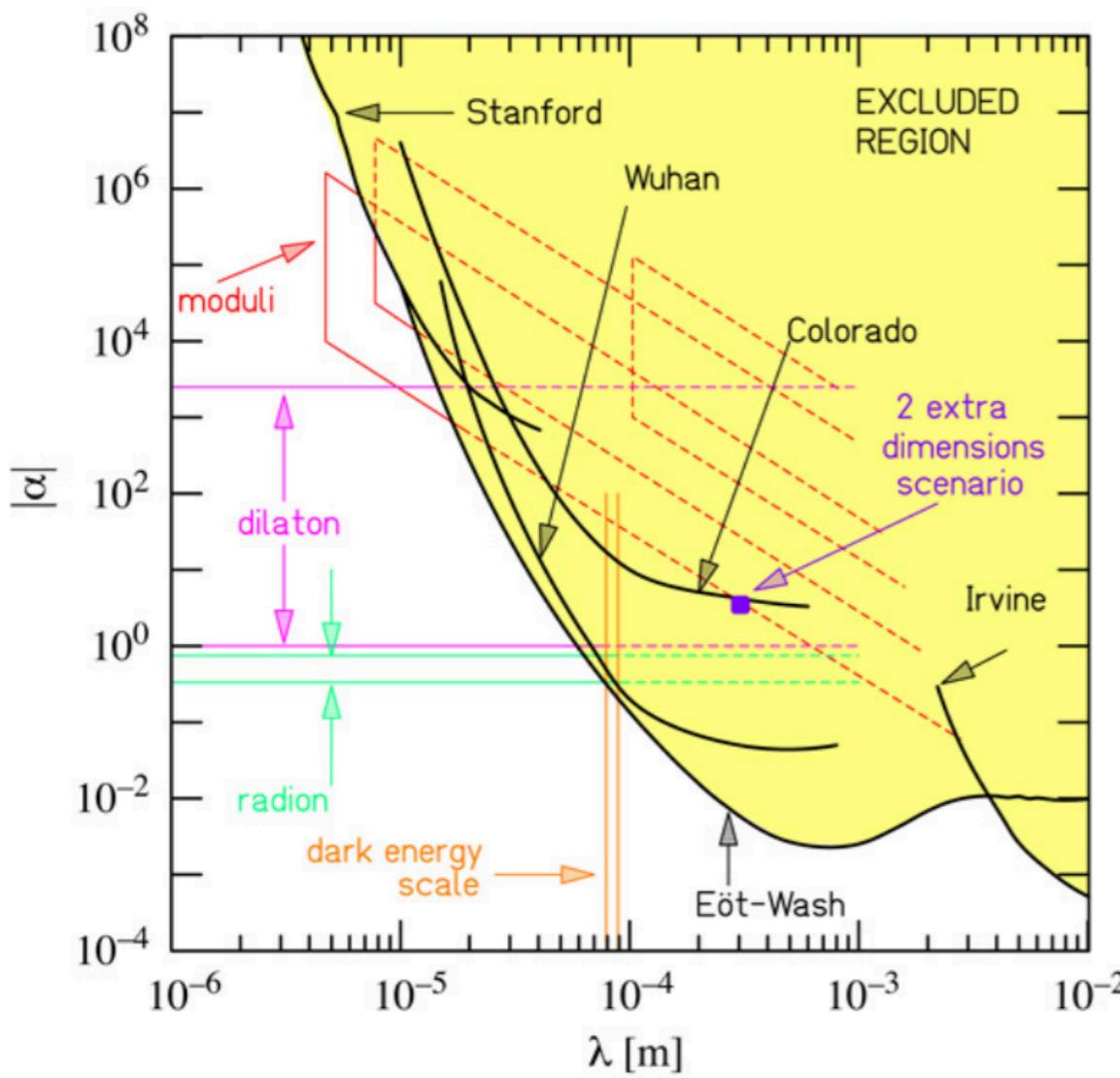
Trick: Environmentally-dependent mass (“Chameleon” fields)

$$\square\phi - \frac{dV_{\text{eff.}}(\phi, \rho_m)}{d\phi} = 0$$



So, where could we search for imprints?

$$V(r) = -G_N \frac{m_1 m_2}{r} (1 + \alpha e^{-r/\lambda})$$



So, where could we search for imprints?

Short-scale tests

Atom interferometry

Neutron interferometry

Casimir-force experiments

Neutrino oscillations

Astrophysical tests

Gravitational waves

Rotation curves

Galaxy clusters

White/brown dwarf stars

Binary pulsars

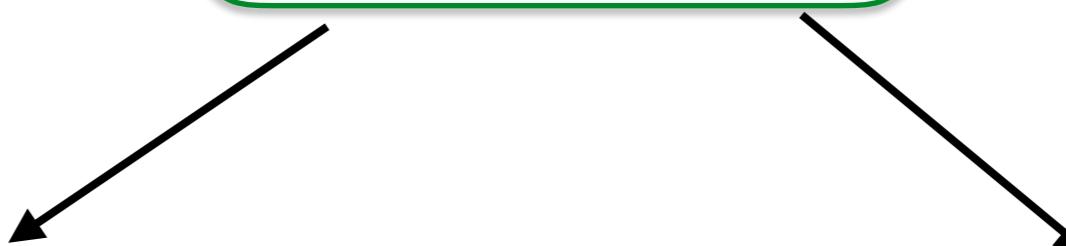
Complementarity of different tests has significantly constrained the allowed theory space of new fifth-forces (*mostly of Yukawa nature*)

An intriguing new prediction at local scales

The most general scalar-tensor theories (DHOST) predict
a new force inside matter sources

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

Fifth-force term

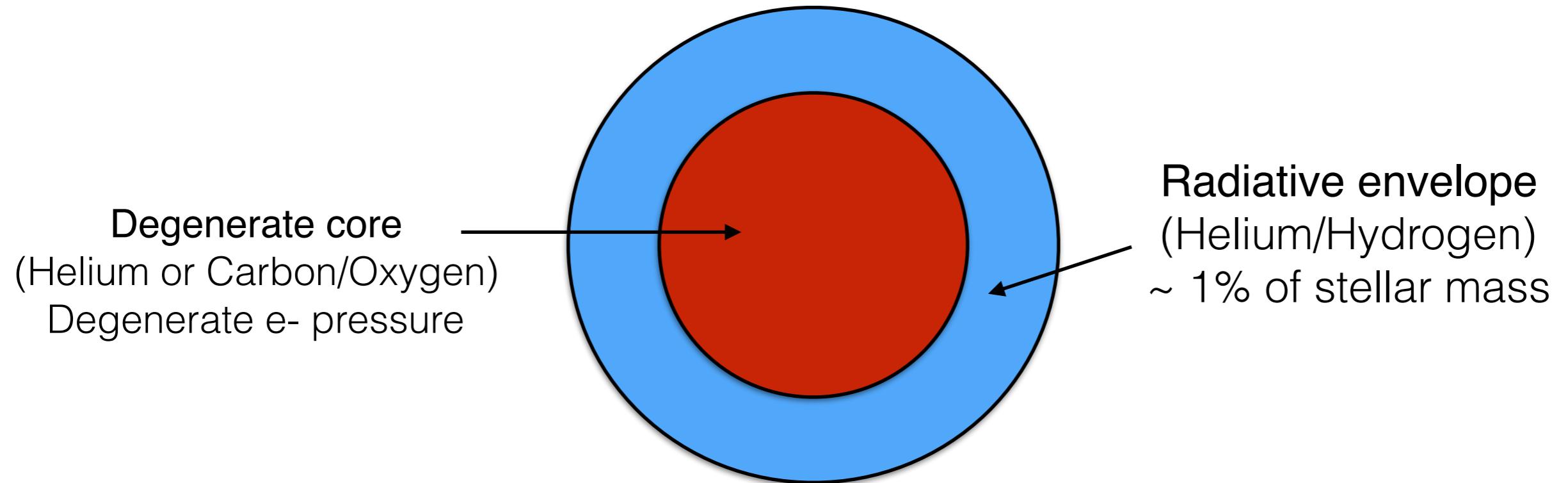


The fifth-force coupling strength Y relates to the parameters controlling the theory's cosmological dynamics

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

The theory can be constrained with stellar-structure observations

New local constraints from white dwarfs



Precision tests require going beyond the Chandrasekhar model:

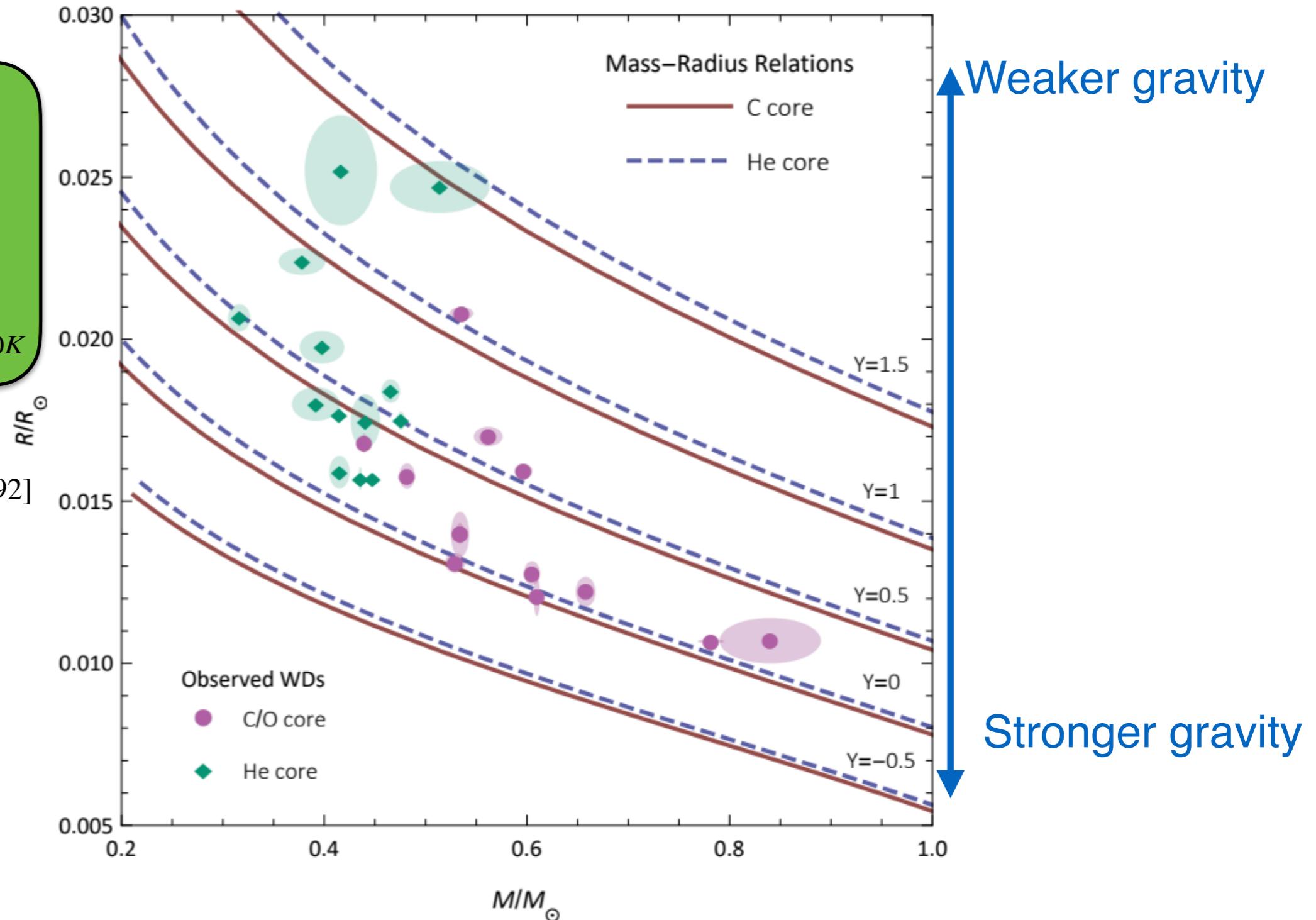
- Coulomb interactions between electrons and ions ($\sim 4\% - 5\%$ decrease in radius)
- Thermal history: temperature, radiative envelope, and core/envelope composition
- Evolution along the cooling track: $\sim 10\% - 40\%$ decrease in radius

The mass-radius relation of white dwarfs

Predicted mass-radius relation for the most general E.o.S at zero temperature (Hamada-Salpeter)

Most complete set of white dwarfs in binaries
Masses $\sim 0.3 - 0.8 M_{\odot}$
Radii $\sim 0.01 - 0.025 R_{\odot}$
Temperature $\sim 7500 - 63000 K$

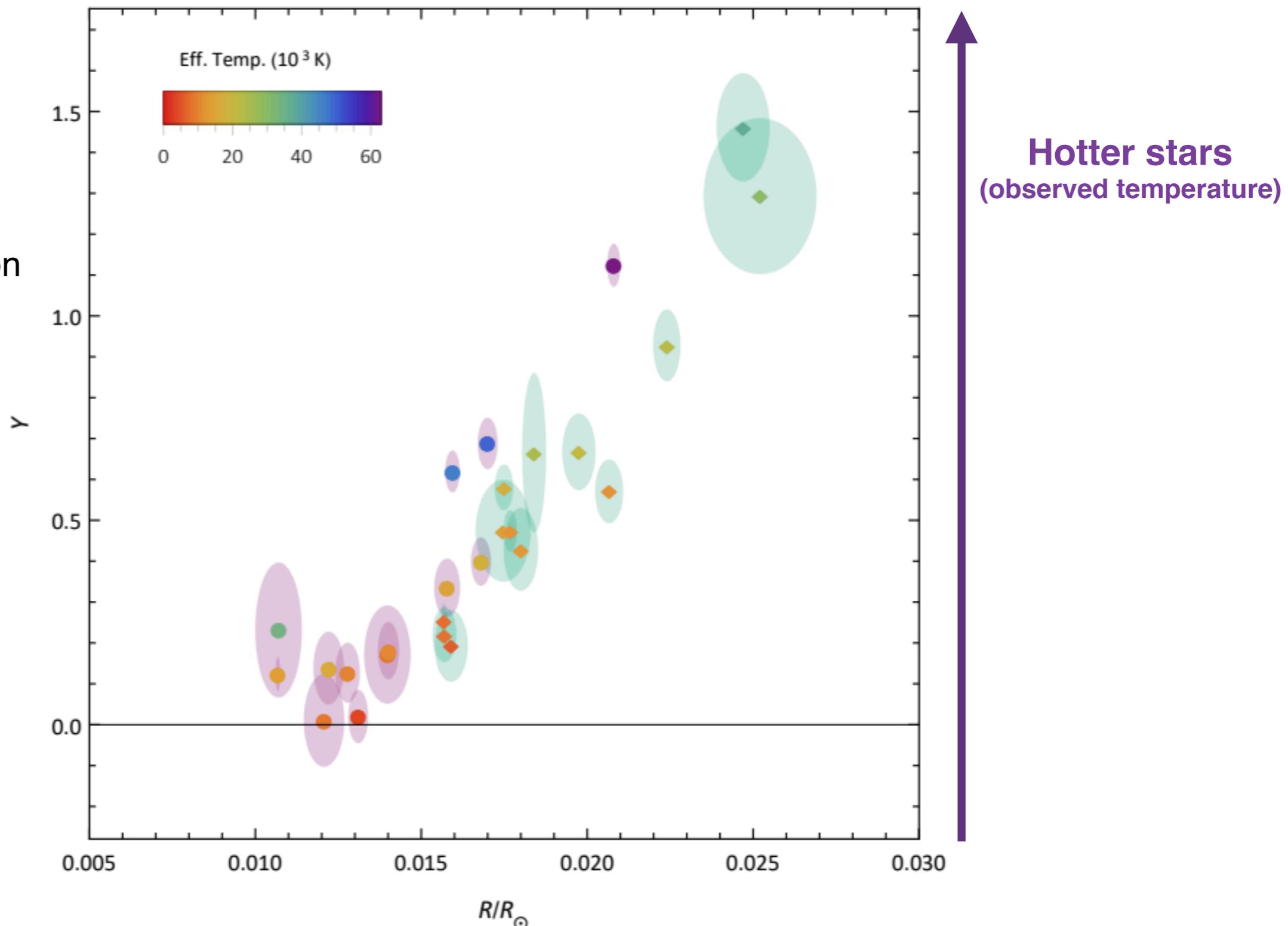
[S. G. Parsons et al,
MNRAS 470 (2017) 4473–4492]



A detection of modified gravity?

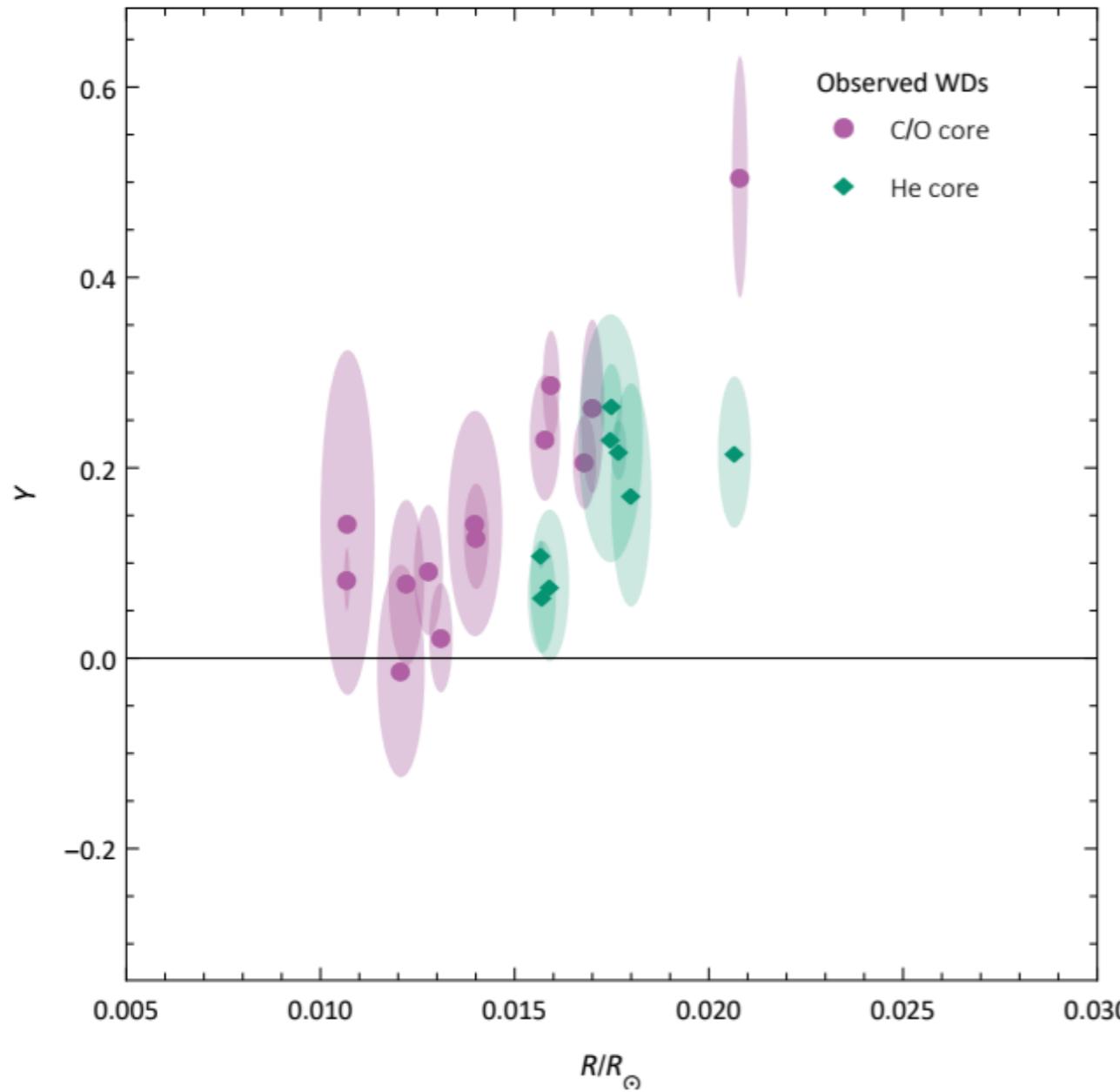
Constraints at zero temperature (Hamada-Salpeter E.o.S)

2 σ contours on Y
marginalised
over core composition



A detection of modified gravity?

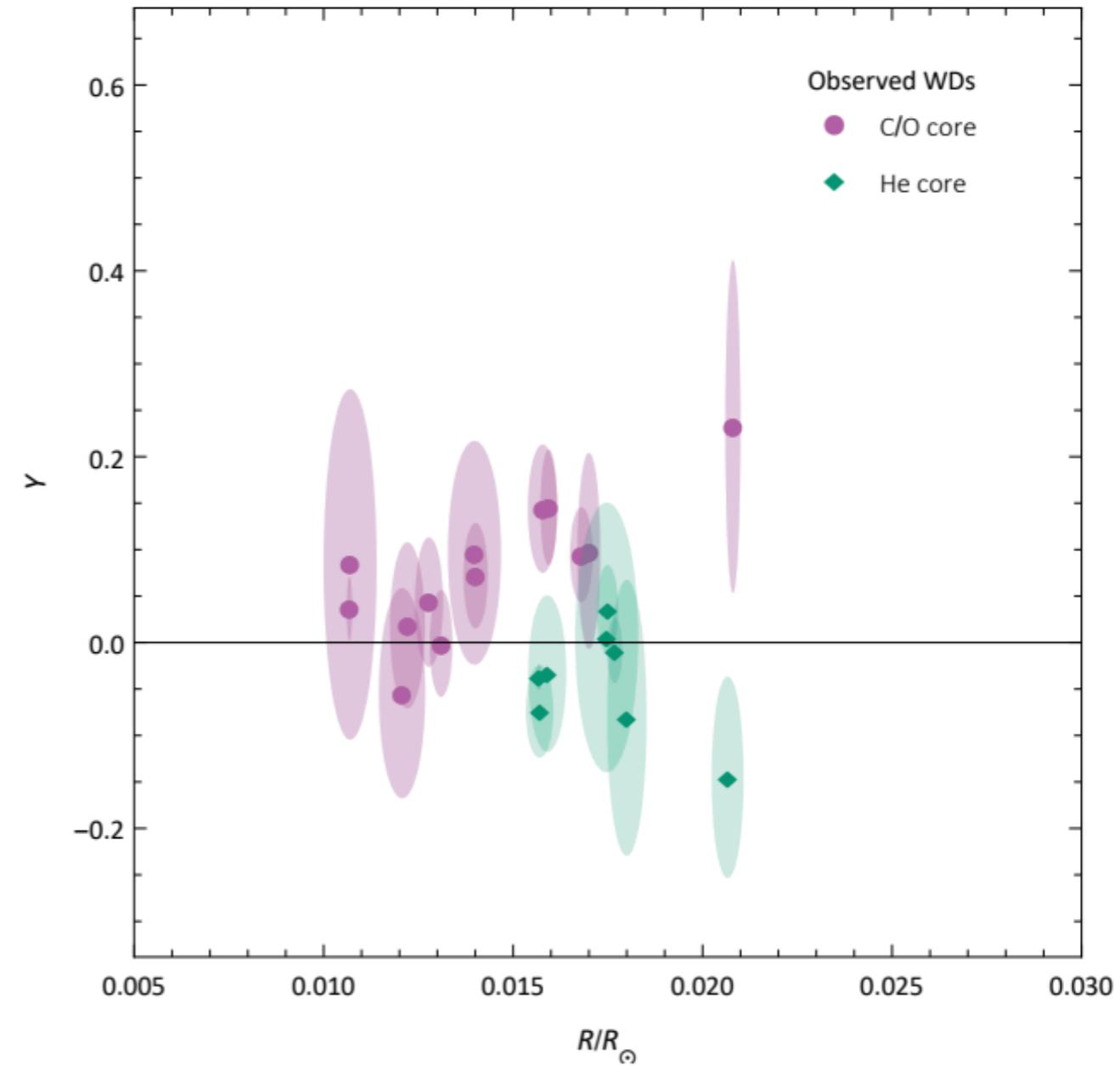
Temperature and envelope-structure matters



(a) Thin envelopes

He-core stars: no envelope

C/O-core stars: $M_{\text{He}}/M = 10^{-2}$

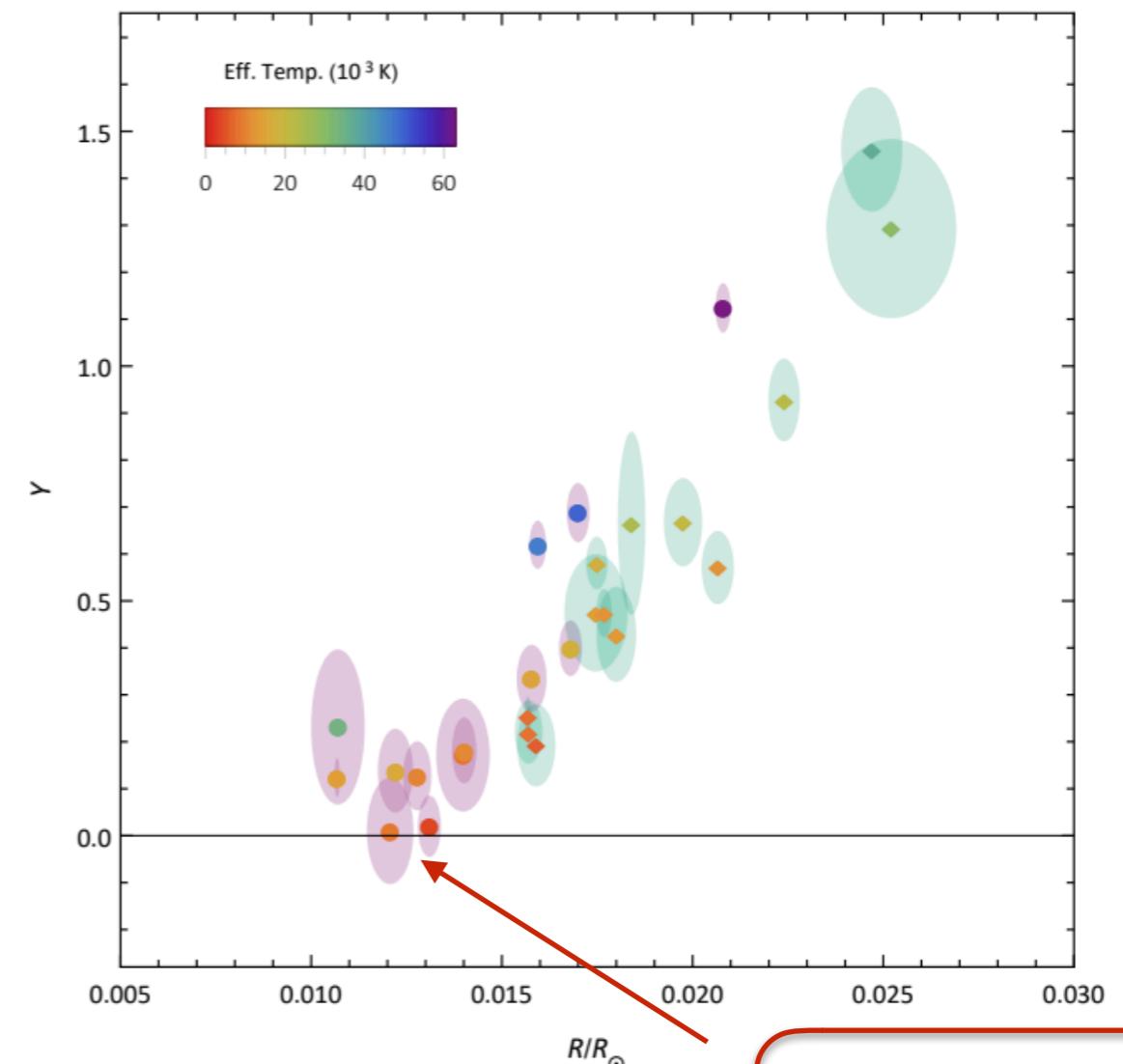
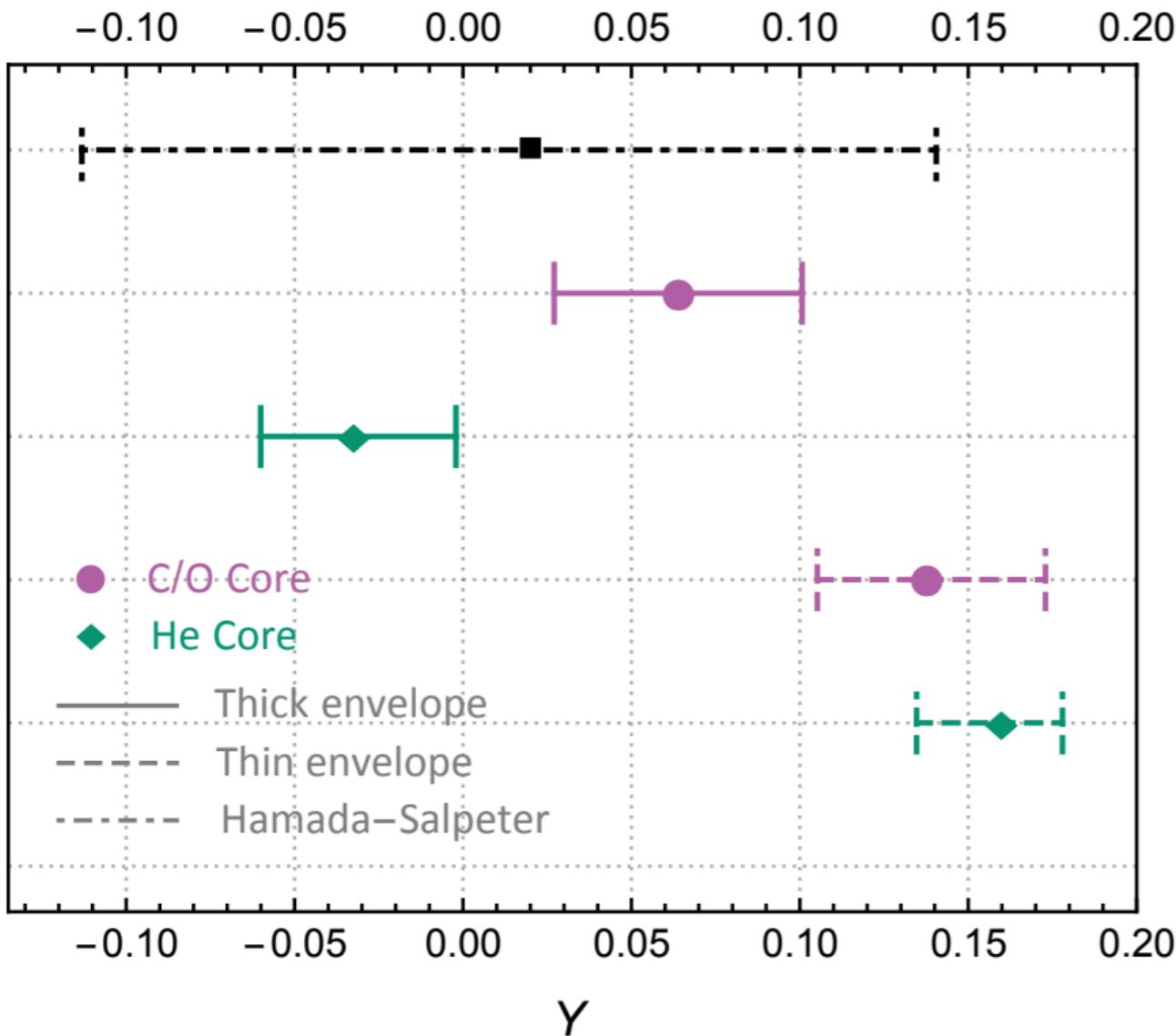


(b) Thick envelopes

He-core stars: $M_{\text{He}}/M = 3 \cdot 10^{-4}$

C/O-core stars: $M_{\text{He}}/M = 10^{-2}$, $M_{\text{H}}/M = 10^{-5}$

A new constraint on general scalar-tensor theories



Bound translates to new tight **constraints on the cosmological parameters** controlling scalar linear fluctuations [A. Dima, F. Vernizzi PRD 97 (2018) no.10, 101302]

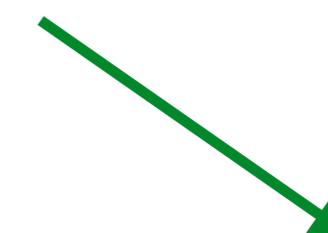
Can we do better?

YES!

Solar pulsations are our most accurate probe of the solar interior

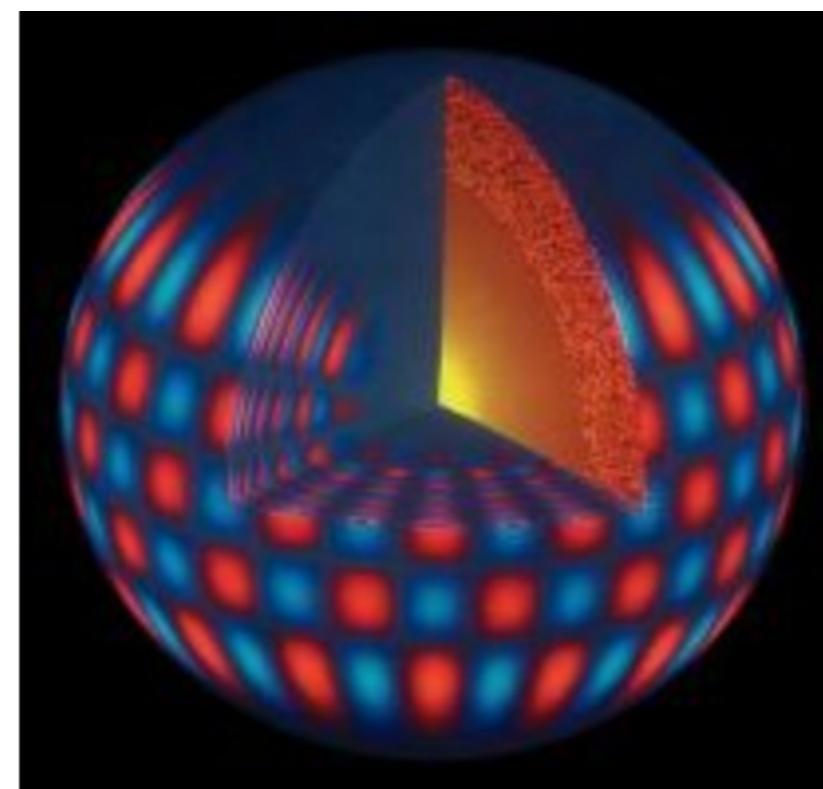


Traditionally, a probe of the assumptions
on the star's chemical makeup through
inversion techniques



A precision probe of
gravity in the stellar interior

Accuracy: $< 10^{-4}$



The triumphs of helioseismology

Speed of sound in the solar interior

J. Christensen-Dalsgaard*, T. L. Duvall Jr†, D. O. Gough‡, J. W. Harvey§
& E. J. Rhodes Jr||

* NORDITA, Blegdamsvej 17, København Ø, Denmark and Department of Applied Mathematics and Theoretical Physics, Silver Street, Cambridge CB3 9EW, UK

† Laboratory for Astronomy and Solar Physics, NASA/Goddard Space Flight Center, Greenbank, Maryland 20771, USA

‡ Institute of Astronomy & Department of Applied Mathematics and Theoretical Physics, Madingley Road, Cambridge CB3 0HA, UK

§ National Solar Observatory, National Optical Astronomy Observatories, Tucson, Arizona 85726, USA

|| Department of Astronomy & Space Sciences Center, University of Southern California, Los Angeles, California 90007, USA

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.

Solar chemical make up

Physics of the solar core

Solar radius

Neutrino physics

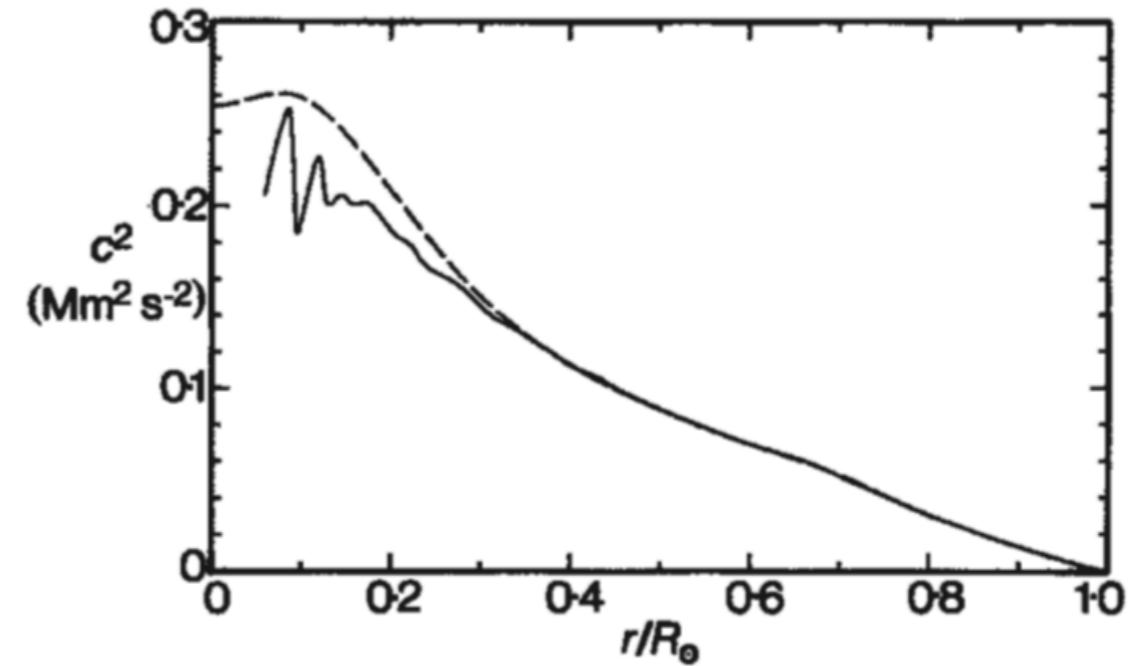
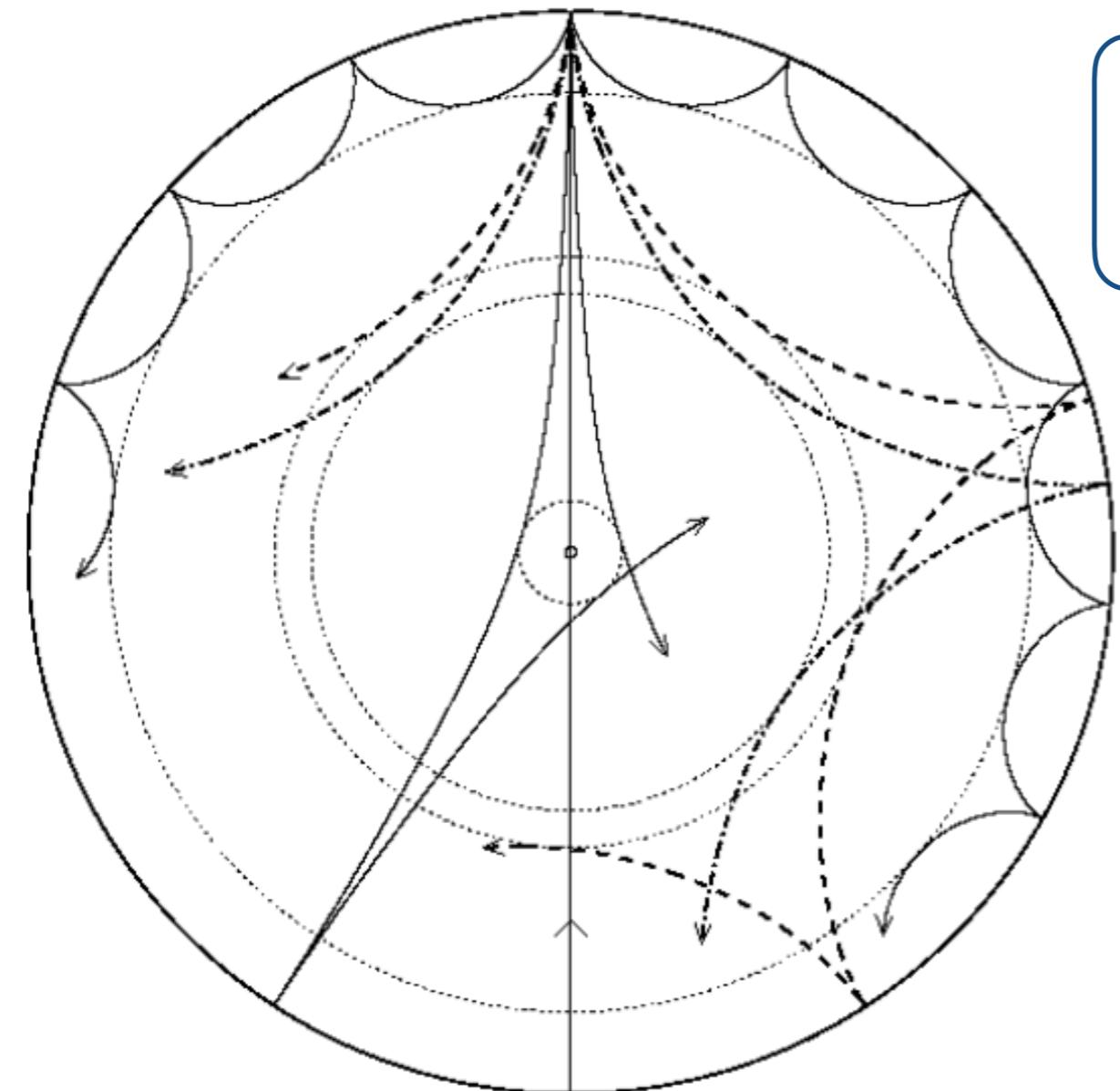


Fig. 4 Square of the interior sound speed c_0^2 in the Sun (continuous line) obtained by inverting the data in Fig. 1. The value of c^2 in solar model is included as a dashed line for comparison.

The basic principle

Physics of trapped acoustic (standing) waves from an interior point to the solar surface

Physical setup: Perturbed Newtonian fluid + gravity



$$\left(\frac{d^2}{dr^2} + k_r^2 \right) \Psi(r) = 0$$

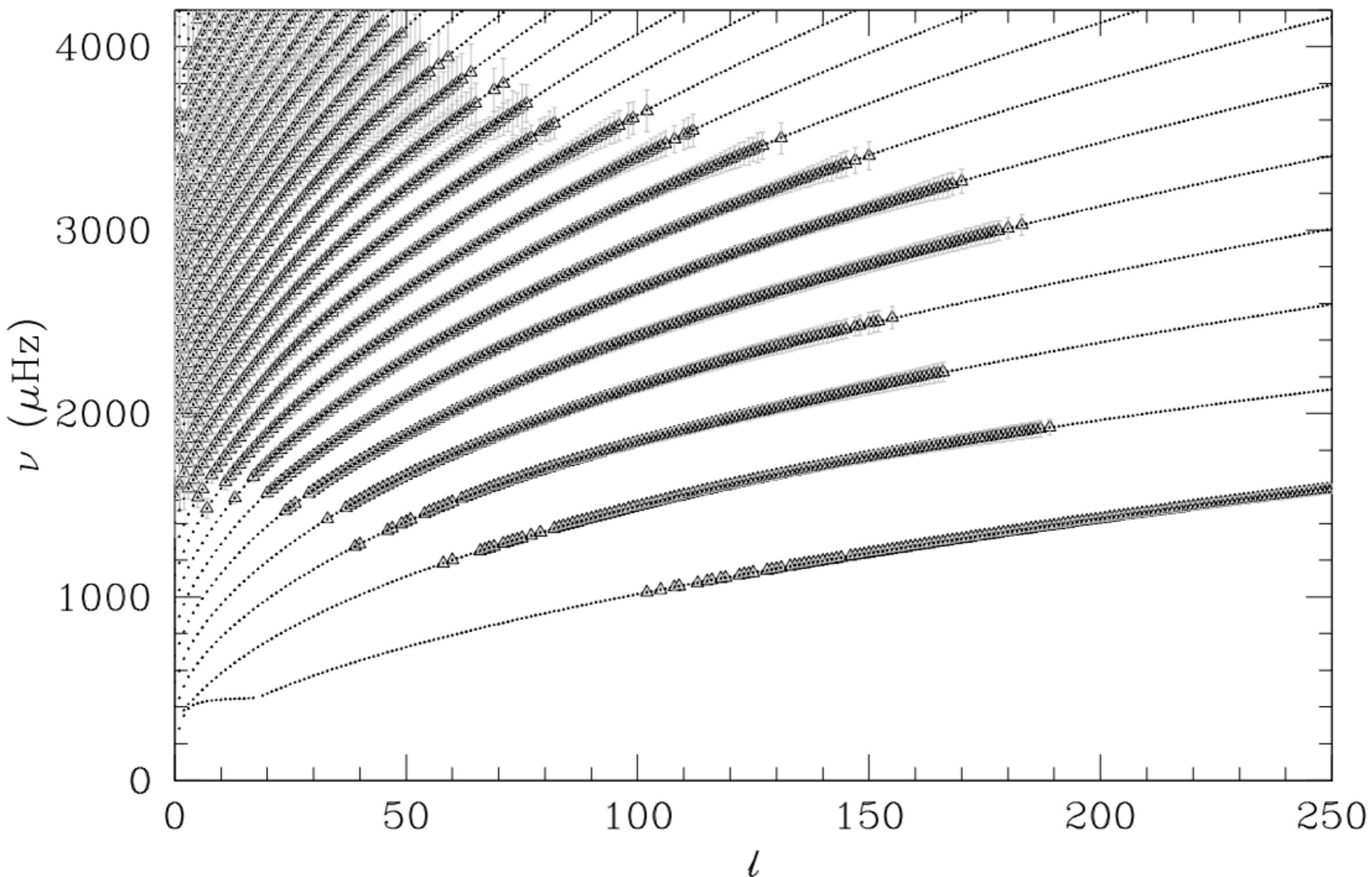
$$\Psi(r) \equiv c_s^2 \rho^{1/2} \nabla \cdot \delta \mathbf{r}$$

$$\omega^2 = c_s^2 |\mathbf{k}|^2$$

$$k_r^2 = \frac{\omega^2}{c_s^2} - \frac{l(l+1)}{r^2}$$

$$k_h^2 = \frac{l(l+1)}{r^2}$$

$$\omega = \left(n + \frac{l}{2} + \frac{1}{4} + \alpha \right) \cdot \omega_0 \quad \omega_0 \equiv \left(2 \int_0^{R_\odot} \frac{dr}{c_s} \right)^{-1}$$

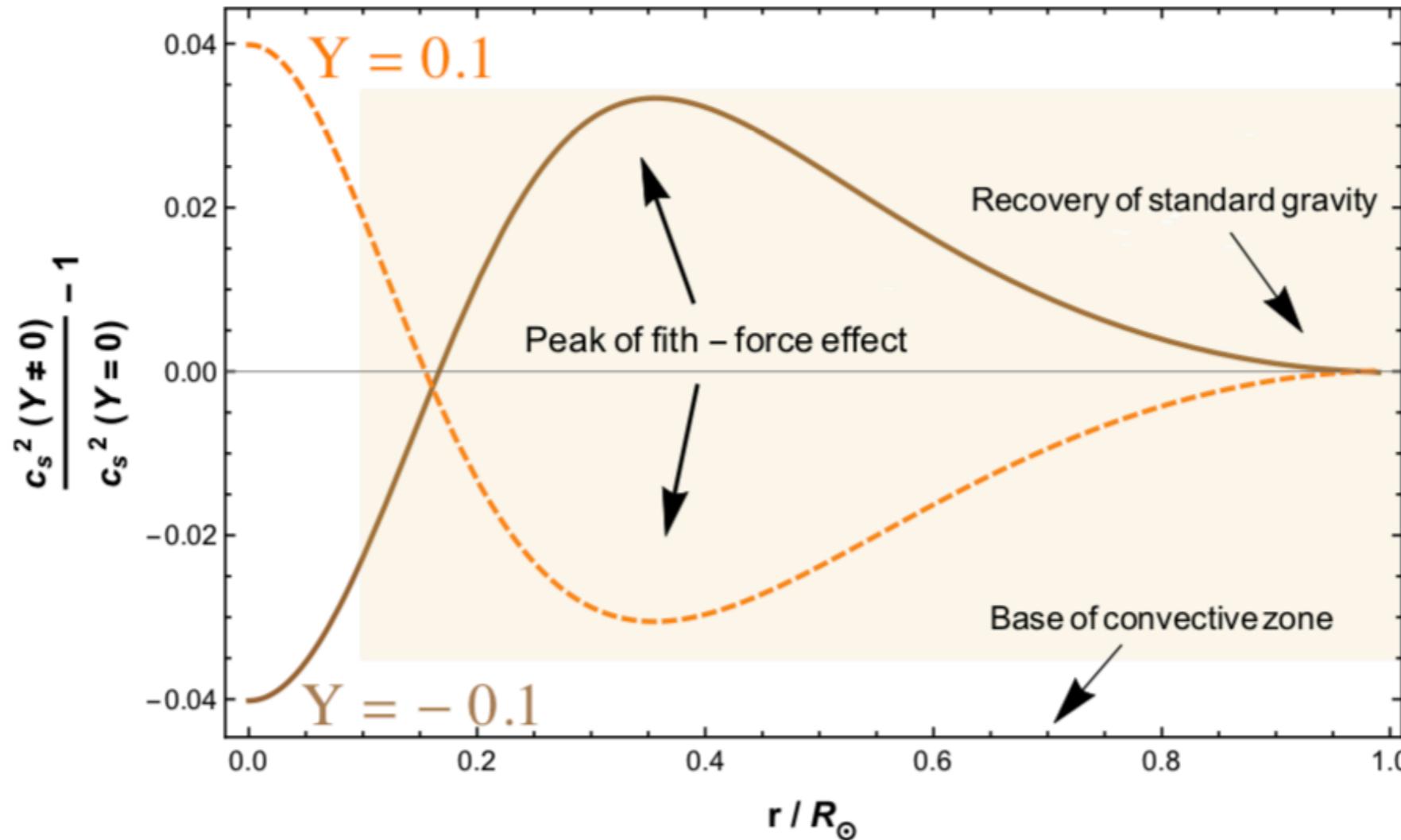


Michelson Doppler Imager data [Scherrer et al. 1995]

Helioseismology as a precision test of gravity

New hydrostatic equilibrium

$$\frac{dP}{dr} = -\frac{GM(r)}{r^2}\rho(r) - \frac{G \cdot Y}{4} \frac{d^2M(r)}{dr^2}\rho(r)$$

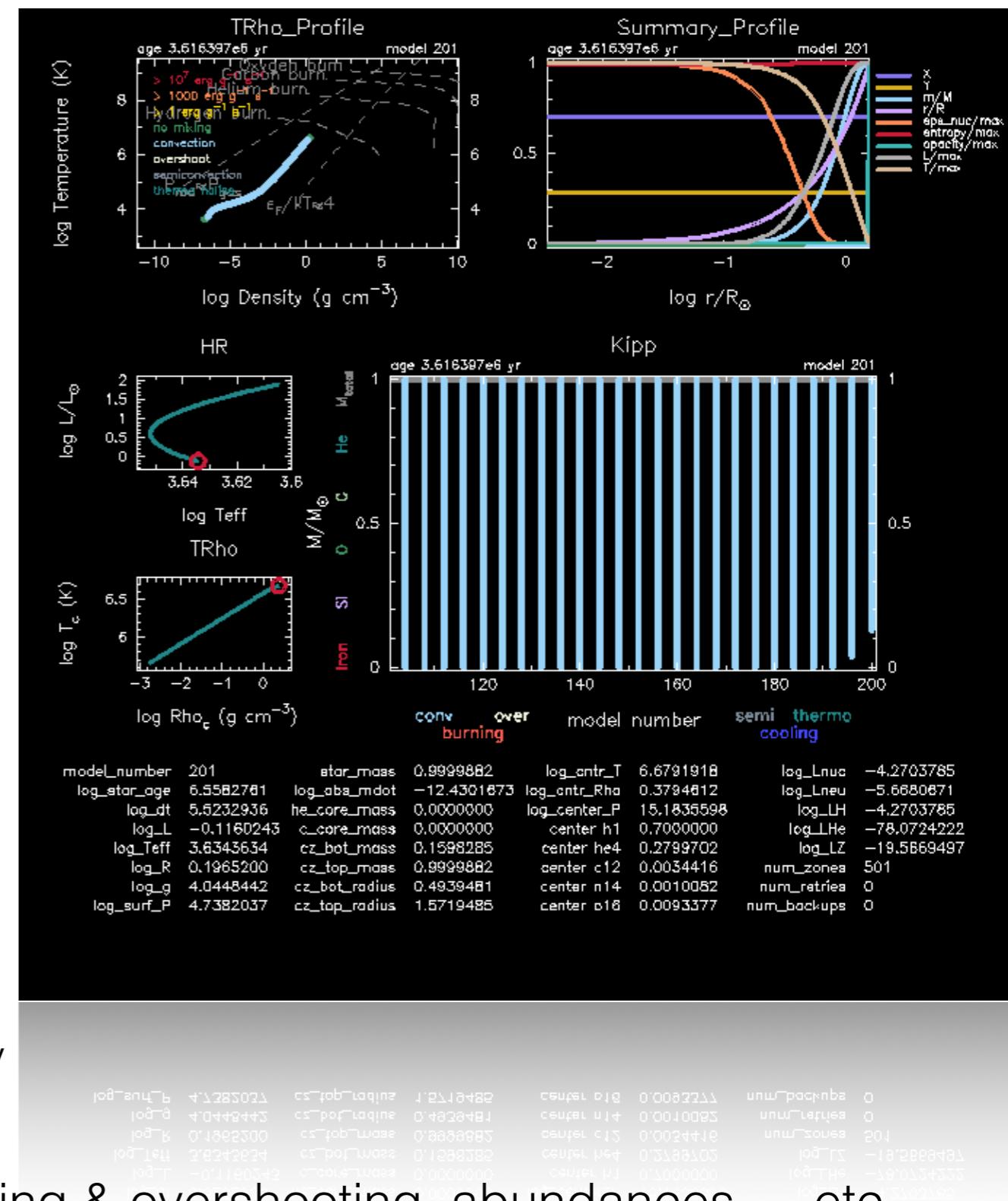
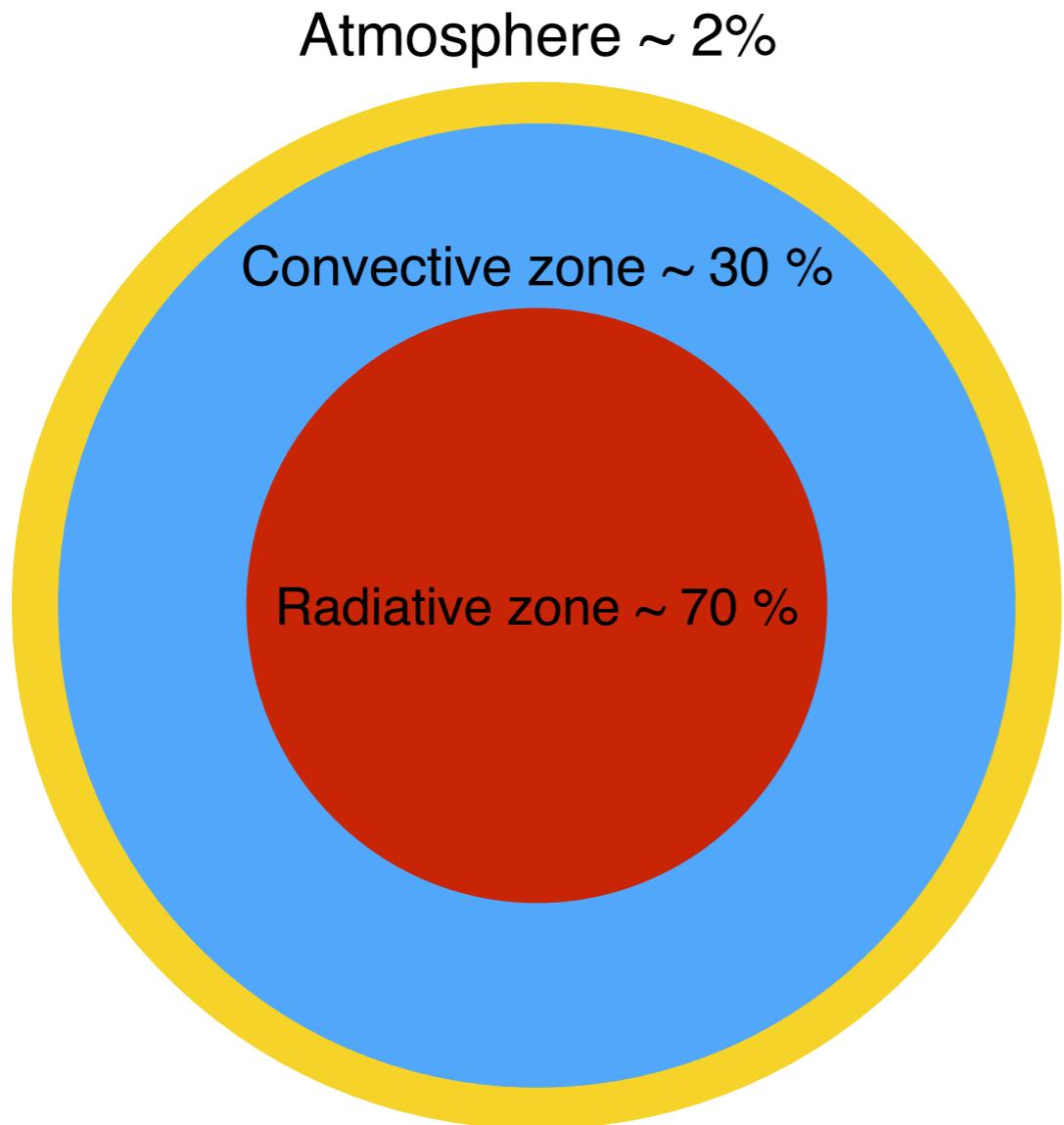


$$f_{\text{acoustic}} = \left(\frac{1}{2} \int_0^R \frac{dr}{c_s} \right)^{-1}$$



$$\frac{f(Y \neq 0) - f(Y = 0.1)}{f(Y = 0)} \sim 0.1\%$$

Modelling the present Sun



Reference model:

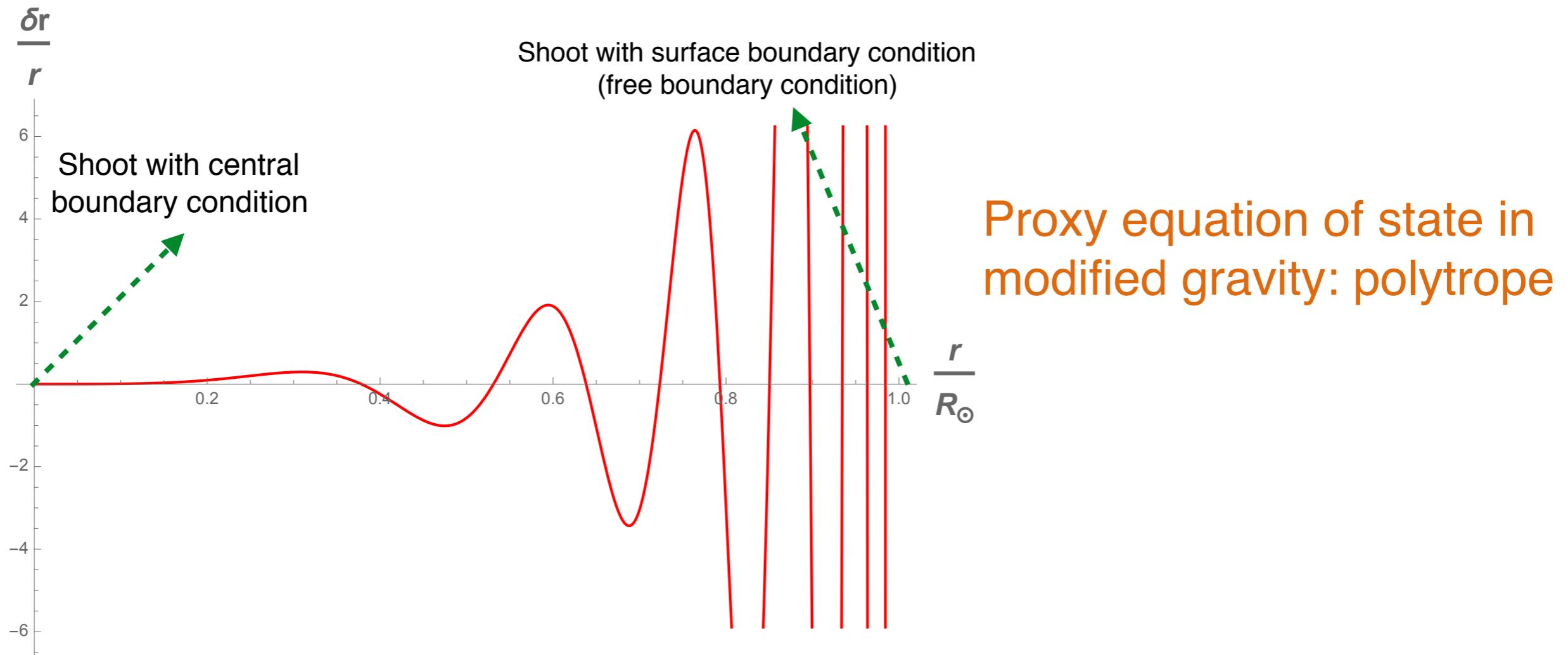
Calibrated (realistic) solar model at standard gravity

Input: Atmospheric model, convection modelling & overshooting, abundances ... etc.

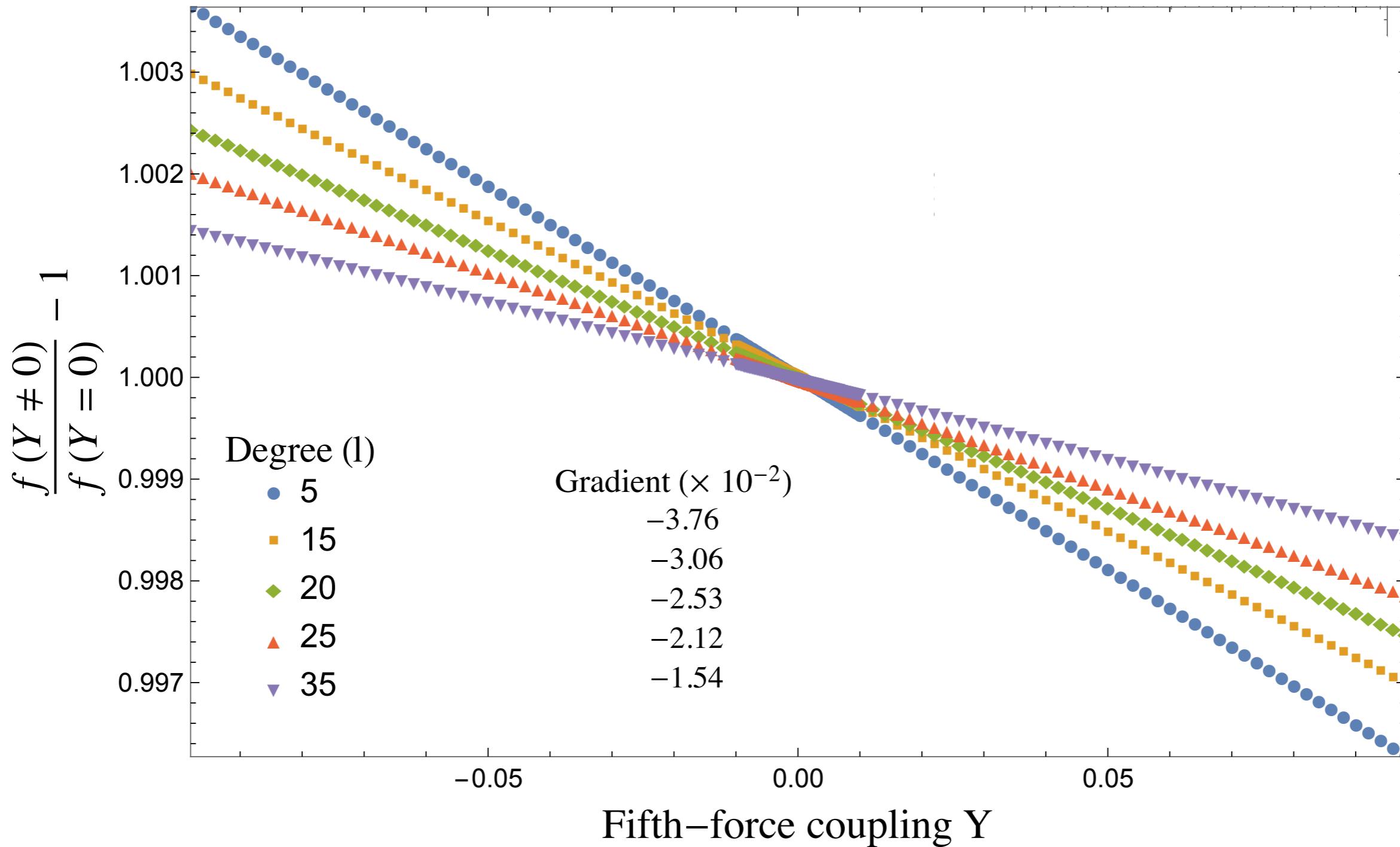
Pulsation spectrum in modified gravity

Pulsation equations solved within the *Cowling* approximation:
Gravitational back-reaction is neglected

Scheme: Double shooting method on a grid of $\sim 10^7$ points and degree range: $5 < l < 40$

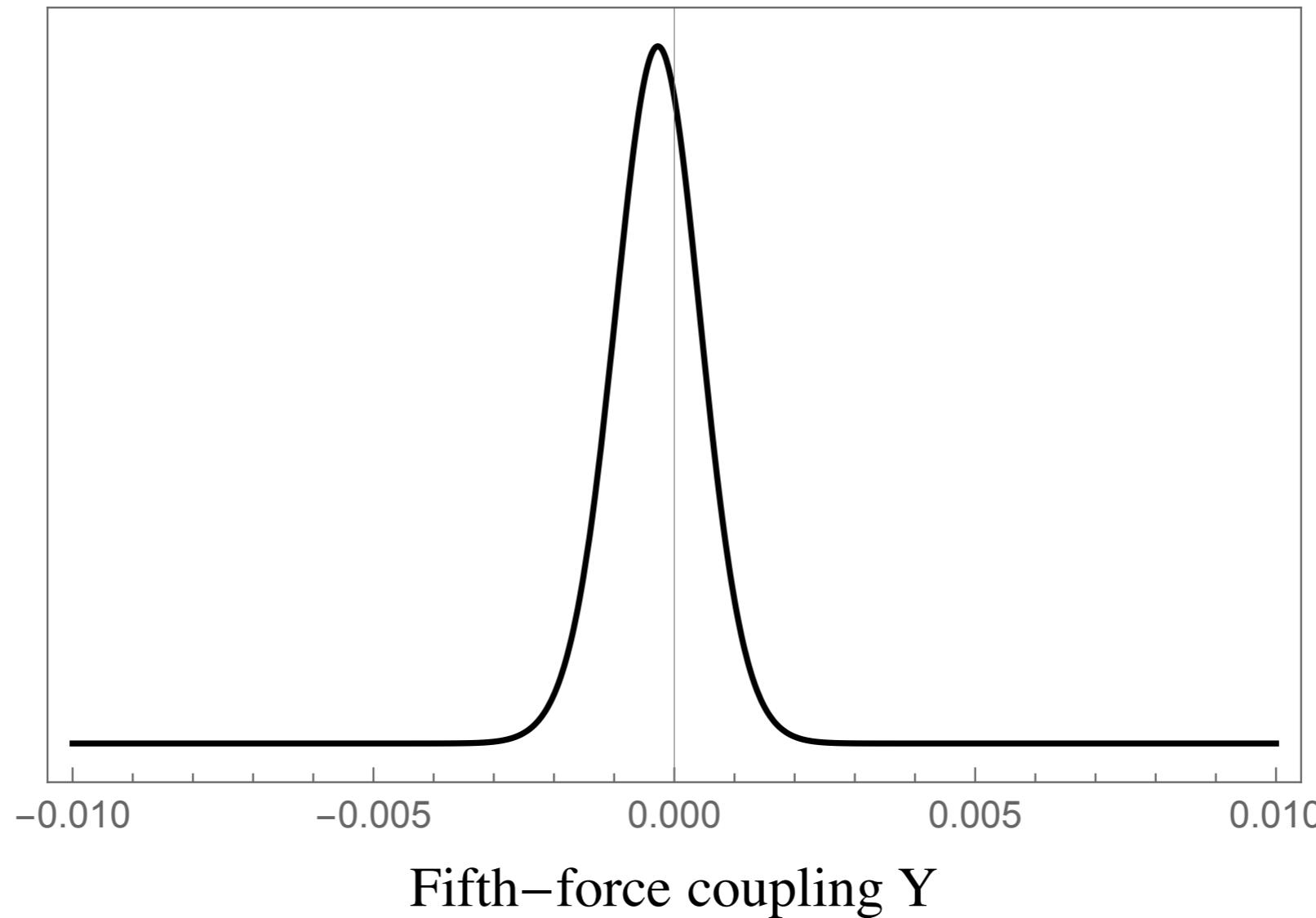


Pulsation spectrum in modified gravity



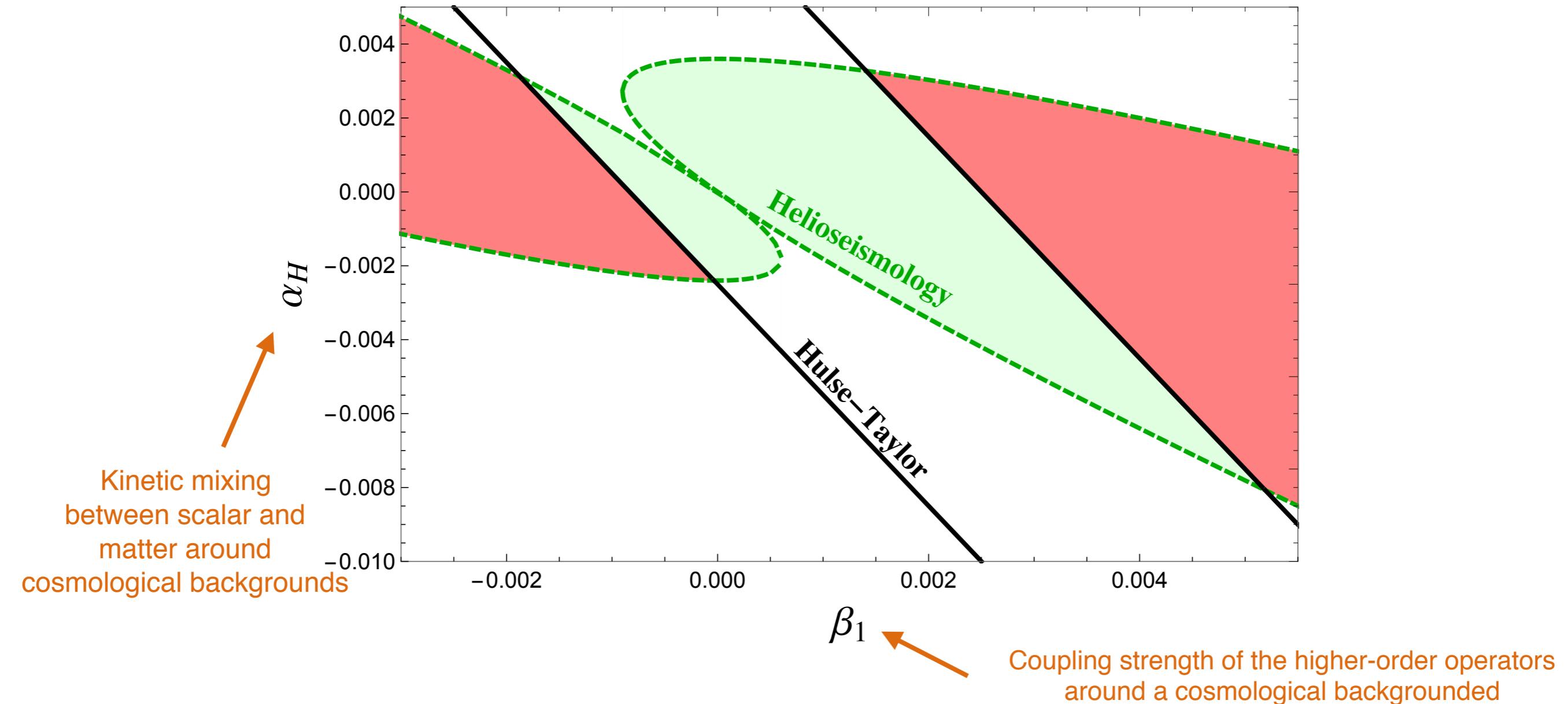
Confrontation with observations

Statistical analysis: Bayesian analysis based on those modes which agree with the standard solar model (Data set: GONG network)



$$-1.8 \cdot 10^{-3} \leq Y \leq 1.2 \cdot 10^{-3} \quad (2\sigma)$$

Cosmological implications



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

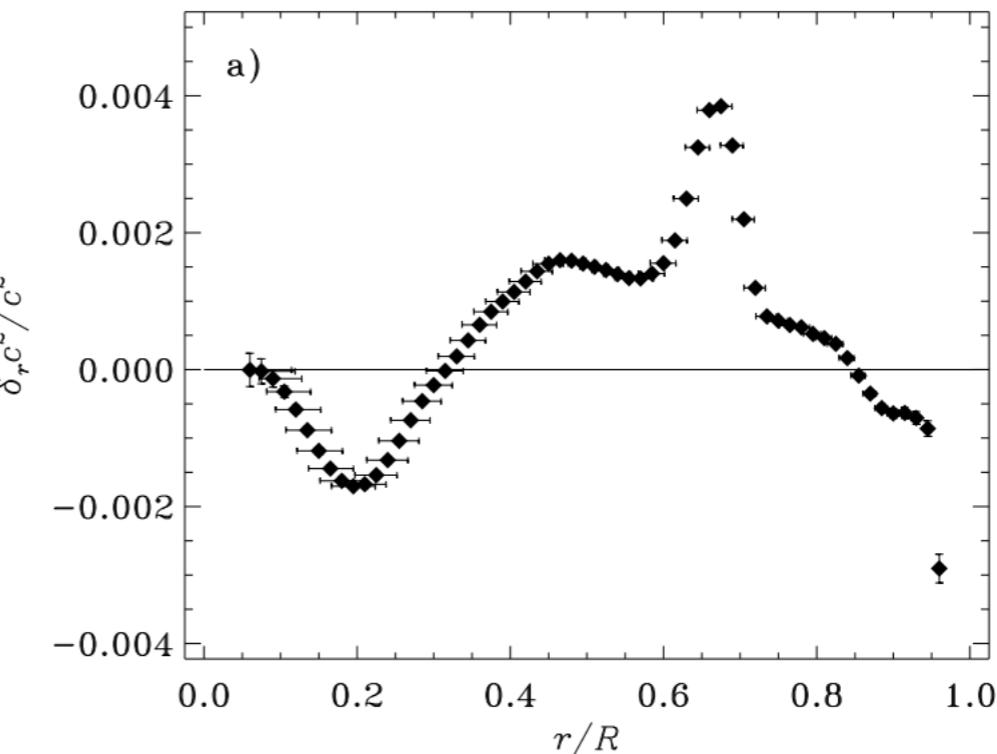
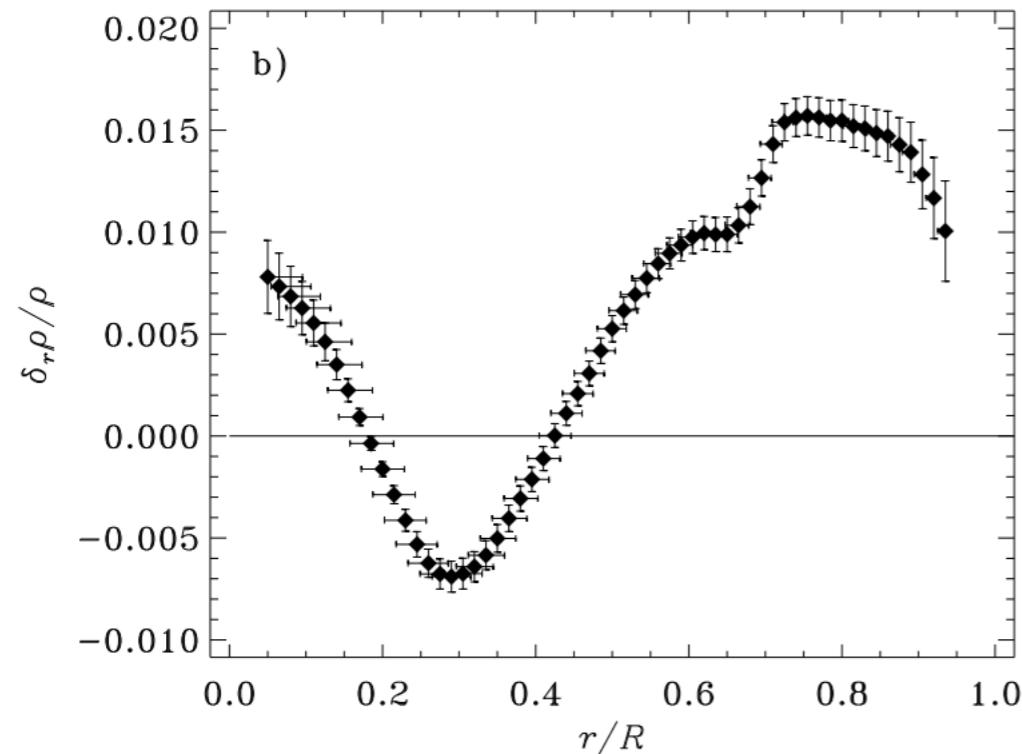
$$-2.4 \cdot 10^{-3} \leq \alpha_H \leq 3.3 \cdot 10^{-3}$$

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

Revisiting helioseismic inversions

Helioseismic inversions provide a powerful diagnostic of the physics of the solar interior

$$\frac{\delta\nu_{n\ell}}{\nu_{n\ell}} = \int_0^R \mathcal{K}_{c^2,\rho}^{n\ell}(r) \frac{\delta c^2}{c^2}(r) \ dr + \int_0^R \mathcal{K}_{\rho,c^2}^{n\ell}(r) \frac{\delta\rho}{\rho}(r) \ dr$$



[Christensen-Dalsgaard & Di Mauro, 2007]

Is there space for deviations from Newtonian gravity?

Summary

Helioseismology can be used as an exciting and precision probe of fifth forces in Nature

Other pulsators such as red giants or white dwarfs can provide powerful, complementary information

New constraints can significantly improve our understanding for fifth forces in the Universe and the nature of dark energy