Solar and Space Physics (Heliophysics) Decadal Survey White Paper:
Probing the Structure and Dynamics of the Solar Core with Gravity Modes

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Synopsis

The structure and dynamics of the energy-generating core of the Sun, and other low-mass stars, remain shrouded in mystery in spite of very important observational efforts to probe them. While increasingly sophisticated observations and the theory of solar neutrinos have afforded important global constraints on the structure of the deep solar interior (within 0.2 $R_\odot$), detailed helioseismic probes such as those provided by acoustic or pressure (*p*)-modes, which have provided revolutionary views of the structure and dynamics of the outer radiative zone and near-surface convection zone, are basically not available for the core, as the non-radial *p*-modes are refracted toward the surface before reaching the greater depths of interest, spending very little time in the deepest layers and thus providing very little information about them. However, the measurement of the properties of a few buoyancy or gravity (*g*)-modes, with buoyancy as the restoring force, should provide extremely powerful probes of both the structure and the dynamics of the solar core. While they have not yet been convincingly observed (because they are evanescent in the outer solar convective zone, where their amplitudes decrease by many orders of magnitude toward the surface) *they are not hypothetical* – their physics is well established and well observed in the Earth's atmosphere and other, more evolved or more massive, stars as well as white dwarfs. *We propose the development of renewed observation approaches and analysis techniques to obtain the properties of deeply probing gravity waves to enable their seismic probing of the Sun's core* – e.g. testing models of angular momentum transport and the mixing of the elements produced by hydrogen fusion. While important advances have been made in the study of the excitation of these modes and their predicted amplitudes, in the absence of an unambiguous detection, *the search for solar g-modes, in order to exploit their helioseismic potential, remains a poster-child for high-risk high-return exploration*.

Introduction

The Global Oscillations at Low Frequencies (GOLF) instrument and *the Luminosity Oscillations Imager* (LOI) package of *the Variability of solar Irradiance and Gravity Oscillations* (VIRGO) instrument onboard the *Solar and Heliospheric Observatory* (SOHO) were designed explicitly to search for and study the solar *g*-modes. The detection of these modes proved a difficult task for two main reasons: a mechanism failure early in the life of GOLF, and the amplitude of the solar *g*-modes turns out to be *significantly* less than was expected before the launch of SOHO. Today we face two challenges that limit the *g*-mode detection and their use as diagnostics of the solar core: (1) their minute surface velocity imprint and (2) the presence of solar "noise" (granulation and super-granulation) in the range of frequencies where *g*-modes are expected to be found, which contributes to poor signal/noise. In order to answer the questions that these important investments asked, the next generation of instruments dedicated to *g*-modes must address these points to observe with better sensitivity. The scientific questions have only grown in importance with the passage of time – the challenge remains pressing.

A new generation of instruments that are more sensitive and particularly the possibility of having one or two instruments off the Sun–Earth line (to very significantly reduce the noise background, as the convective noise would be uncorrelated from one view to the other, while the solar oscillations would be highly correlated) on *FireFly*-E (the ecliptic spacecraft of a small solar orbiting constellation) could significantly advance our knowledge of solar *g*-modes, and enable their use to probe the otherwise inaccessible solar core. The *next-generation Global Oscillation Network Group* (ngGONG) could provide complementary observations from a different spatial perspective.

Investigating solar *g*-modes is high risk (they have not been unambiguously identified yet), but high reward (direct knowledge of the structure and even more so the dynamics of the solar core is <u>very</u> important for advancing our understanding of solar and stellar evolution).

Scientific Motivation and Current Status

Helioseismology (the use of solar surface measurements of pressure/sound waves (*p*-modes), to obtain the eigenfrequencies of resonant, normal modes, to in turn obtain inversions of solar interior properties) has led to a revolution in our understanding of solar interior structure and dynamics (see, e.g., Howe 2009; Basu 2016). Recently, inertial and Rossby modes, driven by the Coriolis force, have been observed in the low-frequency part of the spectrum and exploited as probes of the deep convection zone (Gizon, et al. 2021). These provide strong constraints on models of angular momentum transport and models of mixing at the base of the convection zone, with important consequences on estimating stellar ages. However, several extremely important questions about the deeper solar interior remain, for example the detailed structure and rotation of the solar nuclear-energy-generating core, remain beyond their reach. *g*-modes, driven by the buoyance force, are the only known probes for characterizing the core and deep radiative-zone structure and dynamics. These modes remain challenging to observe, but they are essential for advancing our understanding of the Sun–Earth system, as well as serving as a reference for other main-sequence, solar-like stars. Today, knowledge of the internal dynamics from *p*-modes concerns mainly the convection zone and the outer layers of the radiative zone together containing only 2% of the solar mass. Solar *g*-modes are buoyancy waves trapped below the convection zone in the solar radiative zone and have been *very* difficult to detect at the surface. Therefore, the quest for detecting solar *g*-modes has attracted considerable attention in the past, with several reported detections (Garcia et al. 2007; Fossat et al. 2017). Unfortunately, none of the reported detections have been confirmed so far; e.g. Broomhall et al. (2010); Schunker et al. (2018). See also Appourchaux et al. (2010), for a review; Appourchaux and Pallé (2013), for a discussion of the history of the *g*-mode search; and Appourchaux and Corbard (2019), for some recent developments.

Figure 1 illustrates measurements of the solar interior rotational velocity. While exquisite detail is obtained from very near the solar surface down to near 0.5 $R_\odot$, which is below the base of the convection zone, there is a near-total loss of information below as well as close to the rotation axis (perpendicular to the ecliptic plane). Polar observations from *Solaris* and *Firefly* should elucidate the physics of the polar regions, which are crucial for our understanding of the solar dynamo and the cycle of magnetic activity. *g*-modes are the only known probe of the enormous region (even more so by mass) around the energy-generating core.

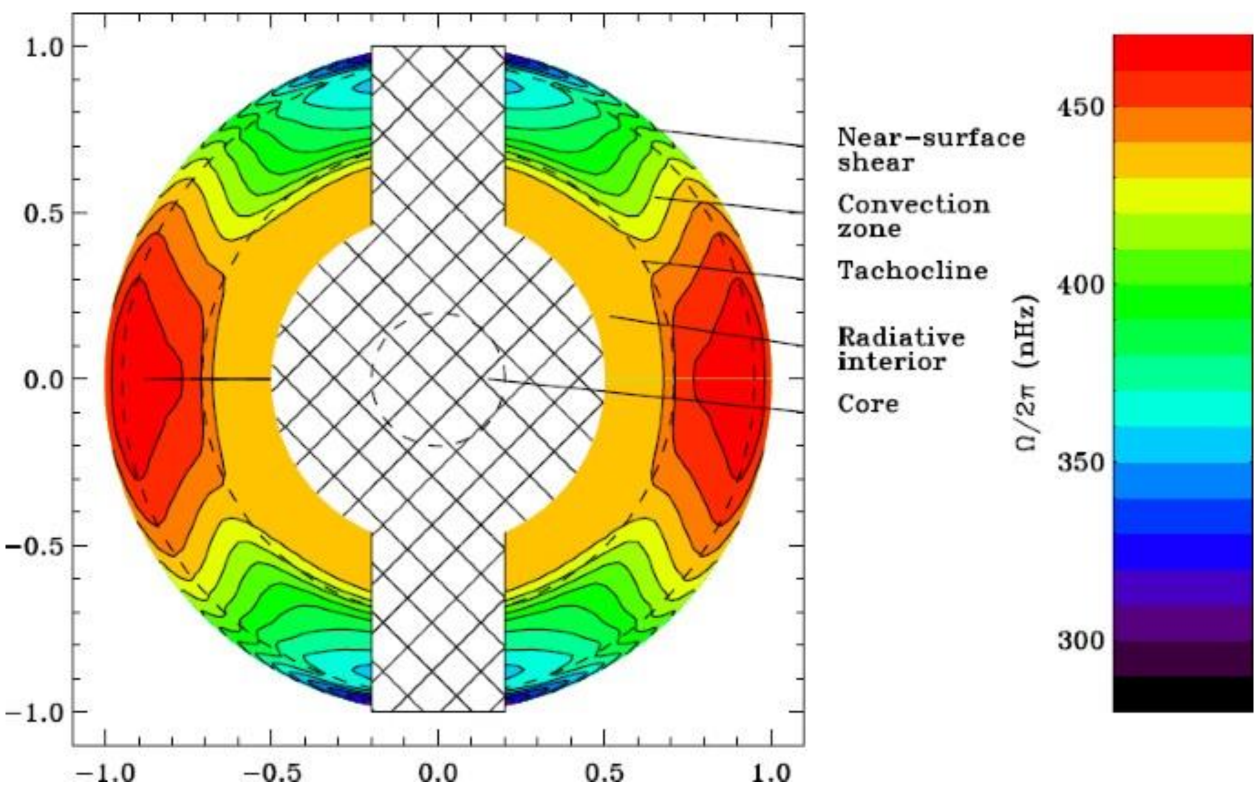

Figure 1. A cross-section through the interior of the Sun, showing the contours of constant rotation and the major features of the rotation profile, for a temporal average over about 12 years of MDI data. **The cross-hatched areas indicate the regions in which it is difficult or impossible to obtain reliable inversion results with the available data.** (Howe, 2009)

Sound waves propagate approximately at the local sound speed, which is proportional to the square root of the temperature, so enormously more rapidly in the 15 $\times 10^6$ K core than at the 6 $\times 10^3$ K surface. Thus, non-radially propagating sound waves are refracted away from the core, back toward the surface. The physics of non-radial *p*-modes excludes them from the core, which is the region that remains to be explored.

Figure 2a illustrates the paths of a typical high spherical harmonic degree (*ℓ*) sound wave or *p*-mode ray that remains very close to the surface, and hence is very insensitive to the structure and dynamics of the core, as well as a very low spherical harmonic degree ray that is also excluded from the solar core, and which is very insensitive to the deep layers because of its very high propagation speed in the deep interior/small dwell time in those layers. Figure 2b illustrates a typical low spherical harmonic degree *g*-mode ray, which is excluded from the outer convection zone, where its amplitude decreases exponentially outward toward the visible surface. (Buoyancy in a convectively stable region allows the propagation of internal *g*-waves, while in a convectively unstable region it leads to convection.)

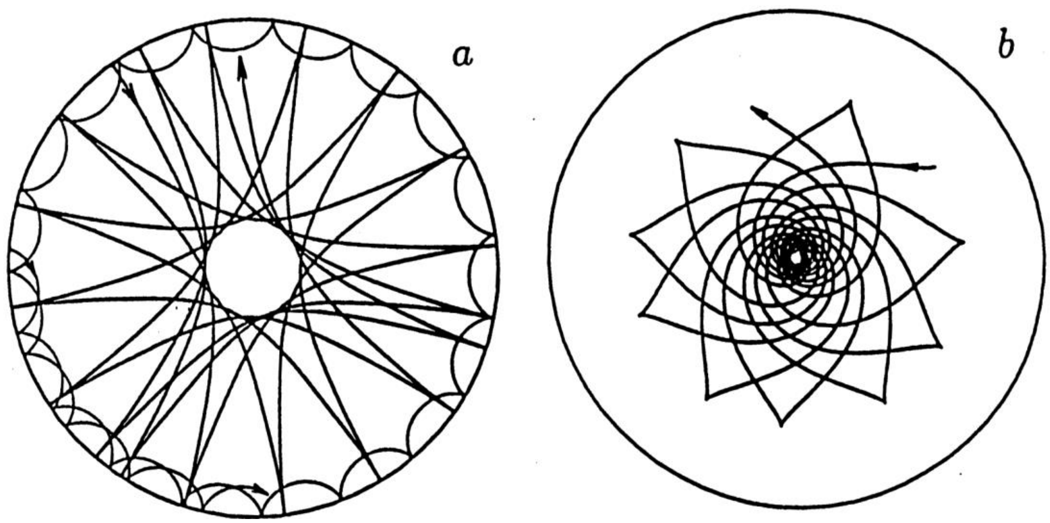

Figure 2: Ray paths of (**a**) *p*-mode rays, which are confined in the outer layers of the Sun by the rapidly increasing temperature (sound speed) inwards, and (**b**) *g*-mode rays, which are confined in the deep interior, below the outer convective envelope. (Courtesy J. Toomre and D.O. Gough)

Figure 3 shows the temporal spectrum with the well observed *p*-modes in the range around 3000 μhz and the predicted *g*-modes around 100 μhz, very distinctly separated.

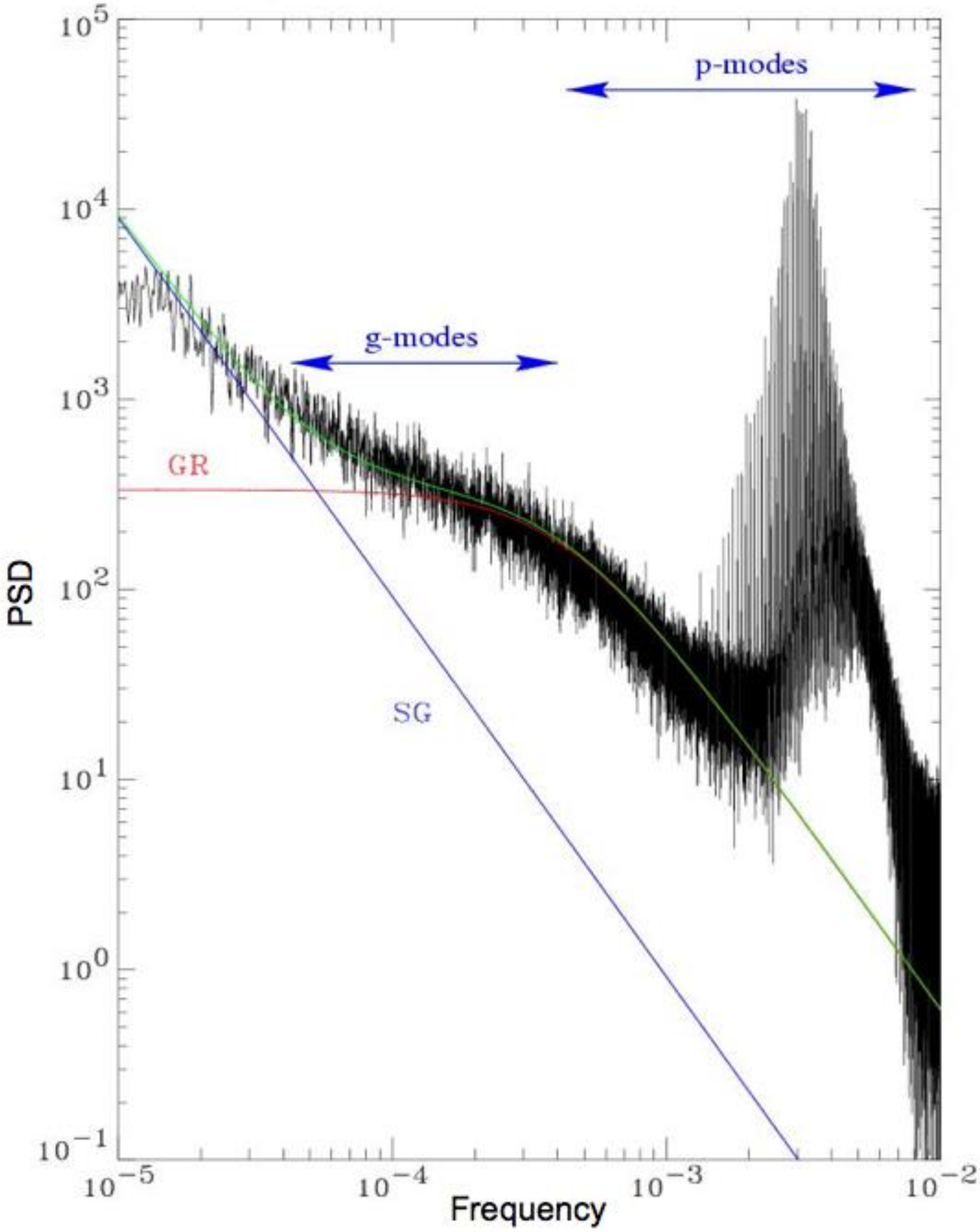

Figure 3: Temporal frequency spectrum [Hz] of the spatially integrated Sun observed by GOLF, showing the distinct frequency ranges of the observed *p*-modes and the long sought *g*-modes, as well as the granulation and super-granulation “noise” backgrounds. (Courtesy R.A. García)

Figure 4 presents (1) a representative *p*-mode eigenfunction showing its oscillatory behavior in the convection zone and its decay below and (2) a representative *g*-mode eigenfunction showing its oscillatory behavior in the deep interior and its decay in the convection zone and outward toward the surface, demonstrating the spatial complementary of the *p*- and *g*-modes – the *g*-modes promise an otherwise inaccessible view of the solar core. In addition to the pure *p*-modes and pure *g*-modes, there should exist a very few "mixed modes" at frequencies between the *p*- and *g*-modes, which exhibit *g*-mode properties in the deep interior and *p*-mode properties in the outer, convection zone, which because of their higher frequency, and thus lower solar "noise" background, may be more easily observed.

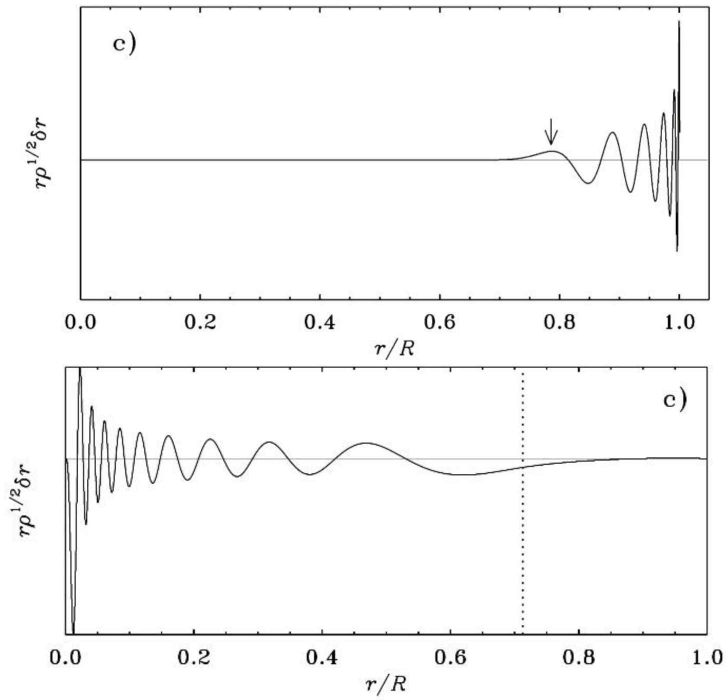

Figure 4: Representative scaled radial displacement *p*-mode and *g*-mode eigenfunctions

Above: scaled *p*-mode radial displacement eigenfunction for $\ell = 60$, $n = 10$, $\nu = 3234$ μhz. The arrow indicates the depth below which the mode becomes evanescent (exponentially decreasing inwards)

Below: scaled *g*-mode radial displacement eigenfunction for $\ell = 4$, $n = -19$, $\nu = 100$ μHz. The dotted line indicates the base of the convection zone. (Christensen-Dalsgaard, 2014)

An Example Solar Core Rotation Inversion with Artificial Data

To illustrate the potential that a few *g*-modes would provide, Figure 5 shows the results from a rotation inversion performed using artificial data generated from one calibrated solar model inferred from eigenfunctions calculated from another solar model. That is, one model served as the "target" for the inversion and was used to generate artificial data while the other served as "reference" model from which the inversion was performed. The target model used the Asplund, Amarsi, and Grevesse (AAG21, 2021) abundances and included macroscopic mixing from the combined effects of meridional circulation, shear-induced turbulence, and the Tayler–Spruit dynamo, following the work of Eggenberger et al. (2022). The “reference” model was a Standard Solar Model calibrated using the Grevesse and Noels (GN93, 1993) abundances. For both models, the Adelberger et al. (2011) nuclear reaction rates were used, alongside the OPAL opacities, the FreeEOS equation of state, and the formalism for diffusion of Thoul et al. (1994), including the revised screening coefficients of Paquette et al. (1986). The rotation splittings were generated from the target model using an actual 1D rotation profile from the full treatment of angular momentum transport as in the Geneva Evolution code (Eggenberger et al. 2008), reintegrating the variational equation in the spherically symmetric case.

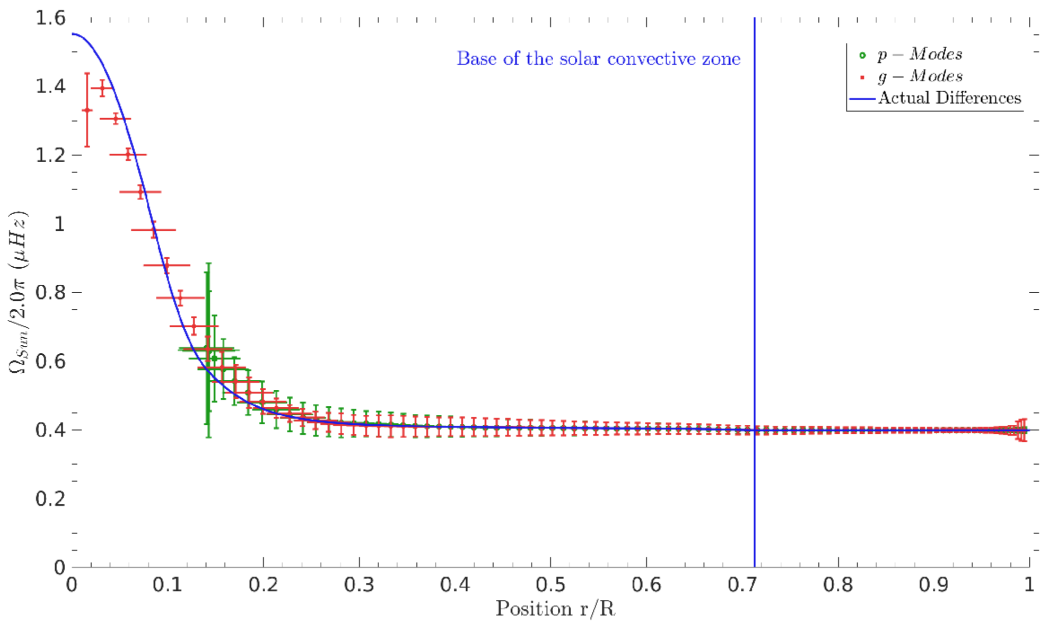

Figure 5: Inversion results for the internal solar rotation using the SOLA method and artificial data. *In blue*: internal rotation profile of a Geneva model including meridional circulation, shear instability, and Tayler–Spruit instability (taken from Eggenberger et al. 2019, 2022) from which rotational splittings have been computed using the first-order variational integral formula. *In green*: SOLA inversion results using *p*-modes only, using splittings of modes from ℓ =1 to 250, taking uncertainties from Davies et al. (2014 for the low-*n*, low-ℓ modes and those of Mathur et al. (2008) for the high-*n* low-ℓ modes. *In red:* SOLA inversion results using *p*-modes as mentioned above to which 10 to 20 *g*-modes around ν =100 μHz with uncertainties on their simulated splittings of 30 nHz have been considered. (Courtesy G. Buldgren)

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Rotation splittings were generated for the *p*-modes using a combination of BiSON and MDI data from Davies et al. (2014) and Basu et al. (2009), with ℓ going from 1 to 250. The uncertainties on the *p*-mode splittings were estimated to be the same as those of the oscillation modes themselves, in the exception of two regimes: the low-ℓ, low-*n* frequencies for which the actual uncertainties from Davies et al. (2014) were used, as well as for the low-ℓ high-*n* frequencies, for which the uncertainties and modes considered in the set were estimated from Mathur et al. (2008). The *g*-mode splittings were generated in the same way, considering modes around 100 μHz that have the highest detection probability according to recent theoretical estimates (Pinçon, Appourchaux, and Buldgen, 2021; Belkacem, Pinçon, Buldgen, 2022) using uncertainties estimated to range from 13 to 1 μHz for modes from around 160 μHz to 38 μ Hz. Tests were attempted with 10 and 20 *g*-modes, considering only the highest-frequency range in the reduced set.

Further tests using less precise splittings, simulated effects of activity on high-frequency *p*-modes and/or inclusion of 2D effects could be carried out. It is very likely that these last two effects would impact the performance of the inversion using *p*-modes only (green), as can be seen from Mathur et al. (2008), while the *g*-modes would be mostly affected by the uncertainties on the *g*-mode splittings. The *p*-mode-only inversion exhibits rapidly increasing uncertainties below 0.2 $R_\odot$ and fails completely below 0.15 $R_\odot$, while with the addition of a few *g*-modes, the inversions recover the "target" rotation with high fidelity down to below 0.015 $R_\odot$ – ten times closer to the center of the Sun!

g-mode observations should have a similar impact for inversions for the structure of the core

Additional Points

In addition to these inversions of the frequencies of a few solar *g*-modes, the amplitudes of *g*-modes are highly sensitive to the nature of their excitation, e.g. by penetrative convection at the base of the convection zone, and the detected amplitudes will provide powerful constraints on the convective motions and turbulence believed to determine their excitation.

Finally, in parallel, other less well studied approaches such as excitation by the general relativity gravity waves (e.g. Burston et al. 2008) should be kept in mind.

Future Needs:

- Support of research into the physics of solar *g*-modes and development of new techniques for their detection with future and legacy data.
- Development and deployment of new, innovative instrumentation for the measurement of solar internal *g*-mode frequencies

Conclusion

Given the great importance of the questions concerning the unknown structure and dynamics of the Sun, and solar-like stars on the one hand, and the uncertainties of the amplitudes, and hence detectability of solar *g*-modes on the other, *the proposed investigation is an archetype of a high risk, high reward investigation*

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