Strong constraints on a sharp change in G as a solution to the Hubble tension

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ABSTRACT

It has been proposed that if the gravitational constant *G* abruptly decreased around 130 Myr ago, then Type Ia supernovae (SNe) in the Hubble flow would have a different luminosity to those in host galaxies with Cepheid distances. This would make Hubble flow SNe more distant, causing redshifts to rise slower with distance, potentially solving the Hubble tension. We find that since the luminosities of Sun-like stars scale as approximately G^7 , the Solar luminosity would have dropped substantially 130 Myr ago in this scenario, pushing Earth into a planetary glaciation. However, there was no Snowball Earth episode in the last 500 Myr. The *G* step model (GSM) also implies that the length of a year would have abruptly increased by about 10%, but the number of days per year has evolved broadly continuously according to geochronometry and cyclostratigraphy. The GSM would drastically alter stellar evolution, causing the Sun to have exhausted about 2/3 of its fuel supply rather than 1/2. This would lead to the helioseismic age of the Sun differing from that of the oldest meteorite samples, but these agree excellently in practice. There is also excellent agreement between the standard expansion history and that traced by cosmic chronometers, but these would disagree severely in the GSM. Moreover, distance indicators that use stellar luminosities would differ drastically beyond 40 Mpc from those that do not. These arguments cast very severe doubt on the viability of the GSM: the solution to the Hubble tension must be sought elsewhere.

Key words: gravitation – cosmological parameters – cosmology: theory – distance scale – Sun: helioseismology – planets and satellites: dynamical evolution and stability

1 INTRODUCTION

Cosmology is currently in a crisis because the redshift z of objects in the local Universe increases with their distance r more steeply than expected in the standard cosmological paradigm known as Λ -Cold Dark Matter (Λ CDM; Efstathiou, Sutherland & Maddox 1990; Ostriker & Steinhardt 1995) if its parameters are calibrated using the pattern of anisotropies in the cosmic microwave background (CMB). Measurements of the CMB with the *Planck* satellite imply that in a Λ CDM context, the Hubble constant $H_0 = 67.6 \pm 0.5$ km/s/Mpc (Tristram et al. 2024), a value we denote H_0^{Planck} (Planck Collaboration VI 2020). In a homogeneously expanding universe, this should be the local redshift gradient cz', where c is the speed of light and $z' \equiv dz/dr$. However, observations using a variety of distance indicators show that cz' is about 10% larger (Scolnic et al. 2024, and references therein). This discrepancy is known as the Hubble tension (for a review, see Di Valentino 2021).

Various solutions have been proposed for the Hubble tension (for a review, see Di Valentino et al. 2021). One can question whether observations of the CMB really imply such a low H_0 , which is not the case in early dark energy models (Poulin et al. 2023, and references therein). If we avoid the difficulties with such approaches by assuming that $H_0 = H_0^{\text{Planck}}$ (Vagnozzi 2021, 2023; Toda et al.

2024), we can question if $H_0 = cz'$, an assumption that is violated if we are living in a large local void (Keenan et al. 2013; Haslbauer et al. 2020; Mazurenko et al. 2024). Here, we focus on a possible scenario in which the local cz' is smaller than typically quoted in the literature. Since the redshifts are spectroscopically determined, such a scenario requires that the distances to the relevant objects be larger than published. The main route to measuring the local cz' involves Type Ia supernovae (SNe) in the 'Hubble flow' at redshifts of about 0.023 - 0.15 or distances of about 100 - 600 Mpc, where peculiar velocities should have little effect on cz' (Camarena & Marra 2018, 2020a,b). To calibrate the absolute SN magnitude, it is necessary to use SNe at distances $\lesssim 40$ Mpc so that the distance to the host galaxy can be determined, typically using Cepheid variables or the tip of the red giant branch (TRGB; Baade 1944; Li & Beaton 2024). The period-luminosity relation of Cepheid variables (the Leavitt law; Leavitt 1907) and the TRGB magnitude can be calibrated in the Milky Way using geometric distances.

The Cepheid–SNe route is the most well-established way to obtain the local cz'. However, a problem with one or more links in this 'distance ladder' could potentially invalidate the measurement. In particular, it is necessary to assume that the same Leavitt law continues to hold in galaxies too distant for geometric anchors. Likewise, SNe in host galaxies with Cepheid distances must be similar to SNe in the Hubble flow. The proposal we will focus on questions this last link in the logical chain by postulating that the gravitational constant

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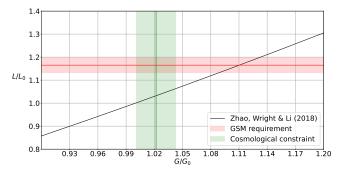


Figure 1. Comparison of constraints on and requirements of the GSM. The black line shows the dependence of the luminosity of a Type Ia SN on G in units of the terrestrial value G_0 (see figure 1 of Zhao et al. 2018). This calculation accounts for changes in the shape of the light curve (Wright & Li 2018), which impacts the standardised SN luminosity L that enters cosmological analyses. Following appendix B of Desmond et al. (2019), we show a power-law fit to the results of Wright & Li (2018), $L \simeq G^{1.46}$. The horizontal red band shows the required value of L in units of the standard value L_0 that would be required to solve the Hubble tension by inflating the distances to SNe in the Hubble flow (Equation 1). In the GSM, these SNe were brighter than the nearby SNe in host galaxies with Cepheid distances because G was larger than today $\gtrsim 130$ Myr ago. The vertical green band shows the cosmological constraint on G using the latest CMB and baryon acoustic oscillation data (Lamine et al. 2024). It is evident that the required enhancement to G is in considerable tension with cosmological constraints. even though the aim of the GSM is to preserve the Planck cosmology. This is even before the more stringent Solar System-scale constraints described in the text.

G changed abruptly $\gtrsim 130$ Myr ago, which corresponds to distances $\gtrsim 40$ Mpc, beyond the present range of Cepheid calibration. The *G* step model (GSM; Marra & Perivolaropoulos 2021; Perivolaropoulos & Skara 2021; Perivolaropoulos 2024; Ruchika et al. 2024a,b) exploits this gap between the outer limit of Cepheid distances to SN host galaxies and the inner limit to what can be considered the Hubble flow. Since the Leavitt law is calibrated empirically and the terrestrial value of *G* applies to the entire Cepheid calibration zone, the GSM does not affect the Cepheid distances to SN host galaxies.

The GSM relies on the fact that *G* affects the SN luminosity *L* that enters into cosmological analyses (Wright & Li 2018; Zhao et al. 2018). The calculation is complicated somewhat by the fact that Type Ia SNe are not standard candles but are standardisable (as indeed are Cepheids). It is well known that the peak luminosity correlates with the time required for the SN light curve to decay (Phillips 1993; Phillips et al. 1999). Changing *G* affects both the peak luminosity and the decay time. Cosmological analyses correct SNe for the latter (and also for the SN colour) using the Tripp formula (Tripp 1998; Brout et al. 2022). It is therefore necessary to use the Tripp-corrected SN luminosity *L*, which has the value L_0 for the terrestrially measured gravitational constant of G_0 . We use Figure 1 to show the power-law fit to the Wright & Li (2018) relation between L/L_0 and G/G_0 ($L \simeq G^{1.46}$; see appendix B of Desmond et al. 2019).

To explain the mismatch between H_0^{Planck} and the local $cz' = 73.0 \pm 1.0 \text{ km/s/Mpc}$ (Riess et al. 2022b), we require that

$$\frac{L}{L_0} = \left(\frac{cz'}{H_0^{\text{Planck}}}\right)^2.$$
 (1)

This is because the reported distances to Hubble flow SNe must be scaled by $\sqrt{L/L_0}$ to account for the proposed higher G in the past. The larger distance would then reduce cz' and solve the Hubble

tension. The horizontal red band in Figure 1 shows the range of L/L_0 that would achieve this. The GSM requires higher G prior to the transition, opposite to the change hinted at by the Tully–Fisher scaling relation (Alestas, Antoniou & Perivolaropoulos 2021).

Since the GSM aims to preserve the Planck cosmology, one may worry whether a higher G prior to recombination would affect the CMB anisotropies. This is an important issue given that CMB observations probe well into the diffusion damping tail, which does in fact constrain the pre-transition value of G relevant to cosmology (Ooba et al. 2016, 2017). These constraints have steadily improved (Ballardini et al. 2022; Sakr & Sapone 2022) and now limit the cosmologically relevant value of G to within a few percent of the terrestrial value (Lamine et al. 2024). As the cosmological observables they consider are barely sensitive to the cosmologically brief post-transition period where G had its modern value, we can interpret their study as constraining the pre-transition G. We show their constraint using the vertical green band in Figure 1. It is clear that the GSM struggles to explain early-Universe observables like the CMB consistently with the local cz' measured via the Cepheid– SNe route

In this work, we consider several other major problems with the GSM on a variety of scales. Section 2 considers how the proposed sharp drop in G would affect the Sun and the rest of the Solar System, especially the Earth. In Section 3, we consider the impact on the evolution of other stars and how that would affect other distance indicators and measures of cosmic expansion. We summarise our results in Section 4 and conclude by considering empirically viable model extensions. In Appendix A, we consider a few more subtle consequences of the GSM and discuss how these might be constrained by future investigations.

2 IMPACT ON THE SOLAR SYSTEM

The GSM has drastic consequences in the Solar System, which we discuss in this section. The effects on the Sun (Section 2.1) would in turn affect Earth, both in terms of its climate (Section 2.2) and its orbit (Section 2.3). On a smaller scale, a sharp drop in G would also affect the Earth–Moon system (Section 2.4).

2.1 Evolution of the Sun

The nuclear reactions in the cores of stars are very sensitive to their central density and temperature, which in turn are governed by the need to maintain hydrostatic equilibrium. Consequently, the Solar luminosity $L_{\odot} \stackrel{\propto}{\sim} G^7$ (Teller 1948; degl'Innocenti et al. 1996). This very steep scaling implies that if G was just 4% higher than today over the vast majority of Solar history, then L_{\odot} would have been 30% larger than with constant G. The more rapid evolution of the Sun would lead to a significant mismatch between its age estimated using asteroseismology and the precisely known 4.567 Gyr age of the Solar System from radioactive dating of the oldest meteorite samples (Connelly et al. 2012). However, asteroseismic observations of the Sun give an age quite consistent with meteorites (Guenther 1998; Bonanno & Fröhlich 2020; Bétrisey et al. 2024). A very substantial inconsistency is to be expected if the Sun was shining 30% brighter than in standard theory until the very recent past, as by now it would have used up 2/3 of its fuel supply rather than 1/2. This problem cannot be alleviated by postulating that G has a somewhat smaller impact on L_{\odot} than assumed above (e.g., with the $L_{\odot} \propto G^4$ scaling proposed in equation 37 of Davis et al. 2012).

2.2 Impact on the terrestrial climate

The GSM implies a severe drop in L_{\odot} , but the sharp drop in G would also expand the Earth's orbital radius r. We will return to this issue in Section 2.3, but our main concern here is that this leads to a further drop in the Solar insolation on the Earth. Taking into account that Earth's specific angular momentum is $\sqrt{GM_{\odot}r}$ given its nearly circular orbit, a drop in G over several years increases r such that $r \propto 1/G$ in order to conserve angular momentum. Combined with the fact that $L_{\odot} \stackrel{\infty}{\simeq} G^7$, the Earth's blackbody temperature $T_{\oplus} \propto G^{9/4}$ (Teller 1948).

In reality, the Earth is of course not a perfect blackbody in equilibrium with the incident Solar radiation. On long timescales, its climate is maintained in the temperature range that allows liquid water oceans thanks to the carbonate-silicate cycle, which relies on the temperature dependence of weathering processes that remove the greenhouse gas CO₂ (Walker, Hays & Kasting 1981). However, reduced weathering would take many Myr to allow volcanic outgassing to build up enough atmospheric CO2 to compensate for such a drastic reduction in Solar insolation. It is therefore inevitable that the Earth would experience a period of significantly reduced temperature. Given that $T_{\oplus} \approx 300$ K today and that the drop in G must be > 5%, we find that T_{\oplus} would have dropped by > 11% to temperatures below the freezing point of water. As water turned to ice near the polar regions, the surface would have become more reflective, further reducing the temperature. This ice-albedo feedback effect (Budyko 1969; Sellers 1973) would most likely lead to a planetary glaciation lasting many Myr.

Historically, there is actually very strong evidence for several such Snowball Earth episodes (for a review, see Banik 2016). However, these all took place $\gtrsim 600$ Myr ago. This corresponds to a distance of almost 200 Mpc, where we can assume a fairly smooth distance-redshift relation. It is not possible to put the GSM that far back in the past because this would lead to a severe mismatch between the luminosities of Hubble flow SNe with redshifts either side of the transition, which have a similar distance. A feature would be produced in the SN Hubble diagram, which is not observed. The only way to 'hide' a substantial transition in L_0 (and hence in apparent magnitude at given z) is if it occurred sufficiently nearby that the redshift cannot be used to reliably determine the distance and thus lookback time. Peculiar velocities would 'blur out' such a local transition, but not one in the Hubble flow region that starts $\gtrsim 100$ Mpc away in standard cosmology. The transition must therefore lie closer to us, and hence cannot be matched to an observed Snowball Earth episode (see Section 4 for the possibility that the issue is instead in the lowest rung of the distance ladder). The lack of any Snowball Earth episode in the past 500 Myr implies that the proposed sharp drop in G did not occur within 150 Mpc, which however is necessary for the GSM to solve the Hubble tension. This already casts very severe doubt on the GSM.

2.3 Geochronometry and cyclostratigraphy

The proposed drop in *G* would increase the length of a year $\propto G^2$. Using the length of a day as a standard clock which would not change rapidly due to a drop in *G*, we see that the number of days per year would undergo a sharp increase on geological timescales. The minimum plausible 5% drop in *G* would cause a 10% increase. This corresponds to each year having only 332 days prior to the transition and the modern 365 days afterwards.

This unusual behaviour can be tested using geochronometry, the idea that fossilised remains of living organisms are sensitive

to familiar cycles. It is common to use tree rings to reconstruct past climate conditions and count the age of a tree in years. Of more importance for our discussion is an underwater analogue to this idea. In particular, corals rely on sunlight, making them very sensitive to day/night cycles. But their growth also varies over the year due to seasons. By studying coral growth patterns in great detail, it is possible to determine the number of days per year many hundreds of Myr in the past (Wells 1963; de Winter et al. 2020). The related technique of cyclostratigraphy exploits the related idea that deposition of sediments is also cyclic (Huang et al. 2024).¹

These studies reveal that the number of days per year continuously declined with time. This is thought to be due to days gradually getting longer thanks to tidal evolution of the Earth–Moon system (Section 2.4). Tides would no doubt also operate in the GSM, but there would be an additional sharp 10% jump superimposed on the secular evolution. However, the geological data reveal only smooth trends, with the results from > 130 Myr ago smoothly extrapolating onto the present value. The data are therefore in tension with a 10% jump in the number of days per year 130 Myr ago.

2.4 Impact on the Earth–Moon tidal evolution

The proposed drop in *G* would enlarge not only Earth's orbit around the Sun, but also the Moon's orbital radius *R* around the Earth. Following similar arguments, the GSM implies that $R \propto 1/G$. Since the lunar tidal stress on the Earth $\propto G/R^3 \propto G^4$, a decrease in *G* would substantially weaken oceanic tides on the Earth, which are largely caused by the Moon. On long timescales, gravitational attraction between the oceanic tidal bulges and the Moon causes it to slowly recede from Earth, a phenomenon which has been directly detected thanks to lunar laser ranging (Folkner et al. 2014). The orbital angular momentum of the Moon ultimately comes from the rotational angular momentum of the Earth, which correspondingly slows down and thus has longer days.

The lunar recession rate and the terrestrial spindown rate must have been much higher prior to the transition. A sharp change in the terrestrial spindown rate would lead to a discontinuity in the time derivative of the number of days per year, which would evolve much more rapidly prior to the transition. No such discontinuity is apparent in the data over the past few hundred Myr (de Winter et al. 2020; Huang et al. 2024). All this makes it unlikely that there was a significant discontinuity 130 Myr ago both in the number of days per year and in how quickly this was evolving with time (though the evolution is not completely uniform; see Huang et al. 2024).

3 IMPACT ON STELLAR PROBES OF THE DISTANCE LADDER

The distance ladder can be calibrated with many different types of star, whose luminosities exhibit a variety of dependences on the value of *G*. Thus, distance indicators calibrated to match each other within 40 Mpc would likely become discrepant beyond the proposed transition. For instance, Cepheid variable pulsations respond differently to main sequence stars (Jain et al. 2013; Sakstein 2013), whose average luminosity is essentially what the surface brightness fluctuation (SBF) technique measures (Cantiello & Blakeslee 2023).

¹ Workers sometimes assume a fixed length of year and report the observed number of days per year as the number of hours per day.

The TRGB magnitude (Anand et al. 2022, 2024) responds still differently (Sakstein et al. 2019), which by comparison with Cepheid distances has allowed workers to place $\approx 5 - 10\%$ constraints on G/G_0 (Desmond et al. 2019; Desmond & Sakstein 2020). Geometric distances to megamasers would not be much affected (Pesce et al. 2020); as all but one of the megamasers considered by those authors are beyond the GSM transition, further constraints could be obtained by comparing megamaser distances to those obtained in ways that are sensitive to *G*.

It has recently become possible to use the Fundamental Plane relation of elliptical galaxies (Djorgovski & Davis 1987; Dressler et al. 1987) to constrain the local redshift gradient anchored to the distance to the Coma Cluster (Said et al. 2024). This lies well beyond the proposed transition, but we have to go across the transition to estimate the distance to Coma and thereby calibrate the zero-point of the Fundamental Plane distance-redshift relation. Different techniques give rather similar distances to Coma, with none suggesting that it lies > 110 Mpc away (Scolnic et al. 2024). However, the local $cz' = H_0^{\text{Planck}}$ only if this is the case. For our discussion, the important point is the agreement between the distance to Coma as found using a variety of different distance indicators, whose absolute calibrations are generally performed closer than the proposed transition. The GSM would alter the SN distance to Coma in a manner that would solve the Hubble tension, but it seems very unlikely that the same can be said for all the other distance indicators. In particular, the luminosities of main sequence stars are much more sensitive to G than the Tripp-corrected SN luminosity (Figure 1). Because of this, it seems difficult to place Coma > 110 Mpc away while retaining agreement with the different available distance indicators, at least if the underestimated distances are due to underestimated G_{\cdot}

Another issue with the GSM concerns the tight scaling relations evident in galaxies, especially the radial acceleration relation (RAR; Lelli et al. 2017) and the related Tully-Fisher (Tully & Fisher 1977) relation in spiral galaxies and the Faber-Jackson (Faber & Jackson 1976) relation and Fundamental Plane in elliptical galaxies. Regardless of the underlying origin of such relations, if the M_{\star}/L ratios of galaxies within 40 Mpc are 30% higher than for more distant galaxies, then the scaling relations could not be as tight as they are observed to be. In addition, there would be substantial differences between samples split according to the transition distance. However, the intrinsic scatter in the RAR is very small (Li et al. 2018; Desmond 2023) and the residuals do not correlate with a wide variety of galaxy properties, including distance (Stiskalek & Desmond 2023). This is highly problematic for the GSM because the Spitzer Photometry and Accurate Rotation Curves (SPARC) dataset in which the RAR is best measured has many galaxies on either side of the proposed transition (Lelli et al. 2016).

3.1 Stellar ages and cosmic chronometers

As discussed in Section 2.1, stars would be much more luminous prior to the proposed transition than in standard models of stellar evolution, which assume constant *G*. This would correspondingly shorten the lifetime of a star born near the Big Bang and just now reaching its red giant phase. As a result, the oldest stars that we observe would be ≈ 3 Gyr younger (see also Davis et al. 2012).

The ages of the oldest stars and stellar populations in the Galactic disc and halo (Cimatti & Moresco 2023) agree quite well with the age of the Universe in the *Planck* cosmology assumed by the GSM (e.g., Banik & Samaras 2024). This agreement applies to standard calculations of the stellar ages. If instead the ages are recalculated assuming higher *G* over nearly the entire lifetime of each star, then there would be an \approx 3 Gyr mismatch. It would be quite unusual if no stars were identifiable from the first 3 Gyr, especially when considering that several galaxies have already been discovered by the JWST at *z* > 14 (Carniani et al. 2024). In the *Planck* cosmology assumed by the GSM, this corresponds to only 0.3 Gyr after the Big Bang, which may be faster than expected in the Λ CDM model (Haslbauer et al. 2022). A more severe version of this age gap problem applies to the covarying coupling constants model, which predicts that the universe is 26.7 Gyr old (Gupta 2023).

It is also possible to constrain the expansion history using cosmic chronometers (CCs; Moresco et al. 2018, 2020). The basic idea is to get the time elapsed between two redshifts by considering 'red and dead' quiescent elliptical galaxies that presumably formed their stars at very early times. The stellar population of such a galaxy would evolve passively, with only the less massive stars remaining at later times. This would change the relative strengths of spectral lines, allowing a determination of the relative age between galaxies at the two considered redshifts. The time difference would be overestimated in the GSM because stars would evolve far faster at higher G, giving the appearance that much more time had elapsed. Observers assuming constant G would then significantly underestimate the Hubble parameter, almost certainly making it no longer consistent with the predicted evolution in the assumed Planck background cosmology. However, the expansion history that it predicts is in excellent agreement with that reconstructed using the CC technique (Gómez-Valent & Amendola 2018; Cogato et al. 2024). It is difficult to understand how this agreement can be preserved in the GSM, even if stellar luminosities scale with G somewhat less steeply than expected theoretically (G^7 ; see Teller 1948; degl'Innocenti et al. 1996). It is also very problematic that a change in G would necessarily apply to both Hubble flow SNe and main sequence stars. This serious problem with the GSM could potentially be avoided in models with a screening mechanism, which we discuss in the next section.

4 SUMMARY AND MODEL EXTENSIONS

The GSM hypothesis postulates that due to a sharp reduction in G by about 10% in the last $\approx 50-300$ Myr, Type Ia SNe in the Hubble flow have a higher luminosity than SNe in host galaxies near enough to have their distance measured using the Leavitt law of Cepheid variables (Marra & Perivolaropoulos 2021; Perivolaropoulos & Skara 2021; Perivolaropoulos 2024; Ruchika et al. 2024a,b). As a result, distances to Hubble flow SNe would have to be revised upwards, reducing the locally measured cz' and plausibly reconciling it with the Λ CDM prediction based on the *Planck* cosmology, which is chosen to fit the CMB anisotropies without regard to the local cz'.

We find that the GSM has several unintended consequences because G affects a plethora of other astrophysical observables besides the luminosity of Type Ia SNe. The main issues we identified with the GSM are:

(i) The Solar luminosity $L_{\odot} \simeq G^7$ (Teller 1948; degl'Innocenti et al. 1996). A sharp drop in *G* and thus L_{\odot} (combined with the resulting expansion of Earth's orbit) would have plunged the Earth into a planetary glaciation due to the ice-albedo feedback effect (Budyko 1969; Sellers 1973). Although there have been several Snowball Earth episodes, none occurred in the time period relevant to the GSM (Banik 2016, and references therein).

(ii) A reduction in G would cause Earth's orbit to expand, increasing the length of a year. However, the number of days would not

change in like manner because the Earth is bound by chemical forces rather than gravity. As a result, the number of days per year would sharply increase by $\gtrsim 10\%$. It is possible to constrain this using geochronometry and cyclostratigraphy (Section 2.3), for instance using corals that are sensitive to both daily and seasonal cycles (Wells 1963). There is no indication of such a rapid change in the number of days per year (de Winter et al. 2020; Huang et al. 2024). Instead, extrapolating trends in the data prior to the *G* transition gives a value close to the present-day value of 365.25.

(iii) The expansion of gravitationally bound orbits would also apply to the Moon. A rapid increase in the Moon's distance from Earth combined with a reduced G would sharply decrease the amplitude of Earth's oceanic tidal bulges. Since gravitational interactions between these bulges and the Moon cause the Earth's spin to slow down, there would be a discontinuity in the time derivative of the number of days per year, which must have evolved much more rapidly prior to the transition. There is again no evidence of this, suggesting that the distance to the Moon did not jump by 10% on a geologically short timescale in the last few hundred Myr.

(iv) The local cz' can be obtained using several other techniques besides the traditional Cepheid-SNe route (e.g. Riess & Breuval 2024, and references therein). Since these give quite similar results, it is unlikely that the evolution of G can be chosen to alter all the distances in step with each other. In particular, the GSM implies that stars were substantially brighter prior to the proposed transition. This would lead to a very severe mismatch between distance techniques that rely on stellar luminosities and those that do not. For instance, we would expect a severe mismatch between redshift distances and SBF distances, which are sensitive to the luminosityweighted mean stellar luminosity (Cantiello & Blakeslee 2023). A drastic difference between the M_{\star}/L ratios of galaxies within and beyond the proposed transition would also introduce a large mismatch in galaxy scaling relations like the Tully-Fisher relation and Fundamental Plane, in particular making it very difficult to understand how galaxy samples that extend both sides of any plausible transition radius follow such a tight RAR (Desmond 2023; Stiskalek & Desmond 2023).

(v) The GSM implies substantially faster stellar evolution prior to the transition, and thus over the vast majority of cosmic history. This would lead to the appearance that stellar populations of quiescent galaxies have aged much more between any two redshifts, causing the cosmic expansion history estimated using the CC technique to differ substantially from the *Planck* cosmology assumed in the GSM. However, there is excellent agreement in practice (Cogato et al. 2024). This also applies to the ages of the oldest stars and stellar populations in the Galactic disc and halo, which yield a cosmic age in good agreement with the *Planck* cosmology (Cimatti & Moresco 2023). The GSM would force a substantial downward revision to these ages, leading to an age gap of \approx 3 Gyr in the early universe lacking any known stellar counterpart.

Our consideration of these issues suggests that the GSM faces insurmountable difficulties when additional constraints are imposed on the evolution of G over the past \sim 300 Myr, the light travel time to the nearest Hubble flow SNe. Moreover, the local redshift gradient can be obtained in several ways that do not rely on the traditional Cepheid–SNe route, yet give similar results. We therefore argue that the GSM is not a viable solution to the Hubble tension.

The GSM focuses on the possibility that the local cz' has been overestimated because of a mismatch between the luminosities of SNe in the Hubble flow and those in more nearby host galaxies with an independent Cepheid or TRGB calibration. The difficulties with the GSM lead us to consider if the problem might lie rather with the first rung, which assumes that the Leavitt law and TRGB magnitude are the same between anchor galaxies and SN host galaxies. One way to violate this assumption would be through a rapid evolution in G, which would need to occur even more recently than in the GSM. This would if anything exacerbate the already very severe problems we have identified with the GSM.

Most if not all of these issues can however be resolved by replacing the GSM with a more physically motivated model in which *G* effectively correlates with environmental density due to screening, naturally hiding the modification within the Galaxy. This may shield the model from anomalous effects in stars and their planetary systems – from which most of the above constraints derive – while still affecting the distance ladder enough to reduce the local cz' down to the *Planck* Λ CDM prediction. Indeed, screening mechanisms are generic in modified gravity theories (for recent reviews, see Baker et al. 2019; Brax et al. 2022).

A model along these lines was developed in Desmond et al. (2019), where it was proposed that the Leavitt law in the anchor galaxies NGC 4258, the Milky Way, and the Large Magellanic Cloud is different to that in SN host galaxies due to screening effectively correlating G with one of various measures of environmental density, including local dark matter density (Sakstein et al. 2019). Such a model does not modify SNe themselves, but there is an effective difference between the period-luminosity relations of Cepheids in galaxies with geometric anchors versus SN host galaxies, which are used to calibrate the SN absolute magnitude. This alters the distances to all Hubble flow SNe by the same factor, with corresponding impact on the local cz' given the lack of any impact on z. Imposing the constraint on G from Cepheid-TRGB consistency, this allows the SH0ES Hubble tension to be reduced to $\approx 2.5\sigma$ (Desmond et al. 2019), while that for the TRGB-calibrated distance ladder is completely resolved (Desmond & Sakstein 2020). Although it is unclear if this remains the case with the latest measurements from the James Webb Space Telescope (JWST; Freedman et al. 2024; Riess et al. 2024), the screening model appears more attractive than the GSM due to its natural circumvention of the constraints we describe here as well as its far stronger theoretical motivation. Variants of this model are studied in Högâs & Mörtsell (2023a,b).

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DATA AVAILABILITY

No new data were created or analysed in this contribution.

APPENDIX A: ADDITIONAL CONSEQUENCES OF THE GSM & FUTURE TESTS

In this section, we collect a few more qualitative or speculative consequences of the GSM which could be used to construct stringent tests with future data and analysis.

The GSM would affect the propagation of gravitational waves (GWs; LIGO Collaboration 2016). It has been argued that GWs would propagate continuously, even during the period in which G varies rapidly (Paraskevas & Perivolaropoulos 2023). Nonetheless, it seems inevitable that the GSM would have different effects on distances based on stellar populations and those obtained using GWs as standard sirens. Further progress is possible using GWs with an electromagnetic counterpart, with one such instance having been reported so far (GW170817; see Virgo & LIGO Collaborations 2017). Its distance of 40 Mpc is right where the transition is proposed to have occurred. In the future, it should be possible to find similar events either side of the transition. This might eventually allow a determination of the maximum mass of neutron stars, which is sensitive to G and would therefore differ either side of the transition (Reyes & Sakstein 2024).

While the GSM would undoubtedly have severe impacts on the Sun (Section 2.1), it can be easier to model slightly less massive stars, yielding less model-dependent constraints on possible evolution of G. Bellinger & Christensen-Dalsgaard (2019) use asteroseismology of the star KIC 7970740 to constrain a model in which G gradually changes as a power-law in time since the Big Bang. The impact would be more severe than the gradual changes over a Hubble time considered by those authors if G were 5% larger than today for nearly the entire 11 Gyr history of KIC 7970740. It would be interesting to constrain the GSM with asteroseismology of this or other stars. However, the age would have to be inferred alongside the other parameters. The Sun offers an advantage in this respect because its age is known from radioactive dating of rock samples.

The GSM would cause bound, nearly circular orbits to expand $\propto 1/G$, an increase which would also affect the Moon (Section 2.4). It is unfortunately still difficult to detect the monthly cycles caused by the changing angle between the Moon and Sun causing cyclic variations in the tidal range. Future work may help to identify these cycles more reliably and thus better constrain the number of days between full Moons, which in the GSM would reveal a discontinuous behaviour.

If the proposed reduction in *G* occurred on a short enough timescale, any bound orbits would be somewhat destabilised. A sudden drop in the equilibrium circular velocity would cause an object initially on a circular orbit to find itself on a wider elliptical orbit. In the case of the Earth, this situation would arise if the transition occurred over $\ll 1$ yr. Its eccentricity would be 'pumped' by a sharp change in *G*. This is disfavoured by the fact that Earth's orbital eccentricity is only 0.017 and that of Venus only 0.007.

There would also be consequences elsewhere in the Solar System, including on the giant planets. In general, the whole Solar System would be somewhat destabilised. This would increase the likelihood of giant impacts on the Earth. Indeed, this very possibility has been related to the extinction of the dinosaurs and many other species in the Cretaceous–Paleogene extinction (Perivolaropoulos 2022), which occurred 66 Myr ago (Renne et al. 2013). This corresponds to a distance of only 20 Mpc, but there are Type Ia SNe with Cepheid calibration out to ≈ 40 Mpc (e.g., Riess et al. 2022a). Even so, recent studies suggest that the GSM can be reconciled with a transition at a lookback time corresponding to only 20 Mpc (Ruchika

et al. 2024a,b). It therefore remains possible that the GSM is associated with the Cretaceous–Paleogene extinction event, though it is not presently known whether the asteroid impact largely responsible for it was an isolated incident or part of a more general increase in giant impacts at that time, as would be expected in the GSM.

The eccentricity pumping effect discussed above could be mitigated if the transition occurred adiabatically, with G remaining roughly constant on an orbital timescale. This is certainly possible from a distance ladder perspective: the GSM would still work if the transition took several kyr or even a few Myr. However, Galactocentric orbits are necessarily much longer than would be available for the proposed transition. This could lead to unusual effects on orbiting stars and gas, possibly leading to an enhanced star formation rate as gas on an initially circular orbit is driven onto a more eccentric orbit. The orbital timescales are even longer for tidal streams due to their larger Galactocentric distance. A sharp drop in G would reduce the Galactic gravity on any satellite, not only directly but also indirectly by allowing the Galactic dark matter halo to expand, leading to less enclosed mass within the orbit of the satellite. This reduction in gravity would lead to a discontinuous curvature of the satellite's trajectory, which might be detectable in the Sagittarius tidal stream (Ibata et al. 2001; Newberg et al. 2002). Fainter tidal streams might be better suited to finding or ruling out the expected signature because the satellite would have a lower internal velocity dispersion, leading to a thinner and more clearly defined stream.

Finally, returning to the smaller scale of the Earth, a change in *G* would affect how it maintains hydrostatic equilibrium. The proposed reduction in *G* would cause it to expand slightly, as overlying layers of rock exert less weight. This may lead to unusual tectonic effects, possibly triggering earthquakes and volcanism. Life on the Earth would have to respond to these effects, and also more directly to the reduced surface gravity. Since complex life was widespread by the time of the proposed transition, it may have had interesting consequences for especially large land animals like dinosaurs – unless the transition is associated with their demise. This of course depends on the duration of the transition, which we have generally assumed would occur over $\gg 1$ yr. Life would undoubtedly adapt to a more gradual change in *G* over several kyr or Myr, though there might be interesting evolutionary consequences.

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