Evidence for missing matter in the inner solar system: does the Sun have a dark disk?

Susan Gardner

Department of Physics and Astronomy
University of Kentucky
Lexington, KY

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Based on G. Alves (USP), SG, P. Machado (Fermilab), & M. Zakeri (UK → EKU), Phys. Rev. D 111, 083057 (2025) [arXiv: 2406.03607] & in preparation

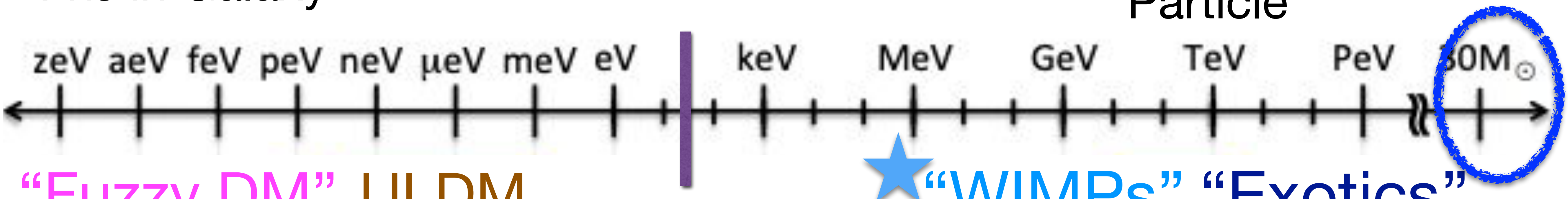
Dark Matter Parallel Session
CIPANP — Madison, WI
June 9, 2025

A Vast Range of Dark Matter Candidates

Particle Masses

Fits in Galaxy

Elementary Particle



“Fuzzy DM” ULDM

“WIMPs” “Exotics”

Phenomenology controlled by deBroglie λ at the Sun’s location:

$n_{DM} \lambda_{dB}^3 >> 1$

Wave-like!

$n_{DM} \lambda_{dB}^3 << 1$

Particle-like!

“Black Holes”!

DD experiments assume a “Standard Halo Model”

Here we probe the non-luminous matter distribution in the inner solar system directly!

Cosmic small-scale structure not known! [Bechtol et al., arXiv:2203.07354]

Non-steady-state effects exist! [Widrow, SG, Yanny, Dodelson, & Chen, 2012; Yanny & SG, 2013…; SG, Hinkel, Yanny, 2020]

Solar System Constraints on Dark Matter

From planetary ephemerides

[Pitaev & Pitaeva, Astro. Lett. 2013; using EPM2011]

The Kepler problem has a conserved vector (**A**): its orbits **close**

→ Broken by GR, background forces, to ensure that the planetary perihelia **precess**

677,000 observations of planets & spacecraft:

[N.B. Cassini, 2004]

strongest:

$$M_{\mathrm{DM\,enclosed}}\Big|_{\mathrm{Saturn}} < 1.7 \times 10^{-10}\, M_{\odot} \quad \text{(67\% CL)}$$

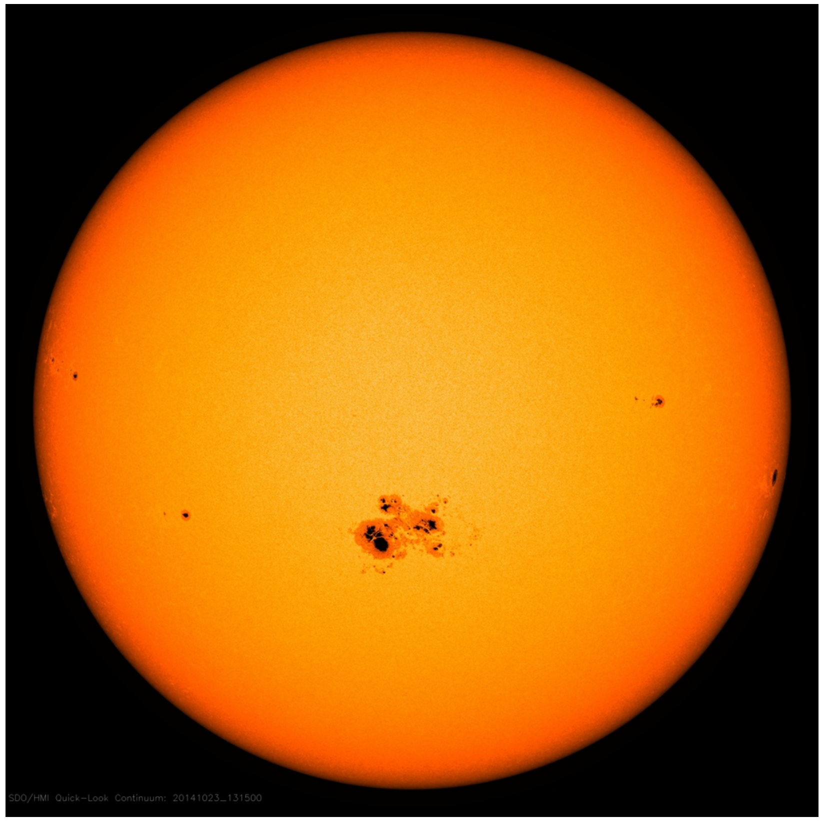
[Pitjeva & Pitjeva, 2013]

9.5 AU from Earth

What else? Thermal heating of planets (str. int. DM),…?

[Mack, Beacom, Bertone, 2007 ; Adler, 2008, 2009; Leane & Smirnov, 2023]

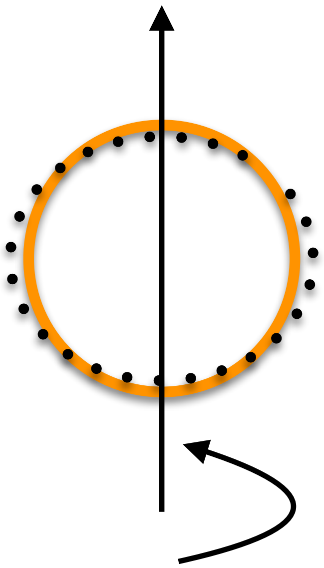
Our Sun



[October, 2014 Credit: NASA/SDO]

Sunspots known since ancient times

Galileo (1610) inferred the Sun **rotates**



Thus the Sun should become slightly oblate ($\sim \mathcal{O}(10^{-7})$)

And J_2, the gravitational quadrupole moment, is nonzero

$\tau_{\rm spin} \sim 27\,{\rm days}\,;\,{\rm tilt} \sim 7.25^\circ$ w.r.t. $\perp$ to orbital plane

$M_\odot \simeq 2 \times 10^{30}\,{\rm kg}$ (Note $G M_\odot$ inferred!)

$R_\odot \simeq 6.96 \times 10^5\,{\rm km} = 4.65 \times 10^{-3}\,{\rm AU}$

J_2 , the Gravitational Quadrupole Moment

can be determined in different ways

There are light & dark assays

- Direct measurements of the visual oblateness [Very challenging!]
- Measurements of the pattern of trapped acoustic waves that distort the observed surface of the Sun [This is **helioseismology** — here different solar models are employed]
- Measurements of Mercury's perihelion precession [Here we assume **Einstein's GR** is the theory of gravity]

N.B. sees all mass within its orbit

Patterns of Gravitational Quadrupole Moments

To probe the distribution of "extra" matter

If the extra matter is spherically distributed

$$J_2^{\rm Orb} < J_2^{\rm Opt}, J_2^{\rm Heli}$$

Extrinsic Intrinsic to Sun

If the extra matter is in the orbital plane

$$J_2^{\rm Orb} > J_2^{\rm Opt}, J_2^{\rm Heli}$$

Thus we consider $J_2^{\rm Heli}$, $J_2^{\rm Orb}$ in the GR limit, i.e.,

$$\delta J_2 \equiv J_2^{\rm Orb}|_{\beta=1\,\eta=0} - J_2^{\rm Heli}$$

to probe for non-luminous (and dark) matter

The Gravitational Quadrupole Moment

From orbital measurements

The parametrized Post-Newtonian (PPN) provides a model-independent framework in which to test GR

{Nordtvedt, 1968; Will & Nordtvedt, 1972}

For a planet in a bound orbit in the equatorial plane:

{MTW, 1973, e.g.}

$$r = \frac{(1-e^2)a}{1 + e\cos[(1-\delta\phi_0/2\pi)\phi]}$$

$$\delta\phi_0 = \frac{2-\beta+2\gamma}{3} \cdot \frac{6\pi M_\odot}{a(1-e^2)} + J_2 \frac{3\pi R_\odot^2}{a^2(1-e^2)^2}$$

perihelion shift

$\beta = \gamma = 1; \eta = 4\beta - \gamma - 3 = 0$ in GR

Cassini: $\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5}$ {Bertotti et al., 2003}

The Gravitational Quadrupole Moment

From MESSENGER (mission to Mercury)

Fits to β and J_2 are strongly correlated, yielding

[Genova et al., 2018]

$$J_2^{\rm Orb} = (2.246 \pm 0.022) \times 10^{-7} \quad ; \quad J_2^{\rm Orb}|_{\beta=1;\eta=0} = (2.2709 \pm 0.0044) \times 10^{-7}$$

Fits that include the Einstein-Lense-Thirring (ELT) and the PPN parameters β, γ are

$$J_2^{\rm Orb}|_{\beta=\gamma=1} = (2.28 \pm 0.06) \times 10^{-7}$$

Orbital J_2 measurements

#	$J_2(\times 10^{-7})$	$\pm J_2(\times 10^{-7})$	Reference
1	2.25	0.09	Park ,11–14 [28]
2	2.246	0.022	Genova, 08–15 [29]
3	2.165	0.12	Fienga, - [146]
4	2.206	0.03	Fienga, - [146]

MESSENGER (Mercury)

Planetary ephemerides

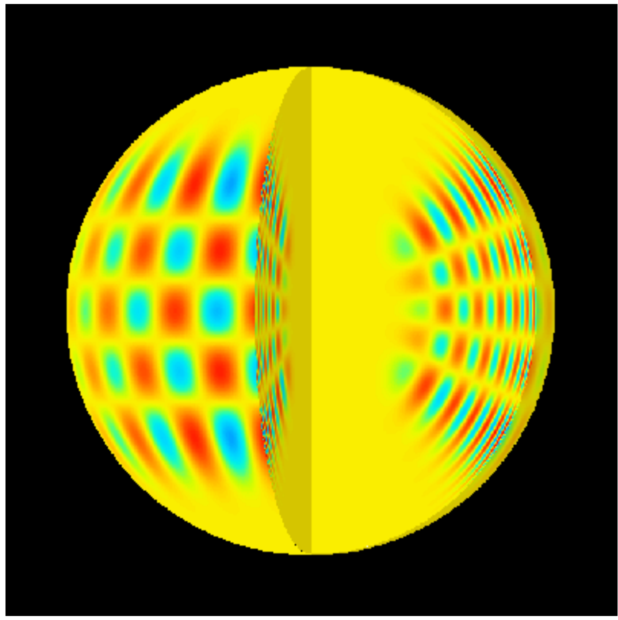
The Gravitational Quadrupole Moment

From helioseismology

— space-based or global network (GONG) —

Helioseismological J_2 measurements

Duration	#	$J_2(\times10^{-7})$	$\pm J_2(\times10^{-7})$	Reference	Solar Model	
	1	36	–	Gough [128]	[129, 130]	
	2	1.7	0.4	Duvall [131]	[129, 130]	
	3	55	13	Hill [132] [a]	– [b]	
	4	2.23	0.09	Pijpers [33]	[133]	
	5	2.22	0.02	Armstrong [134]	[135]	
	6	1.6	0.04	Godier [136, 137] [c]	[138]	
	7	2.201	–	Mecheri [23]	[95] [d]	
	8	2.198	–	Mecheri [23]	[95]	
1995-2011	9	2.220	0.009	Antia [103] [e] [t avg!]		
1996-2008	10	2.204	–	Mecheri [94]	[100]	model SoHO/MDI
	11	2.208	–	Mecheri [94]	[101]	
	12	2.206	–	Roxburgh [139]	[133]	+GONG
	13	2.208	–	Roxburgh [139]	[140]	
	14	2.14	0.09	Pijpers [33]	[133]	
	15	2.18	–	Antia [141]		GONG
1995-2011	16	2.180	0.005	Antia [103] [e] [t avg!]		
2010-2020	17	2.211	–	Mecheri [94]	[100]	model SDO/HMI
	18	2.216	–	Mecheri [94]	[101]	



[http://jsoc.stanford.edu/]

The Gravitational Quadrupole Moment

Outcomes from helioseismology

SDO/HMI

2010-2020 $$J_2^{\text{Heli}} = (2.214 \pm 0.002) \times 10^{-7}$$ ★

SoHO/MDI

1996-2008 $$J_2^{\text{Heli}} = (2.206 \pm 0.002) \times 10^{-7}$$

N.B. $|\Delta J_2| = 0.008 \pm 0.002$ cf. Antia et al., 2008 time dependence (0.009)

$$\delta J_2 \equiv J_2^{\text{Orb}}|_{\beta=1\,\eta=0} - J_2^{\text{Heli}} = (0.057 \pm 0.006) \times 10^{-7}$$

But if the Earth's orbit is not perfectly known (for β, γ free) $\pm 0.006 \rightarrow \pm 0.020$ [Konopliv, Park, Ermakov, 2020]

$\delta J_2 > 0$ implies a non-luminous (and dark) disk!

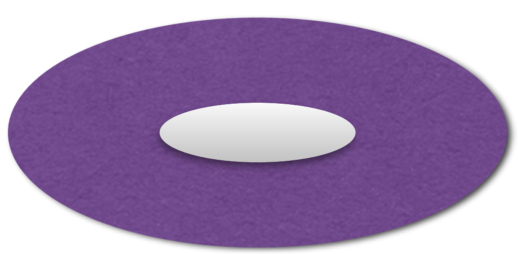
Interpretation of the J_2 Pattern

Consider a thin, dark disk or ring within Mercury's orbit

$$J_2^{\rm ring} = \frac{1}{M_r \bar{R}^2}(I_z - I_x)\,; \quad I_s = \int d^3 r \rho(\mathbf{r})(r^2 - (\mathbf{r}\cdot\hat{\mathbf{e}}^s)^2)$$

$$\begin{aligned} J_2^{\rm ext} &= (1-\epsilon_r)J_2^{\rm int} + \epsilon_r \left(\frac{\bar{R}}{R_\odot}\right)^2 J_2^{\rm ring} \\ &= (1-\epsilon_r)J_2^{\rm int} + \epsilon_r \left(\frac{1}{R_\odot^2}\right)\left[\frac{1}{4}(R_o^2 + R_i^2) - \frac{h^2}{12}\right] \end{aligned}$$

Mass fraction in the ring $\epsilon_r \equiv M_r/M_\odot$ Mean radius $\bar{R} \equiv (R_i + R_o)/2$

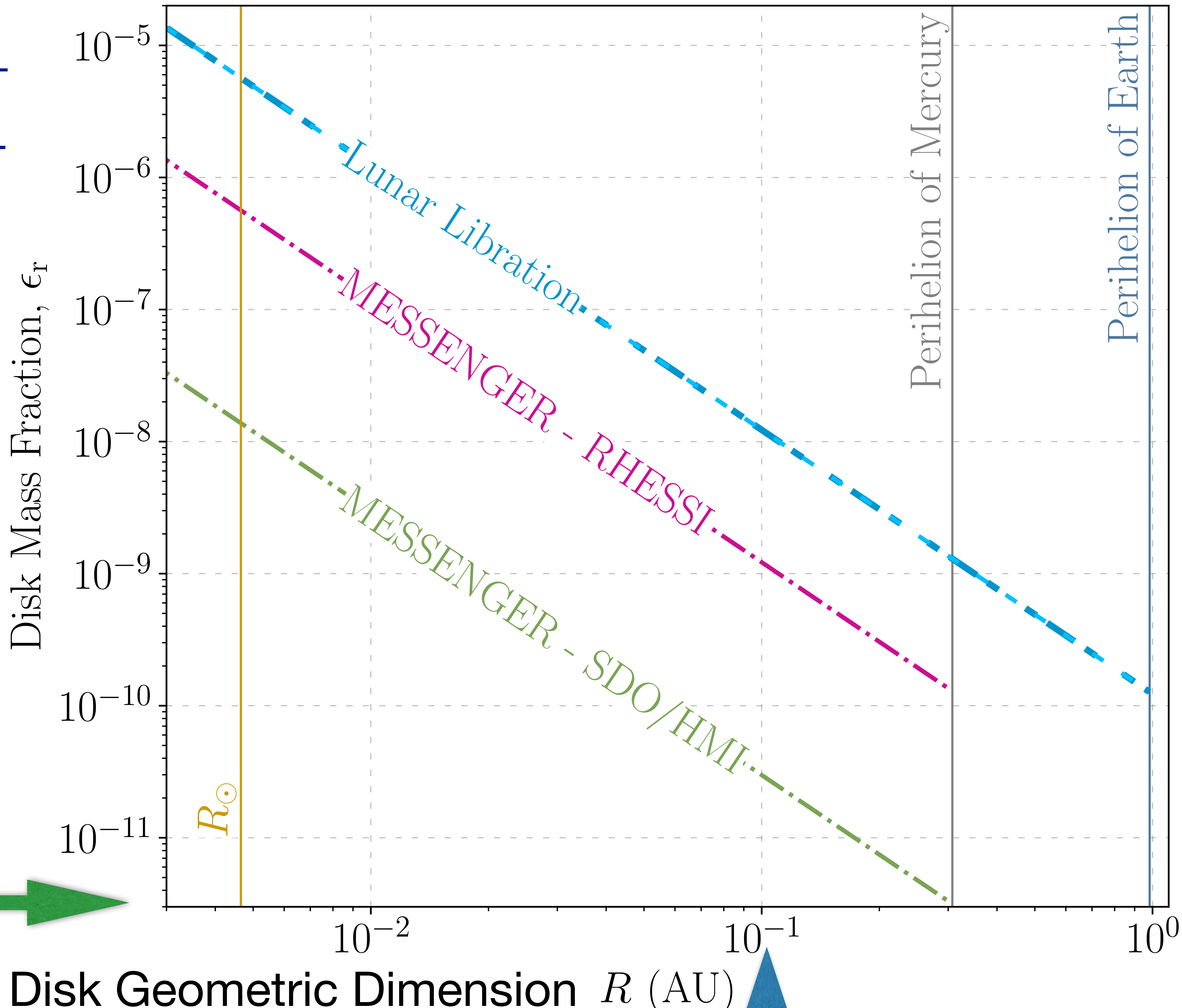


Solve for ϵ_r ; use $\delta J_2 \equiv J_2^{\rm ext} - J_2^{\rm int}$ to constrain non-luminous matter

Mass Limits at 95% CL

$$R \equiv \sqrt{\frac{R_o^2 + R_i^2}{2} - \frac{h^2}{6}}$$

$$\epsilon_r \approx 2\left(\frac{R_\odot}{R}\right)^2 \delta J_2$$



Could be saturated by a ring of $10^{-12}\, M_\odot$ in mass at $R \approx 0.38$ AU

dust ring

Dust Studies

for the detection of non-luminous matter within Mercury's orbit

A ring of dust has been discovered in the path of Mercury's orbit [Stenborg et al., 2018] from the STEREO mission [Kaiser et al., 2008] (excess reddening of light)

Its mass is poorly known, but a mass distribution model suggests that its mass could be about $(1.02 - 4.05) \times 10^{12\pm1}$ kg [Pokorny et al., 2023]

However, this is only about $10^{-18} M_\odot$!

2024

Direct evidence for a circumsolar dust ring has been found by WISPR on the Parker Solar Probe (excess dust - light scattering) at $\approx 25 R_\odot \approx 0.12$ AU

[Stenborg, Vourlidas, Paouris, Howard, ApJ, 972:24, 1 Sept, 2024]

Also note dust impacts on body of PSP via E-field instrument

[Szalay, Pokorny, Malaspina, Plan. Sci. J. 5:266, Dec., 2024]

Future Tests

Assuming normal statistics, we have discovered

$$J_2^{\rm Orb}|_{\beta=1\,\eta=0} - J_2^{\rm Heli} = 0.057 \pm 0.006\,[\pm 0.020]$$

which speaks to non-luminous matter (loosely) distributed within the plane of Mercury's orbit. A significant fraction of it would seem to be **dark matter**

Possible future probes or tests include

- *Detected perturbations in Mercury's orbit can speak to the existence of ultraheavy dark matter.*
- *Studies of light reddening in the inner solar system can be used to separate a dusty, non-luminous component from dark matter.*
- *The JUNO neutrino experiment is poised to measure CNO neutrinos with higher precision than BOREXINO and can test the latter's inference of a nonhomogeneous zero-age Sun, which supports the existence of an early protoplanetary disk, some of which may still remain.*

Also future searches (for TNOs…!) at larger distances from the Sun!

Does the Sun have a dark disk?

G. Alves, SG, P. Machado, M. Zakeri
Phys. Rev. D 111, 083057 (2025) [arXiv: 2406.03607]...

Yes and Yes?!

of non-luminous matter

of dark matter

Gustavo

Pedro

Zaki

Backup Slides

Mass Budget

What can contribute to this missing mass and by how much?

- Dust (grains, diameter 10(100) μm to 1 cm), estimate:

$$7 \times 10^{15\pm(\approx 1)}\,\mathrm{kg} \approx 3 \times 10^{-15\pm(\approx 1)}\,\mathrm{M}_{\odot}$$

- Rocks (assume same composition as dust), estimate 100 with radius 2.5 km would give ~ same mass as dust

- Micrometeroids, asteroids (small??)

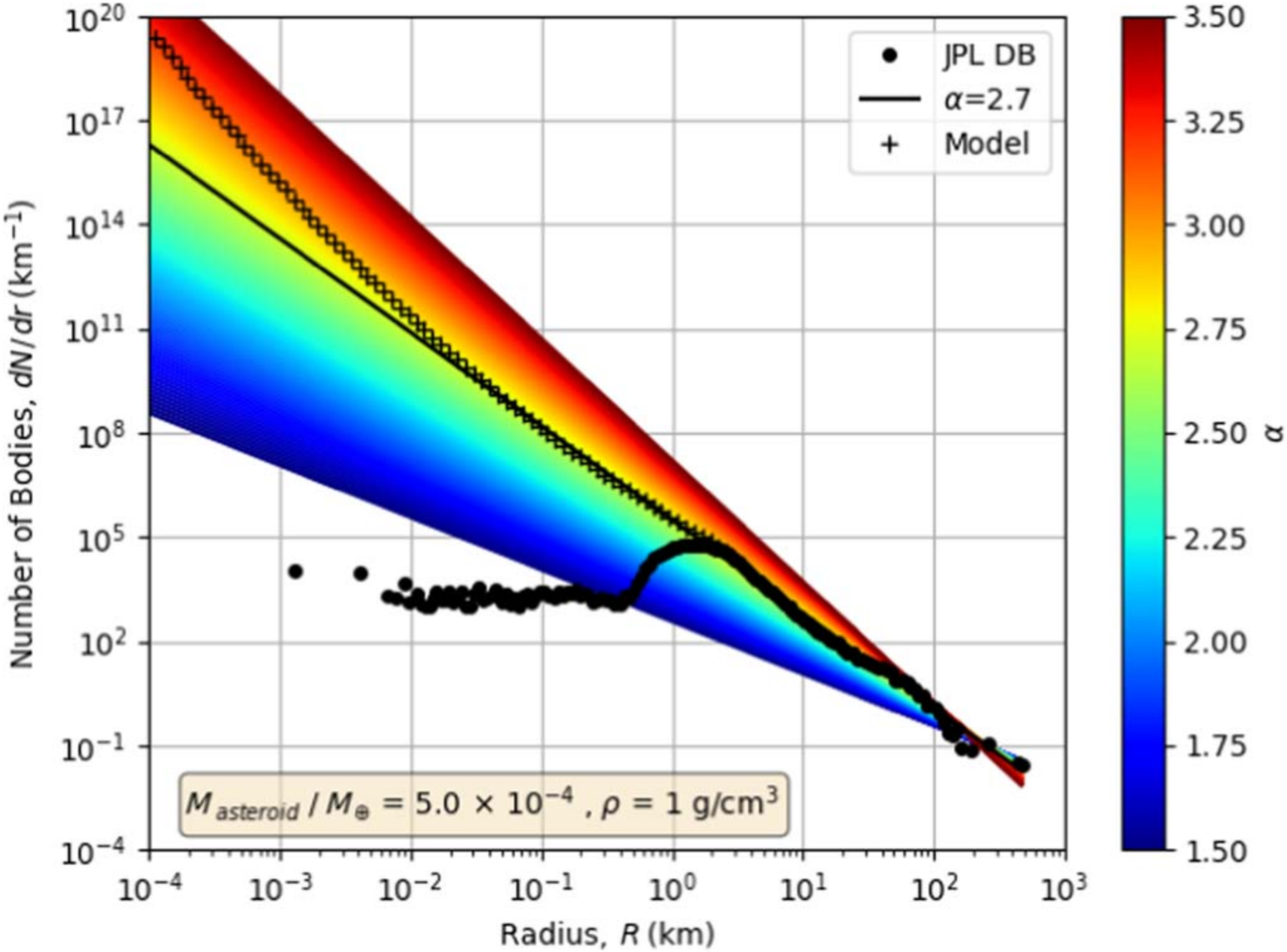
- Galactic Halo Dark Matter $\approx 10^{-19} M_{\odot}$

Although these estimates are uncertain, we appear to have a missing matter problem.

What sorts of DM models could solve it?

Mass Budget (beyond Earth radius)

Conventional SSSB object distribution is poorly known



[de Gaetano (Fermi LAT) et al., 2023]

Models of Dark Matter

That could contribute to a bound, dark ``disk”

- WIMP-like candidates do not capture on the solar system efficiently enough [Peters, 2009…]
- Ultraheavy DM is a possibility — perhaps we have a PBH?! [Tran et al., 2023]
- ULDM is another possibility — can we build macroscopic constructs of it? Yes?!

ULDM Models that form BEC are constrained by observations of the Galactic Center [Della Monica et al., 2023]

ULDM with self-interactions (gravi-atoms) are possible — perhaps Mercury has a massive dark halo [Budker et al., 2023]

Bayesian Analysis

Under a Gaussian prior for δJ_2, the posterior probability that a "disk" does not exist:

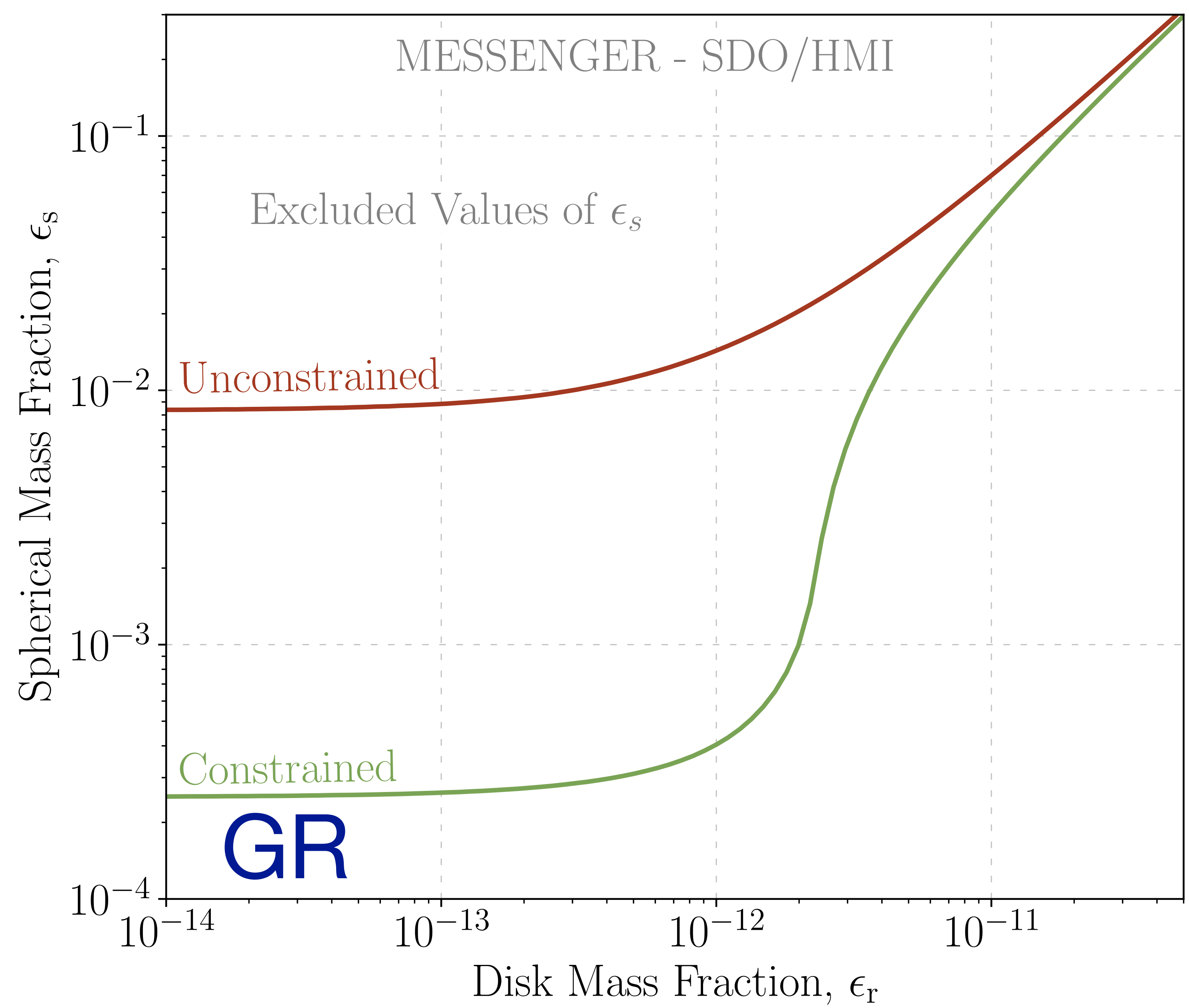
ext / int	constrained	unconstrained
Opt	0.210	0.221
Heli	1.0×10^{-21}	0.091
Heli-All	2.4×10^{-17}	0.089

GR

Note!

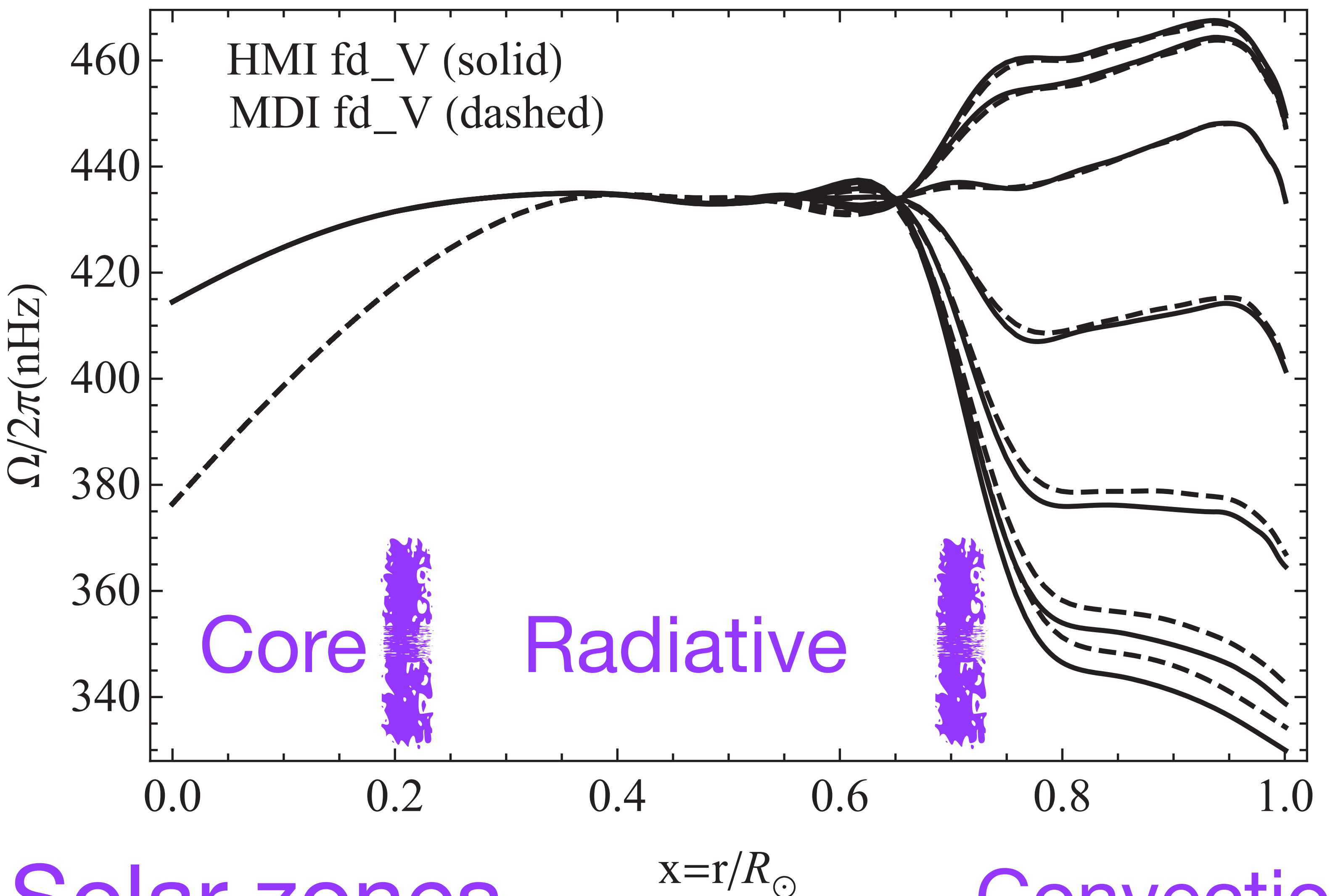
Feldman-Cousins

Mass Limits at 95% CL



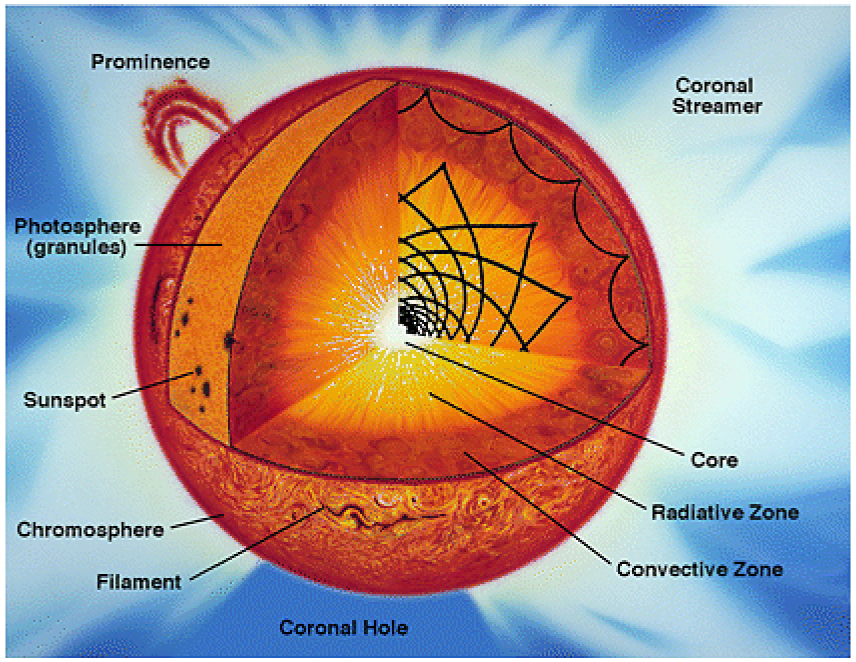
Helioseismology: Systematics?

time-averaged radial profiles of **rotation**



equator

pole



[NASA, mdi graphic]

Solar zones

Convection

Assuming slow rotation, the equilibrium structure of a rotating star is determined by linear theory

[Goldreich & Schubert, 1968; Ulrich & Hawkins, 1981; application to J_{2n}: Pijpers, 1998; Mecheri & Meftah, 2021]

Solar models are used for (non-rotating) inputs: $\rho_0(r); M_r$

The Gravitational Quadrupole Moment

Consider a static, isolated, spherical Sun, perturbed by its rotation (CM at origin)

Its gravitational potential for $r > R_\odot$ is

$$\phi_o(r,\theta) = -\frac{GM_\odot}{r}\left(1 - \sum_{2n}\left(\frac{R_\odot}{r}\right)^{2n} J_{2n}P_{2n}(\cos\theta)\right)$$

If external forces act, then odd terms can appear.

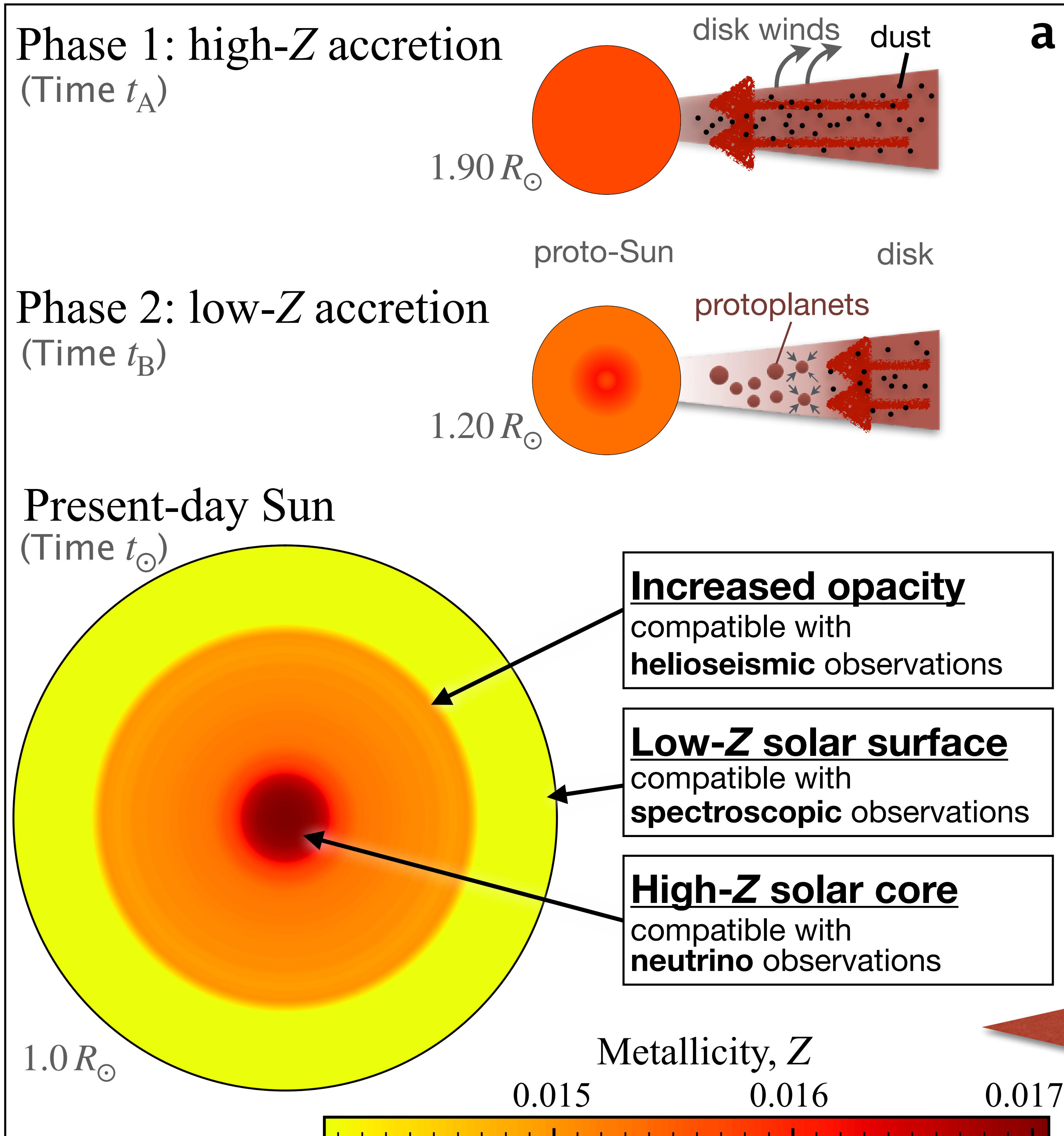
Including the potential from differential rotation & placing the surface at an equipotential yields

$$\Delta_\odot \approx J_1 + \frac{3}{2}J_2 + J_3 + \frac{5}{8}J_4 + \frac{\Omega^2 R_\odot^3}{2GM_\odot} \implies J_2 \approx \frac{2}{3}\left(\Delta_\odot - \frac{\Delta r_{\rm surf}}{R_\odot}\right)$$

$\Delta r_{\rm surf} \approx 7.8$ mas [Dicke, 1970]

Ancillary Evidence

in support of non-luminous matter (over Gyrs) within Mercury's orbit



- CNO ν results [BOREXINO] favor a Sun with metals in its core (but not seen on its surface)
- Metallicity gradient can appear if Sun formed w/i long-lived protoplanetary disk

[Haxton & Serenelli, 2008; Kunitomo & Guillot, 2021; Kunitomo, Guillot, & Bulgen, 2022]

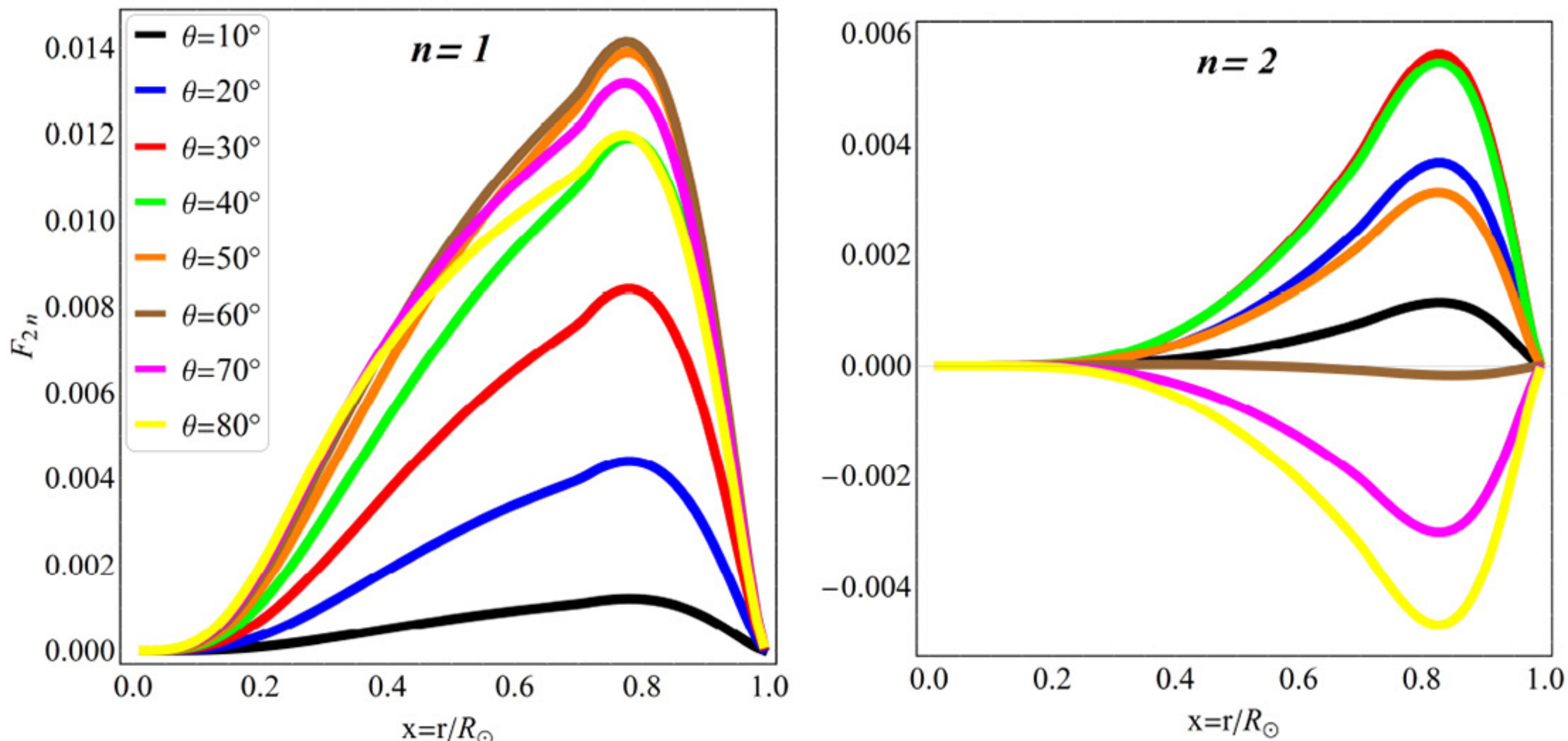
Helioseismology: Systematics?

pole

equator

kernels for J_{2n}

J_2 J_4

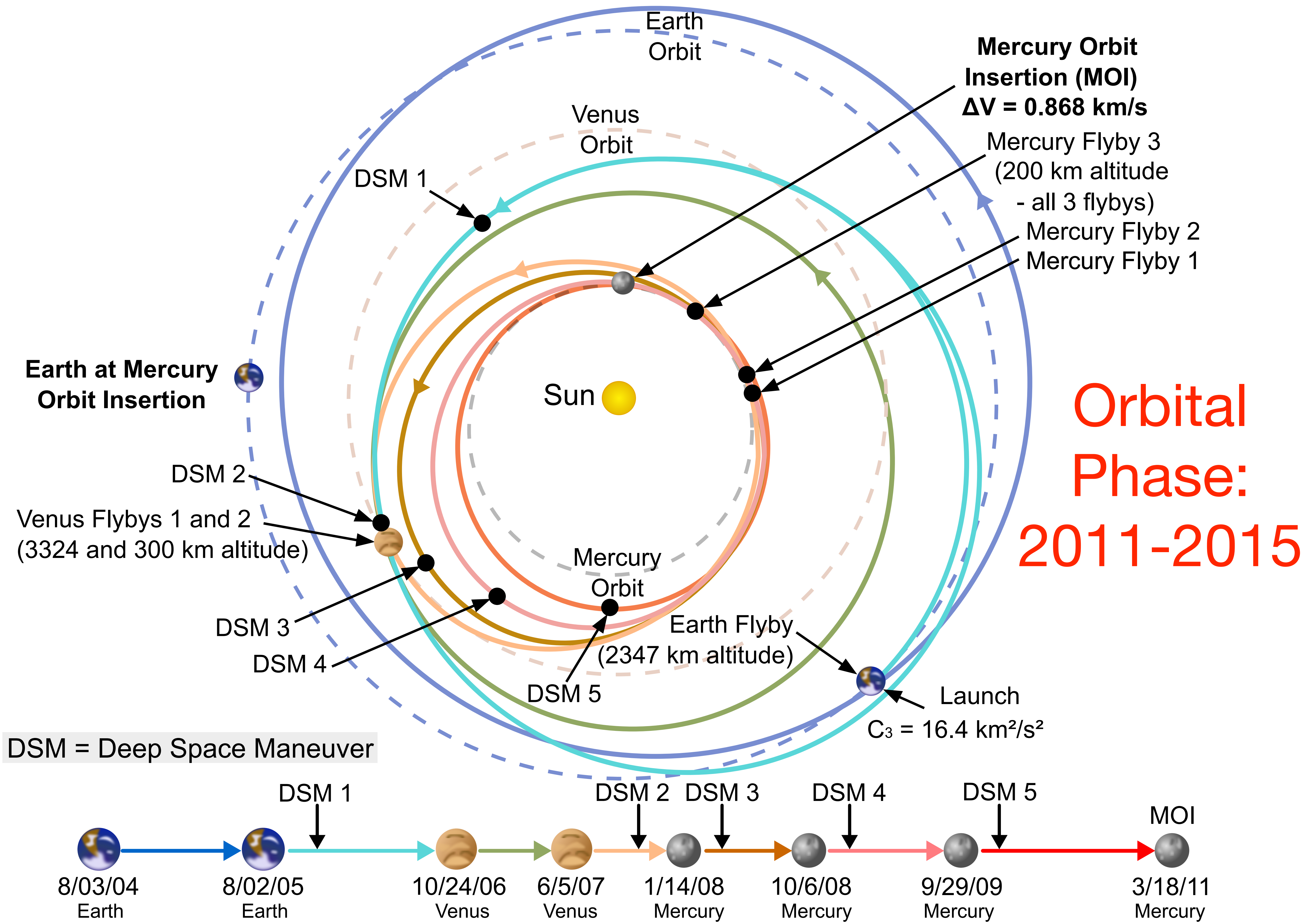


[Mecheri & Meftah, 2021]

Note J_2 kernel largest in radiative zone!

$$J_{2n} = \int_0^1 \int_{-1}^1 du dx\, F_{2n}(x,u)(\omega(x,u))^2$$

The MESSENGER Mission



2008-2011

The Gravitational Quadrupole Moment

From all orbital measurements

Orbital J_2 measurements

#	$J_2(\times 10^{-7})$	$\pm J_2(\times 10^{-7})$	ELT	PPN	Reference
1	180	200	N	N	Lieske, 49–68 [147]
2	13.9	24.7	N	Y	Shapiro, 66–71 [148]
3	25	16	N	Y	Anderson, 11–76 [149]
4	12.3	11.5	N	N	Anderson, – [116]
5	−1.8	4.5	N	Y	Eubanks, – [116]
6	−11.7	9.5	N	Y	Pitjeva, – [116]
7	−1.3	4.1	N	Y	Pitjeva, 64-89 [150]
8	2.4	0.7	N	Y	Pitjeva, – [151]
9	−5	10	N	Y	Williams, 96–00 [152]
10	6.6	9.0	N	N	Afanaseva, 80–86 [153]
11	−6	58	N	N	Landgraf, 49–87 [154]
12	2.3	5.2	N	Y	Anderson, 71–97 [155]
13	1.9	0.3	N	Y	Pitjeva, 61–03 [156]
14	2.22	0.23	N	Y	Pitjeva, – [116]
15	2.25	0.09	Y	Y	Park ,11–14 [28]
16	2.246	0.022	Y	Y	Genova, 08–15 [29]
17	2.46	0.68	N	Y	Standish, - [157]
18	2.295	0.010	N	N	Viswanathan, - [158]
19	1.82	0.47	N	N	Fienga, - [159]
20	1.8	?	N	Y	Konopliv,– [160]
21	2.0	0.20	N	Y	Pitjeva,– [161]
22	2.40	0.25	N	Y	Fienga, - [162]
23	2.27	0.25	N	Y	Fienga, - [163]
24	2.22	0.13	N	Y	Fienga, - [163]
25	2.165	0.12	Y	Y	Fienga, - [146]
26	2.206	0.03	Y	Y	Fienga, - [146]
27	2.40	0.20	N	Y	Verma, - [164]
28	2.010	0.010	N	N	Fienga, - [165]
29	2.2180	0.01	Y	N	Fienga, - [166]

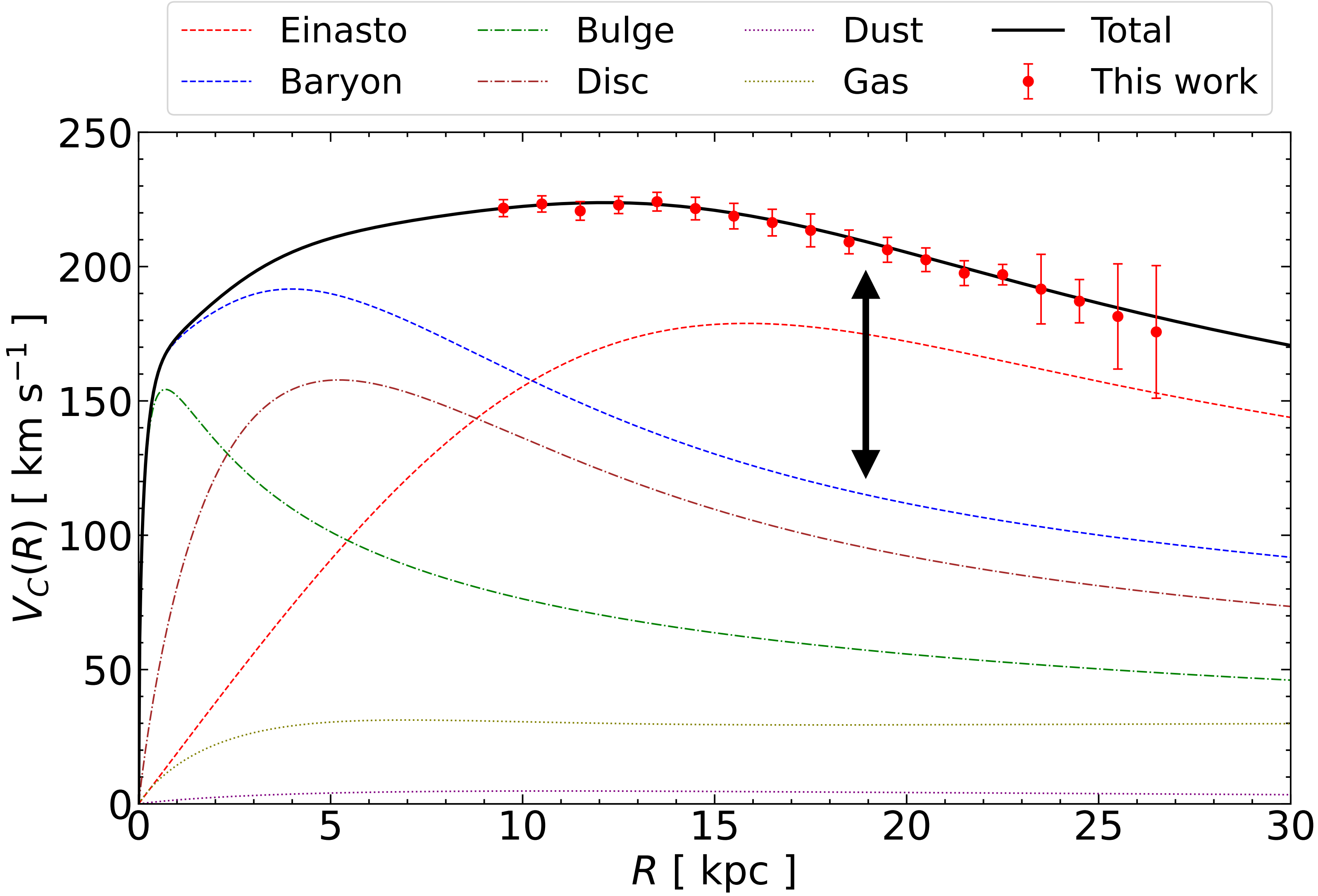
Mercury

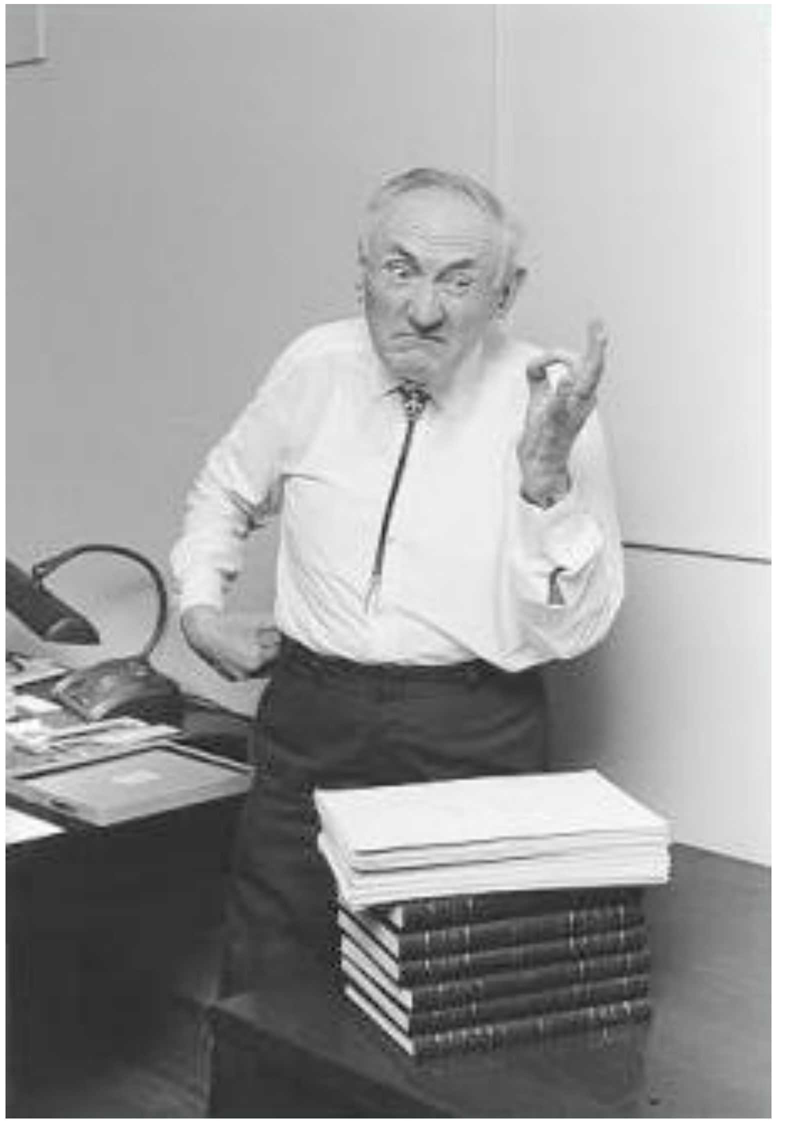
Dark Matter as a "Missing Matter" Problem

Problems at very different length scales persist…

Zwicky, 1933: "dark matter" might exist and solve the puzzle of inferred missing mass [Coma Cluster]

And in the Milky Way: the observed circular speed does not track the luminous mass.



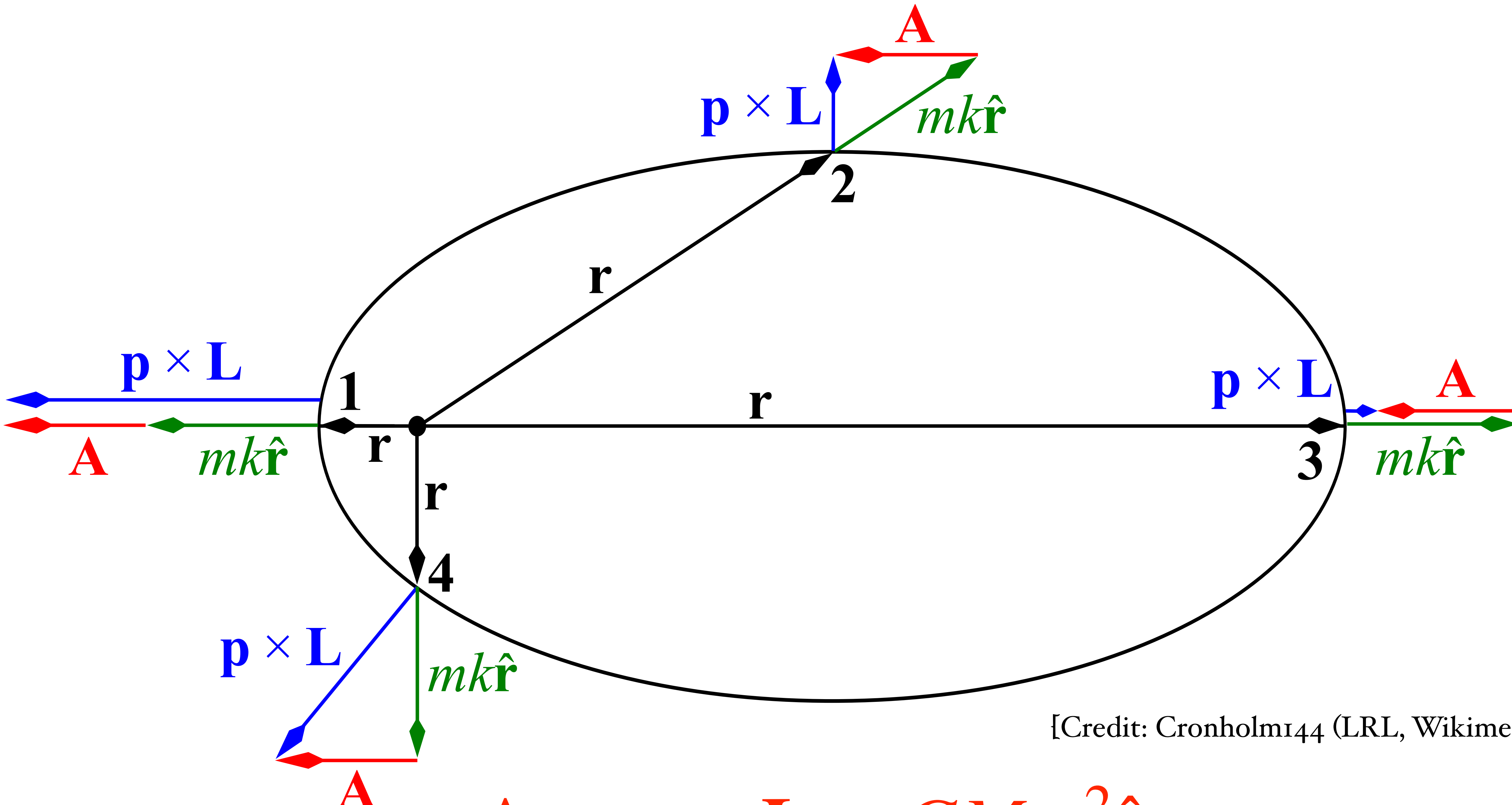


Rotation Curve of our Milky Way with Gaia DR3!

[Jiao et al., A&A, 2023]

The Laplace-Runge-Lenz Vector

and the Kepler problem



[Credit: Cronholm144 (LRL, Wikimedia)]

$$\mathbf{A} = \mathbf{p} \times \mathbf{L} - GMm^2\hat{\mathbf{r}}$$ [Goldstein, e.g.]

E and $\mathbf{L}$ conservation guarantee in-plane orbital precession under perturbations