A local resolution of the Hubble tension

The impact of screened fifth forces on the local distance ladder

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arXiv:1907.03778 arXiv:2003.12876

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Thessaloniki

Outline

- Modified gravity, fifth forces & screening
- Unscreening the distance ladder
- Screening properties of Cepheids in SH0ES
- Effect on H0 ⇒ Possible reduction of tension to 2σ
- Extension to TRGB ⇒ Completely resolve tension

Why modified gravity?

- Self-accelerate the Universe’s expansion (dark energy)
- Dark matter
- Tensions within ΛCDM
- General deviation from Einstein–Hilbert

The Fifth Force

- Generic extensions to the standard model couple new dynamical fields to matter
- ⇒ New (*fifth*) forces, described by strength $\Delta G/G_N$ and range $1/m$

$$\Phi_{\rm tot} = -\frac{G_N M}{r}\left(1 + \frac{\Delta G}{G_N} e^{-mr}\right) = \Phi_N - \frac{\Delta G M}{r} e^{-mr}$$

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- Strongly constrained by local tests
  - Lab: torsion balance, atom interferometry…
  - Solar System: Lunar Laser Ranging, planetary orbits, Cassini...

Screening Mechanisms

Fifth force goes away in dense environments

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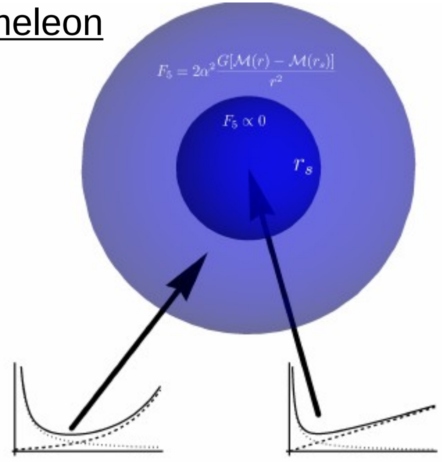
Chameleon: $m_{eff} \rightarrow \infty$ (e.g. f(R))

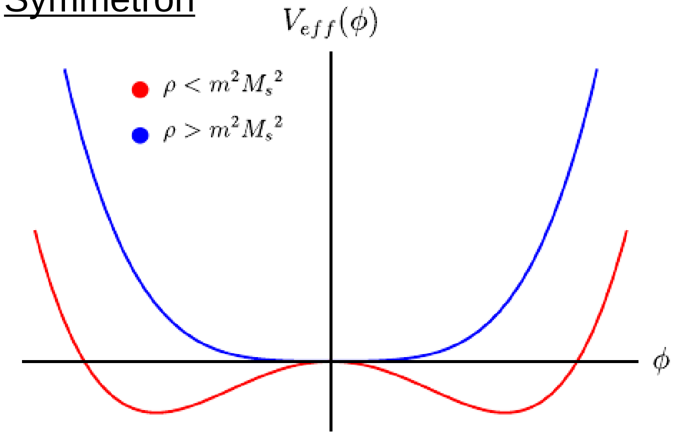
Kinetic: $\partial\varphi \rightarrow \infty$ (e.g. K-mouflage)

Symmetron & Vainshtein: $\Delta G \rightarrow 0$ (e.g. Galileons, DGP)

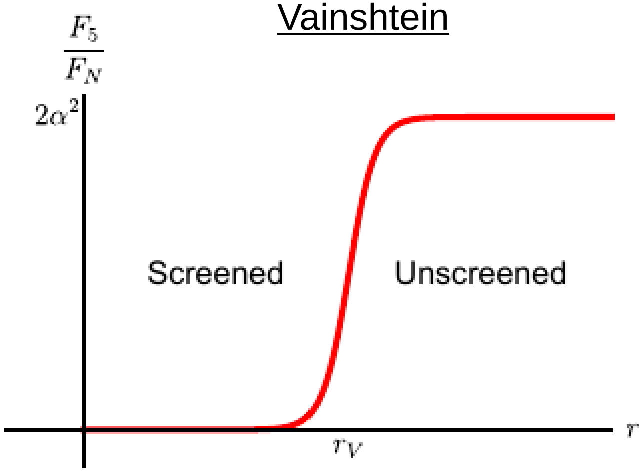
Chameleon



Symmetron



Vainshtein



Effect of Modified Gravity on Stars

Equilibrium:

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{G_N M(r)\rho(r)}{r^2}$$

Higher G → more luminous & shorter lifetime

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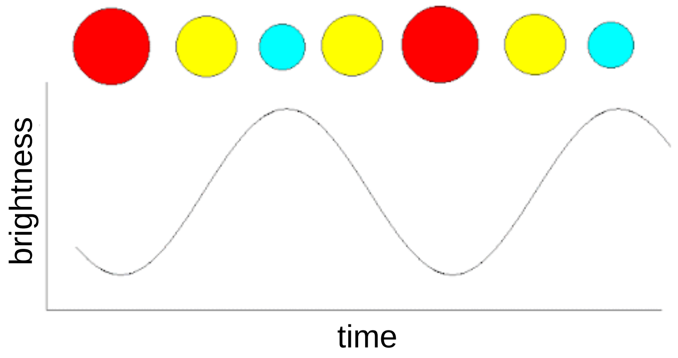
Higher G → more luminous & shorter lifetime

Out of equilibrium:

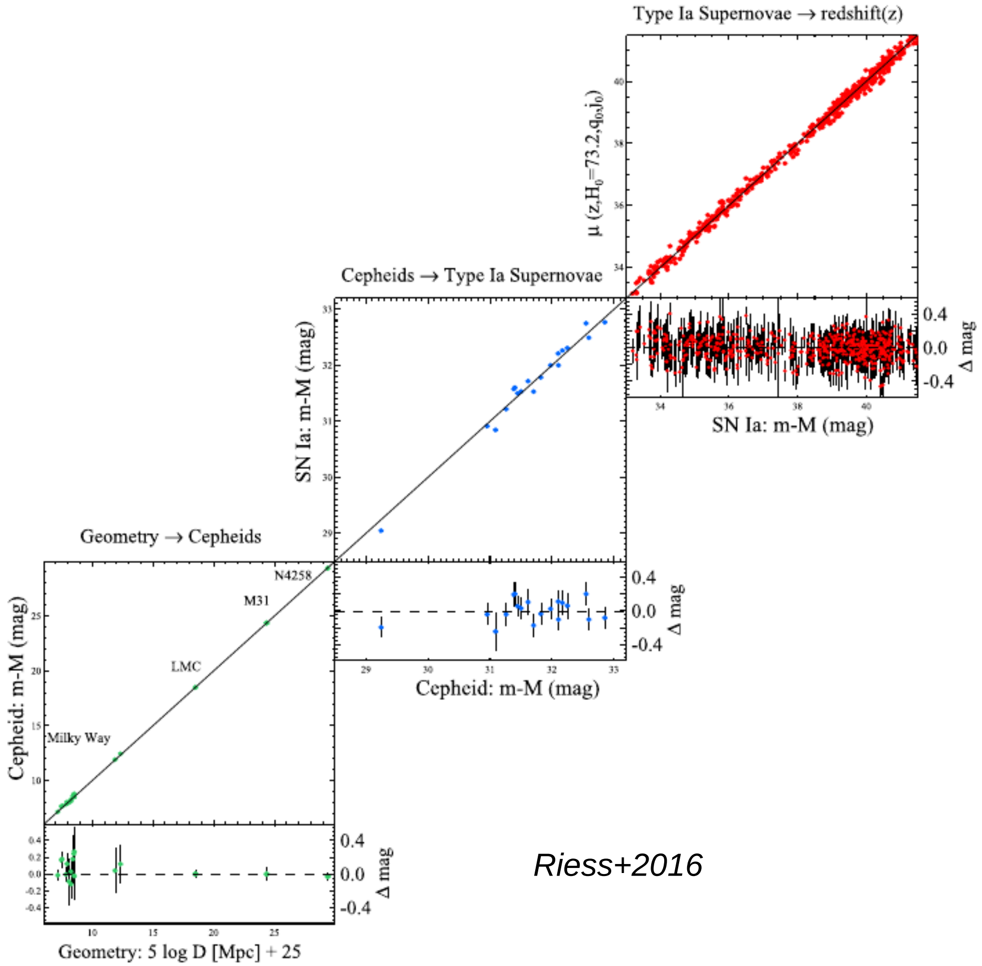
Higher G → faster oscillations / pulsations

$$\ddot{\delta\vec{r}} = -\frac{1}{\rho}\frac{\mathrm{d}P}{\mathrm{d}r} - \vec{\nabla}\Phi$$

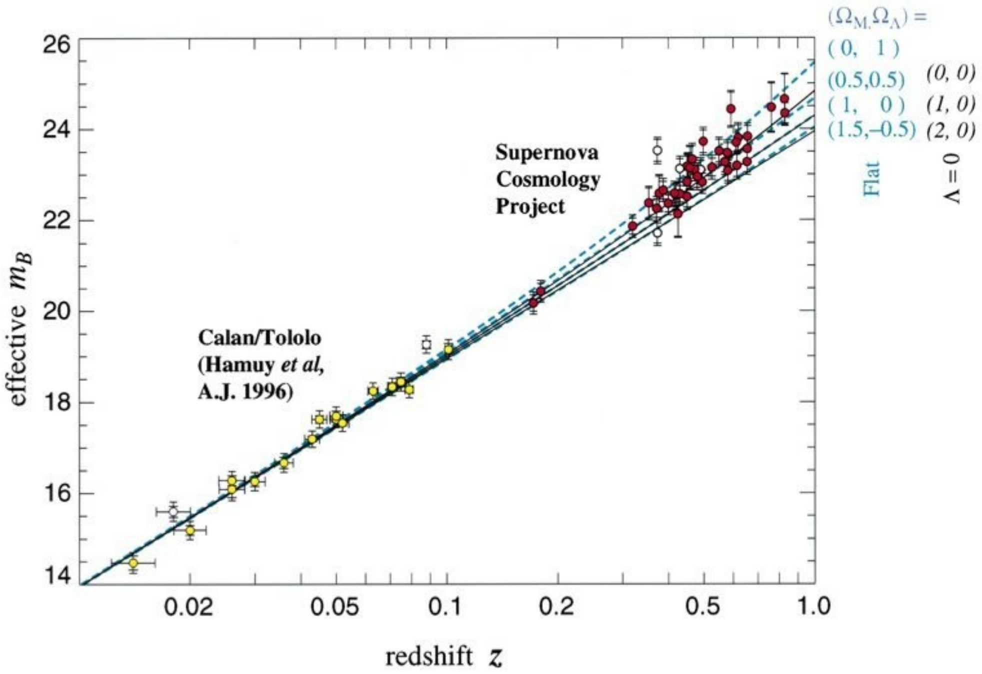
$$\omega^2 \sim \frac{GM}{R^3}$$



The cosmic distance ladder is made of stars

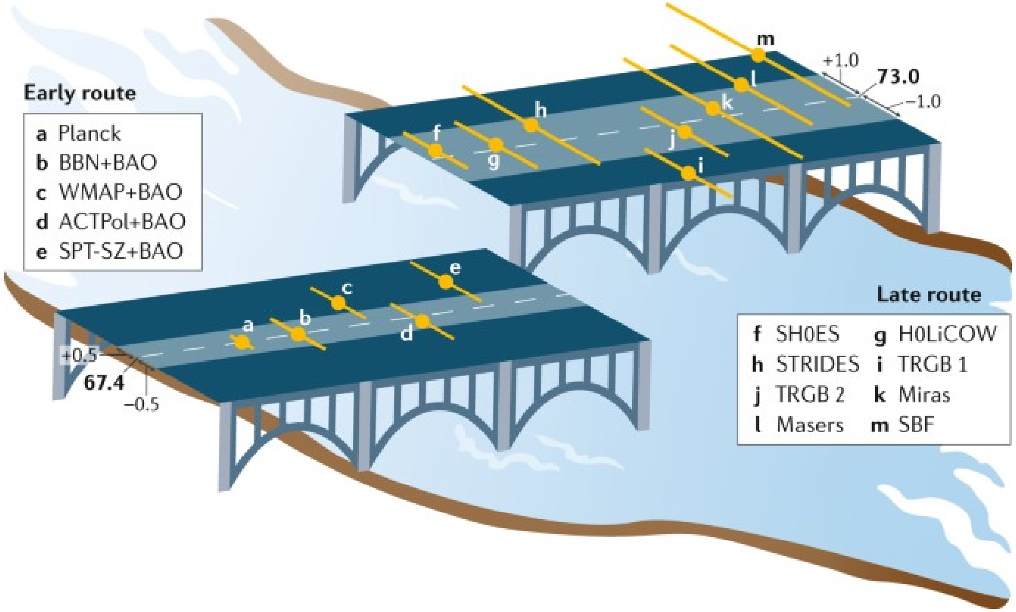


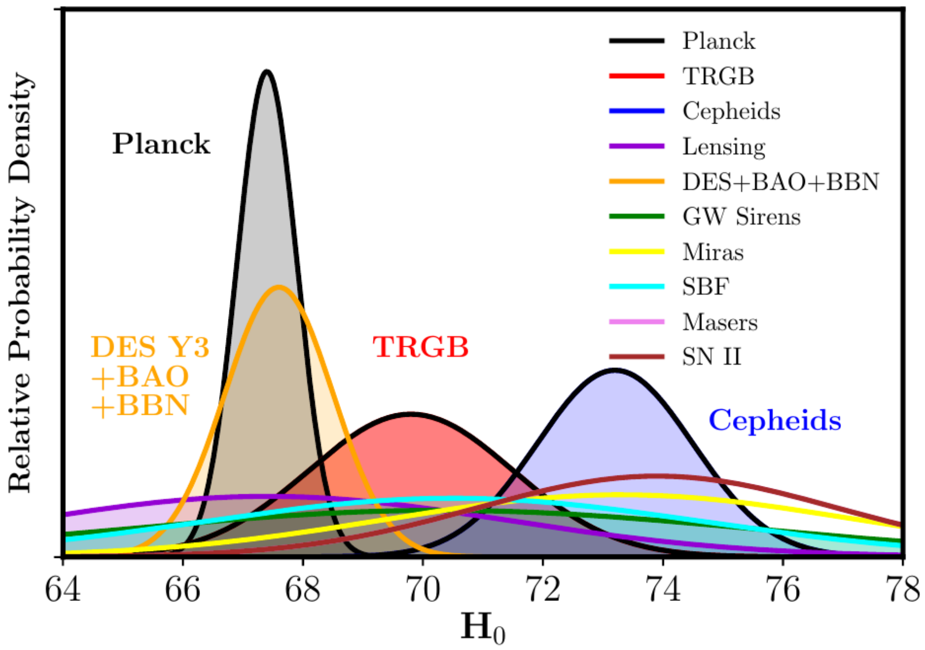
Riess+2016



Perlmutter+1999

The Hubble Tension

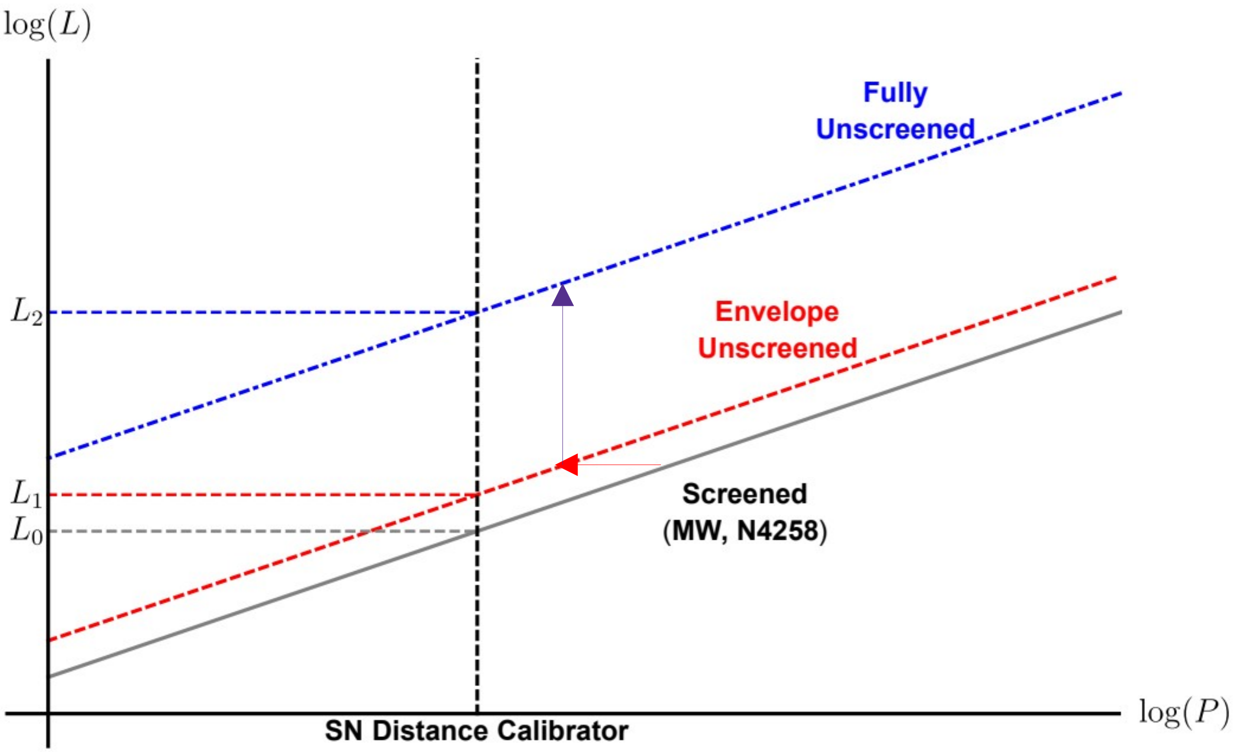




Freedman 2021

Unscreening the Distance Ladder

Cepheid period–luminosity relation



- Assume MW and N4258 are screened ⇒ calibrate Newtonian PLR (grey)
- In a SN host, the standard analysis infers L=L0 at measured P, but really it’s L1 or L2
- Underestimated L ⇒ underestimated D ⇒ overestimated H0 ~ cz/D

Quantifying Fifth Force Effects

Oscillations

$$P \propto (1 + \Delta G/G_N)^{-1/2} \Rightarrow \Delta \log(P) = -\frac{1}{2}\log(1 + \Delta G/G_N),$$

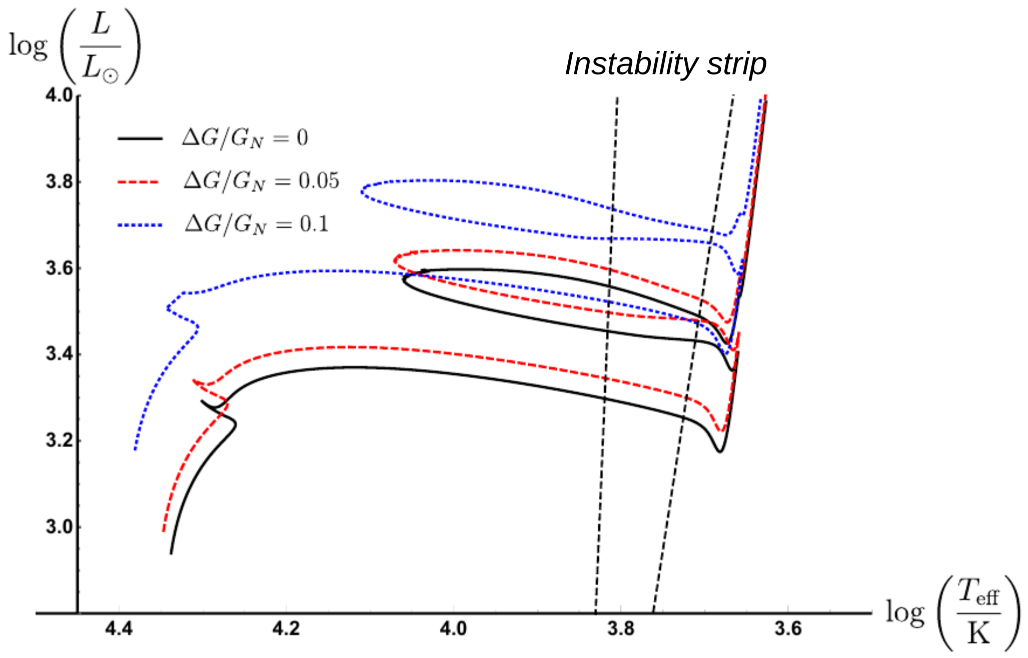
$$\Delta \log(L) = \frac{A}{2}\log(1 + \Delta G/G_N)$$ A ≈ 1.3

Brightness

$$\Delta \log(L) \simeq B \log(1 + \Delta G/G_N)$$ B ≈ 4

Determined using stellar structure simulations with MESA

(Modules for experiments in stellar astrophysics)

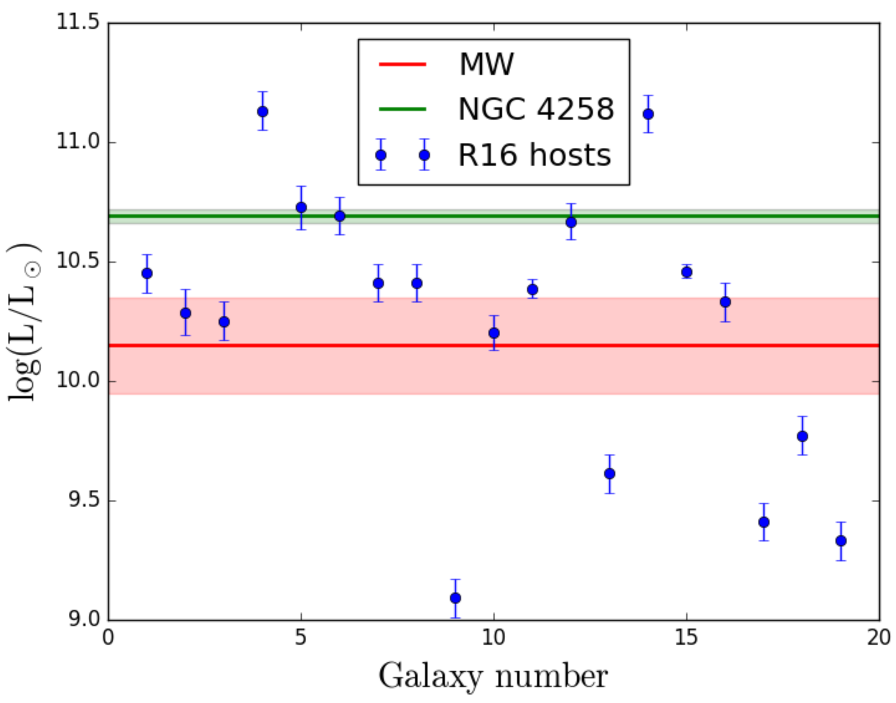


Screening Properties of Cepheids

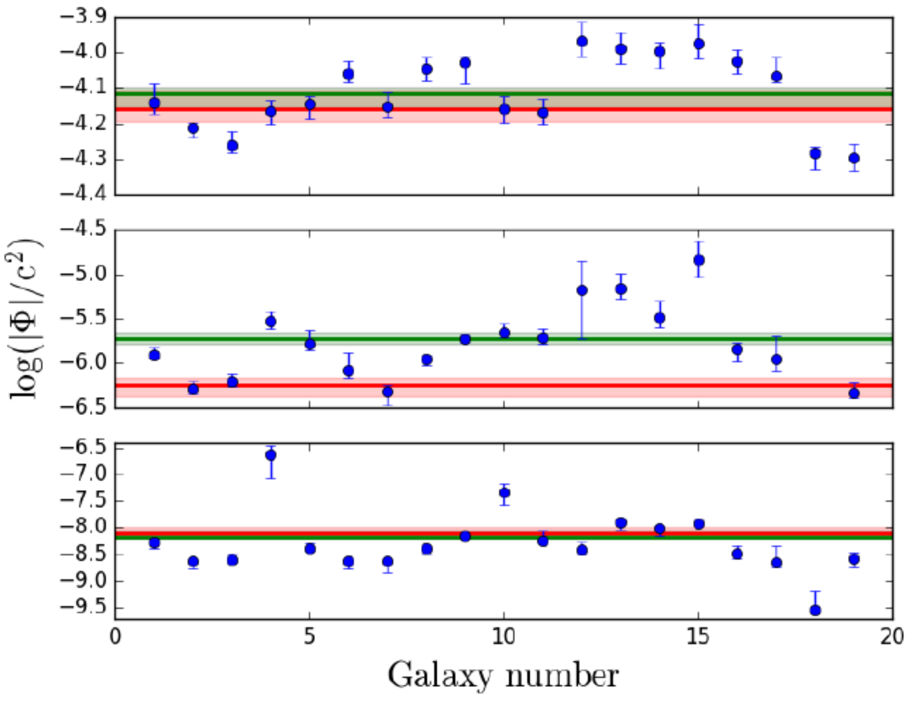
- Proxies for screening:
  - Galaxy luminosity
  - Galaxy dynamical mass
  - Halo virial mass
  - Externally sourced Newtonian potential, acceleration and curvature within 0.5–50 Mpc [**HD**+2017]
  - Local dark matter density [Sakstein, **HD** & Jain 2019, arXiv:1907.03775]
- Determined from NED/EDD data, N-body sims, structure formation models & models of galaxy–halo connection

Screening Properties of Cepheids

Galaxy luminosity



Environmental potential

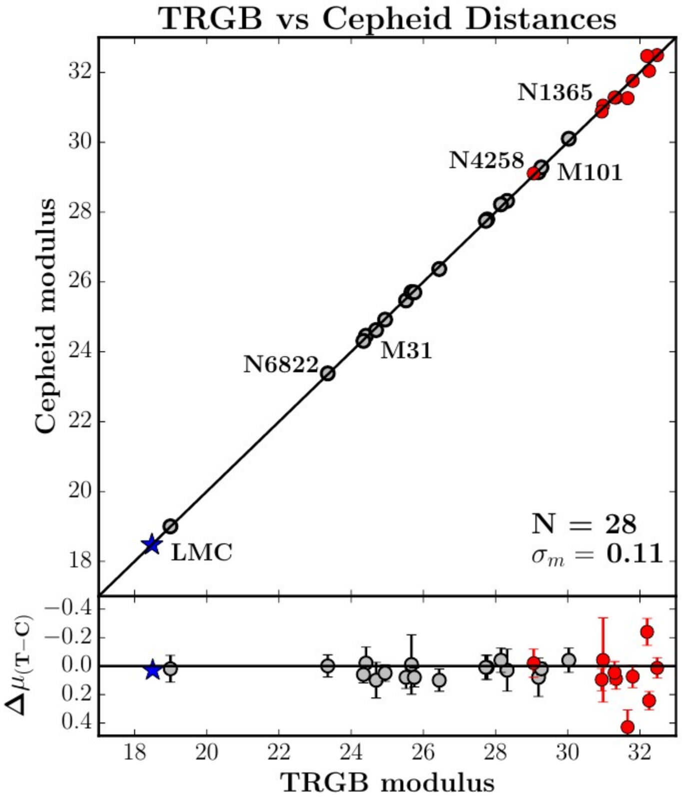


Maximum Fifth Force Strength: Consistency Tests within the Ladder

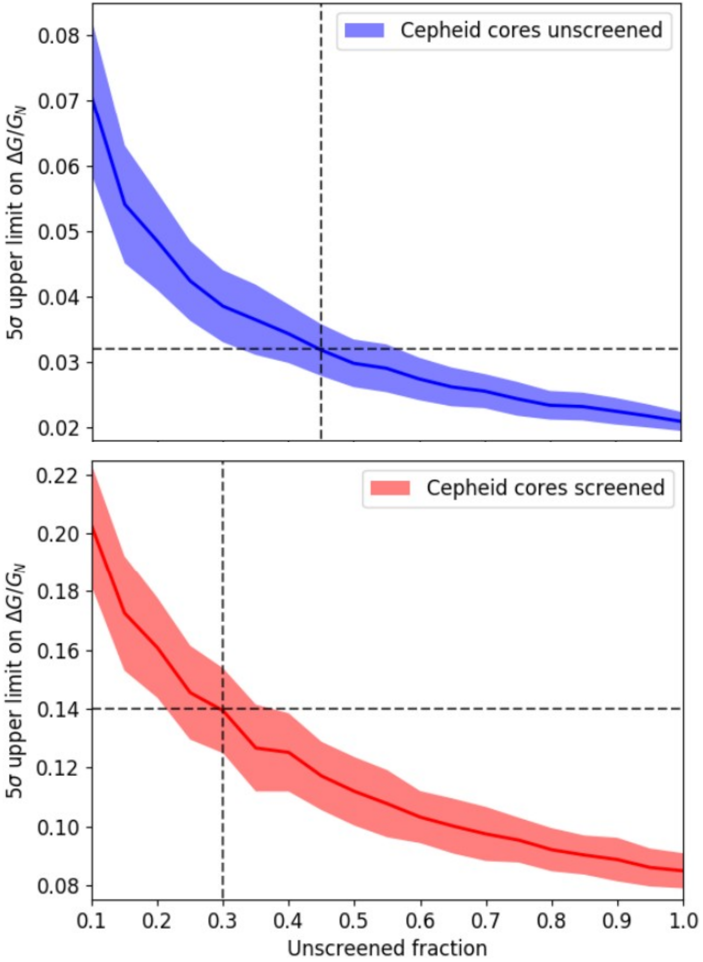
- Consistency of Cepheid & TRGB distances →

- *Also:* Scatter in Cepheid period–flux relation should be minimised for correct fifth force

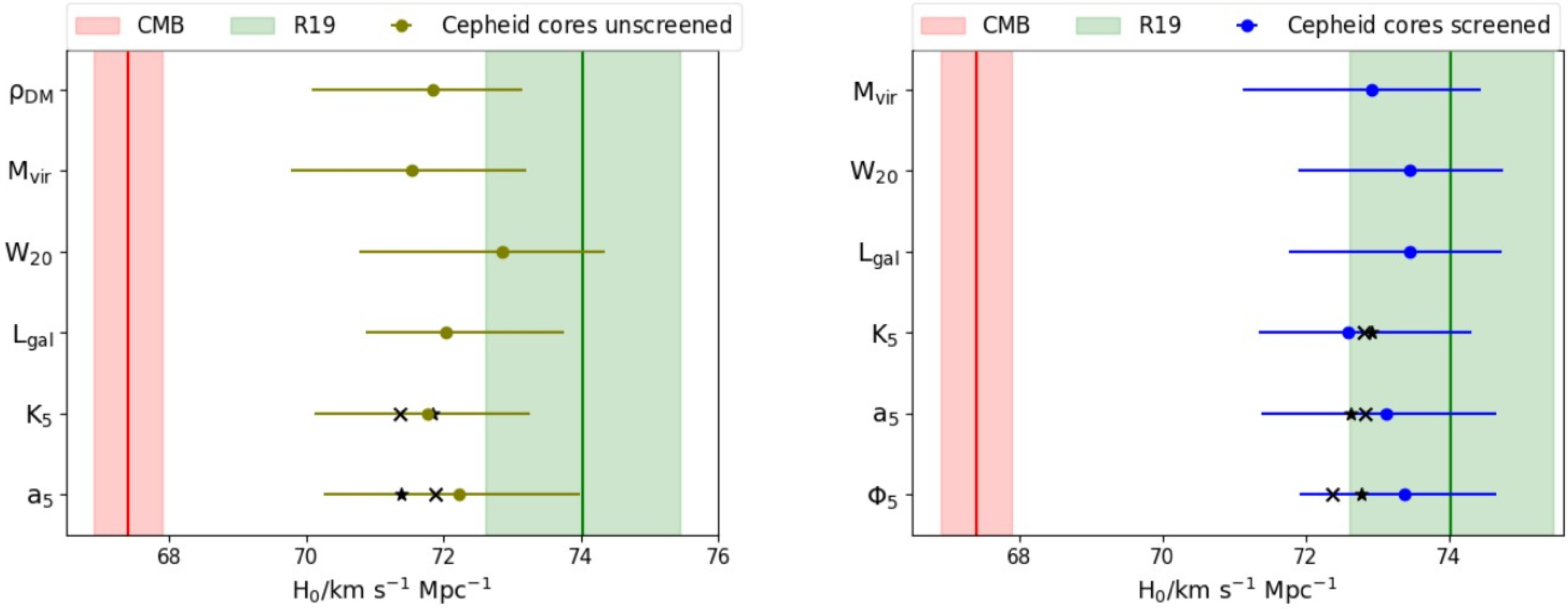
- *As should* difference in inferred SN abs. mag. between screened and unscreened subsamples



Freedman+2019



Effect on H0


CMB
R19
Cepheid cores unscreened
ρDM
Mvir
W20
Lgal
K5
a5
68
70
72
74
76
H0/km s−1 Mpc−1
CMB
R19
Cepheid cores screened
Mvir
W20
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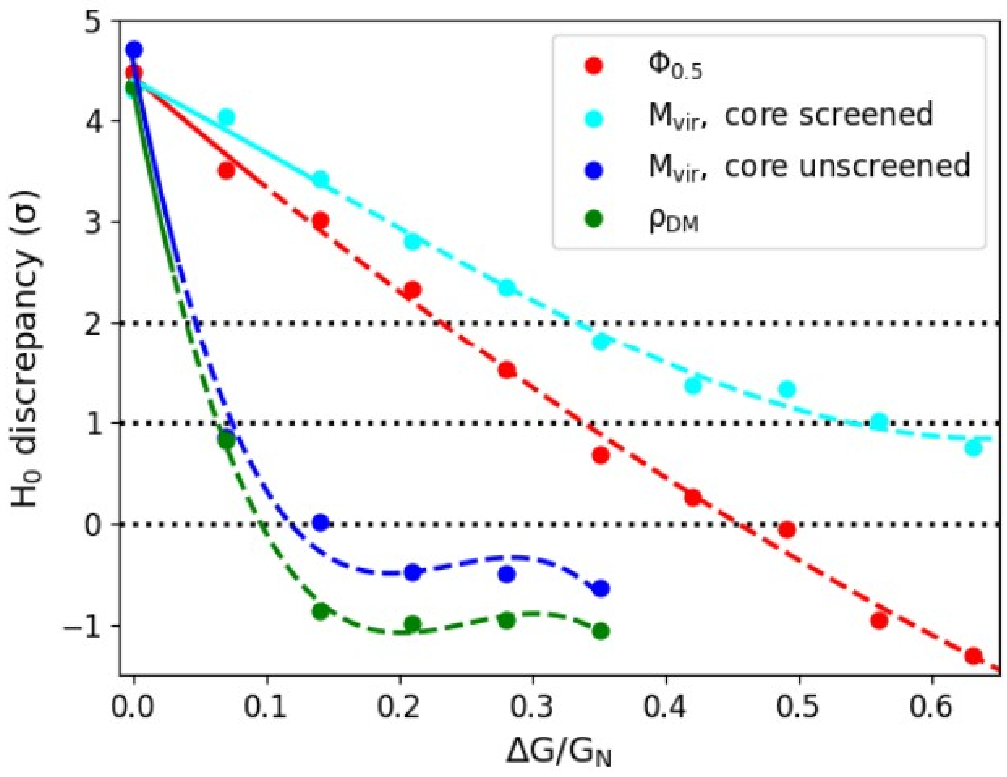
K5
a5
Φ5
68
70
72
74
H0/km s−1 Mpc−1

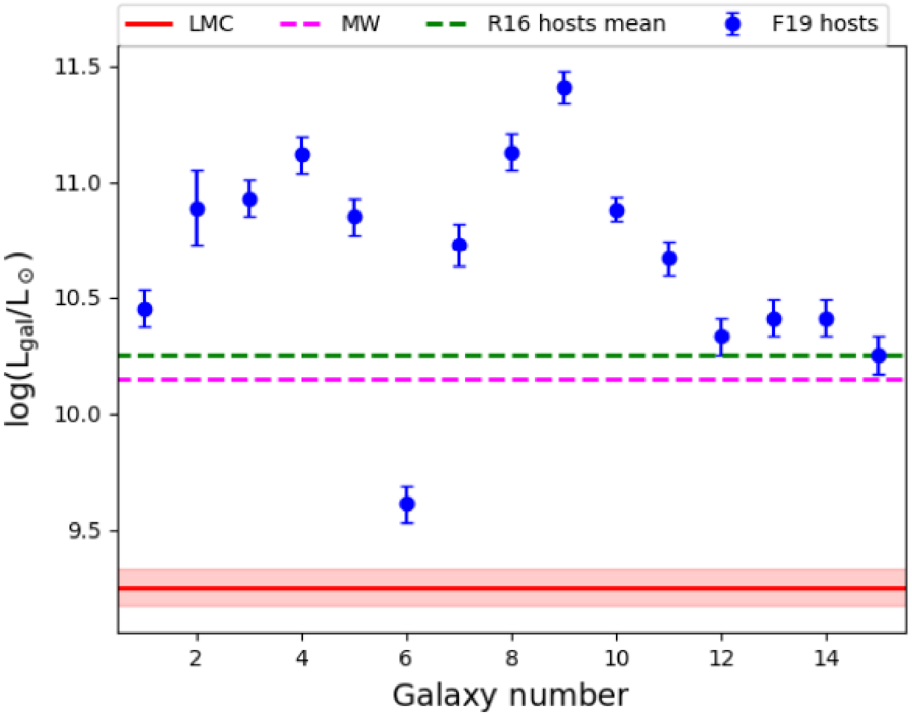
Effect on H0



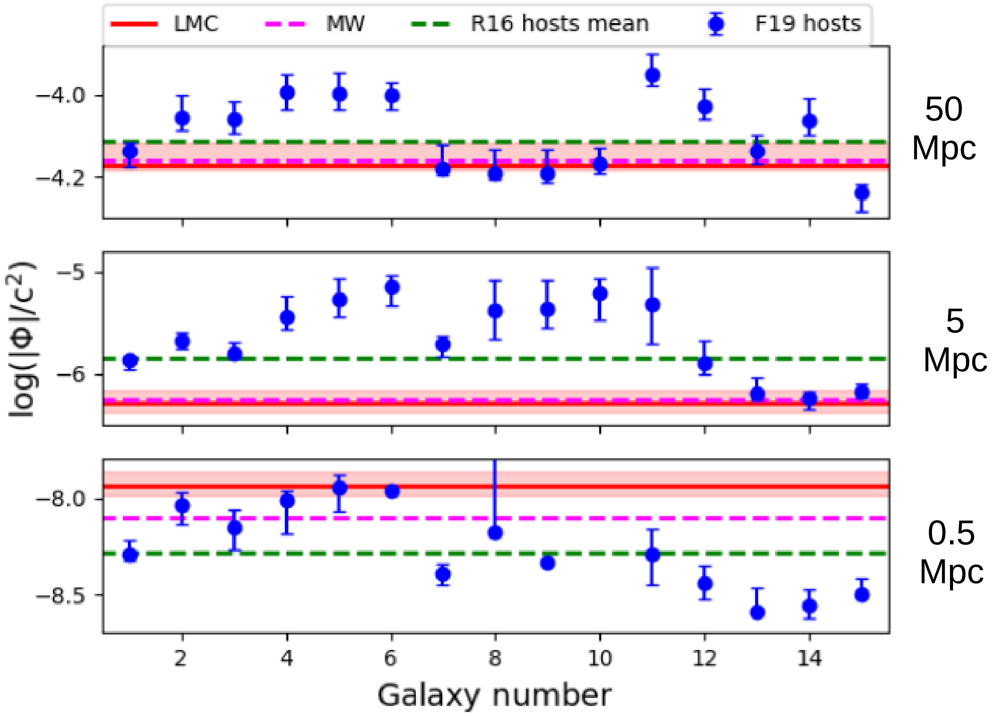
- Best models achieve ~2σ consistency with Planck
- Fifth force ~15% strength of gravity for only envelope unscreened, ~5% for fully unscreened

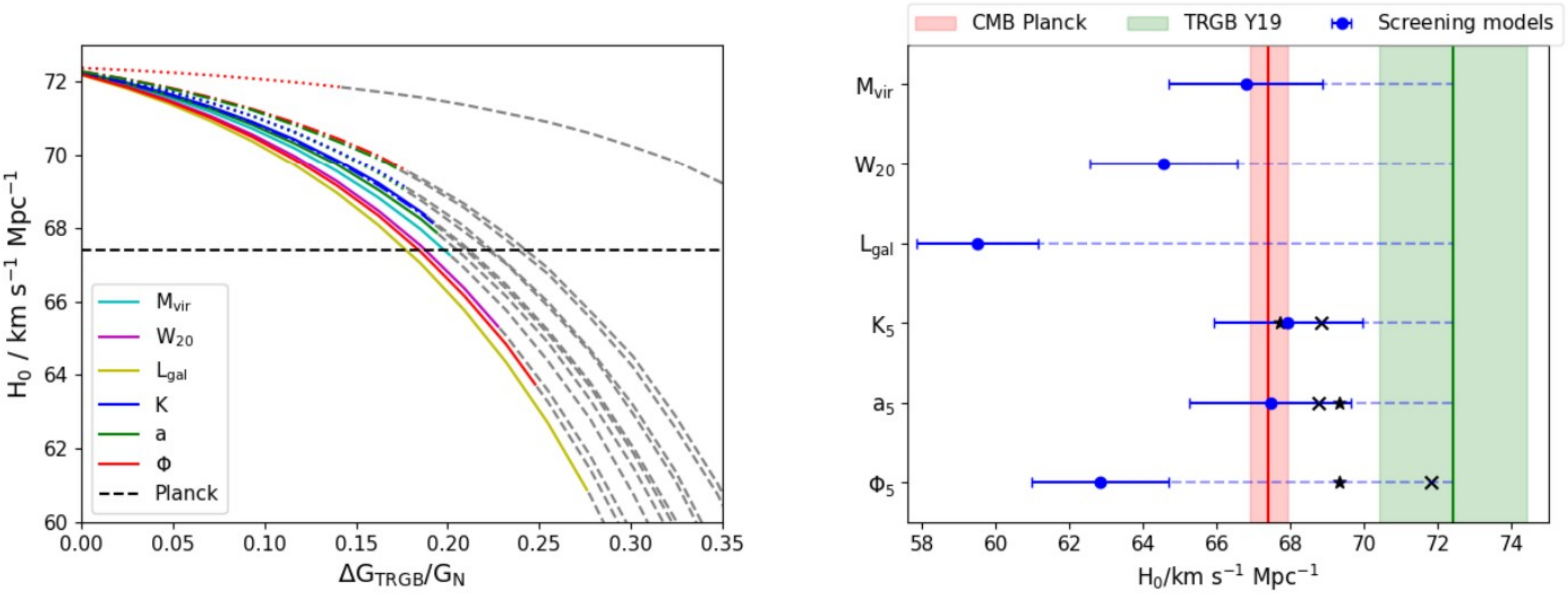
Screened Fifth Forces lower the TRGB-calibrated Hubble Constant too

<u>Galaxy luminosity</u>



<u>Environmental potential</u>





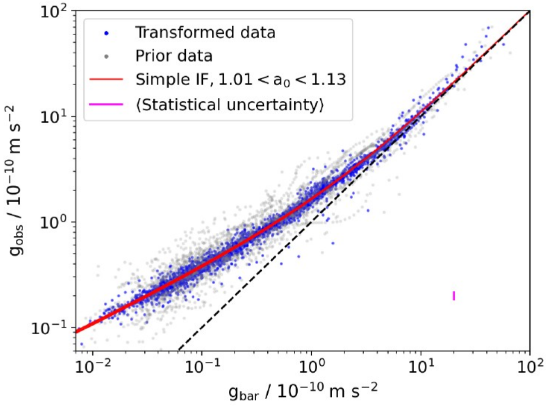
Several screening models fully resolve the tension within the Cepheid–TRGB consistency constraint, even starting from the larger Yuan+2019 H0 value

Conclusions

- Novel *local* resolutions of Hubble tension possible
- Screened fifth forces very well motivated theoretically, and empirically useful too
- Cepheid period–luminosity relation is offset between screened and unscreened galaxies, biasing distances if assumed to be universal
- Best models reduce tension to ~2σ, without botching other parts of the distance ladder
- Works even better for the TRGB-calibrated ladder!
- Most concretely-realised screening mechanisms not viable, but baryon–DM interaction model could be

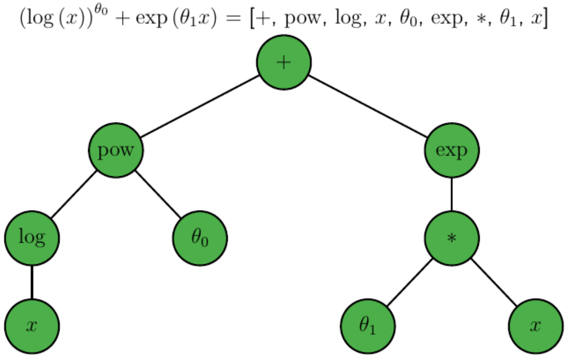
Also talk to me about...

Galaxy dynamics & MOND



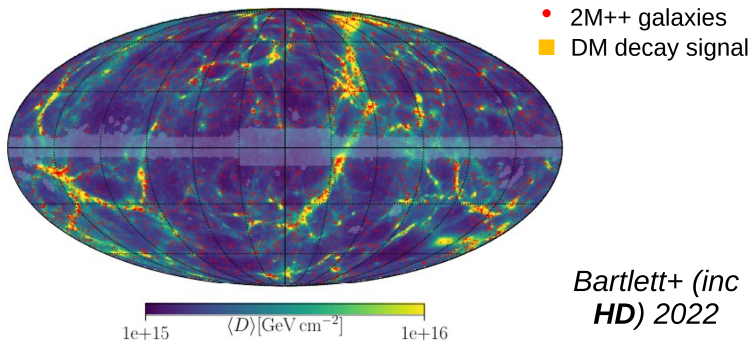
***HD** 2023*

Symbolic regression



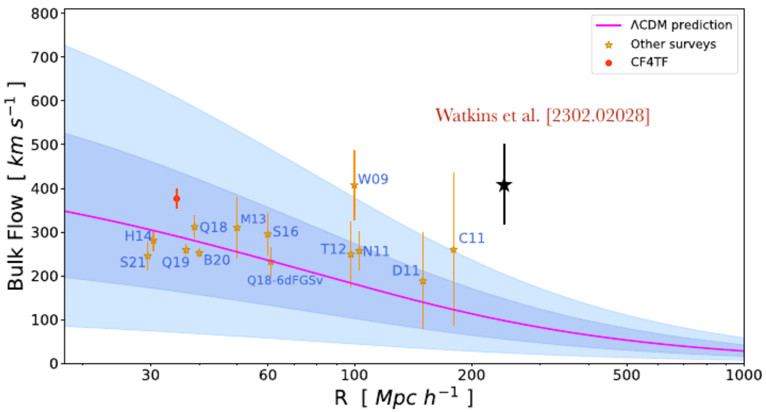
*Bartlett, **HD** & Ferreira 2023*

Field-level inference & constrained simulations



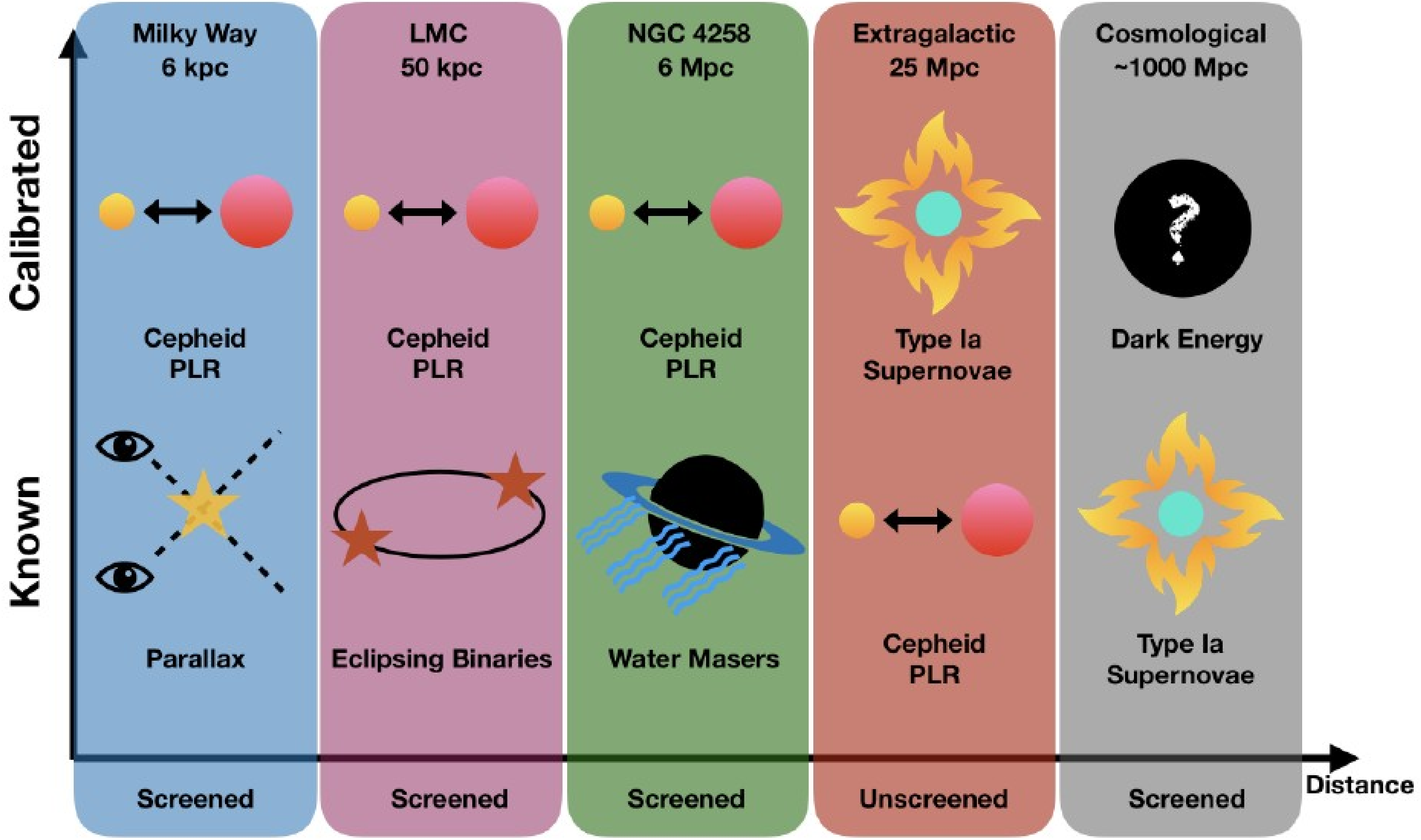
*Bartlett+ (inc **HD**) 2022*

Bulk flows & anisotropies



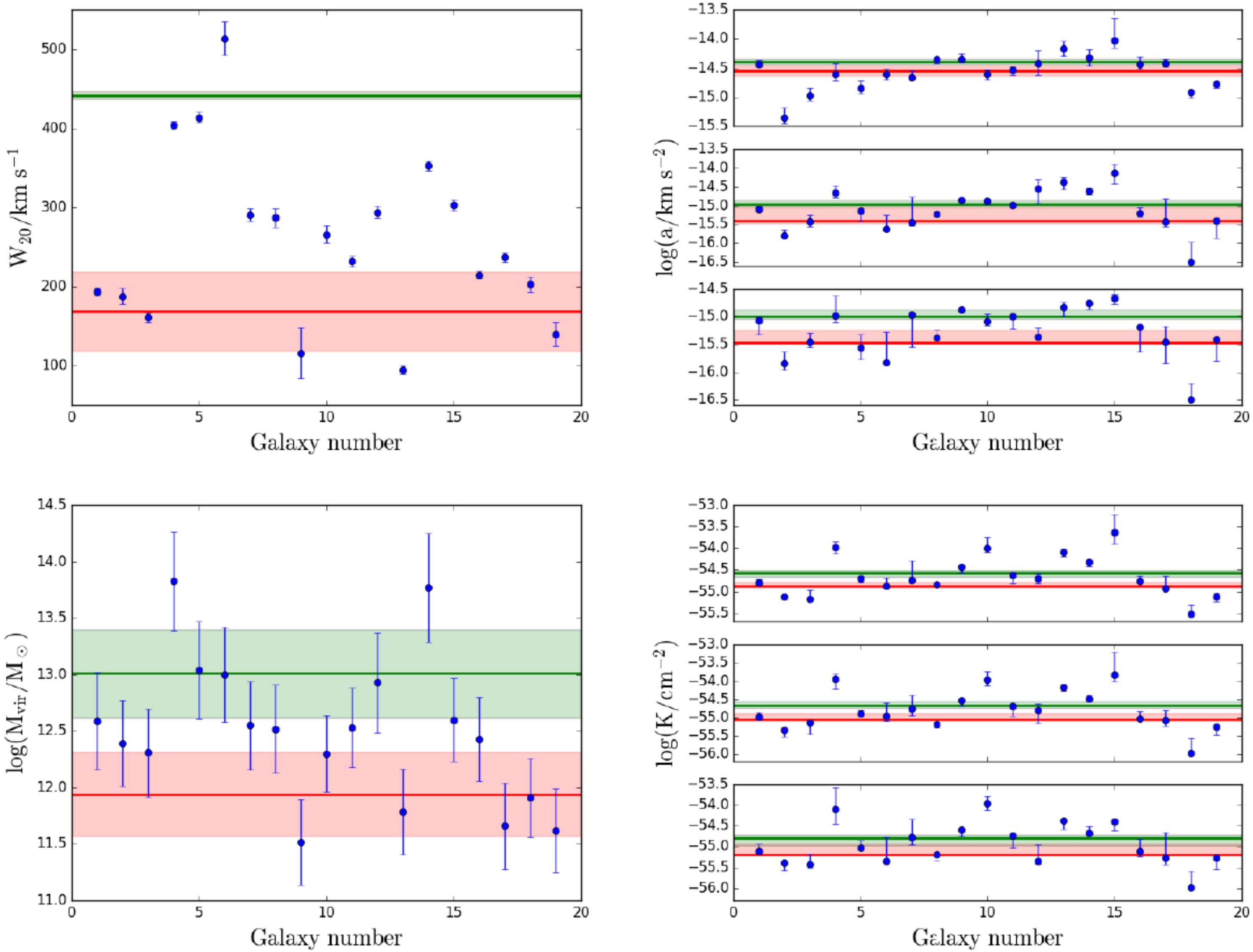
Qin+2021

Extra Slides


Milky Way
6 kpc
LMC
50 kpc
NGC 4258
6 Mpc
Extragalactic
25 Mpc
Cosmological
~1000 Mpc
Calibrated
Known
Cepheid
PLR
Cepheid
PLR
Cepheid
PLR
Type Ia
Supernovae
Dark Energy
Parallax
Eclipsing Binaries
Water Masers
Cepheid
PLR
Type Ia
Supernovae
Distance
Screened
Screened
Screened
Unscreened
Screened

$M_{\rm ceph}/M_\odot$	Slope at 2$^{\rm nd}$ crossing	Slope at 3$^{\rm rd}$ crossing
7	4.45	3.79
8	4.34	3.58
9	4.18	3.46
10	4.00	3.48
11	3.81	3.58
12	3.67	3.92
13	3.58	3.95

TABLE I. Slope B of the $\Delta\log(L) - \log(1 + \Delta G/G_{\rm N})$ relation for a range of Cepheid masses measured at the second or third crossing of the instability strip.



W20/km s−1
Galaxy number
log(a/km s−2)
Galaxy number
log(Mvir/M⊙)
Galaxy number
log(K/cm−2)
Galaxy number

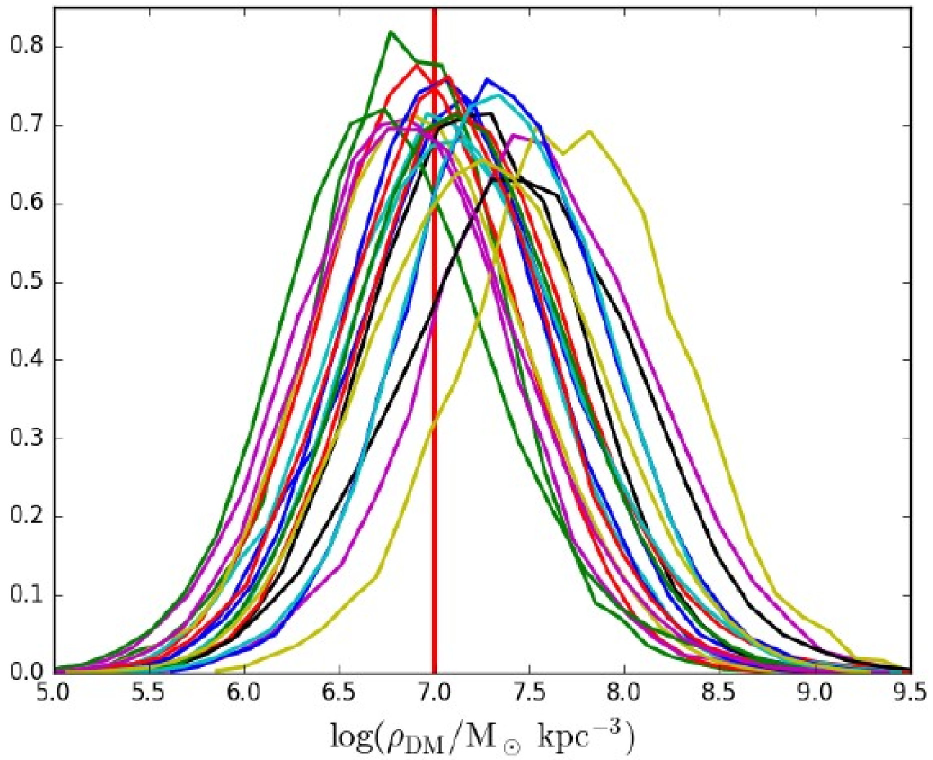


FIG. 4. Normalised frequency distributions of dark matter densities $\rho_{\rm DM}$ at the positions of the R16 Cepheids within their hosts, estimated using the halo properties from Table III. Each curve corresponds to a different galaxy. The local dark matter density, $10^7 M_{\rm sun}$ kpc^{-3}, is shown by the vertical red line: Cepheids to the left of this line live in lower density regions than the Solar System and may therefore be unscreened in the baryon–dark matter interaction model.

$$\log(\bar{L}_{ij}) = \log(L_{ij}) + \frac{A}{2}\log\left(1 + \frac{\Delta G_{ij}}{G_{\rm N}}\right) + B\log\left(1 + \frac{\Delta G_{ij}}{G_{\rm N}}\right),$$

$$\bar{L}_{ij} = \left(1 + \frac{\Delta G_{ij}}{G_{\rm N}}\right)^{\frac{A}{2}+B} L_{ij},$$

$$\bar{d}_{ij} = \left(1 + \frac{\Delta G_{ij}}{G_{\rm N}}\right)^{\frac{A+2B}{4}} d_{ij} \equiv k_{ij}\, d_{ij}, \qquad \bar{D}_i = \left(\frac{\sum_j k_{ij}\Delta m_{ij}^{-2}}{\sum_j \Delta m_{ij}^{-2}}\right) D_i \equiv K_i D_i.$$

$$\sigma(d_i) = \left(\frac{\sum_j k_{ij}^2 \Delta m_{ij}^{-2}}{\sum_j \Delta m_{ij}^{-2}} - K_i^2\right)^{1/2} \qquad \Delta\bar{D}_i = \bar{D}_i\left((\Delta D_i/D_i)^2 + \sigma(d_i)\right)^{1/2}$$

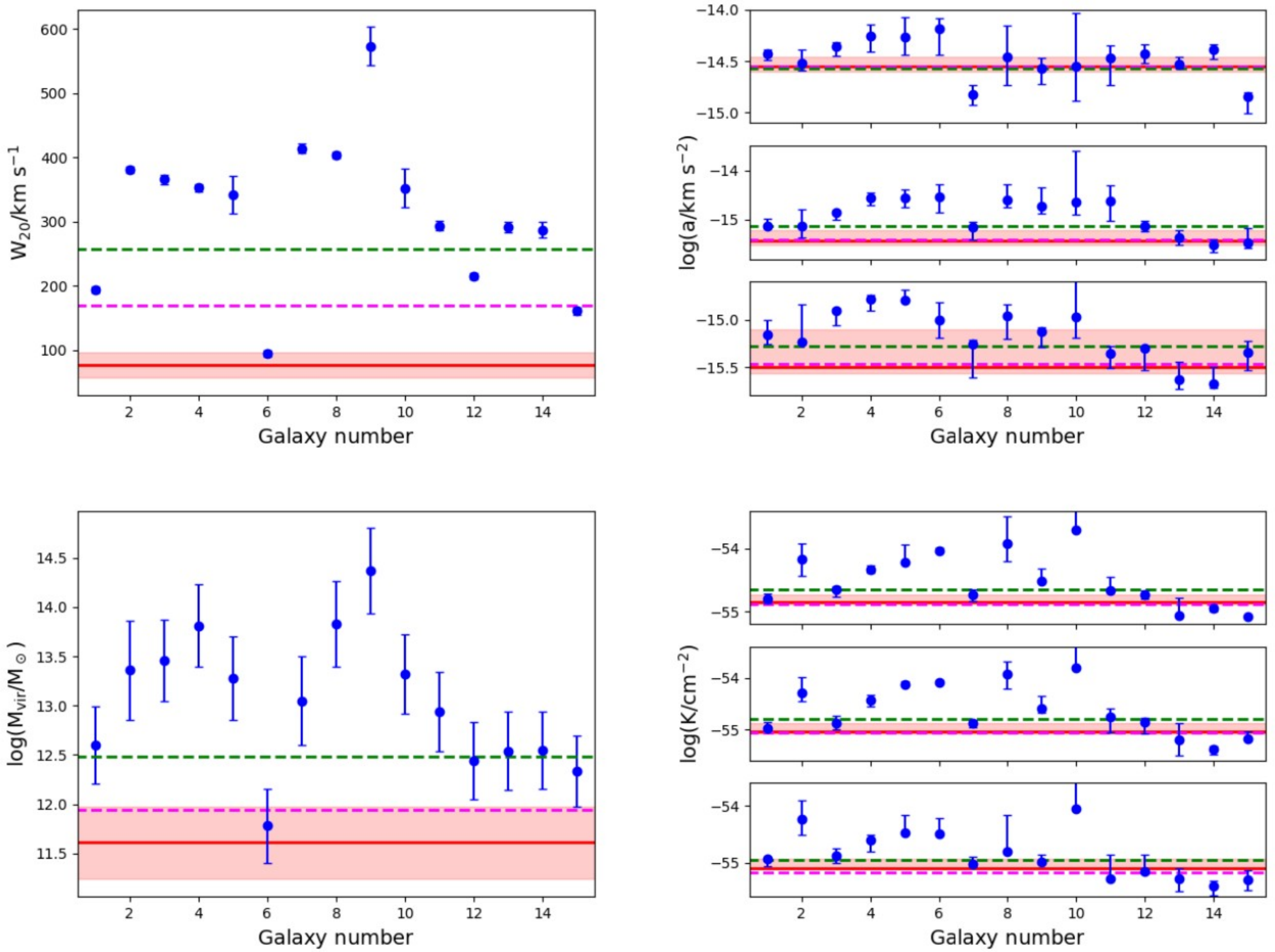
$$H_0 = 10^{M_{\rm SN}/5+5+a_B}\ \mathrm{km\ s^{-1} Mpc^{-1}}$$

$$\bar{H}_0 = H_0^{\rm R19}\frac{\sum_i K_i^{-1}\Delta\bar{H}_{0,i}^{-2}}{\sum_i \Delta\bar{H}_{0,i}^{-2}} \qquad \Delta\bar{H}_0 = \bar{H}_0\left[\left(\frac{\Delta H_0^{\rm R19}}{H_0^{\rm R19}}\right)^2 + \left(\frac{1}{\sum_i \Delta\bar{H}_{0,i}^{-2}} - \frac{1}{\sum_i \Delta H_{0,i}^{-2}}\right)\right]^{1/2}$$

Name	RA/Dec (J2000 °)	D/Mpc	ΔD/Mpc	M_{SN}	ΔM_{SN}	M_V	ΔM_V	W_{20}/km/s	ΔW_{20}/km/s
MW	—	0	0	—	—	-20.60	0.50	169	50
N4258	184.74 / 47.30	7.54	0.20	—	—	-21.90	0.07	442	5
M101	210.80 / 54.35	6.71	0.14	-19.39	0.13	-21.30	0.20	194	5
N1015	39.55 / -1.32	31.58	1.18	-19.05	0.15	-20.89	0.24	188	10
N1309	50.53 / -15.40	31.96	0.81	-19.33	0.13	-20.80	0.20	161	6
N1365	53.40 / -36.14	18.26	0.48	-19.39	0.14	-23.00	0.20	404	5
N1448	56.13 / -44.64	18.29	0.38	-19.11	0.13	-21.99	0.23	414	7
N2442	144.10 / -69.53	20.05	0.49	-19.24	0.15	-21.90	0.20	514	21
N3021	147.74 / 33.55	31.59	1.31	-19.54	0.15	-21.20	0.20	291	8
N3370	161.77 / 17.27	25.97	0.59	-19.16	0.13	-21.20	0.20	287	12
N3447	163.36 / 16.78	24.08	0.48	-19.21	0.13	-17.90	0.20	116	32
N3972	178.94 / 55.32	20.77	0.67	-19.10	0.14	-20.68	0.18	266	11
N3982	179.12 / 55.13	22.25	0.71	-19.51	0.13	-21.14	0.10	232	7
N4038	180.47 / -18.87	18.11	0.93	-19.06	0.16	-21.84	0.19	294	8
N4424	186.80 / 9.42	16.44	2.21	-19.53	0.31	-19.20	0.20	95	5
N4536	188.61 / 2.19	15.18	0.37	-19.29	0.14	-22.97	0.20	353	6
N4639	190.72 / 13.26	20.25	0.66	-19.11	0.14	-21.32	0.07	303	7
N5584	215.60 / -0.39	22.76	0.48	-19.09	0.12	-21.00	0.20	215	5
N5917	230.39 / -7.38	28.35	1.33	-19.26	0.15	-18.70	0.20	237	6
N7250	334.57 / 40.56	19.94	0.72	-19.20	0.14	-19.60	0.20	203	10
U9391	218.65 / 59.34	38.35	1.11	-19.45	0.13	-18.50	0.20	140	15

Name	$\log(R/\mathrm{kpc})$	$\Delta\log(R/\mathrm{kpc})$	$\log(c)$	$\Delta\log(c)$	$\log(V/\mathrm{km/s})$	$\Delta\log(V/\mathrm{km/s})$	$\log(M/M_\odot)$	$\Delta\log(M/M_\odot)$
MW	2.37	0.12	1.07	0.27	2.24	0.12	11.94	0.37
N4258	2.75	0.13	0.93	0.2	2.45	0.13	13.01	0.39
M101	2.61	0.14	0.99	0.22	2.31	0.14	12.59	0.43
N1015	2.54	0.13	1.01	0.23	2.24	0.13	12.39	0.38
N1309	2.51	0.13	1.03	0.23	2.21	0.13	12.31	0.39
N1365	3.02	0.15	0.83	0.16	2.72	0.15	13.83	0.44
N1448	2.76	0.14	0.93	0.20	2.46	0.14	13.04	0.43
N2442	2.75	0.14	0.93	0.19	2.45	0.14	13.00	0.42
N3021	2.59	0.13	1.00	0.23	2.29	0.13	12.55	0.39
N3370	2.59	0.13	1.00	0.22	2.29	0.13	12.52	0.39
N3447	2.25	0.13	1.10	0.28	1.95	0.13	11.52	0.38
N3972	2.51	0.11	1.01	0.23	2.21	0.11	12.30	0.34
N3982	2.59	0.12	0.99	0.23	2.29	0.12	12.53	0.35
N4038	2.72	0.15	0.97	0.19	2.42	0.15	12.93	0.44
N4424	2.34	0.13	1.07	0.26	2.04	0.13	11.79	0.38
N4536	3.00	0.16	0.86	0.17	2.70	0.16	13.77	0.48
N4639	2.61	0.12	1.00	0.22	2.31	0.12	12.60	0.37
N5584	2.56	0.12	1.00	0.24	2.26	0.12	12.43	0.37
N5917	2.30	0.13	1.08	0.29	2.00	0.13	11.66	0.38
N7250	2.38	0.12	1.06	0.26	2.08	0.12	11.91	0.35
U9391	2.29	0.12	1.09	0.28	1.99	0.12	11.62	0.37

Proxy	Unscr frac	Screening properties	$\Delta G/G_N$	$\hat{H}_0$ / km s^{-1} Mpc^{-1}	$\Delta\hat{H}_0$ / km s^{-1} Mpc^{-1}	σ_{H_0}
—	—	0 / 0 / 0 / 0	0	74.0	1.4	4.4
$\Phi_{0.5}$	0.85	1 / 0 / 0 / 0	0.09	72.4	1.4	3.3
Φ_5	0.08	1 / 0 / 0 / 0	0.22	73.4	1.5	3.9
Φ_{50}	0.30	1 / 0 / 0 / 0	0.14	72.8	1.5	3.5
$a_{0.5}$	0.31	1 / 0 / 0 / 0 1 / 1 / 0 / 0	0.14 0.04	72.8 71.9	1.5 1.6	3.5 2.6
a_5	0.31	1 / 0 / 0 / 0 1 / 1 / 0 / 0	0.14 0.04	73.1 72.2	1.5 1.8	3.6 2.6
a_{50}	0.35	1 / 0 / 0 / 0 1 / 1 / 0 / 0	0.13 0.04	72.6 71.4	1.4 1.6	3.5 2.5
$K_{0.5}$	0.39	1 / 0 / 0 / 0 1 / 1 / 0 / 0	0.13 0.03	72.8 71.4	1.4 1.5	3.6 2.5
K_5	0.30	1 / 0 / 0 / 0 1 / 1 / 0 / 0	0.14 0.04	72.6 71.8	1.4 1.5	3.4 2.7
K_{50}	0.26	1 / 0 / 0 / 0 1 / 1 / 0 / 0	0.14 0.04	72.9 71.9	1.5 1.6	3.6 2.7
L_{gal}	0.12	1 / 0 / 0 / 0 1 / 1 / 0 / 0	0.19 0.06	73.5 72.0	1.4 1.4	4.0 3.1
W_{20}	0.20	1 / 0 / 0 / 0 1 / 1 / 0 / 0	0.16 0.05	73.5 72.9	1.5 1.9	3.8 2.8
M_{vir}	0.37	1 / 0 / 0 / 0 1 / 1 / 0 / 0	0.13 0.04	72.9 71.5	1.5 1.8	3.5 2.2
ρ_{DM}	0.45	1 / 1 / 0 / 0 1 / 1 / 1 / 0	0.03 0.03	71.8 72.4	1.5 1.5	2.8 3.3
E. U.	1	0 / 0 / 0 / 1	0.05	71.5	1.4	2.8



W20/km s−1
Galaxy number
log(a/km s−2)
Galaxy number
log(Mvir/M⊙)
Galaxy number
log(K/cm−2)
Galaxy number

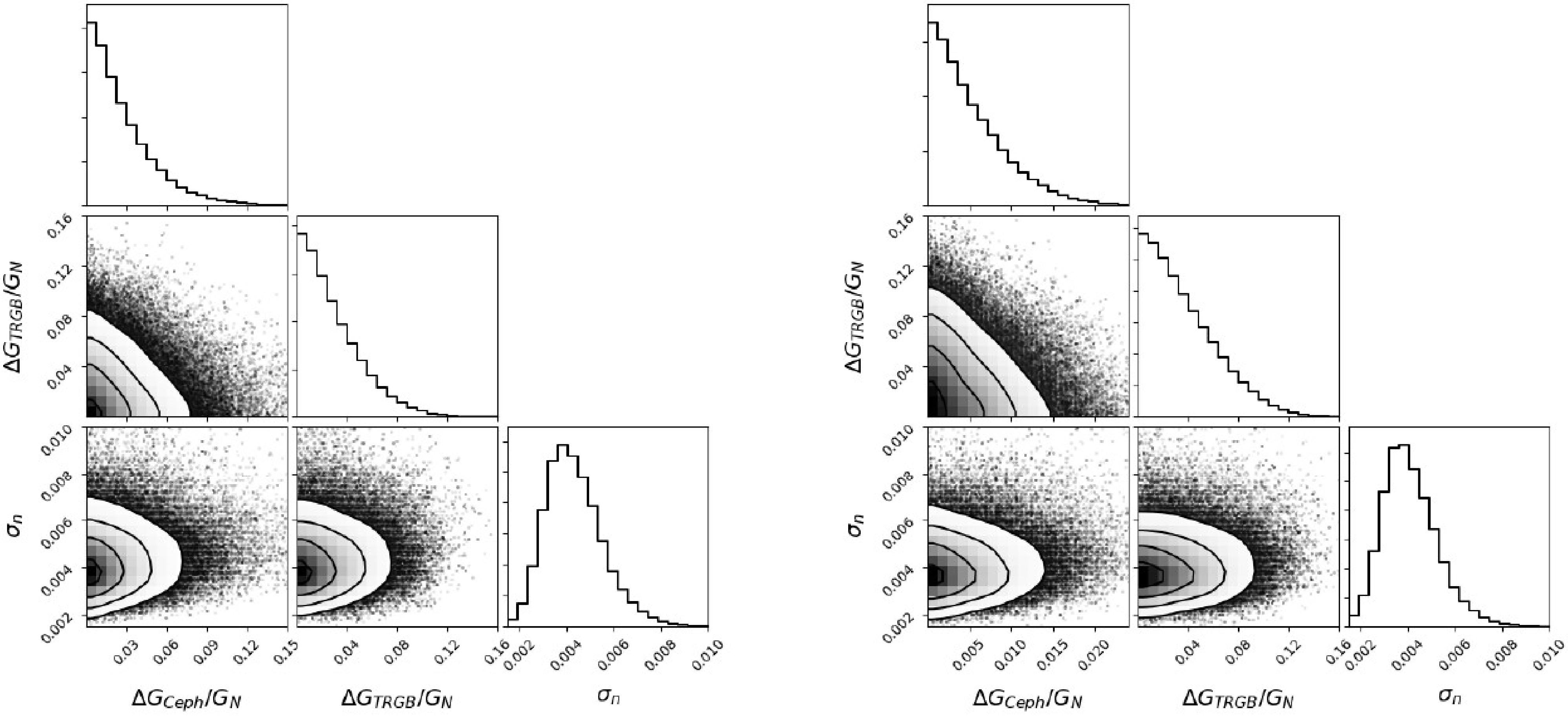


FIG. 3. Corner plots for $\Delta G/G_N$ for Cepheids and TRGB, and additional noise σ_n in the comparison between Cepheid and TRGB distances. These particular constraints assume 30% of the sample is unscreened. *Left:* Cepheid cores screened, *Right*: Cepheid cores unscreened.

Name	$\log(R/\mathrm{kpc})$	$\Delta\log(R/\mathrm{kpc})$	$\log(c)$	$\Delta\log(c)$	$\log(V/\mathrm{km/s})$	$\Delta\log(V/\mathrm{km/s})$	$\log(M/M_\odot)$	$\Delta\log(M/M_\odot)$
LMC	2.28	0.12	1.07	0.30	1.98	0.12	11.61	0.37
MW	2.37	0.12	1.07	0.27	2.24	0.12	11.94	0.37
M101	2.61	0.13	0.97	0.23	2.31	0.13	12.60	0.39
M66	2.86	0.17	0.90	0.18	2.56	0.17	13.36	0.50
M96	2.90	0.14	0.87	0.18	2.60	0.14	13.46	0.41
N4536	3.02	0.14	0.84	0.16	2.72	0.14	13.81	0.42
N4526	2.84	0.14	0.90	0.19	2.54	0.14	13.28	0.42
N4424	2.34	0.13	1.07	0.27	2.04	0.13	11.78	0.38
N1448	2.76	0.15	0.95	0.20	2.46	0.15	13.05	0.45
N1365	3.02	0.14	0.84	0.16	2.72	0.14	13.83	0.43
N1316	3.20	0.14	0.80	0.16	2.90	0.14	14.37	0.43
N1404	2.85	0.13	0.90	0.18	2.55	0.13	13.32	0.40
N4038	2.72	0.13	0.96	0.20	2.43	0.13	12.94	0.40
N5584	2.56	0.13	1.02	0.23	2.26	0.13	12.44	0.39
N3021	2.59	0.13	0.99	0.23	2.29	0.13	12.54	0.40
N3370	2.60	0.13	0.99	0.23	2.30	0.13	12.55	0.39
N1309	2.52	0.12	1.01	0.22	2.22	0.12	12.34	0.36

Proxy	Unscreened fraction	$\Delta G/G_{\rm N}$	$\hat{H}_0$ / km s^{-1} Mpc^{-1}	$\Delta\hat{H}_0$ / km s^{-1} Mpc^{-1}	σ_{H_0}
—	—	0	72.4	2.0	2.4
$\Phi_{0.5}$	0.85	0.14	71.8	2.0	2.1
Φ_5	0.10	0.25	62.8	1.9	-2.4
Φ_{50}	0.36	0.18	69.3	2.2	0.9
$a_{0.5}$	0.38	0.18	68.8	2.3	0.6
a_5	0.27	0.19	67.4	2.2	0.0
a_{50}	0.43	0.17	69.3	2.1	0.9
$K_{0.5}$	0.40	0.18	68.8	2.1	0.7
K_5	0.30	0.19	67.9	2.0	0.3
K_{50}	0.27	0.19	67.7	2.0	0.1
$L_{\rm gal}$	0.04	0.28	59.5	1.6	-4.6
W_{20}	0.14	0.23	64.5	2.0	-1.4
$M_{\rm vir}$	0.20	0.20	66.8	2.1	-0.3