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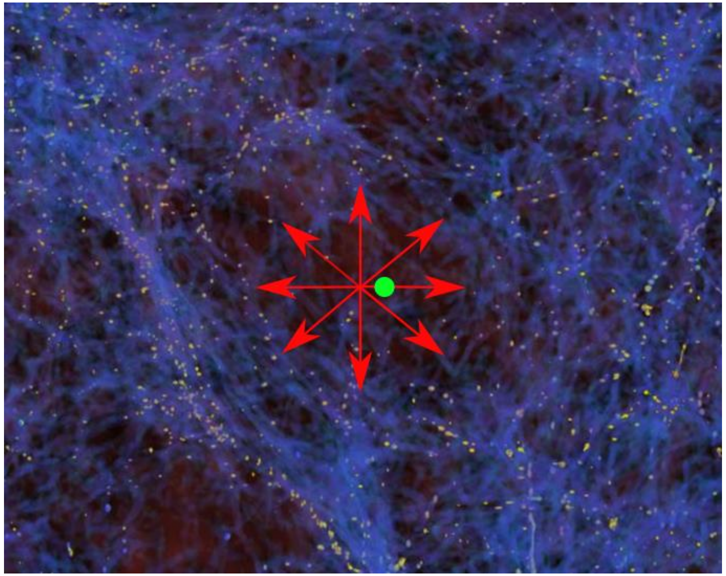
MNRAS, 527, 4388 – 4396 (January 2024)

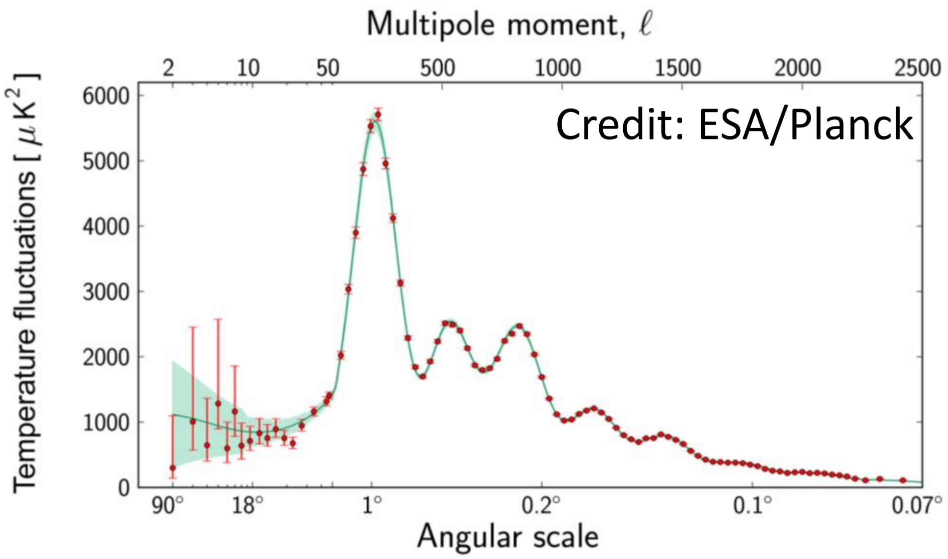
Joint solution to the Hubble and bulk flow tensions using the observed local supervoid and faster structure growth



Two routes to the present expansion rate

- The currently popular ΛCDM model has achieved many successes (e.g. primordial D and He, galaxy cluster mass function at low z, cosmic shear)
- Its parameters are usually calibrated against CMB anisotropies ($z = 1100$)
- ΛCDM then predicts the present expansion rate

$$H_0 \equiv \dot{a}/a$$



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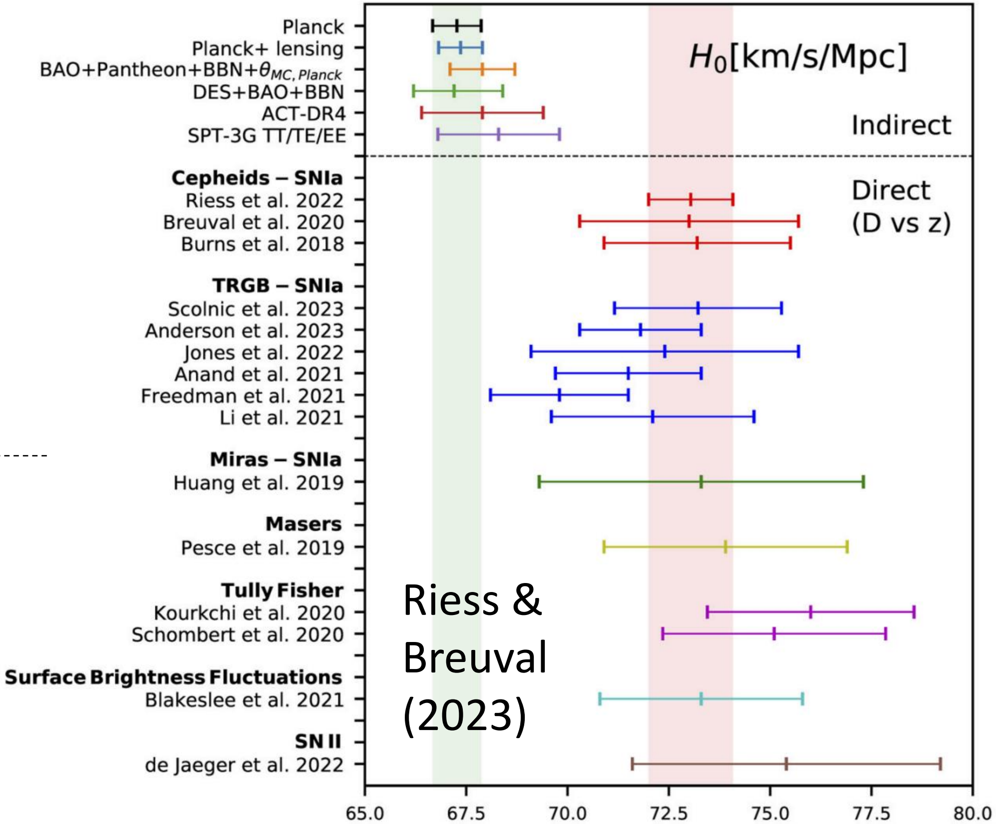
- ΛCDM then predicts the present expansion rate

$$H_0 \equiv \dot{a}/a$$

- Local observations show a nearly linear relation between distance and spectroscopic redshift *z*
- If this is assigned entirely to the difference in *a* at the time of emission and reception, we can infer

$$H_0 = \lim_{z \to 0} c \frac{dz}{dr}$$



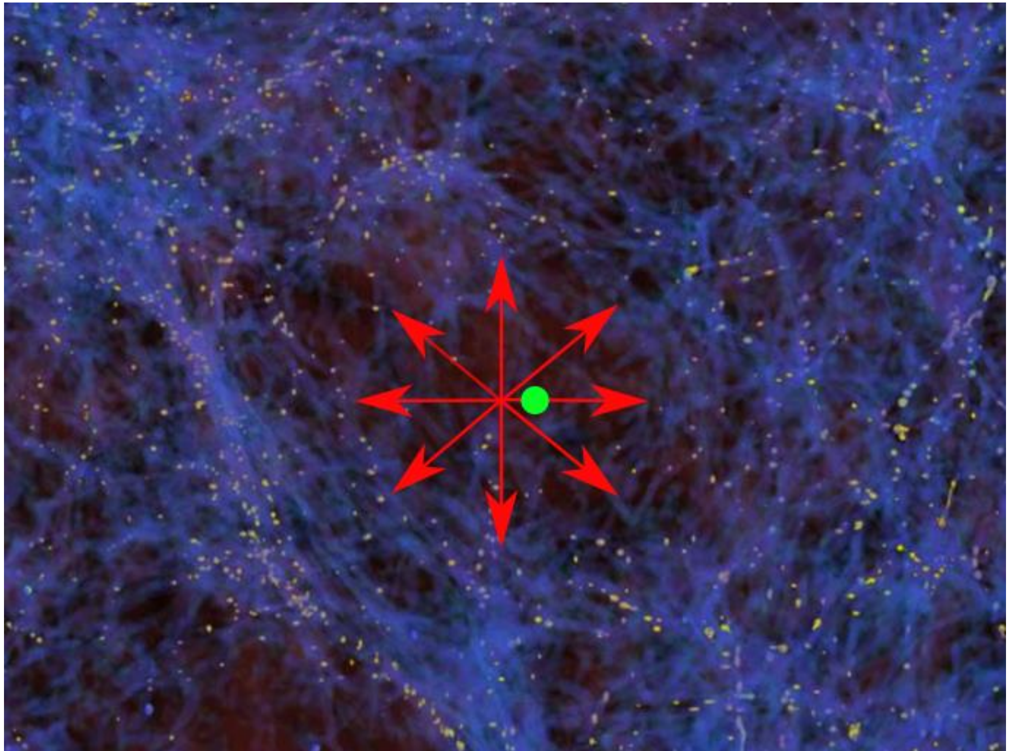
Riess & Breuval (2023)

The impact of local structure

- The local measurement is affected by peculiar velocities, which are velocities in the CMB rest frame (e.g. M31 is approaching us)
- As more distant galaxies are considered, the impact of peculiar velocities should decrease
- But if our location (green dot) is near the centre of a large void, they could rise at first and only start decreasing quite far out

➢ Peculiar velocities might skew local H_0.

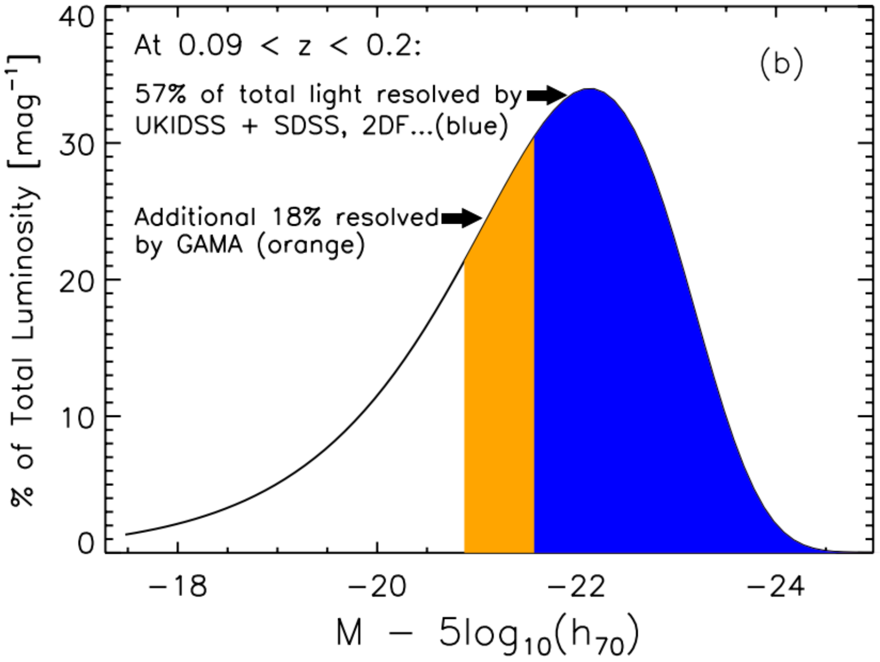
$$H_0 = \lim_{z \to 0 \text{ (but not too low)}} c \frac{dz}{dr}$$



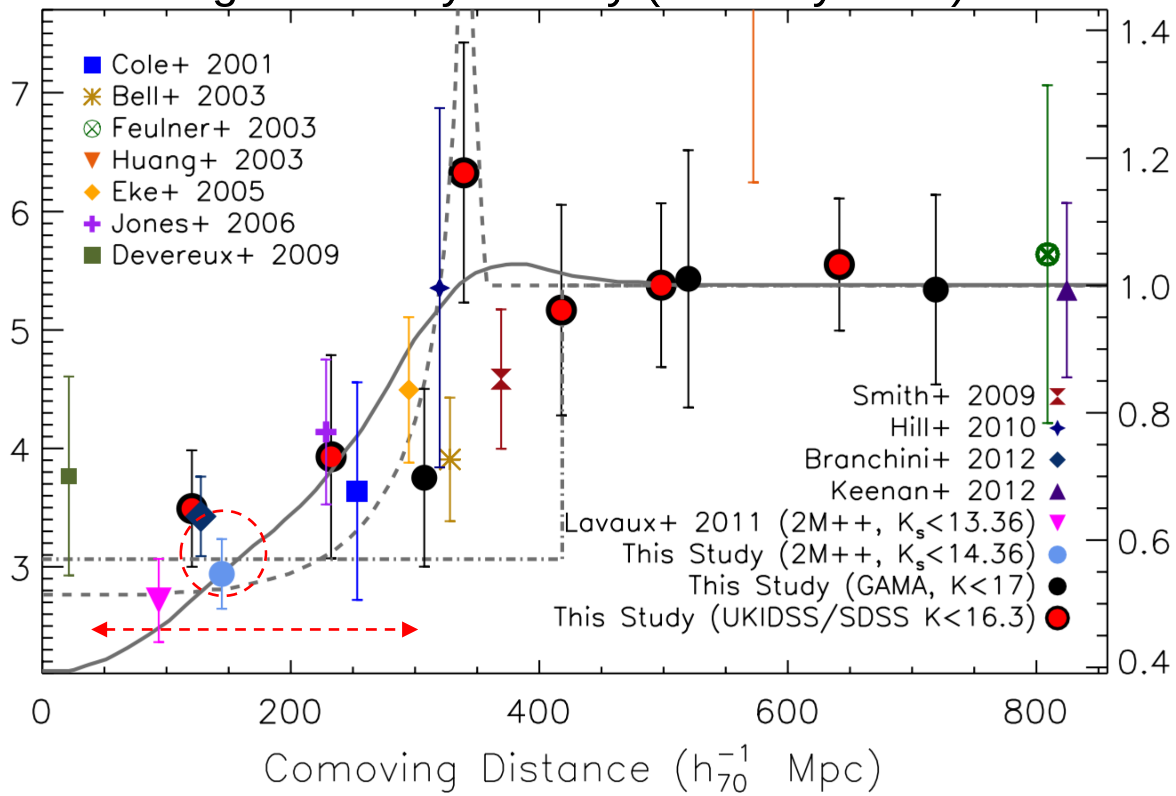
Credit: MIT technology review, annotations: Moritz Haslbauer

The KBC void (Keenan+ 2013)

- Galaxy number counts over 90% of sky and most of the luminosity function show an underdensity at 40 – 300 Mpc.



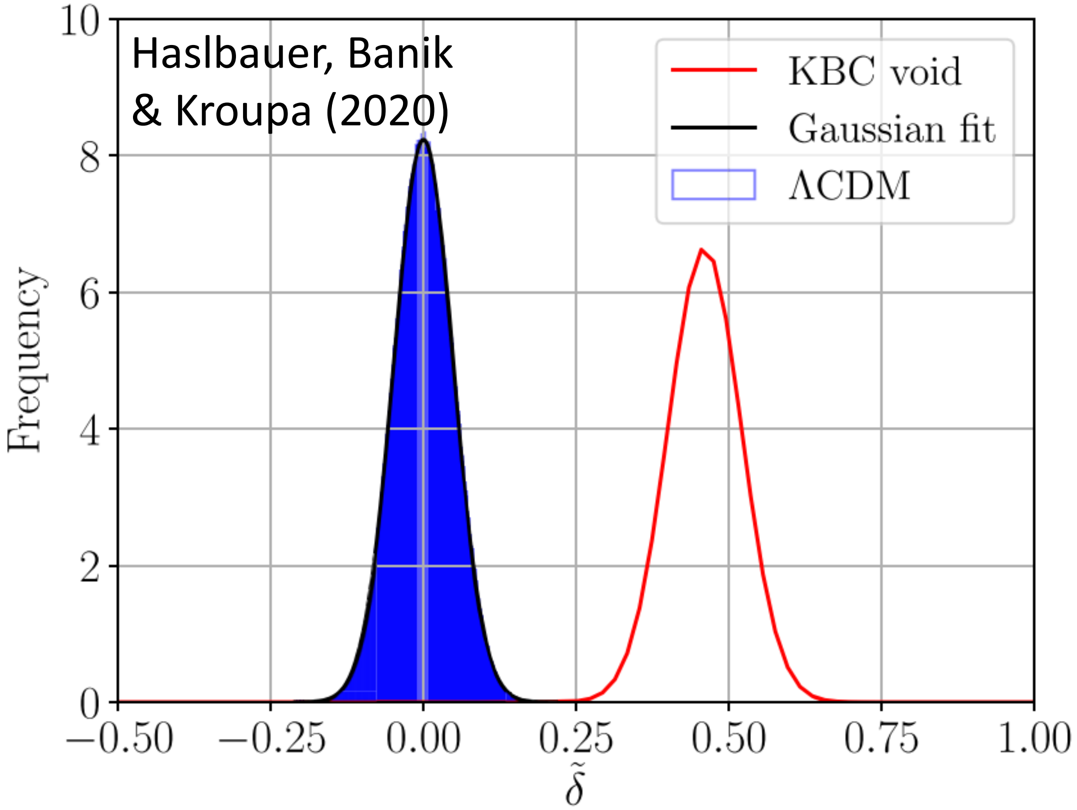
Comoving luminosity density (arbitrary units)



Analogues in ΛCDM

- Uniform grid of 10^6 vantage points in Millennium XXL (Angulo+ 2012), a ΛCDM *N*-body simulation with 4.1 cGpc box size.
- Get total mass in halos with semi-analytic $M_* > 10^{10}\ M_\odot/h$ within 40 – 300 Mpc of each vantage point
- Compare density to cosmic mean value
- Enhance the density contrast 1.5x to allow for redshift space distortions: observers think they are seeing out to some distance *d* based on the redshift *z*, but outflows from local void mean the actual distance <*d*, reducing the galaxy number count

➢ Tension with ΛCDM is 6.04σ.



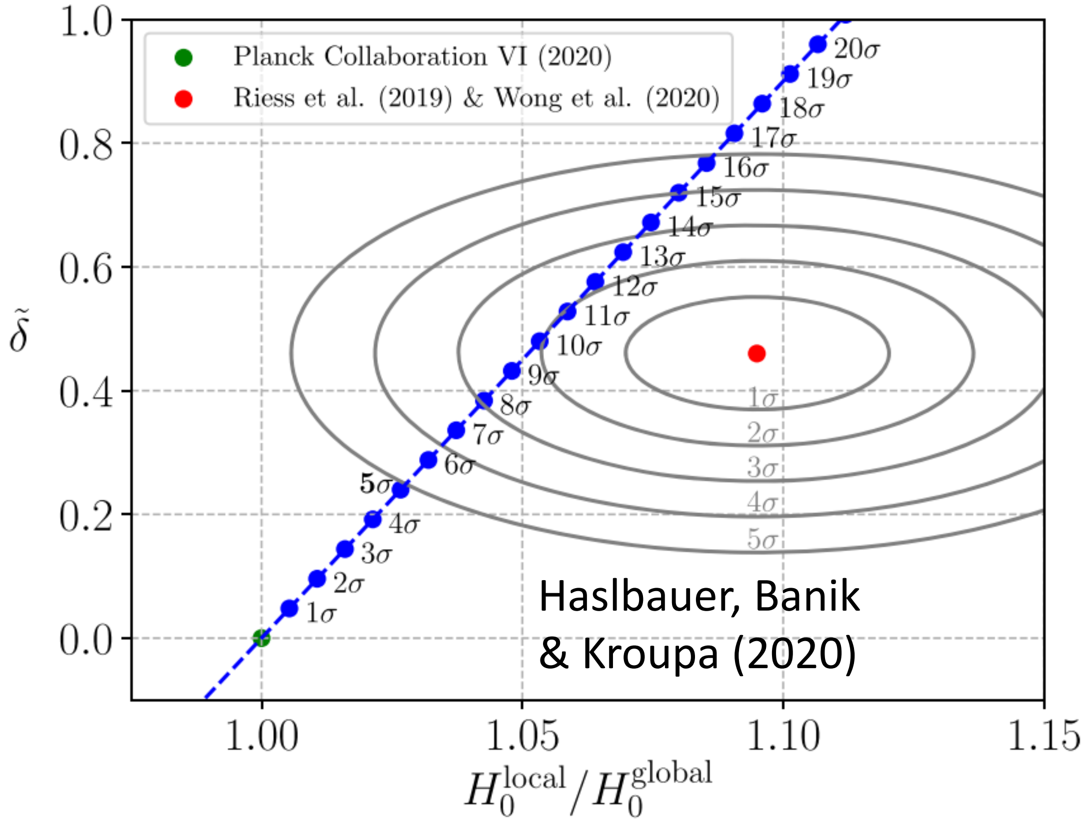
Increasing the cosmic variance

- Cosmic variance in local measurements of H_0 should be quite small in ΛCDM
  - ➢ Cannot solve the Hubble tension
- But structure formation must be enhanced to explain the KBC void (local void also found by Wong+ 2022)
- Can we relate the observed local void to the Hubble tension?

$$\frac{\Delta H}{H} \equiv f\delta\,, \tag{18}$$

where e.g. Marra et al. (2013) showed that for $\delta \ll 1$ in ΛCDM,

$$f = \frac{{\Omega_m}^{0.6}}{3b}\,, \tag{19}$$



Haslbauer, Banik & Kroupa (2020)

MOND simulation of outflow from void

- Start with small initial underdensity at $a = 0.1$, when the expansion rate = H_i

$$\ddot{\boldsymbol{r}} = \boldsymbol{g}_{\text{void}} + \overbrace{\frac{\ddot{a}}{a}\boldsymbol{r}}^{\boldsymbol{g}_{\text{Hubble}}} ,$$

$$\dot{\boldsymbol{r}}_i = H_i \boldsymbol{r}_i ,$$

- Acceleration beyond the cosmic expansion term g_{Hubble} is due to mass deficit interior to r

➢ Need present cosmic mean matter density ρ_0

$$g_{\text{N}} \equiv \frac{G\Delta M}{r^2} , \qquad \text{with}$$

$$\Delta M \equiv \frac{4\pi}{3}\rho_0 \left(\frac{r}{a}\right)^3 - M_{\text{enc}} ,$$

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$$\Delta M \equiv \frac{4\pi}{3}\rho_0 \left(\frac{r}{a}\right)^3 - M_{\text{enc}} ,$$

- To get enhanced structure formation, the gravity is enhanced as in MOND (as proxy for unknown model)

- External field weakens this enhancement and causes void to move as a whole

➢ Important for velocities in CMB frame.

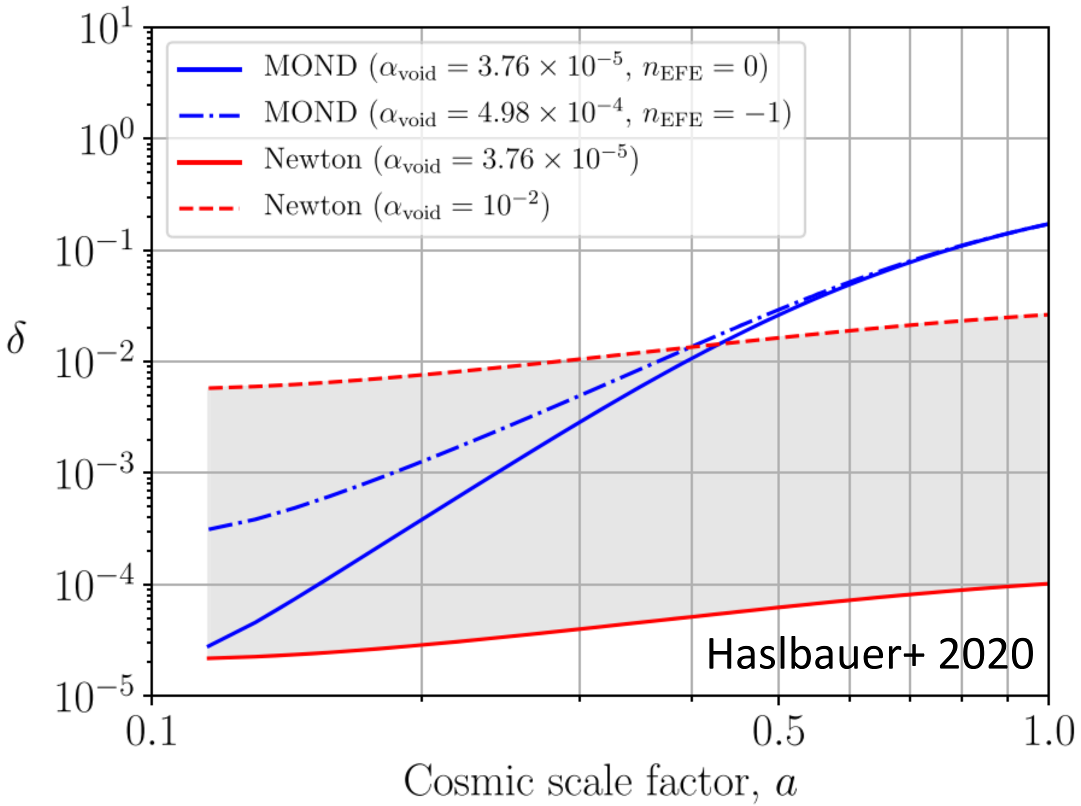
$$g = g_N \left(\frac{1}{2} + \sqrt{\frac{1}{4} + a_0 \left(g_N^2 + g_{N,\text{ext}}^2\right)^{-\frac{1}{2}}}\right)$$

Enhanced structure growth

- Figure: evolution of density contrast on 300 cMpc scale
- Normally, matter-dominated era has

$$\delta \propto a$$

- Structure formation about 4x faster in MOND
  - Same δ today associated with larger peculiar velocity and thus larger enhancement to H_0.



Redshifts are not purely cosmological

- Model includes three sources of redshift:
  - Cosmic expansion
  - Peculiar velocity away from void
  - Gravitational redshift

$$\frac{\lambda_{\text{obs}}}{\lambda_{\text{emit}}} = \frac{1}{a(t)} \overbrace{\sqrt{\frac{c+v_{\text{int}}}{c-v_{\text{int}}}}}^{\text{Doppler}} \overbrace{\exp\left(\frac{1}{c^2}\int g_{\text{void}}\,\mathrm{d}r\right)}^{\text{GR}}$$

- Observers assign redshift entirely to cosmic expansion and thus infer too low a_{app} at emission
- Cosmological parameters affected by time evolution of

$$\Delta a \equiv a - a_{app}$$

  - Biased inference of 1st & 2nd time derivatives of $a(t)$, with obvious cosmological implications.

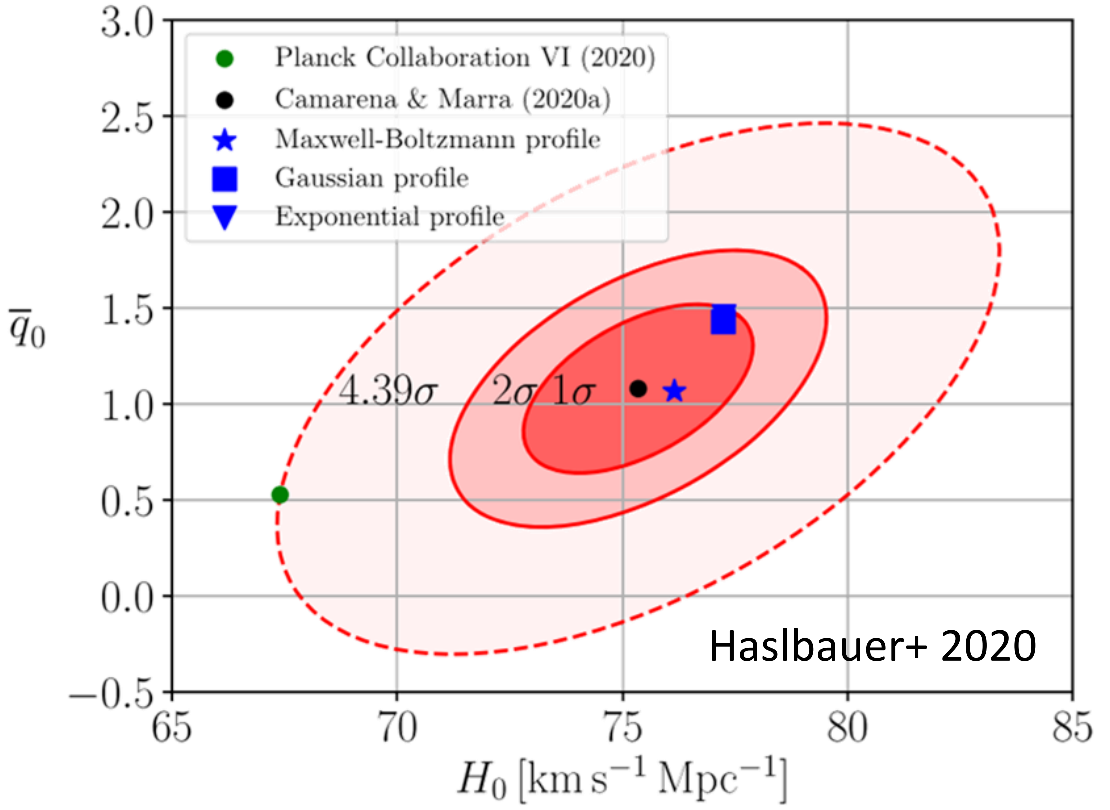
$$\Delta a\,(t) = \Delta\dot{a}\,(t_0)\,(t-t_0) + \frac{1}{2}\Delta\ddot{a}\,(t_0)\,(t-t_0)^2 + \mathcal{O}\,(t-t_0)^3$$

Local Hubble diagram at second order

$$H_0 \equiv \frac{\dot{a}}{a}$$

$$\overline{q}_0 \equiv \frac{a\ddot{a}}{\dot{a}^2}$$

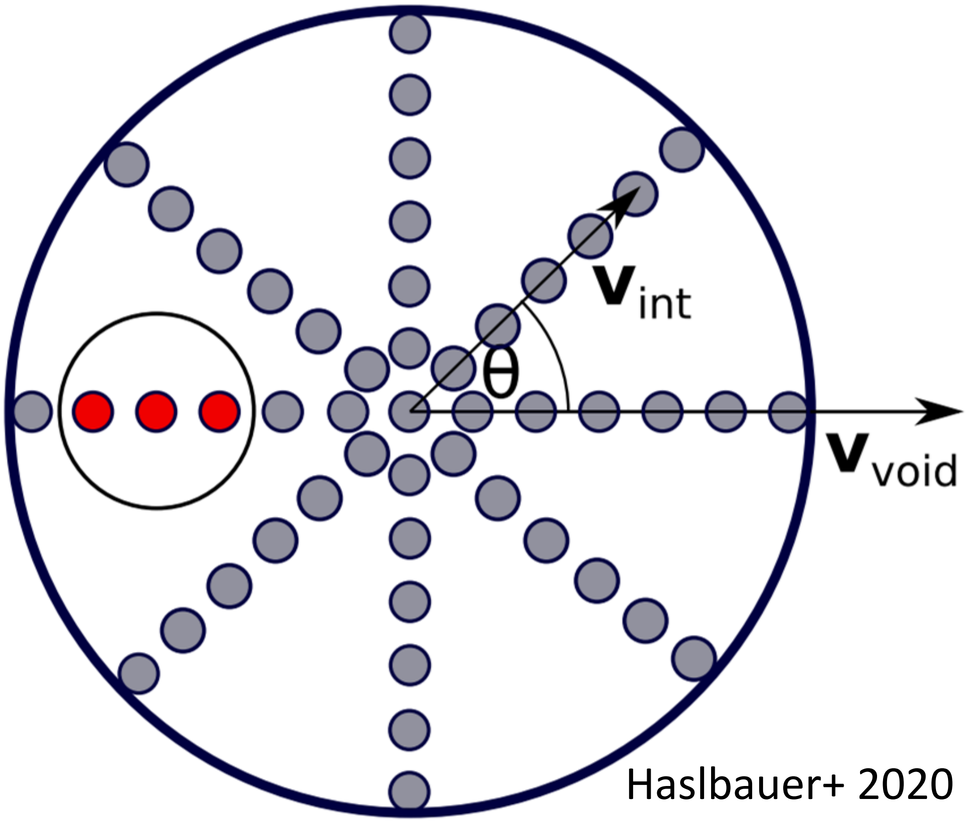
- Local observations get these using supernovae with $z = 0.023 - 0.15$ and second order Taylor expansion in $a(t)$
- Model predictions use quadratic regression on time evolution of Δa, the difference at fixed lookback time between **actual** and **apparent** *a*
- This is added to actual $\dot{a}$ and $\ddot{a}$ in model, which assumes Planck cosmology.



Haslbauer+ 2020

Spherical outflow + systemic velocity

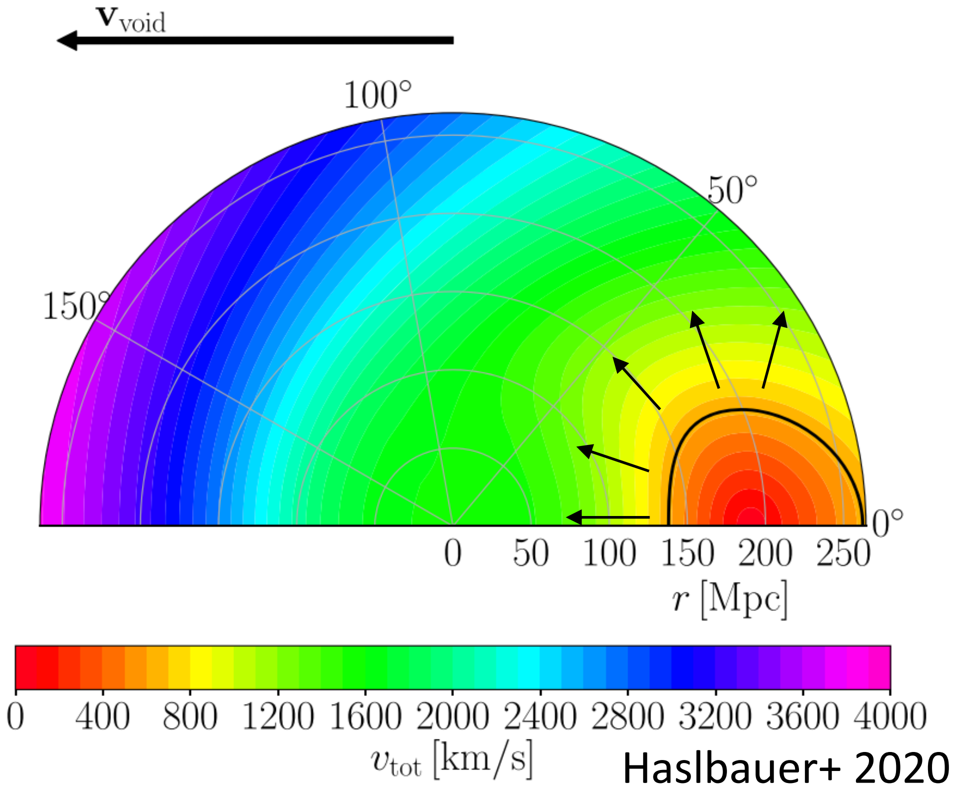
- Model has spherically symmetric outflow + systemic void velocity due to external field
- Void divided into cells
- CMB-frame velocity v_{tot} found in each cell using cosine rule
- Red cells illustrate parts of the void consistent with observed Local Group (LG) peculiar velocity.



Haslbauer+ 2020

Is our location in the void fine-tuned?

- Colour scale: model velocity in CMB frame (velocities axisymmetric about *x*-axis).
- Void velocity is time integral of a^*g_{ext} (factor of *a* accounts for Hubble drag)
- Velocity typically >> v_{LG} = 627±22 km/s (Kogut+ 1993), but about 2% of void volume has slower velocity
  - Estimated tension is 2.3σ
  - We must be close to solid black contour on figure at 627 km/s.

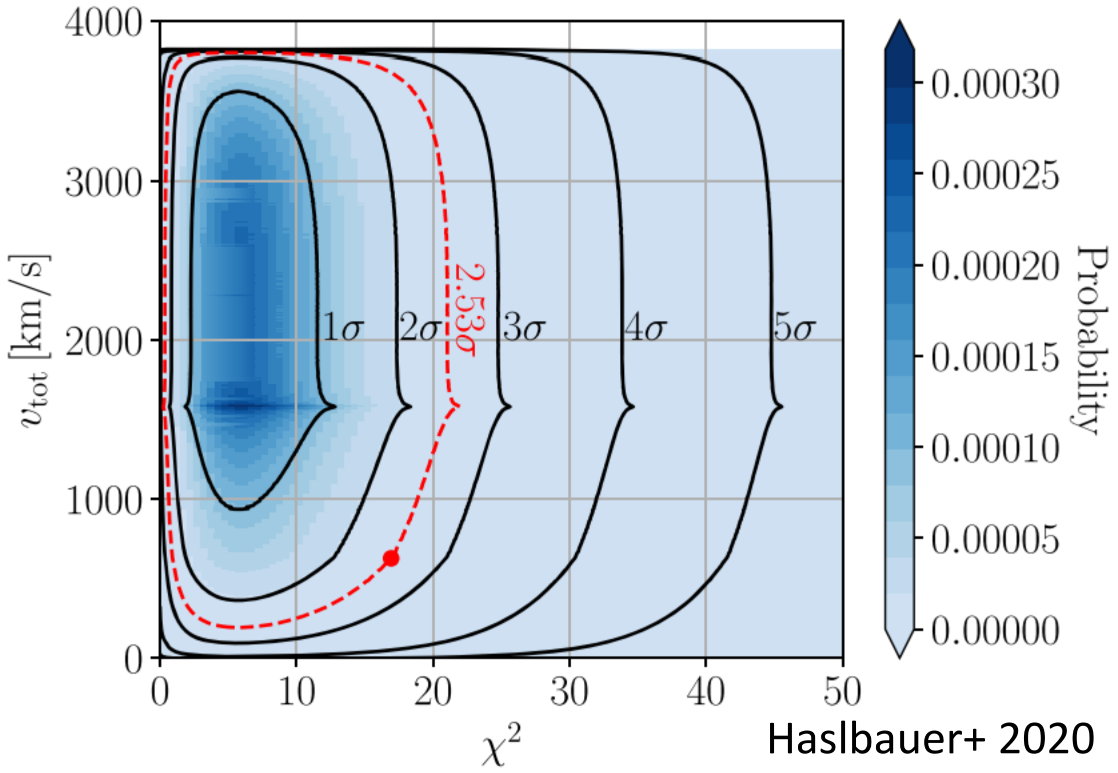


Haslbauer+ 2020

Overall goodness of fit

- Model constrained by:
  - local Hubble diagram
  - galaxy number counts
  - observed LG peculiar velocity
- 3 degrees of freedom assumed:
  - initial void size & strength
  - external field
- LG velocity constraint handled separately: CMB-frame velocity on *y*-axis as its distribution is not Gaussian

❖ Overall goodness of fit equivalent to a tension of 2.53σ (pie chart in appendix).

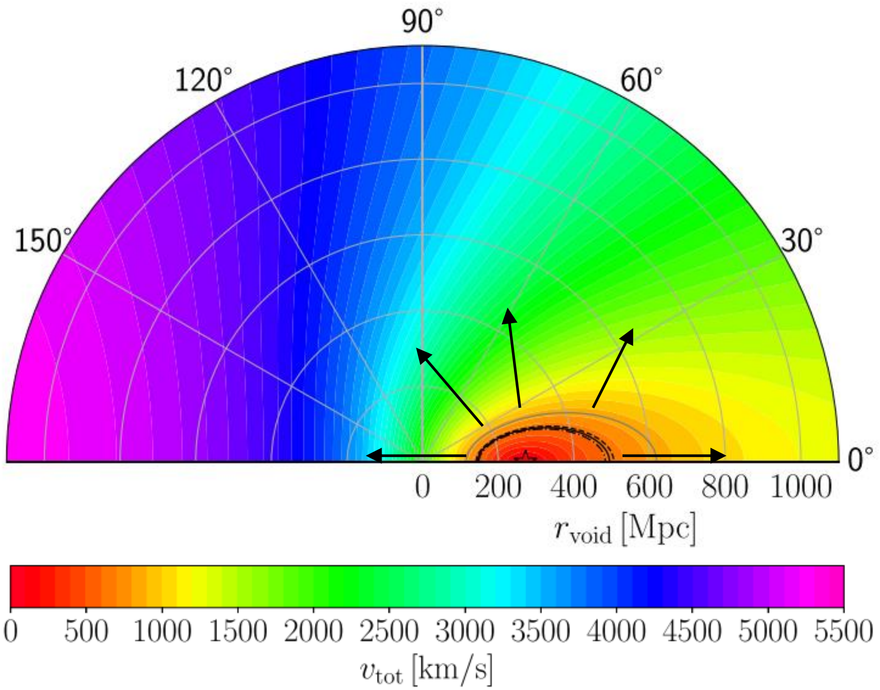


Haslbauer+ 2020

Bulk flow

Void velocity field

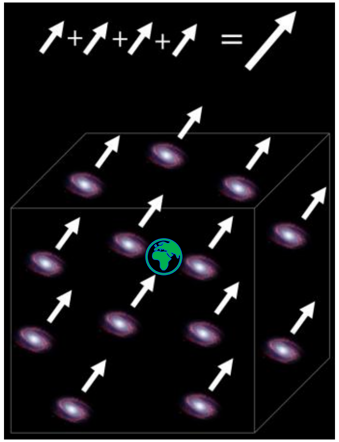
- Can test the void model using the velocity field within a few hundred Mpc
- Main problem is that redshifts are due to cosmic expansion and the Doppler effect
  - ➢ Hard to disentangle
- Off-centre location in void inevitable
  - ➢ Apparent expansion rate would depend on direction.



Mazurenko+ (2024)

Bulk flow definition

- Ideally, we want average of 3D peculiar velocity vectors within spherical region
- Need to make do with line of sight peculiar velocity of each galaxy in this region
- Consider this as a vector pointing along the line of sight (LOS)
- Take average of these LOS peculiar velocity vectors, adjust weights so galaxies get higher weights in more sparsely sampled regions (want to sample the velocity field)
- Galaxies weighted by $1/r^2$ (Peery+ 2018).



Credit: Abbe Whitford (from AstroBites)

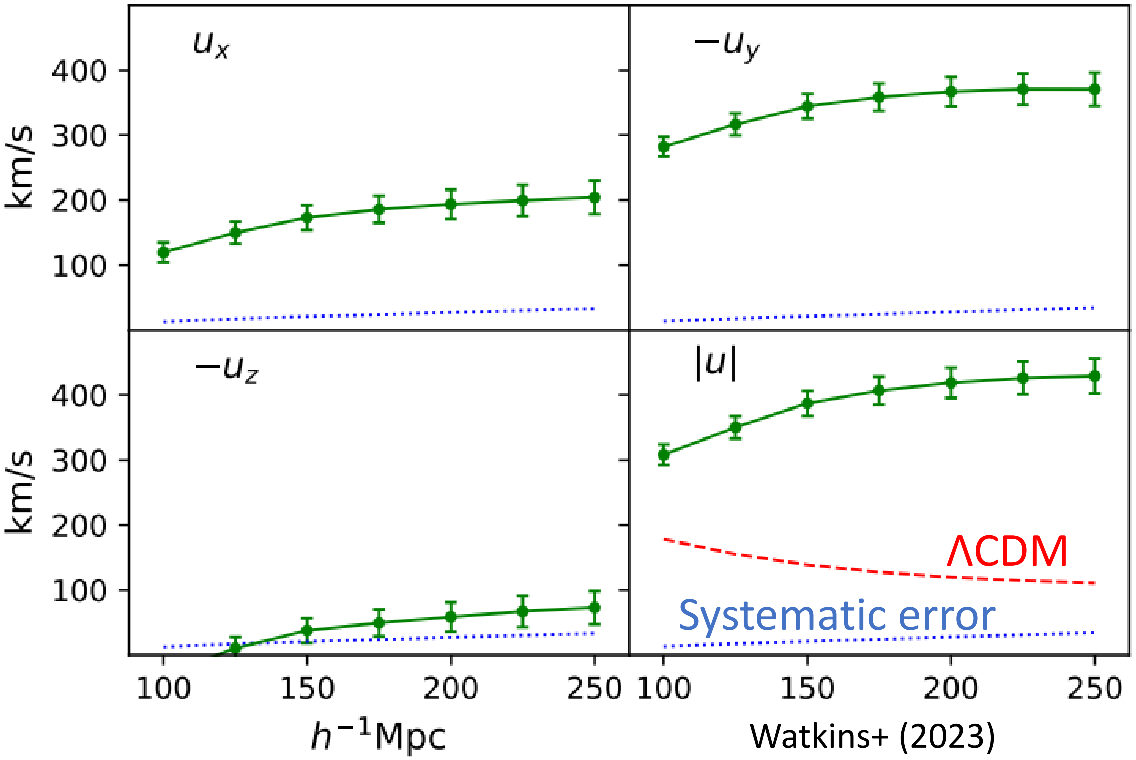
❖ Consequences:

- If all galaxies have the same peculiar velocity $\boldsymbol{v}$, then $v_{\text{bulk}} = v/3$ due to projection effects
- Assumed H_0 has no effect on v_{bulk} as it affects peculiar velocities in spherically symmetric manner, which does not affect the vector average.

AstroBite explaining this (search for: Astrobites bulk flow)

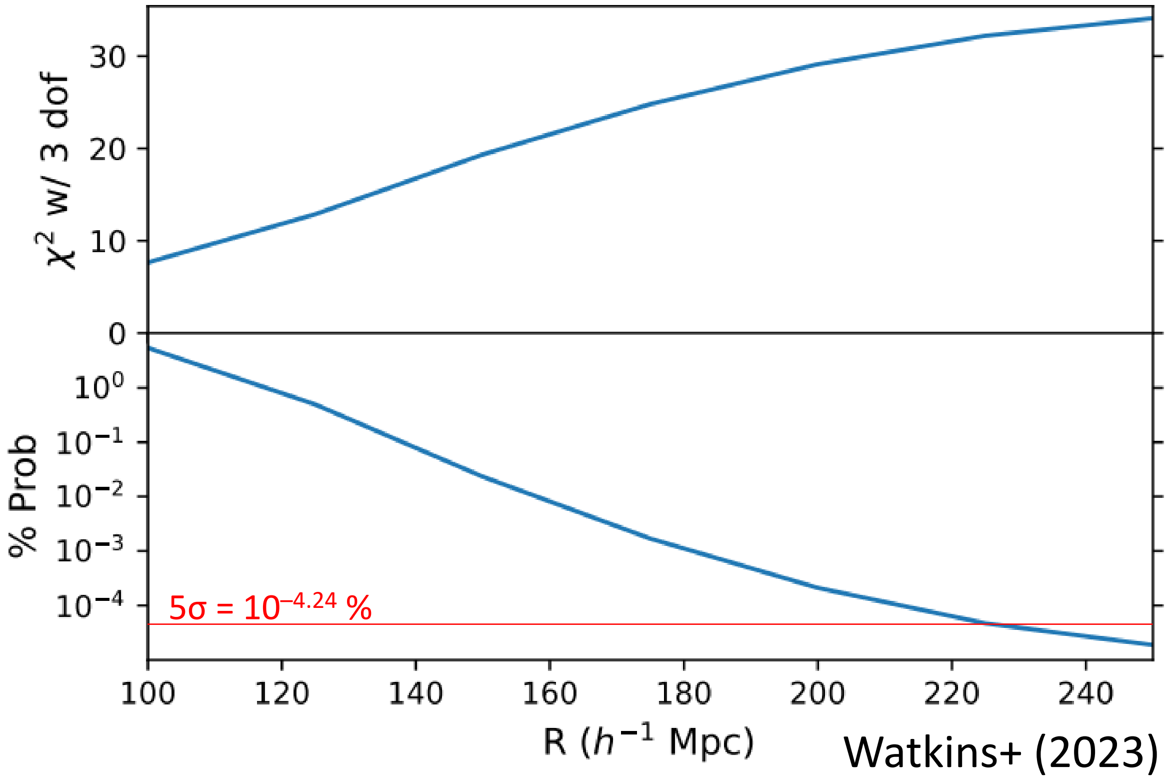
Bulk flow observations

- Need galaxy survey with redshift-independent distances
  - Use CosmicFlows-4 (Tully+ 2023)
- Bulk flow analysis by Watkins+ (2023)
- Subsequent study by independent team (Whitford+ 2023) reports "excellent agreement" out to 173/*h* Mpc, but their method did not extend further out
- The observed bulk flow is independent of the assumed H_0 because changing this affects peculiar velocities in a spherically symmetric manner, not affecting the vector average
  - Bulk flow tension ≠ Hubble tension.



Bulk flow tension

- Expected bulk flow along any direction follows Gaussian distribution
  - ➢ Simple χ^2 analysis with 3 d.o.f.
- Beyond 230/*h* Mpc, tension > 5σ
- Bulk flow tension cannot be solved by adjusting expansion history
  - ➢ Problem lies with growth of structure
- No evidence of problems with ΛCDM in CMB on scale of 300 cMpc, which is about twice the first acoustic peak/BAO scale: well measured.



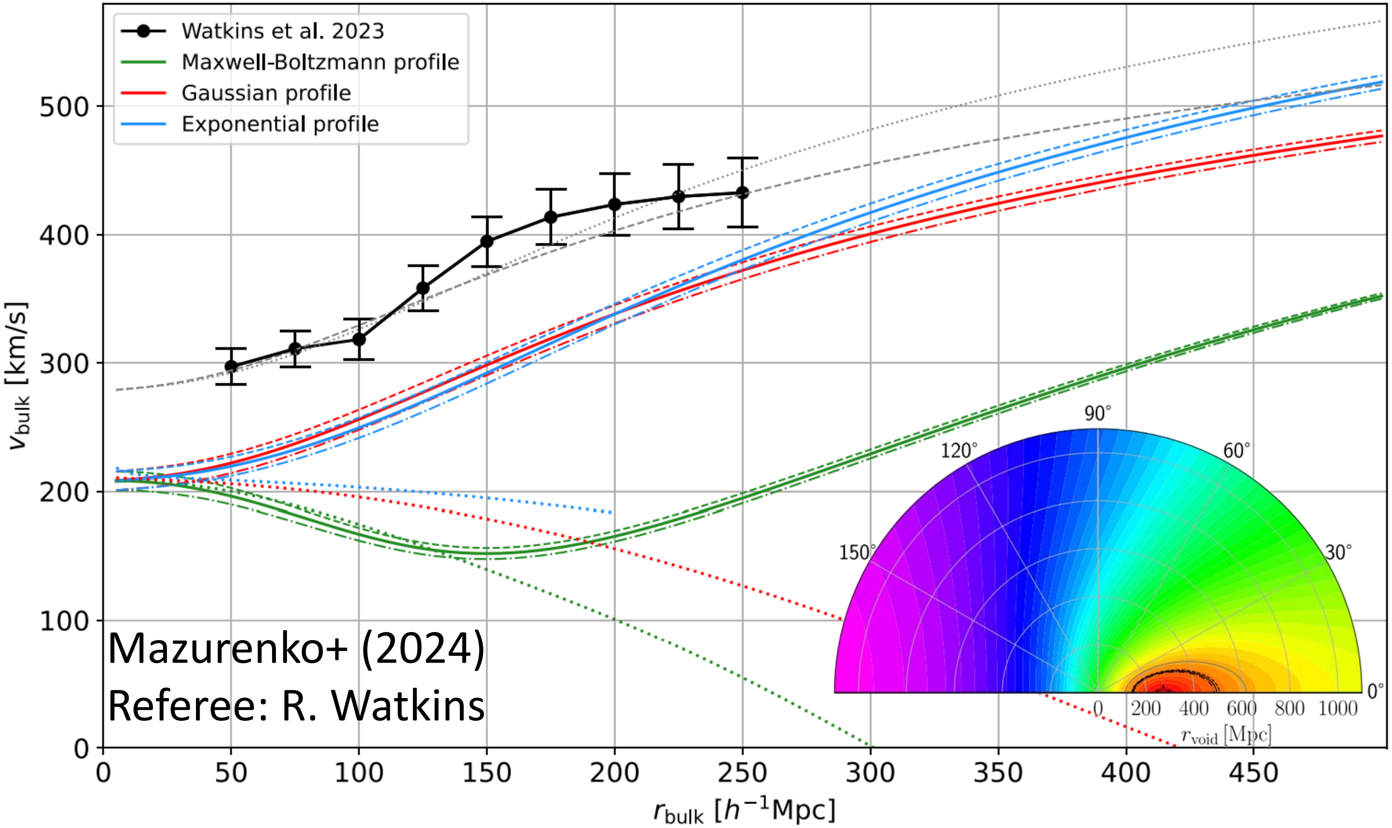
Watkins+ (2023)

Bulk flow results

Legend

- Observations (Watkins+ 2023)
- Different colour = different void density profile
- Downward dotted = outer vantage point
- Solid = inner vantage point
- Slightly above/below them = shifts to v_{LG} by ±22 km/s, which shifts our vantage point within the void

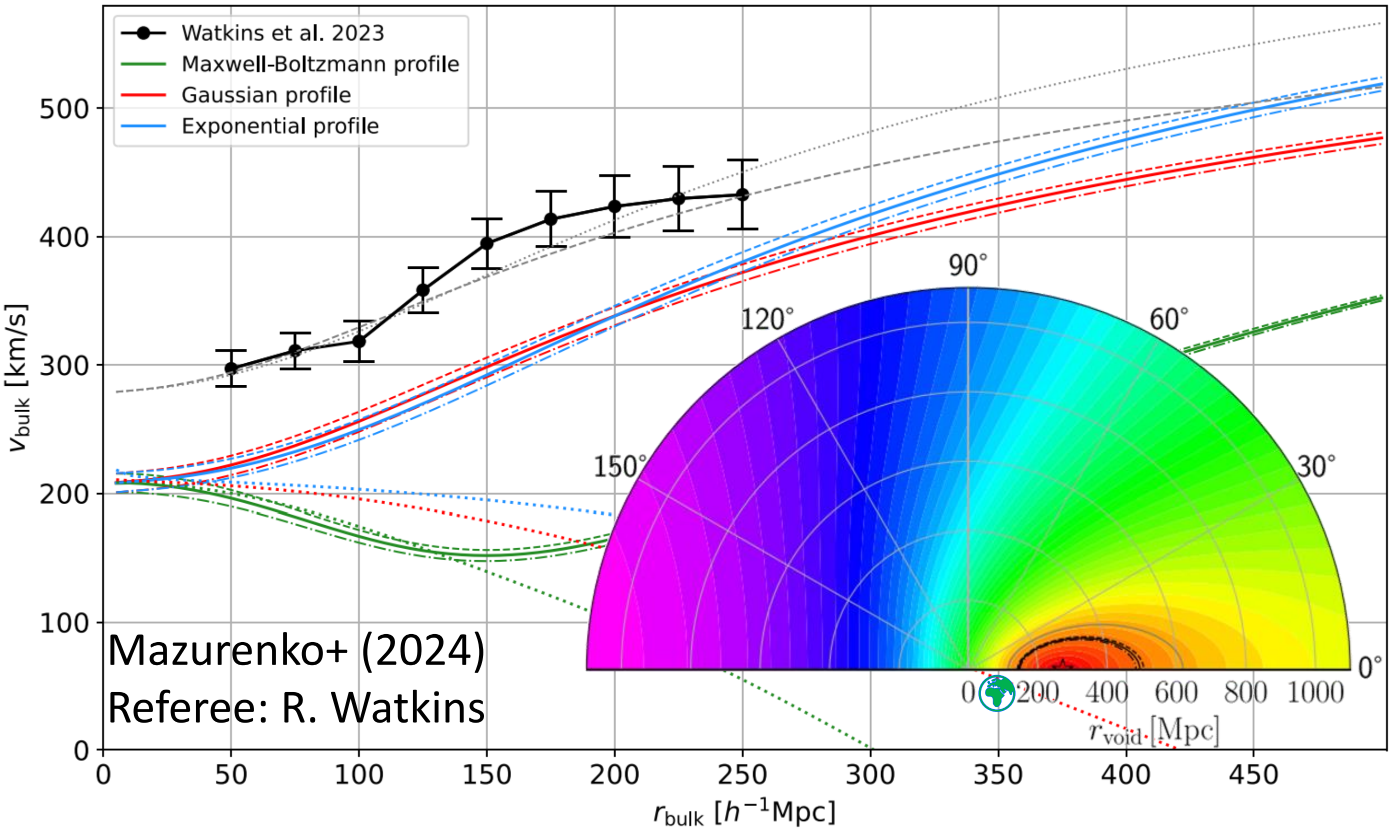
❖ Velocities are in CMB frame.



AstroBite explaining this (search for: Astrobites bulk flow)

Adjusting our location

- Local Group velocity affected by motions on small scales (nearby galaxies/clusters)
- Ideally, we want the average velocity on a scale larger than galactic separations but smaller than the KBC void
  - Set our vantage point using bulk flow within 50/*h* Mpc
  - Grey curves show results if v_{LG} = 840 km/s (dashed = Gaussian, dotted = exp).
  - We are close to the void centre and the void is deepest at its centre.



>230,000 reads of article explaining this for The Conversation

Conclusions

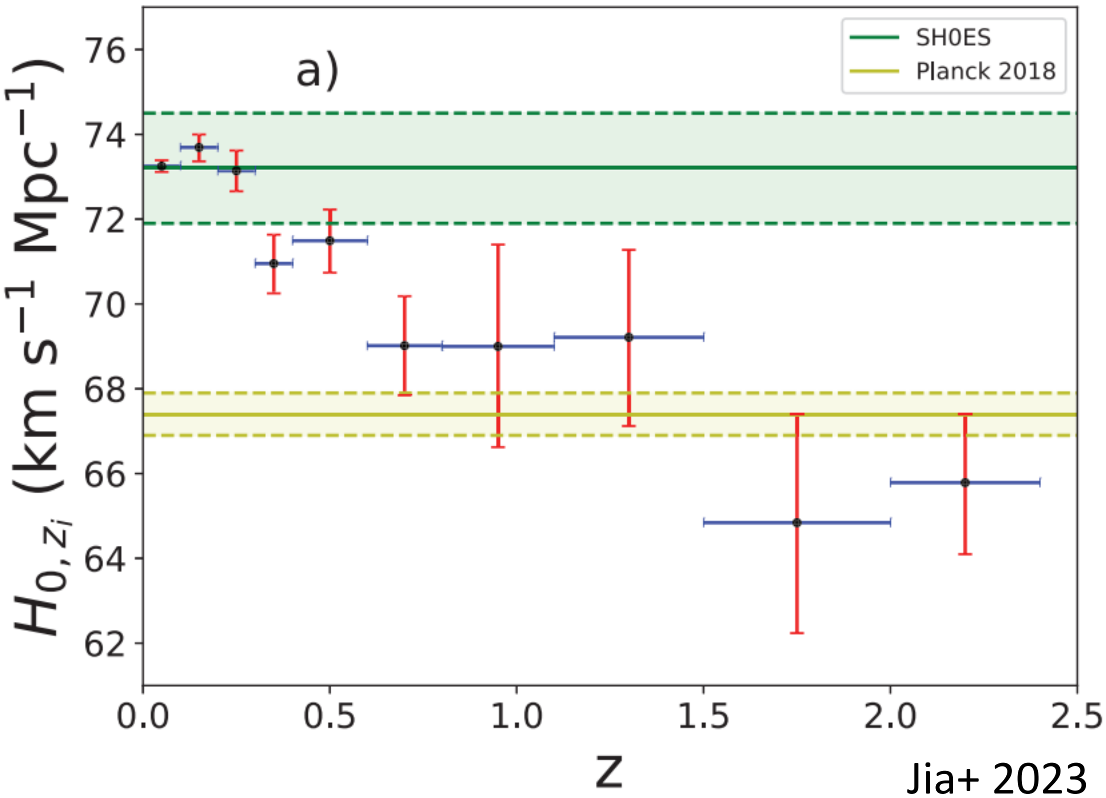
- Galaxy number counts show that we are in an underdensity out to ≈300 Mpc or more (Keenan+ 2013, Wong+ 2022) – good evidence across the whole electromagnetic spectrum (see introduction to Haslbauer+ 2020); significant tension with ΛCDM
- Given the nearly uniform initial conditions in the CMB, this requires significant outflow. Generic arguments indicate that this would enhance the apparent local H_0 by ≈11%
- Locally measured H_0 is larger than predicted in ΛCDM by ≈10% (di Valentino+ 2021)
  - Hubble & void tensions were linked in semi-analytic void model of Haslbauer+ 2020
- Predicted bulk flow curve was later observed (Mazurenko+ 2024; Watkins+ 2023)
- Measurements at $z > 0.5$ or so are consistent with background Planck cosmology
- Early time solutions to the Hubble tension face at least seven difficulties (Vagnozzi+ 2023)
- Very few proposed solutions to the Hubble tension had a different motivation and made a successful *a priori* prediction of a different phenomenon that is unlikely in ΛCDM.

Hubble tension at high z?

- Model has large local void with background Planck cosmology
- Observations at high *z* must recover Planck cosmology as redshifts from peculiar velocities would be small compared to cosmic redshift
- Need to carefully infer H_0 from only the data within a narrow redshift range
- Such analyses do show the expected return to Planck cosmology

➢ No Hubble tension at high *z*

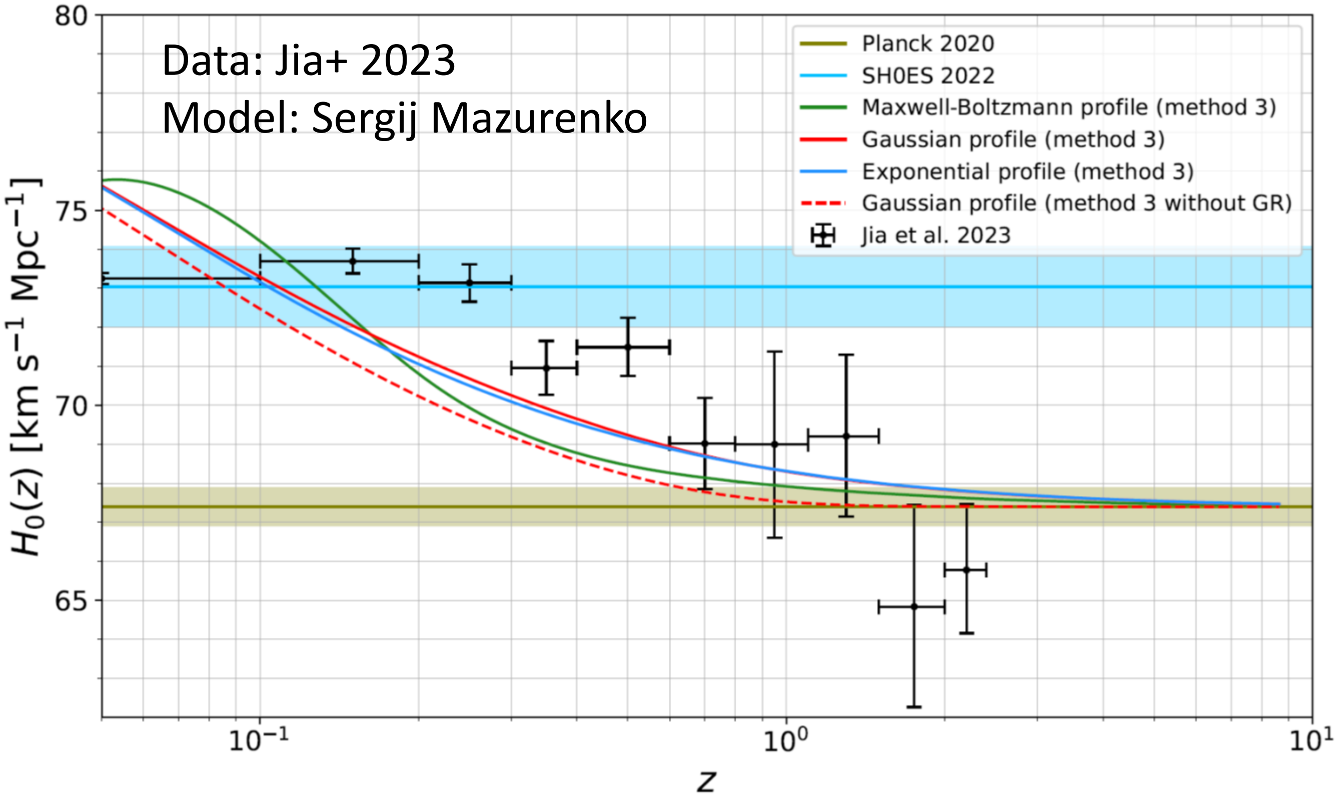
- Systematic calibration error would inflate all H_0 values by common factor.



Jia+ 2023

H_0 (z) in local void scenario

- Estimated H_0 that would be inferred by an observer from data in narrow redshift range if the local void model is correct
- Idea is to suppose observations constrain lookback time independently of *z*, e.g. from luminosity distance
- *z* then used to infer *a* at that time assuming only cosmic expansion causes redshift (wrong in this scenario)
- Data then fit with FRW model.



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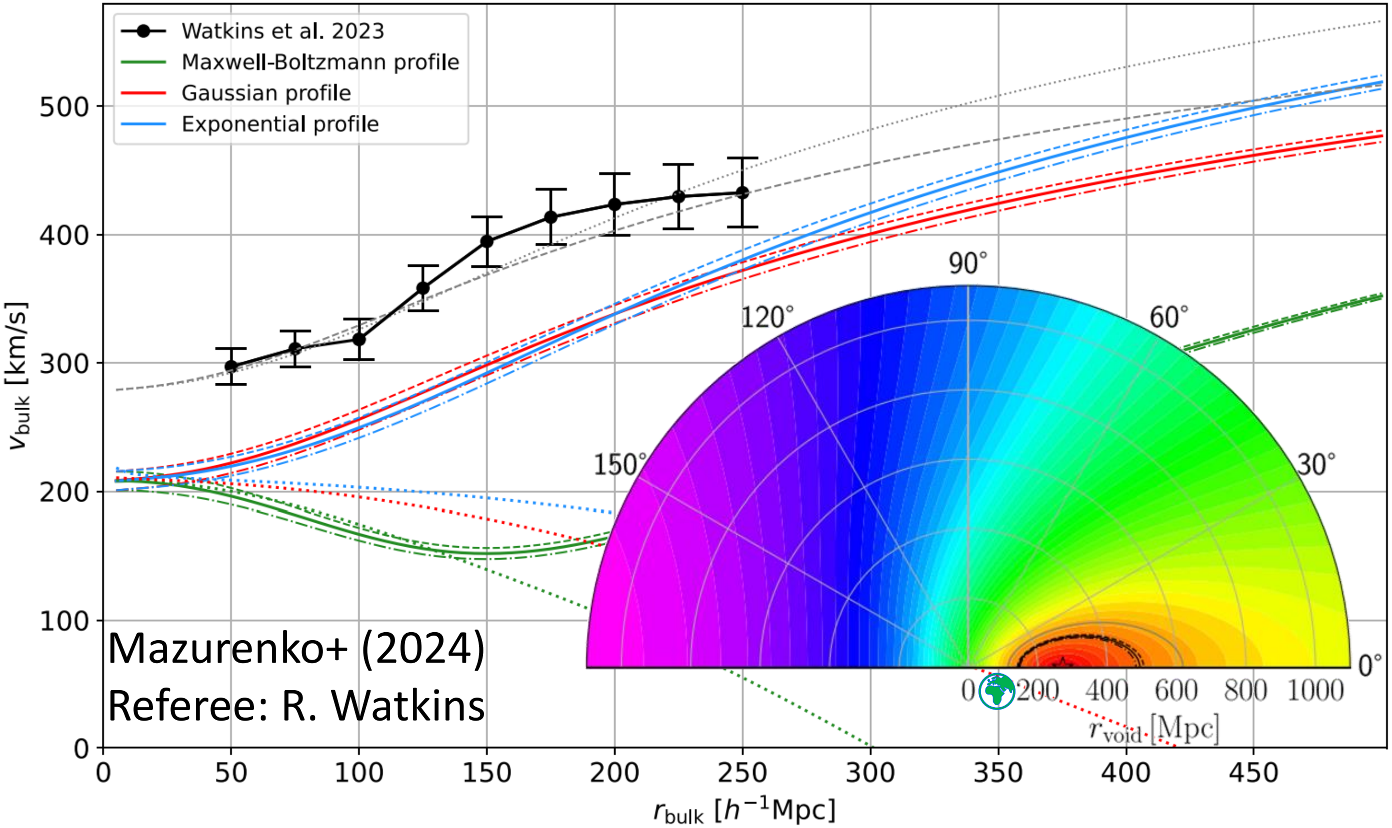
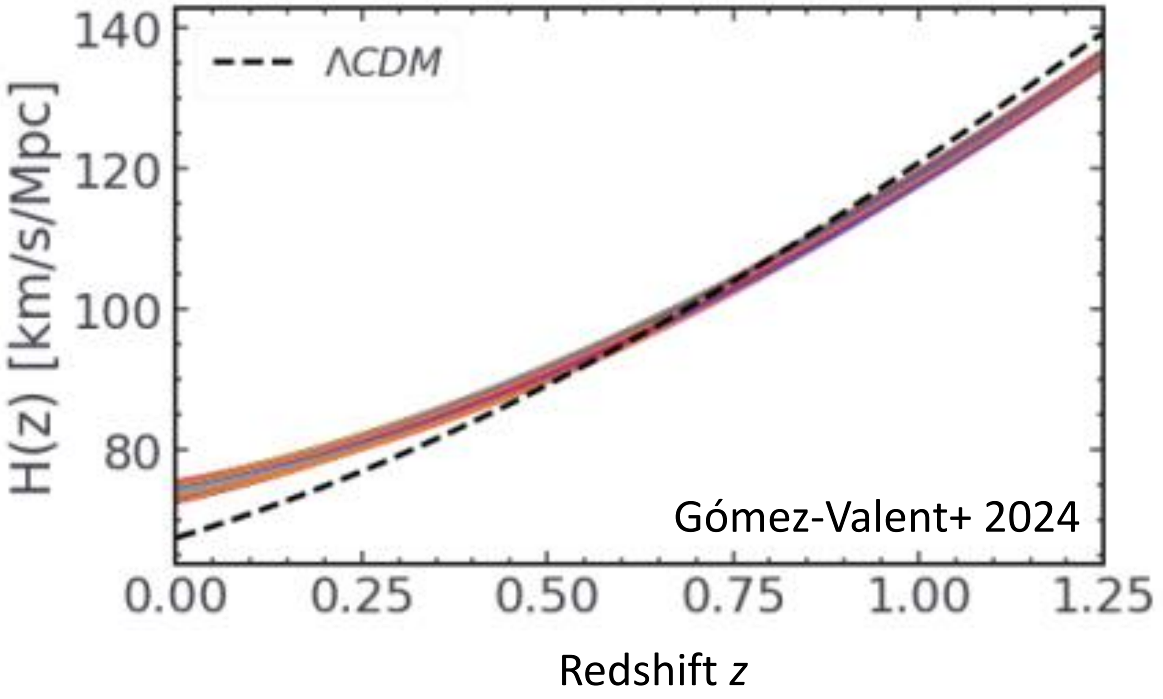


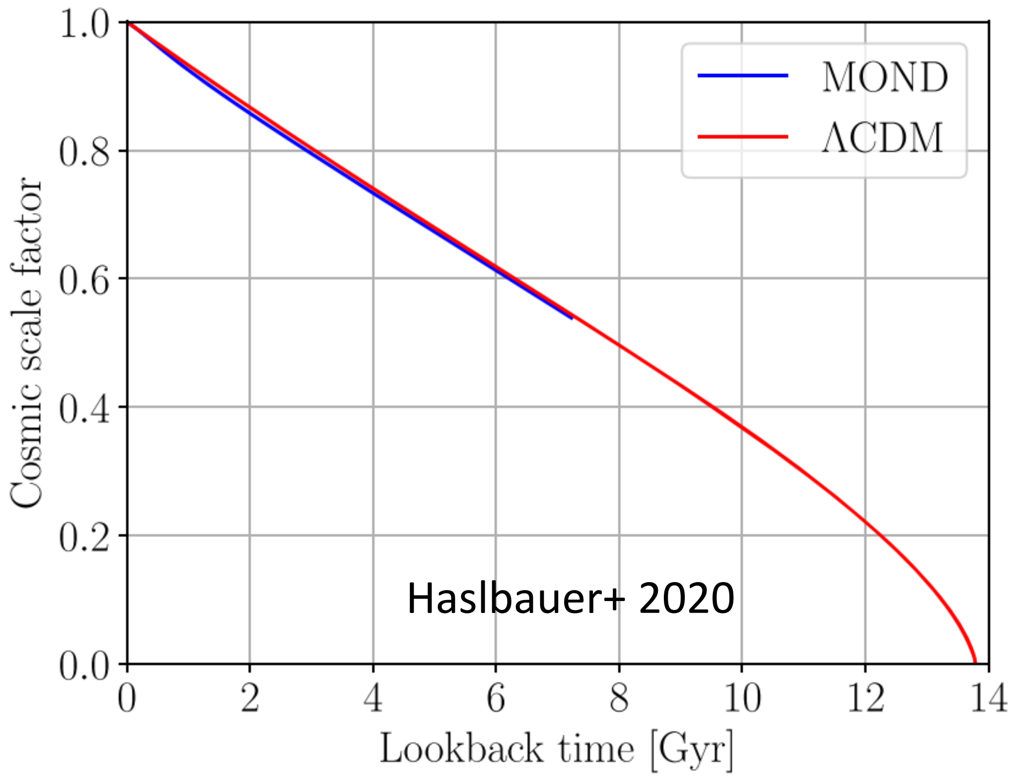
Reconstructed Hubble diagram

- Can infer expansion history *H*(*z*) without assuming any model
- This seems to follow the ΛCDM expectation until recently
- Small compensatory adjustment at high redshift to preserve angular diameter distance to CMB, but there is anyway some uncertainty in the official Planck parameters
- Combined with other difficulties faced by early time solutions to the Hubble tension (Vagnozzi+ 2023; Cimatti & Moresco 2023), recent results favour a more recent or local solution.



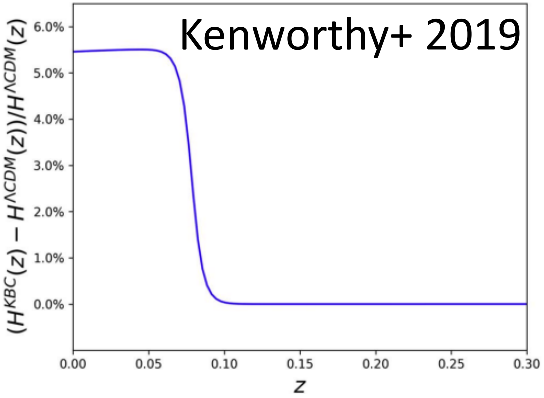
A subtle change can solve the H_0 tension

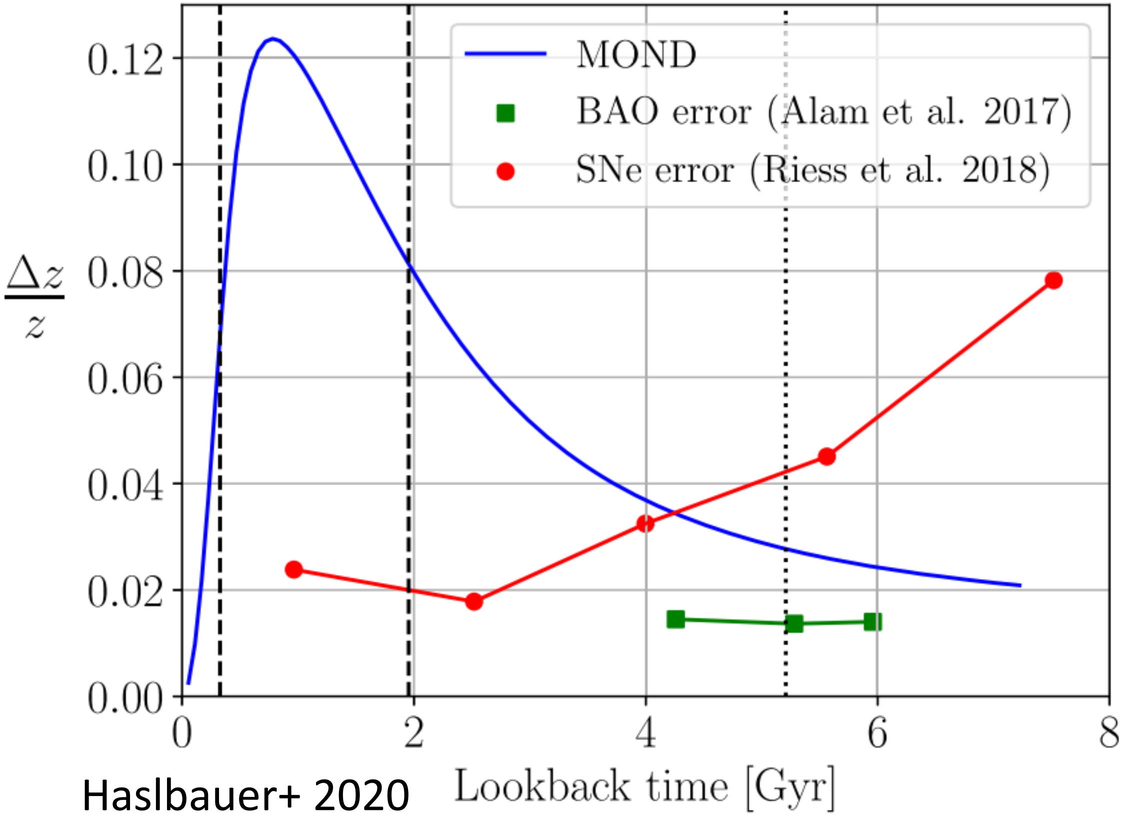
- A subtle difference between the actual and apparent expansion histories can solve the Hubble tension.
- Local void solutions create peculiar velocities out to quite high redshift in MOND due to slower decay of the gravity law
- This means the return to a Planck cosmology could be fairly slow, contradicting the assumptions in the famous Kenworthy+ 2019 paper which argued against the directly observed local void (Planck cosmology assumed to be fully recovered when $z > 0.1$).



The void distorts redshifts quite far out

- Blue curve in figure on right shows that void enhances redshifts about 10% in the range typically used to obtain the local H_0 (between the dashed vertical lines showing z = 0.023 – 0.15)
- Notice that peculiar velocity corrections are important quite far out.



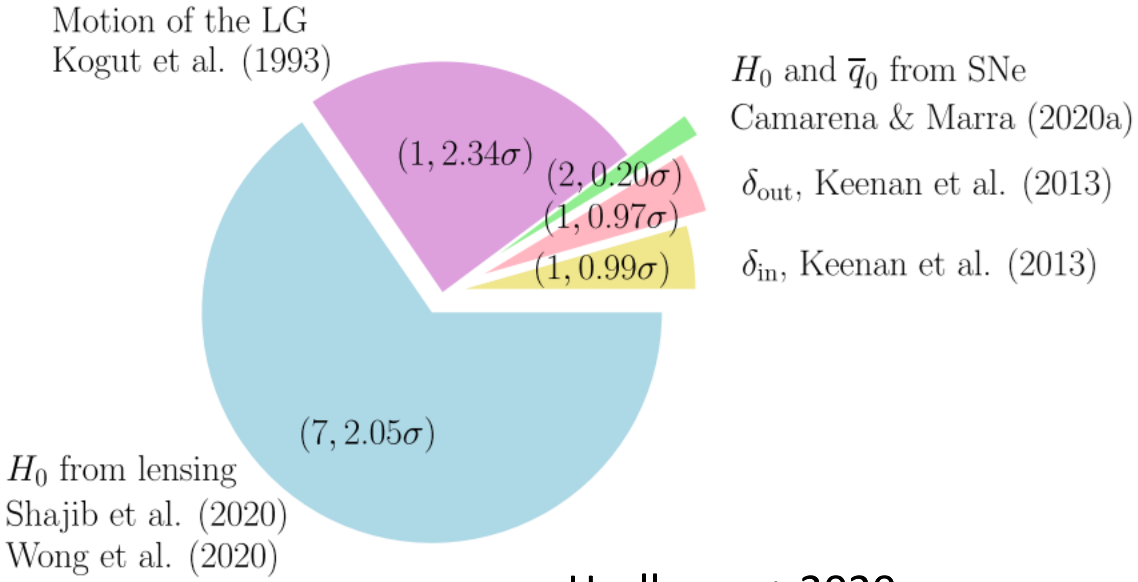


Haslbauer+ 2020

Overall goodness of fit of local void model

- Overall tension is 2.53σ
- Pie chart: summary of individual contributions
- v_{LG} tension is based on fraction of void volume with a slower velocity in CMB frame
- Bulk flows not considered
- ❖ No substantial tensions.

(Degrees of freedom, equivalent tension for 1D Gaussian)



Haslbauer+ 2020