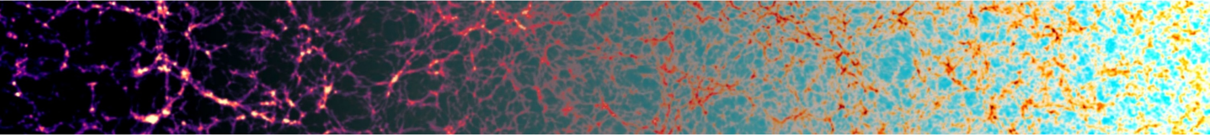

# Supernova-free local ladders for $H_0$

## Cepheids and TRGB stars as a direct test of the Hubble tension

Richard Stiskalek
richard.stiskalek@physics.ox.ac.uk

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University of Oxford
richard-sti.github.io

UNIVERSITY OF OXFORD

Aquila

# Type Ia supernovae are the main drivers of the Hubble tension

## Standard three-rung $H_0$ route

- Geometric anchors calibrate Cepheids or TRGB stars
- Type Ia supernovae extend the ladder into the Hubble flow
- The high-redshift Hubble-flow sample reduces the impact of peculiar velocities

## This talk

- Precise supernova-free distance ladder
- Bayesian forward modelling, including selection effects
- Peculiar velocity modelling with `Manticore` [arXiv:2505.10682]

**Do SNe Ia-free ladders still prefer a high local $H_0$?**

# Talk outline

# Forward-model and Manticore

# Without selection the posterior is a product over detected objects

Latent parameters $\boldsymbol{\theta}_i$ (e.g. host distance) are drawn from a population with parameters $\boldsymbol{\Lambda}$.

## Generative model

$$\boldsymbol{\theta}_i \sim \pi(\boldsymbol{\theta} \mid \boldsymbol{\Lambda}) \qquad \text{(prior)}$$

$$\boldsymbol{d}_i \sim p(\boldsymbol{d} \mid \boldsymbol{\theta}_i, \boldsymbol{\Lambda}) \qquad \text{(likelihood)}$$

*Example:*

$$cz_i \sim \mathcal{N}(H_0\, r_i,\ \sigma_v^2)$$

$$m_i \sim \mathcal{N}(M + \mu_i,\ \sigma_m^2)$$

$\Longrightarrow$

## Posterior without selection

$$\mathcal{P}(\boldsymbol{\Lambda}, \{\boldsymbol{\theta}_i\} \mid \{\boldsymbol{d}\}) \propto \pi(\boldsymbol{\Lambda}) \prod_{i=1}^{n} \mathcal{L}(\boldsymbol{d}_i \mid \boldsymbol{\theta}_i, \boldsymbol{\Lambda}) \pi(\boldsymbol{\theta}_i \mid \boldsymbol{\Lambda})$$

**Selection breaks this: the missing objects carry information about $\Lambda$.**

# The parent population size is unknown — we must marginalise over it

Out of $N$ objects, $n$ are detected and $N - n$ are absent. The joint likelihood over all objects is

$$\mathcal{L}(\boldsymbol{d} \mid \boldsymbol{\Lambda}, N) = \binom{N}{n} \prod_{i \in \mathcal{A}_{\rm obs}} p(S_i = 1 \mid \boldsymbol{d}_i)\, \mathcal{L}(\boldsymbol{d}_i \mid \boldsymbol{\Lambda}) \prod_{j \in \mathcal{A}_{\rm mis}} p(S_j = 0 \mid \boldsymbol{d}_j)\, \mathcal{L}(\boldsymbol{d}_j \mid \boldsymbol{\Lambda})$$

Marginalising over the absent data $\{\boldsymbol{d}_j\}$:

$$\mathcal{L}(\boldsymbol{d}_{\rm obs} \mid \boldsymbol{\Lambda}, N) \propto \binom{N}{n} \underbrace{\left[p(S = 0 \mid \boldsymbol{\Lambda})\right]^{N-n}}_{\text{missing objects}} \underbrace{\prod_{i=1}^{n} p(S_i = 1 \mid \boldsymbol{d}_i)\, \mathcal{L}(\boldsymbol{d}_i \mid \boldsymbol{\Lambda})}_{\text{detected objects}}$$

**We marginalise $N$ out of the likelihood rather than treating it as a free parameter.**

# Marginalising the unknown $N$ introduces an inverse detection-fraction factor

Choosing the prior $\pi(N) \propto 1/N$, the marginal over $N$ can be evaluated analytically:

$$\mathcal{P}(\boldsymbol{\Lambda} \mid \boldsymbol{d}_{\mathrm{obs}}) \propto \pi(\boldsymbol{\Lambda}) \underbrace{\left[p(S=1 \mid \boldsymbol{\Lambda})\right]^{-n}}_{\text{new term}} \prod_{i=1}^{n} p(S_i = 1 \mid \boldsymbol{d}_i)\, \mathcal{L}(\boldsymbol{d}_i \mid \boldsymbol{\Lambda})$$

$$p(S=1 \mid \boldsymbol{\Lambda}) = \iint \mathrm{d}\boldsymbol{d}\, \mathrm{d}\boldsymbol{\theta}\; p(S=1 \mid \boldsymbol{d})\, \mathcal{L}(\boldsymbol{d} \mid \boldsymbol{\theta}, \boldsymbol{\Lambda})\, \pi(\boldsymbol{\theta} \mid \boldsymbol{\Lambda})$$

**$p(S=1 \mid \boldsymbol{\Lambda})$ is the fraction of the parent population the survey would detect**

# The local distance ladder requires a model of the local Universe in two places

## Position prior $\pi(\boldsymbol{r} \mid \boldsymbol{\Lambda})$

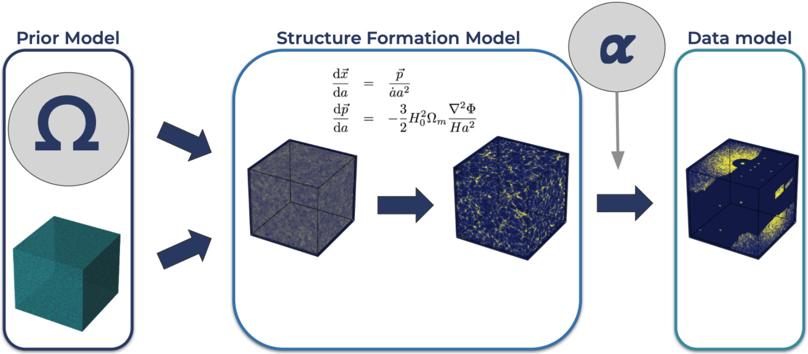
- Hosts are not distributed uniformly
- $\pi(\boldsymbol{r} \mid \boldsymbol{\Lambda}) \propto n_g(\boldsymbol{r})$
- $n_g(\boldsymbol{r})$ typically modelled as a function of the density field $\rho(\boldsymbol{r})$

## Redshift likelihood

- Observed redshift includes a peculiar-velocity contribution
- $cz^{\rm pred} \approx H_0 r + \hat{\boldsymbol{r}} \cdot \boldsymbol{V}_{\rm pec}(\boldsymbol{r})$
- $\boldsymbol{V}_{\rm pec}(\boldsymbol{r})$ is the 3D peculiar velocity field, correlated across nearby hosts

**Both fields are treated as external BORG products.**

# BORG turns galaxy catalogues into posterior samples of the local structure



# Manticore-Local is the latest BORG inference of the Universe

## Inference object

- BORG yields posterior samples of the density and velocity field of the local Universe conditioned on 2M++ galaxy counts

## Example applications

- Void catalogue [arXiv:2507.06866]
- Cluster catalogue [arXiv:2510.16574]
- CMB secondaries [arXiv:2601.15935]
- Cosmic anisotropy [arXiv:2602.06007]

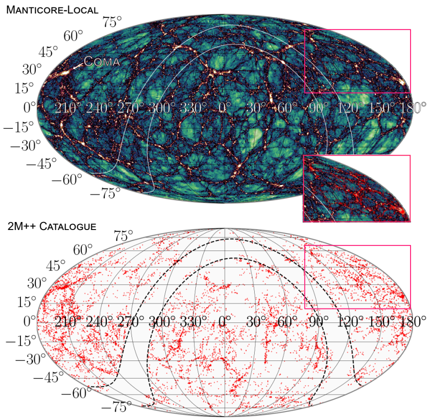



*Image credit: McAlpine et al. 2025 [arXiv:2505.10682]*

# Velocity field olympics: Manticore outperforms competing reconstructions

**How well does a local Universe model explain peculiar velocity data?** [arXiv:2502.00121]

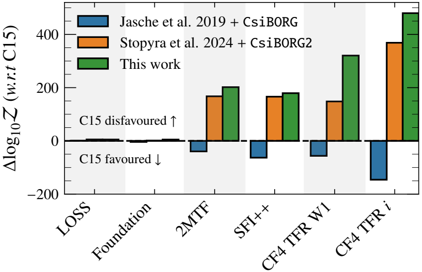



*Image credit: McAlpine et al. 2025 [arXiv:2505.10682]*

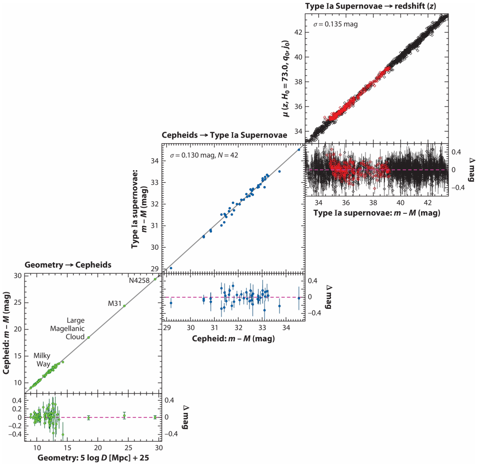
- Tully–Fisher and supernova peculiar-velocity catalogues as benchmarks
- $\Delta \log_{10} Z$ relative to a linear-theory baseline
- `Manticore` (green) favoured in all cases

# Cepheid-only ladder

# Cepheid hosts form a two-rung supernova-free $H_0$ ladder

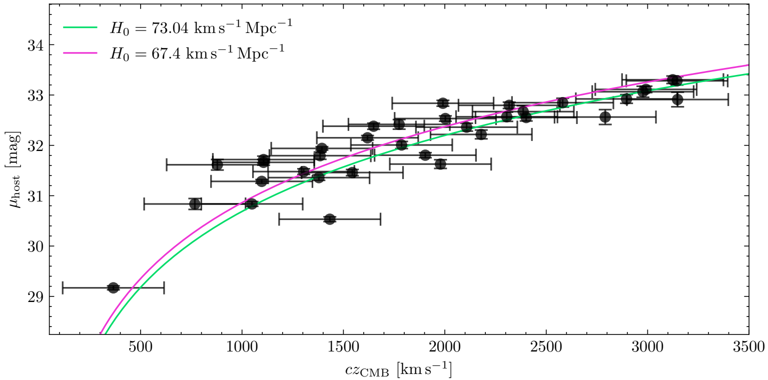
## Three-rung SH0ES ladder

- Rung 1 — Geometry: MW parallaxes, LMC eclipsing binaries, NGC 4258 maser
- Rung 2 — Cepheids: period–luminosity calibration in host galaxies
- Rung 3 — SNe Ia: standard candles into the Hubble flow



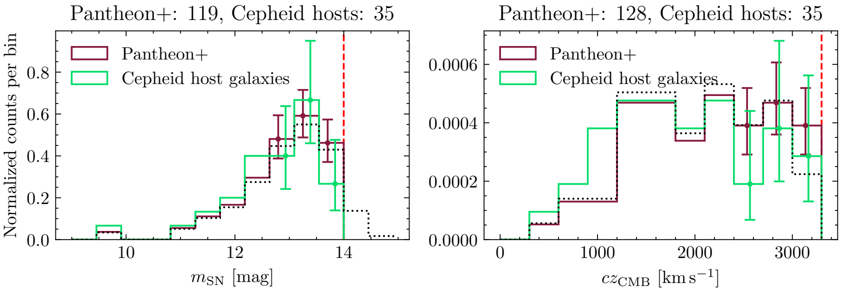

Kamionkowski M, Riess AG. 2023
Annu. Rev. Nucl. Part. Sci. 73:153–80

# 35 Cepheid hosts with redshifts anchor the second rung directly



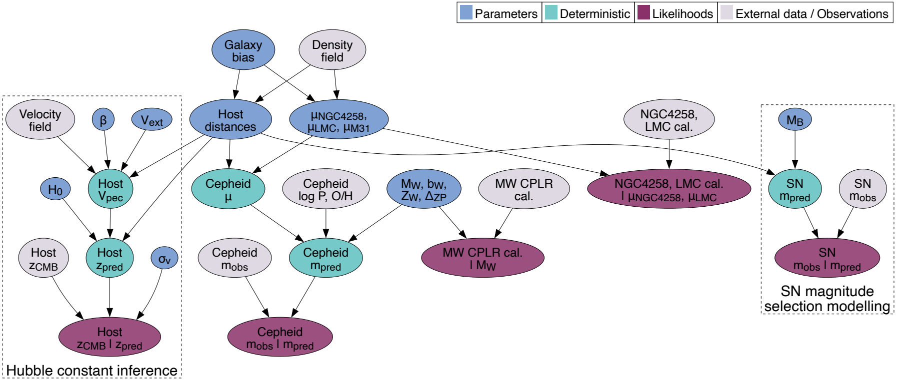

MW, LMC, and NGC 4258 anchors calibrate the Cepheid period–luminosity relation; 35 host redshifts constrain $H_0$ with no SN Ia luminosities.

# The Cepheid host selection can be approximated as a magnitude or redshift cut



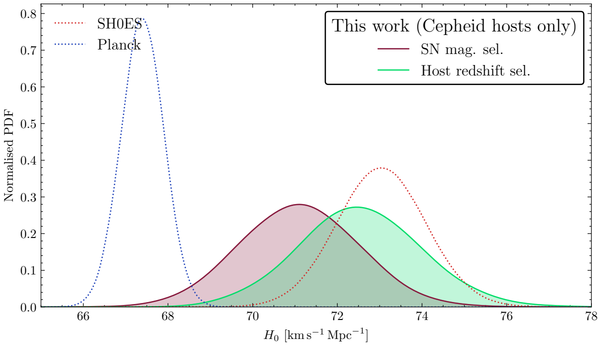

The selection can be approximated as a supernova magnitude- or redshift-selected sample drawn from Pantheon+, which at low $z$ is considered complete.

# The Cepheid forward model jointly fits host redshifts and per-star magnitudes




We forward model the host redshifts and the apparent magnitudes of individual Cepheid stars.

# The Cepheid-only result is below SH0ES by about $1\sigma$




- SN-magnitude selection: $H_0 = 71.1 \pm 1.4\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$
- Redshift selection: $H_0 = 72.5 \pm 1.4\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$
- `Manticore` is favoured over linear peculiar velocity modelling

**35 Cepheid host galaxies are sufficient to achieve $2.8\sigma$ tension with *Planck*.**

# Cepheid ladder is now limited by selection, not raw precision

## Robust pieces and assumptions

- Geometric anchors are well measured
- Cepheid period–luminosity relation is well-understood and has small intrinsic scatter

## Open pieces

- True host-selection rule is not uniquely documented
- Future samples need explicit selection from the start (e.g. JWST, World Habitable Observatory)
- Opportunities to improve the density and velocity field modelling

# TRGB cross-check

# TRGB stars cross-check Cepheids with partially independent distance systematics

## Why TRGB?

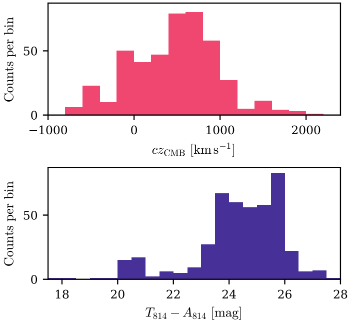
- Population-II halo indicator: orthogonal systematics to Cepheids
- Anand et al. 2021 [arXiv:2101.10007] provide $\sim$401 EDD host distances, ten times more than the Cepheid sample

## Why hard?

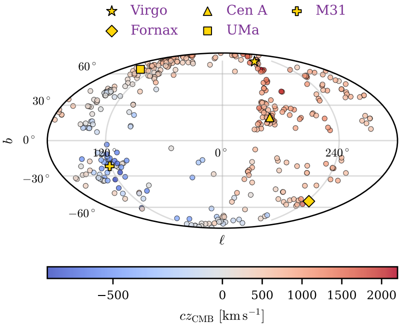
- EDD hosts are very local, correlated peculiar velocities are comparable to cosmological redshifts
- No well-defined catalogue selection

# The EDD TRGB sample is much larger but more local than the Cepheid hosts

## Velocity and tip-magnitude distributions

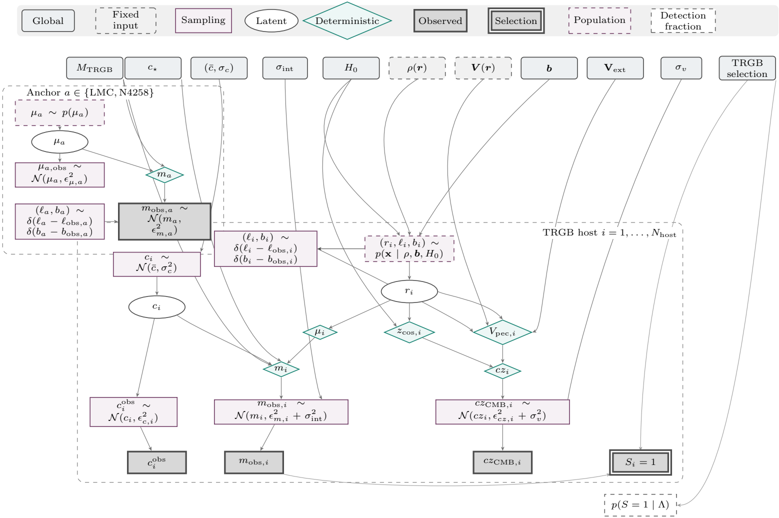



## Sky distribution

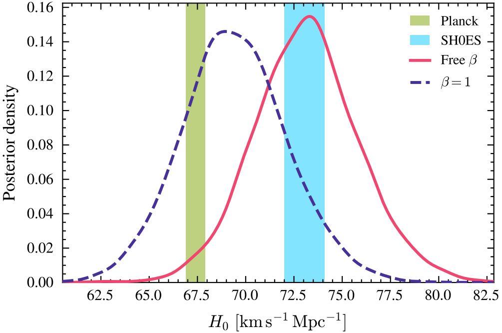



The majority of hosts sit at $cz_{\rm CMB} < 1000\,{\rm km\,s^{-1}}$. We enforce $cz_{\rm CMB} > 0$ and forward-model this boundary.

# The TRGB forward model mirrors the Cepheid framework with tip magnitudes replacing Cepheid periods



# The TRGB result remains sensitive to the velocity modelling




Fixed $\beta = 1$: $69.4 \pm 2.7\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

Free $\beta$: $73.1 \pm 2.7\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

(inferred $\hat{\beta} = 1.03 \pm 0.05$)

$\Delta H_0 \approx 3.7\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ from the reconstruction amplitude alone.

**The preferred model, which allows rescaling of the velocity field by $\beta$, yields $H_0$ above *Planck*, but velocity modelling is a dominant systematic.**

# Conclusion

# Independence of Type Ia supernovae comes at a cost

## The cost

- Peculiar velocities and inhomogeneous Malmquist bias are dominant systematics at $z \lesssim 0.01$
- Host-catalogue selection is not uniquely defined

## What this opens up

- Field-level reconstruction (`BORG`/`Manticore`) conditions the ladder on the local large-scale structure
- New methods for measuring $H_0$ with small, cosmic-variance-dominated samples

# Both SN-free ladders are mildly lower than SH0ES

## Cepheid-only

$H_0 = 71.1 \pm 1.4\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

(SN-magnitude selection; $72.5 \pm 1.4$ for redshift selection)

- $2.8\sigma$ tension with *Planck*; $\sim 1\sigma$ below SH0ES
- *Bottleneck:* host-selection ambiguity

## TRGB-only

$H_0 = 73.1 \pm 2.7\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

(Student-$t$, free $\beta$; $69.4 \pm 2.7$ for fixed $\beta = 1$)

- Independent stellar population cross-check
- *Bottleneck:* peculiar velocity model

**Removing SNe may weaken the Hubble tension at competitive precision, but improvements in velocity modelling and sample selection are needed.**