From Distance Ladder to Network: Methods, Code, and Results from H0DN

github.com/StefCas789/H0DN

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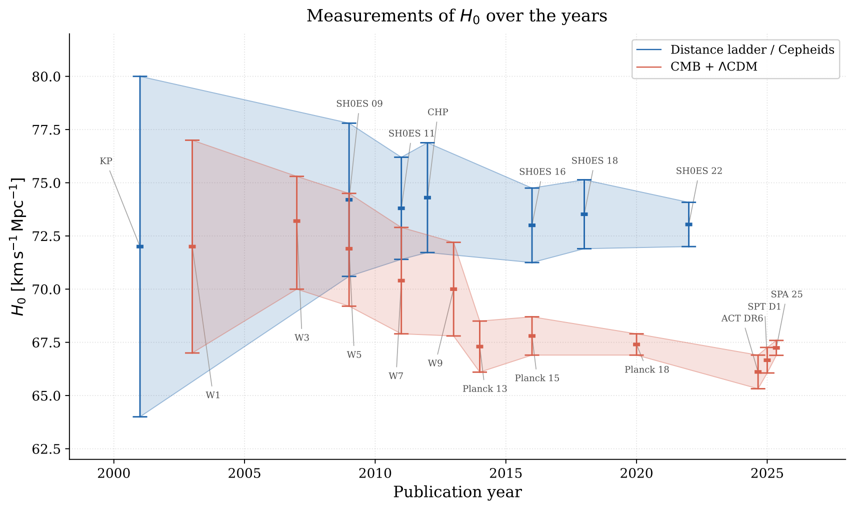
Introduction

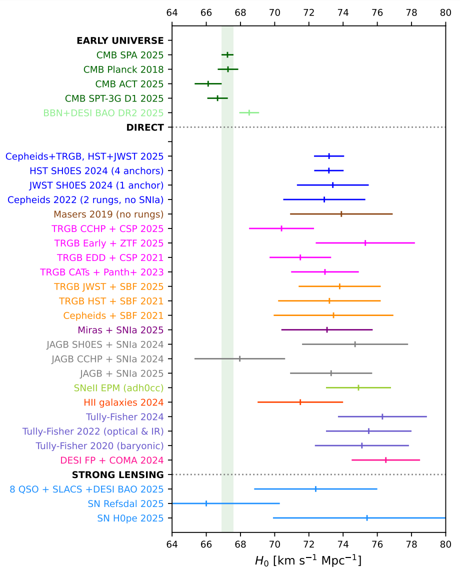
$> 5\sigma$ Disagreement, a Familiar Figure



Adapted from Beaton et al. (2016), ApJ 832, 210

$> 5\sigma$ Disagreement, More Comprehensive Picture

ΛCDM+Early Universe:



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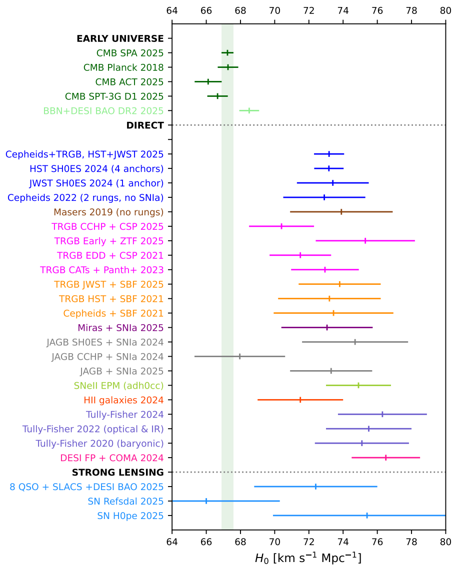
ΛCDM+Early Universe:

- ΛCDM+CMB
  $H_0 = 67.24 \pm 0.35$ km/s/Mpc



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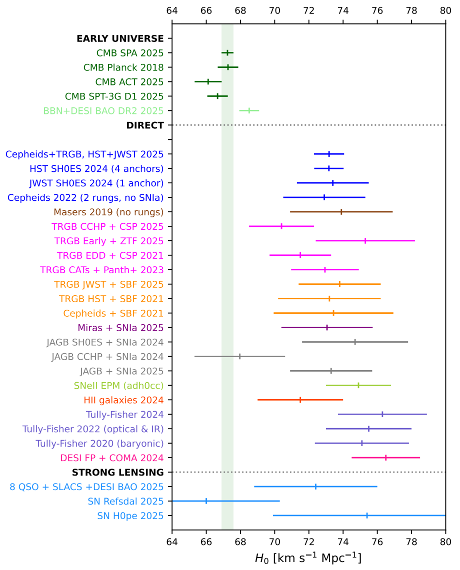
- ΛCDM+BBN+BAO
  $H_0 = 68.51 \pm 0.58 \text{ km s}^{-1} \text{ Mpc}^{-1}$



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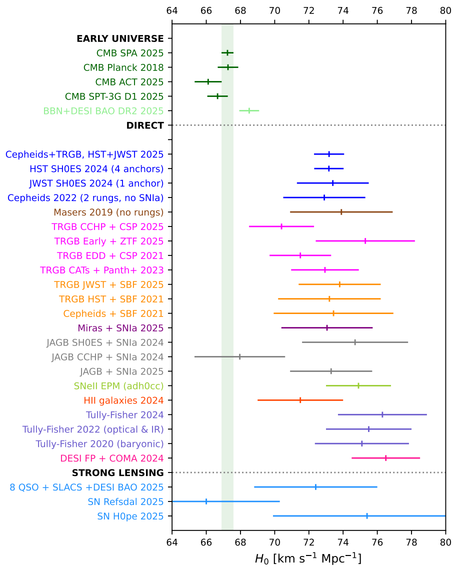
Model-independent Local Distance Measurements:

- $H_0 \approx 73\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$



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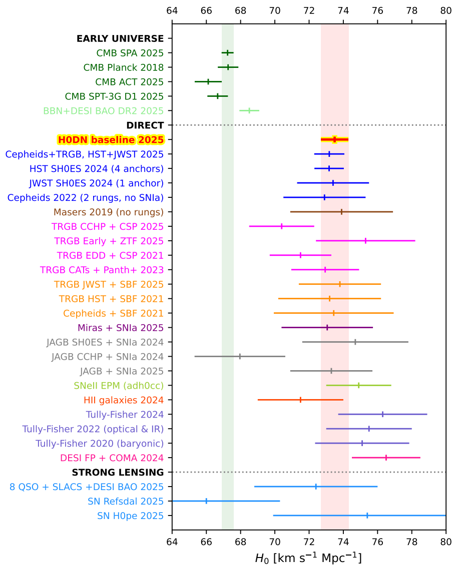
Model-independent Local Distance Measurements:

- $H_0 \approx 73\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$
- H0DN
  $H_0 = 73.50 \pm 0.81\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$
  (7.1σ vs. CMB+ΛCDM)



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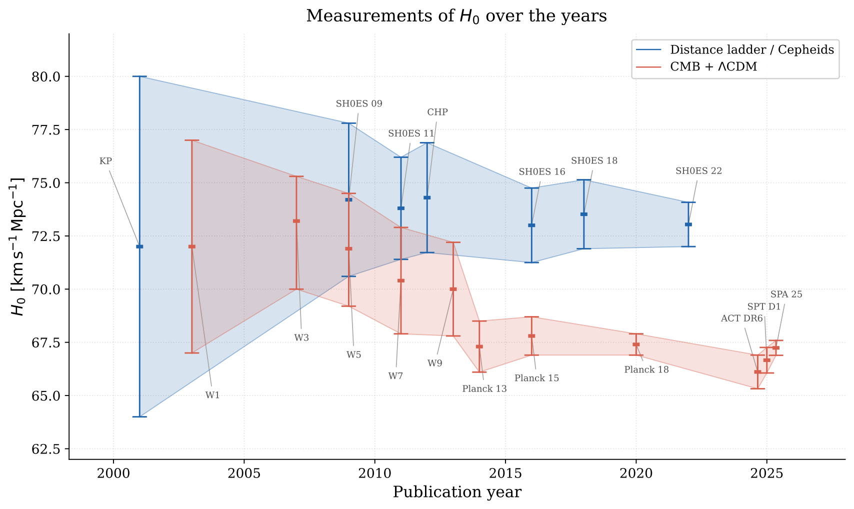

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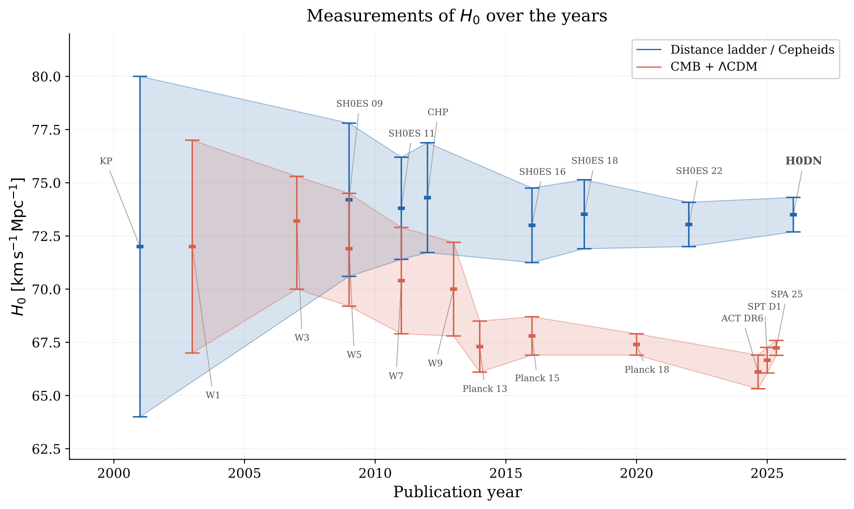

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H0DN: Focus on Community Consensus and Transparency

- ISSI Bern workshop
  "What's under the H_0od?"

The Local Distance Network: a community consensus report on the measurement of the Hubble constant at ~1% precision

H0DN Collaboration

Stefano Casertano,[1] Gagandeep Anand,[1] Richard I. Anderson,[2] Rachael Beaton,[1] Anupam Bhardwaj,[3] John P. Blakeslee,[4] Paula Boubel,[5] Louise Breuval,[6] Dillon Brout,[7] Michele Cantiello,[8] Mauricio Cruz Reyes,[2] Geza Csörnyei,[9] Thomas de Jaeger,[10] Suhail Dhawan,[11] Eleonora Di Valentino,[12] Lluís Galbany,[13,14] Héctor Gil-Marín,[15,16,14] Dariusz Graczyk,[17] Caroline Huang,[18] Joseph B. Jensen,[19] Pierre Kervella,[20,21] Bruno Leibundgut,[22] Bastian Lengen,[2] Siyang Li,[23,24] Lucas Macri,[25] Emre Özülker,[12] Dominic W. Pesce,[18,26] Adam Riess,[1,23] Martino Romaniello,[22] Khaled Said,[27] Nils Schöneberg,[28,29] Dan Scolnic,[30] Teresa Sicignano,[22,31,32] Dorota M. Skowron,[33] Syed A. Uddin,[34,35] Licia Verde[36,15] and Antonella Nota[37]

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- Open access code and data

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Fundamentals

A Generic Distance Ladder

PDI = Primary Distance Indicator
SDI = Secondary distance indicator

Geometric distances to PDI

Anchors

Rung 1 | **Rung 2** | **Rung 3**

A Generic Distance Ladder

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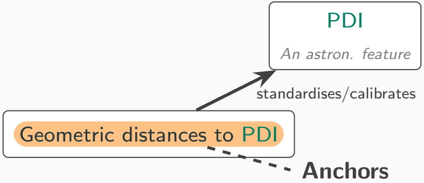

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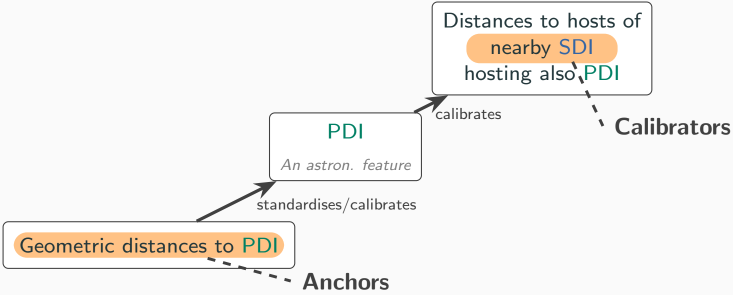

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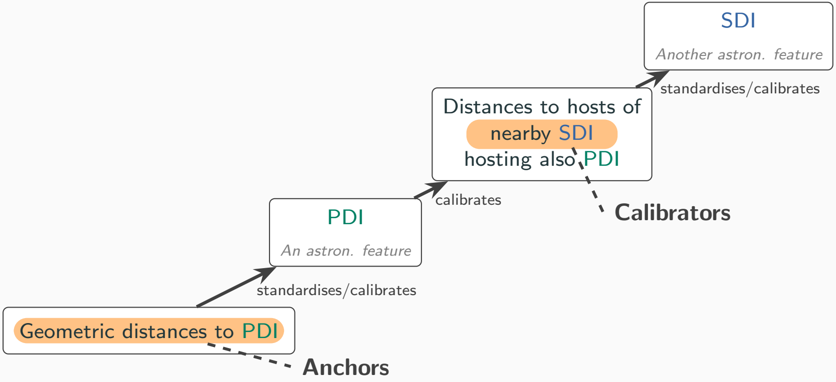

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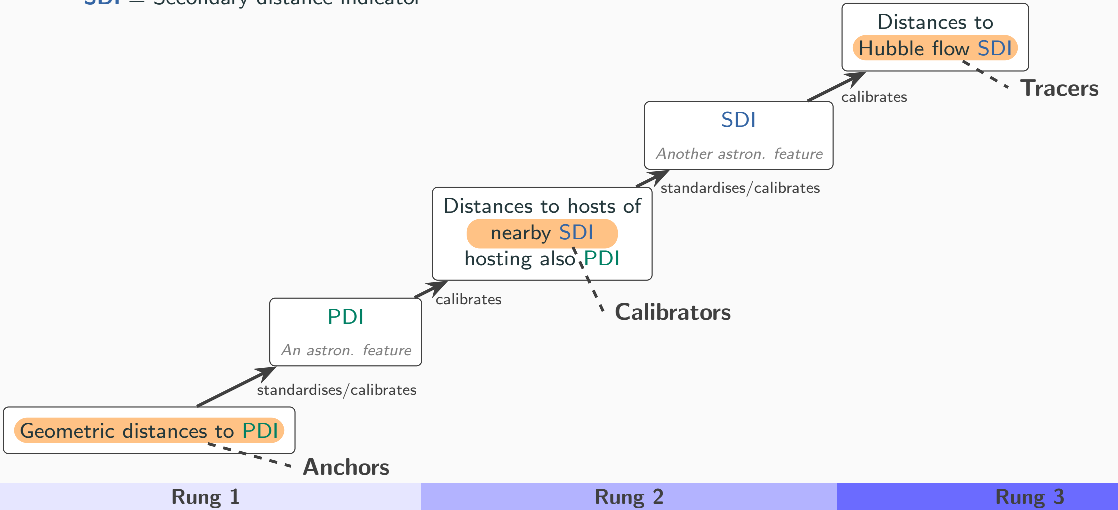

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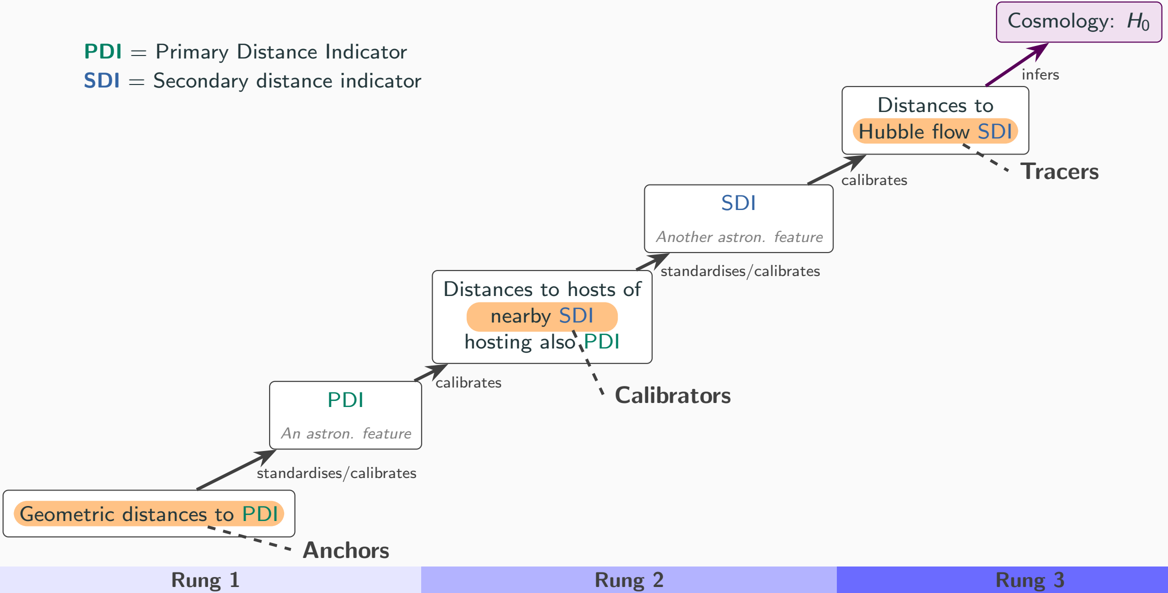
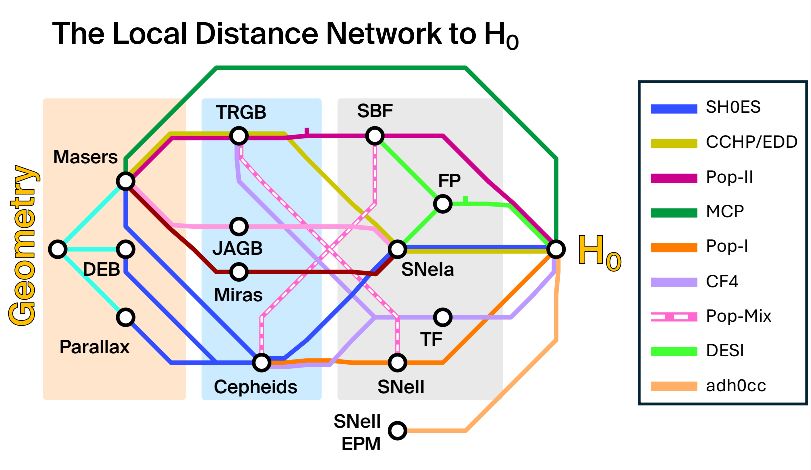
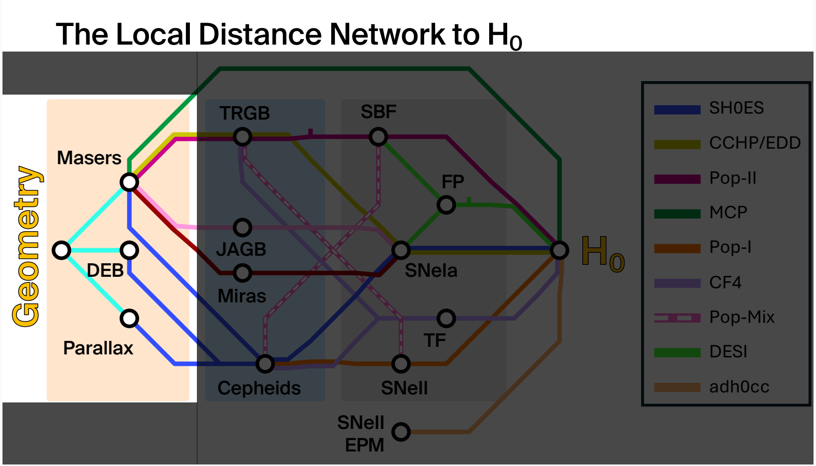




Anchor distances | Primary distance indicators | Secondary distance indicators

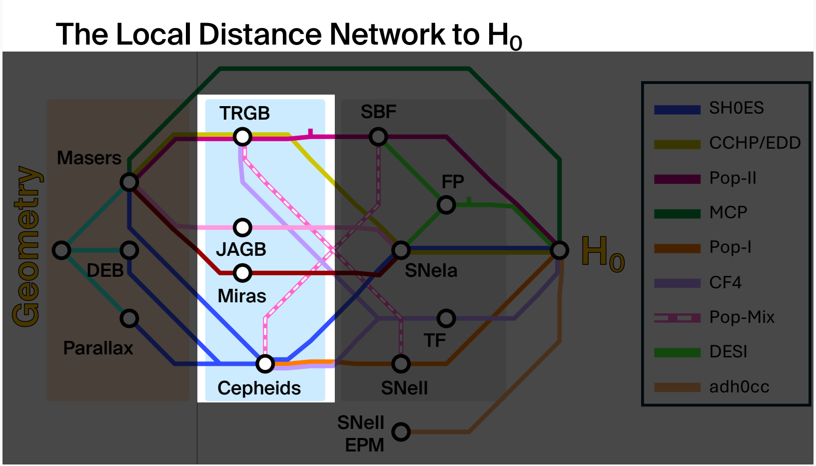
From Ladder to Network



Anchor distances

Primary distance indicators

Secondary distance indicators



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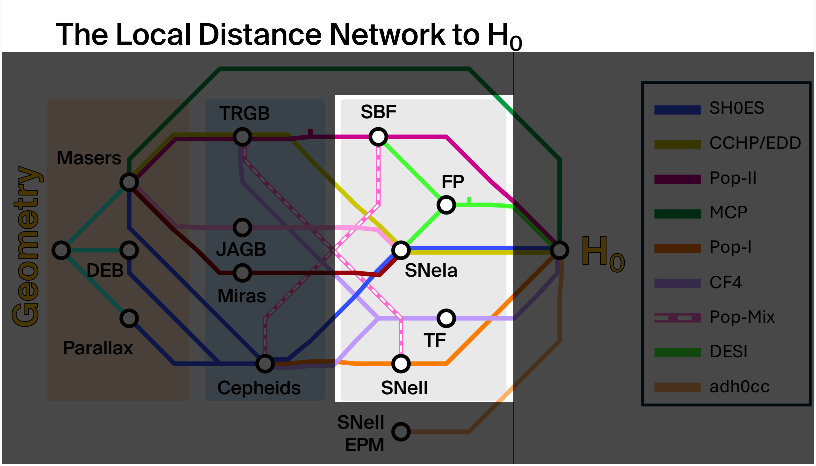

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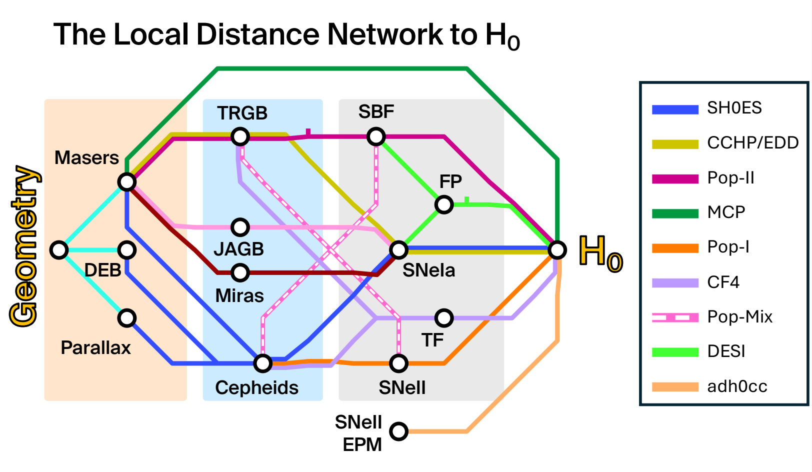
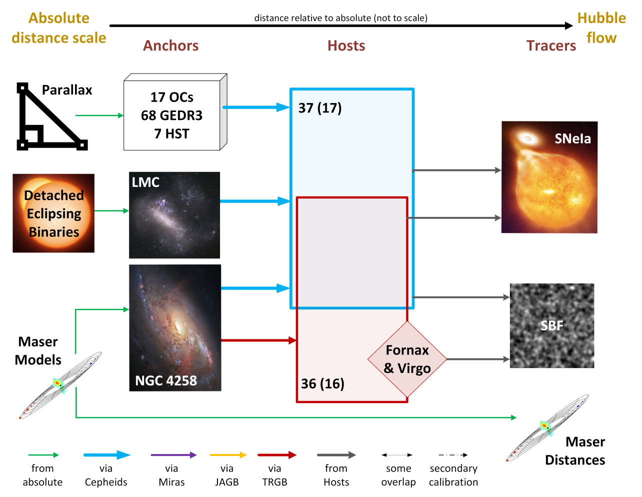


Multiple anchors × Multiple Primary Indicators × Multiple Secondary Indicators × Direct Distances to Tracers
$\longrightarrow$ full covariance-aware combination in a single fit

The Baseline Distance Network



Methodology

One Linear(ized) System Captures the Full Distance Network

System of equations $\mathbf{A}\,\mathbf{X} = \mathbf{Y}$ with the covariance matrix $\mathbf{C}$ for the data $\mathbf{Y}$

$$\chi^2 = \left(\mathbf{Y} - \mathbf{A}\,\mathbf{X}\right)^{\mathsf{T}} \mathbf{C}^{-1} \left(\mathbf{Y} - \mathbf{A}\,\mathbf{X}\right)$$

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- **Y** – Data: measured distances, magnitudes, intercepts
- **C** – Covariance: off-diagonals for shared anchors, MAS, HMS

Generalized Least Squares with Pseudoinverse

- **Best Linear Unbiased Estimator** (BLUE)

  All measurements combined *simultaneously*

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$$\mathbf{W} = \mathbf{C}^{-1}$$

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  E.g., baseline fit has 255 equations but 183 measurements

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  E.g., baseline fit has 255 equations but 183 measurements

- Estimator:

$$\hat{\mathbf{X}} = \left(\mathbf{A}^{\mathsf{T}}\mathbf{W}\mathbf{A}\right)^{-1} \mathbf{A}^{\mathsf{T}}\mathbf{W}\,\mathbf{Y}$$

  where the covariance structure of $\hat{\mathbf{X}}$ is encoded in $\left(\mathbf{A}^{\mathsf{T}}\mathbf{W}\mathbf{A}\right)^{-1}$

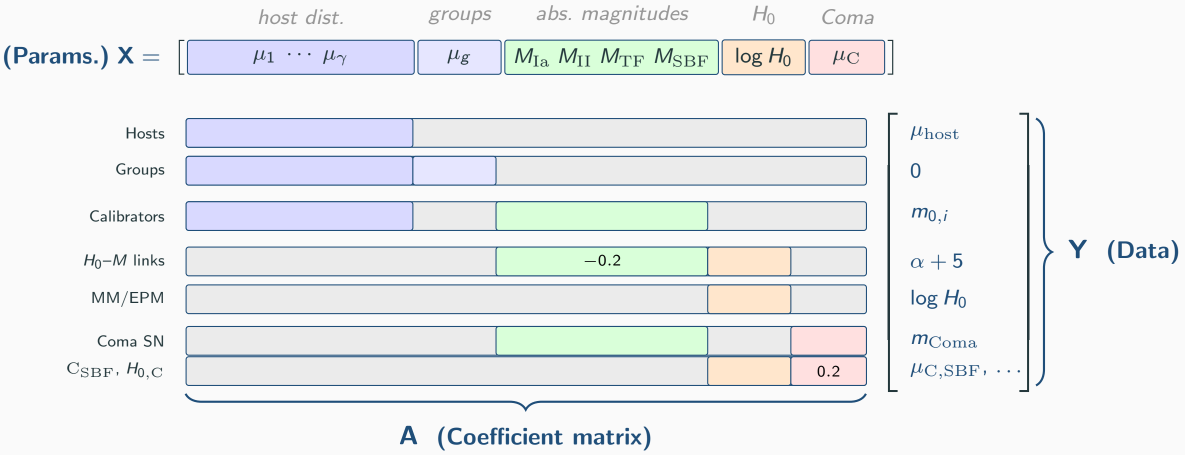
Coefficient Matrix A, Parameter Vector X, and Observation Vector Y

$$\mathbf{X} = \left[\ \mu_1 \quad \cdots \quad \cdots \quad \mu_\gamma \quad \mu_{\rm g,1} \quad \mu_{\rm g,2} \quad M_{\rm Ia} \quad M_{\rm II} \quad M^{\rm off}_{\rm TF} \quad M^{\rm off}_{\rm SBF} \quad \log_{10} H_0 \quad \mu_{\rm C}\ \right]$$

$$\begin{array}{c}
\begin{array}{cccccc}
\text{Host Dist.} & \text{Groups} & \text{— Abs. Mag. —} & H_0 & \mu_{\rm C} & \\
\end{array}\\
\mathbf{A} = \left[\begin{array}{cccc:cc:cccc:c:c}
1 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
0 & \cdots & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \cdots & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\hline
1 & \cdots & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
0 & \cdots & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \cdots & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
\hline
1 & \cdots & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
\vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & 1 & \vdots & 0 & \vdots & \vdots \\
0 & \cdots & 0 & 1 & 0 & 0 & 0 & \vdots & 1 & \vdots & 0 & 0 \\
0 & \cdots & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
\hline
0 & \cdots & 0 & 0 & 0 & 0 & -0.2 & 0 & 0 & 0 & 1 & 0 \\
0 & \cdots & 0 & 0 & 0 & 0 & 0 & -0.2 & 0 & 0 & 1 & 0 \\
0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & -0.2 & 0 & 1 & 0 \\
0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.2 & 1 & 0 \\
\hline
0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
\vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
\hline
0 & \cdots & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\
\vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & 0 & \vdots & \vdots \\
0 & \cdots & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\
\hline
0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
\hline
0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0.2
\end{array}\right]
\begin{array}{l}
\\ \text{Hosts} \\ \\ \\ \\ \text{Groups} \\ \\ \\ \\ \text{Calibrators} \\ \\ \\ \\ H_0\text{–}M \text{ links} \\ \\ \\ \\ \text{MM/EPM} \\ \\ \\ \text{Coma SN} \\ \\ \mathrm{C}_{\rm SBF} \\ H_{0,\rm C}
\end{array}
\end{array}$$

$$\left[\begin{array}{c}
\mu_{{\rm host},1} \\ \vdots \\ \mu_{{\rm host},n-1} \\ \mu_{{\rm host},n} \\ \hline
0 \\ \vdots \\ 0 \\ 0 \\ \hline
m_{0B,1} \\ \vdots \\ m_{0B,k-1} \\ m_{0B,k} \\ \hline
\alpha_{\rm Ia} + 5 \\ \alpha_{\rm II} + 5 \\ \alpha_{\rm TF} + 5 \\ \alpha_{\rm SBF} + 5 \\ \hline
\log_{10}(H_0)_{{\rm MM},1} \\ \vdots \\ \log_{10}(H_0)_{{\rm EPM},m} \\ \hline
m_{0,{\rm Coma},1} \\ \vdots \\ m_{0,{\rm Coma},p} \\ \hline
\mu_{\rm Coma\ SBF} \\ \hline
\log_{10}(H_0)_{\rm C} + 0.2\mu_{\rm C}
\end{array}\right] = \mathbf{Y}$$

Block Structure of $\mathbf{A}\,\mathbf{X} = \mathbf{Y}$



Covariance Matrix C

$$
\mathbf{C} =
\begin{array}{cl}
\begin{array}{ccccccccccccccccccccc}
 & \text{Hosts} & & & \text{Groups} & & & \text{Calib.} & & & \text{Intercepts} & & & & \text{MM/EPM} & & & \text{Coma SN} & & \mathrm{C_s} & H_{0,\mathrm{C}}
\end{array} & \\
\left[\begin{array}{ccc|ccc|ccc|cccc|ccc|ccc|c|c}
\sigma^2_{\mathrm{tot},1} & \cdots & \sigma^2_{\mathrm{HMAS}} & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & 0 \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
\sigma^2_{\mathrm{HMAS}} & \cdots & \sigma^2_{\mathrm{tot},n} & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & 0 \\
\hline
0 & \cdots & 0 & \sigma^2_{\mathrm{g},1} & \cdots & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & 0 \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
0 & \cdots & 0 & 0 & \cdots & \sigma^2_{\mathrm{g},2} & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & 0 \\
\hline
0 & \cdots & 0 & 0 & \cdots & 0 & \sigma^2_1 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & 0 \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & \sigma^2_k & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & 0 \\
\hline
0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & \sigma^2_{\alpha_{\mathrm{Ia}}} & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & 0 \\
0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \sigma^2_{\alpha_{\mathrm{II}}} & 0 & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & 0 \\
0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & 0 & \sigma^2_{\alpha_{\mathrm{TF}}} & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & 0 \\
0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & \sigma^2_{\alpha_{\mathrm{SBF}}} & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & 0 \\
\hline
0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & \sigma^2_1 & \cdots & 0 & 0 & \cdots & 0 & 0 & 0 \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & \sigma^2_m & 0 & \cdots & 0 & 0 & 0 \\
\hline
0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & \sigma^2_1 & \cdots & 0 & 0 & 0 \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & \cdots & \sigma^2_p & 0 & 0 \\
\hline
0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & \sigma^2_{\mathrm{C_s}} & 0 \\
\hline
0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \sigma^2_{\mathrm{C}}
\end{array}\right]
&
\begin{array}{l}
\\ \text{Hosts} \\ \\ \\ \text{Groups} \\ \\ \\ \text{Calibrators} \\ \\ \\ \text{Intercepts} \\ \\ \\ \\ \text{MM/EPM} \\ \\ \\ \text{Coma SN} \\ \\ \mathrm{C_{SBF}} \\ H_{0,\mathrm{C}}
\end{array}
\end{array}
$$

Host block: off-diagonal σ^2_{HMAS} encodes shared anchor, method-anchor-source (MAS), and host-method-source (HMS) uncertainties.

Results

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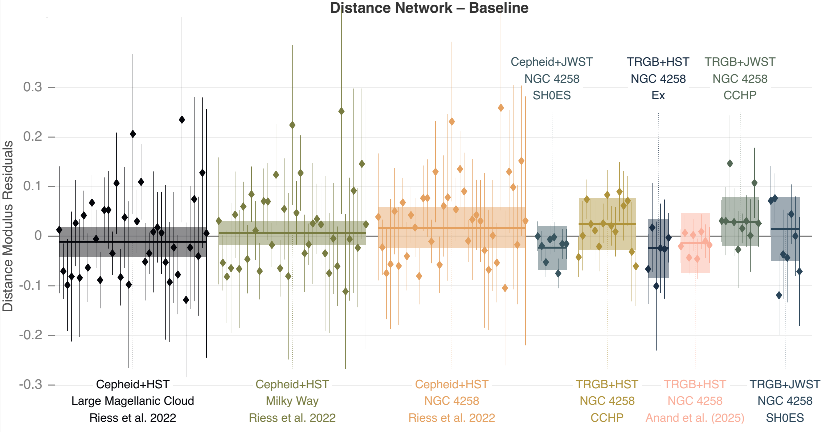
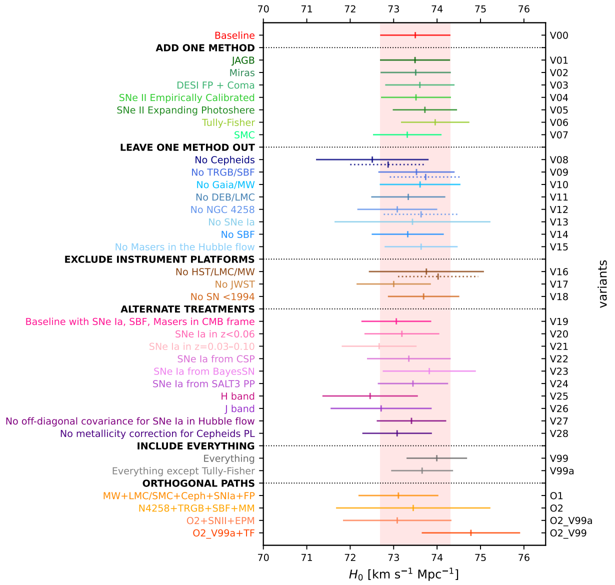


Robust Across 30+ Variants



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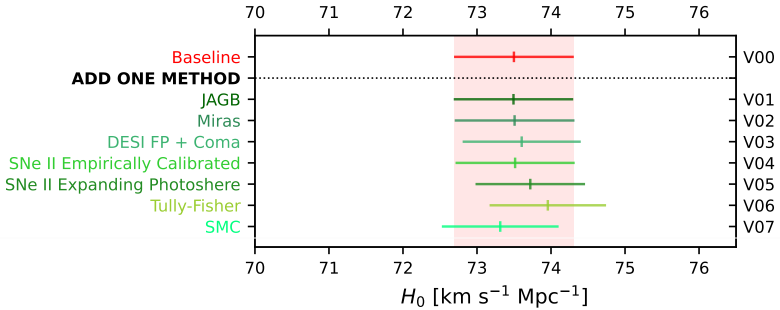

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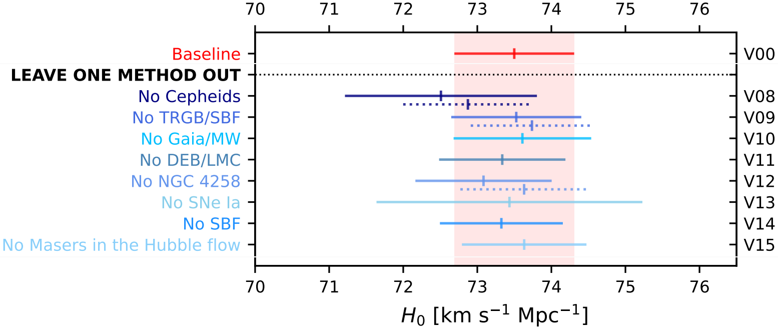

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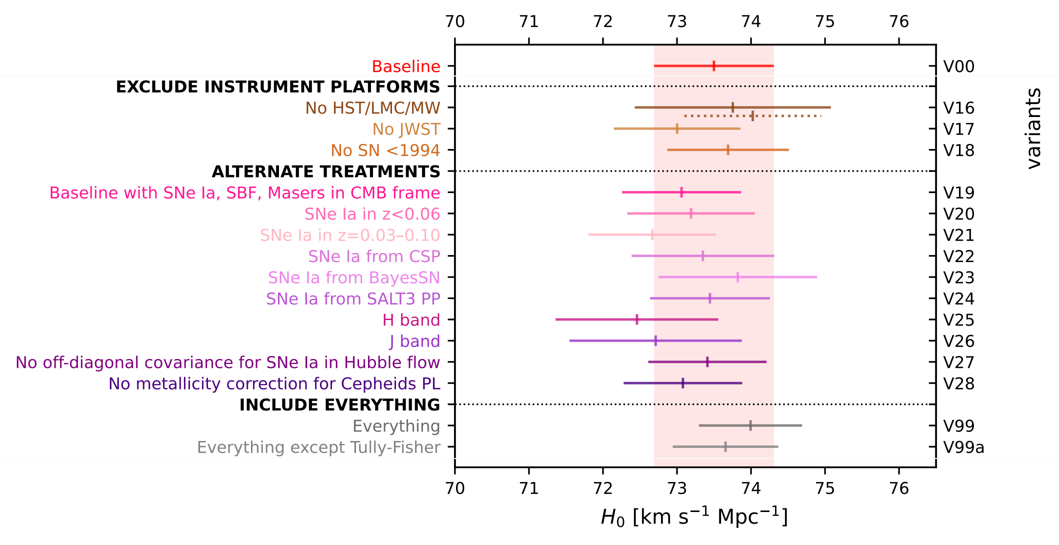

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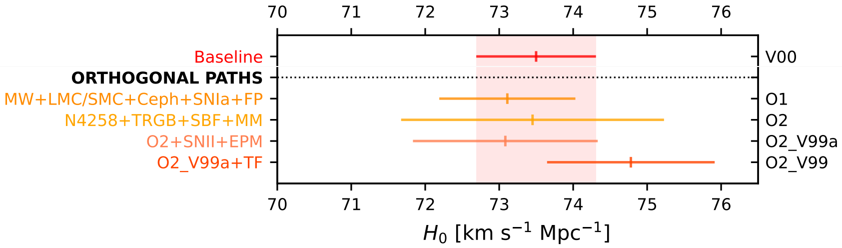

The Code

Development of the Code

- Original code in IDL

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- Both versions along with the data files are available at: `https://github.com/StefCas789/H0DN`

Quick Start

Installation

In the folder containing `pyproject.toml`, install in **editable mode**:

```
pip install -e .
```

Basic Usage

Navigate to the `configs` folder and run the analysis:

```
cd configs
h0_constrainer config.ini
```

This performs a generalized least-squares fit using the configuration and data files in the data directory. The example `config.ini` in `configs/` is heavily commented: most options for choosing a distance network are explained there.

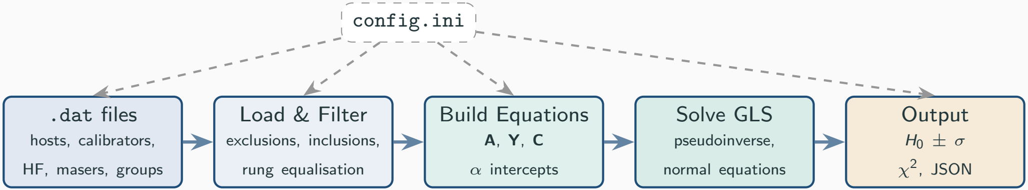
Command-Line Options

```
# Use config.ini in current directory
h0_constrainer

# Use specific configuration file
h0_constrainer my_config.ini

# Run multiple variants (systematic exploration)
h0_constrainer -v variants.ini
```

User Oriented View of the Code



One Config File Controls Everything

- **Define the network** in a single `config.ini` file

`config.ini` (excerpt)

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datadir = ../data
host_data = host_data.dat
sn1a_calib = sn1a_calib.dat
sn1a_hf = sn1a_hf_pp.dat
sn1a_hf_cov = sn1a_covar_pp.dat
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- **Run batches with `variants.ini`** to modify any subset of keys per run

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Data Files Overview

Same files grouped by object/feature type:

Object/Feature type	Compilation	Files
Anchors	-	anchors.dat
Host distances	-	host_data.dat, host_data_nomet.dat
	PP	sn1a_calib.dat, sn1a_hf_pp.dat, sn1a_covar_pp.dat
	BayesSN	sn1a_calib_bayessn.dat, sn1a_hf_bayessn.dat, sn1a_covar_bayessn.dat
	CSP	sn1a_cal_csp_burns.dat, hf_csp_lluis_v2.dat, hf_csp_lluis_v2_cov.dat
SNe Ia	SALT3	hf_salt3.dat, hf_salt3_cov.dat, rung3_salt3.dat
	J	sn1a_calib_J.dat, sn1a_hf_J.dat
	H	sn1a_calib_H.dat, sn1a_hf_H.dat
	Coma	coma_sn.dat
SBF	-	sbf_calib.dat, sbf_hf.dat
SN II	-	sn2_calib.dat, sn2_hf.dat, epm.dat (not a cov file)
Tully-Fisher	-	tf_calib.dat, tf_hf.dat
Other	-	megamaser.dat, epm.dat, groups.dat, coma_sn.dat

Closing

The H_0 Distance Network: Key Takeaways

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- Open source code implementation
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Please report issues, bugs and feature requests...

Thank You