Synthesis & Wrap-Up
What Have We Learned?

CosmoVerse 2026 Summer School

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This week: the cosmic distance ladder

- The Hubble tension: early vs. late universe disagree at 5σ
  - CMB: H_0 = 67 | Local ladder: H_0 = 73 km/s/Mpc
- The cosmic distance ladder connects geometry to H_0
  - Anchors → Cepheids/TRGB → SNe Ia (Hubble flow)
- **Your role:** measure Rung 2 (TRGB) and…

Understand how different measurement choices affect distances & H_0

Six talks, one question: How to measure H_0?

Louise Breuval
- Hubble tension & distance ladders
- Cepheid metallicity dependence
- w/ Teresa, notebook tutorial

Teresa Sicignano
- Cepheid variables
- Stellar abundances & metallicity

Kayla Owens
- Photometry methods & challenges
- TRGB datasets overview

Siyang Li
- TRGB: theory & observations
- TRGB distances to SN Ia hosts
- Data challenge tutorial

Yukei Murakami
- Type Ia SNe as standardizable candles
- SNe Ia notebook tutorial
- Systematics & the future

Your mission for Days 4–5

- Measure TRGB distances to SN Ia host galaxies
  - TRGB notebook → μ → export to trgb_results.csv
- Compute H_0 from your distances
  - H_0 notebook → Restart & Run All → read your result
- Explore how your parameter choices shift H_0
  - Vary τ, color cuts, spatial clipping — run Section 9a stability check

Document everything – as if you need to reproduce your result a year later!

The Cosmic Distance Ladder

Building distances step by step

- No single ruler spans the full observable universe
  - Each method is calibrated against the one below it

Distance ranges:

- Rung 1: Geometric anchors < 10 Mpc
- Rung 2: TRGB 5 – 30 Mpc
- Rung 3: Type Ia Supernovae up to redshift ~0.15 → H_0

Each rung inherits errors from the rung below.

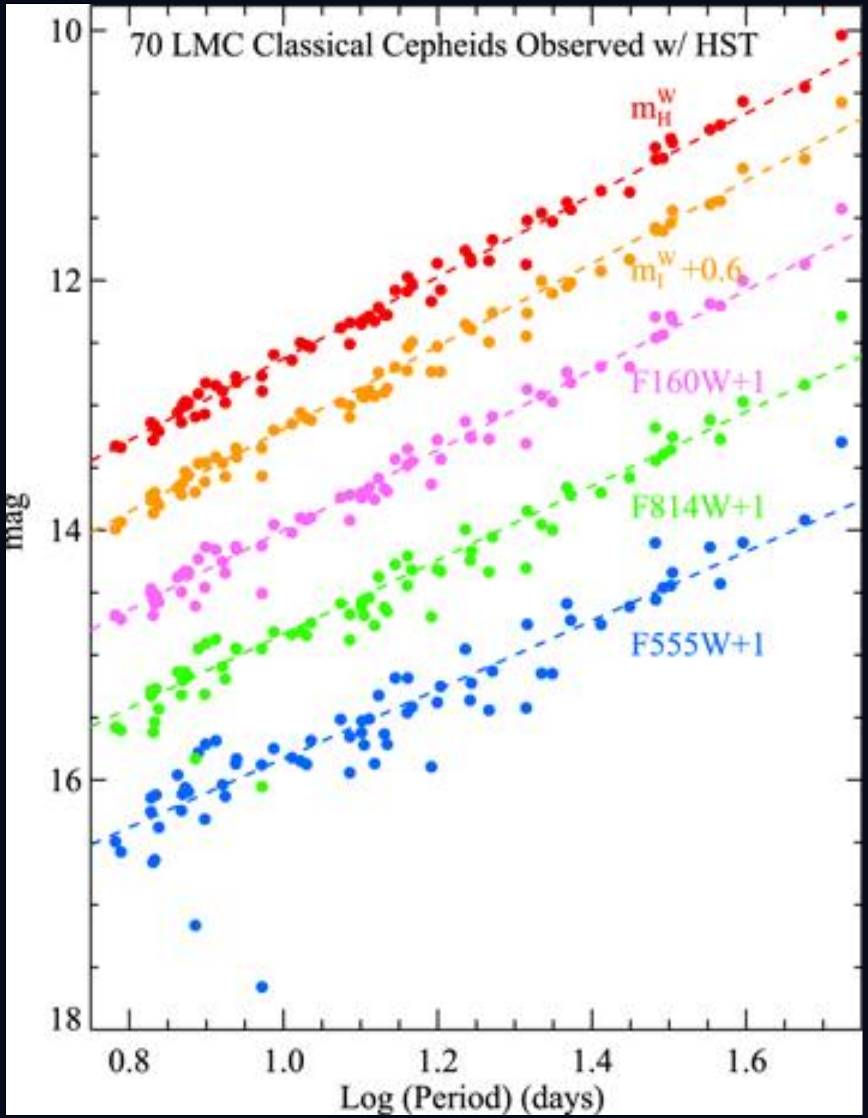
Rung 1: Geometric Anchors

- Parallax: purely geometric
  - Gaia EDR3: parallaxes for > 1 billion stars within ~3 kpc
- Water masers in NGC 4258: d = 7.60 ± 0.23 Mpc
  - Ried+19 — Orbital geometry of masers around the central black hole → direct distance
- Detached eclipsing binaries: LMC &; SMC
  - Pietrzyński et al. 2019 — light curves + spectroscopy → pure geometry

These anchor the entire ladder. Every other rung traces back to these.

Rung 2: Cepheid Variables

- Leavitt's Law: longer pulsation period → more luminous
  - Period-luminosity relation
- Used to measure distances to SNe Ia hosts out to ~50 Mpc
  - SH0ES (Riess et al. 2022): $H_0 = 73.04 \pm 1.04$ km/s/Mpc
- **Metallicity ([Fe/H]) shifts the P-L zero-point.**
  - Local calibrators may differ from distant host galaxies in metallicity

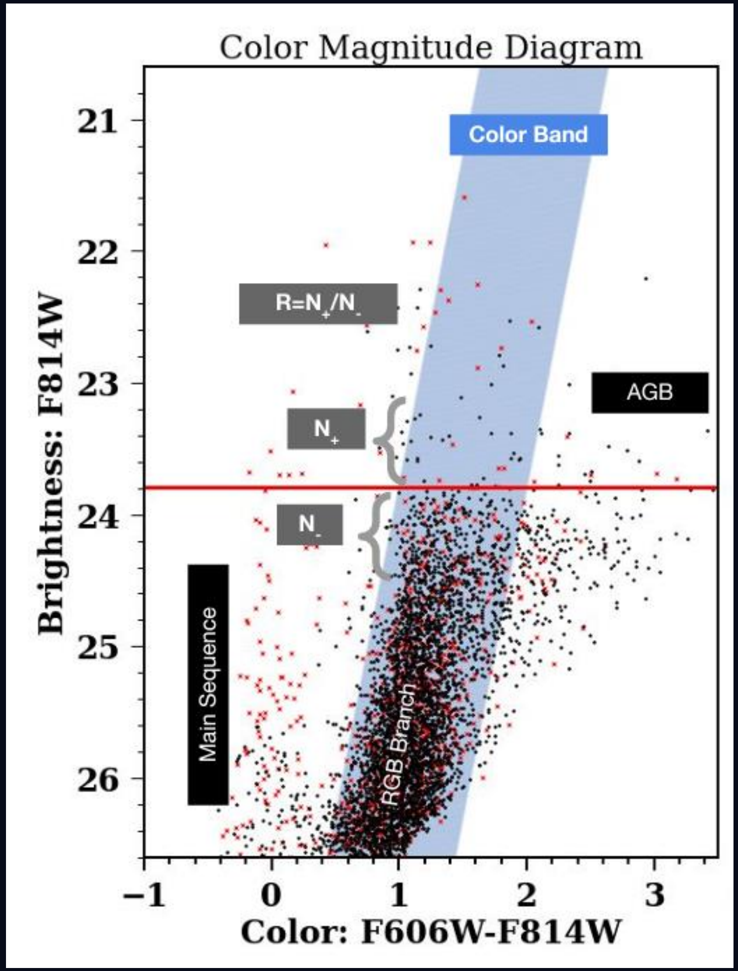


Riess+19

Rung 2: The Tip of the Red Giant Branch

- Old stars reach maximum luminosity at helium ignition
  - Core mass at ignition ≈ 0.50 M⊙ — nearly universal for old populations
- I-band calibration: M_I(TRGB) ≈ −4 mag
  - Anchored on NGC 4258 maser distance and LMC eclipsing binaries
- Requires resolved stellar photometry: HST or JWST
  - Old stellar populations in galaxy halos; limited crowding issue

Largely independent of Cepheid systematic uncertainties.



Wu+22

Rung 3: Type Ia Supernovae

- Thermonuclear explosion of a white dwarf near the Chandrasekhar limit
  - Standardizable via light-curve shape: $M_B \approx -19.3$ mag after correction
- Up to z ~ 0.15 to extend into the Hubble flow

The TRGB calibration sets the SNe Ia zero-point, which sets H_0.

- This is the direct link between your measurements and H_0

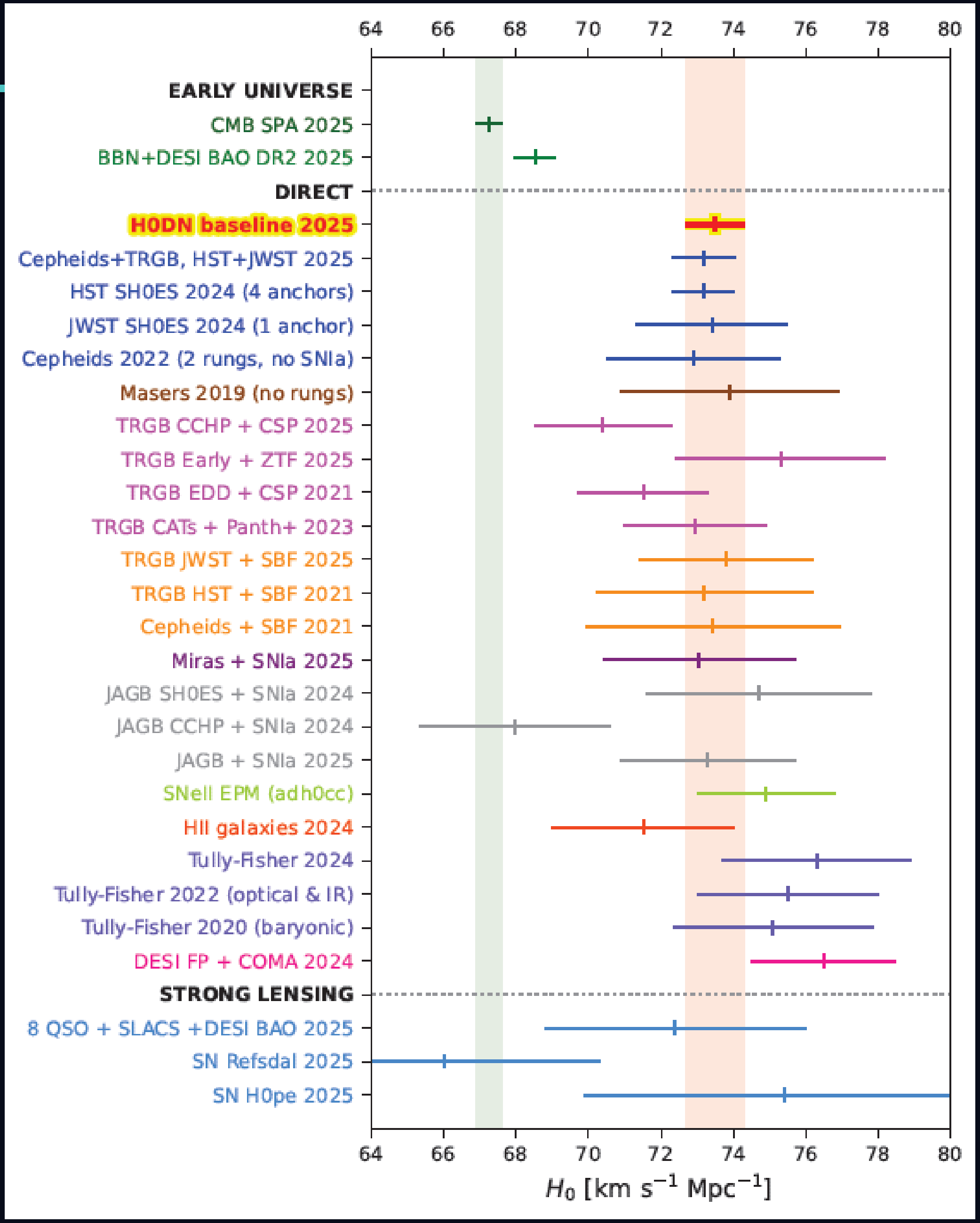
The Current TRGB H_0 Landscape

H_0 from multiple teams
→ Many H_0 using independent methods;
*Note SBF vs SN Ia

Where do differences come from?

→ Documented in literature (e.g. Anand+21, Scolinic+23, Freedman+25, Casertano+25, Li+26)

A chance for YOU to explore in the data challenge!



Casertano+25

Photometry: The Foundation

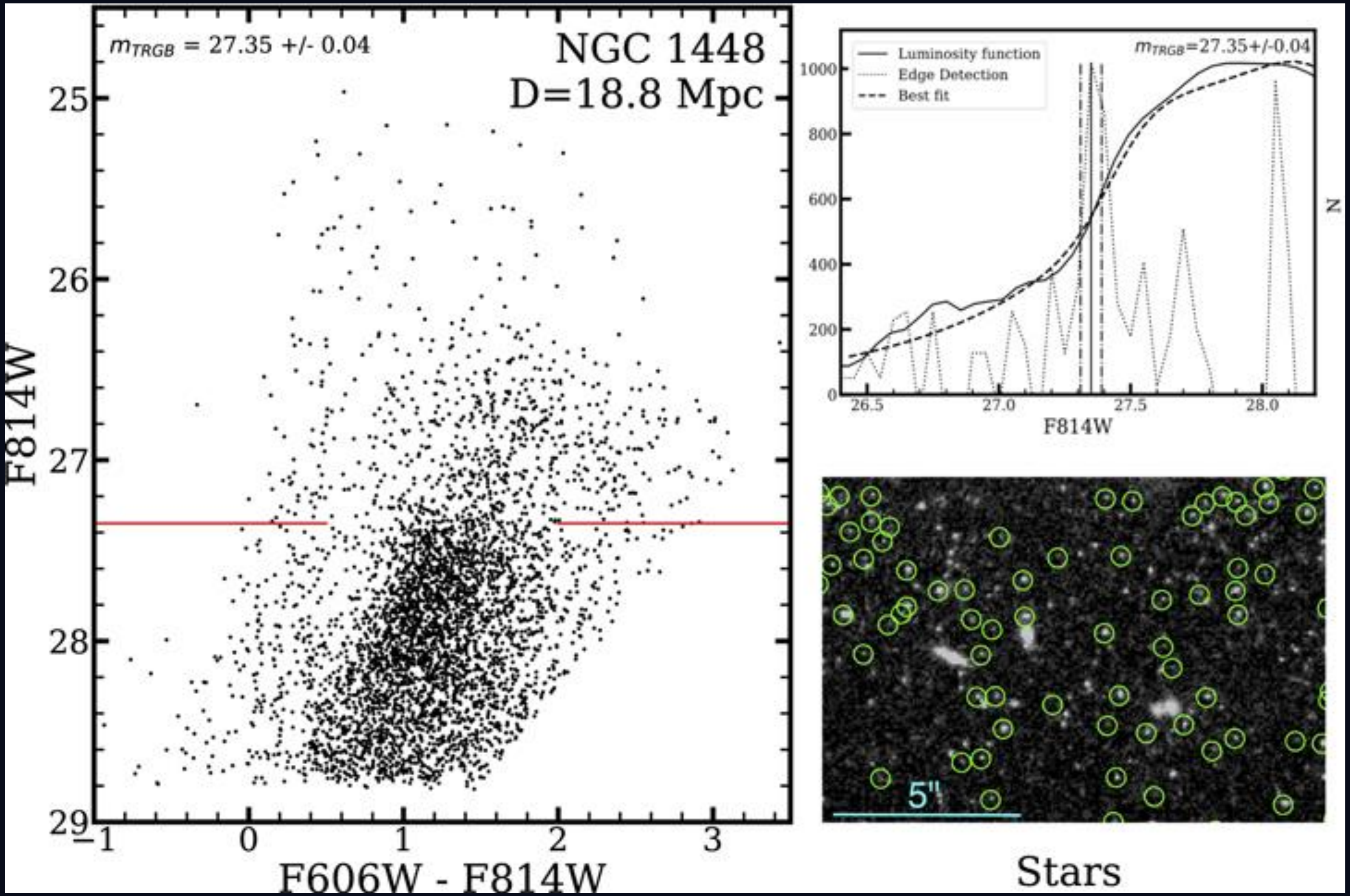
From raw telescope images to stellar catalogs

What Is Photometry?

- Aperture photometry: sum counts in a circular aperture
  - Simple and robust | struggles with overlapping stars
- PSF photometry: fit a model of the telescope point spread function
  - Handles crowding | requires an accurate PSF model for the detector
- HST used for TRGB photometry
  - Stable diffraction-limited PSF | F814W ≈ Cousins I-band

Photometric quality is the foundation of every TRGB measurement.

The Color-Magnitude Diagram



Anand+22

The TRGB: Your Tool This Week

From stellar physics to cosmological distances

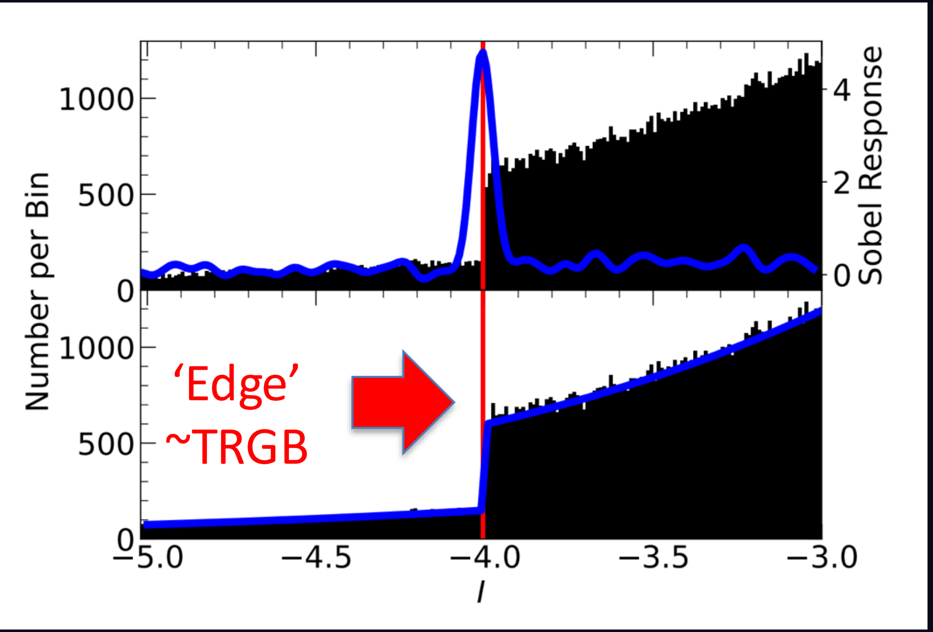
What Is the TRGB?

- Degenerate helium core grows as the star ascends the RGB
  - At core mass ≈ 0.50 $M_\odot$: helium ignites explosively — the helium flash
- The flash terminates the RGB phase; core mass at ignition is universal
  - Nearly universal luminosity at the tip across all old stellar populations
- Sharp discontinuity in the luminosity function
  - Stars exist below the TRGB; essentially none above it

Finding the TRGB = finding the bright edge of a stellar population.

Why the TRGB Is a Standard Candle

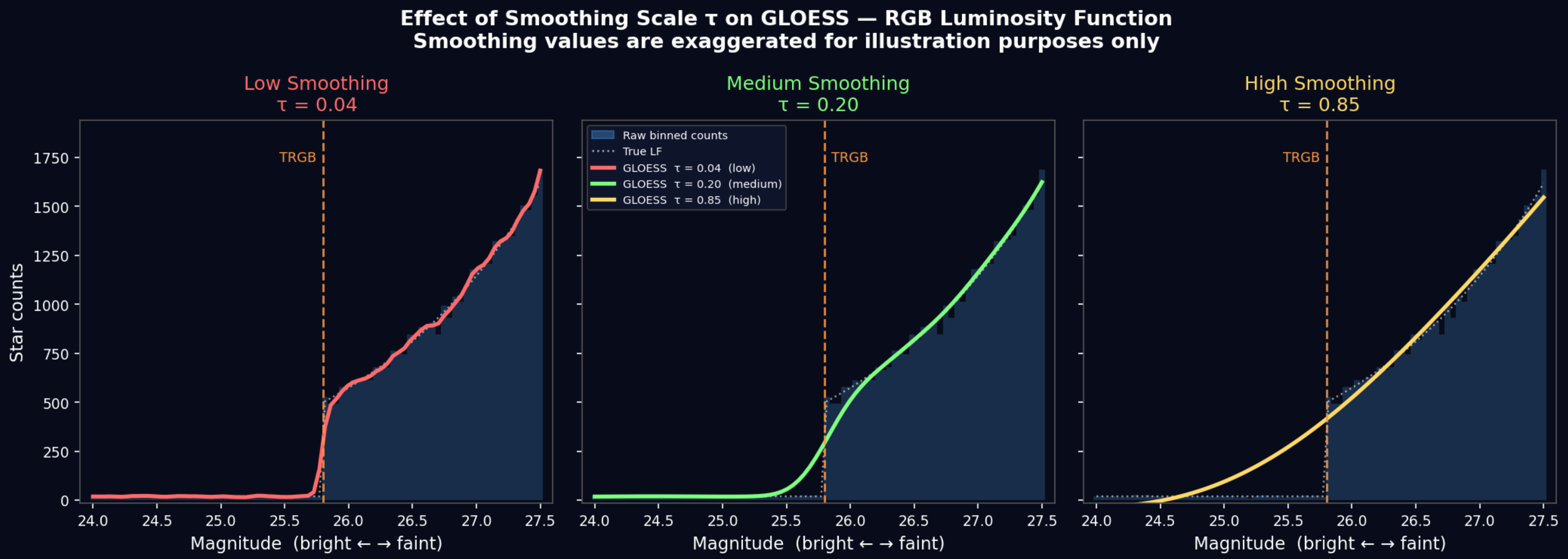
- Power law below TRGB
  - Star counts rise steeply toward fainter magnitudes
- Sharp drop at the TRGB — the bright edge
  - Above the tip: only rare AGB stars; counts ≈ 0
- The raw luminosity function is noisy (Poisson statistics)
  - Must smooth before edge detection → GLOESS



Li & Beaton 24

The TRGB is where the power law ends. Find that edge.

GLOESS: Smoothing the Luminosity Function



Sobel Edge Detection

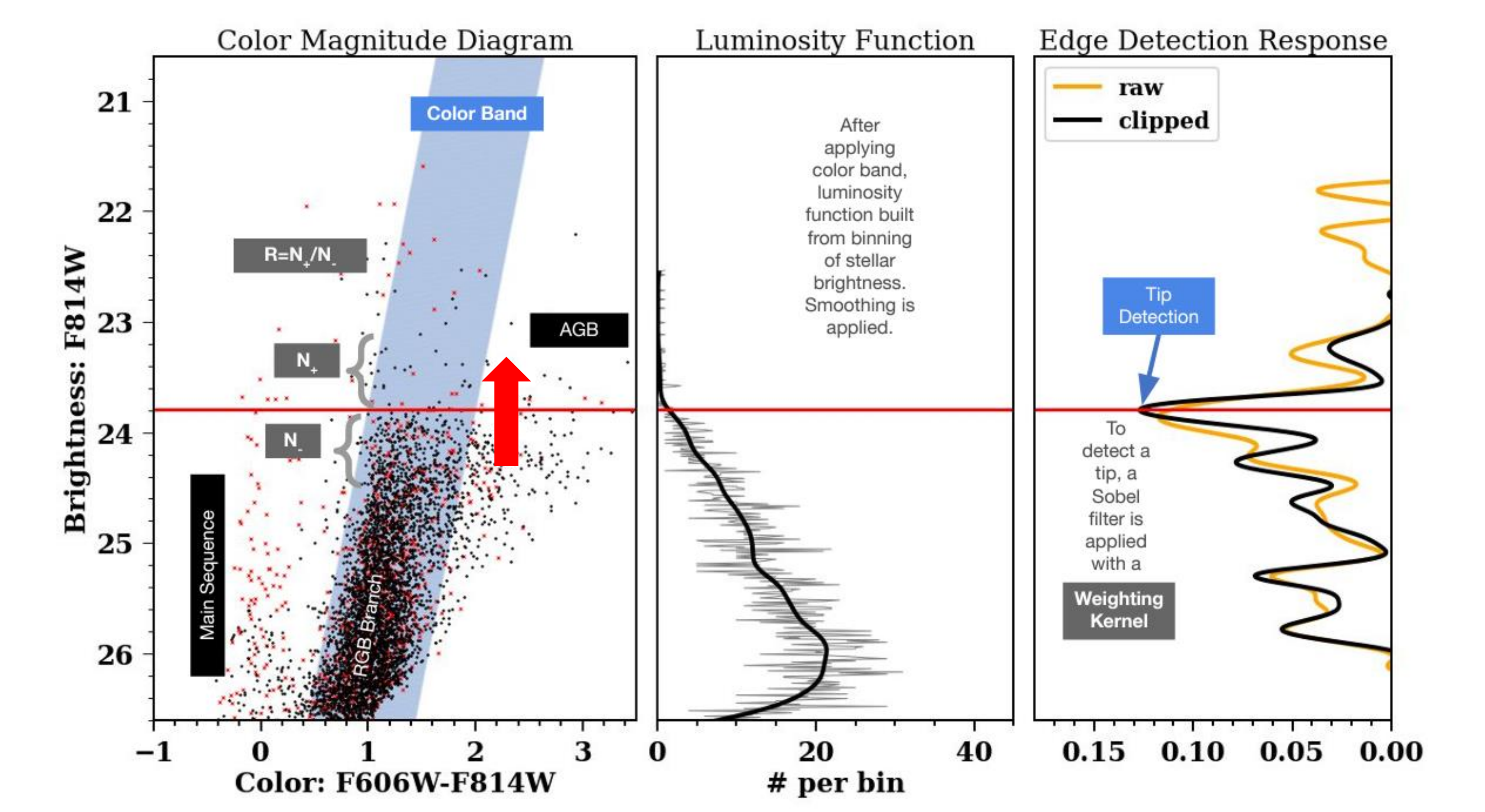
- Derivative of the smoothed LF — peaks at the TRGB

Three weighting schemes:

- Simple: $\phi_i = N(i+1) - N(i-1)$
- Poisson: $\phi_i = [N(i+1) - N(i-1)] / \sqrt{[N(i+1) + N(i-1)]}$
- Hatt: same normalization, per-flux weighting

Peak of the Sobel response = TRGB magnitude.

Measuring the TRGB w/ the Sobel Filter



Wu+23

Systematic 1: Population Effects

- Measured TRGB magnitude can vary with stellar population
  - Empirical field-to-field scatter of ~0.3 mag in the same galaxy
  - Root cause: varying RGB/AGB mix, not just red giants
- CATs solution: standardize via the Contrast Ratio (R)
  - $M(TRGB) = -4.025 \pm 0.035 - (R - 4) \times 0.021$ (Li+23, Wu+22, Scolnic+23)
  - Corrects field-to-field tip scatter before propagating to H_0

You can probe this in the data challenge — compare TRGB across different spatial fields in the same galaxy.

Systematic 2: Blending & Crowding

- Blending: two unresolved stars measured as one → magnitudes biased bright
- Effect on H_0: bright bias → TRGB detected too bright → distance underestimated → H_0 overestimated
  - Bias direction is one-sided and systematic — not statistical noise
- Mitigations
  - Use outer halo fields (spatial clipping removes crowded inner disk)
  - Artificial star tests — inject & recover fake stars to quantify bias
  - JWST: smaller PSF → less blending at the same physical distance

Systematic 3: Dust Extinction

- Dust dims and reddens starlight → apparent TRGB too faint → distance overestimated
- Correction: $A_I = R_I \times E(B-V)$ with $R_I \approx 1.49$ (Schlafly & Finkbeiner 2011)
  - Data challenge uses SF11 dust maps — already applied in the pipeline
- Field selection matters
  - Halo fields: A_I < 0.05 mag
  - Inner disk / high-extinction sightlines: map uncertainty dominates — avoid
  - Watch for NGC 2442, NGC 5643, NGC 7250 — higher extinction in this dataset

Systematic 4: Methodological Variations

- Every TRGB measurement requires subjective choices: τ, color limits, spatial clipping, Sobel weights
- Different defensible choices → different TRGB → different H_0
  - CATS showed the full range spans ~1 km/s/Mpc when varying these parameters
- Best practice: remain agnostic, build variation into errors
  - Make all choices explicit; run sensitivity tests; report σ(method) separately

This is exactly what the data challenge asks you to do — your spread in H_0 is the measurement.

Type Ia Supernovae: Rung 3

From calibrators to the Hubble flow

Type Ia SNe as Distance Indicators

- Standardizable candle – Tripp corrections
  - $M_B \approx -19.3$ mag after standardization
- Residual scatter ~0.15 mag per SN after corrections
  - ~7% distance uncertainty per event → need ~40+ calibrators

The SNe Ia zero-point is set by the TRGB or Cepheid calibration.

- Your TRGB distances enter here directly

Standardizing Type Ia Supernovae

- Phillips (1993): brighter SNe decline more slowly
  - Δm_{15}: magnitude drop in B-band at 15 days post-peak
- SALT2/3 parameterization: x_1 (stretch) and c (color)
  - $M_B^{corr} = M\_B + \alpha \cdot x_1 - \beta \cdot c$

After correction: scatter ≈ 0.15 mag (intrinsic + measurement).

- Host-galaxy environment and progenitor physics are active research areas

The CosmoVerse Data Challenge

Why a Community Data Challenge?

- Same data, same physics — different groups get different H_0
  - Impossible to untangle if each group uses different data and code
- This challenge fixes the dataset; only the TRGB method varies
  - Common photometric catalog | fixed supernova analysis

Output: a public repository of all results, pipelines, and data.

- The community can inspect, reproduce, and build on every result

The Ground Rules

✅ **Free to vary**

- Smoothing bandwidth τ
- Color selection (color_lo, color_hi)
- Spatial clipping radius
- Sobel weighting scheme

These choices are the whole point.

⛔ **Do not change**

- Supernova dataset
- Supernova fitting code (mu_to_H0.py)
- Any file in 2_hubble_constant/data/

Fixed SN side → differences trace to TRGB choices only.

The Two-Notebook Pipeline

Part 1 — TRGB Notebook (1_trgb/)

- Set TARGET_GALAXY → Restart & Run All
  - Adjust τ, color cuts, spatial clipping → inspect plots → run Section 9a
  - Anchor: NGC 4258 maser distance (7.60 Mpc)
- Section 10: export μ to trgb_results.csv

Part 2 — H_0 Notebook (2_hubble_constant/)

- Restart & Run All → reads trgb_results.csv → returns H_0

Exploring the Parameter Space

- Smoothing bandwidth τ: try 0.05, 0.10, 0.15, 0.20 mag
  - Small τ → noisy edge | Large τ → smeared edge | aim for single Sobel peak
- Color cuts: shift color_lo and color_hi by ±0.1 to ±0.2 mag
  - Inspect CMD each time — the right range varies by galaxy
- Section 9a stability check
  - TRGB should not shift > 0.03 mag under small parameter variations

Flag any instabilities. Don't hide them.

Reading Your Diagnostic Plots

- CMD: RGB in selection box? AGB and foreground excluded?
- Luminosity function: clear rise toward faint end? Drop at bright end?
- Sobel response: single clean peak?
  - Multiple peaks of similar height → ambiguous → increase τ
- Bootstrap distribution: unimodal bell curve?
  - Bimodal (two humps) → algorithm jumping → increase τ

Sanity Checking Your Results

- Expected distance range for all challenge galaxies:

  $\mu \approx 30 - 34$ mag ($d \approx 10 - 65$ Mpc)

  – Outside this range: something went wrong — recheck

- Compare to published catalogs

  – EDD (Anand+22) | CATS (Scolnic+23) | CCHP (Freedman+19)

Document your reasoning in notebook text cells.

Connecting the Threads

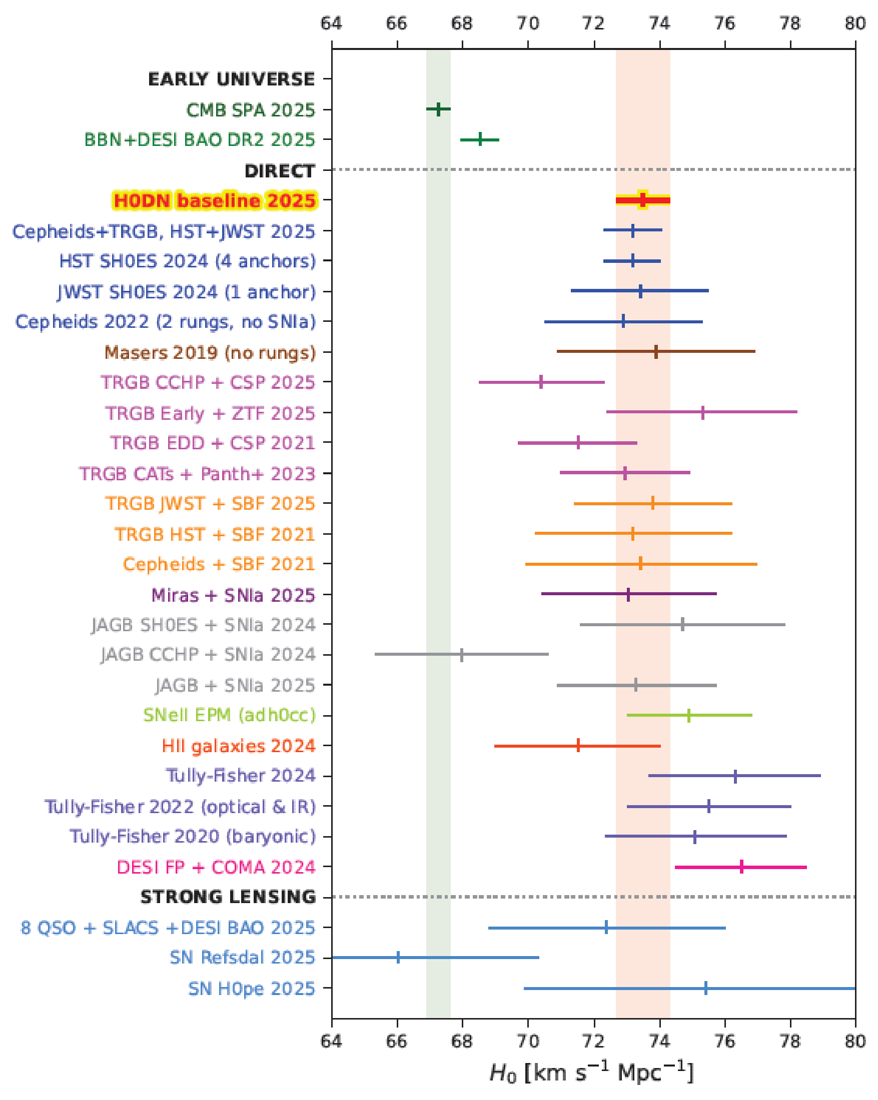
What the data challenge reveals about the state of the field

Is the Hubble Tension Real?

- Option 1: Systematic in the local ladder
  - Multiple independent methods agree
- Option 2: Systematic in CMB analysis
  - Planck confirmed by ACT and SPT
- Option 3: New physics beyond ΛCDM
  - Early dark energy, extra radiation, modified gravity, dynamical dark energy

No single proposed fix has convinced the field — yet.

The H_0 Measurement Landscape



Casertano+25

The Local Distance Network (Casertano+ 2025)

- Goal: combine all rung-1 & rung-3 distance indicators into one covariance-weighted network
  - 37 co-authors, methods: open-source code
- Key innovation: model correlated systematics across methods, not just combine quoted error bars
  - Shared calibrators (NGC 4258, LMC, MW parallaxes) create correlations — treating them as independent would underestimate errors

A Community Consensus: Tension at 7σ

- Community vote on which indicators enter the baseline — transparent, reproducible
  - Variants explored — adding methods one at a time, change < 0.2 km/s/Mpc except TF
  - 1.1% precision — first time the local measurement reaches this level from a community consensus

- Tension with the early Universe
  - 7.1σ from Planck + SPT + ACT | 5.0σ from BBN + BAO (DESI 2025)
- All 12 methods are internally consistent — this is not a one-team result
  - Replacing SN Ia with galaxy-based indicators changes H_0 by < 0.1 km/s/Mpc

$H_0 = 73.50 \pm 0.81$ km/s/Mpc

Take-Home Messages

What to carry forward from this week

The Ladder Is Only as Strong as Its Weakest Rung

- A 2% error in TRGB distance → 2% error in H_0
  - Errors propagate forward through every rung above
- Multiple independent rungs are not redundant — they are essential
  - Cepheids and TRGB at Rung 2: if they agree, confidence grows | if they disagree, something important is being revealed

The ladder is only as strong as its weakest rung.

Methodology Matters

- Varying τ shifts your TRGB
  - ~1–2% distance error → ~1–2 km/s/Mpc in H_0
- The Hubble tension (~7%) is within the range of methodology variation
  - The tension could be systematic — but it has not gone away

Report σ_{method} alongside σ_{stat}. Transparency is crucial.

The Case for Independent Methods

- TRGB and Cepheids share the same geometric anchor — not fully independent
  - A bias in NGC 4258 or the LMC affects both

Truly independent methods:

- Water masers | SBF | JAGB stars
- Gravitational wave standard sirens (LIGO / Virgo)
- Strong lensing time delays (H0LiCOW / TDCOSMO)

More independent paths = more credible constraints.

Science as a Community

- No single group will resolve the Hubble tension alone
  - The field needs transparent, reproducible, comparable results
- This challenge models that process
  - Common dataset | open pipelines | public repository

The goal is not to 'win'. It is to understand.

Open Questions

- What is the correct τ & measurement parameters?
- How do we treat noisy and multiple Sobel peak detections?
- How much do measurement choices change H0?

These are not textbook questions.

- They are open, unsolved problems — and your work this week touches all of them

Thank you to all the lecturers, organizers, and you!

The Hubble tension is real.

Go measure it.

Thank you — questions?