Astrophysical tracers of the late Universe expansion

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ΛCDM tensions ?

- Overall, the standard ΛCDM model is a good representation of the evolution of the Universe
- However, some scratches (tensions !) seem to point out that we need to go beyond the cosmological constant
- Most of the tensions appear between the early and the late Universe measurements
- There are inconsistencies between specific measurements as well, using different probes
- The key issue are the systematic errors which are very difficult to assess reliably
- An attractive possibility is to use numerous methods based on different tracers of the Universe expansion

Two broad classes of expansion tracers

- Statistical properties of the distributions
  - Cosmic Microwave background
  - Barion Acoustic Oscillations
  - Weak lensing of galaxies
  - Cosmic chronometers
  - TRGB
  - ….

- Individual objects/phenomena as tracers of expansion
  - Supernovae Ia
  - Strong gravitational lensing
  - Water masers
  - Gravitational waves
  - Time delays in Active Galactic Nuclei
  - ….

Formally, one object is enough to get the distance

Individual objects/phenomena

The list of objects is long, in general all objects which can be used for distance determination should be included, although some of those do not go to large (cosmological) distances but simply serve as steps in the distance ladder.

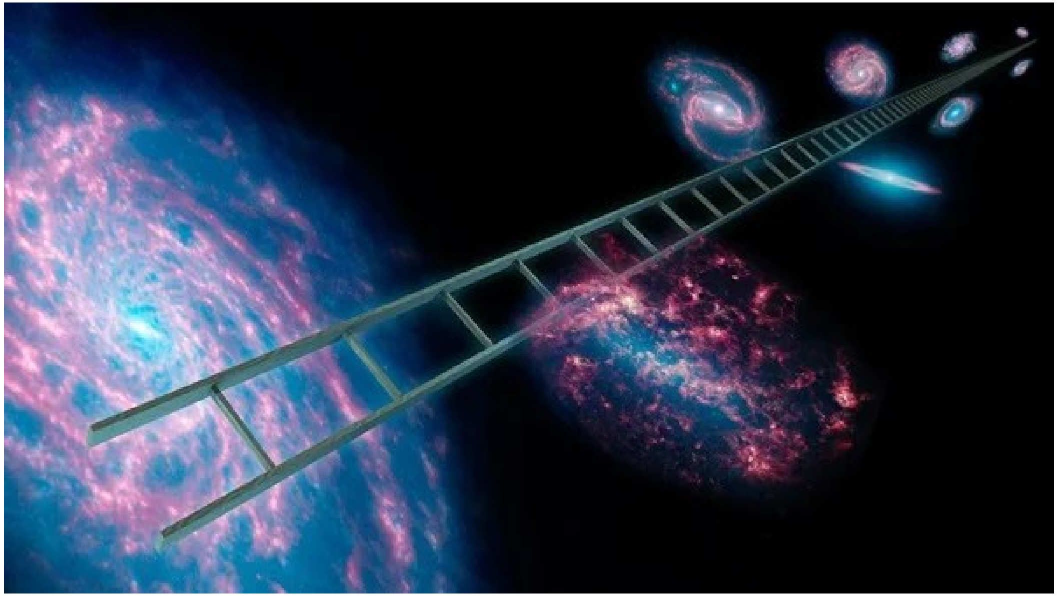
- Cepheid stars (P – L relation)
- RR Lyrae stars (L roughly constant)
- SN Ia (L roughly constant)
- SN II (L roughly constant)
- Tully-Fischer relation (L – v relation)
- Faber-Jackson relation (L – v relation)
- Surface Brightness Fluctuations
- Water maser in AGN (geometrical !)
- HII regions (L roughly constant)
- Gamma-ray bursts ($L – E_{peak}$)
- Radio jets (size roughly constant)
- Gravitational waves (standard siren)
- Sunyaev-Zeldovich (galaxy clusters)

- Fast Radio Bursts (dispersion measure)
- AGN (R – L for continuum)
- AGN (R – L for emission lines)
- AGN (L_X/L_{UV} -L)
- AGN – strong gravitational lensing
- AGN – trigonometric paralax for dust
- AGN max luminosity
- AGN X-ray excess variance and FWHM

Only some of those methods currently give well constraining results.

Distance ladder/direct jump

Methods based on individual objects can be still broadly divide into methods requiring (or being part of) the distance ladder based direct local measurements (paralaxes, binary stars) and those which allow to measure the distance directly, at the basis of some background knowledge.

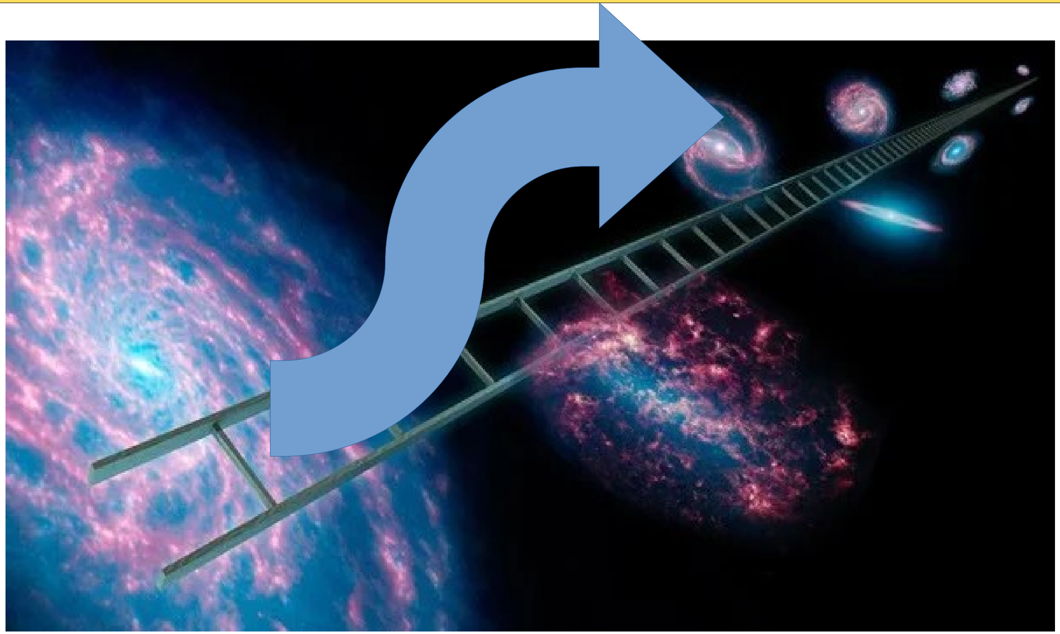


From Astronomy Magazine

Distance ladder/direct jump

Methods based on individual objects can be still broadly divide into methods requiring (or being part of) the distance ladder based direct local measurements (paralaxes, binary stars) and those which allow to measure the distance directly, at the basis of some background knowledge.

Examples of methods requiring distance ladder are SN Ia, or AGN R-L. Such methods cannot give directly H_0, although collectively they still can constrain cosmology.



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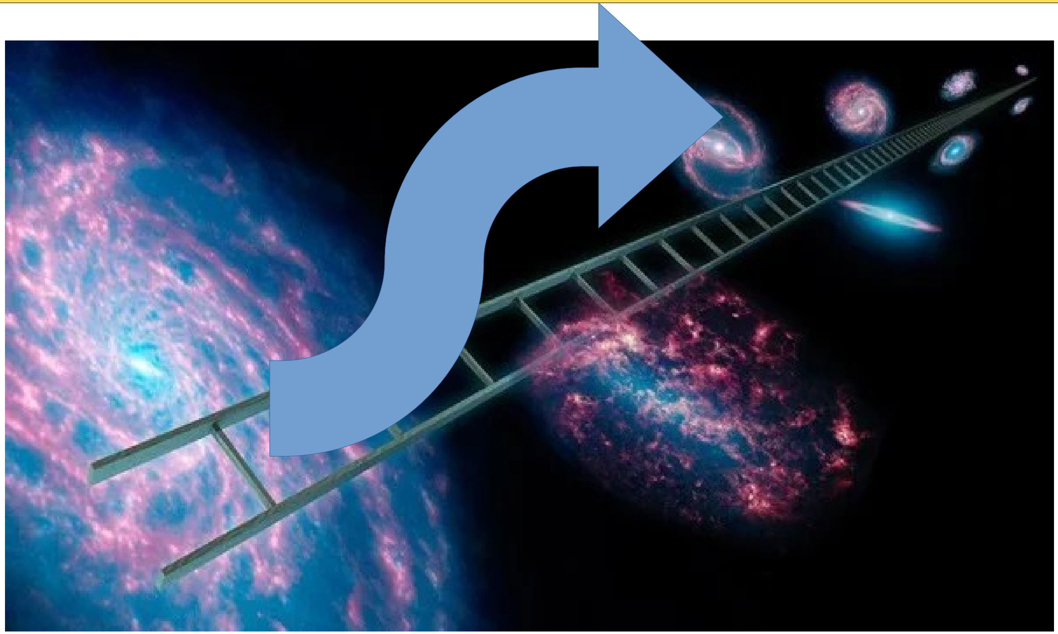
Distance ladder/direct jump

Methods jumping directly to the location are:

- Water maser in AGN (geometrical !)
- Gravitational waves (standard siren)
- Sunyaev-Zeldovich (galaxy clusters)
- Fast Radio Bursts (dispersion measure)
- AGN (R – L for continuum)
- AGN – strong gravitational lensing
- AGN – trigonometric paralax for dust



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Selected direct jump methods

- Water maser in AGN

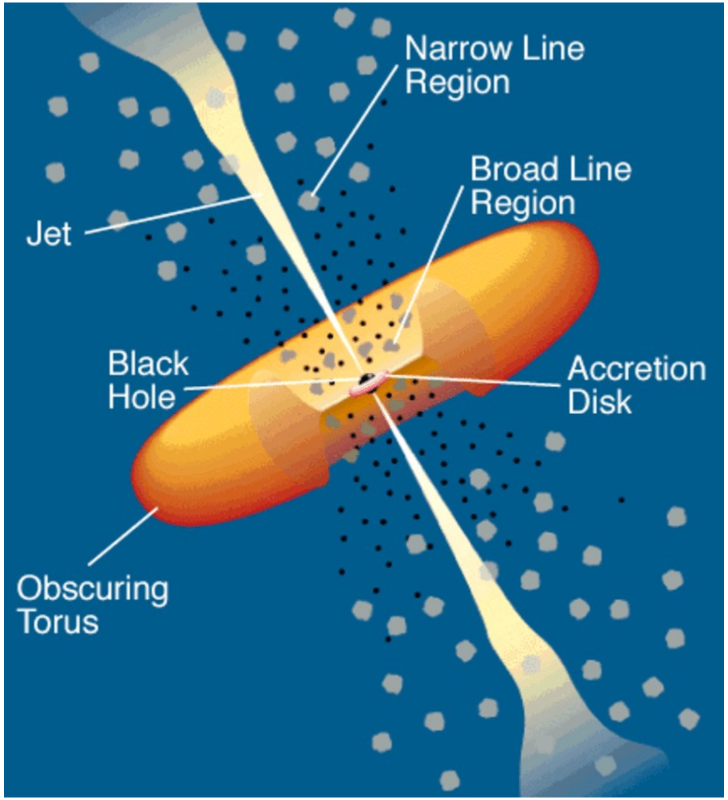
It gives very precise distance for NGC 4258, D= 7.54 ± 0.17 ± 0.15 Mpc. This is a very nearby source, redshift 448 +/- 3 km/s, so by itself it is not suitable for H_0 determination but it serves as the anchor for many other methods.

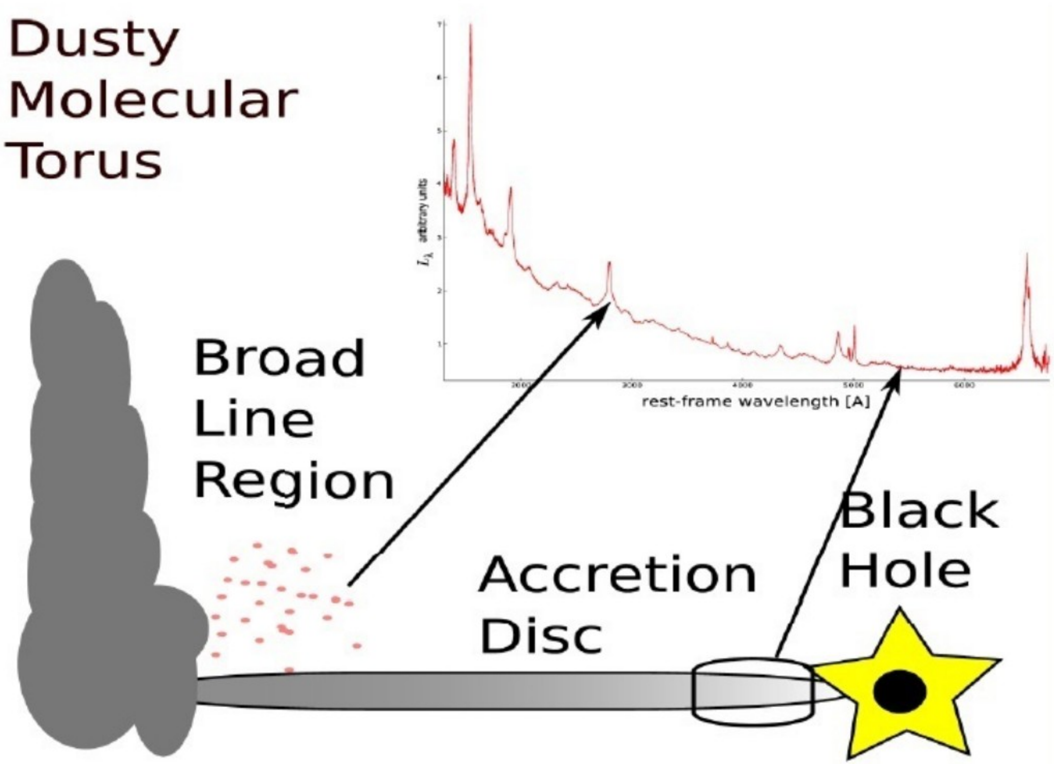
- Gravitational waves (standard siren): GW170817 implies $H_0 = 70^{+12}_{-8}$ km/s/Mpc *(LIGO/VIRGO 2017)*

- Fast Radio Bursts (dispersion measure): 98 objects, H0 = 57.7 +/-12 km/s/Mpc *(Piratova-Moreno et al. 2025)*

- AGN – strong gravitational lensing: HE 0435−1223, H0 = $71.9^{+2.4}_{-3.0}$ km/s/Mpc *(Holicow V, 2017)*

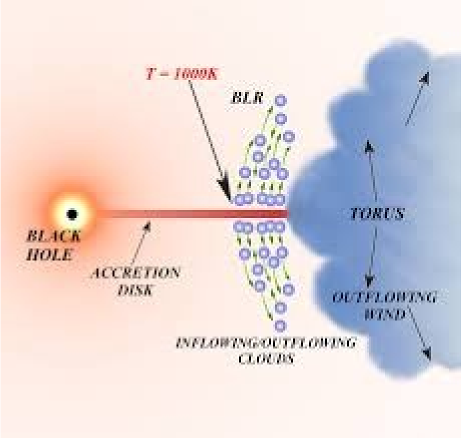
Our method - AGN continuum time delay

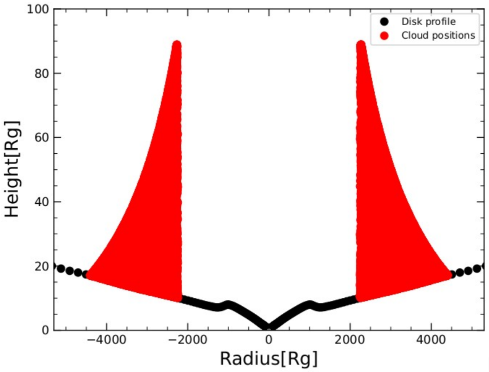


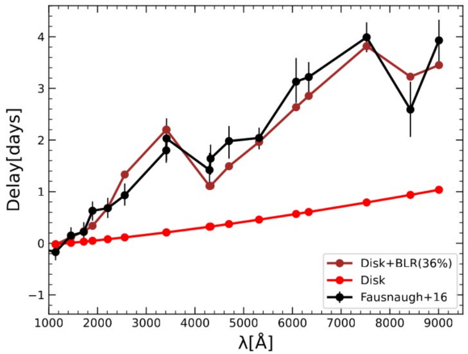


FRADO:dust-driven wind model of BLR

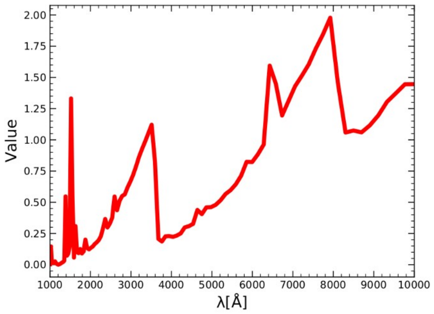
NGC 5548 (z = 0.017175

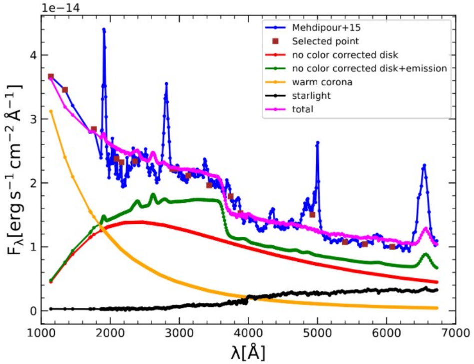






CLOUDY software for computations of the radiative trasfer in clouds and spectral shape of BLR



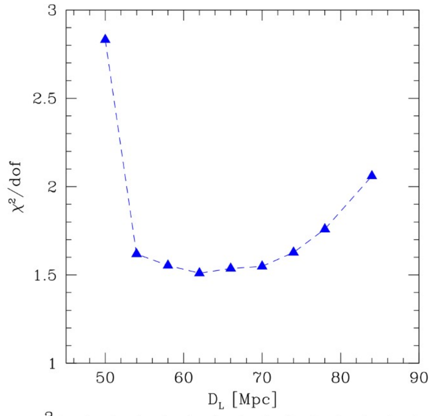


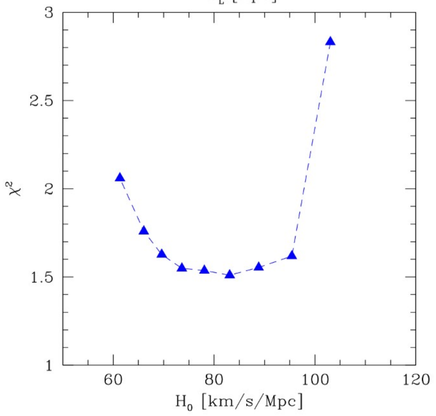
Jaiswal et al. 2025)

Our method - AGN continuum time delay

Results for NGC 5548: H0 = $79.8^{+5.5}_{-16.4}$ km/s/Mpc

We will try to improve the fitting accuracy for this source, as well as to apply our method to other sources with available data.





Most of the methods I discussed still need to improve the accuracy, and the number of targets. New measurements are expected from the incomming survey data (e.g. Vera Rubin LSST).

Interesting last comment

Perivolaropoulos (2025) – Abstract:

Statistical analysis reveals a significant distinction between the two samples. The distance ladder-based sample yields a best fit $H_0 = 72.8 \pm 0.5$ km s^{-1} Mpc^{-1} with $\chi^2/dof = 0.51$ indicating some correlations. The one-step measurements result in $H_0 = 69.0 \pm 0.48$ km s^{-1} Mpc^{-1} with $\chi^2/dof = 1.37$ indicating some internal tension.

With incoming new data (thousands of AGN, for example) systematic errors in each method will be a key issue.

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Thank you!