Cosmic Distance Scale Summary

- Local measurements of the H_0 are now good to $\approx$5%, and may be improved in the future
- Concept of distance ladder; many uncertainties & calibration problems, model dependence, etc
- Cepheids as the key local distance indicator
- SNe as a bridge to the far-field measurements
- Far-field measurements (SZ effect, lensing, CMB)
- Ages of oldest stars (globular clusters), white dwarfs, heavy elements consistent with CMB age
- CMB provides more precise determinations of the H_0 and other cosmological parameters.
- However, **persistent discrepancy between the CMB based & Cepheid based measurements**.

This may be a sign of a new physics.

XIV. A. 1929 Hubble's Original Observations Galaxy Recession & Hubble Constant Calculation

The relationship between the expansion of the universe & the distance, H_0, was discovered by Edwin Hubble in 1929 from astronomical observations of Cepheid Variables, and is known as Hubble's Law. Hubble estimated velocity from redshift, z, where He assumed that z = v/c. The distance, d, is measured from parallax or a luminosity of a standard candle.Then $\mathbf{v = H_0 * r}$. Hubble thought that the redshift, z, was from the Doppler effect, v/c. He estimated the value of H_0 as 500 km/s per Mpc. Which is grossly in error because he **underestimated the distance to the galaxies**. The large number from the redshift velocity divided by a too small distance. Note: H = r/v. Therefore H is the reciprocal of time from expansion.

$$H_{HubbleData} := READPRN(\text{"Hubble Dataset.txt"})$$

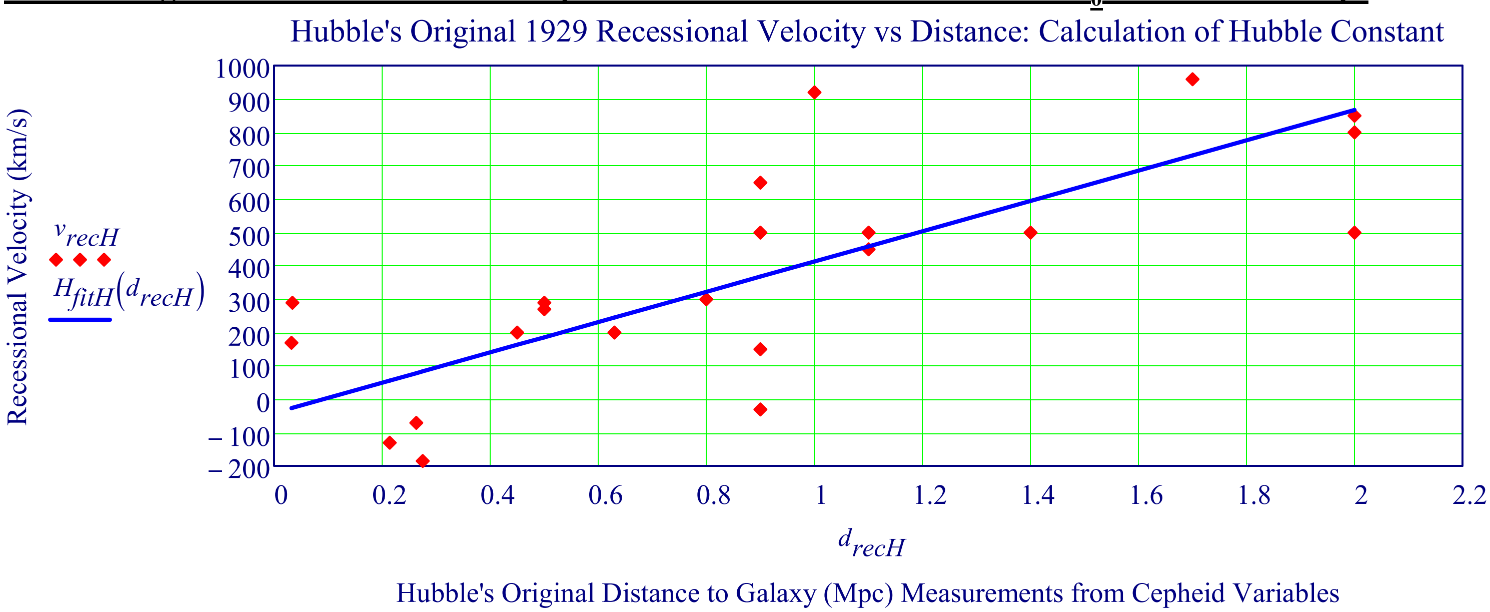
Distance Data (Mpc) | **Recessional Velocity (km/s) Data from Redshift, r**

$$d_{recH} := H_{HubbleData}^{\langle 0 \rangle} \qquad v_{recH} := H_{HubbleData}^{\langle 1 \rangle}$$

$$ab4 := line(d_{recH}, v_{recH}) \qquad H_{fitH}(d) := ab4_0 + ab4_1 \cdot d$$

$$H_{Hubble} := ab4_1 \qquad H_{Hubble} = 500 \frac{km}{s} \cdot Mpc^{-1}$$

Hubble's original estimate estimate from Cepheids was in error. The current value is H_0 is 73 ± 1 km/sec/Mpc



The Physical Meaning of the Hubble Constant in terms of Expansion Rate per Distance:
The Hubble constant tells us how quickly any two distant points in the universe are moving apart per unit distance. For example, if H_0 equals 2.3 *10^{-18} m s^{-1} , it means that for every meter between two points, the separation increases by 2.3 *10^{-18} meters per second.

<u>Standard Candle #2:</u> Type Ia supernova For example, **all observations seem to indicate that Type Ia supernovae that are of known distance have the same brightness** (corrected by the shape of the light curve); however, the possibility that the distant Type Ia supernovae have different properties than nearby Type Ia supernovae exists. The use of Type Ia supernovae is crucial in determining the correct cosmological model. If indeed the properties of the Type Ia's are different at large distances, i.e. if the extrapolation of their calibration to arbitrary distances is not valid, ignoring this variation can dangerously bias the reconstruction of the cosmological parameters.

$parsec := 3 \cdot 10^{13} \cdot km$ $\qquad Mpc := 3 \cdot 10^{19} km$ $\qquad v = H_0 \cdot r$ $\qquad H_0 := 73 \frac{km}{s} \cdot (Mpc)^{-1}$

NASA/IPAC EXTRAGALACTIC DATABASE of Type IA Supernova (3645 Distance Measurements)

Read Data for 3,716 distances to 1,210 galaxies with v < 1/8 c

https://ned.ipac.caltech.edu/level5/NED1D/ned1d.html

$H_{NASA} := READPRN(\text{"Galaxy NED-1D d \& v Only.txt"})$

Number of Data Points

$rows(H_{NASA}) = 3645$

Galaxy Luminal Distance (Mpc)	Recessional Velocity (km/s)	Redshift z	Corrected for Redshift
$d_{rec} := H_{NASA}^{\langle 0 \rangle}$	$v_{rec} := H_{NASA}^{\langle 1 \rangle}$	$z := \frac{v_{rec} \cdot km}{c \cdot s}$	$d_{recz} := \overrightarrow{\frac{d_{rec}}{1+z}}$

Current Estimate of Hubble's Constant:

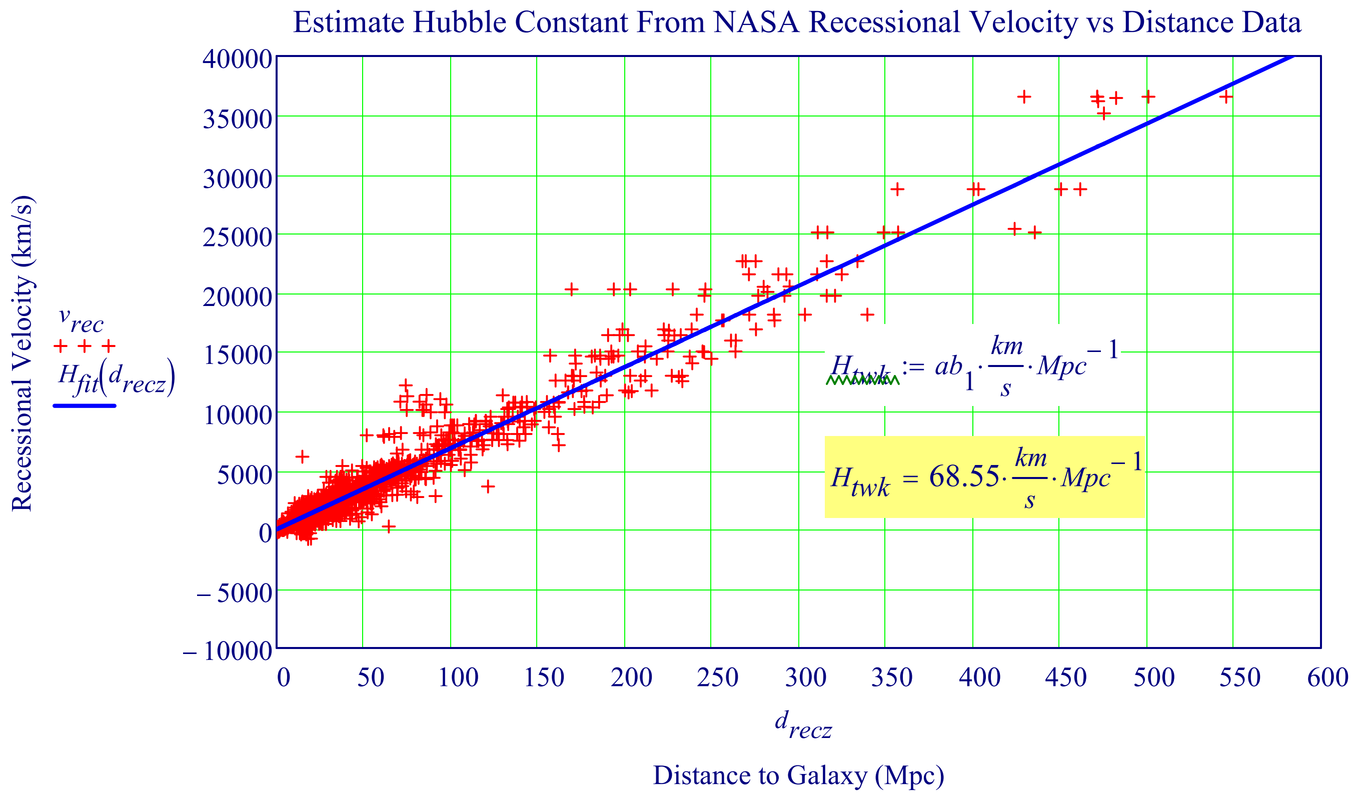
Find Slope of Recessional Velocity (km/s) to Corrected Distance (Mpc)

Fit Line to Data: $ab := line(d_{recz}, v_{rec})$ $\qquad H_{fit}(d) := ab_0 + ab_1 \cdot d$ $\qquad ab_0 = 23.882$

$H_{twk} := ab_1 \cdot \frac{km}{s} \cdot Mpc^{-1}$

Calculated H_{twk} within less than a 2% Error.

$H_{twk} = 68.55 \cdot \frac{km}{s} \cdot Mpc^{-1}$



Standard Candle 2: *Hubble Space Telescope Light Curves Of Type 1a SN*

Supernova Cosmology Project

"Amanullah et al. (The Supernova Cosmology Project), Ap.J., 2010
https://supernova.lbl.gov/Union/figures/SCPUnion2_mu_vs_z.txt

$q_0 := -0.53$

$mu\_z := READPRN(\text{"mu\_vs\_z - No Name No OL.txt"})$ $\quad mu\_z := csort(mu\_z, 0)$ $\quad z_{mu} := mu\_z^{\langle 0 \rangle}$

Fit Straight Line, Fit(z), to Data: $\chi := line\left(log(z_{mu}), mu\_z^{\langle 1 \rangle}\right)$ $\quad Fit(z) := \chi_0 + \chi_1 \cdot z$

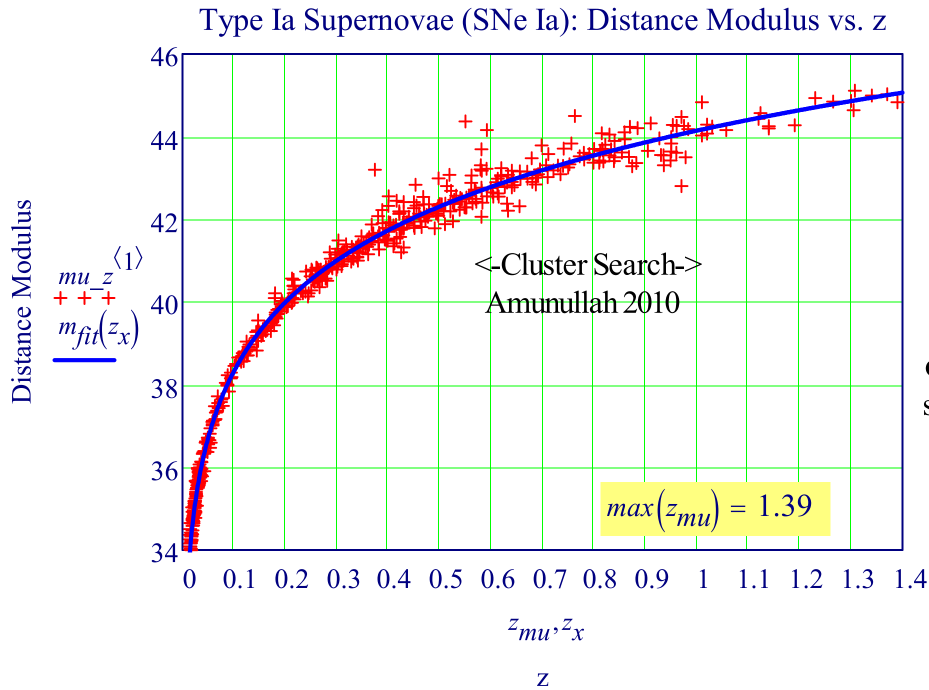
Power Function Fit

$m_{fit}(z) := a \cdot z^b + c$

Modern Version of the SN Hubble Diagram

The solid line represents the best fitted cosmology for a flat Universe including the CMB and BAO constraints.

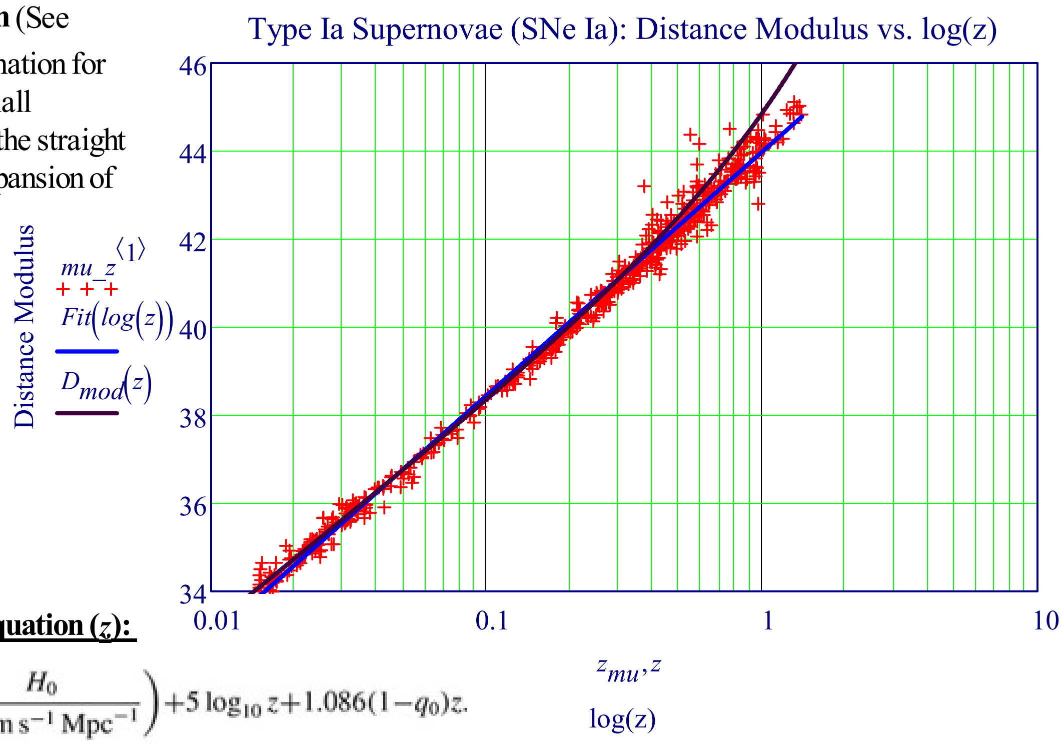
Distance Modulus vs Redshift for Type Ia Supernovae



Type Ia Supernovae are believed to be caused by the thermonuclear explosions of a carbon-oxygen white dwarf in a binary system. The process involves mass transfer to the white dwarf from the companion. When the white dwarf reaches the Chandrasekhar mass, the explosion occurs. **Since the explosions occur at the same mass**, the explosions should be **nearly identical**. Furthermore, luminosity evolution should not occur since the **physics of the explosion is the same in the past.**

Fit a Line to Modern Version of Hubble Diagram

$D_{mod}(z)$ is Ryden's Equation (See below), which is an approximation for the Distance Modulus for small redshift. The deviation from the straight line Fit(z) tells us that the expansion of the universe is **speeding up**.



Ryden's Distance Modulus Equation (z):

$$m - M \approx 43.23 - 5\log_{10}\left(\frac{H_0}{68\ \mathrm{km\,s^{-1}\,Mpc^{-1}}}\right) + 5\log_{10} z + 1.086(1 - q_0)z.$$

B. Reconstructing Cosmic History: *JWST-Extended Mapping of the Hubble Flow from z~0 to z~7.5 with HII Galaxies* https://arxiv.org/html/2404.16261v1

Abstract

Over twenty years ago, Type Ia Supernovae (SNIa) observations revealed an accelerating Universe expansion, suggesting a significant dark energy presence, often modelled as a cosmological constant, Λ. Despite its pivotal role in cosmology, the standard ΛCDM model remains largely underexplored in the redshift range between distant SNIa and the Cosmic Microwave Background (CMB). **This study harnesses the James Webb Space Telescope'**s advanced capabilities to extend the Hubble flow mapping across an unprecedented redshift range, from $z \approx 0$ to $z \approx 7.5$. Utilising a dataset of 231 HII galaxies and extragalactic HII regions, we employ the $L-\sigma$ relation, correlating the luminosity of Balmer lines with their velocity dispersion, to define a competitive technique for measuring cosmic distances. This approach **maps the Universe's expansion over more than 12 billion years, covering 95% of its age**. Our analysis, using Bayesian inference, constrains the parameter space

$$\{h, \Omega_m, w_0\} = \{0.731 \pm 0.039, 0.302^{+0.12}_{-0.069}, -1.01^{+0.52}_{-0.29}\}$$

(statistical) for a flat Universe. These results provide new insights into cosmic evolution and suggest uniformity in the photo-kinematical properties of young massive ionizing clusters in giant HII regions and HII galaxies across most of the Universe's history.

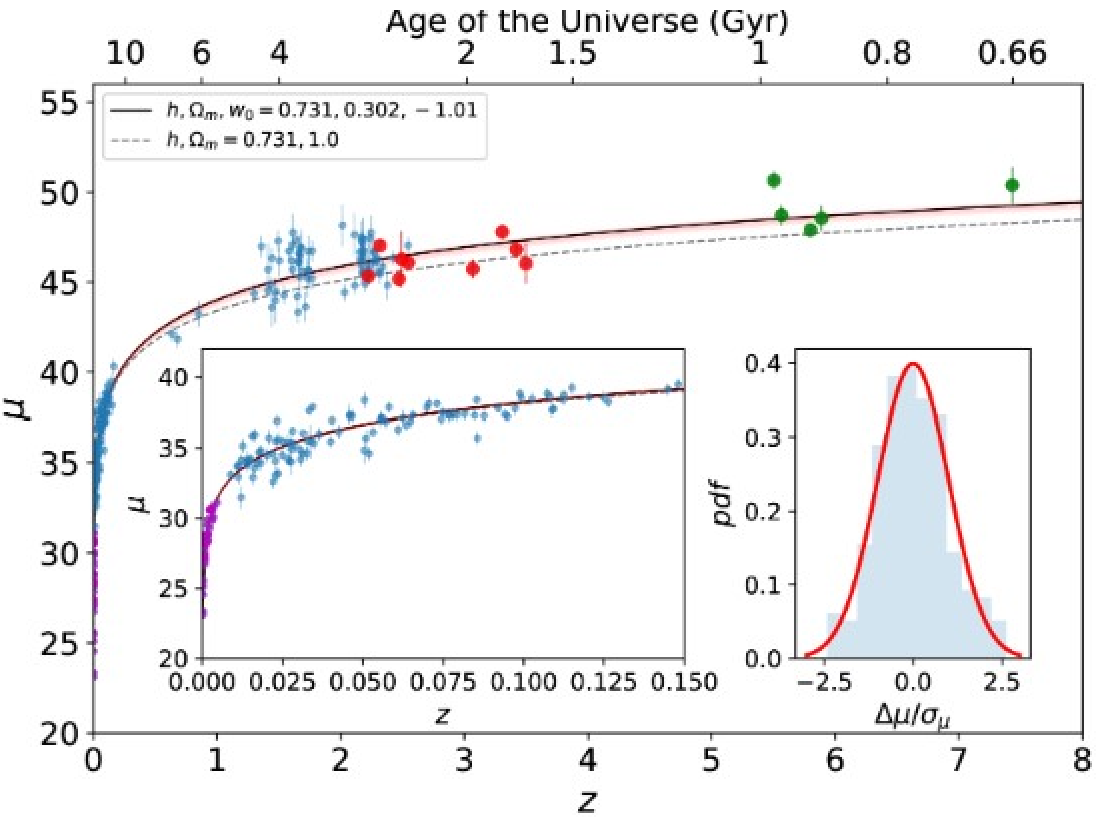
In the pursuit of a more versatile analysis framework, we have also established an h-free likelihood function. This involves a **rescaling of the luminosity distance (d_L)** through the introduction of a **dimensionless luminosity distance**, $D_L(z,\theta)$, defined as:

$$D_L(z,\theta) = (1+z)\int_0^z \frac{dz'}{E(z',\theta)}$$

In this formulation, d_L is expressed as $d_L = cD_L/H_0$. This rescaling technique is employed to ascertain cosmological parameters independently of the Hubble constant. Here $E(z,\theta)$ for a flat Universe is given by:

$$E^2(z,\theta) = \Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_w(1+z)^{3y}\exp\left(\frac{-3w_a z}{1+z}\right)$$

with $y = (1 + w_0 + w_a)$ and Ω_r the radiation density parameter such that we can define $\Omega_w = 1 - \Omega_m - \Omega_r$



Overview of the Rungs of the Cosmic Distance Ladder

1. Geometric Methods (Nearby)

Parallax

The most fundamental method. As Earth orbits the Sun, nearby stars shift slightly against background stars.
Works reliably out to a few thousand light years (Gaia extends this to hundreds of millions of stars).
Radar ranging Distances within the solar system are measured by bouncing radio signals off planets.

2. Standard Candles in the Milky Way

Cepheid Variable Stars

Their pulsation period is directly related to intrinsic luminosity. Calibrated by parallax.

RR Lyrae Variables

Fainter but numerous, useful for globular clusters and nearby galaxies.

3. Extragalactic Standard Candles

Type Ia Supernovae

Explosions of white dwarfs reaching a critical mass. They have nearly uniform peak luminosity, making them "standardizable candles." Used out to redshifts z ~ 1–2.

Tip of the Red Giant Branch (TRGB)

The brightness of the brightest red giants is nearly constant; good for nearby galaxies.

4. Standard Rulers

Baryon Acoustic Oscillations (BAO)

Imprints from sound waves in the early universe provide a "standard ruler" visible in the large-scale distribution of galaxies.

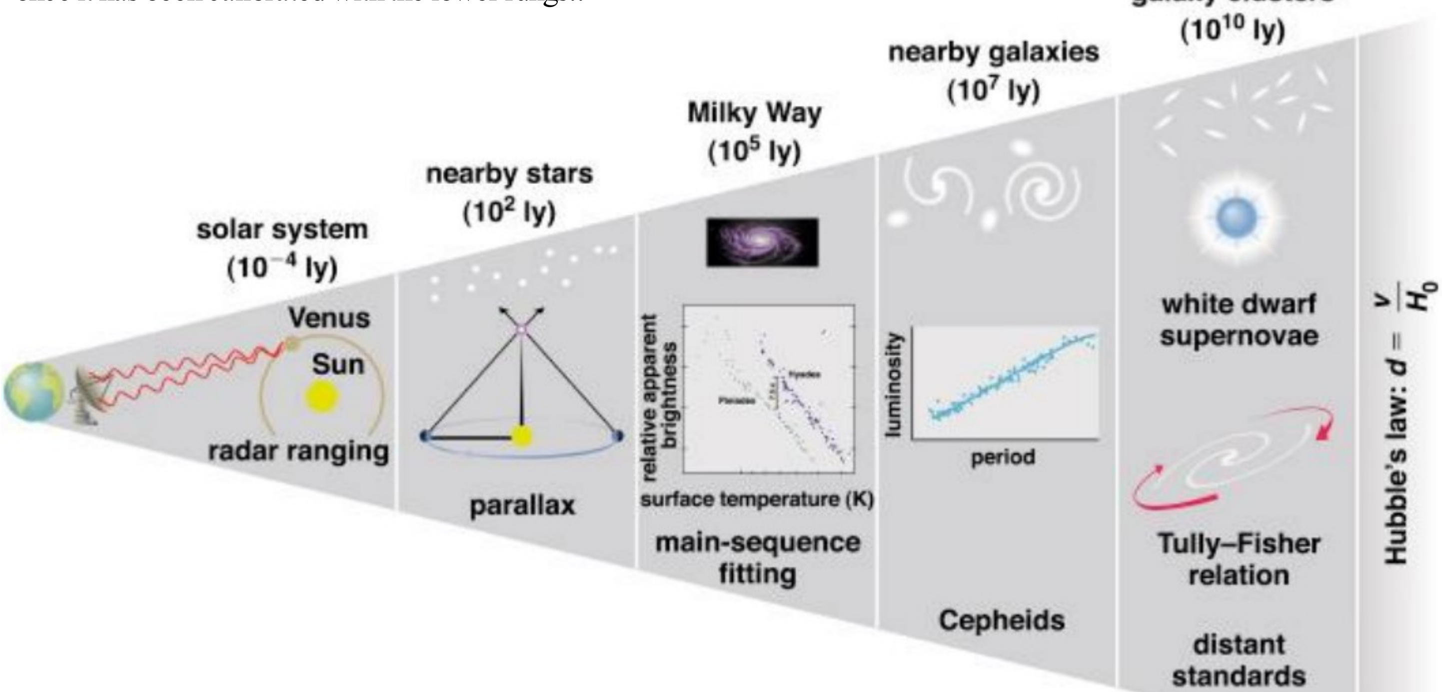
CMB Acoustic Peaks

Fluctuations in the CMB at $z \approx 1100$ encodes the size of the sound horizon, a fundamental calibration scale.

5. Redshift–Distance Relation

Hubble's Law

Beyond a few hundred million light years, galaxies' redshift can be related to distance via the Hubble constant, once it has been calibrated with the lower rungs..



Three Redshift, z, regimes that can be used to determine the Hubble Constant

1. Low-Redshift Hubble Law (Linear Regime)

The original Hubble's Law is:

$$v = H_0\, d \quad \text{or} \quad z \approx \frac{H_0 d}{c} \quad \text{for small } z$$

This relation is strictly linear only for $z \lesssim 0.1$.

At higher redshift, cosmological effects (dark energy, matter density, curvature) change the relation between redshift and distance, so assuming a simple linear Hubble law introduces systematic errors.

👉 Largest redshift for "direct" Hubble Law use: about $z \approx 0.1$ (sometimes $z \approx 0.2$ at most).

2. Intermediate Redshifts ($0.1 \lesssim z \lesssim 2$)

Beyond $z \sim 0.1$, the Universe's expansion history deviates from a straight line. To determine H_0 at these distances, one **must assume a cosmological model** (ΛCDM, with Ω_m, $\Omega\Lambda$, etc.). Methods like Type Ia supernovae or BAO (Baryon Acoustic Oscillations) use model-dependent fitting of the expansion curve to infer H_0.

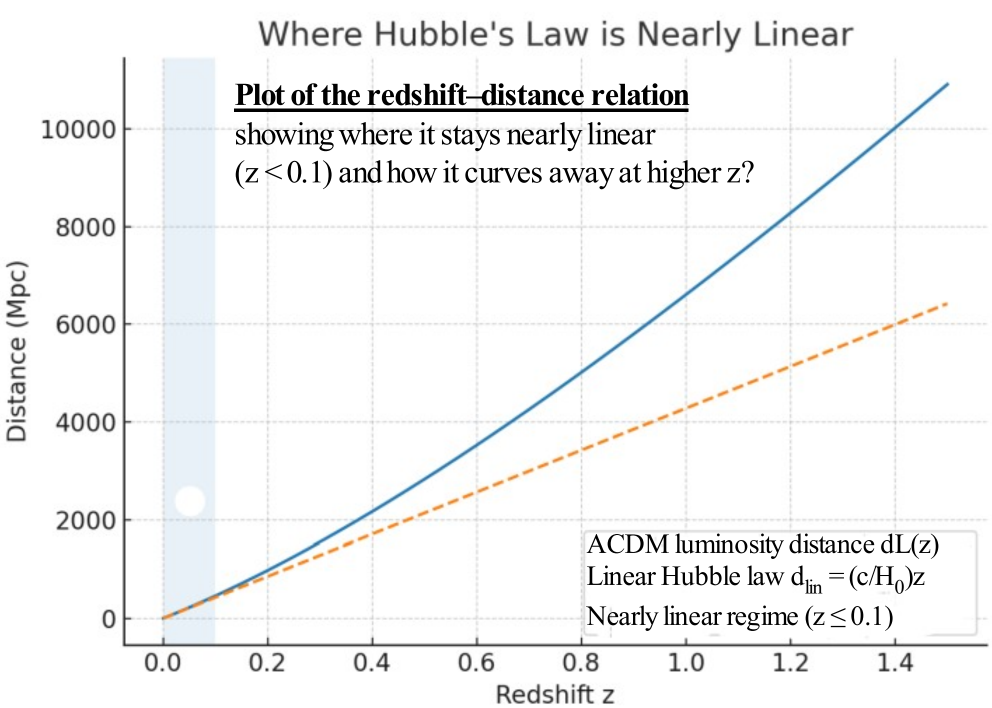
3. High Redshift ($z \gtrsim 1000$, CMB)

The Cosmic Microwave Background (CMB, $z \approx 1100$) is often used to measure H_0, but this requires assuming a full cosmological model and extrapolating forward to today's expansion. This is not a "direct" measurement of H_0, but an indirect, **model-dependent inference**.

Summary:

Direct Hubble Law (linear): reliable only for $z \lesssim 0.1$.
Intermediate z (0.1–2): requires ΛCDM assumptions (supernovae, BAO).
Very high z (CMB at $z \sim 1100$): indirect inference, strongly model-dependent.
plot of the redshift–distance relation showing where it stays nearly linear ($z < 0.1$) and how it curves away at higher z?

So the largest redshift for using Hubble's Law in its simplest, nearly linear form is about $z \sim 0.1$.
If one allows cosmological modeling, then effectively any redshift can be used—including $z \approx 1100$ from the CMB.

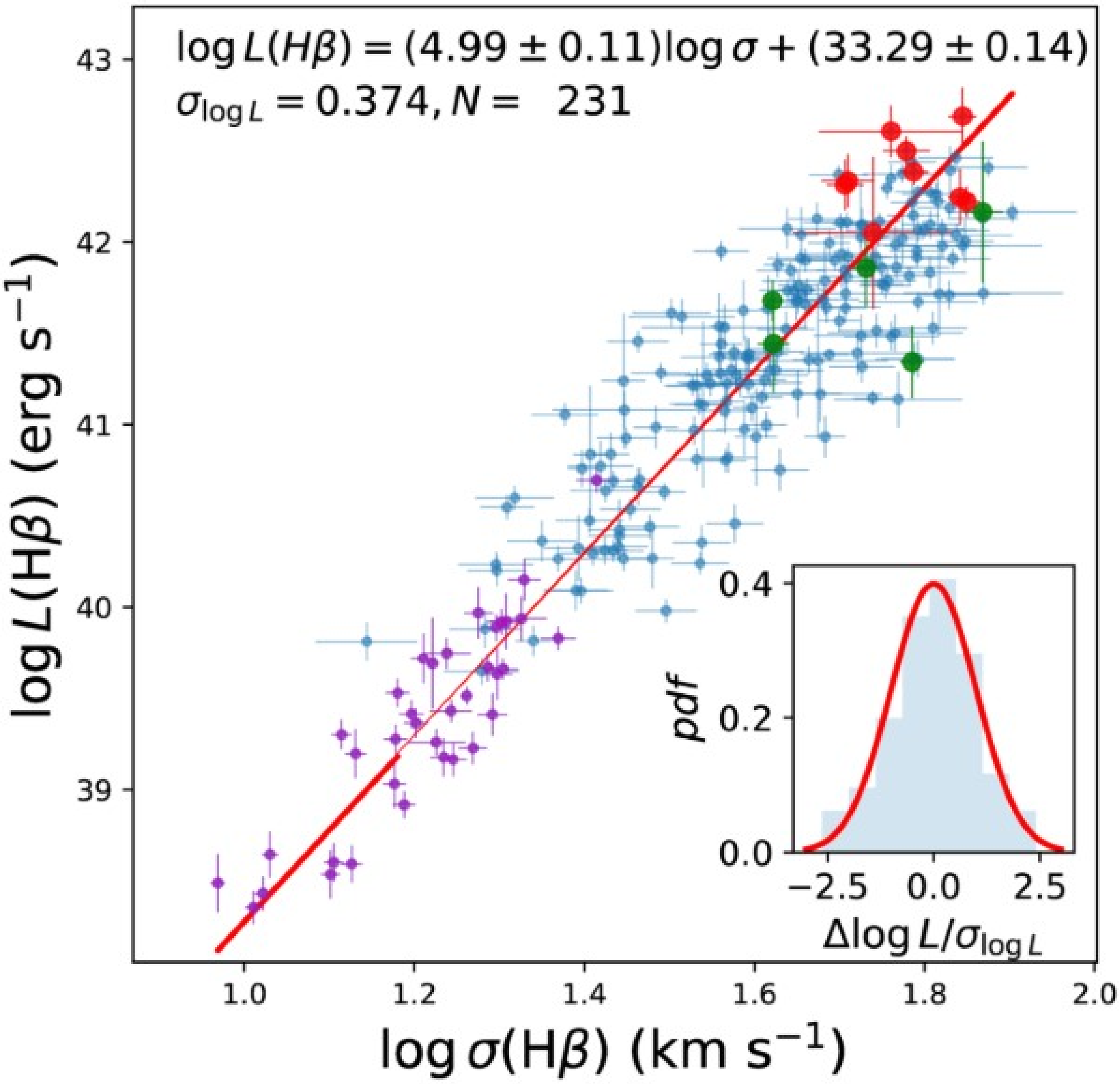


Deviation from linear Hubble law
(ΛCDM, H_0=70, Ω_m=0.3, Ω_Λ=0.7)

z	d_L (Mpc)	Linear d (Mpc)	Fractional deviation
0.02	87	85.655	0.01539
0.05	222	214.137	0.03807
0.1	460	428.275	0.07478
0.2	980	856.55	0.1442
0.5	2833	2141.37	0.32295
1	6608	4282.75	0.54285
1.5	10910	6424.12	0.69823

Above Figures:

Hubble diagram for GEHRs and HIIGs, here z is the redshift and μ is the distance modulus. In magenta we present the 'anchor' sample of 36 GEHRs which have been analysed in [26], in blue we present the full sample of 181 HIIGs which have been analysed in [18], **while in red we present the 9 new HIIGs** from [27] and in **green the 5 new HIIGs studied with JWST** by [28]. The black line is the cosmological model that best fits the data with the red shaded area representing the 1σ uncertainties to the model, while the grey dashed line is a flat cosmological model without dark energy. The inset at the left shows a close-up of the Hubble diagram for $z \leq 0.15$. The inset at the right presents the pulls probability density function (pdf) of the entire sample of GEHRs and HIIGs and the red line shows the best Gaussian fit to the pdf.



The $L-\sigma$ relation of GEHRs and HIIGs. The data points follow the same color code for the different samples as in the previous figure. The red line shows the best linear fit to the data, including the uncertainties in both axis. At the top of the figure we present the values of the slope and intercept of the best fit including their uncertainties. We also show the standard deviation of the ***log L*** around the best fit and the total number of objects in the sample. The inset shows the pulls distribution of the entire sample of GEHRs and HIIGs and the red line shows the best Gaussian fit to the distribution.

[18] González-Morán, A. L. et al.Independent cosmological constraints from high-z H II galaxies: new results from VLT-KMOS data.MNRAS 505, 1441–1457 (2021).

[26] Fernández Arenas, D. et al.An independent determination of the local Hubble constant.MNRAS 474, 1250–1276 (2018).

[27] Llerena, M. et al.Ionized gas kinematics and chemical abundances of low-mass star-forming galaxies at z ~ 3.A&A 676, A53 (2023).

C. Using Gravitational Waves to Find Hubble's Constant, Hg

The gravitational wave signal emitted by the merger of two compact objects can be used as a self-calibrating standard candle. Unlike the methods to Measure the Hubble Constant, $H_{0,}$ in the followings Section X, the LIGO measurement does not use a "distance ladder". By detecting gravitational waves from merging binary neutron stars or black holes, LIGO can provide a measurement of the distance to the source and the rate at which it is movingaway from us. There are now operational detectors at LIGO Hanford and LIGO Livingston in the USA, Virgo in Italy, and KAGRA in Japan. The detectors measure the strain amplitude of a gravitational wave by using laser inferometry to detect the minuscule changes in the length of perpendicular beams as a wave passes by. The purpose of the two sites in the USA is to later out local seismic vibrations. The wave amplitude is related to the chirp mass M_c which is in turn derivable from the waveform calculated for a merger. A implied form of the relevant equations are:

For Definitions of Parameters See Sections V, VII, XII, XXIC, XXID.

Compare the Theoretical Magnitude-Redshift to Perlmutter 1999 SB 1A

Given the Luminosity Red Shift Relation (for k > 0):

$$D_L(z) = \frac{c\,(1+z)}{H_0\sqrt{\Omega_K}} \sinh\left[\sqrt{\Omega_K}\int_0^z \frac{H_0}{H(z')}\,dz'\right]$$

$$m_{bol}(z,\Omega_m) := 5\log(1+z) + 5\log(\chi_{em}(z,\Omega_m)) + 24$$

LIGO Parameters

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = \frac{1}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3}\dot{f}\right]^{3/5}$$

$$\mathcal{M}_z = (1+z_{\text{obs}})\mathcal{M}$$

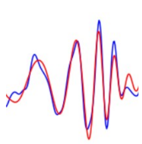
$$h(t) = \frac{\mathcal{M}_z^{5/3} f(t)^{2/3}}{d_L} F(\theta, i)\cos\Phi(t)$$

where the Luminosity Distance, $D_L(z)$ is given as the red shift integral of the Hubble parameter $H(z)$, and the Hubble constant H_0. f is the frequency, m_1 and m_2 the merging masses, $\Phi(t)$ the phase, and Rh(t) the measured dimensionless strain of the strongest harmonic (Abbott et al. 2016). The rest-frame chirp mass is red shifted by zcobs, and F is a function of the angle between the sky position of the source and detector arms, and the inclination I between the binary orbital plane and line of sight.

The LIGO-Virgo detector network had a detection horizon of ~ 190 Mpc for binary neutron star (BNS) events (Abbott et al. 2017a), For example, the counterpart associated with GW170817 had brightness ~ 17 mag in the I band at 40 Mpc

When a **binary neutron star** (BNS) system merges, there is an **accompanying burst of light from matter outside** the combined event horizon. For this reason, it is known as a "**bright siren**". If the ash can be observed, the host galaxy is identified and one can use its redshift in the above equation.

The **event GW170817** was just such a BNS merger. Given the search region, an optical counterpart was found in NGC 4993 at a distance, d_L, of ~ 40 Mpc. Around f_c = 3000 cycles of the wave resolved the chirp mass in the detector frame as $M_c = 1.197\,M_\odot$ to accuracy of 1 part in 10^3, consistent with a BNS merger. The main remaining uncertainty is then the inclination angle I. The Black Hole Merger, GW150914, was 1.3 Billion Light-Years away.



$$f_c = 3000\,Hz$$
$$M_z = 1.197\,M_\odot$$
$$d_L = 43.8\,Mpc$$

$$H_g = H_g(M_z, f, d_L, F, \Phi)$$

This Gives: $H_g = 70\,\frac{km}{s}\cdot Mpc^{-1}$

Abbott, B. P., et al. 2017a, PRL, 119, doi:10.1103/PhysRevLett.119.161101
—. 2017b, ApJL, 848, doi:10.3847/2041-8213/aa920c
—. 2017c, ApJL, 848, doi:10.3847/2041-8213/aa91c9

MEASURING THE EXPANSION OF THE UNIVERSE WITH GRAVITATIONAL WAVES
https://www.ligo.org/science/Publication-GW170817Hubble/flyer.pdf

D. Real Time Measurement of Cosmic Expansion Within Our Lifetime

A Measurement of the Cosmic Expansion Within our Lifetime, Fulvio Melia, arXiv:2112.12599v1

Methodology: Measurement of Spectroscopic Velocity Shifts - Redshift Drift

The goal is to measure Incremental Changes in red shift, δz, over a "short" time interval, δt. Because of the small magnitude of the drift of redshift with time, measurements must be made over many decades.

Introduction: Objects receding from us with the general Universal expansion become fainter with time, and their spectra are redshifted according to their distance. The rate at which these quantities change is characterized by the expansion speed and acceleration, but is scaled to the age of the Universe ($t_0 \approx 13.5$ Gyr), which is considerably longer than a human lifetime. It would therefore be farfetched to even consider ‘watching the Universe expand in real time. And yet, there is great interest at the prospect of actually measuring the evolving redshift of distant sources via a campaign lasting several decades. For example, using the European Extremely Large Telescope for observations.

Red Shift Drift

Cosmology today is based on the Friedmann-Lemaıtre-Robertson-Walker (FLRW) metric (**See Section IV**) for a spatially homogeneous and isotropic three-dimensional space, expanding or contracting according to a time-dependent expansion factor, ***a(t)***: This form of the FLRW metric is written using the coordinates of a comoving observer, for whom ***t*** is the cosmic time (and is the same everywhere), ***r*** is the comoving radius, which remains fixed for any source lacking so-called peculiar motion. Every physical distance in FLRW should be product of a fixed comoving radius ***r*** and ***a(t)***.

Cosmic Acceleration

The most reliable information on ***a(t)*** comes in EM waves, shifted in frequency, ν, by the combined effects of kinematic and gravitationally induced redshift effects. The null geodesic equation describing the propagation of such waves along the −ˆr direction, with fixed θ and φ, is obtained from the equation: $c\,dt = -a(t)\,dr$

Thus, an electromagnetic signal emitted at r_e, at time t_e, will reach the observer at time t_0 given by

$$\int_{t_e}^{t_0} \frac{dt}{a(t)} = r_e$$

See Section V. Distances in Cosmology

this equation tells us how t_0 changes as a function of t_e due to the evolution of $a(t)$ between these two times. For example, if we consider the emission and detection of two crests of the wave, one a t_e and t_0, and the second at

$t_e + \delta t_e$ and $t_0 + \delta t_0$, then

$$\int_{t_e+\delta t_e}^{t_0+\delta t_0} \frac{dt}{a(t)} = \int_{t_e}^{t_0} \frac{dt}{a(t)}$$

By definition: $z \equiv \frac{\lambda_0 - \lambda_e}{\lambda_e}$

Doppler Shift

$$1 + z = \sqrt{\frac{1+v/c}{1-v/c}}$$

substituting $\nu = c/\lambda$ and $\frac{\nu_e}{\nu_0} = \frac{\delta t_0}{\delta t_e}$, gives $1 + z = \frac{a(t_0)}{a(t_e)}$

this relation gives us the redshift corresponding to cosmic evolution over millions and billions of years. It is hardly useful as a probe of the change occurring over a mere human lifetime. It is necessary for us to derive from this Equation **an expression yielding the incremental changes in z expected during a much shorter time interval δt_0**.

Differentiating the above equation for $1+z$ with respect to the observer’s time δt_0, we find that

$$\frac{dz}{dt_0} = [1 + z(t_0)]H(t_0) - \frac{a(t_0)}{a(t_e)^2}\frac{da(t_e)}{dt_e}\frac{dt_e}{dt_0}$$

Given Hubble Parameter: $H(t) = \frac{1}{a(t)}\frac{da(t)}{dt}$ and $dt_0 = [1 + z(t_0)]\,dt_e$

this finally gives: $$\frac{dz}{dt_0} = (1+z)H_0 - H(z)$$

During a monitoring campaign, the surveys will measure the spectroscopic velocity shift, Δv, defined in terms of the redshift drift Δz over an observation time Δt. The goals is to measure spectroscopic velocity shifts of < 1 cm s^{-1} yr^{-1}. Then the redshift drift can then be used to determine the real time values of the standard ratios for mass, radiation and dark energy:

$$H\_H_{0\nu}(z, \Omega_m) := \sqrt{\Omega_m \cdot (1+z)^3 + \Omega_{r0} \cdot (1+z)^4 + \Omega_{\Lambda 0}}$$

Refer to Section V. Distances in Cosmology

For example, in the simplified approach of assuming a spatially flat Universe (i.e., $k = 0$) and dark energy in the form of a cosmological constant Λ (with $w_{de} = -1$),

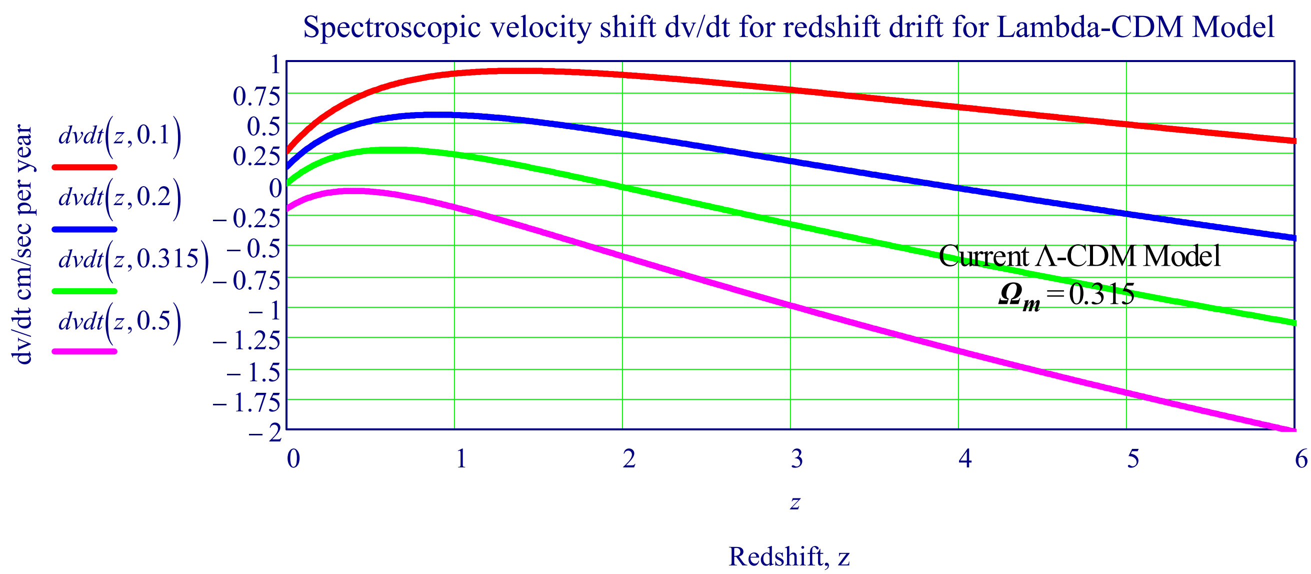
the monitoring of Δv should provide a direct measurement of Ω_m, and therefore of $\Omega_{de} \equiv \Omega_\Lambda = 1 - \Omega_m$.

To illustrate the potential for carrying out this groundbreaking work, we show in the Figure below the variation of $\Delta v/\Delta t$ (in units of cm s^{-1} yr^{-1}) with redshift and the matter density Ω_m.

$$dvdt(z, \Omega_m) := c \cdot \frac{\left[(1+z) - H\_H_{0\nu}(z, \Omega_m)\right] \cdot H_0}{(1+z) \cdot cm \cdot s^{-1} \cdot yr^{-1}}$$

Plot Below Shown *with Ω_m values of 0.1, 0.2, 0.315, and 0.5*

Example of How Measurement of Universe's Real Time Cosmic Expansion by Spectroscope drift can be used to Fit Cosmological Model Parameter Values to these Measurements of Cosmic Drift (Δv/Δt cm/sec /year)



Spectroscopic velocity shift $\Delta v/\Delta t$ associated with the redshift drift predicted by the Planck-ΛCDM model ($k = 0, \Omega_m = 0.315, H_0$ = 69.8 km s^{-1} Mpc^{-1} ; thick black line), and several variations with alternative values of Ω_m (indicated in the plot).

In every case, dark energy is assumed to be a cosmological constant, Λ, with $w_{de} = -1$ and $\Omega_\Lambda = 1 - \Omega_m$.

Notice, e.g., that the redshift drift with time is positive at low redshifts, and then turns negative or the more distant sources. This **unambiguous prediction by the standard model** is simply based on the temporal evolution of the matter (ρ_m) and dark-energy (ρ_{de}) densities, which sees the Universe dominated by ρ_m at z > 0.7, giving way to the latter towards the present. In ΛCDM, dark energy functions as an agent of acceleration, whereas a matter-dominated cosmos is always decelerating. Planck-ΛCDM has been quite successful in accounting for a broad range of cosmological observations, but careful scrutiny reveals several major fundamental problems with its theoretical foundation.

There are few instances in science when the anticipated impact of an experiment carries this much weight.