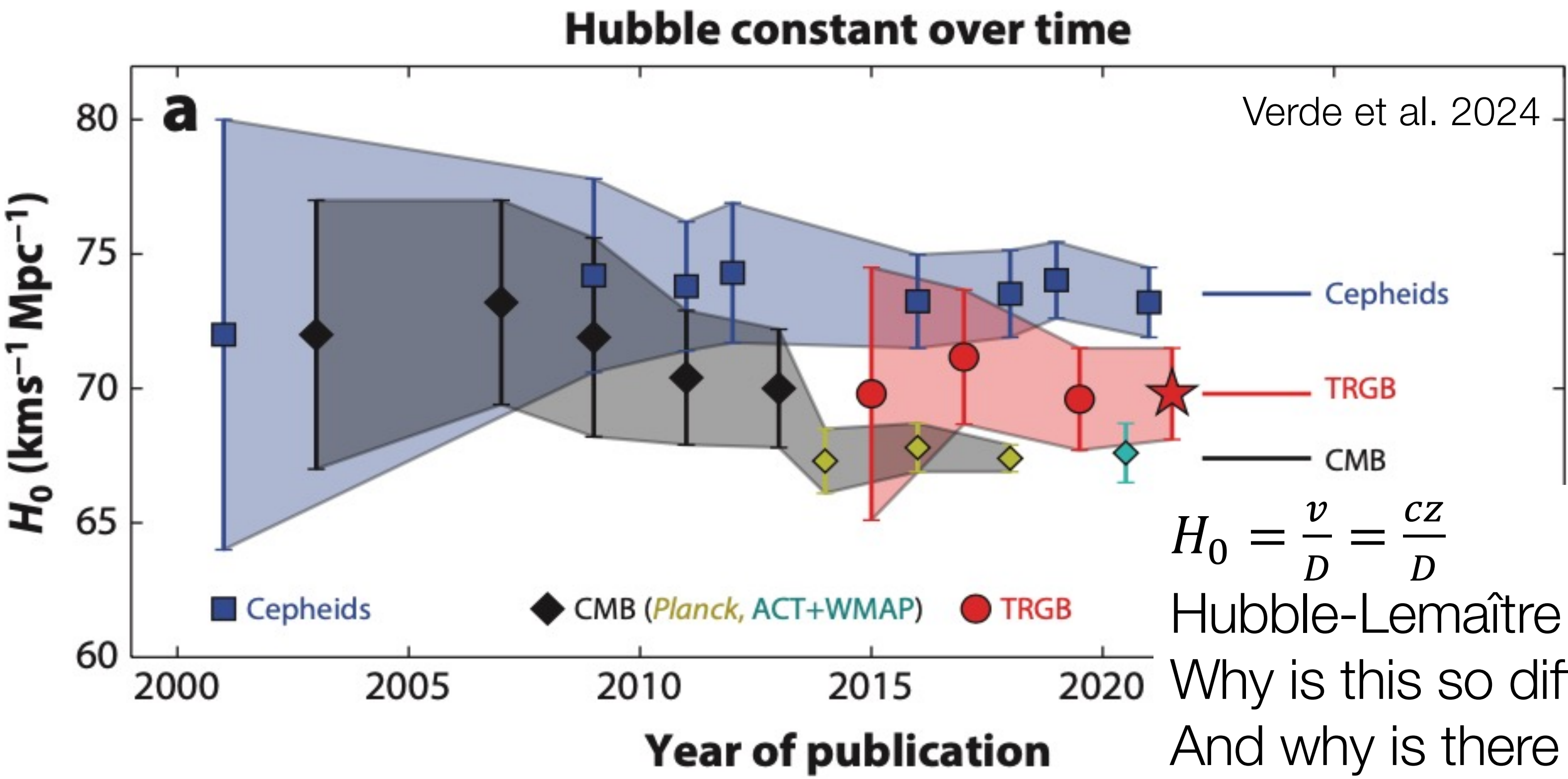
A new local pathway to the Hubble constant

Bruno Leibundgut
ESO and TUM
and the adH0cc Team


SHIPYARD
ENGINEERING TOOL

Hubble Tension – the problem



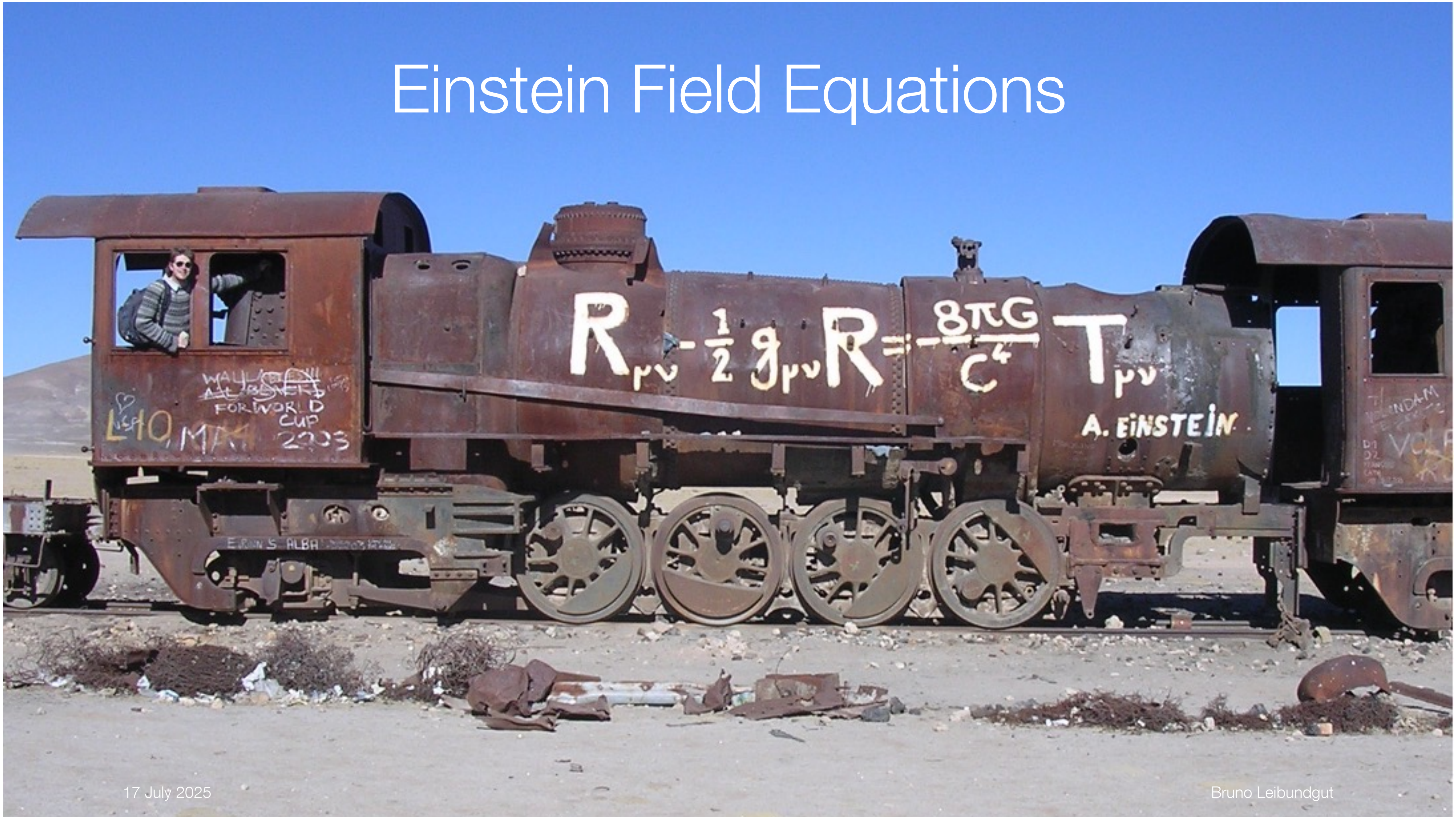
$$H_0 = \frac{v}{D} = \frac{cz}{D}$$

Hubble-Lemaître law

Why is this so difficult?

And why is there such a fuss?

Einstein Field Equations

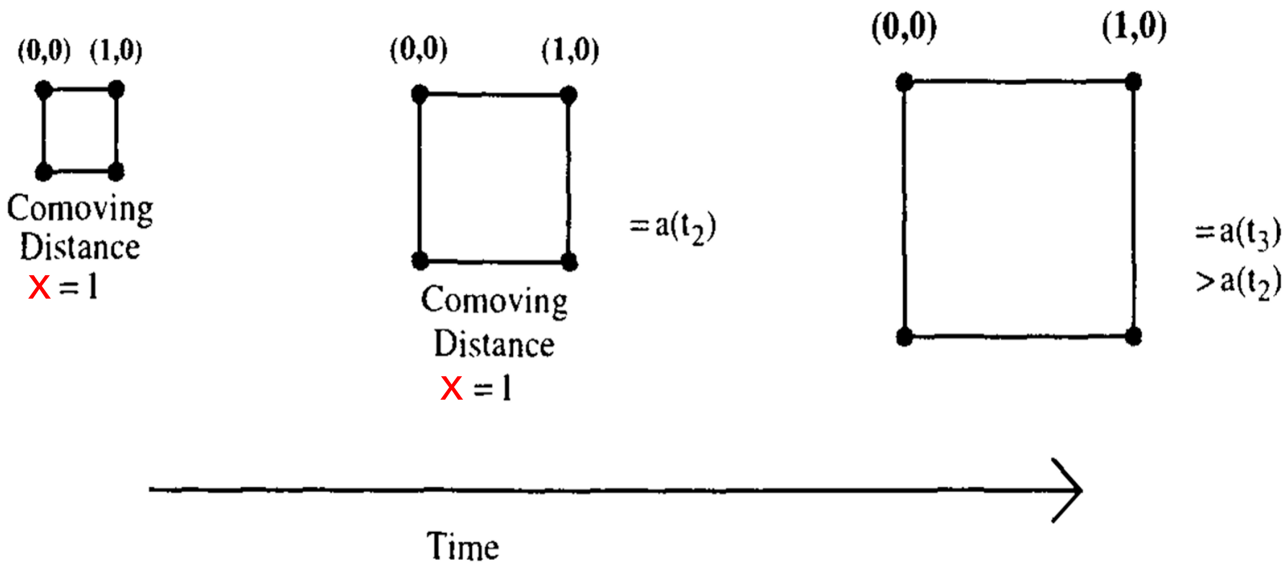


Dealing with an expanding Universe

Cosmic Distances

Separate the observed distances $r(t)$ into the expansion factor $a(t)$ and the fixed part x (called *comoving* distance)

$$r(t) = a(t)x$$



Friedmann Equation

Time evolution of the scale factor is described through the time part of the Einstein equations

Assume a metric for a homogeneous and isotropic universe and a perfect fluid

$$\frac{\dot{a}^2}{a^2} + \frac{k}{a^2} = \frac{8\pi G}{3}\rho(t)$$

$$g_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & a^2 & 0 & 0 \\ 0 & 0 & a^2 & 0 \\ 0 & 0 & 0 & a^2 \end{pmatrix}$$

$$T^{\mu\nu} = \begin{pmatrix} \rho c^2 & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix}$$

Friedmann Equation

Time evolution of the Einstein Equations

– (plus cosmological principle)

– (describe evolution of the scale factor a)

$$\frac{\dot{a}^2}{a^2} = H^2 = \frac{8\pi G}{3}\rho(t) - \frac{k}{a^2} = \frac{8\pi G}{3}\left(\rho_M + \rho_\gamma + \rho_{vac}\right) - \frac{k}{a^2}$$

Use the critical density $\rho_{crit} = \frac{3H_0^2}{8\pi G} \approx 2 \cdot 10^{-29}\ g\ cm^{-3}$

Define the ratio to the critical density $\Omega = \frac{\rho}{\rho_{crit}}$

Most compact form of Friedmann equation

$$1 = \Omega_M + \Omega_\gamma + \Omega_{vac} + \Omega_k$$ (with $\Omega_k = -\frac{k}{a^2 H^2}$)

Dependence on Scale Parameter

Different dependencies of the energy densities on the scale parameter a

$$\rho_M \propto a^{-3} \quad \rho_\gamma \propto a^{-4} \quad \rho_{vac} = const$$

Using critical densities leads to

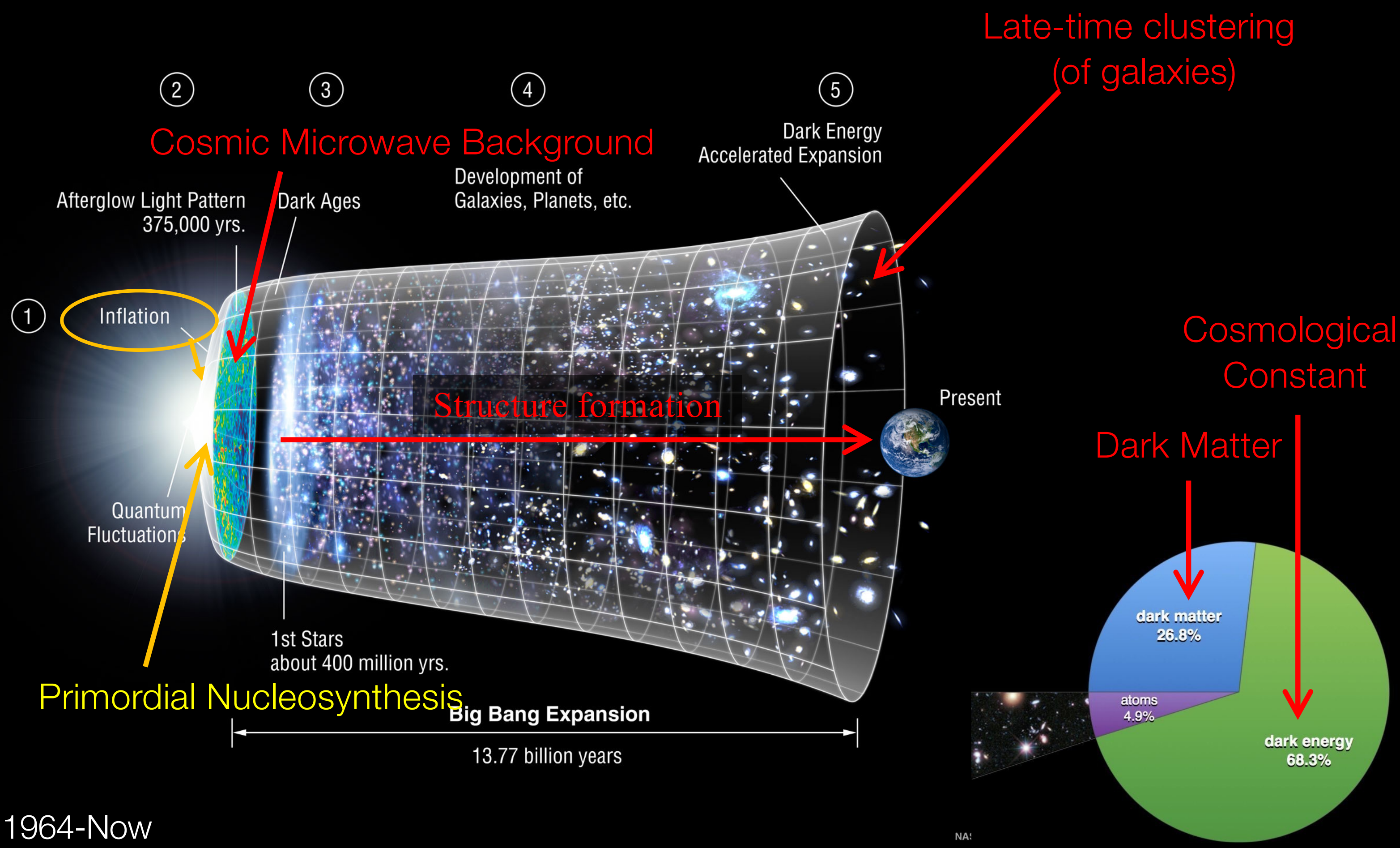
$$\rho(\mathrm{a}) = \frac{3H_0^2}{8\pi G}\left[\Omega_M \left(\frac{a_0}{a}\right)^3 + \Omega_\gamma \left(\frac{a_0}{a}\right)^4 + \Omega_\Lambda + \Omega_k \left(\frac{a_0}{a}\right)^2\right]$$

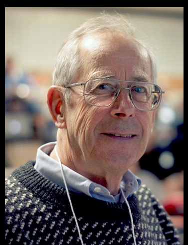
and the Friedmann equation

$$H^2 = H_0^2\left[\Omega_M (1+z)^3 + \Omega_\gamma (1+z)^4 + \Omega_\Lambda + \Omega_k (1+z)^2\right]$$

with $\left(\frac{\mathrm{a_0}}{\mathrm{a}} = 1 + \mathrm{z}\right)$

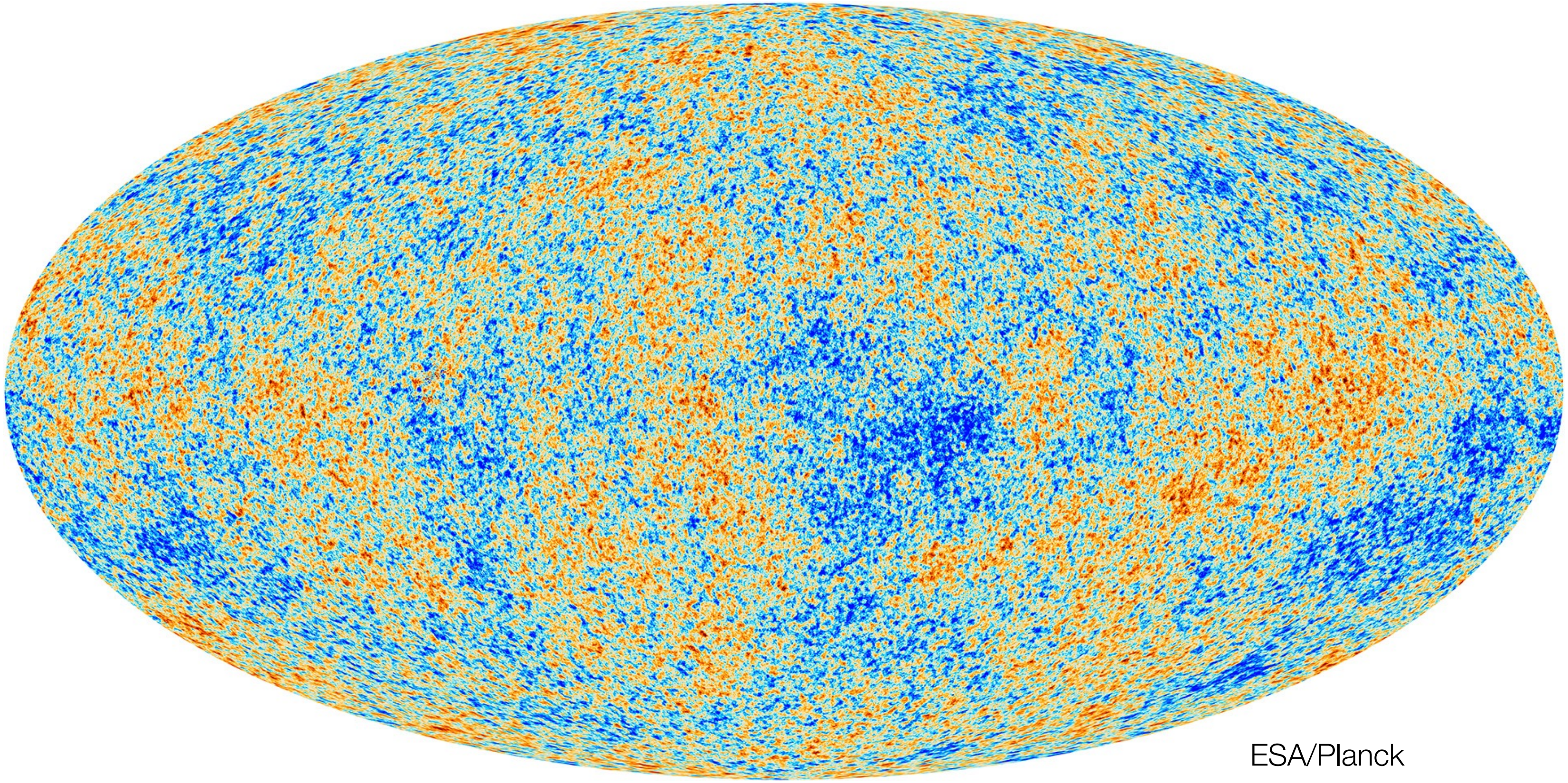
The Evolution of the Universe – The ΛCDM Model





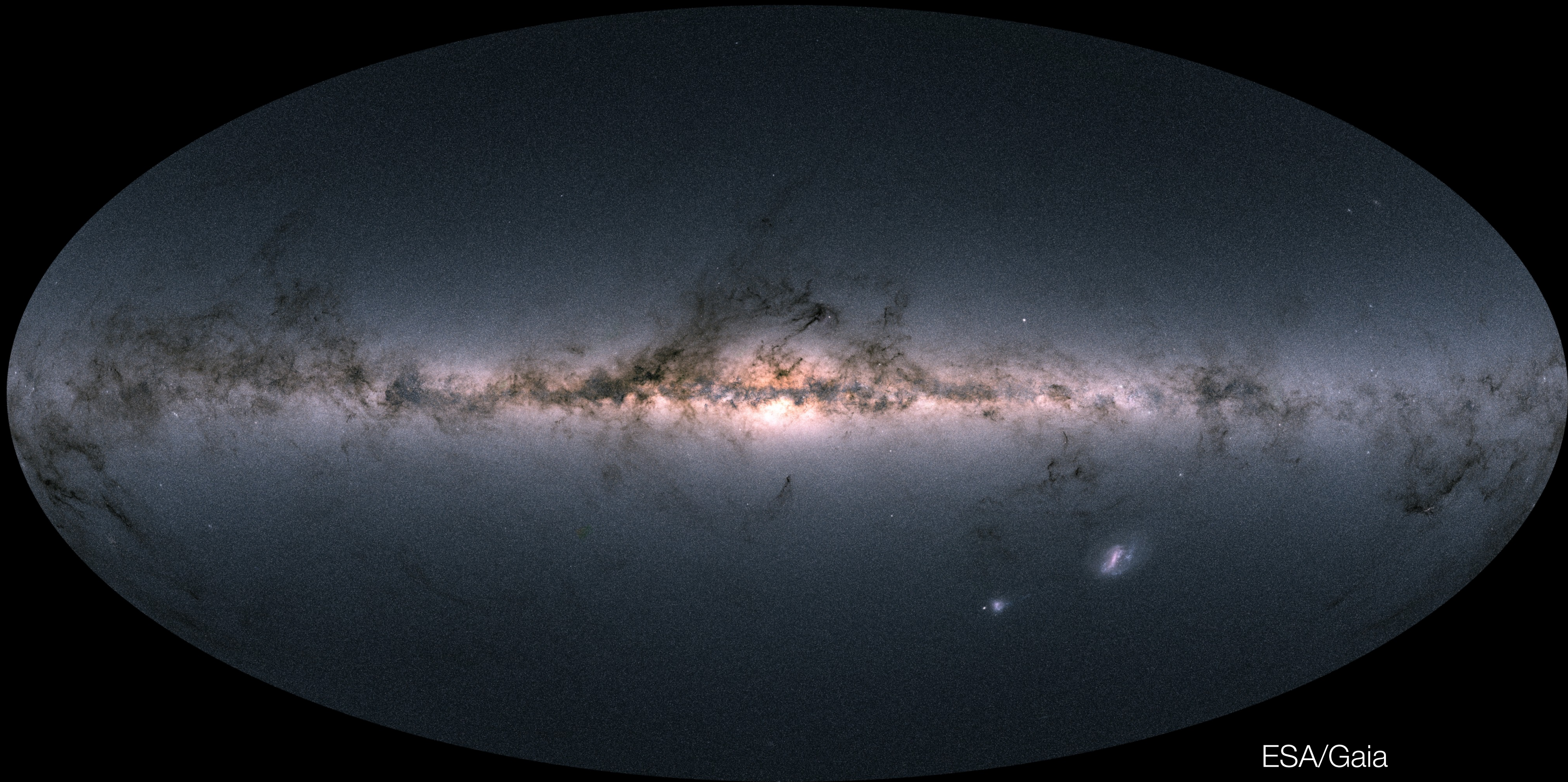
Years active: 1964-Now

The Universe 300000 years after the Big Bang



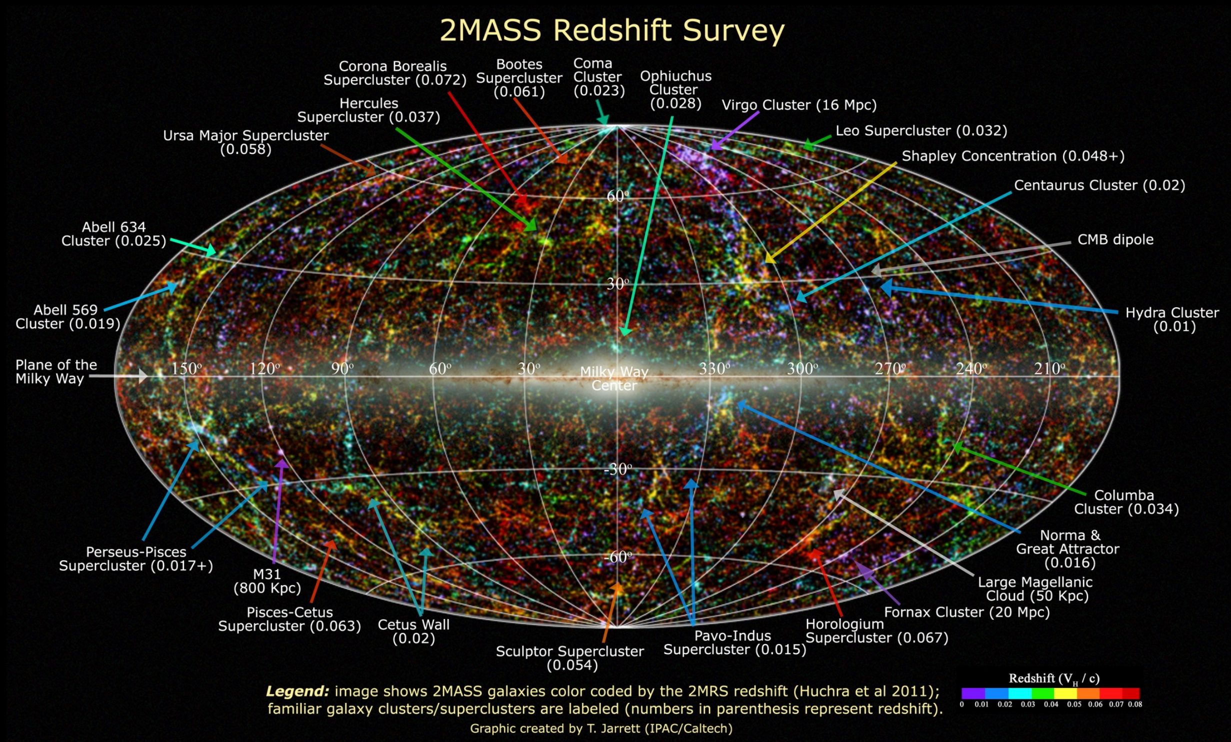
ESA/Planck

The Universe today

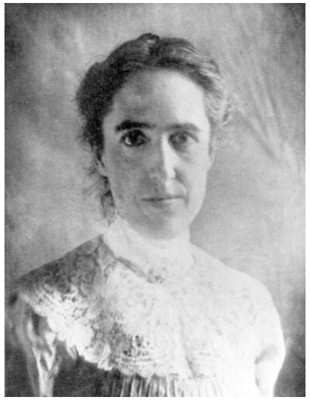

ESA/Gaia

Extragalactic Distances

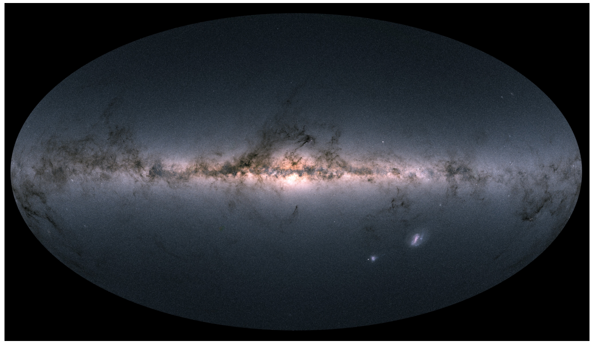
Required for a 3D picture of the (local) universe



Cepheid Stars



Wikipedia



Henrietta Swan Leavitt discovered the Period-Luminosity relation

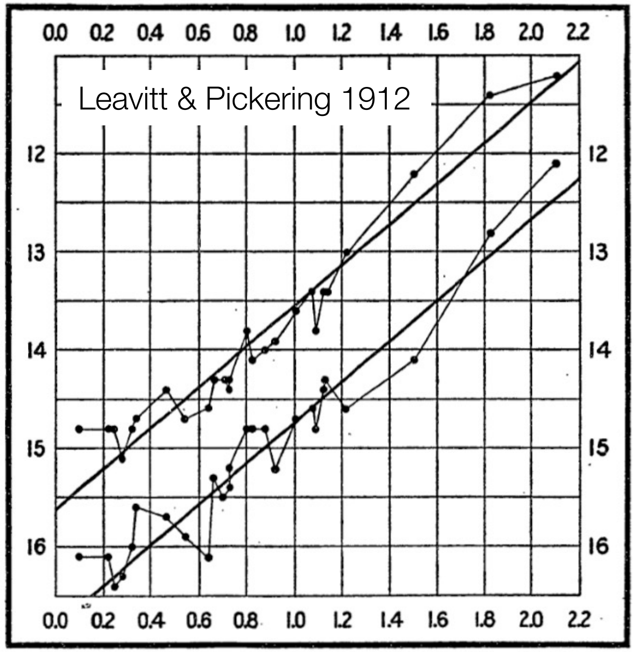
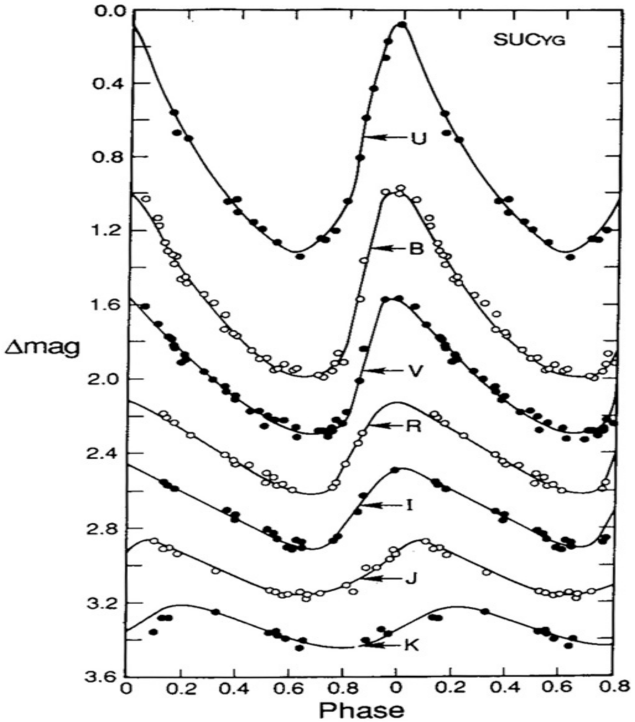
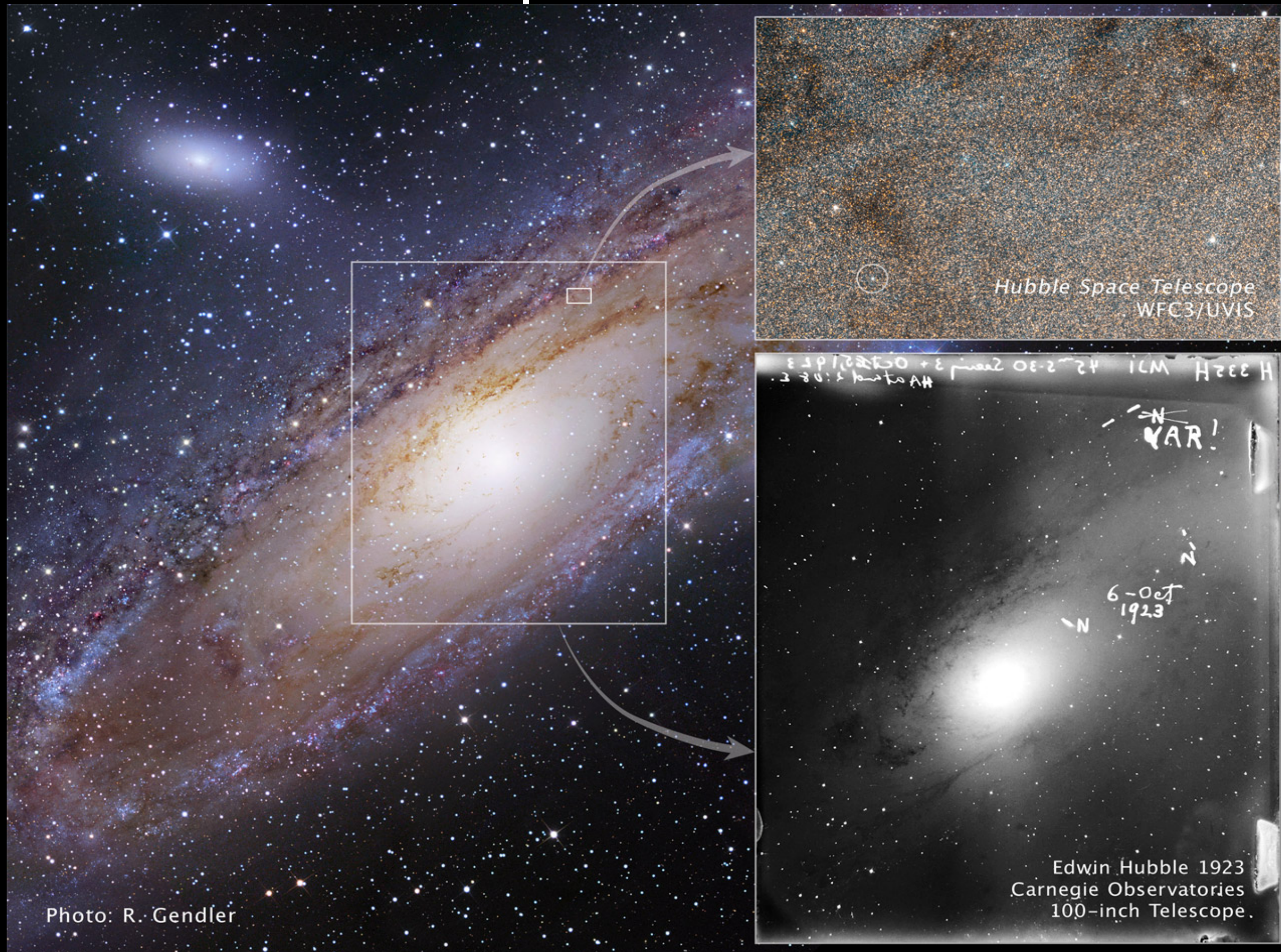


FIG. 2.

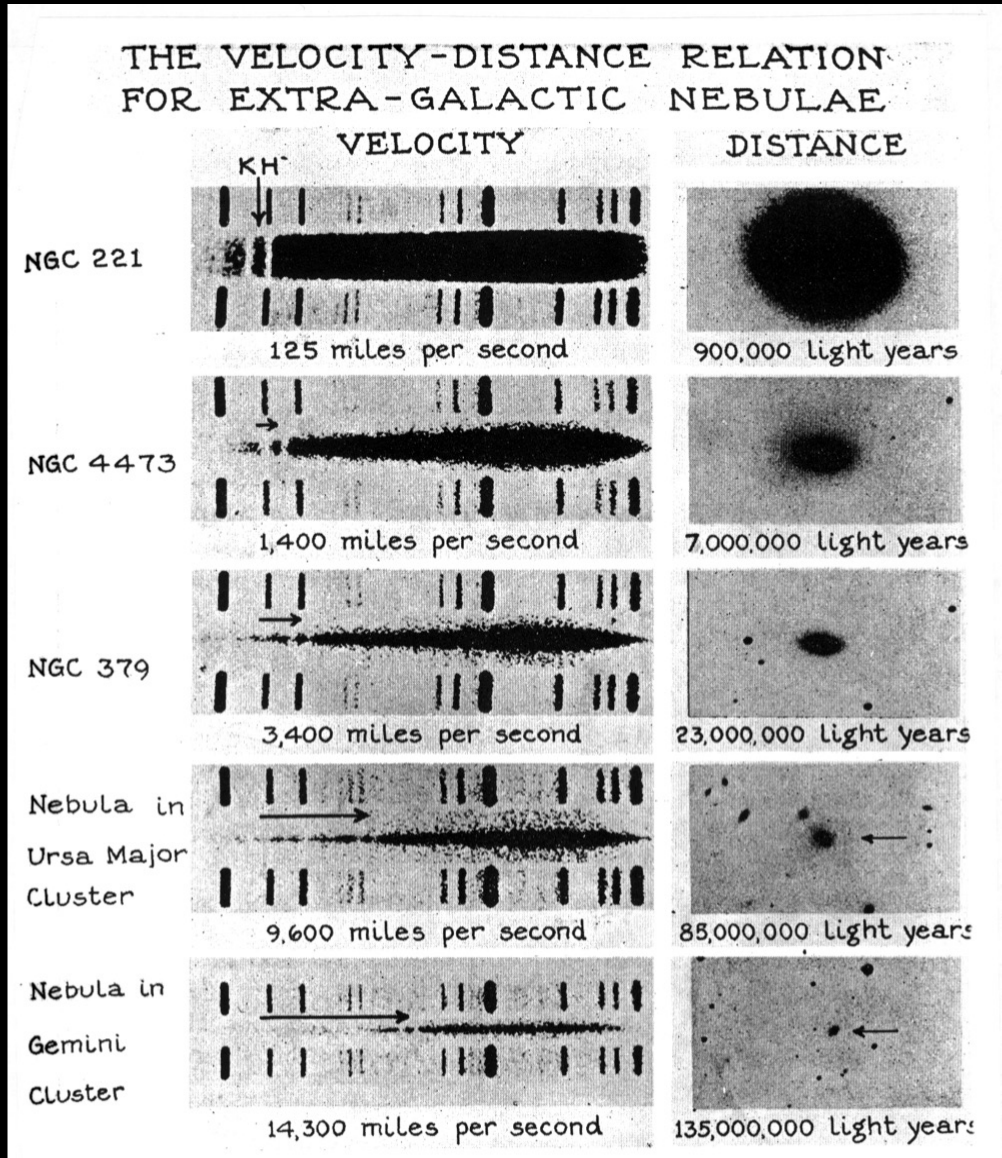


Madore & Freedman (1991)

Hubble discovers Cepheid stars in Andromeda



The expansion of the universe



Hubble/Humason 1936

Expanding Universe

Expansion rate critical for cosmic evolution

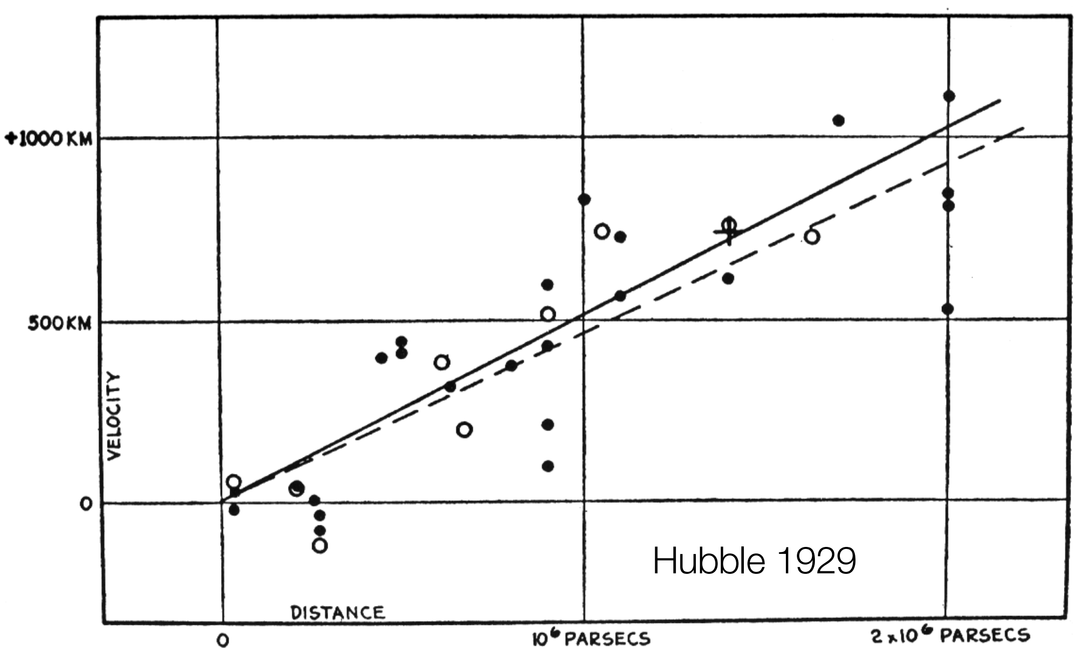


FIG. 9. *The Formulation of the Velocity-Distance Relation.*

STScI

History of H_0

Expansion rate by G. Lemaître (1927)

de l'observateur. En effet, la période de la lumière émise dans des conditions physiques semblables doit être partout la même lorsqu'elle est exprimée en temps propre.

$$\frac{v}{c} = \frac{\delta t_2}{\delta t_1} - 1 = \frac{R_2}{R_1} - 1 \qquad (22)$$

mesure donc l'effet Doppler apparent dû à la variation du rayon de l'univers. *Il est égal à l'excès sur l'unité du rapport des rayons de l'univers à l'instant où la lumière est reçue et à l'instant où elle est émise.* v est la vitesse de l'observateur qui produirait le même effet. Lorsque la source est suffisamment proche nous pouvons écrire approximativement

$$\frac{v}{c} = \frac{R_2 - R_1}{R_1} = \frac{dR}{R} = \frac{R'}{R}\,dt = \frac{R'}{R}\,r$$

où r est la distance de la source. Nous avons donc

Footnote!

(2) En ne donnant pas de poids aux observations, on trouverait 670 Km./sec à $1{,}16 \times 10^6$ parsecs, 575 Km./sec à 10^6 parsecs. Certains auteurs ont cherché à mettre en

Intermezzo
Age of the Universe

A matter-dominated universe has the following age

$$t_0 = \frac{2}{3H_0}$$

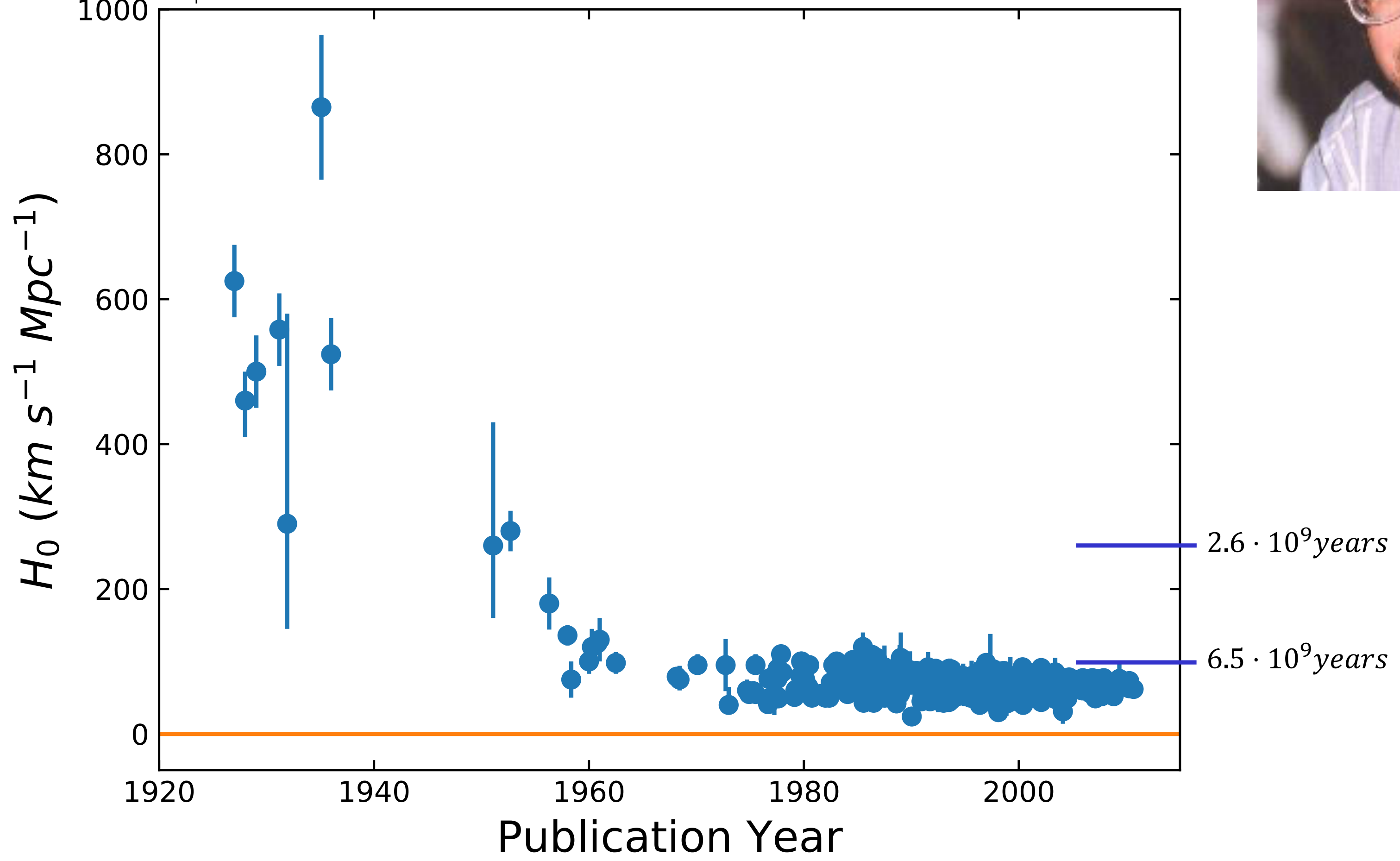
H_0 (km/s/Mpc)	t_0 (yr)
500	$1.30 \cdot 10^{9}$
250	$2.61 \cdot 10^{9}$
100	$6.52 \cdot 10^{9}$
80	$8.15 \cdot 10^{9}$
70	$9.32 \cdot 10^{9}$
60	$1.09 \cdot 10^{10}$
50	$1.30 \cdot 10^{10}$
30	$2.17 \cdot 10^{10}$

→ age of the Earth: $4.5 \cdot 10^{9}$ years

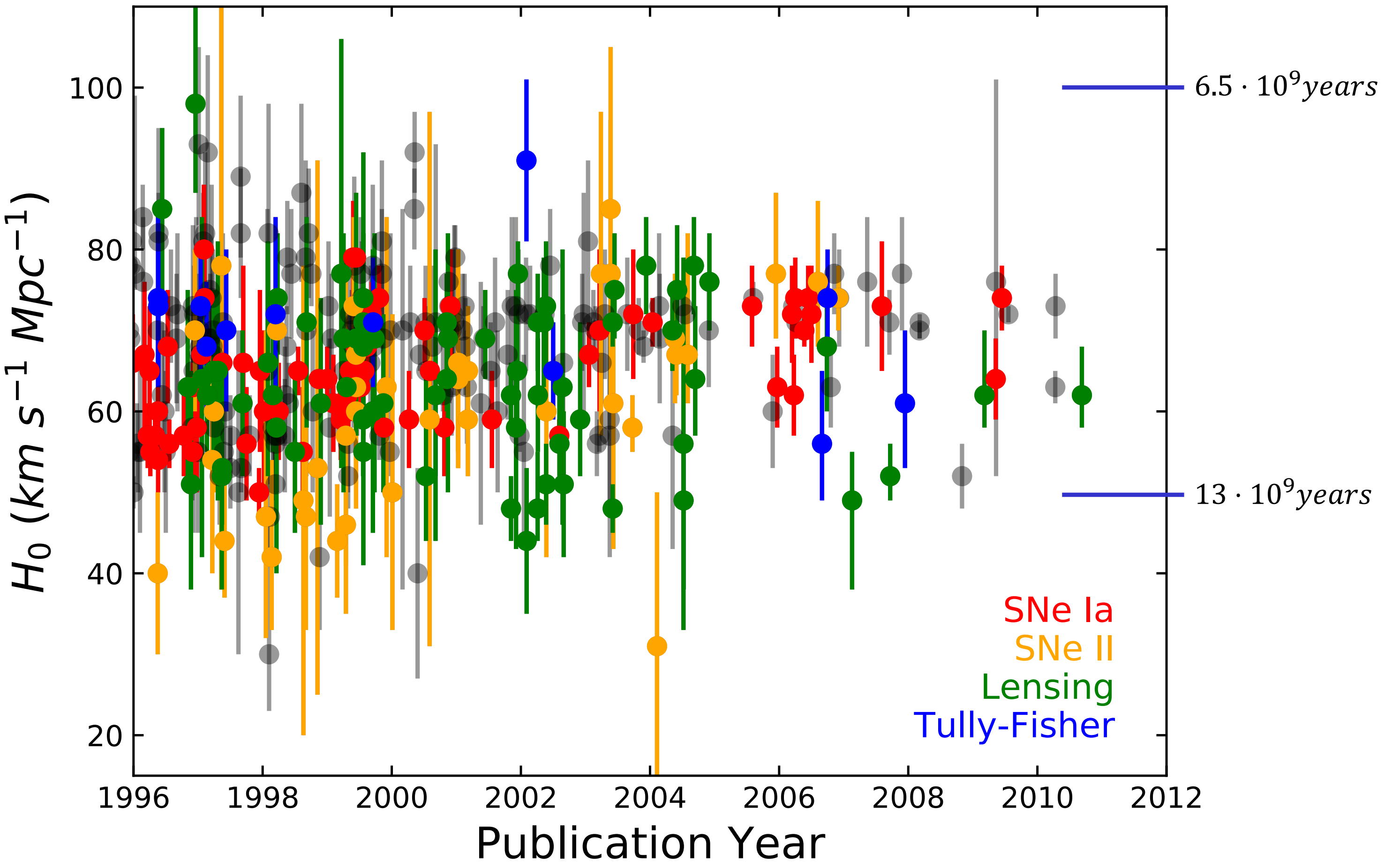
→ oldest stars: $\sim 13 \cdot 10^{9}$ years

History of H_0

https://www.cfa.harvard.edu/~dfabricant/huchra/hubble/



History of H_0



What about the age?

Change assumption:

- Cosmic expansion is accelerated (distant supernovae)
- Universe is not matter dominated, but Dark Energy dominated

Age: $t_0 \approx \frac{1}{H_0}$

H_0 (km/s/Mpc)	t_0 (yr) ($\Omega_M = 1$)	t_0 (yr) ($\Omega_M = 0.3;\ \Omega_\Lambda = 0.7$)
500	$1.30 \cdot 10^9$	$1.89 \cdot 10^9$
250	$2.61 \cdot 10^9$	$3.77 \cdot 10^9$
100	$6.52 \cdot 10^9$	$9.43 \cdot 10^9$
80	$8.15 \cdot 10^9$	$1.18 \cdot 10^{10}$
70	$9.32 \cdot 10^9$	$1.35 \cdot 10^{10}$
60	$1.09 \cdot 10^{10}$	$1.57 \cdot 10^{10}$
50	$1.30 \cdot 10^{10}$	$1.89 \cdot 10^{10}$
30	$2.17 \cdot 10^{10}$	$3.14 \cdot 10^{10}$

Oldest stars $\sim 13 \cdot 10^9$ years

Why is this so difficult?

Absolute measurement

- Much more difficult than a relative measurement
  - “much harder than measuring the acceleration of the universe” (A. Riess)
- Requires cosmological distance measurements
  - Two problems
    - Large distances with unreliable distance indicators
      - » Example: Cepheids can be measured only in the nearby universe
    - Inhomogeneous matter distribution in the local universe
      - » Leads to deviations from the pure expansion of the universe

Extragalactic Distances

The Astronomical Journal, 146:69 (14pp), 2013 September
Courtois et al.

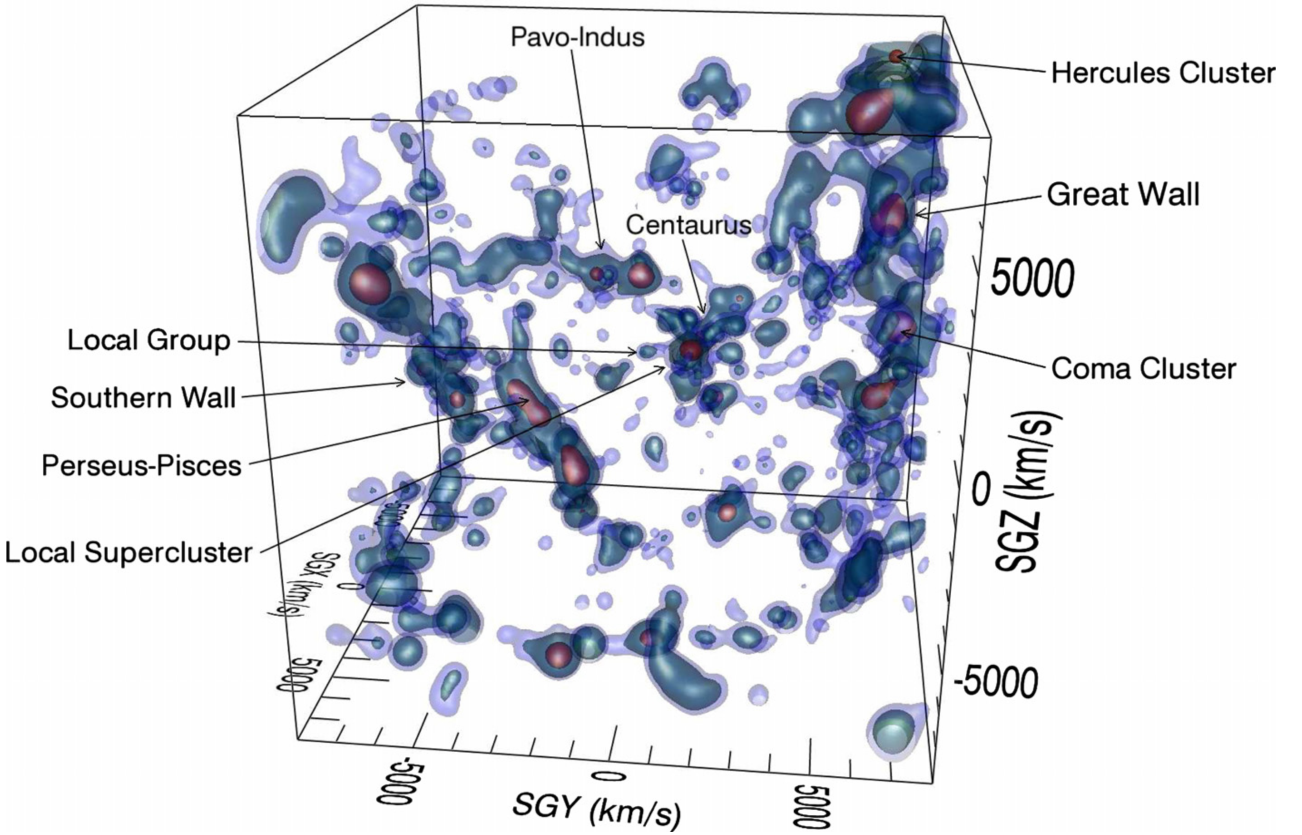
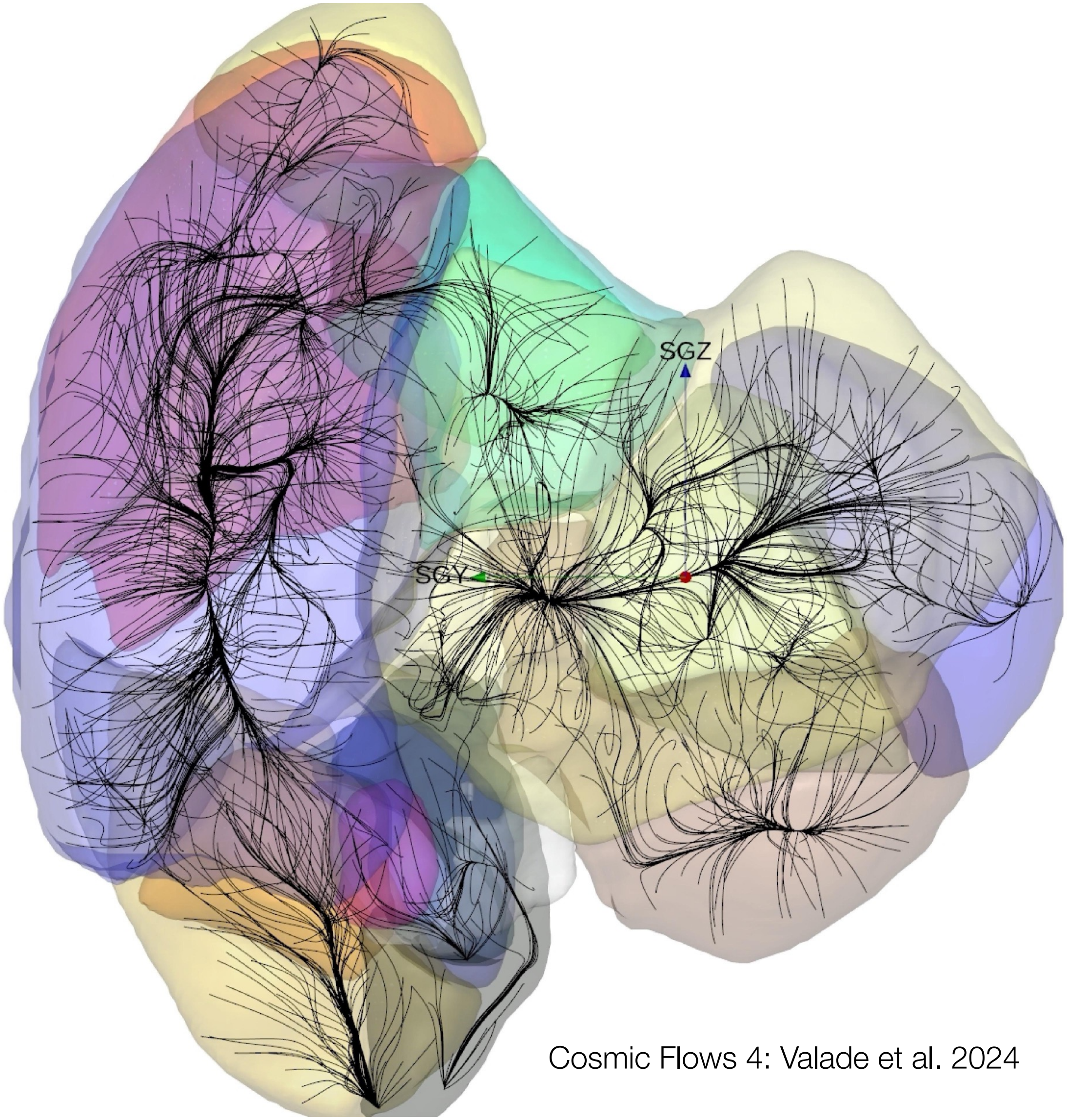


Figure 8. Perspective view of the V8k catalog after correction for incompleteness and represented by three layers of isodensity contours. The region in the vicinity of the Virgo Cluster now appears considerably diminished in importance. The dominant structures are the Great Wall and the Perseus–Pisces chain, with the Pavo–Indus feature of significance.

Local Flows

Inhomogeneous mass distribution in the local universe

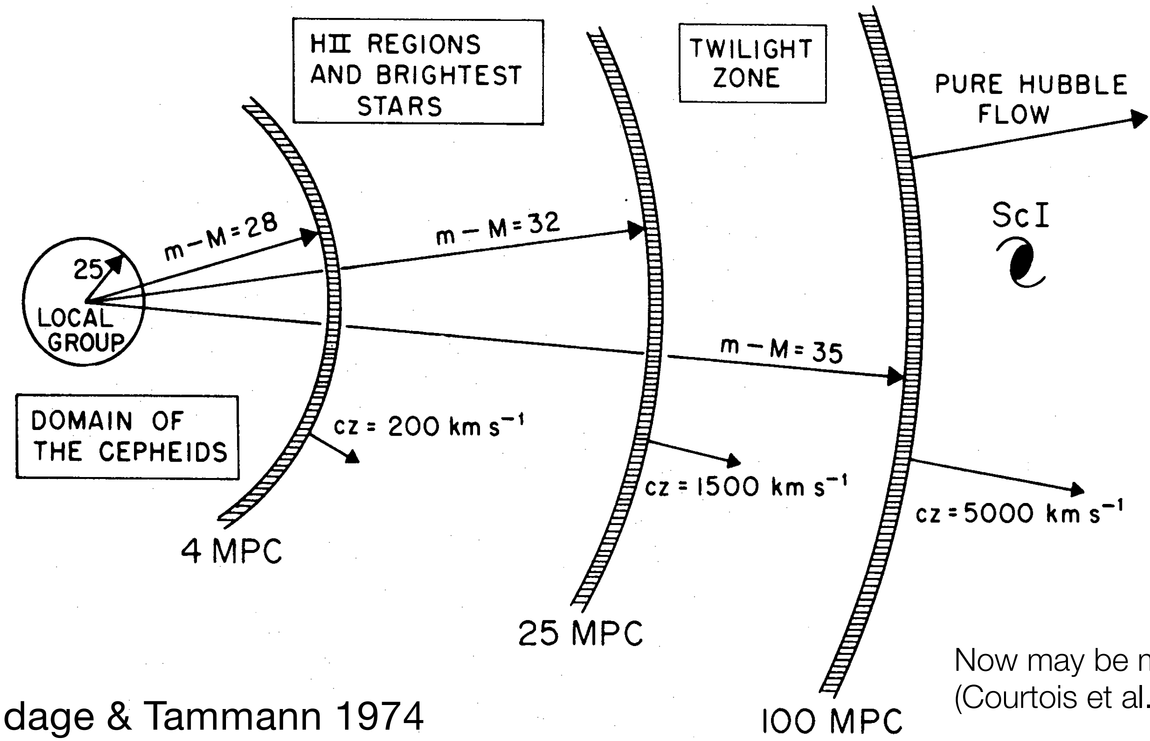


Cosmic Flows 4: Valade et al. 2024

Measuring H_0

Classical approach

→ distance ladder to reach (smooth) Hubble flow



Sandage & Tammann 1974

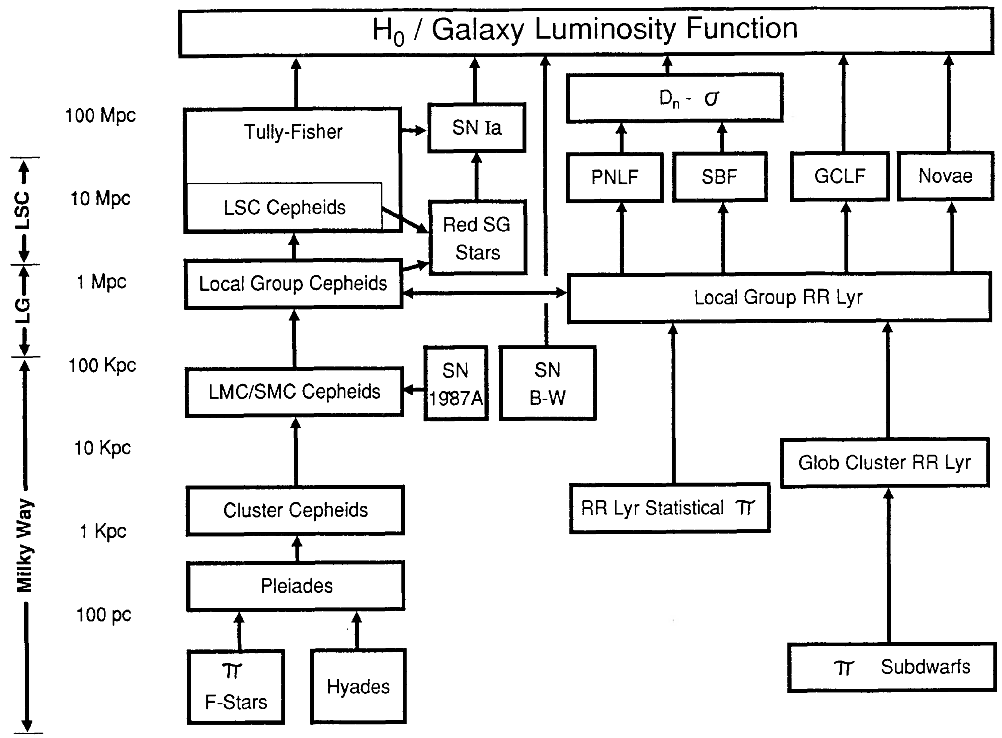
Now may be more like 200 to 300 Mpc (Courtois et al. 2025)

Classic Distance Ladder

Primary distance indicators (within the Milky Way)

- trigonometric parallax
- proper motion
- apparent luminosity
  - main sequence
  - red clump stars
  - RR Lyrae stars
  - eclipsing binaries
  - Cepheid stars

Jacoby et al. 1992



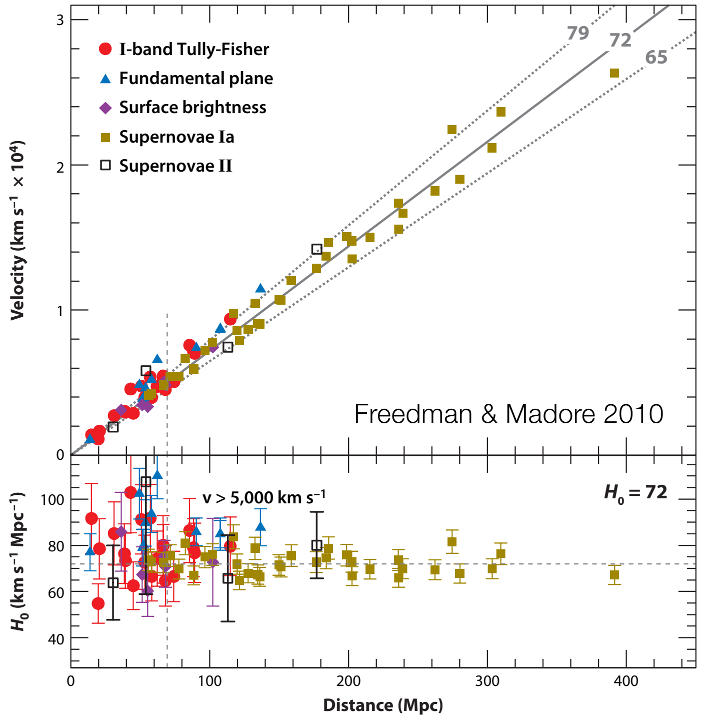
Pathways to Extragalactic Distances

Classic Distance Ladder

Gruber Cosmology Prize

Secondary distance indicators
(beyond the Local Group)

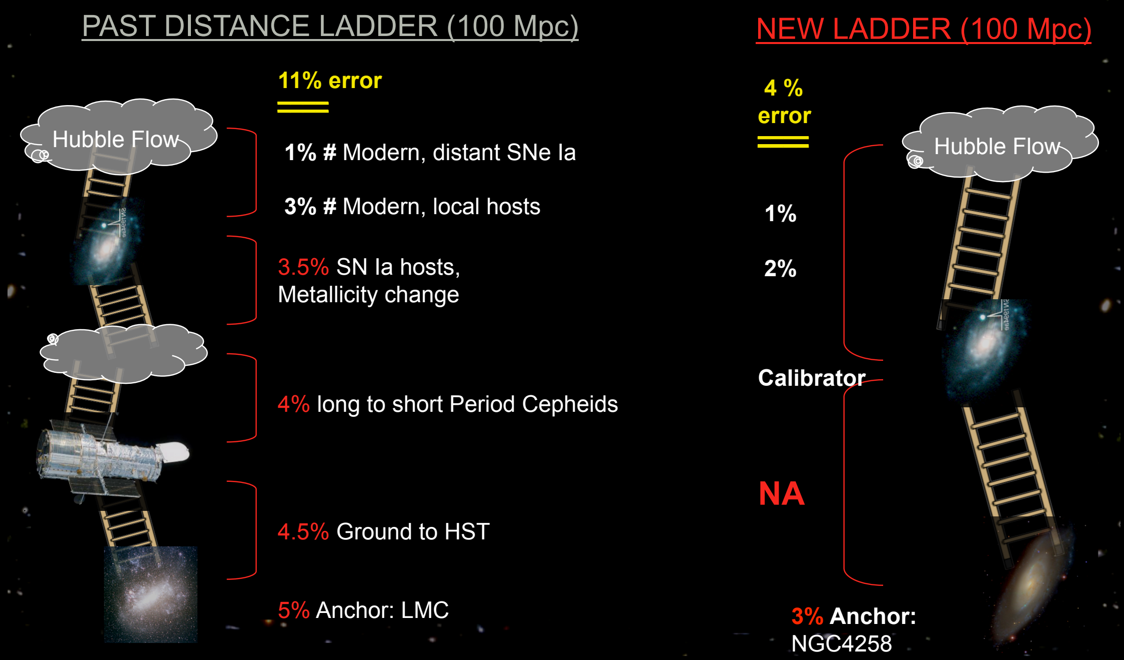
- Important check
  - Large Magellanic Cloud
- Tully-Fisher relation
- Fundamental Plane
- Supernovae (mostly SN Ia)
- Surface Brightness Fluctuations



Hubble Constant

Calibration of *M(SN Ia @ max)*

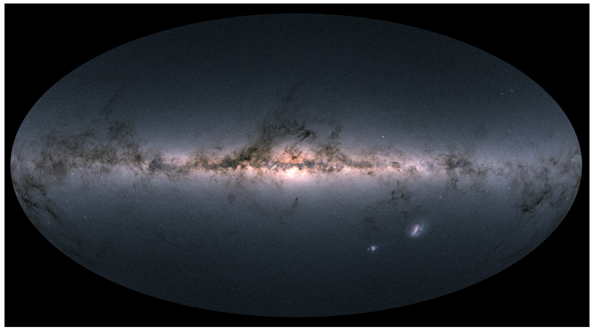
Distance ladder

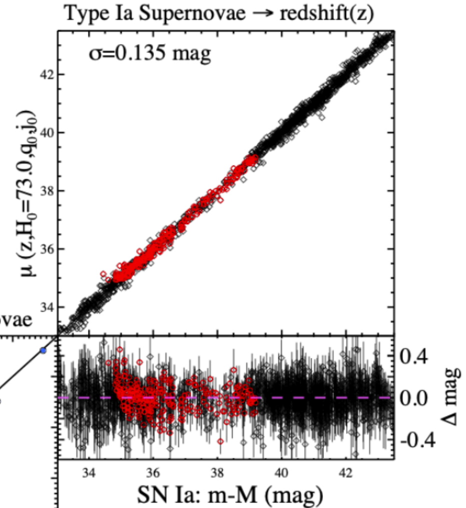


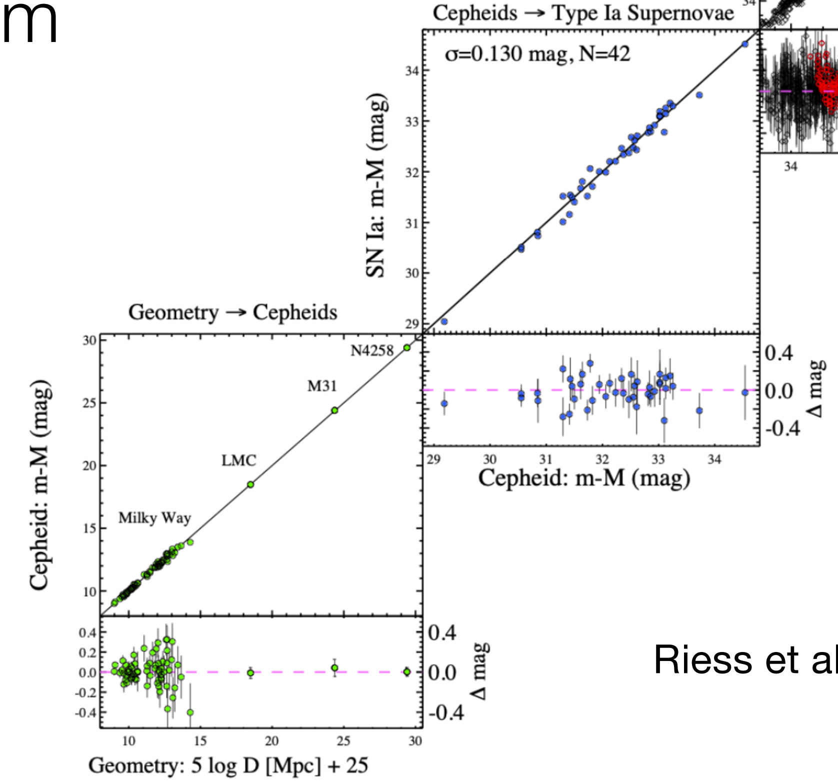
Adam Riess

Hubble Constant

Supernova Ia
Hubble diagram







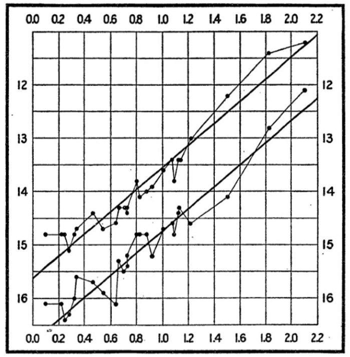


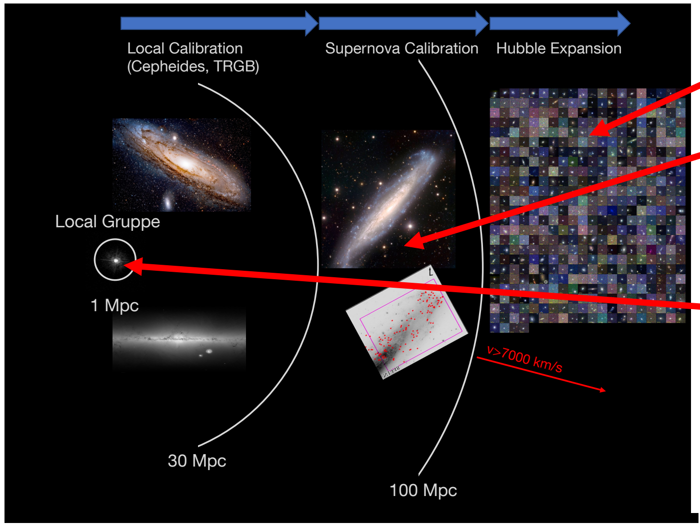
Fig. 2.

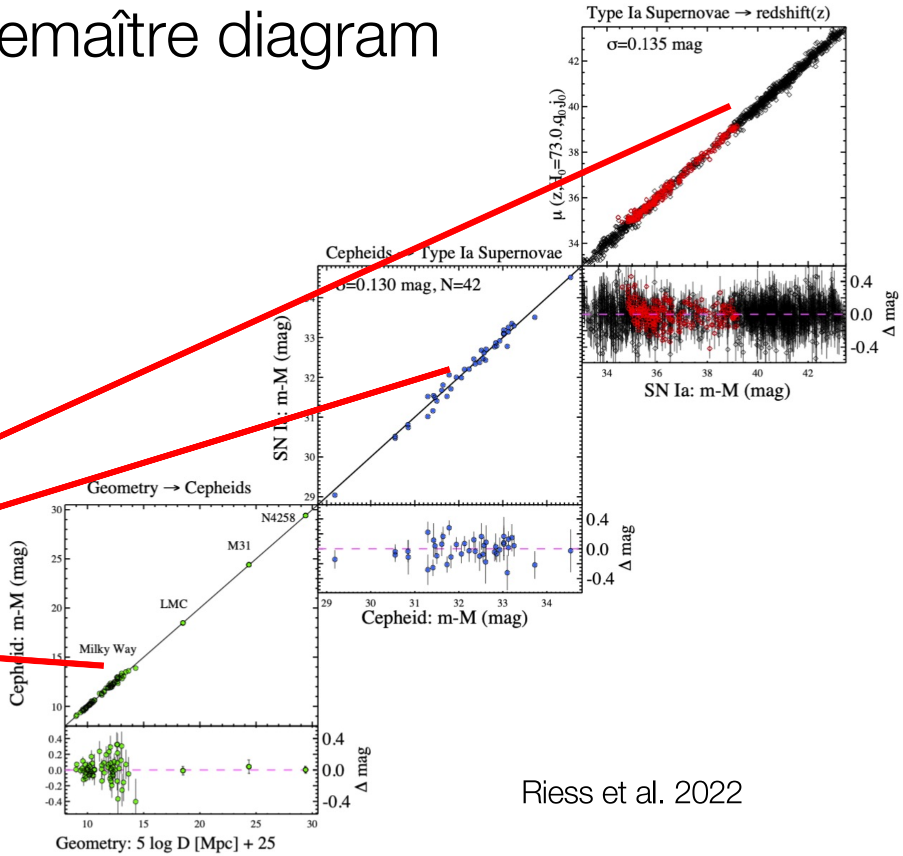
Riess et al. 2022

Bruno Leibundgut

Hubble Constant H_0

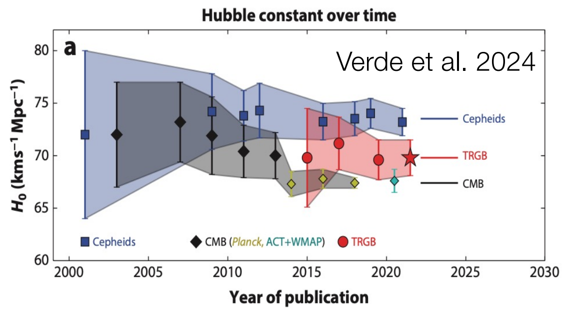
Supernova Ia Hubble-Lemaître diagram



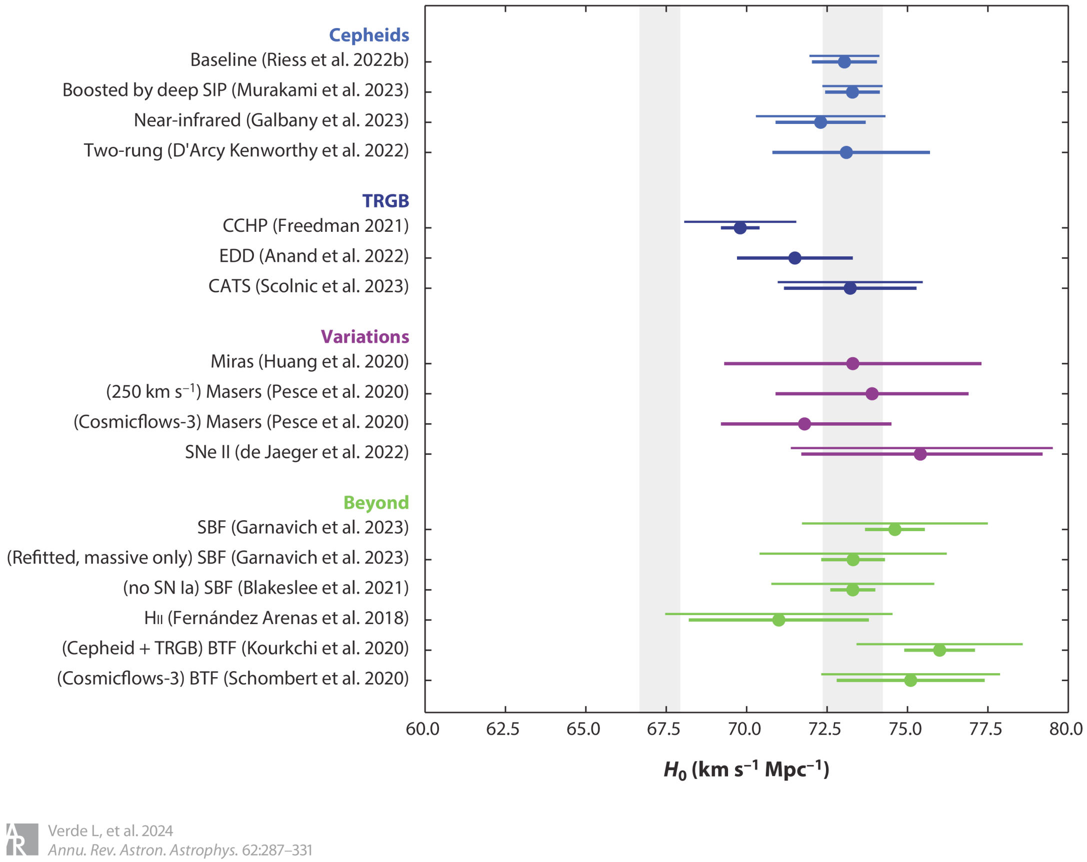


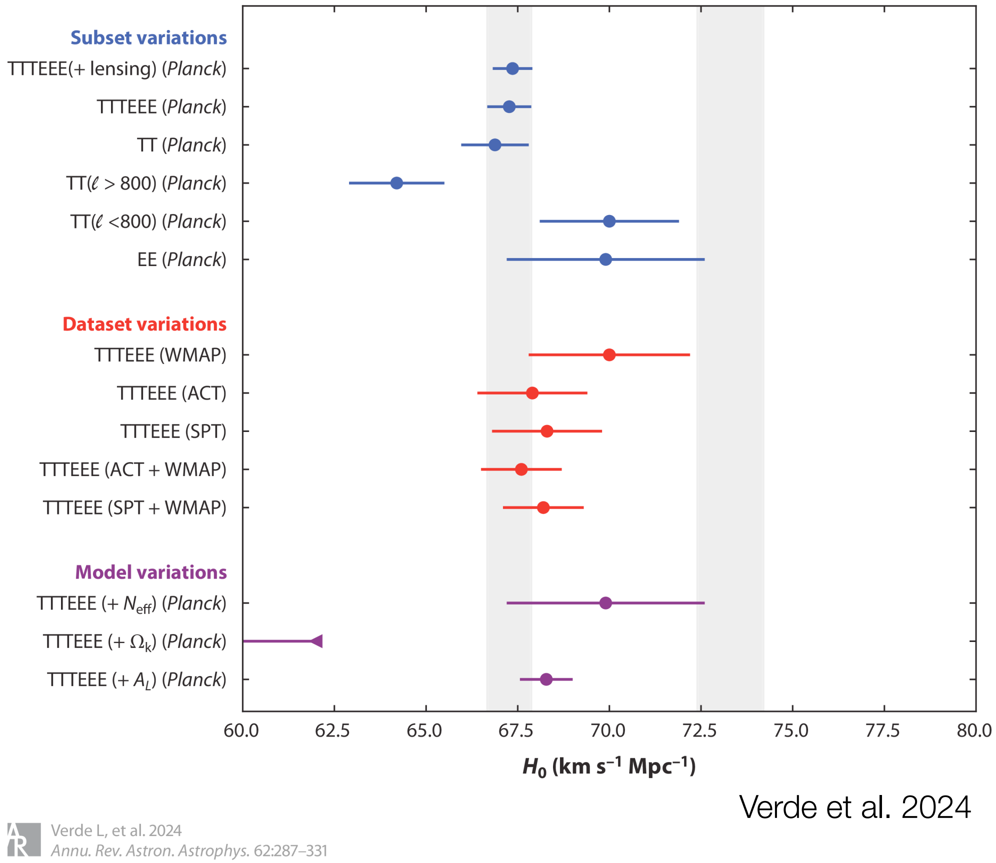
Riess et al. 2022

H_0 State of the Art



late universe



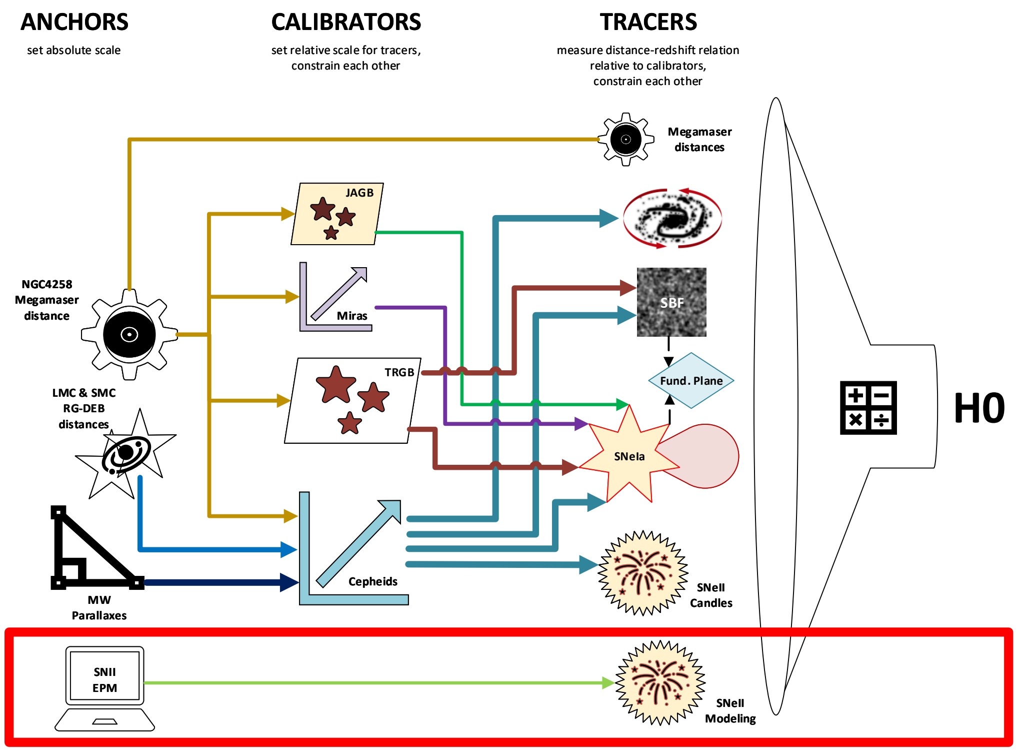


Verde et al. 2024

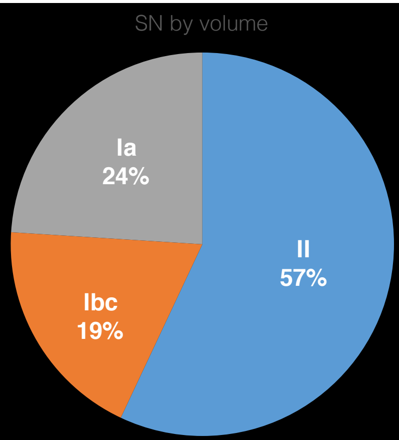
Ideal (local) Method

- Independent of a cosmological model
  - → low redshift (z<0.1)
- No distance ladder
  - → keep cumulative errors small
- Overall accuracy <3%

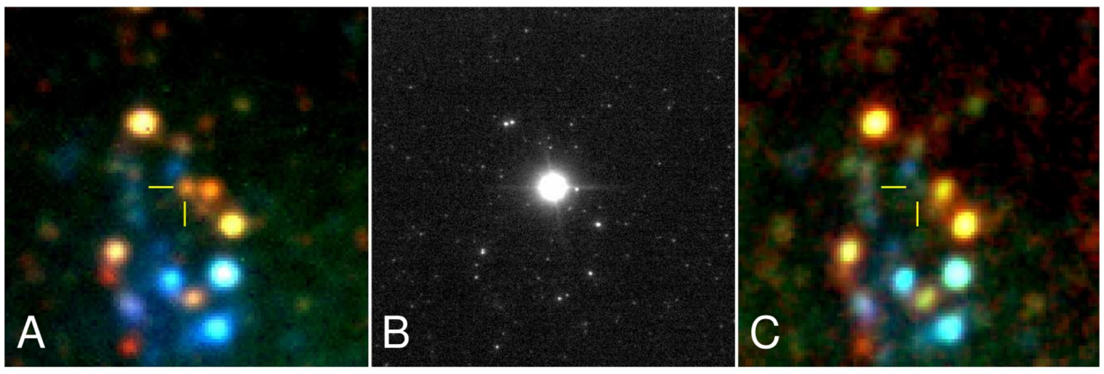
⇢ Type II Supernovae



Type II Supernovae



Core-collapse explosions of massive, red-supergiant stars



Mattila et al. 2010

- Peak absolute mags between -16 and -18

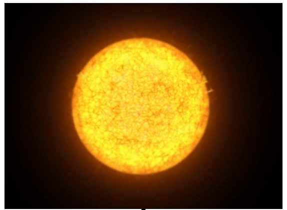
  → observable up to z ≈ 0.4

- Most common type of SN by volume

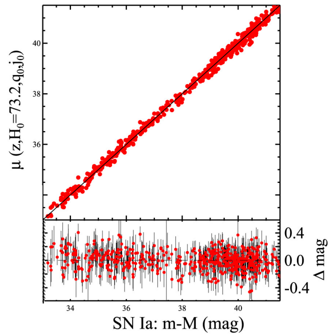
Christian Vogl

Why type II supernovae?

Luminosity ~ Period



Type II supernovae



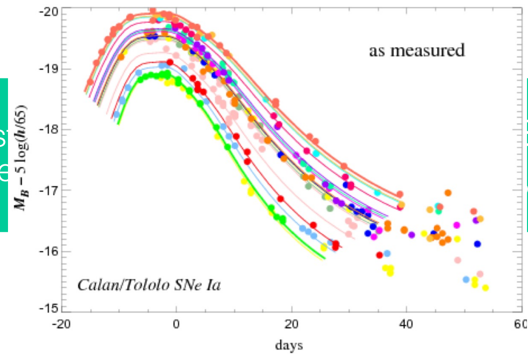
Type II supernovae:

simple physics

one-s
measure

sics
ed

Luminosity ~ light curve width



Riess et al. 2016

J. Spyromilio
S. Blondin
B. Leibundgut
S. Suyu
C. Vogl
A. Floers
S. Taubenberger
M. G. Cudmani
A. Holas
W. Hillebrandt
G. Csörnyei
S. Kressierer
C. Lippmann

S. Smartt
R. Kotak
C. Lemon
A. Gal-Yam
R. Bruch
W. Kerzendorf
J. Shields

adH0cc – Basics

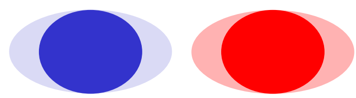
- accurate determination of H_0 with core-collapse (supernovae)
- Individual distances (to about 10%) to Type II supernovae in the Hubble flow ($0.03 < z < 0.08$)
- Distance determination based on calibrated physics
  - – No distance ladder, i.e. no empirical calibration
  - – Ideal for H_0

Christian Vogl

EPM in a nutshell

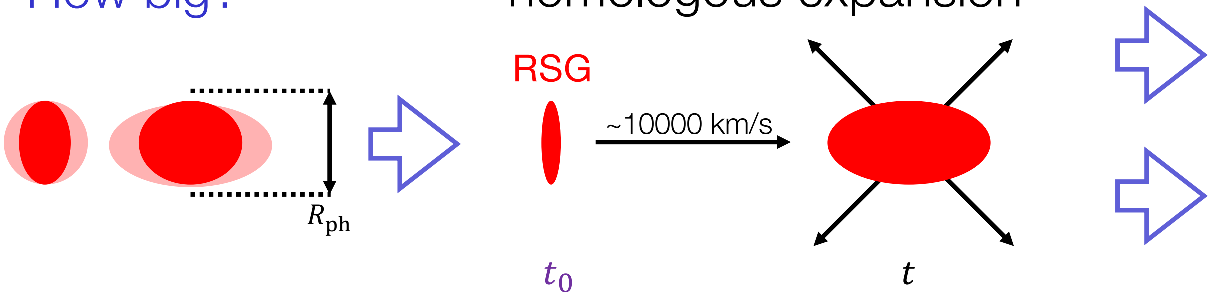
Luminosity ~ Radius^2 x Temperature^4

How hot?



How big?

homologous expansion

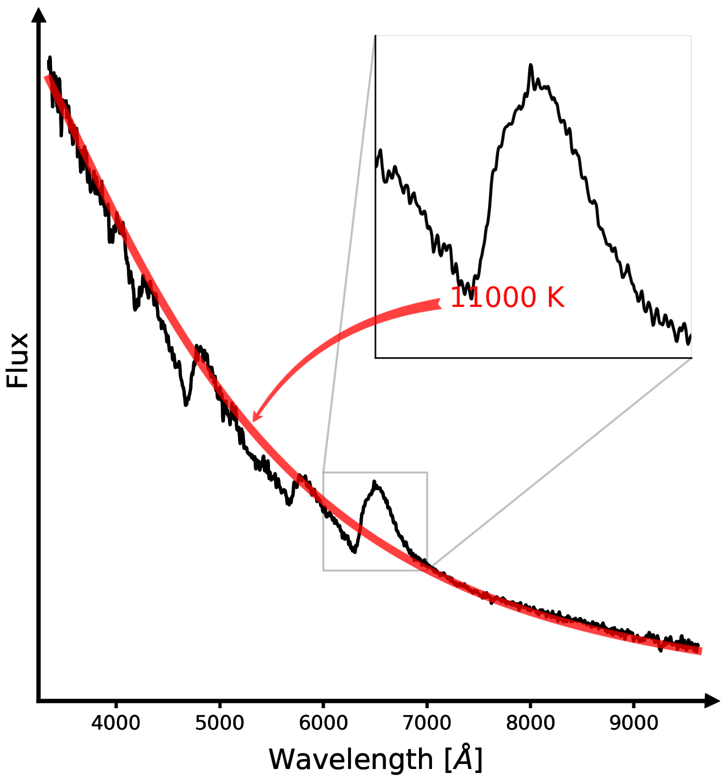


How old?

How fast?

Radius = velocity x time since explosion

EPM: it's all in the spectra



C. Vogl

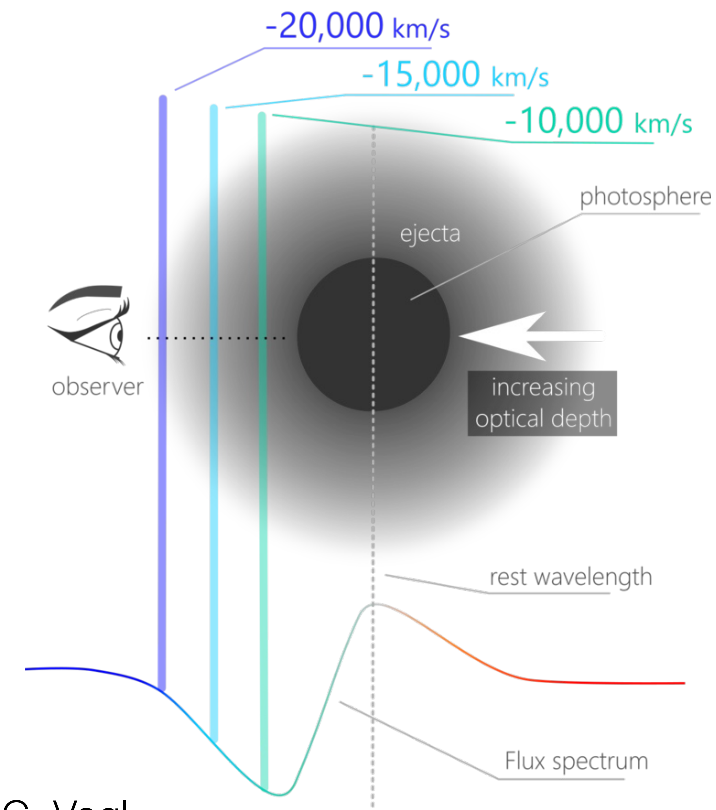


Image: Héloïse Stevance

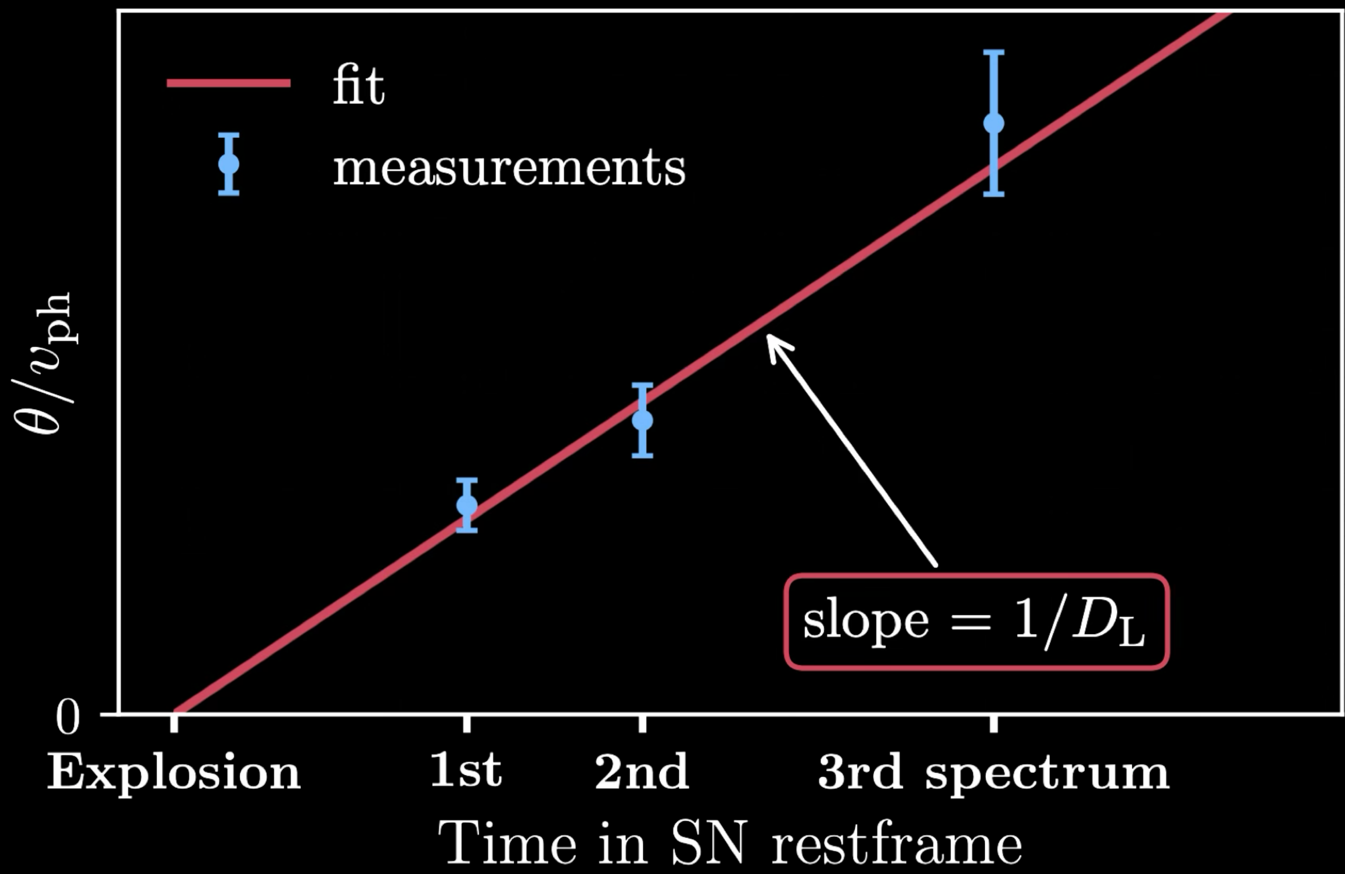
adH0cc analysis

Distances

- Explosion time t_0
- SN atmosphere
  - v_{ph}, F_{ph}, (T, n)
- Observed flux f_{obs}

$$\theta = \frac{R}{D} = \sqrt{\frac{f_{obs}}{F_{ph}(T,n)}}$$

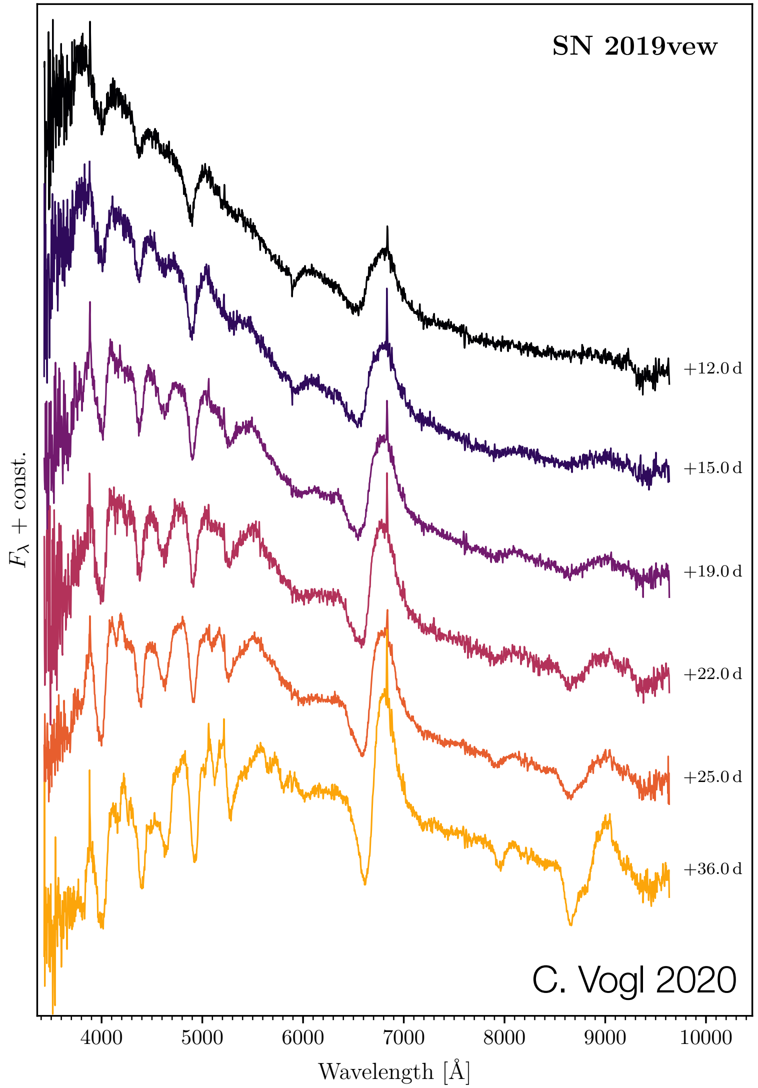
$$R_{ph} = \frac{v_{ph}(t - t_0)}{1 + z}$$



adH0cc

Critical observables

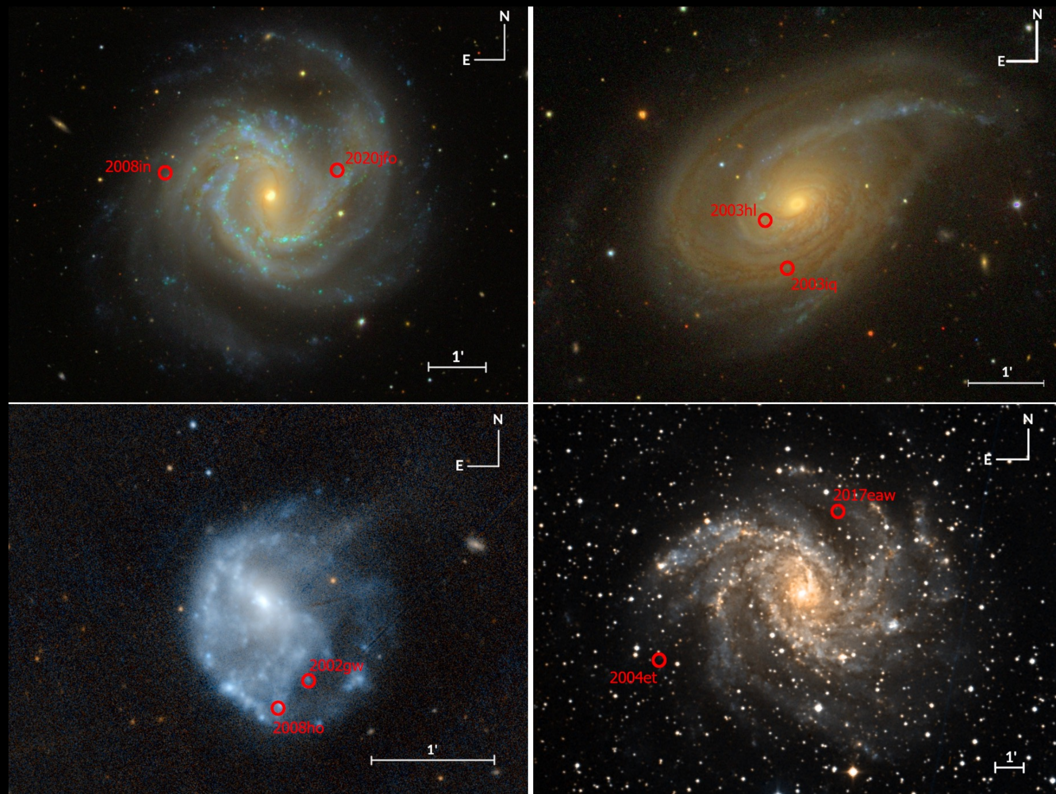
- time of explosion
- spectral coverage
  - before max until well into the plateau
- photometry
  - simultaneously with spectroscopy



Testing tailored EPM

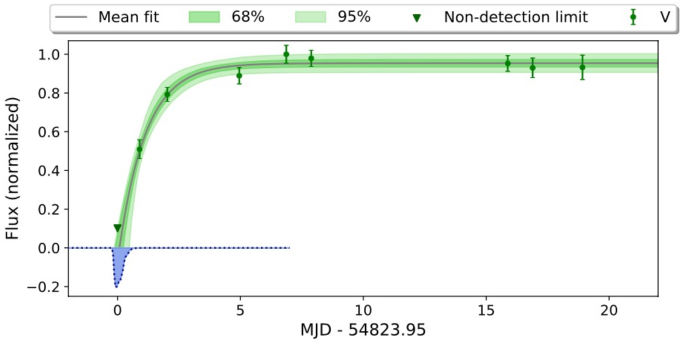
Determine distances to supernovae in the same galaxy ('siblings')

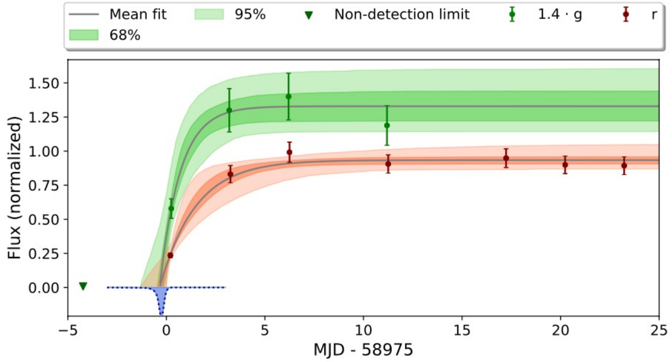
Literature data

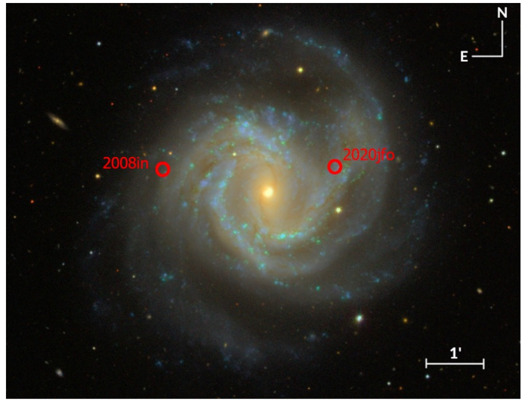


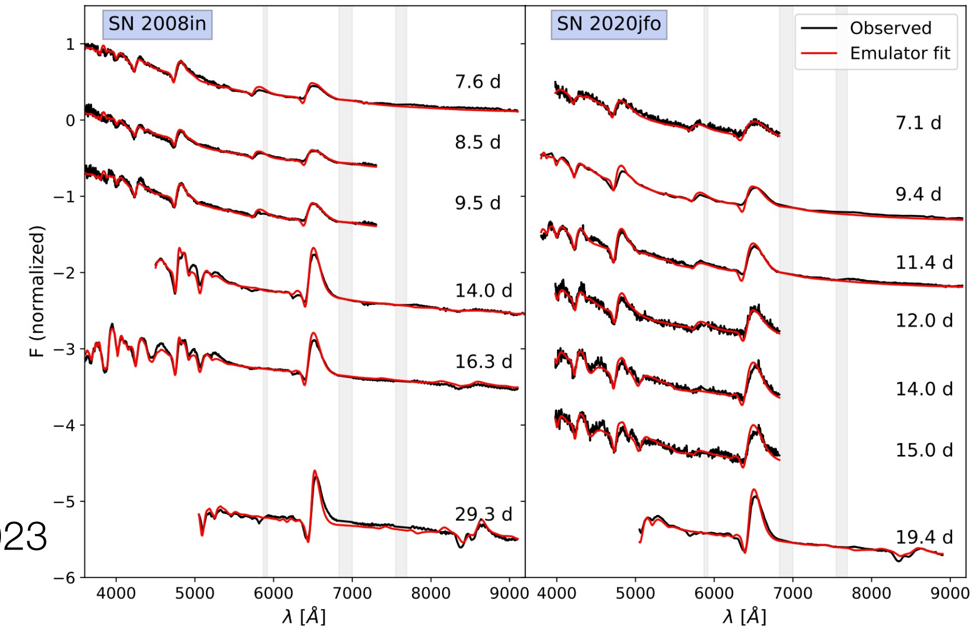
Csörnyei et al. 2023

M61/NGC 4303



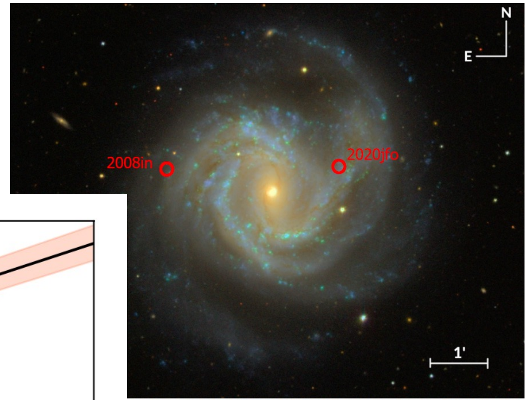




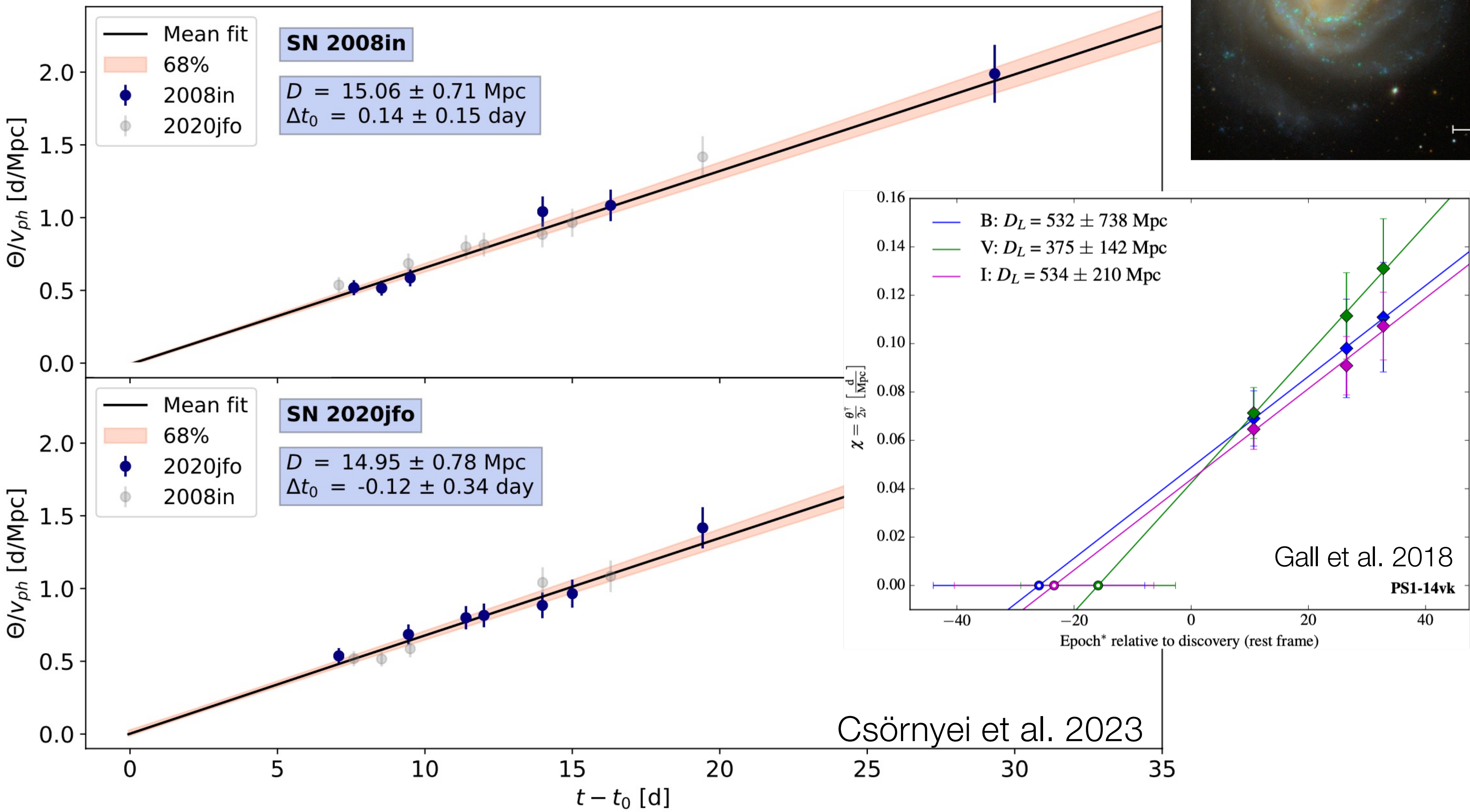


Csörnyei et al. 2023

M61/NGC 4303

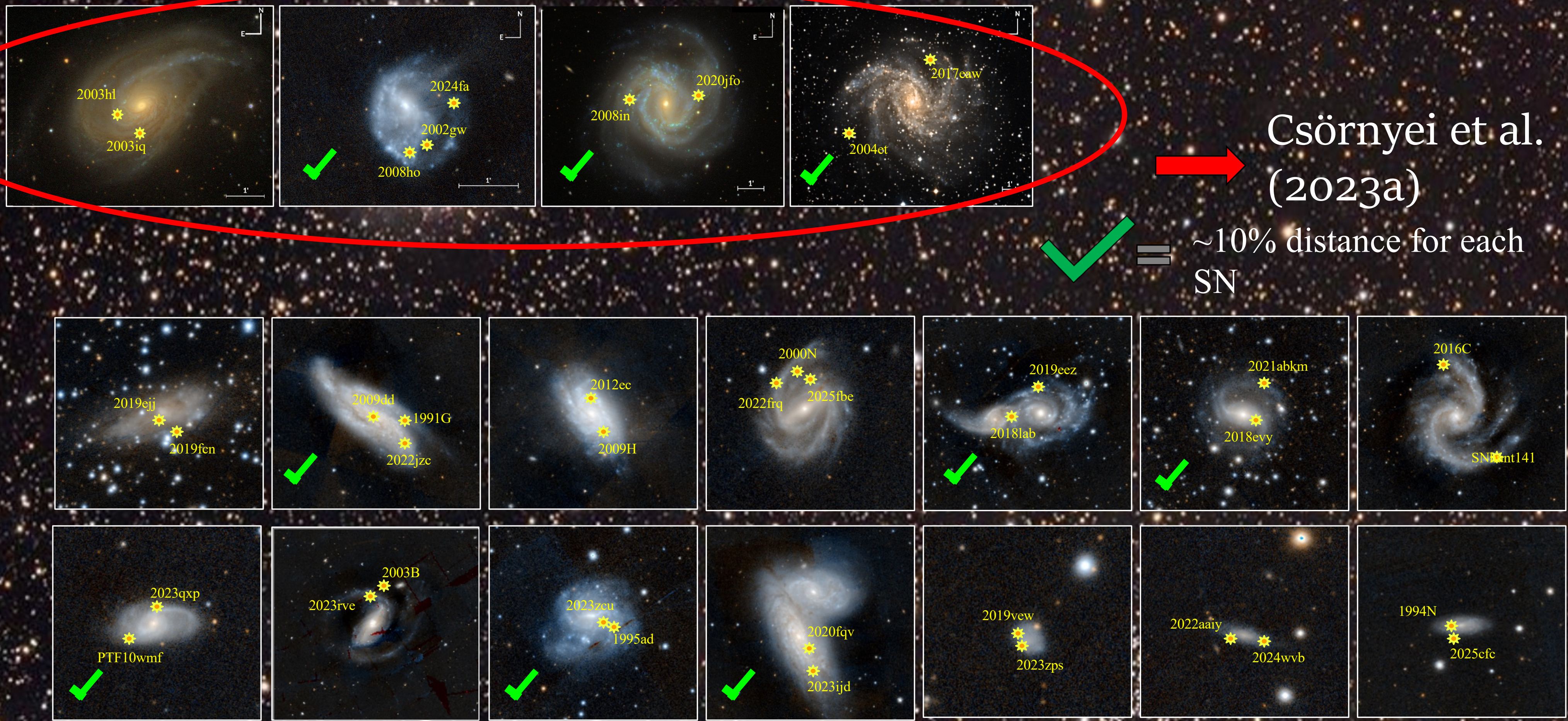


N
E
2008in
2020jfo
1'



Mean fit
68%
2008in
2020jfo
SN 2008in
D = 15.06 ± 0.71 Mpc
Δt0 = 0.14 ± 0.15 day
SN 2020jfo
D = 14.95 ± 0.78 Mpc
Δt0 = -0.12 ± 0.34 day
Θ/vph [d/Mpc]
t − t0 [d]
0.0
0.5
1.0
1.5
2.0
0
5
10
15
20
25
30
35
Csörnyei et al. 2023
B: DL = 532 ± 738 Mpc
V: DL = 375 ± 142 Mpc
I: DL = 534 ± 210 Mpc
χ = θ/2v [d/Mpc]
Epoch* relative to discovery (rest frame)
Gall et al. 2018
PS1-14vk

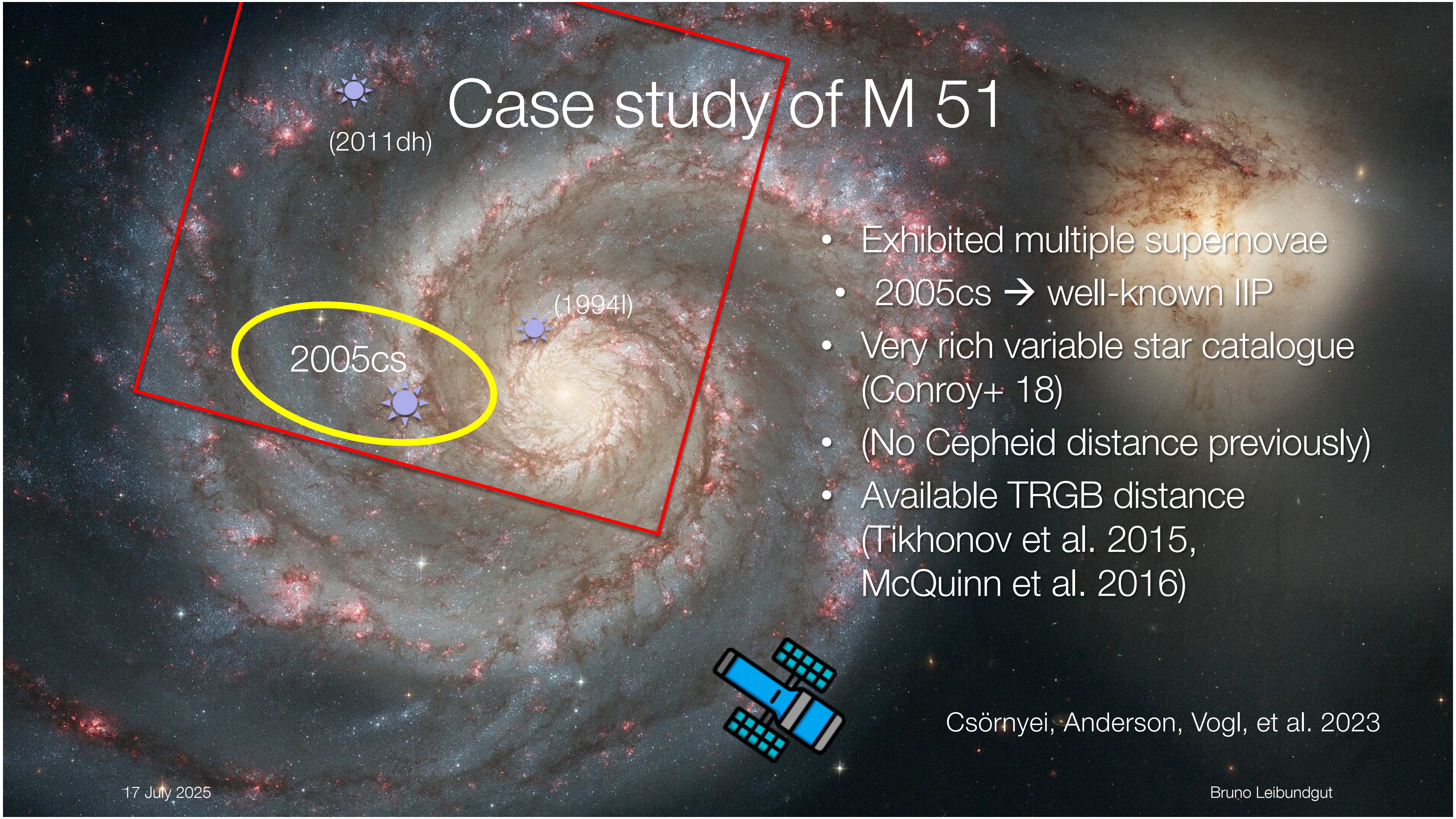
Sample v.2.0



→ Csörnyei et al. (2023a)

✓ = ~10% distance for each SN

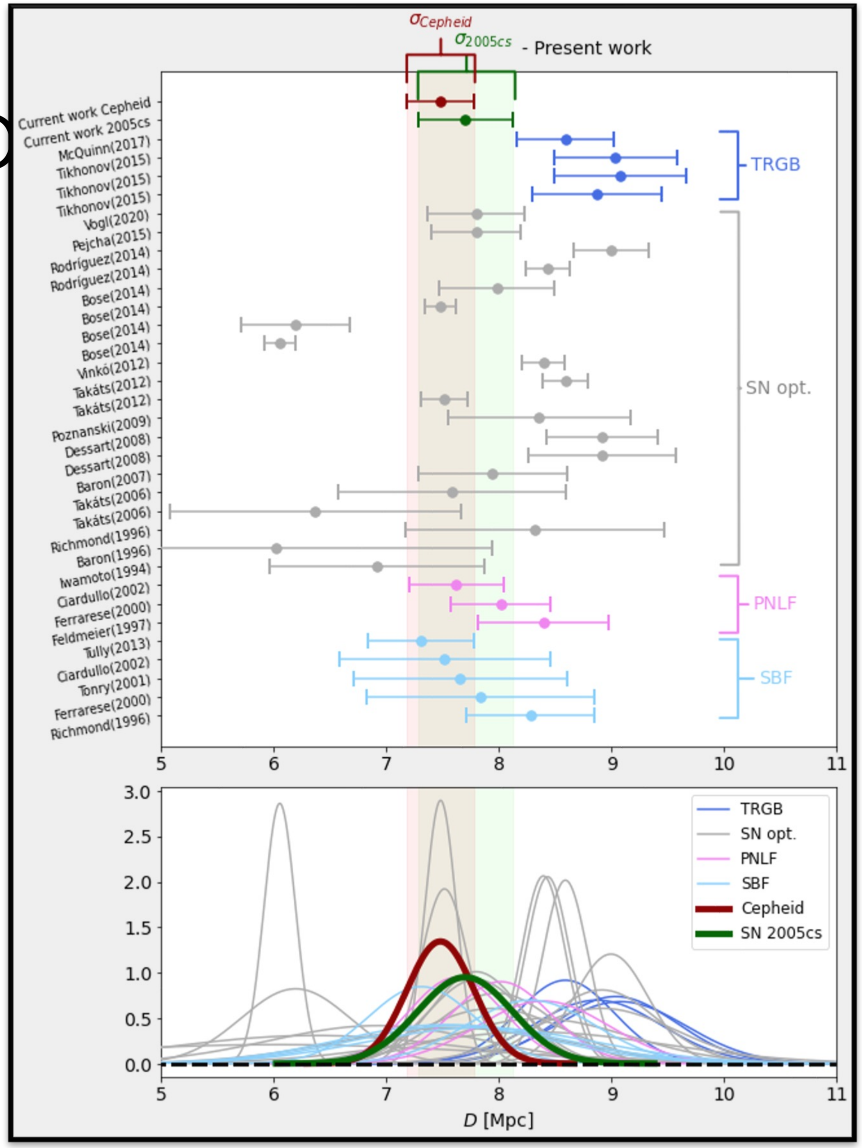
Case study of M 51



- Exhibited multiple supernovae
  - 2005cs → well-known IIP
- Very rich variable star catalogue (Conroy+ 18)
- (No Cepheid distance previously)
- Available TRGB distance (Tikhonov et al. 2015, McQuinn et al. 2016)

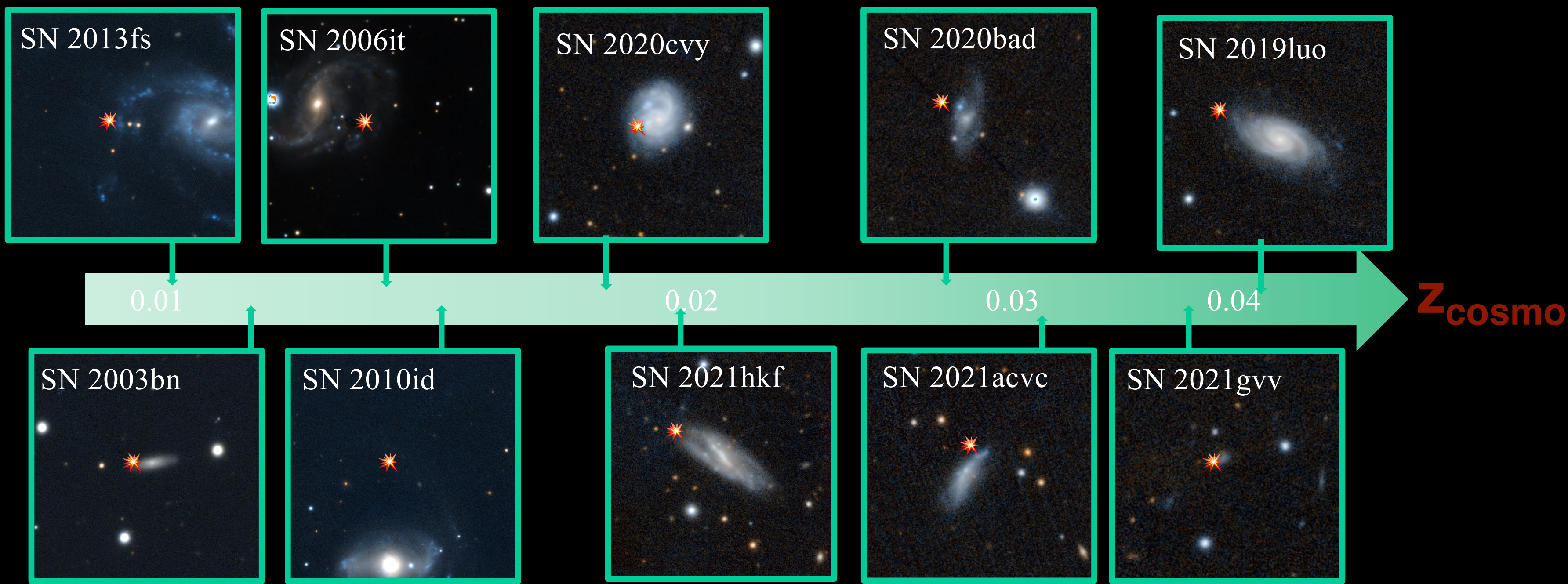
Csörnyei, Anderson, Vogl, et al. 2023

Distance to

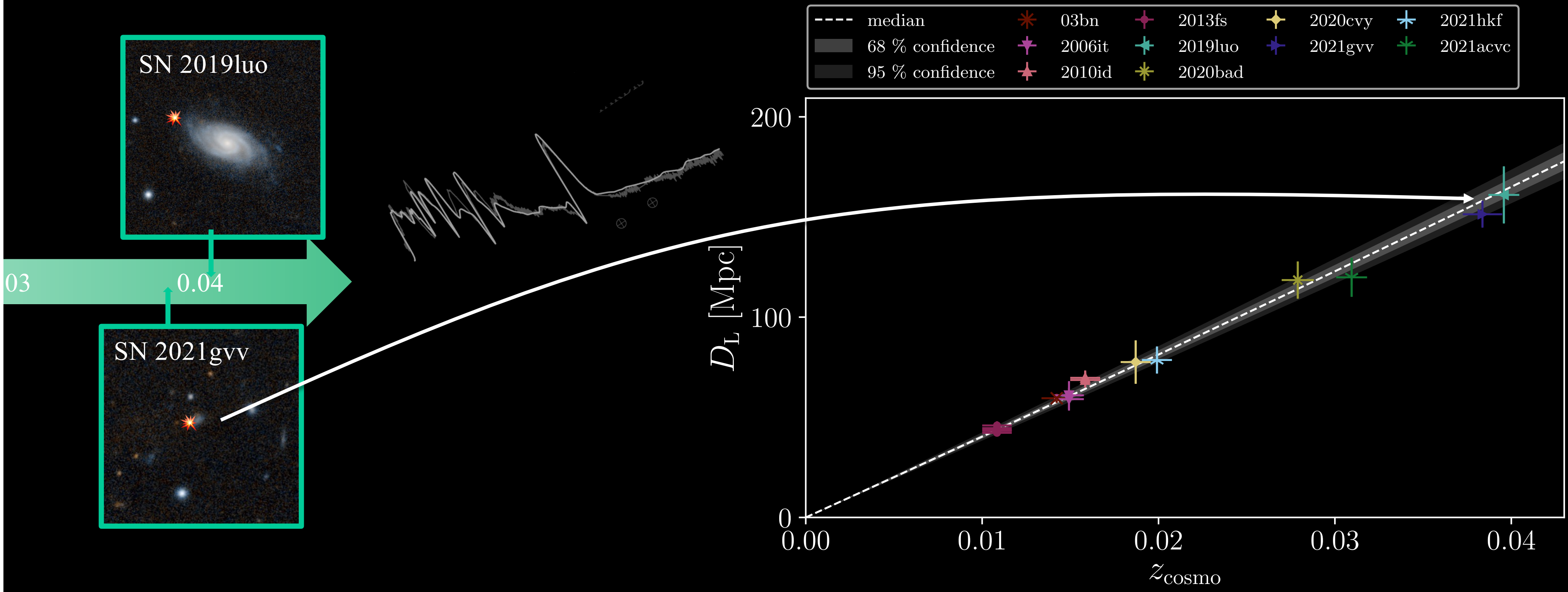


Csörnyei, Anderson, Vogl et al. (2023)

H_0 – data


SN 2013fs
SN 2006it
SN 2020cvy
SN 2020bad
SN 2019luo
0.01
0.02
0.03
0.04
z_{cosmo}
SN 2003bn
SN 2010id
SN 2021hkf
SN 2021acvc
SN 2021gvv

H_0 – results



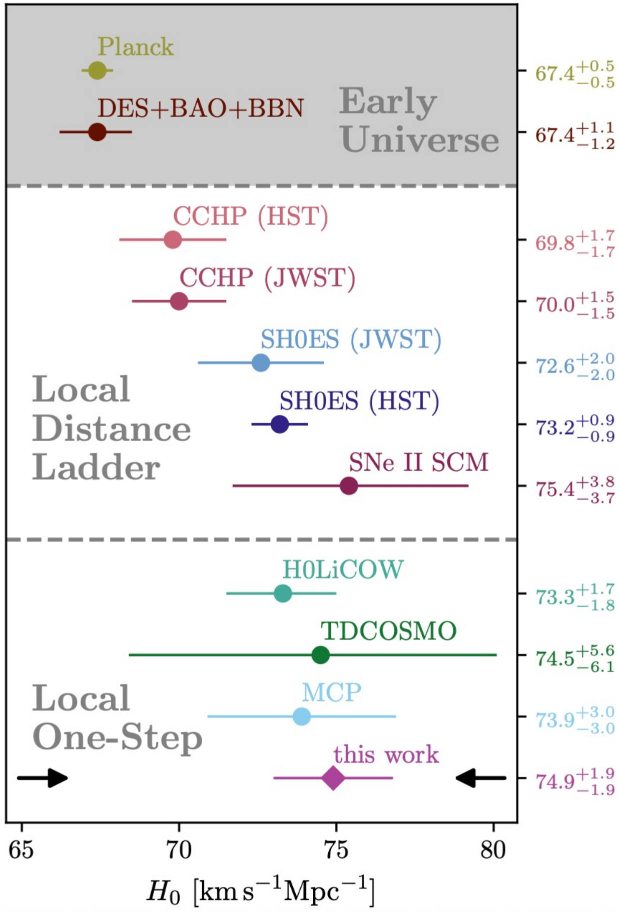
Vogl, Taubenberger, Csörnyei et al. 2025

adH0cc literature analysis

(Vogl et al. 2025)

- 10 SNe IIP
- Redshift 0.01<z<0.04
- Explosion date measured to better than 2 days
- Spectroscopy within 35 days of explosion
- Photometry in 2 filters

$$H_0 = (74.9 \pm 1.9)\ km\ s^{-1}\ Mpc^{-1}$$



adH0cc proposal

European Organisation for Astronomical Research in the Southern Hemisphere

OBSERVING PROGRAMMES OFFICE • Karl-Schwarzschild-Straße 2 • D-85748 Garching bei München • e-mail: opo@eso.org • Tel.: +49 89 320 06473

APPLICATION FOR OBSERVING TIME | LARGE PROGRAMME | PERIOD: **104A**

Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of CoIs and the agreement to act according to the ESO policy and regulations, should observing time be granted.

1. Title | Category: **A–7**

An independent measurement of the local Hubble Constant

2. Abstract / Total Time Requested

Total Amount of Time: 0 nights VM, 150.0 hours SM | Total Number of Semesters: 3

An accurate measurement of the Hubble constant, H_0, is critical for the determination of all other cosmological parameters. The most recent determinations have revealed a 4.4σ discrepancy between the local value of H_0, based on the distance ladder approach with Cepheid stars and type Ia supernovae, and the determination from the cosmic microwave background. If this holds up, then ΛCDM is not the complete model of the Universe. A measurement of the local H_0 which does not rely on the distance ladder represents a critical and independent check. We propose to use an extended version of the expanding photosphere method (EPM) of 12 type II-P supernovae to measure distances in the redshift range $0.04 < z < 0.1$. This range avoids significant uncertainties from peculiar velocities of the host galaxies and contributions from the non-linear expansion. There have been significant improvements of EPM in recent years. Simplified blackbody models with average dilution factors have been replaced by state-of-the-art spectral fitting. Good-S/N spectroscopy can be obtained with FORS2 to determine the atmospheric parameters in the supernovae at different epochs. The objects from this project will be combined with our existing data of 20 lower-z type II-P supernovae from the SNfactory ($0.01 < z < 0.05$). With these 32 objects we can independently determine the local H_0 to 3%.

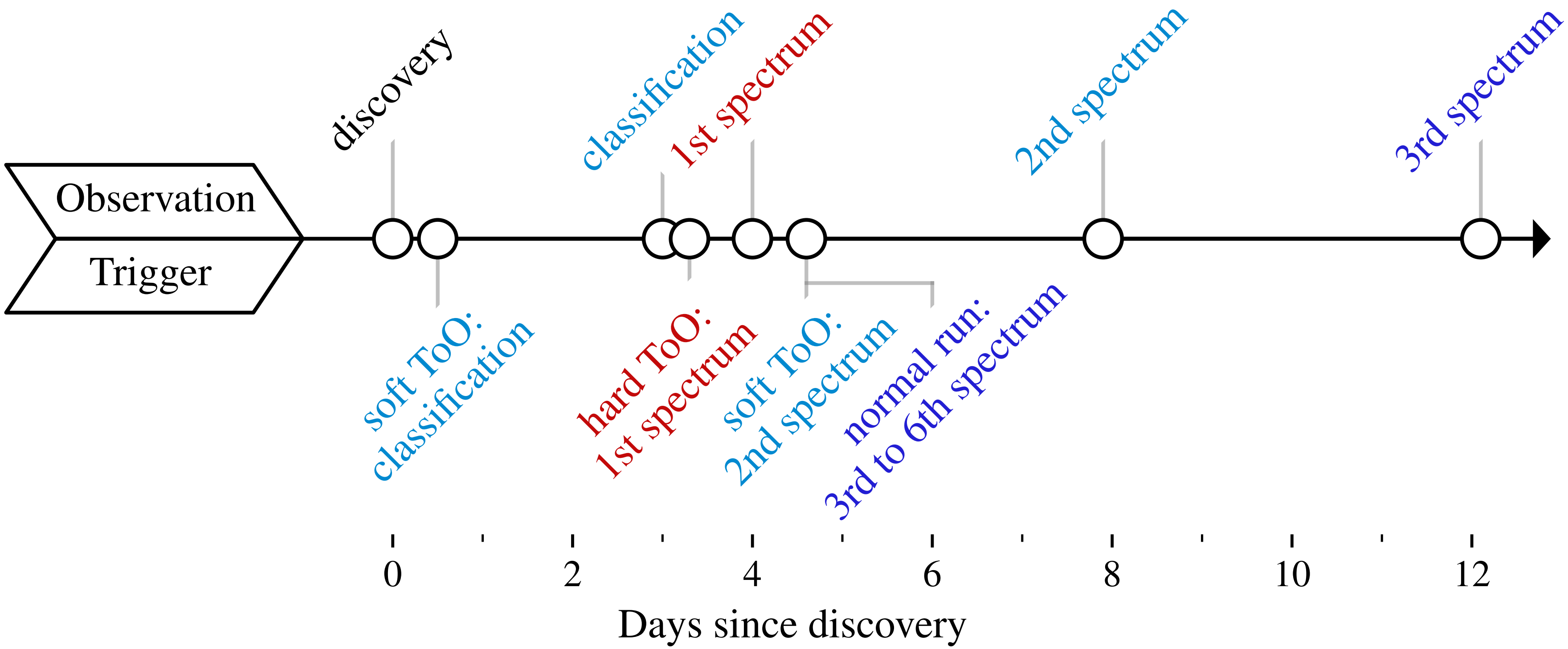
Submission: March 2019
Proposal: 1104.A-0380

FORS2
- low-resolution spectroscopy
  - classification and 6 epochs
- BVRI photometry
  - simultaneous with spectroscopy

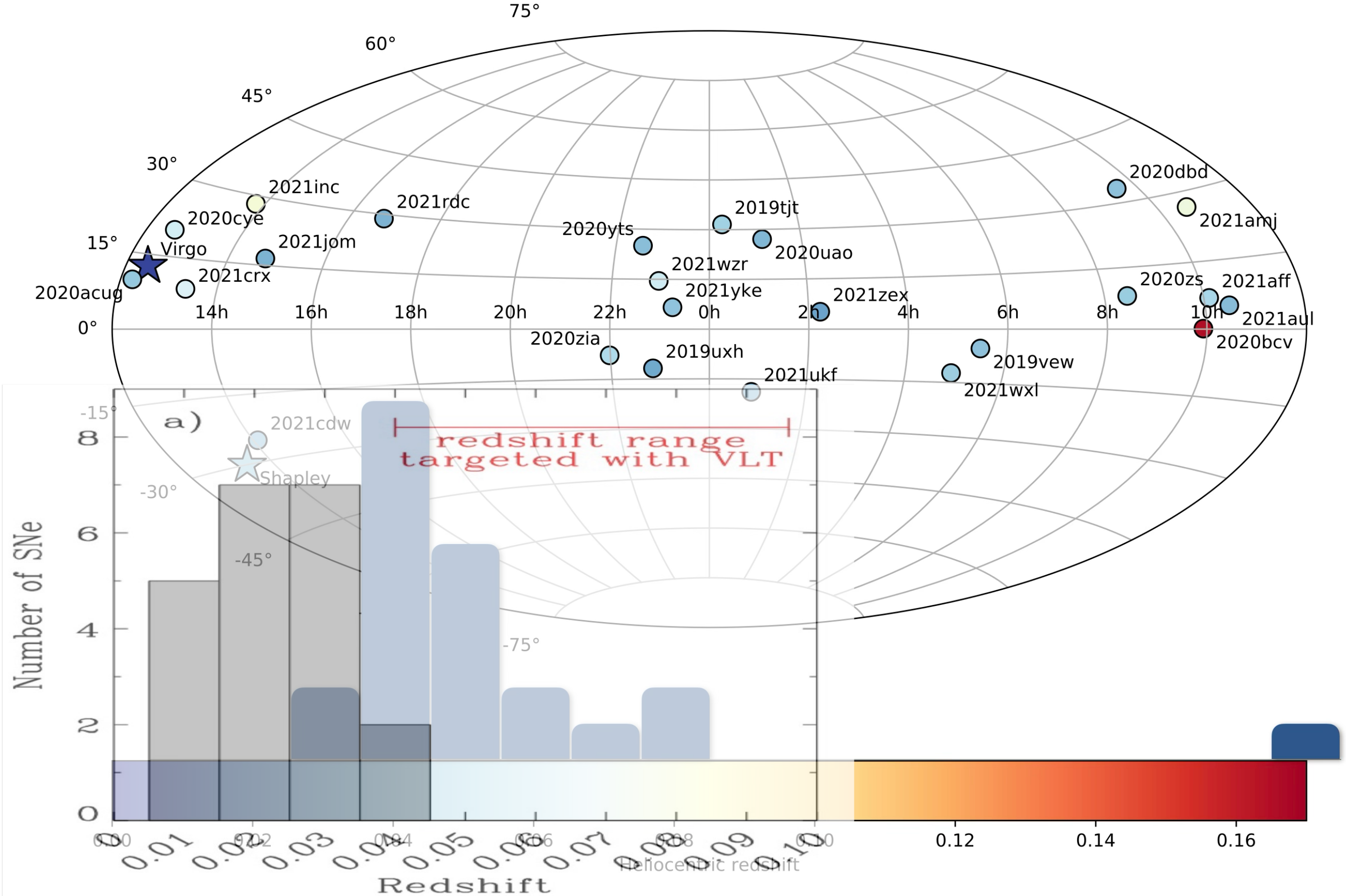
Plan:
12 SNe II-P; 0.04<z<0.1
Combine with 18 SNFactory SNe IIP
H_0 to 3% accuracy

adH0cc observations

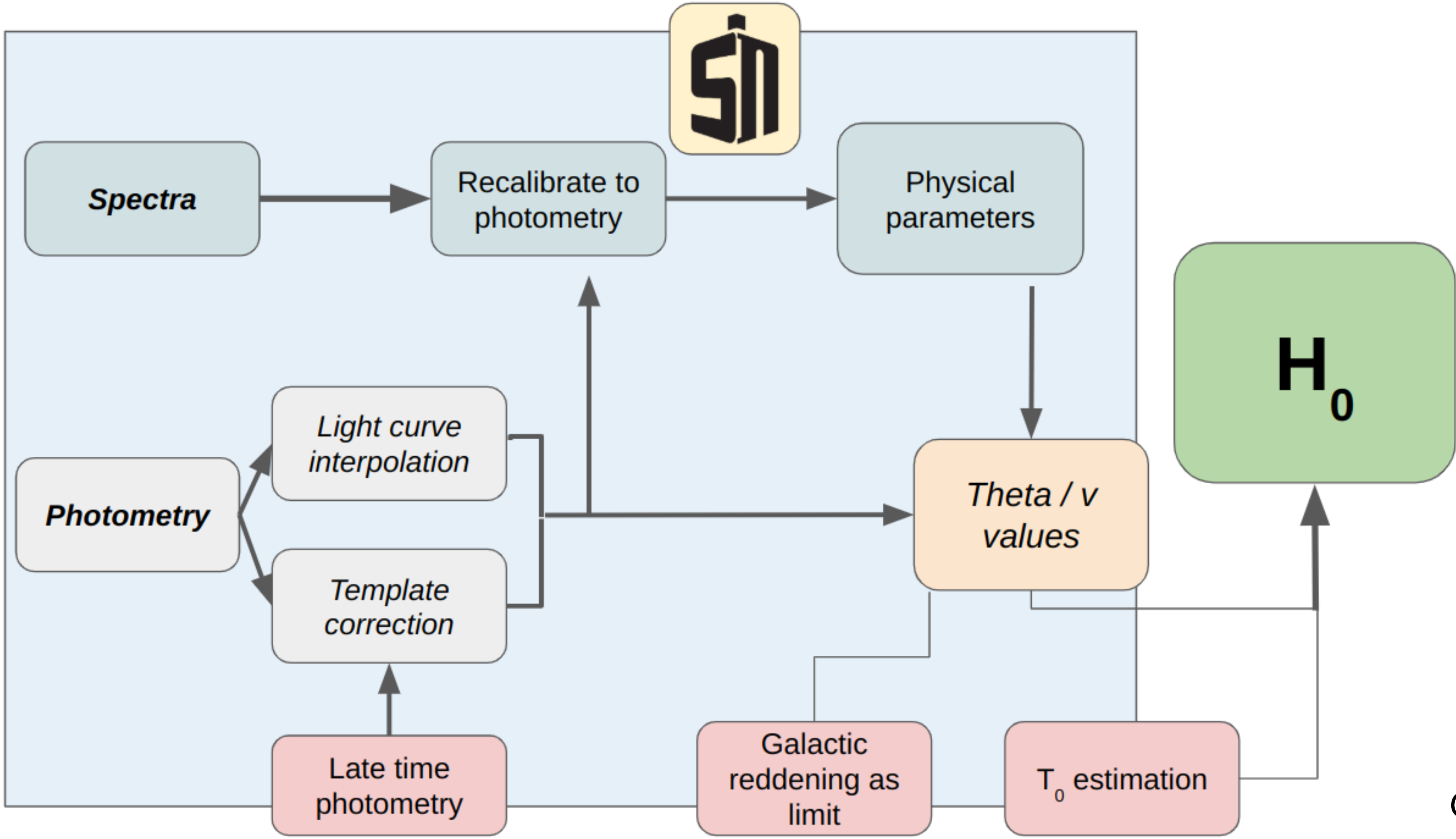
Elaborate scheduling to obtain an optimal coverage (6 epochs per SN)



adH0cc observations



adH0cc analysis

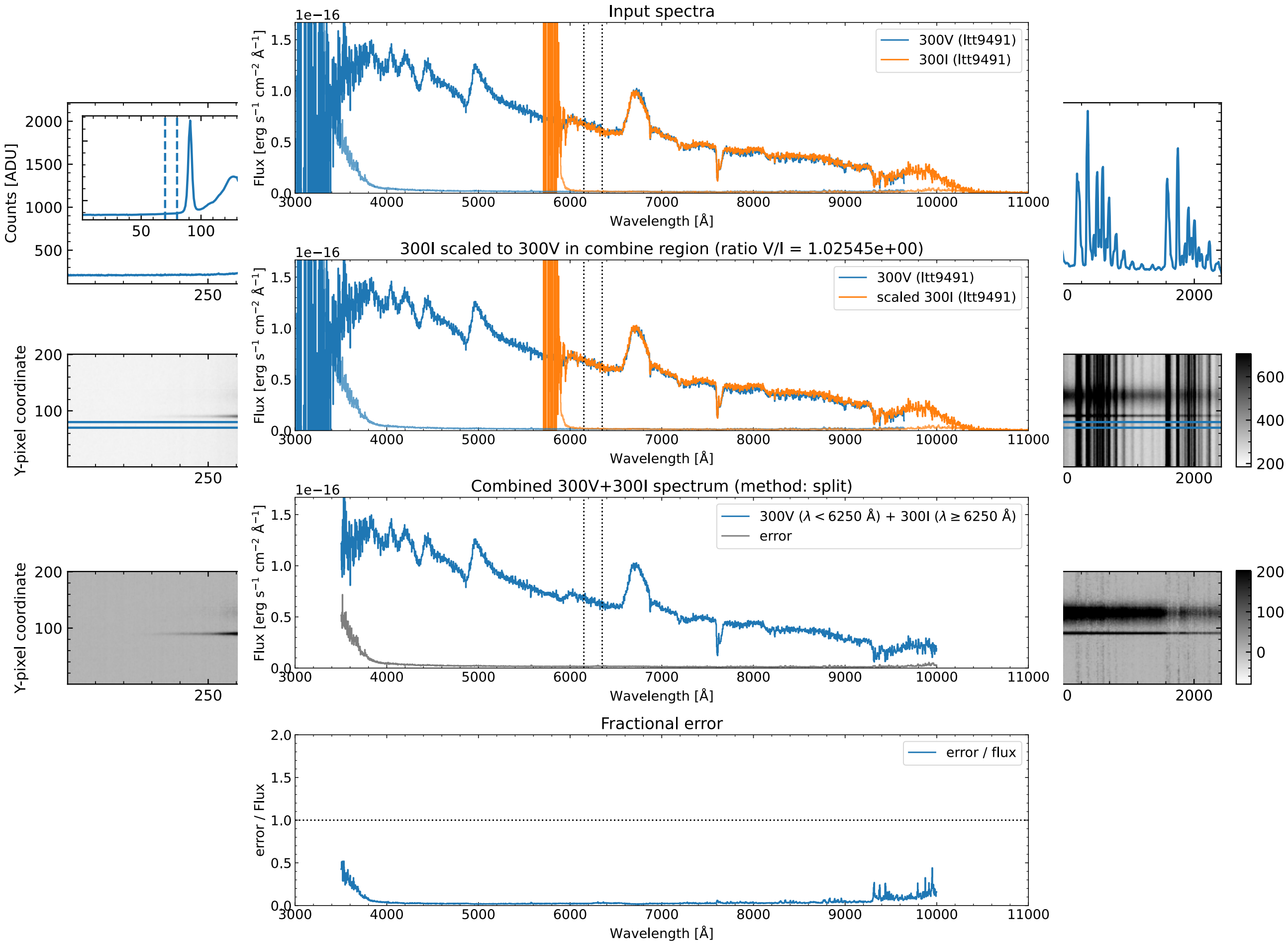


Geza

adH0cc spectroscopy

FORS2 spectra
(Stéphane, Andreas, Jason)

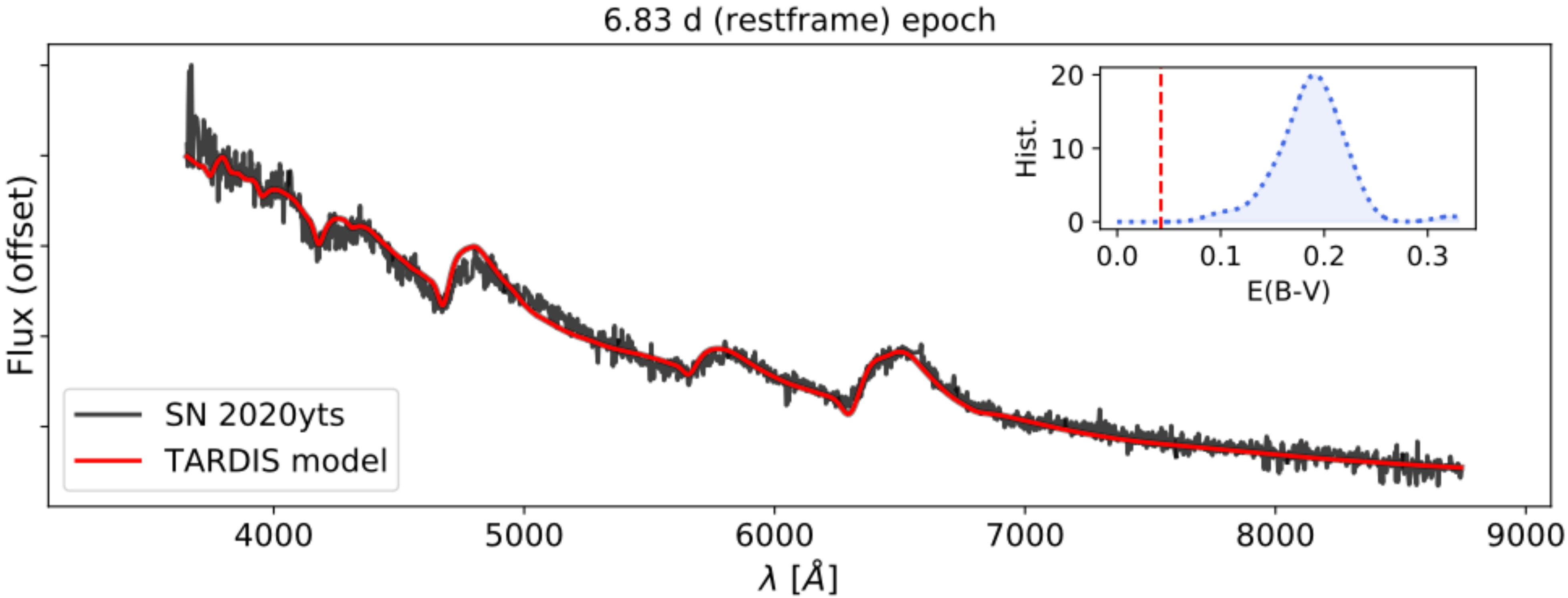
- simulateneous to the photometry
- 300V and 300I grisms



adH0cc distances

Spectral fits (TARDIS)

(Christian, Geza)

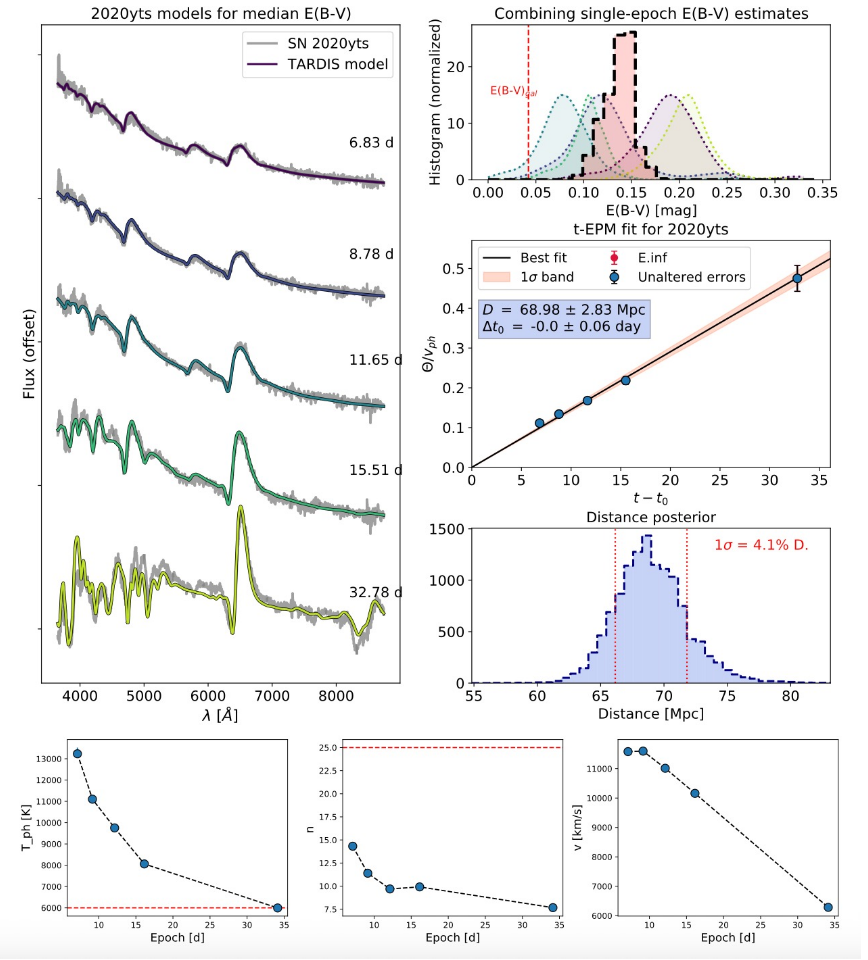


adH0cc distances

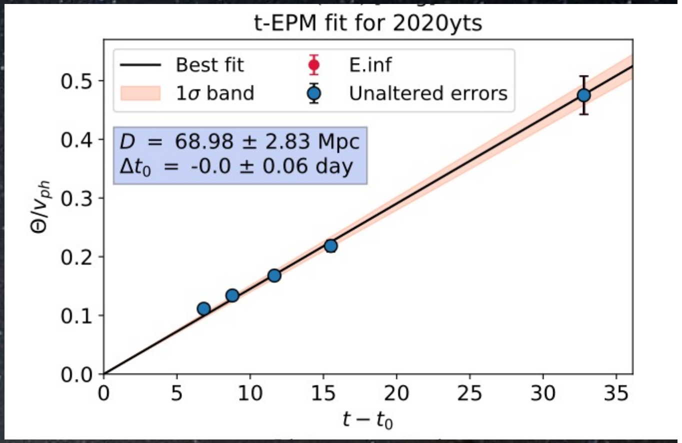
Spectral fits
(Christian, Geza)

→v_{ph}, F_{ph} (T, n)

→E(B-V) from the spectral fit to correct f_{obs}



adH0cc summary



Improved Expanding Photosphere method

- Fit every spectrum to obtain temperature, density gradient and an estimate of the reddening
    - No longer use a fudge factor based on unique models
- Anchor the size expansion through an accurate explosion date

→Tailored Expanding Photosphere Method

→Vogl et al. 2025, A&A accepted (arXiv:2411.04968)

→Significantly improved accuracy

adH0cc summary

- Tested method with literature data
  - $H_0 = (74.9 \pm 1.9)\ km\ s^{-1}\ Mpc^{-1}$
- Tested method with siblings
  - 4 galaxies with good agreement (literature)
  - FORS2 monitoring programme for new siblings
    - already tripled the sample in two years
- Analysis of 19 SNe
  - From a FORS2 Large Programme
  - Analysis still ongoing