The Hubble Tension

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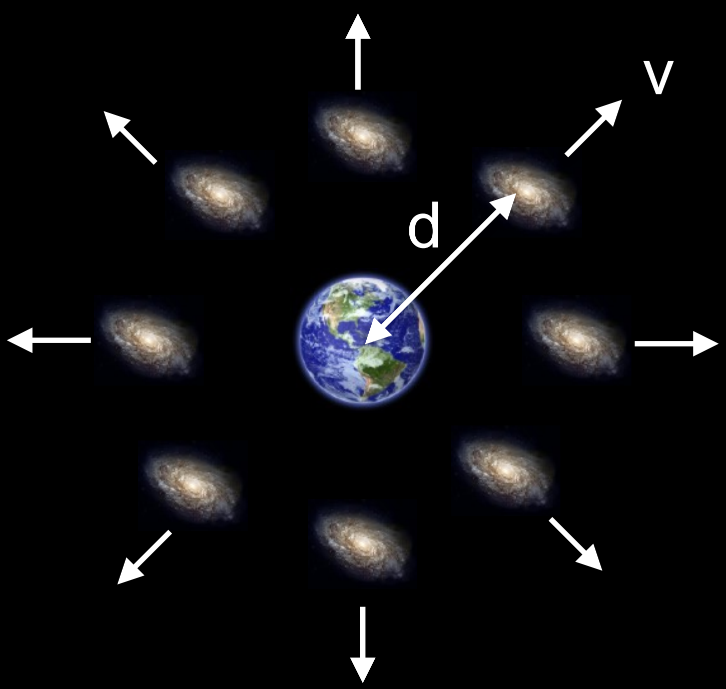
Brookhaven Forum 2021: Opening New Windows to the Universe

Expanding Universe

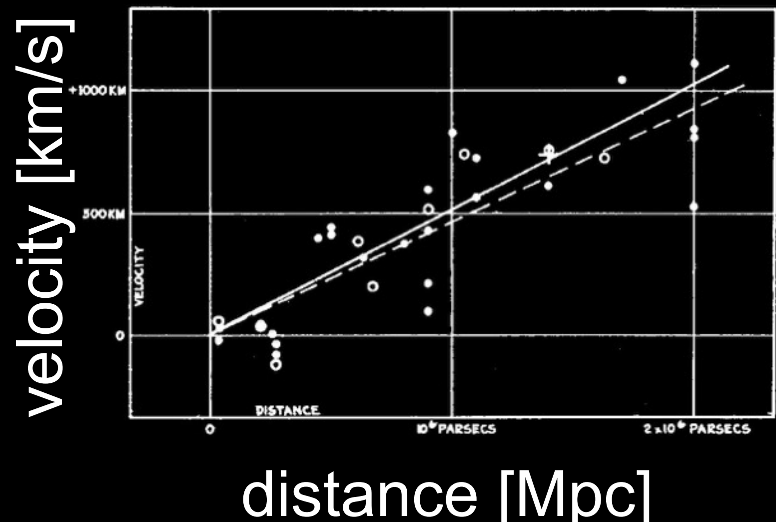
1920s Discovery



Lemaître & Hubble independently measured the expansion rate

$$v = H_0 \times d$$

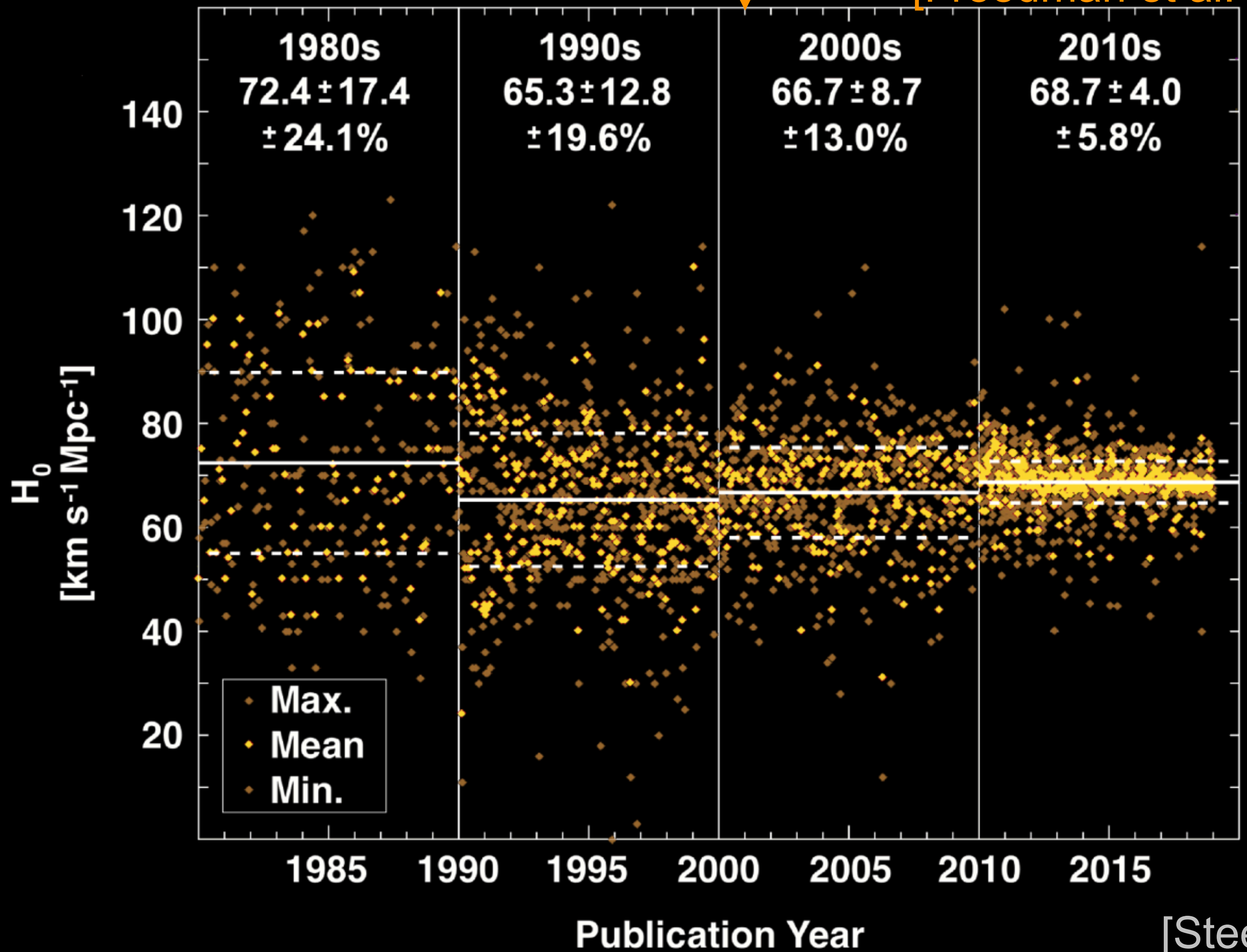
Hubble Constant



H_0 sets age and size of Universe! [Hubble 1929]

Measurements in the last decades

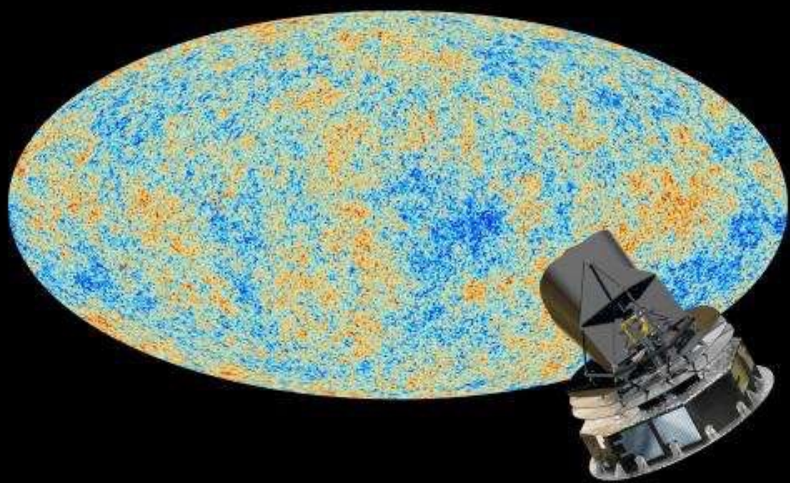
HST Key Project: 72 ± 8
[Freedman et al. 2001]



[Steer 2020]

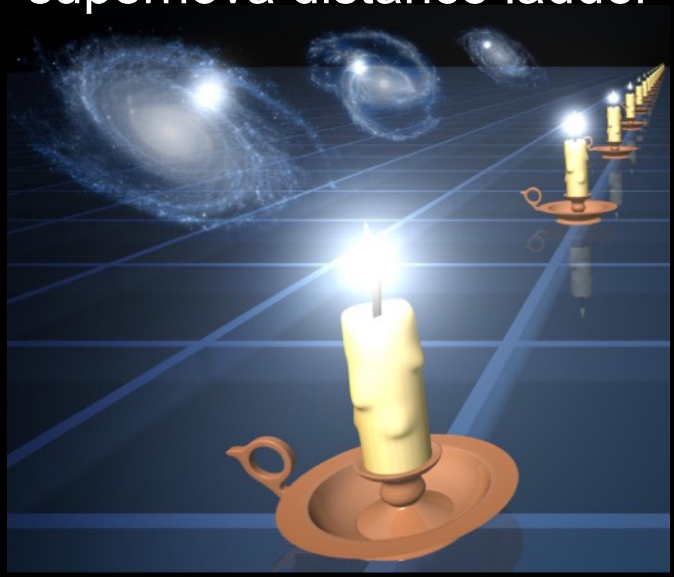
Tension in H_0

Measurement from early universe:
Cosmic Microwave Background



[Planck collaboration 2020]

Measurement from local universe:
supernova distance ladder



[credit: NASA/JPL-Caltech]

SH0ES [Riess et al. 2021]

67.4 ± 0.5
assuming ΛCDM

69.6 ± 0.8 ± 1.7
CCHP [Freedman et al. 2020]

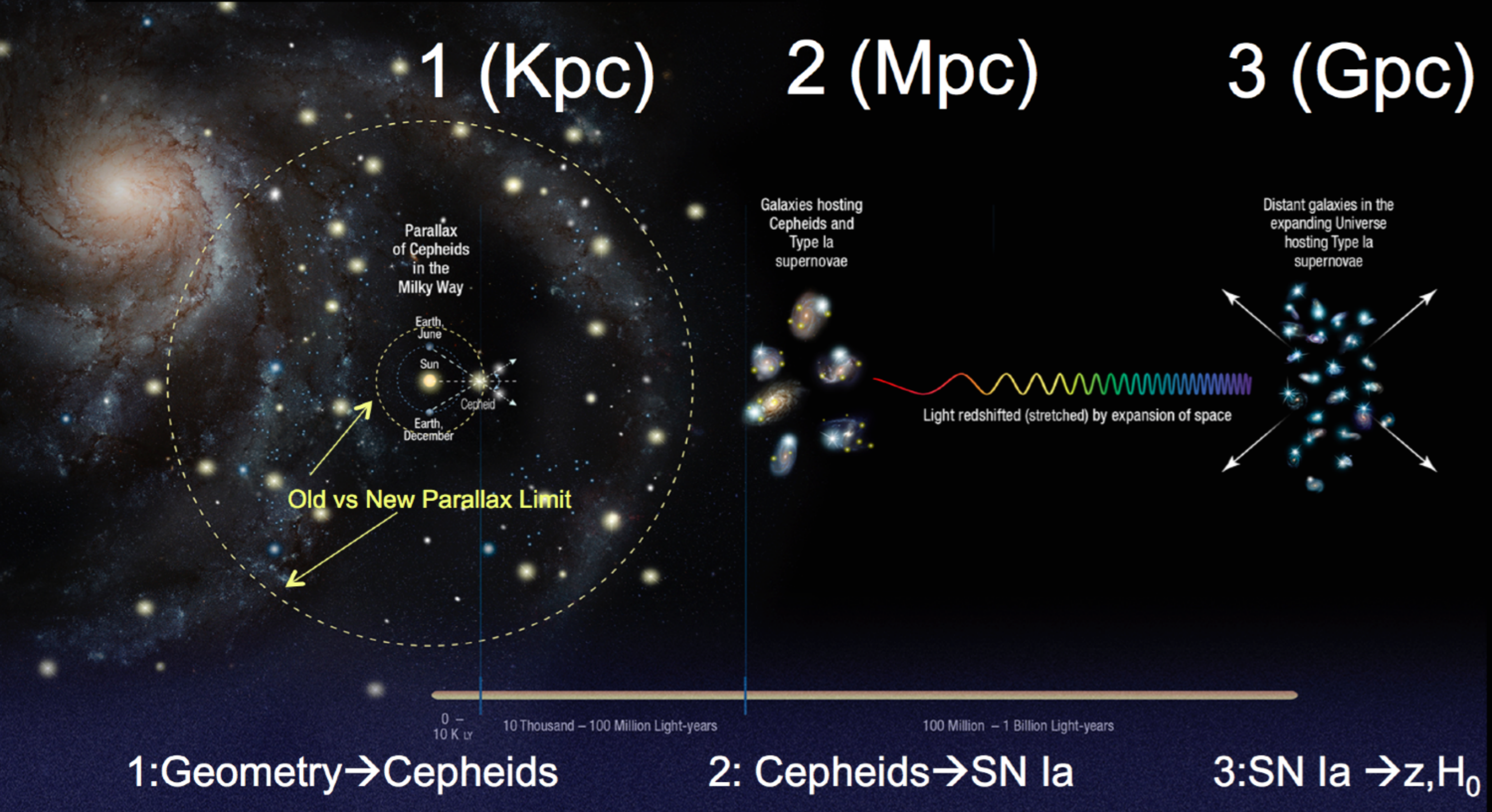
73.2 ± 1.3

H_0 [km^{-1}s^{-1}Mpc^{-1}]

New physics beyond standard cosmological model ΛCDM?

Distance Ladder

ladder to reach objects in Hubble flow ($v_{peculiar} << v_{Hubble} = H_0$ d)



[slide material courtesy of Adam Riess]

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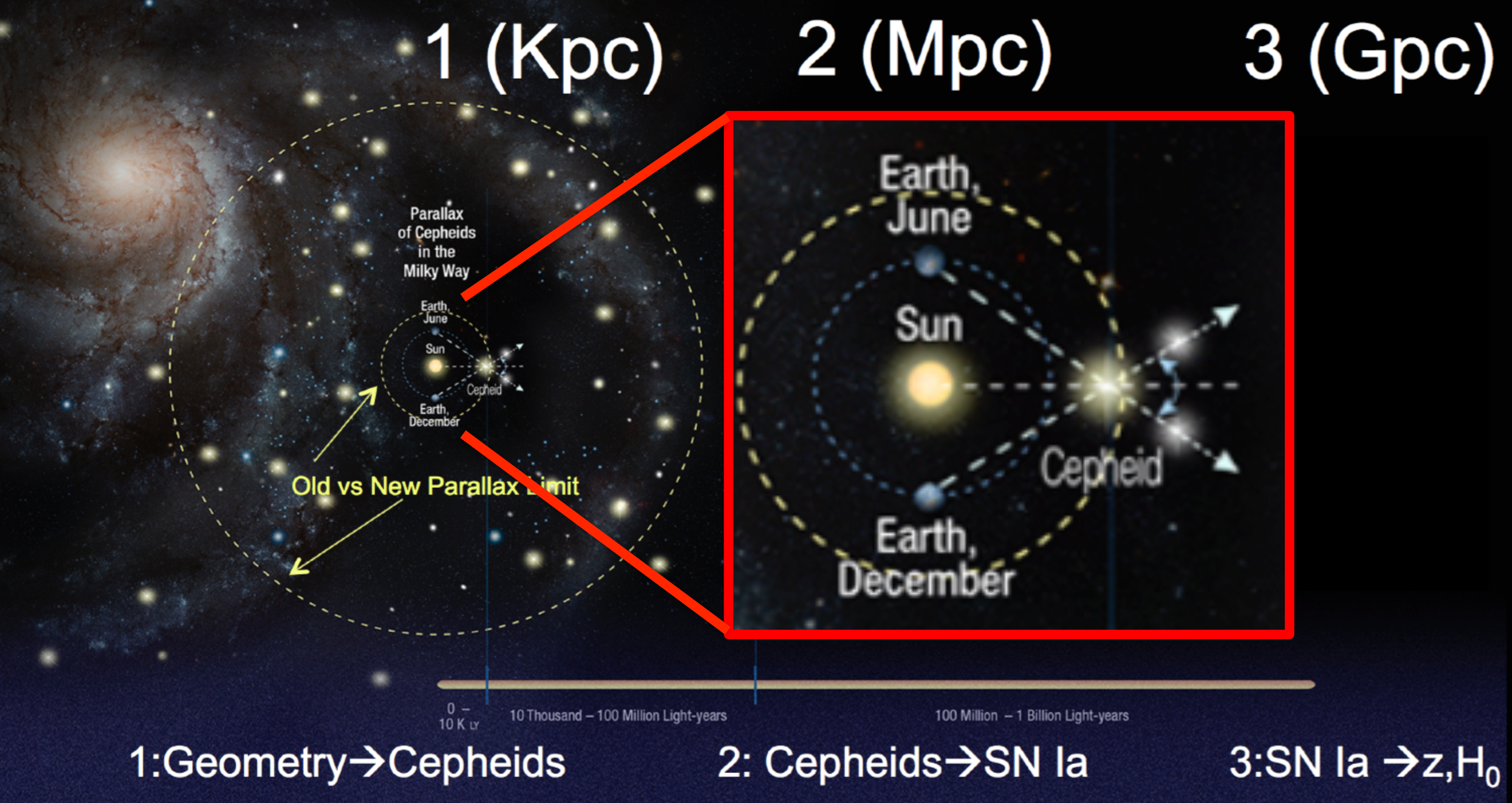
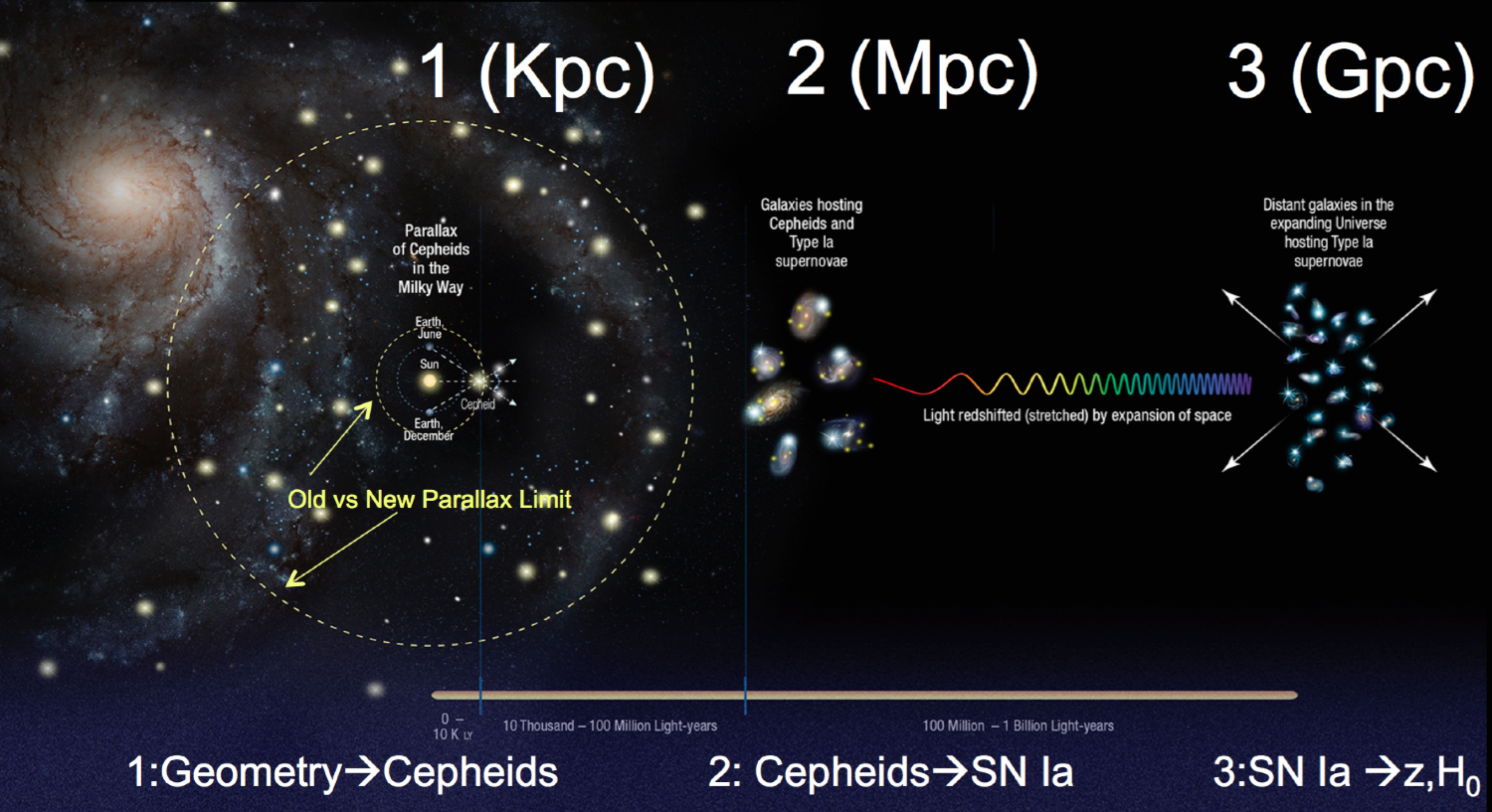


[slide material courtesy of Adam Riess]

Distance Ladder

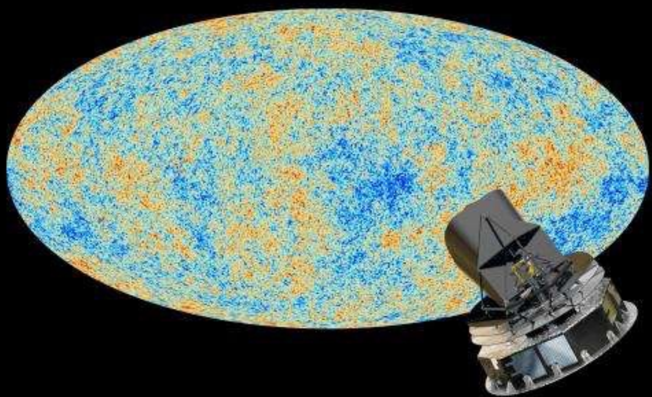
ladder to reach objects in Hubble flow ($v_{peculiar} << v_{Hubble} = H_0$ d)



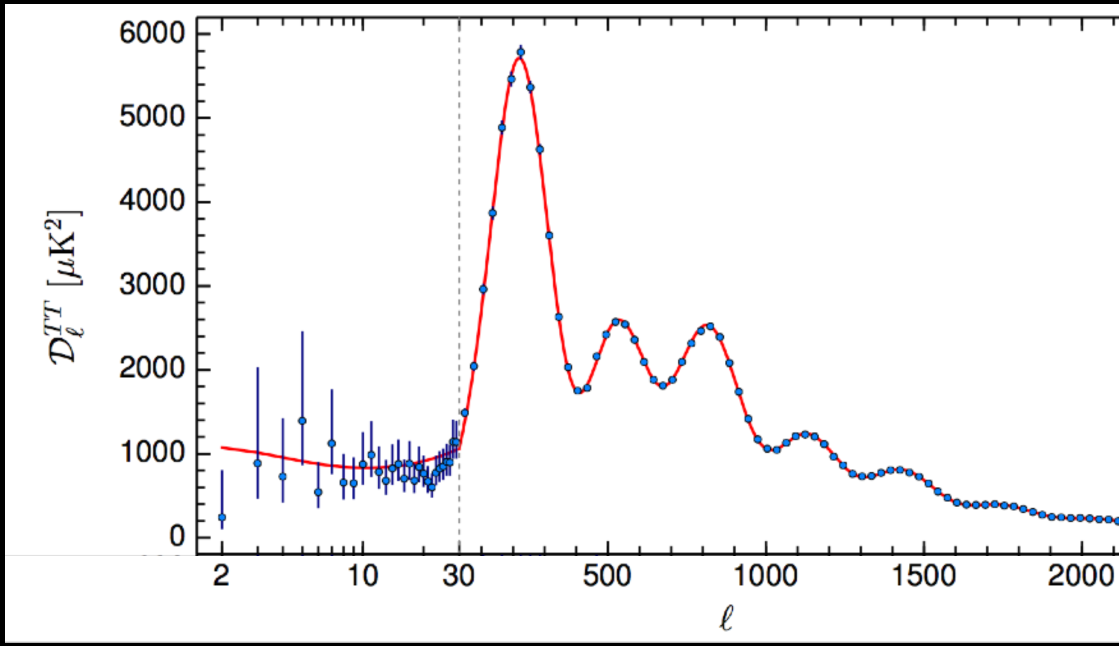
[slide material courtesy of Adam Riess]

Cosmic Microwave Background

CMB Temperature fluctuations



[Planck Collaboration 2016]

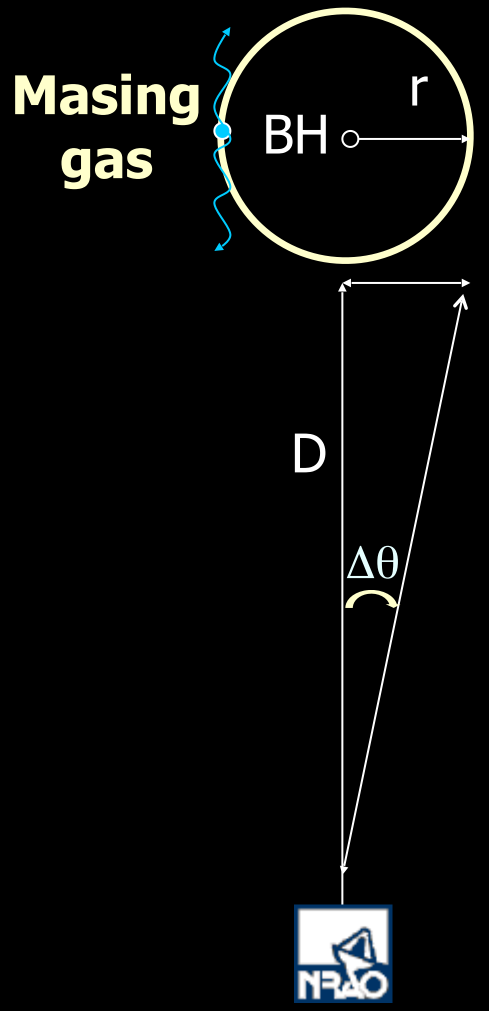


(1) Ratio of peak heights ➜ $\Omega_m h^2$, $\Omega_b h^2$ [h = H_0 / 100 km/s/Mpc]
(2) Location of the first peak in **flat ΛCDM** ➜ $\Omega_m h^{3.2}$

- Under **flat ΛCDM** assumption, (1) and (2) yield
  $h = 0.674 \pm 0.005$ [Planck collaboration 2020]
- Without **flat ΛCDM** assumption, *h* highly degenerate with other cosmological parameters (e.g., curvature, *w*, $N_{\rm eff}$)

Megamasers

Direct distance measurement without any calibration on distance ladder



1. Distance : $D = r / \Delta\theta$ (for $D >> r$)

2. Gravitational acceleration in a circular orbit :

$$a = V_0^2 / r \quad \Rightarrow \quad r = V_0^2 / a$$

$$\boxed{D = V_0^2 / a\,\Delta\theta}$$

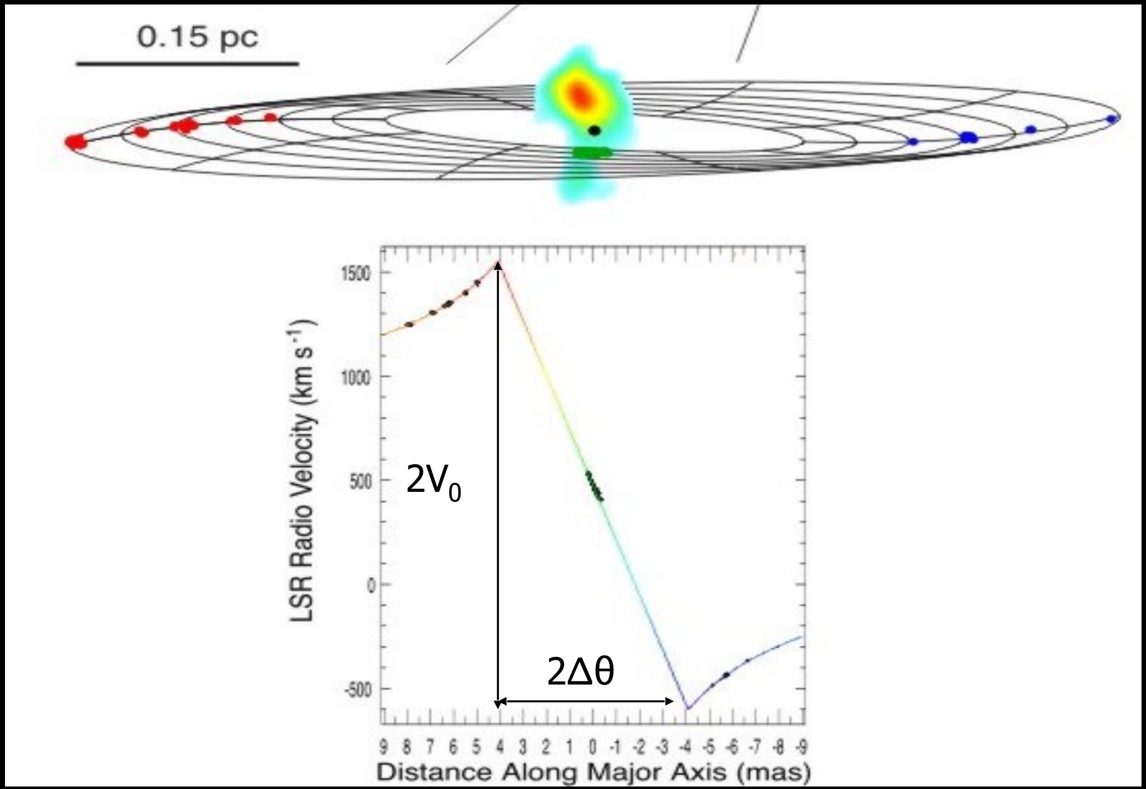
$$\boxed{D = V_0^2 \sin i / a\,\Delta\theta}$$

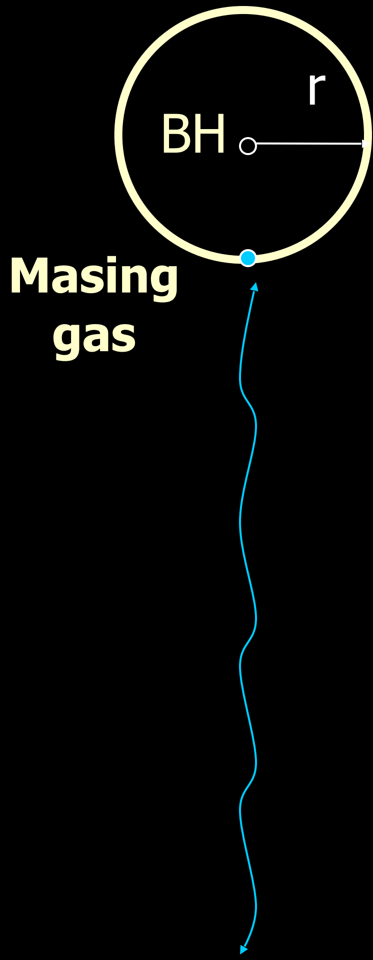
[slide material courtesy of Cheng-Yu Kuo]

Megamasers

$$D = V_0^2 \sin i \,/\, a\, \Delta\theta$$

How to measure V_0, $\Delta\theta$, a and i?





[slide material courtesy of Cheng-Yu Kuo]

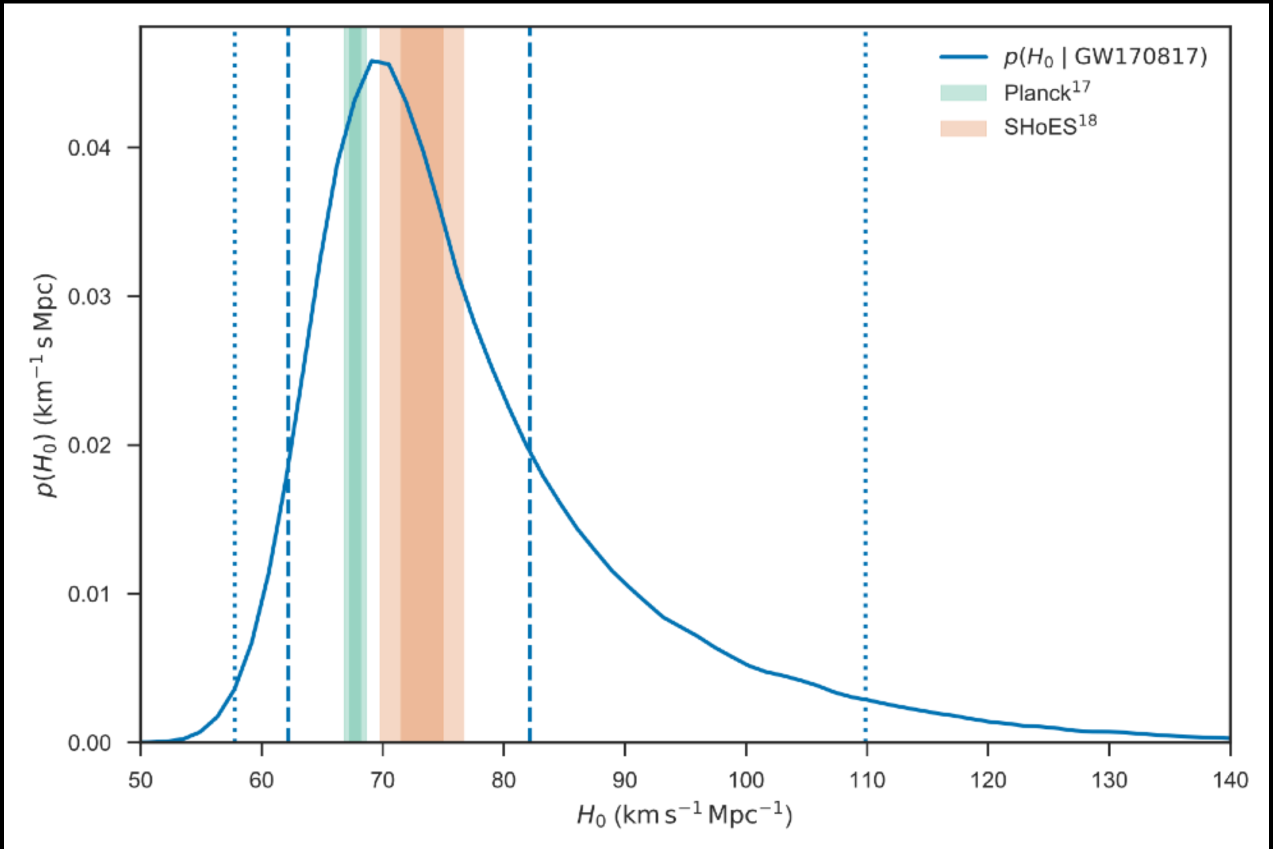
Standard Siren

Gravitational wave form ➜ luminosity distance D
Measure recessional velocity of EM counterpart v

$H_0 = v / D$

[Image credit: M. Garlick]

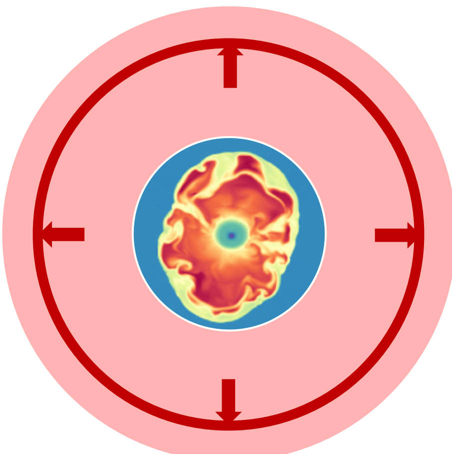
GW170817: First measurement of H_0



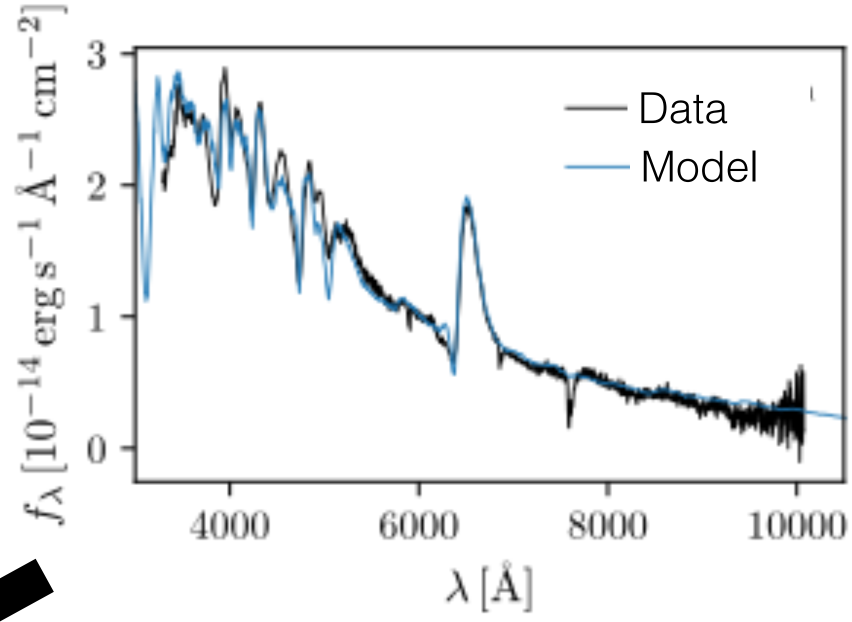
[LIGO, VIRGO, 1M2H, DES, DLT40, LCO, VINROUGE, MASTER collaborations, 2017]

Type II supernovae

Radiation comes from photosphere in simple hydrogen-rich medium



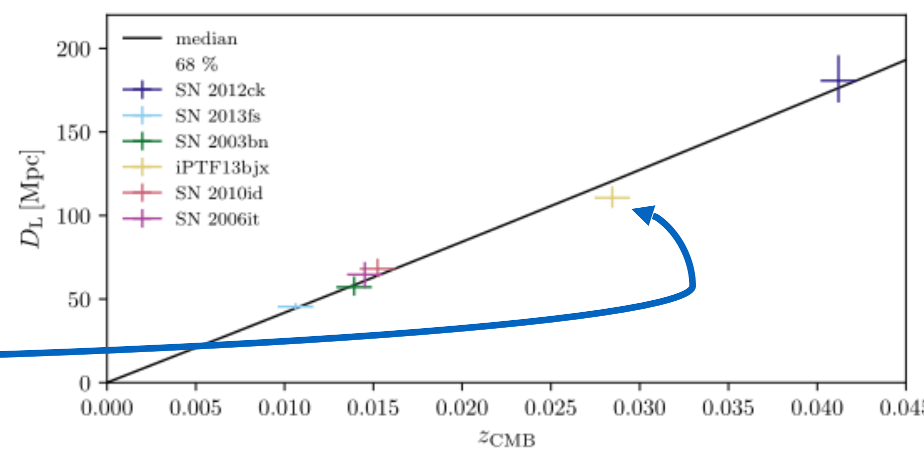
can be modeled accurately



Luminosity

Distance

Hubble constant



[slide material courtesy of Christian Vogl]

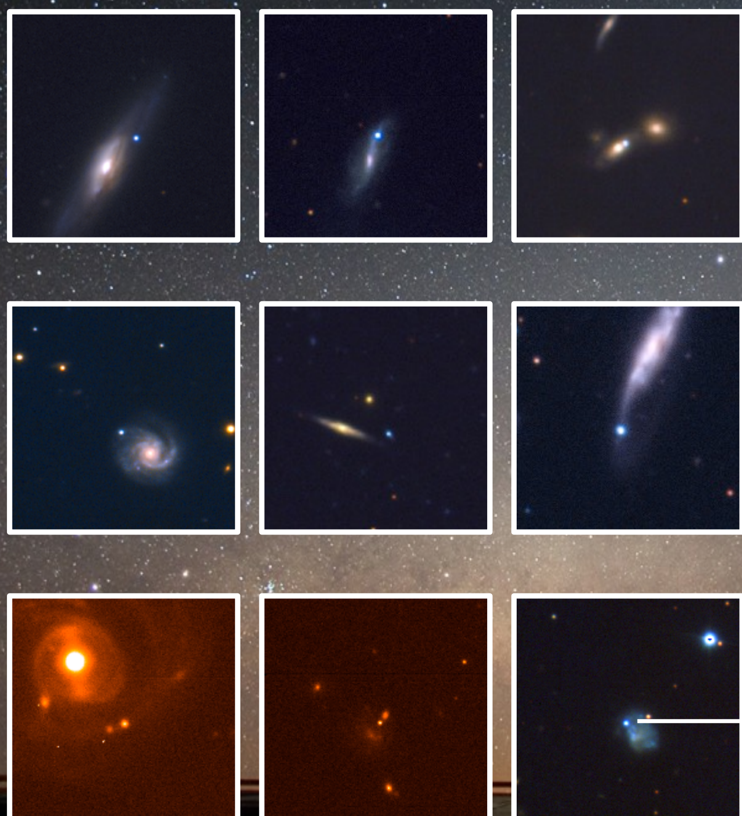
adH0cc

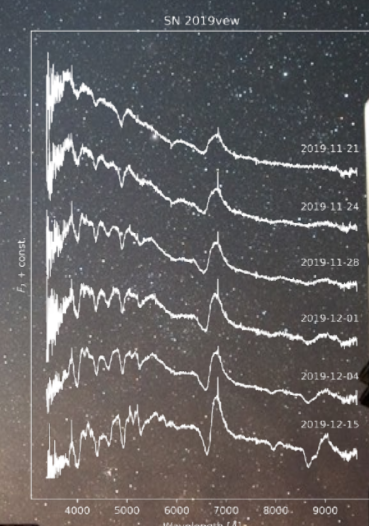
accurate determination of H_0 from core-collapse supernovae

https://adh0cc.github.io/

VLT large programme: ~150 hours over three semesters

MPA, ESO, TUM, GSI, QUB, LAM, Turku, WIS, EPFL





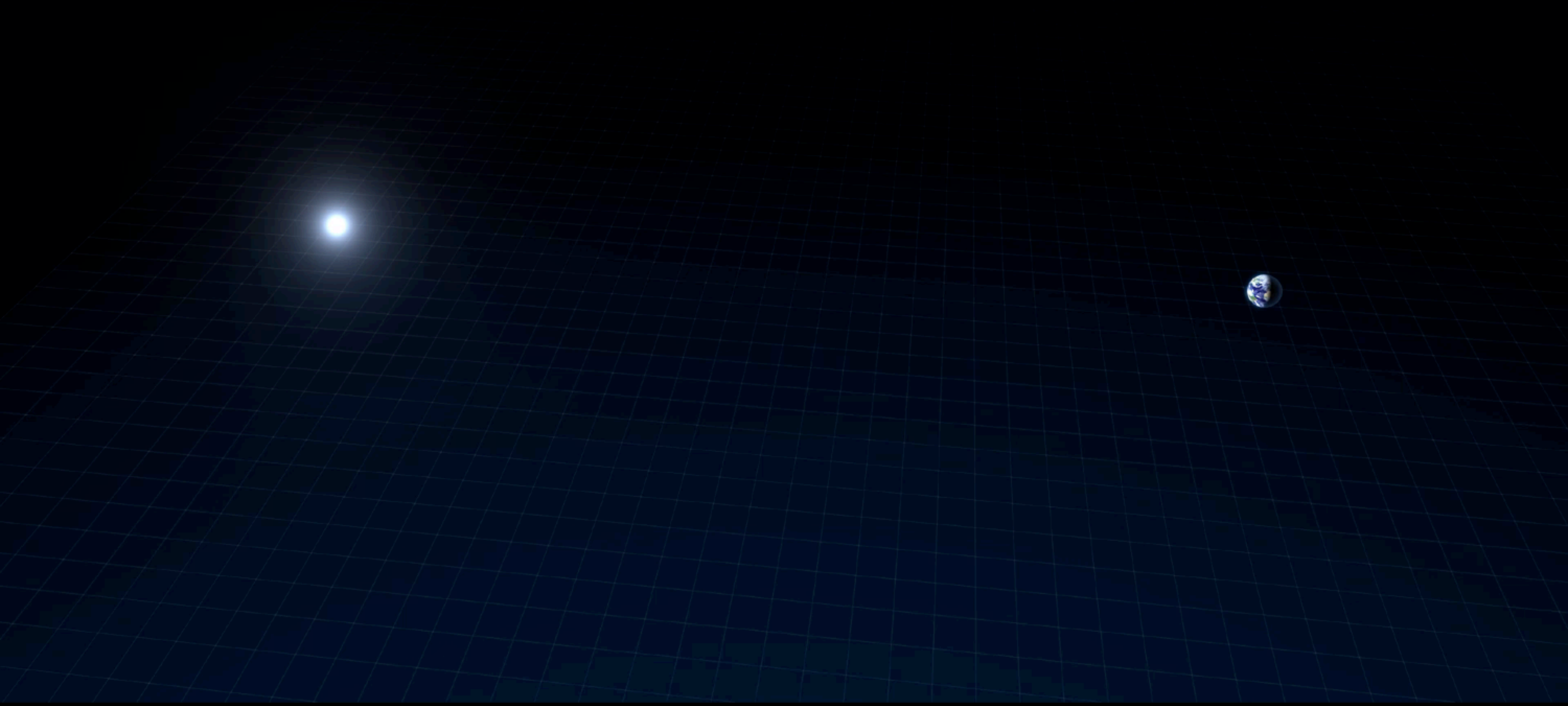
Observations are finished:
26 objects at z > 0.03

→ H_0 to < 3%

[slide material courtesy of Christian Vogl]

Image: ESO/Y. Beletsky

Strong gravitational lensing

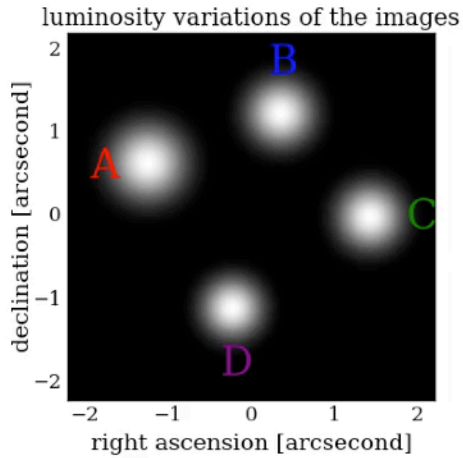


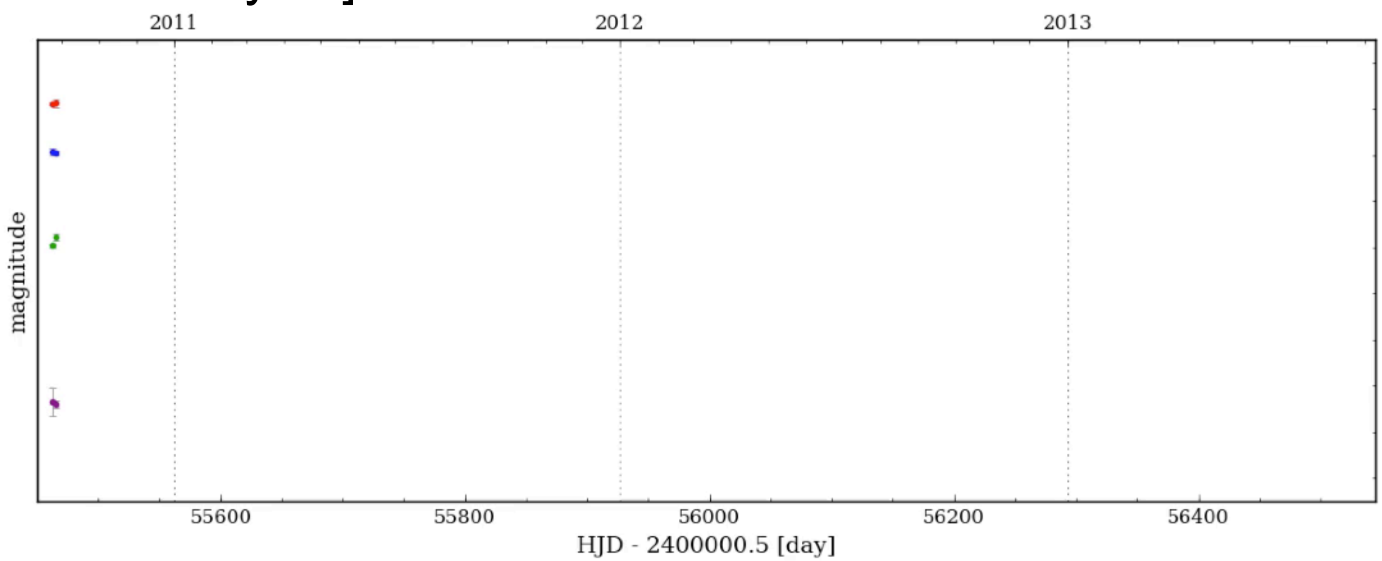
[Credit: ESA/Hubble, NASA]

Cosmology with time delays

[**COS**mological
MOnitoring of
GRAv**I**tational
Lenses;

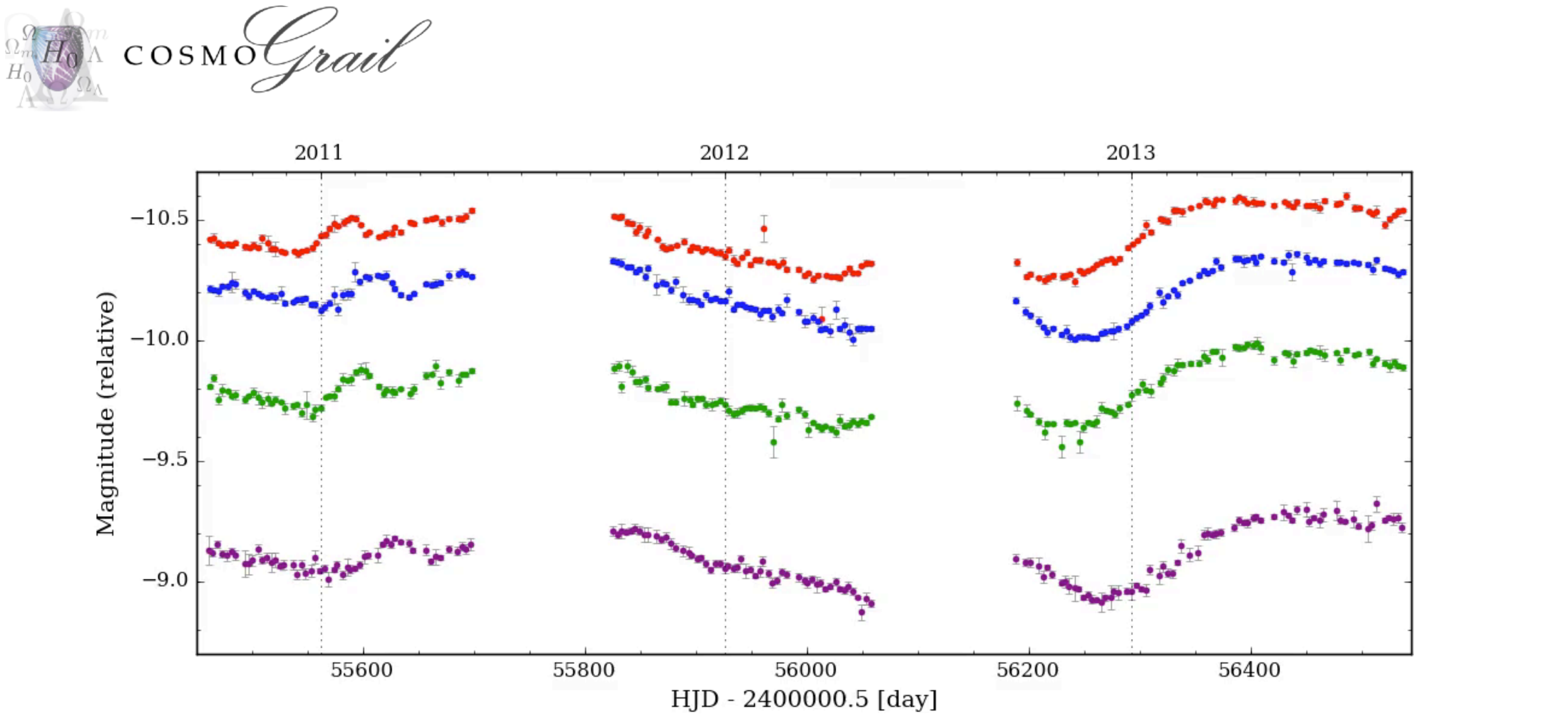
PI: F. Courbin,
G. Meylan]





[Credit: V. Bonvin]

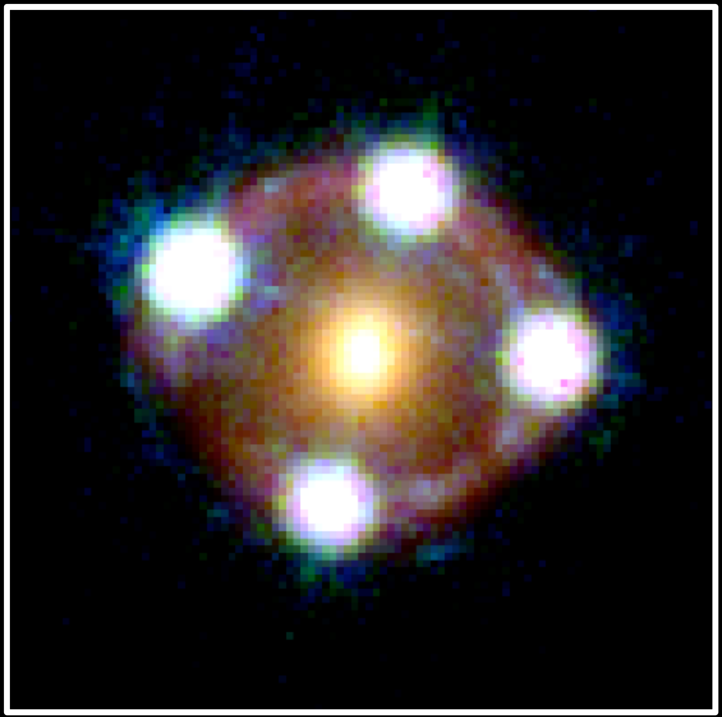
Cosmology with time delays



[Credit: V. Bonvin]

Cosmology with time delays

HE0435-1223



[Suyu et al. 2017]

Time delay:

$$t = \frac{1}{c} D_{\Delta t} \, \phi_{\text{lens}}$$

Time-delay distance:

$$D_{\Delta t} \propto \frac{1}{H_0}$$

Obtain from lens mass model

[Refsdal 1964]

For cosmography, need:
(1) time delays
(2) lens mass model
(3) mass along line of sight

Advantages:
- simple geometry & well-tested physics
- one-step physical measurement of a cosmological distance

TDCOSMO H_0 measurements

No assumption on the radial mass density profile of the lens galaxy

Galaxies are described by power law/stars+NFW mass profile

$73.3^{+1.7}_{-1.8}$ km s^{-1} Mpc^{-1}

H0LiCOW

$74.0^{+1.7}_{-1.8}$ km s^{-1} Mpc^{-1}

TDCOSMO (NFW + stars/constant M/L)

$74.2^{+1.6}_{-1.6}$ km s^{-1} Mpc^{-1}

TDCOSMO (power-law)

Assuming SLACS lenses and TDCOSMO lenses share the same anisotropy property

$73.3^{+5.8}_{-5.8}$ km s^{-1} Mpc^{-1}

TDCOSMO+SLACS$_{IFU}$ (anisotropy constraints from 9 SLACS lenses)

Assuming SLACS lenses and TDCOSMO lenses share the same anisotropy and radial mass density property

$67.4^{+4.1}_{-3.2}$ km s^{-1} Mpc^{-1}

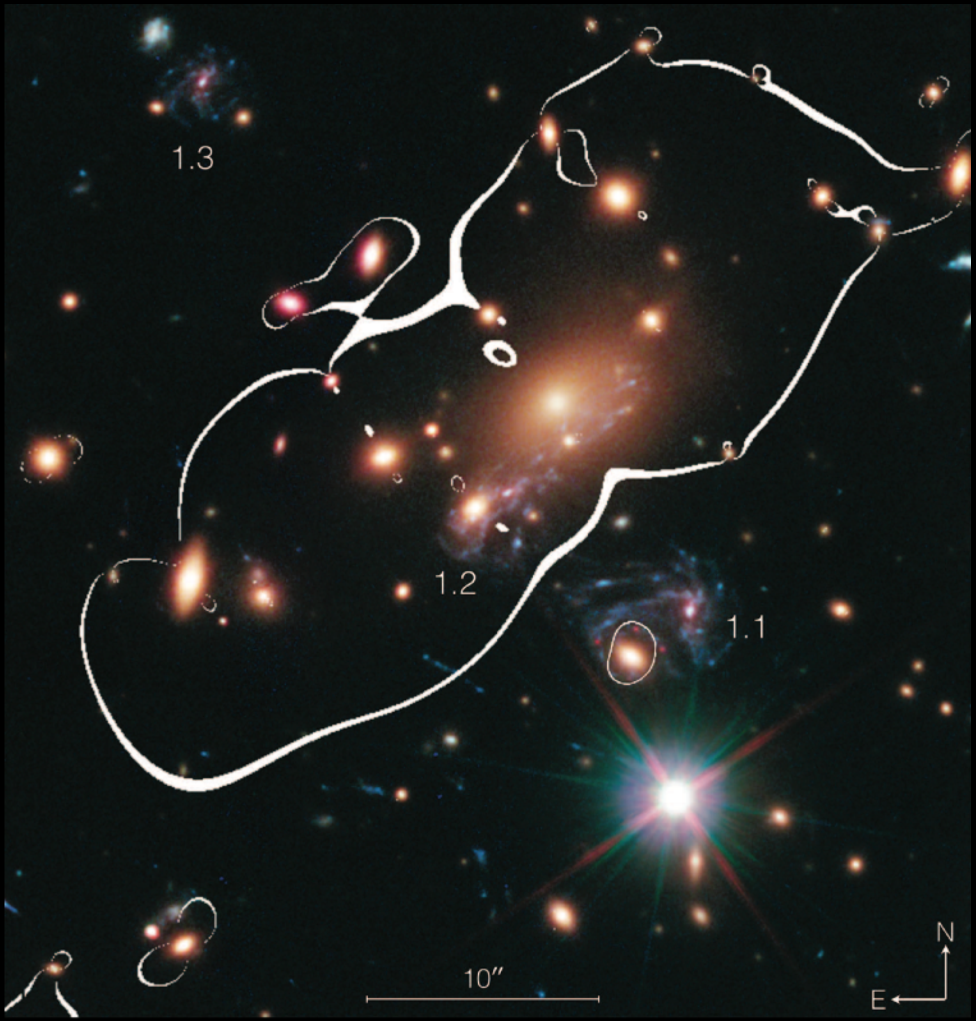
TDCOSMO+SLACS$_{SDSS+IFU}$ (anisotropy and profile constraints from SLACS)

Birrer et al. 2020
Millon et al. 2020
Shajib et al. 2020
Wong et al. 2020
Chen et al. 2019

[Slide credit: Geoff C.-F. Chen]

Strongly lensed supernovae

SN Refsdal

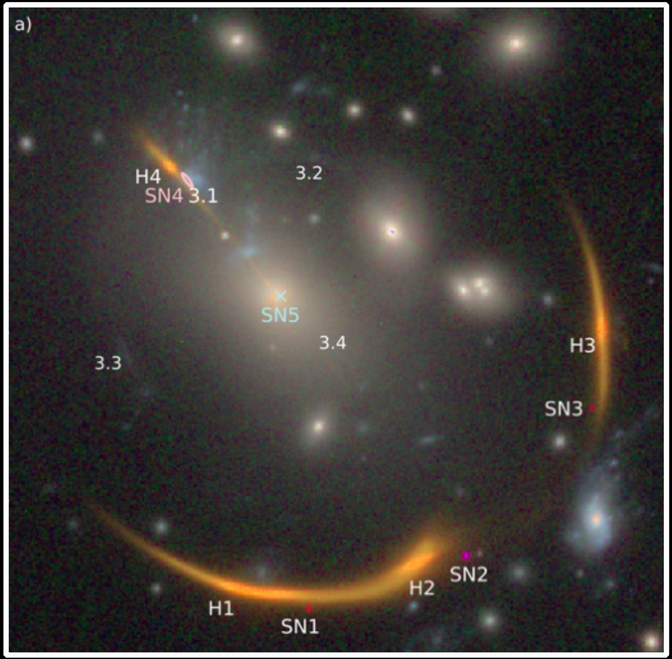


[Kelly et al. 2015]

iPTF16geu

[Goobar et al. 2017; image credit: NASA/ESA]

SN Requiem



[Rodney et al. 2021]

HOLISMOKES

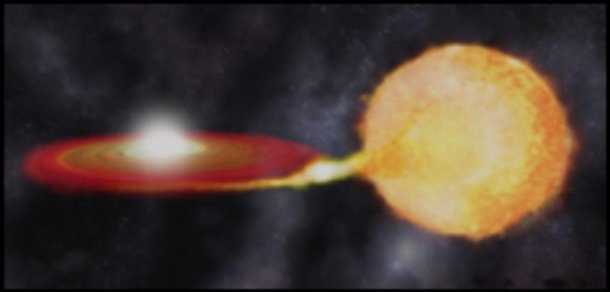
Highly **O**ptimised **L**ensing **I**nvestigations of **S**upernovae, **M**icrolensing **O**bjects, and **K**inematics of **E**llipticals and **S**pirals

PI: S. H. Suyu

Lensed supernovae provide great opportunities for

1) Measuring the expansion rate of our Universe
2) Constraining the progenitor of Type Ia supernova

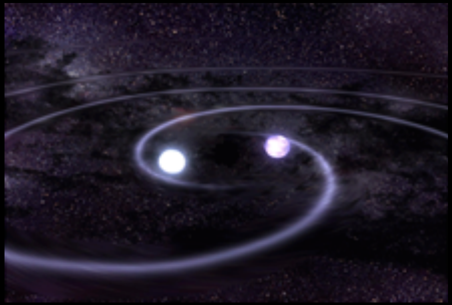
single degenerate



White dwarf (WD) accreting from non-degenerate companion

or

double degenerate

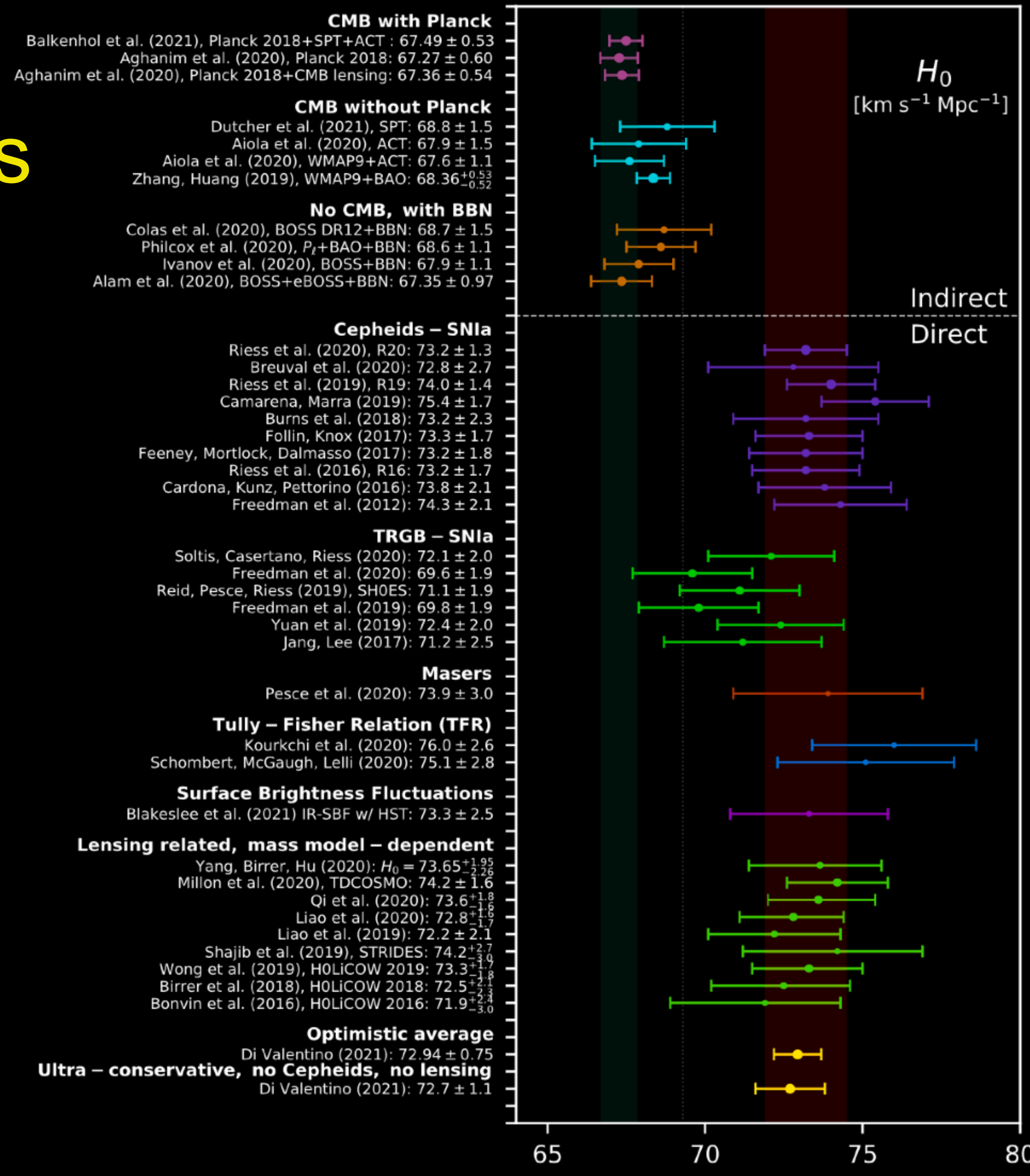


WDs merging

[Suyu, Huber, Cañameras et al. 2020]

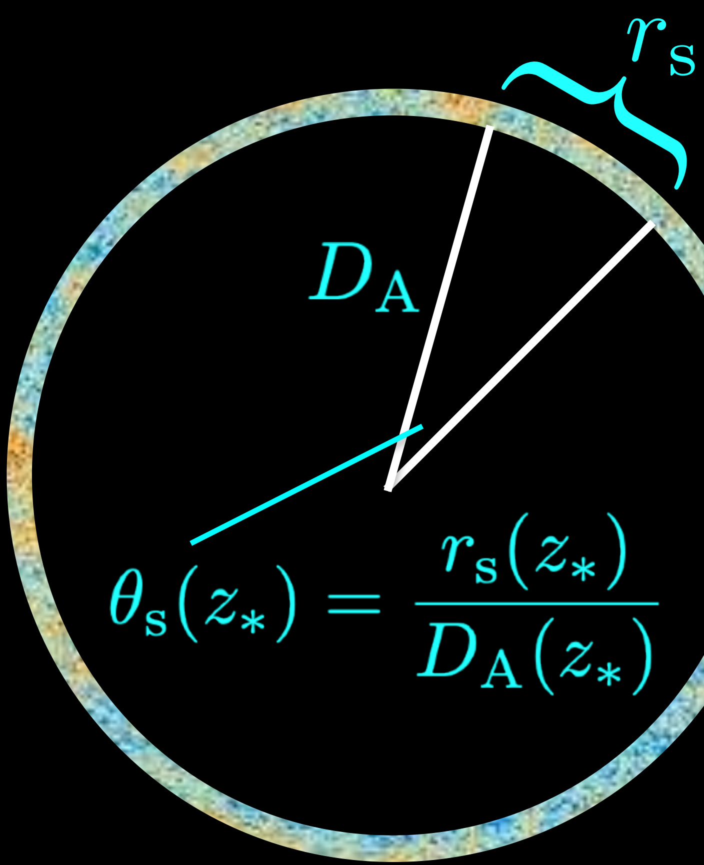
Recent H_0 measurements

[Di Valentino et al. 2021]



How to resolve the Hubble tension?

Cosmic Microwave Background (CMB)



Last scattering surface

$r_\mathrm{s}(z_*)$ = sound horizon at last scattering surface

$D_\mathrm{A}(z_*)$ = angular diameter distance

$\theta_\mathrm{s}(z_*)$ = angular scale of the sound horizon

➜ measured with 0.03% precision by Planck Collaboration (2020)

[parts of slide content courtesy of Elisa Ferreira]

How to resolve the Hubble tension?

r_s: pre-recombination physics
➜ depends on physical densities
(baryons, radiation, CDM, neutrinos)

$$\theta_{\mathrm{s}} = \frac{r_{\mathrm{s}}(z_*)}{D_{\mathrm{A}}(z_*)}$$

D_A: post-recombination physics
➜ information on H_0

$\theta_{\mathrm{s}}(z_*)$ = angular scale of the sound horizon

$r_{\mathrm{s}}(z_*)$ = sound horizon at last scattering surface

$D_{\mathrm{A}}(z_*)$ = angular diameter distance

[parts of slide content courtesy of Elisa Ferreira]

How to resolve the Hubble tension?

$$\theta_{\rm s} = \frac{r_{\rm s}(z_*)}{D_{\rm A}(z_*)} = \frac{\int_{z_*}^{\infty} c_s(z)dz/H(z)}{\int_0^{z_*} c\,dz/H(z)}$$

where in flat LCDM cosmological model:

$$H(z) = 100\,h(z)\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

$$h(z) = \sqrt{\Omega_{\rm r}h^2(1+z)^4 + \Omega_{\rm m}h^2(1+z)^3 + \Omega_\Lambda h^2}$$

$$h = \frac{H_0}{100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}}$$

Solution to resolve Hubble tension given fixed θ_s:
change $r_s(z_*)$ or h through changes to H(z), c_s, or z_*

[parts of slide content courtesy of Elisa Ferreira]

Ways to change H(z)

- early dark energy
- additional relativistic species
  (extra "dark" radiation at recombination)
  - sterile neutrinos
  - thermal axions
  - decaying dark matter
  - self-interacting dark matter
- spatial curvature of the Universe (non-flat)
- late dark energy
- …

[e.g., Di Valentino et al. 2021 for review]

Early vs. late time solutions

$$\theta_s = \frac{r_s(z_*)}{D_A(z_*)} = \frac{\int_{z_*}^{\infty} c_s(z)dz/H(z)}{\int_0^{z_*} c\,dz/H(z)}$$

Early Universe Solutions

- Change only early time physics, late time almost unaffected
- fixed $\theta_s(z_*)$
  ➜ decrease $r_s(z_*)$
  ➜ decrease $D_A(z_*)$
  ➜ increase H_0

[e.g., Poulin+2019; Agrawal+2019; Smith+2019; Knox & Melia 2019; Di Valentino+2021]

Late Universe Solutions

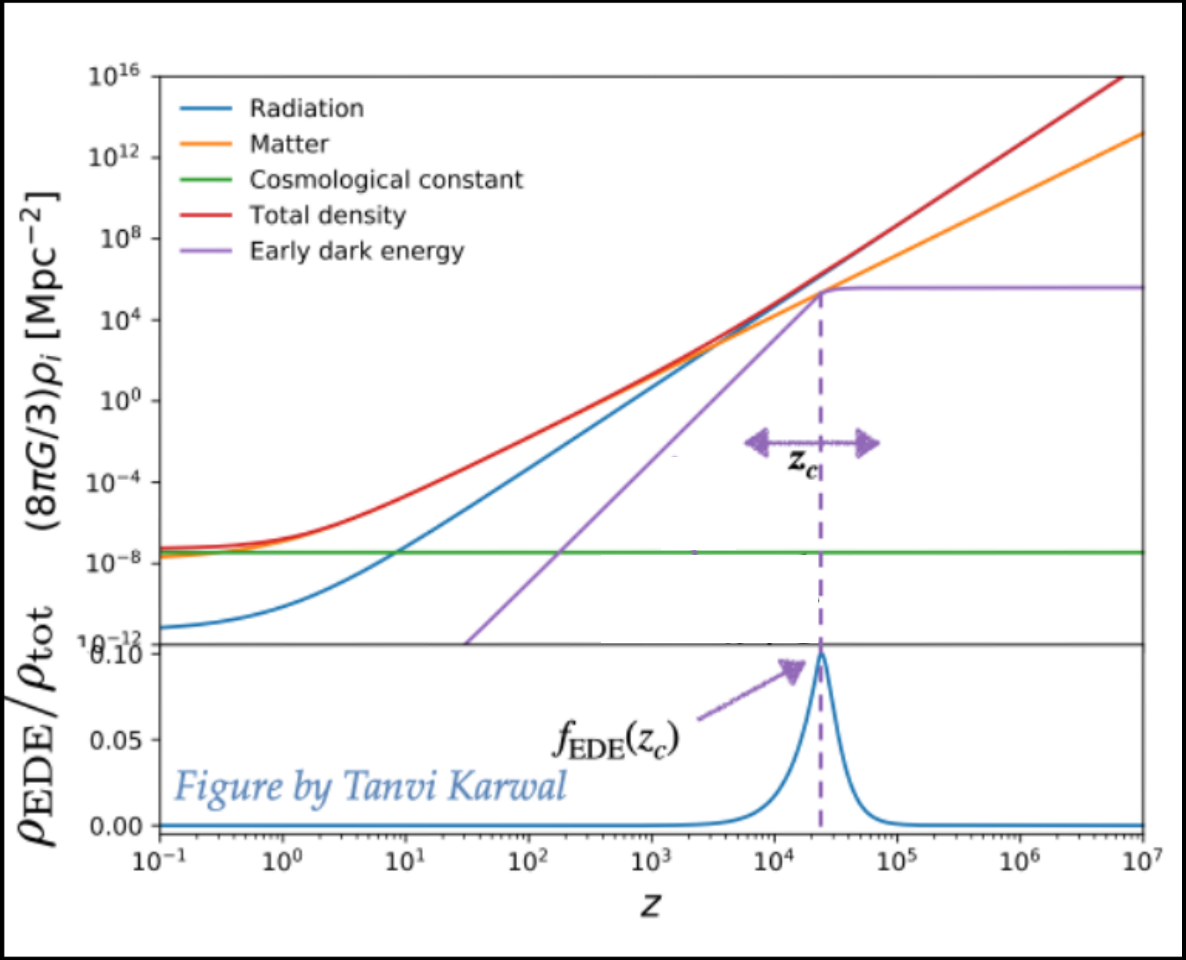
- Change only late time physics, early universe unaffected
- Little room for change in the physics
- *Currently the solutions do not resolve the tension, only alleviates!*

[e.g.,Knox & Melia 2019; Arendse+2020; Di Valentino+2021]

[parts of slide content courtesy of Elisa Ferreira]

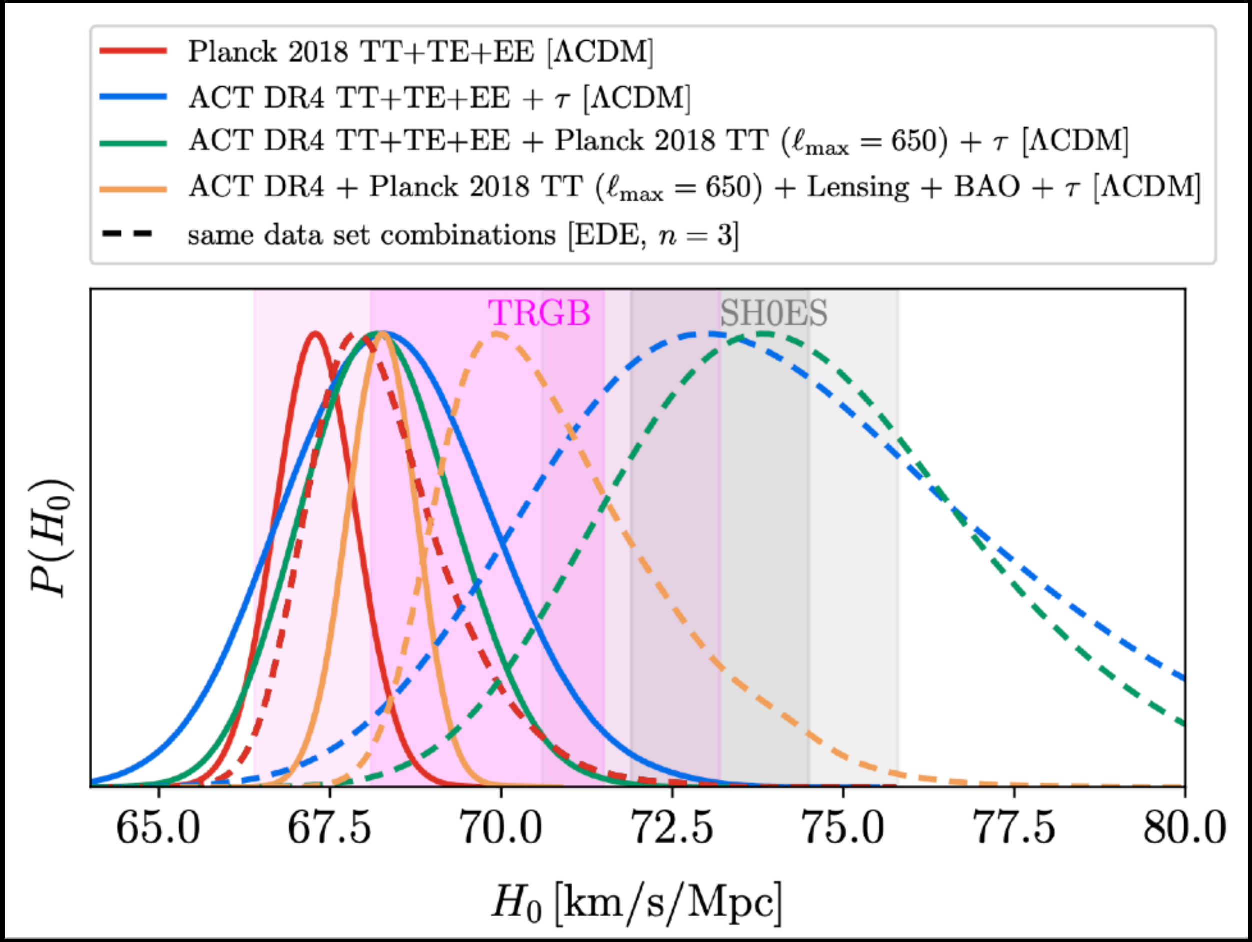
Early Dark Energy

Idea: add an extra component (to increase H(z)) that starts acting around matter-radiation equality, behaves as dark energy and dilutes faster than matter



[parts of slide content courtesy of Elisa Ferreira]

H_0 with Early Dark Energy



[Hill et al. 2021]

ACT + large-scale Planck TT + Planck CMB lensing + BAO data
➜ the existence of EDE at > 99.7% CL.
➜ f_{EDE} = 0.091+0.020/-0.036, with H_0 = 70.9+1.0/-2.0 km/s/Mpc

Debate ongoing whether early dark energy exists

Summary

- Intriguing tension in the measurements of the H_0 (>4σ) from Planck and from the SH0E program
- Independent measurements of H_0 are crucial to validate or refute the tension
- Several methods with the potential of reaching 1% precision in H_0 in the coming years
- New physics to resolve the H_0 tension are more likely to be at the early Universe, including early dark energy