# Time delays (supernovae and gravitational lens)

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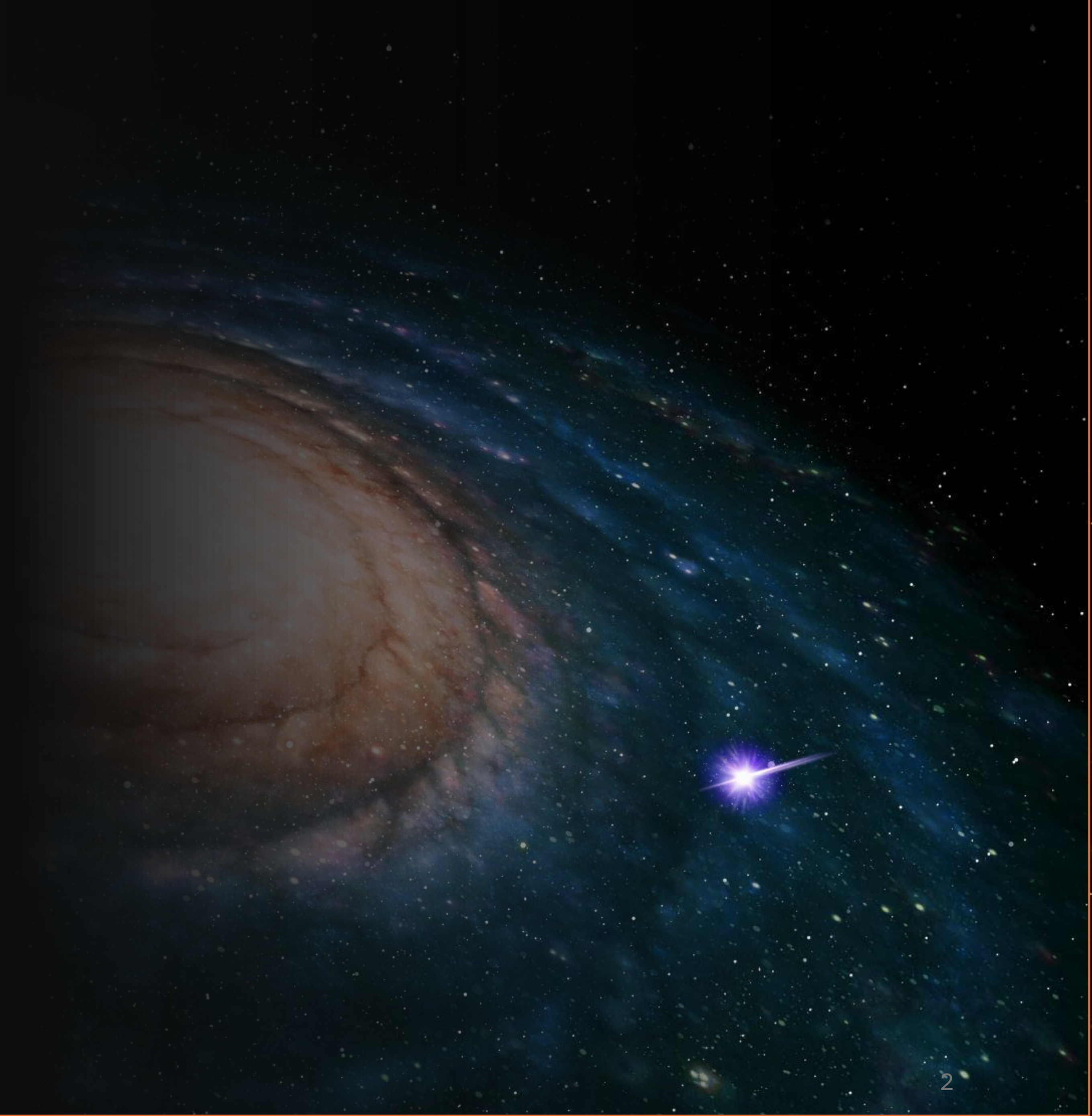
# Outline

- Time Delays - Basic
- Cosmic Ladder
- Gravitational Lensing
- Time Delays – Lensing Supernovae
- Recent Work
- Problems

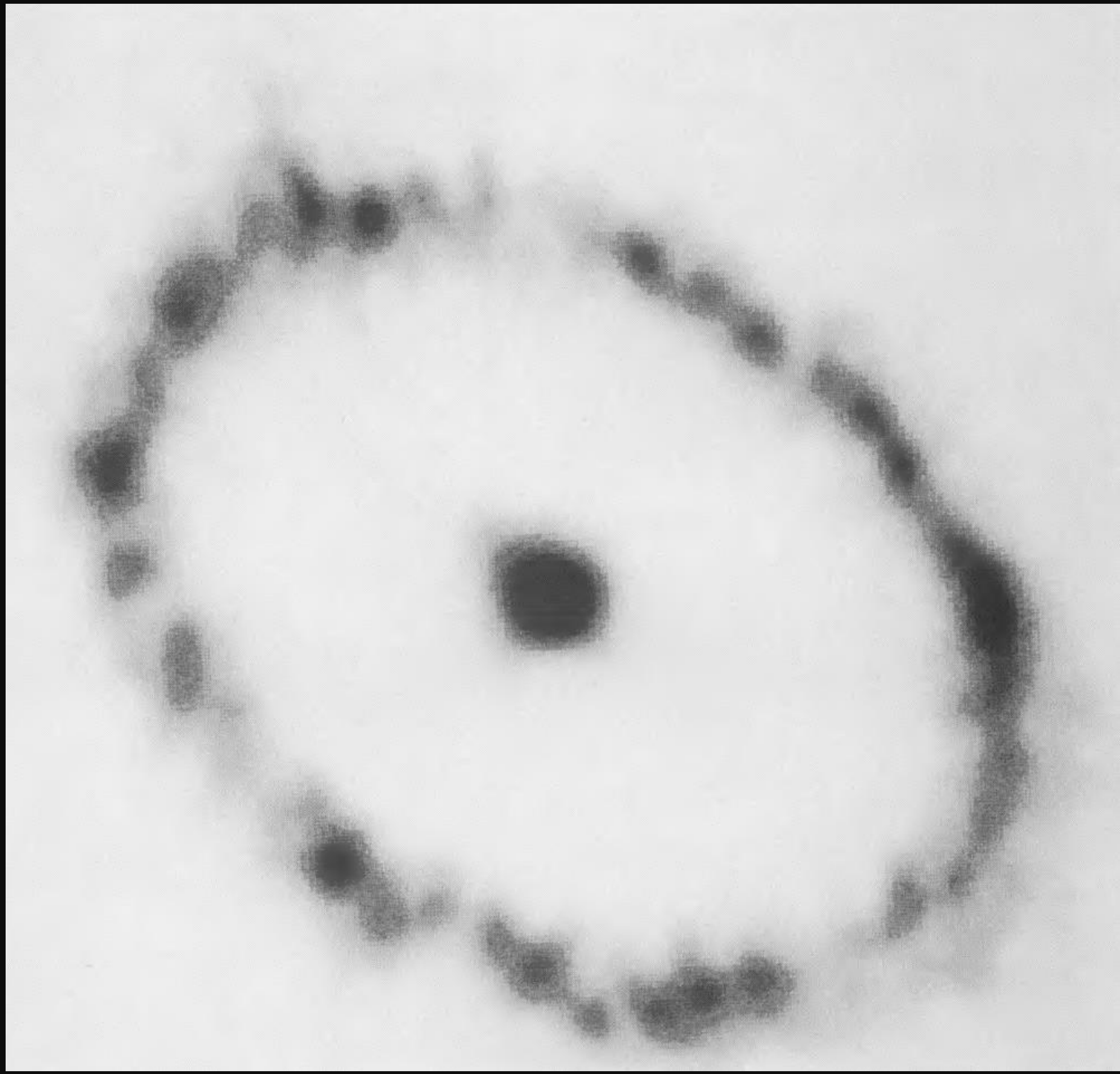


# Time Delay - Basic

NASA, ESA, CSA, Mikako Matsuura, Richard Arendt Claes Fransson, Josefin Larsson, Alyssa Pagan

# Time Delay - Basic

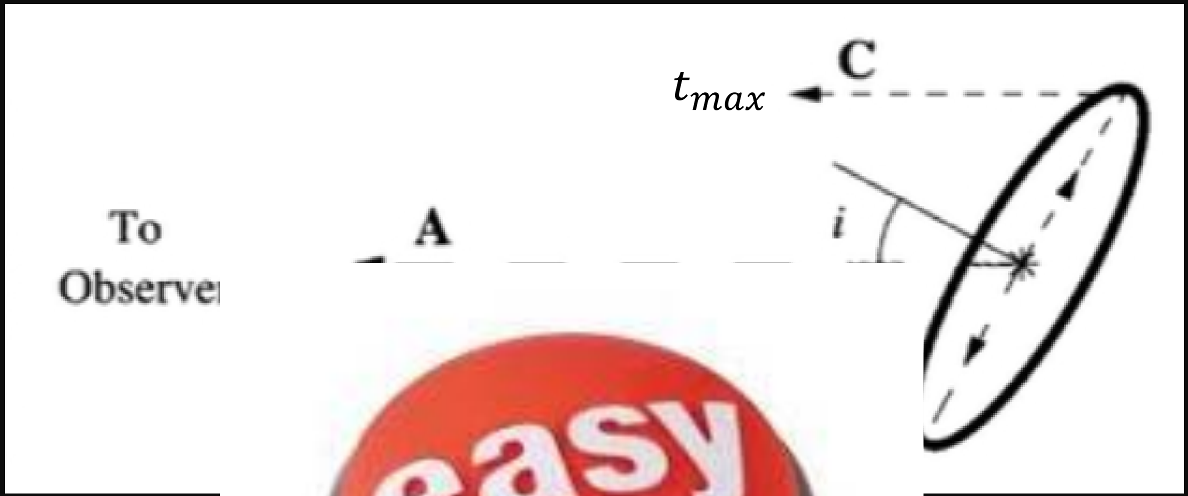
- HST image of SN1987A in narrow [O III] filter
- IUE detected highly ionized oxygen ~90 days after initial explosion.
- Rose to a maximum ~400 days.
- Combination of line reprocessing + inclination.

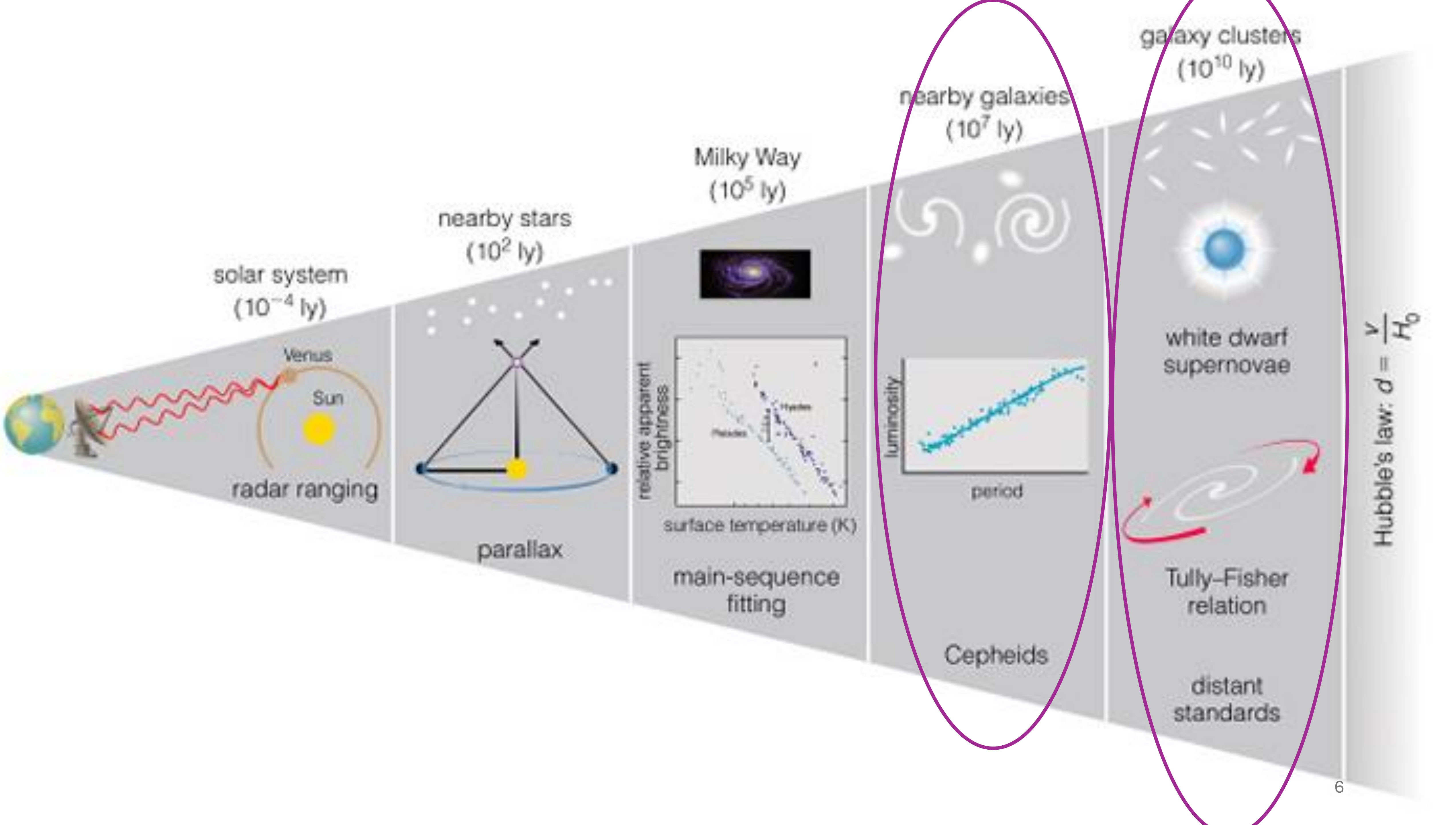


(Panagia 1991)

# Time Delay - Basic

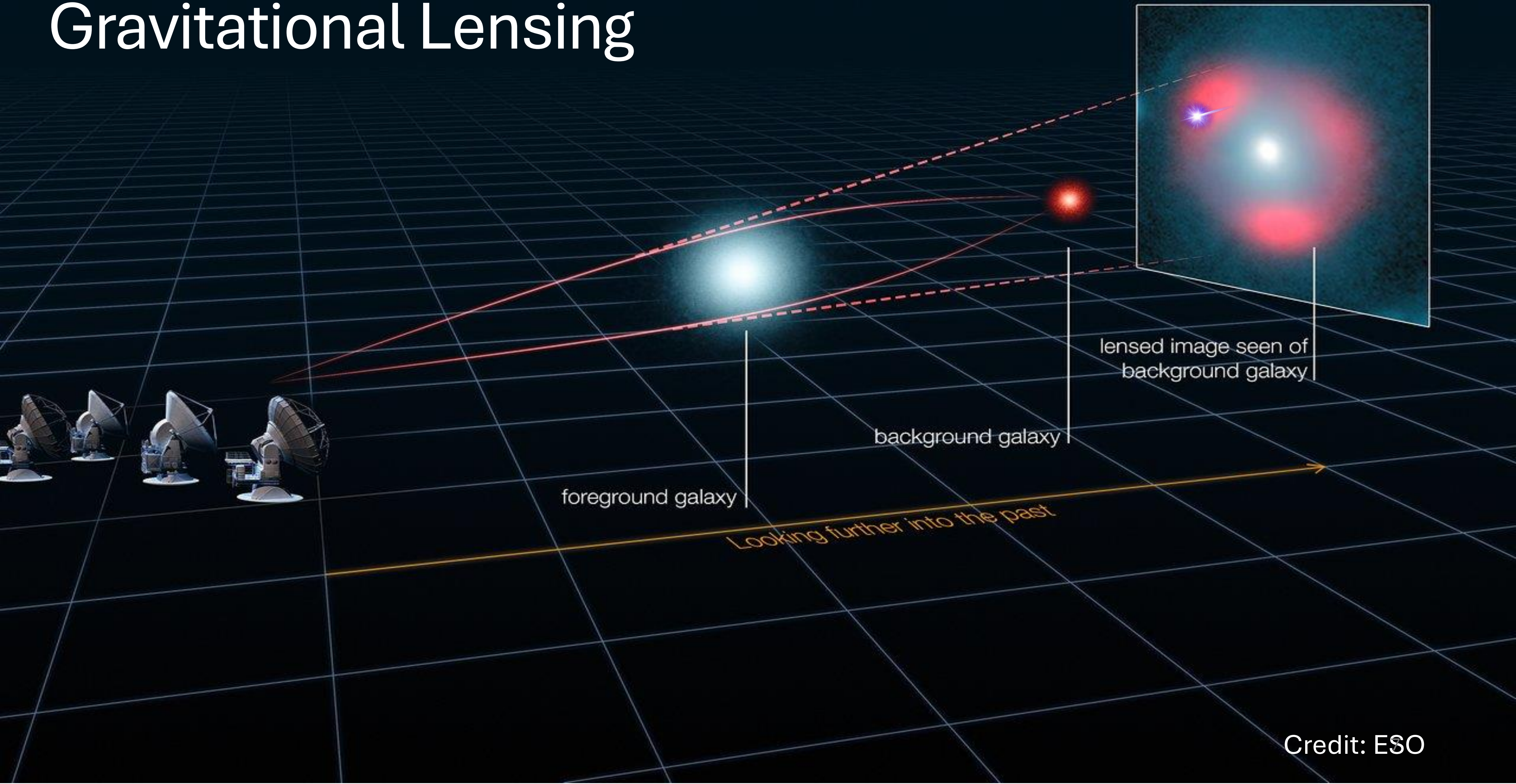
- $t_0 = \frac{r_{ring}}{c}(1 - \sin(i))$
- $t_{max} = \frac{r_{ring}}{c}(1 + \sin(i))$
- Solve for $r_{ring}$ and $i$.
- Get $\theta_{ring}$ from angular size on HST image.
- $r_{ring}$ / $\theta_{ring}$ $= D$ by simple trig.
- $0.42pc/1.66arcsec = 52 \pm 3\ kpc$.
- $i = 42 \pm 5°$.



solar system
($10^{-4}$ ly)
Venus
Sun
radar ranging
nearby stars
($10^2$ ly)
parallax
Milky Way
($10^5$ ly)
relative apparent brightness
surface temperature (K)
main-sequence fitting
nearby galaxies
($10^7$ ly)
luminosity
period
Cepheids
galaxy clusters
($10^{10}$ ly)
white dwarf supernovae
Tully–Fisher relation
distant standards
Hubble's law: $d = \frac{v}{H_0}$

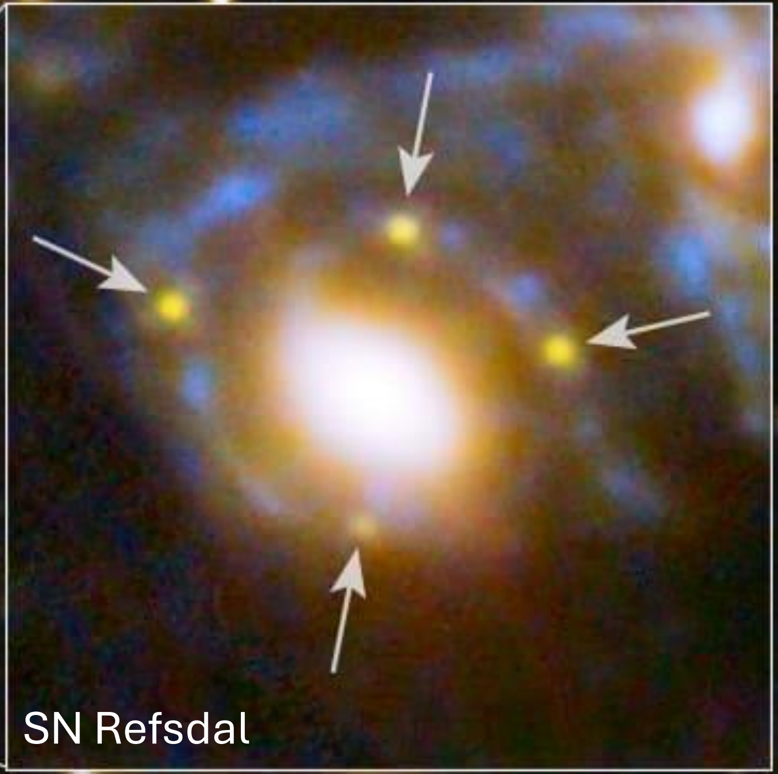
# Gravitational Lensing




Credit: ESO

# Time Delay – Lensing Supernovae

- Delays in between the leading image and trailing images are caused by two main effects:
- Difference in lengths of optical paths
- Shapiro delay – “difference in gravitational potential experienced by two separate paths of photons”

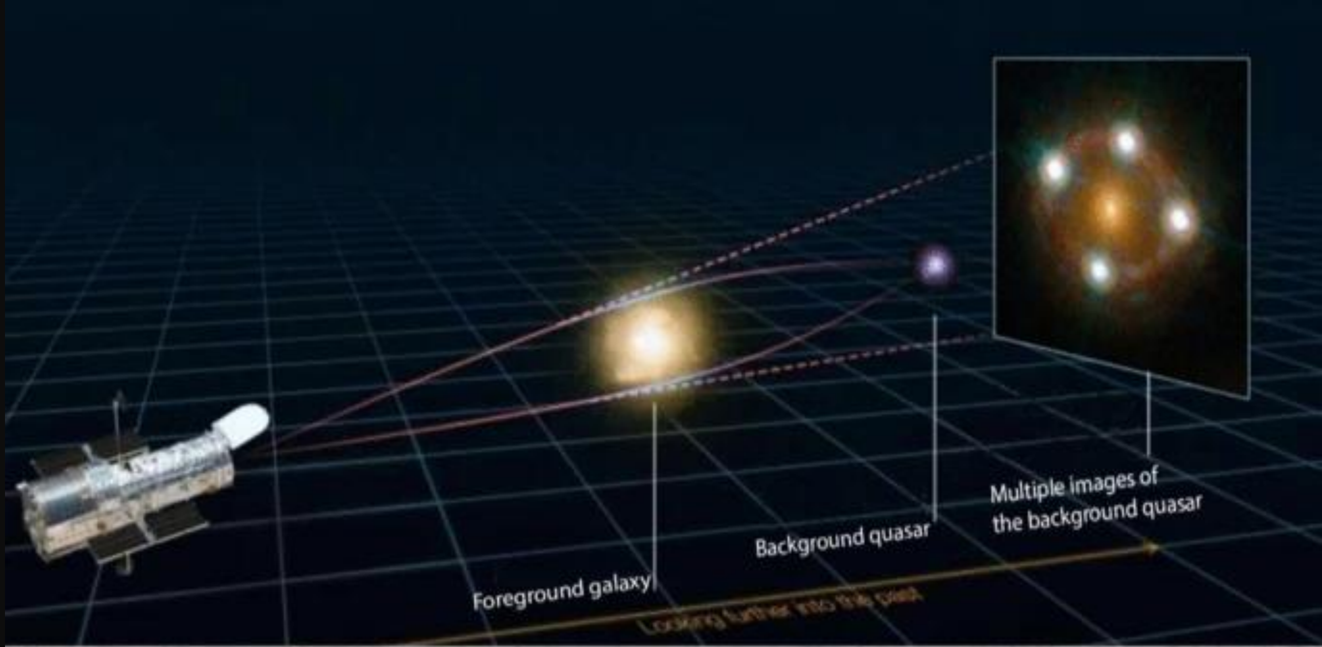


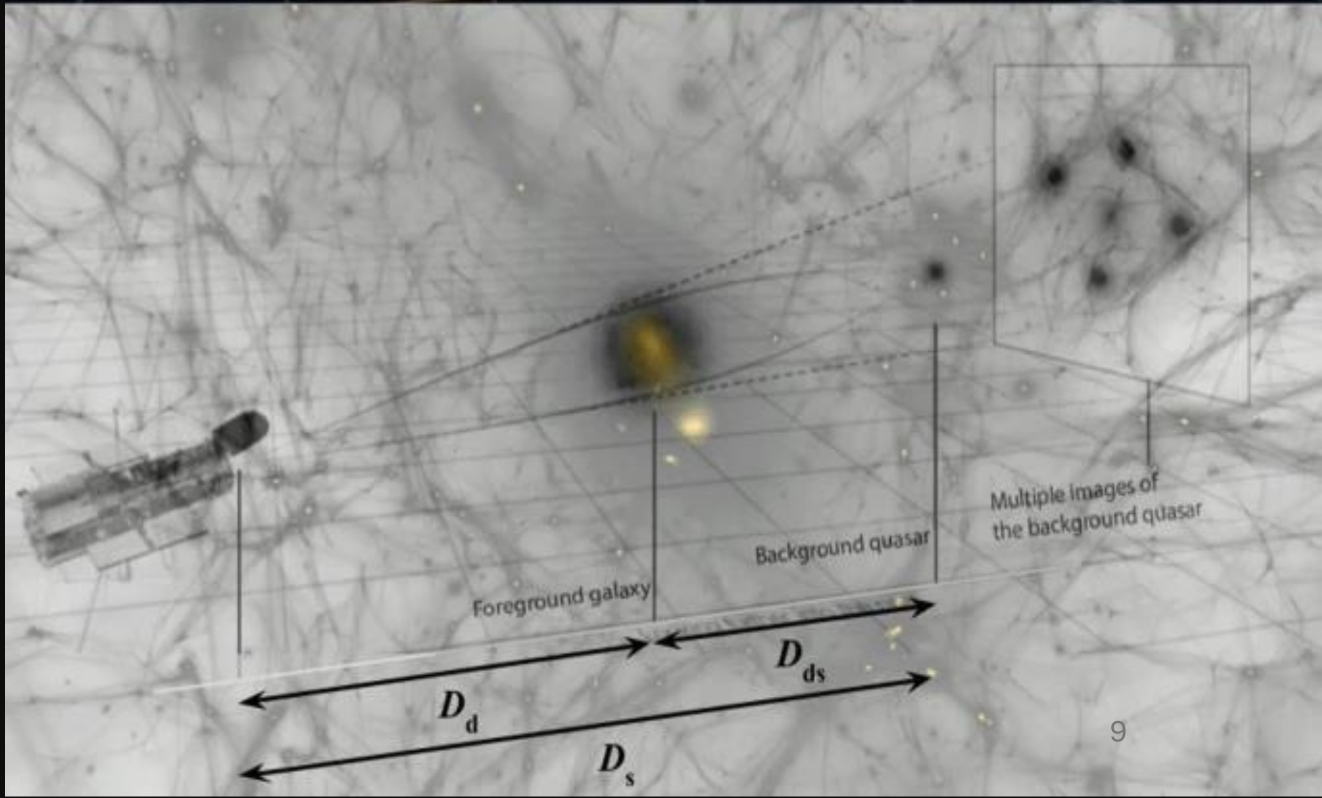



Credit: NASA/ESA/JHU/UCLA/UC Berkeley/STScI)

# Time Delay - Lensing

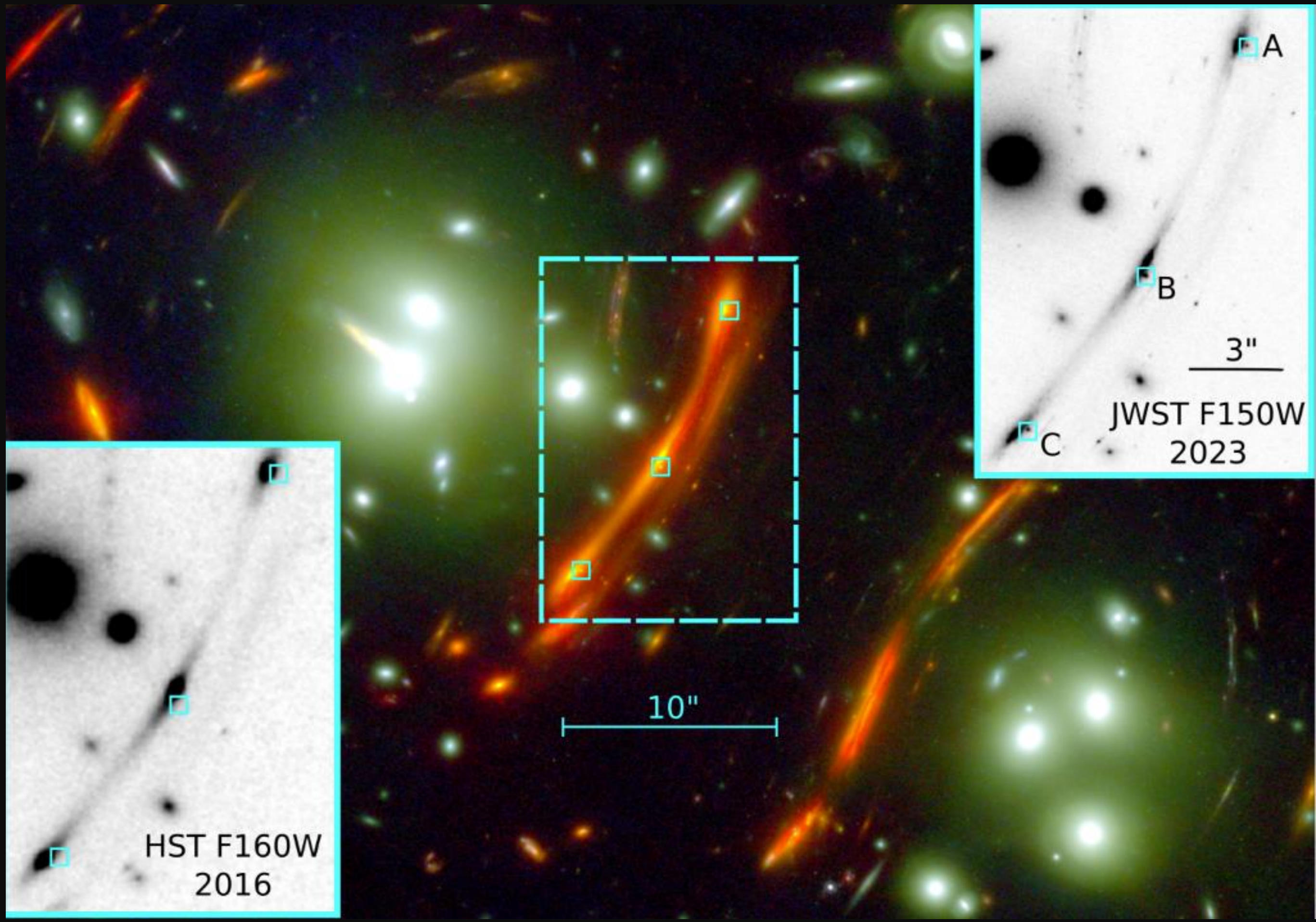
- $\Delta\tau_{AB} = \frac{D_{\Delta t}}{c} \Delta\varphi_{AB}$
- $\Delta\tau_{AB}$ -> time delay between brightness fluctuations of image A and B
- $\Delta\varphi_{AB}$ -> Fermat potential
- $\Delta\varphi_{AB}$ -> “lens” model predicts this
- $D_{\Delta t}$ -> Time delay distance
- $D_{\Delta t} \equiv (1 + z_d)\frac{D_d D_s}{D_{ds}}$
- $D_{\Delta t}\ \alpha\ H_0^{-1}$



# “SN H0pe”

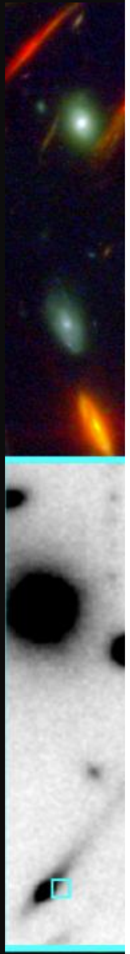
- Galaxy-cluster field PLCK G165.7+67.0 (z = 0.348, ~1.4 Gpc).
- Triply-imaged SN Ia discovered at (z=1.78, ~3.6 Gpc), (spectroscopic redshift distance.)
- Goal to measure and constrain $H_0$

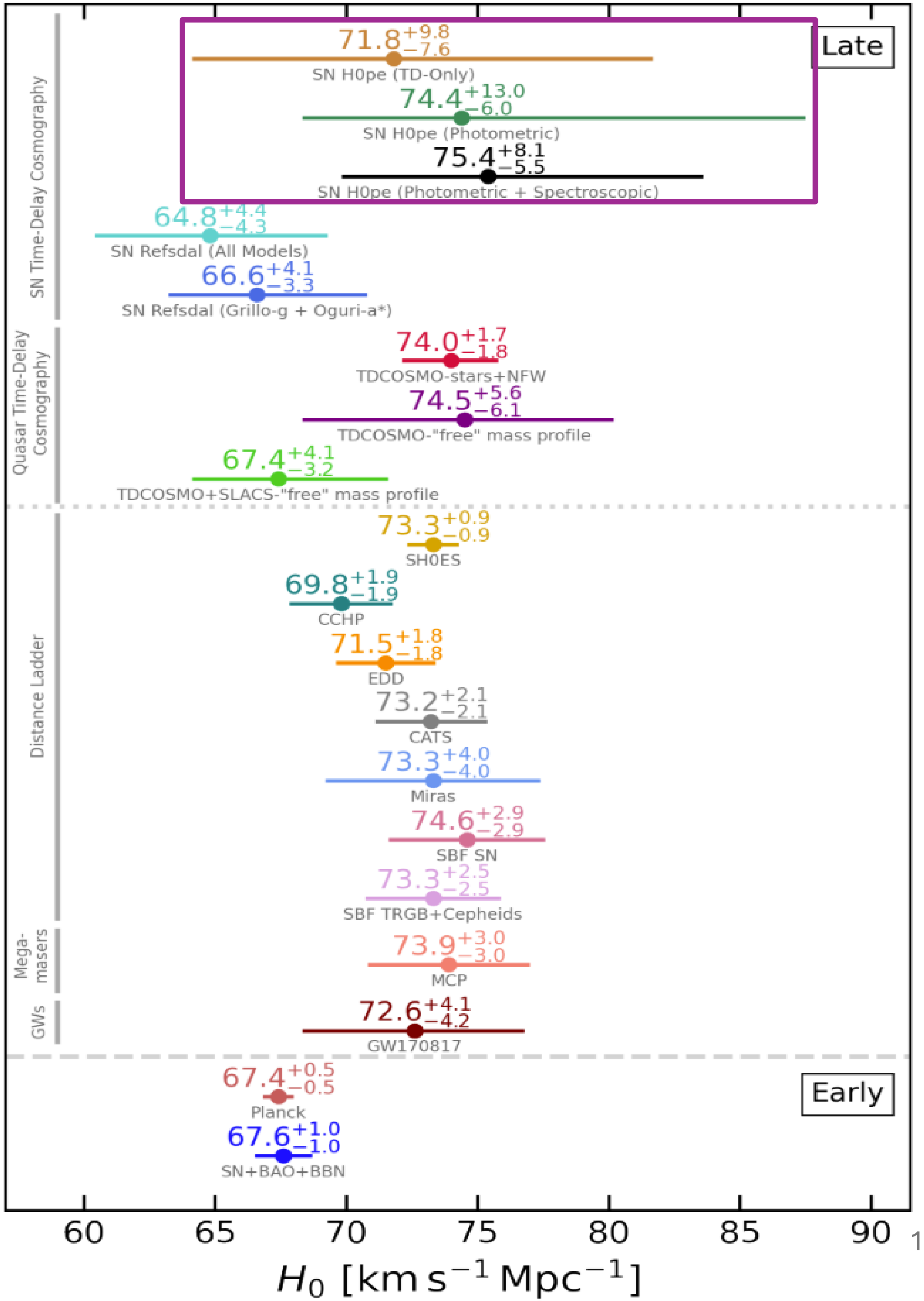


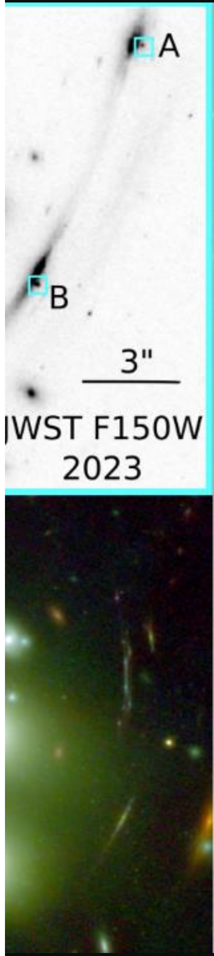

Frye et. al (2024)

# “SN H0pe”

- Seven different teams constructed lens models.
- All supplied same initial input parameters:
- 21 image systems, some with spectroscopic redshifts, 161 cluster member galaxies with the same positions, F200W brightnesses, and morphological parameters
- No teams knew of time delay or magnification measurements.





# Problems - Rarity

- 1/1000 SNe are strongly lensed.
- Assume every galaxy has the same SNe rate as the MW (2/century)
- 1/500000 SNe/yr per galaxy could be lensed.
- Hubble on its own observed about 100 billion galaxies. (NASA)
- ~200 strongly lensed SNe.
- Only 7 confirmed and measured (Sheu et. al 2023).

# Problems – Models and Observations

Observations:

- Need follow-up campaigns.
- New lensed images can take up to ~years to appear.
- Need lots of high res images and more sky coverage.

Models:

- Uncertainties in mass distributions of lenses. (very difficult to model!)

# Problems – Hubble Constant

- Hubble Tension – Different ways to measure and constrain the expansion rate of the Universe yields different values (more than a few $\sigma$ disagreements).
- Signals either new physics, or a mistake in measurements/models.
- With incoming larger samples with the newly launched Euclid + upcoming Vera Rubin and Nancy Roman, in combination with more follow-up JWST programs, it is expected time delay cosmography will reach precisions of ~1% on $H_0$.

# Questions