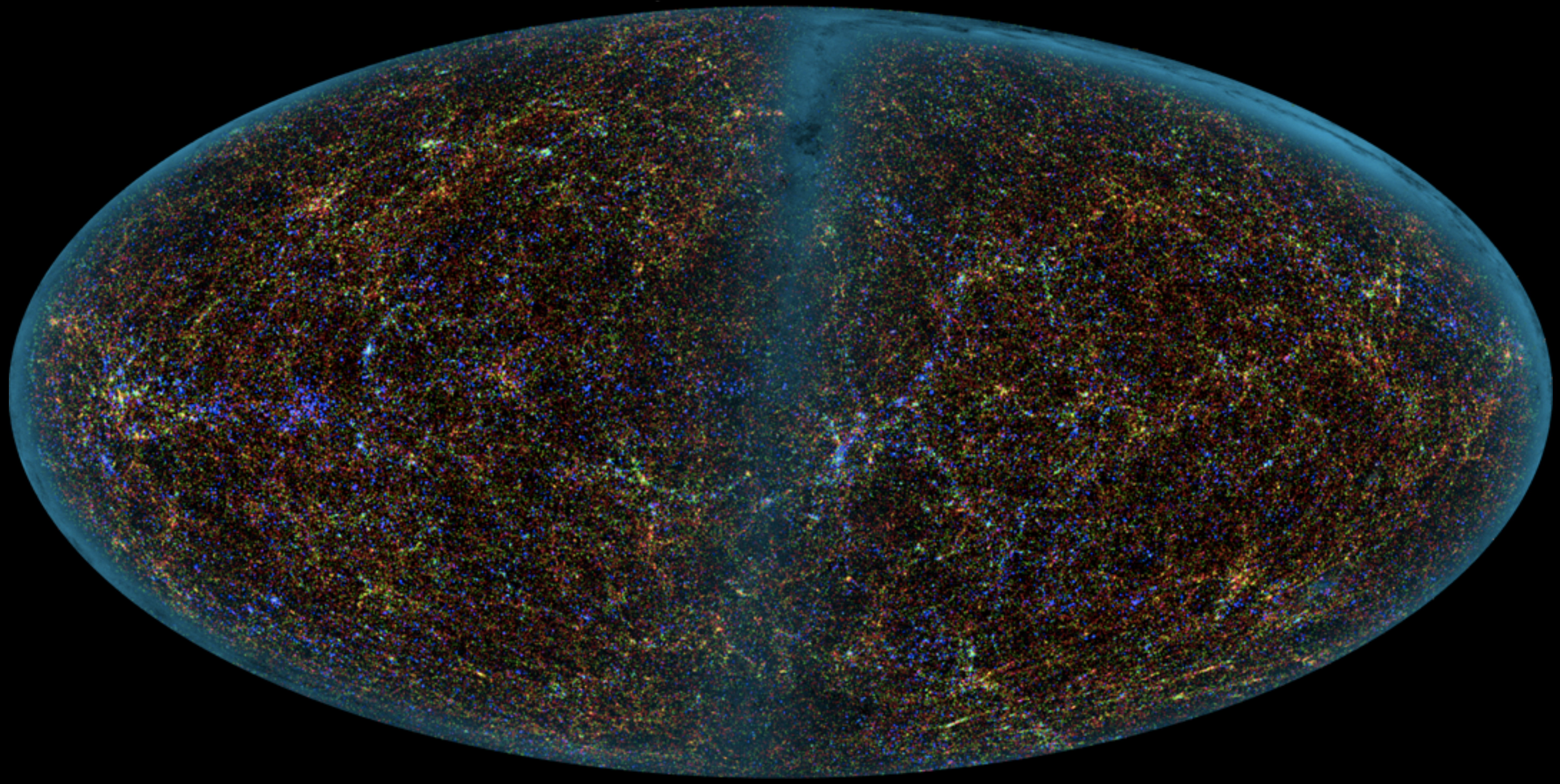
Cosmology

and Large Scale Structure



Today
Distance Scale III
Absolute methods
H_0 tension

homework 3 due next time

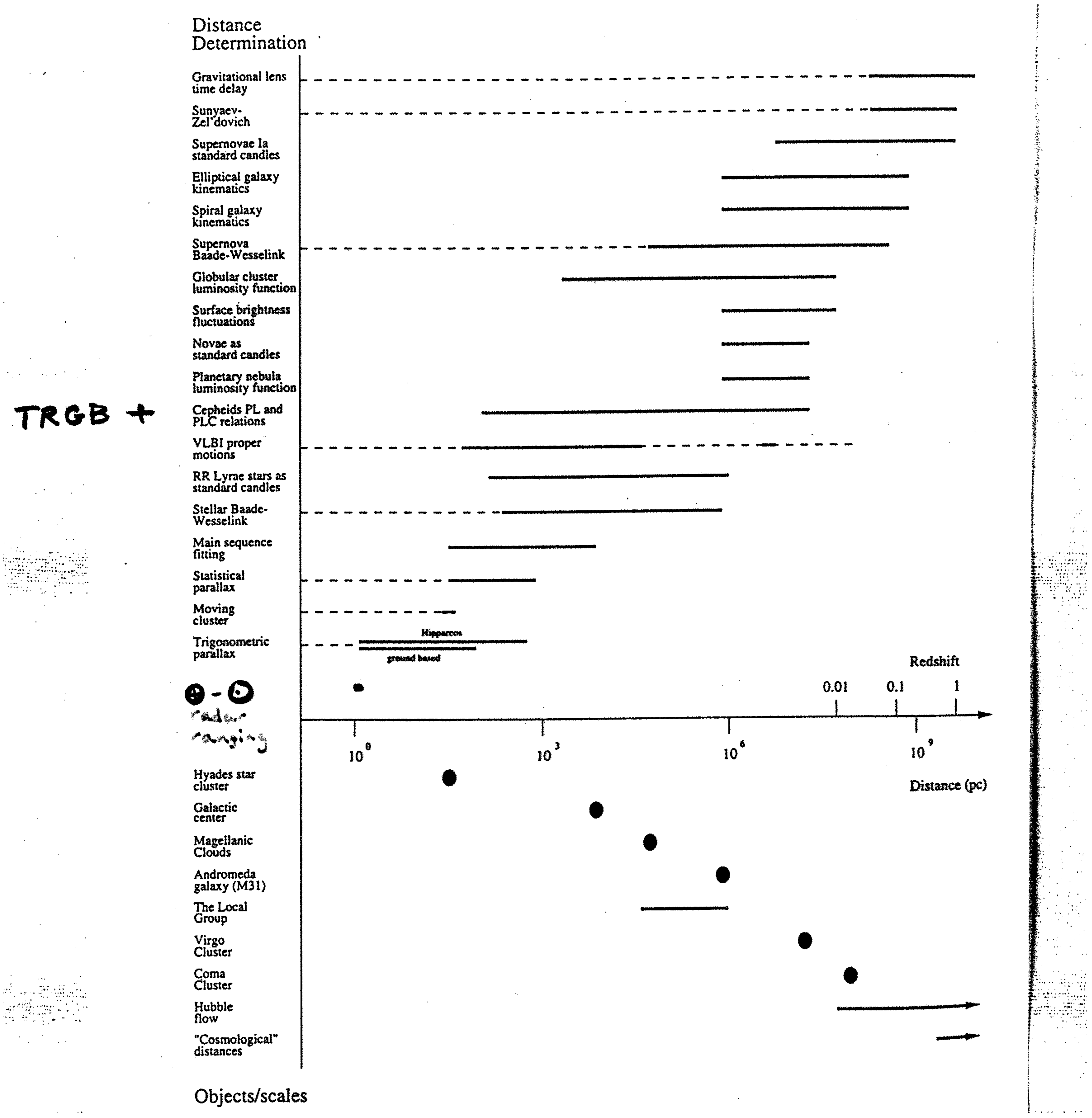
8 October 2024

http://astroweb.case.edu/ssm/ASTR328/

Distance Scale

- Solar System
  - earth-sun distance
- Trigonometric Parallax
  - statistical & secular parallax; moving clusters
- Main Sequence Fitting
- Bright Star Standard Candles
  - Cepheids, RR Lyraes, TRGB
- Secondary Distance Indicators
  - Type Ia SN, Tully-Fisher, Fundamental Plane, SB Fluctuations
- Absolute Methods
  - Gravitational lens time delay, SZ effect, water masers

Distance Scale Ladder



distance modulus $m - M = 5\log(d) - 5$

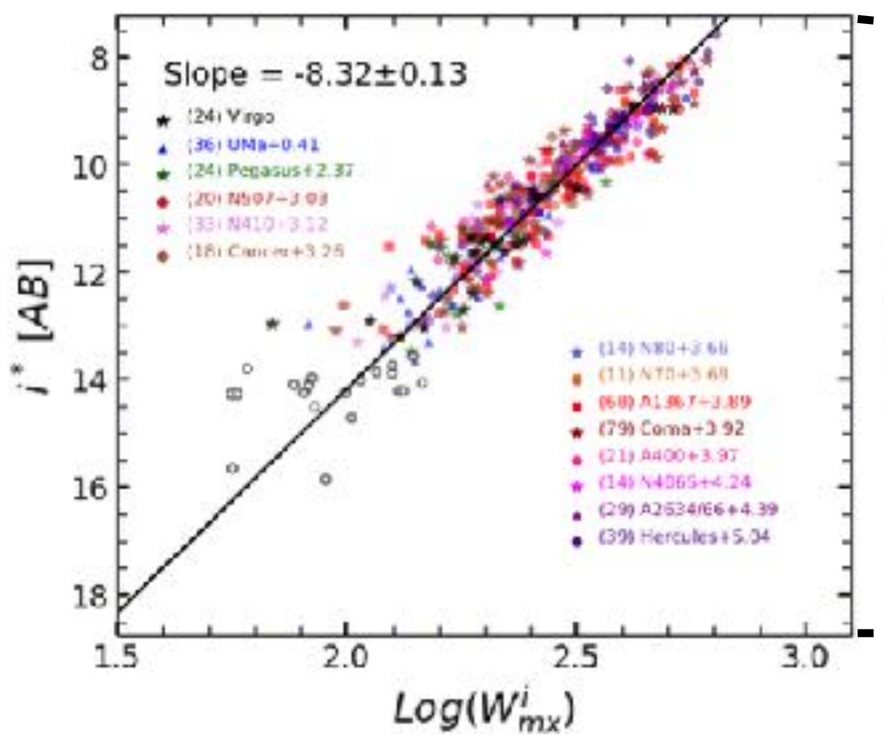
3. Tully-Fisher relation

Amplitude of rotation speed correlates with mass

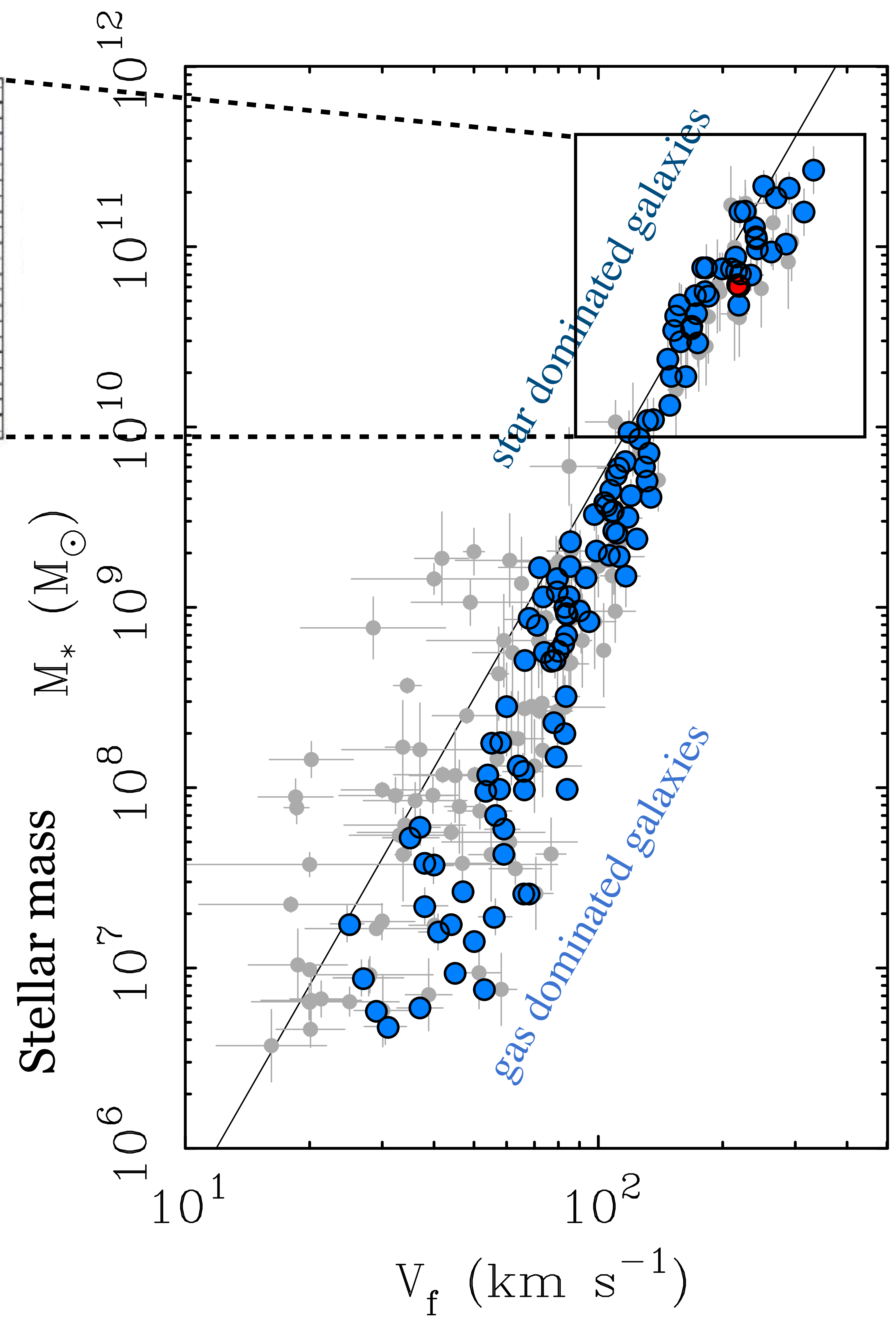
$\frac{\sigma_D}{D} < 20\%$ — ● — at least 3 points within 5% defining V_f

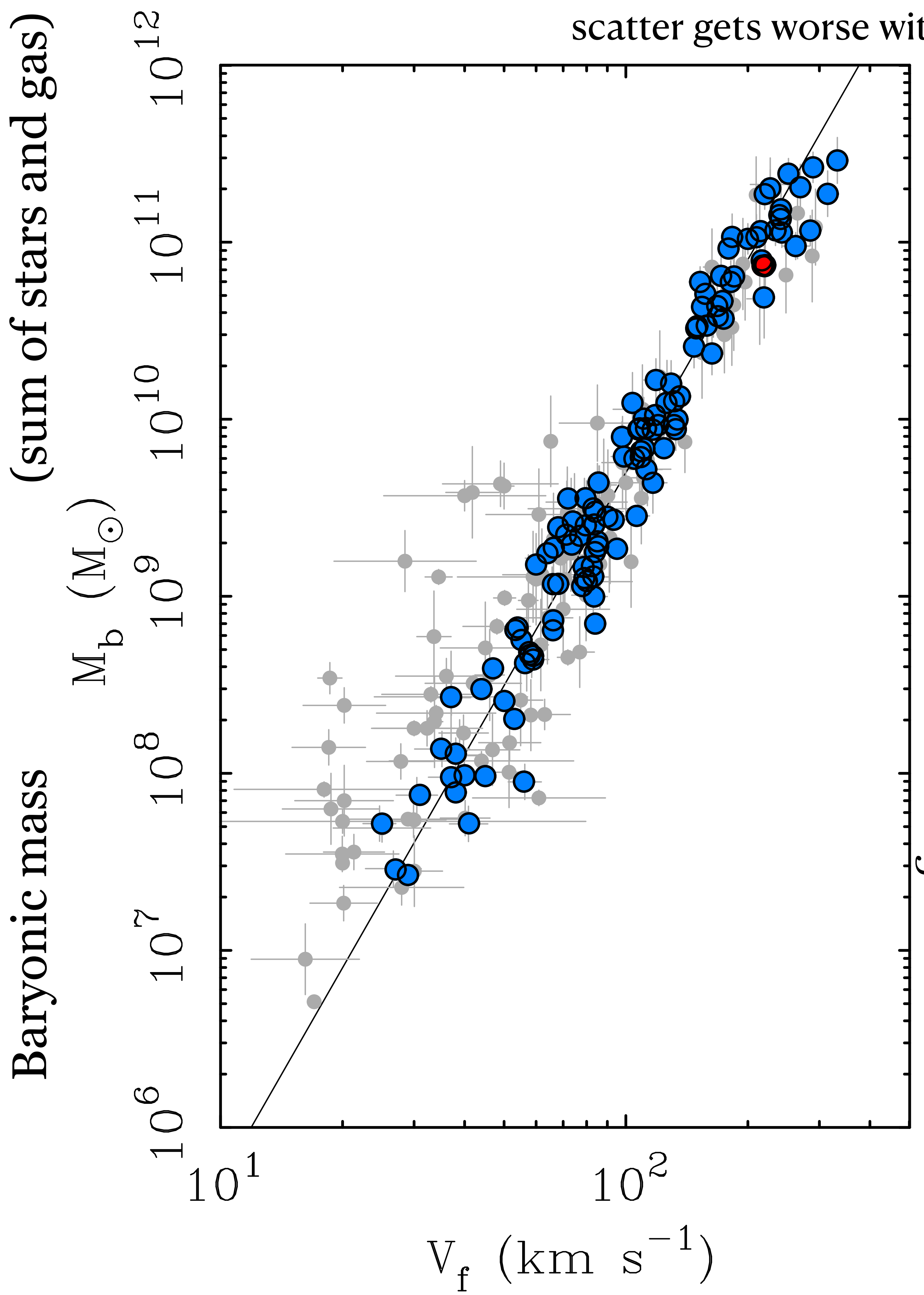
● — all other data

scatter gets worse with lower data quality



Traditional TF only works when restricted to star dominated galaxies





$M_b = M_* + M_g$

flat rotation speed

Example application:
Calibrate BTFR with 50 galaxies having distances that are known via either Cepheids of Tip of the Red Giant Branch measurements.

Applied to ~100 galaxies with high quality rotation curves, this provides a local measurement of the Hubble constant:

$$H_0 = 75.1 \pm 2.3 \text{ (stat) } \pm 1.5 \text{ (sys) km s}^{-1}\text{ Mpc}^{-1}$$

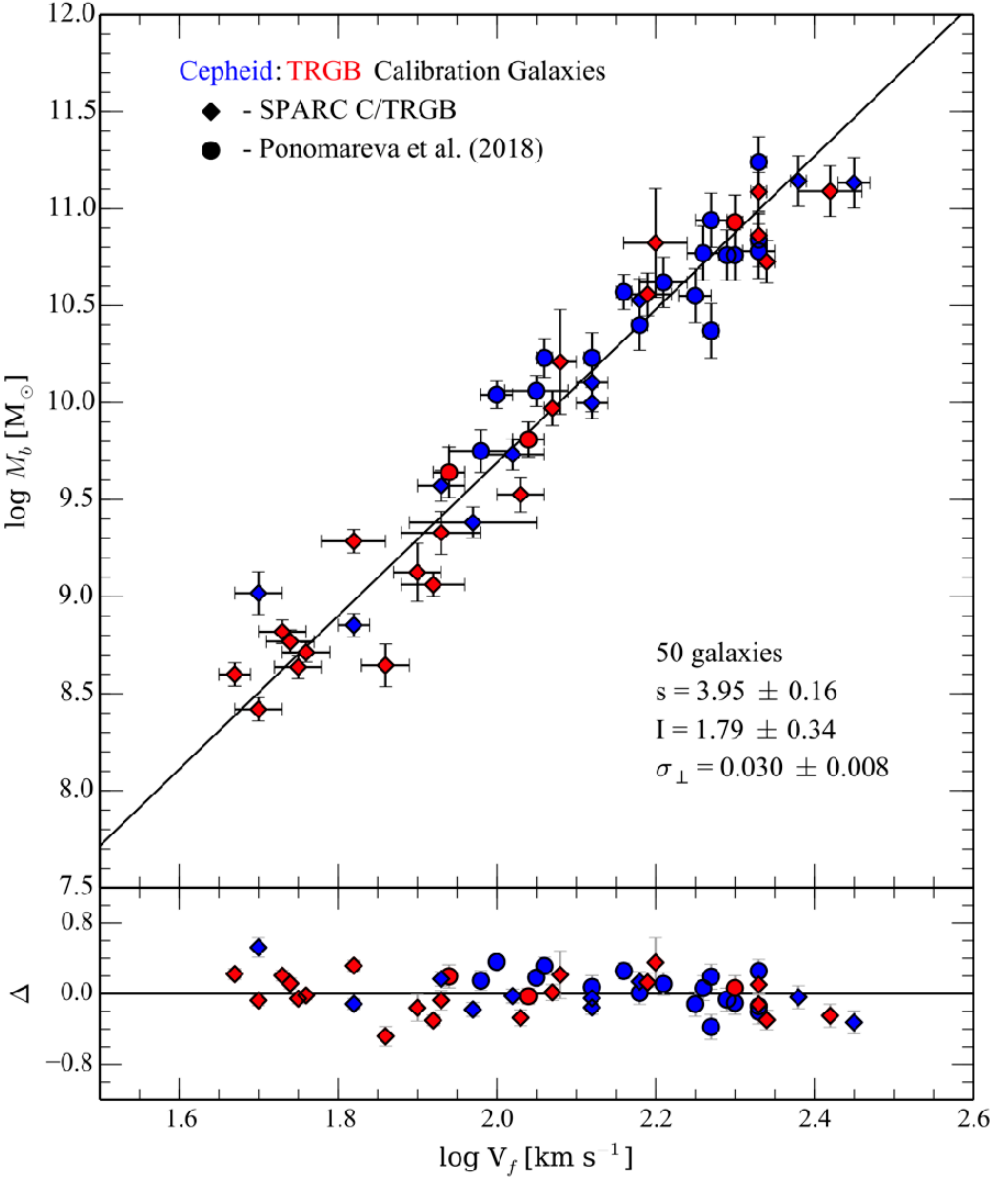
Schombert, McGaugh, & Lelli 2020, *AJ*, **160**, 71

This is consistent with the application of the traditional luminosity-line width Tully-Fisher relation to a much larger sample of ~10,000 galaxies.

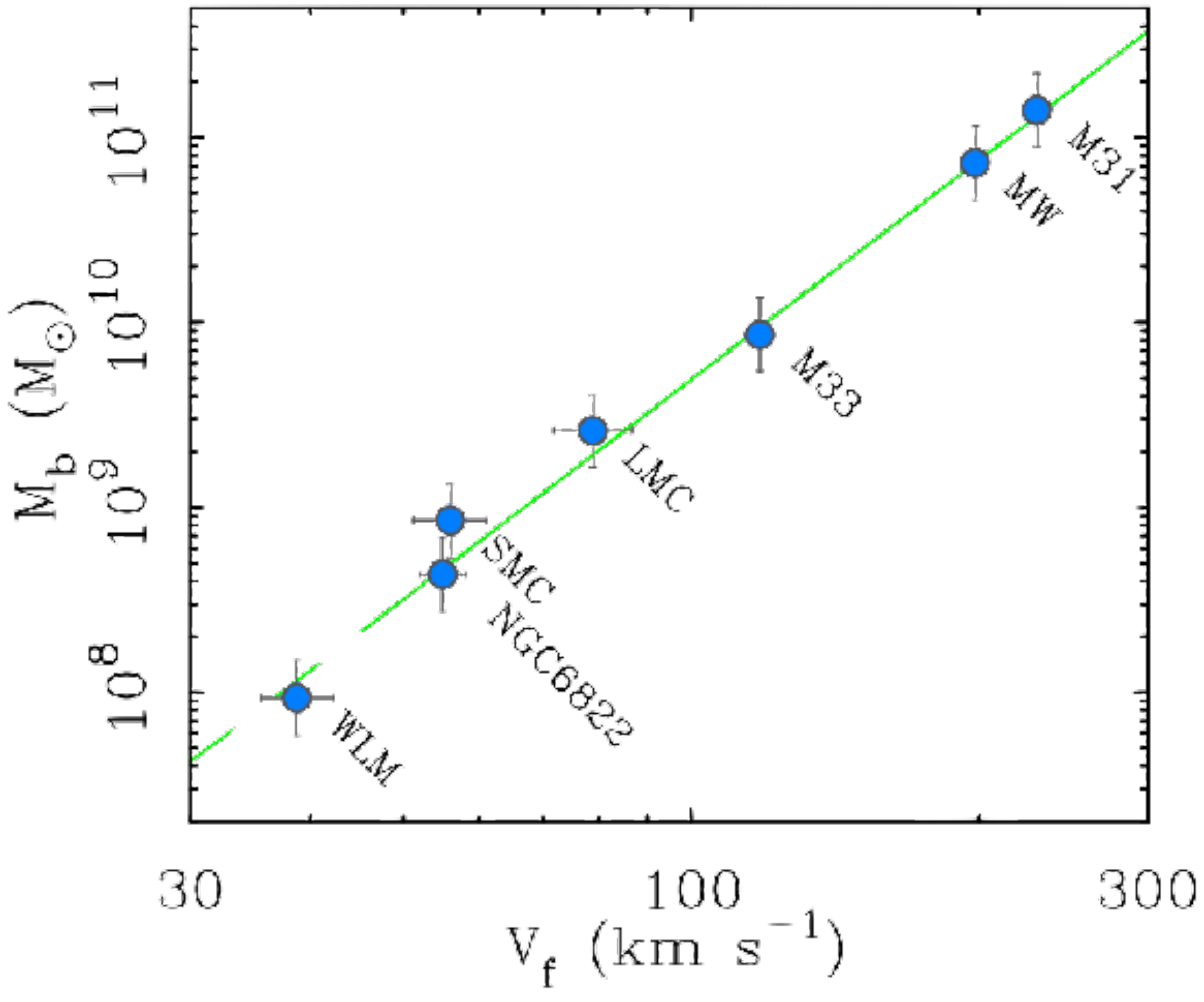
$$H_0 = 74.6 \pm 0.8 \text{ (stat) km s}^{-1}\text{ Mpc}^{-1}$$

Tully, *et al*. 2023, *ApJ*, **944**, 94

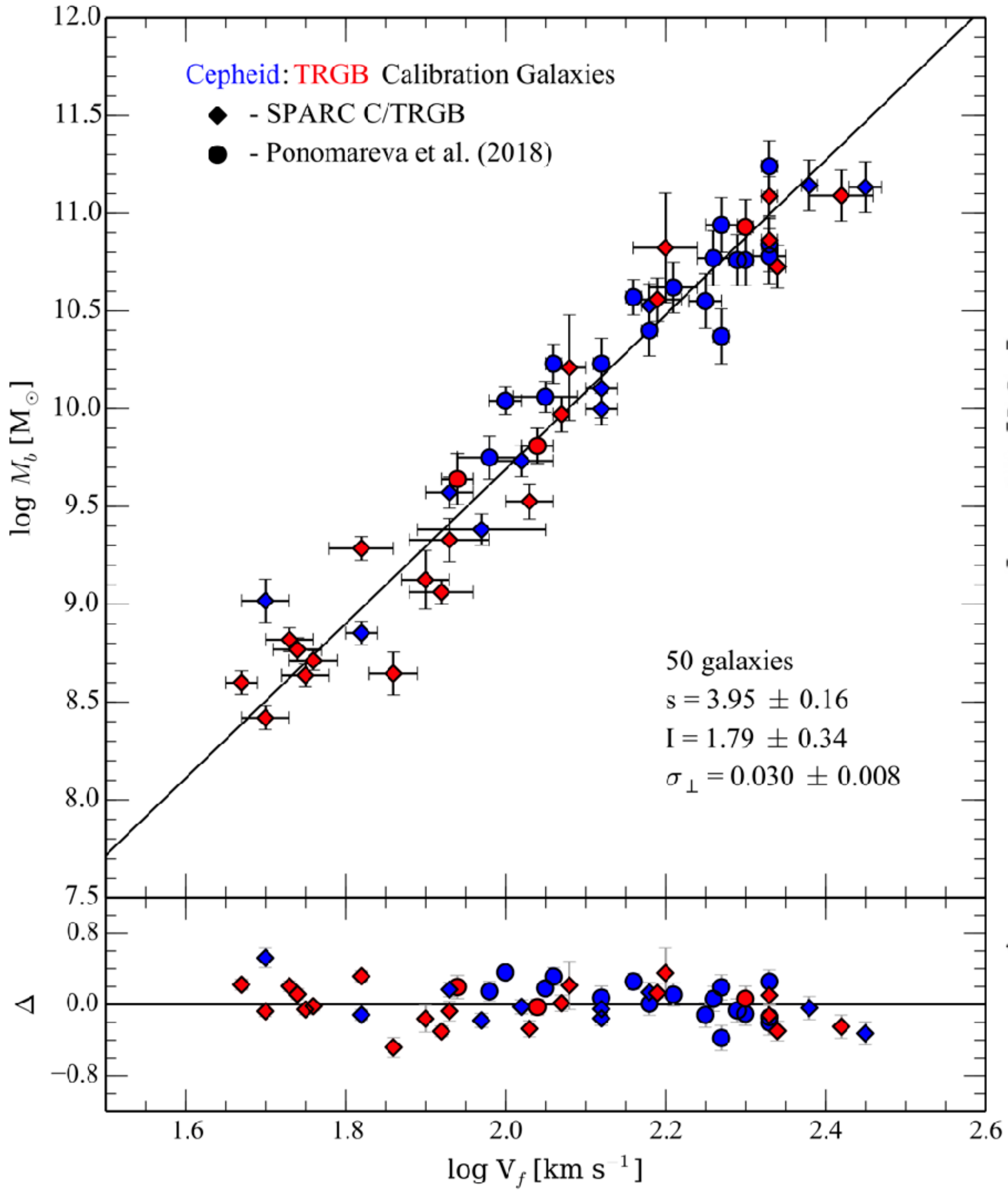
systematic uncertainty ~ 3 km/s/Mpc



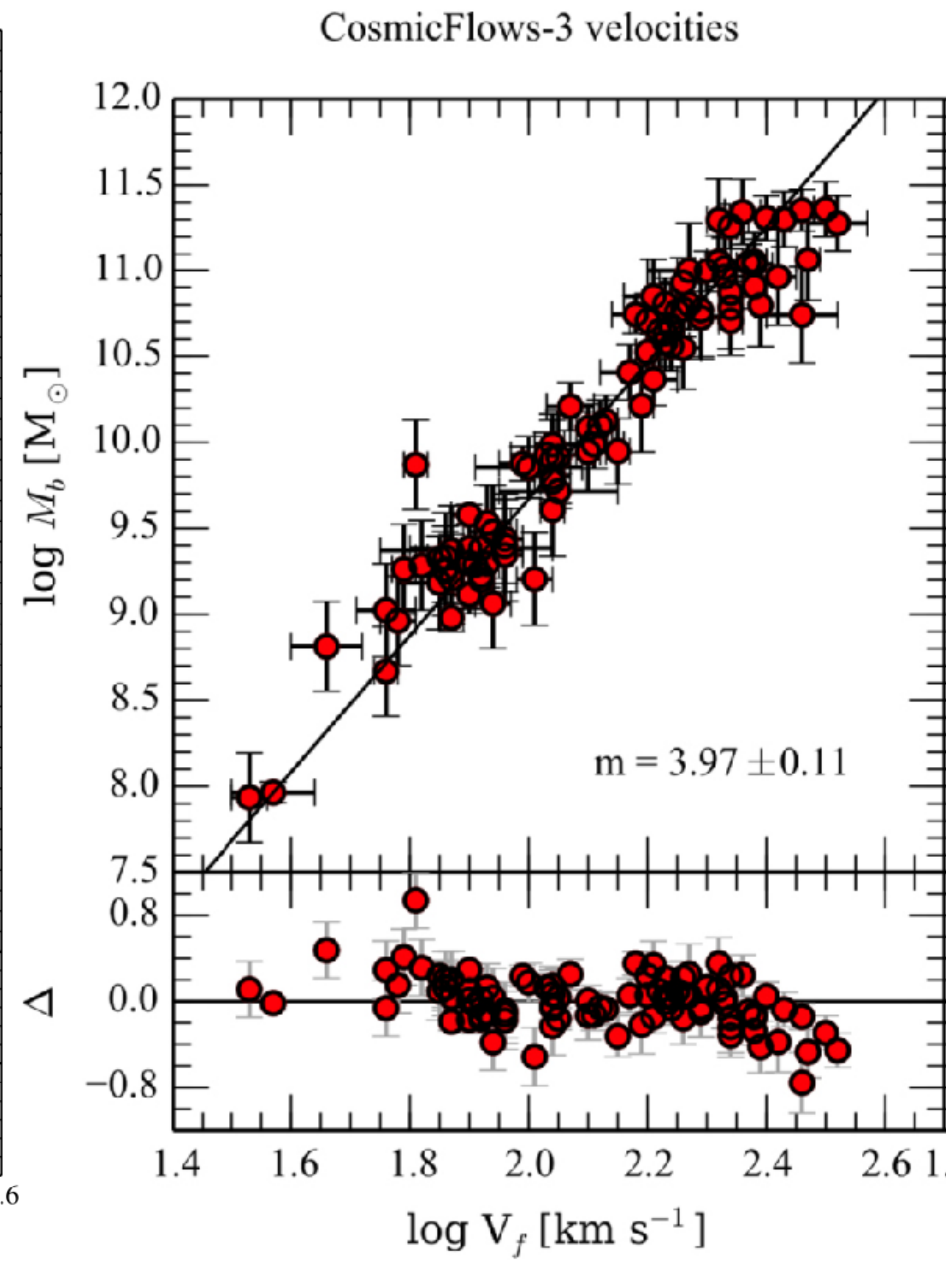
Check: Local Group - very nearby galaxies



Calibration: galaxies with Cepheid or TRGB distances



Application: galaxies further out

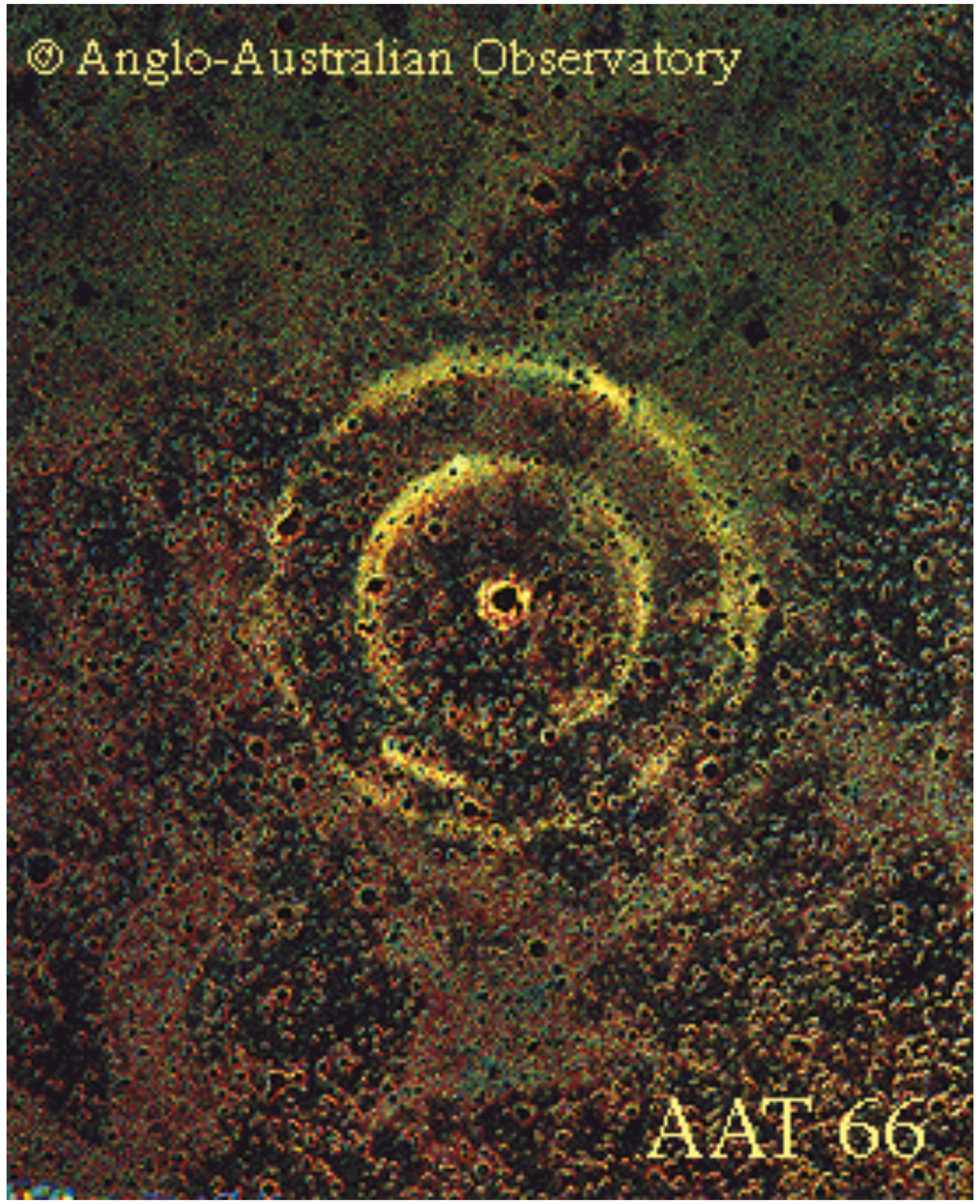


The largest known systematic uncertainty at present is peculiar velocities - the mapping of observed velocities to the expansion frame.

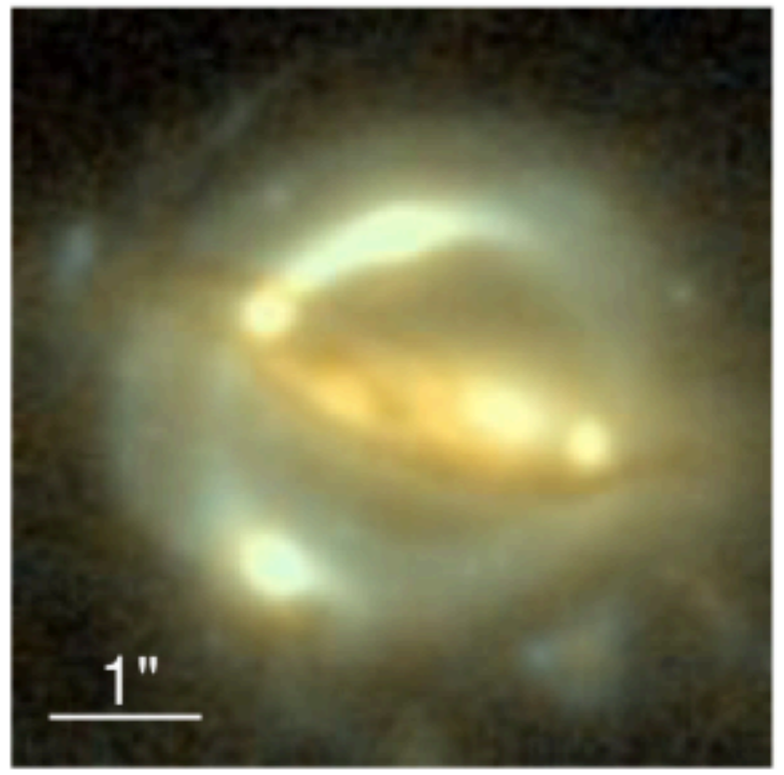
Distance Scale

- Absolute Methods
  - Light echo
  - Gravitational lens time delay
  - Sunyaev-Zeldovich (SZ) effect
  - water masers

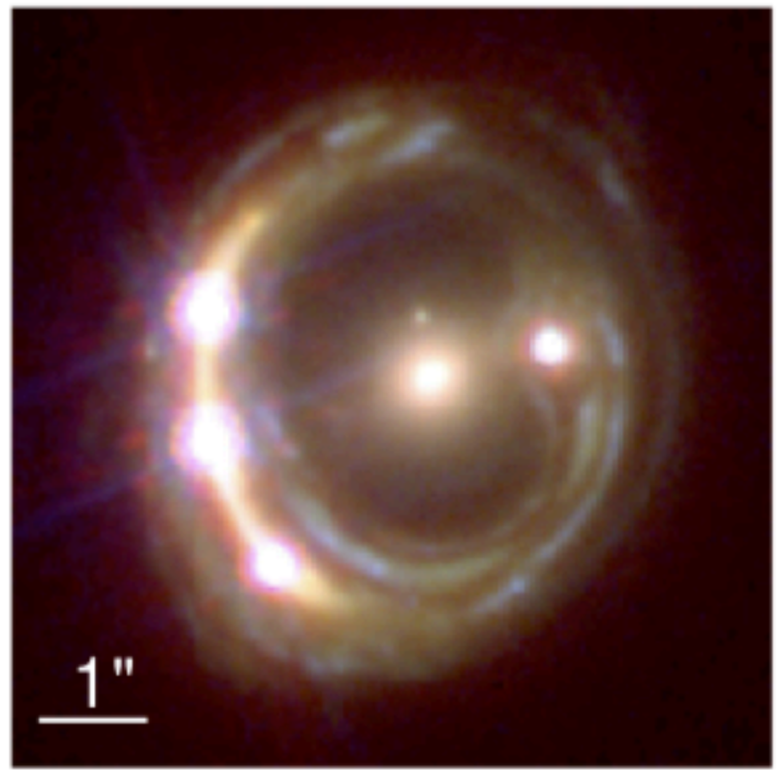
Light echos



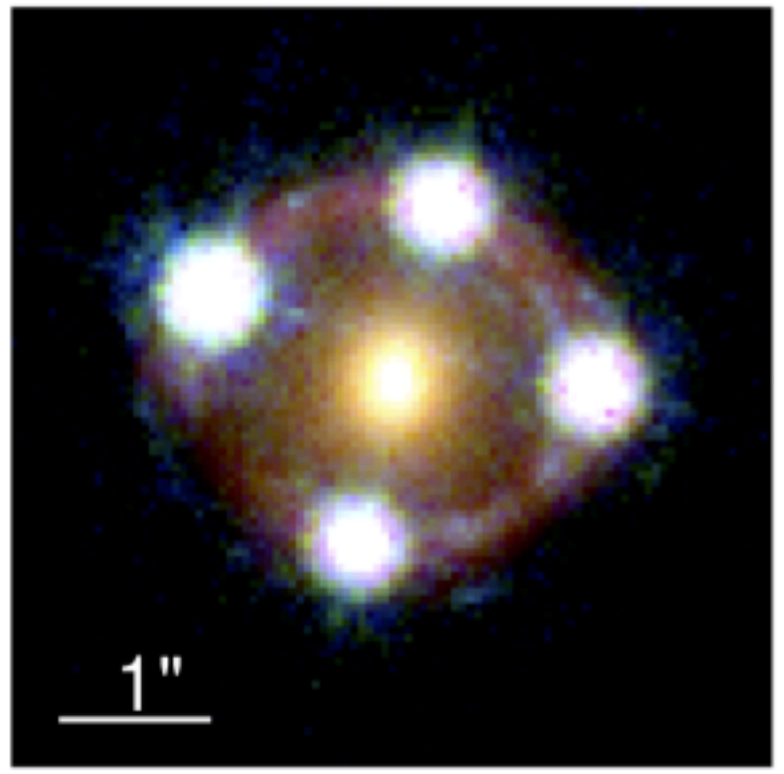
Gravitational Lenses



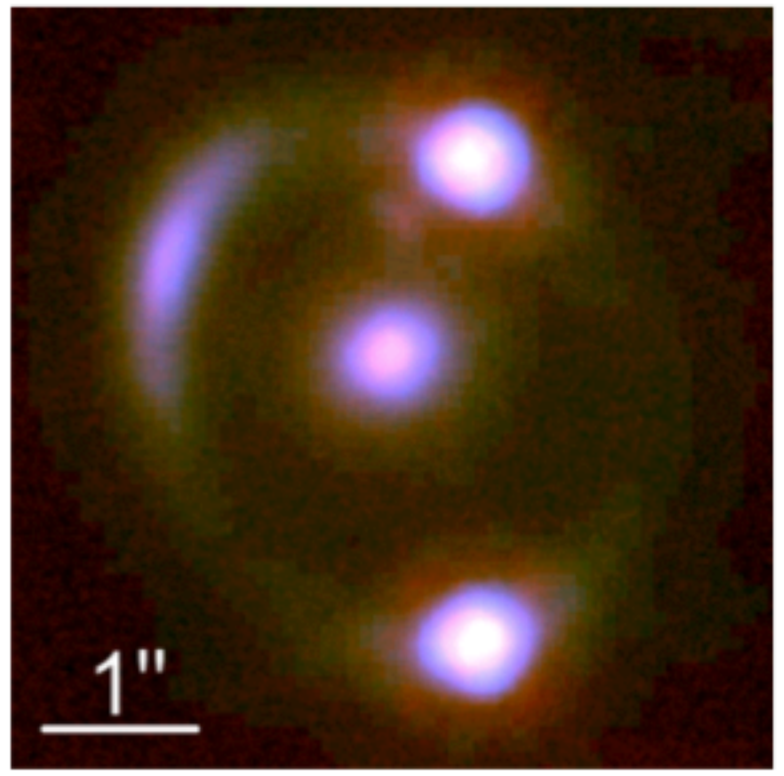
(a) B1608+656



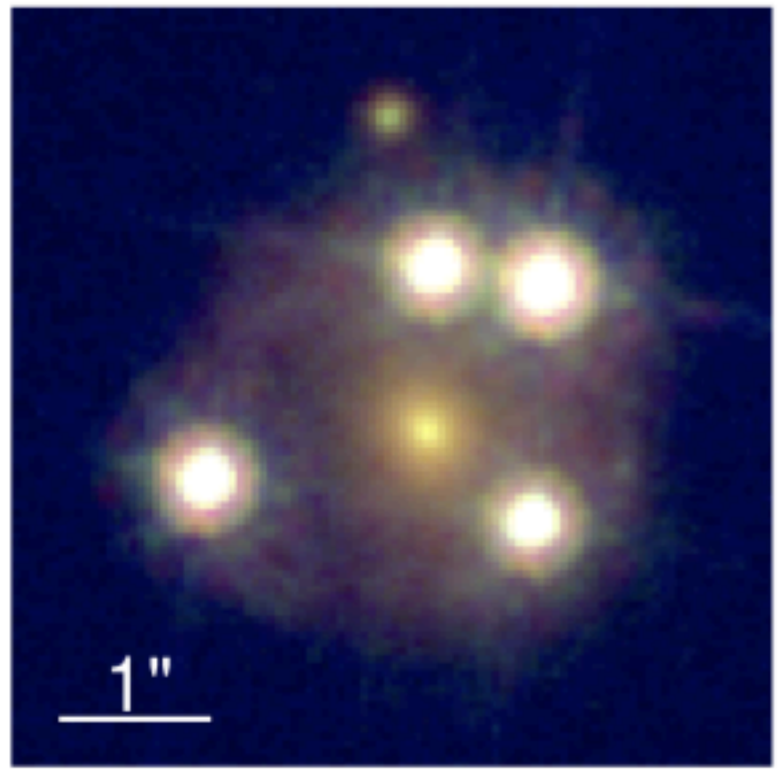
(b) RXJ1131−1231



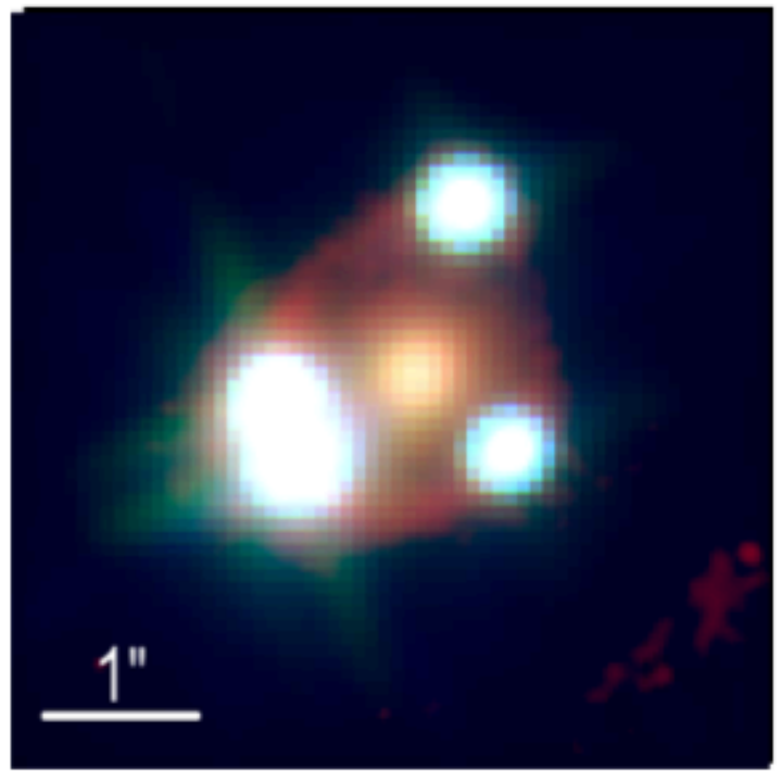
(c) HE 0435−1223



(d) SDSS 1206+4332

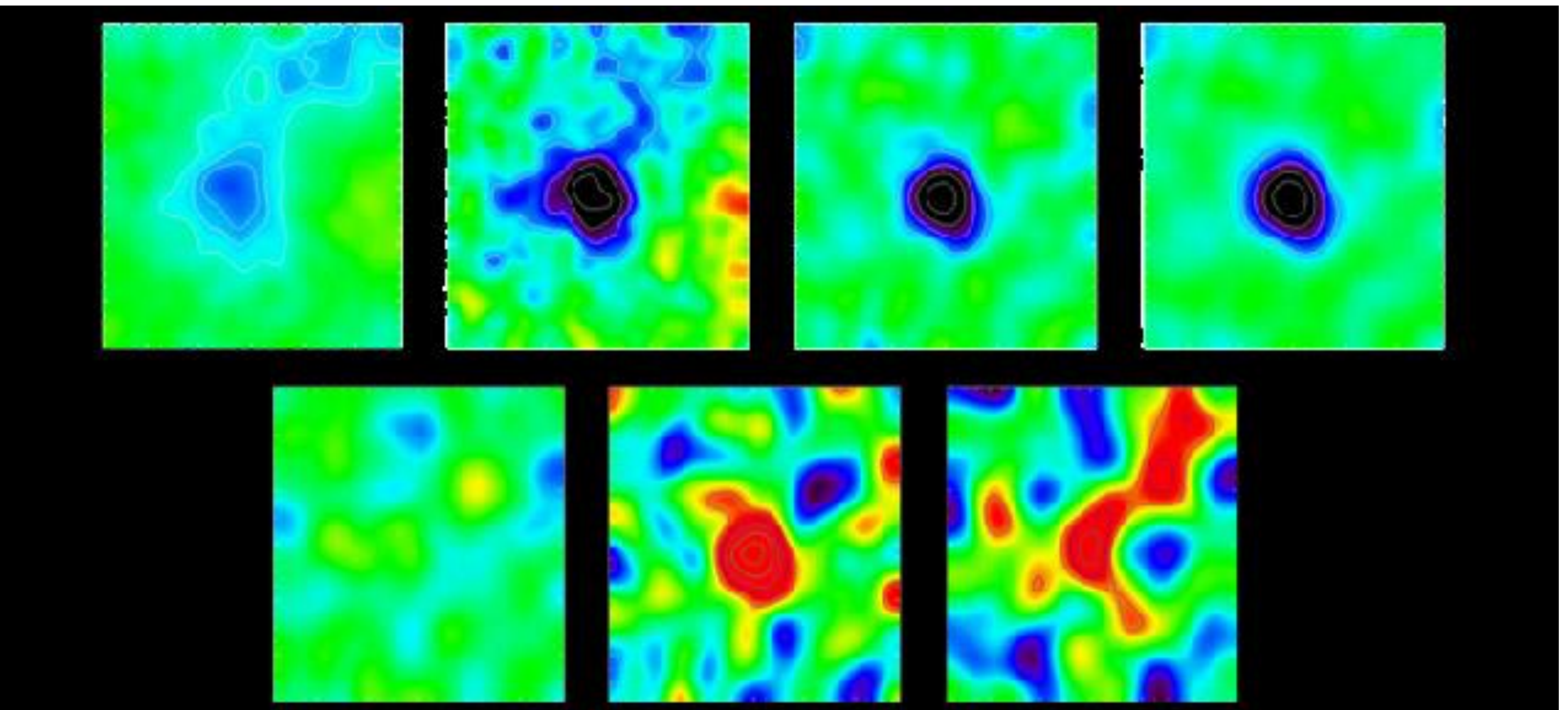


(e) WFI2033−4723



(f) PG 1115+080

S-Z effect



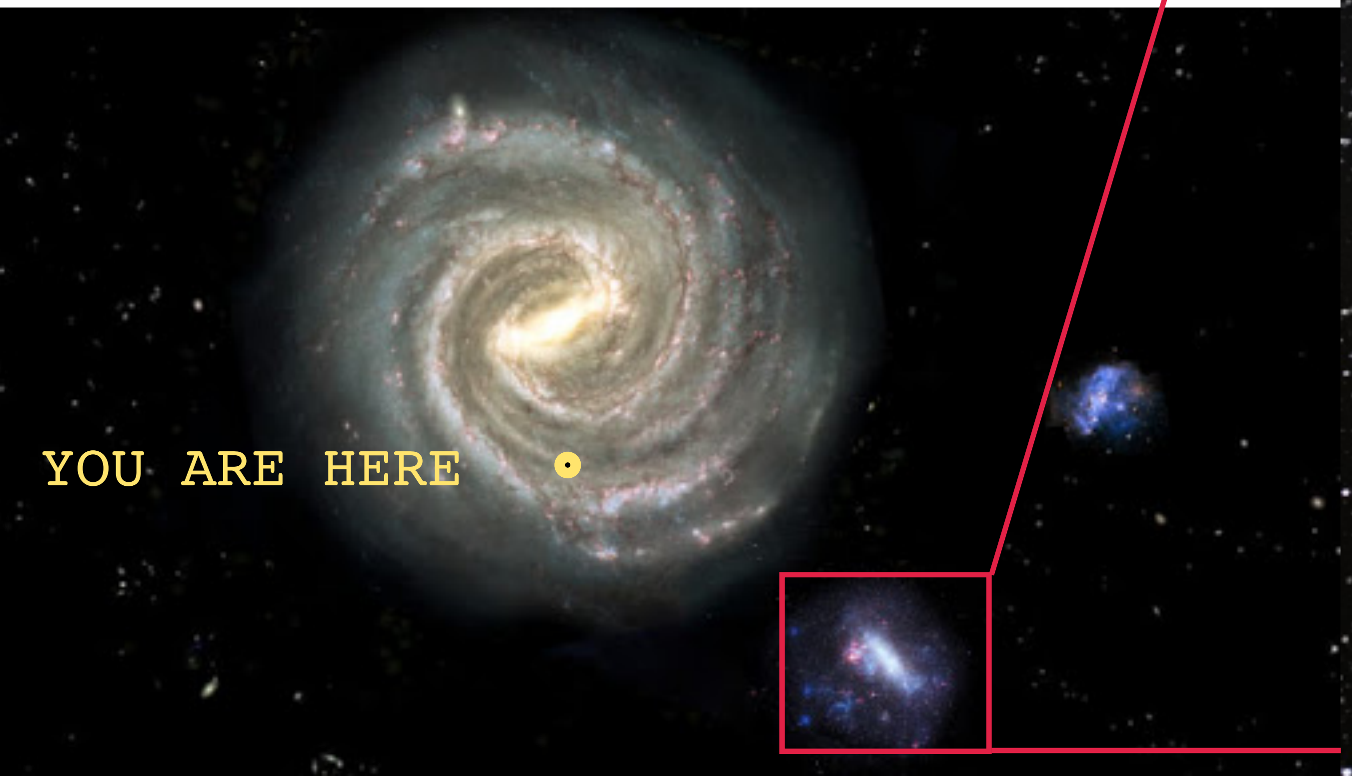
Distance Scale

- Absolute Methods
  - Light echo
    - combines geometry & speed of light

Supernova 1987A occurred in the Large Magellanic Cloud, a satellite galaxy of the Milky Way.

The LMC is an important step in the distance ladder. The mean of over 200 measurements gives $m - M = 18.49 \pm 0.13$ (49.9 kpc; Crandall & Ratra 2015).

Pietrzyński et al. (2019) model depth variations; find a mean LMC distance of $\mu = 18.477 \pm 0.0263$ (49.6 kpc).



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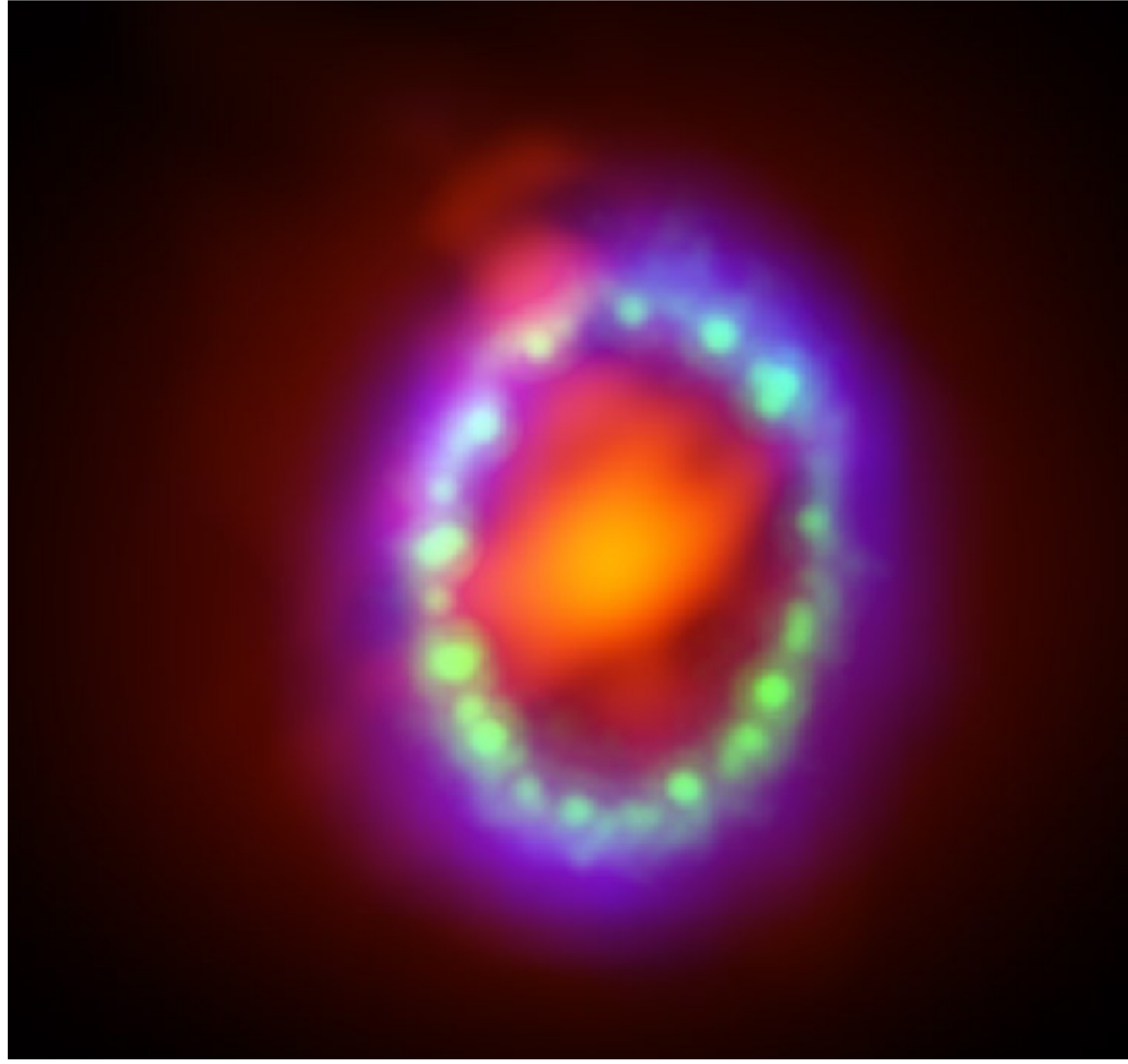


Ring around SN 1987A

Flash of supernova seen directly, then seen reflected by encircling ring of dust with a time delay that depends on size, distance, and the speed of light.

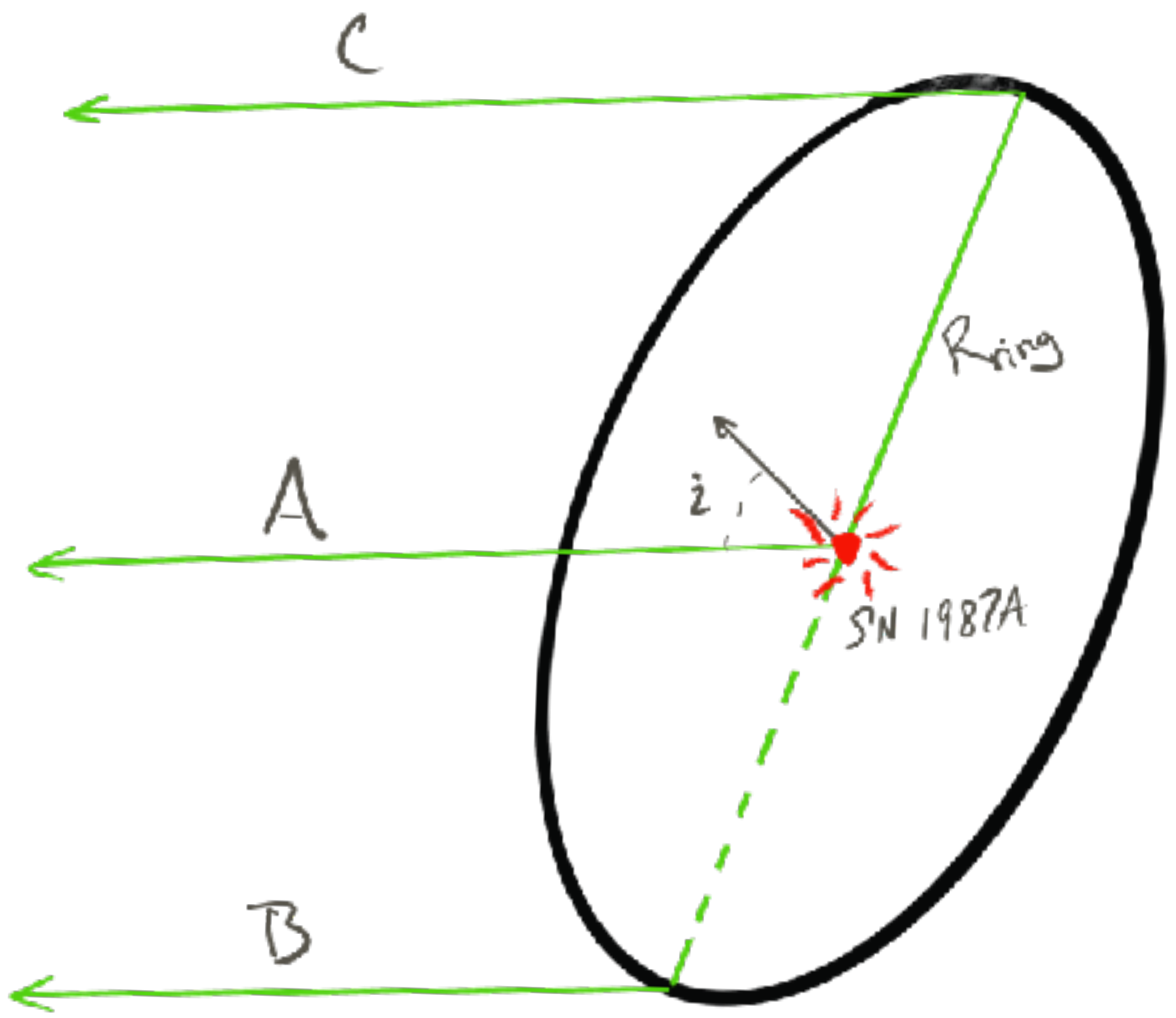
time delays: $\Delta t_B = \frac{R_{\text{ring}}}{c}(1 - \sin i)$ $\Delta t_C = \frac{R_{\text{ring}}}{c}(1 + \sin i)$

measured time delays: $\Delta t_B = 90$ days $\Delta t_C = 400$ days

Two equations with two unknowns: $R_{\text{ring}} = 0.42 \pm 0.03$ pc $i = 43^\circ$

Angular size of major axis $\theta_{\text{ring}} = 1.66''$

$$\theta_{\text{ring}} = \frac{R_{\text{ring}}}{d_{\text{LMC}}} \rightarrow d_{\text{LMC}} = 51.9 \pm 3.1 \text{ kpc}$$ (Crotts et al. 1995)



Distance Scale

- Absolute Methods
  - Gravitational lens time delay

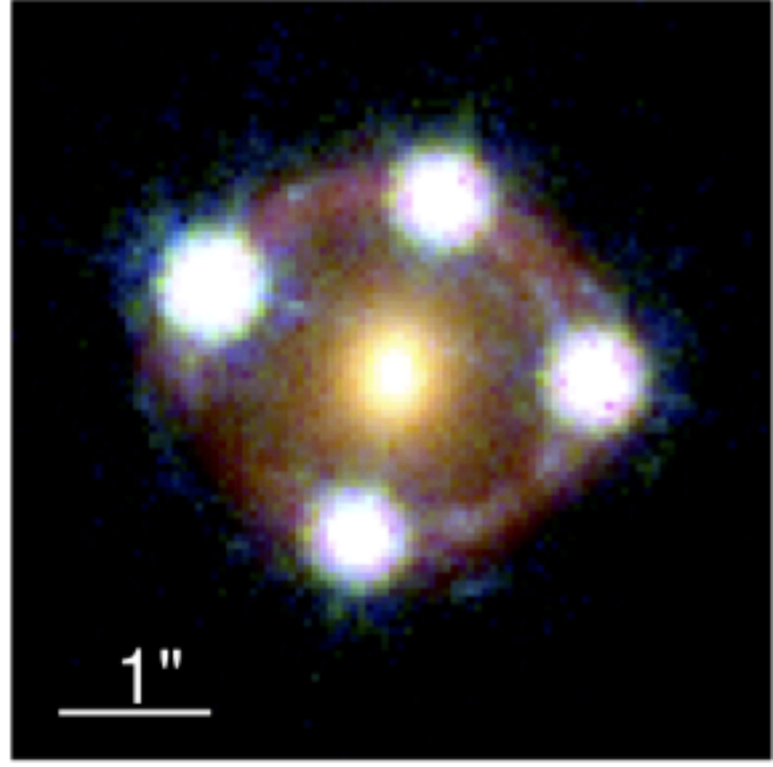
There is a delay between the arrival times of the multiple images that occur in gravitational lenses:

$$\Delta t_i = (1 + z_i)\left(\frac{1}{2c}\frac{D_L D_S}{D_{LS}}\alpha_i^2 - \frac{2}{c^3}\int \Phi(s)ds\right)$$

The time delay is tricky to measure, but in principle this gives a direct geometrical estimate of the distance: it's like parallax to cosmic distances, bypassing all the rungs in the distance ladder.

Can use distance-redshift relation to replace $D_L(z_L)$ and $D_S(z_S)$ with H_0 and q_0.

D_L	lens distance
D_S	source distance
D_{LS}	lens-source separation
α_i	observed image-lens angle
$\Phi(s)$	gravitational potential of lens



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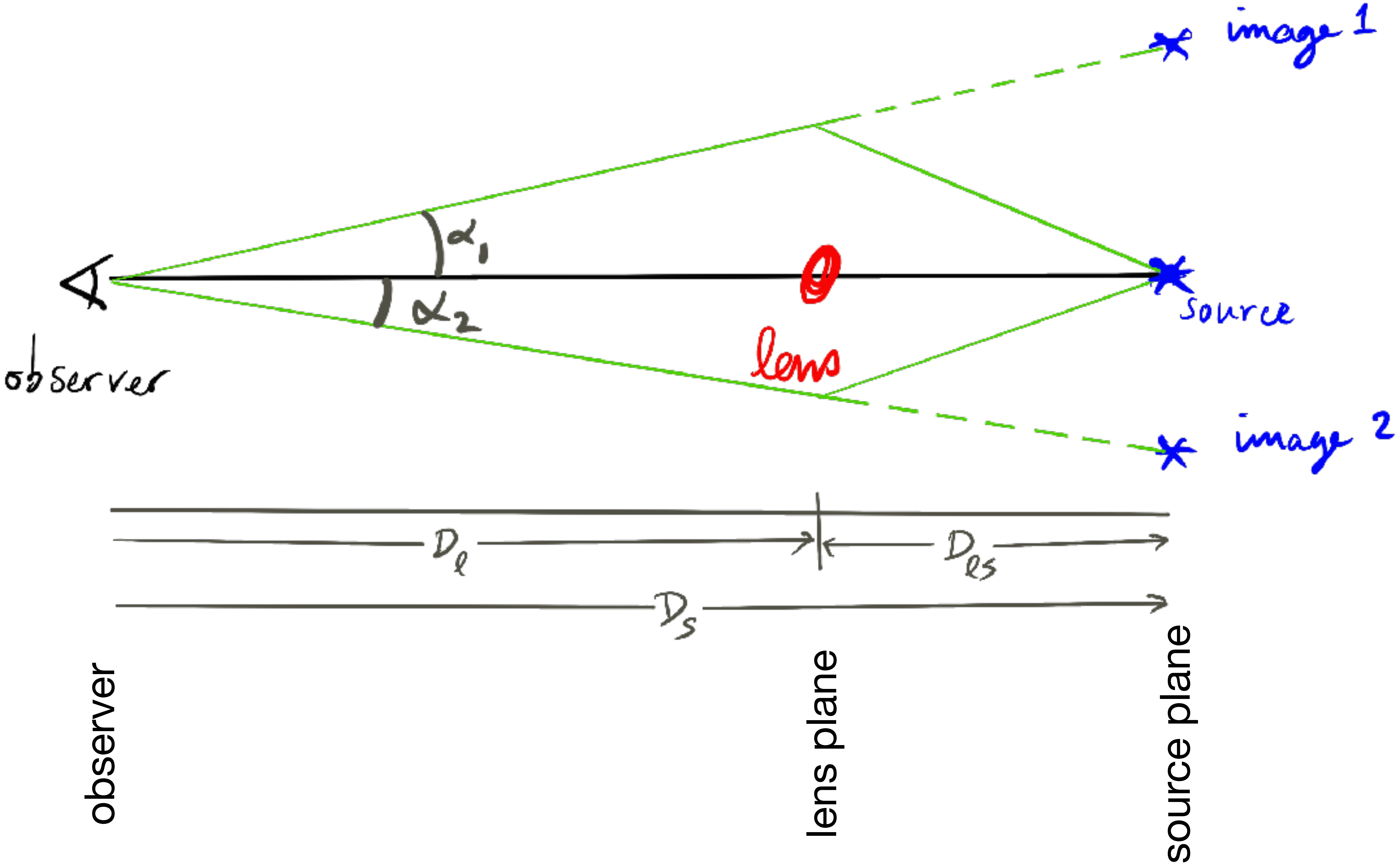

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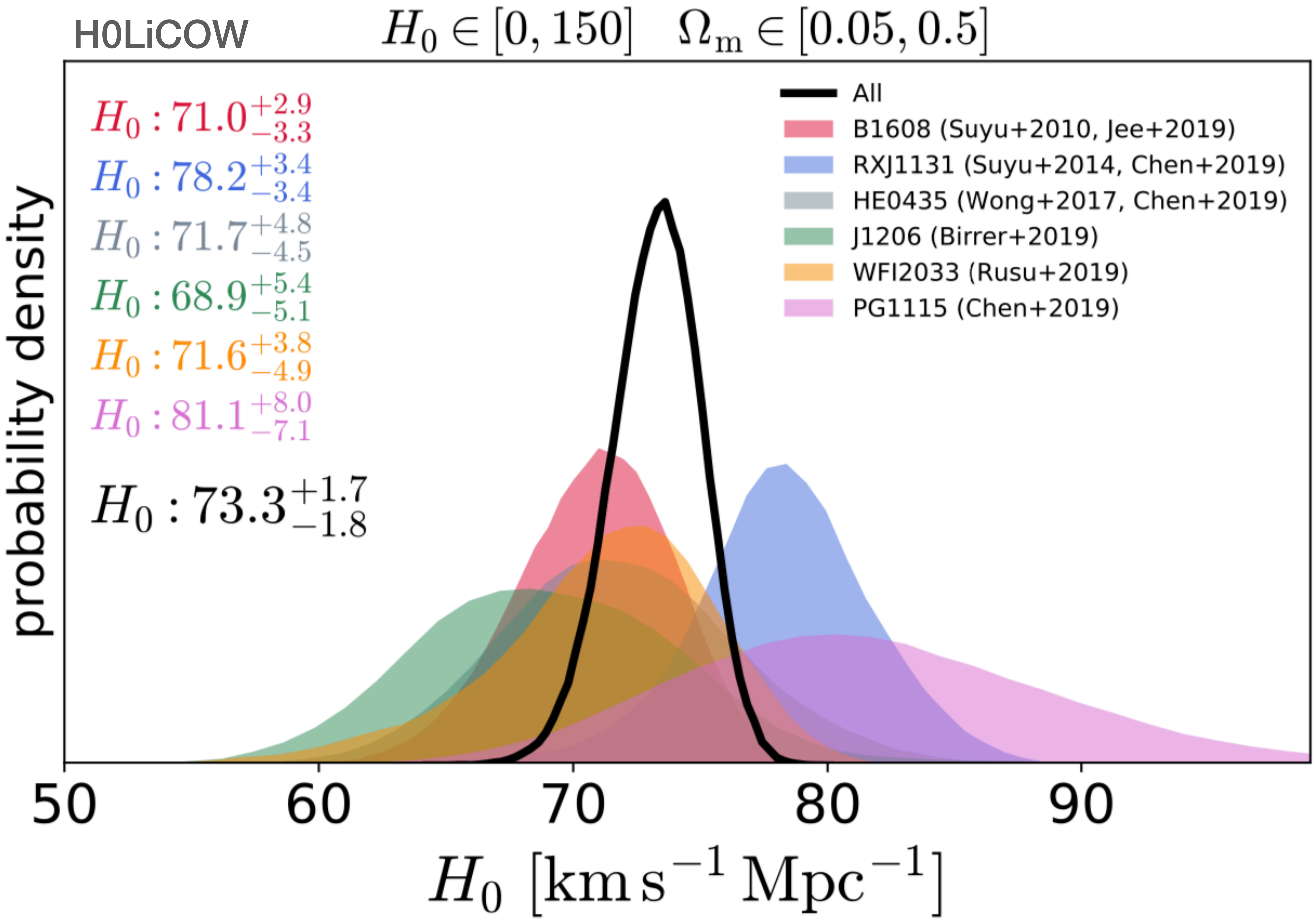
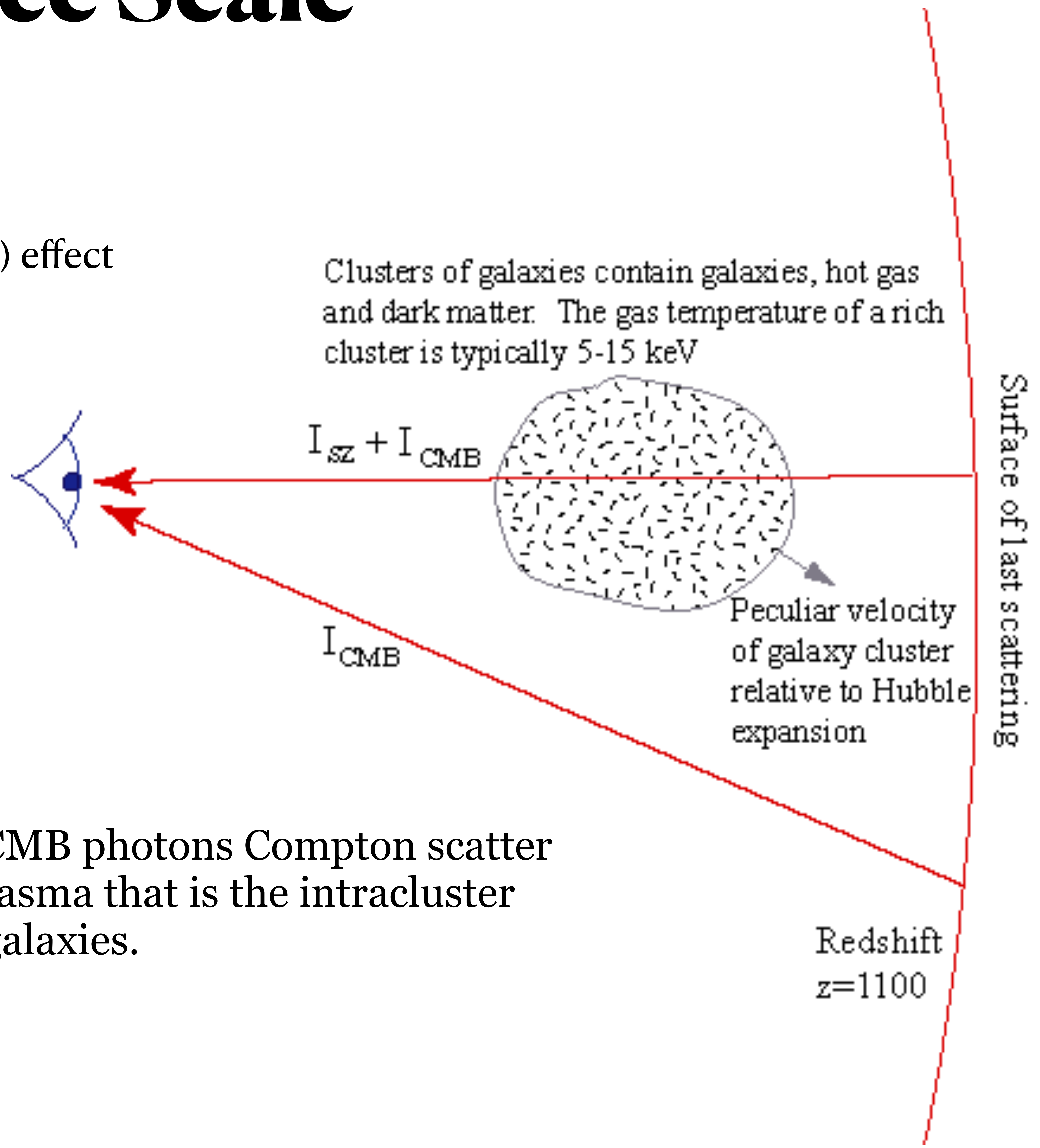


$$H_0 = 73.3^{+1.7}_{-1.8}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

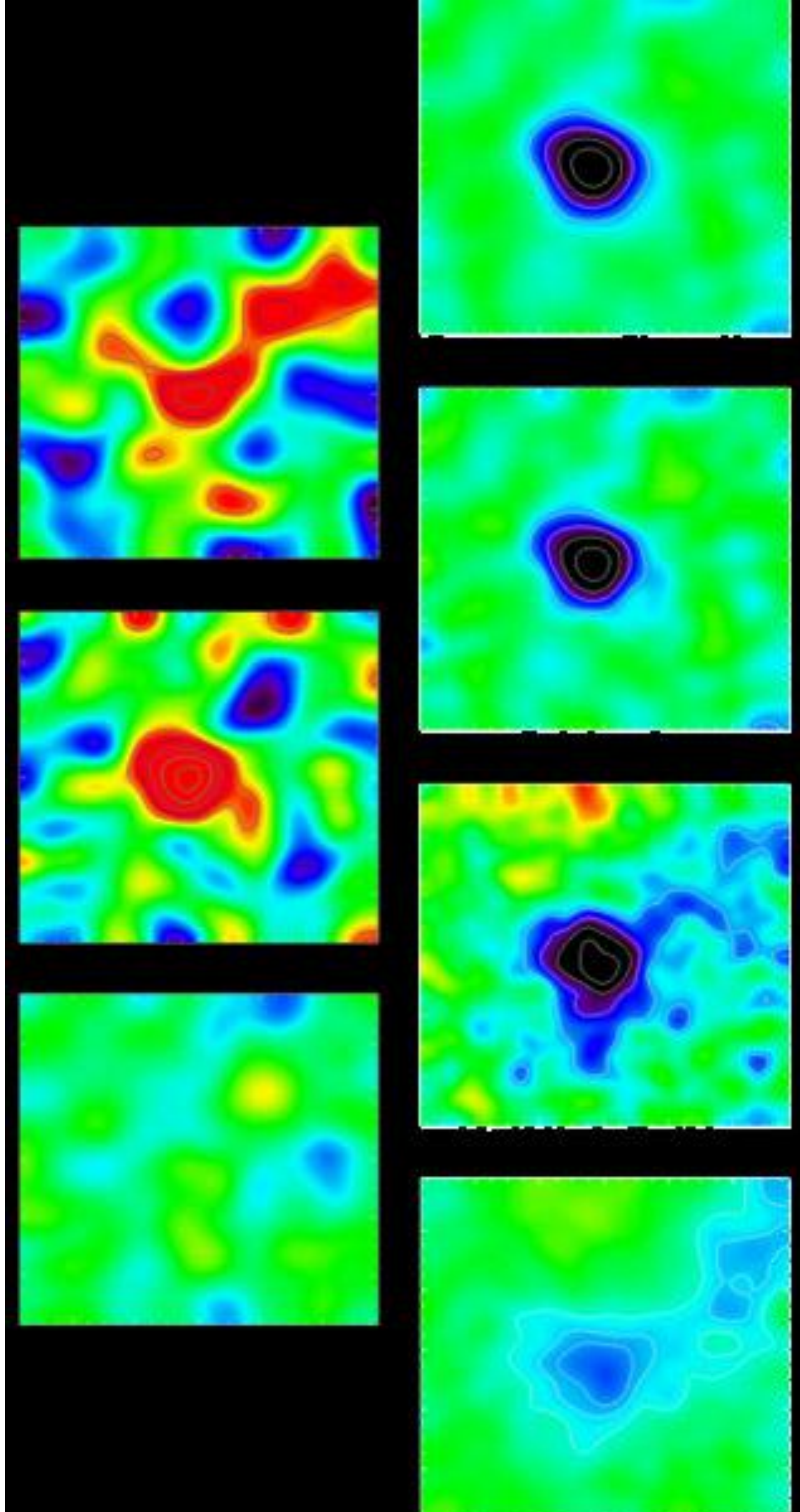
Wong *et al*. 2019, MNRAS, 498, 1420

Distance Scale

- Absolute Methods
  - Sunyaev-Zeldovich (SZ) effect



The SZ effect occurs when CMB photons Compton scatter off of electrons in the hot plasma that is the intracluster medium of rich clusters of galaxies.



frequency dependent change in intensity

$$\frac{\delta I_{nu}}{I_\nu} = -y \frac{xe^x}{e^x - 1}\left[4 - x\coth\left(\frac{x}{2}\right)\right]$$

where $x = \dfrac{h\nu}{kT_{rad}}$ and $y = \displaystyle\int \sigma_T n_e \frac{kT_g}{m_e c^2} d\ell$

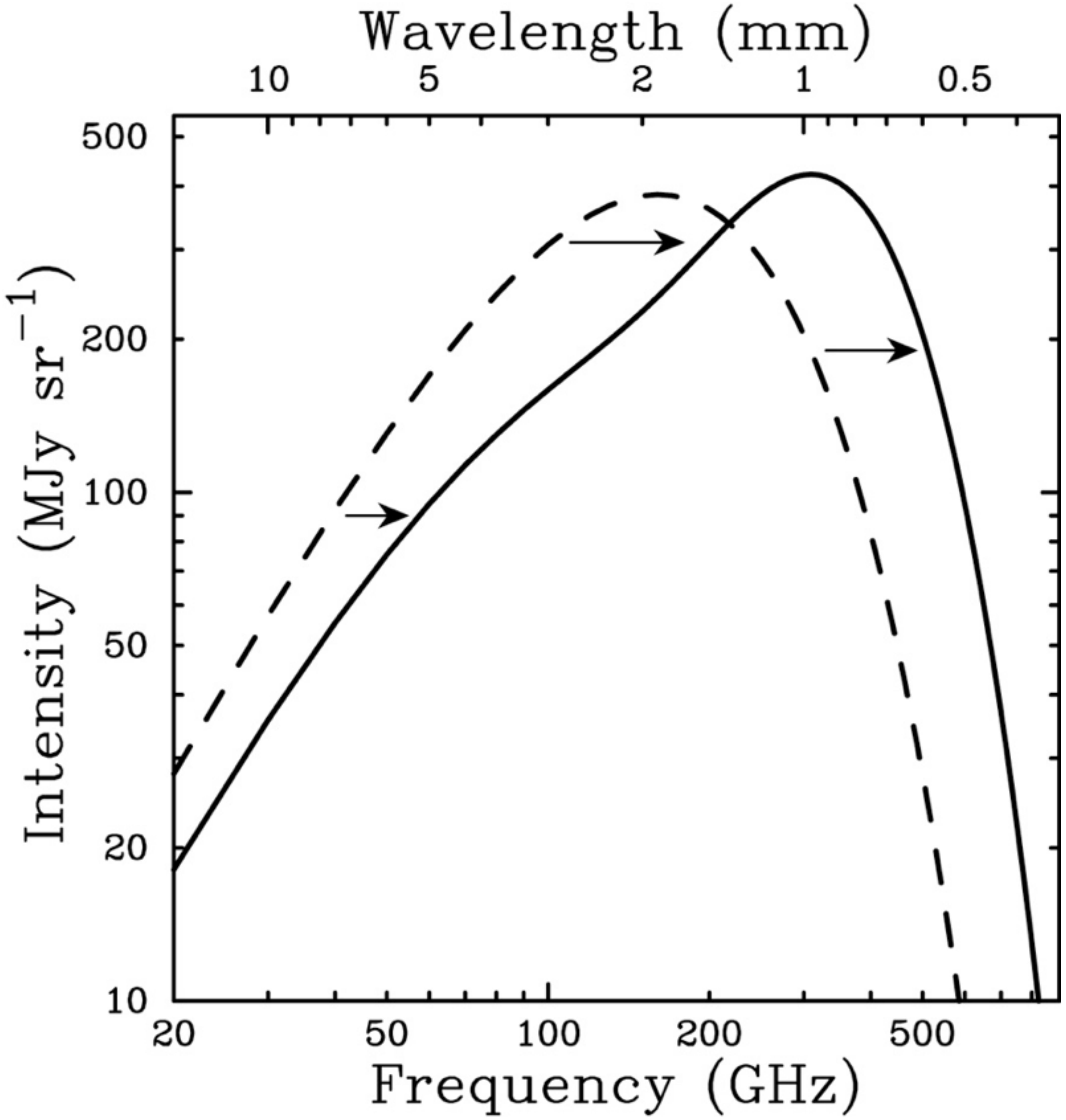
CMB (T_{rad})

electron density (n_e)

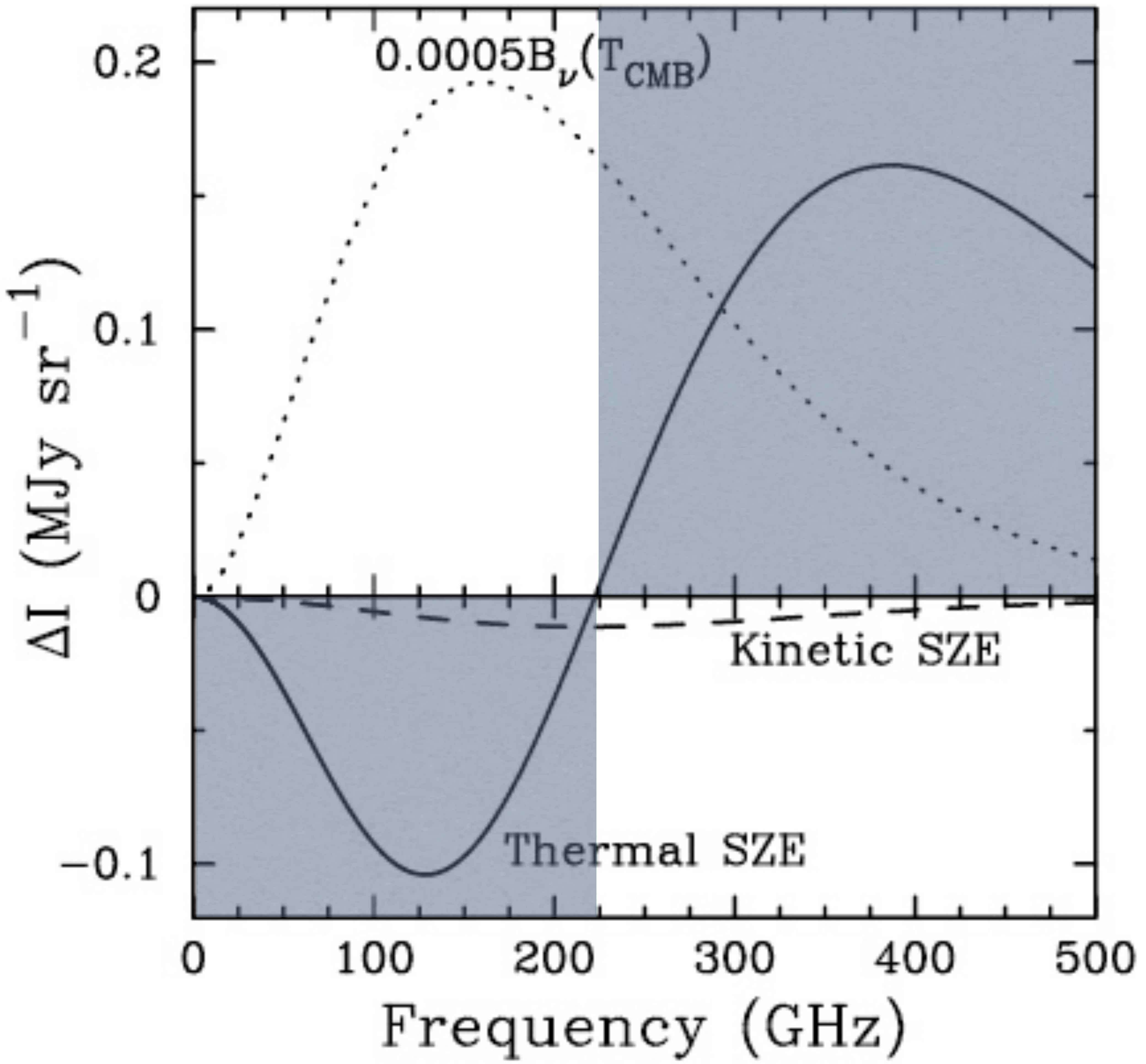
Thomson scattering cross-section (σ_T)

y is the Compton y-parameter which quantifies how much effect the plasma has

The SZ effect occurs when CMB photons Compton scatter off of electrons in the hot plasma that is the intracluster medium of rich clusters of galaxies. Results in a net increase in the effective radiation Temperature.



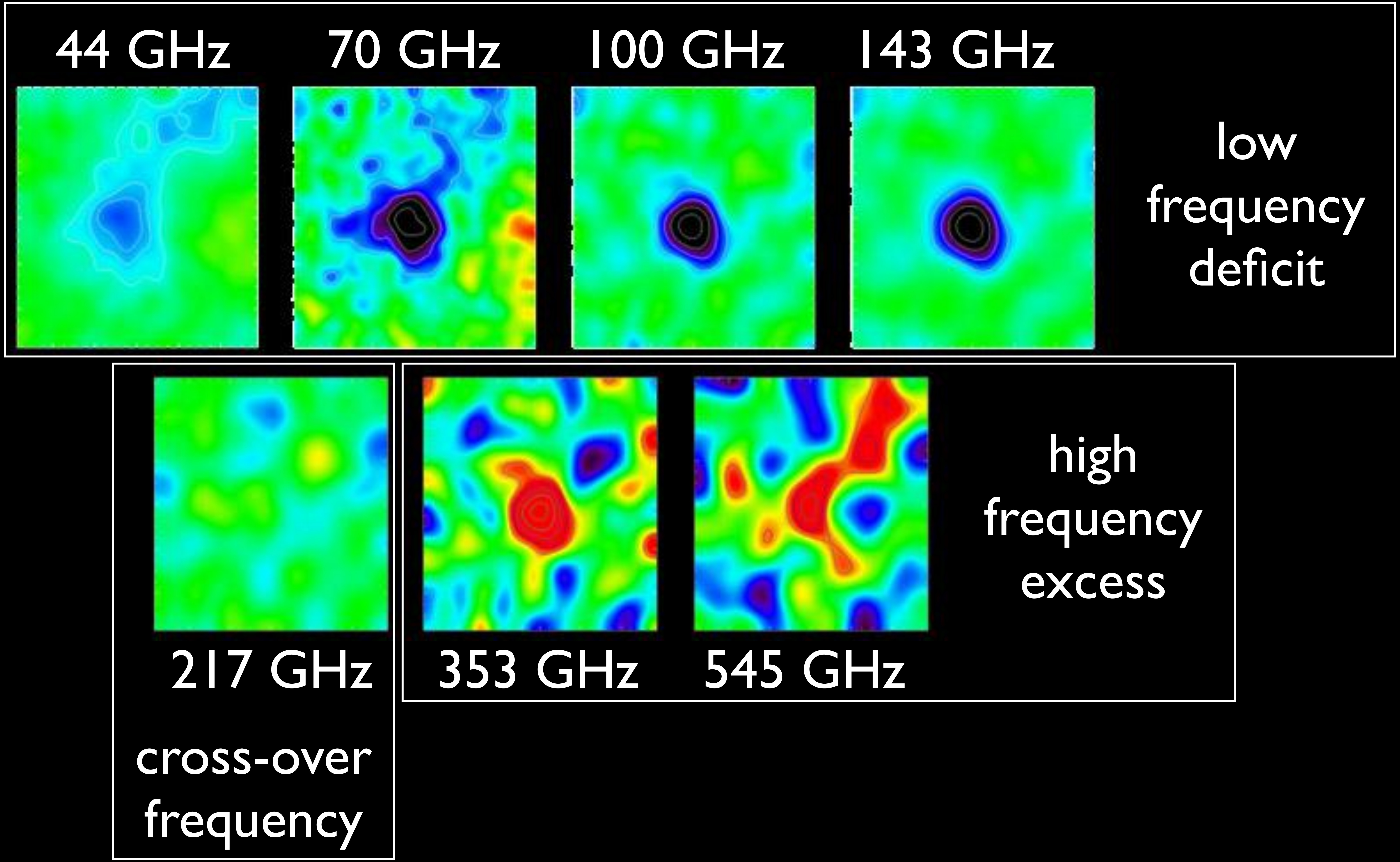
intensity boosted

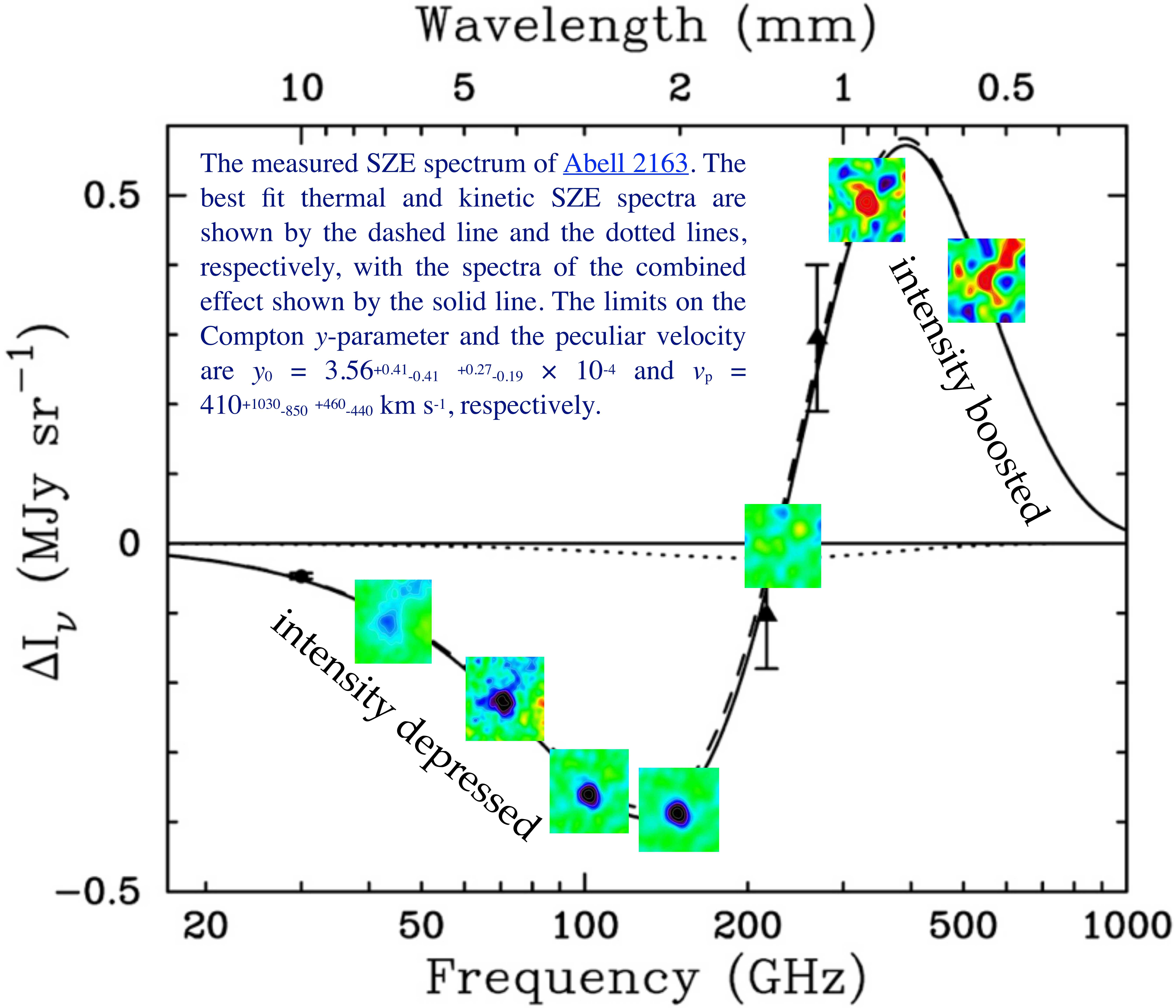


intensity depleted

SUNYAEV–ZEL'DOVICH EFFECT

detected by Planck




Wavelength (mm)
10
5
2
1
0.5
The measured SZE spectrum of Abell 2163. The best fit thermal and kinetic SZE spectra are shown by the dashed line and the dotted lines, respectively, with the spectra of the combined effect shown by the solid line. The limits on the Compton y-parameter and the peculiar velocity are $y_0 = 3.56^{+0.41}_{-0.41}\ {}^{+0.27}_{-0.19} \times 10^{-4}$ and $v_p = 410^{+1030}_{-850}\ {}^{+460}_{-440}$ km s^{-1}, respectively.
intensity boosted
intensity depressed
0.5
0
−0.5
ΔI_ν (MJy sr^{-1})
20
50
100
200
500
1000
Frequency (GHz)

integrated change in CMB temperature

$$\int \Delta T d\Omega \propto \frac{N_e \langle T_e \rangle}{D_A^2} \propto \frac{M \langle T_e \rangle}{D_A^2}$$

depends on the total number of electrons, their temperature, and the area they subtend on the sky.
In effect measures Pressure, or mass if T known.

D_A is the angular diameter distance.
At high z, it varies slowly, while the density increases as $(1+z)^3$

... SZ effect weak, but nearly independent of redshift!

Distance Scale

- Absolute Methods
  - Sunyaev-Zeldovich (SZ) effect

Cluster optical depth $\tau_{SZ} = 2\sigma_T n_e R_c$ where
σ_T is the Thomson scattering cross-section, n_e is the electron density, and R_c is the cluster radius.

The X-ray flux is $f_X = \dfrac{4\pi}{3}\dfrac{R_c^3 \epsilon(\nu)}{4\pi D^2}$

where the Bremsstrahlung emissivity is $\epsilon(\nu) = A n_e^2 T_X^{1/2} e^{-\frac{h\nu}{kT_X}}$

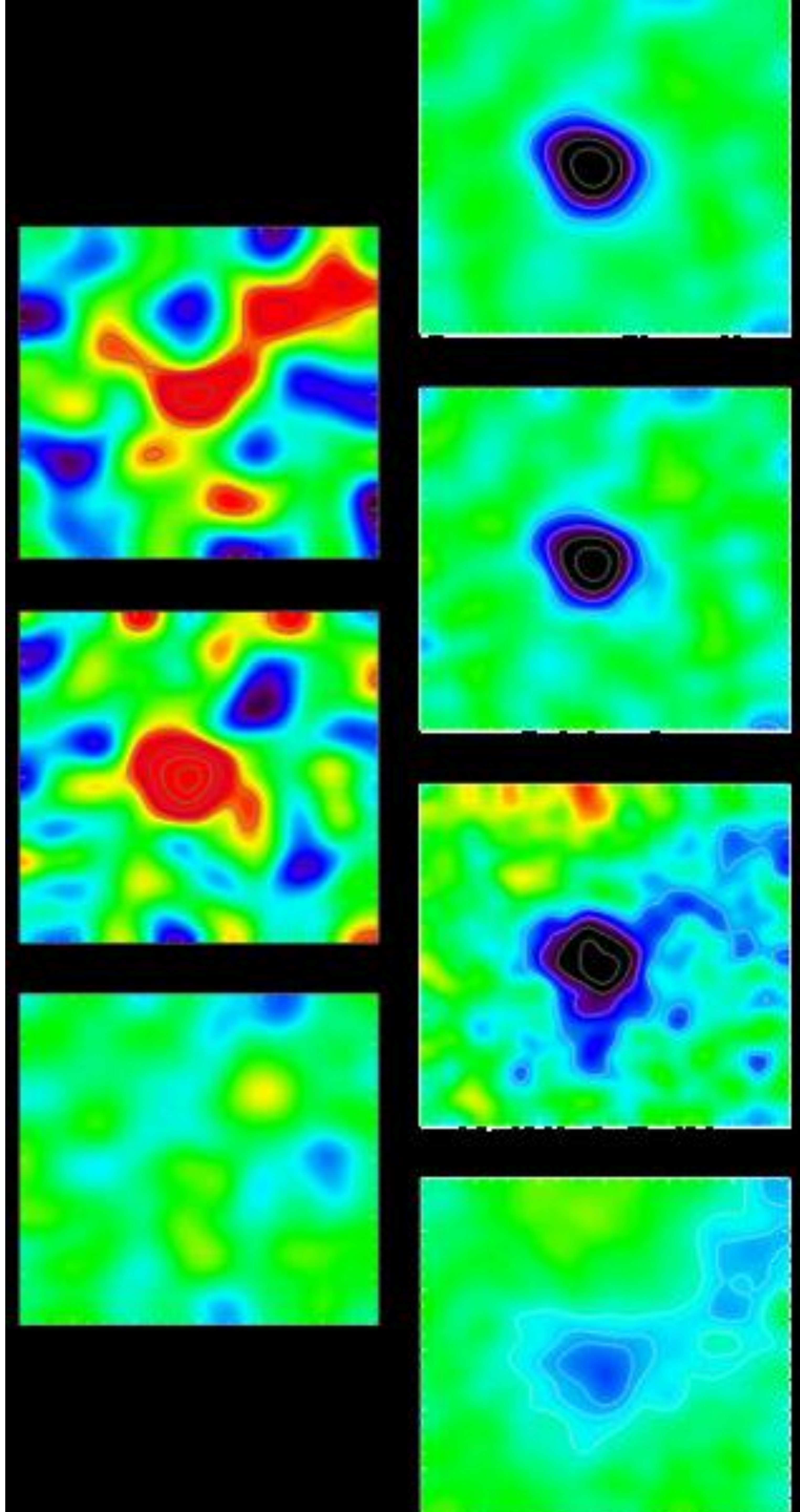
All of which can be combined to give the distance

$$D = \frac{A}{24\sigma_T}\frac{e^{-\frac{h\nu}{kT_X}}}{\sqrt{T_X}}\frac{\theta_X}{f_X}\frac{\tau_{SZ}^2}{(1+z)^2}$$

by equating the angular diameter θ_X with the path length $2R_c$ experienced by the CMB photons

$$H_0 = 69 \pm 8 \text{ km s}^{-1}\text{ Mpc}^{-1}$$

Schmidt *et al*. 2004



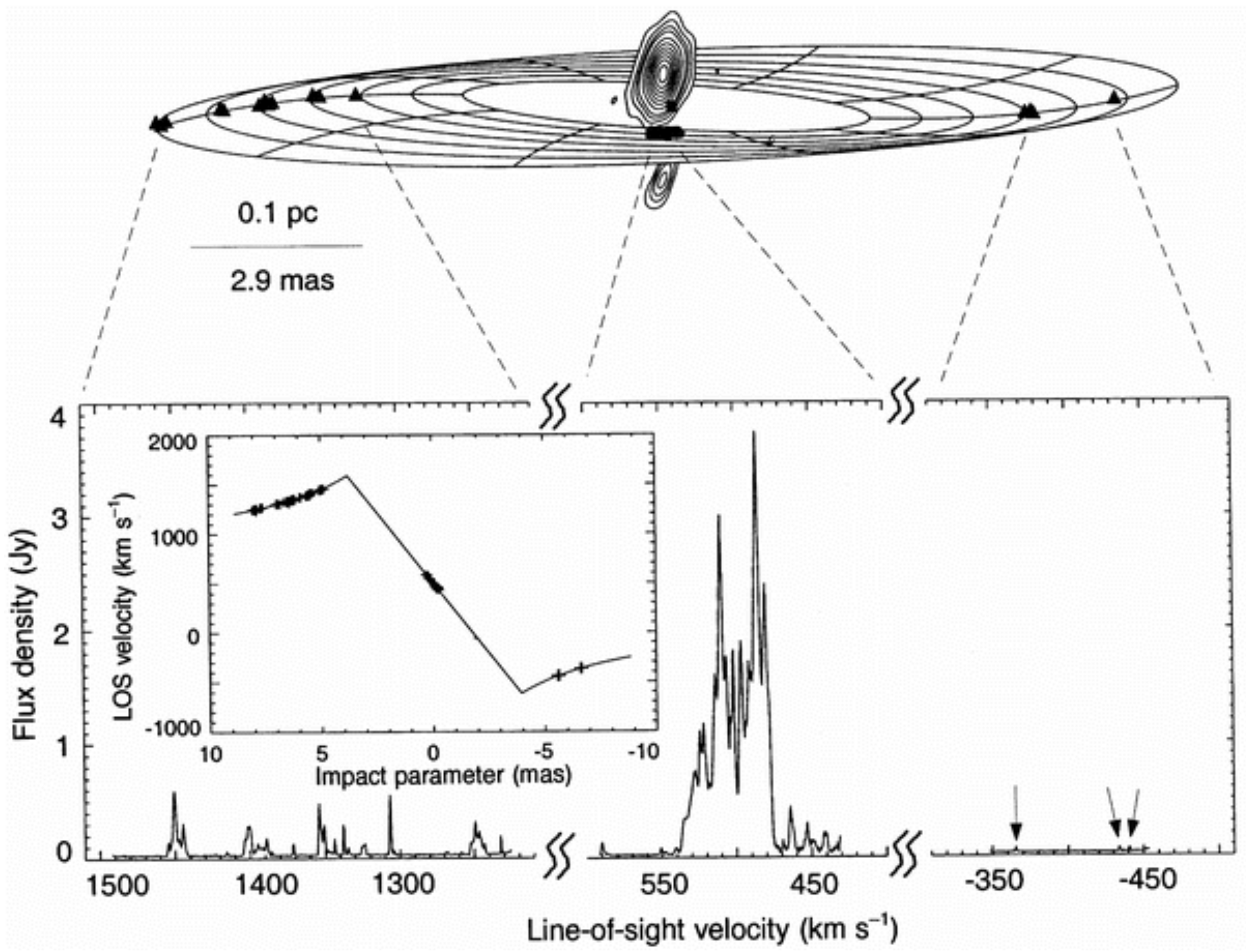
Distance Scale

- Absolute Methods
    - water masers

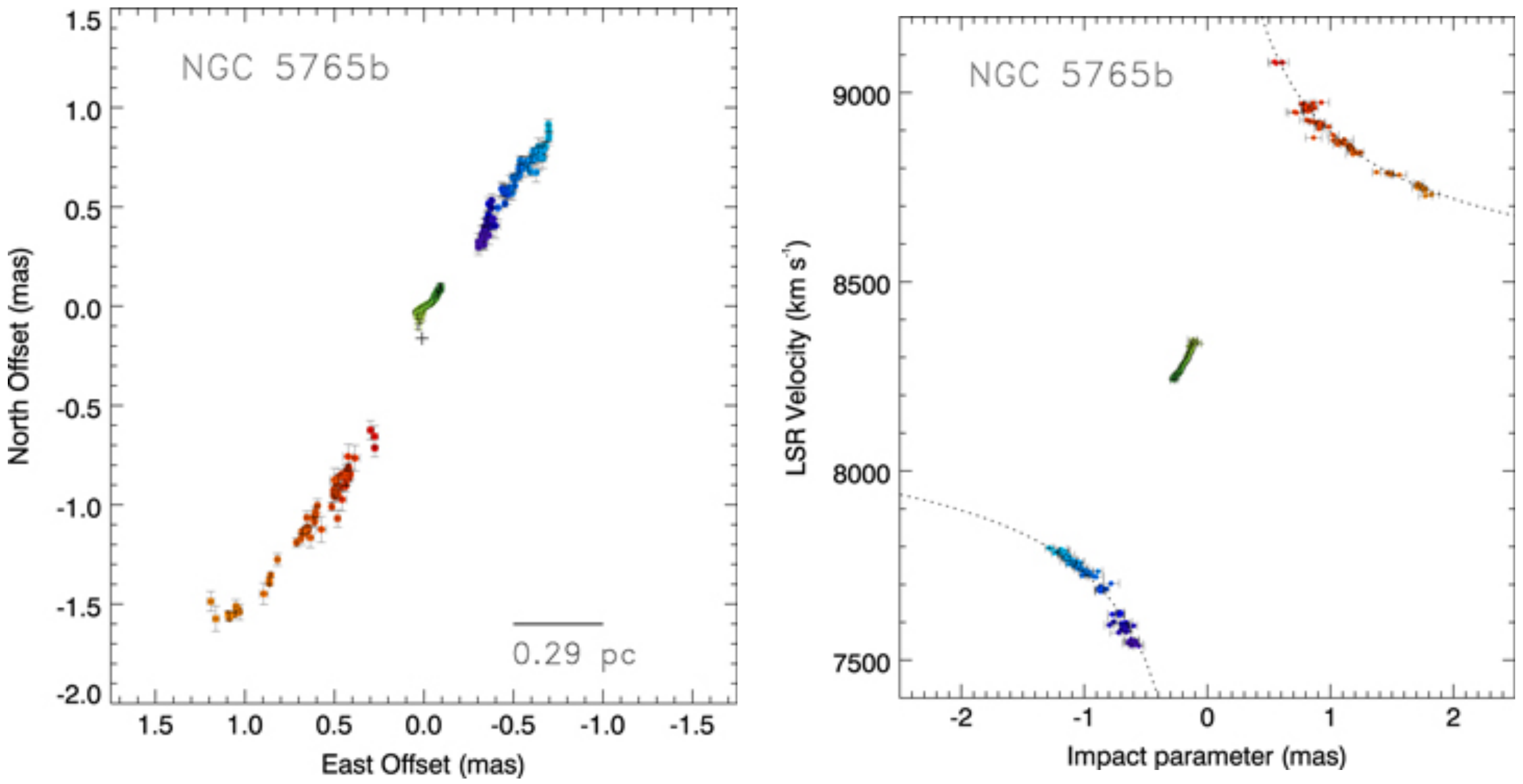
Conditions in the ISM are sometimes right to produce masers - the amplification of molecular lines due to level inversion, e.g., H_2O at 1.35 cm.

Sometimes found orbiting the central supermassive black holes of nearby galaxies. Can watch them orbit by tracking their positions with VLBI (proper motions at microarcsecond accuracy). Can also measure their radial velocities via the Doppler effect. We understand orbits around point masses, so these all combine to provide a geometric distance measurement that is independent of other rungs in the distance ladder.

NGC 4258 (Herrnstein et al 1999)



NGC 5765 (Gao et al 2016)



The dotted line shows the best-fit Keplerian rotation curve assuming an edge-on thin-disk model without disk warping. This model gives an enclosed mass of 4.4 ± 0.44 $\times 10^7 M_\odot$ and a recession velocity of 8304 km s^{-1}.

Distance Scale

- Absolute Methods
  - water masers

Herrnstein et al (1999) detect accelerations as well as velocities:

To convert the maser proper motions and accelerations into a geometric distance, we express $\langle \dot{\theta}_x \rangle$ and $\langle \dot{v}_{\rm LOS} \rangle$ in terms of the distance and four disk parameters:

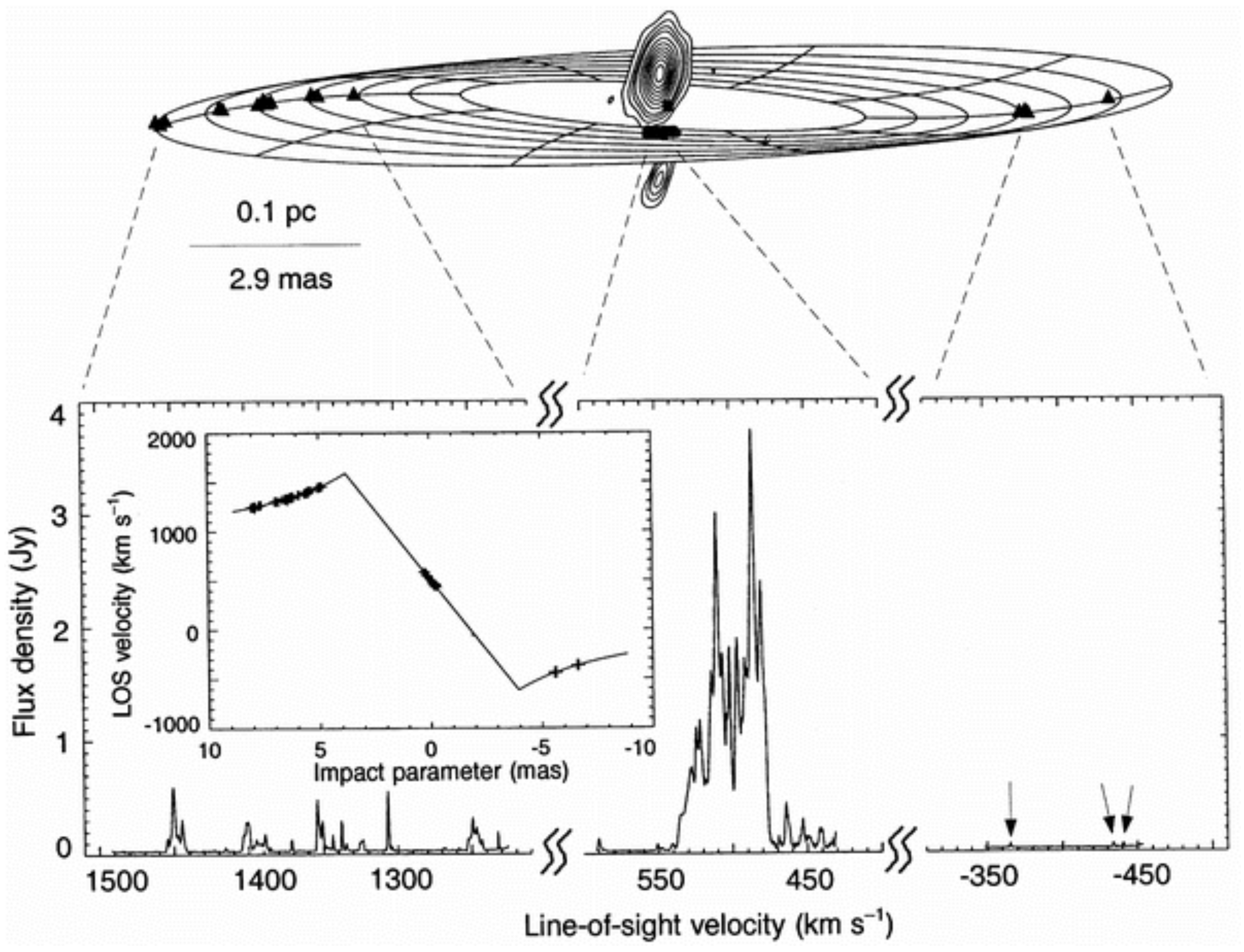
$$\langle \dot{\theta}_x \rangle = 31.5 \left[\frac{D_6}{7.2}\right]^{-1} \left[\frac{\Omega_s}{282}\right]^{1/3} \left[\frac{M_{7.2}}{3.9}\right]^{1/3} \left[\frac{\sin i_s}{\sin 82.3°}\right]^{-1} \left[\frac{\cos \alpha_s}{\cos 80°}\right] \mu\text{as yr}^{-1} \quad (1)$$

and

$$\langle \dot{v}_{\rm LOS} \rangle = 9.2 \left[\frac{D_6}{7.2}\right]^{-1} \left[\frac{\Omega_s}{282}\right]^{4/3} \left[\frac{M_{7.2}}{3.9}\right]^{1/3} \left[\frac{\sin i_s}{\sin 82.3°}\right]^{-1} \text{km s}^{-1} \text{ yr}^{-1} \quad (2)$$

Here D_6 is the distance in Mpc, α_s is the disk position angle (East of North) at $\langle r_s \rangle$, and $M_{7.2}$ is $M/D \sin^2 i_s$ as derived from the high-velocity rotation curve and evaluated at $D = 7.2$ Mpc and $i_s = 82.3°$ (in units of $10^7 M_\odot$). $\Omega_s \equiv (GM_{7.2}/\langle r_s \rangle^3)^{1/2}$ is the projected disk angular velocity at $\langle r_s \rangle$ as determined by the slope of the systemic position–velocity gradient (in units of km s^{-1} mas^{-1}; see Fig. 1). In the denominators of each of the terms of equations (1)and (2), we include *apriori* estimates for each of these disk parameters, derived directly from the positions and velocities of the masers.

NGC 4258 (Herrnstein et al 1999)



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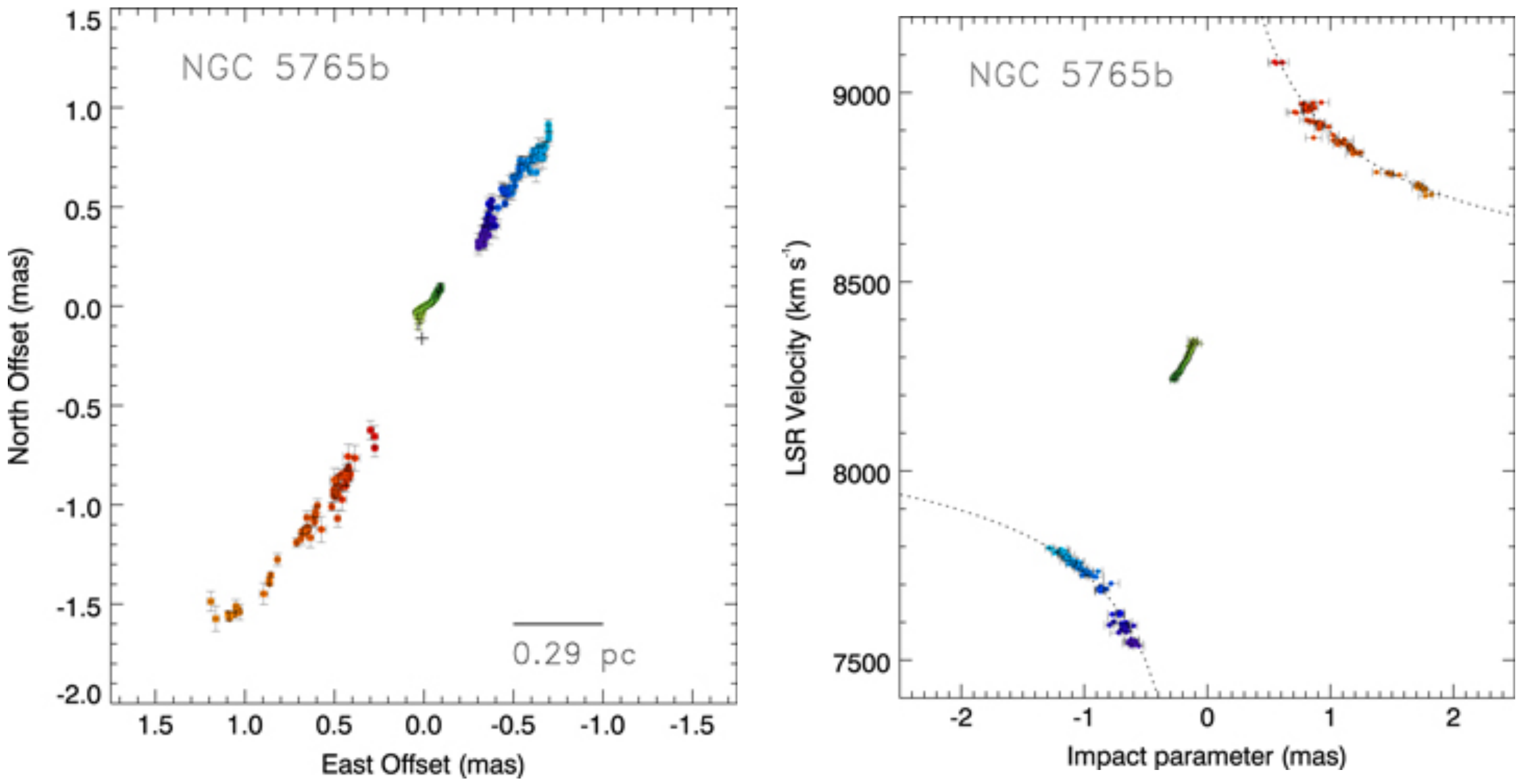

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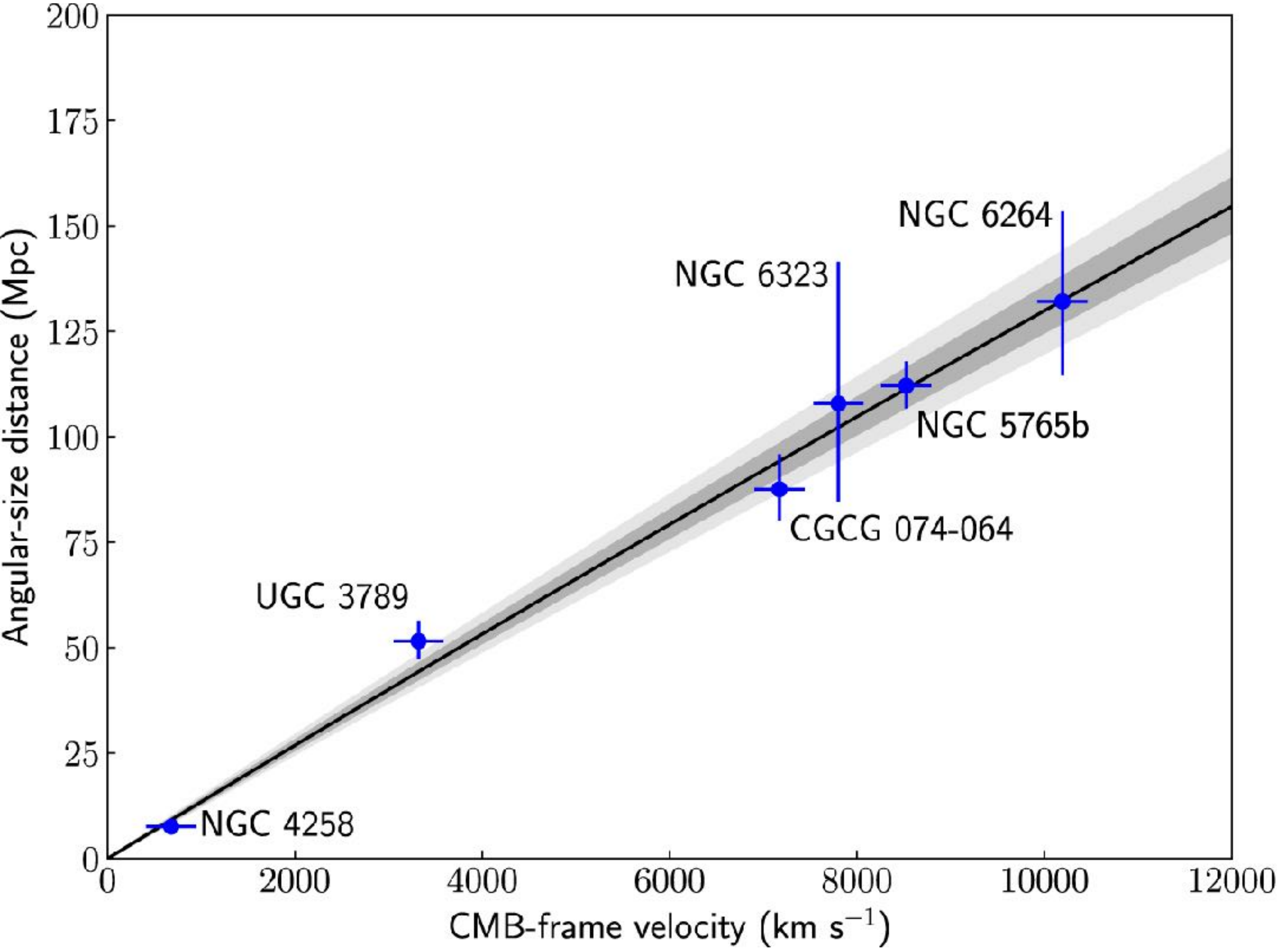
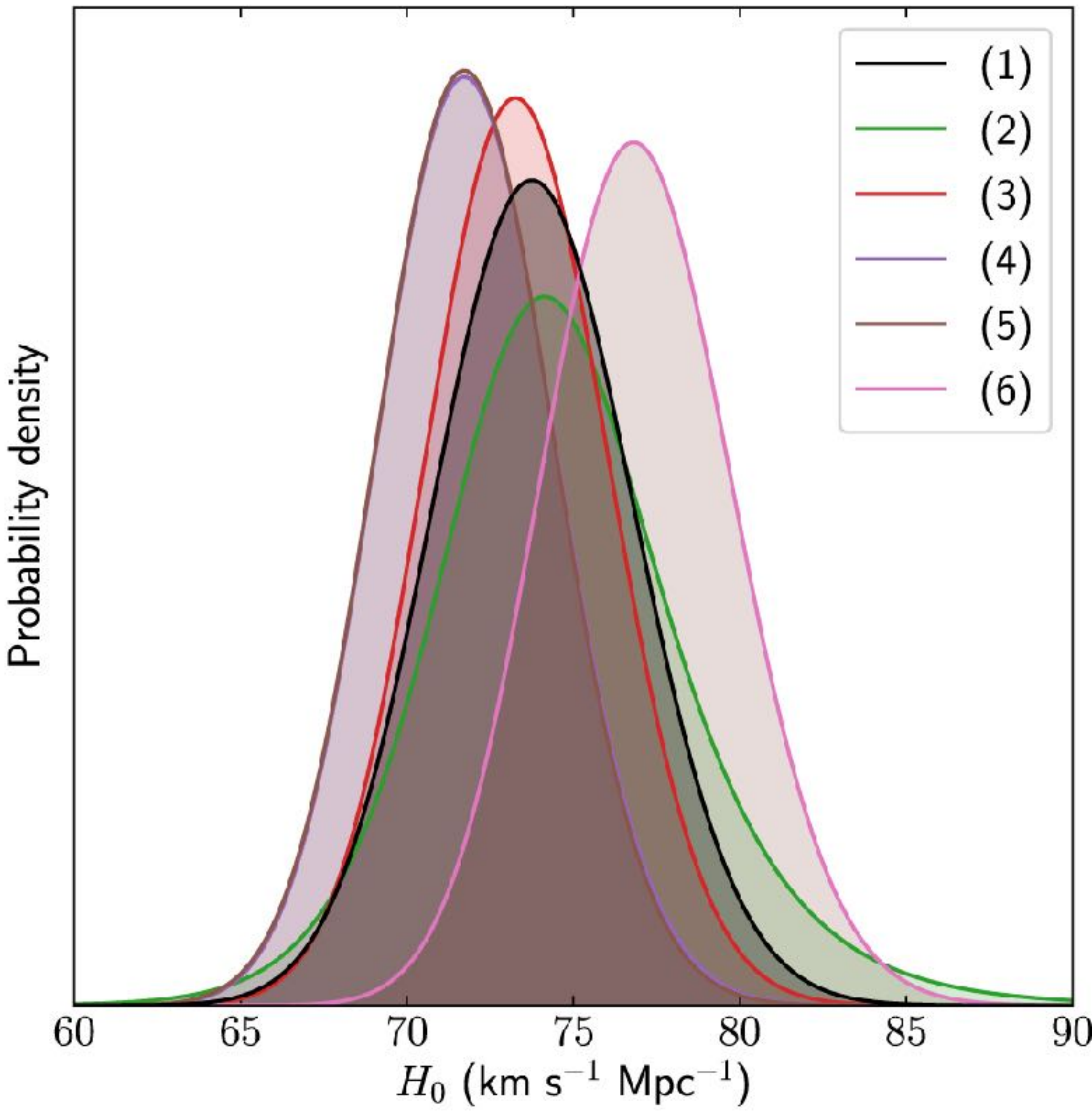
Megamaser Cosmology Project. XIII (Pesce et al. 2020)



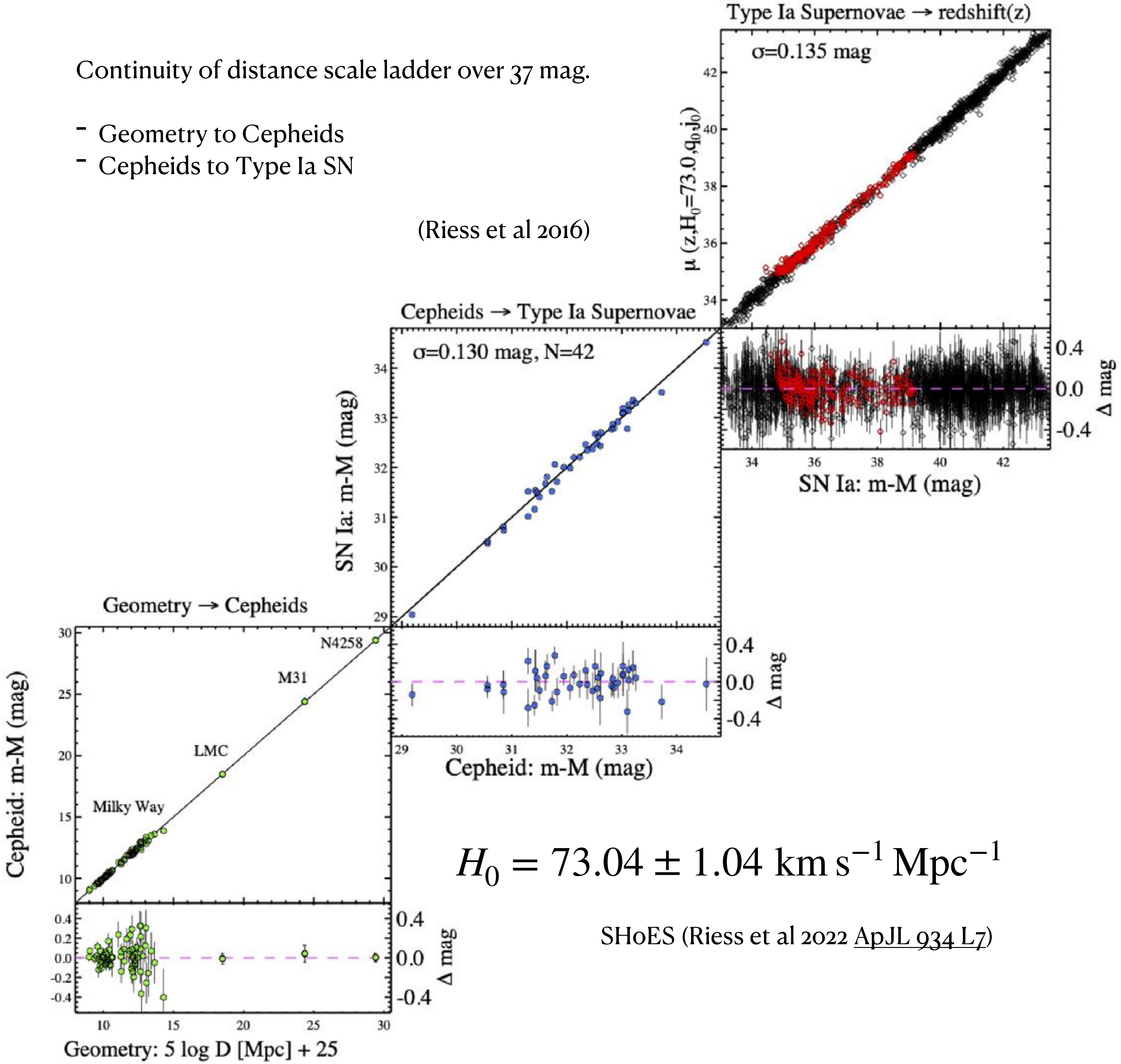


$$H_0 = 73.9 \pm 3.0 \ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Continuity of distance scale ladder over 37 mag.

- Geometry to Cepheids
- Cepheids to Type Ia SN

(Riess et al 2016)



$$H_0 = 73.04 \pm 1.04 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

SHoES (Riess et al 2022 ApJL 934 L7)

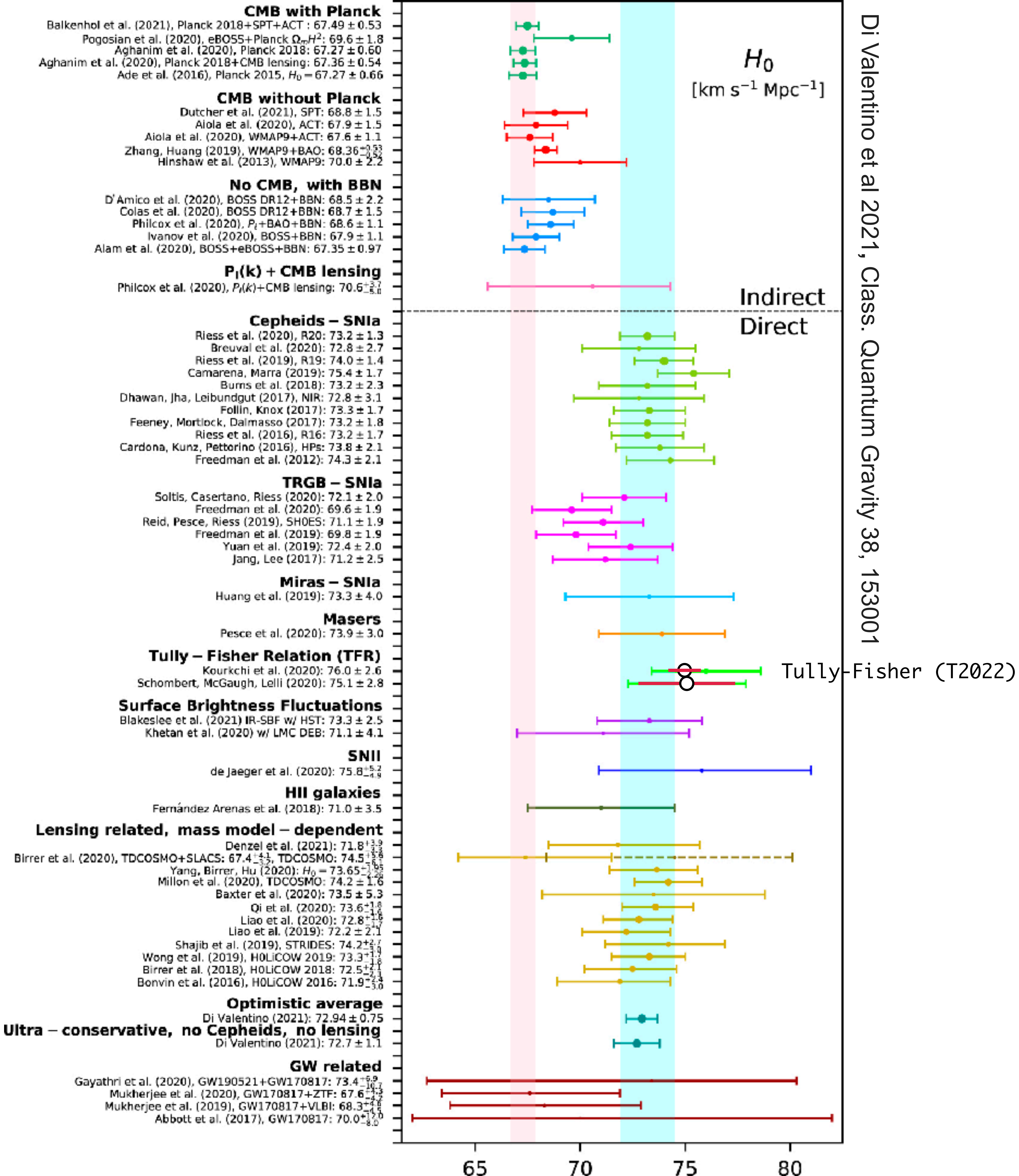
Hubble constant tension

Traditional distance ladder measurements favor H_0 in the low-to-mid 70s.
These are "local," low redshift measurements ("late" in red at right).

Multi-parameter fits to power spectrum data from the CMB and large scale structure favor Ho in the mid-to-upper 60s. The CMB is from higher redshift ("early" in blue at right).

The difference is formally significant at over 4σ. This becomes 17σ if we take the recent Tully-Fisher uncertainty at face value!

The tension appears to be real



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Independent measurements; open points have uncertainties $> 3\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$