Mysteries under a *strong* lens

Charles Dalang

Department of Physics & Astronomy
Queen Mary University of London

4th May 2023

Based on
C.D., M. Millon, T. Baker, [arXiv:2301.05574]

Palais des Papes

Queen Mary University of London

Time delay cosmography

H0LiCOW/TDCOSMO collab.
COSMOGRAIL
C.D., M. Millon, T. Baker, 2023

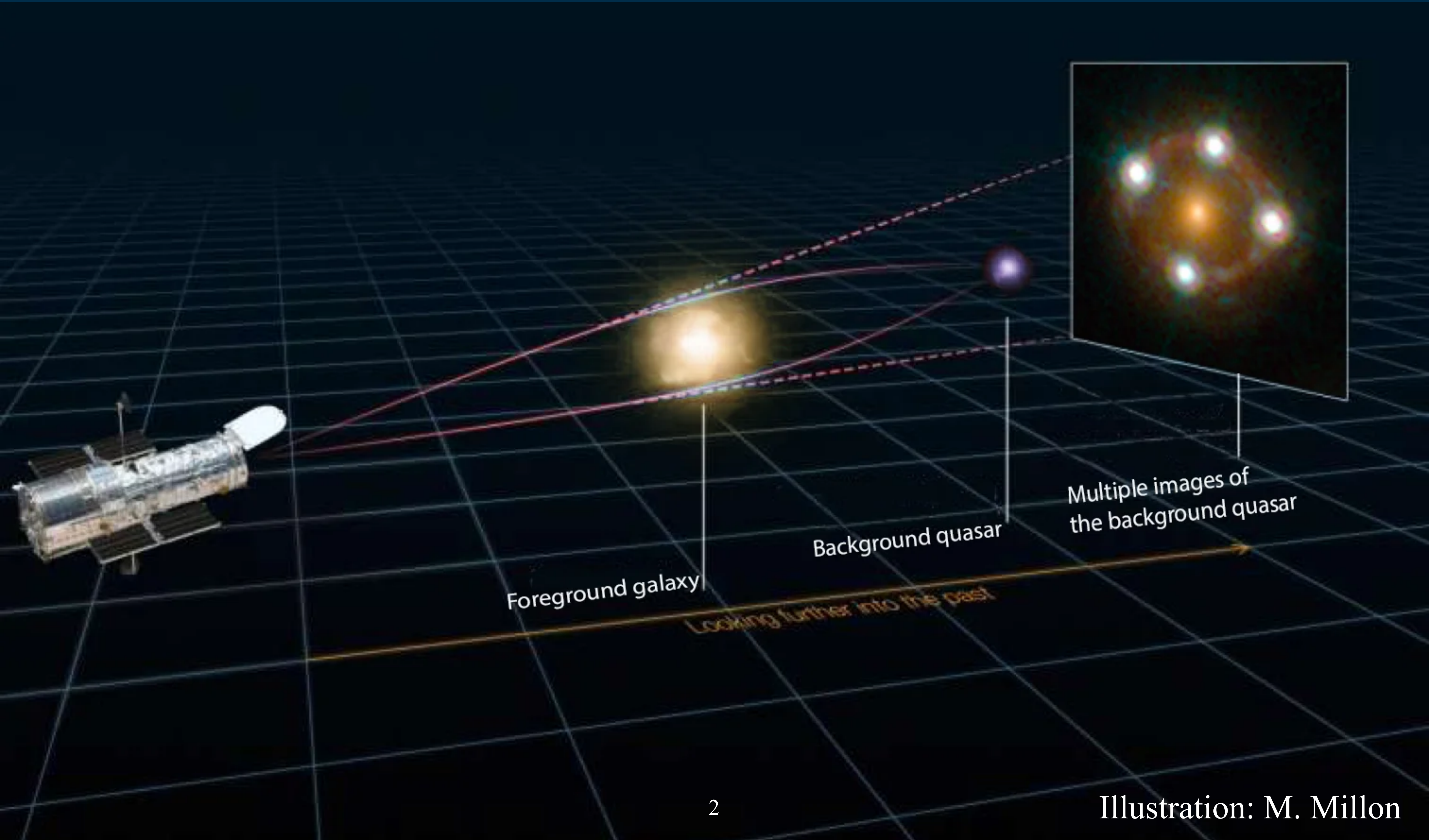
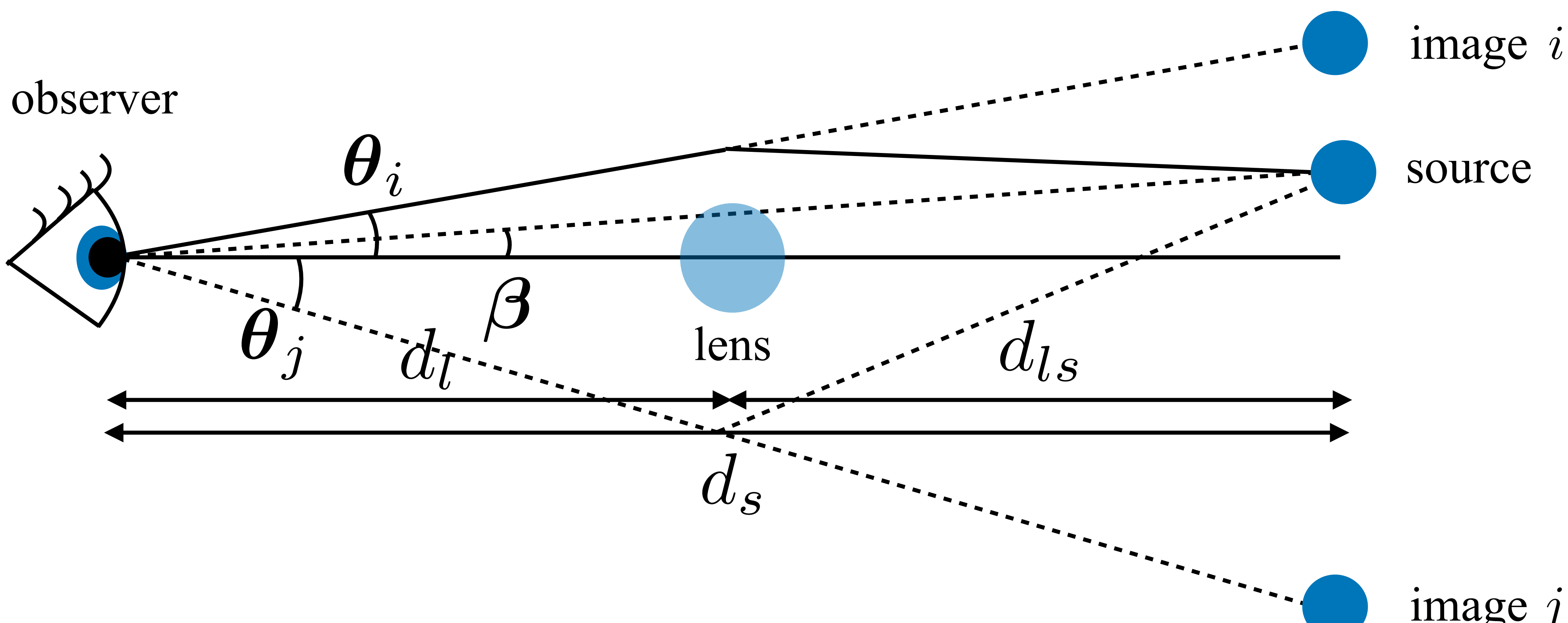


Illustration: M. Millon

Time delay cosmography

K. Wong et al., 2019
H0LiCOW/TDCOSMO

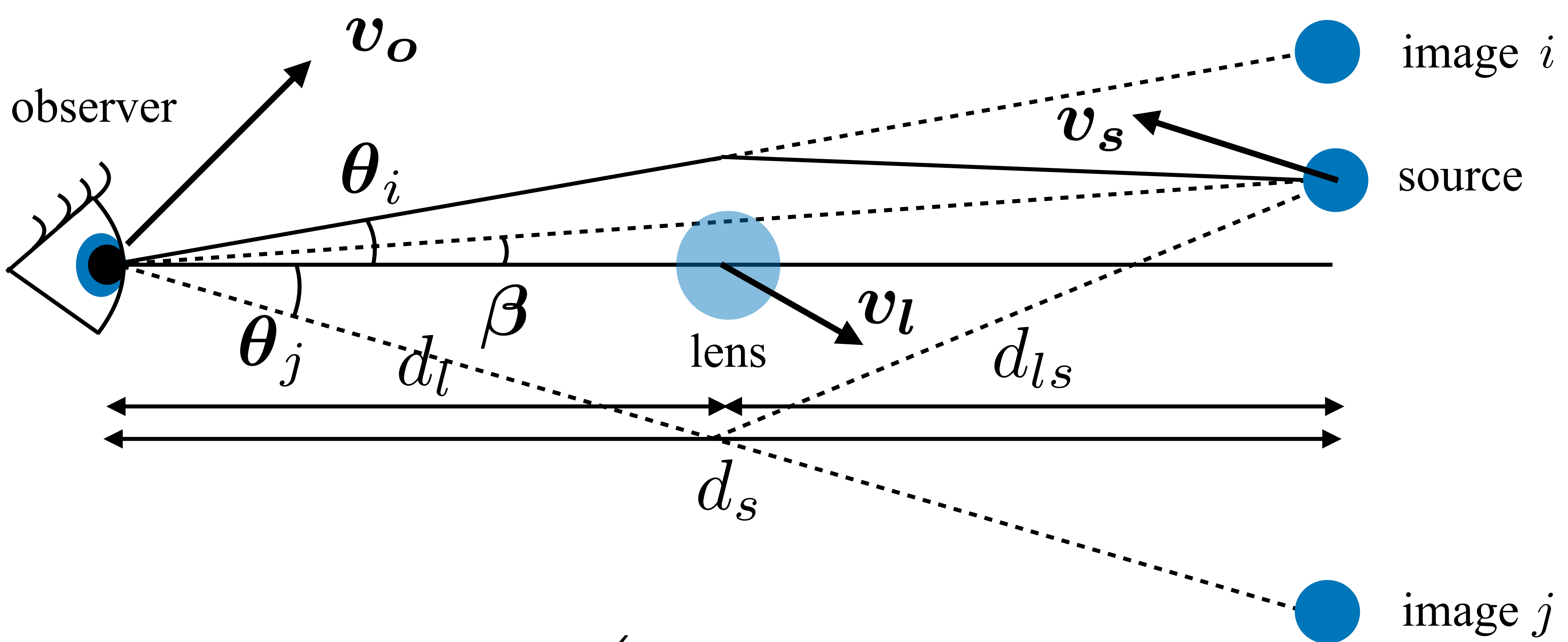


$$c\Delta t_{ij} = (1+z_l)\frac{d_l d_s}{d_{ls}}\left(\frac{(\boldsymbol{\theta}_i-\boldsymbol{\beta})^2}{2} - \frac{(\boldsymbol{\theta}_j-\boldsymbol{\beta})^2}{2} - \left[\Psi(\boldsymbol{\theta}_i) - \Psi(\boldsymbol{\theta}_j)\right]\right)$$
$$\propto H_0^{-1}$$

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

Time delay cosmography

K. Wong et al., 2019
H0LiCOW/TDCOSMO
C.D., M. Millon, T. Baker, 2023



$$c\Delta t_{ij} = (1+z_l)\frac{d_l d_s}{d_{ls}}\left(\frac{(\boldsymbol{\theta}_i-\boldsymbol{\beta})^2}{2} - \frac{(\boldsymbol{\theta}_j-\boldsymbol{\beta})^2}{2} - \left[\Psi(\boldsymbol{\theta}_i) - \Psi(\boldsymbol{\theta}_j)\right]\right)$$

$$\propto H_0^{-1}$$

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

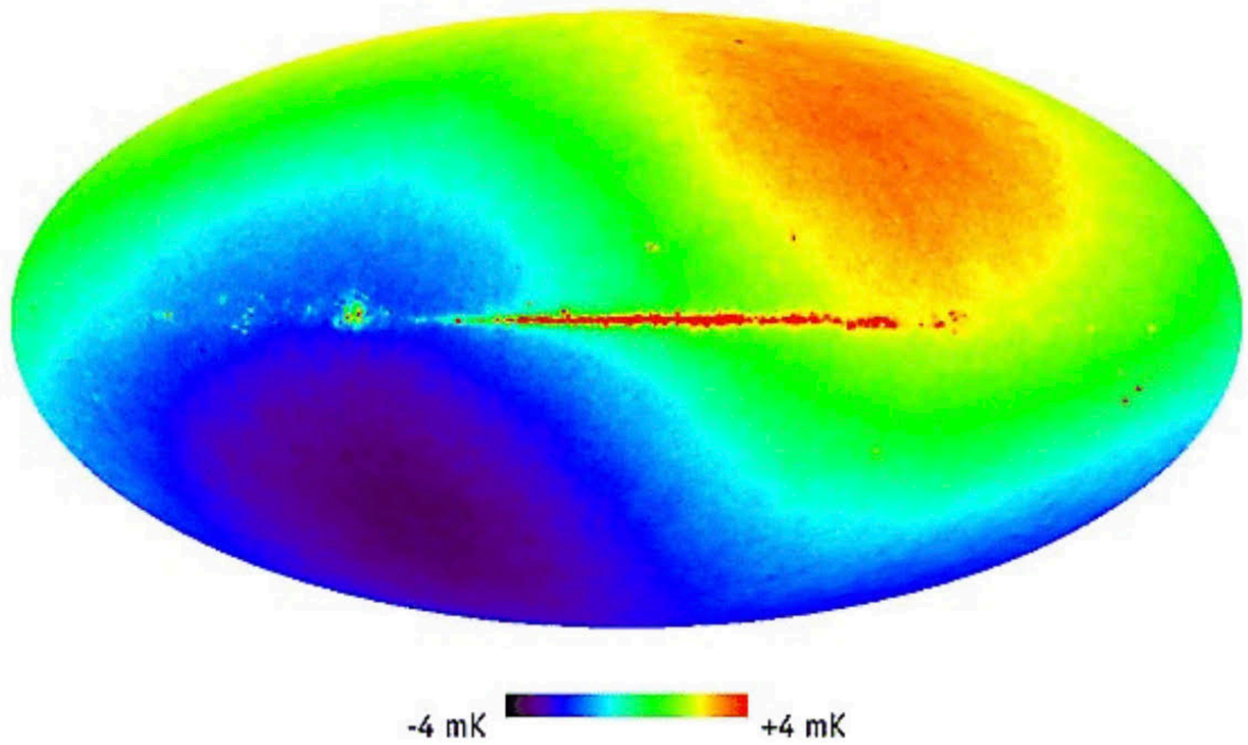
Old and new themes

J. Peebles, D. Wilkinson, 1968
E. Conklin, 1969, 1971, 1972
P. Henry, 1971
G. Ellis, J. Baldwin, 1984
M. Rubart & D. Schwarz 2013
J. Colin et al. 2017
C. Bengaly et al. 2018
N. Secrest et al. 2021, 2022
T. Siewert et al. 2021

1) H_0 tension $(4-6)\sigma$ tension

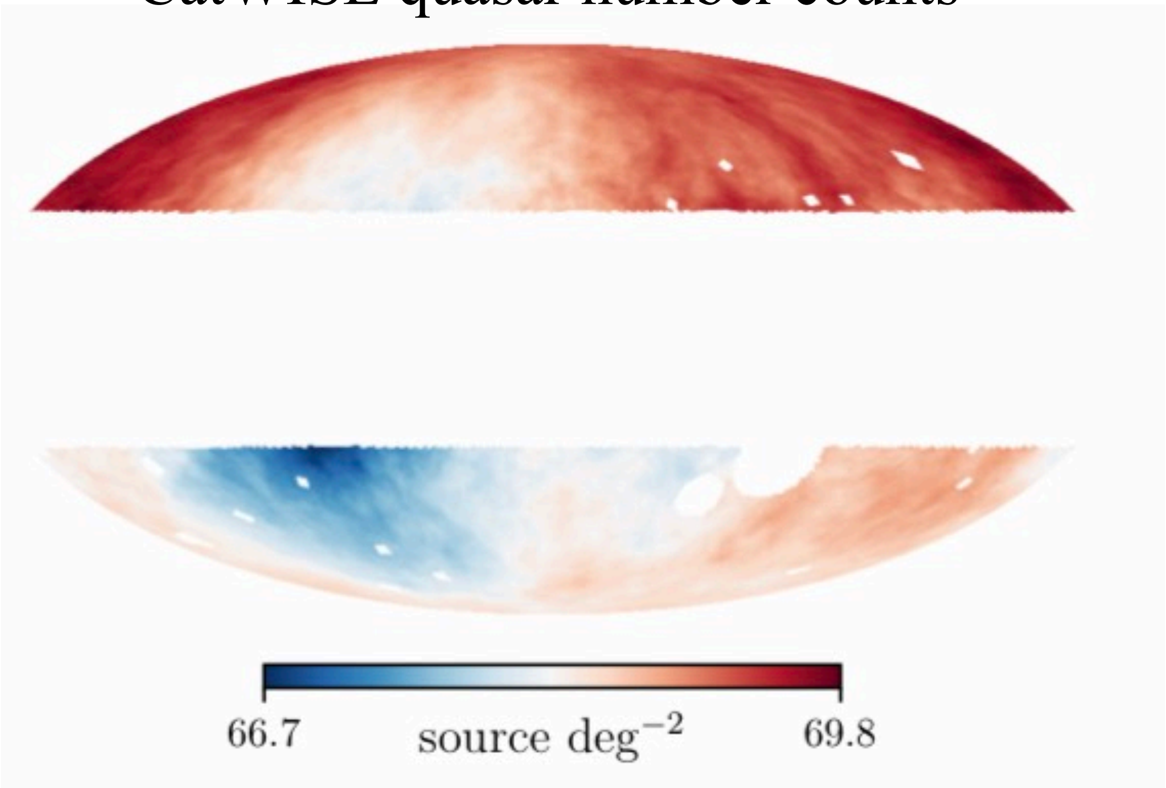
2) Cosmic dipole tension

Primeval fireball



$$||\boldsymbol{v}_o|| = (369.82 \pm 0.11)\text{km s}^{-1}$$

CatWISE quasar number counts



$$||\boldsymbol{v}_o|| = (796 \pm 87)\text{km s}^{-1}$$

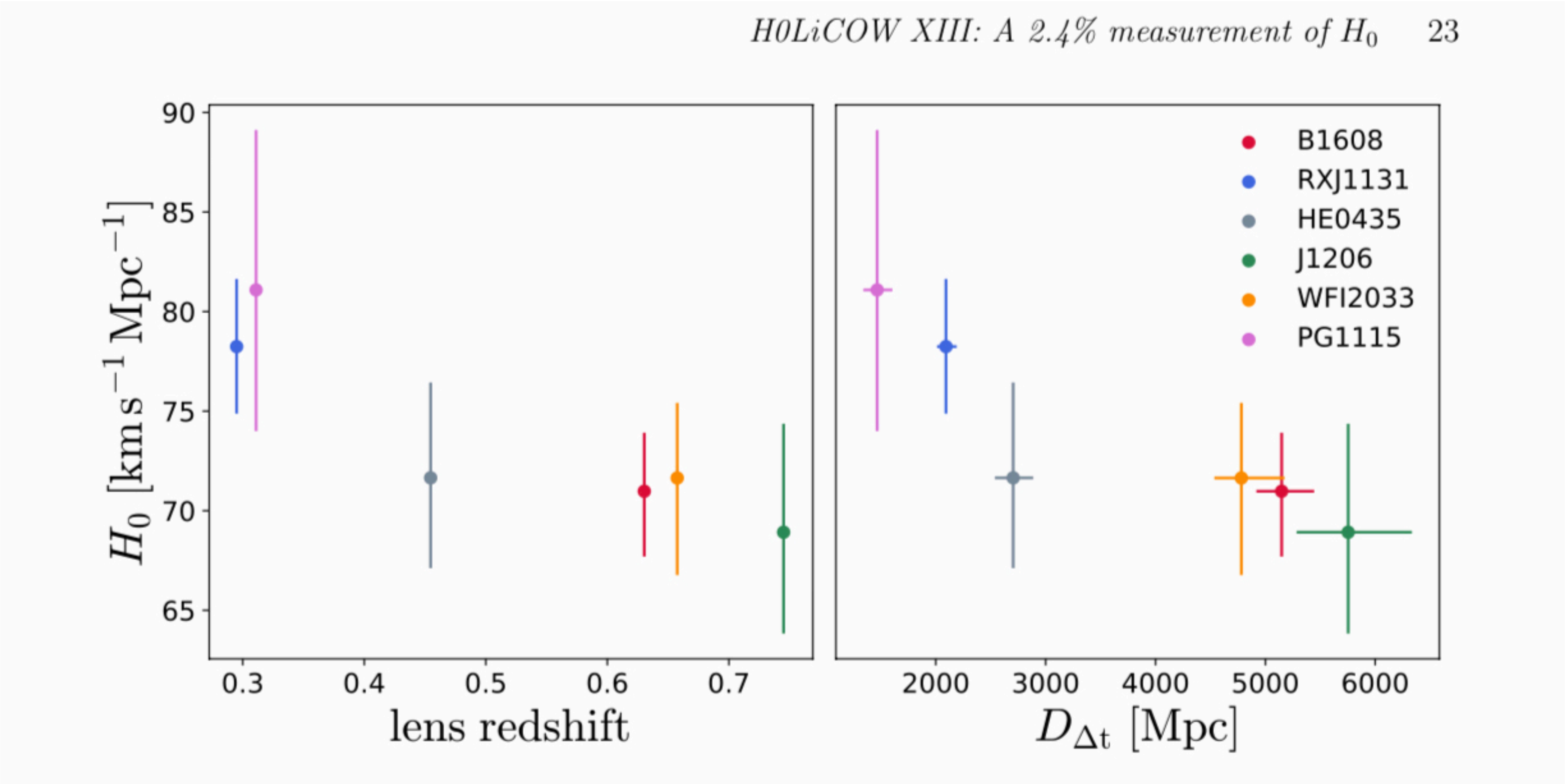
$(2-5)\sigma$ tension

Charles Dalang

Queen Mary University of London

Trend with lens redshift

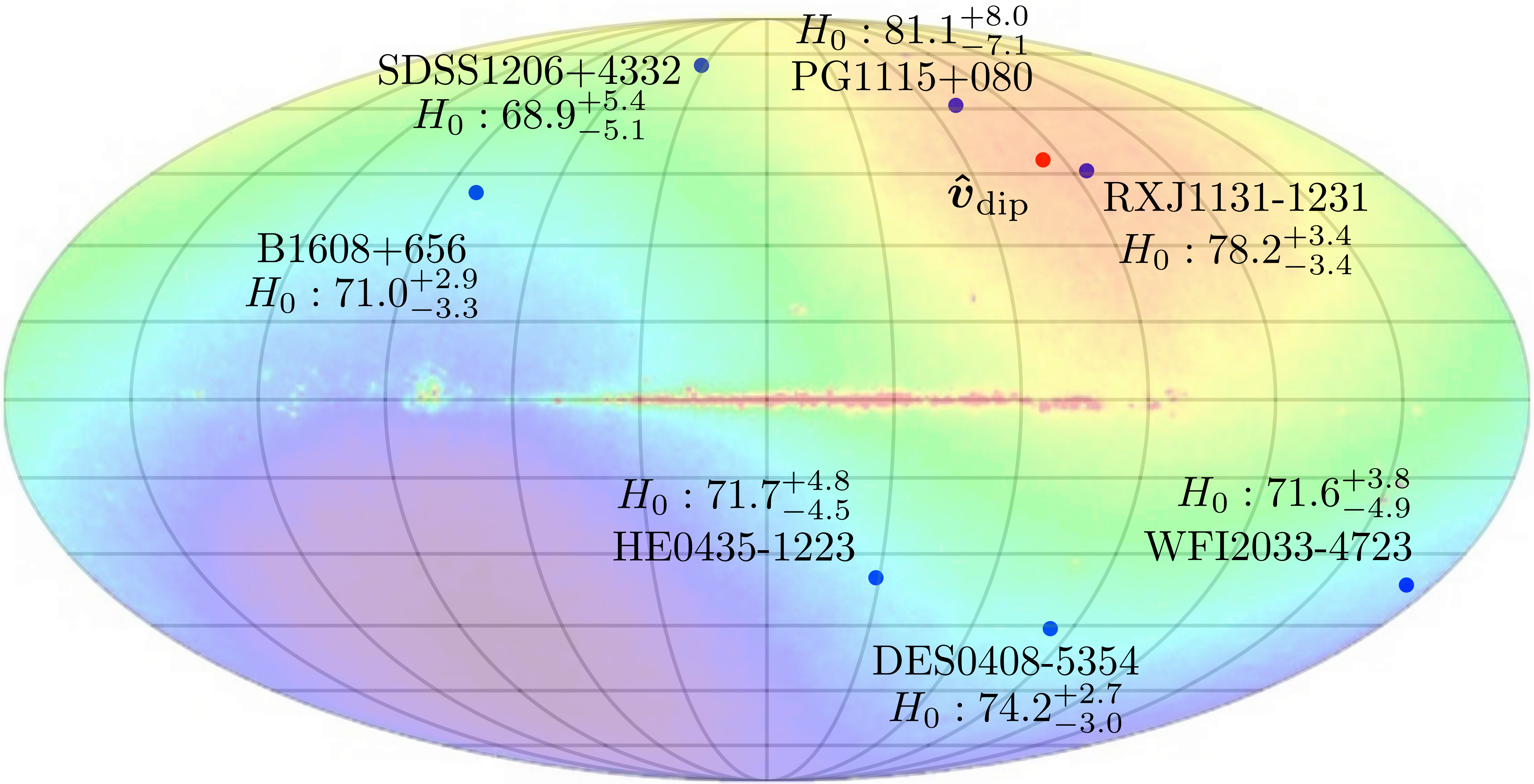
K. Wong et al., 2019



Queen Mary University of London

Sky distribution of the lenses

H0LiCOW
Chethan Krishnan, Roya Mohayaee, Eoin Ó. Colgáin, M. M. Sheikh-Jabbari, and L. Yin. Hints, 2022
C.D., M. Millon, T. Baker, 2023



Progress

C.D., M. Millon, T. Baker, 2023

$$c\Delta t_{ij} = (1+z_l)\frac{d_l d_s}{d_{ls}}\left(\frac{(\boldsymbol{\theta}_i - \boldsymbol{\beta})^2}{2} - \frac{(\boldsymbol{\theta}_j - \boldsymbol{\beta})^2}{2} - \left[\Psi(\boldsymbol{\theta}_i) - \Psi(\boldsymbol{\theta}_j)\right]\right)$$

What are the observables? $\{\Delta t'_{ij}, z'_l, z'_s, \boldsymbol{\theta}'_{\boldsymbol{i}}, \boldsymbol{\theta}'_{\boldsymbol{j}}\}$

Physical effects from a boost $\beta = \frac{||\boldsymbol{v}_o||}{c} \simeq \mathcal{O}(10^{-3})$

1) Time dilation $\Delta t' = \Delta t\sqrt{1-\beta^2}$

2) Doppler shift $1 + z' = (1+z)\frac{\sqrt{1-\beta^2}}{1+\beta\cos(\theta)}$

3) Aberration $\theta' = \theta - \beta\sin(\theta) + \mathcal{O}(\beta^2)$

Accumulation of biases

C.D., M. Millon, T. Baker, 2023

$$\underset{\text{(true)}}{H_0} = \underbrace{\frac{\chi[z_l']\chi[z_s']}{\chi[z_l', z_s']} \frac{[\hat{\phi}(\boldsymbol{\theta}_i', \boldsymbol{\beta}_i'') - \hat{\phi}(\boldsymbol{\theta}_j', \boldsymbol{\beta}_j'')]}{\Delta t_{ij}'}}_{=H_0' \ \text{(inferred)}} \left(1 + \frac{c\Delta T_{ij}}{c\Delta t_{ij}'} \frac{v_o}{c}\right)$$

H_0 bias

$$\frac{\Delta H_0}{H_0'} = \frac{\Delta T_{ij}}{\Delta t_{ij}'} \frac{v_o}{c}$$

$$c\Delta T_{ij} = (1+z_l') \frac{d[z_l']d[z_s']}{d[z_l', z_s']} \left[(\tilde{\theta}_i' - \tilde{\beta}_i'')(\Theta_i - B_i'') - (\tilde{\theta}_j' - \tilde{\beta}_j'')(\Theta_j - B_j'') - (P_i - P_j) \right]$$

angle bias | lens model bias

$$+ \frac{1+z_l'}{d^2[z_l', z_s']} \left[Z_L d[z_l'] d[z_l', z_s'] d[z_s'] + d[z_l'] d[z_l', z_s'] D_S - d[z_l'] D_{LS} d[z_s'] + D_L d[z_l', z_s'] d[z_s'] \right]$$

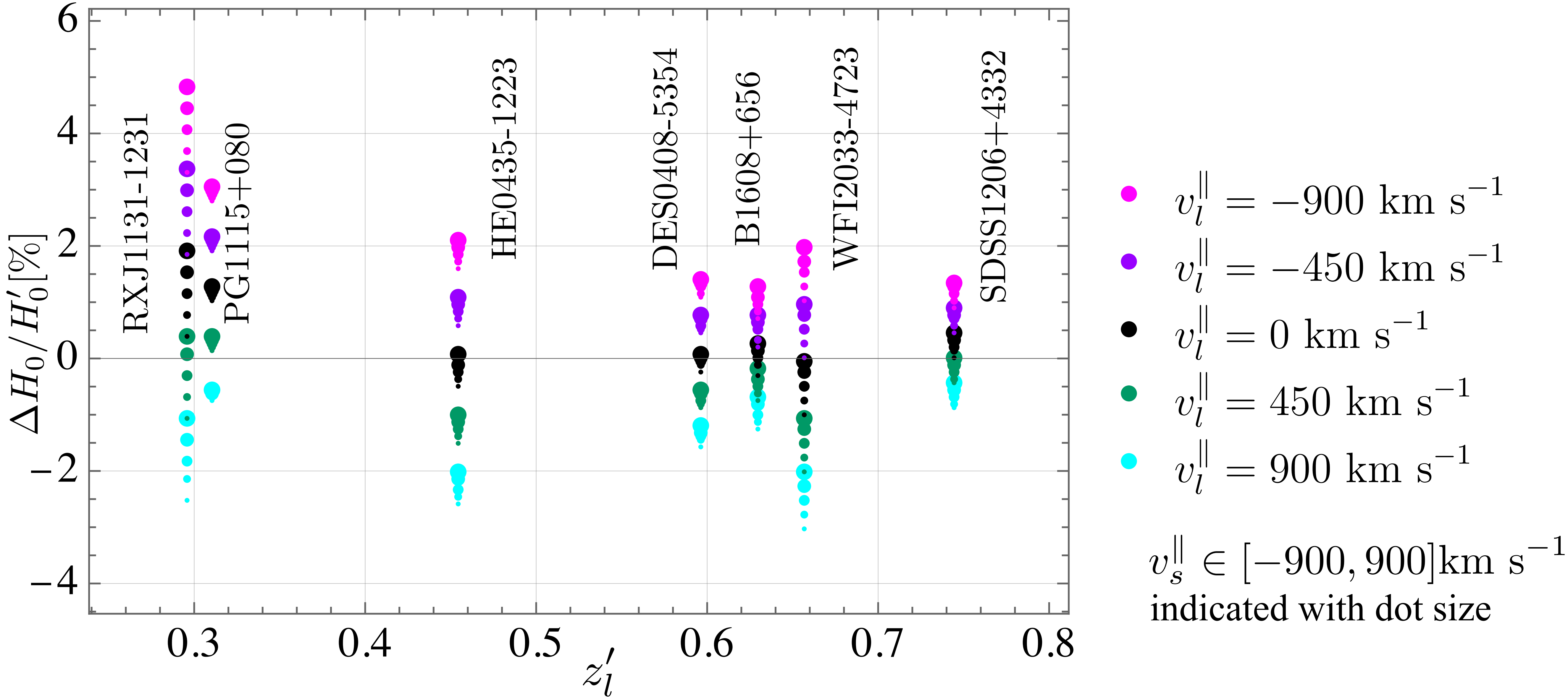
redshift and distance biases

$$\times \left[\hat{\phi}(\tilde{\theta}_i', \tilde{\beta}_i'') - \hat{\phi}(\tilde{\theta}_j', \tilde{\beta}_j'') \right],$$

Time-delay cosmography

C.D., M. Millon, T. Baker, 2023

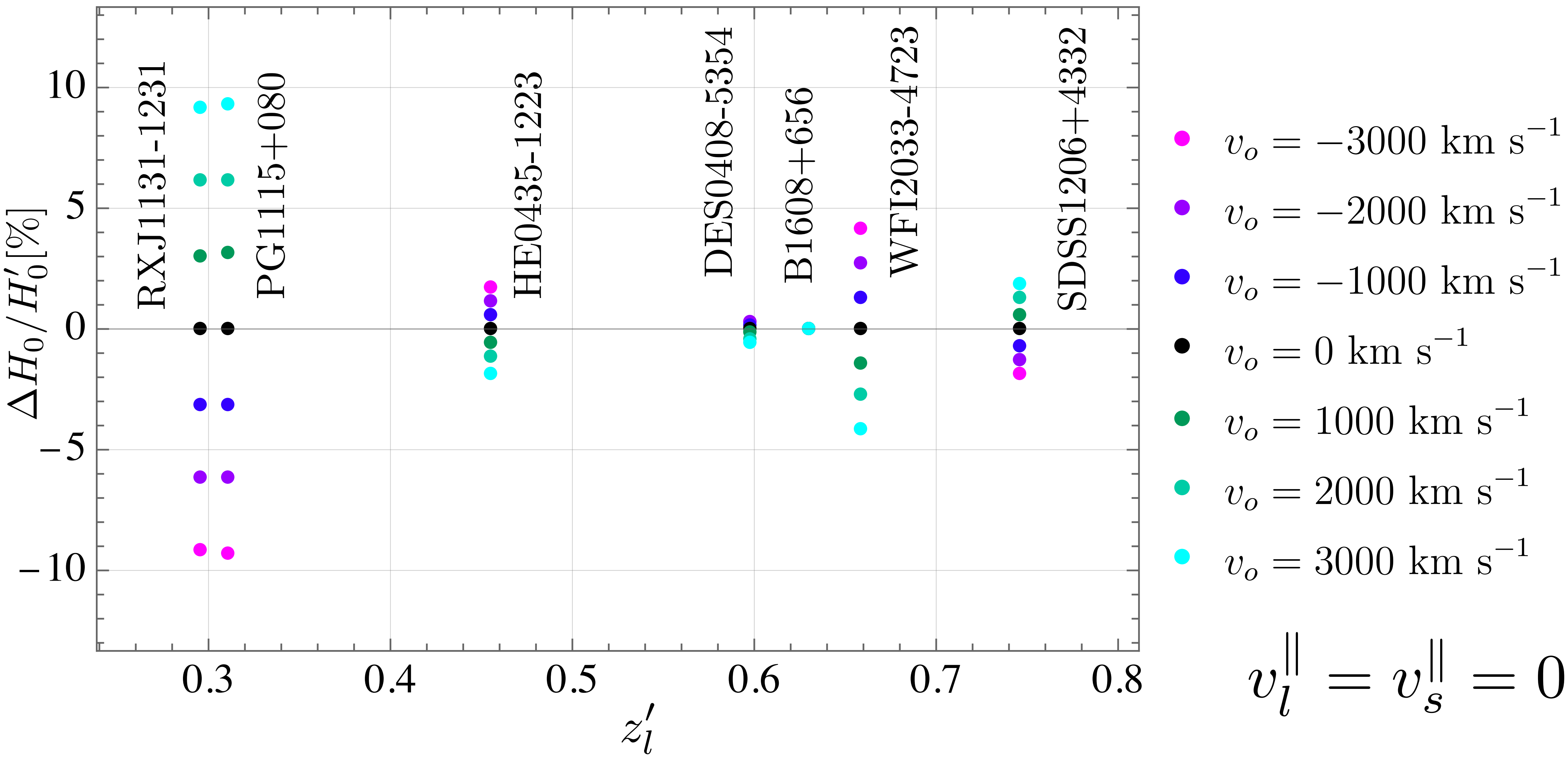
$$H_0 = H_0' \left(1 + \frac{\Delta H_0}{H_0'}\right)$$



Time-delay cosmography

C.D., M. Millon, T. Baker, 2023

$$H_0 = H_0' \left(1 + \frac{\Delta H_0}{H_0'}\right)$$



$$v_l^{||} = v_s^{||} = 0$$

Conclusions

- The peculiar velocities have an impact on time delay cosmography,
- Corrections can reach the percent level for a single system.
- Combined, this is below 0.25% random uncertainty on H_0 and 0.24 % systematic bias.
- It goes in the *wrong* way to solve the Hubble tension or explain the trend with lens redshift.

Thank you!

I am happy to answer any questions you may have :)

Doppler shift

C.D., M. Millon, T. Baker, 2023

Angular diameter distances from redshift

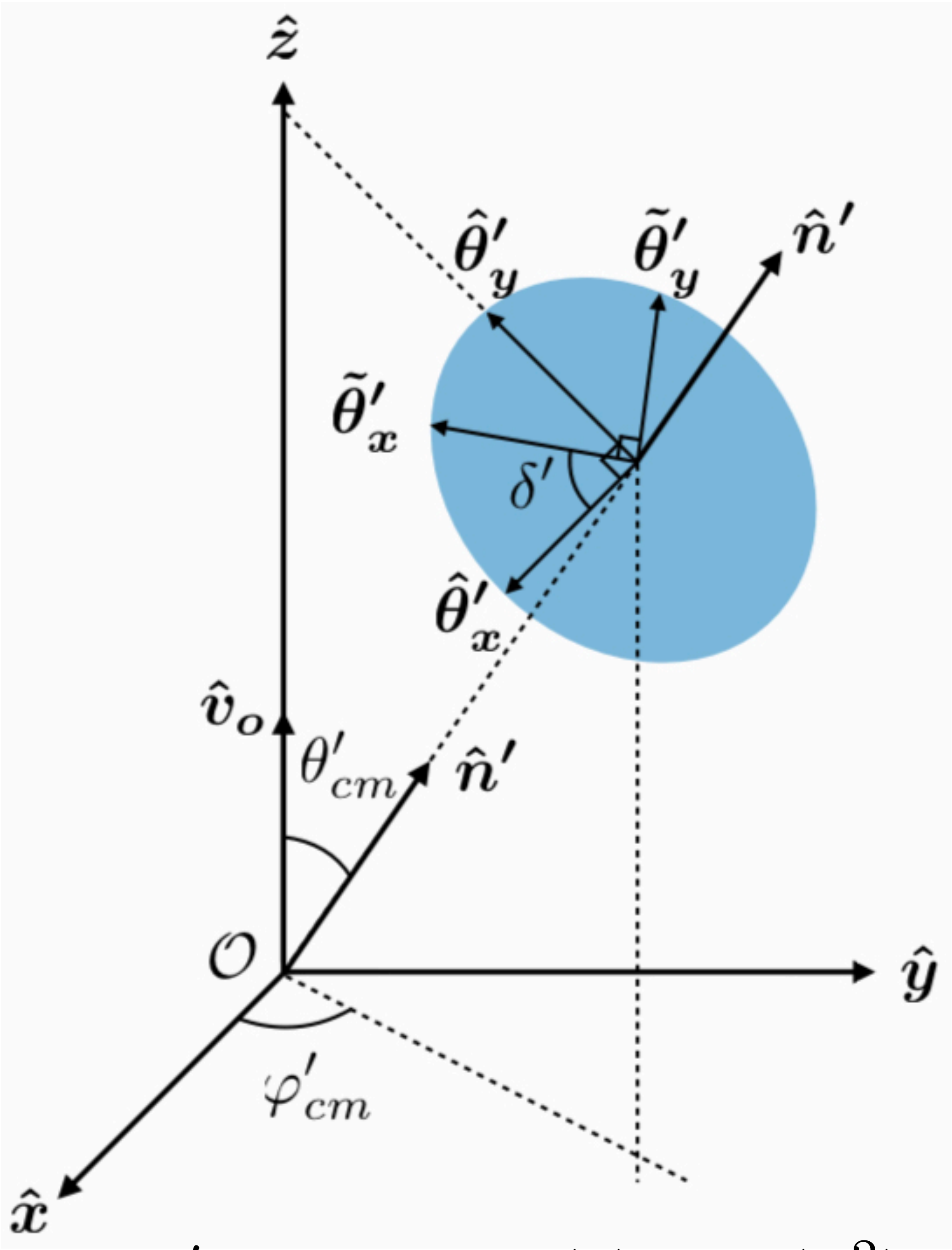
$$D_A(z) = \frac{c}{(1+z)H_0}\int_0^z \frac{\mathrm{d}z'}{\sqrt{\Omega_{m0}(1+z')^3+\Omega_{\Lambda 0}}}$$

Observed redshift $$1+z' = (1+z)\frac{\sqrt{1-\beta^2}}{1+\beta\cos(\theta)}$$

Cosmological redshift

Aberration

C.D., M. Millon, T. Baker, 2023



$$\theta' = \theta - \beta \sin(\theta) + \mathcal{O}(\beta^2)$$

comoving

$$\tilde{\theta}_i = \tilde{\theta}'_i + \Theta_i \frac{v_o}{c} \, .$$

observed corrections