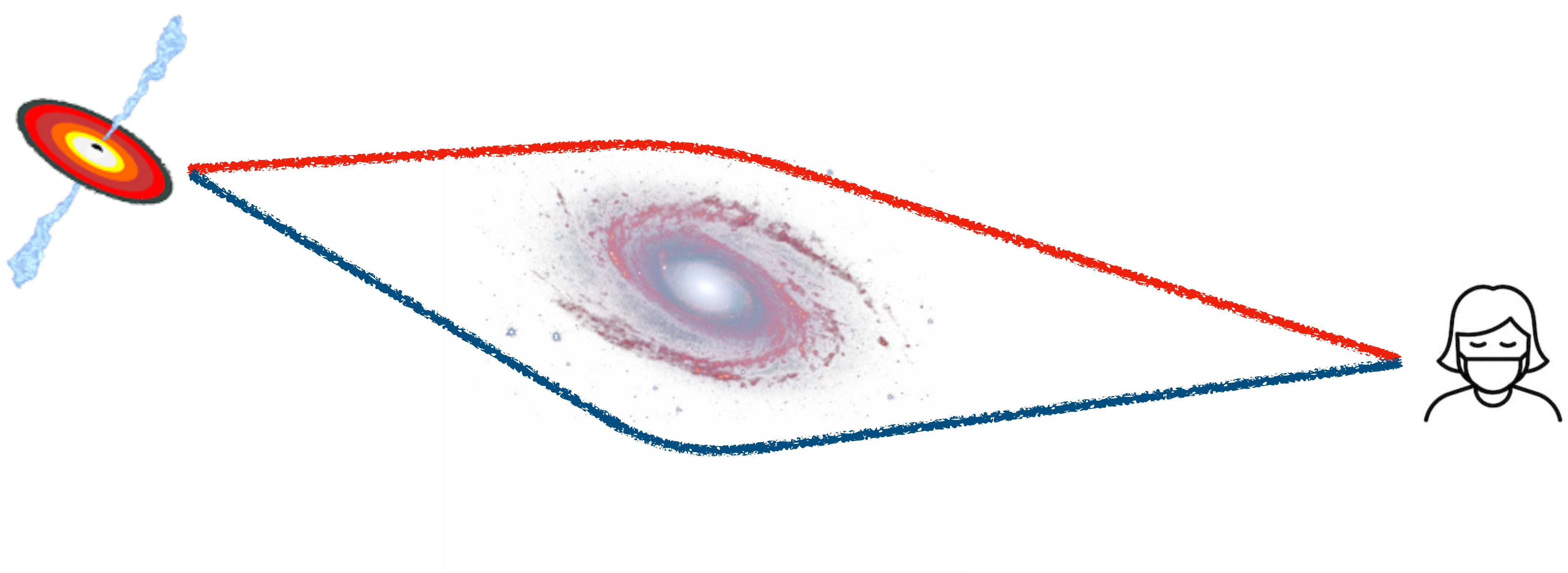
Gravitational lensing measurements of the Hubble parameter: challenges and opportunities

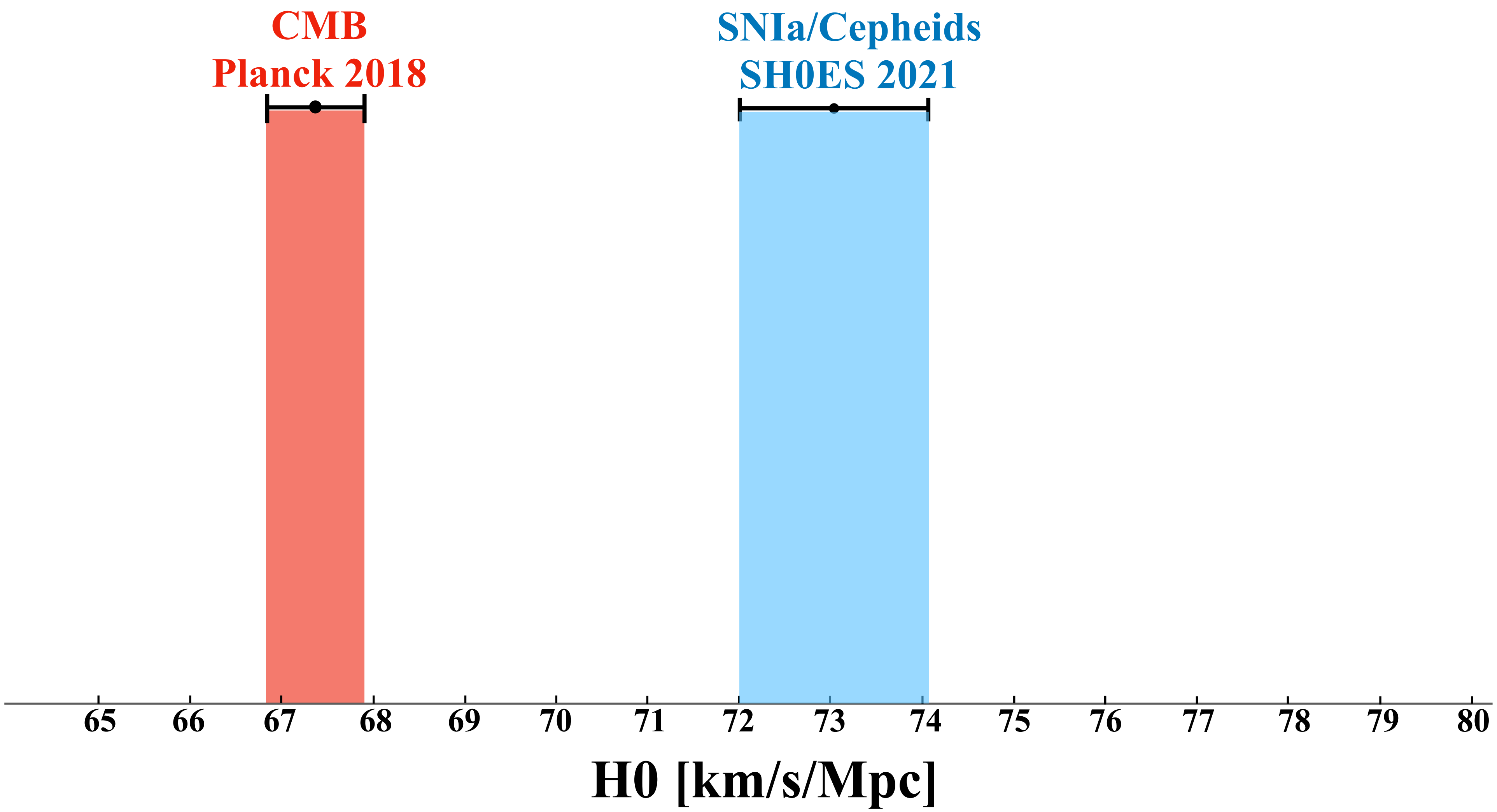
Kfir Blum (Weizmann Institute)

KB, Castorina, Simonović, 2001.07182
KB, Teodori, 2105.10873
Teodori, KB, Castorina, Simonović, Soreq, 2201.05111



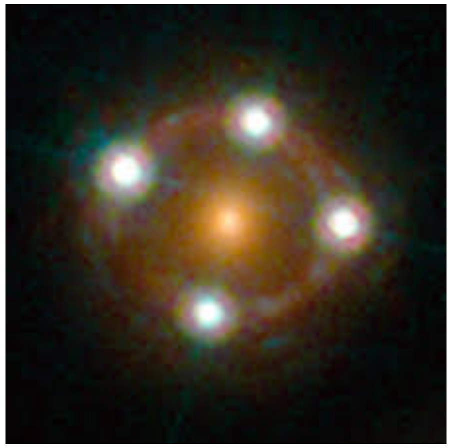
CAU-BSM Workshop 10/02/2022

H$_0$ tension



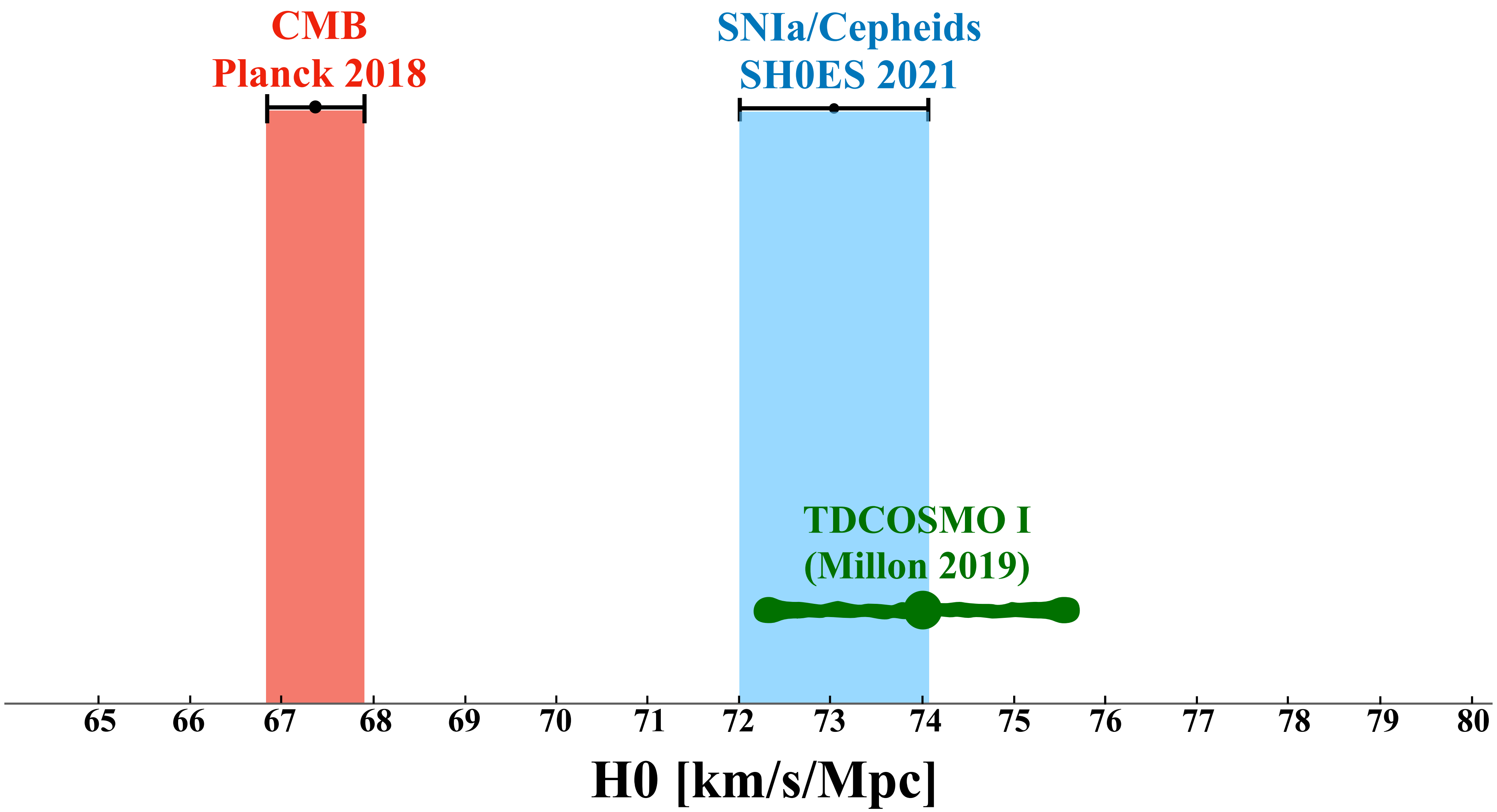
CMB
Planck 2018
SNIa/Cepheids
SH0ES 2021
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
H0 [km/s/Mpc]

SNIa and **gravitational lensing agree**



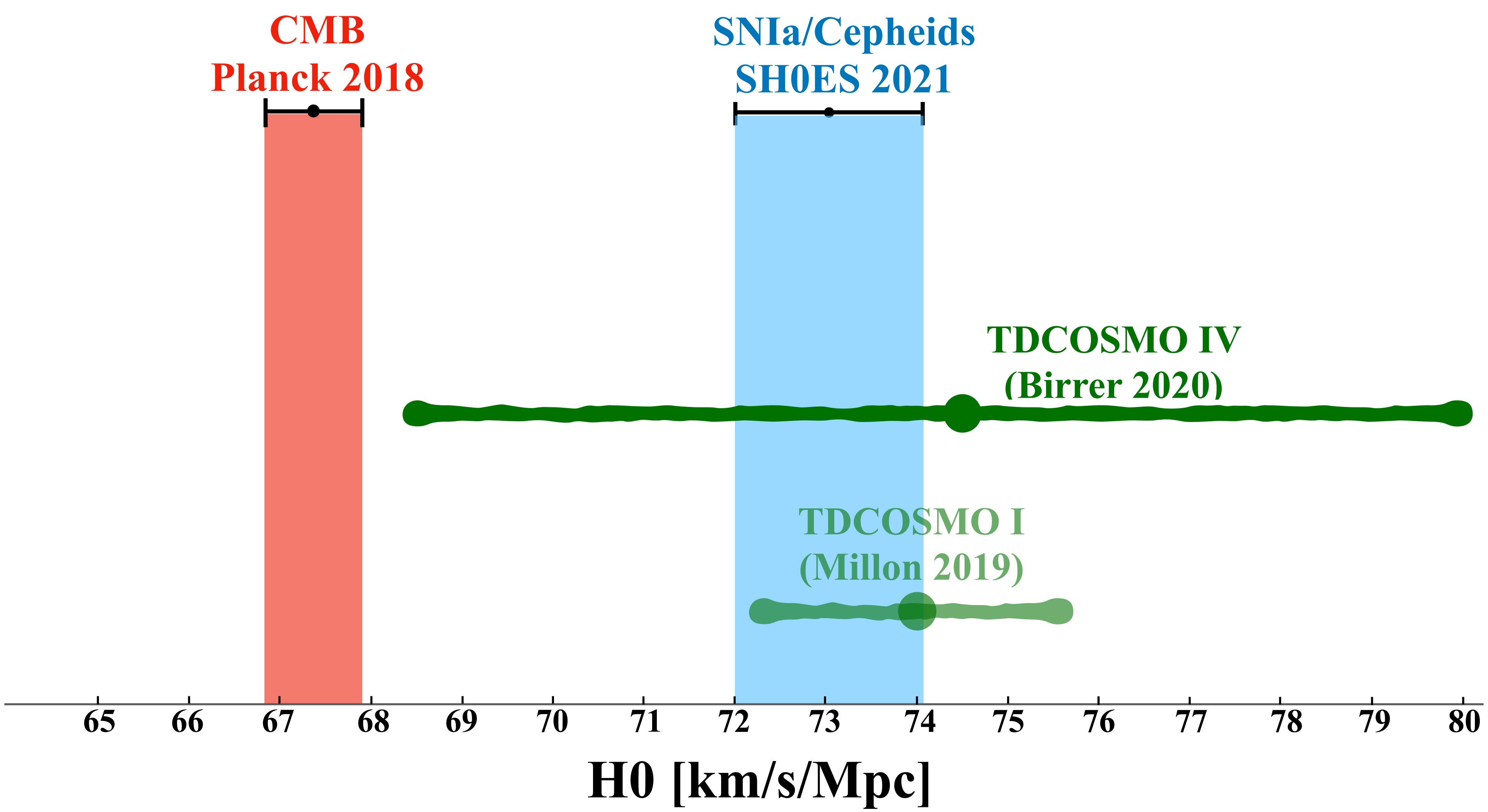
TDCOSMO
http://www.tdcosmo.org/projects.html

- H0LiCOW
- COSMOGRAIL
- STRIDES
- SHARP
- COSMICLENS



SNIa and **gravitational lensing**

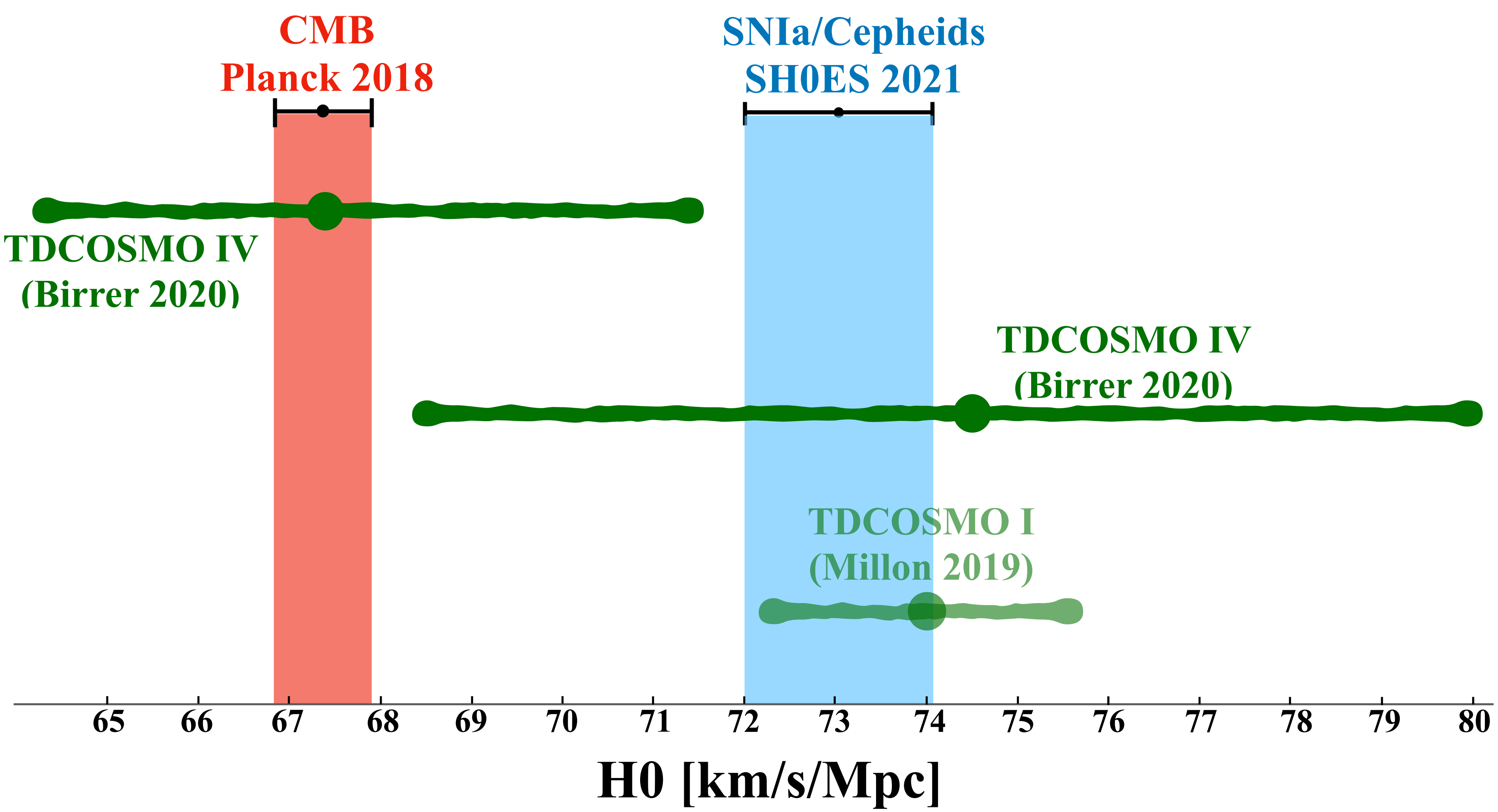
A bit later: lensing out of the game?



SNIa and **gravitational lensing**

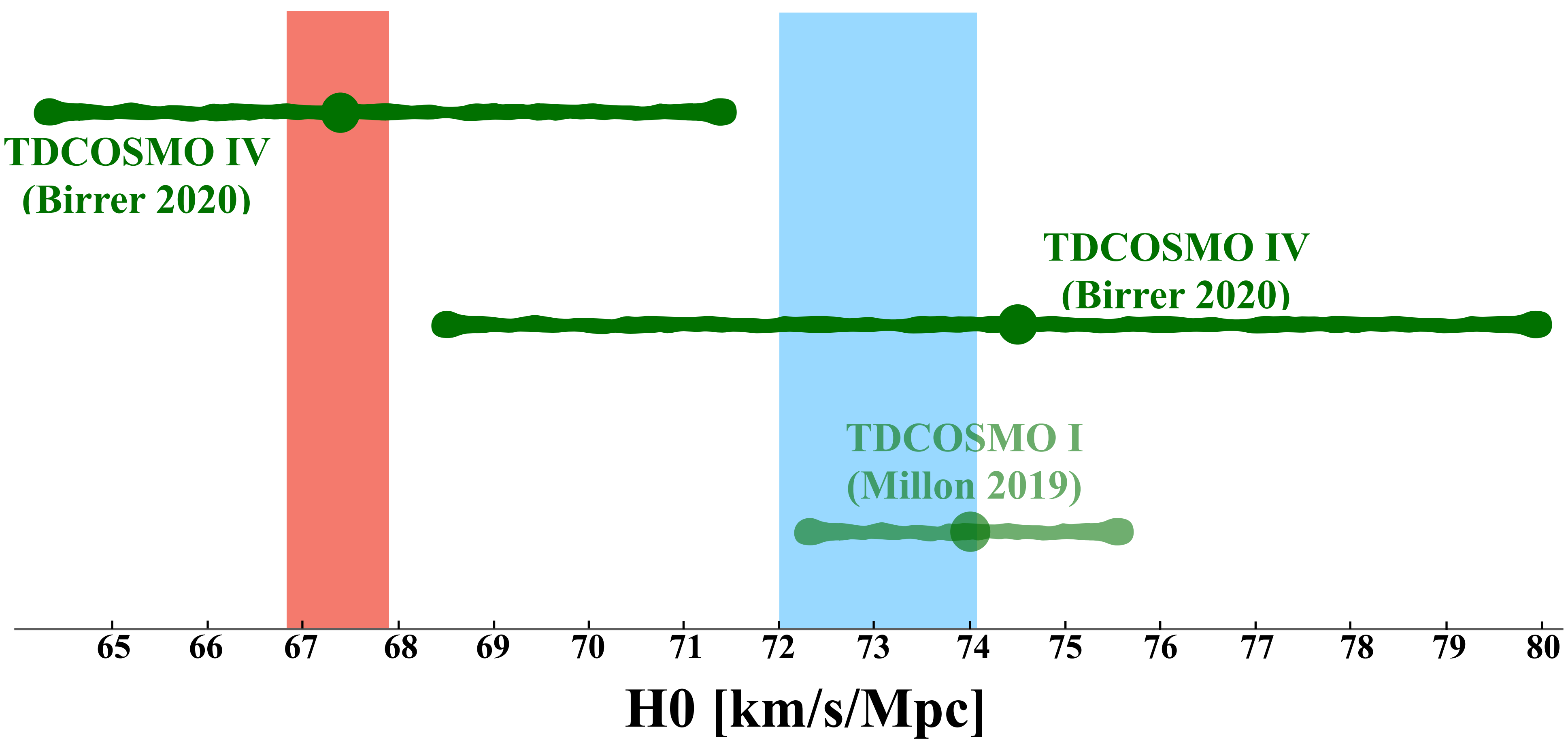
A bit later: lensing out of the game?

… agrees with CMB?



Plan:

1. Recap: how lensing measures H0
2. Challenges: modeling degeneracy
3. Opportunities: galactic structure



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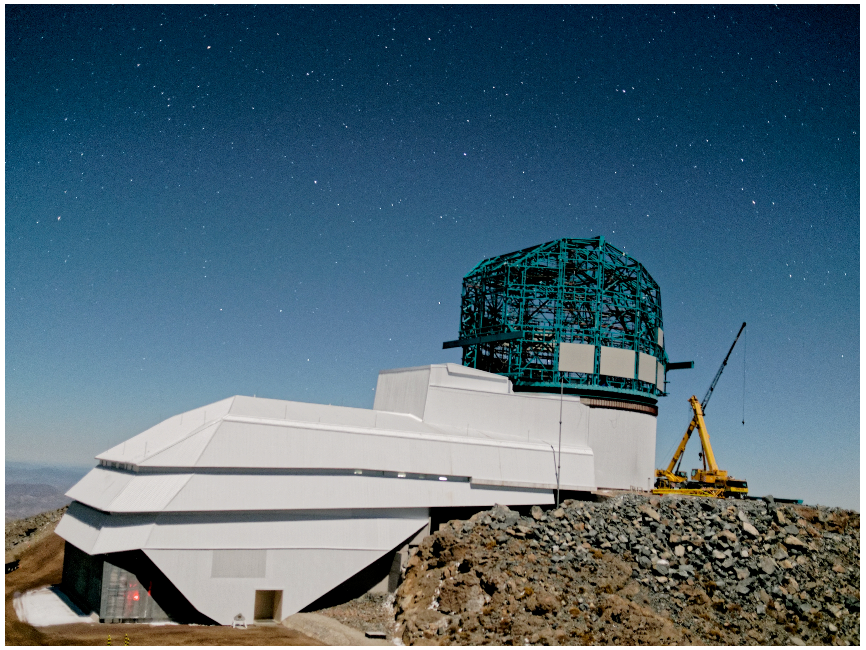
What is dark matter?

Where are the missing baryons?

LSST: 100's of strongly lensed variable quasars

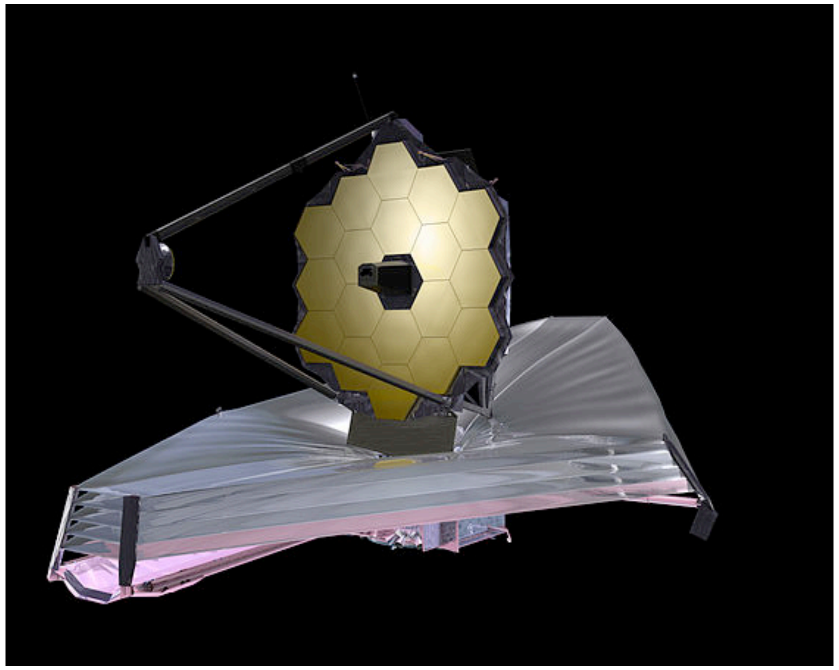
Oguri, Marshall, 1001.2037



JWST: improved kinematics

Yıldırım, Suyu, Halkola, 1904.07237

Birrer, Treu, 2008.06157



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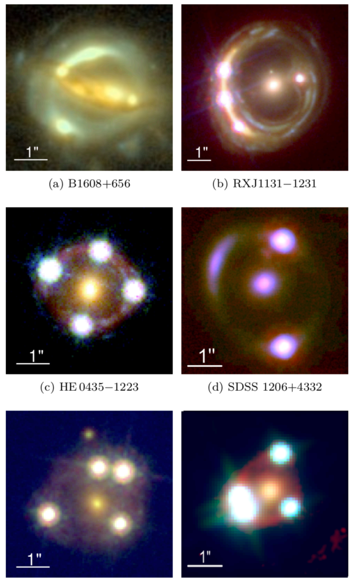

(a) B1608+656 (b) RXJ1131−1231

(c) HE 0435−1223 (d) SDSS 1206+4332

(e) WFI2033−4723 (f) PG 1115+080

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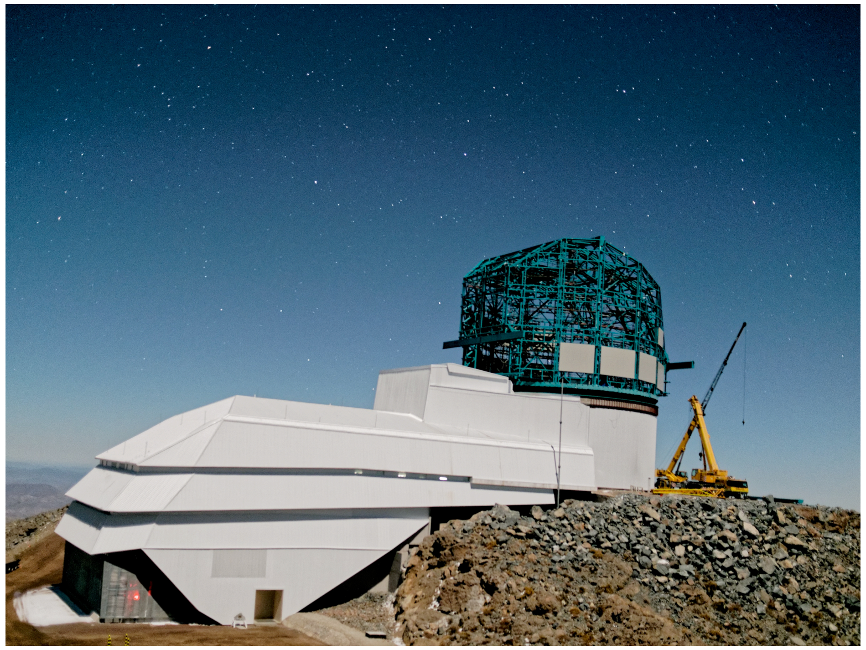

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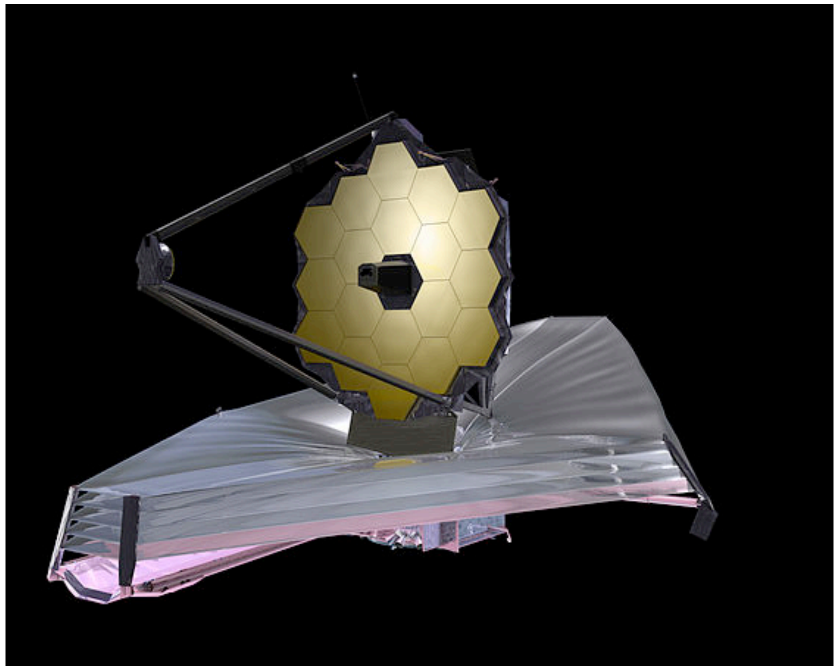

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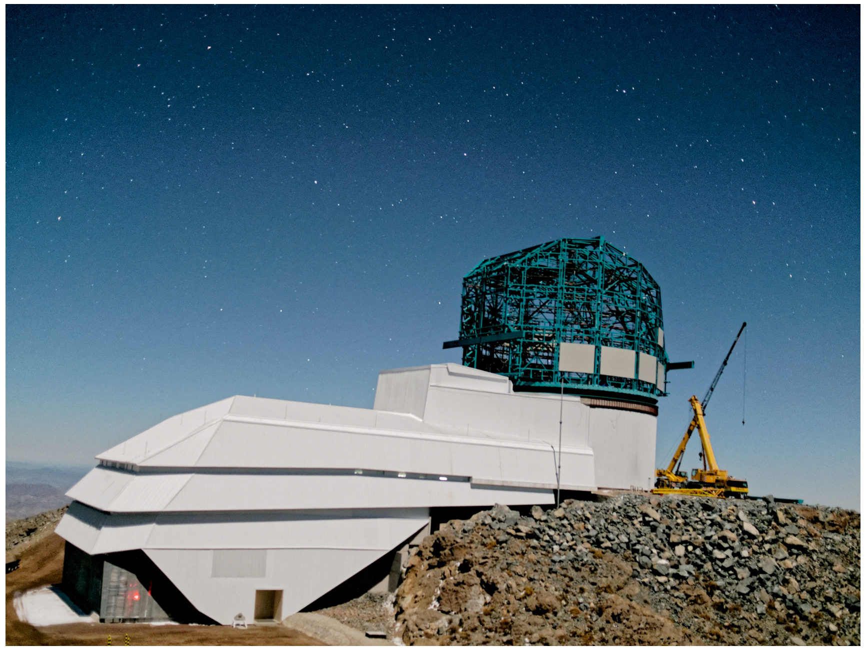

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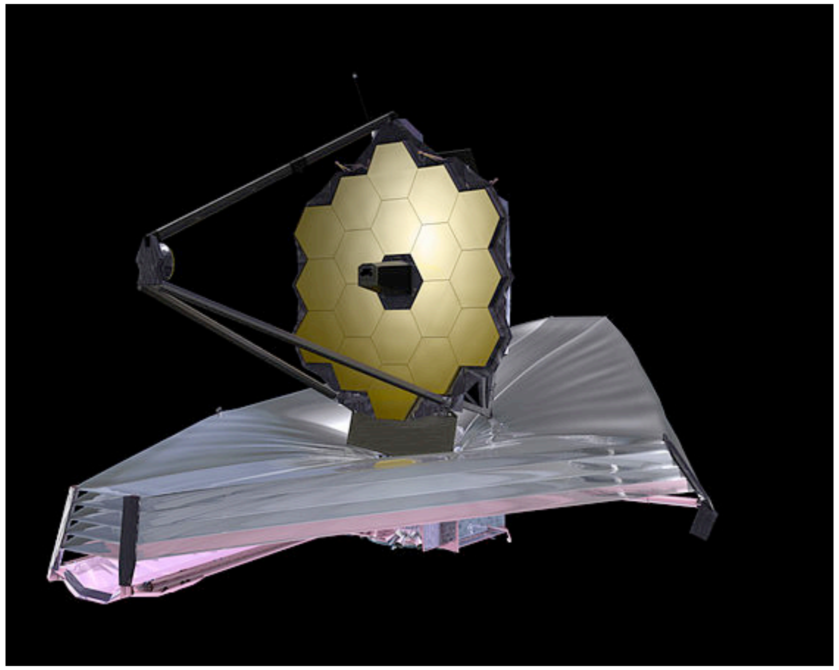
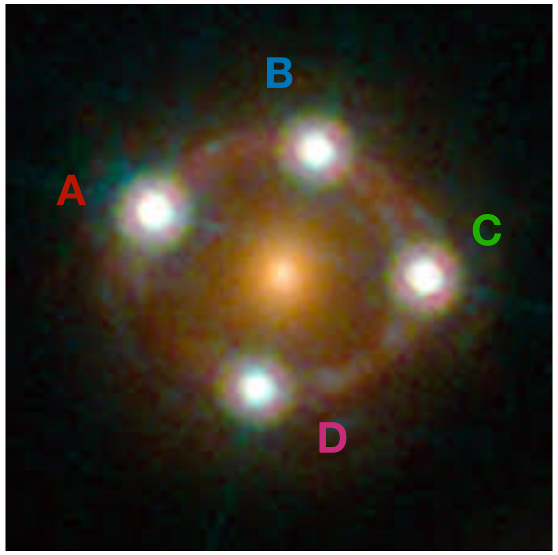


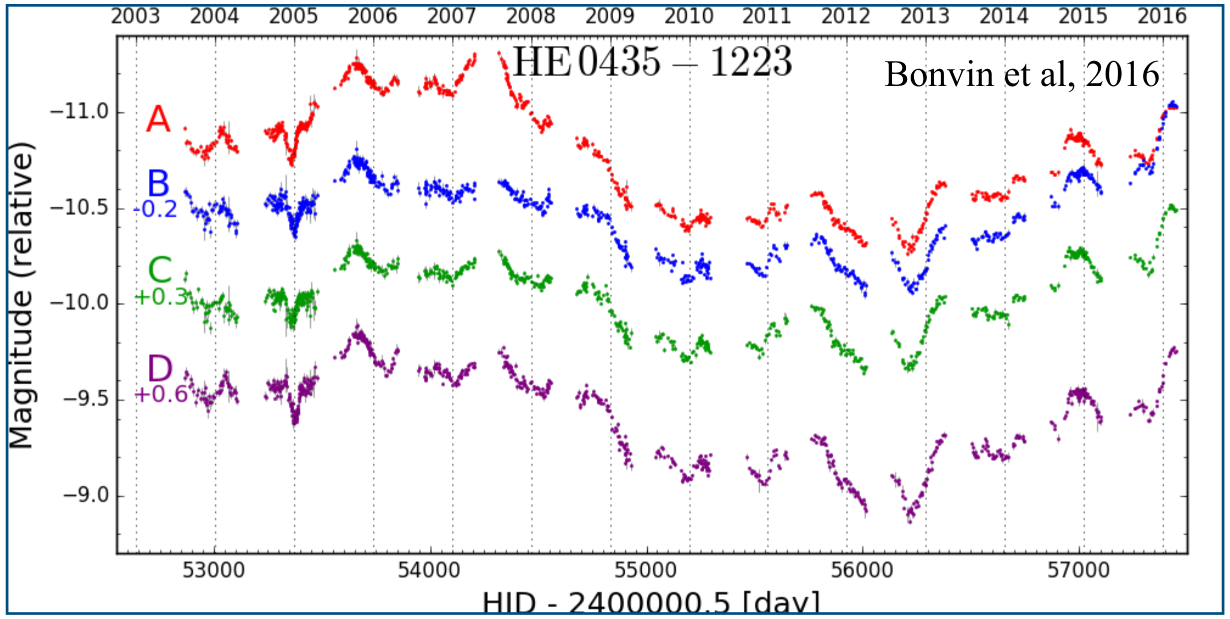
1. Recap: how lensing measures H0

Observables:

- Extended source image



- Time delay Δt_{AB}



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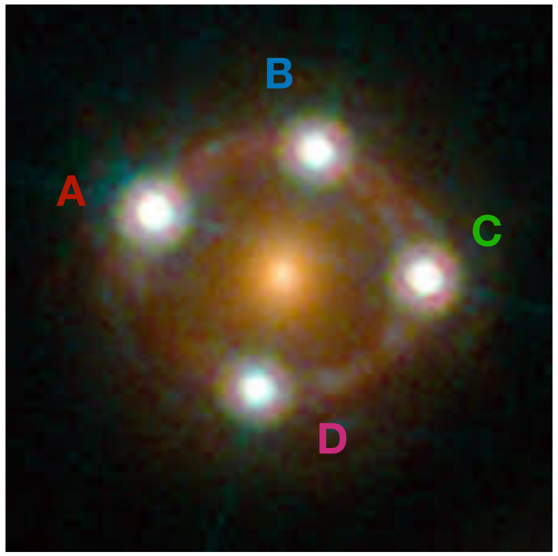

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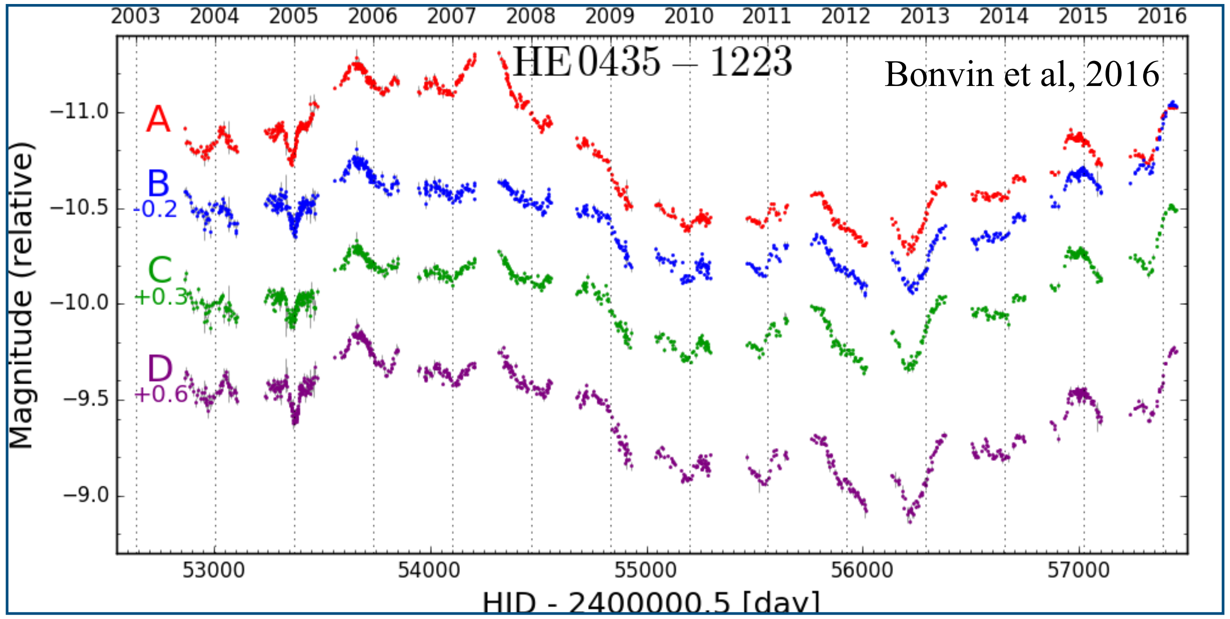
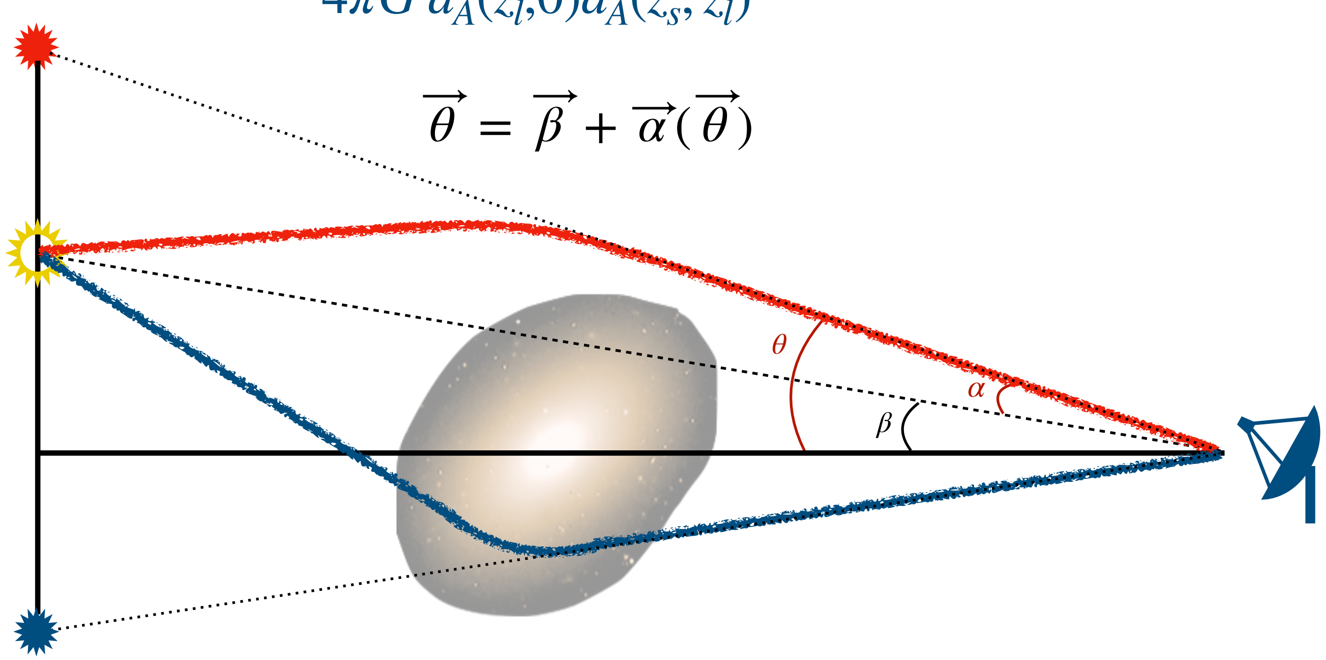


$$\kappa(\vec{\theta}) = \frac{\Sigma(\vec{\theta})}{\Sigma_{\rm crit}} = \frac{1}{2}\vec{\nabla}_\theta \cdot \vec{\alpha} = \frac{1}{2}\vec{\nabla}^2_\theta \psi$$

$$\Sigma_{\rm crit} = \frac{d_A(z_s,0)}{4\pi G\, d_A(z_l,0) d_A(z_s, z_l)}$$

$$\vec{\theta} = \vec{\beta} + \vec{\alpha}(\vec{\theta})$$



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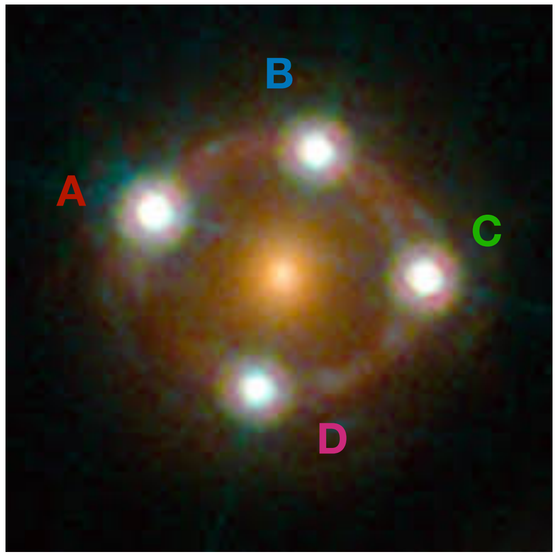

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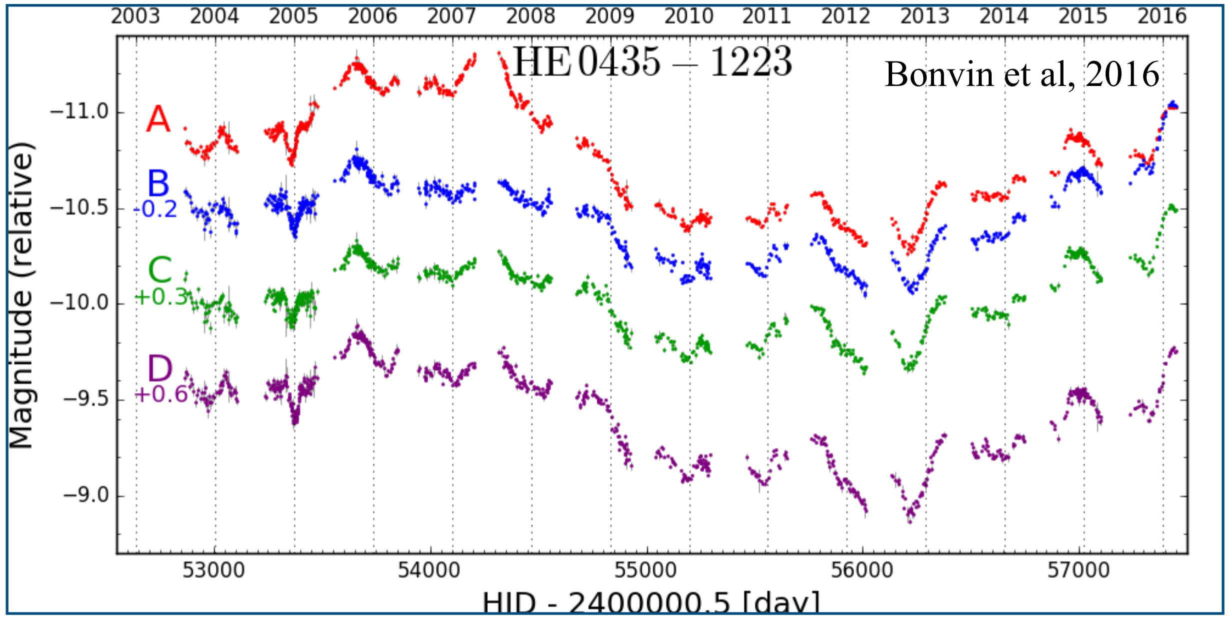

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$$\Delta t_{AB} = D_{\Delta t}\, \Delta\tau_{AB}$$

$$\Delta\tau_{AB} = \frac{\vec{\theta}_A^2}{2} - \vec{\beta}\cdot\vec{\theta}_A - \psi(\vec{\theta}_A) - (A \leftrightarrow B)$$

$$\Sigma_{\rm crit} = \frac{d_A(z_s,0)}{4\pi G\, d_A(z_l,0) d_A(z_s,z_l)}$$

$$D_{\Delta t} = (1+z_l)\frac{d_A(z_l,0)d_A(z_s,0)}{d_A(z_s,z_l)}$$

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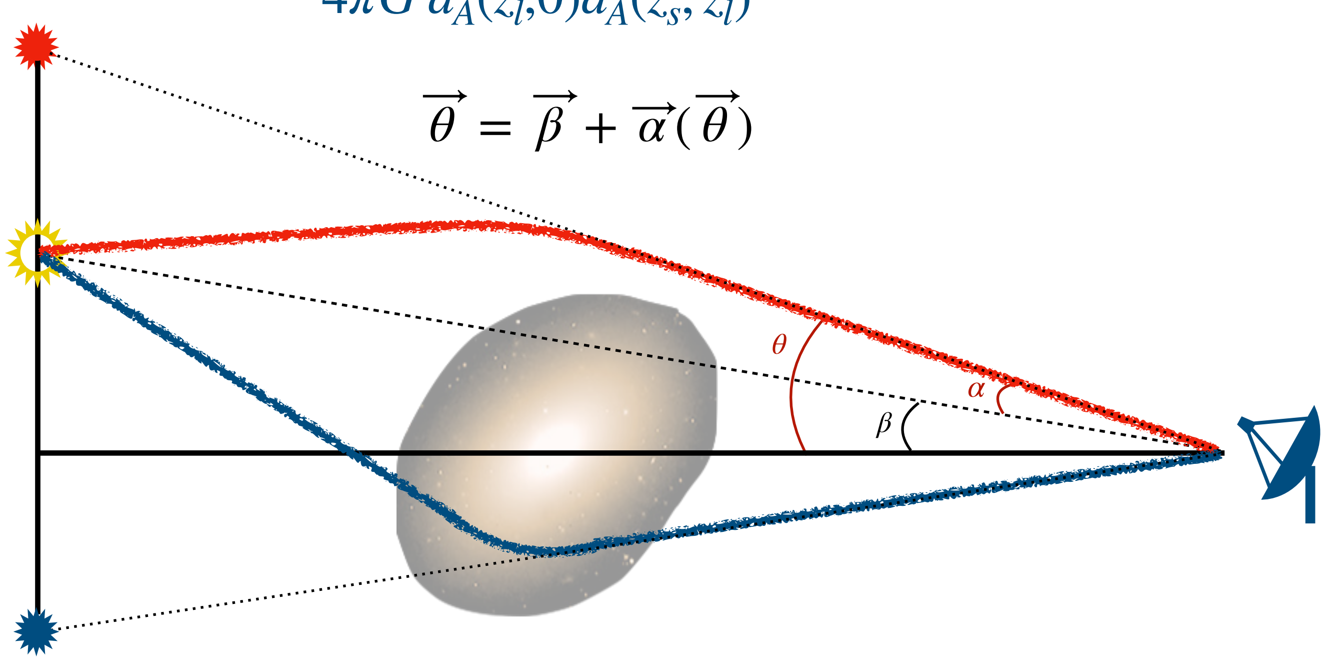

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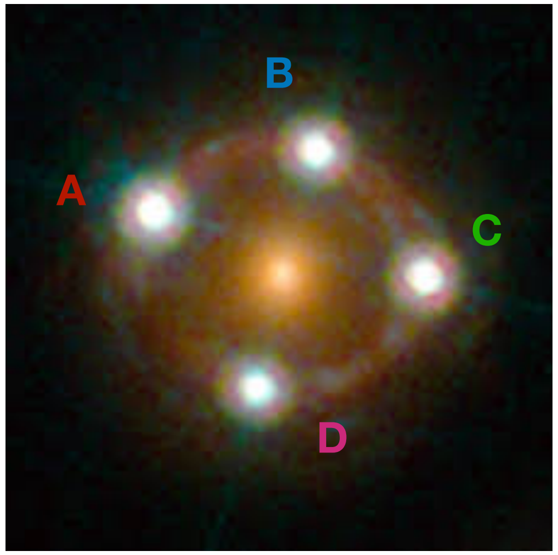
- Extended source image



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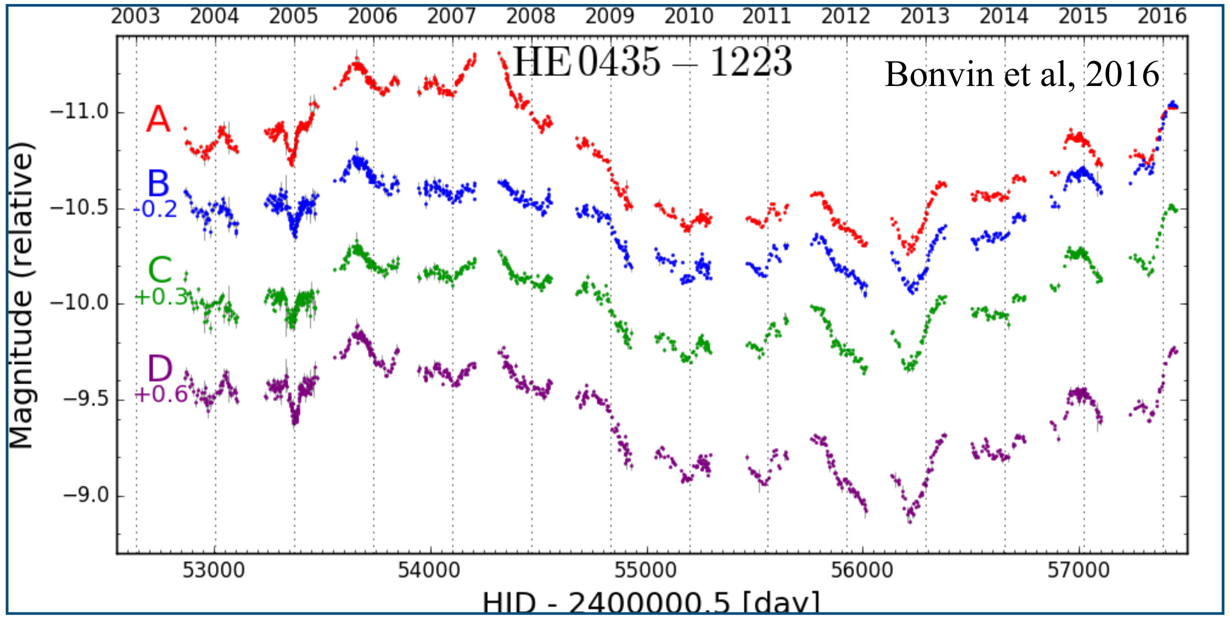

$$\kappa(\vec{\theta}) = \frac{\Sigma(\vec{\theta})}{\Sigma_{\rm crit}} = \frac{1}{2}\vec{\nabla}_\theta \cdot \vec{\alpha} = \frac{1}{2}\vec{\nabla}^2_\theta \psi \qquad \Delta t_{AB} = D_{\Delta t}\,\Delta\tau_{AB} \qquad \Delta\tau_{AB} = \frac{\vec{\theta}_A^2}{2} - \vec{\beta}\cdot\vec{\theta}_A - \psi(\vec{\theta}_A) - (A \leftrightarrow B)$$

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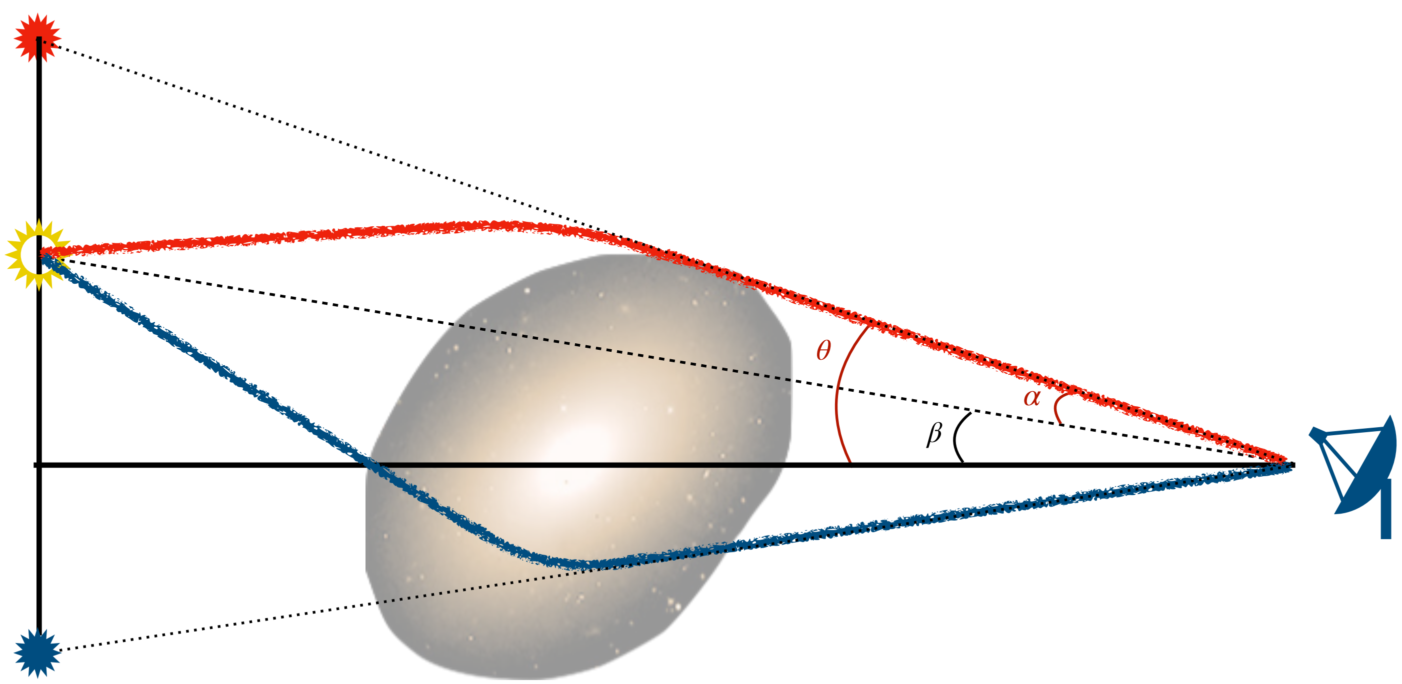
1. From the image, reconstruct a model $\kappa(\vec{\theta}),\ \vec{\beta} \ \rightarrow\ \Delta\tau$
2. Given the model and Δt, extract $D_{\Delta t} = \frac{\Delta t}{\Delta \tau} \propto 1/H_0$

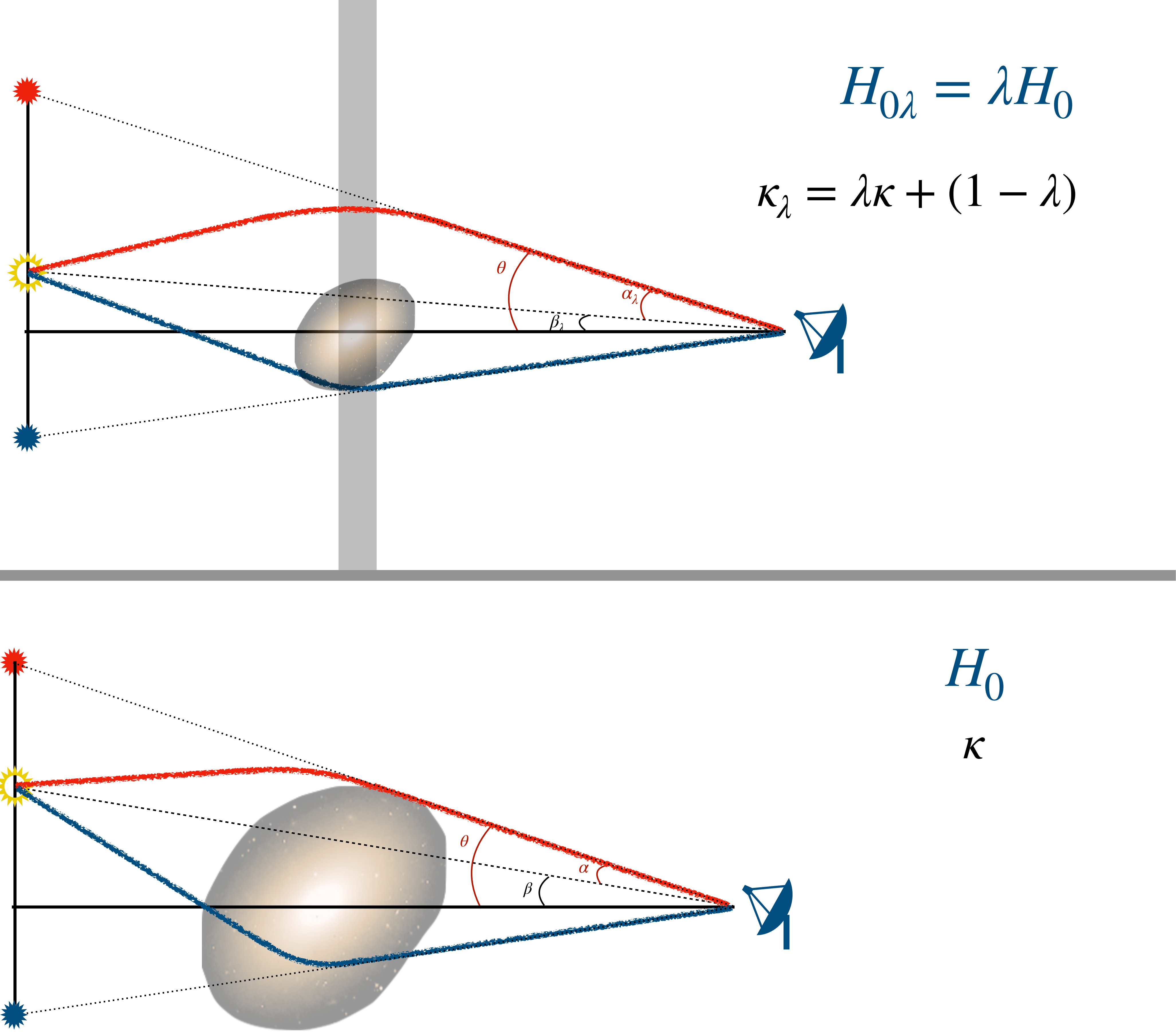
2. Challenges: modeling degeneracy

$$
\begin{aligned}
\vec{\theta} &= \vec{\beta} + \vec{\alpha} \\
&= \vec{\beta}_\lambda + \vec{\alpha}_\lambda \\
&= \lambda\vec{\beta} + \lambda\vec{\alpha} + (1-\lambda)\vec{\theta} \\
&= \lambda(\vec{\beta} + \vec{\alpha} - \vec{\theta}) + \vec{\theta} \\
&= \vec{\theta}
\end{aligned}
$$

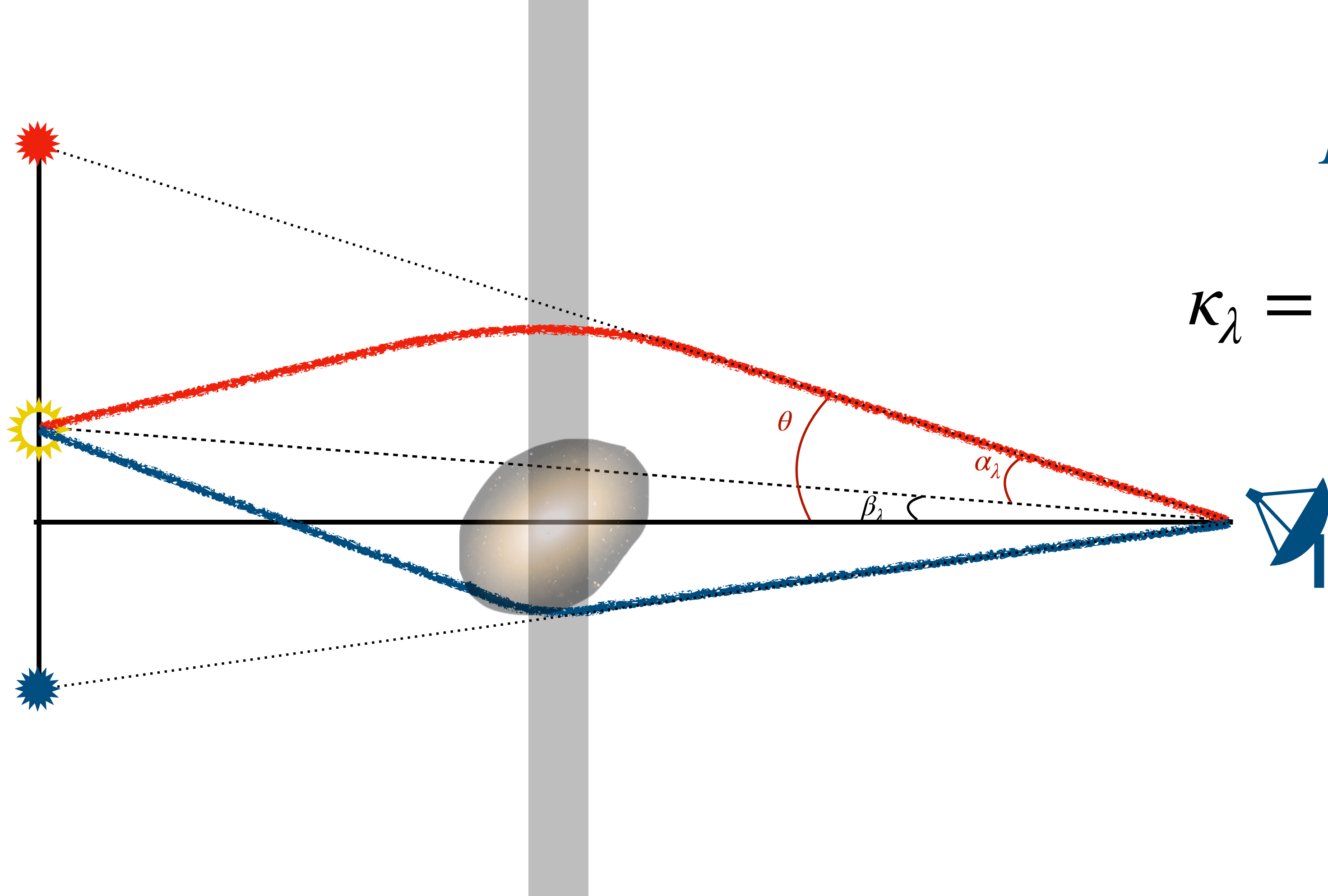


H_0

κ



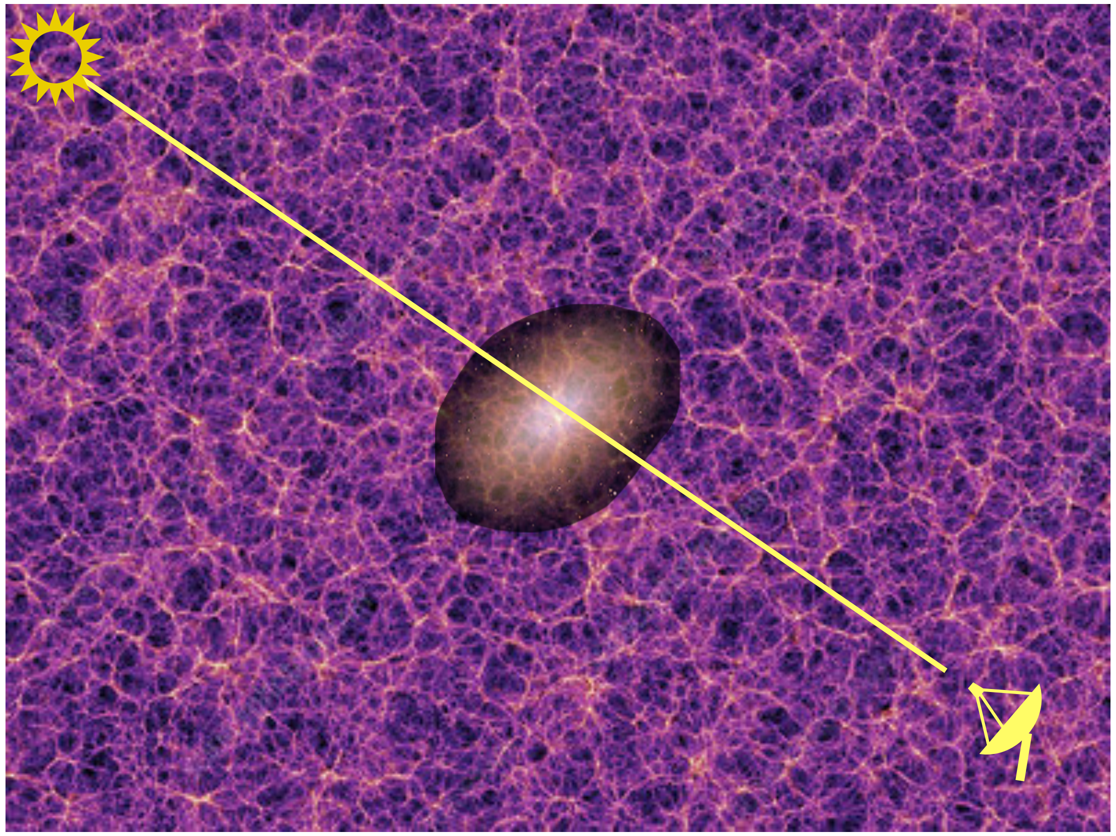
$H_{0\lambda} = \lambda H_0$
$\kappa_\lambda = \lambda\kappa + (1-\lambda)$
θ
α_λ
β_λ
H_0
κ
θ
α
β

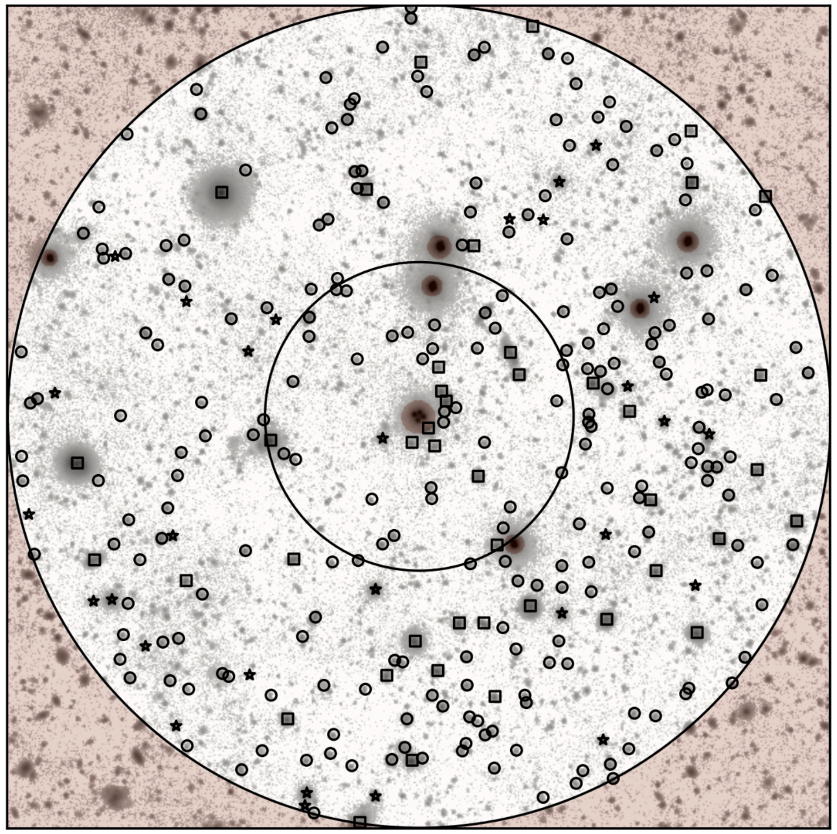


$$H_{0\lambda} = \lambda H_0$$

$$\kappa_\lambda = \lambda\kappa + (1 - \lambda)$$

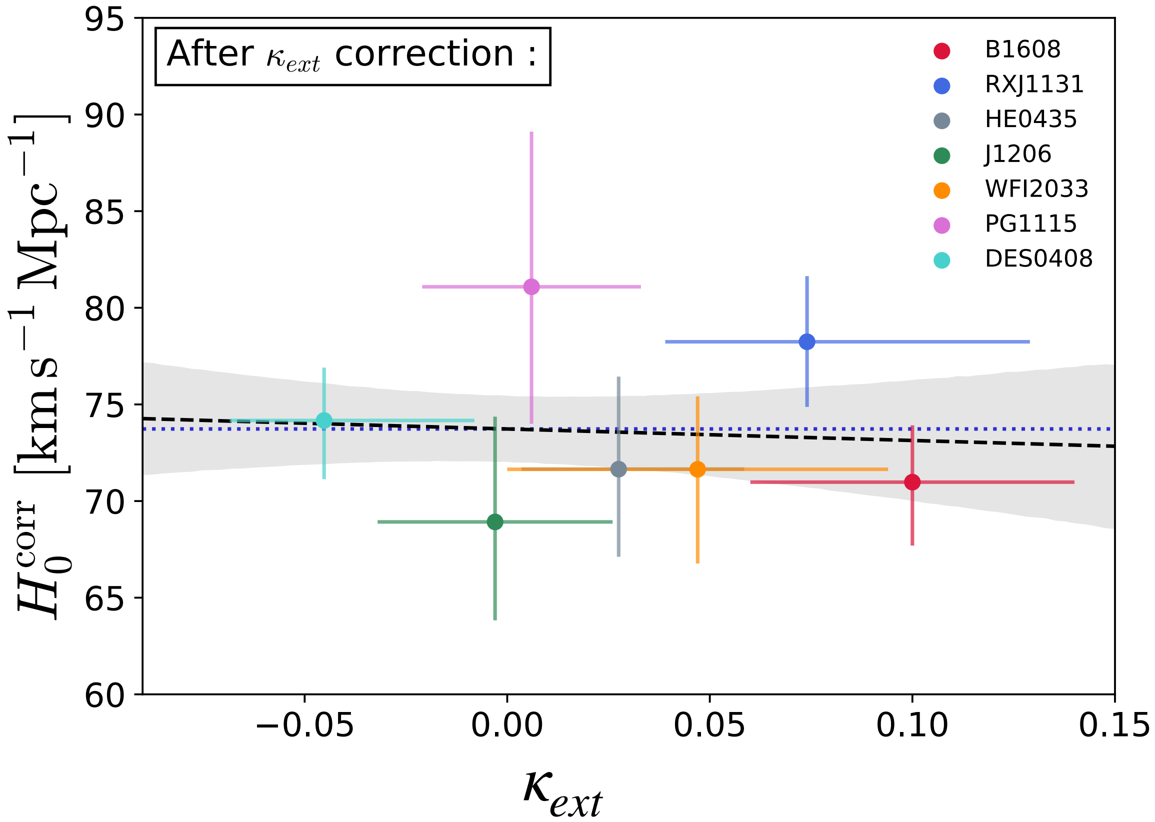
Modelling
external
convergence

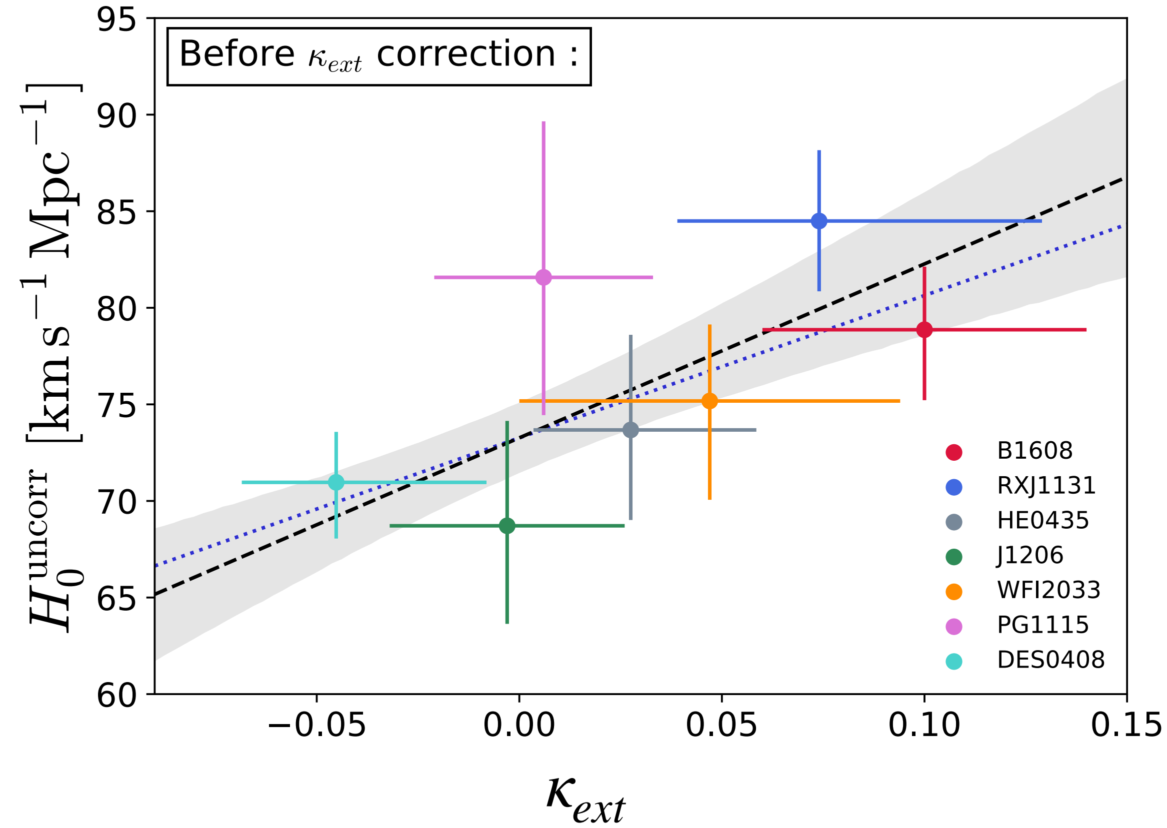




Rusu et al, 1607.01047 (H0LiCOW III)

Millon et al, 1912.08027 (**TDCOSMO I**)





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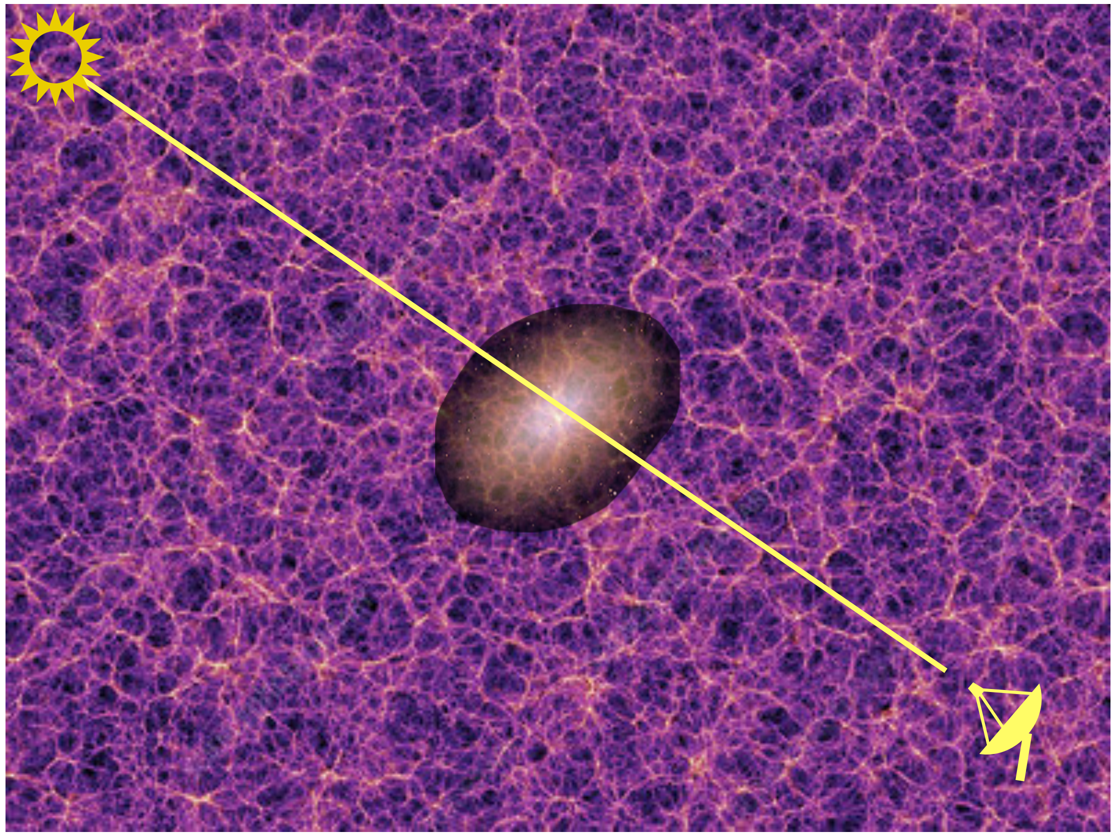

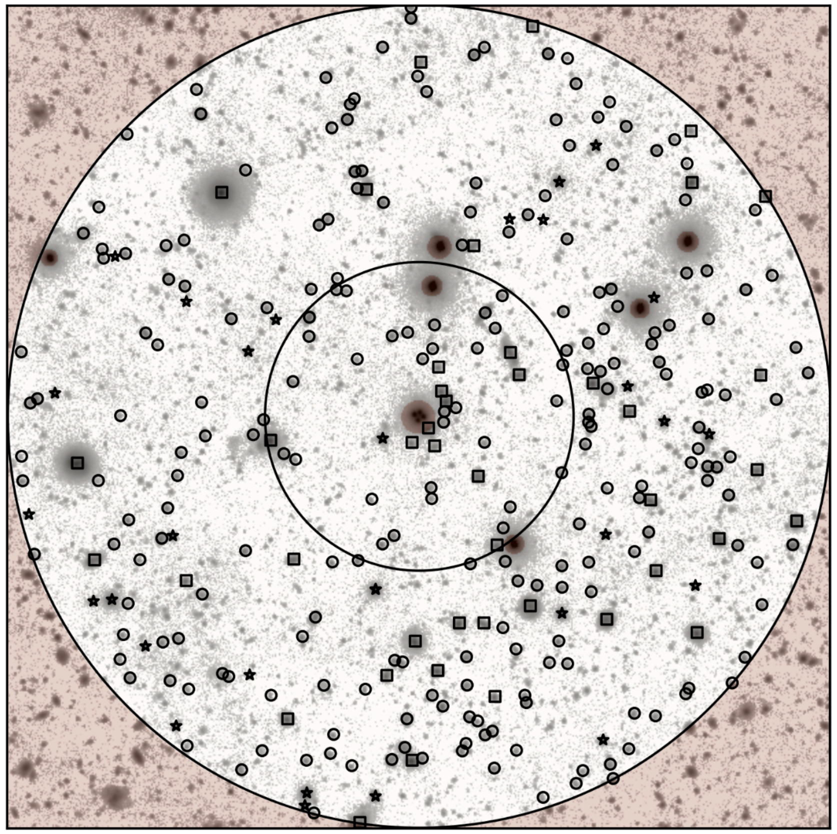

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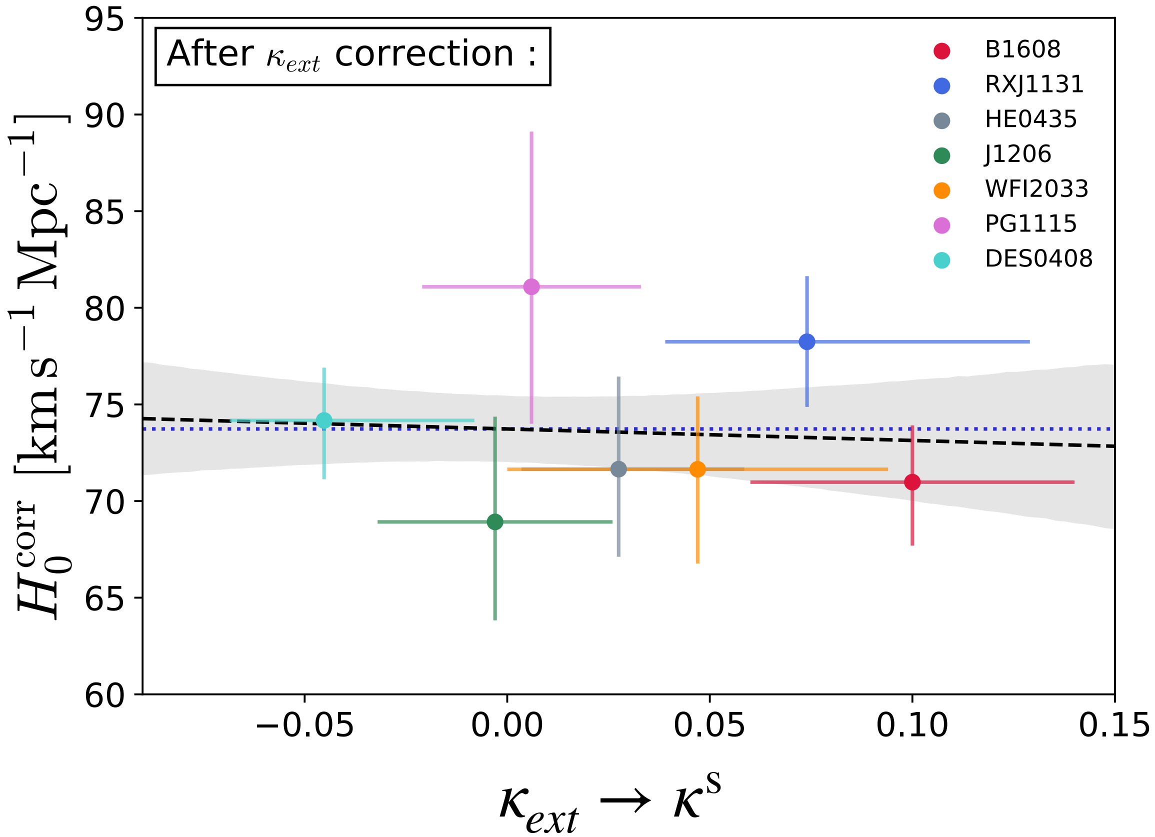
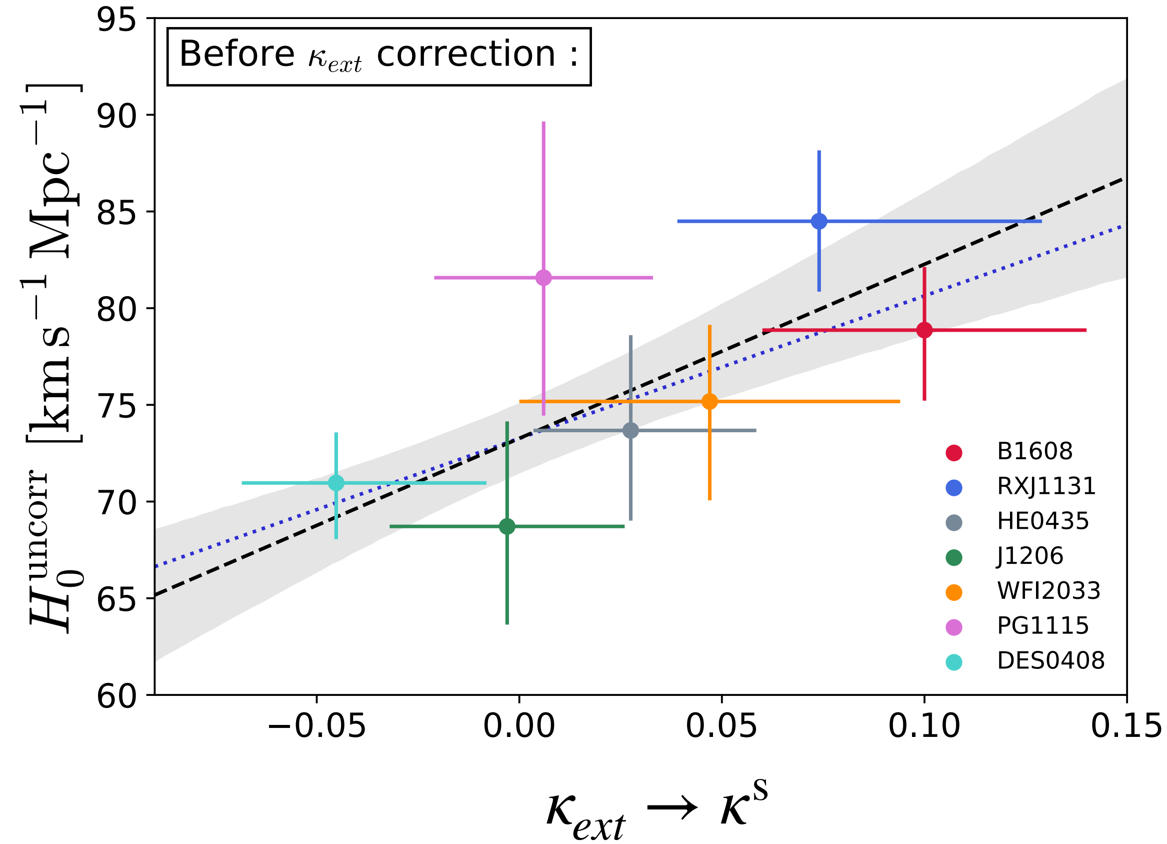
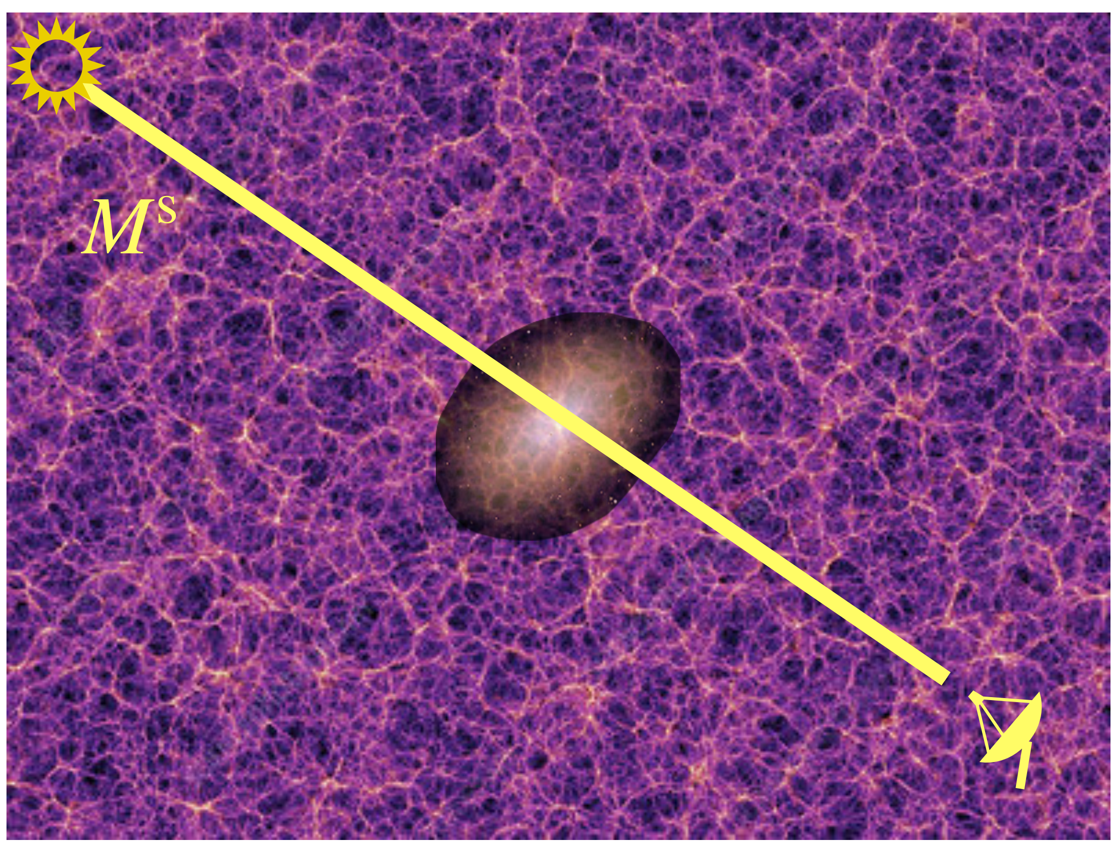
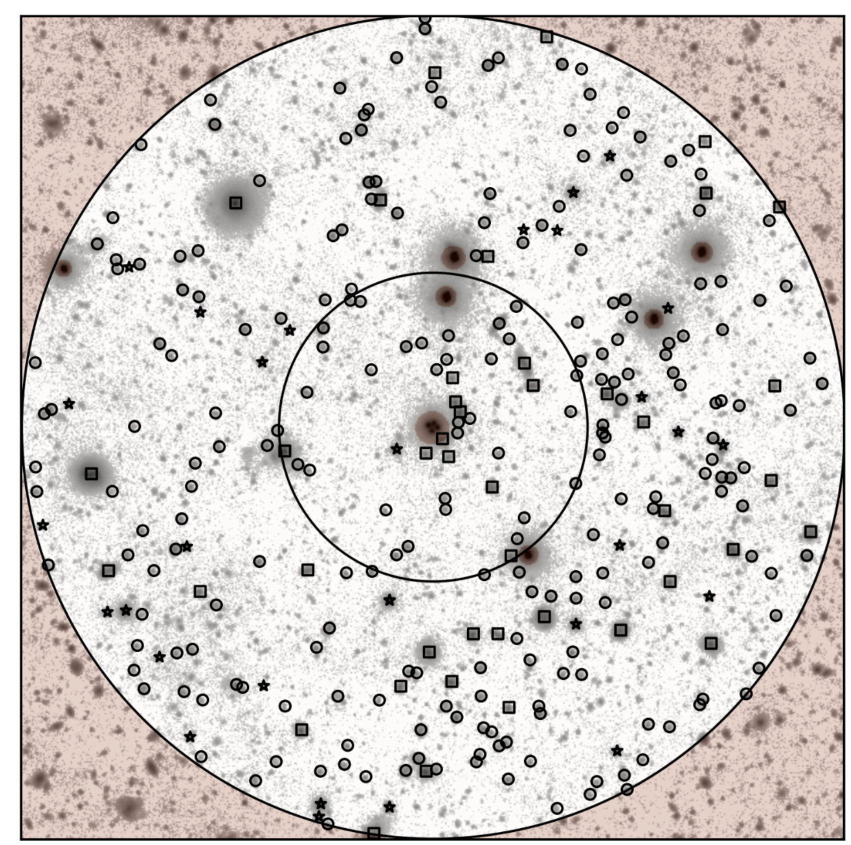




Modelling ***external*** convergence



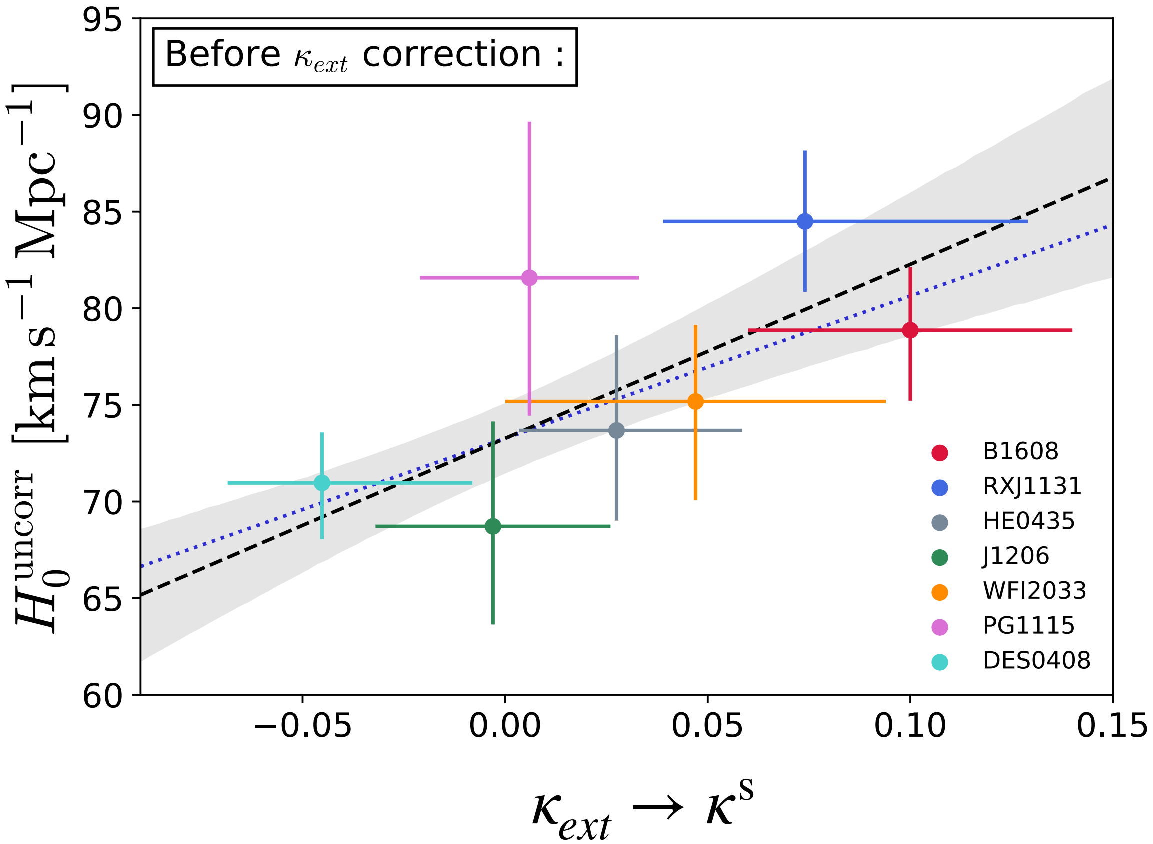


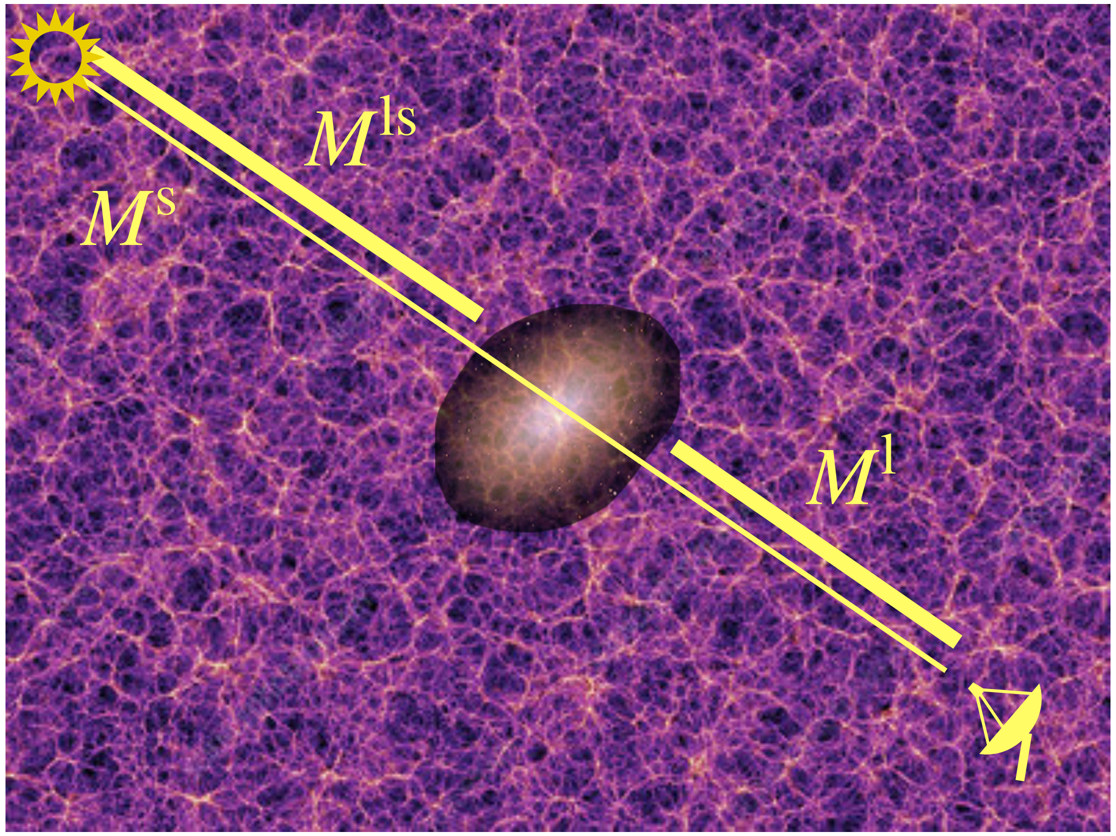
Rusu et al, 1607.01047 (H0LiCOW III)

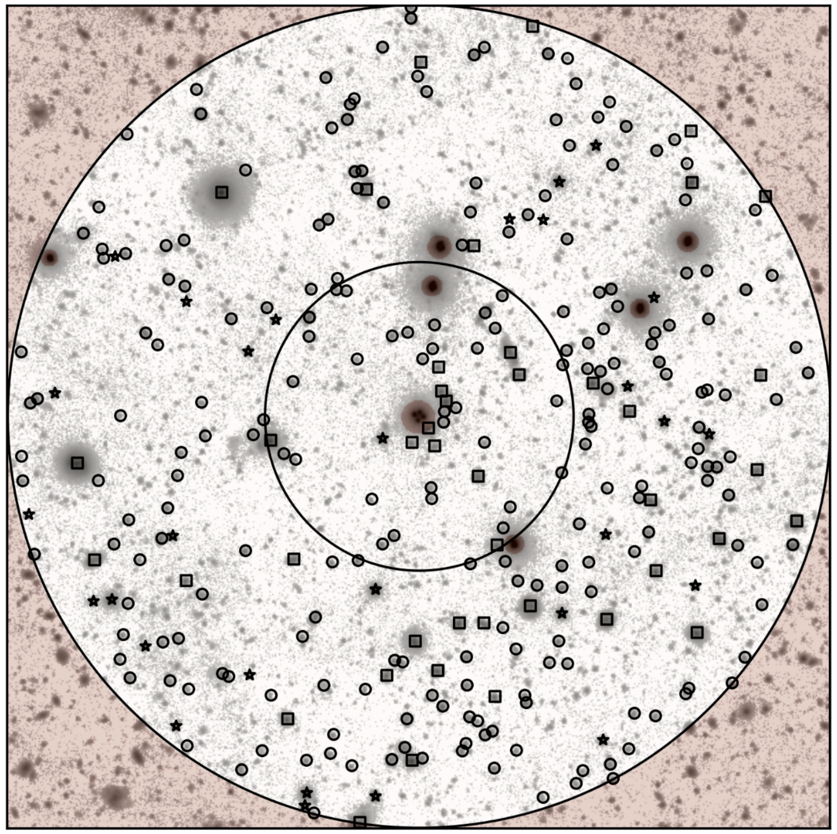
Weak lensing degeneracy:

$$H_0^{\rm uncorr} = \frac{1-\kappa^{\rm ls}}{1-\kappa^{\rm l}} \frac{1}{1-\kappa^{\rm s}} H_0$$

Millon et al, 1912.08027 **(TDCOSMO I)**







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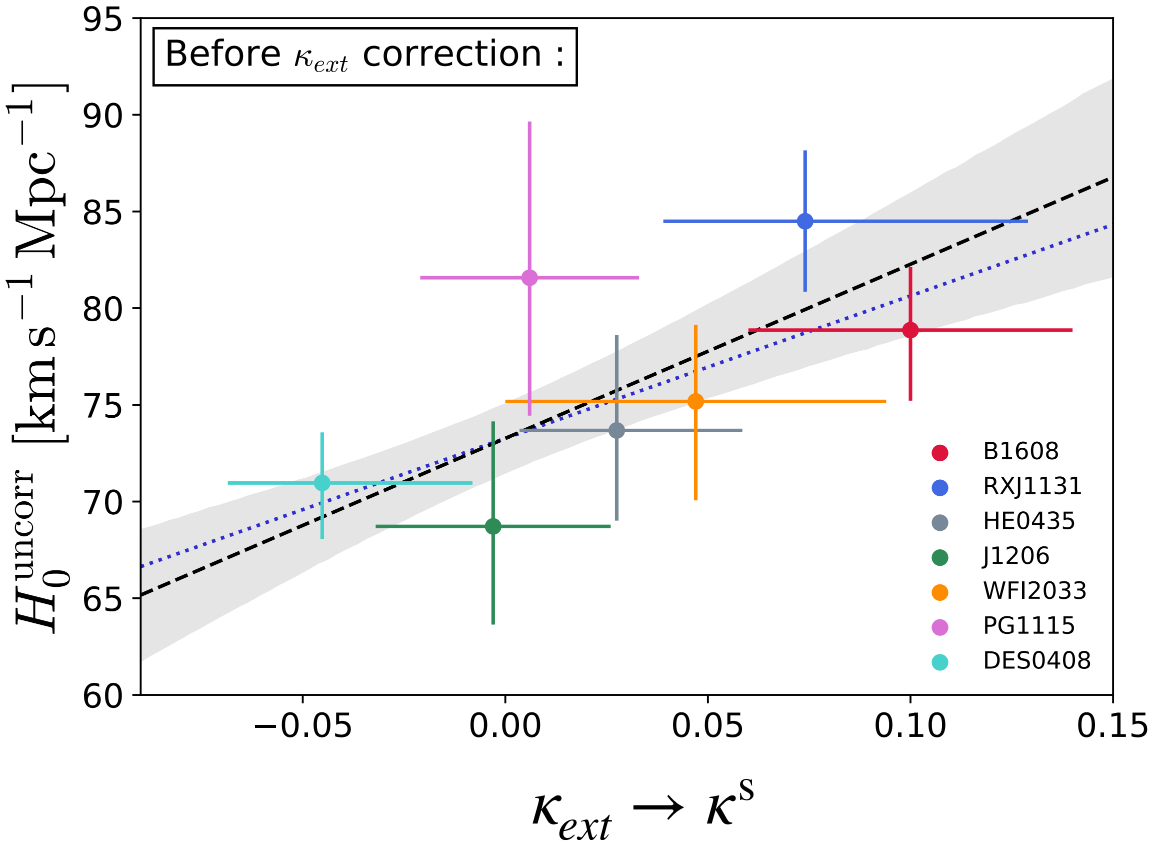
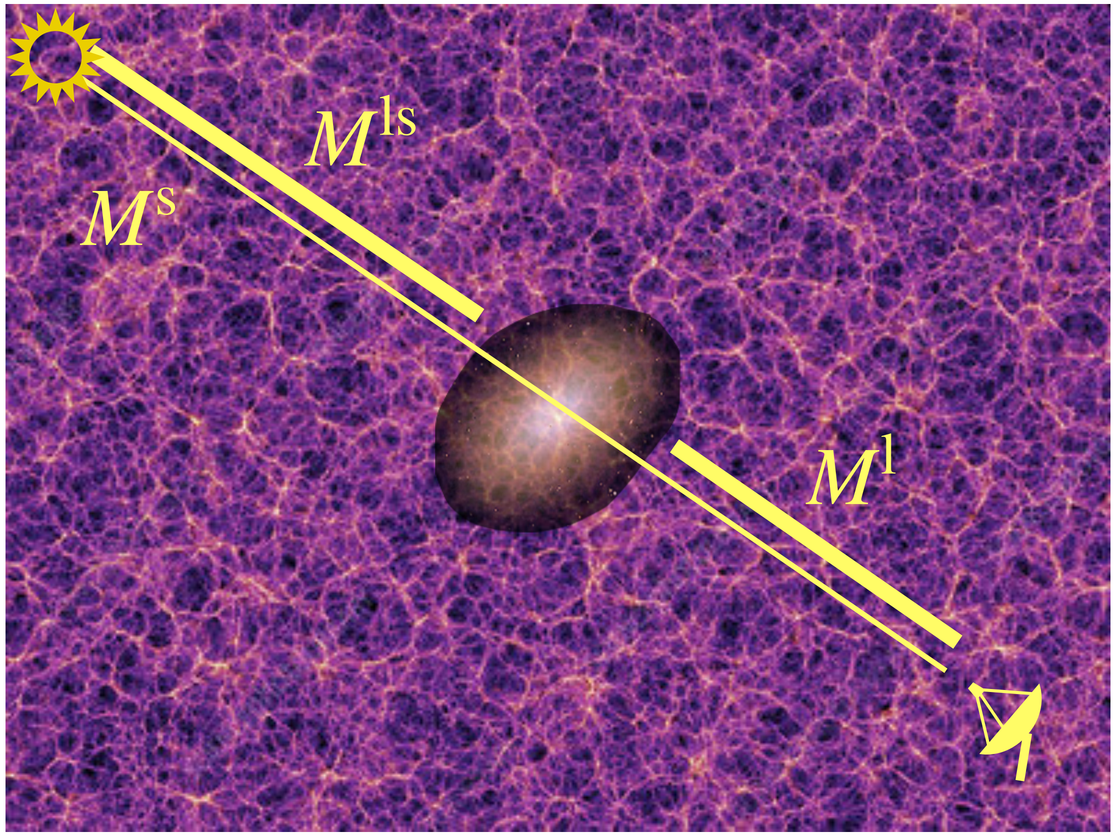
$$H_0^{\rm uncorr} = \frac{1-\kappa^{\rm ls}}{1-\kappa^{\rm l}}\frac{1}{1-\kappa^{\rm s}} H_0$$

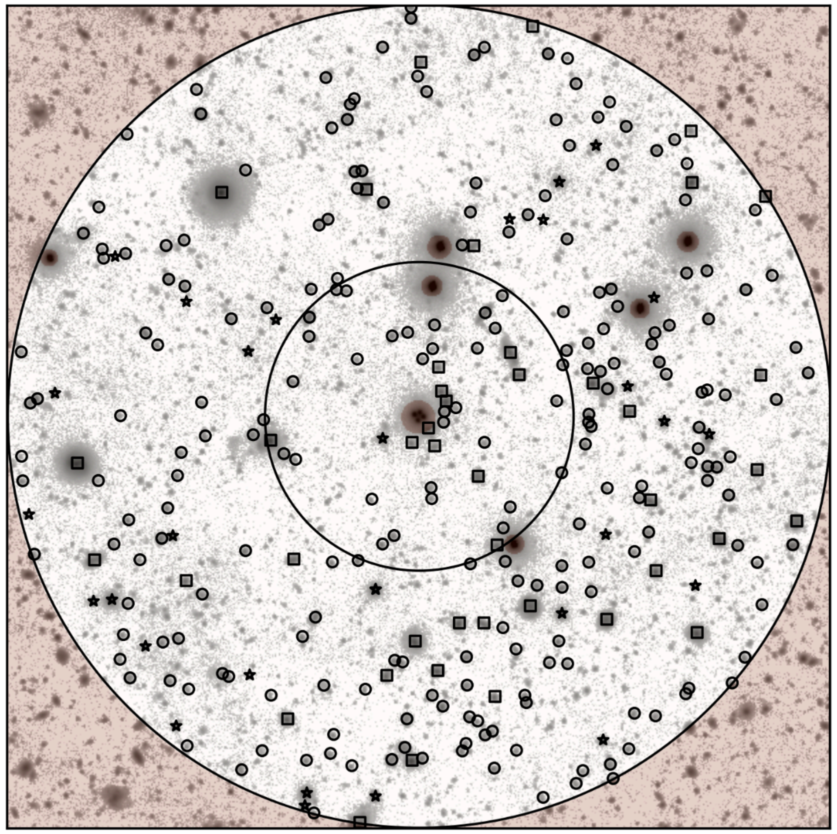
Weak lensing correction in H0LiCOW / TDCOSMO is probably *a little bit* off.

Birrer et al, 2007.02941 (TDCOSMO IV)
Teodori, et al, 2201.05111

Millon et al, 1912.08027 **(TDCOSMO I)**







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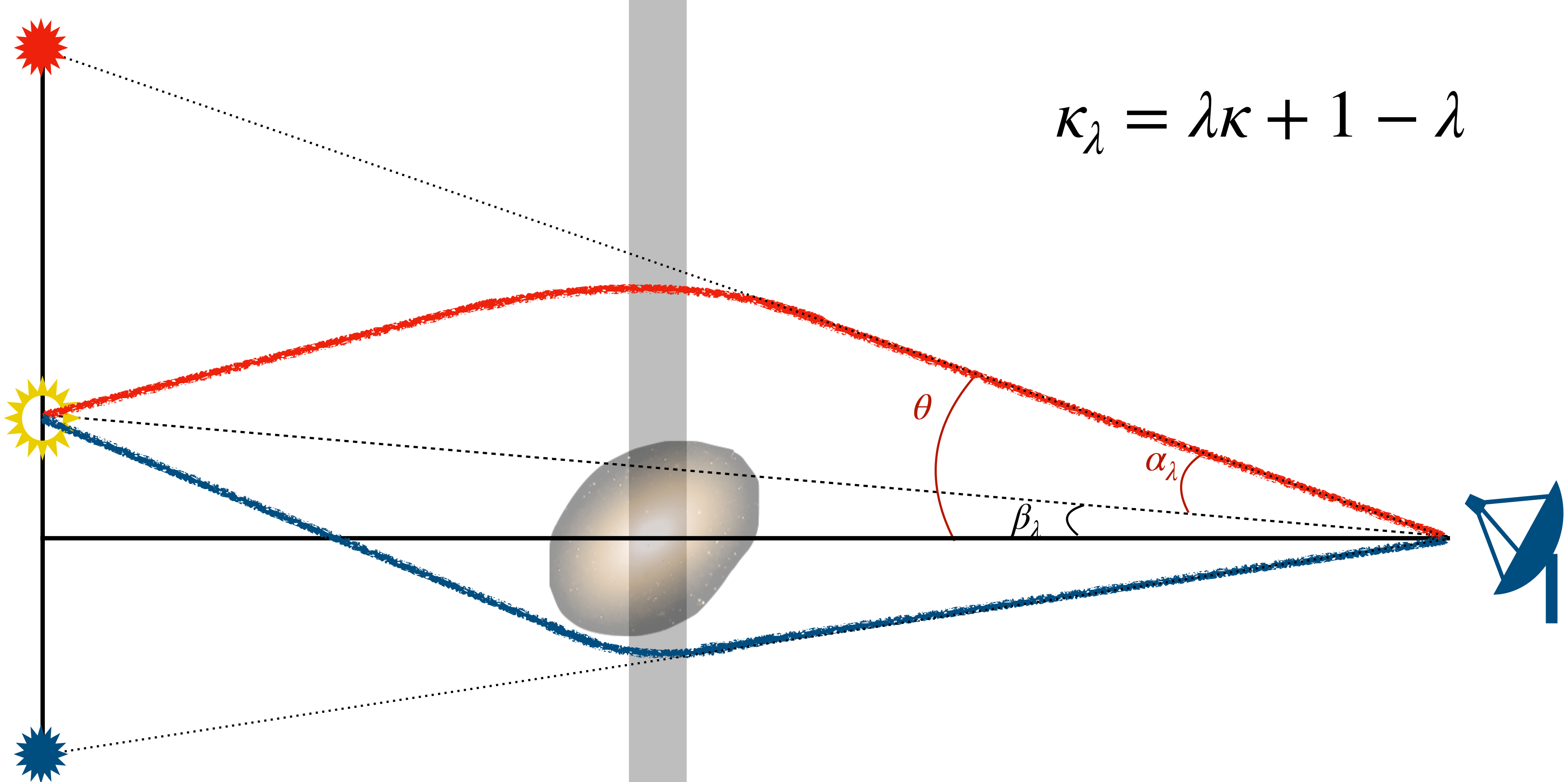
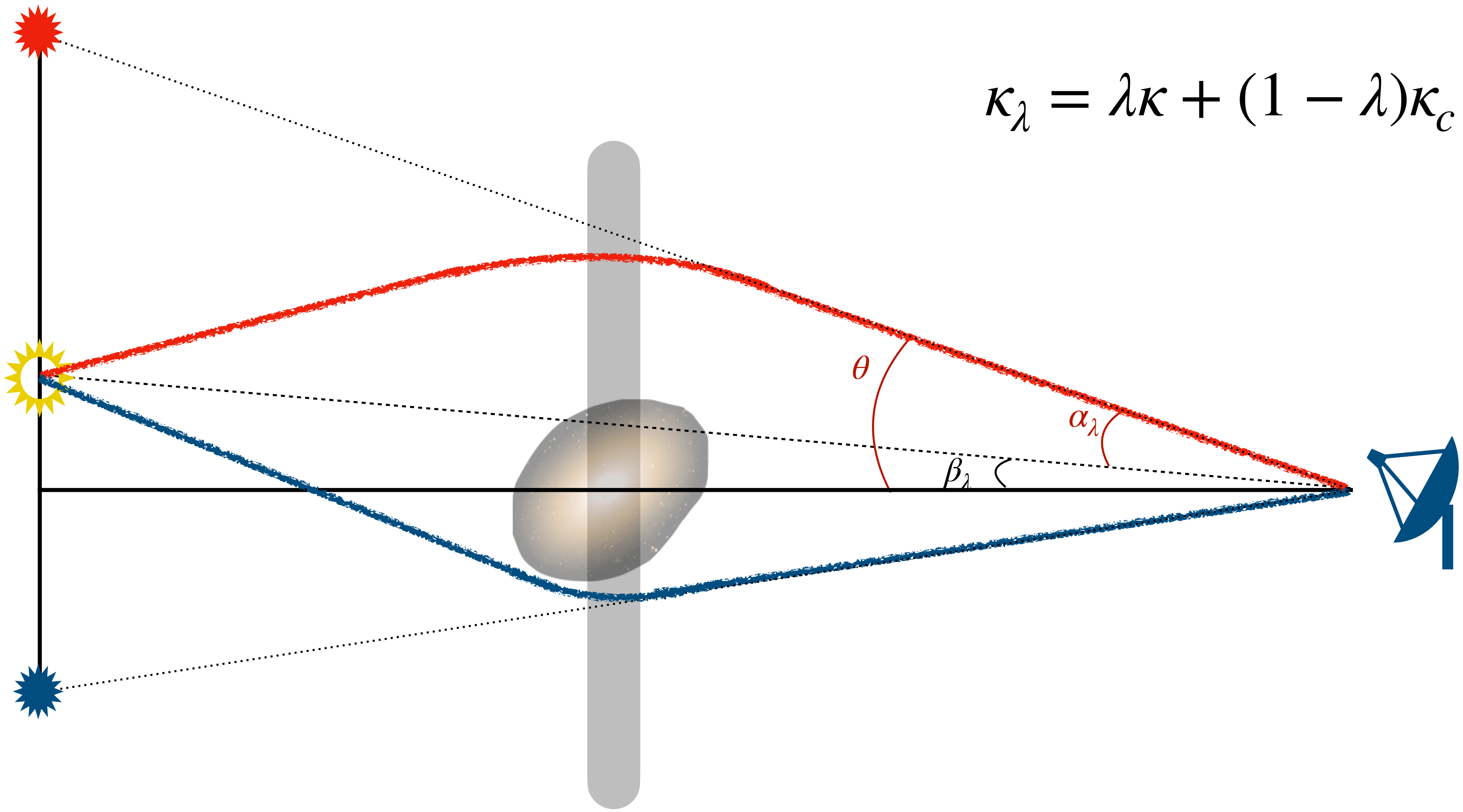


$$\kappa_\lambda = \lambda\kappa + 1 - \lambda$$

Internal vs. External Convergence

Internal vs. External Mass Sheet Degeneracy

$$\kappa_\lambda = \lambda\kappa + (1-\lambda)\kappa_c$$



Internal vs. External Convergence

Internal vs. External Mass Sheet Degeneracy

Schneider, Sluse, 1306.0901
KB, Castorina, Simonović, 2001.07182

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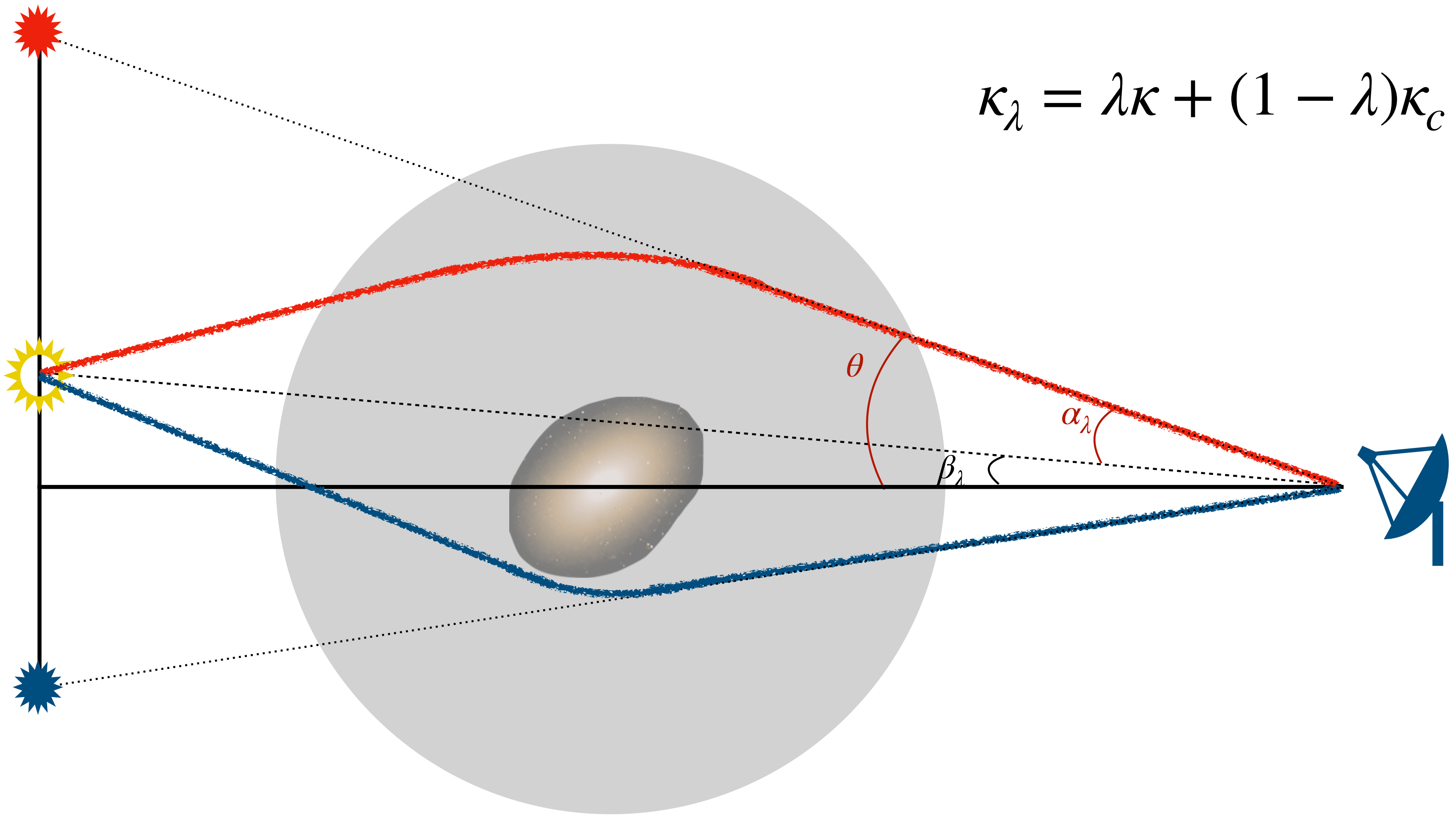

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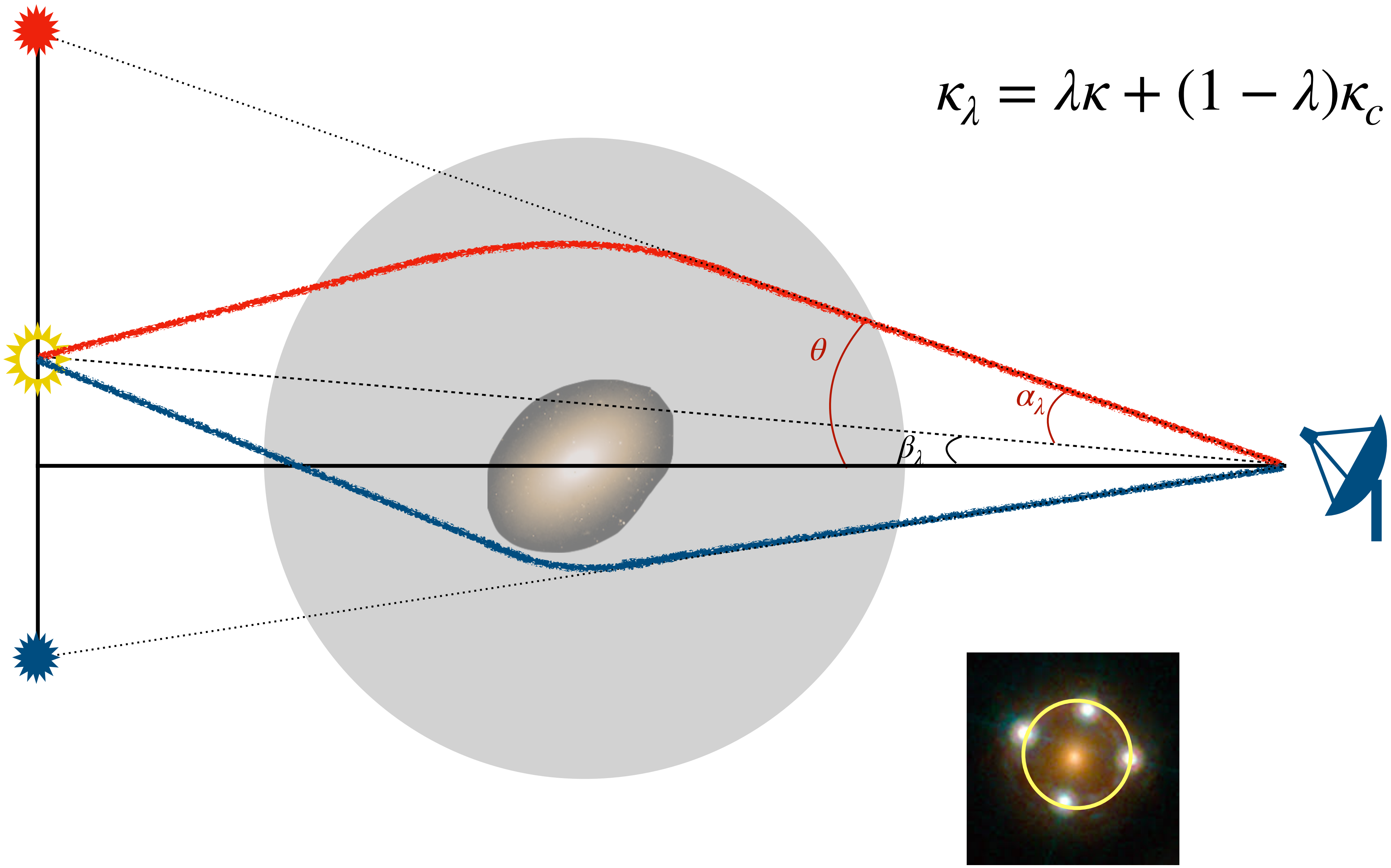
Internal vs. External Mass Sheet Degeneracy

KB, Castorina, Simonović, 2001.07182

A core component in lens halos could solve lensing H0 tension.



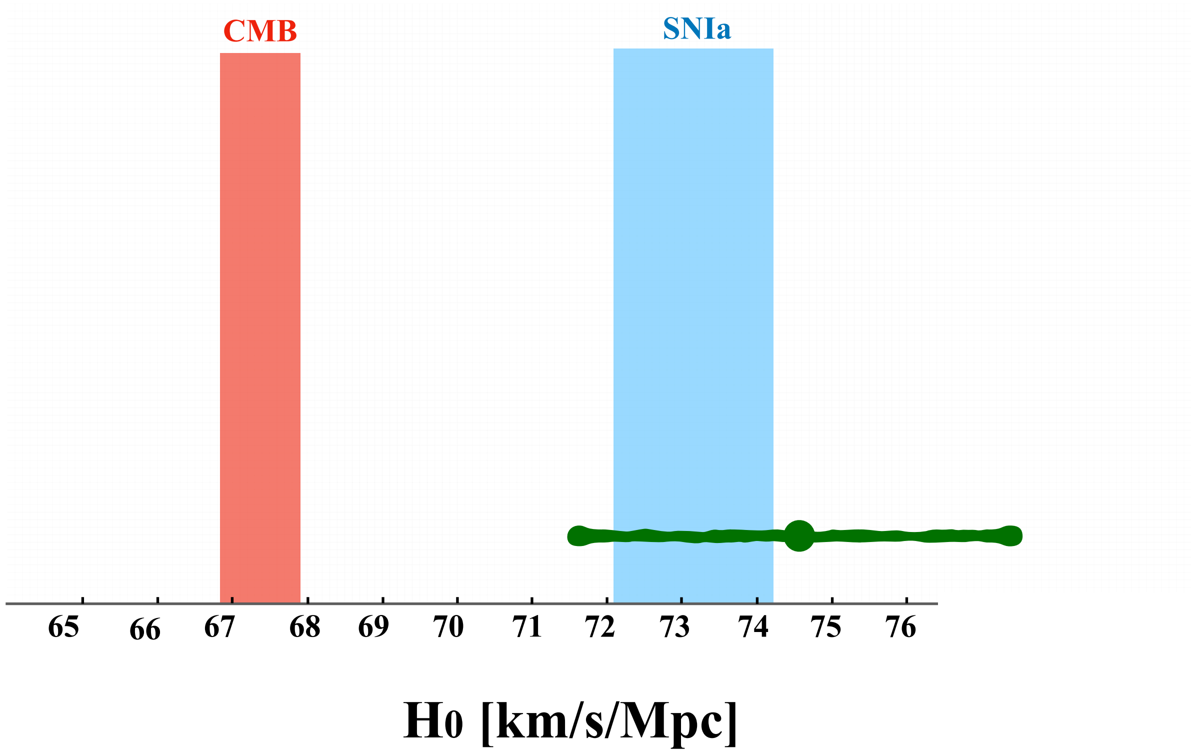
$$\kappa_\lambda = \lambda\kappa + (1-\lambda)\kappa_c$$

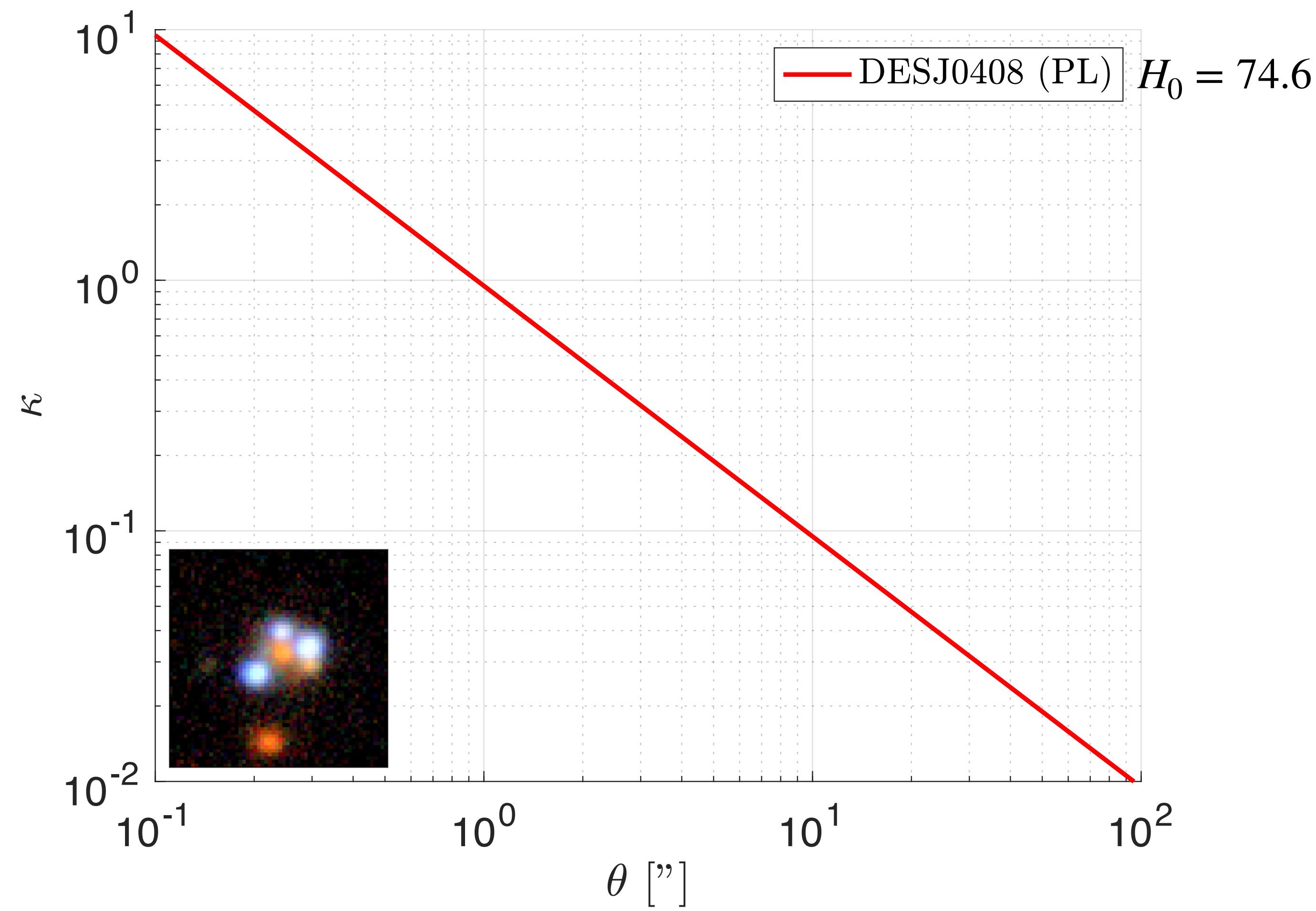
Example: $\rho_c(r) = \dfrac{1}{\sqrt{\pi}\,\Gamma\left(\frac{3}{2}\right)} \dfrac{\Sigma_c R_c^3}{\left(R_c^2 + r^2\right)^2}$

$$\theta_{E\lambda} = \theta_E(1+\delta)$$

$$\delta = -\frac{3}{4(\gamma-1)}\,\frac{1-\lambda}{\lambda}\,\frac{\theta_E^2}{\theta_c^2} + \mathcal{O}\left(\frac{\theta_E^4}{\theta_c^4}\right)$$

2. Challenges: modeling degeneracy





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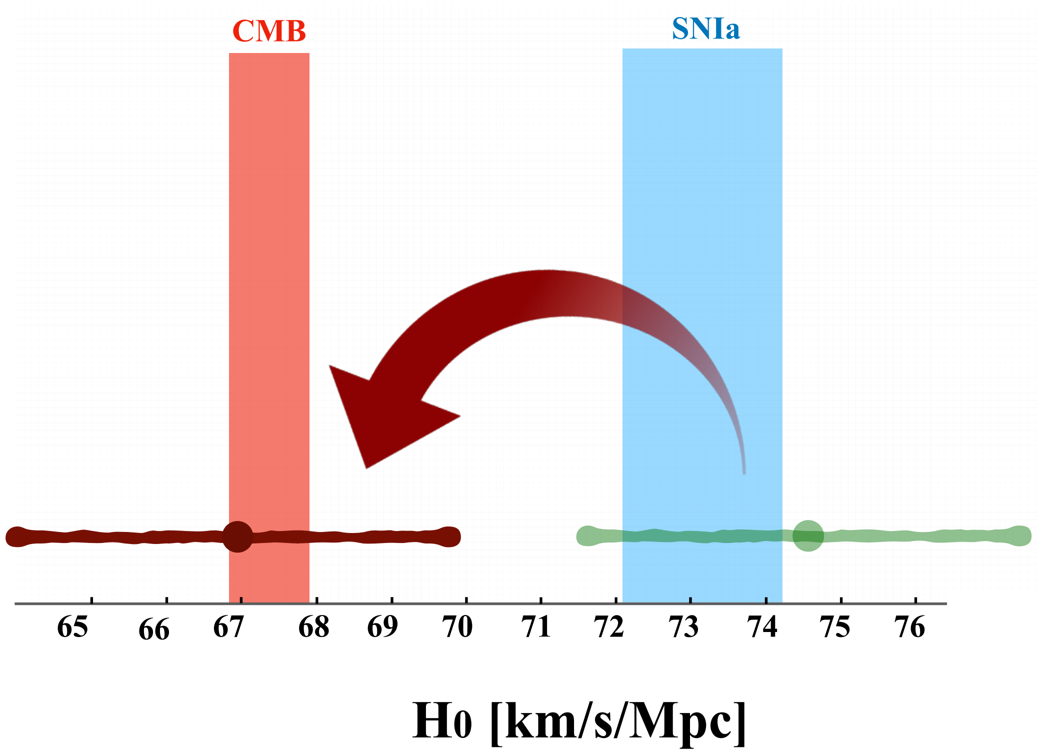
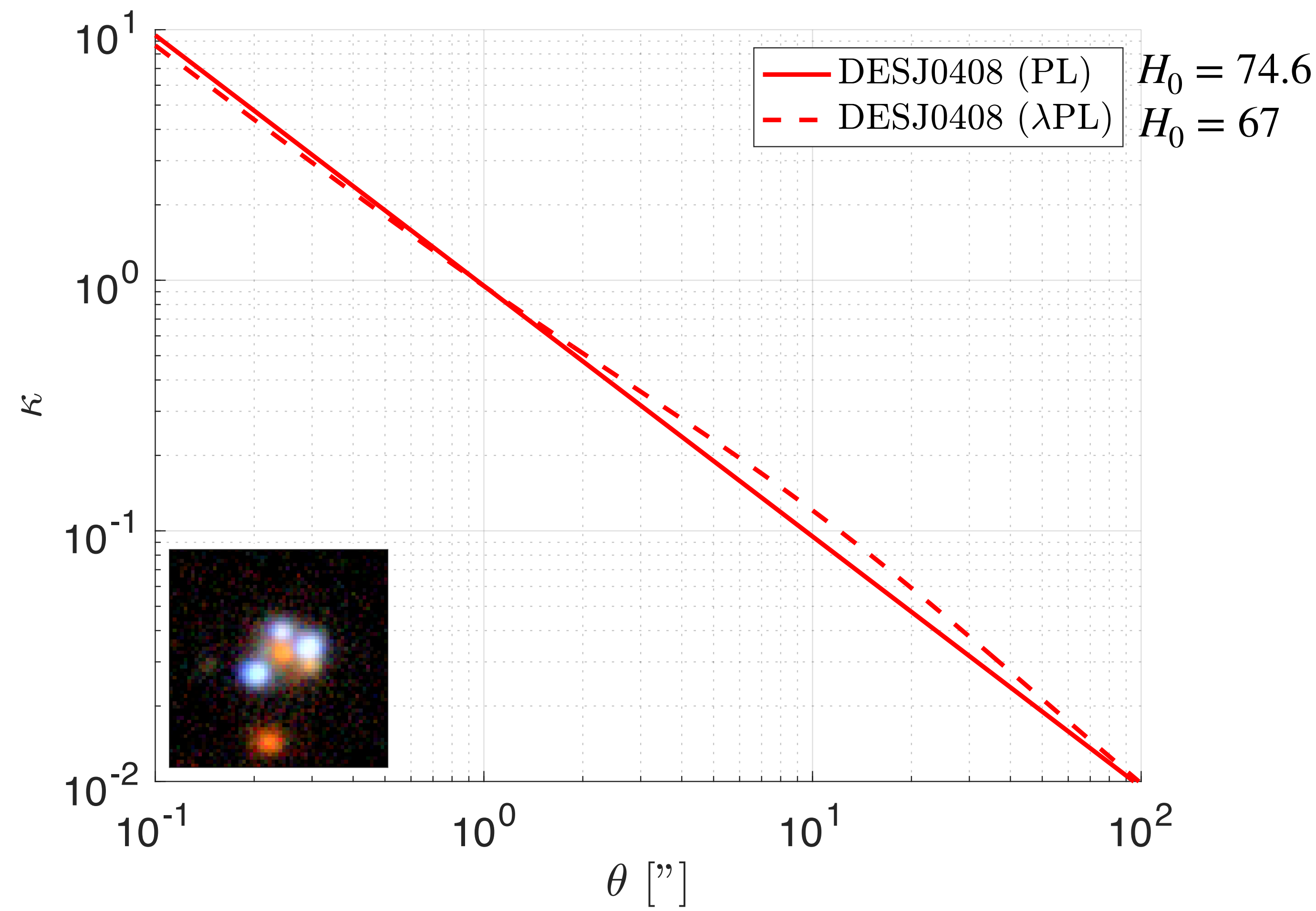
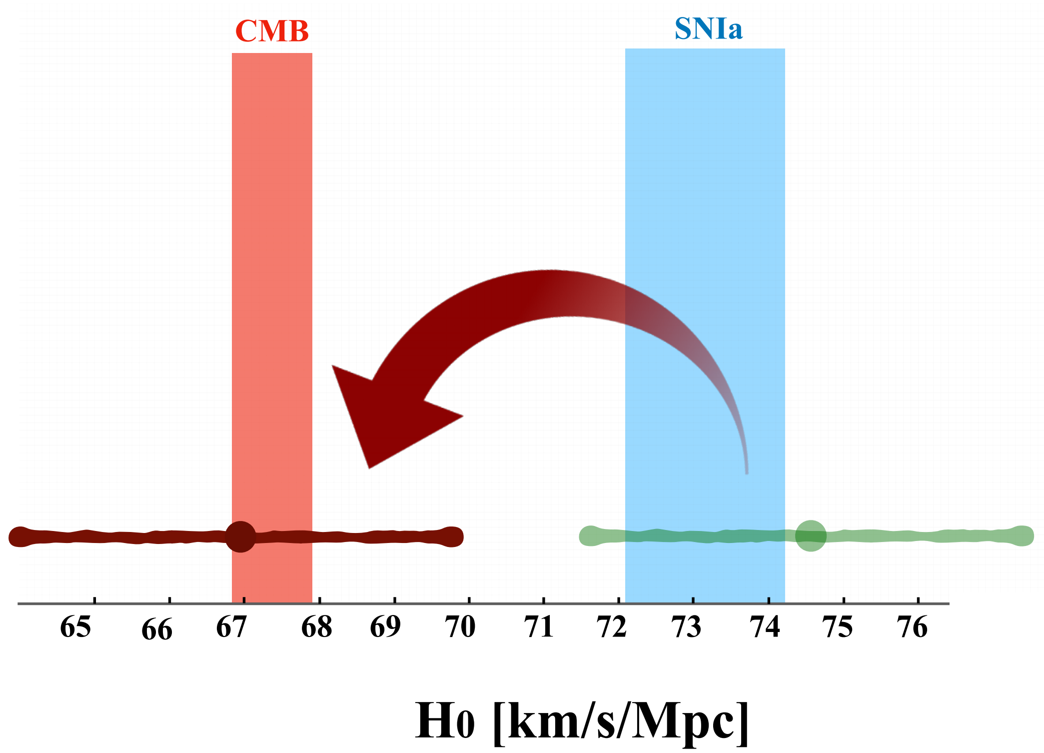
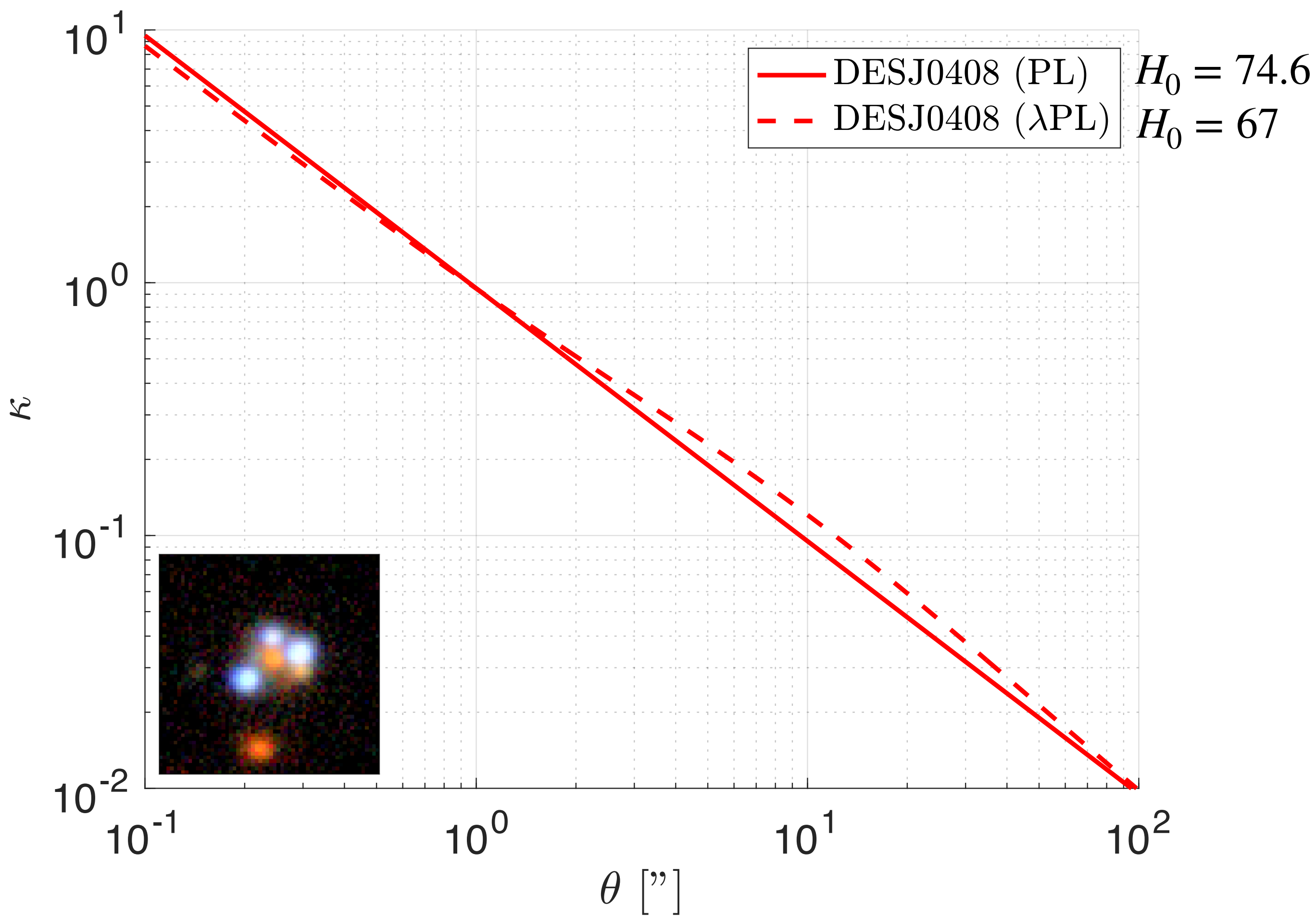




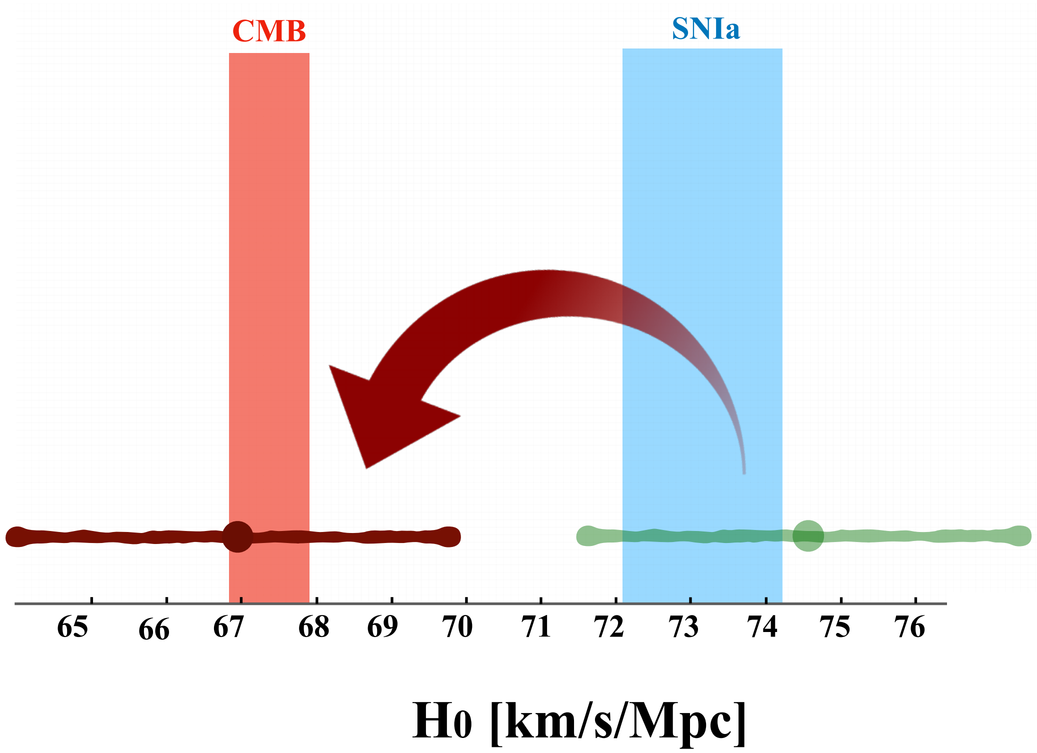
3. Opportunities: galactic structure

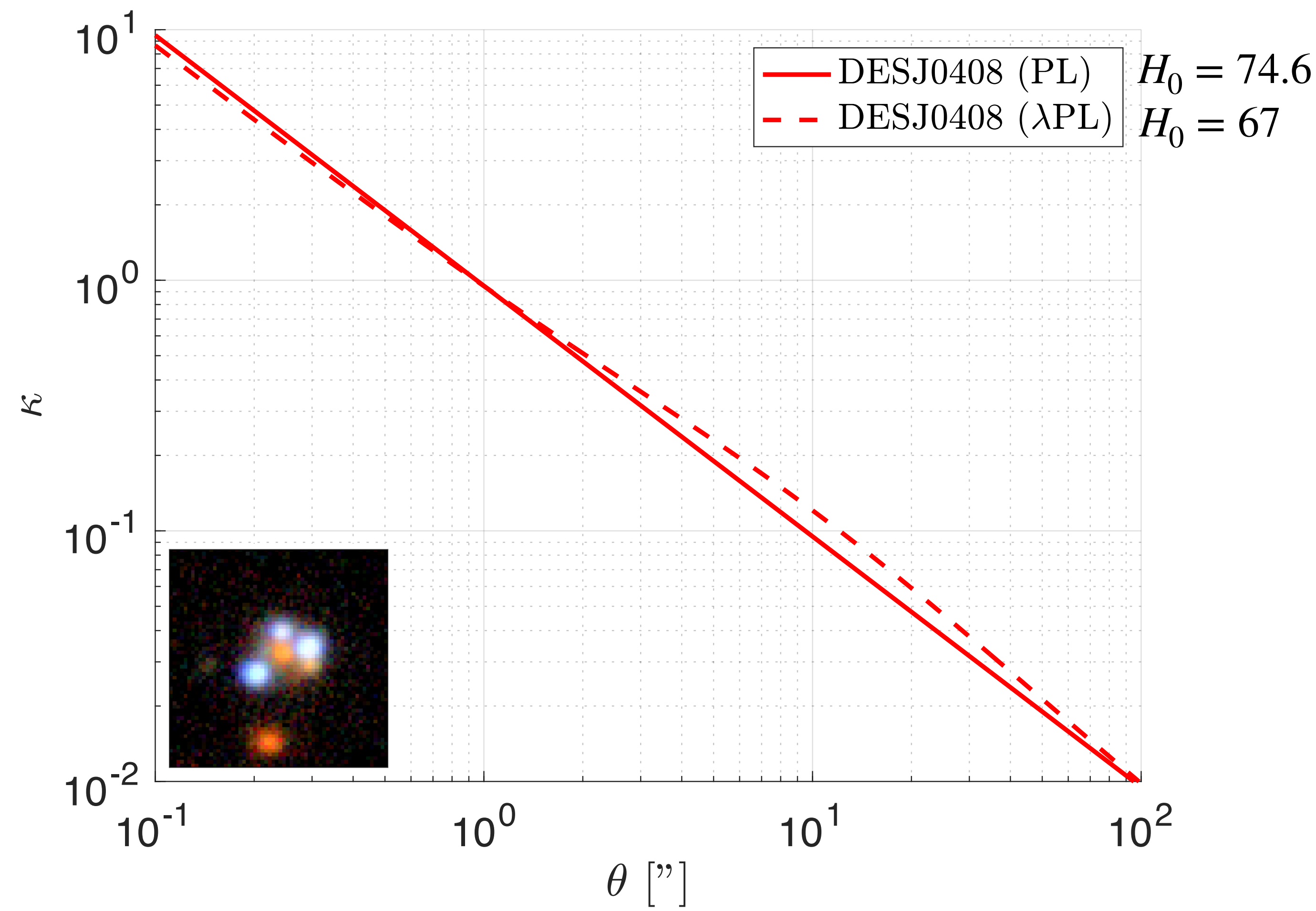




3. Opportunities: galactic structure

What do we learn about galaxies if we add CMB/LSS prior?





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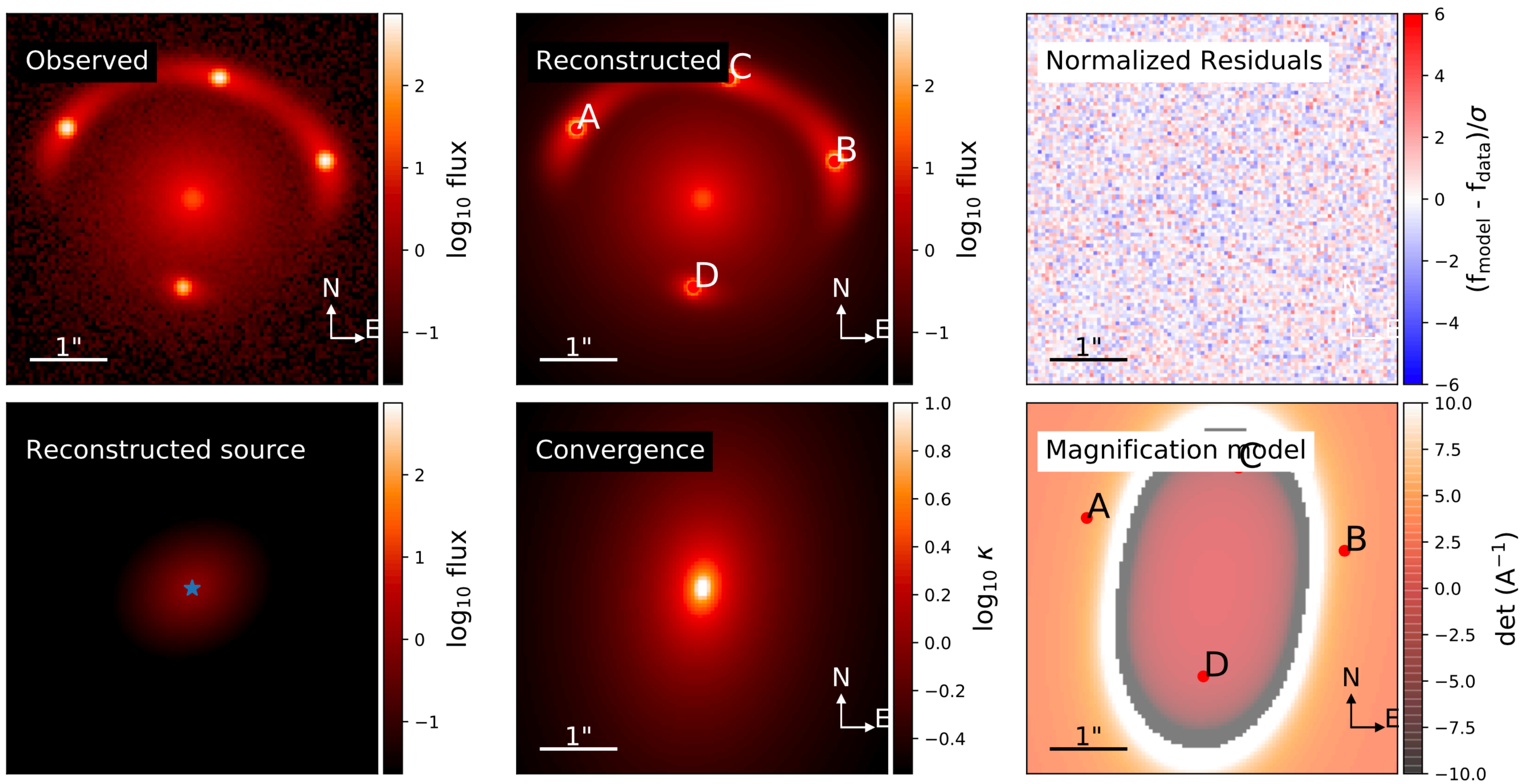
What do we learn about galaxies if we add CMB/LSS prior?

Expect evidence for core component, reflecting precision on H0

KB, Castorina, Simonović, 2001.07182
KB, Teodori, 2105.10873



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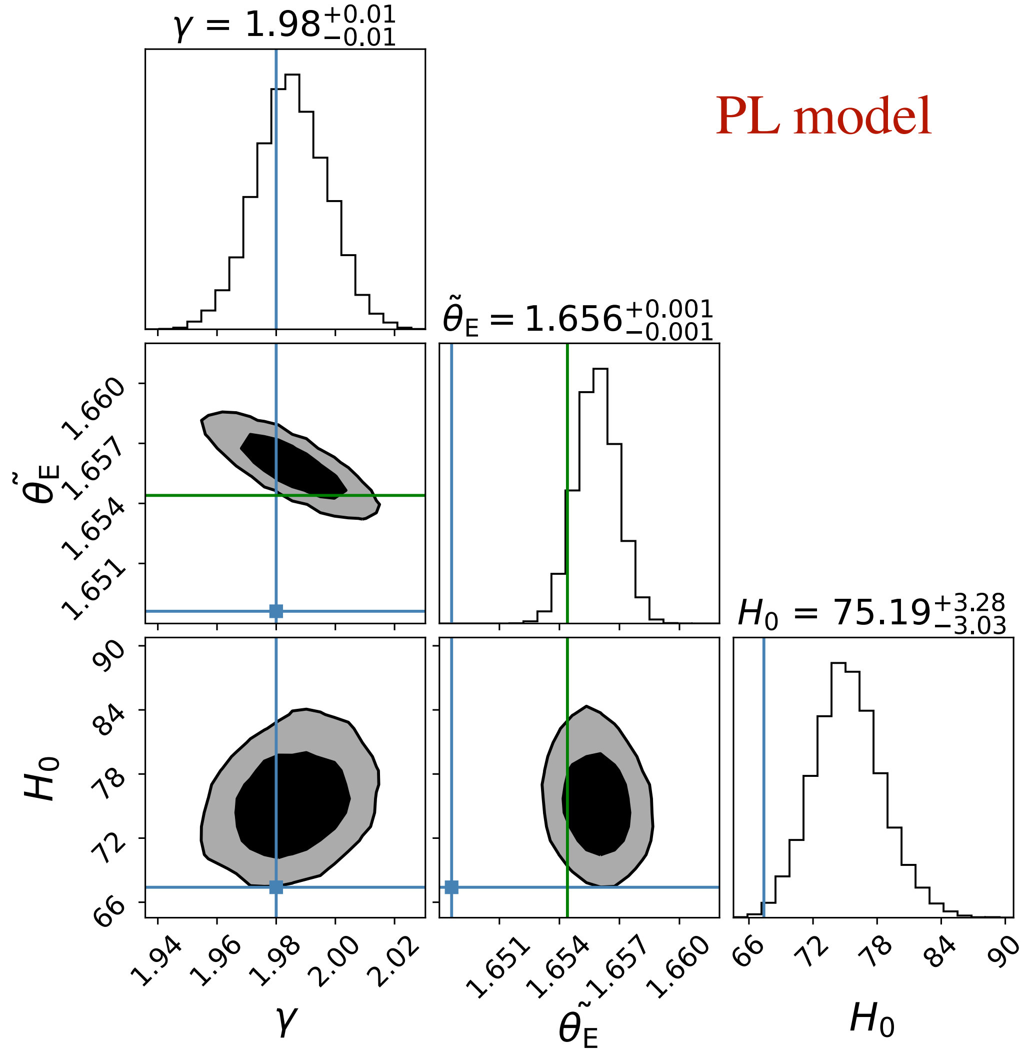
Mock inference using power-low model.

Truth has H_0=67.4 km/s/Mpc, and a 10% core!



PL model

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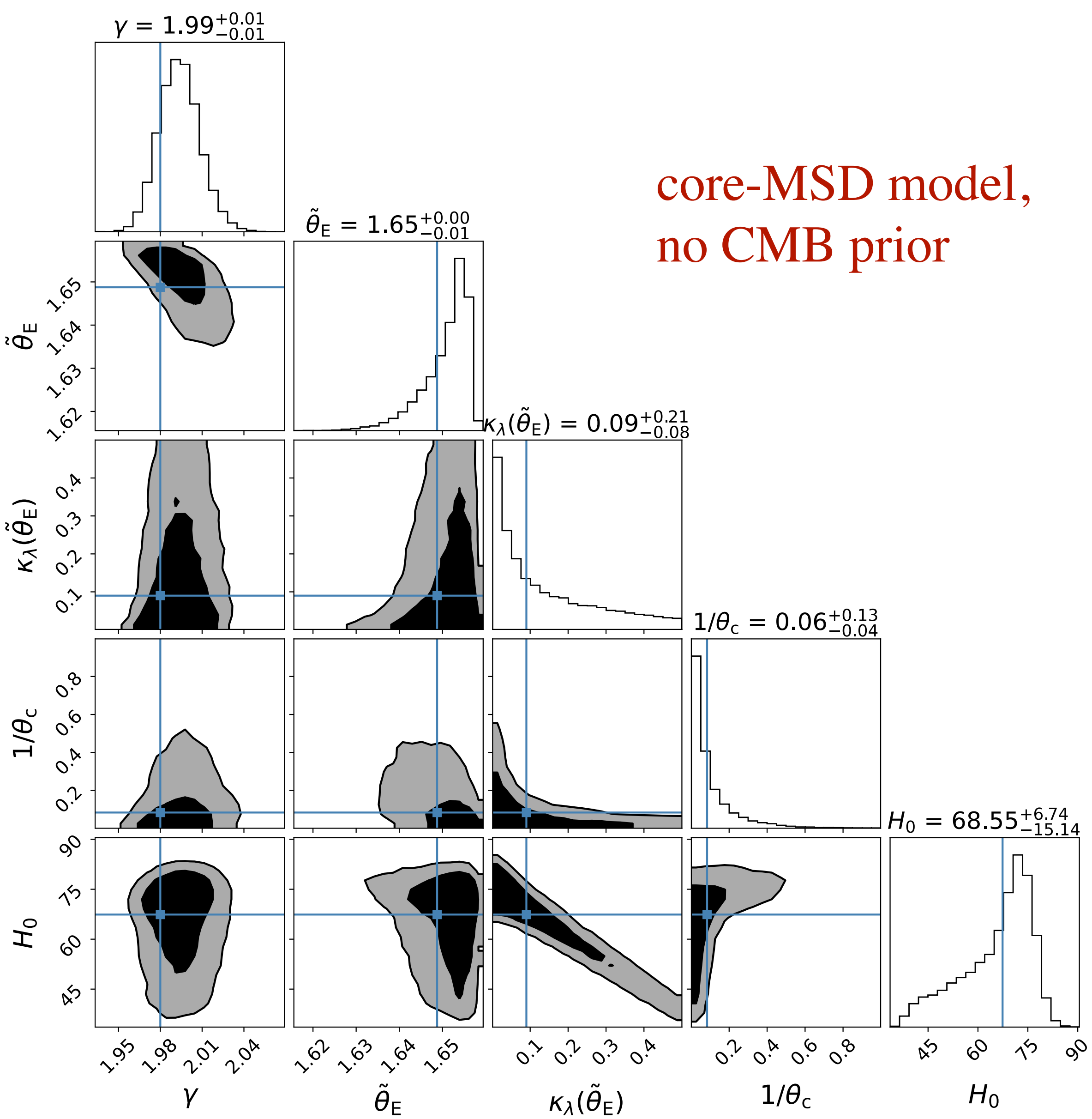
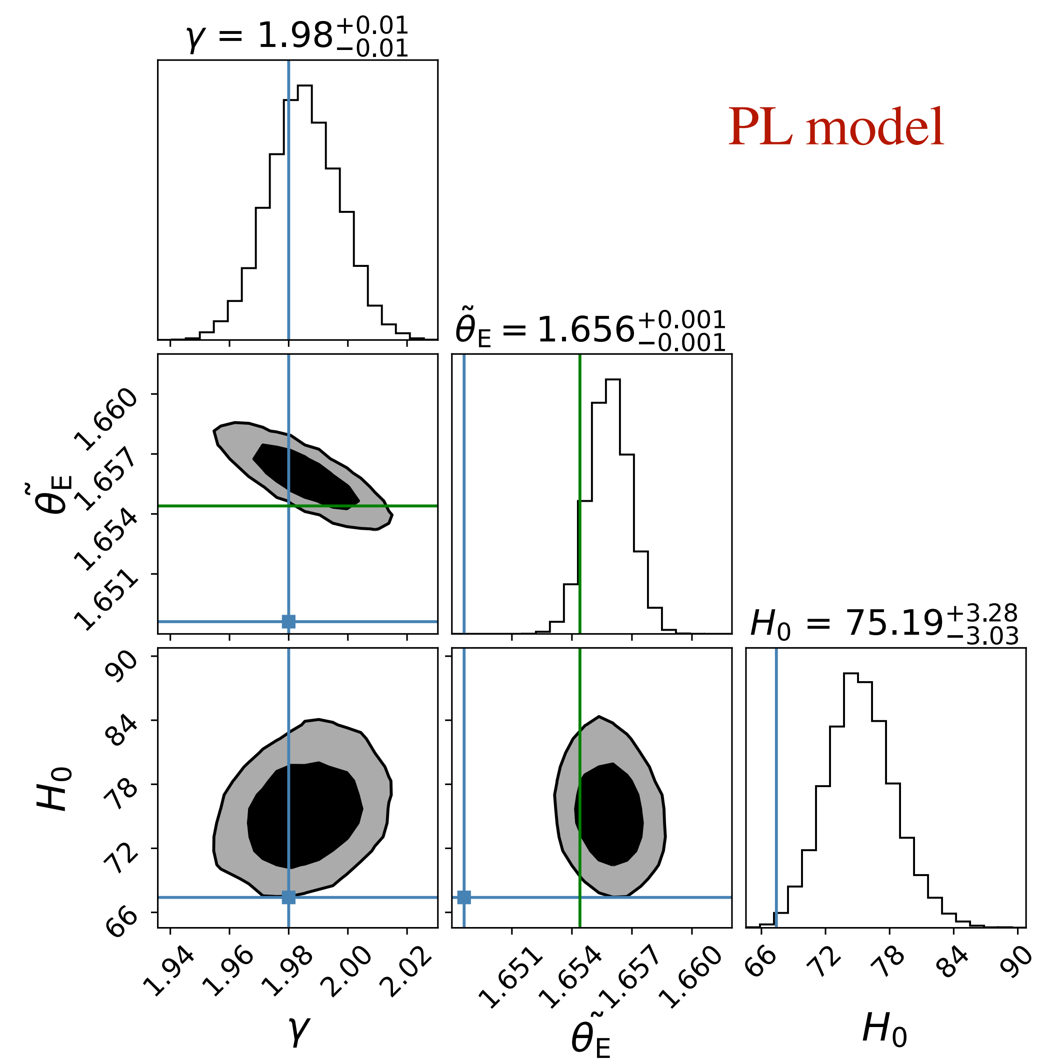


core-MSD model,
no CMB prior



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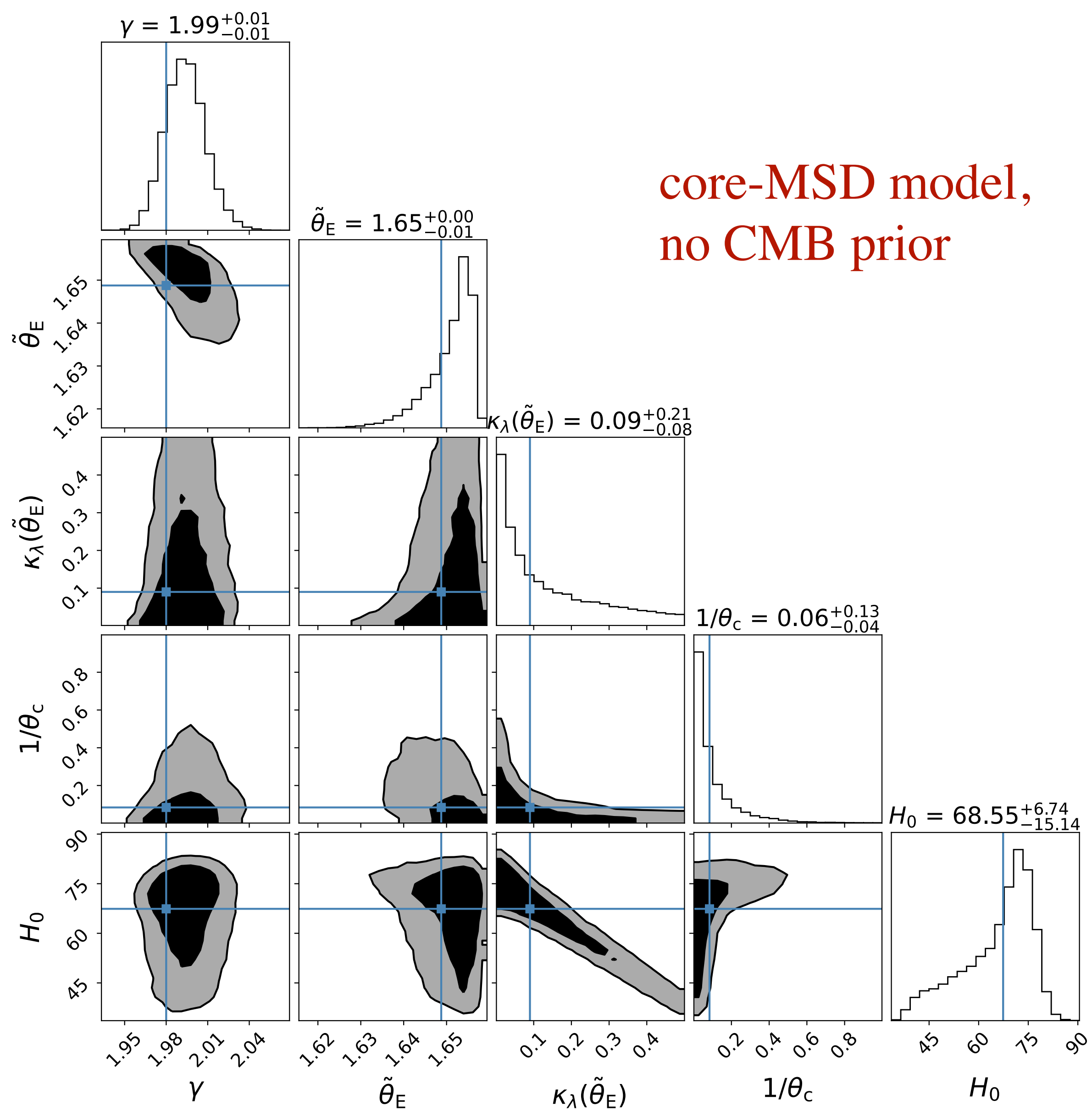

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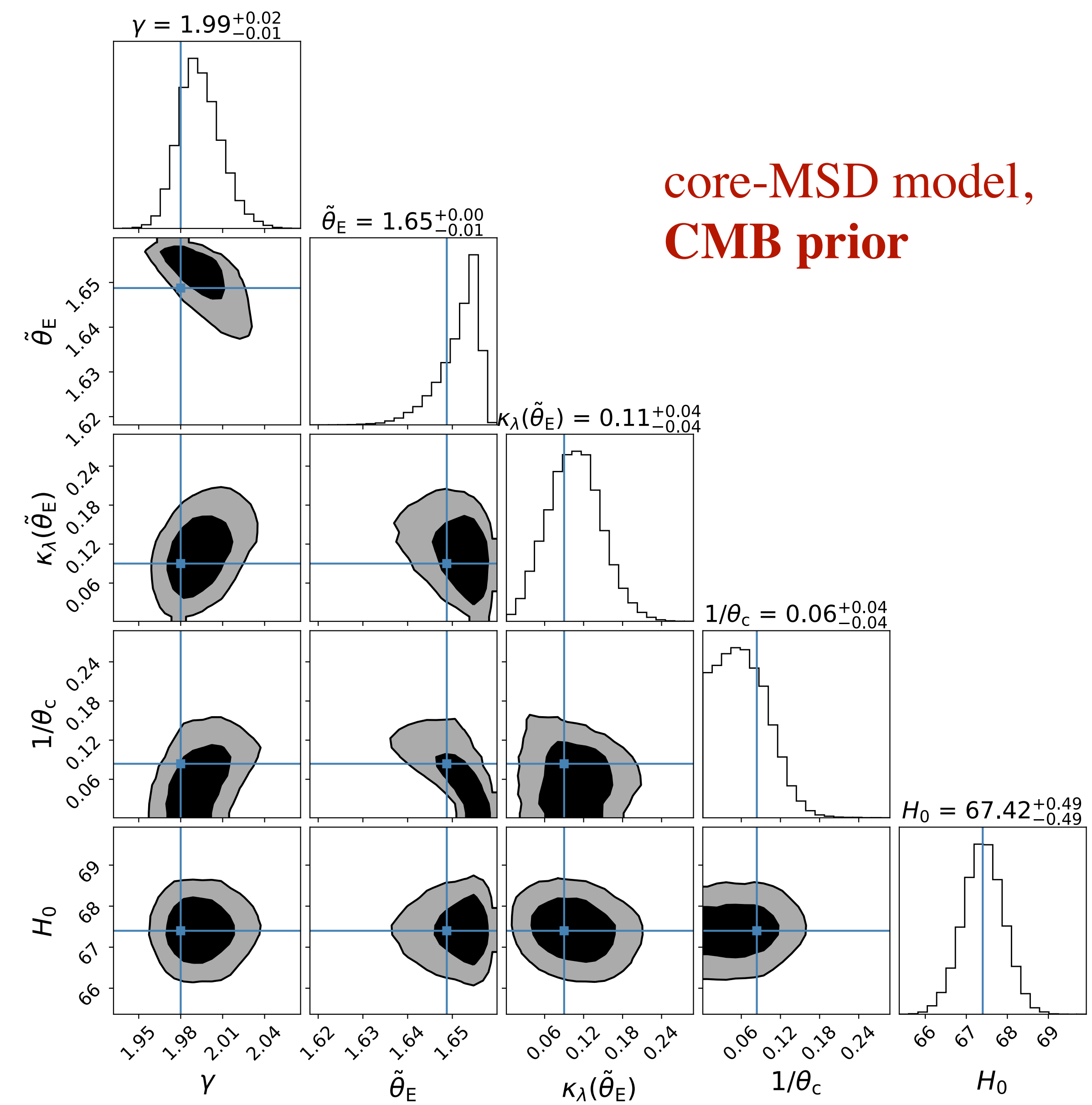

core-MSD model,
CMB prior

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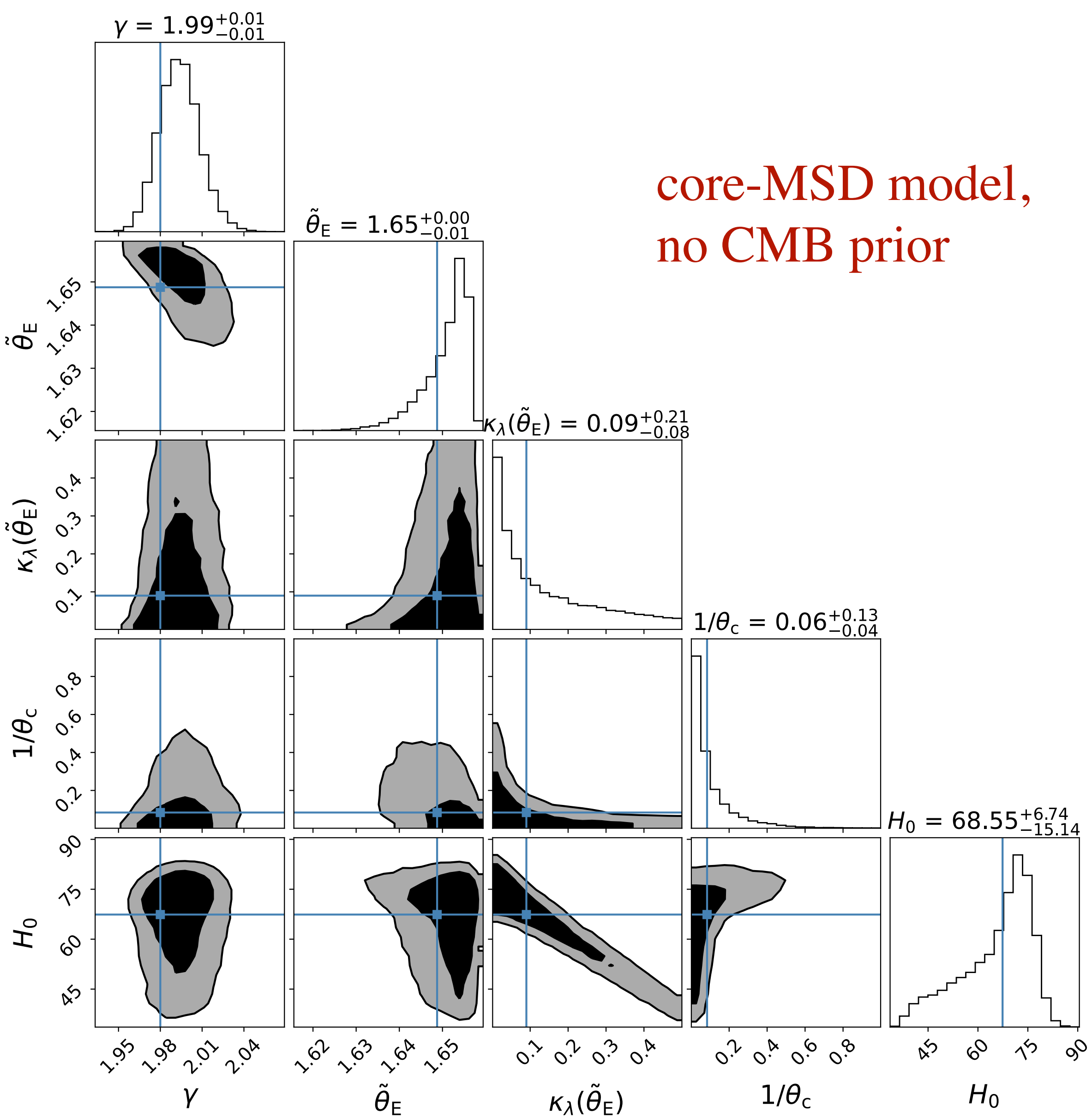
KB, Teodori, 2105.10873
Could reach >2σ *per system*



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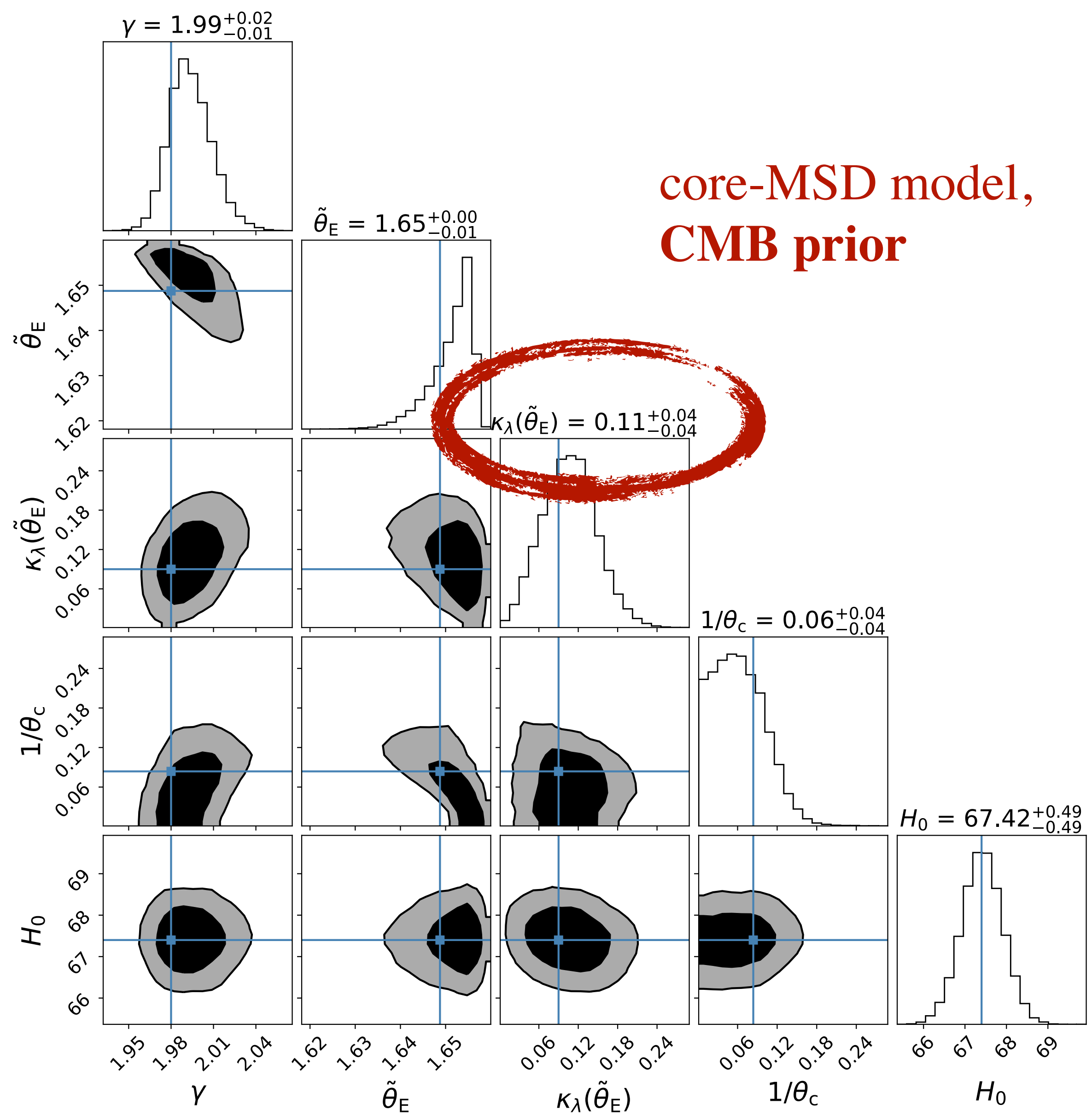

core-MSD model,
CMB prior

A step towards covering internal MSD (no CMB prior) :

Birrer et al 2020 (**TDCOSMO IV**)

Data sets	H_0 [km s^{-1}Mpc^{-1}]	$\lambda_{\text{int},0}$	α_λ	$\sigma(\lambda_{\text{int}})$	a_{ani}	$\sigma(a_{\text{ani}})$	$\sigma_{\sigma^{\text{P}},\text{sys}}$
TDCOSMO-only	$74.5^{+5.6}_{-6.1}$	$1.02^{+0.08}_{-0.09}$	$0.00^{+0.07}_{-0.07}$	$0.01^{+0.03}_{-0.01}$	$2.32^{+1.62}_{-1.17}$	$0.16^{+0.50}_{-0.14}$	-
TDCOSMO + $\text{SLACS}_{\text{IFU}}$	$73.3^{+5.8}_{-5.8}$	$1.00^{+0.08}_{-0.08}$	$-0.07^{+0.06}_{-0.06}$	$0.07^{+0.09}_{-0.05}$	$1.58^{+1.58}_{-0.54}$	$0.15^{+0.47}_{-0.13}$	-
TDCOSMO + $\text{SLACS}_{\text{SDSS}}$	$67.4^{+4.3}_{-4.7}$	$0.91^{+0.05}_{-0.06}$	$-0.04^{+0.04}_{-0.04}$	$0.02^{+0.04}_{-0.01}$	$1.52^{+1.76}_{-0.70}$	$0.28^{+0.45}_{-0.25}$	$0.06^{+0.02}_{-0.02}$
TDCOSMO + $\text{SLACS}_{\text{SDSS+IFU}}$	$67.4^{+4.1}_{-3.2}$	$0.91^{+0.04}_{-0.04}$	$-0.07^{+0.03}_{-0.04}$	$0.06^{+0.08}_{-0.04}$	$1.20^{+0.70}_{-0.27}$	$0.18^{+0.50}_{-0.15}$	$0.06^{+0.02}_{-0.02}$

KB, Castorina, Simonovic 2020

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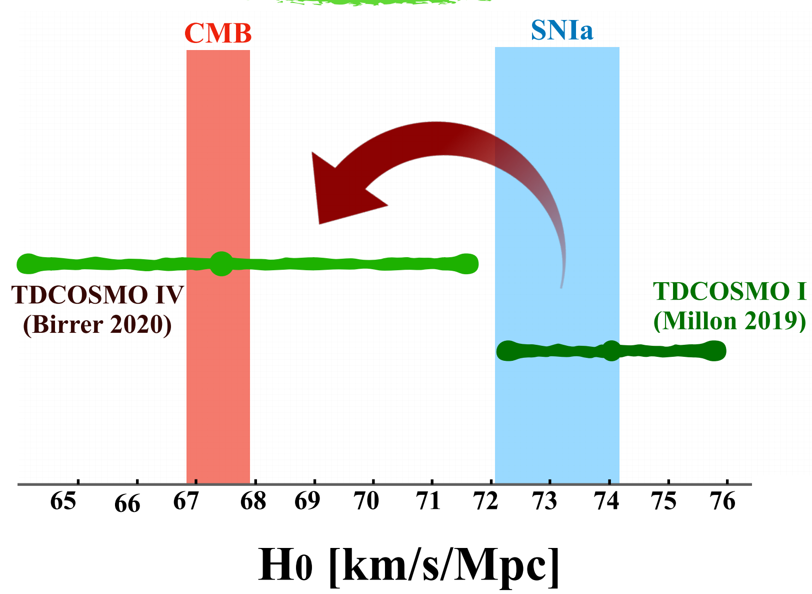

Hint from SLACS *kinematics?*

(but see comments in KB, Teodori, 2105.10873)

KB, Castorina, Simonovic 2020

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``Internal MSD” (and a CMB prior) may require a non-minimal density profile.

- Why would galaxies be non-minimal?
- Why should galaxies have a core component?

``Internal MSD" (and a CMB prior) may require a non-minimal density profile.

- Why would galaxies be non-minimal? ***Why not? (What is dark matter?)***
- Why should galaxies have a core component? ***Can think of several reasons.***

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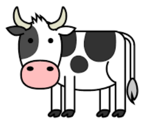
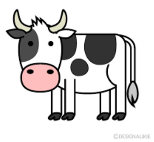
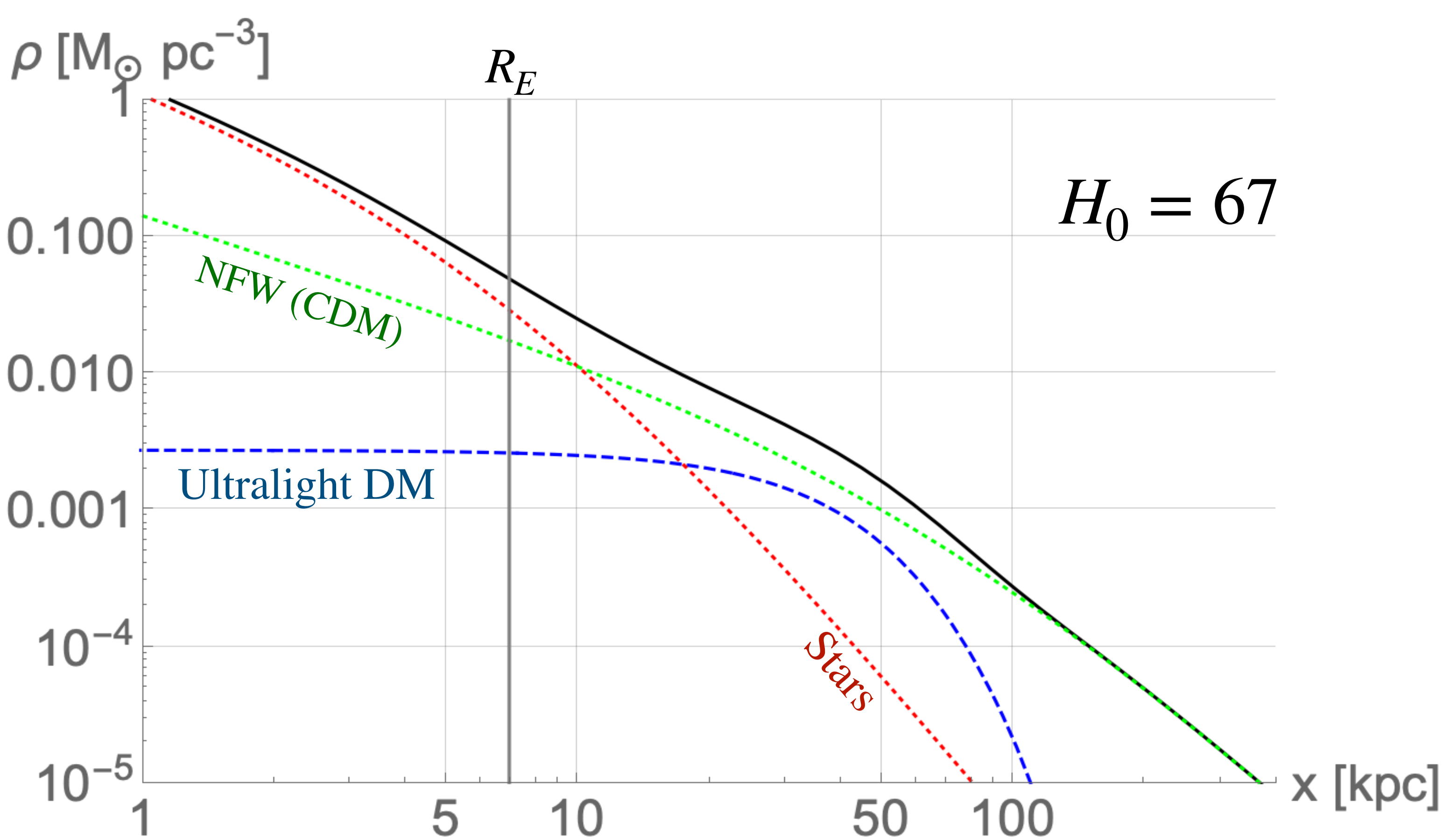


Why would galaxies be non-minimal? ***Why not? (What is dark matter?)***



Why should galaxies have a core component? ***Can think of several reasons.***

Dark matter not boring NFW? …a little bit of **ultralight dark matter?**



KB, Teodori, 2105.10873

20 % of total DM, $m = 2.5 \times 10^{-25}$ eV

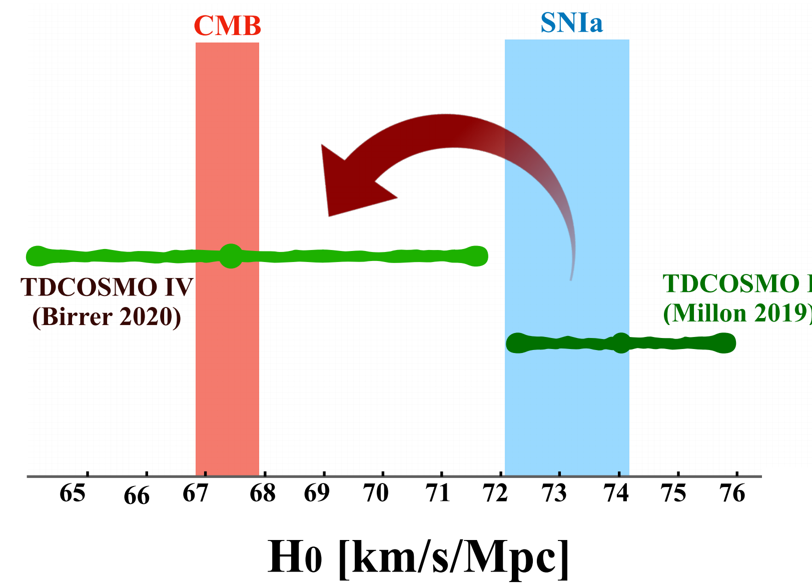
Dynamical relaxation consistent at O(1).
Cosmology OK.

Summary

Lensing H0 sensitive to galaxy profile at few % level:
Unexpected feature in the galaxy profile,
or fundamental breakdown of ΛCDM ?

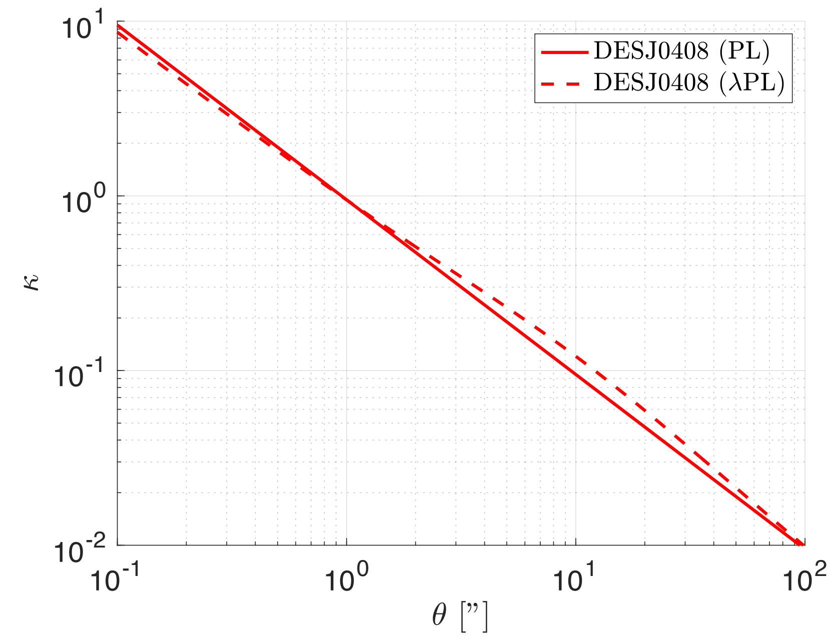
Weak lensing: include all segments of line of sight.
Lacking in published results. Likely few % bias on H0.

Teodori, et al, 2201.05111



Adding a core to a density profile is an approximate MSD.
10% core solves the lensing H0 tension?

KB, Castorina, Simonović 2001.07182

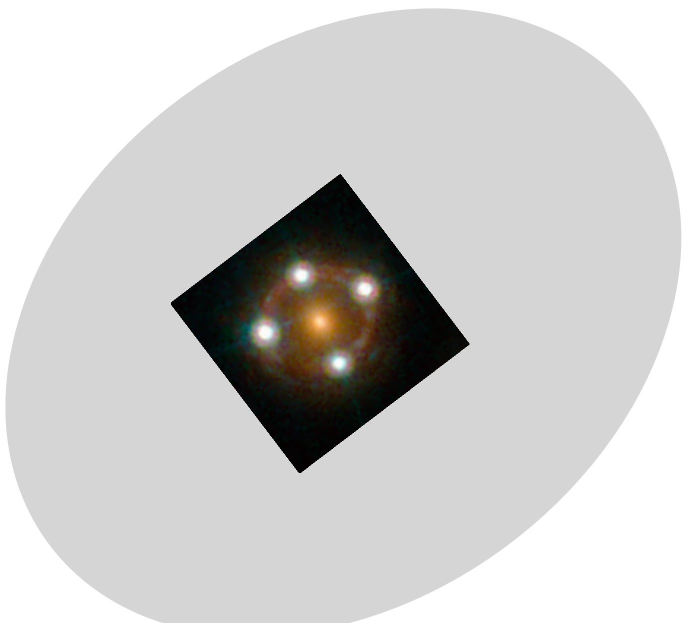


Could point to interesting dark matter dynamics.
If we go there, may as well adopt CMB (*or SNIa!*) prior on H0.

Ultralight DM (axion-like):

Vanilla vacuum misalignment. Dynamically makes a core.
Correct ballpark to solve lensing H0 tension, if 10^{-25} eV $\lesssim m \lesssim 10^{-24}$ eV
Dynamical relaxation consistent at O(1) level.

KB, Teodori 2105.10873



Thank you!

Xtra

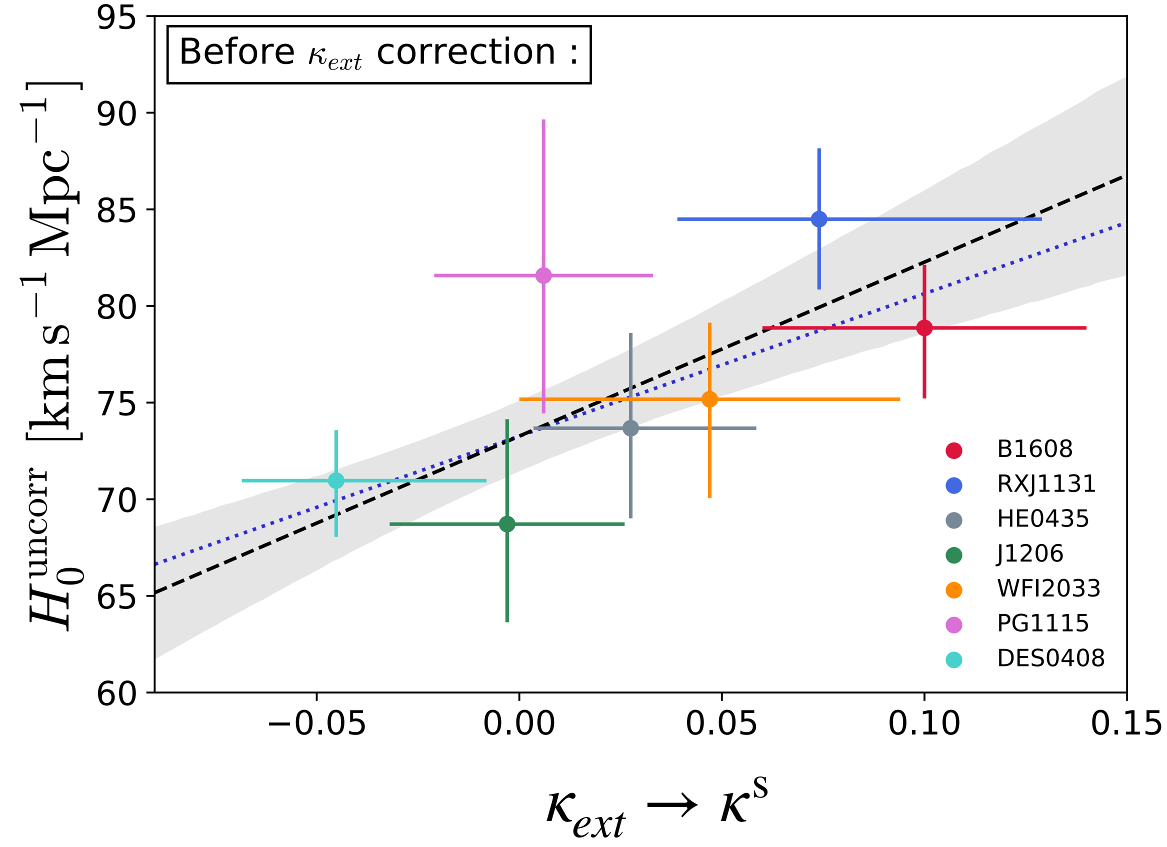
Weak lensing degeneracy:

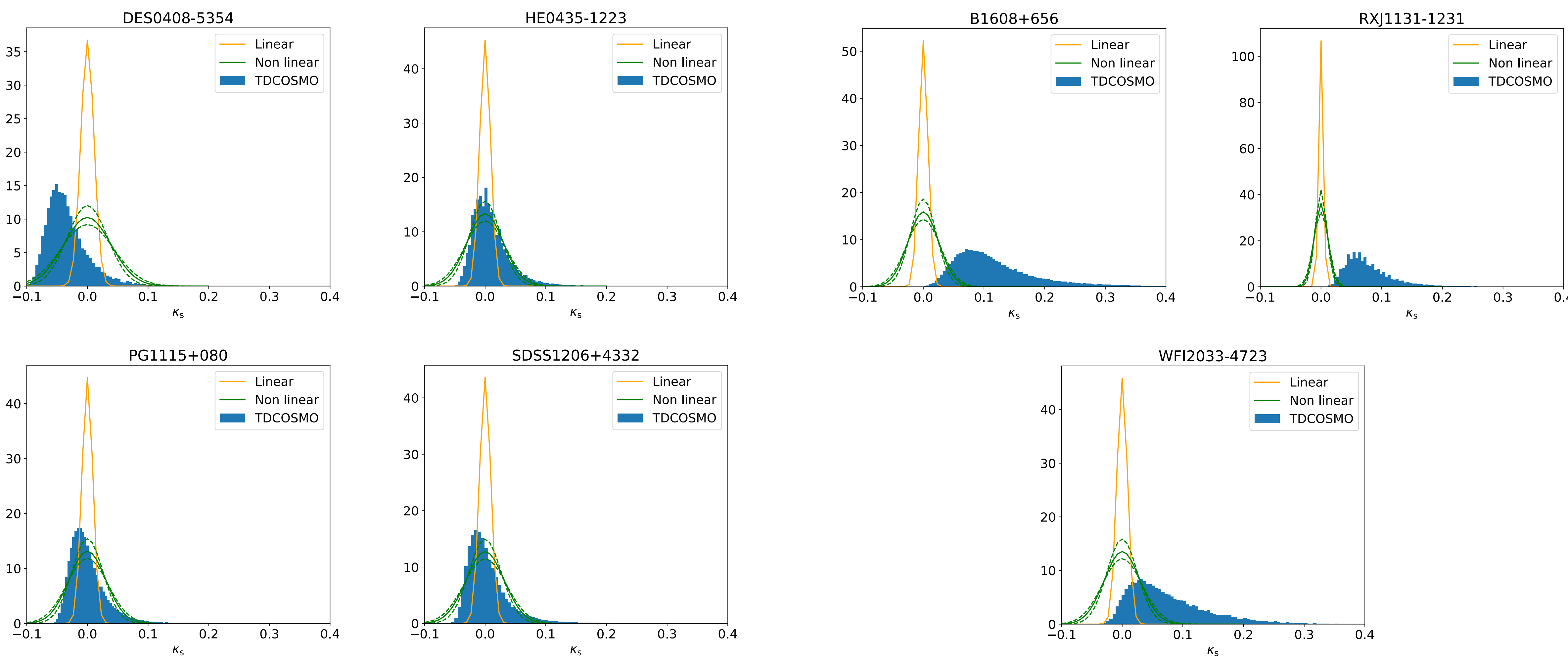
$$H_0^{\text{uncorr}} = \frac{1-\kappa^{\text{ls}}}{1-\kappa^{\text{l}}}\,\frac{1}{1-\kappa^{\text{s}}}\,H_0$$

Weak lensing correction in H0LiCOW / TDCOSMO is probably *a little bit* off.

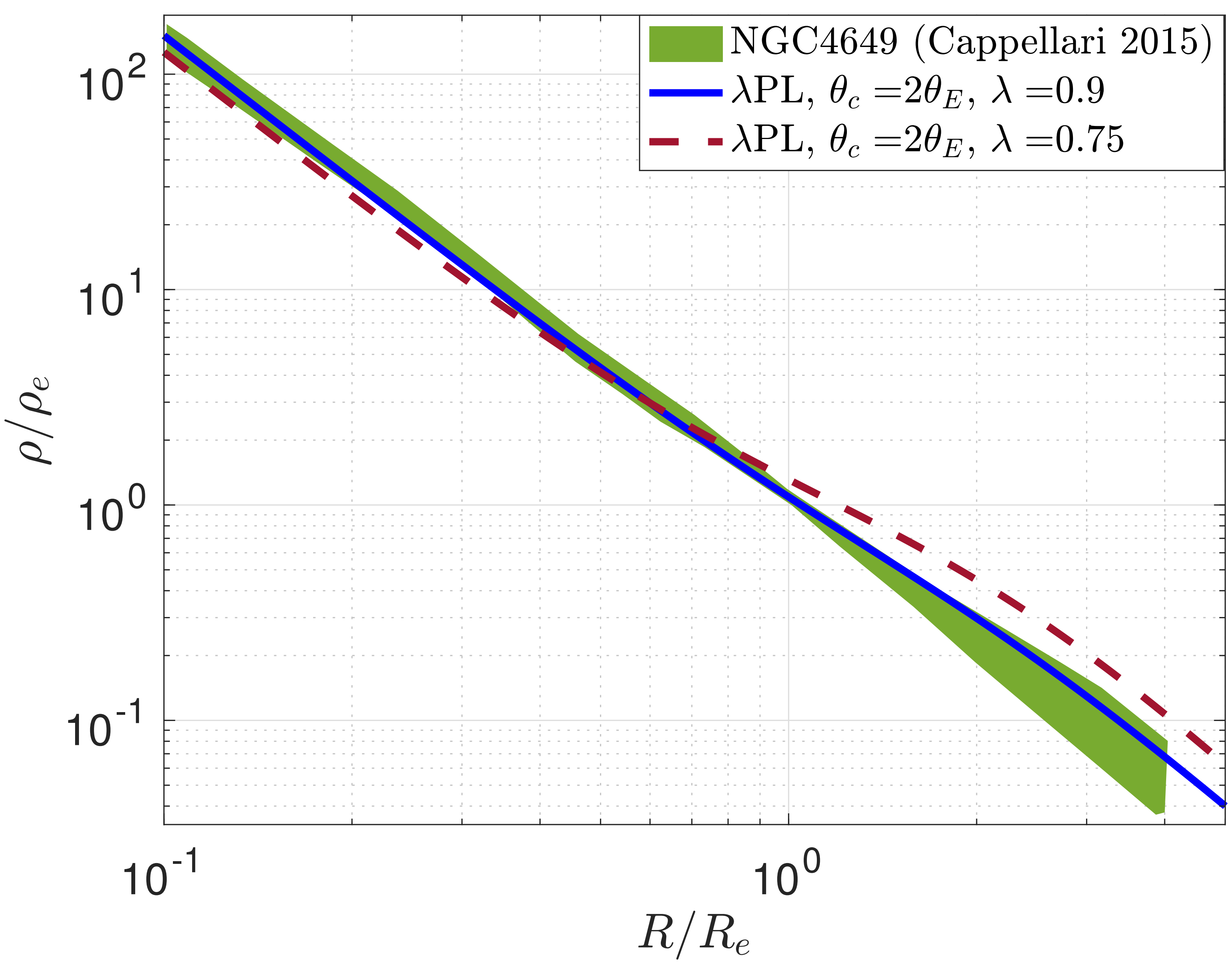
Birrer et al, 2007.02941 (TDCOSMO IV)
Teodori, et al, 2201.05111

Millon et al, 1912.08027 **(TDCOSMO I)**





Stellar kinematics (of *other* elliptical galaxies)

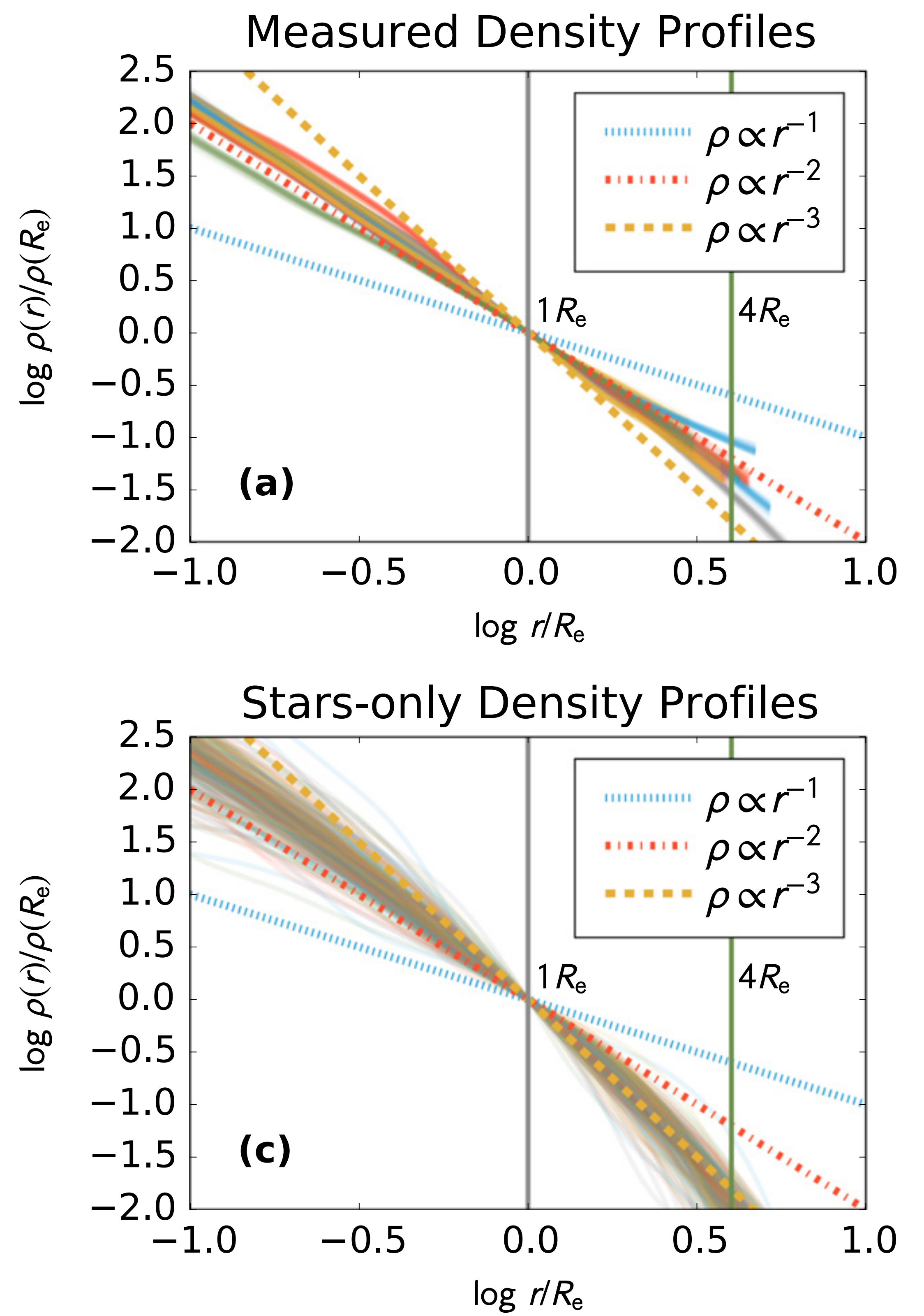


Stellar kinematics (of *other* elliptical galaxies)

Cappellari et al, 1504.00075

$$\rho_{\rm DM}(r) = \rho_s \left(\frac{r}{r_s}\right)^{\alpha} \left(\frac{1}{2} + \frac{1}{2}\frac{r}{r_s}\right)^{-\alpha-3}. \quad (3)$$

Our models have seven free parameters. Some are poorly constrained but are not of interest here. They are just "nuisance parameters," marginalized out to derive the total mass profiles studied here. The parameters are (i) the inclination i; (ii) the anisotropy $\beta_z \equiv 1 - \sigma_z^2/\sigma_R^2$, with σ_z and σ_R the stellar dispersion in cylindrical coordinates, for the MGE Gaussians with $\sigma_j < R_e$; (iii) the anisotropy for the remaining Gaussians at larger radii; (iv) the stellar $(M/L)_{\rm stars}$; (v) the break radius of the dark halo, constrained to be $10 < r_s < 50$ kpc; (vi) the halo density ρ_s at r_s; and (vii) the dark halo slope α for $r \ll r_s$.



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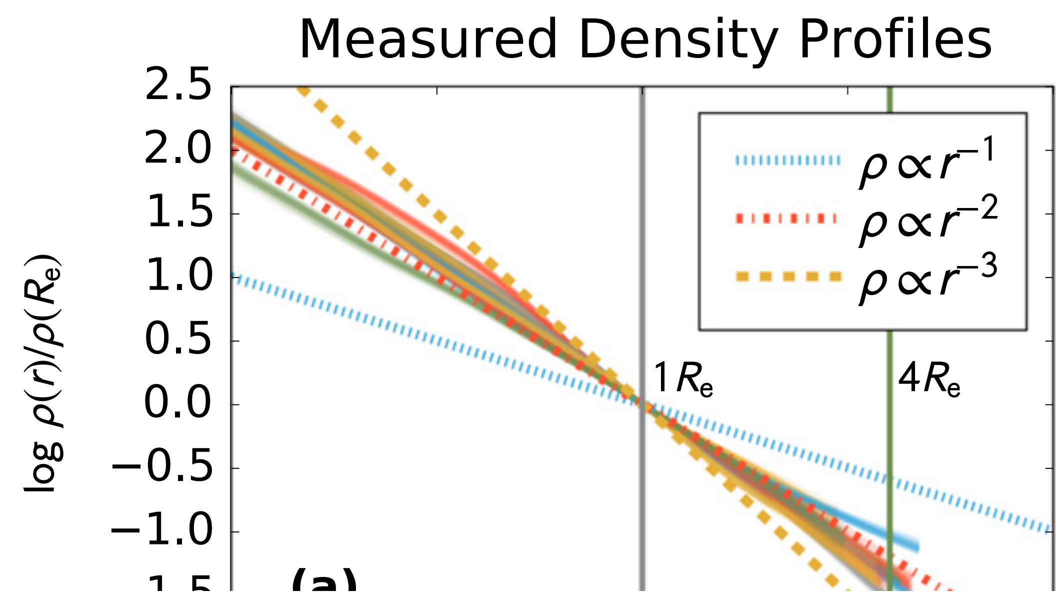
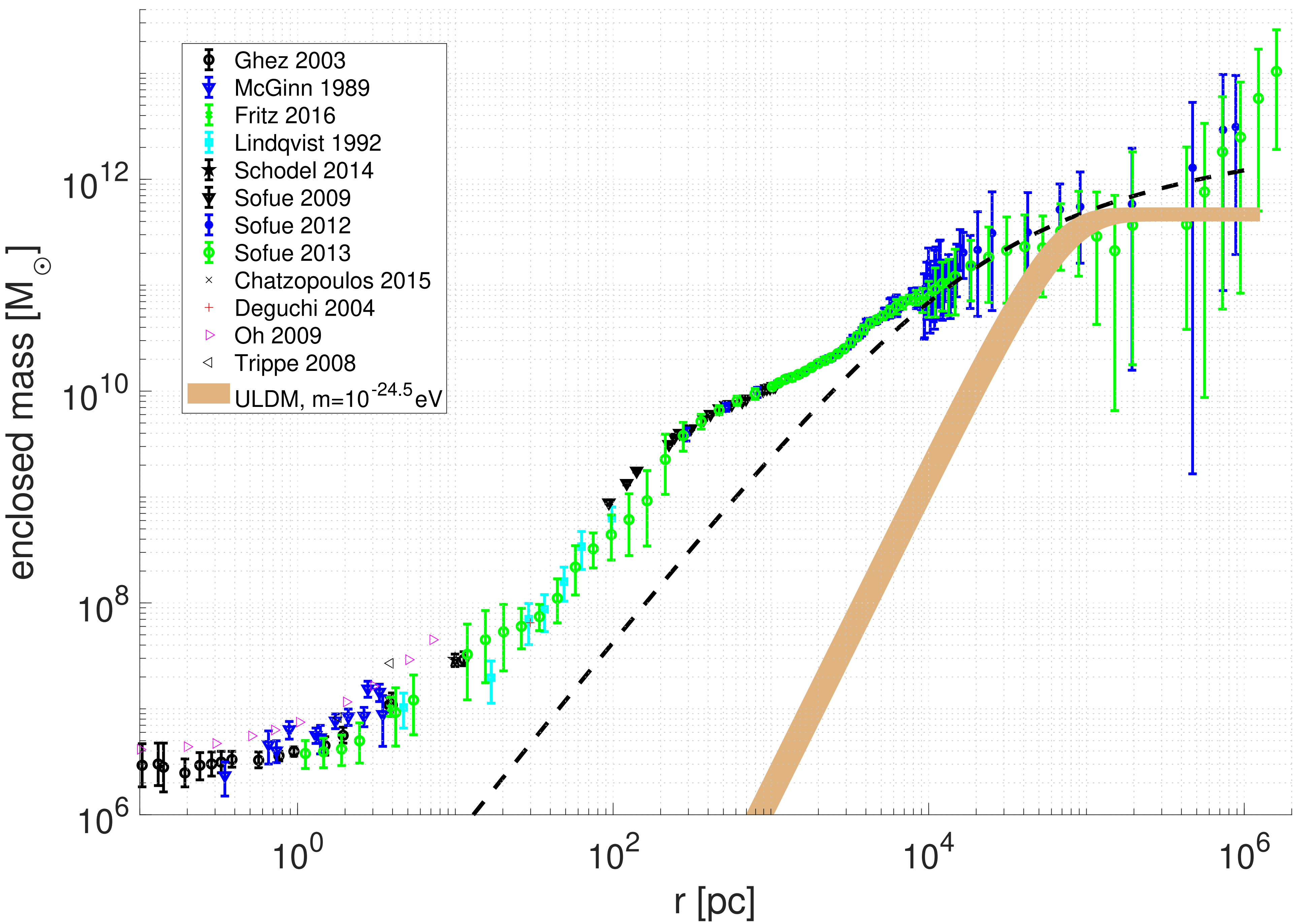


A friend:

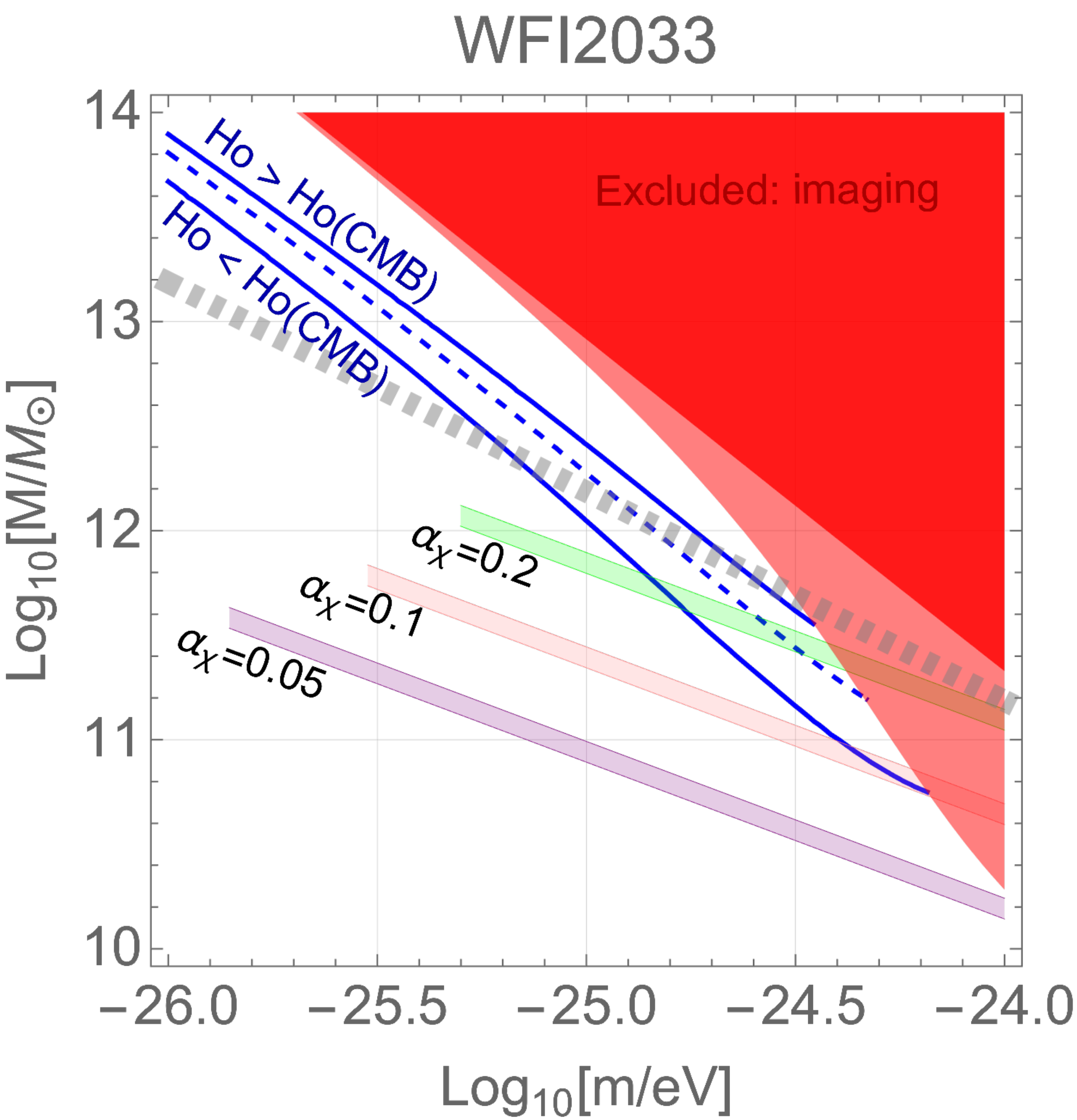
...a cored structure of the kind you propose would be difficult to exclude from measurements of the stellar kinematics. Part of the reason is the mass profile-velocity anisotropy degeneracy. Another part is simply that no one has tried: most modelers fit the system to a small number of components (stars, gas, dark matter, central black hole) with constant mass-to-light ratio and none of these look like the core you propose. It would be straightforward for some of the modelers to try adding cores.

I suppose some critics will say that your **cores are ad hoc**, but I think they are **less ad hoc than most of the modifications to cosmology needed to explain the Hubble discrepancy!**

Stellar kinematics (of *other* galaxies, e.g., Milky Way)



Ultralight DM as a solution of the lensing H0 tension:



Dynamical relaxation consistent at O(1), can become a bottleneck:

$$\tau \sim \frac{\sqrt{2}}{12\pi^3}\frac{m^3\sigma^6}{G^2\rho^2\ln\Lambda}$$

(But see Eggemeier, Niemeyer 2019, Chen et al 2020, Schwabe et al 2020; for effect of background density.)

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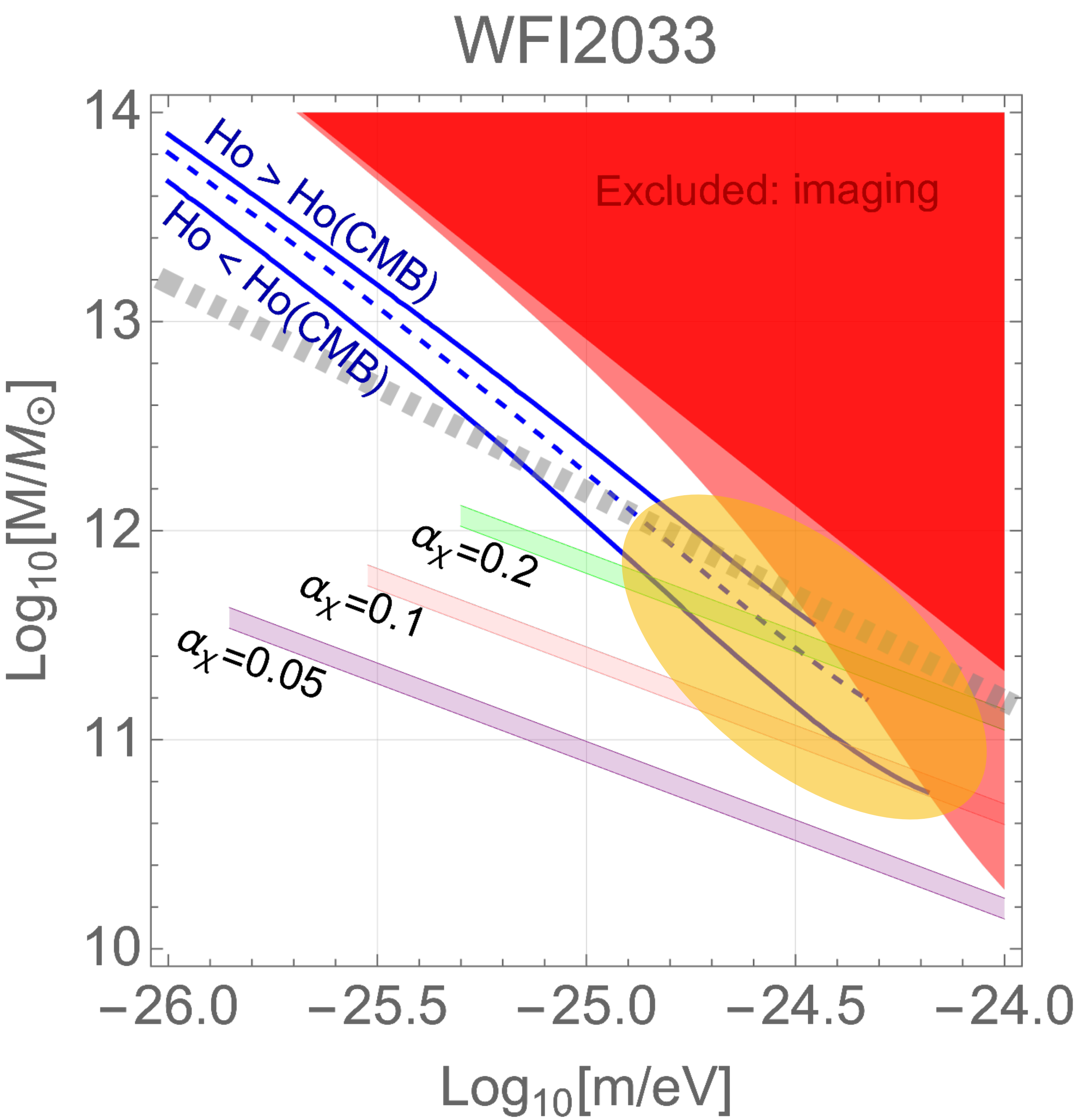

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E. Di Valentino et al 2103.01183

H0 tension