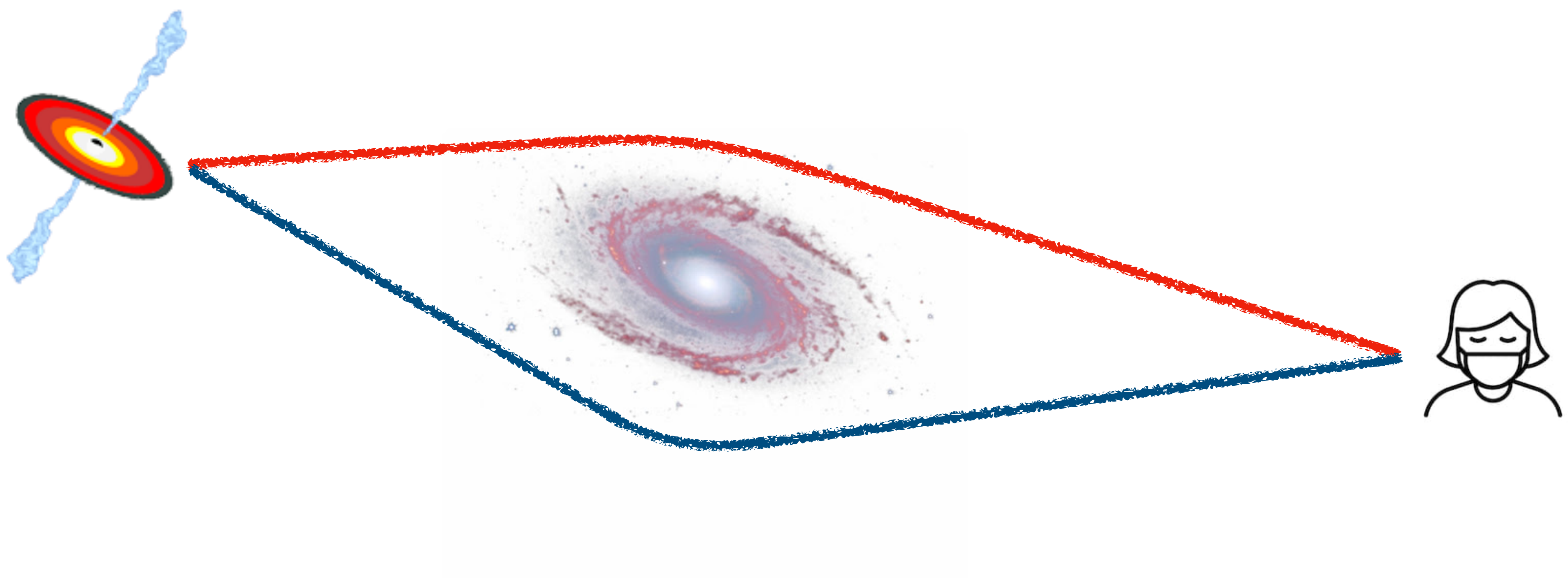
Gravitational lensing measurements of the Hubble parameter: challenges and opportunities

Kfir Blum (Weizmann Institute)

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



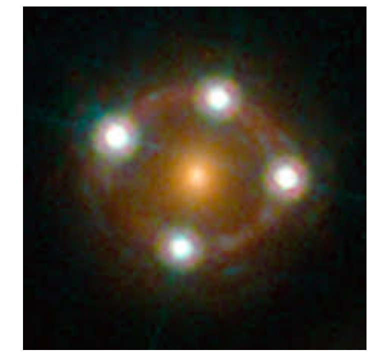
BCCP March 1 2022

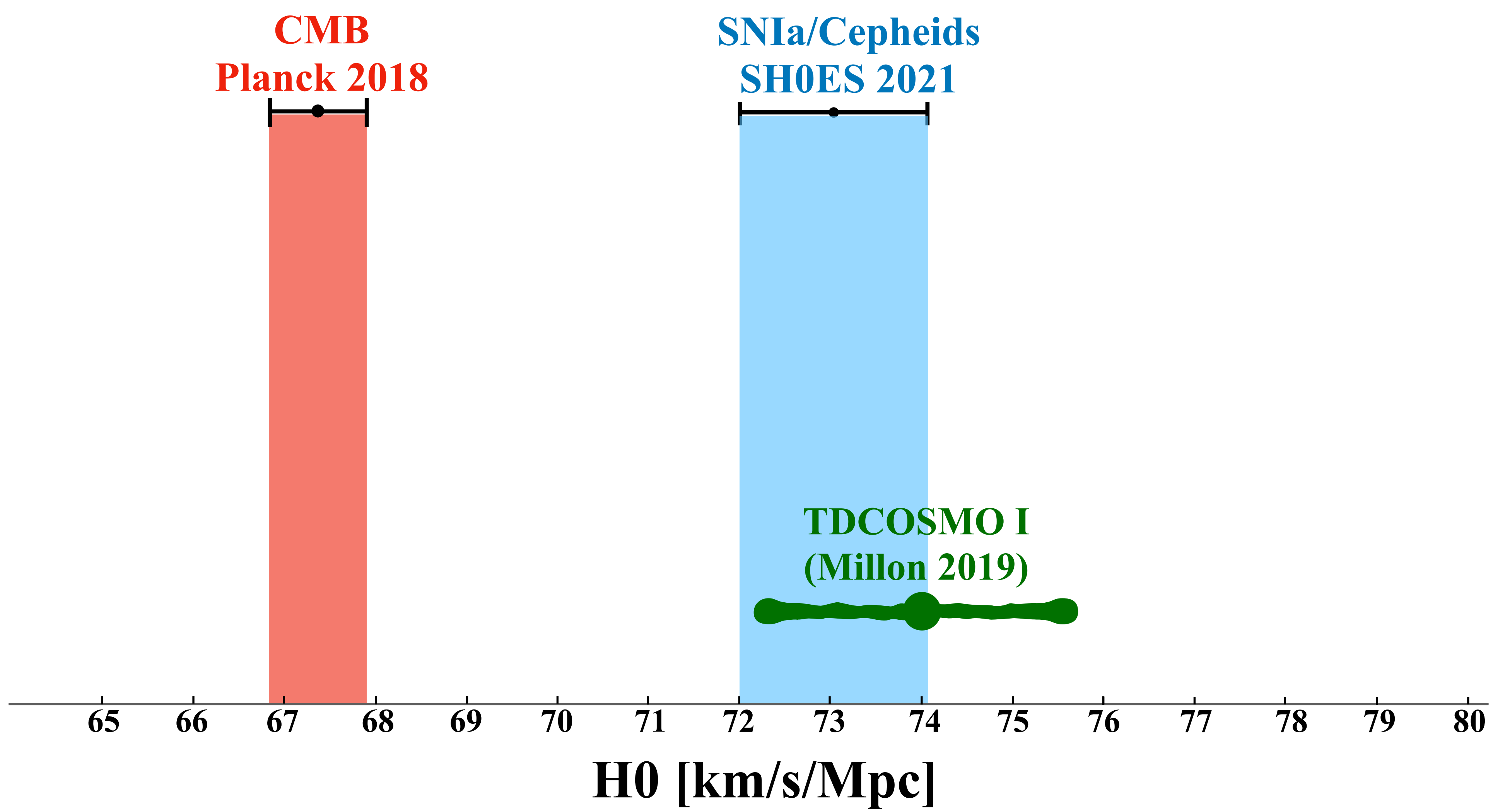
H0 tension

SNIa and **gravitational lensing agree?**

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

- H0LiCOW
- COSMOGRAIL
- STRIDES
- SHARP
- COSMICLENS





H0 tension

SNIa and **gravitational lensing** ***dis*****agree?**

…lensing out of the game?

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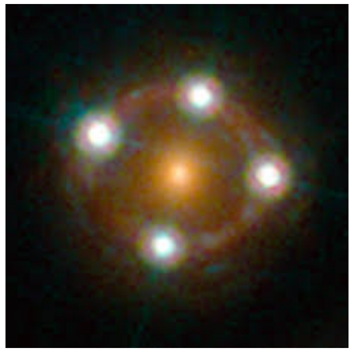
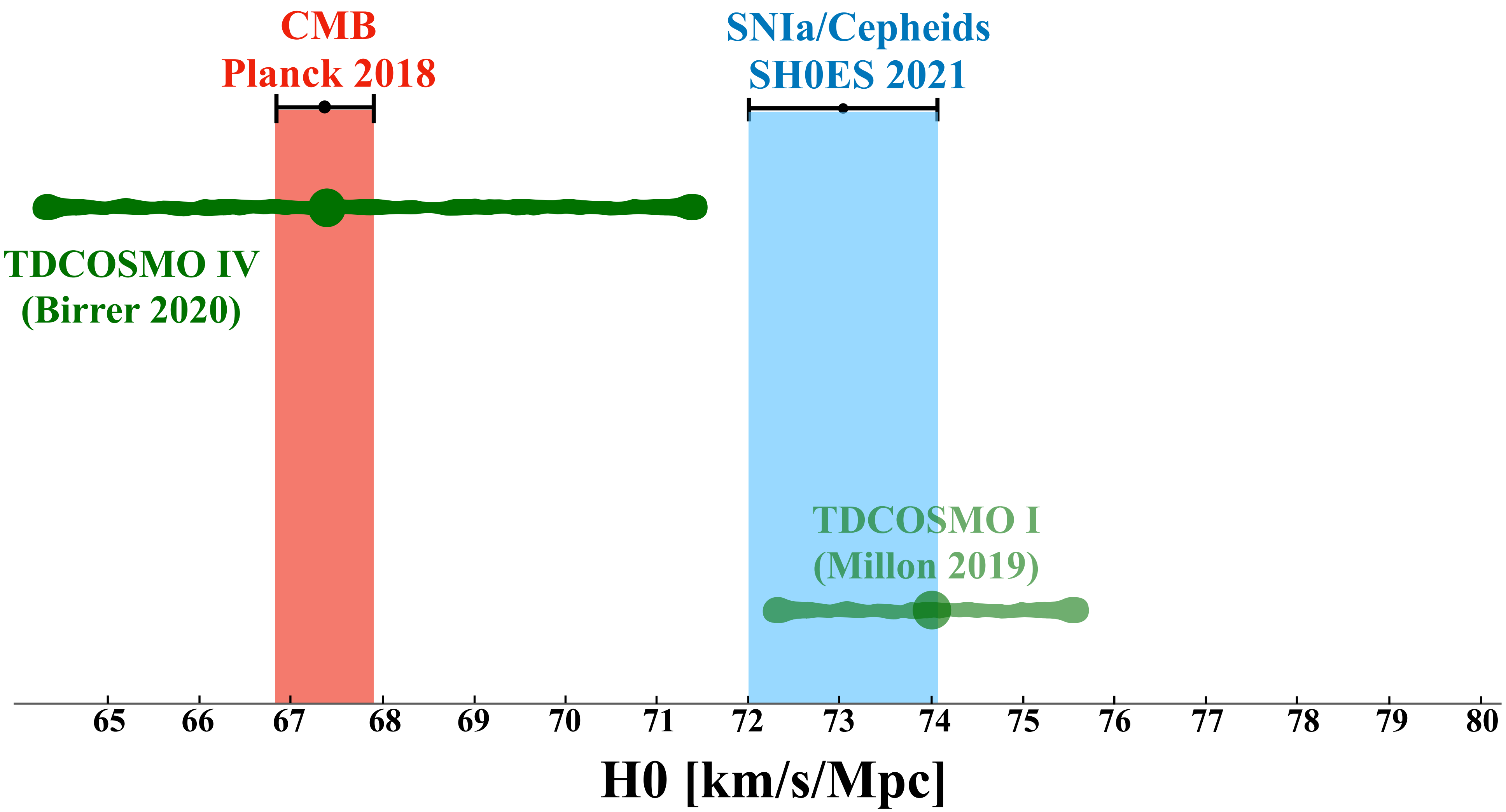
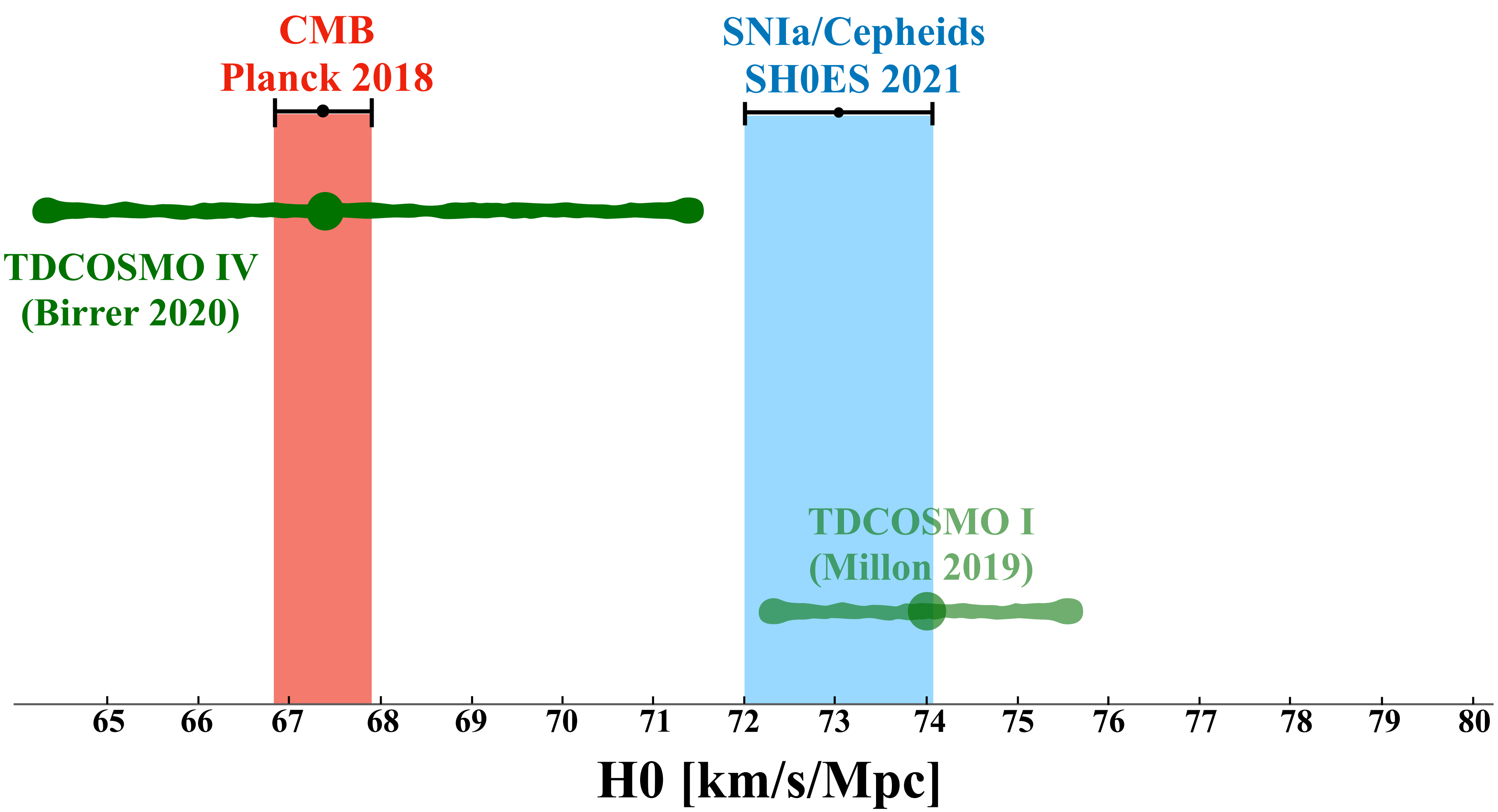




Plan:

1. Recap: how lensing measures H0
2. Challenges: modeling degeneracy (TDCOSMO I —> IV)
3. Opportunities: galactic structure



Plan:

1. Recap: how lensing measures H_0
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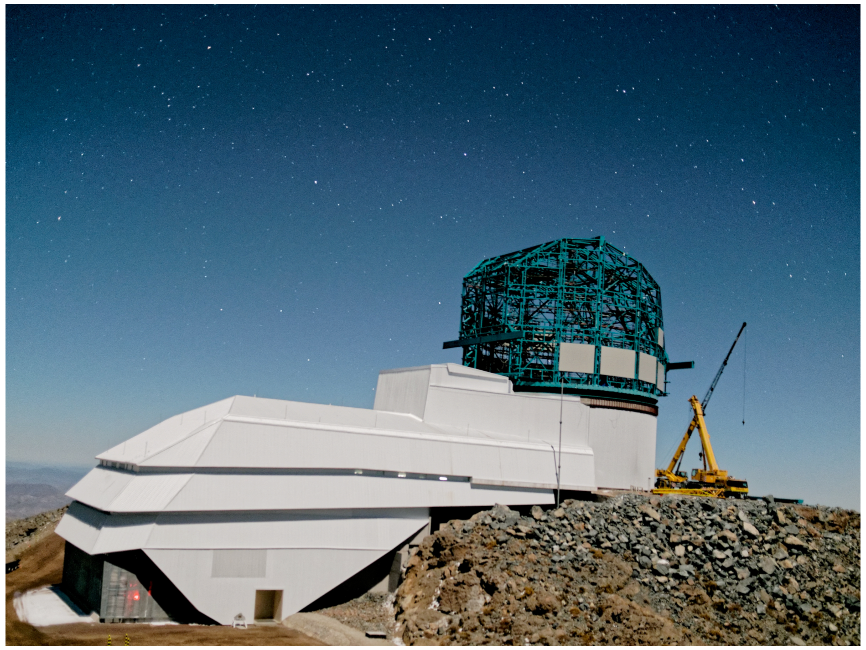
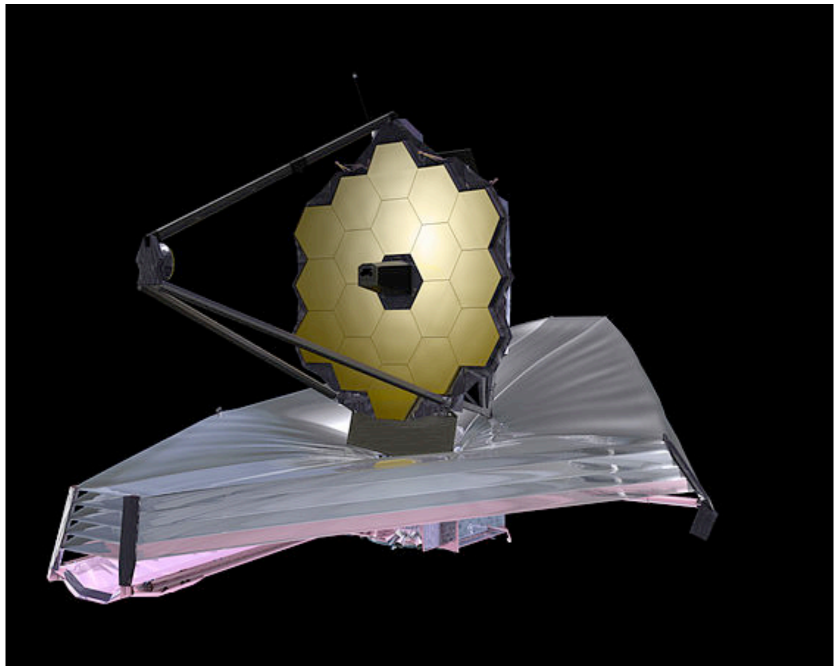
3. **Opportunities: galactic structure**

LSST: 100's of strongly lensed variable quasars
Oguri, Marshall, 1001.2037



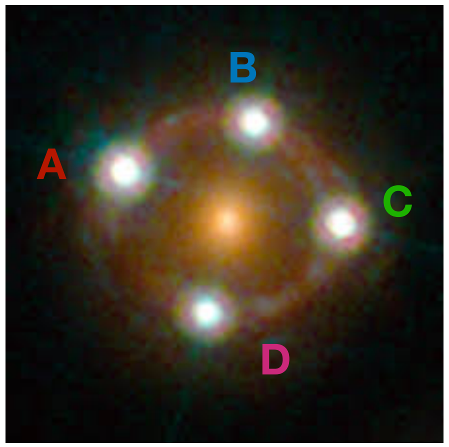
JWST: improved kinematics
Yıldırım, Suyu, Halkola, 1904.07237
Birrer, Treu, 2008.06157



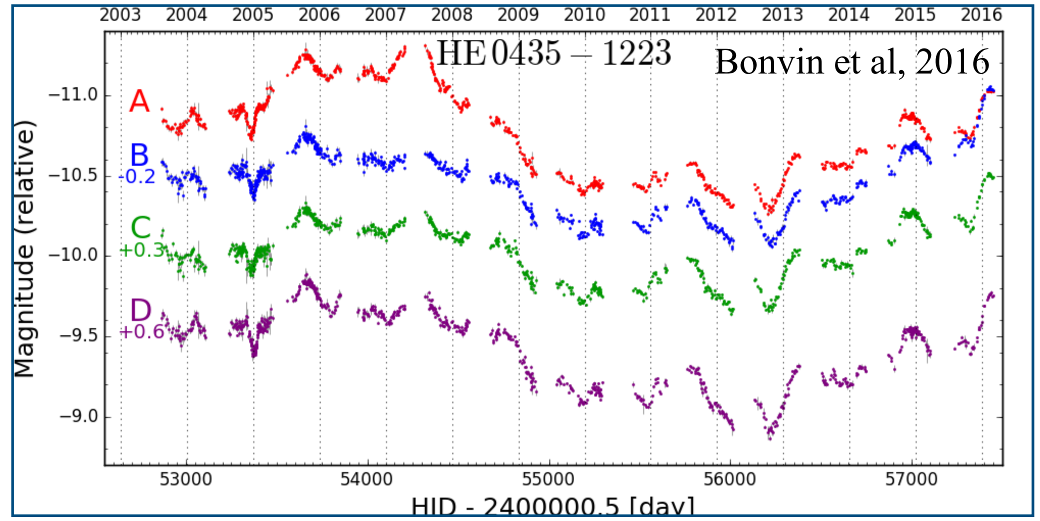
1. Recap: how lensing measures H0

Observables:

- Extended source image



- Time delay Δt



1. Recap: how lensing measures H0

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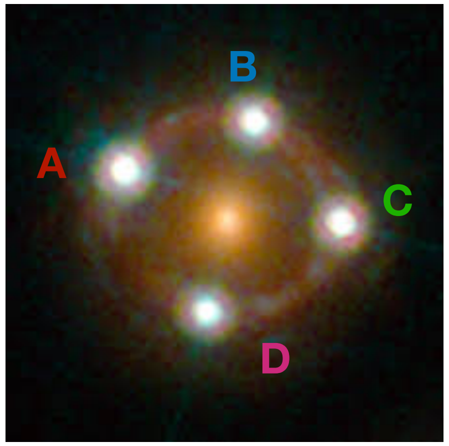
$$\vec{\theta} = \vec{\beta} + \vec{\alpha}(\vec{\theta})$$



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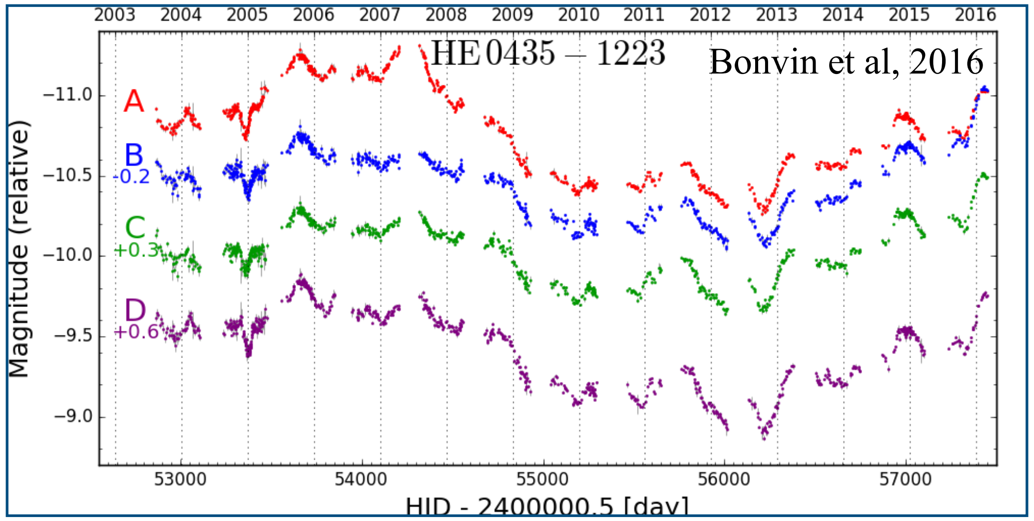
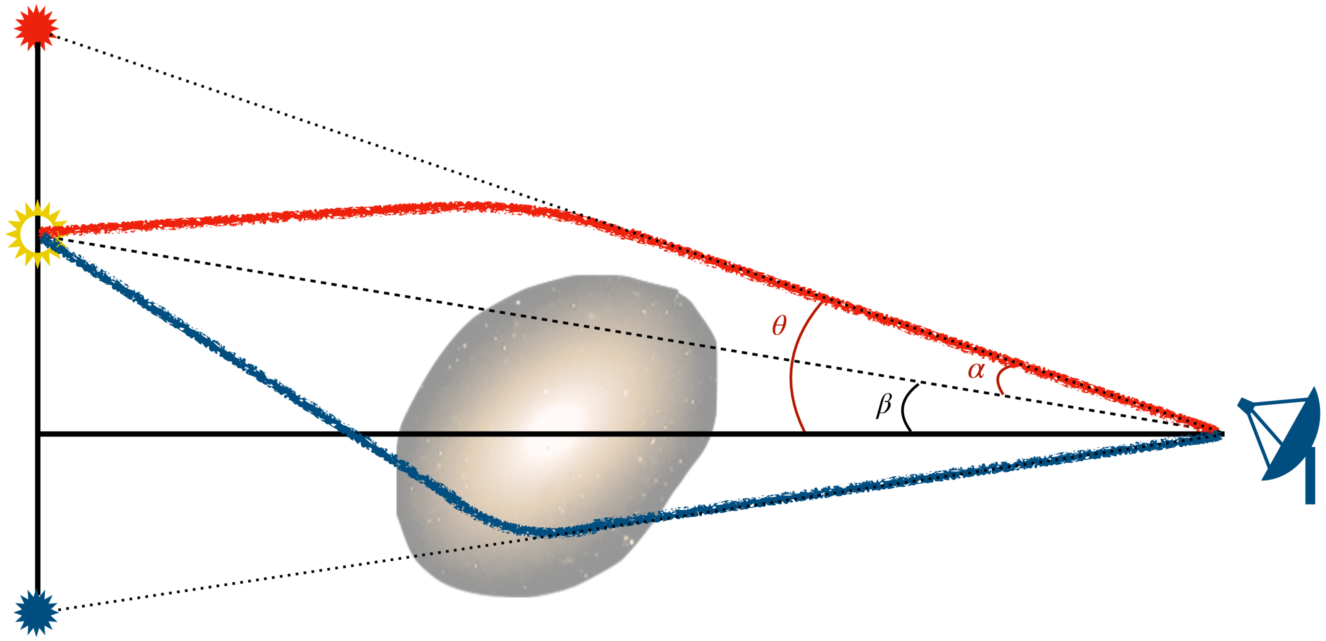


$$\kappa(\vec{\theta}) = \frac{\Sigma(\vec{\theta})}{\Sigma_{\mathrm{crit}}} = \frac{1}{2}\vec{\nabla}_{\theta}\cdot\vec{\alpha} = \frac{1}{2}\vec{\nabla}^2_{\theta}\psi$$

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



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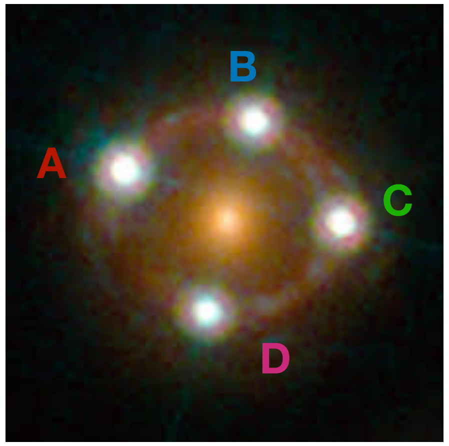
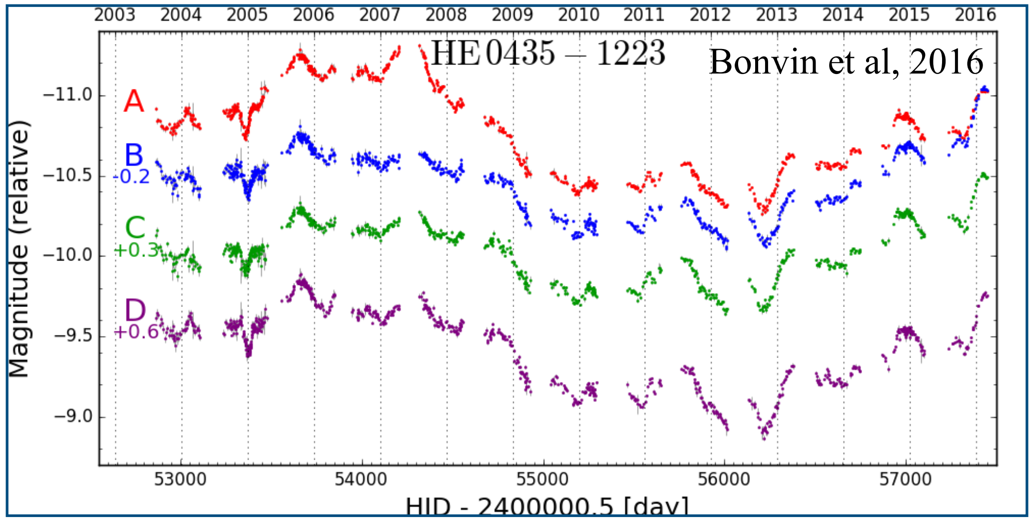


- Time delay $\Delta t_{AB} = D_{\Delta t}\,\Delta\tau_{AB}$



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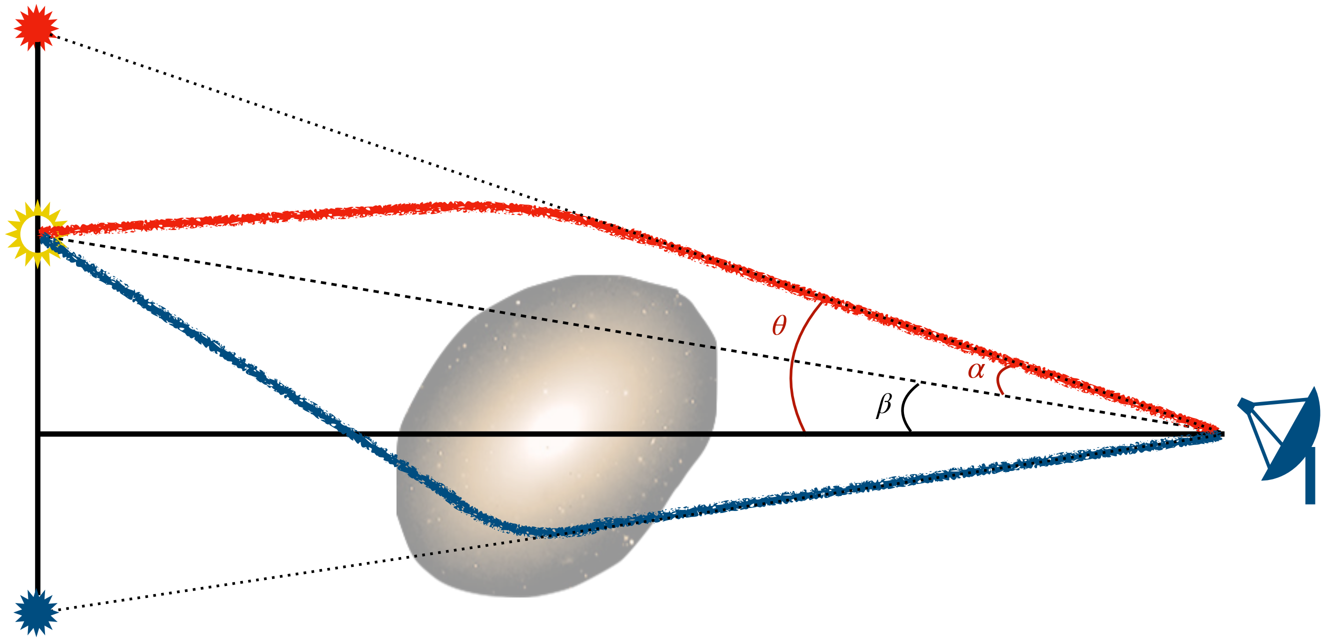
$$\Sigma_{\rm crit} = \frac{d_A(z_s,0)}{4\pi G\, d_A(z_l,0) d_A(z_s,z_l)}$$

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



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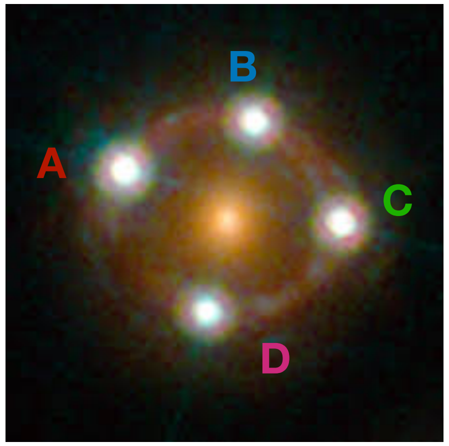

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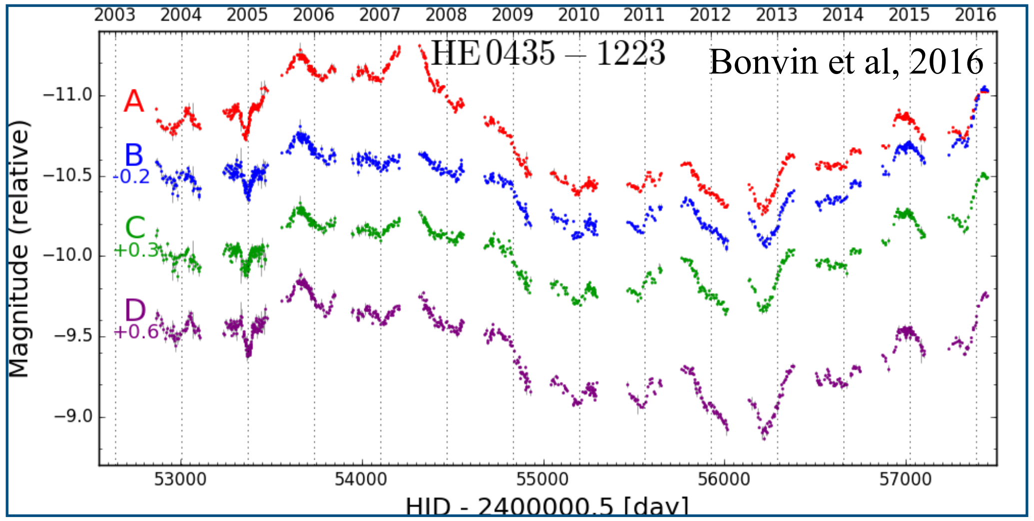

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1. From the image, reconstruct a model $\kappa(\vec{\theta}),\ \vec{\beta} \ \rightarrow\ \tau(\vec{\theta})$
2. Given the model and Δt, extract $D_{\Delta t} = \frac{\Delta t}{\Delta \tau} \propto \frac{1}{H_0}$

2. Challenges: modeling degeneracy

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

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

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$$
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$$

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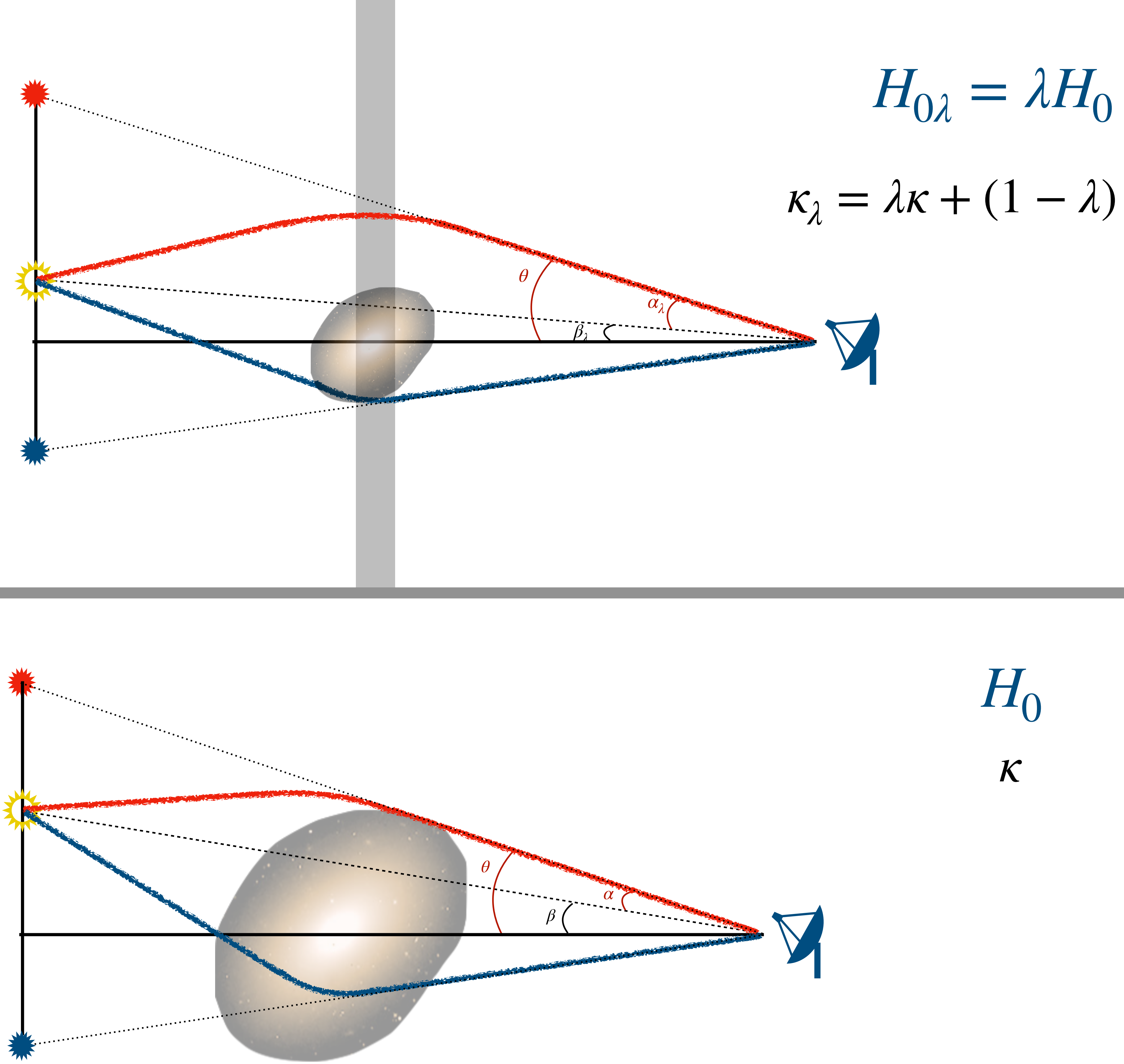
$$\tau(\vec{\theta}) = \frac{\vec{\theta}^2}{2} - \vec{\beta}\cdot\vec{\theta} - \psi(\vec{\theta})$$

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

$$\vec{\nabla}_\theta \tau(\vec{\theta}) = 0$$

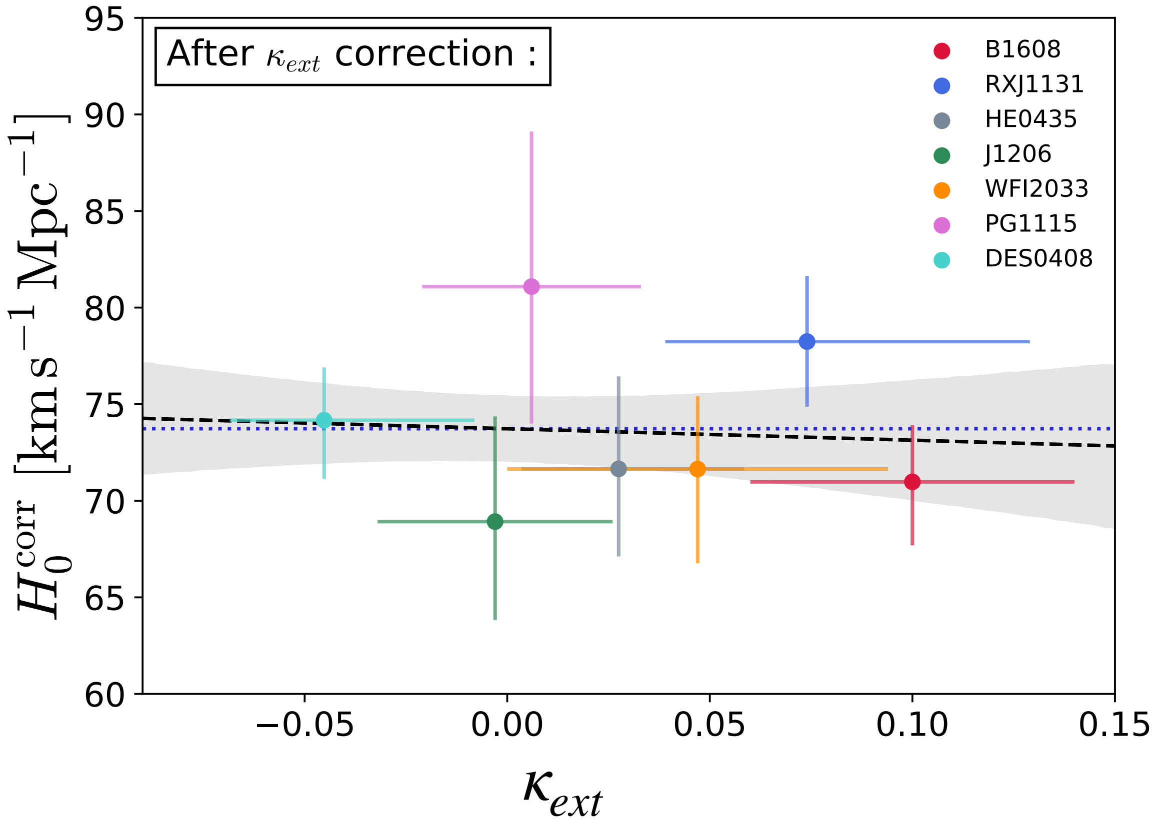
Imaging + time delay **cannot** measure H0.
It cannot access the overall normalization of $\tau(\vec{\theta})$,
and the normalization of $\tau(\vec{\theta})$ is essentially H0.

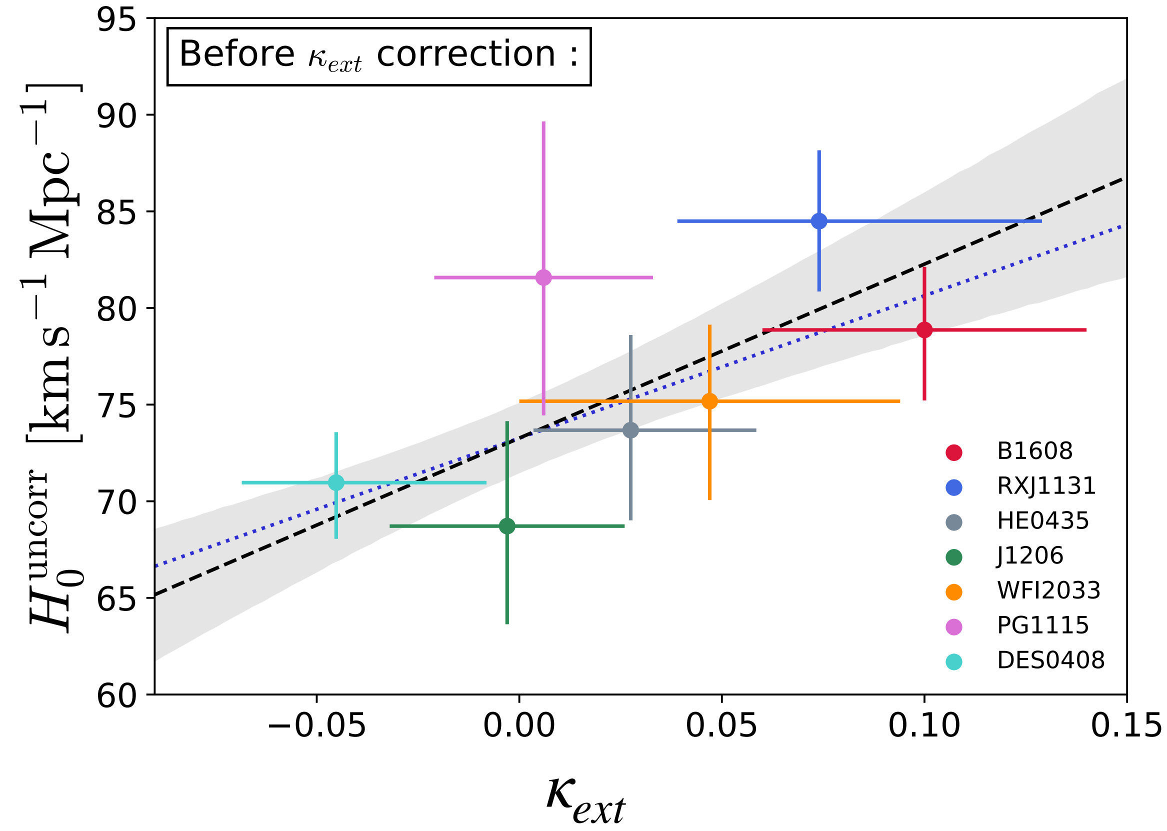
$$D_{\Delta t} = \frac{\Delta t}{\Delta \tau} \propto \frac{1}{H_0}$$



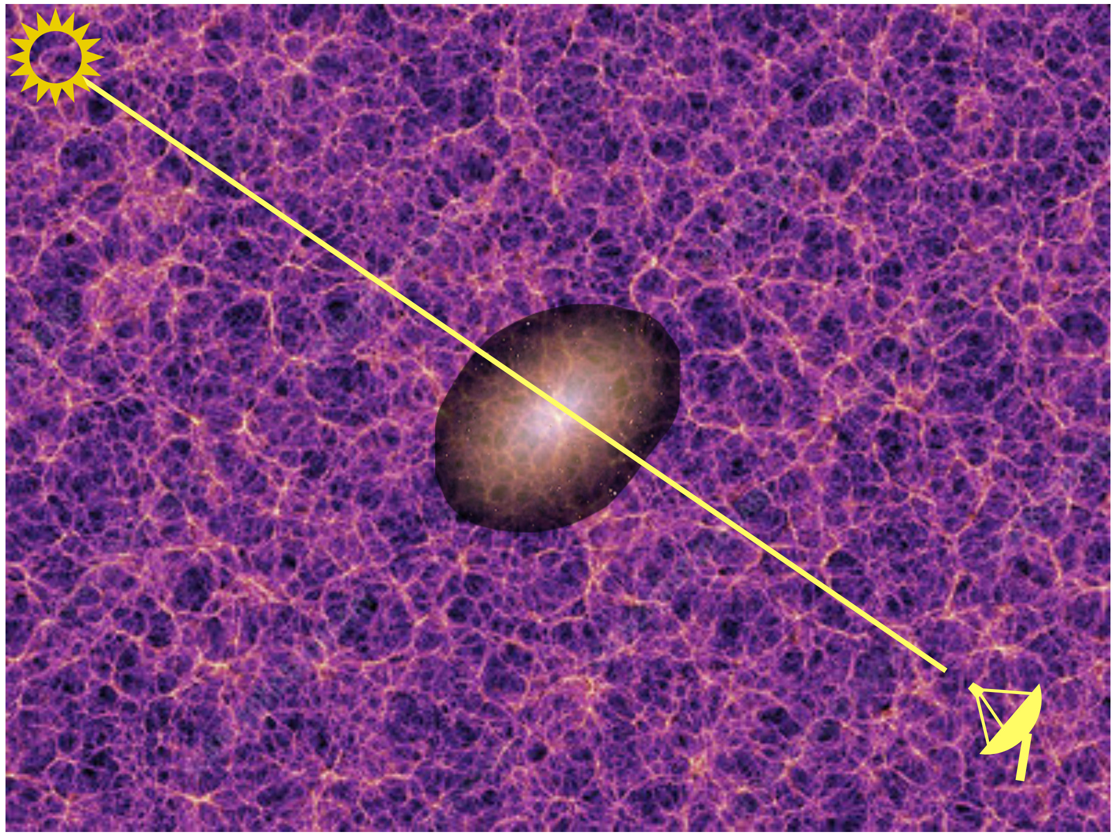
$H_{0\lambda} = \lambda H_0$
$\kappa_\lambda = \lambda\kappa + (1-\lambda)$
θ
α_λ
β_λ
H_0
κ
θ
α
β

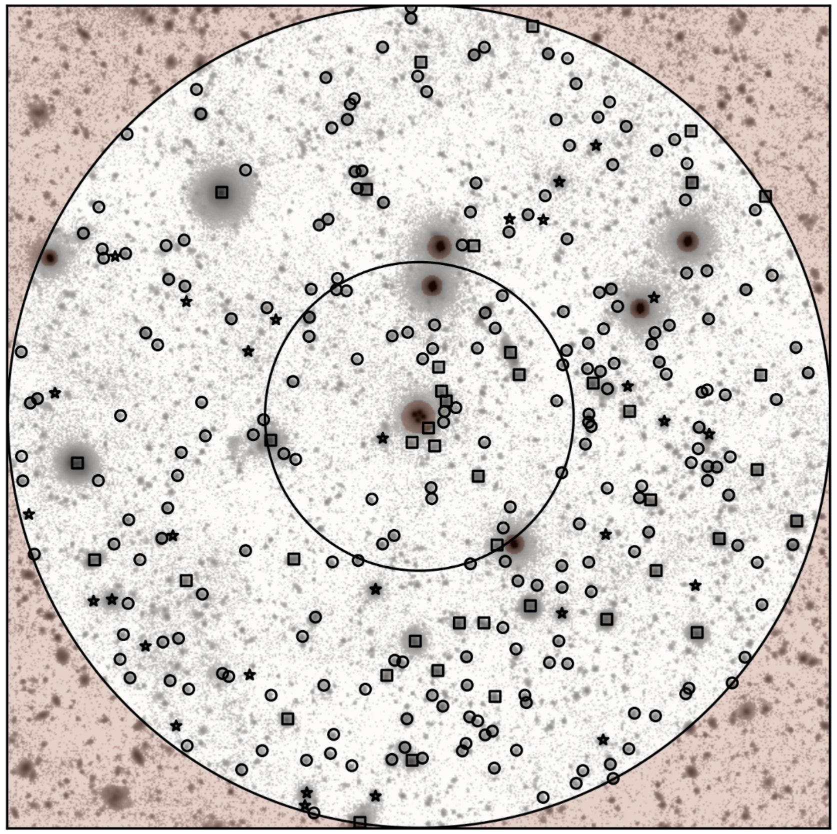
Millon et al, 1912.08027 (**TDCOSMO I**)





Modelling
external
convergence

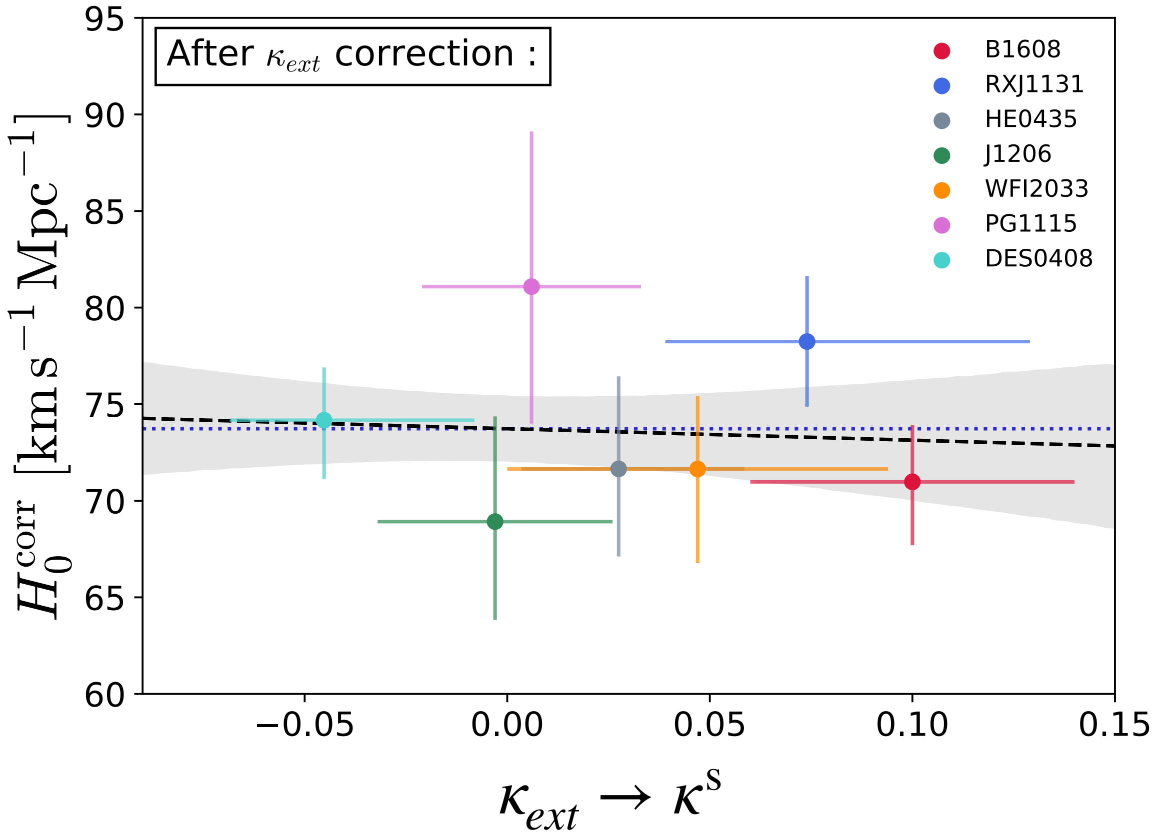


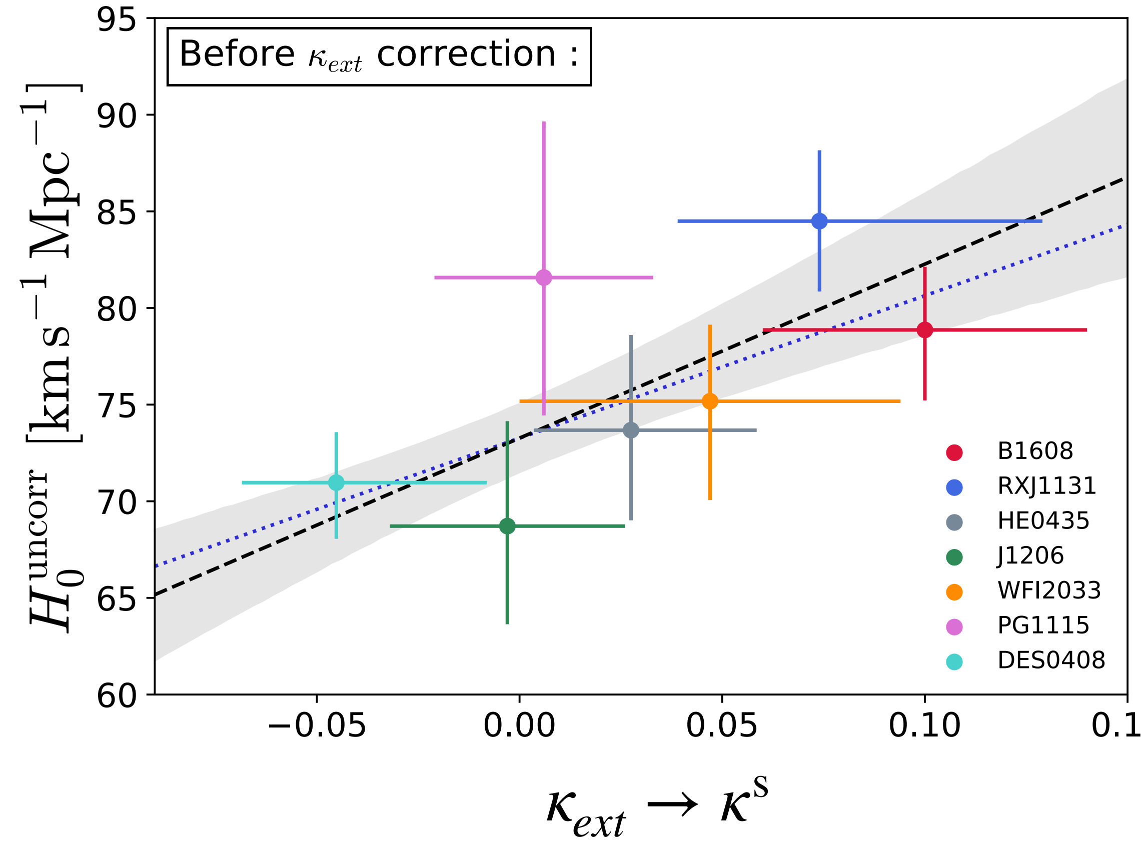


Rusu et al, 1607.01047 (H0LiCOW III)

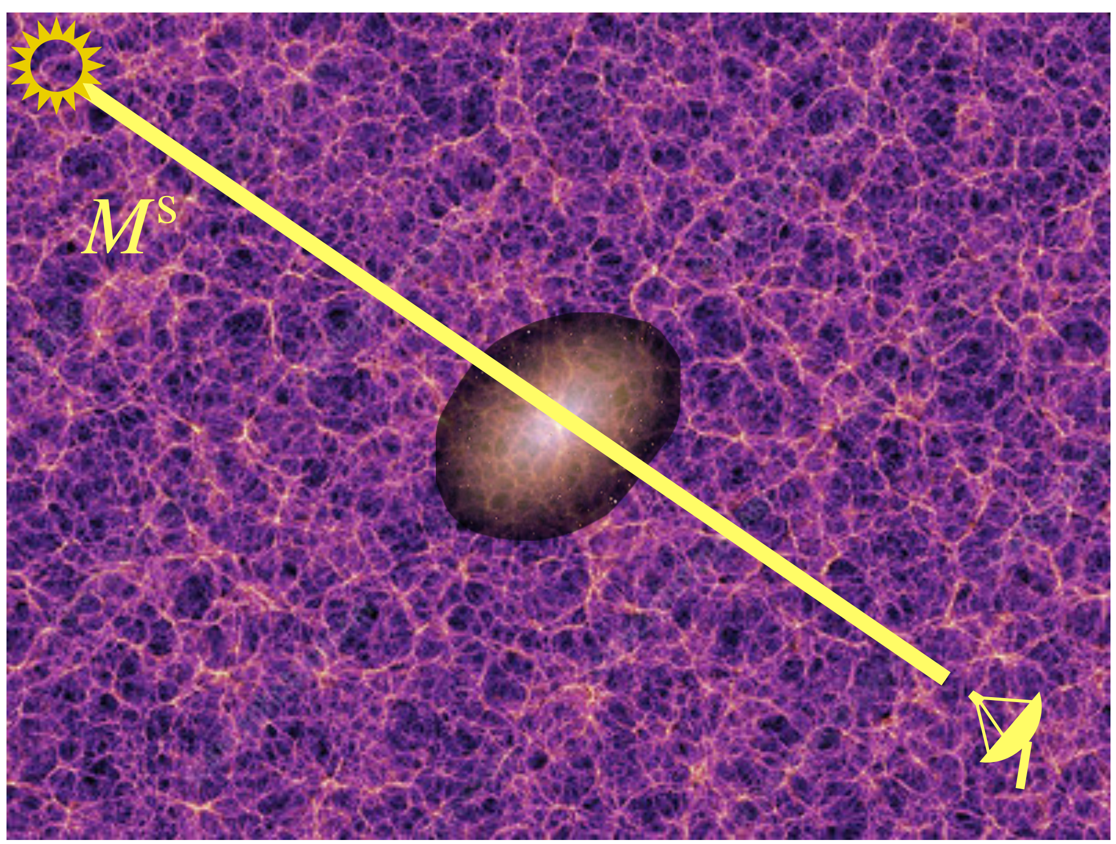
Some comments on external convergence

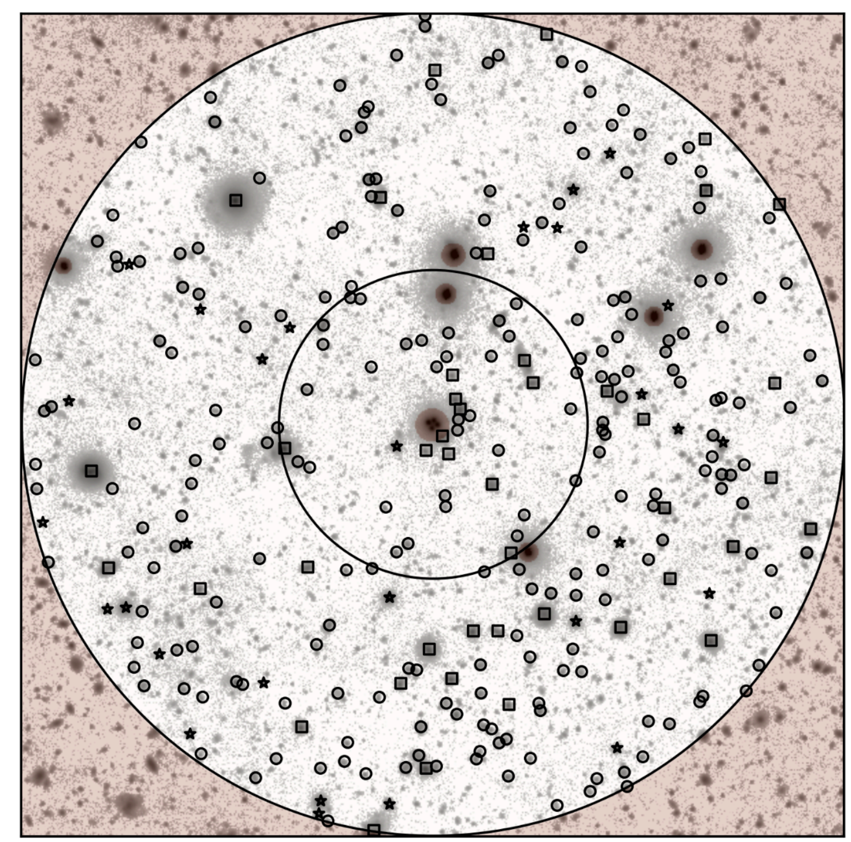
Millon et al, 1912.08027 (**TDCOSMO I**)





Modelling ***external*** convergence





Rusu et al, 1607.01047 (H0LiCOW III)

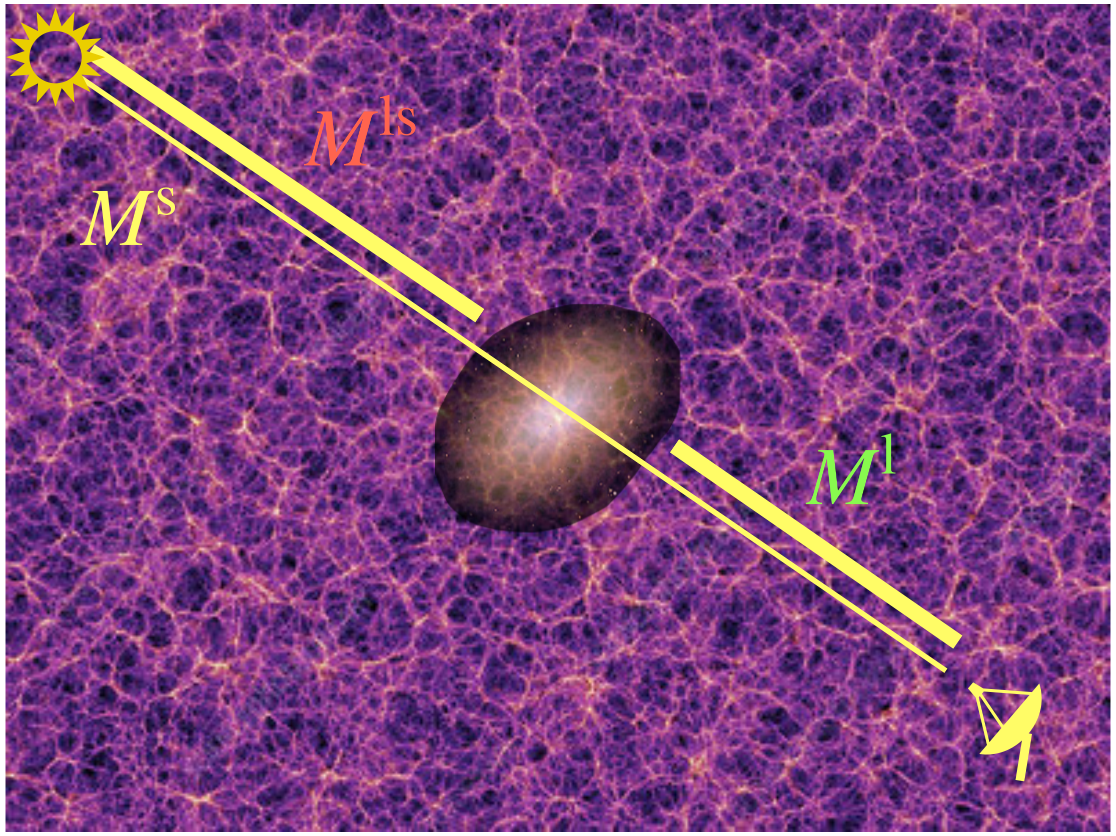
$M(0,\eta_s) = M^s = \kappa^s - \Gamma^s$

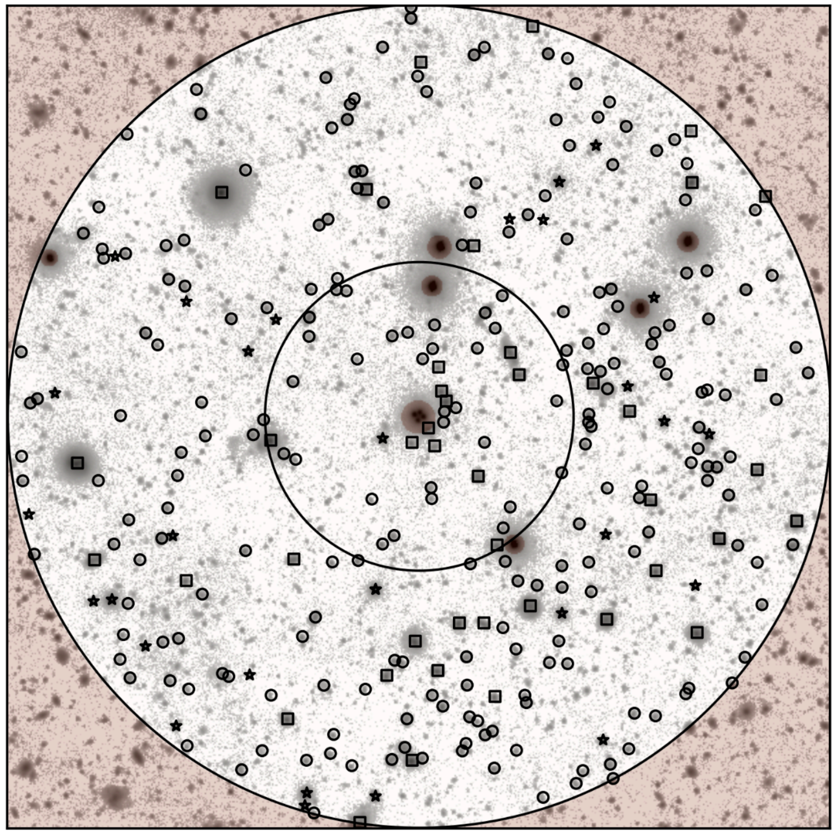
$M(\eta_l,\eta_s) = M^{ls} = \kappa^{ls} - \Gamma^{ls}$

$M(0,\eta_l) = M^l = \kappa^l - \Gamma^l$

$$M_{ij}(\eta_1,\eta_2) \approx 2\int_{\eta_1}^{\eta_2} \mathrm{d}\eta' \, \frac{(\eta_2-\eta')(\eta'-\eta_1)}{(\eta_2-\eta_1)\eta'^2} \partial_i\partial_j\Phi_{\mathrm{t}}(0,\eta')$$

$$\tau\left(\vec{\theta}\right) = \frac{1}{2}\vec{\theta}^T\left(1 - M^s - M^l + M^{ls}\right)\vec{\theta} - \vec{\beta}^T\left(1 - M^l + M^{ls}\right)\vec{\theta} - \psi\left(\left(1 - M^l\right)\vec{\theta}\right)$$





Rusu et al, 1607.01047 (H0LiCOW III)

Imaging degeneracy:

λ_s, λ_{ls}, λ_l

$$M^{s} - 1 \longmapsto \lambda_s \left(M^{s} - 1\right)$$

$$M^{ls} - 1 \longmapsto \lambda_{ls} \left(M^{ls} - 1\right)$$

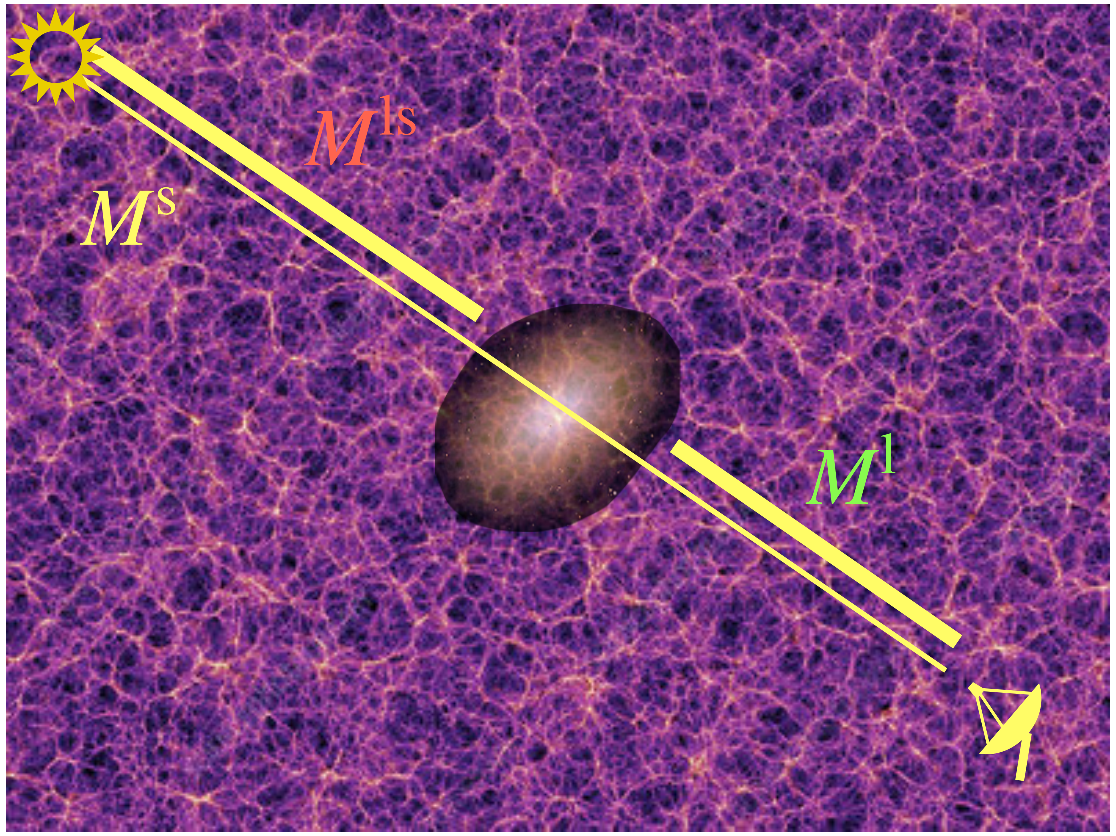
$$M^{l} - 1 \longmapsto \lambda_l \left(M^{l} - 1\right)$$

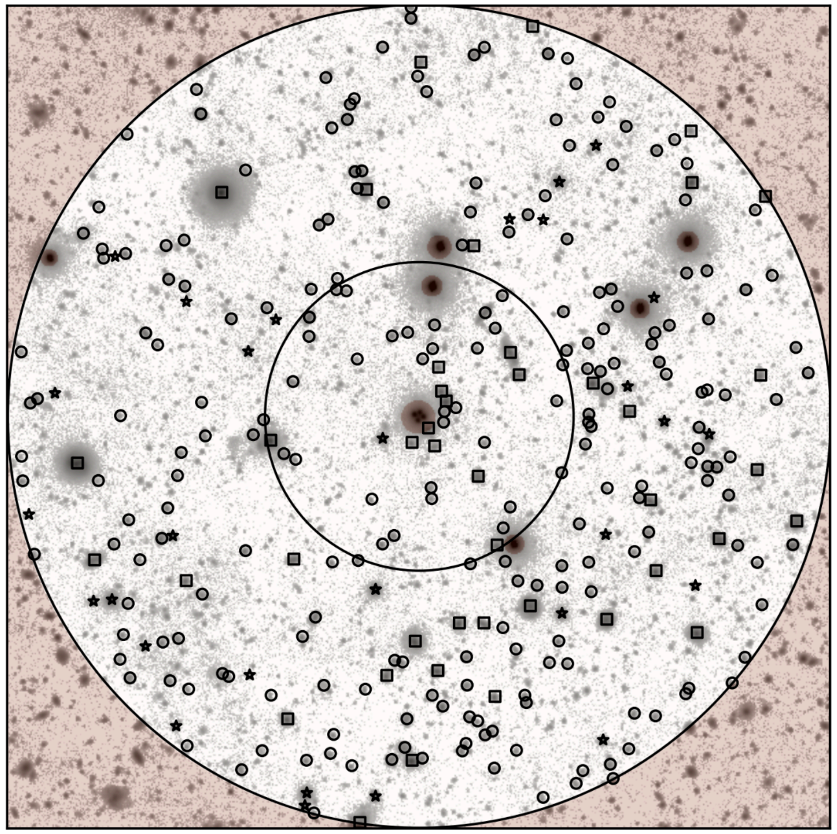
$$\psi\left(\vec{\theta}\right) \longmapsto \lambda_s \lambda_{ls}{}^{-1} \lambda_l \, \psi\left(\lambda_l{}^{-1} \vec{\theta}\right)$$

$$\vec{\beta} \longmapsto \lambda_s \vec{\beta}$$

$$\boxed{\begin{array}{l} \tau\left(\vec{\theta}\right) \longmapsto \lambda_s \lambda_{ls}^{-1} \lambda_l \, \tau\left(\vec{\theta}\right) \\ H_0^{\mathrm{uncorr}} \longmapsto \lambda_s \lambda_{ls}^{-1} \lambda_l \, H_0 \end{array}}$$

$$\tau\left(\vec{\theta}\right) = \frac{1}{2} \vec{\theta}^{T} \left(1 - M^{s} - M^{l} + M^{ls}\right) \vec{\theta} - \vec{\beta}^{T} \left(1 - M^{l} + M^{ls}\right) \vec{\theta} - \psi\left(\left(1 - M^{l}\right) \vec{\theta}\right)$$





Rusu et al, 1607.01047 (H0LiCOW III)

$$\kappa^{\rm s} \longmapsto \lambda_{\rm s}\kappa^{\rm s} + 1 - \lambda_{\rm s}, \qquad \Gamma^{\rm s} \longmapsto \lambda_{\rm s}\Gamma^{\rm s}$$

Imaging degeneracy: $$\kappa^{\rm ls} \longmapsto \lambda_{\rm ls}\kappa^{\rm ls} + 1 - \lambda_{\rm ls}, \qquad \Gamma^{\rm ls} \longmapsto \lambda_{\rm ls}\Gamma^{\rm ls}$$

$\lambda_{\rm s}$, $\lambda_{\rm ls}$, $\lambda_{\rm l}$

$$\kappa^{\rm l} \longmapsto \lambda_{\rm l}\kappa^{\rm l} + 1 - \lambda_{\rm l}, \qquad \Gamma^{\rm l} \longmapsto \lambda_{\rm l}\Gamma^{\rm l}$$

$$\boxed{\begin{array}{l} \tau\left(\vec{\theta}\right) \longmapsto \lambda_{\rm s}\lambda_{\rm ls}^{-1}\lambda_{\rm l}\,\tau\left(\vec{\theta}\right) \\ H_0^{\rm uncorr} \longmapsto \lambda_{\rm s}\lambda_{\rm ls}^{-1}\lambda_{\rm l}\,H_0 \end{array}}$$

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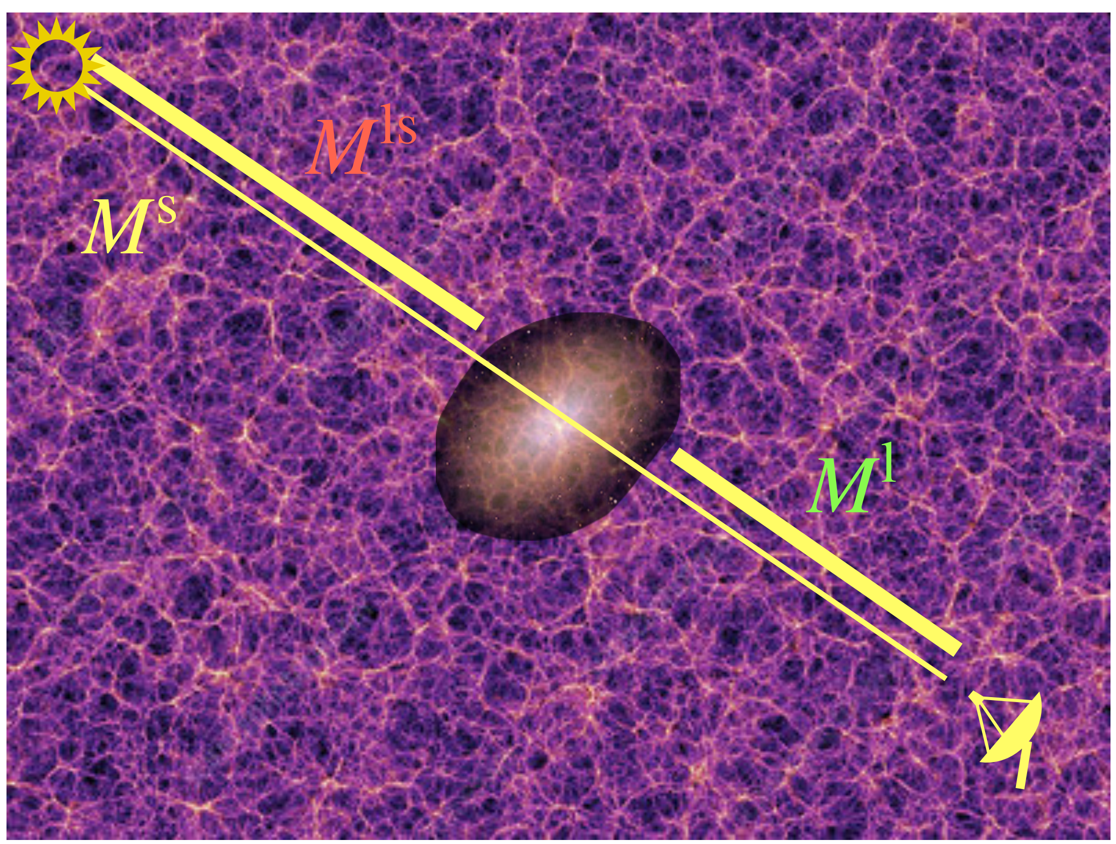
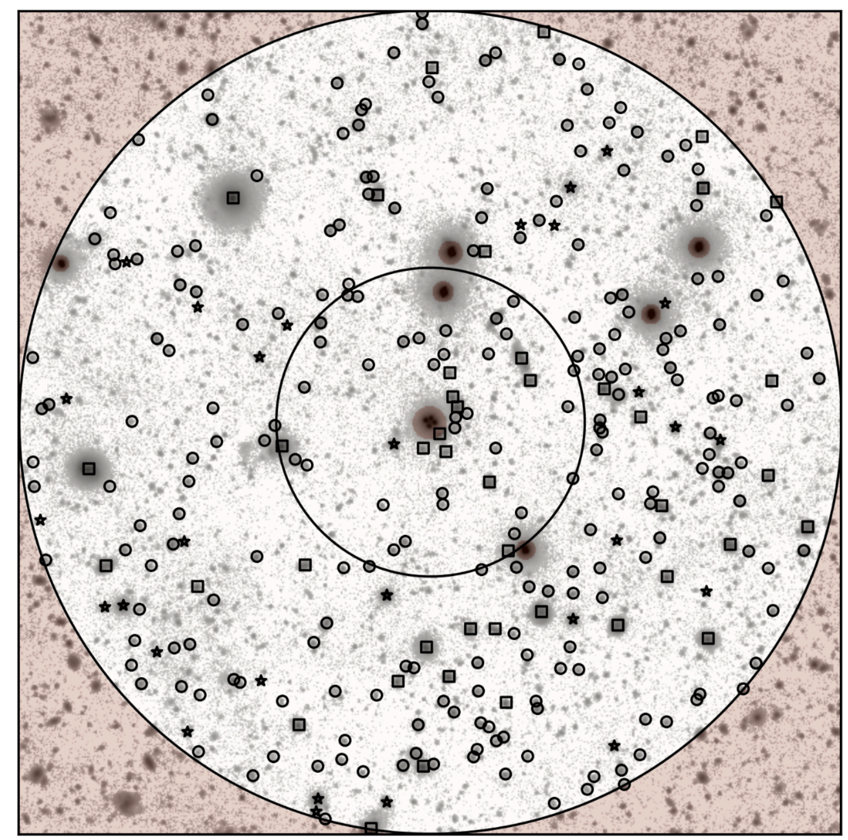




Rusu et al, 1607.01047 (H0LiCOW III)

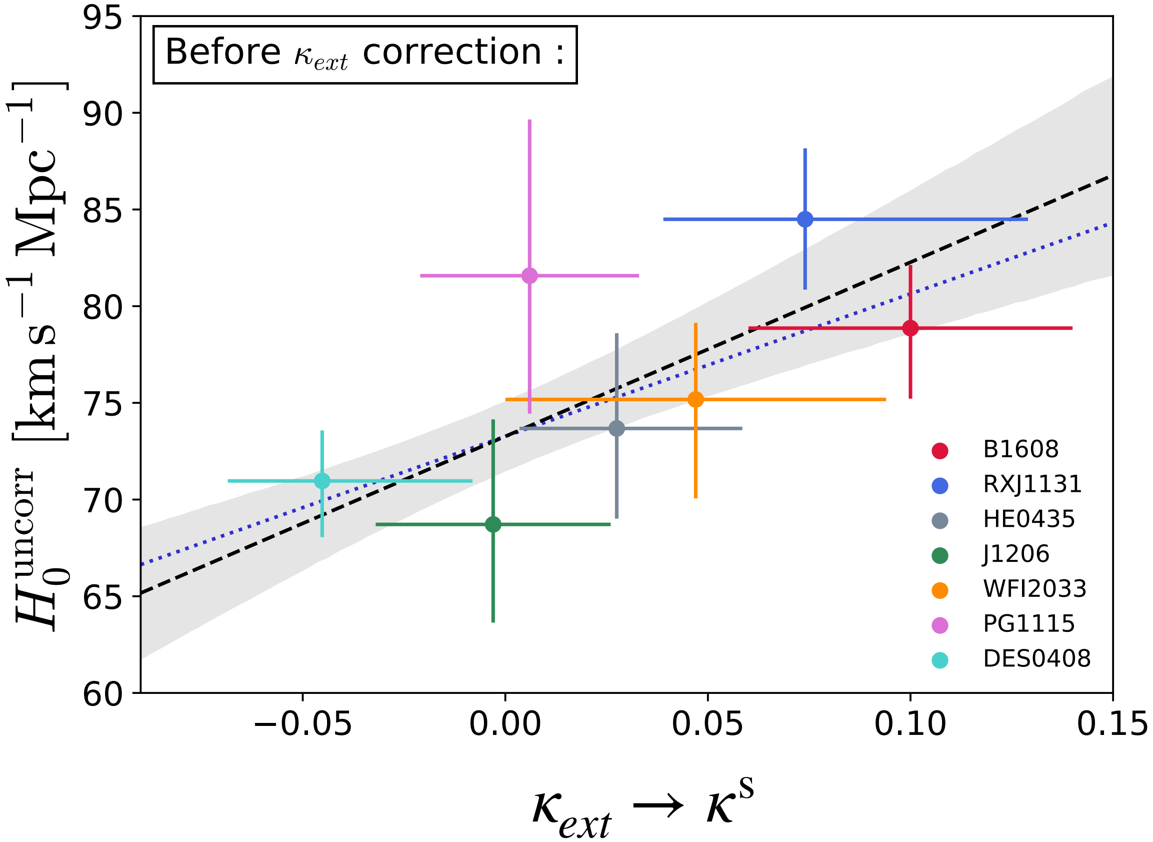
Weak lensing degeneracy:

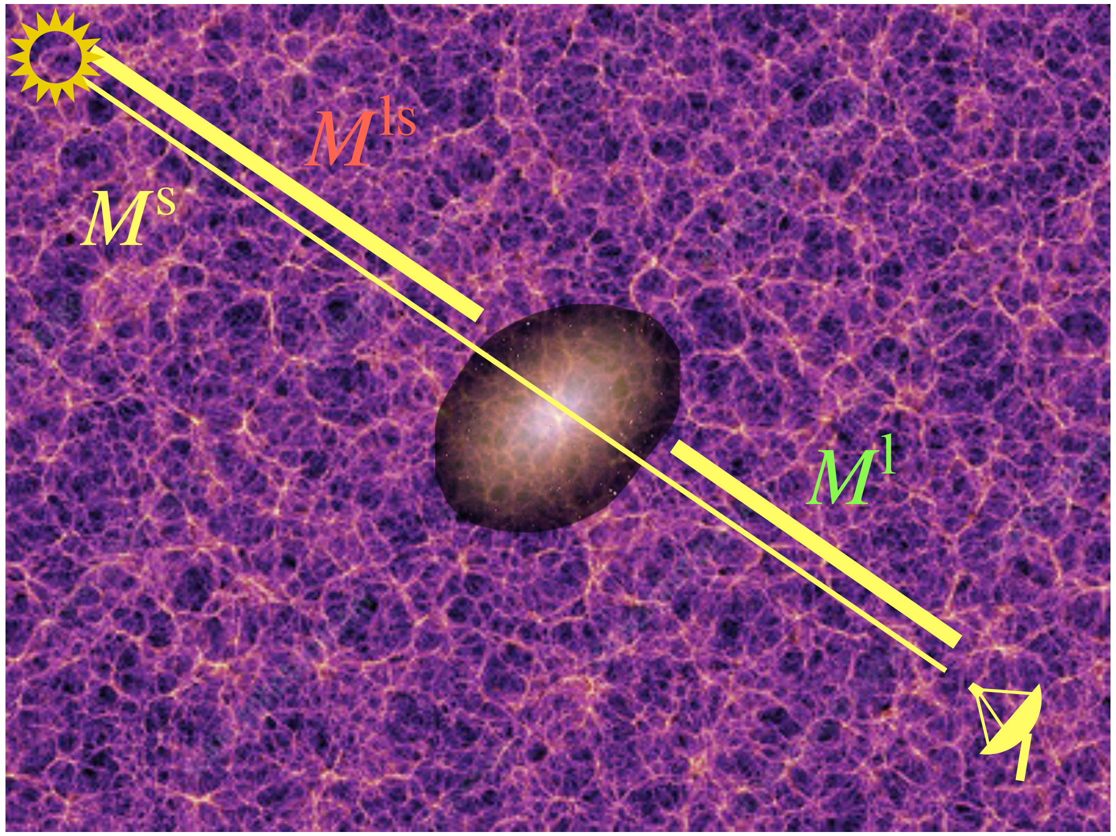
$$H_0^{\rm uncorr} = \frac{1-\kappa^{\rm ls}}{1-\kappa^{\rm l}} \frac{1}{1-\kappa^{\rm s}} H_0$$

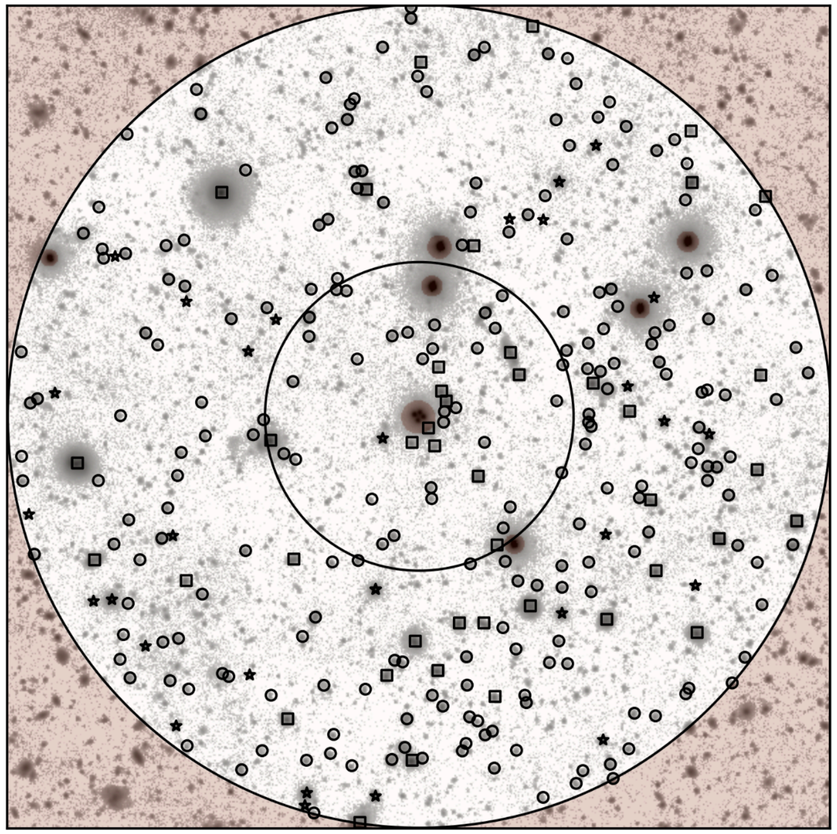
Weak lensing correction in H0LiCOW / TDCOSMO is *a little bit* off.

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

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







Rusu et al, 1607.01047 (H0LiCOW III)

* Thanks to Simon Birrer for catching a mistake in our draft!

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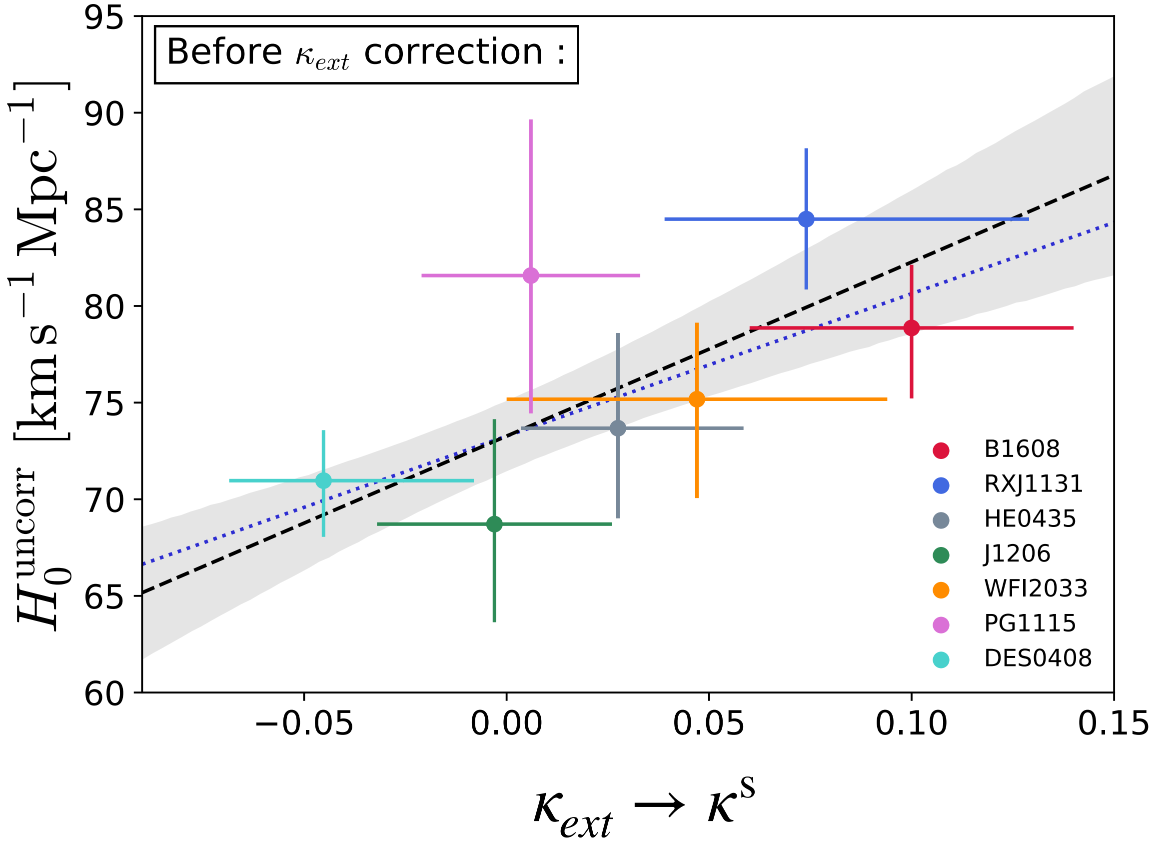
Millon et al, 1912.08027 **(TDCOSMO I)**



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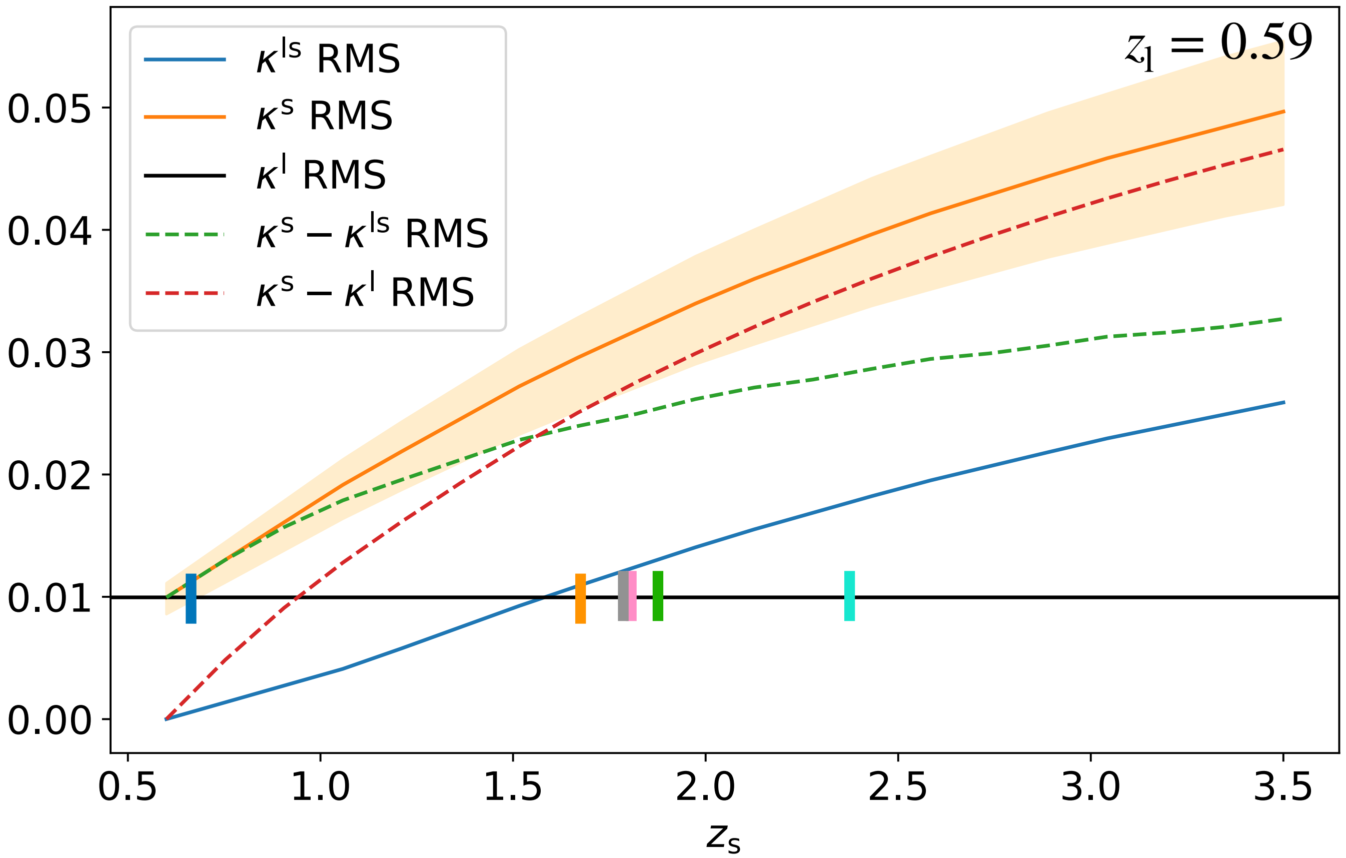
We can try to roughly estimate this, but a real estimate probably needs ray-tracing calibrated to characteristic field of the individual lens



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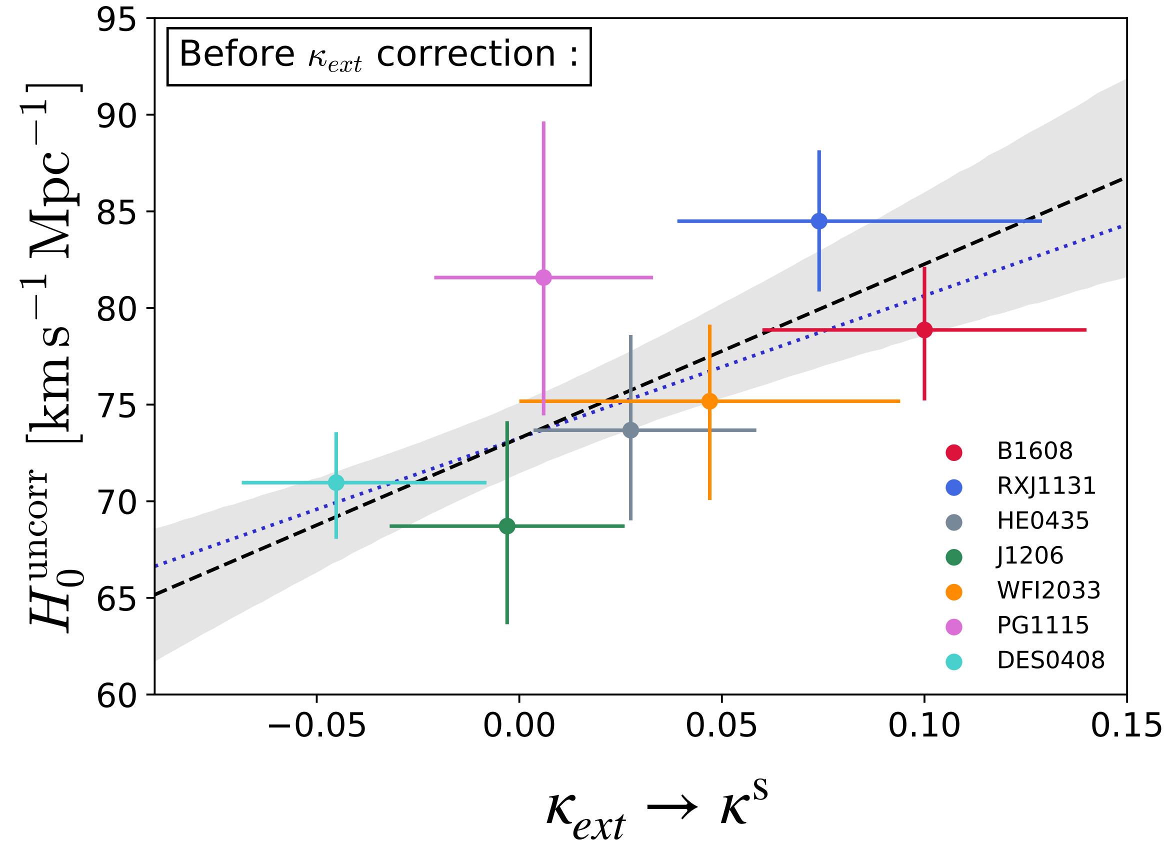

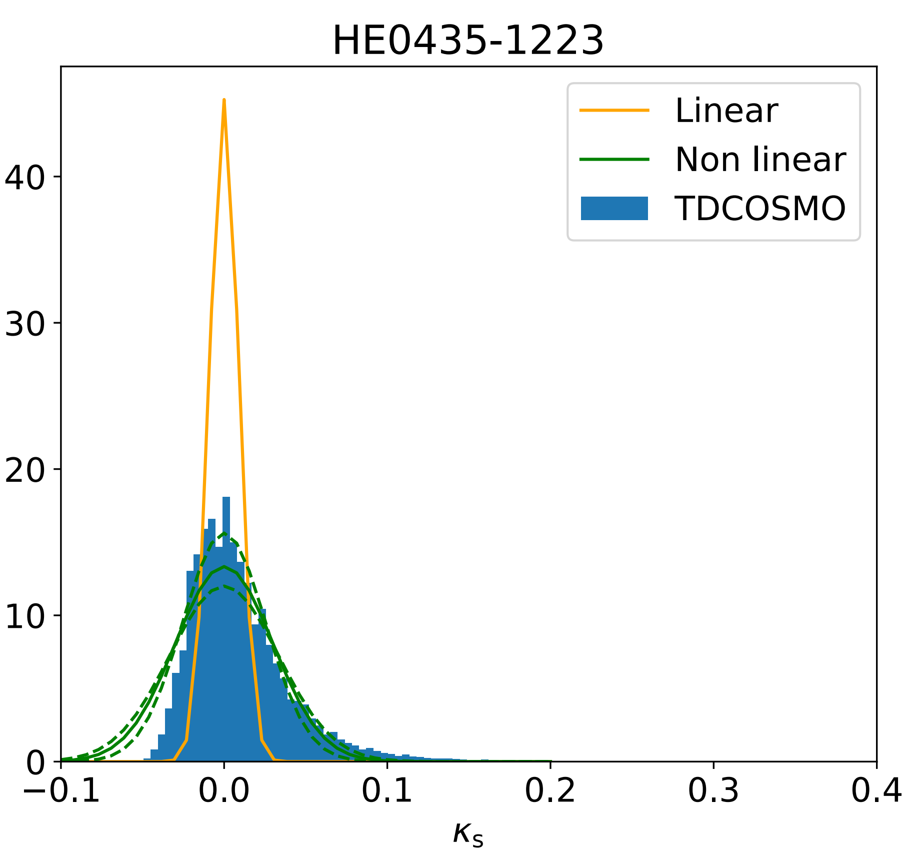

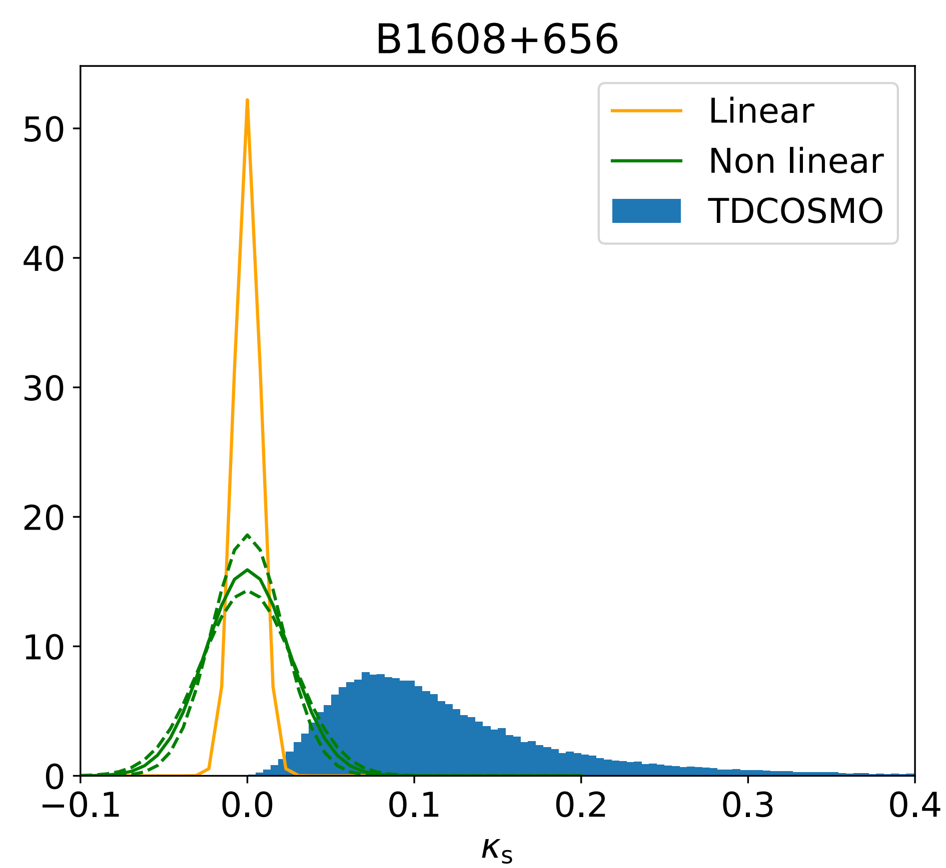

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Joint imaging+kinematics likelihood also a bit off:

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Joint imaging+kinematics likelihood also a bit off:

Suppose truth intrinsic lens is a power law: $\vec{\alpha}(\vec{\theta}) = \left(\frac{\theta}{\tilde{\theta}_{\mathrm{E}}}\right)^{1-\gamma_{\mathrm{PL}}}\vec{\theta}$

Imaging analyses model the observed deflection:

$$\vec{\alpha}^{\mathrm{model}}(\vec{\theta}) = \frac{(1-\kappa^{\mathrm{ls}})(1-\kappa^{\mathrm{l}})^{2-\gamma_{\mathrm{PL}}}}{1-\kappa^{\mathrm{s}}}\left(\frac{\theta}{\tilde{\theta}_{\mathrm{E}}}\right)^{1-\gamma_{\mathrm{PL}}}\vec{\theta} \quad = \left(\frac{\theta}{\theta_{\mathrm{E}}}\right)^{1-\gamma_{\mathrm{PL}}}\vec{\theta}$$

At the same time, stellar kinematics measures:

$$\begin{aligned}\sigma^2(\theta) &= 2G\Sigma_{\mathrm{crit}}d_{\mathrm{A}}(z_{\mathrm{l}},0)\frac{\sqrt{\pi}\,\Gamma\left(\frac{\gamma_{\mathrm{PL}}}{2}\right)}{\Gamma\left(\frac{\gamma_{\mathrm{PL}}-1}{2}\right)}\tilde{\theta}_E^{\gamma_{\mathrm{PL}}-1}\theta^{2-\gamma_{\mathrm{PL}}} \\ &= \frac{1-\kappa^{\mathrm{s}}}{(1-\kappa^{\mathrm{ls}})(1-\kappa^{\mathrm{l}})^{2-\gamma_{\mathrm{PL}}}}\frac{d_{\mathrm{A}}(z_{\mathrm{s}},0)}{d_{\mathrm{A}}(z_{\mathrm{s}},z_{\mathrm{l}})}J(\theta_{\mathrm{E}},\gamma_{\mathrm{PL}})\end{aligned}$$

Weak lensing degeneracy:

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

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

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

Joint imaging+kinematics likelihood also a bit off:

Suppose truth intrinsic lens is a power law: $\vec{\alpha}(\vec{\theta}) = \left(\frac{\theta}{\tilde{\theta}_{\mathrm{E}}}\right)^{1-\gamma_{\mathrm{PL}}}\vec{\theta}$

Imaging analyses model the observed deflection:

$$\vec{\alpha}^{\mathrm{model}}(\vec{\theta}) = \frac{(1-\kappa^{\mathrm{ls}})(1-\kappa^{\mathrm{l}})^{2-\gamma_{\mathrm{PL}}}}{1-\kappa^{\mathrm{s}}}\left(\frac{\theta}{\tilde{\theta}_{\mathrm{E}}}\right)^{1-\gamma_{\mathrm{PL}}}\vec{\theta} \quad = \left(\frac{\theta}{\theta_{\mathrm{E}}}\right)^{1-\gamma_{\mathrm{PL}}}\vec{\theta}$$

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$$= \boxed{\frac{1-\kappa^{\mathrm{s}}}{(1-\kappa^{\mathrm{ls}})(1-\kappa^{\mathrm{l}})^{2-\gamma_{\mathrm{PL}}}}}\frac{d_{\mathrm{A}}(z_{\mathrm{s}},0)}{d_{\mathrm{A}}(z_{\mathrm{s}},z_{\mathrm{l}})}J(\theta_{\mathrm{E}},\gamma_{\mathrm{PL}})$$

Instead, post-processing weak lensing correction applied in TDCOSMO I and IV for the kinematics, was equivalent to setting:

$$\sigma^2 \to (1-\kappa^{\mathrm{ext}})\,\sigma^2$$

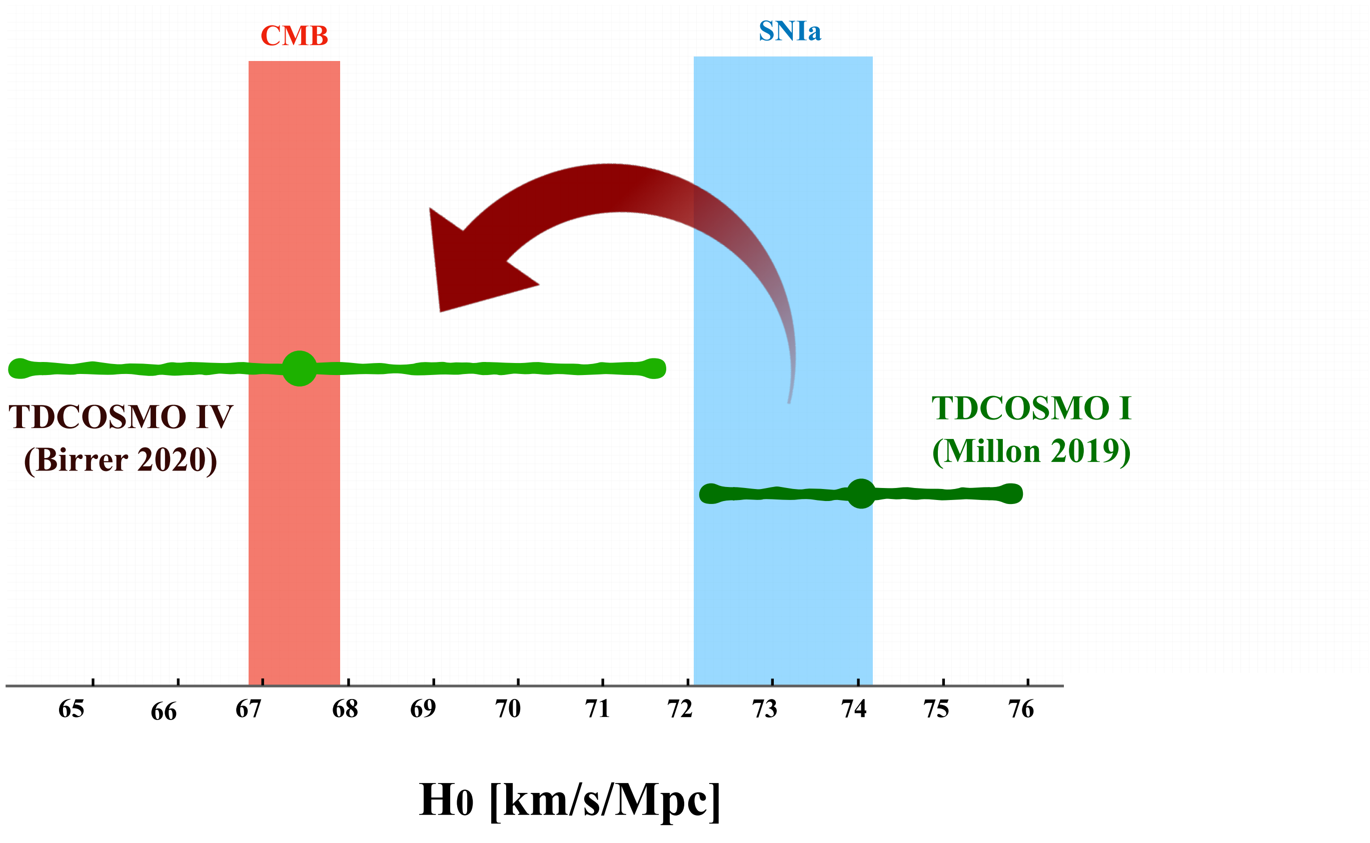
With: $1-\kappa^{\mathrm{ext}} \to \dfrac{(1-\kappa^{\mathrm{s}})(1-\kappa^{\mathrm{l}})}{1-\kappa^{\mathrm{ls}}}$

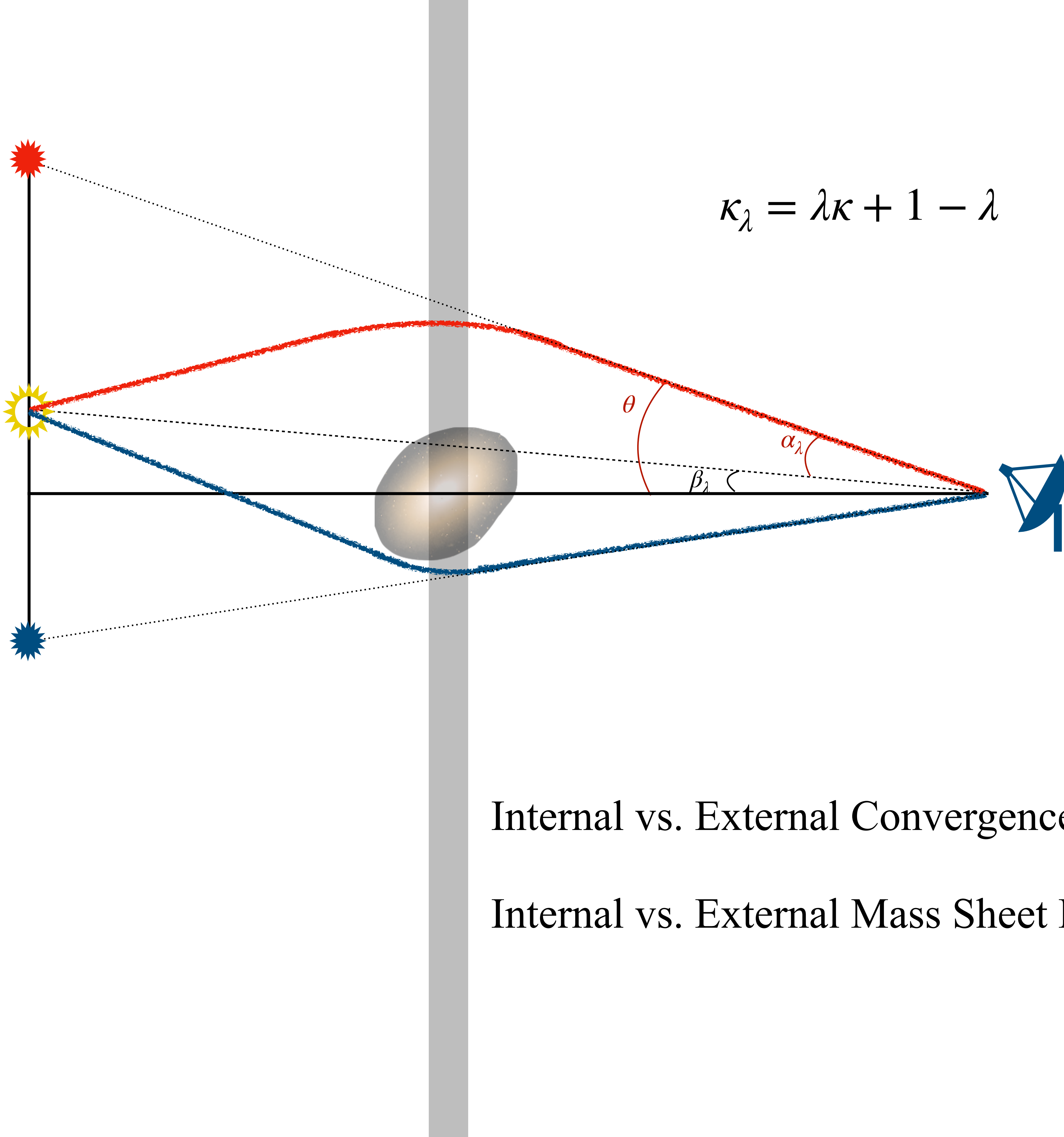
Along with: $H_0^{\mathrm{inferred}} = (1-\kappa^{\mathrm{ext}})\,H_0^{\mathrm{model}}$

Leading to kinematics-induced bias:

$$\boxed{\frac{H_0^{\mathrm{inferred}}}{H_0} \approx 1-(3-\gamma_{\mathrm{PL}})\kappa^{\mathrm{l}}}$$

Potentially bigger problem: ``internal convergence''



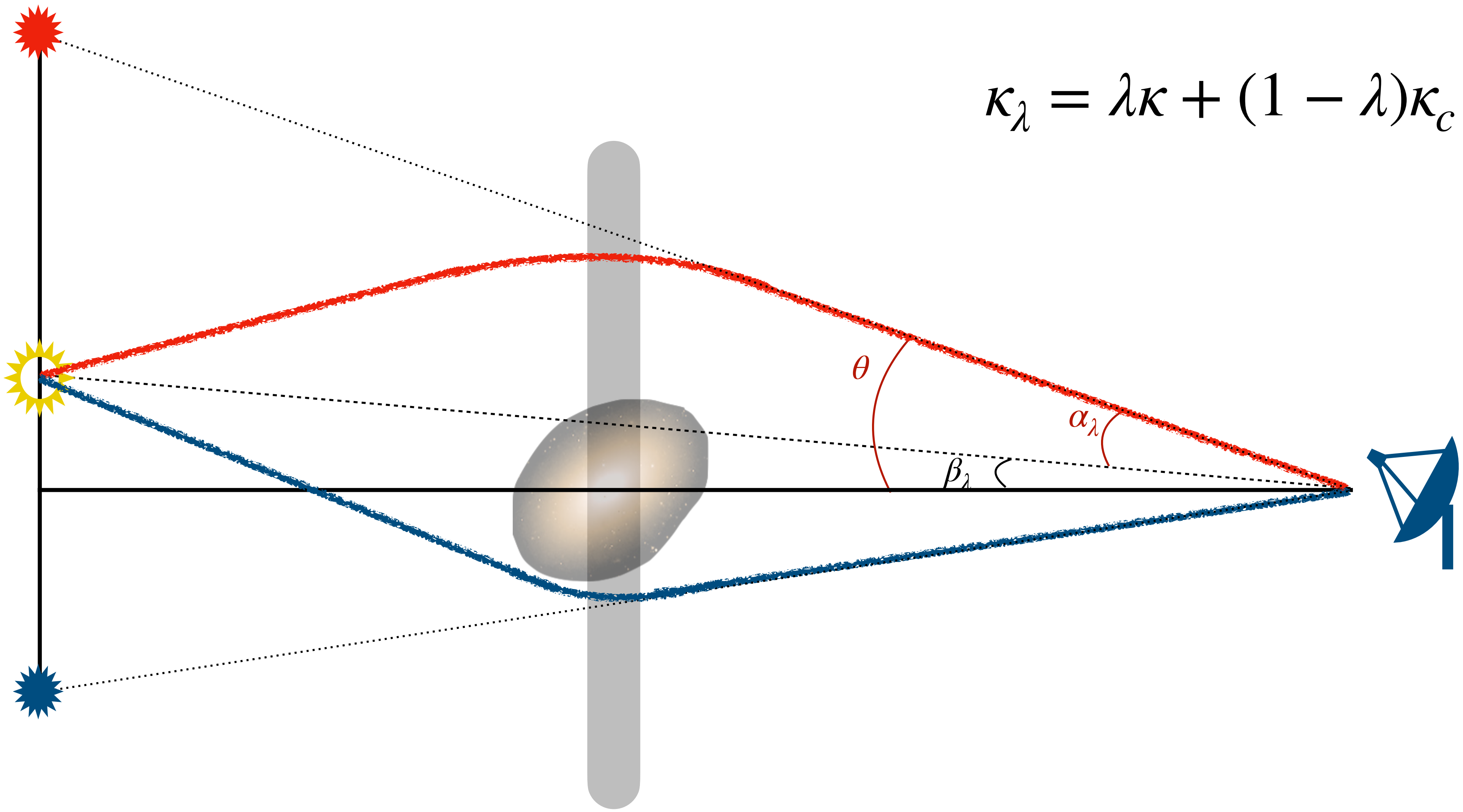


$$\kappa_\lambda = \lambda\kappa + 1 - \lambda$$

Internal vs. External Convergence

Internal vs. External Mass Sheet Degeneracy

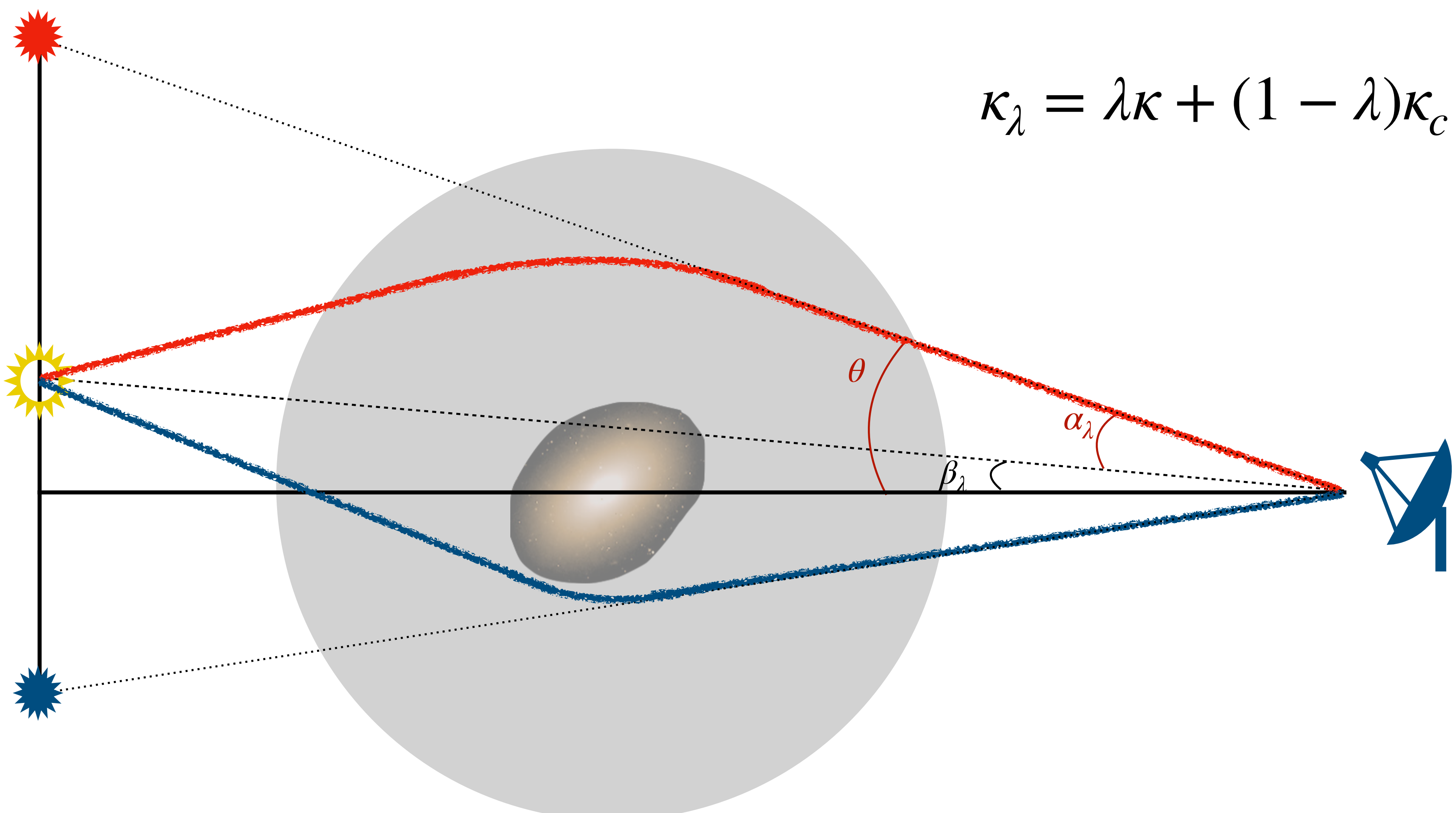
$$\kappa_\lambda = \lambda\kappa + (1 - \lambda)\kappa_c$$



Internal vs. External Convergence

Internal vs. External Mass Sheet Degeneracy

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



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

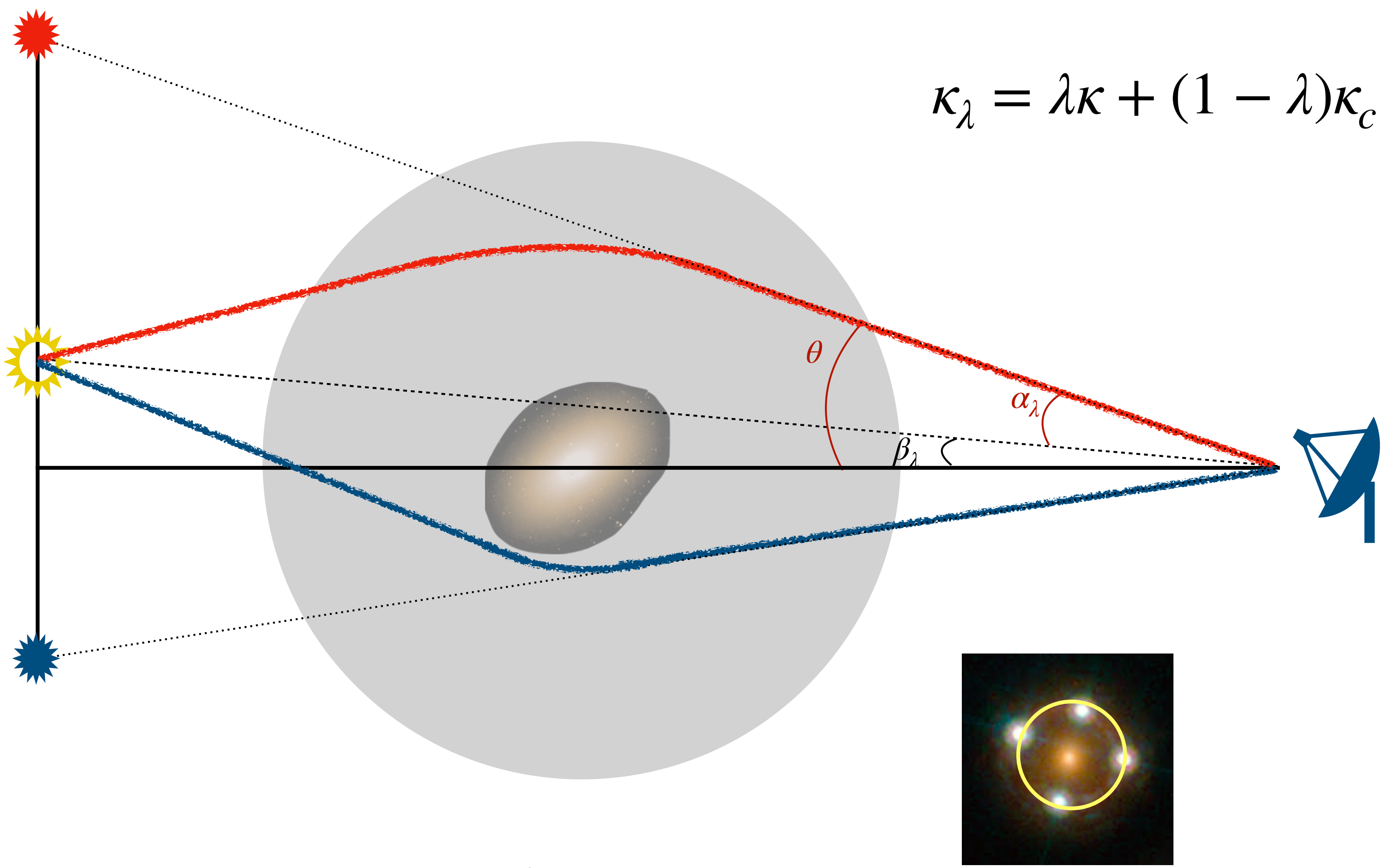
Internal vs. External Convergence

Internal vs. External Mass Sheet Degeneracy

KB, Castorina, Simonović, 2001.07182

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

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



Example:

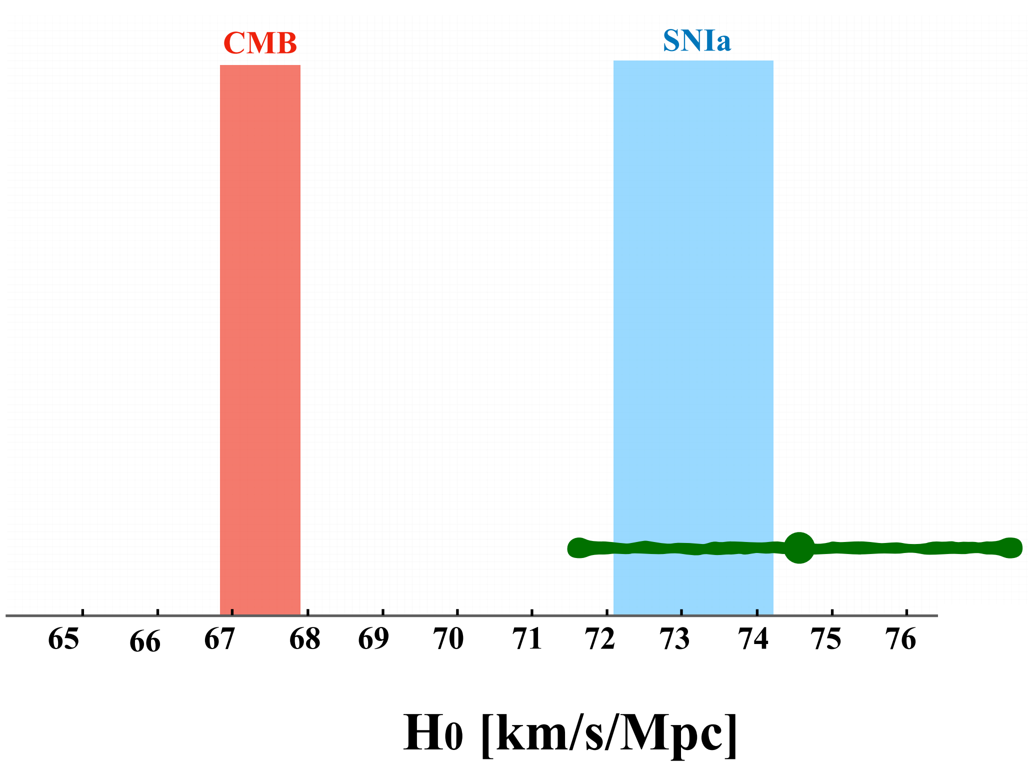
$$\rho_c(r) = \frac{1}{\sqrt{\pi}\,\Gamma\left(\frac{3}{2}\right)} \frac{\Sigma_c R_c^3}{\left(R_c^2 + r^2\right)^2}$$

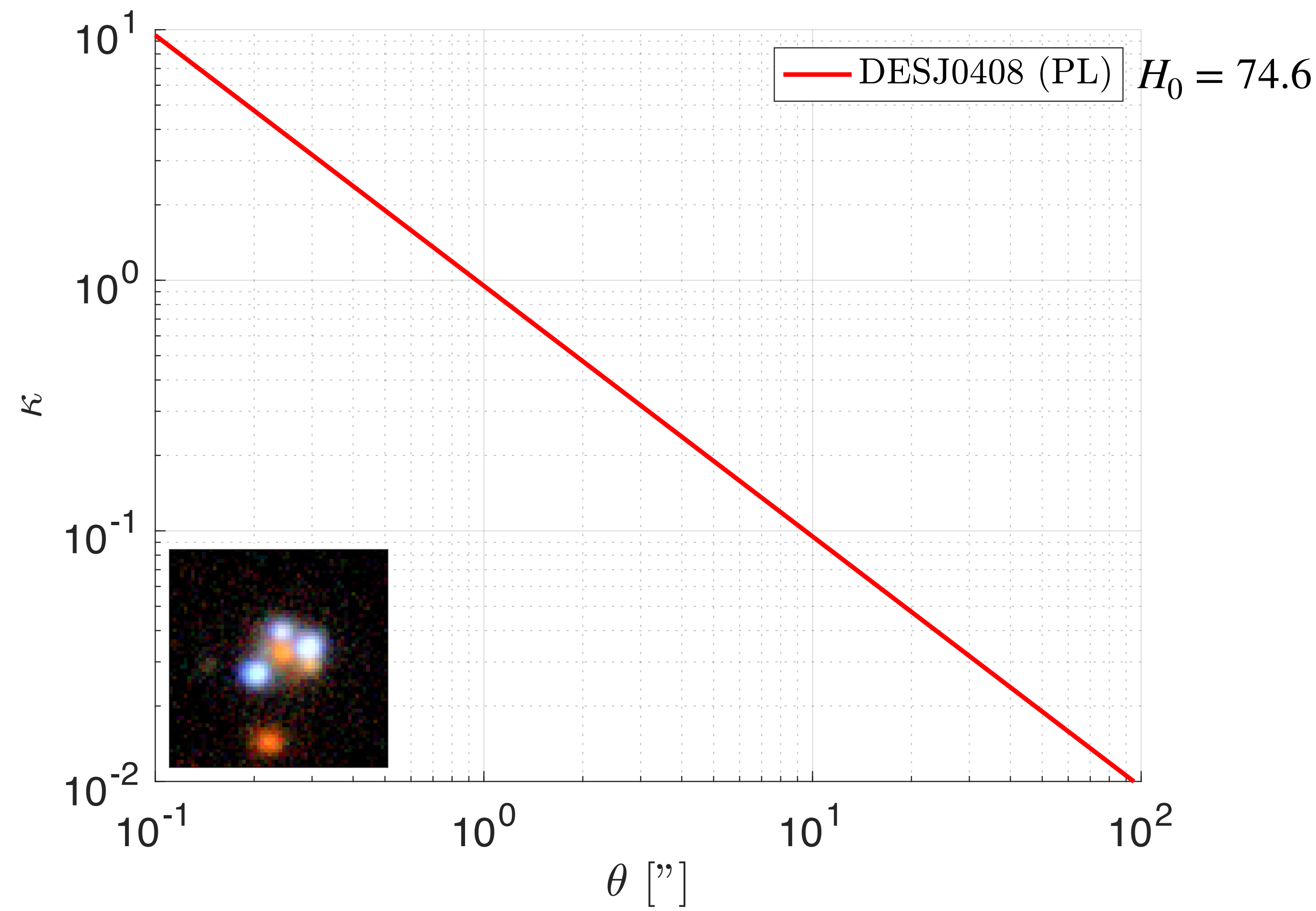
$$\kappa_c(\theta) = \left(1 + \frac{\theta^2}{\theta_c^2}\right)^{-\frac{3}{2}}$$

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

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

2. Challenges: modeling degeneracy





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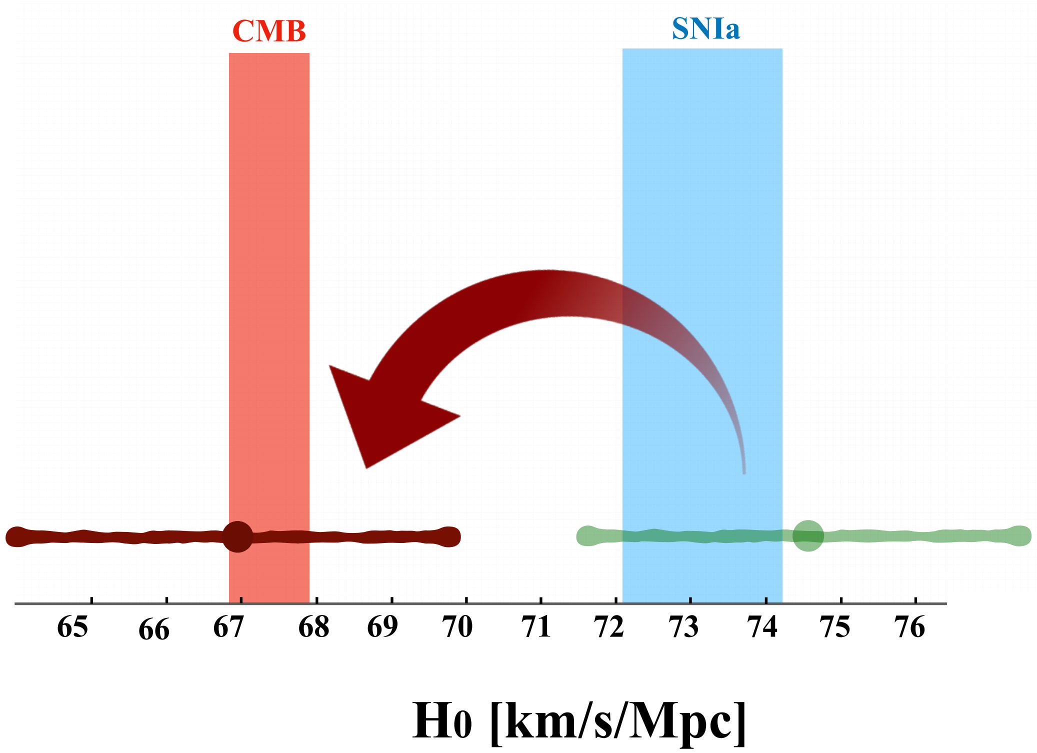
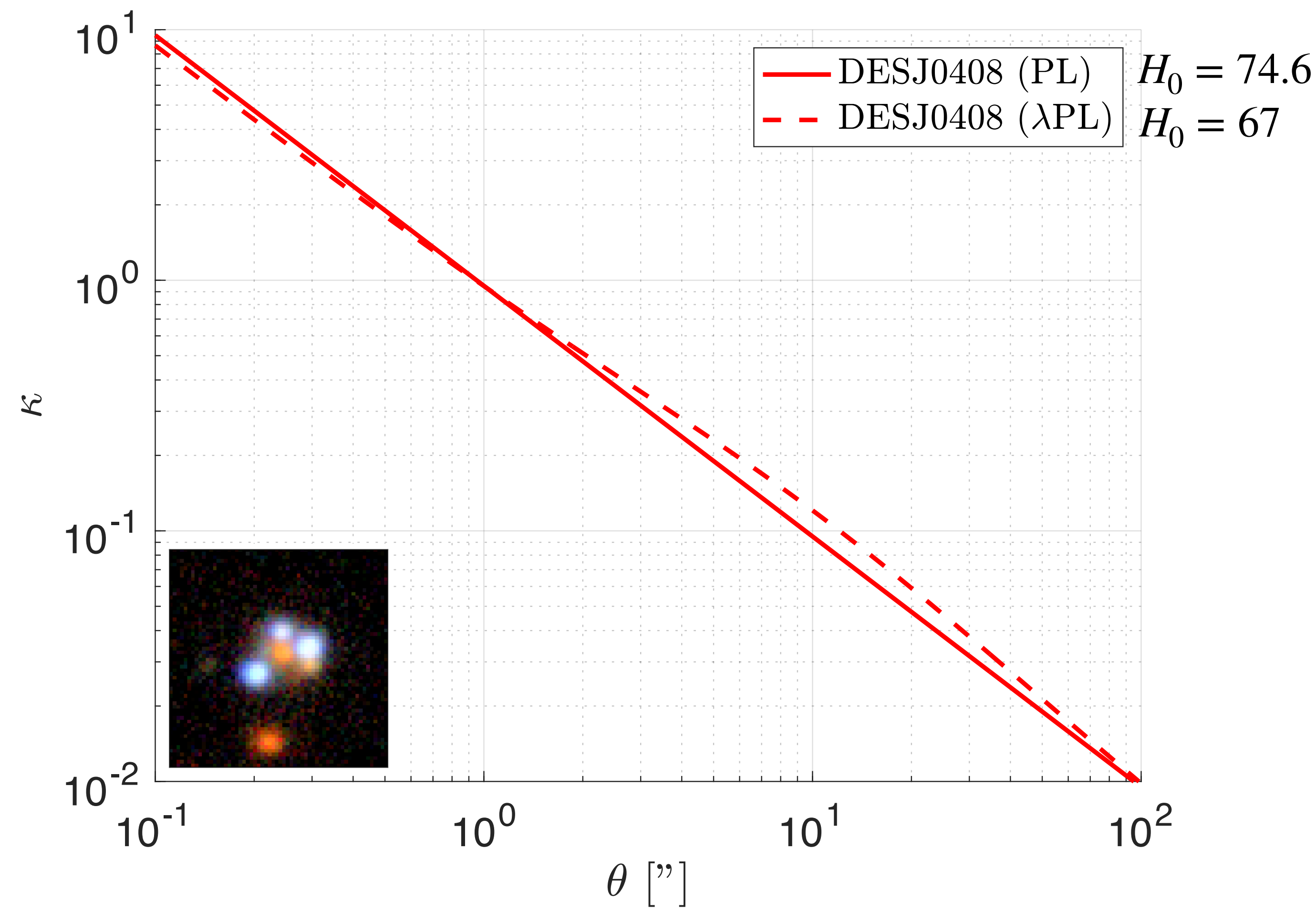
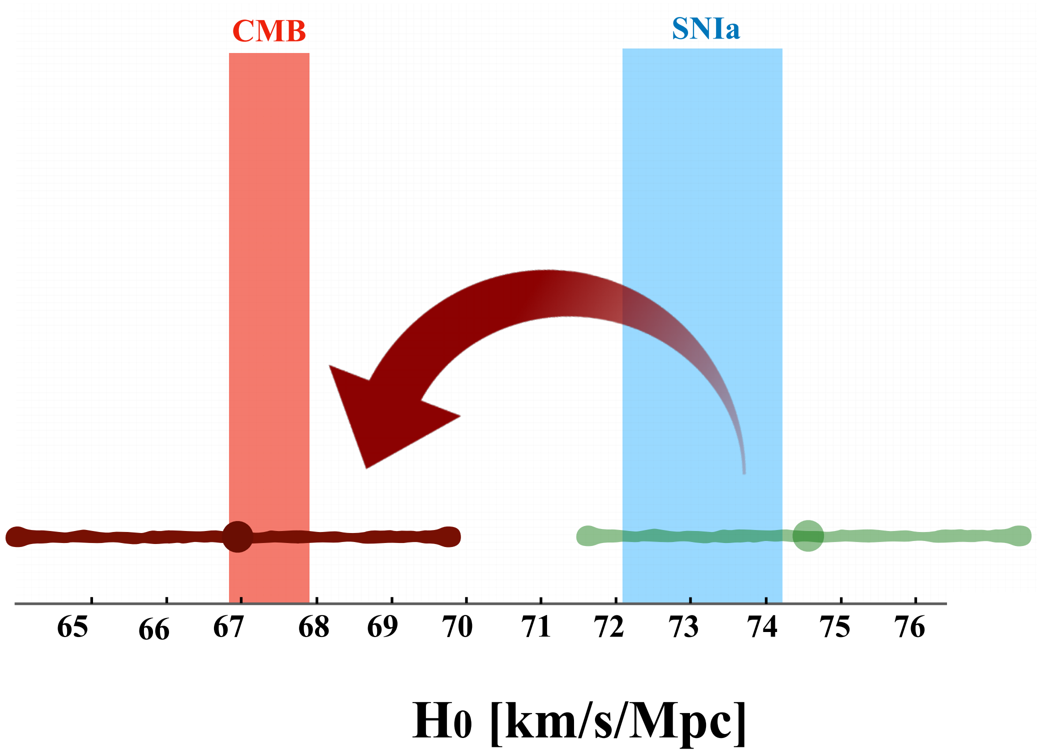
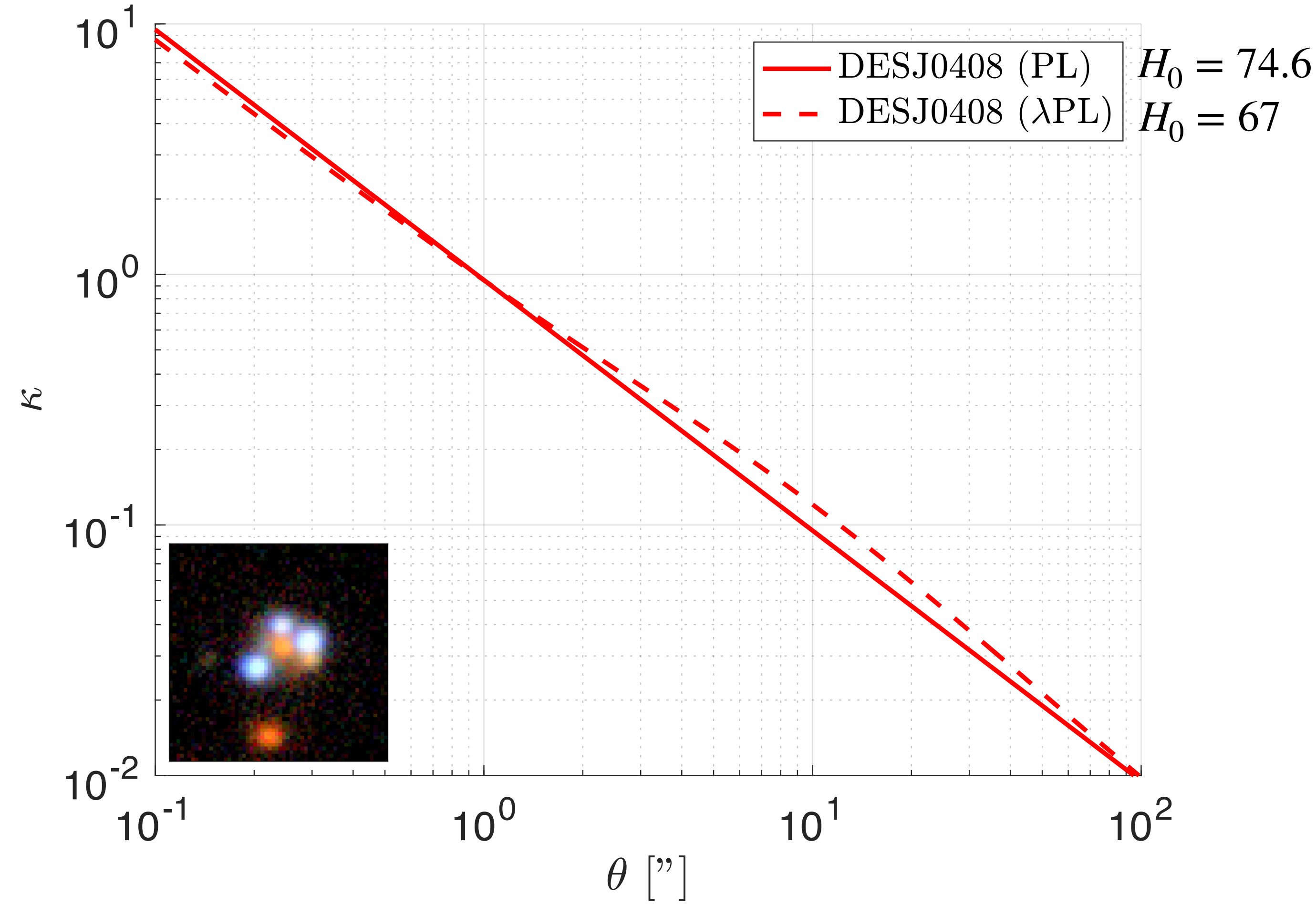




3. Opportunities: galactic structure

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





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RXJ1131	$76.1^{+3.6}_{-4.3}$	$0.88^{+0.06}_{-0.04}$	1.98	1.6	19	0.295	Chen et al. (2016)
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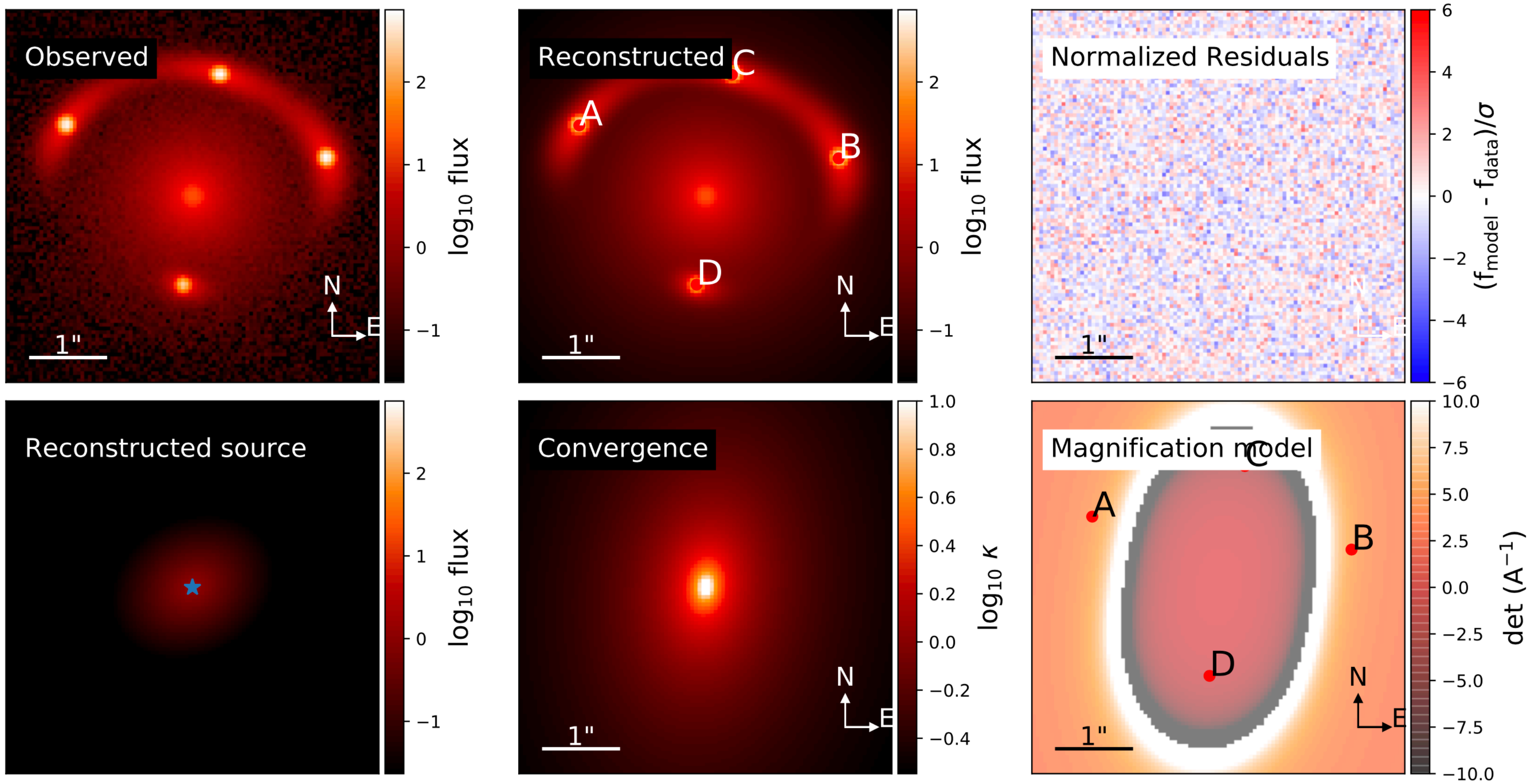
What do we learn about galaxies if we add CMB/LSS prior?

Expect evidence for core component, reflecting precision on H0

KB, Teodori, 2105.10873



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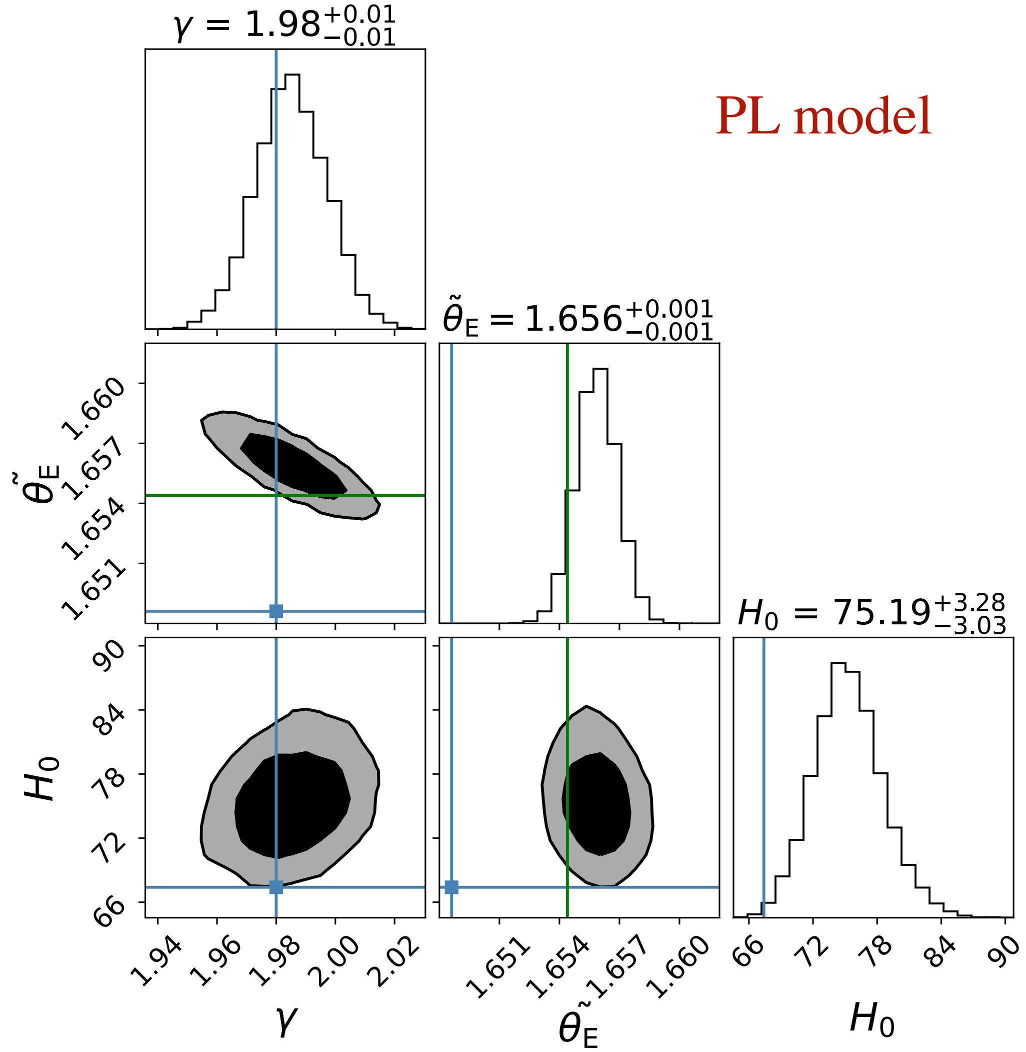

PL model

Mock inference using power-low model.

Truth has H0=67.4 km/s/Mpc, and a 10% core!

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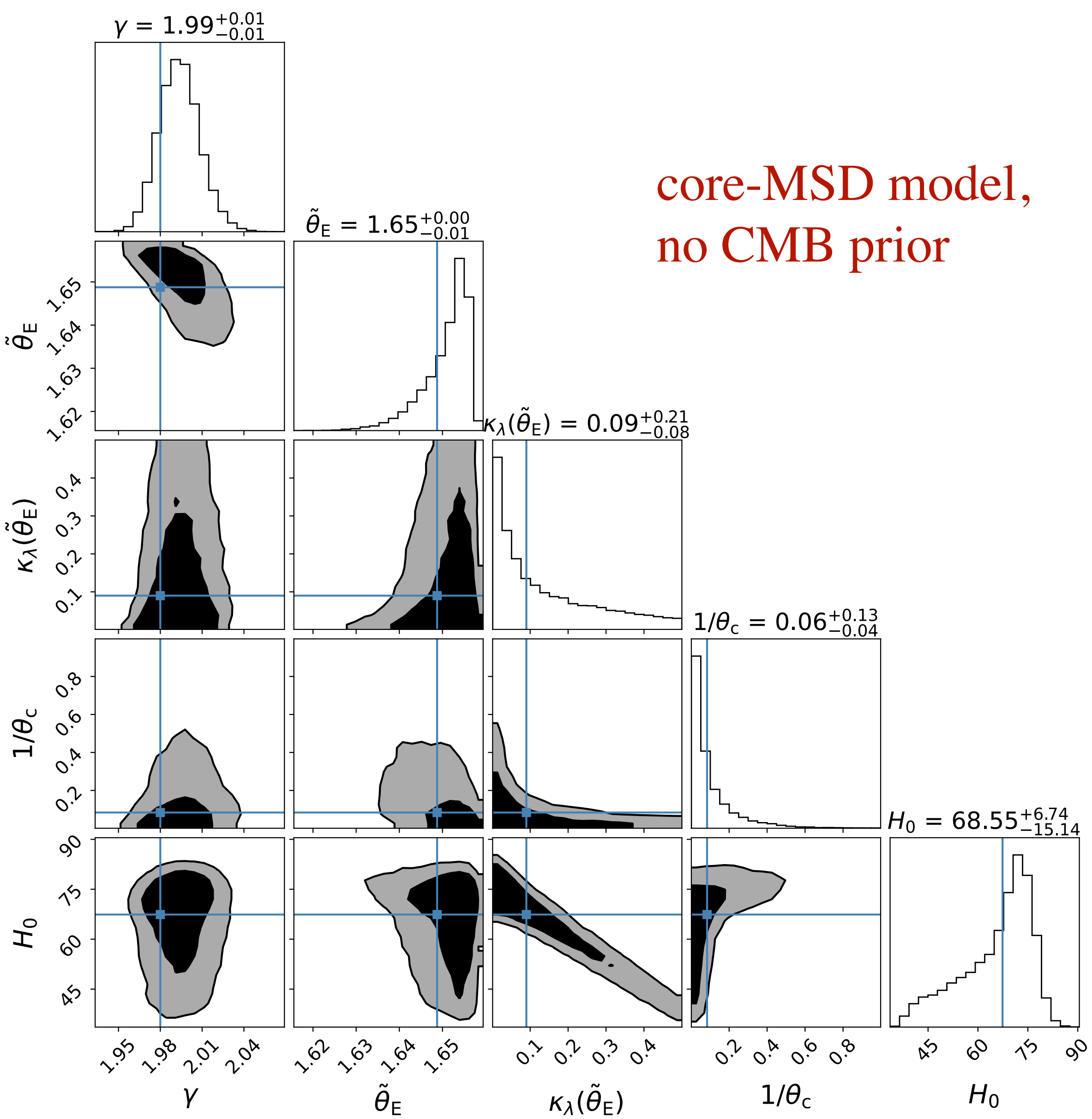

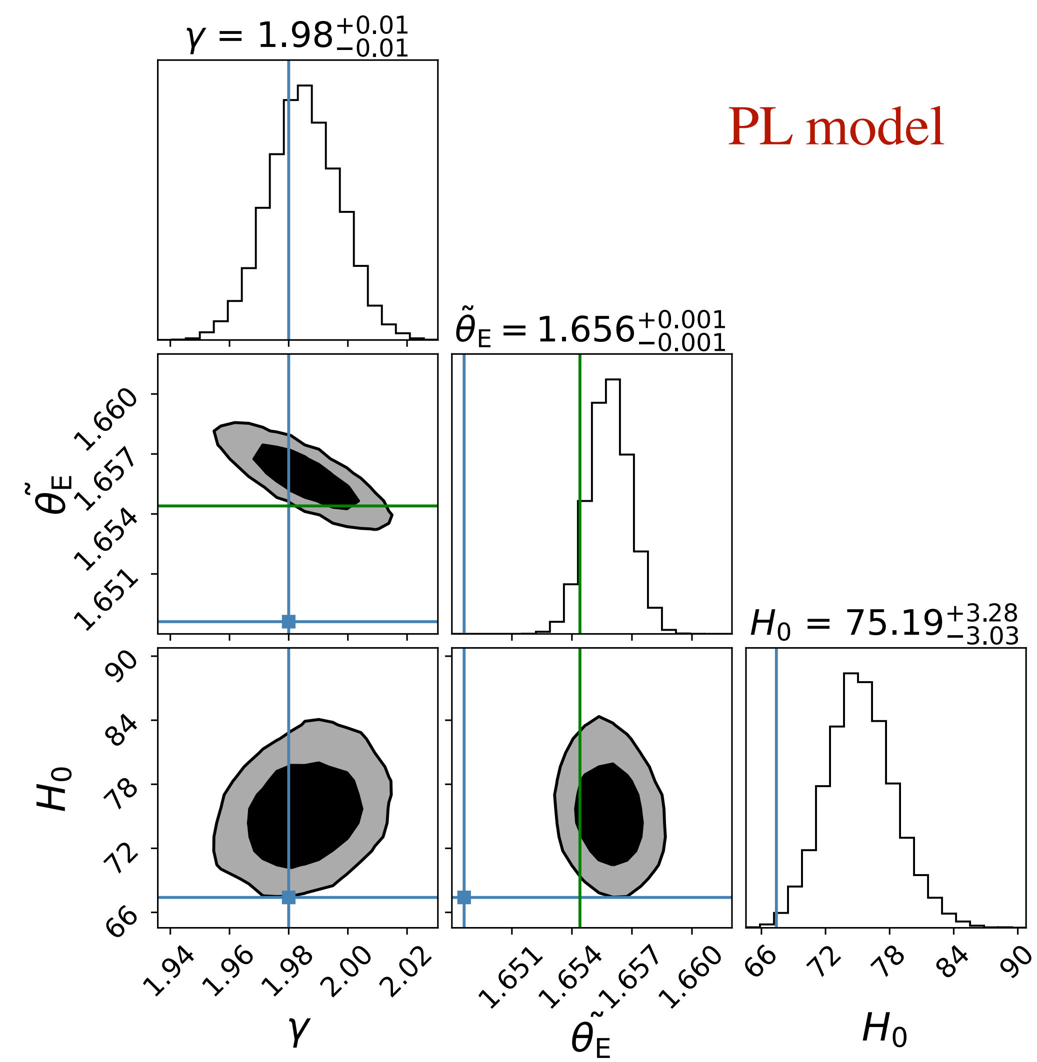

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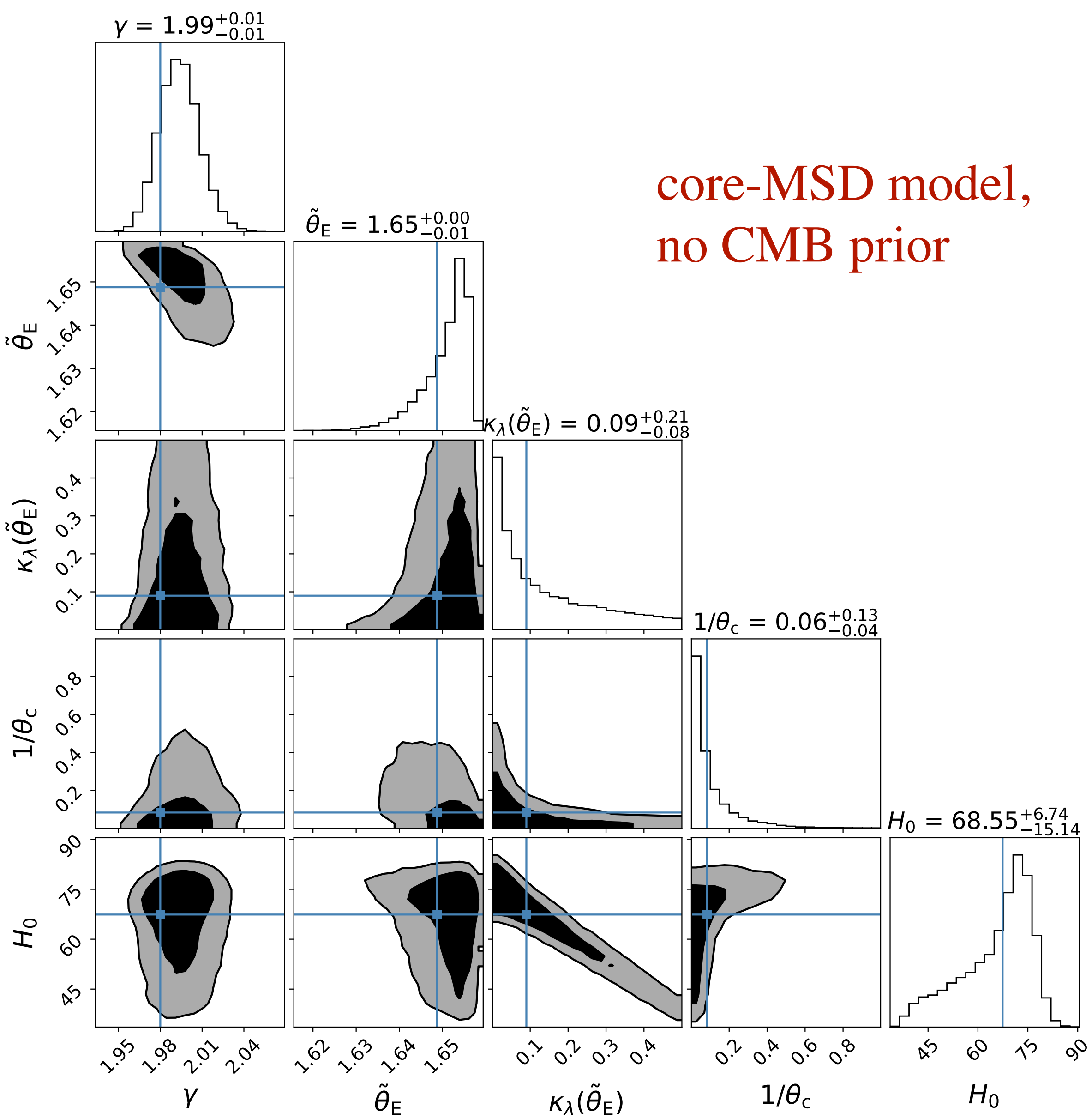
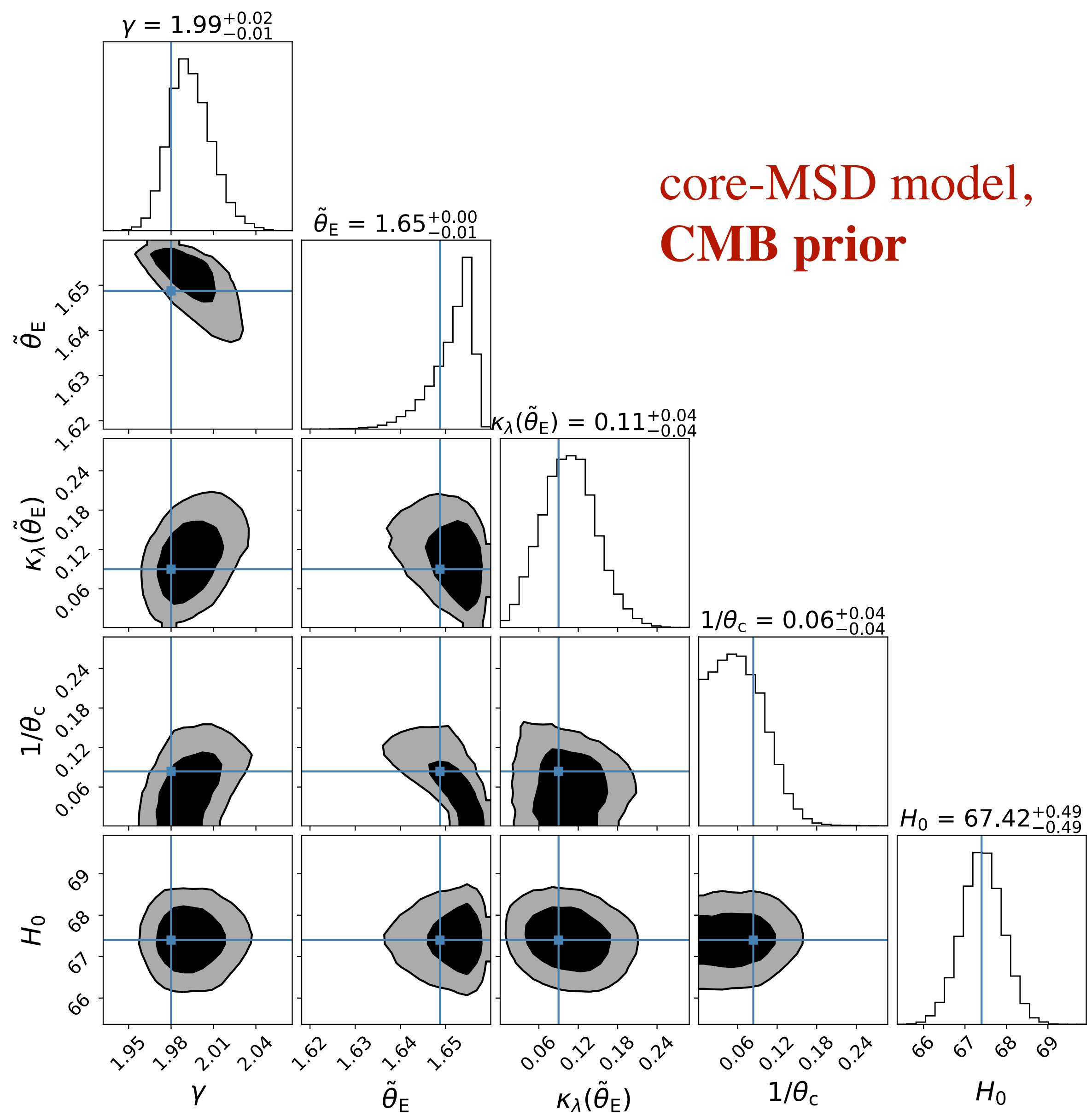


core-MSD model,
no CMB prior



core-MSD model,
CMB prior

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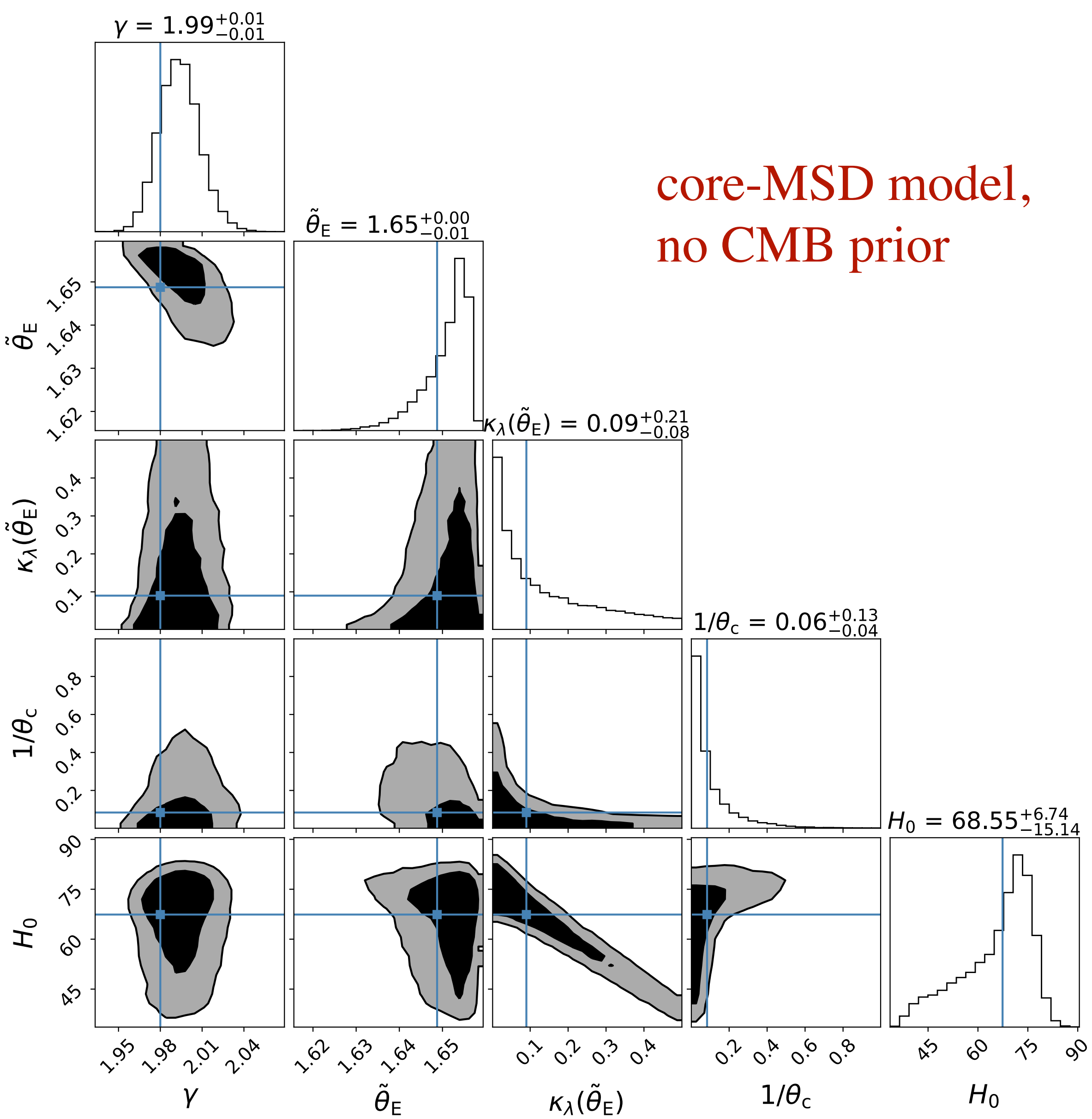
Expect evidence for core component, reflecting precision on H0

KB, Teodori, 2105.10873

Could reach >2σ *per system*



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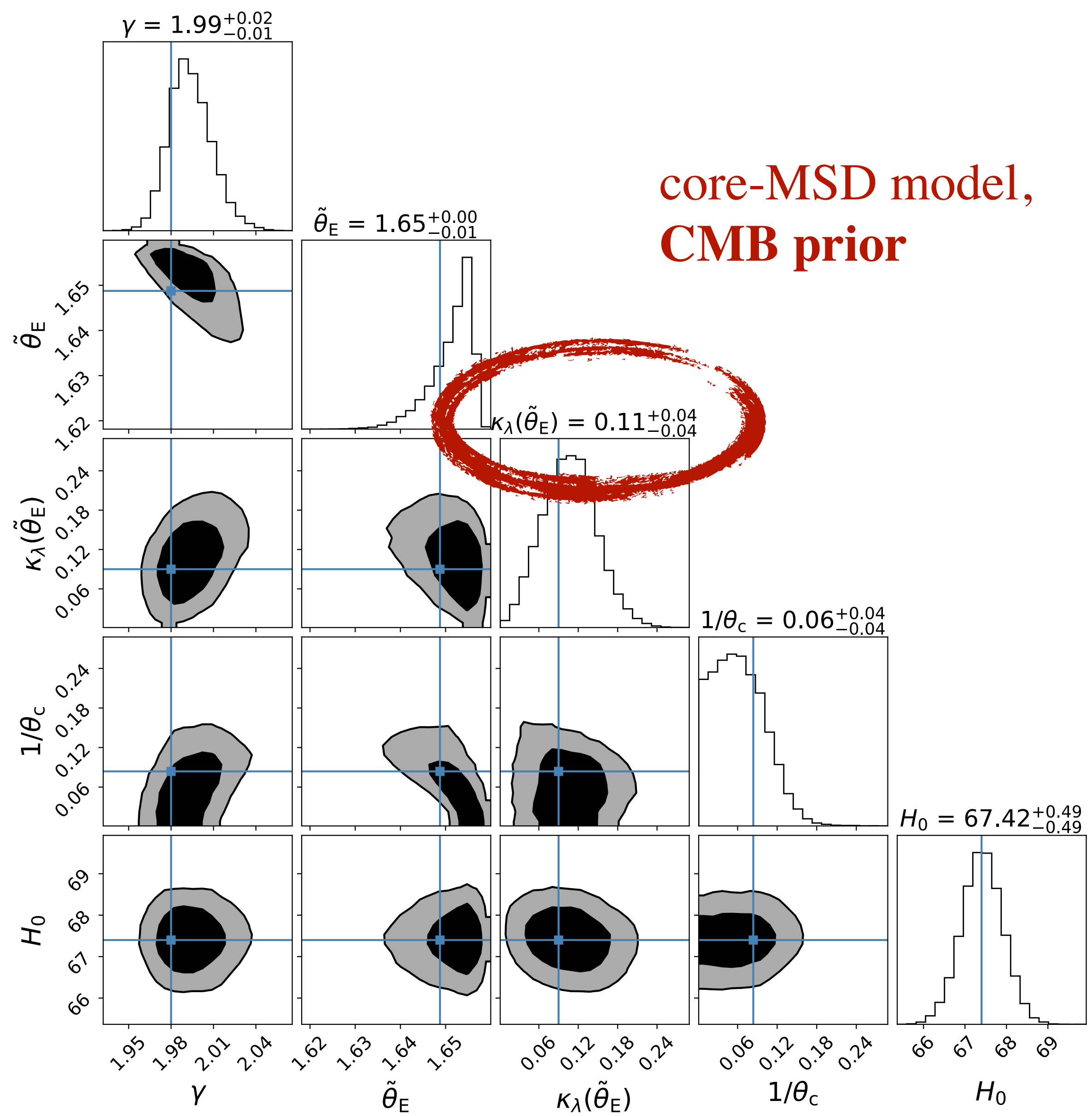

core-MSD model,
CMB prior

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

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

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

KB, Castorina, Simonovic 2020

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TDCOSMO + SLACS$_{\rm IFU}$	$73.3^{+5.8}_{-5.8}$	$1.00^{+0.08}_{-0.08}$	$-0.07^{+0.06}_{-0.06}$	$0.07^{+0.09}_{-0.05}$	$1.58^{+1.58}_{-0.54}$	$0.15^{+0.47}_{-0.13}$	-
TDCOSMO + SLACS$_{\rm SDSS}$	$67.4^{+4.3}_{-4.7}$	$0.91^{+0.05}_{-0.06}$	$-0.04^{+0.04}_{-0.04}$	$0.02^{+0.04}_{-0.01}$	$1.52^{+1.76}_{-0.70}$	$0.28^{+0.45}_{-0.25}$	$0.06^{+0.02}_{-0.02}$
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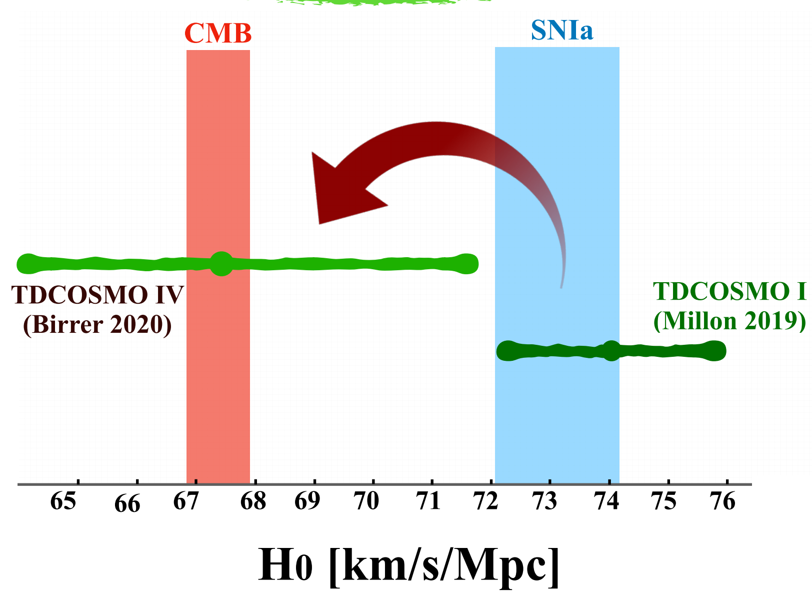

Hint from SLACS *kinematics?*

(but see comments in KB, Teodori, 2105.10873)

KB, Castorina, Simonovic 2020

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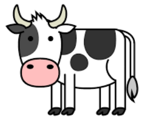
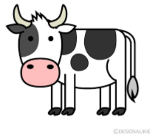
``Internal MSD" may require a non-minimal density profile.

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

``Internal MSD" 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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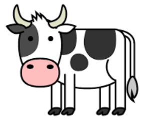
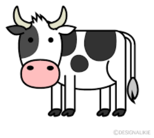


Why would galaxies be non-minimal?

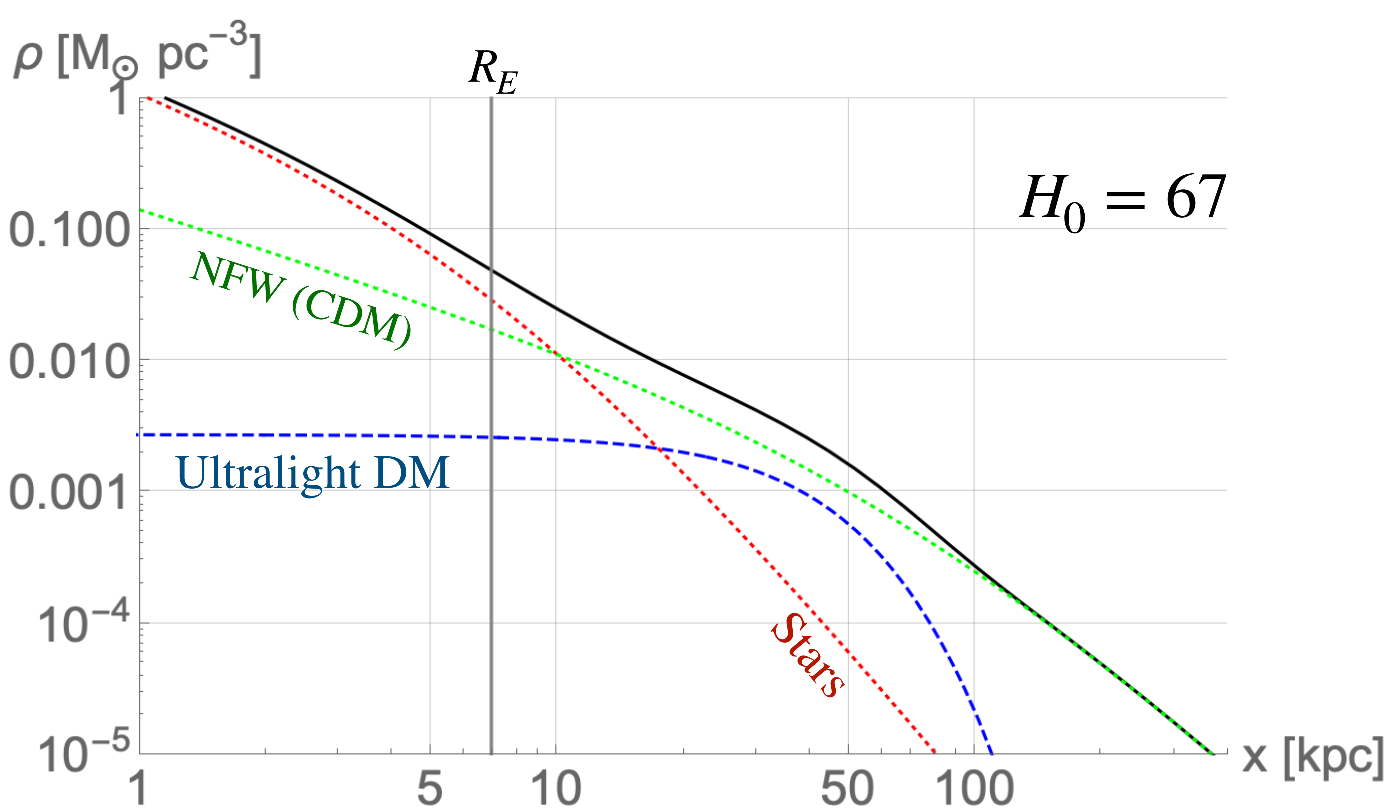
Why not? (What is dark matter?)



Why should galaxies have a core component?

Can think of several reasons.

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

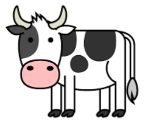


KB, Teodori, 2105.10873

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

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

``Internal MSD” may require a non-minimal density profile.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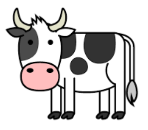
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``Missing” baryons?

X-ray: NASA/CXC/SAO/S.Randall et al., Optical: SDSS

Werner & Mernier, 2001.10023

Mass models of TDCOSMO lens systems: stars/DM ~ 0.05.

Much below cosmological baryon/DM ratio.
This is typical, puzzle of missing baryons.

Missing baryons probably in extended CGM.

What is the convergence due to the CGM?
— What is the radial scale of the CGM?

Should have enough mass to make an effect, *if mostly within ~50 kpc*.

Summary

Lensing H_0 sensitive to galaxy profile at few % level:
Feature in the galaxy profile, or breakdown of ΛCDM ?

Weak lensing: include all segments of line of sight.
Lacking in published results. Likely ~ % bias on H_0.

Teodori, et al, 2201.05111

Adding a core to a density profile is an approximate MSD.
10% core explains the lensing H_0 tension?

KB, Castorina, Simonović 2001.07182

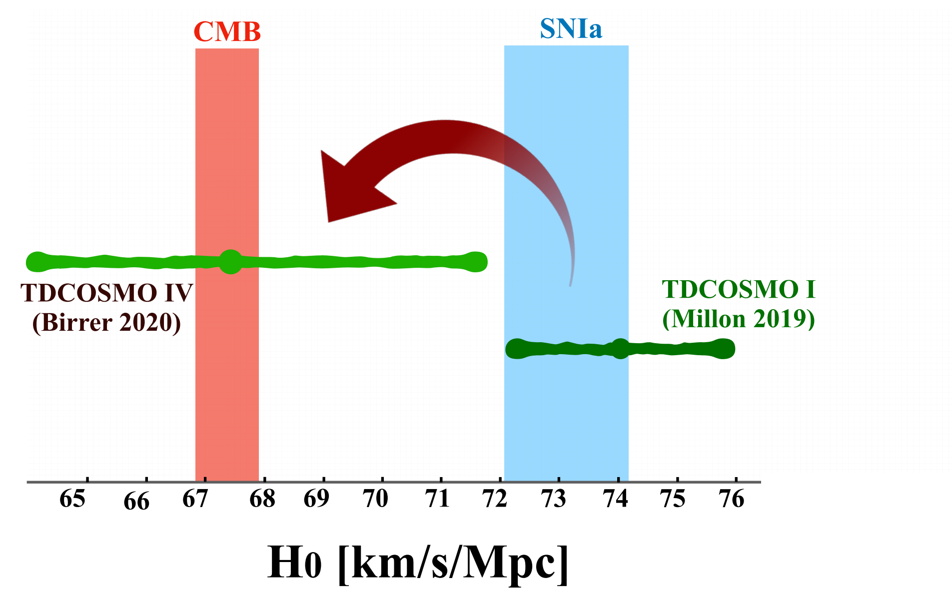
Could point to interesting dark matter dynamics.
If we go there, may as well adopt CMB (*or SNIa!*) prior on H_0.

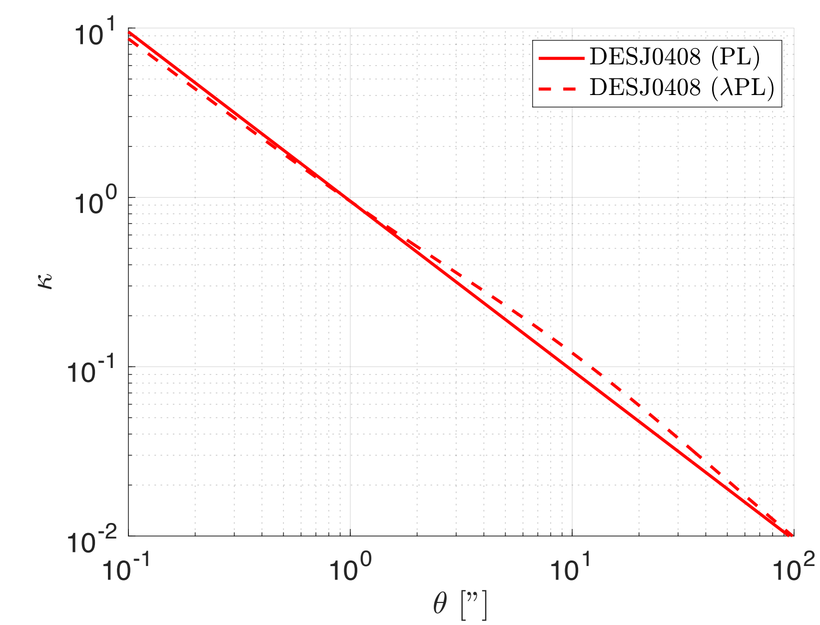
Ultralight DM (axion-like):

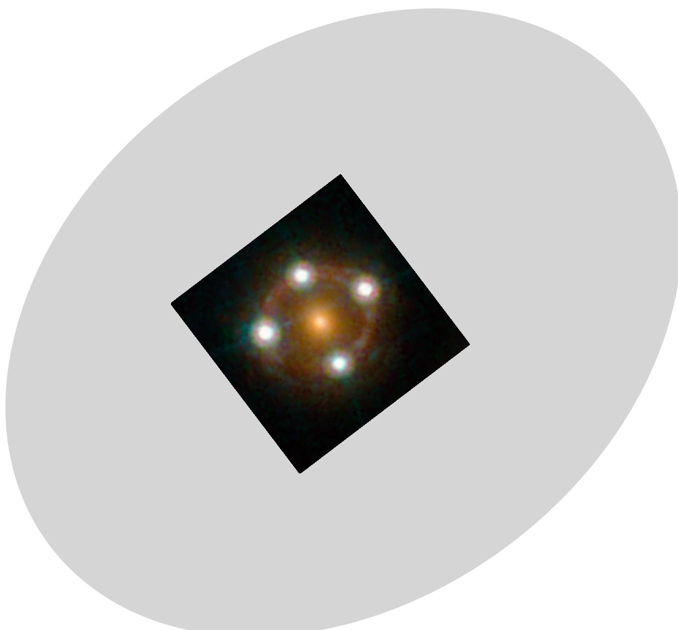
Vanilla vacuum misalignment. Dynamically makes a core.
Correct ballpark to solve lensing H_0 tension, if
Dynamical relaxation consistent at O(1) level. $10^{-25}\ \mathrm{eV} \lesssim m \lesssim 10^{-24}\ \mathrm{eV}$

KB, Teodori 2105.10873

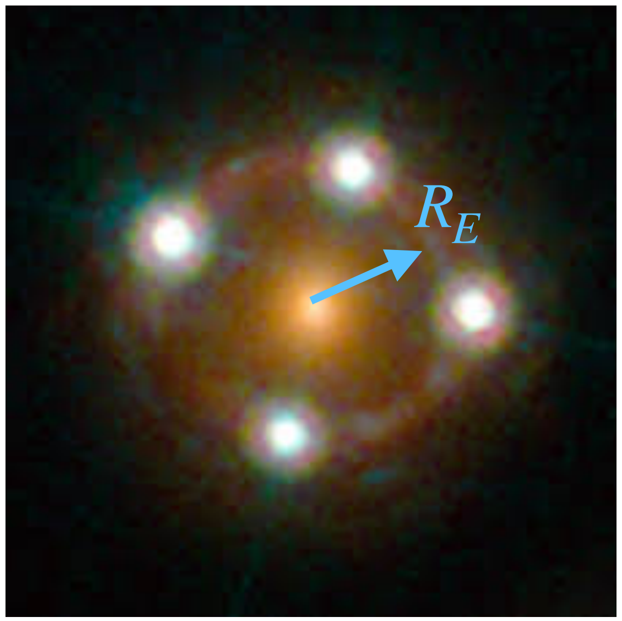
Thank you!







Xtra



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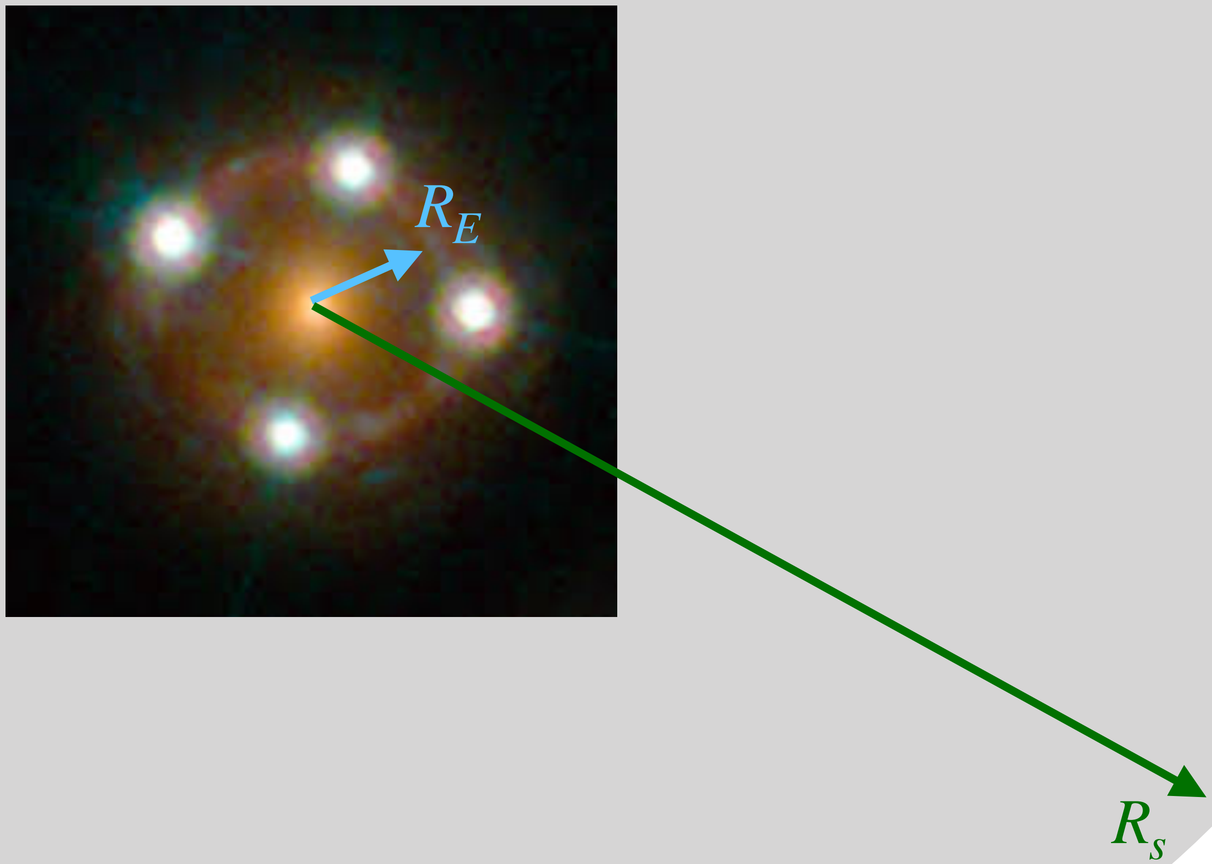
DESJ0408	$74.6^{+2.5}_{-2.9}$	$0.9^{+0.03}_{-0.03}$	2	1.9	13	0.6	Shajib et al. (2019)
WFI2033	$72.6^{+3.3}_{-3.5}$	$0.92^{+0.05}_{-0.04}$	1.95	0.9	11	0.6575	Rusu et al. (2019)
J1206	$67.0^{+5.7}_{-4.8}$	$1^{+0.08}_{-0.08}$	1.95	1.2	4.7	0.745	Birrer et al. (2019)



	H_0	$\lambda = 67/H_0$	γ	θ_E ["]	θ_s ["]	lens redshift z_l	ref
RXJ1131	$76.1^{+3.6}_{-4.3}$	$0.88^{+0.06}_{-0.04}$	1.98	1.6	19	0.295	Chen et al. (2016)
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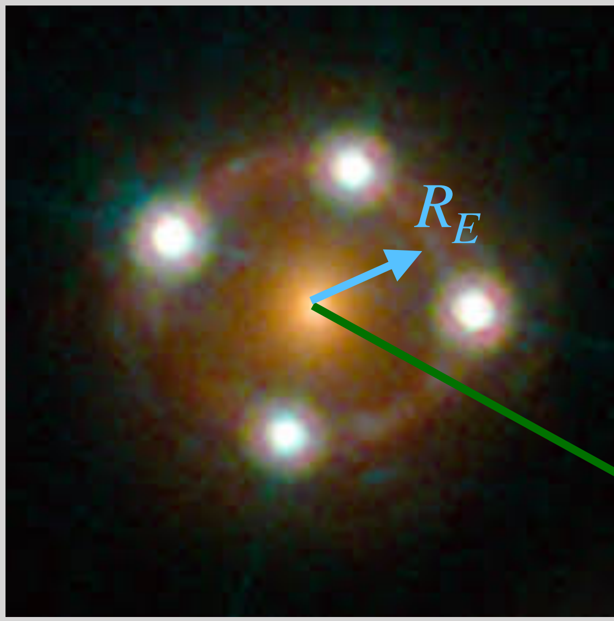

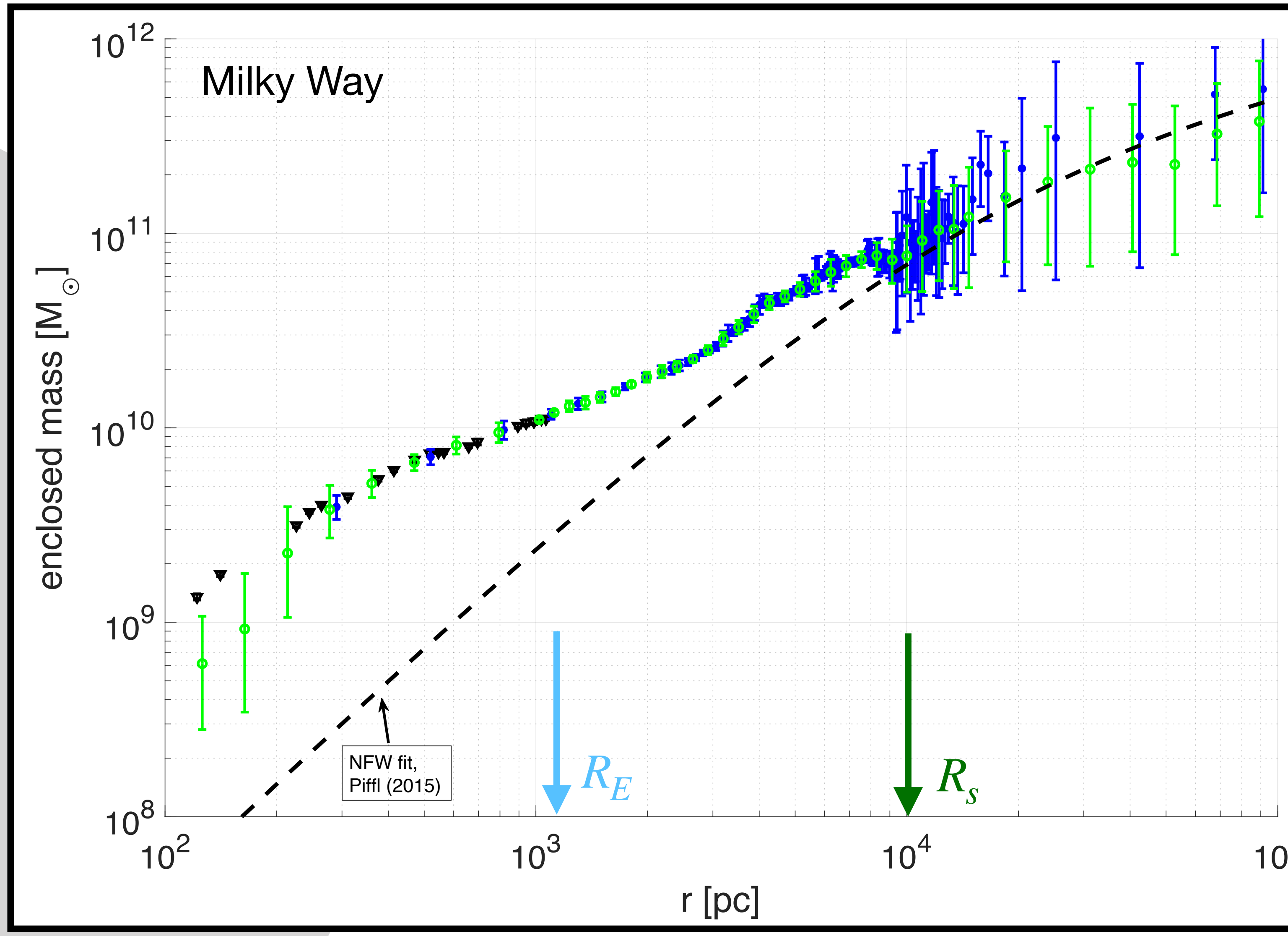

R_s

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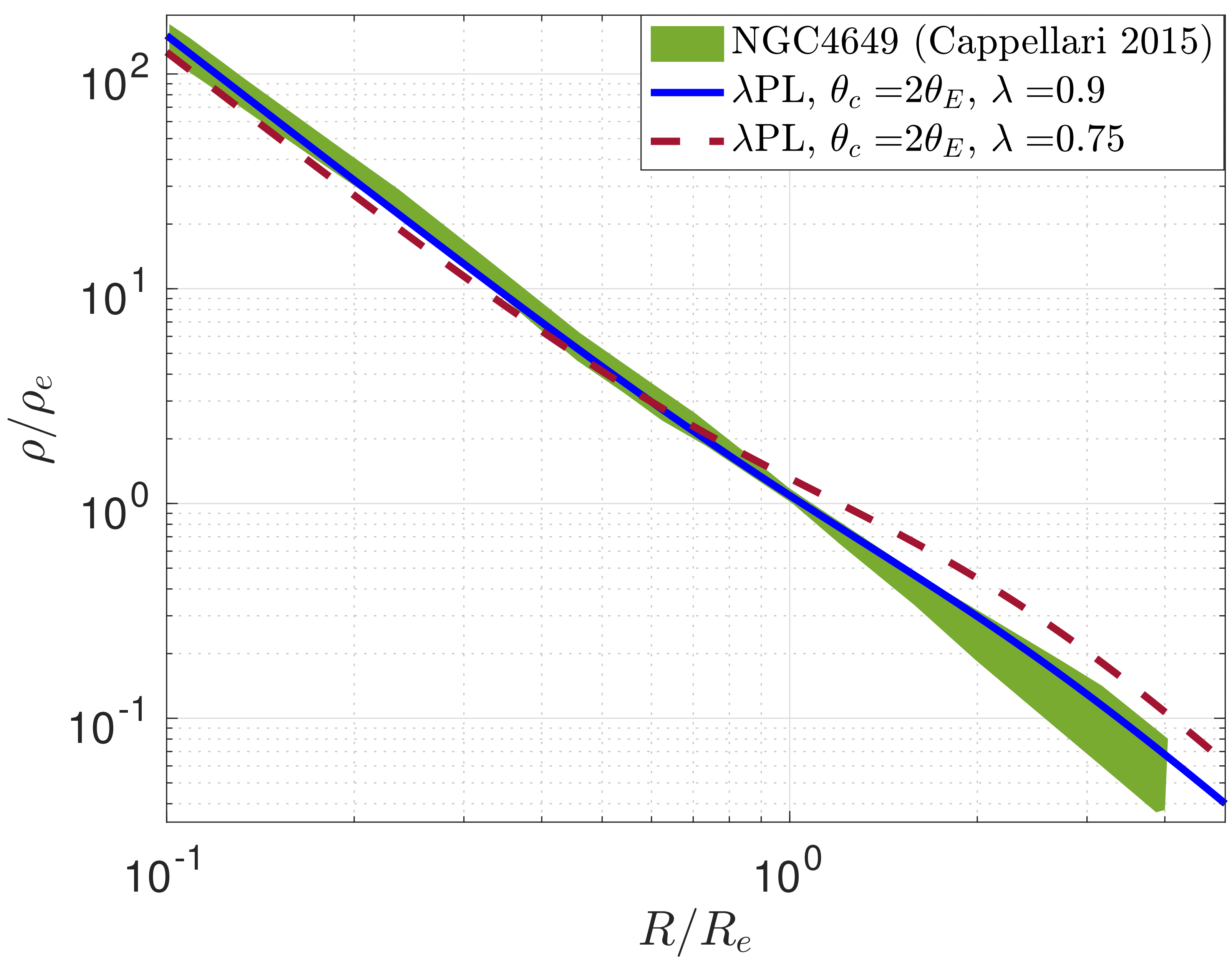
Stellar kinematics (of *other* elliptical galaxies)

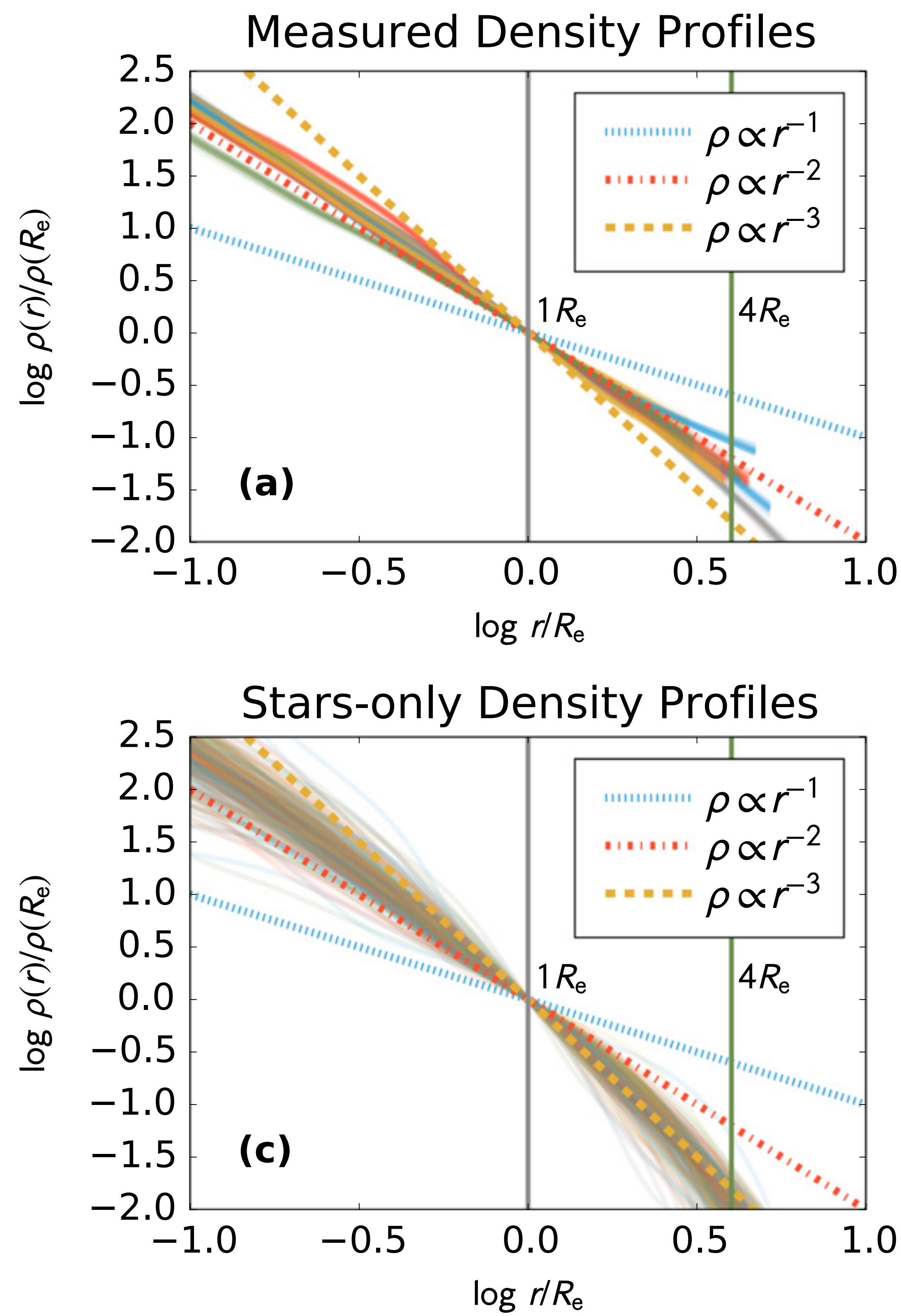


Stellar kinematics (of *other* elliptical galaxies)

Cappellari et al, 1504.00075

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

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 $\sigma_j < R_{\rm e}$; (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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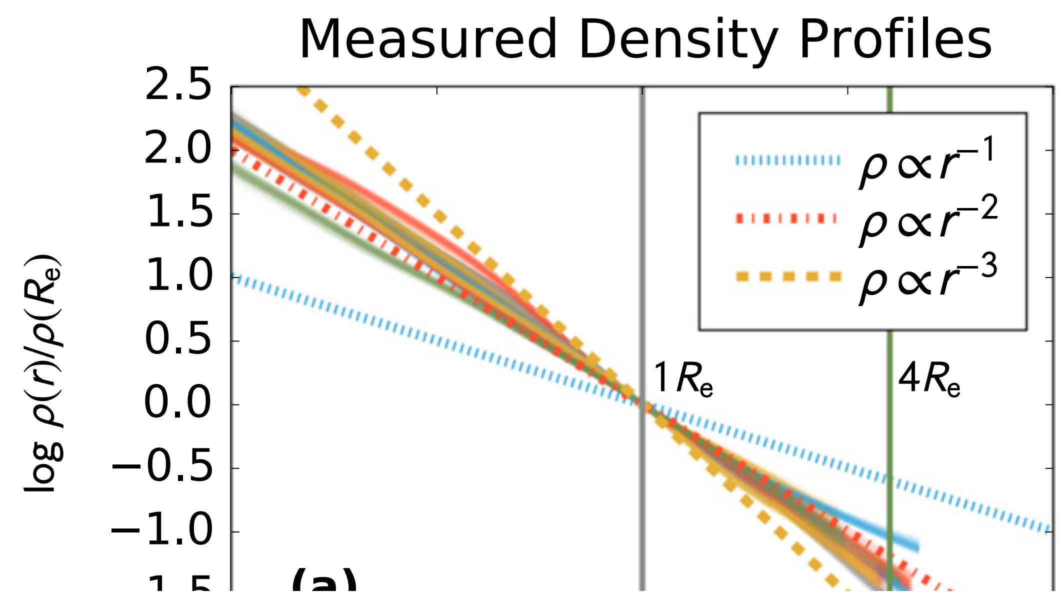
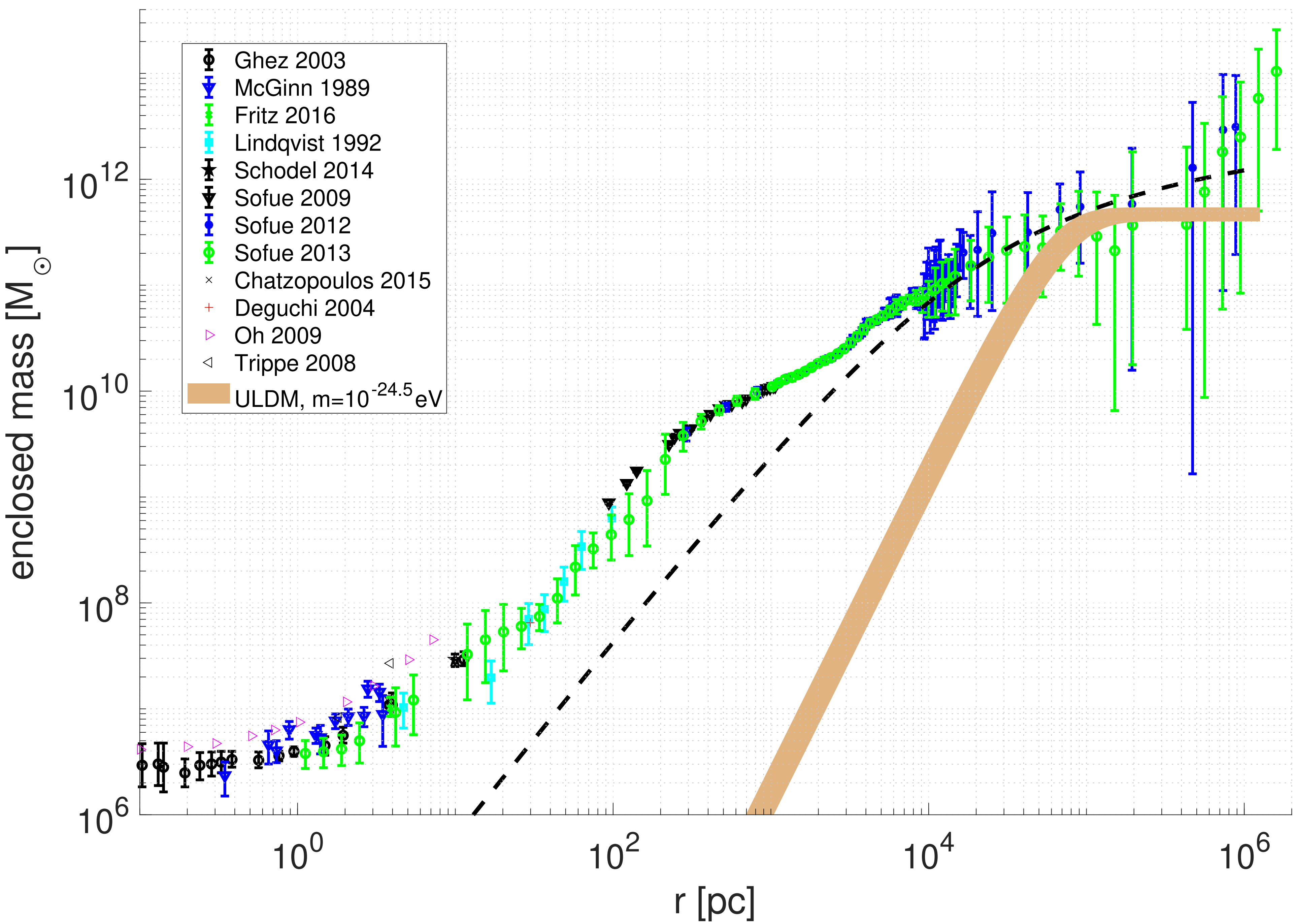


A friend:

...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 dark matter (ULDM)

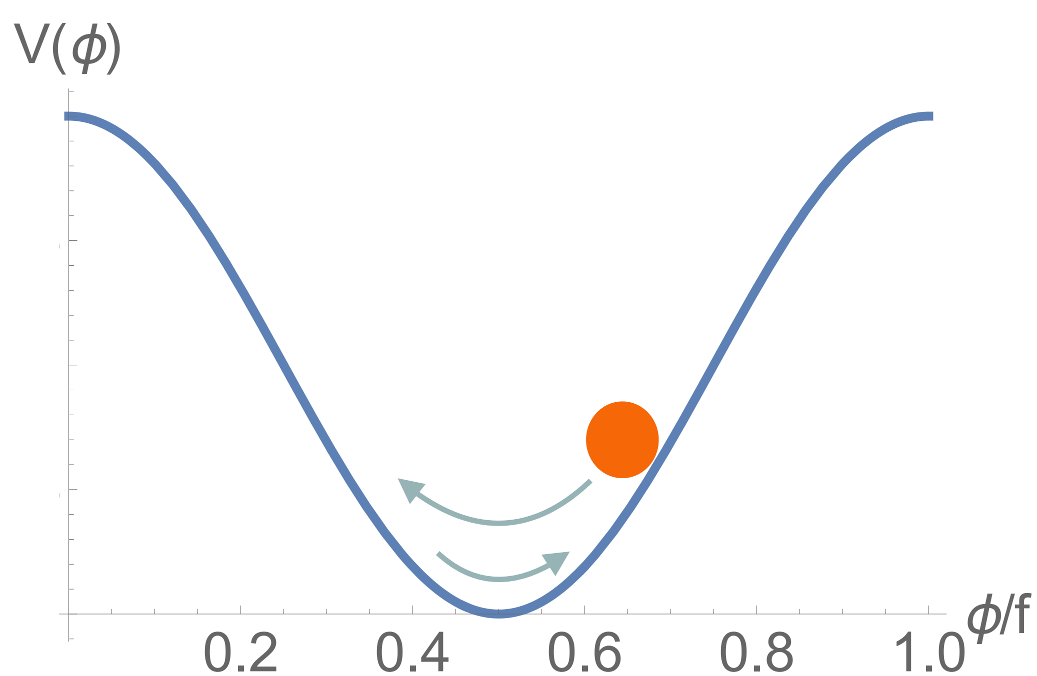
Light fields (Goldstone bosons) feature in many models. Svrcek & Witten 2006; Arvanitaki et al 2010

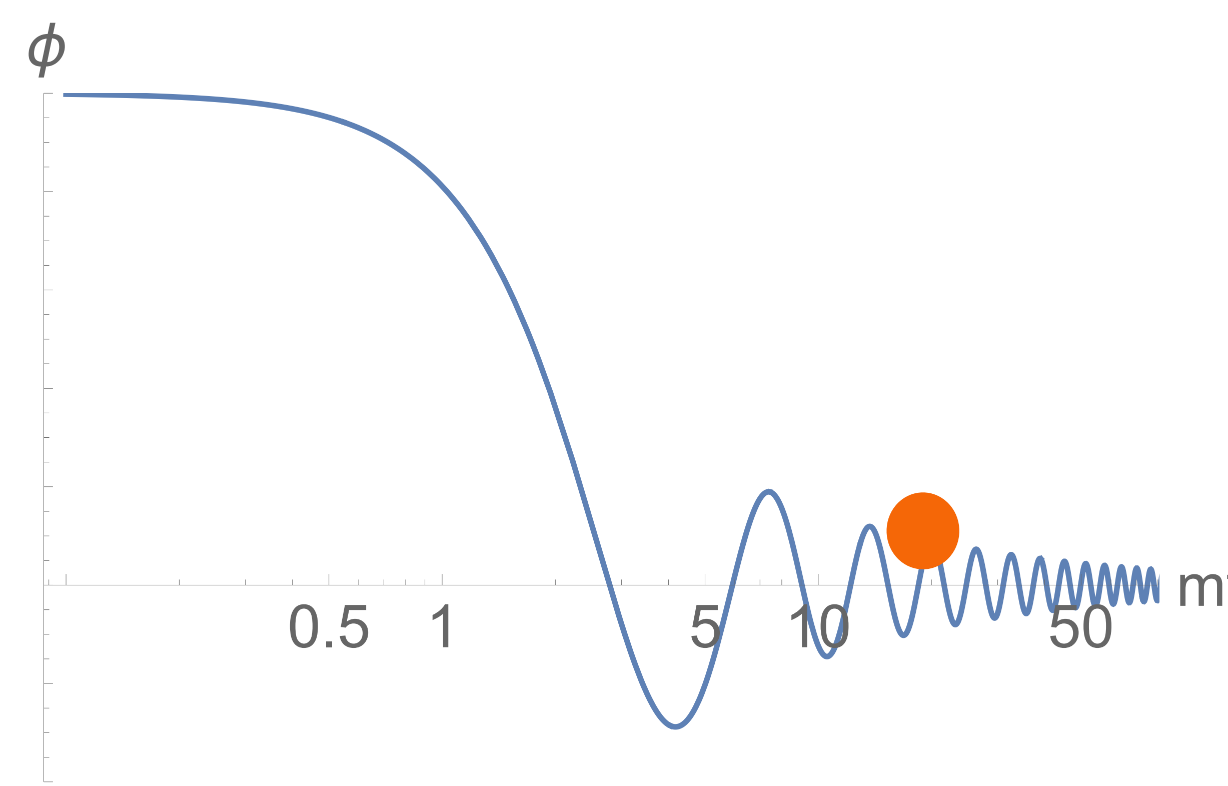
Cosmology: field initially displaced from minimum of the potential, starts to oscillate when $t \sim 1/m$.

When $t \gg 1/m$, correct equation of state for dark matter.

Contribution to energy density today:

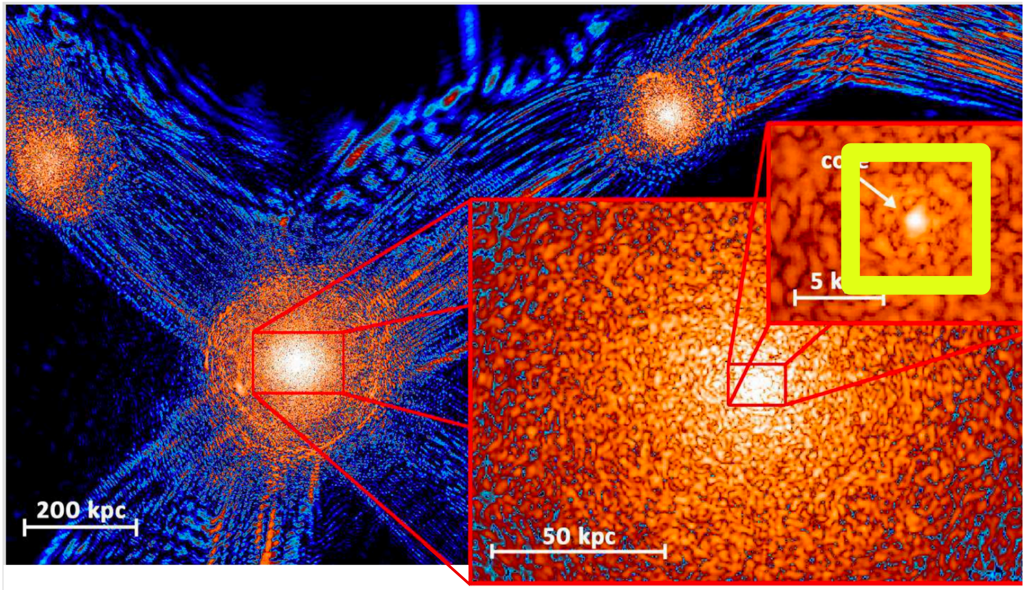
$$\Omega_m \approx 0.3 \left(\frac{m}{10^{-21}\ \text{eV}}\right)^{\frac{1}{2}} \left(\frac{f}{10^{17}\ \text{GeV}}\right)^2$$



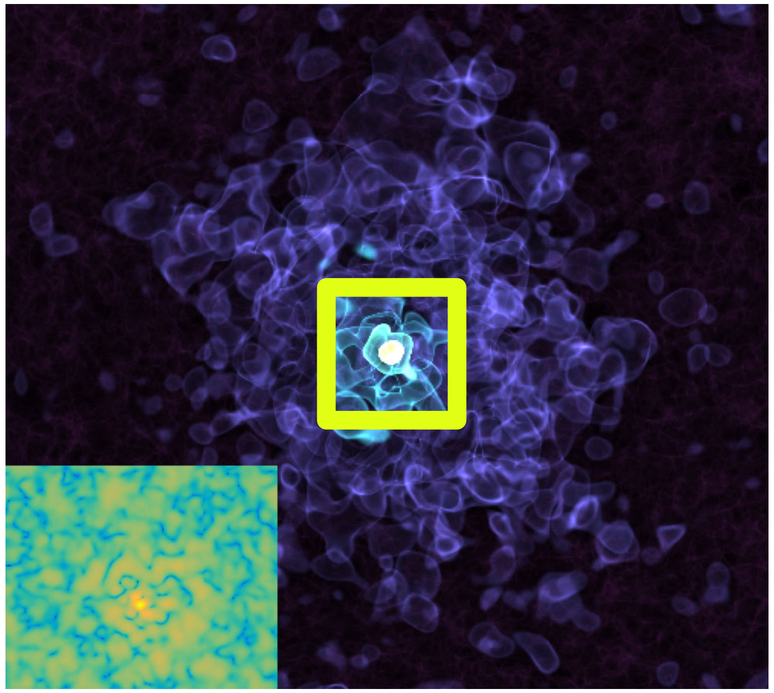


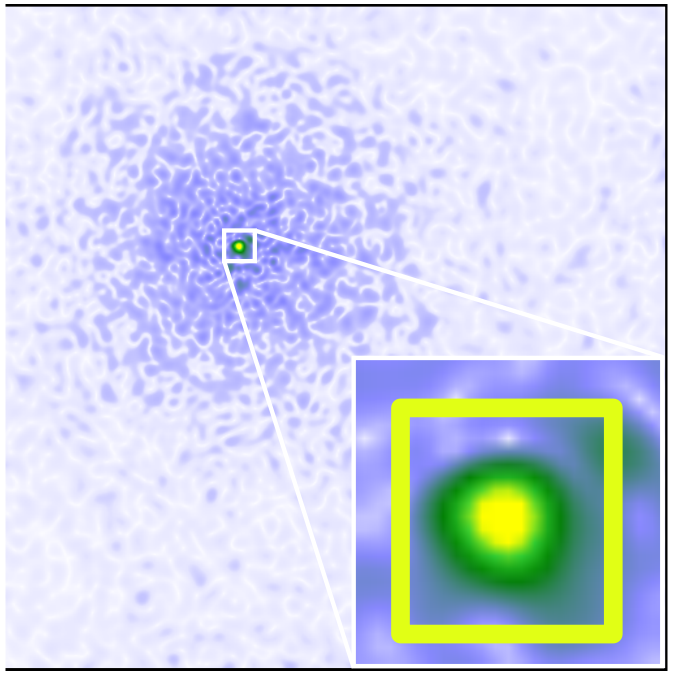
ULDM in galaxies

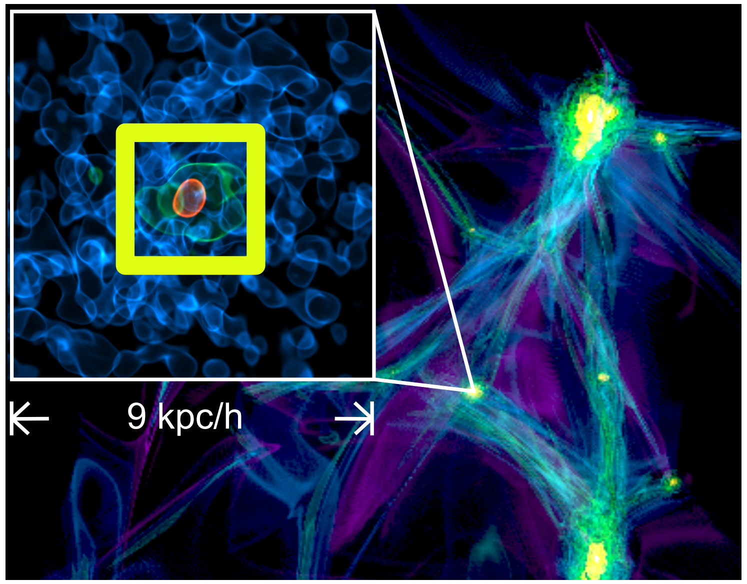
Inner part of simulated galaxies forms a **core**



Schive et al 2014


Mocz et al 2017


Levkov et al 2018



Veltmaat et al 2018

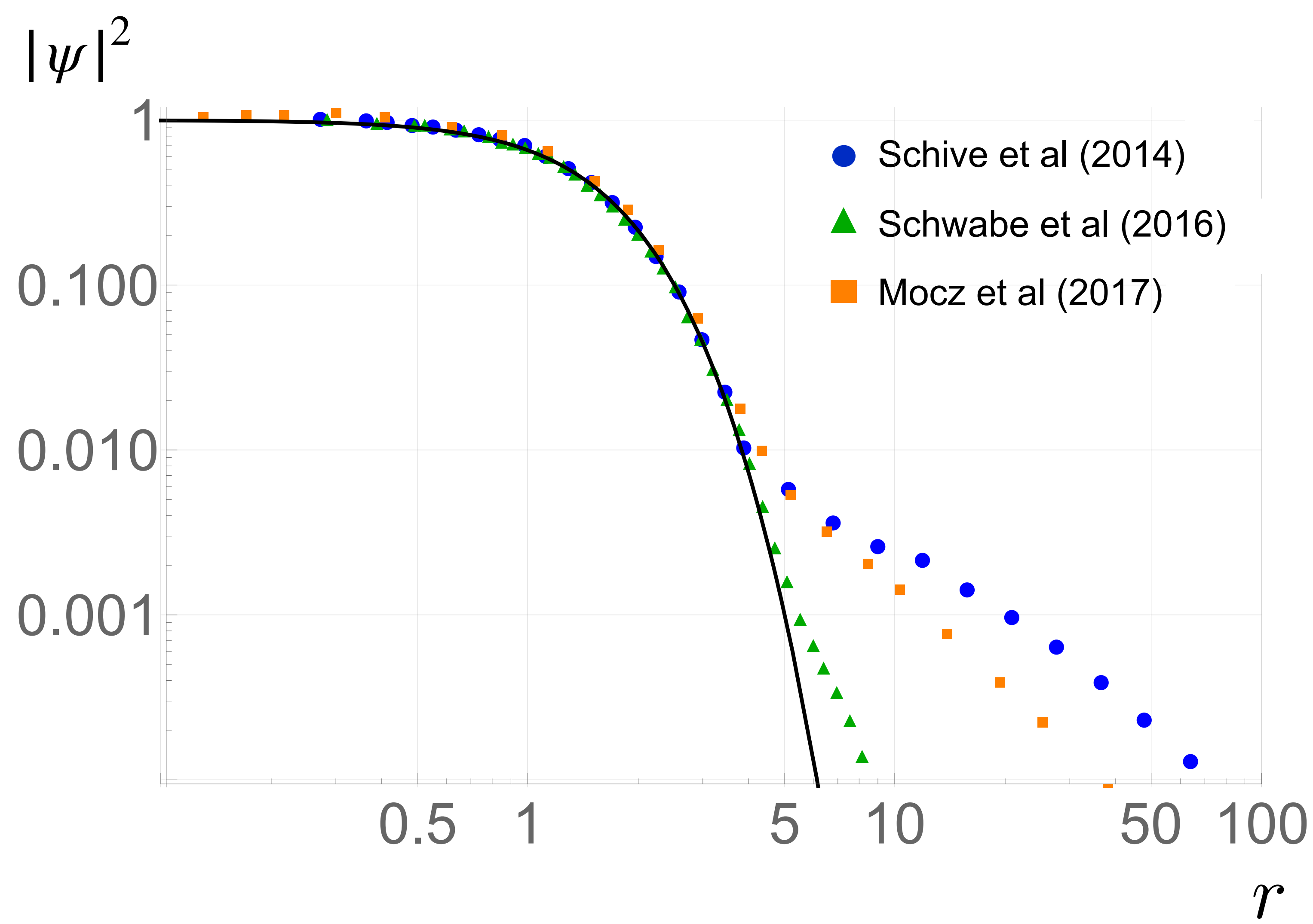
Self-gravitating ULDM / Nonrelativistic limit

Free scalar field $\phi(x,t) = \frac{1}{\sqrt{2m}} e^{-imt} \psi(x,t) + cc$

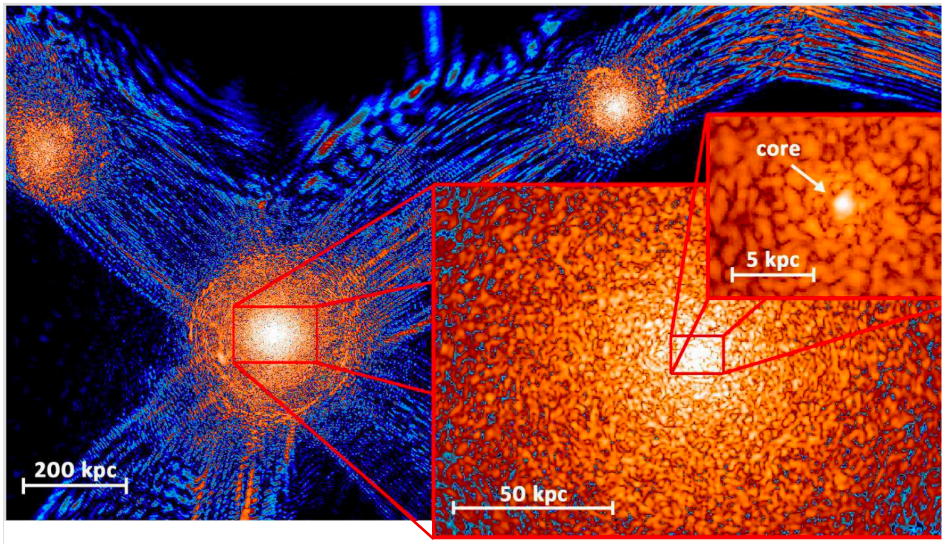
On scales of order de Broglie wavelength: coherent ground state

Numerical simulations find the ground state.

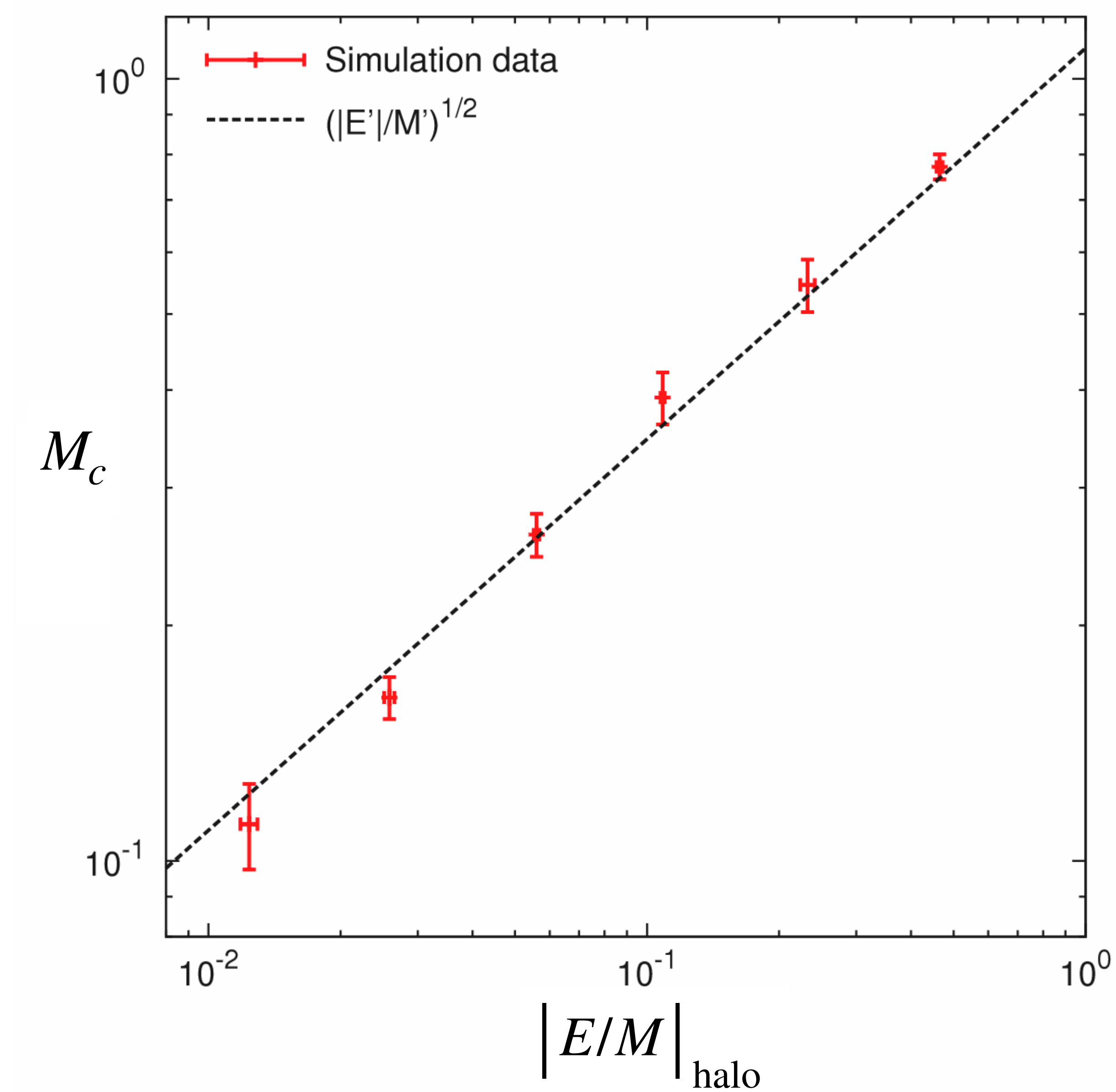
Bar, Blas, KB, Sibiryakov 2018



Core — halo relation: empirical evidence



Schive et al 2014; Veltmaat et al 2018

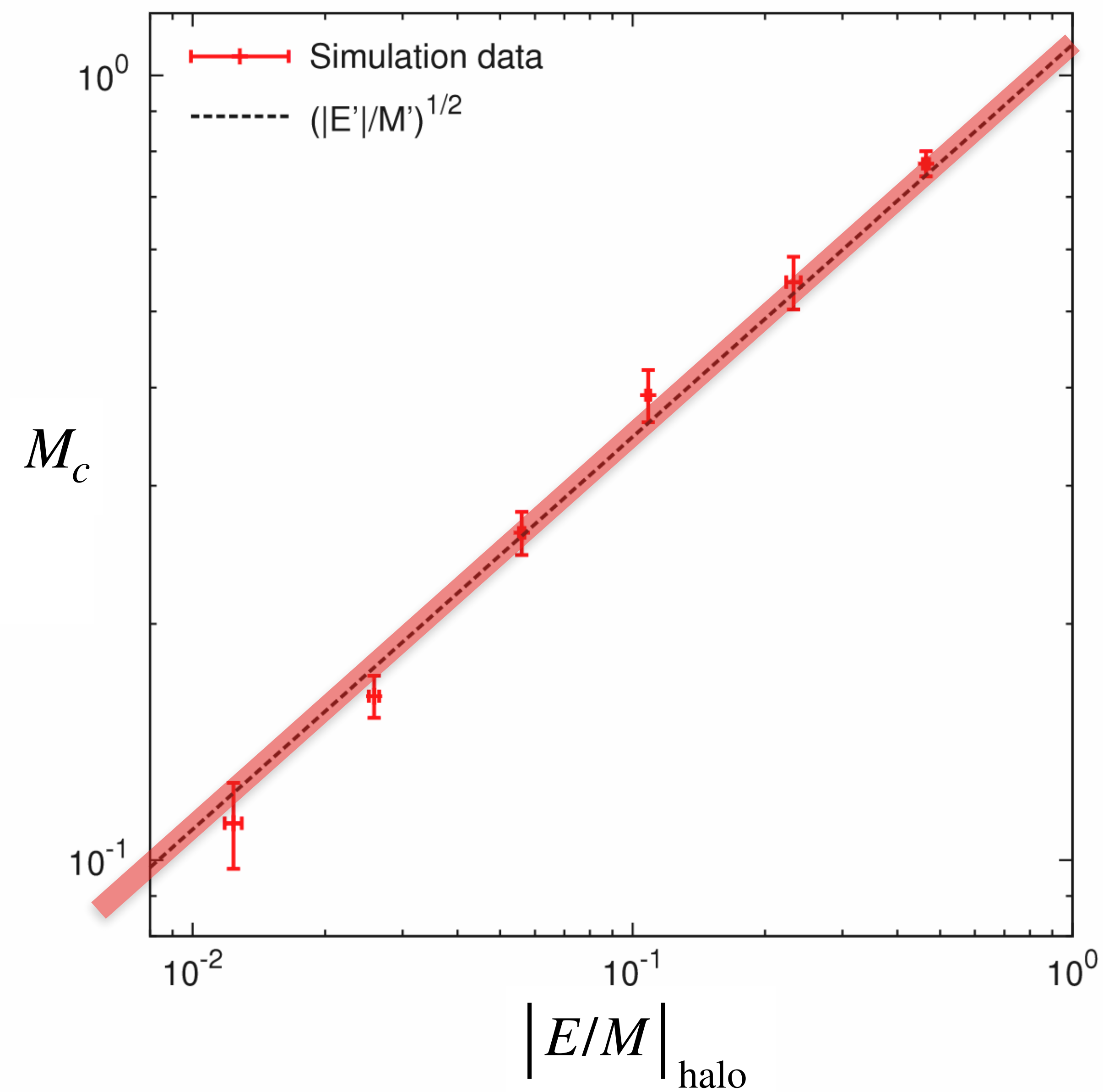


Core — halo relation: theoretical insight

Bar, Blas, KB, Sibiryakov 2018
Bar, KB, Sato, Eby 2019

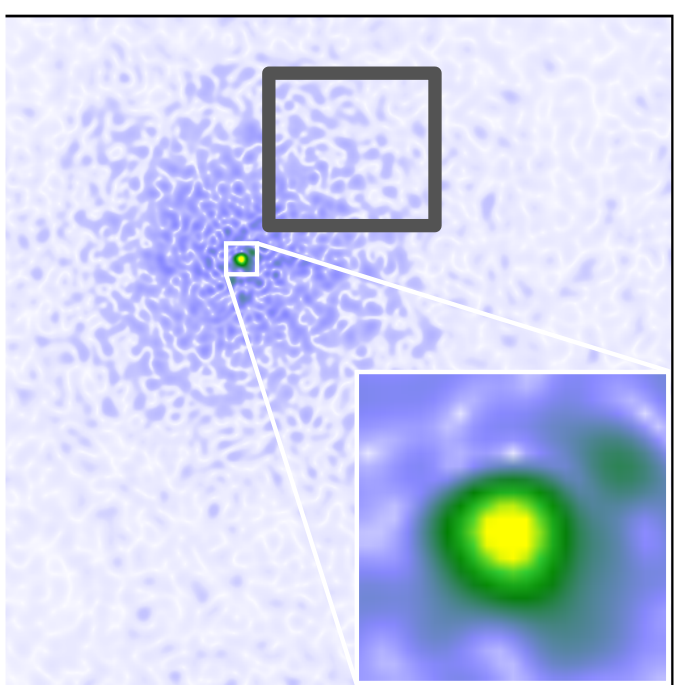
$$\boxed{\left.\frac{K}{M}\right|_{\rm core} = \left.\frac{K}{M}\right|_{\rm halo}}$$

Schive et al 2014; Veltmaat et al 2018



Dynamical relaxation:

Hui et al 2017; Bar-Or, Tremaine 2018
Bar, KB, Lacroix, Panci 2019

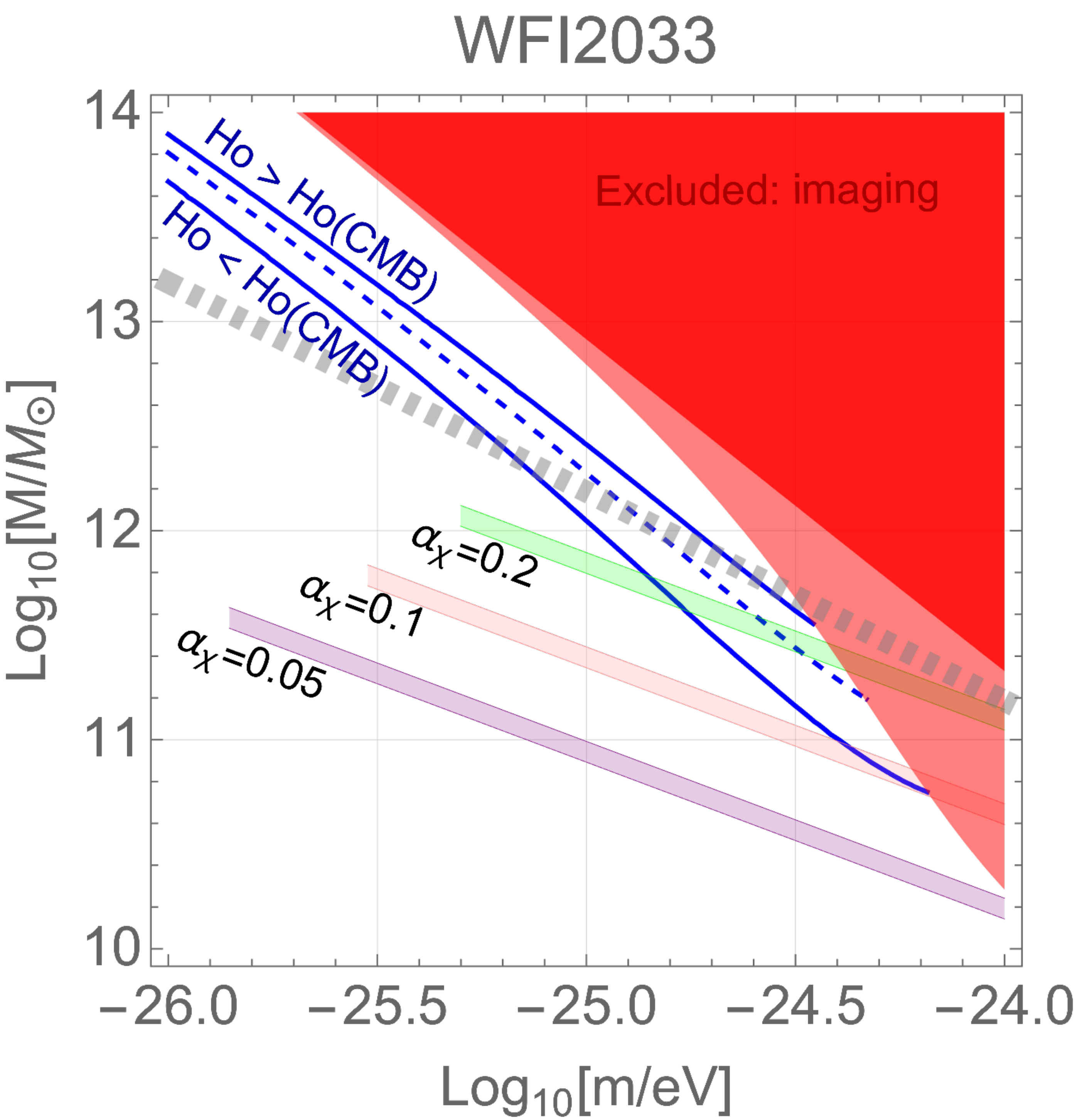


Levkov et al 2018

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

Also:
Eggemeier, Niemeyer 2019,
Chen et al 2020,
Schwabe et al 2020

ULDM as a solution of the lensing H_0 tension?



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

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

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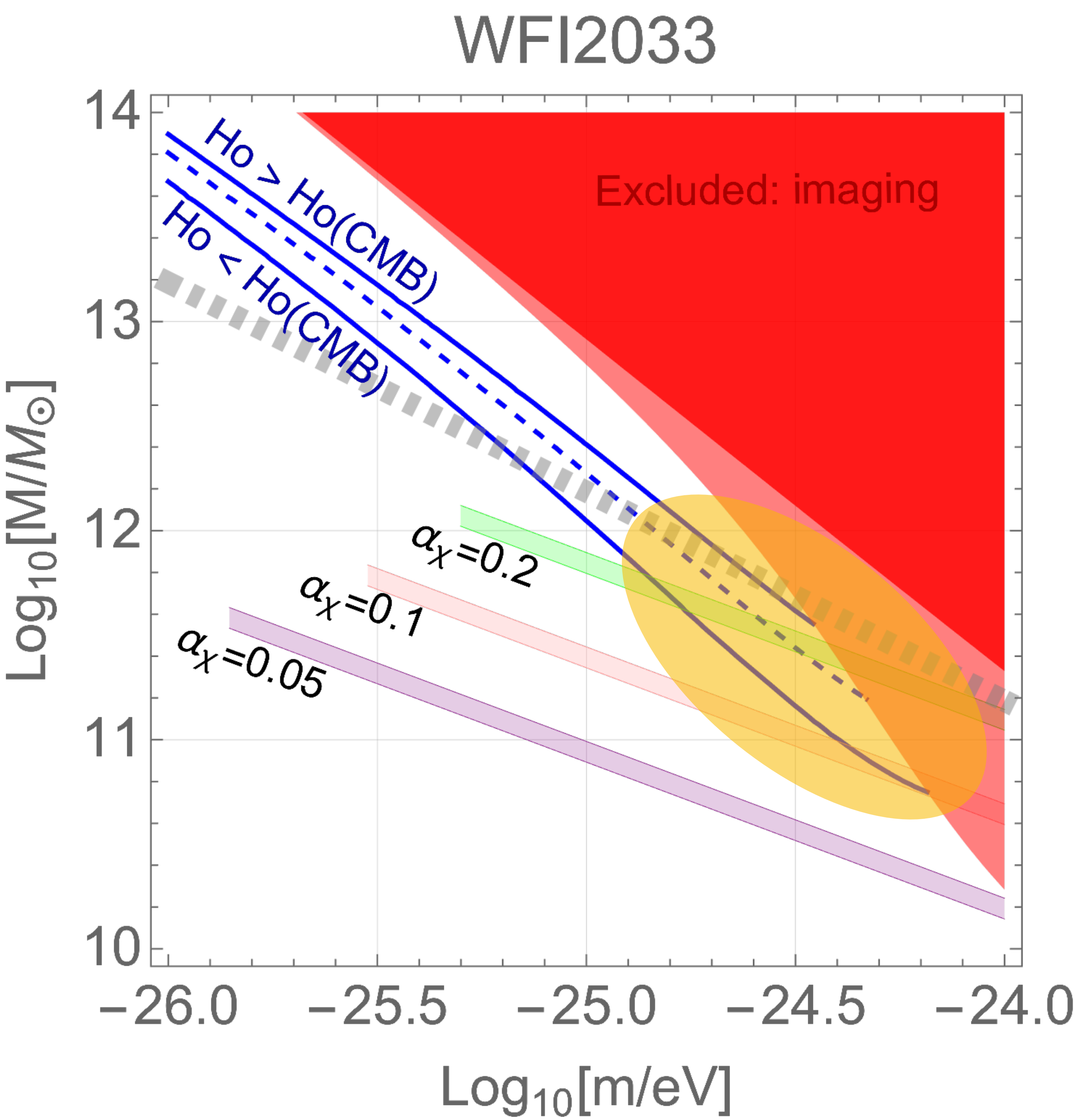

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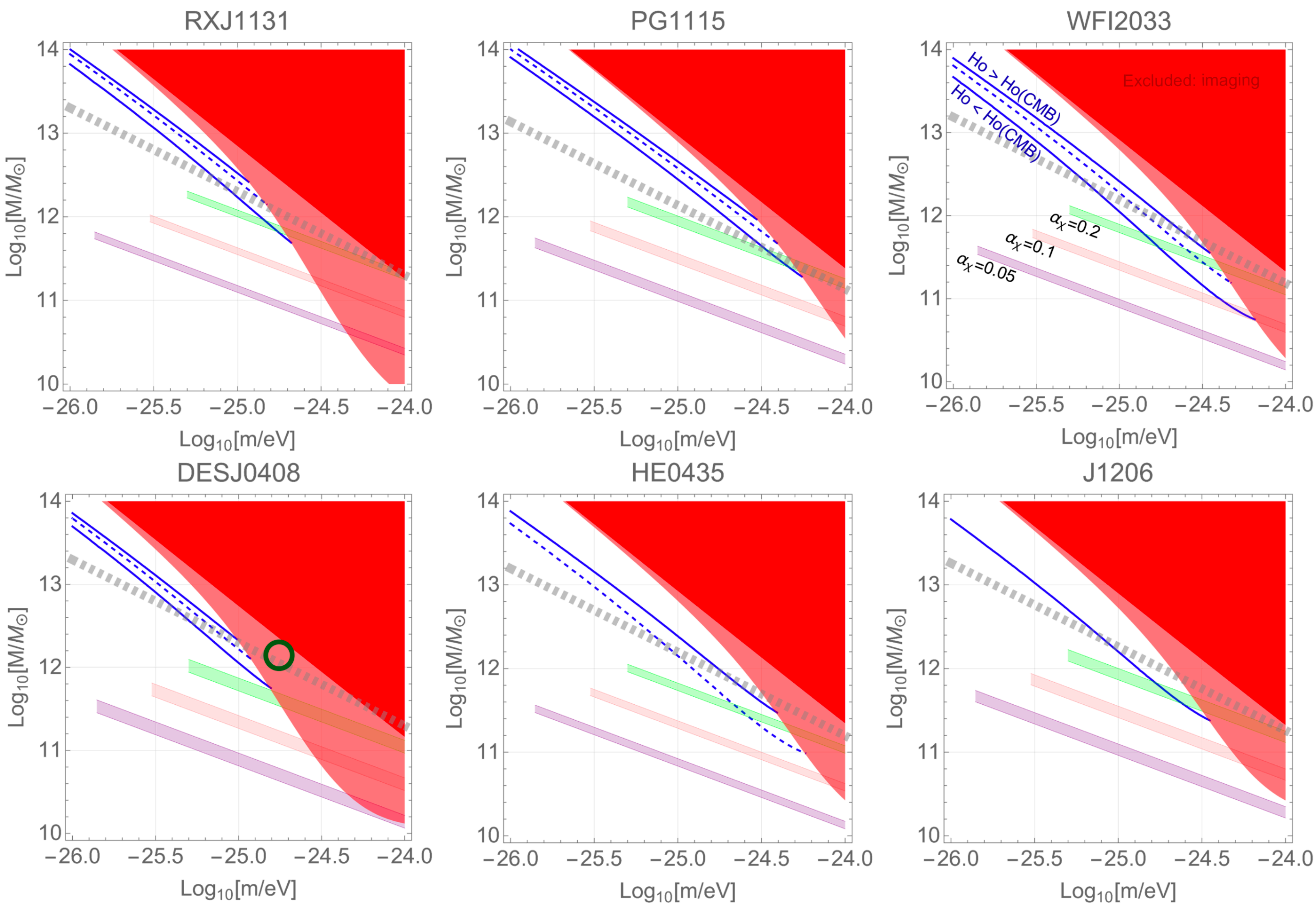
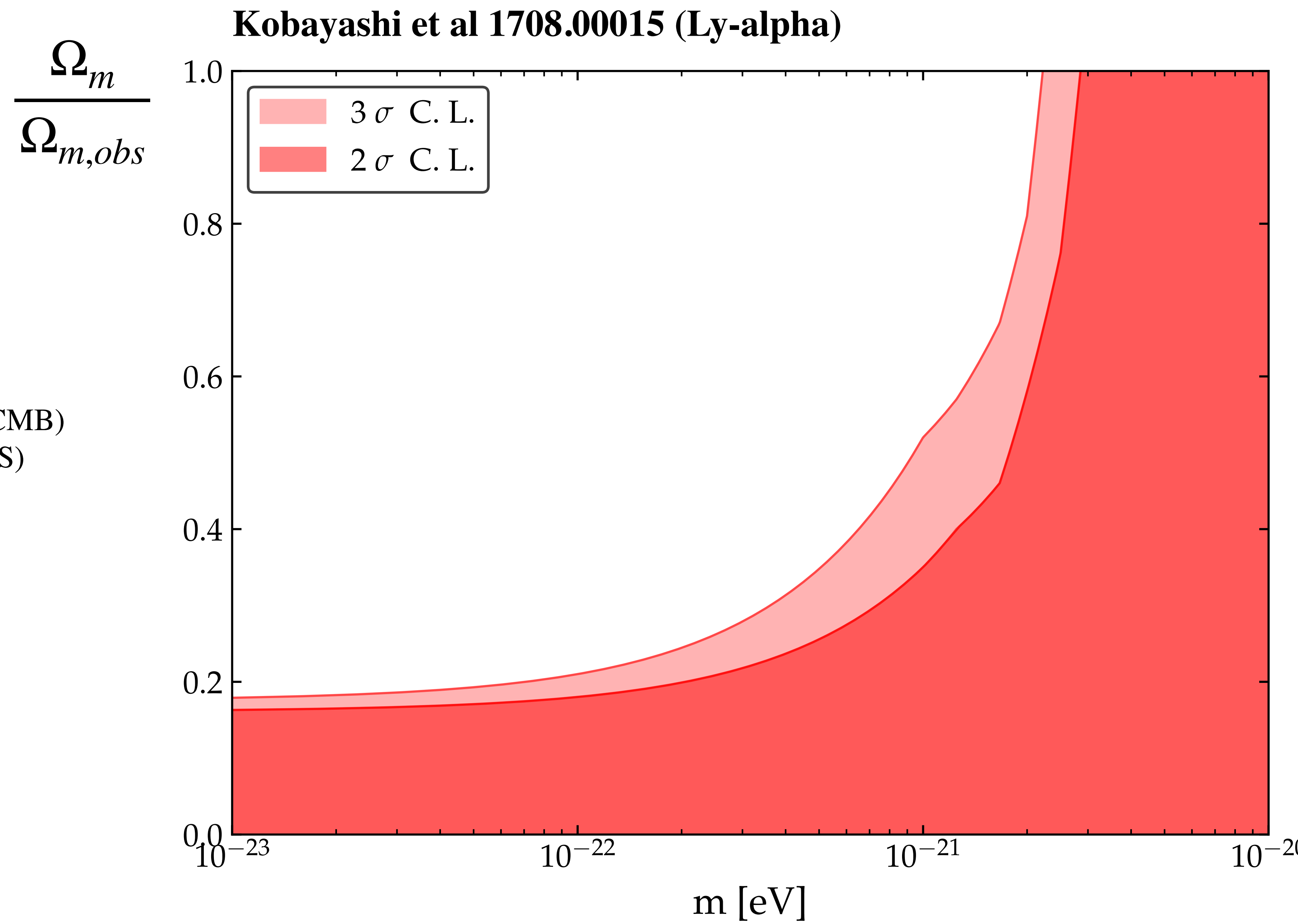


Cosmological constraints: ULDM can only make up a fraction of the DM



Also:
Hlozek, Marsh, Grin 1708.05681 (CMB)
Lague et al, 2104.07802 (CMB+LSS)

$$\frac{\Omega_m}{\Omega_{m,obs}} \approx \left(\frac{m}{10^{-21}\ \mathrm{eV}}\right)^{\frac{1}{2}} \left(\frac{f}{10^{17}\ \mathrm{GeV}}\right)^{2} \approx 0.1 \left(\frac{m}{10^{-25}\ \mathrm{eV}}\right)^{\frac{1}{2}} \left(\frac{f}{3\times 10^{17}\ \mathrm{GeV}}\right)^{2}$$

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)**