Weizmann Institute

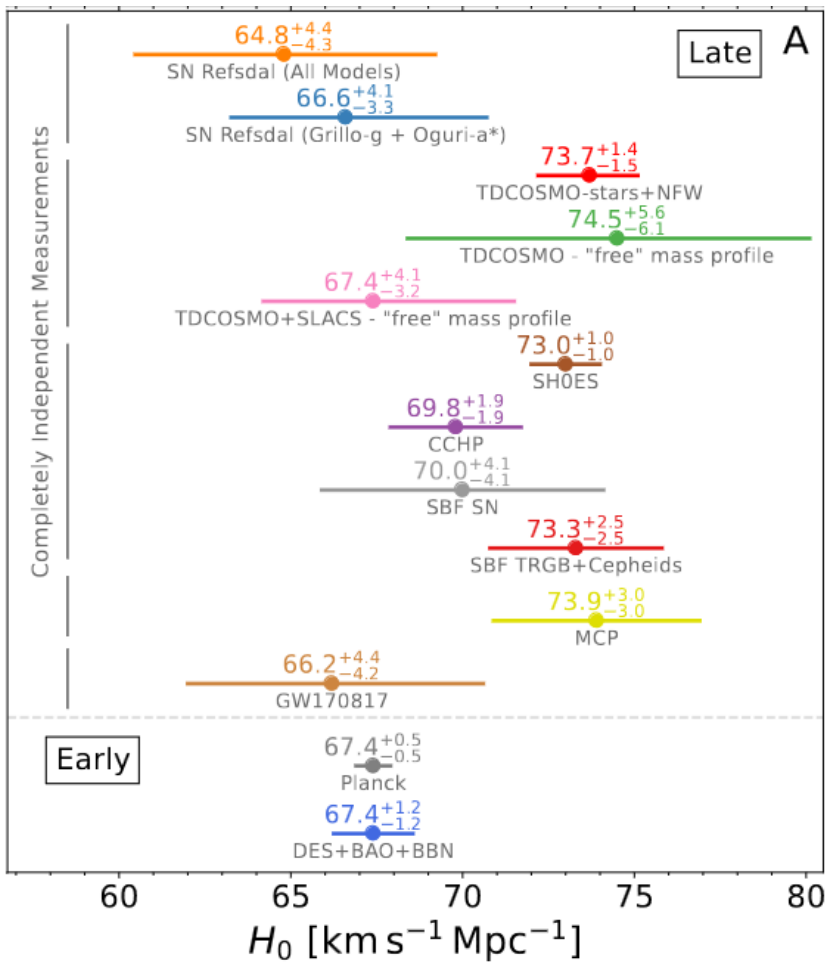
Degeneracies in Hubble constant measurements using gravitational lensing

New Physics from Galaxy Clustering II

Teodori Luca

November, 2023

The H_0 tension



credit: P.L. Kelly et al 2023

- CMB and LSS (early);
- Distance ladder (late);
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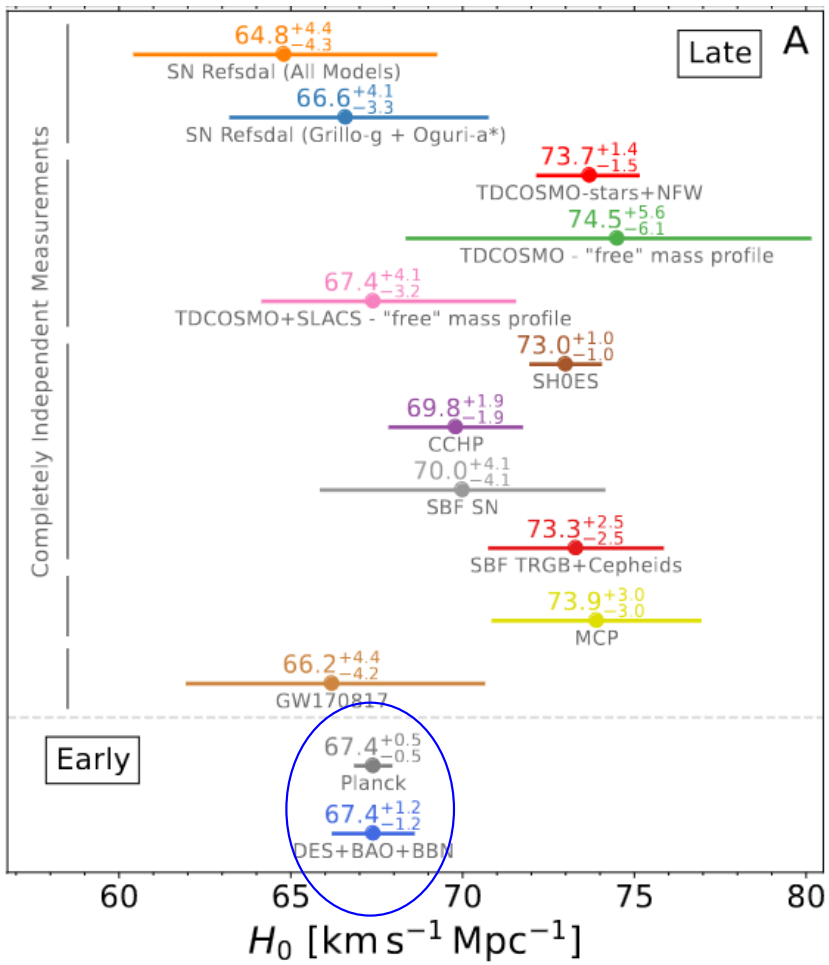

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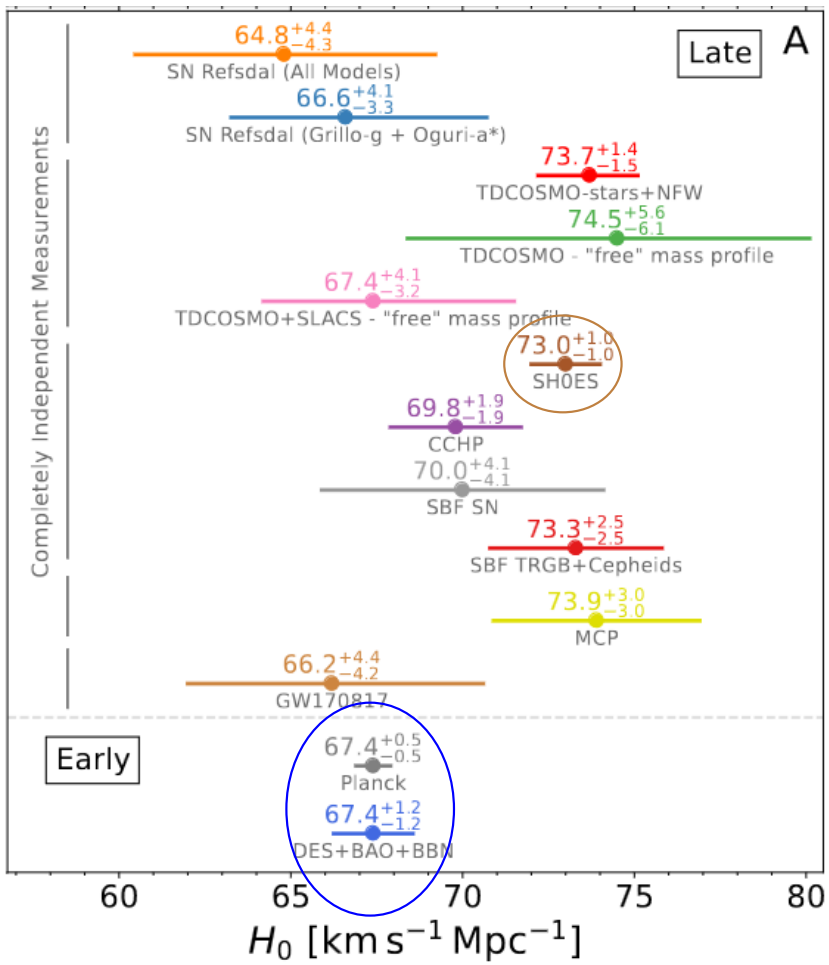

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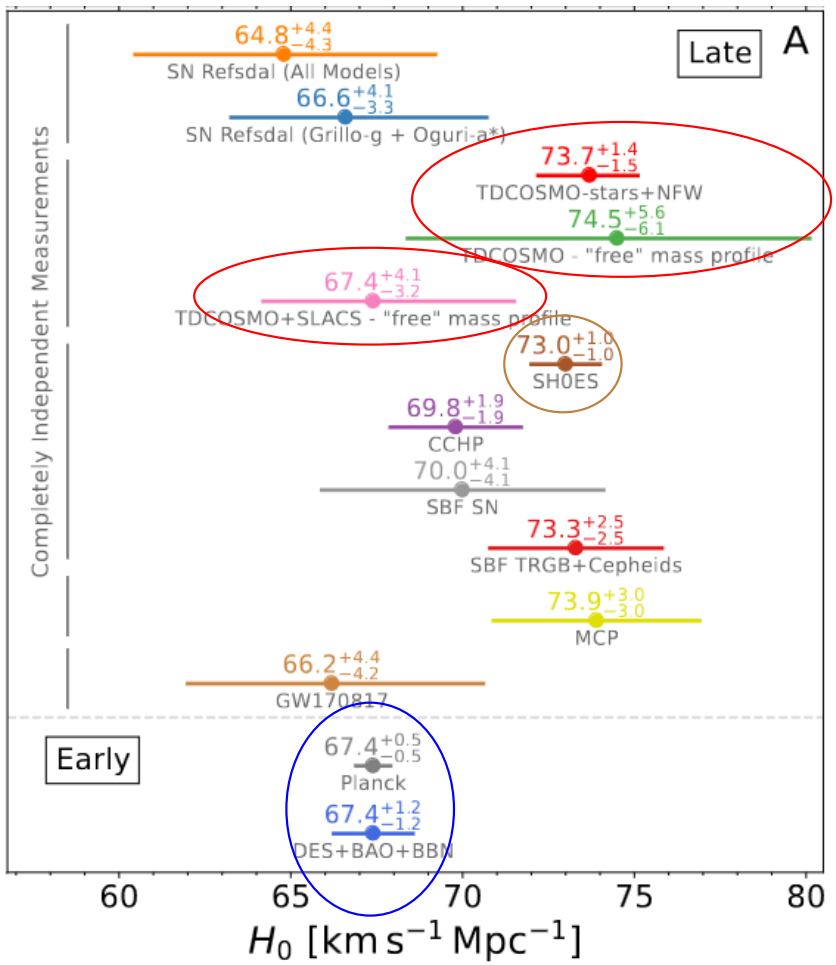

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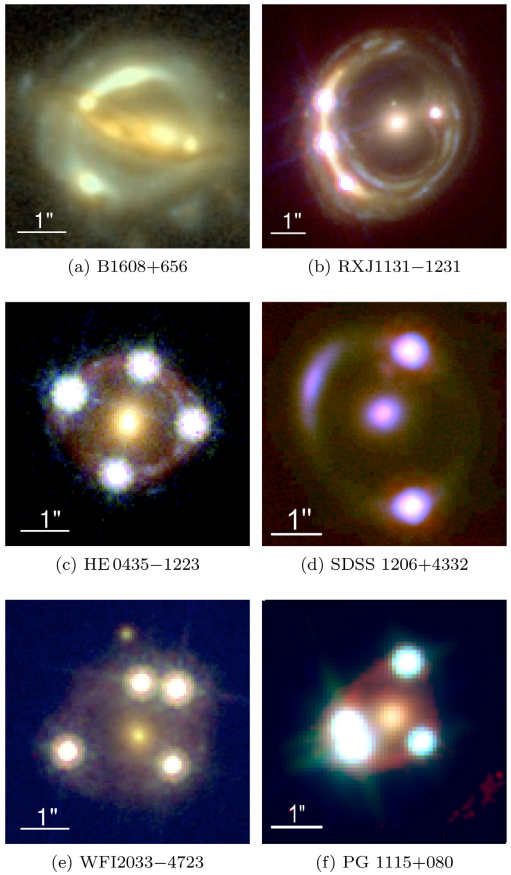


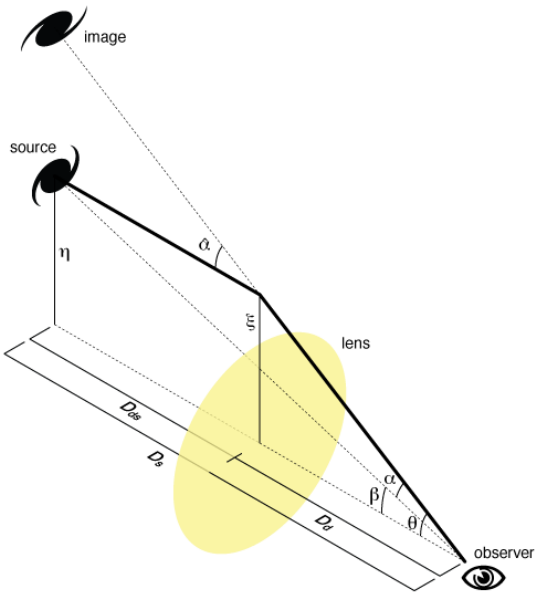
(a) B1608+656 (b) RXJ1131−1231

(c) HE 0435−1223 (d) SDSS 1206+4332

(e) WFI2033−4723 (f) PG 1115+080

Strong Gravitational Lensing in Elliptical Galaxies

How to measure H_0



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- $\hat{\alpha} = 2\int \nabla_\perp \Phi \, d\lambda \implies \vec{\beta} = \vec{\theta} - \frac{D_{LS}}{D_S}\hat{\alpha}(\vec{\theta})$
- Convergence $\kappa \sim \int dz\, \rho$.
- Lens model + time delay measurement

$$\Delta t_{ij} \propto \frac{1}{H_0}\,.$$

- Degeneracies: source position and mass of galaxy unknown

$$\vec{\beta} \to \lambda\vec{\beta}\,,\ \kappa \to \lambda\kappa + (1-\lambda) \implies H_0 \to \lambda H_0$$

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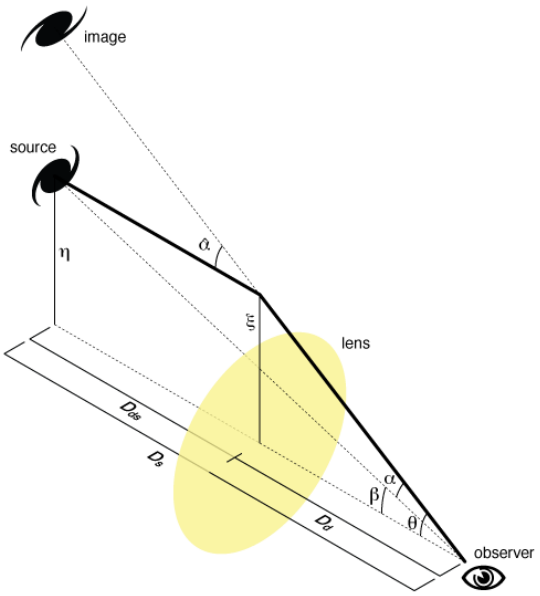

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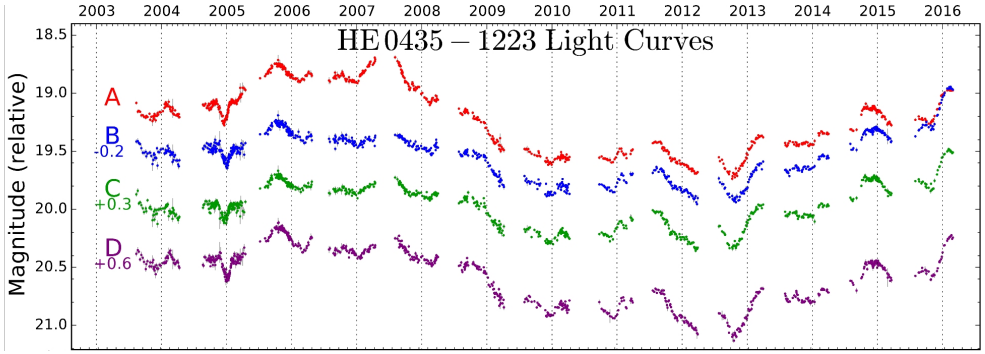

from V. Bonvin et al (2016)

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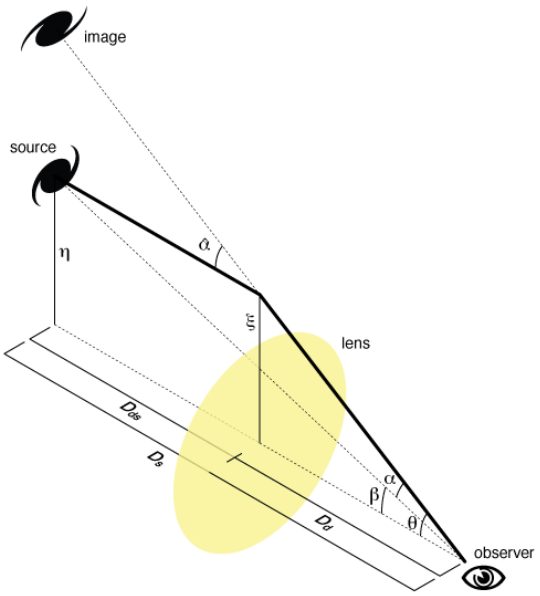

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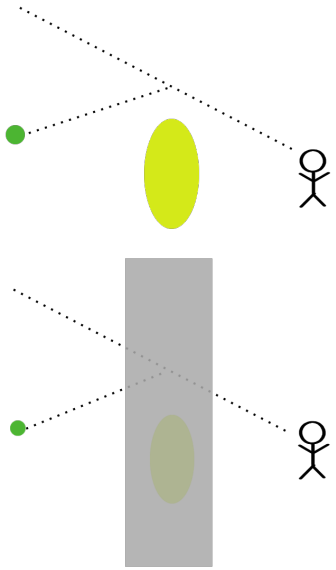

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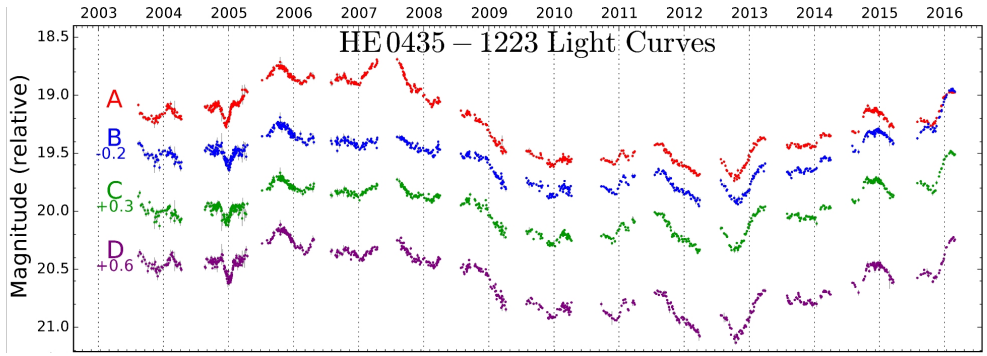

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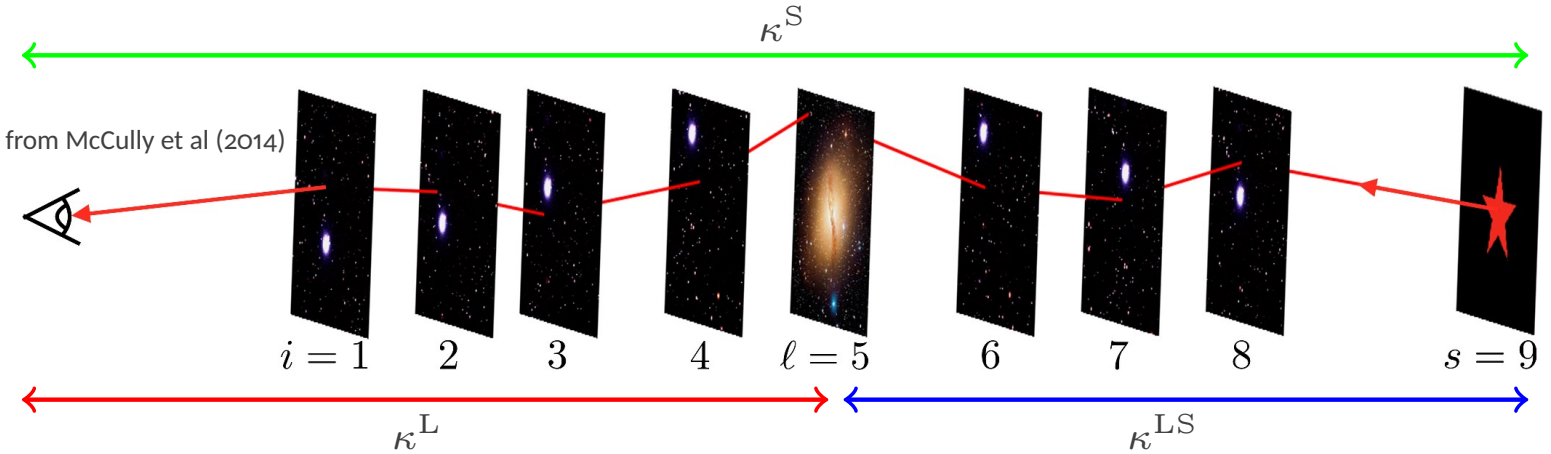
Examples of mass sheets



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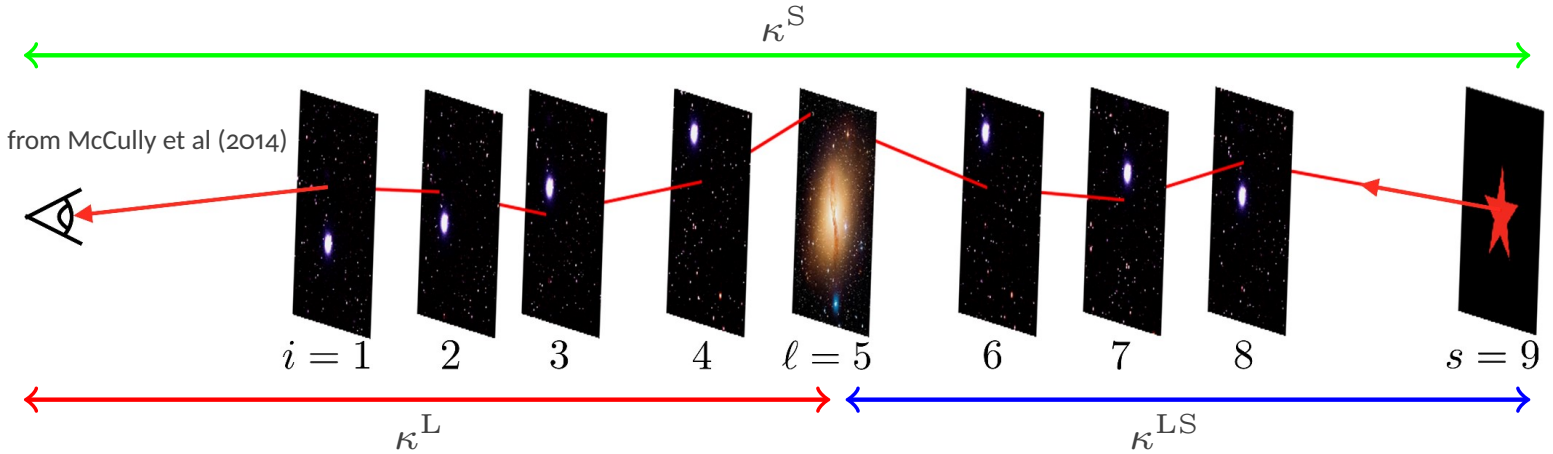

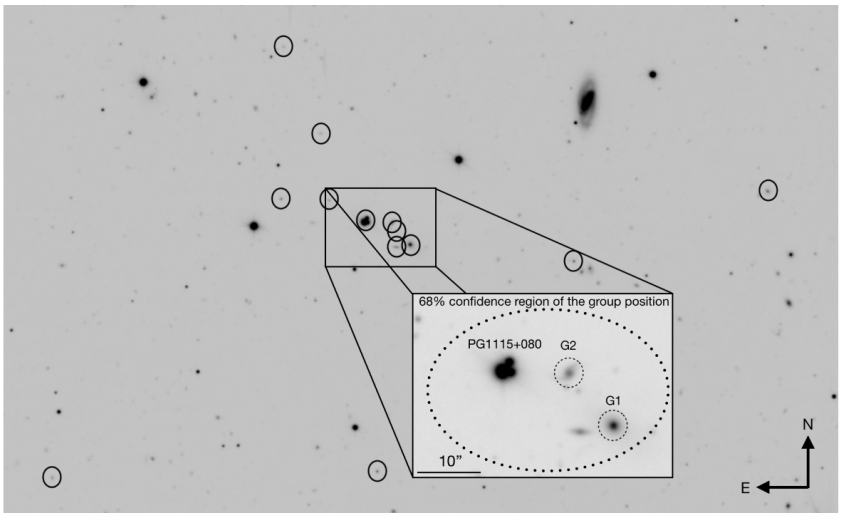

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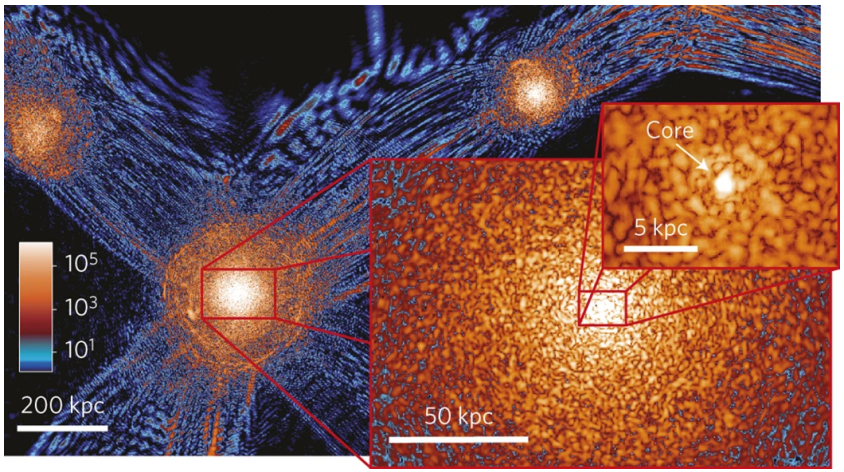
Internal Mass sheet degeneracy: ULDM example



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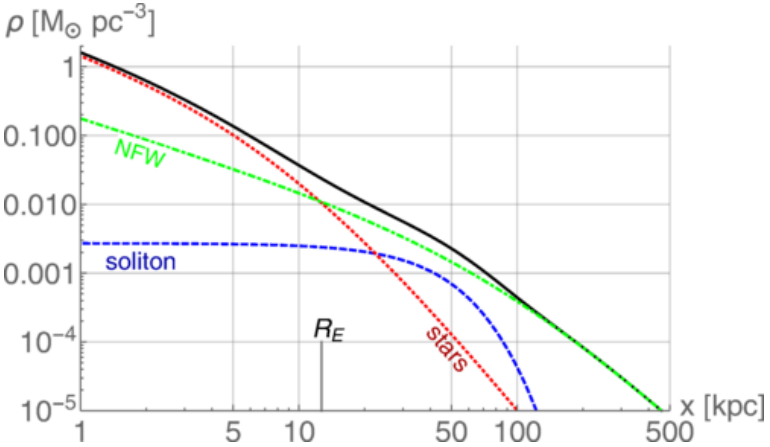

Blum, Teodori 2021

- Possible mass sheets also from internal DM halo
- Possible cores from non-trivial DM models, e.g. Ultralight dark matter, cores

$$\lambda_{\rm deBroglie} = \frac{1}{mv} \sim 20\,{\rm kpc}\,\frac{1\times 10^{-24}\,{\rm eV}}{m}$$

- Kinematics measurements fundamental to constrain MSD, reminding that exact MSD $\neq$ approximate MSD
- Sensitivity to galaxy features which are hard to probe otherwise.

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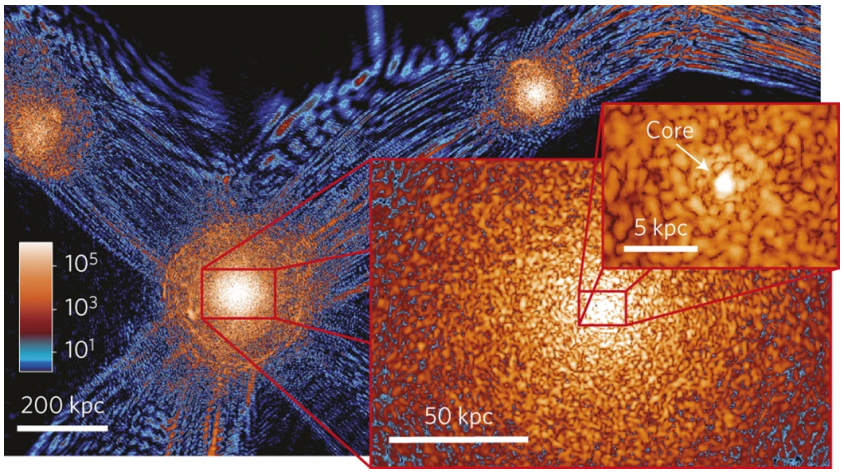

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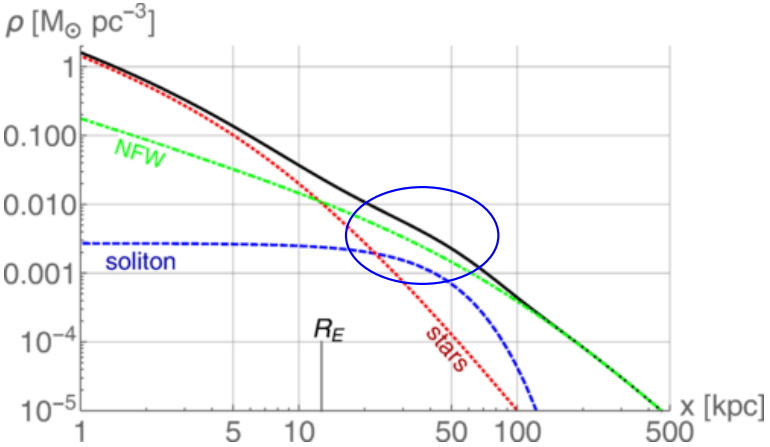

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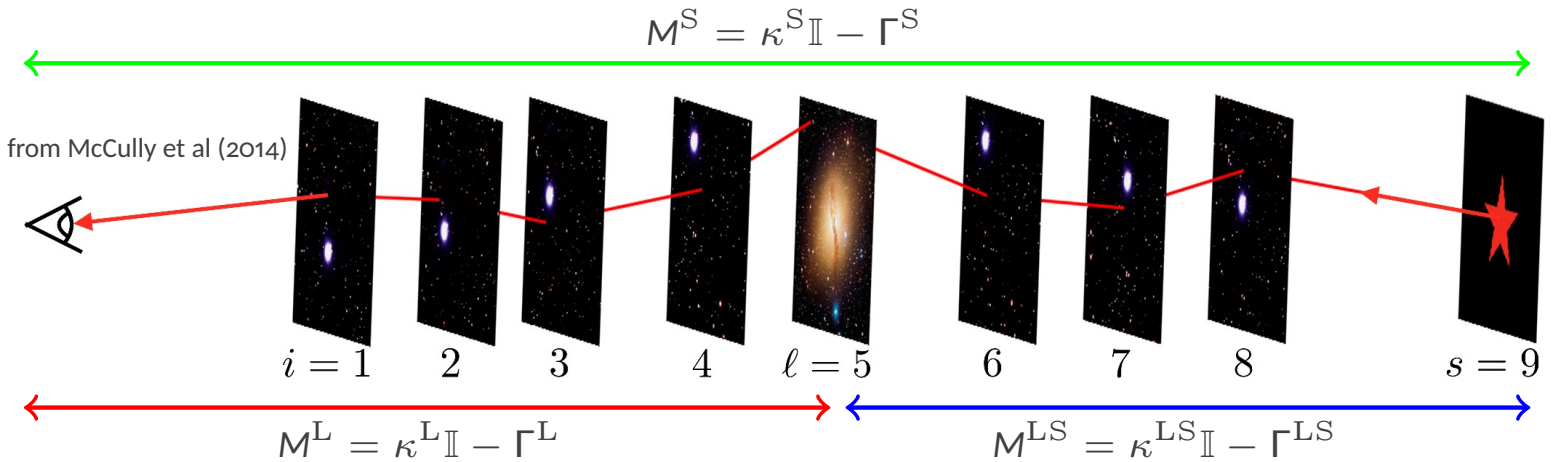
Conclusions

Can we measure H_0 with Gravitational Lensing?

- Challenge: modeling degeneracies; important to point out all the shortcomings to lensing collaborations, in other to achieve an *accurate* H_0 measurement.
- Promising! New data arriving, including precise stellar kinematics, new lensed systems (among which, “clean” multiple source systems) etc.
- With an H_0 prior, we can measure galactic features which are difficult to spot otherwise, and a better characterization of the weak lensing field

The multilens equation

The tidal approximation



Lens equation in tidal approximation

$$\vec{\beta} = (\mathbb{I} - M^{\rm S})\vec{\theta} - (\mathbb{I} - M^{\rm LS})\vec{\alpha}((\mathbb{I} - M^{\rm L})\vec{\theta})$$

Degeneracy ("revised" MSD)

$$\begin{aligned} 1 - M^{\rm R} &\longmapsto \lambda_{\rm R}(1 - M^{\rm R}), \\ \vec{\beta} &\longmapsto \lambda_{\rm S}\vec{\beta}, \\ \vec{\alpha}(\vec{\theta}) &\longmapsto \lambda_{\rm S}\,\lambda_{\rm LS}^{-1}\,\vec{\alpha}(\lambda_{\rm L}^{-1}\,\vec{\theta}), \\ \Psi(\vec{\theta}) &\longmapsto \lambda_{\rm S}\,\lambda_{\rm LS}^{-1}\,\lambda_{\rm L}\,\Psi(\lambda_{\rm L}^{-1}\,\vec{\theta}). \end{aligned}$$

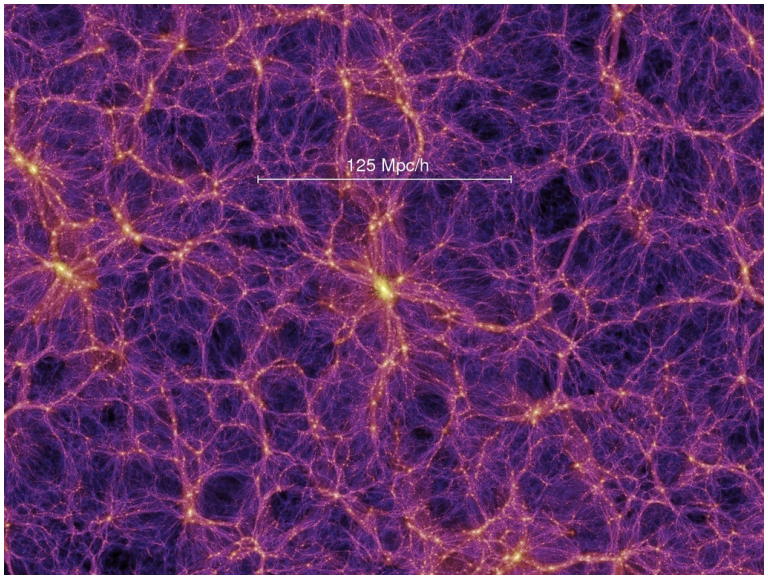
Choose

$$\lambda_{\rm S} = \frac{1}{1-\kappa^{\rm S}}, \quad \lambda_{\rm LS} = \frac{1}{1-\kappa^{\rm LS}}, \quad \lambda_{\rm L} = \frac{1}{1-\kappa^{\rm L}},$$

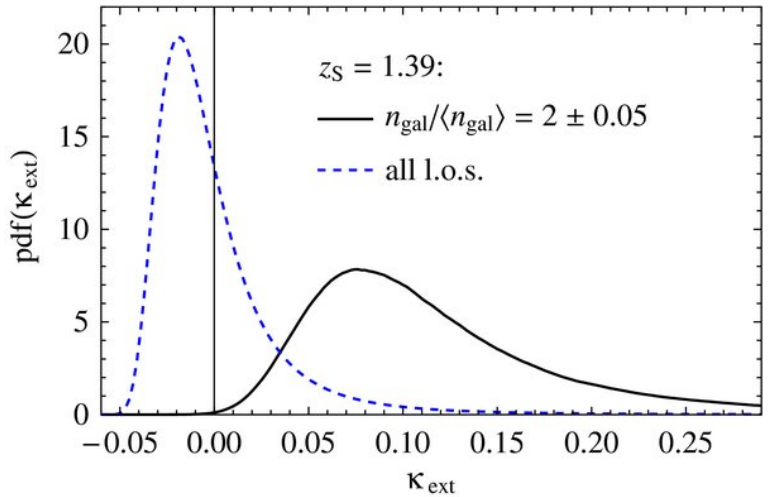
external convergence removed from the modeling

Interpreting the Mass Sheet Degeneracy

Springer et al 2005



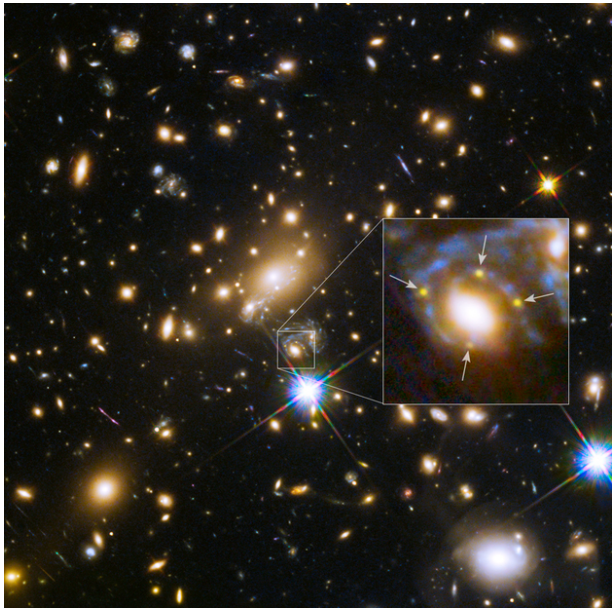
Suyu et al 2010



- Change $\lambda_{\rm S}$: changing one's mind about the true $\kappa^{\rm S}$
- $$\kappa^{\rm R} \longmapsto \lambda_{\rm R}\kappa^{\rm R} + (1 - \lambda_{\rm R})$$
  $$\Gamma^{\rm R} \longmapsto \lambda_{\rm R}\Gamma^{\rm R}$$
- Time delays do change!
  $$\Delta\tau \to \lambda_{\rm S}\lambda_{\rm LS}^{-1}\lambda_{\rm L}\Delta\tau$$
  $$H_0 \to \lambda_{\rm S}\lambda_{\rm LS}^{-1}\lambda_{\rm L}H_0$$
- Estimate $\kappa^{\rm S}$ via ray-tracing through Millennium Simulation and characterization of the lens field
- Degeneracy is limited by priors on weak lensing quantities and constraints on mass of lens galaxy (stellar kinematics)

Multi-source systems and MSD

Cluster MACS J1149.5+2223. Credit: NASA



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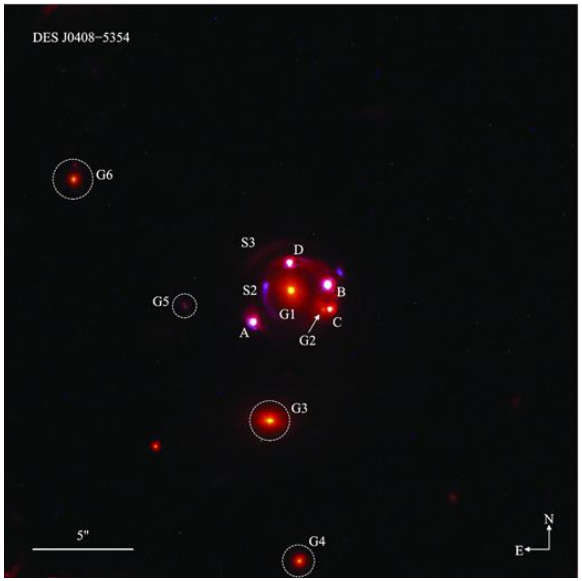

- New lens equation (ignoring lens-lens coupling)

$$\vec{\beta}_i = (\mathbb{I} - M_i^{\mathrm{S}})\vec{\theta} - (\mathbb{I} - M_i^{\mathrm{LS}})c_i\vec{\alpha}_1((\mathbb{I} - M^{\mathrm{L}})\vec{\theta})$$

$$c_i := \frac{D_{\mathrm{S}_1} D_{\mathrm{LS}_i}}{D_{\mathrm{LS}_1} D_{\mathrm{S}_i}}\ , \quad \left(\hat{\alpha}\frac{D_{\mathrm{LS}}}{D_{\mathrm{S}}} =: \vec{\alpha}\right)$$

- MSD untouched! But I cannot rescale away all external convergences $\Longrightarrow$ differential external convergences
- Observable:

$$c_i \frac{\left|\vec{\alpha}_1^{\mathrm{model}}(\vec{\theta})\right|}{\left|\vec{\alpha}_2^{\mathrm{model}}(\vec{\theta})\right|} \approx \left(1 + \delta\kappa_{12}^{\mathrm{S}} - \delta\kappa_{12}^{\mathrm{LS}}\right)$$