Weizmann Institute

Comments on the Mass Sheet Degeneracy in Cosmography Analyses

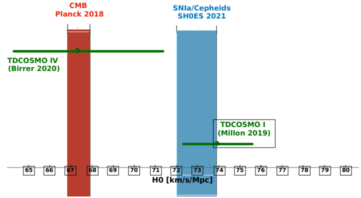
IPS 2022

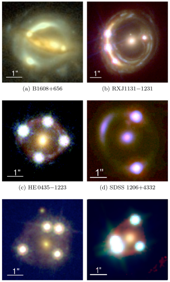
Teodori Luca

Based on LT, K. Blum, E. Castorina, M. Simonović and Y. Soreq (2022) [2201.05111]

February 22, 2022

Measuring H_0 with lensing





(a) B1608+656 (b) RXJ1131−1231

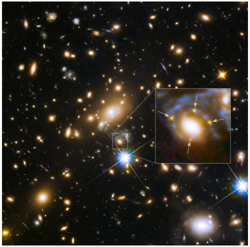
(c) HE0435−1223 (d) SDSS 1206+4332

(e) WFI2033−4723 (f) PG 1115+080

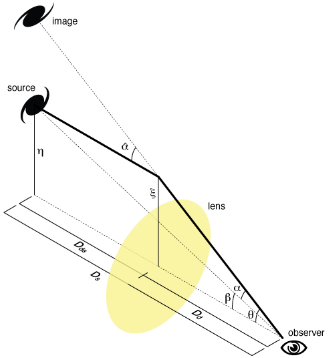
Wong et al. 2019

- TDCOSMO collaboration (COSMOGRAIL, HoLiCOW, STRIDES, SHARP, COSMICLENS)
- Unaccounted galactic density profile features (core?): internal mass sheet degeneracy
- Large scale structure “on the way”: external mass sheet degeneracy (weak lensing)
- Can multiple source systems help?

credit: NASA



Strong Gravitational Lensing in Elliptical Galaxies



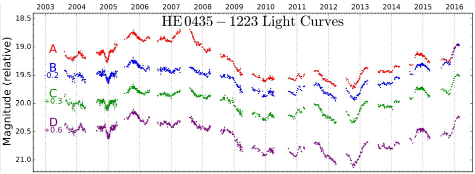
credit: Wikipedia

- $\hat{\alpha} = 2\int \boldsymbol{\nabla}_{\perp}\Phi\,\mathrm{d}\lambda \implies \vec{\beta} = \vec{\theta} - \frac{D_{\mathrm{LS}}}{D_{\mathrm{S}}}\hat{\alpha}(\vec{\theta})$
- Lens model + time delay measurement

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

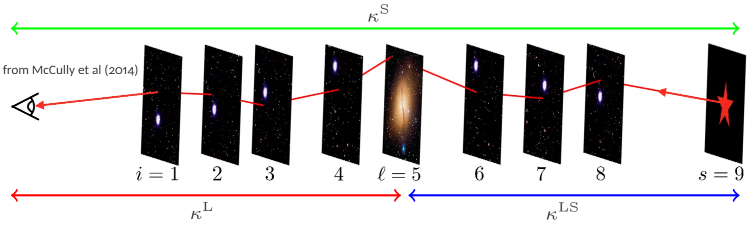
- Degeneracies: source position and mass of galaxy unknown

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



from V. Bonvin et al (2016)

Effects of Large Scale Structure



External convergences κ are unobservable, can be removed from modeling (not completely true in multiple source systems!)

Bias in time delays:

$$\frac{H_0^{\rm inferred}}{H_0^{\rm true}} = \frac{1-\kappa^{\rm LS}}{1-\kappa^{\rm L}}$$

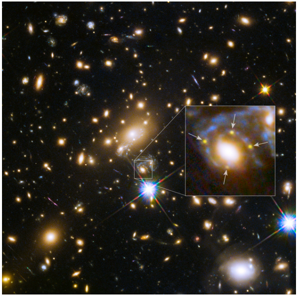
Stellar kinematics can constrain mass in the galaxy. Bias:

$$\frac{H_0^{\rm inferred}}{H_0^{\rm true}} \approx 1+\kappa^{\rm L}$$

- Which direction? Difficult to say without ray-tracing

Multi-source systems and MSD

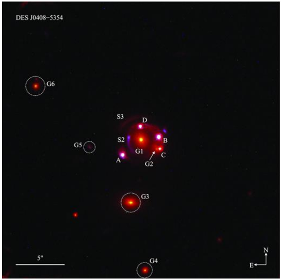
Cluster MACS J1149.5+2223. Credit: NASA



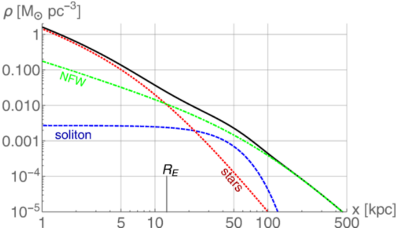
- Large unaccounted cores have similar effects to weak lensing κ^{S} (internal mass sheet degeneracy), but it can have larger effects
- $1 - \lambda = \kappa_{\mathrm{c}1} \implies \kappa_{\mathrm{c}1} \simeq \frac{\delta H_0}{H_0}$
- Observable (C_i involves ratio of angular diameter distances):

$$\delta\kappa^{\mathrm{S}}_{1i} - \delta\kappa^{\mathrm{LS}}_{1i} + \kappa_{\mathrm{c}1}\,(1 - C_i)$$

Shajib et al 2019

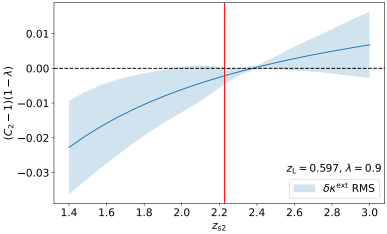


Blum, Teodori 2021

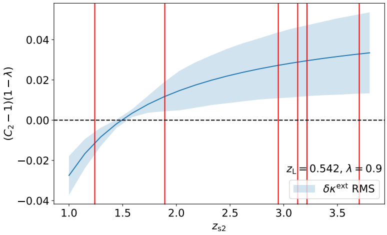


External convergence reinterpretation?

DESJ0408-5354



Cluster MACS J1149.5+2223

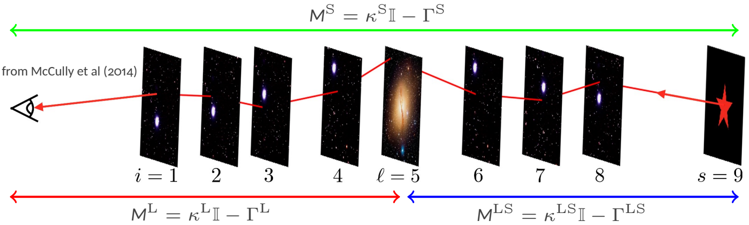


- With $\delta\kappa^{\mathrm{ext}} := \delta\kappa^{\mathrm{S}}_{21} - \delta\kappa^{\mathrm{LS}}_{21}$,

  $$\delta\kappa^{\mathrm{ext}} \to \delta\kappa^{\mathrm{ext},\lambda} = \delta\kappa^{\mathrm{ext}} + \kappa_{\mathrm{c1}}\,(C_2 - 1)$$

- “Good systems” we have now cannot say much; clusters have still a lot of modeling uncertainties.
- With future surveys, many more multisource systems $\implies$ we could spot the core!

- 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 etc.
- Effects from observer-lens and lens-source sightlines *must* be taken into account for a non-biased inference of time delays and non-biased stellar kinematics constraint.
- With multi-source systems, you might spot the core (still not possible yet).
- With an H_0 prior, we can measure galactic features like large cores, difficult to spot otherwise, and a better characterization of the weak lensing field



Lens equation in tidal approximation

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

Degeneracy (“revised” MSD)

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

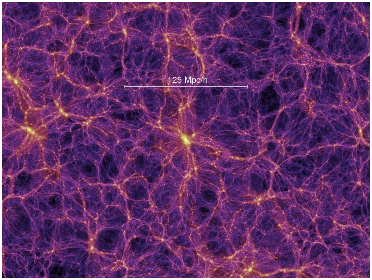
Choose

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

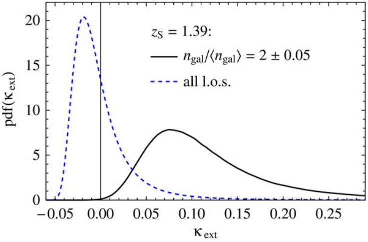
external convergence removed from the modeling

Interpreting the Mass Sheet Degeneracy

Springer et al 2005



Suyu et al 2010



- Change λ_{S}: changing one's mind about the true κ^{S}
-

$$\kappa^{\mathrm{R}} \longmapsto \lambda_{\mathrm{R}}\kappa^{\mathrm{R}} + (1-\lambda_{\mathrm{R}})$$
$$\Gamma^{\mathrm{R}} \longmapsto \lambda_{\mathrm{R}}\Gamma^{\mathrm{R}}$$

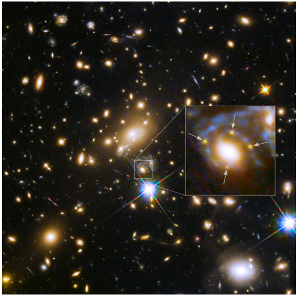
- Time delays do change!

$$\Delta\tau \to \lambda_{\mathrm{S}}\lambda_{\mathrm{LS}}^{-1}\lambda_{\mathrm{L}}\Delta\tau$$
$$H_0 \to \lambda_{\mathrm{S}}\lambda_{\mathrm{LS}}^{-1}\lambda_{\mathrm{L}}H_0$$

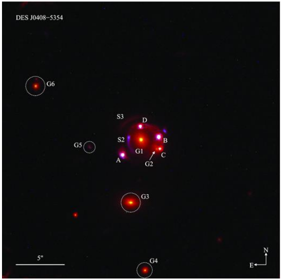
- Estimate κ^{S} via ray-tracing through Millennium Simulation and characterization of the lens field
- Degeneracy is limited by priors on weak lensing quantities and constraints on mass of lens galaxy (stellar kinematics)

Multi-source systems and MSD

Cluster MACS J1149.5+2223. Credit: NASA



Shajib et al 2019



- New lens equation (ignoring lens-lens coupling)

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

$$C_i := \frac{D_{\mathrm{S}_1} D_{\mathrm{LS_i}}}{D_{\mathrm{LS}_1} D_{\mathrm{S_i}}}\ ,\ \left(\hat{\alpha}\frac{D_{\mathrm{LS}}}{D_{\mathrm{S}}} =: \vec{\alpha}\right)$$

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

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