Weizmann Institute

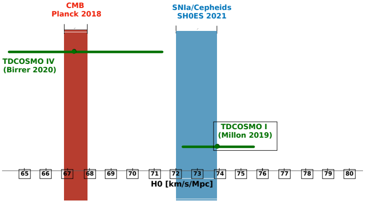
Degeneracies in Cosmography Analyses

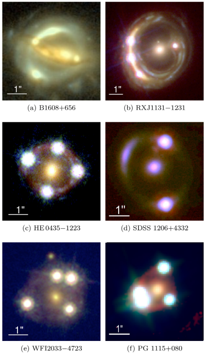
MMS annual meeting 2023

Teodori Luca

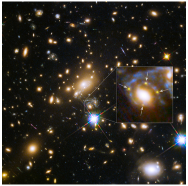
June, 2023

Measuring H_0 with lensing



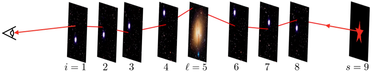


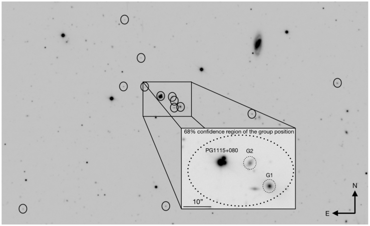
Wong et al. 2019



credit: NASA

- TDCOSMO collaboration (COSMOGRAIL, HoLiCOW, STRIDES, SHARP, COSMICLENS)
- Unaccounted galactic density profile features (core? Nearby group?): internal mass sheet degeneracy
- Large scale structure "on the way": external mass sheet degeneracy (weak lensing)

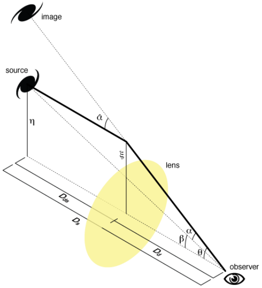




Outline

- Small recap: how to measure H_0 from gravitational lensing
- Large scale structures
- Non-trivial dark matter dynamics (Ultralight dark matter)
- Nearby group

Strong Gravitational Lensing in Elliptical Galaxies



credit: Wikipedia

- $\hat{\alpha} = 2 \int \nabla_\perp \Phi \, \mathrm{d}\lambda \implies \vec{\beta} = \vec{\theta} - \frac{D_{\mathrm{LS}}}{D_{\mathrm{S}}} \hat{\alpha}(\vec{\theta})$
- Convergence $\kappa \sim \int \mathrm{d}z \, \rho$.
- 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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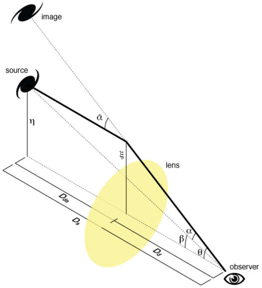

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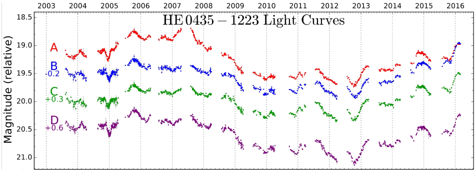

from V. Bonvin et al (2016)

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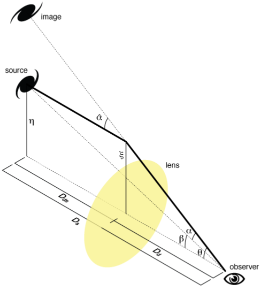

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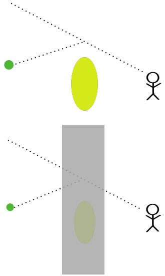

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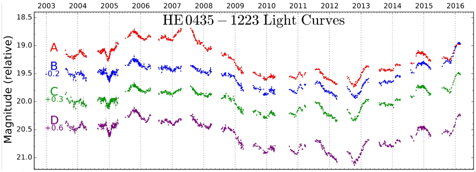

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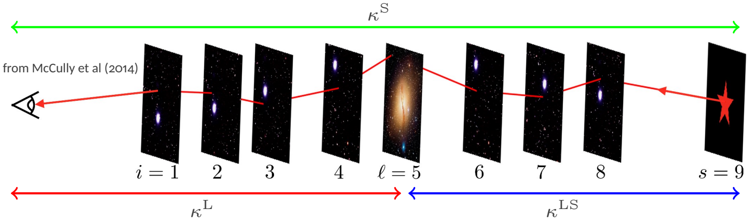
Effects of Large Scale Structure



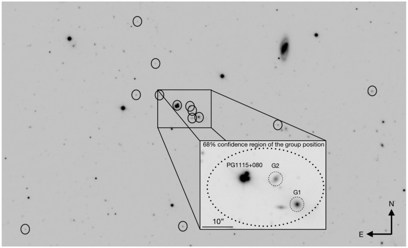
External convergences κ are unobservable, can be removed from modeling (not completely true in multiple source systems!)

- κ^{S} works as a MSD, κ^{LS} and κ^{L} can be reabsorbed in lens parameters

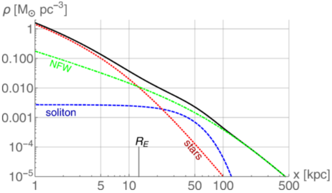
- Bias in time delays:

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

Internal Mass sheet degeneracy



credit: Shajib et al 2019



Blum, Teodori 2021

- Possible cores from non-trivial DM models, e.g. Ultralight dark matter, cores

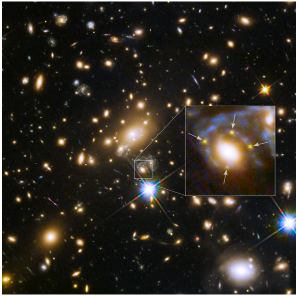
$$\lambda_{\rm deBroglie} = \frac{1}{mv} \sim 20\,\text{kpc}\,\frac{1\times 10^{-24}\,\text{eV}}{m}$$

- Effect of galaxy group. Galaxy kinematics can constrain how much mass in the group.
- Kinematics measurements fundamental to constrain MSD, reminding that exact MSD $\neq$ approximate MSD

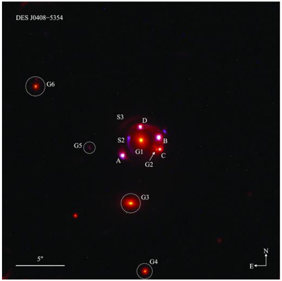
$$M \to (1-\kappa_{\rm c})M + M_{\rm c}\ ,\ M_{\rm c} \sim \kappa_{\rm c}\frac{r^3}{r_{\rm c}}$$

Multi-source systems and MSD

Cluster MACS J1149.5+2223. Credit: NASA



Shajib et al 2019

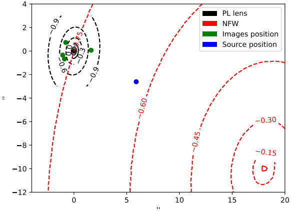


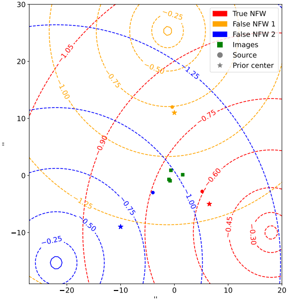
- External convergences and convergences from approximate cores (from non-trivial DM or groups) are unobservable, in single source systems
- For multiple source systems, observable (C_i involves ratio of angular diameter distances):

$$\gamma_{1i} := \delta\kappa_{1i}^{\mathrm{S}} - \delta\kappa_{1i}^{\mathrm{LS}} + \kappa_{\mathrm{c}1}\,(1 - C_i)$$

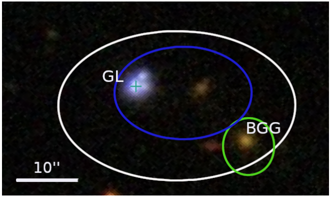
- If γ_{1i} is too large to be explained by external convergences, it might be an indication of a non-zero, unaccounted κ_{c}!

Discrete flexion degeneracy from a NFW group





- Lens galaxies often reside in groups
- First order α expansion $\sim$ convergence; second order: flexion F, G.
- $F \sim \mathrm{e}^{\mathrm{i}\phi} F_0$, $G \sim \mathrm{e}^{3\mathrm{i}\phi} G_0$
- Falling into the false center yields a bias in H_0 (due to the different convergence inferred)
- Measuring the velocity dispersion of galaxies $\implies$ find a prior on mass, mitigating the MSD.



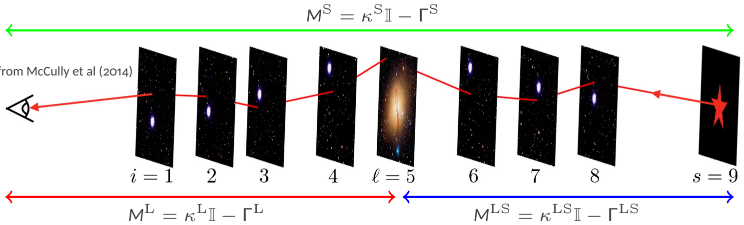
Summary

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 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).
- The presence of a group nearby can bias the H_0 inference if the flexion degeneracy is not taken into account.
- 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

The multilens equation

The tidal approximation



Lens equation in tidal approximation

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

Degeneracy ("revised" MSD)

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

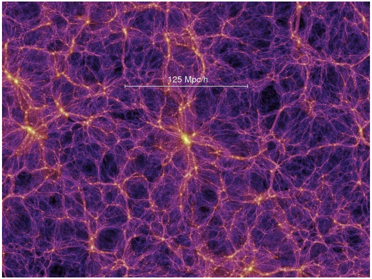
Choose

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

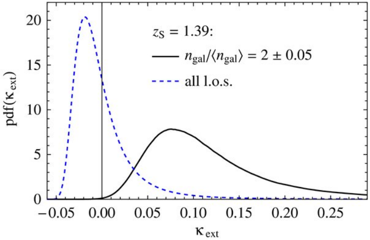
external convergence removed from the modeling

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}
-

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

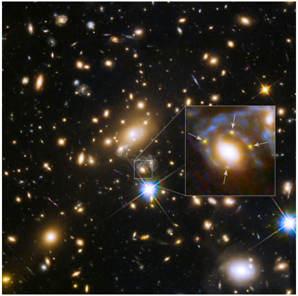
- Time delays do change!

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

- 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



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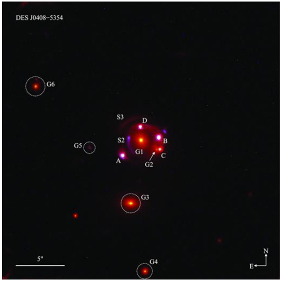

- New lens equation (ignoring lens-lens coupling)

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

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

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

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