Future Strong Lensing Time Delay constraints on Dark Energy

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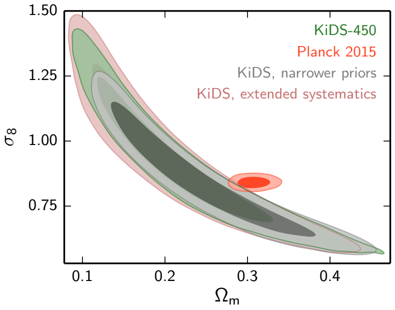
Paris, December 10th, 2019

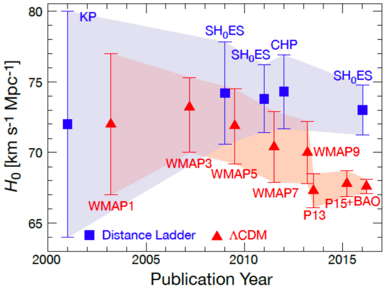
based on :
B. Shiralilou, MM, G. Papadomanolakis, S. Peirone, F. Renzi, A. Silvestri arXiv:1910.03566

Cosmological tensions

Despite the success of ΛCDM to explain cosmological observations, the improvement of data quality started to highlight tensions between the values of parameters obtained with different methods.



Joudaki et al. MNRAS 471 (2017)



Freedman arXiv:1706.02739

Tensions and Dark Energy

One can attempt to solve tensions changing the expansion history of the Universe at late times, i.e.

$$w(z) = w_0 + w_a \frac{z}{1+z}$$

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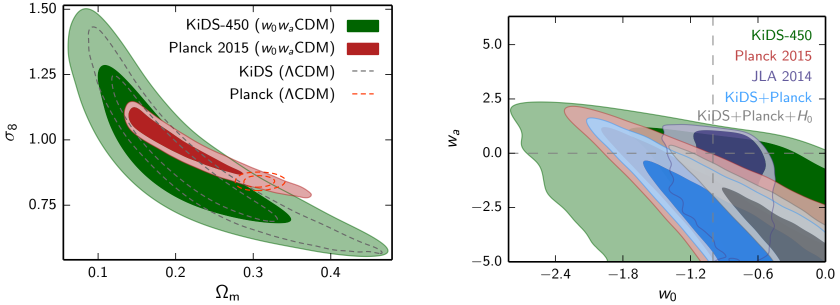

$$T(S_8) = 0.91\sigma \text{ with } \Delta DIC = -6.4$$

Joudaki et al. MNRAS 471 (2017)

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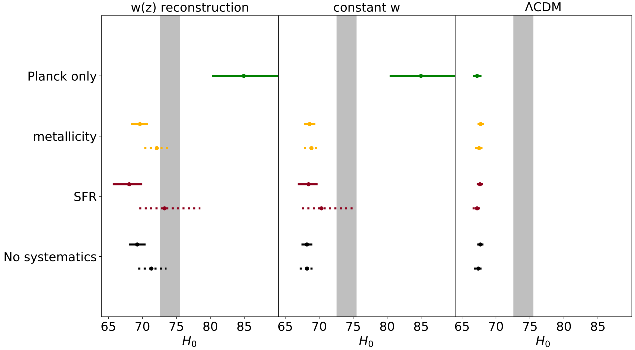


MM, I. Tutusaus arXiv:1906.09189

Improved probes and new probes

In the near future, observations will further improve with new supernovae datasets available, as well as high quality Large Scale Structures observations (Euclid, LSST, ...). This will allow to improve our measurements and check the "stability" of the tensions on cosmological parameters.

At the same time, we will be able to obtain measurements from completely new probes, such as Gravitational Waves and Strong Lensing measurements.

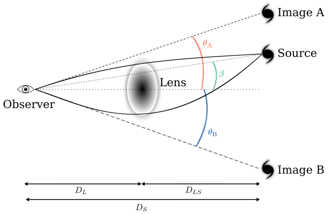
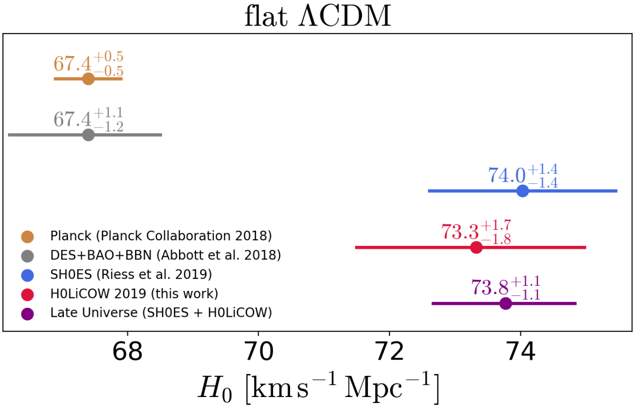


Image from Simone Peirone

Observing time delays between multiple images of a source in strongly lensed systems allows to extract cosmological information.

Current results for SLTD

Currently SLTD measurements from H0LiCOW are already getting competitive



Wong et al. arXiv:1907.04869

How is cosmological information obtained?

Observing the delay between different images of the same source, one can obtain cosmological information

$$\Delta t_{AB} = (1 + z_l)\frac{D_l D_s}{c\, D_{ls}}\left[\phi(\boldsymbol{\theta_A}, \boldsymbol{\beta}) - \phi(\boldsymbol{\theta_B}, \boldsymbol{\beta})\right]$$

Moreover, perturbers that are very massive or close to the lens galaxy or structures that lie along the LOS lead to a rescaling of the value of the observed time delay distance:

$$D'_{\Delta t} = \frac{D_{\Delta t}}{1 - \kappa_{\rm ext}}$$

From observations of the lens galaxy, one can obtain cosmological information also on the velocity dispersion projected along the line of sight

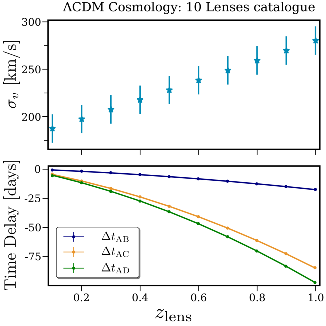
$$(\sigma_v)^2 = (1 - \kappa_{ext})\frac{D_s}{D_{ls}}\; \mathcal{F}(\gamma', \theta_E, \beta_{\rm ani}, r_{\rm eff})$$

However this requires to be able to measure the property of the lens system, encoded in ϕ and $\mathcal{F}$.

Suyu et al. ApJ (2010)

Strong Lensing mock dataset

We build mock data using the parameters of a single well measured H0LiCOW lens (HE0435-1223), generate the images and the time delays. We then generate N data point obtained from the same lens and uniformly distributed for $0 < z < 1$.



Assumptions:

- lens parameters of HE0435-1223 for all systems
- fixed redshift difference between source and lens
- ΛCDM

Ideal and realistic analysis

To produce our forecasted data we use the parameters of HE0435-1223

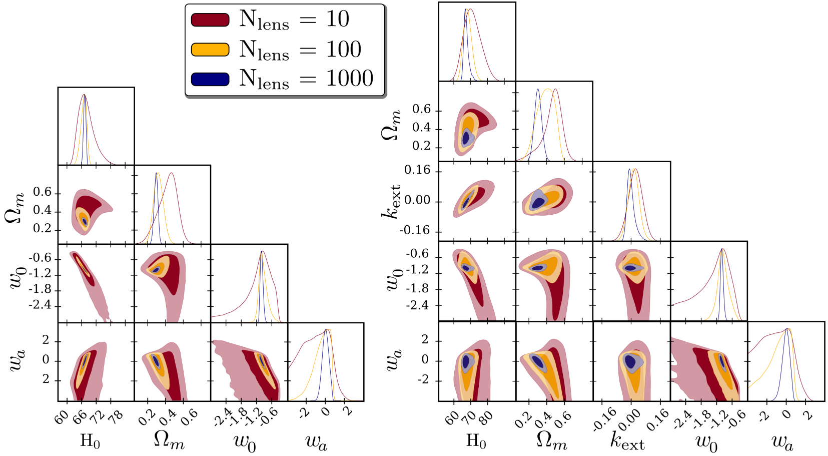
Parameter	θ_E ($''$)	q	θ_q ($^\circ$)	γ'	γ_{ext}	$\varphi_{\rm ext}$ ($^\circ$)	$\kappa_{\rm ext}$	$r_{\rm eff}$ ($''$)	$r_{\rm ani}$ ($''$)
Value	1.18	0.8	-16.8	1.93	0.03	63.7	-0.03	1.33	3.5

We analyze this varying all cosmological parameters, while taking two approaches for the nuisance parameters entering the lens modeling $\vec{\pi}_{\rm nuis} = (r_{\rm ani}, \kappa_{\rm ext}, \gamma')$

- Ideal case:
  $P(\pi_{\rm nuis}) = \delta_D(\pi_{\rm fid})$
- Realistic case:
  $P(\kappa_{\rm ext}) = \mathcal{G}(-0.03, 0.05),\ P(\gamma') = \mathcal{G}(1.93, 0.02),\ P(r_{\rm ani}) = [0.665, 6.65]$

Forecasted results

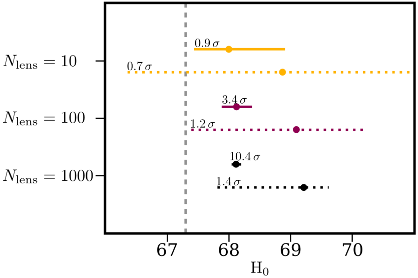
We explored the possibility to use SLTD by itself to measure DE property as well as H_0. We created simulated datasets with different number of lenses in ideal and realistic settings



Shiralilou, MM et al. arXiv:1910.03566

Do cosmology assumptions matter?

In the previous case we assumed a ΛCDM cosmology to generate the data and fitted it with extended models.
What if the Universe is not ΛCDM and we wrongly assume it?



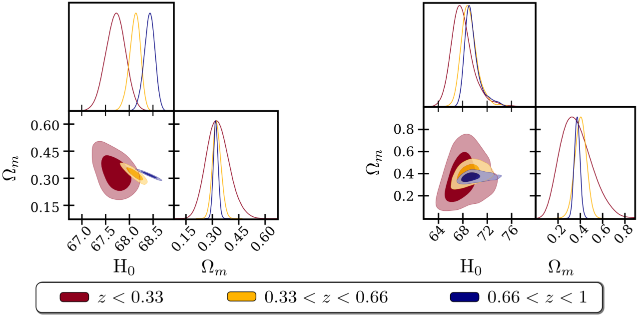
Using the same assumptions as before we generate data with a *w*CDM fiducial ($w_0 = -0.9$)

Such fiducial is then analyzed assuming $w = -1$

Shiralilou, MM et al. arXiv:1910.03566

A model consistency check

If we have a large enough number of systems, we can bin our data ($w = -0.9$) and run a consistency check



The same dataset gives different H_0 values in different redshift bins if the assumed model is wrong!

Shiralilou, MM et al. arXiv:1910.03566

Take home messages

- Strong Lensing Time Delay observations are now reaching a maturity to constrain cosmological models.
- Assuming a 1000 **perfectly observed** lenses one could reach a precision of 2% on H_0 assuming a CPL Dark Energy, with errors on DE parameters $\sigma_{w_0} \approx 0.05$ and $\sigma_{w_a} \approx 0.3$.
- SLTD measurements can be significantly biased if the wrong cosmological model is assumed, but having enough lenses one can perform internal consistency checks.

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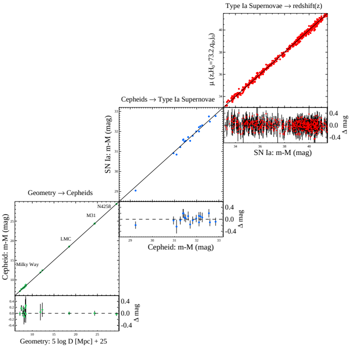
What's next?

- More realistic mock datasets need to be used: $\kappa_{\rm ext}$ different for each lens, uncertain lens parameters...
- Can $\kappa_{\rm ext}$ contain cosmological information? LOS effects could be used to constrain cosmological models, e.g. modified gravity.

High/low redshift tensions

Low redshift experiment measure directly local parameters (H_0, Ω_i, σ_8...), with more or les dependence on the cosmological assumptions



Riess et al. arXiv:1604.01424

CMB measurements instead deal with high redshift physics and thanks to the assumption of a cosmological model can provide values for local parameters

1. measure the angular size of the sound horizon at recombination
2. assume ΛCDM expansion history
3. obtain H_0

Lens modeling

For a generic light ray, the time delay with respect to its unperturbed path is given by

$$t(\boldsymbol{\theta_i}, \boldsymbol{\beta}) = (1 + z_l)\frac{D_l D_s}{c\, D_{ls}}\left[\frac{(\boldsymbol{\theta_i} - \boldsymbol{\beta})^2}{2} - \psi_\perp(\boldsymbol{\theta}_i)\right]$$

$\boldsymbol{\beta}$ and $\boldsymbol{\theta}_i$ are the source and image position, and $\psi_\perp(\boldsymbol{\theta_i})$ is the projected gravitational potential calculated on the lens plane.

The combination $(\boldsymbol{\theta_i} - \boldsymbol{\beta})^2/2 - \psi_\perp(\boldsymbol{\theta_i})$ is only dependent on the geometry and mass distribution of the deflectors; it is usually referred to as the *Fermat potential* $\phi(\boldsymbol{\theta_i}, \boldsymbol{\beta})$.

Having a model for the mass of the lens one can obtain the Fermat potential

$$\psi_{\rm SPEP}(\boldsymbol{\theta}) = \frac{2A(\theta_E, q, \gamma')^2}{(3-\gamma')^2}\left[\frac{\theta_1^2 + \theta_2^2/q^2}{A(\theta_E, q, \gamma')^2}\right]^{(3-\gamma')/2}$$

Lens kinematics

To obtain σ_v one needs the 3D gravitational potential of the lens galaxy Φ. We use spherically symmetric power law profile and connect the local density to the lens characteristics

$$\rho_{\rm local}(r) = \pi^{-1/2}\,(\kappa_{\rm ext} - 1)\,\Sigma_{\rm cr}\;R_{\rm E}^{\gamma'-1}\frac{\Gamma(\gamma'/2)}{\Gamma\left(\frac{\gamma'-3}{2}\right)}\,r^{-\gamma'}$$

The three-dimensional radial velocity dispersion σ_r is then found solving a spherical jeans equation:

$$\frac{\partial(\rho^*\sigma_r^2)}{\partial r} + \frac{2\beta_{ani}(r)\rho^*\sigma_r^2}{r} + \rho^*\frac{\partial\Phi}{\partial r} = 0$$

where $\beta_{ani} = r^2/(r^2 + r_{\rm ani}^2)$ is the anisotropy distribution of the stellar orbits. The luminosity-weighted velocity dispersion σ_s is then given by :

$$I(R)\sigma_s^2 = 2\int_R^\infty \left(1 - \beta_{ani}\left(\frac{R}{r}\right)^2\right)\frac{\rho^*\sigma_r^2\,r\,dr}{\sqrt{r^2 - R^2}}$$

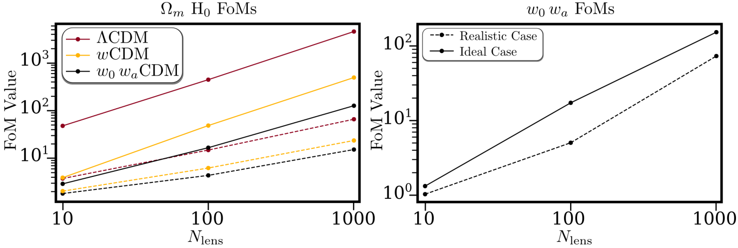
with R the projected radius and $I(R)$ the projected Hernquist profile.

Suyu et al. ApJ (2010)

Figure of Merit for SLTD

Using the covariance between parameters obtained from the MCMC we can get a Figure of Merit for these observations

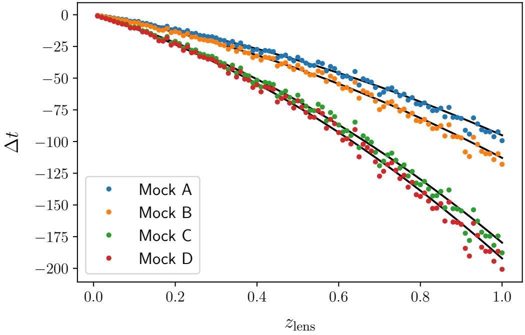
$$\mathrm{FoM}(\alpha,\beta) = \sqrt{\det(\tilde{C}^{-1}_{\alpha\beta})}$$



FoM for SLTD can reach levels competitive with upcoming experiments.

A more realistic SLTD mock

Our mock data are **very** simplified. In order to go toward a more realistic data simulation, one can relax the assumption of the same κ_{ext} for all the lenses.



Can the single κ_{ext} nuisance parameter catch this variation or will the results be biased by it?

Alternatives to the ΛCDM model

We need a component driving the accelerated expansion phase, and we are not satisfied with Λ.
To produce an accelerated expansion without a cosmological constant, one has necessarily to modify something in the paradigm

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Ways to construct models alternative to ΛCDM:

- to modify $T_{\mu\nu}$ introducing new energy components (Dark Energy).
- to drop the assumption of non interactive fluids.
- to modify the Einstein tensor $G_{\mu\nu}$ changing the Lagrangian of General Relativity (Modified Gravity).

Deviations from Λ and GR

We need a model independent approach to avoid testing every model!
We can identify the key features of ΛCDM and parameterize deviations from them

$$w_{\rm DE} = -1$$

$$k^2\Psi = -4\pi G a^2 \rho\Delta$$

$$k^2\left[\Phi + \Psi\right] = -8\pi G a^2 \rho\Delta$$

$$\frac{\Phi}{\Psi} = 1$$

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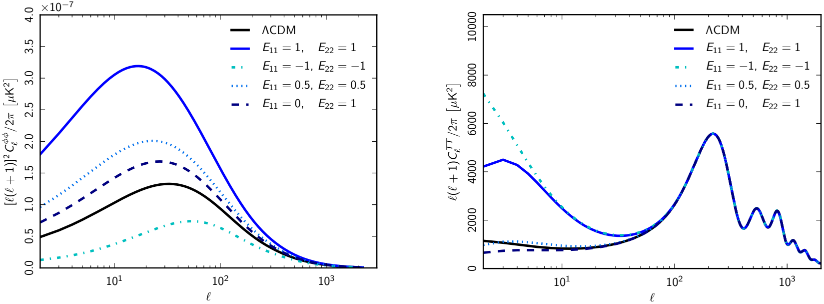
$$\frac{\Phi}{\Psi} = 1$$

$$w_{\rm DE} = w(a)$$
$$k^2\Psi = -4\pi G\mu(a,k) a^2 \rho\Delta$$
$$k^2\left[\Phi+\Psi\right] = -8\pi G\Sigma(a,k) a^2\rho\Delta$$
$$\frac{\Phi}{\Psi} = \eta(a,k)$$

Parametrized deviations from GR

$$k^2\Psi = -4\pi G\mu(a,k)a^2\rho\Delta \qquad \frac{\Phi}{\Psi} = \eta(a,k)$$

$$\mu(a,k) = 1 + E_{11}\Omega_{DE}(a) \qquad \eta(a,k) = 1 + E_{22}\Omega_{DE}(a)$$



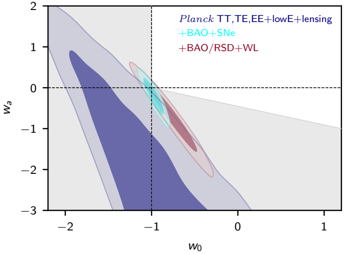
Planck 2015 results. XIV. Dark energy and modified gravity

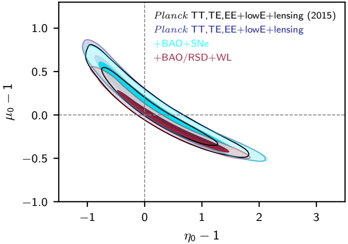
Planck results on MG

Such an approach allowed to constrain deviations from the ΛCDM paradigm.
Constraints on $w_{\rm DE}$ and $\mu - \eta$ were obtained (separately)

CPL parameterization

$$w_{\rm DE}(a) = w_0 + w_a(1-a)$$





Late time MG

$$\mu(a,k) = 1 + E_{11}\Omega_{DE}(a)$$

$$\eta(a,k) = 1 + E_{22}\Omega_{DE}(a)$$

Planck 2018 results. VI. Cosmological parameters 1807.06209