Measuring Angular Diameter Distances using Time-delay Strong Lenses

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27/10/2015

Outline

- **Part I : Measuring angular diameter distances using time-delay lenses**
  Jee, Komatsu and Suyu 2014 (arXiv:1410.7770)

- **Part II : Cosmological prediction**
  Jee, Komatsu, Suyu & Huterer 2015 (arXiv:1509.03310)
  Lensing as a complementary cosmological probe

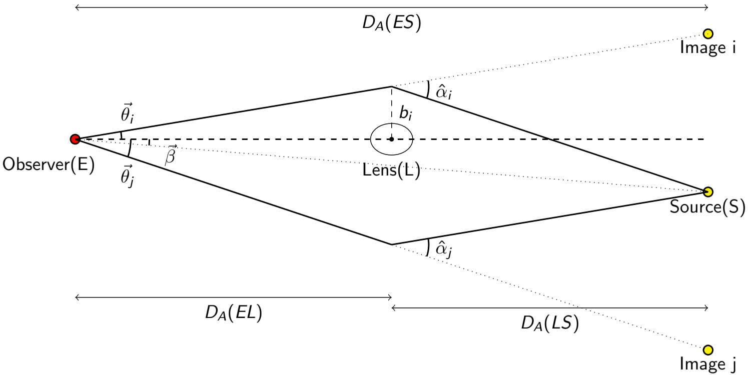
Motivation & goal

Measuring cosmological distances : direct measurement of the expansion history of the universe

- Standard ruler / standard candle
- Object with a known physical size / brightness
- Examples: BAO / SNe
- Precise measurement of distances / multiple redshift coverage ($z<1$)
- Few redshift bins / systematics in intrinsic brightness

$\Rightarrow$ Other efficient ways to measure the distances?

Strong lens with time delay



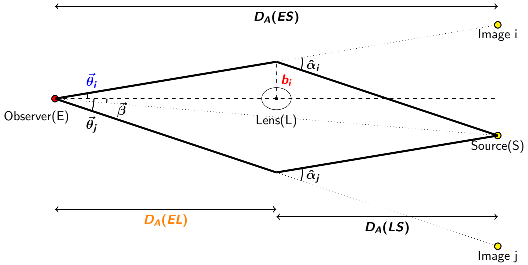
$$\Delta t_{i,j} = \frac{1+z_{\mathrm{L}}}{2c} \frac{D_A(EL)\, D_A(ES)}{D_A(LS)} \phi(\vec{\theta}, \vec{\beta}) \equiv \frac{D_{\Delta t}}{2c} \phi(\vec{\theta}, \vec{\beta}) \qquad (1)$$

Time-delay distance $D_{\Delta t}$

- Strong lens with variable sources
- Measure of distance-like quantity, $D_{\Delta t}$
- External convergence (mass external to the lens lies along the line-of-sight) as the main source of uncertainty (Suyu et al. 2006)

$\Rightarrow$ Alternative way to measure the distance using strong lenses?

Physical Intuition



When the lens mass distribution is known,

- Time delay → Mass estimate
- Velocity dispersion → Potential

⇒ Combine them to get the **physical size** (b) of the system

Observation of strong lensing arc gives the **angular size** (θ) of the system

⇒ The system can be used as a standard ruler to measure the **angular diameter distances** to the lens galaxy ($D_A(EL) = \frac{b}{\theta}$)

Model

Total lens mass model

- Spherically symmetric power-law density profile

Stellar density model

- Hernquist / Jaffe model

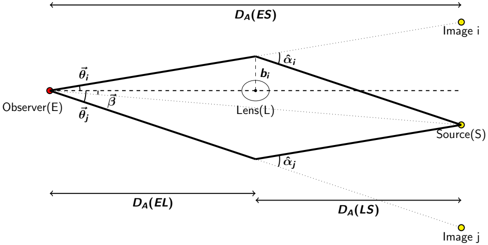
External convergence

- Mass-sheet transformation (MST)

Velocity dispersion model

- Anisotropic (Osipkov-Merritt / Agnello et al. 2014 parametrization)
- Aperture averaged vs. spatially resolved velocity dispersion

Power-law density profile and the deflection angle



Density profile

$$\rho = \rho_0 \left(\frac{r}{r_0} \right)^{-\gamma} \tag{2}$$

Deflection angle at the lens plane

$$\hat{\alpha} = \frac{2GM(b)}{c^2 b} \frac{\sqrt{\pi}\Gamma[0.5(-1+\gamma)]}{\Gamma(\gamma/2)} \propto \sigma_r^2(b) \tag{3}$$

Scaled deflection angle

$$\vec{\alpha} = \hat{\alpha} \frac{D_A(LS)}{D_A(ES)} \tag{4}$$

Power-law density profile and the time delay

Time delay

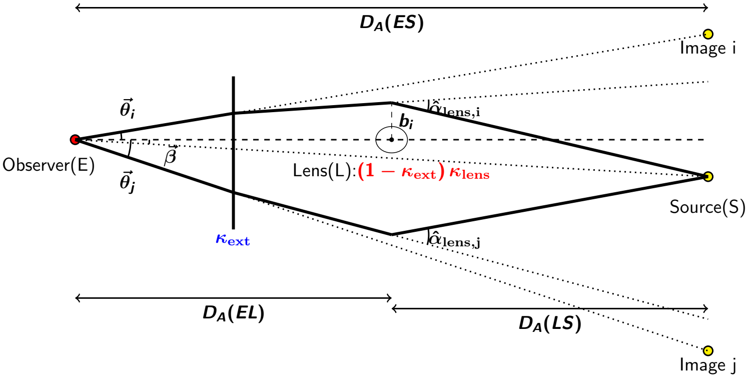
$$\begin{aligned}\Delta t_{i,j} =& \frac{(1+z_{\mathrm{L}})}{2c}\frac{D_A(EL)D_A(ES)}{D_A(LS)}\left[(\vec{\alpha}_i+\vec{\alpha}_j)\cdot(\vec{\theta}_i-\vec{\theta}_j)-\frac{2}{3-\gamma}(\vec{\alpha}_i\cdot\vec{\theta}_i-\vec{\alpha}_j\cdot\vec{\theta}_j)\right]\\ =& \frac{(1+z_{\mathrm{L}})}{2c}D_A(EL)\left[(\hat{\alpha}_i+\hat{\alpha}_j)\cdot(\vec{\theta}_i-\vec{\theta}_j)-\frac{2}{3-\gamma}(\hat{\alpha}_i\cdot\vec{\theta}_i-\hat{\alpha}_j\cdot\vec{\theta}_j)\right]\end{aligned} \tag{5}$$

$\Rightarrow$ The angular diameter distance becomes

$$D_A(EL) = \frac{c^3\Delta t_{i,j}}{4\pi\sigma_r^2(r)(1+z_{\mathrm{L}})}(\Delta\tilde{\theta}_{i,j})^{-1} \tag{6}$$

where $\Delta\tilde{\theta}_{i,j}$ is a function of θ_i, θ_j and γ.

Mass-sheet transformation



Mass-sheet transformation : effect

Time-delay after the MST

$$\Delta t_{i,j,\mathrm{MST}} = (1 - \kappa_{\mathrm{ext}})\, \Delta t_{i,j} \tag{7}$$

Velocity dispersion after the MST

$$\sigma^2_{\mathrm{MST}} = (1 - \kappa_{\mathrm{ext}})\, \sigma^2 \tag{8}$$

$\Rightarrow D_A(EL) \propto \frac{\Delta t}{\sigma^2}$ invariant under the MST

No need to model the external convergence!!

Uncertainty in D_A

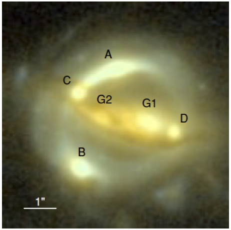


Figure: B1608+656

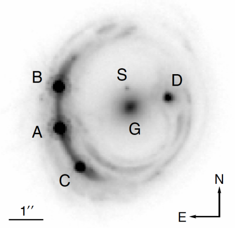
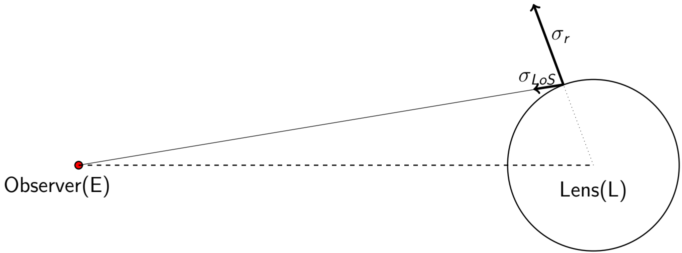


Figure: RXJ1131-1231

Tests on B1608+686 & RXJ1131−1231
(Data and figures from Suyu et al. 2010 & Suyu et al. 2013, and references therein, respectively)

- Uncertainties from γ and $\Delta t_{i,j}$ are negligible
- Velocity dispersion is the biggest source of uncertainty
- Uncertainty in D_A is $\sim 13 - 14\%$ with current data
- Potential estimation (velocity dispersion) seems to play an important role

Anisotropic velocity dispersion



Jeans equation relates the **radial** velocity dispersion σ_r to potential

Observable : **Line-of-Sight** velocity dispersion σ_{LoS}

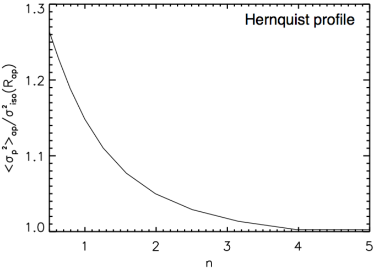
- Luminosity weighted
- Aperture-averaged

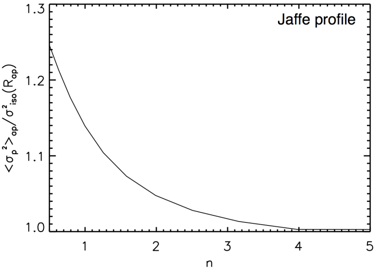
$\Rightarrow$ What if the velocity dispersion is anisotropic ($\sigma_r \neq \sigma_T \neq \sigma_{LoS}$)?

Aperture-averaged velocity dispersion

Measured velocity dispersion is luminosity-weighted, aperture-averaged

$$\langle\sigma_p^2\rangle_{\rm ap} \equiv \frac{\int_{\rm ap} \sigma_s^2 I_X R\; dR\; d\theta}{\int_{\rm ap} I_X R\; dR\; d\theta} \tag{9}$$





The aperture-averaged velocity dispersion varies significantly due to the anisotropy

Sweet-spot method: anisotropy models

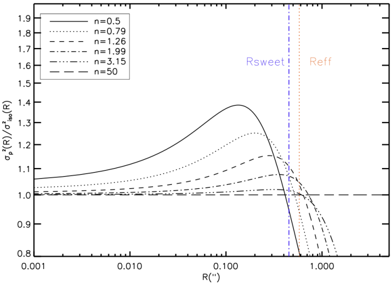


Figure: Osipkov-Merritt anisotripy
$\beta_{in} = 0$, $\beta_{out} = 1$

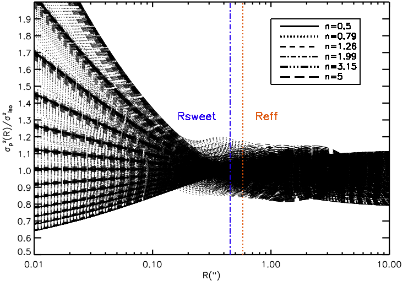
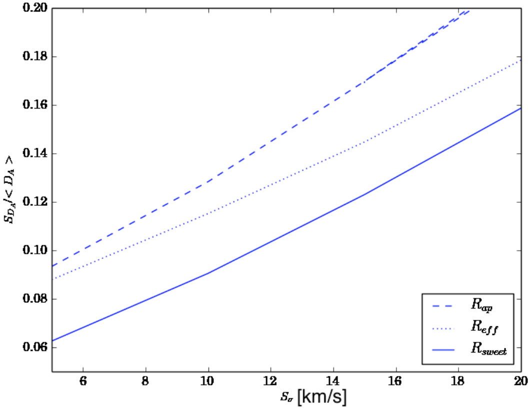


Figure: Agnello et al. 2014
$\beta_{in} = [-0.6, 0.6]$, $\beta_{out} = [-0.6, 0.6]$

Expectation

Uncertainties on measured velocity dispersion [km/s] vs. the fractional uncertainty on D_A inferred



$\sim$ 7% precision is achievable with 5% precision measurement on σ^2 (2.5% on σ) from a single system!

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Method

Fisher information matrix **F**

$$F_{ij} = \sum_{\alpha\beta} \frac{\partial d_\alpha}{\partial \theta_i} \mathbf{Cov}^{-1}_{\alpha\beta} \frac{\partial d_\beta}{\partial \theta_j} \tag{10}$$

Data vector

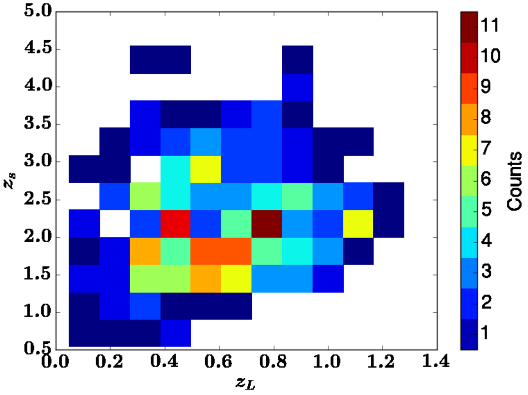
- $\vec{d} = (D_A, D_{\Delta t})$
- No correlation assumed between the two distances
- Assuming 5% precision measurement of distance from each lens

Cosmological models

- owCDM : open ($\Omega_k \neq 0$) w (w=const) CDM
  $\vec{\theta} = (\Omega_{de},\Omega_k,w,h)$
- ow_zCDM : open ($\Omega_k \neq 0$) w_z ($w = w_0 + (1-a)w_a$) CDM
  $\vec{\theta} = (\Omega_{de},\Omega_k,w,w_a,h)$

Lens mock catalog

- Constraints depend on the redshift distribution of lenses and sources
- Mock catalog from LSST prediction (Oguri & Marshall, 2010)



Breaking the Ω_k-w degeneracy

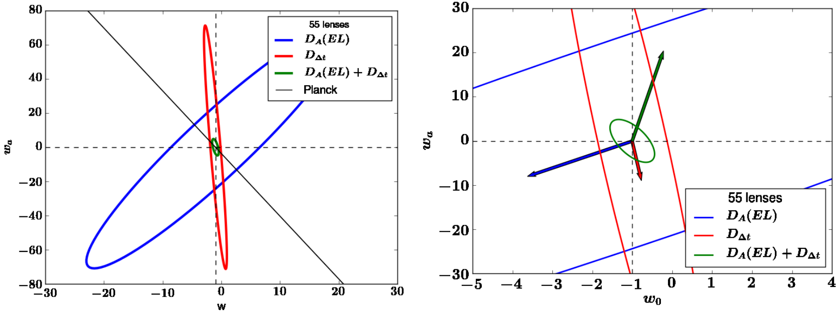


Figure: ow_zCDM

- Ω_k-w degeneracy is broken as we add D_A information to $D_{\Delta t}$

Lensing combined with Planck distance priors

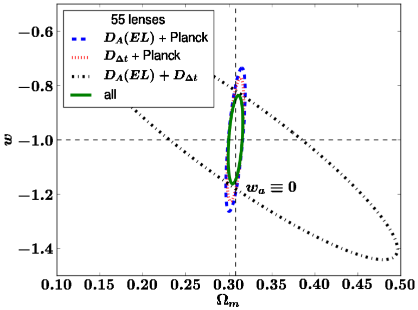


Figure: owCDM

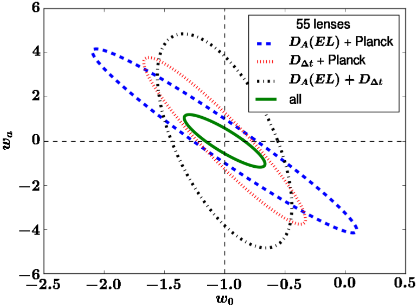


Figure: ow$_z$CDM

- Including D_A tightens the constraints on both w and w_a
- Significant improvement in constraining w_a (by a factor of 3)

Lensing vs. BAO and SNe

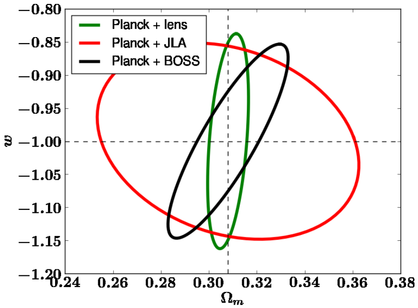


Figure: owCDM

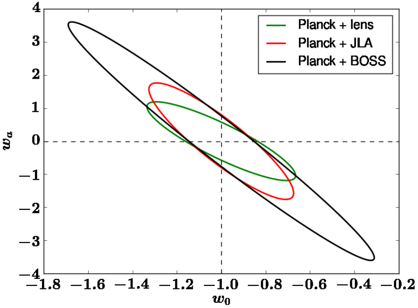


Figure: ow$_z$CDM

- $\Omega_k \neq 0$ degrades the constraining power of SNe on Ω_m
- BAO (DR11) cannot break the degeneracy between w and w_a with only 2 redshift bins

Lensing combined with CMB, BAO and SNe

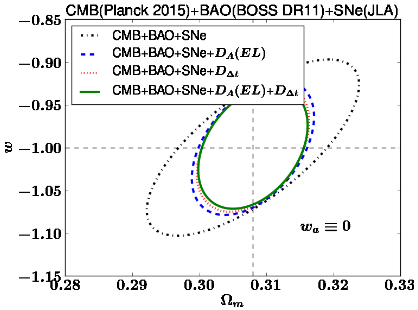


Figure: owCDM

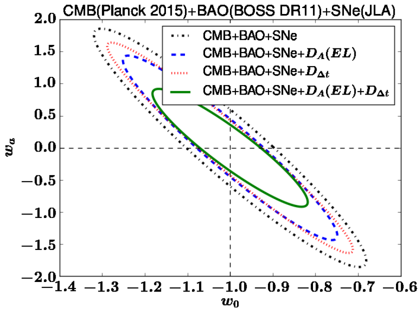


Figure: ow_zCDM

- owCDM: 25% improvement in w
- ow_zCDM: 50% improvement in w_a

Summary

- Strong lenses with time delay can be used as "rulers" to measure the angular diameter distances to the lenses
- The external convergence cancels out : The main source of uncertainty in measuring the time-delay distances is not there
- The biggest uncertainty on D_A is from the velocity dispersion and its anisotropy
- Using spatially resolved velocity dispersion profile at the sweet spot radius will improve the precision
- **arXiv:1410.7770** for more details in D_A measurement!
- Constraints on cosmology (esp. w and w_a) can be significantly improved using D_A and $D_{\Delta t}$ from lensing
- **arXiv:1509.03310** for the forecast from LSST lenses

Anisotropic velocity dispersion : modeling

General form for the anisotropy parameterization used

$$\beta_{\rm ani}(r) = \frac{\beta_{\rm in} r^2 + \beta_{\rm out} r_{\rm a}^2}{r^2 + r_{\rm a}^2} = 1 - \frac{\sigma_T^2(r)}{\sigma_r^2(r)} \tag{11}$$

- Anisotropic radius parametrization : $r_{\rm a} = nR_{\rm eff}$
- Isotropic core, radial envelope

Jeans equation

$$\frac{1}{\rho_*}\frac{d(\sigma_r^2 \rho_*)}{dr} + 2\beta_{\rm ani}\frac{\sigma_r^2}{r} = -\frac{GM(\leq r)}{r^2} \tag{12}$$

Projection & luminosity weighting (Hernquist / Jaffe profile)

$$\sigma_p^2(R) = I_X(R)\sigma_s^2(R) = 2\int_R^\infty (1 - \beta_{\rm ani}\frac{R^2}{r^2})\frac{\rho_*(r)\sigma_r^2(r) r dr}{\sqrt{r^2 - R^2}} \tag{13}$$

Sweet-spot method: motivation

Radius where the scatter in anisotropic velocity dispersion is minimized

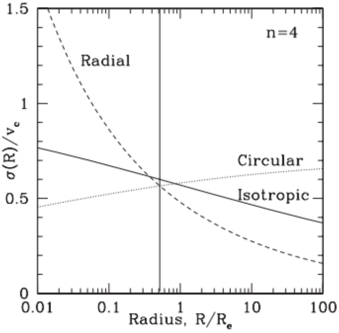


Figure: Churazov et al. 2010