Measuring Angular Diameter Distances Using Time-delay Lenses

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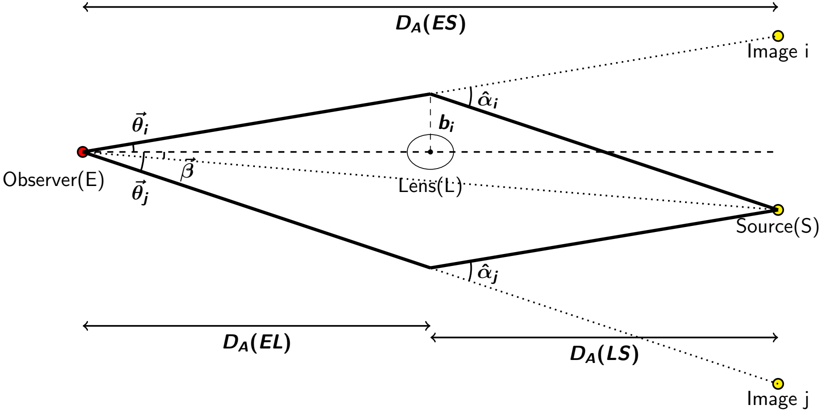
Strong lens with time delay



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

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

- Strong lens with variable sources
- Measure of distance-like quantity, $D_{\Delta t}$
- Sensitive only to the Hubble constant H_0
- 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?

Measuring D_A using time-delay lenses

Paraficz & Hjorth (2009)

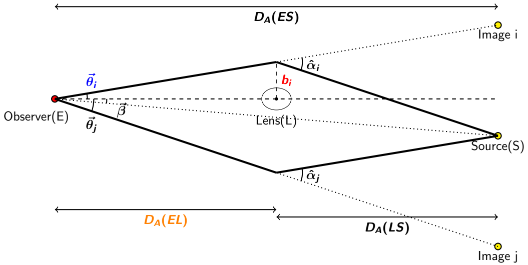
- Singular isothermal sphere (SIS) density profile
- Combine lensing dynamics (velocity dispersion) and the time-delay
- Measured the angular diameter distance using time delay $\Delta t_{i,j}$, velocity dispersion σ^2, lens redshift z_{L} and the image positions θ_i, θ_j

$$D_A(EL) = \frac{c^3 \Delta t_{i,j}}{4\pi\sigma^2(1+z_{\mathrm{L}})} \frac{1}{(\theta_j - \theta_i)} \tag{2}$$

Limitations

- Spherically symmetric mass distribution, isotropic velocity dispersion
- No study on the effect of external convergence

Physical Intuition



When the mass distribution is known,

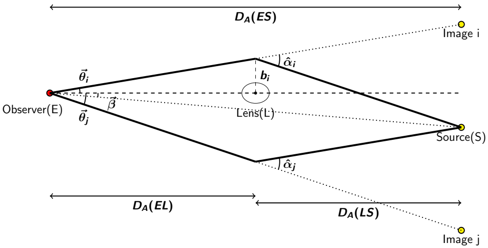
- Time delay $\rightarrow$ Mass estimate
- Velocity dispersion $\rightarrow$ Potential

$\Rightarrow$ Combine them to get the **physical size** (b) of the system

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

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

Power-law density profile and the deflection angle



Density profile

$$\rho = \rho_0 \left(\frac{r}{r_0} \right)^{-\gamma} \tag{3}$$

Deflection angle at the lens plane

$$\hat{\alpha} = \frac{2GM(b)}{c^2 b} \frac{\sqrt{\pi}\Gamma[0.5(-1+\gamma)]}{\Gamma(\gamma/2)} \propto \sigma_r^2(b) \tag{4}$$

Scaled deflection angle (to the source plane)

$$\vec{\alpha} = \vec{\theta} - \vec{\beta} = \hat{\alpha} \frac{D_A(LS)}{D_A(ES)} \tag{5}$$

Power-law density profile and the time delay

Time delay

$$\begin{aligned}\Delta t_{i,j} =& \frac{(1+z_{\rm L})}{2c}\frac{D_A(EL)D_A(ES)}{D_A(LS)}\left[(\vec{\alpha_i}+\vec{\alpha_j})\cdot(\vec{\theta_i}-\vec{\theta_j})-\frac{2}{3-\gamma}(\vec{\alpha_i}\cdot\vec{\theta_i}-\vec{\alpha_j}\cdot\vec{\theta_j})\right]\\ =& \frac{(1+z_{\rm L})}{2c}D_A(EL)\left[(\hat{\alpha}_i+\hat{\alpha}_j)\cdot(\vec{\theta_i}-\vec{\theta_j})-\frac{2}{3-\gamma}(\hat{\alpha}_i\cdot\vec{\theta_i}-\hat{\alpha}_j\cdot\vec{\theta_j})\right]\end{aligned} \tag{6}$$

$\Rightarrow$ The angular diameter distance becomes

$$D_A(EL) = \frac{c^3\Delta t_{i,j}}{4\pi\sigma_r^2(r)(1+z_{\rm L})}(\Delta\tilde{\theta}_{i,j})^{-1} \tag{7}$$

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

Mass-sheet transformation : properties

Used to model the external convergence

Family of the *source-position transformation*

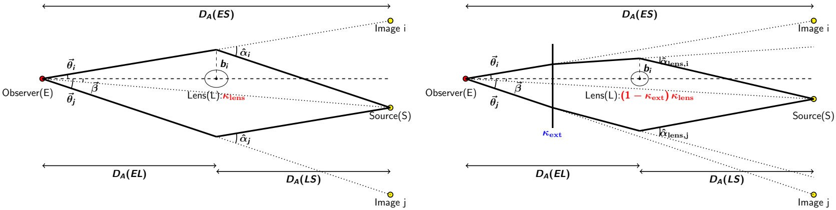
Can reproduce strong lens observables as

- Image position
- Flux ratio

Changes

- Source position (not an observable)
- Time delay

$$\kappa_{\rm lens} \quad \rightarrow \quad \kappa_{\rm MST} = \kappa_{\rm ext} + (1 - \kappa_{\rm ext})\, \kappa_{\rm lens} \tag{8}$$



Mass-sheet transformation : effect

Time-delay after the MST

$$\Delta t_{i,j,\mathrm{MST}} = (1 - \kappa_{\mathrm{ext}})\, \Delta t_{i,j} \tag{9}$$

Velocity dispersion after the MST

$$\sigma^2_{\mathrm{MST}} = (1 - \kappa_{\mathrm{ext}})\, \sigma^2 \tag{10}$$

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

No need to model the external convergence

Uncertainty on D_A

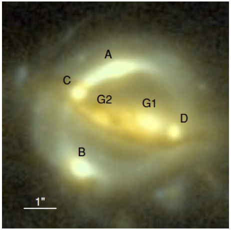


Figure: B1608+656

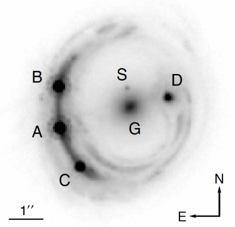


Figure: RXJ1131-1231

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 on D_A is $\sim 13 - 14\%$ with current data
- Potential estimation (velocity dispersion) seems to play an important role: How to take into account the anisotropic velocity dispersion?

Anisotropic velocity dispersion : modeling

Osipkov-Merritt anisotropy

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

- Anisotropy parametrization : $r_{\rm a} = nR_{\rm eff}$
- Isotropic core & radial envelope

Jeans equation

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

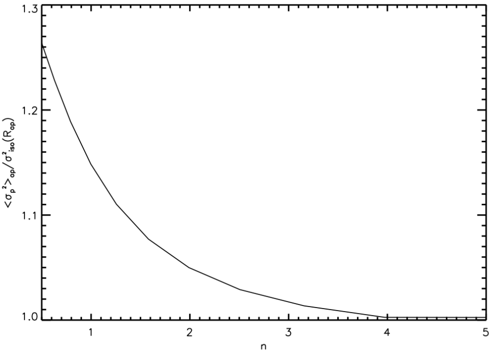
Projection & luminosity weighting (Hernquist profile)

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

Aperture-averaged velocity dispersion

Measured velocity dispersion is luminosity-weighted, aperture-averaged

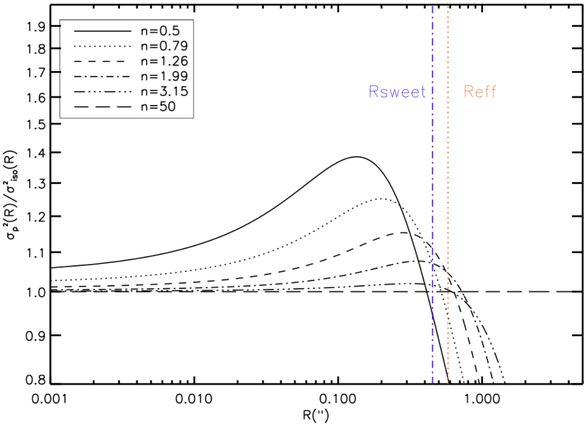
$$\langle \sigma_p^2 \rangle_{\rm ap} \equiv \frac{\int_{\rm ap} \sigma_s^2 I_H R \; dR \; d\theta}{\int_{\rm ap} I_H R \; dR \; d\theta} \quad (14)$$



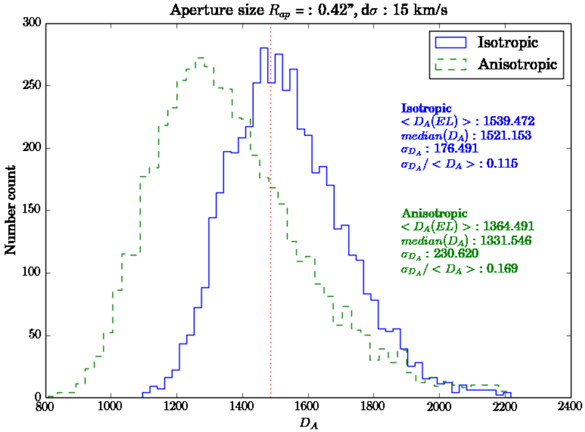
The velocity dispersion varies significantly due to the anisotropy!

Sweet-spot method

Radius where the scatter in anisotropic velocity dispersion is minimized

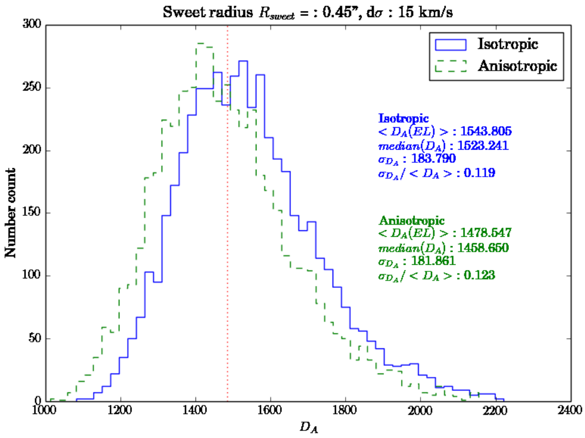


Monte-Carlo simulation 1: D_A measured at $\langle\sigma_p^2\rangle_{\mathrm{ap}}$



Anisotropic velocity dispersion biases the distribution, and the width of the distribution is increased

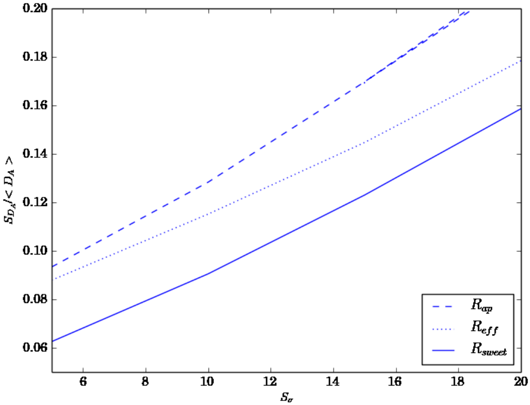
Monte-Carlo simulation 2: D_A measured at $\sigma_p^2(R_{\rm sweet})$



Anisotropic velocity dispersion does not bias the distribution, and the width of the distribution does not change significantly

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 from a single system!

Summary

- Strong lens with time delay can be used as a standard ruler to measure the **angular diameter distances** to the lens
- 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
- More studies on anisotropy parametrization are required
- **arXiv:1410.7770** for more details!