Strong Lensing: Some Cosmological Applications

- **Strong Lensing Provides a Measure of Angle vs. Redshift**
  - **That is, the Angular Size Redshift Relation**
- **Recall That For an Isothermal Mass Distribution:**

$$\rho(r) \sim r^{-2},\ \mathrm{M}(r) \sim r,\ \Sigma(\xi) = \frac{\sigma^2}{2\pi G r},\ \theta_E = \frac{\sigma^2}{c^2}\frac{D_{ds}}{D_s}$$

So if we could measure the velocity dispersion of the lensing galaxy over some spectrograph aperture (r_{ap}), we could compute the dynamical mass:

$$M(dyn) = \frac{\sigma^2 r_{ap}}{G}$$

and compute the corresponding projected mass density within the Einstein radius using a model for extrapolation. If $\rho(r) \sim r^{\gamma}$:

$$M_E(dyn) = \frac{\sigma^2 D_d \theta_E}{G}\left(\frac{\theta_{ap}}{\theta_E}\right)^{2-\gamma} f(\gamma)$$

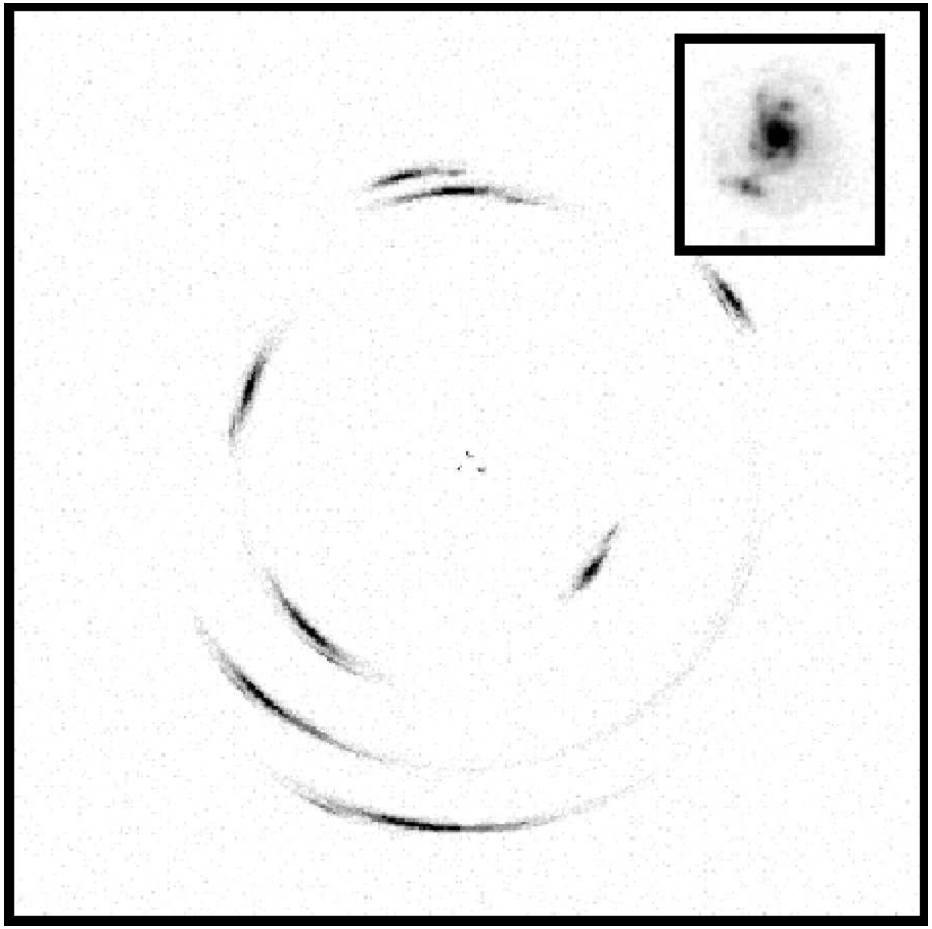
where $f(\gamma)$ is a correction for anisotropy (1 for an isothermal). In this case:

$$\theta_E = \left(\frac{\sigma_{ap}}{c}\right)^2 \frac{D_{ds}}{D_s}\left(\frac{\theta_{ap}}{\theta_E}\right)^{2-\gamma} f(\gamma)^{-1}$$

(c.f. Link & Pierce 1998; ; Treu 2010; Biesiada 2011)

Strong Lensing and Cosmology - I

- **Thus Cosmological Constraints Can Be Extracted from Strongly Lensed Systems**
  - **Problems Arise Due to:**
    - **the small size of spectrograph apertures requiring significant extrapolations to the Einstein radius (uncertainty in the power law index)**
    - **the uncertainties due to the degree of velocity anisotropy**
- **In the Case of Two or More Sources with a Single Lensing Mass the Ratio of the θ_E Depends Only on Cosmology and not the Mass Distribution for an Isothermal. With Three Sources One Can Also Solve for the Power Law Index (Link & Pierce 1998)**
  - **Technique Eliminates Need to Measure Velocity Dispersions, only Need Source Redshifts**
  - **Galaxy-Galaxy Lensing is Rare, but a Few Double Lensed Sources are Known**
  - **Method Works Best for Clusters of Galaxies**
  - **Complications Arise From Dark Matter Sub-structure and From Cluster Members**



Simulated gravitational arcs at different redshift. Inset shows HDF galaxy used.

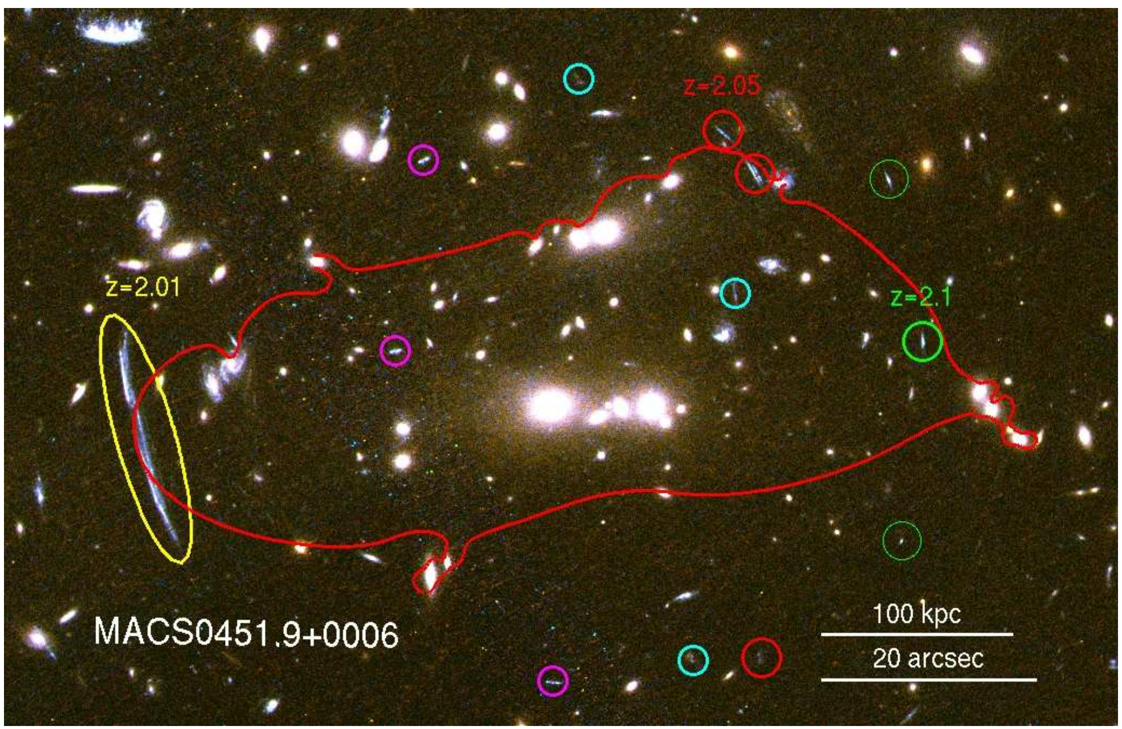
Strong Lensing and Cosmology - II

- **When Applied to Real Clusters the Complications Rise Dramatically**
  - Clusters Have Lots of Substructure
  - Cluster Members Themselves Produce Lensing
    - Assume a Constant Mass/Light Ratio?
  - Cluster Dark Matter Could be Clumpy
    - Clusters Have Lots of Arcs So More Information
    - Reconstruct Dark Matter Distribution with Maximum Likelihood?
    - Method Applied by Jullo et al. 2010 (similar results to BAO or SN Ia at the time)

HST-ACS images of two clusters with gravitational arcs. Left: Abell 2218, Right: CL 0024+1654

Strong Lensing and Cosmology - III

- **Given the Uncertainties in the Method & Success of SN Ia + BAO More Interest of Late in Using Clusters as Telescopes**
- **Modeling of System Allows the Magnification Over the FOV to Be Estimated and the Critical Curves Traced**
  - **Magnifications Can Approach 50x Enabling the Discovery of High Redshift Galaxies**
  - **Location of Critical Curves Used to Search for High-z Galaxies (e.g. Kneib et al. 2004)**



HST-ACS image of MACS0451.9+0006. The critical curve shown in red.

Abell 2218. Lyman-break galaxy at z ~ 6.8 is circled.

Strong Lensing and Cosmology - IV

- **Magnification via Strong Lensing Appears Just Sufficient to Measure Cosmological Parallax (e.g. McGough & Pierce 2020)**
  - **CMB Dipole Provides Absolute Reference of Our Motion Through Space**
  - **Our Line-of-Sight Changes so the Impact Parameter (β) of a Lensed Source Changes Over Time**
- **Parallax Distance is a New Measure of Cosmology:**

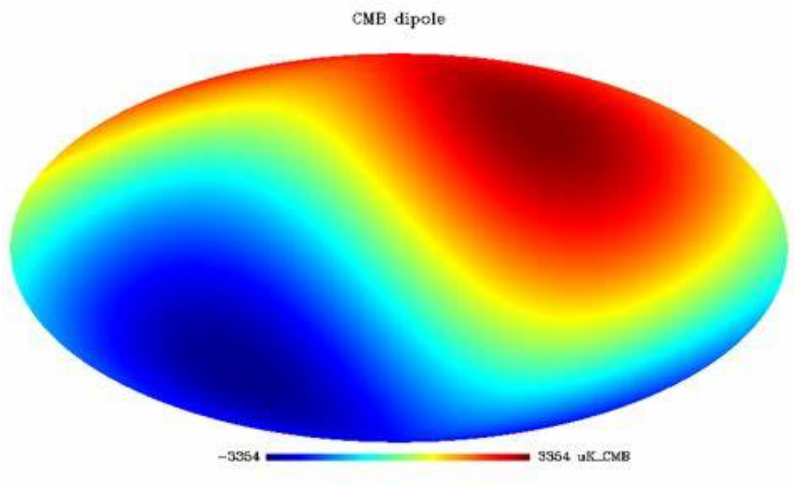
Luminosity Distance (SN Ia): $D_L = (1+z)D_M$

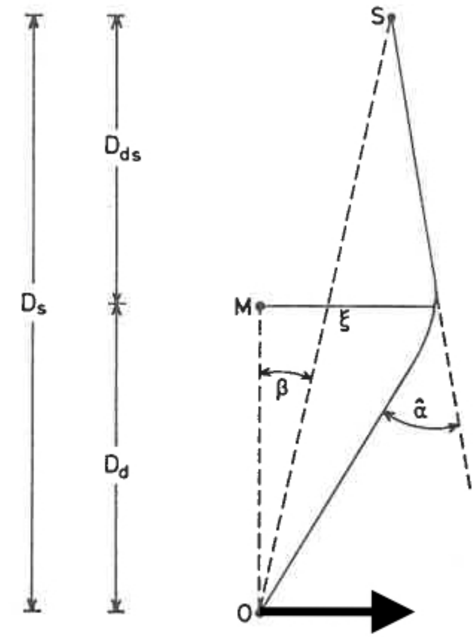
Angular-size Distance (BAO): $D_A = (1+z)^{-1}D_M$

Parallax Distance: $D_P = D_M$

where D_M is the transverse co − moving distance.

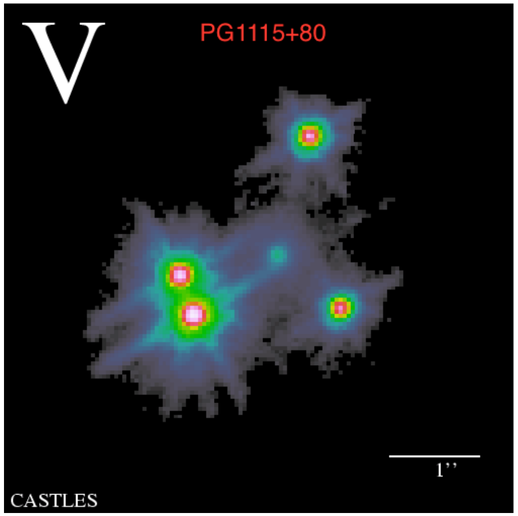
  - **Signal is Purely Geometrical**
  - **Gravitational Lensing Magnifies the Effect**
  - **Signal Accumulates Over Time**
- **Not Currently Measurable with GAIA or VLBI**
- **Next Generation of ELTs with Adaptive Optics**
  - **Will Provide 4 μ arcsec Astrometry**
  - **Sufficient for Cosmological Parallaxes**
- **Might Become Measurable with Upgraded Gravity**

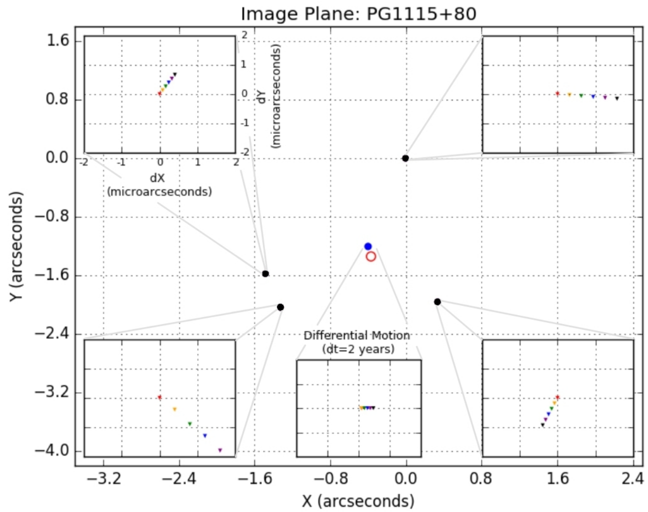


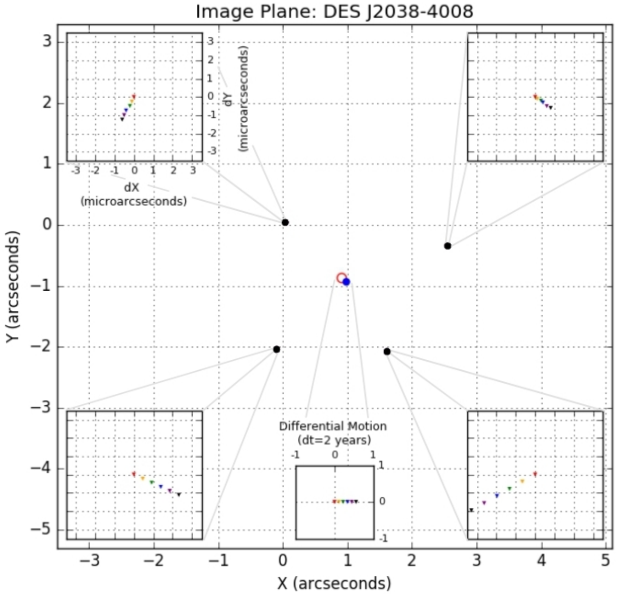


Strong Lensing and Cosmology – IV cont.

- **Our Simulations Gravitationally Lensed Quasars Show That Measurement is Feasbible**
  - **A Sample of ~ 300 Systems Would Enable Cosmological Constraints ~ 5X Better Than SN Ia and/or BAO**







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- **Richards,**