MEASURING COSMOLOGICAL PARALLAXES: PATH FINDING RECONNAISSANCE WITH GNAOS AND GEMS

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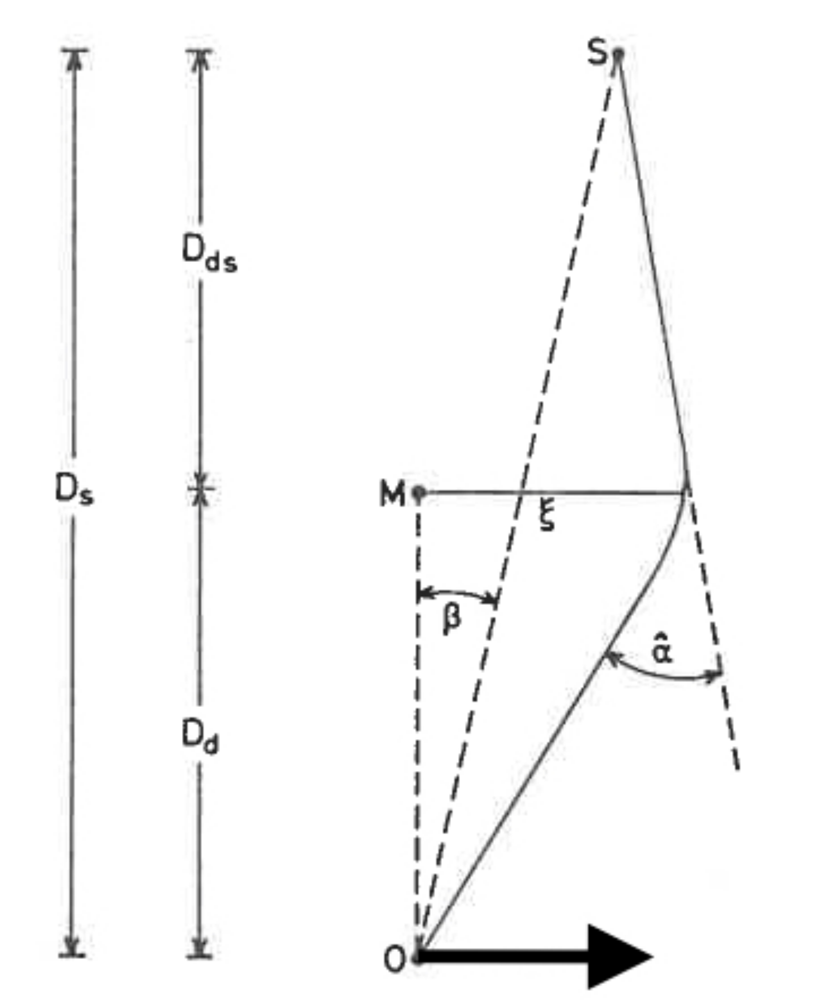
MOTIVATIONS: COSMOLOGICAL DISTANCES

- Recall Standard Measures for ($\Omega_K = 0$) Includes:
  - Luminosity Distance (SN Ia): D_L=$(1+z)D_M$
  - Angular-size Distance (BAO): $D_A = (1+z)^{-1}D_M$
- Transverse (Parallax) Distance: $D_P = D_M$
  - New and Independent
  - Traditionally Dismissed as Too Difficult (10^{-9} as with 1 AU baseline) but:

    1) Earth's Motion wrt CMB Provides Secular Parallax Baseline
    - Baseline Increases 78 AU/year (precision absolute reference)
    - Still difficult: we need ~ 10^{-6} arcsec astrometry over 10 years!

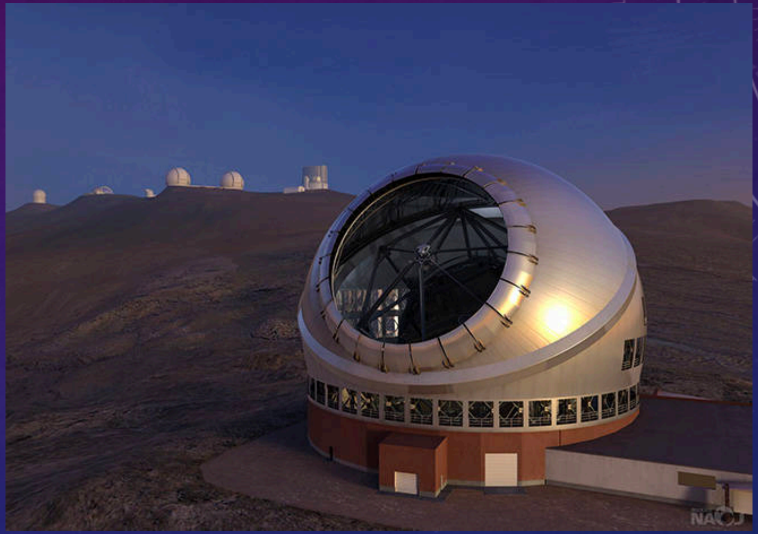
    2) Signal is Magnified in Lensing Systems -> Cosmological Parallax)
    - Magnifications of ~ 5-7x (-> 4 x 10^{-6} arcsec) over 10 yrs, comparable to ELT Performance Requirements
  - Plausible measurement of cosmological parallax over 10yrs

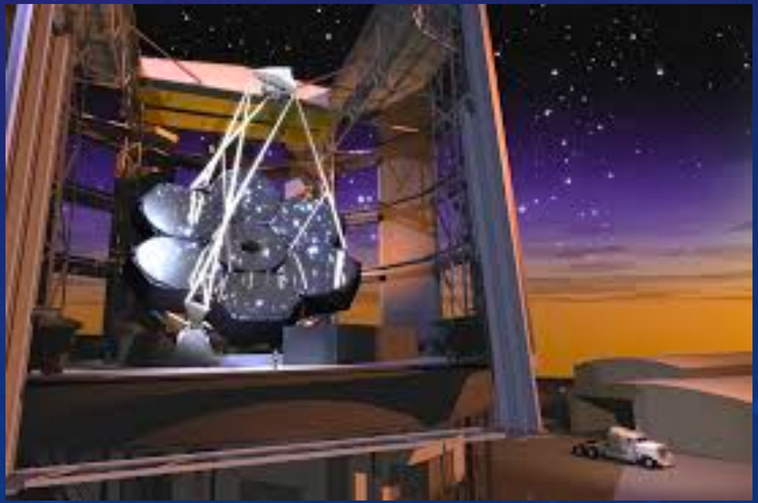


NARROW-FIELD ASTROMETRY WITH AO ON EXTREMELY LARGE TELESCOPES (ELTS)

- **ELTs + AO will Provide High-Strehl, Near-IR Imaging**
- **Unprecedented Imaging Resolution & Astrometry**
  - **8 mas FWHM: 10x Hubble's, 5x JWST's**
  - **4-6 µas Astrometry Possible Over Small Fields**

    (Cameron et al. 2008; Ammons et al 2012)
- **Cosmological Parallaxes Plausible**
  - **Signal Comparable to Milky Way SMBH Requirements (e.g., IRIS on TMT)**
  - **AO on TMT & GMT Would Provide All Sky Coverage of Parallactic Plane (maximizing parallactic signal)**



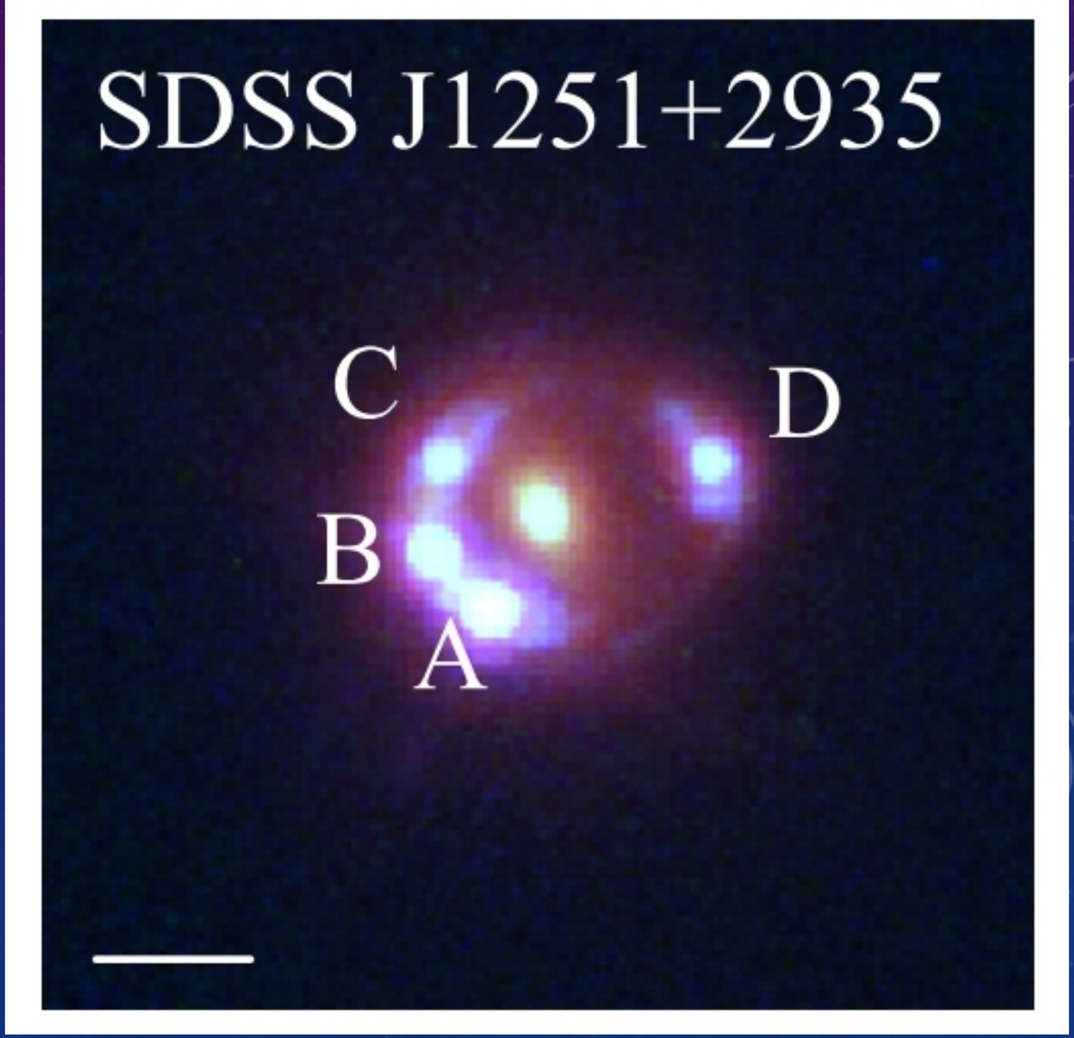


COSMOLOGICAL PARALLAX USING STRONG LENSES

- Advantages of Strongly Lensed Quasars
  - Large Δz Results in Differential Parallax
  - Ideally Suited for Small Field of View of ELTs
  - Single Source and Lens Simplifies Modeling
  - Point-source Images Ideal for Precision Astrometry

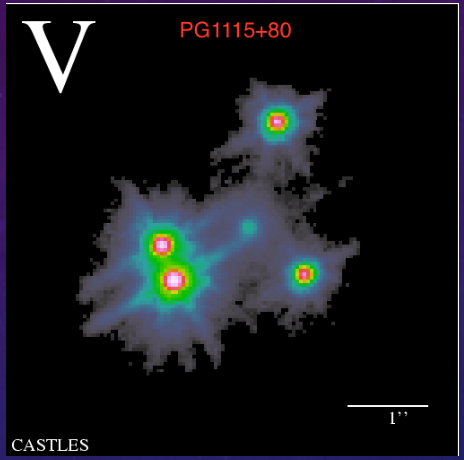
    (high s/n -> precision astrometry)
  - Approximately 1500 – 3000 Quad Systems Predicted from LSST, EUCLID & WFIRST (Oguri & Marshall, 2010)
  - Our Simulations of STRIDES Sample Systems
    - Magnifications from strong lensing systems ~ 3-5x (-> 4 x 10^{-6}arcsec over 10 yrs), signal similar to Galactic center SMBH requirements for ELTs
    - Plausible Measurement with ELTs Over 10yr
  - What's Missing?: sub-halo and field masses

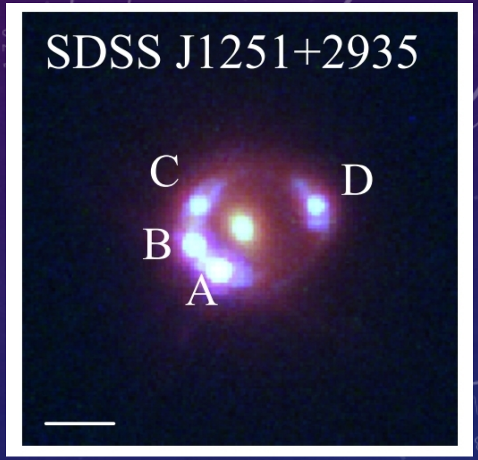
    (See simulation details today in poster 108.11 by McGough & Pierce)

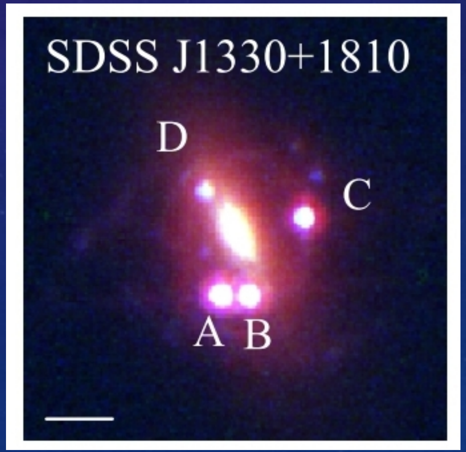


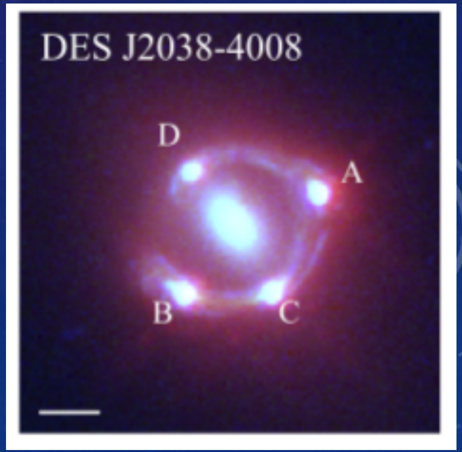
COSMOLOGICAL PARALLAX SIMULATIONS OF STRONGLY LENSED QUASARS

- **Selected Subset From STRIDES Systems (Shajib et al. 2019)**
  - Quad Systems with Known Redshifts and HST Archival Images
  - Use Lensmodel (Keeton, 2001) to Model System
  - Compute Differential Cosmological Parallax for ΛCDM
    - Adopt the WMAP Best-fit Parameters
    - Compute the Expected Position of Source Relative to Lens (every 2 years over 10 year baseline)
    - For a Fixed Lens Model Adjust Source Position
    - Compute New Image Locations
    - Compare with TMT/IRIS Astrometry









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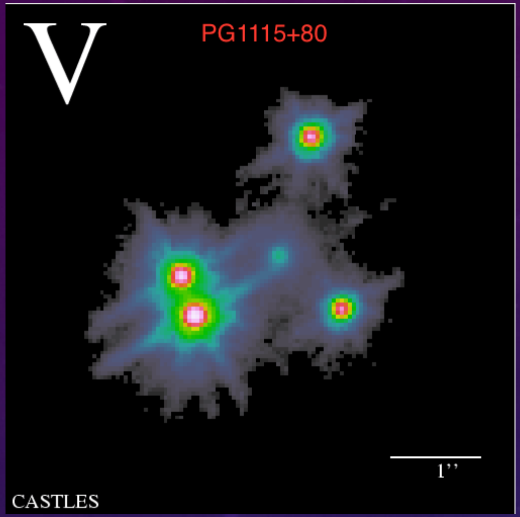
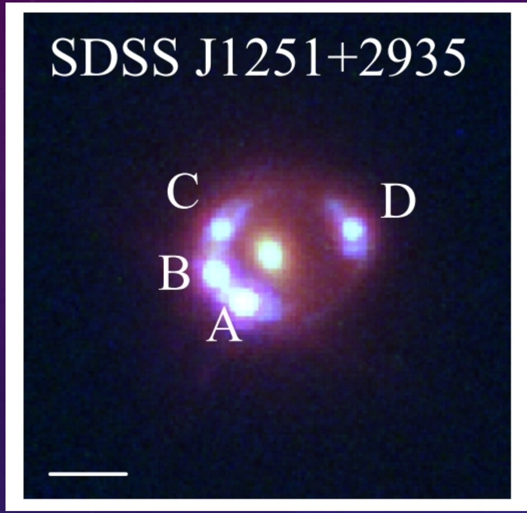
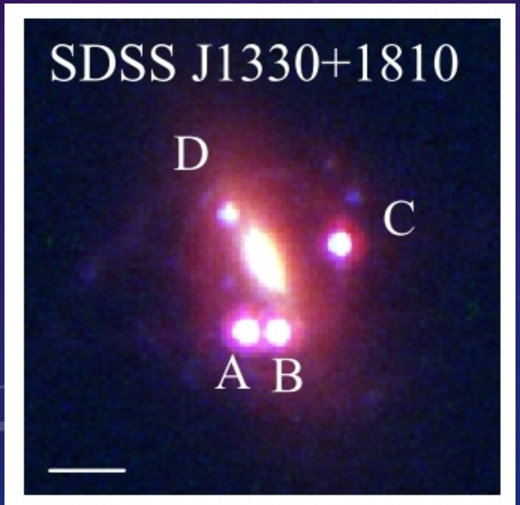
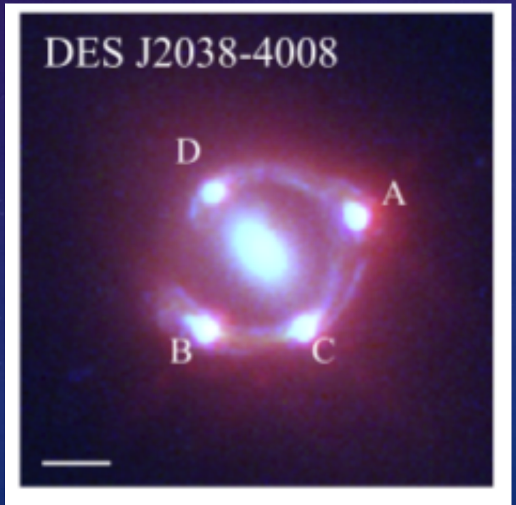
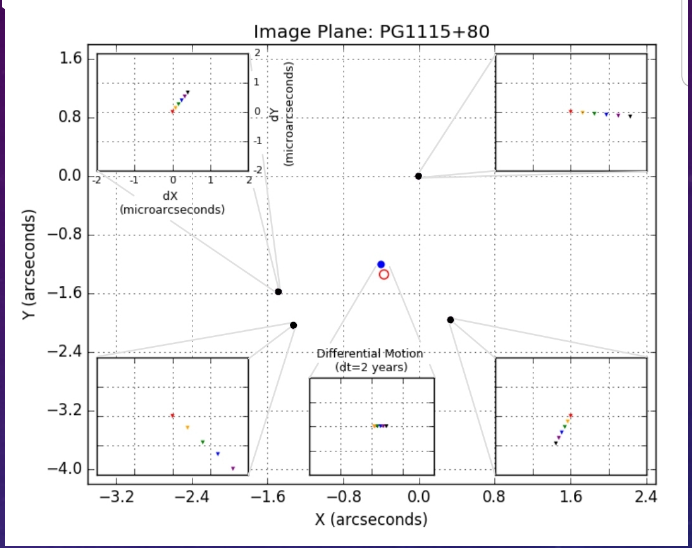
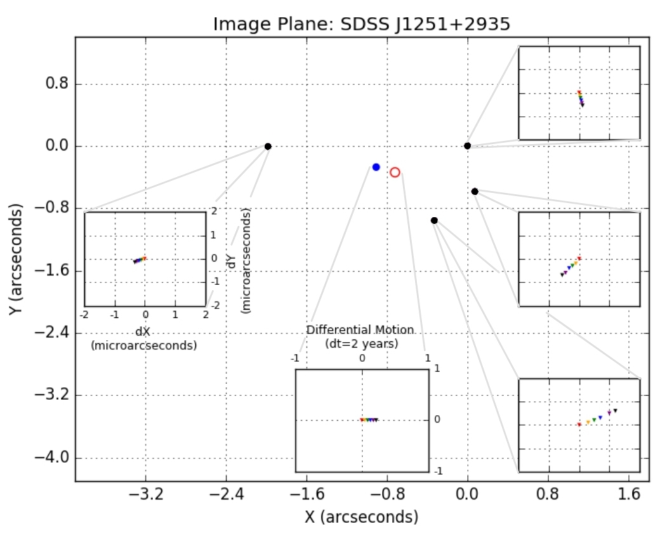


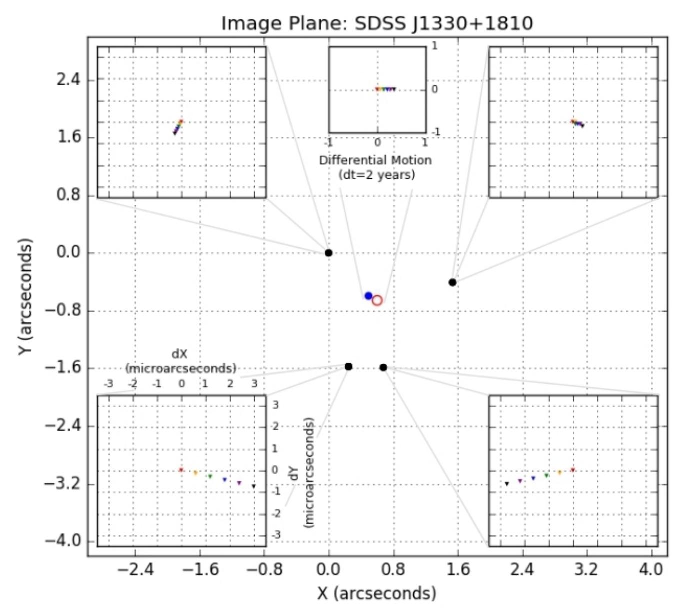


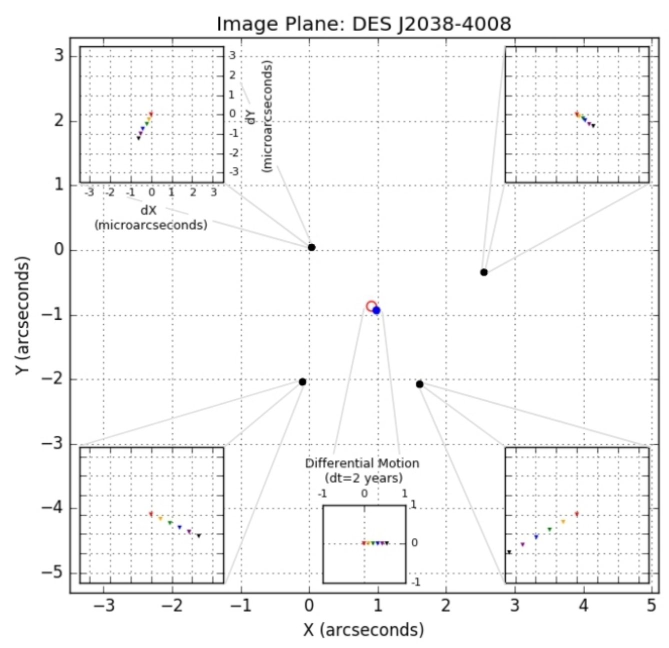








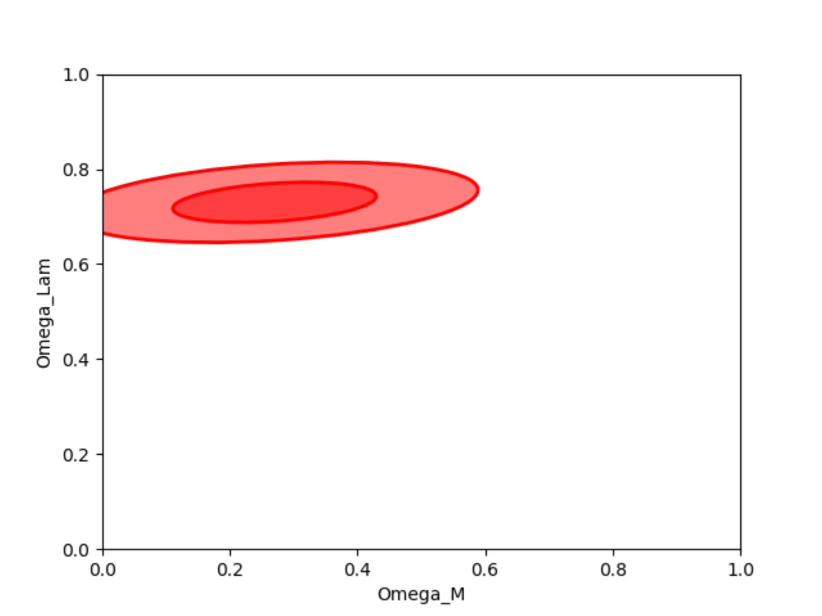


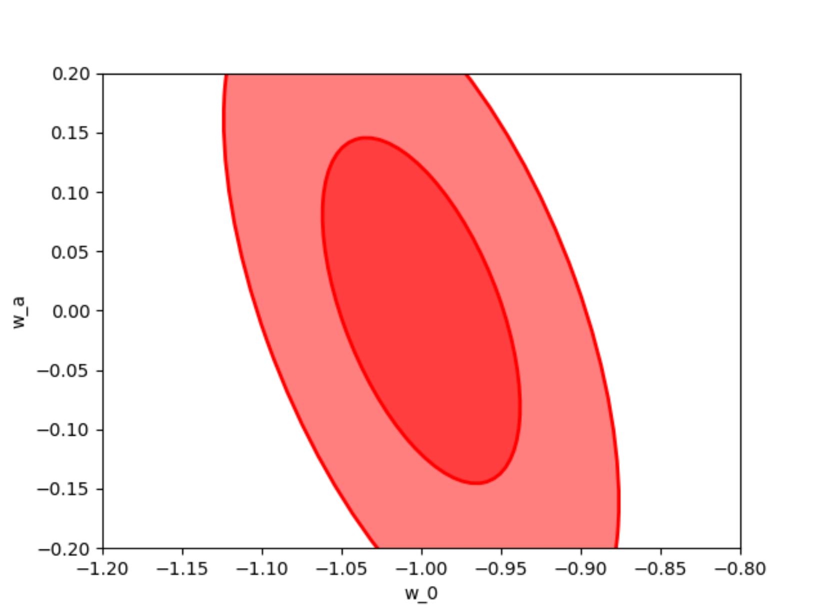


PREDICTIONS FOR A SAMPLE OF 300 LENSED QUASAR SYSTEMS

- **We Considered a Sample of 300 Quad Systems (+- 30-deg from Parallactic Plane)**
- **Assumed our 4 μas Simulation Results are Typical**
- **Assumed an ELT Astrometric Precision $\delta\pi = 4 \times 10^{-6}$ arcsec**
- **Assumed Random Peculiar Source Motions of 300 km/sec**
- **Fisher Matrix Modeling (Ding and Croft 2009)**
  - **Cosmological Constraints of 5% (1-σ)**
  - **Interestingly Different Constraints from SN Ia & BAO**
  - **Provides Simultaneous Constraint on H_0 of 2 %**

    (e.g., 71 +- 1.5 km/sec/Mpc)
- **Measurement of Cosmological Parallaxes Look Feasible**





GEMINI IMAGING SURVEY OF LENSED QUASARS

- **Wide-field Surveys to Identify Strongly Lensed Systems**
  - **DES, LSST, WFIRST, Euclid**
    - **DES is Finding Hundreds of Lensed Quasars (1” separations)!**
- **Reconn. Imaging & Spectroscopy with Gemini N & S (NIR with AO)**
    - **Ideally, We’d Like 50 mas FWHM from GNAOS and An Upgraded GEMS**
    - **IFU Spectroscopy of Lens & Source -> Redshifts**
    - **Snapshot Survey 1000 Systems**
- **Allowing Down-selection to Most Promising Systems**
  - **Location wrt Parallactic Plane (CMB “equator”)**
  - **Morphology of Lensed Quasars & Galaxies**
  - **Preliminary Lensing Models for Magnifications and Caustic Locations**
- **Gemini Survey Will Also Enable Development of Better Modeling Tools**
  - **Better Analysis and Modeling Techniques (Statistics)**
  - **Forward vs. Reverse Modeling for Resolved Sources**

SUMMARY

- ELTs Will Provide Cosmological Parallaxes
  - ELT Time Will Be Extremely Expensive
- Gemini Can Provide Valuable Reconn. Survey Allowing:
  - Imaging For System Morphologies
  - IFU or GMOS Spectroscopy For Redshifts
  - Preliminary Lens Modeling to Identify Most Promising Systems
  - Sample Sizes Could Be a Few x 1000!
  - Efficient AO Target Acquisition Would Provide Necessary Survey Data
  - At ELT First-light We Will Have a Data-based Model of Cosmological Parallax

ADDITIONAL SLIDES

TRANSVERSE EXTRAGALACTIC MOTIONS AND THE PARALLACTIC DISTANCE

- Parallactic Distance is Related to the Transverse Co-moving Distance (Weinberg 1971)

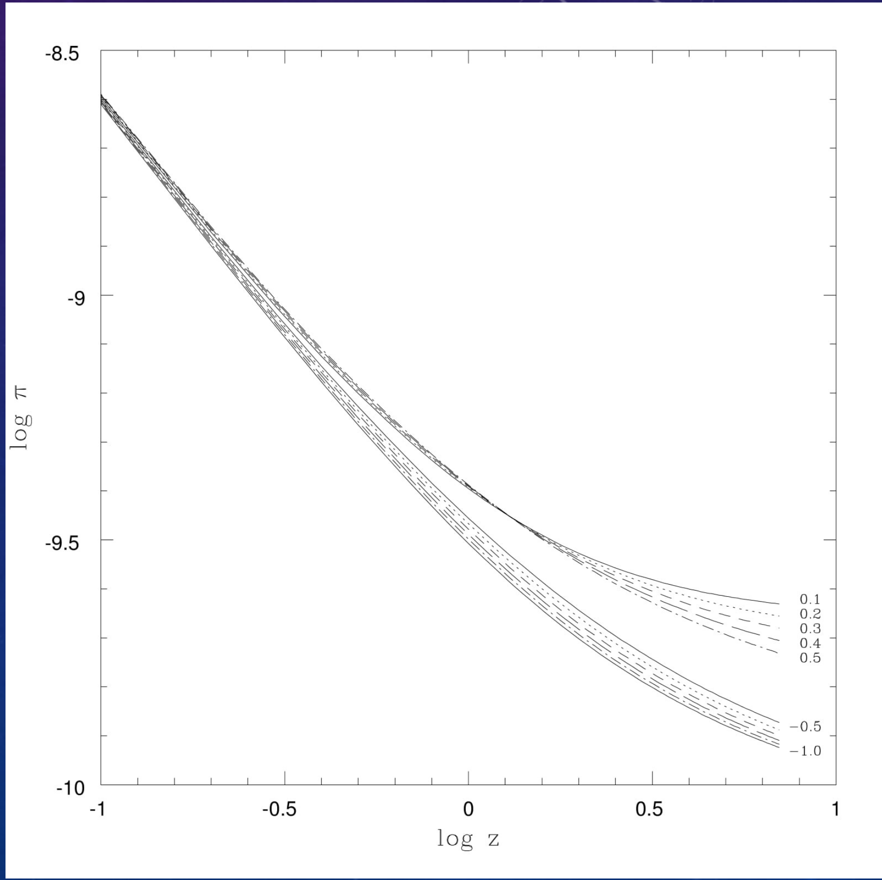
$D_P = R(t_0)\frac{D_m}{(1-kD_M^2)^{1/2}}$ where D_M is the transverse co-moving distance (Hogg 2000)

$$D_M(z) = \frac{D_H}{\sqrt{\Omega_K}} sinh\left[\sqrt{\Omega_K}\frac{D_c(z)}{D_H}\right] \quad \Omega_K > 0,$$
$$D_M(z) = D_c(z) \quad \Omega_K = 0$$
$$D_M(z) = \frac{D_H}{\sqrt{\Omega_K}} sin\left[\sqrt{\Omega_K}\frac{D_c(z)}{D_H}\right] \quad \Omega_K < 0$$

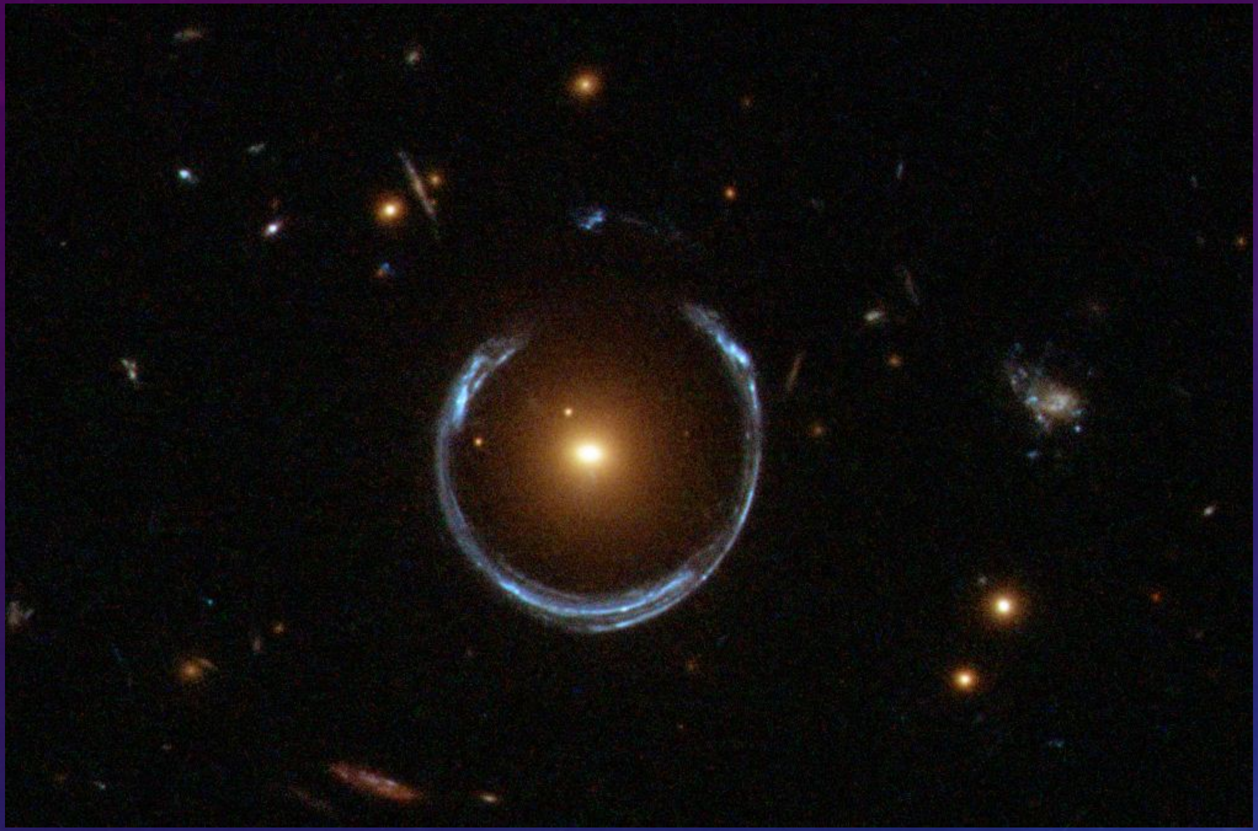
- where $D_H = \frac{c}{H_0}$ and $D_C = \frac{c}{H_0}\int_0^z \frac{dz}{H(z)}$ (the co-moving line of sight distance) where $H(z)$ is the Friedmann equation (Peebles 2000, Huterer & Turner 2003): $\frac{H^2(z)}{H_0^2} = E(z)$ For Dark Energy:

$$E^2 = \Omega_M(1+z)^3 + \Omega_K(1+z)^2 + \Omega_x exp\left[3\int_0^z (1+w(x)dln(1+x))\right]$$

- Numerical Integration -> parallactic distance = 206265 AU/π $< 10^{-9}$ arcsec!

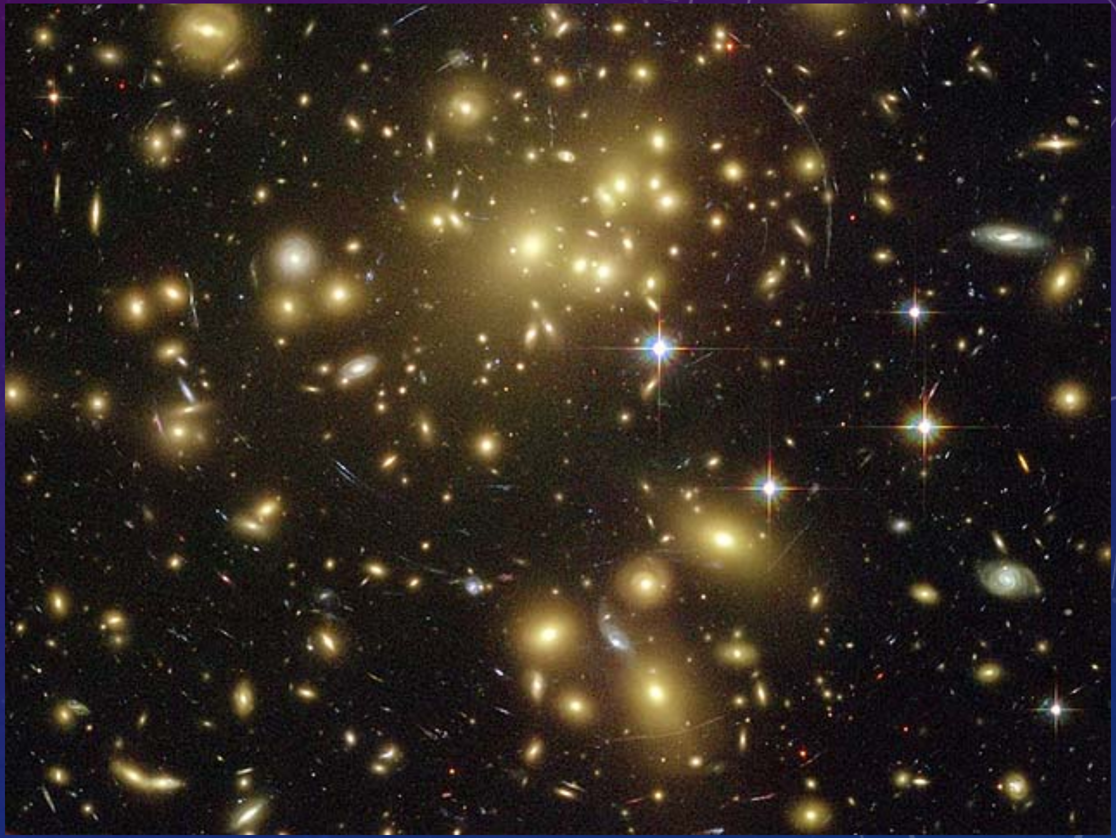


LENSING OPTIONS FOR RESOLVED SOURCES



Galaxy-Galaxy Lensing (10 arcsec)

- Simple Lens Models but Complex Source
- Arc Structure Offers More “Sources” (root-N)
- Challenges for Measurement & Modeling
- Halo Sub-structure & Microlensing?



Cluster-Galaxy Lensing (multiple arcs)

- More Complex Lens Models
- Multiple Sources & DM Sub-structure
- All with Random Transverse Motions

NOTES ON LENSING FROM EXTENDED SOURCES

- **Extended Sources Near Lens Caustics**
  - **For Point Masses θ_E is Proportional to Impact Parameter (just differentiate for changing deflection)**
  - **For Isothermal Potentials θ_E is Independent of Impact Parameter**
    - **Einstein Radii Don't Change Much**
    - **Large Chances in Arc Magnifications (Extent)**
  - **Arc Morphology Constrains Source Position**
    - **Can Predict Apparent Motion of Source wrt Caustic**
  - **Large Changes in Image Structure (if present) with Small Changes in Impact Parameter**
    - **Concentrate on Most Favorable Systems**