New Opportunities with Gravitational Lensing

Roger Blandford

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with help from:

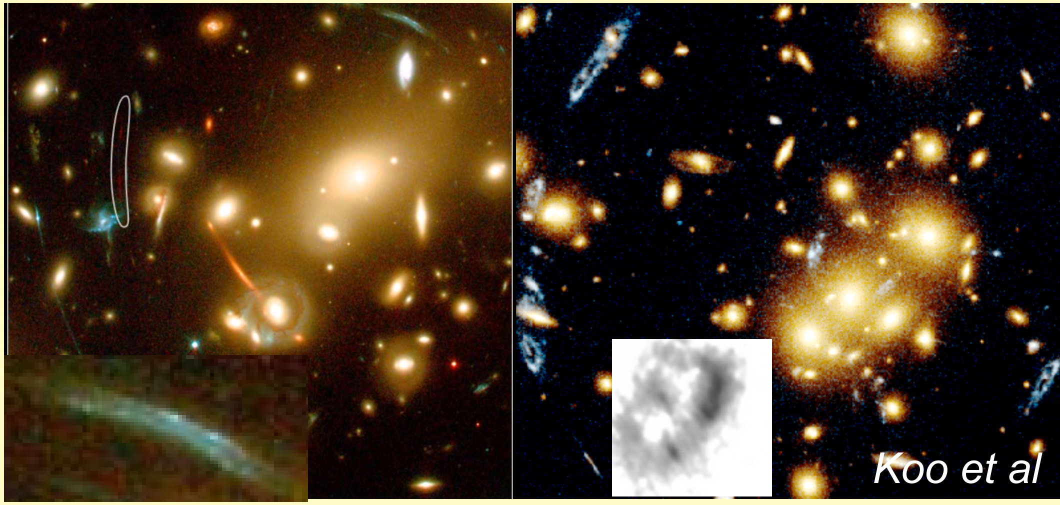
Ted Baltz, Marusa Bradac, Chris Fassnacht, Leon Koopmans, Phil Marshall, Eric Morganson, Masamune Oguri, Sherry Suyu, Tomasso Treu…

New Opportunities

- Catastrophes
- Largest lenses
- Potential inversion/Hubble Constant
- Flatness Test
- Faint Galaxy Lensing

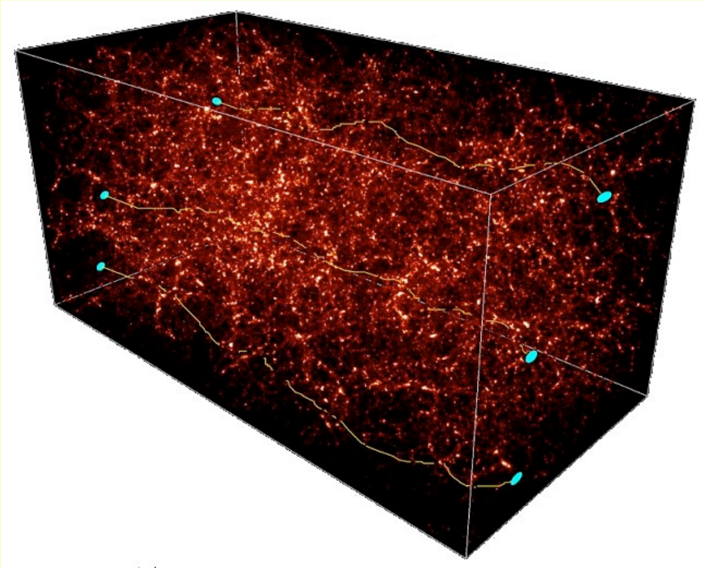
Gravitational Lensing

- **Strong**
  - Clusters
    - Potential, telescopes
  - Galaxies
    - H_0
  - Stars
    - Galactic astronomy
- Weak
  - Cosmic shear
    - Dark Matter and Energy
  - CMB distortion
    - Foreground
  - Galaxy - Galaxy Lensing
    - Galactic structure

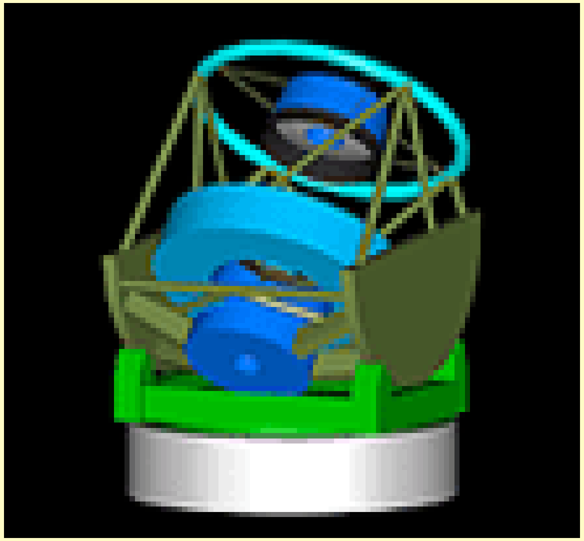


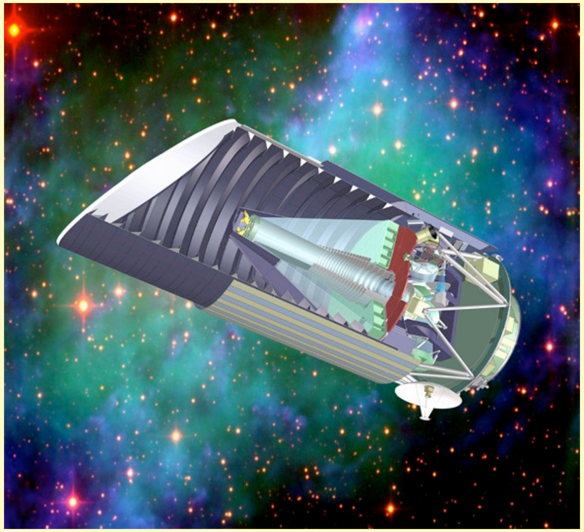
Statistics
vs
Best cases

=> Surveys



Present and Future Surveys





- HST
  - GOODS, UDF; COSMOS?
- LSST
  - Half sky to V~26.5; ~BG
- SNAP
  - Deep survey to V~30; ~MG
  - Wide survey to V~26; ~BG

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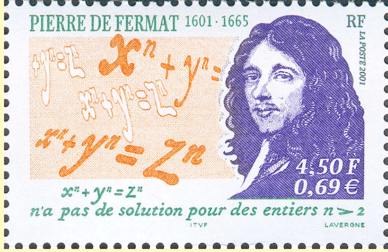
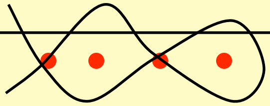
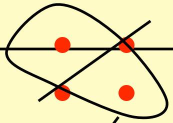
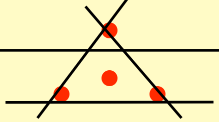
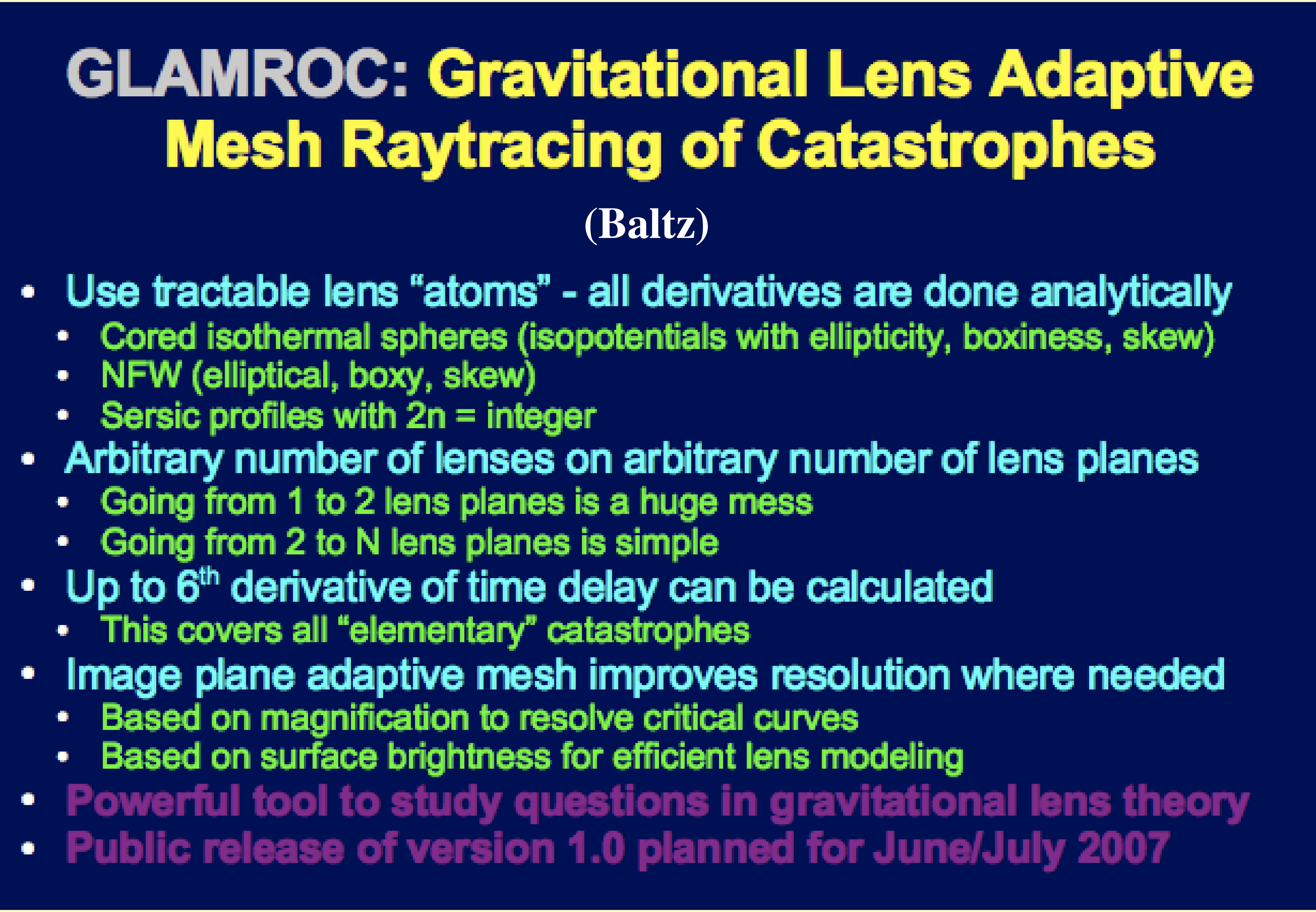
Catastrophes and Metamorphoses



	State	Control	Images	Pattern
Fold	1	1	2	• •
Cusp	1	2	3	• ● •
Lips	1	3	3	• • •
Beak to Beak	1	3	1	●
Swallowtail	1	3	4	
Hyperbolic Umbilic	2	3	4	
Elliptic Umbilic	2	3	4	

How common?



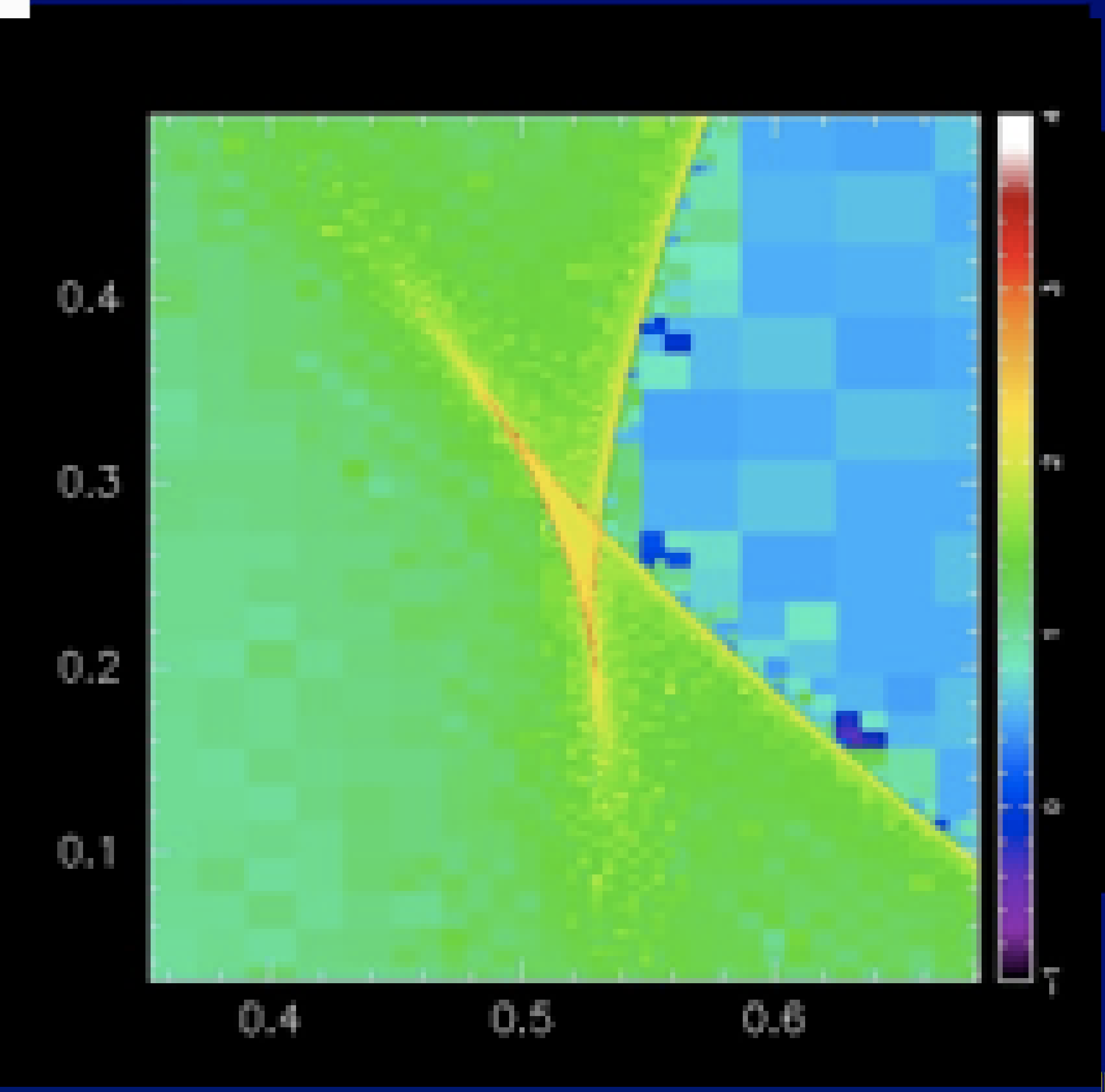
GLAMROC: Gravitational Lens Adaptive Mesh Raytracing of Catastrophes

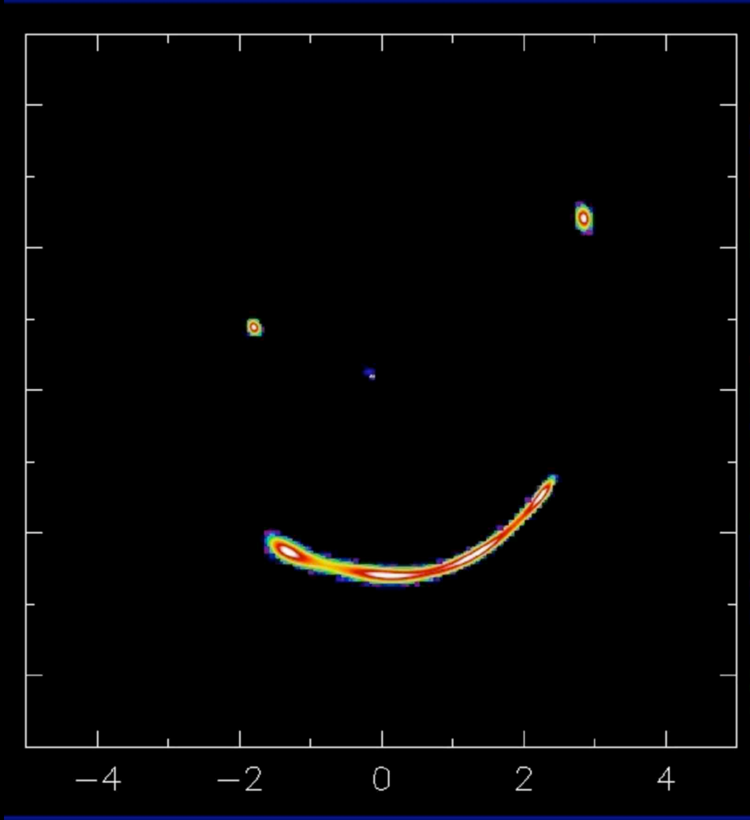
(Baltz)

- Use tractable lens “atoms” - all derivatives are done analytically
  - Cored isothermal spheres (isopotentials with ellipticity, boxiness, skew)
  - NFW (elliptical, boxy, skew)
  - Sersic profiles with 2n = integer
- Arbitrary number of lenses on arbitrary number of lens planes
  - Going from 1 to 2 lens planes is a huge mess
  - Going from 2 to N lens planes is simple
- Up to 6th derivative of time delay can be calculated
  - This covers all “elementary” catastrophes
- Image plane adaptive mesh improves resolution where needed
  - Based on magnification to resolve critical curves
  - Based on surface brightness for efficient lens modeling
- Powerful tool to study questions in gravitational lens theory
- Public release of version 1.0 planned for June/July 2007

GLAMROC: Gravitational Lens Adaptive Mesh Raytracing of Catastrophes

Baltz





Outside galaxies

Sensitive to substructure

Catastrophe Program

- Define observational swallowtails, hyperbolic and elliptic umbilics
- Compute expected incidence of observed catastrophes in large surveys
- Examine best cases as super telescopes and probes of small scale structure
- Compare with observations as statistical check on cosmology

New Opportunities

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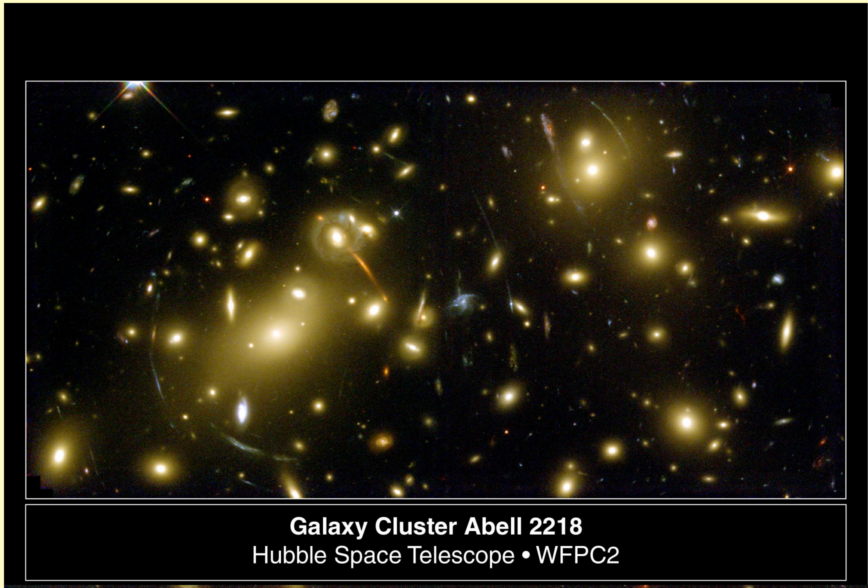
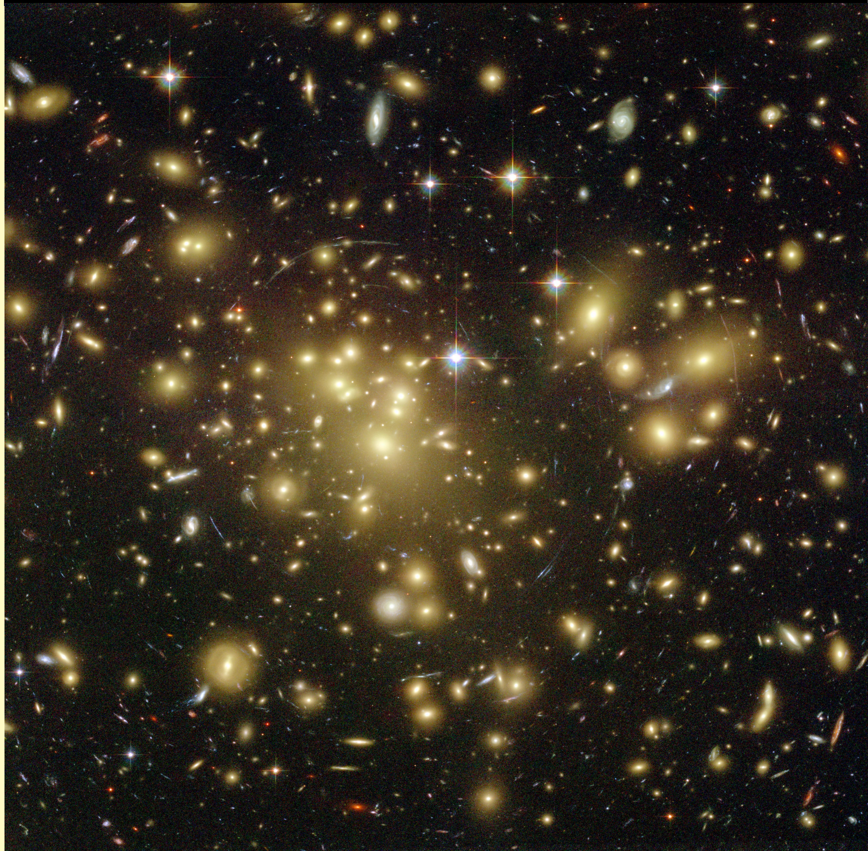
Largest Lenses



Galaxy Cluster Abell 2218
Hubble Space Telescope • WFPC2

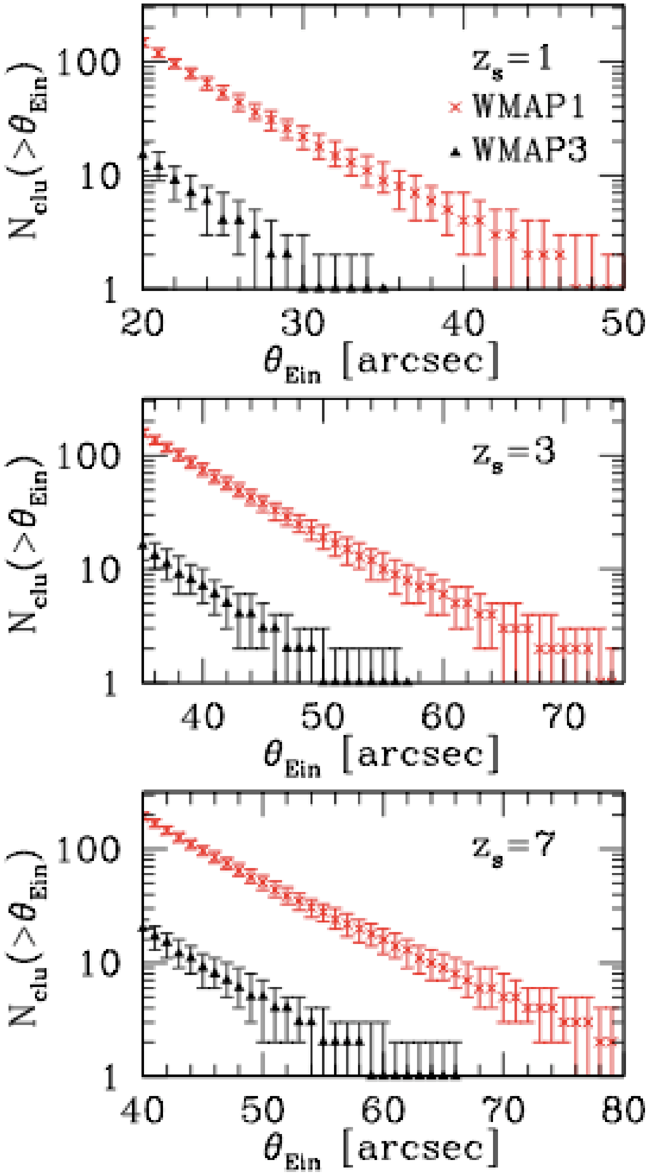


What are the largest lenses (critical curves at large z) on the sky?
Tests structure growth on large, linear scales

Oguri +RB

Largest Einstein Radii

- Observable measure of large scale structure
  - All sky surveys
  - Weak lensing
  - Sunyaev-Zel'dovich
- Sensitive to:
  - **Non-gaussianity**
  - Cosmic variance
  - Normalization (σ_8)
  - Source redshift
  - Nonlinearity
  - Gas dynamics



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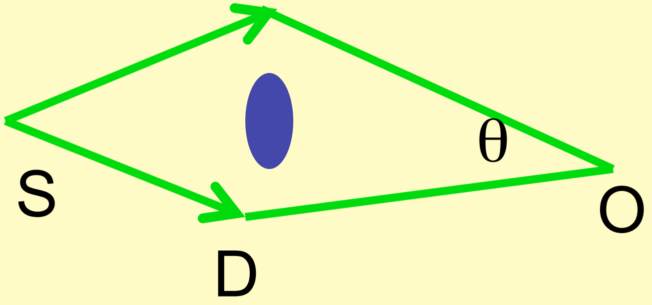
The Measure of the Universe

- H_0=100h km s^{-1} Mpc^{-1}
- Historically, range ~ 10 x Error!
- Recent determinations
  - HST KP (Freedman et al)
    - <h>=0.72+/-0.02+/-0.07
  - Masers (Macri et al)
    - h=0.74+/-0.03+/-0.06
  - WMAP (Spergel et al)
    - h=0.73+/-0.03 (FΛCDM)
  - BAO (Eisenstein et al)

Gravitational Lens Method

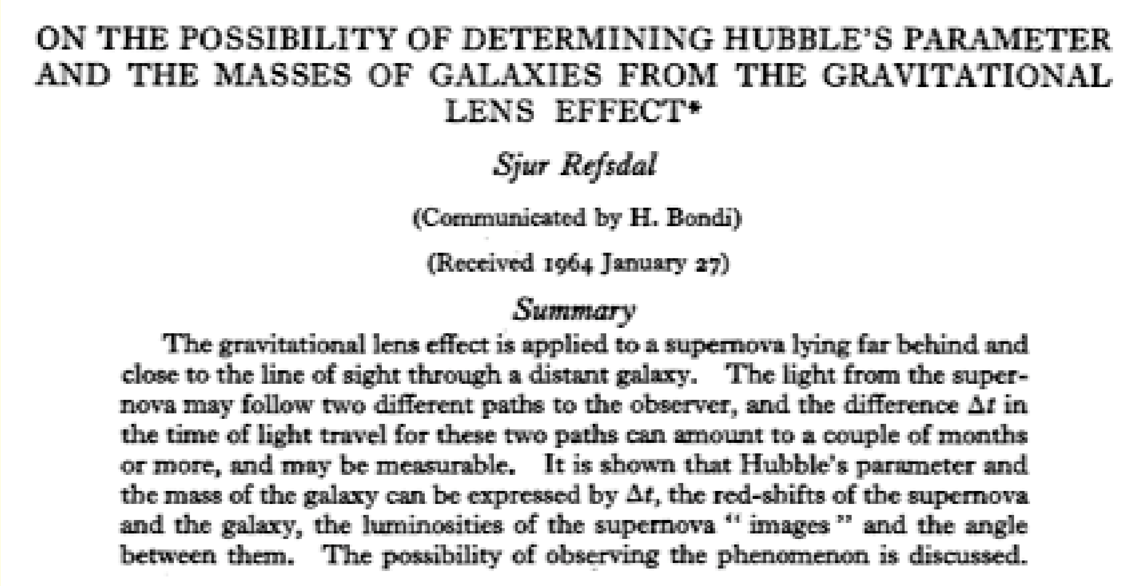


$$\Delta t = a^{-1}\,(\xi.\psi_{,\xi}/2-\psi)$$

- Direct measurement
- Insensitive to world model

$$\frac{\partial \ln h}{\partial \ln[k,\Omega,w..]} \sim 0.02-0.15$$

- Sensitive to lens redshift
- Mass sheet degeneracy
- <h>=0.72+0.08-0.11 (Saha)
  =0.69+/-0.06+/-0.08 (Oguri)



ON THE POSSIBILITY OF DETERMINING HUBBLE'S PARAMETER AND THE MASSES OF GALAXIES FROM THE GRAVITATIONAL LENS EFFECT*

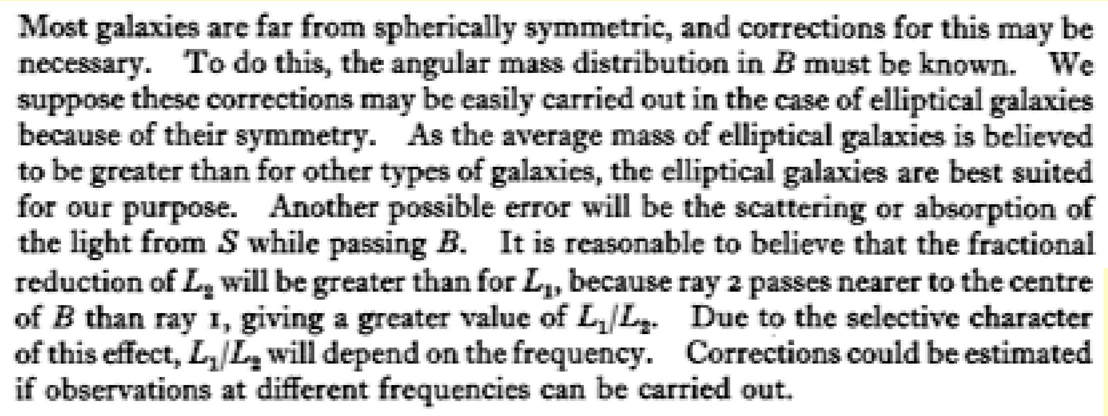
Sjur Refsdal

(Communicated by H. Bondi)

(Received 1964 January 27)

Summary

The gravitational lens effect is applied to a supernova lying far behind and close to the line of sight through a distant galaxy. The light from the supernova may follow two different paths to the observer, and the difference Δt in the time of light travel for these two paths can amount to a couple of months or more, and may be measurable. It is shown that Hubble's parameter and the mass of the galaxy can be expressed by Δt, the red-shifts of the supernova and the galaxy, the luminosities of the supernova "images" and the angle between them. The possibility of observing the phenomenon is discussed.

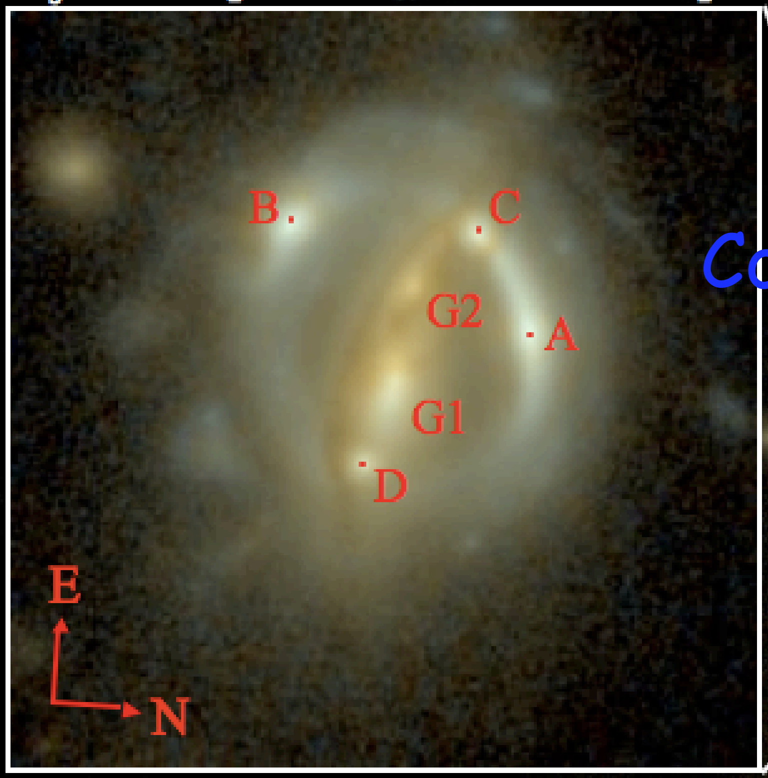


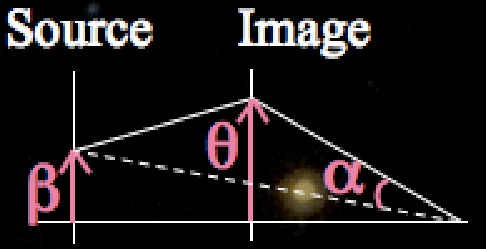
Most galaxies are far from spherically symmetric, and corrections for this may be necessary. To do this, the angular mass distribution in B must be known. We suppose these corrections may be easily carried out in the case of elliptical galaxies because of their symmetry. As the average mass of elliptical galaxies is believed to be greater than for other types of galaxies, the elliptical galaxies are best suited for our purpose. Another possible error will be the scattering or absorption of the light from S while passing B. It is reasonable to believe that the fractional reduction of L_2 will be greater than for L_1, because ray 2 passes nearer to the centre of B than ray 1, giving a greater value of L_1/L_2. Due to the selective character of this effect, L_1/L_2 will depend on the frequency. Corrections could be estimated if observations at different frequencies can be carried out.

"There's gold in them thar hills."

B1608+656

$z_d = 0.63$ [Myers et al. 1995]
$z_s = 1.39$ [Fassnacht et al. 1996]





$$\vec{\alpha}(\vec{\theta}) = \vec{\nabla}\psi(\vec{\theta})$$

Time delay function:

Compare with observations as

$$T(\vec{\theta},\vec{\beta}) \sim \frac{1}{\boxed{H_0}} \underbrace{\left[\frac{1}{2}(\vec{\theta}-\vec{\beta})^2 - \psi(\vec{\theta})\right]}_{\text{Fermat pot. } \phi}$$

Goal

- Relative time delays [Fassnacht et al. 1999, 2002]
  $\Delta t_{AB} = 31.5 \pm 1.5$ days
  $\Delta t_{CB} = 36.0 \pm 1.5$ days
  $\Delta t_{DB} = 77.0 \pm 1.5$ days
- Extended source intensity

B1608+656 provides opportunity to measure H_0 to high precision.
⇒ pixellated potential reconstruction

B1608+656

h=0.72+/-0.02+/-0.04

(Suyu,thesis)

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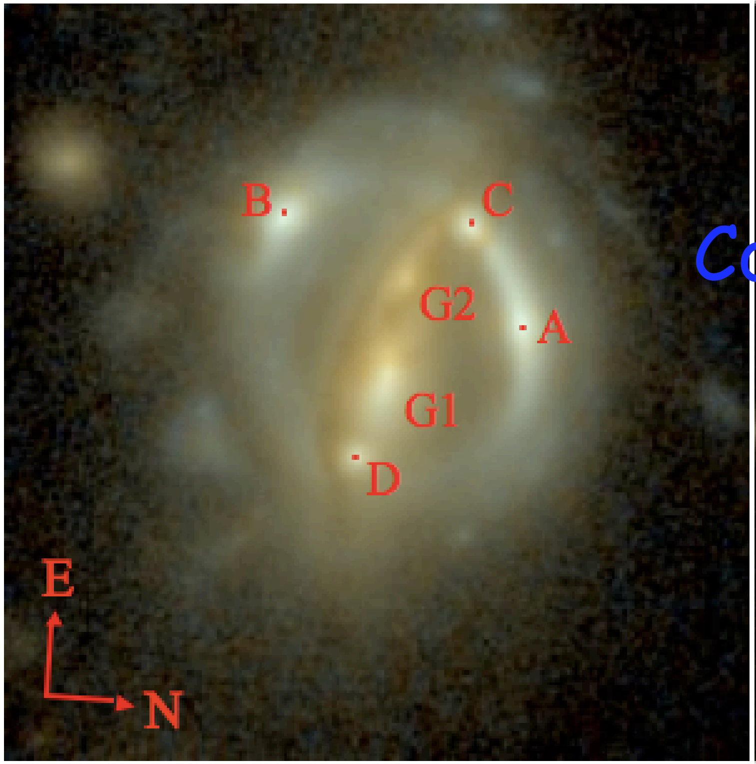

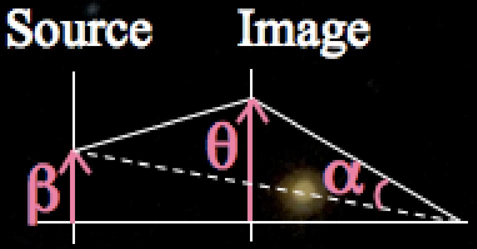

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Mapping from the Source to the Image

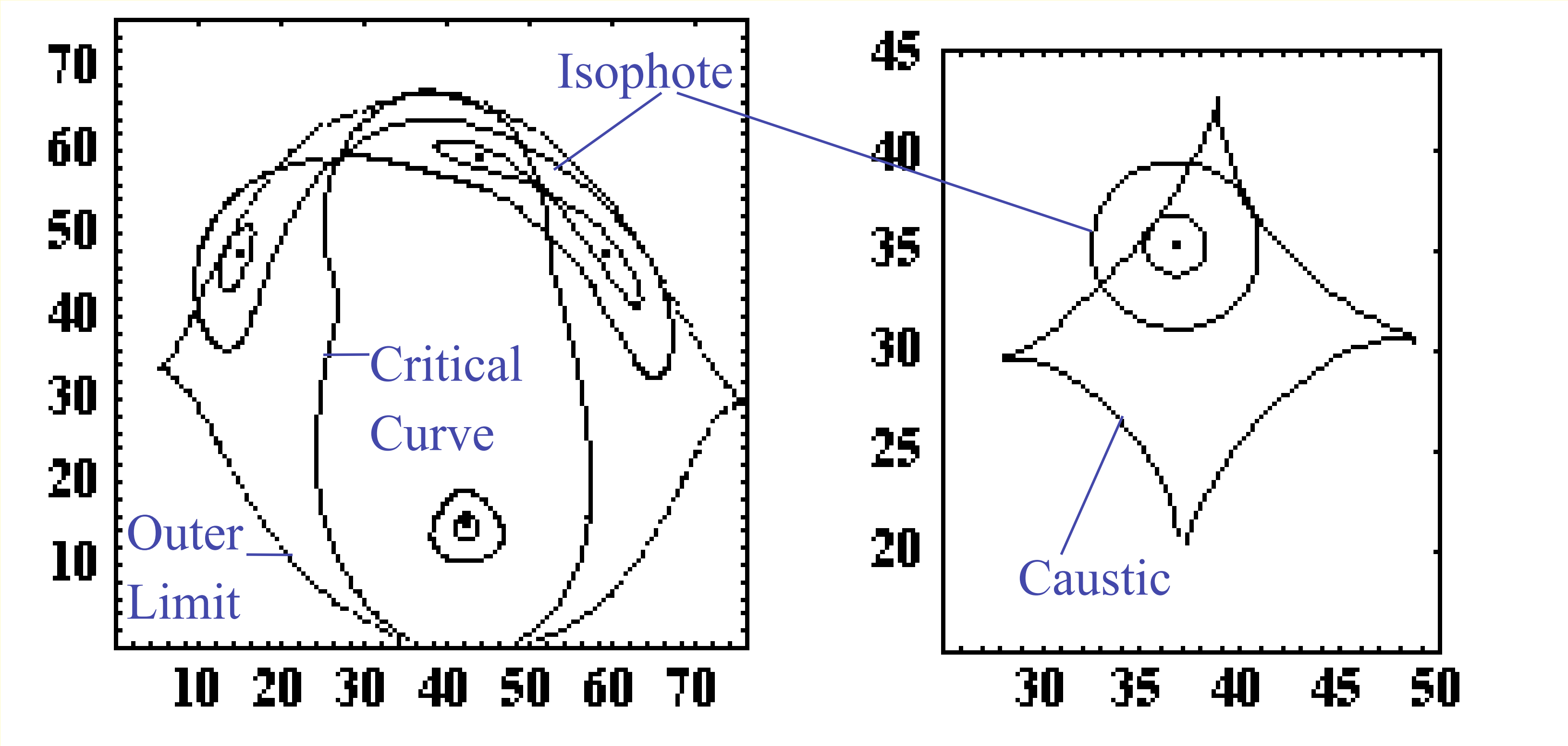


Image Plane

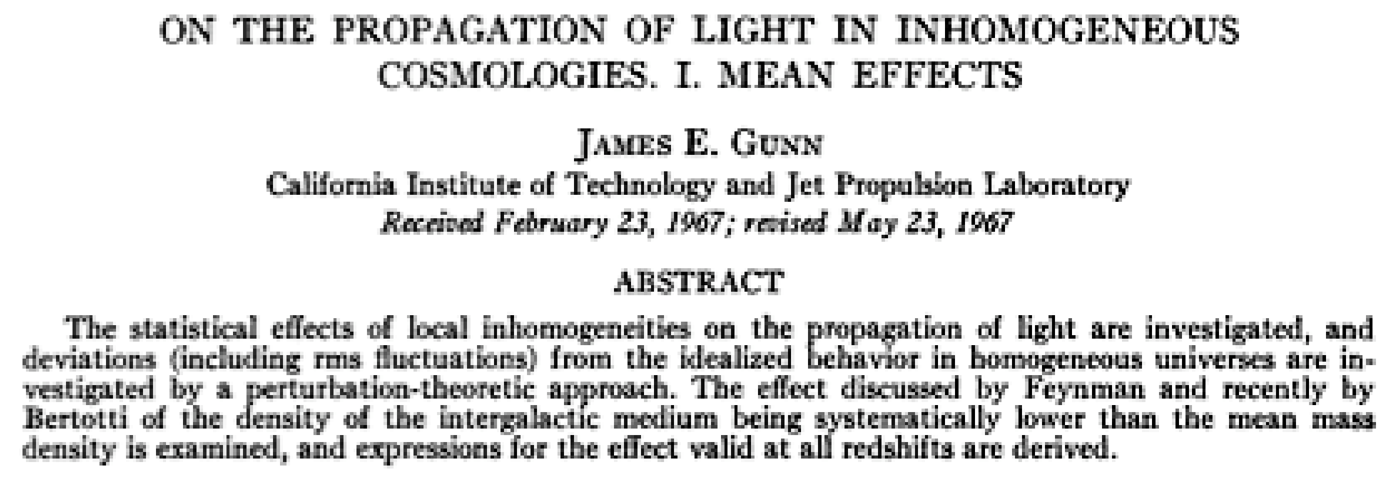
Source Plane

- Isophotes cross on critical curve
- Crossing contours are tangent to inner/outer limits
- Existing models fail these tests
- Deflection has no curl => Unique inversion (in principle)

B1608+656 (Suyu et al)

- Bayesian Source and Potential Reconstruction:
  - iterative and perturbative potential correction scheme works for potential perturbations of ~5%
- HST observations of B1608+656:
  - obtained a representative suite of PSF, dust, and lens galaxies' light models using ACS and NICMOS images
- Potential reconstruction of B1608+656:
  - corrected initial potential SPLE1+D(isotropic) on a grid of pixels for each set of PSF, dust, lens galaxies' light models.
  - Bayesian techniques can be used to compare objectively different PSF, dust, lens galaxy light, and lens potential model and used to quantify modeling (statistical) error.
  - Mass sheet degeneracy is the strongest systematic error
  - H_0=72 ± 2(stat.) ± 4(syst.) km s^{-1} Mpc^{-1}

Light propagation in inhomogeneous cosmology



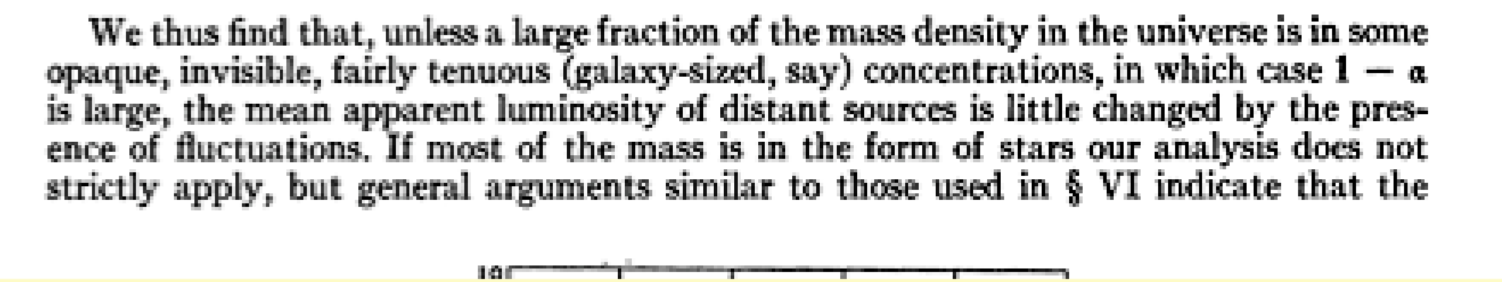
ON THE PROPAGATION OF LIGHT IN INHOMOGENEOUS COSMOLOGIES. I. MEAN EFFECTS

JAMES E. GUNN
California Institute of Technology and Jet Propulsion Laboratory

Received February 23, 1967; revised May 23, 1967

ABSTRACT

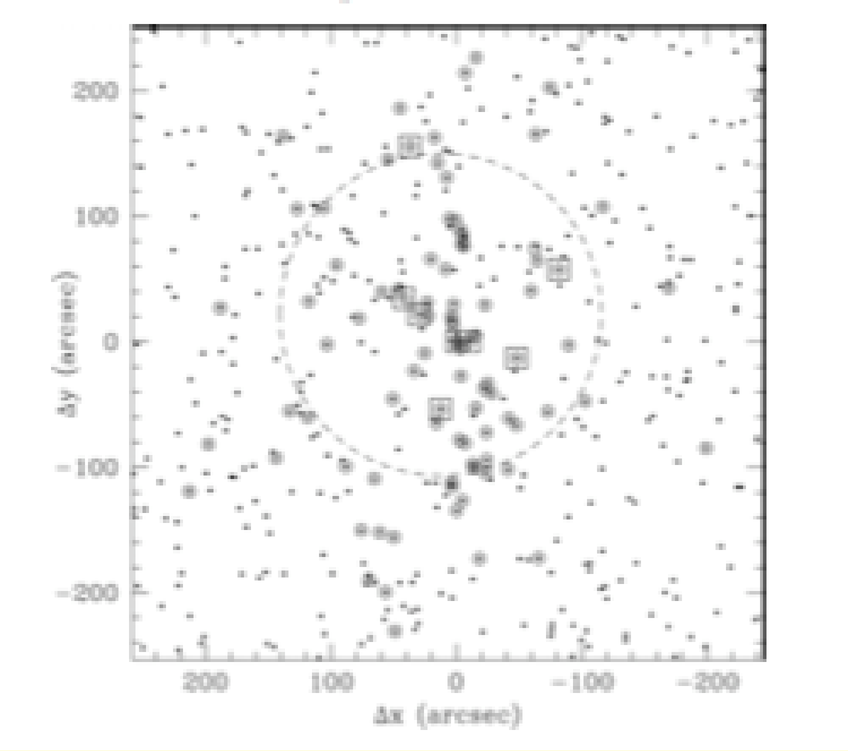
The statistical effects of local inhomogeneities on the propagation of light are investigated, and deviations (including rms fluctuations) from the idealized behavior in homogeneous universes are investigated by a perturbation-theoretic approach. The effect discussed by Feynman and recently by Bertotti of the density of the intergalactic medium being systematically lower than the mean mass density is examined, and expressions for the effect valid at all redshifts are derived.



We thus find that, unless a large fraction of the mass density in the universe is in some opaque, invisible, fairly tenuous (galaxy-sized, say) concentrations, in which case $1 - \alpha$ is large, the mean apparent luminosity of distant sources is little changed by the presence of fluctuations. If most of the mass is in the form of stars our analysis does not strictly apply, but general arguments similar to those used in § VI indicate that the

B1608+656 Groups

- z=0.265
  - Off center => $\gamma \sim 0.1$
- z=0.63 (G1, G2)
  - σ =150+/-60 km s^{-1}
- z=0.426, 0.52
  - Centered lens => γ ~0
- Try to calibrate corrections due to lens mass sheet and propagation



Fassnacht et al

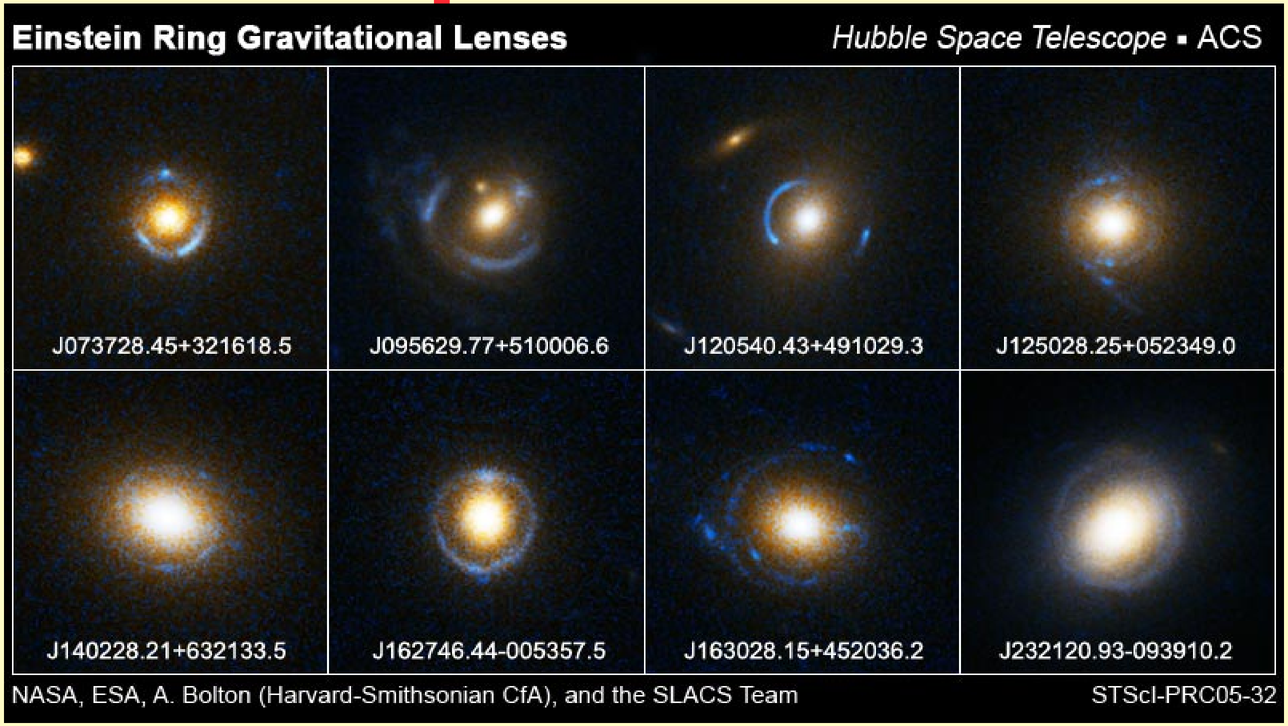
Propagation in Inhomogeneous Universe

$$d^2\xi / d\lambda^2 = -4\pi w \xi / a^2$$

$$\lambda = \int dta$$

- Follow congruence from observer, source to lens
- Empty universe
- Refill with homogeneous background plus sheets
- Propagate (ξ,ξ') between sheets and deflect at sheets
- Convergence = $4\,\pi\,\Sigma$
- Shear = $4\,\pi\,(\Sigma - \langle\Sigma\rangle)$
- Alternative approach to

Elliptical Lenses



~ 70 so far. 20,000 from SNAP?

HAGGLES Project (Marshall…)

Measure galaxy mass model - isothermal?

String search (Morganson)

New Opportunities

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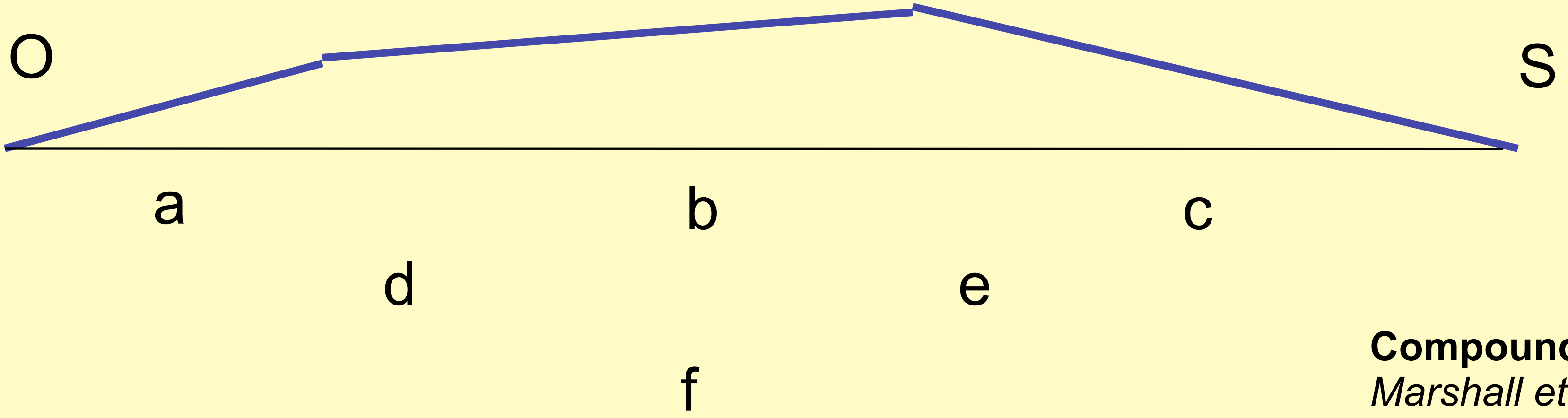
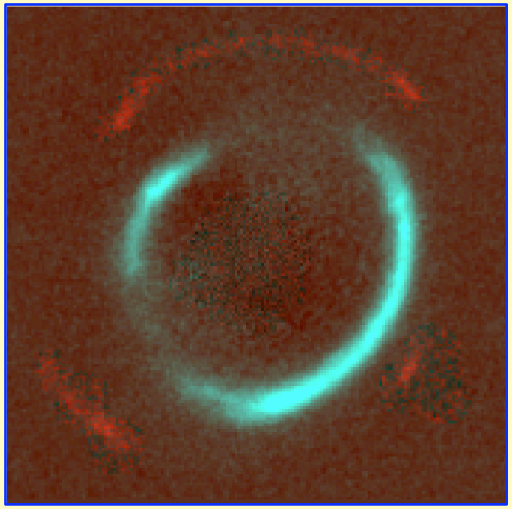
- **Flatness Test**
- Faint Galaxy Lensing

How to verify flatness geometrically (in principle)



Compound lenses
Marshall et al



CMB tests involve GR dynamics
Single lenses plus mass model=> b/d,c/f,e/f
Generically, $d\,e = a\,c + b\,f$

$$d\,(a,b) = [a(c/f) + b](e/f)^{-1}$$
$$= a + b, \quad \text{if flat}$$

SNAP:
- ~ 20,000 single lenses
- ~ 60 compound lenses

New Opportunities

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- **Faint Galaxy Lensing**

Faint Galaxies

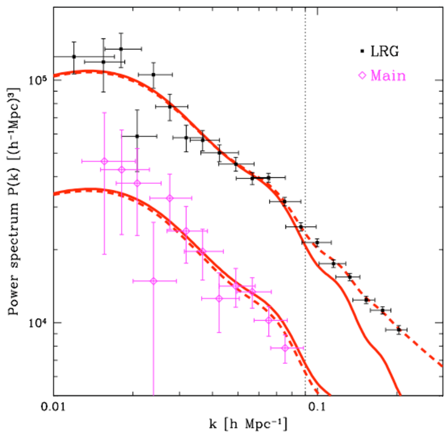
- Integral counts to V ~ 30 on HUDF
  - ~ 2.5 x 10^6 psd ~ 100 BG
- Local Luminosity function
  - Φ*~0.01 Mpc^{-3}
  - V(z<4) ~ 10^{12} Mpc^3
  - =>N ~ Φ*V~10BG
- =>Faint sources are assembling subunits and should be clustered?

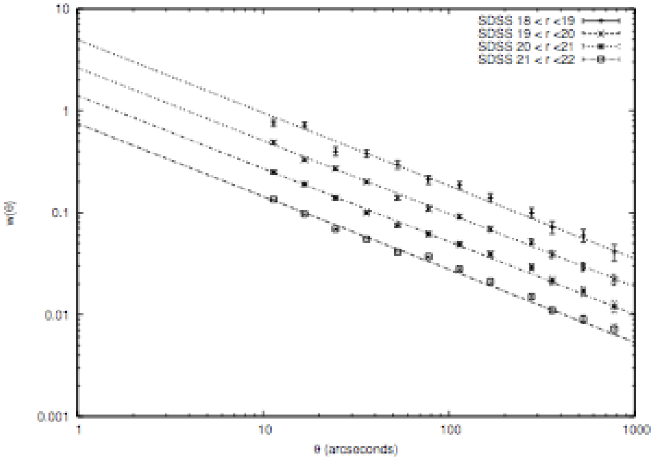
Galaxy Correlation Function

- Gravitational clustering (Peebles et al)
- Two point spatial correlation function

  $\xi \sim \langle\delta(x)\delta(x+r)\rangle \sim (r/8\mathrm{Mpc})^{-1.8}$

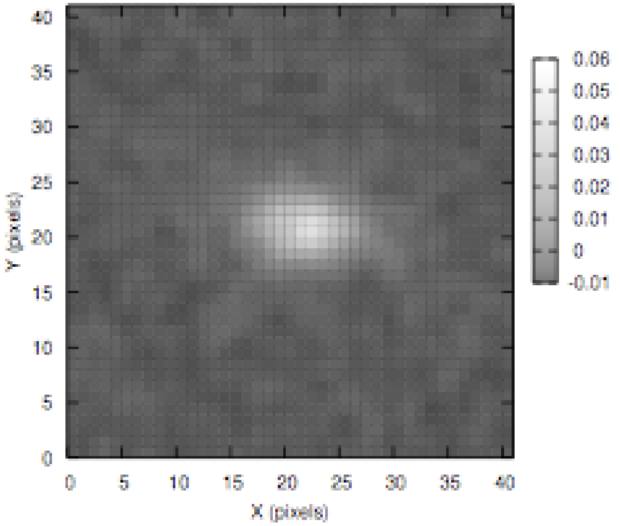
  - Long range
- Angular correlation function
  - $w(18) \sim(\theta/25'')^{-0.8}$
- $z(18) \sim 8\mathrm{Mpc}\ (25'')^{.8/1.8} \sim 500\mathrm{Mpc}$
  - $\sim 10^{0.17m}$
- cf 8Mpc/500Mpc ~ 1^{o}

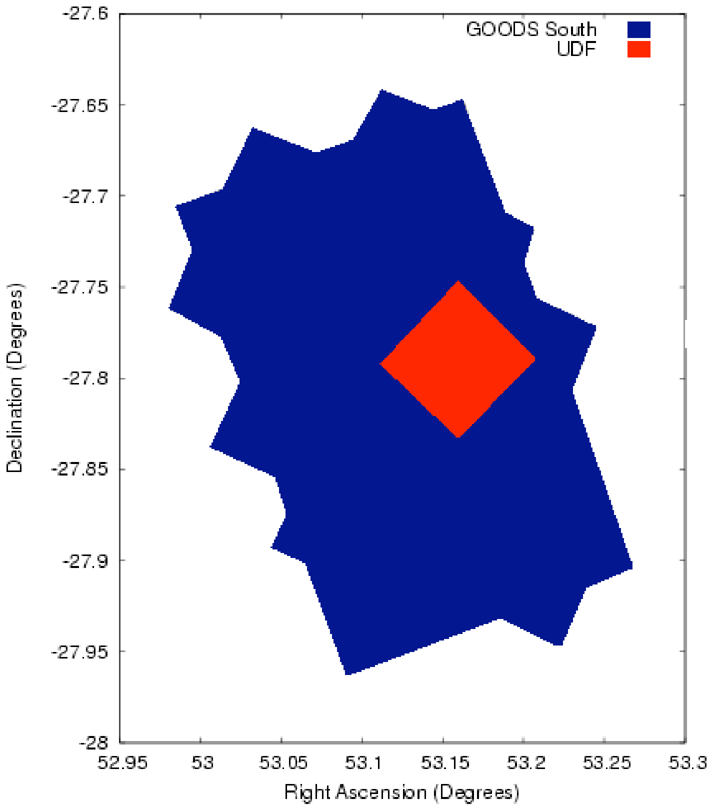




Faint Galaxy

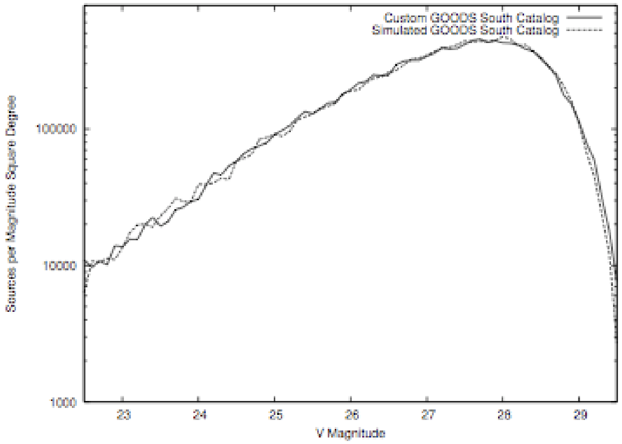
- HST-GOODS N+S
    - 160 arcmin^2 x 2
    - $25 < V < 28$
    - 60000 sources x 2
- HST-UDF
    - 11 arcmin^2
    - $27 < V < 29$
    - 9000 sources

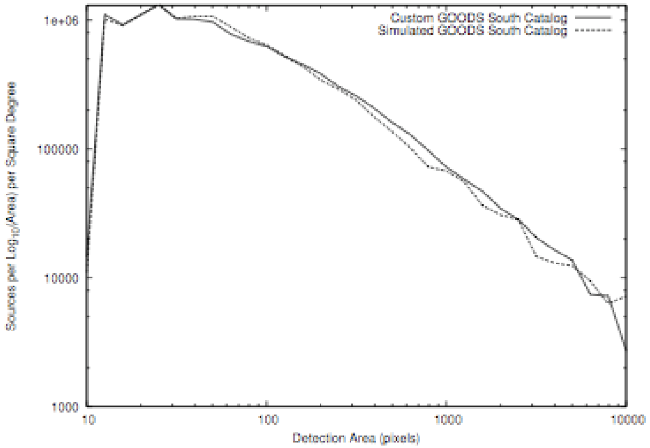


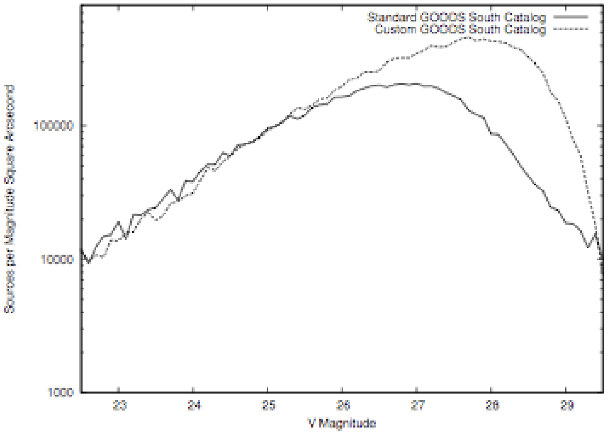


Simulated Catalogs

- Anisotropic de Vaucouleurs
- Tiny Tim PSF
- Zodiacal light, readout noise
- Masking, edge effects
- Deblending of close pairs
- Match observed clustering
- 1 percent false positives
  - 10pixels @ 1.7σ
- 1-1.5^m below "official" catalogs
- Procedure must be applied consistently including simulations

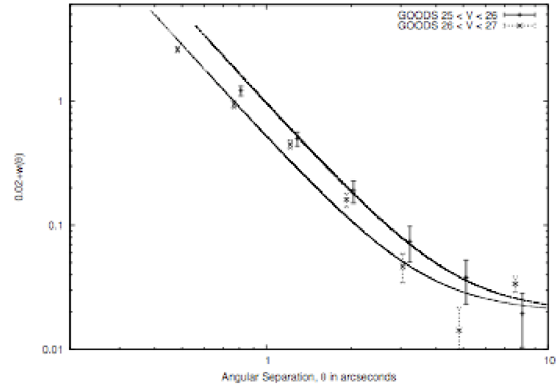


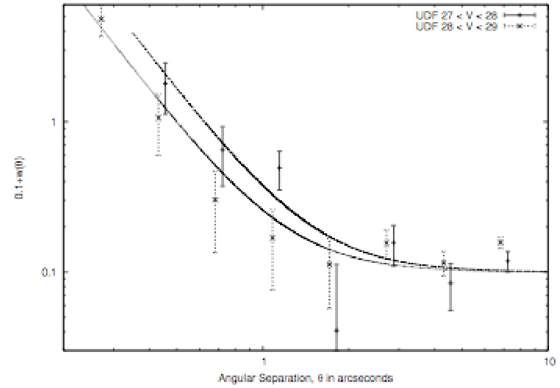


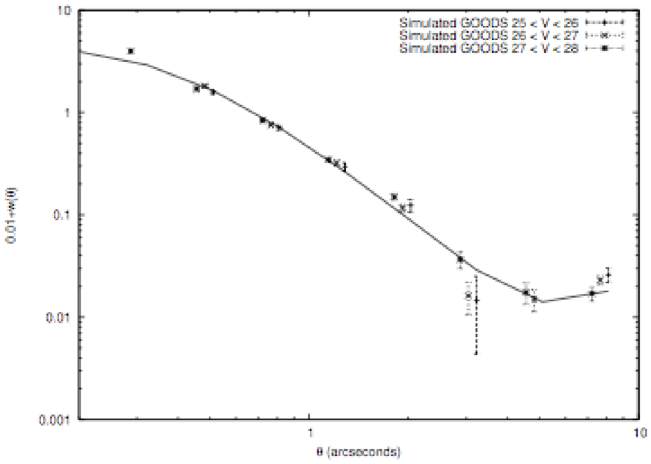


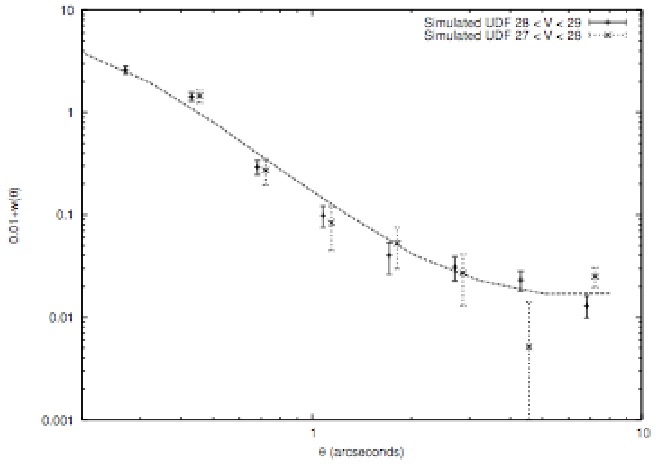
Angular Correlation Function

- Sextractor -> Oxtractor
- $1+w_{est} = \langle DD\rangle\langle RR\rangle/\langle RD\rangle^2$
- Maximum Likelihood Estimator
- Consistent with Brainerd et al Villumsen on large angular



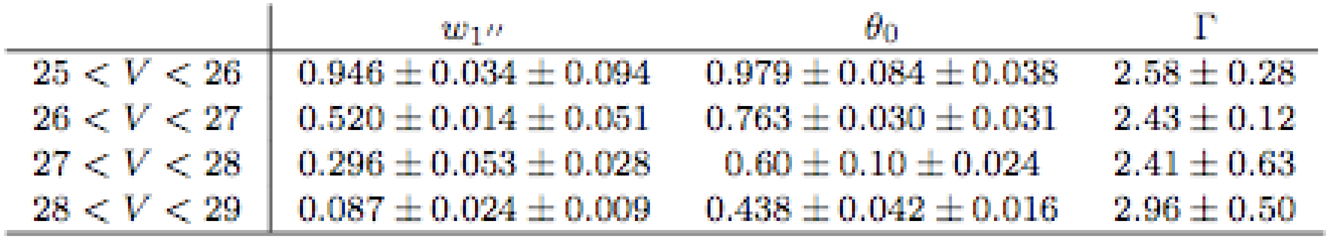




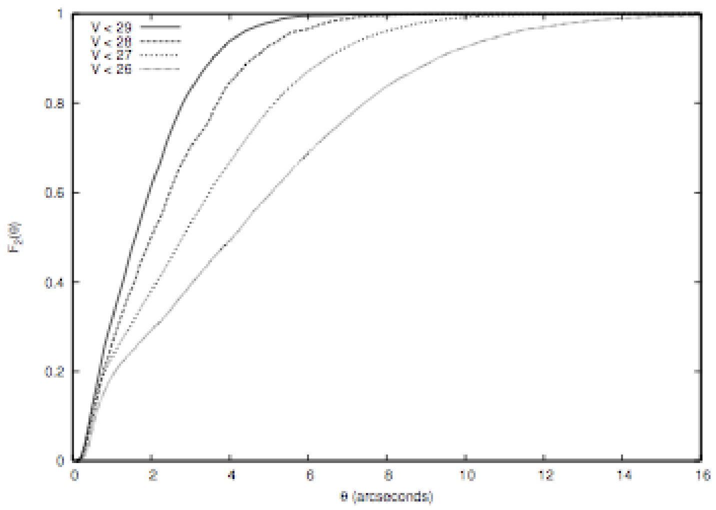


Results

- No clustering for $\theta > 2''$
- $w = (\theta/\theta_o)^{-2.5}$
  - GOODS <-> UDF
  - NOT gravitational



	$w_{1''}$	θ_0	Γ	N(BG)
$25 < V < 26$	$0.946 \pm 0.034 \pm 0.094$	$0.979 \pm 0.084 \pm 0.038$	2.58 ± 0.28	10
$26 < V < 27$	$0.520 \pm 0.014 \pm 0.051$	$0.763 \pm 0.030 \pm 0.031$	2.43 ± 0.12	20
$27 < V < 28$	$0.296 \pm 0.053 \pm 0.028$	$0.60 \pm 0.10 \pm 0.024$	2.41 ± 0.63	40
$28 < V < 29$	$0.087 \pm 0.024 \pm 0.009$	$0.438 \pm 0.042 \pm 0.016$	2.96 ± 0.50	70

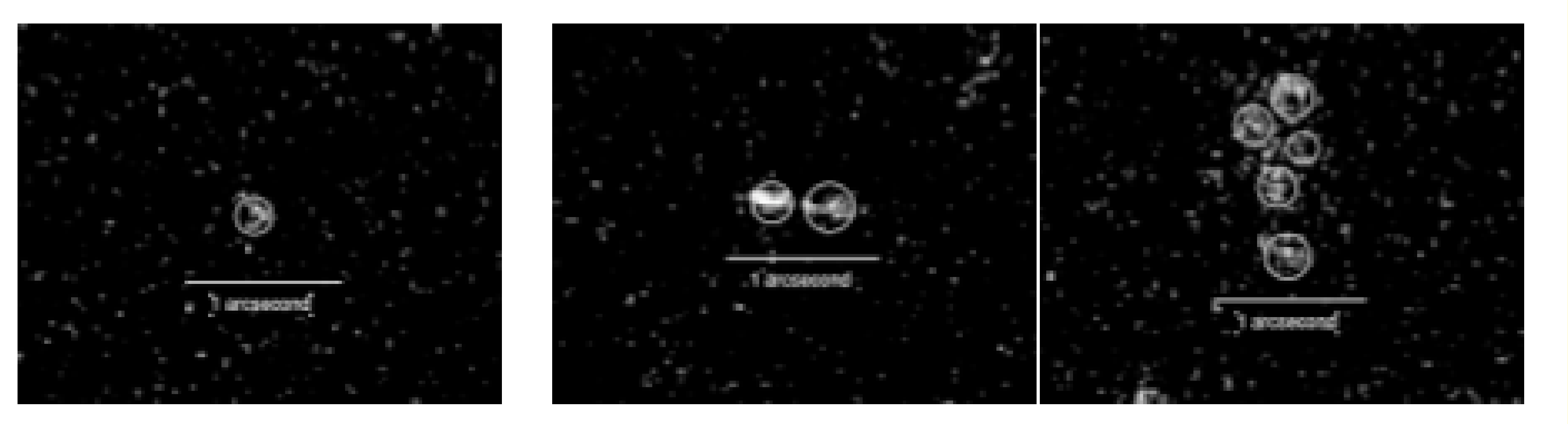


Interpretation

z	1"(kpc)	V=30 ($\log[L / L_{sun}]$)
0.1	2	5
0.5	6	6
1	8	7
2	8	8
5	6	9

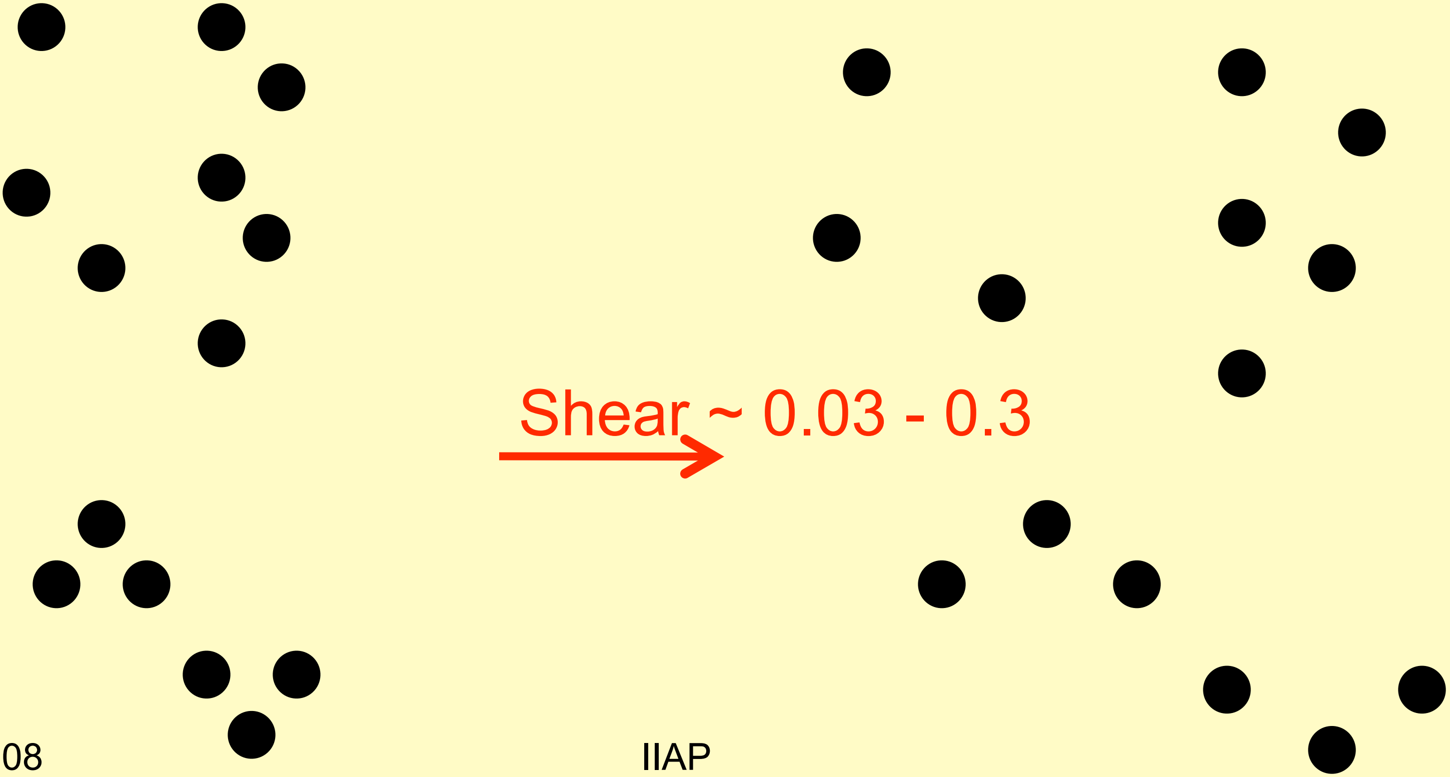
- Luminosity models

Poissonian sources, common or separate potential wells



Positional Lensing

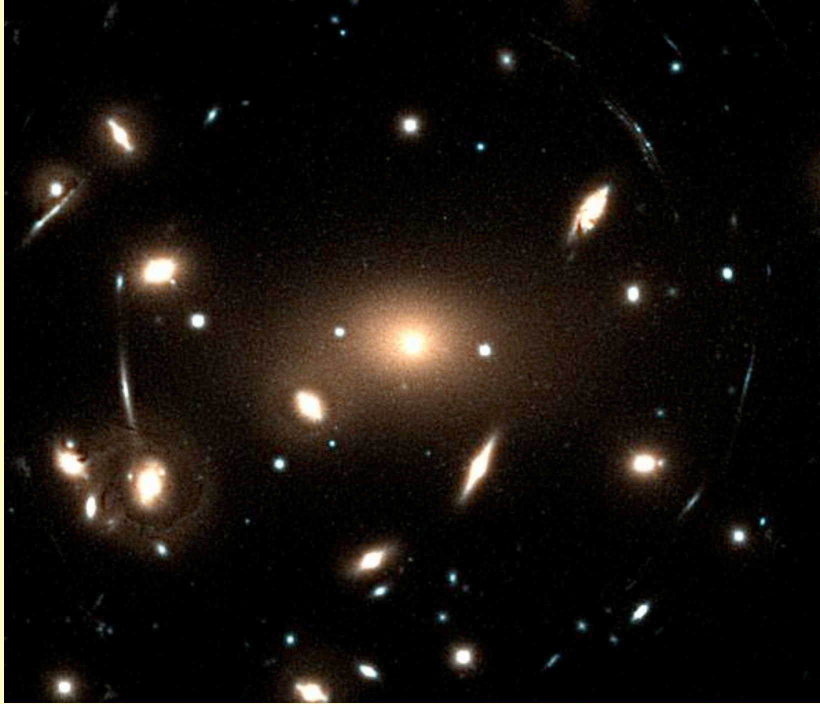
- Shapeless, faint sources
- Just measure positions

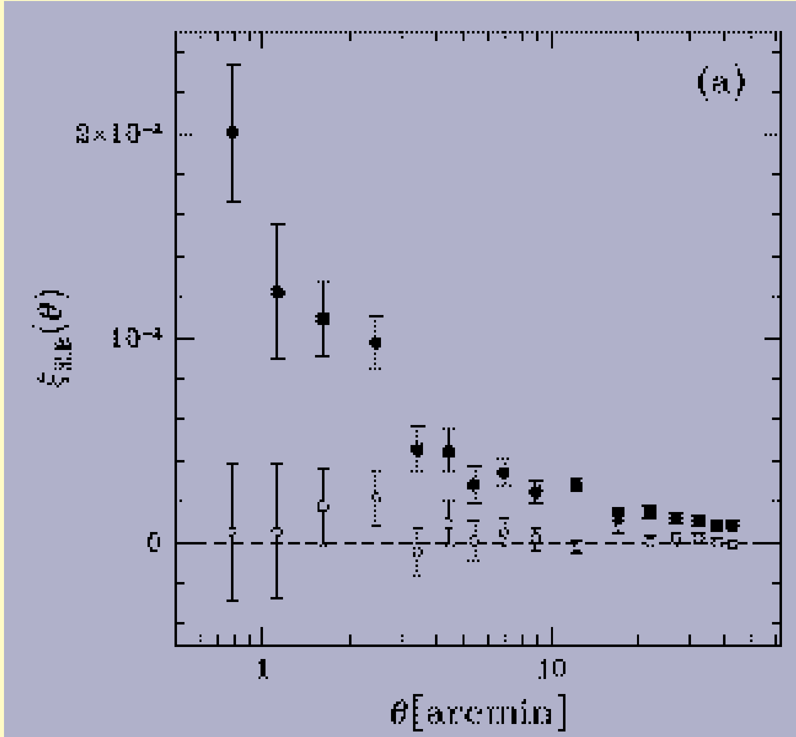


Shear ~ 0.03 - 0.3

Weak Lensing

- Distortion of background galaxy shapes
  - V~26
- Historical Sequence
  - Cluster lensing
  - Galaxy-galaxy lensing
  - Cosmic Shear
- Reprise with faint pairs
  - May be hard to detect faint sources with in clusters and close to galaxy lenses



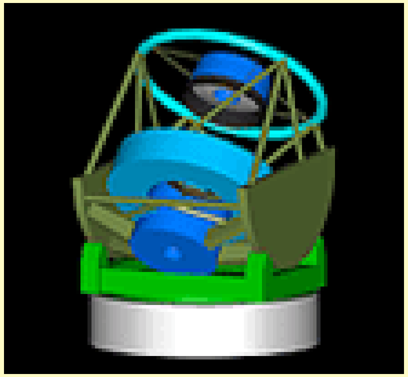


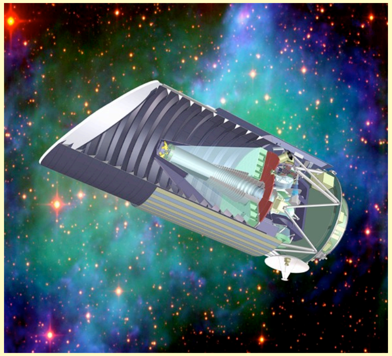
Faint source redshifts

- Cosmic shear => growth of structure $\delta(z)$
- Photo-z => source redshifts $\Phi_{26}(z)$

$$\kappa,\gamma \approx \int dzdz' G(z,z')\Phi(z)\delta(z')$$

- $\Phi_{26}(z)$, γ_{26} => $\delta(z)$
  - Tomography
- $\delta(z)$, γ_{30} => $\Phi_{30}(z)$
- HST
  - GOODS, UDF; COSMOS?
- LSST
  - Half sky to V~26.5; ~BG
- SNAP





Redshift distribution of faint sources?

- Correlation function will be rendered anisotropic by intervening lenses
  - Clusters of galaxies
    - eg Abell 2218
  - Elliptical galaxy lenses
    - Seek using HAGGLES (Marshall)
    - 20 psd with SNAP
  - Cosmic Shear
    - Cross correlate with measured cosmic shear in 2D and 3D
    - SNAP Deep(AB=30), wide(28) and panoramic (27) surveys

Summary

- Great progress in using lenses as tools for cosmology and astrophysics
- "Clean" physics but serious systematic effects
- Still many unexplored aspects observationally. eg
  - Catastrophes
  - Largest Lenses
  - Hubble Constant
  - Flatness Test
  - Faint Galaxy Lensing