Weak lensing by line-of-sight halos as the origin of flux-ratio anomalies in quadruply lensed QSOs

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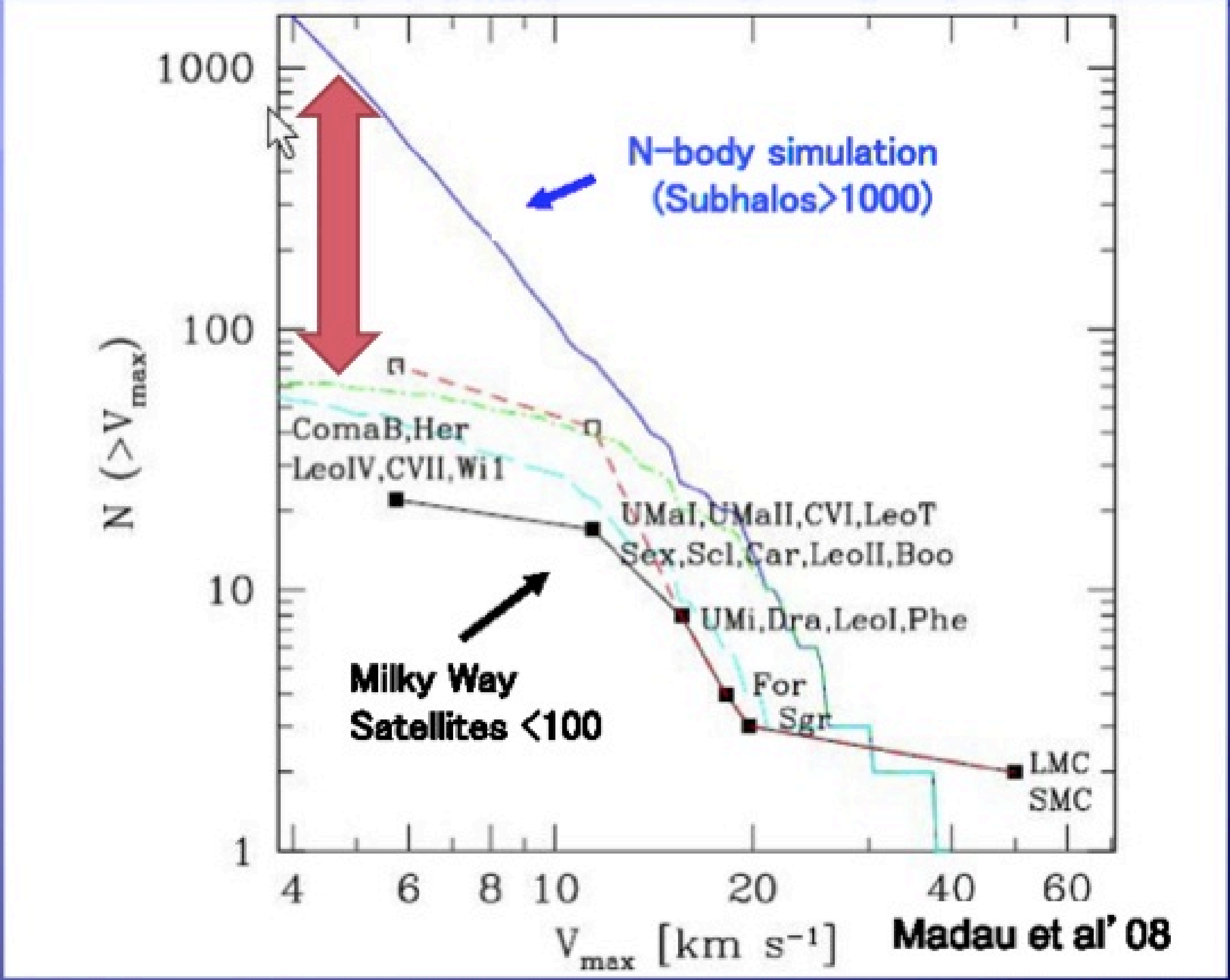
Nano-Workshop at IAP

Outline

- Introduction
- Magnification perturbation
- Non-linear power spectrum
- Contribution to the flux ratios
- Summary
- Future work

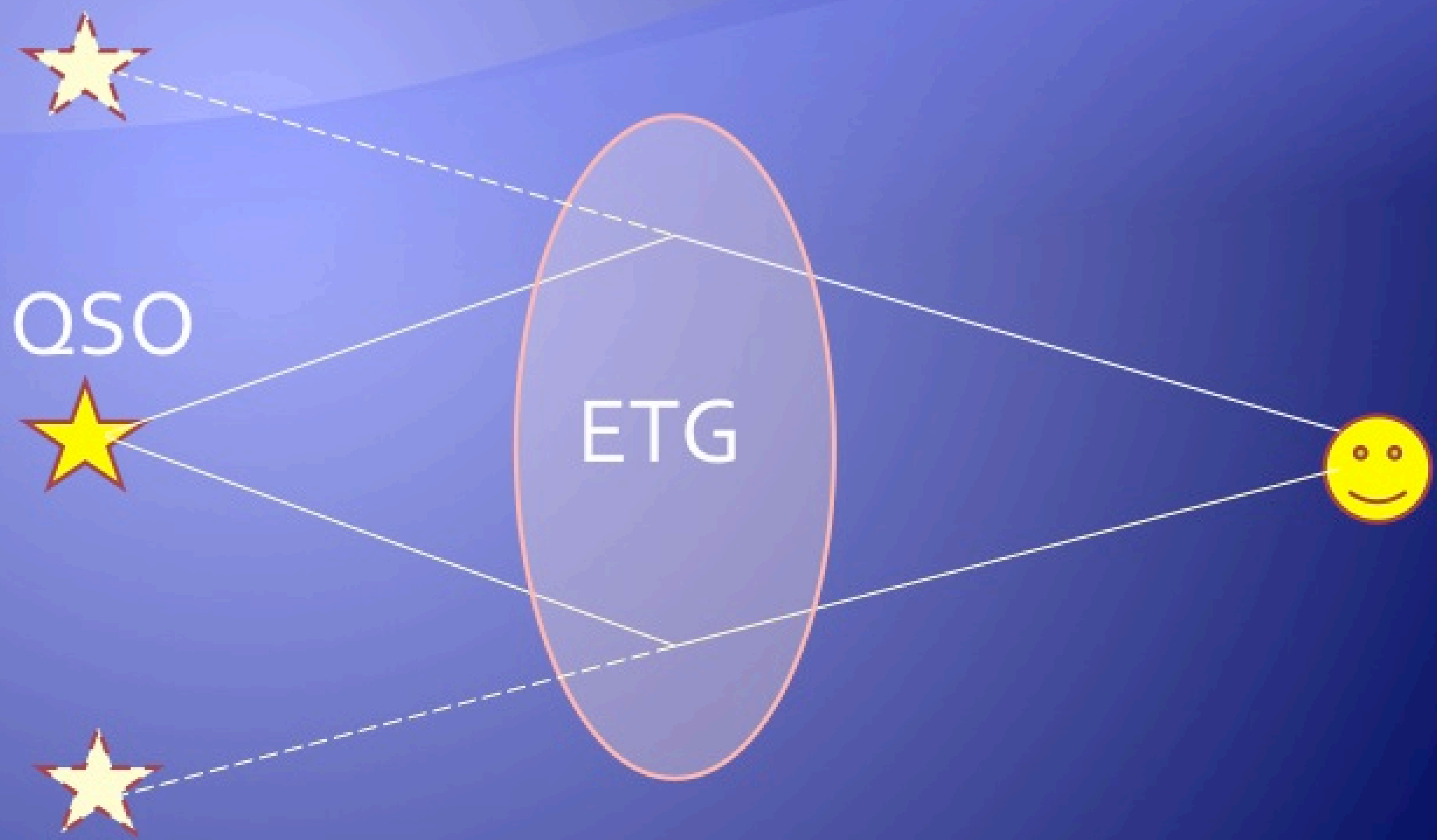
Introduction

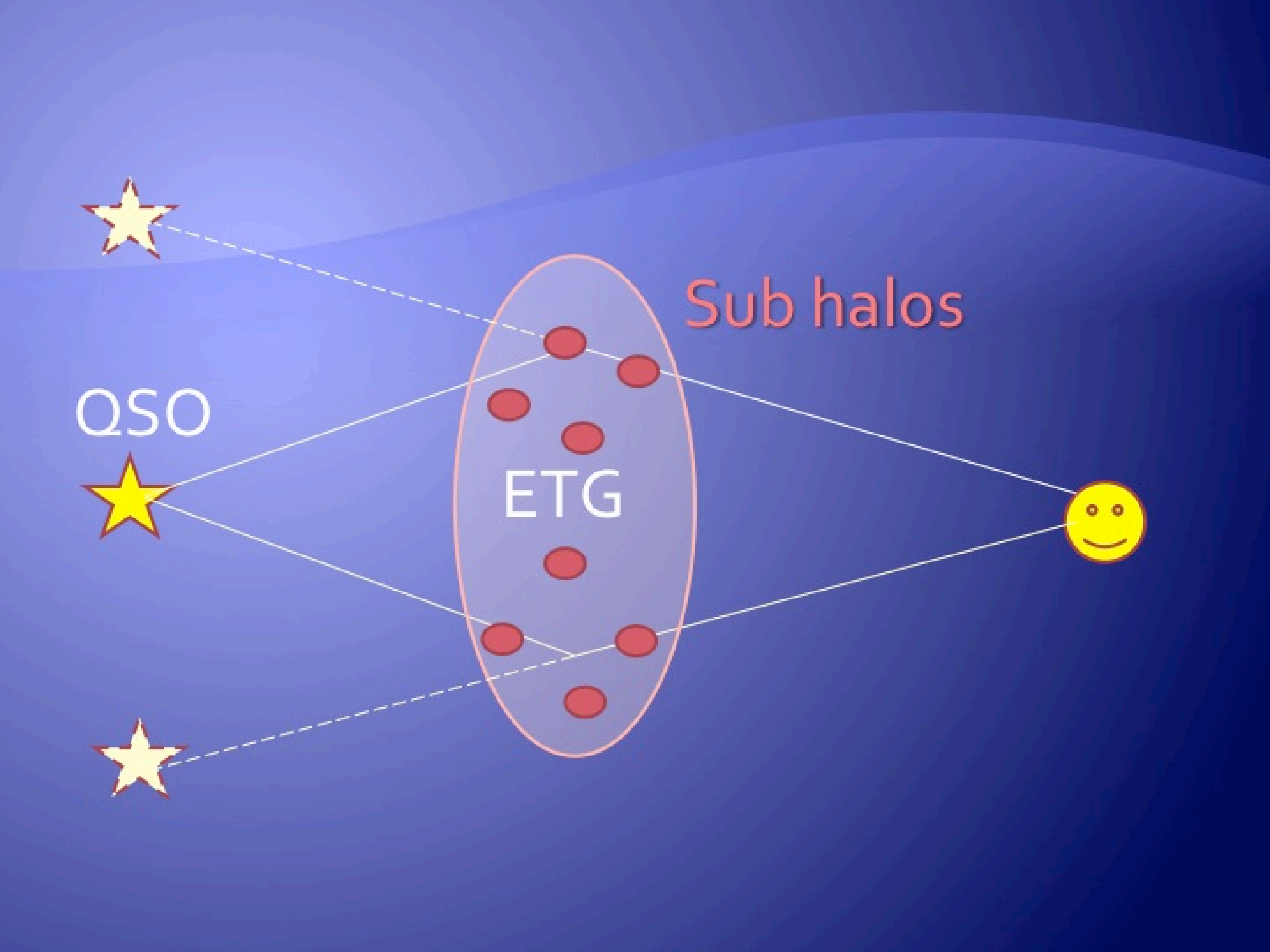
Missing Satellite Problem



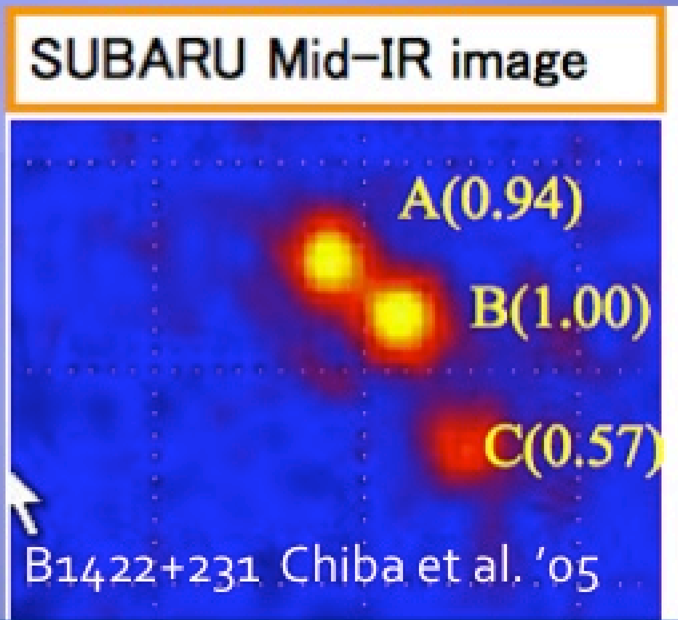
Suppression Mechanism

- Baryon physics (reionization, tidal disruption due to disk)
- New physics (warm dark matter, super WIMPs)
- Need to probe clustering property of halos with $M<10^9$ solar mass


QSO
ETG


Sub halos
QSO
ETG

Flux- ratio anomalies



Cusp-caustic relation

$$\frac{A+B+C}{|A|+|B|+|C|}=0$$

- Positions can be well fit to the model.
- Flux-ratios fits are poor.

(Mao & Schneider '98 Metcalf & Madau'01, Chiba '02 Dalal& Kochanek'02)

Flux- ratio anomalies

- Predicted subhalos too low for anomalies
  (Maccio & Mirranda 2006, Amara et al. 2006;
  Xu et al. 2009, 2010; Chen 2009; Chen et al. 2011)

- Luminous satellites may contribute significantly
  (McKean et al. 2007, Shin & Evans 2008;
  MacLeod et al. 2009)

- Line-of-sight halos?
  (Chen et al. 2003, Metcalf 2005, Xu et al. 2011)

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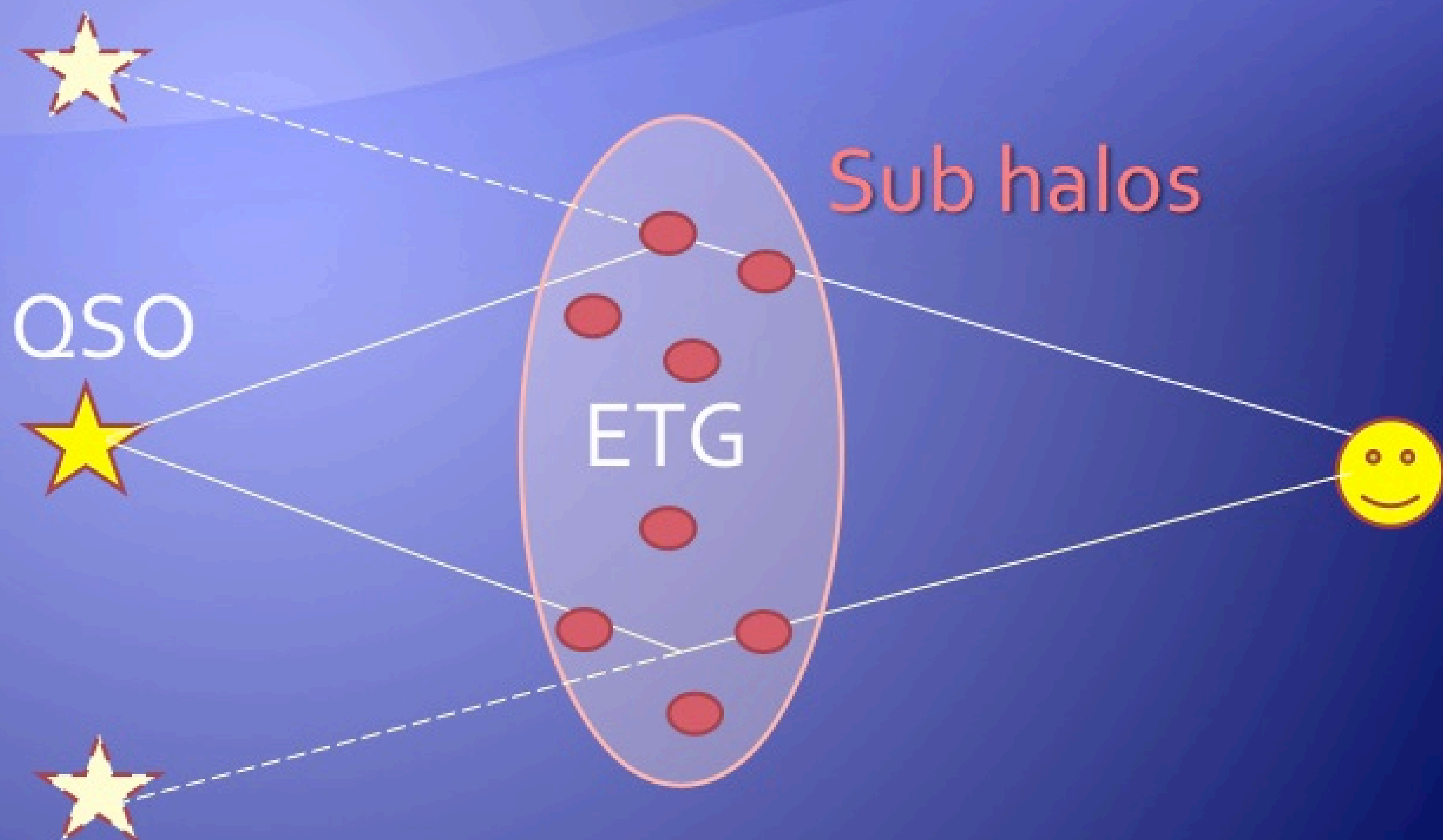
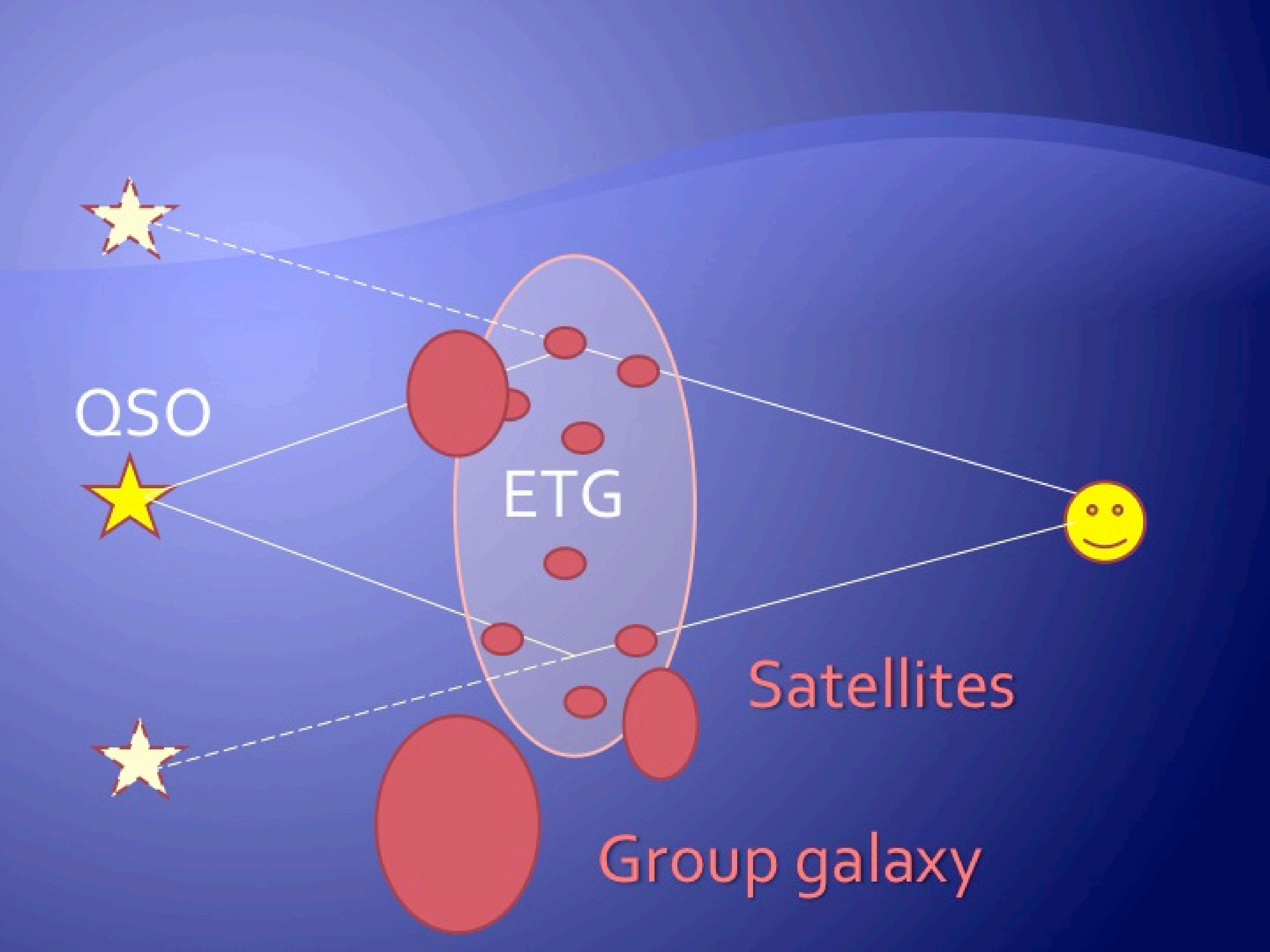
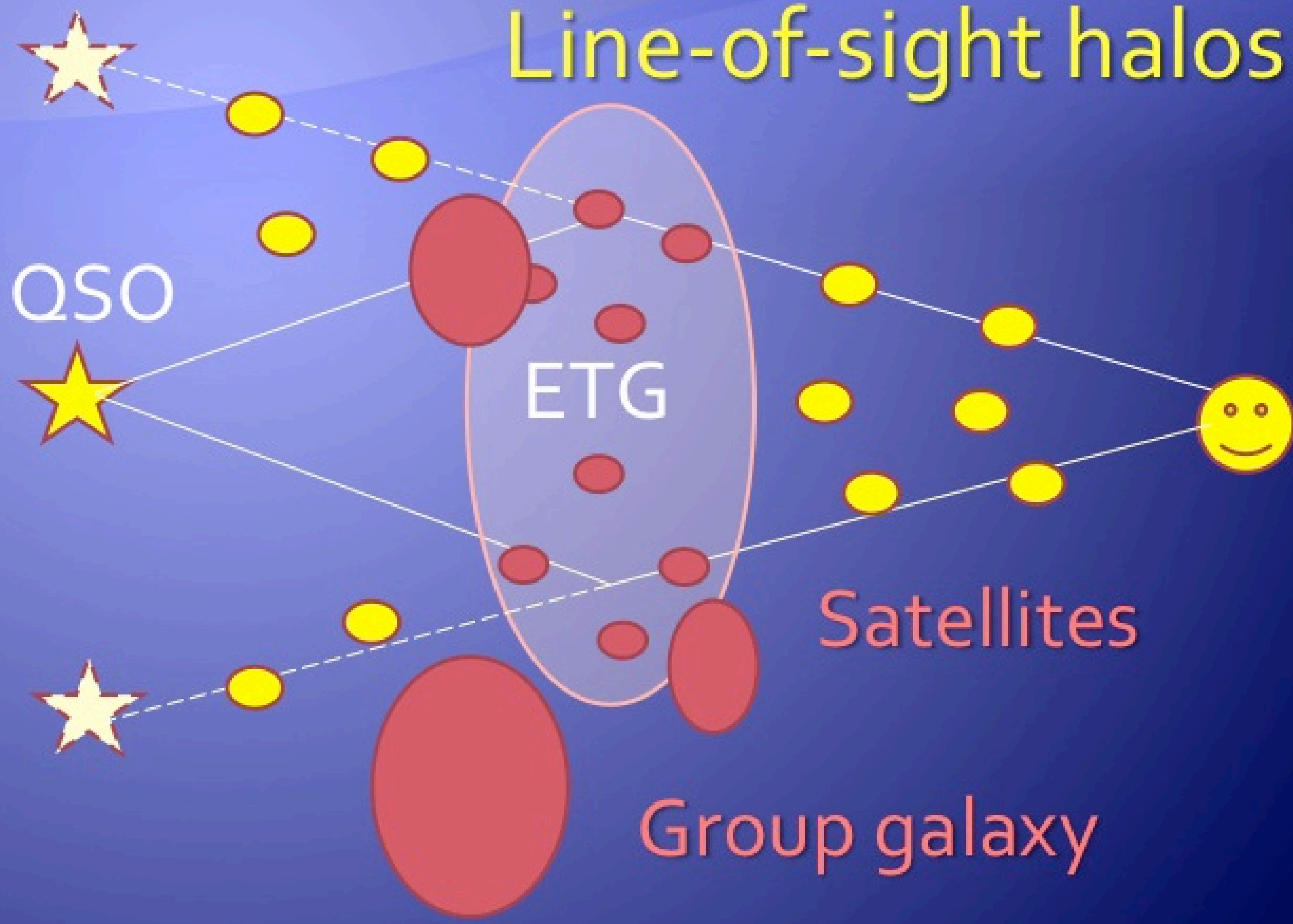
Flux- ratio anomalies




QSO
ETG
Satellites
Group galaxy


Line-of-sight halos
QSO
ETG
Satellites
Group galaxy

Our work

- Semi-analyitic estimate based on VERY high resolution N-body simulation fully incorporating clustering effects >10^5 solar mass halos

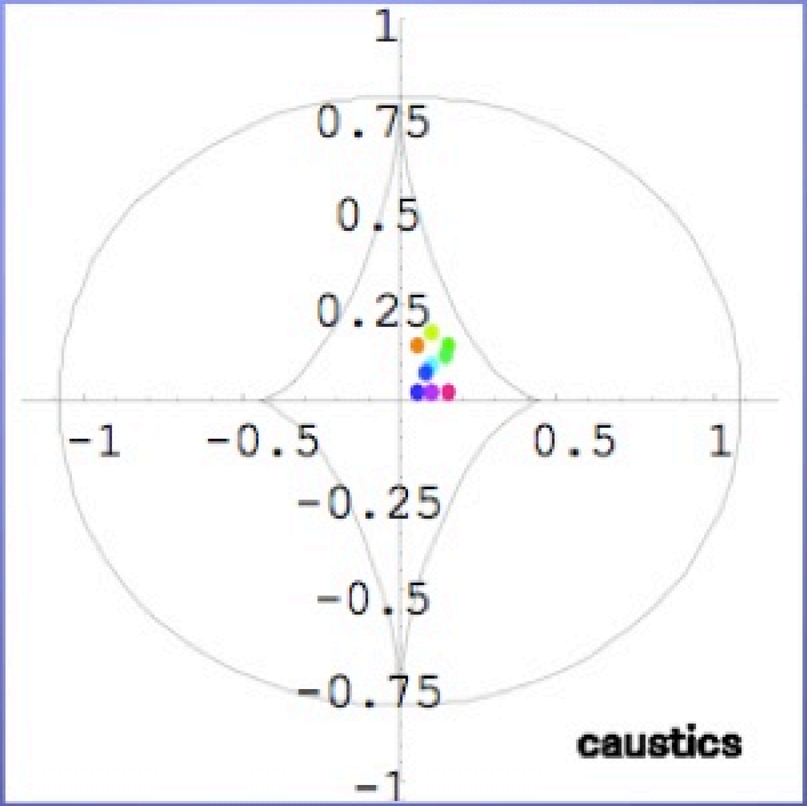
- Astrometric shifts taken into account

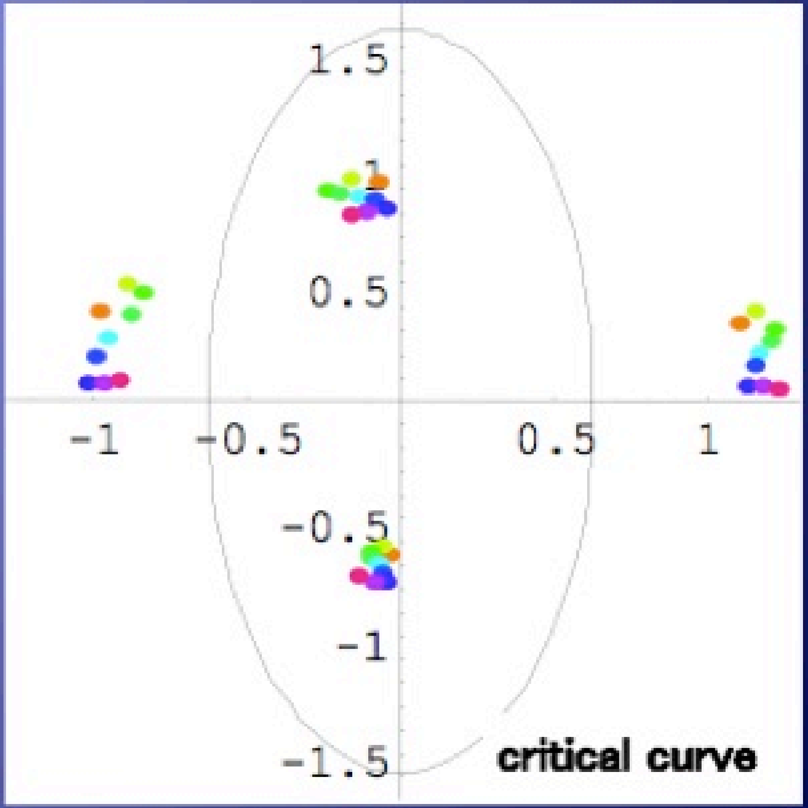
- New static rather than 'classic' cusp-caustic relations

- Only MIR lenses. Source sizes =O[1 pc]

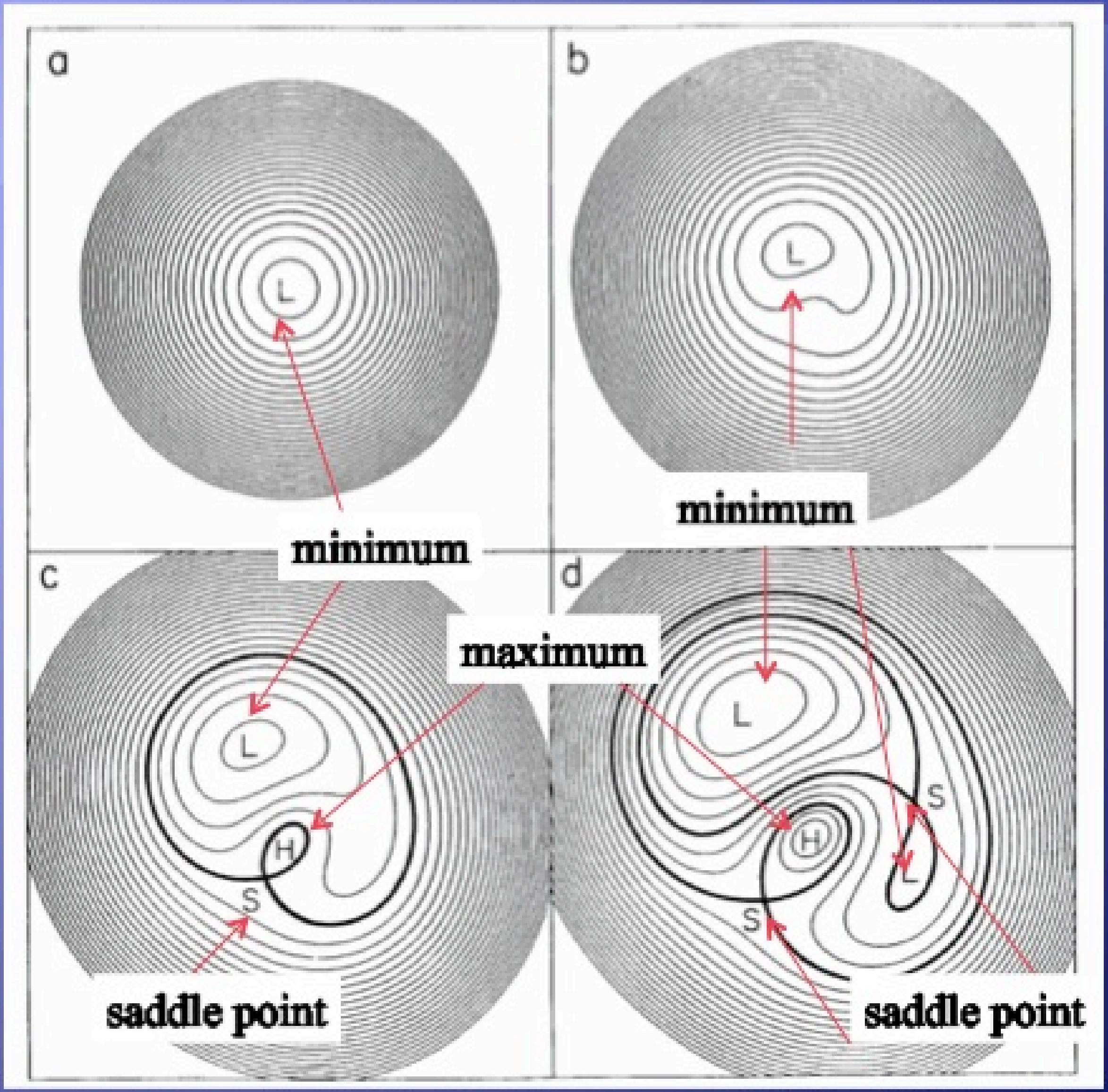
Magnification perturbation

Parity of lensed images



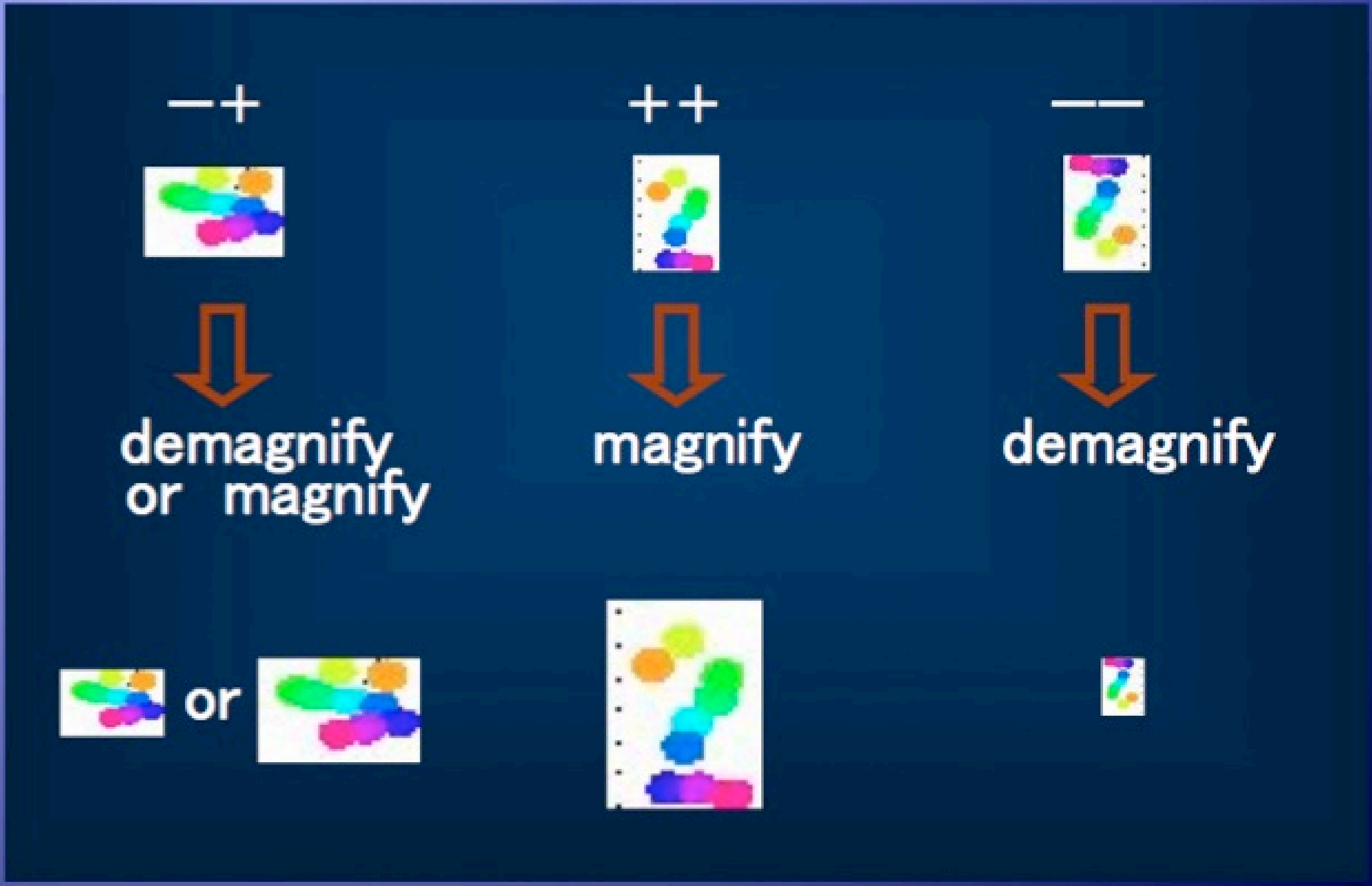


Arrival time surface



Blandford & Narayan 1986

Systematic (de)magnification



New statistic η

A,C: minima B:saddle, $\kappa \downarrow B < 1$

$$\delta_i^\mu \equiv \delta\mu_i/\mu_i.$$

:magnification contarst

η: effective magnification perturbation

$$\eta^2(\mathrm{A,B,C}) = \frac{1}{4}[(\delta_A^\mu - \delta_B^\mu)^2 + (\delta_C^\mu - \delta_B^\mu)^2].$$

$$\eta^2 \approx \frac{1}{4}\left[\left(\frac{AB_0}{A_0B} - 1\right)^2 + \left(\frac{CB_0}{C_0B} - 1\right)^2\right].$$

New statistic η

$$\langle \eta^2 \rangle = \frac{1}{4}\Big[(J_A + J_B)\sigma_\kappa^2(0) - 2J_{AB}\xi_\kappa(\theta_{AB})$$

$$+ (J_B + J_C)\sigma_\kappa^2(0) - 2J_{BC}\xi_\kappa^2(\theta_{\rm BC})\Big],$$

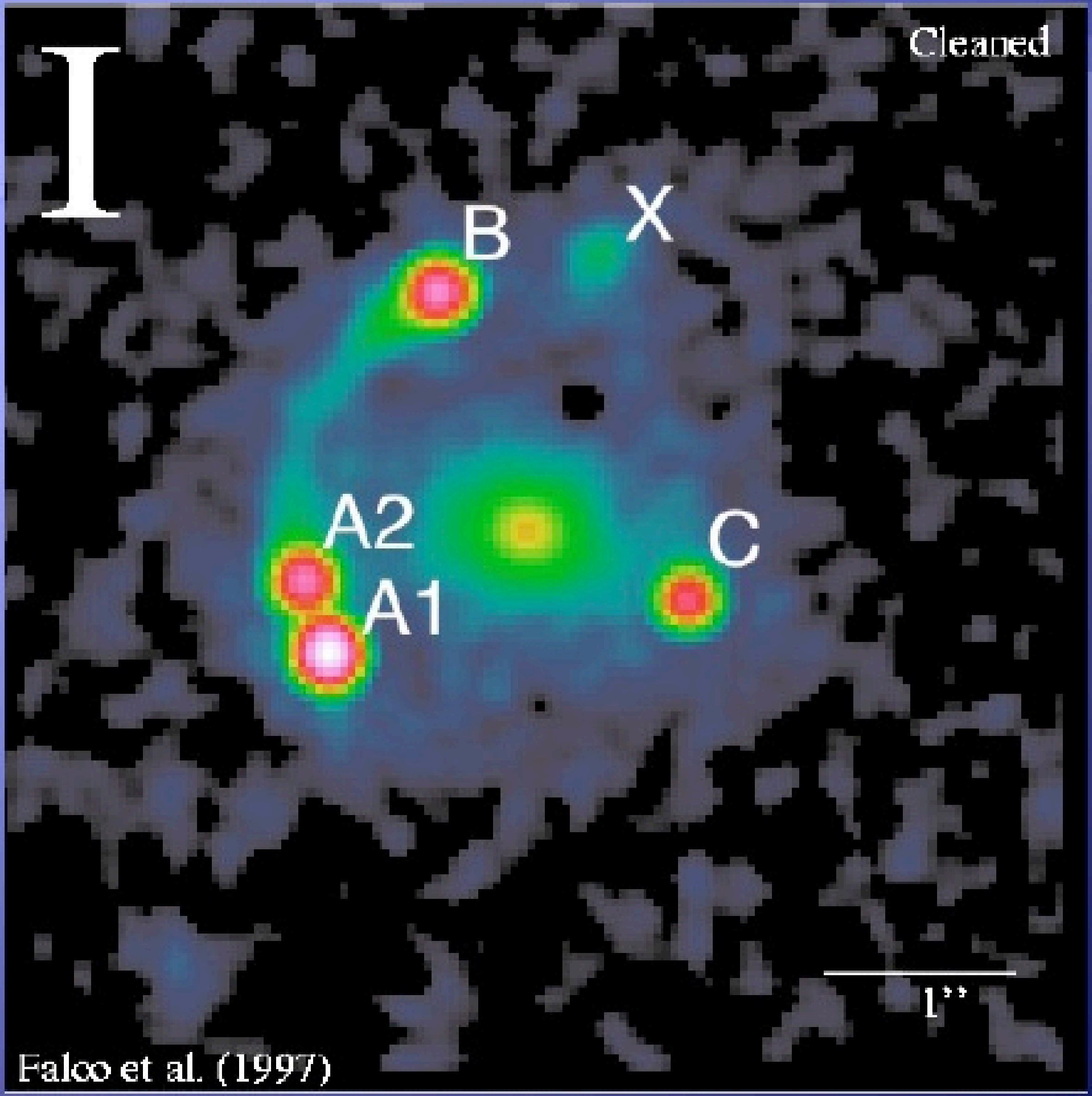
where

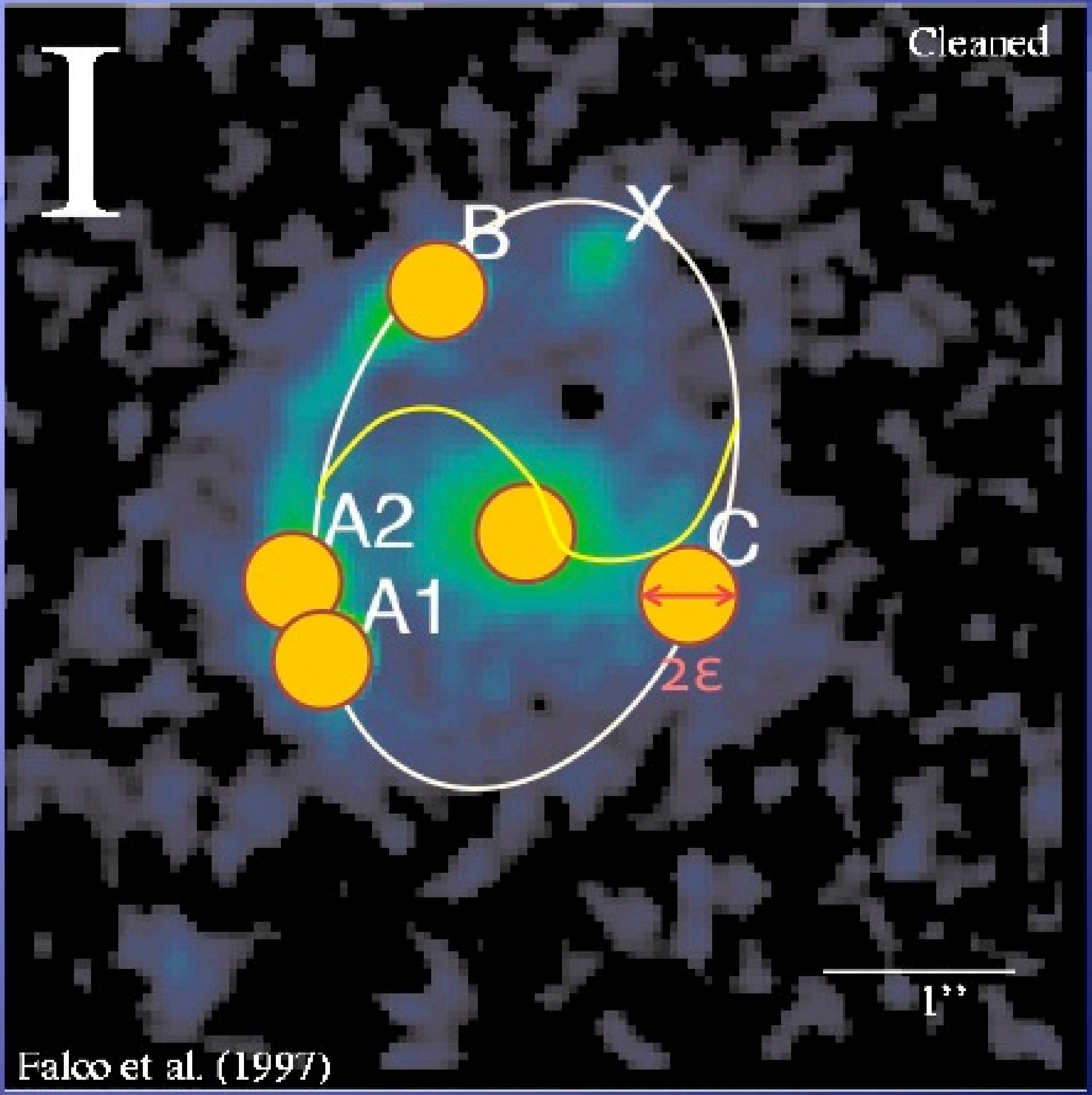
$$J_i = \mu_i^2(4(1-\kappa_i)^2 + 2\gamma_i^2),$$

and

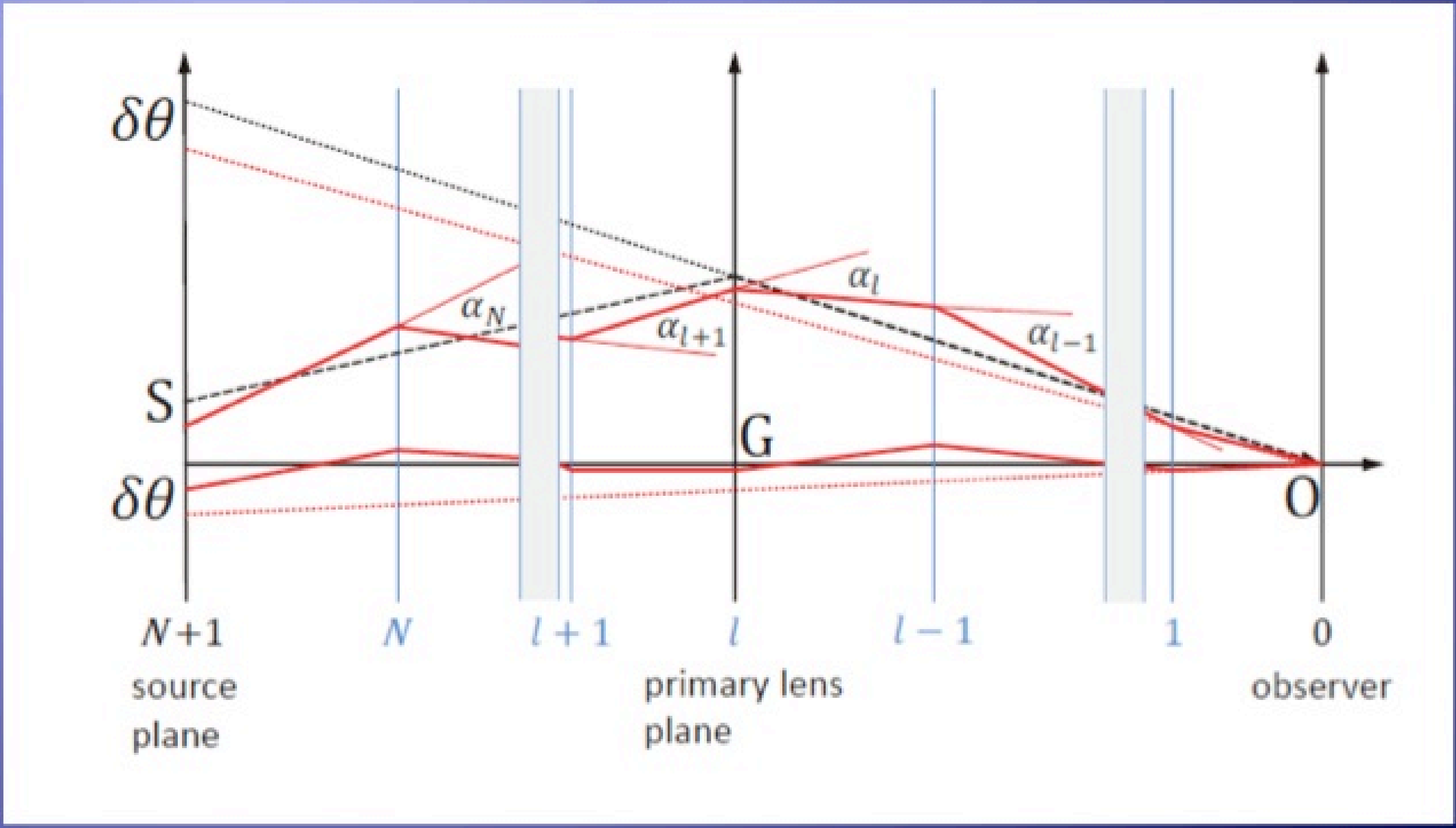
$$J_{ij} = \mu_i\mu_j(4(1-\kappa_i)(1-\kappa_j) + 2\gamma_i\gamma_j),$$

κ: background convergence γ: background shear


I
Cleaned
B
X
A2
A1
C
1''
Falco et al. (1997)


I
Cleaned
B
X
A2
A1
C
2ε
1''
Falco et al. (1997)

Astrometric shifts



Astrometric shifts

2-point correlation in shift of image separated by θ

$$\xi_{\delta\theta}(\theta) \quad \equiv \quad \langle \delta\theta(0)\delta\theta(\theta) \rangle$$

Given by power spectrum P(k)

$$2\langle \delta\theta^2(0) \rangle - 2\langle \delta\theta(0)\delta\theta(\theta_{AB}) \rangle < \epsilon^2,$$

Given by accuracy in position of centroid ε

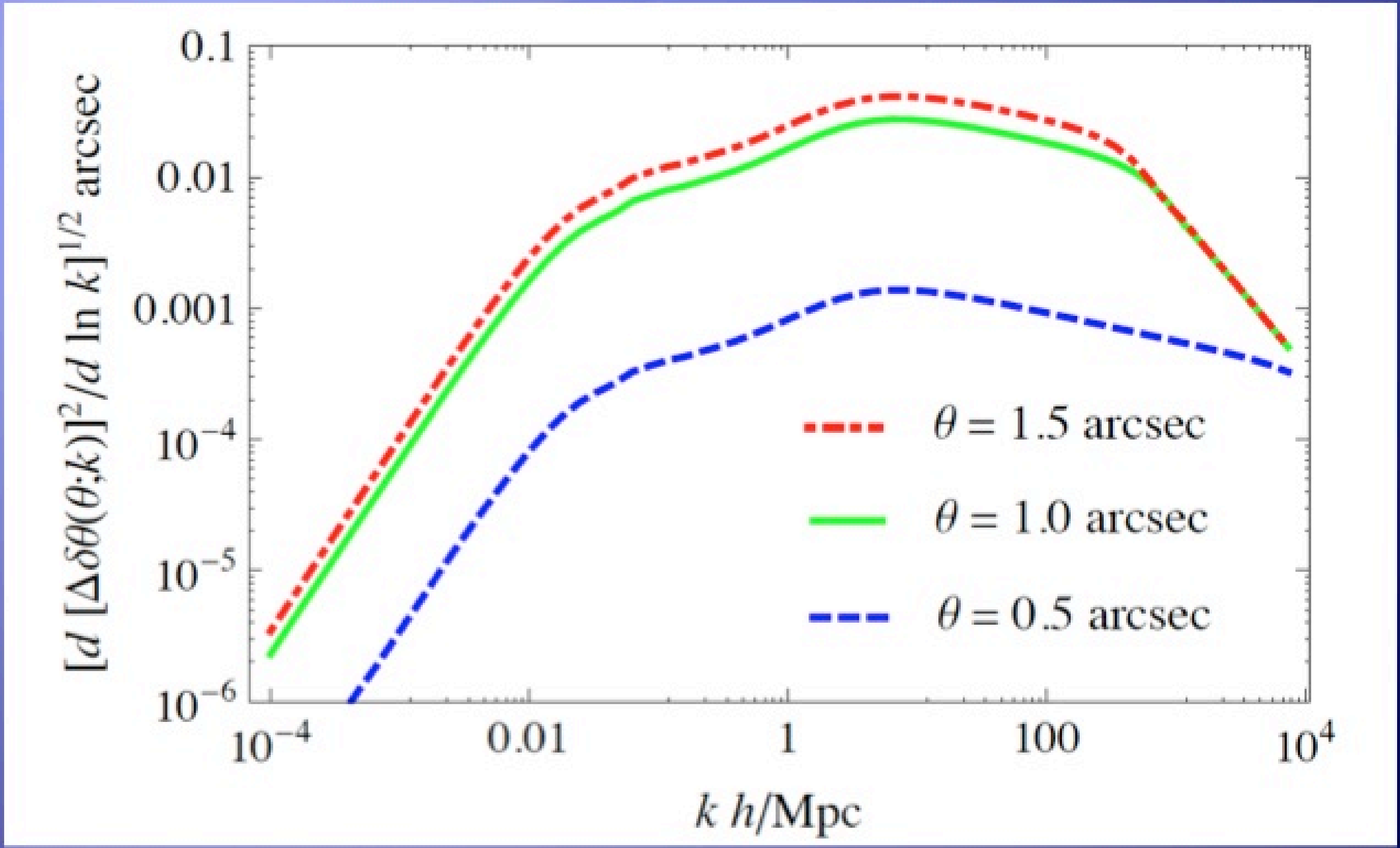
Astrometric shifts

$$k_{lens} \equiv 2\pi/L_{lens} \text{ where } L_{lens} \sim 4r(z_L)\theta_E$$

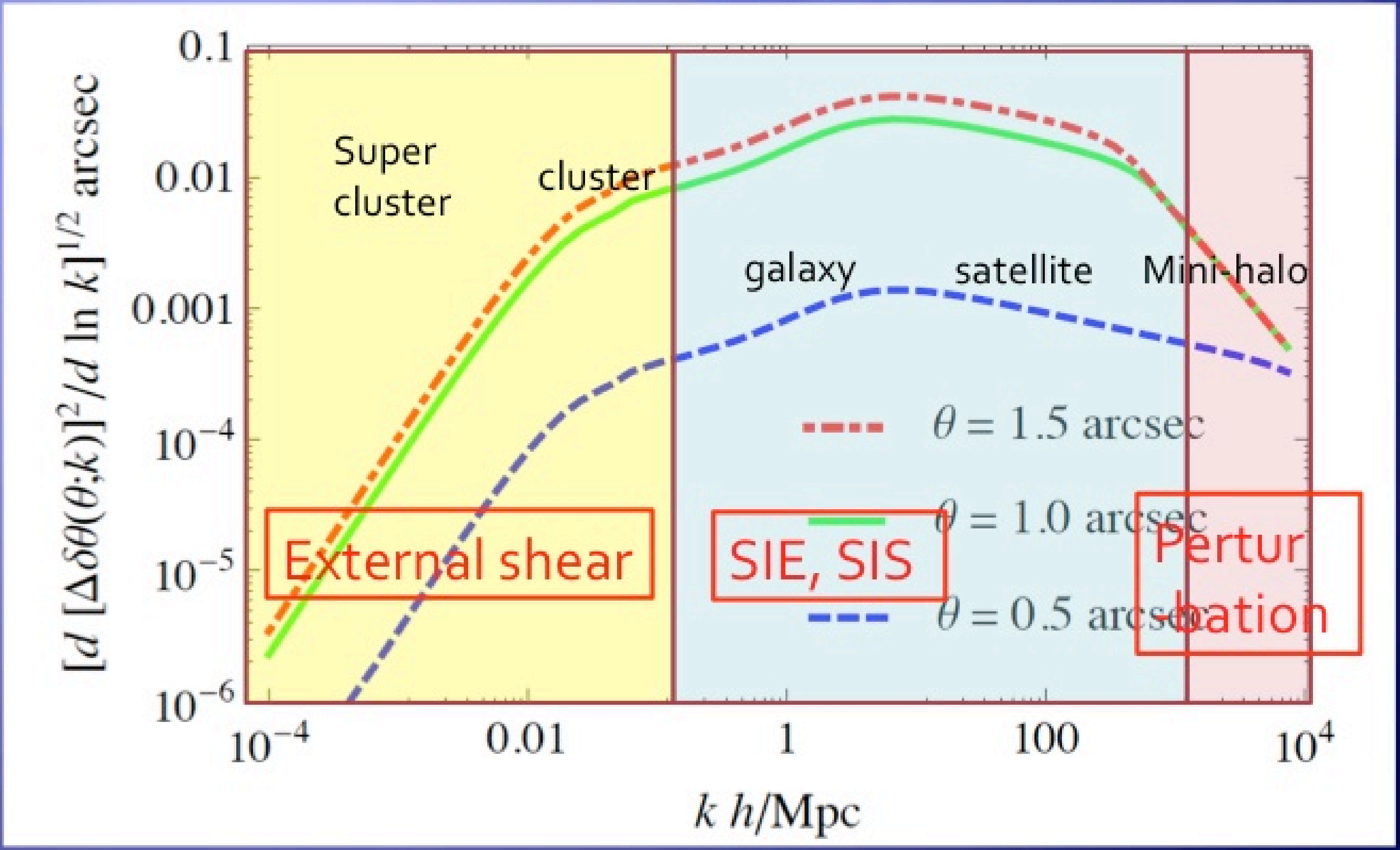
Minimum wavelength given by the size of Einstein radius

$$k_{lens} = O[100\text{–}1000]\,h/\mathrm{Mpc}$$

Astrometric shifts



Astrometric shifts



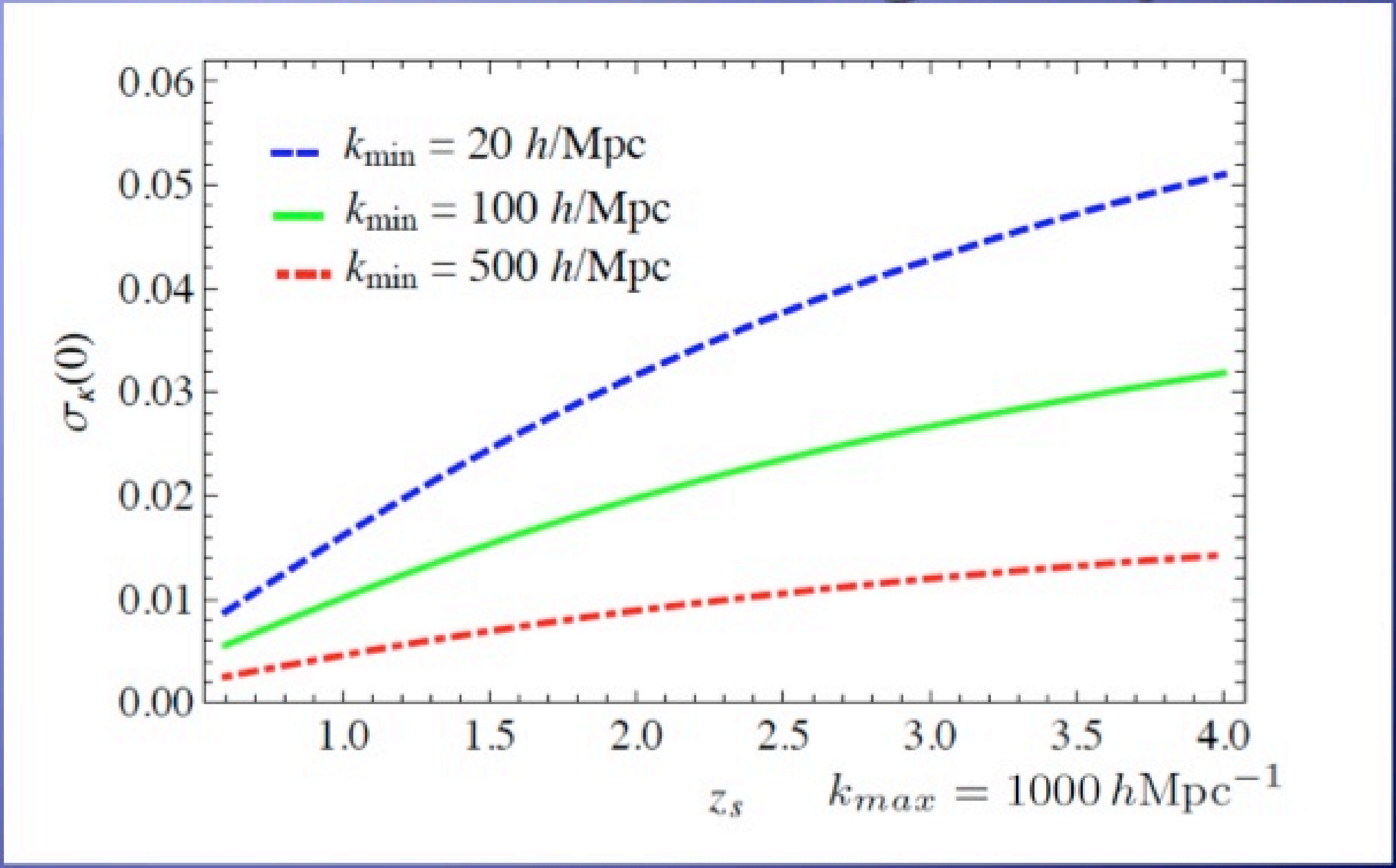
Constrained convergence power

- Accuracy in lensed images and lens = maximum contribution
- Size of the Einstein ring
  (absorbed into background shear)
- These two give the largest scale of modes k_{min} that can affect the flux-ratios

New statistic η

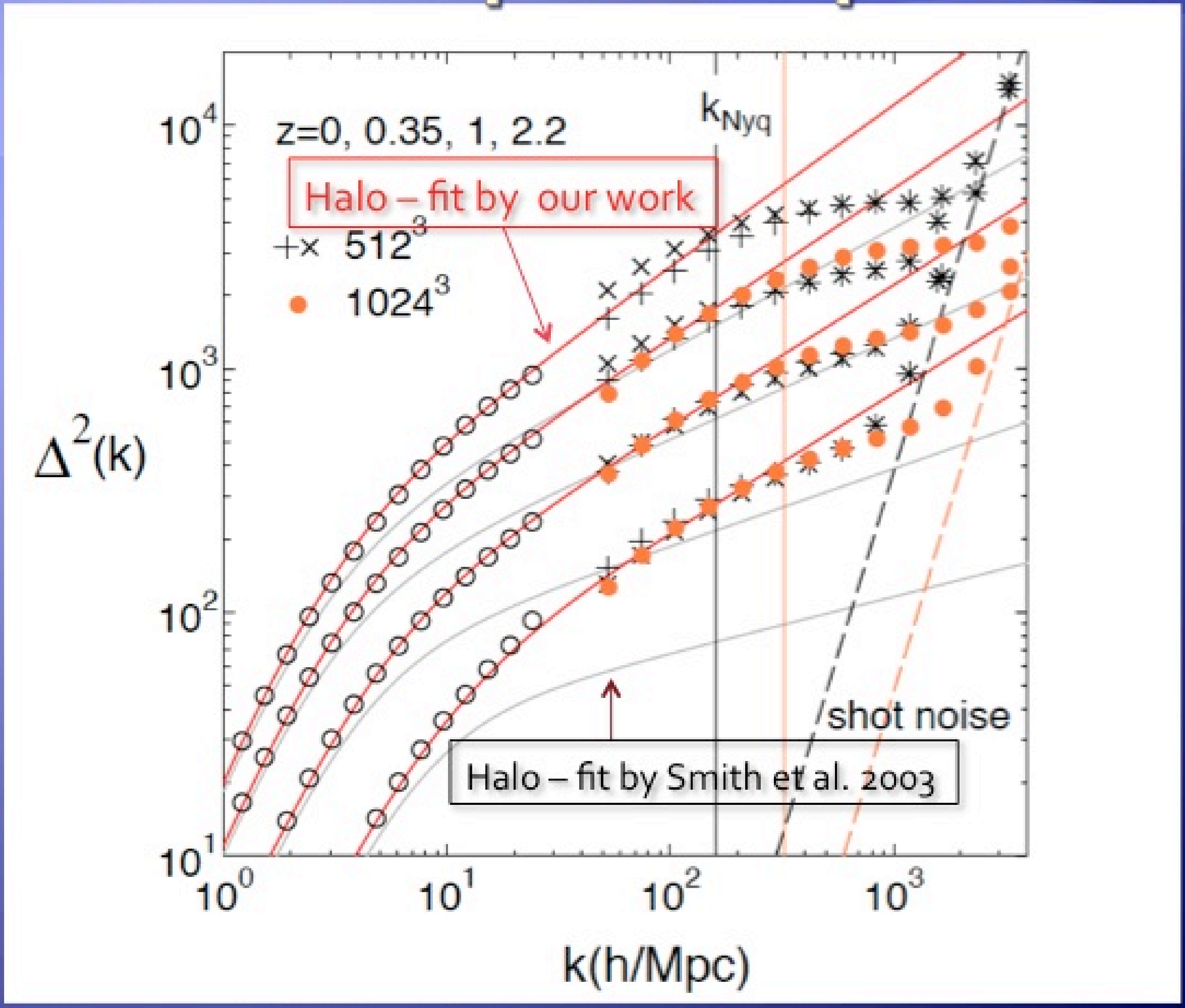
$$
\begin{aligned}
\xi_\kappa(\theta) &\equiv \langle \delta\kappa(0)\delta\kappa(\theta)\rangle \\
&= \frac{9H_0^4\Omega_{m,0}^2}{4c^4}\int_0^{r_S} dr r^2 \left(\frac{r-r_S}{r_S}\right)^2 [1+z(r)]^2 \\
&\times \int_0^\infty \frac{dk}{2\pi} k W(k;k_{cut}(r;\epsilon)) P_\delta(k;r) J_0(g(r)k\theta),
\end{aligned}
$$

Constrained convergence power

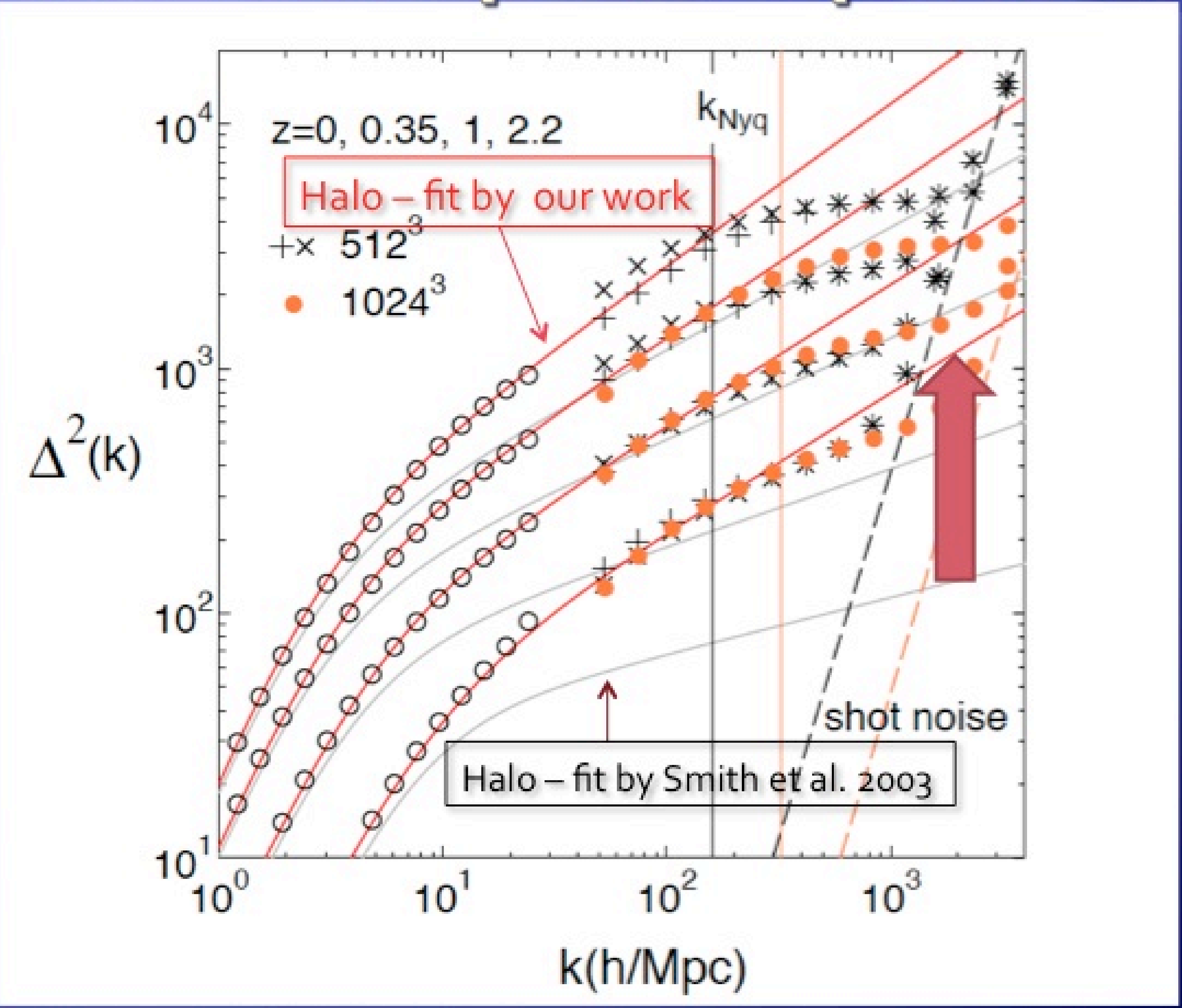


Non-linear power spectrum

Non-linear power spectrum



Non-linear power spectrum



Contribution to the flux ratios

MIR QSO-galaxy quads

- 6 samples:5 continuum 1 line [OIII]
- SIE-ES model possibly with SIS for a luminous satellite (gravlens by Keeton)
- Astrometric shifts given by position errors (CASTLES) in lensed images and lens & size of critical curves -> minimum wavelength.

MIR quadruple lenses

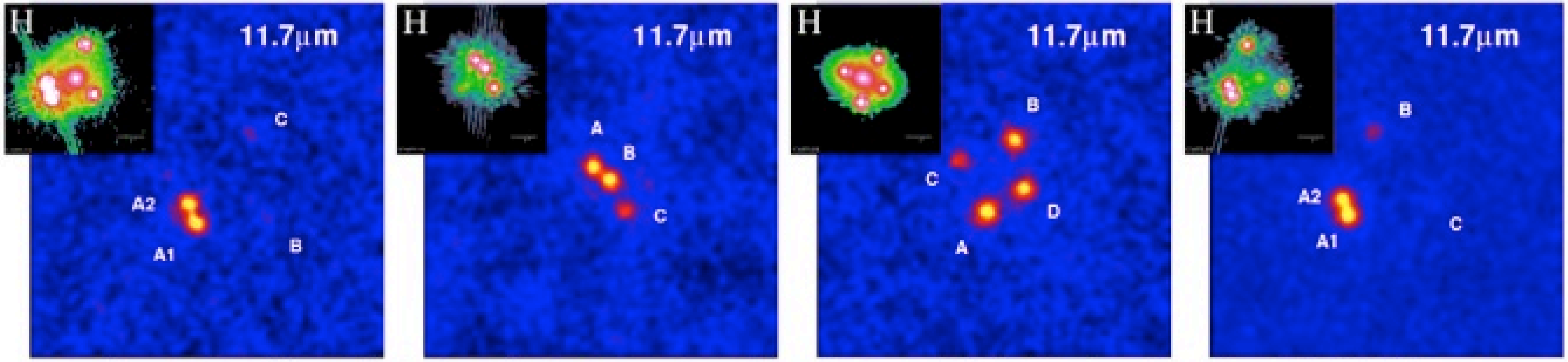


Figure 2: The mid-infrared images of quadruply lensed QSOs obtained by COMICS attached on Subaru telescope. From left to right, PG1115+080, B1422+231, Q2237+030, and MG0414+0534. The insets are their HST images for comparison (taken from CASTLES, http://cfa-www.harvard.edu/glensdata/).

- Source size estimated from dust reverberation method ~ 1~3pc >>Einstein radius of stars (by Chiba et al 2005 & Minezaki et al. 2009)

MIR quadruple lenses

Table 1. Observed MIR Flux Ratios

Lens	z_L	z_S	N	Flux Ratio			$\langle\epsilon\rangle$ ($''$)	$\langle\theta\rangle$ ($''$)	Reference
RXJ1131-1231($\star$)				A/B	C/B				
	0.295	0.658	3	$1.63^{+0.04}_{-0.02}$	$1.19^{+0.03}_{-0.12}$		0.017	1.9	1, 2
Q2237+0305				B/A	C/A	D/A			
	0.04	1.695	4	0.84 ± 0.05	0.46 ± 0.02	0.87 ± 0.05	0.0046	0.9	1, 3
PG1115+080				A2/A1					
	0.31	1.72	2	0.93 ± 0.06			0.020	1.2	1, 4
H1413+117				B/A	C/A	D/A			
	1.88($\star\star$)	2.55	4	0.84 ± 0.07	0.72 ± 0.07	0.40 ± 0.06	0.020	0.6	5
MG0414+0534				A2/A1	B/A1				
	0.96	2.639	3	0.90 ± 0.04	0.36 ± 0.02		0.0042	1.2	1, 3
B1422+231				A/B	C/B				
	0.34	3.62	3	0.94 ± 0.05	0.57 ± 0.06		0.0042	1.1	1, 4

References:1. CASTLES; 2. Sugai et al. 2007; 3. Minezaki et al. 2009; 4. Chiba et al. 2005; 5. MacLeod et al. 2009

Note: ($\star$): [OIII] line flux ratios. ($\star\star$): The lens redshift z_L is obtained from a best-fit model using the observed positions of the images and the primary lens, the flux ratios, and the time-delays between the images assuming $H_0 = 70\,\mathrm{km/s/Mpc}$.

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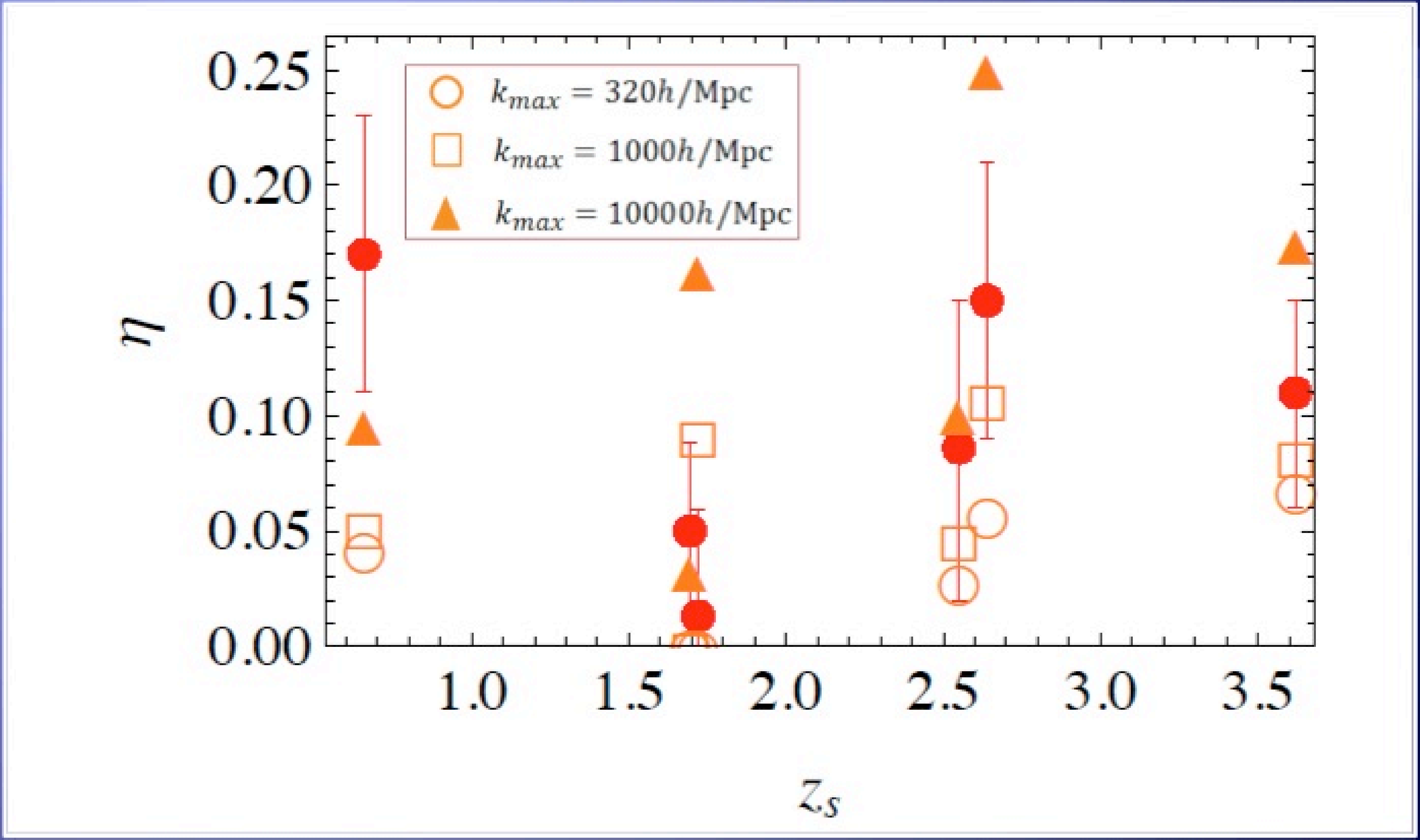
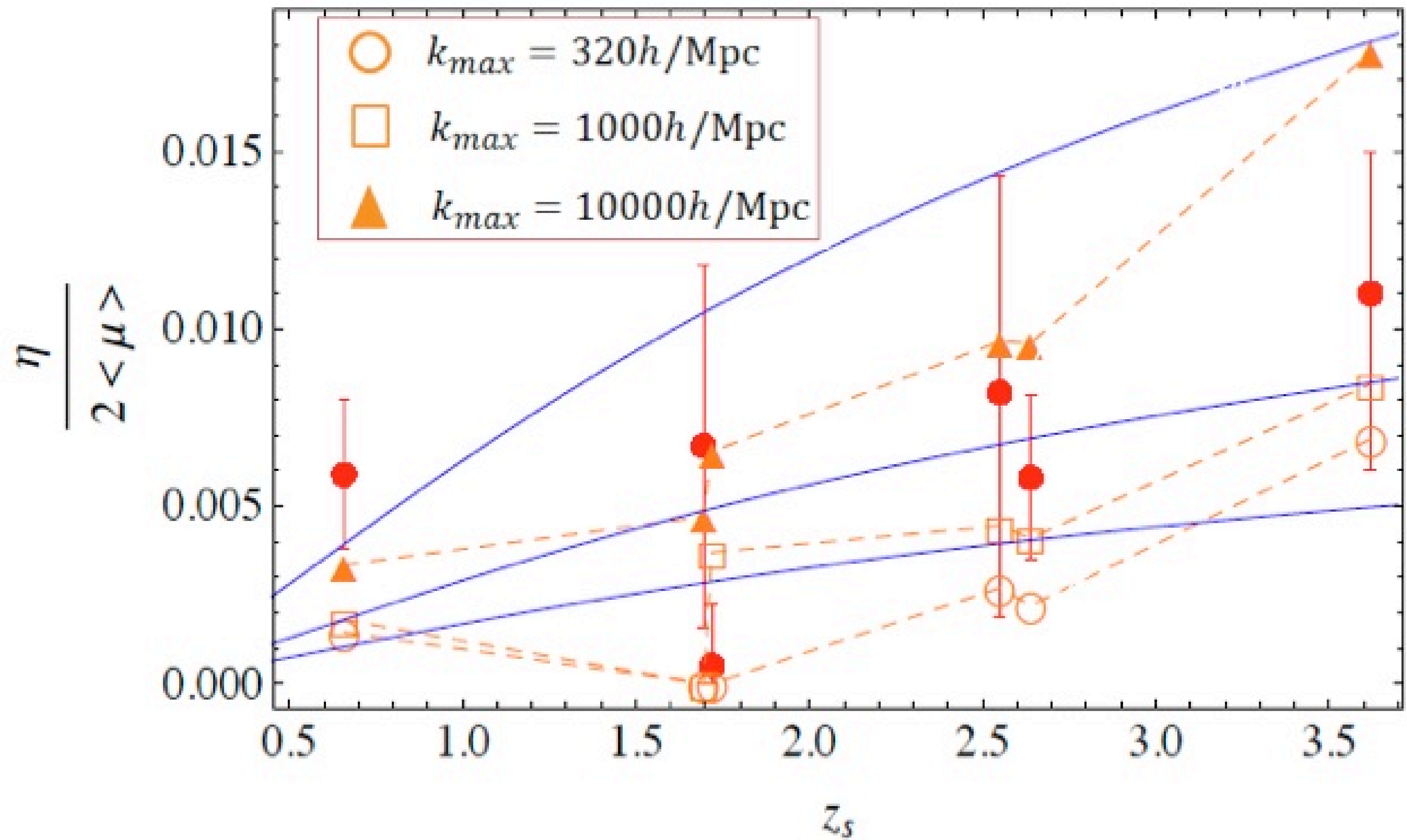
Result I



$k_{max} = 320h/\mathrm{Mpc}$
$k_{max} = 1000h/\mathrm{Mpc}$
$k_{max} = 10000h/\mathrm{Mpc}$
η
0.25
0.20
0.15
0.10
0.05
0.00
1.0
1.5
2.0
2.5
3.0
3.5
z_s

Result II



$k_{max} = 320h/\mathrm{Mpc}$
$k_{max} = 1000h/\mathrm{Mpc}$
$k_{max} = 10000h/\mathrm{Mpc}$
0.015
0.010
0.005
0.000
$\frac{\eta}{2<\mu>}$
0.5
1.0
1.5
2.0
2.5
3.0
3.5
z_s

Summary

- Clustering line-of-sight halos with M=10^3-7 solar mass can explain the observed anomalous flux ratios without any substructures inside a lensing galaxy.

- The estimated amplitudes of convergence perturbation increase with the source redshift as predicted by theoretical models.

- Unique probe into mini-halos M<10^6 solar mass

Future work

- Consistency check using light-ray tracing simulations

- Minimum change in astrometric shift for lensed image & lens.

- Check of SIE+ES, luminous group/satellite galaxies

- Extention to radio lenses incorporating finite source-size effects