
# Sensitivity of Gravitational Arc Statistics to Dark Energy

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BRASIL UM PAÍS DE TODOS

2009 60 ANOS CBPF

- **Work with J. Estrada, E. Roulet, S. Mollerach**

DARK ENERGY SURVEY

Fermilab

Instituto Balseiro Bariloche

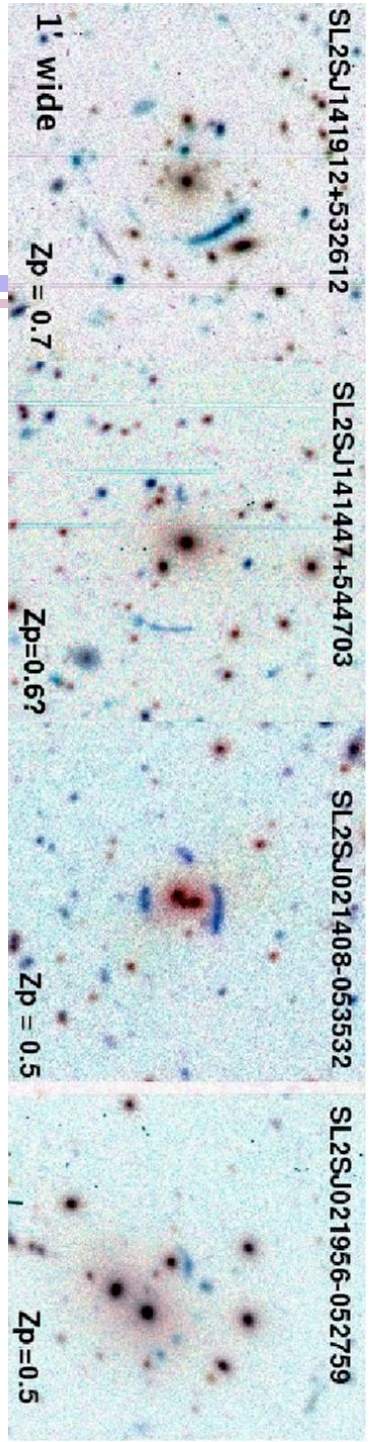
CNEA

# Arcs: strong lensing effect

- Unique probe of inner structure of galaxy clusters
  - Pure gravity
  - Constrain dark matter models
- May provide complementary cosmological probes
- Arcs are there!
- Arcs are pretty


# Motivations

- Lensing sensitive to cosmological distances
- Claimed strong dependence of $N_{arcs}$ on $\Omega_\Lambda$ (e.g., Cooray 1998, Bartelmann et al., 1998)
- Dependence of arcs on Dark Energy (e.g., Meneghetti et al. 2005)
- Overabundance of arcs at z > 0.6 (Gladders et al. 2003)
- Growing number of events
- “Ancillary science” for many surveys
- Dark Energy Survey, SOAR Gravtiational Arc Survey



# Arc Statistics

- Semi analytic modeling for arc abundance
- Observable: Average number of arcs per cl

$$f_{\rm arcs}(M_i, z_i) = \frac{N_{\rm arcs}}{N}$$

- Why?
  - Does not depend
  - Less se
  - 
  - with cosmological and astrophysical
  - ors
- Needs: lens arc cross section, source distribution, cosmology, detection efficiency, observational conditions

All arc statistics results are either wrong or incomplete

# Semi analytic modeling for arc abundance

- Expected number of arcs per cluster

$$f_{arcs}\left(\Pi_L, z_L\right) = \int \frac{\mathrm{d}\sigma\left(\Pi_L, z_L; \Pi_S, z_S; Q_P\right)}{\mathrm{d}Q_P} \frac{\mathrm{d}n\left(z_S, \Pi_S,\right)}{\mathrm{d}\Pi_S} F\left(Q_P|Q_O\right) P\left(Q_O\right) \mathrm{d}z_S\, \mathrm{d}\Pi_S\, \mathrm{d}Q_O$$

cross section for arc formation

source distribution

Observational effects

Selection function (detection efficiency)

- $\Pi_L$: set of *lens* properties (mass, ellipticity, etc.), $z_L$: lens redshift
- $\Pi_S$: set of *source* properties (angular size, magnitude, etc., $z_s$: source redshift), which are mapped into *images* with properties $Q_P$
- $Q_O$: *observed* image properties after convolution with seeing, etc., of a source with properties $Q_P$ (changing size, diluting surface magnitude, etc.)

# Importance of magnification

Most studies of arc statistics *ignore* the effect of magnification, because gravitational lensing *conserves surface brightness*.

- Arcs are detected by their *signal* over the *background*
- The signal to noise ratio is $\frac{s}{n} = \frac{FA}{\sqrt{bA}}$
- The gravitational lensing effect changes only the image area through the magnification μ: $A_{lensed} = \mu \times A$
- Taking this into account, the lensed object has

$$\boxed{(s/n)_{lensed} = \sqrt{\mu}\,(s/n)}$$

Magnification enhances arc detectability and should be taken into account

This effect is neglected in “binary” arc simulations!

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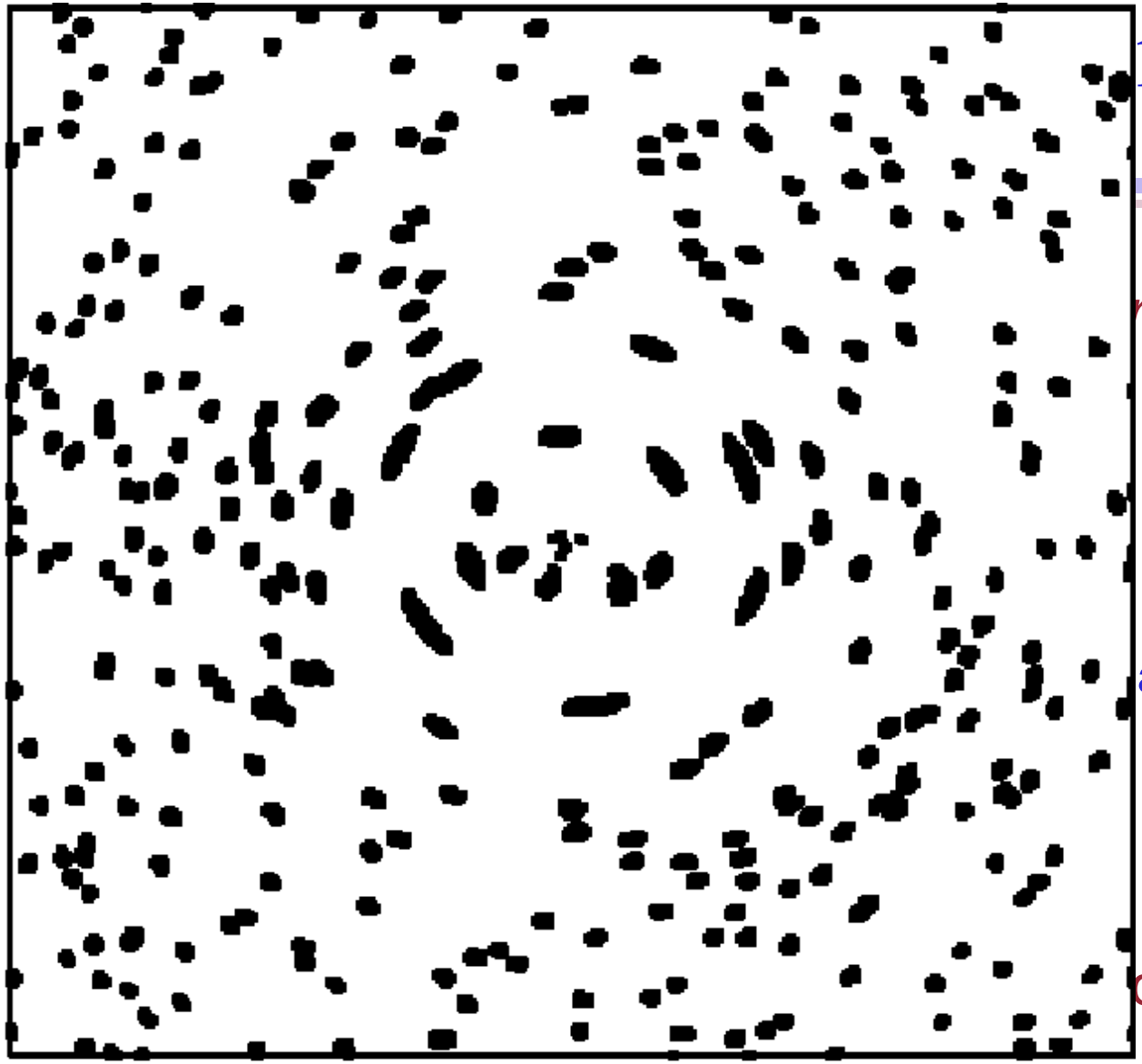


This effect is neglected in “binary” arc simulations!

# Scaling with magnification

- Magnification changes effective $m_{\mathrm{lim}}$:

$$m_{lim}^{eff} = 2.5\log(\sqrt{\mu}) + m_{lim}$$

- Compute *magnification dependent* cross section
  - Excellent approximation:

$$\sigma = \sigma_0 \times \begin{cases} 1, & \text{if } \mu < \bar{\mu}/2 \\ \left(\dfrac{\bar{\mu}}{2\mu}\right)^2, & \text{if } \mu > \bar{\mu}/2 \end{cases}$$

  - Consistent with behavior close to caustics

# A Simple Example

- Including only magnification

$$f_{arcs}(\Pi_L, z_L) = \int \frac{\mathrm{d}\sigma(\Pi_L, z_L; \Pi_S, z_S; Q_P)}{\mathrm{d}Q_P} \frac{\mathrm{d}n(z_S, \Pi_S,)}{\mathrm{d}\Pi_S} F(Q_P|Q_O)\, P(Q_O)\, \mathrm{d}z_S\, \mathrm{d}\Pi_S\, \mathrm{d}Q_O$$

$\delta(F_P - \mu F_S)$

Independent of morphology

$m_{\mathrm{lim}}$ only

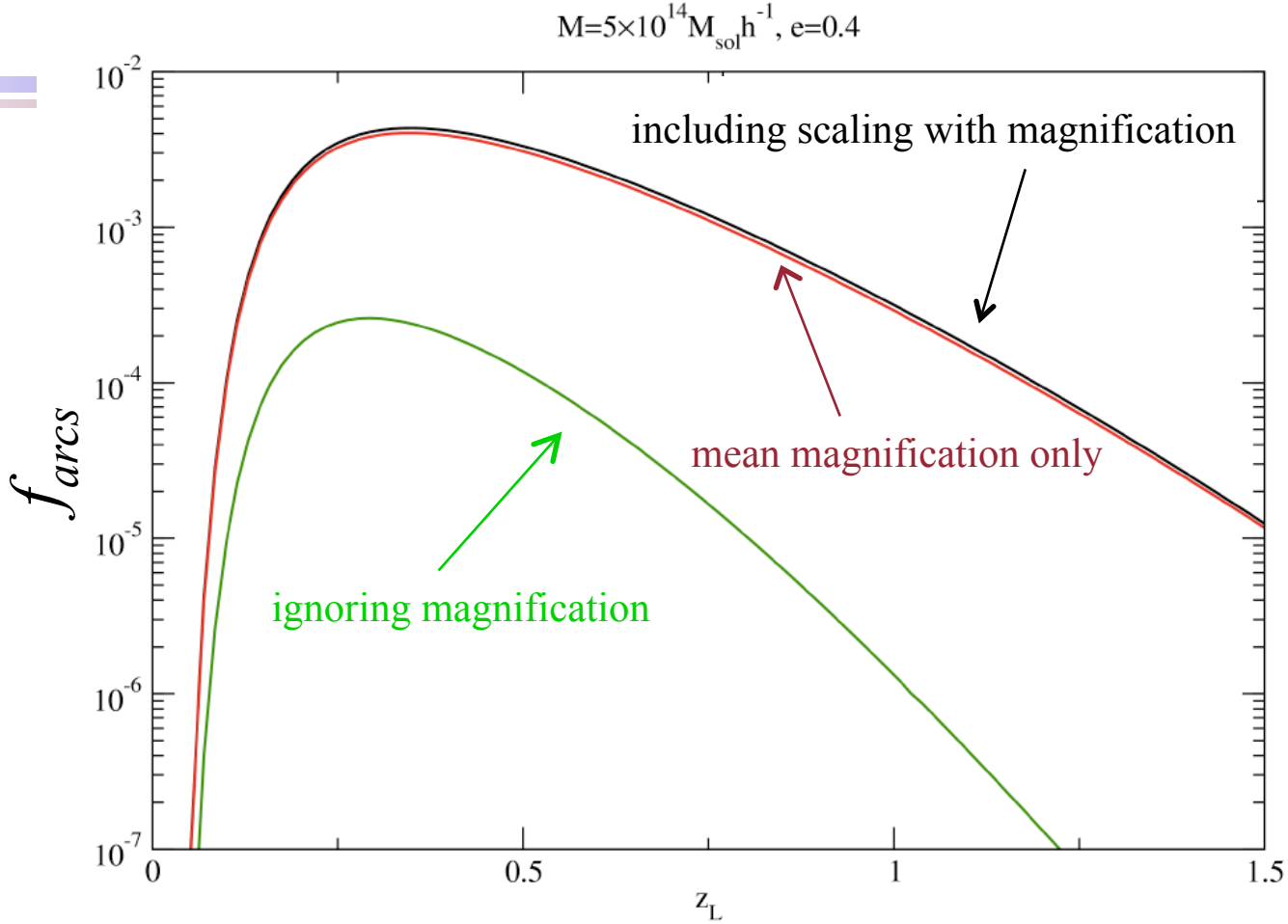
$\delta\left((L/W)_0 - (L/W)_P\right)$

$\theta(L/W - R_{th}) \times$

$\theta\left(s/n - (s/n)_{th}\right)$

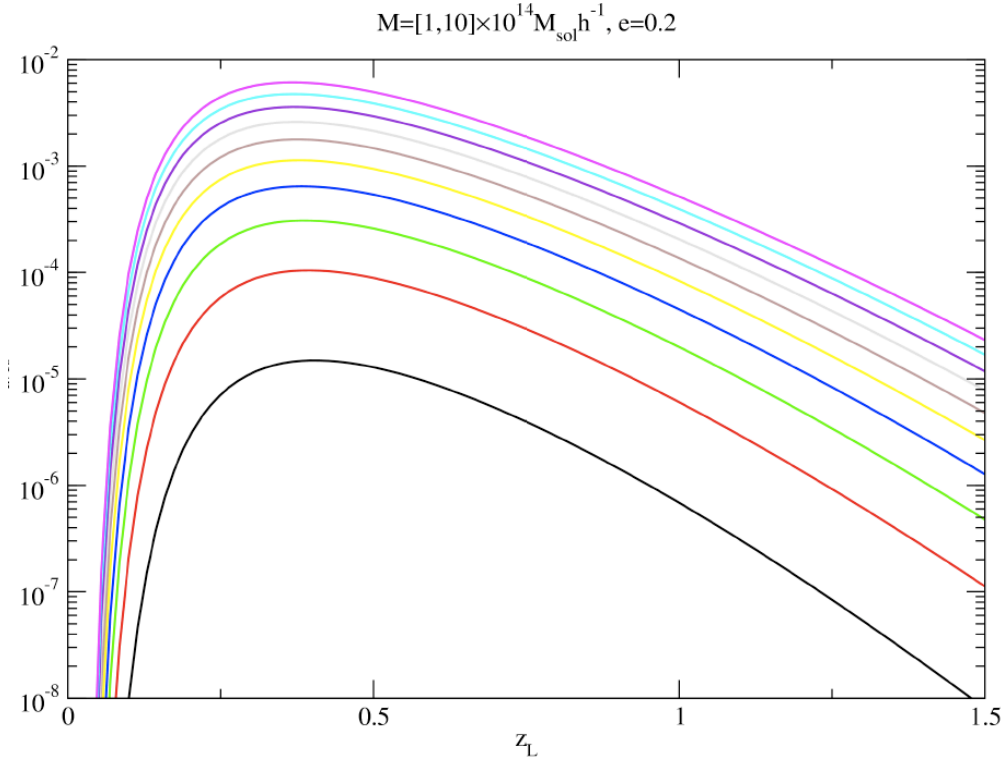
$$f_{\mathrm{arcs}}(M, e, z_L) = \int_{z_L}^{\infty} \int_{\mu_{\min}(M,\ldots;z_S,z_L)}^{\infty} \frac{d\sigma(M,..;z_S,z_L;\mu)}{d\mu} n(z_S;\mu)\, d\mu\, dz_S$$

# Results



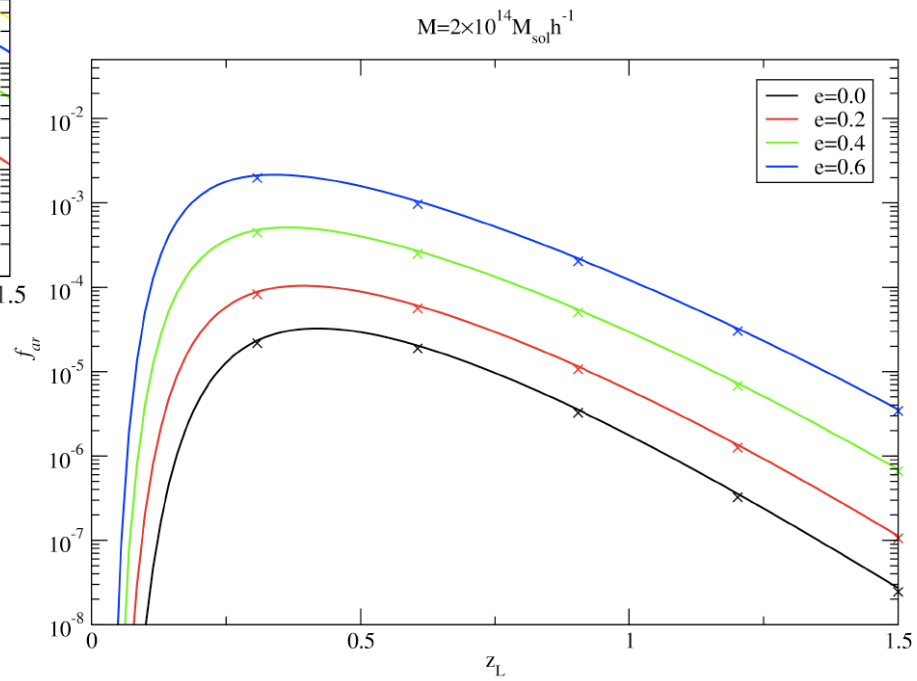

- Magnification ***must*** be taken into account in semi-analytic calculations and in "binary" image simulations
- Mean magnification is enough for estimations
- Scaling with magnification must be taken into account for "precision cosmology"

# Sensitivity to cluster parameters

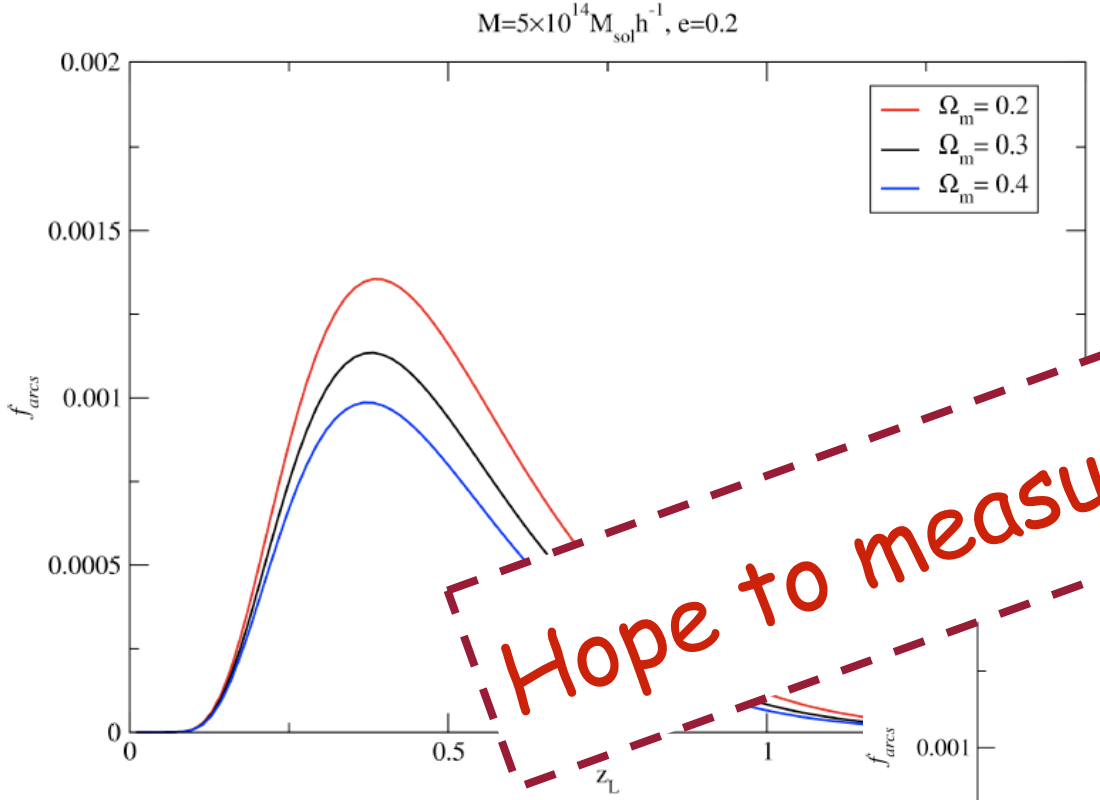



Mass

Ellipticity



# Sensitivity to cosmological parameters (ΛCDM)

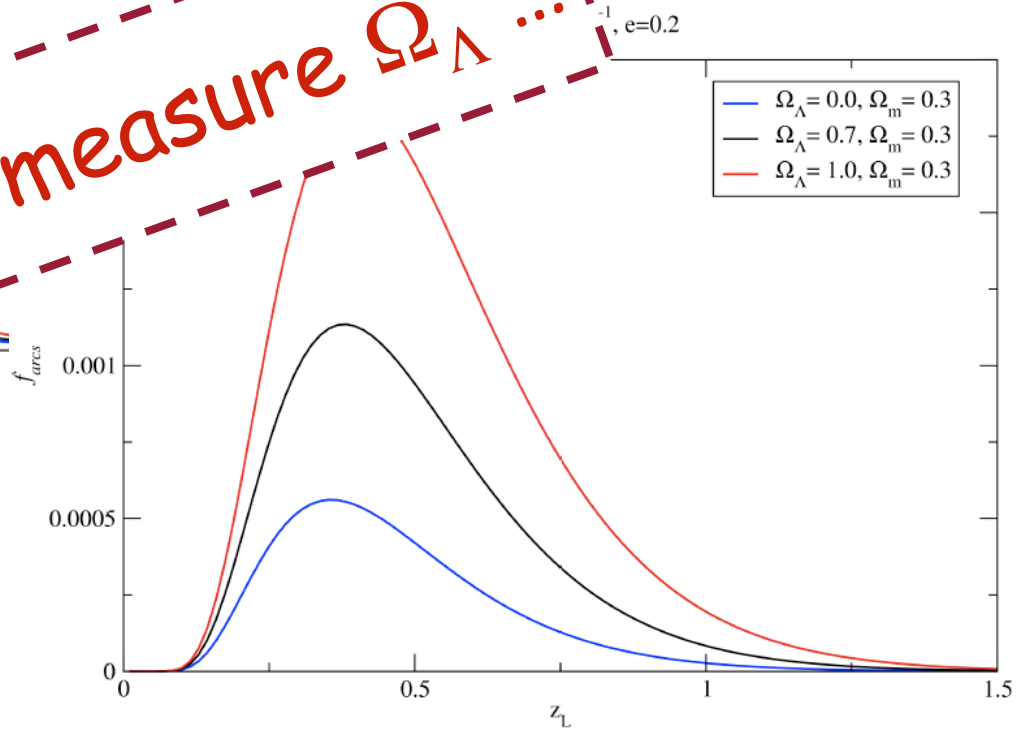



Flat

30% increase in farcs for 0.6 to 0.8

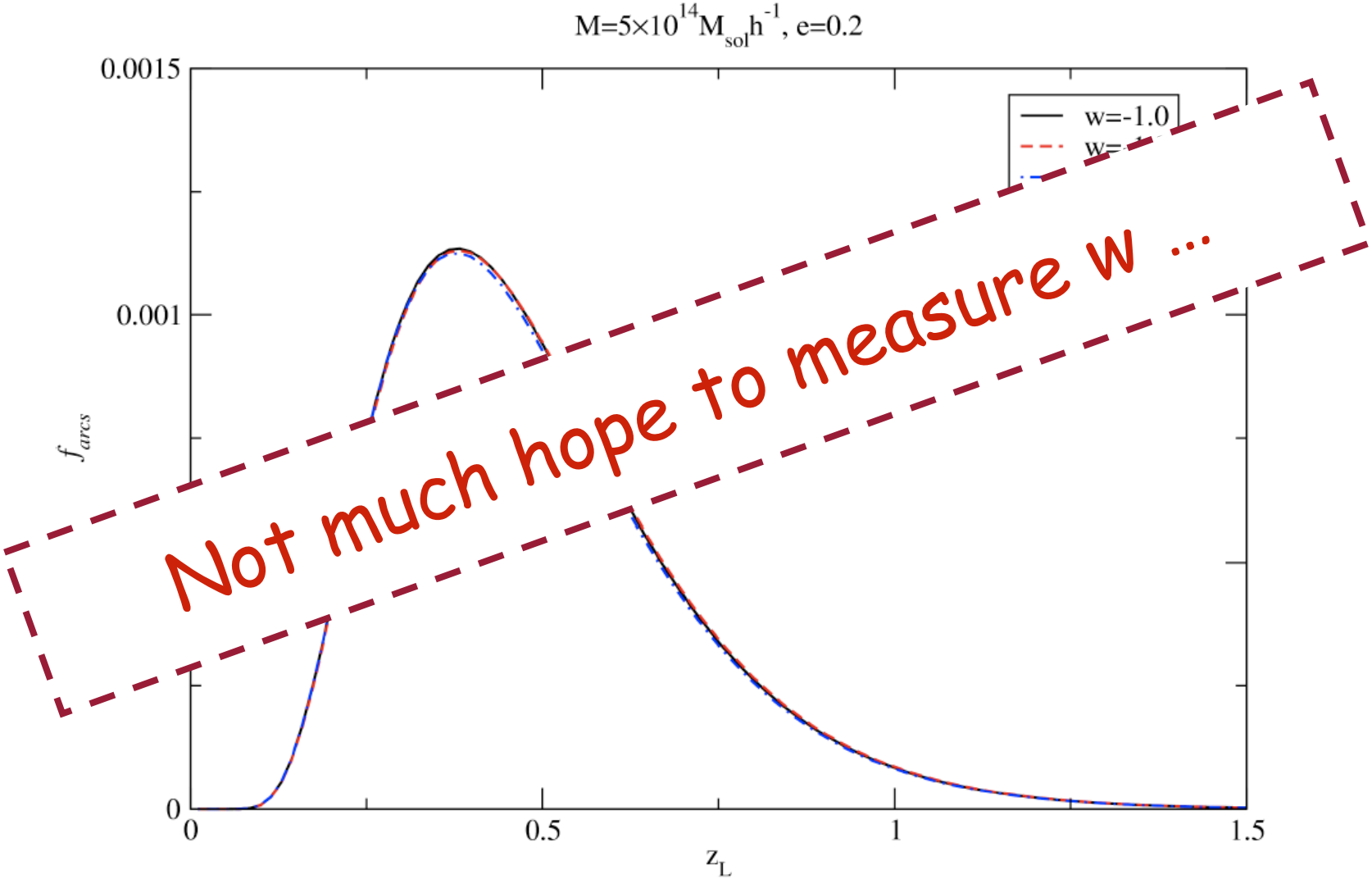
Hope to measure $\Omega_\Lambda$ ...

Fixed $\Omega_M$



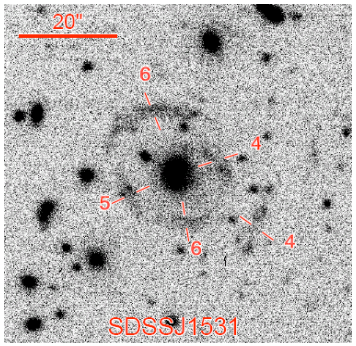

Factor of 4 increase from OCDM to concordance

# Equation of state parameter

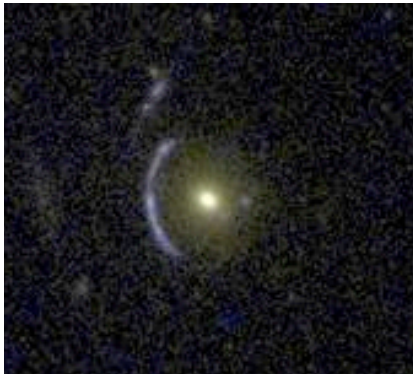


# “Strong Lensing Surveys”

## Homogeneous arc samples




- Up to 2005
  - EMSS, LCDCS, RCS, XBACS (Smith et al., Campusano et al.): ~ 10 w/arcs
- 2006-2007
  - $SL^2S$, SDSS, LOCUSS/MACS (unpublished): ~ $10^2$ arcs
- 2008-2010
  - RCS2, $SL^2S$, ?: > $10^2$ arcs
- 2011
  - DES: ~ $10^3$ arcs
- > 2015
  - LSST, JDEM, EUCLID?: ~ $10^4$ – $10^5$ arcs



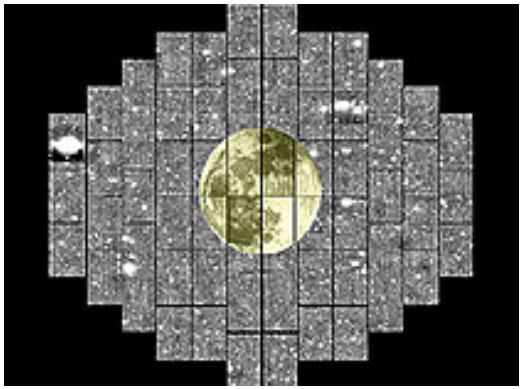
# DES in a nutshell

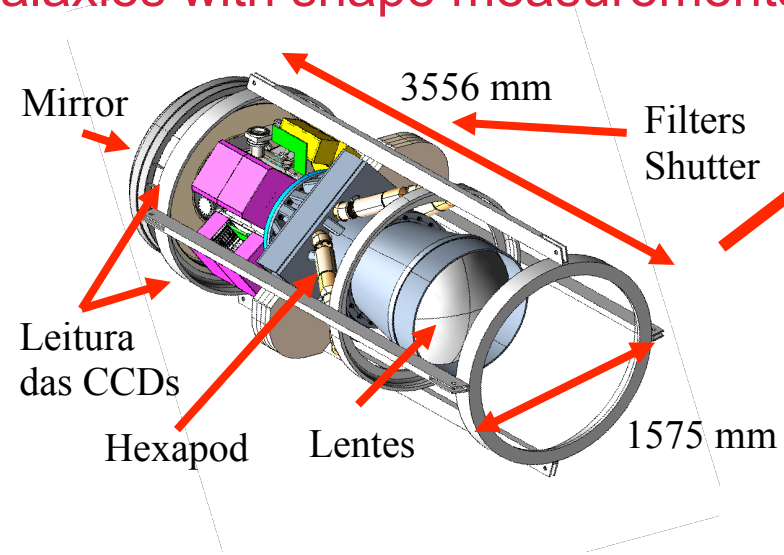
DARK ENERGY SURVEY

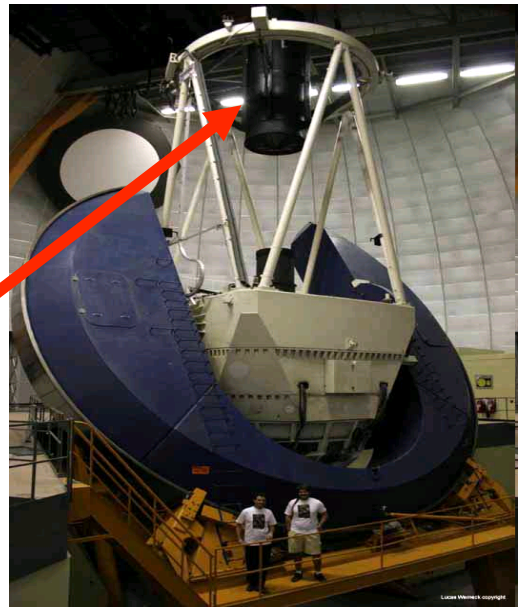
DES-BRAZIL

## *The Dark Energy Survey*

- *Blanco CTIO 4m*
- DECam: 500 Megapixels, ~ 3 deg$^2$
- Red sensitive CCDs
- 30% of CTIO in 5 yr (525 nights)
- *g*, *r*, *i*, *Z*, *Y* = 24.6, 24.1, 24.3 (23.9)
- 5000 deg$^2$, median seeing ≤ 0.9”
- 300 million galaxies with shape measurements





# Arc abundance in DES

- Expected total number of arcs ≈ 1000 (scaling from RCS and CFHTLS, DES Strong Lensing Study Group White paper, 2009)
- Predictions from Hubble Volume halo catalog (NFW elliptical lenses)
- Source distribution in R-band from COMBO-17

# Arc fraction statistics

- $f_{arcs}$ binned in cluster mass and redshift:

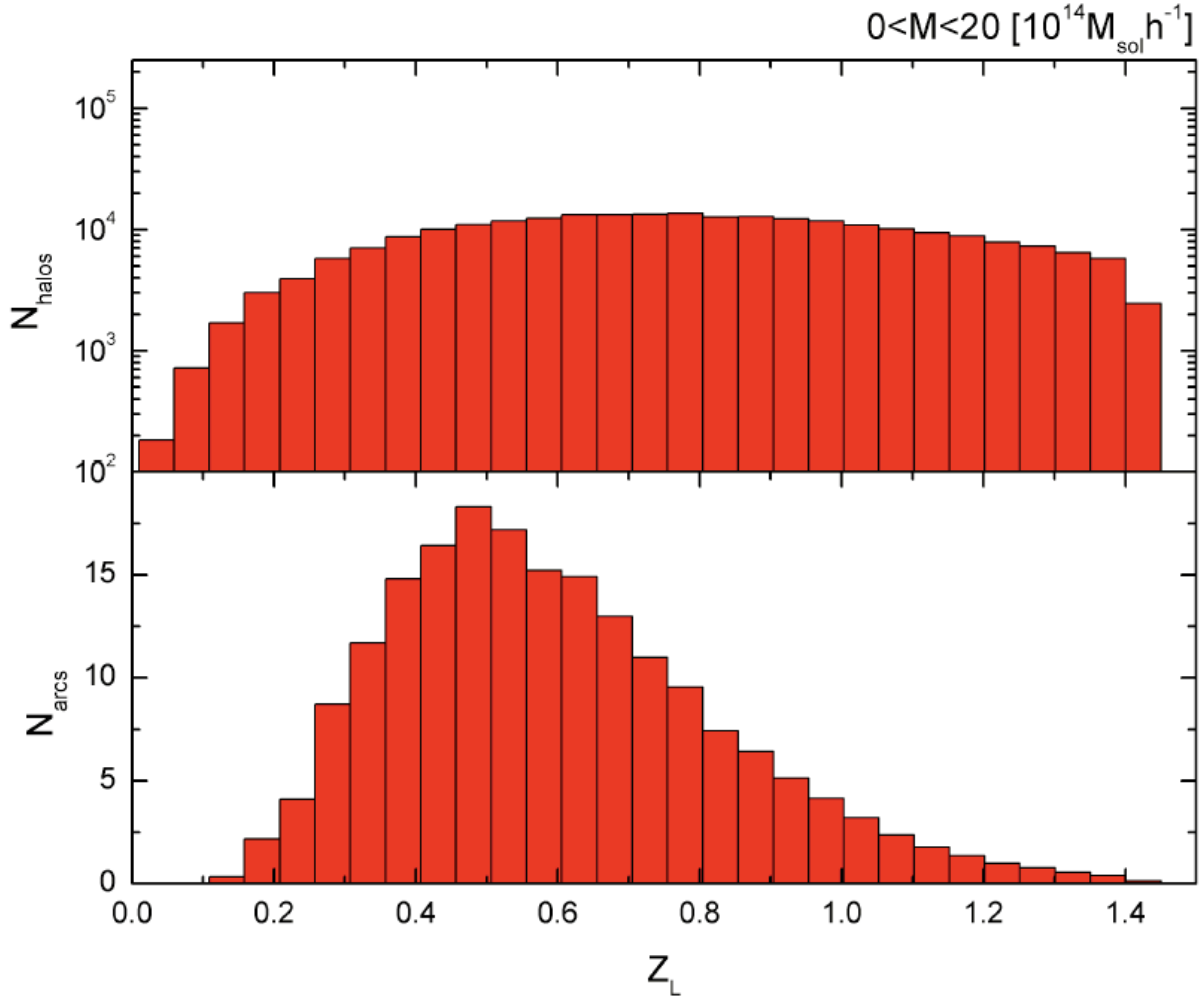
$$\chi^2 = \sum_{i,j} \frac{\left(f^0_{ij} - f^t_{ij}(\vec{p})\right)^2}{\sigma^{f\,2}_{ij}},$$

- Parameters $p$
  - Cluster structure: $c(M) = B_c\, c^0(M)$
  - Background galaxy distribution: $z_* = a_z z^0_*$
  - Cosmological constant $\Omega_\Lambda$
- Poisson error bars on $f$ ($N_{arcs\_tot} \approx 1000$)

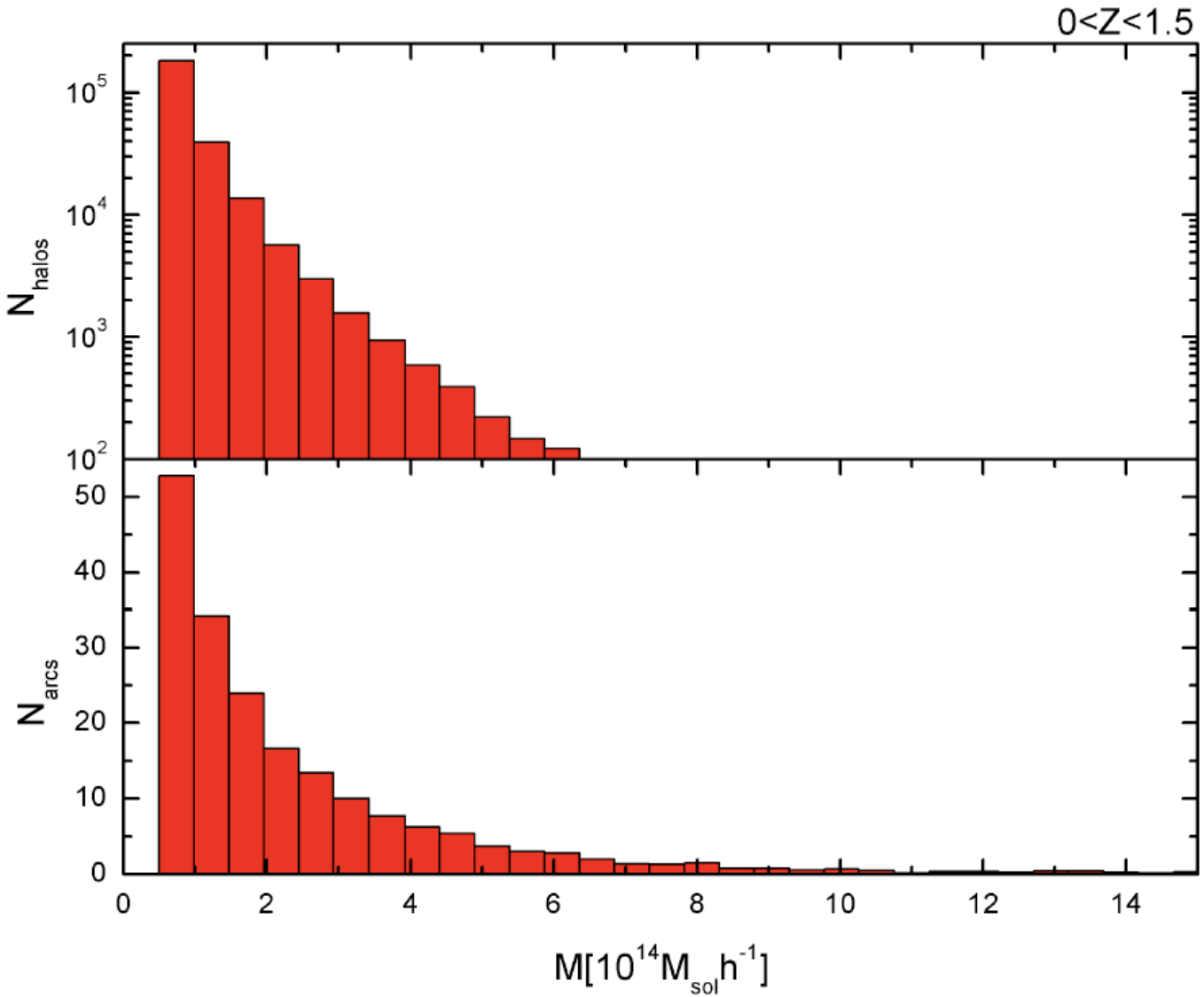
$$f_{\rm arcs}(M_i, z_i) = \frac{N_{\rm arcs}}{N_{\rm halos}(M_i, z_i)}$$

# Scaling of $N_{\rm arcs}$ with $z_{\rm L}$

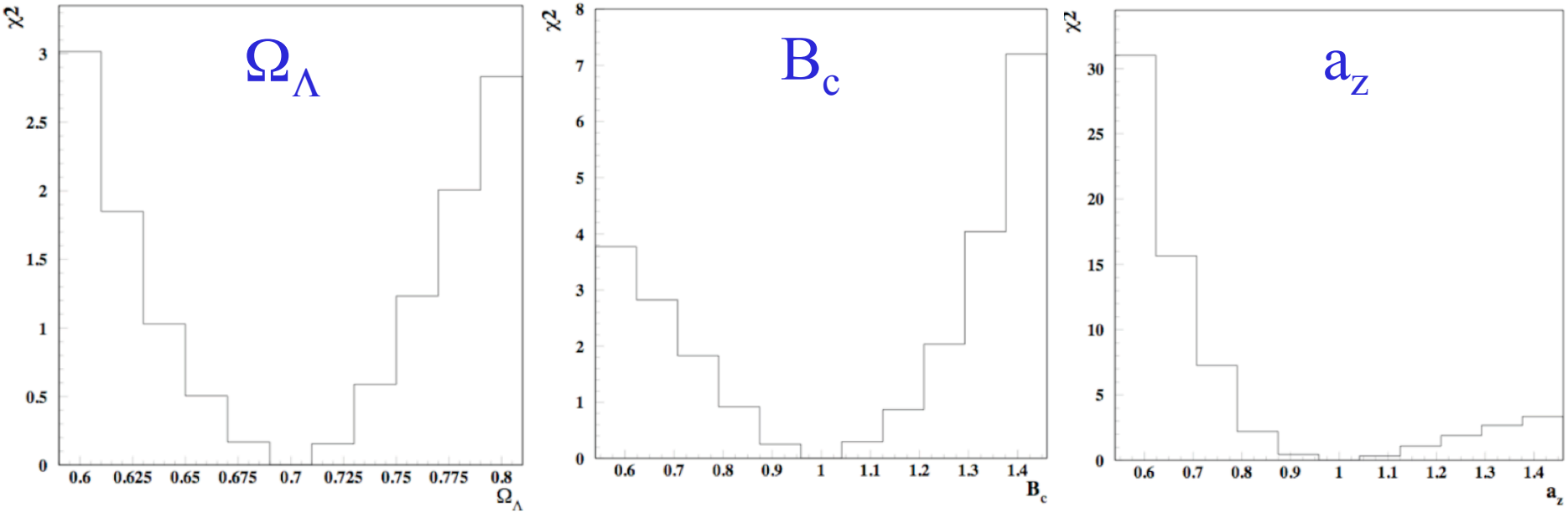
$$N_{\rm arcs}(M_i, z_i) = f_{\rm arcs}(M_i, z_i) \times N_{\rm halos}(M_i, z_i)$$



# Scaling of $N_{arcs}$ with $M$



# Constraints for DES




$\sigma_{\Omega\Lambda} \approx 0.1$ $\sigma_{Bc} \approx 0.3$ $\sigma_{az} \approx 0.3$

- "Optimistic" constraints for DES ($N_{arcs} \approx 3000$)
  - $\sigma_{\Omega\Lambda} \approx 0.03$, $\sigma_{Bc} \approx 0.1$, $\sigma_{az} \approx 0.05$
  - Marginalizing over $a_z$, for known cosmolgy, $\sigma_{Bc} \approx 0.2$

# Caveats…

- Local eigenvalue ratio (circular infinitesimal sources)
- Elliptical NFW: no substructures, assymetries, tri-axialuty, baryons….
- Neglecting seeing
- No errors on farcs
  - considering only the mean, not its distribution
  - cluster properties, sources, …
- Full image simulations in progress

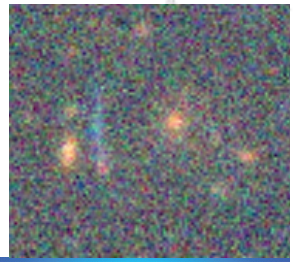
…but qualitative results are not expected to change significantly

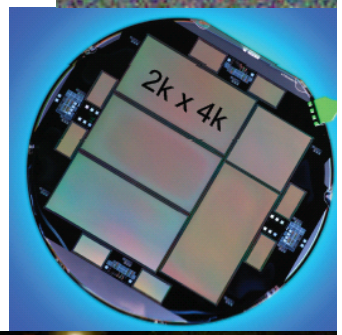
# Other arc probes

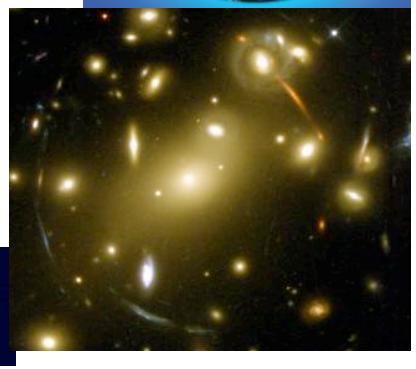
- Inverting the lens equation
  - Strong degeneracy with source morphology and position
- Strong Lensing "Tomography"
  - "golden lenses" with arcs at several *z* (see, e.g., Meneghetti et al. 2005)
  - Constraints on $\eta = (D_{LS}/D_S)_{zs1}/(D_{LS}/D_S)_{zs2}$
  - Expect 10 – 20 double lenses in DES
- Need follow-ups

# Discussion

- Arc abundance is not expected to provide a sensitive probe for DE
- Could be useful for cluster structure and high-z galaxy distribution
- Explore other lensing observables for Dark Energy
- Follow-ups needed for individual lenses (and possible!)
- Simulations are a necessary tool





# Thank you!