Arcs and what they teach us

Bernard Fort's birthday party
IAP, July 4, 2007

Matthias Bartelmann, Heidelberg University

The first arc(s)

Astron. Astrophys. 172, L14–L16 (1987)

Letter to the Editor

A blue ring-like structure in the center of the A 370 cluster of galaxies

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Astron. Astrophys. 191, L19–L21 (1988)

Letter to the Editor

The giant arc in A 370: spectroscopic evidence for gravitational lensing from a source at $z = 0.724$

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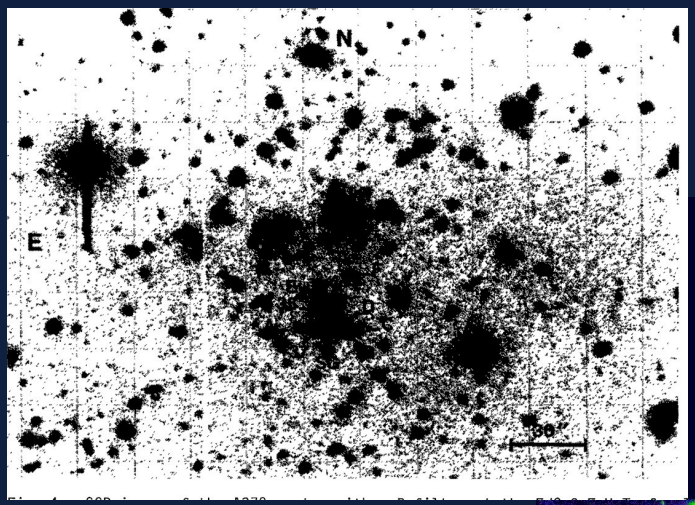
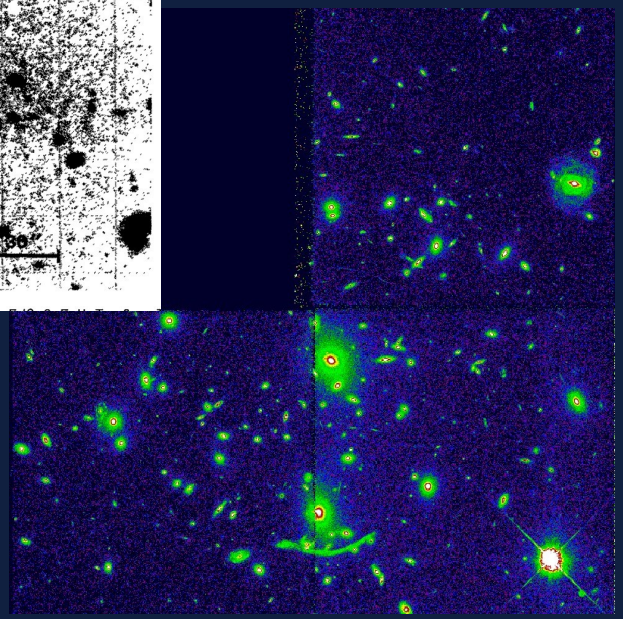
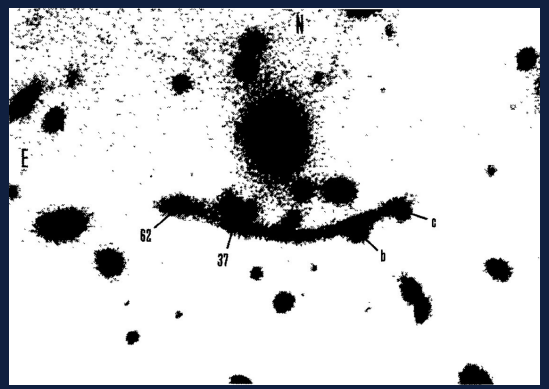
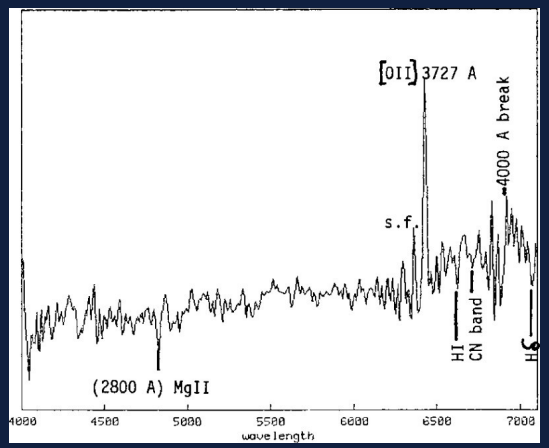


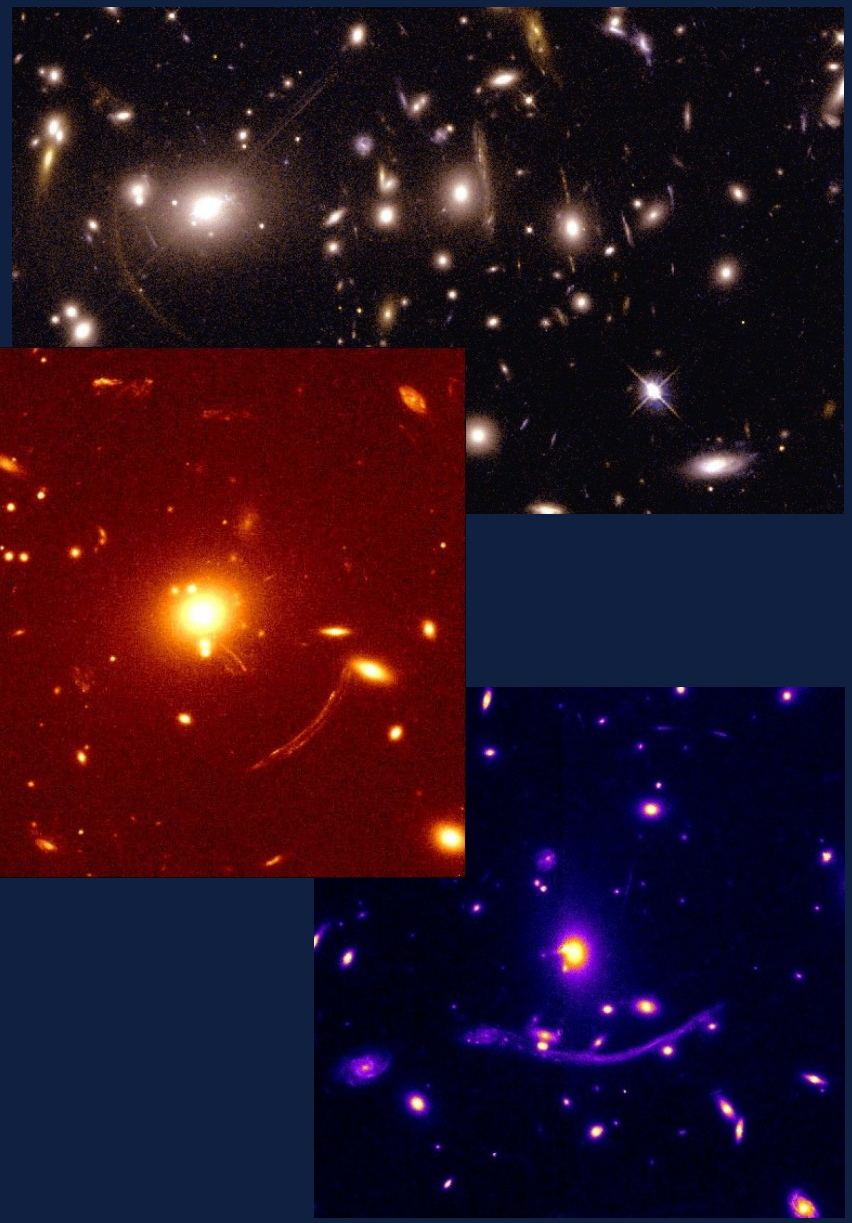






The first lessons

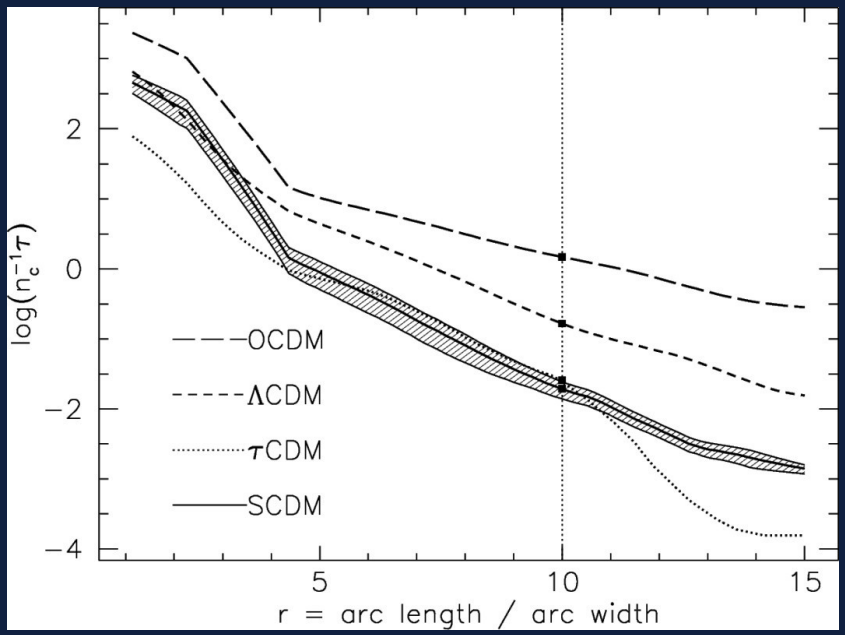
- Axial asymmetry, otherwise bright counterarcs (Grossman & Narayan 1988, Kovner 1989)
- Smoothly distributed dark matter, otherwise more curvature (Hammer et al. 1989, Bergmann et al. 1990); straight arc in A 2390 (Pelló et al. 1991, Kassiola et al. 1992)
- Steep density profiles, otherwise thick arcs (Hammer & Rigaut 1989)
- Radial arcs confirm small core radii (Fort et al. 1992, Miralda-Escudé 1993, Mellier et al. 1993)



The arc statistics problem

- Giant arcs: L/W > 10, R < 21.5 (Wu & Hammer 1993)
- Approximately ~ 0.2-0.3 giant arcs in X-ray bright ($L_X > 10^{44}$ erg/s) clusters (Le Fèvre et al. 1994, Gioia & Luppino 1994, Luppino et al. 1999)
- Asymmetry is crucial to even qualitatively understand these numbers (Bartelmann et al. 1995, Hattori et al. 1997, Molikawa et al. 1999)
- *Arc statistics problem*: clusters simulated in ΛCDM fail to reproduce arc abundance (Bartelmann et al. 1998)

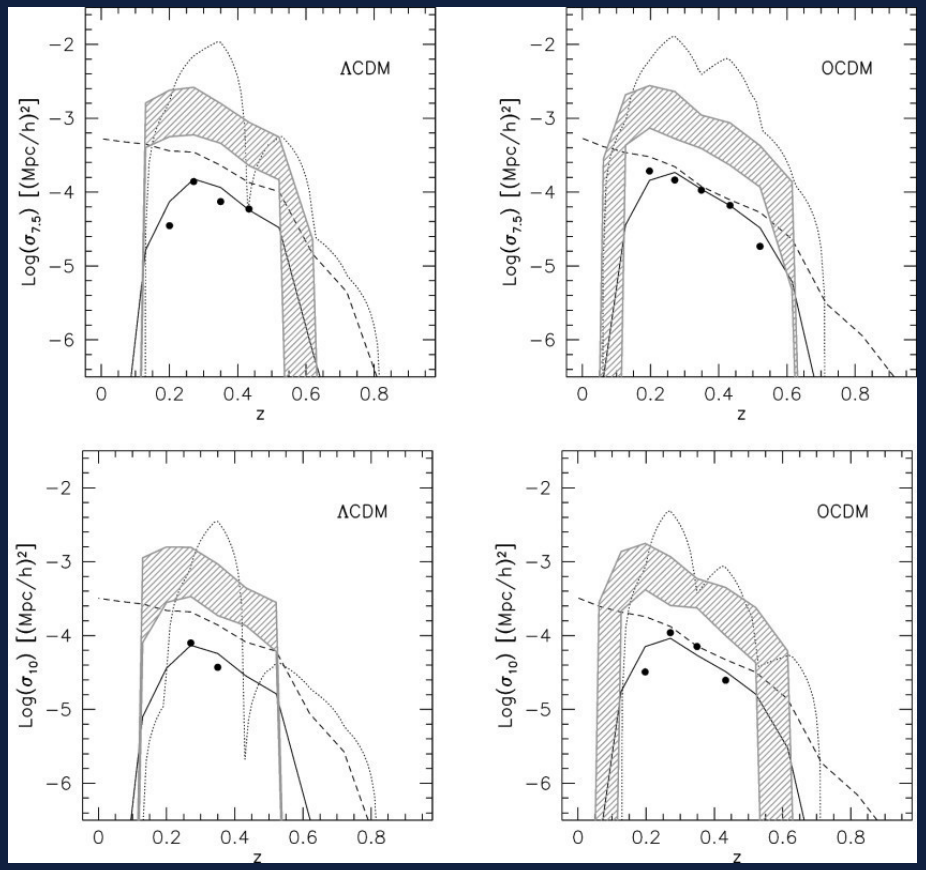
ΛCDM simulations with σ_8=0.9 and σ_8=1.12!



Expectation for ΛCDM:
~ 280 arcs on the full sky
Extrapolation from observations:
~ 1500 - 2300

Is there a problem?

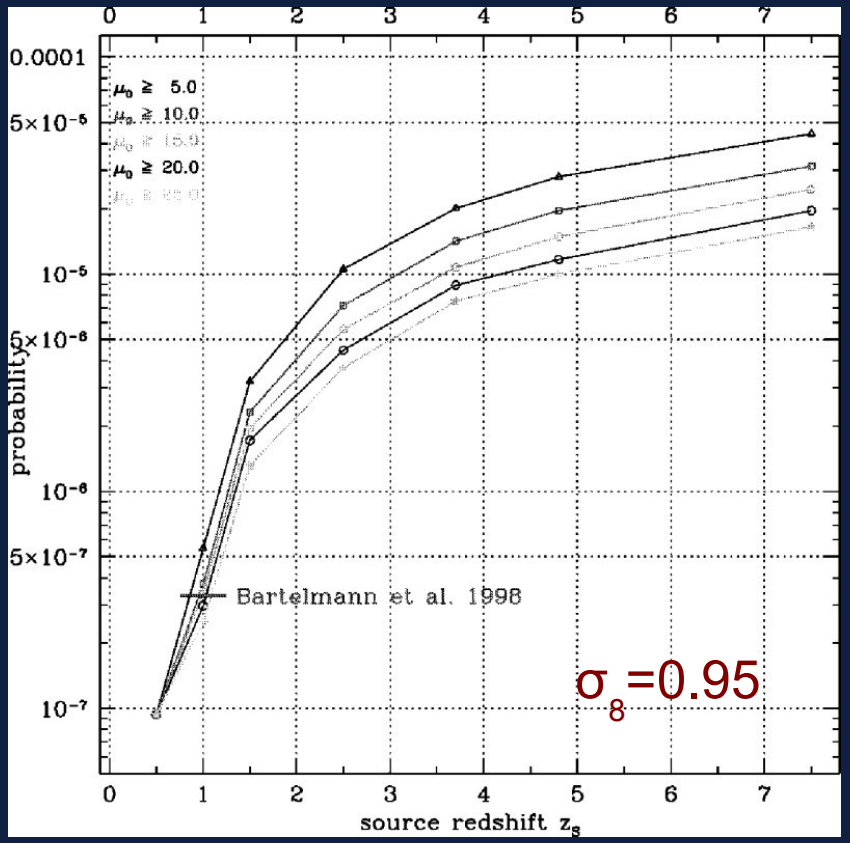
- Analytic models cannot reproduce the Λ-dependence (Cooray 1999, Kaufmann & Straumann 2000)
- Reasons:
  - Cluster concentration depends on Λ
  - Elliptical analytic models are inadequate

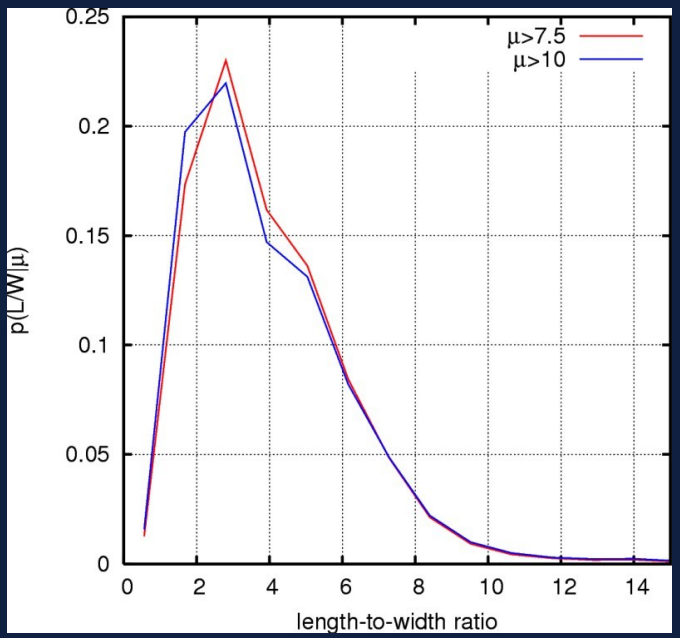


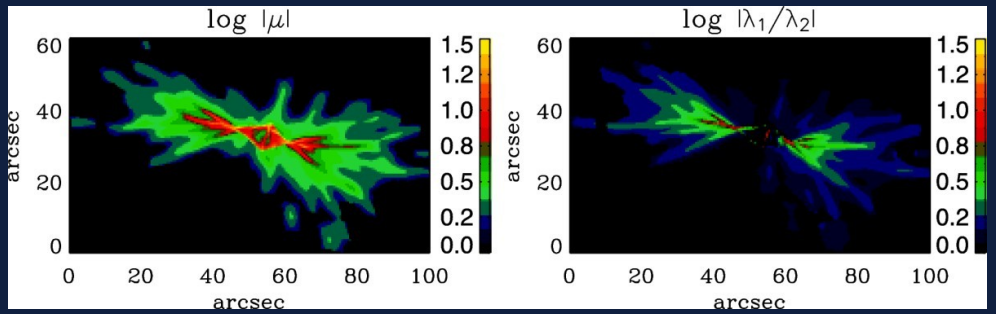
(Meneghetti et al. 2003)

Is there a problem?

- *No!* ΛCDM perfectly reproduces observed arc abundance (Wambsganß et al. 2004); reason: very steep dependence on source redshift
- But: magnification is not a good proxy for L/W ratio!



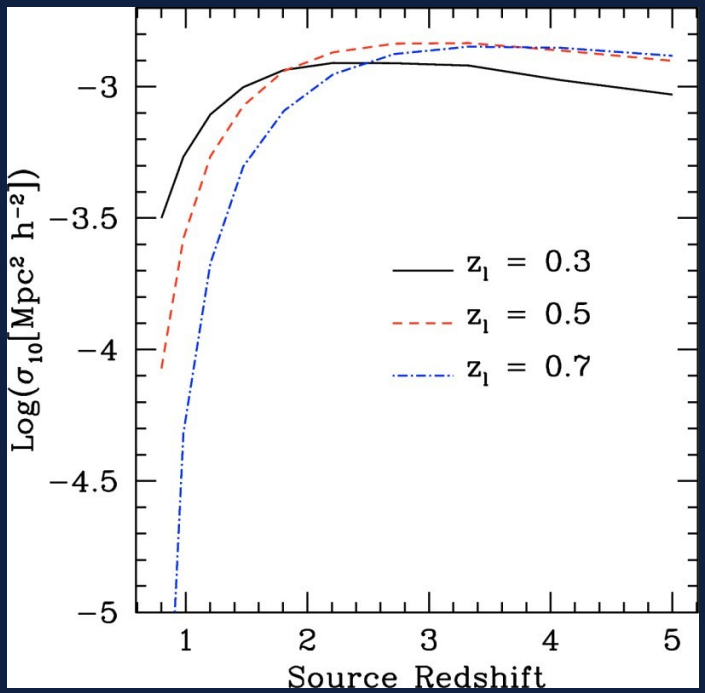




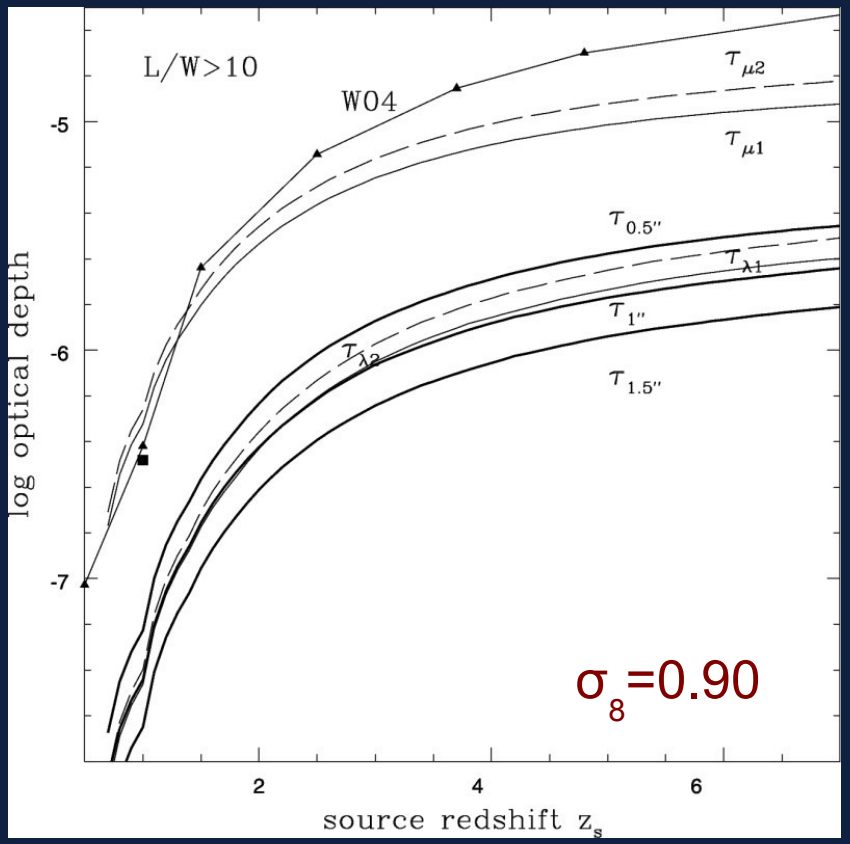
(Li et al. 2005)

Is there a problem?

- *Yes!* Redshift dependence is weaker (Li et al. 2004, Fedeli et al. 2006)
- Overall amplitude is much lower if L/W is measured instead of μ



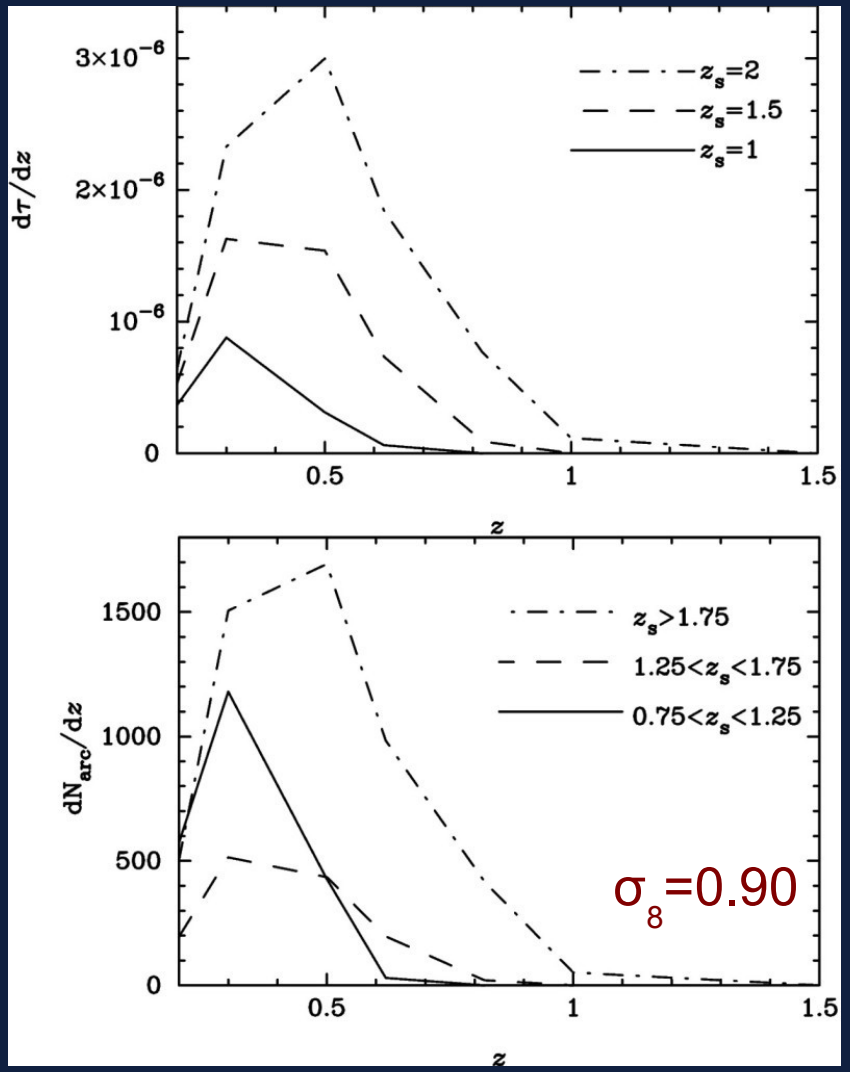
(Fedeli et al. 2006)



(Li et al. 2004)

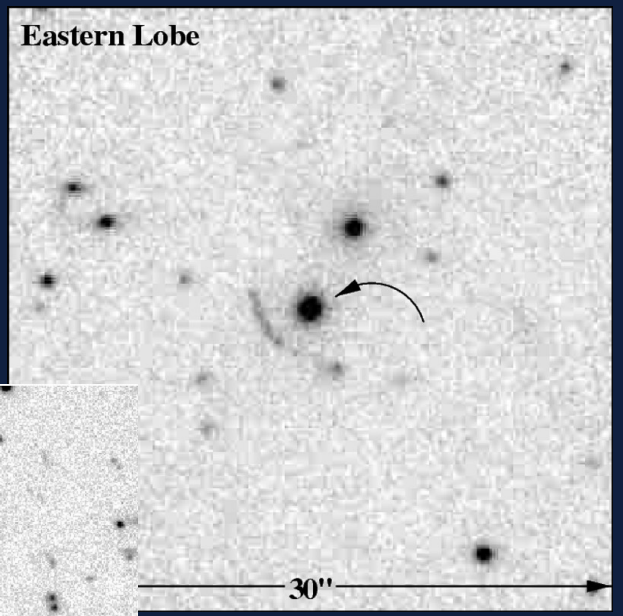
Is there a problem?

- *No!* Dalal et al. (2004) approximately confirm optical depth of B98, but
  - Take redshift dependence into account (shallower than Wambsganß et al. 2004),
  - Estimate lower observed arc abundance,
  - Estimate higher background source density
- Find perfect agreement between simulations and observations

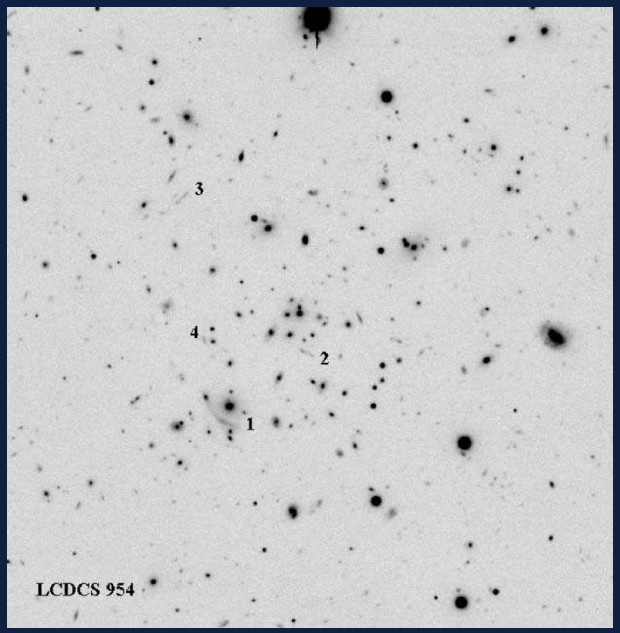


Is there a problem?

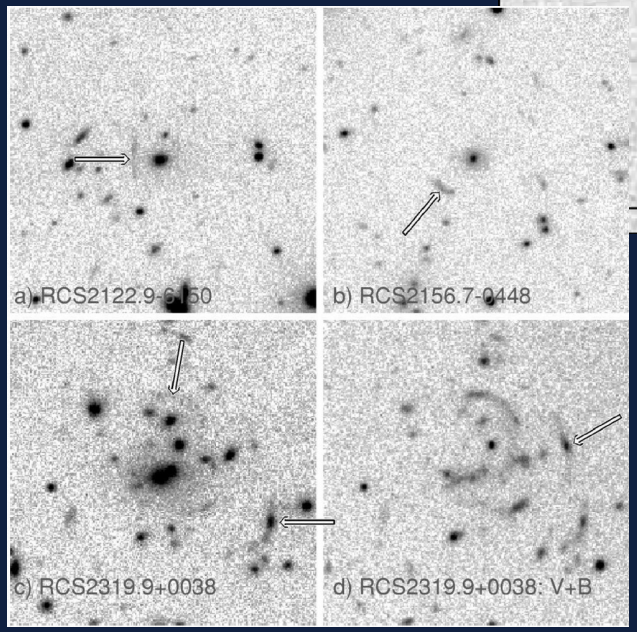
- *Yes!* Number of arcs in distant clusters is unexpectedly large (Gladders et al. 2003, Zaritsky & Gonzalez 2003, Thompson et al. 2001)



(Thompson et al. 2001, z~1.2)



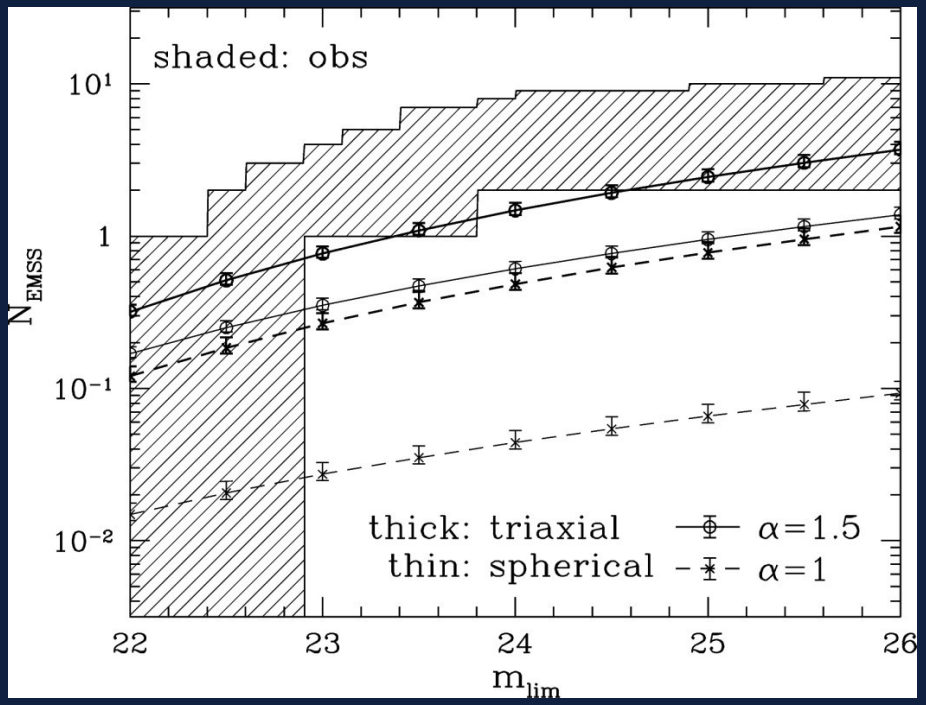
(Zaritsky & Gonzalez 2003 z=0.67)



(Gladders et al. 2003 z_{photo} ~ 1.0-1.2)

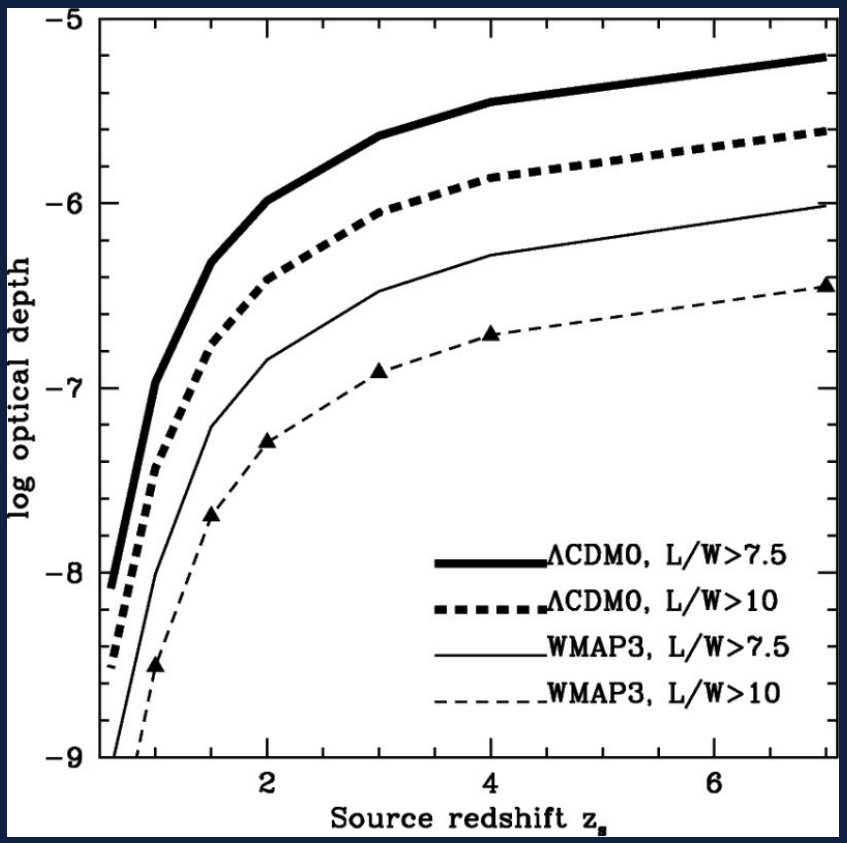
Is there a problem?

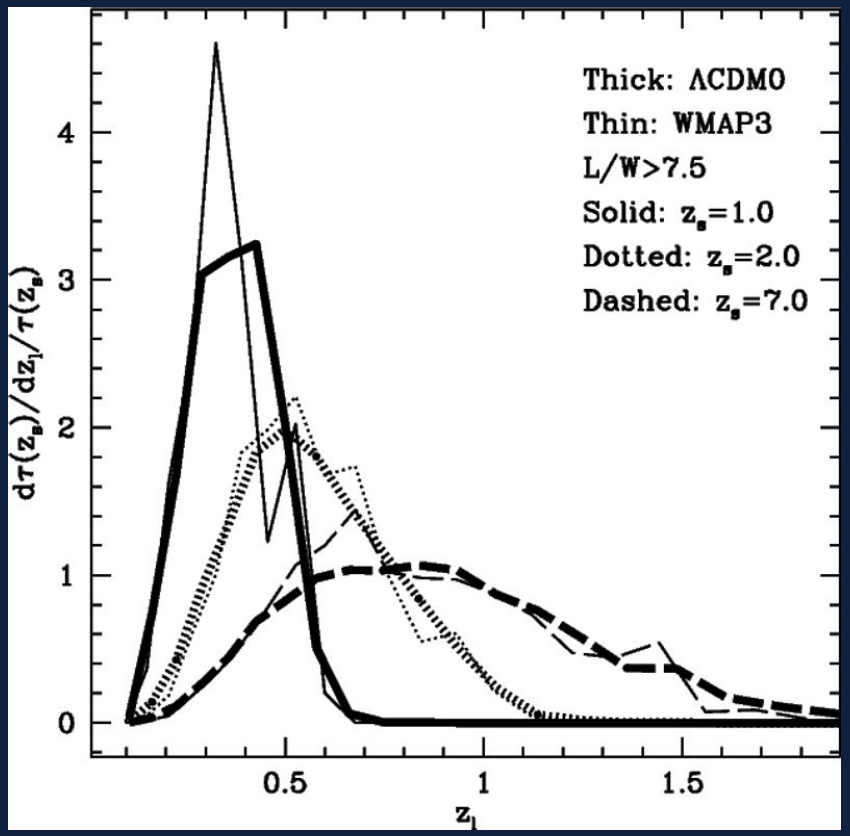
- *No!* Halo triaxiality and steep density profiles help strong lensing reproduce observed arc abundance (Oguri et al. 2003)
- But: numerically simulated clusters are triaxial



Is there a problem?

- *Yes!* WMAP-3 normalisation makes expected arc abundance drop steeply (Li et al. 2006)

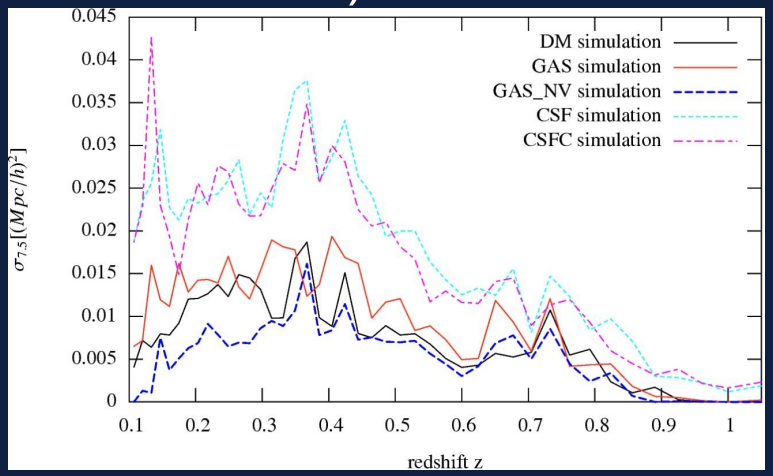


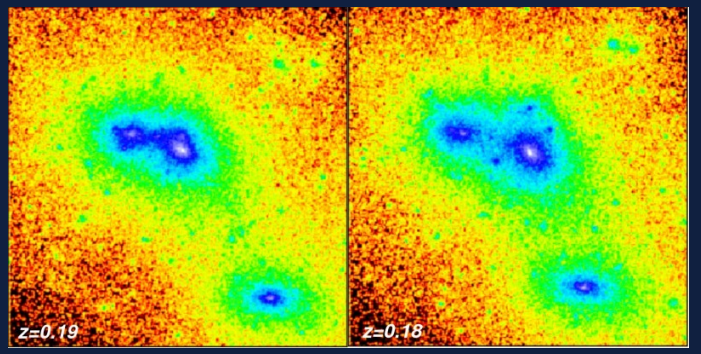


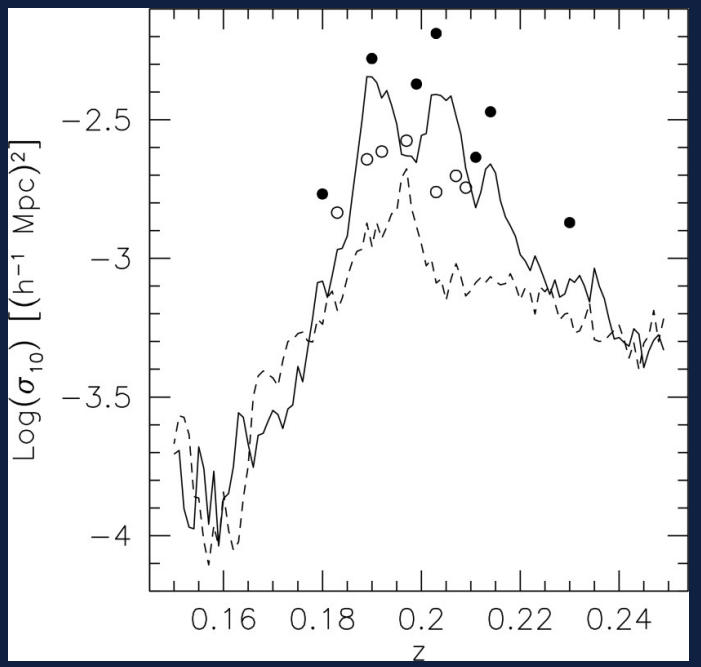
σ_8=0.74 for WMAP-3

Towards better predictions

- What is important for strong cluster lensing?
  - Galaxies, cDs? No! (Flores et al. 2000, Meneghetti et al. 2000, 2003)
  - Mergers? Definitely! (Torri et al. 2004)
  - Gas? Perhaps! (Puchwein et al. 2006)

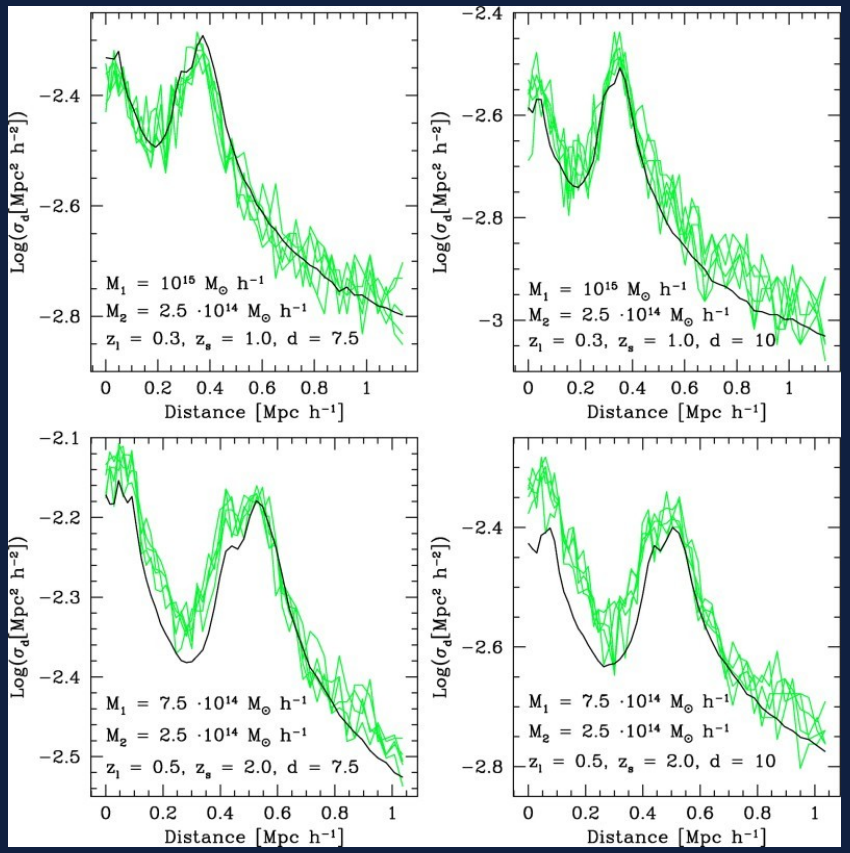




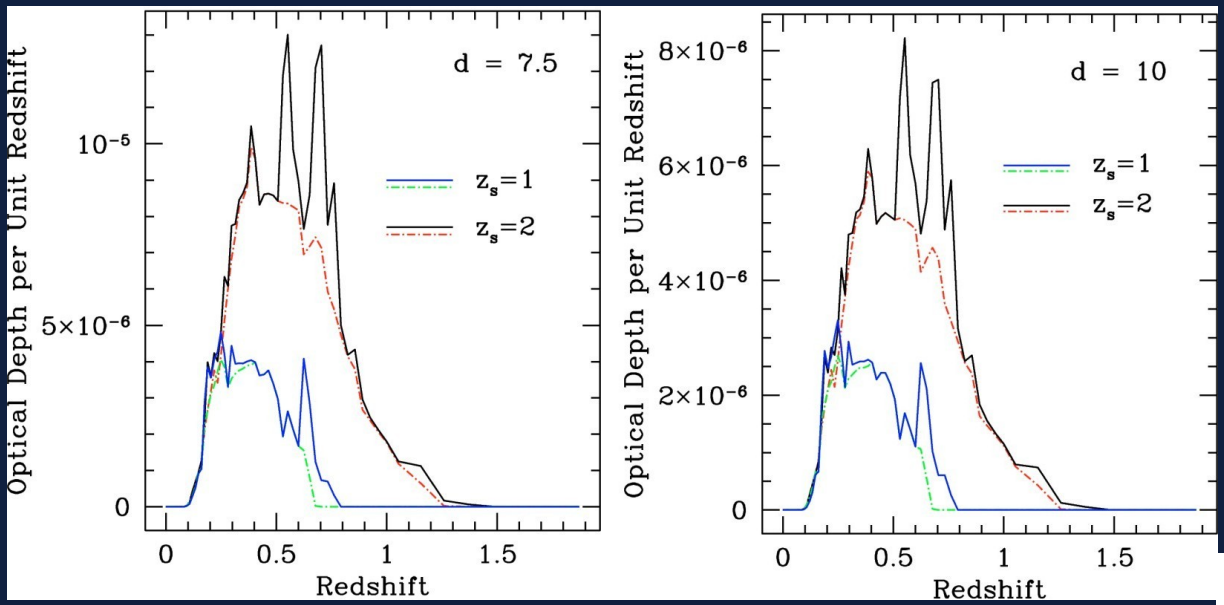


Semi-analytic method for computing arc cross sections

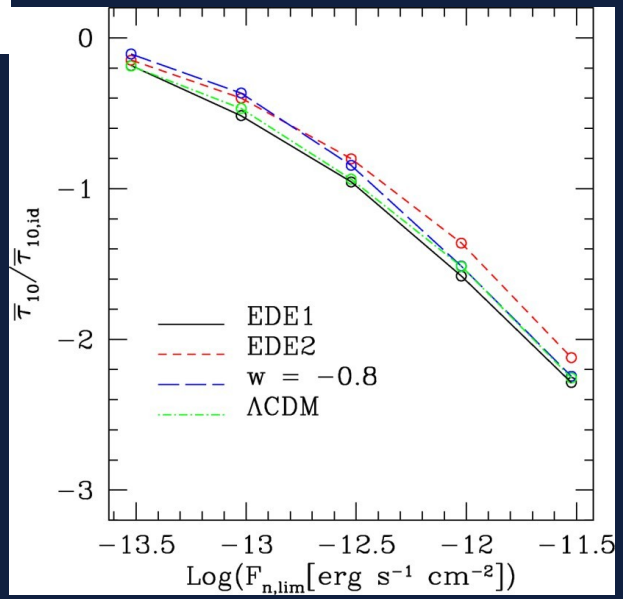
- Based on line integral along caustic curve (Fedeli et al. 2006)
- Takes finite source size and ellipticity into account
- Agrees very well with fully numerical simulations
- Can be combined with extended Press-Schechter theory and elliptical NFW models
- Allows parameter studies and testing cosmologies



Statistical importance of mergers, X-ray selection

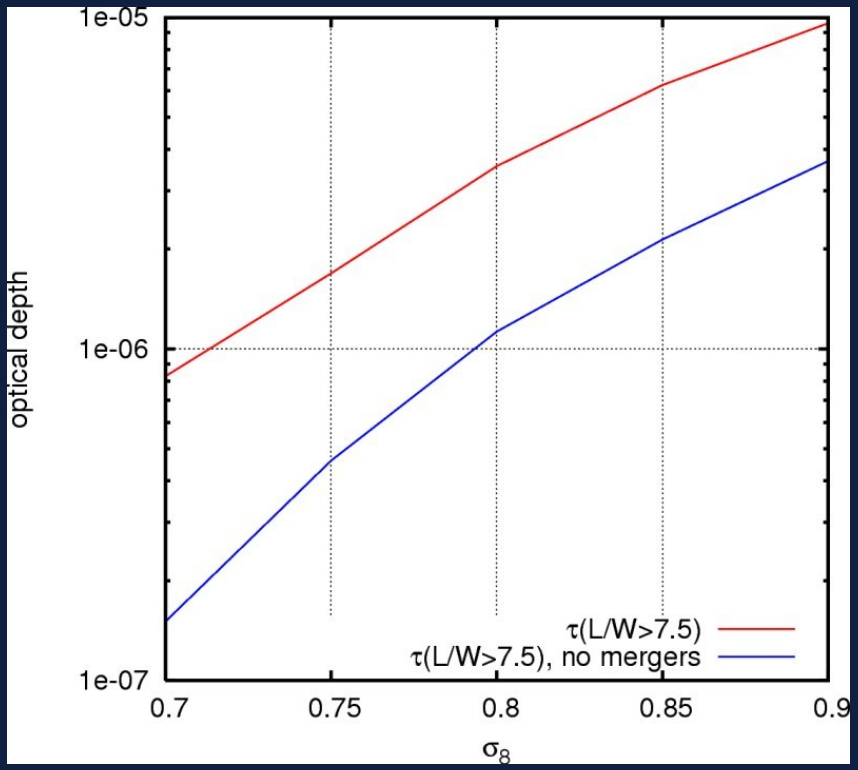


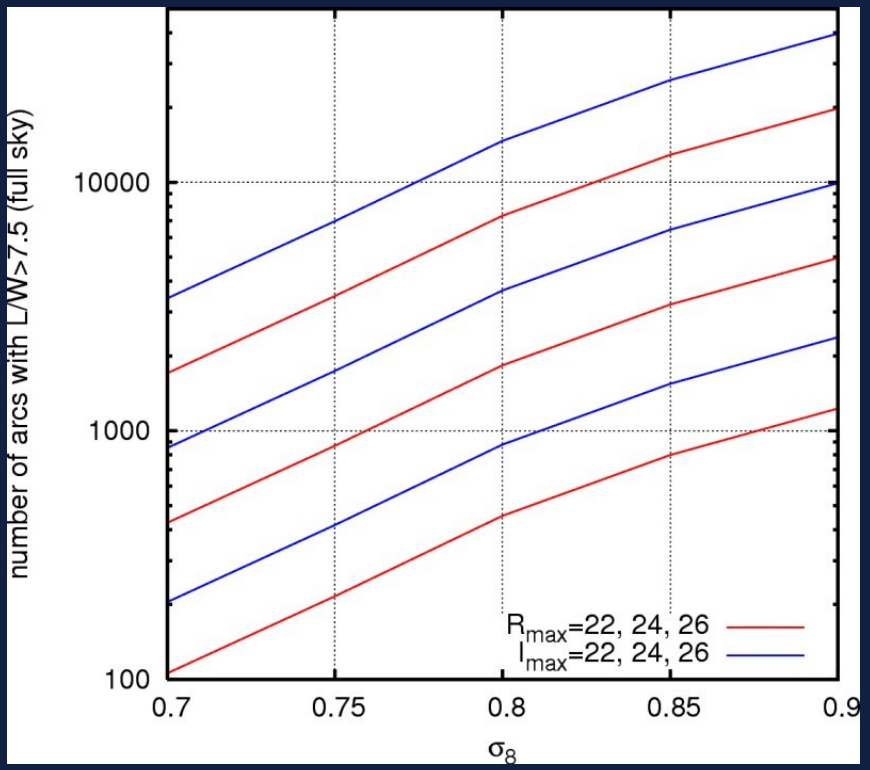
Semi-analytic, differential optical depth (Fedeli et al. 2006)
effects of source redshift and mergers



Fraction of optical depth contributed by X-ray selected clusters (Fedeli et al. 2007)

Optical-depth and arc-number predictions

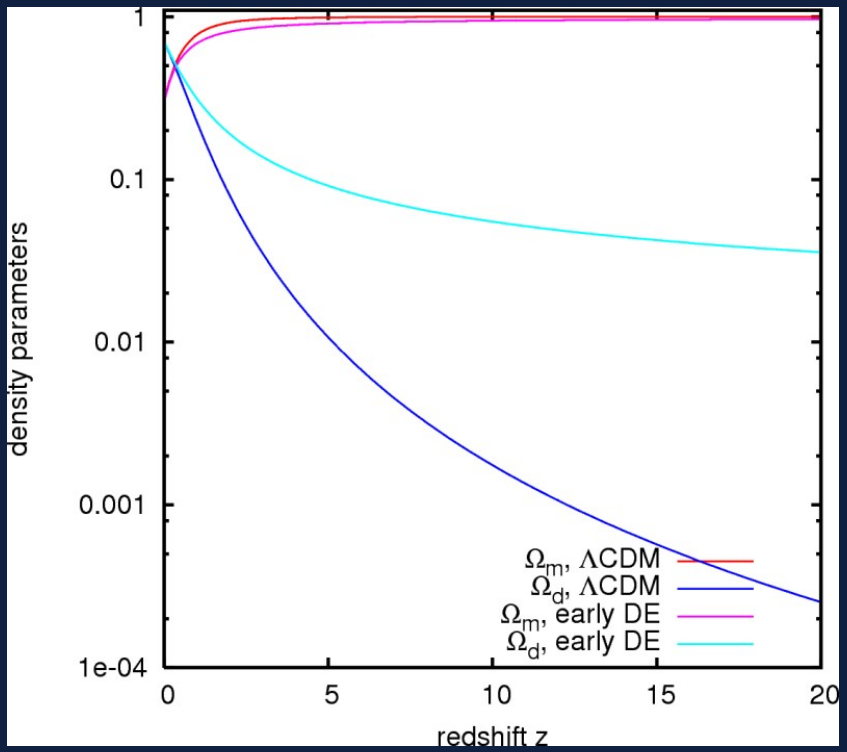


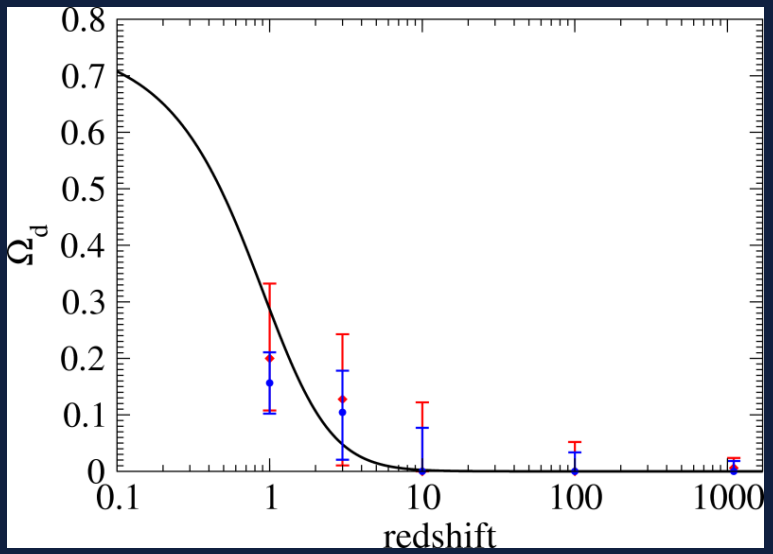


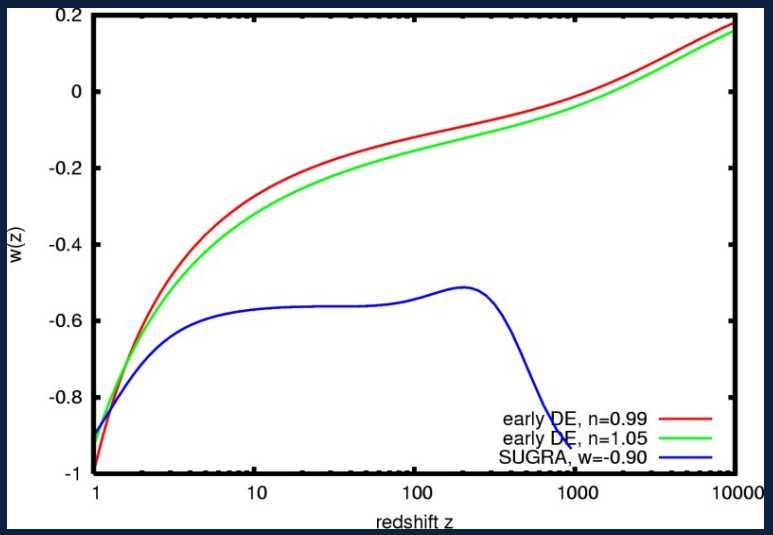
Steep dependence of optical depth on σ_8: mergers are more important for low σ_8 (Fedeli et al. 2007)

Predicted number of arcs on the full sky:
There *is an acute arc statistics problem*, specifically for the σ_8 of WMAP-3

A possible way out

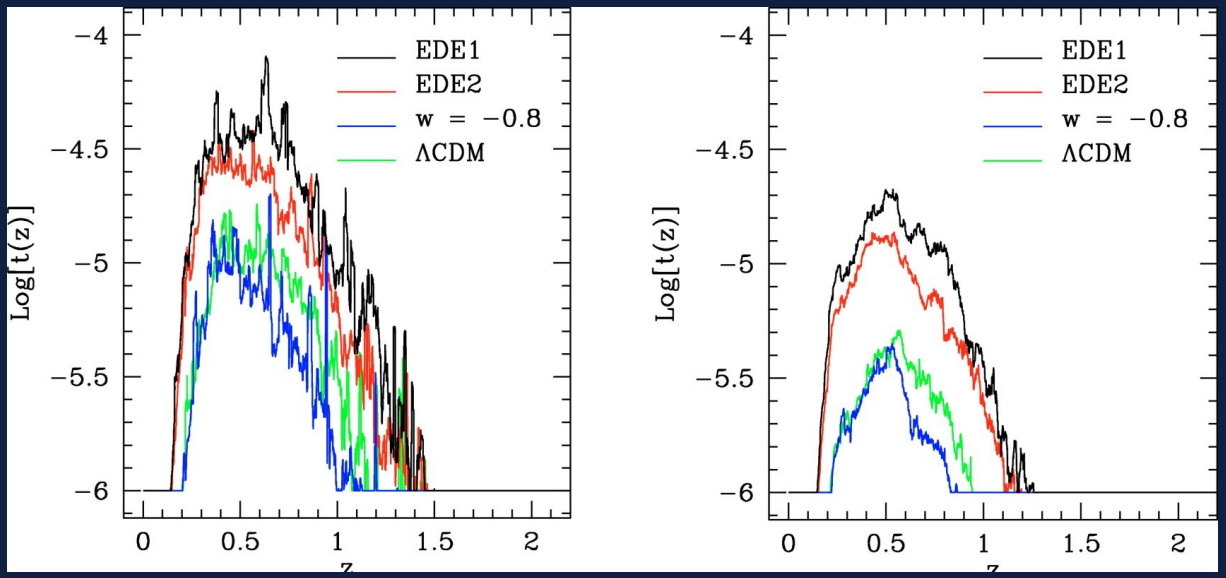


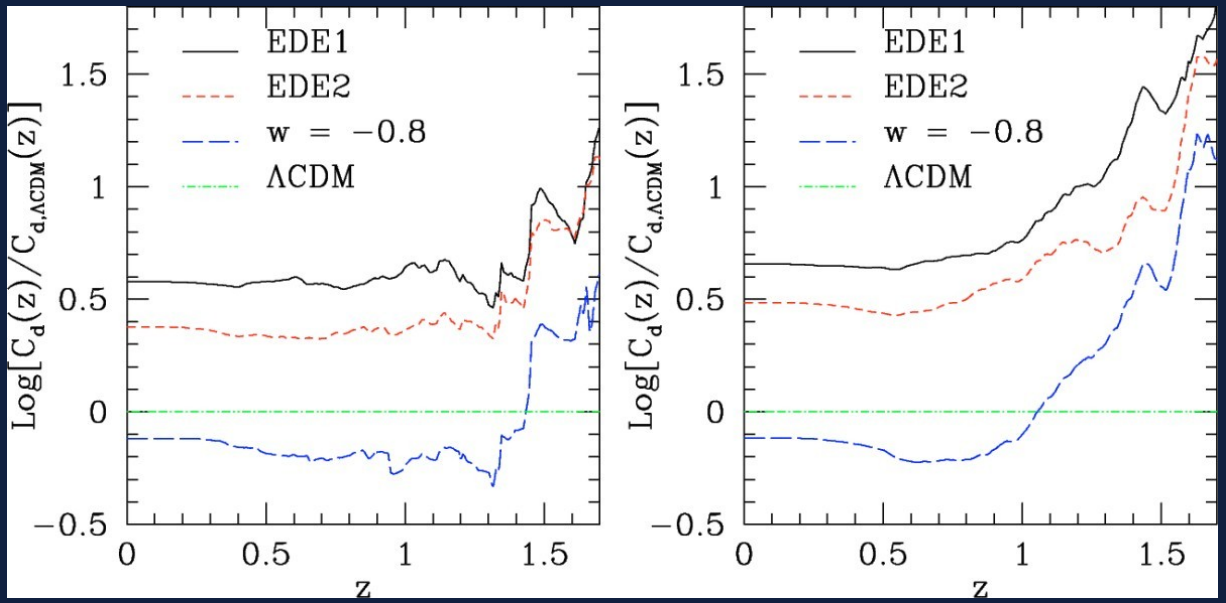




Early dark energy: dynamical dark energy with low density at early times compatible with all relevant data (Wetterich et al.)

A possible way out

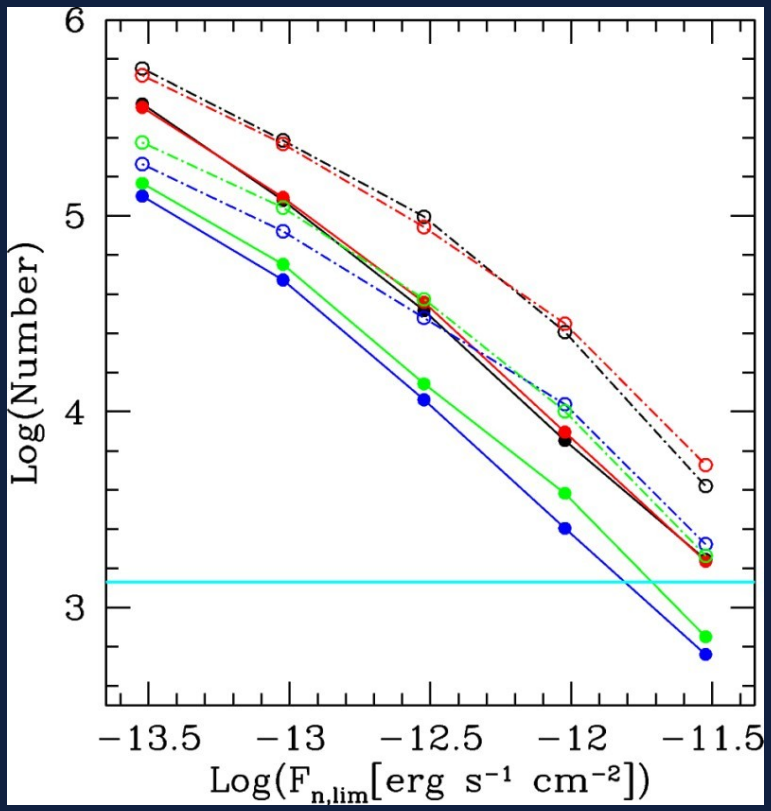




Early dark energy lowers threshold for nonlinear structure formation (Bartelmann et al. 2006)

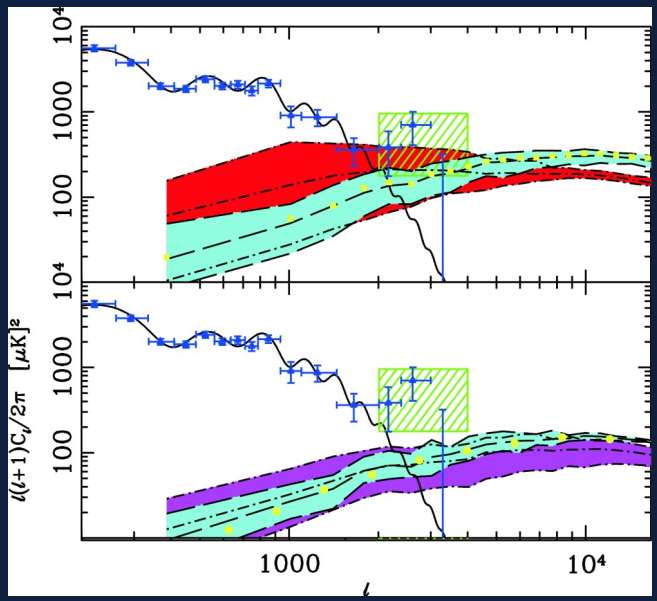
Increases optical depth for strong lensing, in particular at high redshift (Fedeli & Bartelmann 2007)

A possible way out

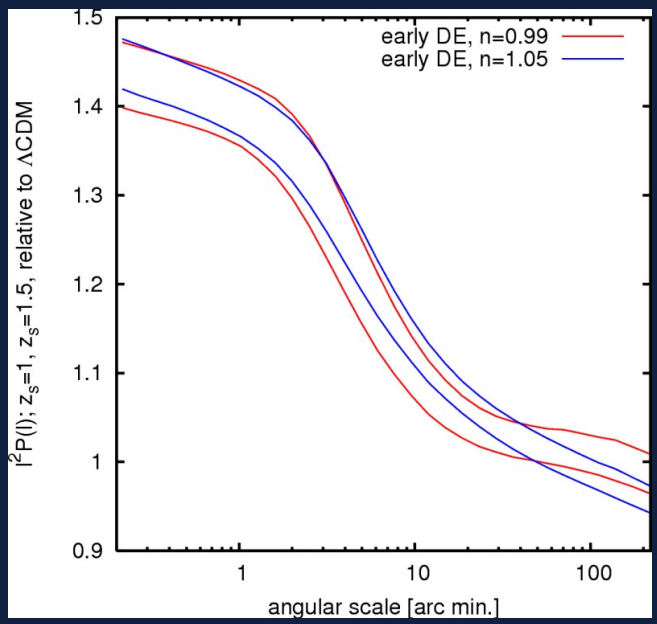


Can reconcile X-ray cluster counts with low σ8 (Fedeli et al. 2007)

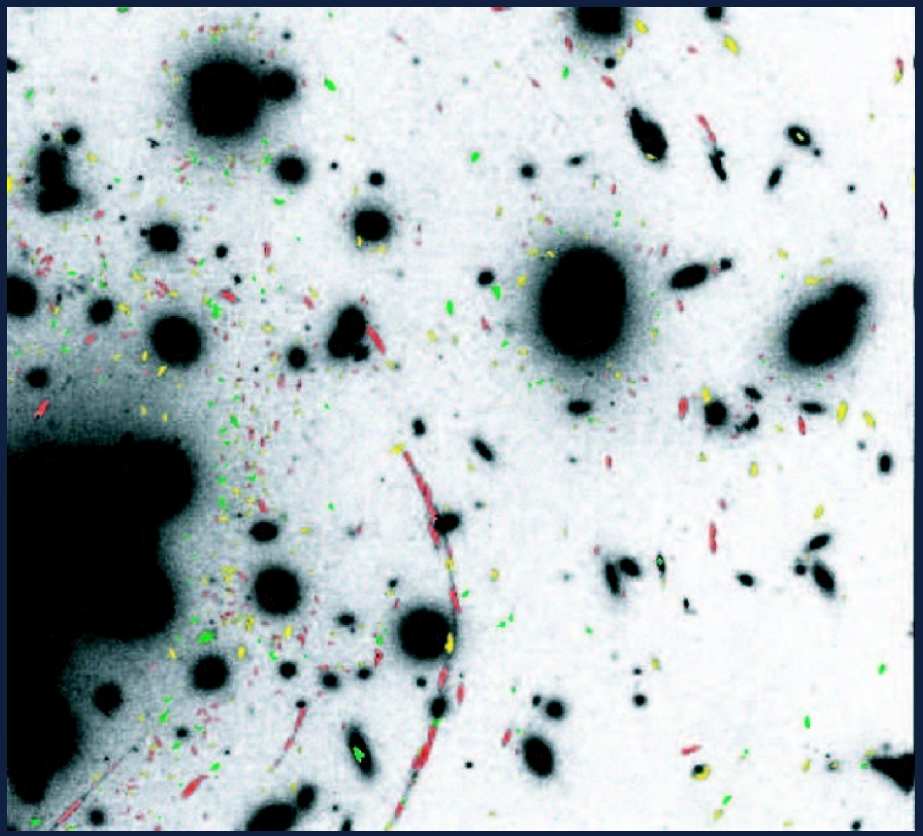
Solves the CBI anomaly at no extra cost

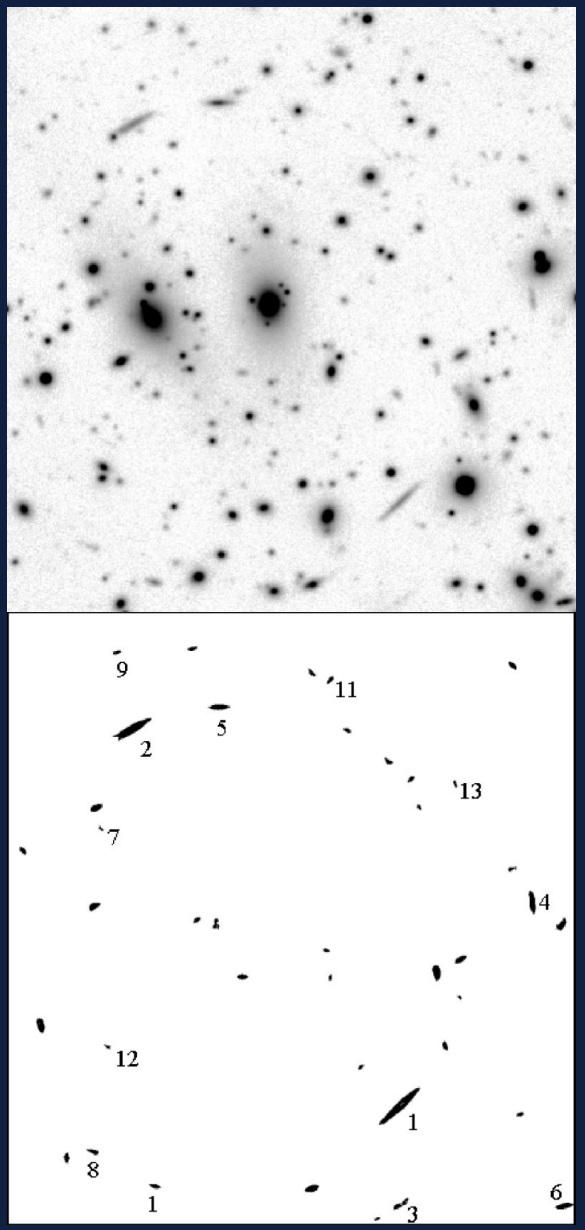


Modifies the weak-lensing power spectrum



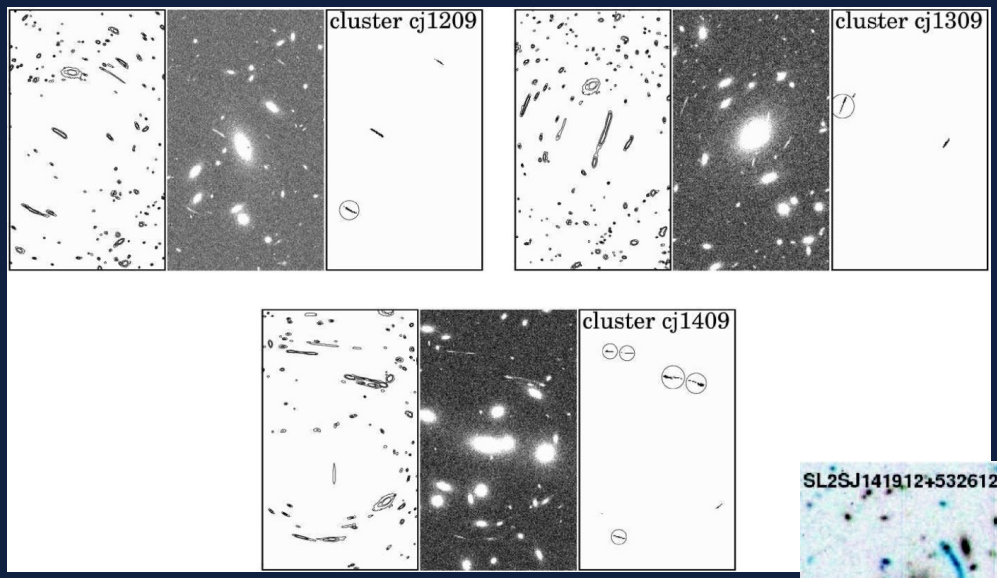
Finding arcs?



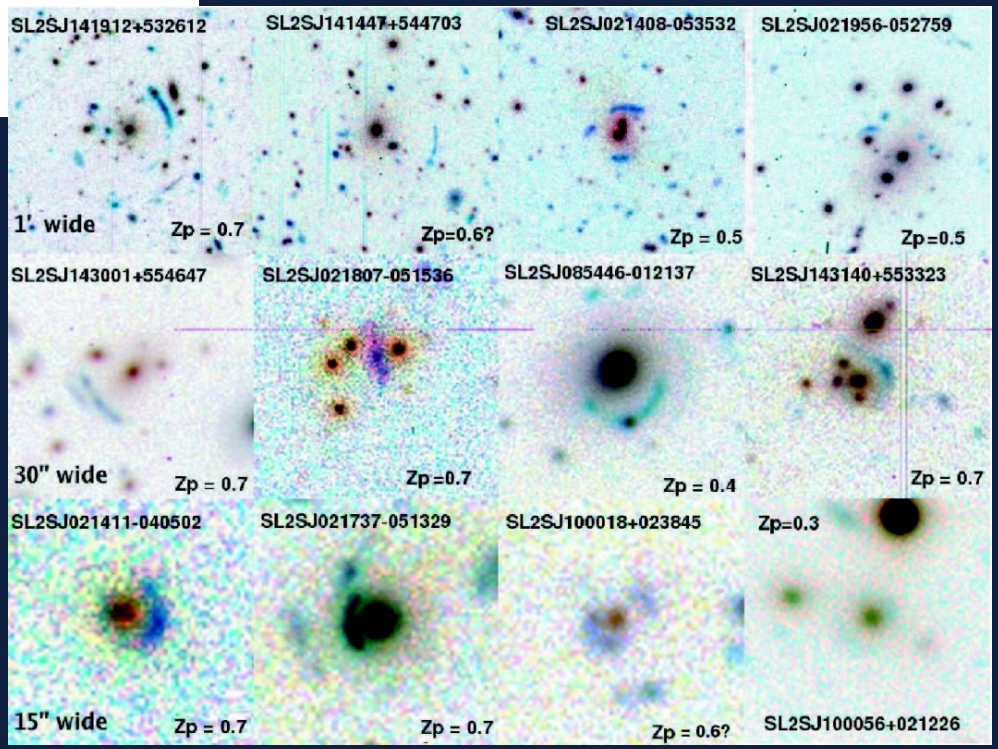


Lenzen et al. 2004
apply anisotropic diffusion on segmented image

Finding arcs?

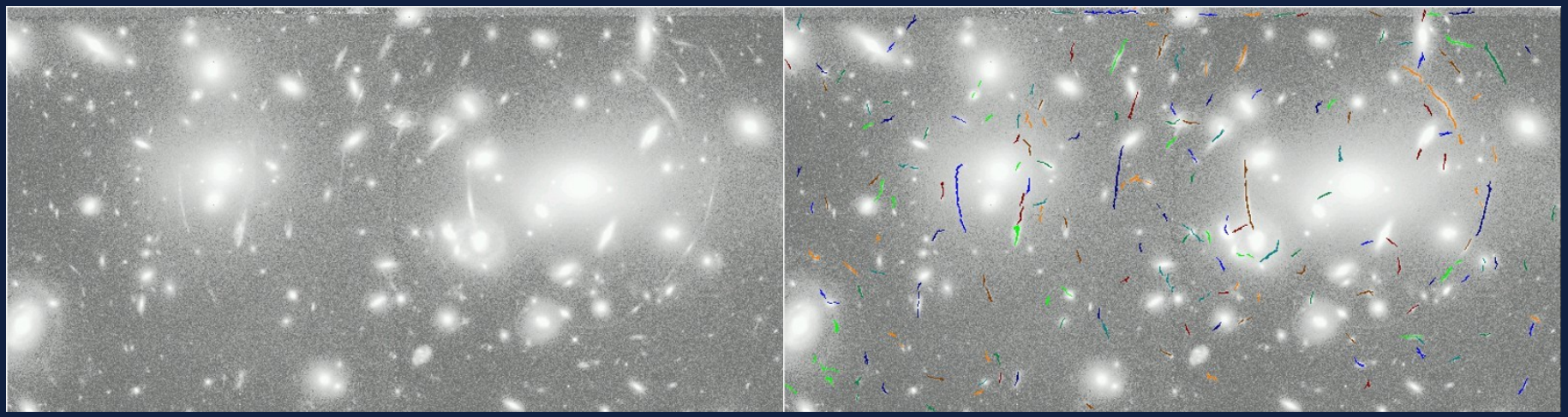


Horesh et al. 2005:
Combination of SExtractor with IRAF

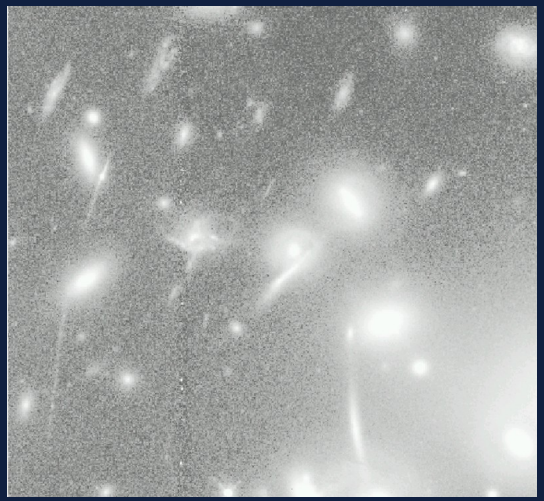


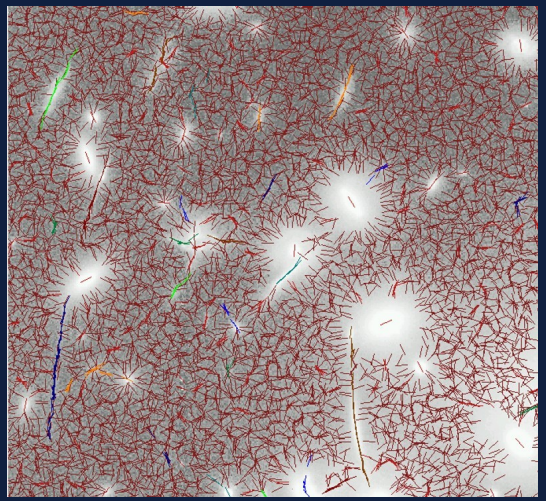
Cabanac et al. 2007:
Identification of strongly lensed images by multiples, colour and other criteria

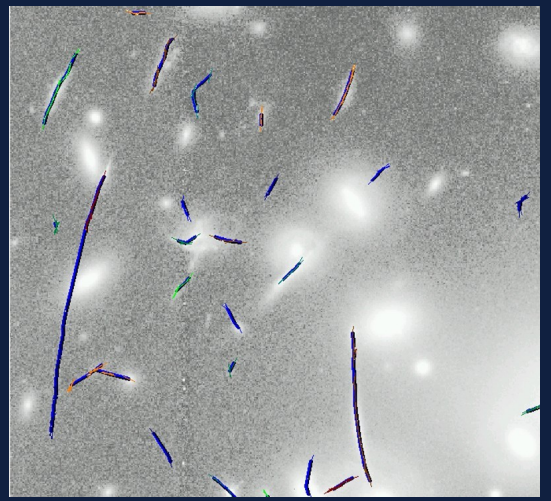
Finding arcs?



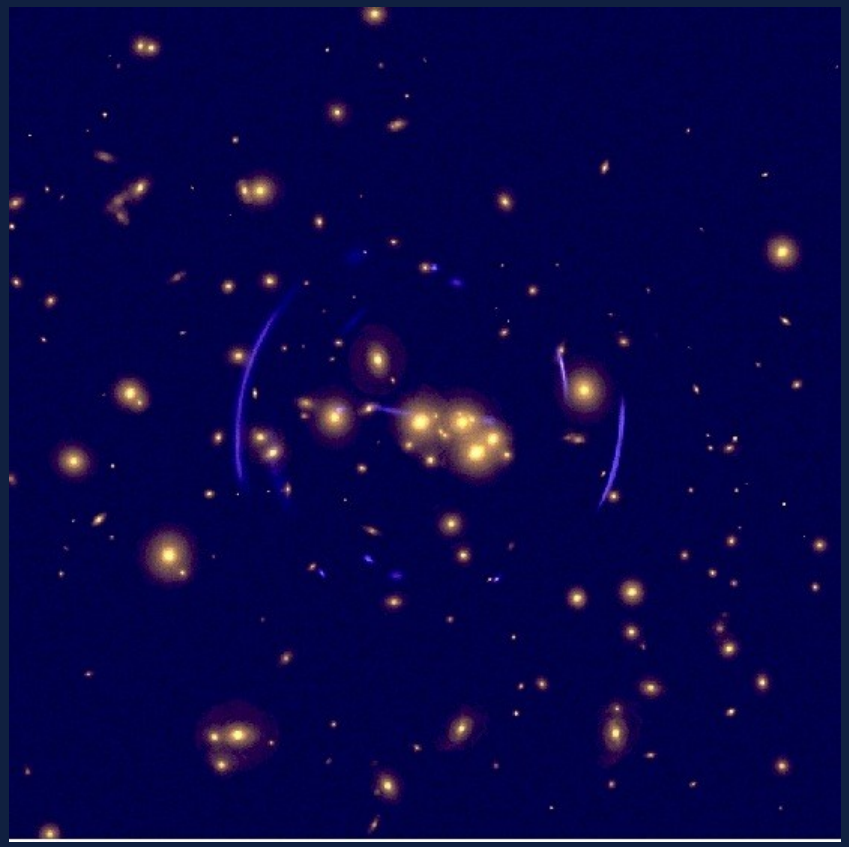
Arcfinder (Seidel & Bartelmann 2007): avoids filtering and smoothing



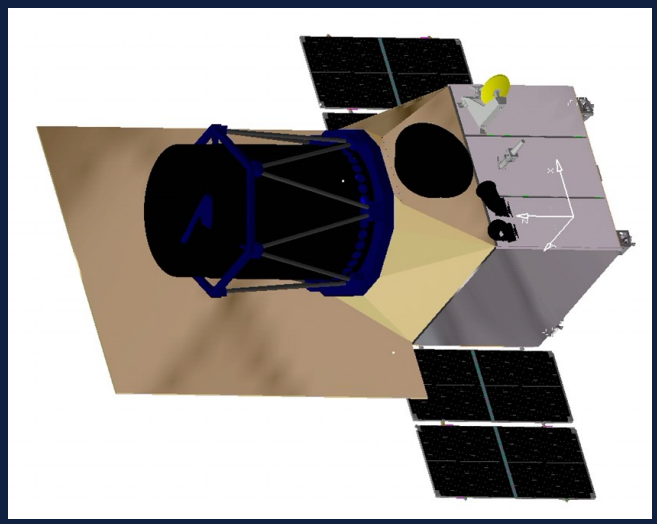




Dune forecast



- With proposed specification (I_{AB}≤25 on 20000 sq. deg.), expect to find
  - ≈ 3000 large arcs (if σ_8≈0.8)
  - ≈ 10^5 galaxies lensed by galaxies
  - ≤ 1000 multiply-imaged QSOs



Summary

- There is still a substantial problem in understanding the observed arc abundance.
- Many effects need to be included for precise predictions of optical depths:
  - Cluster mergers
  - Cluster asymmetries
  - Scatter in concentrations, ellipticities, and so on
- Early dark energy may help reconciling arc statistics with low σ_8 and explaining arcs in distant clusters.
- Reliable, fast, automatic search algorithms for arcs exist.