Statistics of Giant Arcs

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Paris, July 3, 2007

XXIIIrd IAP Colloquium in Honour of Bernarc Fort

"From giant arcs to CMB lensing: 20 years of gravitational distortion"

Statistics of Giant Arcs

Why?

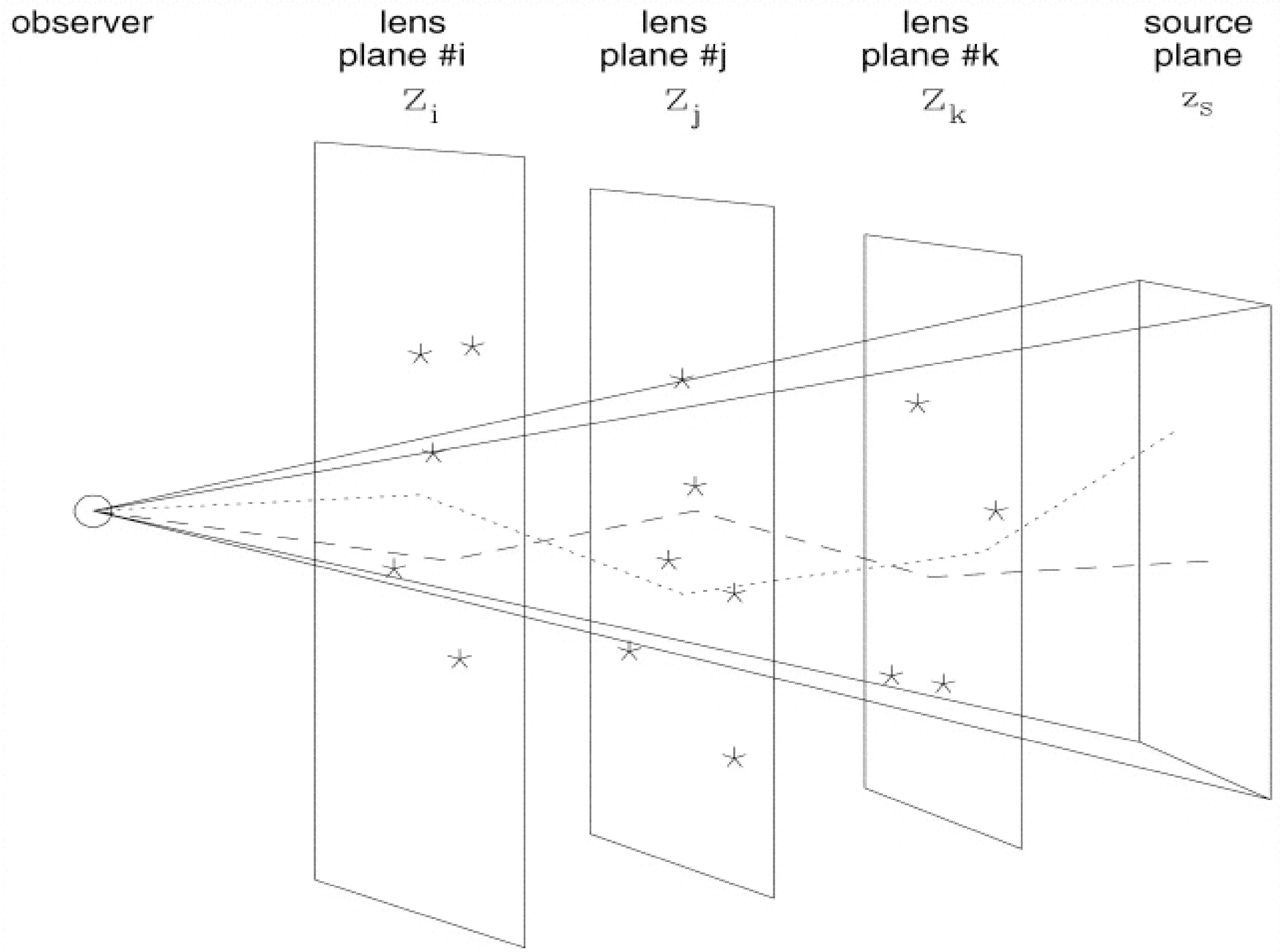
- Produced by most massive galaxy clusters in the universe
- Sensitive measure of cosmological model

What?

- Count highly magnified, strongly tangentially distorted, curved images of galaxies that are located “behind” a massive galaxy cluster

How?

- Ray tracing through realistic matter distribution from N-body simulations : multi-plane lensing (cf. Bartelmann et al. 1998, Jain et al. 2000, Hilbert et al. 2007 ...)


observer
lens
plane #i
z_i
lens
plane #j
z_j
lens
plane #k
z_k
source
plane
z_S

Ingredients for multi-lens plane approach:

n-body simulations with:
TPM (Tree-Particle-Mesh) code (w/Ostriker, Bode)

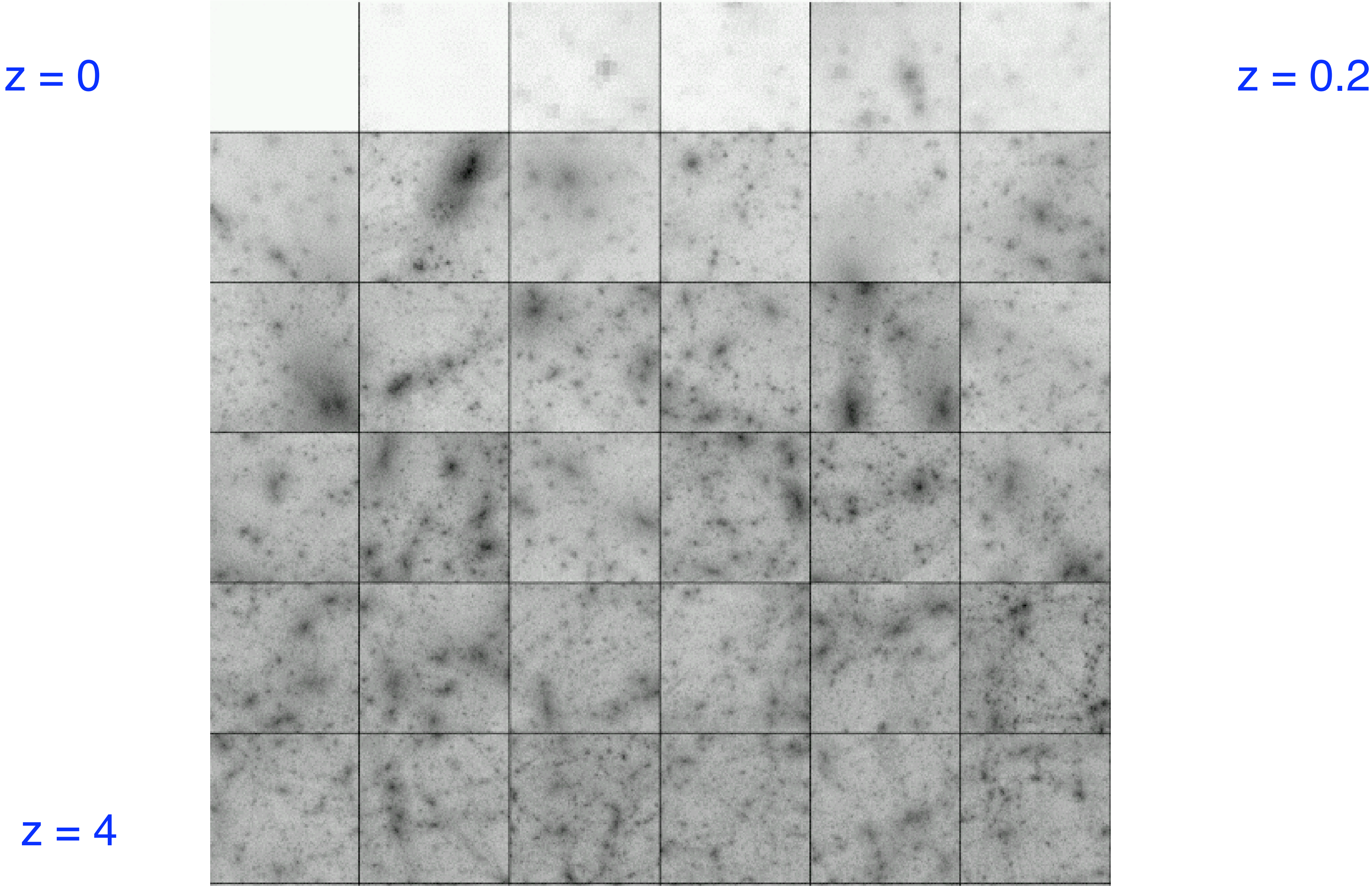
- large box size L (in order to cover primordial fluctuations with large wavelength) L = 320 Mpc/h
- small "smoothing length" l (in order not to smooth small fluctuations) l = 3.2 kpc/h
- large number of particles N (in order to resolve cores of individual galaxy mass halos)

$$N = 1024^3 = 1,073,741,824$$

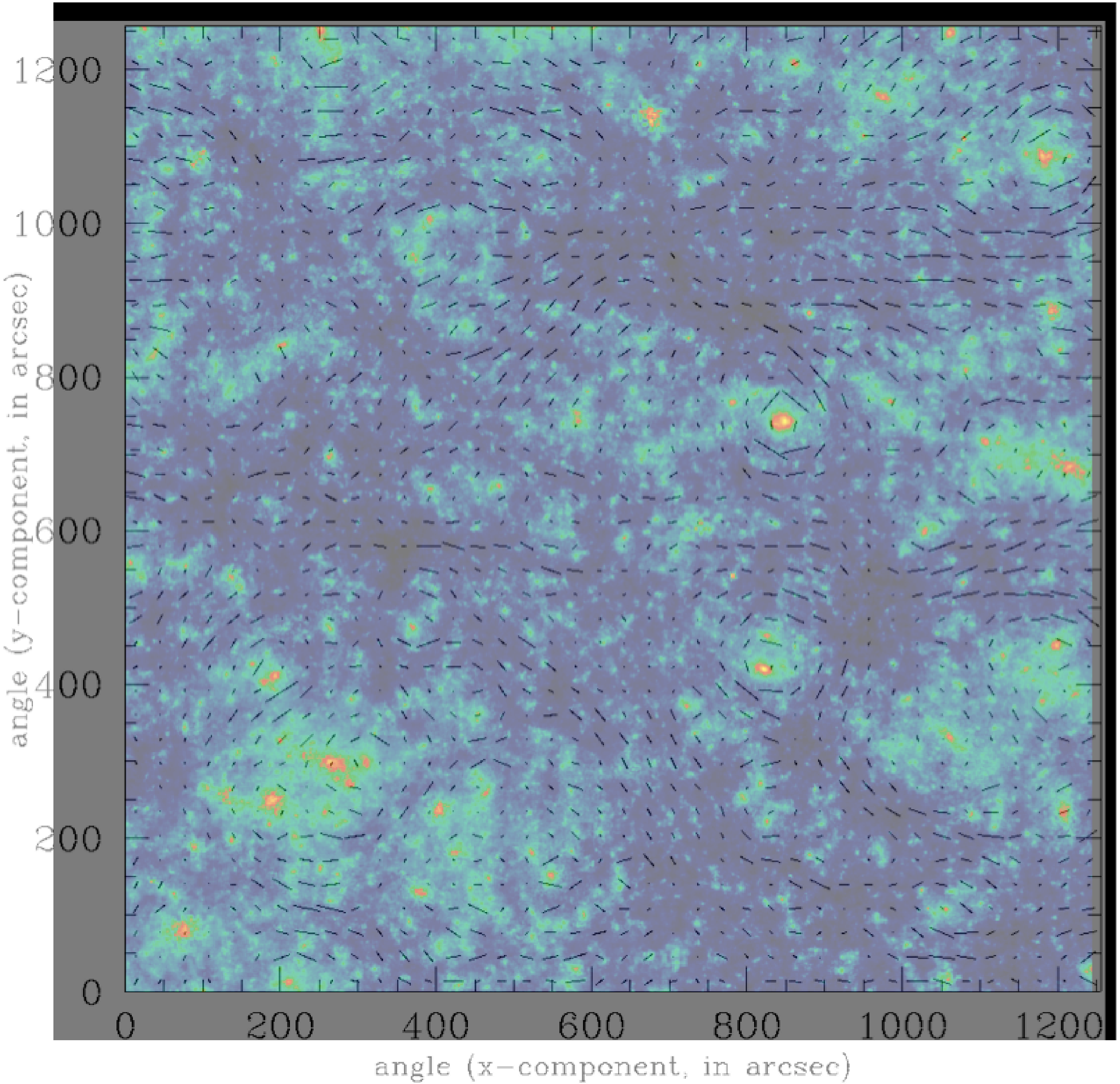
Parameters of cosmological model:

- TPM-code: Bode & Ostriker (2003)
- matter content: $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$
- Hubble constant: $H_0 = 70$ km/sec/Mpc
- amplitude of mass fluctuations: $\sigma_8 = 0.95$
- particle mass: $m_p = 2.54 * 10^9 \, M_\odot$
- mass output at 19 redshifts, matching comoving distances of $D = (160 + n * 320)$ Mpc/h
- actual lens planes: fixed ANGULAR size, varying physical sidelength ($x = 35.6$ Mpc/h at highest $z_L = 6.4$)

Example for lens planes as a function of redshift:



Ray tracing simulations: matter & shear

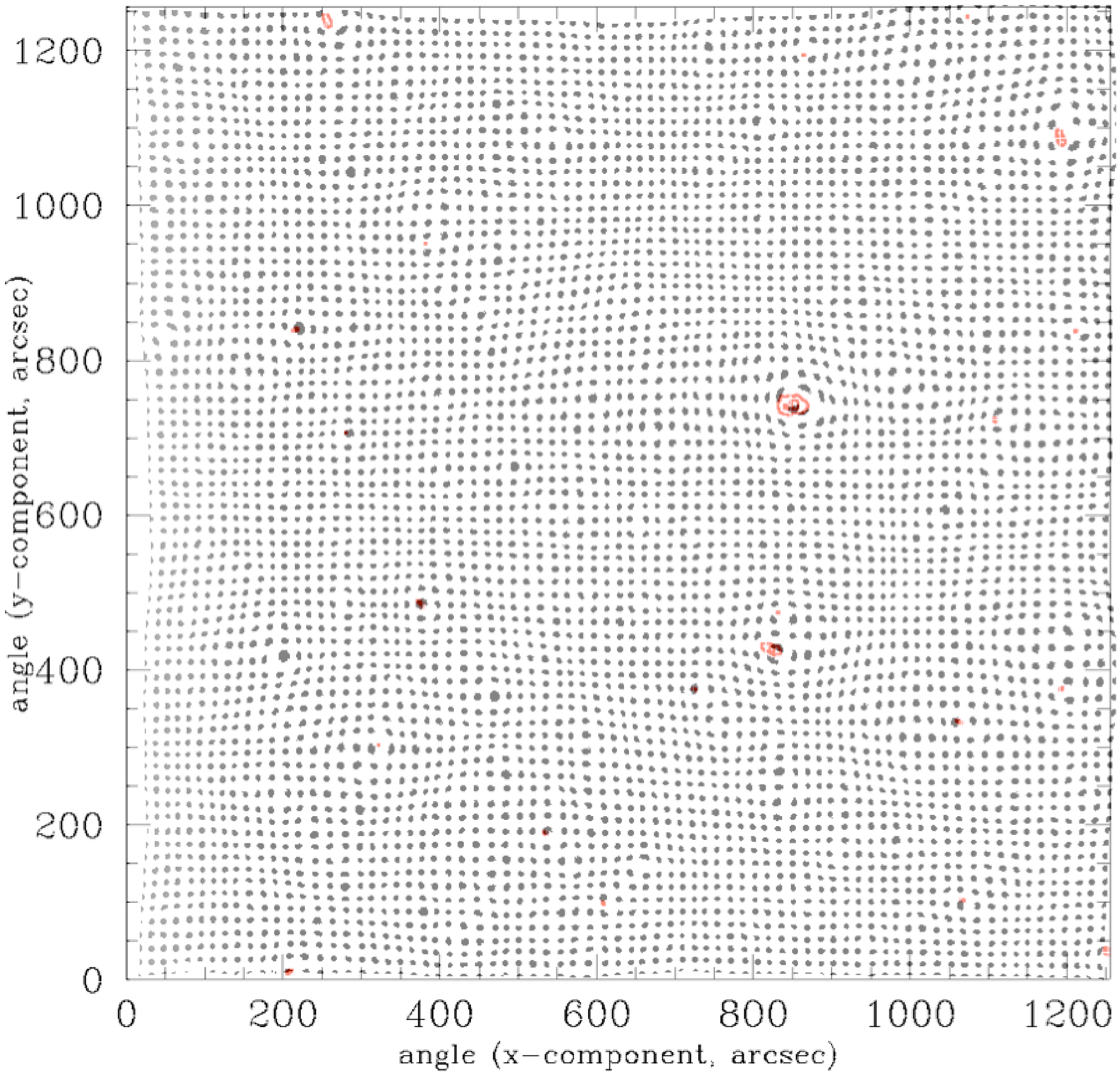


integrated matter distribution

plus

shear

Ray tracing simulations: critical lines & images



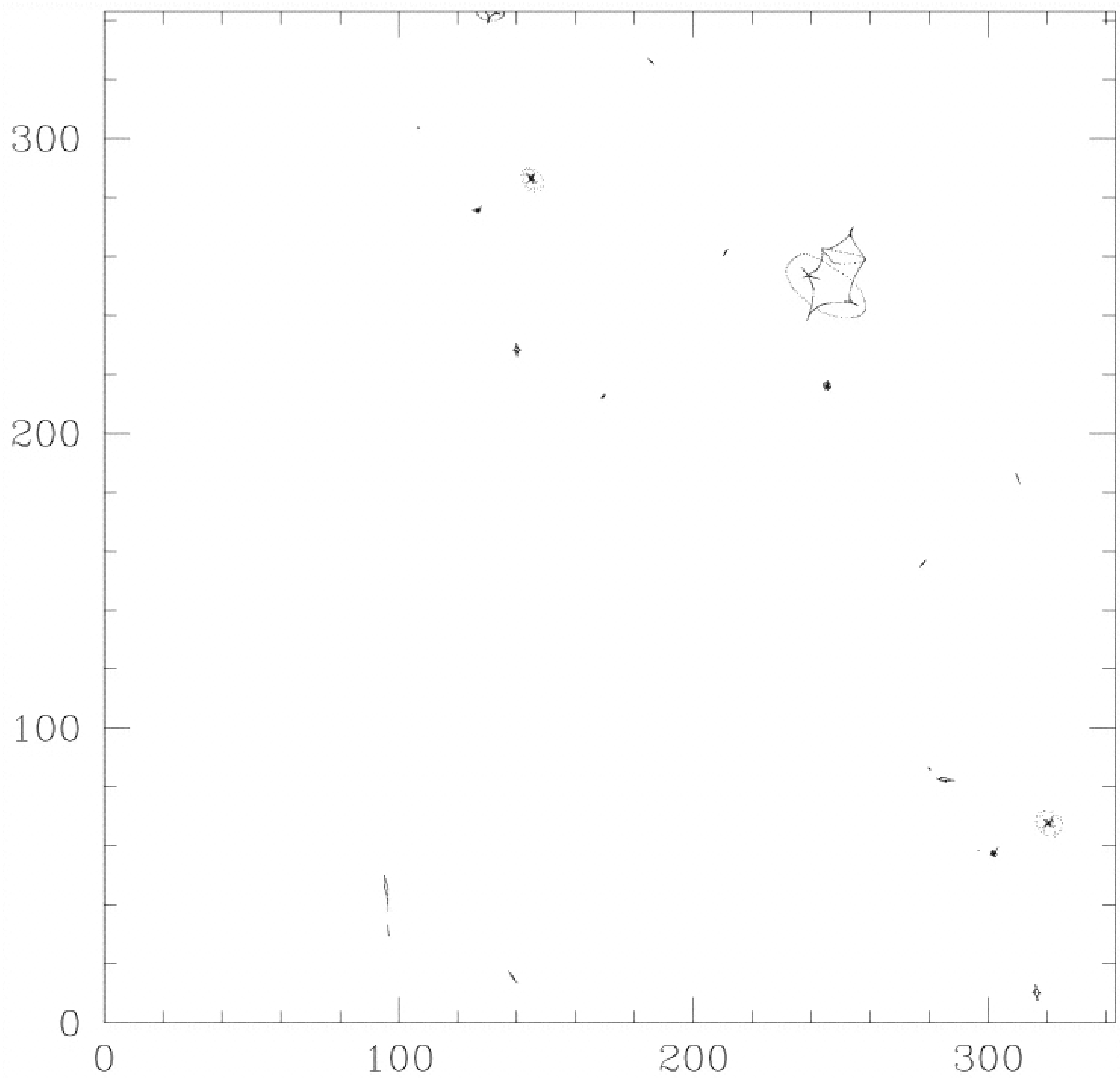
critical lines
in image plane

plus

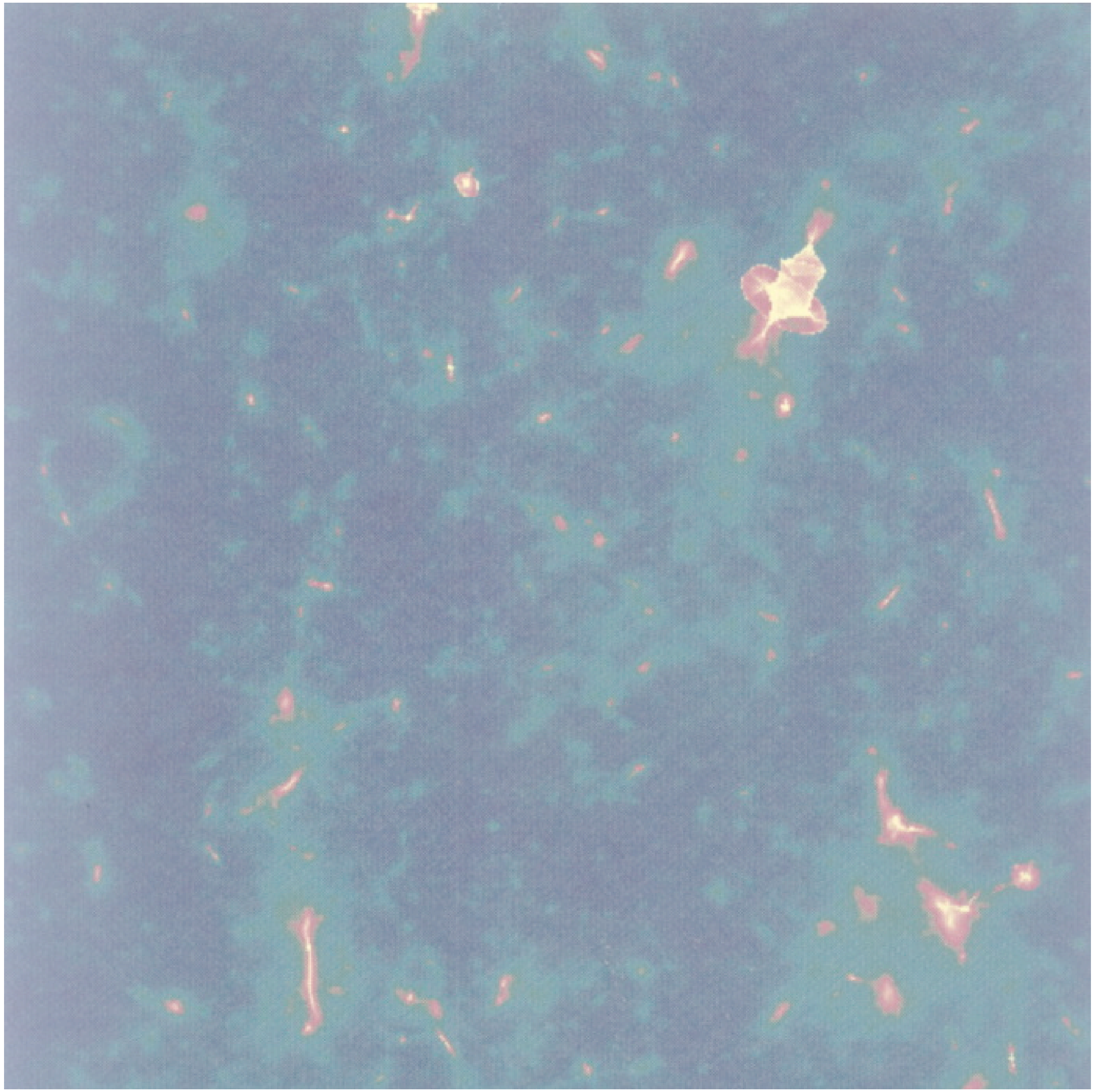
images

(for regular grid of circular sources at $z_s = 4.8$)

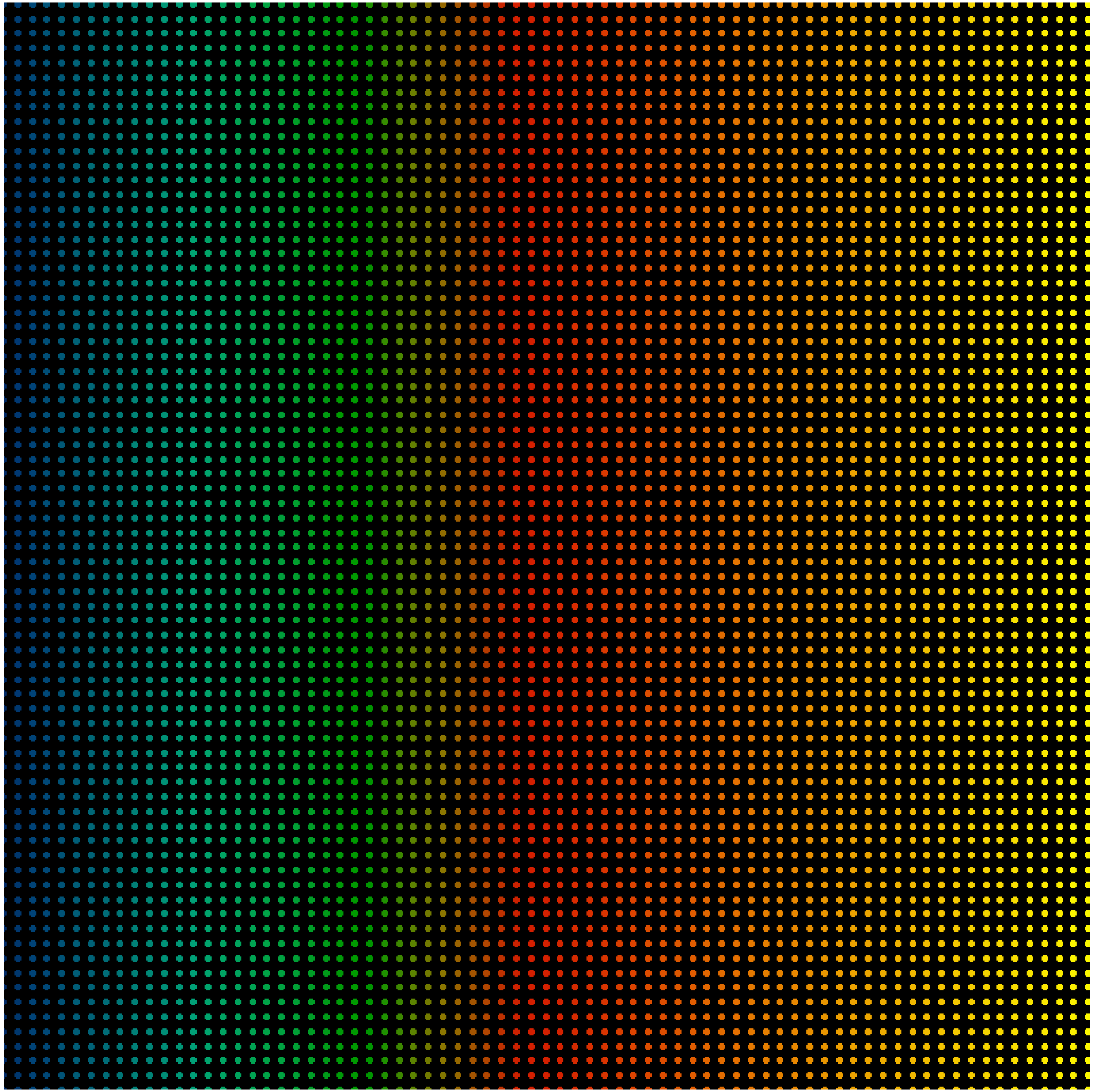
Magnification distribution in source plane:



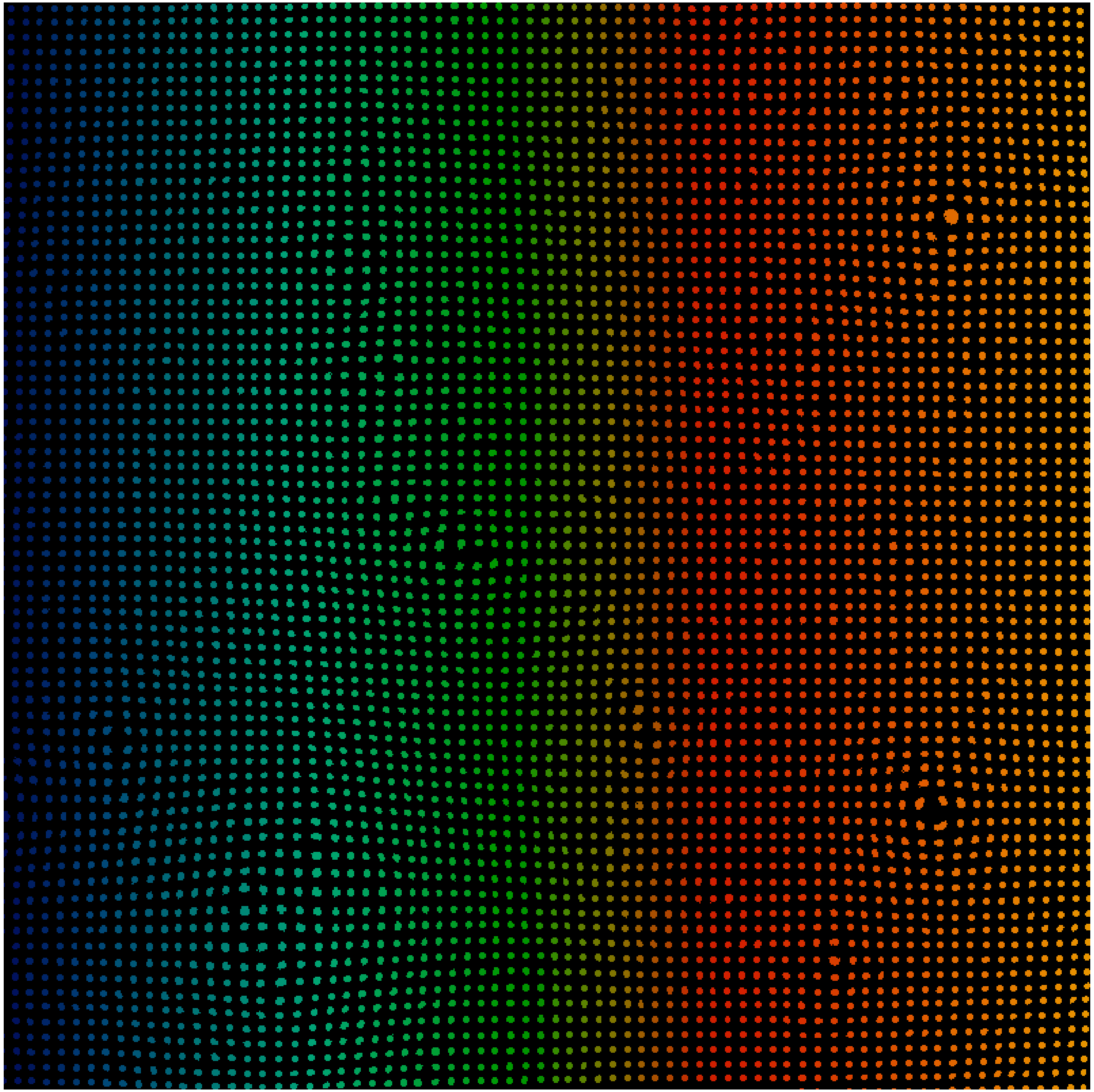
Magnification distribution in source plane:



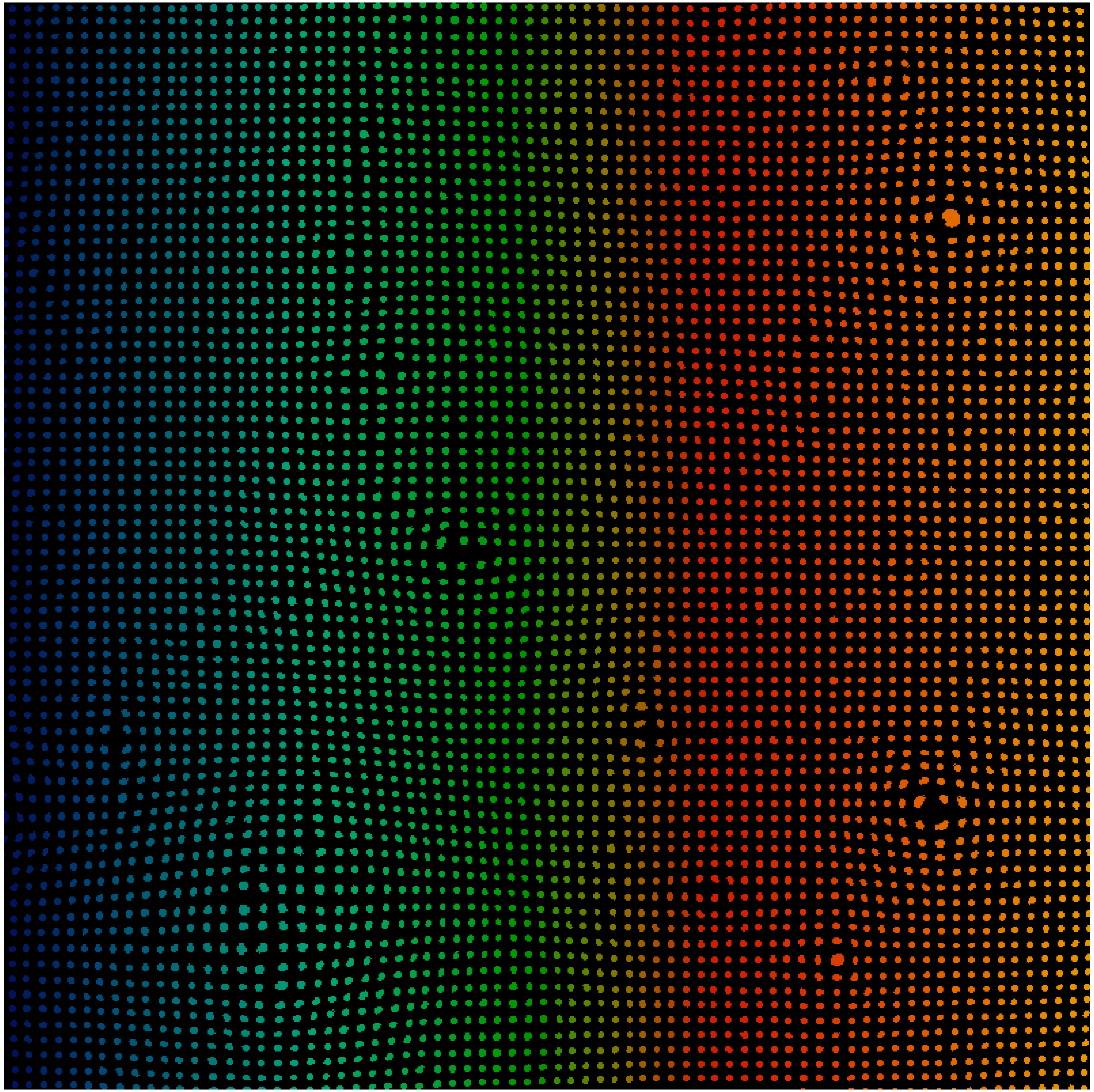
Examples for lensed structures with increasing z:



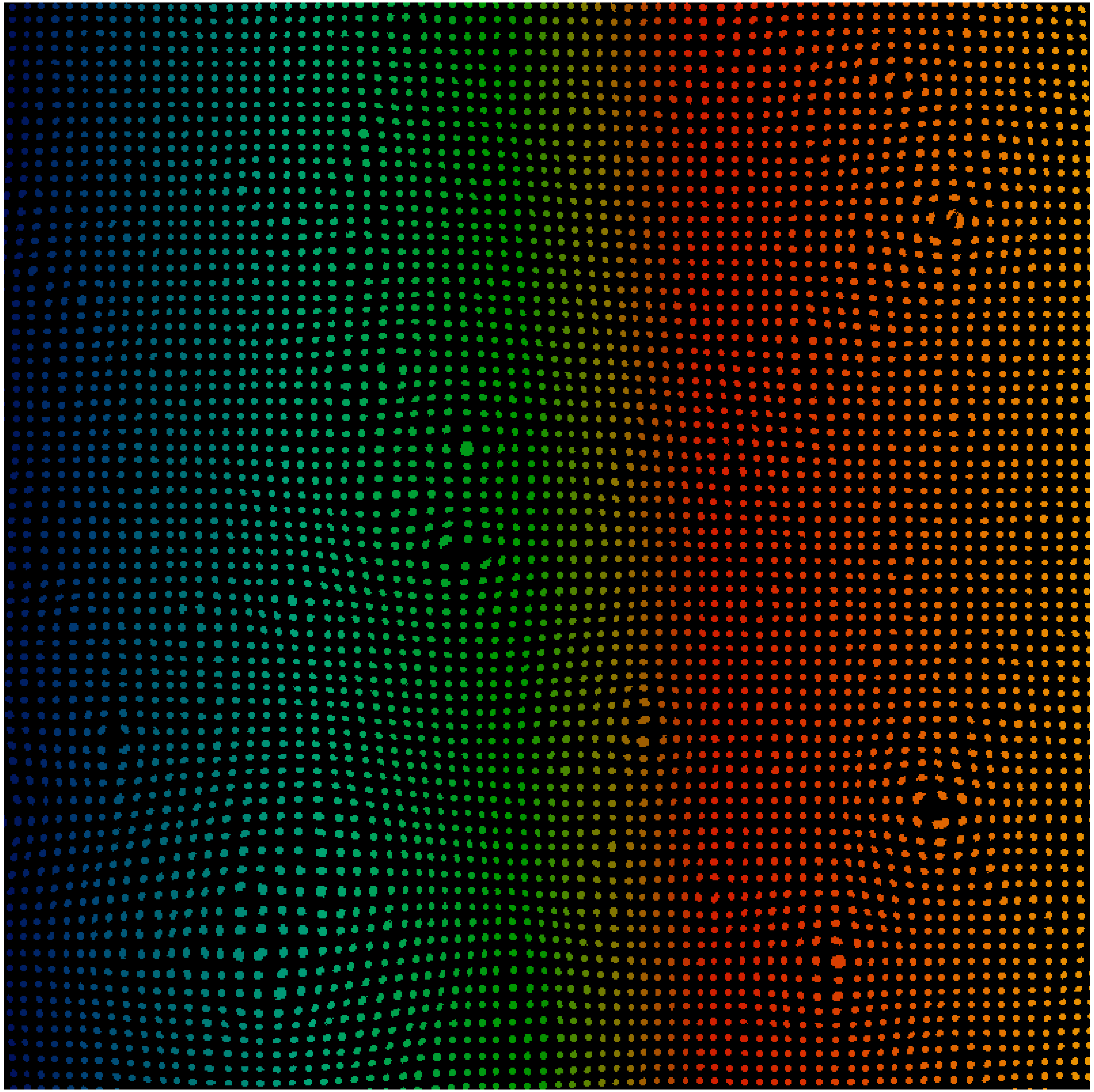
Examples for lensed structures with: $z_s = 1.1$



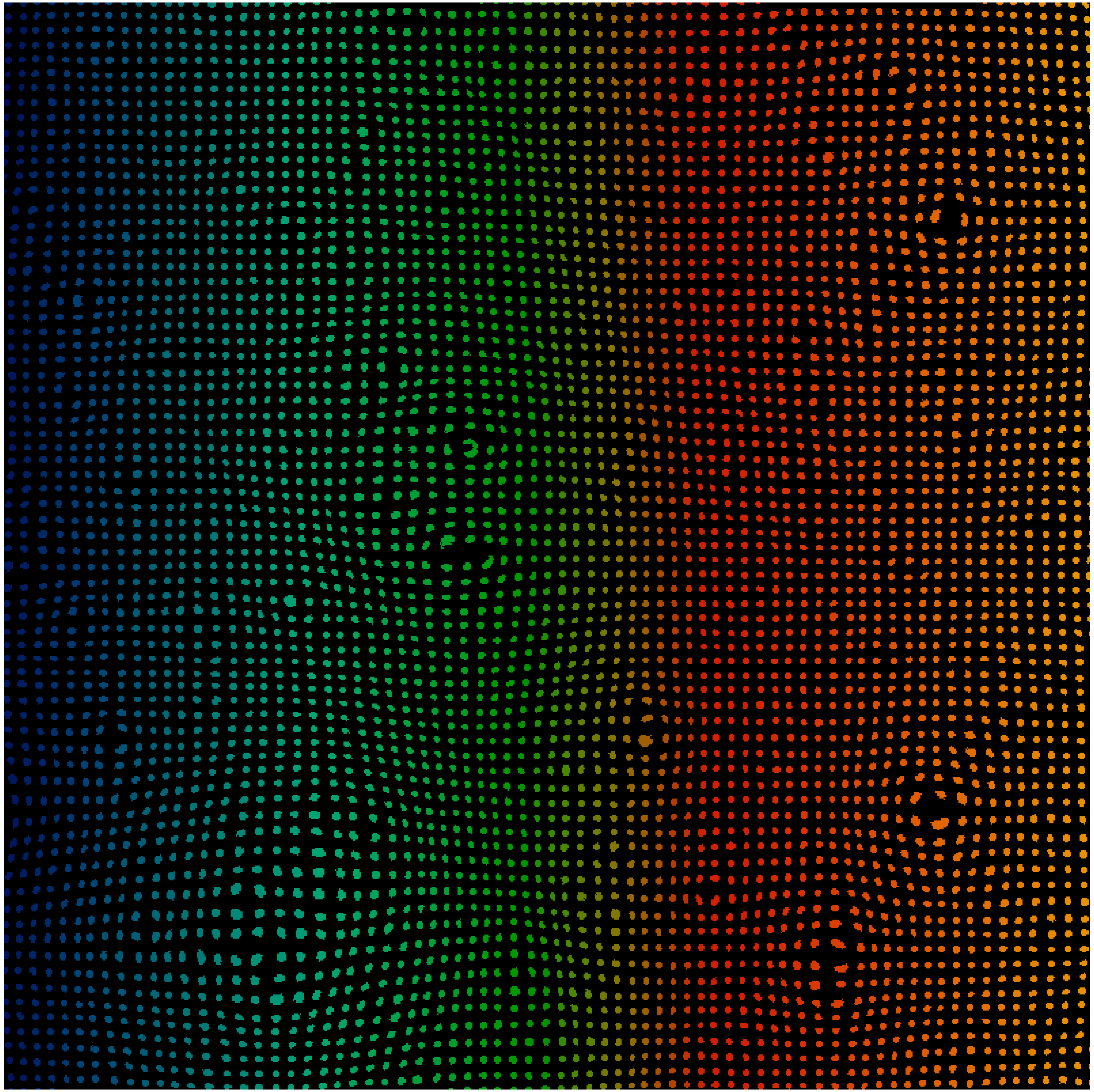
Examples for lensed structures with: $z_S = 1.5$



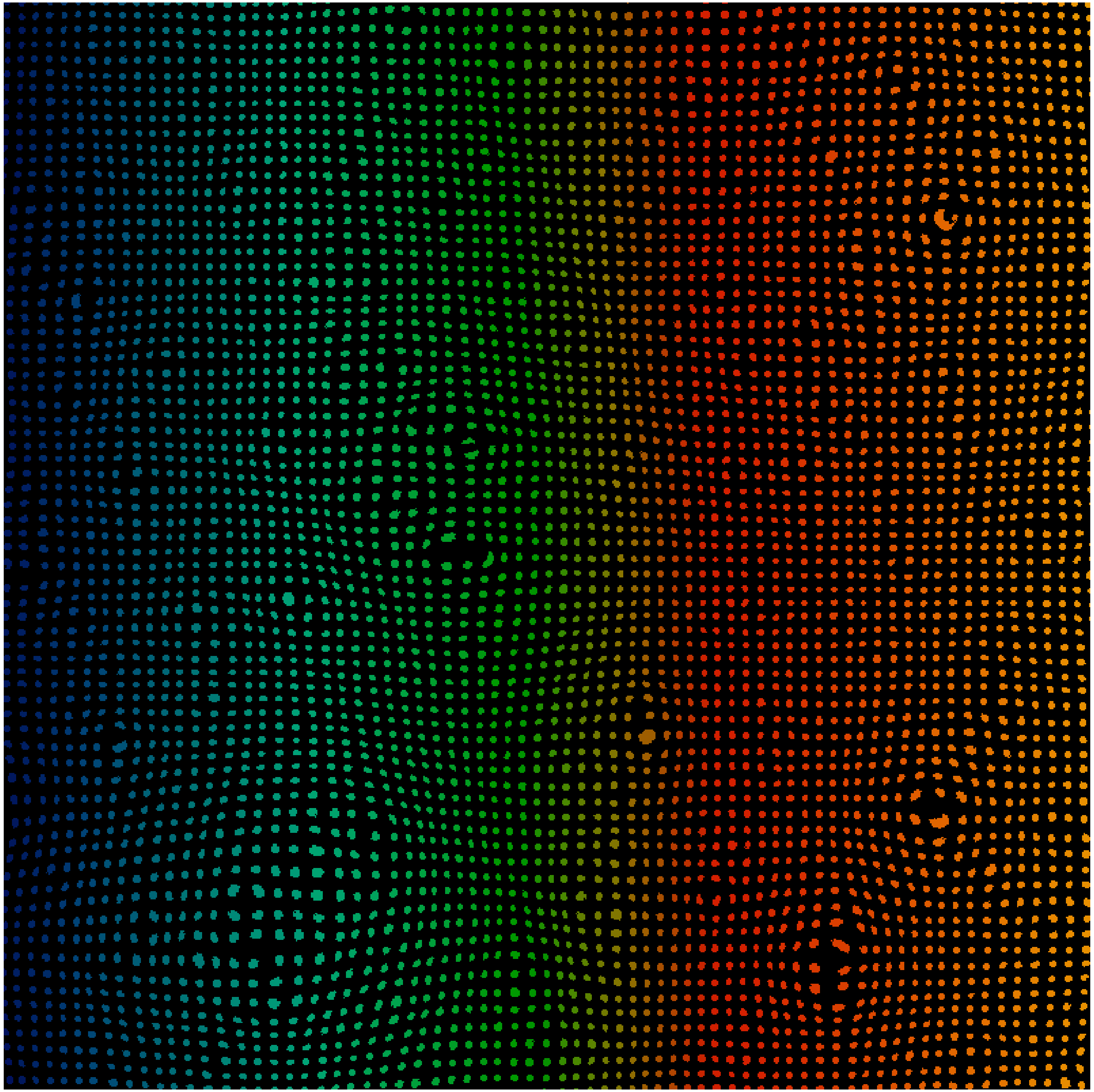
Examples for lensed structures with: $z_s = 2.5$



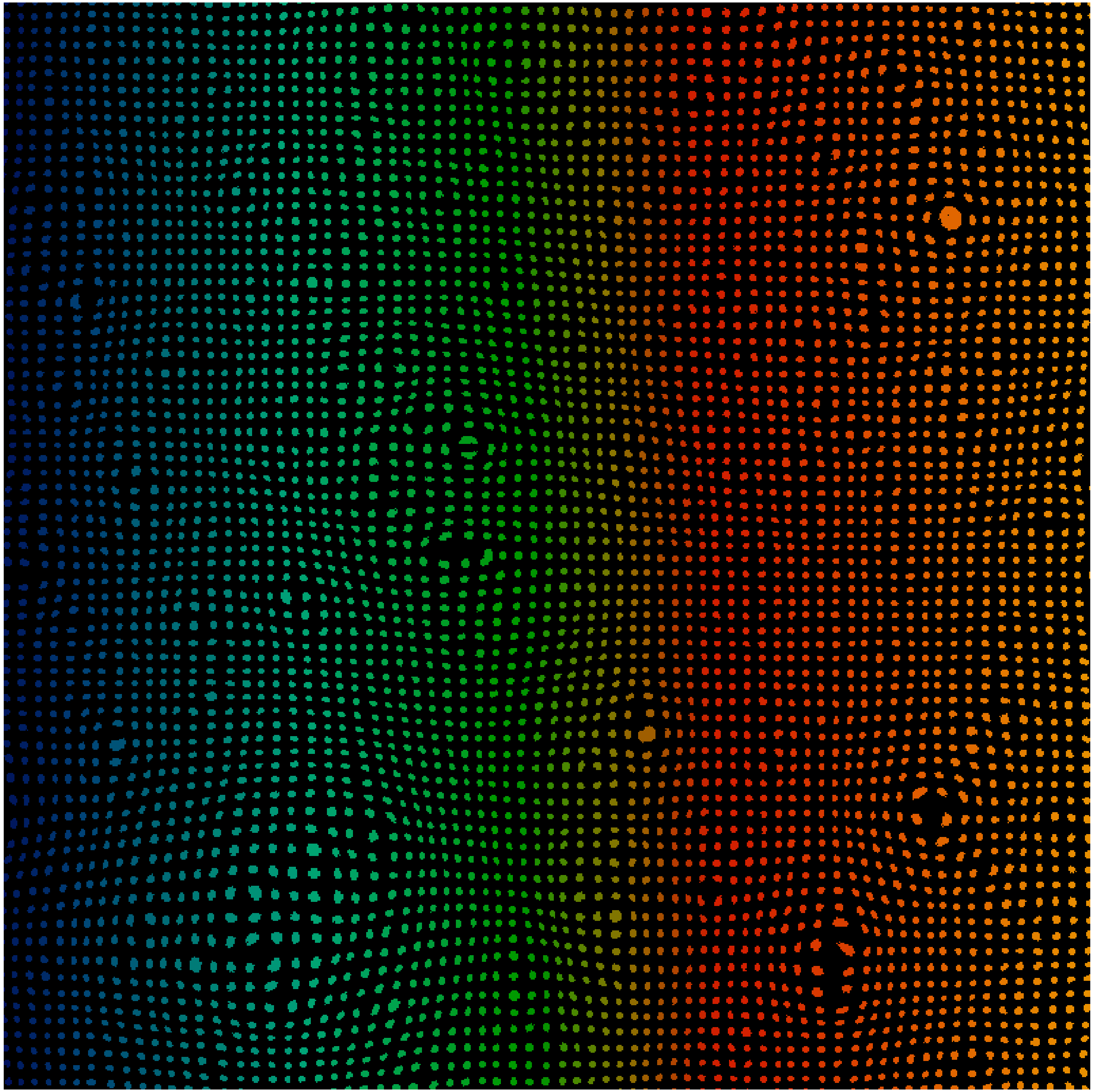
Examples for lensed structures with: $z_s = 3.8$



Examples for lensed structures with: $z_s = 5.4$



Examples for lensed structures with: $z_s = 7.2$



Scientific questions addressed here:

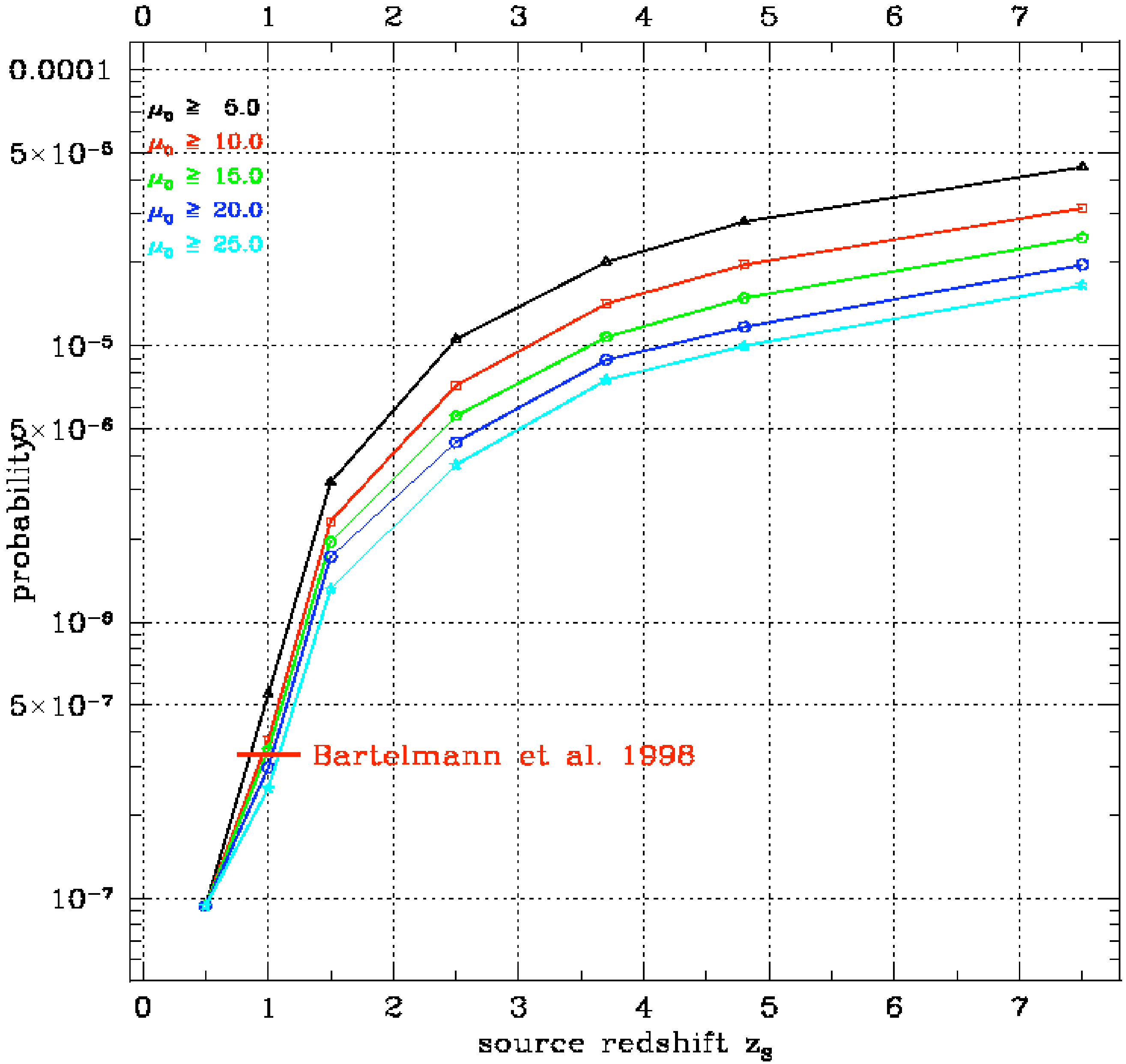
- Frequency of giant luminous arcs:
  in concordance with concordance cosmological model?

- Importance of secondary (tertiary, ...) lens planes:
  how frequently is strong lensing supported by sub-critical lens planes?

- Effect of baryon cooling:
  more arcs when baryons are considered

- Effect of cosmology/normalization/σ_8/WMAP-1 vs. WMAP-3
  fewer arcs for lower normalization

Frequency of giant luminous arcs:



Probability for the occurance of giant arcs ...

...is a strong function of source redshift!

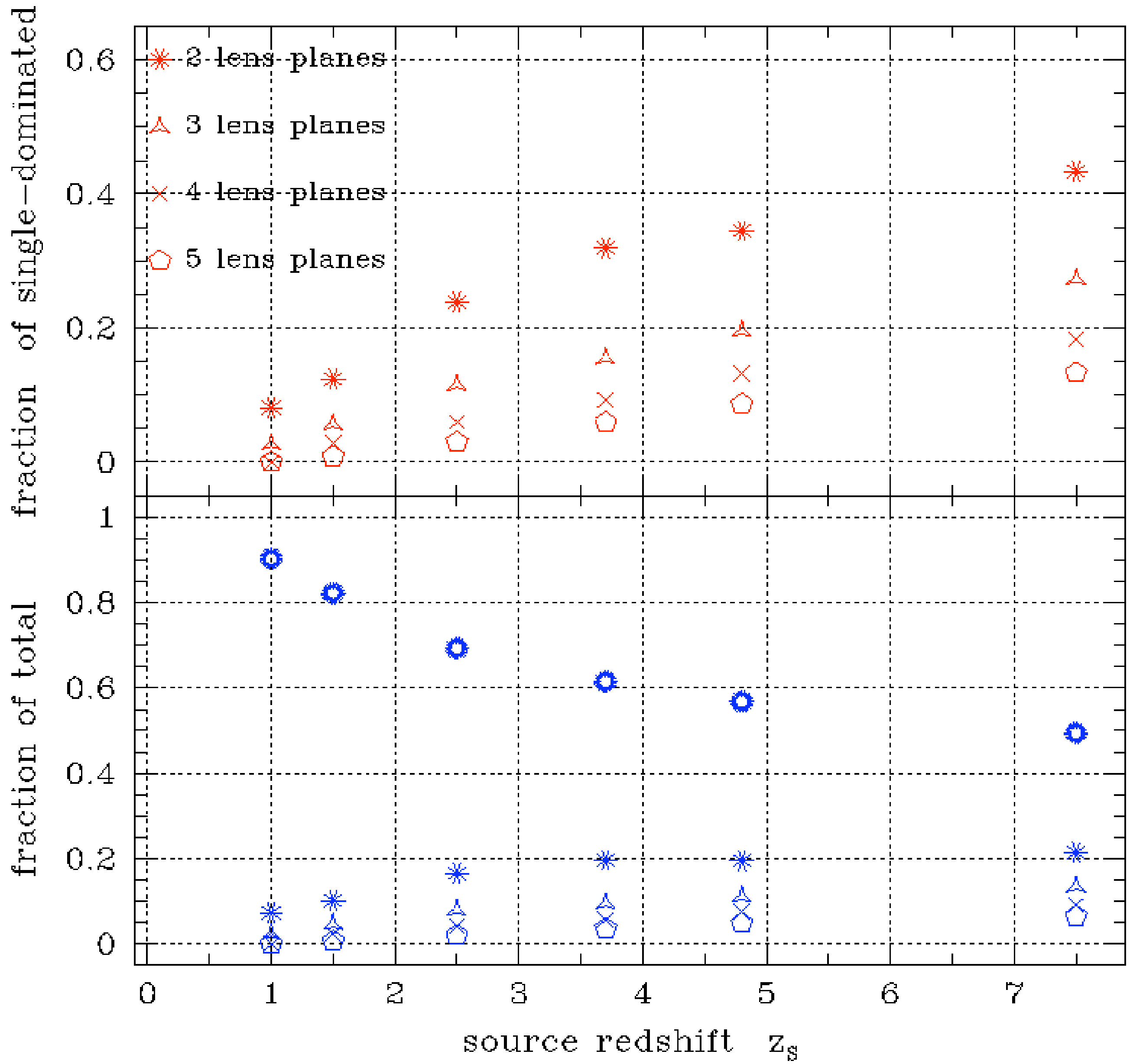
Wambsganss, Bode, Ostriker: ApJ 606, L93 (2004)

Importance of secondary (tertiary) lens planes:

how frequently is strong lensing supported by sub-critical lens planes?

- Most strong lens systems are modelled assuming "thin" lens approximation: Is this correct/justified?
- For some multiple quasars: different redshifts for lensing galaxies measured (cf. Blandford/Fassnacht: B1608+656)

Importance of secondary (tertiary) lens planes:



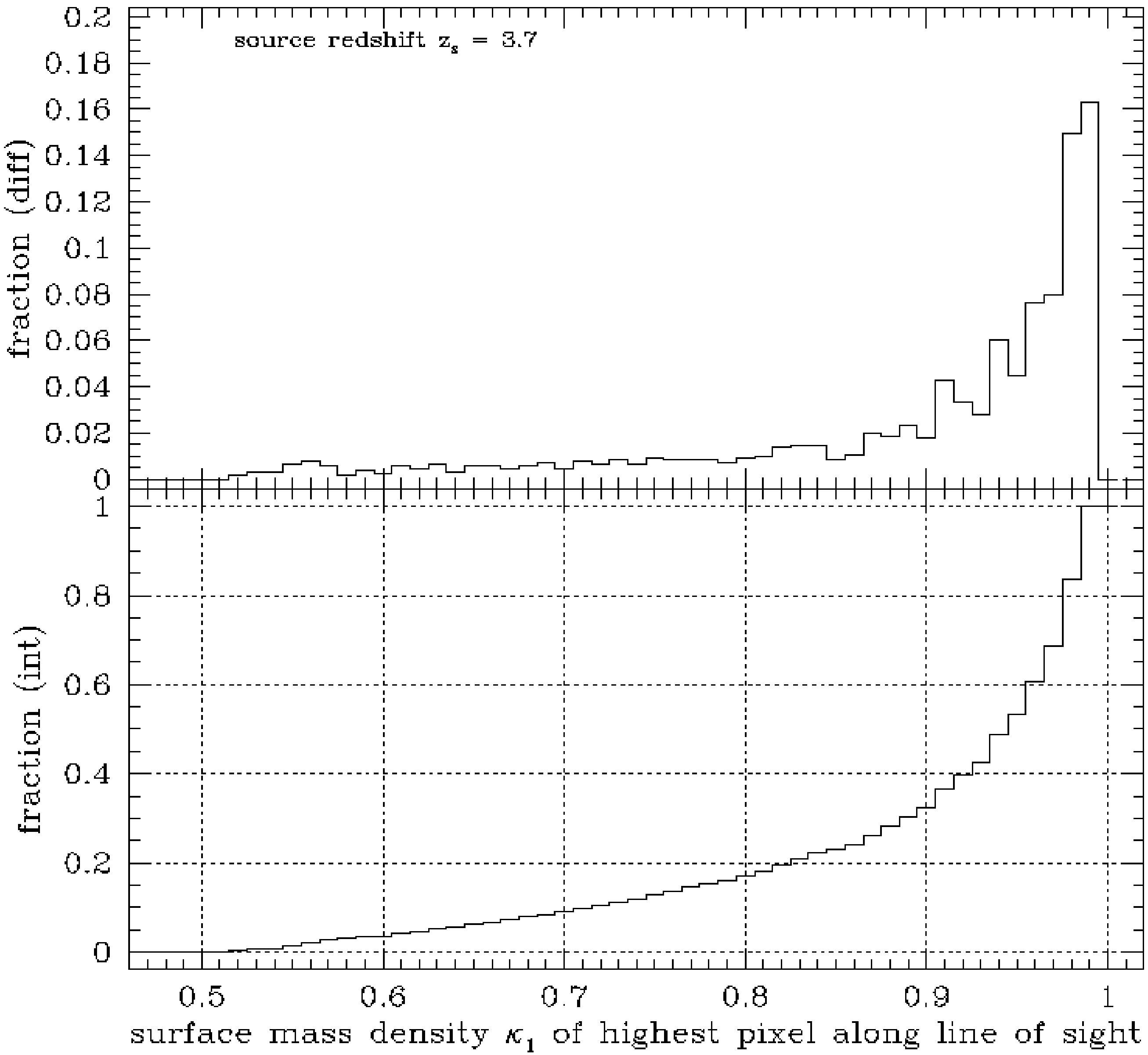
for increasing source redshift:

increasing importance of secondary, tertiary, ... lens planes!

Wambsganss, Bode, Ostriker
ApJ 635, L31(2005)

(cf. Hennawi et al. 2007, Hilbert et al. 2007)

Importance of secondary (tertiary) lens planes:



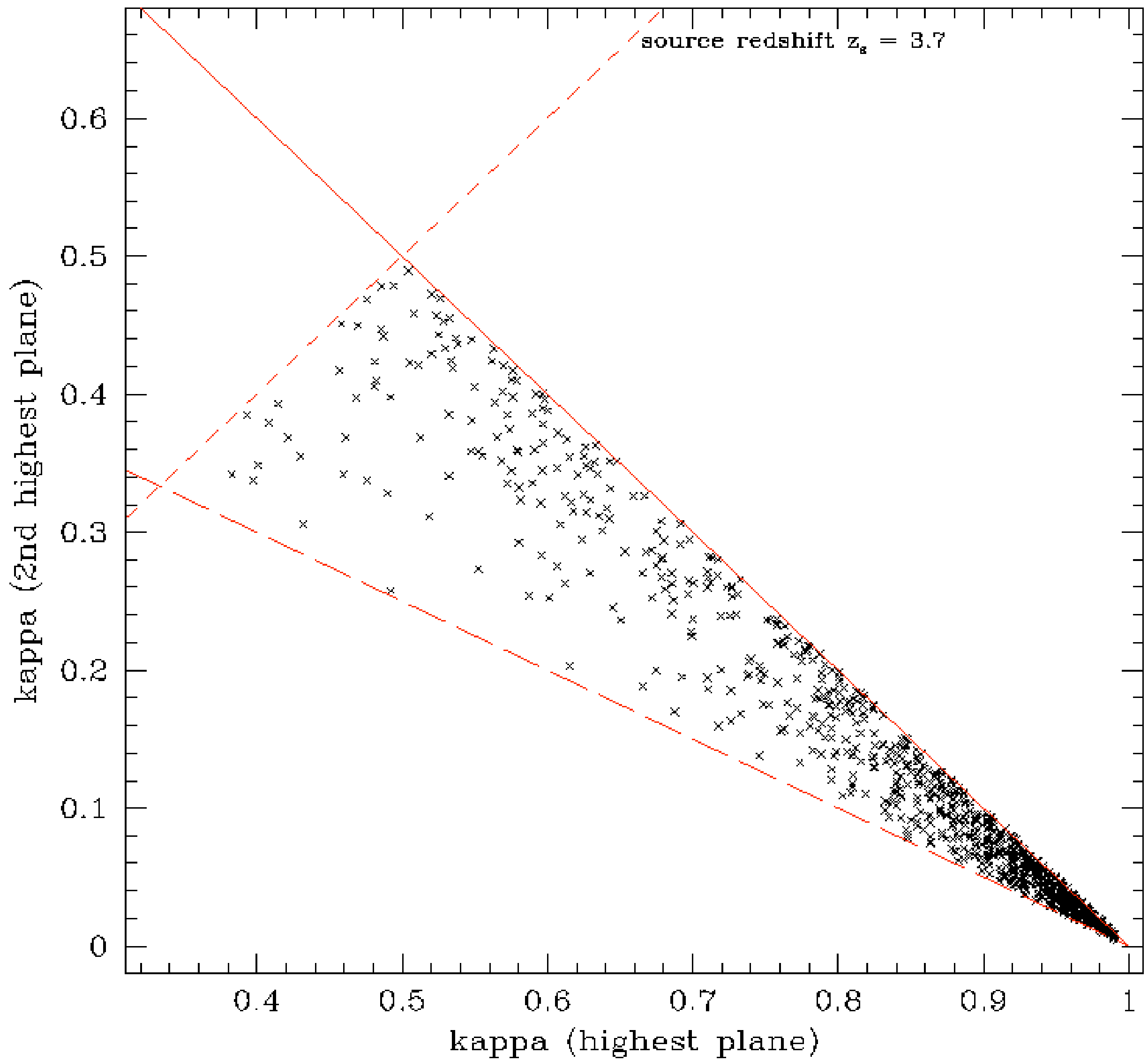
For two lens planes:
heavily dominated
by ONE lens plane

secondary contribution
"minor"

Wambsganss, Bode, Ostriker
ApJ 635, L31(2005)

(cf. Hennawi et al. 2007, Hilbert et al. 2007)

Importance of secondary (tertiary) lens planes:



For three lens planes:

mostly dominated by one lens plane

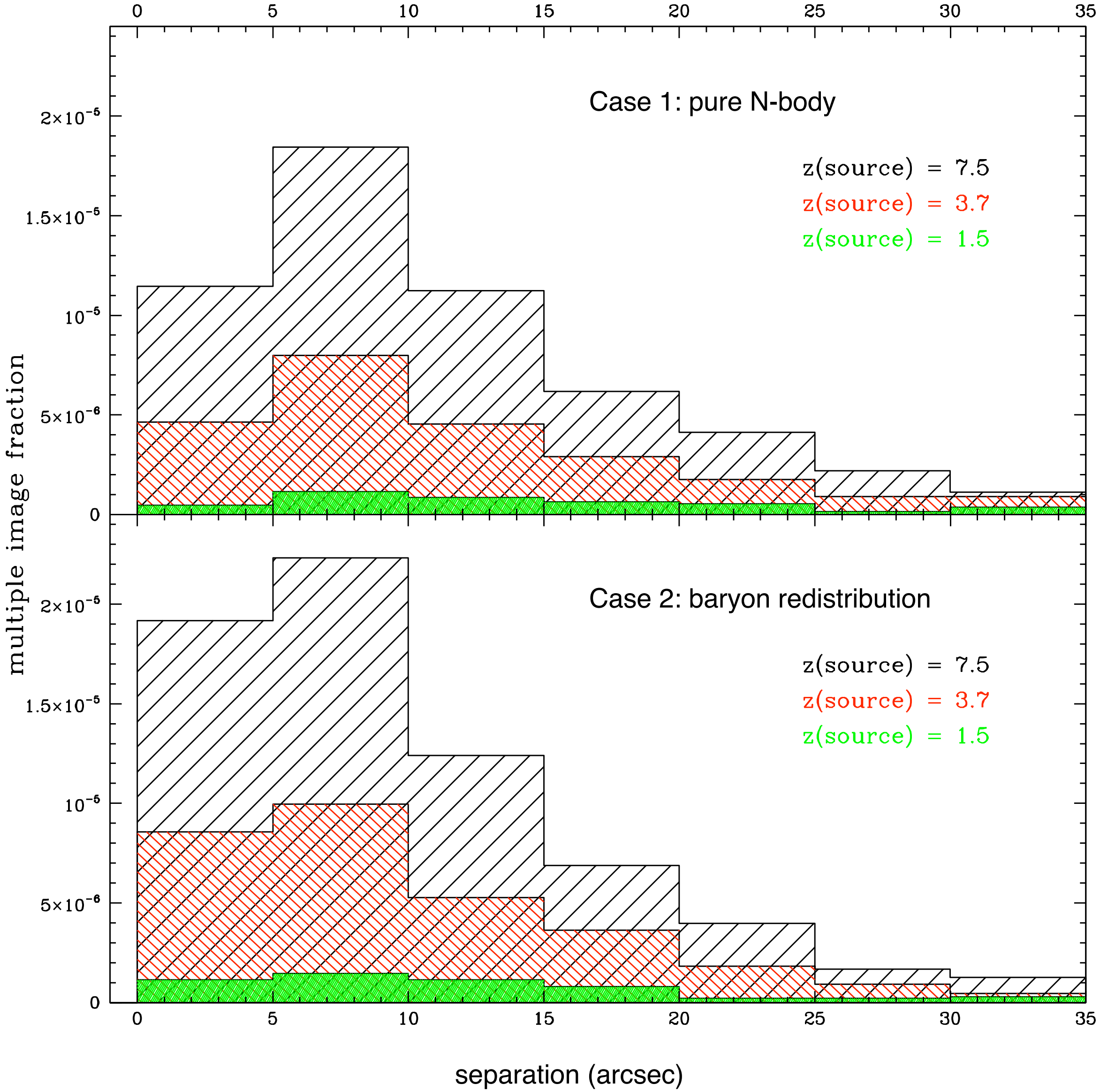
Wambsganss, Bode, Ostriker
ApJ 635, L31(2005)

The effect of baryonic cooling on arc statistics

- locate halos & identify mass likely to be cooled into stars
- rearrange mass such that inner part is isothermal
- recipe/requirements:
  - fraction of “rearranged” mass = stellar mass in universe
  - cosmic buildup of mass in stellar systems parallels what is known from observations
  - individual mass profiles consistent with kinematic data of lensing galaxies

Wambsganss, Ostriker, Bode
arXiv:0707.1482

The effect of baryonic cooling on arc statistics

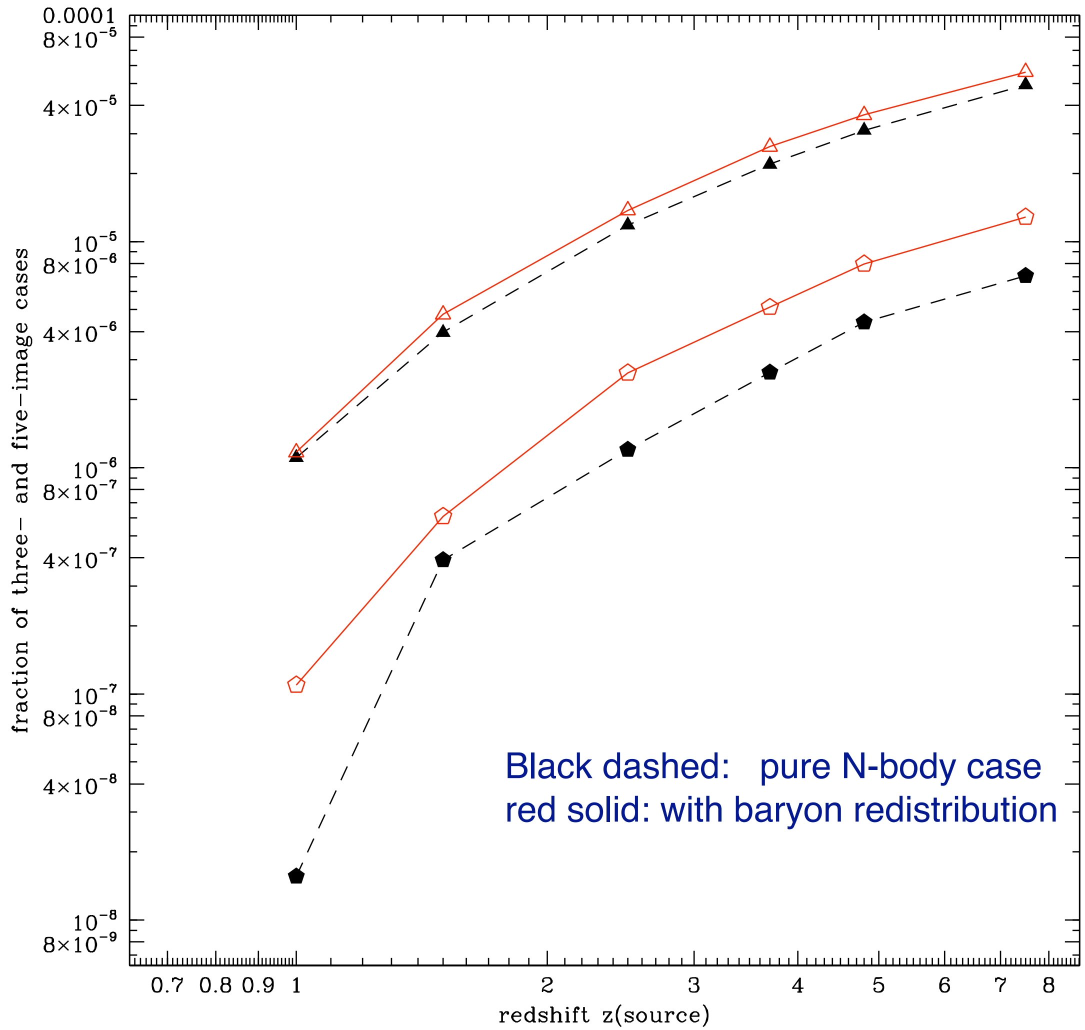


Number of multiple images/giant arcs increases by about 25% if baryon cooling is considered

(cf. Lin et al. 2006, Rozo et al. 2006, Hilbert et al. 2007)

Wambsganss, Ostriker, Bode
arXiv: 0707.1482

The effect of baryonic cooling on arc statistics



Number of multiple images/giant arcs increases by about 25% if baryon cooling is considered

Wambsganss, Ostriker, Bode: arXiv:0707.1482

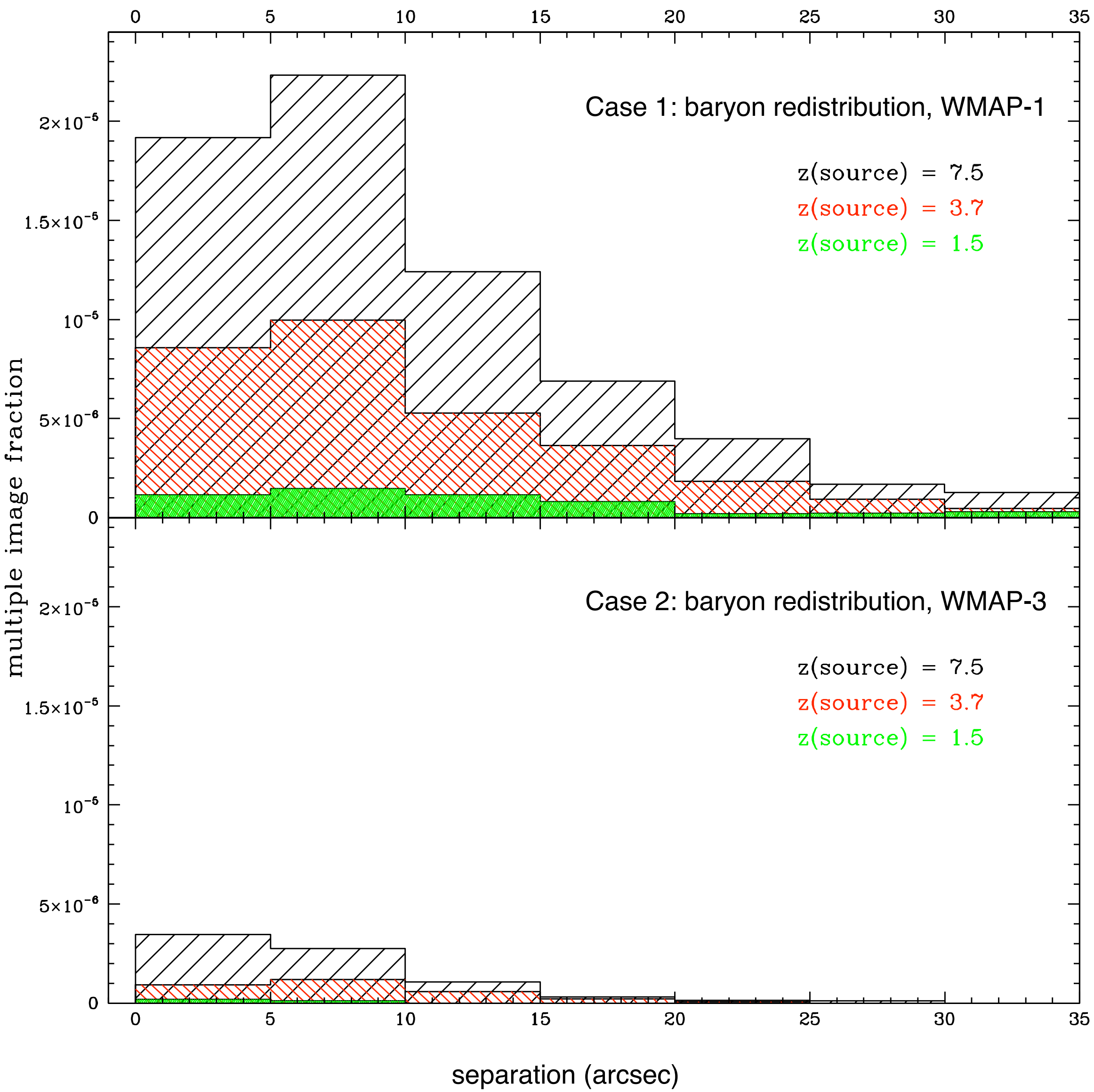
(cf. Lin et al. 2006, Rozo et al. 2006, Hilbert et al. 2007)

Frequency of triple/quintuple images as a function of redshift

Parameters of “WMAP-3” cosmological model:

- matter content: $\Omega_M = 0.26$, $\Omega_\Lambda = 0.74$
- Hubble constant: $H_0 = 74$ km/sec/Mpc
- amplitude of mass fluctuations: $\sigma_8 = 0.77$
- particle mass: $m_p = 2.20 * 10^9 \, M_\odot$

Arc statistics for WMAP-1 vs. WMAP-3 normalization



Result:

Frequency of arcs is reduced by factor 8-10 for a WMAP-3 normalization compared to a WMAP-1 normalization (cf. Li et al. 2006)!

Summary

Statistics of Giant Arcs is a very powerful probe for a comparison of cosmological models with observations

- arc frequency is strongly increasing function of source redshift
- secondary lens planes contribute occasionally (cf. Hennawi et al. 07, Hilbert et al. 07)
- baryon cooling increases arc frequency by about 25% (cf. Lin et al. 06, Rozo et al. 06)
- WMAP-1 normalized model in rough agreement with observations (slightly on the high side ...)
- WMAP-3 normalization decreases arc frequency by about a factor 8-10, compared to WMAP-1 parameters (cf. Li et al. 06)

→ **Strong Lensing offers Strong Tests for Cosmology**

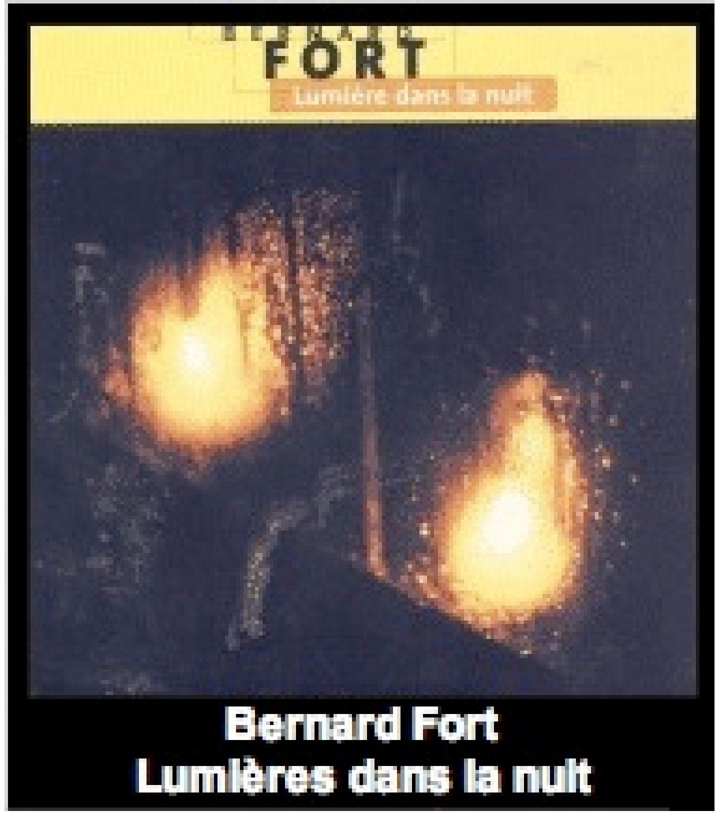
(more talks to come: Bartelmann, Hilbert, Meneghetti, ...)

TO DO:

- more/better data: deep, very large area surveys: Pan-STARRS, DUNE, LSST
- constrain/explore cosmological model parameters
- (useful: clear definition of “what is an arc?”)

Google "Bernard Fort",

on "Splendid":



"Bernard Fort, the man responsible for *Lumières dans la nuit*, has degrees that most of us don't and presumably knows what he's doing. He may also be qualified to pass judgment on exactly what criteria must be satisfied in order for a field ... to qualify as a *good* field ... . The rest of us must remain ignorant."

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

G. Soucail, B. Fort, Y. Mellier, and J. P. Picat

Observatoire de Toulouse, 14 Avenue E. Belin, F-31000 Toulouse, France

Received April 24, accepted August 15, 1986

Summary

We report on a serendipitous observation from our first multispectroscopic run on the distant X-ray emitter Abell cluster A370 (z=0.373). We discovered a very particular ring-like structure of galaxies with a diffuse component lying near one of the very luminous galaxies of the cluster core. A very first analysis suggests that it may be the result of qalaxy/galaxy interactions in the dense region or of star formation occuring from a cooling flow of the Intra-Cluster-Medium (hereafter I.C.M.).

A gravitational lens effect on a background quasar is a possibility owing to the curvature of the structure news and views

Nature **325**, 572 - 573 (18 February 1987);

Giant luminous arcs discovered in two clusters of galaxies

BOHDAN PACZYNSKI

Princeton University Observatory, Princeton, New Jersey 08544, USA.

Astron. Astrophys. 184, L7–L9 (1987)

Letter to the Editor

Further data on the blue ring-like structure in A 370

G. Soucail[1], Y. Mellier[1], B. Fort[1], F. Hammer[2], and G. Mathez[1]

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Received July 21, accepted August 5, 1987

Summary : We present the latest data collected in November 1986 on the very blue giant ring-like structure recently discovered in the center of the cluster Abell 370 z=0.374). The spectrum of the eastern end of the structure is analyzed in details : it does not show any of the strong emission lines characterizing a QSO, and all the typical features expected in a gas or in a galaxy at the cluster redshift are missing. Such a result seems to rule out several models involving in-situ star formation. Moreover, the large scale spectral energy distribution looks like the continuum of a spiral galaxy redshifted to z=0.59. So, the interpretation in terms of gravitational lensing is proposed. The results of a multi-point mass model allows one to reconstruct the entire ring-like structure, taking into account the spectroscopic and photometric data already collected by our team on A370. However, some properties remain difficult to understand, considering the similar structures discovered in two other clusters.

Key Words : Clusters of galaxies - Gravitational lensing - Arcs

The morphology of object #62 deserves further comment: this rather faint object does not exhibit the central intensity peak wich characterizes the brightness profile of the surrounding galaxies of similar angular size. On the contrary, its brightness is rather flat, around the level observed all along the arc. Indeed, the latter is a regular structure with the same surface brightness over more than 20" on the sky. This is also observed on an image of A370 taken by Ellis (1987) in the U-band, where the arc appears by far brighter than any cluster member.

Ellis, R., 1987, private communication

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

ASTRONOMY AND ASTROPHYSICS

Letter to the Editor

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

G. Soucail, Y. Mellier, B. Fort, G. Mathez, and M. Cailloux

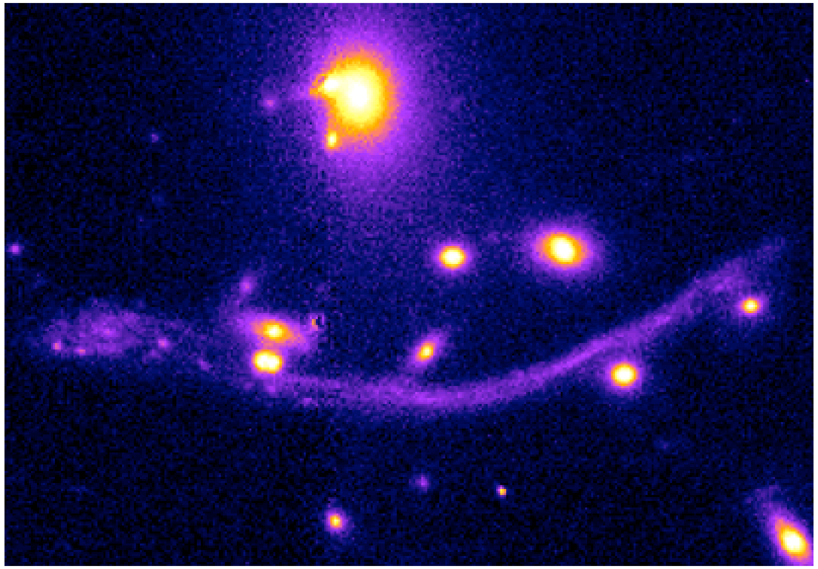
Observatoire de Toulouse, 14 Avenue E. Belin, F-31400 Toulouse, France

Received November 17, accepted December 22, 1987

Summary:

In this Letter we present new spectroscopic data on the giant luminous arc in the distant cluster of galaxies Abell 370 ($z = 0.374$), obtained at the 3.60 m telescope at ESO with EFOSC/PUMA2. From the spectral analysis of the arc it is now well established that all its segments (including the eastern end) have the same spectrum. Some emission and absorption features identified in the spectrum definitely prove that the arc is the image of a late type galaxy at a redshift of 0.724. Gravitational lensing of a background galaxy by the cluster core results as the most convincing model of the observed configuration.

Summary+



Happy Birthday

Luminous arc

20 years !!!

Summary+

Happy Birthday

Luminous Bern**arc** Fort

3.25 × **20 years !!!**