

# *Gravitational Lensing from Cosmic Shear to Microlensing*

OATS

*Trieste 29/10/2014*

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Bologna*

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*Alessandro Romeo, Bologna*

*Nicolas Tessore, Bologna*





*Outline:*

*Very Short Introduction to Gravitational Lensing -*

*Weak lensing -*

*simulating weak lensing*

*Strong Lensing -*

*simulating strong lensing*

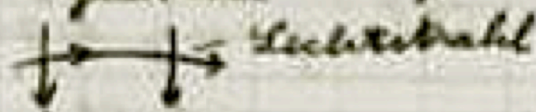


Zürich 14. I. 13.

Aus

Hoch geehrten Herr Kollege!

Eine einfache theoretische Überlegung macht die Annahme plausibel, dass Lichtstrahlen in einem Gravitationsfelde eine Deviation erfahren.



An Sonnensande müsste diese Ablenkung  $0,84^\circ$  betragen und wie  $\frac{1}{R}$  abnehmen (R = Sonnenradius - Mittelpunkt).

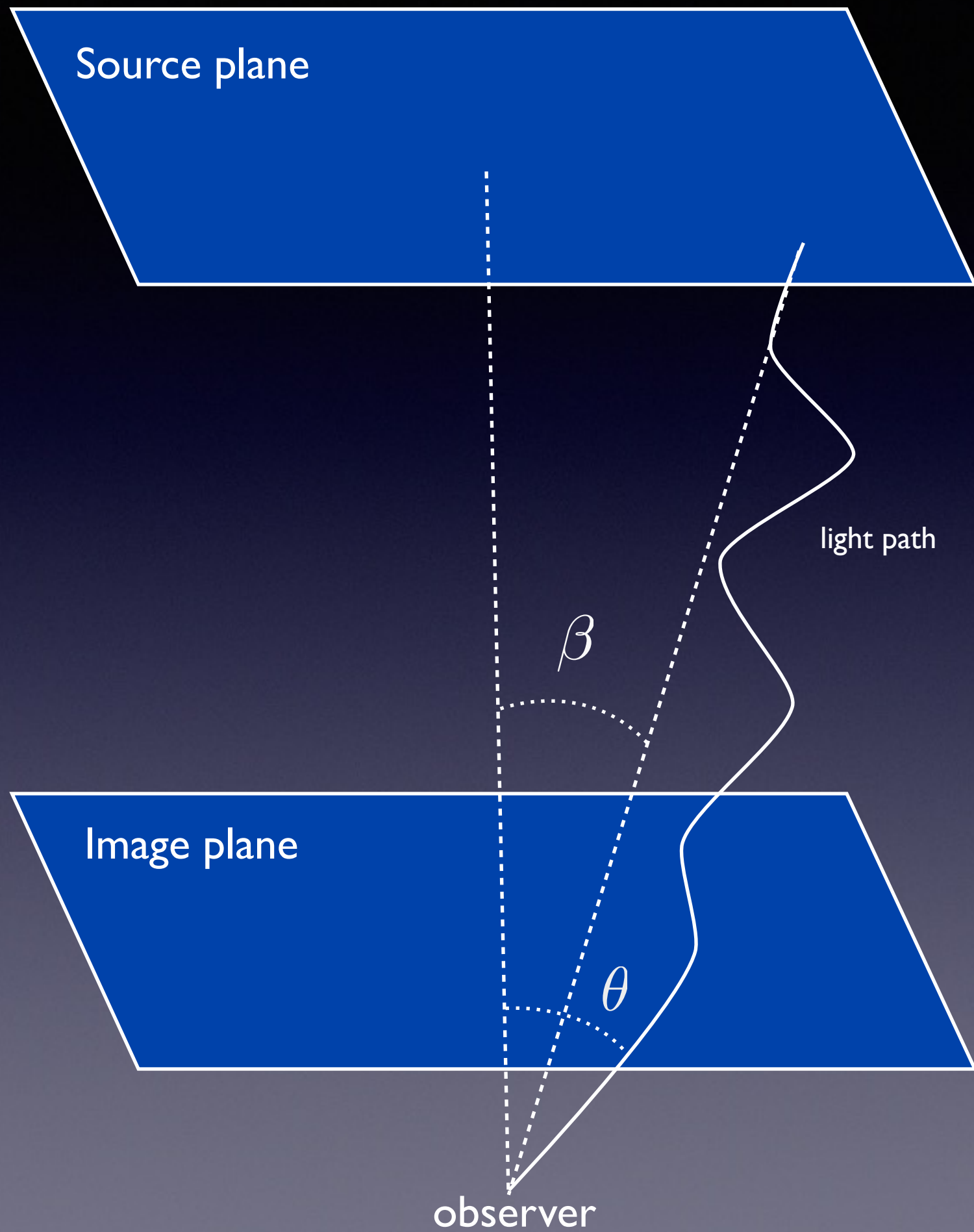


Es wäre deshalb von grösstem Interesse, bis zu wie grosser Sonnen-nähe <sup>helle</sup> Fixsterne bei Anwendung der stärksten Vergrösserungen bei Tage (ohne Sonnenfinsternis) gesehen werden können.



## Lensing Equation

$$\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$$



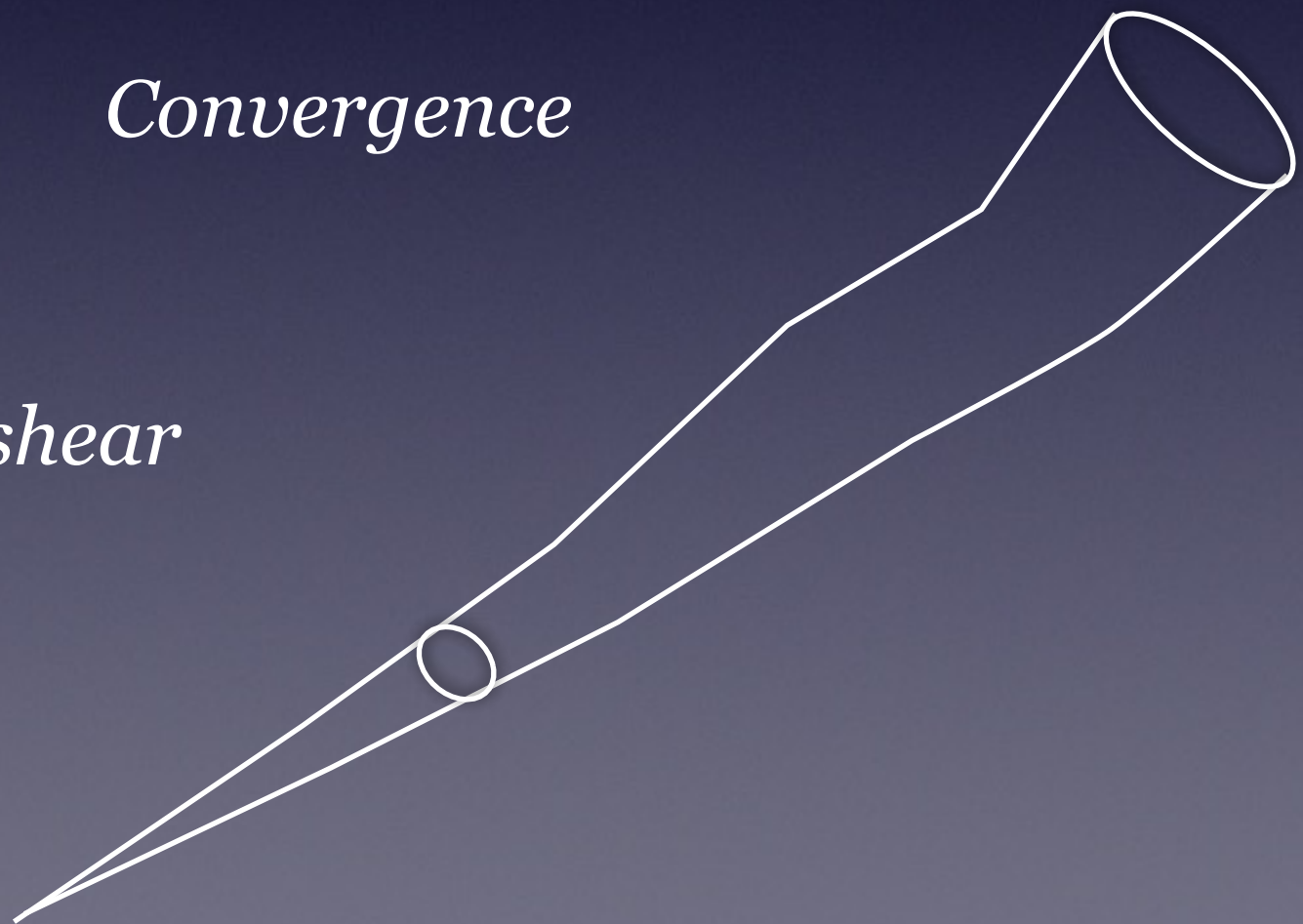


$$\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$$

$$\frac{\partial \vec{\beta}}{\partial \vec{\theta}} = \mathbf{A} = \begin{pmatrix} 1 - \kappa - \gamma_1 & \gamma_2 \\ \gamma_2 & 1 - \kappa + \gamma_1 \end{pmatrix}$$

$$\kappa \equiv 1 - \frac{1}{2} \text{tr} \mathbf{A} \quad \textit{Convergence}$$

$$\{\gamma_1, \gamma_2\} \quad \textit{shear}$$





# Propagation of a light ray

$$\frac{d^2 x_{\perp}}{d\lambda^2} = -2\nabla_{\perp}\phi_N$$

## Single Lens Plane

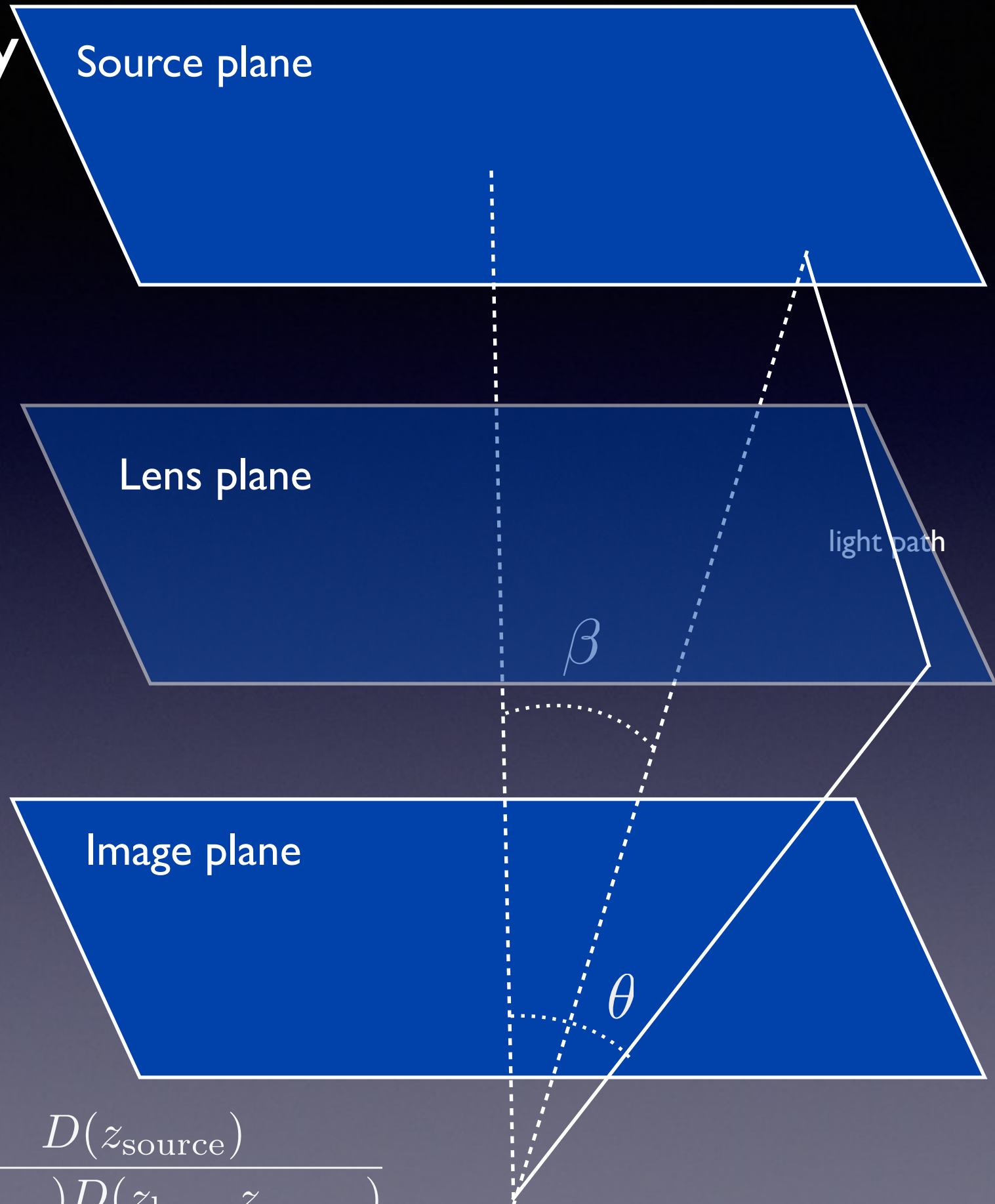
$$\vec{\alpha} = \nabla\phi$$

$$\nabla^2\phi = 2\kappa$$

$$\kappa(\theta) = \frac{\Sigma(\theta)}{\Sigma_{\text{crit}}}$$

$$= \frac{\text{surface density}}{\text{critical density}}$$

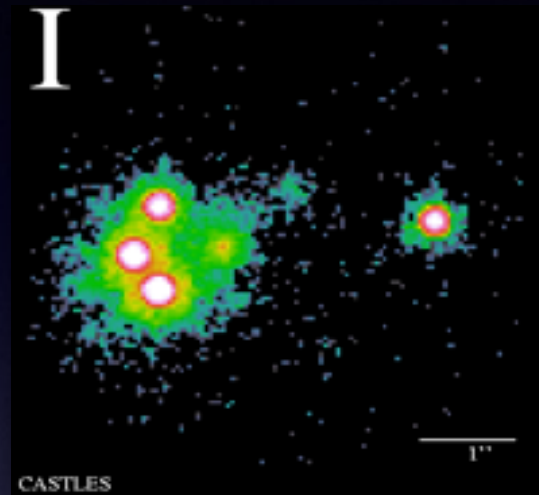
$$\Sigma_{\text{crit}}(z_{\text{lens}}, z_{\text{source}}) = \frac{c^2}{4\pi G} \frac{D(z_{\text{source}})}{D(z_{\text{lens}})D(z_{\text{lens}}, z_{\text{source}})}$$





$\kappa, \gamma \gtrsim 1$       *Strong Lensing*

*Multiple Images*



*Highly Distorted Images*





$$\kappa, \gamma \ll 1$$

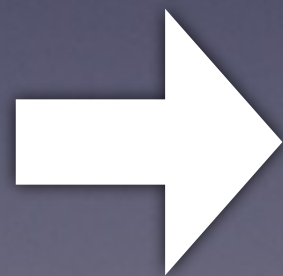
# Weak Lensing

- 1) Deflection (and shear) field is a potential field even for multiple planes
- 2) The ellipticity of a galaxy is an unbiased estimator of the shear

$$\vec{\alpha} = \nabla \phi$$

$$\nabla^2 \phi = 2\kappa$$

$$\mathbf{D}\phi = \gamma$$



$$\epsilon = \epsilon_{\text{intrinsic}} + \gamma$$

$$\langle \epsilon \rangle_{\text{orientation}} = \gamma$$

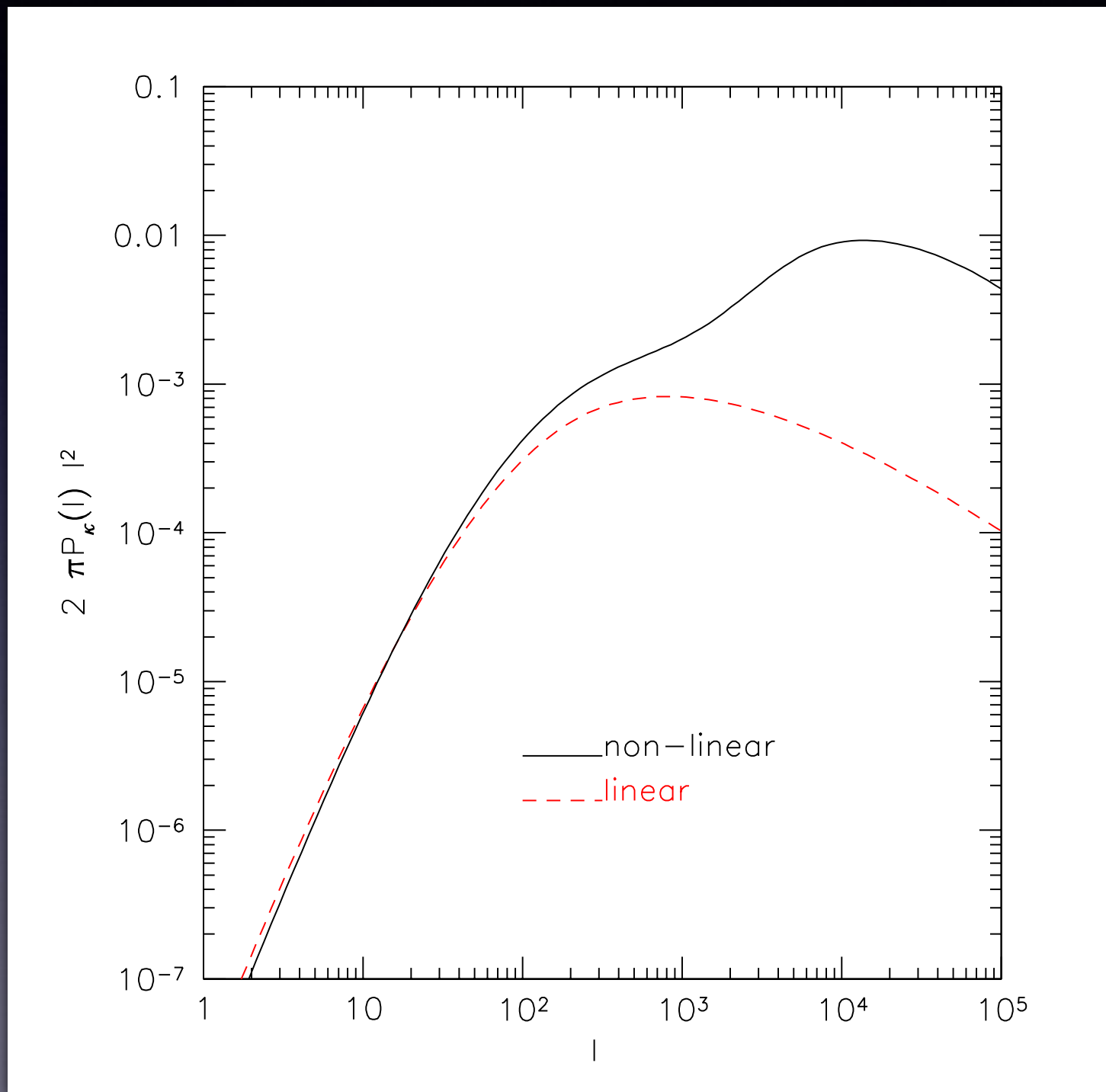
$$\nabla^2 \mathbf{D}^{-1} \langle \epsilon \rangle = 2\kappa$$





# Cosmic Shear

## Convergence Power Spectrum

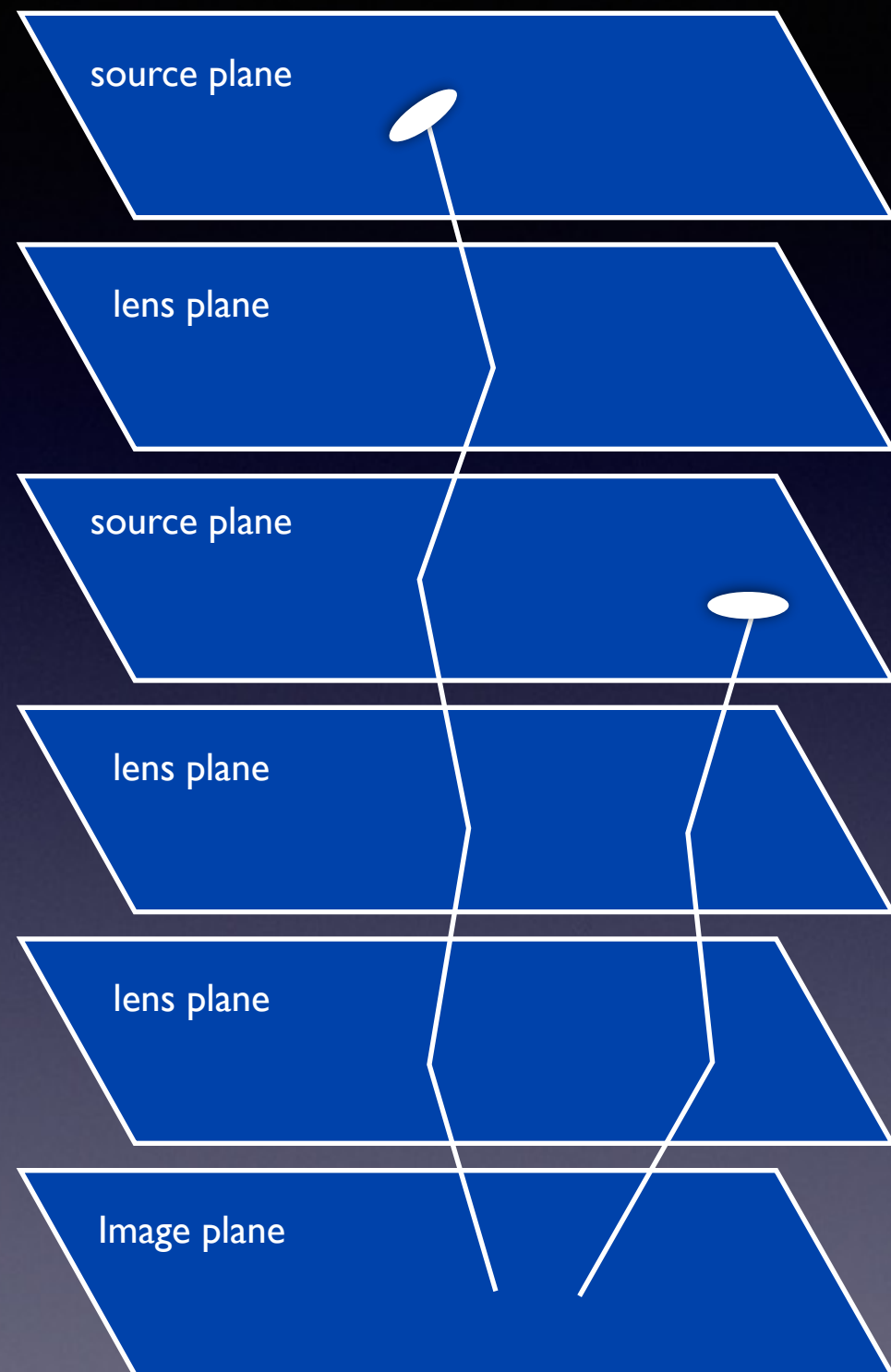
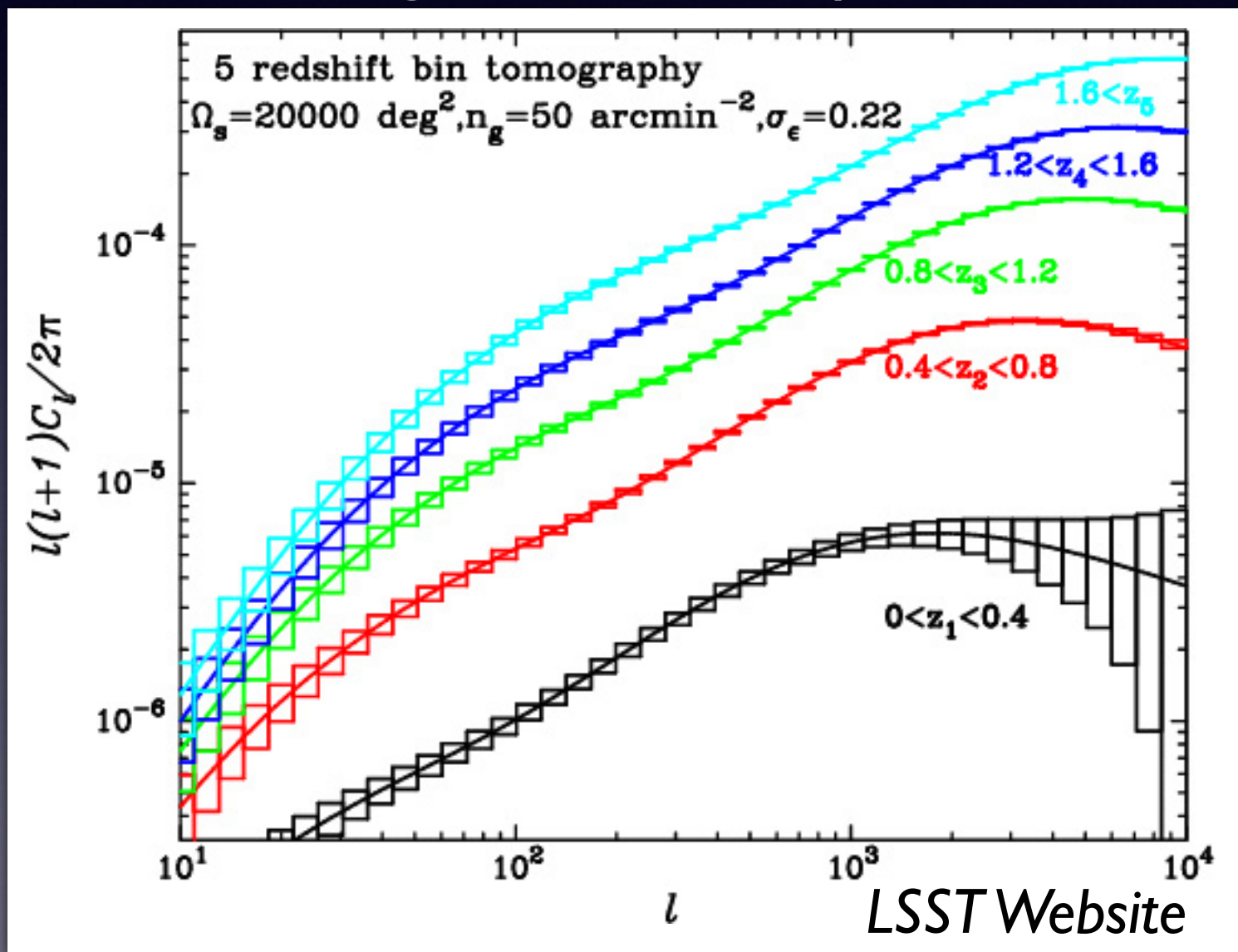


*Non-linear structure is clearly important*

# Cosmic Shear

## Tomographic lensing

### Convergence Power Spectrum





# lensing simulation with *GLAMER*

## calculating deflection angle

analytic model or from particles:

- tree code deflection solver
- modified algorithm to handle halos efficiently

adaptive smoothing for Nbody/hydro particles

multiple lens planes:  
3d along light paths

## lens model

- single analytic lens
- multiple analytic halos
- Nbody/SPH particles
- point masses (stars)
- pixelized mass map

## the grid of rays

adaptive grid refinement

full image reconstruction or just shear and convergence

## source model

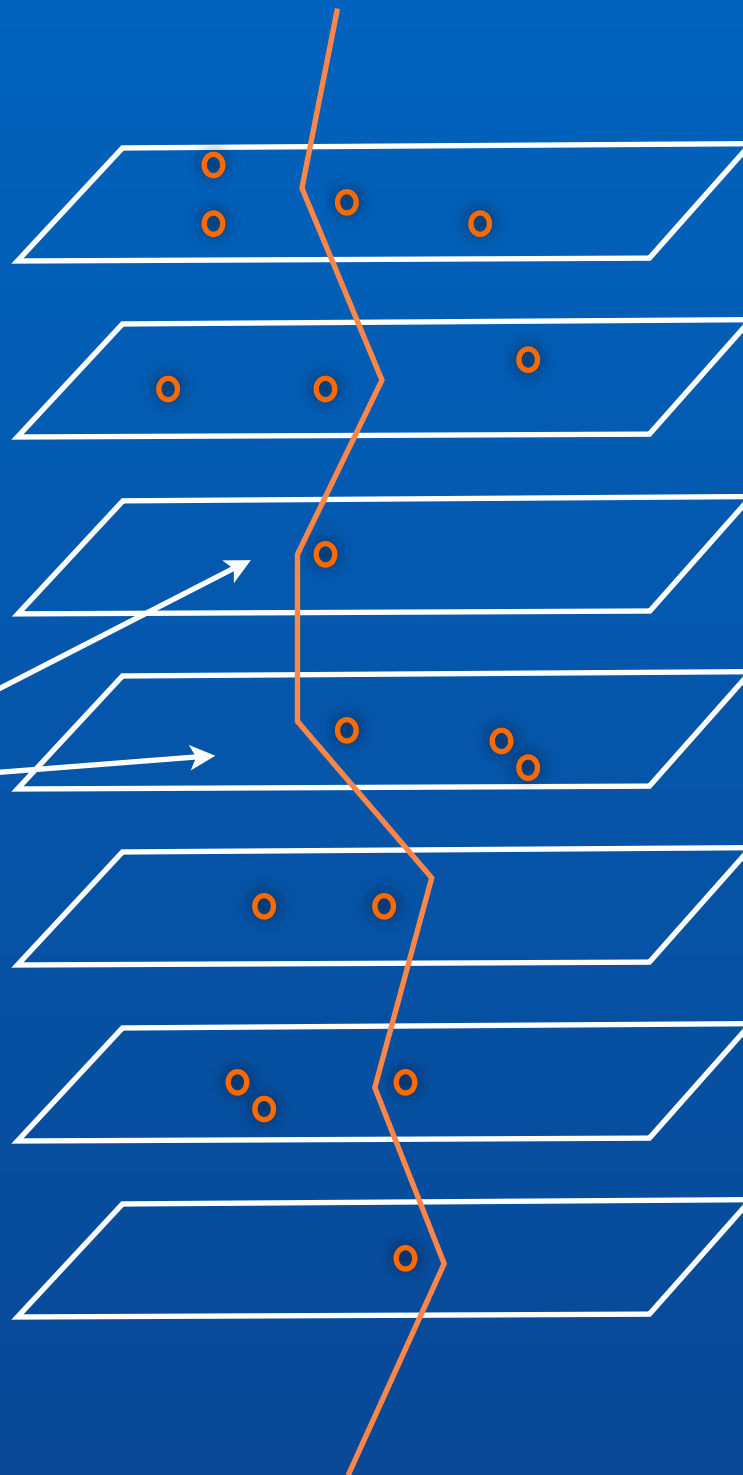
analytic model for surface brightness and direct pixelized images

multi-plane lensing

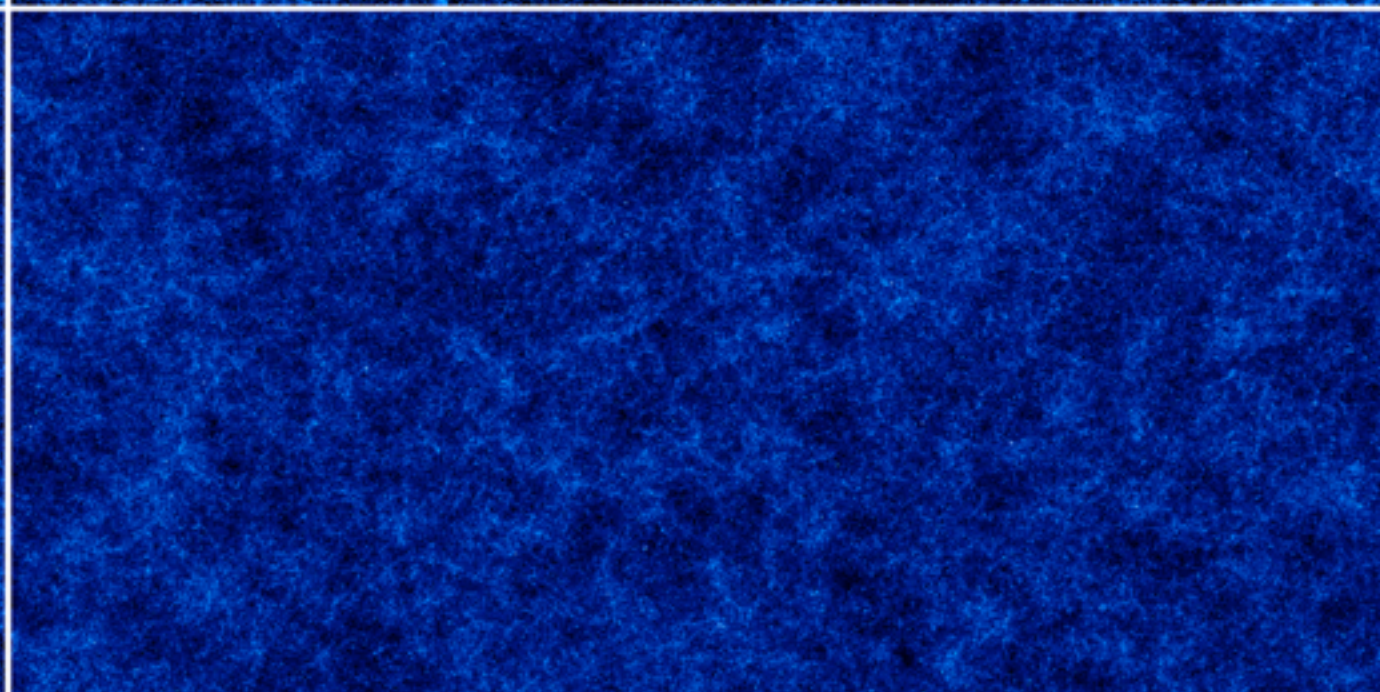
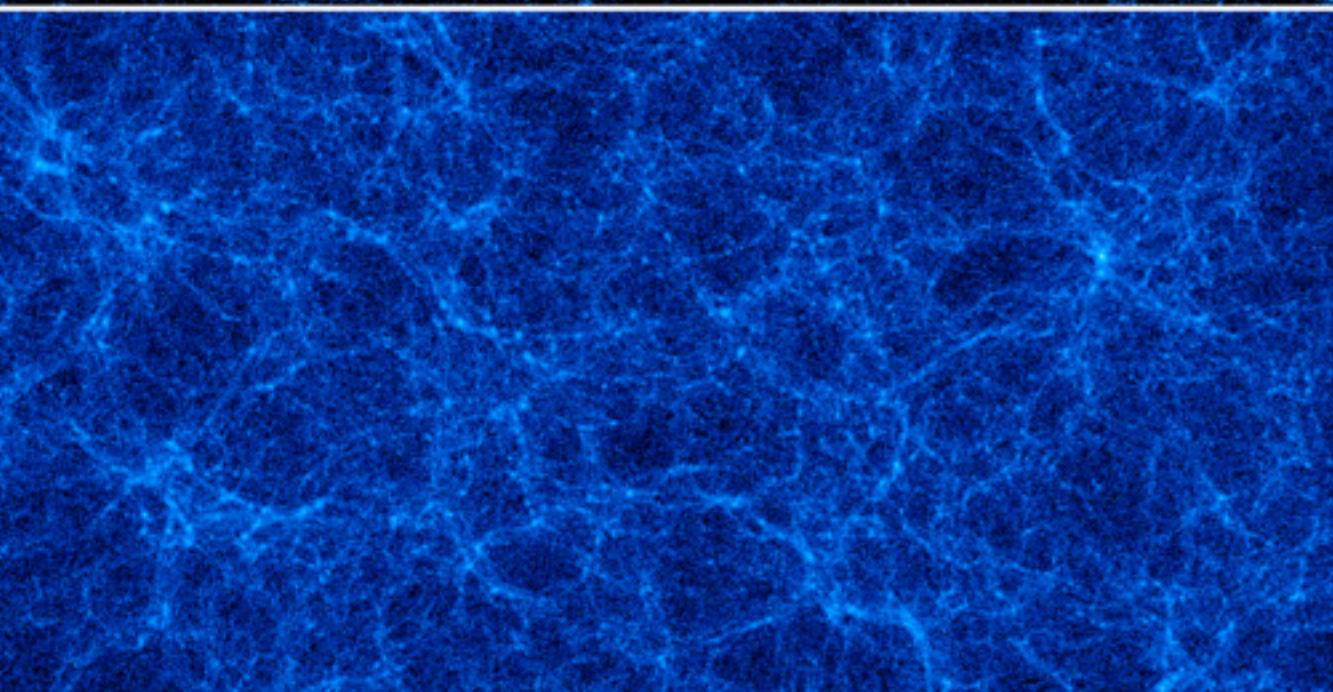
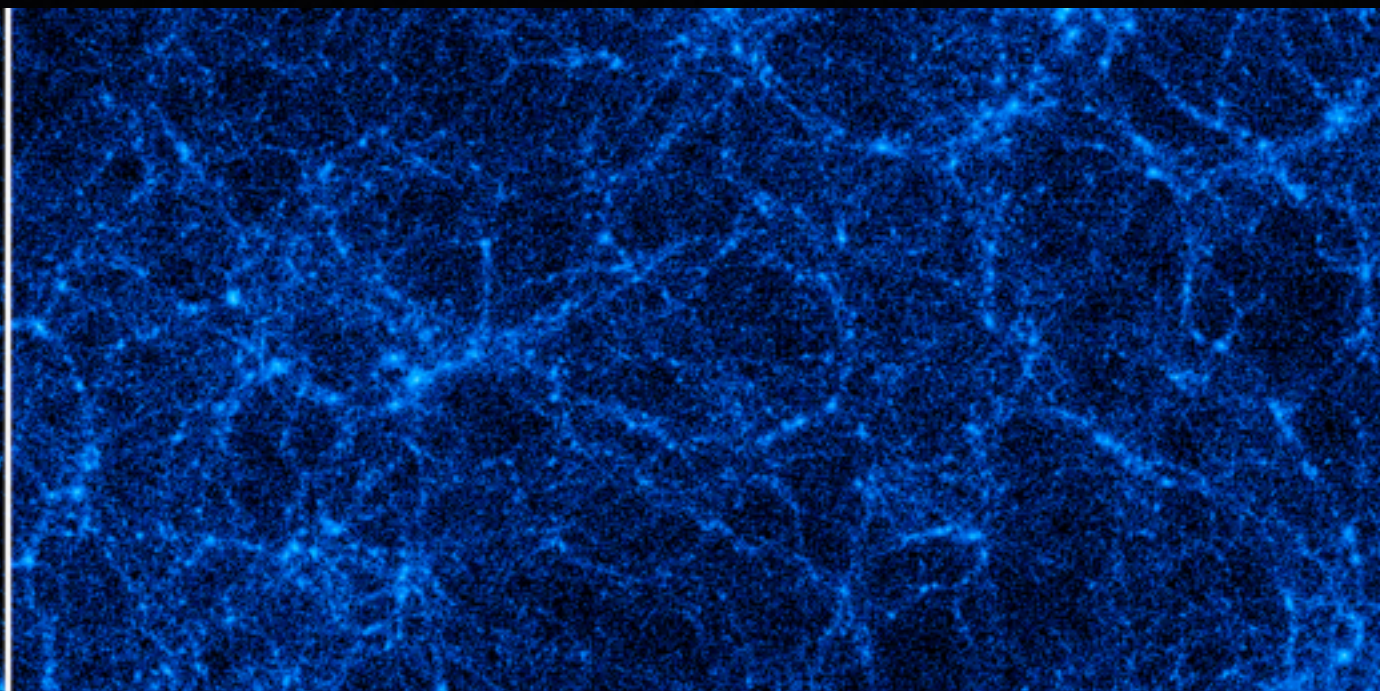
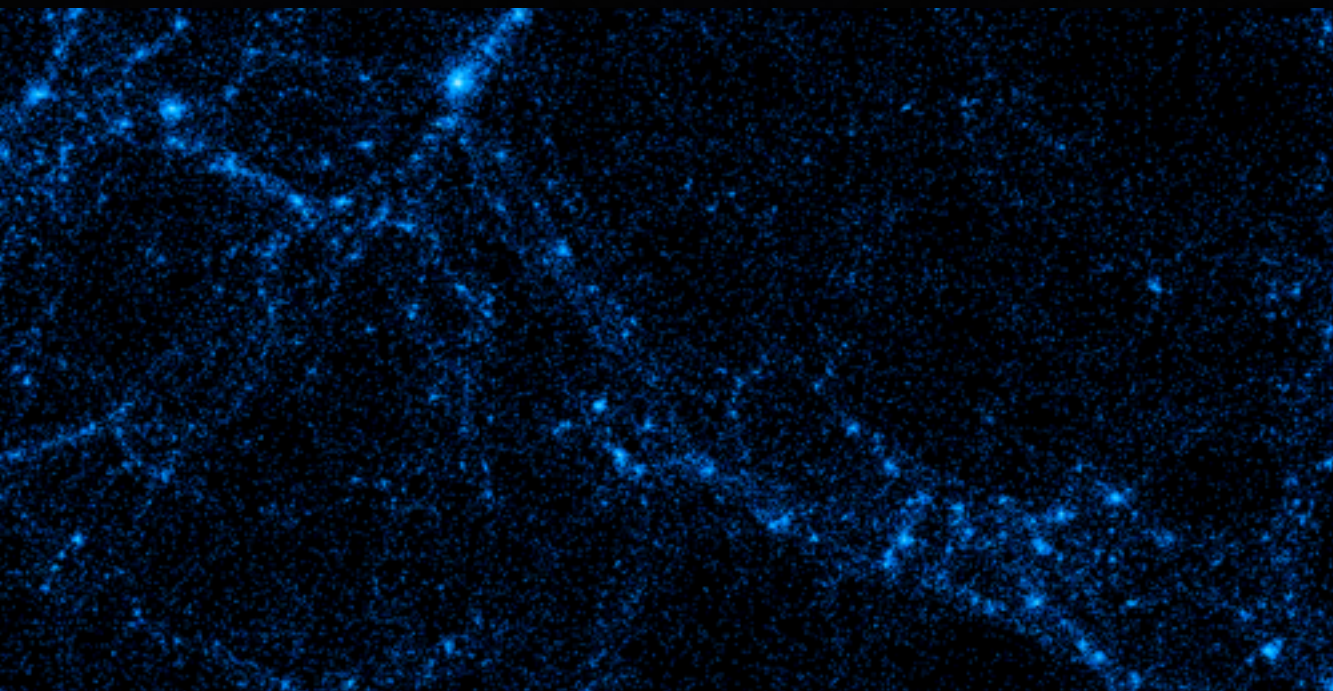
source

particles,  
“halos”  
or  
mass map

observer

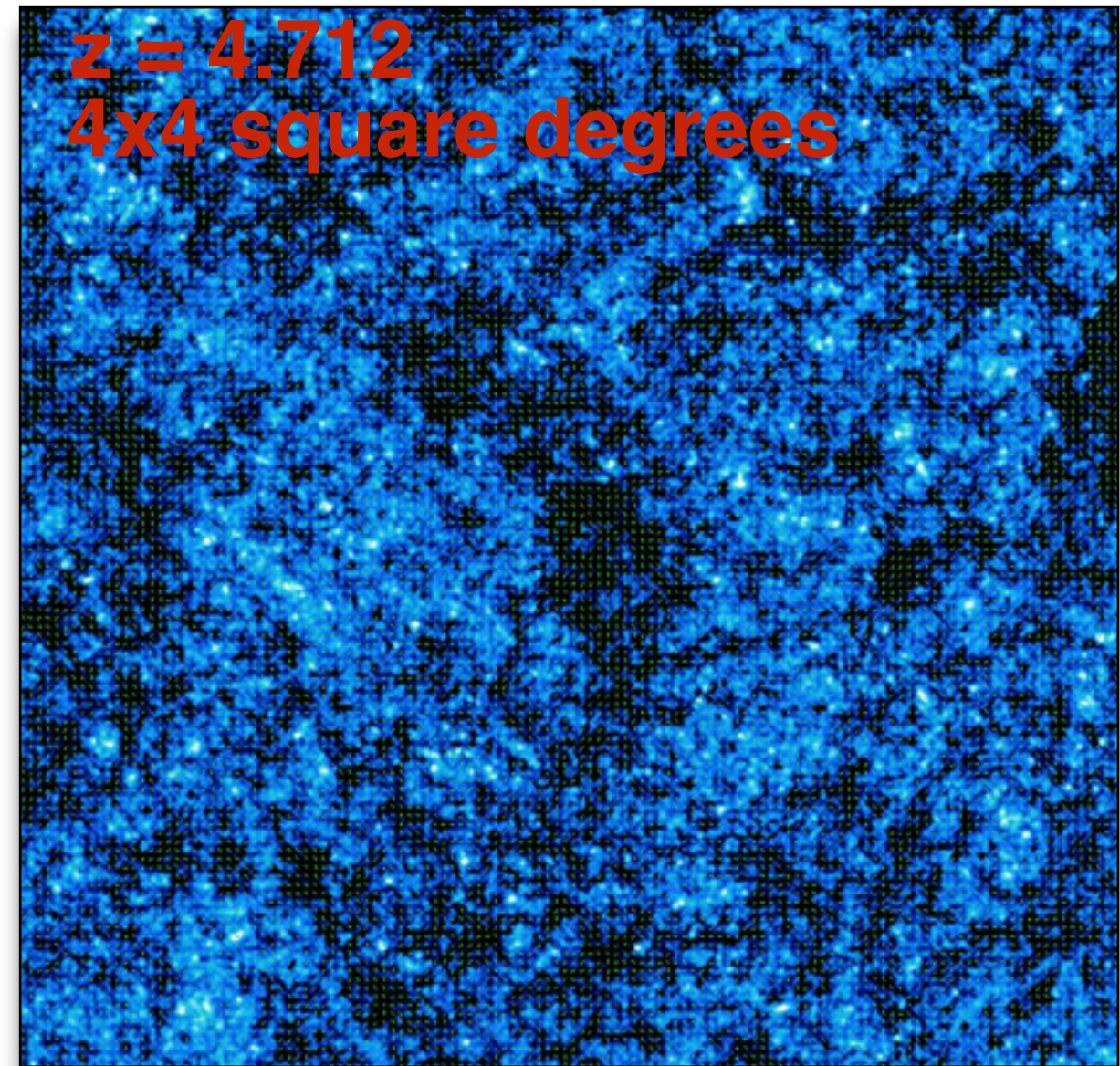
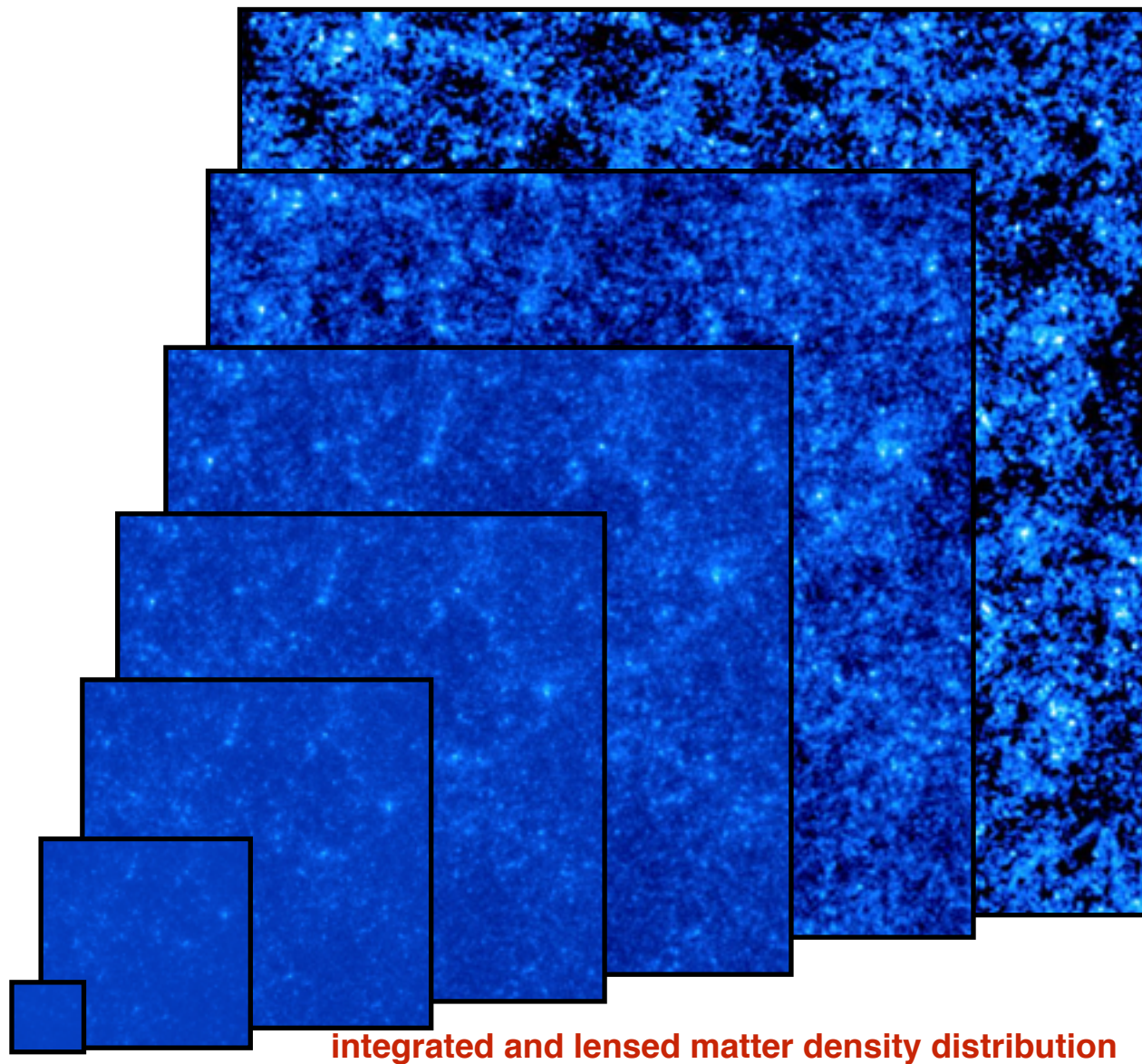








# Building up the cone from the MultiDark simulation



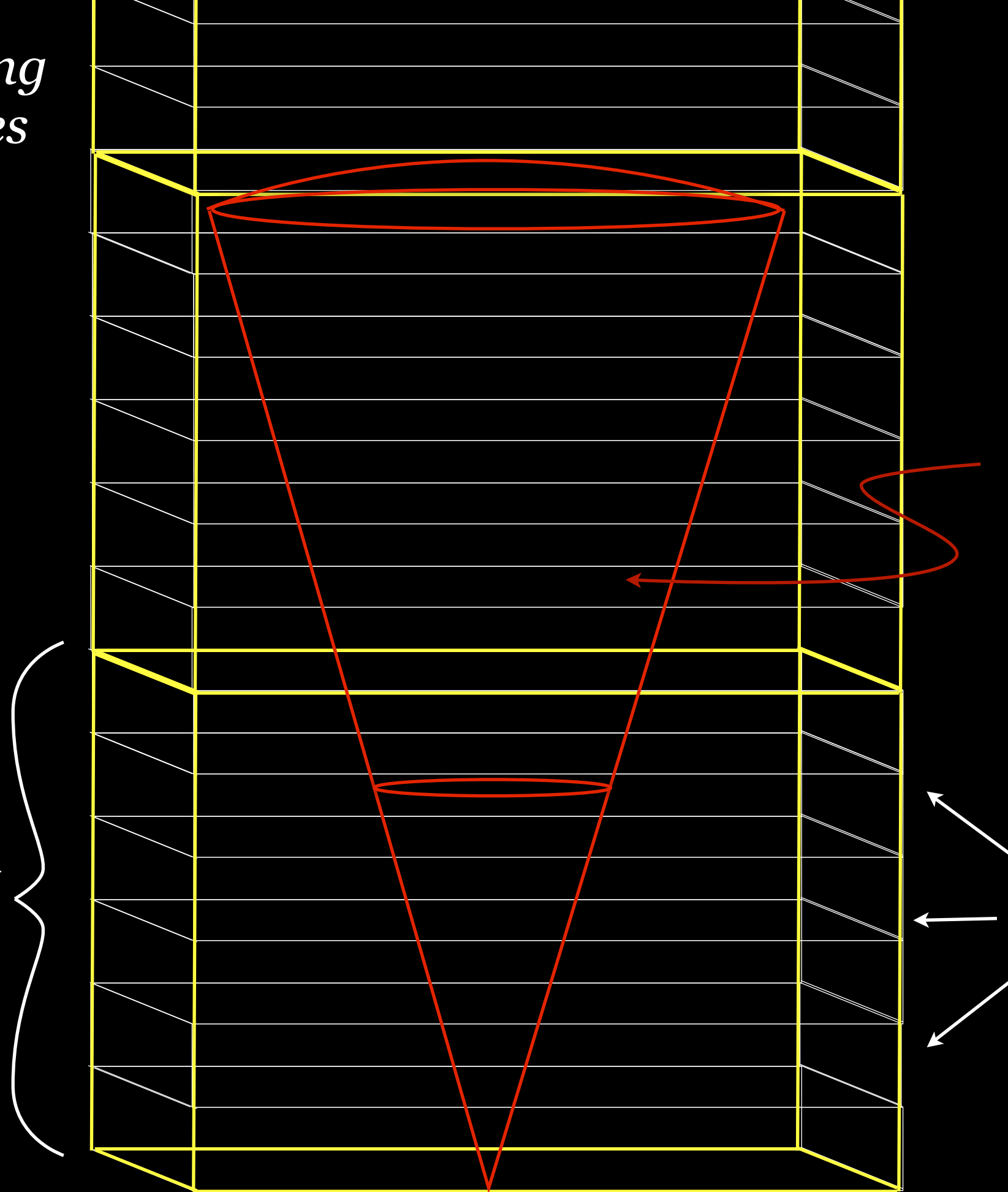


*constructing  
light-cones*

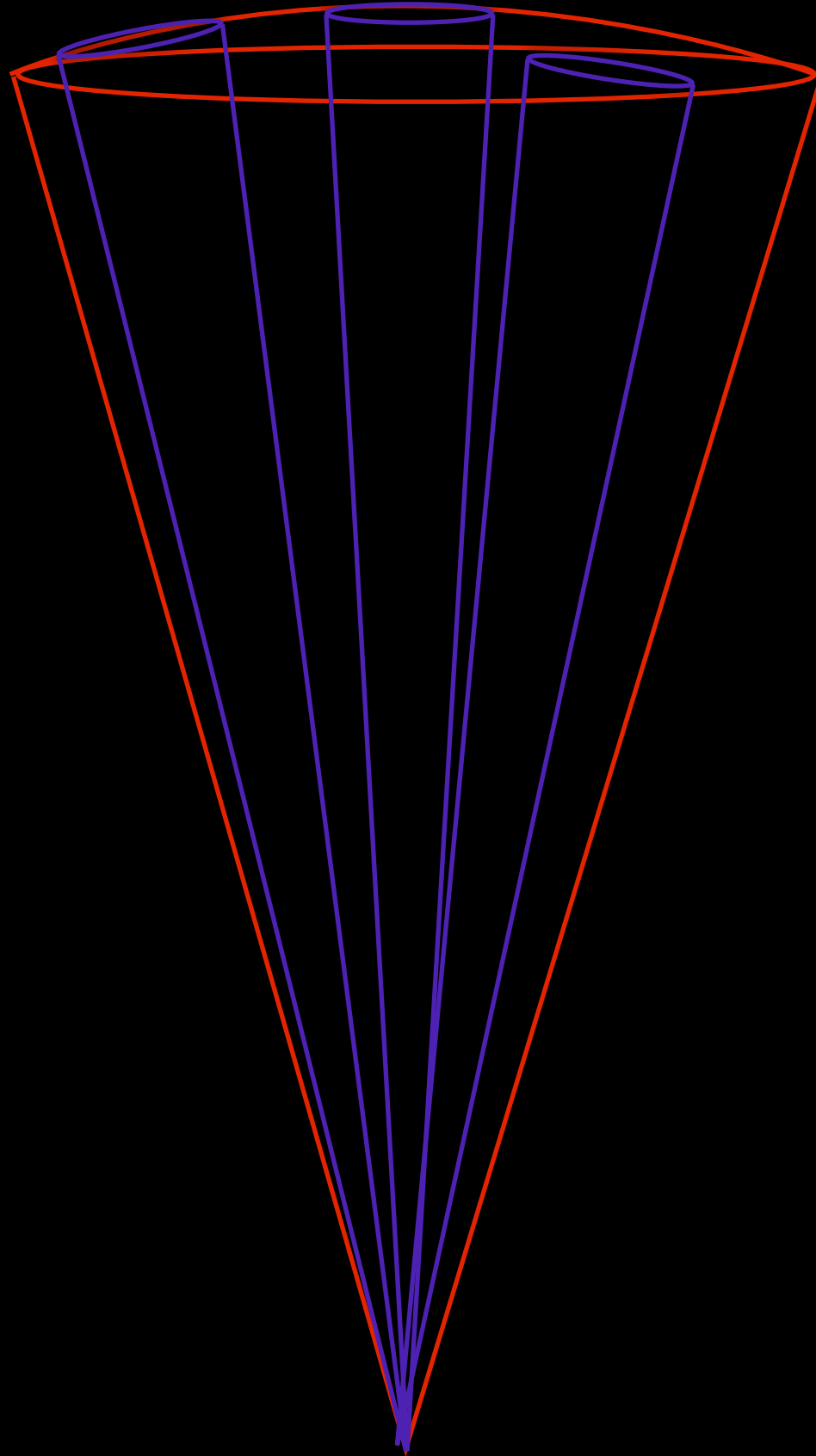
*simulation  
box*

*light-cone*

*simulation  
snapshots*

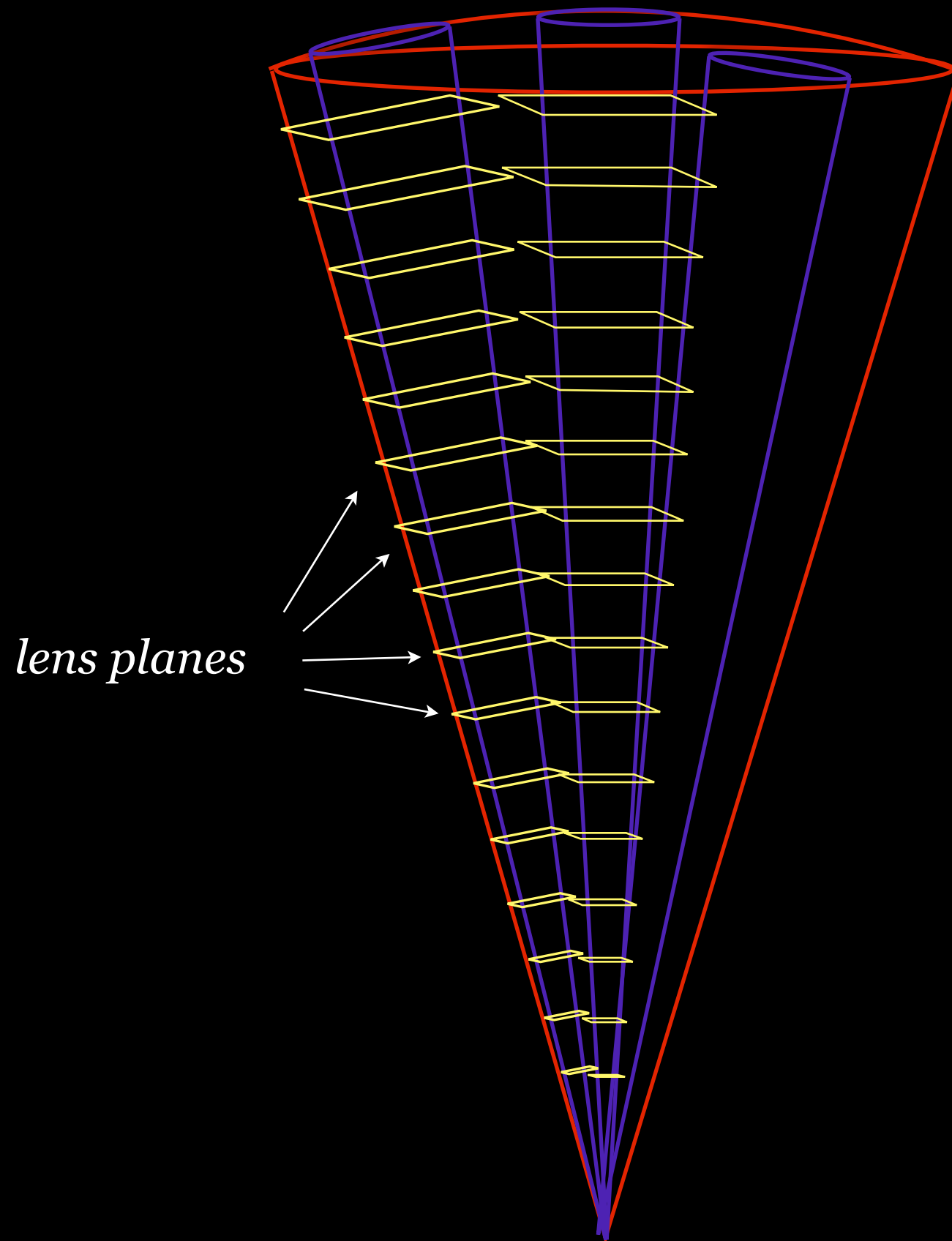


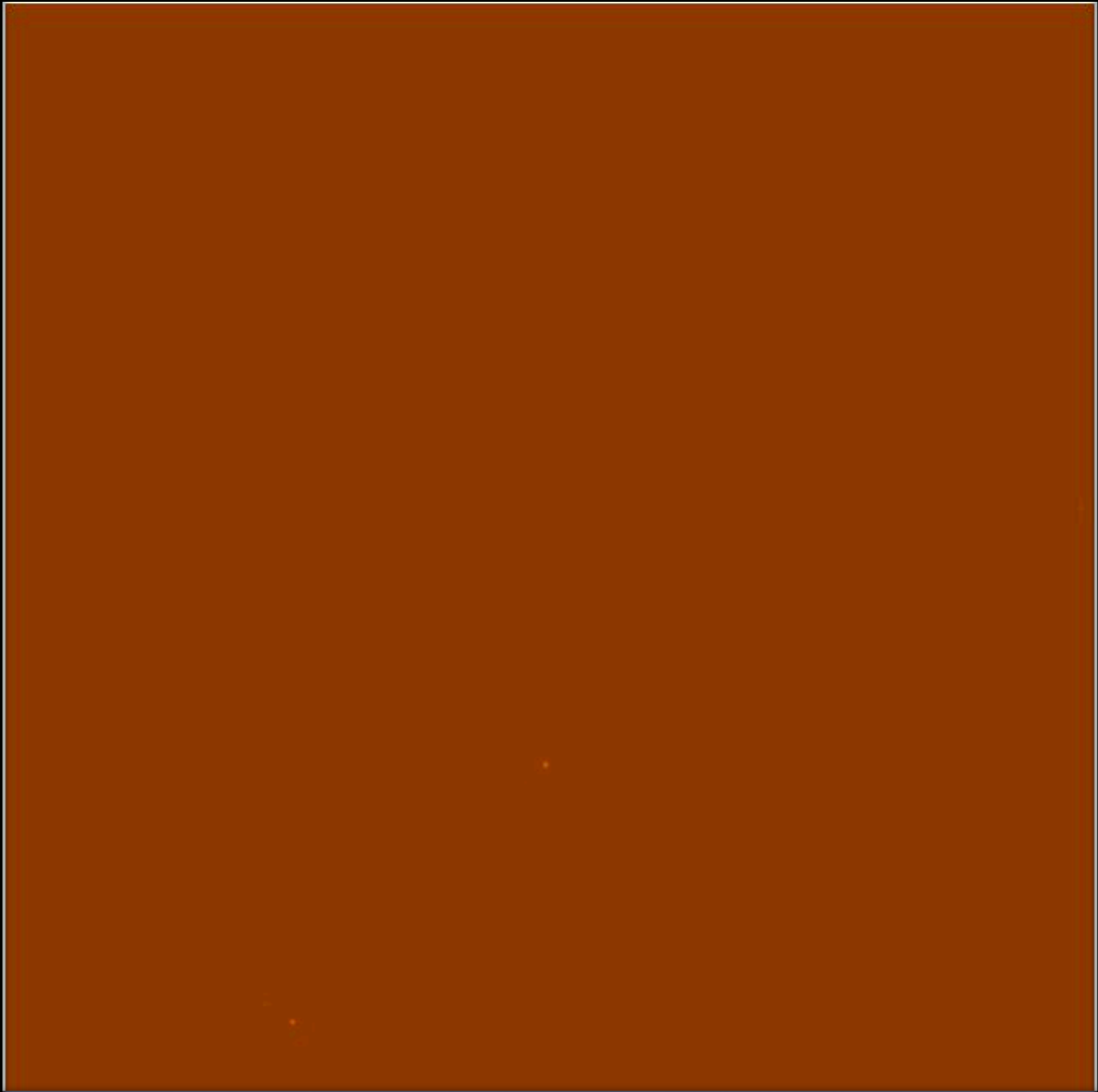
*constructing  
light-cones*



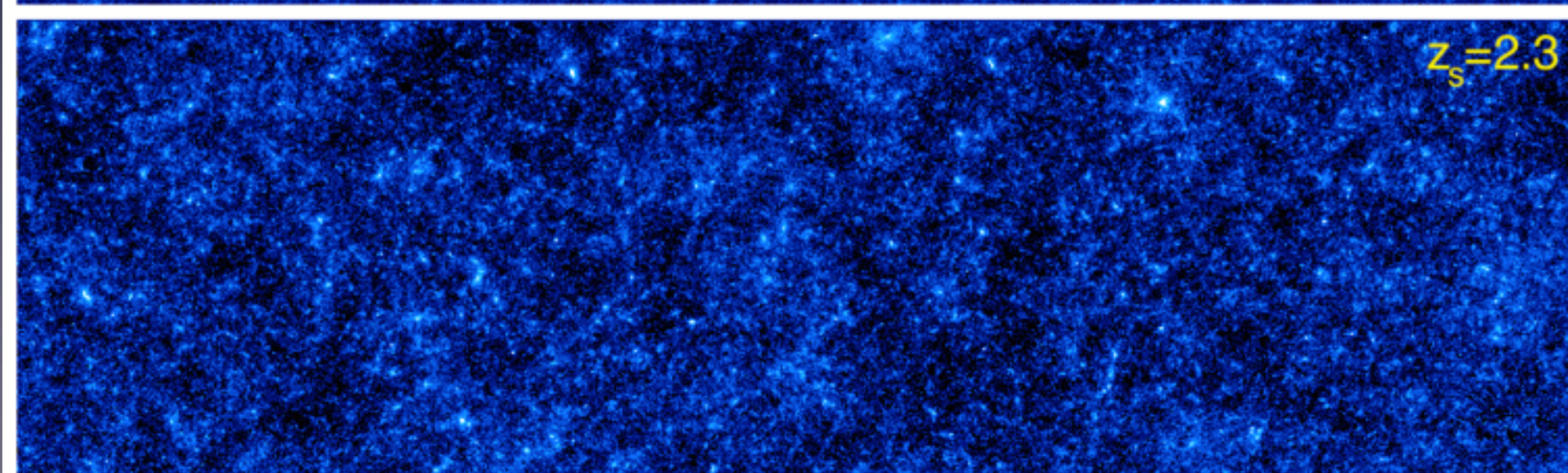
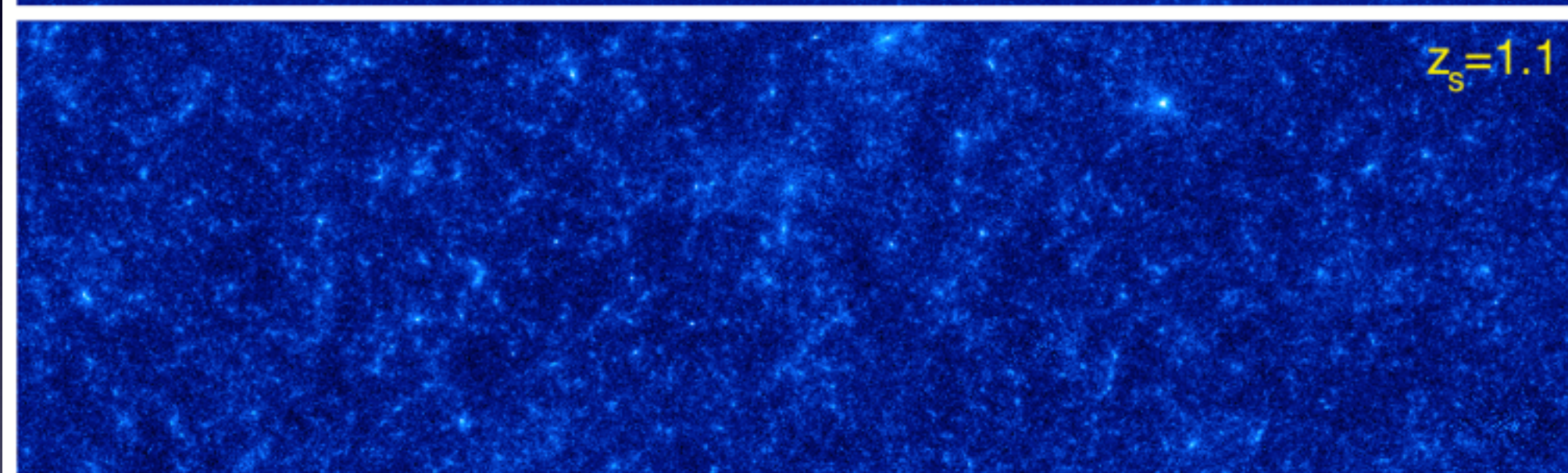
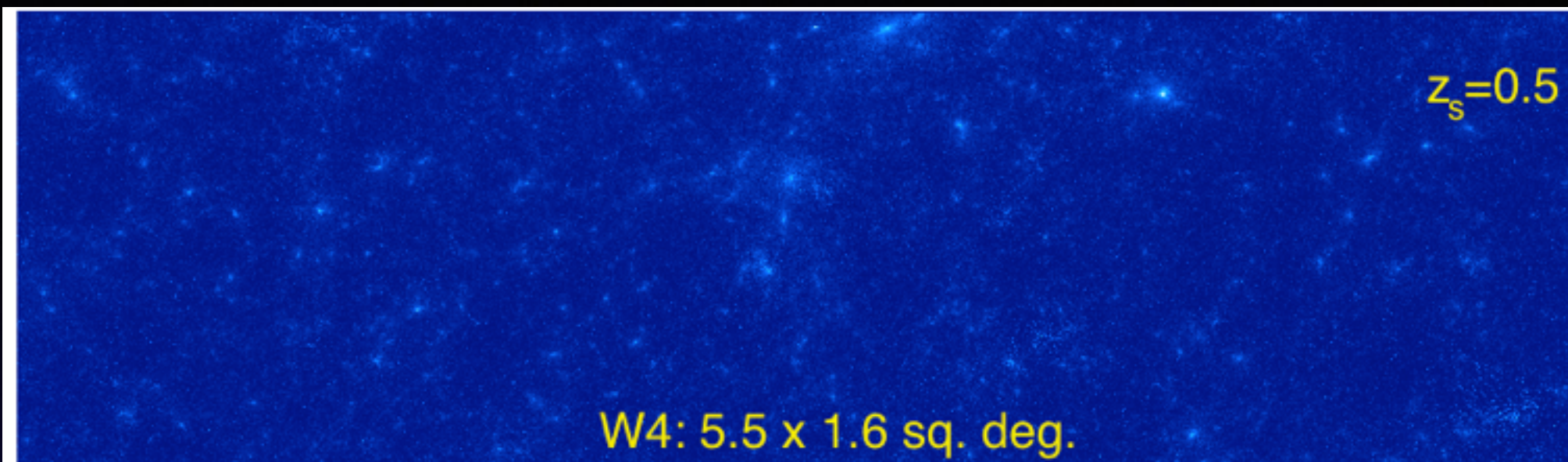


*constructing  
light-cones*

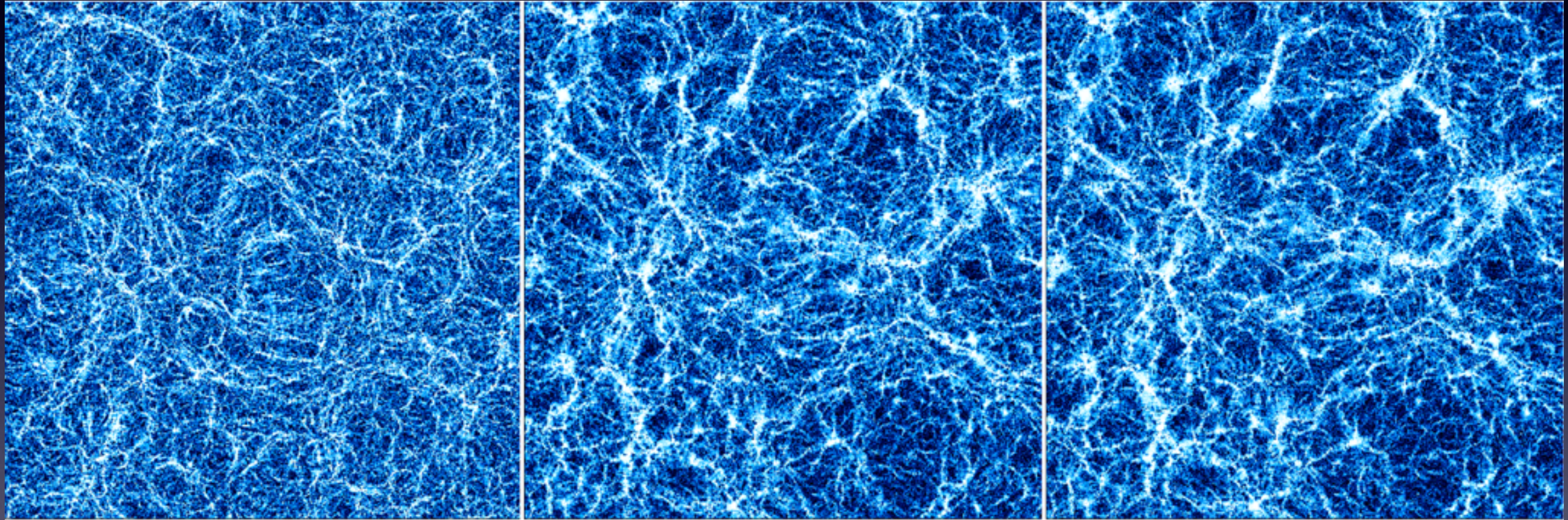




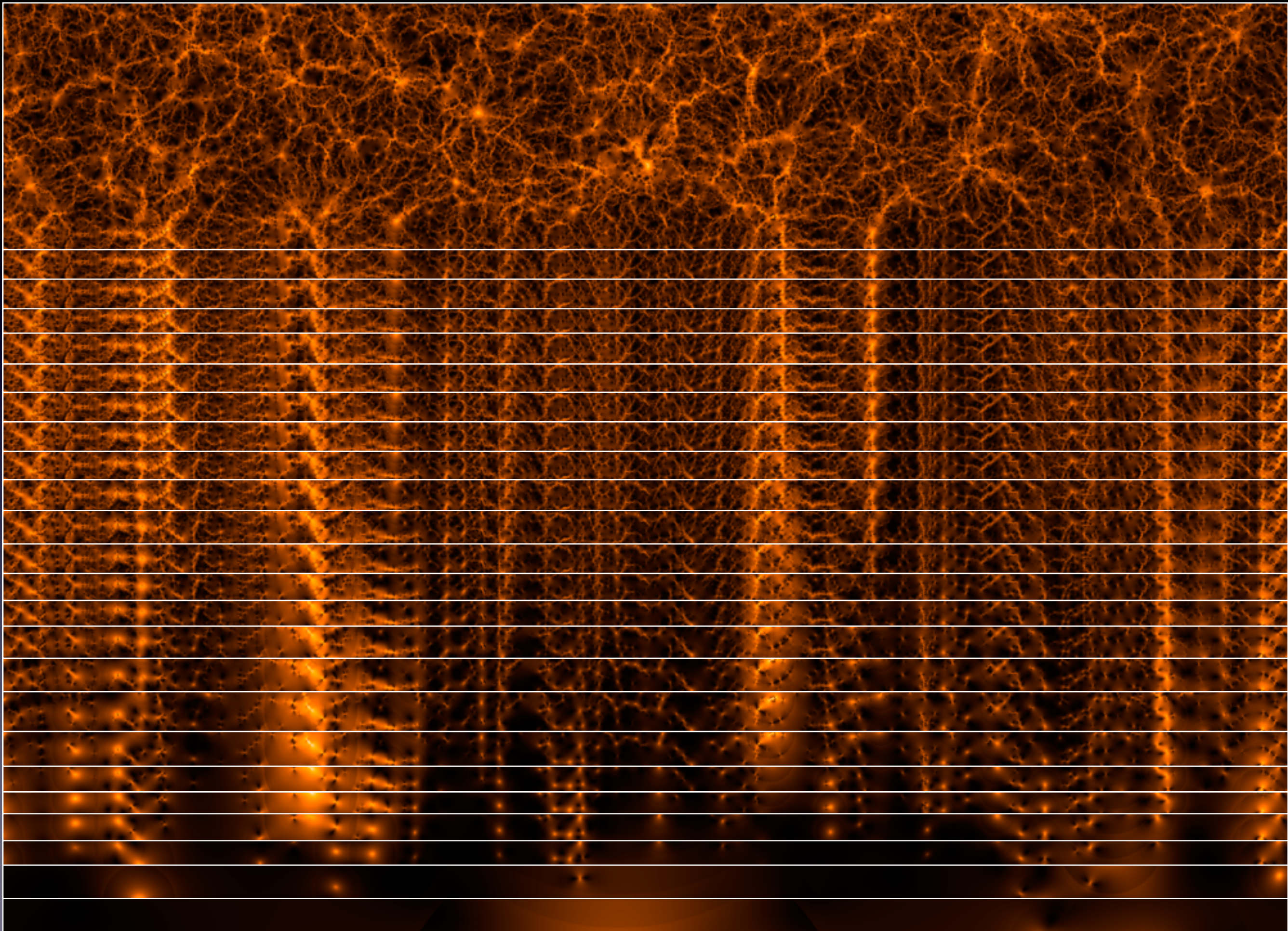






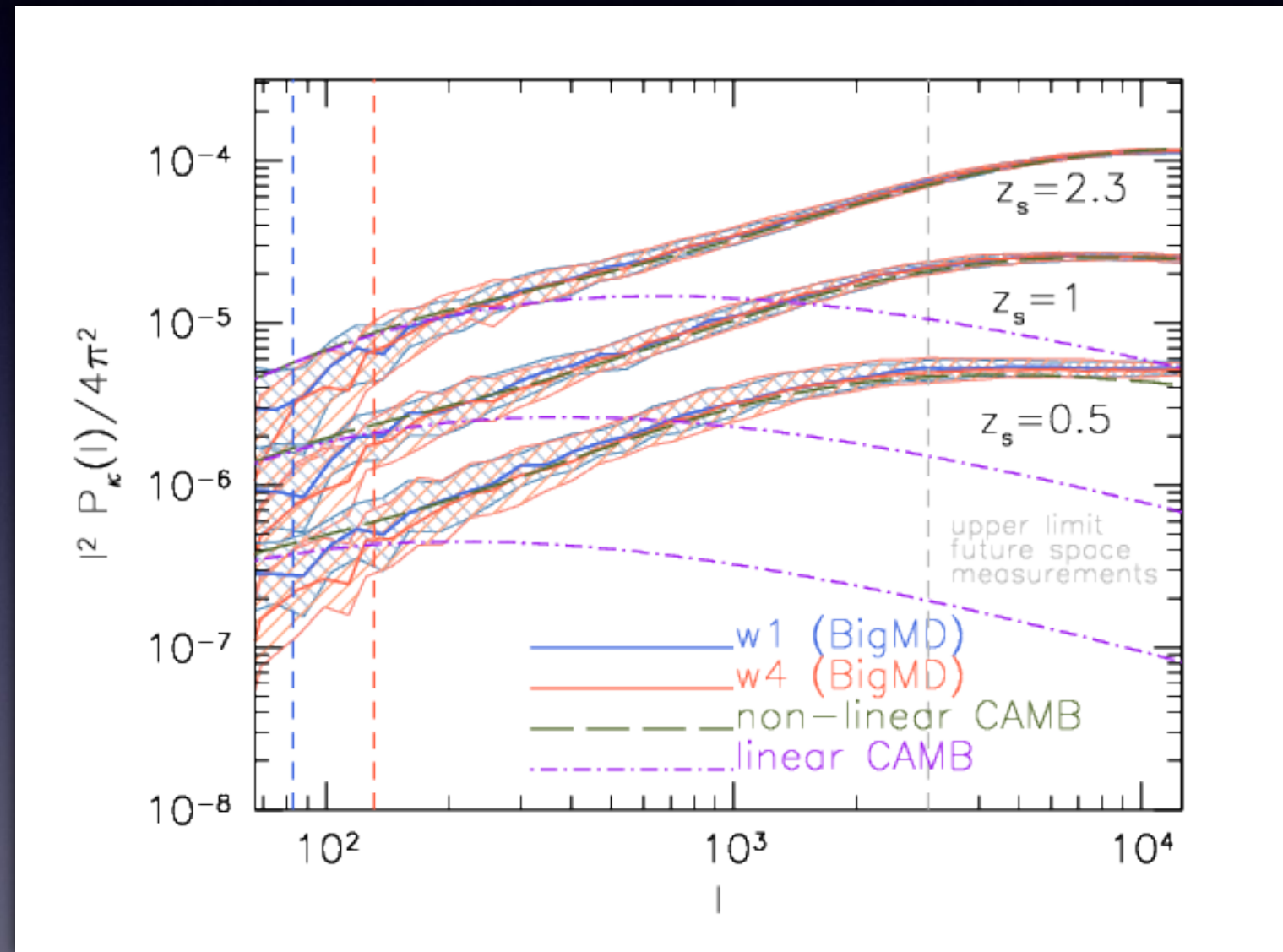






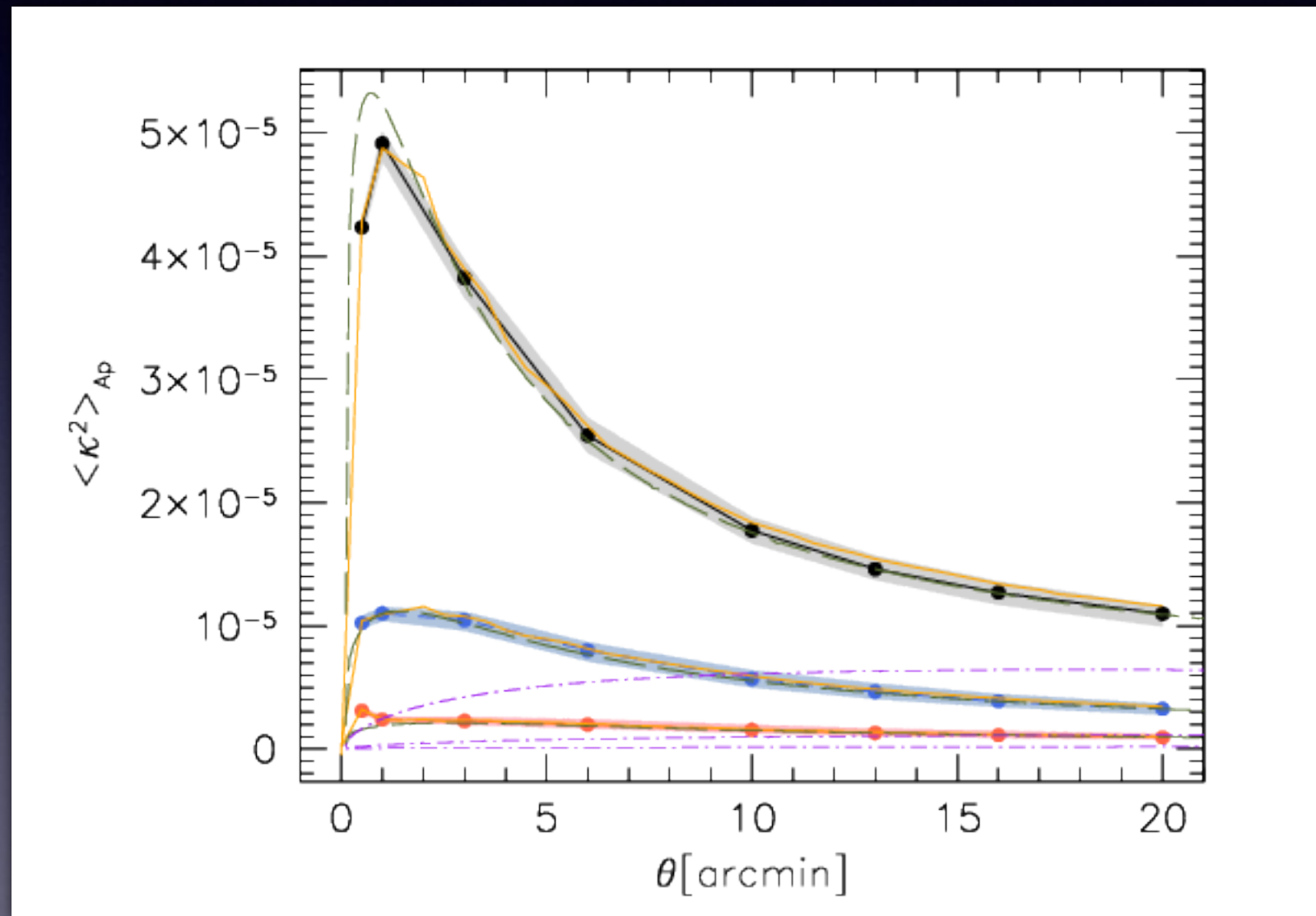


# Convergence Power Spectrum



Giocoli, Jullo, Metcalf et al

# *Variance of the Compensated Aperture Filter*



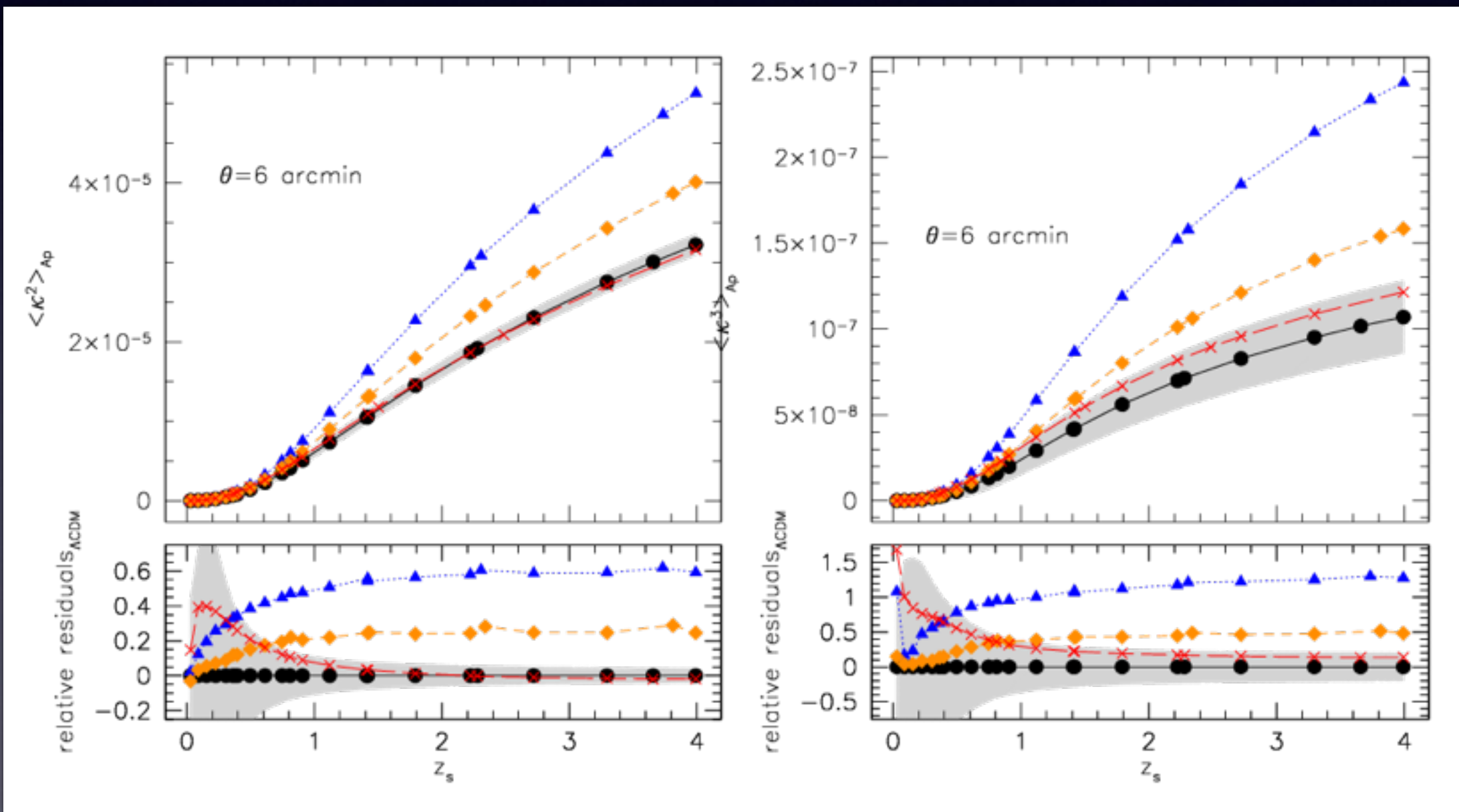
*Giocoli, Jullo, Metcalf et al*

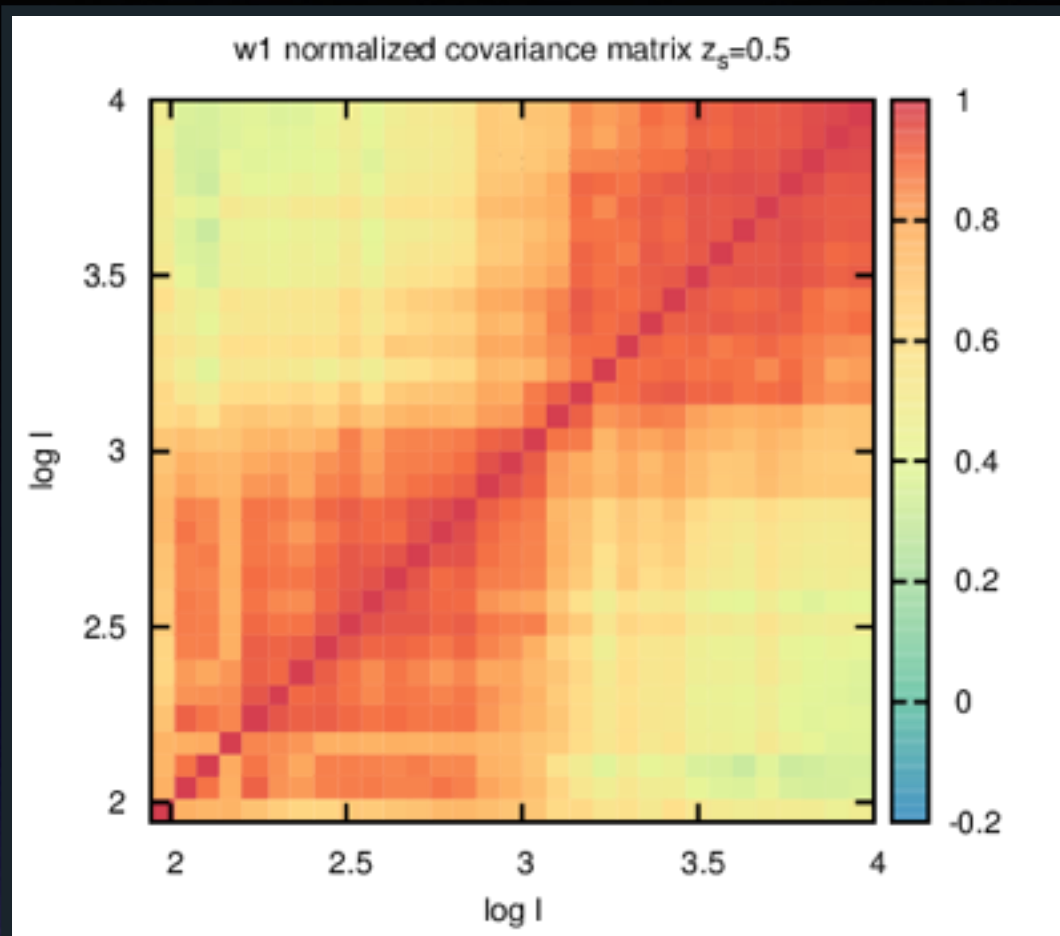


# Lensing with the CoDECS simulation

Baldi, M. 2012  
Giocoli, et al. in prep.

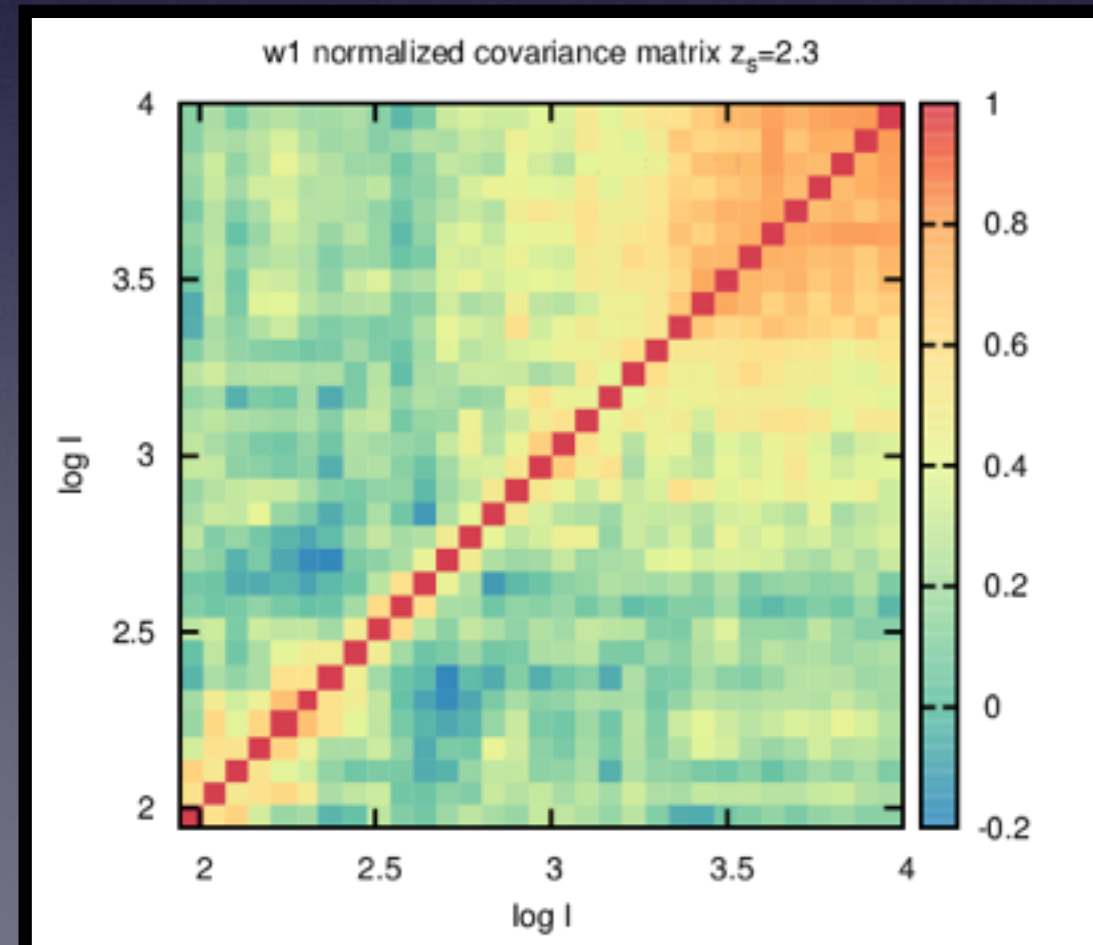
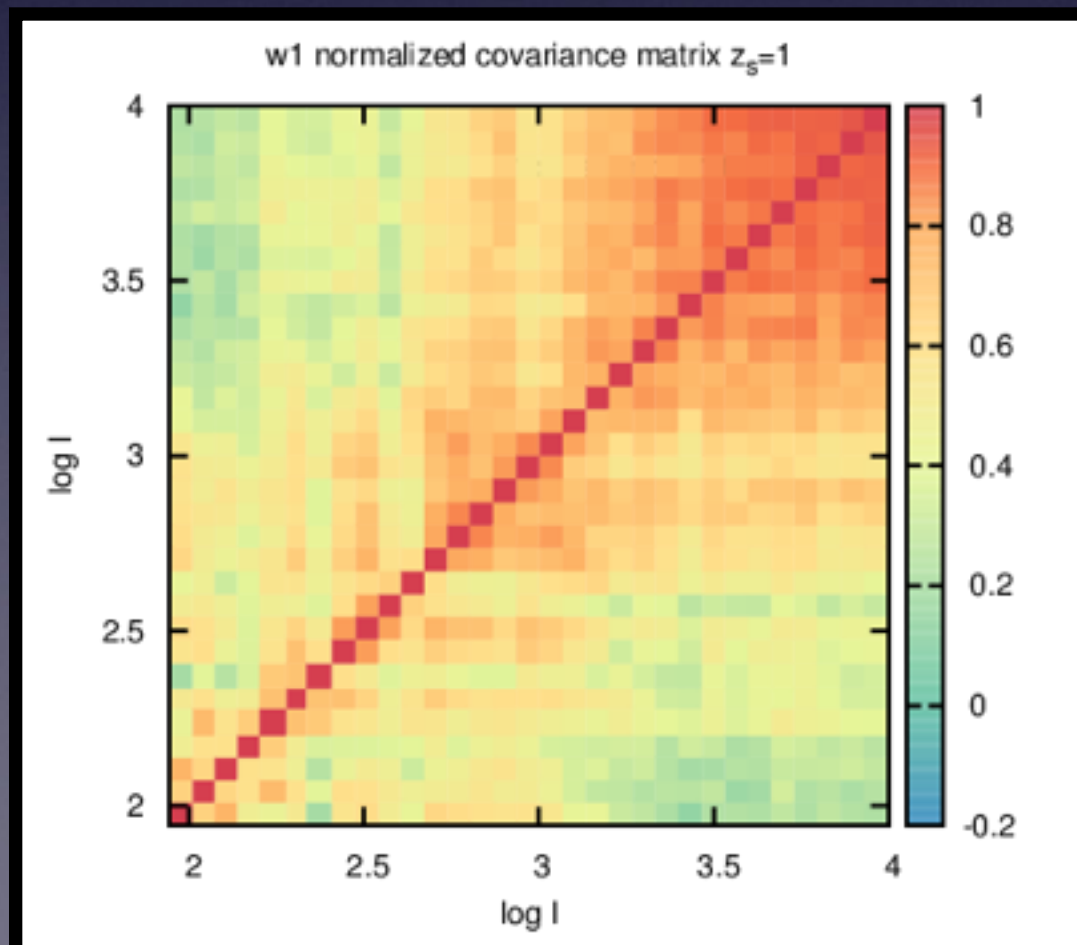
## Coupled Dark Energy Models





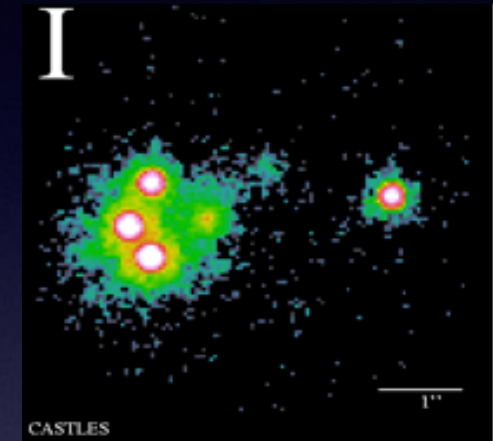
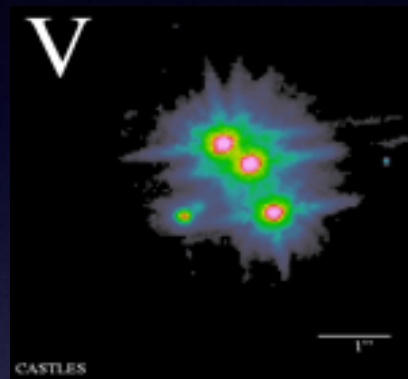
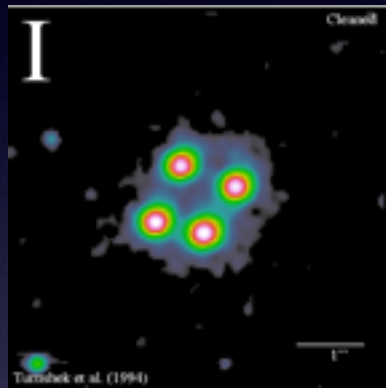
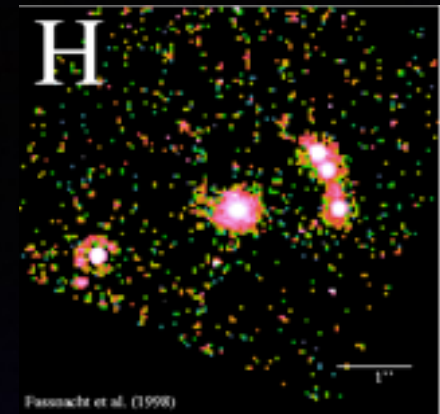
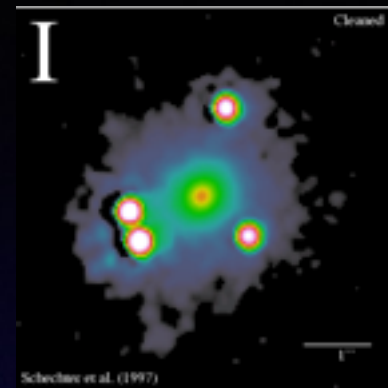
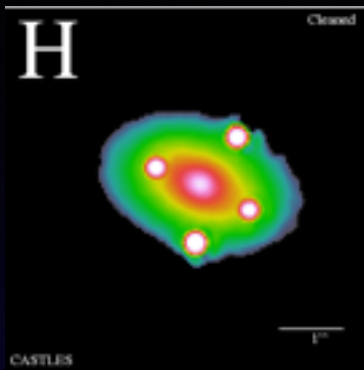
*correlation matrix  
for  $P(k)$*

$$M(l, l') = \langle [P(l) - \bar{P}(l)][P(l') - \bar{P}(l')] \rangle$$

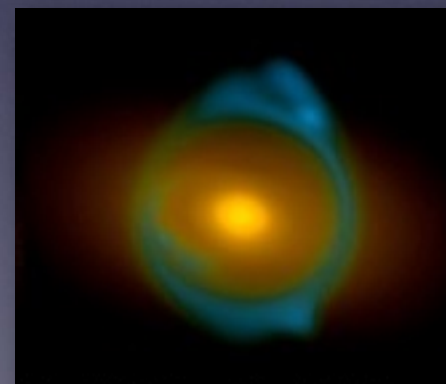
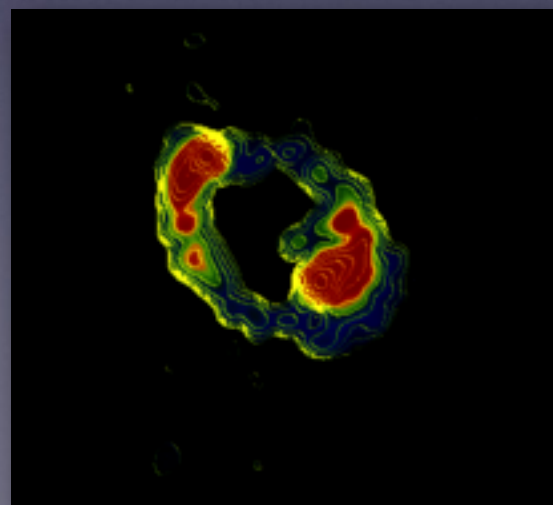


# Galaxy Scale Strong Lenses

## Galaxy - QSO Lenses

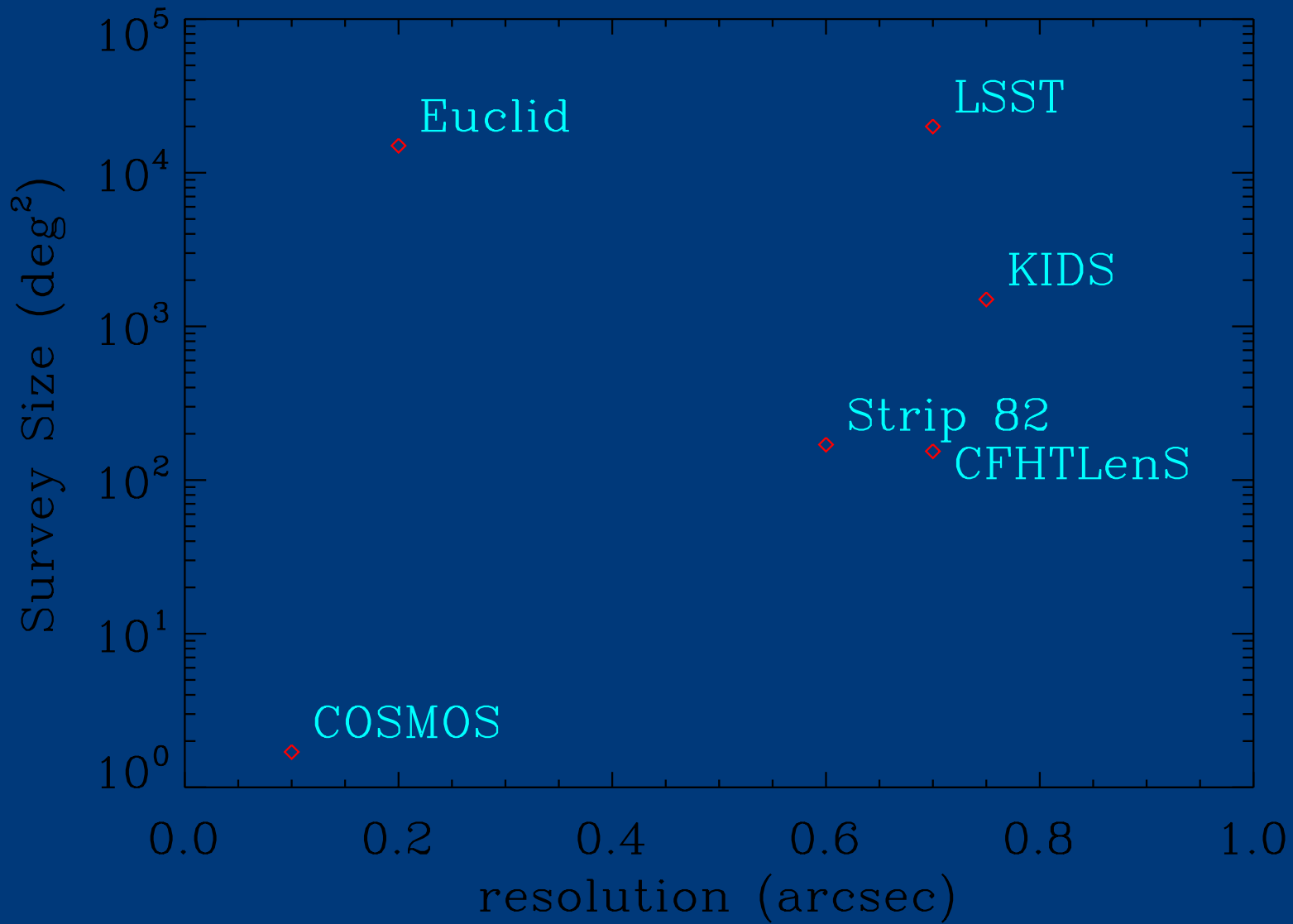


## Galaxy - Galaxy Lenses

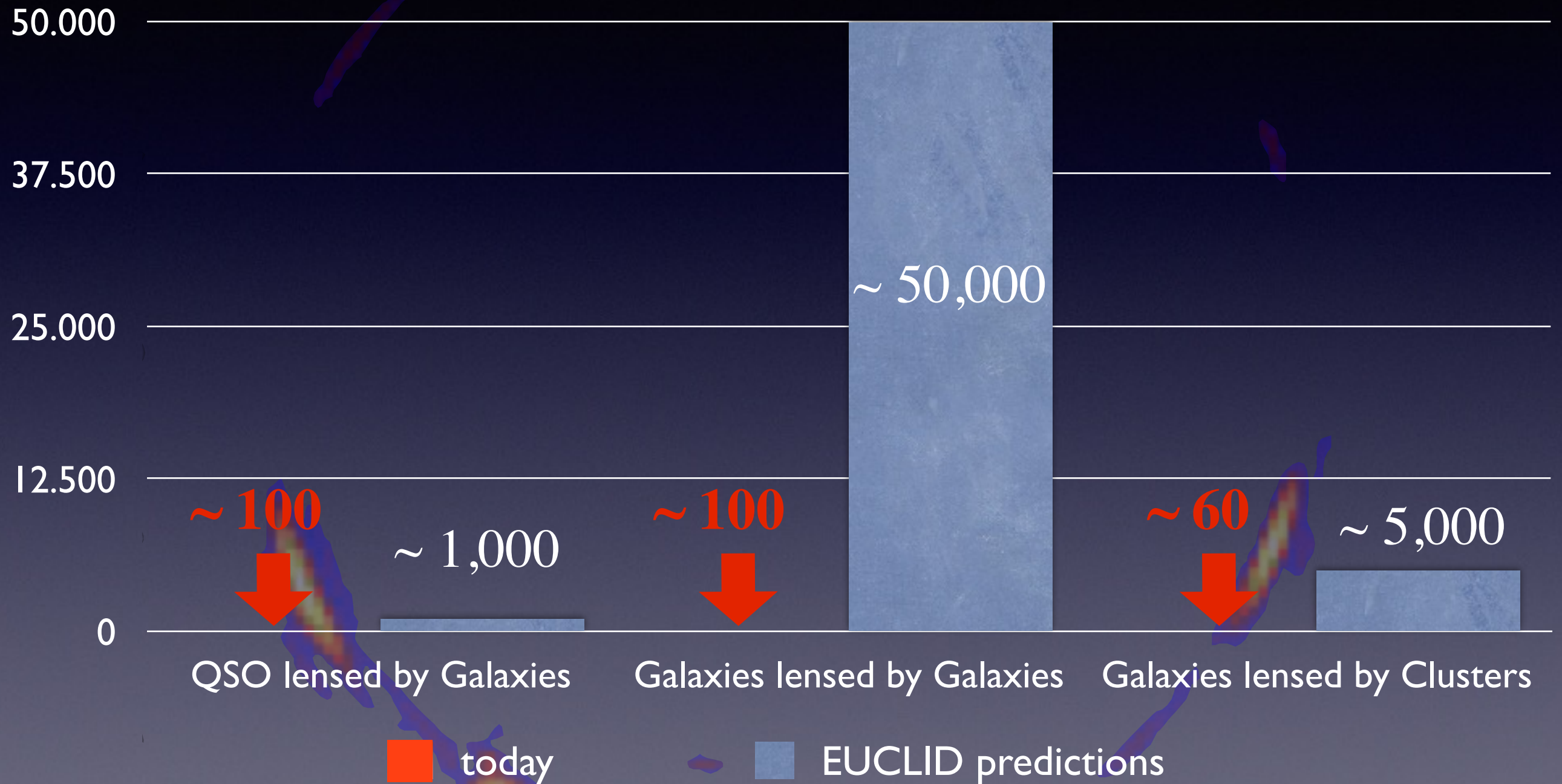




# *Imaging Surveys*



# Expected Number of Strong Gravitational Lenses



Future Data Sets : KIDS, DES, Pan-Starrs, LSST, EUCLID



# lensing simulation with *GLAMER*

## calculating deflection angle

analytic model or from particles:

- tree code deflection solver
- modified algorithm to handle halos efficiently

adaptive smoothing for Nbody/hydro particles

multiple lens planes:  
3d along light paths

## lens model

- single analytic lens
- multiple analytic halos
- Nbody/SPH particles
- point masses (stars)
- pixelized mass map

## the grid of rays

adaptive grid refinement

full image reconstruction or just shear and convergence

## source model

analytic model for surface brightness and direct pixelized images

Source Plane

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Image Plane

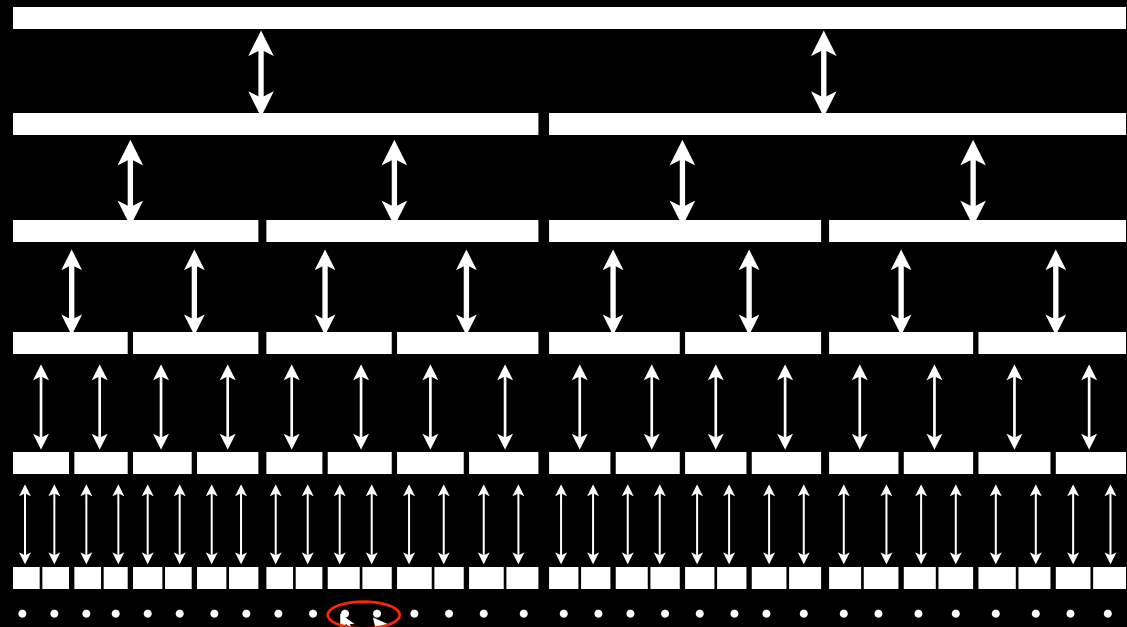
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$$\vec{\alpha}(\vec{x}), \kappa(\vec{x}), \vec{\gamma}(\vec{x})$$
$$\phi(\vec{x}), \varrho(\vec{x})$$

$$\vec{y} = \vec{x} - \vec{\alpha}(\vec{x})$$

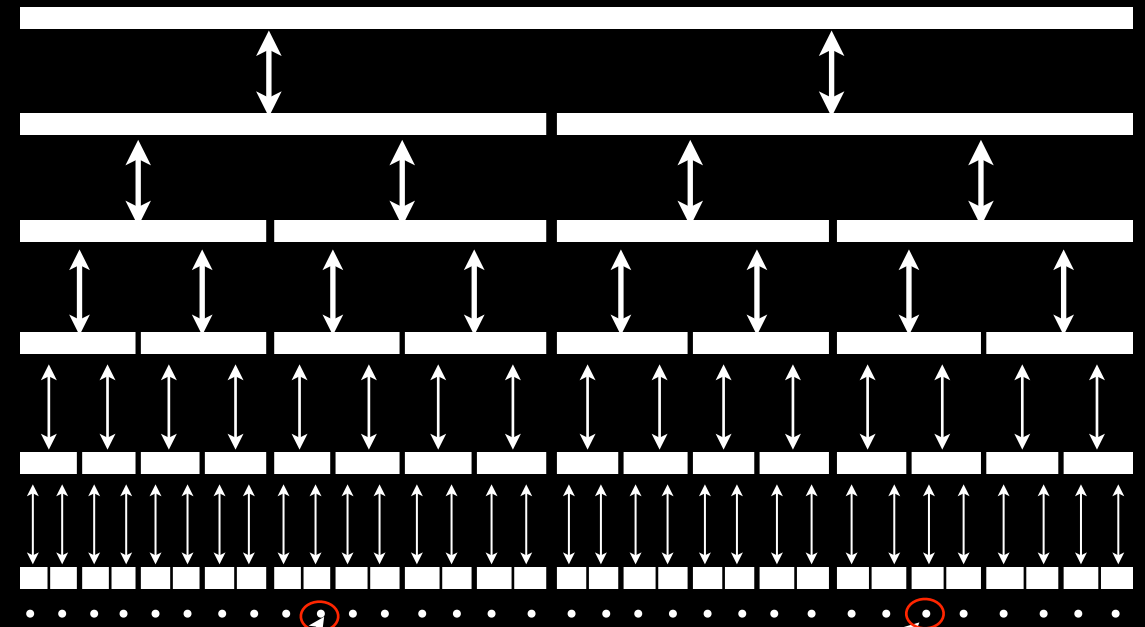


# Source Plane

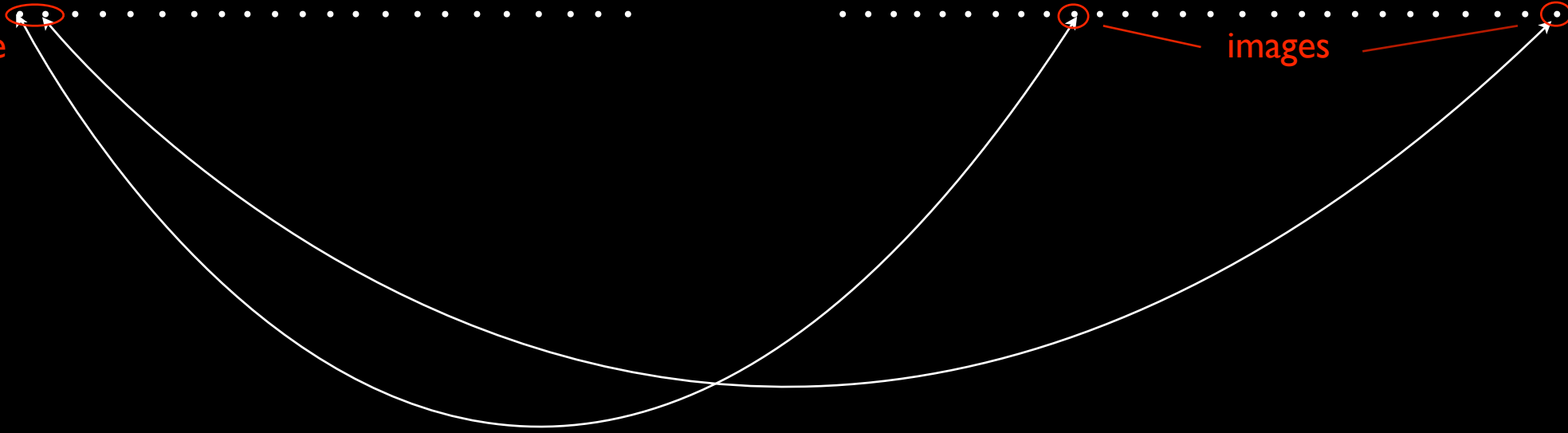


source

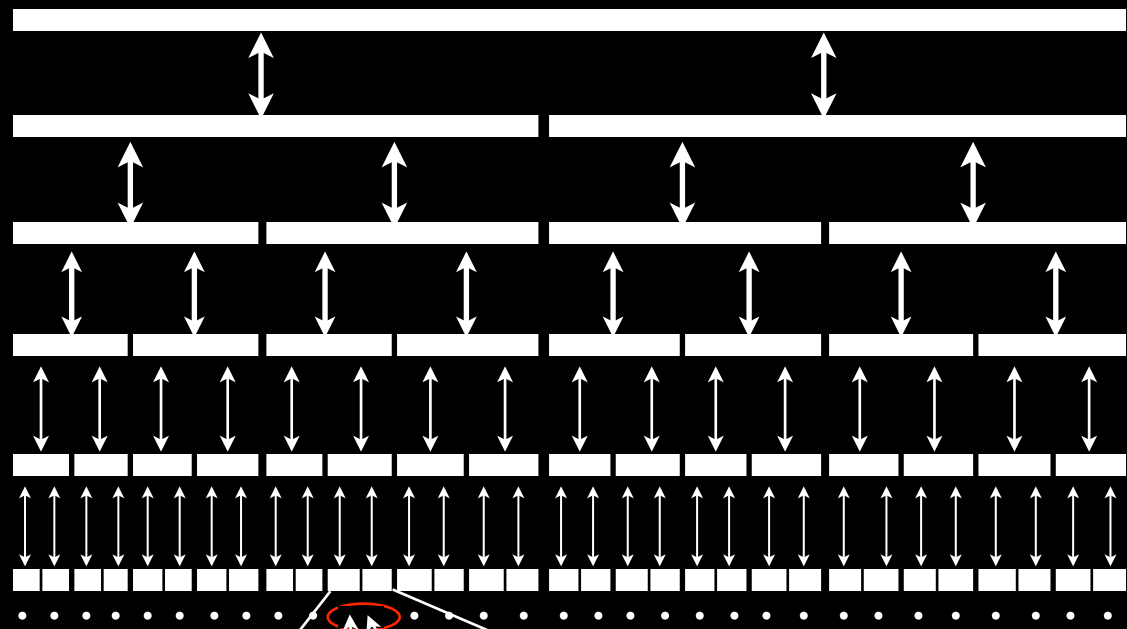
# Image Plane



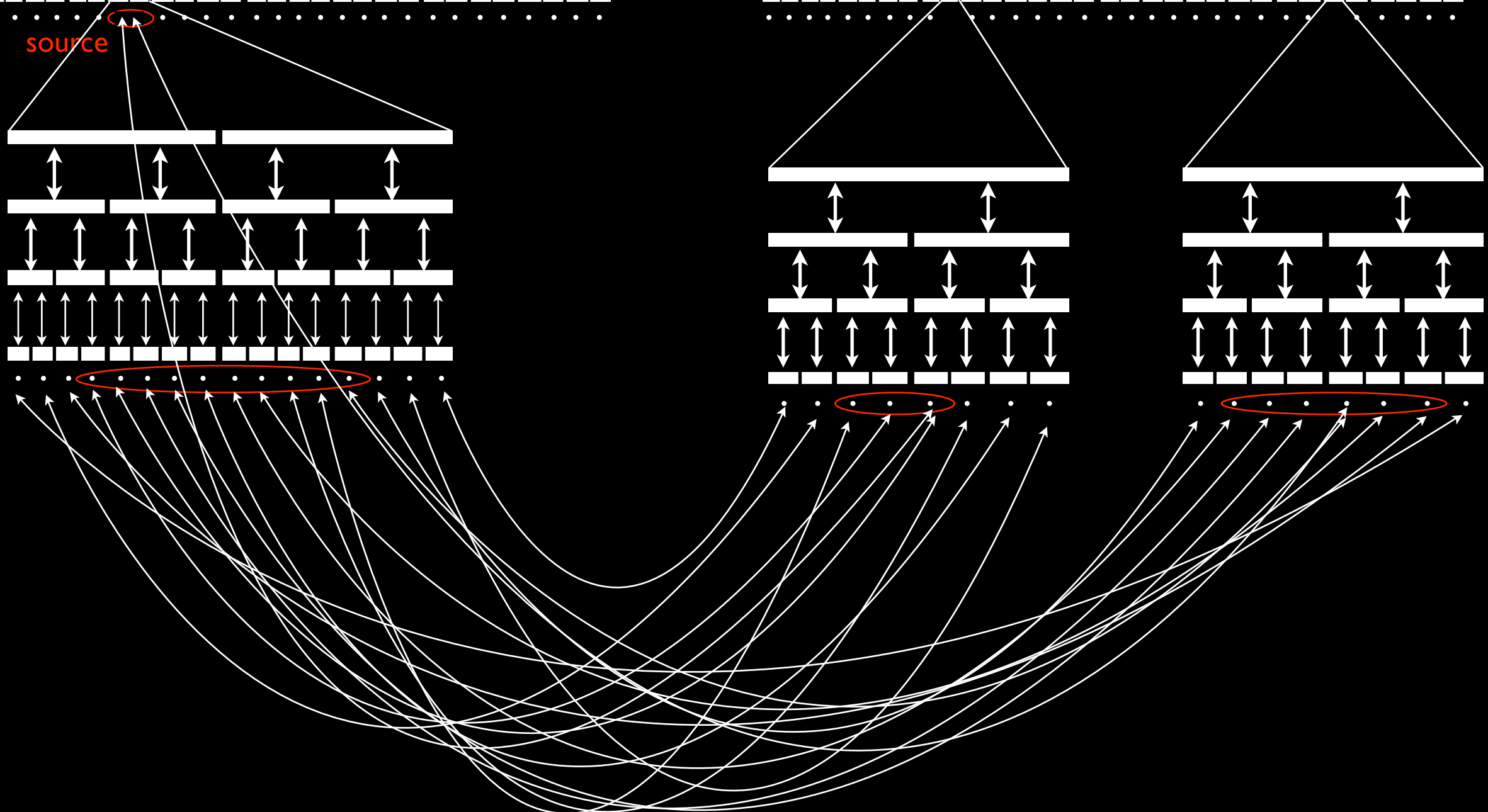
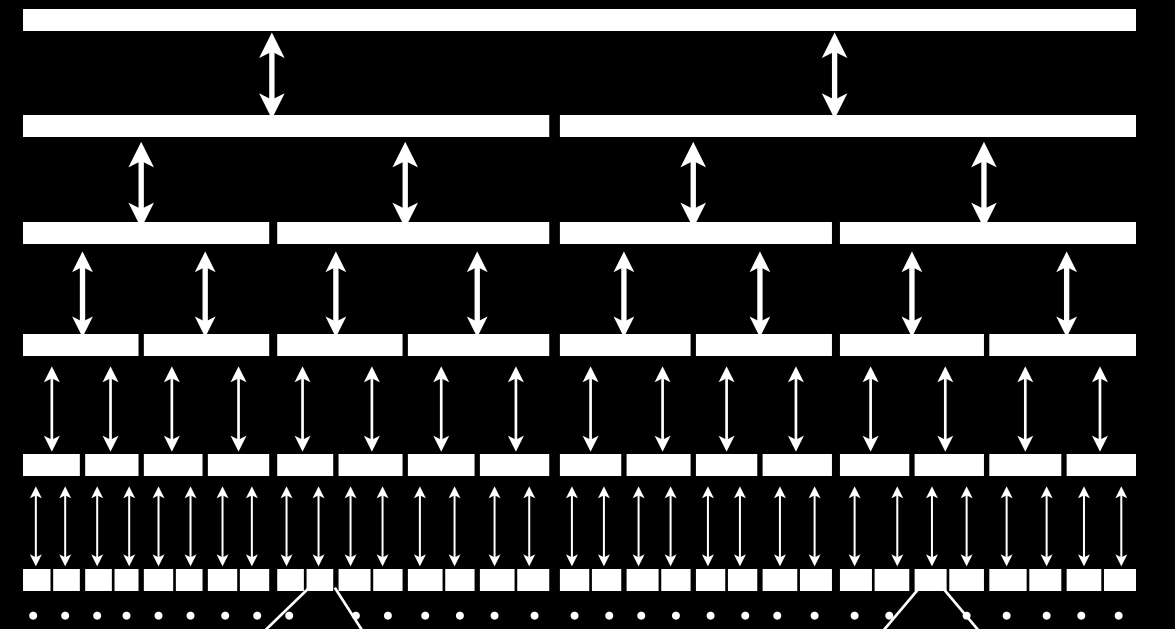
images



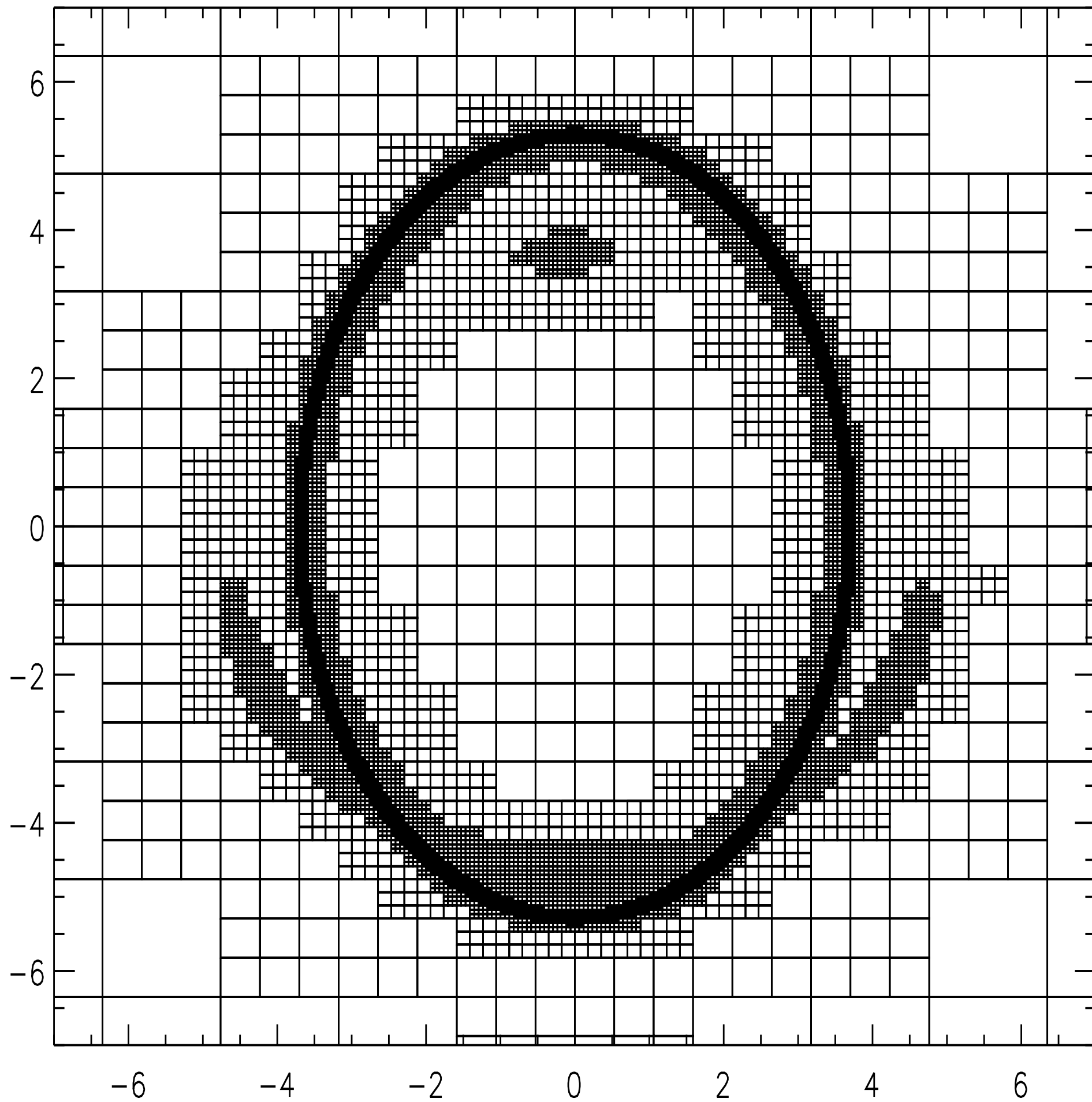
# Source Plane

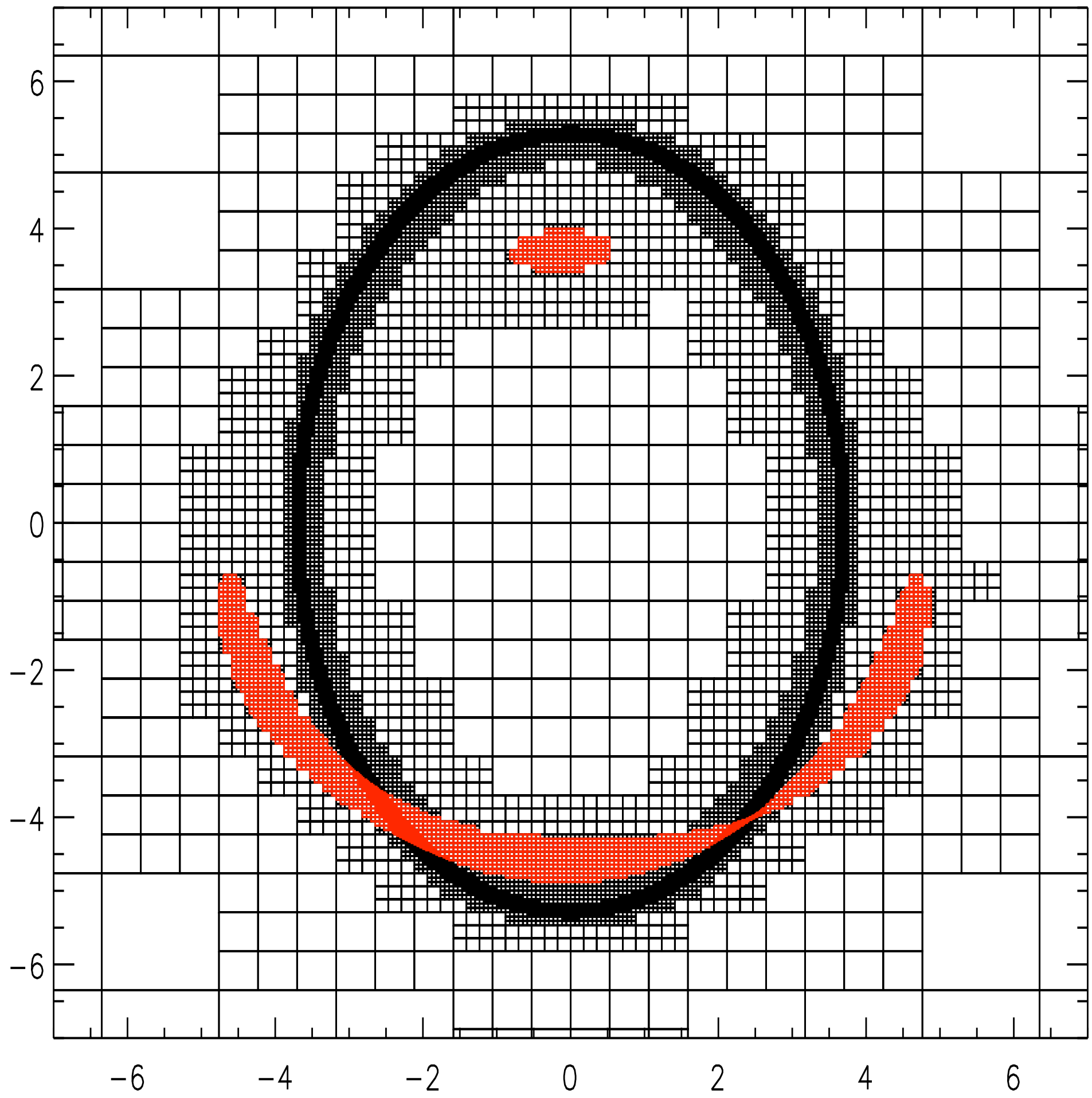


# Image Plane

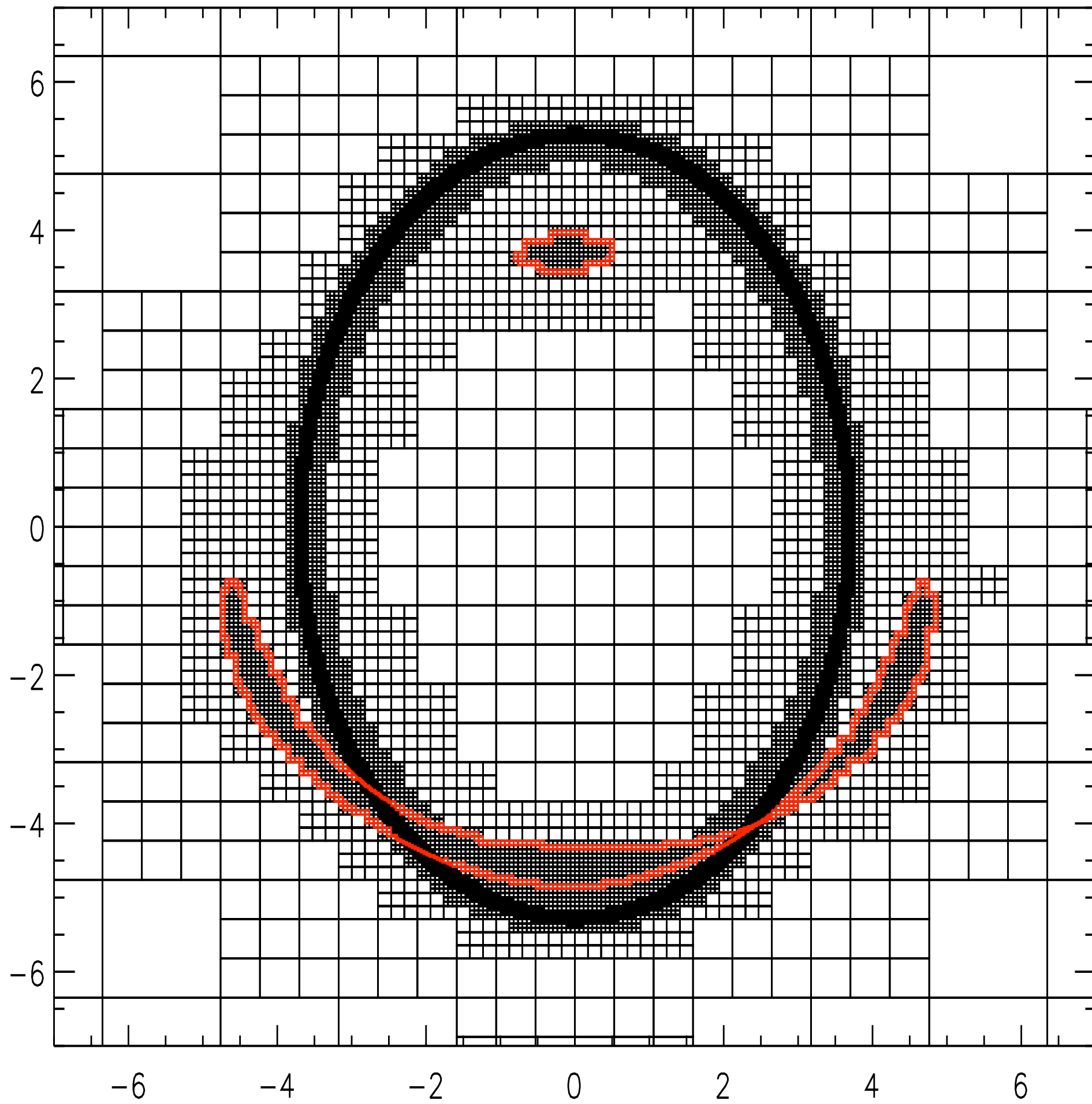


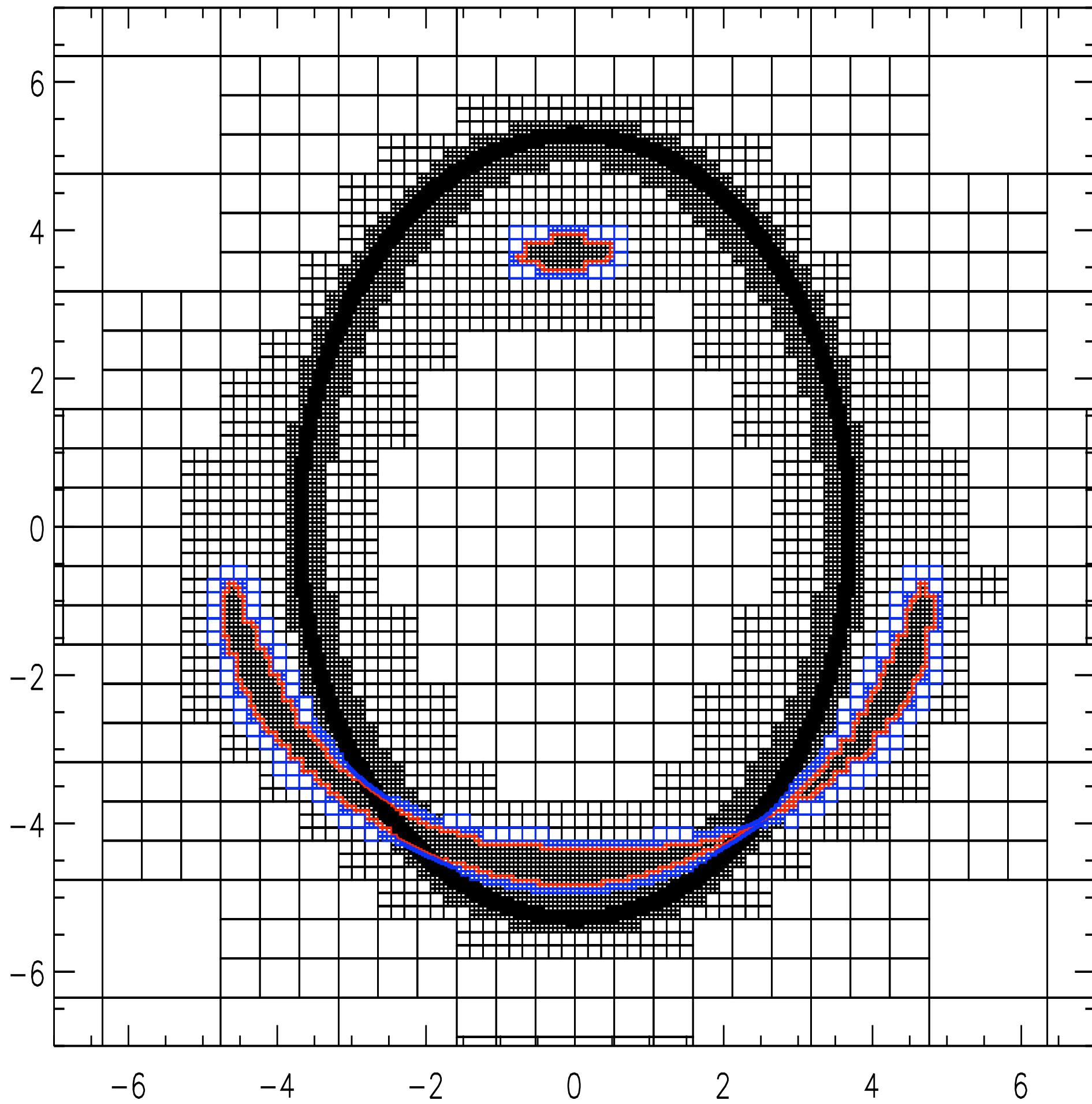




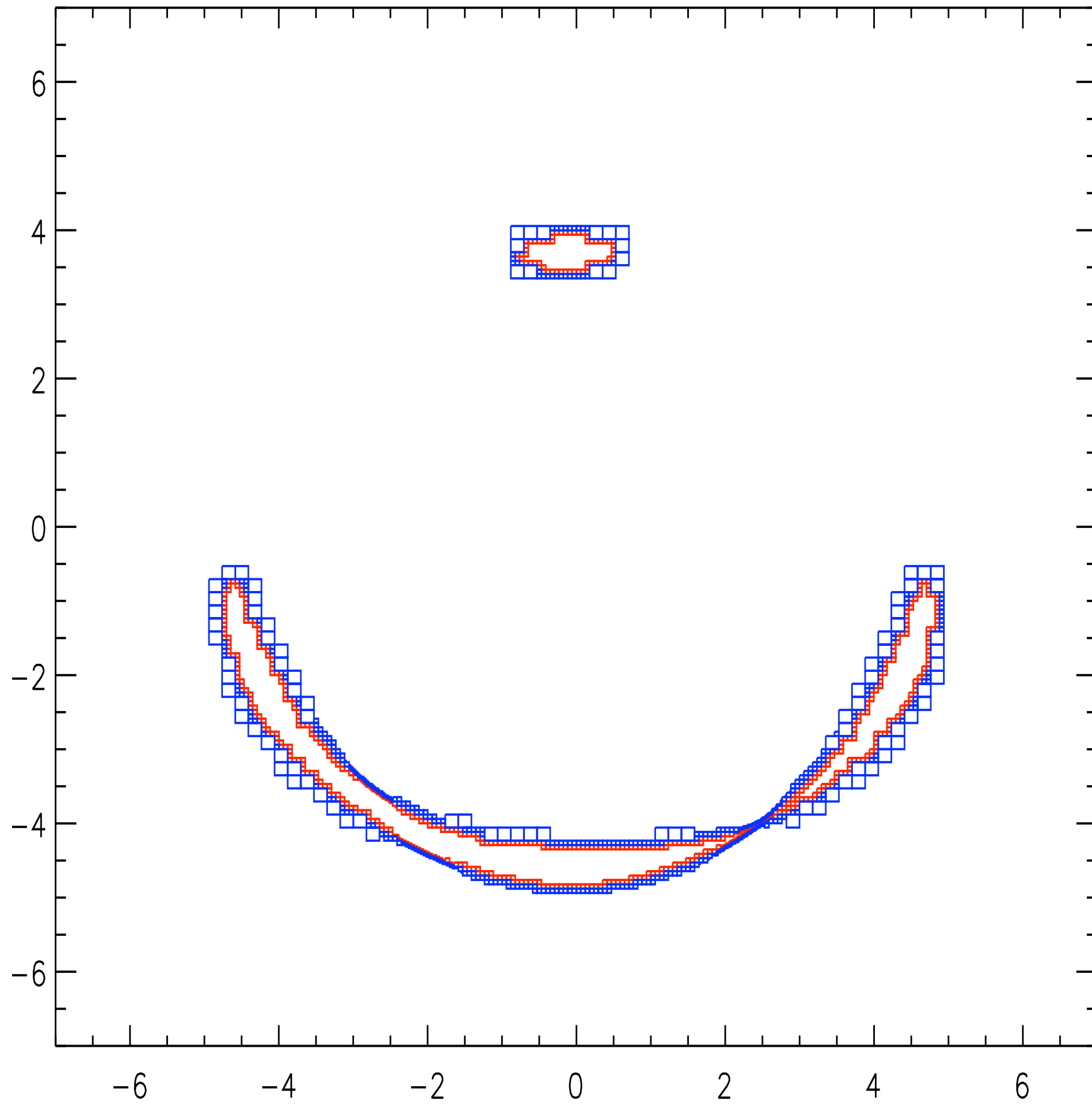




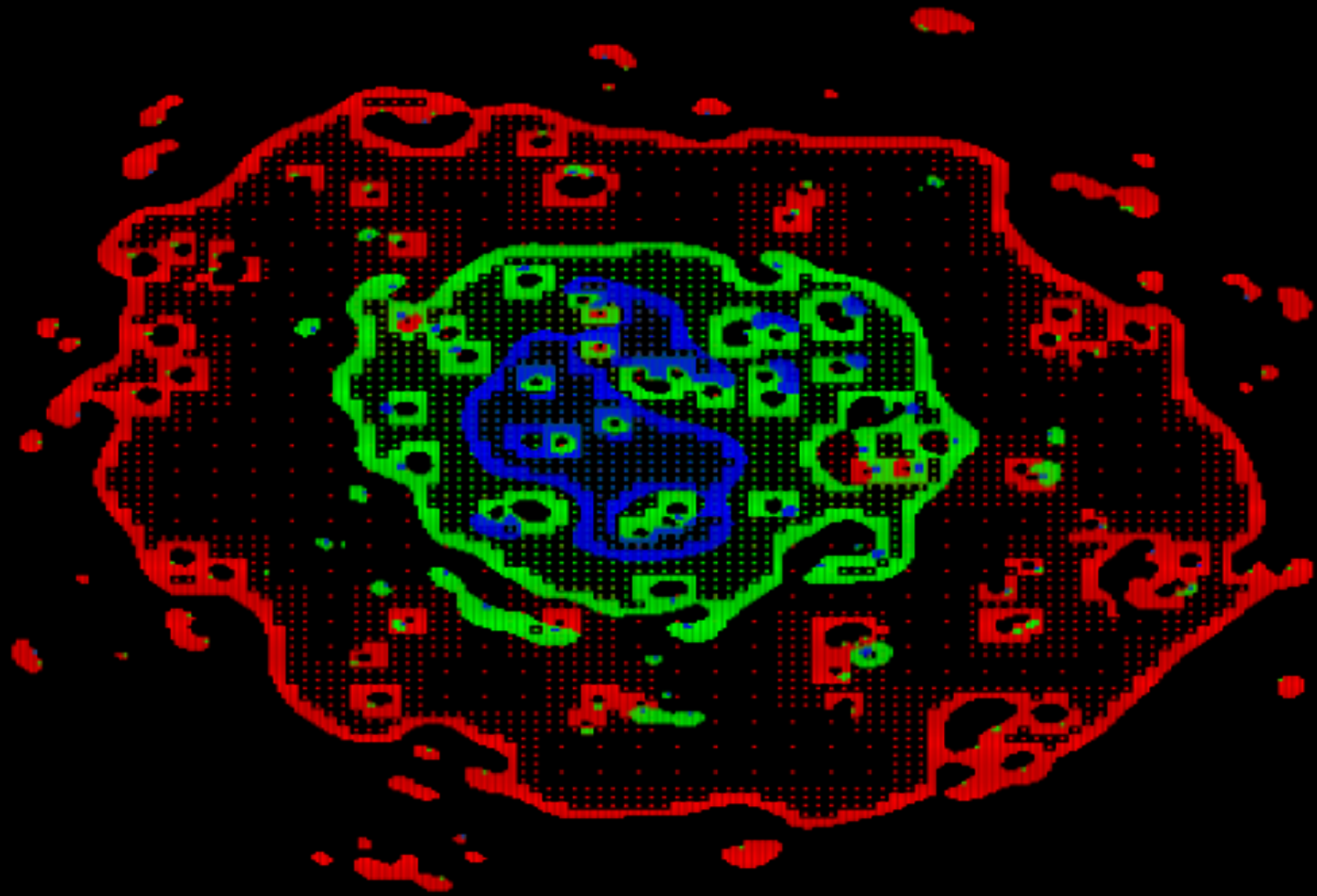






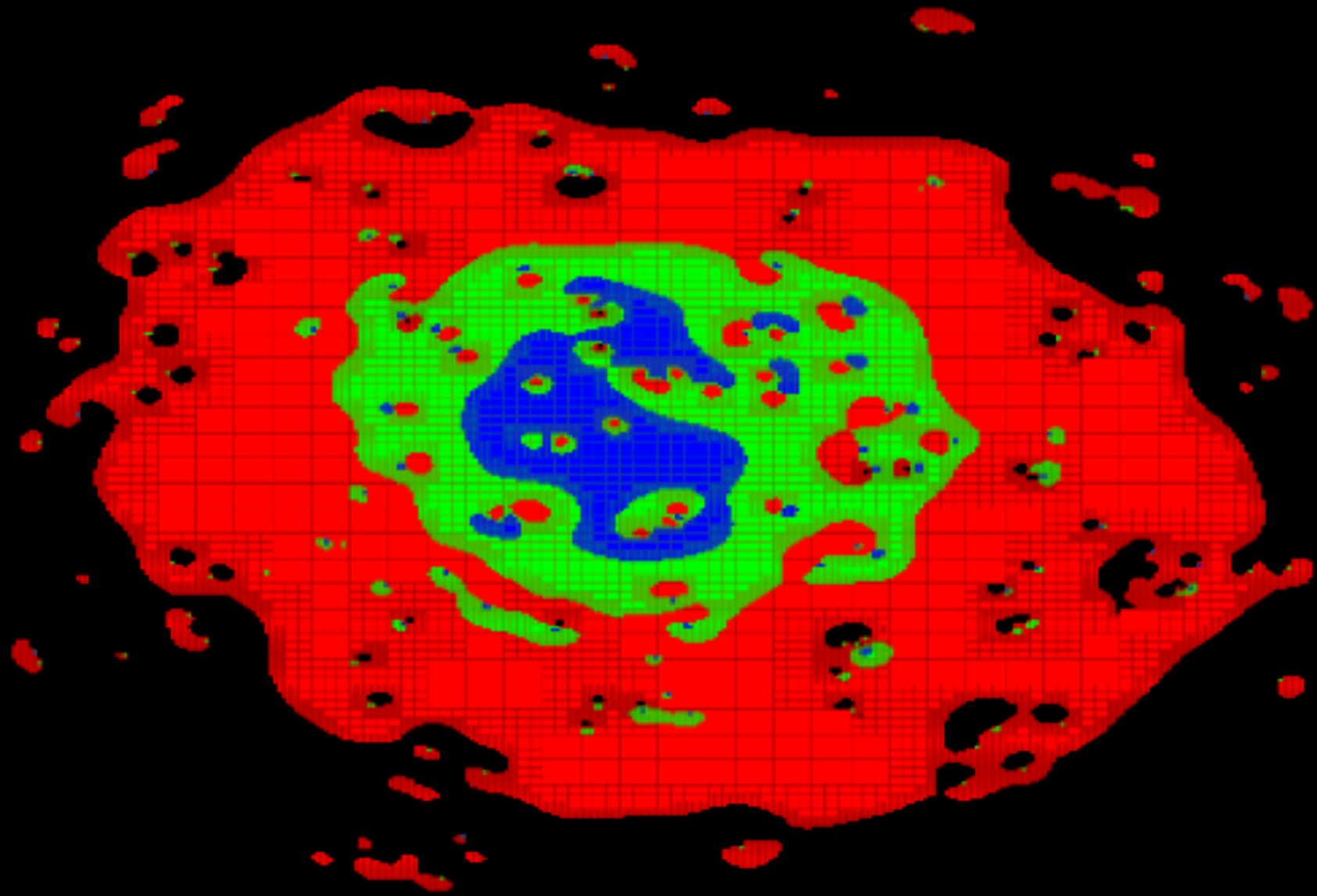


# QSO Microlensing

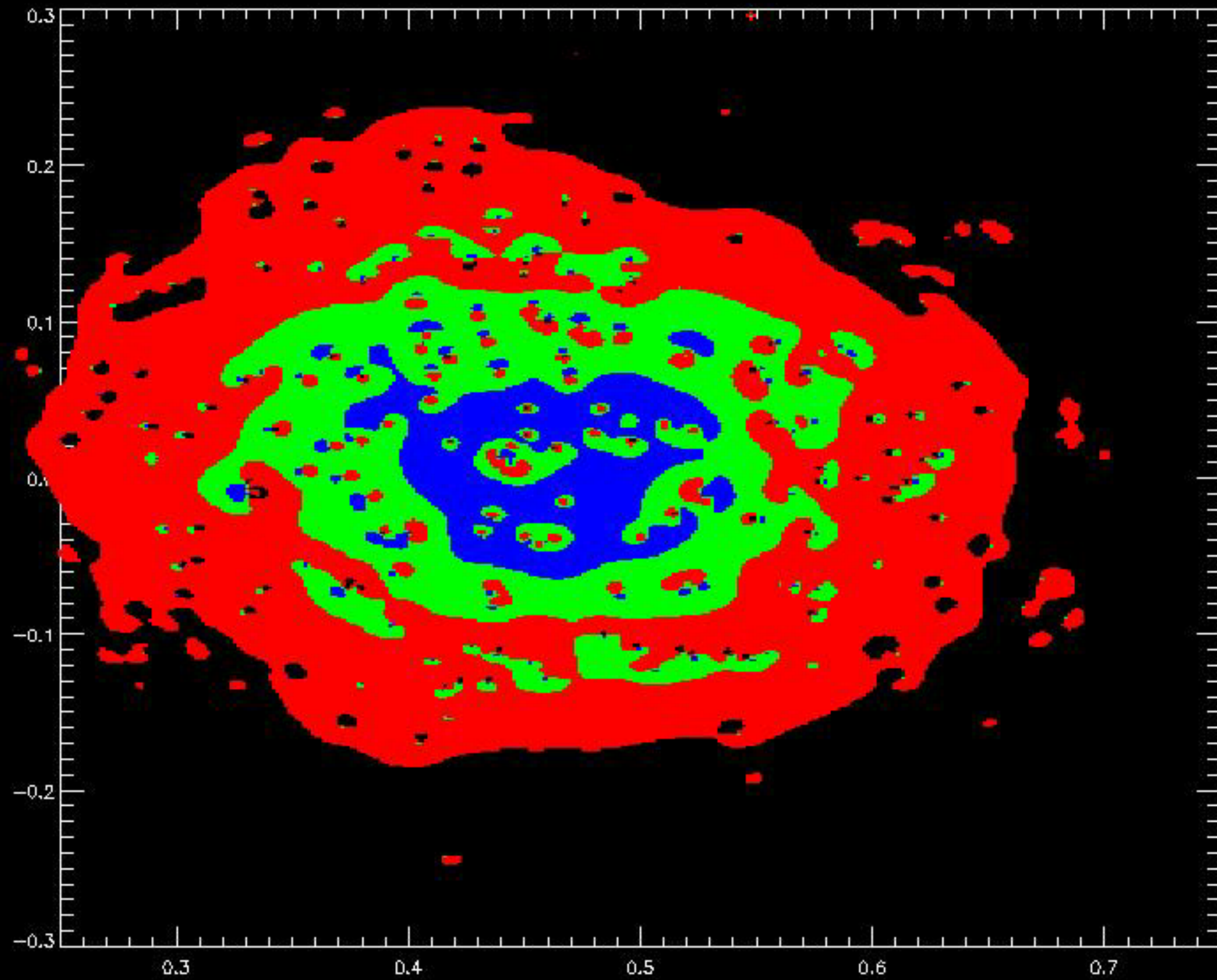




# QSO Microlensing



# QSO Microlensing



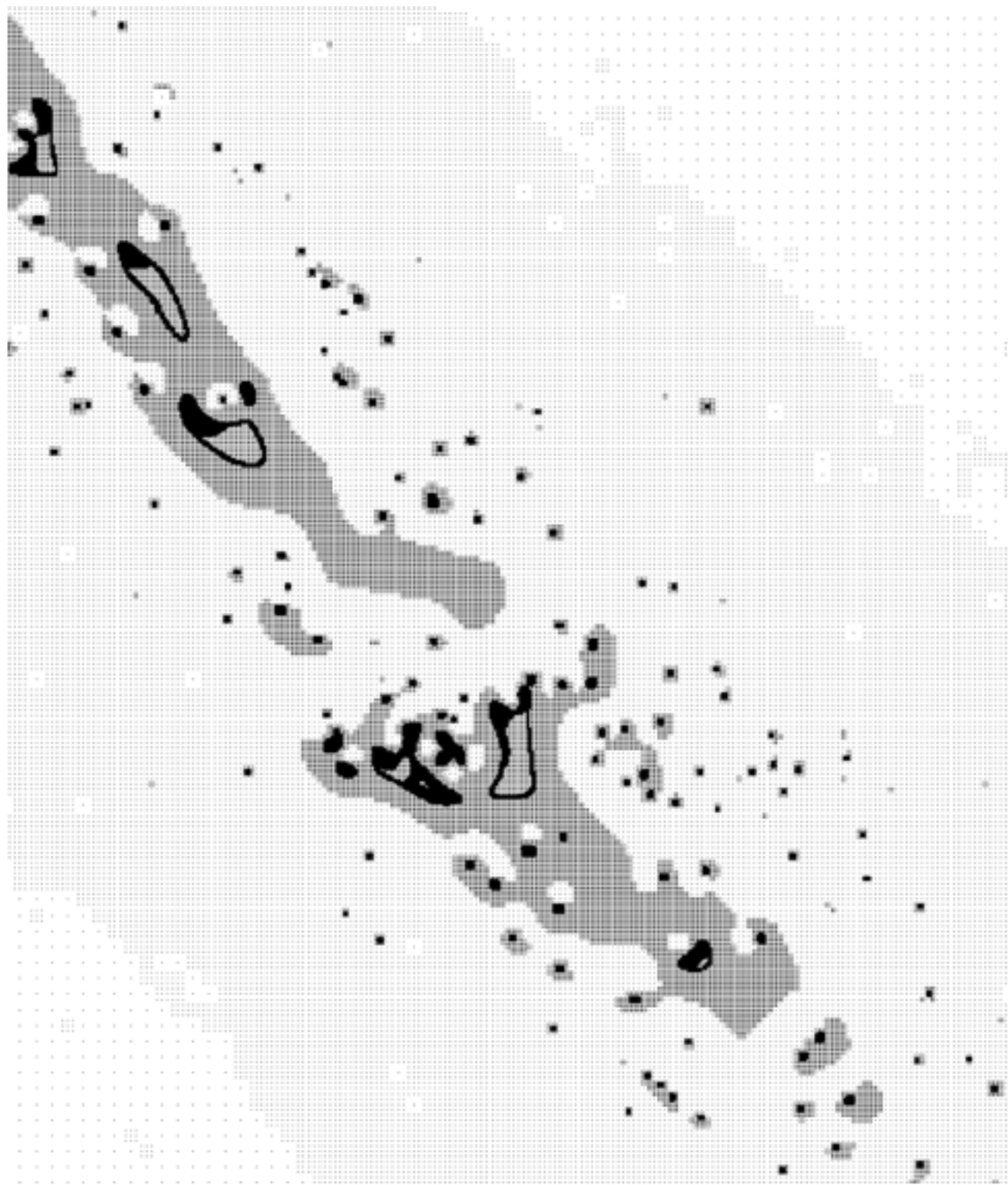


# *Microlensing Example*

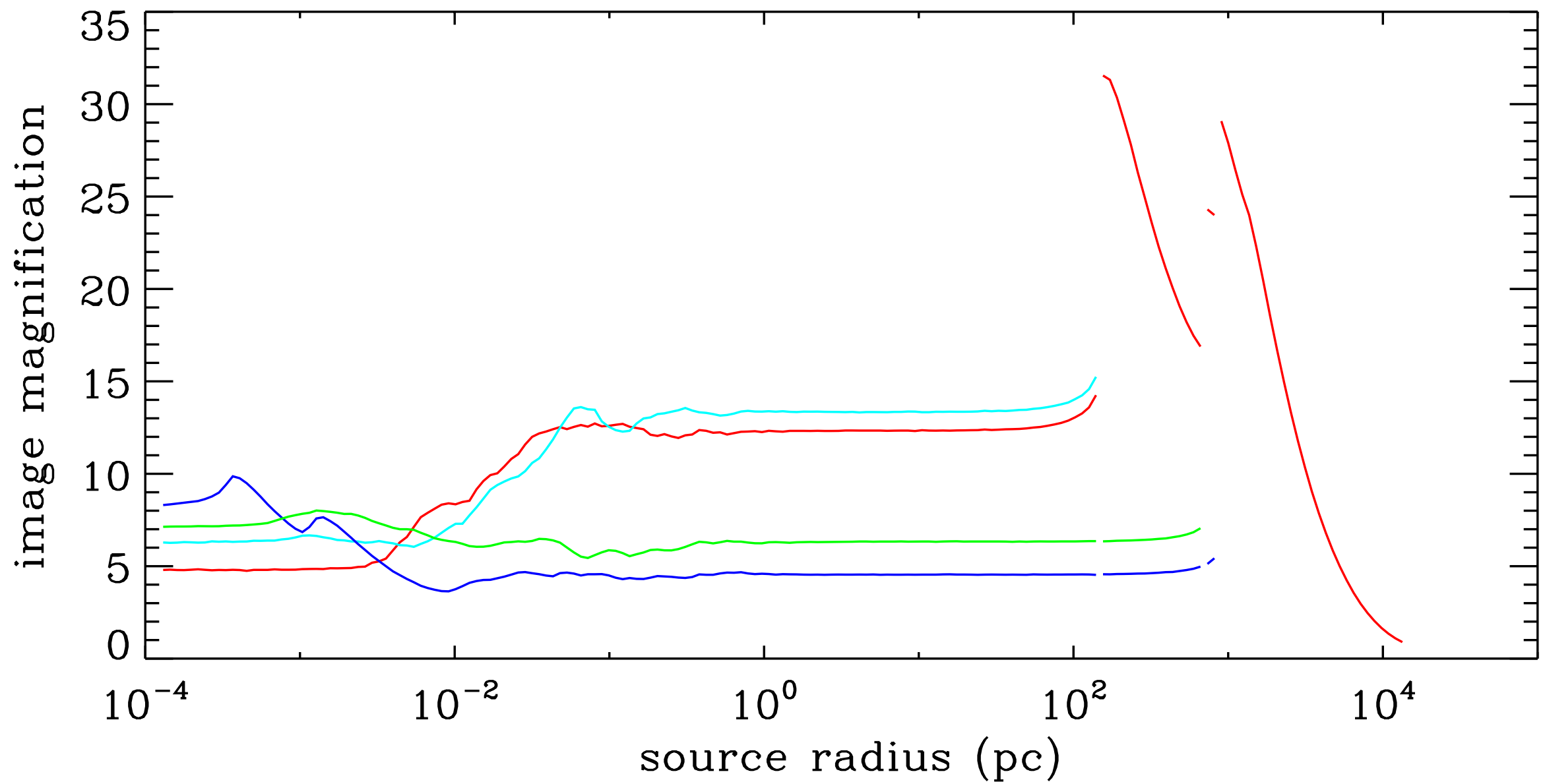
*Images*



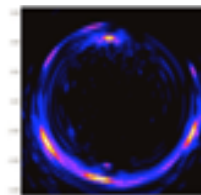
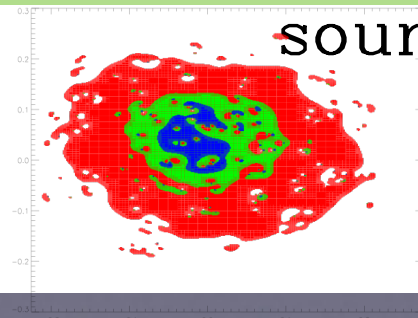
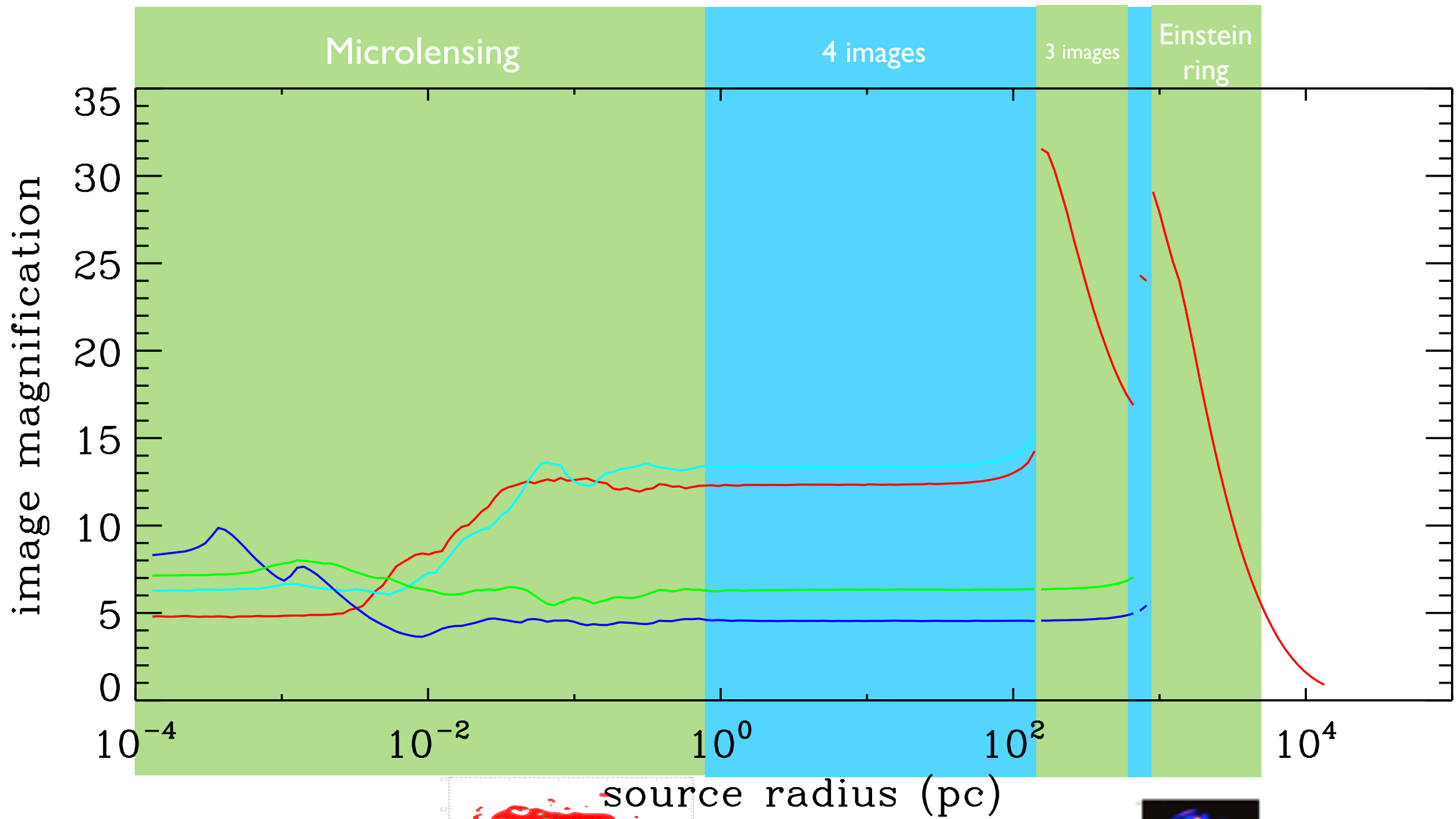
*Adapted grid*



# Gravitational Lensing on all Scales

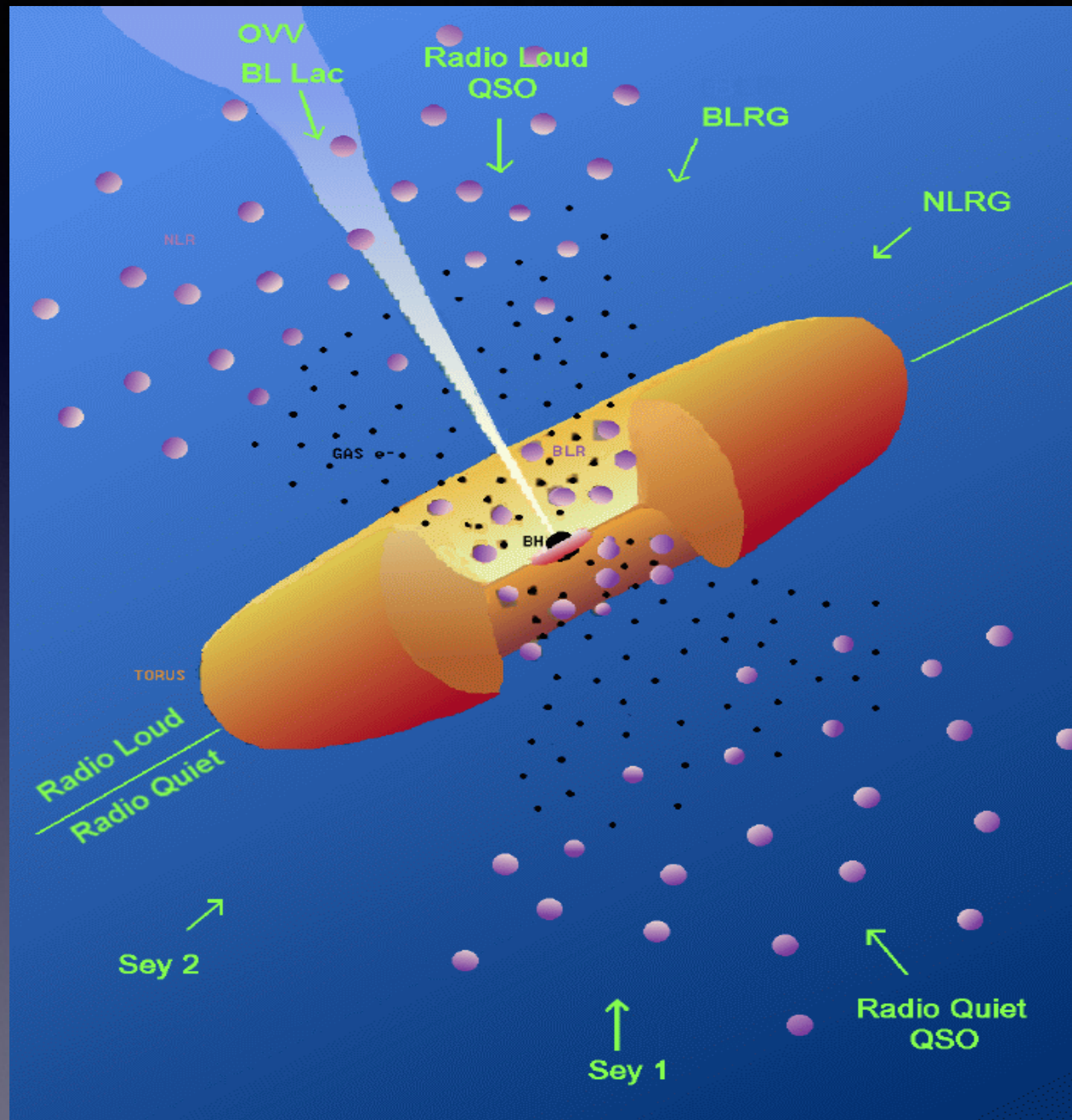


# Gravitational Lensing on all Scales

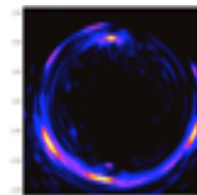
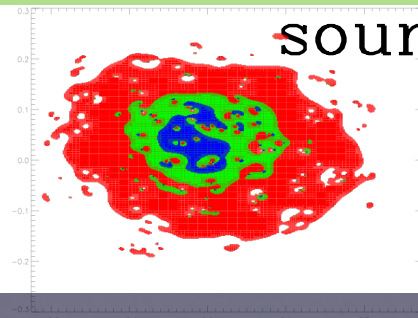
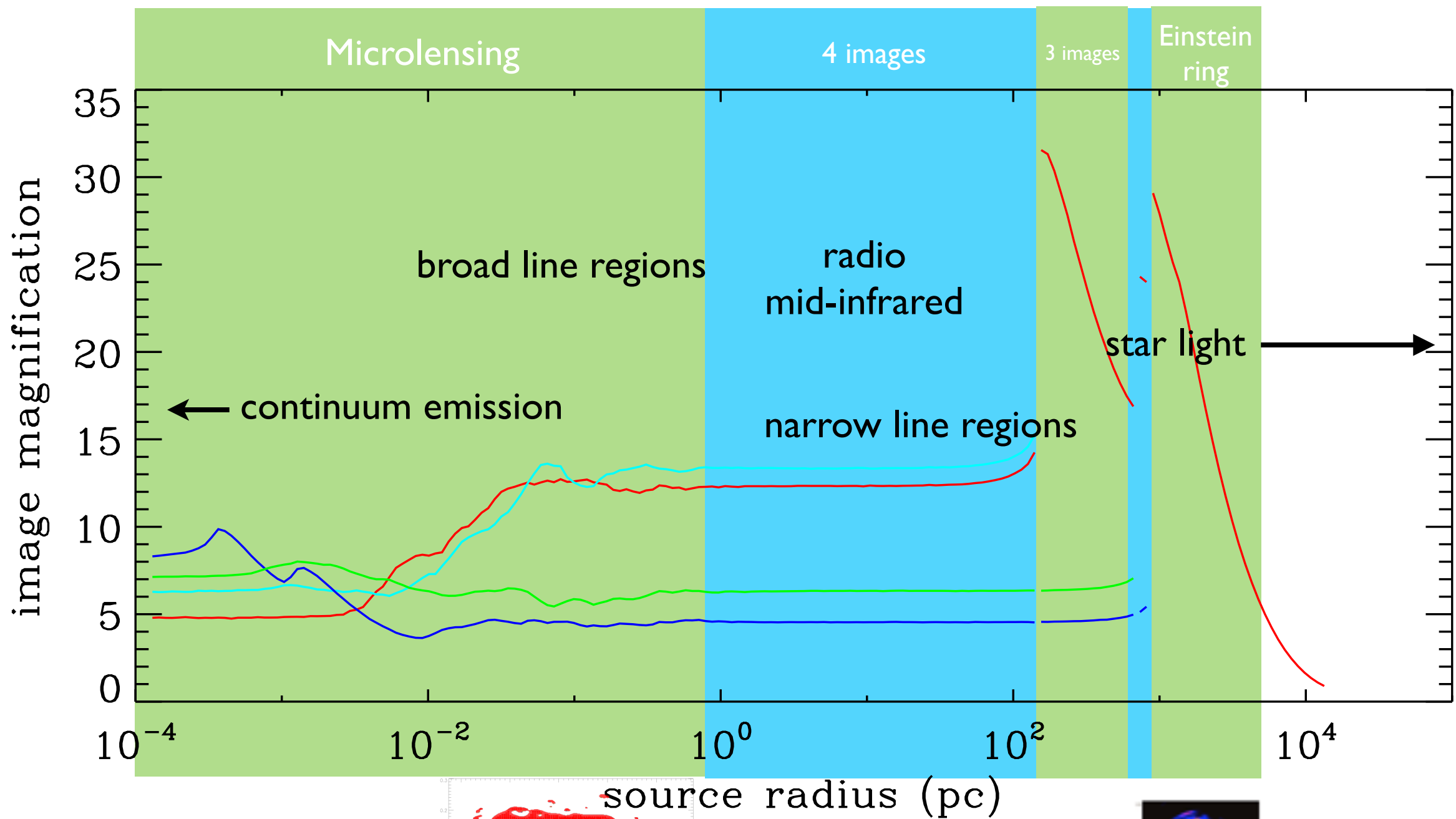




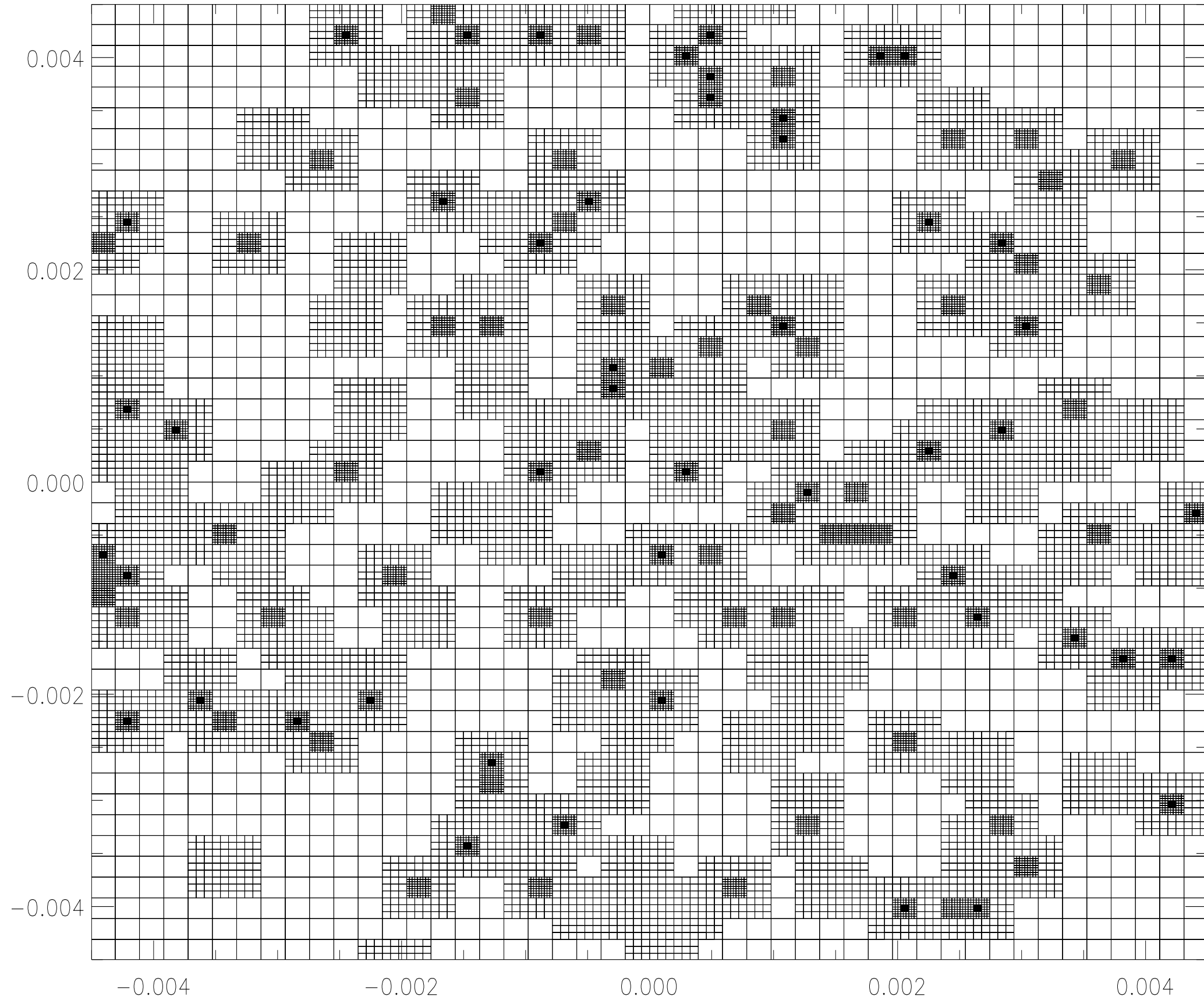
# Anatomy of an active galactic nuclei and QSOs



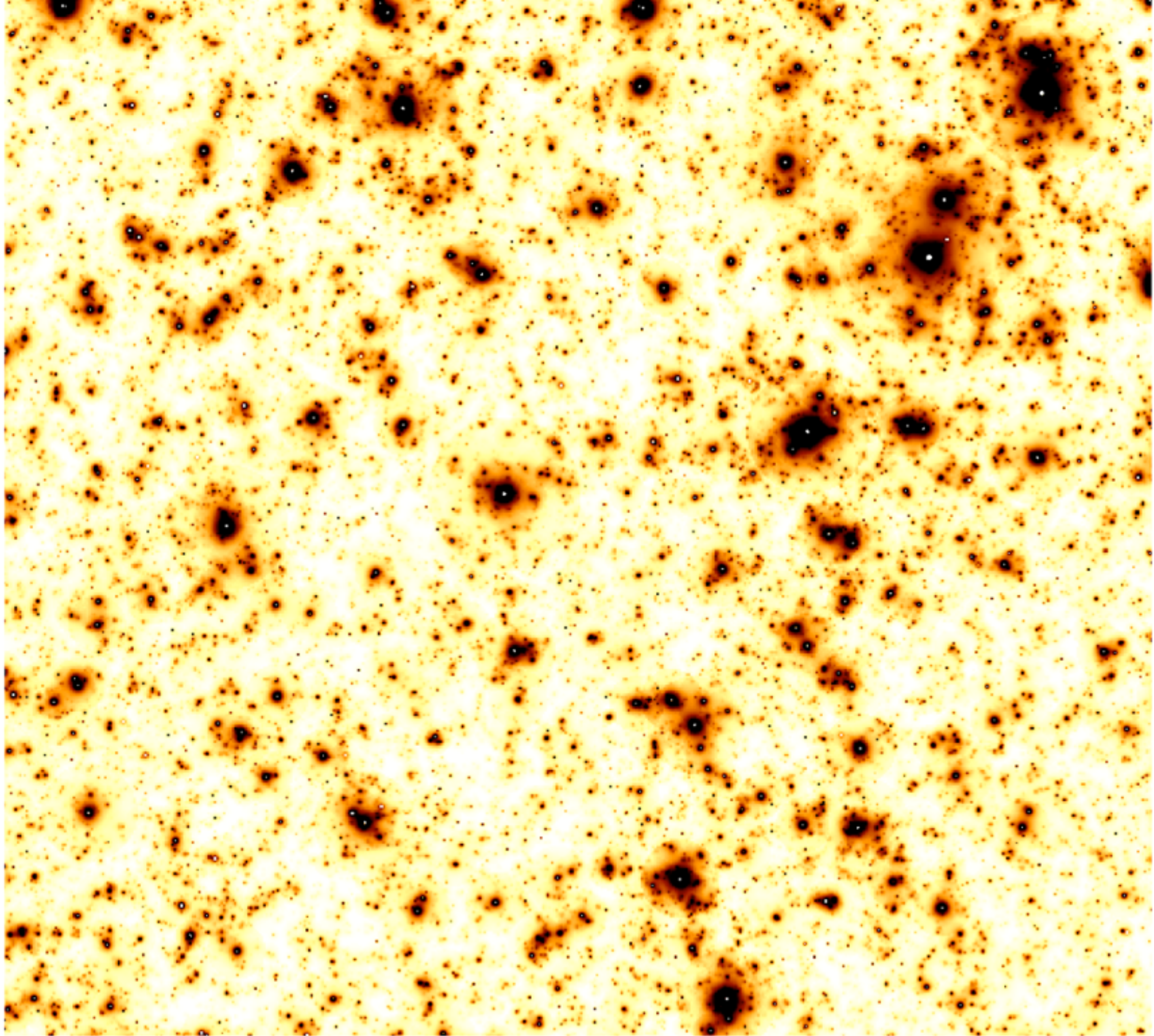
# Gravitational Lensing on all Scales



# Adaptive Grid Refinement







0.56

0.62

0.68

0.74

0.8

0.86

0.92

0.98

1



# lensing simulation with *GLAMER*

## calculating deflection angle

analytic model or from particles:

- tree code deflection solver
- modified algorithm to handle halos efficiently

adaptive smoothing for Nbody/hydro particles

multiple lens planes:  
3d along light paths

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- point masses (stars)
- pixelized mass map

## the grid of rays

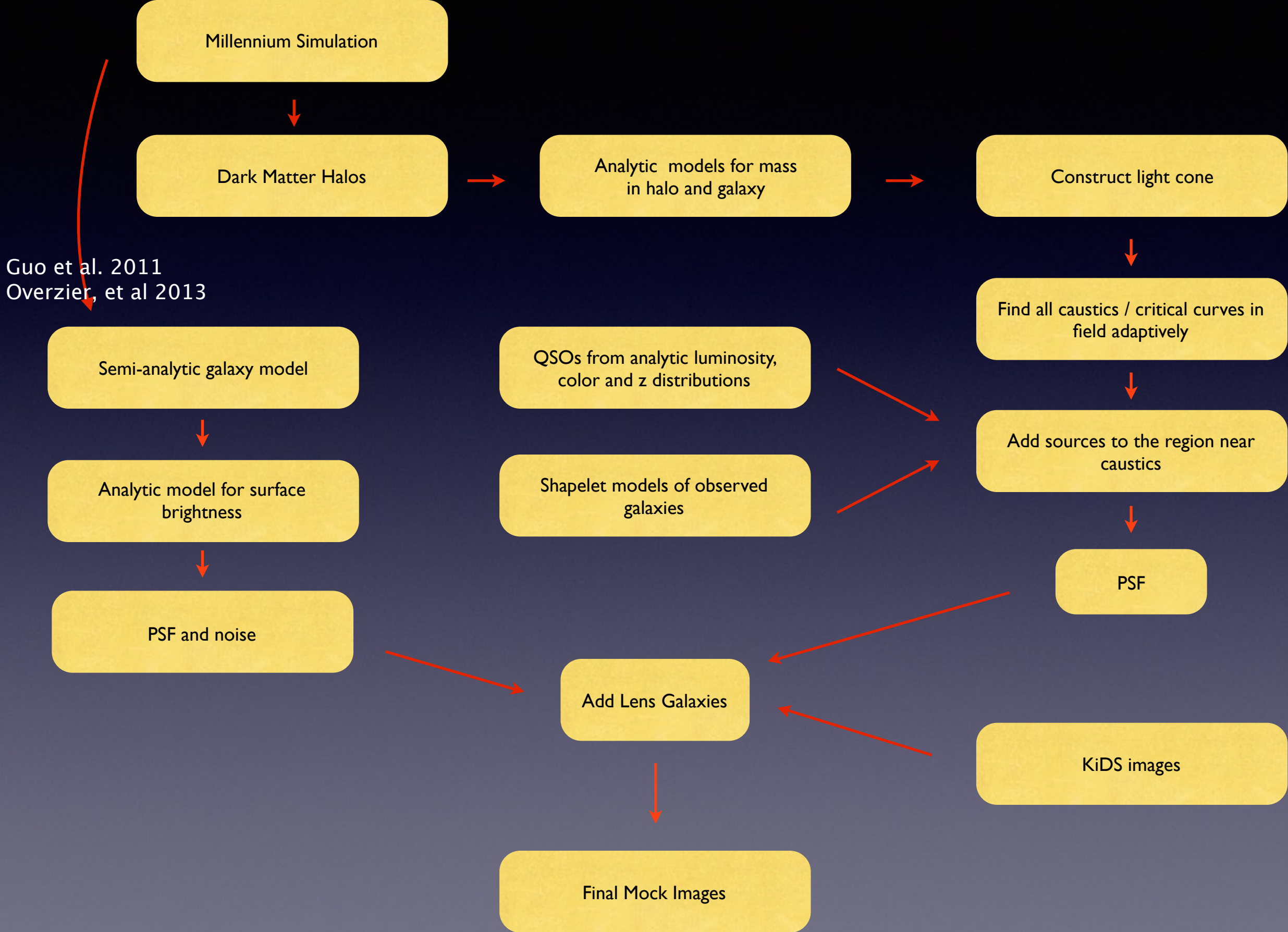
adaptive grid refinement

full image reconstruction or just shear and convergence

## source model

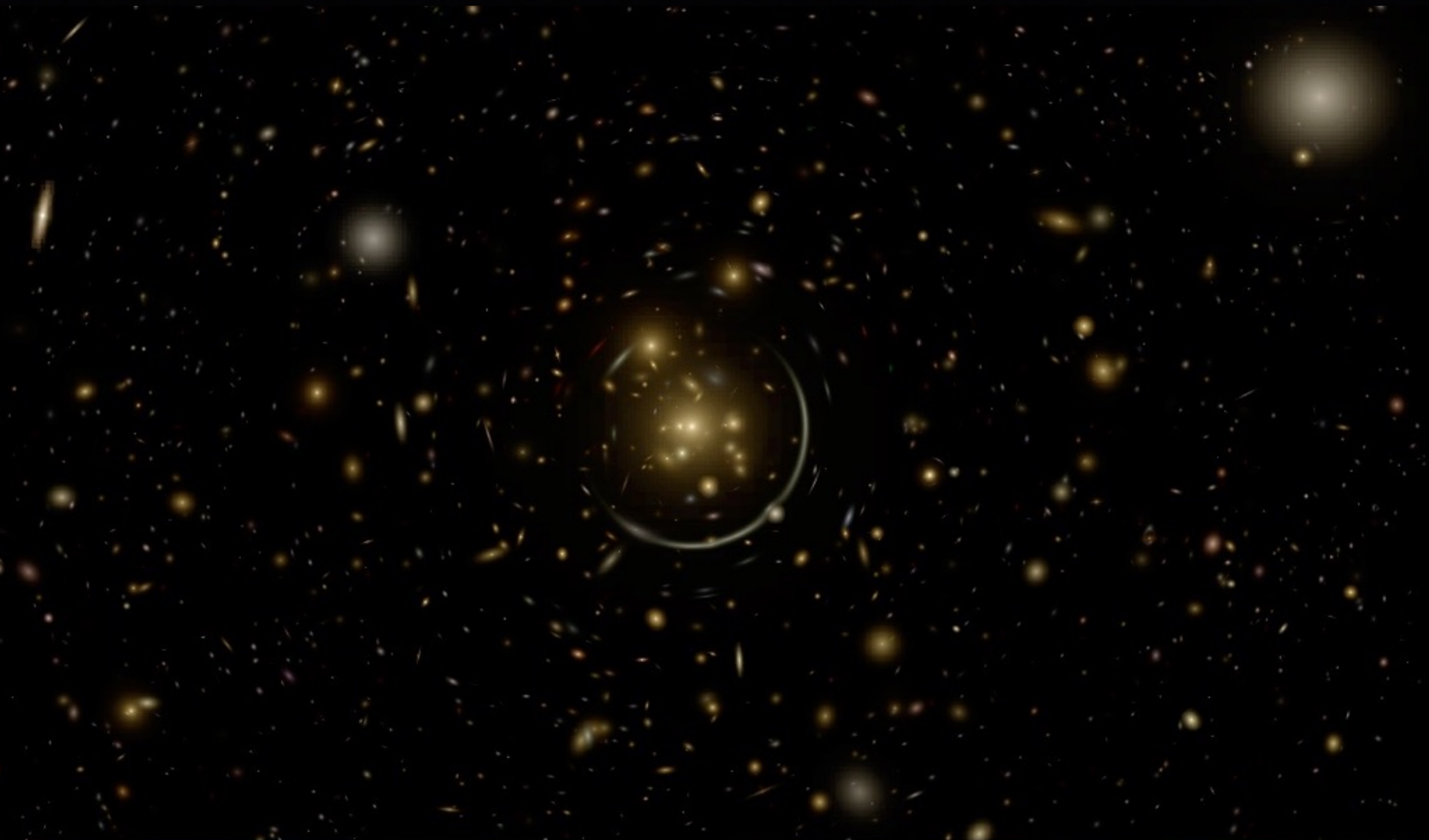
analytic model for surface brightness and direct pixelized images

# Making of Mock Images





# Field Lensing Simulations

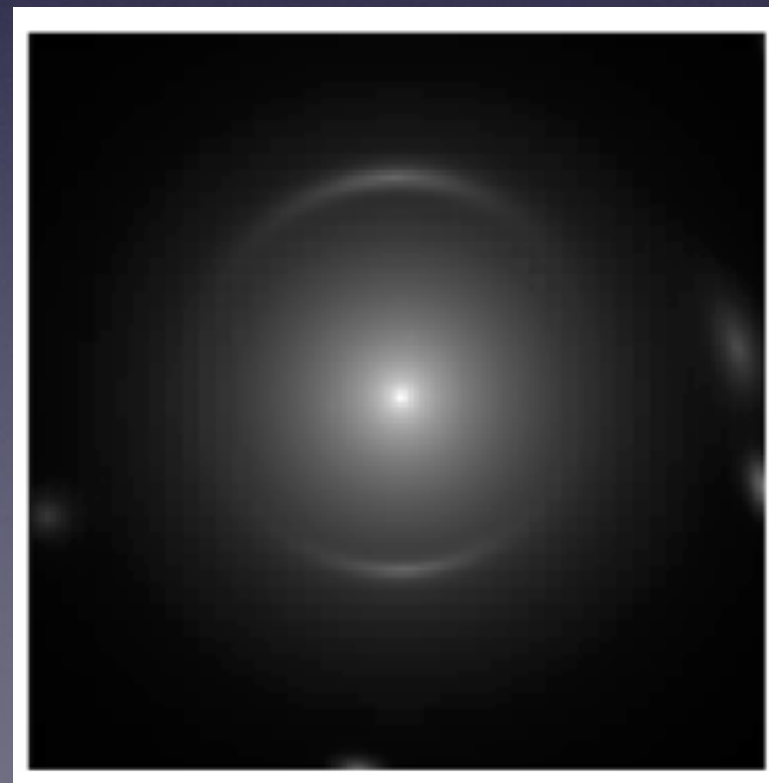
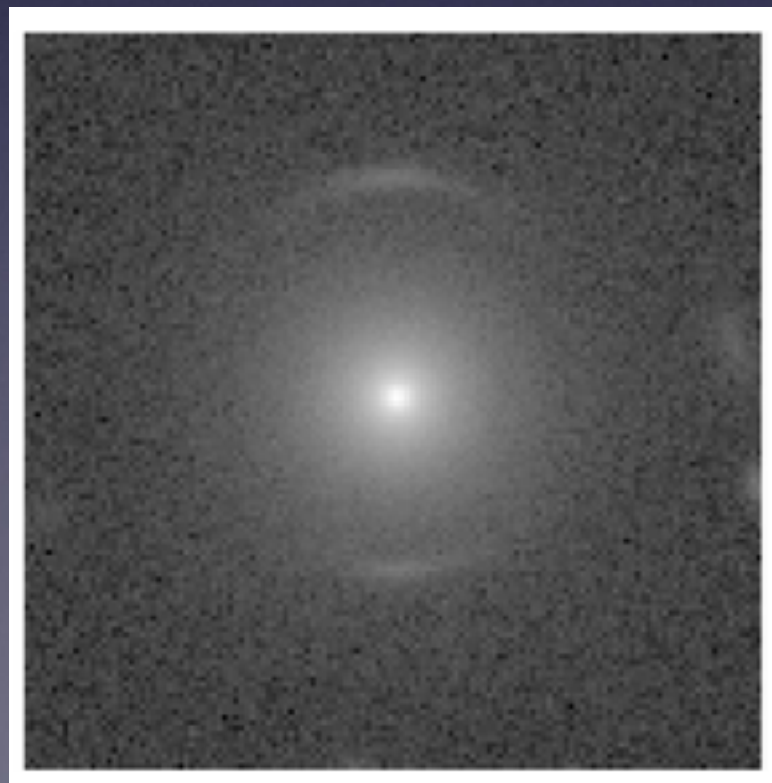
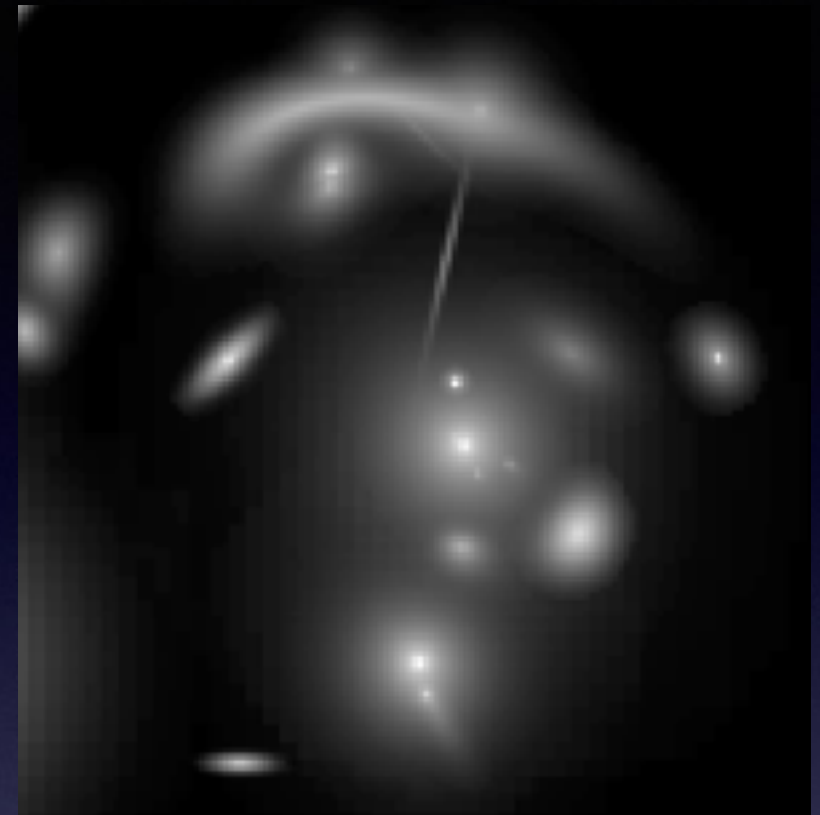
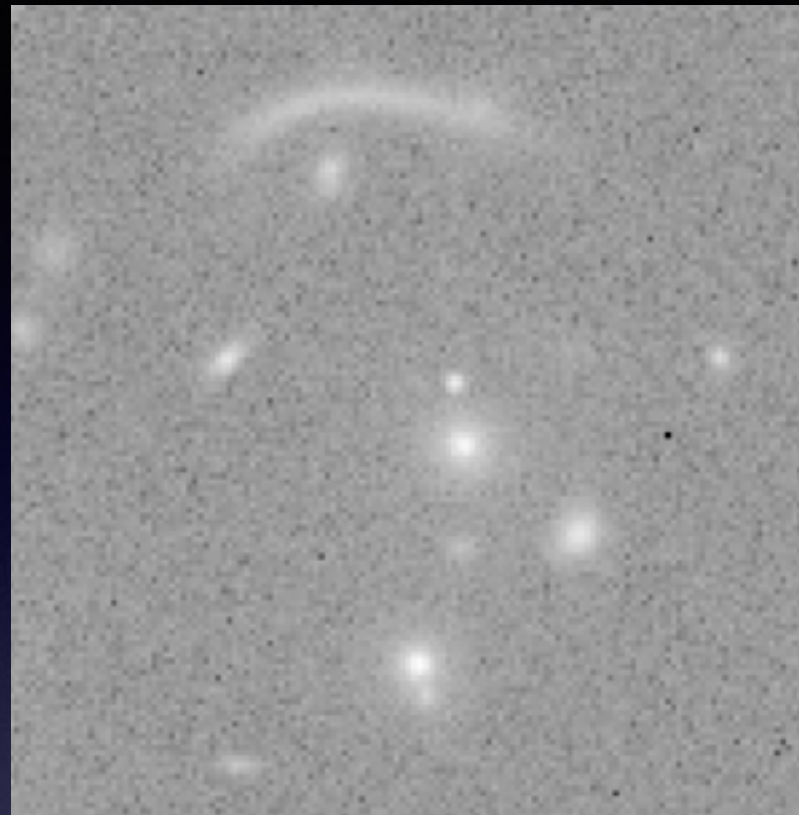
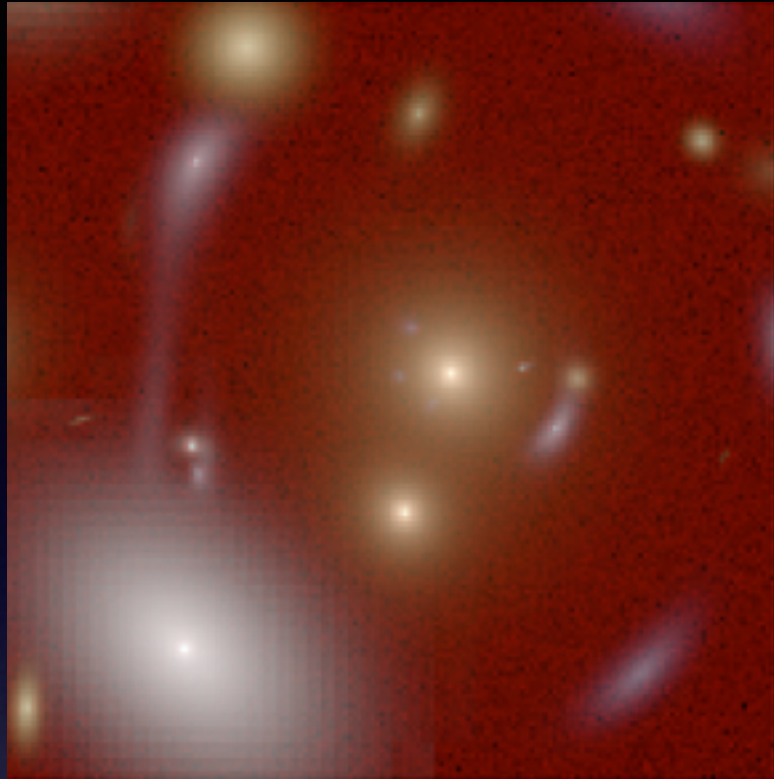


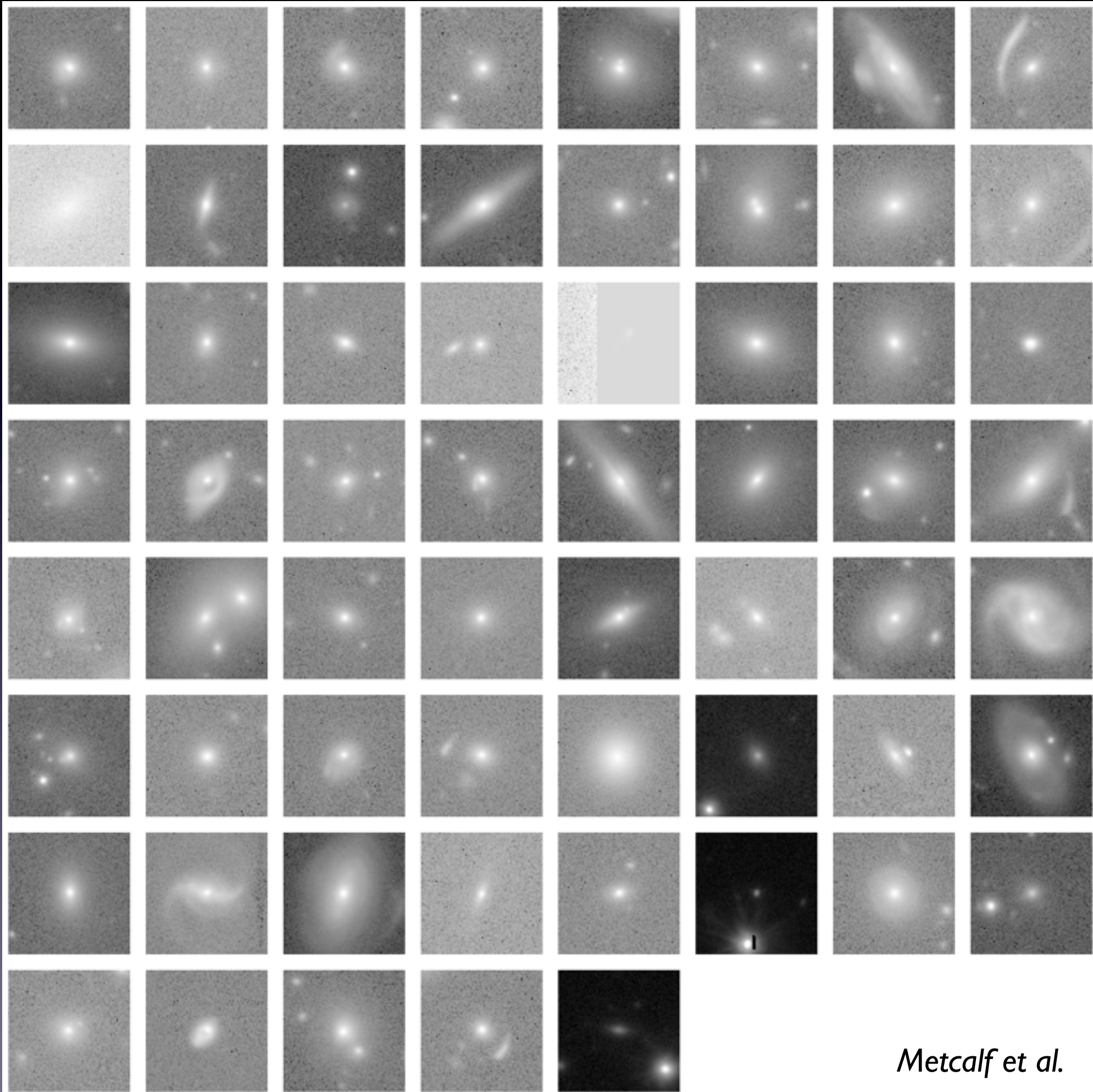
# Field Lensing Simulations





# Field Lensing Simulations

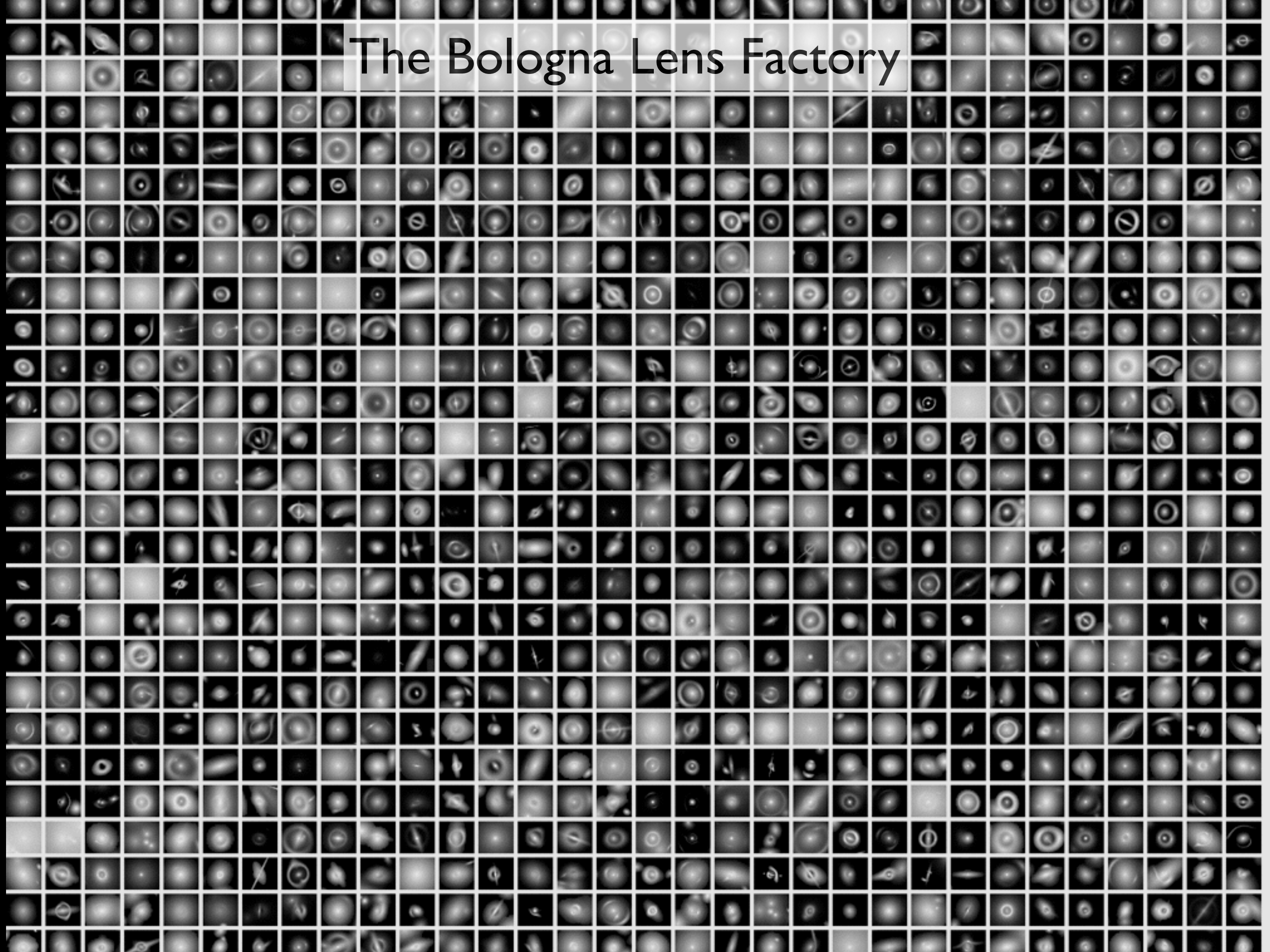




*Metcalf et al.*

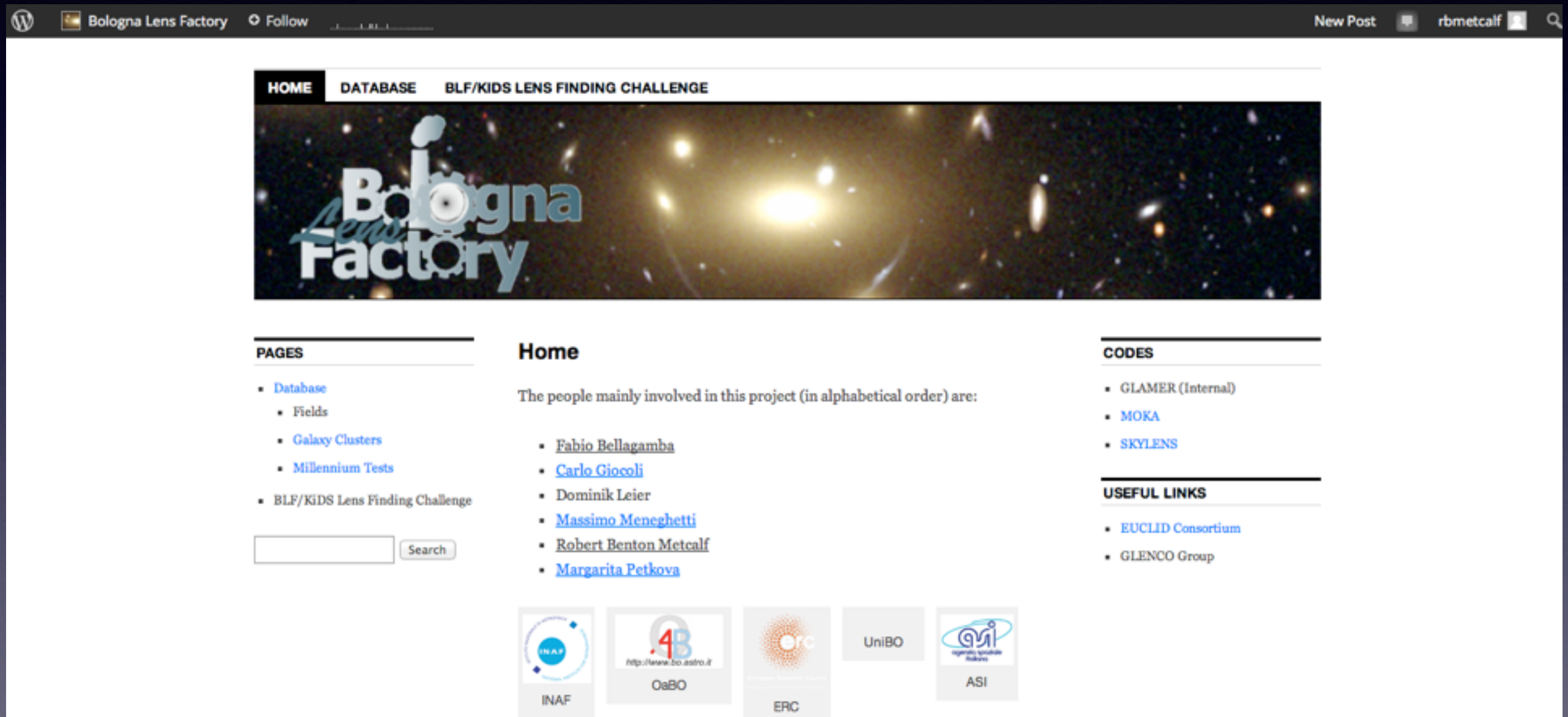


# The Bologna Lens Factory





# Bologna Lens Factory / KiDS Lens Finding Challenge



The screenshot shows the homepage of the Bologna Lens Factory website. At the top, there is a navigation bar with the site name "Bologna Lens Factory", a "Follow" button, and a search icon. The main content area features a large banner image of a galaxy cluster with the "Bologna Lens Factory" logo overlaid. Below the banner, there are three columns of content. The left column, titled "PAGES", lists "Database" (with sub-items "Fields", "Galaxy Clusters", and "Millennium Tests") and "BLF/KiDS Lens Finding Challenge". Below this is a search box. The middle column, titled "Home", lists the people involved in the project: Fabio Bellagamba, Carlo Giocoli, Dominik Leier, Massimo Meneghetti, Robert Benton Metcalf, and Margarita Petkova. The right column, titled "CODES", lists "GLAMER (Internal)", "MOKA", and "SKYLENS". Below this is a "USEFUL LINKS" section with "EUCLID Consortium" and "GLENGO Group". At the bottom, there are logos for INAF, OaBO, ERC, UniBO, and ASI.

**HOME** DATABASE BLF/KIDS LENS FINDING CHALLENGE

**Bologna Lens Factory**

**PAGES**

- Database
  - Fields
  - Galaxy Clusters
  - Millennium Tests
- BLF/KiDS Lens Finding Challenge

Search

**Home**

The people mainly involved in this project (in alphabetical order) are:

- Fabio Bellagamba
- Carlo Giocoli
- Dominik Leier
- Massimo Meneghetti
- Robert Benton Metcalf
- Margarita Petkova

**CODES**

- GLAMER (Internal)
- MOKA
- SKYLENS

**USEFUL LINKS**

- EUCLID Consortium
- GLENGO Group

INAF OaBO ERC UniBO ASI

<http://bolognalensfactory.wordpress.com>

# *Gravitational Microscope*

*Detection of small-scale dark objects in galaxy-galaxy and galaxy-quasar lenses*

# *Lens Modeling of Clusters & Galaxies*

*Measuring the distribution of mass and its relation to observed galaxies*

*Predicting the magnification so they can be used as gravitational telescopes*

*Doing cosmology with galaxy cluster lensing*

# *Lensing of the 21 cm sky*

*A new method for measuring weak gravitational lensing that will be available for future radio telescopes such as SKA.*

# *Weak Lensing Simulations*

*Studying systematic effects that will influence cosmological constraints using weak lensing surveys.*

*Studying the influence of baryons and small scale halo structure on weak lensing*

*Testing alternative gravity theories*

# *Quasar Microlensing*

*Measuring the dark matter content of distant galaxies using microlensing statistics*



