Ray-Tracing through the Millennium Simulation

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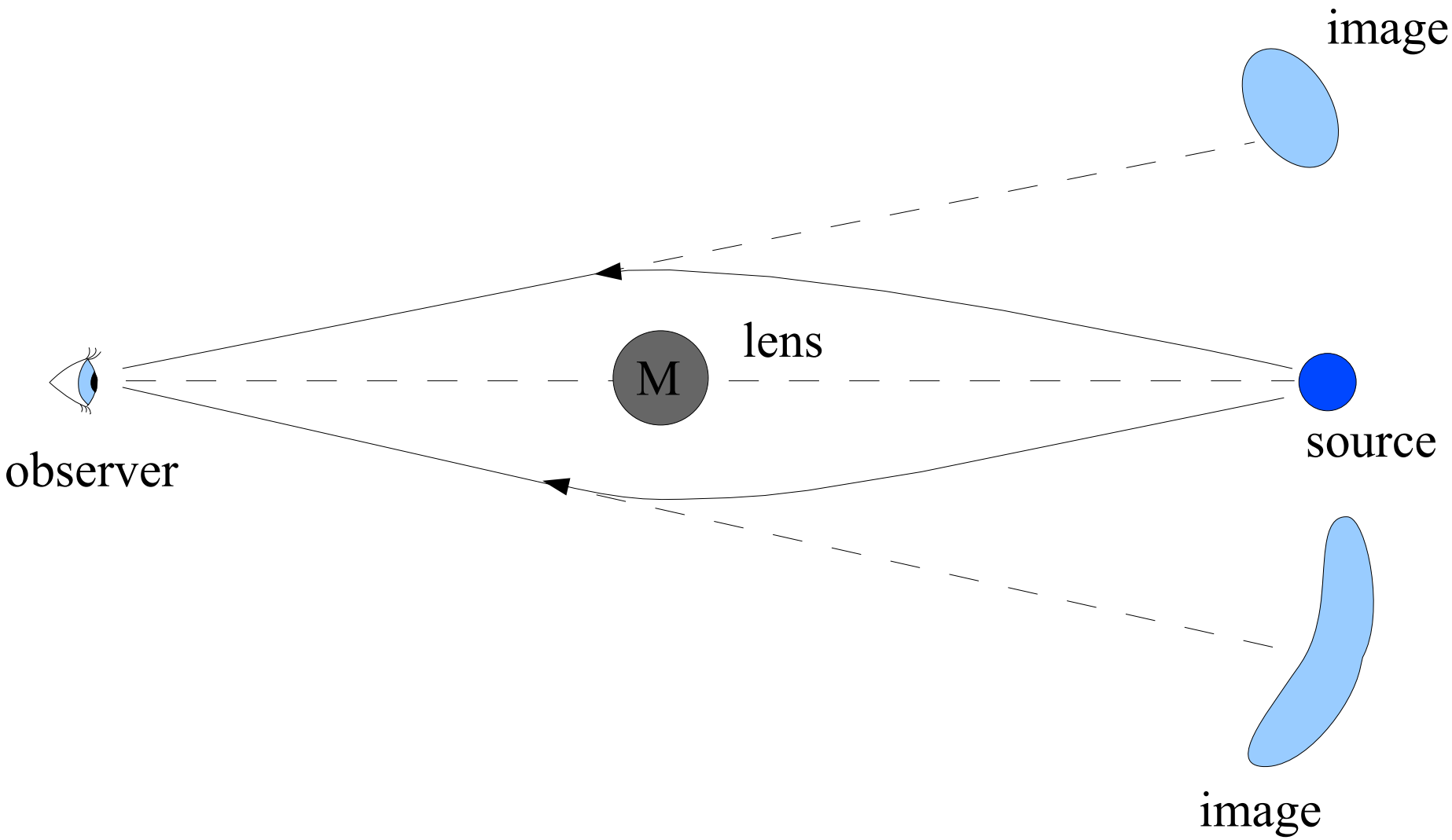
Outline

- Introduction
- Ray-tracing
- Results
  - Strong lensing
  - Weak lensing
  - Lensing of pregalactic HI
- Summary

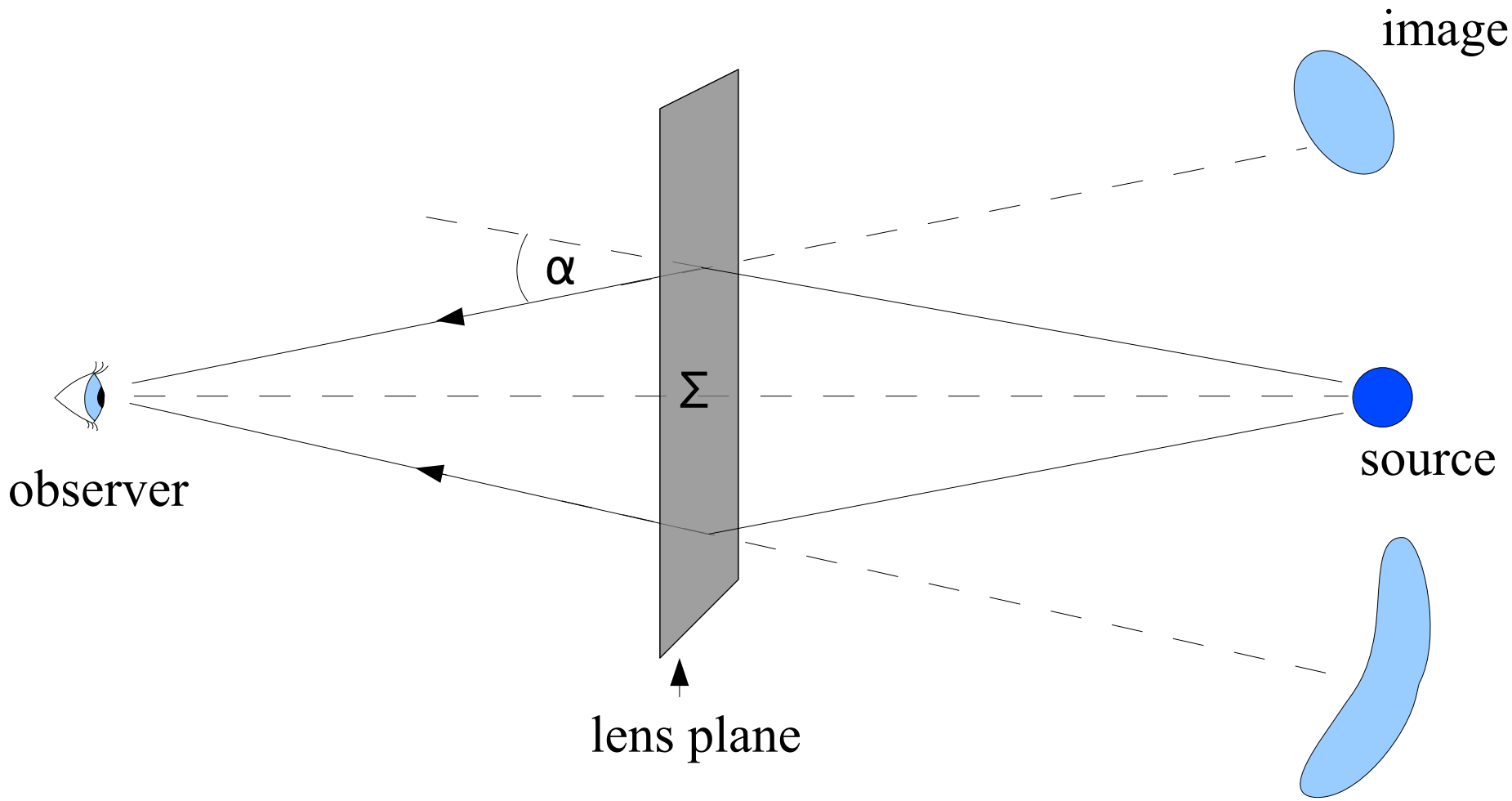
Introduction

- Gravitational lensing (GL):
  - tool to measure matter distribution in our universe
- Millennium Simulation (MS):
  - 10^{10} particles in 500 Mpc/h box from z=127 to z=0
  - matter structures from galaxy halos to galaxy clusters and large-scale structure
- use ray-tracing through MS to:
  - obtain predictions for GL observations
  - study capability of GL to measure mass distribution

Gravitational Lensing

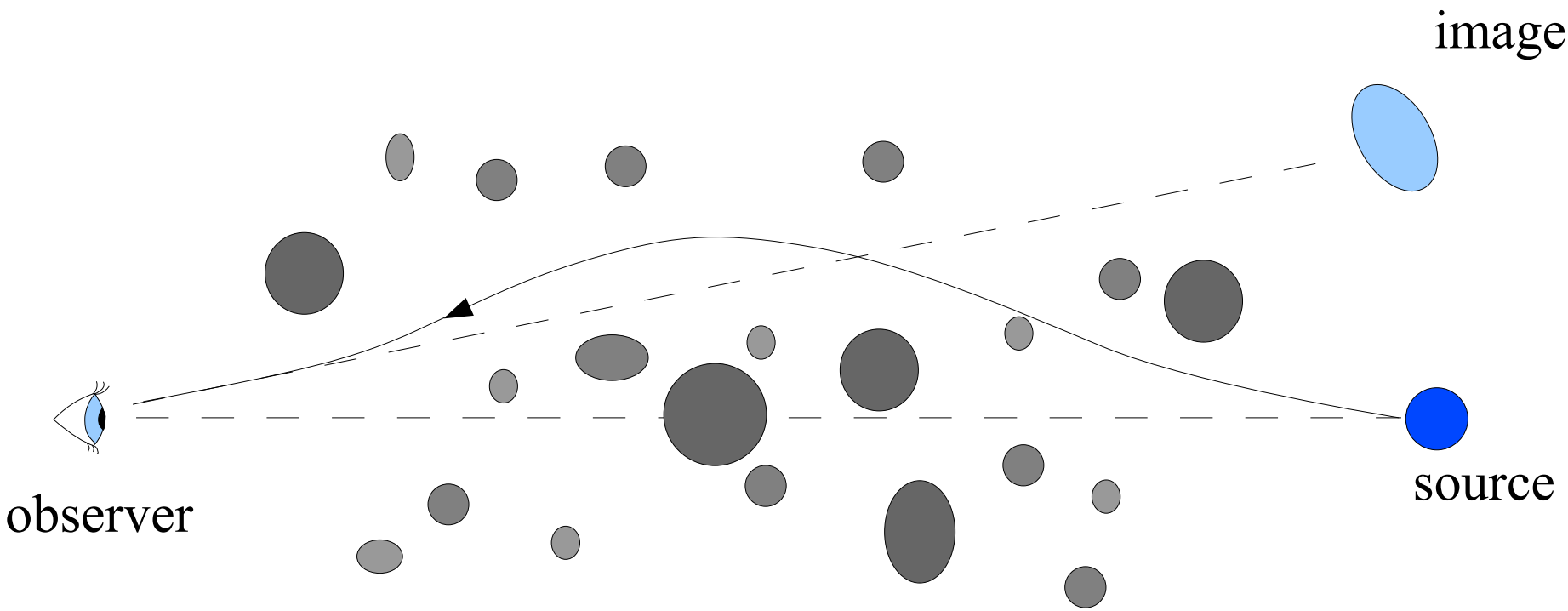


Gravitational Lensing

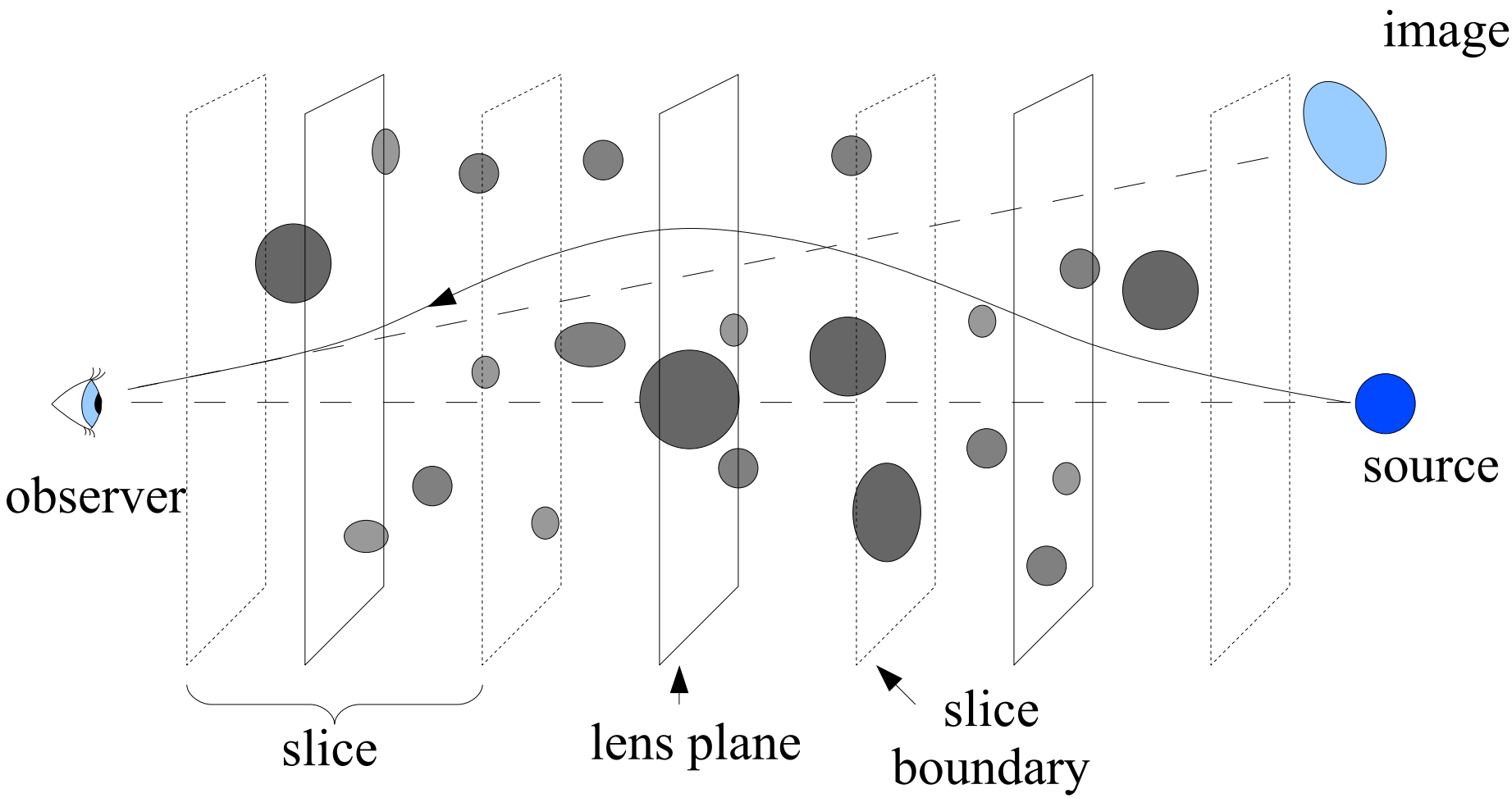


$$\Psi = (\nabla^2)^{-1}\Sigma \;\rightarrow\; \alpha = \nabla\Psi$$

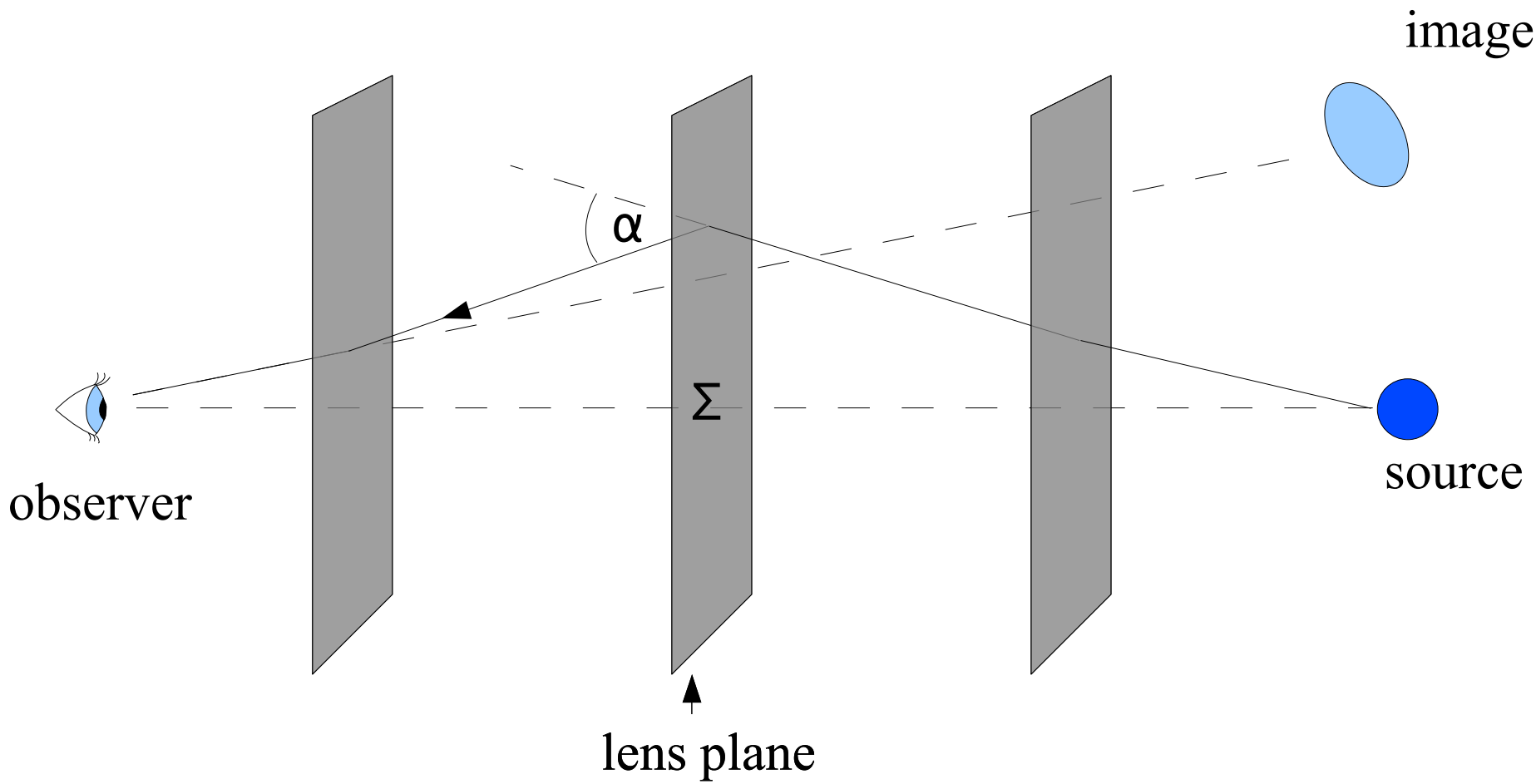
Multiple-Lens-Plane Approximation



Multiple-Lens-Plane Approximation

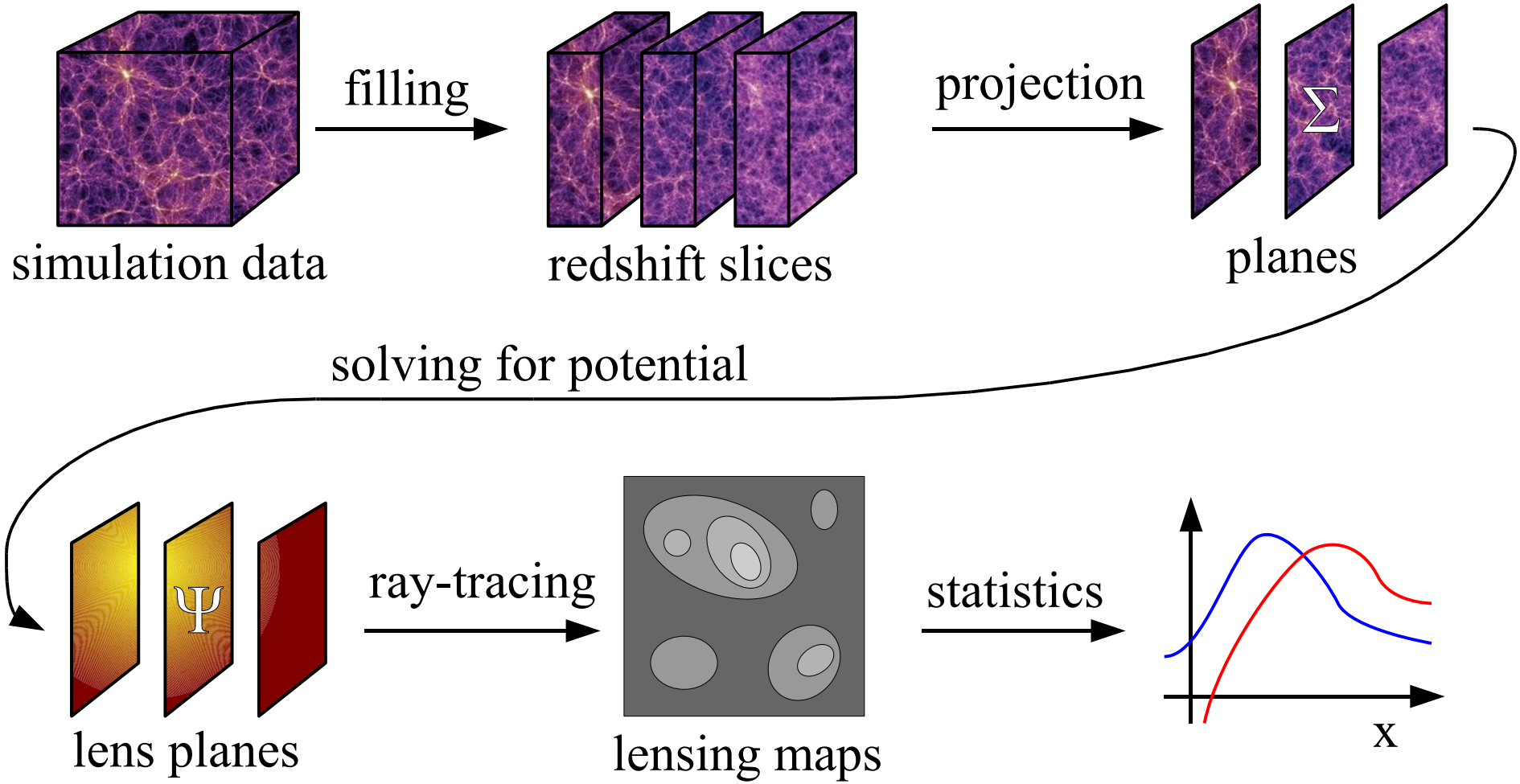


Multiple-Lens-Plane Approximation



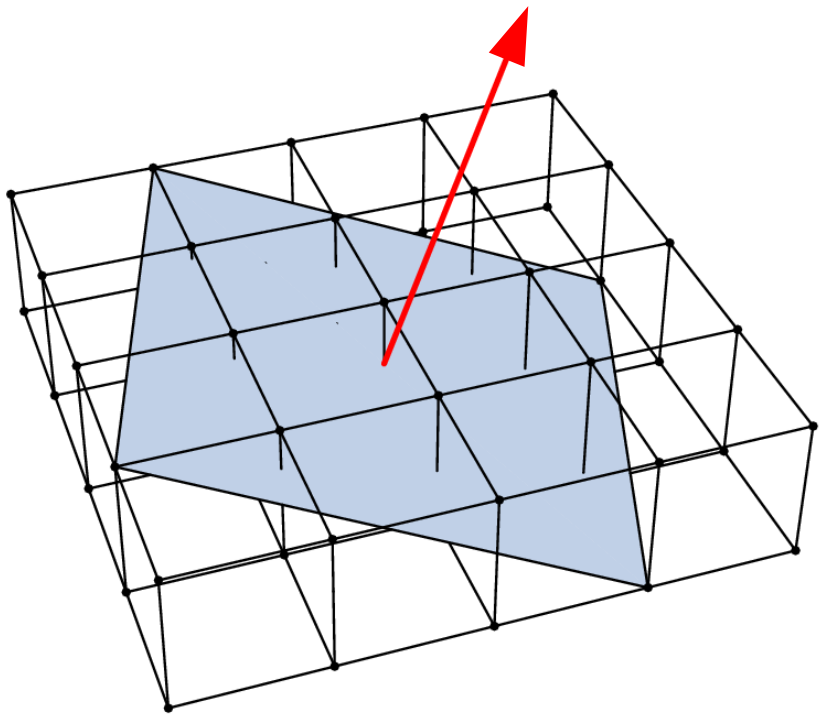
$$\Psi = (\nabla^2)^{-1}\Sigma \;\rightarrow\; \alpha = \nabla\Psi$$

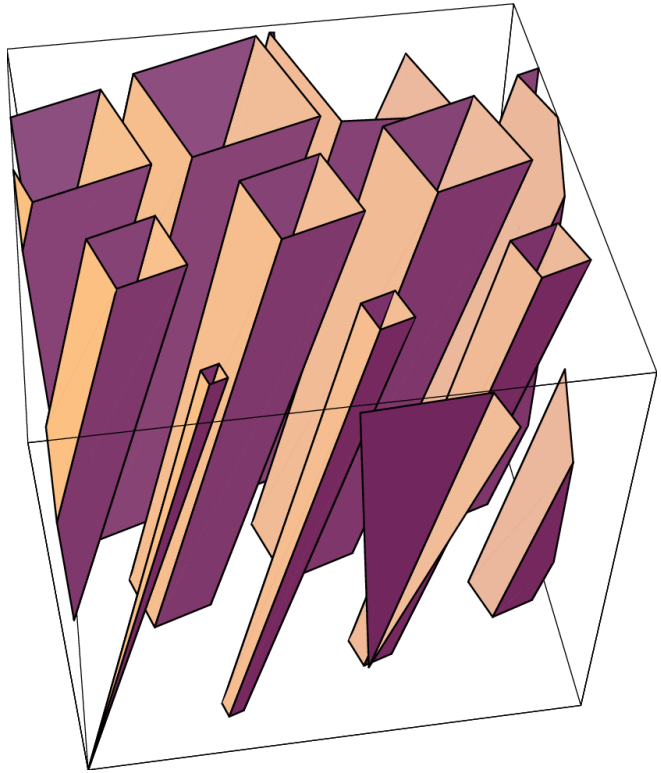
The Ray-Tracing Algorithm



Some Implementation Details

- tilted l.o.s., slices, planes:





→ large lens planes: 1.55 Gpc/h x 1.65 Gpc/h

Some Implementation Details

- PMPM method to obtain lensing potential:
  - project particles onto meshes (adaptive smoothing)
  - Ψ^{long} by FFT on coarse mesh covering whole plane
  - Ψ^{short} by FFT on local fine meshes (2.5kpc/h)
  - $\Psi = \Psi^{long} + \Psi^{short}$
- finite difference → ray deflections / distortions

Strong lensing

- random sample 120 000 000 l.o.s.
- consider l.o.s.
  - with large magnification $|\mu| > 10$,
  - with large length-to-width ratio $r > 10$,
  - belonging to multi-image systems (type II or III)
- compare results DM ↔ DM+stars
- identify strong lenses and their properties

Hilbert et al. 2007, MNRAS, 382, 121
Hilbert et al., arXiv:0712.1593

Optical Depths

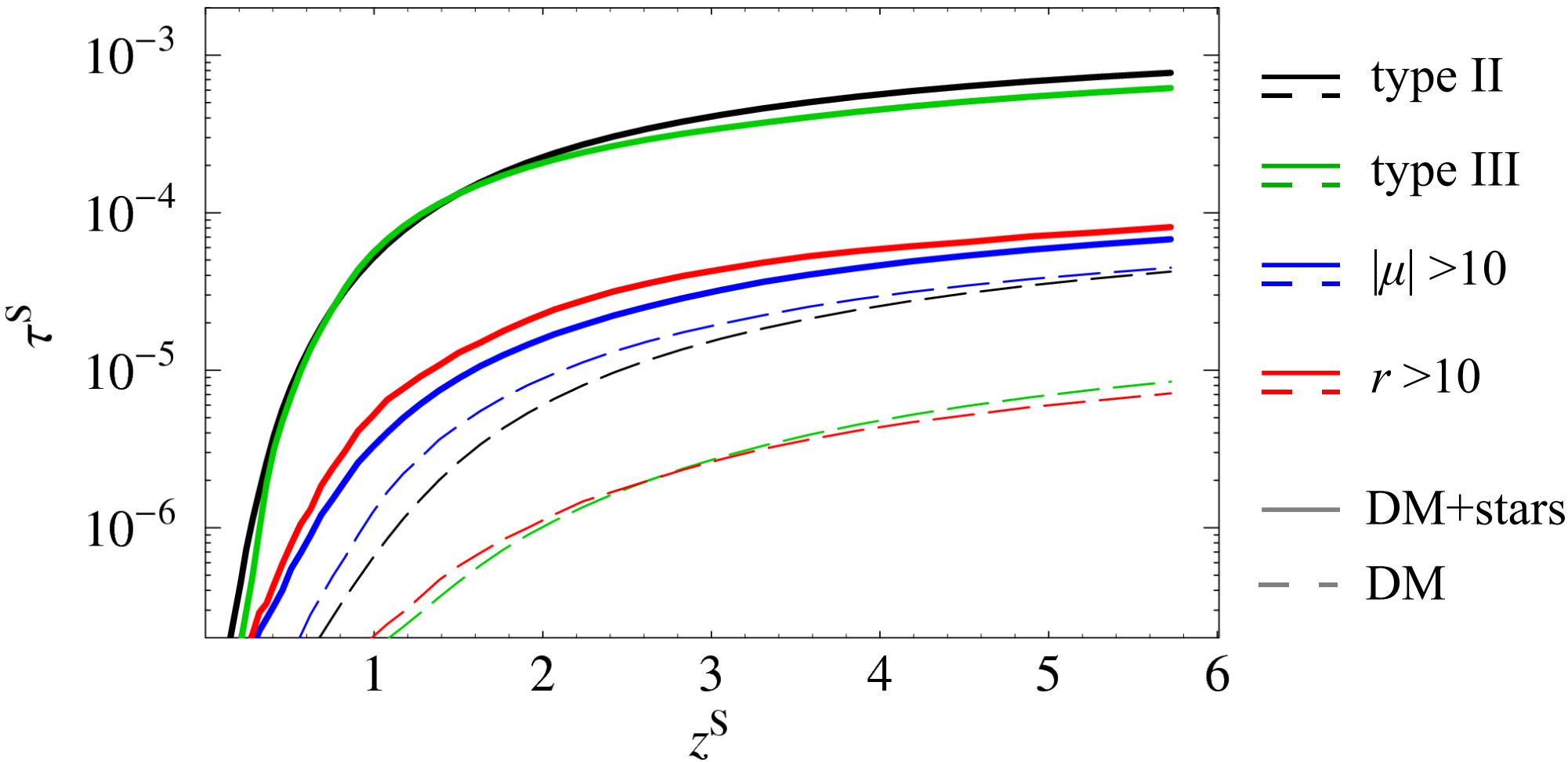
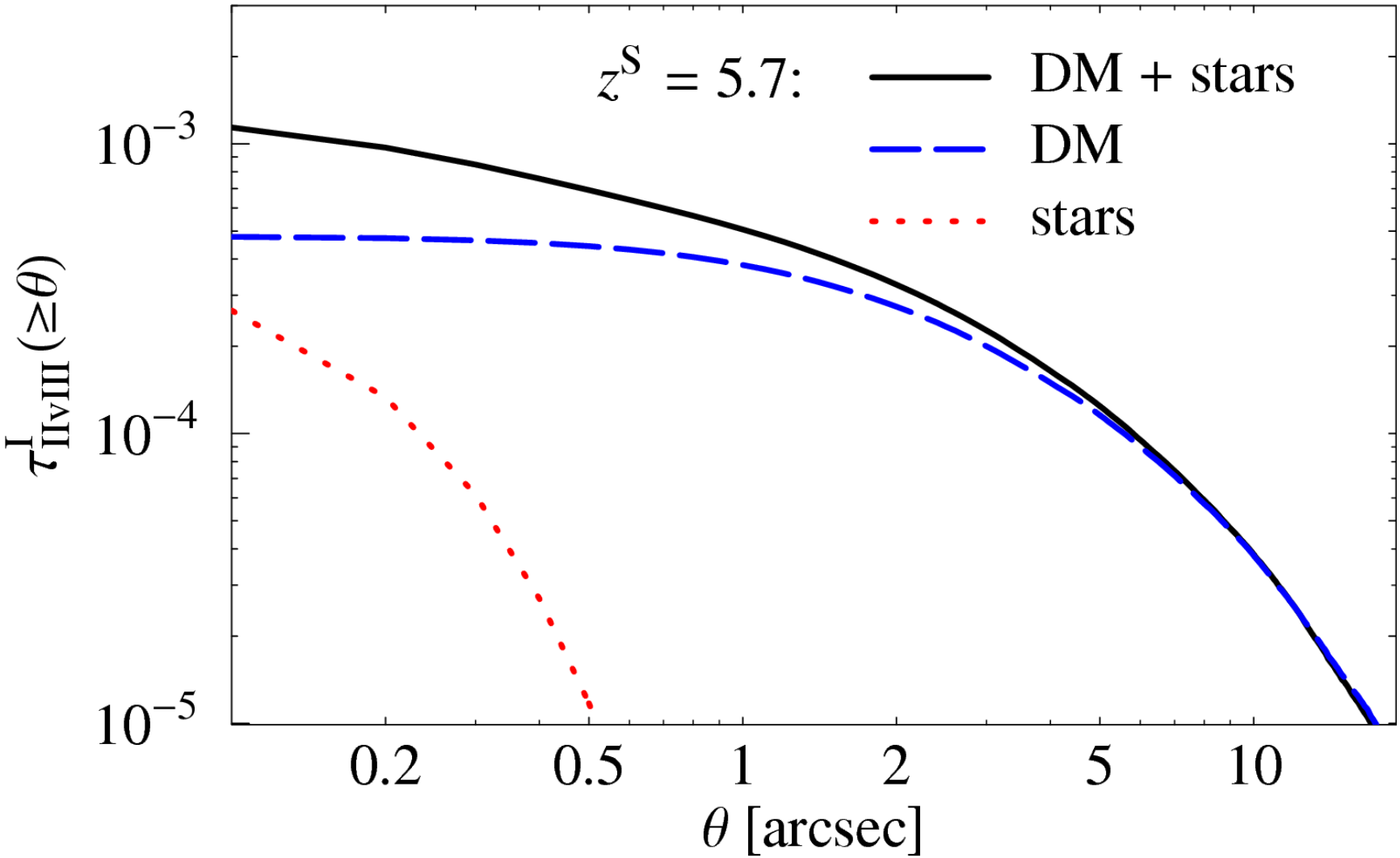
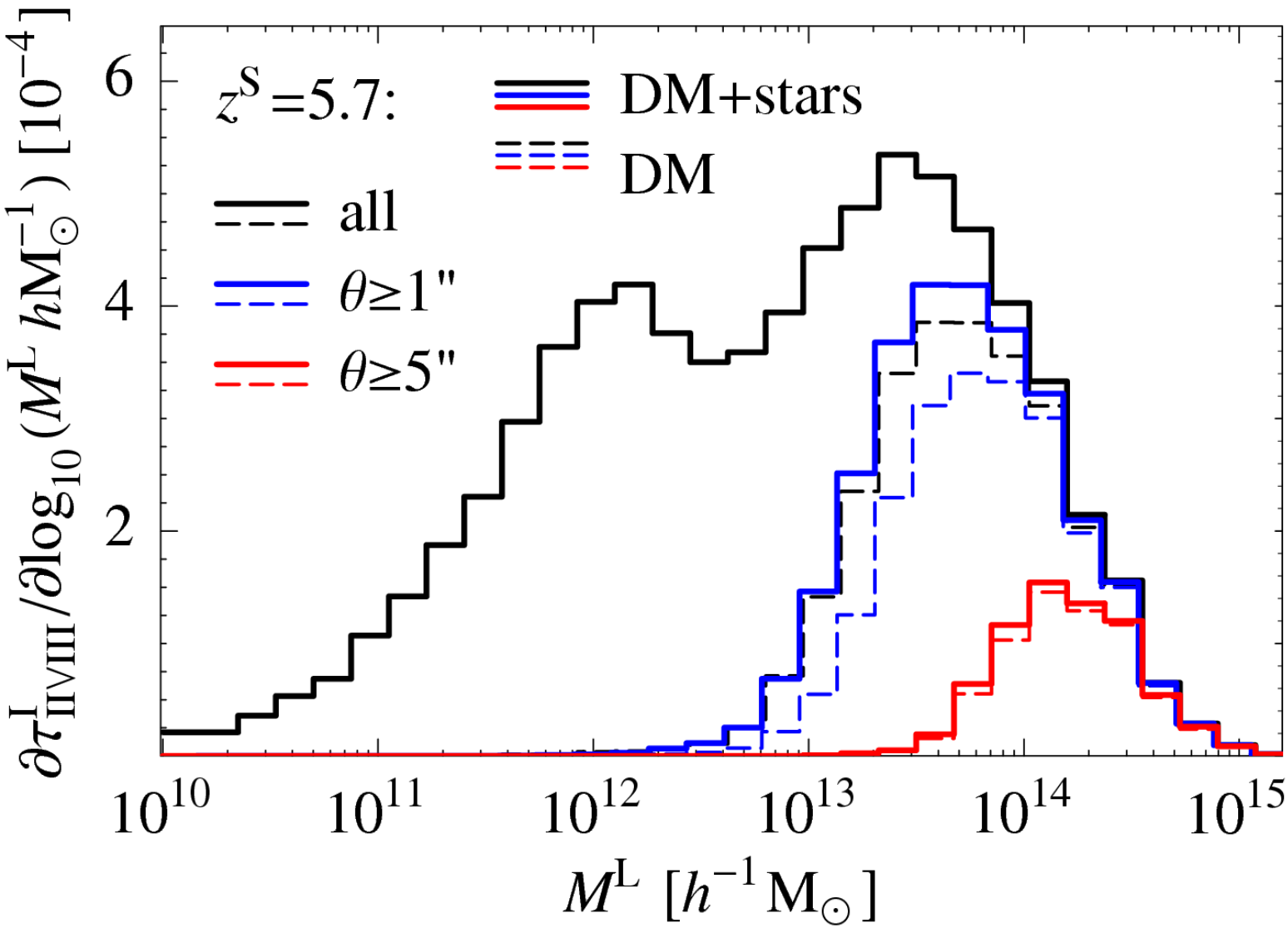


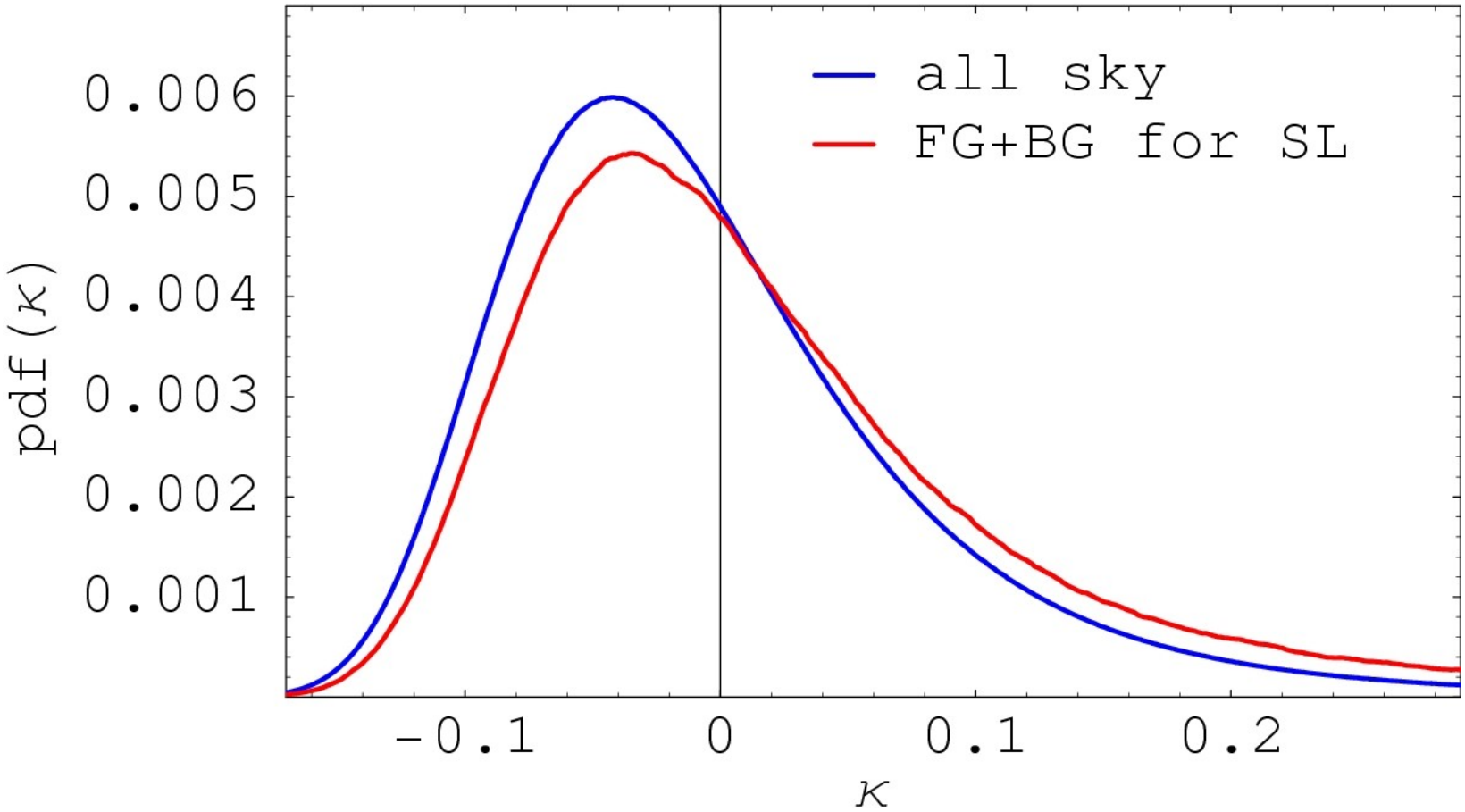
Image Splittings



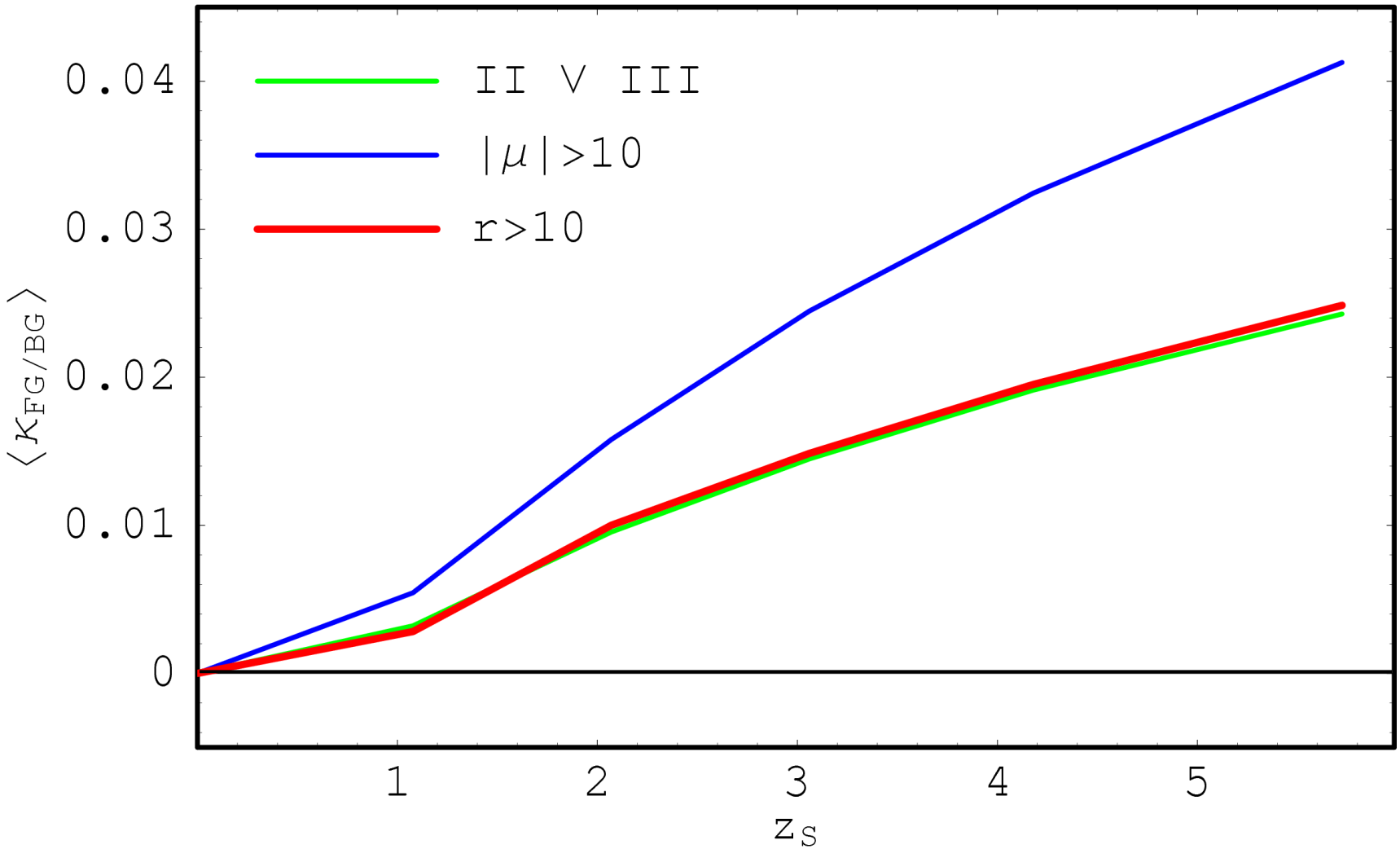
Lens Masses


z^S=5.7:
DM+stars
DM
all
$\theta \geq 1''$
$\theta \geq 5''$
$\partial\tau^L_{\rm II/VIII}/\partial\log_{10}(M^L\ hM_\odot^{-1})\ [10^{-4}]$
6
4
2
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
$M^L\ [h^{-1}M_\odot]$

Additional Matter along L.O.S.



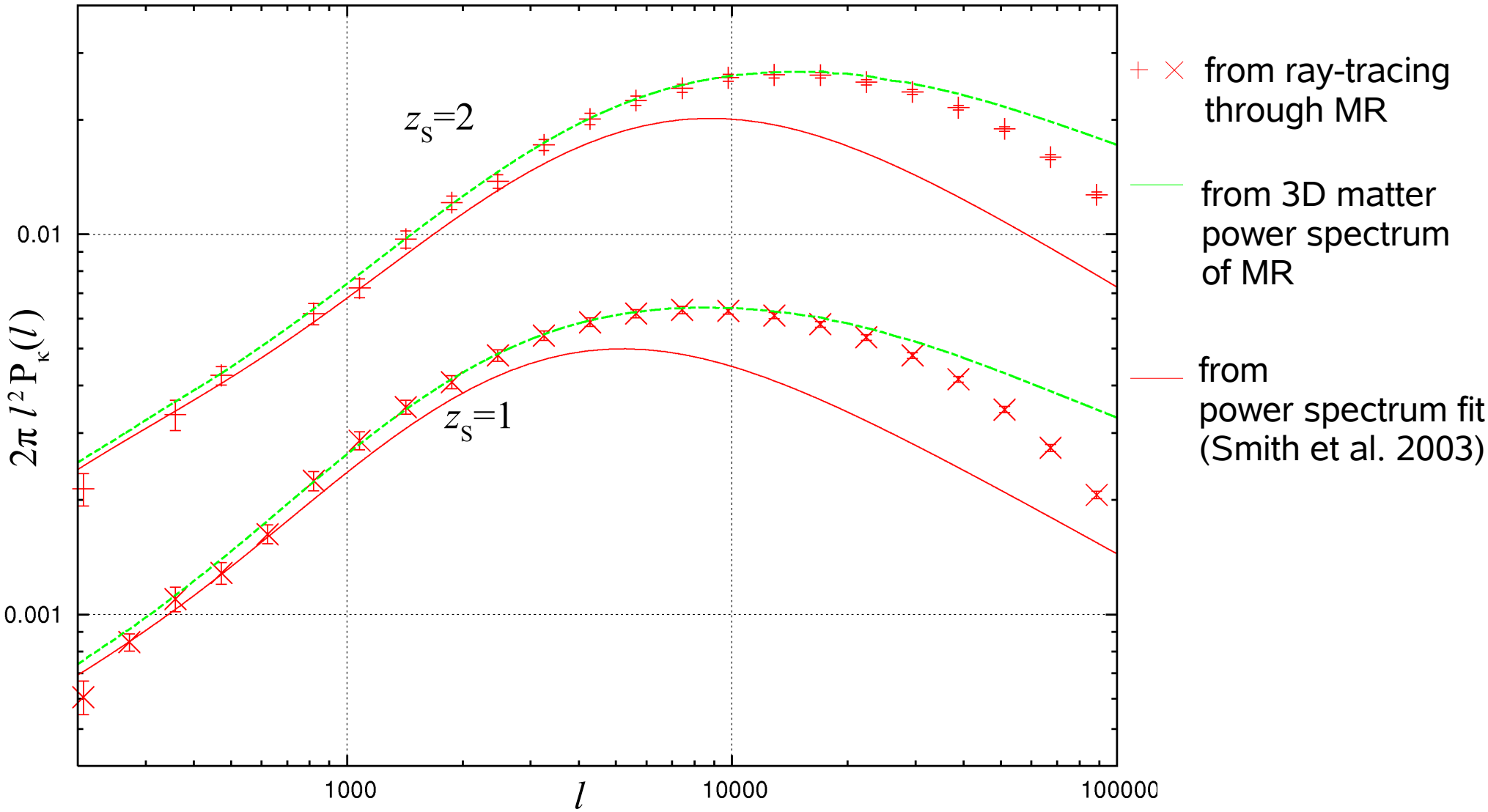
Additional Matter along L.O.S.



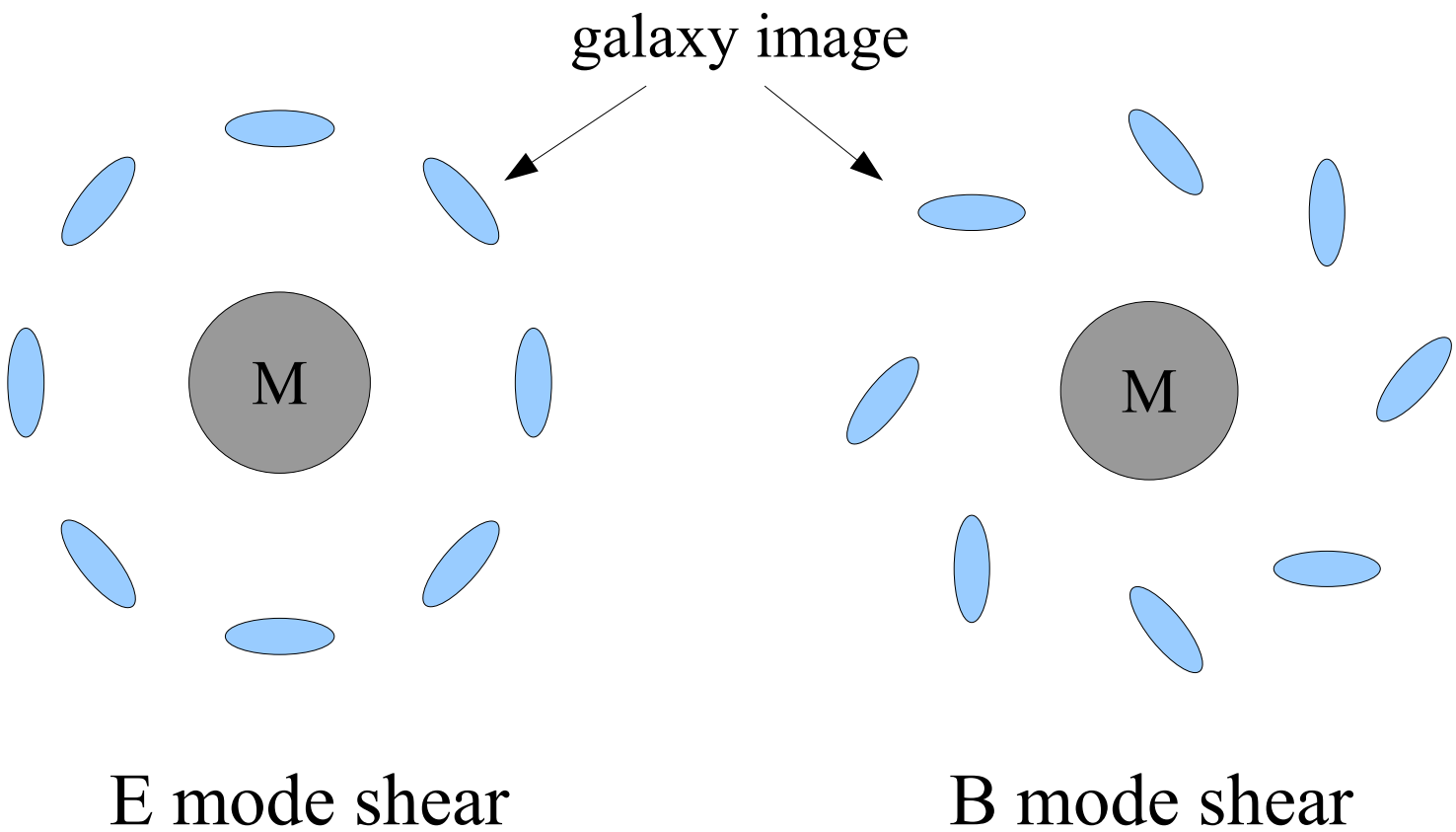
Weak Lensing

- ray-tracing over finite fields to simulate
  - cosmic shear surveys
  - galax-galaxy lensing (GGL)
- estimate how well GL constrains
  - mean mass profile of galaxies
  - relation between DM and galaxies in groups, clusters, and large-scale structure
- study systematics, etc.

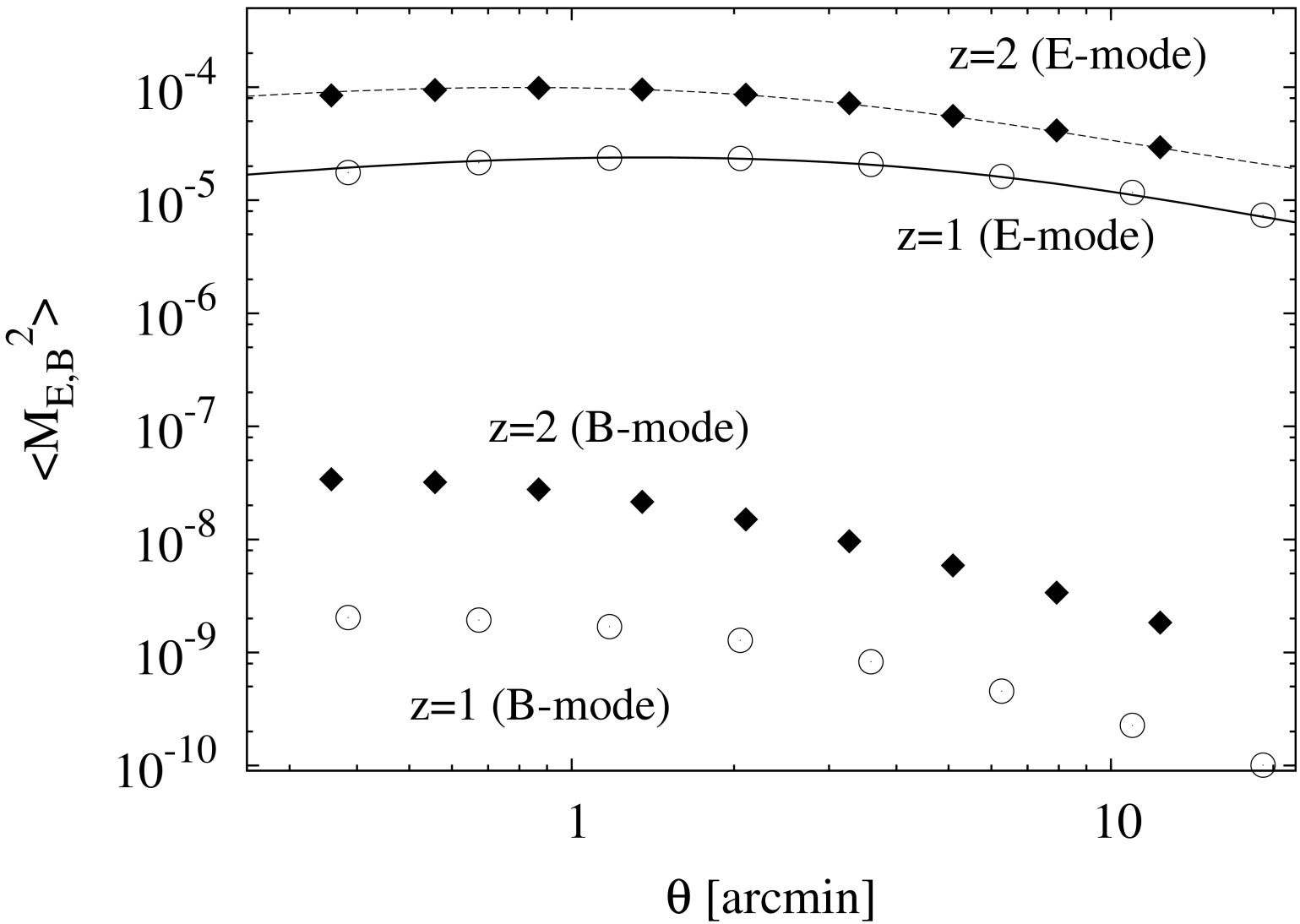
Shear Power Spectra



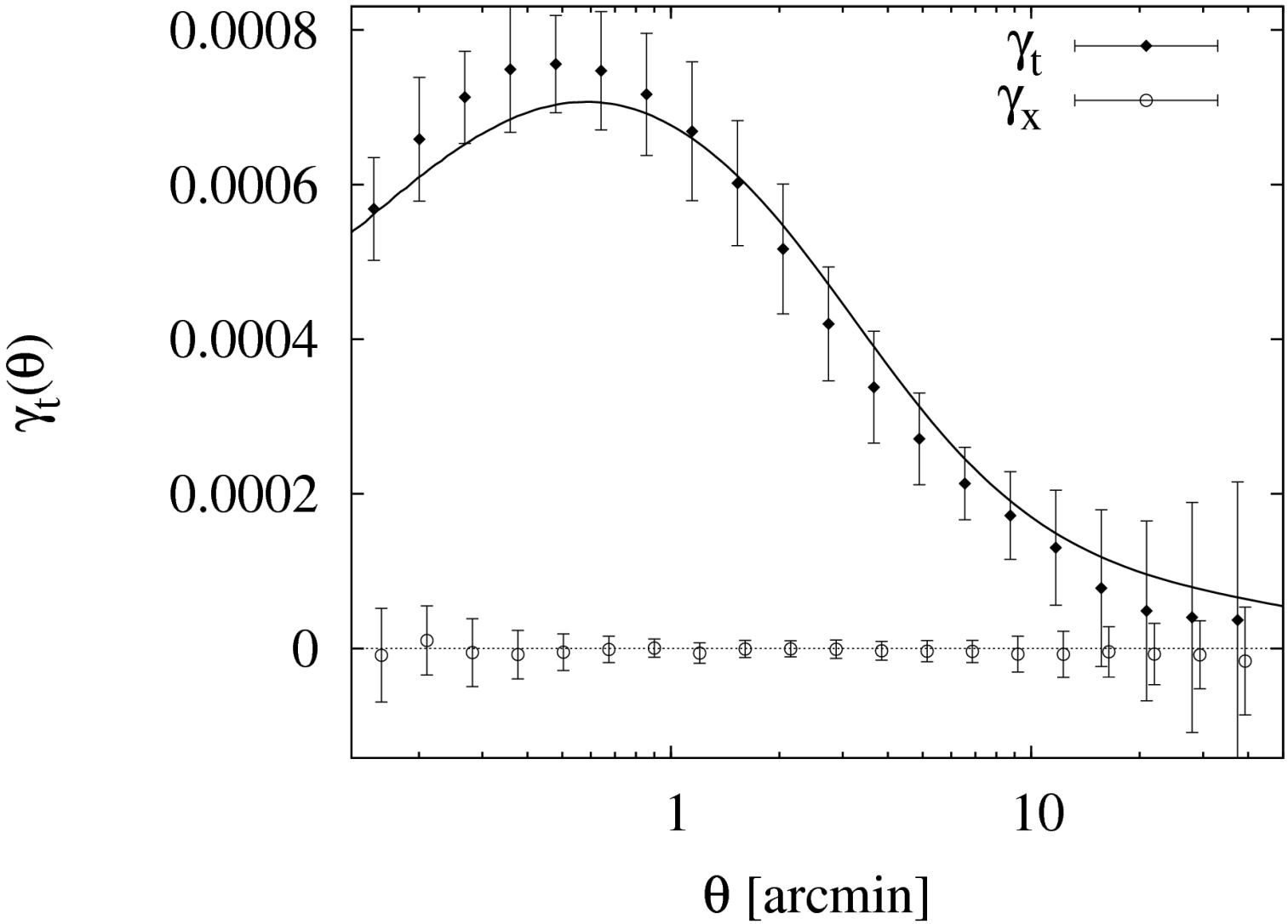
E/B-mode decomposition



Aperture Mass



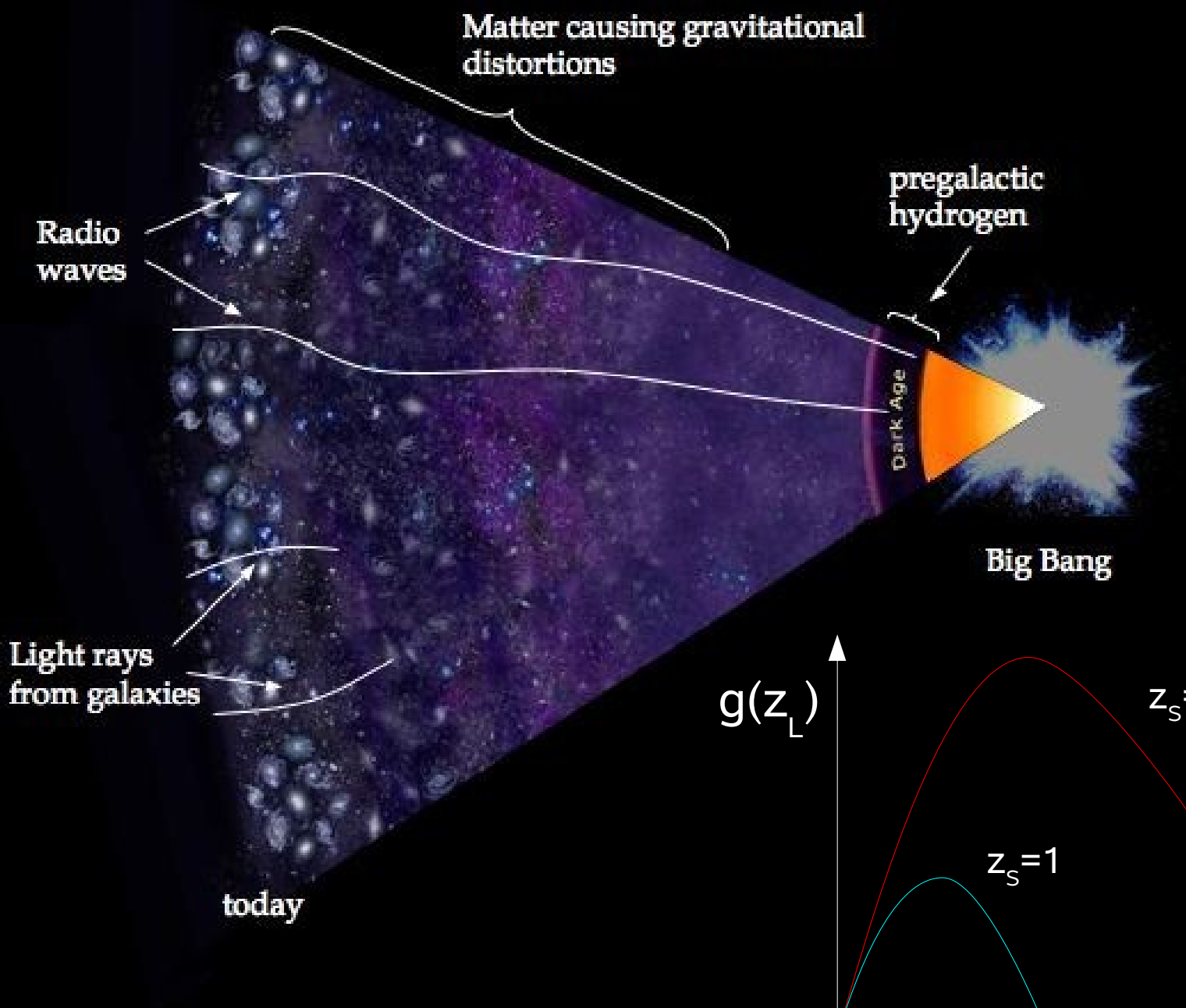
Galaxy-Galaxy Lensing

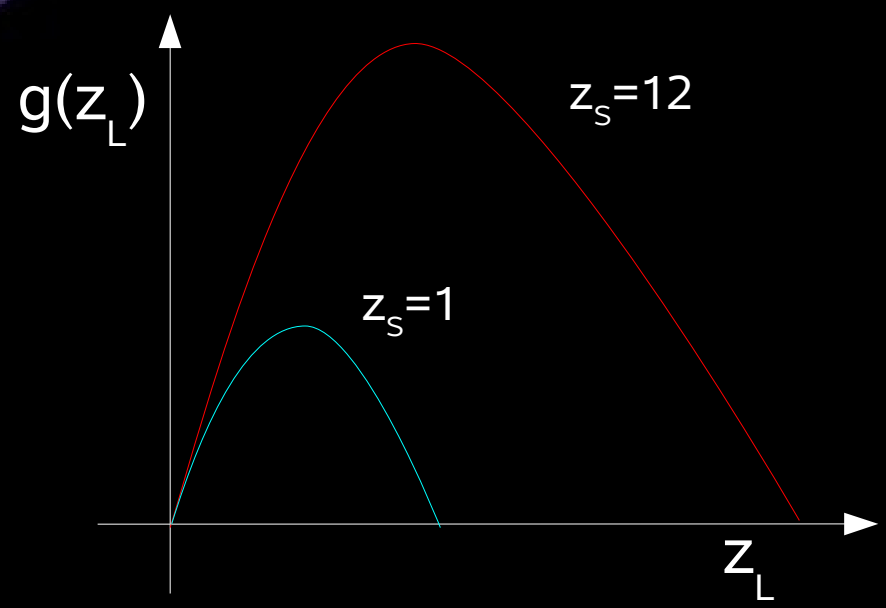


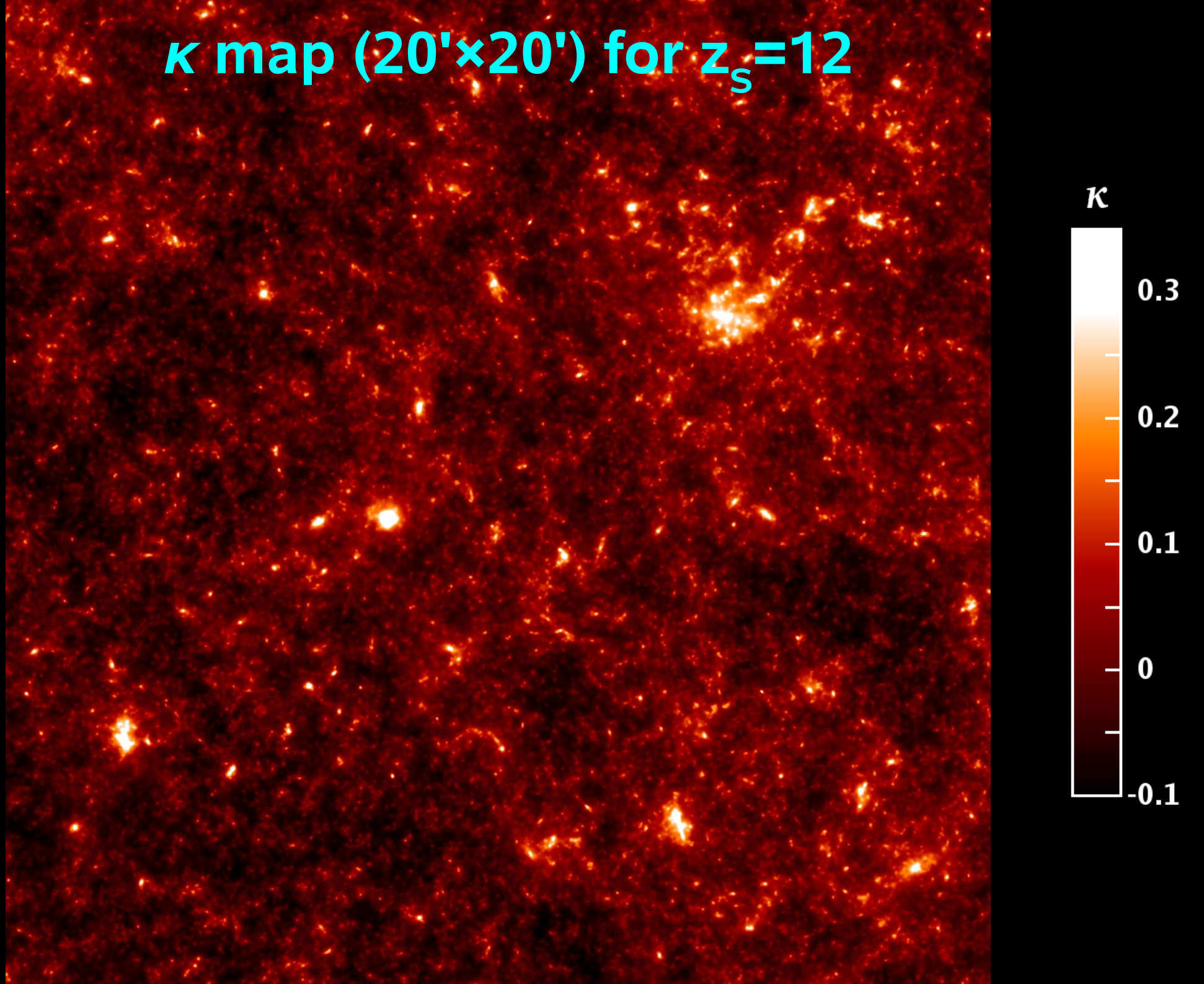
Convergence Maps

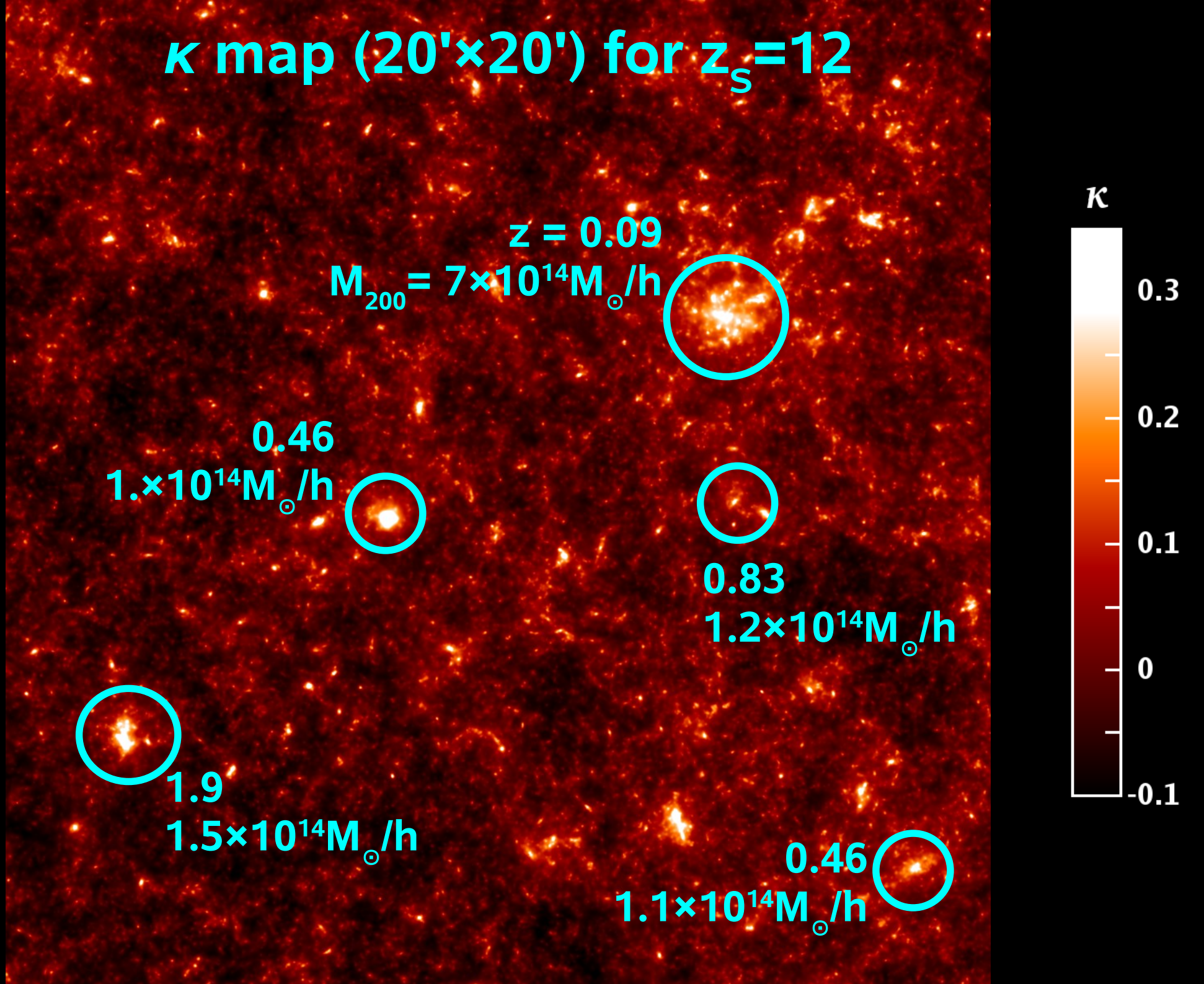
- up to now:
  image distortions of distant galaxies used
- future (?):
  image distortions of structures in pregalactic H as seen by radio telescopes
- use ray-tracing through MS to simulate convergence maps for (future) surveys

Metcalf & White 2007, MNRAS, 381, 447
Hilbert et al. 2007, MNRAS, 382, 1494


Matter causing gravitational distortions
pregalactic hydrogen
Radio waves
Dark Age
Big Bang
Light rays from galaxies
today

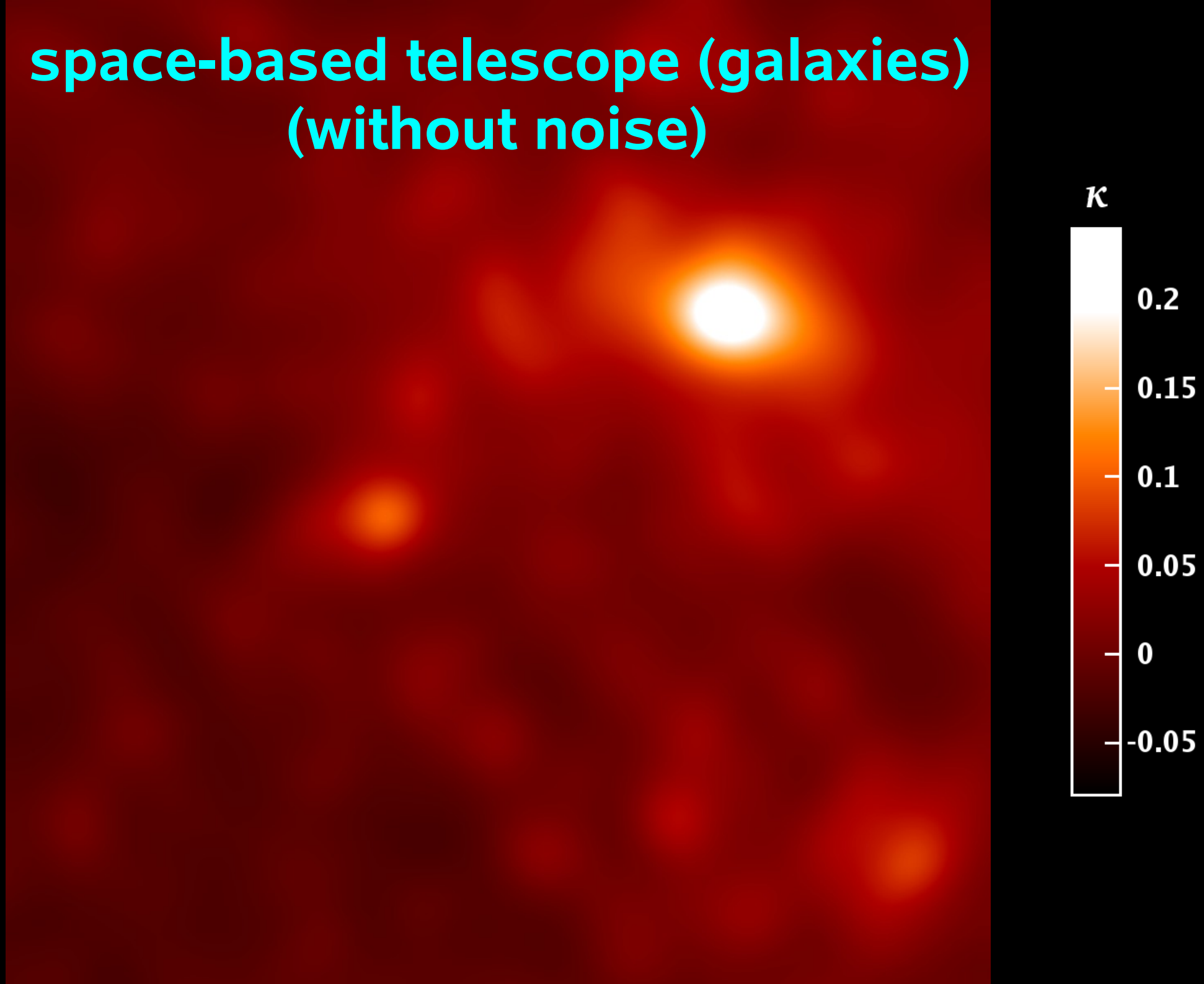

g(z_L)
z_S=12
z_S=1
z_L

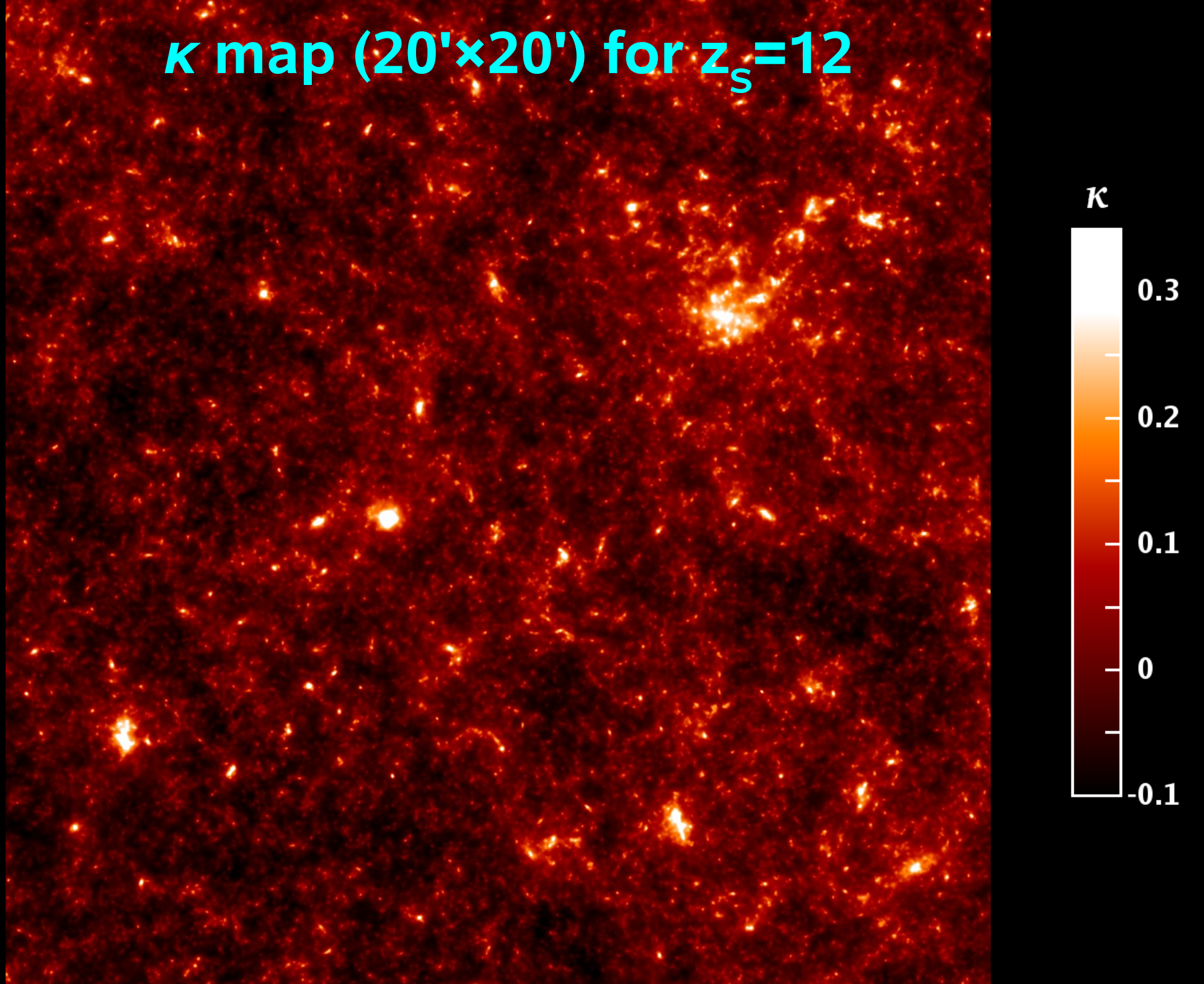

κ map (20'×20') for z_s=12
κ
0.3
0.2
0.1
0
-0.1


κ map (20'×20') for z_S=12
z = 0.09
M_{200}= 7×10^{14}M$_\odot$/h
0.46
1.×10^{14}M$_\odot$/h
0.83
1.2×10^{14}M$_\odot$/h
1.9
1.5×10^{14}M$_\odot$/h
0.46
1.1×10^{14}M$_\odot$/h
κ
0.3
0.2
0.1
0
-0.1

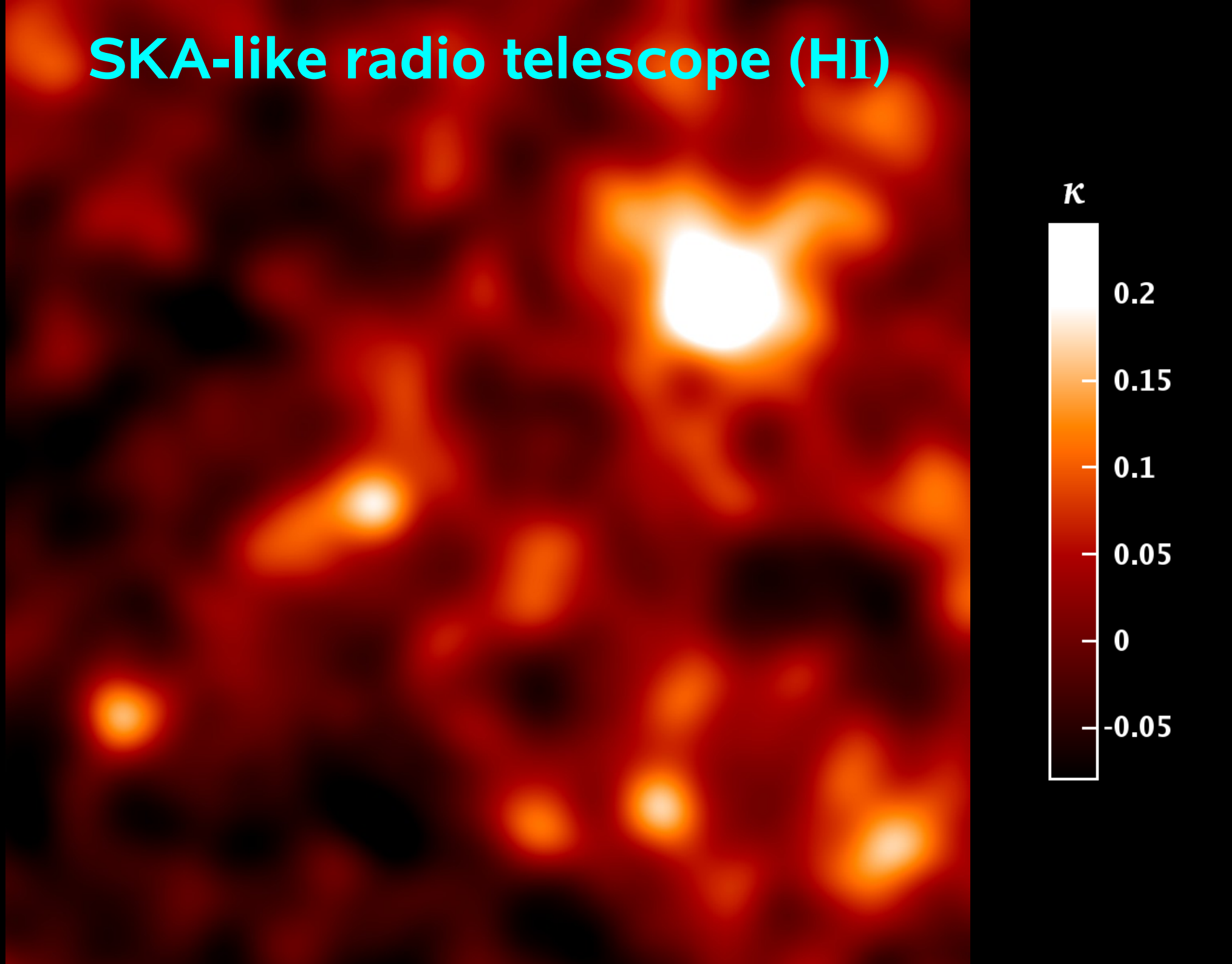
space-based telescope (galaxies)

space-based telescope (galaxies) (without noise)

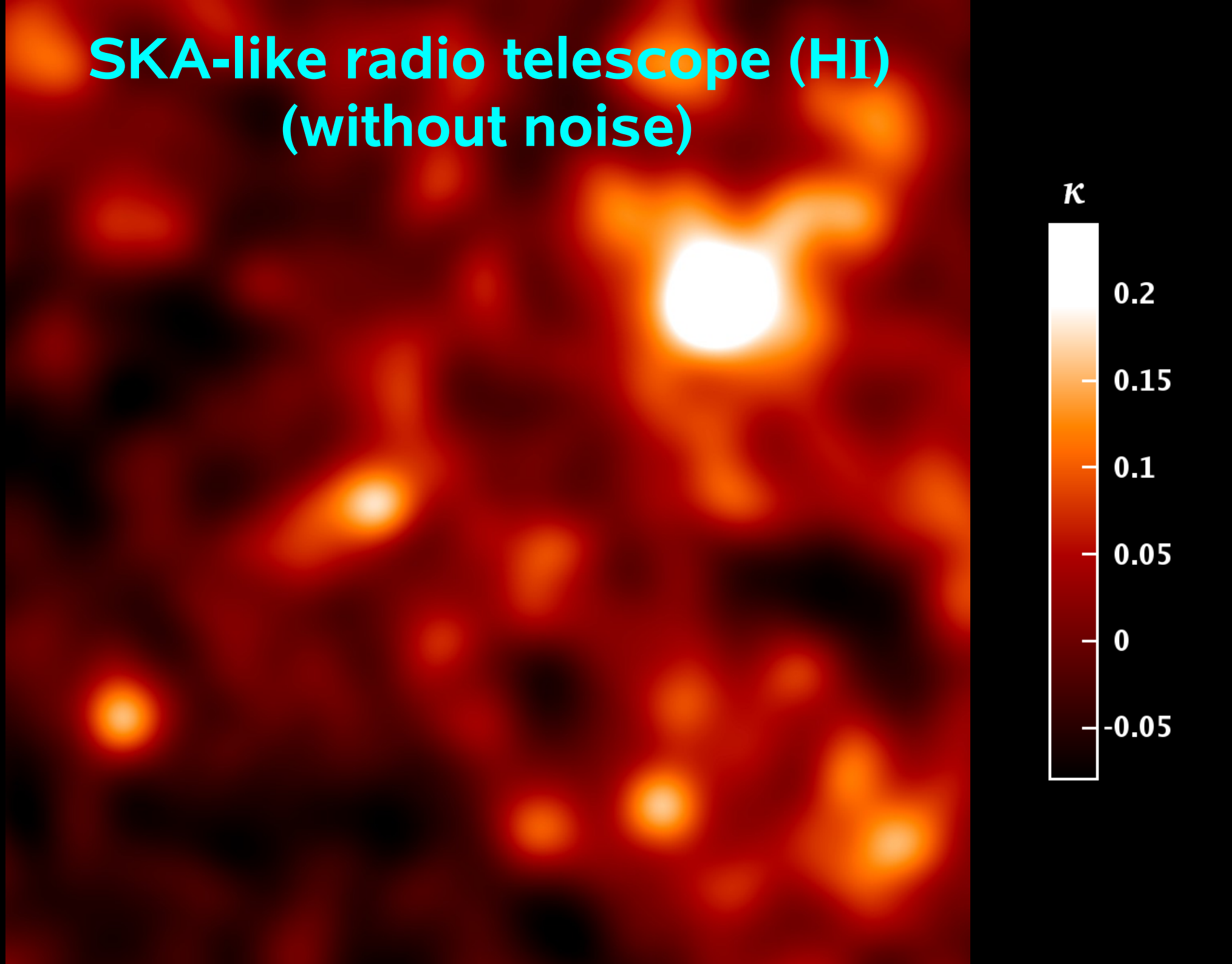


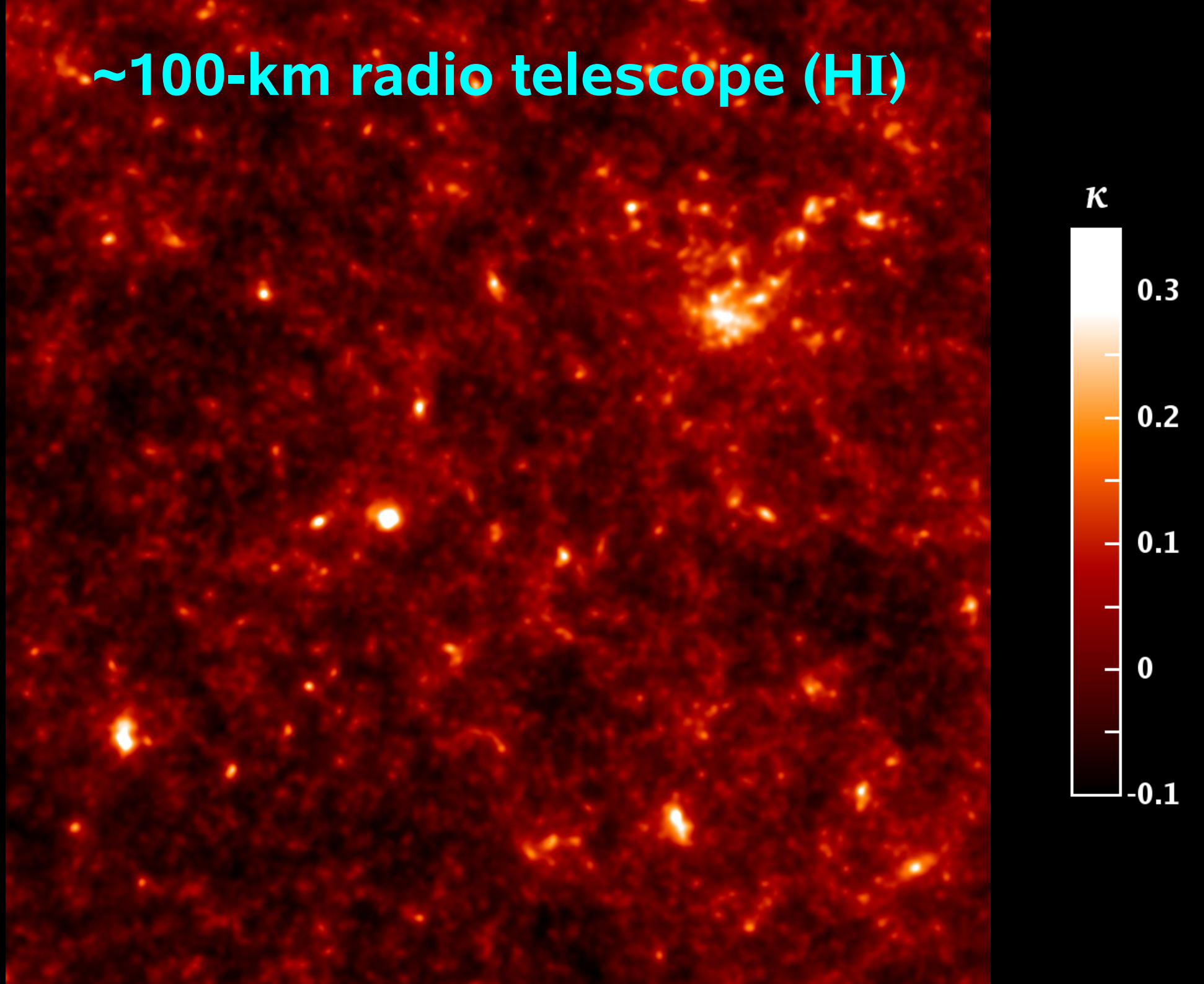

κ map (20'×20') for z_s=12
κ
0.3
0.2
0.1
0
-0.1

SKA-like radio telescope (HI)



SKA-like radio telescope (HI) (without noise)




~100-km radio telescope (HI)
κ
0.3
0.2
0.1
0
-0.1

Summary

- GL: tool to measure cosmol. mass distribution
- Millennium Sim.: high resolution + large volume
- ray-tracing code adapted to MS
- first results:
  - strong-lensing optical depths
  - properties of strong lenses
  - convergence maps
  - shear correlations and power spectra

Possible Future Projects

- galaxy-galaxy lensing: galaxy bias, selection effects, comparison to halo models, ...
- 3-point statistics (GGGL)
- flexion
- ...

Thanks
for
Your Attention!