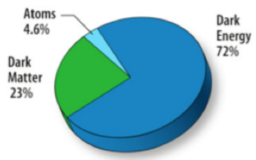
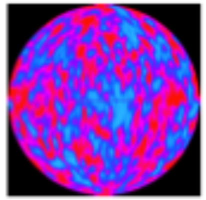
We have learned

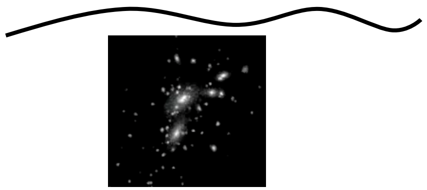
1. The standard cosmological model



$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\rho - \frac{c^2 K}{a^2} + \frac{c^2 \Lambda}{3}$$

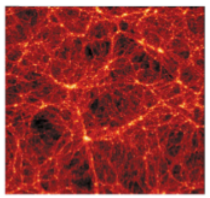


2. Growth of density fluctuations

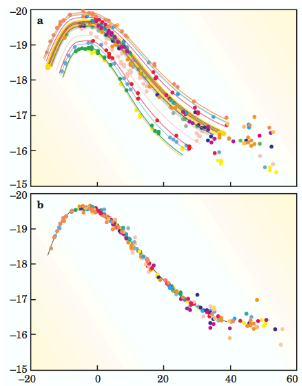


$$\sigma^2(M) = \frac{1}{2\pi^2}\int P(k)W^2(kR)k^2\mathrm{d}k.$$

3. The nature of dark matter



4. Mysterious dark energy



その前に: ダークエネルギーの進化

アインシュタイン方程式にFRW計量を入れると

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\rho - \frac{c^2 K}{a^2} + \frac{c^2\Lambda}{3}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\rho + 3p) + \frac{c^2\Lambda}{3}$$

上の式を時間部分し、下の式を使うと

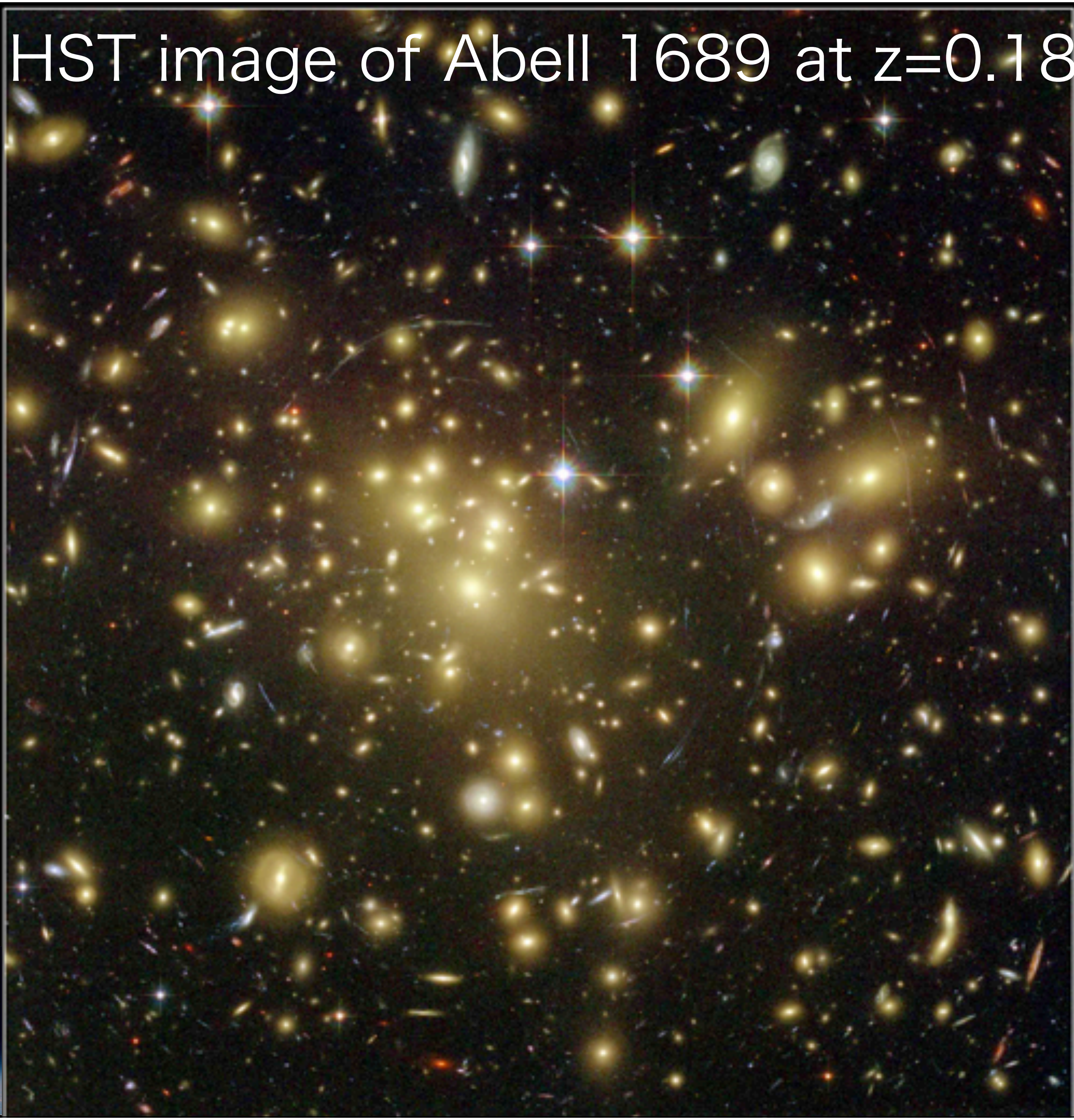
$$\dot{\rho} \;=\; -3\left(\rho + p\right)\frac{\dot{a}}{a}$$ (密度の進化の式)

$p = w\rho$ に対しては

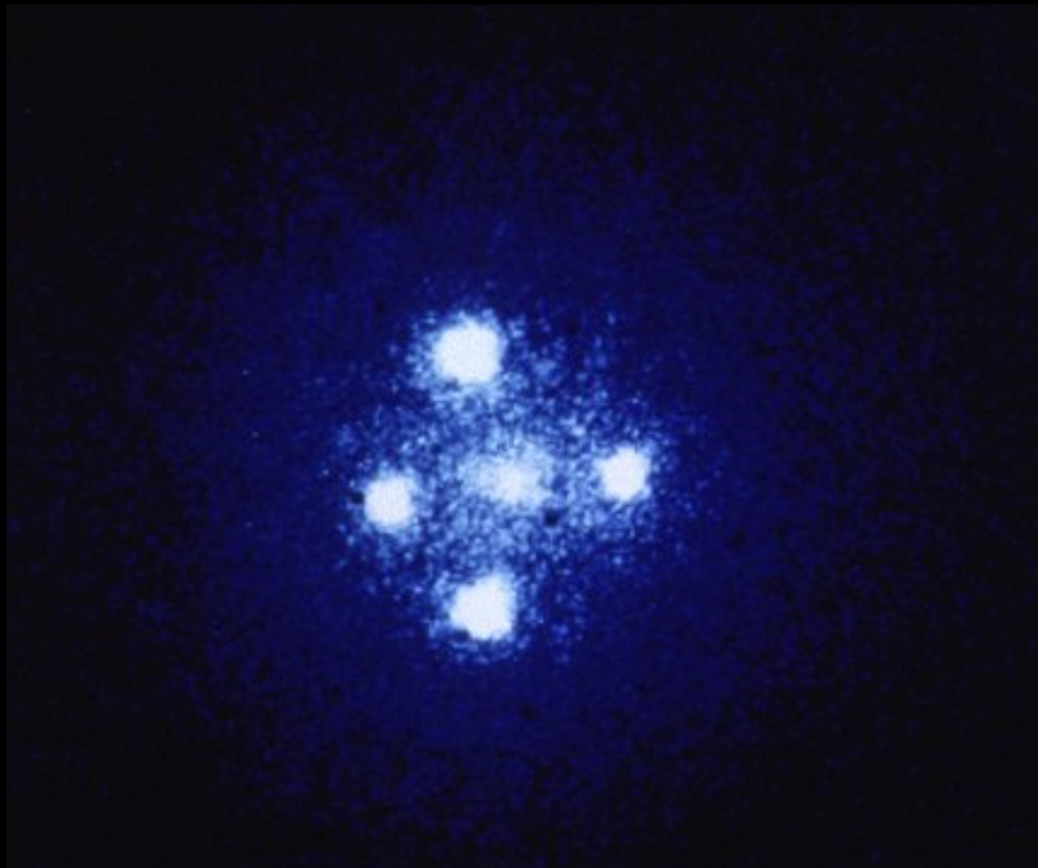
$$\rho \propto \exp\left(-3\int \frac{\mathrm{d}a'}{a'}(1 + w(a'))\right)$$

重力レンズ宇宙論

HST image of Abell 1689 at z=0.18



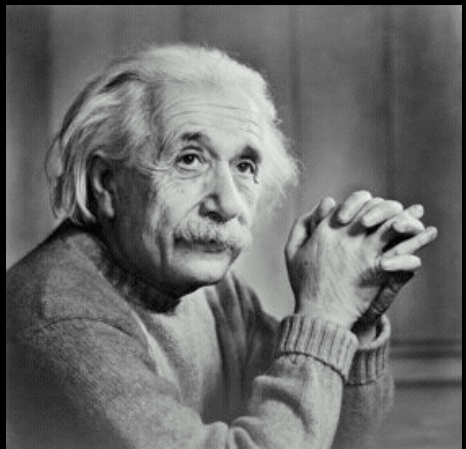
QSO-galaxy lens

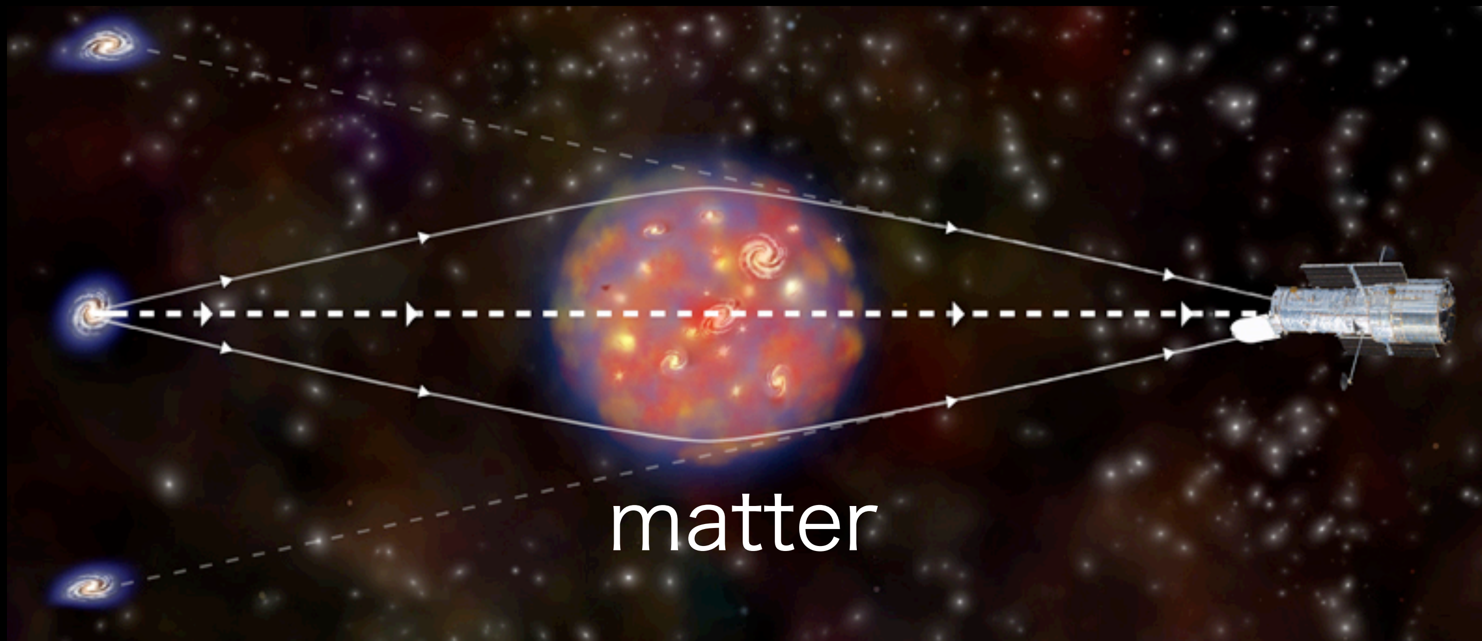


Galaxy-galaxy lens

Gravitation lensing

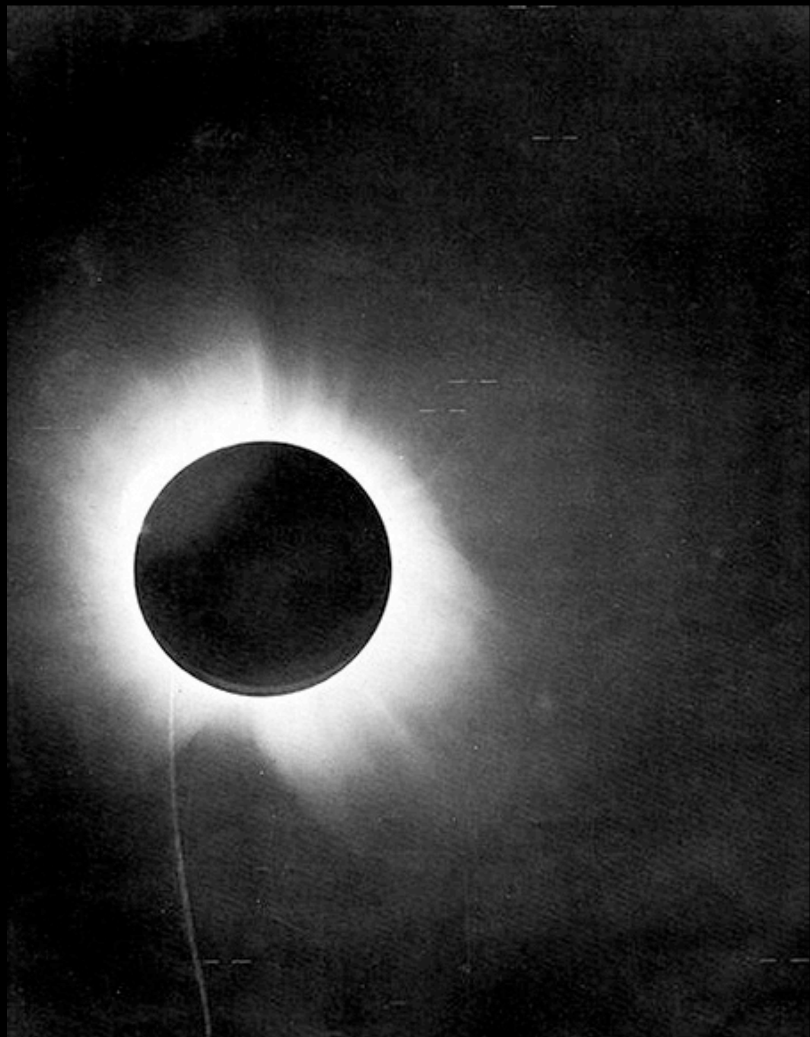
General relativistic effect





Light rays are deflected near a massive object. (It is space-time that is curved.)

May 29, 1919



板書

Quiz 13: Deflection of light

Calculate the deflection angle for a light-ray passing through near the surface of the sun.

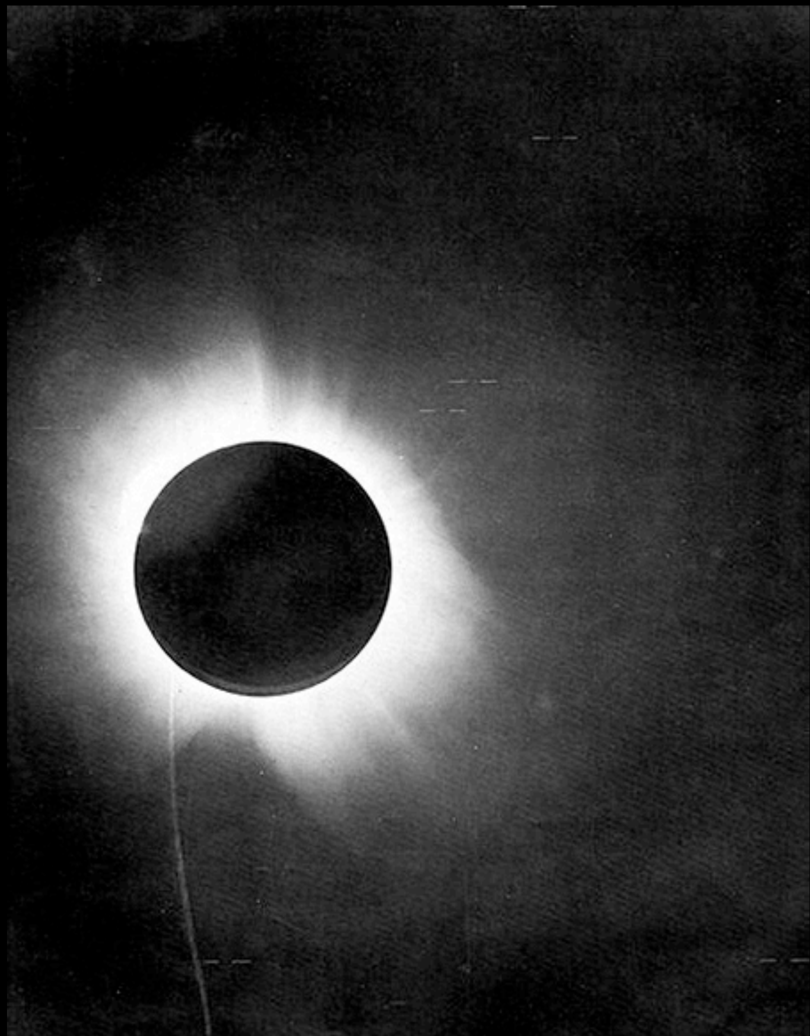
$M_{sun} \sim 2 \times 10^{30}$ kg, $R_{sun} \sim 7 \times 10^{5}$ km

Calculate the typical deflection angle for a galaxy having an isothermal density profile

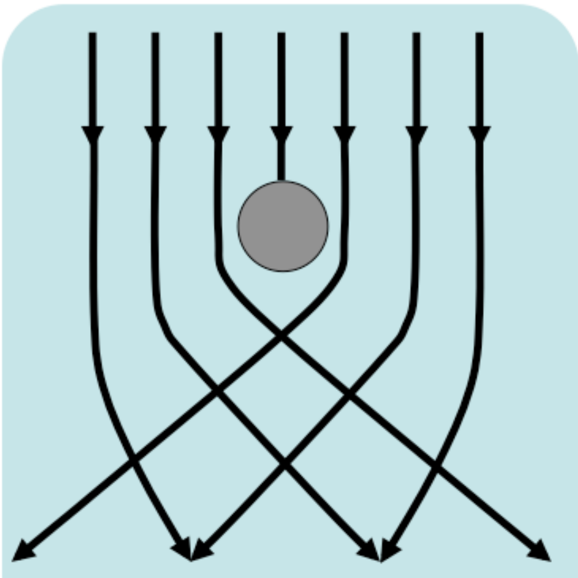
$\rho(r) = C\, r^{-2}$

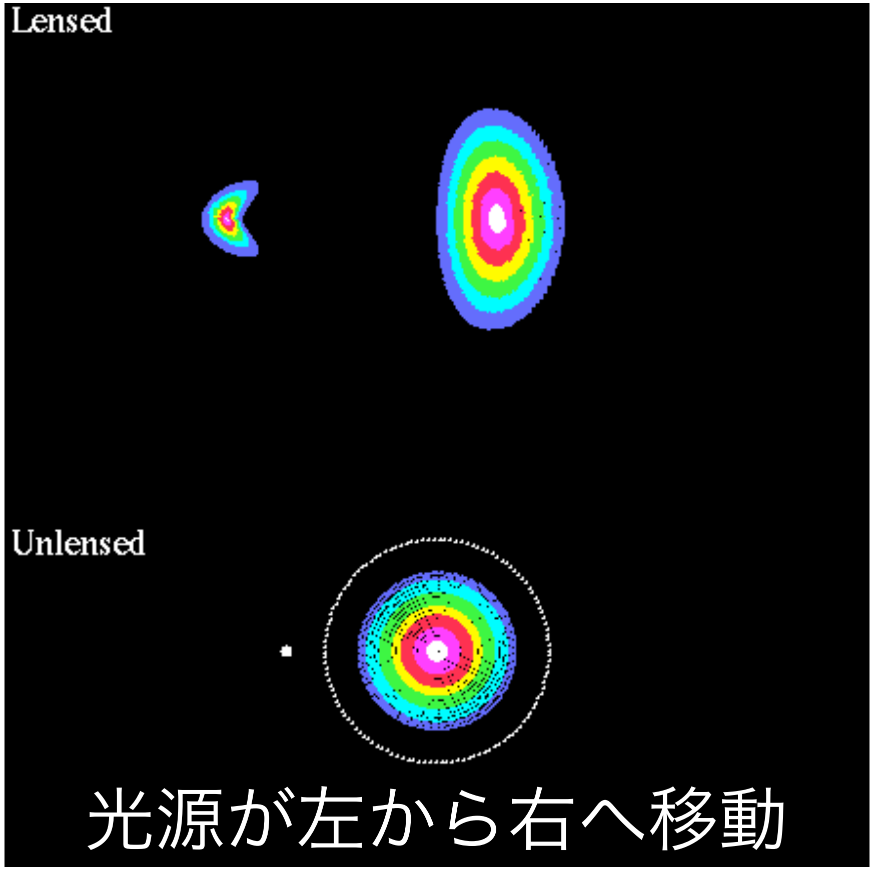
Use $M_{gal} \sim 10^{12}\, M_{sun}$, $R_{gal} \sim 100$ kpc

May 29, 1919

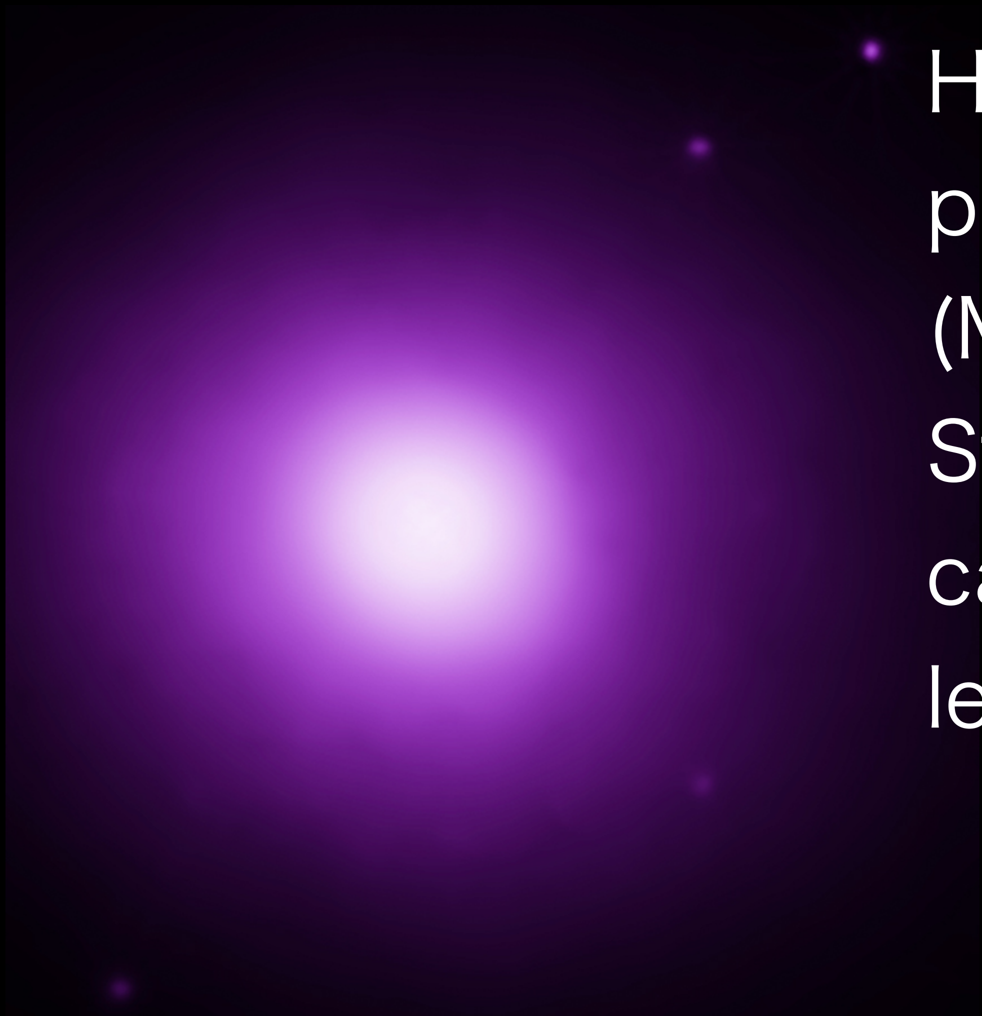


Different from optical lens





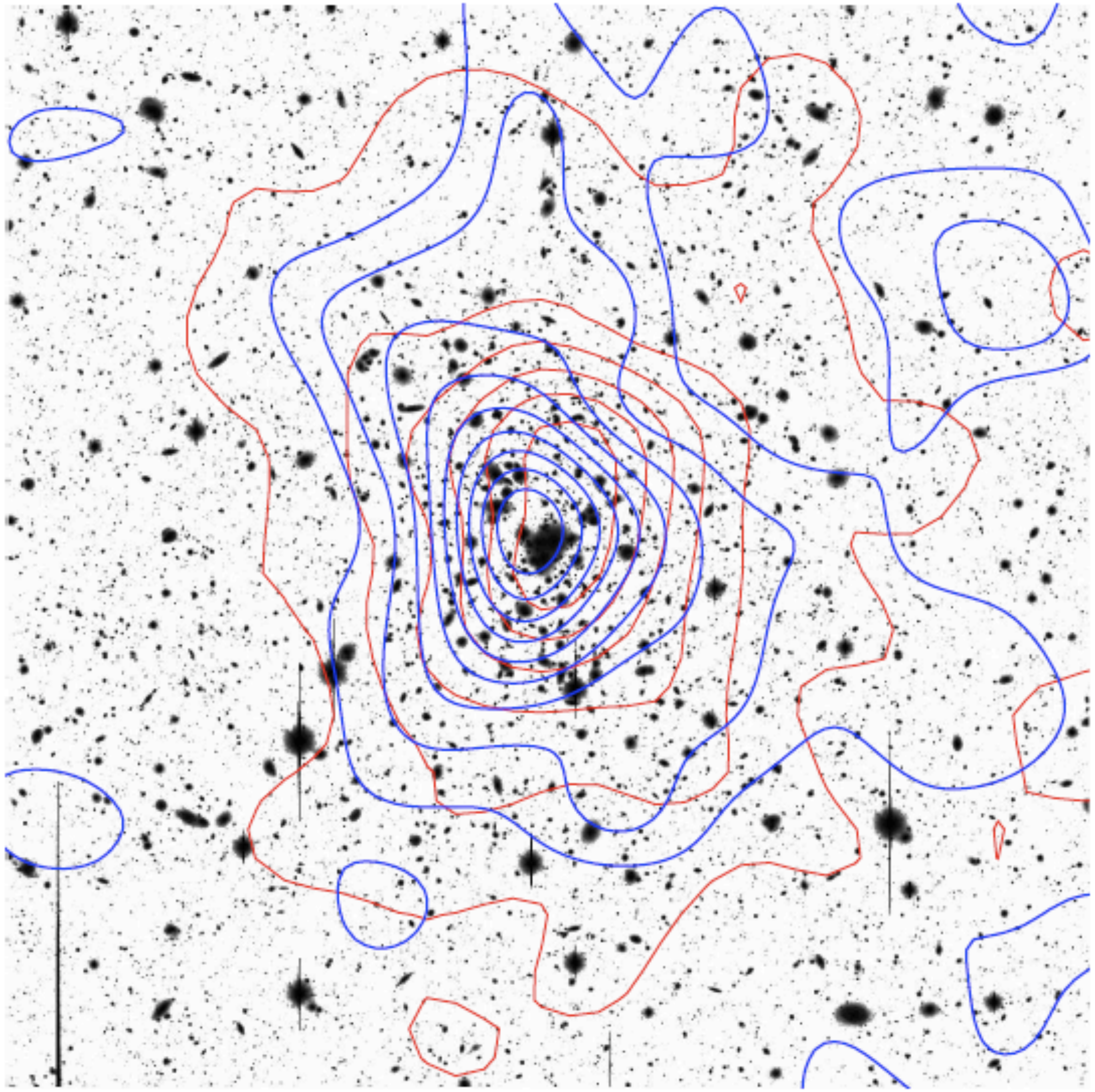
X-ray image of a cluster



Hot intra-cluster plasma with $T \sim 10^7$ K ($M \sim 10^{14}\ M_{sun}$)

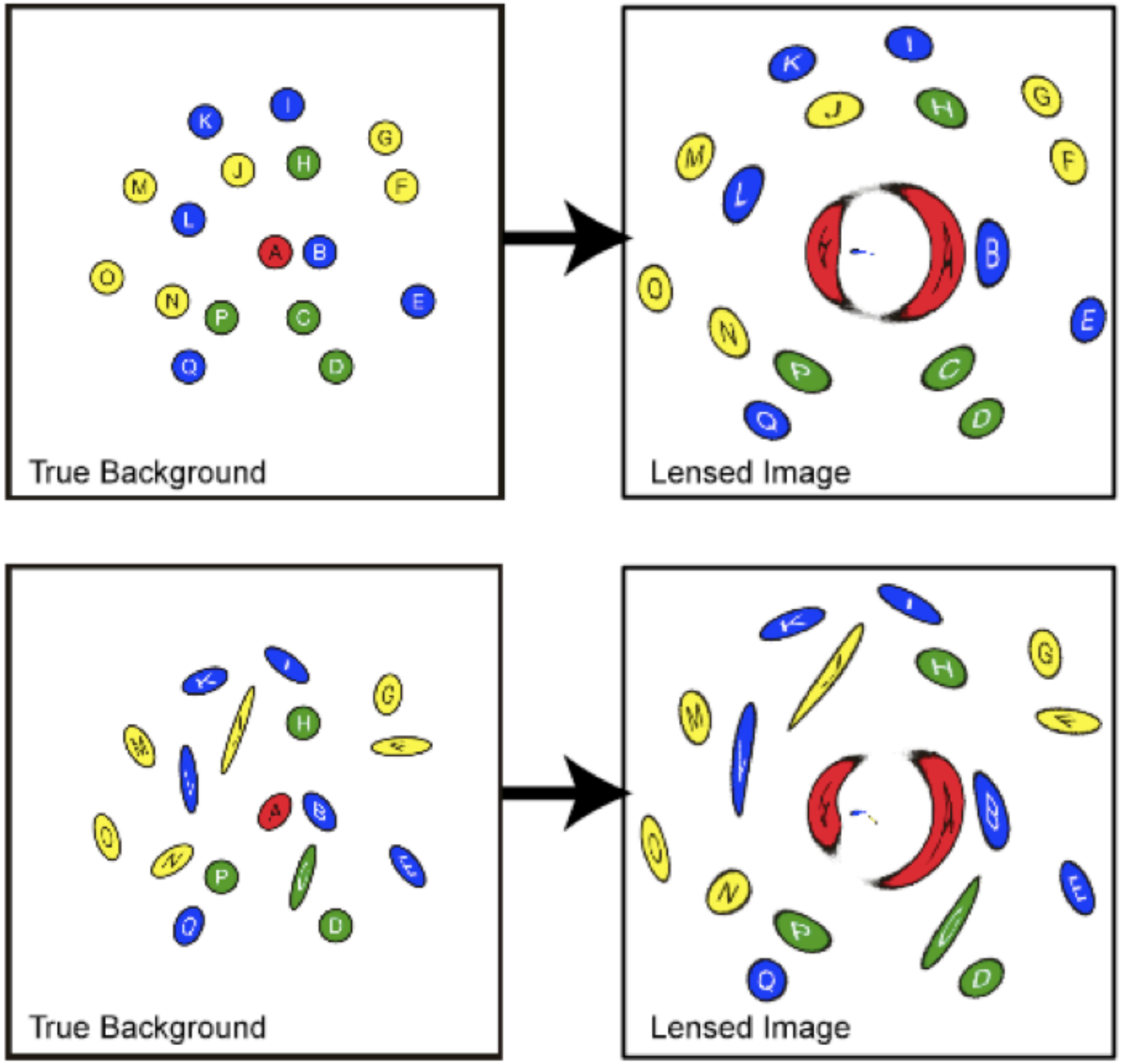
Still not enough to cause gravitational lensing.

Mass distribution



Blue contours show the mass distribution around the same cluster.

Weak lensing

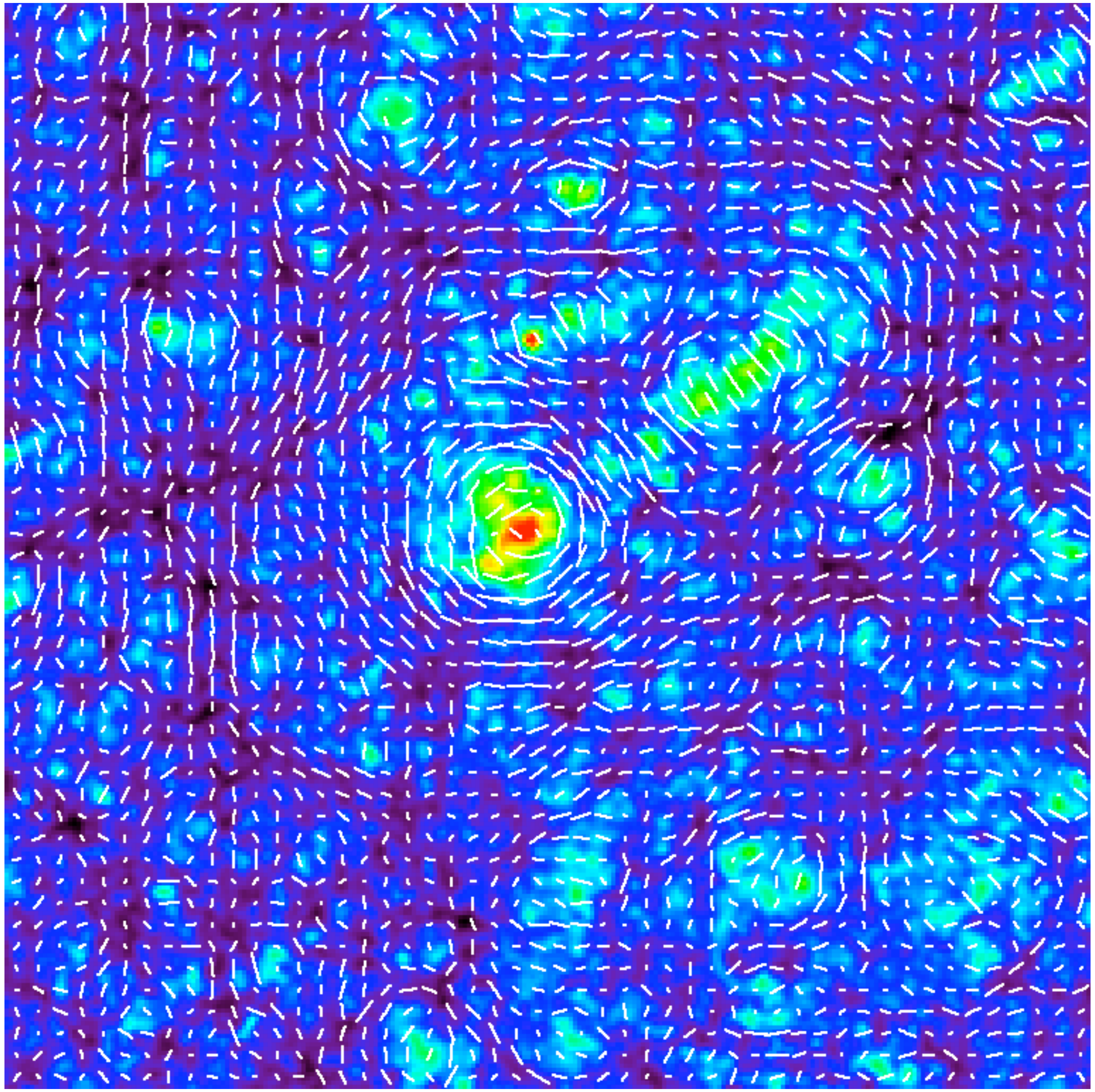


Images of background galaxies are magnified and distorted.

Strong lensing produces multiple lensed-images and large distortion.

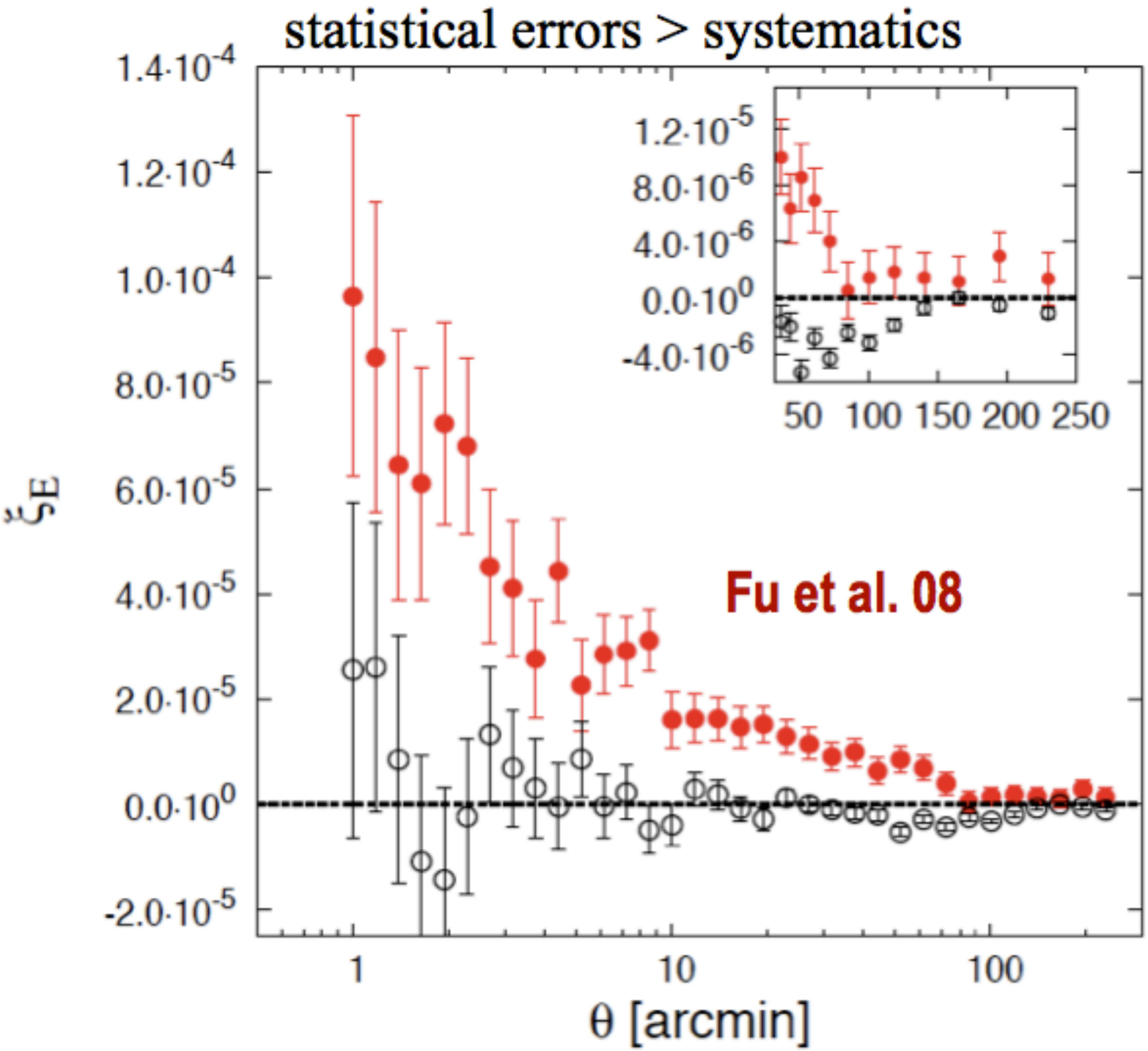
Weak lensing causes small strectch and coherent alignment.

Lensing shear map



White lines show the amplitude and the direction of local shear ~ the 2nd derivative of the 2D (projected) gravitational pot.

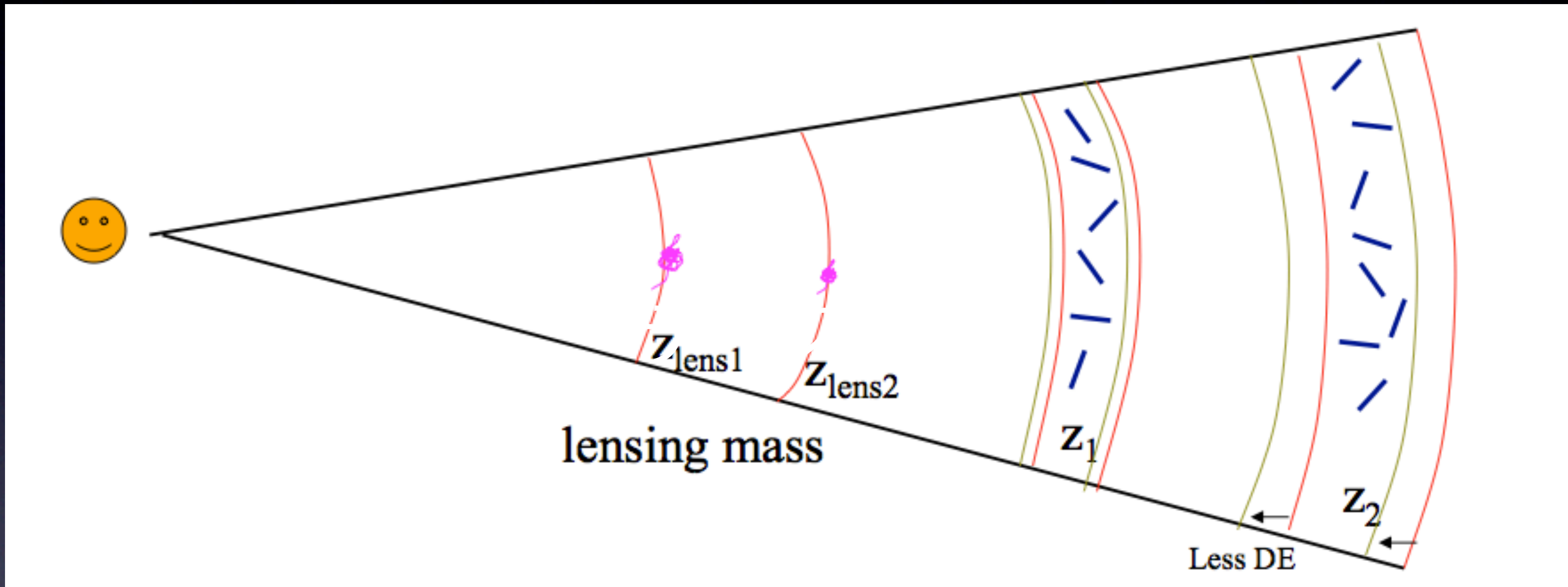
The state-of-art: CFHT WL Survey



- ~60 sq deg^2 (effective area: ~30 sq. deg^2)
- *i'*_AB~24.5, <z>~0.9
- Calibrate source redshift with the CFHT deep survey and the VVSD
- **~20σ detection,** over a range of few arcminutes to a few degrees
- 170 deg^2 results will be released this year?

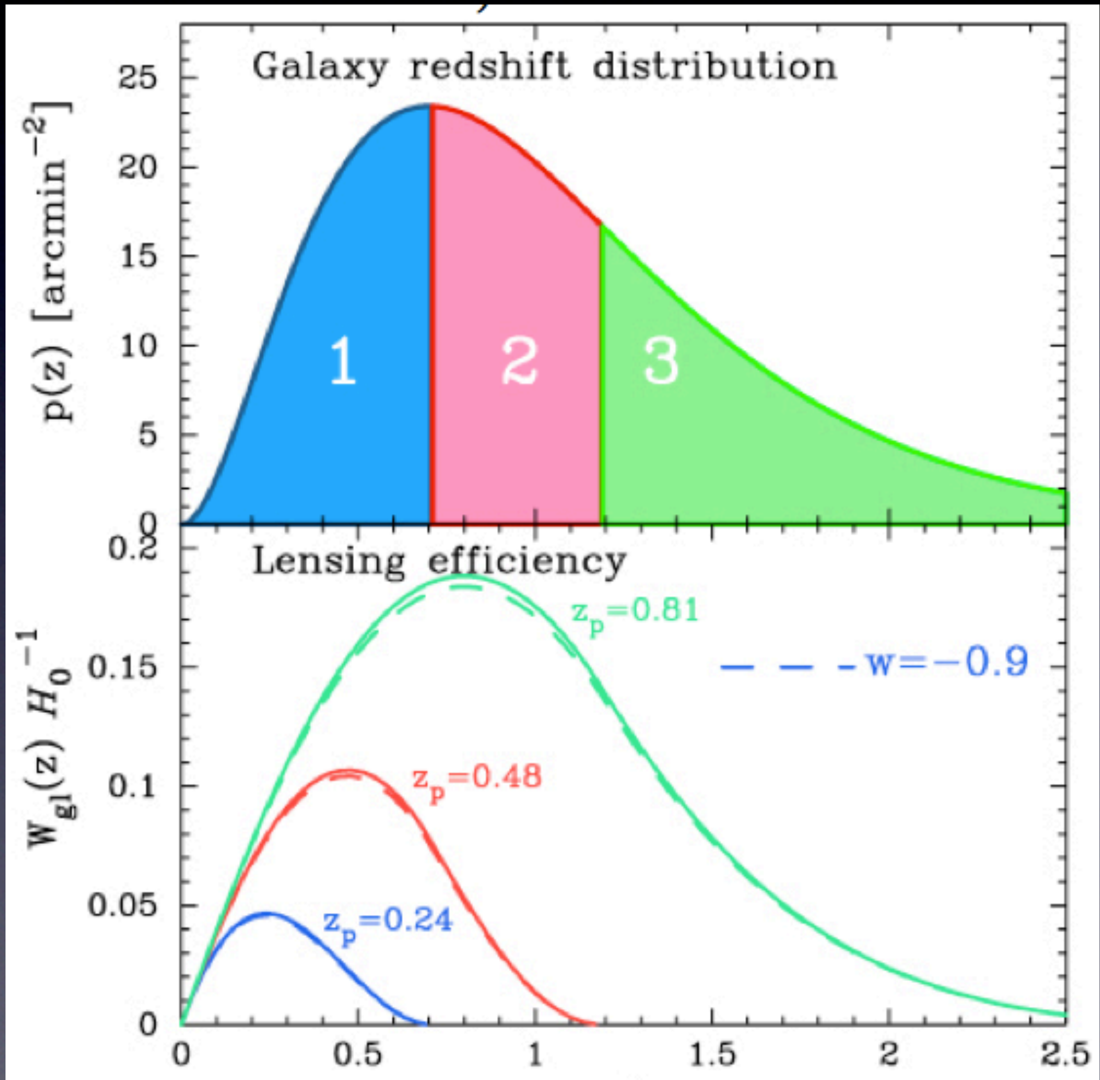
Slide from M. Takada

Lensing tomography



Selecting source galaxies by redshift enables to probe structure at different distances.

Lensing tomography

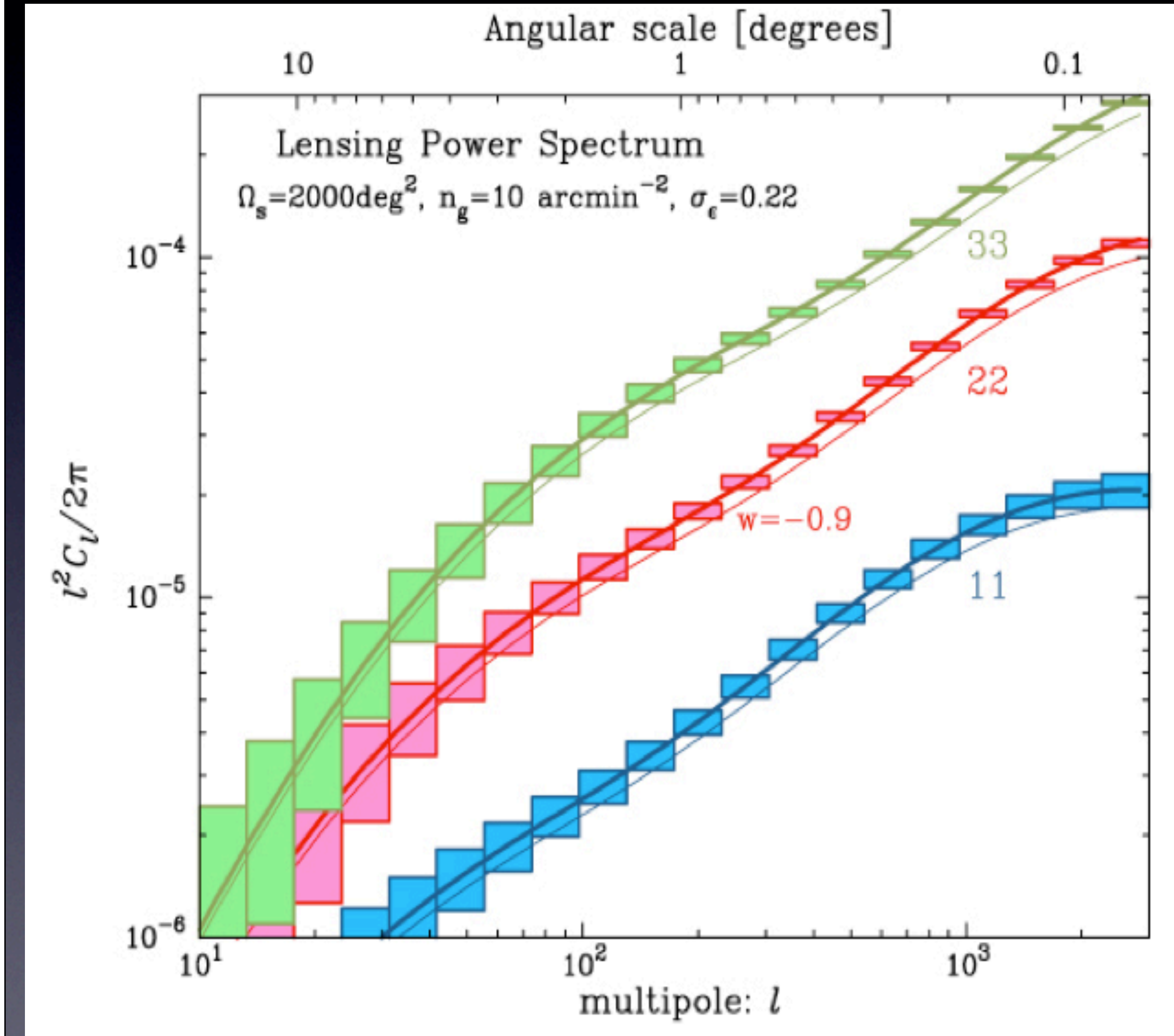


Lensing efficiency has a broad shape even for a single source redshift.

↓

To do "coarse" tomography, one doesn't need precise redshifts of all the source galaxies.

Power spectrum



Exact shapes less important. (Featureless anyway)

The overall amplitude and the evolution give strong constraints on cosmological parameters.

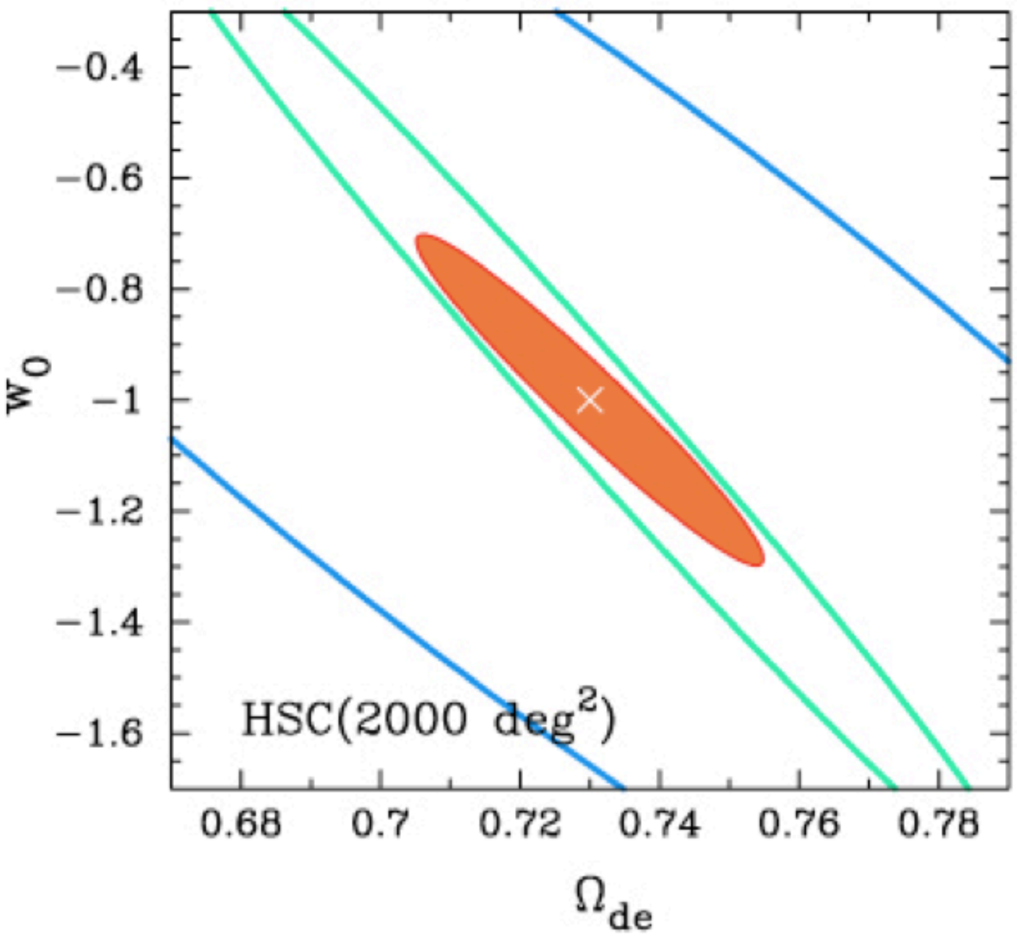
遠方宇宙の暗黒物質の可視化

国際協同コスモスプロジェクト

120万個の銀河の重力レンズ解析から３次元構造を再構築

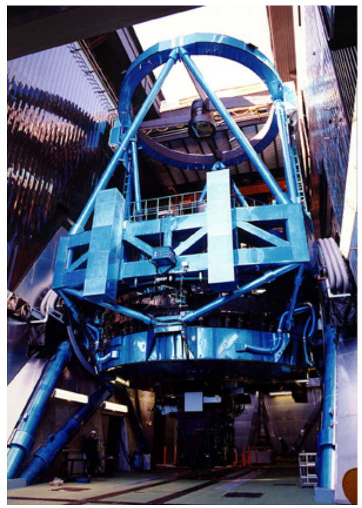
Massey et al. 2007, Nature

Probing dark energy

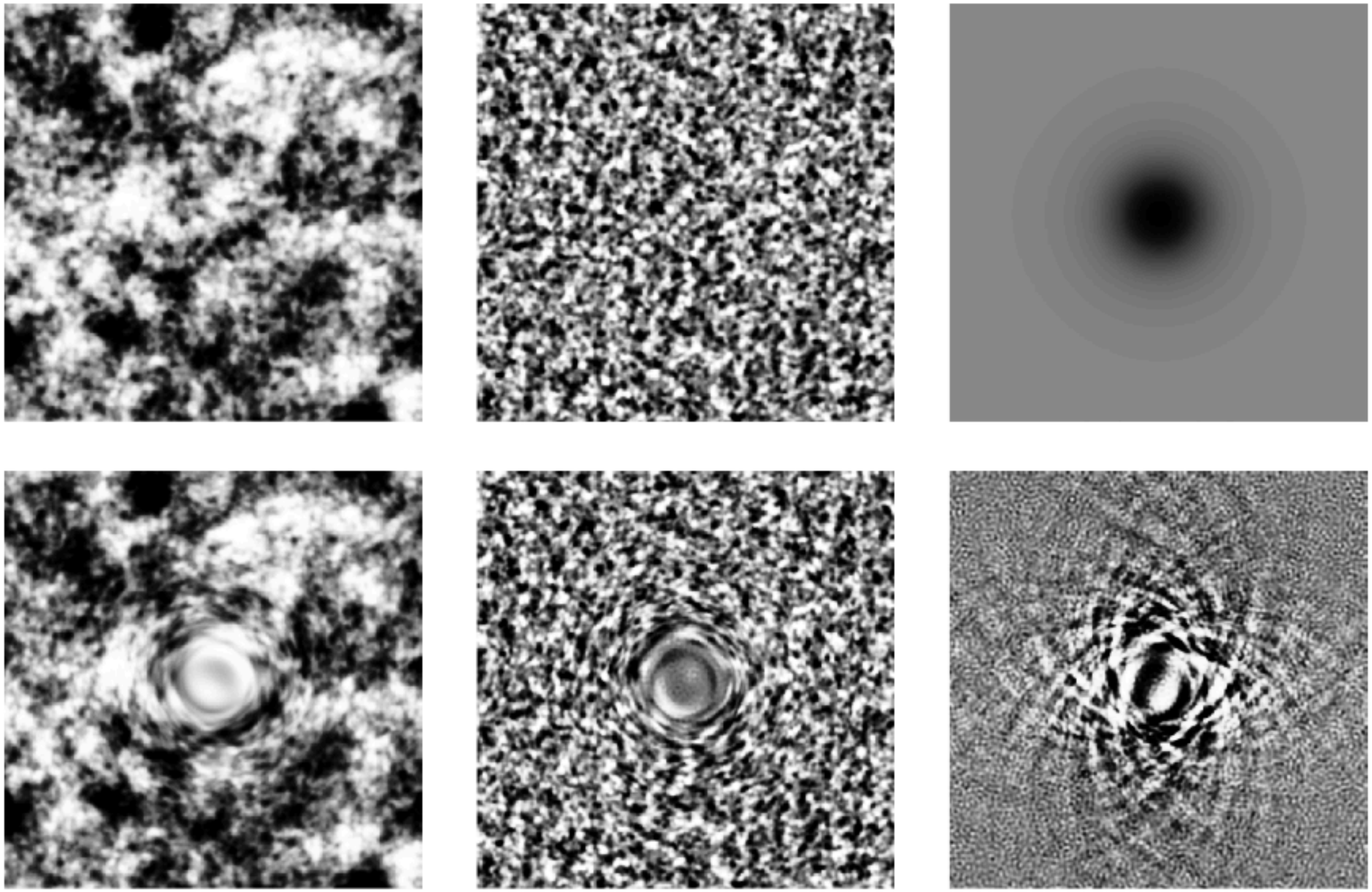


Weak lensing tomographic surveys will probe the growth of large-scale structure, which in turn probes the equation of state of dark energy:

$$P = w\,\rho$$

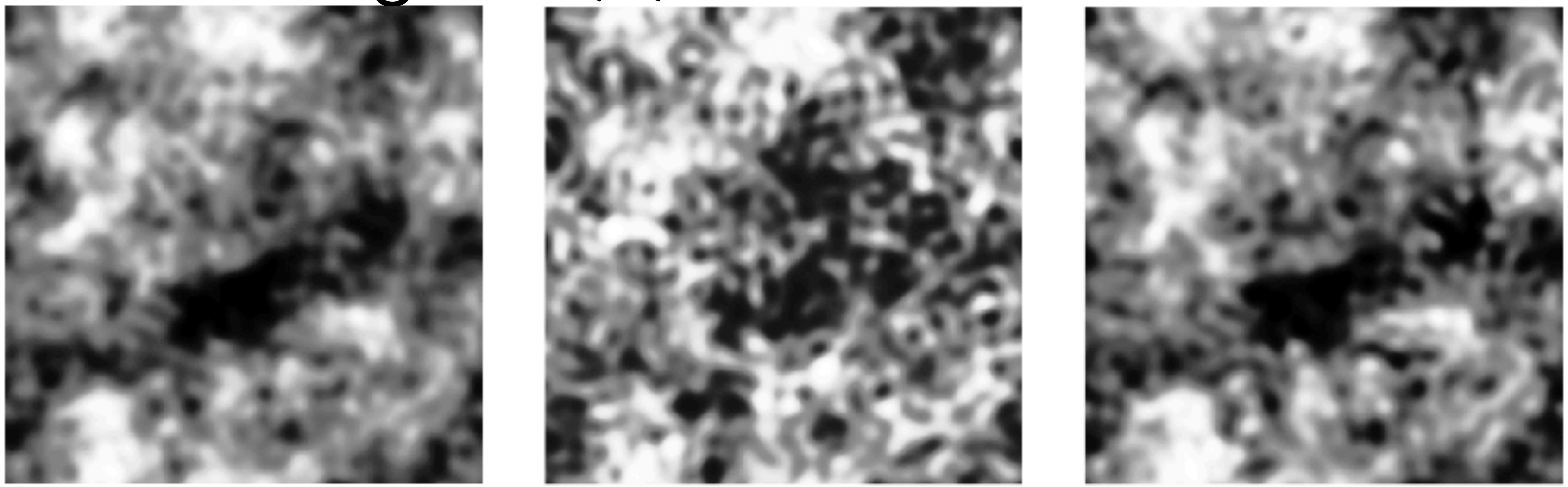


Sources other than galaxies I: CMB lensing



Sources other than galaxies I: CMB lensing

10x10 deg2 QQ reconst. EB reconst.



Okamoto-Hu02

Sources other than galaxies II: HI 21cm lensing

Multiple lens planes as a function of frequency (redshift)

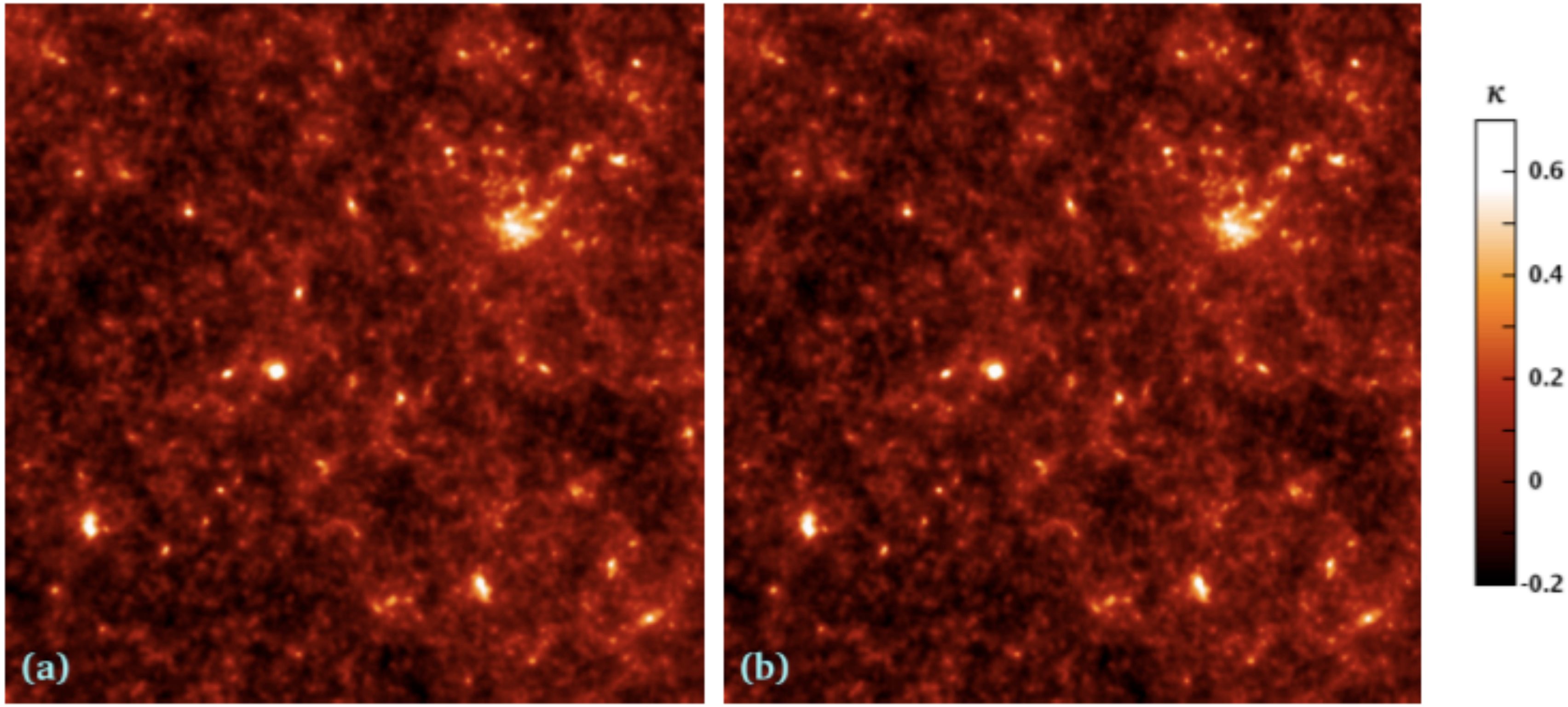


Figure 2. 21-cm-based convergence maps for the $20' \times 20'$ field shown in Fig. 1(a), but smoothed assuming a telescope beam with $\lambda = 6''$. Whereas (a) is noise-free, noise has been added in (b) at the irreducible value for a map of this resolution. The colour scale indicated by the bar at right is the same as in Fig. 1(a).

Metcalf-White07