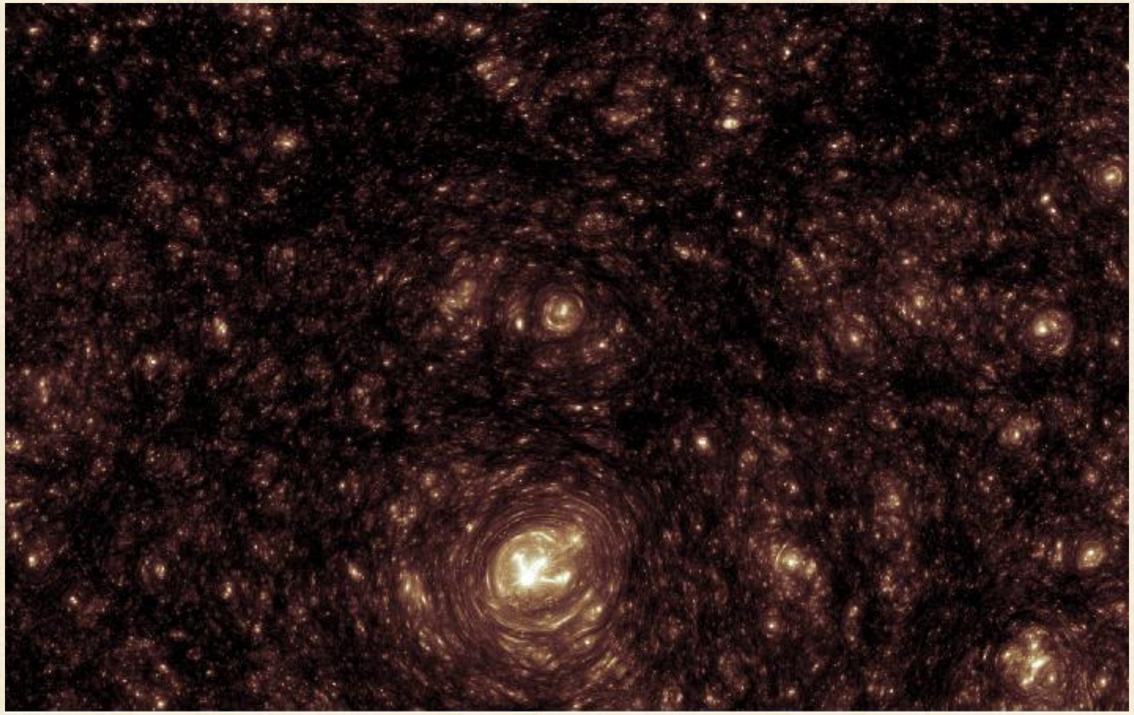
Prediction of Gravitational lensing signal through Horizon-AGN light cone



C. Gouin, R. Gavazzi, Y. Dubois and C. Pichon

1. Introduction to Gravitational Lensing

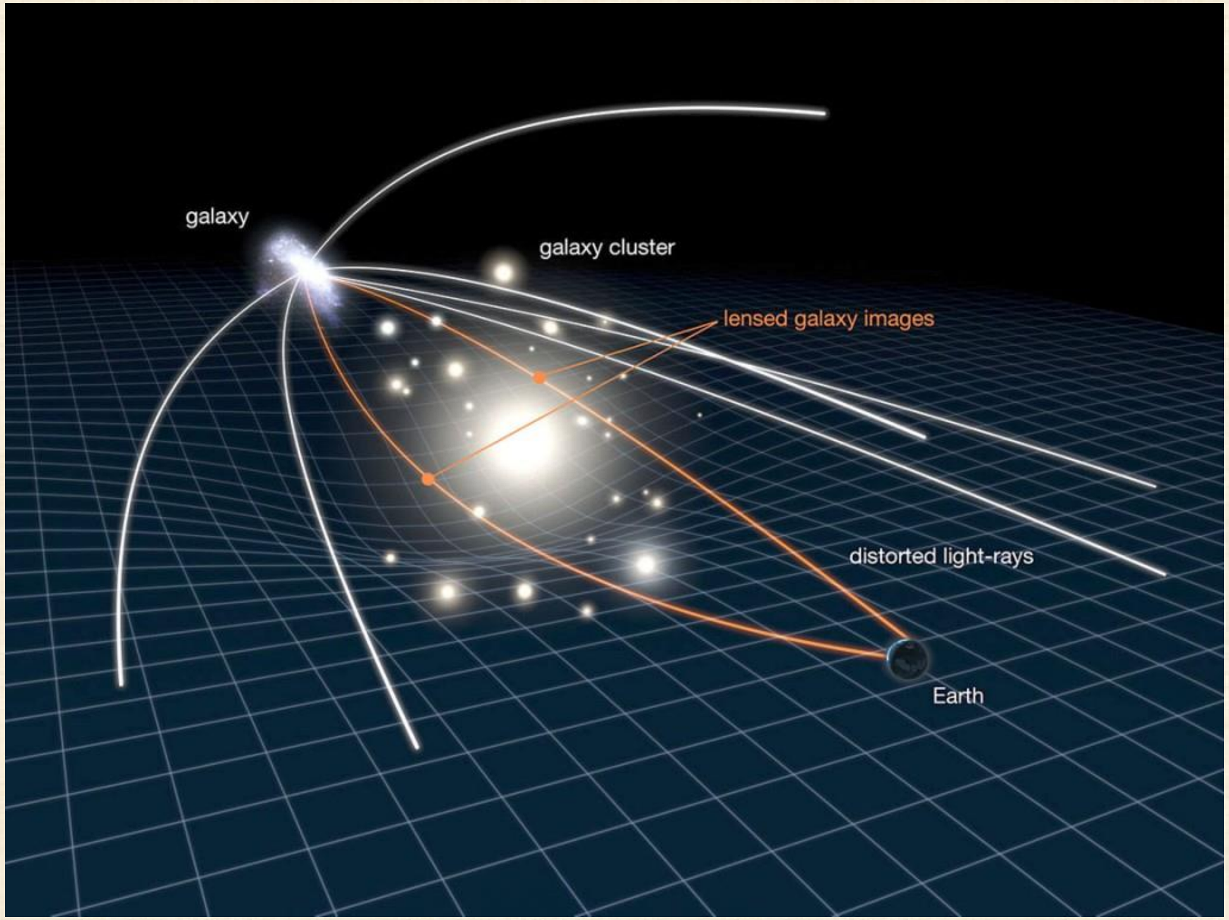
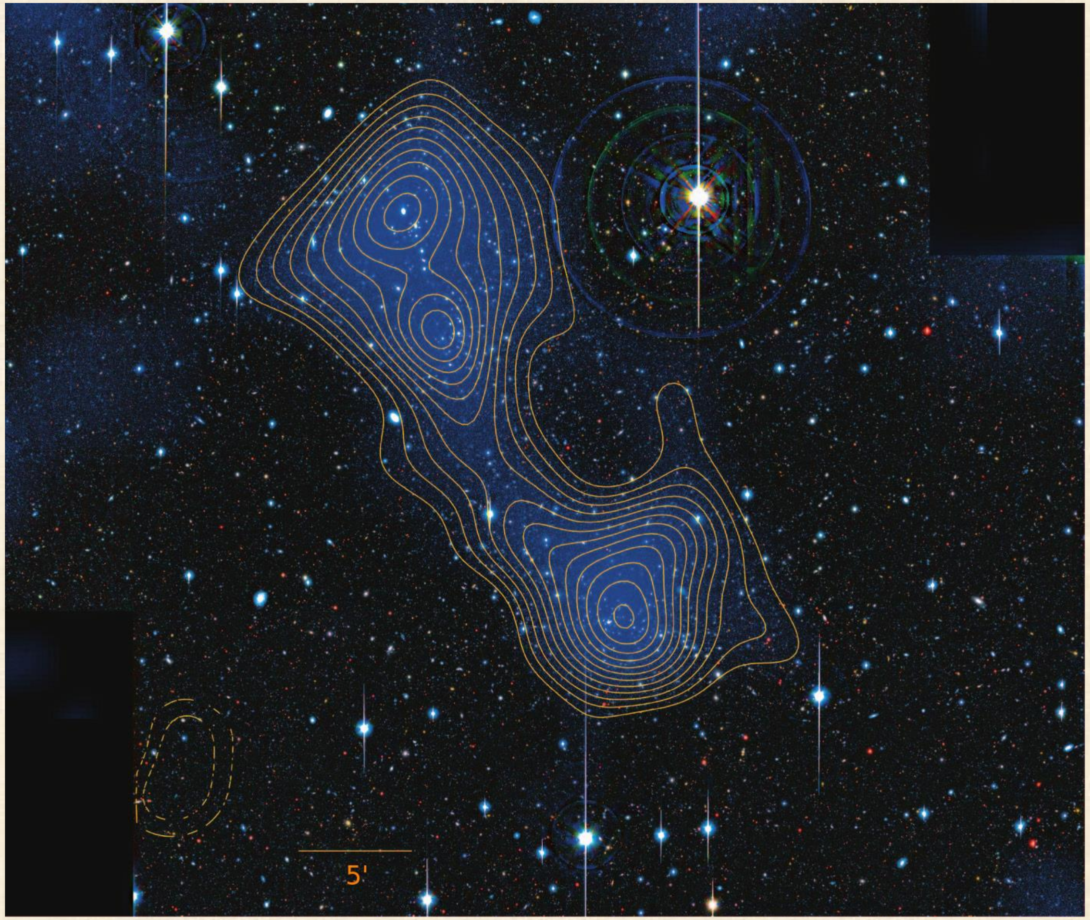
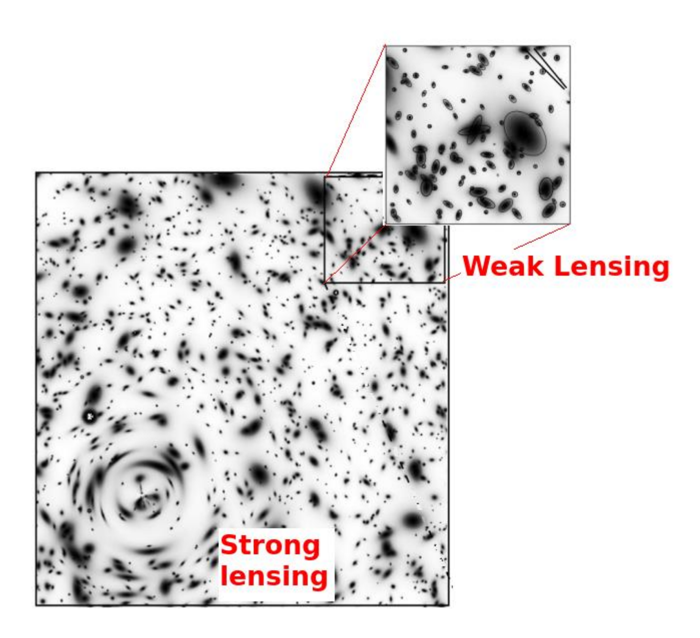


Image : NASA /ESA



Mass recontruction of Abell 222/223 by WL Dietrich and al, 2012

1. Introduction to Gravitational Lensing



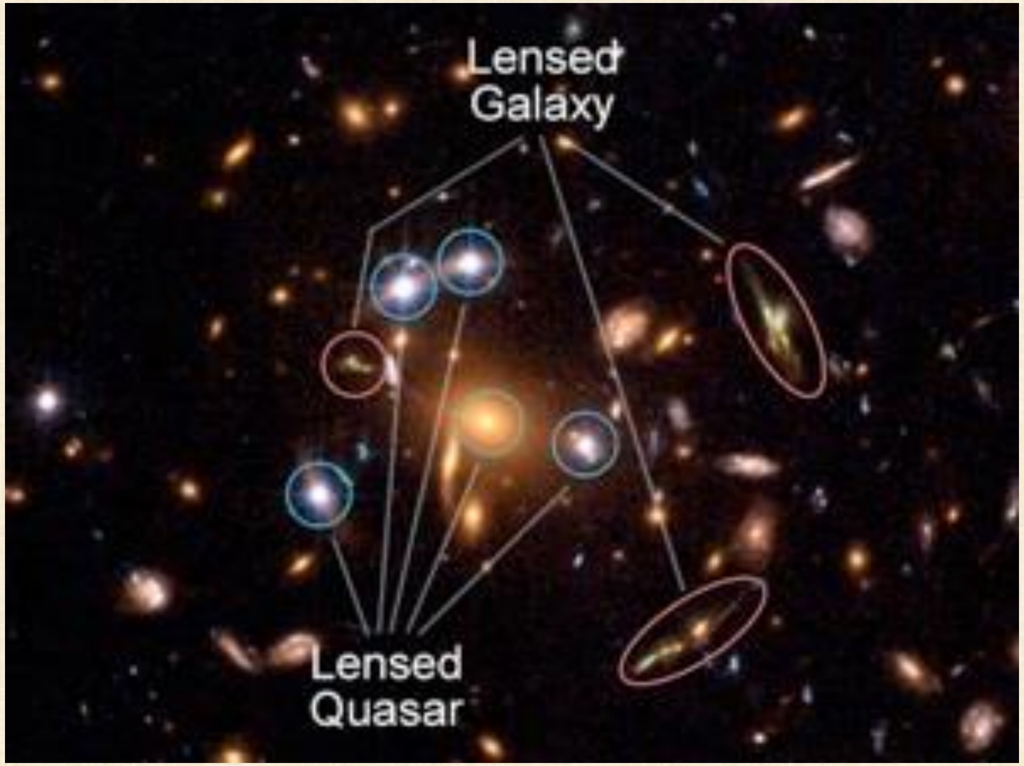
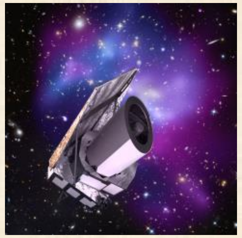


Image : NASA / ESA, K. Sharon (Tel Aviv) E. Ofek (Caltech)

⇒ Strong Lensing probe the internal region of galaxies

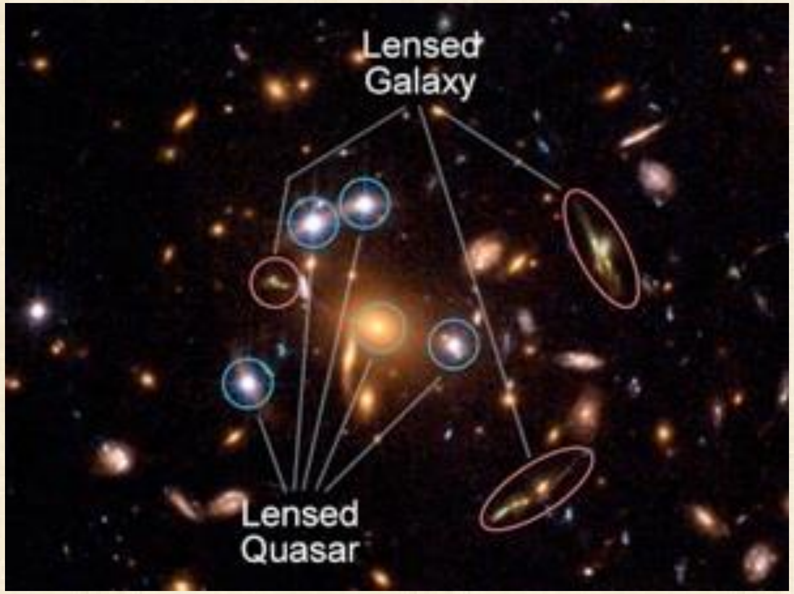
⇒ Weak lensing signal probe the outskirts of galaxies



Euclid space mission

Calibration of GL signal using hydrodynamical cosmological simulation

1. Prediction of GL signal from hydrodynamical cosmological simulation

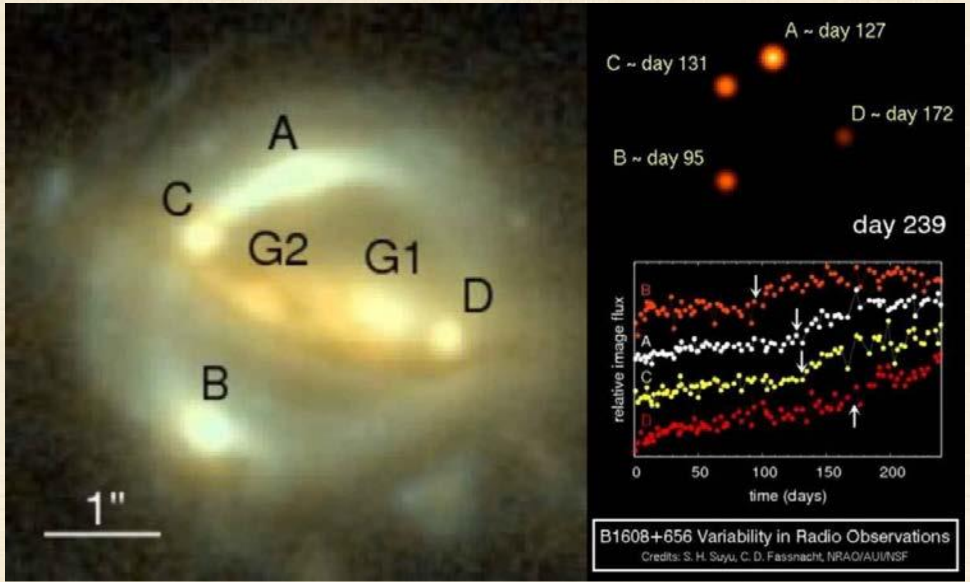


On small scales

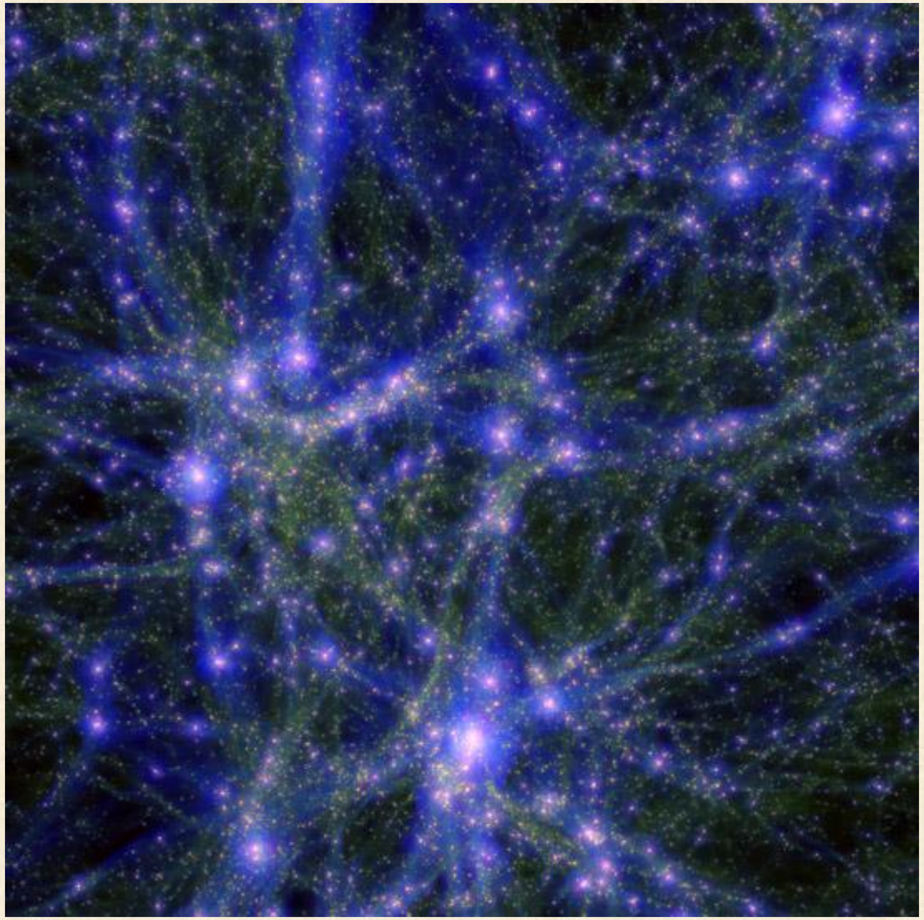
- The slope of the central density profile
  - Cups core problem?
- cross section of strong lensing
  - Is arc abundance changed by baryonic processes ?
- Time delay

  Contraint the Hubble constant

  The distribution of mass along the l.o.s ?



1. Prediction of GL signal from hydrodynamical cosmological simulation



Horizon AGN simulation

Baryonic processes modeled in Horizon AGN Simulation with RAMSES code :

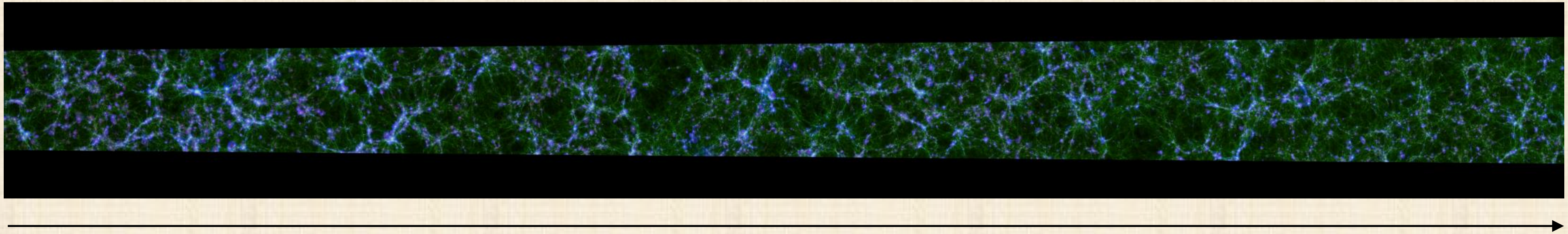
- Gas dynamics, gas cooling/heating
- Star formation
- SN & AGN feedback

Horizon AGN ~ 100 000 galaxies within a box 100 Mpc/h

(See Presentation of Sugata Kaviraj)

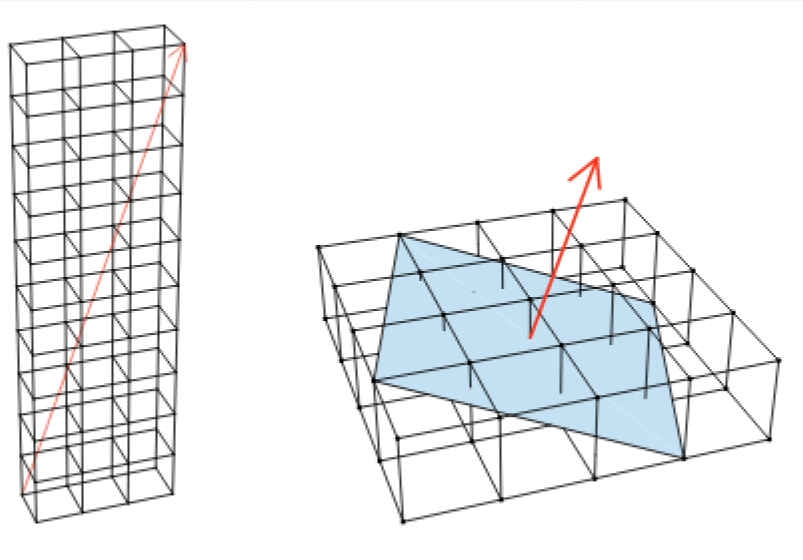
2. Ray tracing through Horizon AGN light cone

Horizon AGN light cone



redshift

Goal : Tracing light ray through the light cone



S.Hilbert and al , 2009

Example of light cone creation in a box simulation

2. Ray tracing through Horizon AGN light cone

Thin lens theory

Lensing equation :

$$\vec{\beta} = \vec{\theta} - \frac{D_{LS}}{D_s}\,\vec{\alpha}$$

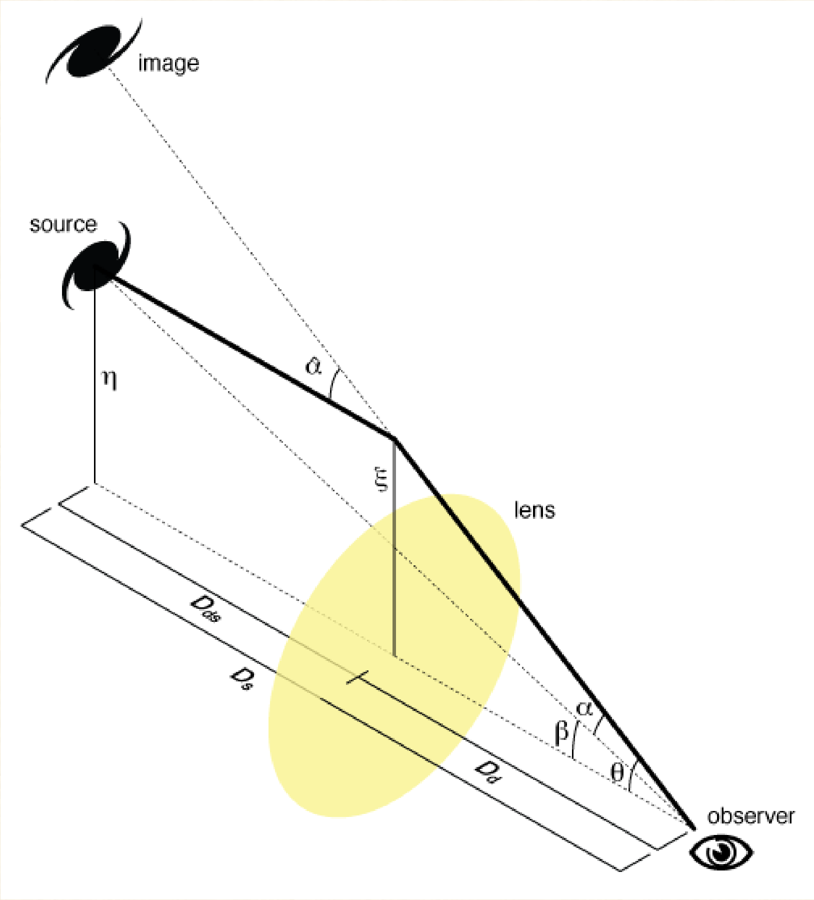
Lensing potential (2D projected) :

$$\varphi(\vec{\theta}) = \frac{2\ D_{LS}}{c^2 D_s\, D_L}\int d\chi\, \phi_{3D}$$

$$\vec{\alpha} = \vec{\nabla}_\theta \varphi$$

Matrix amplification :

$$A^{-1} = \frac{\partial \vec{\beta}}{\partial \vec{\theta}} = \begin{pmatrix} 1-\kappa & 0 \\ 0 & 1-\kappa \end{pmatrix} + \begin{pmatrix} -\gamma_1 & -\gamma_2 \\ -\gamma_2 & \gamma_1 \end{pmatrix}$$



2. Ray tracing through Horizon AGN light cone

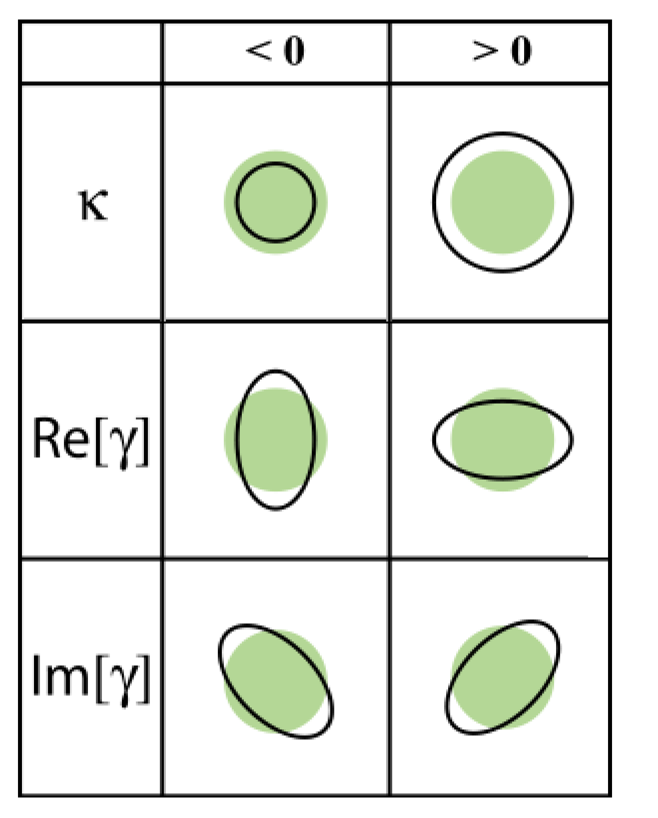
thin lens theory

Lensing quantities :

Convergence : $\kappa = \frac{\Sigma}{\Sigma_{crit}} = \frac{1}{2}\,\Delta\varphi$

Shear real : $\gamma_1 = \frac{1}{2}\left(\frac{\partial^2\varphi}{\partial\theta_1^2} - \frac{\partial^2\varphi}{\partial\theta_2^2}\right)$

Shear imaginary : $\gamma_2 = \frac{\partial^2\varphi}{\partial\theta_1\partial\theta_2}$



Resolution of differential lens equation in Fourier space

Differential equation

$$\kappa = \frac{1}{2}\Delta\varphi$$

$$\gamma_1 = \frac{1}{2}\left(\frac{\partial^2\varphi}{\partial\theta_1^2} - \frac{\partial^2\varphi}{\partial\theta_2^2}\right)$$

$$\gamma_1 = \frac{1}{2}\left(\frac{\partial^2\varphi}{\partial\theta_1^2} - \frac{\partial^2\varphi}{\partial\theta_2^2}\right)$$

$$\vec{\alpha} = \vec{\nabla}_\theta\varphi$$

Fourier space

$$\hat{\psi} = -2\,\frac{\hat{\kappa}}{(k_1+k_2)^2}$$

$$\widehat{\gamma_1} = -\frac{1}{2}(k_1^2 - k_2^2)\hat{\psi}$$

$$\widehat{\gamma_2} = -\,k_1 k_2\,\hat{\psi}$$

$$\widehat{\alpha_1} = -i\,k_1\,\hat{\psi}$$

$$\widehat{\alpha_2} = -i\,k_2\,\hat{\psi}$$

2. Ray tracing through Horizon AGN light cone

Multiple lens planes

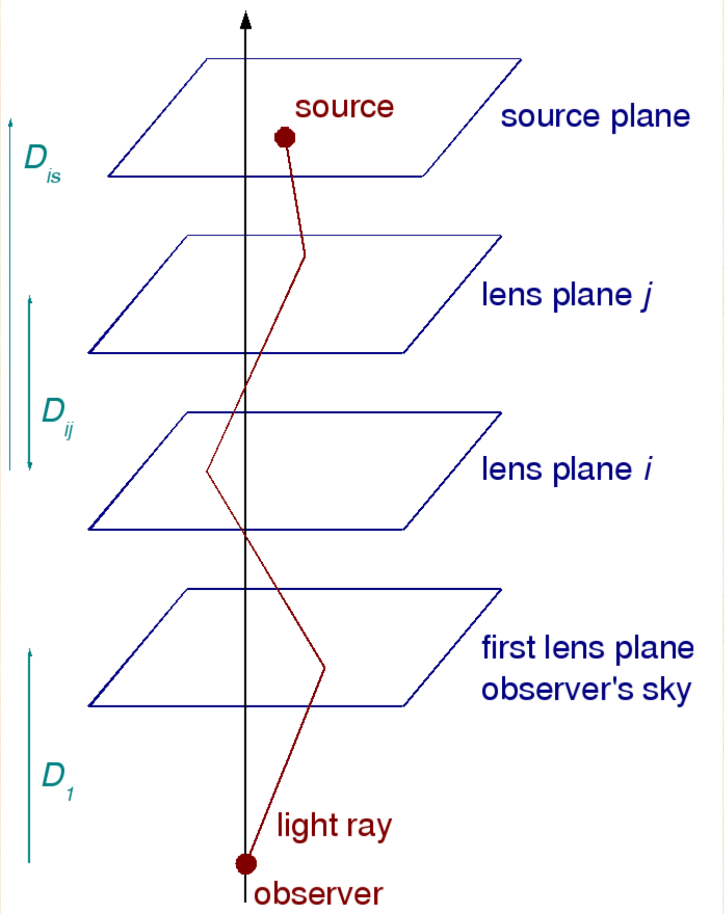
Lens equation applies on each of the multiple lens planes :

Source position :

$$\overrightarrow{\beta_k} = \vec{\theta} - \sum_{i=1}^{k-1} \frac{D_{ik}\, D_s}{D_k\, D_{is}} \overrightarrow{\alpha_i}(\overrightarrow{\beta_i})$$

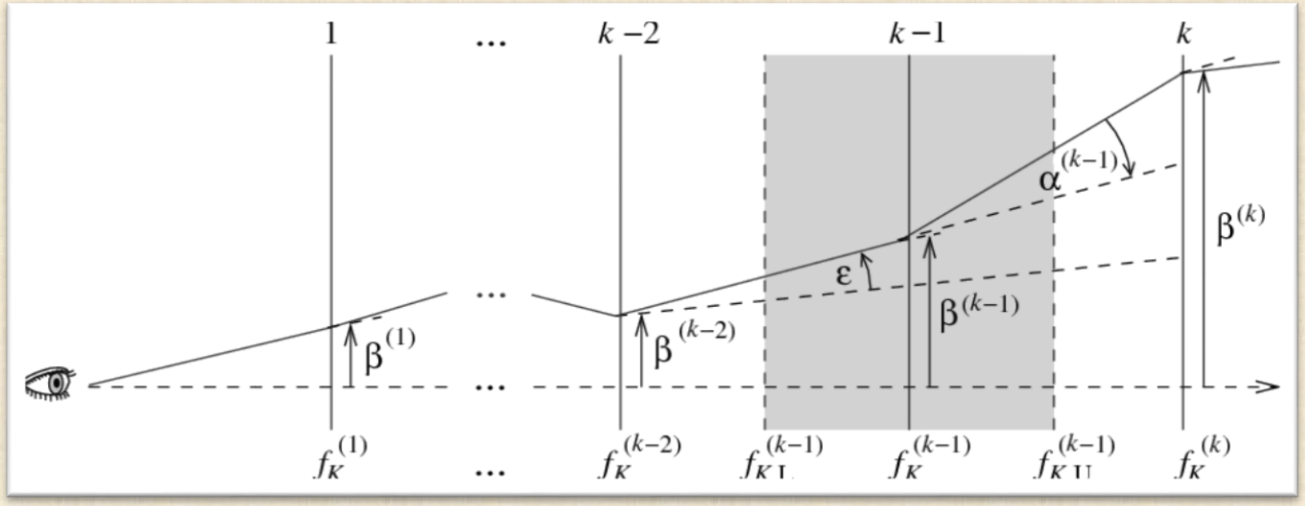
Equation for the jacobian of the lens mapping for the k-th lens plane:

$$A^k = \frac{\partial \overrightarrow{\beta_k}}{\partial \vec{\theta}} = I - \sum_{i=1}^{k-1} \frac{D_{ik}\, D_s}{D_k\, D_{is}} \frac{\partial \overrightarrow{\beta_i}}{\partial \vec{\theta}} \frac{\partial\, \overrightarrow{\alpha_i}}{\partial\, \overrightarrow{\beta_i}}$$



2. Ray tracing through Horizon AGN light cone

Multiple lens planes



Credit to S. Hilbert and al, 2009

iterative method : Much less memory-demanding (store 3 planes, instead of several tens or hundreds)

Recurrence relation for source position :

$$\beta^k \propto \beta^{k-1}, \beta^{k-2}, \alpha^{k-1}$$

Recurence relation for amplification matrix :

$$A^k \propto A^{k-1}, A^{k-2}, \frac{\partial \alpha^{k-1}}{\partial \beta^{k-1}}$$

2. Lensing signal from Horizon AGN light cone

Linking RAMSES accelerations with deflections

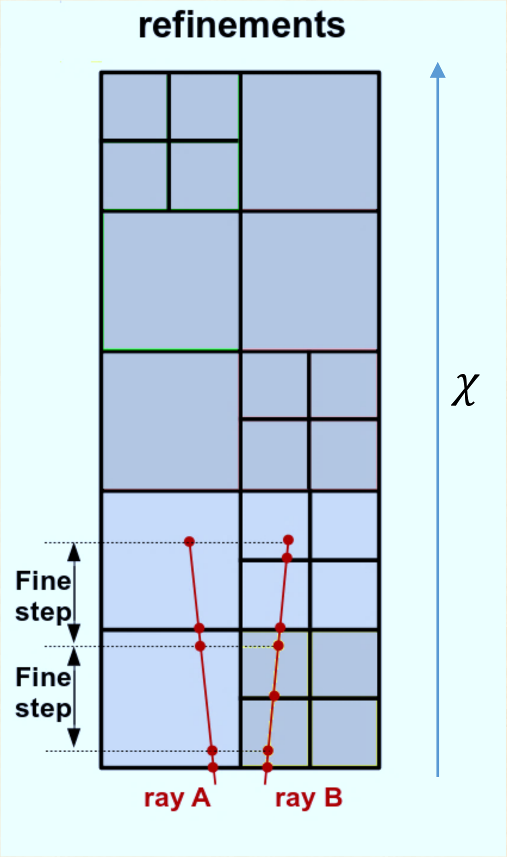
Acceleration field are sample by particles :

$$\vec{a} \rightarrow \overrightarrow{F_g} \rightarrow \vec{\nabla}\phi$$

And $\vec{\alpha} = \frac{2\, D_{LS}}{c^2 D_L} \int \overrightarrow{\nabla_{\perp}} \phi \, \mathrm{d}\chi$ (integrate along l.o.s)

Using the gas component :

- Gas particles follow the RAMSES grid
- Given the size of RAMSES cells : $\sigma = \left(\frac{m_{gas}}{\rho_{gas}}\right)^{1/3}$



RAY-RAMSES, A. Barreira and al, 2016

2. Linking RAMSES accelerations with deflections

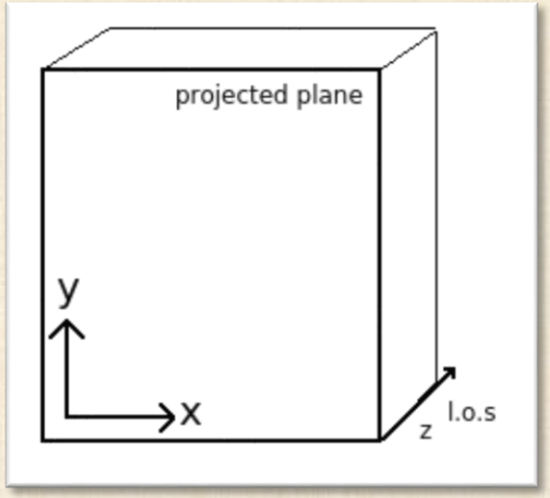
Adaptative Gaussian kernel 2D (x y direction)

Each gas particle is defined by $\sigma_p, \overrightarrow{x_p}$, and is treated as truncated gaussian kernels

$$f(x) = e^{\frac{(x-x_p)^2}{2\,\sigma_p{}^2}} \text{ for } \frac{x_{pixel} - x_{part}}{\sigma_p} \leq 4$$

With pixel weight

$$\mathrm{F_x} = \int_{x\_pixel\_min}^{x\_pixel\_max} e^{\frac{(x-x_p)^2}{2\,\sigma_p{}^2}} \, dx$$



Along the l.o.s (z direction) : $\mathrm{F_z} \propto \sigma_\mathrm{p}$

Tabulation of the erf function (time consuming)

Linking RAMSES accelerations with deflections

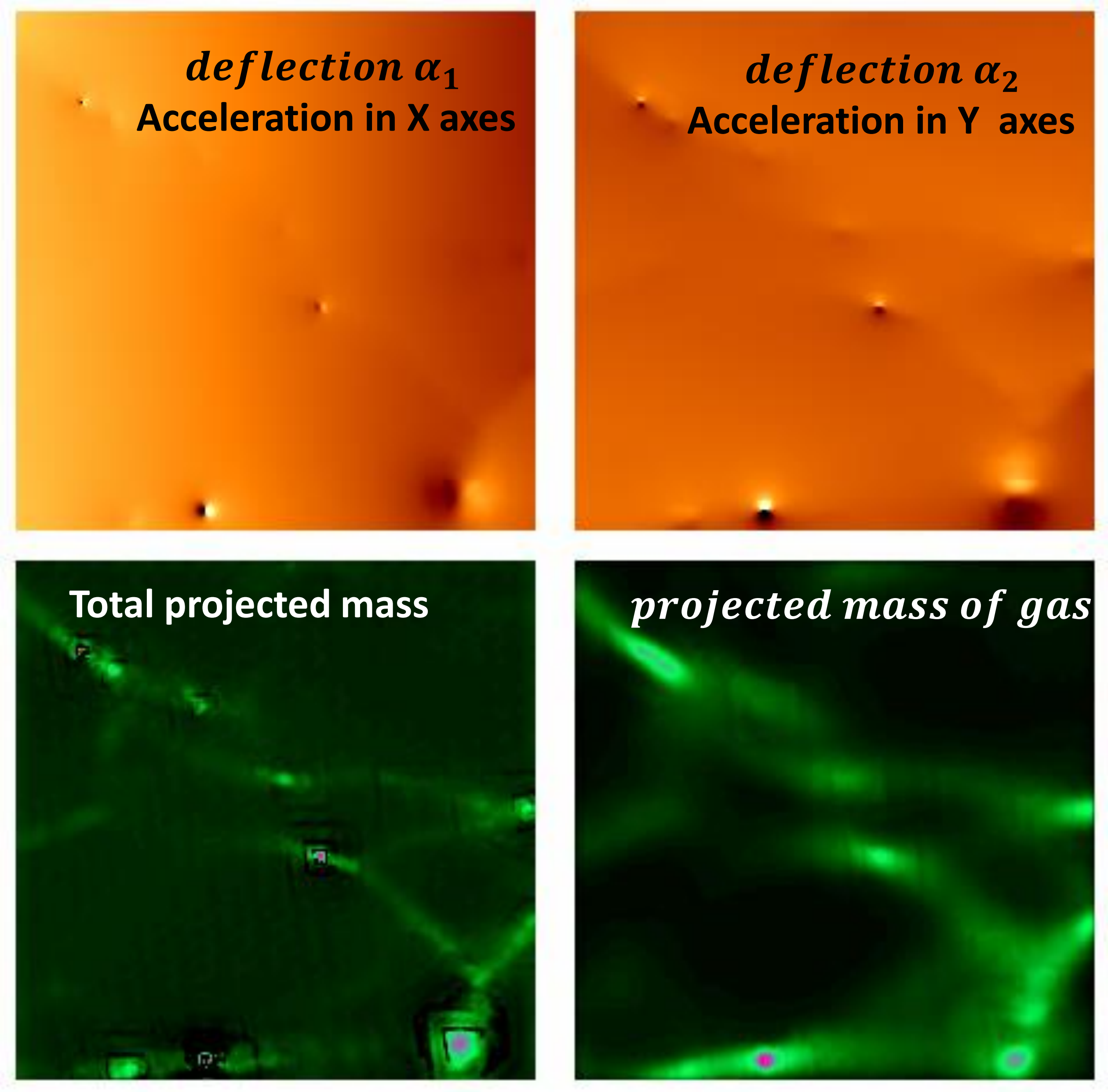
Recontructed convergence from the deflection ($\propto acceleration$)

$$\vec{\nabla}.\vec{\alpha} \ = 2\,\kappa$$

artefact problems :

- Integration of acceleration along the RAMSES grid seems wrong ….

work in process…



Using the projected mass Identify the contribution of Differents components

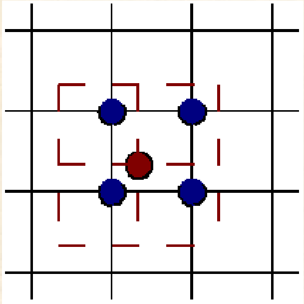
Convergence map $\boldsymbol{\kappa}$ by projected DM particles

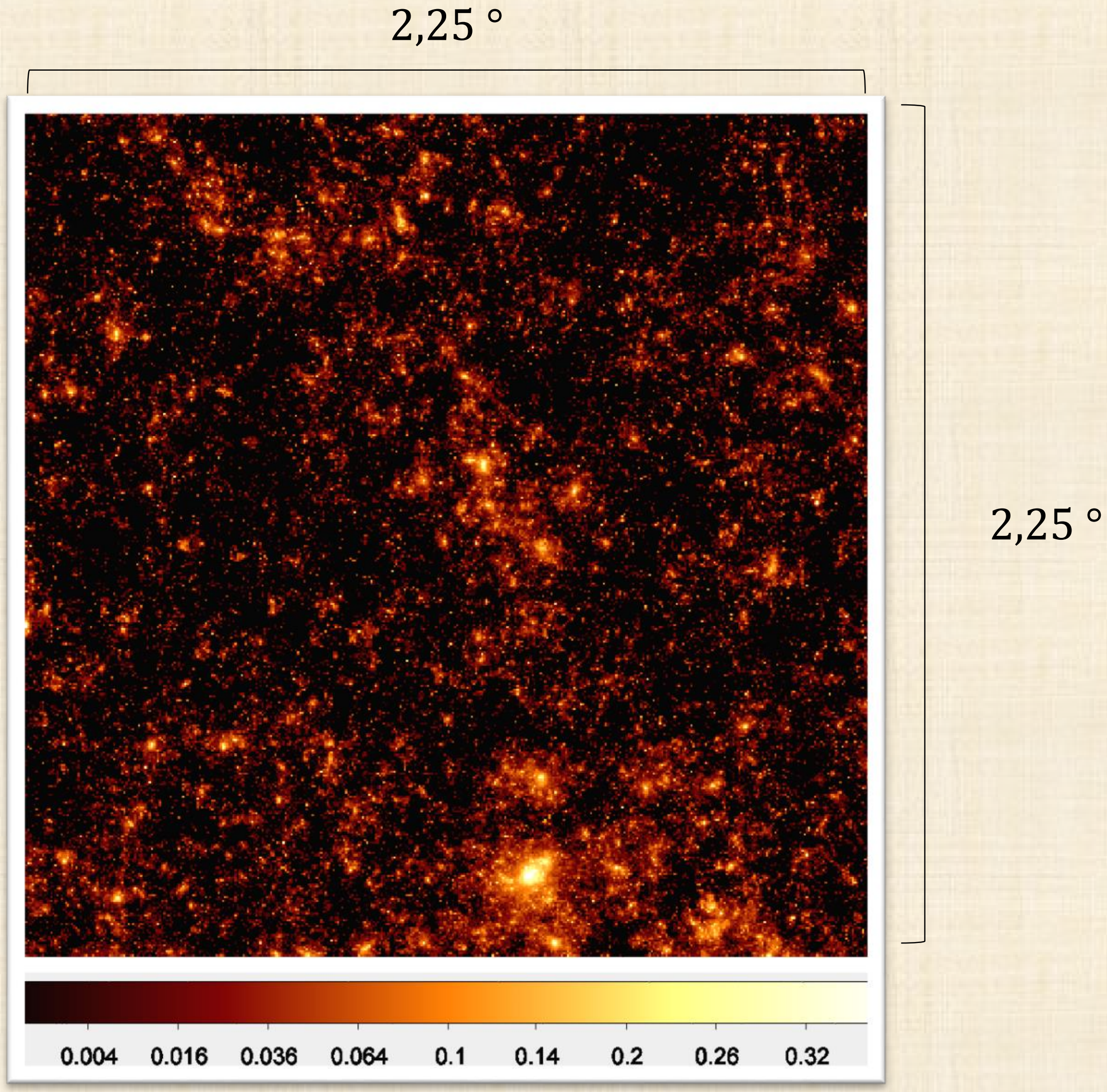
- Redshift of source plane $z_s \sim 3$
- Propagation light ray
- Angular resolution : $\Delta\theta = 1\ arcsec$
- 16 lightcone slices = 1 lens plane

  From $\mathrm{z}{\sim}0$ to $z{\sim}3$: 1064 lens planes

- DM particles only

  with Cloud In Cell

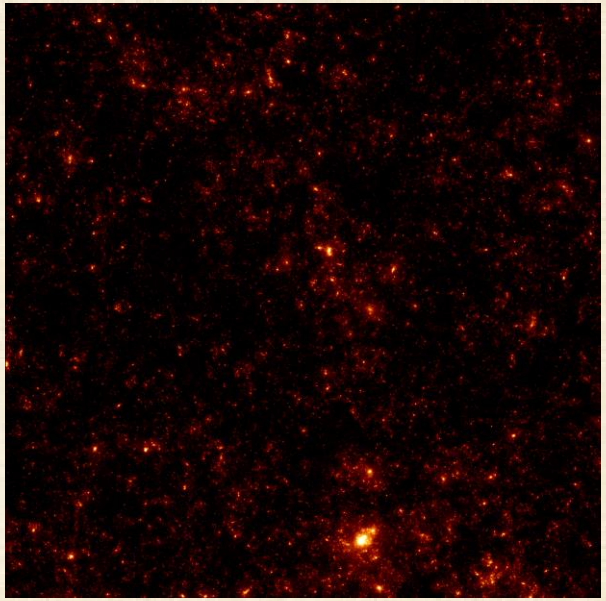




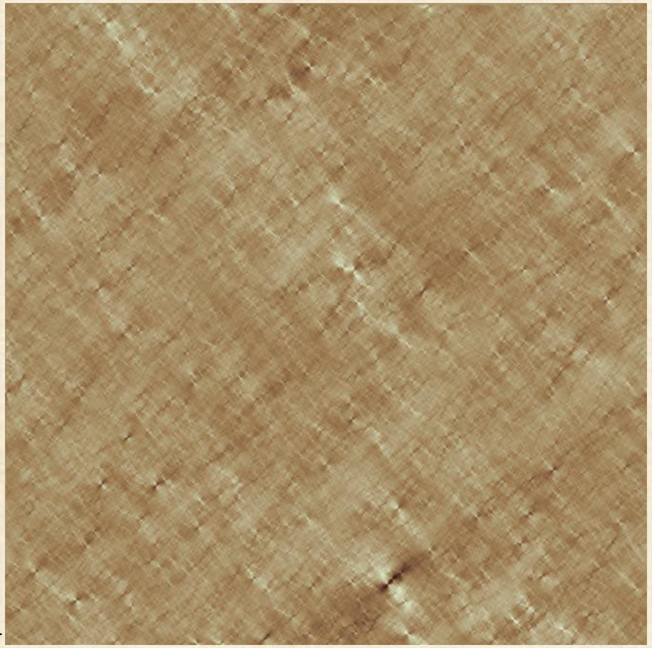
$convergence\ \ \kappa$

Using the projected mass
Classical approach

Lensing quantities

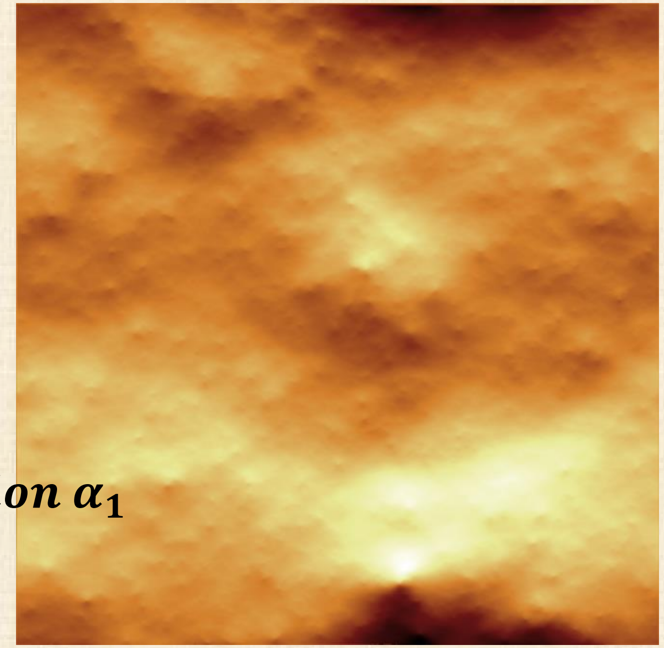


convergence $\boldsymbol{\kappa}$

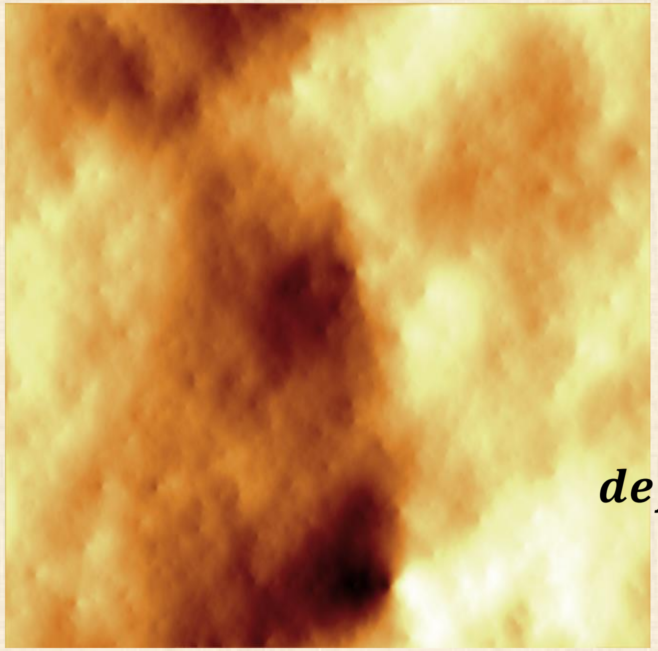


shear $\boldsymbol{\gamma_1}$

shear $\boldsymbol{\gamma_2}$



defection $\boldsymbol{\alpha_1}$



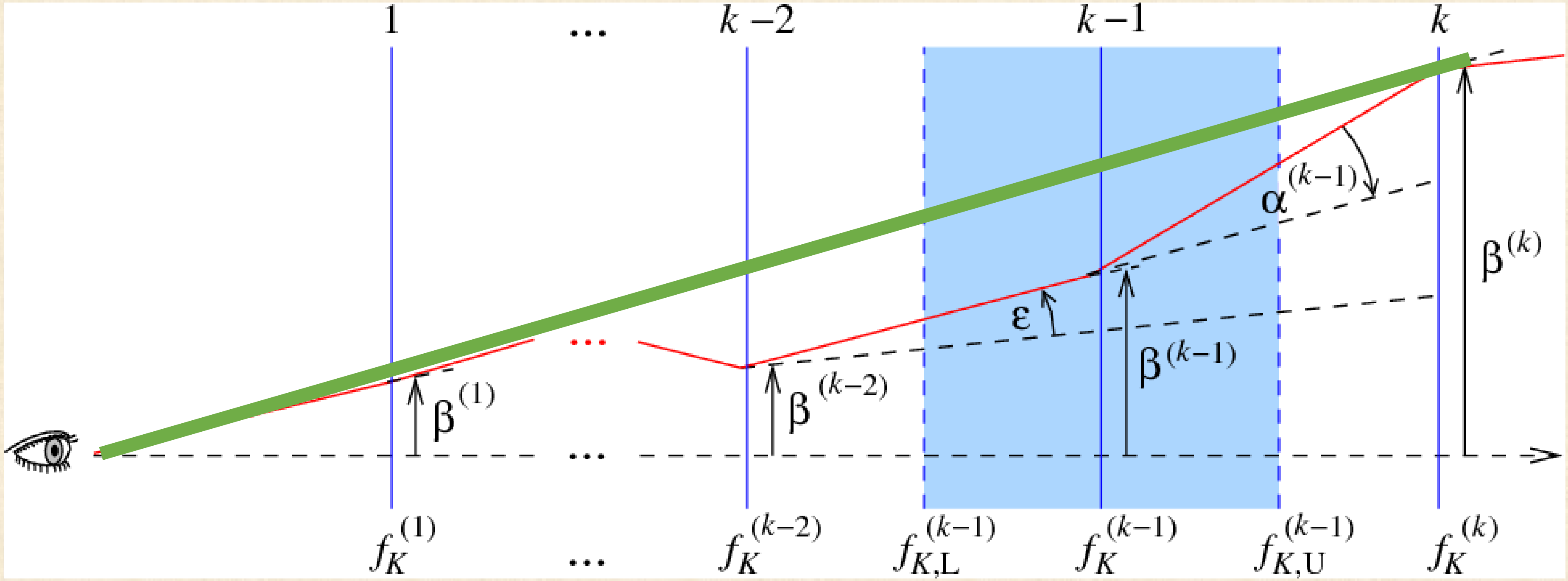
deflection $\boldsymbol{\alpha_2}$

Test : comparaison of the propagation of light ray with Born approximation

Born approximation

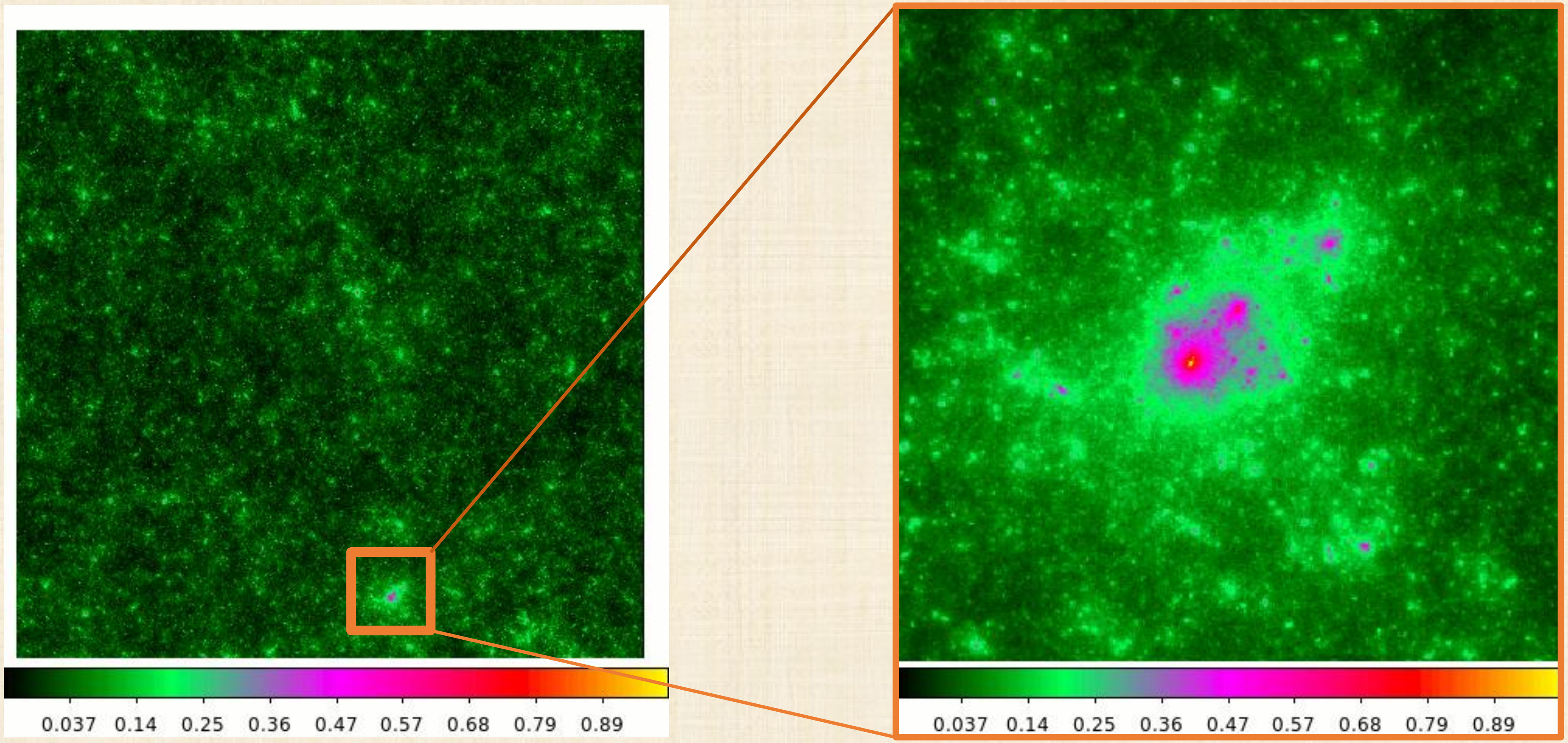
- Summation of mass contribution along a undistrubed path

(ignore deviation of light path at each lens plane)



Comparaison of the propagation of light ray / Born approximation

Born approximation is appropriate at large scale but not adapted to SL at small scale



Short term goal

Adding gravitational lensing signal on mock observation of galaxies (S. Kaviraj and al, 2016)

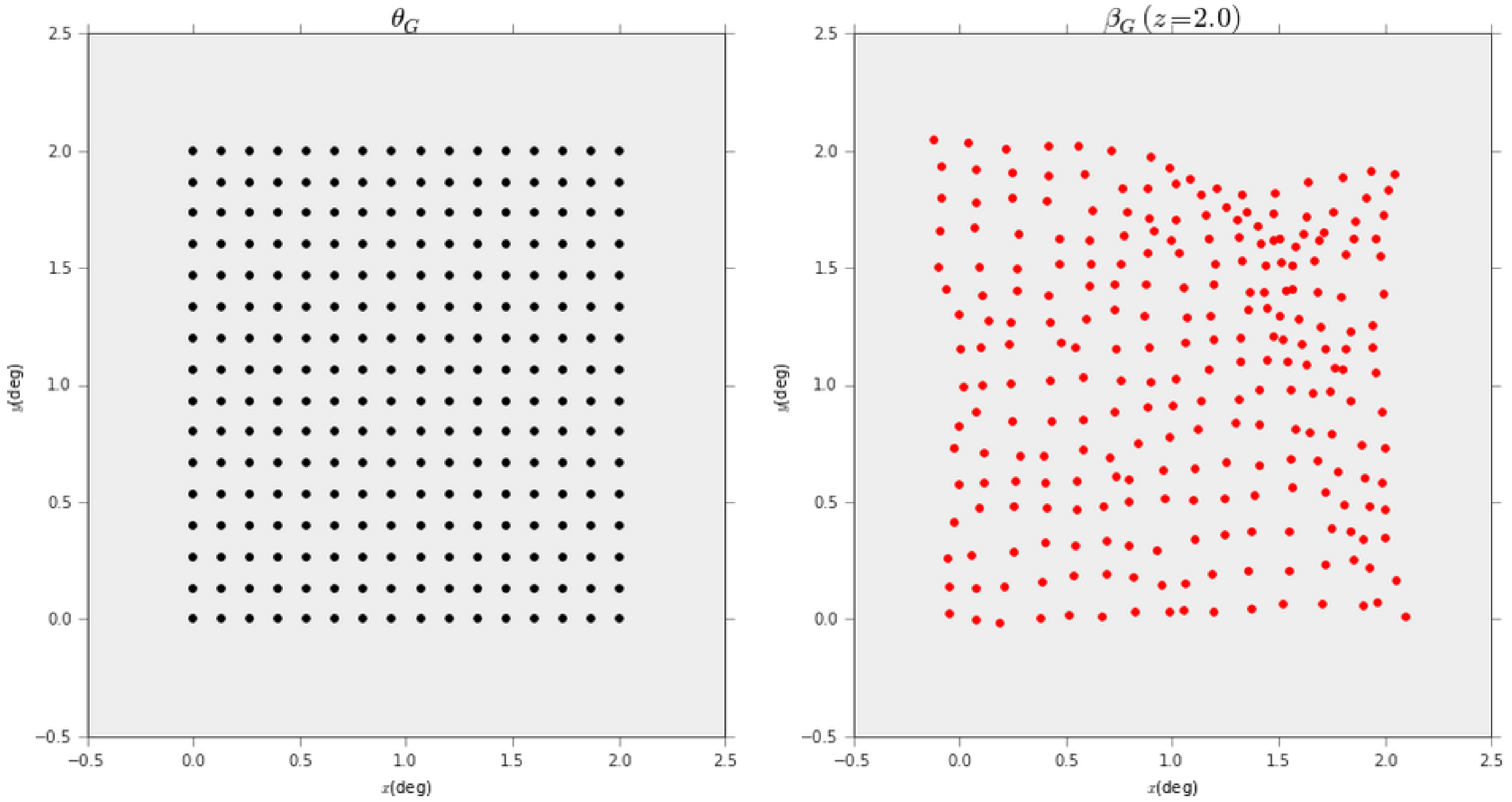
Mock image ©LaigleC

Lensed Mock image by an arbitrary lens

Thank you for your attention

2. Ray tracing through Horizon AGN light cone

From a regular grid image to the source position : $\vec{\beta} = \vec{\theta} - \vec{\alpha}$



credit to LensTools 0.4.8.4

Details on recursive relation

Lens equation apply on the multiple lens planes approximation :

$$\overrightarrow{\theta_j} = \overrightarrow{\theta_1} - \sum \frac{D_{ij}\, D_s}{D_j\, D_{is}} \overrightarrow{\alpha_i}$$

Recursion relation :

$$A^k(\vec{\theta}) = I - \sum_{i=1}^{k-1} \frac{D_{ik}\, D_s}{D_k\, D_{is}} A^i \; U^i$$

$$A_i = \frac{\partial \overrightarrow{\beta_i}}{\partial \overrightarrow{\theta_1}} \; and \; U^i = \frac{\partial \overrightarrow{\alpha_i}}{\partial \overrightarrow{\beta_i}}$$

The number of sub-haloes is it reduced by the presence of baryons? (Guilia Despali & Simona Vegetti, 2016)

- Investigate EAGLE and ILLUSTRIS simulation / concentrate on ETGs
- Especially at low mass ($\leq 10^{10} Mo/h$), by different amounts depending on the model
- They attempt to predict the DM fraction in subhaloes and the slope of mass function α

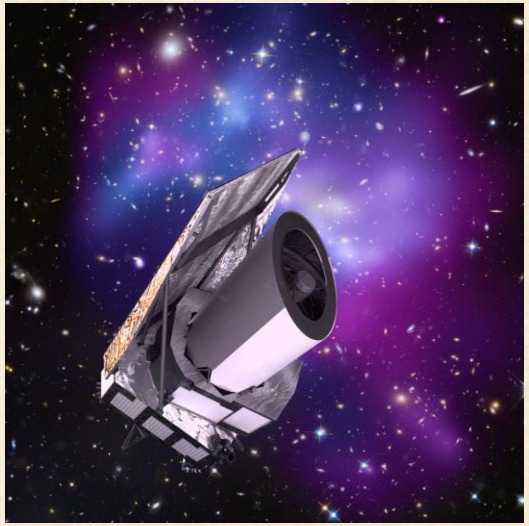
Strong lensing details

Study of substructure via :

The relative flux of multiply imaged quasar

Their effect on surface brightness of einstein rings & lensed arc

Euclid



Time delays

SL : measured time delay between the multiple images & models of mass distribution

→ determination of time delay distance → cosmological parameters

Excess time : $t(\theta,\beta) = \frac{D_{\Delta t}}{c}\left(\frac{(\theta-\beta)^2}{2} - \psi(\theta)\right)$ with $D_{\Delta t}$ time delay distance

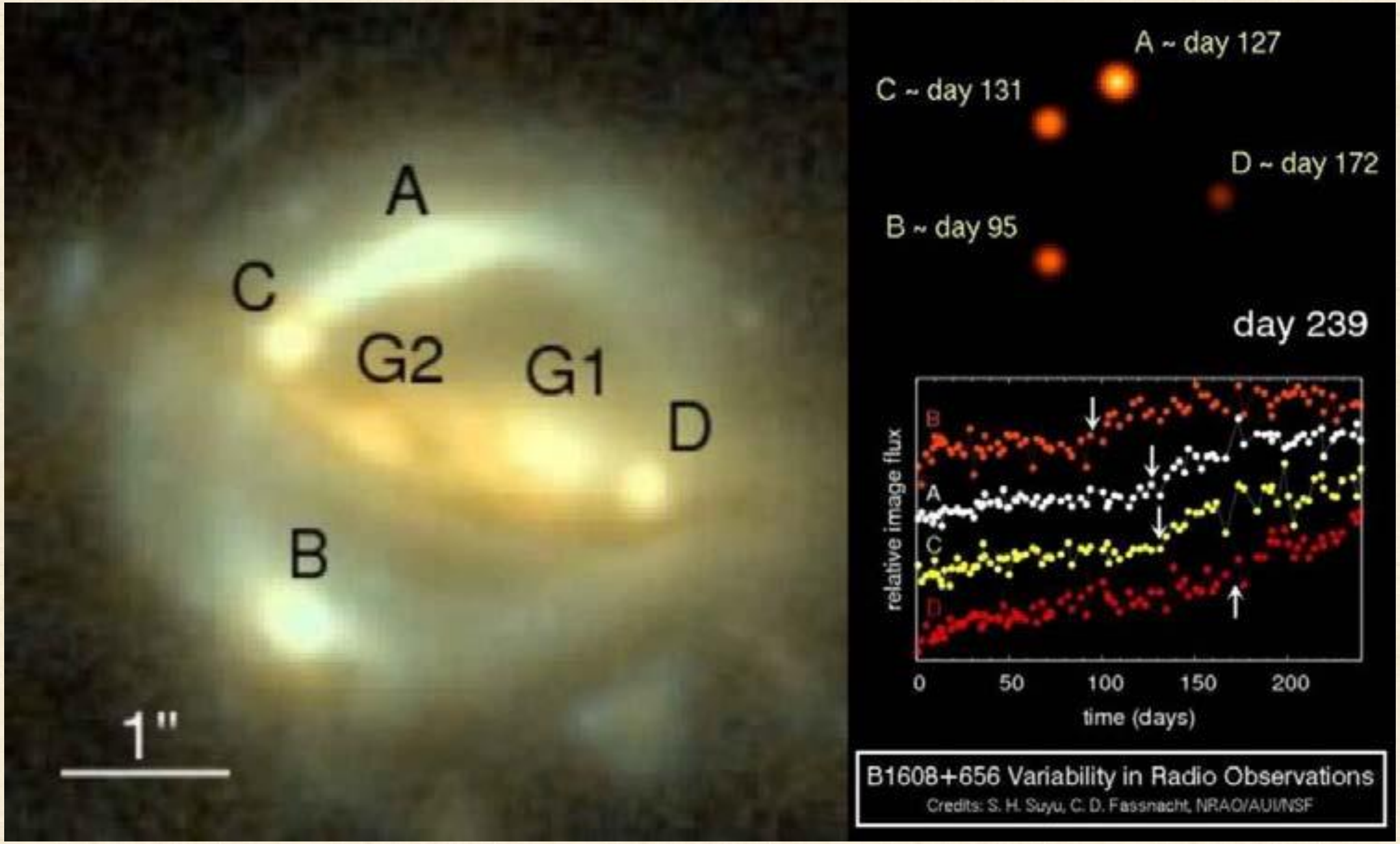
Time delay distance : $D_{\Delta t} = (1+z_d)\ \frac{D_d D_s}{D_{ds}}$

Time delay $\Delta t_{ij} = t(\theta_i,\beta) - t(\theta_j,\beta) = \frac{D_{\Delta t}}{c}\left(\frac{(\theta_i-\beta)^2}{2} - \psi_i(\theta_i) - \frac{(\theta_j-\beta)^2}{2} - \psi_j(\theta_j)\right)$

Image configuration+morphology → Σ, ψ + source vary in time Δt → obtaint $D_{\Delta t}$

Contraint cosmological parameter by distance redshift test $D_{\Delta t} \propto \frac{1}{H_0}$

Time delay


A
C
G2
G1
D
B
1"
A ~ day 127
C ~ day 131
D ~ day 172
B ~ day 95
day 239
relative image flux
B
A
C
D
0
50
100
150
200
time (days)
B1608+656 Variability in Radio Observations
Credits: S. H. Suyu, C. D. Fassnacht, NRAO/AUI/NSF

« Lens galaxies in Illustris simulation : power law & the bias of Hubble constant from time delay » Xu and al 2015

The total density profile in central region is usualy described by Pow law $\rho \propto r^{-\gamma'}$

Radial scale : transition from dominance of BM to DM

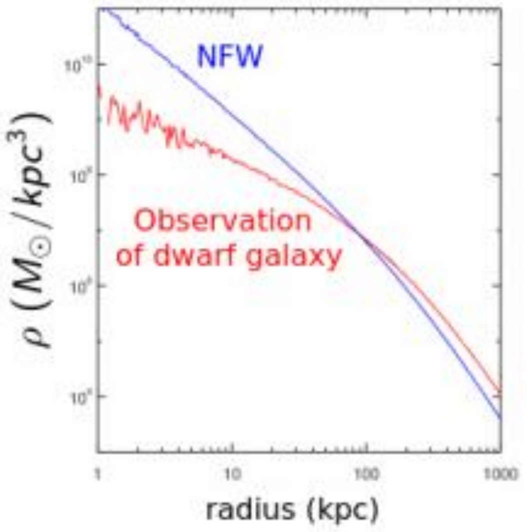
PL affect the product of time delay → bias the determination of Ho

They study dynamic and SL on simulated galaxies (Illustris)

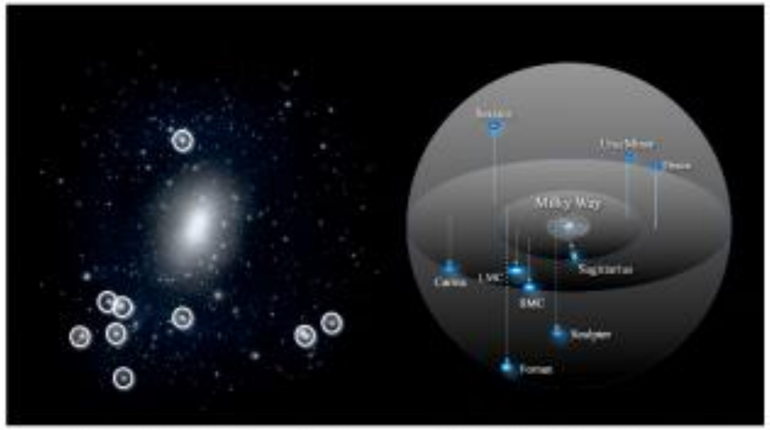
Find : the bias on Ho introduce by PL assumption can reach 20-50 %

Testing the CDM Paradigm on Small Non Linear Scales

- density profile of DM halo
  fitting by universal NFW
  profile
  - *Cusp-core problem*



- Missing satellites
  $\rho\ (M_\odot/kpc^3)$
  CDM model clearly
  over-predicts the number of
  substructure in the Milky Way



Simulated Cold Dark Matter Halo (Weinberg and al 2013)