Propagating light through the large-scale structure of the Universe

Michel-Andrès Breton

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Our universe

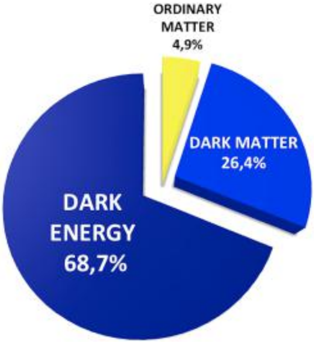

FIGURE – Planck (2018) assuming ΛCDM

Our universe

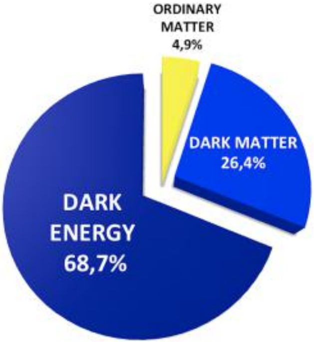

FIGURE – Planck (2018) assuming ΛCDM

- Nature of dark sector is unknown
- Dark sector not directly observable

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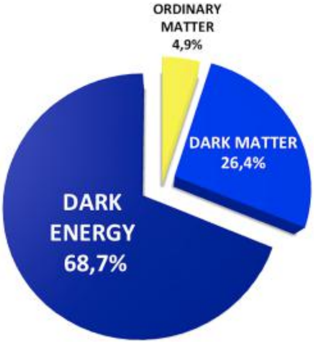

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- Galaxy rotation curves
- CMB
- etc...

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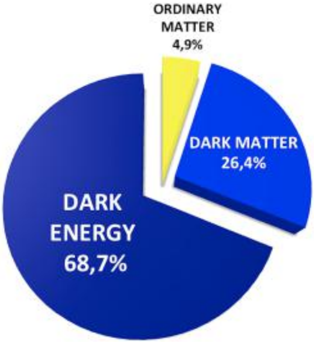

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Future surveys will observe billions of galaxies

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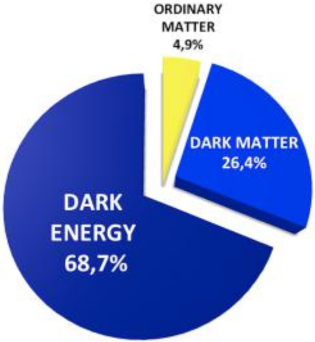

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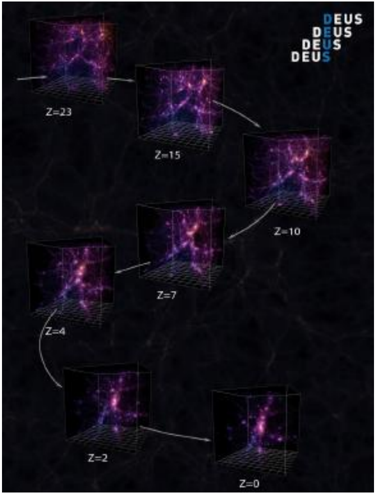
Question

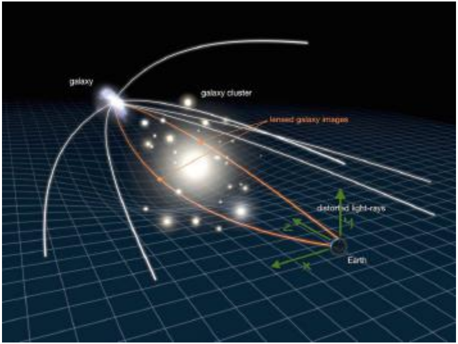
What are these dark matter and dark energy components which dominate the energy content of our universe ?

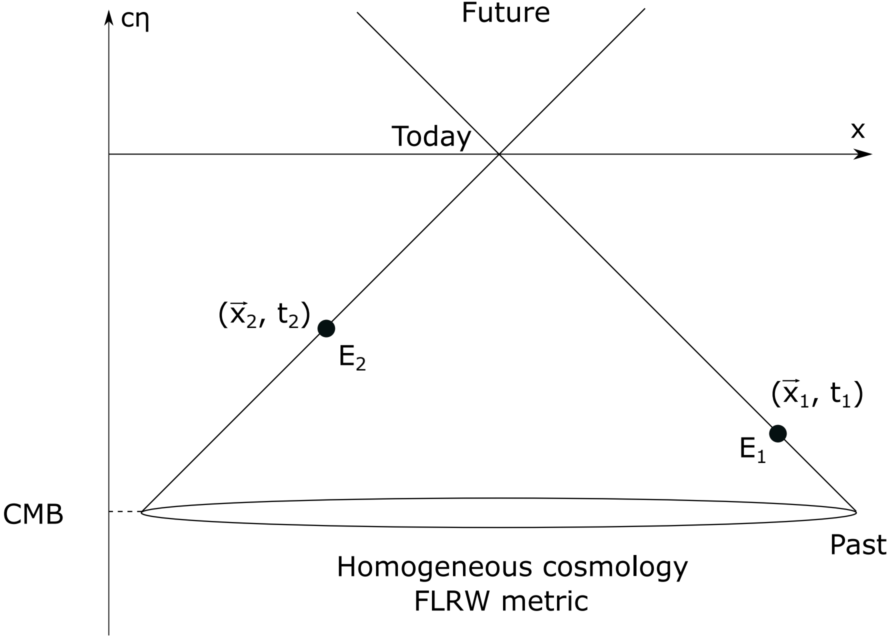
Impact of the dark components on

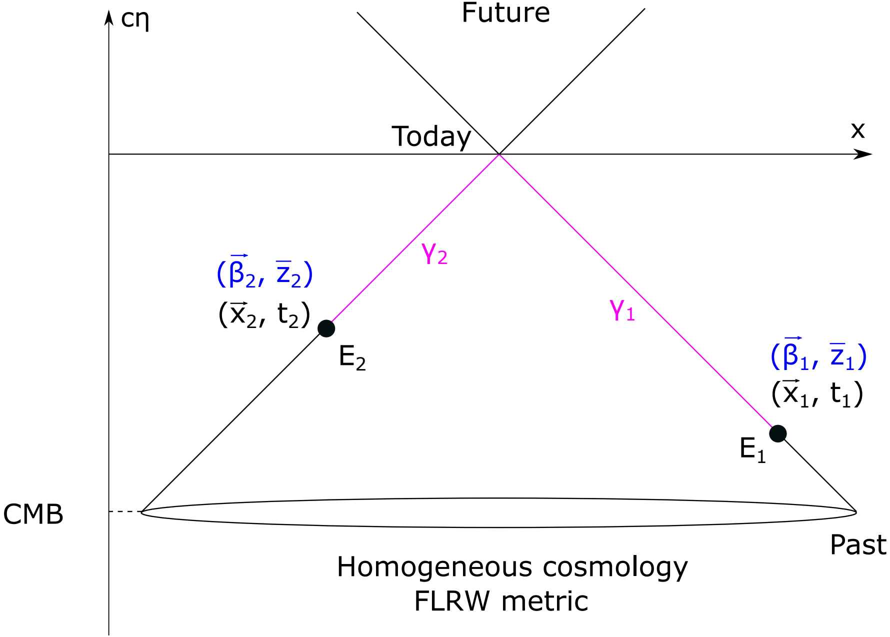
Structure formation



Photon propagation




cη
Future
Today
x
$(\vec{x}_2, t_2)$
E_2
$(\vec{x}_1, t_1)$
E_1
CMB
Past
Homogeneous cosmology
FLRW metric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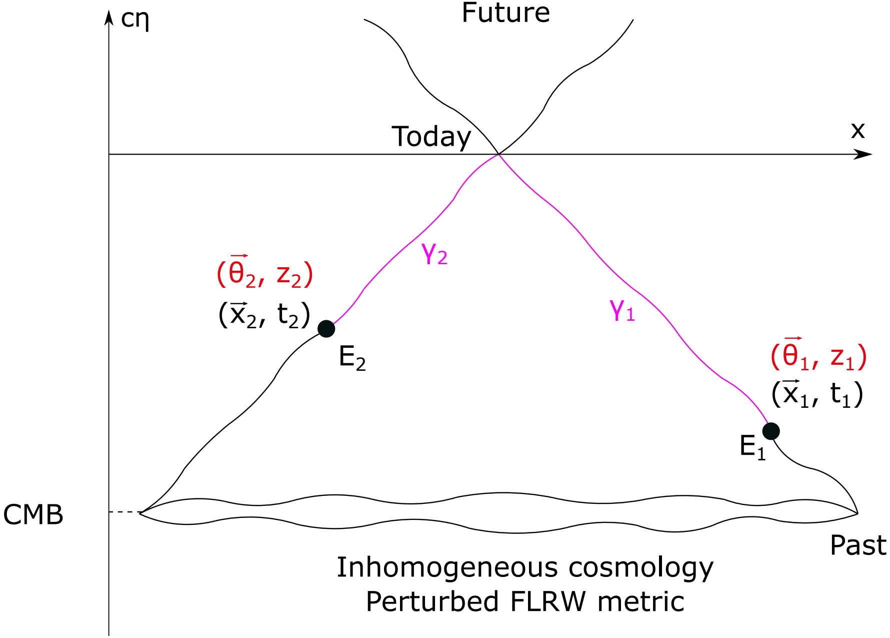

$c\eta$
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E_1
CMB
Past
Inhomogeneous cosmology
Perturbed FLRW metric

These distortions blur the original signal BUT they also give informations about our universe !

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Problematic

How to properly map the *'real'* universe to the *observed* universe in order to extract relevant cosmological information?

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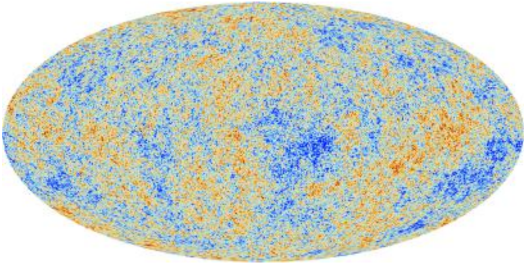
Program

- Initial conditions → Matter dynamics → Structure formation (HPC Sim)
- Kinematics of photons → What we observe (HPC Sim)
- Statistical tools → Comparison to theory (Stats/Theory)
- Likelihood analysis & parameter constraints (Stats)

Numerical simulations



- Early universe
- Small density fluctuations
- Gaussian distribution

$\searrow$ Non-linear evolution $\searrow$

- Late universe
- Virialised structures
- Non-gaussian distribution

N-body or Hydrodynamical simulation ?

N-body simulation

Compute the dynamics for dark matter particles

- Compute force and equation of motion
- Fast - Largest simulations with $\sim 16.364^3$ particles
- Physics well understood
- Not realistic at small scales (< 1 Mpc)

Hydro simulation

Compute the dynamics for dark matter and baryons

- Compute the moments of Boltzmann equation
- Slow - Largest simulations with $\sim 4096^3$ particles
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Different methods to compute the force

Particle-Particle (PP)

Direct pair-counting algorithm. Scales as $O(N^2)$

Particle-Mesh (PM)

Compute Poisson equation on a grid. Scales as $O(N \log N)$

Particle-Particle Particle-Mesh (P^3M)

PP at short range, PM at large range. Scales as $O(N^2$ and $N \log N)$

Tree methods

Far enough particles (or cells) are aggregated. Scales as $O(N \log N)$

Fast-multipole method (FMM)

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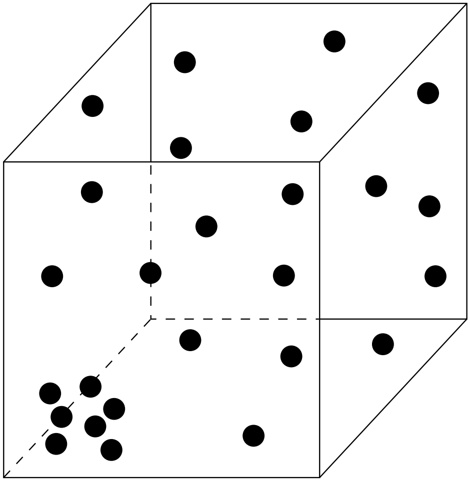
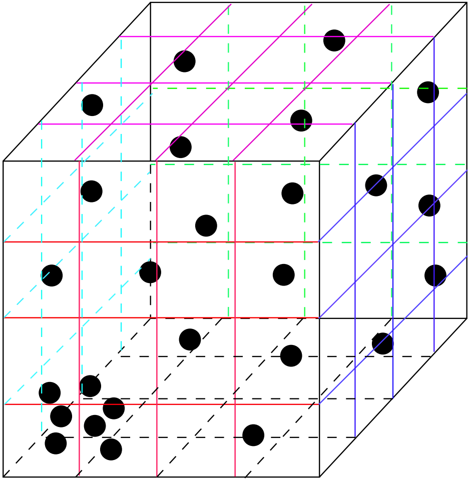


- Particle distribution in snapshot

Particle-Mesh (PM)



- Particle distribution in snapshot
- Compute density in cells

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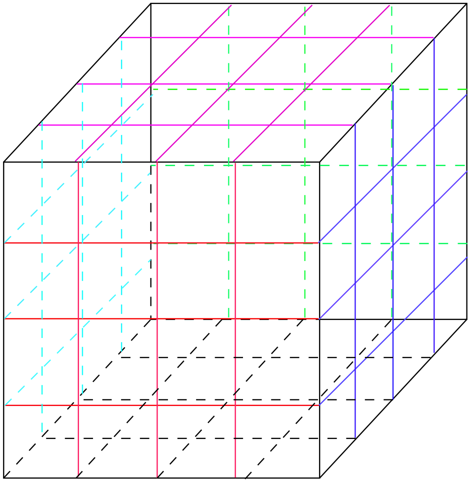

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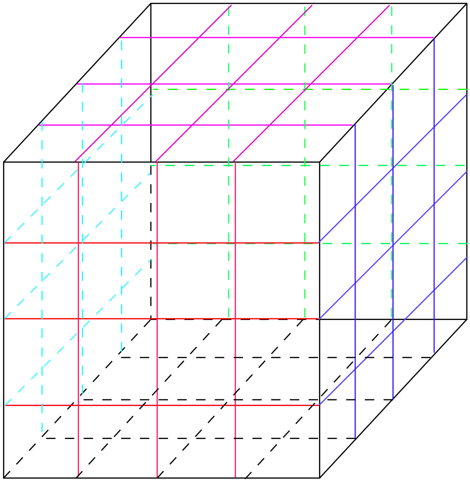

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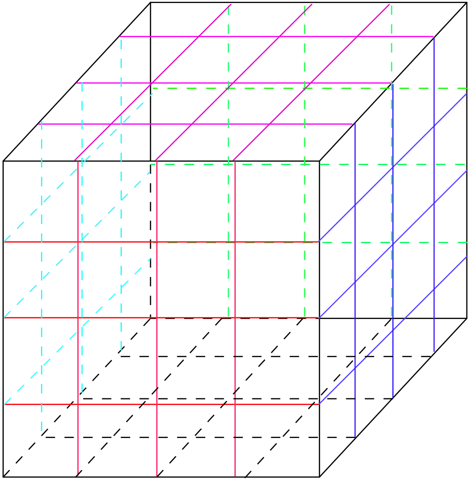

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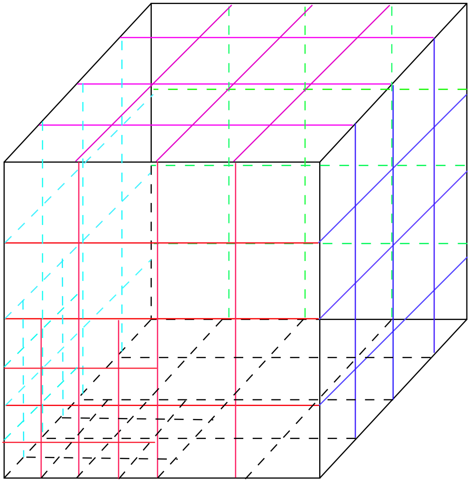
- Equation of motion

Particle-Mesh with Adaptive Mesh Refinement (PM-AMR)



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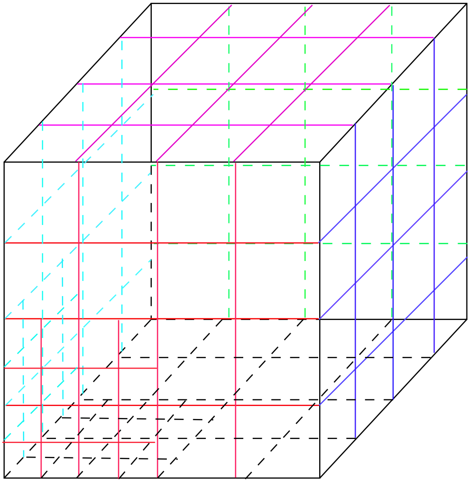

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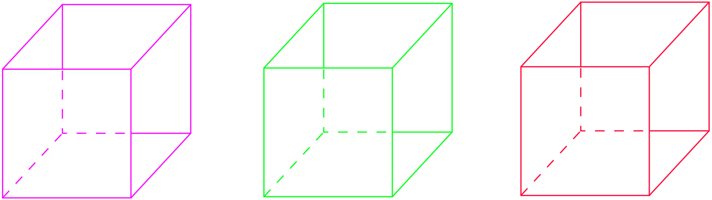
- And same with AMR ! (multigrid method, Guillet & Teyssier 2011)
- Particles : $\{\boldsymbol{x}_p, \boldsymbol{v}_p\}$
  Cells : $\{\boldsymbol{x}_c, \Phi, \nabla_{\boldsymbol{r}}\Phi, \rho\}$

N-body simulation outputs

Snapshots : Particles + cells at some given constant redshifts (or time)



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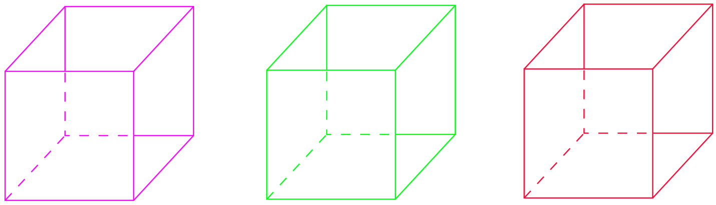
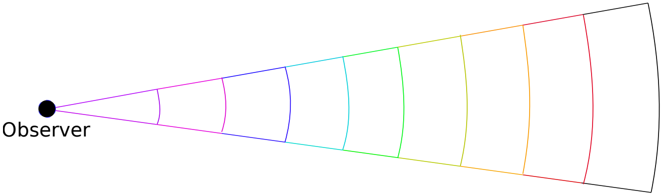


Lightcone : Particles + cells in concatenated shells from each step



Ray-tracing

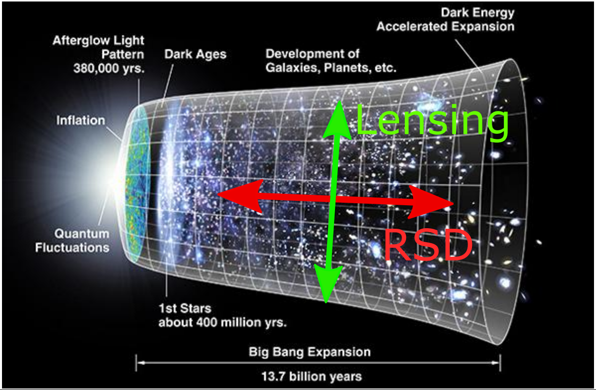
The inhomogeneous universe

Light propagation in a perturbed FLRW metric :

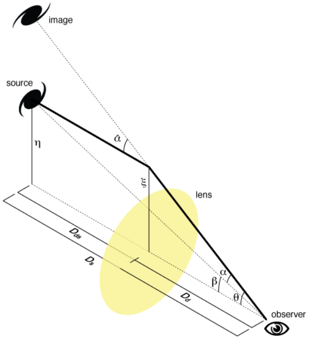
$ds^2 = -(1+2\Psi)dt^2 + a(t)^2(1-2\Phi)[dx^2 + dy^2 + dz^2]$

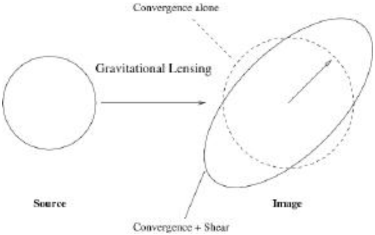
$1 + z = \frac{(g_{\mu\nu}k^\mu k^\nu)_s}{(g_{\mu\nu}k^\mu k^\nu)_o} \neq$ homogeneous FLRW redshift (Redshift-space distortions)

apparent angles $\neq$ true angles (Lensing)



Weak Lensing (WL)





Lens equation

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

- $\vec{\beta}$ true angle
- $\vec{\theta}$ angle seen
- $\vec{\alpha}$ deflection angle

Approximation : $\vec{\alpha} \ll 1$

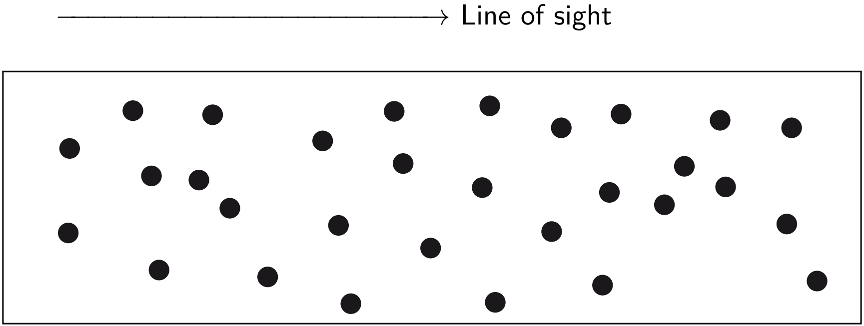
Distortion matrix

$$A_{ij} = \frac{\partial \beta_i}{\partial \theta_j} = \text{convergence} + \text{shear}$$

convergence : $(1 - \kappa) \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$

shear : $- \gamma \begin{pmatrix} \cos 2\phi & \sin 2\phi \\ \sin 2\phi & -\cos 2\phi \end{pmatrix}$

Standard approach for raytracing : The Born approximation



- Get the particle distribution in a lightcone pencil beam

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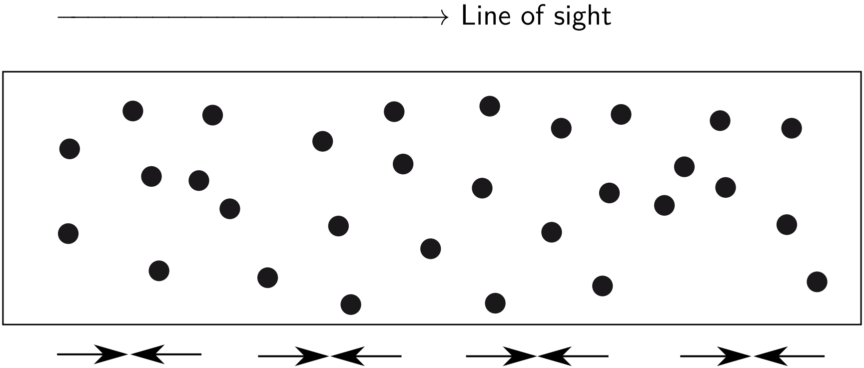

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- Project the density onto a plane (the lens !)

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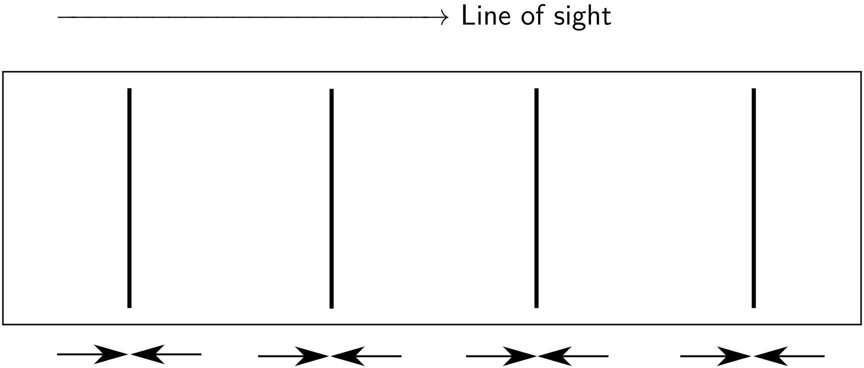

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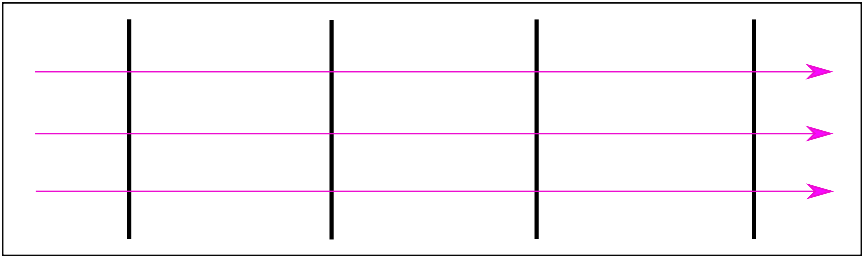
⟶ Line of sight



- Get the particle distribution in a lightcone pencil beam
- Project the density onto a plane (the lens !)
- Compute the Poisson equation to estimate the potential at the lens
- Sum the contributions of lenses along a given direction

Improved model : Post-Born

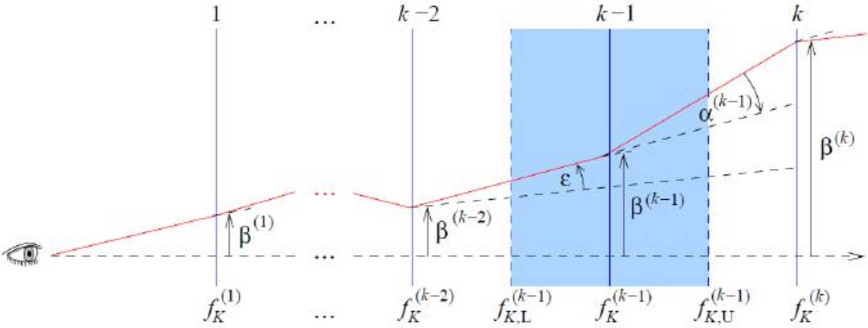


FIGURE – Hilbert et al. (2009)

Some limitations of standard approaches

- Approximations (Born, Post-Born, Lens equation, Flat sky. . .)
- Need to assume Ω_m to compute distances between lenses
- Restricted to “usual” weak lensing analysis

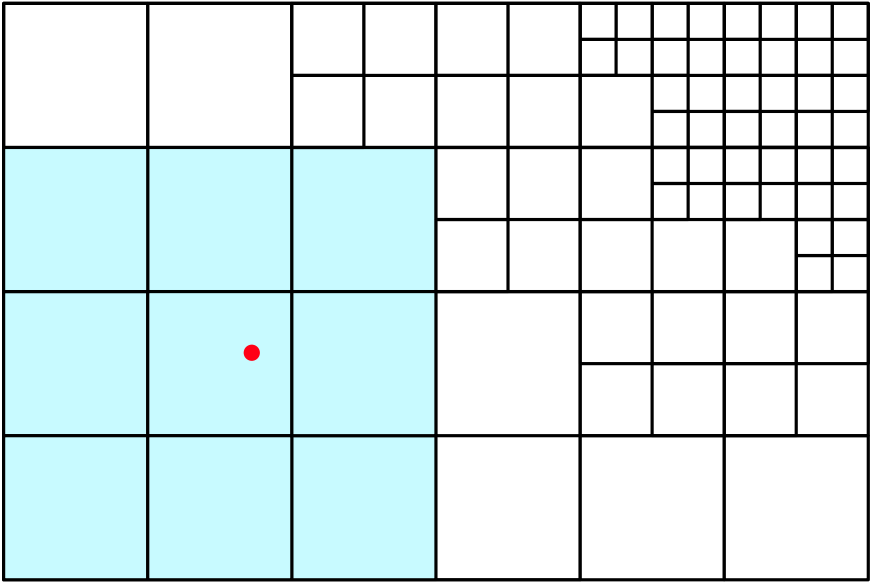
Ray-tracing : the MAGRATHEA-PATHFINDER code

A code for 3D AMR ray-tracing [Reverdy 2014 (thesis), MAB & Reverdy (2021)]

Our approach : Direct geodesic integration of photons

- C++11 Template Metaprogramming, MPI, multi-threading
- Backward integration using the geodesic equations
- RK4 integrator with 4 steps per AMR cell
- 3D interpolation with inverse TSC scheme

Integration and interpolation : TSC scheme [MAB & Reverdy (2021)]



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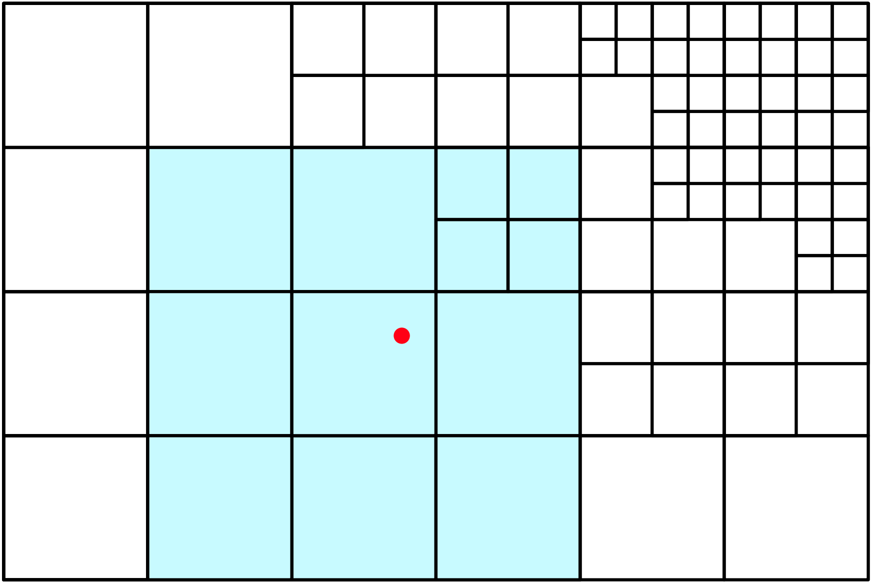

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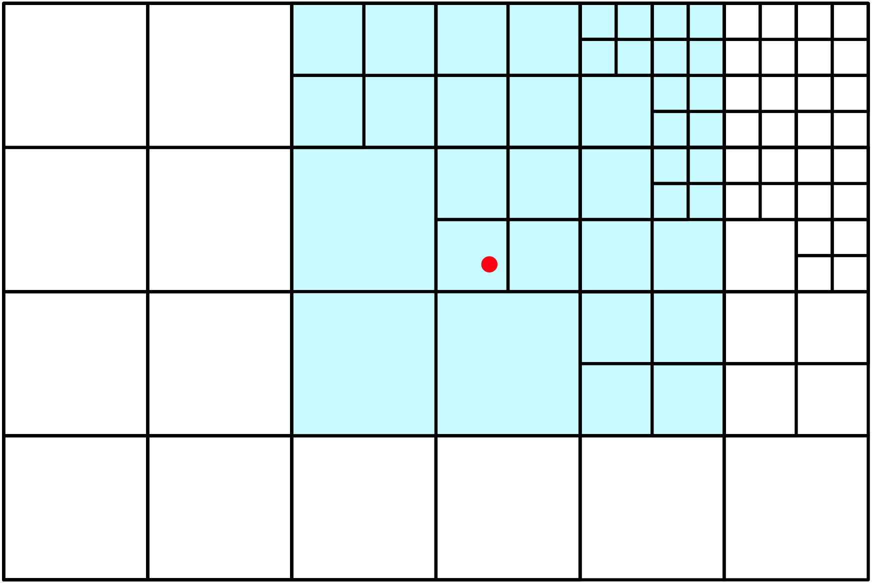

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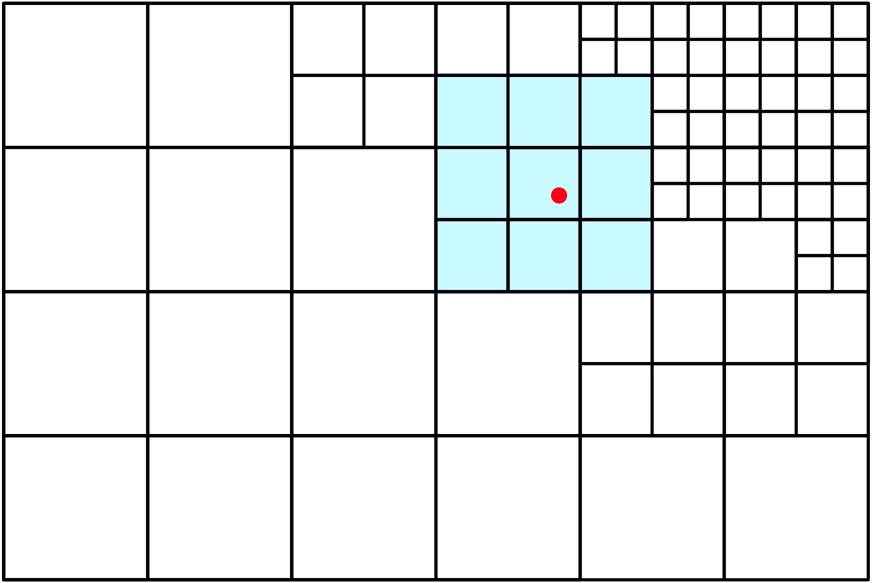

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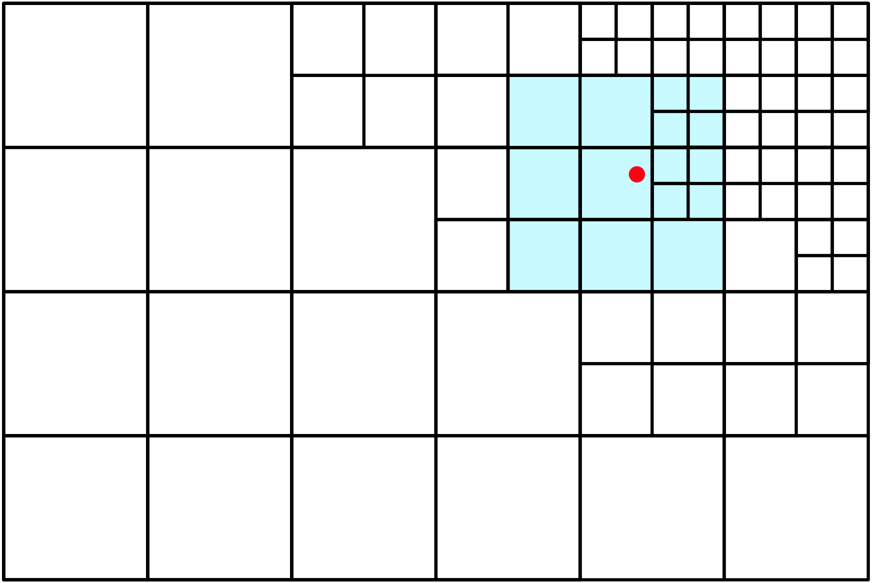

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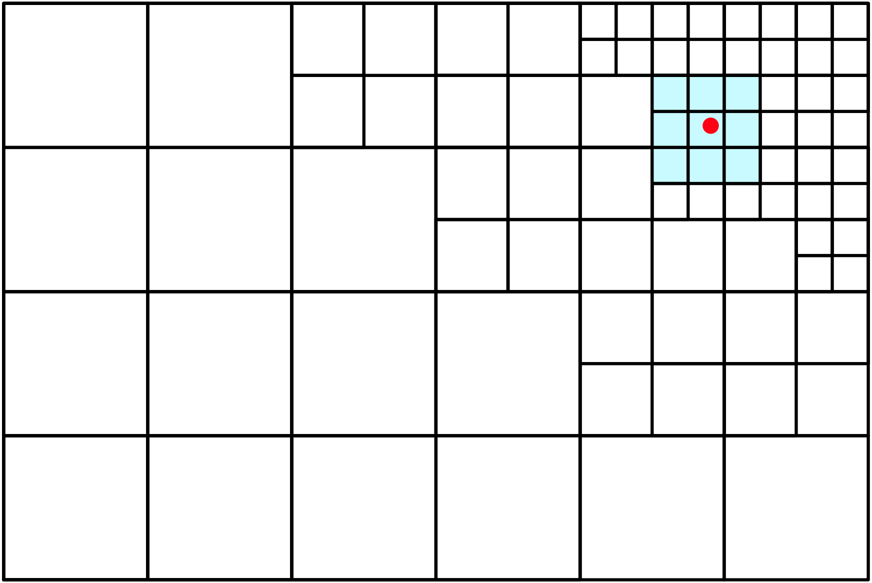
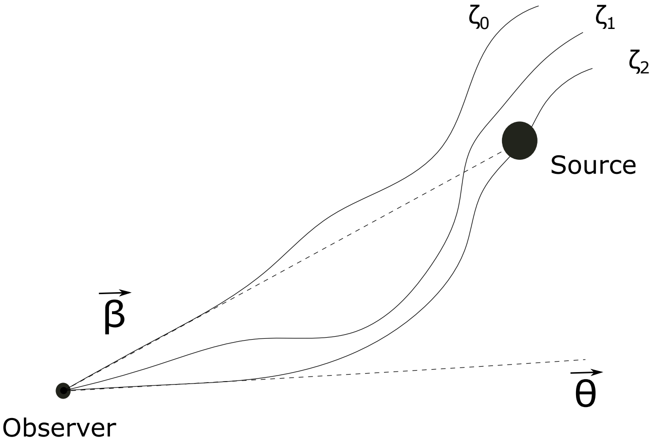


Geodesics finder

Null-geodesic finder

Find the connection between the observer and a source
→ Production of realistic observables ! [MAB et al. (2019)]



Applications

Weak lensing with finite beams

Usually weak lensing assumes infinitesimal light beams. In reality, these beams are *finite*. Here we study the impact of beam finiteness on the convergence/shear.

The clustering of galaxies

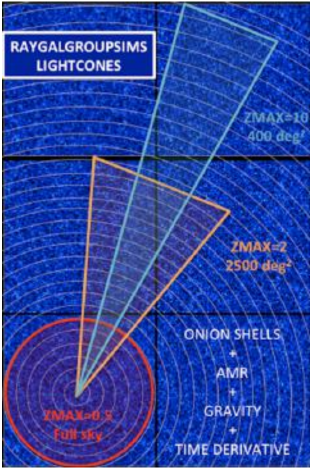
Study the apparent distribution of sources beyond usual distortions dues to peculiar velocities.

Simulation

The RayGal simulation suite [MAB et al. (2019), Rasera et al. (2021)]

Newtonian N-body simulations of interacting dark matter particles

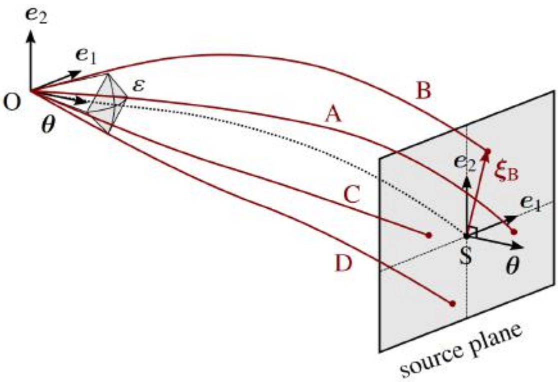
Code : RAMSES [Teyssier 2002]
PM - AMR method
Gravity lightcone
RAYGALGROUPSIMS :
4096^3 particles, 2.625 Gpc/h box size
$M_{\rm part} = 1.9 \times 10^{10} M_\odot$
Lightcone halo detection : pFoF [Roy et al, 2014]
Initial conditions : MPGRAFIC [Prunet+08]
Calibrated on WMAP7 [Komatsu et al. 2011]
2 cosmologies :
$\Lambda CDM\ - wCDM$



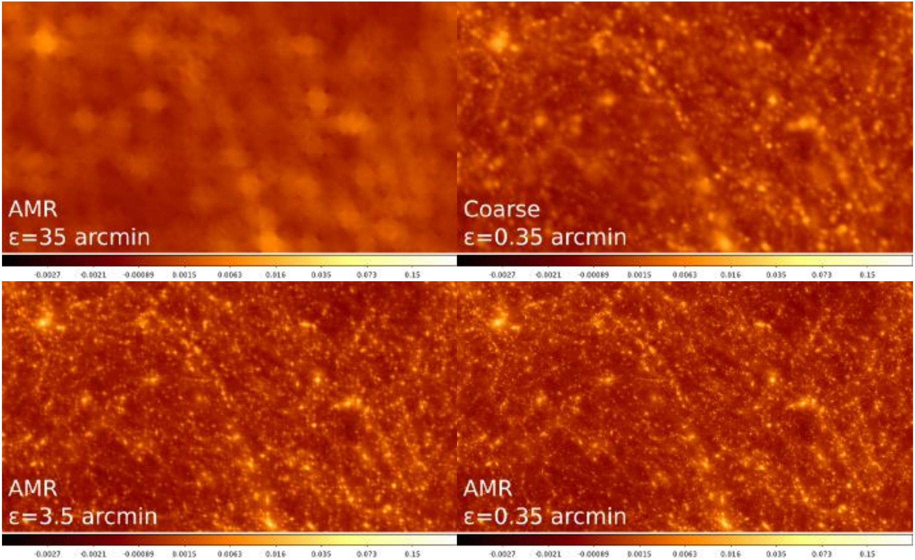
Weak lensing with finite beams

Geometry of the light beam [MAB & Fleury (2021)]

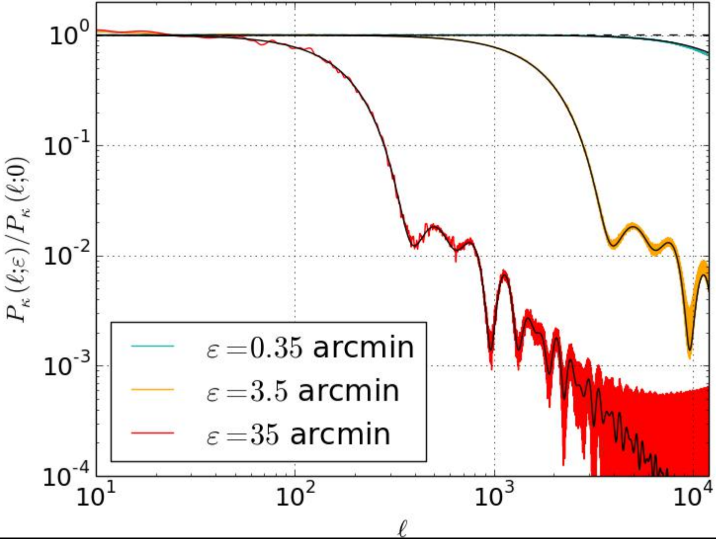
- Ray-bundle method
- Every photon follows $ds^2 = 0$
- Relevant for extended sources
- Compute $A_{ij} = \partial\beta_i/\partial\theta_j$



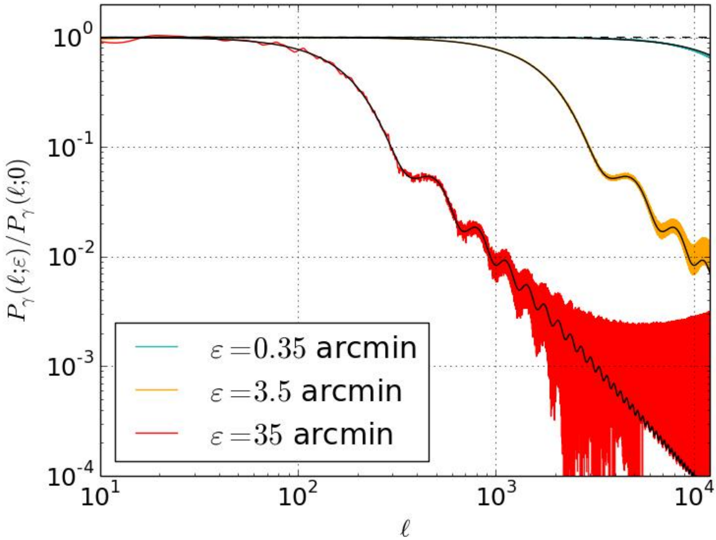
Convergence maps with finite beam [MAB & Fleury (2021)]



Convergence power specrum with finite beam [MAB & Fleury (2021)]

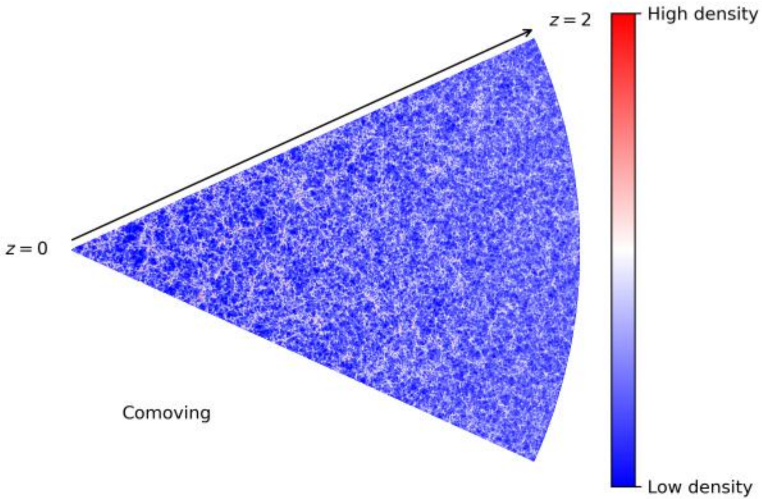


Shear power specrum with finite beam [MAB & Fleury (2021)]



Galaxy clustering analysis

RayGal simulation light-cone [Rasera et al. (2021)]



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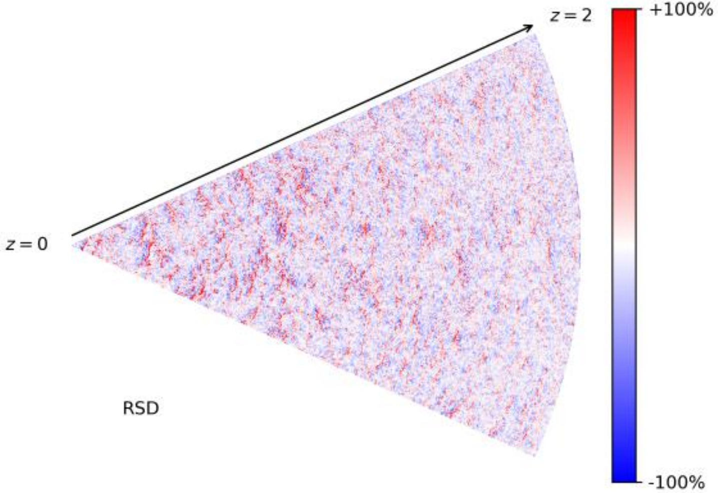

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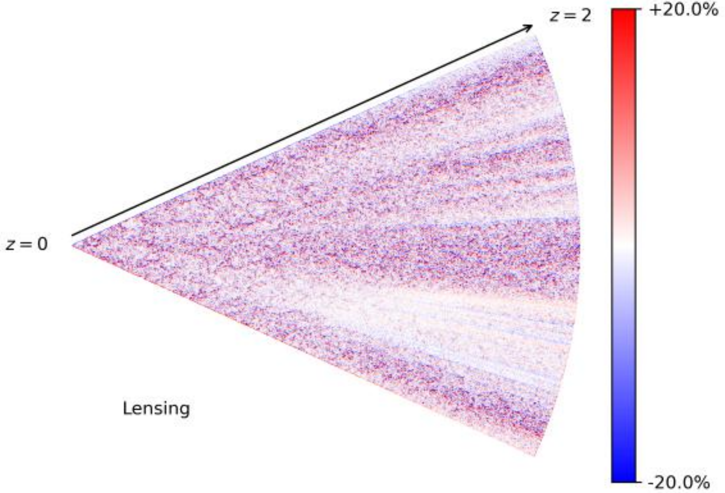

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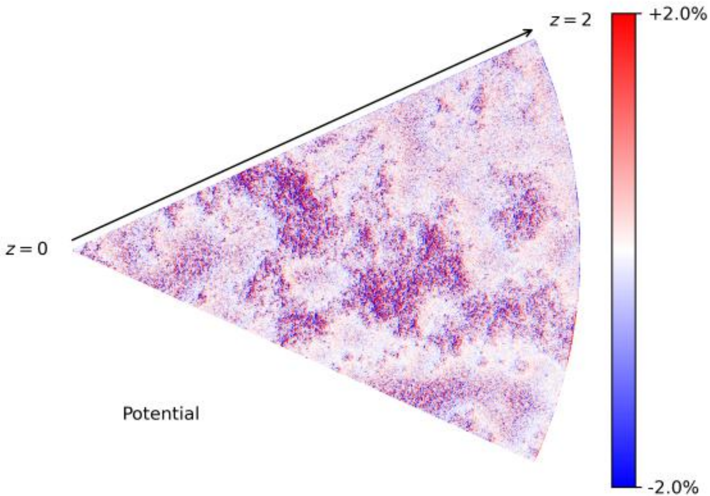
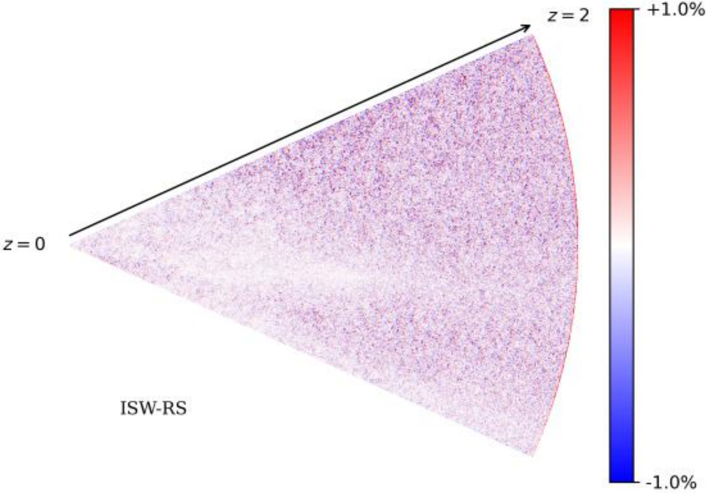


RayGal simulation light-cone [Rasera et al. (2021)]



Multipoles of the 2PCF in the RayGal simulation

redshift bins : $[\mathbf{0.8 - 1.0}]$ and $[\mathbf{1.6 - 1.9}]$

ξ_ℓ	Doppler	v_o	Grav. redshift	Lensing*	T. Doppler	ISW
ξ_0	$> 20\%$	3%	$< 1\%$	$1 - 10\%$	$< 1\%$	$< 1\%$
ξ_2	$> 20\%$	2%	$< 1\%$	2%	$< 1\%$	$< 1\%$
ξ_4	$> 20\%$	-	$< 1\%$	$1 - 10\%$	$< 1\%$	$< 1\%$

*Angular displacement only

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Number counts heavily impacted by peculiar velocities (Doppler effect) and gravitational lensing through the change in observed angular positions and magnified fluxes !

Galaxy Clustering Redshift-Space Distortions

- Observed galaxy distribution modified by peculiar velocities
- Peculiar velocities depend on the growth rate of structures $f(z) = \Omega_m(z)^\gamma$
- Ω_m the amount of matter, $\gamma \sim 0.55$ in GR

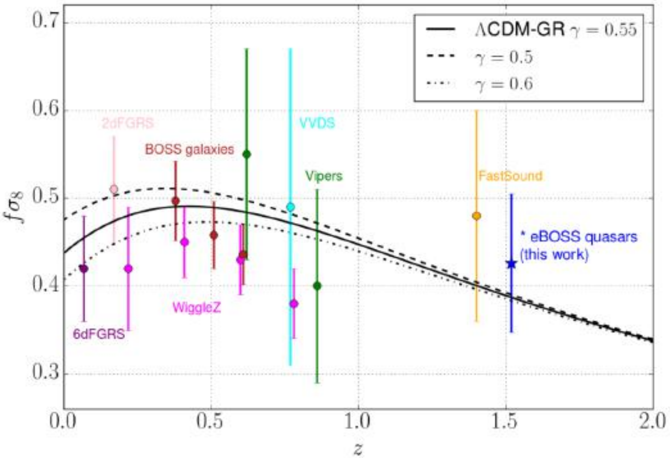
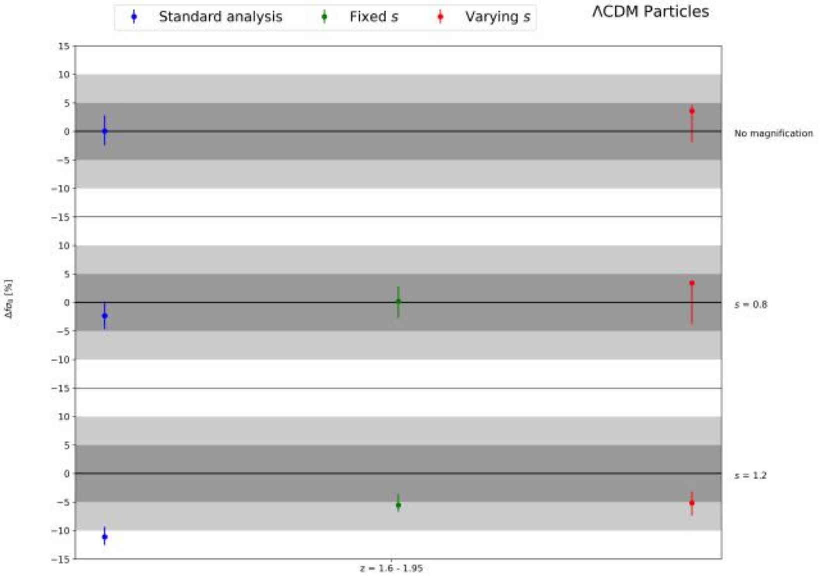


Figure from Zarrouk et al. (2018)

Impact of lensing on the growth rate [MAB et al. (2021)]



Summary

An end-to-end pipeline

- Compute dynamics for the matter field using N-body simulations
- Extract lightcone from the simulation
- Perform ray-tracing on the lightcone to produce realistic observables
- Compare these observables to theoretical predictions
- Infer possible biases on cosmological parameter constraints
- Wide range of applications for our ray-tracing methods

Raytracing integration

$$ds^2 = a(t)^2[-(1 + 2\Phi/c^2)d\eta^2 + (1 - 2\Phi/c^2)\delta_{ij}dx^i dx^j]$$

Geodesic equation

$$\frac{d^2\eta}{d\lambda^2} = -\frac{2a'}{a}\frac{d\eta}{d\lambda}\frac{d\eta}{d\lambda} - \frac{2}{c^2}\frac{d\phi}{d\lambda}\frac{d\eta}{d\lambda} + 2\frac{\partial\phi}{\partial\eta}(\frac{d\eta}{d\lambda})^2$$

$$\frac{d^2x}{d\lambda^2} = -\frac{2a'}{a}\frac{d\eta}{d\lambda}\frac{dx}{d\lambda} + \frac{2}{c^2}\frac{d\phi}{d\lambda}\frac{dx}{d\lambda} - 2\frac{\partial\phi}{\partial x}(\frac{d\eta}{d\lambda})^2$$

$$\frac{d^2y}{d\lambda^2} = -\frac{2a'}{a}\frac{d\eta}{d\lambda}\frac{dy}{d\lambda} + \frac{2}{c^2}\frac{d\phi}{d\lambda}\frac{dy}{d\lambda} - 2\frac{\partial\phi}{\partial y}(\frac{d\eta}{d\lambda})^2$$

$$\frac{d^2z}{d\lambda^2} = -\frac{2a'}{a}\frac{d\eta}{d\lambda}\frac{dz}{d\lambda} + \frac{2}{c^2}\frac{d\phi}{d\lambda}\frac{dz}{d\lambda} - 2\frac{\partial\phi}{\partial z}(\frac{d\eta}{d\lambda})^2$$

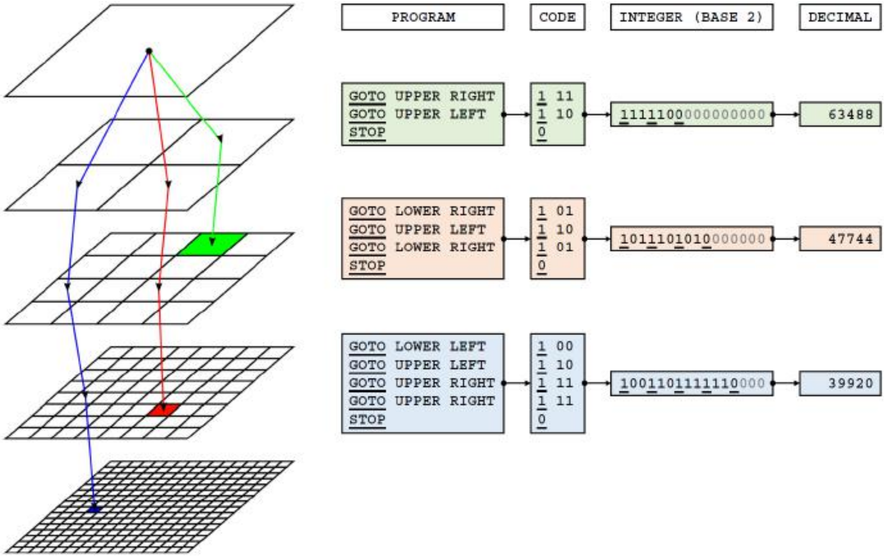


FIGURE – MAGRATHEA indexing, from Reverdy (2014)

Redshift-space number count (linear) decomposition

$$
\begin{aligned}
\Delta^{\rm std} &= b\delta - \frac{1}{\mathcal{H}}\nabla_r(\boldsymbol{v}\cdot\boldsymbol{n}), && (1)\\
\Delta^{\rm acc} &= \frac{1}{\mathcal{H}c}\dot{\boldsymbol{v}}\cdot\boldsymbol{n}, && (2)\\
\Delta^{\rm q} &= -\frac{\dot{\mathcal{H}}}{c\mathcal{H}^2}\boldsymbol{v}\cdot\boldsymbol{n}, && (3)\\
\Delta^{\rm div} &= -\frac{2}{\mathcal{H}\chi}\boldsymbol{v}\cdot\boldsymbol{n}, && (4)\\
\Delta^{\rm pot,(1)} &= \frac{1}{\mathcal{H}c}\boldsymbol{\nabla}_r\psi\cdot\boldsymbol{n}, && (5)\\
\Delta^{\rm pot,(2)} &= \left(\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}+\frac{2c}{\mathcal{H}\chi}\right)\psi/c^2 - \frac{1}{\mathcal{H}c^2}\dot{\psi}, && (6)\\
\Delta^{\rm shapiro} &= (\phi+\psi)/c^2, && (7)\\
\Delta^{\rm lens} &= -\frac{1}{c^2}\int_0^{\chi}\frac{(\chi-\chi')\chi'}{\chi}\nabla_\perp^2(\phi+\psi)d\chi', && (8)\\
\Delta^{\rm isw} &= \frac{1}{\mathcal{H}c^2}(\dot{\phi}+\dot{\psi}), && (9)\\
\Delta^{\rm LC} &= \boldsymbol{v}\cdot\boldsymbol{n}/c, && (10)\\
\Delta_{\rm neglect} &= \left(\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}+\frac{2c}{\mathcal{H}\chi}\right)\frac{1}{c^2}\int_\eta^{\eta_0}\frac{\partial(\phi+\psi)}{\partial\eta}d\eta' + \frac{2}{\chi c^2}\int_0^{\chi}(\phi+\psi)d\chi'. && (11)
\end{aligned}
$$