Are current redshift-space distortions models and methodology accurate enough for Euclid?

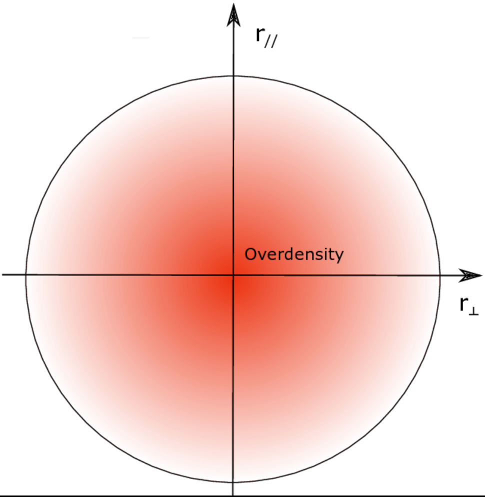
Michel-Andrès Breton

13/11/2019

Real space

Assuming statistical homogeneity and isotropy :

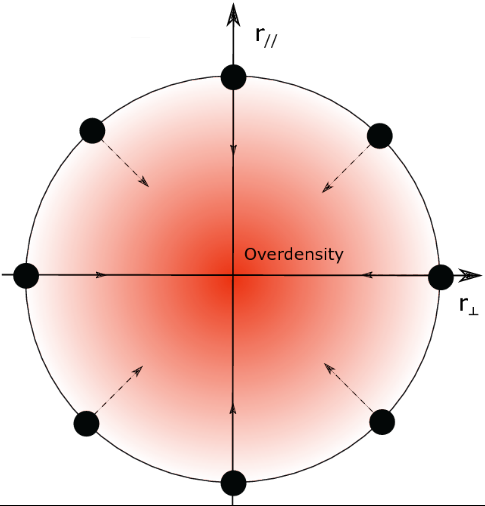
$$\langle \delta(\boldsymbol{x})\delta(\boldsymbol{x}+\boldsymbol{r})\rangle \overset{\text{homogeneity}}{=} \xi(\boldsymbol{r}) \overset{\text{isotropy}}{=} \xi(r)$$



Peculiar velocities

Accounting for the Doppler effect :

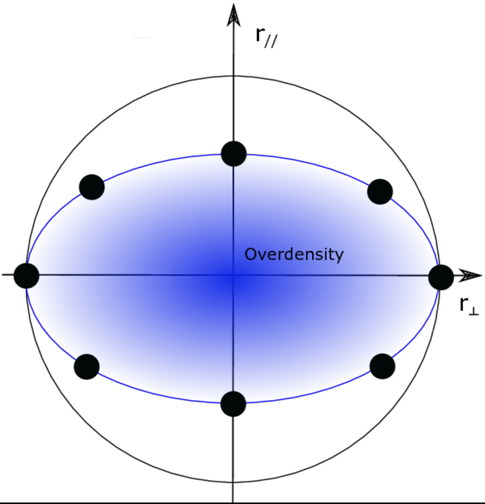
$$\boldsymbol{s} = \boldsymbol{x} + \boldsymbol{v} \cdot \boldsymbol{n} / \mathcal{H}$$



The Kaiser formula

Squeezing of the 2PCF along the line of sight (linear theory) :

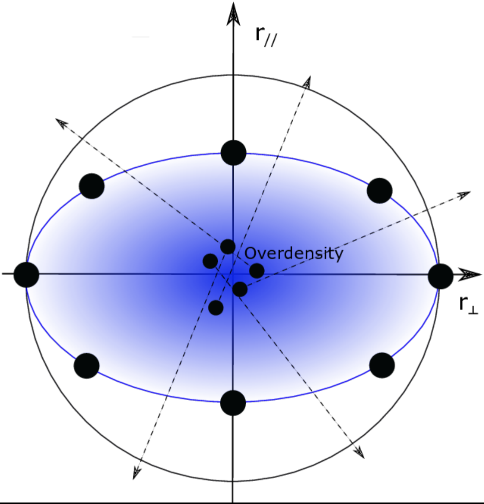
$$P_g = (b + f\mu^2)^2 P_m$$



Non-linear scales ?

High small-scale velocity dispersion :

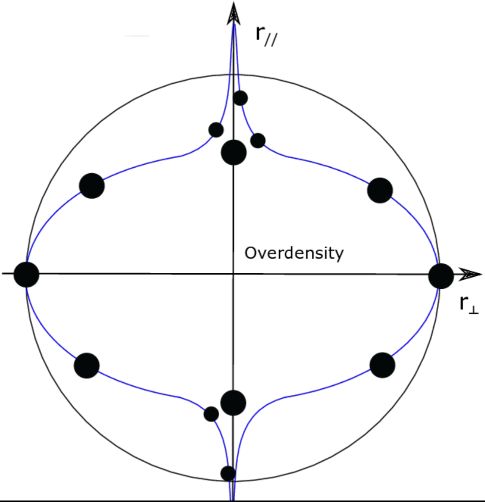
$$P_g = (b + f\mu^2)^2 P_m + ??$$



Finger-of-God effect

Elongation of the 2PCF along the line of sight at small scales (non-linear) :

$$P(\boldsymbol{k}) = \int d^3\boldsymbol{r} e^{i\boldsymbol{k}\cdot\boldsymbol{r}} \langle e^{ik\mu f \Delta u_z}[\delta(\boldsymbol{x}) + \nabla_z\{fu_z(\boldsymbol{x})\}][\delta(\boldsymbol{x'}) + \nabla_z\{fu_z(\boldsymbol{x'})\}]\rangle$$



The perturbed light-cone (+ terms at observer)

$$1 + z = \frac{a_0}{a}\left\{1 + \frac{\boldsymbol{v}\cdot\boldsymbol{n}}{c} - \frac{\psi}{c^2} + \frac{1}{2}\left(\frac{v}{c}\right)^2 - \frac{1}{c^2}\int_{\eta}^{\eta_0}\frac{\partial(\phi+\psi)}{\partial\eta}d\eta'\right\} \quad (1)$$

$$\boldsymbol{\theta} = \boldsymbol{\beta} + \boldsymbol{\alpha} \quad (2)$$

- Hubble flow
- Doppler (standard RSD)
- Gravitational redshift
- Transverse Doppler (2^{nd} order)
- ISW/RS
- Weak Lensing

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etc... modify the observed galaxy distribution

(Yoo et al. 2009 ; Yoo 2010 ; Bonvin & Durrer 2011 ; Challinor & Lewis 2011)

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etc... modify the observed galaxy distribution

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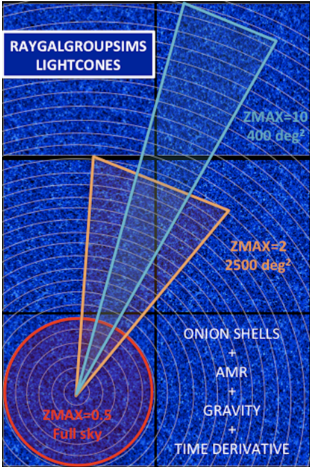
+ NON-LINEAR EVOLUTION + NON-LINEAR MAPPING !

Newtonian N-body simulations of interacting (dark matter) particles in an FLRW metric

Code : RAMSES (Teyssier 2002)
PM - AMR method
Gravity lightcone
RAYGALGROUPSIMS (Rasera et al., in prep) :
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
2 cosmologies :
$\underline{\Lambda CDM} - WCDM$



Ray-tracing

Our approach : Direct geodesic integration of photons. No Born approximation !

MAGRATHEA, a library for ray-tracing (Reverdy, 2014)

- C++11 Template Metaprogramming
- Take action in the instanciation process
- MPI parallelized + Multithreading

Raytracing characteristics

- $ds^2 = 0$ (photon)
- $\frac{d^2x^\alpha}{dv^2} + \Gamma^\alpha_{\beta\gamma}\frac{dx^\beta}{dv}\frac{dx^\gamma}{dv} = 0$
- Potential from Newtonian simulation $\rightarrow \psi = \phi$
- Backward integration starting from the observer today
- RK4 integrator with 4 steps per AMR cell

Geodesics finder

Find null geodesics

Find the connection between Observer O and Source S
Using Newton's method :
$x = (x_1, ..., x_n)$
$x_{k+1} = x_k - F(x_k)/F'(x_k)$

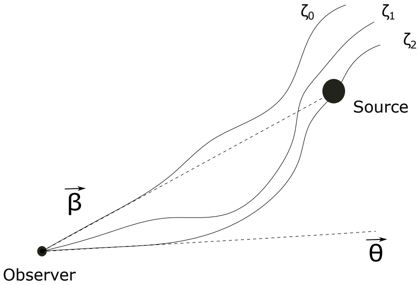
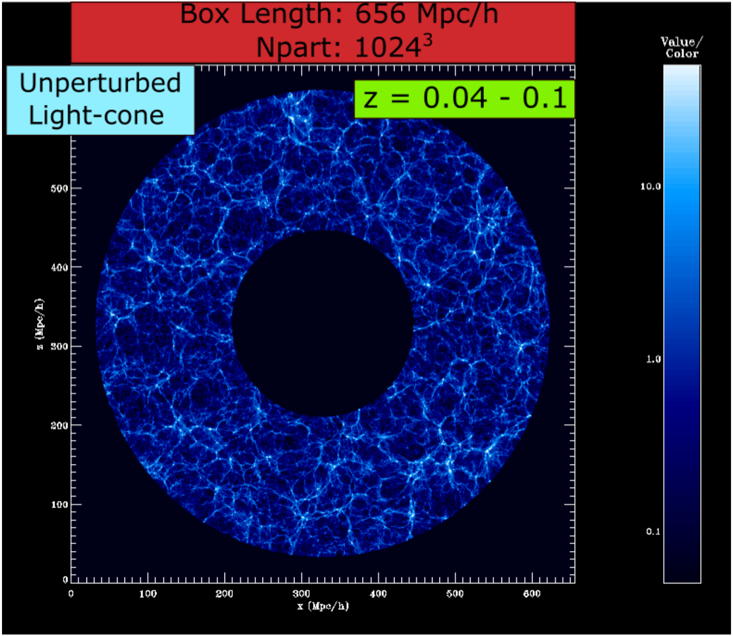
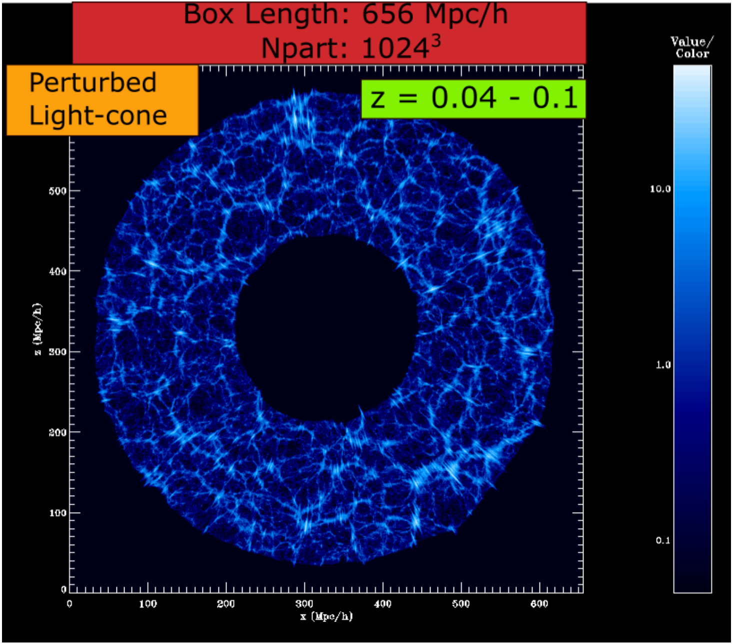


FIGURE – Illustration of the geodesic-finder algorithm (MAB+18).


Box Length: 656 Mpc/h
Npart: 1024^3
Unperturbed
Light-cone
z = 0.04 - 0.1
Value/
Color
10.0
1.0
0.1
z (Mpc/h)
500
400
300
200
100
0
0
100
200
300
400
500
600
x (Mpc/h)



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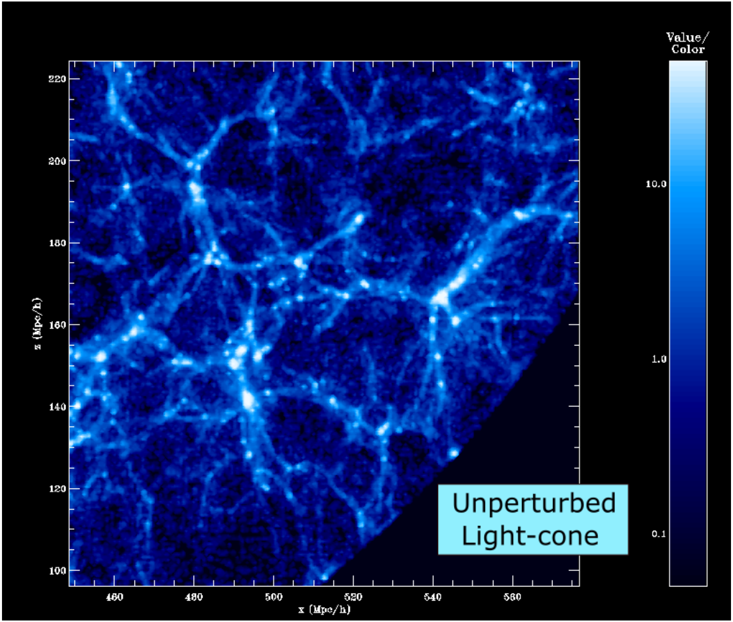
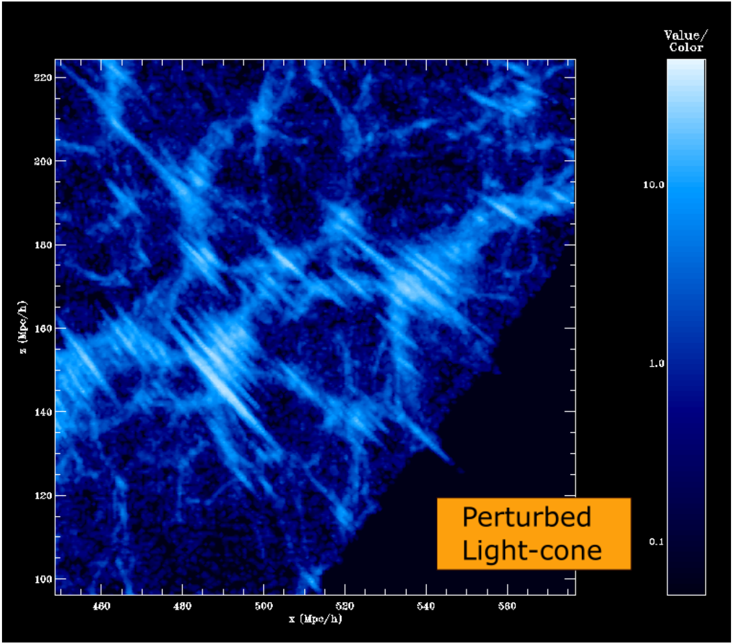
600


Value/
Color
10.0
1.0
0.1
220
200
180
160
140
120
100
z (Mpc/h)
460
480
500
520
540
560
x (Mpc/h)
Unperturbed
Light-cone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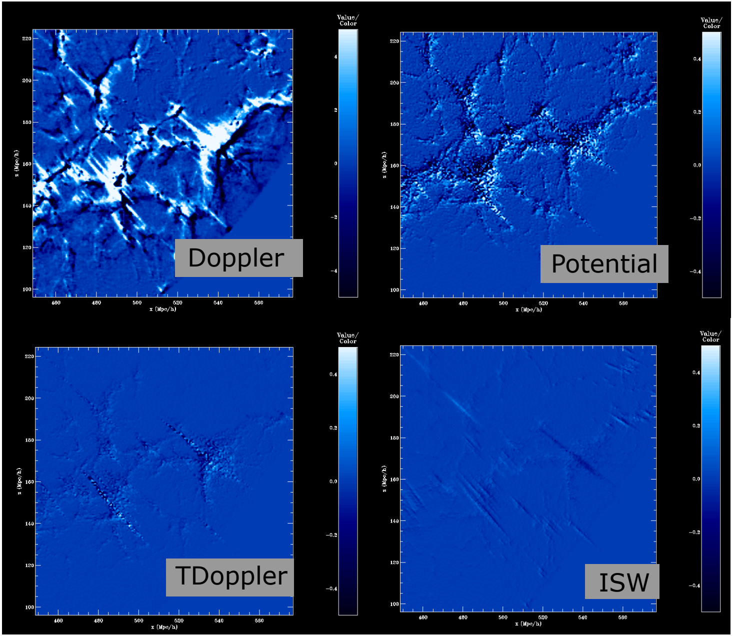

Doppler
Potential
TDoppler
ISW

Multipoles of the correlation function

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

ξ_ℓ^*	Doppler	v_o	Grav. redshift	Lensing**	T. Doppler	ISW
ξ_0	$> 20\%$	3%	$< 1\%$	$1 - 10\%$	$< 1\%$	$< 1\%$
ξ_1	$> 20\%$	$< 1\%$	$> 20\%$	$< 1\%$	$< 1\%$***	$< 1\%$
ξ_2	$> 20\%$	2%	$< 1\%$	2%	$< 1\%$	$< 1\%$
ξ_4	$> 20\%$	-	$< 1\%$	$1 - 10\%$	$< 1\%$	$< 1\%$

*Particle auto-correlation for monopole and quadrupole. Halos cross-correlation for dipole.

**Angular displacement only. No luminosity threshold !

***May be important under 2 Mpc/h

On the impact of gravitational lensing

Modification of observed number count

$$\Delta = b\delta - 2\kappa$$

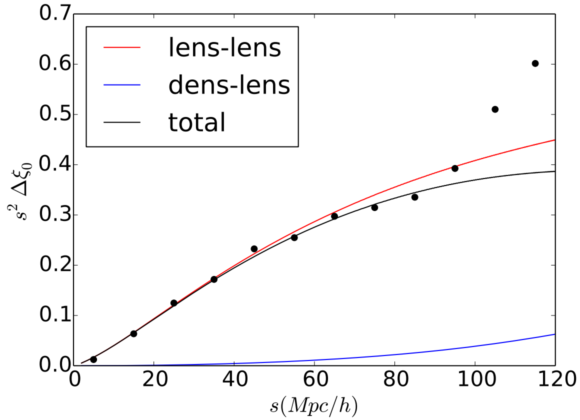


FIGURE – $z = 1.6 - 1.9$

Linear theory seems good until $r \approx 100\ Mpc/h$

Modification of observed number count with selection function

$$\Delta = b\delta + (5s - 2)\kappa$$

$s = d \log_{10} N(< m)/dm$, the slope of the number count w.r.t magnitude

In EUCLID Flagship mocks :

- $z = 1$
  $s = 0.7$
- $z = 2$
  $s = 1$

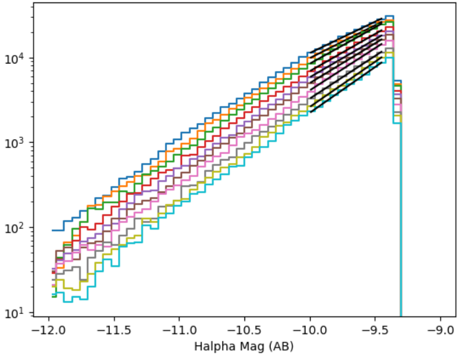
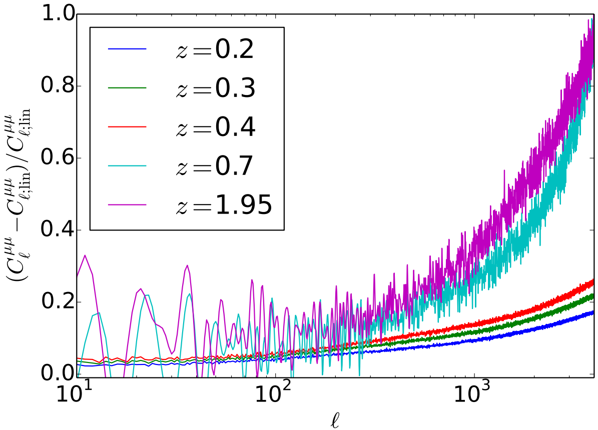


FIGURE – Fig. courtesy : E. Jullo

About the linear approximation for magnification

- All the previous number count perturbations were derived using the *linear approximation* : $\mu = 1 + 2\kappa$
- This might not be good at all (see also Unruh, Schneider, Hilbert et al. 2019)



Summary

- "Standard" RSD only accounts for the Doppler effect
- Overall this is a good approximation
- For the highest EUCLID redshift bins we might want to investigate the impact of lensing
- Linear theory = ok
- Non-linear theory = not ok
- We are currently estimating these effects on Flagship mocks

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

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

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

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

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

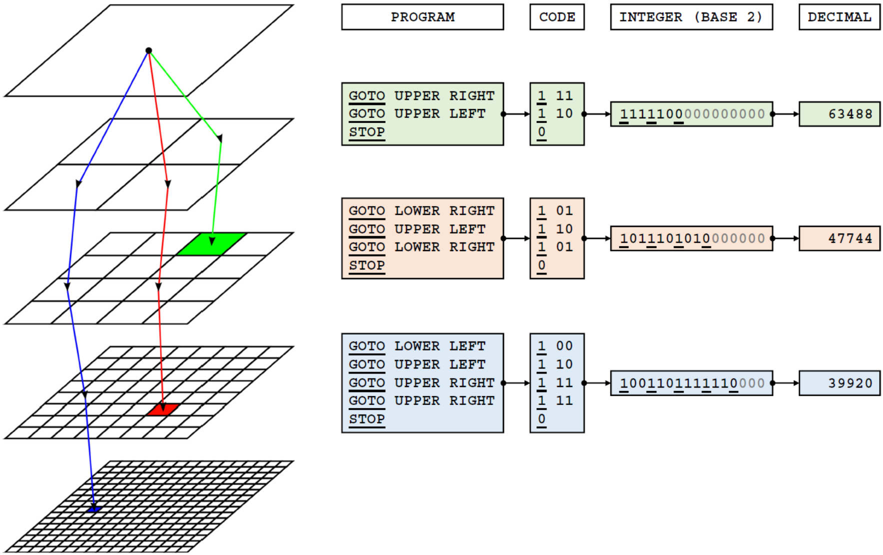


FIGURE – MAGRATHEA indexing, from Reverdy (2014)

Redshift-space number count (linear) decomposition

$$\Delta^{\rm std} = b\delta - \frac{1}{\mathcal{H}}\nabla_r(\boldsymbol{v}\cdot\boldsymbol{n}), \quad (3)$$

$$\Delta^{\rm acc} = \frac{1}{\mathcal{H}c}\dot{\boldsymbol{v}}\cdot\boldsymbol{n}, \quad (4)$$

$$\Delta^{\rm q} = -\frac{\dot{\mathcal{H}}}{c\mathcal{H}^2}\boldsymbol{v}\cdot\boldsymbol{n}, \quad (5)$$

$$\Delta^{\rm div} = -\frac{2}{\mathcal{H}\chi}\boldsymbol{v}\cdot\boldsymbol{n}, \quad (6)$$

$$\Delta^{\rm pot,(1)} = \frac{1}{\mathcal{H}c}\boldsymbol{\nabla}_r\psi\cdot\boldsymbol{n}, \quad (7)$$

$$\Delta^{\rm pot,(2)} = \left(\frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + \frac{2c}{\mathcal{H}\chi}\right)\psi/c^2 - \frac{1}{\mathcal{H}c^2}\dot{\psi}, \quad (8)$$

$$\Delta^{\rm shapiro} = (\phi+\psi)/c^2, \quad (9)$$

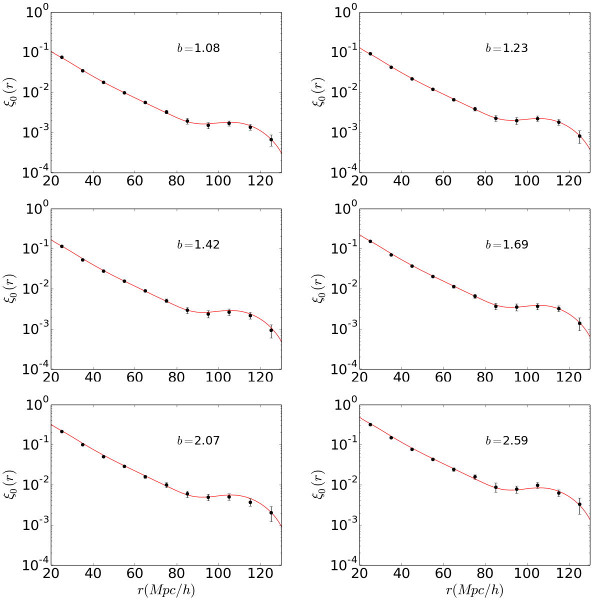
$$\Delta^{\rm lens} = -\frac{1}{c^2}\int_0^{\chi}\frac{(\chi-\chi')\chi'}{\chi}\nabla_{\perp}^2(\phi+\psi)d\chi', \quad (10)$$

$$\Delta^{\rm isw} = \frac{1}{\mathcal{H}c^2}(\dot{\phi}+\dot{\psi}), \quad (11)$$

$$\Delta^{\rm LC} = \boldsymbol{v}\cdot\boldsymbol{n}/c, \quad (12)$$

$$\Delta_{\rm neglect} = \left(\frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + \frac{2c}{\mathcal{H}\chi}\right)\frac{1}{c^2}\int_{\eta}^{\eta_0}\frac{\partial(\phi+\psi)}{\partial\eta}d\eta' + \frac{2}{\chi c^2}\int_0^{\chi}(\phi+\psi)d\chi'. \quad (13)$$

Validation : Standard RSD monopole



- Halo auto-correlation
- 6 different populations binned in mass

nb of halos	halo mass ($M_\odot$)	bias
5.4×10^6	2.8×10^{12}	1.08
3.4×10^6	5.6×10^{12}	1.22
1.9×10^6	1.1×10^{13}	1.42
1.0×10^6	2.2×10^{13}	1.69
4.0×10^5	4.5×10^{13}	2.07
2.0×10^5	9.0×10^{13}	2.59

- Prediction : RegPT (Taruya+12)