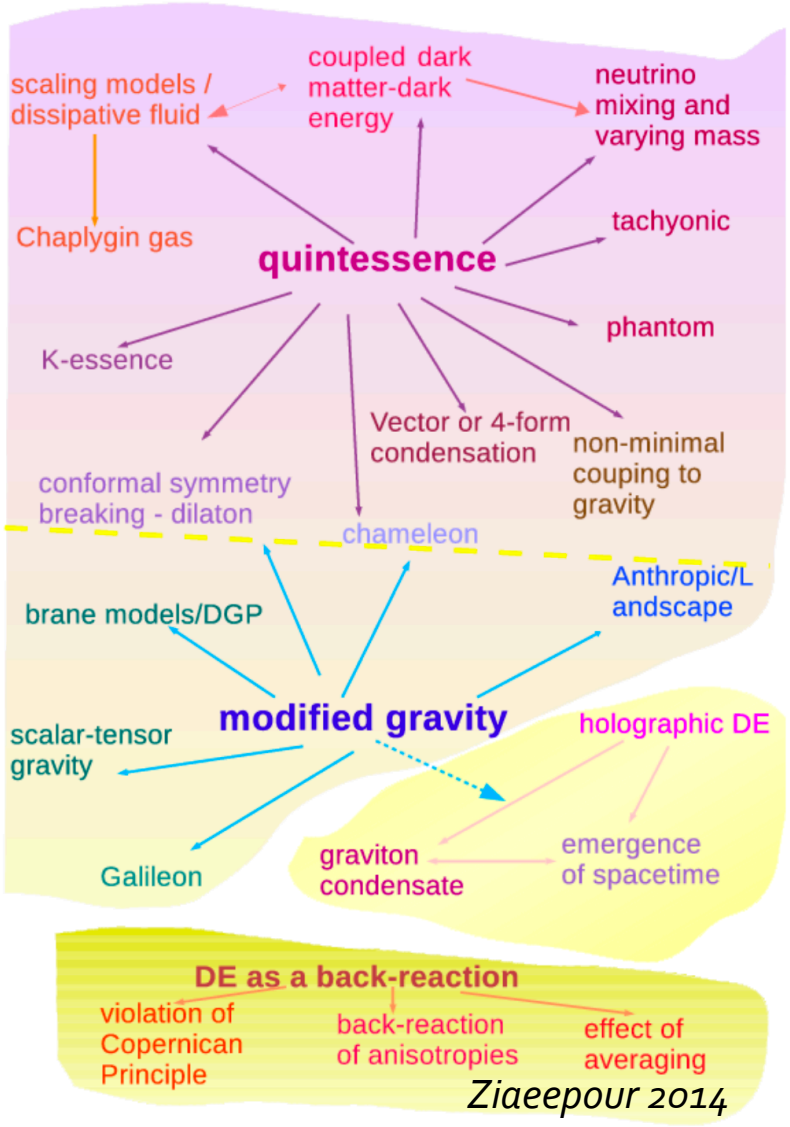
Imprints of relativistic effects on the asymmetry of the halo cross-correlation function: from linear to non-linear scales

Yann RASERA (LUTH/Paris Obs./Paris 7 Univ.)

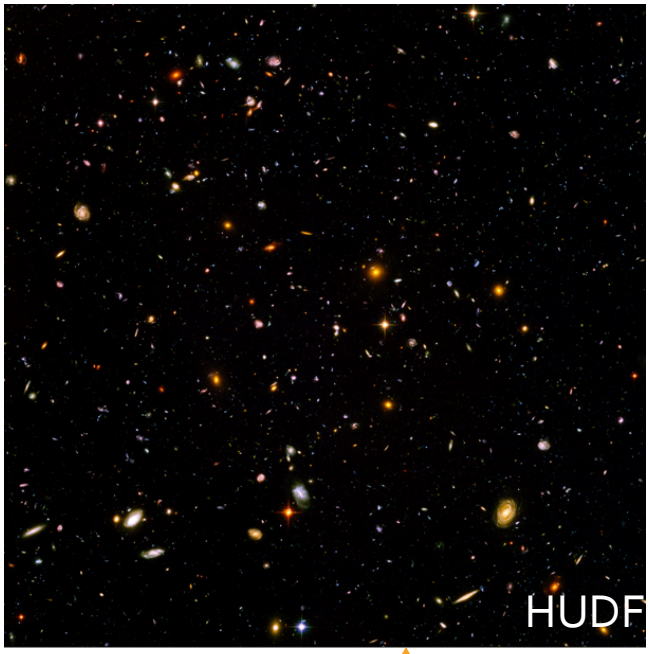
Work with: Michel-Andrès Breton (LUTH), Atsushi Taruya (YITP), Osmin Lacombe (YITP, Polytechnique), Shohei Saga (YITP), Fabrice Roy (LUTH), Vincent Reverdy (LUTH,University of Illinois), Ichihiko Hashimoto (YITP), Pier-Stefano Corasaniti (LUTH)

WHAT IS THE NATURE OF THE DARK SECTOR?

- **VARIOUS POSSIBILITIES FOR DE**



- **SEARCH FOR NEW OR REFINED PROBES IN THE NON-LINEAR REGIME OF STRUCTURE FORMATION**



Non linear imprints of DARK SECTOR on COSMIC STRUCTURES ?
How to probe DARK SECTOR with COSMIC STRUCTURES?

- **MANY OTHERS FOR DM**

STANDARD APPROACH TO STRUCTURE FORMATION

- Scalar perturbation of FLRW metric in newtonian gauge

$$ds^2 = -(1+2\Psi)dt^2 + a^2(t)(1-2\Phi)\delta_{ab}dx^a dx^b$$

- Boltzmann equation (i.e weak-field Einstein-Boltzmann) for DM&baryons

$$\frac{\partial f}{\partial t} + \frac{\mathbf{p}}{ma^2}\cdot\nabla f - m\nabla\psi\cdot\nabla_{\mathbf{p}} f = \left(\frac{\partial f}{\partial t}\right)_{\rm coll}$$

- Poisson equation (i.e. weak field Einstein equations) for gravity

$$\Delta\phi = 4\pi G a^2\bar{\rho}\delta + 3\frac{a'}{a}\left(\phi' + \frac{a'}{a}\psi\right)$$

$$\Psi = \Phi$$

- Geodesics equations for light

$$\frac{d\mathbf{e}}{d\eta} = -\nabla_\perp(\phi+\psi)$$

STANDARD APPROACH TO STRUCTURE FORMATION

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+MODIF???

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+MODIF???

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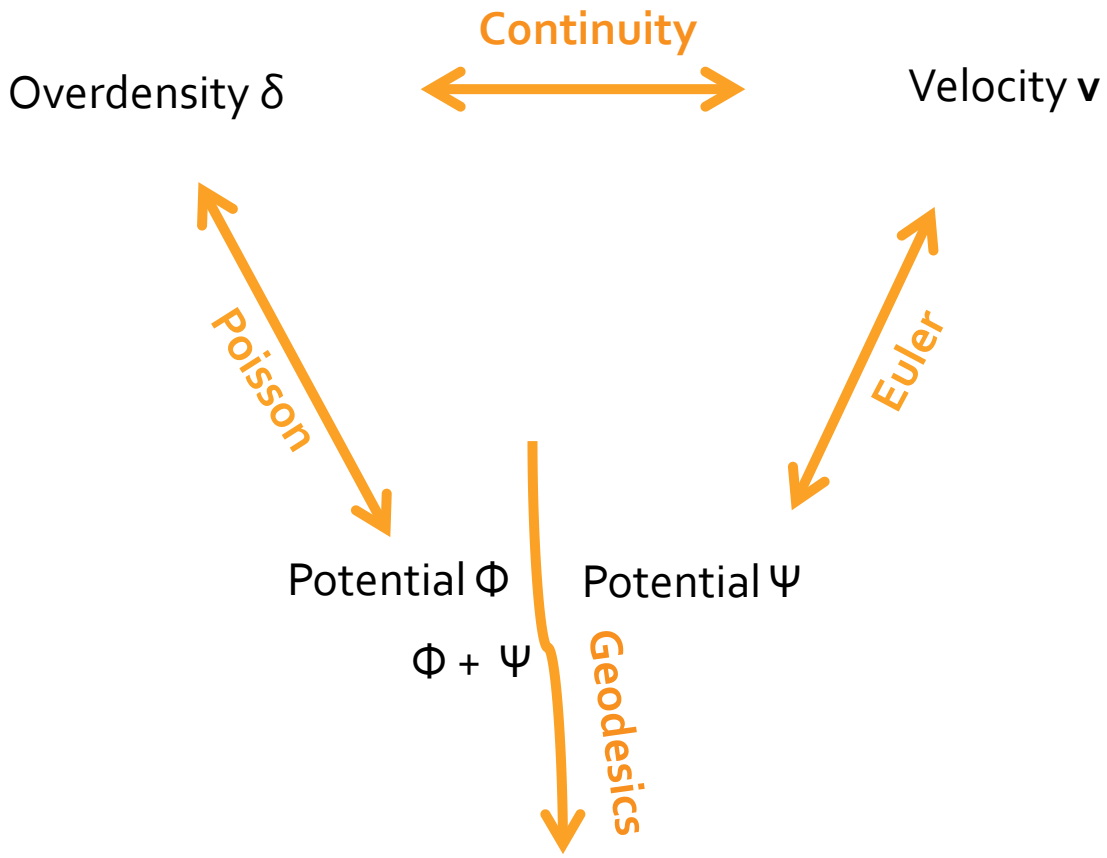
STANDARD APPROACH TO STRUCTURE FORMATION

CAN WE POSSIBLY TEST ALL THESE HYPOTHESIS AT COSMOLOGICAL SCALES ?



Simplified view

Adapted from Bonvin&Fleury 2018

STANDARD APPROACH TO STRUCTURE FORMATION

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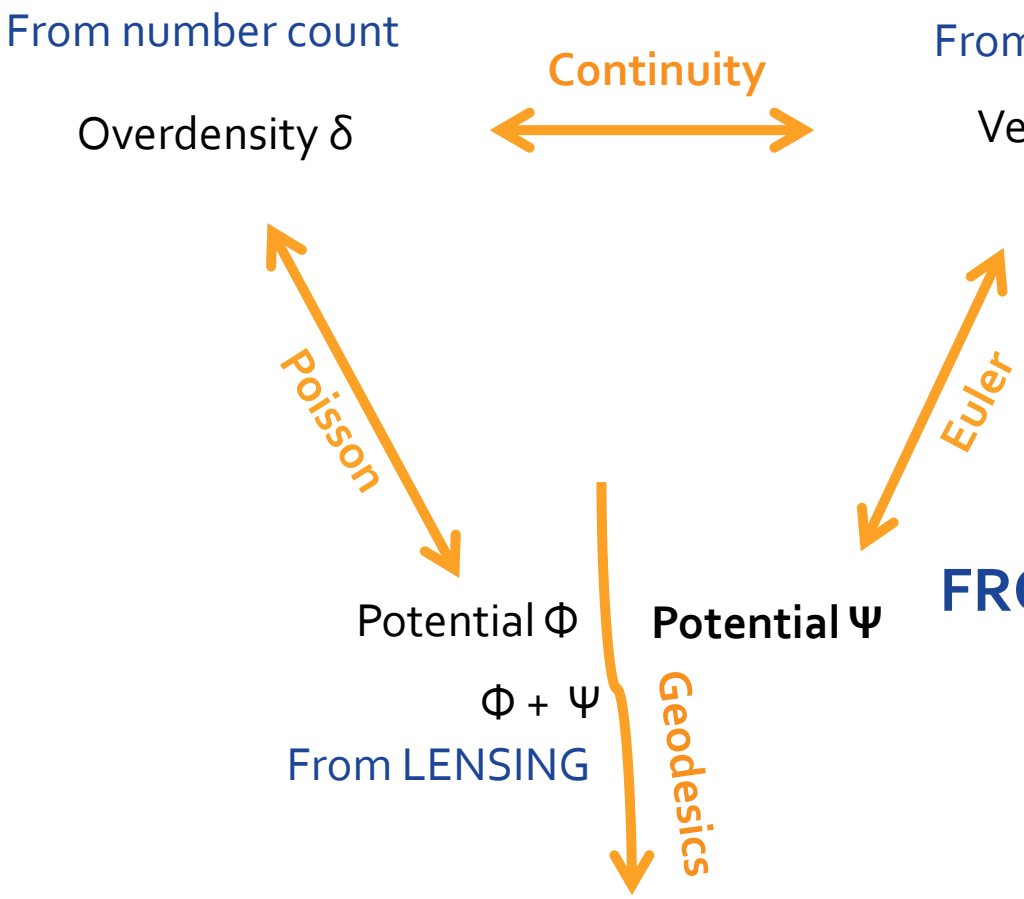
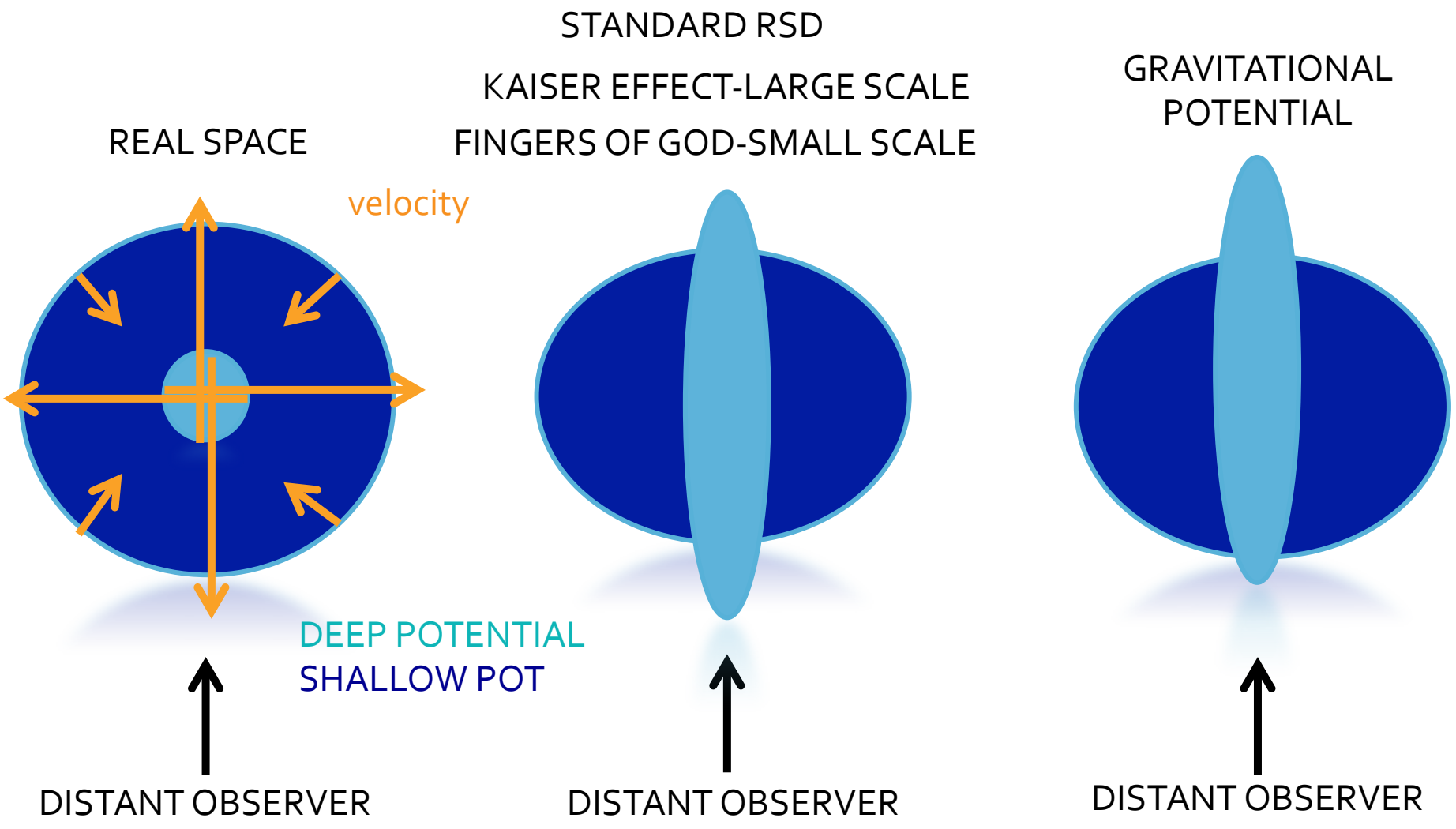


FROM RELATIVISTIC DIPOLE RSD ?

Simplified view

Adapted from Bonvin&Fleury 2018

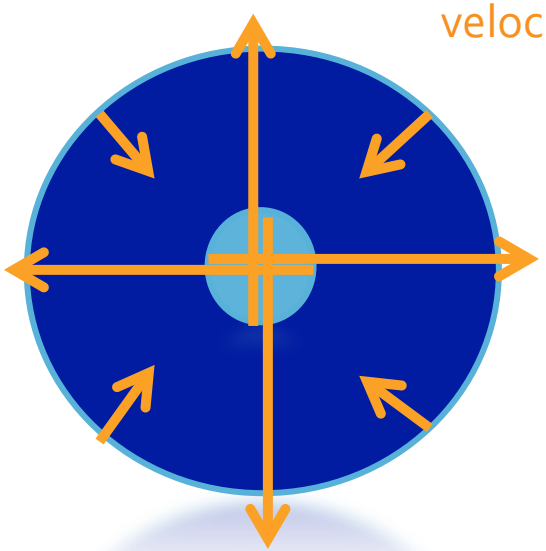
Apparent distribution of sources: example of redshift space distortion



Apparent distribution of sources: example of redshift space distortion

MONOPOLE

REAL SPACE



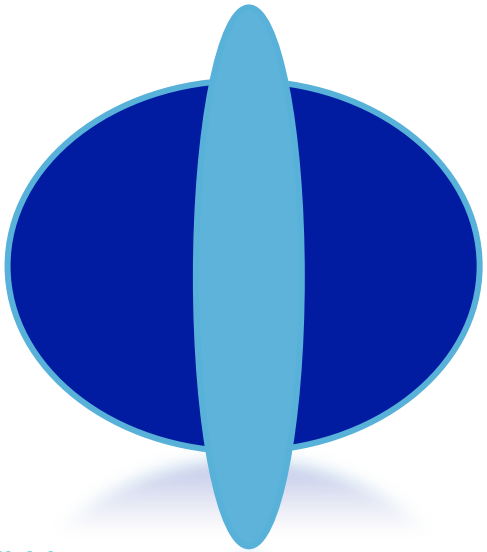
DISTANT OBSERVER

EVEN MULTIPOLES

STANDARD RSD

KAISER EFFECT-LARGE SCALE

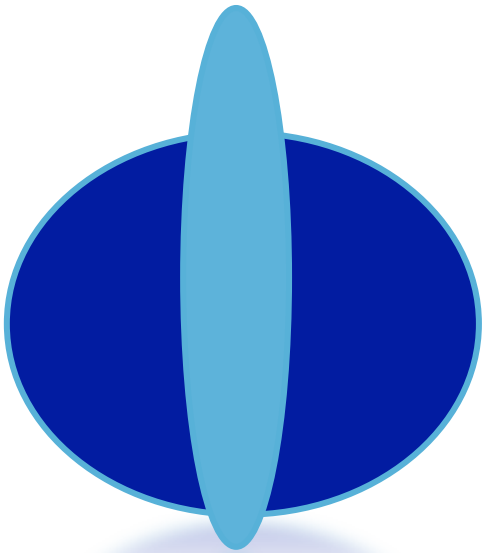
FINGERS OF GOD-SMALL SCALE



DISTANT OBSERVER

DIPOLE

GRAVITATIONAL POTENTIAL



DISTANT OBSERVER

RELATIVISTIC RSD

Some references (non exhaustive)

- Yoo et al, 2010; Bonvin&Durrer 2011; Yoo 2011; Lewis&Challinor 2011
=> LARGE SCALE – LINEAR – ANALYTICAL - CORRELATION - EVEN MULTIPOLES

- Bonvin et al, 2014
=> LARGE SCALE – LINEAR – ANALYTICAL – ODD MULTIPOLES

- Croft 2013
=> INTERMEDIATE SCALE– HALO MODEL– ANALYTICAL & DISTANT OBSERVER – SHELL ESTIMATOR

- Cai et al, 2017
=> GALAXY CLUSTER SCALE AND AROUND– NON LINEAR & DISTANT OBSERVER– SIMULATION – SHIFT

- Cappi 1995; Kaiser 2013; Zhao et al 2013
=> GALAXY CLUSTER SCALE– STATIC&SPHERICAL– ANALYTICAL – SHIFT

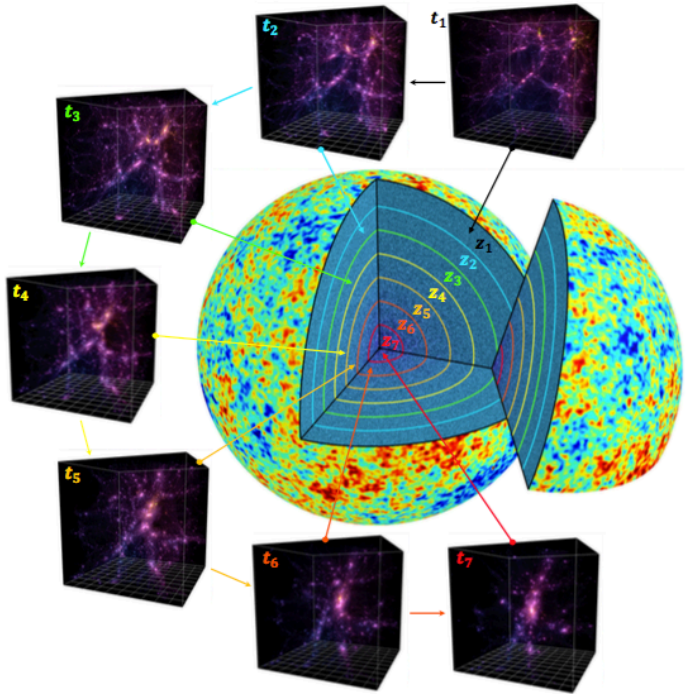
- Wojtak et al, 2011
=> GALAXY CLUSTER– GRAVITATIONAL Z CLAIMED DETECTION–OBSERVATION– SHIFT

HOW TO CREATE A GENERAL THEORETICAL FRAMEWORK VALID AT ALL SCALES?

RayGalGroupSims
(Raytracing Galaxy Group Simulations)

- **Characteristics**
  - LCDM-W7 cosmology (other cosmologies on-going)
  - Size: **2.6 Gpc/h**. Resolution: 5 kpc/h
  - Number of particles**: 4096^3** . Number of cells: 0.4 trillion
  - Code: RAMSES (Teyssier 2002)
  - Method: PM-AMR (Adaptive Mesh Refinement)

ONION SHELL APPROACH



- **Light-cone**
  - Onion-shell method (high time resolution)
  - AMR cells (high spatial resolution)
  - DM Particles
  - Halos (pFoF b=0.2, Roy et al, 2014)
  - **Gravity !**

DIRECT INTEGRATION OF GEODESICS EQUATIONS IN PERTURBED FLRW WITHIN AMR GRID

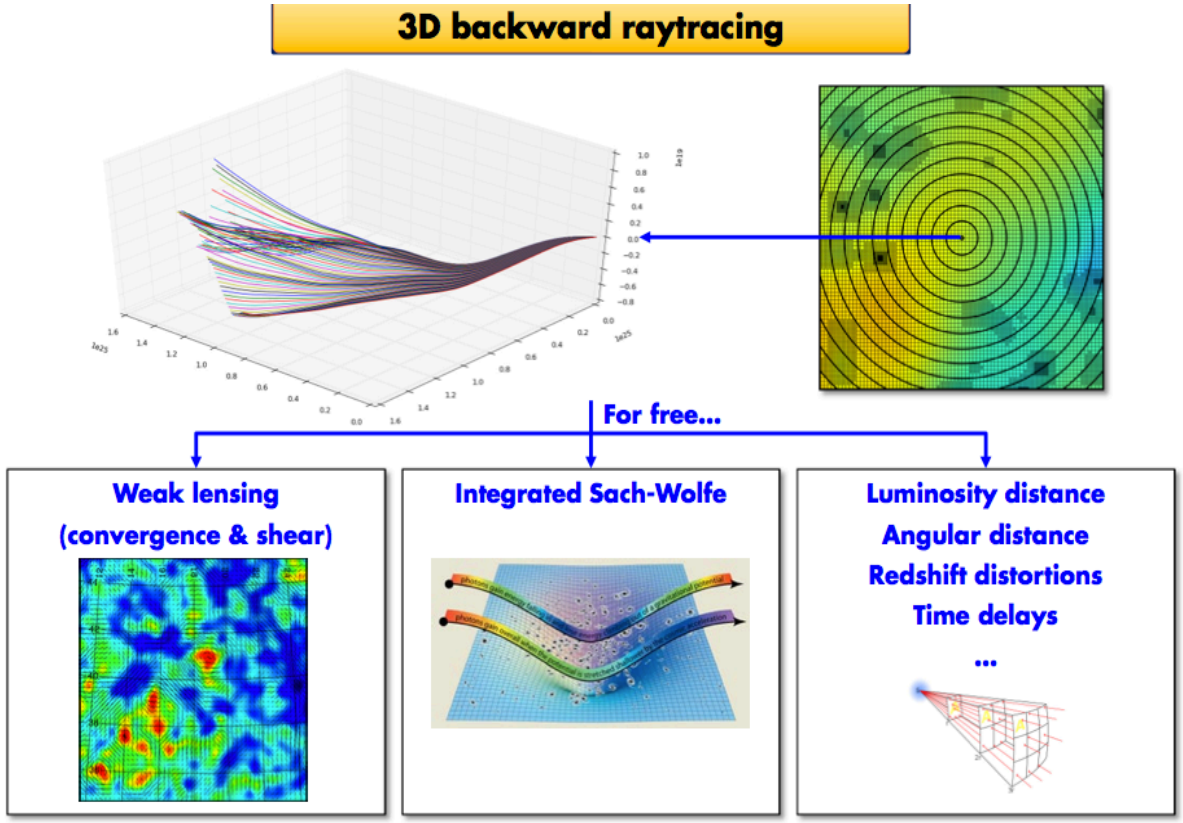
- Geodesic equations:

$$\frac{\mathrm{d}^2 x^\alpha}{\mathrm{d}\lambda^2} = -\Gamma^\alpha_{\beta\gamma} \frac{\mathrm{d}x^\beta}{\mathrm{d}\lambda} \frac{\mathrm{d}x^\gamma}{\mathrm{d}\lambda}$$

- Redshift definition:

$$1 + z = \frac{\nu_s}{\nu_o} = \frac{(g_{\mu\nu} k^\mu k^\nu)_s}{(g_{\mu\nu} k^\mu k^\nu)_o}$$

- MAGRATHEA library (V.Reverdy, M-A Breton, J.Adamek)



- SELF CONSISTENT CALCULATION OF WEAK LENSING **AND** REDSHIFT SPACE DISTORTIONS **AND** OTHER RELATIVISTIC TERMS

- LITTLE NUMBER OF CONTROLED ASSUMPTIONS

ITERATIVE ROOT FINDER AND RAYGALGROUPSIMS HALO CATALOG

Find null geodesics

Find the connection between Observer O and Source S
Using Newton's method :

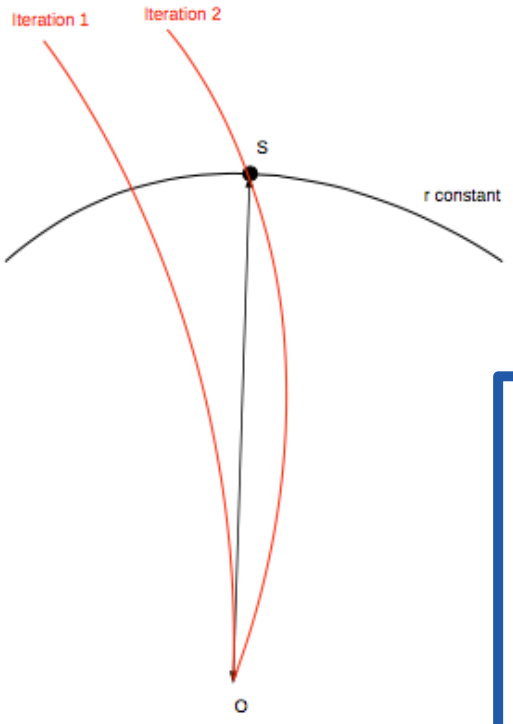
$x = (x_1, ..., x_n)$

$x_{k+1} = x_k - F(x_k)/F'(x_k)$

Output

« NEW » : Catalogs of sources taking into account weak lensing effects and redshift space distortions
In the catalogs :

$\vec{\beta}$, $\vec{\theta}$, $\bar{z}$, z, errors, A_{ij}



Breton et al, 2018

10 millions halos with relativistic effects between 10^{12}Msun and 10^{14}Msun Full-sky Z<0.5 (higher z soon)

YOU CAN DOWLOAD IT
(JUST TYPE **RAYGALGROUPSIMS** ON YOUR FAVORITE SEARCH ENGINE)
VERY SIMPLE: ASCII FILES + README

Apparent distribution of sources: redshift space distortions with the relativistic terms

- **APPARENT POSITION SOURCE: we have access to direction $\vec{\beta}$ and redshift z_O**
- **POSITION INTERPRETED ASSUMING HOMOGENEOUS FLRW (ex: dr≈c dz/H if no lens)**
- **REDSHIFT AND ANGLE MODIFICATIONS**

$$z_O = \frac{a_O}{a_S}\left(1 + \frac{\vec{v_S}.\vec{n}}{c} - \frac{\phi_S - \phi_O}{c^2} + \frac{v_S^2}{2c^2} - 2\int_{\eta_S}^{\eta_O} \frac{\dot{\phi}}{c^2} d\eta\right) - 1$$

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

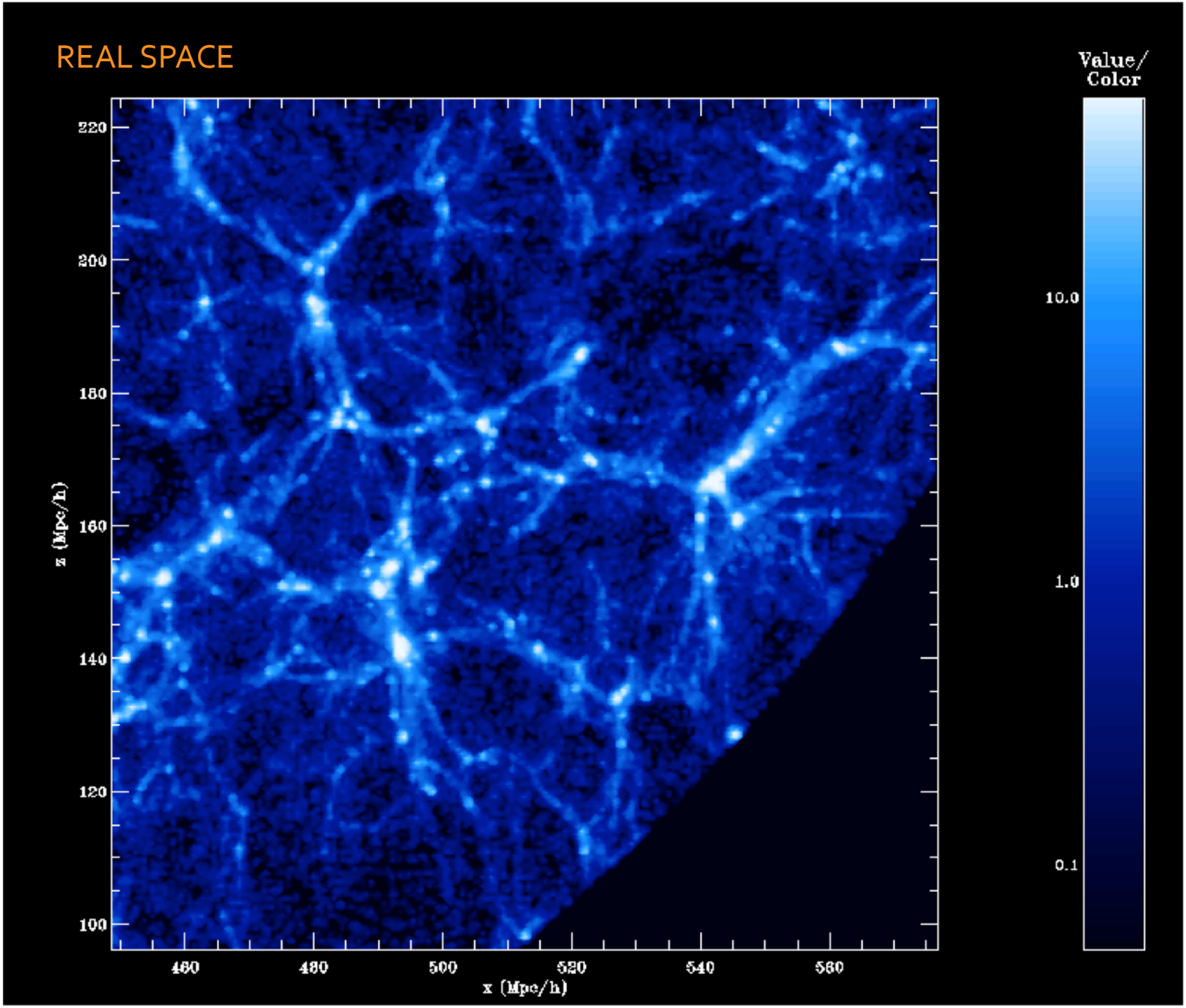
HOMOGENEOUS | RSD | GRAVITATIONAL REDSHIFT | TRANSVERSE DOPPLER | INTEGRATED TERMS: ISW & LENSING

- **OBSERVED DENSITY IS GIVEN BY (NON-LINEAR MAPPING)**

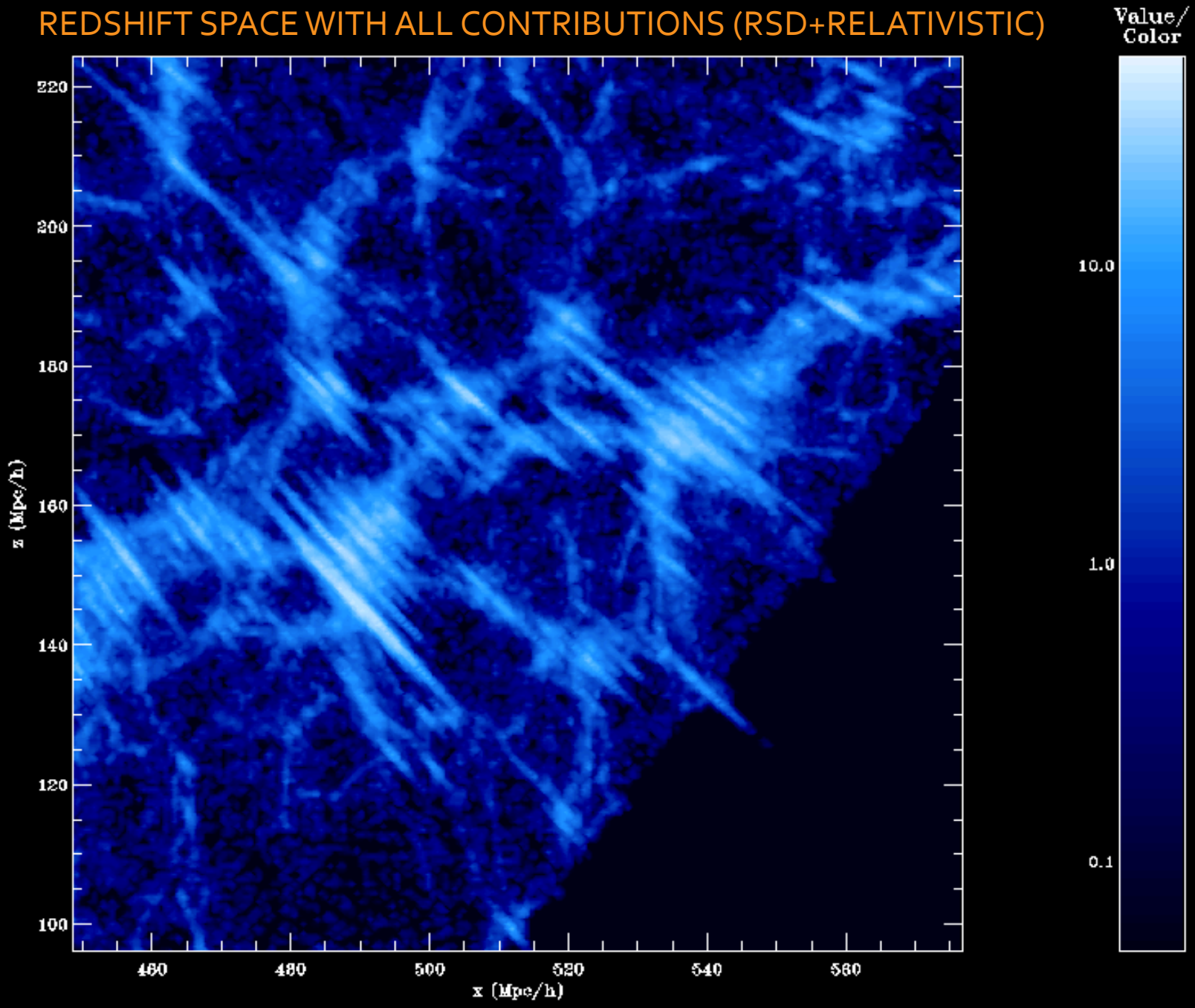
$$(1 + \delta_{obs}) dV_{obs} = (1 + \delta_{real}) dV_{real}$$

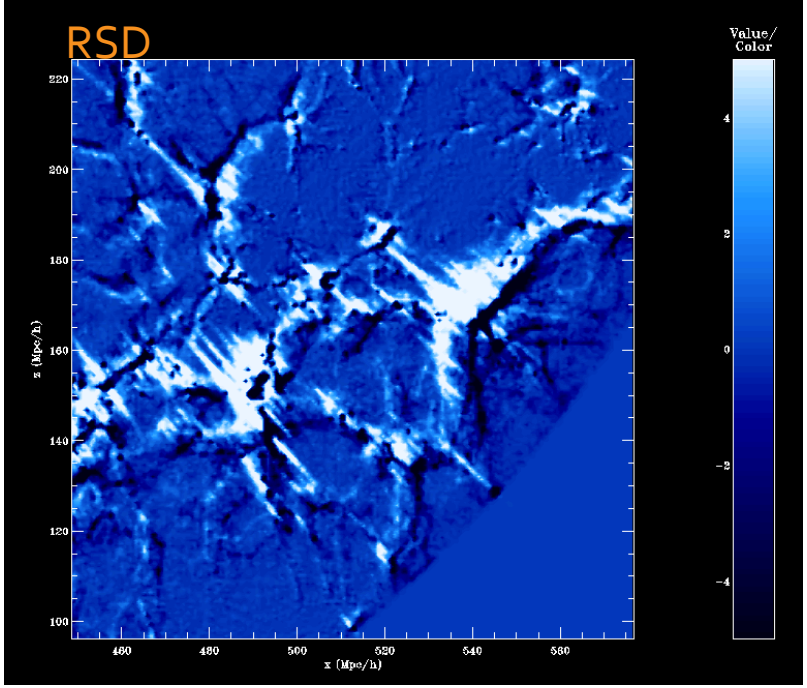
- **NEEDS VERY ACCURATE REDSHIFT: COMBINATION OF DEEP ACCURATE SPECTRO MEASUREMENT AND LARGE SURVEYS!**

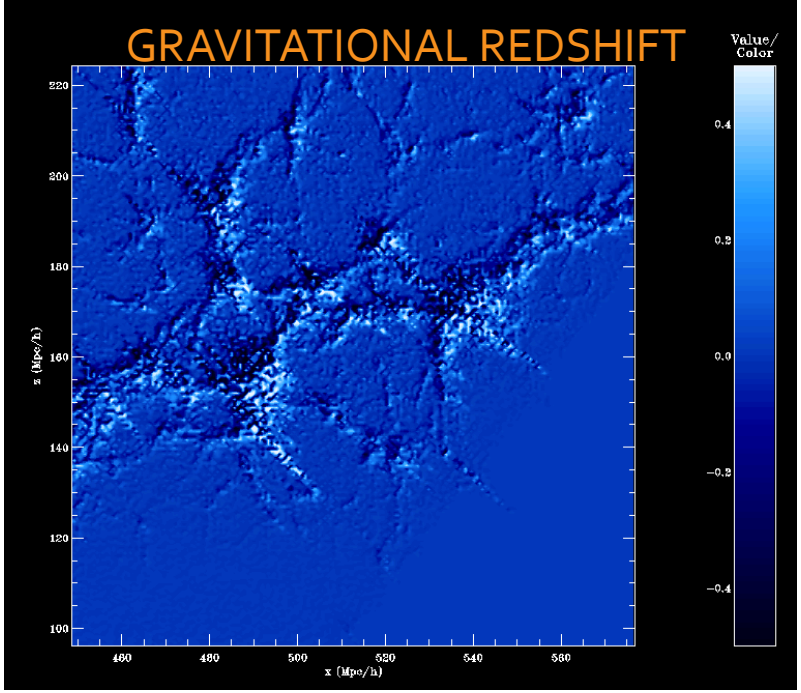
REAL SPACE

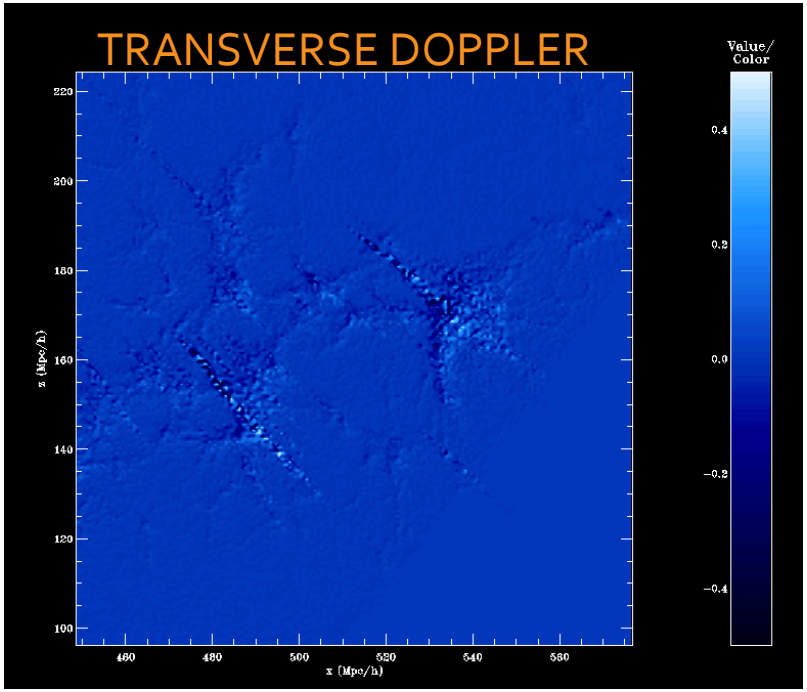

Value/
Color
10.0
1.0
0.1
220
200
180
160
140
120
100
z (Mpc/h)
460
480
500
520
540
560
x (Mpc/h)

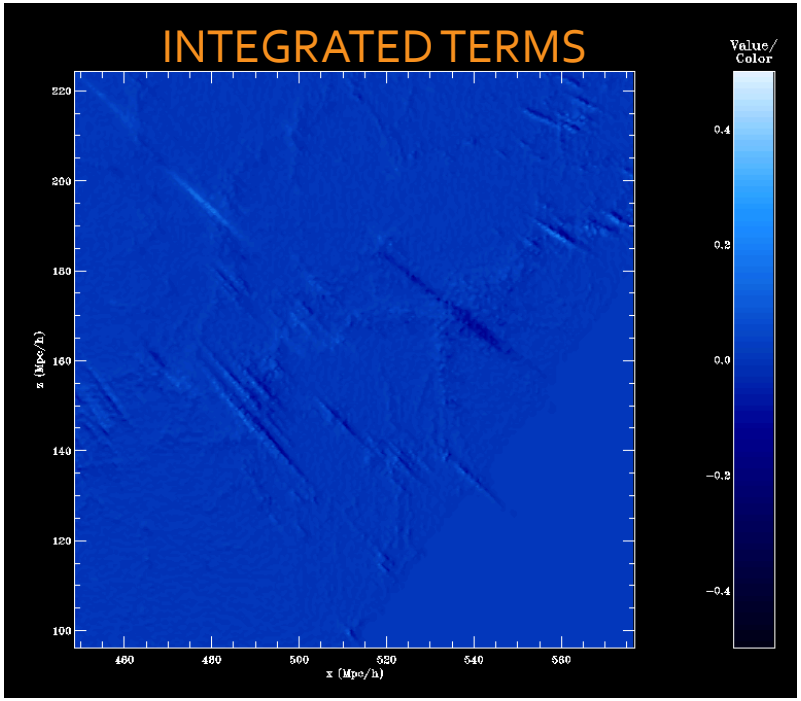
REDSHIFT SPACE WITH ALL CONTRIBUTIONS (RSD+RELATIVISTIC)




RSD
Value/
Color
z (Mpc/h)
x (Mpc/h)


GRAVITATIONAL REDSHIFT
Value/
Color
z (Mpc/h)
x (Mpc/h)


TRANSVERSE DOPPLER
Value/
Color
z (Mpc/h)
x (Mpc/h)

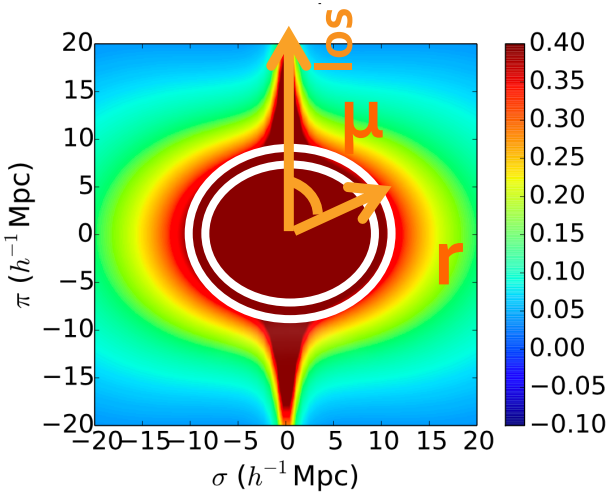

INTEGRATED TERMS
Value/
Color
z (Mpc/h)
x (Mpc/h)

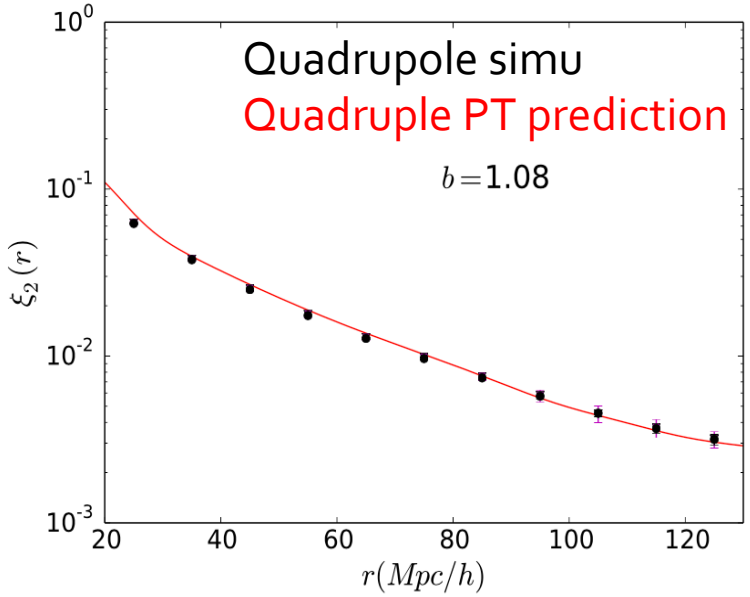
Dipole of halo-halo cross-correlation

- Multipole

  $\xi_l(r) = < \delta_1(\mathbf{x})\, \delta_2(\mathbf{x}+\mathbf{r})\, P_l(\mu) >$

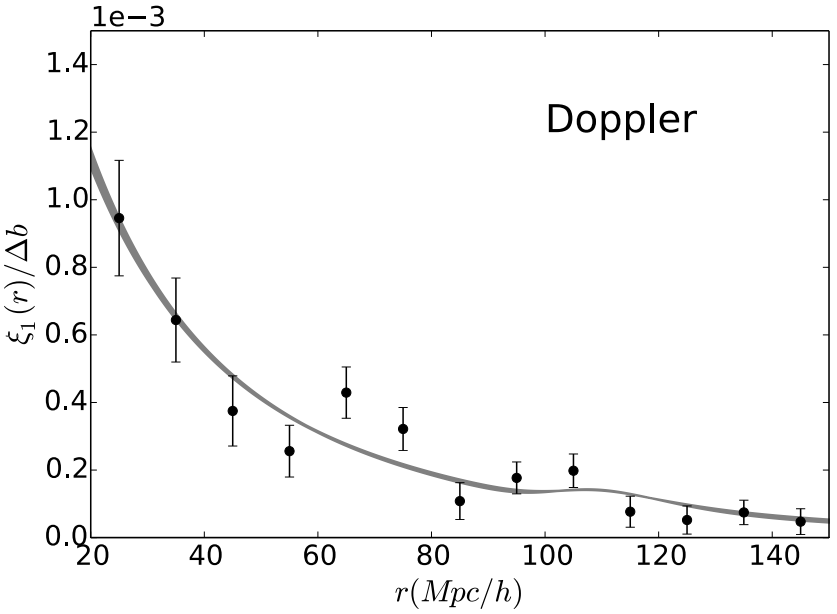
- Monopole: l=0 => density
- Quadrupole: l=2 => velocity
- Dipole: l=1 => relativistic effects

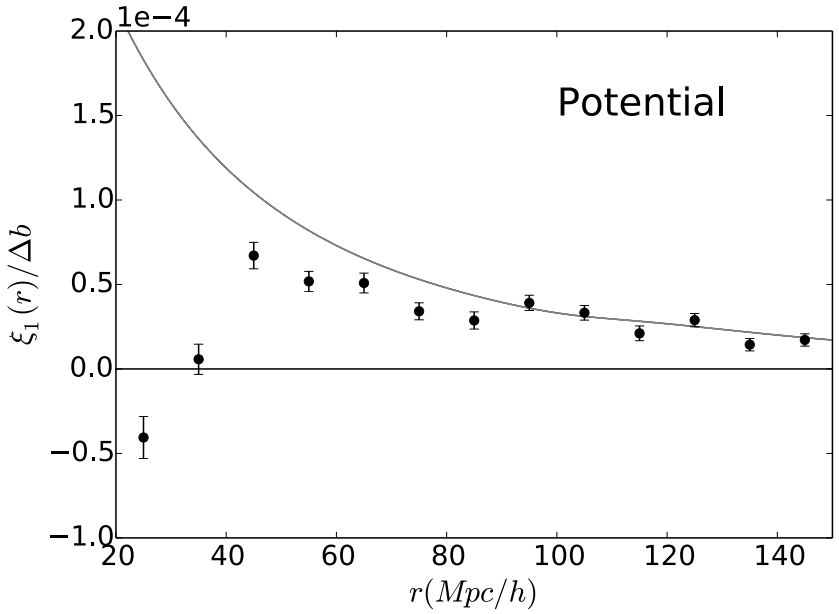




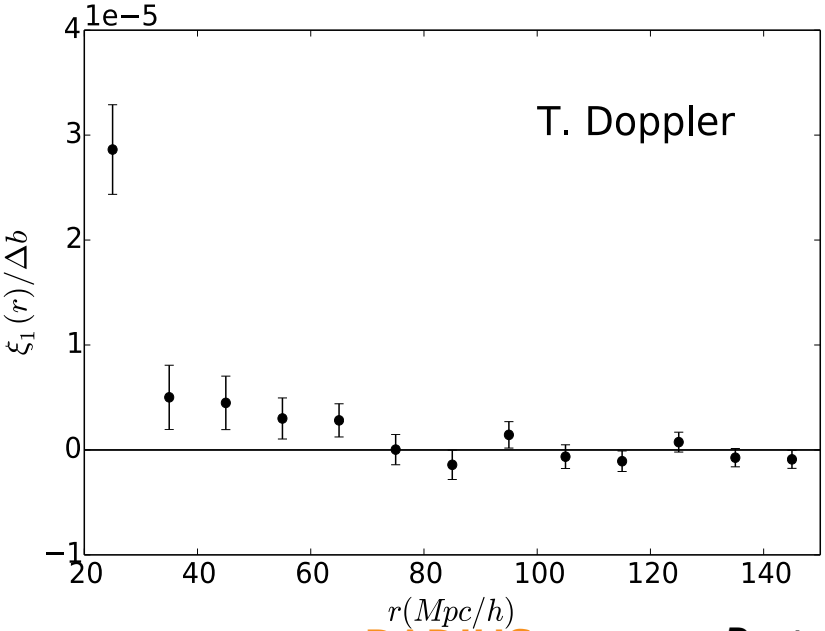
LARGE SCALES (20-150 Mpc/h): SIMU (POINTS) VS LINEAR (LINES)

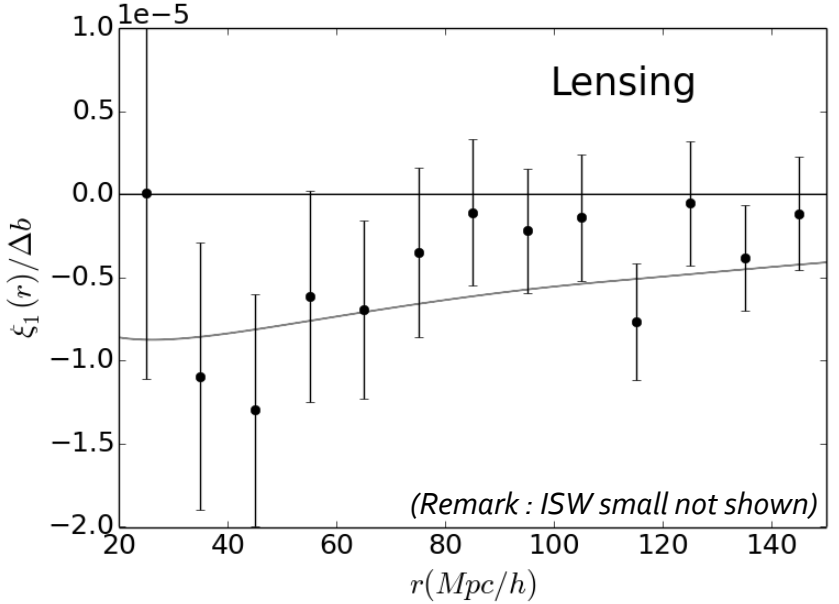
DIPOLE





DIPOLE



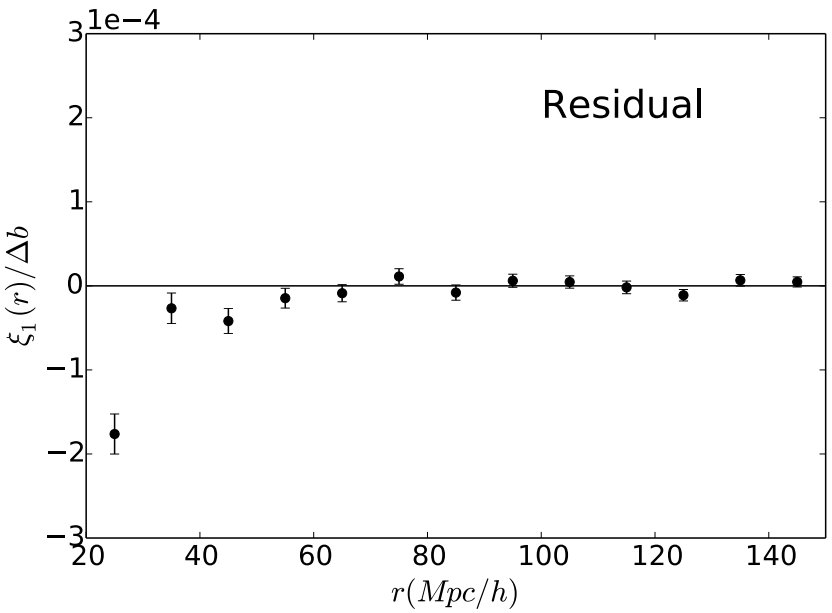


RADIUS

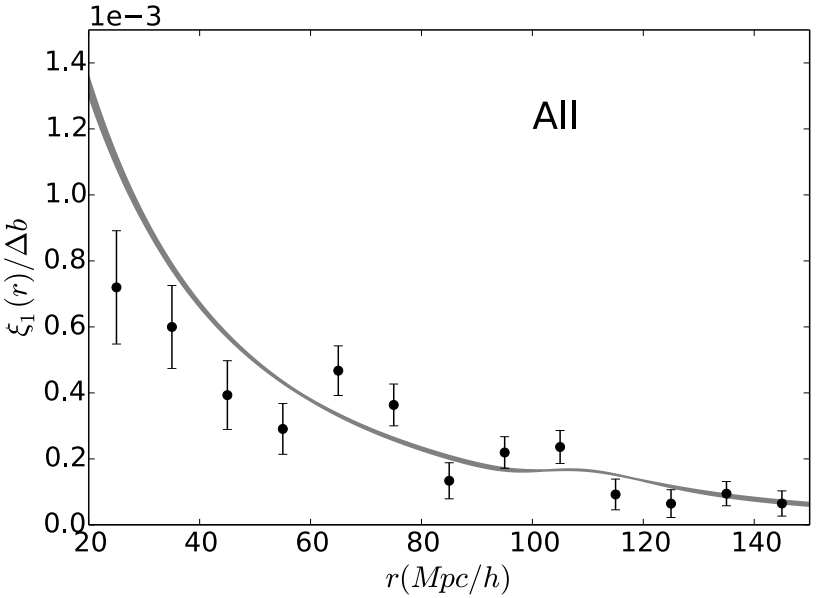
Breton et al, 2018

RADIUS

DIPOLE



RADIUS

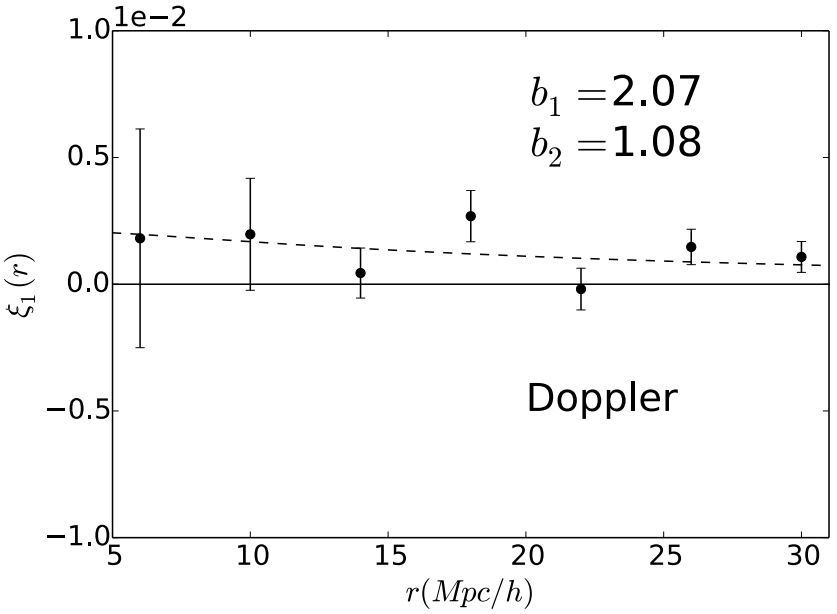


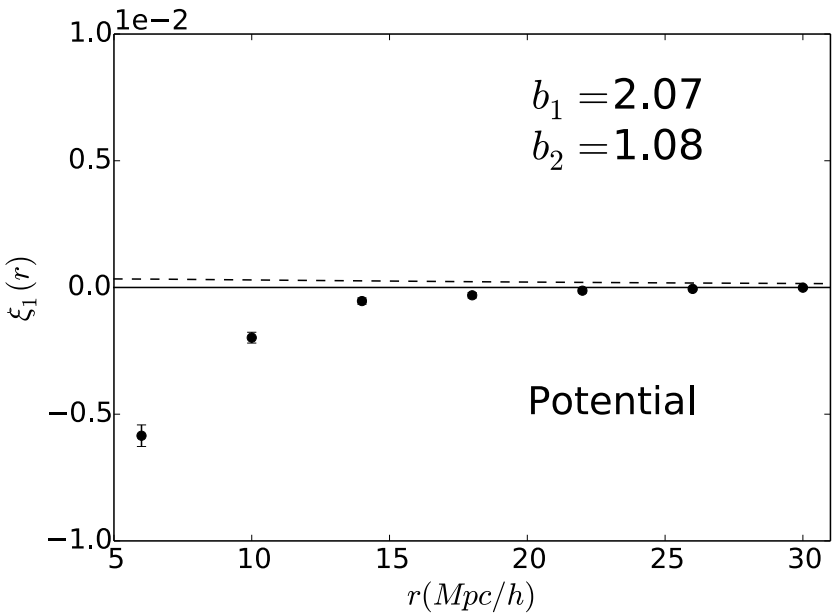
RADIUS

- We can measure and decompose these effects in simu with 10 millions halos
- Match linear prediction at large linear scale
- Doppler contribution dominates: WARNING not standard, related to the divergence of line of sight
- Deviation from linear theory near 30 Mpc/h.
- Residuals=> non-linear mapping between real and redshift space+ cross-terms

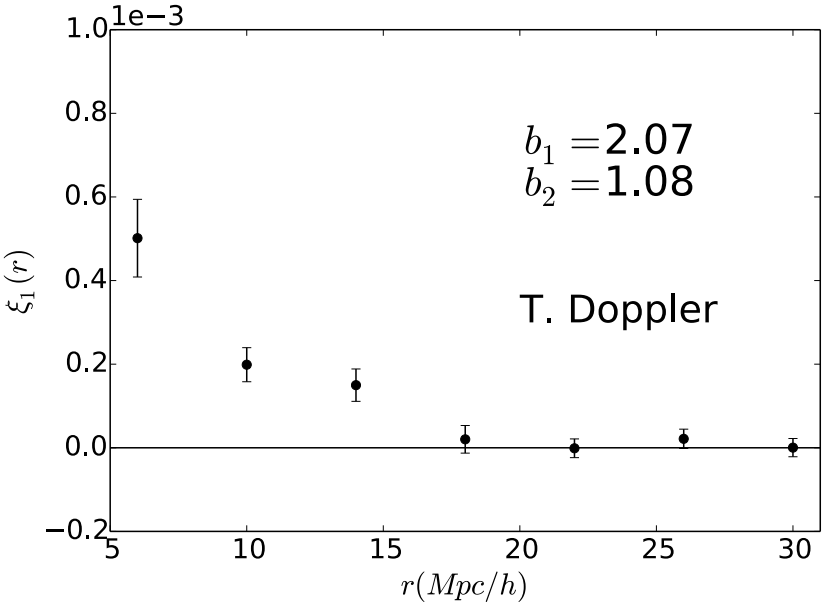
SMALL SCALES (5-30 Mpc/h): SIMU (POINTS) VS LINEAR (DASHED LINES)

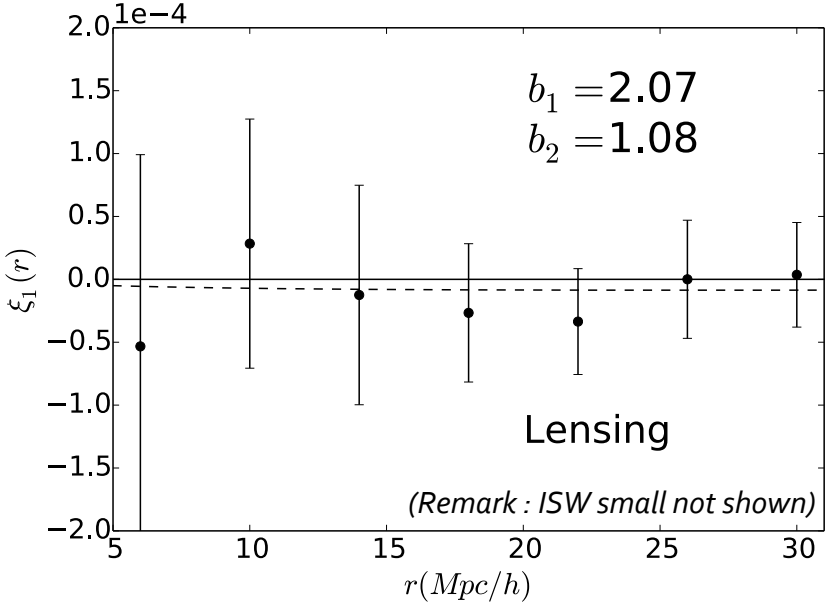
DIPOLE





DIPOLE



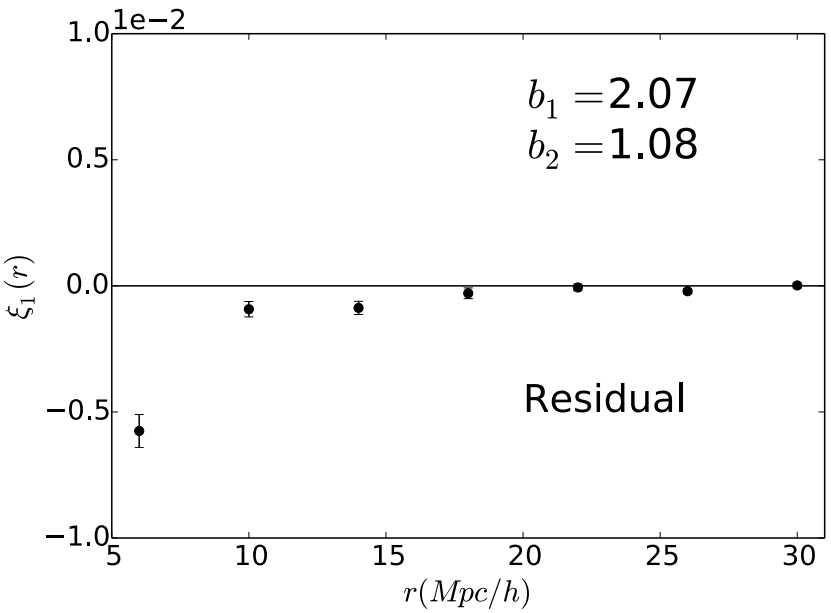


RADIUS

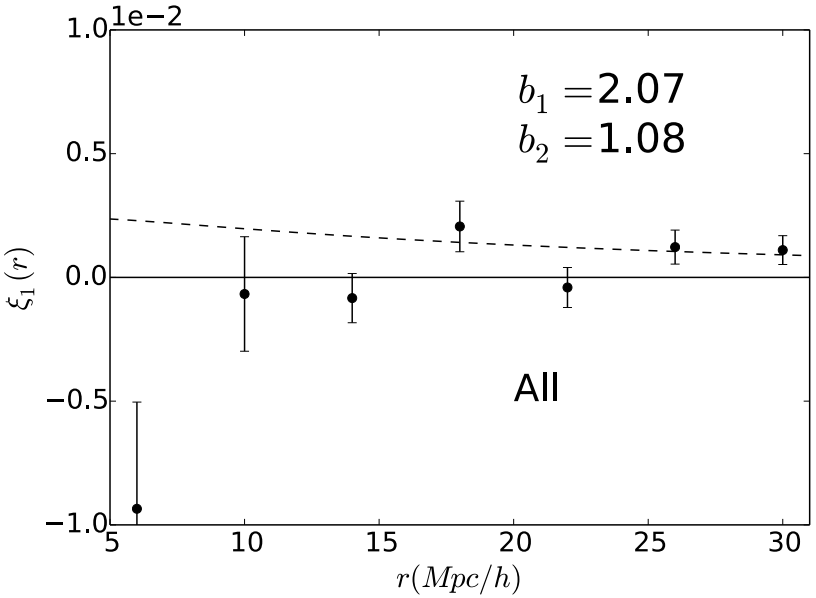
Breton et al, 2018

RADIUS

DIPOLE



RADIUS



RADIUS

- Strong deviations with linear predictions
- Below 10 Mpc/h the potential dominates the signal!
- Residuals are important: new contribution from velocity and potential together
- Error bars can be decreased by considering smaller halo mass (for the faint population).

CONCLUSION

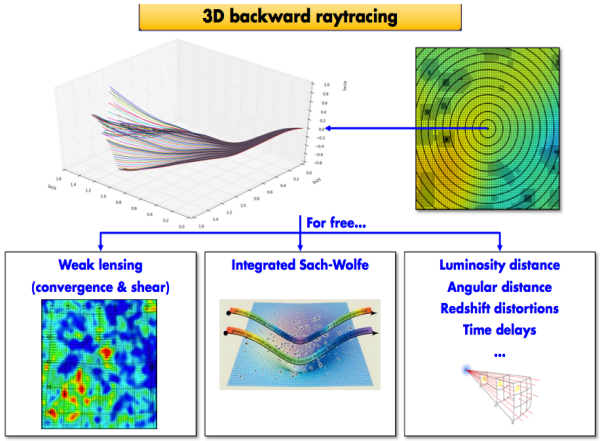
•Search for new probes of dark sector=> Can we directly measure the potential to test all our hypothesis?

• Goal: Test of the dipole of the halo-halo cross-correlation => need to model all relativistic effect (i.e. like for CMB but in non-linear regime)

•Relativistic effects and the mapping from real space to redshift space
- For the first time all the effects are modeled accurately at first order in weak field
- The most important contribution after RSD is the gravitational potential at low redshift

•Requirement: need very accurate spectro-redshift

•Very general approach, many extensions:
- Higher redshift. Exemple: Lyman-α (Irsic et al, 2015)
- Gpc scale: gauge effect
- Smaller scale: baryons, strong lensing
- Other possible applications: doppler lensing, ISW, fluctuations of distances, observational effects on dipole…



•PUBLIC DATA
- Don't hesitate to download the RAYGALGROUPSIMS relativistic halo catalog to make your own test
- Very simple ASCII files with angular position, redshift and distortion matrix
- More data soon (deeper light-cone, healpix map, rays, etc)

THANK YOU FOR YOUR ATTENTION