A quick introduction to the RayGal data for the investigation of relativistic effects

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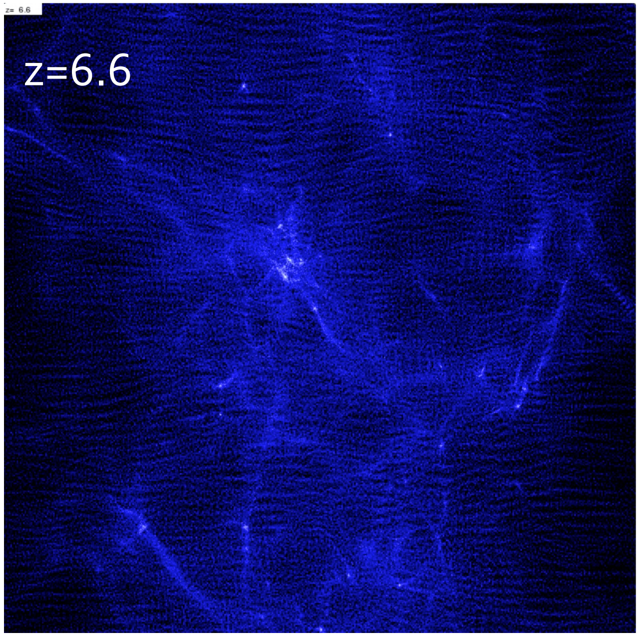
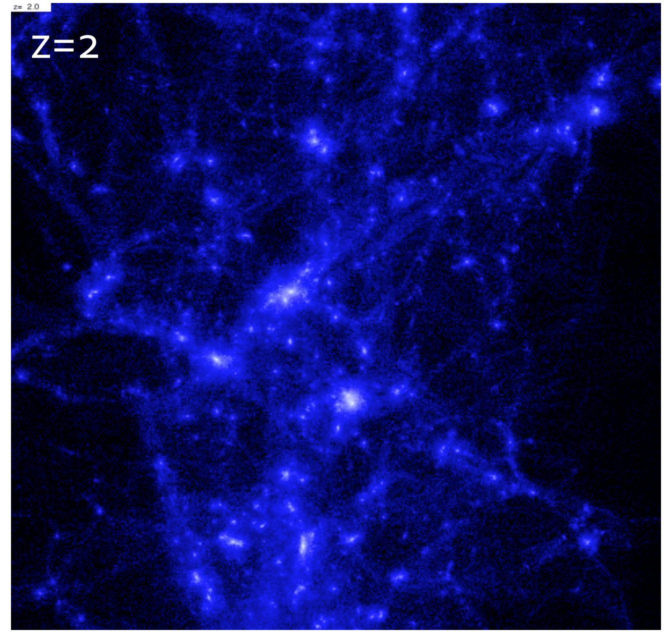
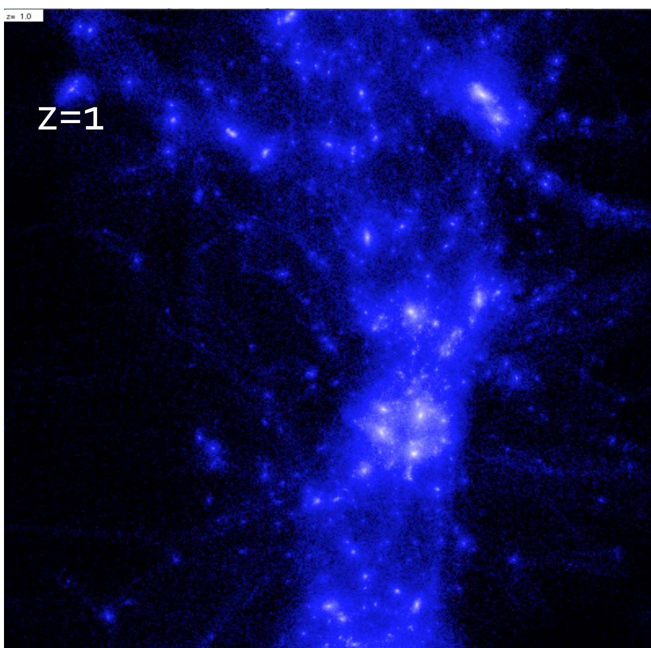
Atelier Outils 2023

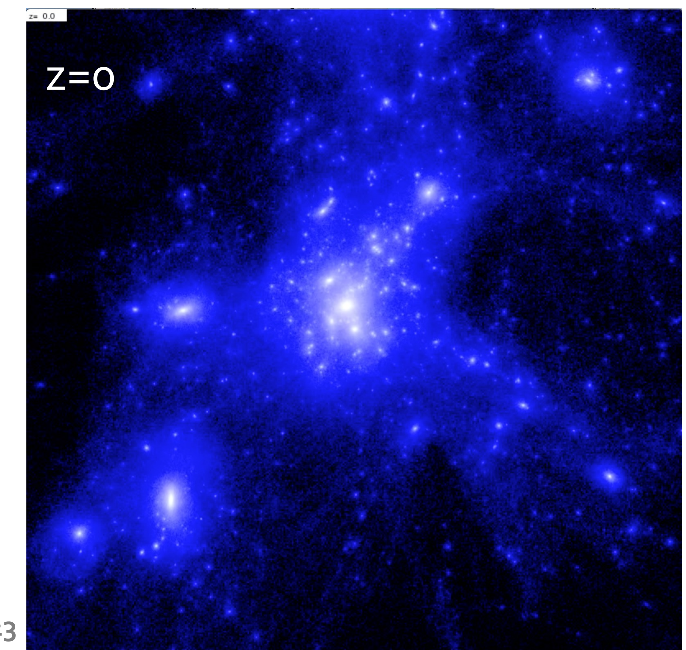
LUTH

STEP 1 : RUN simulations (see Wednesday morning hands on) : 2 very large ones (4096^3)



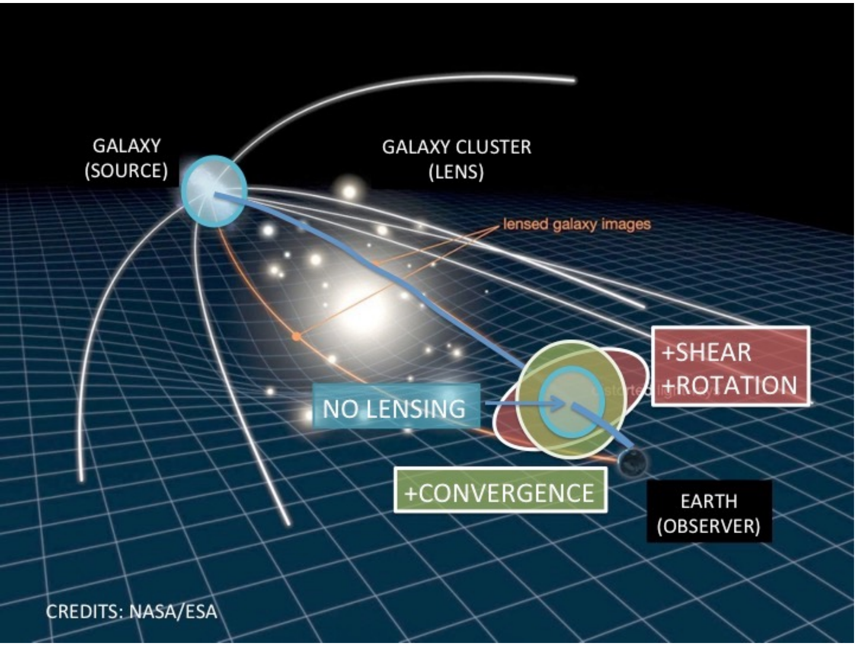






Step 2-> compute WL or RSD (usual way)

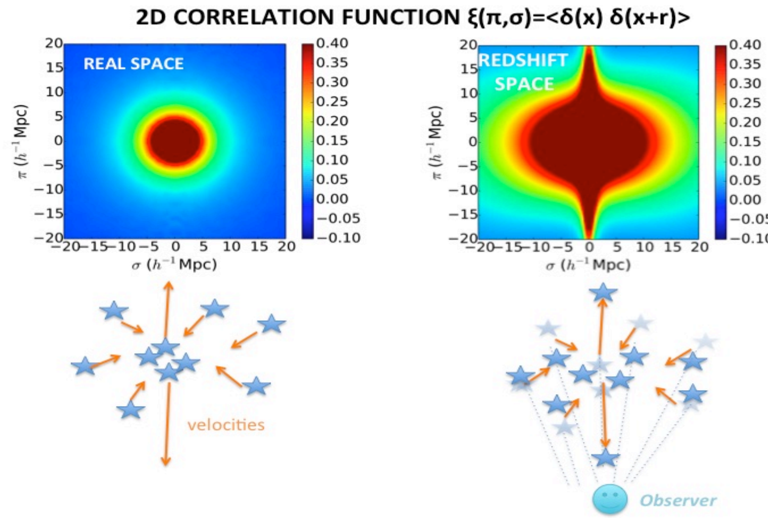
LENSING



Many approximations-> Example of approximations: no-RSD, flat sky, Born, multiple-lens, replications

OR

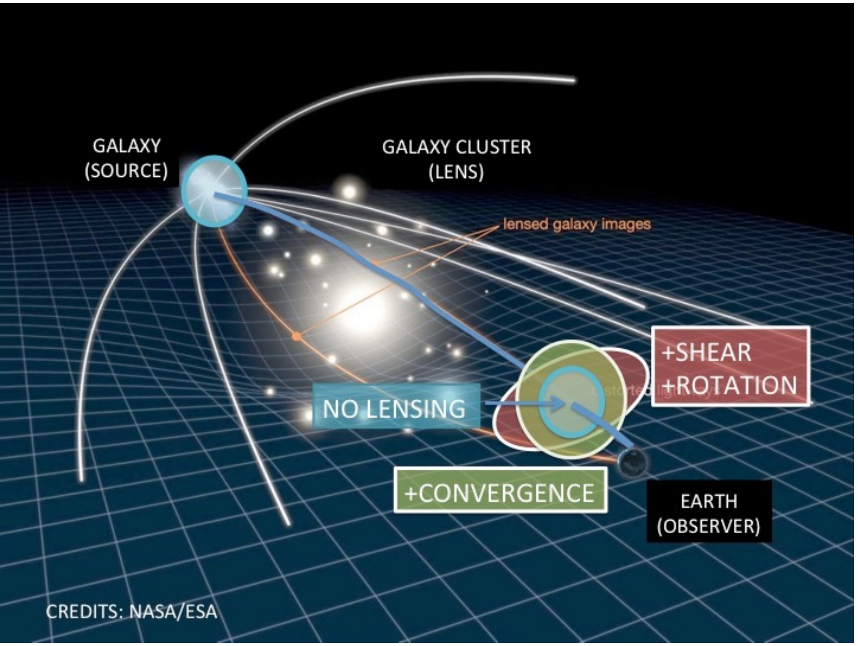
Redshift-Space Distortions (RSD)



Many approximations-> Example of approximations: no-lensing, distant observer, no gravitational redshift (i.e. Doppler only), no light-cone effect

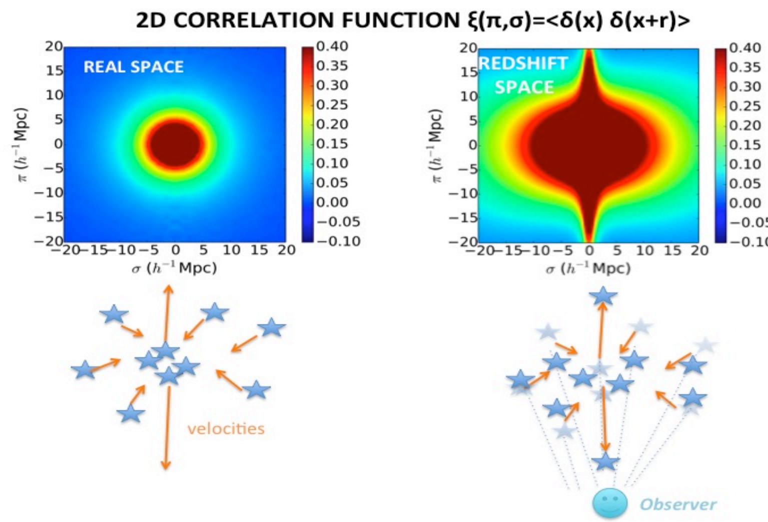
Step 2 ->RayGal way: (Weak-Field) Relativistic approach

LENSING



AND

Redshift-Space Distortions (RSD)



AND OTHERS (gravitational redshift, ISW effect, transverse Doppler, etc)

- Relativistic approach at large scales: Yoo+ 2010; Bonvin&Durrer 2011; Yoo 2011; Lewis&Challinor 2011

=>Mostly uses **the same formalism as for CMB** (i.e. weak field GR) but applied to galaxies (Example of implementation CLASSgal within CLASS Di Dio et al, 2013)

⇒ LIMITATION OF ORIGINAL WORKS: **LINEAR** REGIME

- Relativistic approach at cluster scale and around: Kaiser2013, Zhao2013, Croft2013, Cai+2017

=> LIMITATION: How to connect with linear predictions ?

PROPOSAL: DIRECT INTEGRATION OF GEODESICS EQUATIONS IN PERTURBED FLRW WITHIN AMR GRID

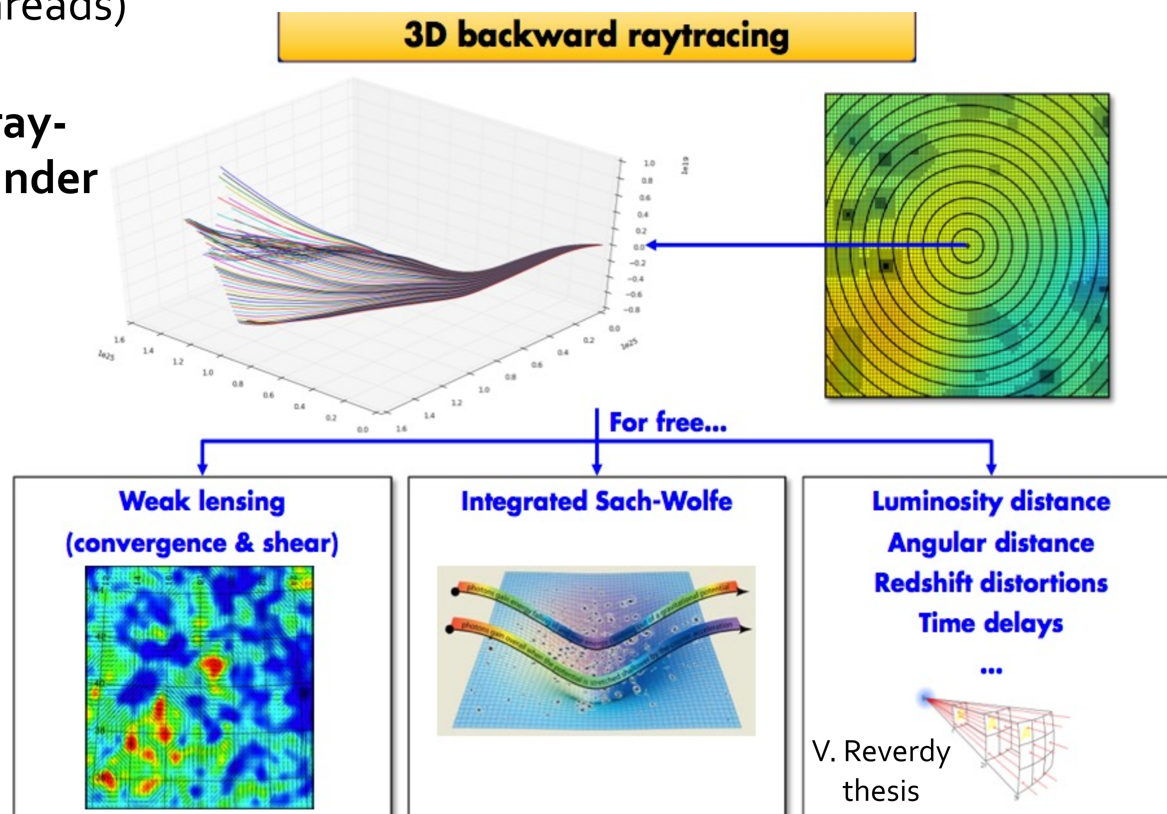
- Geodesic equations:

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

- 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 (Reverdy 2014): optimized/light AMR (MPI+p-threads)
- **MAGRATHEA-PATHFINDER: ray-tracing, WL, RSD, geodesics finder (Breton&Reverdy, 2021)**
- SELF CONSISTENT CALCULATION OF WEAK LENSING **AND** REDSHIFT SPACE DISTORTIONS **AND** OTHER RELATIVISTIC TERMS
- LITTLE NUMBER OF CONTROLED ASSUMPTIONS

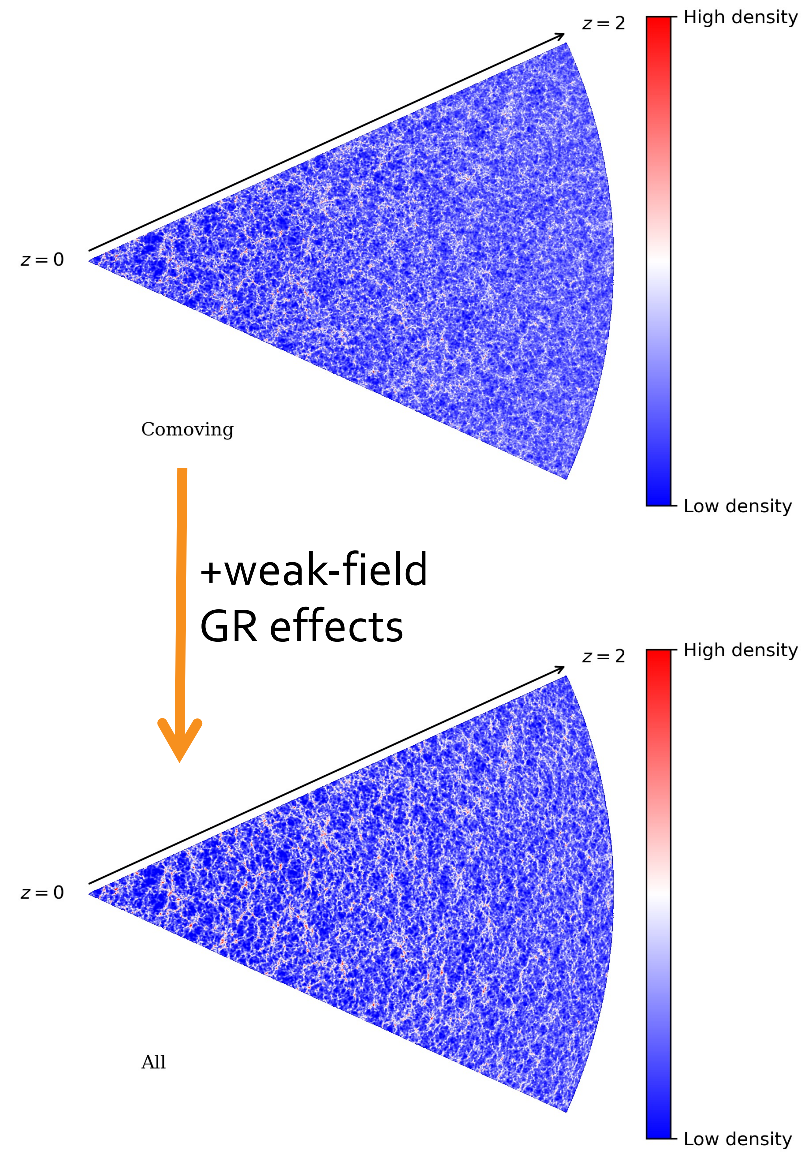


RayGal simulation suite with General Relativistic Ray-Tracing

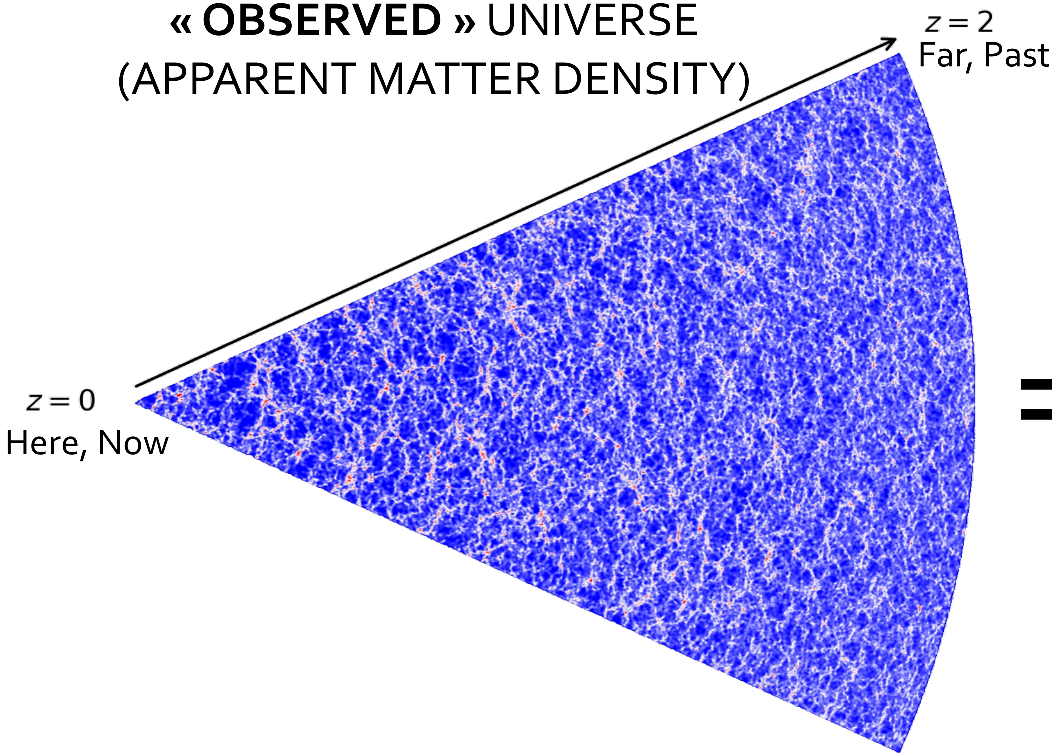
Breton et al. 2019; Rasera et al. 2021

Weak-field GR approach from linear to non-linear scales…

- **Large and well resolved HPC N-body simulations** (4096^3 part. L=2.625 Gpc/h)
- Standard cosmology (w=-1) + **alternative dark energy model** (w=-1.2)
- **Ray-tracing** including all **general relativistic effects** in the weak field regime at high-resolution
- **Billion light-rays** launched
- For the first time, **identification of light rays going exactly from the source to the observer.**
- Unique **halos catalogues including beyond state-of-the-art weak-lensing and redshift space distortions** (Doppler effect, gravitational redshift, weak-lensing, ISW).



SIMULATION
OF A SLICE OF THE
« **OBSERVED** » UNIVERSE
(APPARENT MATTER DENSITY)



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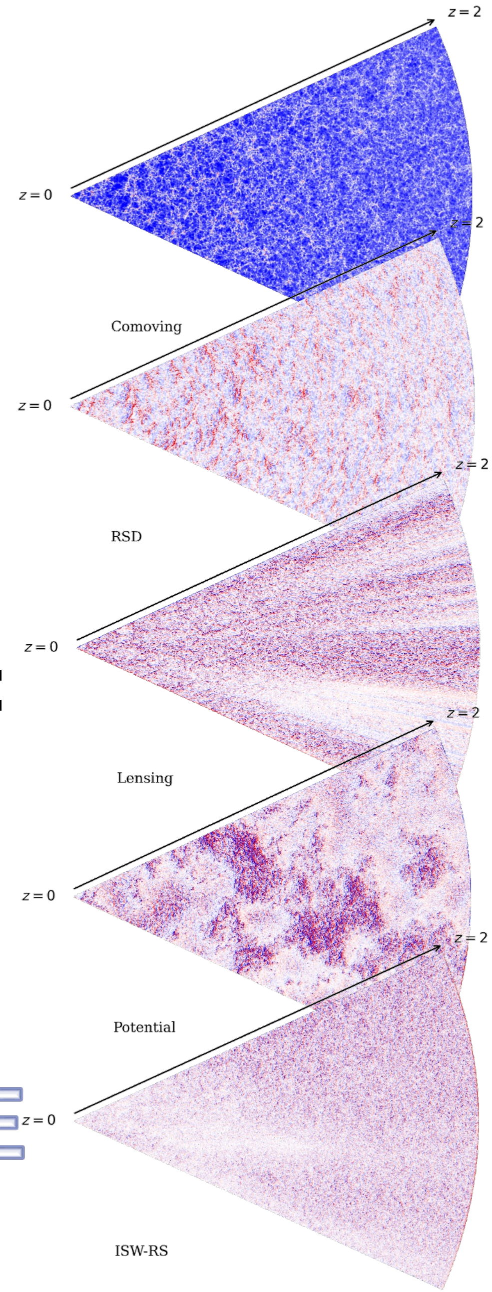


« TRUE »
UNIVERSE
+
DOPPLER
EFFECT
+
WEAK
LENSING
+
GRAVITATIONAL
REDSHIFT
+
INTEGRATED
SACHS WOLFE
EFFECT

THE RAYGAL UNIVERSE

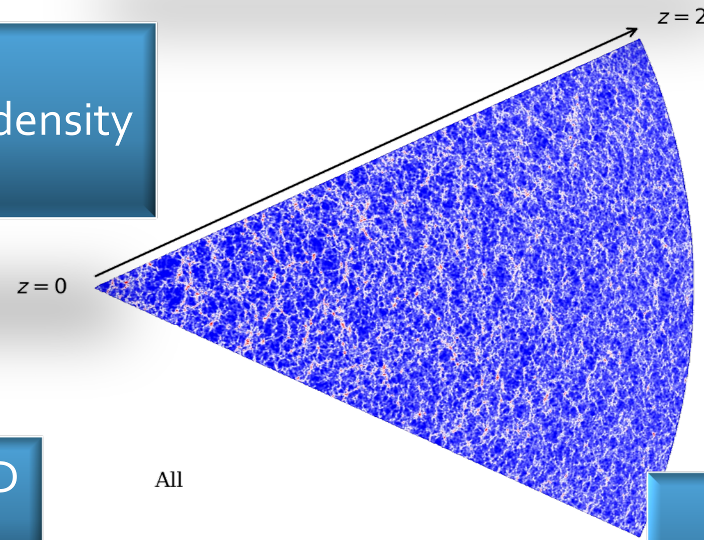
70 billion particles ⇨ cosmic structure formation
1 billion photons ⇨ general relativistic effects

https://cosmo.obspm.fr/public-datasets/
(or type « **RayGal data** » on any search engine)

Very generic, built from 1st principles=> many applications

Bias of distance-redshift relation
Breton&Fleury, 2021

3x2pts in WL
Convergence-matter overdensity
Rasera et al. 2022



Dipole in RSD
Breton et al. 2019
Taruya et al. 2020
Saga et al. 2020, 2021

Magnification bias in RSD
Breton et al. 2022

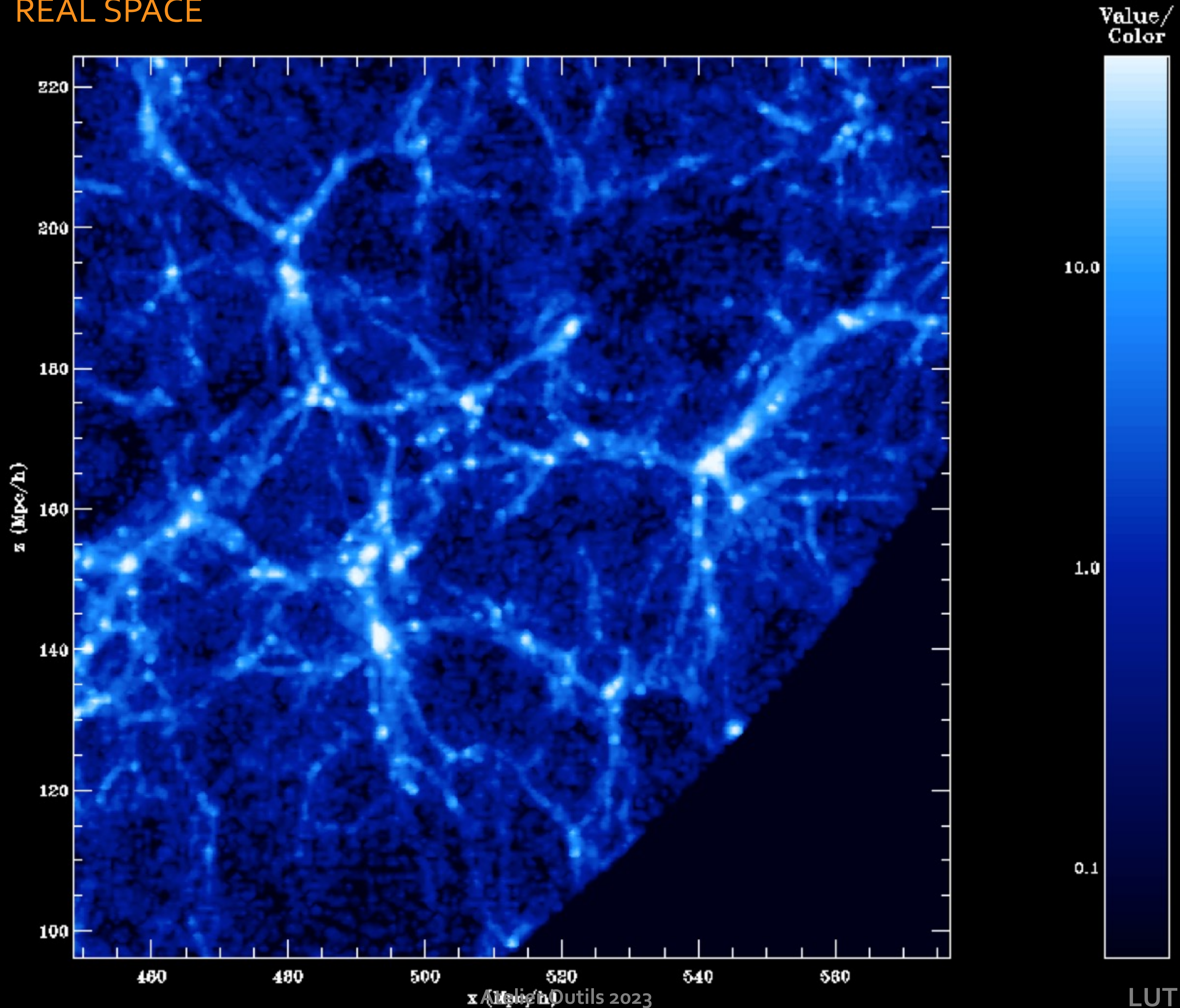
Gravitational redshift or WL in clusters

CMB-galaxies cross-correlations

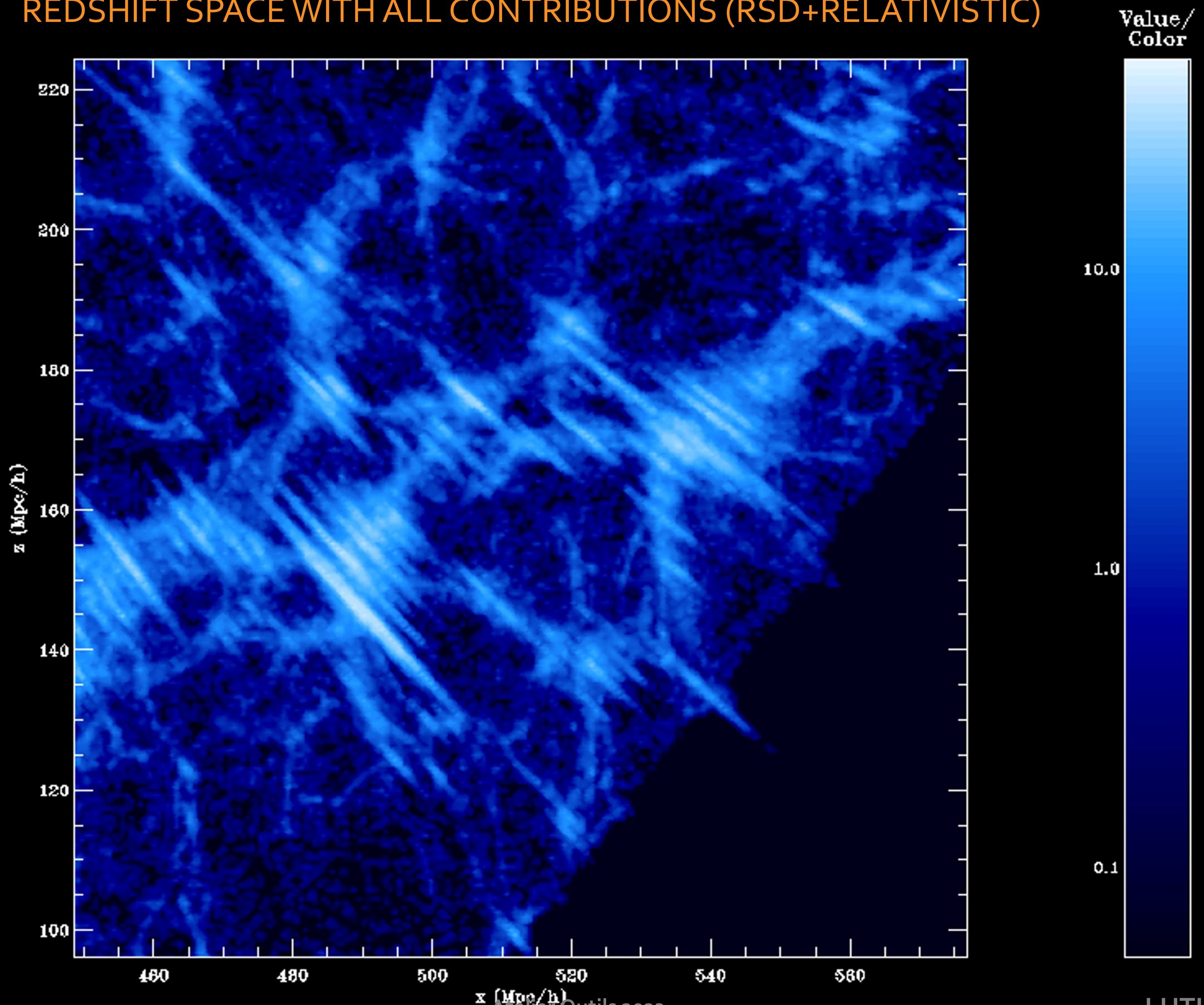
I am pretty sure you have an idea : the (cross-)correlation of (several) cosmological observables!

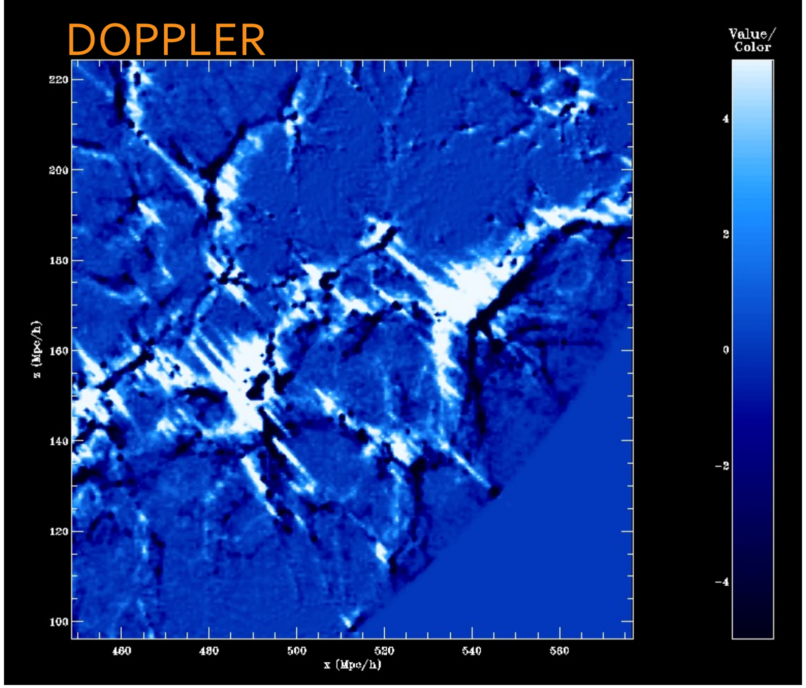
Example of application: Relativistic Redshift Space Distortions

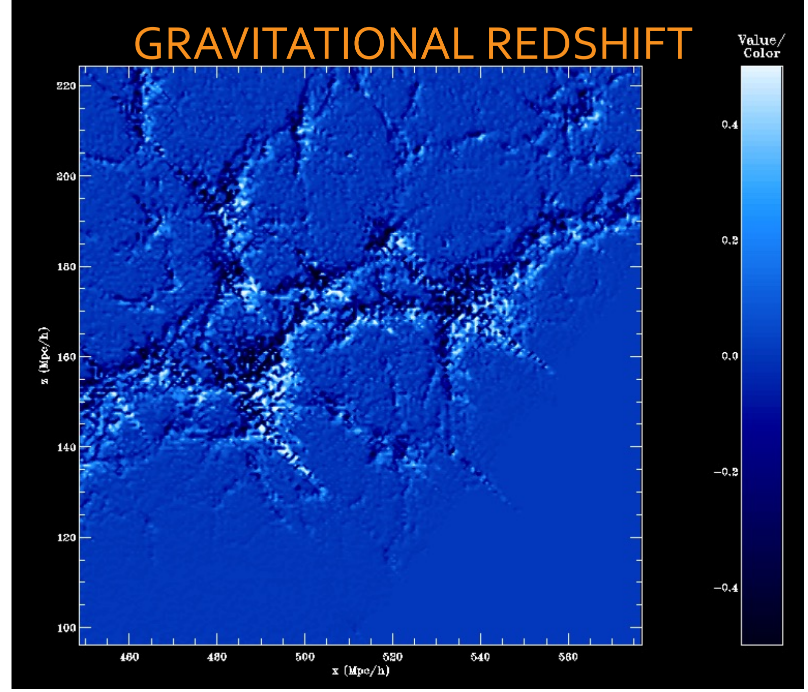
REAL SPACE


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

REDSHIFT SPACE WITH ALL CONTRIBUTIONS (RSD+RELATIVISTIC)




DOPPLER
Value/
Color
4
2
0
-2
-4
220
200
180
160
140
120
100
z (Mpc/h)
460
480
500
520
540
560
x (Mpc/h)


GRAVITATIONAL REDSHIFT
Value/
Color
0.4
0.2
0.0
-0.2
-0.4
220
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z (Mpc/h)
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480
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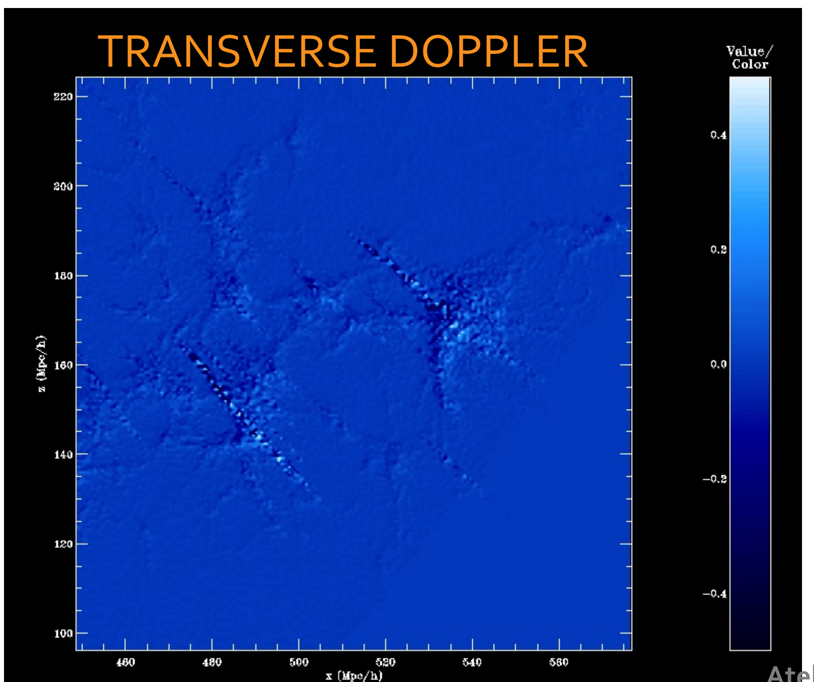
520
540
560
x (Mpc/h)


TRANSVERSE DOPPLER
Value/
Color
0.4
0.2
0.0
-0.2
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z (Mpc/h)
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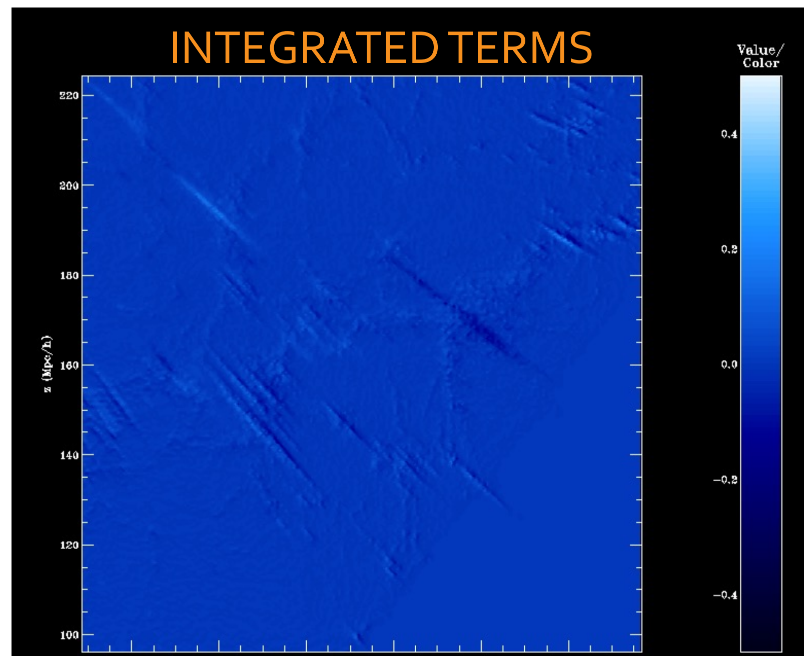
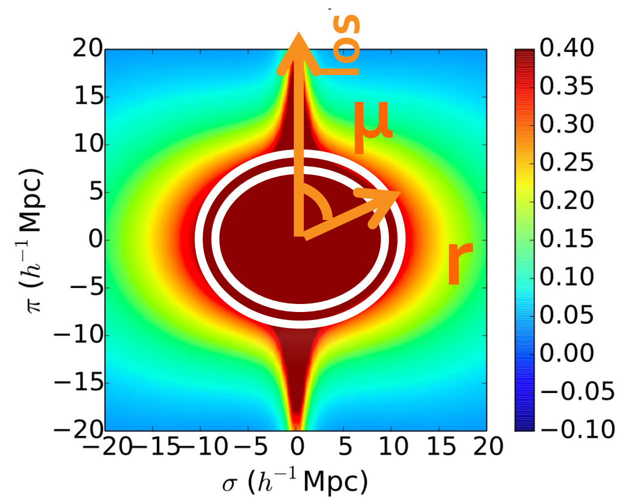
560
x (Mpc/h)


INTEGRATED TERMS
Value/
Color
0.4
0.2
0.0
-0.2
-0.4
220
200
180
160
140
120
100
z (Mpc/h)
460
480
500
520
540
560
x (Mpc/h)

Multipoles 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



Expected Impact of relativistic effects in a Euclid like spectroscopic survey: even multipoles

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	$> 20\%$	-	$< 1\%$	$1 - 10\%$	$< 1\%$	$< 1\%$

Breton et al. 2022

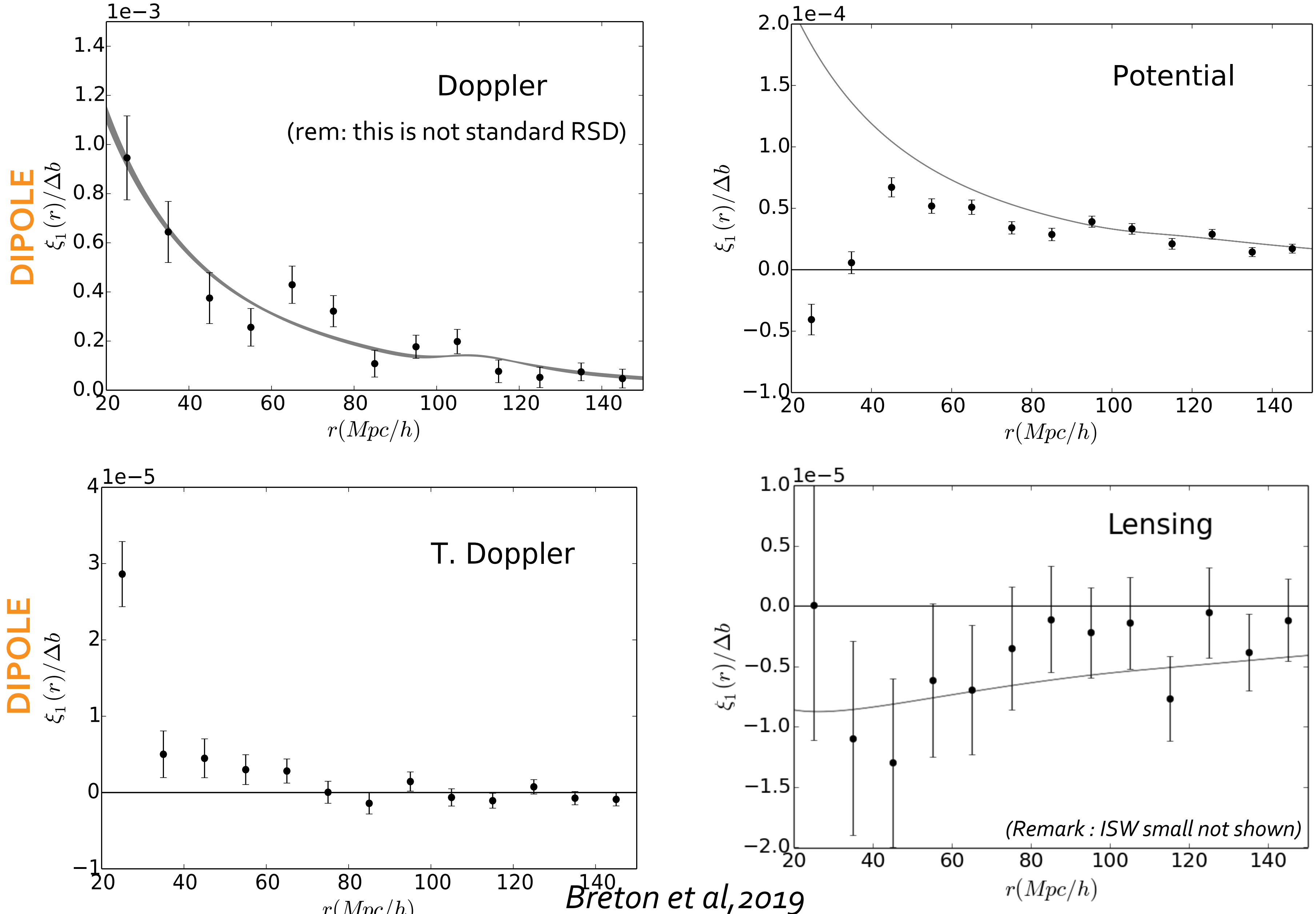
- **Dipole (l=1)** should be zero with standard RSD

=> Sensitive **to relativistic effects !**

Courtesy: M-A Breton

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

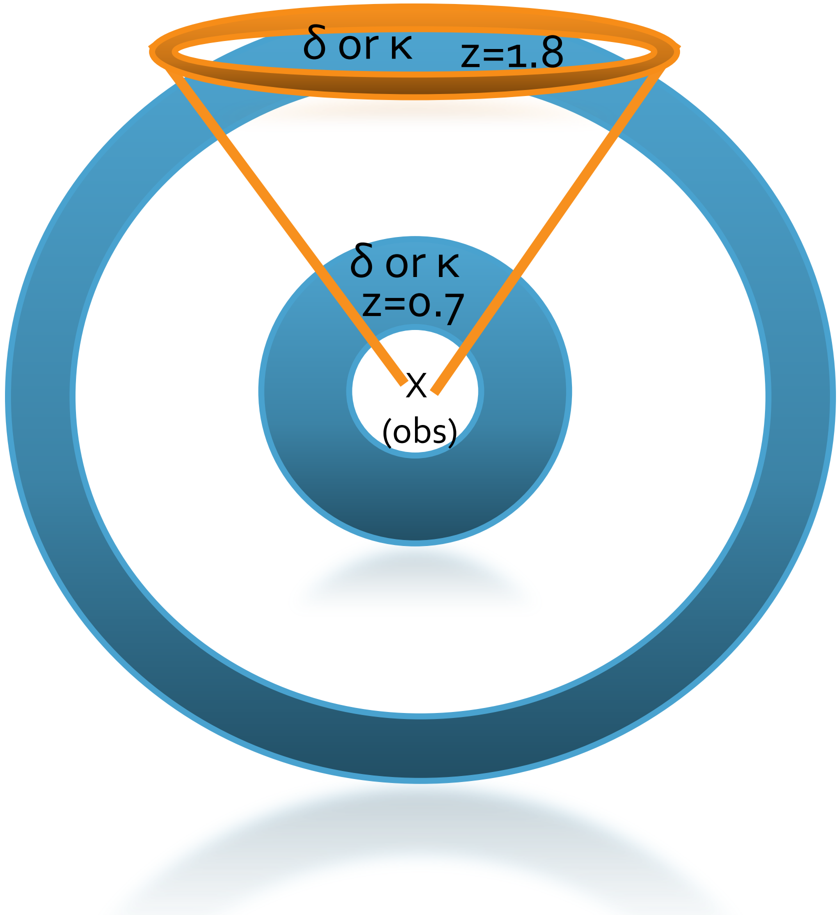
MW-size halo-Group size halo cross-correlation



Breton et al, 2019

Example of application:
Lensing-matter clustering

Set up: two shells extracted from RayGal

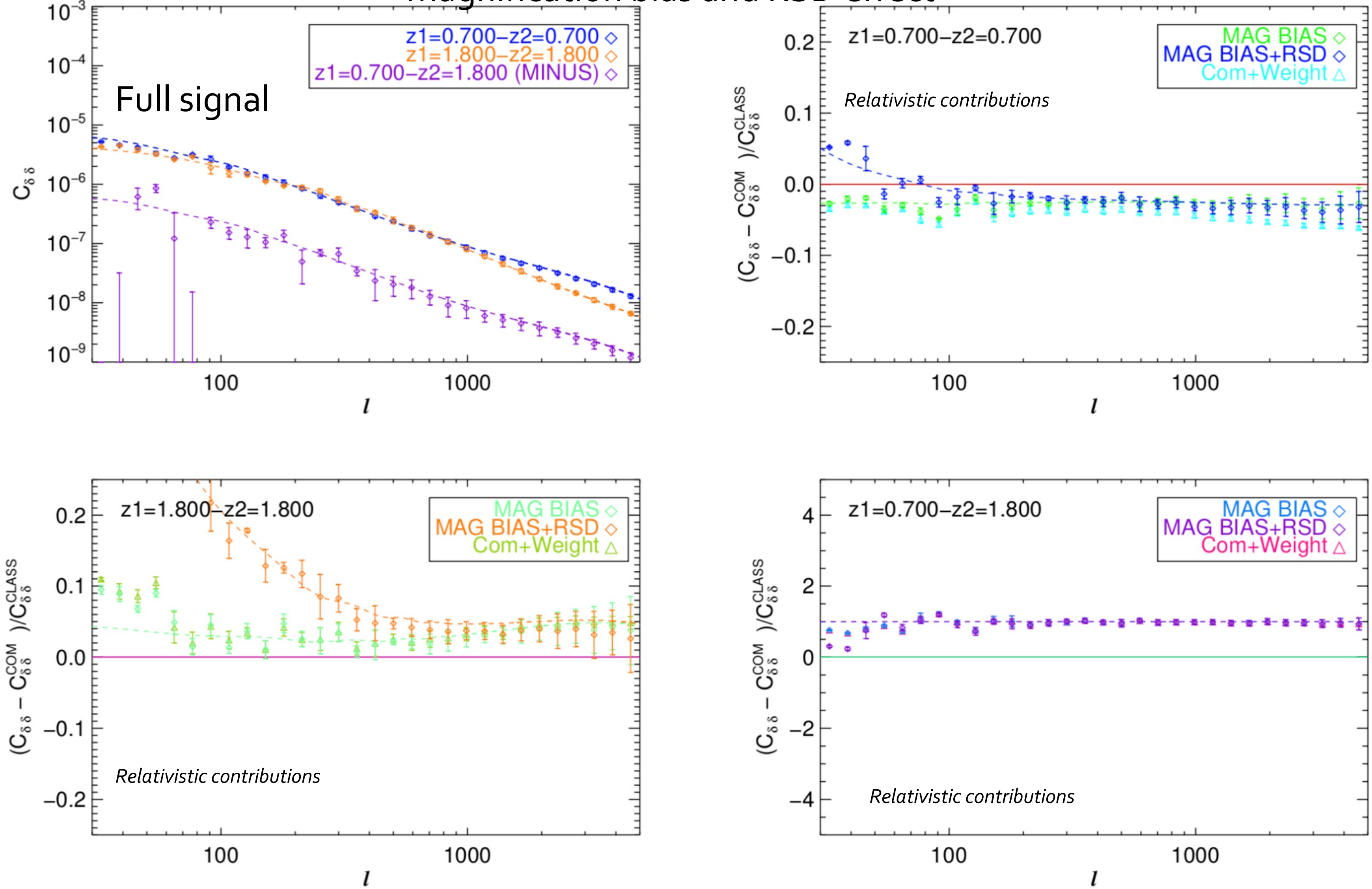


<δ δ> : clustering
<κ κ> : weak-lensing
<δ κ> : galaxy-galaxy lensing

- We consider two-shells within a 2500 deg^2 light-cone at z=0.7+-0.2 and z=1.8+-0.1
- We compute the observed matter overdensity δ and apparent weak-lensing convergence κ
- For reference we also compute the comoving matter overdensity and Born convergence=> deviation= non-trivial relativistic effects (magnification bias MB and RSD)
- We compute all angular cross-spectra with Spice and compare to Class analytical predictions
- Because of Magnification Bias: $\delta_{obs} \approx \delta_{com} - 2\kappa_{Born}$ and $\kappa_{obs} \approx \kappa_{Born} (1-2\,\kappa_{Born})$.

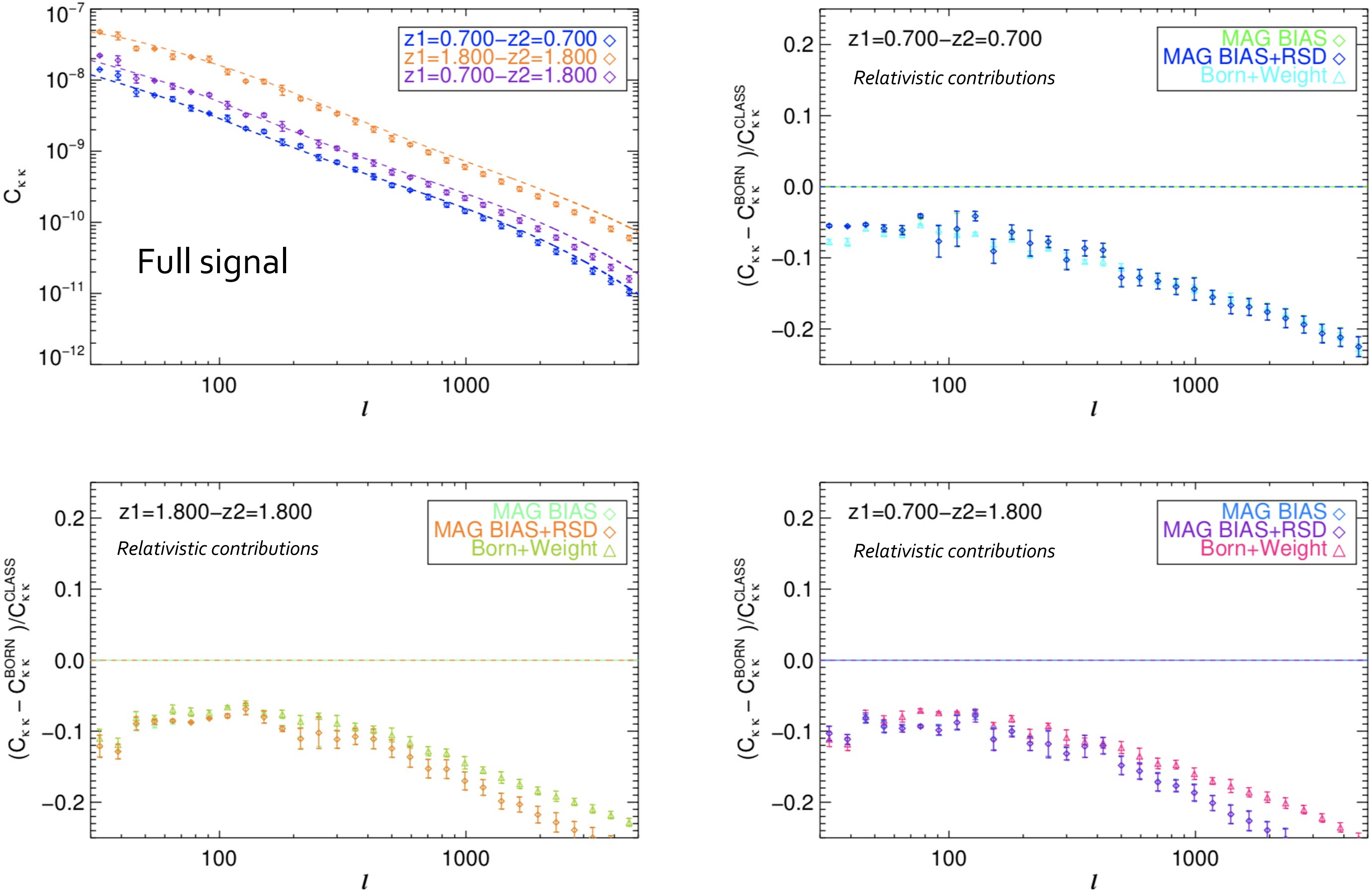
Matter angular (cross-)power spectra:
magnification bias and RSD effect

Rasera et al. 2022



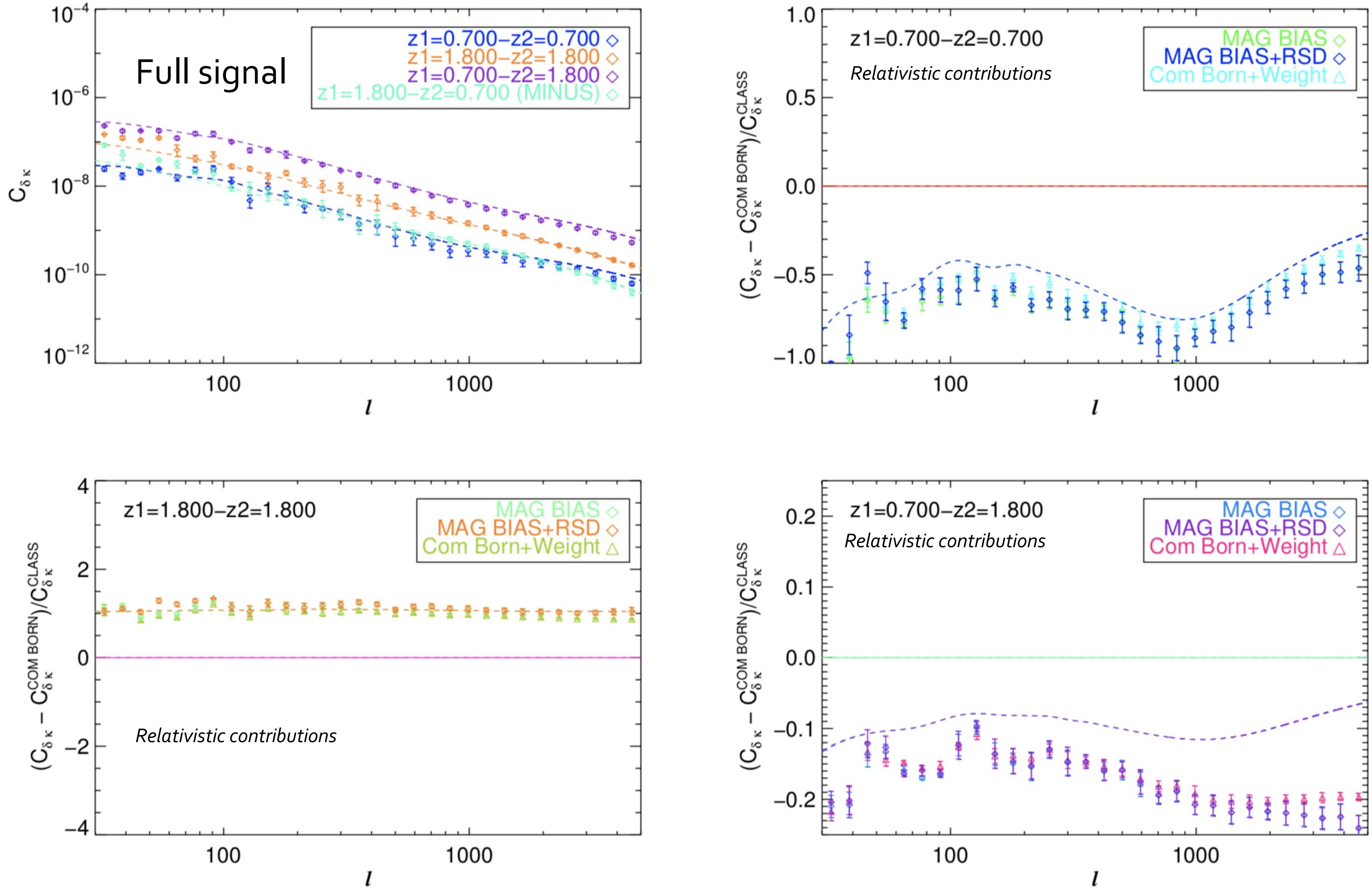
- P(k) calibrated on RayGal - Good agreement with Class (dashed lines)
- Not shown here at low redshift Class doesn't capture Fingers-of-god effect

Convergence angular (cross-)power spectra: magnification bias and RSD effect



- Cannot compute the effect of magnification bias on the convergence with Class
- MB effect on convergence Cl means that shear and convergence power spectra differ!

Density-convergence (cross-)power spectra: magnification bias and RSD effect



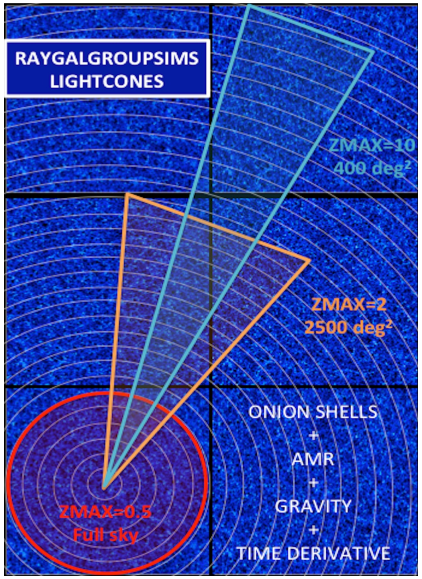
- Interesting non- trivial configurations : including one with the convergence at lower or equal redshift than the density shell => the cosmological signal is not negligible
- MB effect in Class is included but only for the densitys

CONCLUSION

• Goal: Understand the connection from the "real universe" to the "apparent universe" to find new probes of DE=> need to model all relativistic effect (i.e. like for CMB but in non-linear regime)

•New PUBLIC DATA

- Don't hesitate to download the RAYGALGROUPSIMS (or in short RayGal) relativistic halo catalogues and maps to make your own test (traditional snapshot data are also available)
- Very simple files with angular position, redshift and distortion matrix



•Relativistic effects in RSD

- For the 1st time all the dipole effects are modeled accurately in weak field from lin. to NL scales
- The most important contribution after wide-angle RSD is the gravitational potential at low redshift
- Detectability of grav. Pot. in DESI, SKA and possibly Euclid.

•Relativistic effects and weak-lensing (3x2pts):

- good agreement with CLASS at quasi-linear scales
- new effects in NL regime (Finger-of-gods effect in angular correlation, magnification bias on the convergence power spectra, non-trivial configuration in galaxy-galaxy lensing).

•Very general approach, many extensions:

- Many Other possible applications (theory/simulation/observation) : doppler lensing, ISW, fluctuations of cosmic distances, cluster studies (WL, RSD, gravitational redshift), etc…

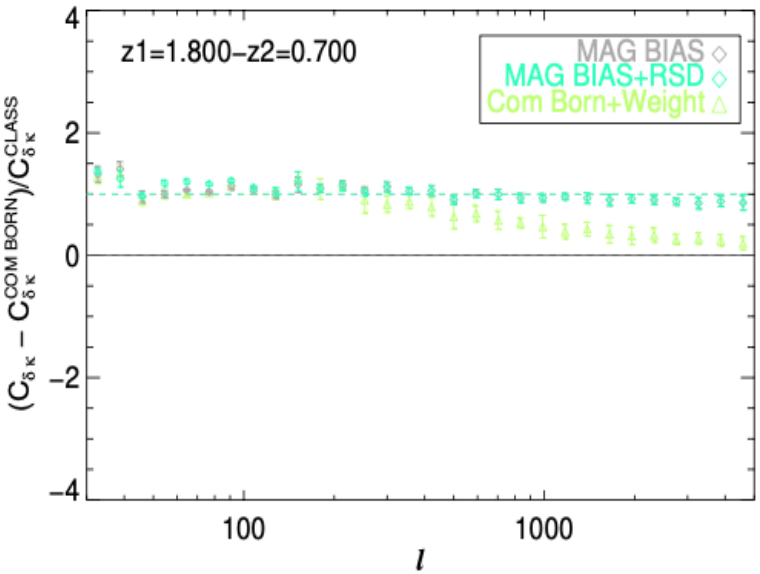


Fig. 13. Non-trivial reverse configuration of gravitational convergence at $z = 0.7$ and matter density at $z = 1.8$, similar to the bottom-right panel of Fig. 12. MB is in grey, MB+RSDs in cyan, and the $|\mu_{\rm Born}|^{-1}$ weight MB estimate in light green. Relativistic effects almost reach 100%, in agreement with CLASS. This configuration turns out to be a sensitive probe of the lensing convergence spectrum.

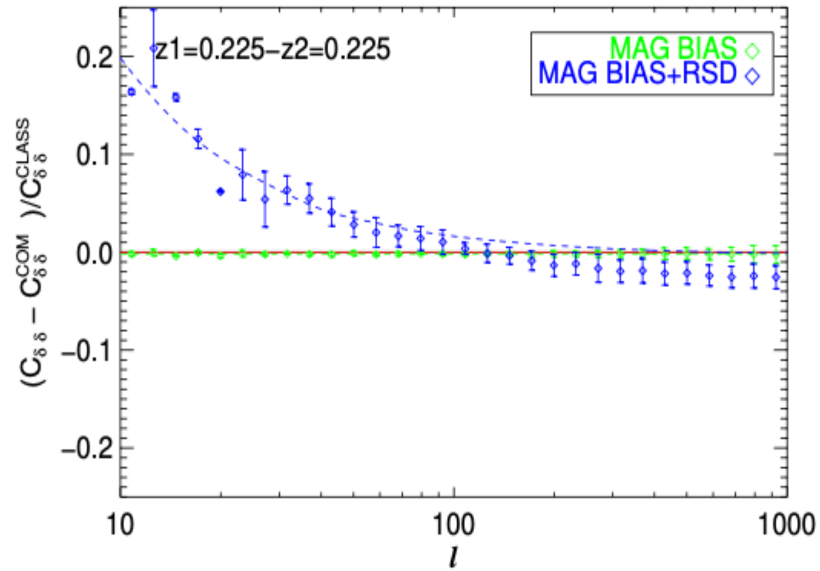


Fig. 14. Relativistic effects at low redshift on matter power spectrum $C_{\delta_1\delta_2}(\ell, z_1 = 0.225, z_2 = 0.225)$ (symbols are RAYGAL measurements, and lines are CLASS predictions). The MB effect (green) and RSDs(+MB) effect (blue) are shown. The trends are similar compared to higher redshifts, but the RSD effect plays a dominant role and the MB effects are smaller. Finger-of-God effects (ignored by CLASS) are also present.

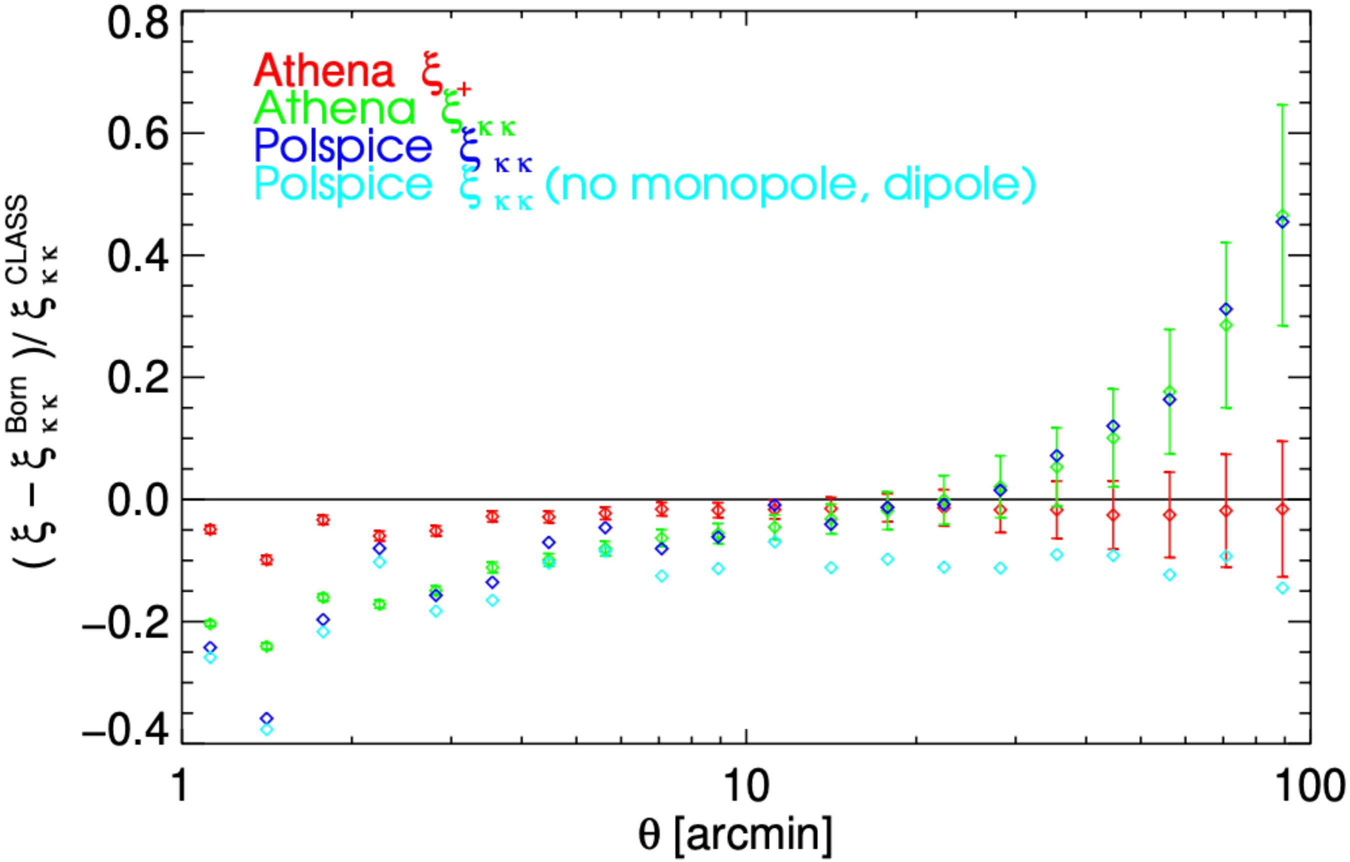


Fig. B.1. Relative difference between lensing angular two point correlation function on the source catalogue accounting for the dilution bias and the Born convergence angular two point correlation function. In red and green diamonds we show the measurements of cosmic shear and convergence correlation funtion using ATHENA, and in blue and light blue we show the results using the same methodology as in Sect. 3, keeping and removing the monopole and dipole, respectively.