Relativistic effects on large scale structures*: a leap into the non-linear regime with RayGal simulations

Yann RASERA (LUTH/Paris Cité Univ./Paris Obs./PSL/CNRS/IUF)

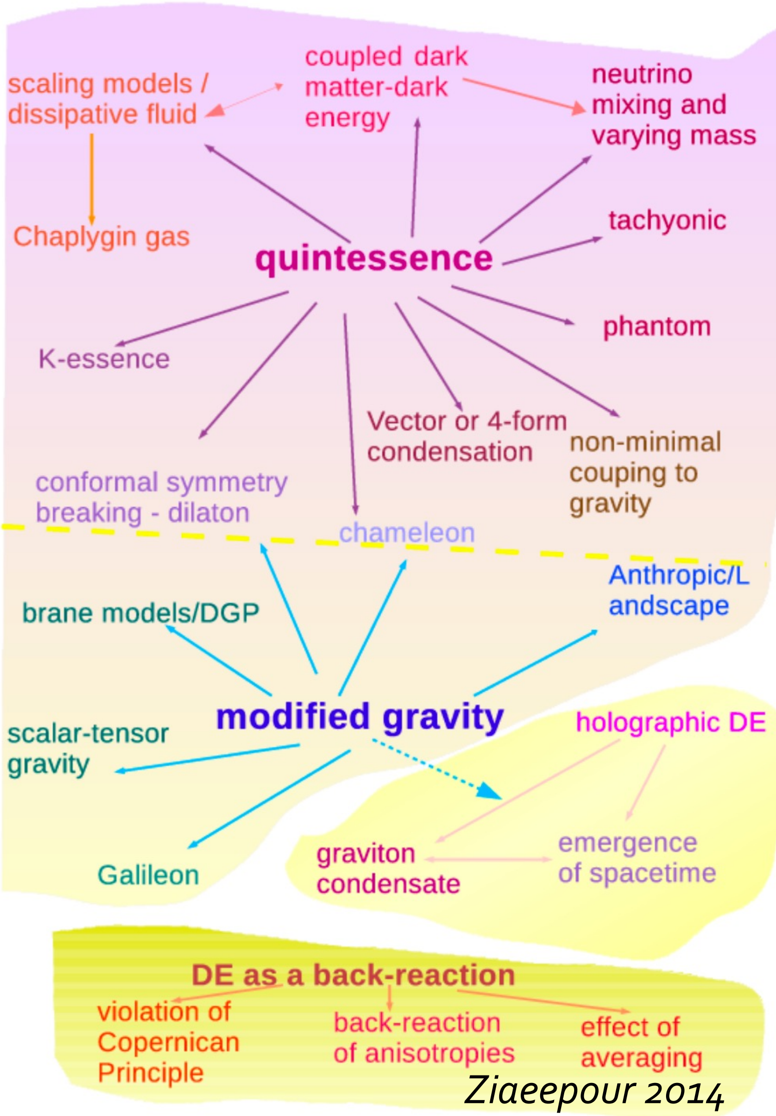
Work with:* Michel-Andrès Breton (ICE), *P-S. Corasaniti (LUTH), J.Allingham (Technion), F.Roy (LUTH), V.Reverdy (LAPP), T.Pellegrin (LPP), S.Saga (IAP), A.Taruya (YITP), J-M Alimi (LUTH), S.Agarwal (AIMS), S.Anselmi (INFN)

* I will mostly skip the introduction, please check C.Bonvin &S.Castello talks

LAPP

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

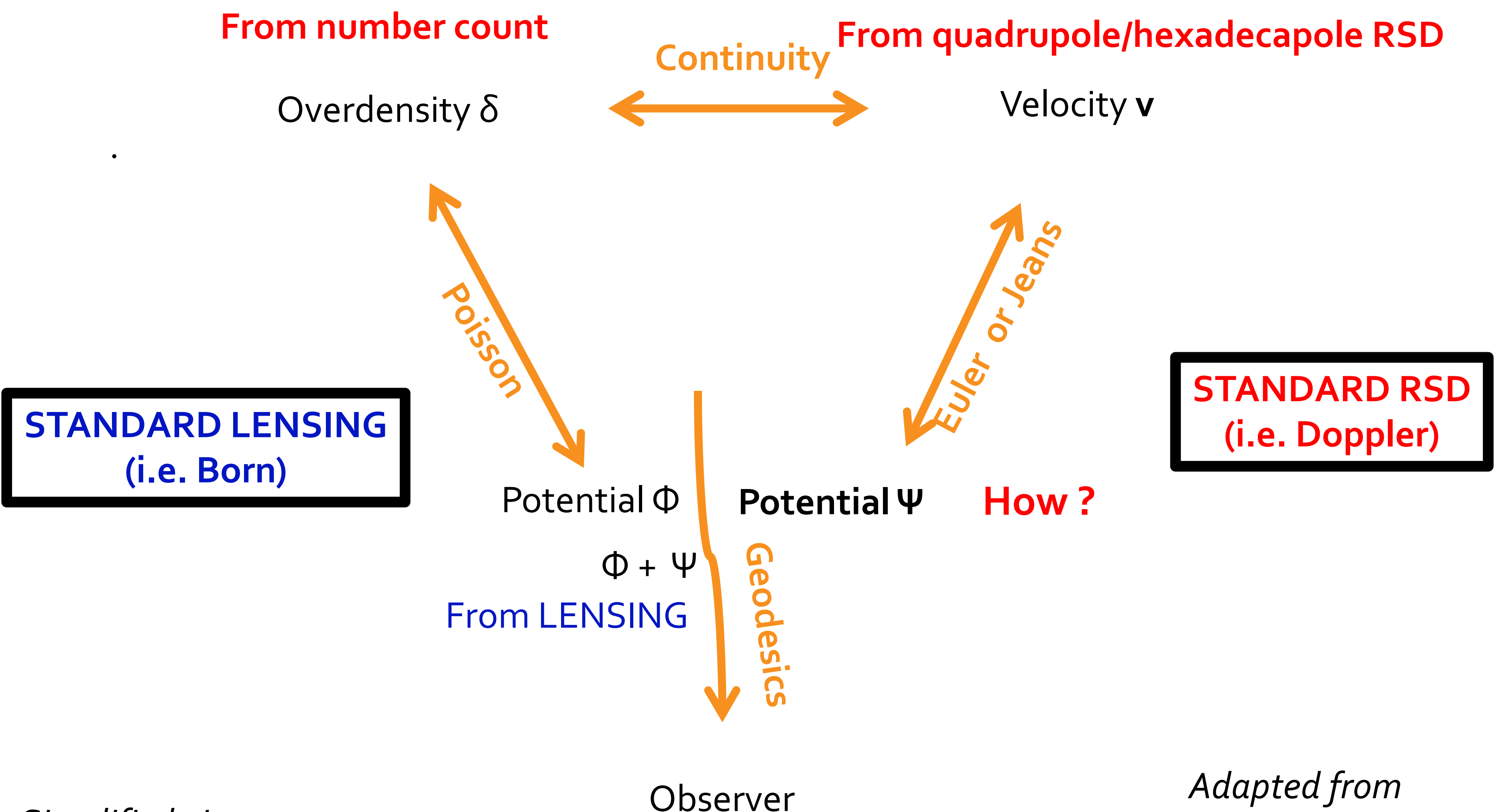
Non linear imprints of
DARK SECTOR on COSMIC STRUCTURES ?
How to probe
DARK SECTOR with COSMIC STRUCTURES?

THE COSMIC PROGRAM

(beyond a(t))

CAN WE POSSIBLY TEST ALL THE MAIN HYPOTHESIS AT COSMOLOGICAL SCALES ?

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



Simplified view
Assume a(t) known

Adapted from
Bonvin&Fleury 2018

THE COSMIC PROGRAM

(beyond a(t))

CAN WE POSSIBLY TEST ALL THE MAIN HYPOTHESIS AT COSMOLOGICAL SCALES ?

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

From number count

(relativistic contribution ~0.5-5%)

Overdensity δ

Continuity

From quadrupole/hexadecapole RSD

(relativistic contribution ~0.5-5%)

Velocity **v**

Poisson

Euler or Jeans

RELATIVISTIC LENSING

RELATIVISTIC RSD

Potential Φ

Potential Ψ

FROM DIPOLE !

(relativistic contribution ~100%)

Φ + Ψ

From LENSING

(relativistic contribution ~0.1-50%)

Geodesics

Observer

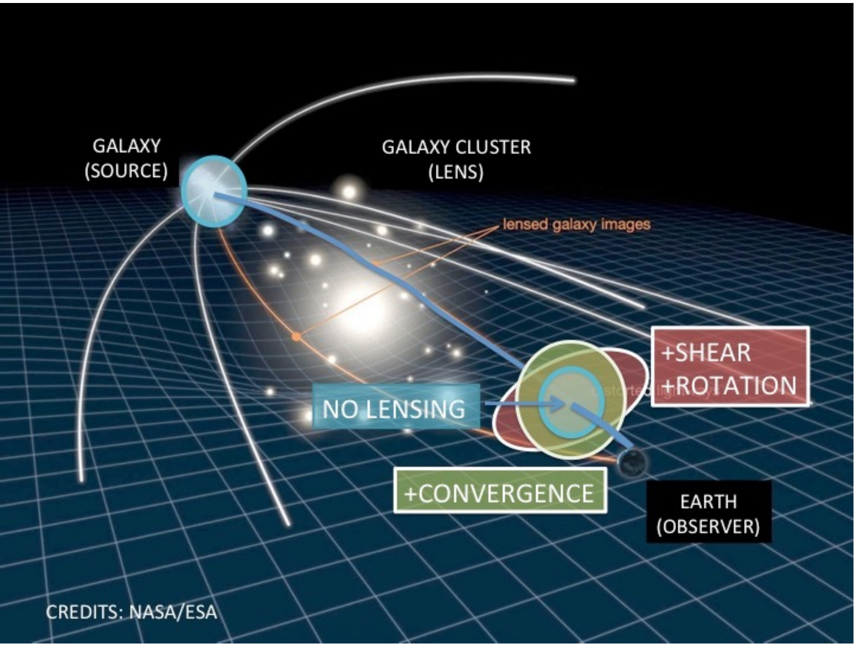
Simplified view

Assume a(t) known

Adapted from Bonvin&Fleury 2018

Usual approach: compute WL maps <u>or</u> RSD catalogs

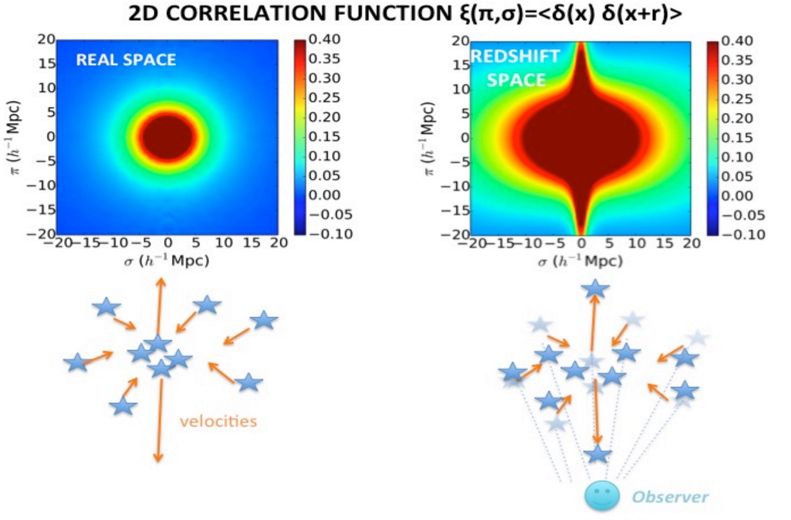
LENSING



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

OR

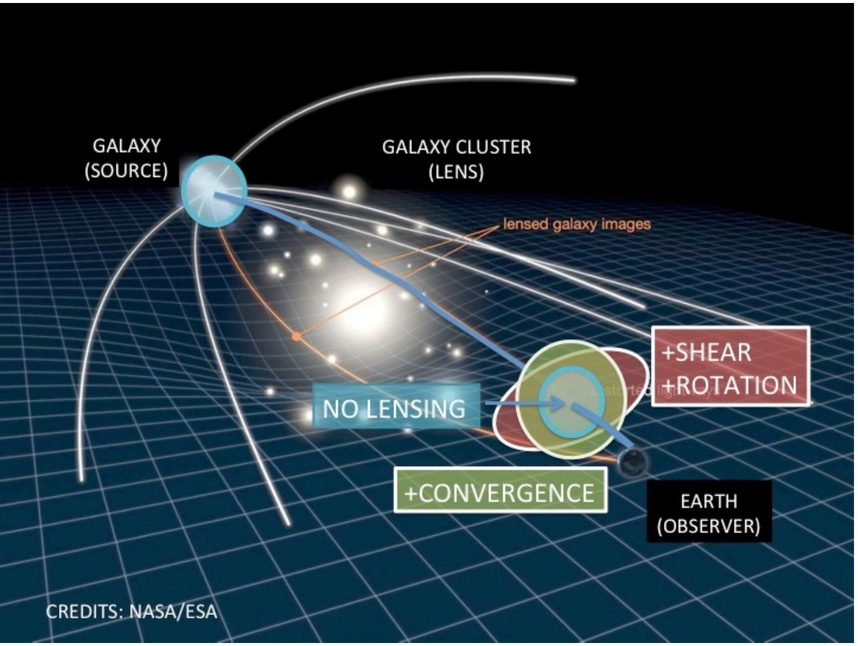
Redshift-Space Distortions (RSD)



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

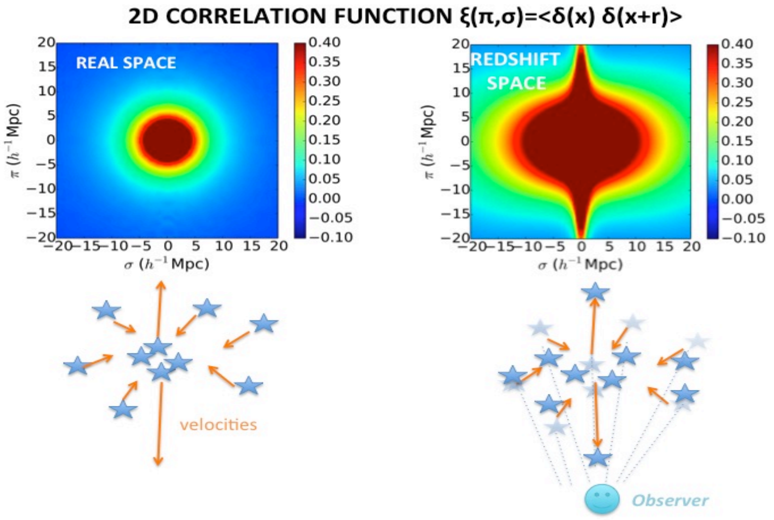
Relativistic approach: compute what is really observed following (weak-field) GR

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** (SEE CAMILLE BONVIN AND SVEVA CASTELLO'S TALKS)

Use **similar formalism as for CMB** (i.e. weak field GR) but applied to galaxies

->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 ?

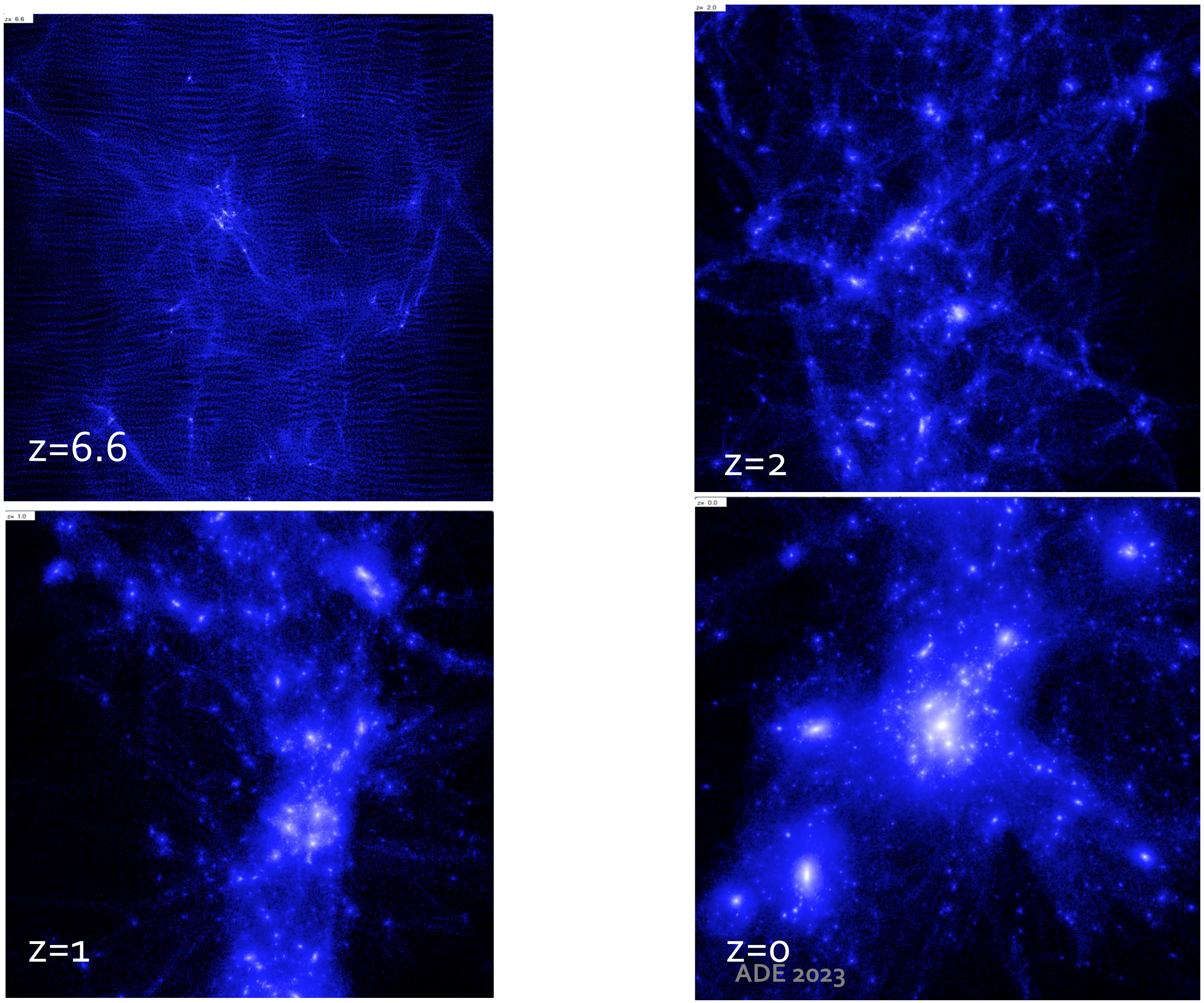
=> GR effects WITH SIM IS A HOT TOPIC: Killedar12, Reverdy14, Adamek16, Giblin17, Borzyszkowski17, Breton19, Adamek19 , Lepori20, Guandalin21, Lepori21, Rasera22, …

HOW TO ADRESS THE NON-LINEAR REGIME?

The RayGal way…

STEP 1: RUN RAYGAL N-BODY SIMULATIONS

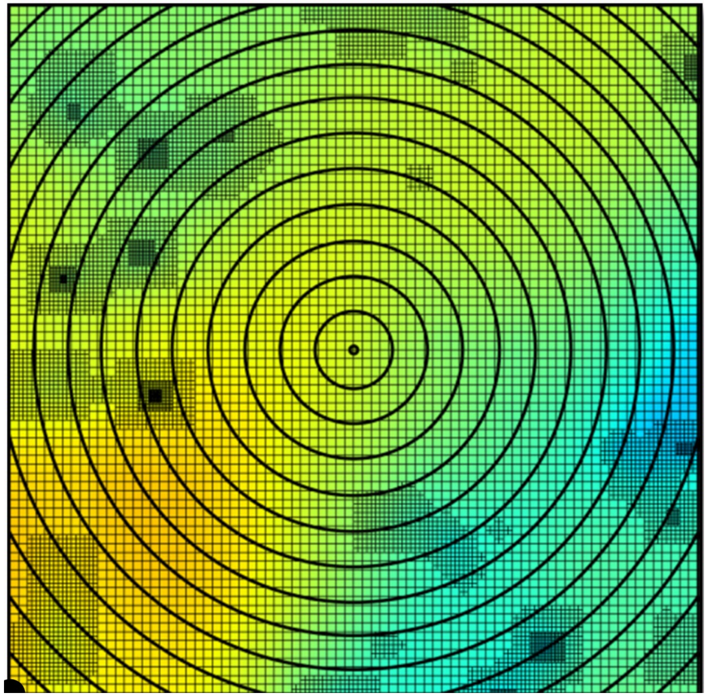
- Goal: Build a (virtual) « real » universe by running N-Body sims
- N-body solver: RAMSES Particle-Mesh with Adaptive Mesh Refinement (PM-AMR)
- Specs: 4096^3 particles, $(2.6\ \mathrm{Gpc/h})^3$, ΛCDM & wCDM (w=-1.2)
- #halos: >10 millions of halos from Milky-Way size to cluster size



Illustrative example of the formation of one large halo in a simulation

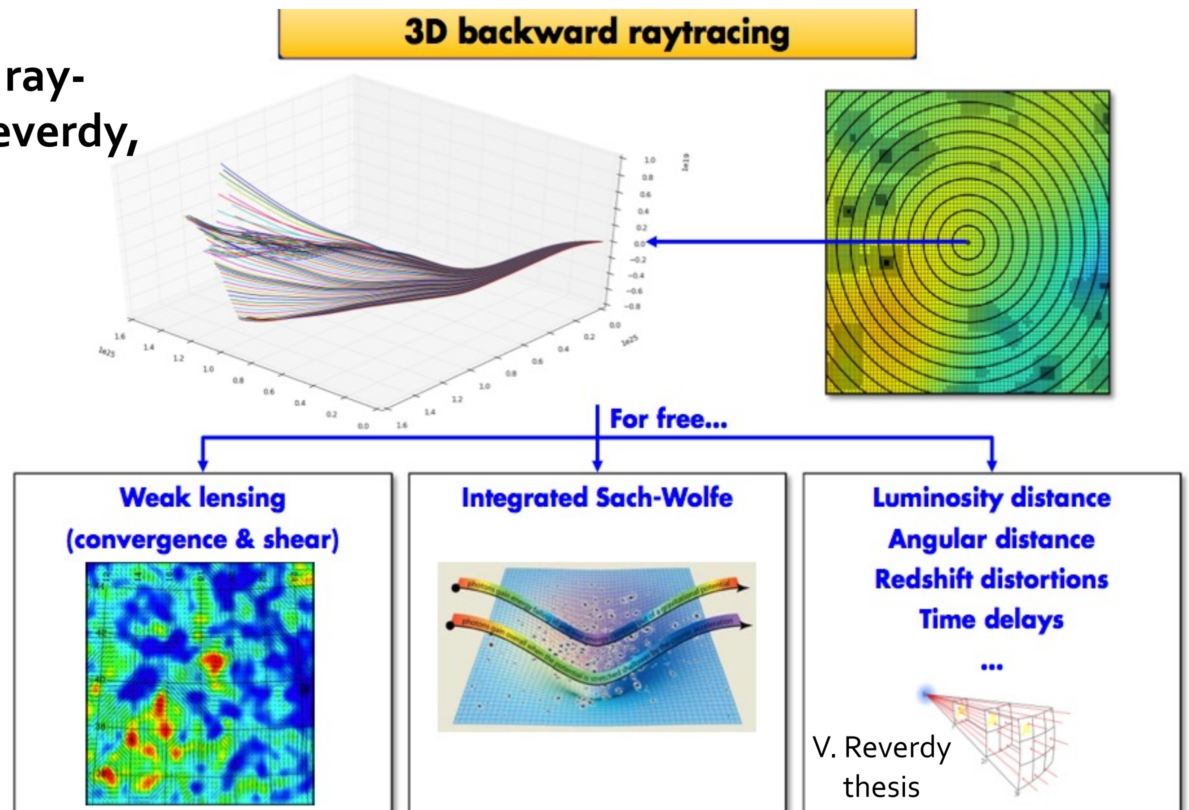
STEP 2: BACKUP A GRAVITY LIGHCONE

- What: Gravity (and particles) lightcone
- Where: At light-travel distance from the observer (center of the box)
- Remark: also backup in the vicinity of the null-FLRW lightcone (called « thick » light-cone)
- Which quantities: Potential (i.e. metric), gradient of the potential (i.e. gravitational field), time derivative of the potential
- Type of light-cone: wide (fullsky, zmax=0.5), deep (2500 deg^2,zmax=2), very deep (400 deg^2,zmax=10)



STEP 3 : DIRECT INTEGRATION OF BILLION WEAK-FIELD 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 (Breton&Reverdy, 2021)**
- Self-consistent calculation of WL <u>AND</u> RSD AND other relativistic effects
- Little number of controled assumptions: weak-field GR + neglect horizon-scale GR effects on DM dynamics (Chisari & Zaldarriaga, 2011, Adamek et al. 2016)



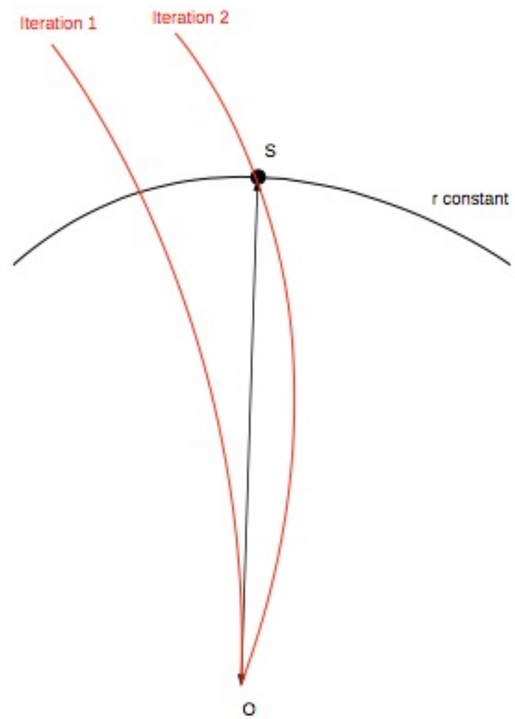
STEP 4: MAGRATHEA-PATHFINDER'S ITERATIVE GEODESICS FINDER

Find null geodesics

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

Output

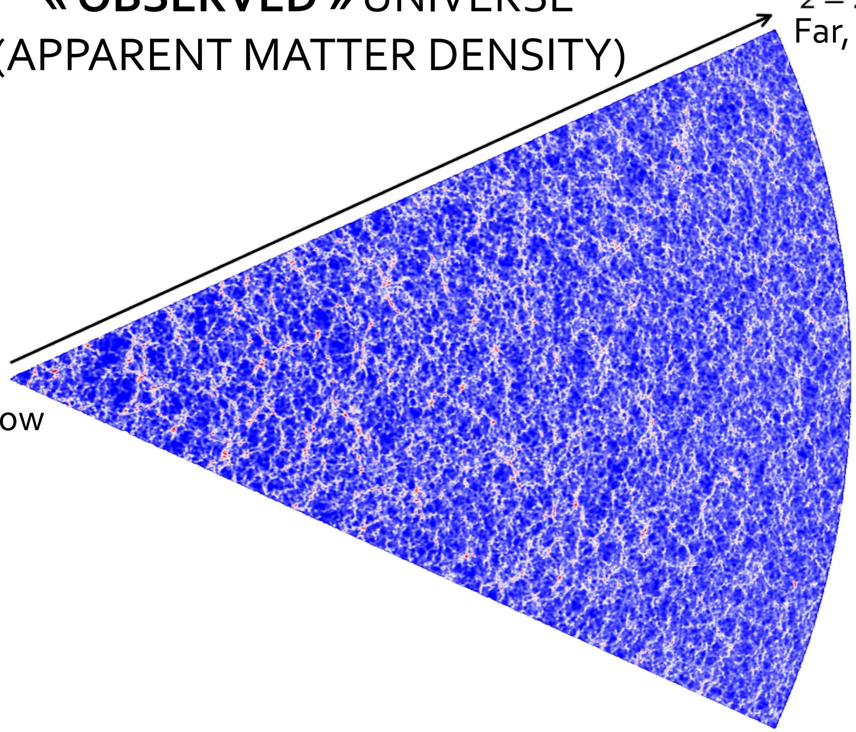
« NEW » : Catalogs of sources taking into account weak lensing effects and redshift space distortions
In the catalogs :
$\vec{\beta}, \vec{\theta}, \bar{z}, z,$ errors, A_{ij}



Breton et al,2019

- Weak-lensing using the ray-bundle approach
- Launch a beam of photons and directly compute its distortion (i.e. distortion matrix)
- Account for finite beam effect (i.e. the size of a galaxy is not zero as in the usual WL formalism)

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



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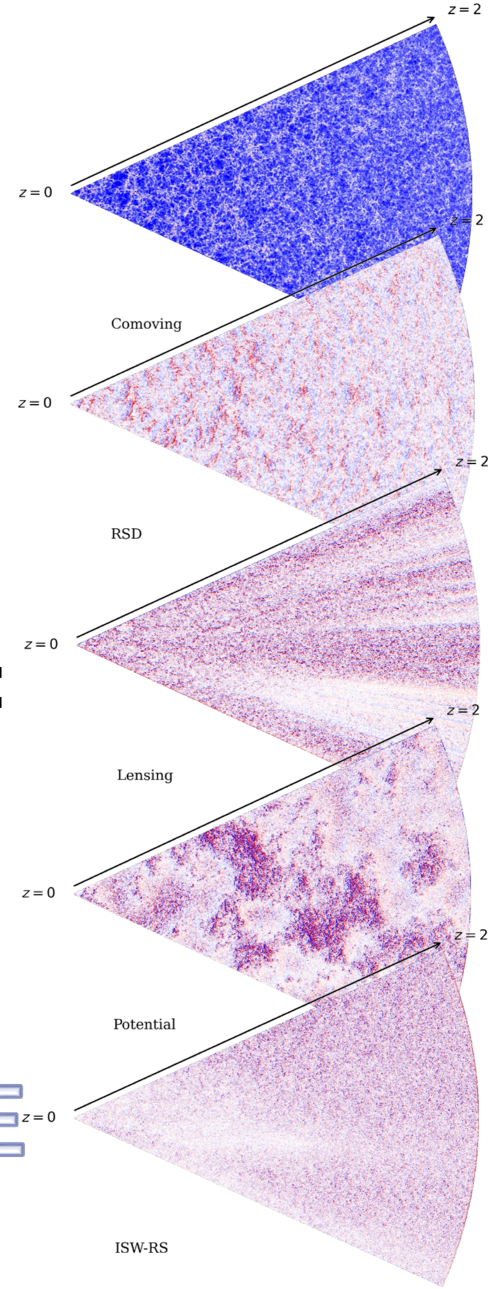


« TRUE » UNIVERSE

+

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

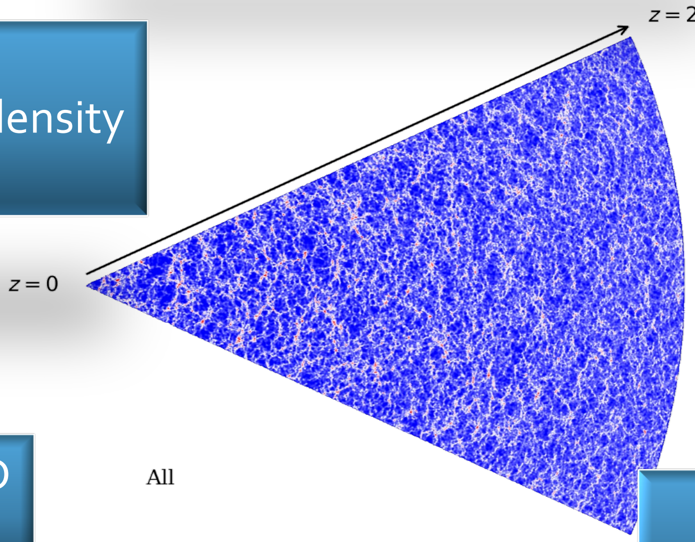
OPEN DATA: https://cosmo.obspm.fr/public-datasets/

(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

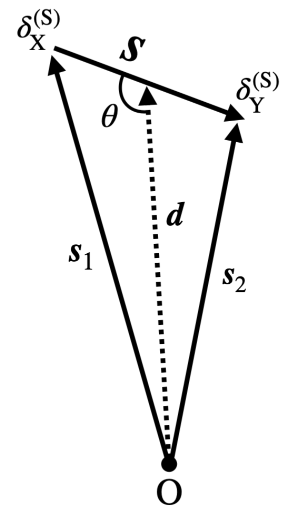
Gravitational redshift or WL in clusters

CMB-galaxies cross-correlations

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

Application 1:
Relativistic Redshift Space Distortions

GEOMETRY AND QUANTITIES



- Geometry: Center of pair of halos + average in spherical shells
- Quantity : halo density
- Statistic: halo-halo cross-correlation (i.e. multi-population)
- Projection: Multipoles

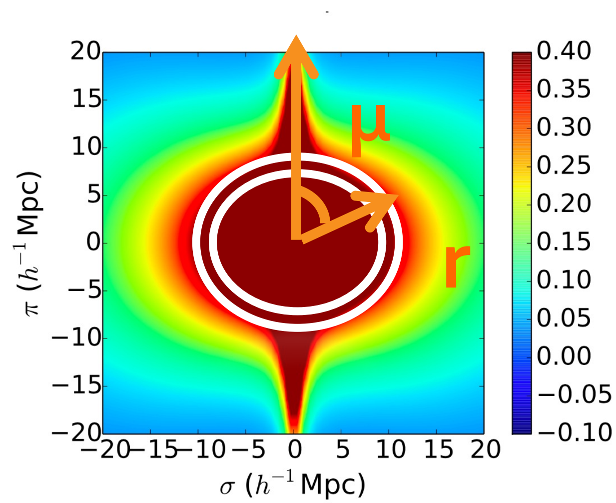
$$\xi_l(r) = \langle \delta_1(\mathbf{x})\, \delta_2(\mathbf{x}+\mathbf{r})\, P_l(mu) \rangle$$

- DEFINITION:

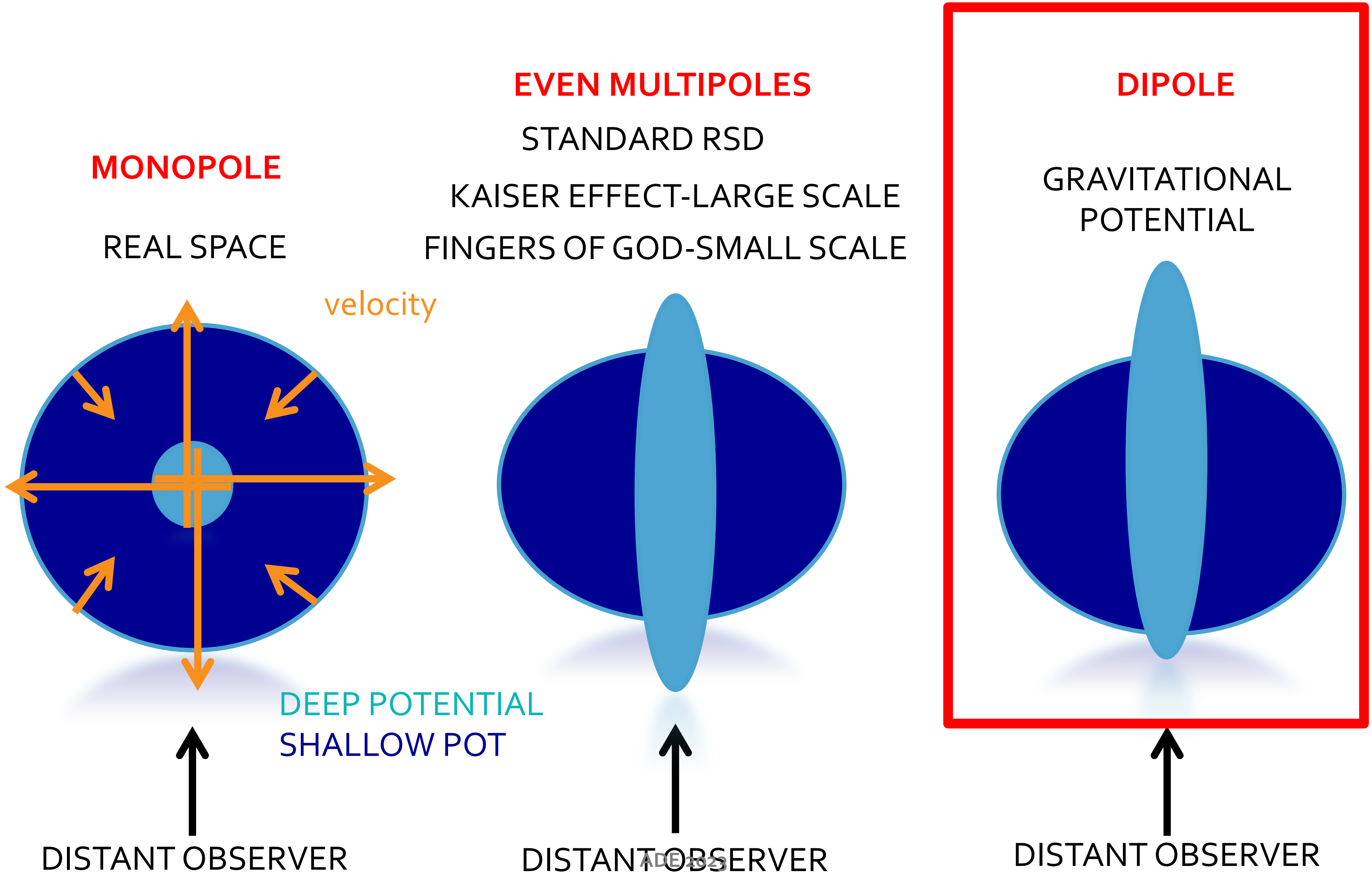
NON-TRIVIAL RELATIVISTIC EFFECT=
BEYOND STANDARD RSD (IE. DOPPLER + DISTANT OBSERVER)

- THEORY (for comparison): Linear

(Bonvin & Durrer 2011; Bonvin et al, 2014)



IMPORTANT TAKE HOME MESSAGE
THE DIPOLE IS A PROBE OF THE GRAVITATIONAL POTENTIAL IN THE NL REGIME

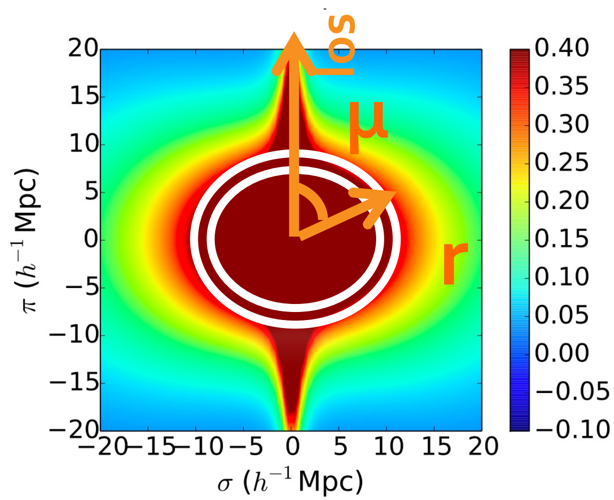


Relativistic RSD: Even multipoles

- Multipole

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

- Monopole: l=0 => density
- Quadrupole/hexadecapole: l=2,4 => velocity



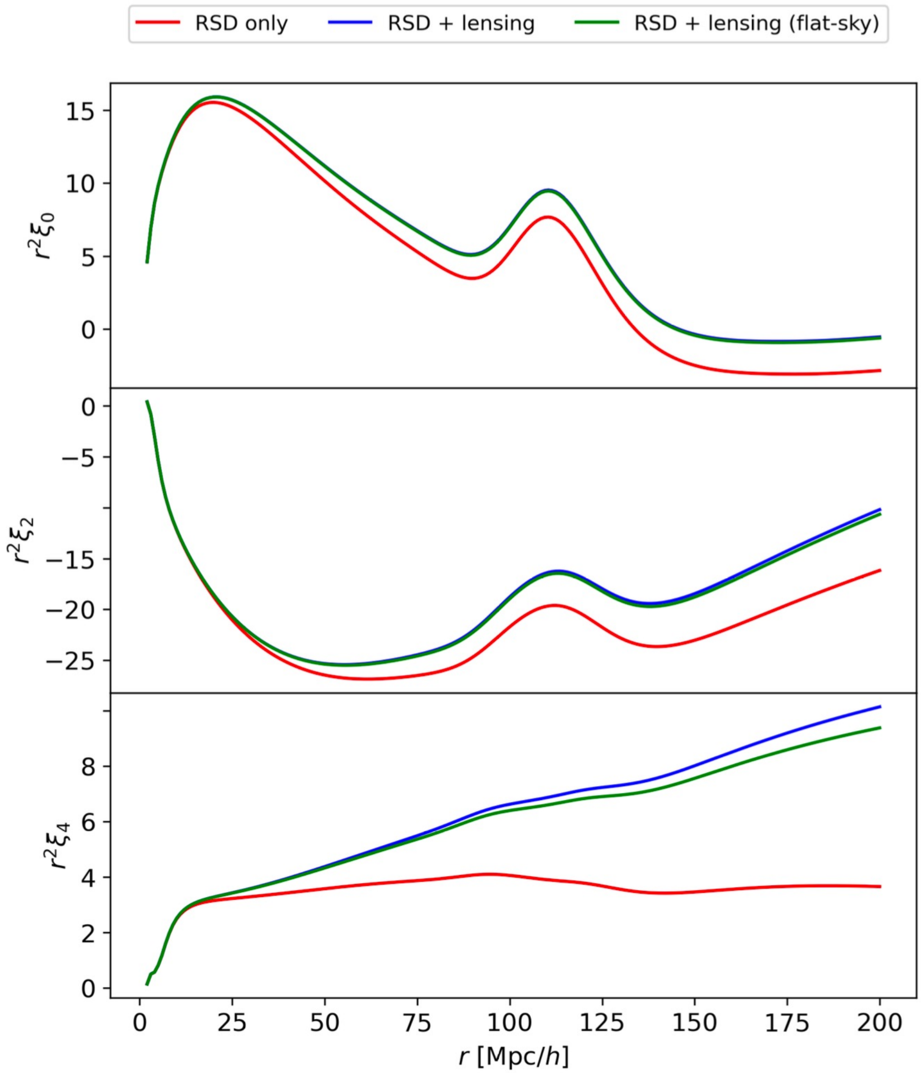
Expected Impact of relativistic effects in a Euclid like spectroscopic survey: even multipoles

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

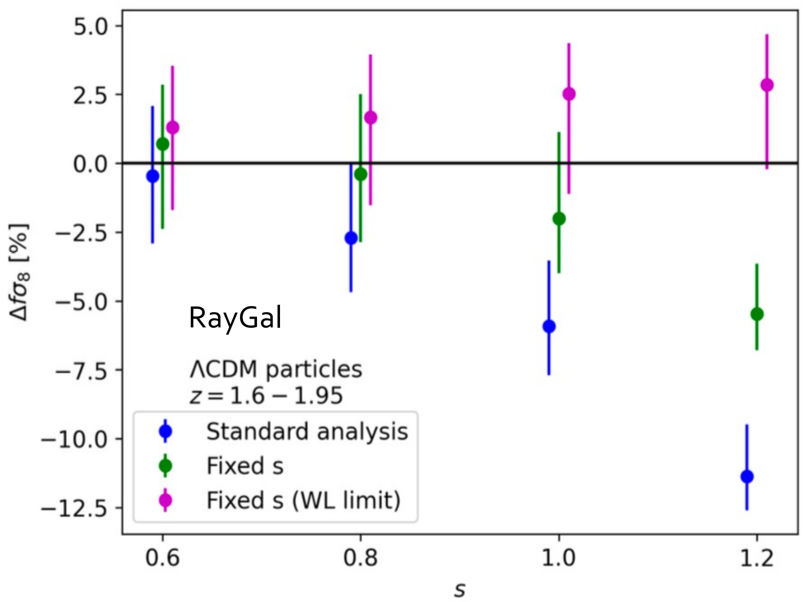
Breton et al. 2022

Courtesy: M-A Breton

Relativistic RSD: Even multipoles effect of lensing



Breton et al. 2022



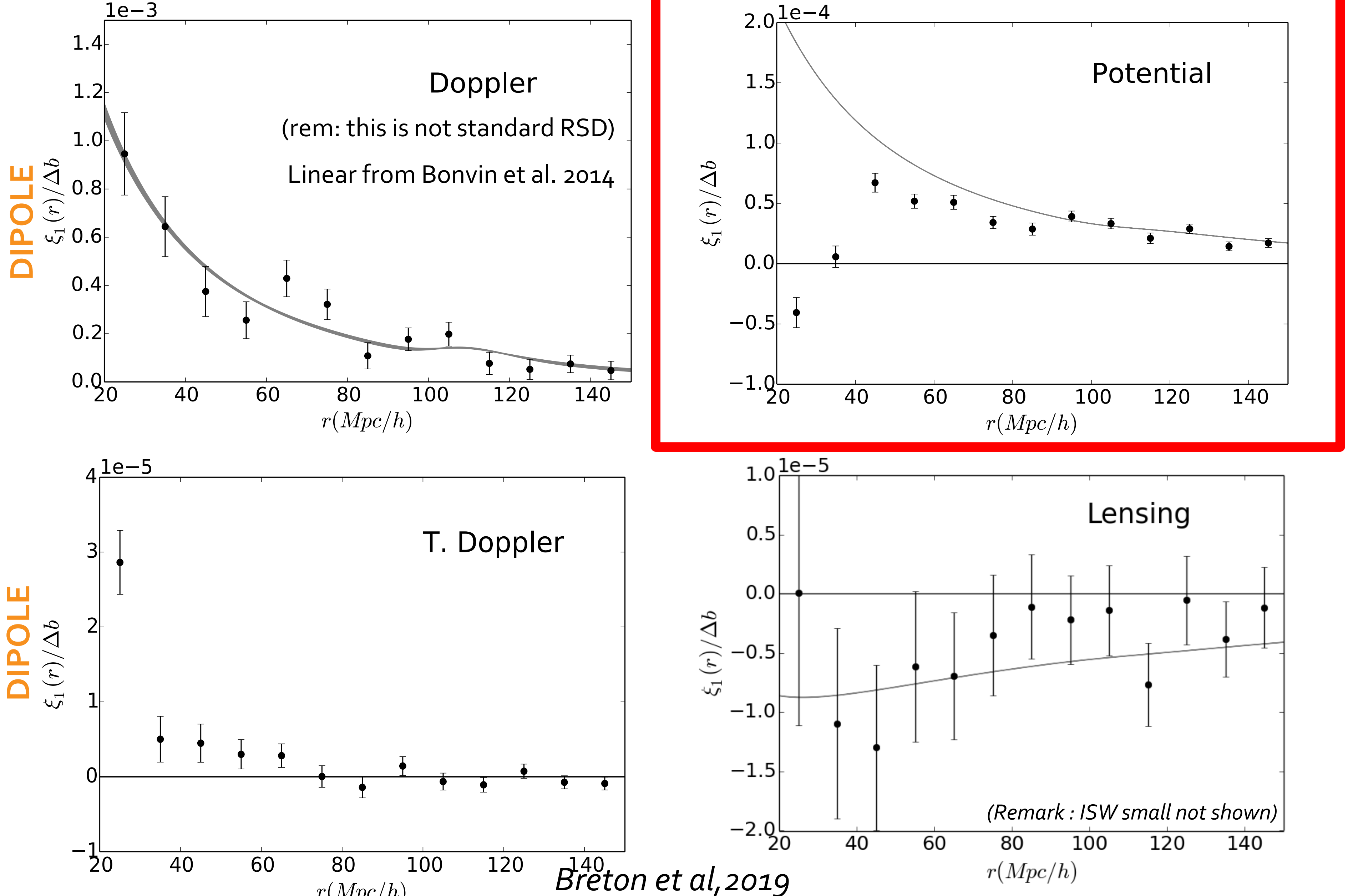
$$s(z, m_{\rm lim}) \equiv \frac{\partial \log_{10} \bar{N}(z, L > L_{\rm lim})}{\partial m}\bigg|_{m_{\rm lim}}.$$

s~1.1 for Euclid spectro survey

- Left: Effect of lensing on RSD (linear theory)
- Right: Growth rate inference at z=1.8 (b=1, s=1.2) for a Euclid-like survey built from RayGal data

<u>Relativistic RSD</u>: DIPOLE LARGE SCALES (20-150 Mpc/h): SIMU (POINTS) VS LINEAR (LINES)

MW-size halo-Group size halo cross-correlation

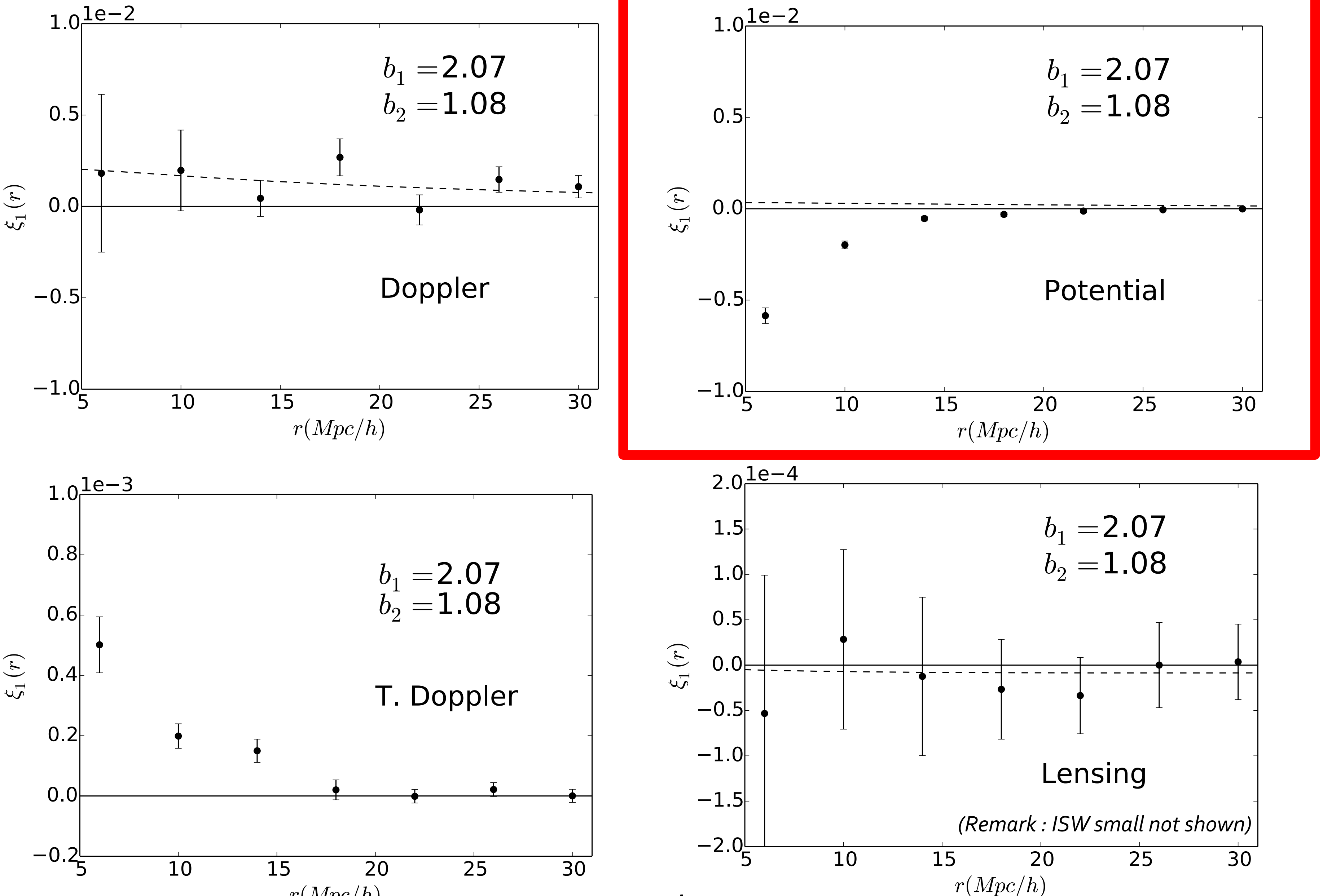


Breton et al, 2019

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

DIPOLE

DIPOLE



RADIUS

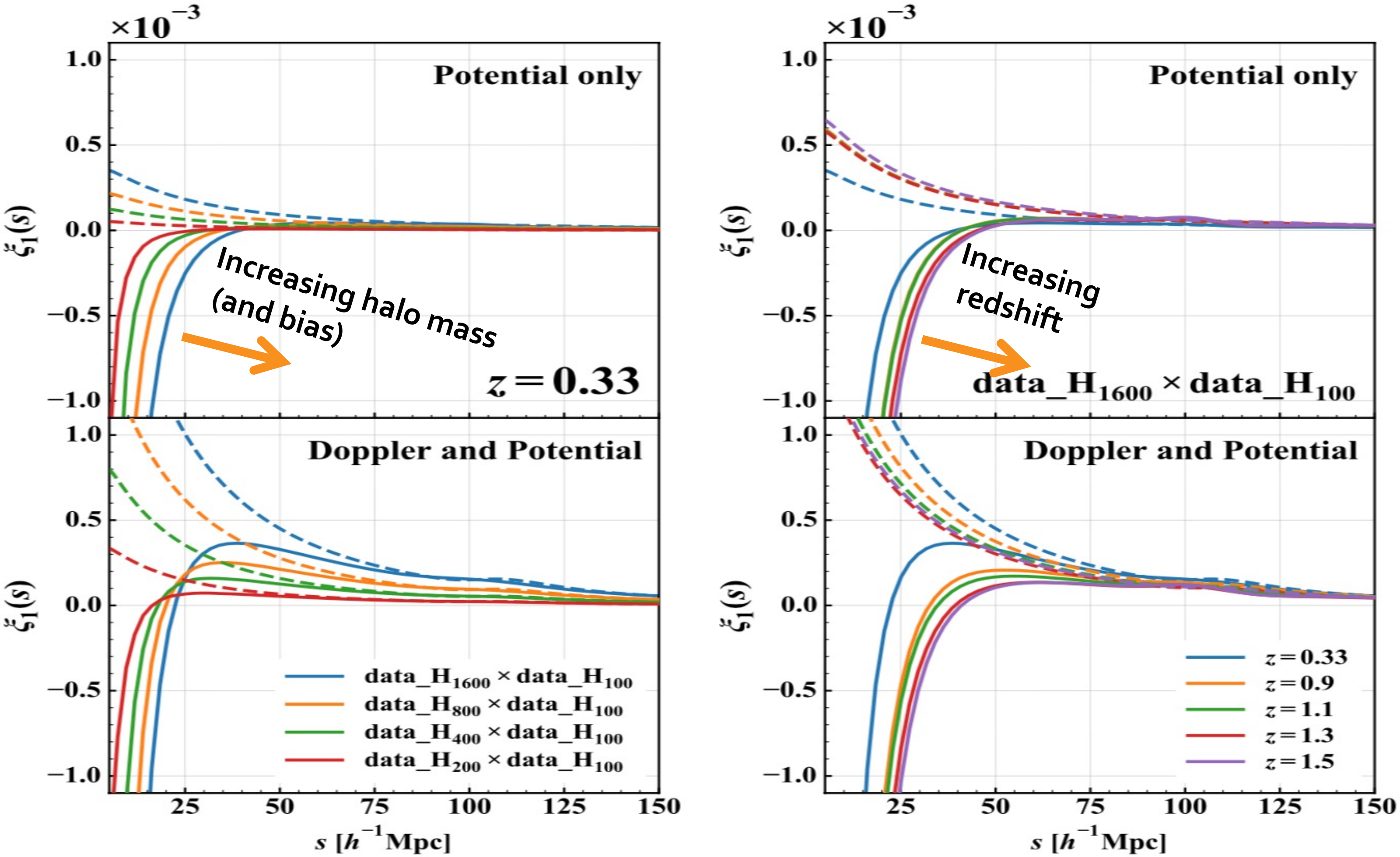
RADIUS

Breton et al, 2019

ADE 2023

Non-linear Analytical predictions

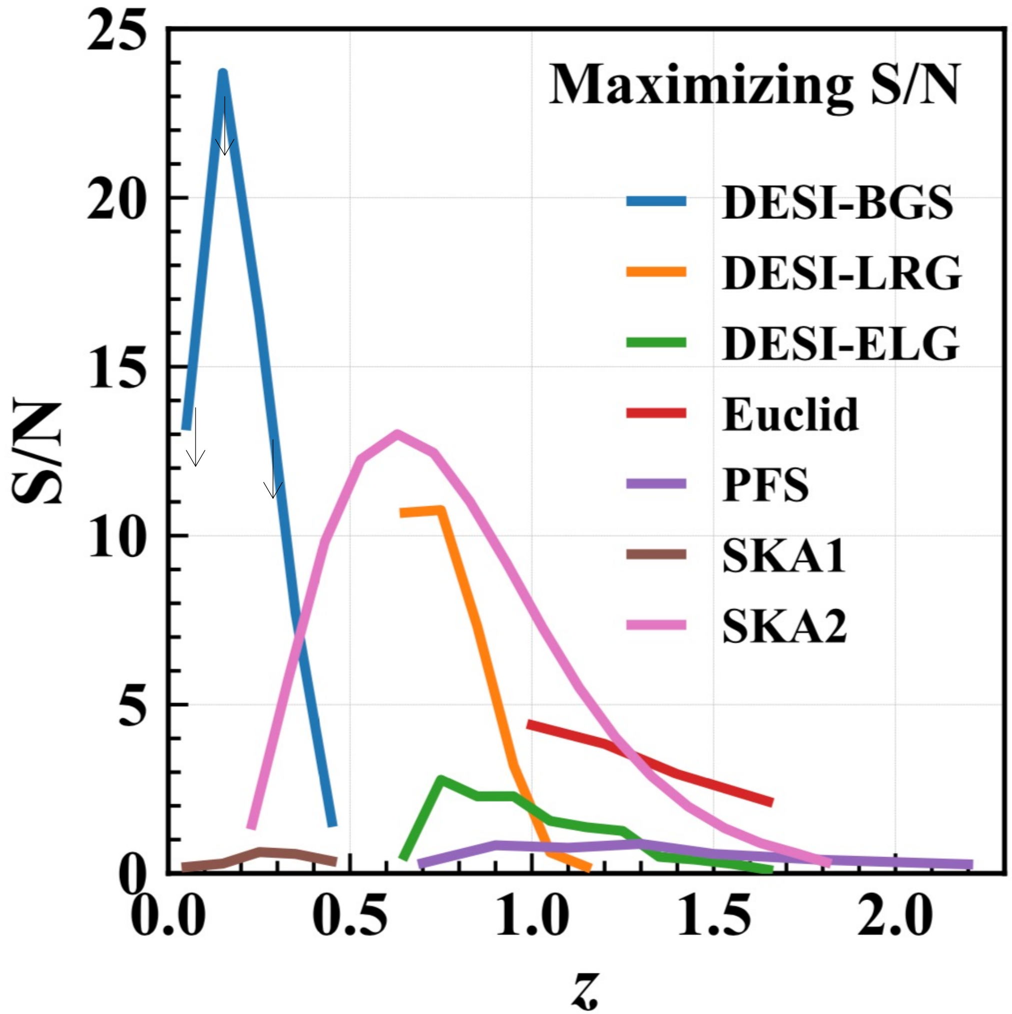
Taruya et al,2019
Saga et al, 2020



- Zeldovich prediction+NL halo term (e.g. NFW potential) => good prediction below 50 Mpc/h (unlike linear one)
- Increasing halo mass or redshift=> increase sign flip scale

Detectability

Saga et al., 2022

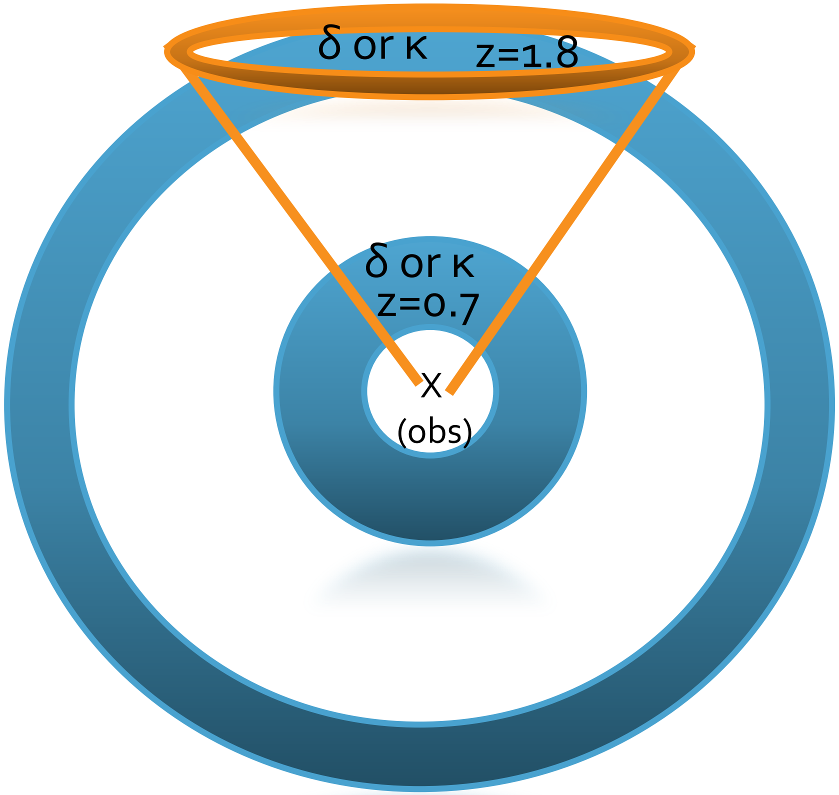


- *Caution: DESI-BGS is only an upper bound, you can skip this curve (accurate HOD modeling is required)*
- **S/N>10 for DESI and SKA.**
- **New probe of the gravitational potential at cosmic scales**
- **New test of the equivalence principle: Saga et al.2023**

Application 2:
Relativistic Lensing Matter Clustering

GEOMETRY AND QUANTITIES

- Quantities: Observed matter overdensity δ and apparent weak-lensing convergence κ



- Statistics: C_l

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

- Geometry: centered on observer, 2500 deg^2 light-cone : shells at z=0.7+-0.2 and z=1.8+-0.1

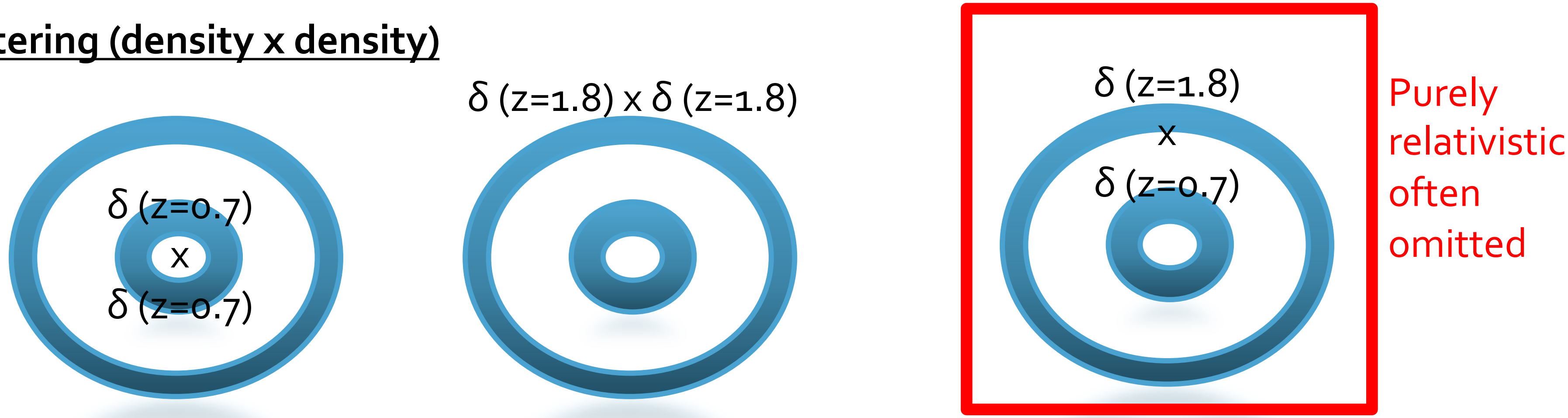
- DEFINITION:

NON-TRIVIAL RELATIVISTIC EFFECTS= DEVIATION FROM COMOVING MATTER OVERDENSITY AND BORN CONVERGENCE (ie. mostly magnification bias MB and RSD)

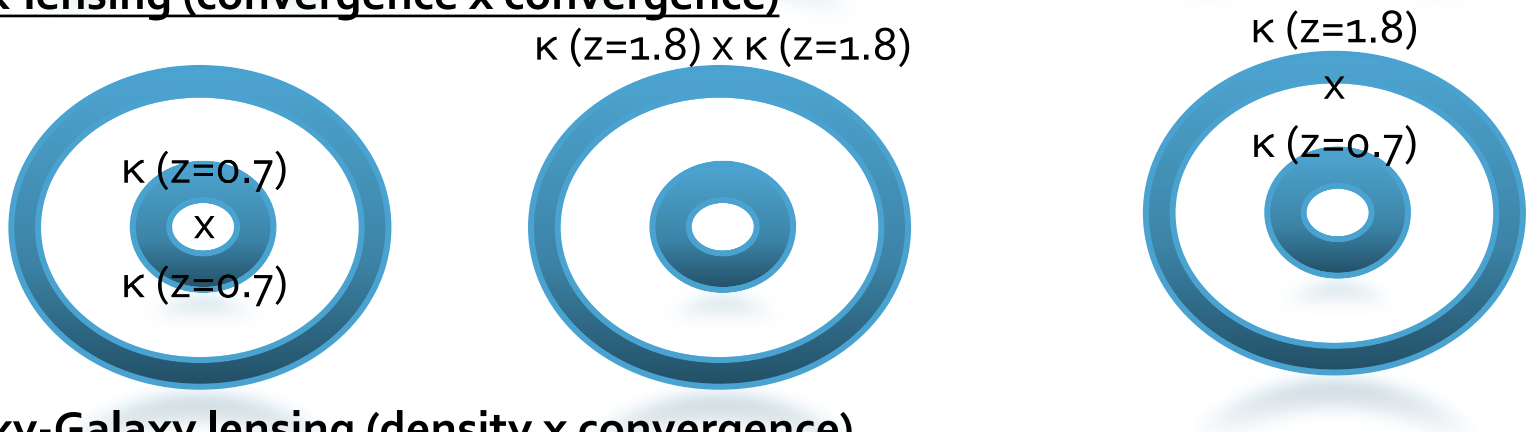
- THEORY (for comparison): CLASS

-> Linear with all relativistic effects
 + Non-linear prescription= halofit, linear mapping, RSD no Finger of God, Born lensing, etc.

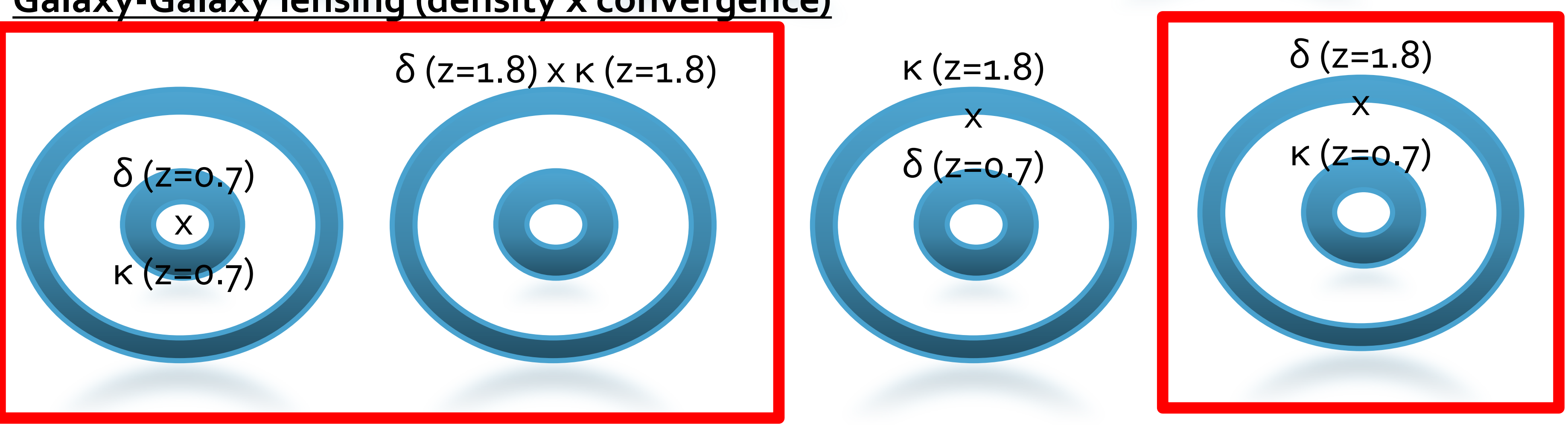
Clustering (density x density)



Weak-lensing (convergence x convergence)

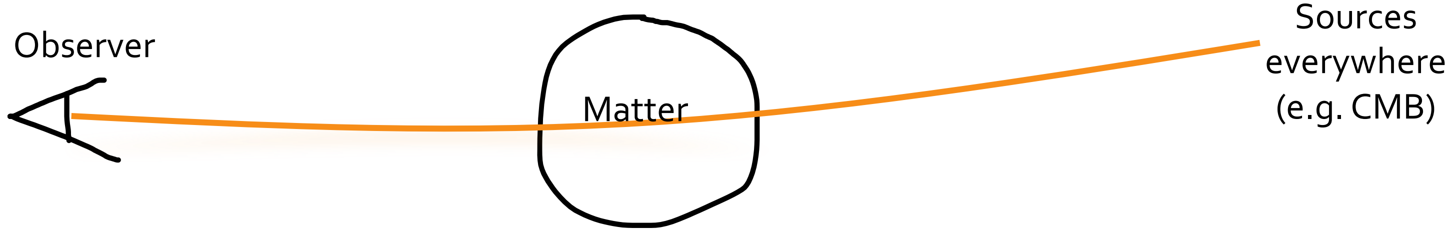


Galaxy-Galaxy lensing (density x convergence)



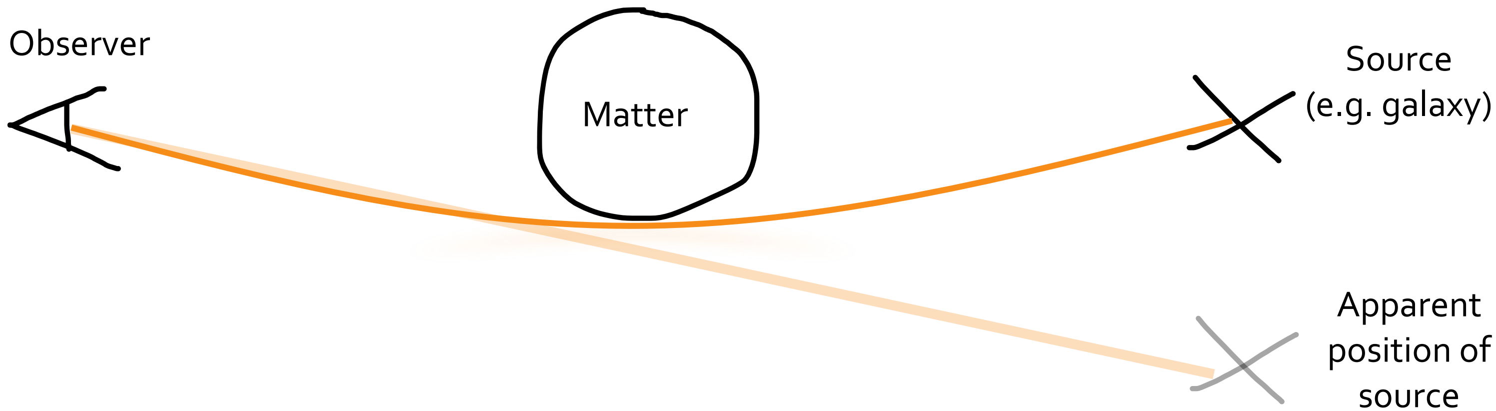
IMPORTANT TAKE HOME MESSAGE
SOURCE AVERAGING VERY DIFFERENT FROM ANGULAR AVERAGING

ANGULAR AVERAGING:



Usual approach: Born, post-Born, multiple-lens => minor correction

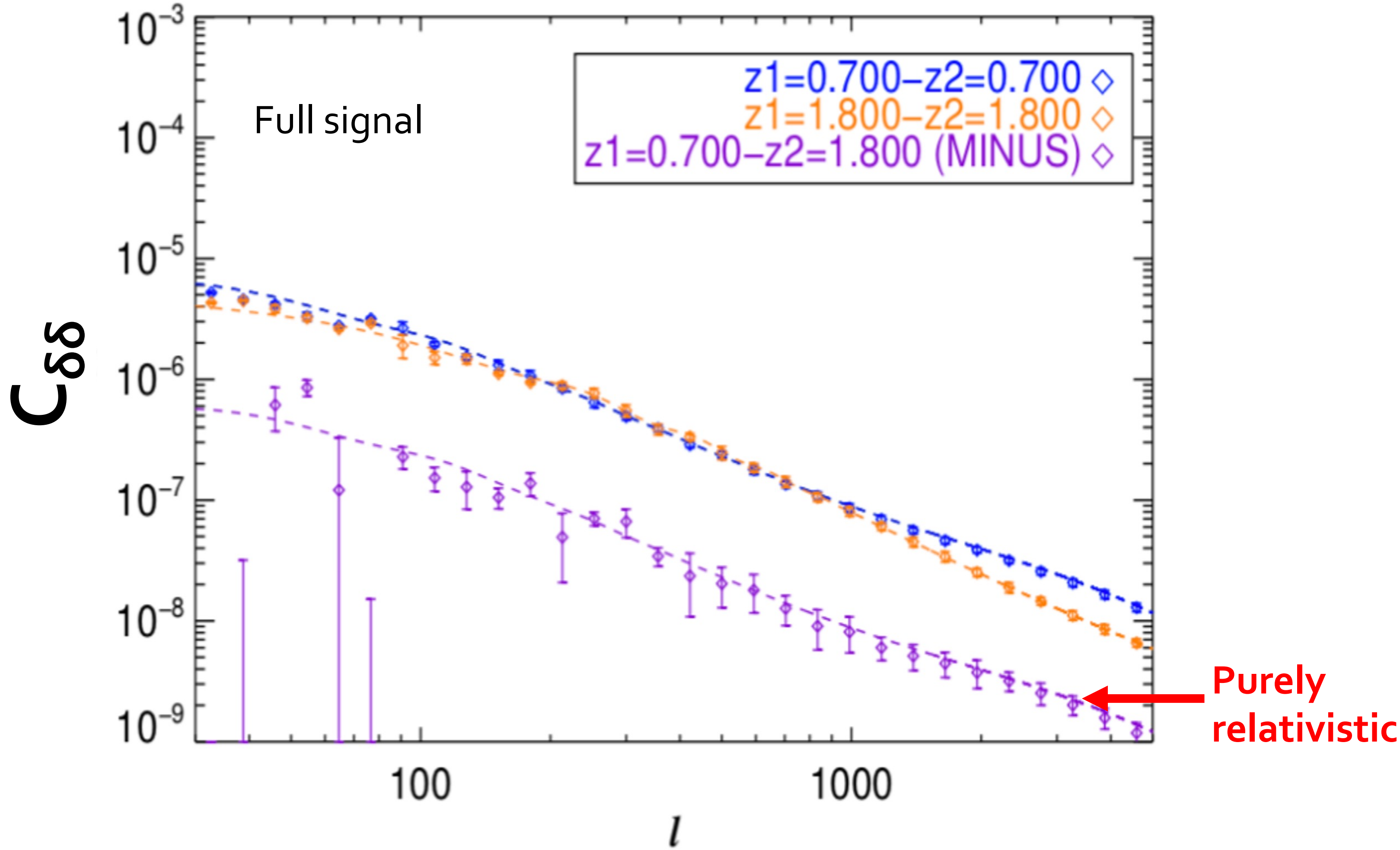
SOURCE AVERAGING:



In Magrathea, geodesics finders => light crosses exactly the source and the observer
strong effects (**magnification bias** etc), not only a post-born correction

Rasera et al. 2022

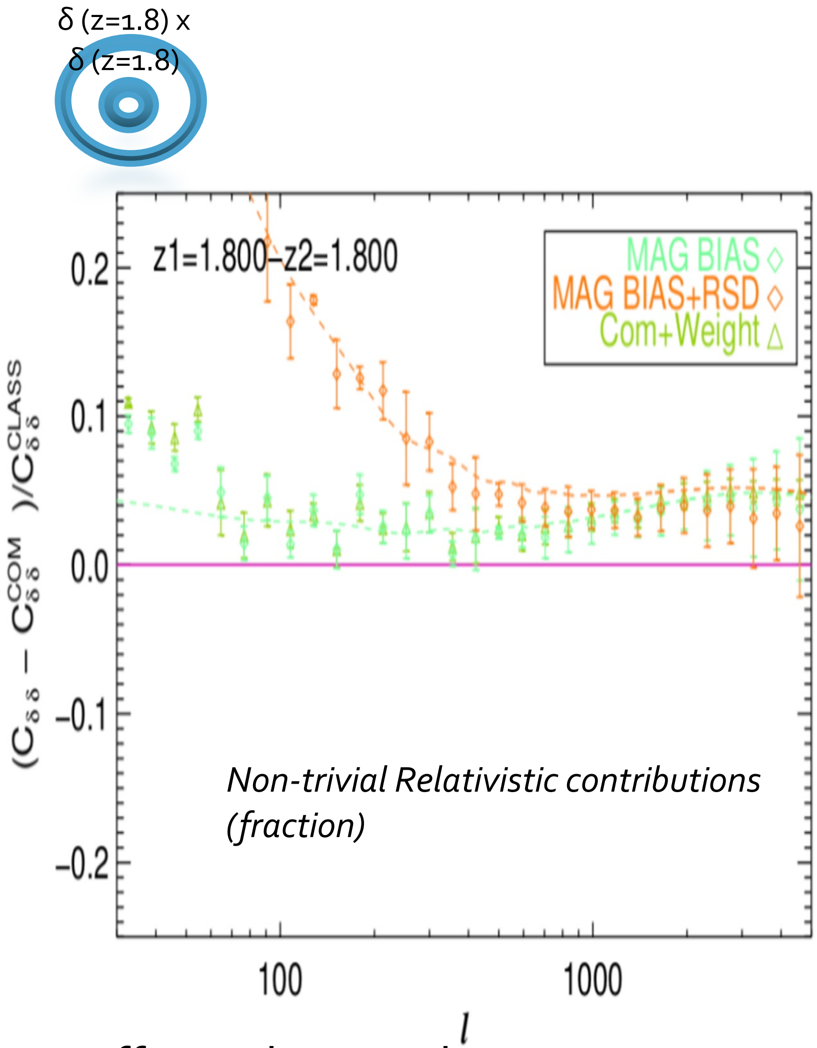
Matter angular (cross-)power spectra with relativistic contributions

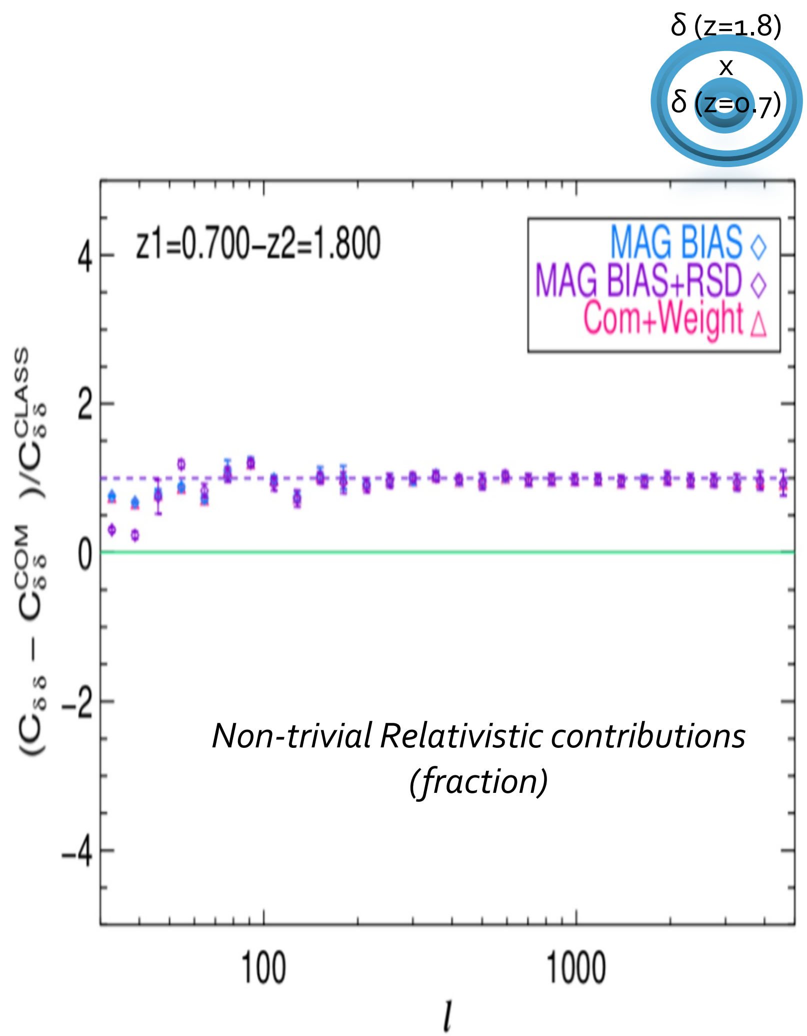


- **Good agreement with Class** (dashed lines)
- 3D matter P(k) calibrated on RayGal (otherwise halofit errors induce ~5% errors)

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

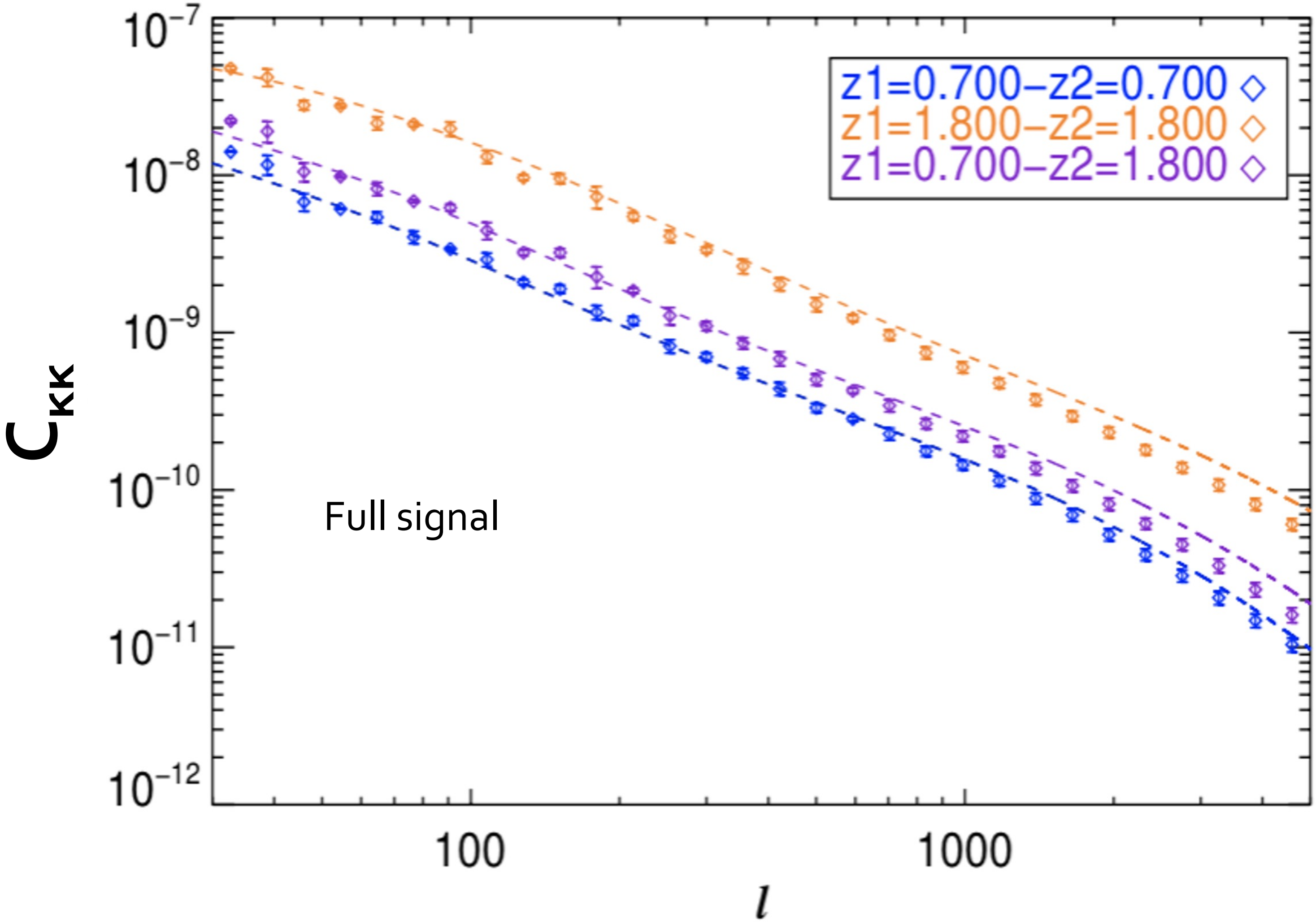
Rasera et al. 2022





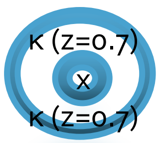
- RSD effect at large scale
- Magnification Bias (MB) => $\delta_{obs} \approx \delta_{com} - 2\kappa_{Born}$ (for flux-limited survey $-2\kappa \rightarrow (5s - 2)\kappa$)
- MB effect at every scale (+ dominate for distance shell)
- Not shown here at low redshift **Class doesn't capture Fingers-of-god effect**

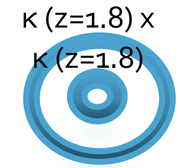
Convergence angular (cross-)power spectra
spectra with relativistic contributions



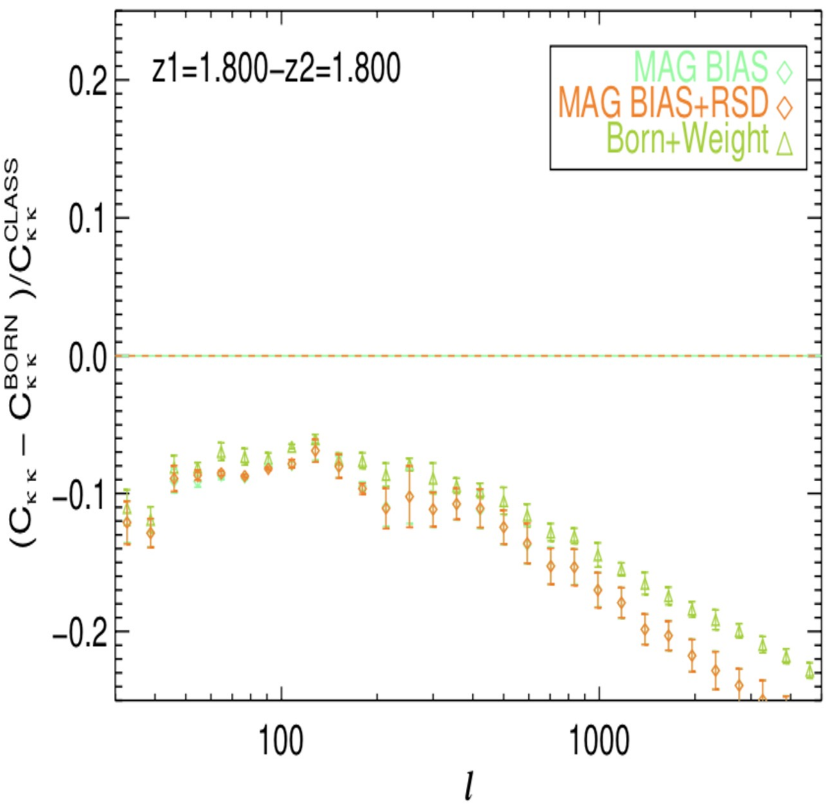
- **Reasonable agreement with class at large scales**

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

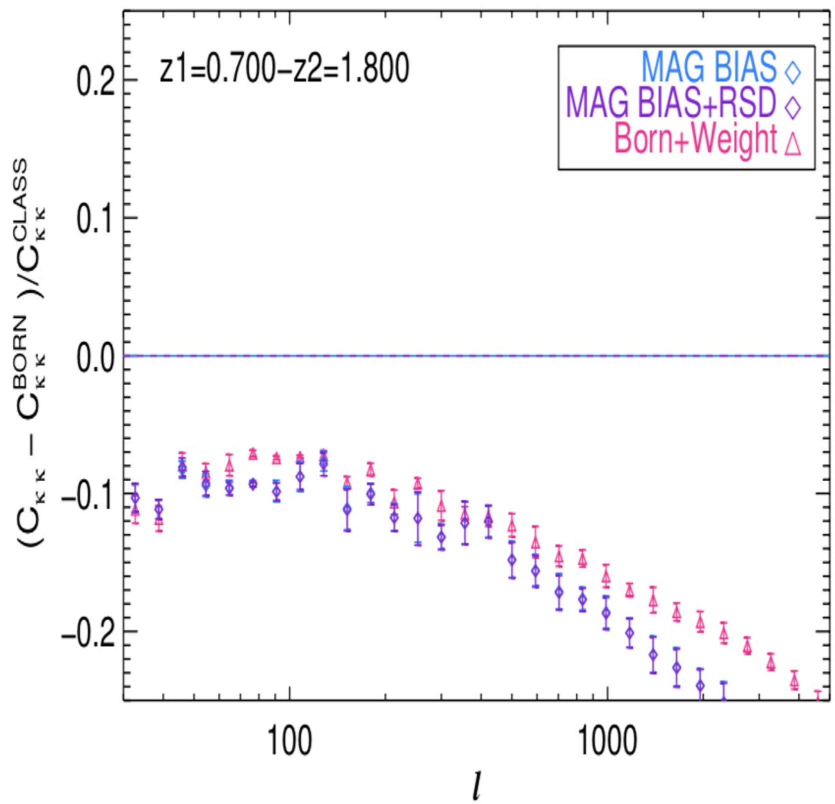




Non-trivial Relativistic contributions (fraction)

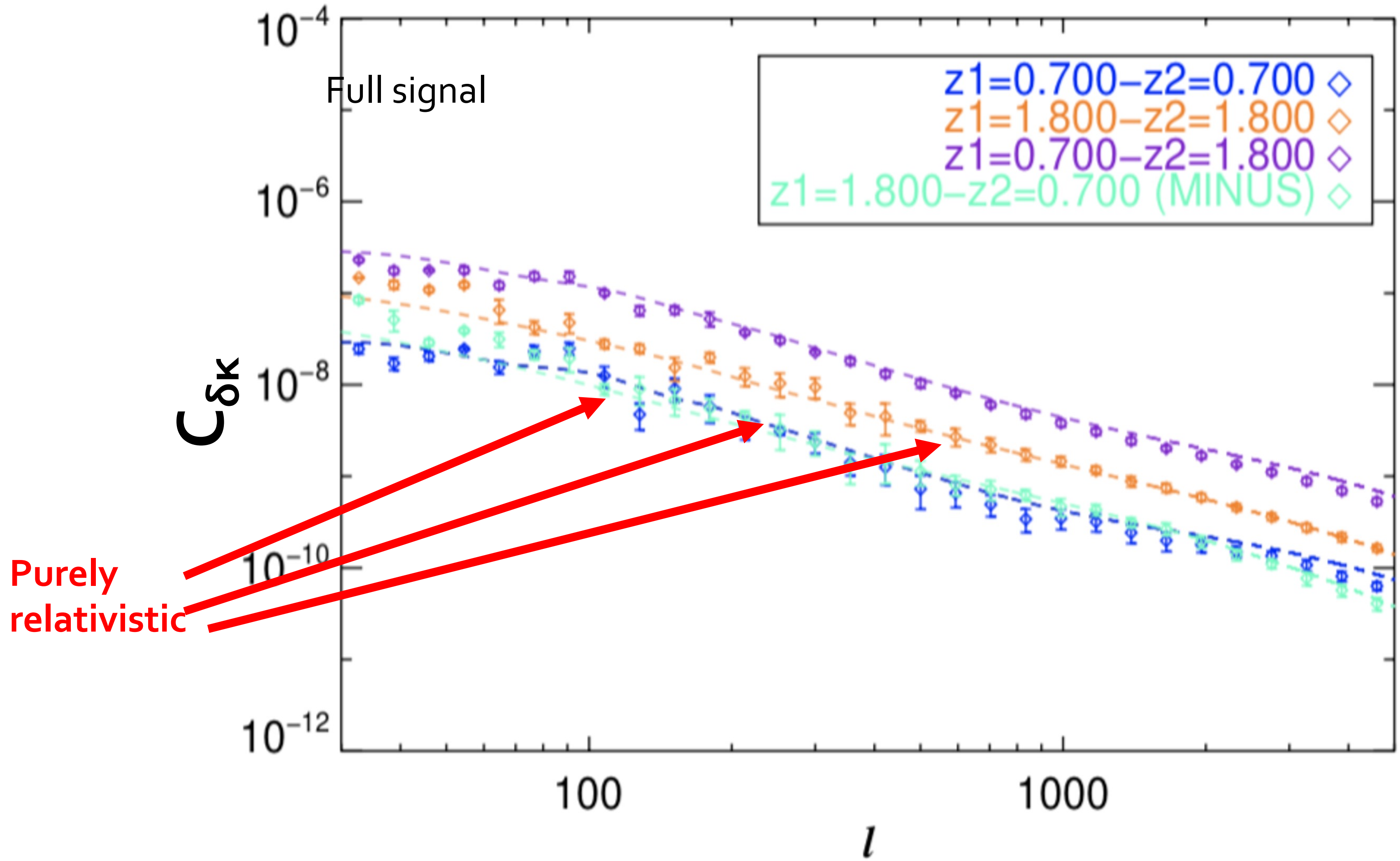


Non-trivial Relativistic contributions (fraction)



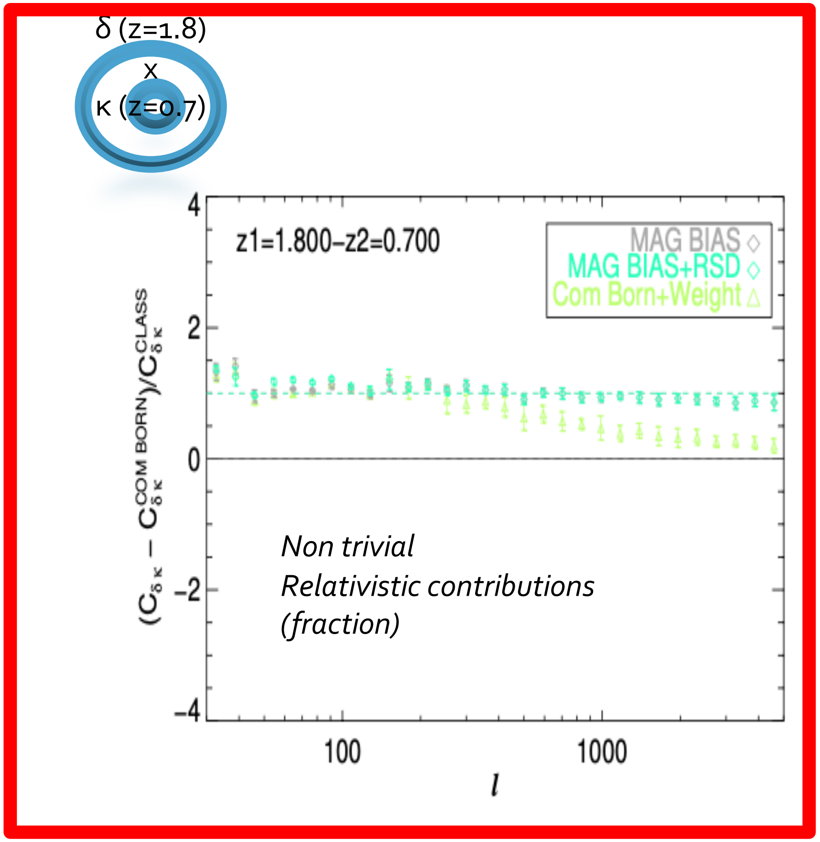
- **Cannot compute the effect of magnification bias on the convergence with Class (as it is related to the bispectrum)**
- $\kappa_{obs} \approx \kappa_{Born}\,(1-2\,\kappa_{Born})$.
- MB effect on convergence Cl means that **shear and convergence power spectra differ**!

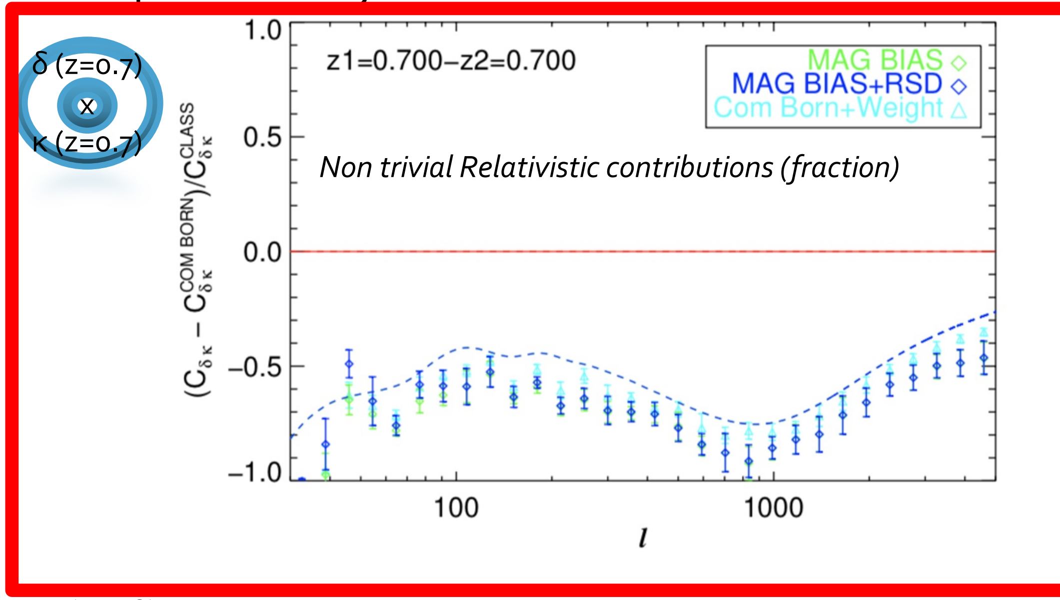
Density-convergence (cross-)power spectra with relativistic contributions

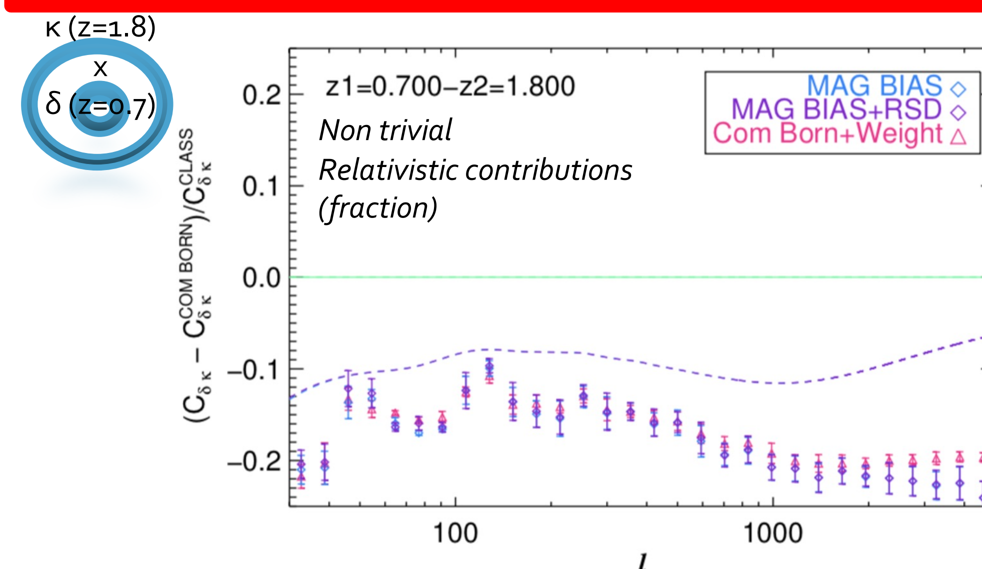


- **Good agreement with Class**

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

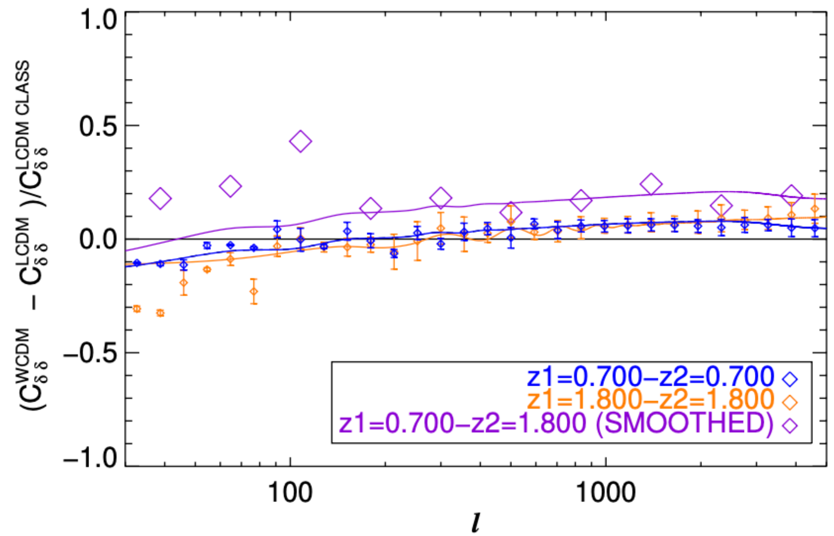


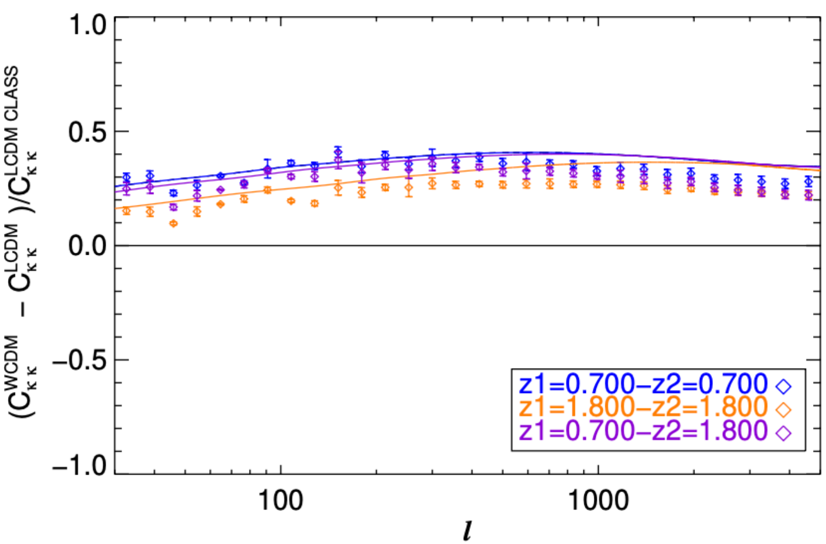


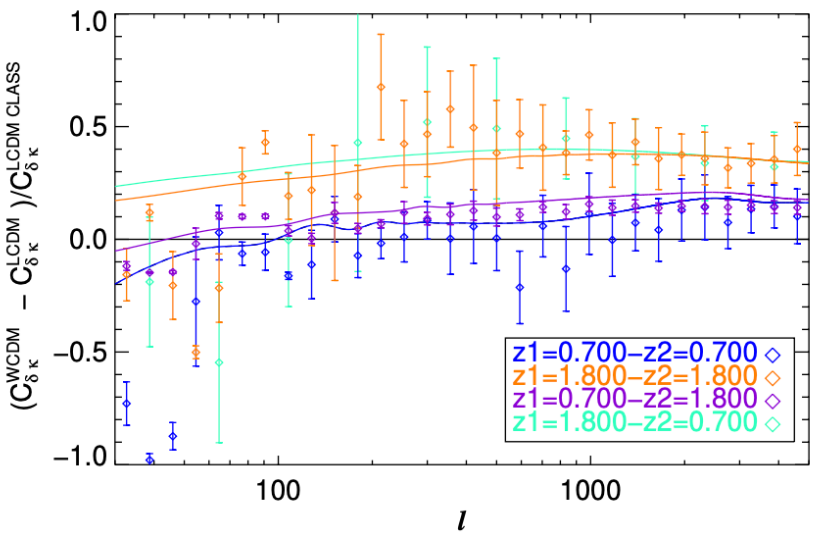


- MB => $\delta_{obs}\approx\delta_{com}-2\kappa_{Born}$ & $\kappa_{obs}\approx\kappa_{Born}(1-2\kappa_{Born})$.
- MB effect in Class is included but only for the density not the convergence => deviations
- Interesting **non- trivial configurations : including some with the convergence at lower or equal redshift than the density shell** => the cosmological signal is not negligible

Cosmological dependance (relative difference betweenWCDM (w=-1.2) &LCDM)







=> RELATIVISTIC LENSING-MATTER CLUSTERING IS A POWERFUL COSMOLOGICAL PROBE

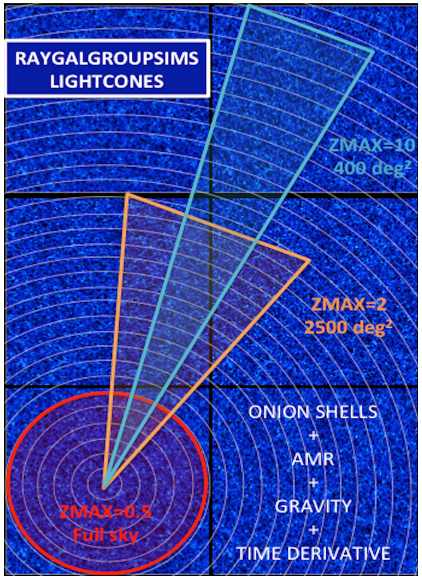
ADE 2023

CONCLUSION

• **Goal**: Understand the **connection from the "real universe" to the "apparent universe"** to find new probes of DE=> need to model **all weak-field 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
- Magrathea geodesics-finder => SOURCE AVERAGING available



•Relativistic effects in RSD

- For the 1st time **all the (kinematical) DIPOLE effects are modeled accurately in weak field from lin. to deep 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 (Saga et al, 2022).

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

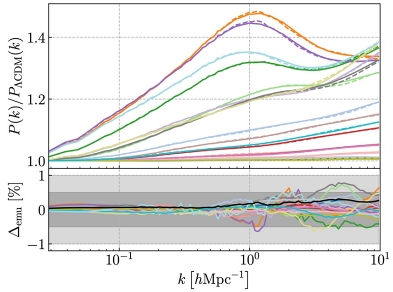
- good agreement with CLASS at quasi-linear scales
- **subtle effects in NL regime** (**Finger-of-gods** effect in angular correlation, **MAGNIFICATION BIAS** on the convergence power spectra, **non-trivial configuration in GGL**)=> powerful cosmo probe

•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...

ONGOING WORK

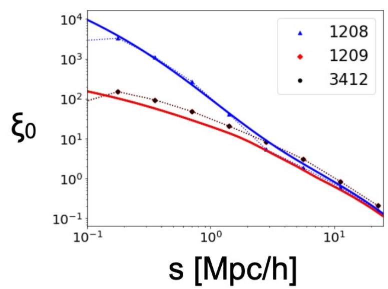
•OTHER MODELS: e-Mantis emulator for the3D matter power-spectrum in F(R) GRAVITY by I.SAEZ-CASARES
Saez-Casares et al. 2023 https://pypi.org/project/emantis/ (+application to Euclid forecast on going)

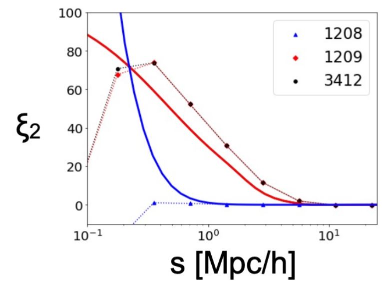


pypi v1.0.4 DOI 10.5281/zenodo.7738362

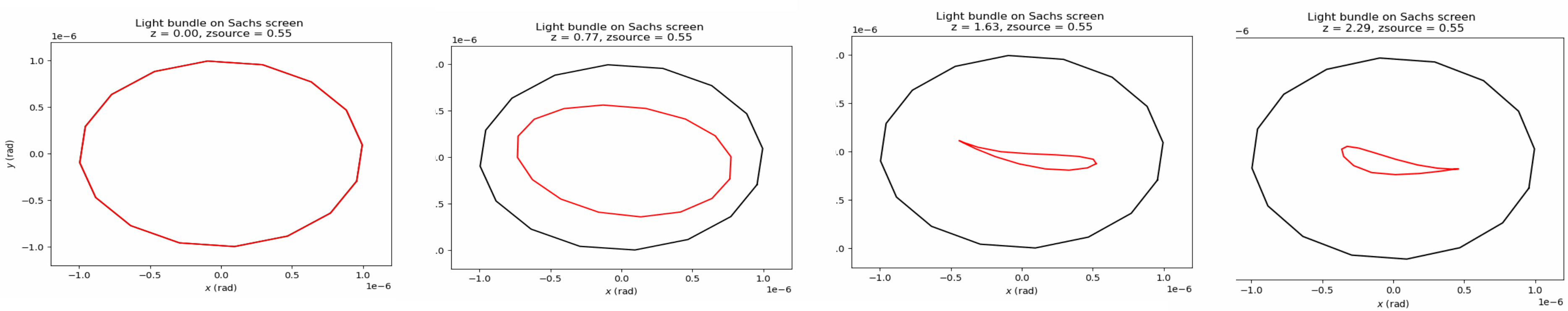
e-MANTIS: Emulator for Multiple observable ANalysis in extended cosmological TheorIeS

• OTHER PROBES: relativistic effect in the halo-matter cross-correlation (S. SAGA, preliminary results)





•TOWARD STRONG LENSING: Strong-lensing weak-lensing connexion (M-A BRETON: New simulation 220 Mpc/h 2048^3 particles + narrow light-cone). Preliminary results: evolution of a light bundle.



•ProGraceRay ANR project (2024-2028): the suite of all of this! Ad: we are looking for a postdoc about MODIFIED GRAVITY & N-body simulations (see inspirehep or jobregister if interested)

BACKUP SLIDES

Philosophy exam for everybody in the room

What is the link between

THE « REAL » UNIVERSE

and

THE OBSERVED UNIVERSE

?

PROBLEMS

- **Redshift perturbations**: modification of the apparent redshift (i.e. infered distance) of structures
- **Weak-lensing**: modification of the apparent angular position, shapes, luminosities of structures

=> The cosmological signal is blured

BUT

Redshift perturbations-> information about velocity fields (and more) at source location

Weak Lensing -> information about potentials along the line-of-sight

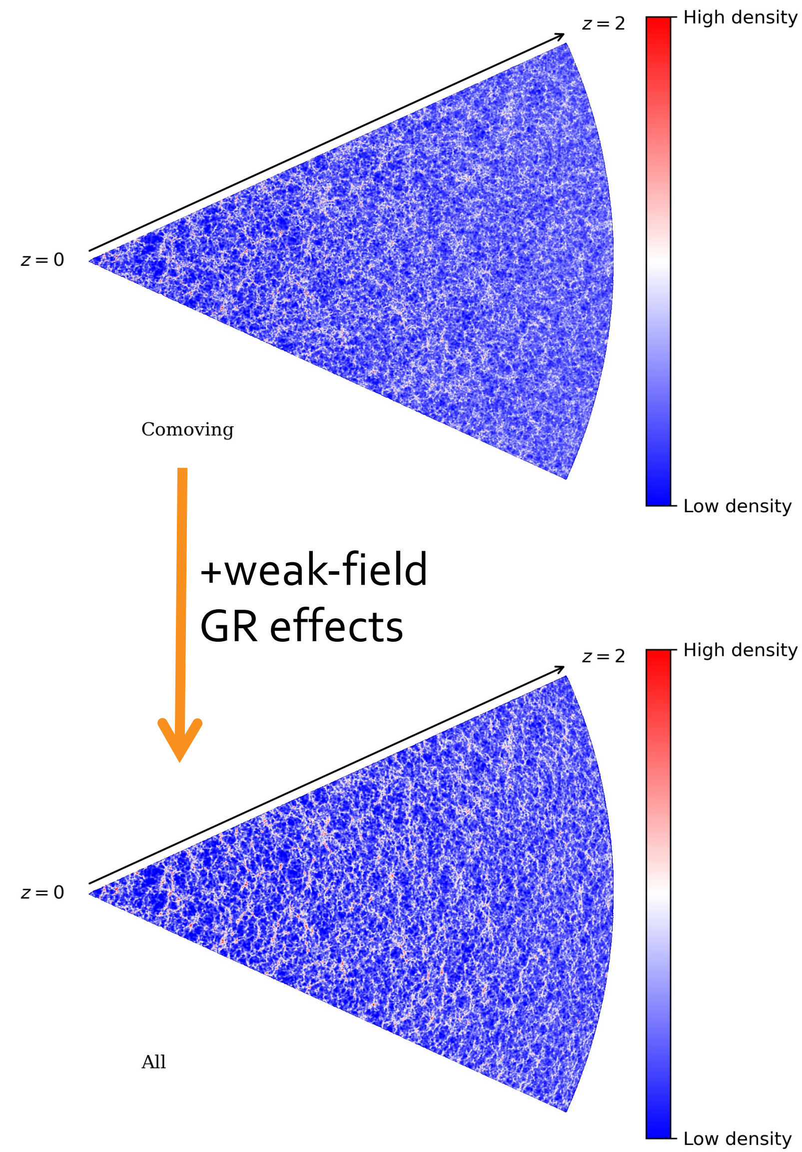
$\Rightarrow$ **NEW COSMOLOGICAL INFORMATIONS FROM WEAK LENSING (WL) AND RELATIVISTIC REDSHIFT SPACE DISTORTIONS (RSD)**

RayGal simulation suite with General Relativistic Ray-Tracing

Breton et al. 2019; Rasera et al. 2022

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).



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**

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

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

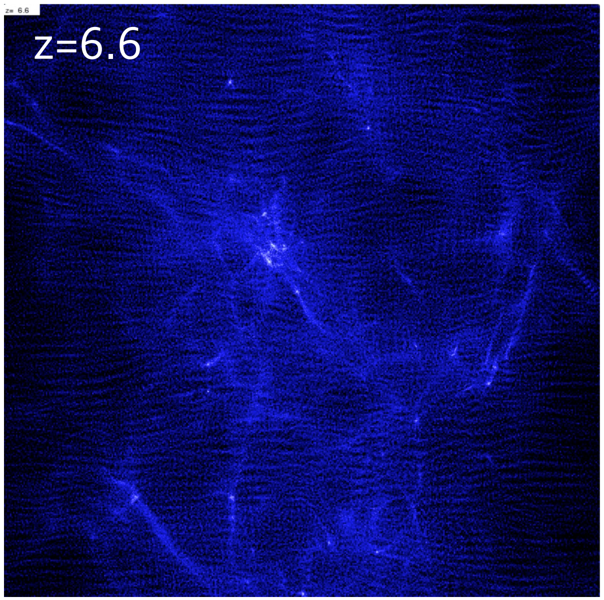
HOMOGENEOUS | DOPPLER | GRAVITATIONAL REDSHIFT | TRANSVERSE DOPPLER | ISW-RS | LENSING

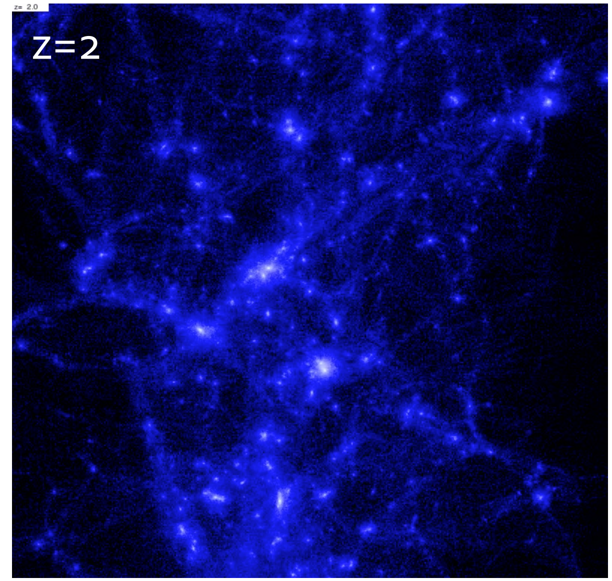
- **OBSERVED DENSITY IS GIVEN BY (NON-LINEAR MAPPING)**

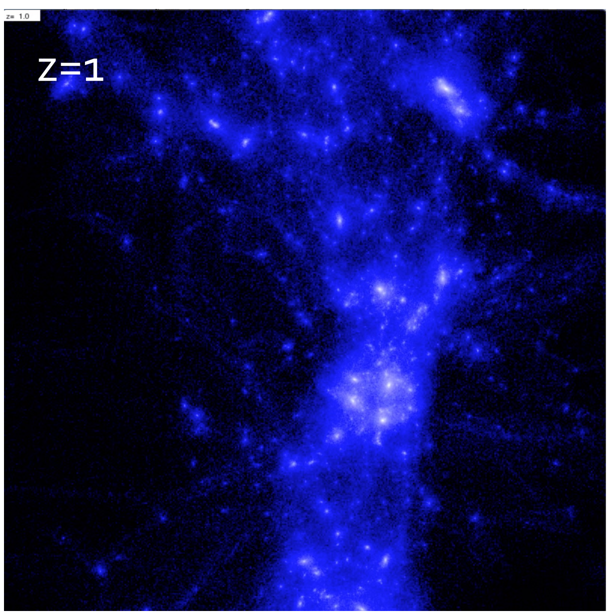
$$(1 + \delta_{obs})dV_{obs} = (1 + \delta_{real})dV_{real}$$

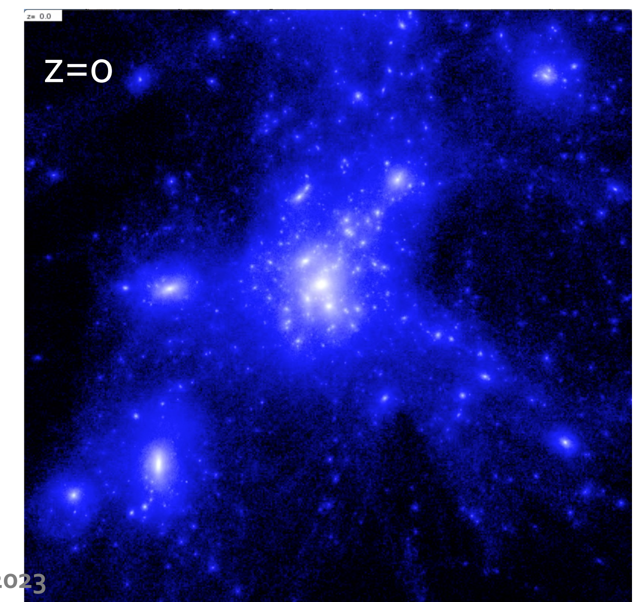
A tentative answer with modern physics (i.e. weak field general relativity) and modern methods (i.e. simulations)

STEP 1 : Build a (virtual) « real » universe by running N-Body sims: 4096^3 particles, $(2.6\ \mathrm{Gpc}/h)^3$, ΛCDM & wCDM



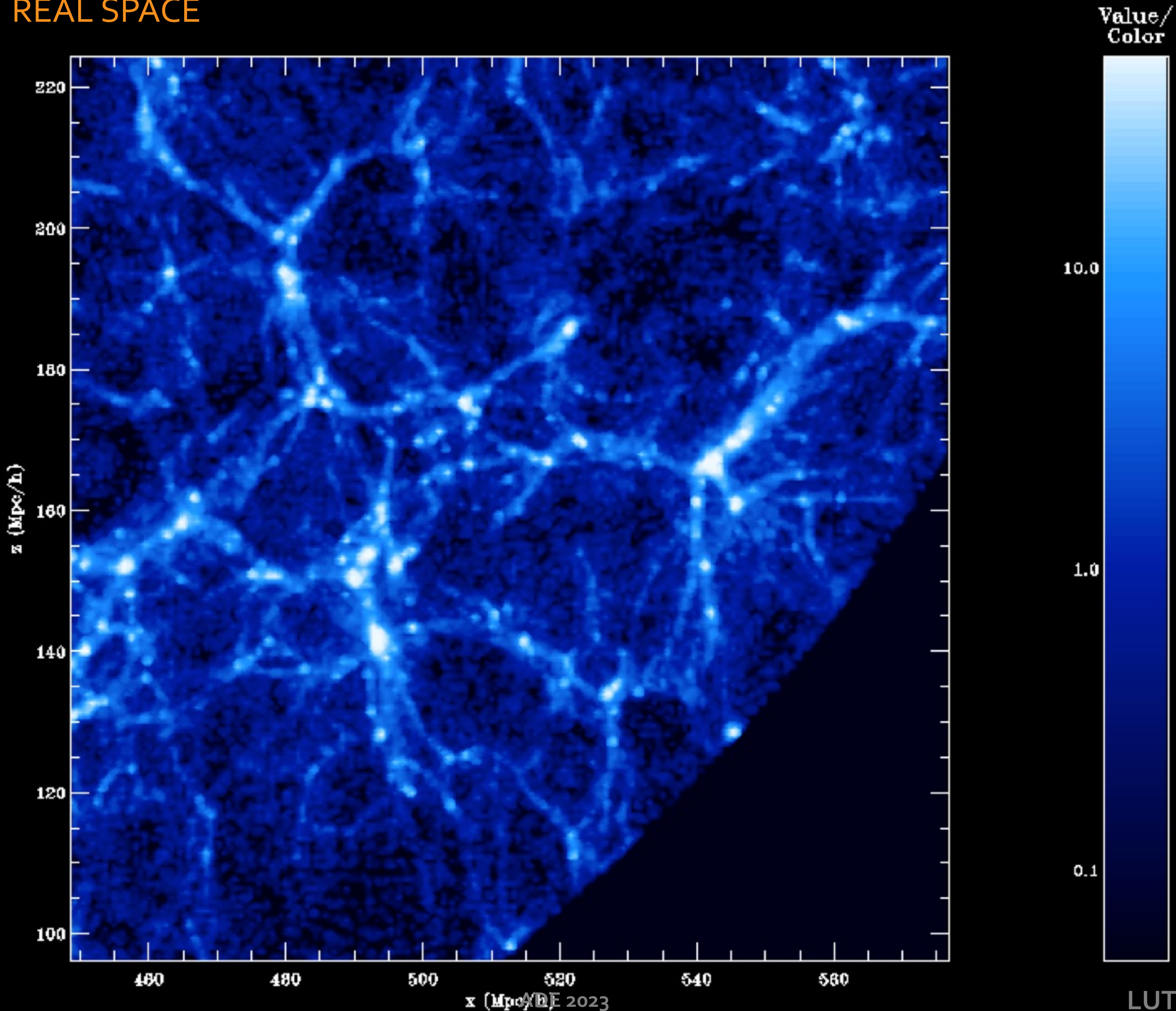




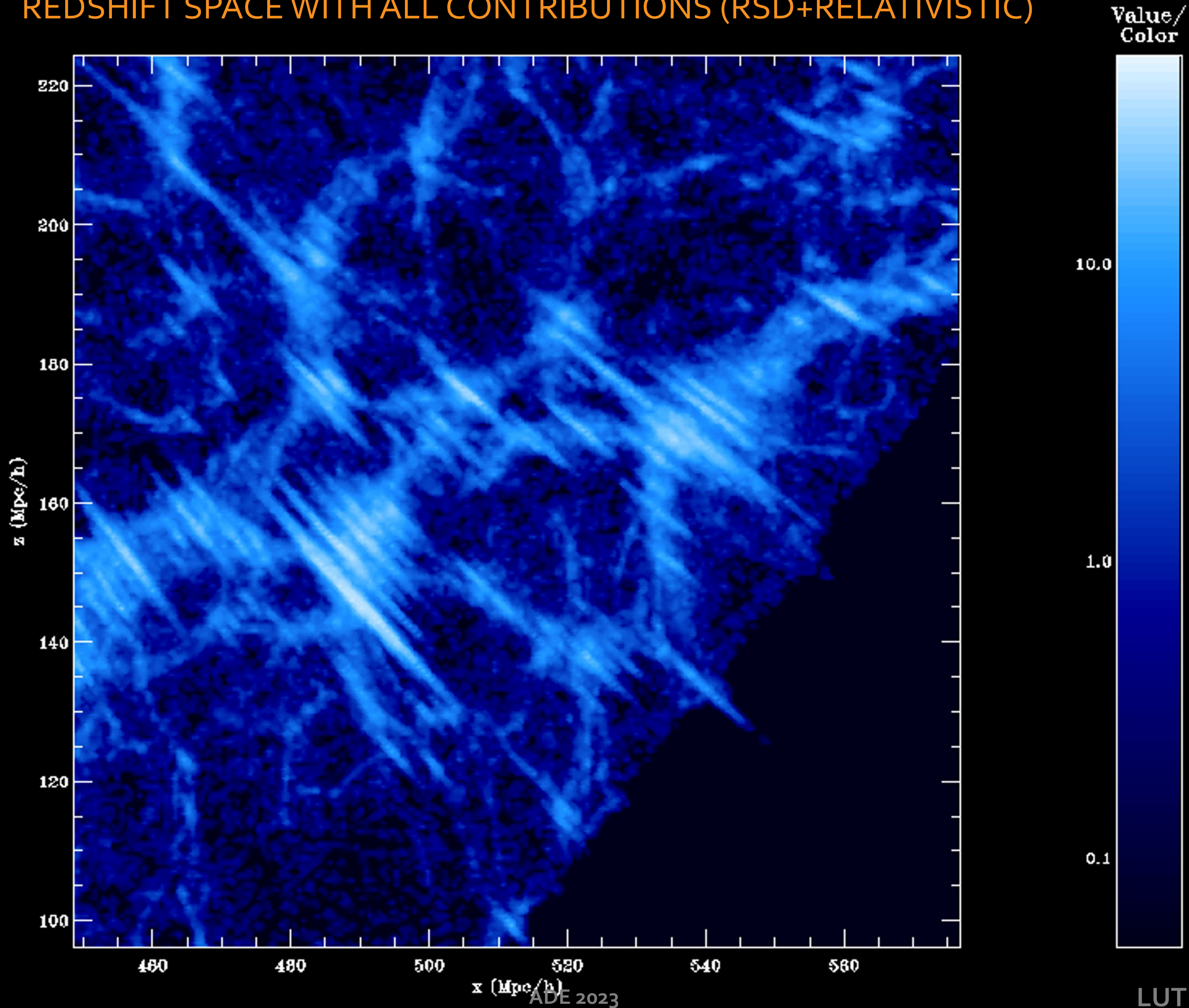


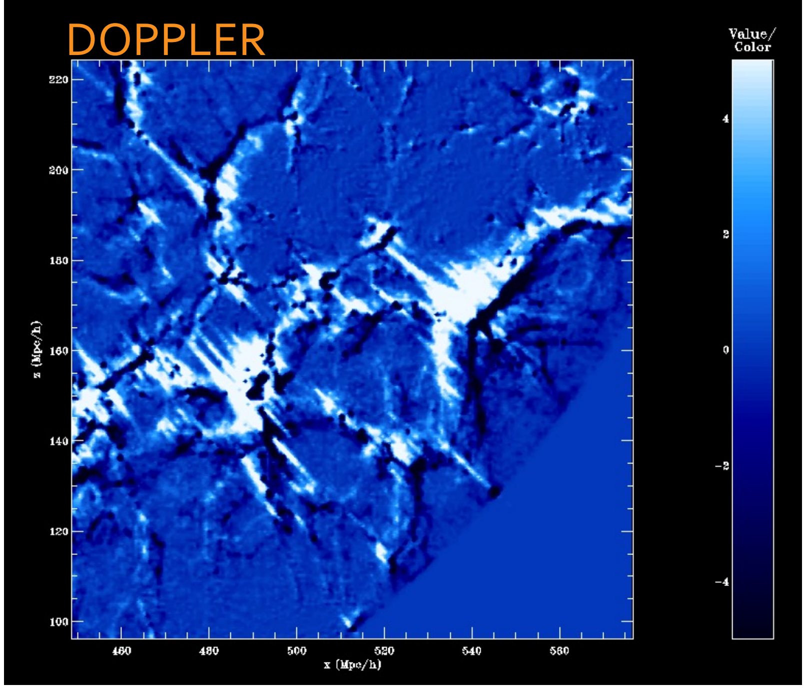
Illustrative example of the formation of one large halo in a simulation

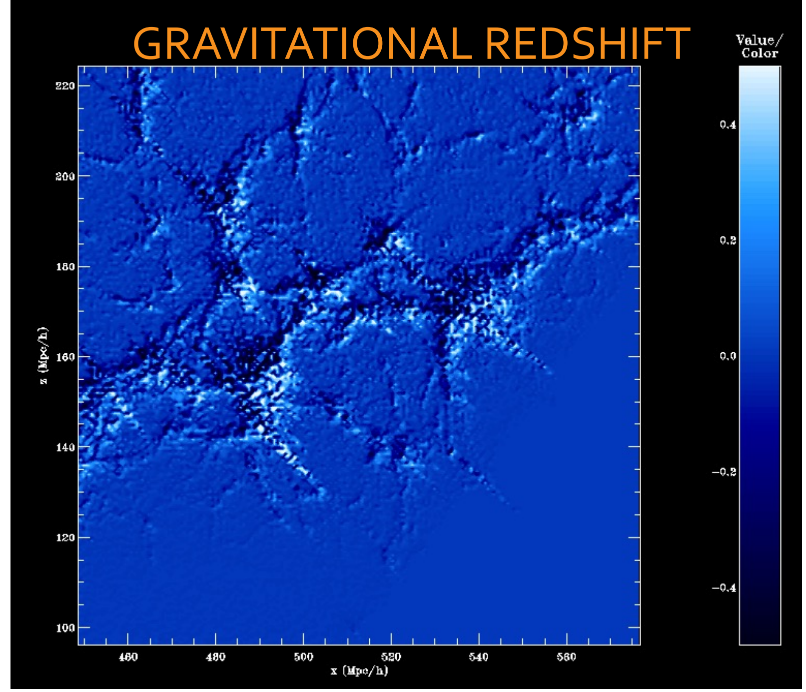
REAL SPACE

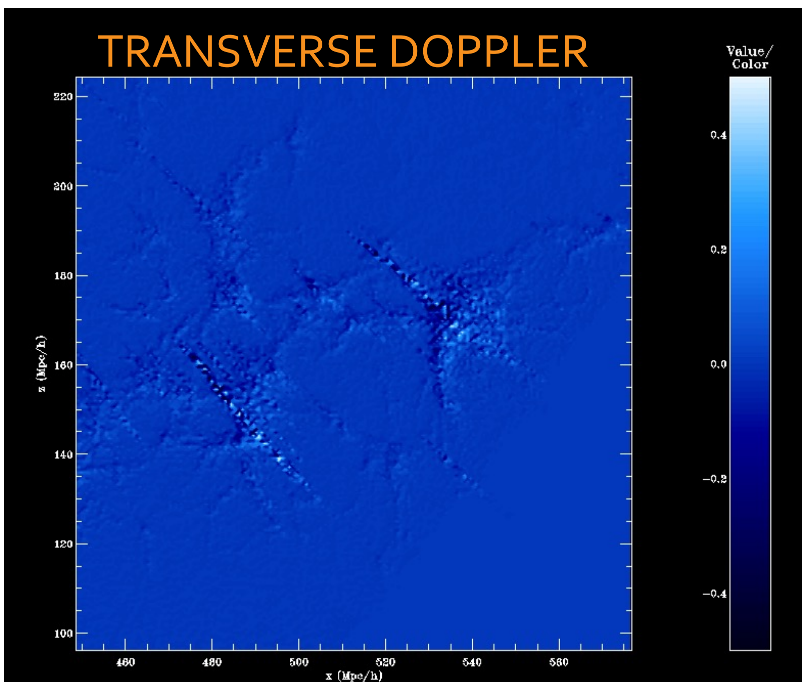

Value/
Color
10.0
1.0
0.1
220
200
180
160
140
120
100
z (Mpc/h)
460
480
500
520
540
560
x (Mpc/h)

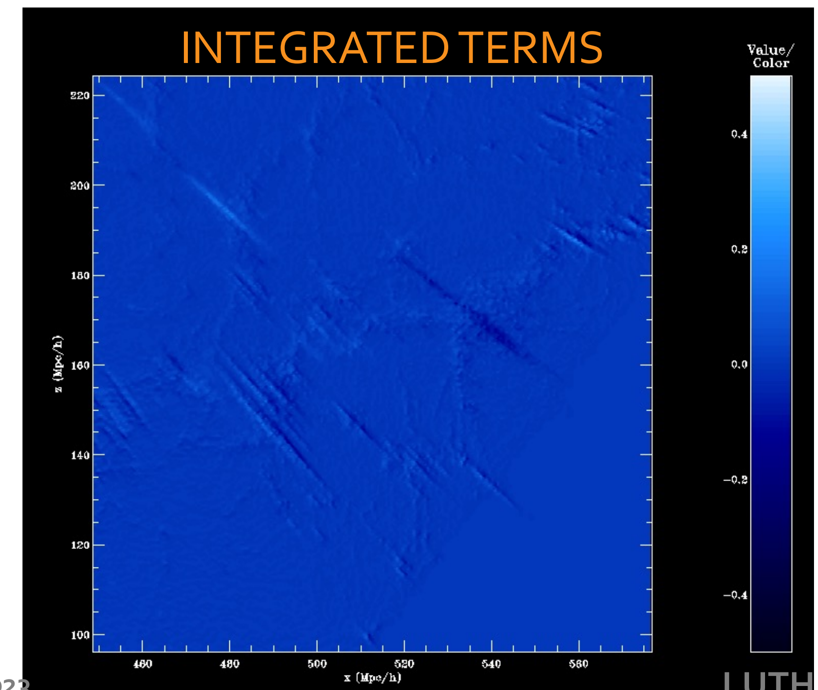
REDSHIFT SPACE WITH ALL CONTRIBUTIONS (RSD+RELATIVISTIC)

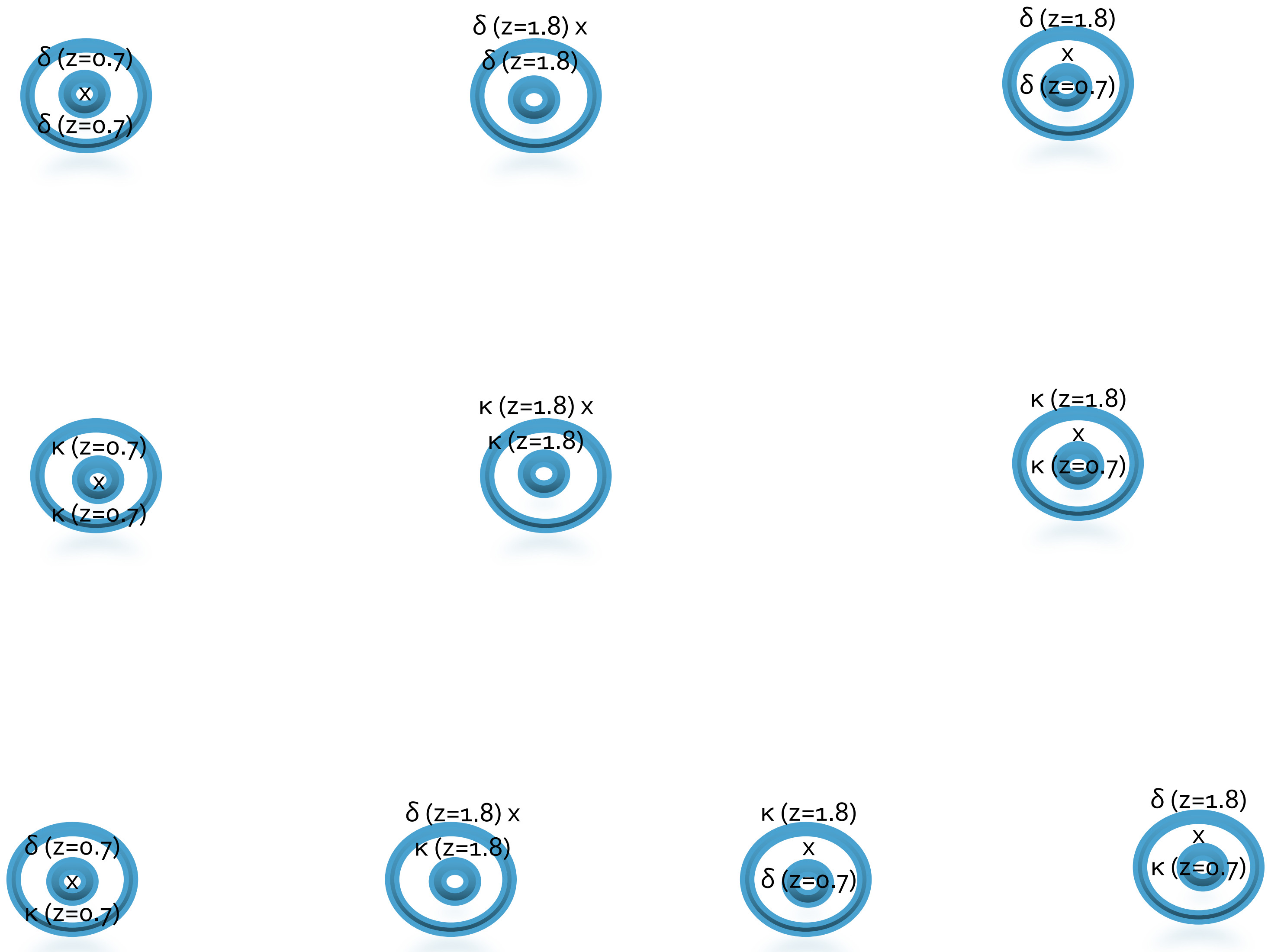



DOPPLER
Value/ Color
z (Mpc/h)
x (Mpc/h)


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)



δ (z=0.7)
x
δ (z=0.7)
δ (z=1.8) x
δ (z=1.8)
δ (z=1.8)
x
δ (z=0.7)
κ (z=0.7)
x
κ (z=0.7)
κ (z=1.8) x
κ (z=1.8)
κ (z=1.8)
x
κ (z=0.7)
δ (z=0.7)
x
κ (z=0.7)
δ (z=1.8) x
κ (z=1.8)
κ (z=1.8)
x
δ (z=0.7)
δ (z=1.8)
x
κ (z=0.7)

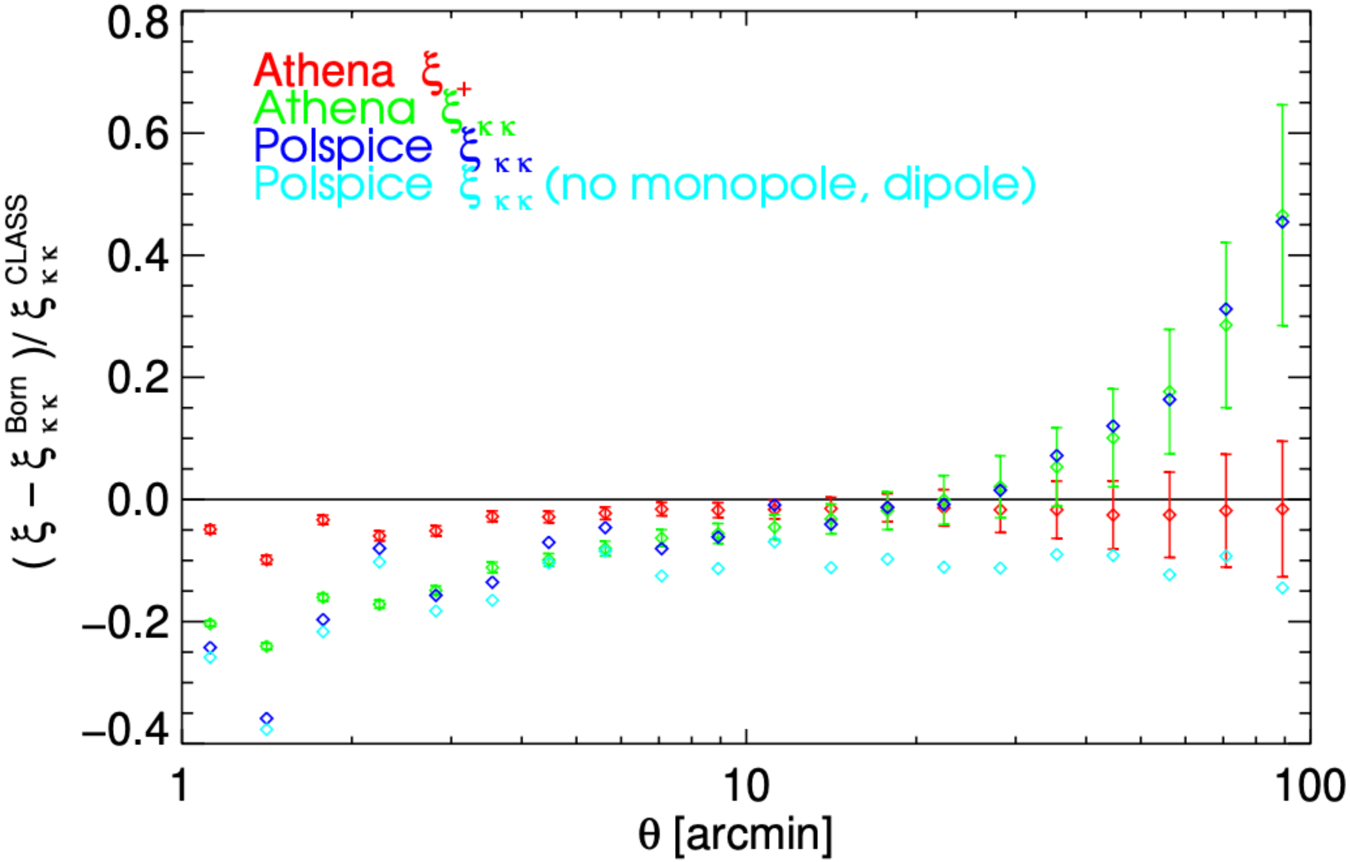


Fig. B.1. Relative difference between lensing angular two point correlation function on the source catalogue accounting for the dilution bias and the Born convergence angular two point correlation function. In red and green diamonds we show the measurements of cosmic shear and convergence correlation 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.

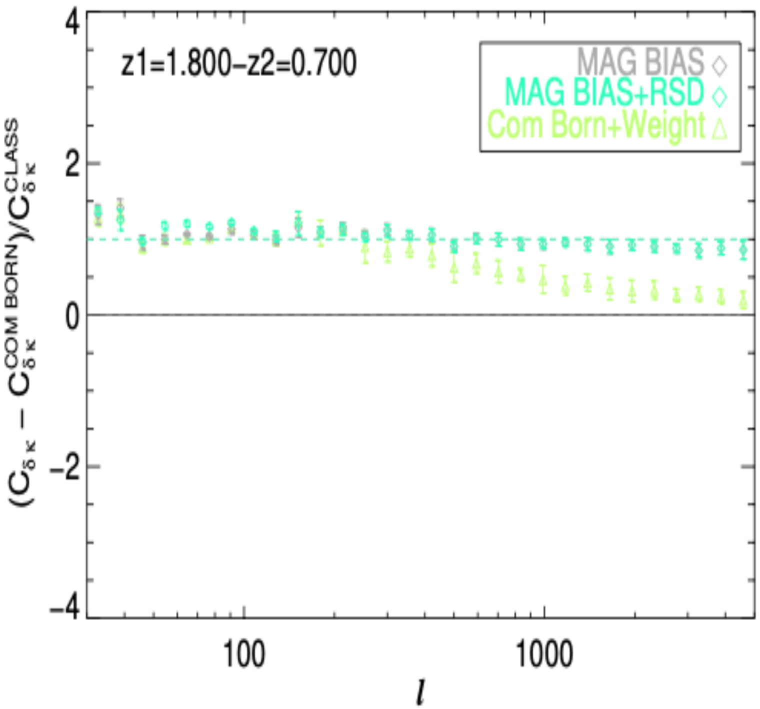


Fig. 13. Non-trivial reverse configuration of gravitational convergence at $z = 0.7$ and matter density at $z = 1.8$, similar to the bottom-right panel of Fig. 12. MB is in grey, MB+RSDs in cyan, and the $|\mu_{Born}|^{-1}$ weight MB estimate in light green. Relativistic effects almost reach 100%, in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

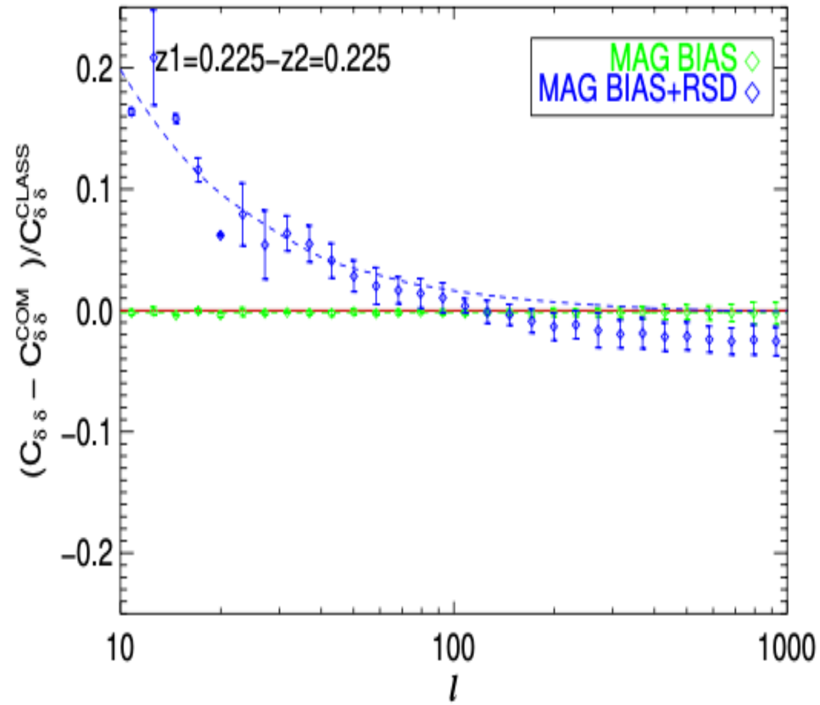


Fig. 14. Relativistic effects at low redshift on matter power spectrum $C_{\delta_1\delta_2}(\ell, z_1 = 0.225, z_2 = 0.225)$ (symbols are RAYGAL measurements, and lines are CLASS predictions). The MB effect (green) and RSDs(+MB) effect (blue) are shown. The trends are similar compared to higher redshifts,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