Cosmological N-body simulations and relativistic ray-tracing

Yann RASERA (LUX/Université Paris Cité /Paris Observatory/IUF)

Work with:

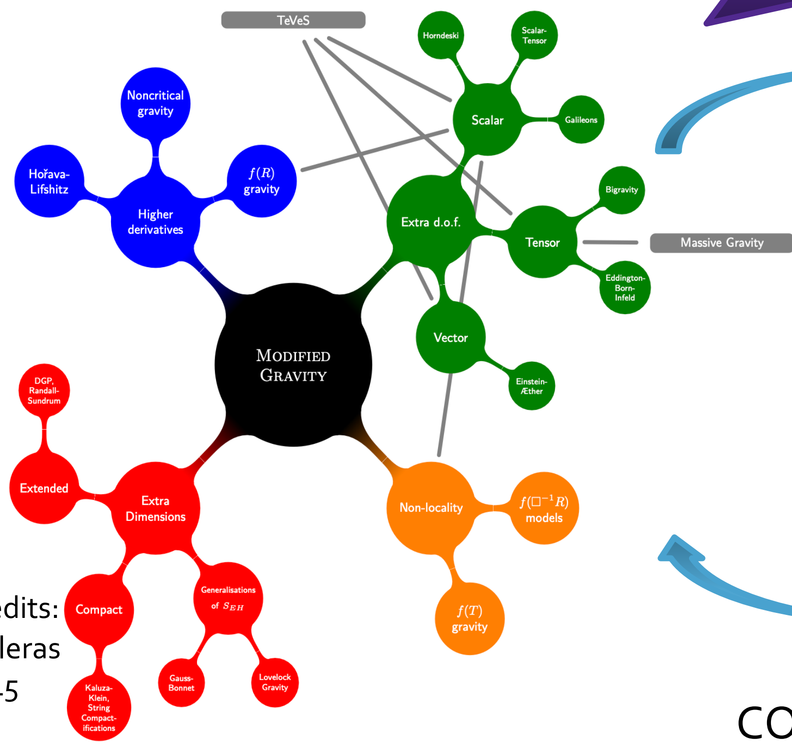
Michel-Andrès Breton (CEA), F.Castillo (LUX), M.Corioni (Trieste Univ.), Iñigo Saez-Casares (Milan University), V.Reverdy (LAPP), S.Saga (YITP), A.Taruya (YITP), P-S. Corasaniti (LUX), J.Allingham (Technion), F.Roy (LUX), T.Pellegrin (LPP), S.Anselmi (INFN), A.Le Brun (LUX)

Université Paris Cité

WHAT IS THE NATURE OF GRAVITY AT COSMOLOGICAL SCALES?

ACCURATE PREDICTIONS

SIMULATIONS



Credits: Trilleras 2015

ROBUST CONSTRAINTS

Modified gravity theories

Large-Scale Structure surveys

HOW DO WE PROCEED IN THE PROGRACERAY ANR-FUNDED RAMSES-POWERED PROJECT ?

N-BODY SIMULATIONS « GENERIC » MODIFIED GRAVITY MODELS

See Talk by Himanish Ganjoo

HYDRO SIMULATION « GENERIC » MODIFIED GRAVITY MODELS

Hey, wait a minute we just started! Work by Wangzheng Zang and collaborator (Y.Dubois., etc) @IAP

RELATIVISTIC RAY-TRACING

This Talk (work by M-A. Breton, M.Corioni, F.Castillo, etc.)

2 POINTS STATISTICS (3x2pts)

HIGHER ORDER STATISTICS

Talk work @OAS by Fabien Castillo More in the future @ LUX

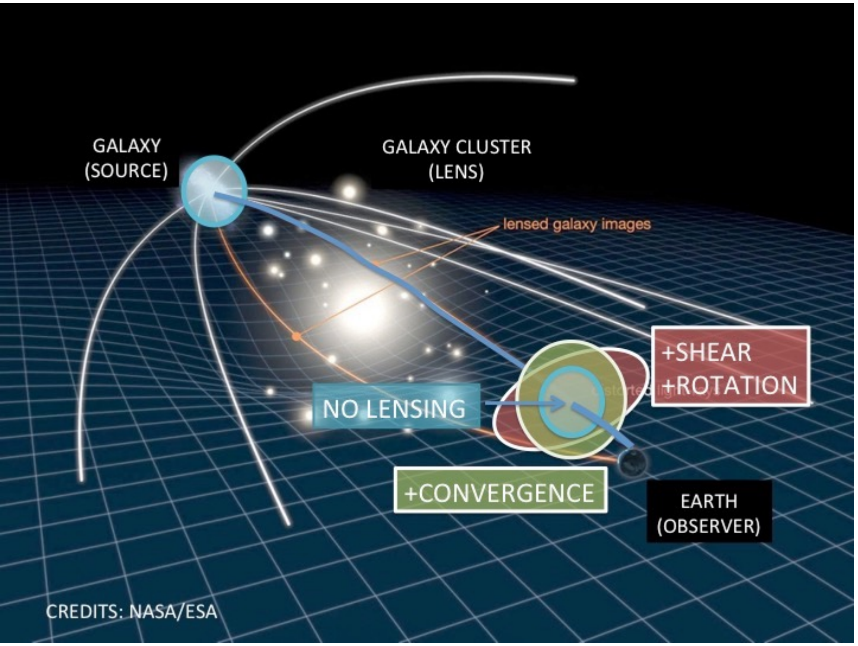
EMULATION PREDICTIONS

Talk of Last year About e-MANTIS Work by I.Saez-Casares

anr agence nationale de la recherche

Usual approach: compute WL maps or RSD catalogs

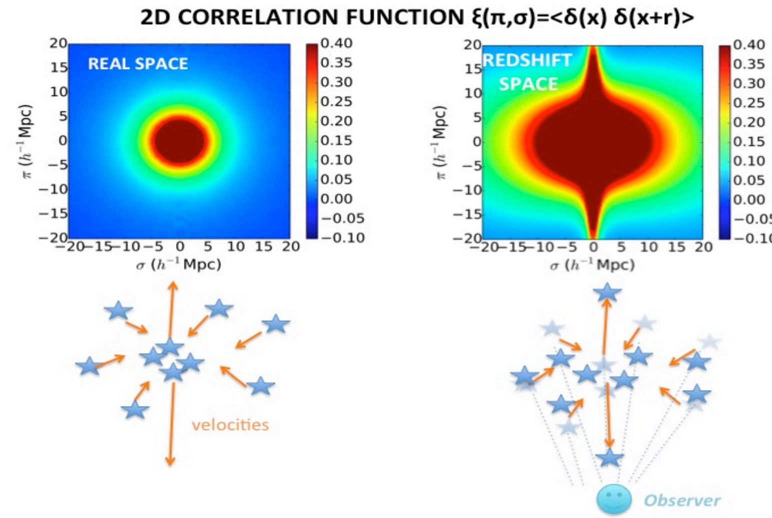
LENSING



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

OR

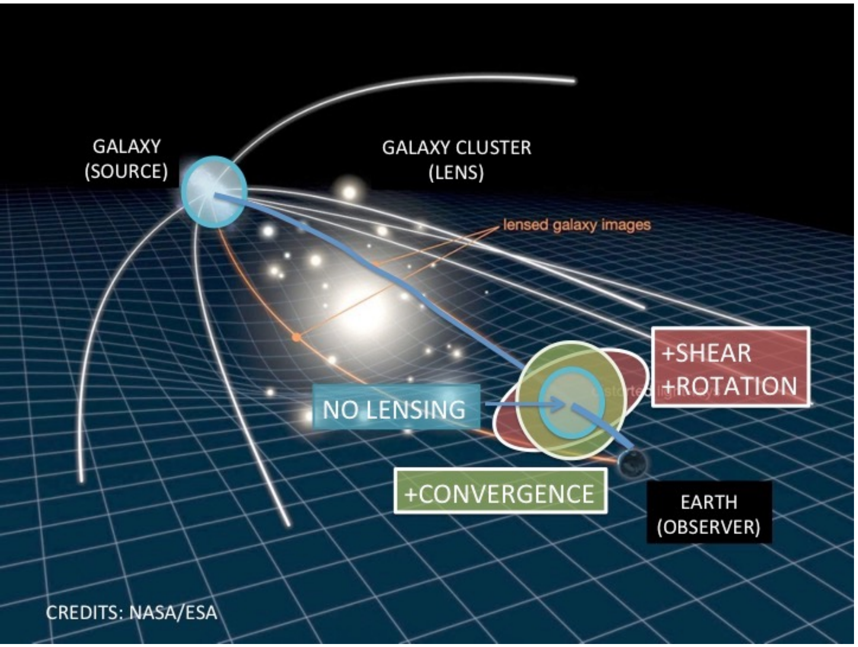
Redshift-Space Distortions (RSD)



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

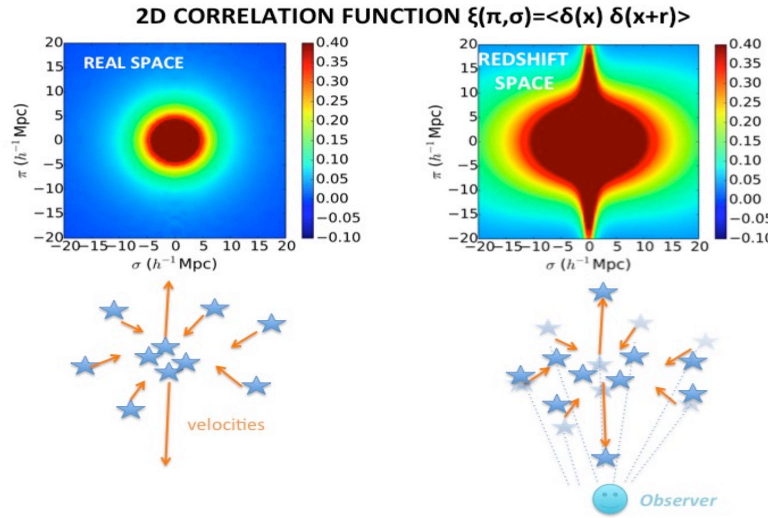
Relativistic approach: compute what is really observed following (weak-field) GR

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**
- 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

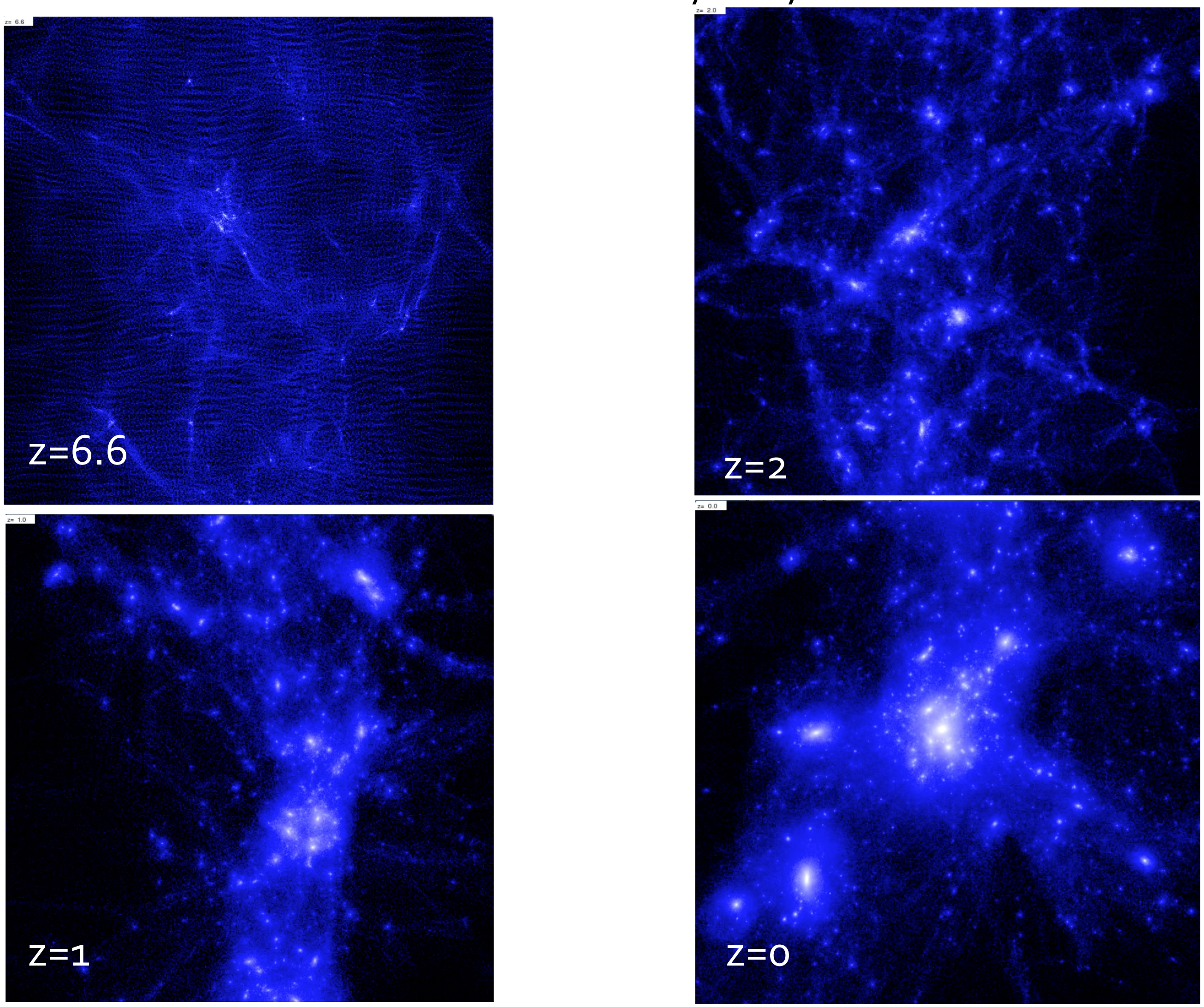
-> LIMITATION: How to connect with linear predictions ?

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

HOW TO PROCEED?

STEP 0: RUN AN N-BODY SIMULATIONS (e.g. RayGal)

- Goal: Build a (virtual) « real » universe by running N-Body sims with RAMSES
- 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

WHAT IS RAMSES ?

WHAT IS RAMSES ?

JUST KIDDING…. GOOD NEWS I CAN SKIP THIS SLIDE…

HOW TO PROCEED?
Step1: BACKUP A PARTICLES AND A GRAVITY LIGHTCONE

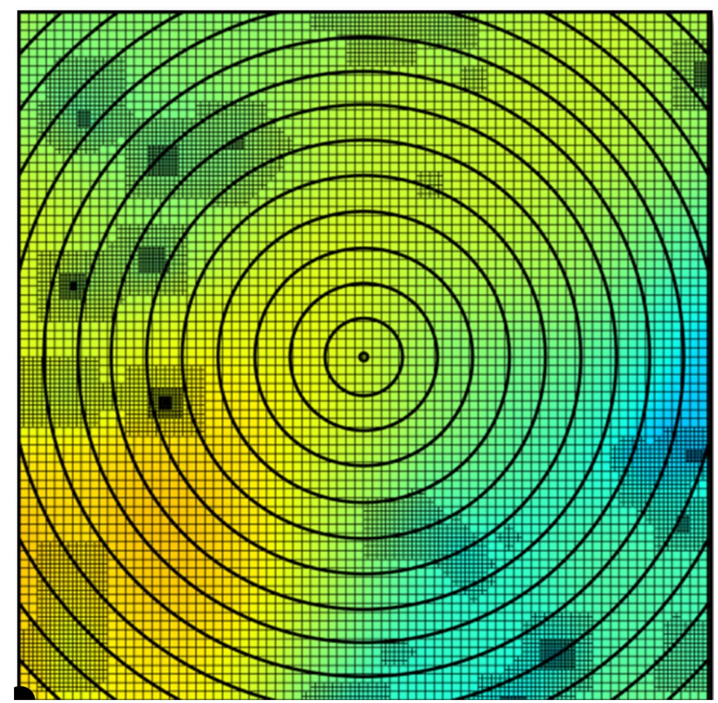
- What: particles lightcone (see Fosalba et al.2008, Teyssier et al. 2009) + gravity lightcone

- 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: Cells: potential (i.e. metric), gradient of the potential (i.e. gravitational field), time derivative of the potential + particles

- Type of light-cone: wide (fullsky, zmax=0.5), deep (2500 deg^2,zmax=2), very deep (400 deg^2,zmax=10)



STEP 2 : DIRECT INTEGRATION OF BILLION WEAK-FIELD GEODESICS EQUATIONS IN PERTURBED FLRW WITHIN AMR GRID

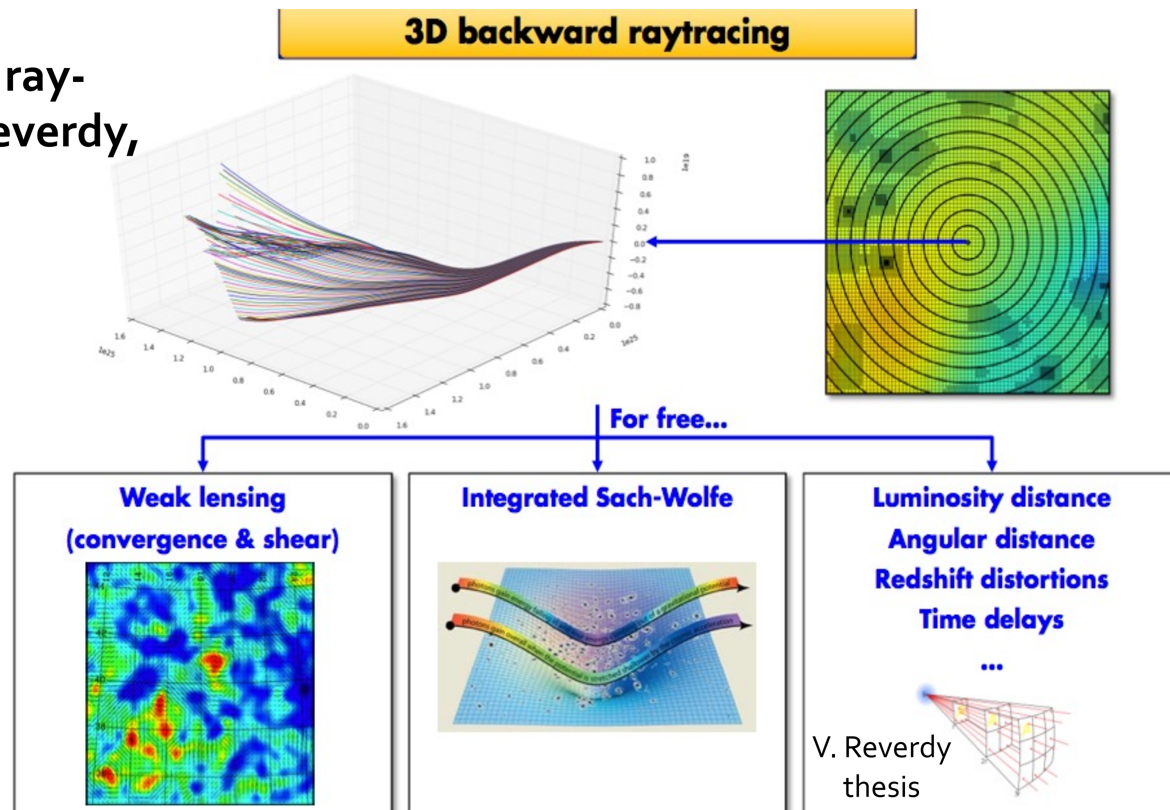
- Geodesic equations:

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

- 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 3: MAGRATHEA-PATHFINDER'S ITERATIVE GEODESICS FINDER

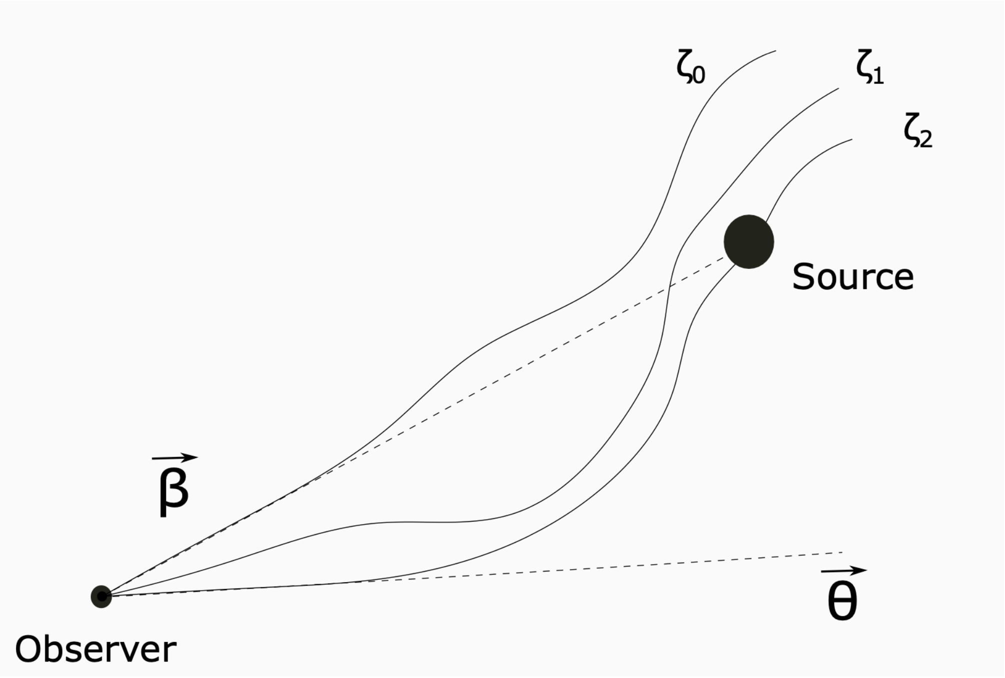
Breton et al, 2019, 2022

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

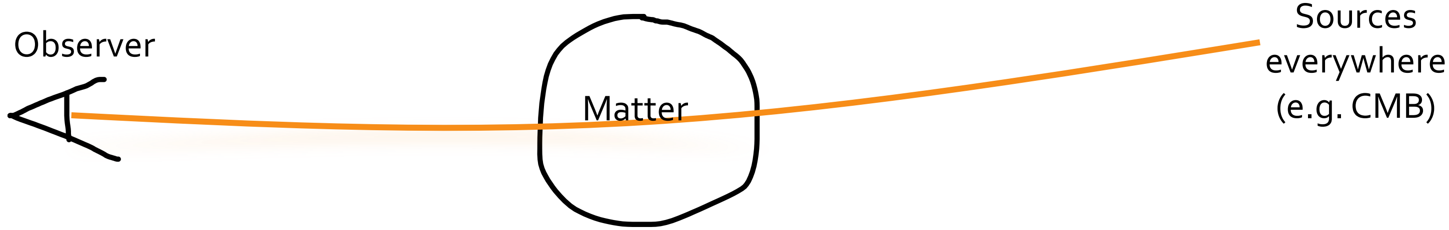
« NEW » : Catalogs of sources taking into account weak lensing effects and redshift space distortions
In the catalogs :
$\vec{\beta}, \vec{\theta}, \bar{z}, z$, errors, A_{ij}



- 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)

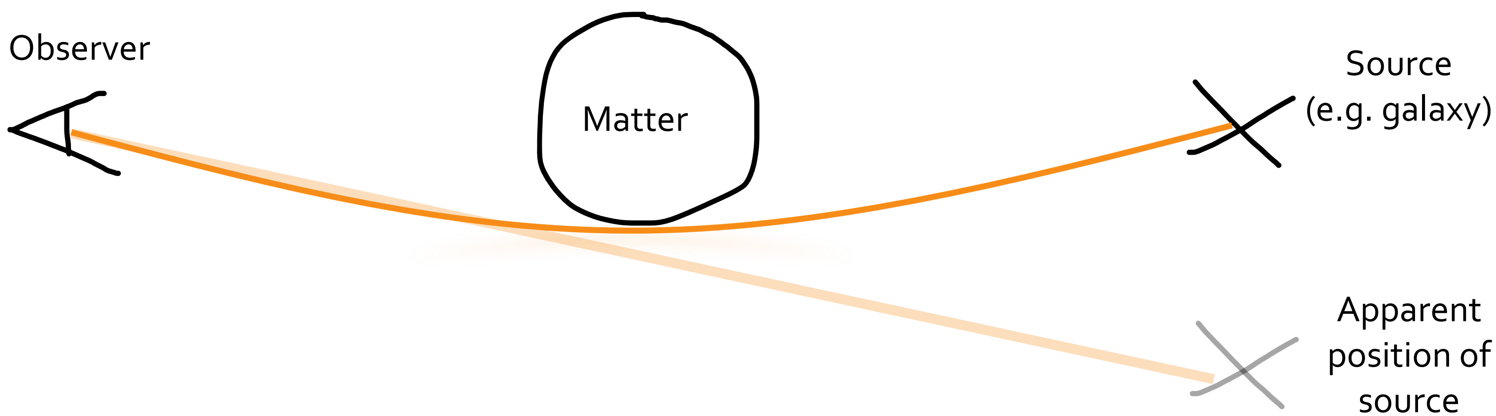
IMPORTANT TAKE HOME MESSAGE
SOURCE AVERAGING VERY DIFFERENT FROM ANGULAR AVERAGING

ANGULAR AVERAGING:



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

SOURCE AVERAGING:

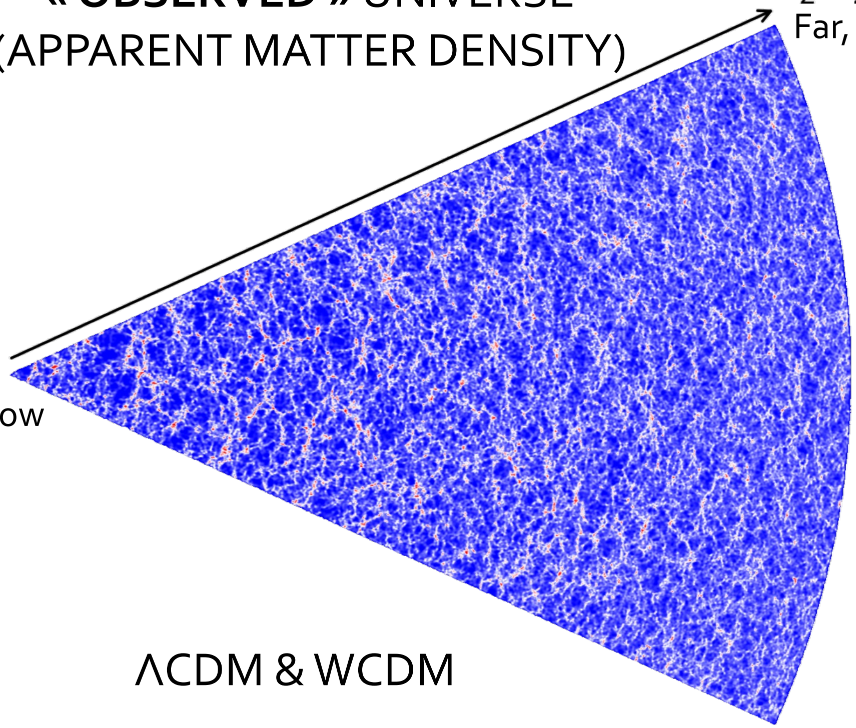


In Magrathea, geodesics finders => light crosses exactly the source and the observer
strong effects (**magnification bias** etc), not only a post-born correction

THE RAYGAL UNIVERSE

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

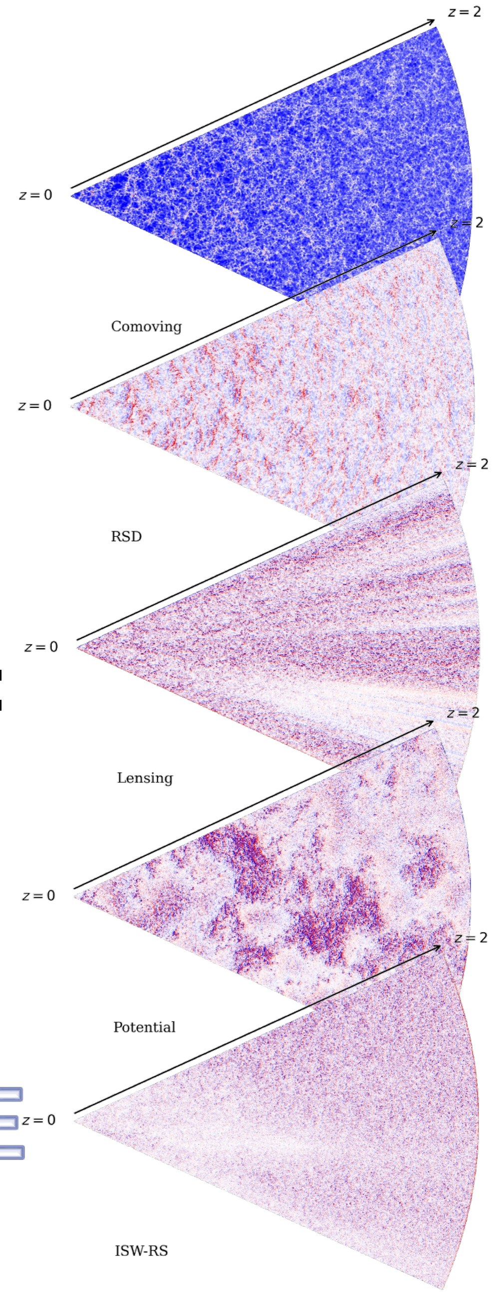
$z = 2$
Far, Past



$z = 0$
Here, Now

ΛCDM & WCDM

=



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

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)

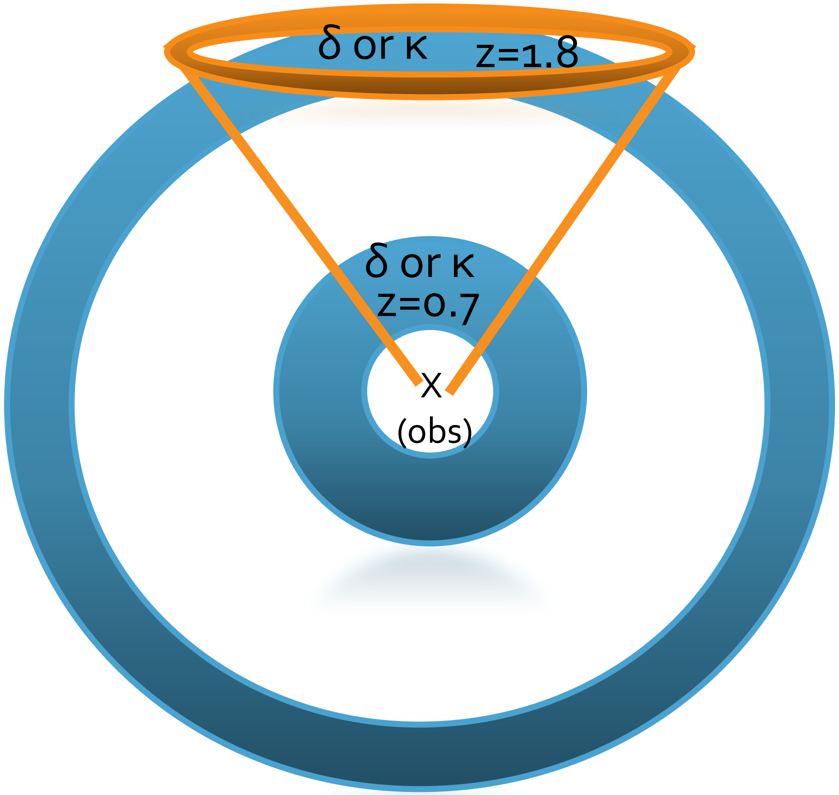
Example of application: relativistic 3x2pts correlations

(I will skip a natural application which is

relativistic redshift-space distortions

see Breton+19 for this)

GEOMETRY AND QUANTITIES



- Quantities: Observed matter overdensity δ and gravitational 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

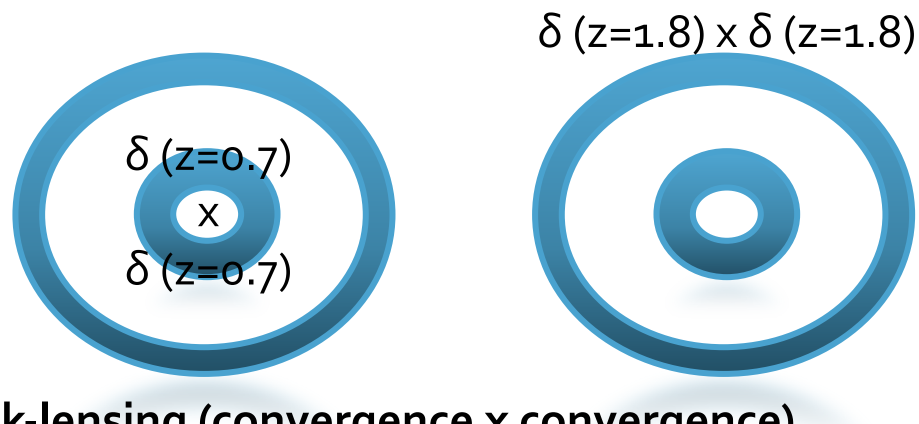
- DEFINITION:

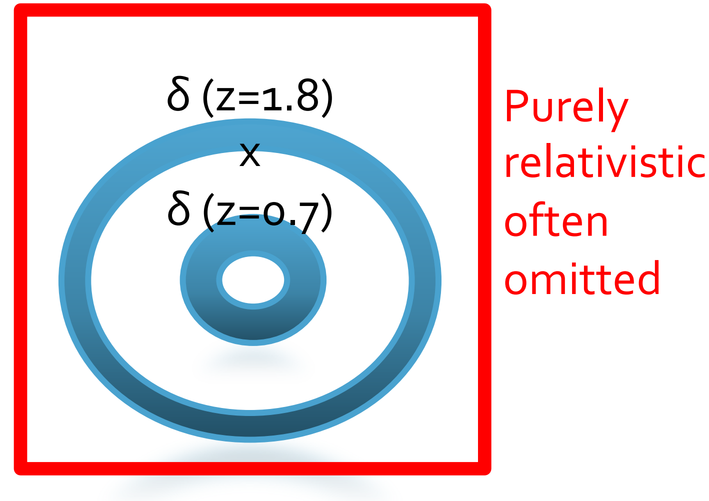
NON-TRIVIAL RELATIVISTIC EFFECTS= DEVIATION FROM COMOVING MATTER OVERDENSITY AND BORN CONVERGENCE (ie. mostly magnification bias MB and RSD)

- THEORY (for comparison): CLASS

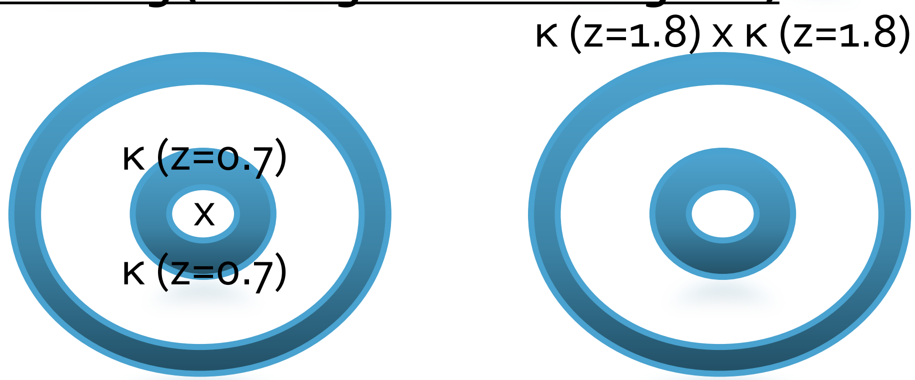
-> Linear with all relativistic effects
+ Non-linear prescription= halofit, linear mapping, RSD no Finger of God, Born lensing, etc.

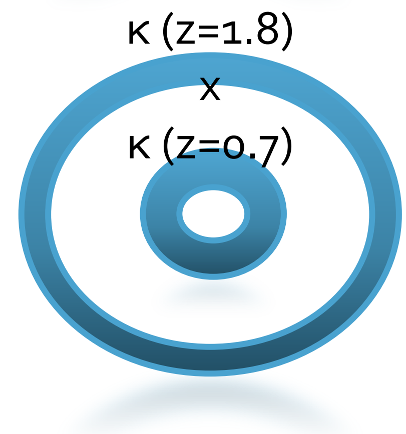
Clustering (density x density)



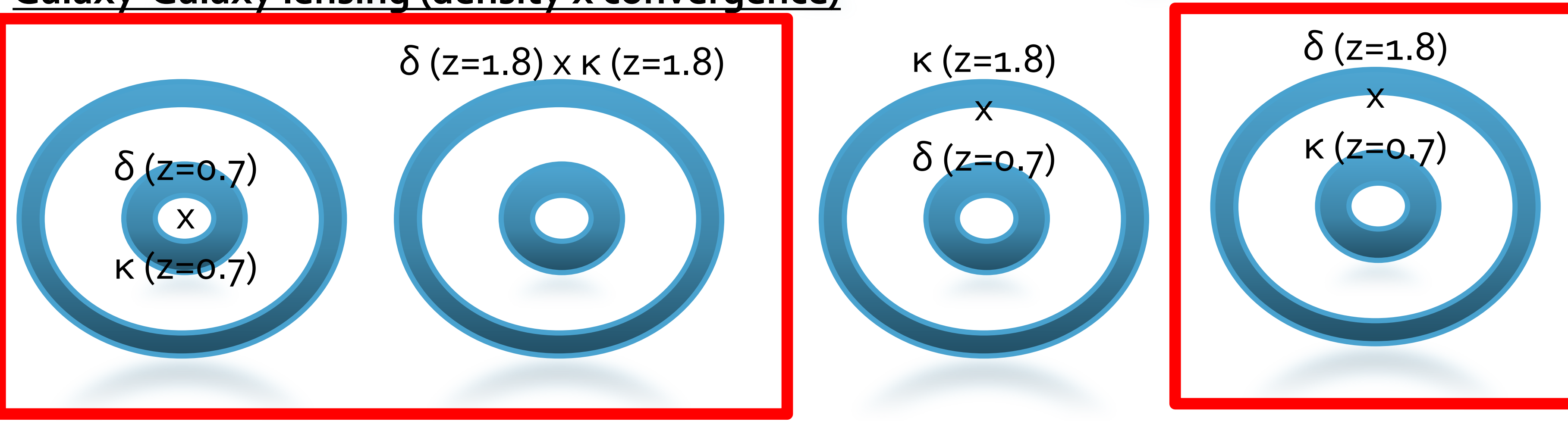


Weak-lensing (convergence x convergence)



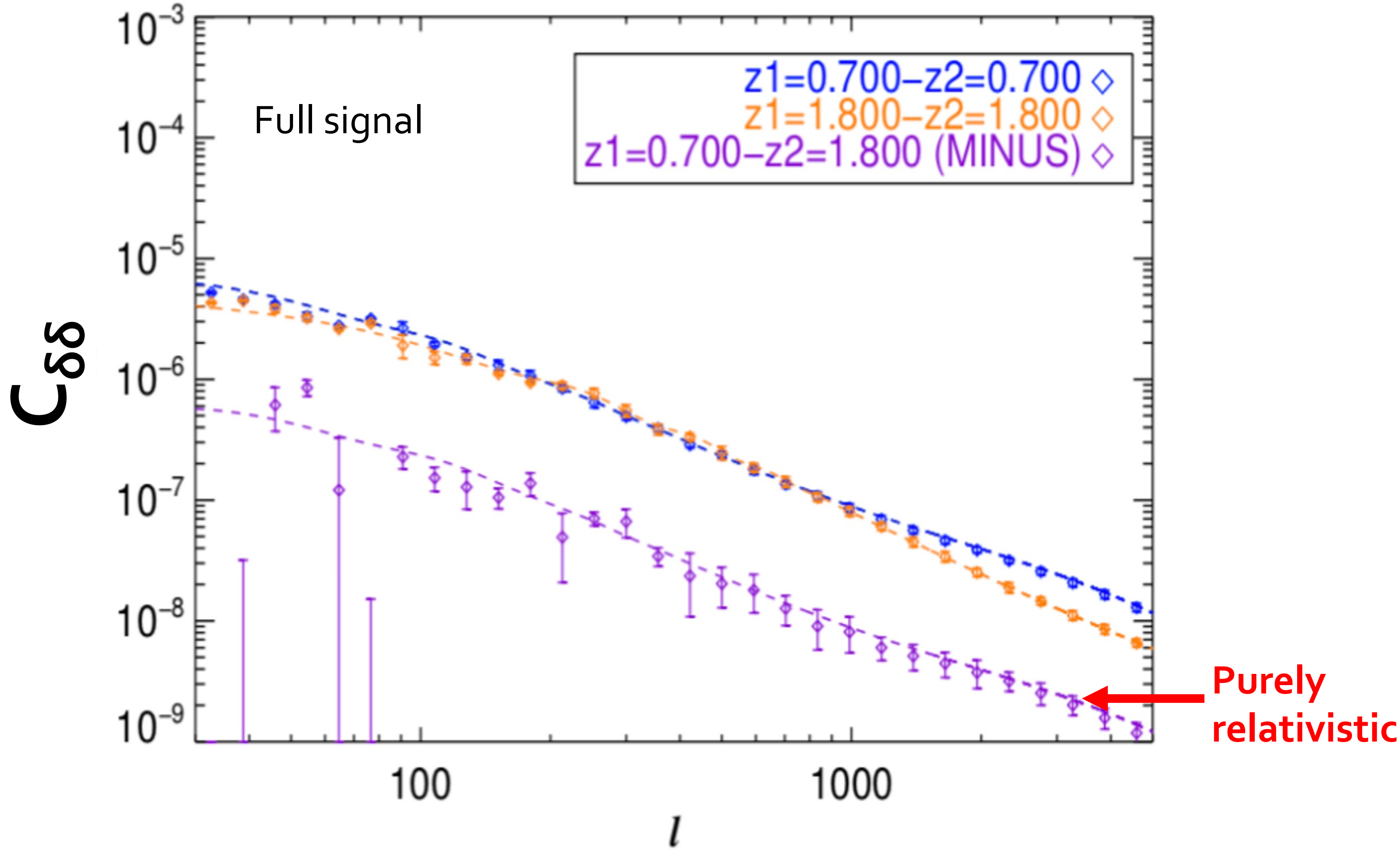


Galaxy-Galaxy lensing (density x convergence)



Rasera et al. 2022

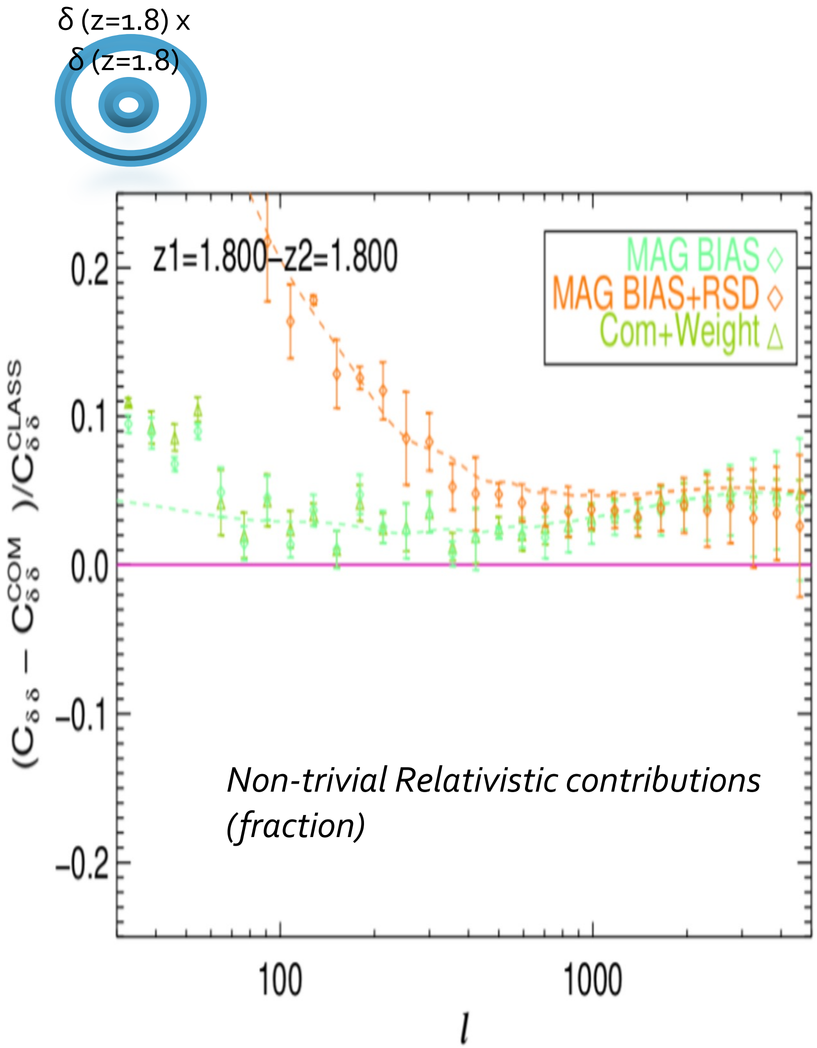
Matter angular (cross-)power spectra with relativistic contributions

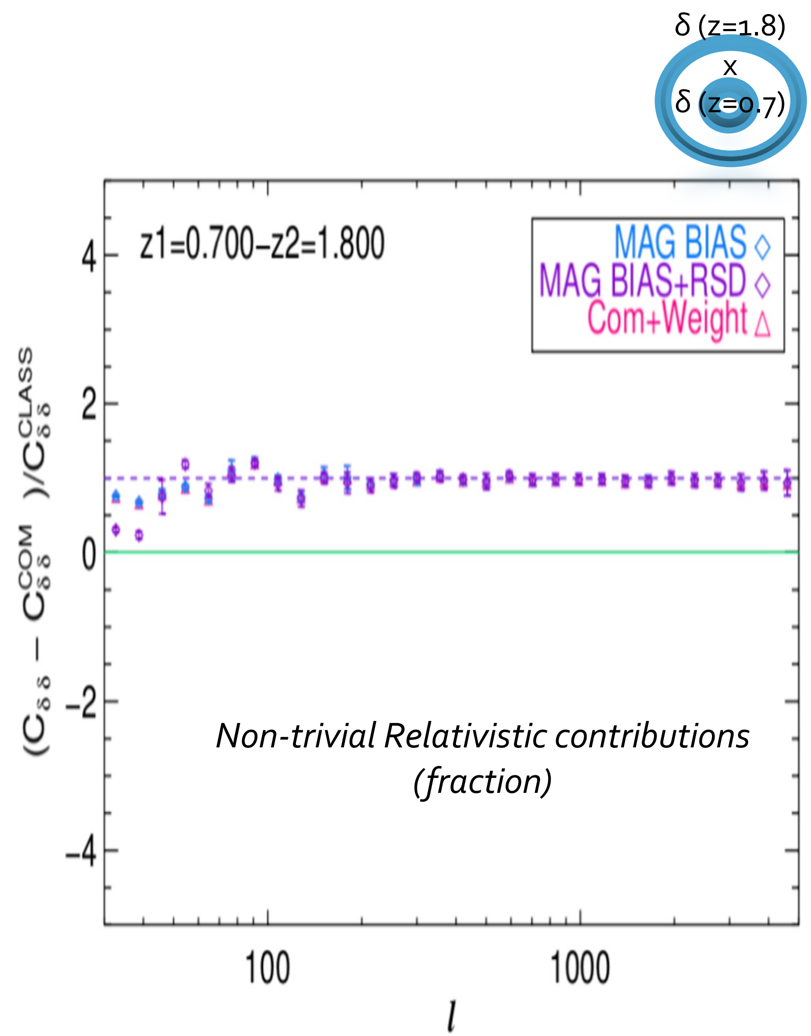


- **Good agreement with Class** (dashed lines)
- 3D matter P(k) calibrated on RayGal (otherwise halofit errors induce ~5% errors)

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

Rasera et al. 2022

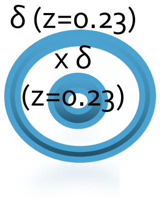


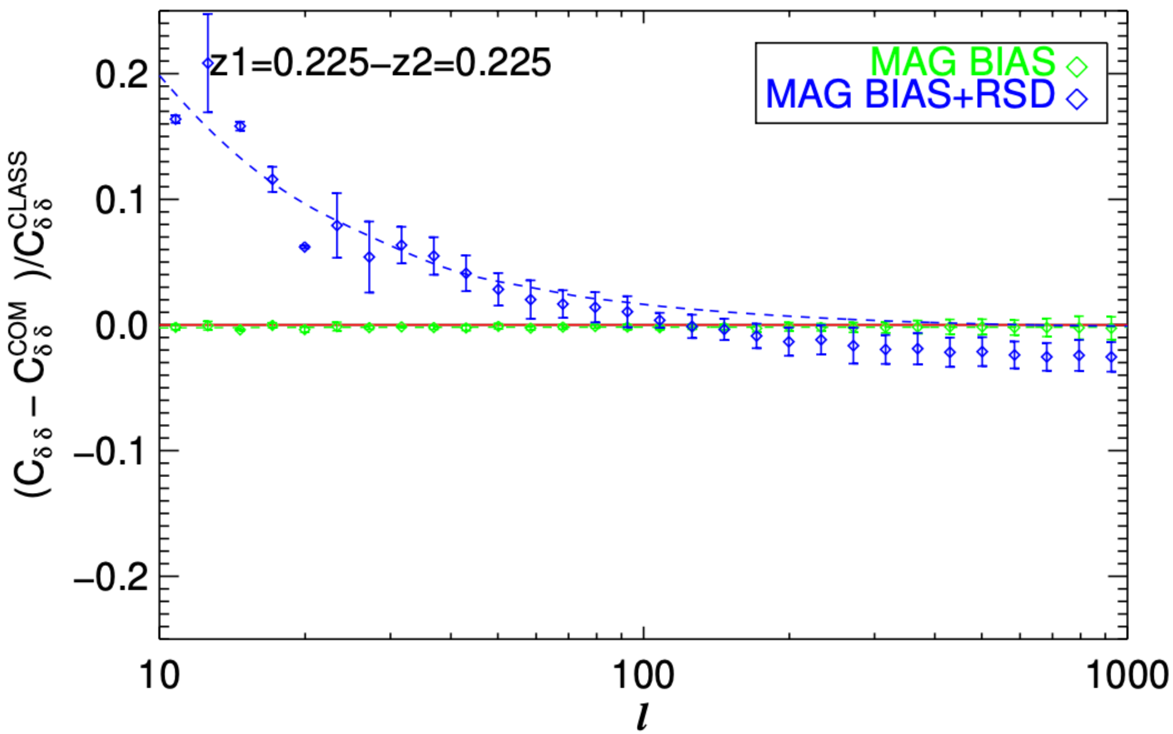


- RSD effect at large scale
- Magnification Bias (MB) => $\delta_{obs} \approx \delta_{com} - 2\kappa_{Born}$ (for flux-limited survey $-2\kappa \rightarrow (5s - 2)\,\kappa$)
- MB effect at every scale (+ dominate for distance shell)

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

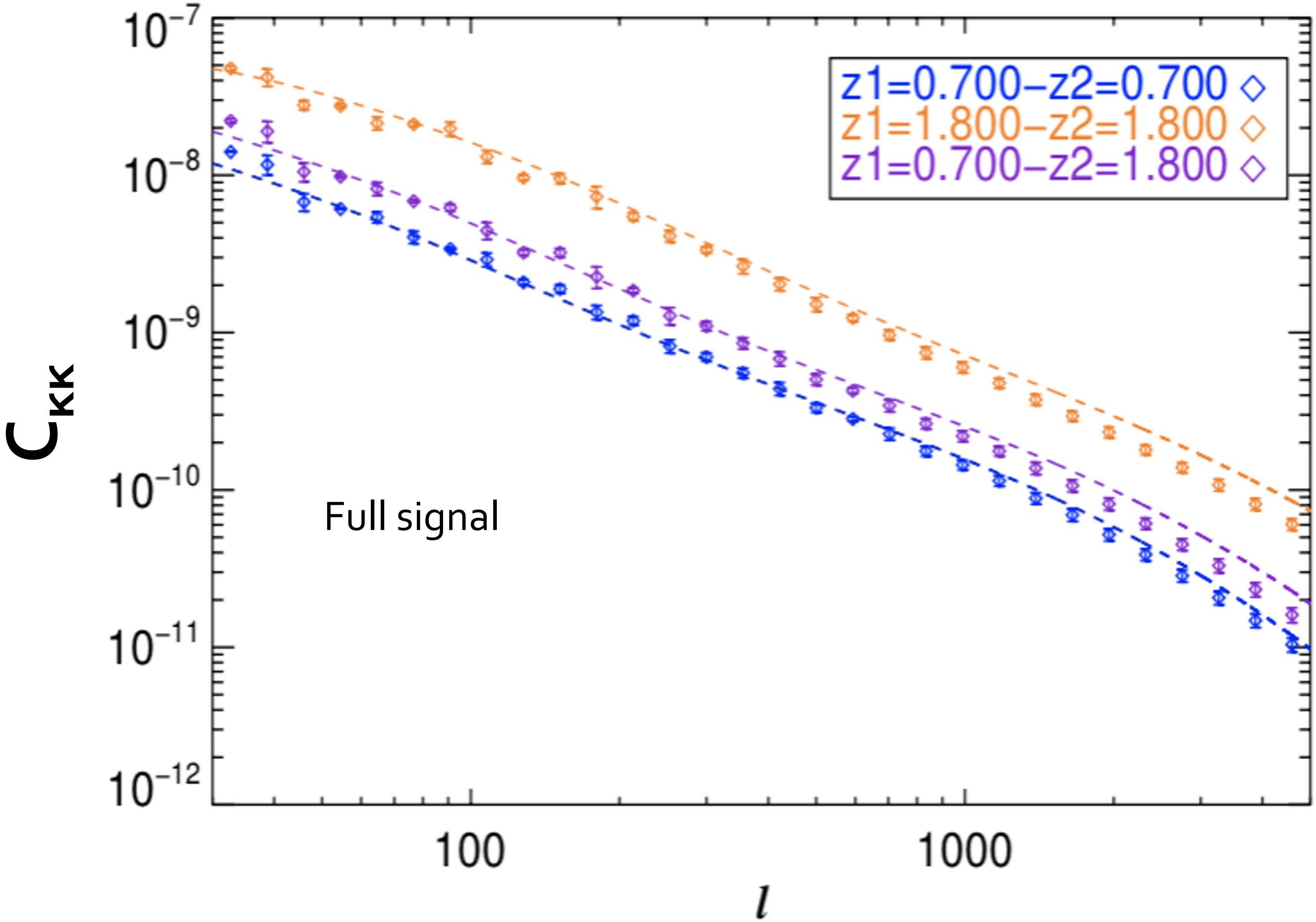
Rasera et al. 2022





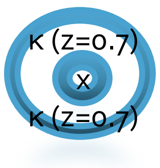
- Remark: Same autocorrelation but at smaller redshift z=0.225
- Agreement at large scale but **Class doesn't capture Fingers-of-god effect at small scales**

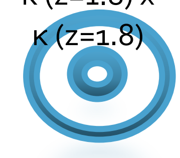
Convergence angular (cross-)power spectra
spectra with relativistic contributions



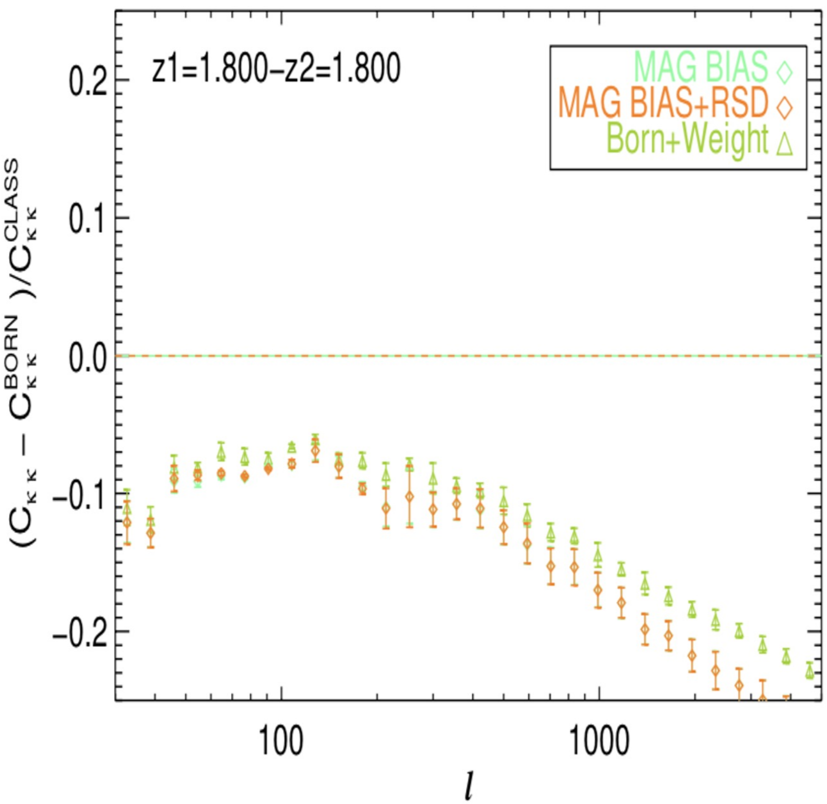
- **Reasonable agreement with class at large scales**

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

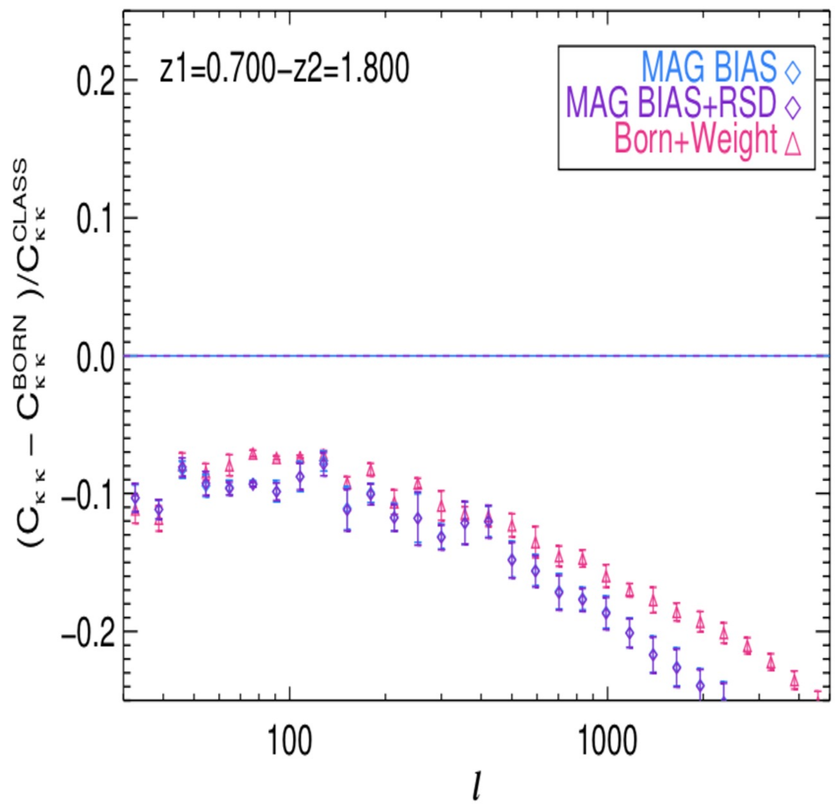




Non-trivial Relativistic contributions (fraction)

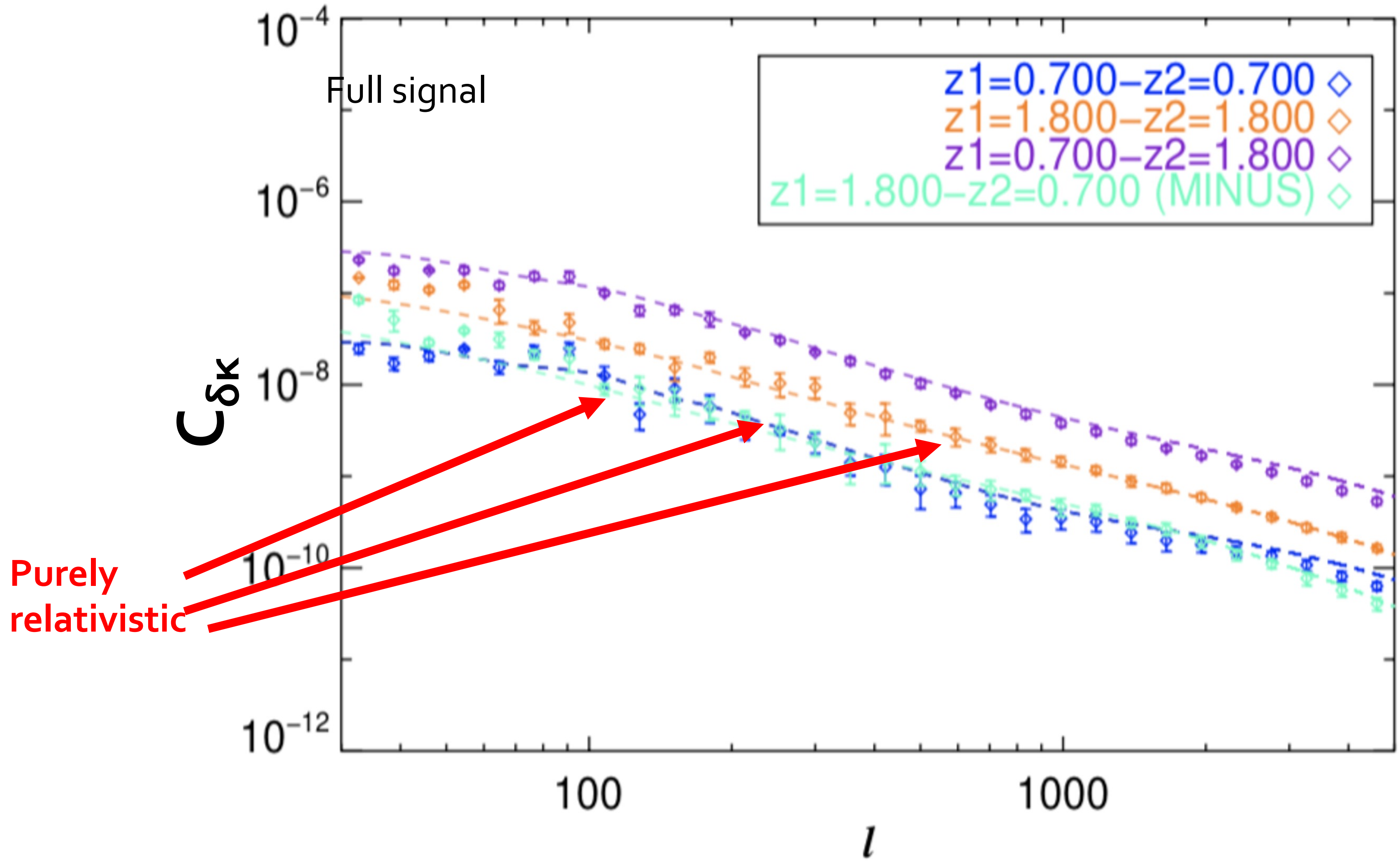


Non-trivial Relativistic contributions (fraction)



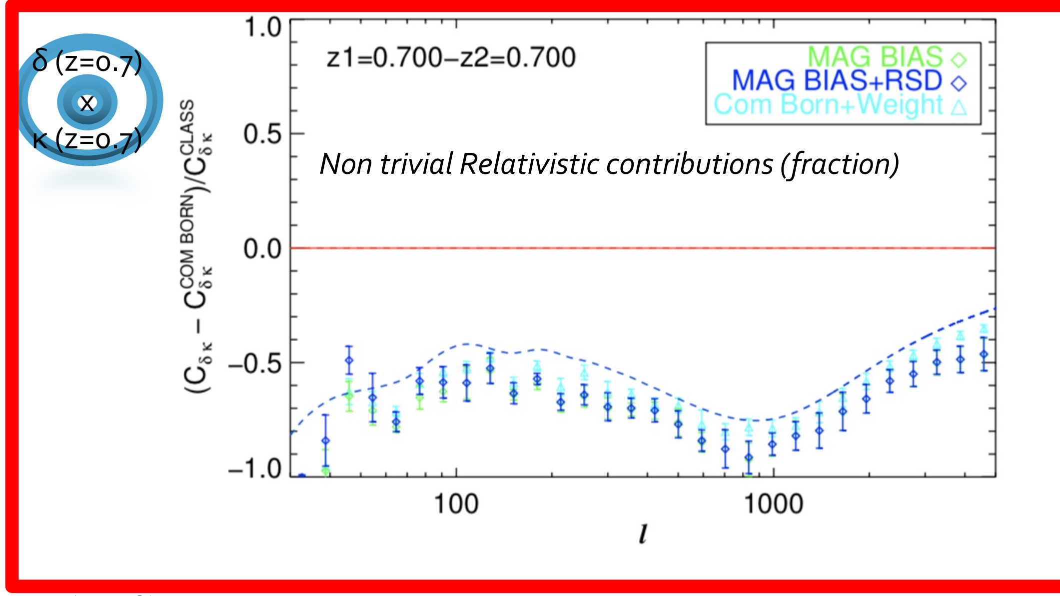
- **Cannot compute the effect of magnification bias on the convergence with Class (as it is related to the bispectrum)**
- $\kappa_{obs} \approx \kappa_{Born} (1\text{-}2\ \kappa_{Born})$.
- MB effect on convergence Cl means that **shear and convergence power spectra differ**!

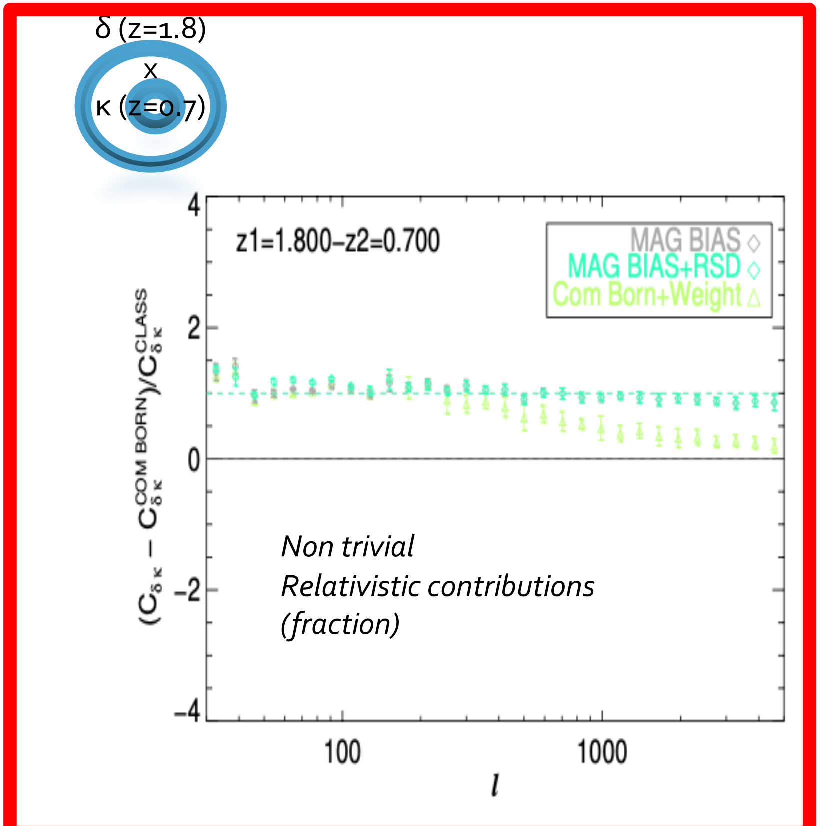
Density-convergence (cross-)power spectra with relativistic contributions

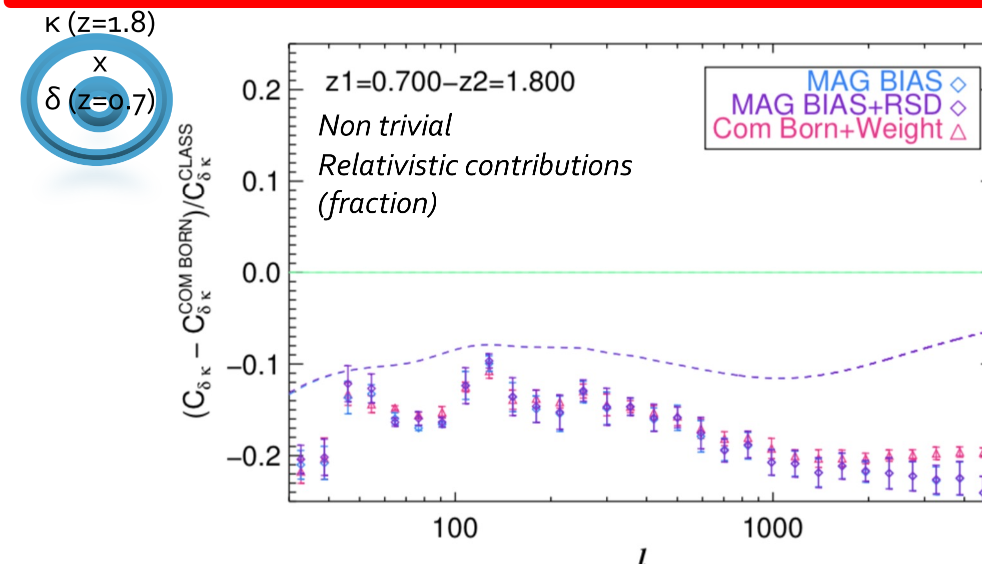


- **Good agreement with Class**

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







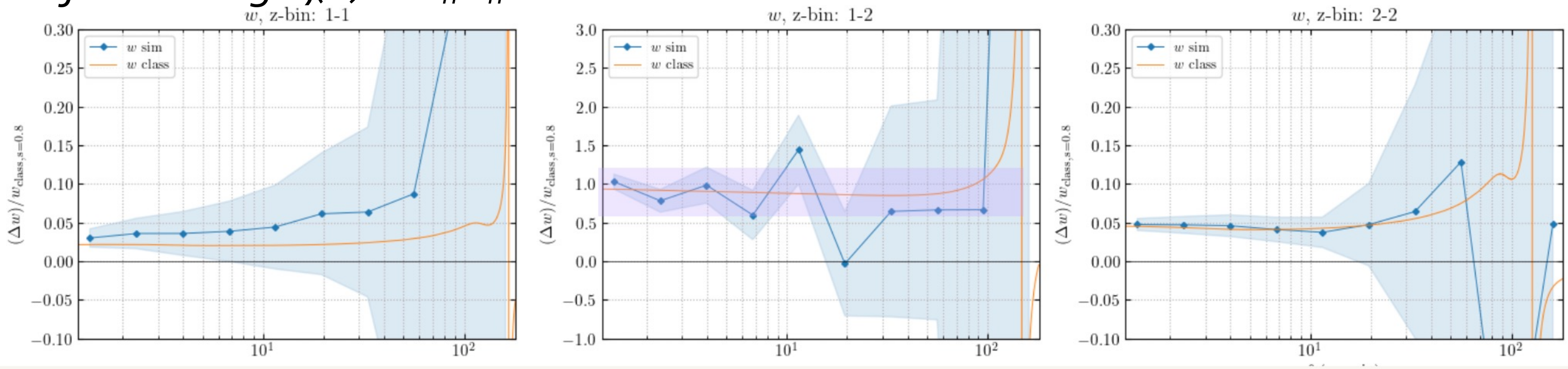
- MB => $\delta_{obs} \approx \delta_{com} - 2\kappa_{Born}$ & $\kappa_{obs} \approx \kappa_{Born}\,(1 - 2\,\kappa_{Born})$.
- MB effect in Class is included but only for the density not the convergence => deviations
- Interesting **non- trivial configurations : including some with the convergence at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

ONGOING WORK (M.Corioni, F.Castillo)
Going closer to observations and exploring more models…

- Observed matter overdensity δ -> Halo overdensity (in the future galaxies)
- Gravitational weak-lensing convergence κ -> shear γ
- Volume limited survey -> Flux-limited survey
- ProGraceRay simulation suite to explore wo-wa-CDM space (ongoing)
- Focusing on small scale in configuration space: angular power Spectrum -> angular correlation function

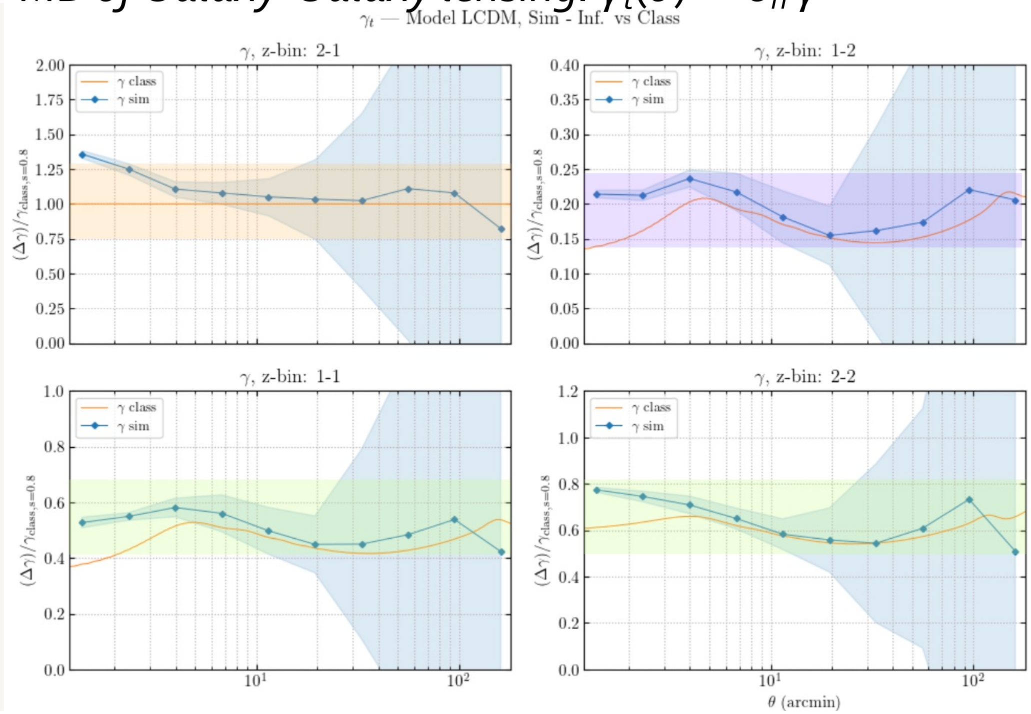
Magnification bias (MB) of 3x2pts correlation functions (preliminary)

MB of Clustering: $\xi(\vartheta)=<\delta_h\,\delta_h>$

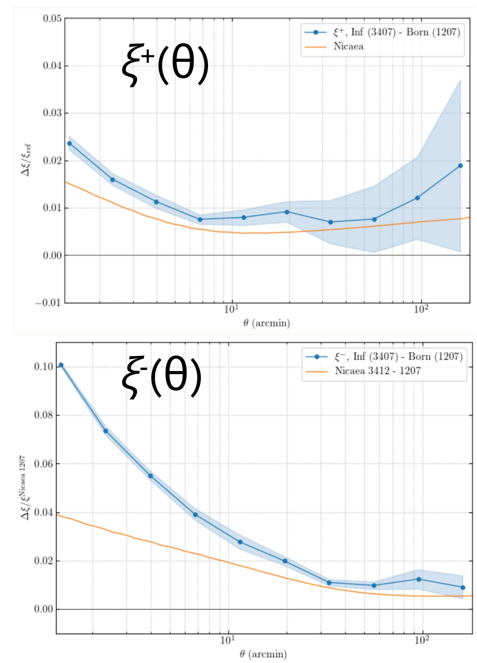


Crédits: M.Corioni

MB of Galaxy-Galaxy lensing: $\gamma_t(\vartheta)=<\delta_h\,\gamma>$



MB of shear correlation <γγ>



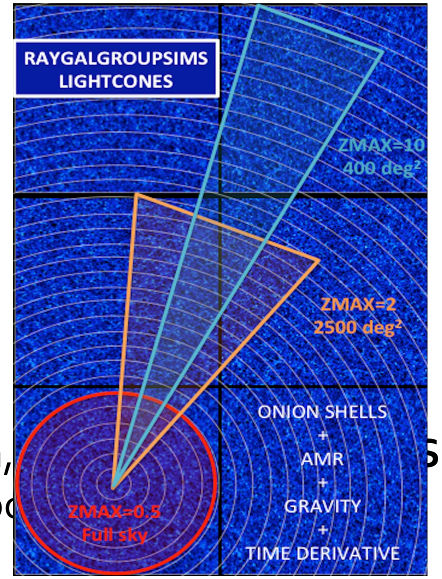
- Similar results... but MB effects on the shear is smaller since < γ γκ> < < κ κκ>
- MB predictions on shear correlation function by Nicaea-> large scales only
- Study on going... Cosmology dependence... etc. (F.Castillo)

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 and weak-lensing (3x2pts):**

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

•**Relativistic effects in RSD => not shown here see Breton+19**

•**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: towards more realistic catalogs in modified gravity cosmologies…**

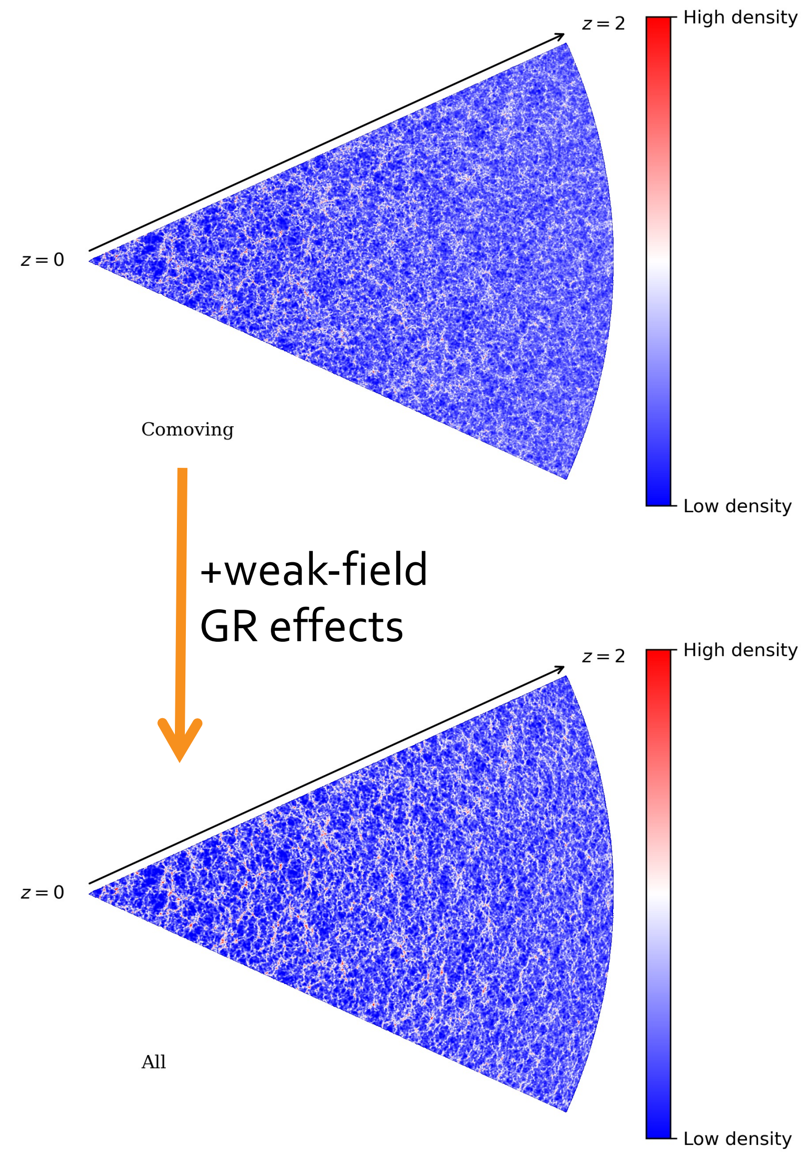
BACKUP SLIDES

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).



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

A laboratory to test relativistic effects…

<dL> & <dA>: Bias of distance-redshift relation (Breton&Fleury, 2021)

$<\delta_{gal}\,\delta_{gal}\,P_{0,2,4}>$: Magnification bias in RSD (Breton et al, 2022)

$<\delta_{halo}\,\delta_{halo}\,P_1>$: Dipole in RSD (Breton et al. 2019 Taruya et al. 2020 Saga et al. 2020, 2021)

$<\delta\,\delta>$, $<\delta\,\kappa>$, $<\kappa\,\kappa>$:WL Convergence x matter overdensity (Rasera et al. 2022)

Possible examples:

$<\delta_{gal}\,\delta_{gal}>$, $<\delta_{gal}\,\gamma>$, $<\gamma\,\gamma>$: Relativistic effects on 3x2pts => **Doable**

$<\gamma\,\gamma>$: Finite beam lensing => **Doable**

< w w>=> Doable (to be checked)

$<z_{grav}>$: Gravitational redshift in cluster/voids (also with TD, WA&LC effect)= **Doable**

$<\delta_{gal}$ ISW>, $<\gamma$ ISW>=> **Doable**

$<\delta_{gal}\,\delta_{gal}\,\delta_{gal}>$, $<\gamma\,\gamma\,\gamma>$, $<\delta_{gal}\,\delta_{gal}$ ISW>, ……..Bispectrum=> **Doable**

Peculiar velocity polyspectra (also with gravitational redshift, etc)=> **Doable**

Etc.…

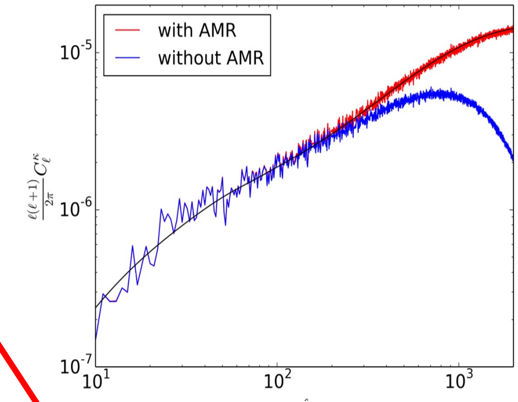
Velocity/potential of the observer => Implemented in Magrathea, need to be run

<Flexion γ>, <Flexion Flexion> => Implemented in Magrathea, need to be run

Gpc clustering (e.g. for PNG)=> needs to correct w/ analytical models or full GR sims

You probably have many other ideas…

DM DYNAMICS: NEWTONIAN 👎
RESOLUTION: ADAPTIVE 👍
WEAK-LENSING: GEODESICS INTEGRATION 👍
RSD: INCLUDE RELATIVISTIC EFFECTS 👍
AVERAGE: ANGULAR OR SOURCE 👍
e.g. RayGal sims (this work)

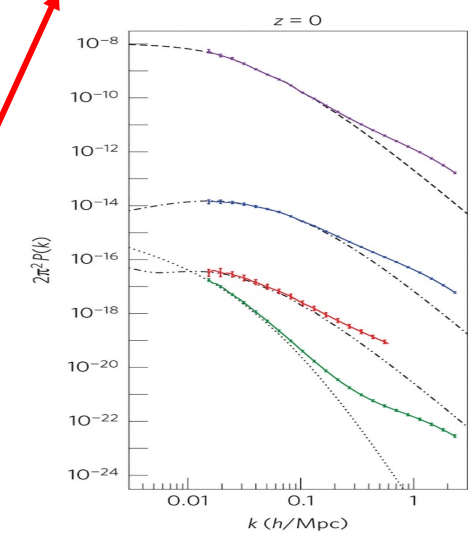


Breton & Reverdy 2022

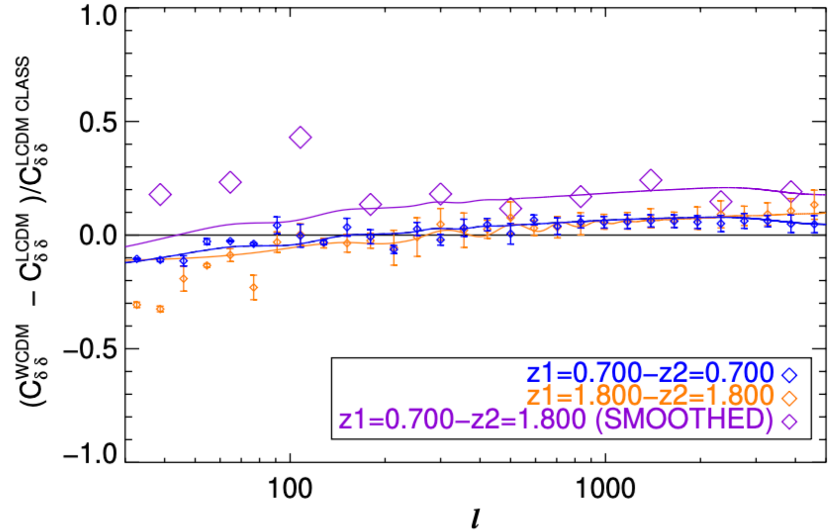
DM DYNAMICS: NEWTONIAN 👎
RESOLUTION: ADAPTIVE 👍
WEAK-LENSING: BORN 👎
RSD: STANDARD 👎
AVERAGE: ANGULAR 👎
e.g. usual N-body sims

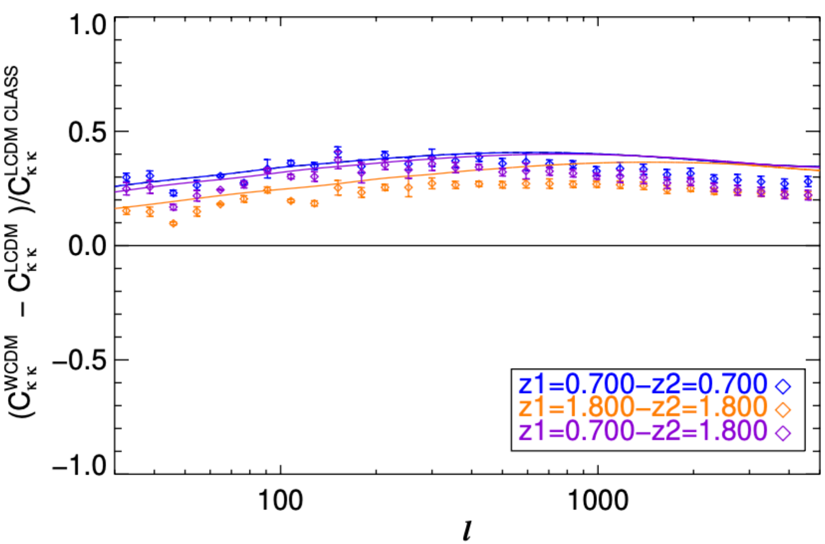
DM DYNAMICS: FULL GR 👍
RESOLUTION: ADAPTIVE 👍
WL: GEODESICS INTEGRATION 👍
RSD: INCLUDE RELATIVISTIC EFFECTS 👍
AVERAGE: ANGULAR OR SOURCE 👍
e.g. Ultimate futuristic sims

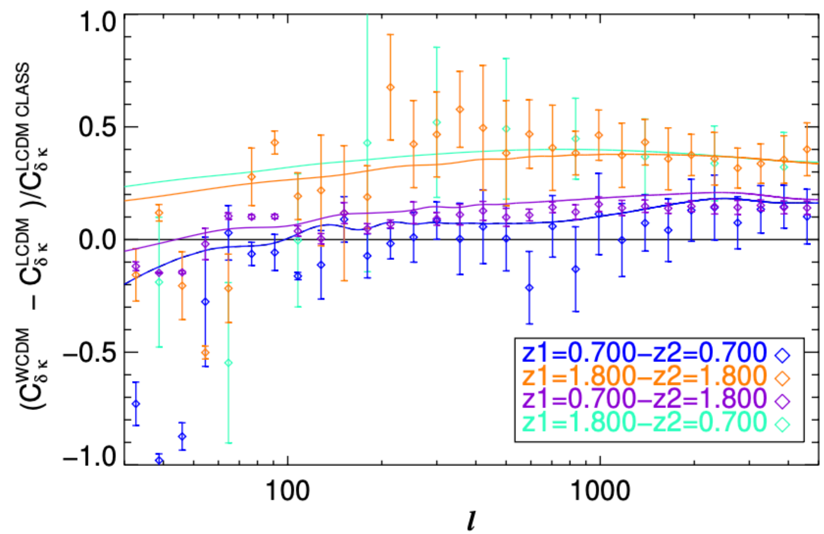
DM DYNAMICS: WEAK-FIELD GR 👍
RESOLUTION: FIXED 👎
WEAK-LENSING: GEODESICS INTEGRATION 👍
RSD: INCLUDE RELATIVISTIC EFFECTS 👍
AVERAGE: ANGULAR OR SOURCE 👍
e.g. Gevolution sims



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







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

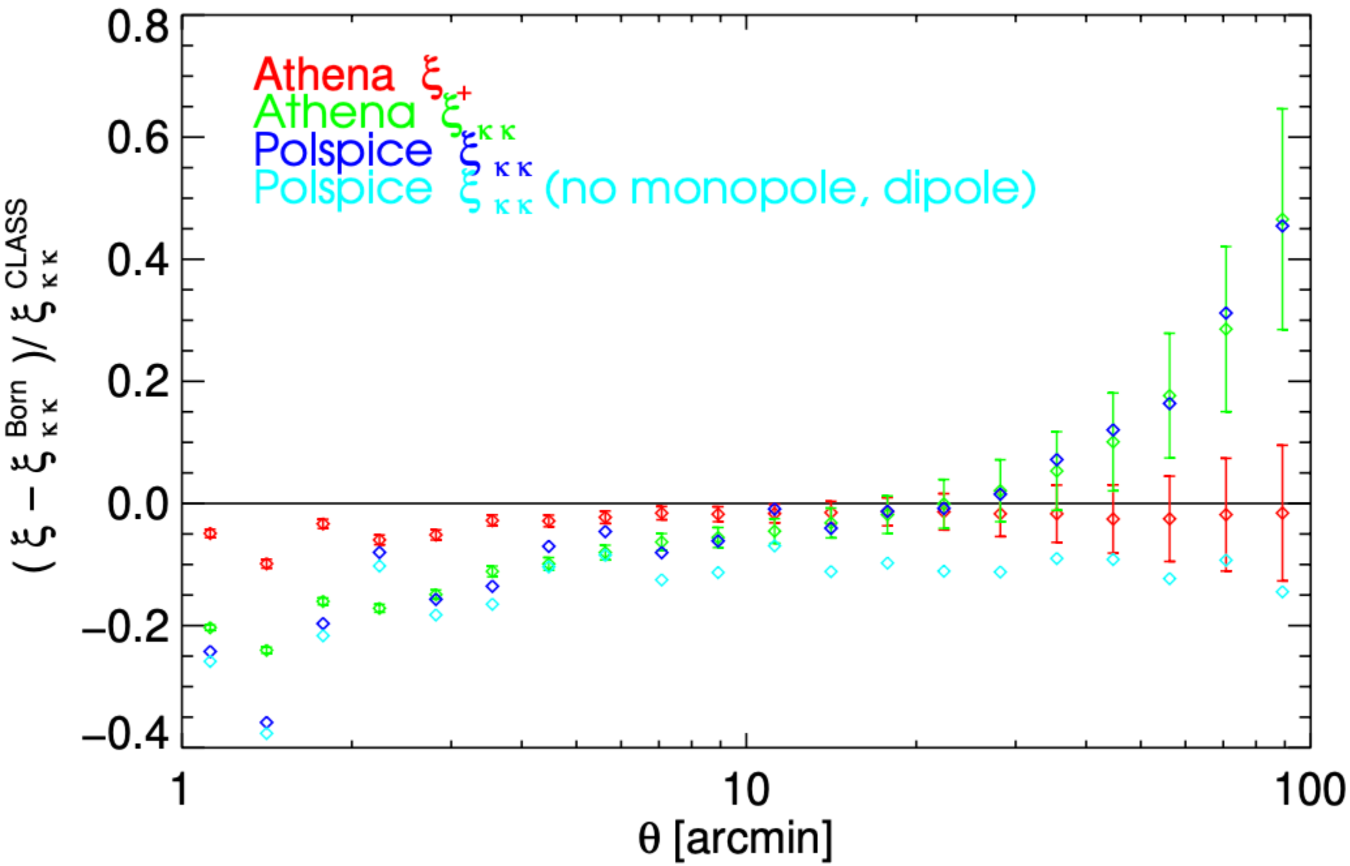


Fig. B.1. Relative difference between lensing angular two point correlation function on the source catalogue accounting for the dilution bias and the Born convergence angular two point correlation function. In red and green diamonds we show the measurements of cosmic shear and convergence correlation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