Dark energy, N-body simulations and relativistic effects

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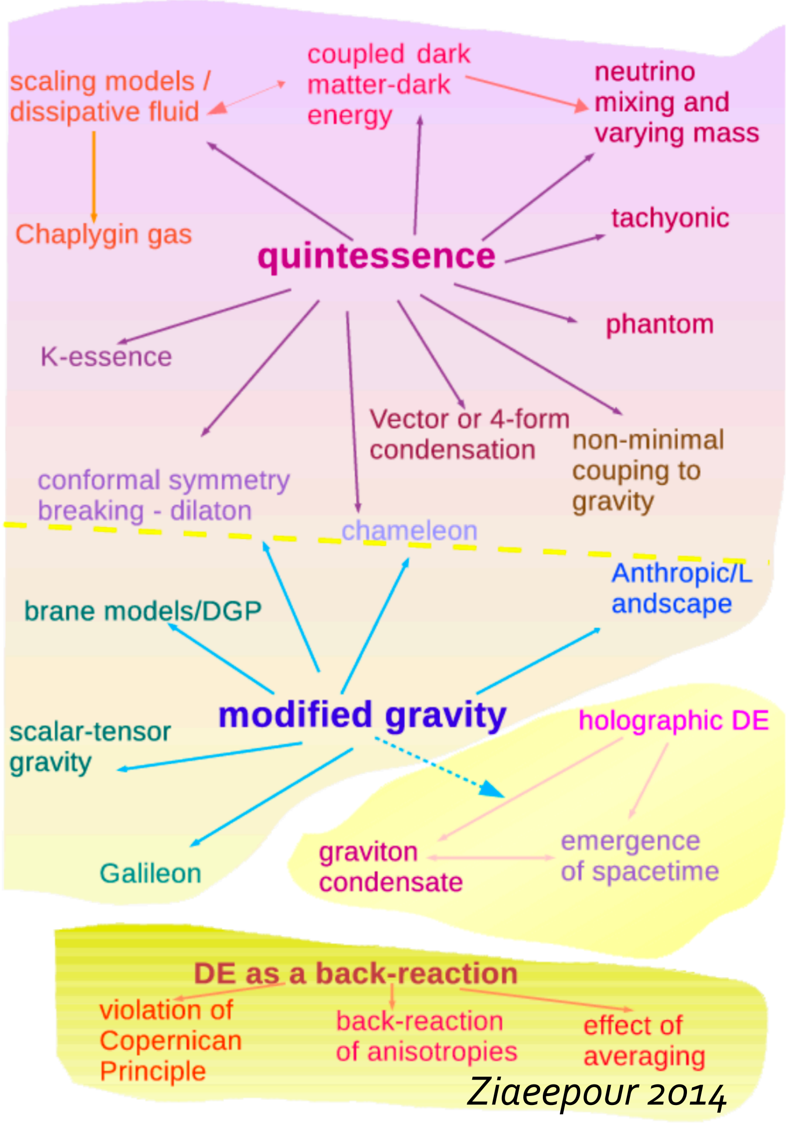
Work with:* *Michel-Andrès Breton (LAM), *Joseph Allingham (Sidney Univ), Théo Pellegrin (LUTH), Atsushi Taruya (YITP), Shohei Saga (YITP), Vincent Reverdy (ENS), Fabrice Roy (LUTH), Pier-Stefano Corasaniti (LUTH), and collaborators*

WHAT IS THE NATURE OF THE DARK SECTOR?

- **VARIOUS POSSIBILITIES FOR DE**



scaling models /
dissipative fluid

coupled dark
matter-dark
energy

neutrino
mixing and
varying mass

Chaplygin gas

quintessence

tachyonic

phantom

K-essence

Vector or 4-form
condensation

non-minimal
couping to
gravity

conformal symmetry
breaking - dilaton

chameleon

Anthropic/L
andscape

brane models/DGP

modified gravity

holographic DE

scalar-tensor
gravity

Galileon

graviton
condensate

emergence
of spacetime

DE as a back-reaction

violation of
Copernican
Principle

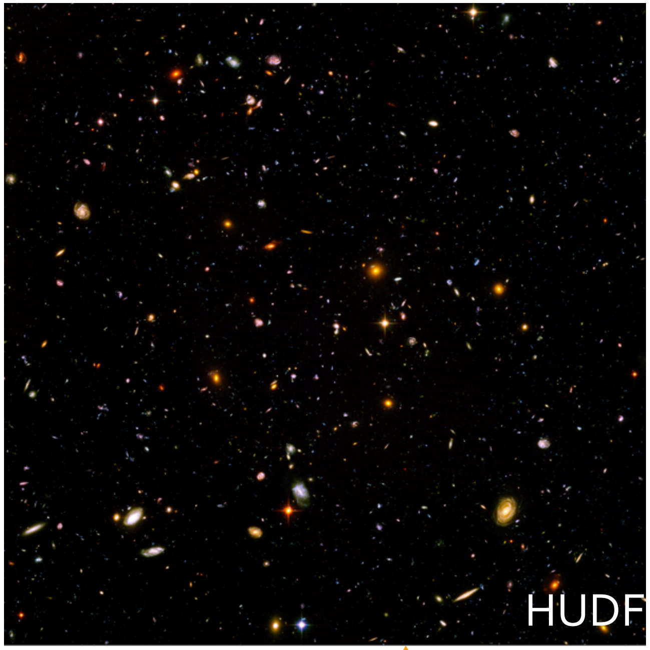
back-reaction
of anisotropies

effect of
averaging

Ziaeepour 2014

- **MANY OTHERS FOR DM**

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



HUDF

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

I. Cosmological models

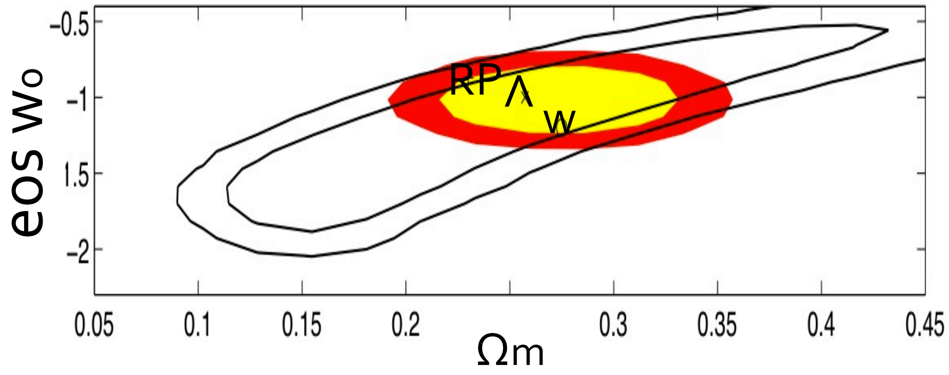
COSMOLOGICAL MODELS

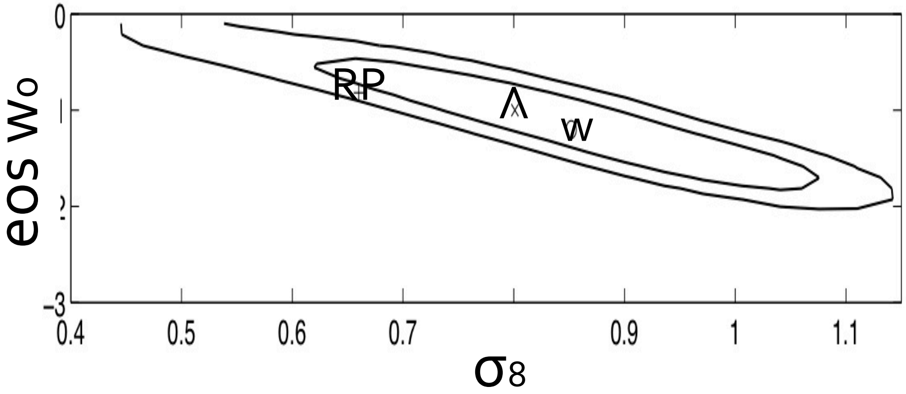
REALISTIC DARK ENERGY MODELS

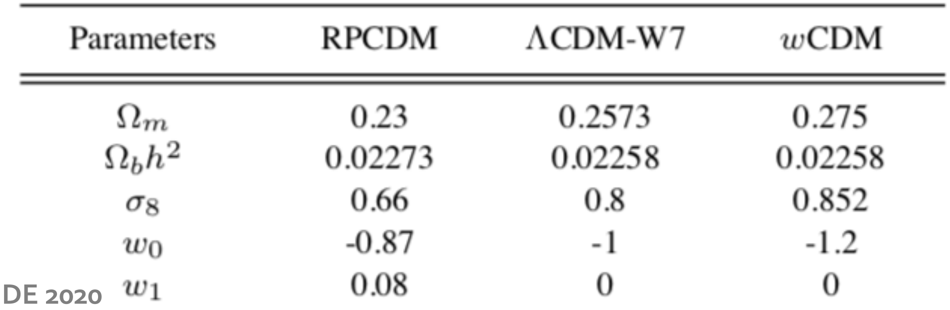
- **3 DE models**
  - Λ-CDM (w=-1)
  - Quintessence model with Ratra-Peebles potential RP-CDM (w(z)>-1)
  - Ghost model w-CDM (w=-1.2)

- **Pre-selection of viable dark energy models:**
  - Likelihood analysis of the combined SNIa UNION dataset and WMAP7-years data
  - CAMB modified to take into account quintessence clustering

- **Varying the equation of states implies:**
  - lower matter density for larger w
  - lower amplitude of power spectrum for larger w



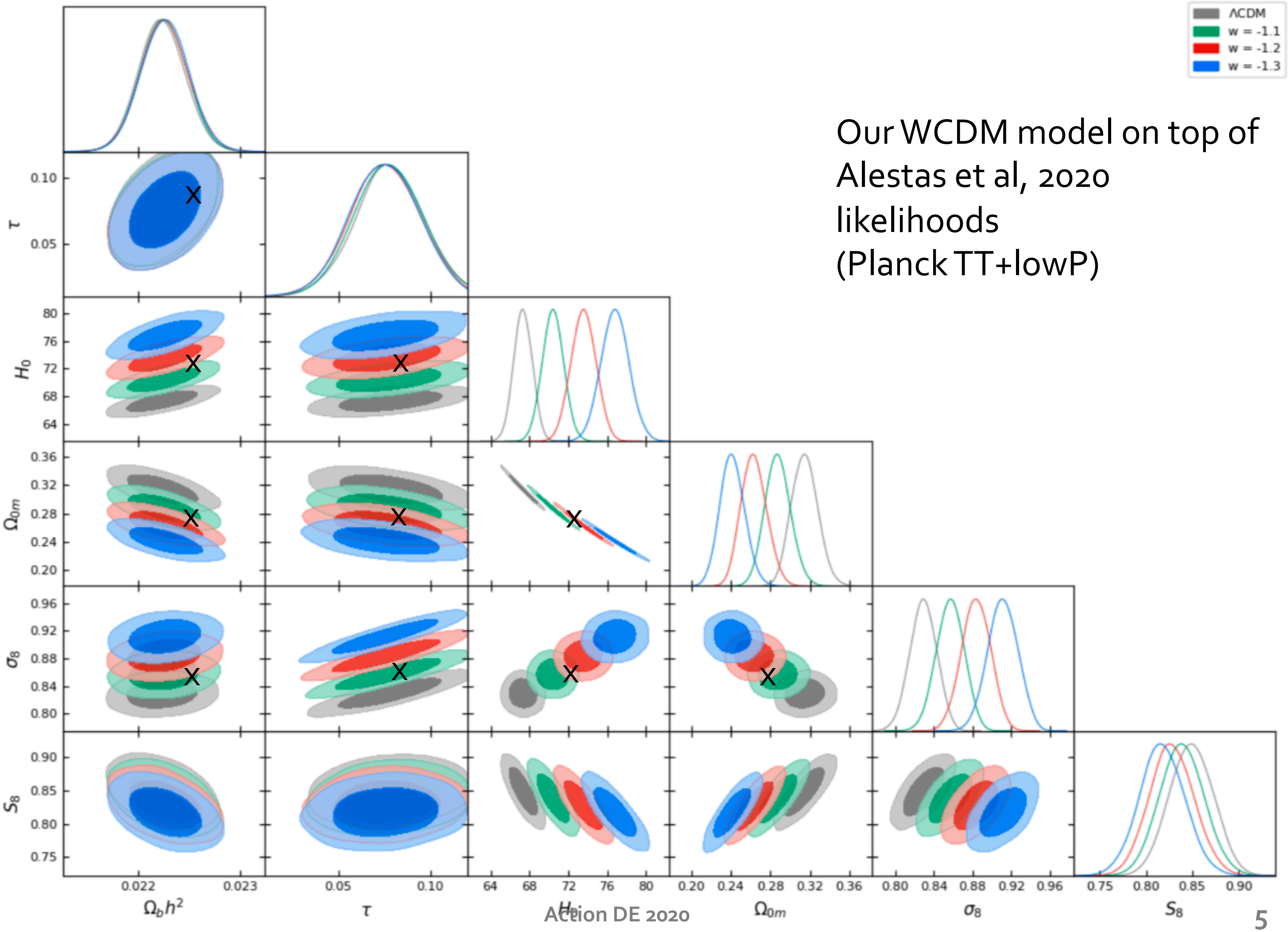




Parameters	RPCDM	ΛCDM-W7	wCDM
Ω_m	0.23	0.2573	0.275
$\Omega_b h^2$	0.02273	0.02258	0.02258
σ_8	0.66	0.8	0.852
w_0	-0.87	-1	-1.2
w_1	0.08	0	0

COSMOLOGICAL MODELS

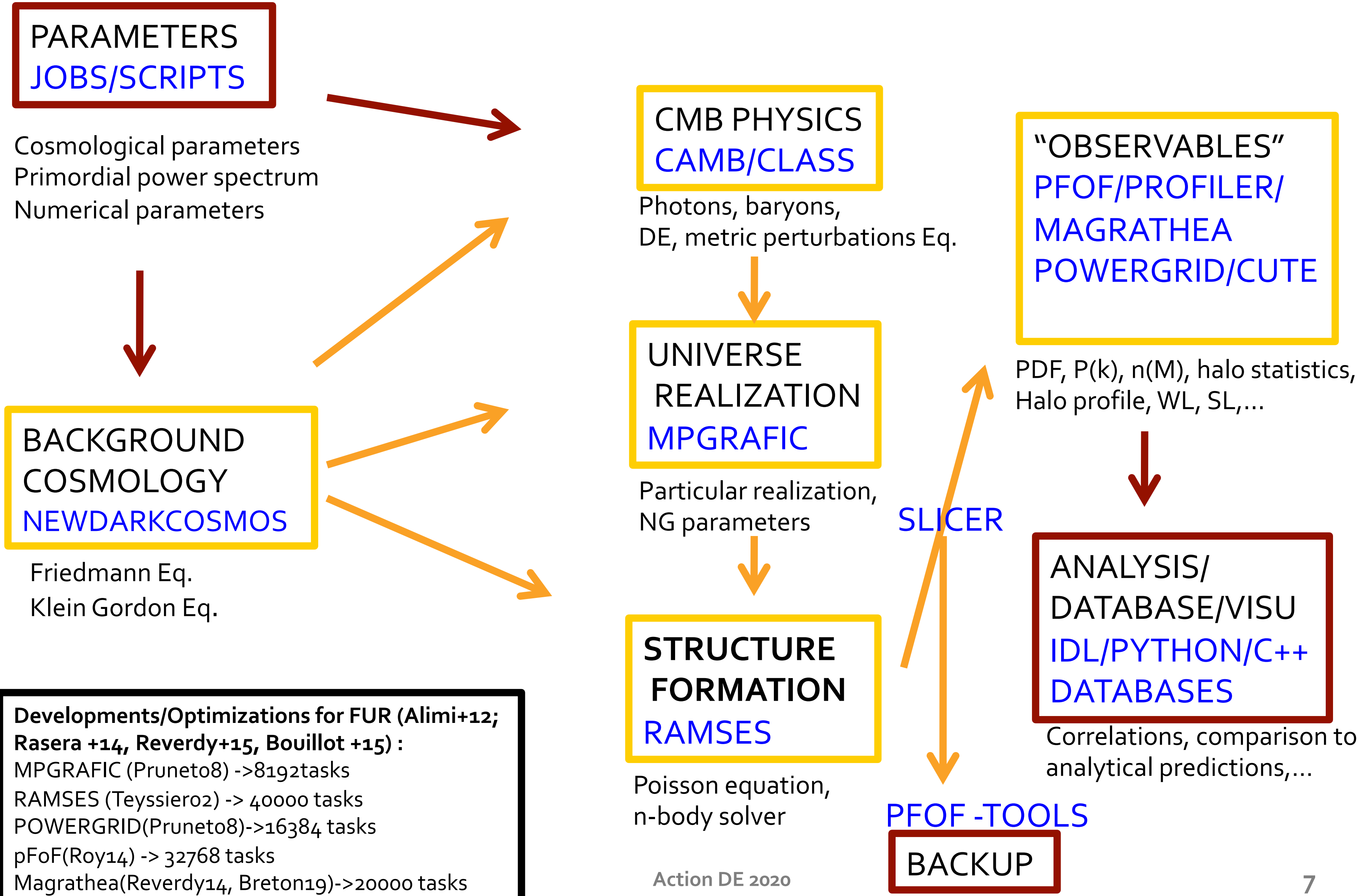
Rough comparison of our WCDM model to Planck constraints



Our WCDM model on top of Alestas et al, 2020 likelihoods
(Planck TT+lowP)

II. Cosmological N-body simulations

COSMOLOGICAL N-BODY SIMULATIONS: TOOLS



PARAMETERS
JOBS/SCRIPTS

Cosmological parameters
Primordial power spectrum
Numerical parameters

BACKGROUND COSMOLOGY
NEWDARKCOSMOS

Friedmann Eq.
Klein Gordon Eq.

CMB PHYSICS
CAMB/CLASS

Photons, baryons,
DE, metric perturbations Eq.

UNIVERSE REALIZATION
MPGRAFIC

Particular realization,
NG parameters

STRUCTURE FORMATION
RAMSES

Poisson equation,
n-body solver

SLICER

PFOF -TOOLS

BACKUP

"OBSERVABLES"
PFOF/PROFILER/
MAGRATHEA
POWERGRID/CUTE

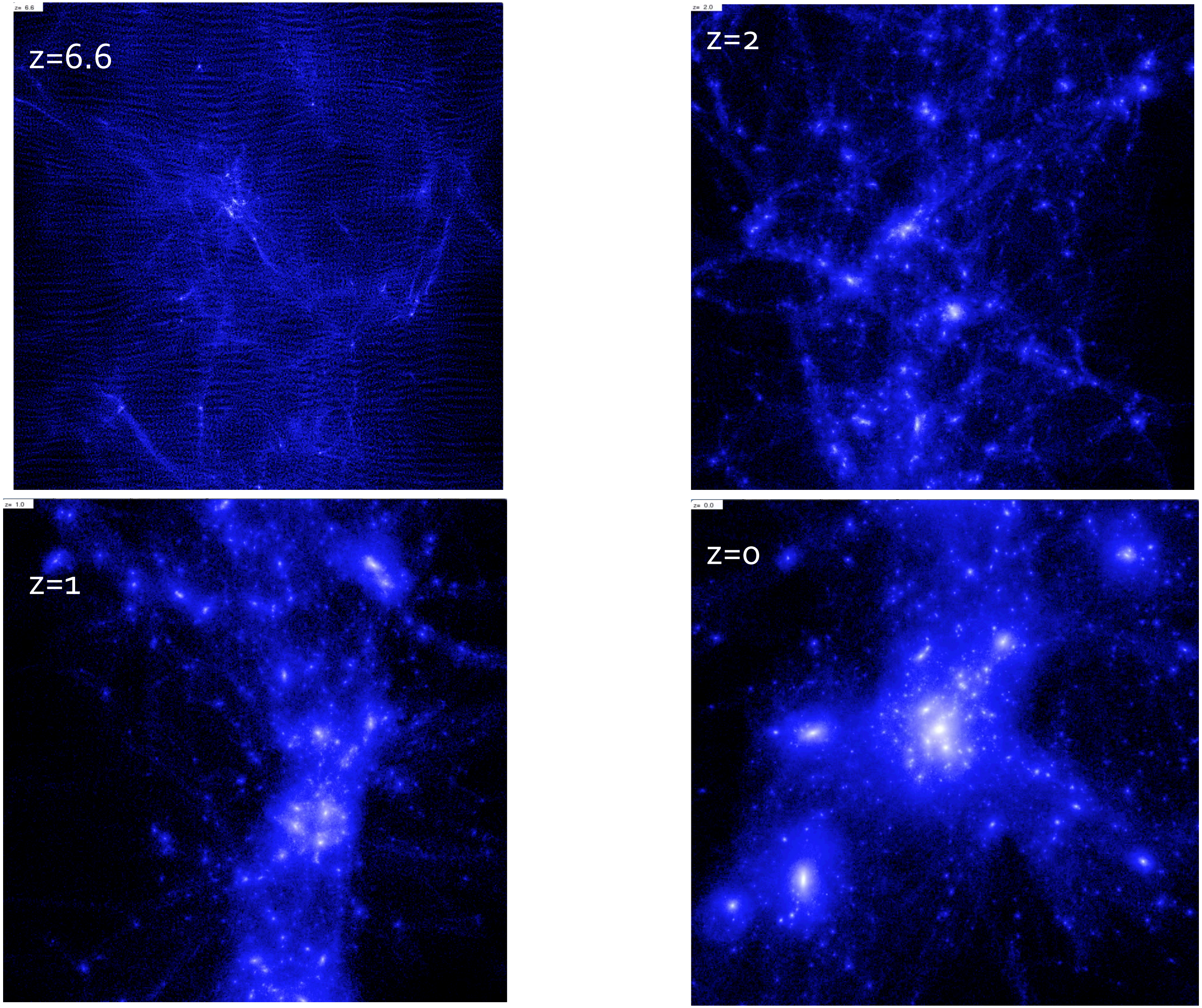
PDF, P(k), n(M), halo statistics,
Halo profile, WL, SL,…

ANALYSIS/
DATABASE/VISU
IDL/PYTHON/C++
DATABASES

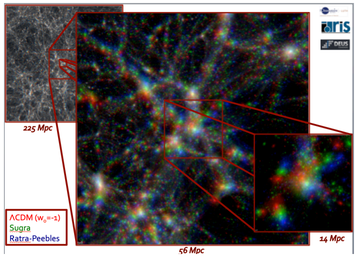
Correlations, comparison to
analytical predictions,…

Developments/Optimizations for FUR (Alimi+12; Rasera +14, Reverdy+15, Bouillot +15) :
MPGRAFIC (Pruneto8) ->8192tasks
RAMSES (Teyssiero2) -> 40000 tasks
POWERGRID(Pruneto8)->16384 tasks
pFoF(Roy14) -> 32768 tasks
Magrathea(Reverdy14, Breton19)->20000 tasks

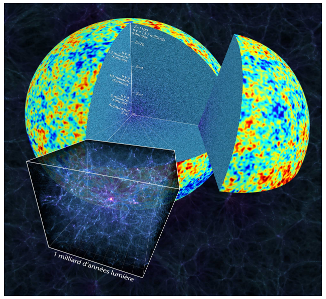
- **Example: formation of one massive halo in LCDM (projected dark matter density)**



COSMOLOGICAL N-BODY SIMULATIONS: DATA

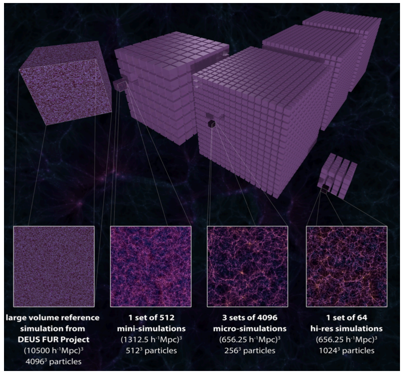


Dark energy Universe Simulations Series
(various DE models and resolutions=> imprints of DE)

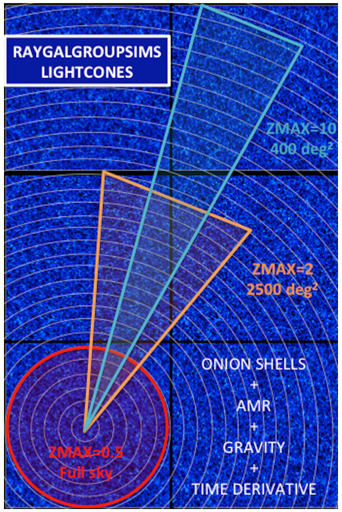


Full Universe Runs
(size of observable universe=> rare events)

Public datasets @ COS Team/LUTH
https://cosmo.obspm.fr/public-datasets/



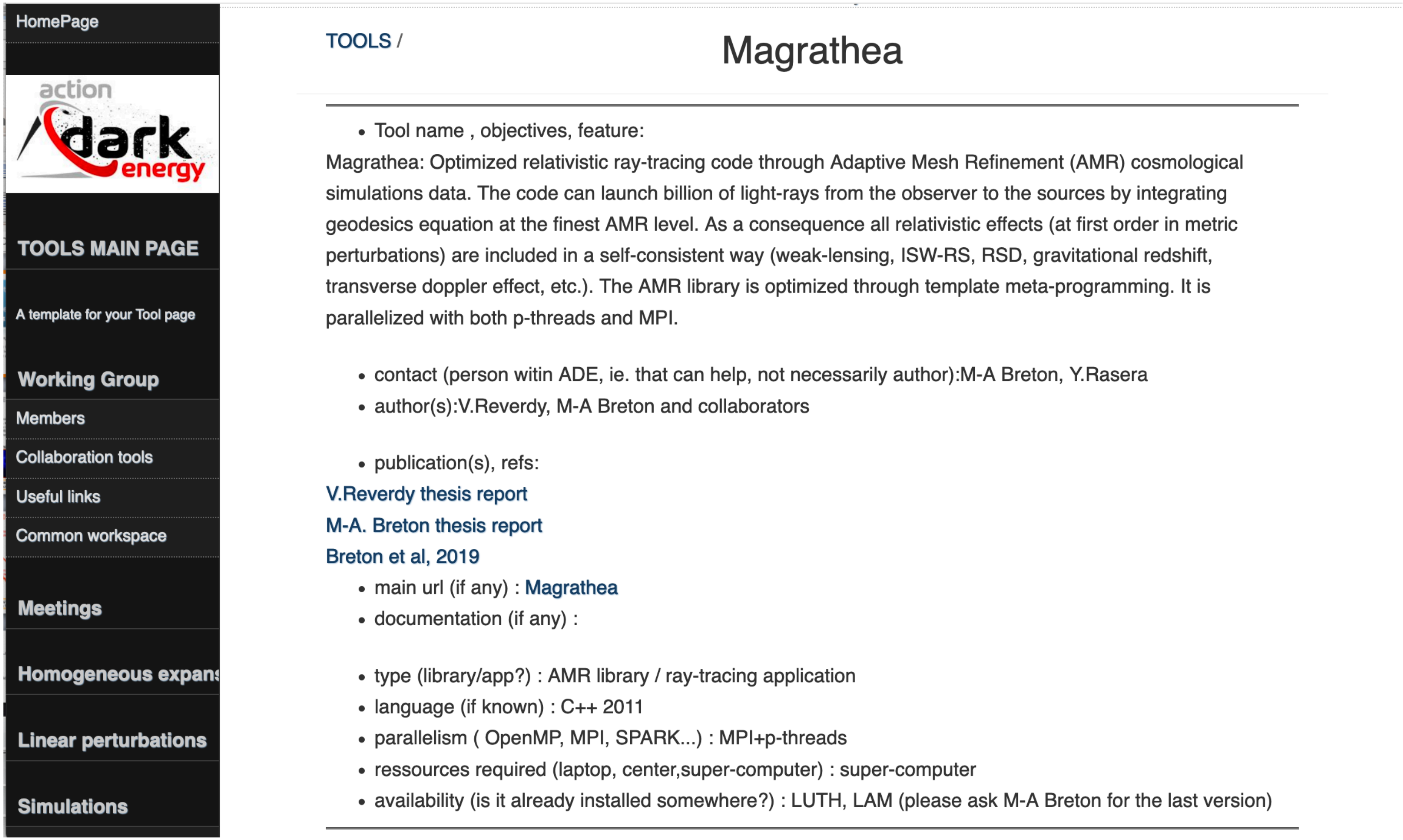
Parallel Universe Runs
(various realisations=> covariances)
LCDM online
New: Various DE models=> soon online



RayGalGroupSims
(statistics, resolution and raytracing=> relativistic RSD and WL)
LCDM online
New: WCDM sim => soon online

BY THE WAY…

YOU PROBABLY HAVE SOME FANCY TOOLS OR DATA TO SHARE… =>
DON'T FORGET TO FILL IN THE ACTION DARK ENERGY WIKI.
https://action-dark-energy.obspm.fr/
The idea is to know which tools are already here in the community…
You can just follow the template or make some improvisation. Example:



Magrathea

- Tool name , objectives, feature:

Magrathea: Optimized relativistic ray-tracing code through Adaptive Mesh Refinement (AMR) cosmological simulations data. The code can launch billion of light-rays from the observer to the sources by integrating geodesics equation at the finest AMR level. As a consequence all relativistic effects (at first order in metric perturbations) are included in a self-consistent way (weak-lensing, ISW-RS, RSD, gravitational redshift, transverse doppler effect, etc.). The AMR library is optimized through template meta-programming. It is parallelized with both p-threads and MPI.

- contact (person witin ADE, ie. that can help, not necessarily author):M-A Breton, Y.Rasera
- author(s):V.Reverdy, M-A Breton and collaborators

- publication(s), refs:

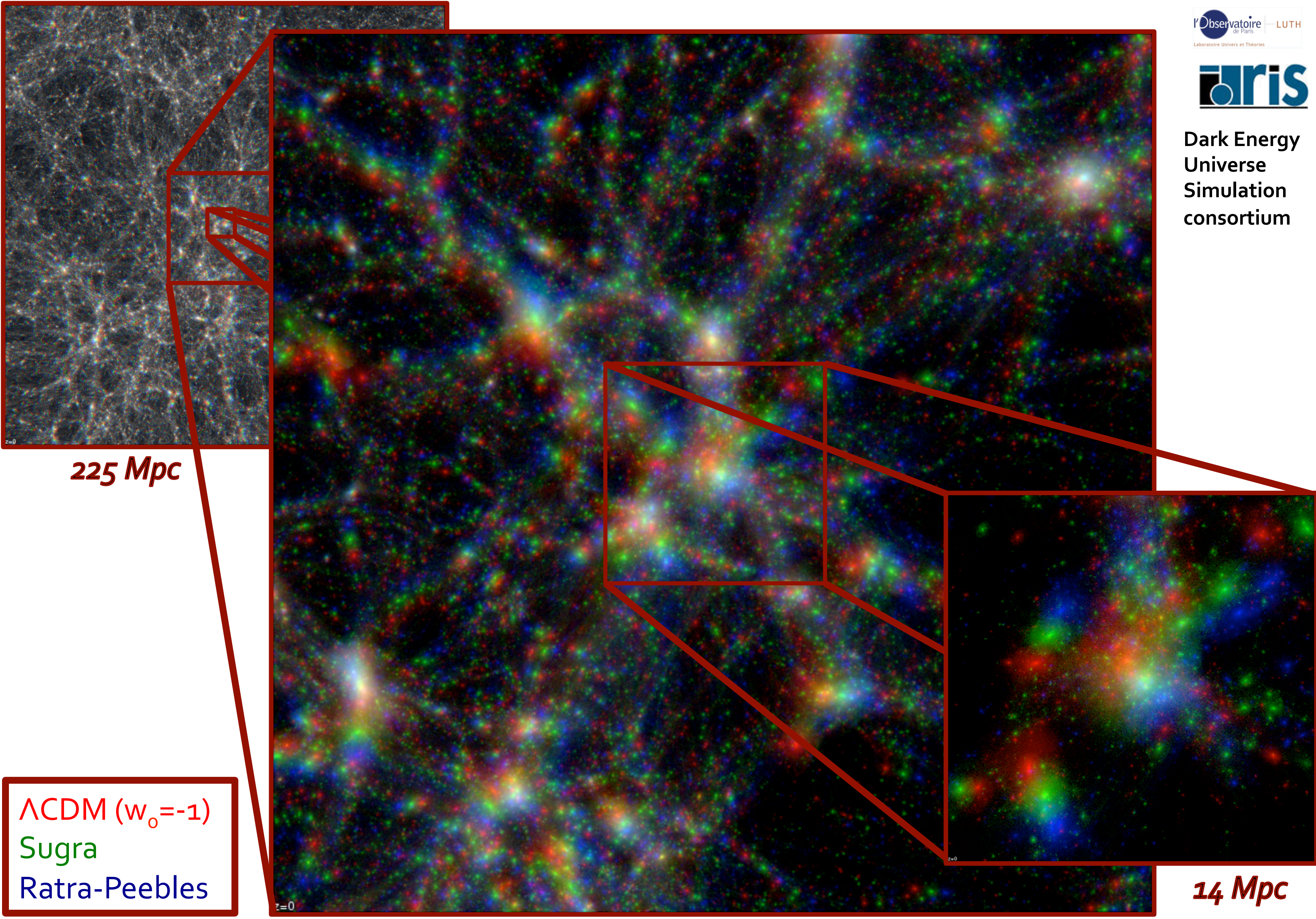
V.Reverdy thesis report
M-A. Breton thesis report
Breton et al, 2019

- main url (if any) : Magrathea
- documentation (if any) :

- type (library/app?) : AMR library / ray-tracing application
- language (if known) : C++ 2011
- parallelism (OpenMP, MPI, SPARK...) : MPI+p-threads
- ressources required (laptop, center,super-computer) : super-computer
- availability (is it already installed somewhere?) : LUTH, LAM (please ask M-A Breton for the last version)

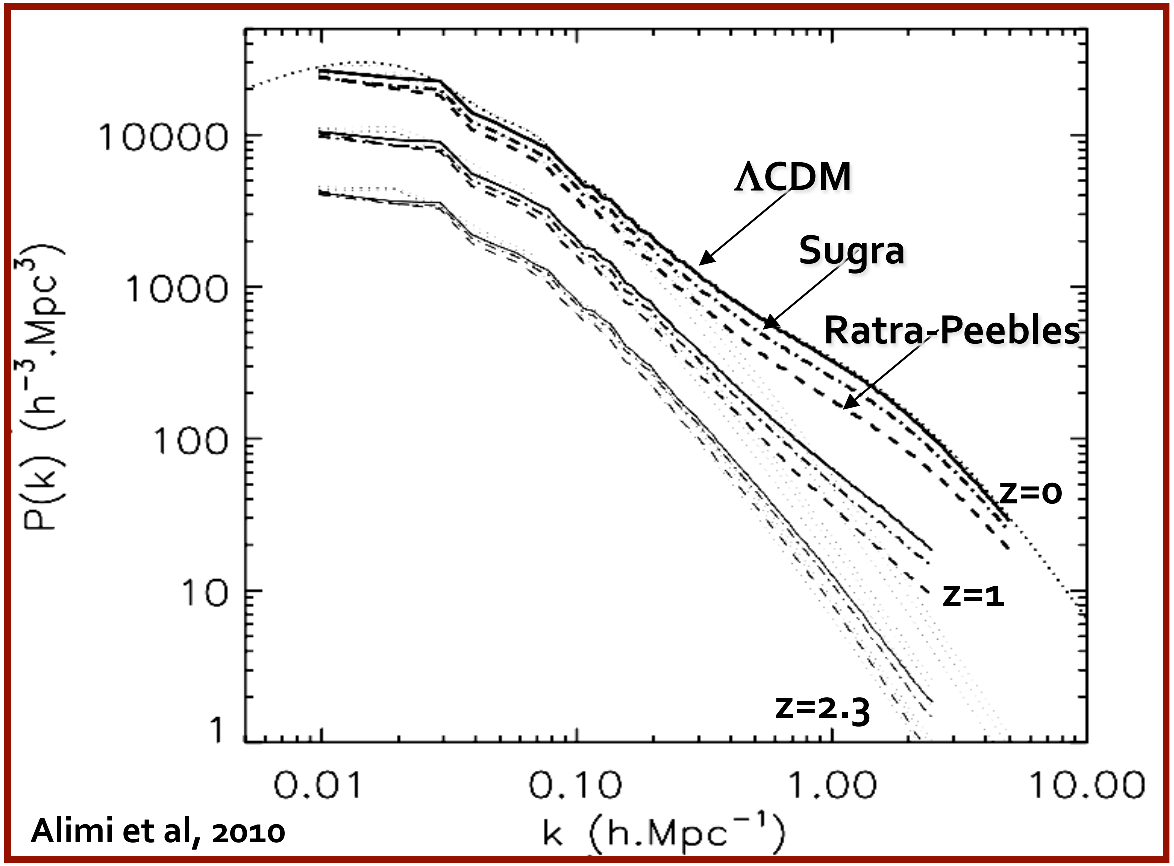
III. Imprints of dark energy on cosmic structure formation

Dark Energy
Universe
Simulation
consortium



Dark Energy Universe Simulation Series

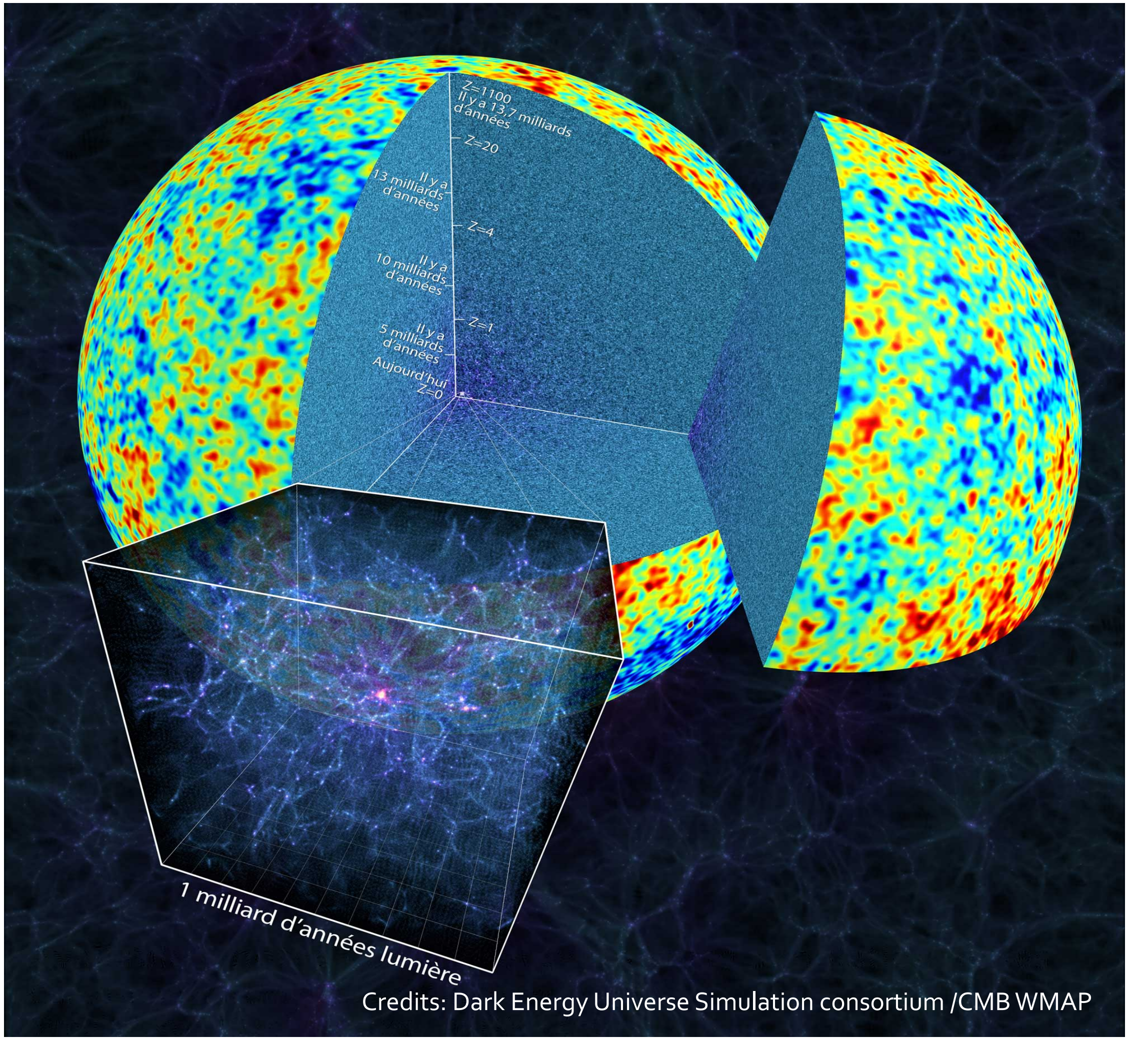
THE GLOBAL PICTURE



Alimi et al, 2010

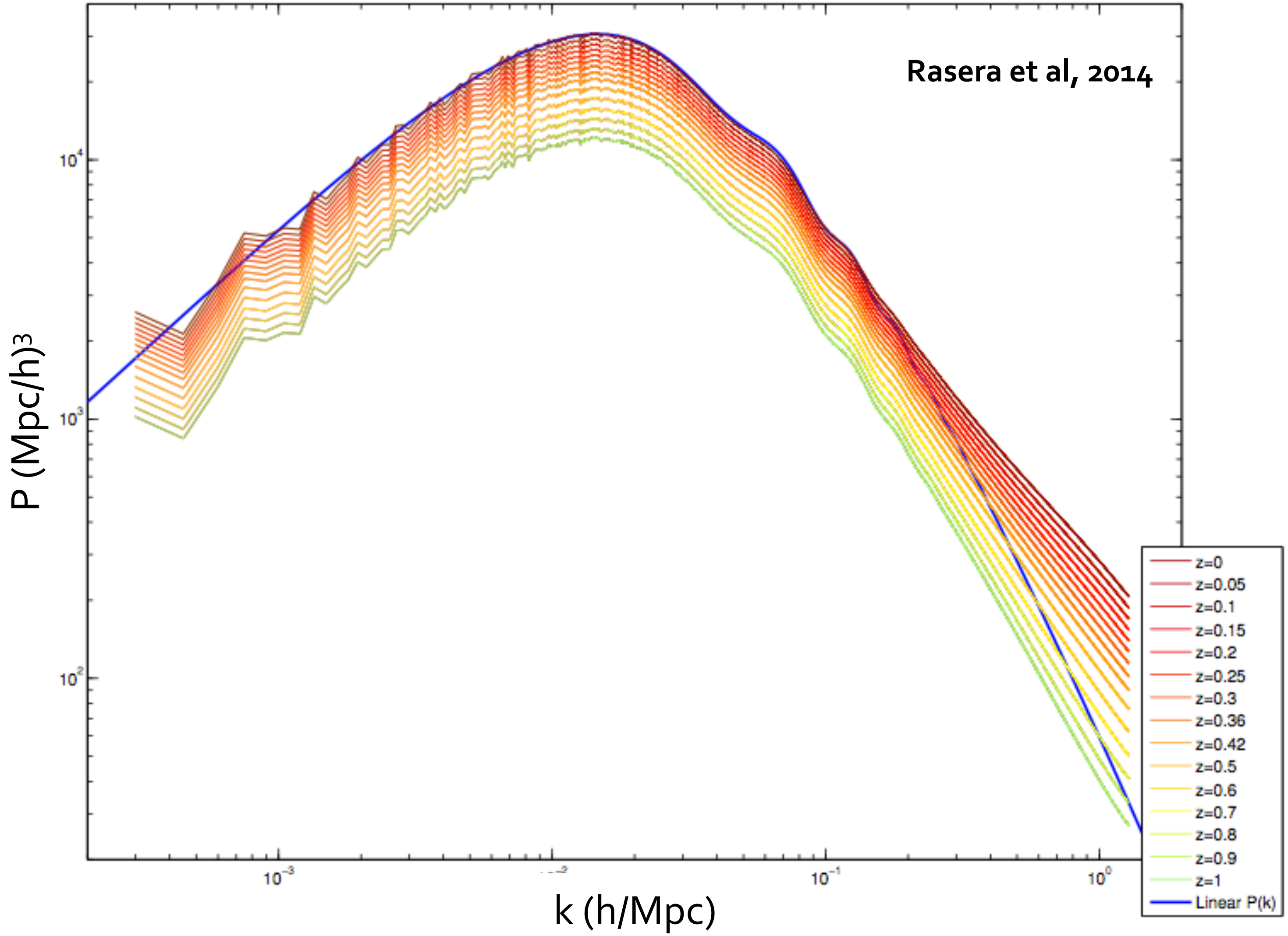
- **Imprints of DE on linear, quasi-linear and NL regime**
- **NL imprint is non trivial: depends on all history of structure formation!**

Full Universe Runs

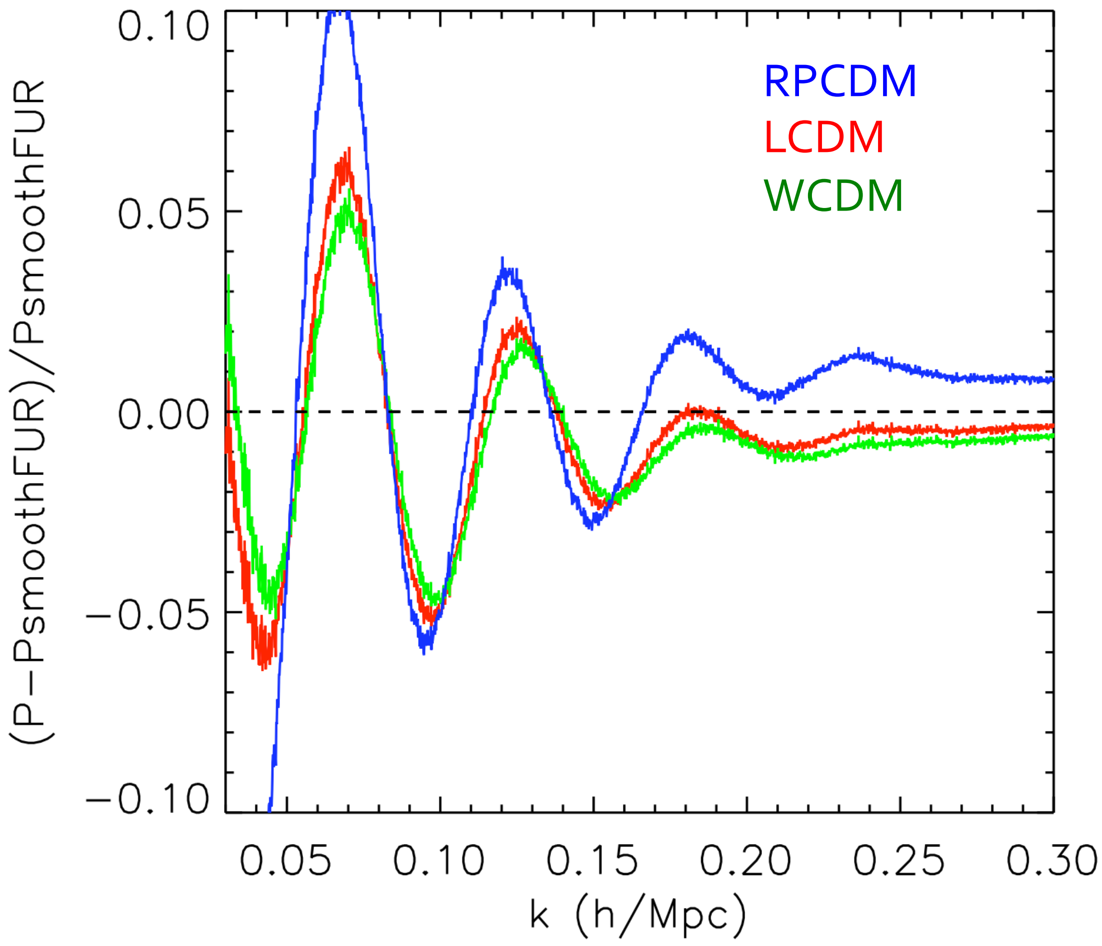


Credits: Dark Energy Universe Simulation consortium /CMB WMAP

ZOOMING ON BAO

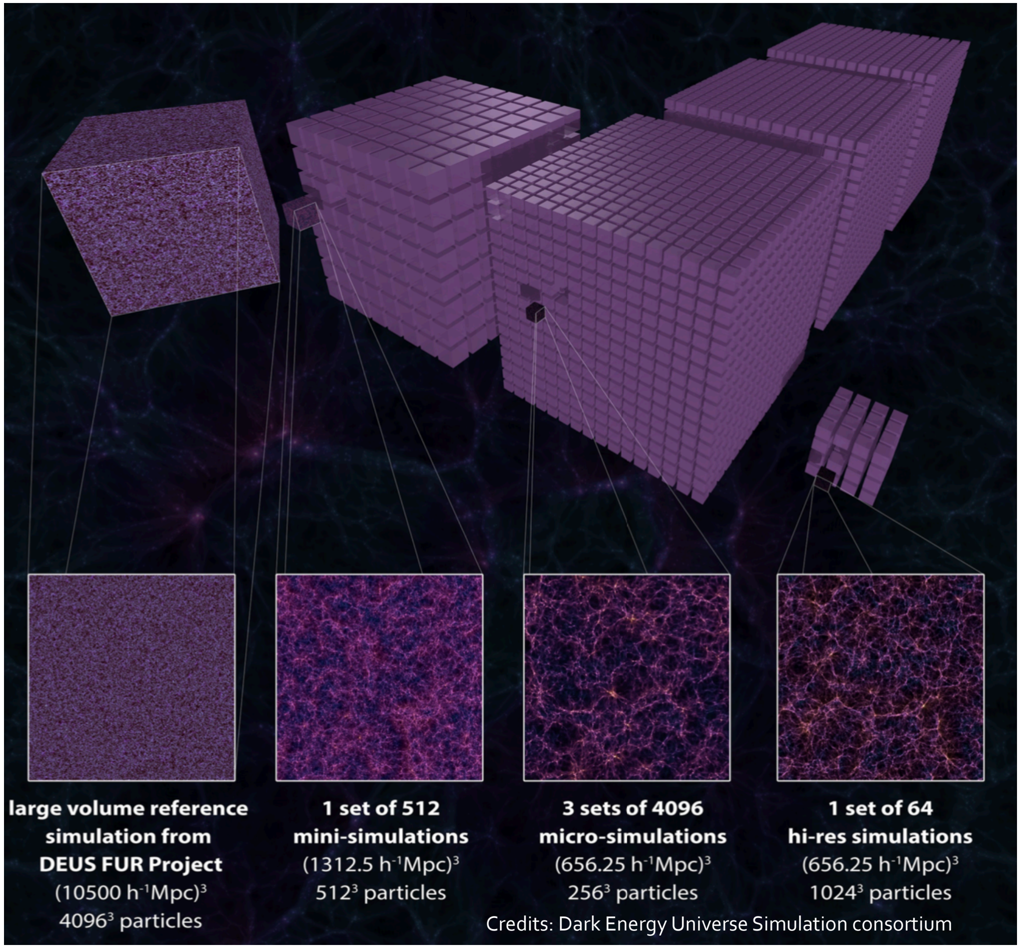

Rasera et al, 2014

- Low redshift matter power spectra in real space from Full Universe Run
- BAO visible by eye in the raw data
- Low redshift is most difficult to predict with perturbation theory



- Cosmology alters: peak positions, damping and also broad-band shape
- In principe BAO should be able to constrain the damping=> D^+

Parallel Universe Run

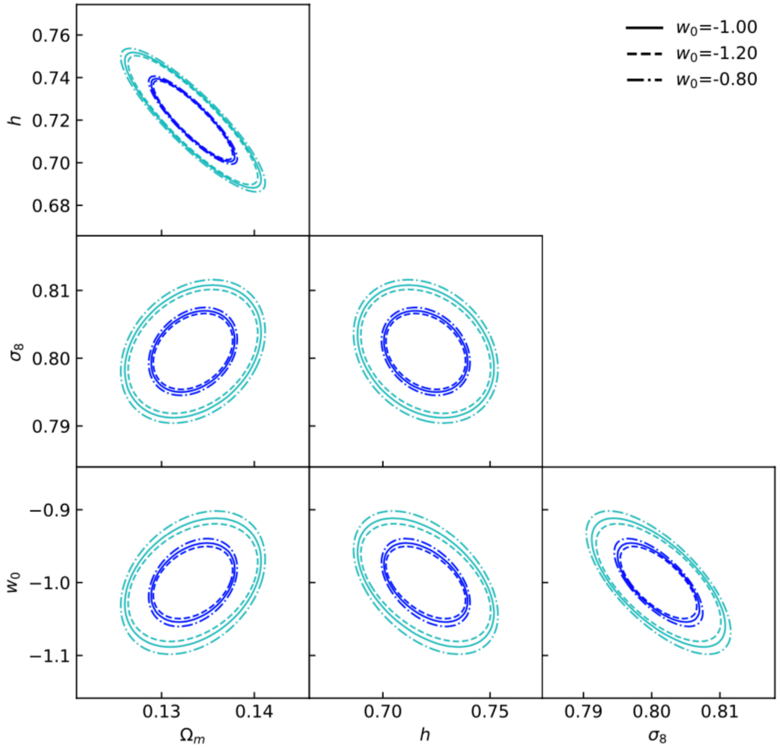


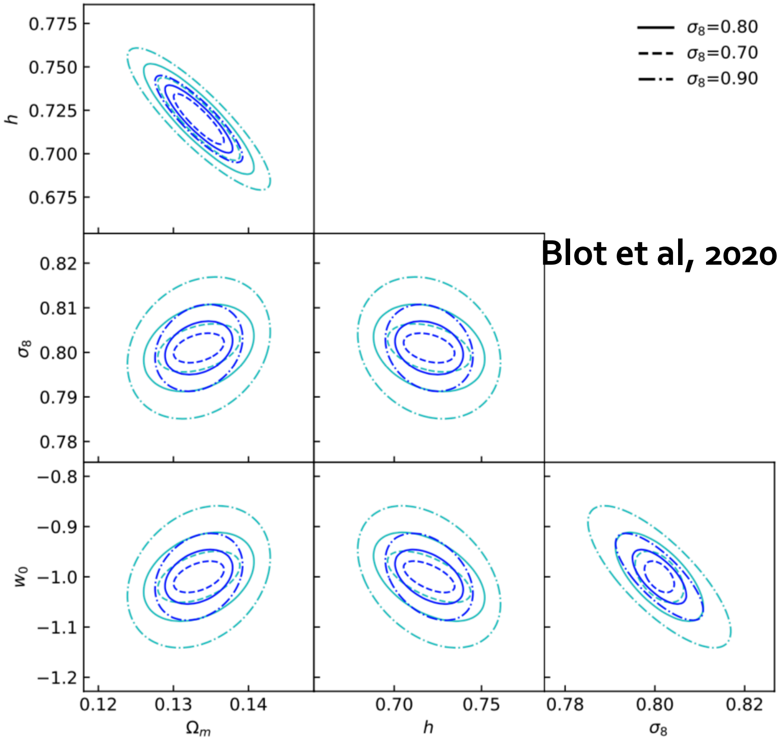
Credits: Dark Energy Universe Simulation consortium

$n_{\rm model}$	Ω_m	σ_8	h	w_0
1	**1.0000**	0.801	0.72	-1.0
2	*0.2573*	*0.801*	*0.72*	*-1.0*
3	0.2573	0.801	0.72	**-1.2**
4	0.2573	0.801	0.72	**-0.8**
5	0.2573	**0.700**	0.72	-1.0
6	0.2573	**0.900**	0.72	-1.0
7	**0.3100**	0.801	0.72	-1.0
8	**0.2046**	0.801	0.72	-1.0
9	0.2573	0.801	**0.67**	-1.0
10	0.2573	0.801	**0.77**	-1.0

New set: Blot et al, 2020, in prep
512 sims per cosmology
(328.125 Mpc/h)^3

Initial set of Blot et al, 2014





Blot et al, 2020, in prep

PRELIMINARY RESULTS: constraints on cosmological parameters from matter power spectra using covariances from wrong cosmology

- Using the wrong cosmology to compute the covariances leads to non-negligible errors in the likelihoods (even in the vicinity of LCDM)

III. Quel est le lien entre l’Univers “réel” et l’Univers tel qu’on le perçoit ?

Sujet d’examen Baccalauréat Philosophie 2020 ☺
Vous avez 3 heures …

III. What is the link between real space and “redshift-space” (or “observed” space) ?

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

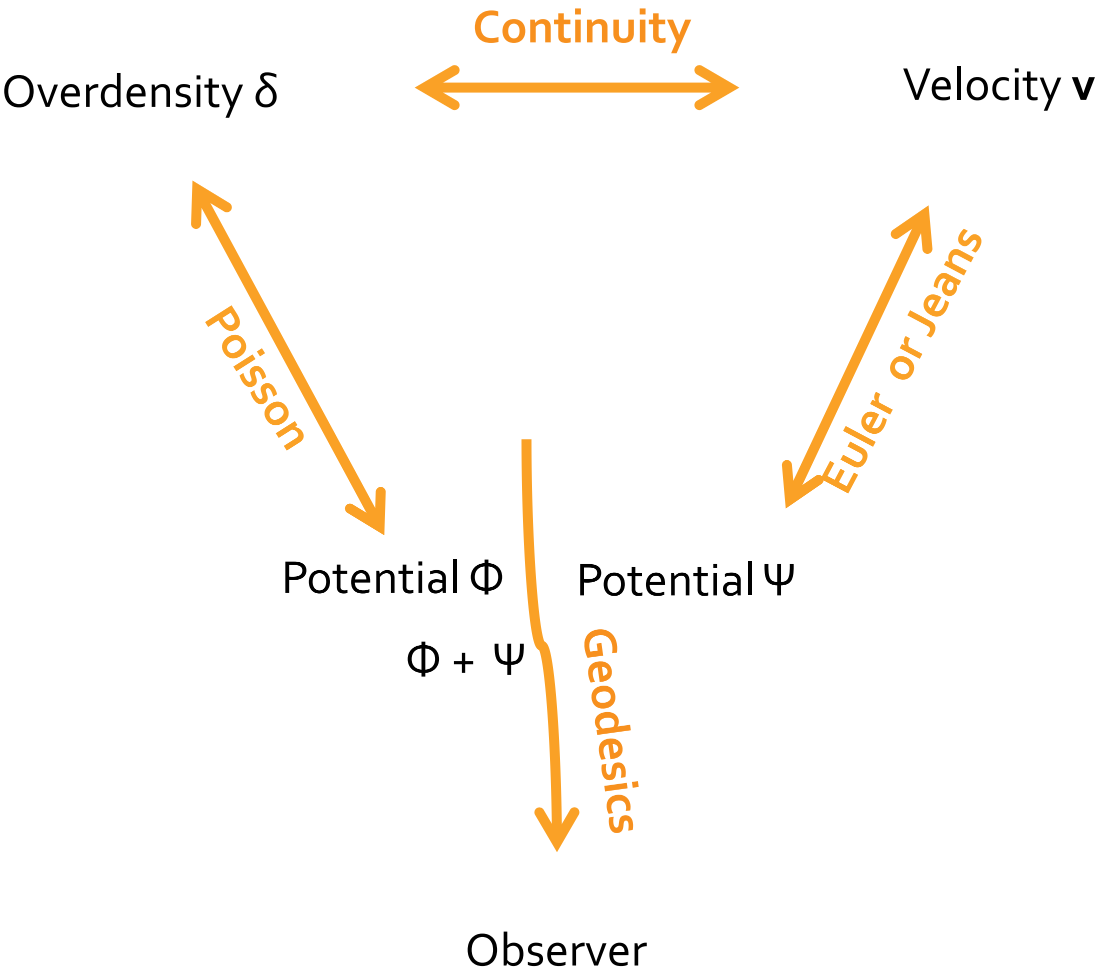
⇒ **NEW COSMOLOGICAL INFORMATIONS FROM WEAK LENSING (WL) AND RELATIVISTIC REDSHIFT SPACE DISTORTIONS (RSD)**

THE COSMIC PROGRAM

(beyond a(t))

CAN WE POSSIBLY TEST ALL THESE HYPOTHESIS AT COSMOLOGICAL SCALES ?

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



Continuity

Overdensity δ

Velocity **v**

Poisson

Euler or Jeans

Potential Φ

Potential Ψ

Φ + Ψ

Geodesics

Observer

Simplified view
Assume a(t) known

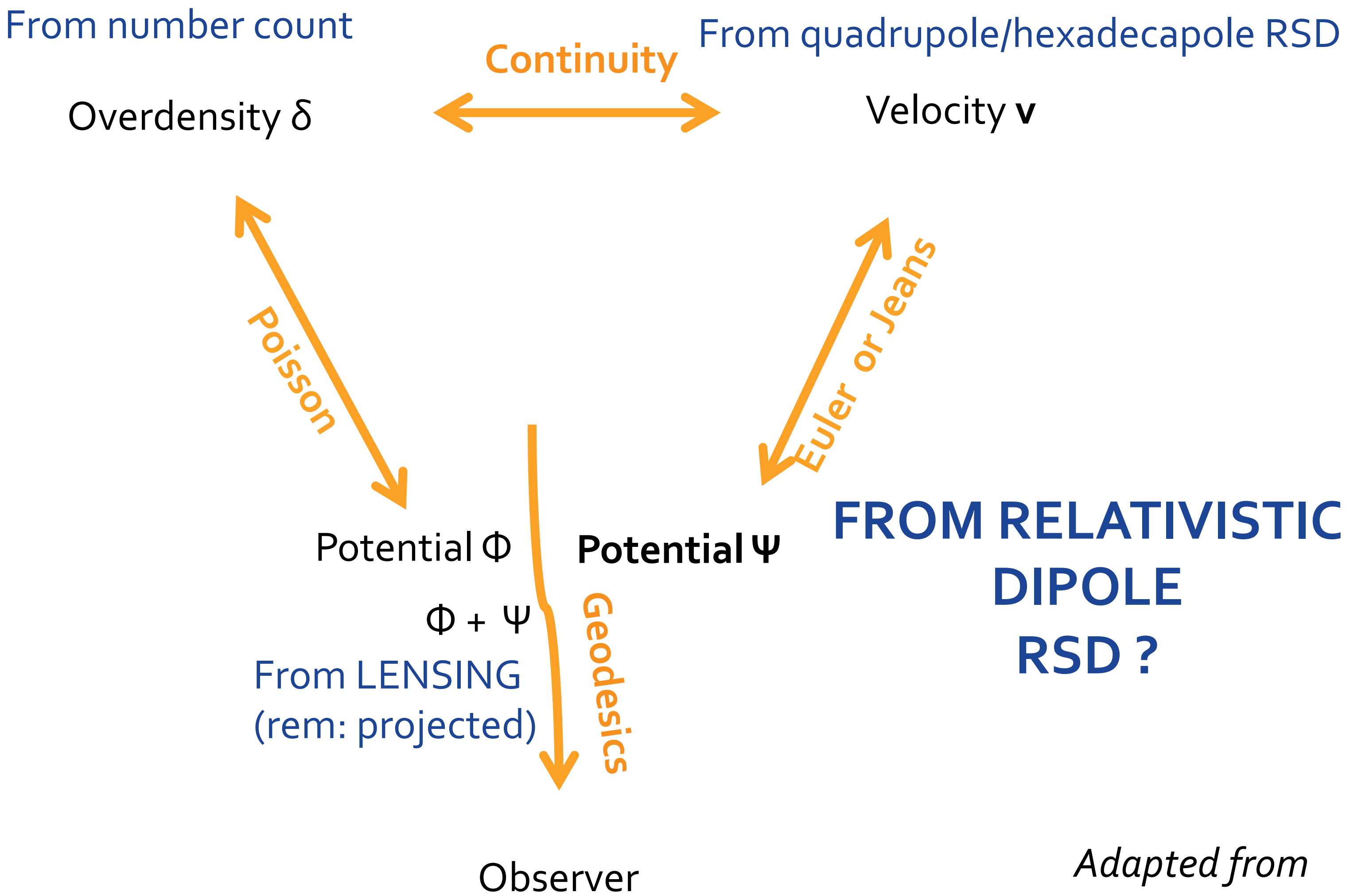
Adapted from
Bonvin&Fleury 2018

THE COSMIC PROGRAM

(beyond a(t))

CAN WE POSSIBLY TEST ALL THESE 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

Overdensity δ

Continuity

From quadrupole/hexadecapole RSD

Velocity **v**

Poisson

Euler or Jeans

Potential Φ

Potential Ψ

Φ + Ψ

From LENSING
(rem: projected)

Geodesics

Observer

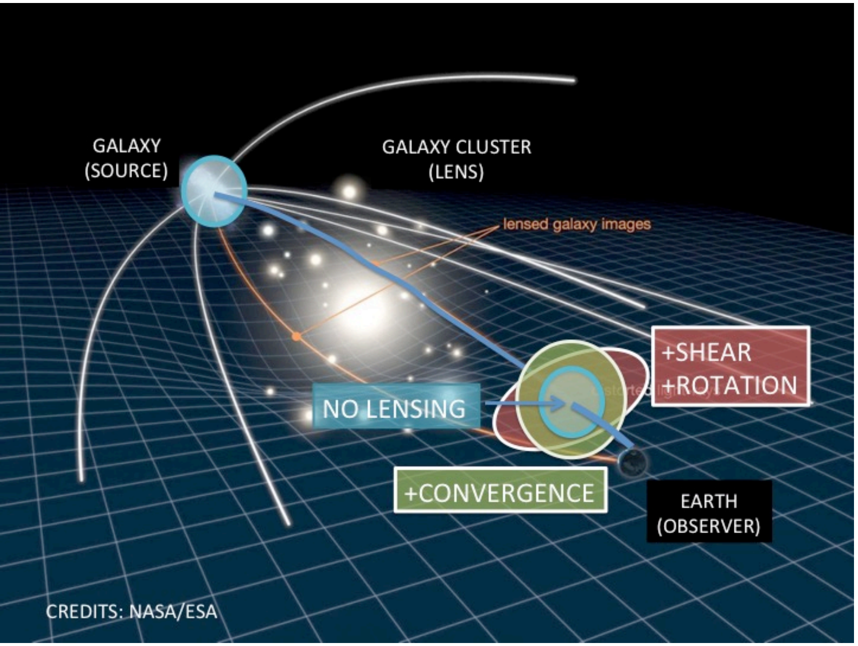
FROM RELATIVISTIC DIPOLE RSD ?

Simplified view
Assume a(t) known

Adapted from Bonvin&Fleury 2018

Usual approach

LENSING

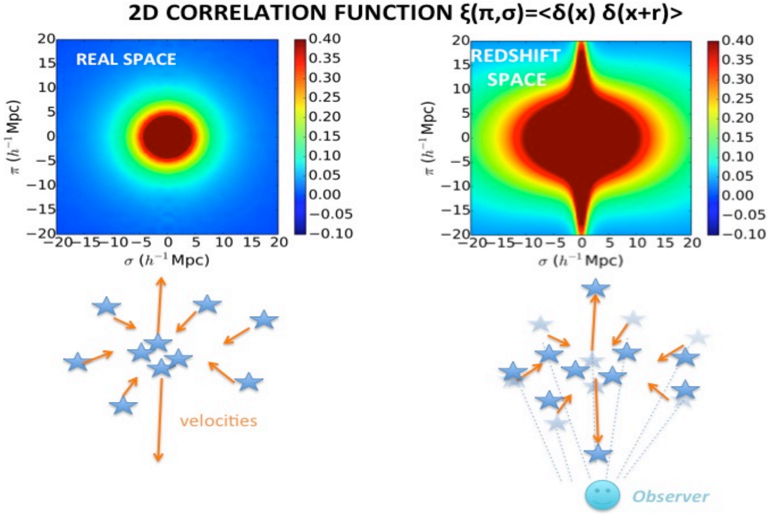


CREDITS: NASA/ESA

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

OR

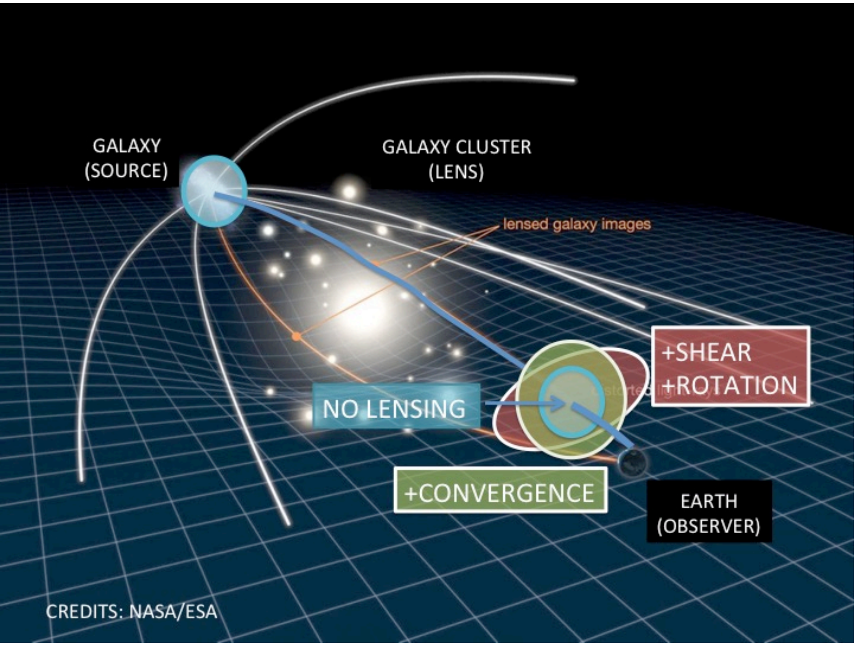
Redshift-Space Distortions (RSD)



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

(Weak-Field) Relativistic approach

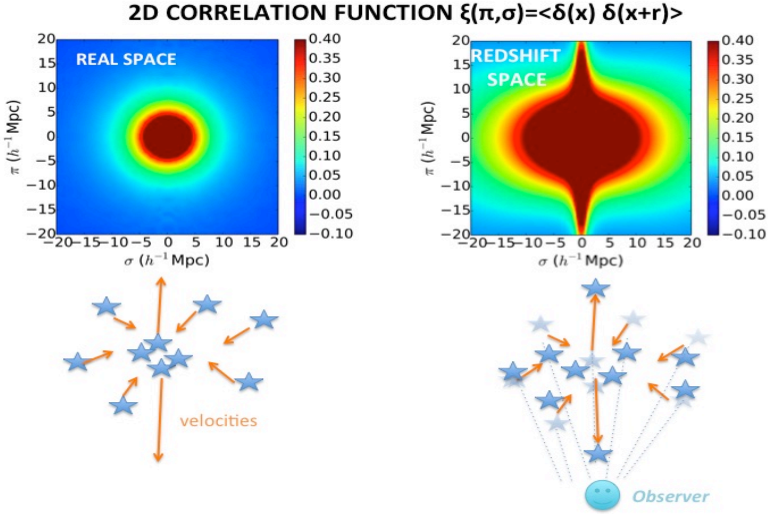
LENSING



CREDITS: NASA/ESA

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

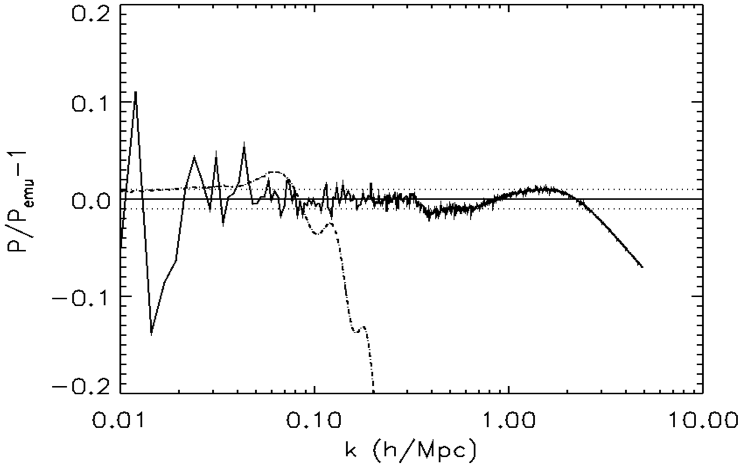
- Relativistic approach at cluster scale and around: Kaiser2013, Zhao2013, Croft2013, Cai+2017

=> LIMITATION: How to connect with linear predictions ?

OUR APPROACH: **RayGalGroupSims (Raytracing Galaxy Group Simulations)**

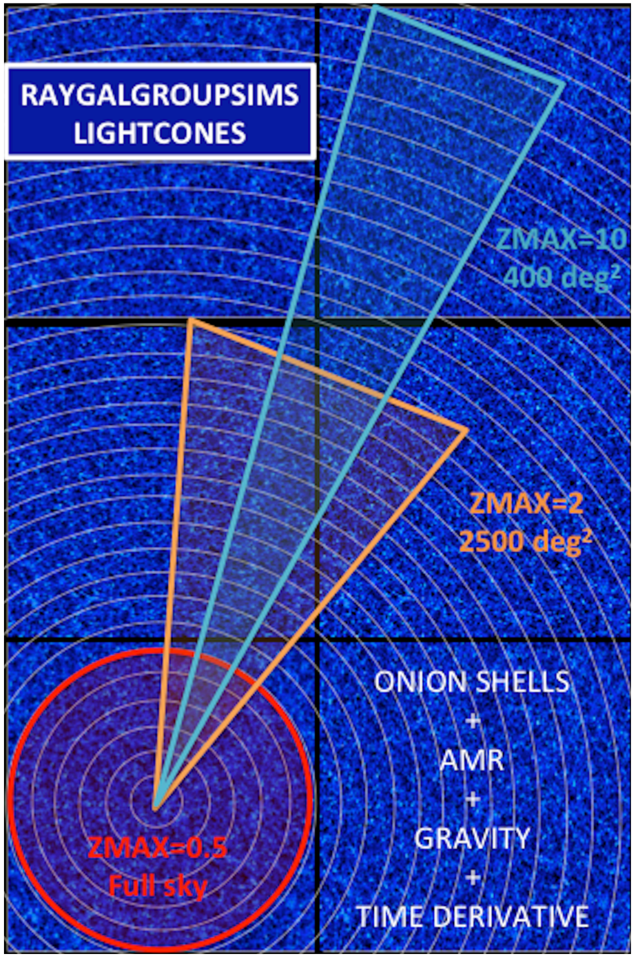
- **Characteristics**
  - LCDM cosmology and **WCDM (new)**
  - Size: **2.6 Gpc/h**. Resolution: 5 kpc/h
  - # of particles**: 4096^3** . Number of cells: 0.4 trillion
  - Code: RAMSES (Teyssier 2002)
  - Method: PM-AMR (Adaptive Mesh Refinement)
  - Validation P(k) at 1% up to k=2 h/Mpc

Relative deviation of P(k) to Cosmic Emulator



- **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 !**

ONION SHELL APPROACH



DIRECT INTEGRATION OF GEODESICS EQUATIONS IN PERTURBED FLRW WITHIN AMR GRID

- Geodesic equations:

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

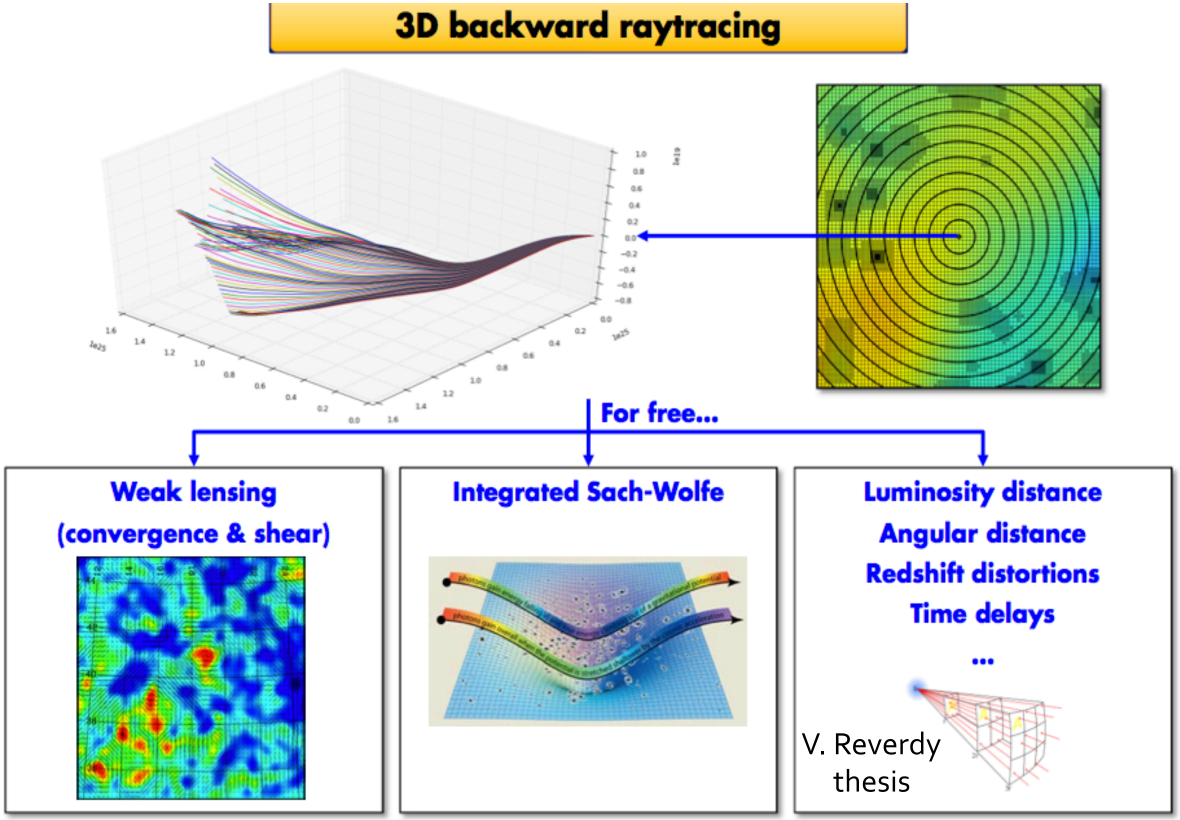
- Redshift definition:

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

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

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

- LITTLE NUMBER OF CONTROLED ASSUMPTIONS



3D backward raytracing

For free...

Weak lensing (convergence & shear)

Integrated Sach-Wolfe

Luminosity distance
Angular distance
Redshift distortions
Time delays
...

V. Reverdy thesis

ITERATIVE ROOT FINDER
AND RAYGALGROUPSIMS HALO CATALOG

Find null geodesics

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

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

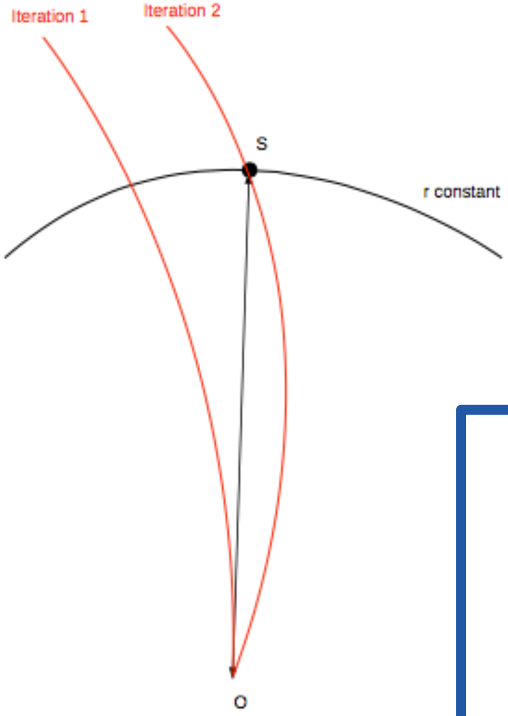
$x_{k+1} = x_k - F(x_k)/F'(x_k)$

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,2019

- 10 millions halos with relativistic effects between 10^{12}Msun and 10^{14}Msun
- 100 millions particles
- Full-sky light-cone z<0.5 Narrow LC z<2 2500 deg²

Rem: Distortion matrix A_{ij} account for finite beam effect

YOU CAN DOWNLOAD IT
(JUST TYPE **RAYGALGROUPSIMS** ON YOUR FAVORITE SEARCH ENGINE OR GO TO COS TEAM WEBSITE)
VERY SIMPLE: ASCII FILES + README

IIIa. Relativistic Redshift Space Distortions

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

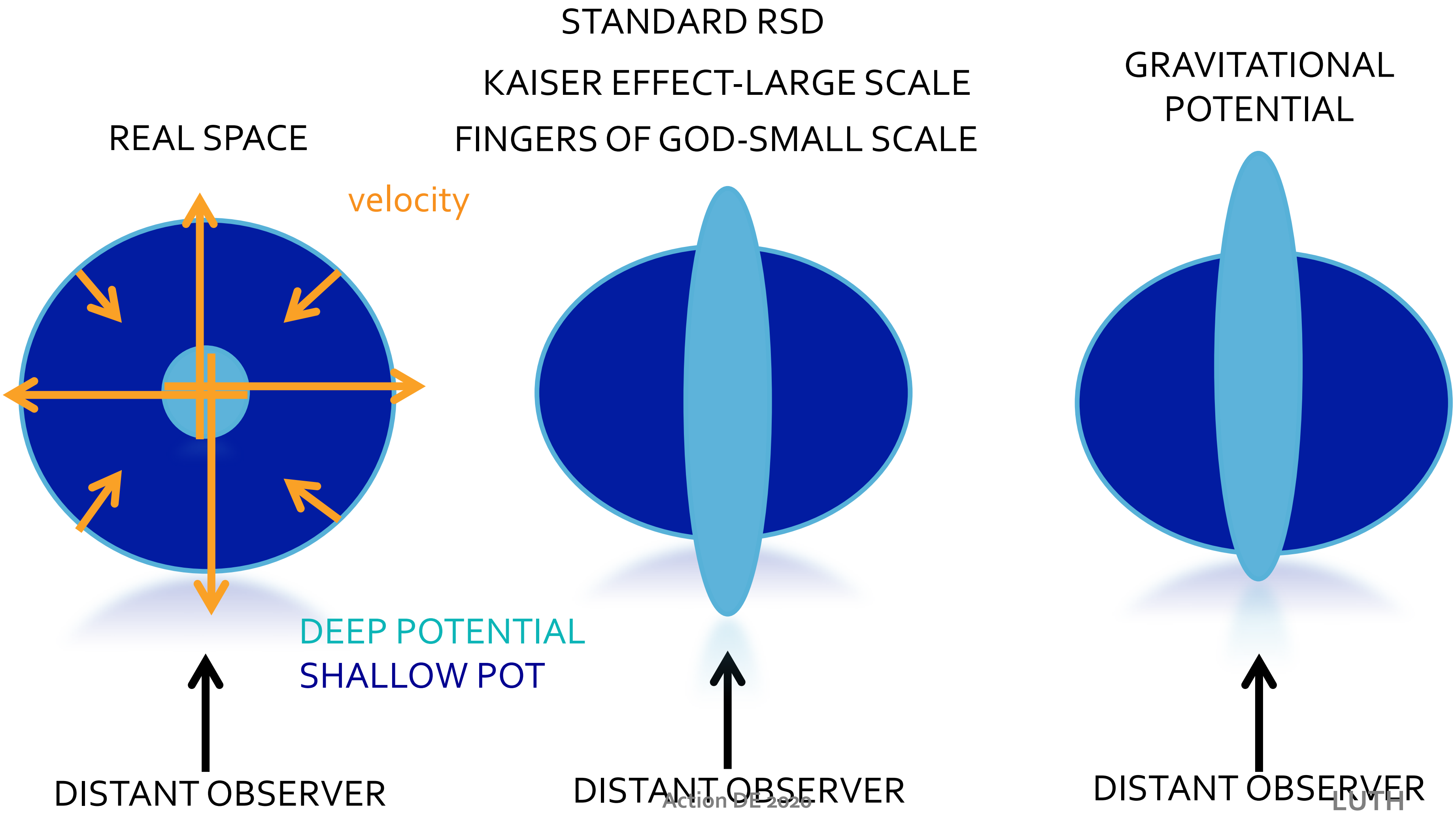
$$z_O = \underbrace{\frac{a_O}{a_S}}_{\text{HOMOGENEOUS}}\left(1 + \underbrace{\frac{\vec{v_S}.\vec{n}}{c}}_{\text{DOPPLER}} \underbrace{- \frac{\phi_S - \phi_O}{c^2}}_{\text{GRAVITATIONAL REDSHIFT}} + \underbrace{\frac{v_S^2}{2c^2}}_{\text{TRANSVERSE DOPPLER}} \overbrace{- 2\int_{\eta_S}^{\eta_O} \frac{\dot{\phi}}{c^2} d\eta}^{\text{ISW-RS}}\right) - 1$$

$$\underbrace{\vec{\beta} = \vec{\theta} - \vec{\alpha}}_{\text{LENSING}}$$

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

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

Apparent distribution of sources: example of redshift space distortion



STANDARD RSD

KAISER EFFECT-LARGE SCALE

FINGERS OF GOD-SMALL SCALE

GRAVITATIONAL POTENTIAL

REAL SPACE

velocity

DEEP POTENTIAL

SHALLOW POT

DISTANT OBSERVER

DISTANT OBSERVER

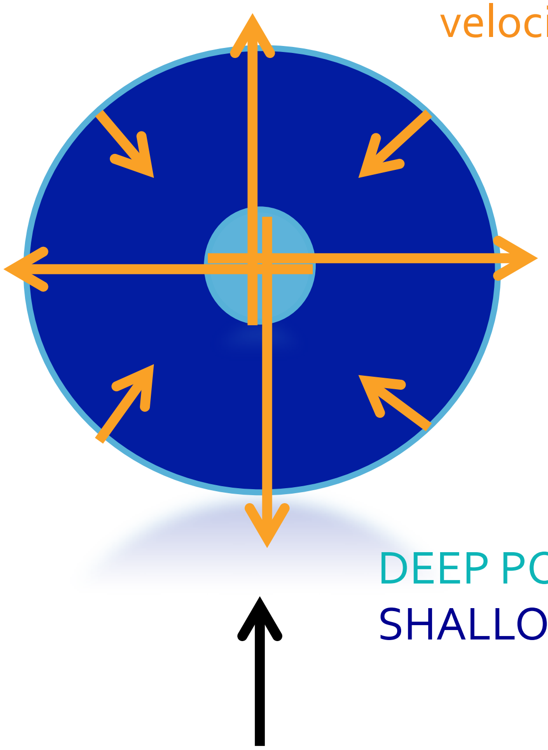
DISTANT OBSERVER

Apparent distribution of sources: example of redshift space distortion

MONOPOLE

REAL SPACE

velocity



DEEP POTENTIAL

SHALLOW POT

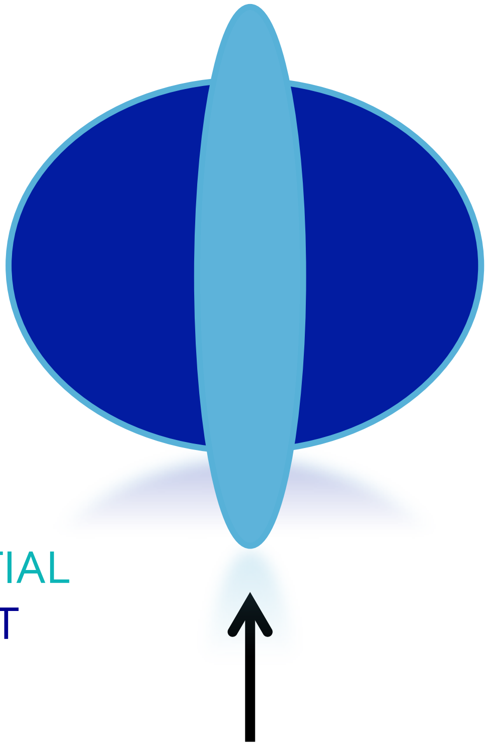
DISTANT OBSERVER

EVEN MULTIPOLES

STANDARD RSD

KAISER EFFECT-LARGE SCALE

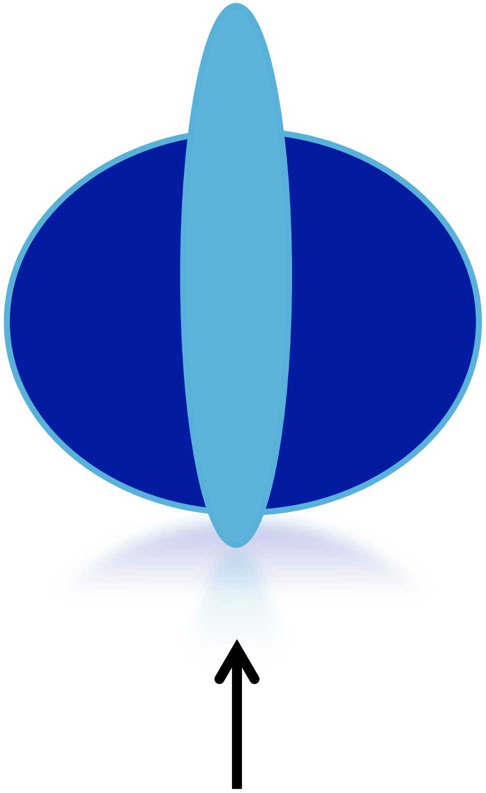
FINGERS OF GOD-SMALL SCALE



DISTANT OBSERVER

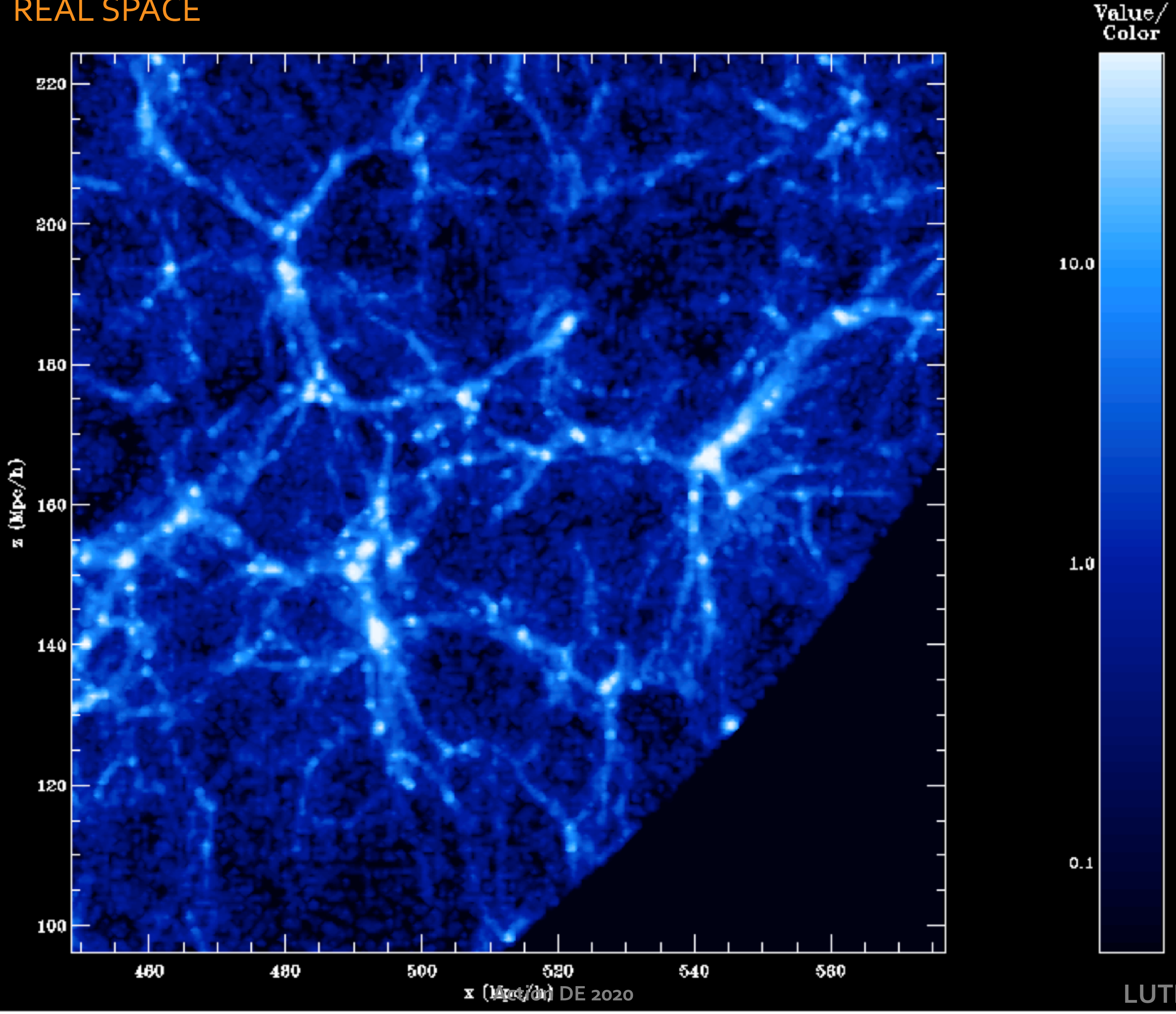
DIPOLE

GRAVITATIONAL POTENTIAL

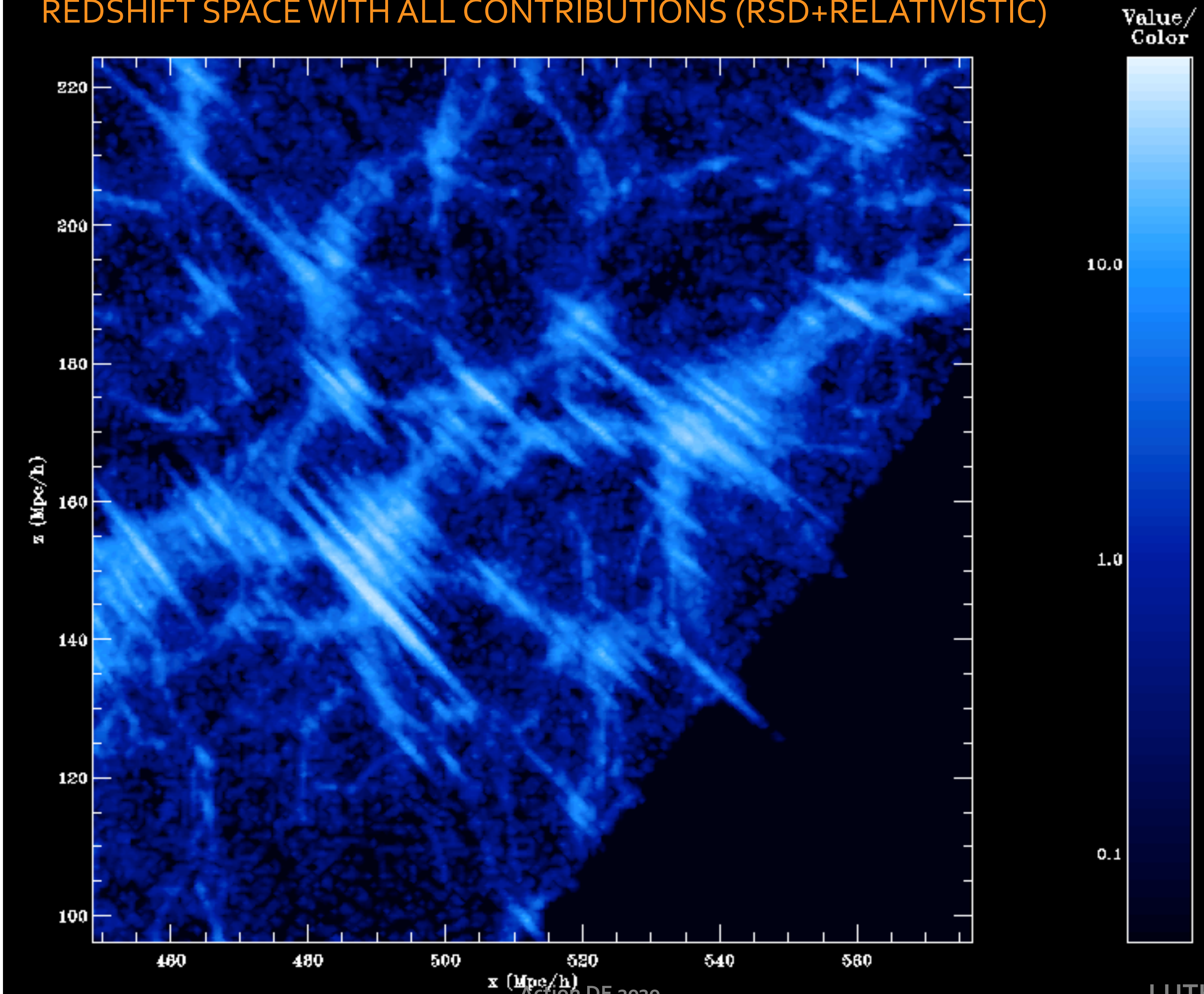


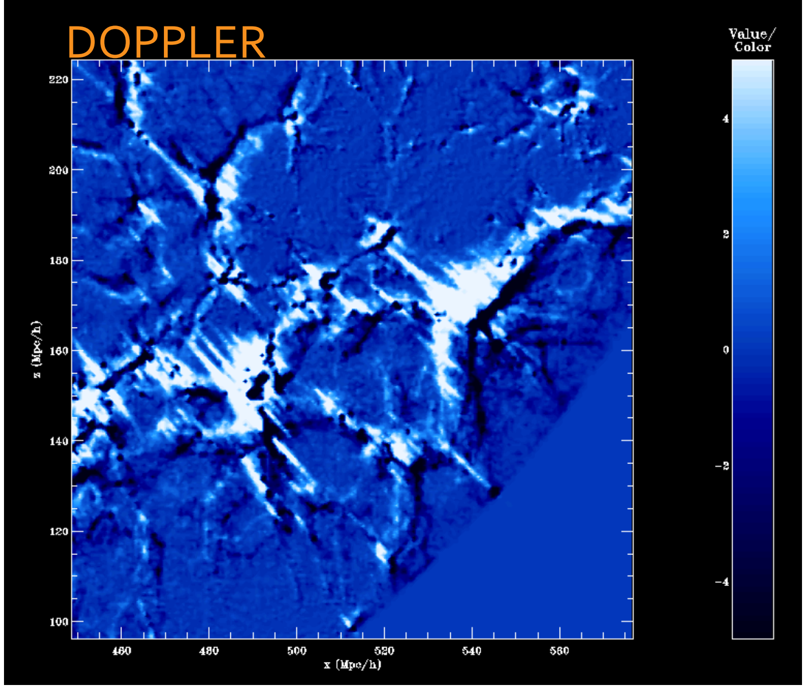
DISTANT OBSERVER

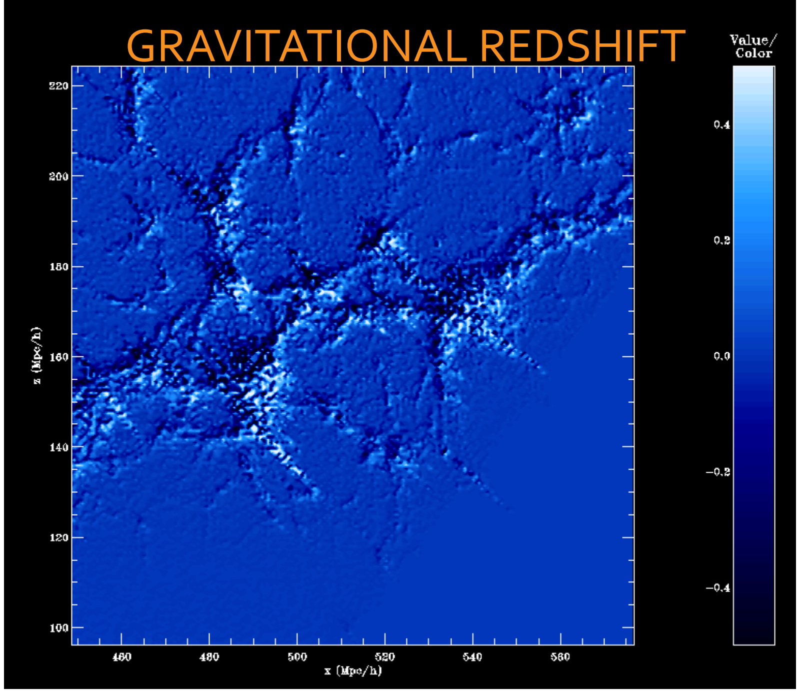
REAL SPACE

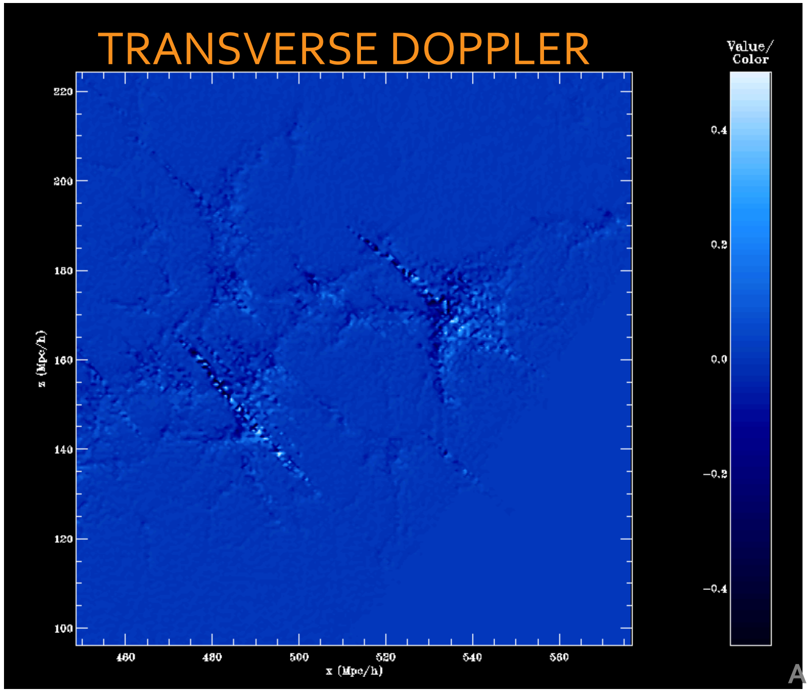

Value/
Color
10.0
1.0
0.1
z (Mpc/h)
220
200
180
160
140
120
100
460
480
500
520
540
560
x (Mpc/h)

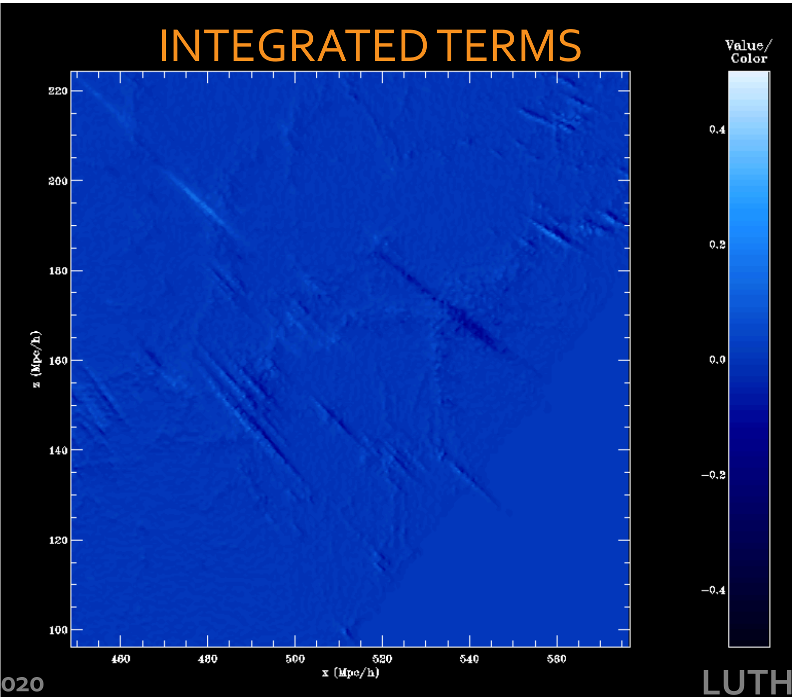
REDSHIFT SPACE WITH ALL CONTRIBUTIONS (RSD+RELATIVISTIC)




DOPPLER


GRAVITATIONAL REDSHIFT


TRANSVERSE DOPPLER


INTEGRATED TERMS

Dipole of halo-halo cross-correlation

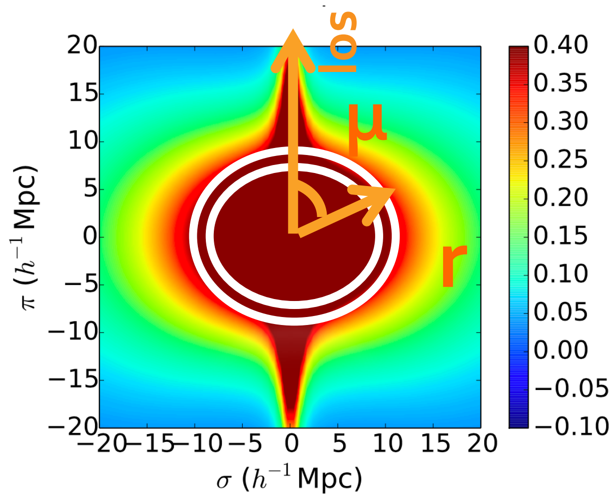
- Multipole

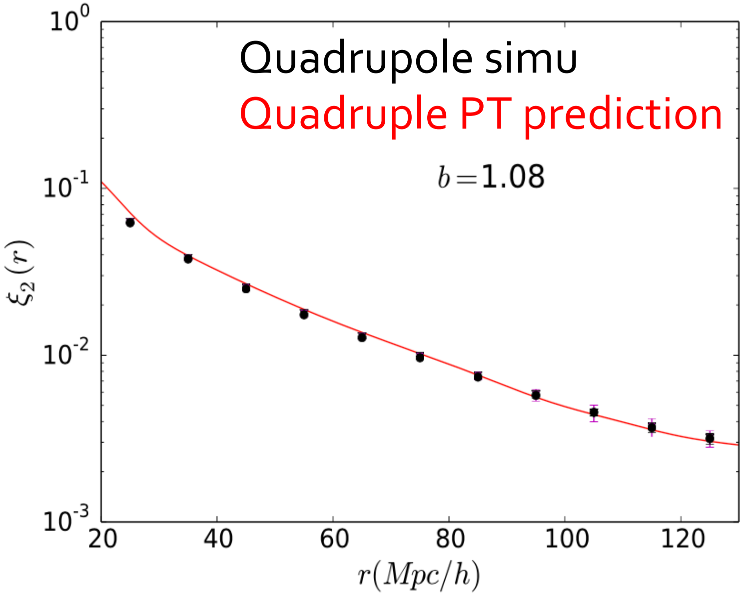
  $\xi_l(r)=<\delta_1(\mathbf{x})\ \delta_2\ (\mathbf{x}+\mathbf{r})\ P_l(mu)>$

- Monopole: l=0 => density

- Quadrupole: l=2 => velocity

- Dipole: l=1 => relativistic effects

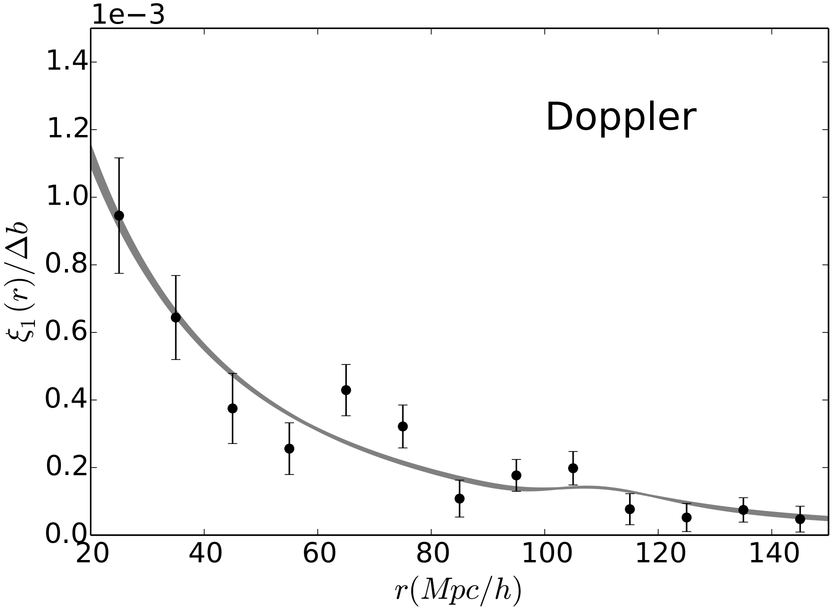


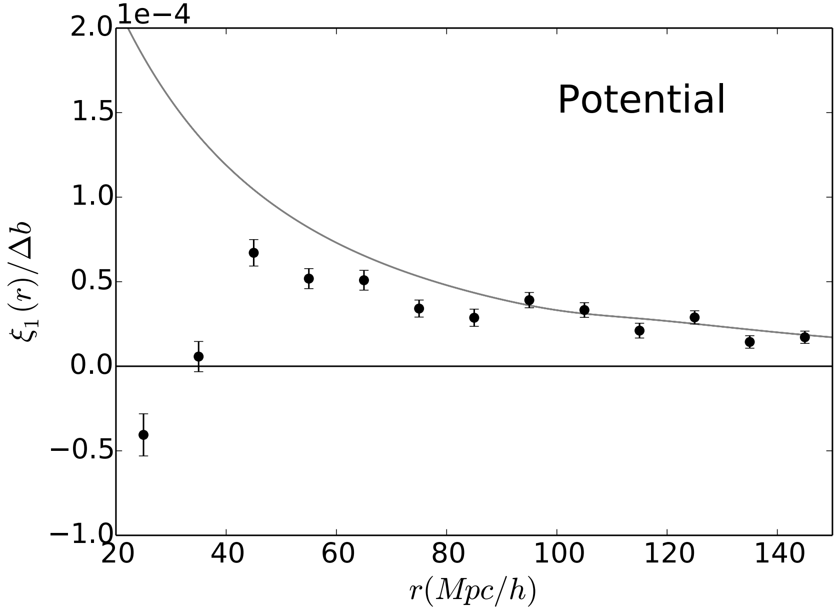


LARGE SCALES (20-150 Mpc/h): SIMU (POINTS) VS LINEAR (LINES)

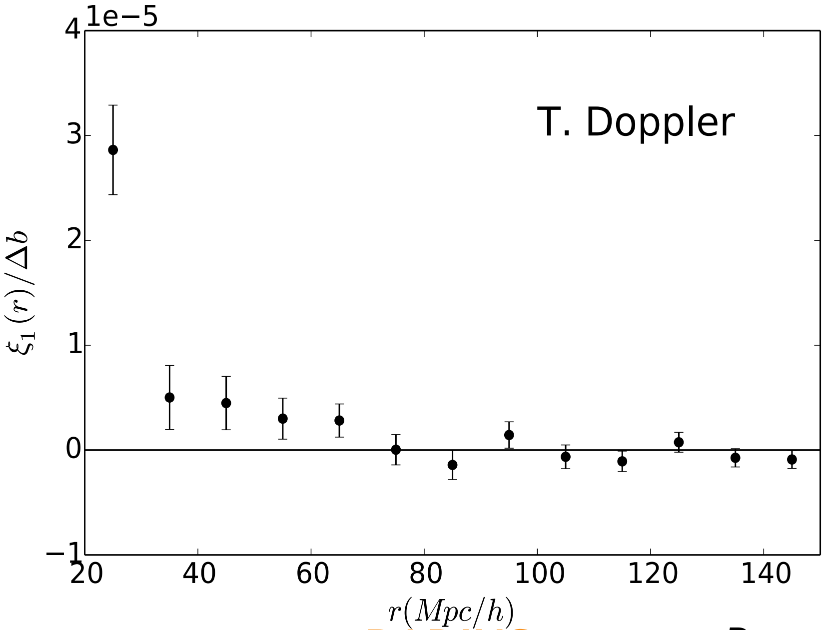
MW-size halo-Group size halo cross-correlation

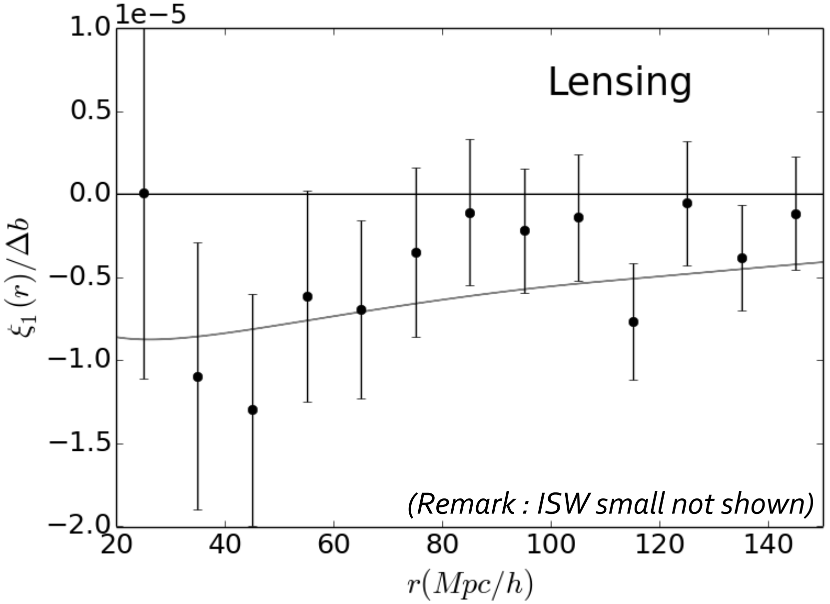
DIPOLE





DIPOLE



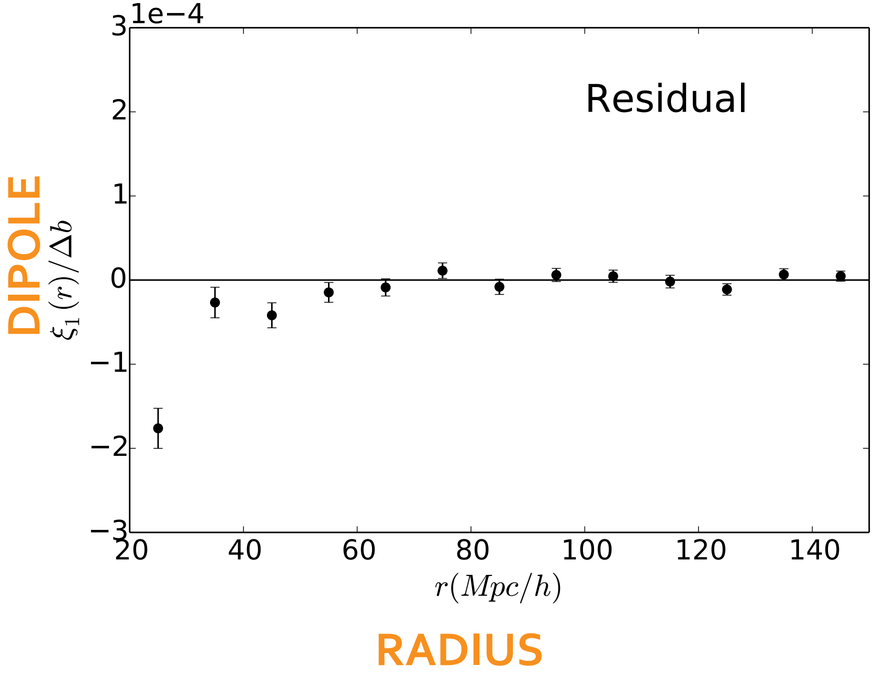


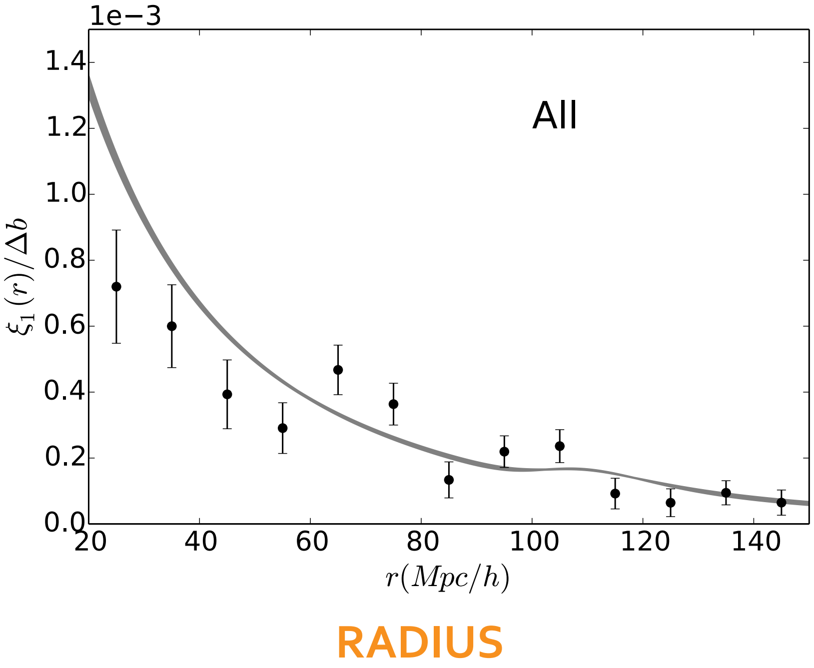
(Remark : ISW small not shown)

RADIUS

Breten et al, 2018

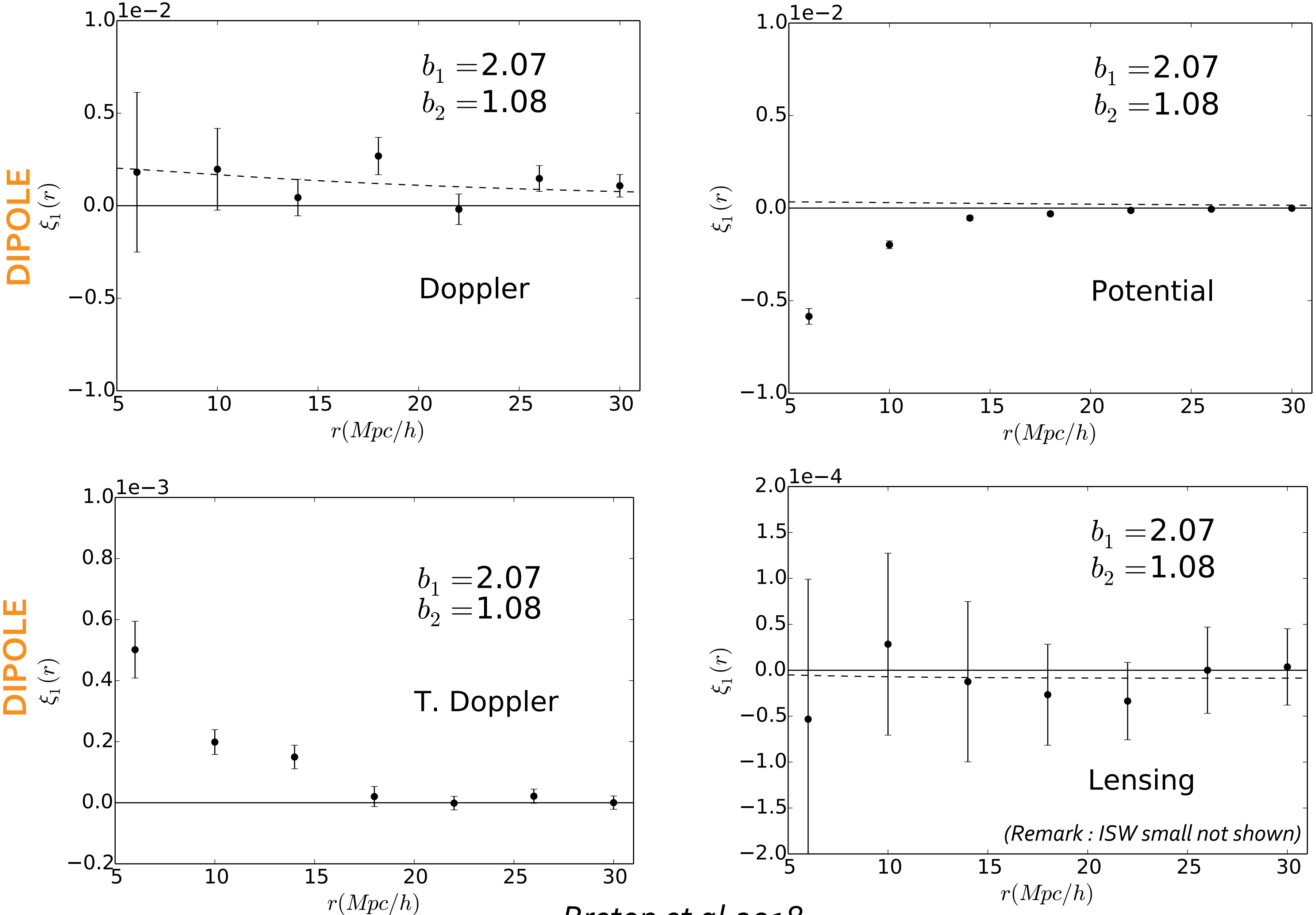
RADIUS





- 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

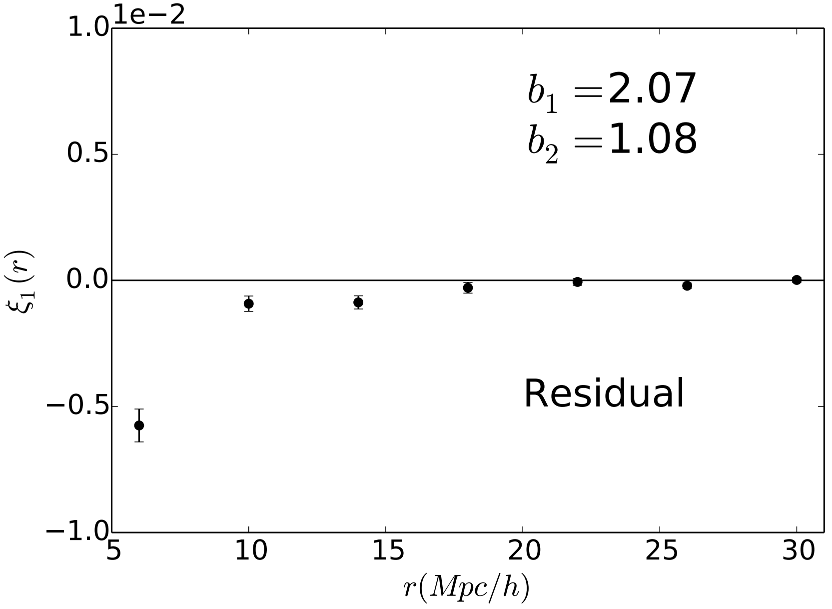
SMALL SCALES (5-30 Mpc/h): SIMU (POINTS) VS LINEAR (DASHED LINES)



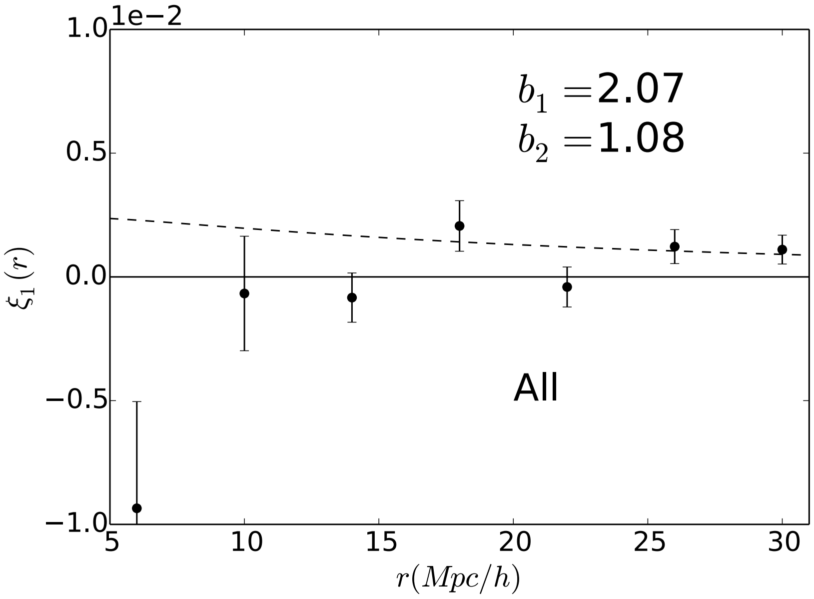
Breton et al, 2018

RADIUS **RADIUS**

DIPOLE



RADIUS

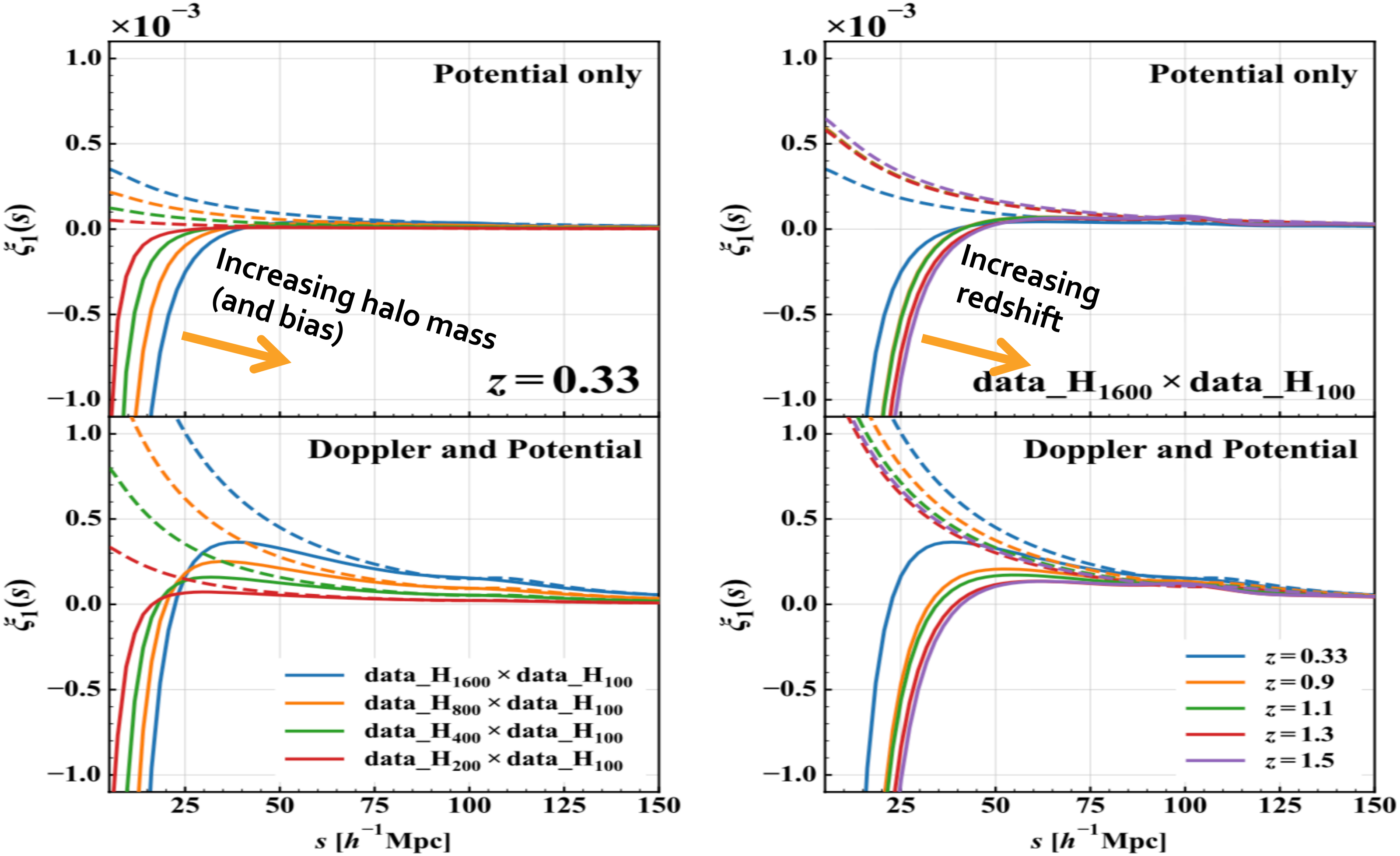


RADIUS

- 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).

Analytical predictions

Taruya et al,2019
Saga et al, 2020

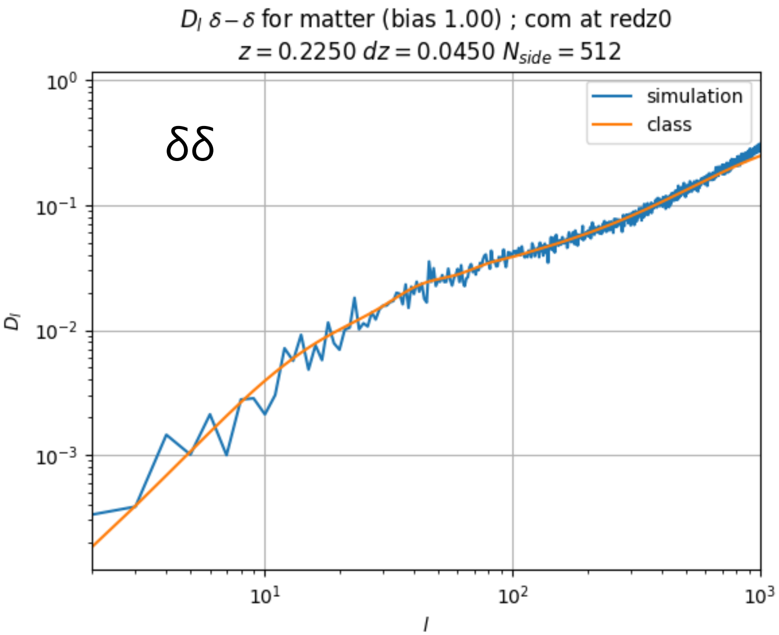


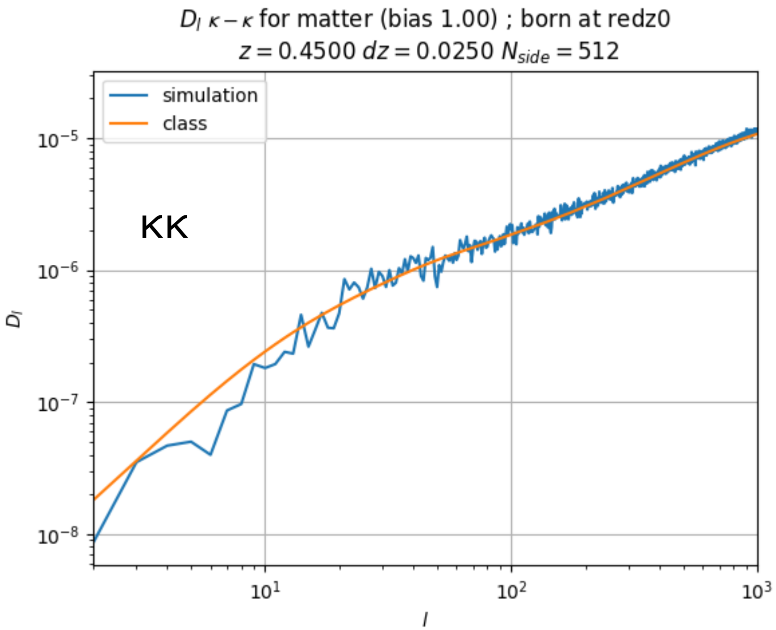
- Zeldovich prediction+NL halo term=> good prediction below 50 Mpc/h (unlike linear one)
- Increasing halo mass or redshift=> increase sign flip scale

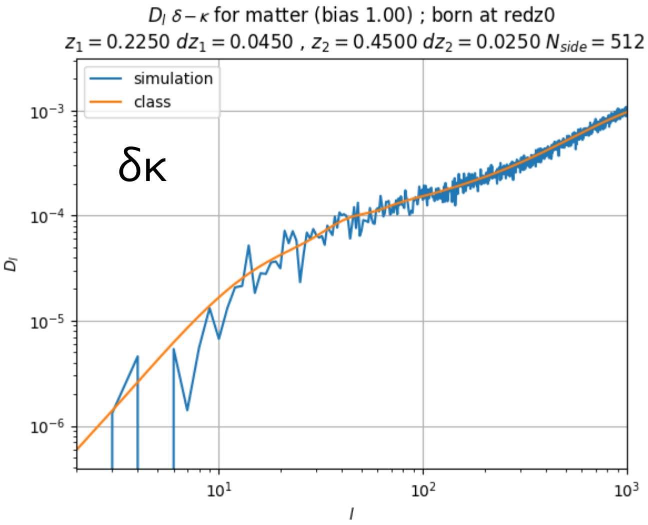
IIIb. Relativistic effects and weak-lensing

(ongoing work with T.Pellegrin,
J.Allingham and M-A Breton)

Low redshift ($z<0.5$) $l(l+1)C_l/(2\pi)$ vs CLASS **in real space** (with non-linear P(k) interpolated from RayGalGroupSims)

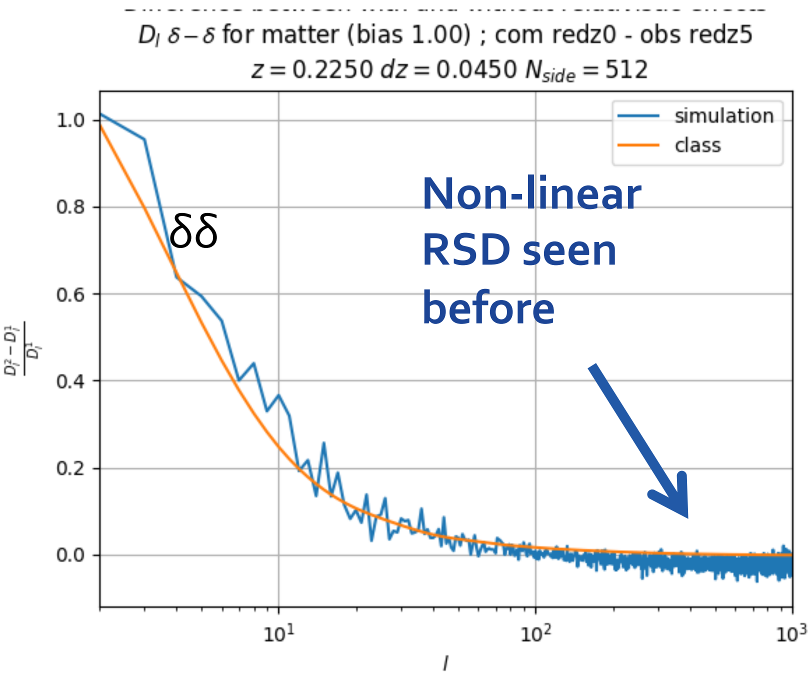

D_l $\delta-\delta$ for matter (bias 1.00) ; com at redz0
$z=0.2250$ $dz=0.0450$ $N_{side}=512$


D_l $\kappa-\kappa$ for matter (bias 1.00) ; born at redz0
$z=0.4500$ $dz=0.0250$ $N_{side}=512$

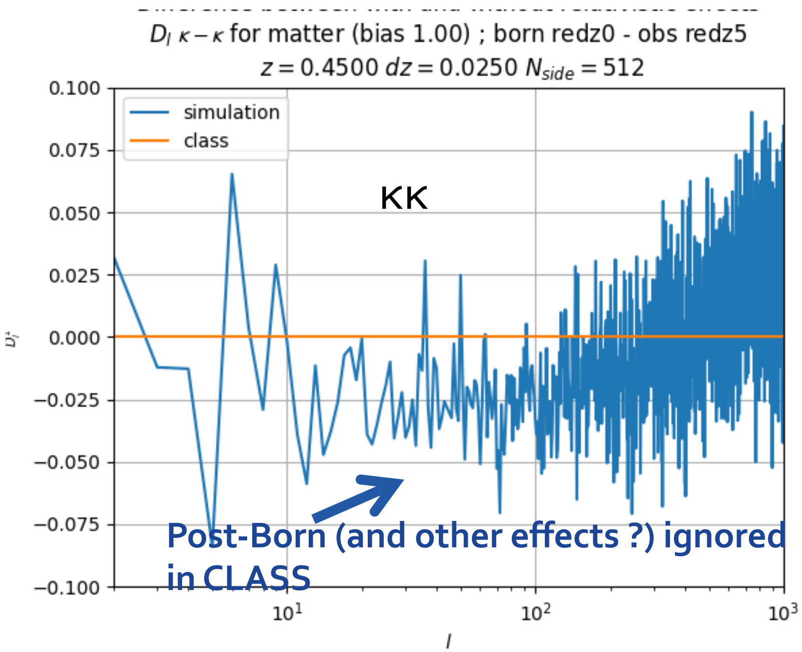

D_l $\delta-\kappa$ for matter (bias 1.00) ; born at redz0
$z_1=0.2250$ $dz_1=0.0450$, $z_2=0.4500$ $dz_2=0.0250$ $N_{side}=512$

- We compute the cross spectra for two shells at z1=0.225 and z2=0.45
- Extremely good agreement if P(k) calibrated to RayGalGroupSims+ no standard RSD + no relativistic effects + Born approximation
- Currently investigating up to z=2 and l=5000

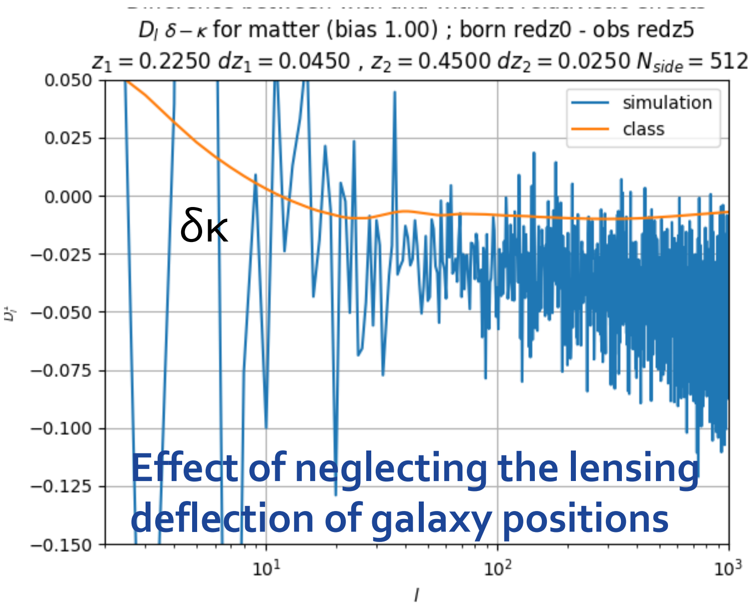
PRELIMINARY: Relative contribution **of relativistic effects** to low redshift (z<0.5) Cl vs CLASS



Non-linear RSD seen before



Post-Born (and other effects ?) ignored in CLASS



Effect of neglecting the lensing deflection of galaxy positions

Remark : Yes we will smooth the noisy curves ☺

- Effect of RSD on <δδ> well captured at large scale BUT Finger-of-God effect neglected in CLASS
- Neglecting lensing deflections of galaxy positions can make the galaxy-galaxy lensing <δκ> wrong (errors can even reach 50% according to class if sources and lenses are close , Ghosh et al,2018).
- For some reason our convergence power spectrum is different from CLASS by few % : WHY? Post-Born effect? Other?

CONCLUSION

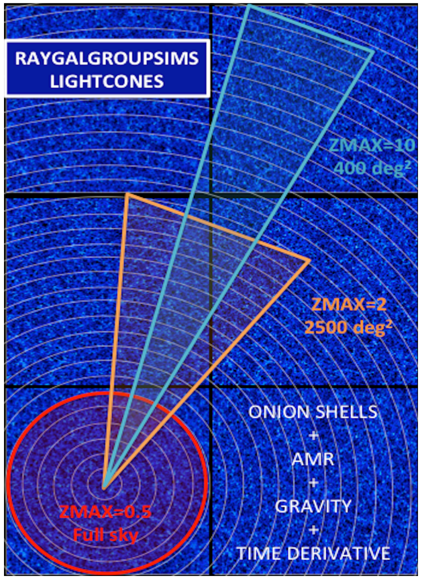
- Search for new probes of dark sector=> Can we directly measure the potential to test all our hypothesis?

- 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 1st time all the dipole effects are modeled accurately in weak field from lin. to NL scales
  - The most important contribution after RSD is the gravitational potential at low redshift

- Relativistic effects and weak-lensing: comparison to CLASS ongoing.

- 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!

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

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