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Numerical simulations for cosmology

(with a special focus on dark energy)

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Colloque National Dark Energy 2018

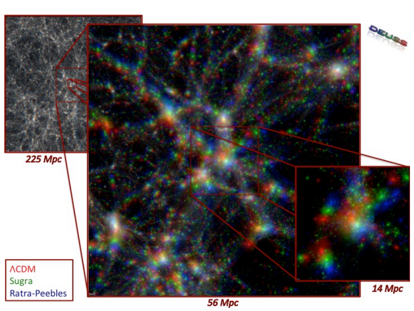
October 24th, 2018

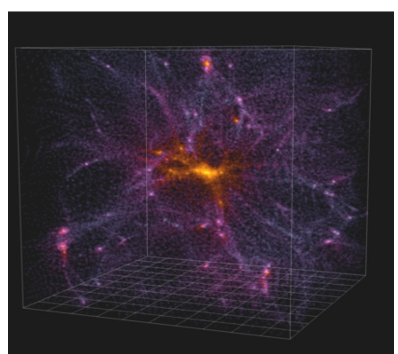
I. Why do we need simulations for the dark energy problem ?

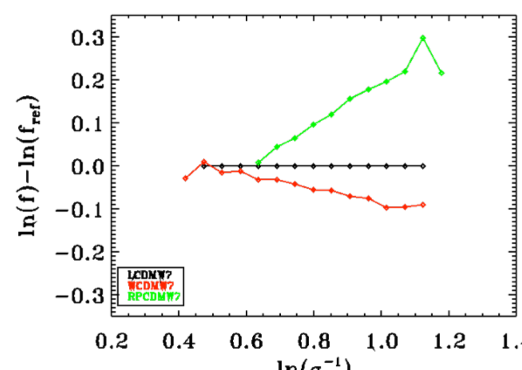
II. Simulations: how to proceed ?

III. What kind of results? Illustrative example about the imprints of minimally coupled dark energy on *cosmic structure formation*

IV. Conclusion and perspective



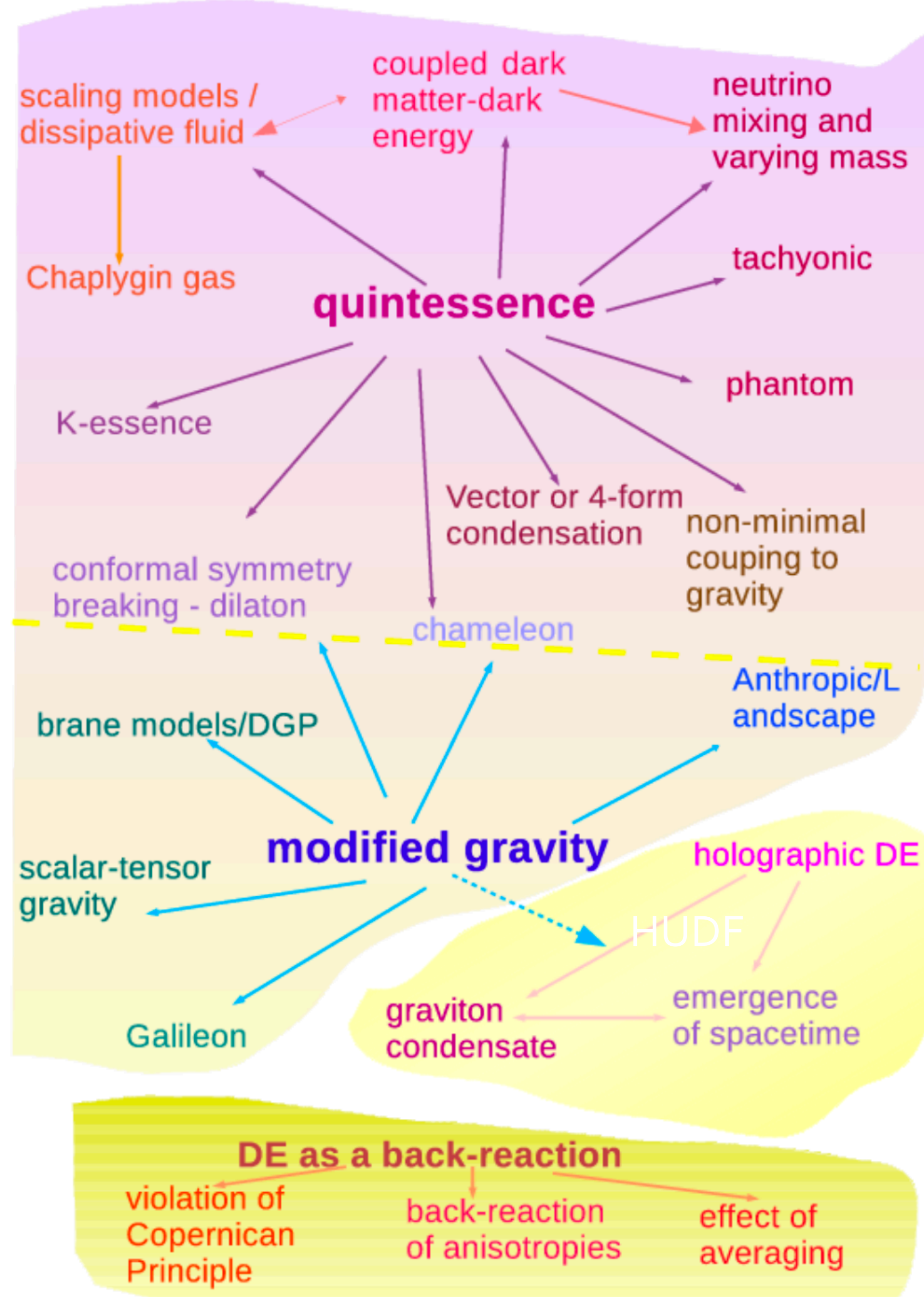




I. Why do we need simulations for the dark energy problem ?

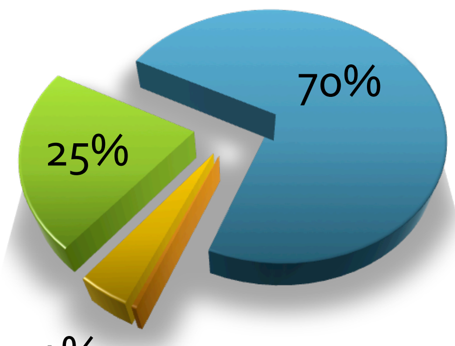
WHAT IS THE NATURE OF DARK ENERGY ?

VARIOUS POSSIBILITIES



Ziaeepour 2014

- **MAIN OBSERVATIONAL CONSTRAINTS FOR DE**
  - **Homogenous**: SNIa (UNION, SNLS)-> luminosity distances
  - Early **linear**: CMB (WMAP, Planck) ->angular distances

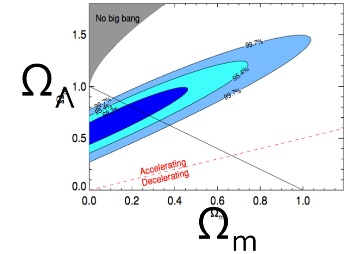


dark energy

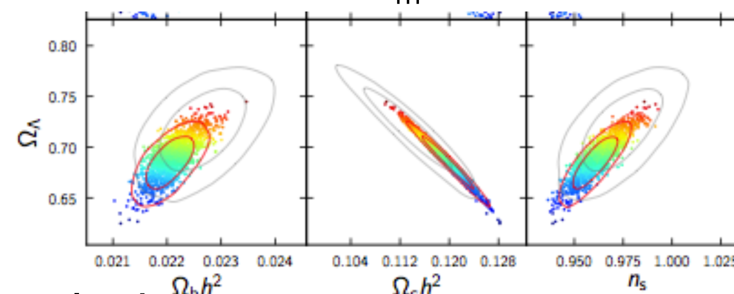
dark matter

gas (H,He) 4%

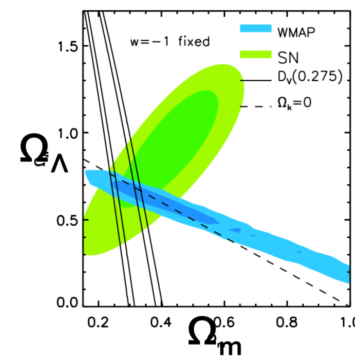
0,5% stars



Conley et al. 2011

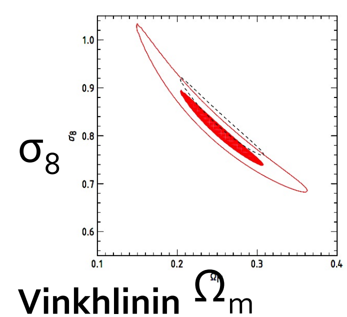


Planck et al. 2013

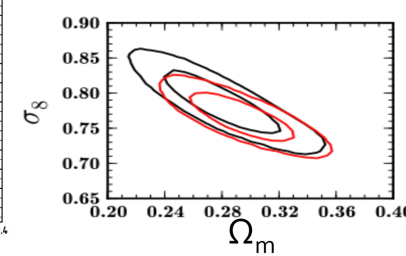


Percival et al. 2010

- Non linear:
  - -Baryon Acoustic Oscillations (SDSS, 2dF, BOSS, wiggleZ) -> angular&radial distance + **linear** assumptions for peak position + assumptions shape
  - -Weak lensing (CFHTLS, Planck)-> matter power spectrum **prescription** + projection
  - -Cluster Counts (Chandra, XMM, Planck) -> linear growth rate + **universal mass function assumption** + geometry



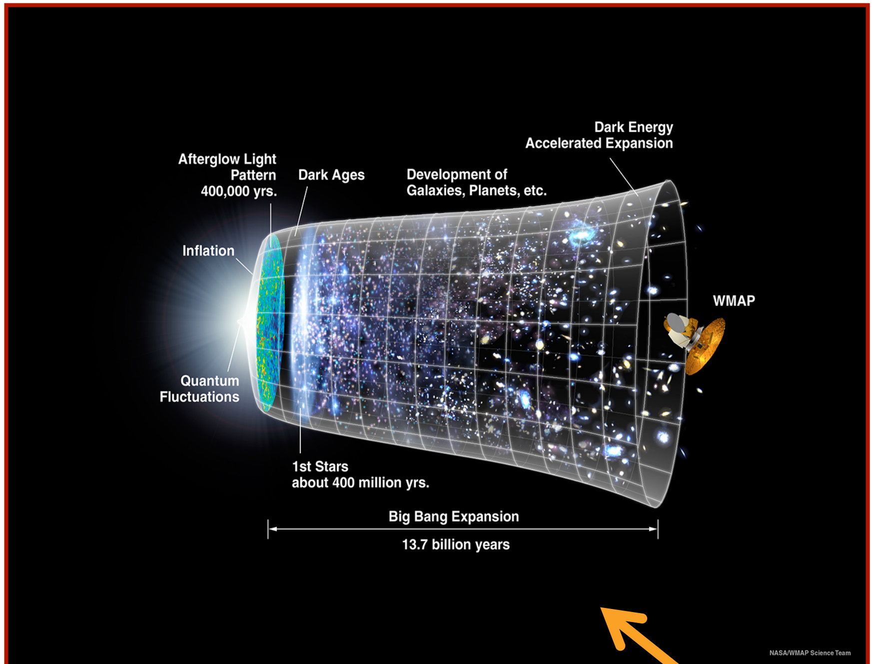
Vinkhlinin et al.2009

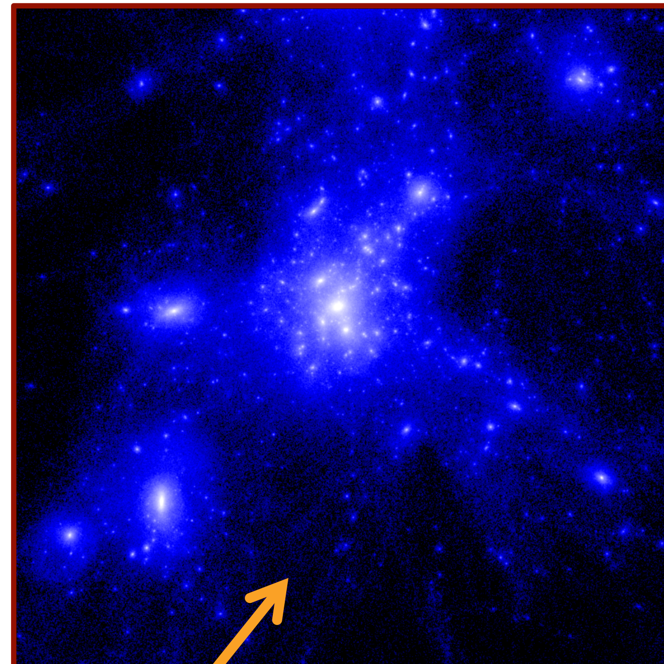


Planck et al. 2013b

WHAT IS THE NATURE OF DARK ENERGY ?

•NEW OR REFINED PROBES: NON-LINEAR REGIME OF STRUCTURE FORMATION





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

NON-LINEARITIES => NUMERICAL SIMULATIONS

II. Simulations: how to proceed ?

STRUCTURATION: INHOMOGENEOUS UNIVERSE

- **Scalar perturbation of FRW metric in newtonian gauge**

$$ds^2 = -c^2dt^2\left(1+2\frac{\psi}{c^2}\right)+a^2\left(1-2\frac{\phi}{c^2}\right)\left(\frac{dr^2}{1-kr^2}+r^2d\theta^2+r^2sin(\theta)^2d\phi^2\right)$$

- **Geodesics equations+ Poisson equation**

Chisari&Zaldarriaga, 2011
Adamek et al, 2016

$$\frac{d^2\mathbf{x}}{d\eta^2}+\frac{a'}{a}\frac{d\mathbf{x}}{d\eta} = -\nabla\phi+3\phi'\frac{d\mathbf{x}}{d\eta}, \quad d\eta=\frac{dt}{a}$$

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

- **Evolution equation: Boltzmann equation in an expanding universe**

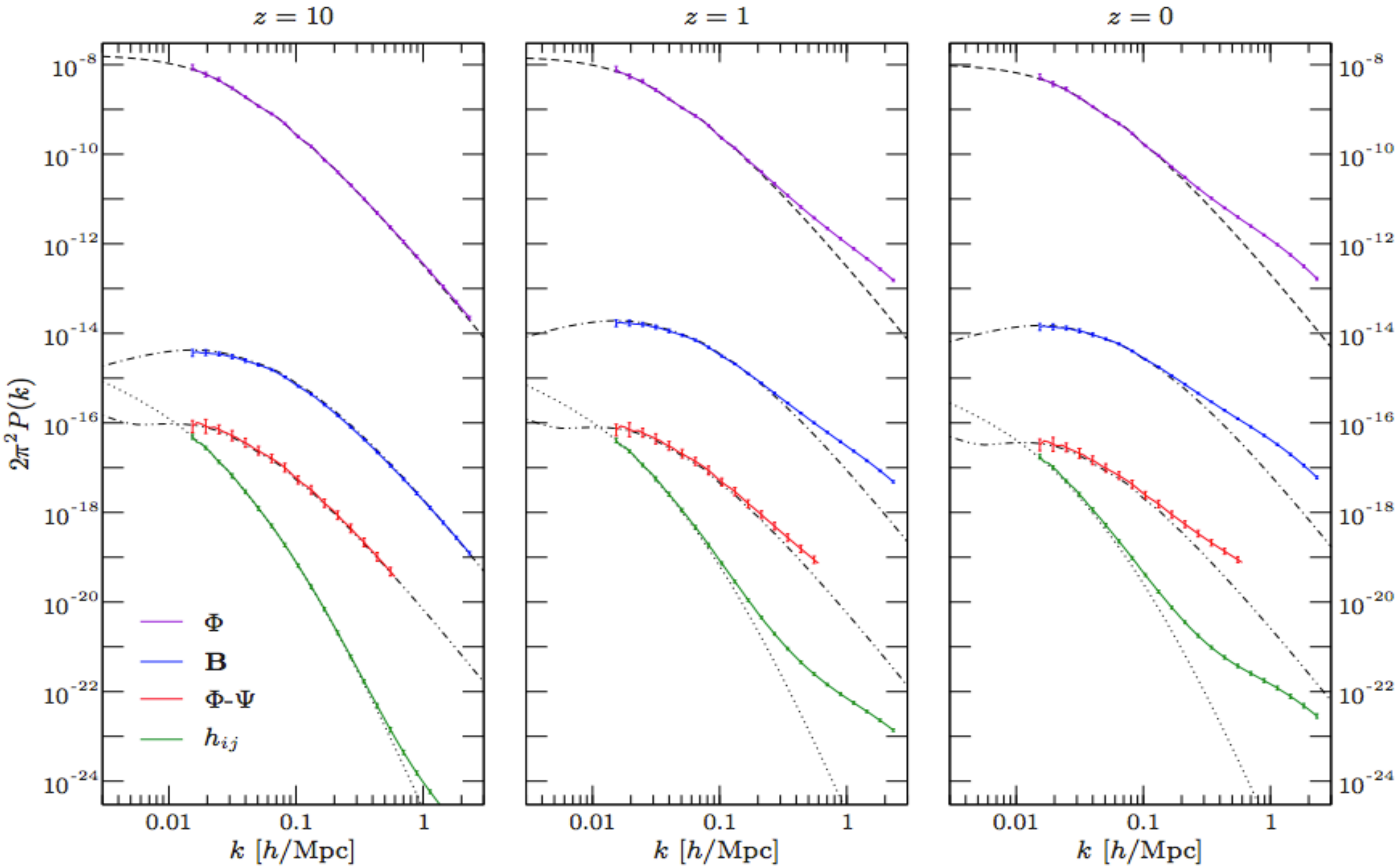
$$\frac{\partial f}{\partial t}+\frac{\mathbf{p}}{ma^2}\cdot\nabla f-m\nabla\Phi\cdot\nabla_{\mathbf{p}}f=\left(\frac{\partial f}{\partial t}\right)_{\mathrm{coll}}$$

Collisionless
Dark Matter

$$\mathbf{p}=\mathrm{m}\mathrm{a}^2\dot{\mathbf{x}}$$

SHOULD WE CARE ABOUT RELATIVISTIC EFFECTS FOR THE DYNAMICS ?

Adamek, Daverio, Durrer & Kunz, 2016



⇒ Relativistic effects seem (a priori) weak for the dynamics.

⇒ See the talk of N.Kaiser for the question of backreaction which is related

⇒ Special care: all of this was done in the weak field approximation + in Poisson Gauge + at finite resolution + in LCDM + with no neutrino + torus topology

METHODS FOR SOLVING VLASOV-POISSON EQUATIONS

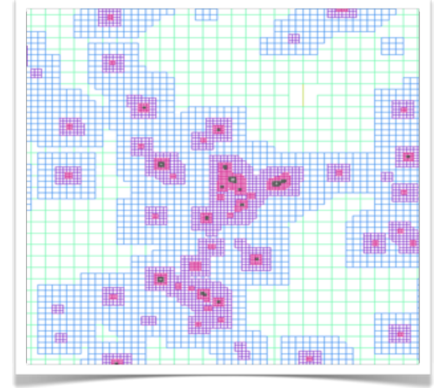
- **Main approaches**
  - Solving the N-body pb for all single particles of DM => not tractable because $N_{DM}>10^{30}$
  - Solving the equation in 6D with a grid method (Yoshikawa et al, 2013)=> very intense
  - Solving in 6D but taking advantage that the phase space is mostly empty (Hahn et al, 2013; Sousbie&Colombi 2016) => very accurate but still intense
  - Fluid approach => the hierarchy of moments never stops
  - Sampling the phase space with particles (i.e. this is a Monte Carlo method) => N-Body approach, widely used because good compromise between accuracy/simplicity/speed. Be careful each particle represents a "cloud" of DM particles not a single DM particle!

- **N-body approach**
  - PP approach => too slow $O(N^2)$ operations
  - PM approach => use a fixed grid to compute Poisson : O(NlnN) but fixed resoution

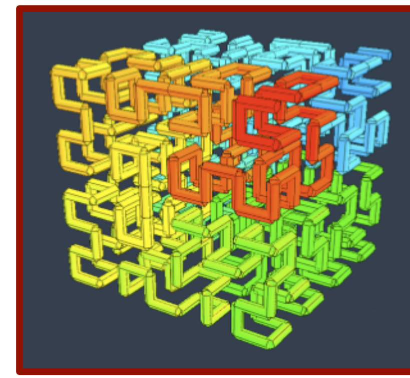
  - Tree code => use group of particles to compute the force from far away particles (example PKDGRAV, HOT)
  - PM-AMR => PM but with adaptive grid (example RAMSES, ART, ENZO)
  - Various hybrid methods such as TreePM (example GADGET, TPM)

  => in any case O(N) or O(N ln N) + adaptive resolution

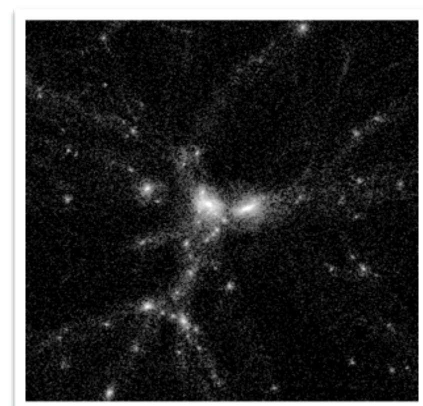
The example of RAMSES (Teyssier, 2002) => PM – AMR method



- **Purpose**
  - Compute the formation of large scale structures in an expanding universe
  - Ingredient : dark matter
  - Good force resolution thanks to a hierarchy of AMR grids
  - Overdensity based refinement criterion: pseudo-lagrangian approach
  - Parallelized with MPI using a Peano-Hilbert domain decomposition



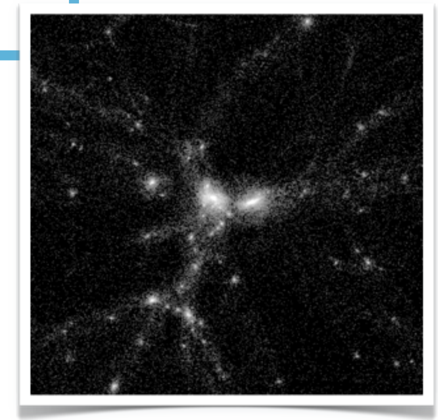
- **Physics/Methods**
  - Expansion rate: use of supercomoving coordinates
  - Periodic boundary conditions
  - N-Body solver: Particle-Mesh
  - Density: Cloud in Cell
  - Poisson equation: solved by multigrid method (Guillet&Teyssier)
  - Time-step: adaptive



Taking into account dark energy dynamics (non exhaustive)

- **Lambda**
  - Dark energy density is a constant in space and time
  - Sim examples: many, not the goal of this talk
- **W and (Wo-Wa) parameterization**
  - Minor-modification of FLRW equations
  - Sim examples: Coyote Universe, Abacus cosmos, Full Universe Run,…
- **Minimally coupled dark energy (quintessence or similar)**
  - Solve Klein Gordon equation for scalar fields => change background expansion and linear calculation (CAMB, CLASS) because quintessence doesn't collapse.
  - Sim example: Dark Energy Universe Simulation Series, Full Universe Run, Codecs,…
- **Coupled dark energy**
  - G is changed as well as the effective mass of DM particles
  - Sim Examples: Codecs, sim by Maccio et al, 2004,…
- **Modified gravity (scalar tensor or similar)**
  - Need to solve a non-linear Poisson equation (cannot use FFT for example) for the scalar field
  - Sim examples (using parallel code with adaptive resolution): f(R) (Li et al, 2012; Puchwein et al, 2013; Llinares et al, 2014), DGP (Li et al, 2013), Galileon (Li et al, 2013), Symmetron (Llinares &Mota 2013; Llinares 2014),….

Don't forget initial conditions generation and post-processing: these are critical and heavy steps

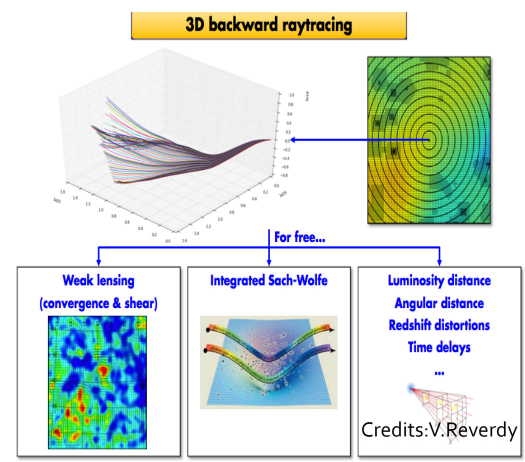


- **Initial condition generators**
  - Assume gaussian random field
  - Use of Lagrangian Perturbation theory

- **Structure finder (halo, voids)**
  - Use local or enclosed overdensity to define group of particles

- **Dark matter to light connection (depend on the source):**
  - Dark matter: DM emission
  - Galaxies: Abundance matching, Halo occupation distribution, SAM, hydro simulations
  - Lyman-alpha: probabilistic approach, …

- **Ray-tracer**
  - Launch light-rays to replace structures in redshift space
  - Weak-lensing, Redshift Space Distortions



- **Estimator of the 2/3/4 points correlation function (power spectrum/bispectrum/trispectrum)**
  - Pair counts
  - Grid method
  - Fourier method

Our cosmological pipeline as an example

PARAMETERS
JOBS/SCRIPTS

Cosmological parameters
Primordial power spectrum
Numerical parameters

BACKGROUND COSMOLOGY
DARKCOSMOS

Friedmann Eq.
Klein Gordon Eq.

CMB PHYSICS
CAMB

Photons, baryons,
DE, metric perturbations Eq.

UNIVERSE REALIZATION
MPGRAFIC

Particular realization,
NG parameters

STRUCTURE FORMATION
RAMSES

Poisson equation,
n-body solver

SLICER

PFOF-MULTI

BACKUP

"OBSERVABLES"
PFOF/PROFILER/
MAGRATHEA
POWERGRID/

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

ANALYSIS/
DATABASE/VISU
IDL/PYTHON/C++
DEUVO/DEUSX

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, Breton18)->20000 tasks

III What kind of results? Illustrative example about the imprints of minimally coupled dark energy on *cosmic structure formation*

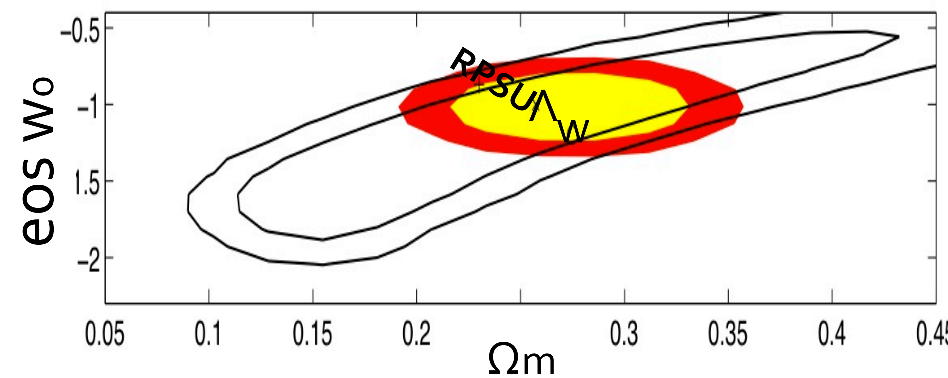
COSMOLOGICAL MODELS

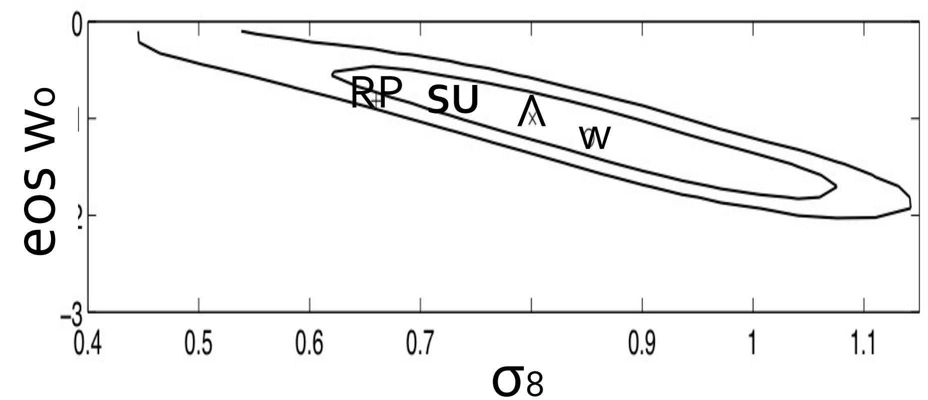
REALISTIC DARK ENERGY MODELS

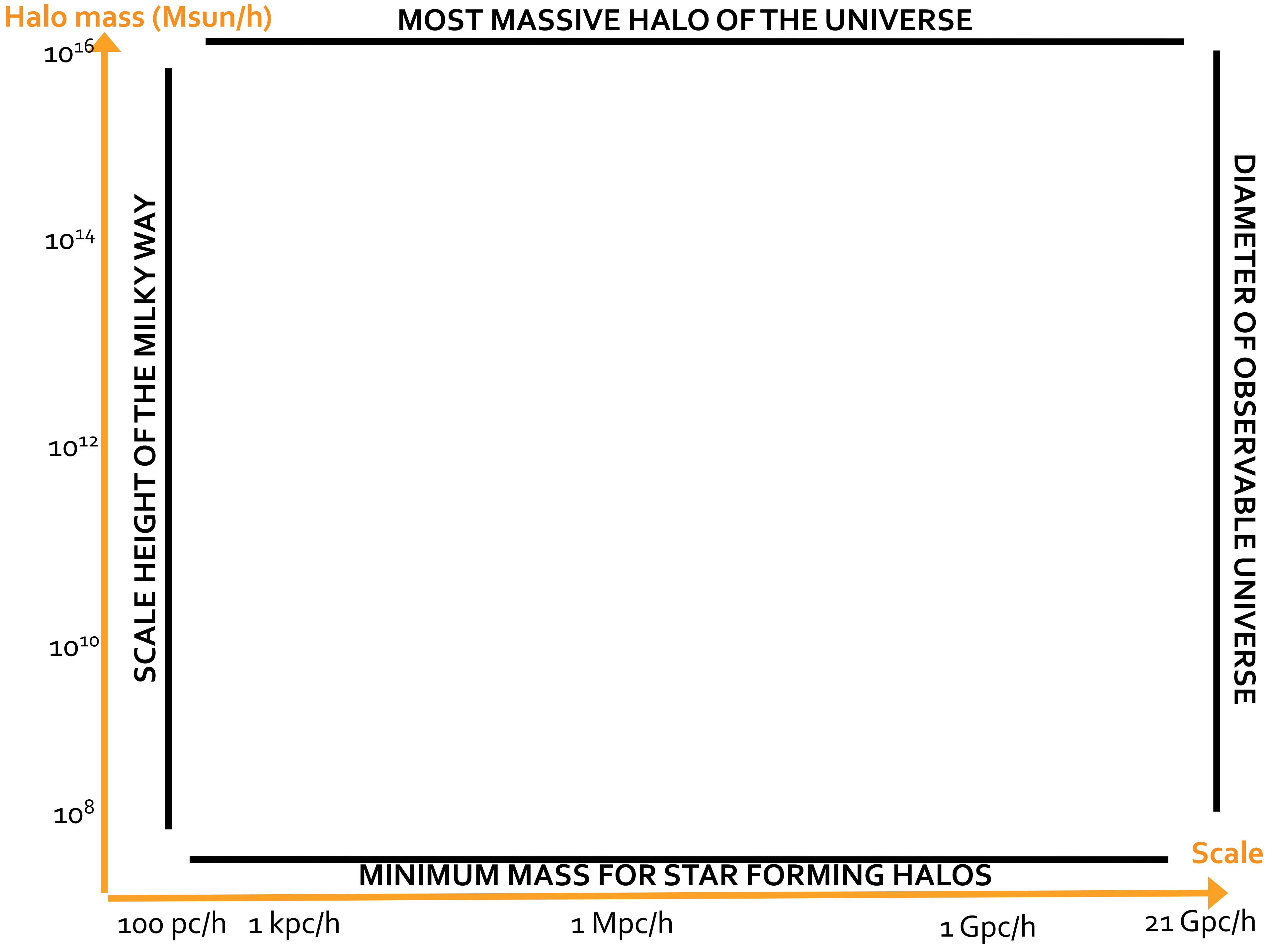
- **4 DE models**
  - Λ-CDM (w=-1)
  - Quintessence model with Ratra-Peebles potential RP-CDM (w(z)>-1)
  - Quintessence model with Sugra potential SU-CDM (w(z)>-1)
  - Ghost model w-CDM (w=-1.2)

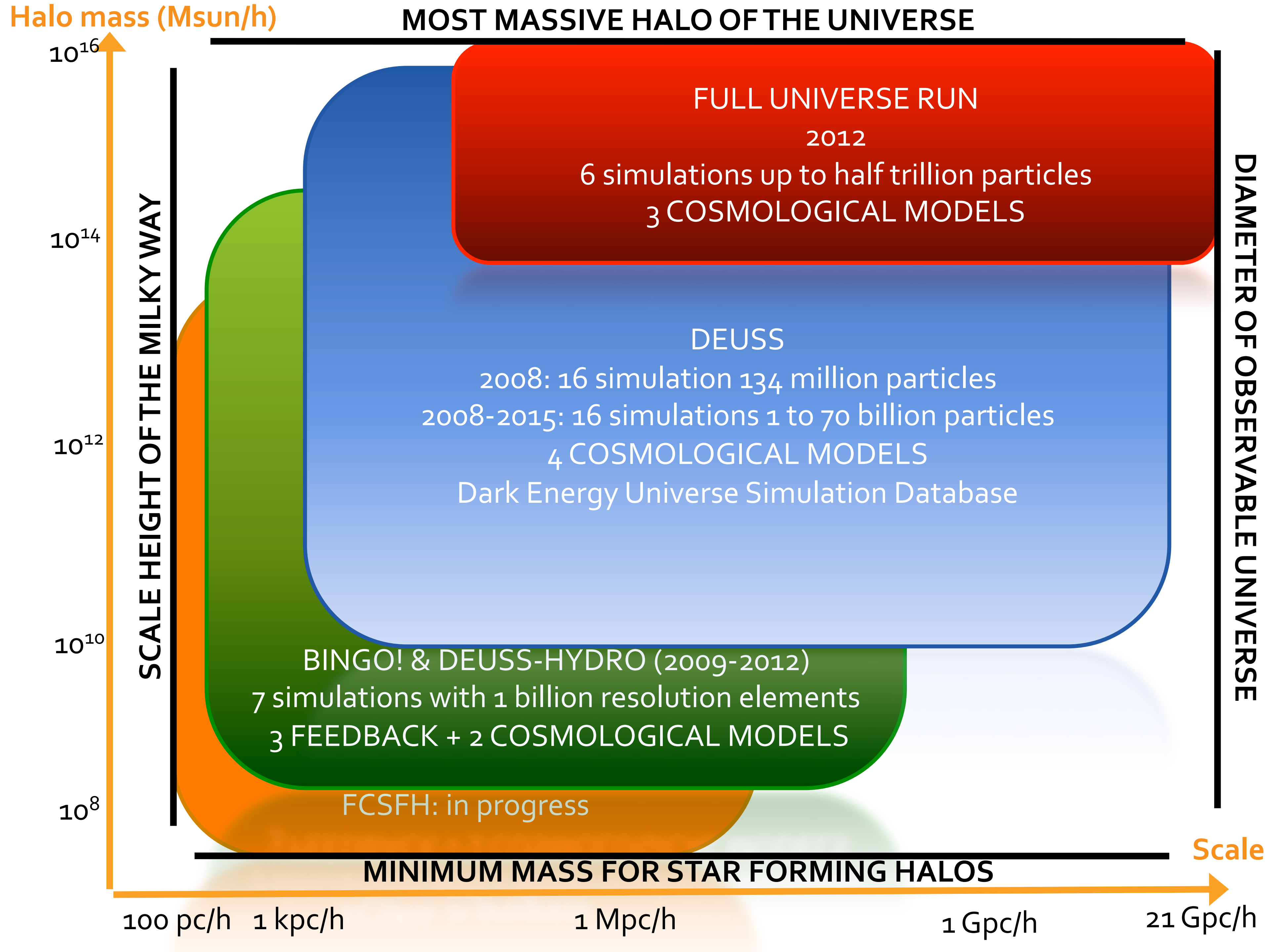
- **Pre-selection of viable dark energy models:**
  - Likelihood analysis of the combined SNIa UNION dataset and WMAP7-years data
  - CAMB modified to take into account quintessence clustering

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






Halo mass (Msun/h)
MOST MASSIVE HALO OF THE UNIVERSE
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
SCALE HEIGHT OF THE MILKY WAY
DIAMETER OF OBSERVABLE UNIVERSE
MINIMUM MASS FOR STAR FORMING HALOS
Scale
100 pc/h
1 kpc/h
1 Mpc/h
1 Gpc/h
21 Gpc/h


Halo mass (Msun/h)
MOST MASSIVE HALO OF THE UNIVERSE
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
SCALE HEIGHT OF THE MILKY WAY
FULL UNIVERSE RUN
2012
6 simulations up to half trillion particles
3 COSMOLOGICAL MODELS
DEUSS
2008: 16 simulation 134 million particles
2008-2015: 16 simulations 1 to 70 billion particles
4 COSMOLOGICAL MODELS
Dark Energy Universe Simulation Database
BINGO! & DEUSS-HYDRO (2009-2012)
7 simulations with 1 billion resolution elements
3 FEEDBACK + 2 COSMOLOGICAL MODELS
FCSFH: in progress
DIAMETER OF OBSERVABLE UNIVERSE
MINIMUM MASS FOR STAR FORMING HALOS
Scale
100 pc/h
1 kpc/h
1 Mpc/h
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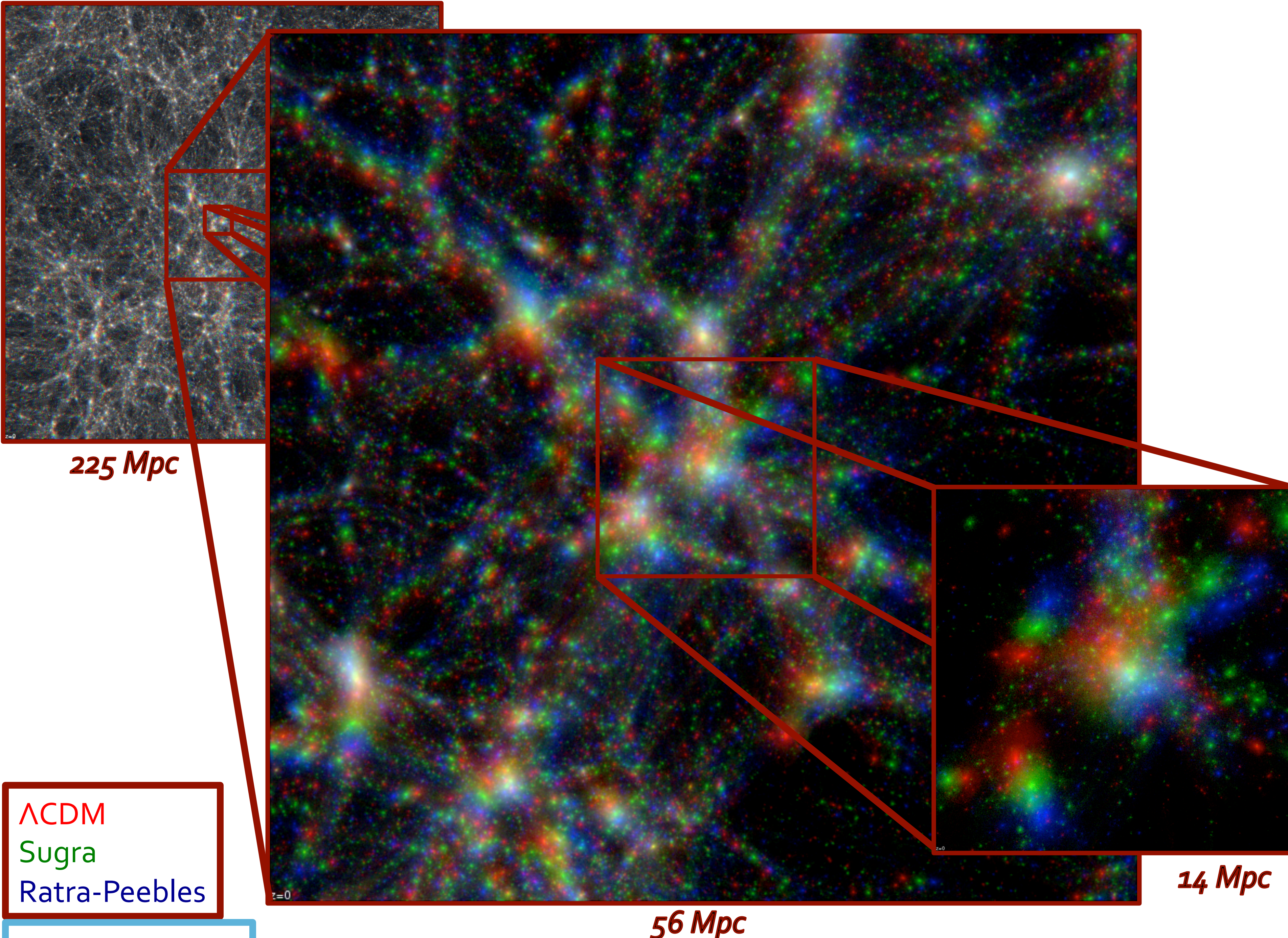
21 Gpc/h



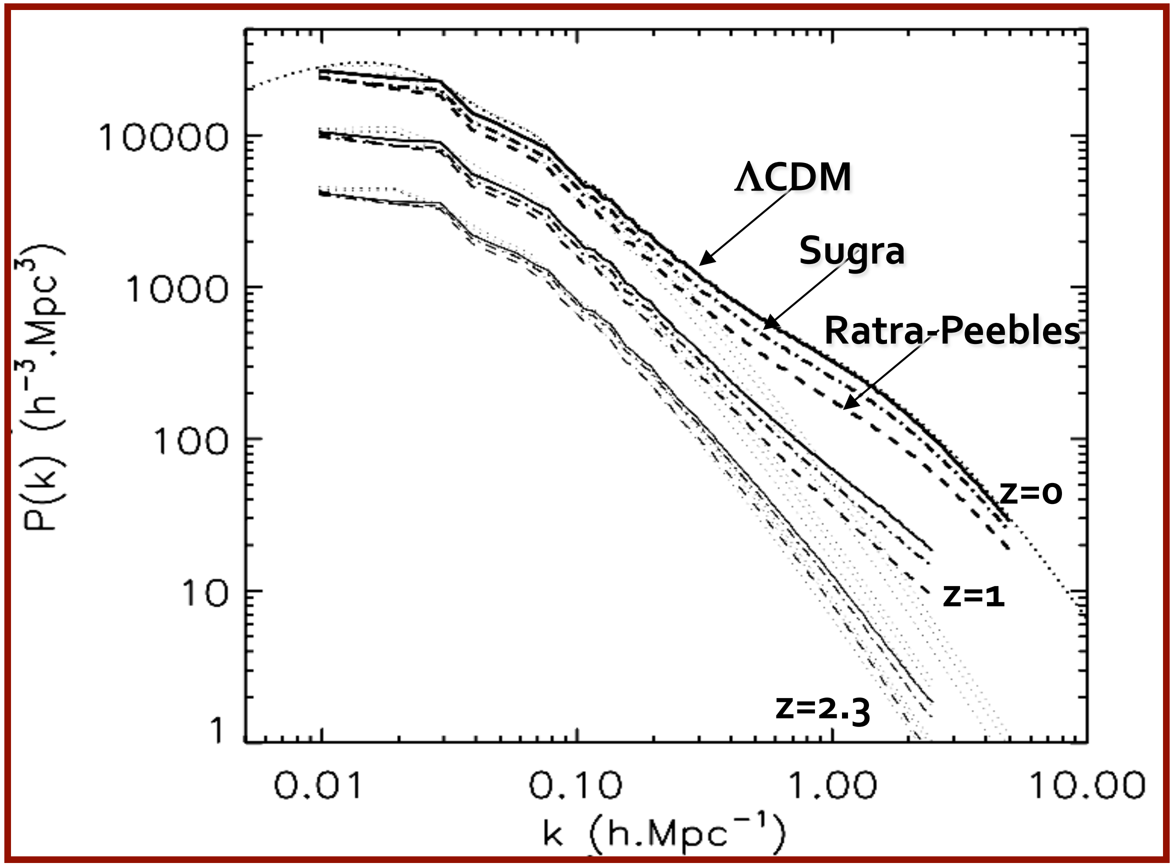
ΛCDM
Sugra
Ratra-Peebles

DEUSS

IMPRINTS OF DE ON THE MATTER POWER SPECTRUM

Power spectrum estimator: POWMES (Colombi et al, 2009)

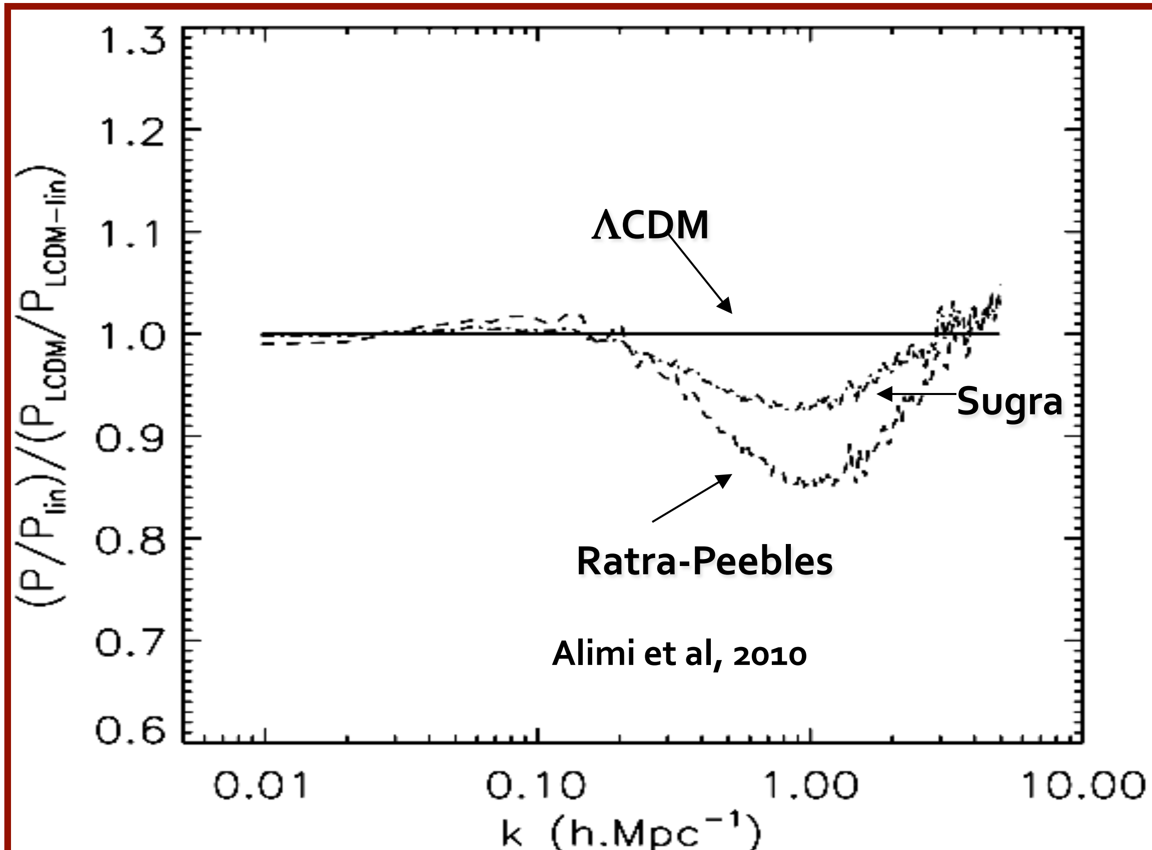
3 cosmologies are in good agreement with SDSS



- **GOAL: isolate contributions to the non-linear matter power spectrum**
- **First (linear regime):** linear power spectrum normalization and shape

IMPRINTS OF DE ON THE MATTER POWER SPECTRUM

Let's remove the linear contribution and take ΛCDM as a reference

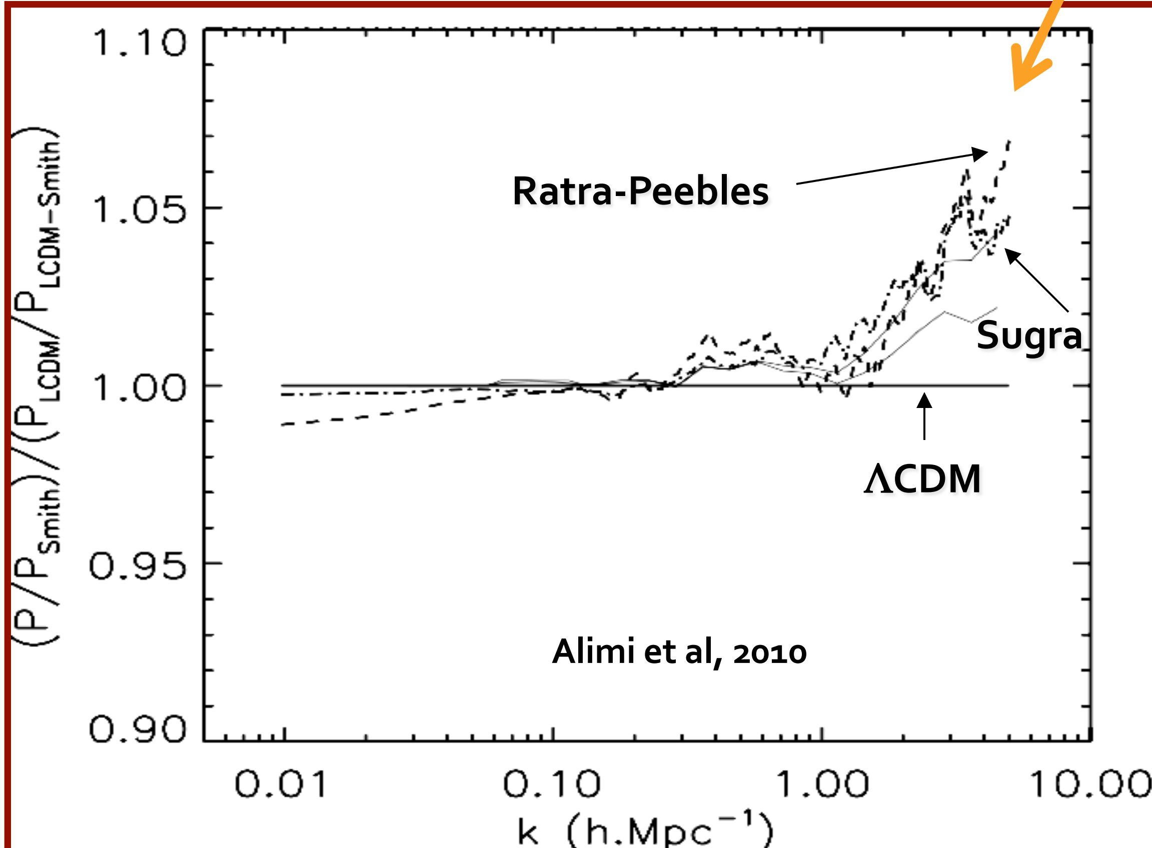


- **Second contribution (quasi-linear regime):** non-linear amplification of linear growth rate
- **Third contribution (sable-clustering regime):** saturation-virialization

IMPRINTS OF DE ON THE MATTER POWER SPECTRUM

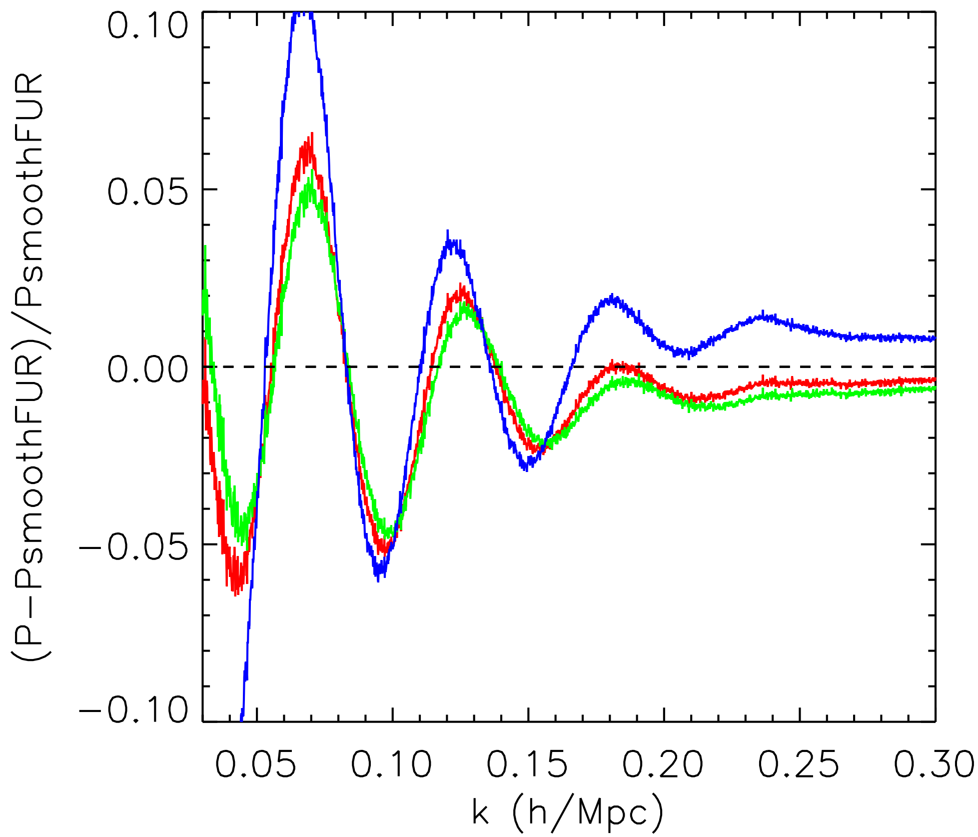
HALO SCALE

Let's remove previous contributions: normalization by Smith et al, 2003



- Deviations from self-similar predictions
- Flaw: Most of the current predictions are instantaneous
- **Fourth contribution** : history of structure formation

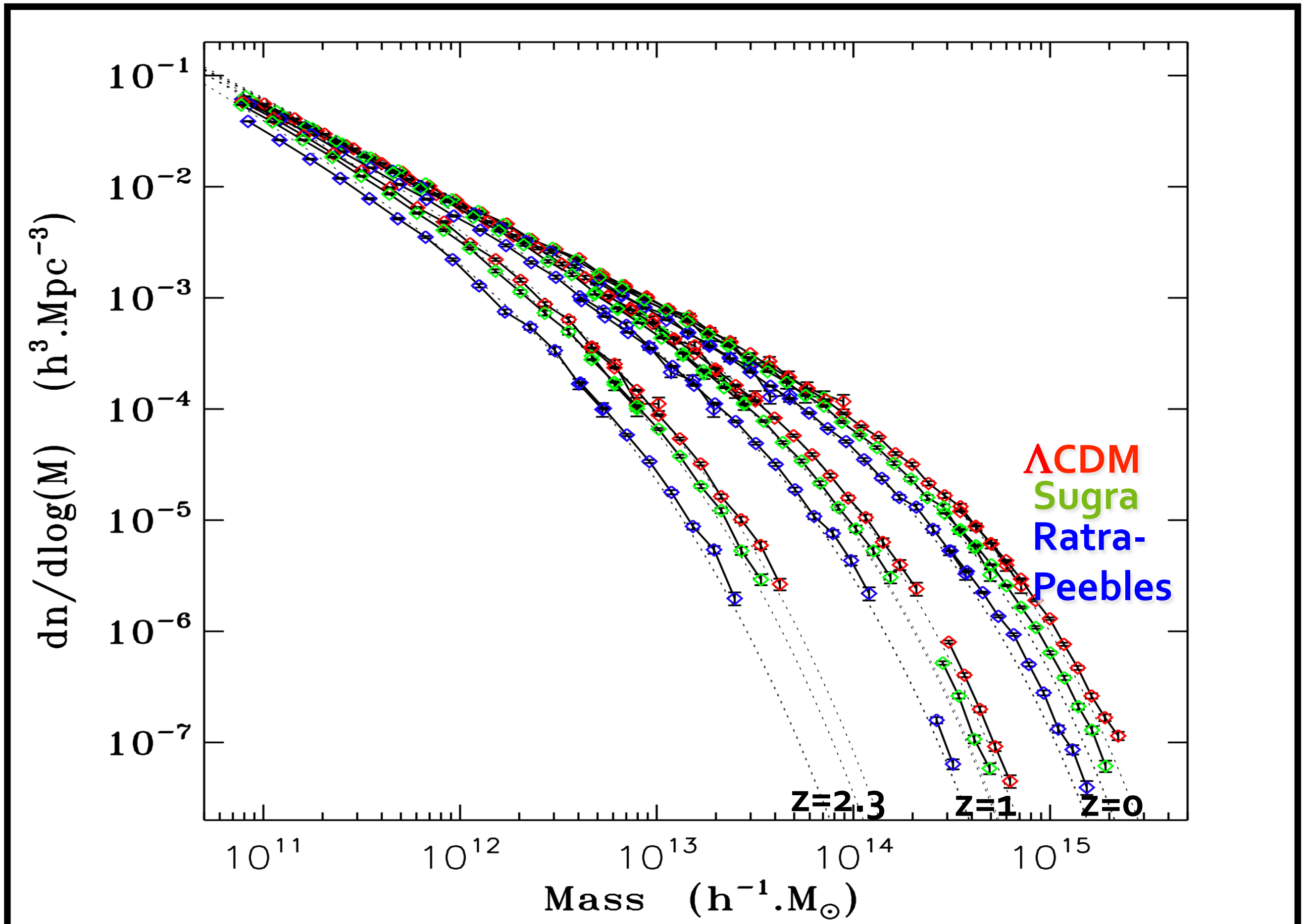
IMPRINTS OF DE ON BAO



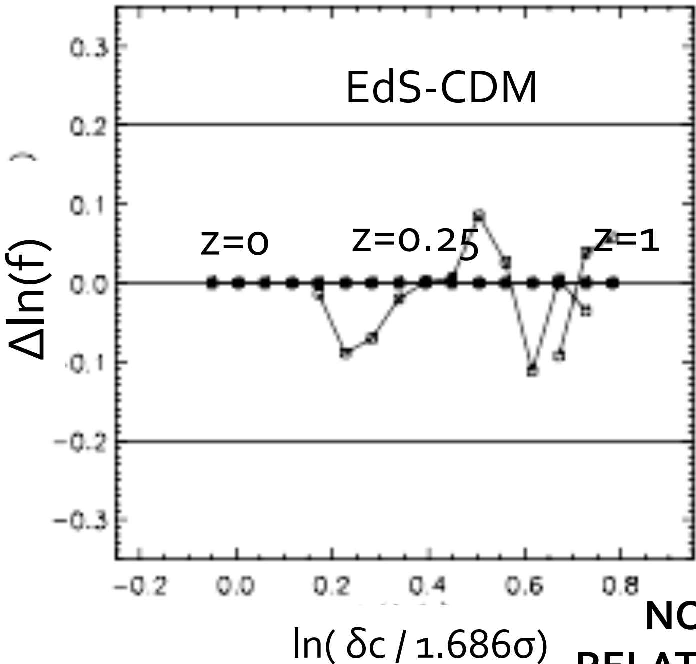
From Full Universe Run

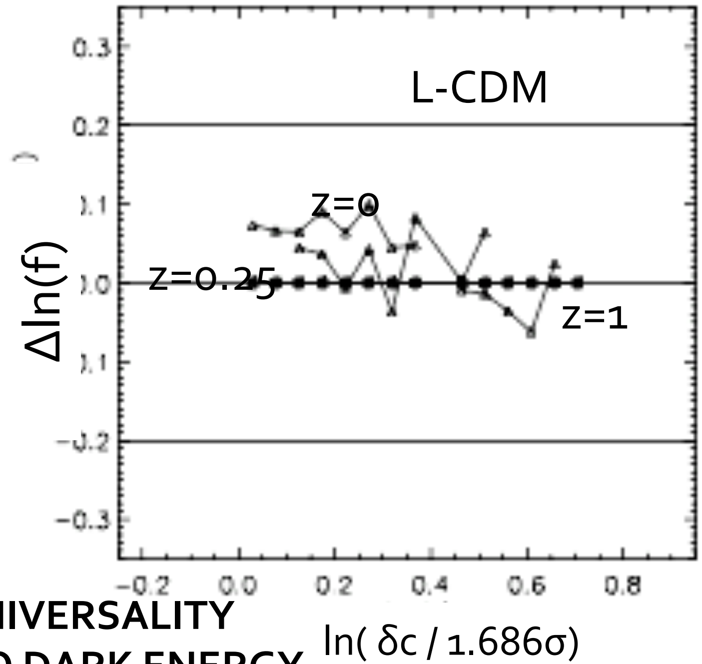
- Non trivial shift, damping, tilt…

IMPRINTS OF DE ON THE HALO MASS FUNCTION



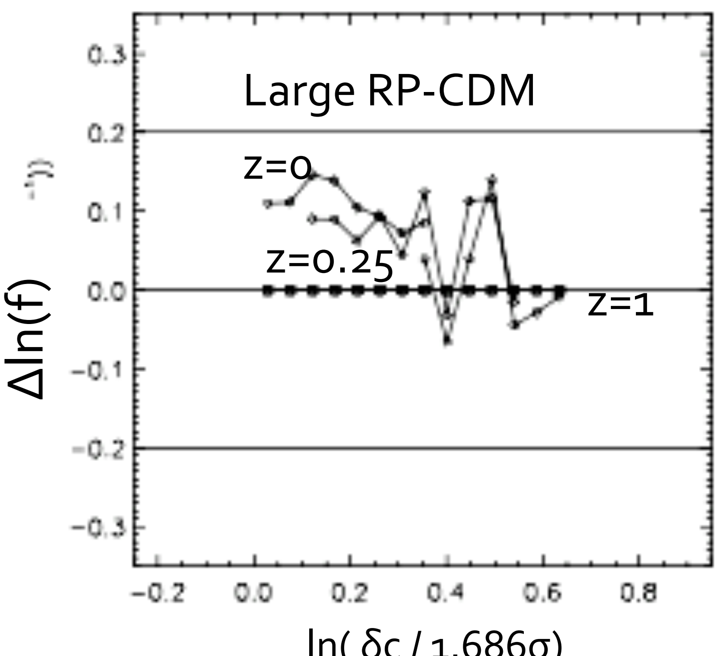
- DE changes the amplitude and shape of the mass function dn/DM
- DE changes the multiplicity function $f(\sigma, z; X) \equiv \frac{M}{\rho_0} \frac{\mathrm{d}n_X(M,z)}{\mathrm{d}\ln\sigma^{-1}}$

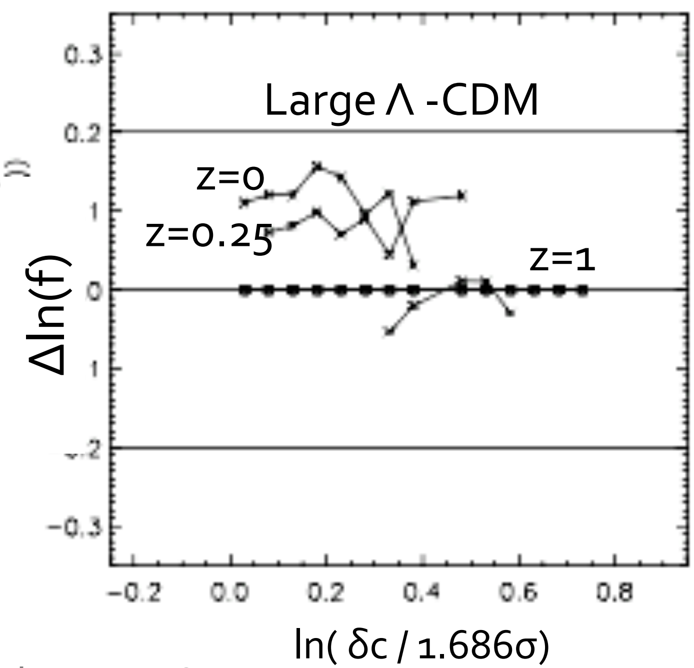




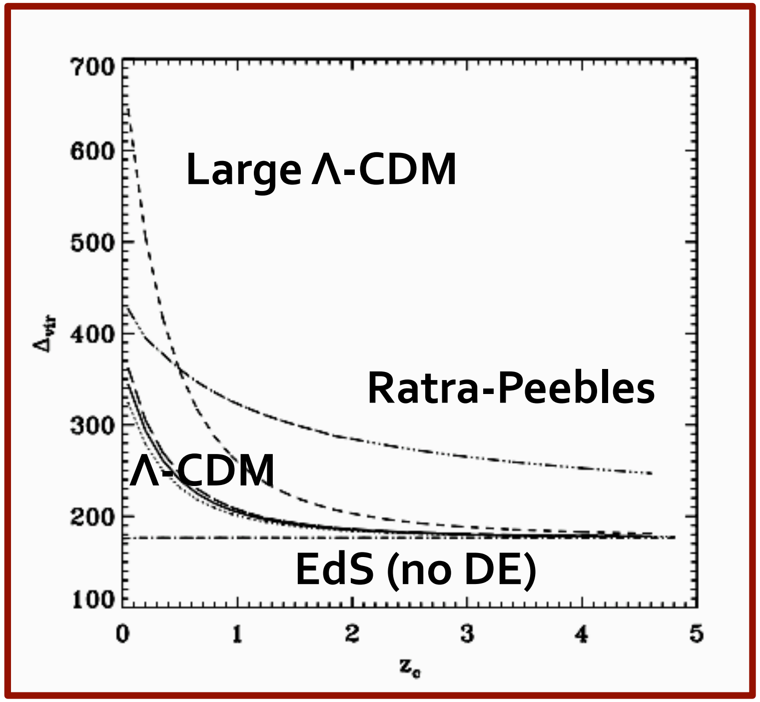
NON UNIVERSALITY RELATED TO DARK ENERGY

Courtin et al 2011



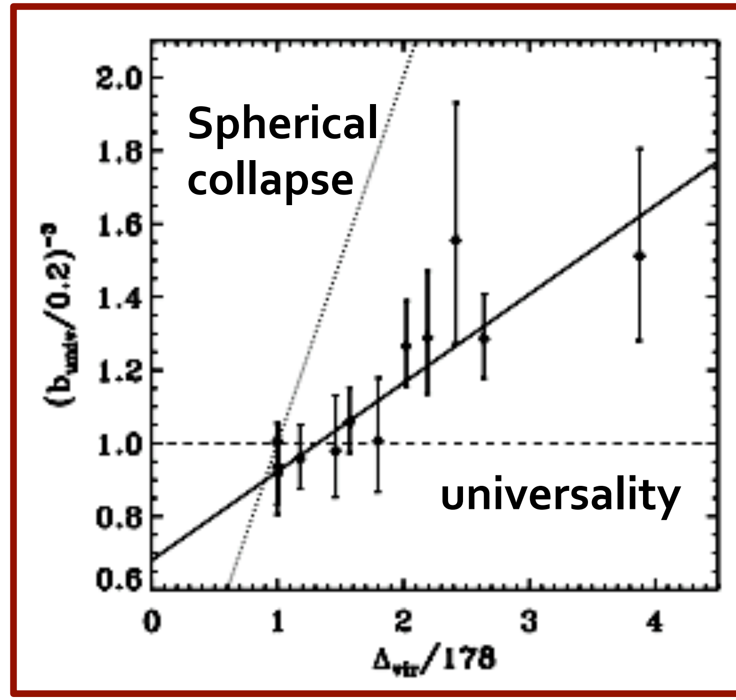


Virial overdensity from spherical collapse



redshift

Virial overdensity from mass function



Virial overdensity from spherical collapse

NON-UNIVERSALITY

The halo mass function at z=0 does depend of the underlying dark energy model.

Deviations below 20% are ***NEW PROBES FOR DARK ENERGY****!!!*

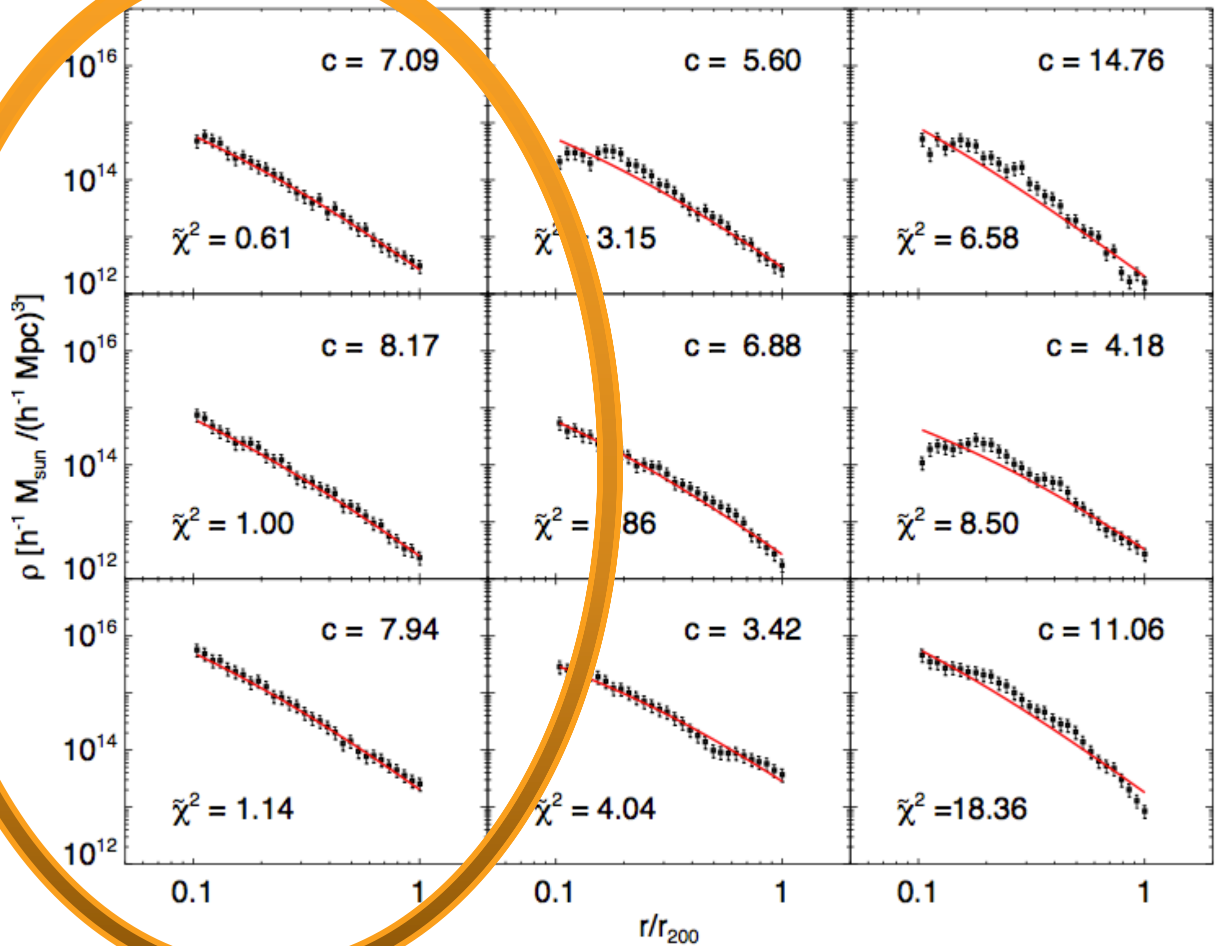
They depend on the amount and equation of state of dark energy.

The mass function can be predicted at the 5% level.

Rem: different from "non-universality" in Tinker et al, 2008 which is related to SO halo finder

3D DENSITY PROFILE

NFW fit $\rho_{\mathrm{NFW}}(r) = \frac{M_{200}}{4\pi[\ln(1+c) - c/(1+c)]} \times \frac{1}{r\left(\frac{r_{200}}{c}+r\right)^2}$



IMPRINTS OF DE ON DM HALO PROFILE

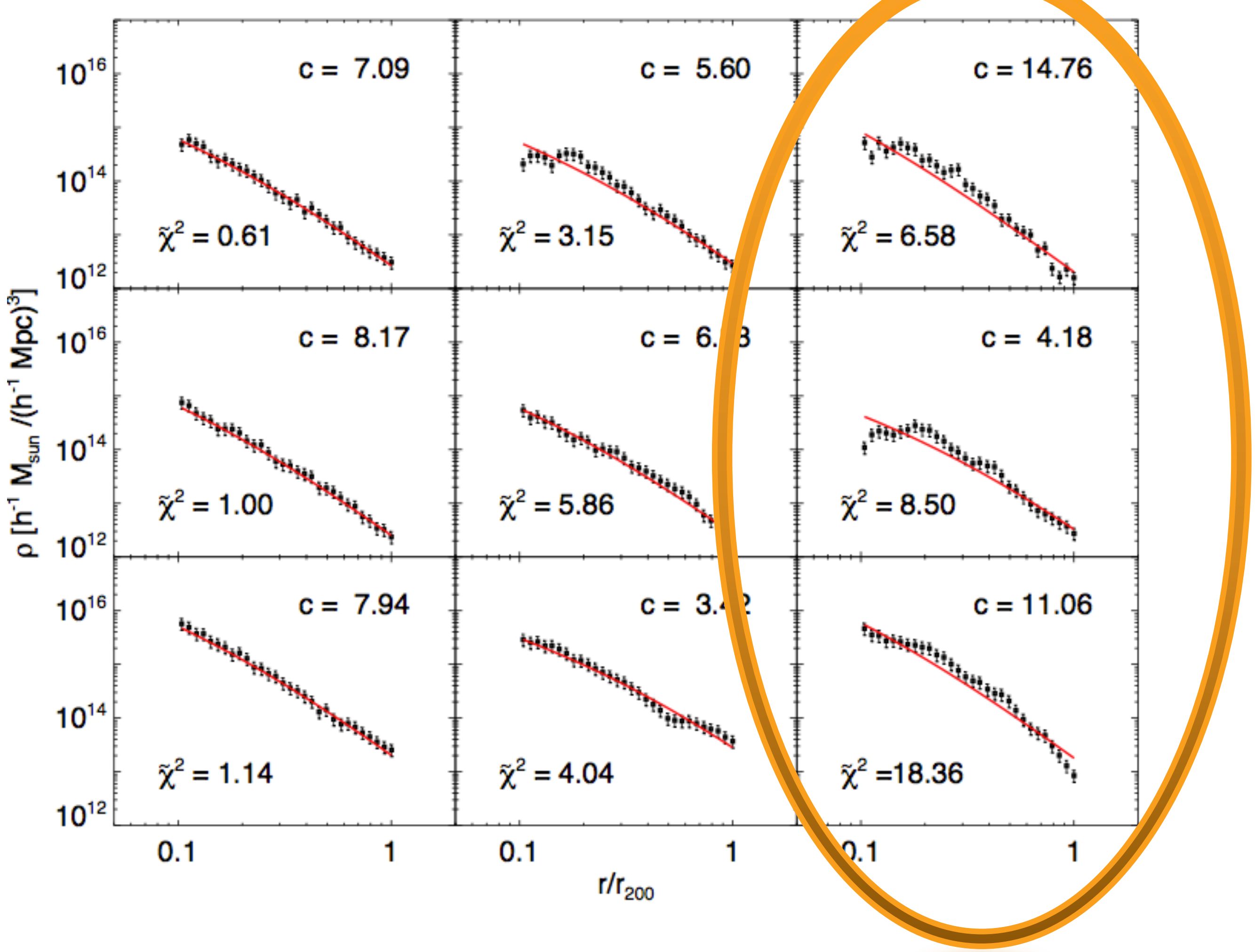
cosmology	$\frac{c_0}{c_0^{\Lambda\mathrm{CDM}}}$	$\frac{D_+(\infty)}{D_+^{\Lambda\mathrm{CDM}}(\infty)}$	$\frac{D_+(z_{\mathrm{coll}})}{D_+^{\Lambda\mathrm{CDM}}(z_{\mathrm{coll}})}$
ΛCDM	1	1	1
RP	1.06 ± 0.011	1.07	1.07 ± 0.0003
SUGRA	1.16 ± 0.013	1.22	1.19 ± 0.004
DECDM	1.18 ± 0.013	1.19	1.18 ± 0.001
OCDM	1.49 ± 0.018	1.64	1.61 ± 0.01

Dolag et al, 2004

- PRO: interesting correlation between concentration and linear growth rate history (Dolag et al, 2004) or mass accretion history (Zhao et al, 2009 and references therein)
- CON: use a small sub-sample of all halos OR select relaxed halos OR use median
- CON: sensitive to the details of fitting procedure

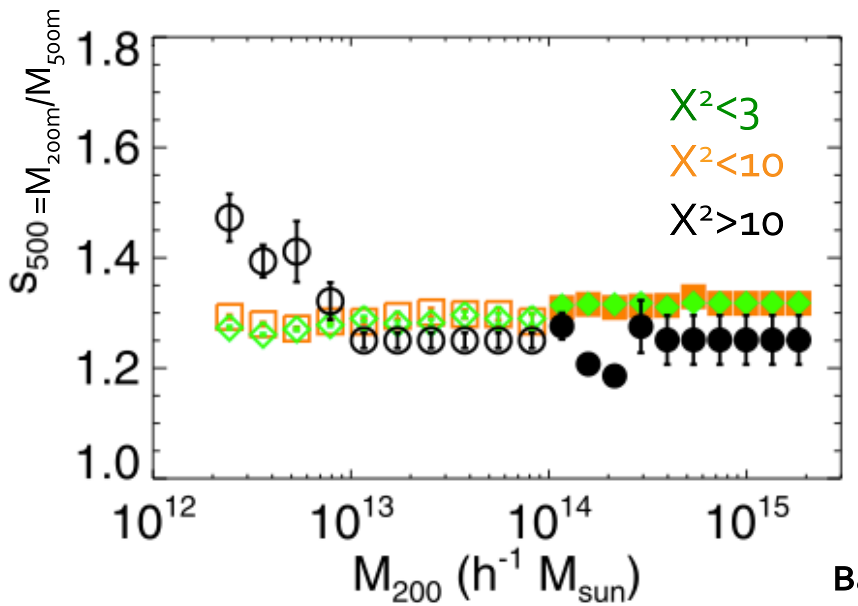
3D DENSITY PROFILE

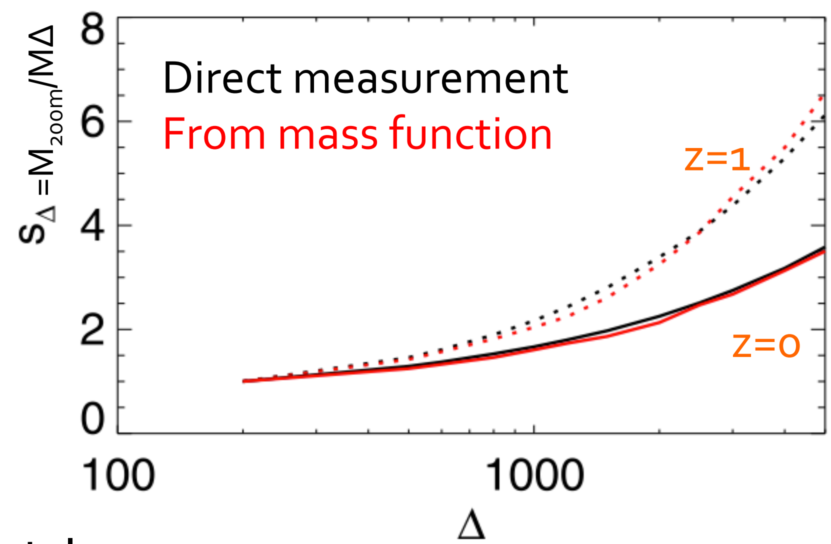
NFW fit $\rho_{\rm NFW}(r) = \dfrac{M_{200}}{4\pi[\ln(1+c) - c/(1+c)]} \times \dfrac{1}{r\left(\frac{r_{200}}{c} + r\right)^2}$



- A fraction of halos density profile are not well fitted by simple function form (such as Navarro-Frenk-White (NFW) formula)
- This fraction depends on cosmology => informations are lost

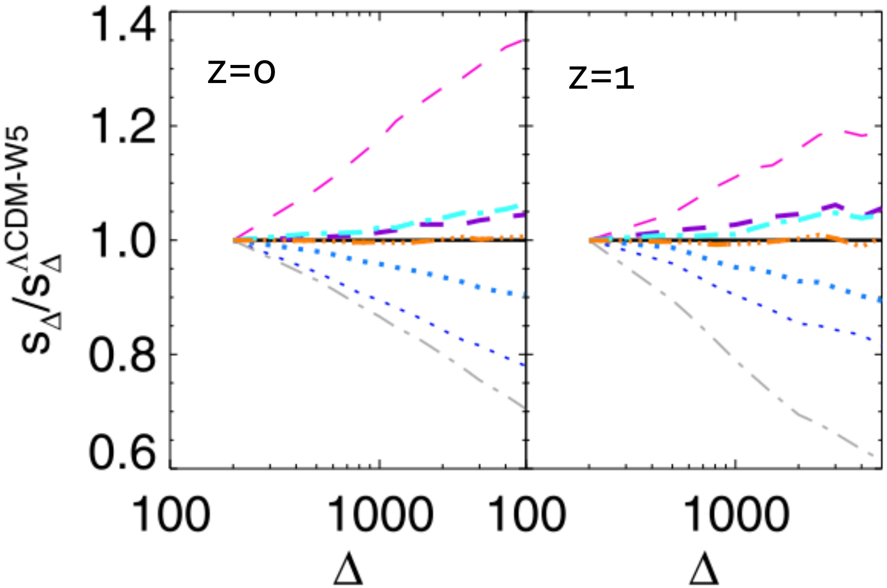
NICE PROPERTIES OF "SPARSITY"

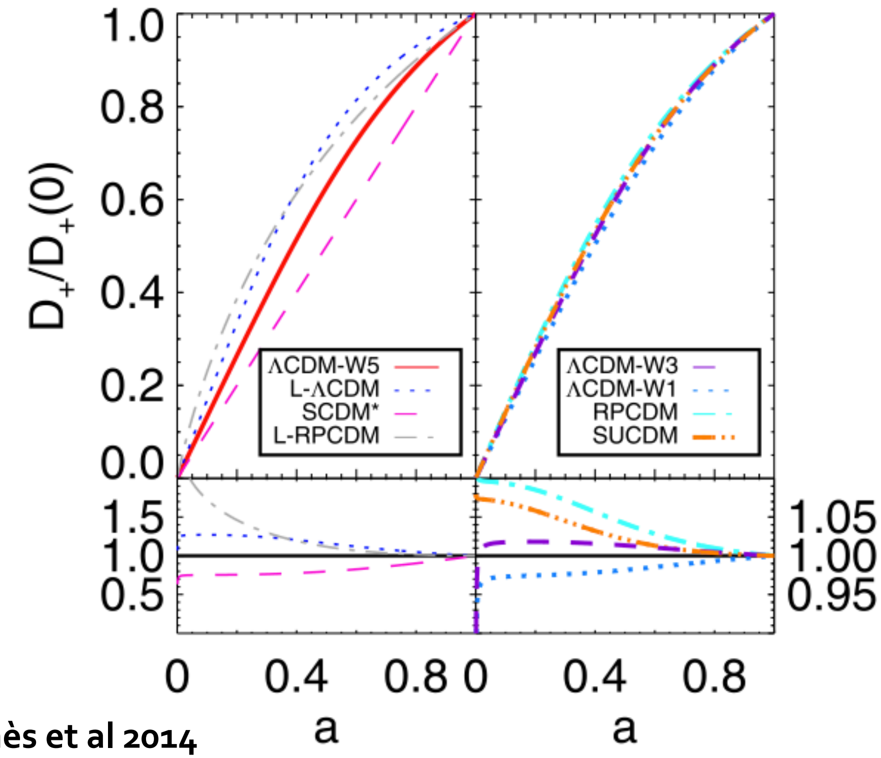




Balmès et al 2014

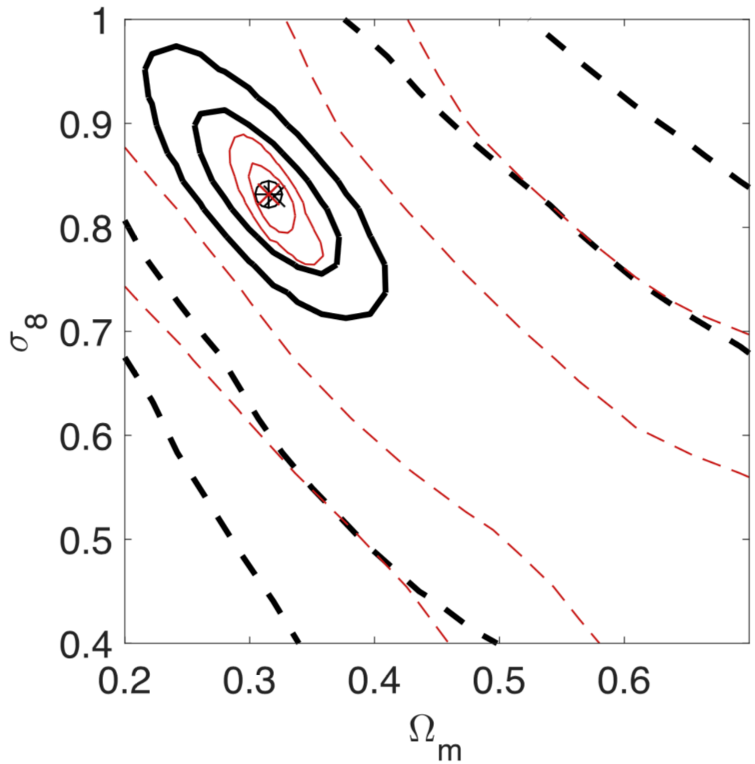
- Non-parametric measure of the profile -> SPARSITY: $s_{\Delta_1\Delta_2} \equiv \frac{M_{\Delta_1}}{M_{\Delta_2}}$
- Nice properties: very weak dependance on mass
- Direct link with the mass function: $\int_{M_2}^{M_1} \frac{\mathrm{d}n}{\mathrm{d}\ln M_\Delta} \frac{\mathrm{d}\ln M_\Delta}{M_\Delta} = \langle s_\Delta \rangle \int_{\langle s_\Delta \rangle M_2}^{\langle s_\Delta \rangle M_1} \frac{\mathrm{d}n}{\mathrm{d}\ln M_{200}} \frac{\mathrm{d}\ln M_{200}}{M_{200}},$
- No fiting procedure : only 2 points needed!





Balmès et al 2014

- Generalization of the result to the average « sparsity » (ie average profile) of all halos
- More robust: non parametric

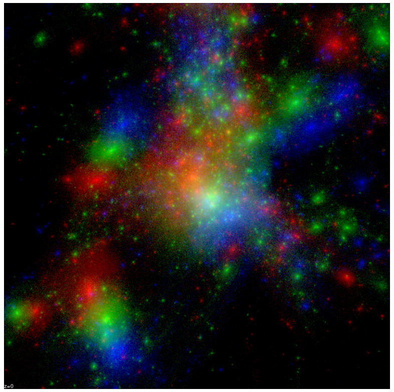


Corasaniti et al, 2017

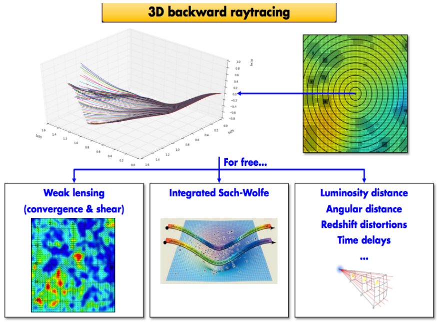
•Black lines: 1 and 2-sigma contours assuming 1% (continuous) and 20% (dashed) average error on sparsity
=> profile of dark matter halos can be a probe of the dark energy

V/ Conclusion and perspective

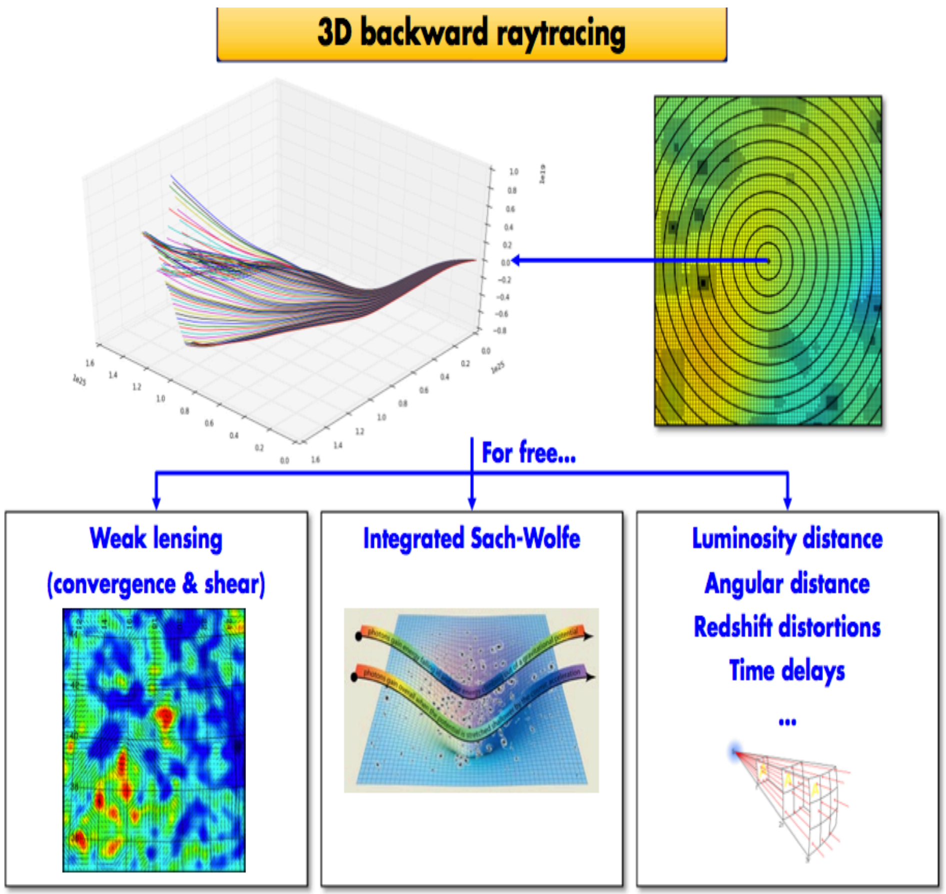
- Main questions
  - What is the nature of dark energy? => Many possibilities.
  - New or refined probe in non-linear regime? => simulations
  - Sims: Bridge between theory/analytical models/observations
- Simulations
  - Weak-field + collisionless Boltzmann => Vlasov Poisson
  - N-body approach
  - Importance of initial conditions generation, halo detection, ray-tracer, etc.

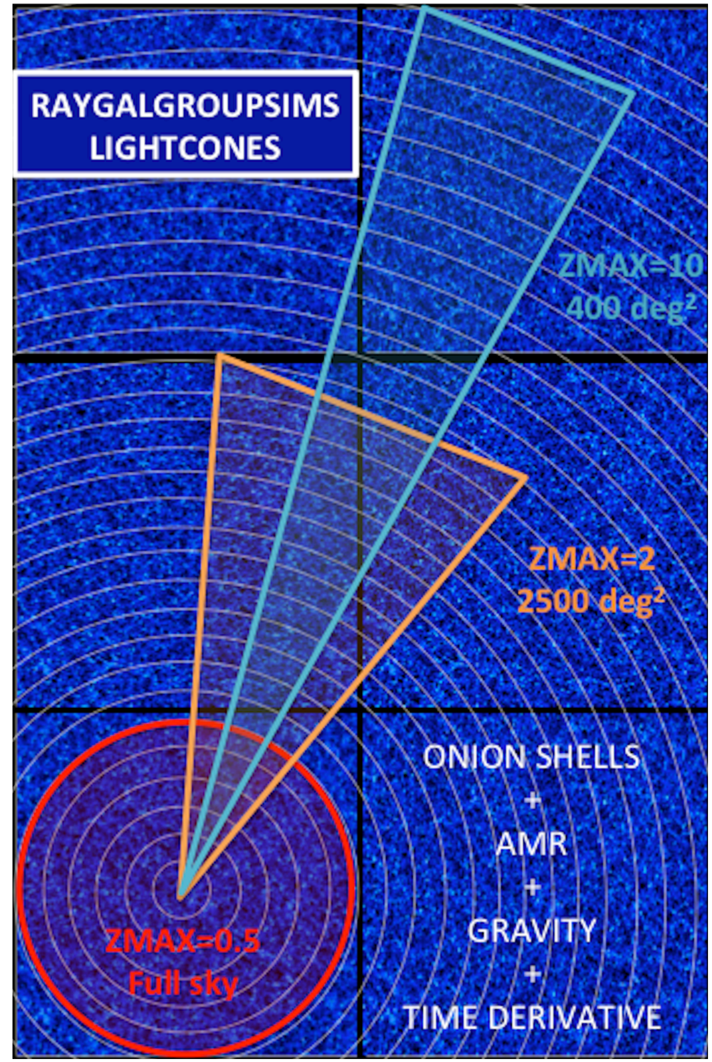


- Simulated models
  - LCDM, wCDM, quintessence, coupled dark energy models
  - f(R), scalar tensor
  - Still very limited compared to the gigantic space of possibilities
- Imprints of minimally coupled dark energy on cosmic structures
  - Choice of "realistic" models (Viable/Solar system/GW/CMB/SNIA)
  - Power spectrum+Mass function+Halo profile
  - Weak Lensing, Redshift Space Distortion (on going Breton+18)
- Imprints of other dark energy models on cosmic structure
  - Similar philosophy but specific signatures=> vast literature
- Future:
  - Larger and/or more resolved sims
  - Wider class of DE models
  - Baryon effects
  - New observables and observational constraints



TOWARDS NEW PROBES OF THE DARK SECTOR





- Various applications of our relativistic ray-tracer Magrathea (Reverdy 2014; Breton et al, 2018)
- **Relativistic halo catalogs (RSD, WL, etc) from RayGalGroupSims simulation** now available
- WCDM sim is on going

=> FEEL FREE TO ASK QUESTION TO MICHEL-ANDRES BRETON WHO IS HERE