Predicting Large-Scale Lyman-α Forest Statistics with

Lyman-α Mass Association Scheme (2014, ApJ, 784, 11)

Sébastien Peirani (OCA - Lagrange)

D. Weinberg, S. Colombi, J. Blaizot, Y. Dubois, J. Devriendt, C. Pichon

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LyMAS

↓

Limace

Slug

Lyman-α **M**ass **A**ssociation **S**cheme (2014, ApJ, 784, 11)

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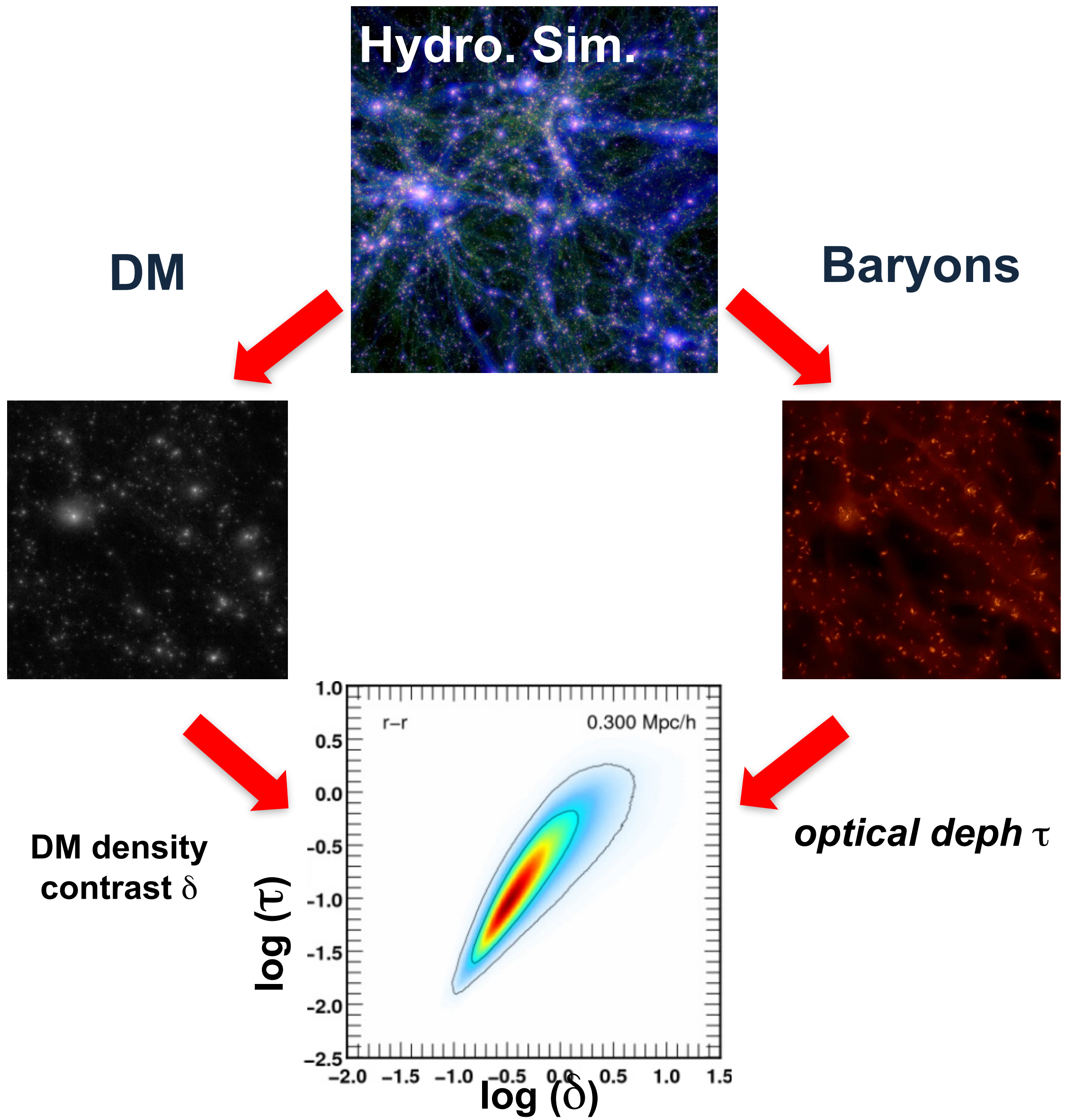
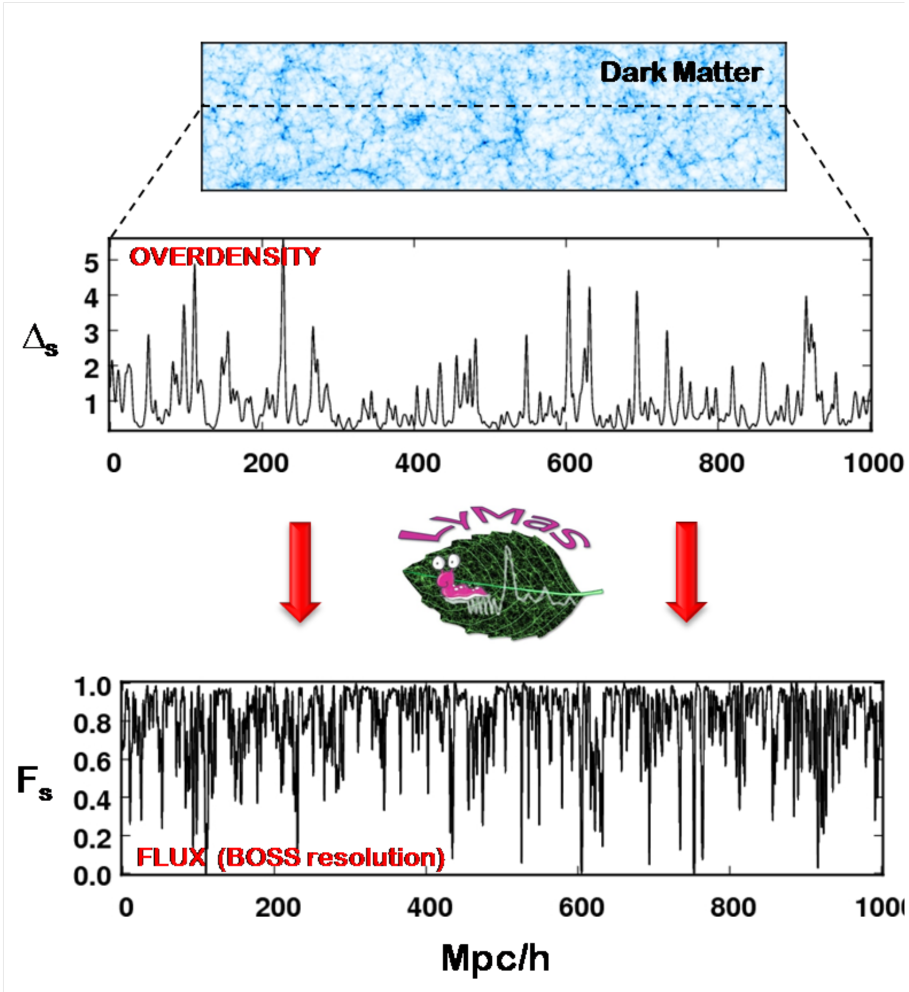
LyMAS: Lyα Mass Association Scheme





Motivations

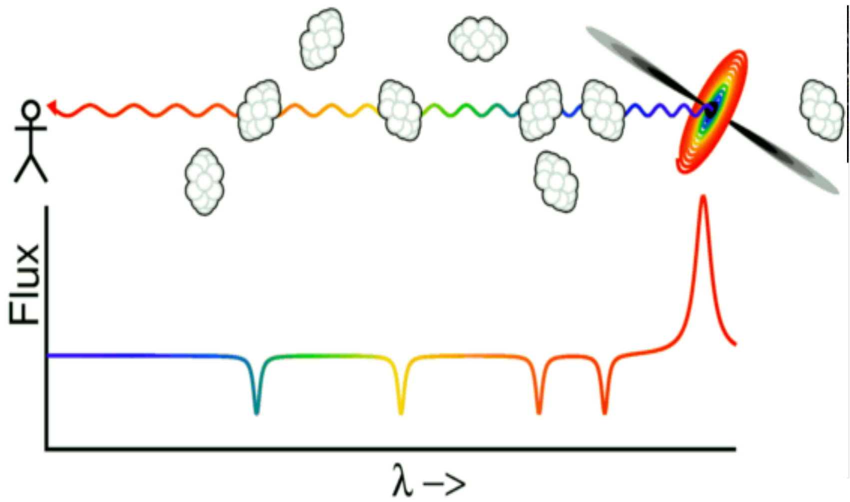
1) Test a cosmological + galaxy formation model by considering Lyman-α at large scales (Gpc)

2) Improve the theoretical predictions, in particular at low scales (few Mpc)

Construction of Mock Ly-α spectra for large surveys

Existence of a tight correlation between density and temperature

(Katz, Weinberg & Hernquist 1996; Hui & Gnedin 1997)

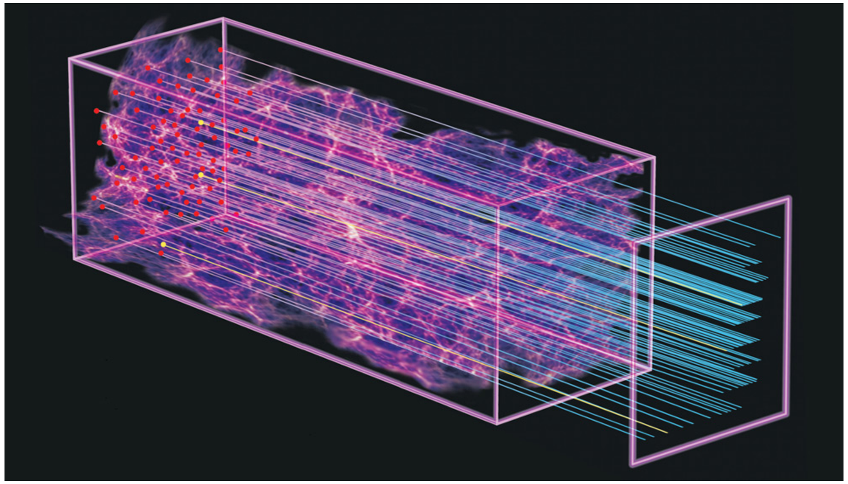


"Fluctuating Gunn-Peterson Approximation"

Lyα Optical depth τ ⟷ DM overdensity Δ

(FGPA, Katz, Weinberg & Hernquist 1998; Croft et al. 1998)

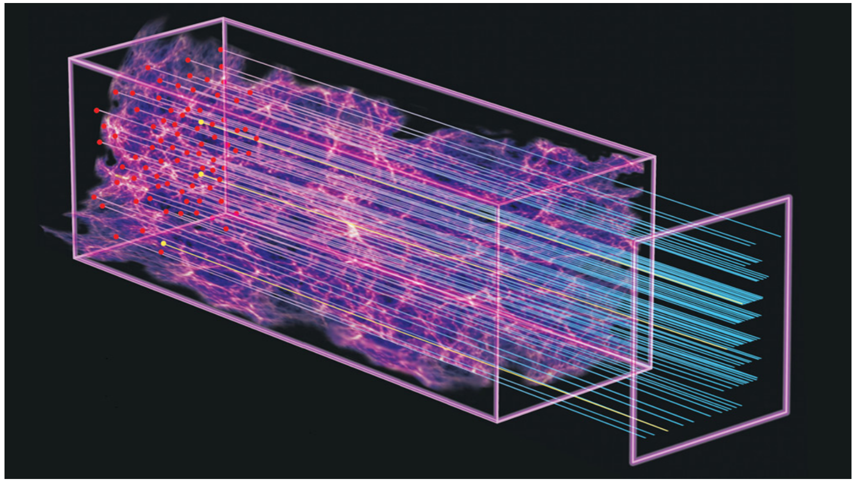
Mock Ly-α : log-normal density field + FGPA



Log-normal density field
- **Gaussian initial conditions**
- **DM density field from N-body simulation**

Construction of Mock Ly-α spectra for large surveys

Mock Ly-α : log-normal density field + FGPA



Log-normal density field
- Gaussian initial conditions
- DM density field from N-body simulation

Problems of this approach:

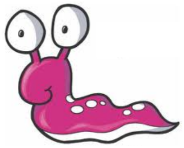
- Model Gpc^3 volume while retaining good resolution on the gas Jeans scale
- The choice of the smoothing scale for DM produces ambiguity in the predictions
- The FGPA assumes a deterministic relation between ρ and $F=e^{-\tau}$

$$F = e^{-A\left(\frac{\rho}{\bar{\rho}}\right)^{2-0.6(\gamma-1)}}$$

γ-1 : index of the gas temperature-density relation

A : normalization constant

Plan



1. Introduction
2. Hydro simulations and hydro spectra
3. Deterministic mapping
4. LyMAS Probabilistic mapping
5. LyMAS Coherent mapping
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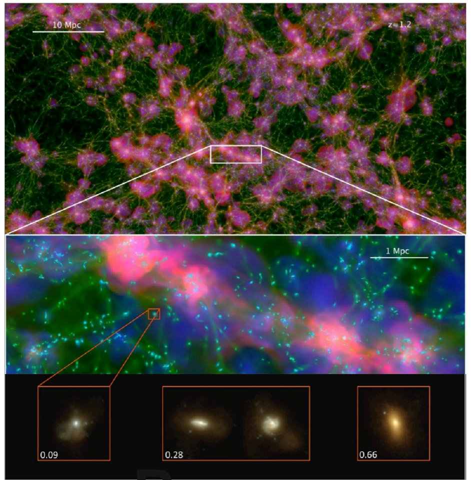
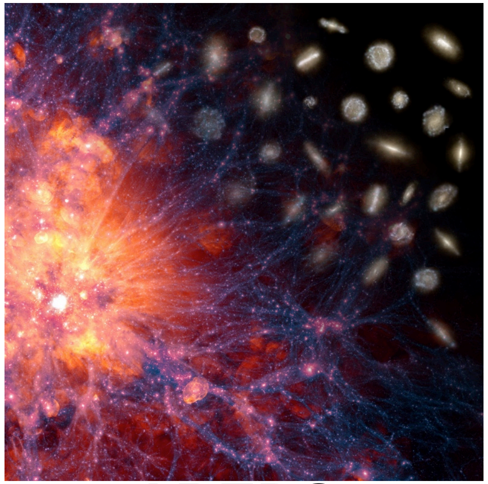
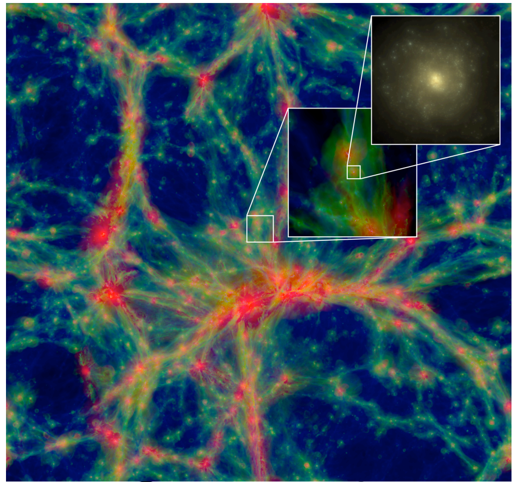
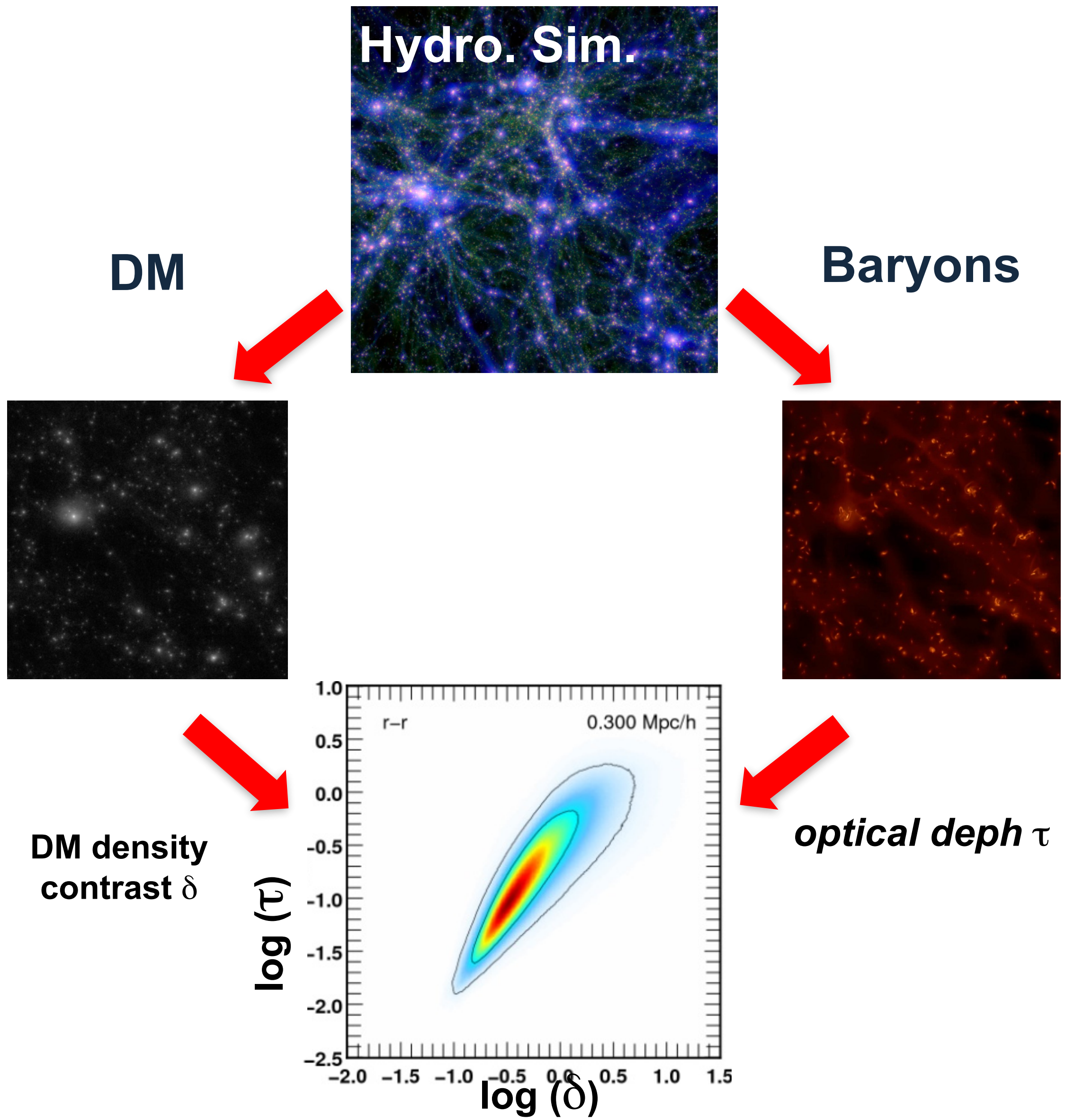
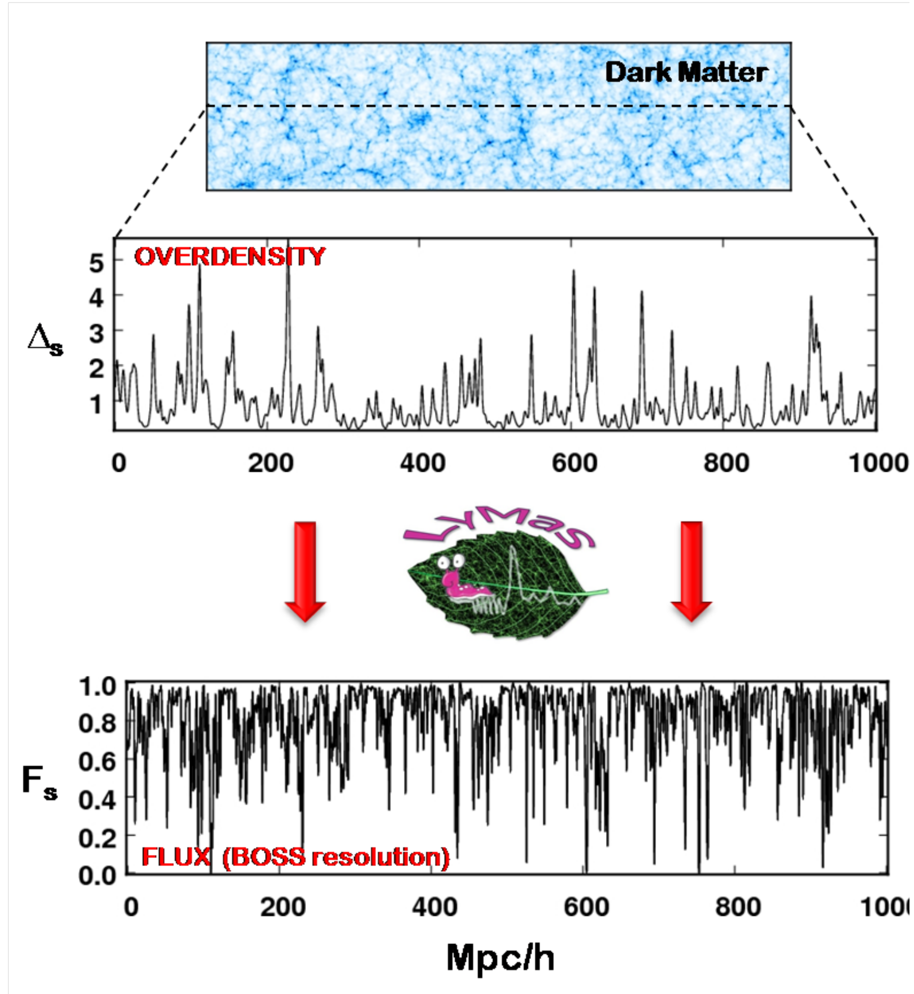
Hydro simulations

	Dubois et al. 2014	Vogelsberger et al. 2014	Schaye et al. 2015
	Horizon-AGN	Illustris	EAGLE
			
	Ramses	**AREPO**	**Gadget-2**
L_{box}	**142 Mpc**	**106.5 Mpc**	**100 Mpc**
M_{dm}	**8.3×10^7 $M_\odot$**	**6.3×10^6 $M_\odot$**	**9.7×10^6 $M_\odot$**
ε_{dm}	**1 kpc**	**0.7 kpc**	**0.7 kpc**
	AMR	**moving mesh**	**SPH**
	6.6×10^9 cells	**5.3×10^9 cells**	**3.4×10^9 gas parts.**
$M_{g,*}$	**2×10^6 $M_\odot$**	**1.3×10^6 $M_\odot$**	**1.8×10^6 $M_\odot$**

see also MassiveBlackII (DiMatteo 2016), Magneticum Pathfinder simulations (Dolag et al.), Sherwood simulations (Bolton et al. 2016),…

LyMAS: Lyα Mass Association Scheme

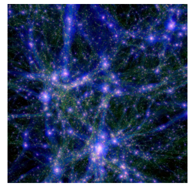




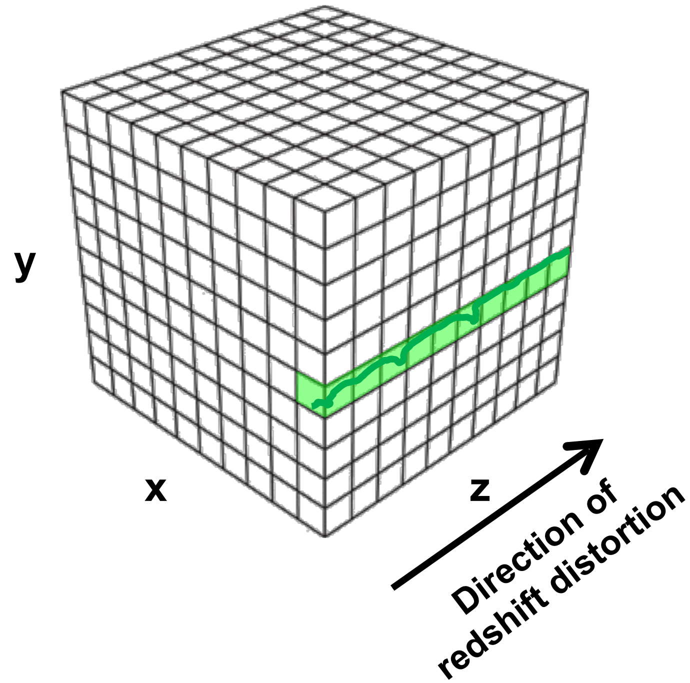
Extracting Lyα spectra

For a given los, the opacity at observer-frame frequency υ_{obs}:

$$\tau(\upsilon_{obs}) = \sum_{cells} n_{HI}\sigma(\nu_{obs})dl$$



Grid of density transmitted Flux (1024^3 voxels)



n_{HI} : numerical density of neutral H atoms in each cell

dl : physical cell size

$\sigma(v_{obs})$: the cross section of Hydrogen to Lyα photons

$$\sigma(\upsilon_{obs}) = f_{12}\frac{\pi e^2}{m_e c}\times\frac{H(a,x)}{\sqrt{\pi}\,\Delta\nu_D}$$

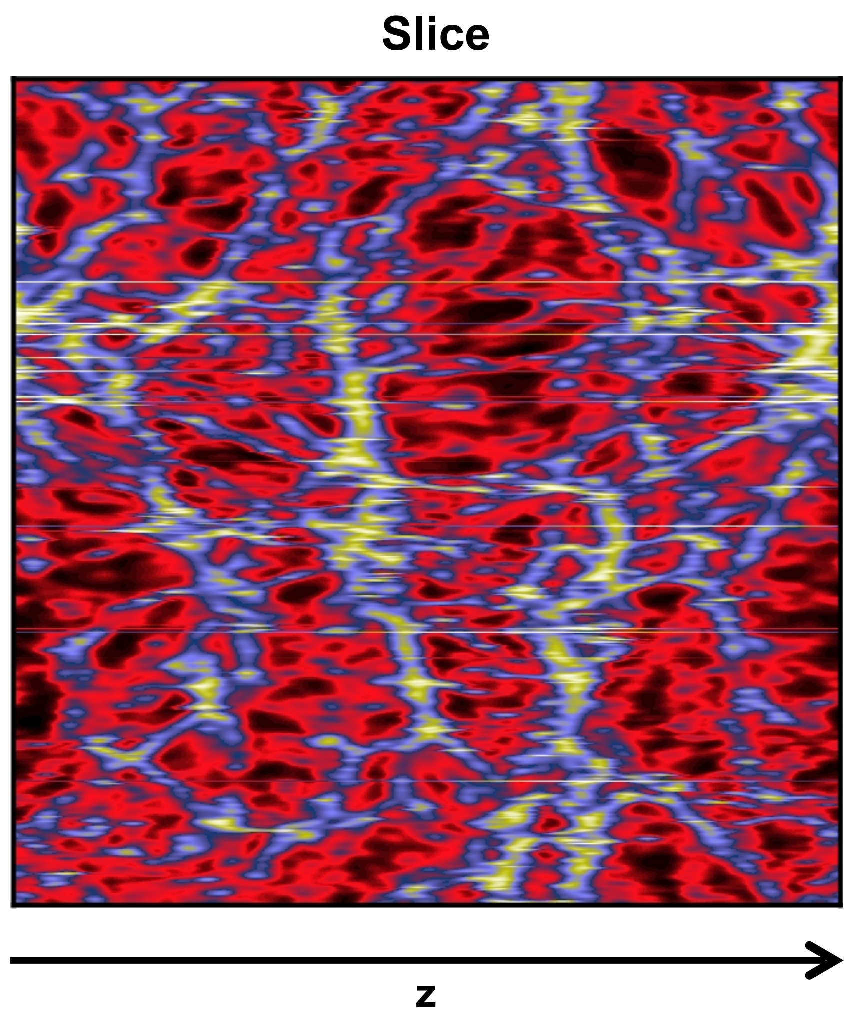
$f_{12} = 0.4162$: Lyα oscillator strength

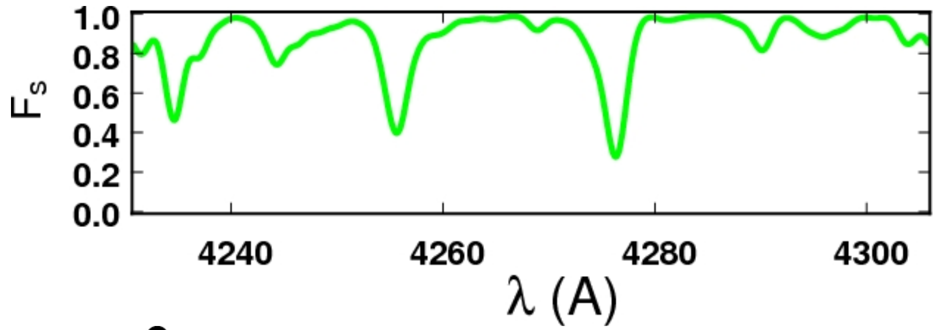
$$\Delta\upsilon_D = (2k_B T/m_H)^{1/2}\times\nu_\alpha/c$$

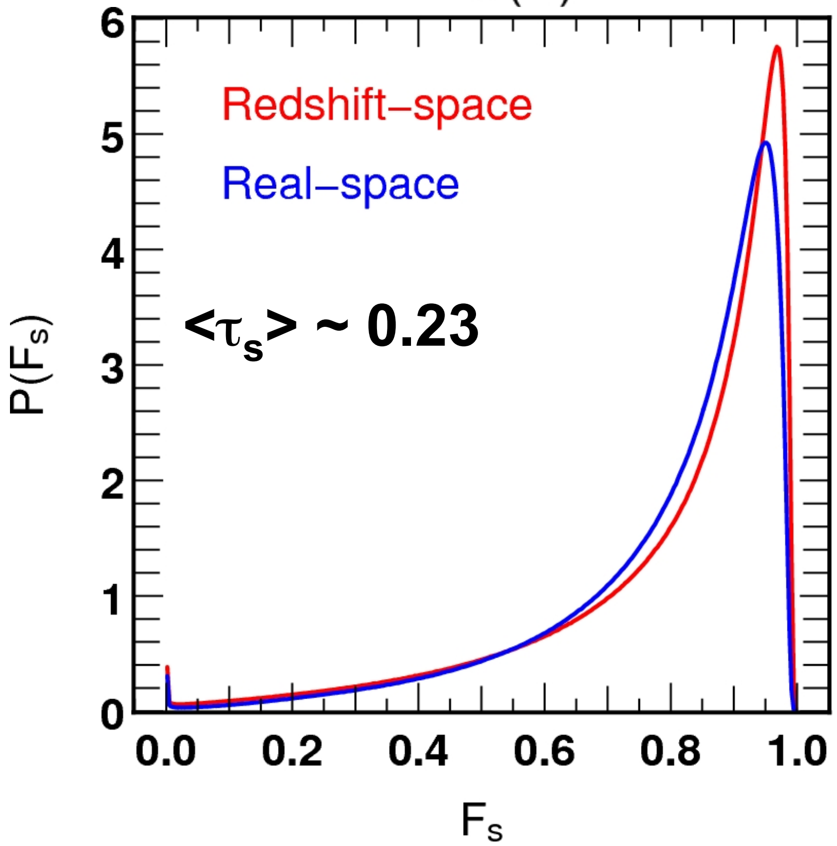
$$a = \Delta\upsilon_L/(2\Delta\upsilon_D) \qquad \Delta\upsilon_L \approx 9.9\,10^7\,s^{-1}$$

$$H(a,x) = \frac{a}{\pi}\int_{-1}^{1}\frac{e^{-y^2}}{a^2+(x-y)^2}dy$$: the Hjerting function

Extracting Lyα spectra







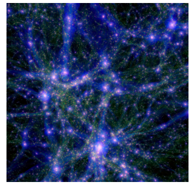
1-d smoothed at the BOSS resolution

Extracting Dark matter skewers

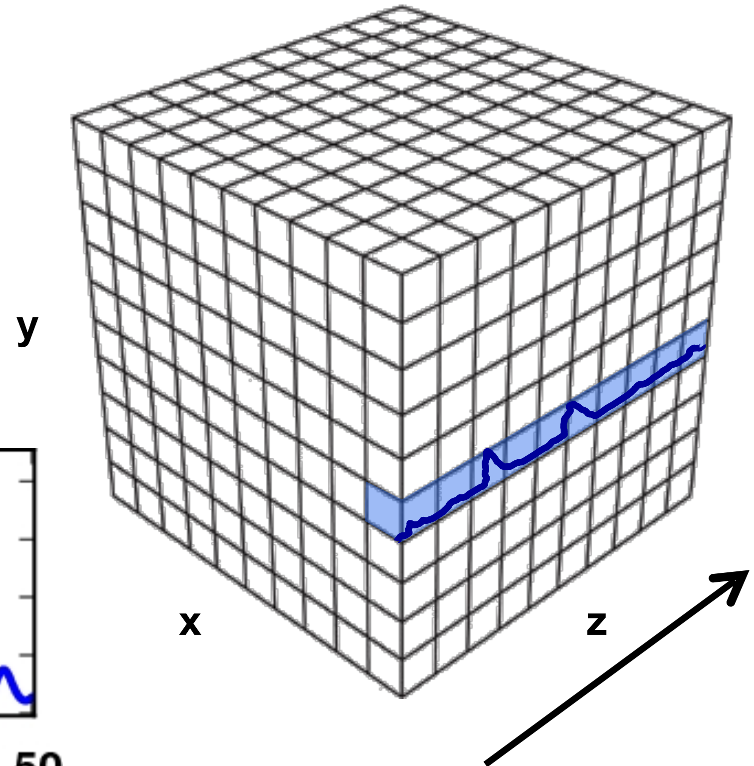
1. Adaptive interpolation of the DM particle distribution on a high resolution grid. (Colombi, Chodorowski & Teyssier 2007)

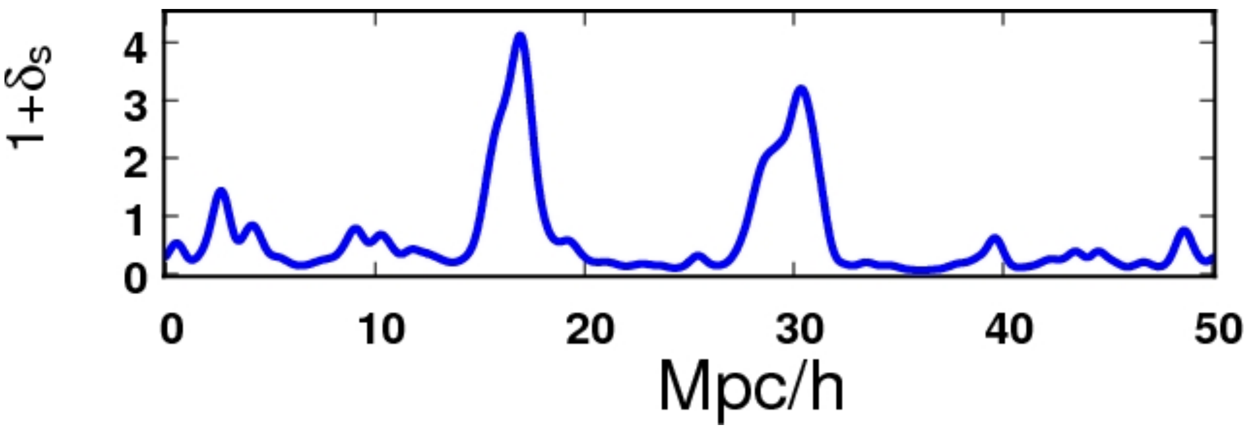
2. Smoothing with a Gaussian window in Fourier space

3. Extraction of the skewers from a grid of lines of sight aligned along the z axis



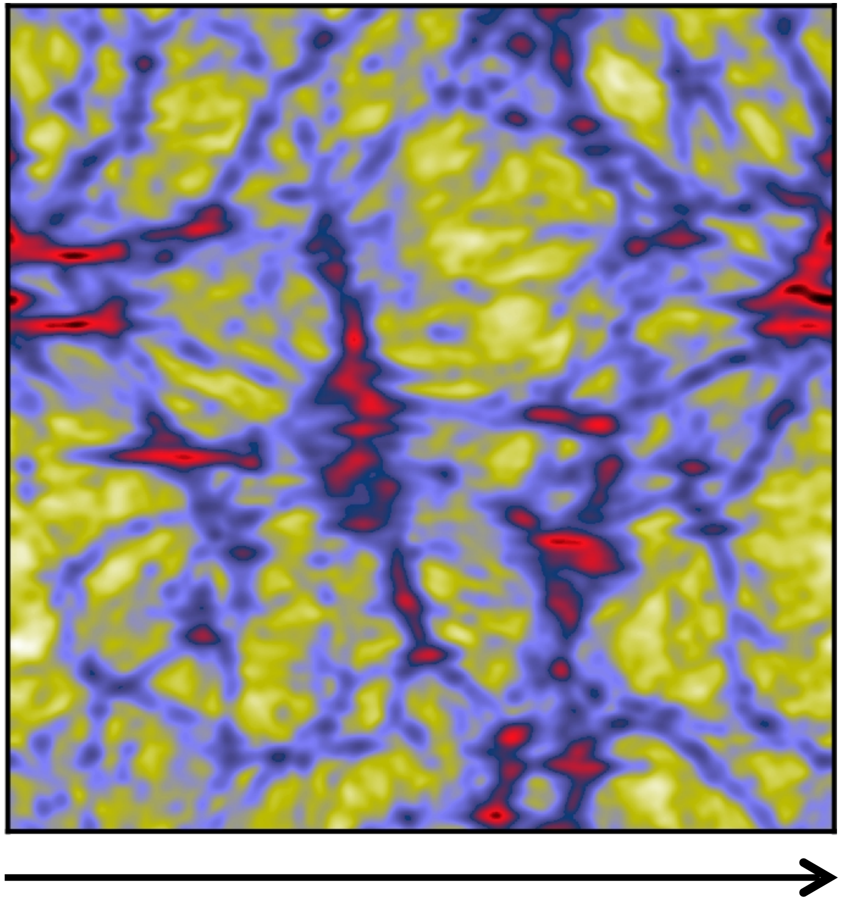
Grid of density field $1+\delta$ (1024^3 pixels)



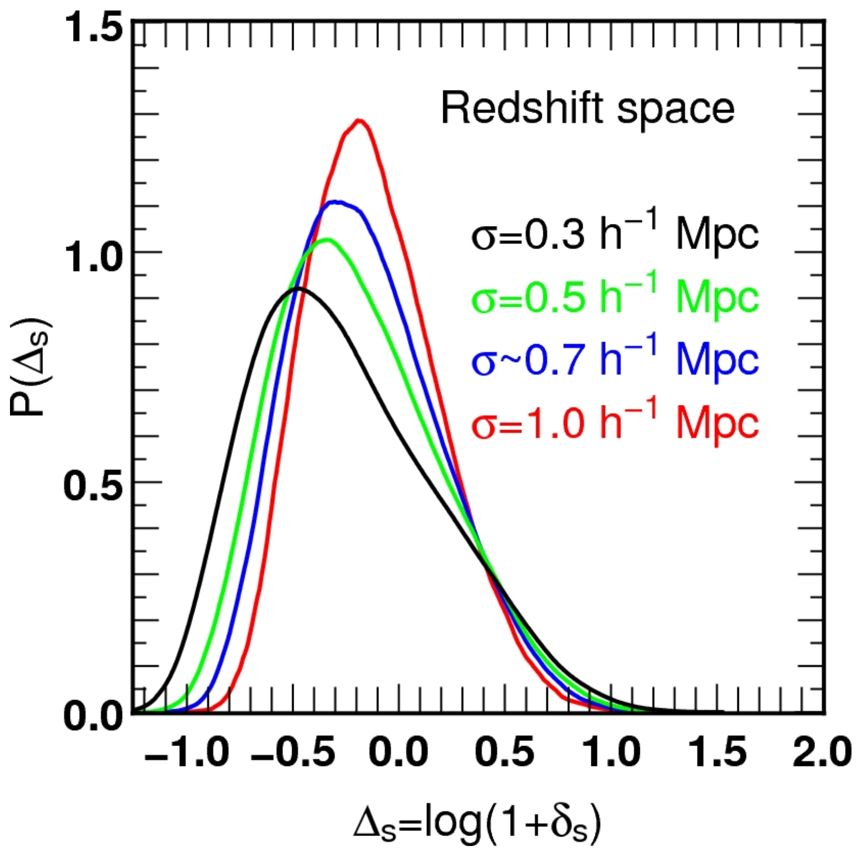


Extracting Dark matter skewers

Slice

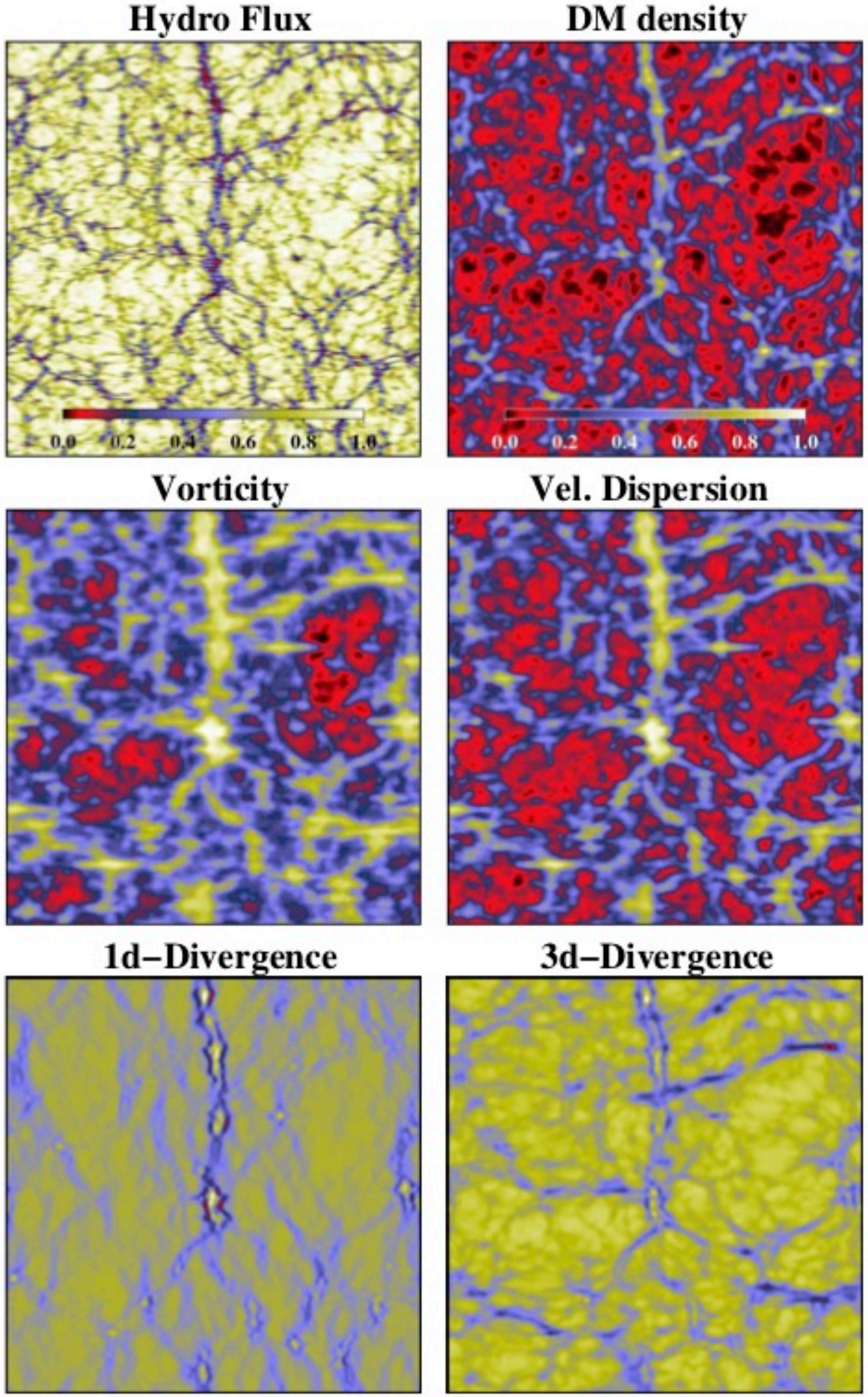


PDF

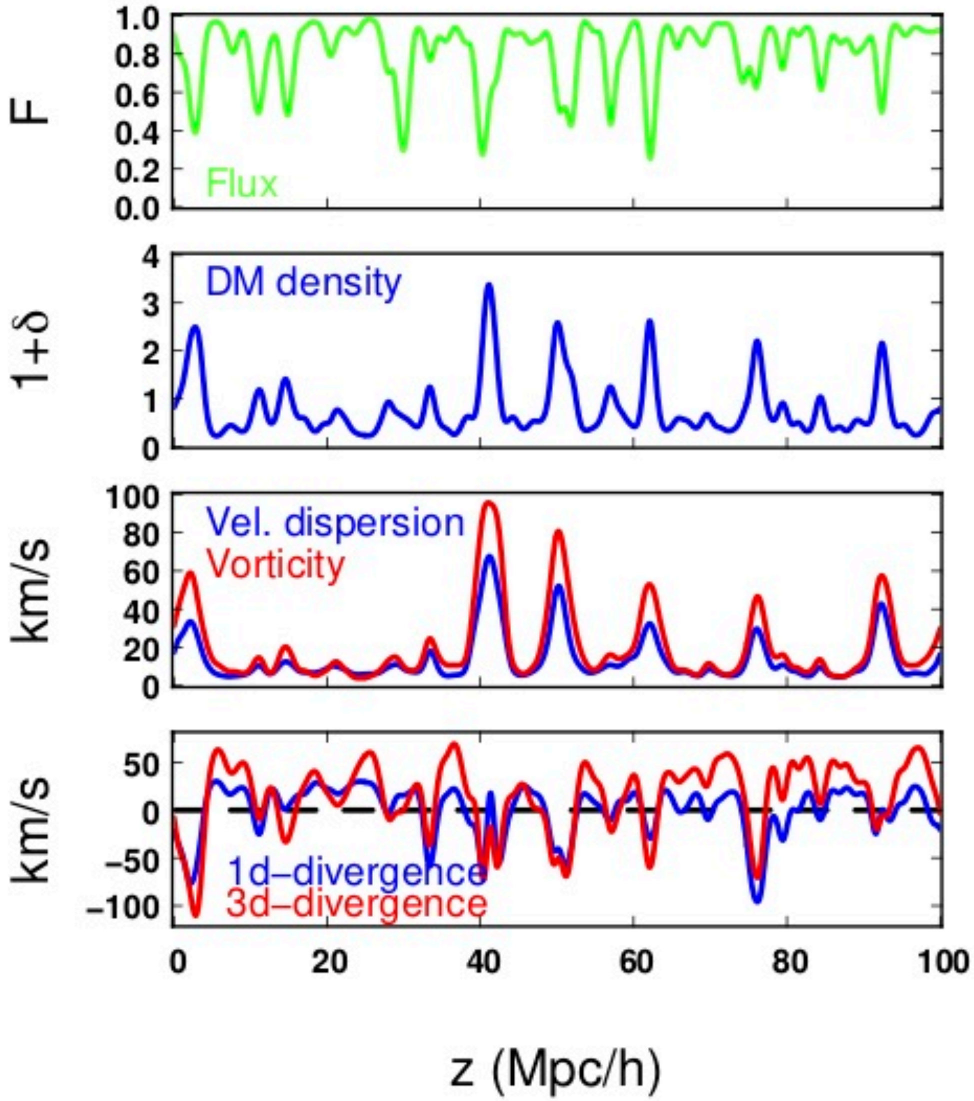


3-d smoothed at different scales

Extracting Dark matter skewers



(Peirani et al. in prep)



Extracting Dark matter skewers

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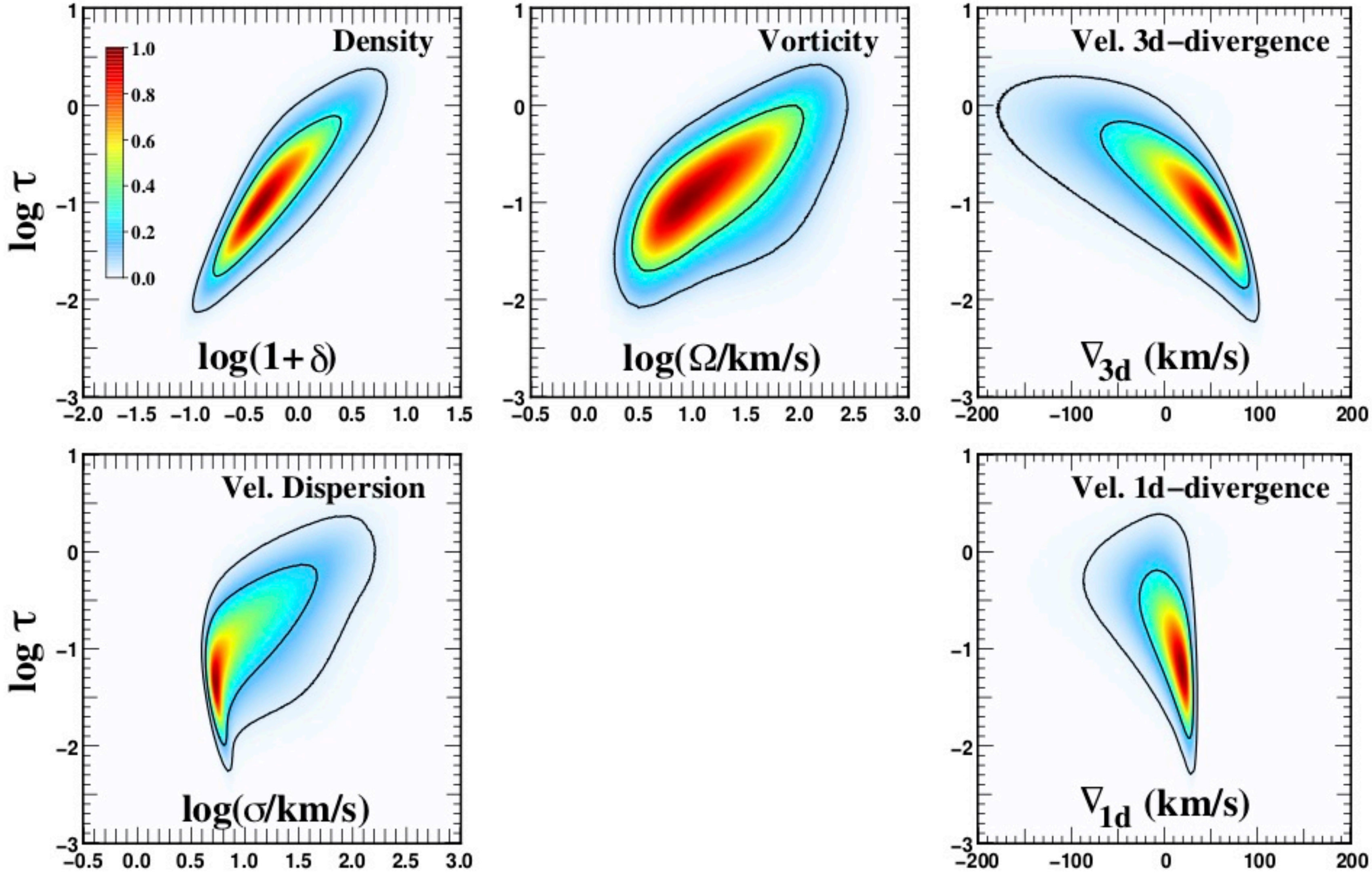
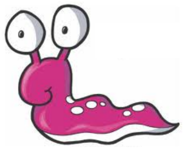


Plan



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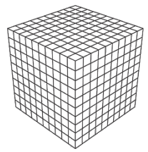
Deterministic mapping

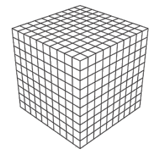
Construction of an "optimal" deterministic relation: $F_s = f(1+\delta_s)$ (Gallerani+ 2011)

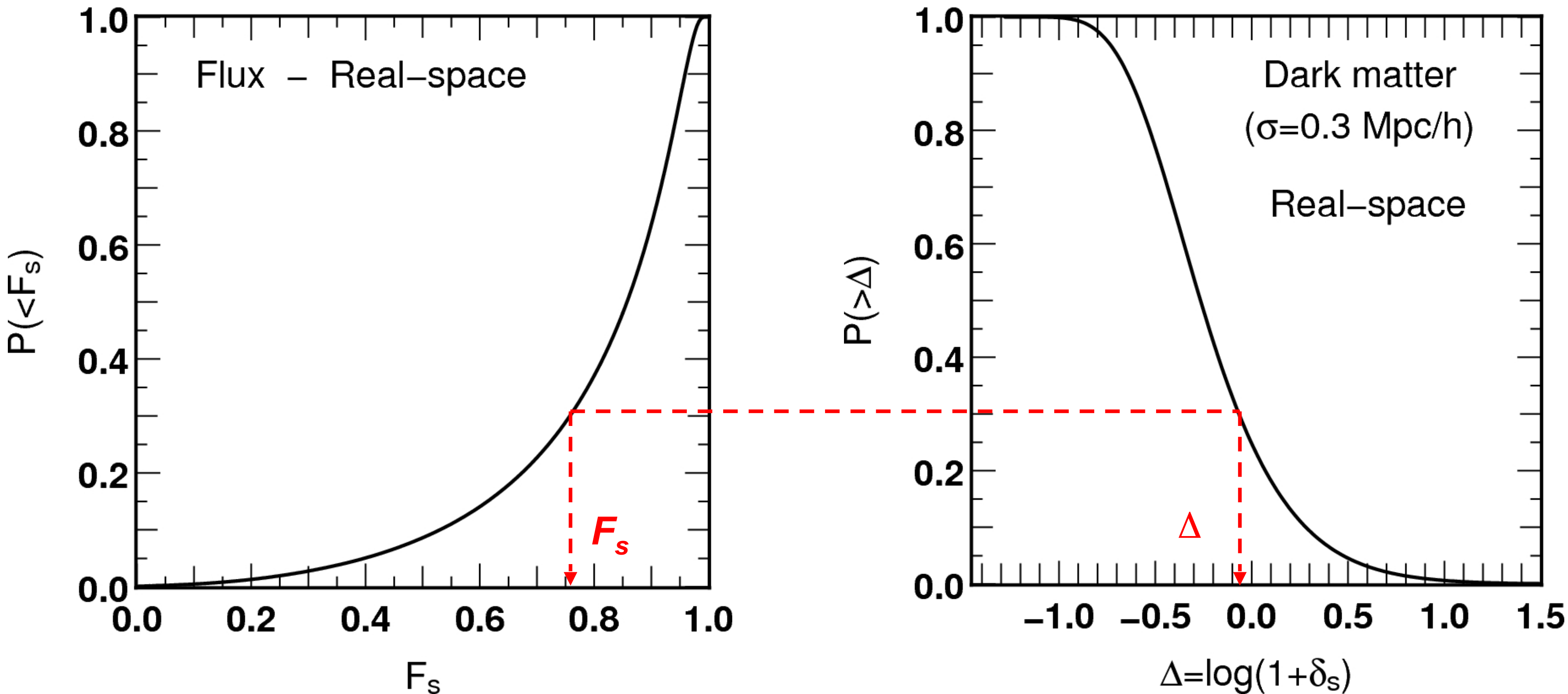
$$\int_0^{F_S} P(F_S{}')\, dF_S{}' = \int_{\delta_S}^{\infty} P(\delta_S{}')\, d\delta_S{}'$$

Grid of transmitted flux F_s



Grid of DM density contrast $1+\delta_s$

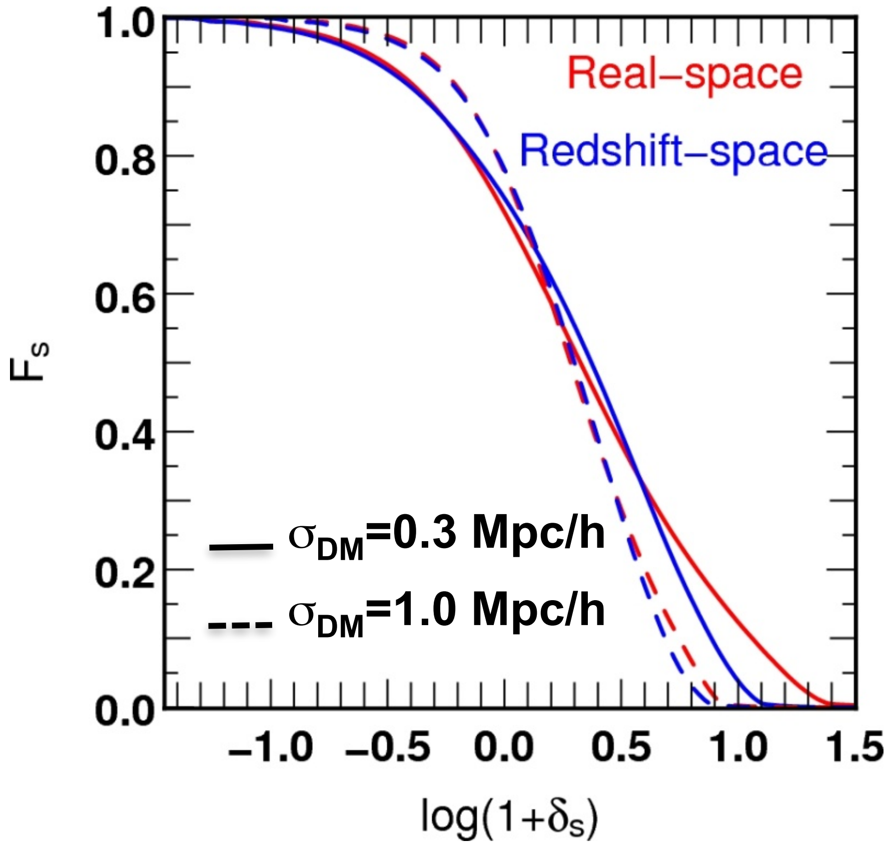


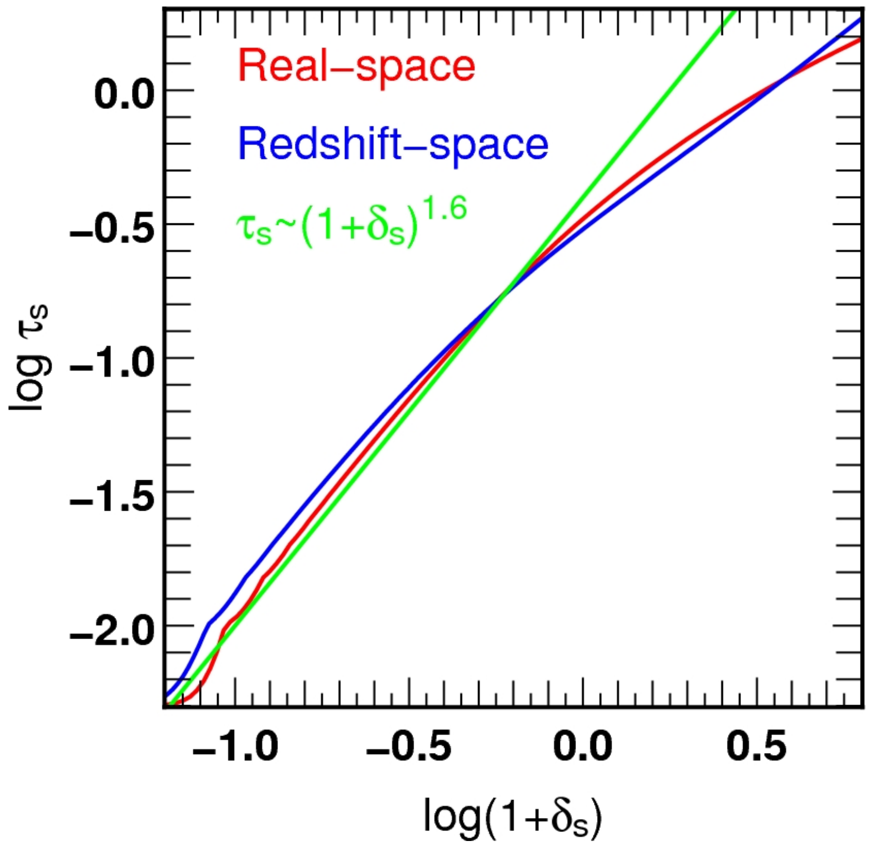


Deterministic mapping

1. Construction of a deterministic relation: $F_s = f(1+\delta_s)$

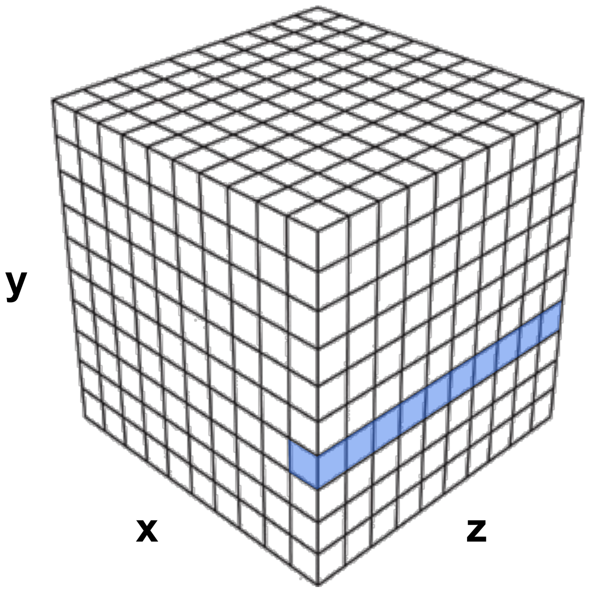
Optical depth: $\tau_s = -\ln F_s$



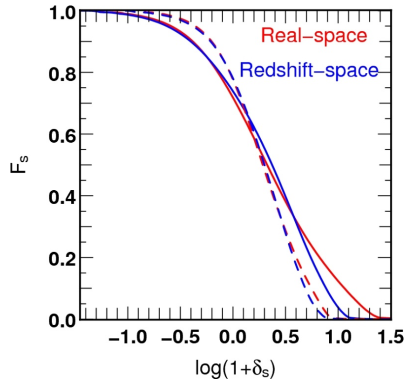


Deterministic mapping

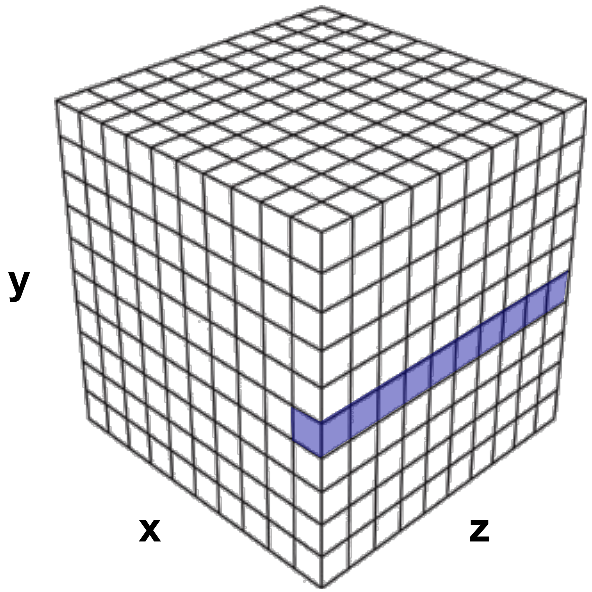
Grid of density contrast $1+\delta_s$
1024^3 pixels

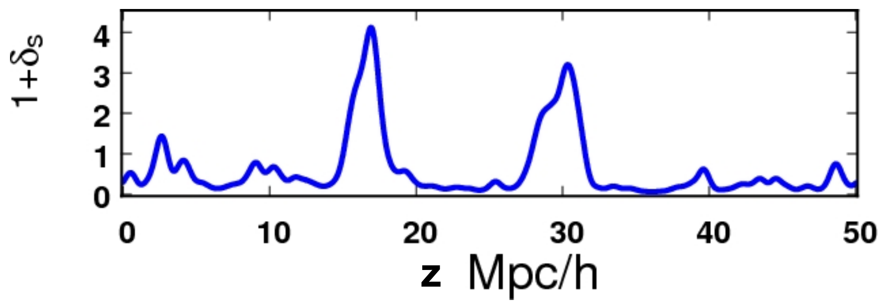


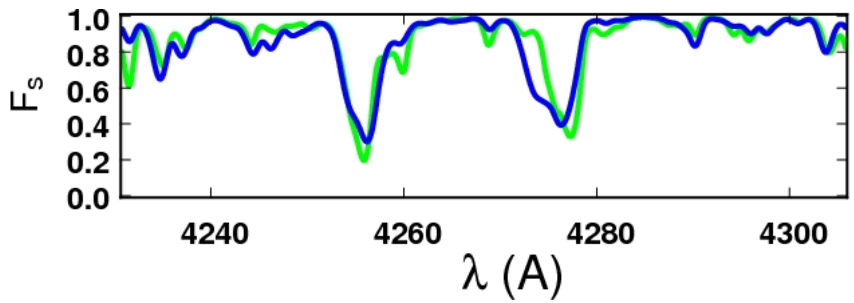
Grid of predicted transmitted flux F_s
1024^3 pixels



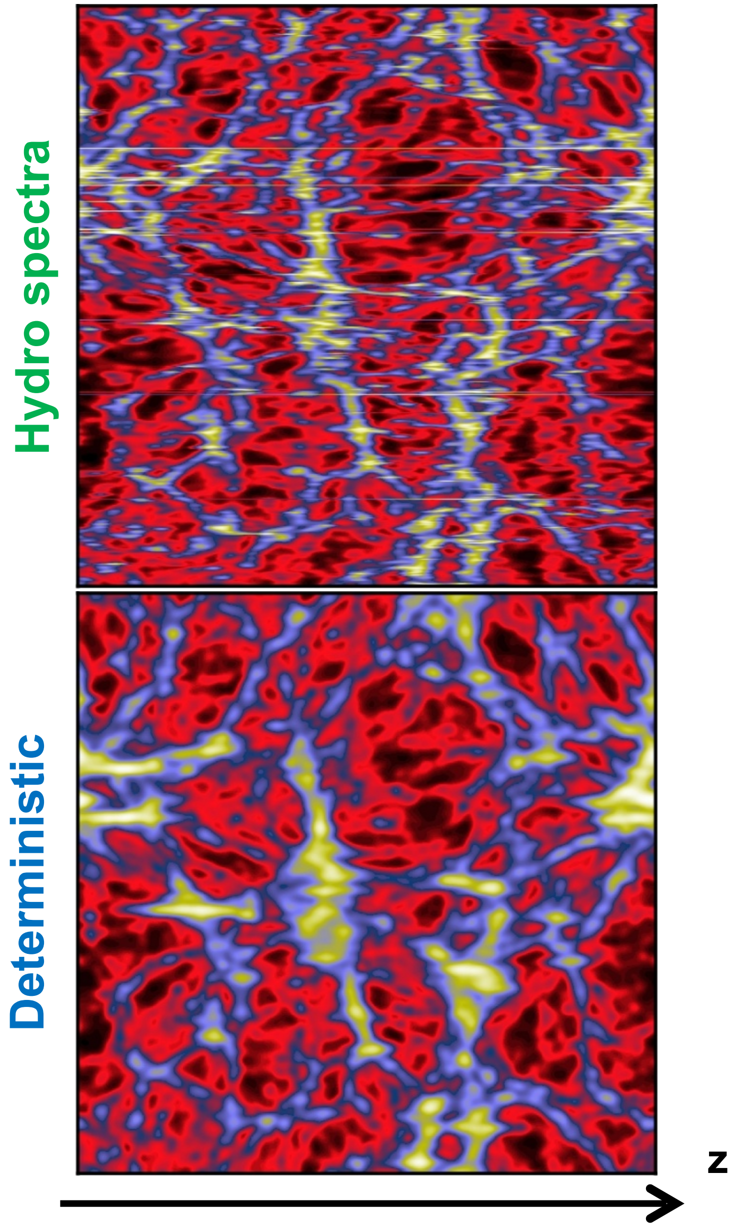
$$F_s = f(1+\delta_s)$$

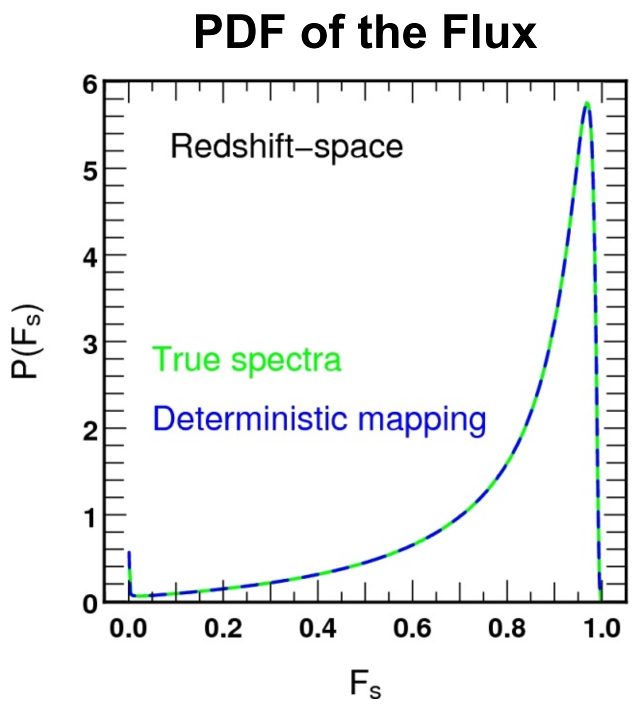


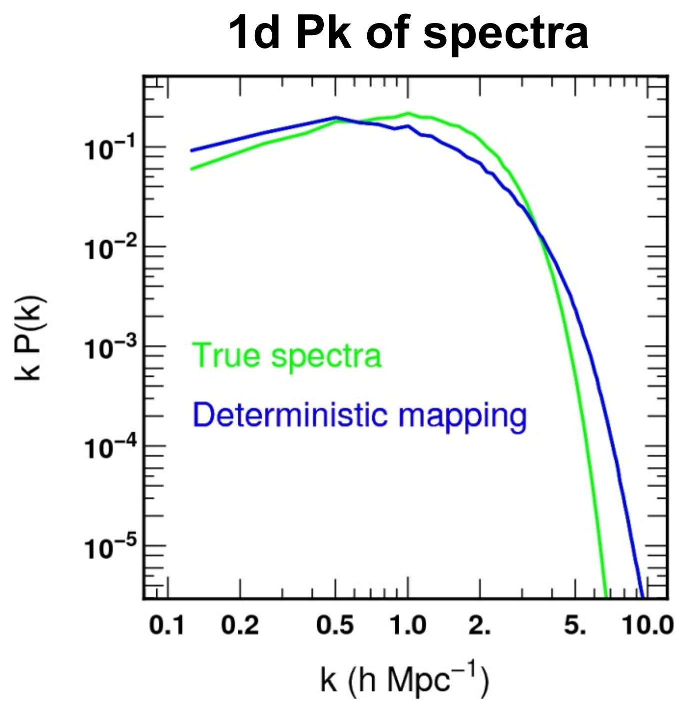


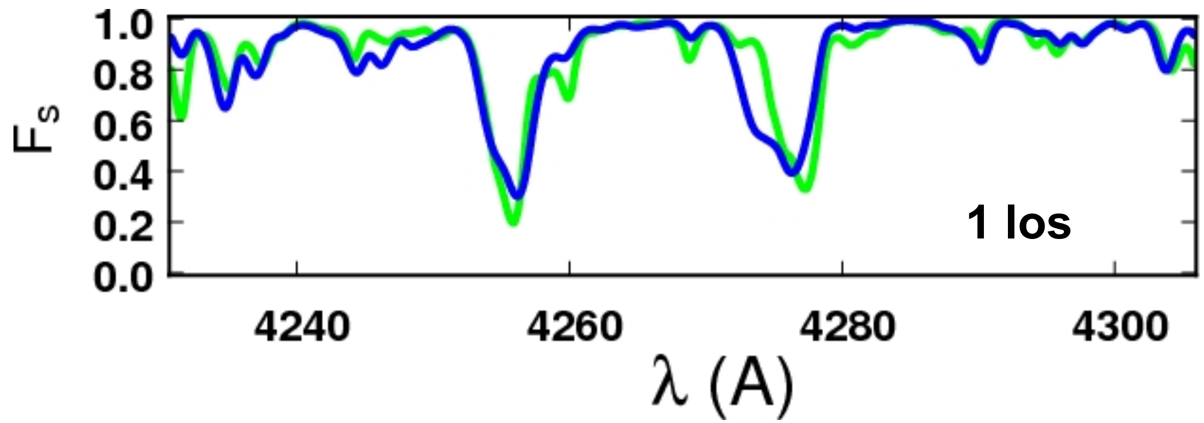


Deterministic mapping

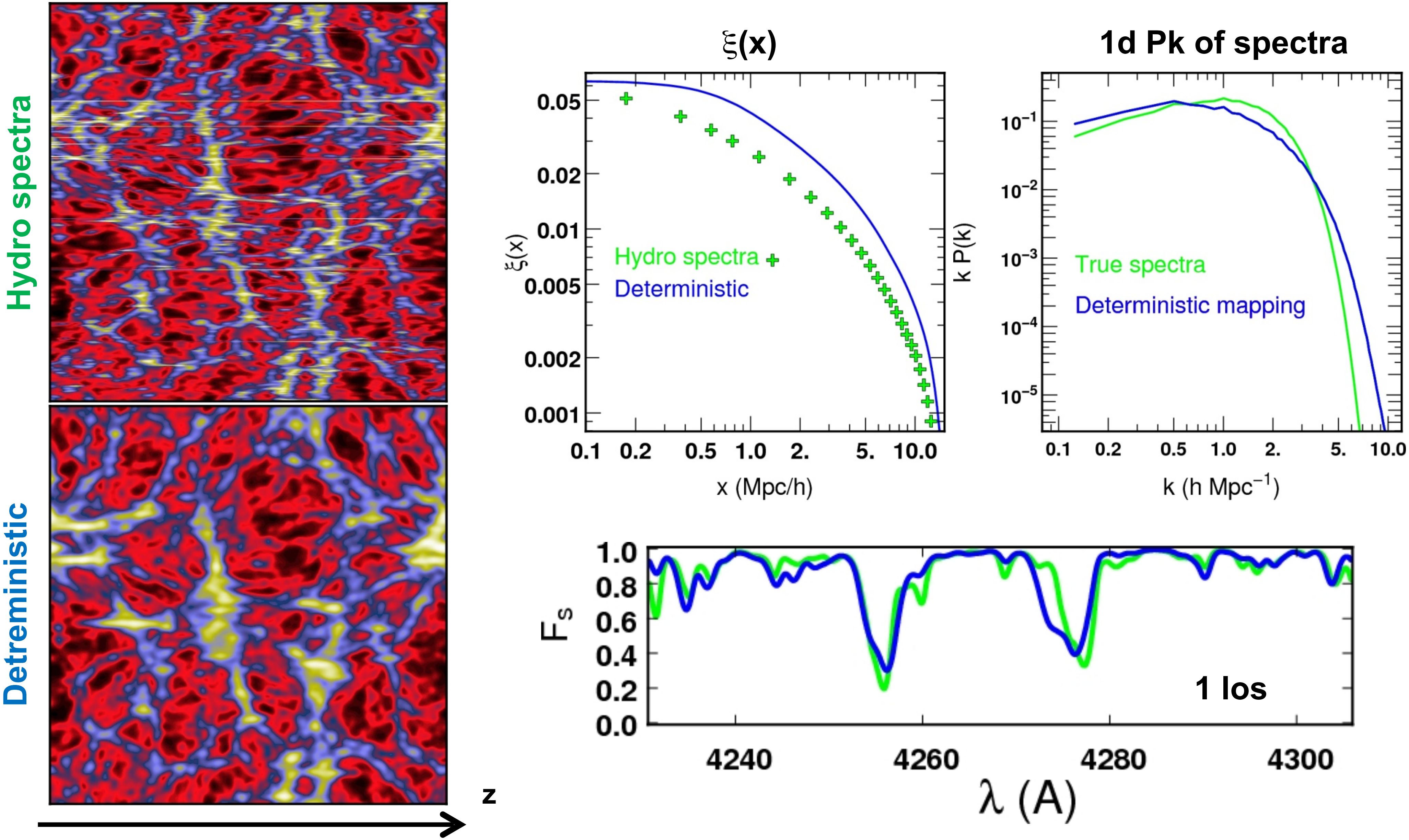








Deterministic mapping



Plan

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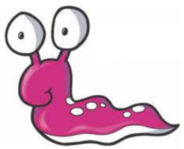

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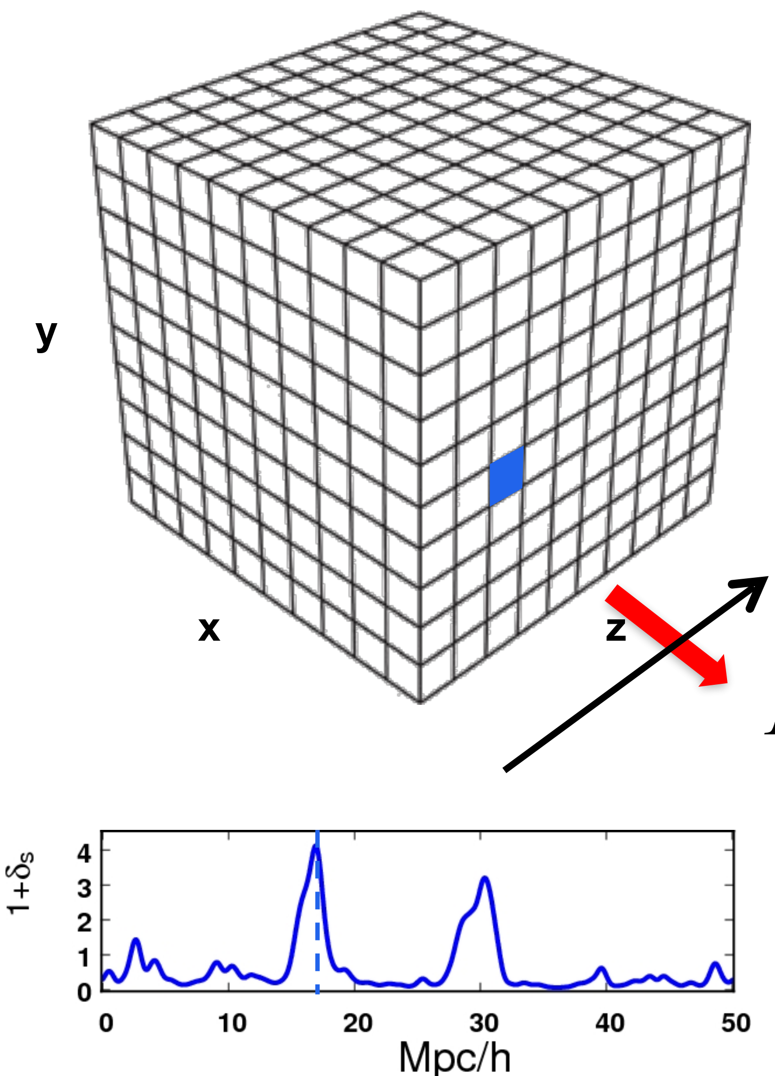
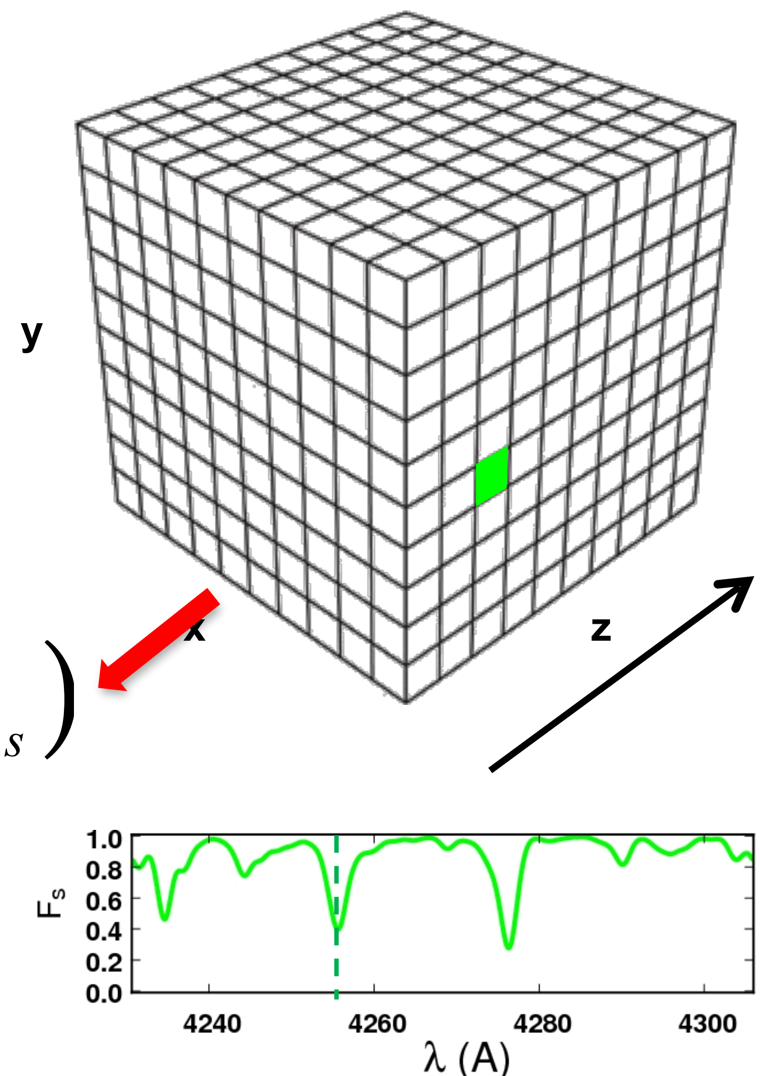
Predicting conditional Flux distributions

Grid of density contrast $1+\delta_s$
1024^3 pixels



$$P\left(F_s \middle| 1+\delta_s\right)$$

Grid of transmitted flux F_s
1024^3 pixels



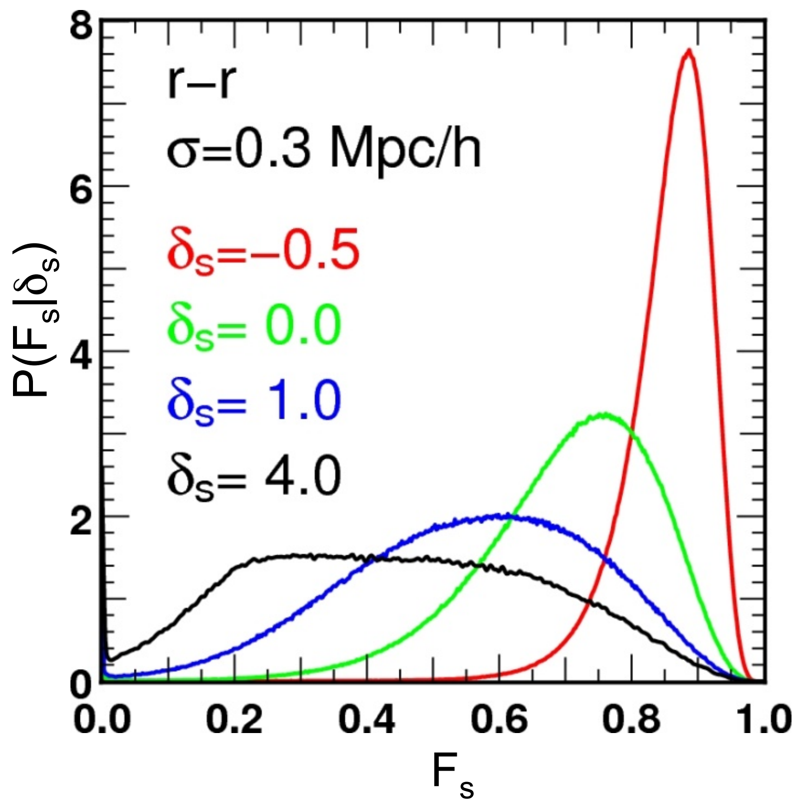
Predicting conditional Flux distributions

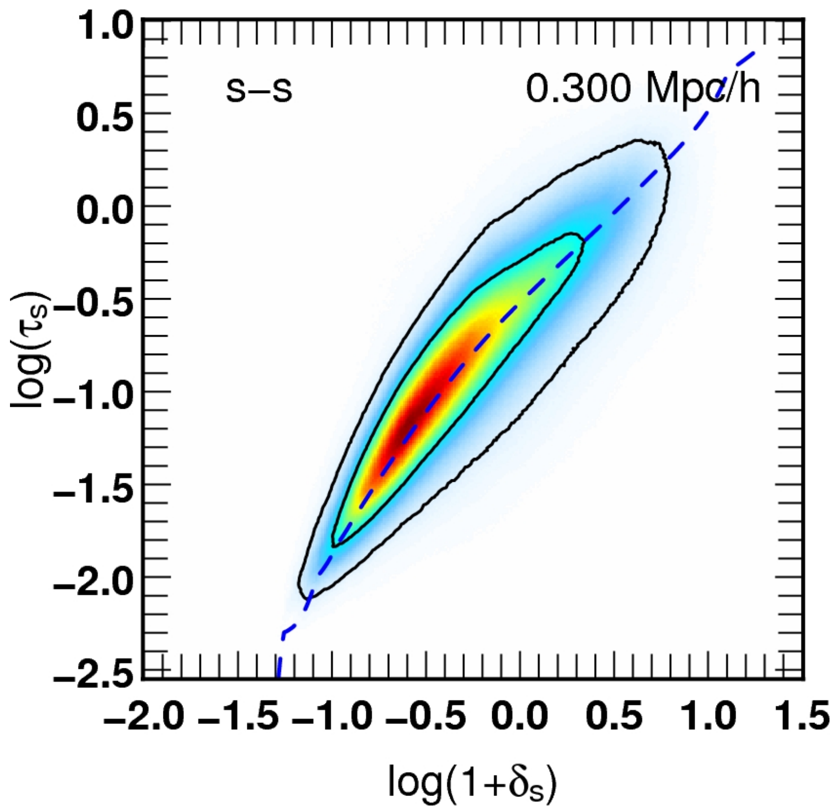
$$P(F_s|1+\delta_s)$$

Optical depth: $\tau_s = -\ln F_s$

$$P(\tau_s|1+\delta_s)$$

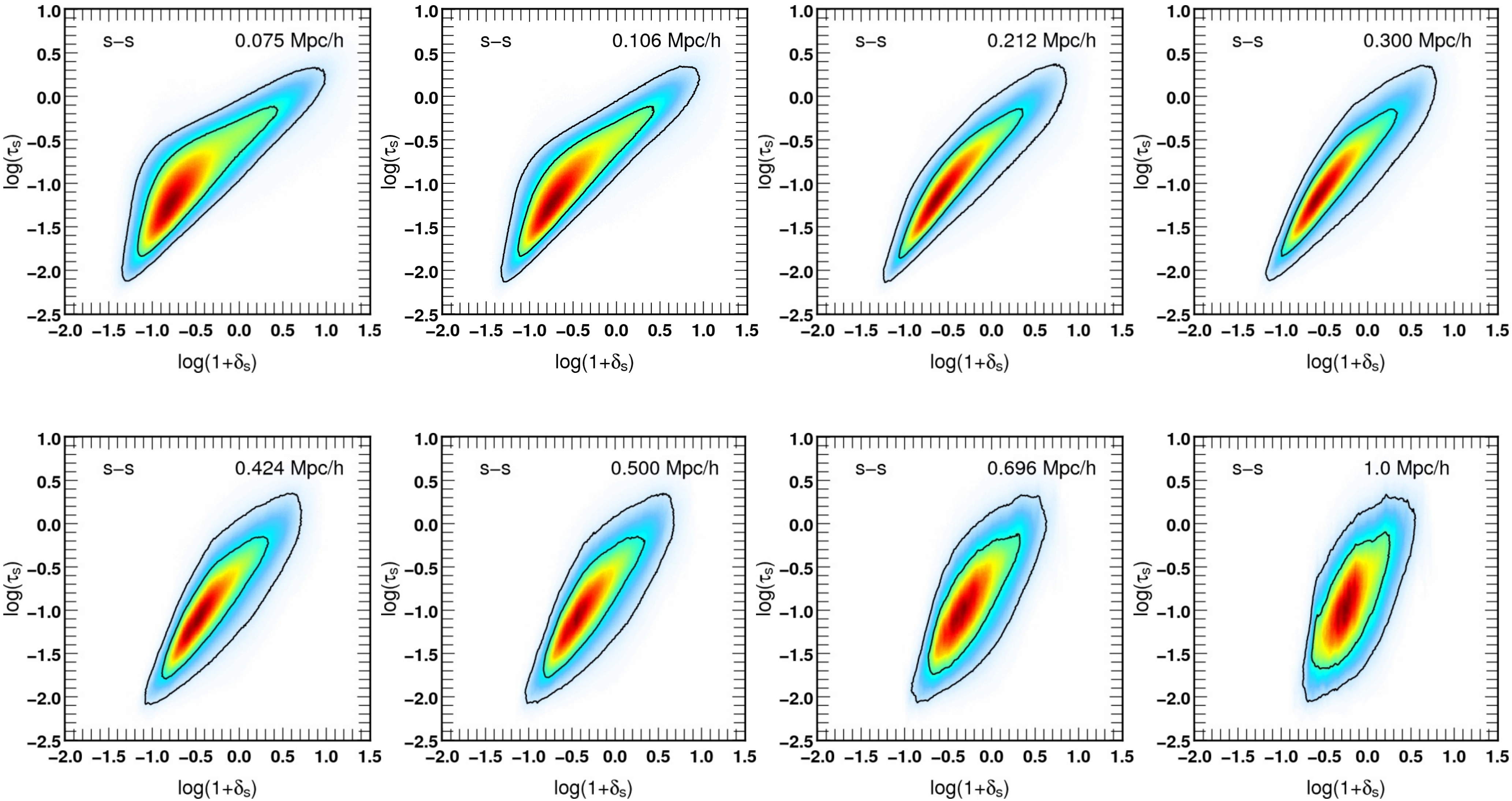
Ex:





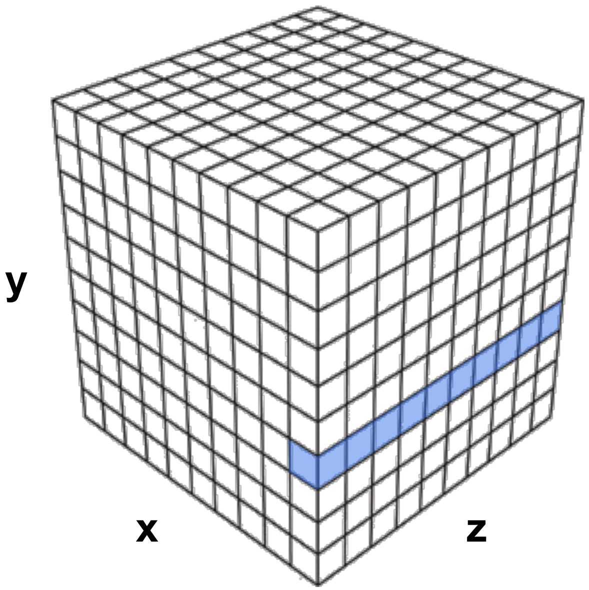
Predicting conditional Flux distributions

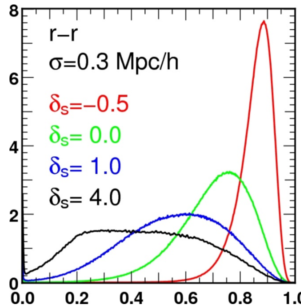
Redshift-space



Probabilistic mapping

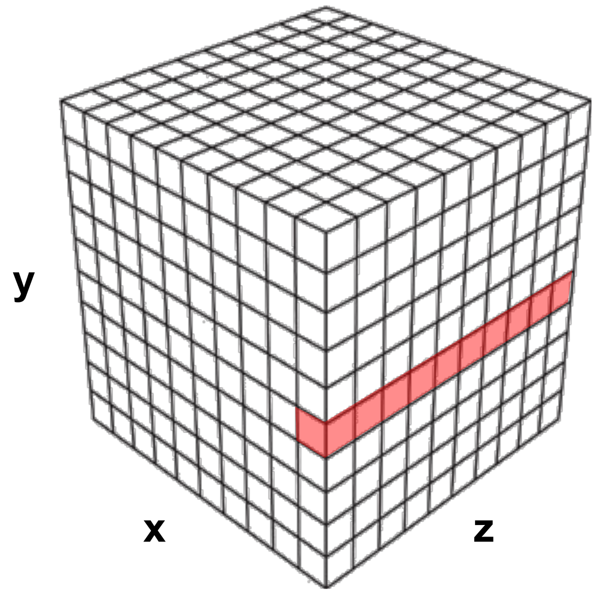
Grid of DM density contrast $1+\delta_s$
1024^3 pixels

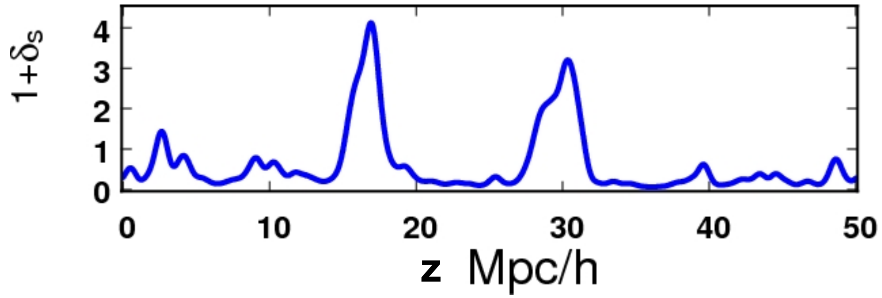


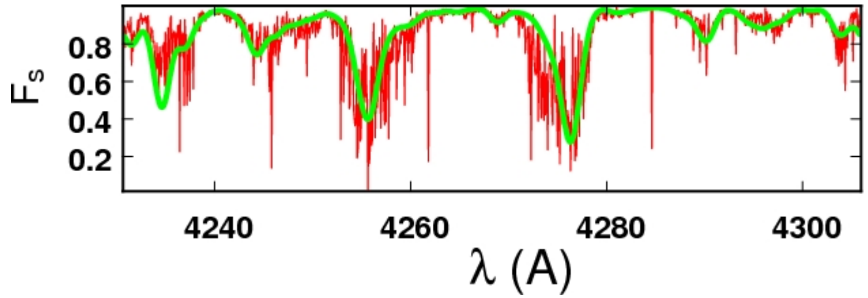


$$P\left(F_s \middle| 1+\delta_s\right)$$

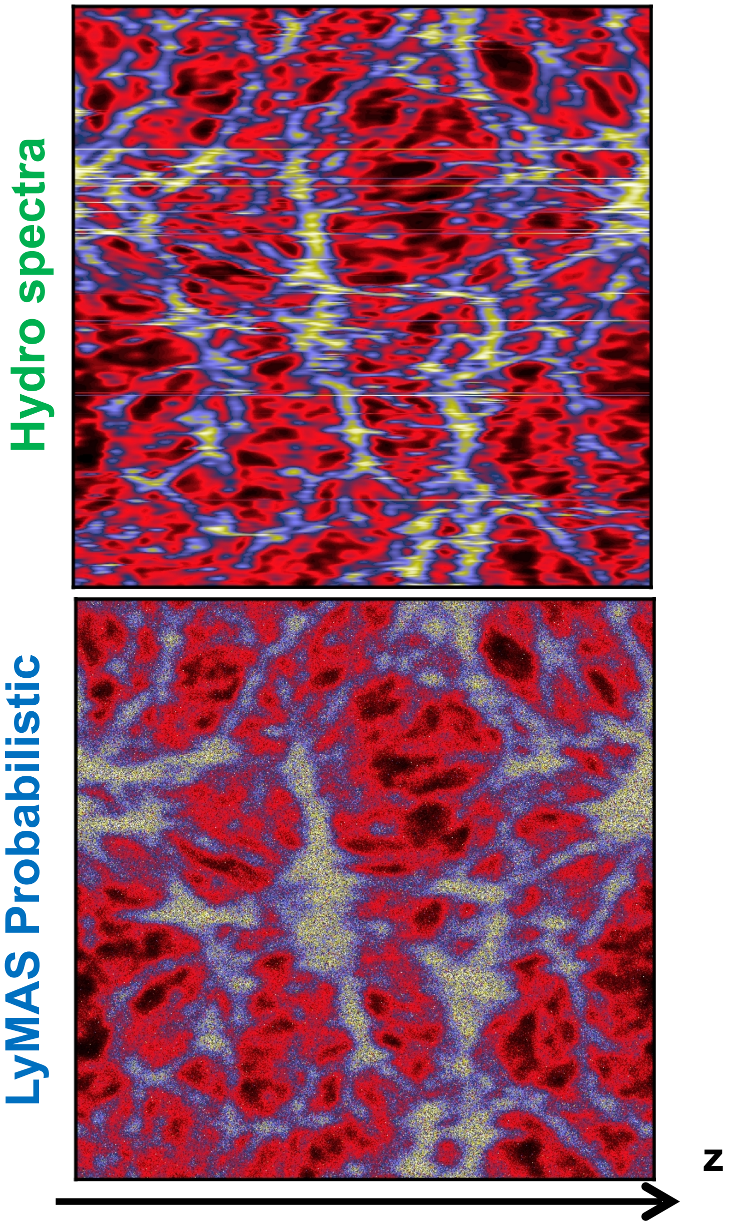
Grid of predicted transmitted flux F_s
1024^3 pixels

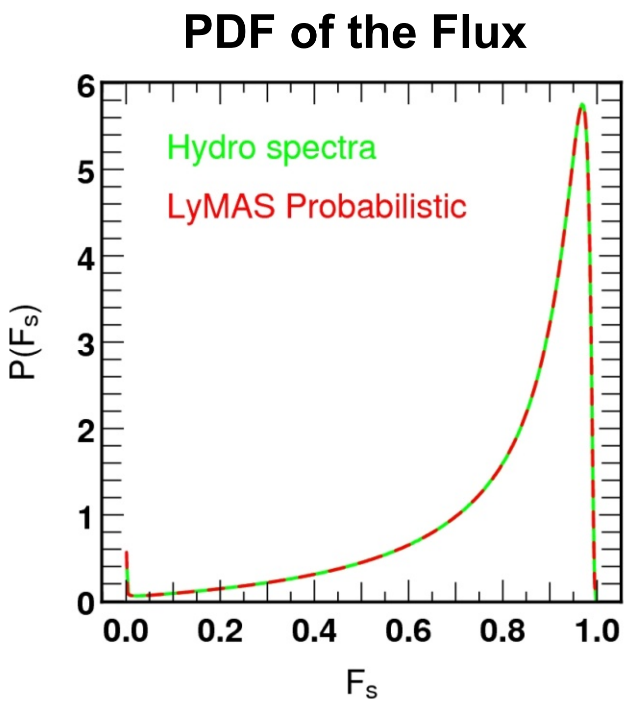


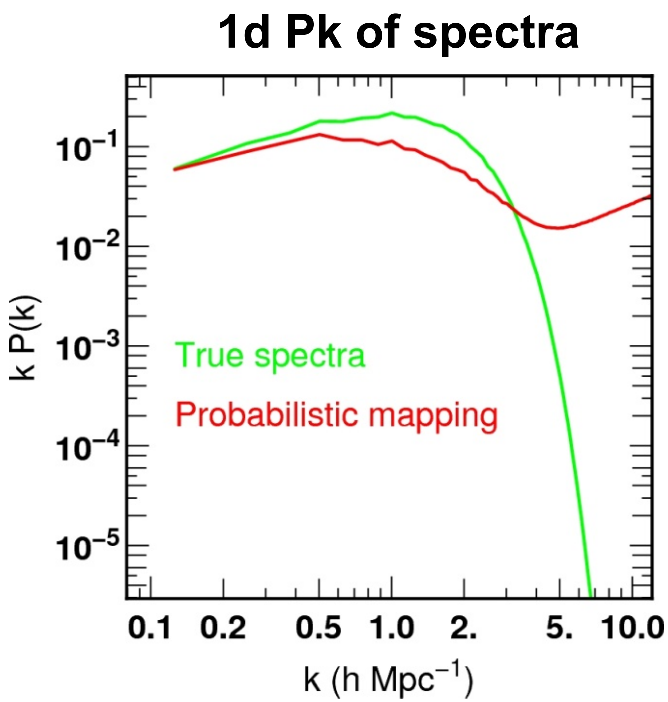


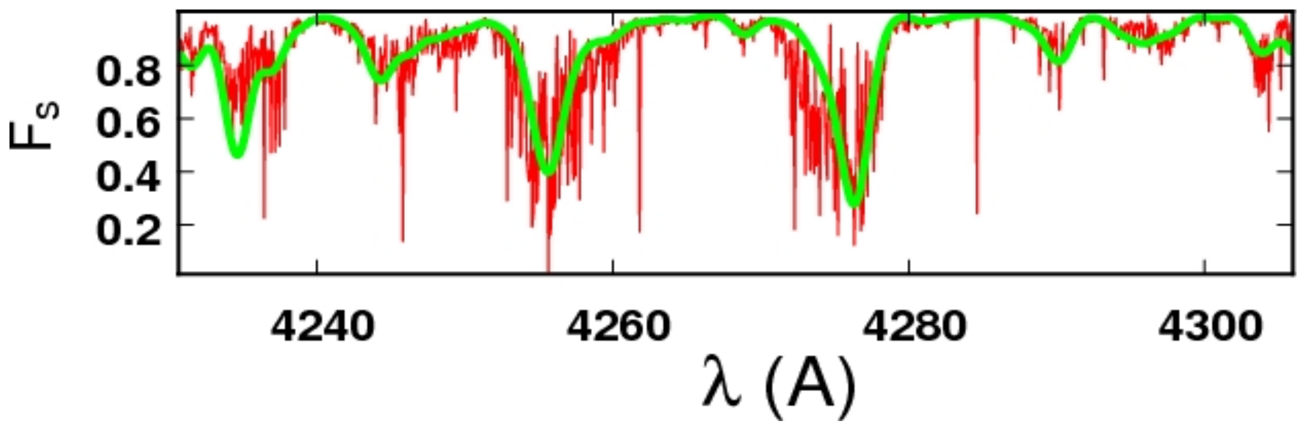


Probabilistic mapping

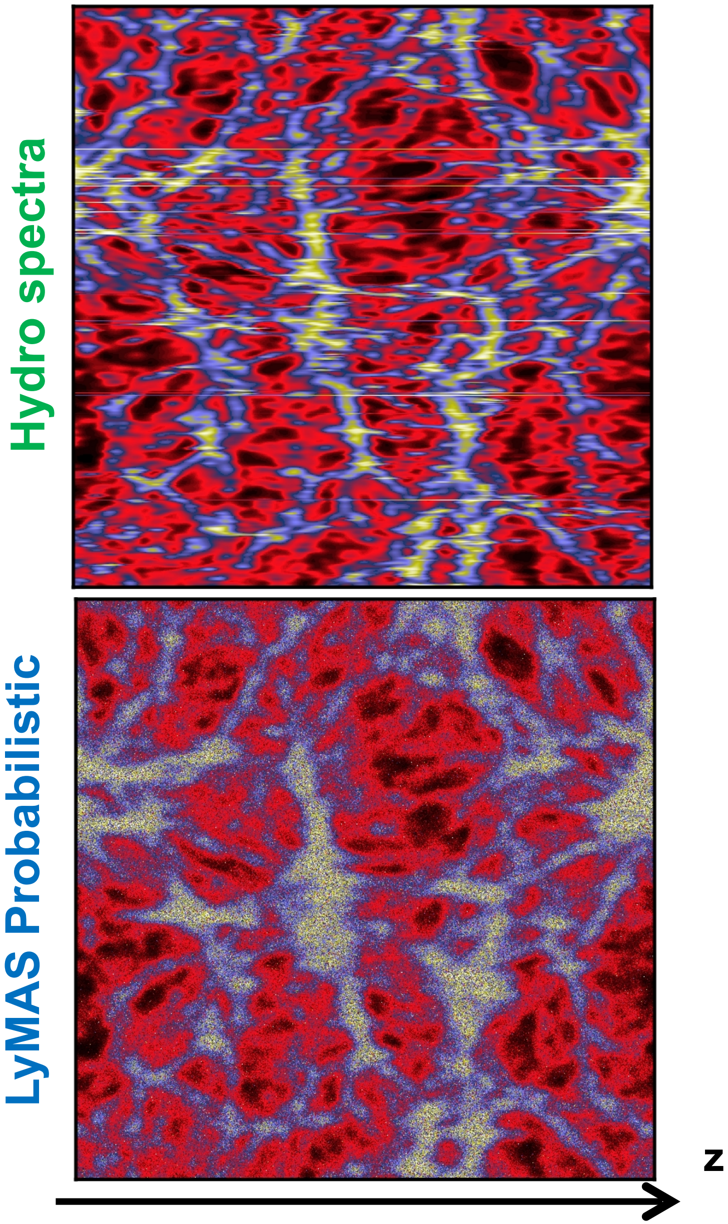


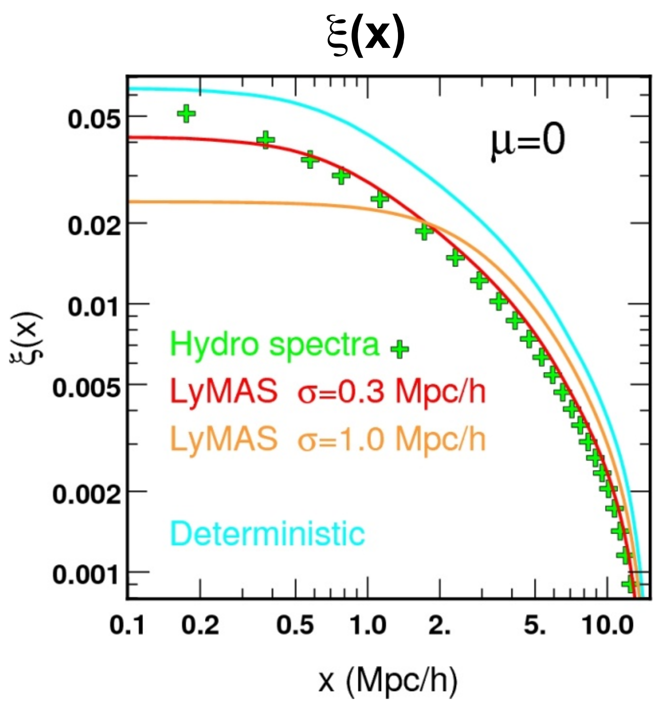


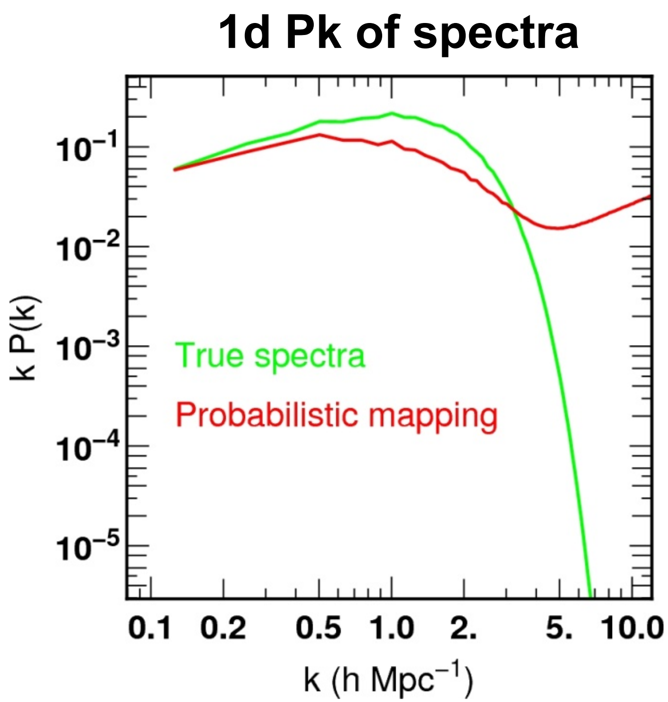


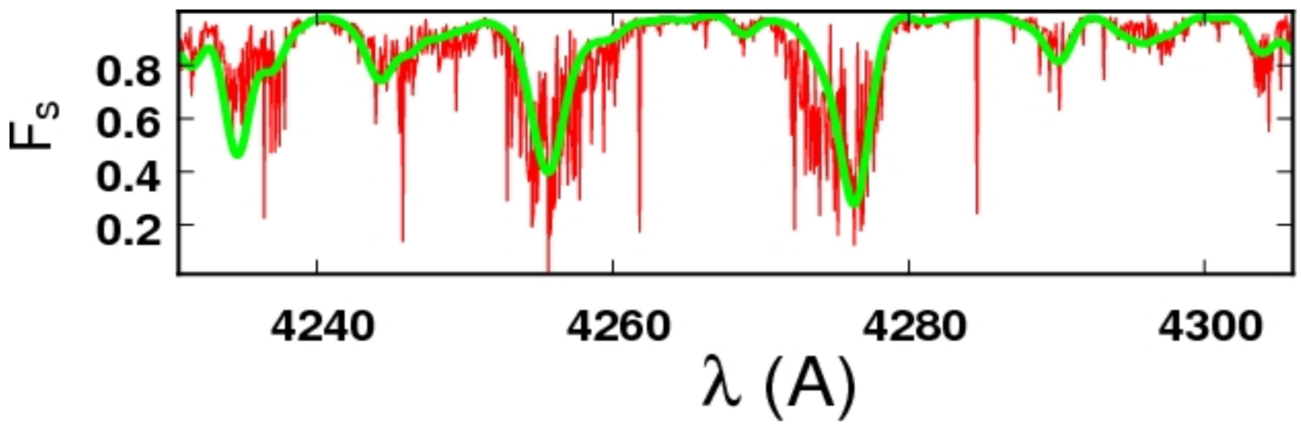


Probabilistic mapping









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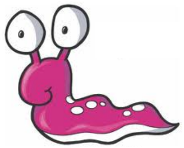
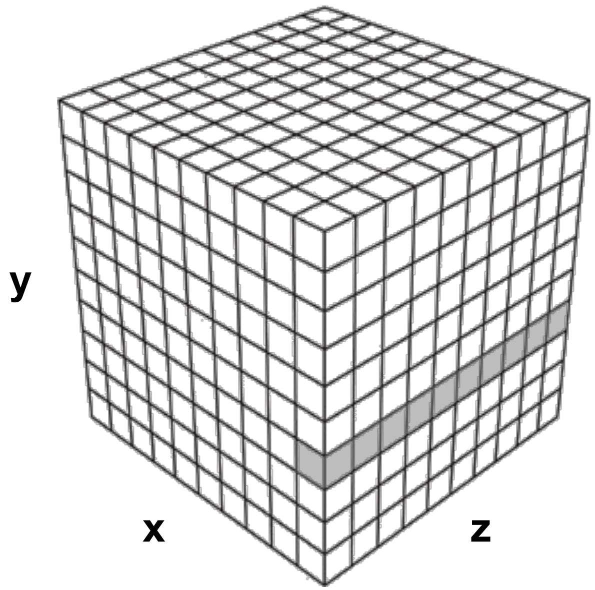
4. LyMAS Probabilistic mapping



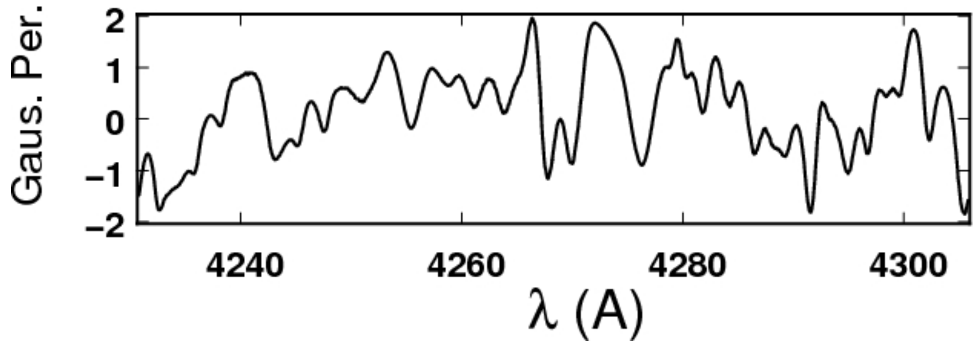
5. LyMAS Coherent mapping
6. Application to large N-body simulations
7. Next

Coherent mapping

1. From each DM skewer Generate 1-d Gaussian field with specific power spectrum



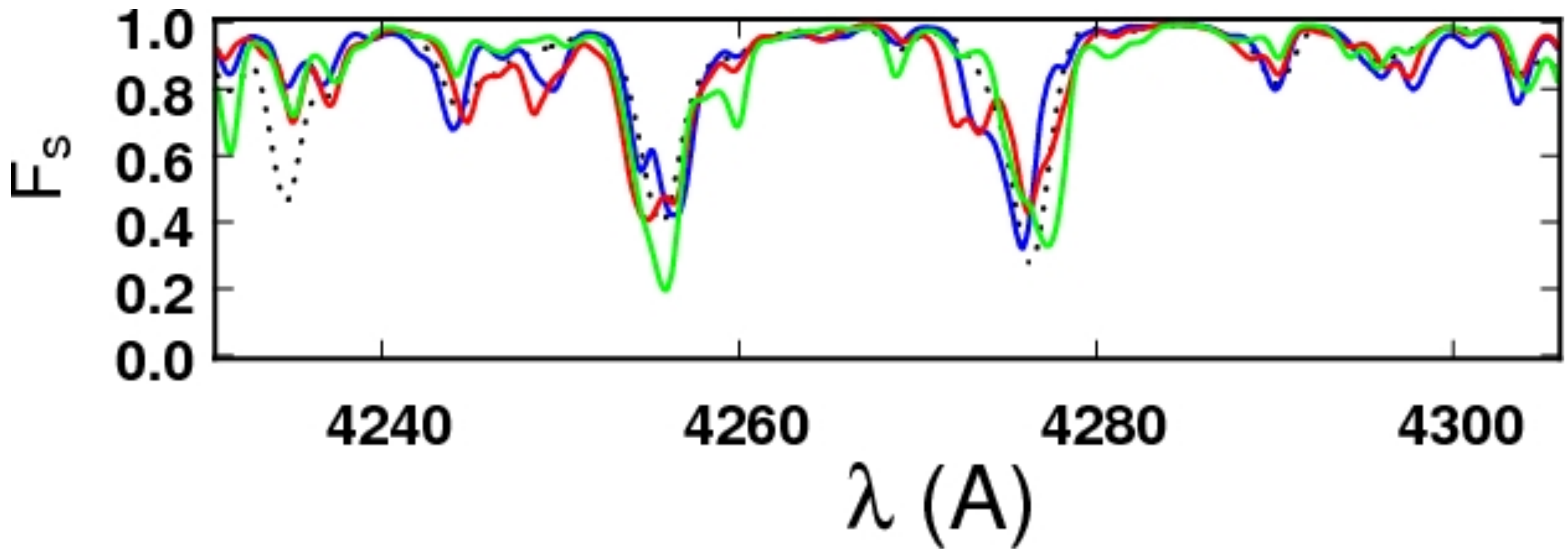
- derived from $P(F_s | 1+\delta_s)$ statistics (Peirani et al. 2014)
- Derived from Wiener filtering + DM velocity field (Peirani et al. in prep)



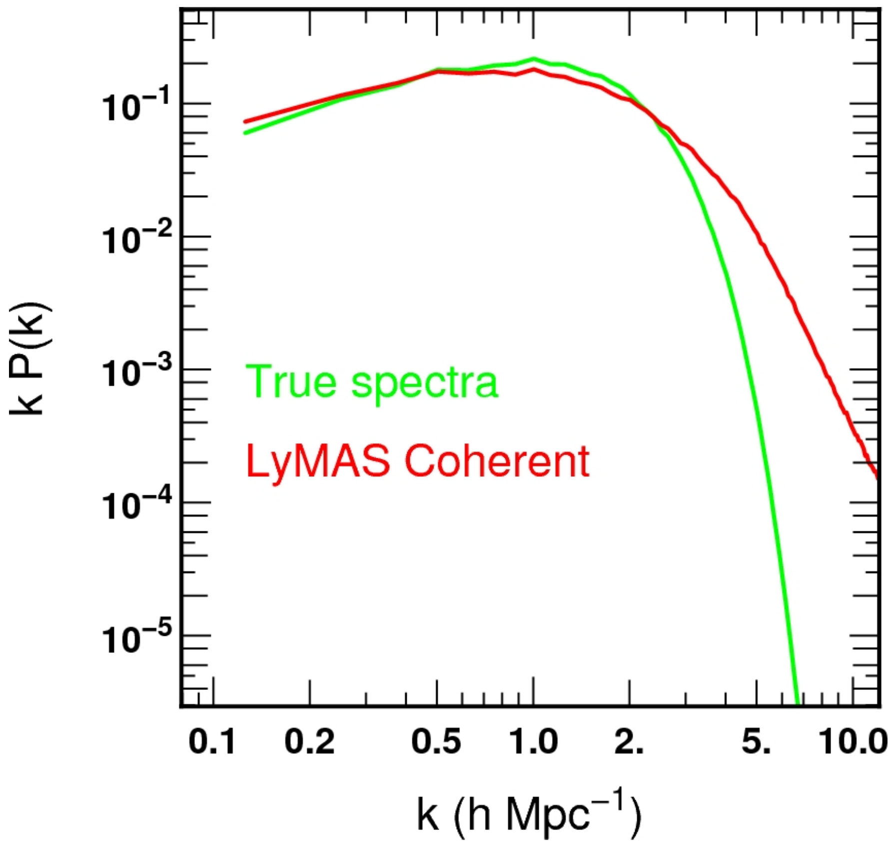
2. One iteration:

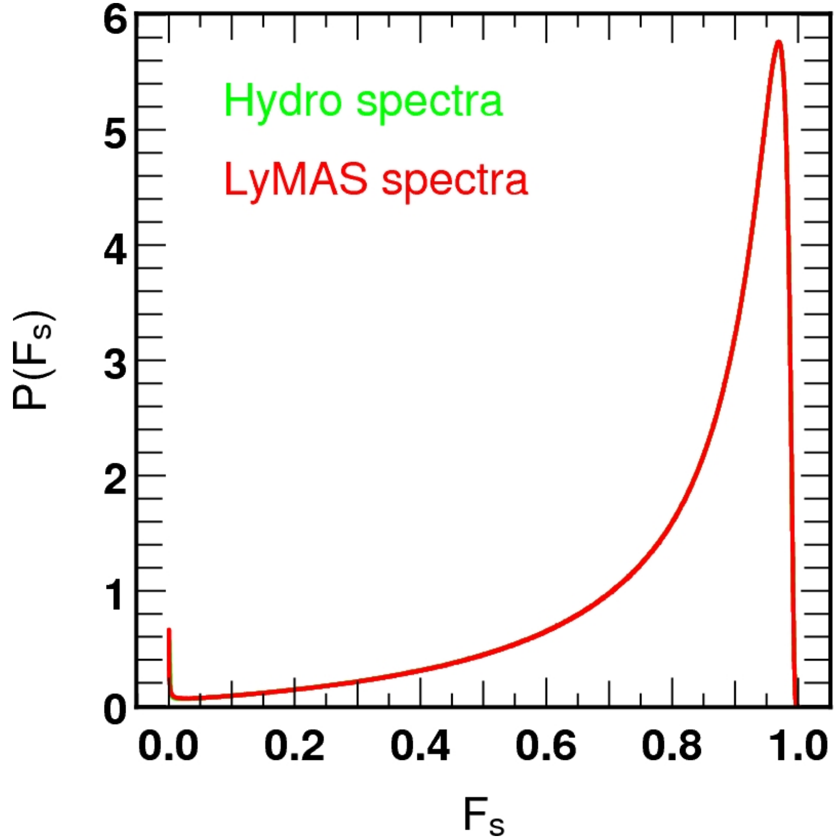
- Pk rescaling: multiply each Fourier components by the ratio $[P_F(k)/P_{PS}(k)]^2$
- Flux rescaling

Coherent mapping

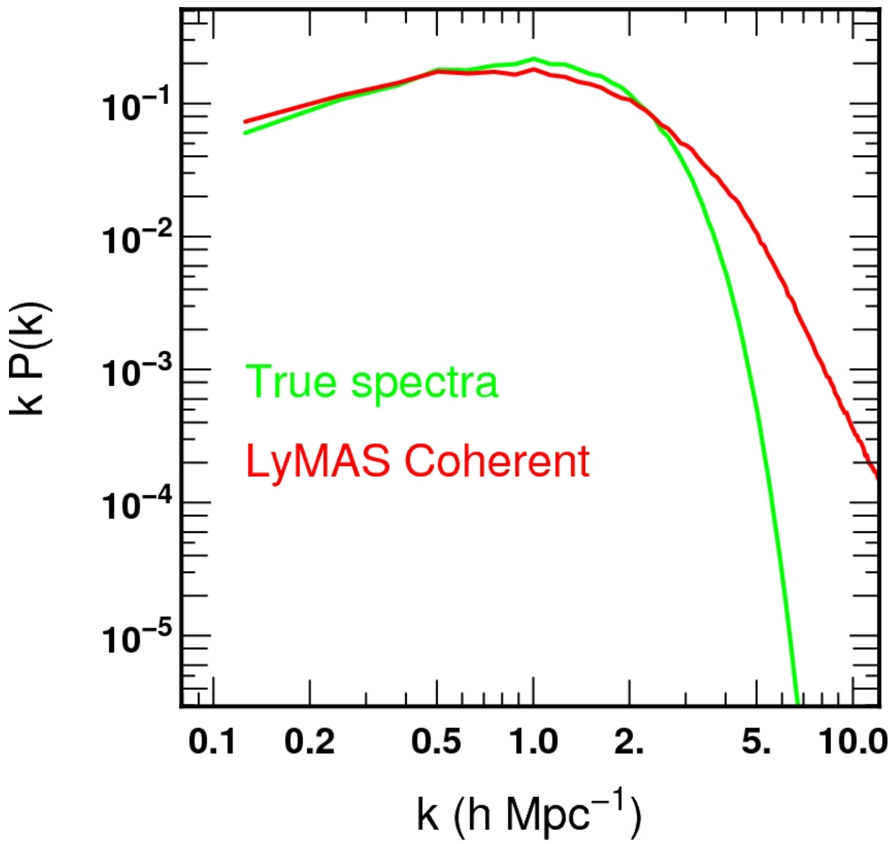


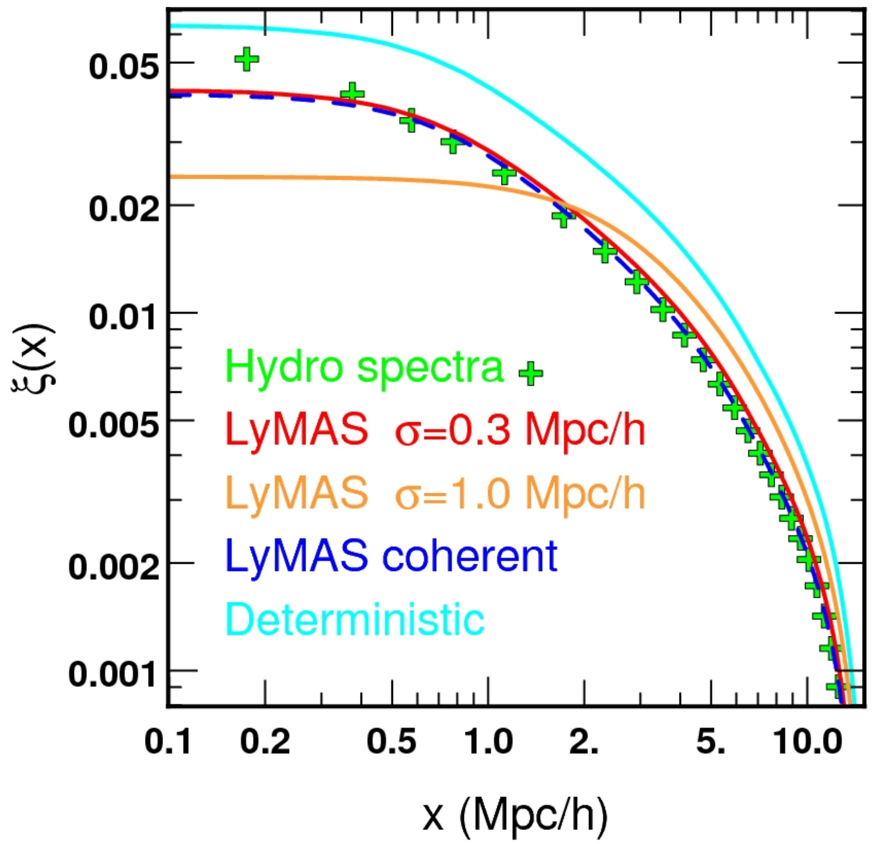
Coherent mapping





Coherent mapping

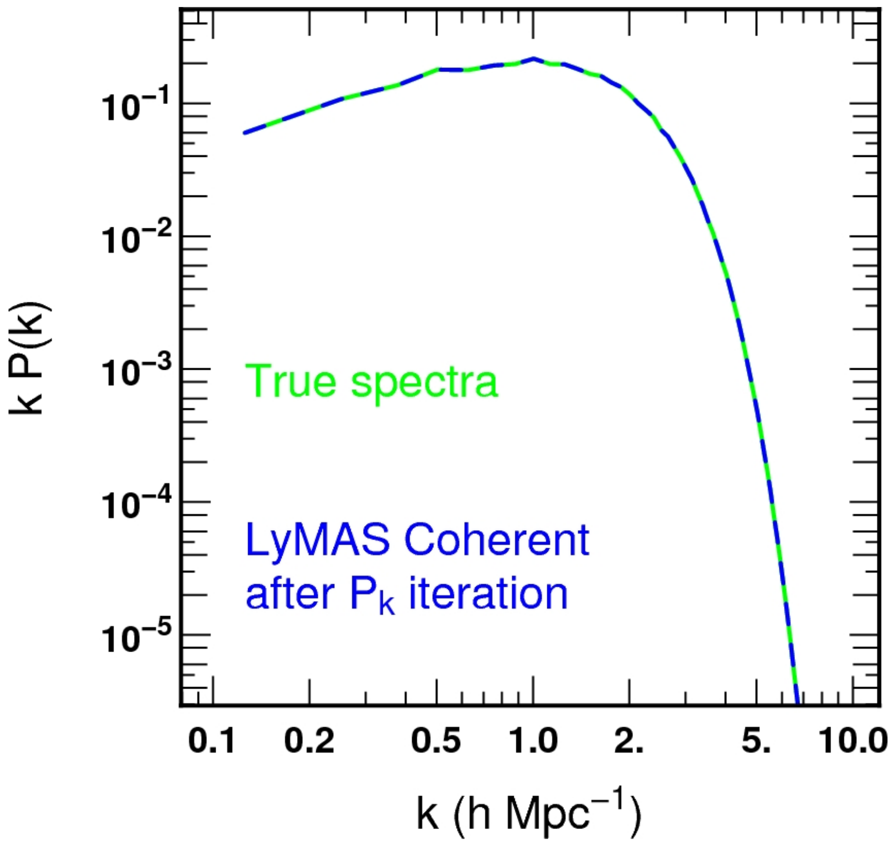


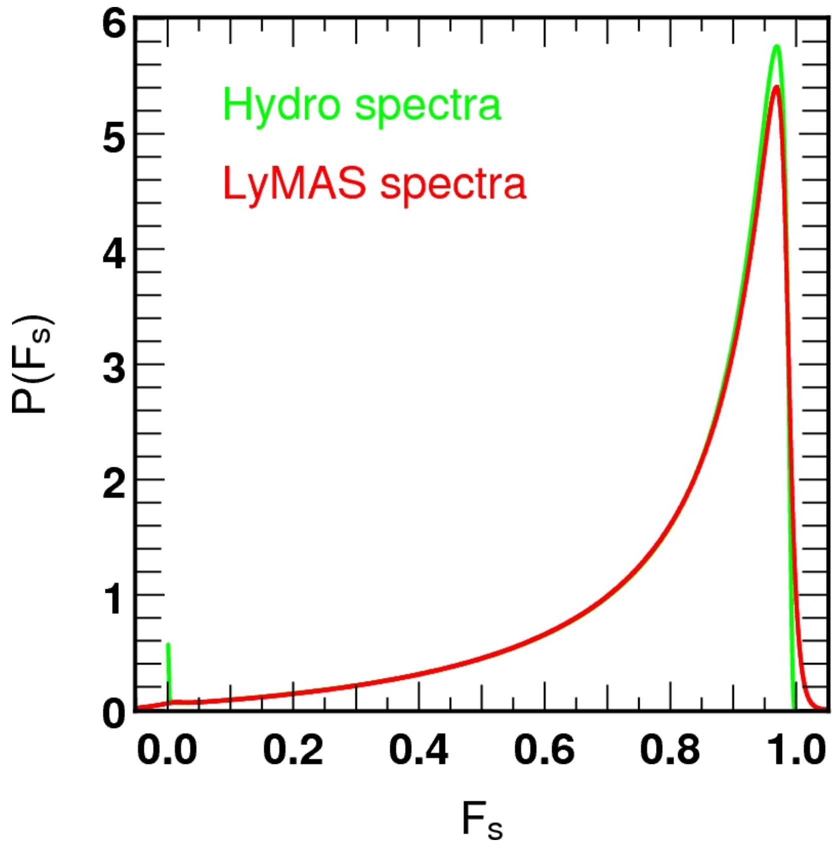


Coherent mapping

4. Iteration on 1d-Pk:

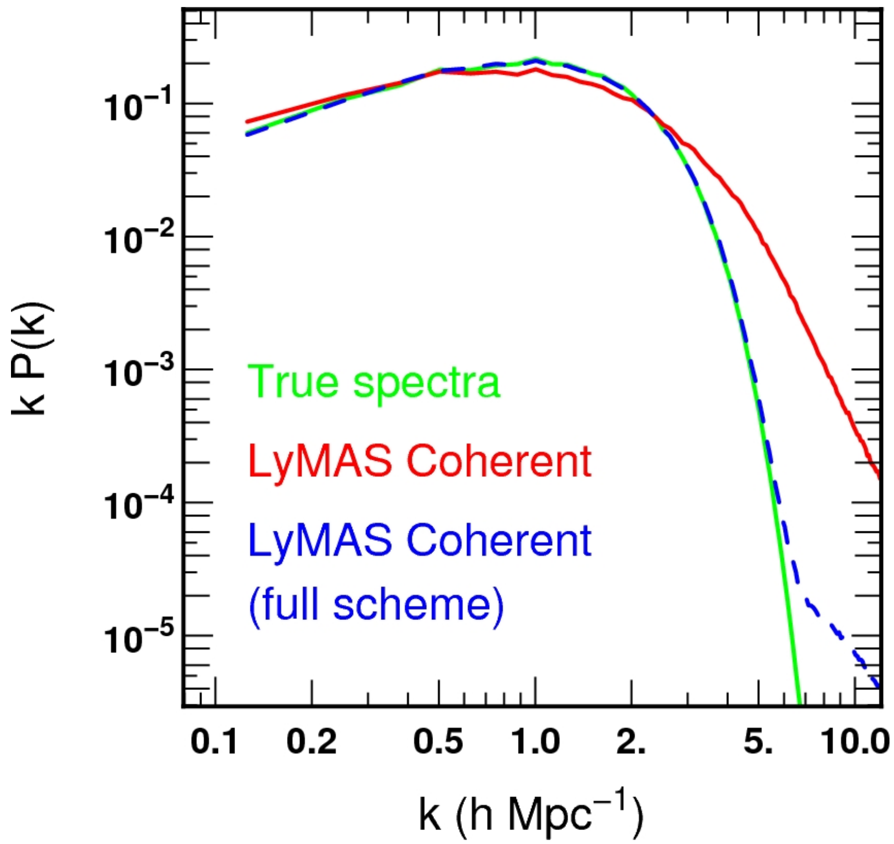
(multiply each Fourier components by the ratio $[P_F(k)/P_{PS}(k)]^2$)

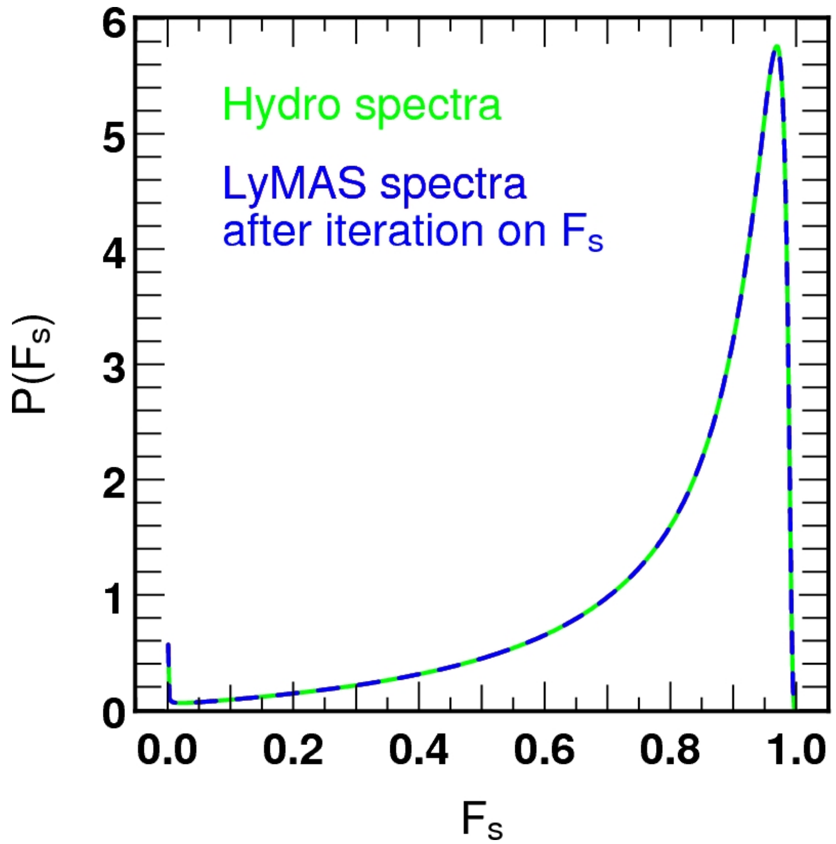




Coherent mapping

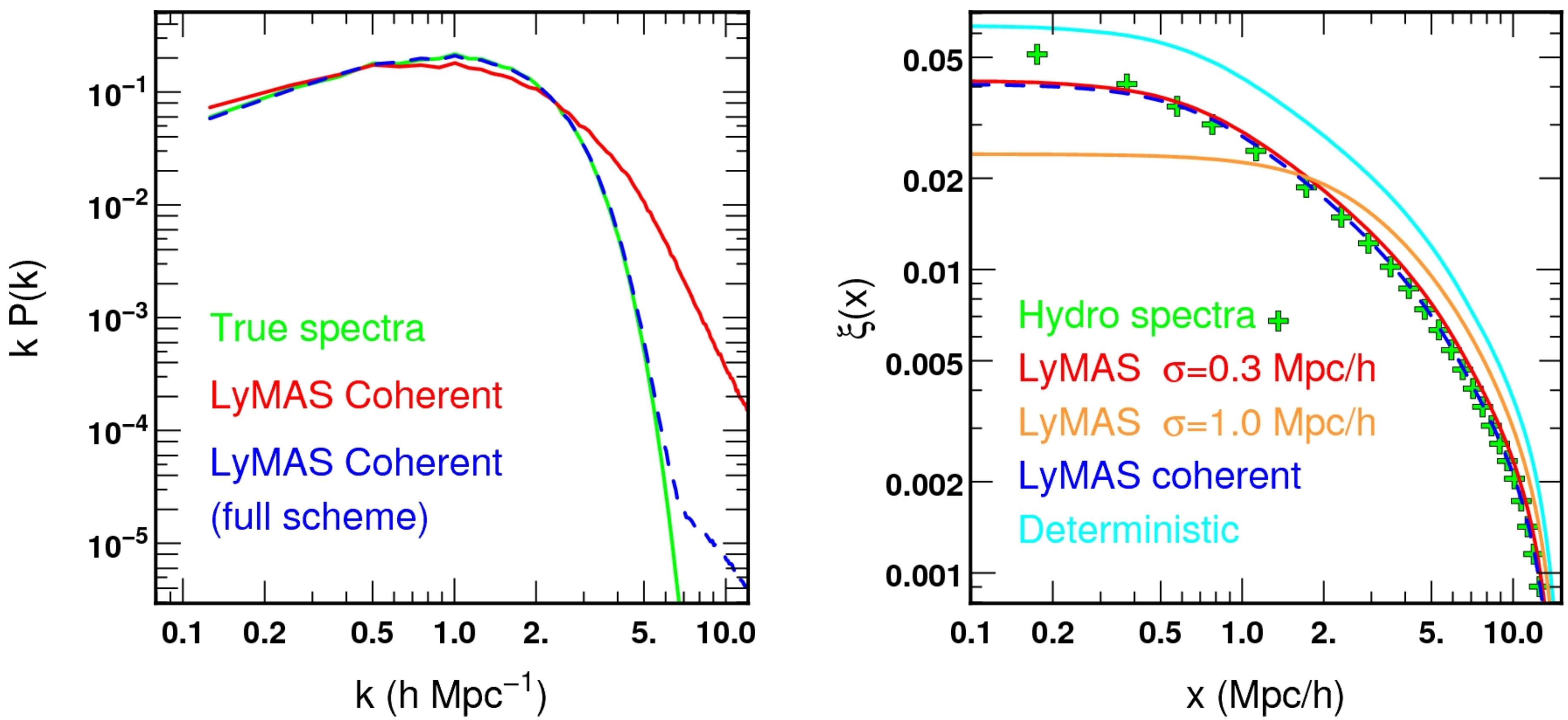
4. Iteration on F_s:





Coherent mapping

4. Iteration on F_s:



Mapping

Hydro Spectra F_s

1d P_k

PDF(F_s)

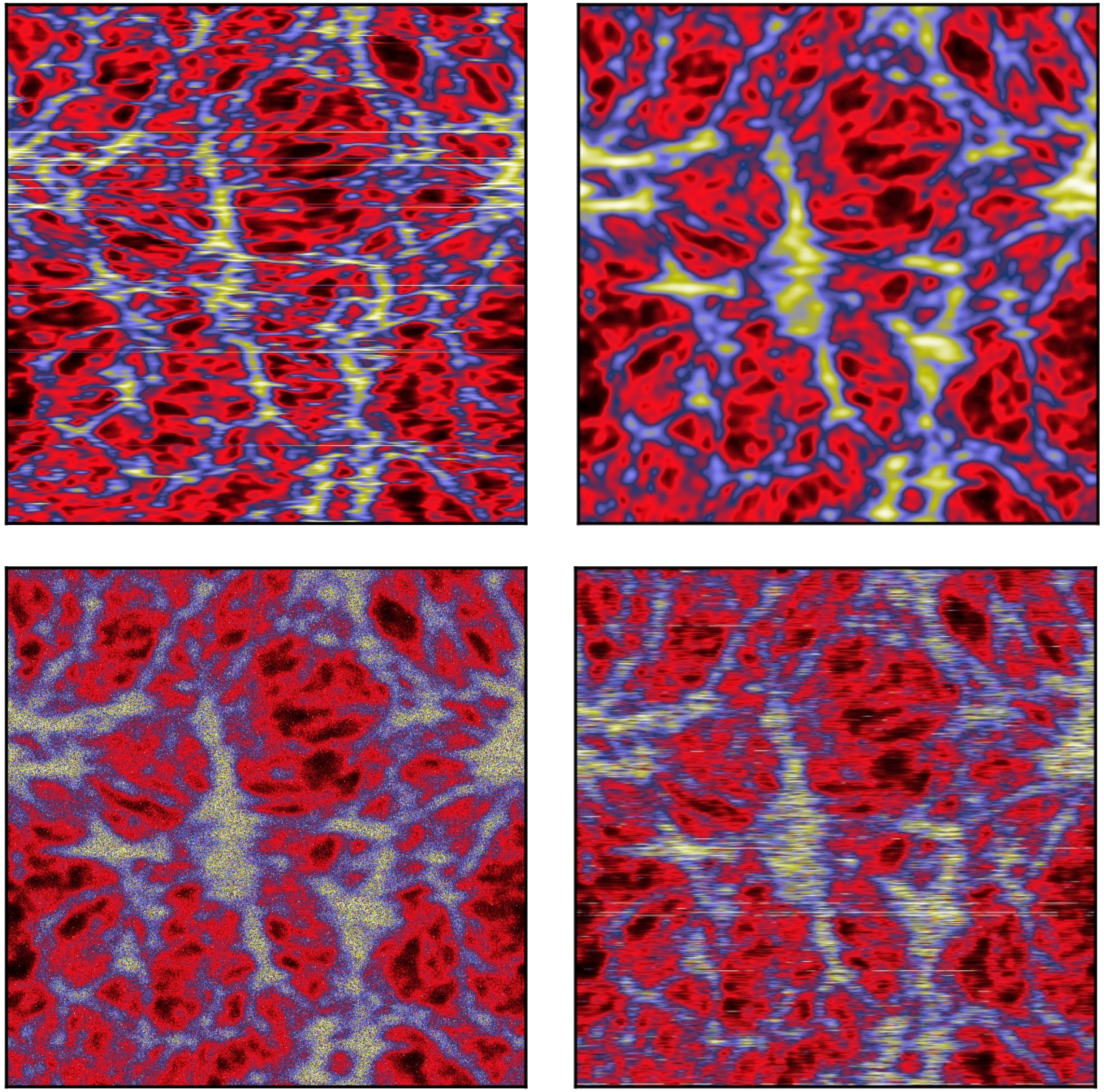
ξ(x)

Deterministic mapping

~~1d P_k~~

PDF(F_s)

~~ξ(x)~~



LyMAS probabilistics

~~1d P_k~~

PDF(F_s)

ξ(x)

LyMAS coherent

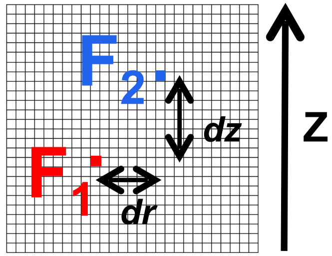
1d P_k

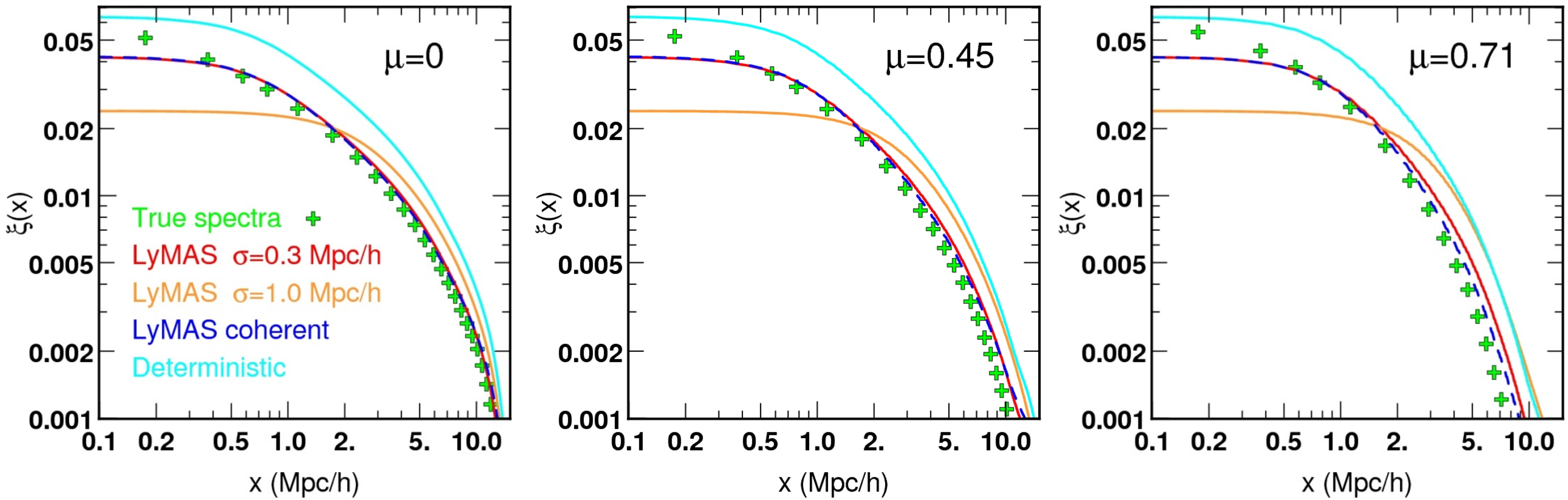
PDF(F_s)

ξ(x)

Correlation function

$$\zeta = \frac{\langle F_1(r,z)F_2(r+dr,z+dz)\rangle}{\langle F\rangle^2} - 1$$

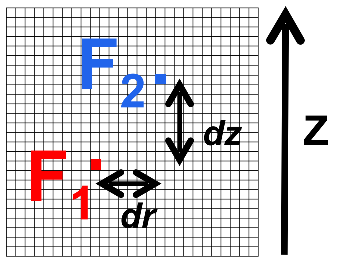


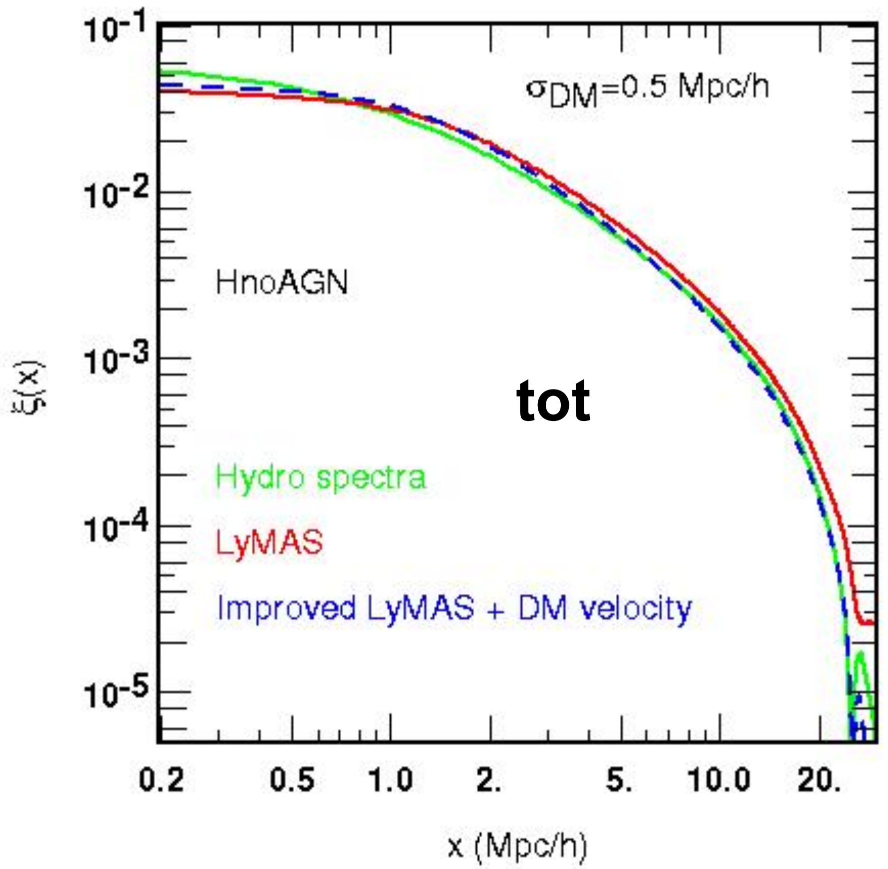


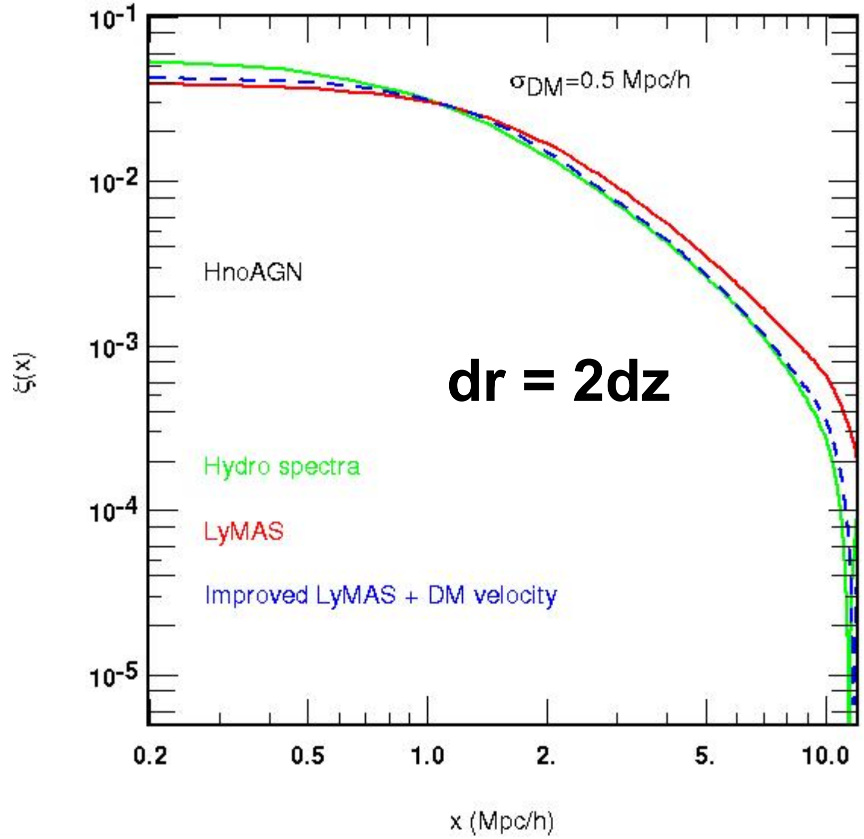
$dz = 0$ $\qquad dr = 0.5dz$ $\qquad dr = dz$

What's next?

1) Improved mocks (Peirani et al. 2020 in prep)

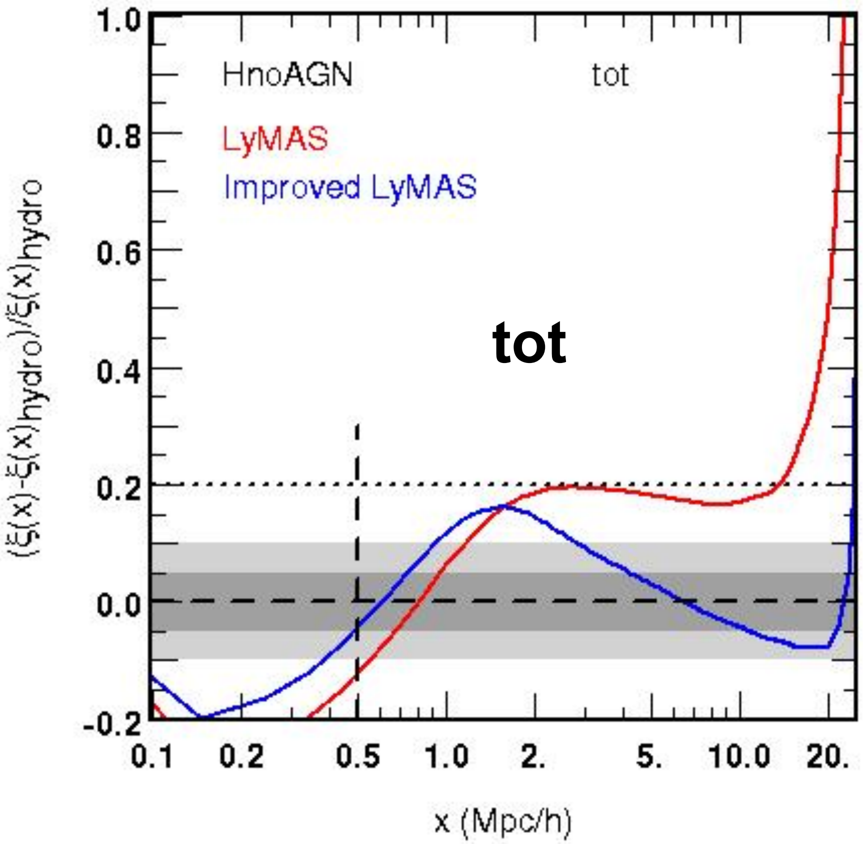


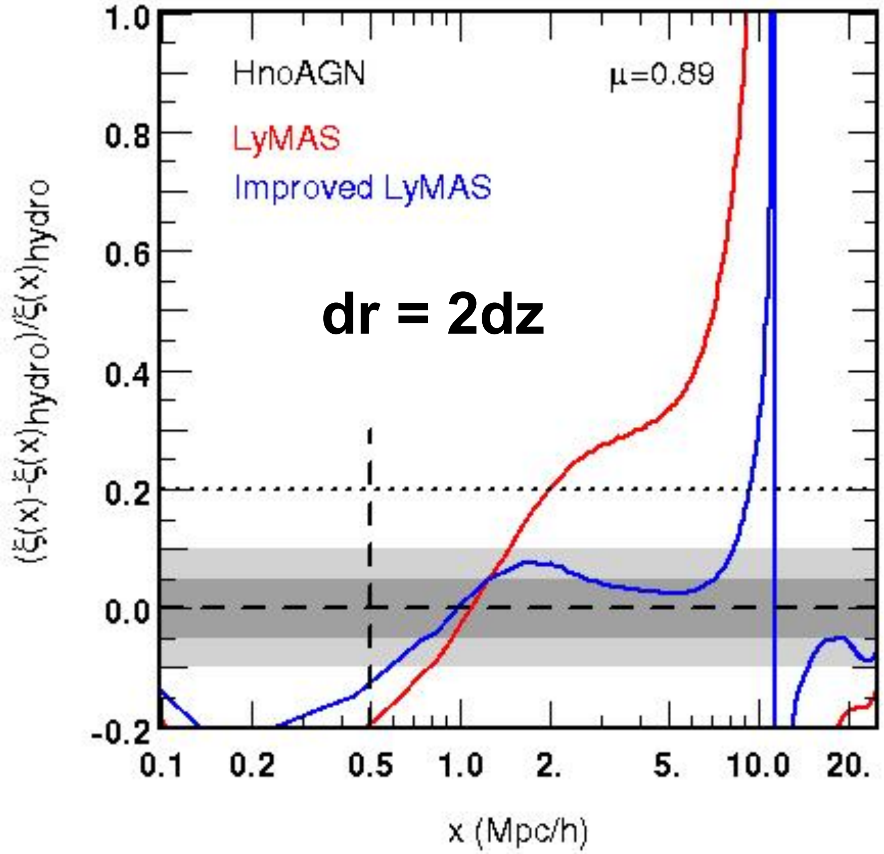




What's next?

1) Improved mocks (Peirani et al. 2020 in prep)





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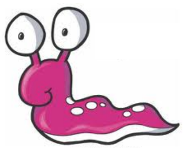


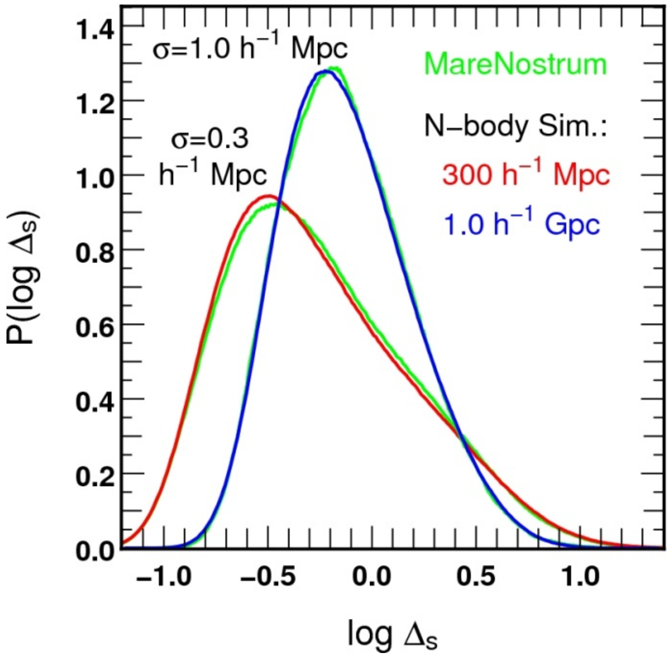
6. Application to large N-body simulations
7. Next

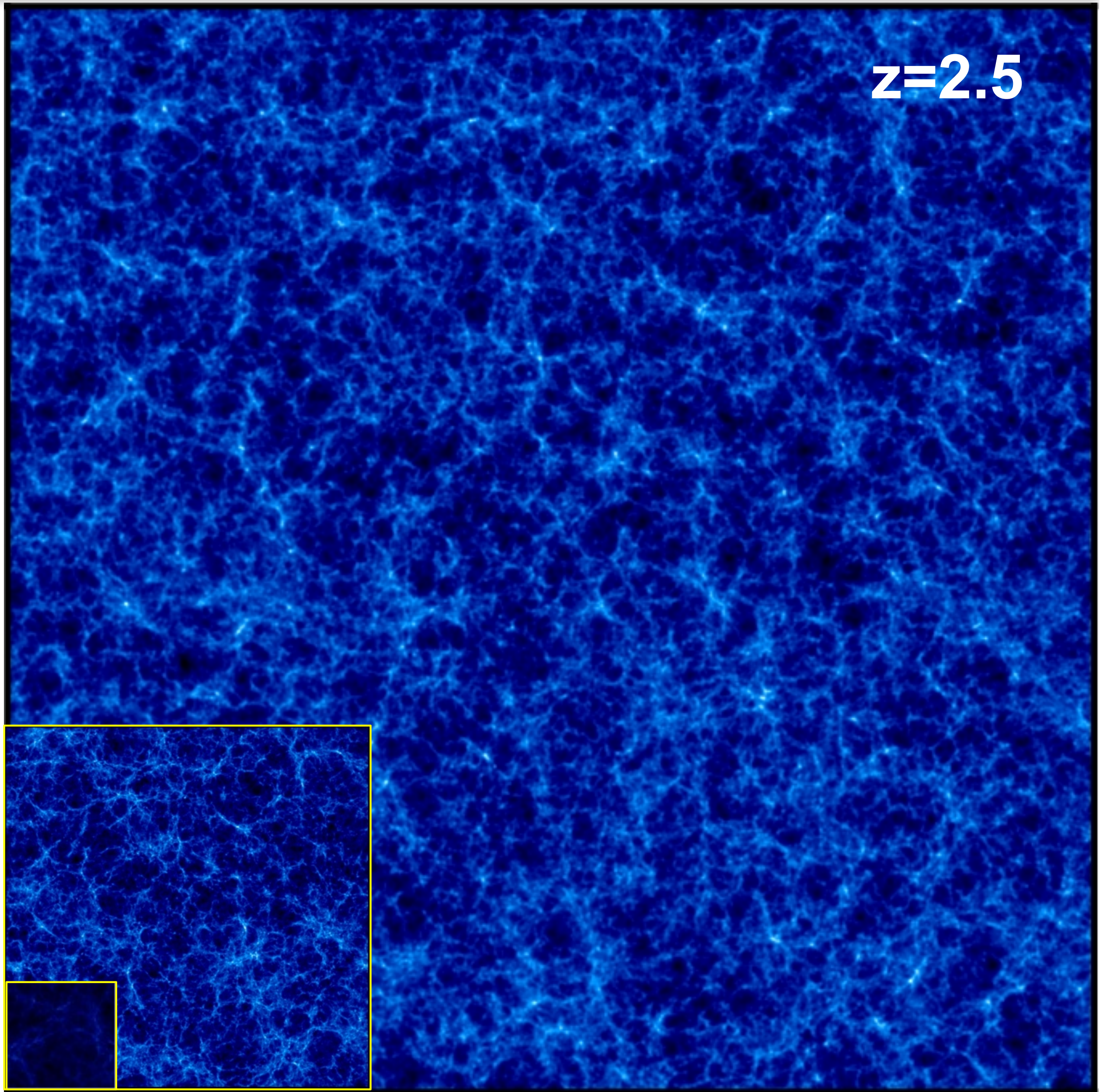
Application to large cosmological DM simulations

Gadget2 (Springel 2005)

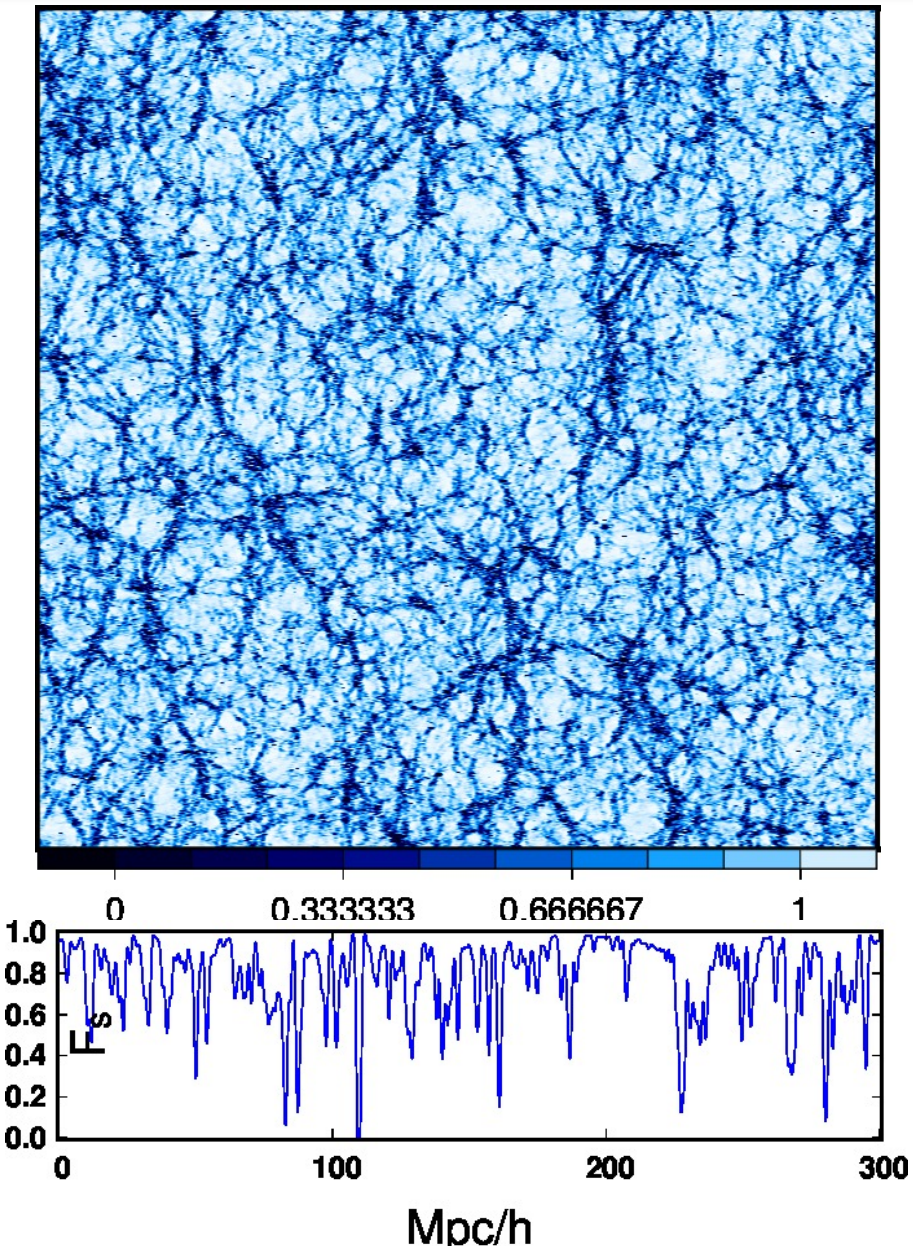
300 Mpc/h - 2048^3 particles - WMAP7 cosmology σ_{DM}=0.3 Mpc/h

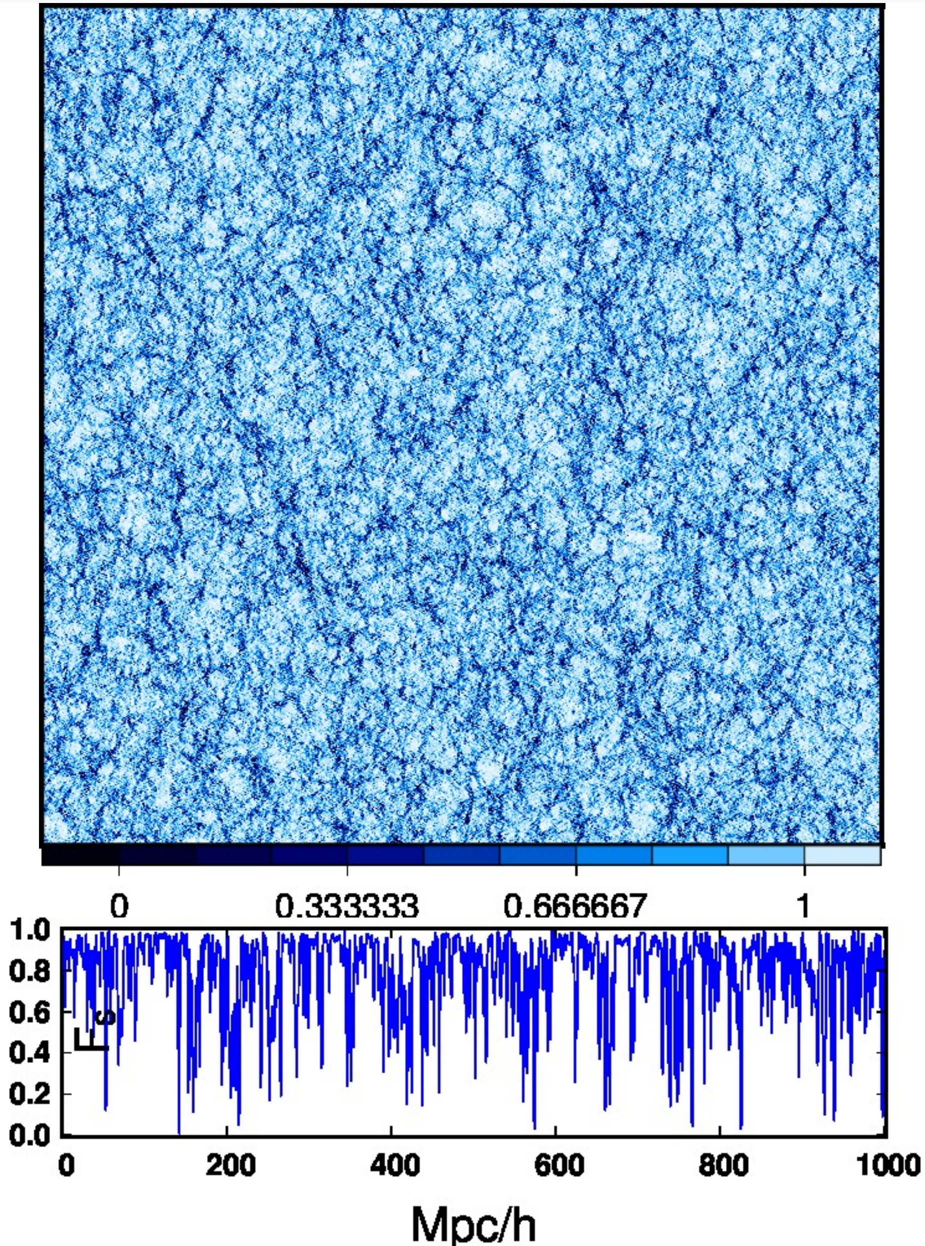
1.0 Gpc/h - 2948^3 particles - WMAP7 cosmology σ_{DM}=1.0 Mpc/h



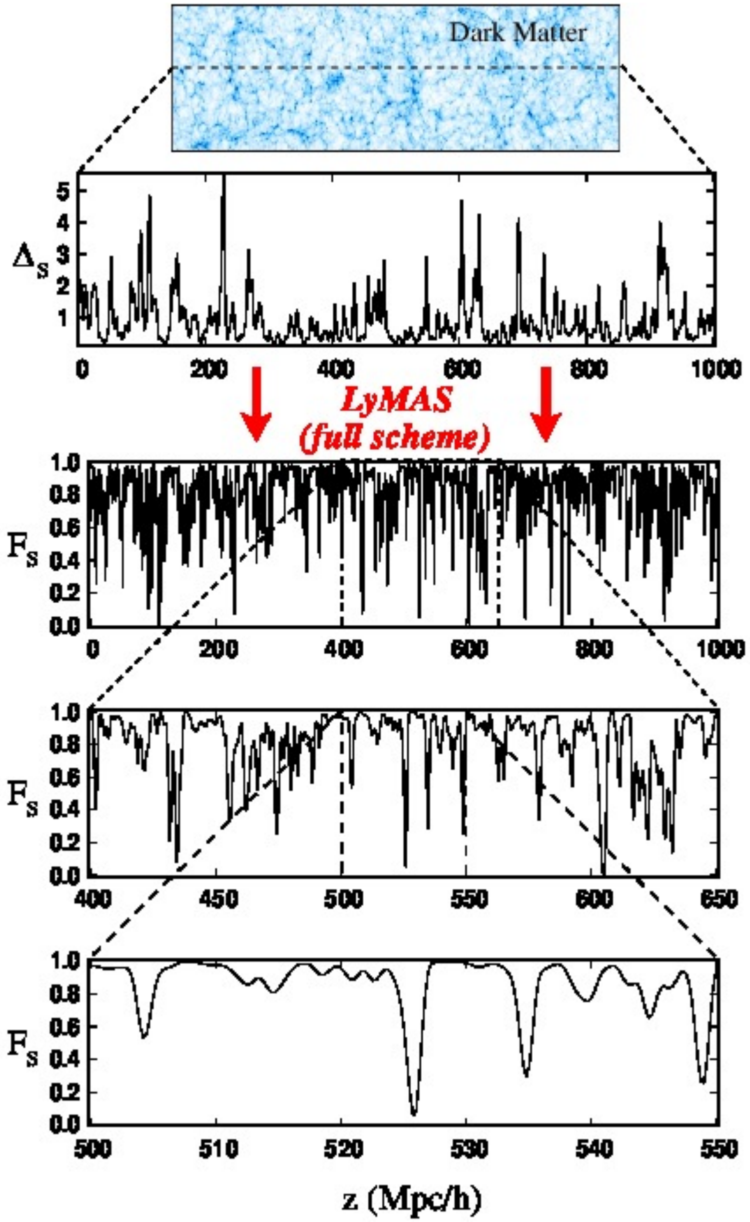


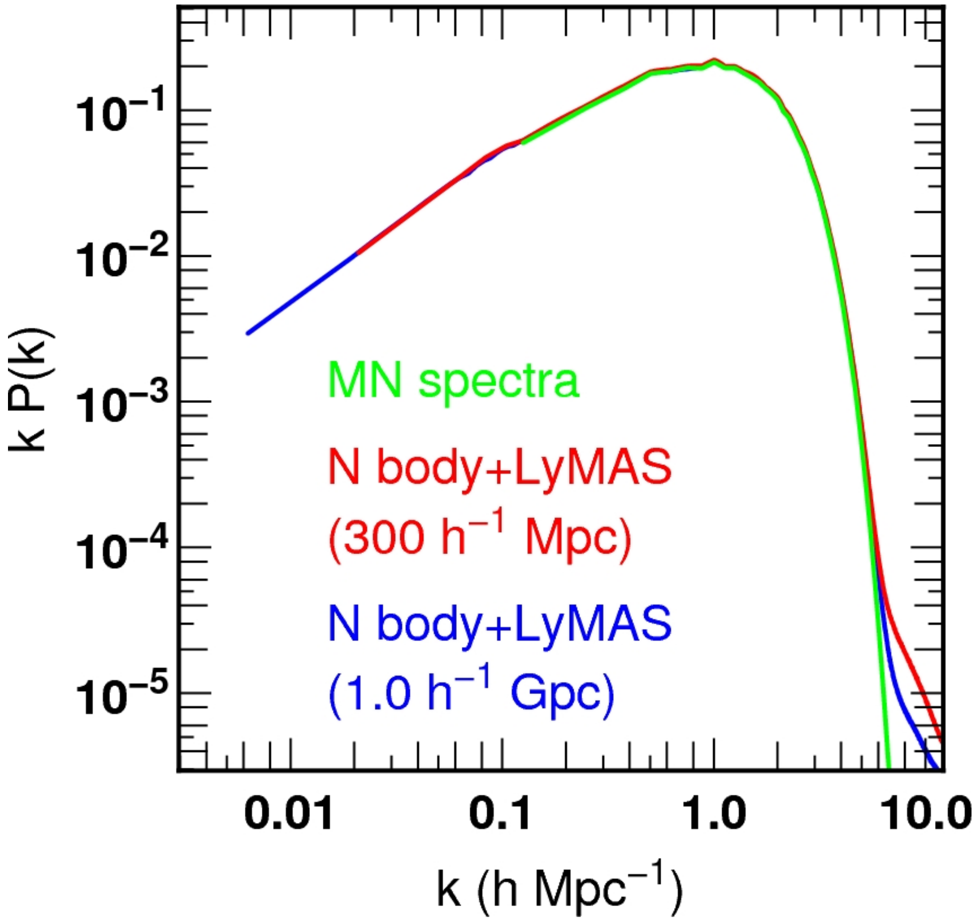
Application to large cosmological DM simulations





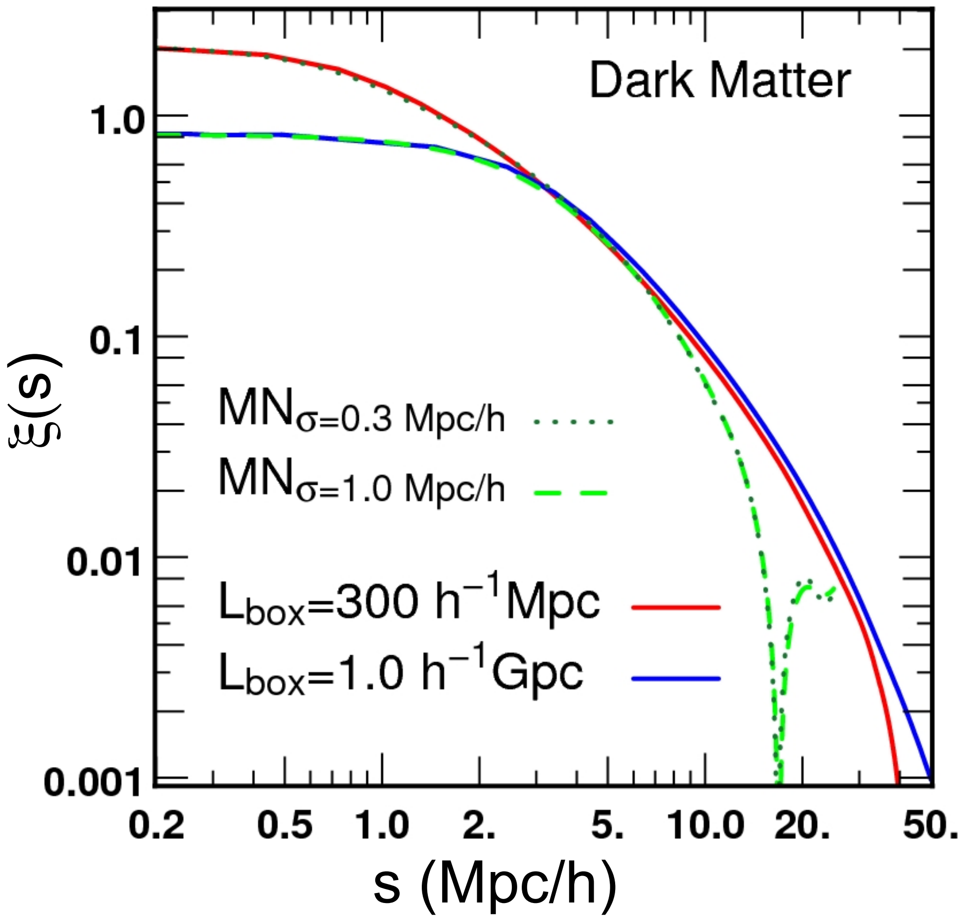
Application to large cosmological DM simulations

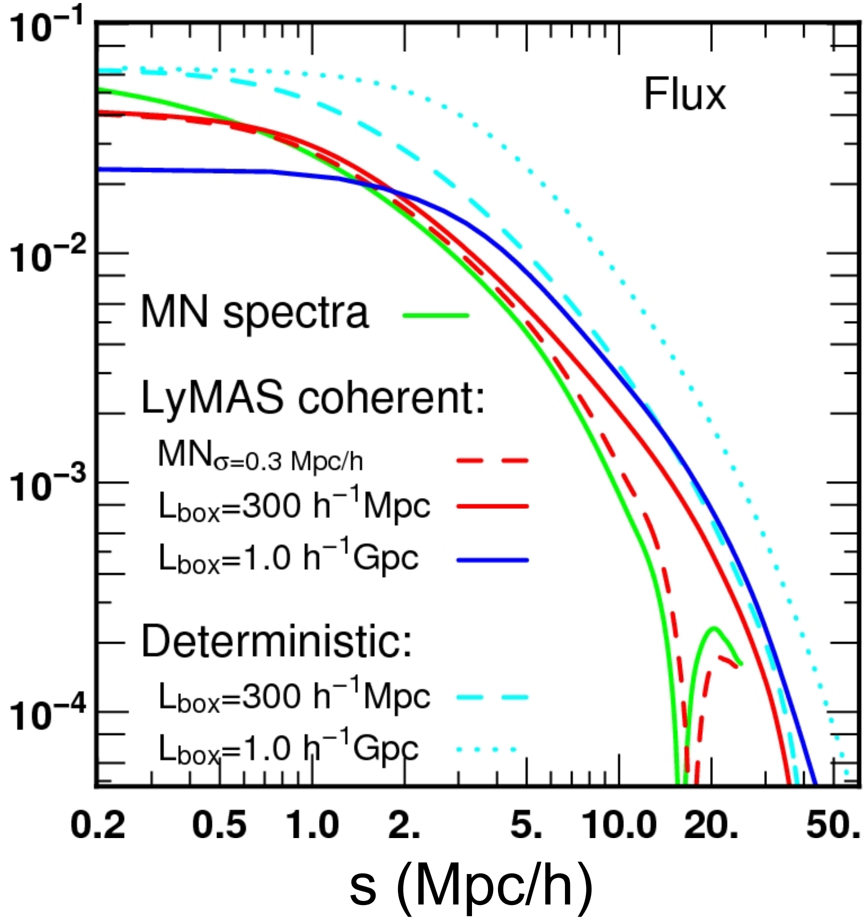




Application to large cosmological DM simulations

Correlation function:

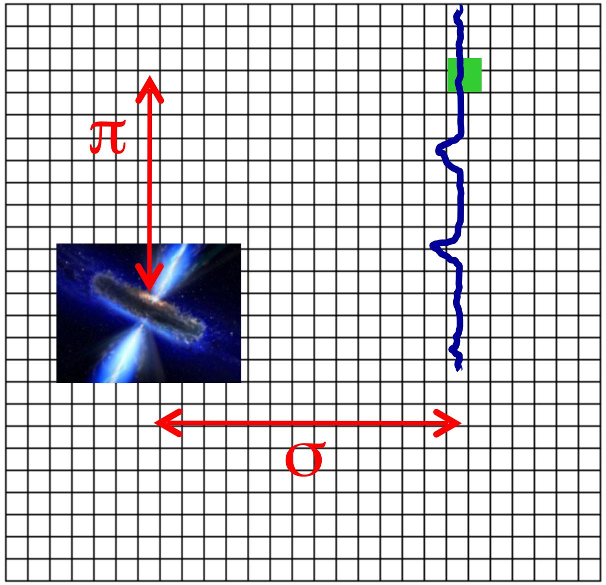




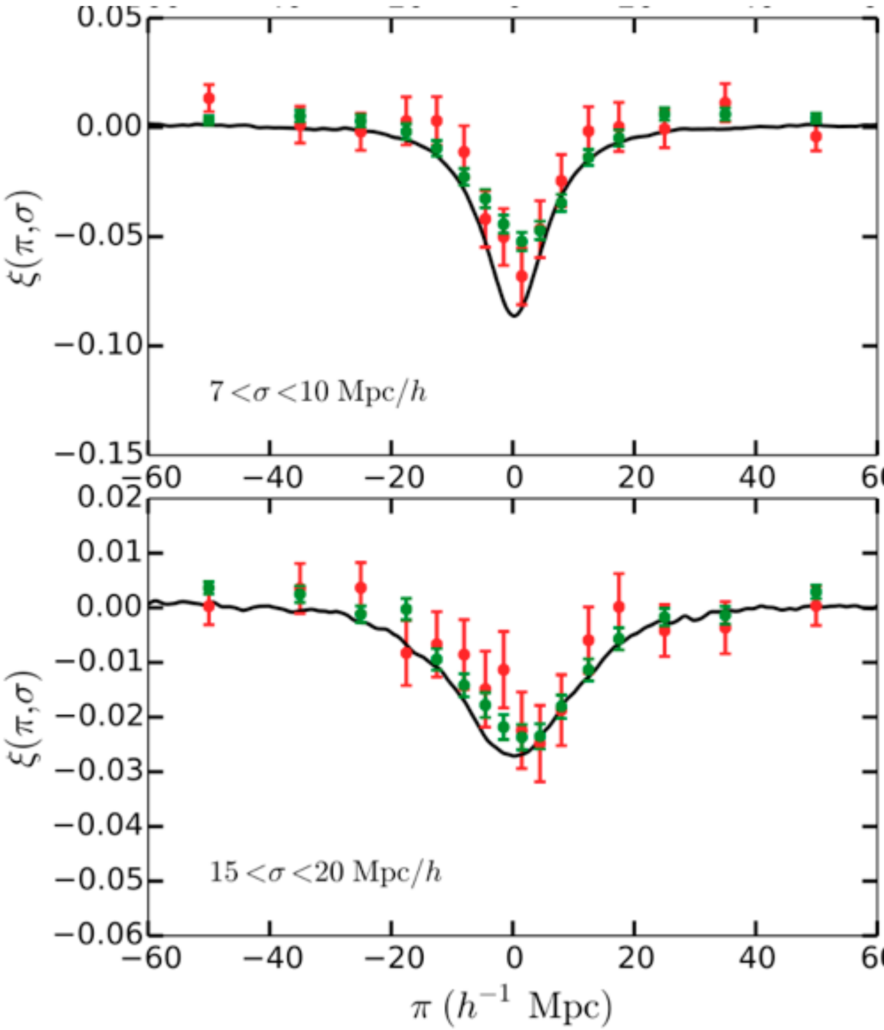
Cross correlation quasar Lyα in BOSS survey

Font-Ribera et al. (2013)

(SDSS DR9)



LyMAS mocks: WMAP7 – 1 Gpc/h – 2048^3 particles – AGN and noAGN



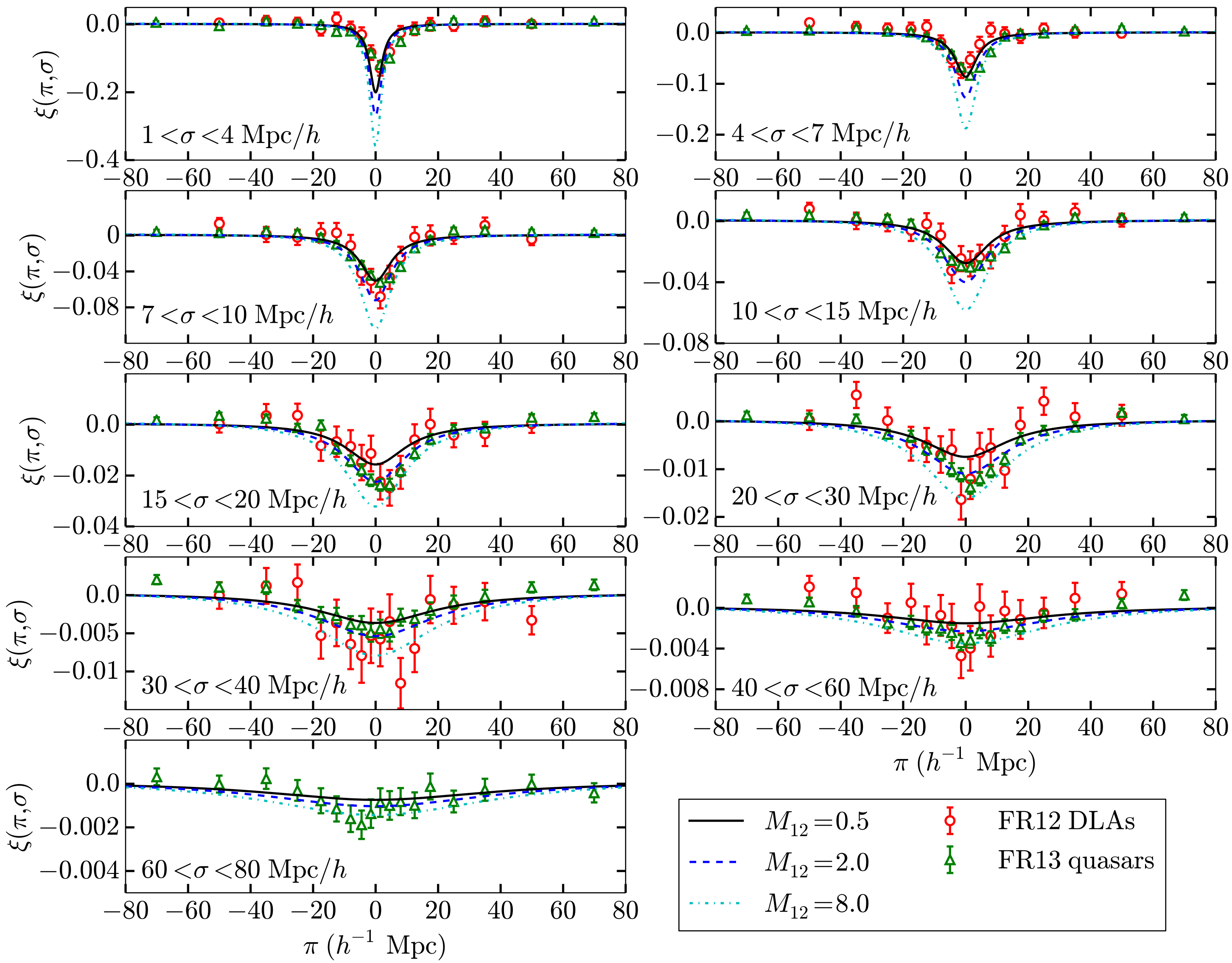
"Modelling the Lya forest cross correlation with LyMAS"

Lochhass, Weinberg, Peirani, Dubois, Colombi, Blaizot, Font-Ribera, Pichon & Devriendt, 2016

Cross correlation quasar Lyα in BOSS survey

1.0 Gpc/h - 2048[3] particles - WMAP7 cosmology

σ_{DM}=1.0 Mpc/h



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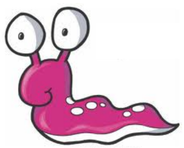


7. Next

Numerical modeling improvements

1. **Algorithms**
   - QSO continuum
   - Redshift evolution
   - Noises
   - Non constant spectral resolution
   - Etc…

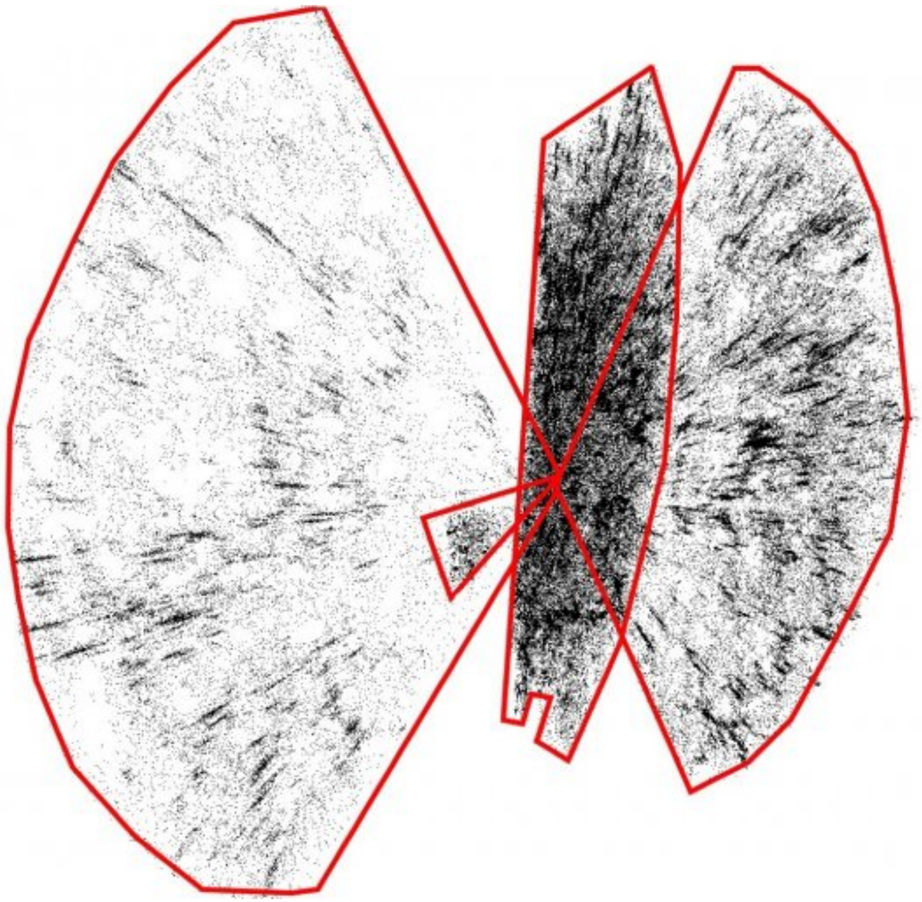
2. **Simulations and more realistic catalogs of spectra**
   - N-body simulations : ≥ 2 Gpc/h (BAO study)
   - Light cones
   - Etc…

Mock catalogs of galaxies

"MoLUSC: a MOck Local Universe Survey Constructor"

2008, ApJ, 678, 569

T. Sousbie, H. Courtois, G. Bryan & J. Devriendt



Mock catalogs of galaxies

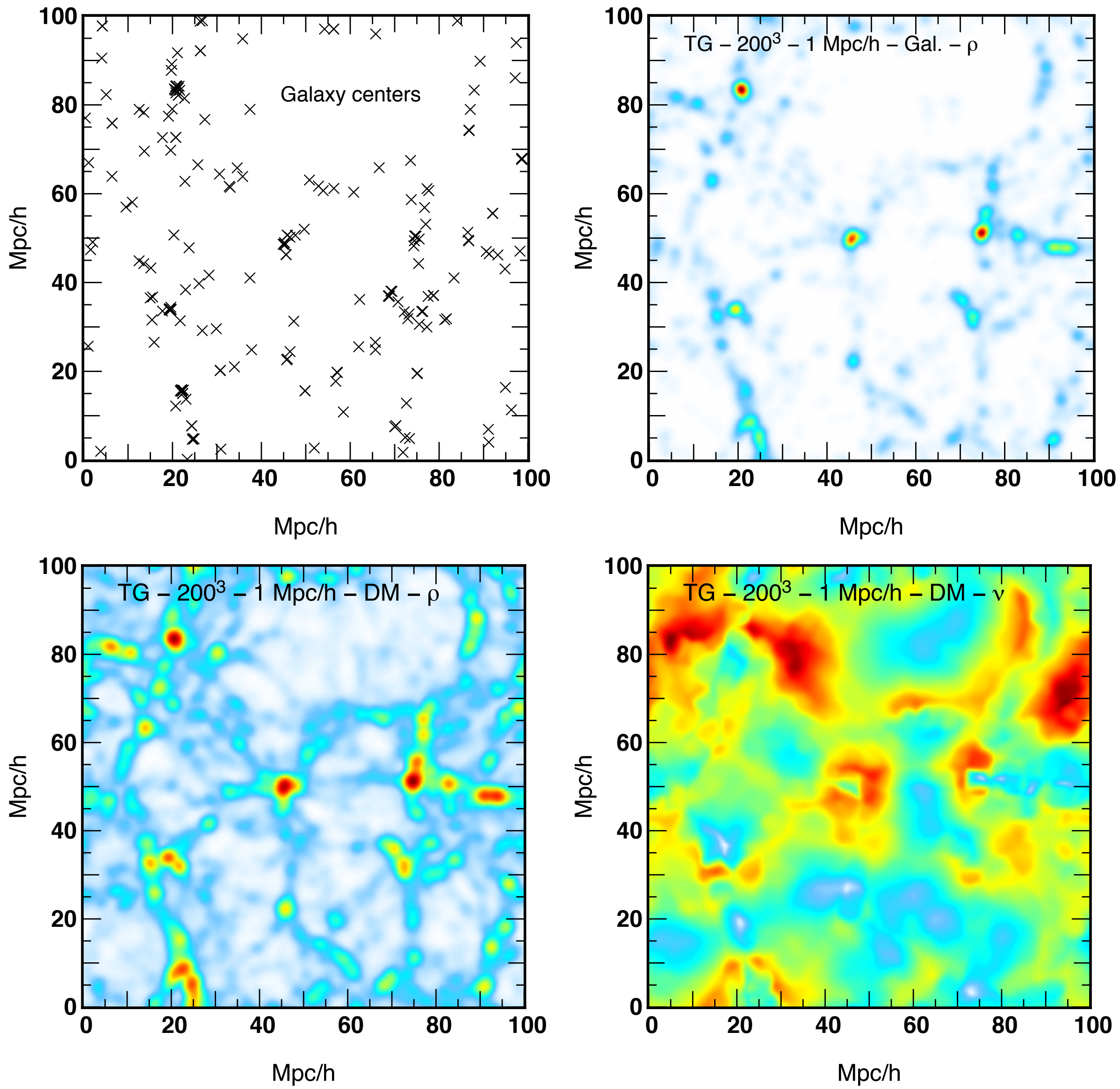
Calibrations from the Horizon-AGN at z=0

$$P\left(F_s \middle| 1+\delta_s\right)$$

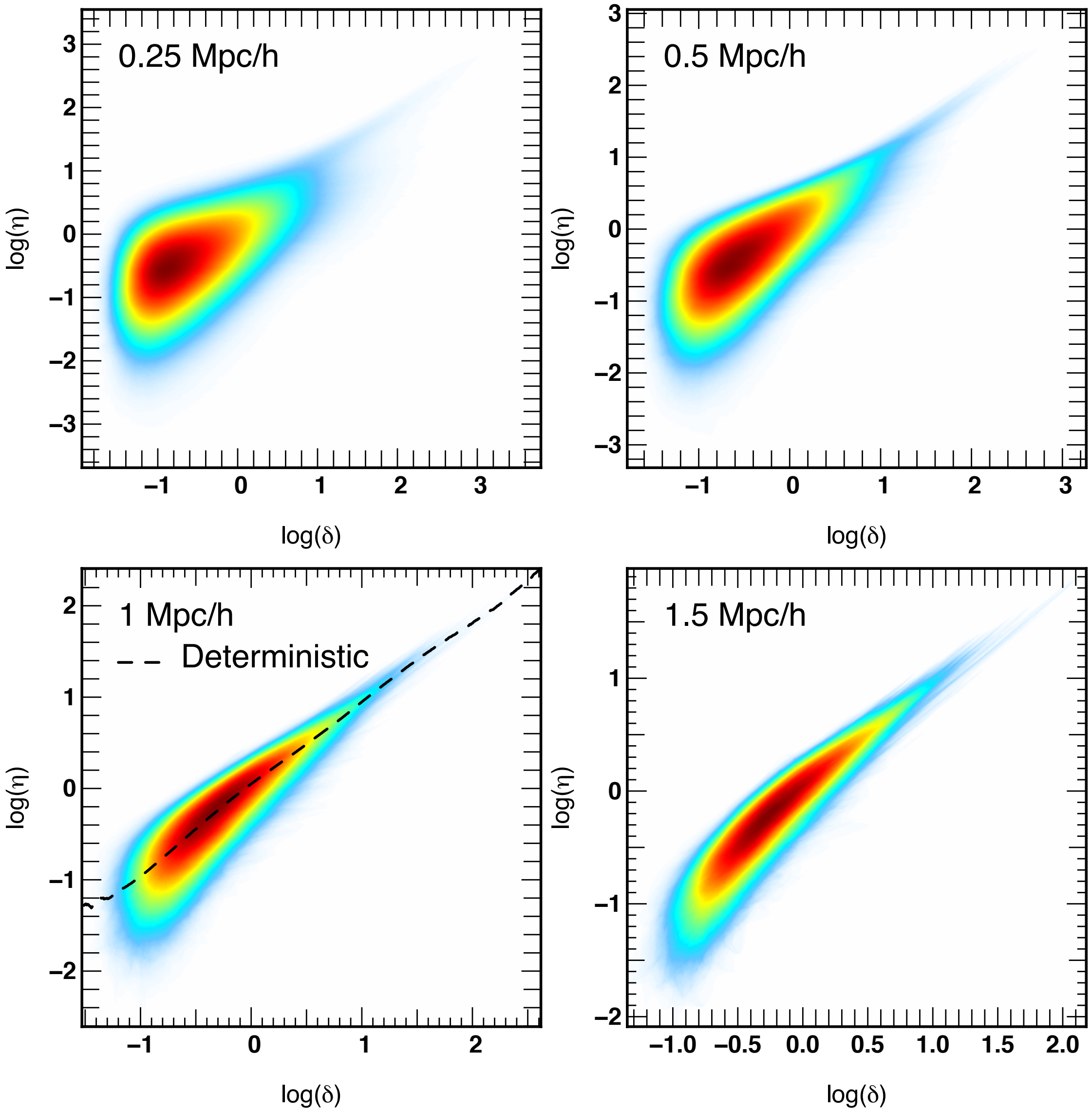
⬇

$$P(n_G \mid 1 + d_s)$$

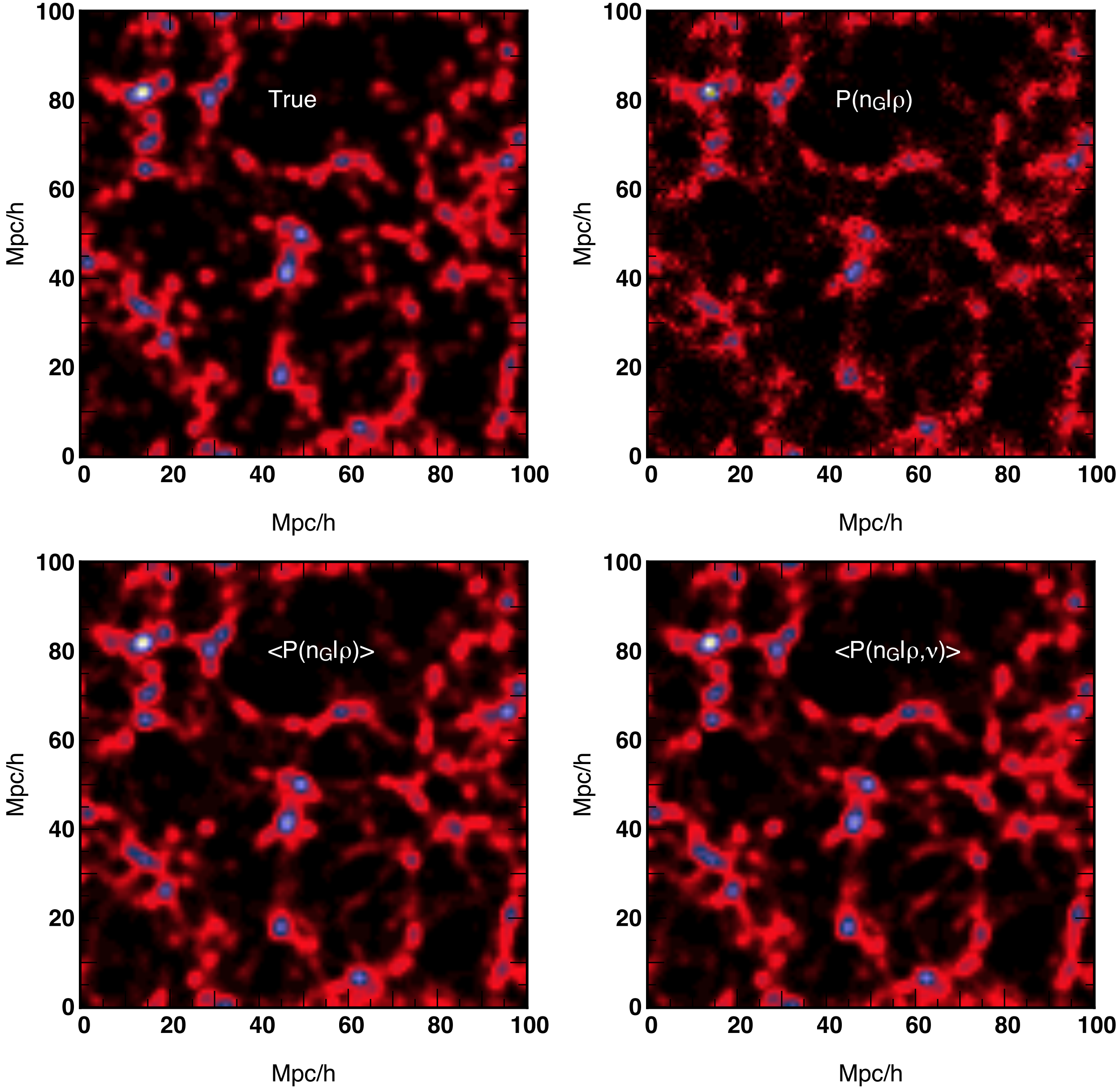
(with S. Colombi, Y. Dubois, J. Devriendt, T. Nishimichi, G. Lavaux)



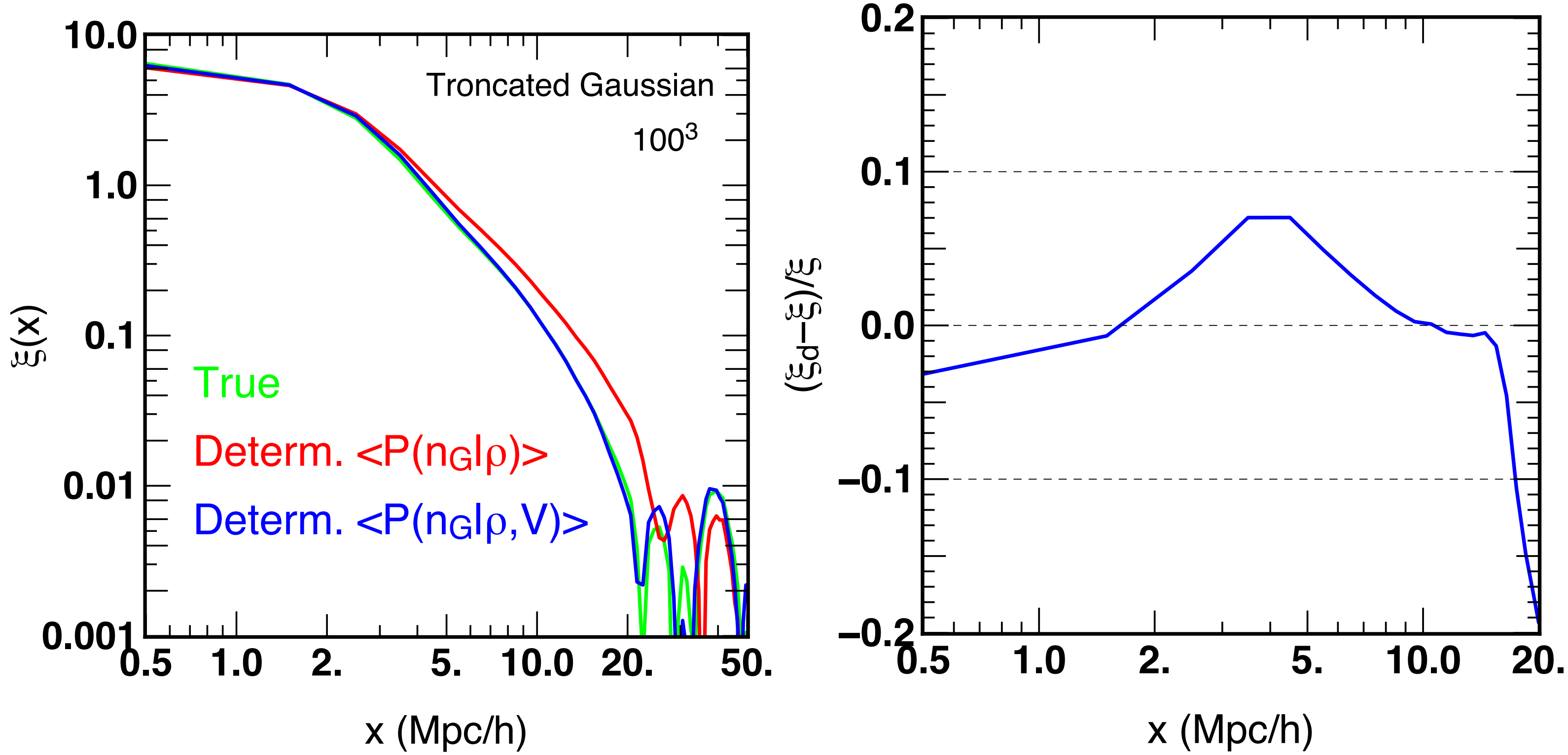
Mock catalogs of galaxies



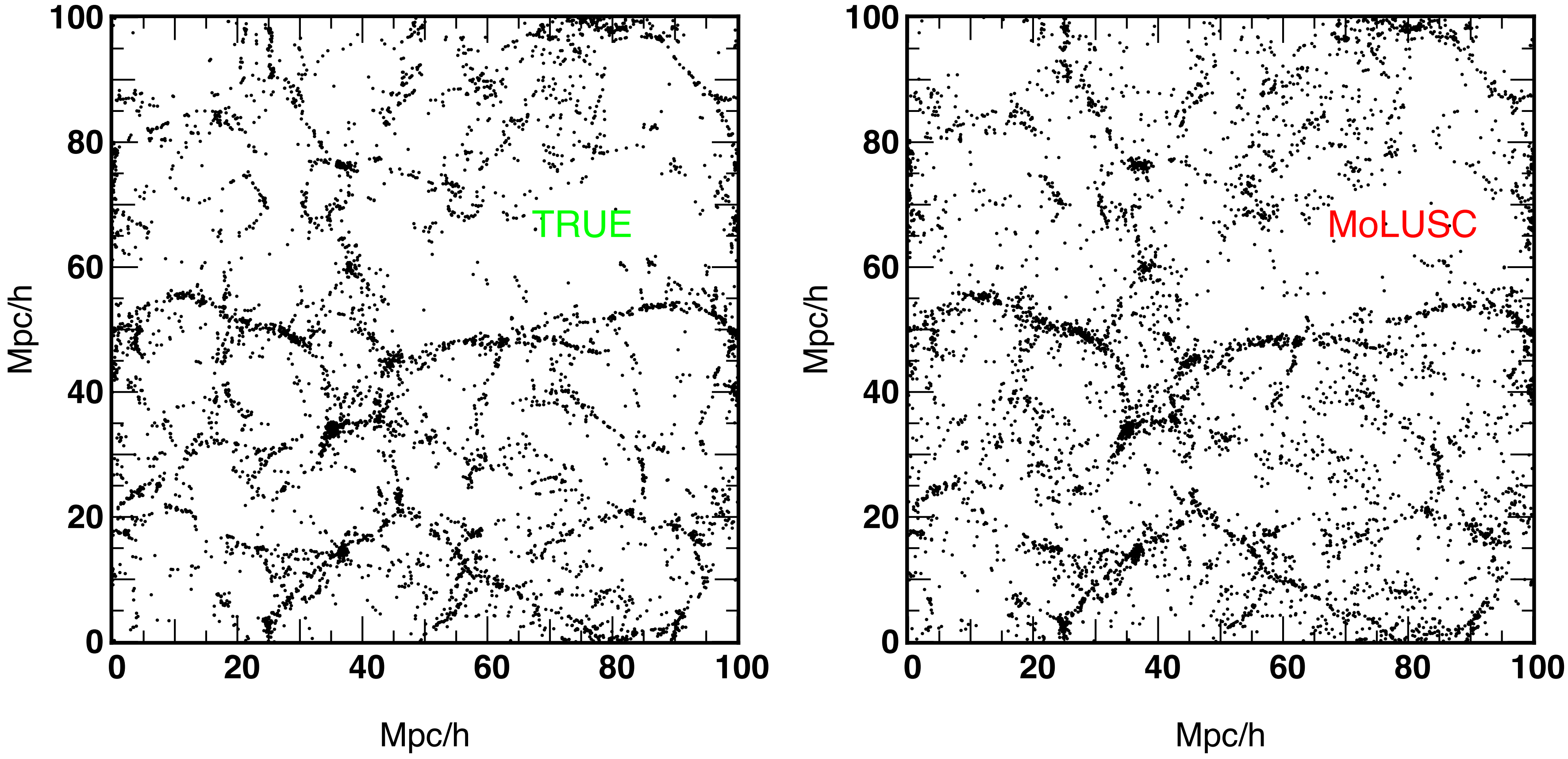
Mock catalogs of galaxies

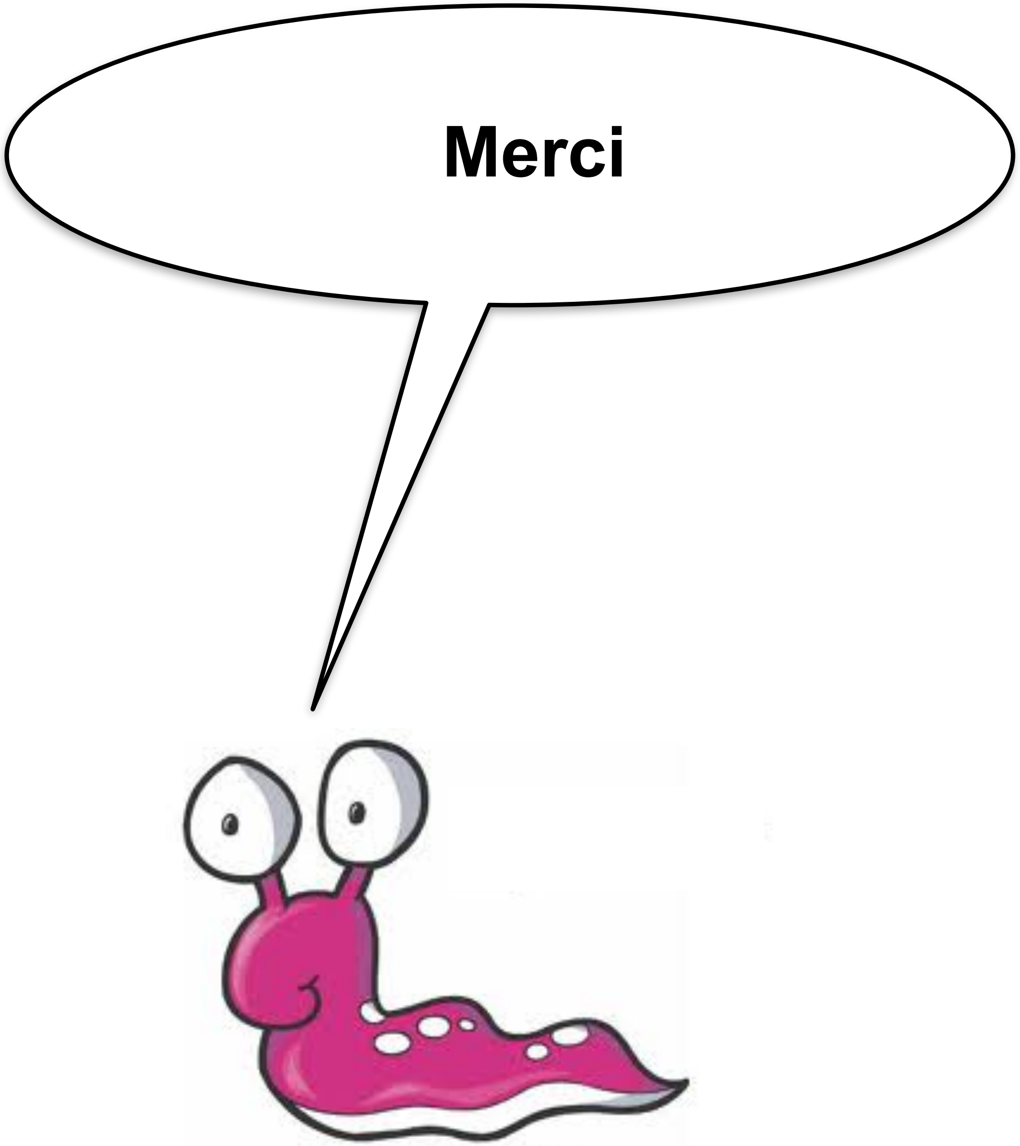


Mock catalogs of galaxies



Mock catalogs of galaxies




Merci

Available mocks

1) WMAP1 (Marenostrum)
300 Mpc/h (4096^2 spectra)
1 Gpc/h (4096^2 spectra)

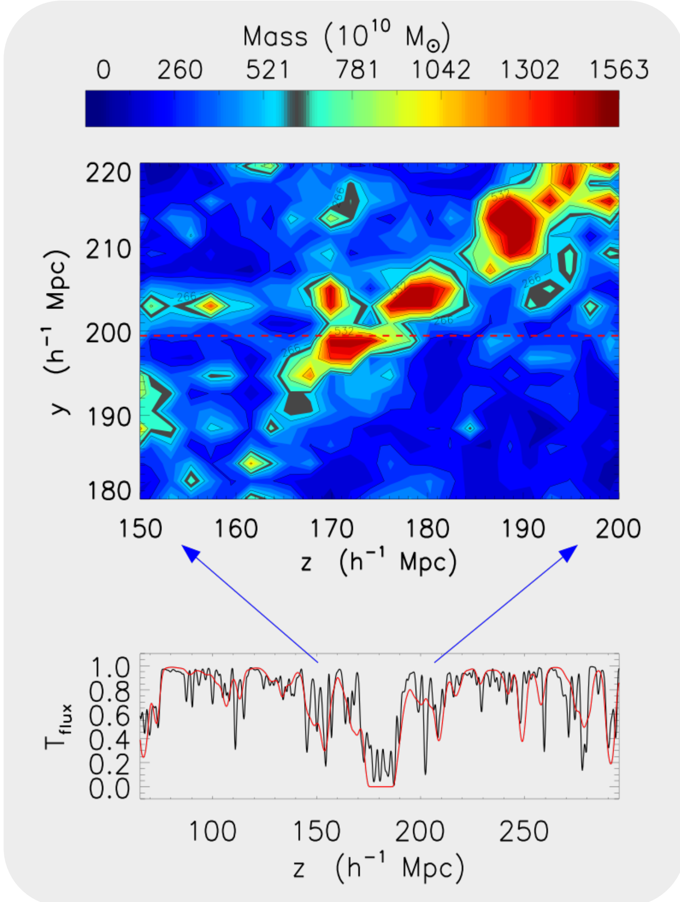
from Gadget2 (1024^3 parts. and σ_{DM}=0.3 and 1 Mpc/h)

2) WMAP7 (Horizon-AGN)
1 Gpc/h (4096^2) from Gadget2 (2048^3 parts. and σ_{DM}=0.5 Mpc/h)

+ 5 hydro simulations (100 Mpc/h): 512^2 spectra each

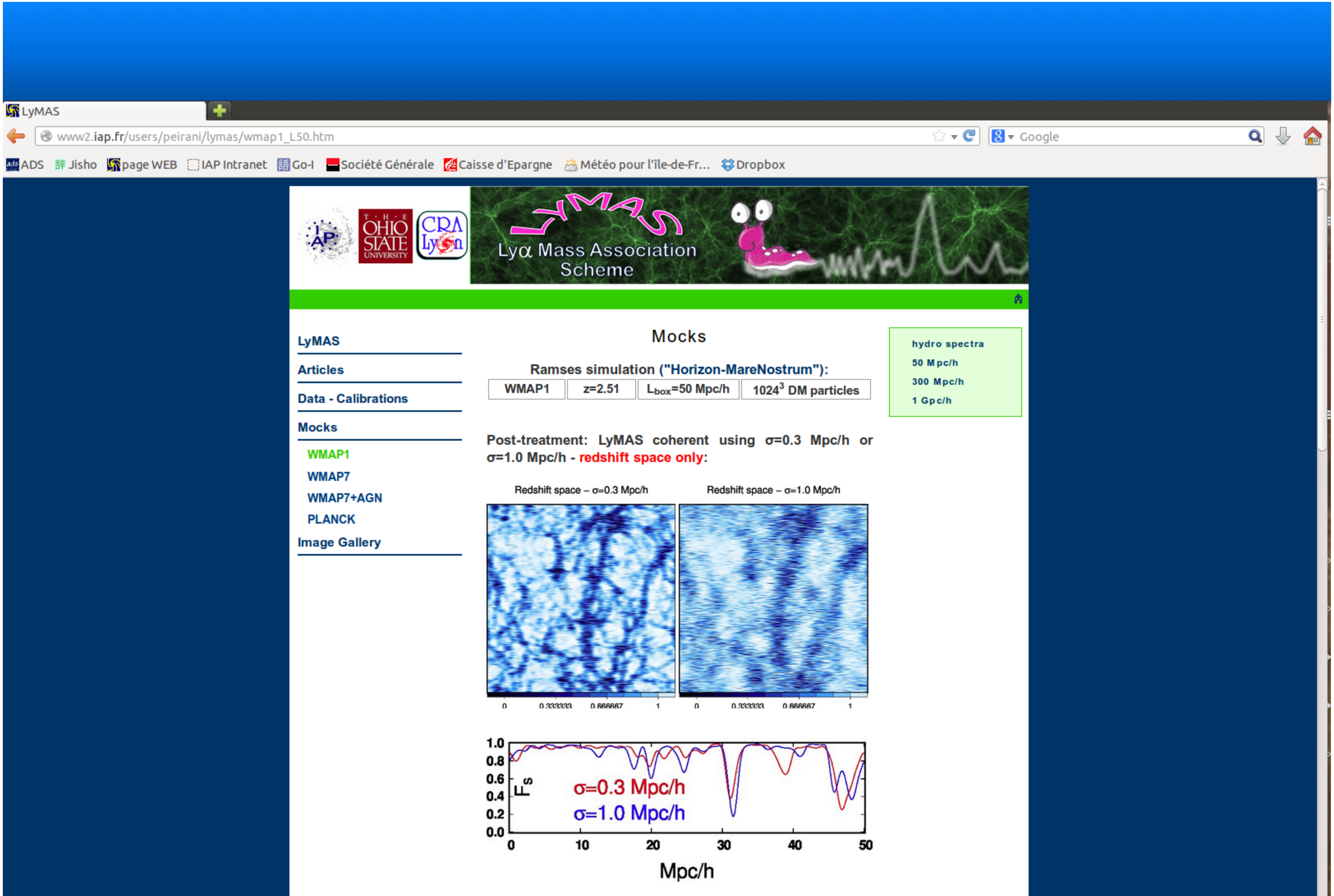
3) WMAP7 (Horizon-AGN)
1 Gpc/h (4096^2 spectra) using improved LyMAS (summer 2020)

MAMMOTH + LyMAS

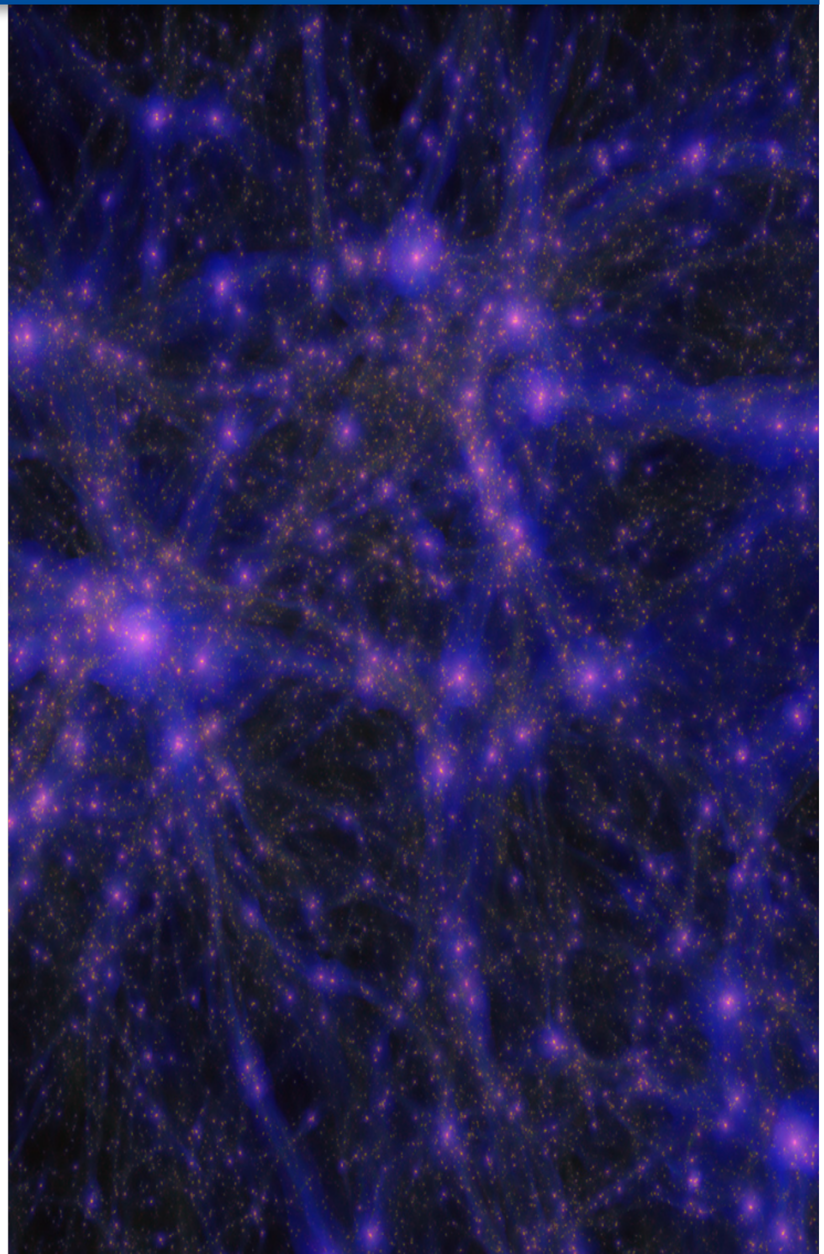


"MApping the Most Massive Overdensity Through Hydrogen (MAMMOTH): I – Cai, Fan, Bian, Peirani et al. 2016, ApJ 833, 135

Web : www2.iap.fr/users/lymas/lymas.htm



MareNostrum (2006)

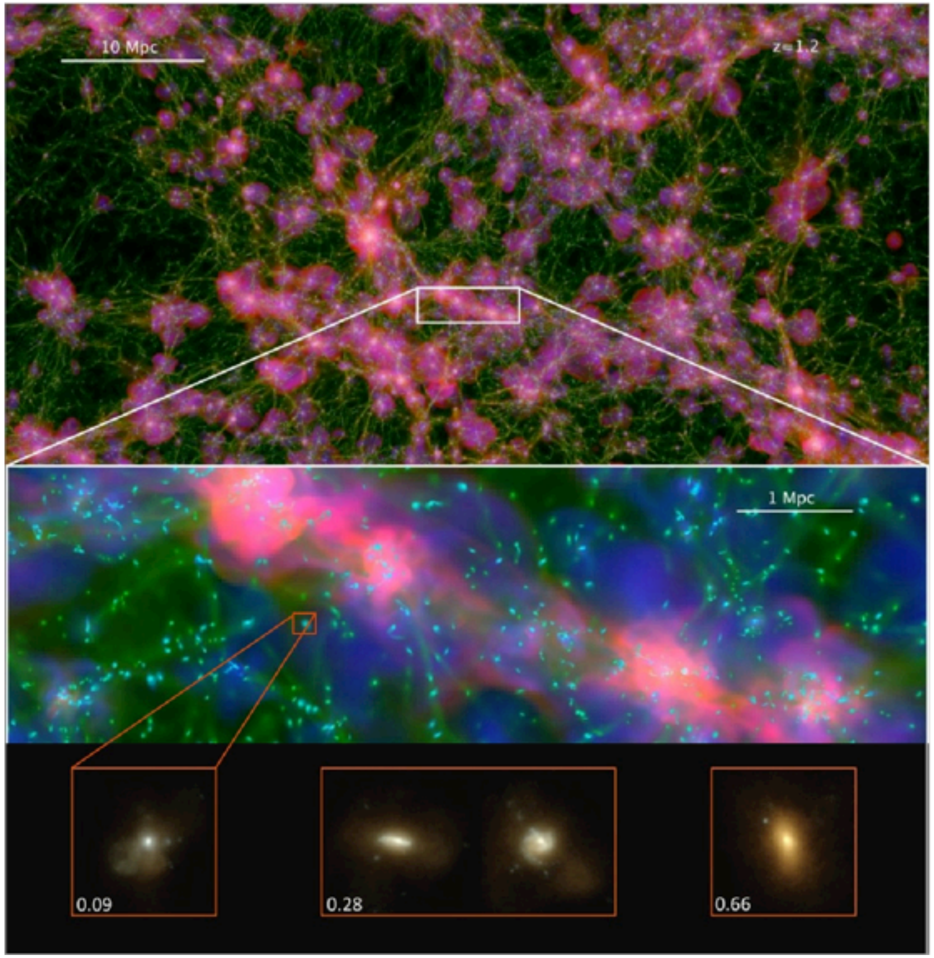


- Horizon-MareNsotrum simulation

  (PI J. Devriendt, R. Teyssier, G. Yepes)
  - **L_{box}=50 Mpc/h**
  - **1024^3 DM particles $M_{DM,res}$=8x10^6 M_{sun}**
  - **Finest cell resolution dx=1 kpc (-1 level of refin.)**
  - **Gas cooling & UV background heating**
  - **Low efficiency star formation**
  - **Stellar winds + SNII + SNIa**
  - **O, Fe, C, N, Si, Mg, H metals w/ solar composition**
  - **AGN feedback radio/quasar**
- Outputs
  - **Simulation outputs**
  - **Lightcones (1°x1°) performed on-the-fly**
    - **Dark Matter (position, velocity)**
    - **Gas (position, density, velocity, pressure, chemistry)**
    - **Stars (position, mass, velocity, age, chemistry)**
    - **Black holes (position, mass, velocity, accretion rate)**
- z=1.5 using 1.3 Mhours using 2048 cores

Horizon-AGN

- Horizon-AGN simulation
  - L_{box}=100 Mpc/h
  - 1024^3 DM particles $M_{DM,res}=8\times10^7\ M_{sun}$
  - Finest cell resolution dx=1 kpc (-1 level of refin.)
  - Gas cooling & UV background heating
  - Low efficiency star formation
  - Stellar winds + SNII + SNIa
  - O, Fe, C, N, Si, Mg, H
  - AGN feedback radio/quasar
- Outputs
  - Simulation outputs
  - Lightcones (1°x1°) performed on-the-fly
    - Dark Matter (position, velocity)
    - Gas (position, density, velocity, pressure, chemistry)
    - Stars (position, mass, velocity, age, chemistry)
    - Black holes (position, mass, velocity, accretion rate)
- z=0.05 using 10 Mhours using 4096 cores

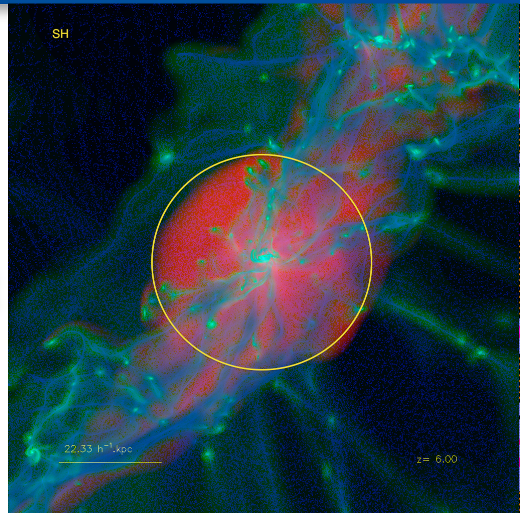


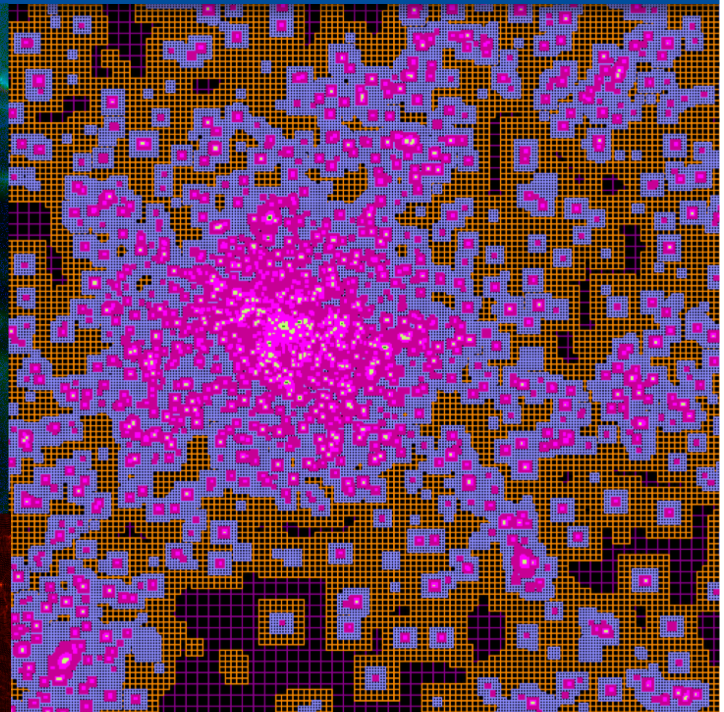
Dubois et al. (2014)

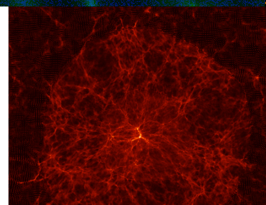
RAMSES: an adaptive Mesh Refinement (AMR) code

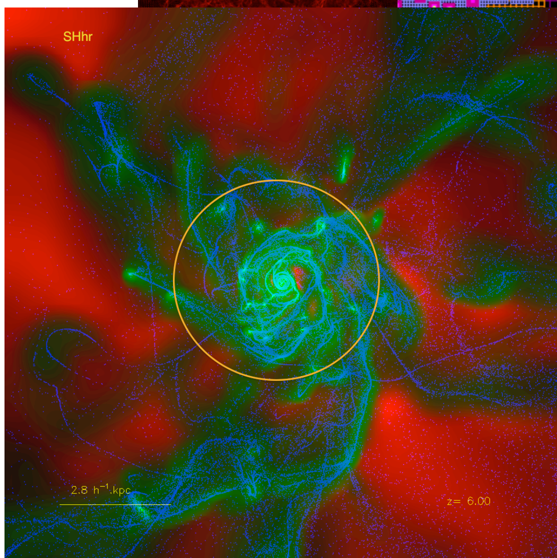
- Language :
  - Fortran 90
  - MPI parallel
- Method : adaptive grid refinement
- Equations :
  - Hydrodynamics
  - Gravity
  - Atomic/Metal cooling + UV-heating
  - (Magneto-hydrodynamics)
  - (Radiative transfer)
- Sub-grid physics :
  - Star formation
  - Supernovae & Stellar Winds
  - Active Galactic Nuclei (AGN)
- Cosmology

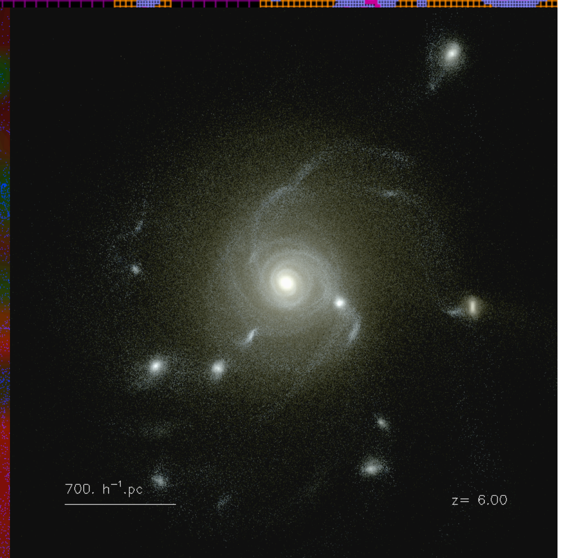
See Teyssier, 2002





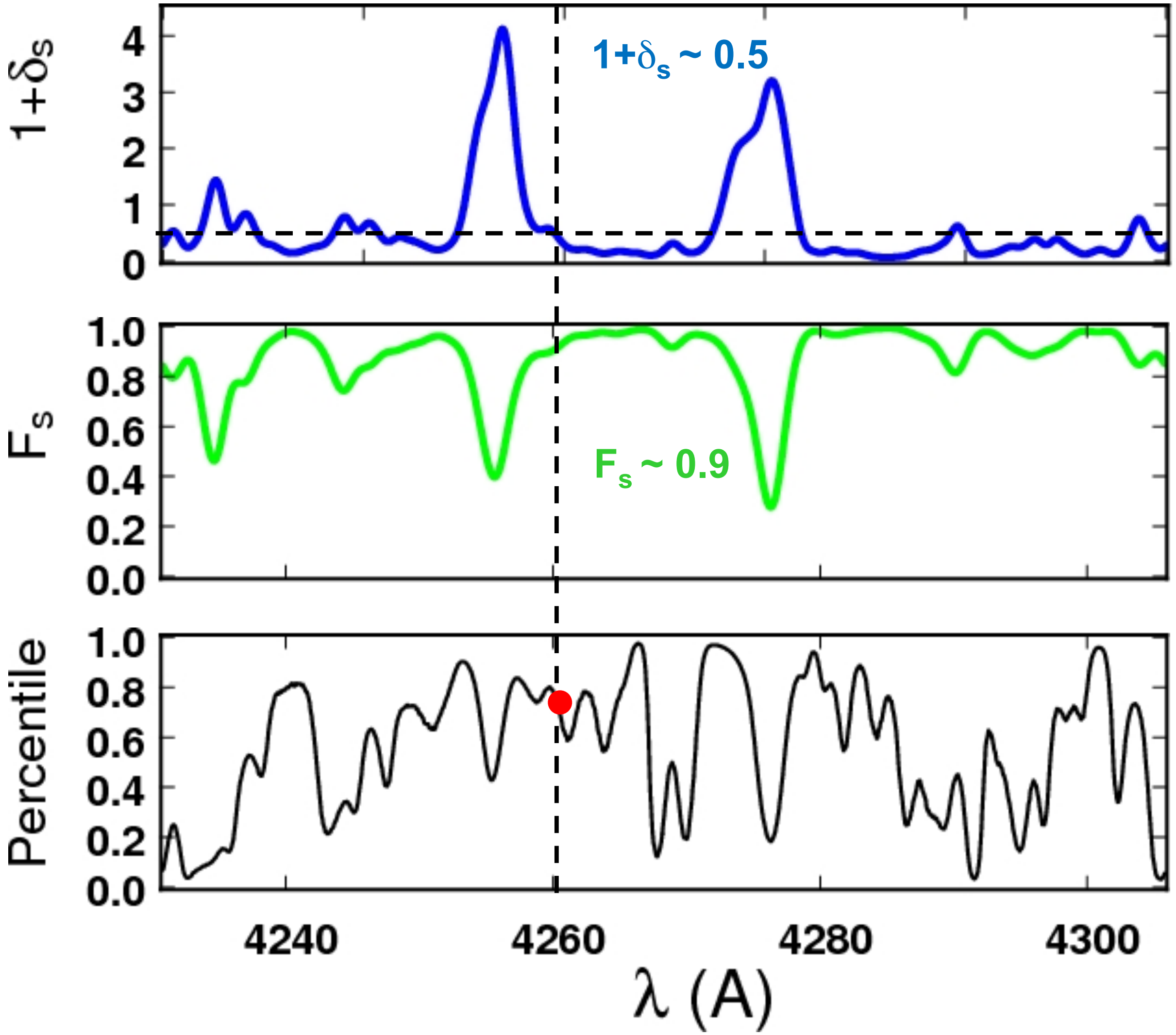


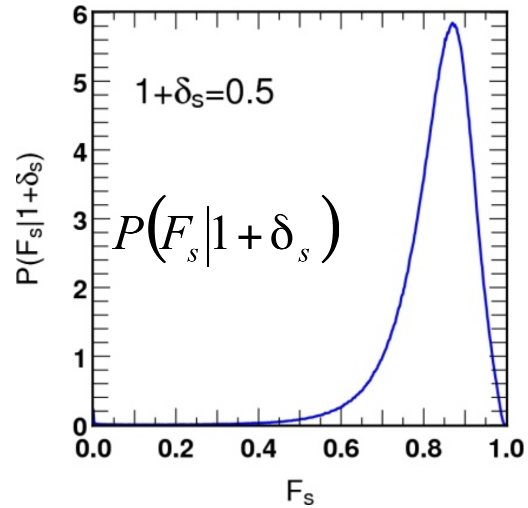




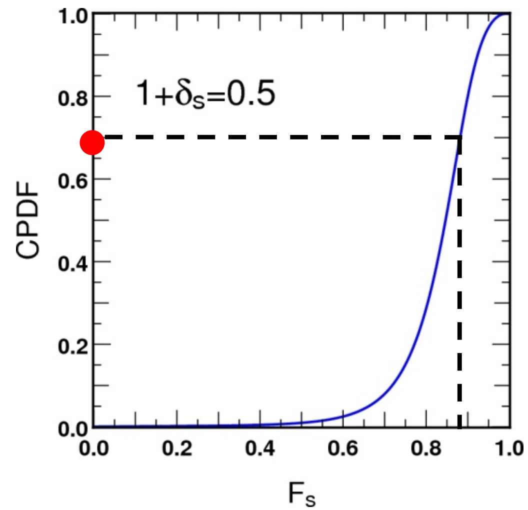
Coherent mapping

1. Construction of "percentile spectra": $Per(F_S, \delta_S) = \int_0^{F_S} P(F_S' | \delta_S)\, dF_S'$





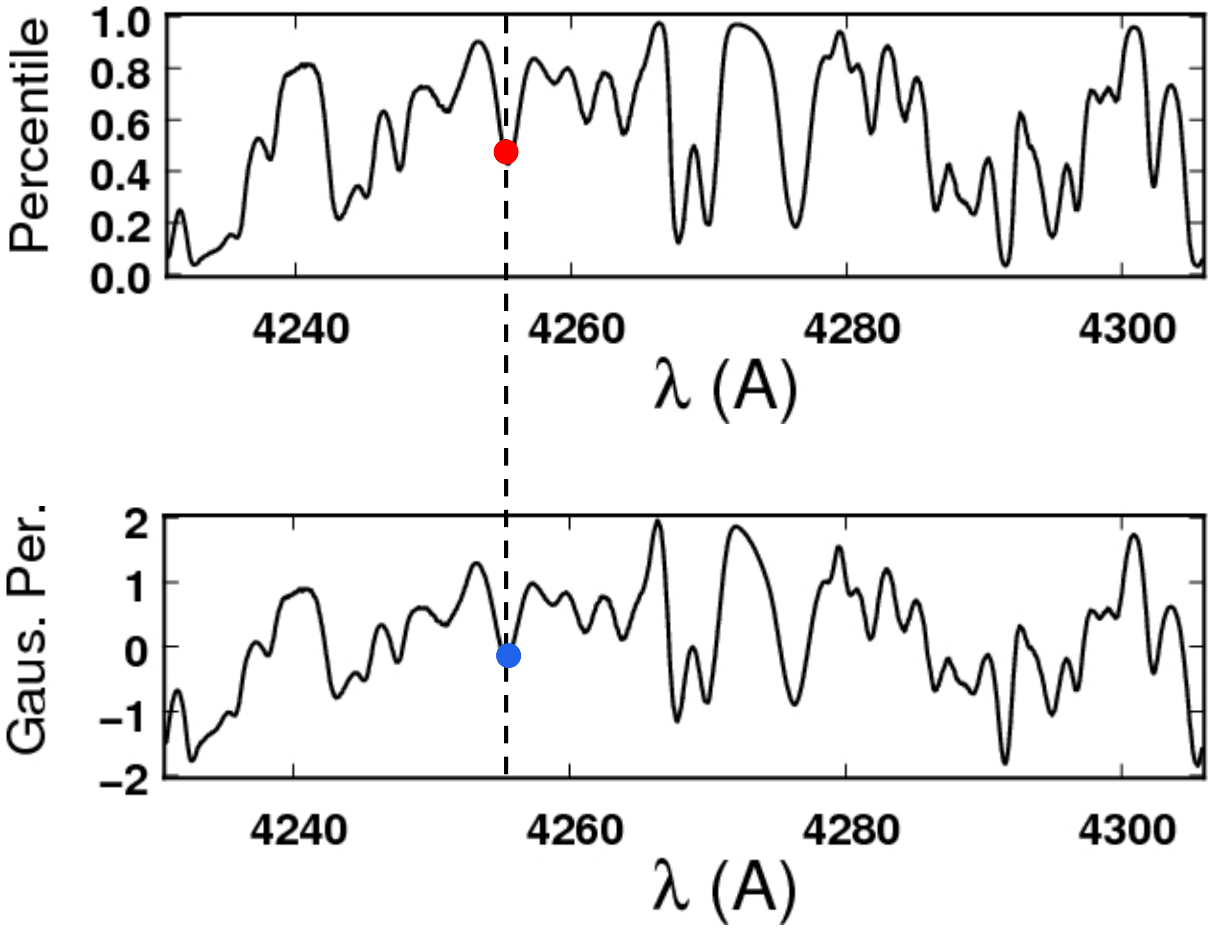
Cumulative PDF



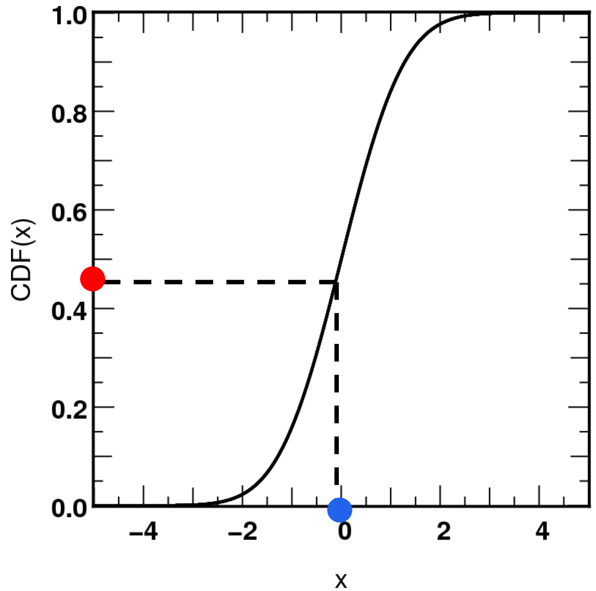
Coherent mapping

2. Construction of "Gaussianized" percentile spectra (Weinberg 1992):

$$G_{Per}(x) = y \qquad (2\pi)^{-1/2}\int_{-\infty}^{y} e^{-\frac{z^2}{2}}\,dz = Per(x)$$



Cumulative PDF of Gaussian function



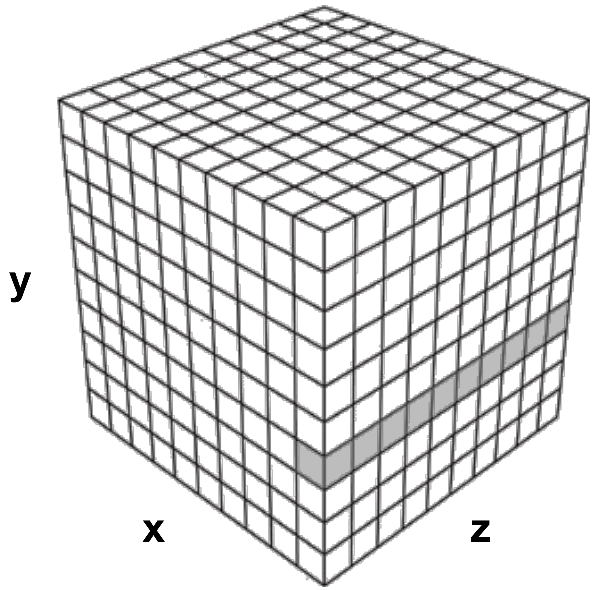
$$CDM(x) = \frac{1}{2}\left[1 + erf\left(\frac{x-\mu}{\sqrt{2\sigma^2}}\right)\right]$$

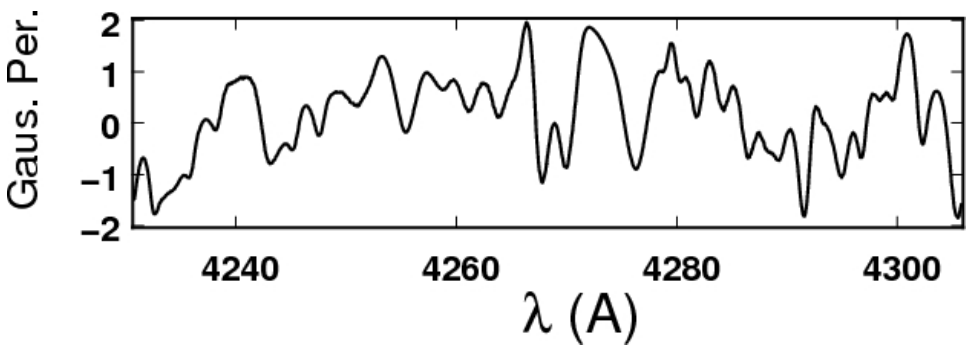
$$\mu = 0$$

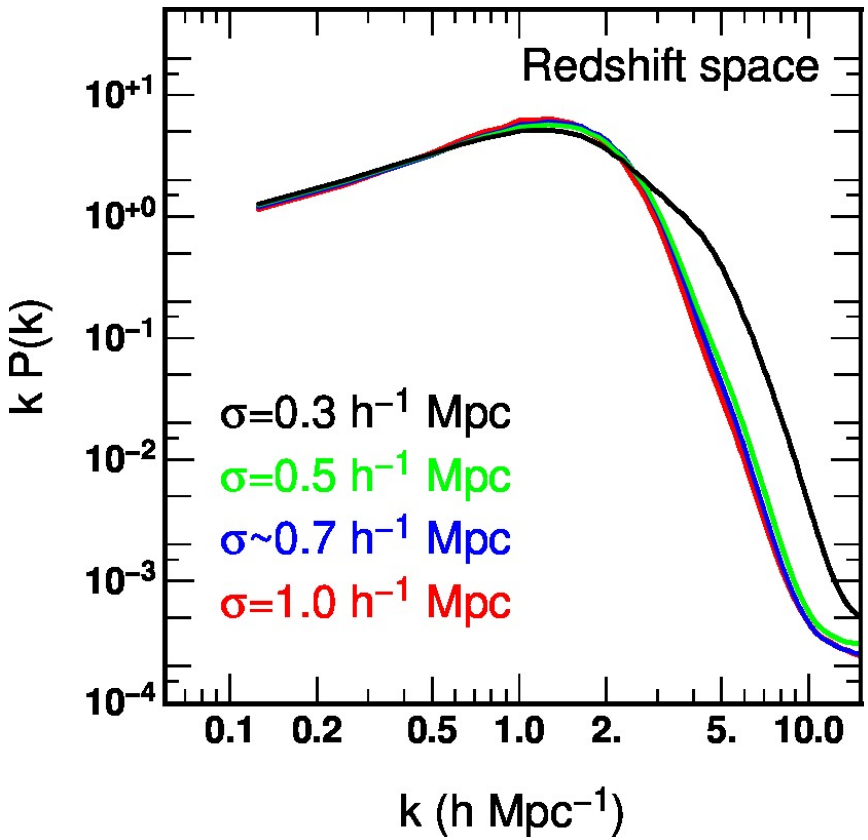
$$\sigma^2 = 1$$

Coherent mapping

3. Derive the 1d power spectrum of the "Gaussianized percentile spectra":





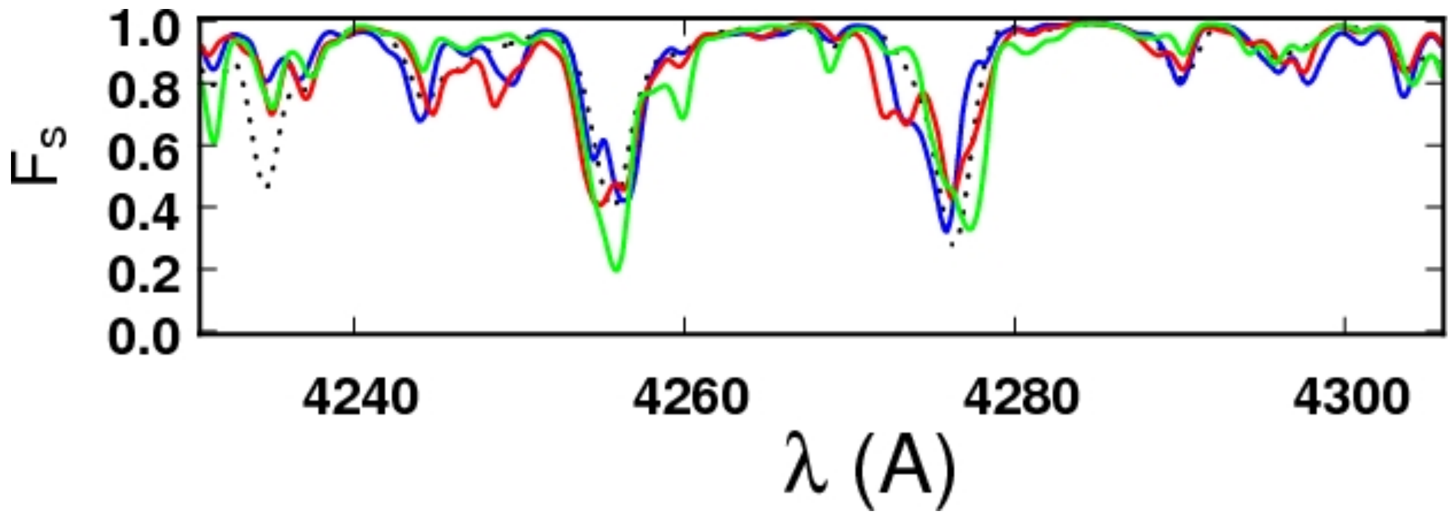


Coherent mapping

1. For each DM skewer, create a realization of G.Per(x) of the 1-d gaussian field

2. Get a realization of Per(F) by "degaussianization"

3. Get the flux field by drawing the flux at each pixel from the location of in $P(F_s|1+\delta_s)$ implied by the value of Per(F)



4. One iteration:

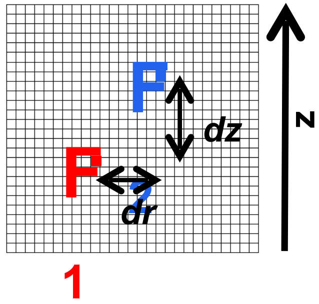
   - Pk rescaling: multiply each Fourier components by the ratio $[P_F(k)/P_{PS}(k)]^2$
   - Flux rescaling

Application to large cosmological DM simulations

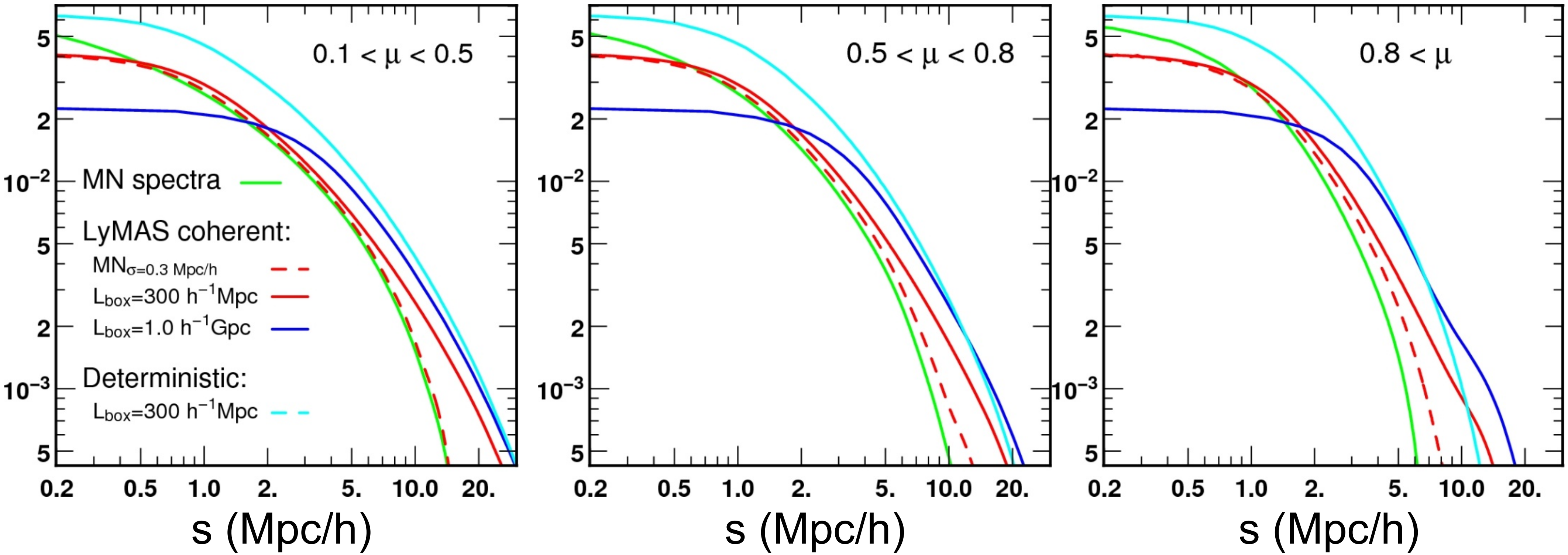
Correlation function:

$$\mu = \frac{dz}{\sqrt{dr^2 + dz^2}}$$

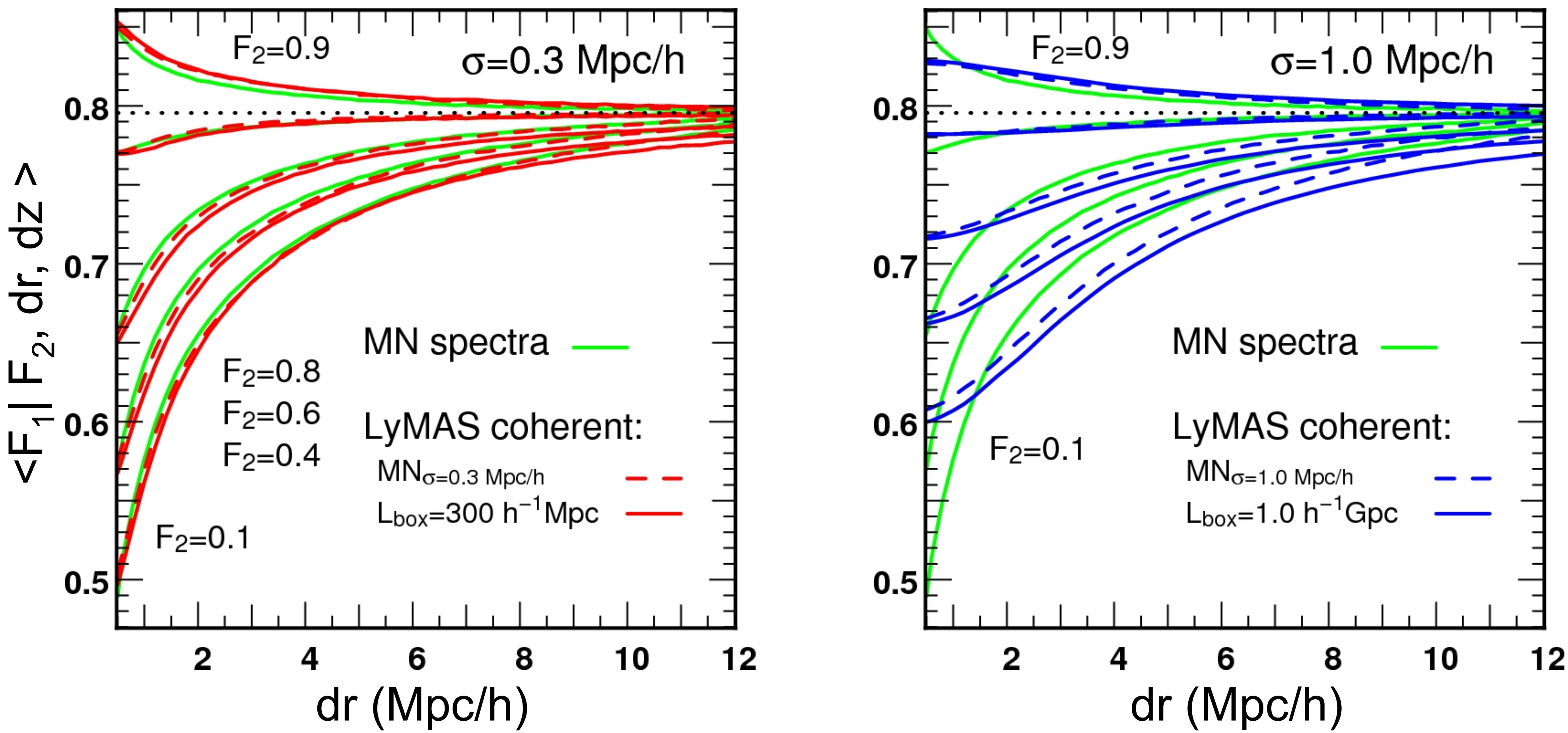
$$s = \sqrt{dr^2 + dz^2}$$



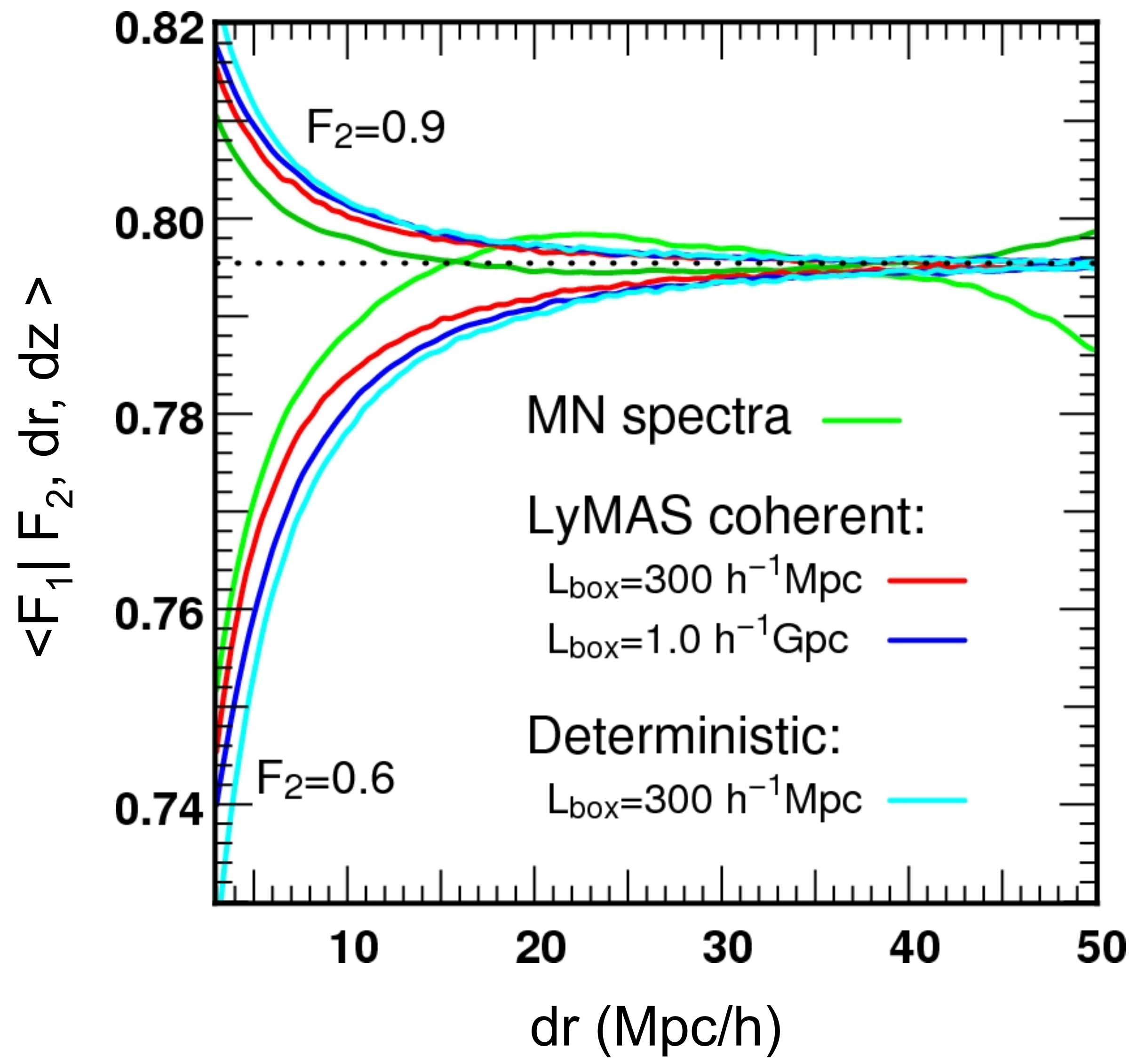
ξ(s)



Application to large cosmological DM simulations



Application to large cosmological DM simulations



Cross correlation quasar Lyα in BOSS survey

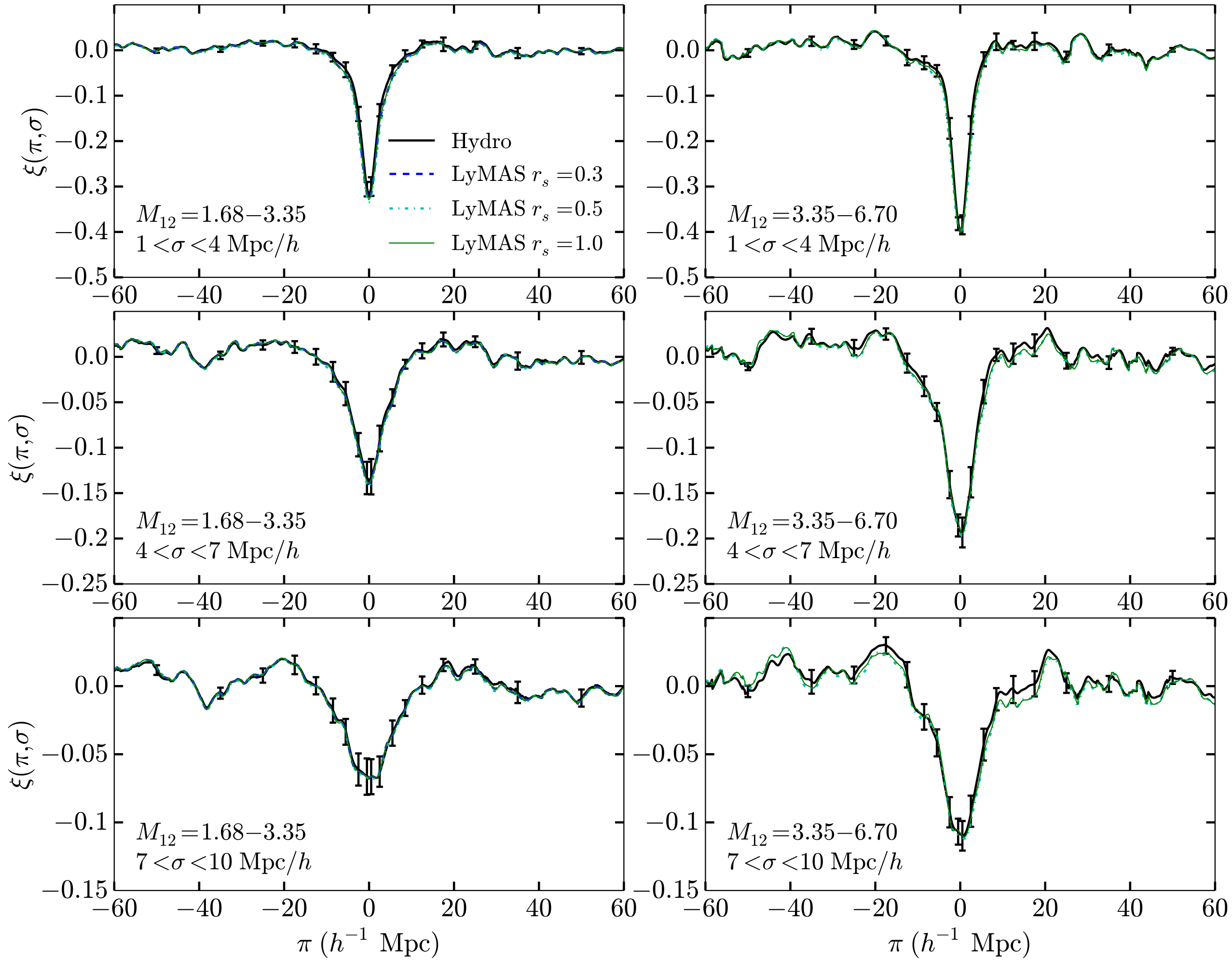
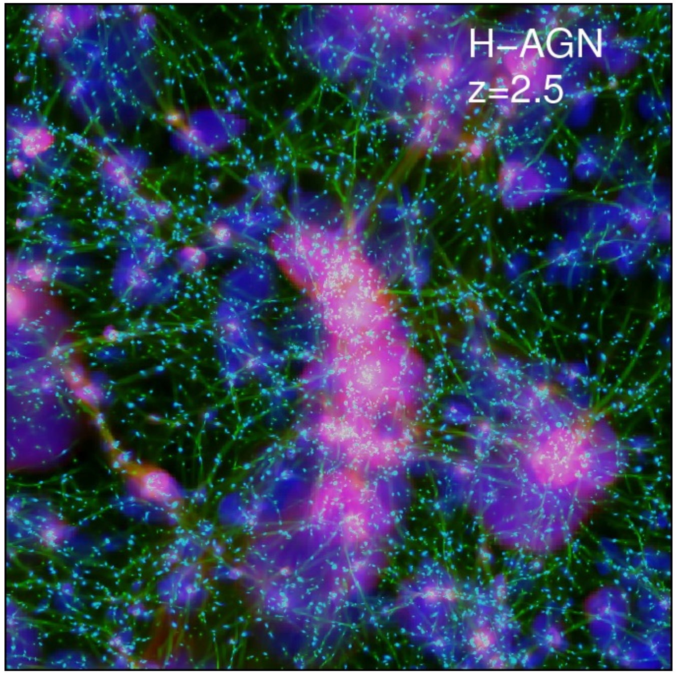


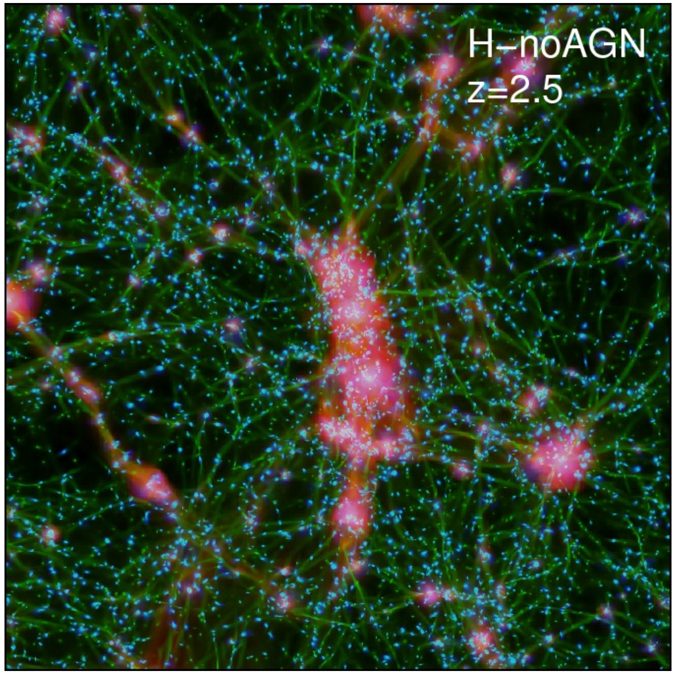
Figure 2. The cross-correlation between dark matter halos and Ly-α forest flux calculated from true gas spectra (black solid) and from LyMAS applied to the matter distribution with 0.3 h^{-1} Mpc 3-d dark matter smoothing (blue dashed), 0.5 h^{-1} Mpc smoothing (cyan dot-dashed), or 1.0 Mpc h^{-1} Mpc smoothing (green solid) in the (100 h^{-1} Mpc)^3 simulation. Rows show transverse separation bins $\sigma = 1-4,\ 4-7$, and $7-10\ h^{-1}$ Mpc, and columns show dark matter halo mass bins $M_{12} = 1.68-3.35$ and $3.35-6.70$. Similar agreement holds in other mass and separation bins. Error bars are computed from the standard deviation of the mean among 16 subvolumes.

Horizon-AGN – Horizon-noAGN (2014)

Horizon-AGN



Horizon-noAGN



Gas density

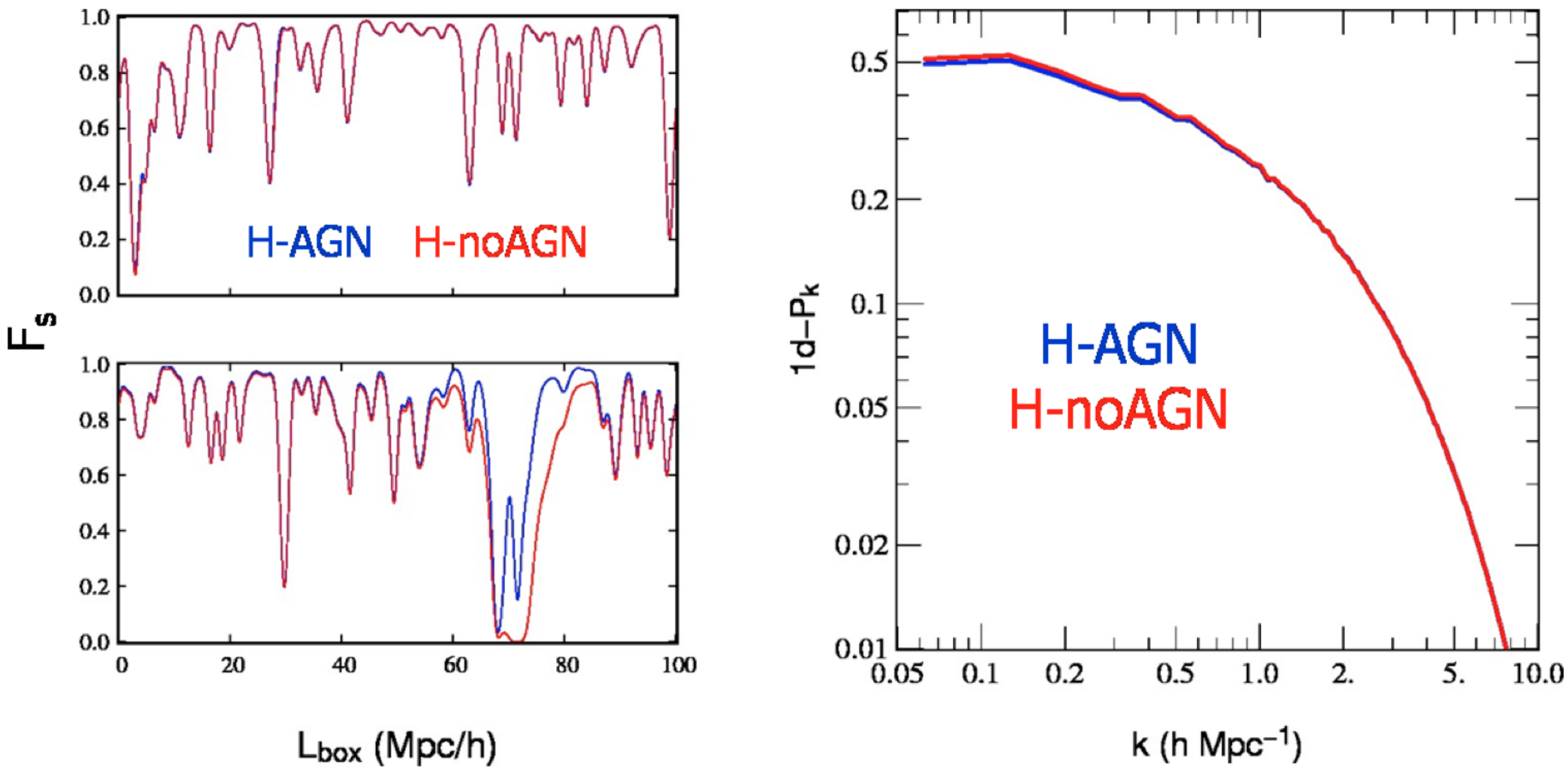
Gas temperature

Gas metallicity

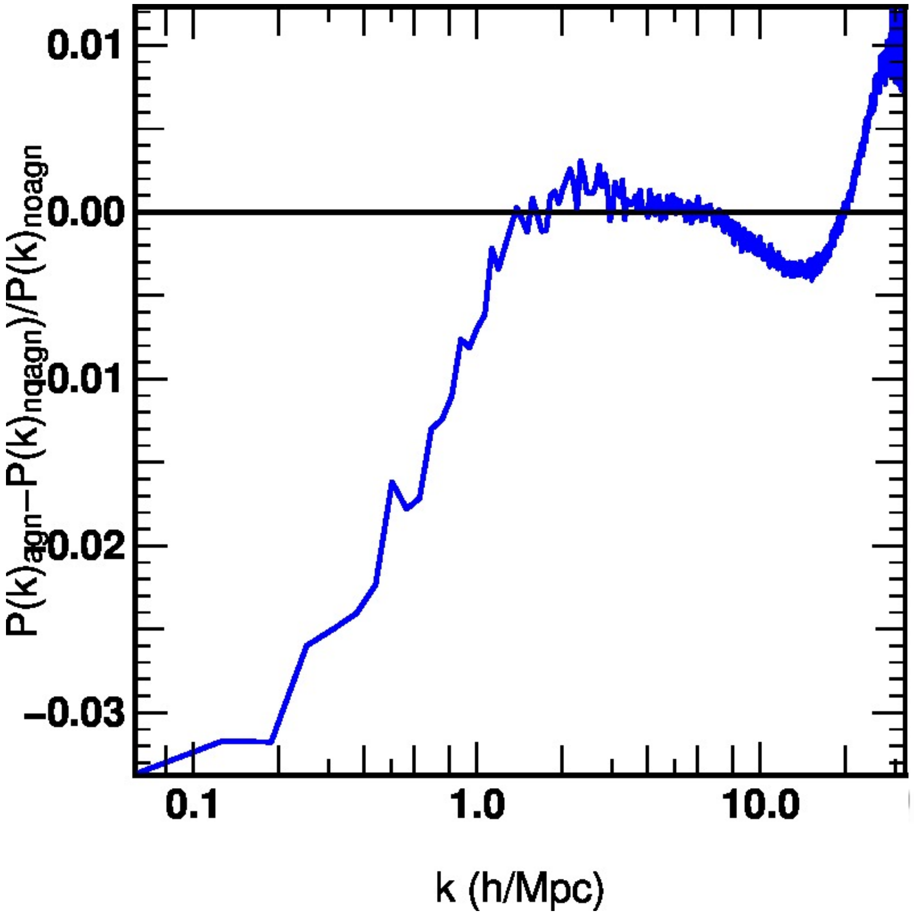
- L_{box}=100 Mpc/h
- 1024^3 DM particles $M_{DM,res}=8\times10^7\ M_{sun}$
- Finest cell resolution dx=1 kpc (-1 level of refin.)
- Gas cooling & UV background heating

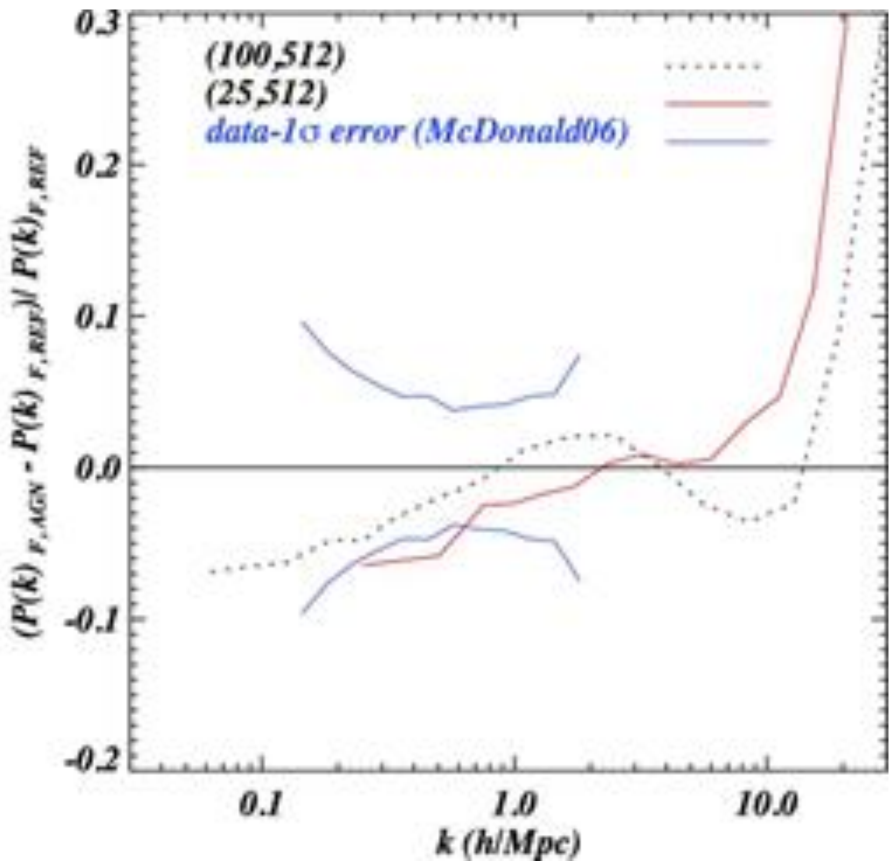
- Low efficiency star formation
- Stellar winds + SNII + SNIa
- O, Fe, C, N, Si, Mg, H
- AGN feedback radio/quasar

AGN vs noAGN



AGN vs noAGN

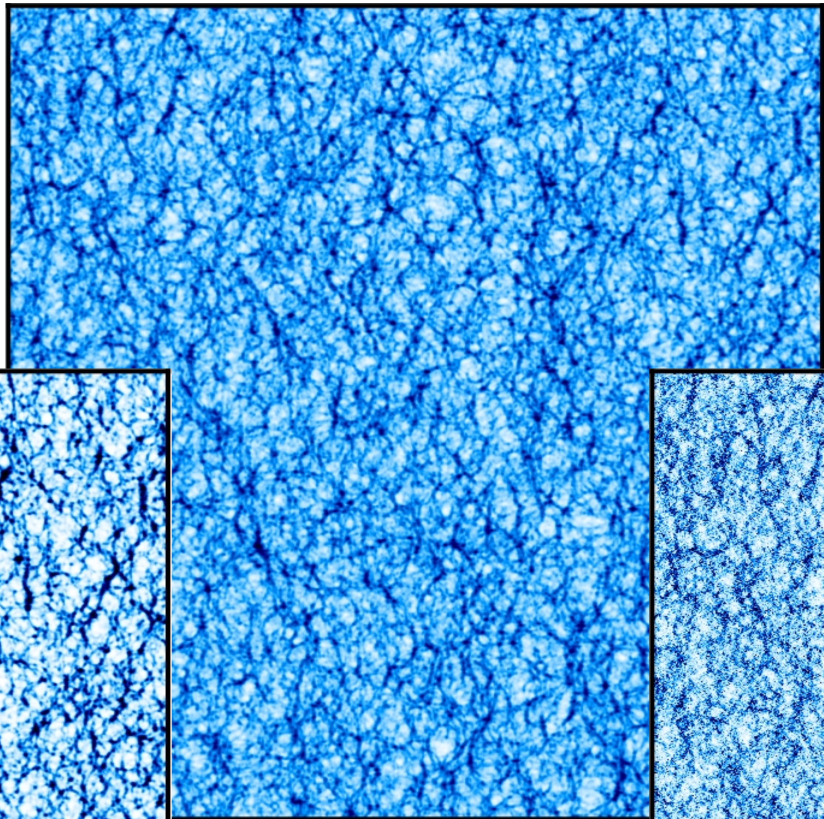




(Viel et al. 2013)

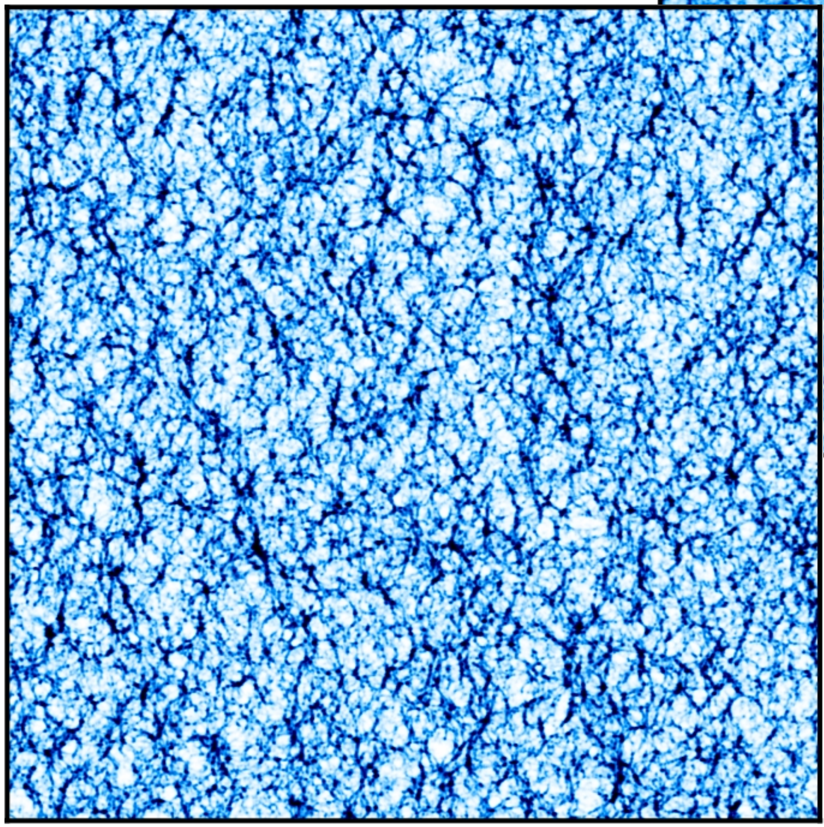
Application to large cosmological DM simulations

1 Gpc/h



DM

Deterministic



LyMAS