Predicting Large-Scale Lyman-α Forest Statistics from the Dark Matter Density Field

Sébastien Peirani (IAP)

Lyman-α Mass Association Scheme

Peirani, Weinberg, Colombi, Blaizot et al., 2014, ApJ, 784, 11

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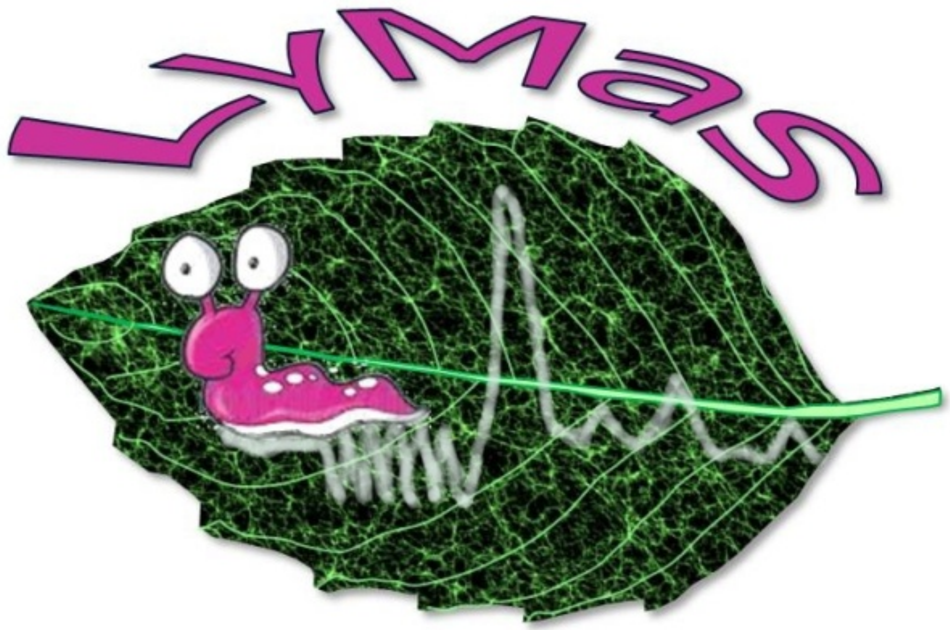

LyMAS

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Limace

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Lyman-α Mass Association Scheme

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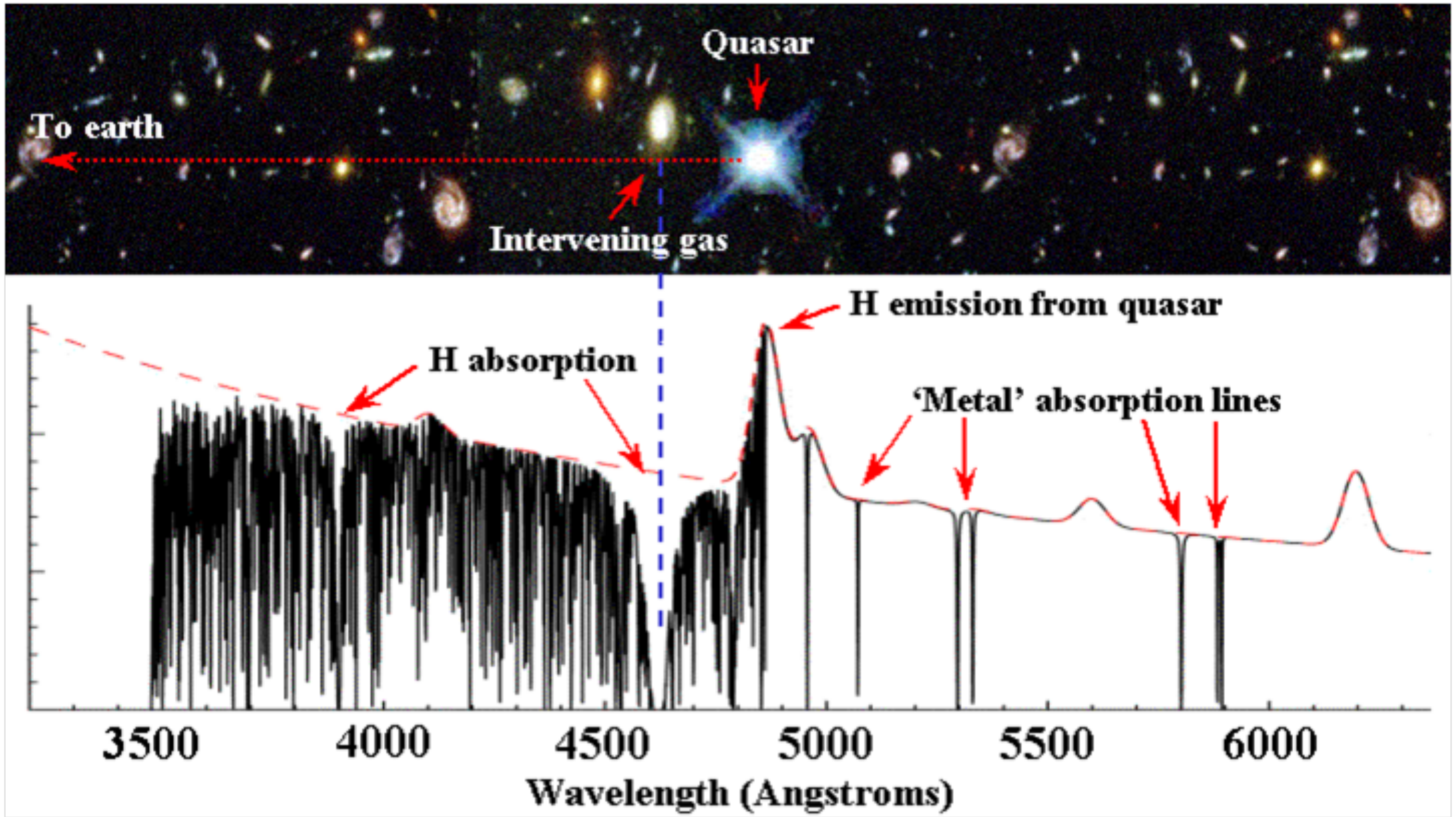
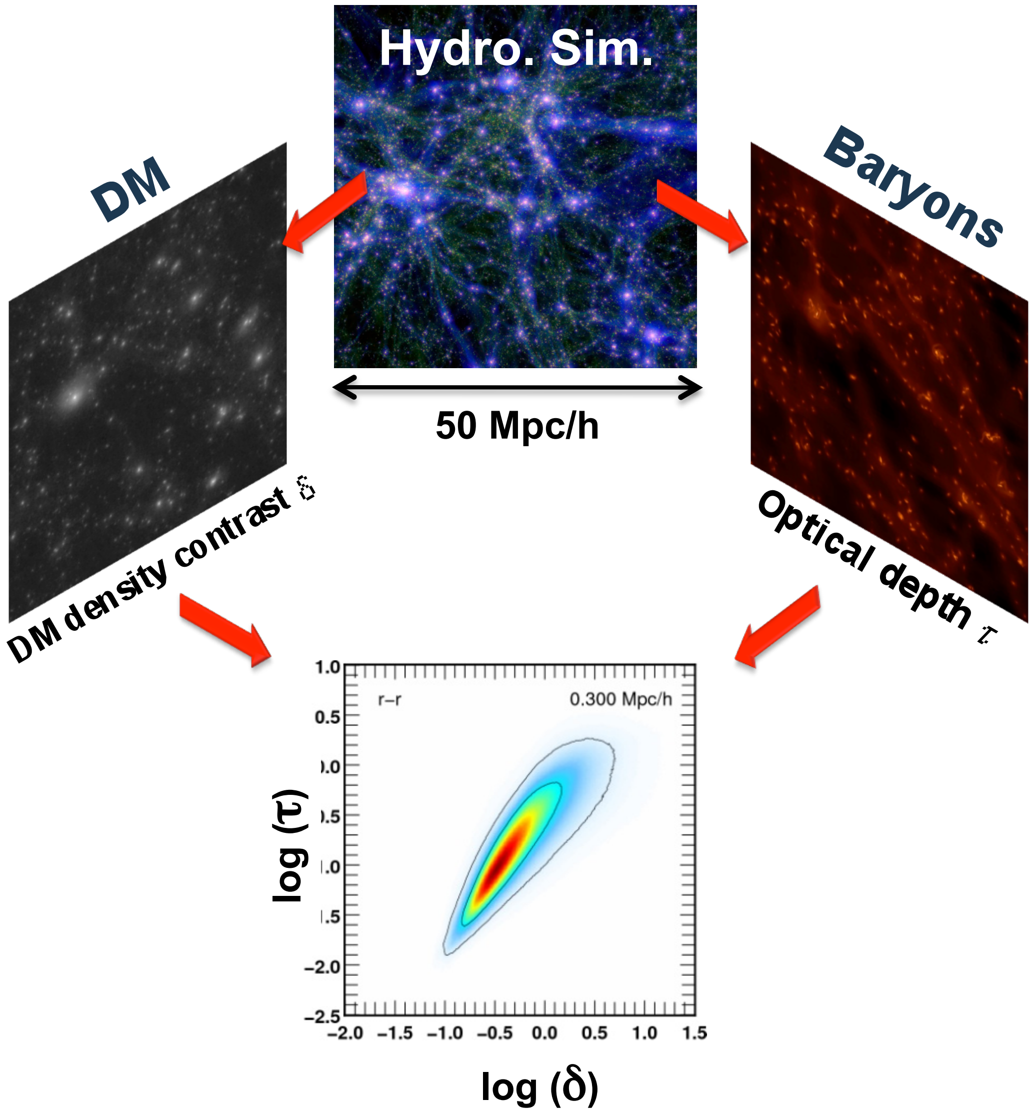
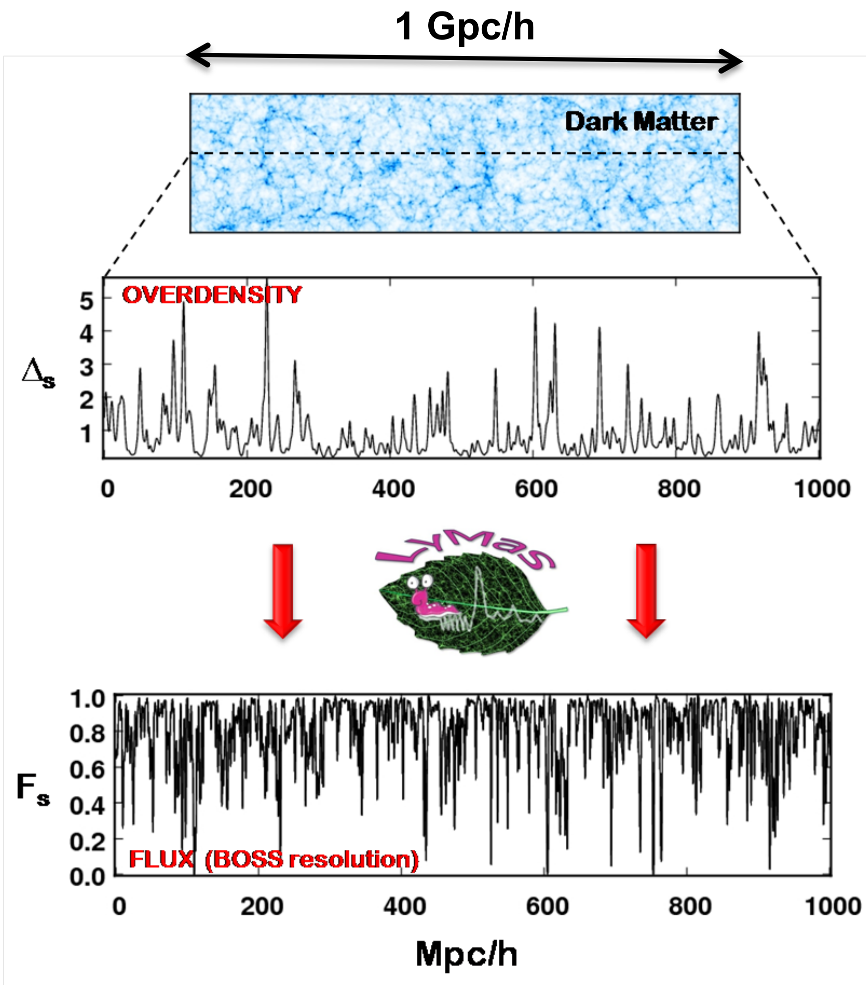
Quasar spectrum



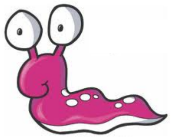
Light from distant quasars is partially absorbed as it passes through clouds of hydrogen gas

LyMAS: Lyα Mass Association Scheme





Plan



1. Introduction
2. Hydro simulations and hydro spectra
3. Deterministic mapping
4. LyMAS Probabilistic mapping
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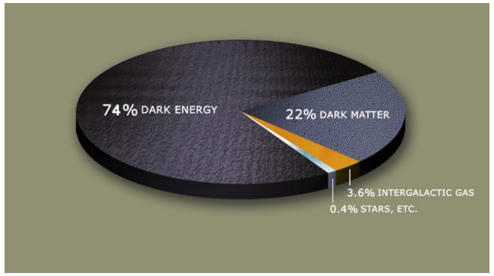
6. Application to large N-body simulations
7. Next

How to probe dark energy?

Equation of state:

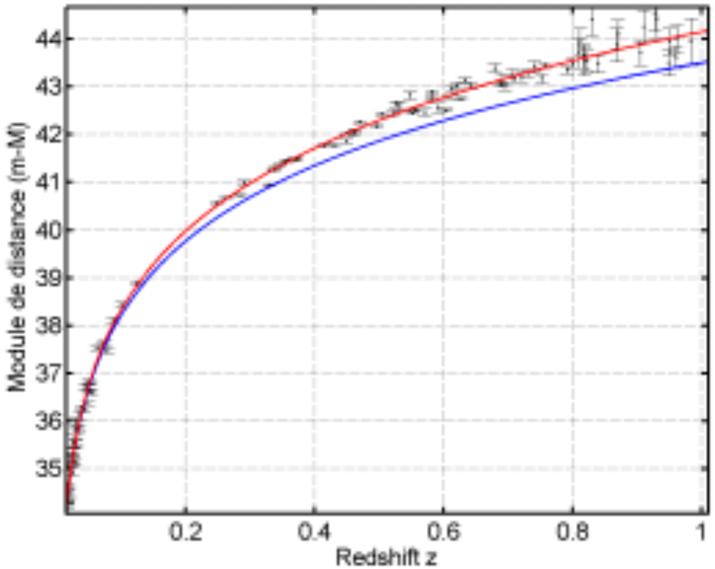
$$w = \frac{P}{\rho}$$

$$w(z) = w_0 + \frac{z}{1+z} w_a$$



Main observational methods to probe dark energy and its redshift evolution:

- **Type Ia supernovae**
- **Galaxy clusters**
- **Weak gravitational lensing**
- **BAO**



(SNLS 1st year) Astier et al. 2006

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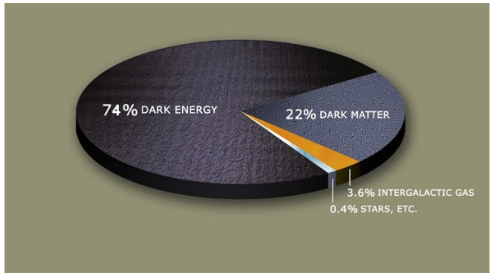

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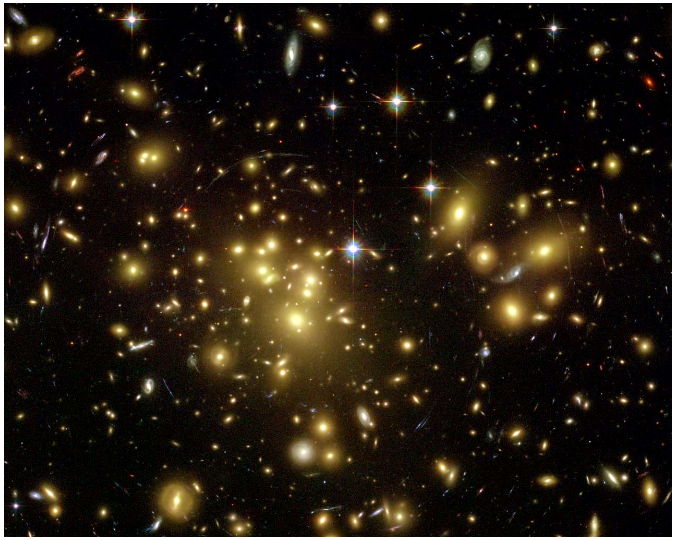

(Abell1689)

How to probe dark energy?

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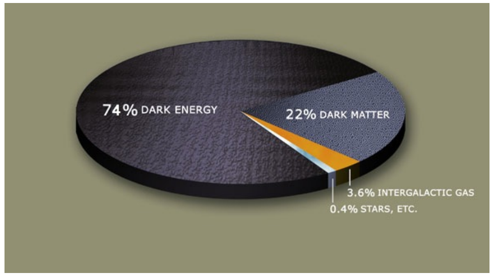

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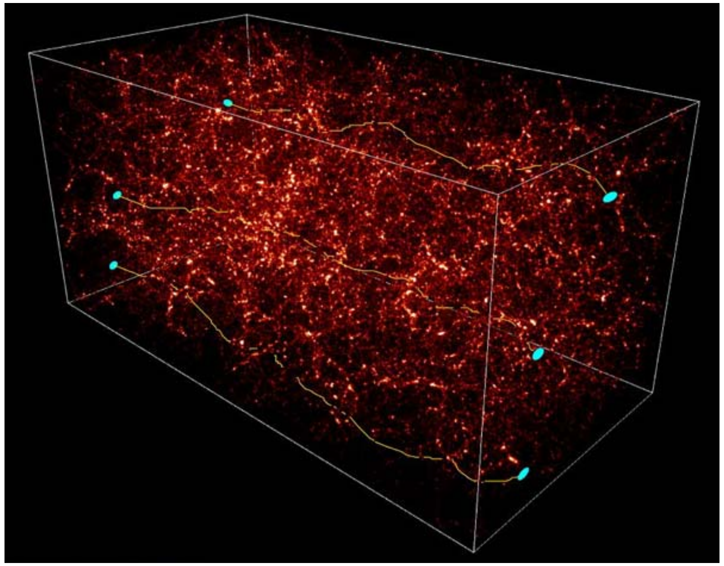

(courtesy of S. Colombi and CFHT team)

How to probe dark energy?

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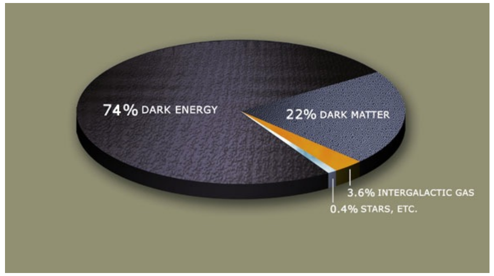

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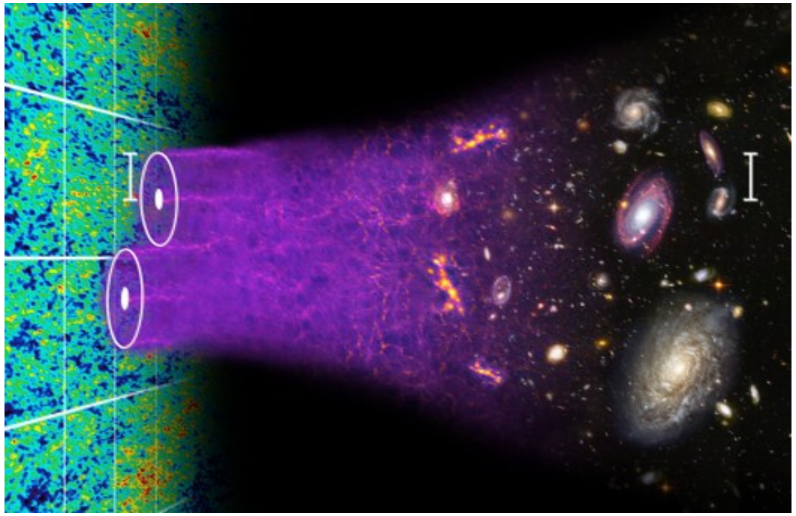
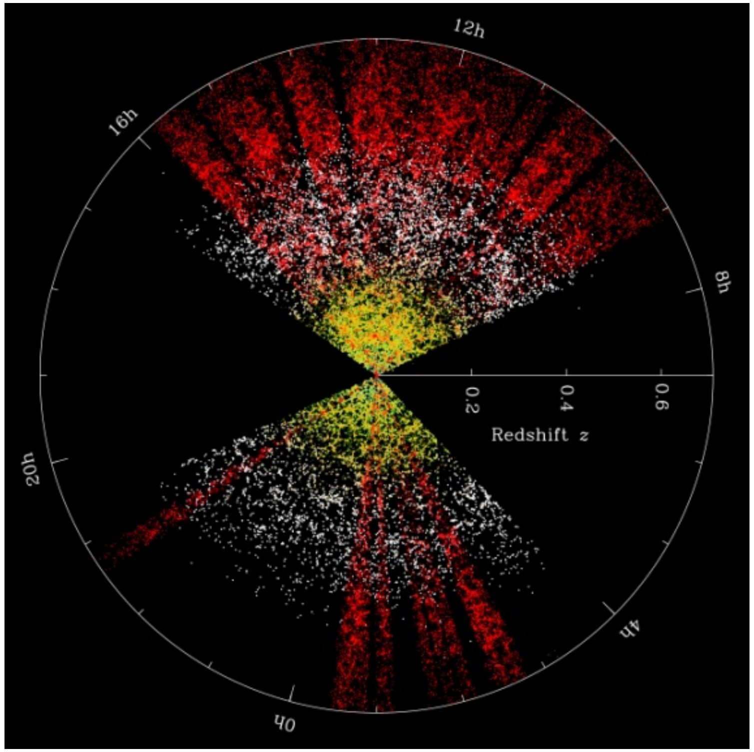


(courtesy of C. Blake and S. Moorfield)

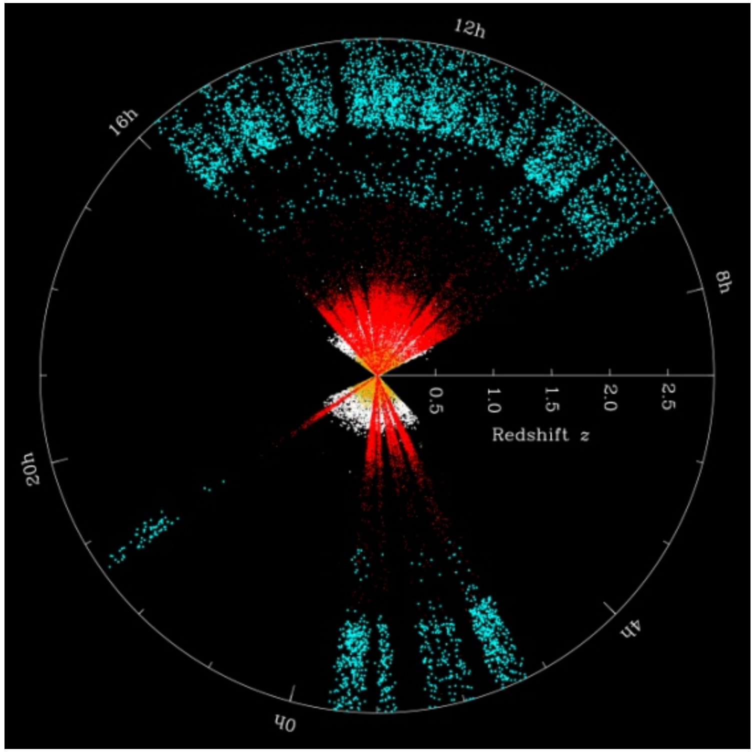
BAO probes

Luminous Red galaxies (LRGs)



(see Eisenstein et al. (2005) using SDSS DR3)

Lya Forest



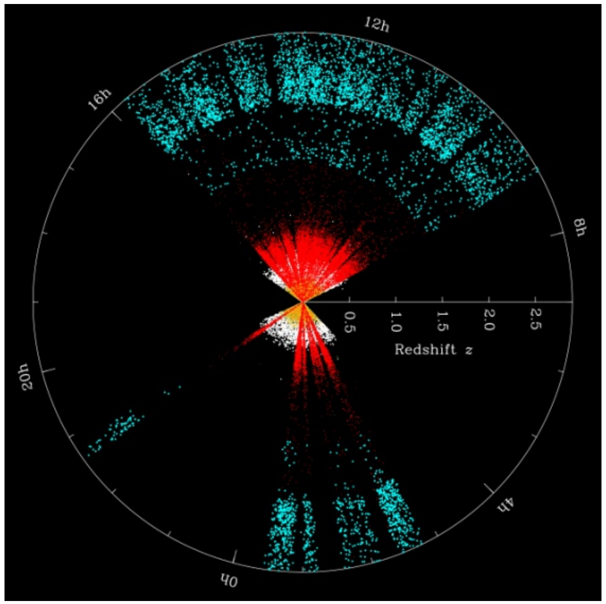
(courtesy of M. Blanton – SDSS-III)

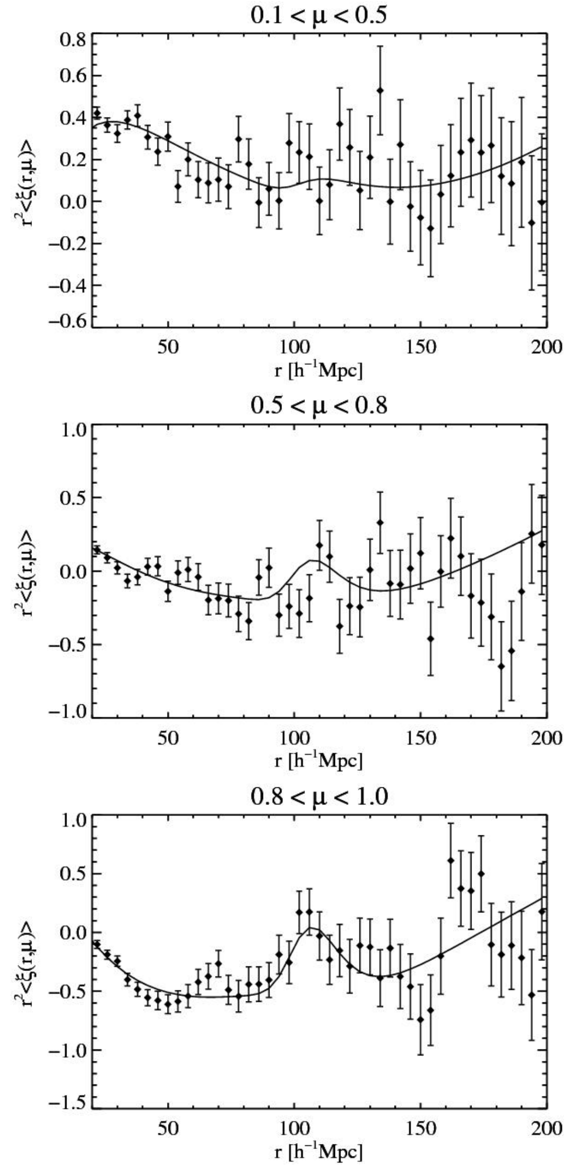
First detection of BAO through Ly-α forest analysis

Busca et al. (2013)

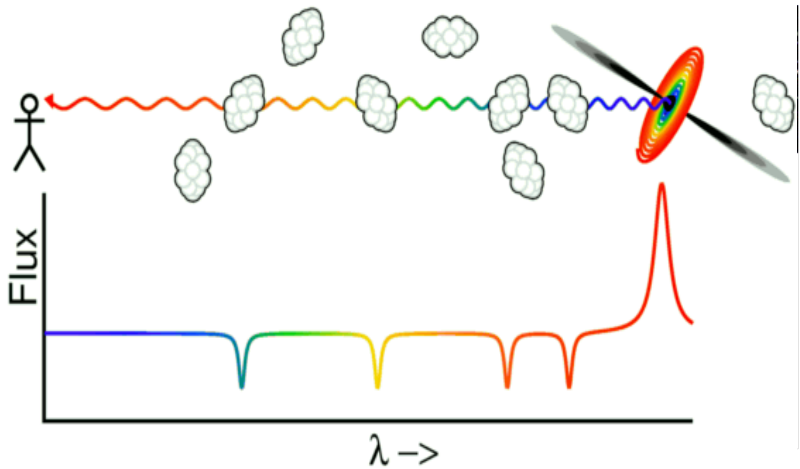
Slosar et al. (2013)

Using ~ 50000 quasars in the redshift range 2.1 ≤ z ≤ 3.5 from BOSS DR9





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)

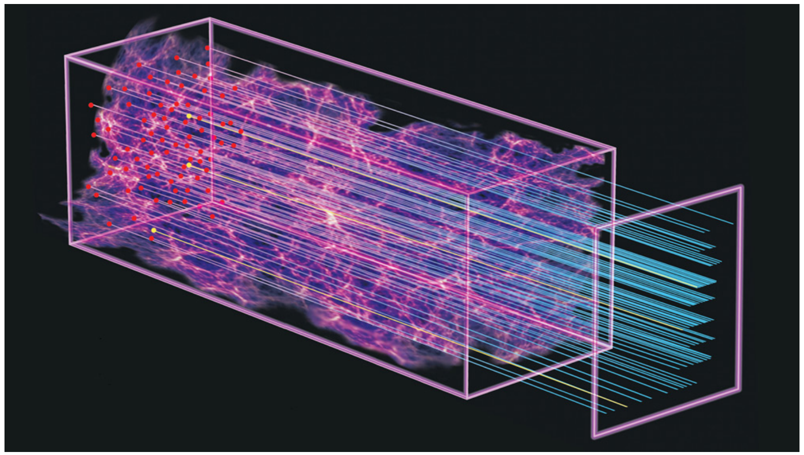
⬇

"Fluctuating Gunn-Peterson Approximation"

Lyα Optical depth τ ⟺ DM overdensity Δ

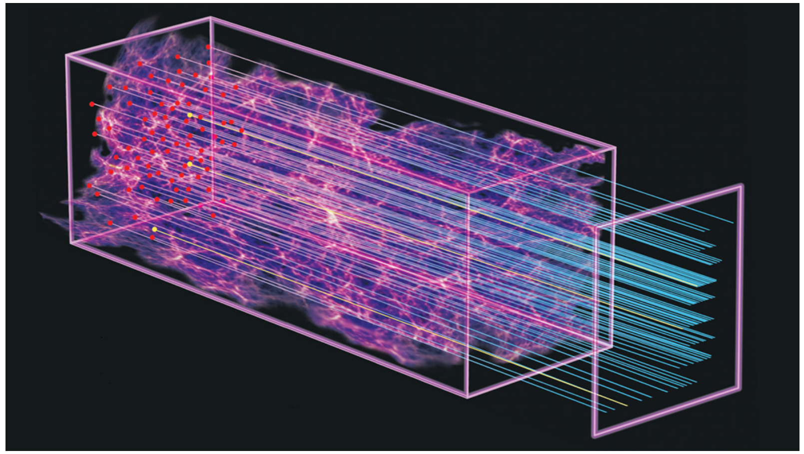
(FGPA, Katz, Weinberg & Hernquist 1998; Croft et al. 1998)

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:

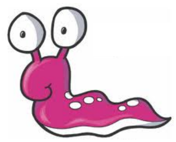
- **Model Gpc^3 volume while retaining good resolution on the gas Jeans scale**
- **The choice of the smoothing scale for DM produces ambiguity in the predictions**
- **The FGPA assumes a deterministic relation between ρ and $F=e^{-\tau}$**

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

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

A : normalization constant

Plan



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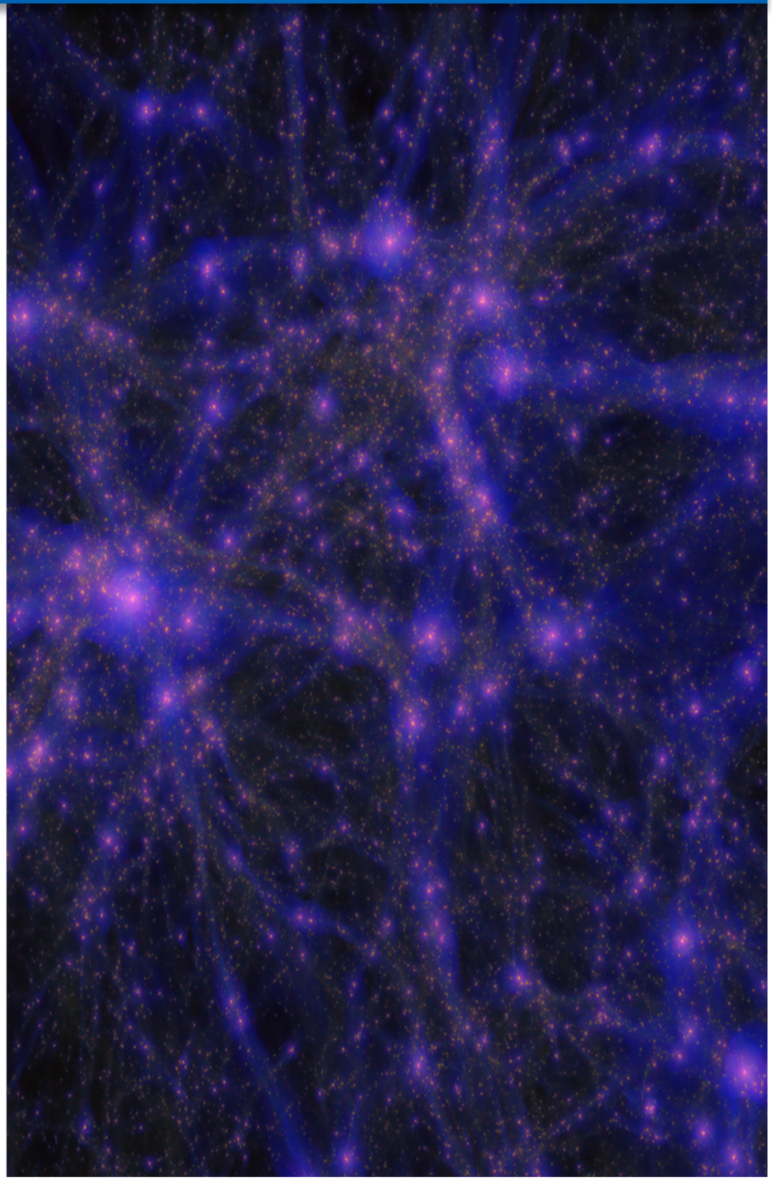
MareNostrum (2006)

- Horizon-MareNsotrum simulation

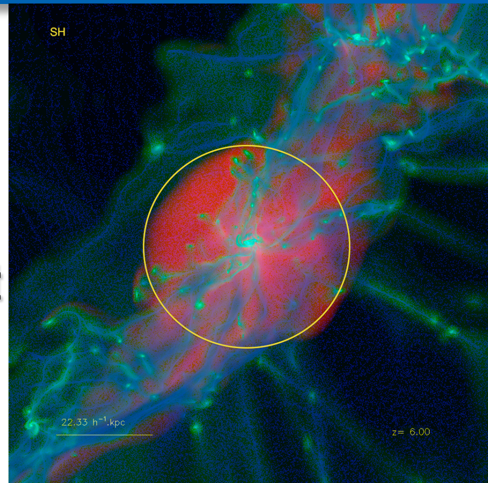
  (PI J. Devriendt, R. Teyssier, G. Yepes)
  - L_{box}=50 Mpc/h
  - 1024^3 DM particles $M_{DM,res}=8\times10^6$ M_{sun}
  - Finest cell resolution dx=1 kpc (-1 level of refin.)
  - Gas cooling & UV background heating
  - Low efficiency star formation
  - Stellar winds + SNII + SNIa
  - O, Fe, C, N, Si, 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

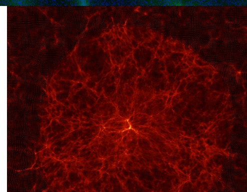


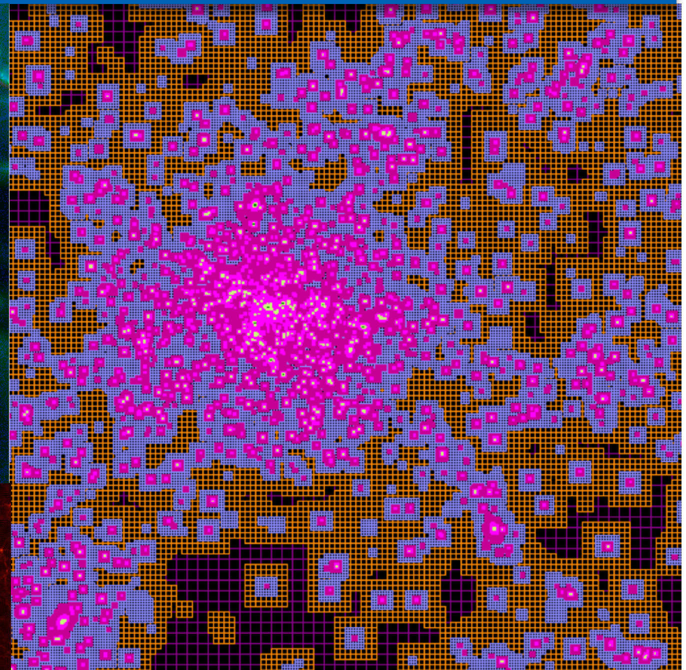
RAMSES: an adaptive Mesh Refinement (AMR) code

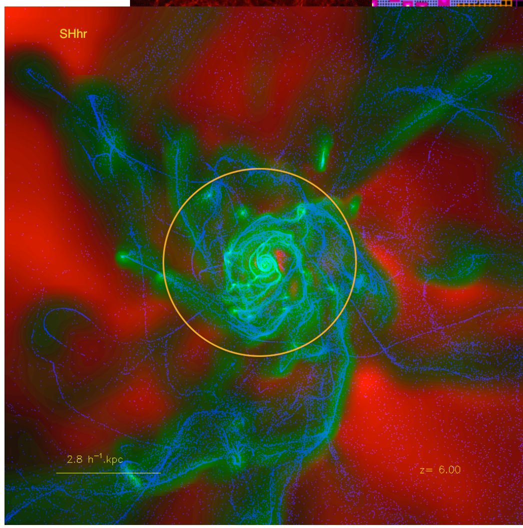
- Language :
  - Fortran 90
  - MPI parallel
- Method : adaptive grid refinement
- Equations :
  - Hydrodynamics
  - Gravity
  - Atomic/Metal cooling + UV-heating
  - (Magneto-hydrodynamics)
  - (Radiative transfer)
- Sub-grid physics :
  - Star formation
  - Supernovae & Stellar Winds
  - Active Galactic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

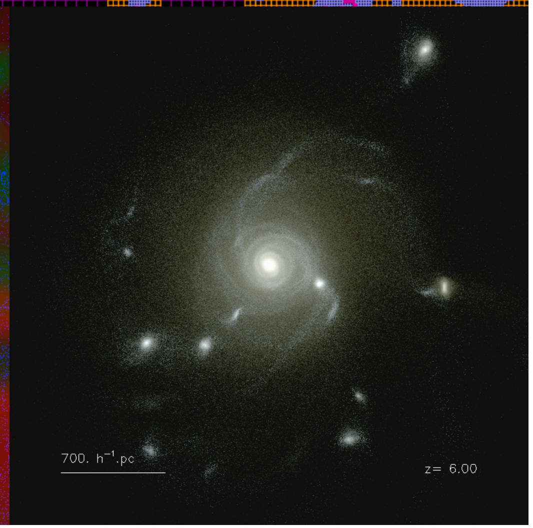
See Teyssier, 2002



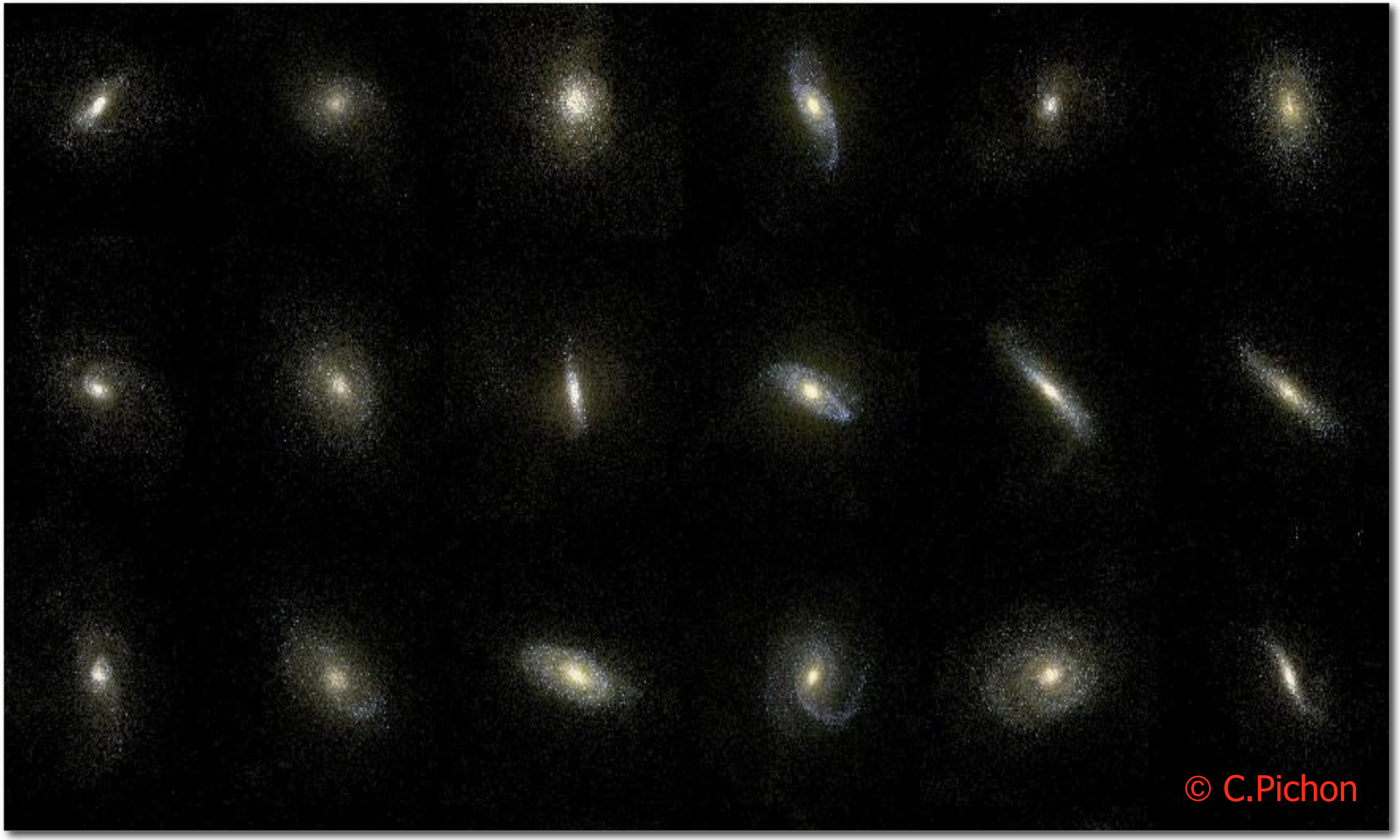








The MareNostrum Galaxy Gallery

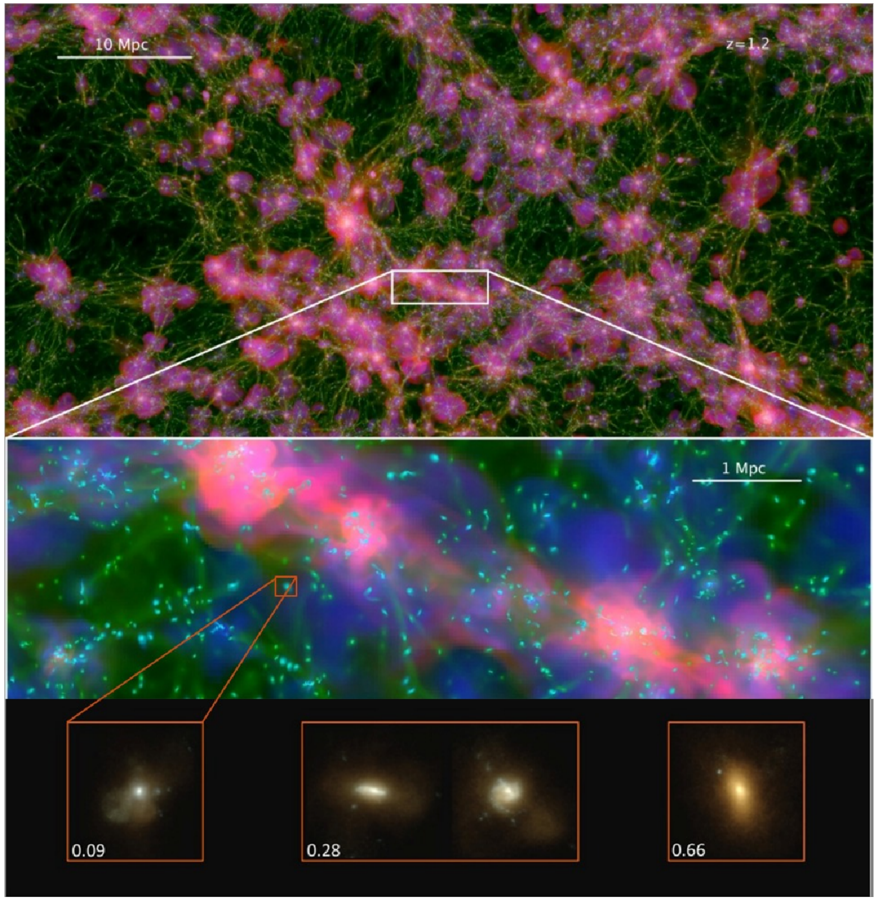


Stars are shown in true observed colors (I K and IRAC @ 8 microns)

http://www.projet-horizon.fr

Horizon-AGN

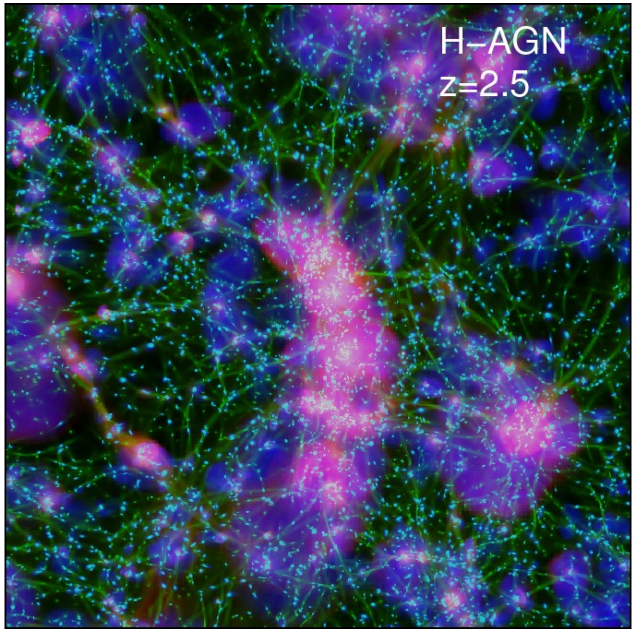
- **Horizon-AGN simulation**
  - L_{box}=100 Mpc/h
  - 1024^3 DM particles $M_{DM,res}=8\times10^7 M_{sun}$
  - Finest cell resolution dx=1 kpc (-1 level of refin.)
  - Gas cooling & UV background heating
  - Low efficiency star formation
  - Stellar winds + SNII + SNIa
  - O, Fe, C, N, Si, Mg, H
  - 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**



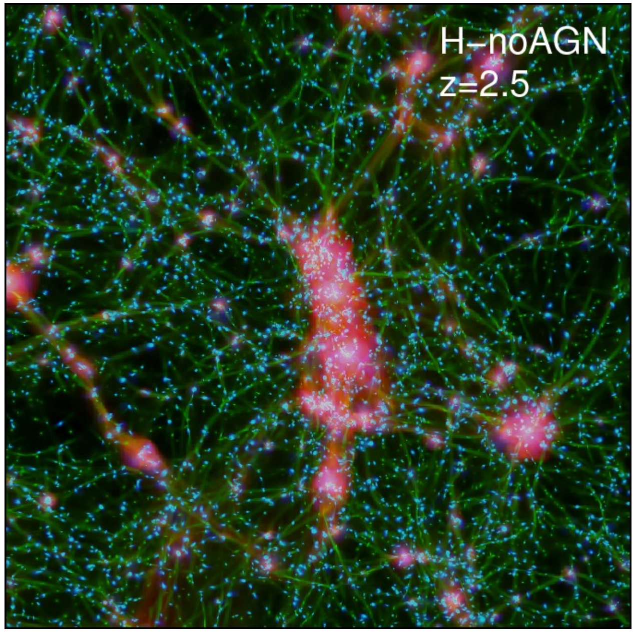
Dubois et al. (2014)

Horizon-AGN – Horizon-noAGN (2014)

Horizon-AGN (Dubois)



Horizon-noAGN (Peirani)



Gas density

Gas temperature

Gas metallicity

- L_{box}=100 Mpc/h
- 1024^3 DM particles $M_{DM,res}=8x10^7 M_{sun}$
- Finest cell resolution dx=1 kpc (-1 level of refin.)
- Gas cooling & UV background heating

- Low efficiency star formation
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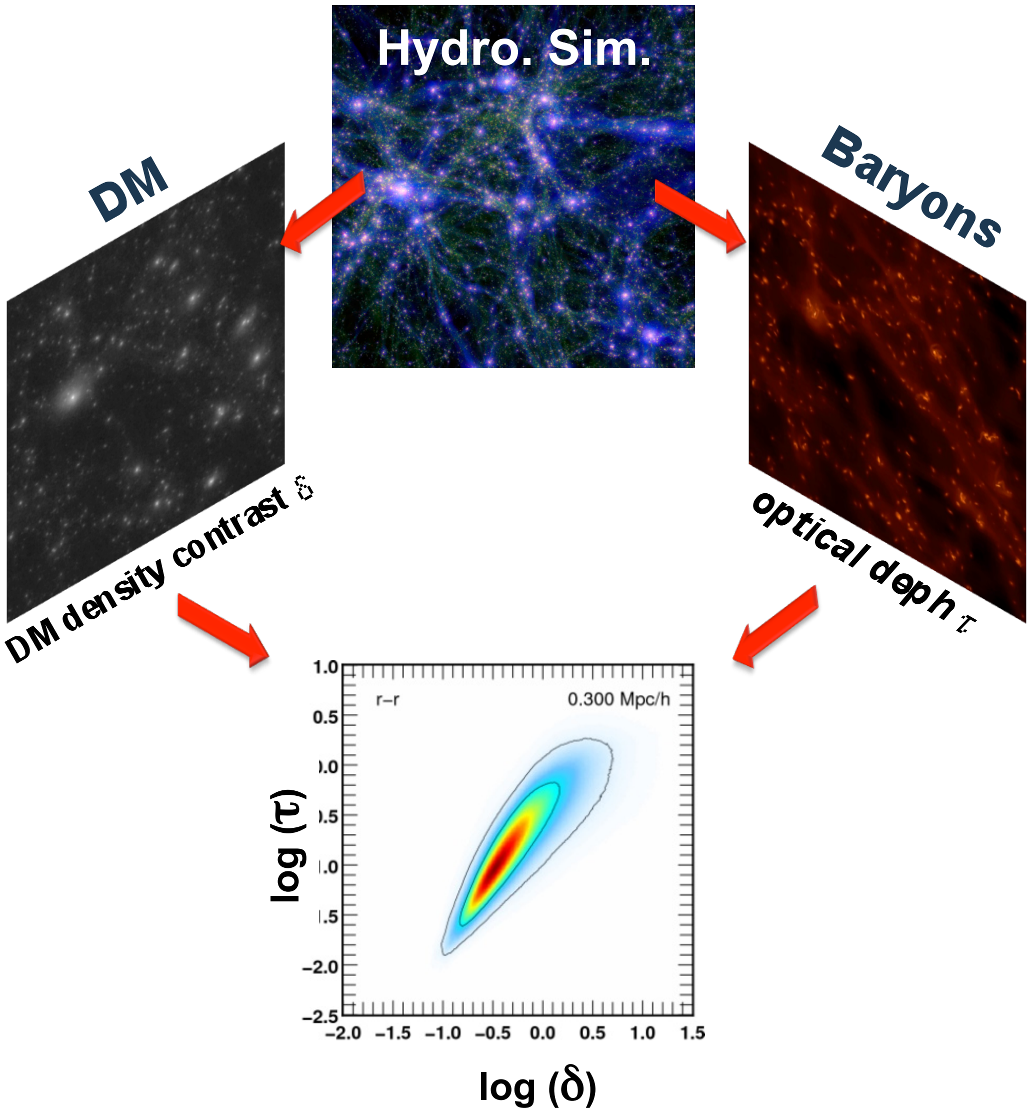
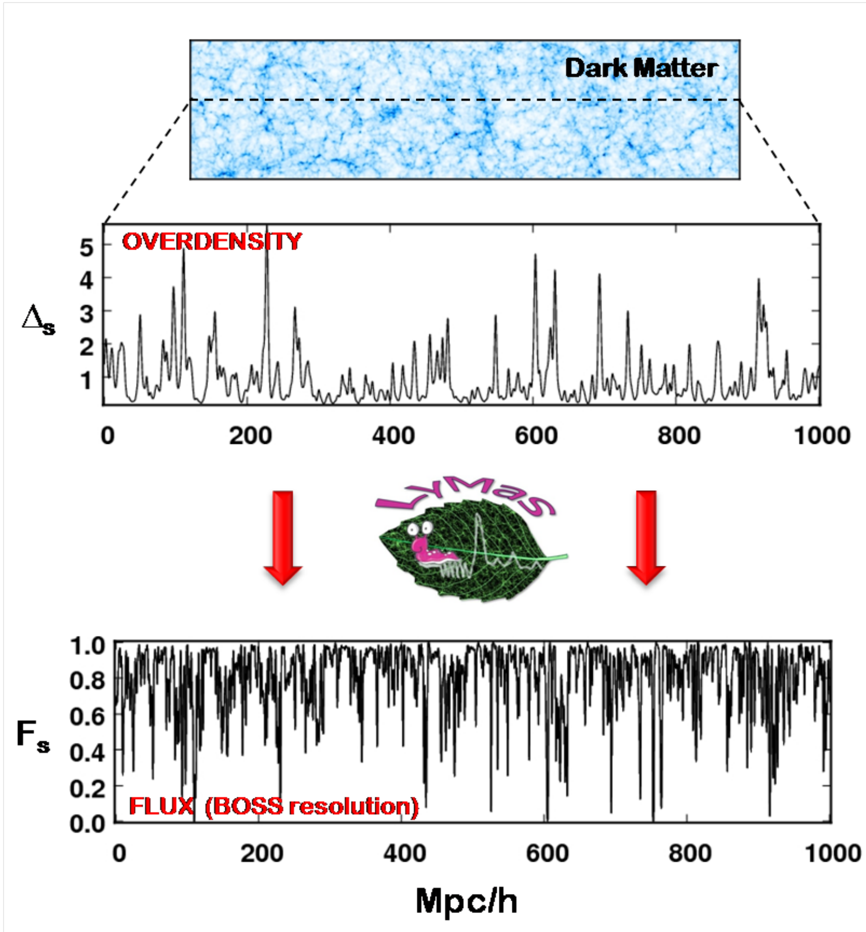
LyMAS: Lyα Mass Association Scheme

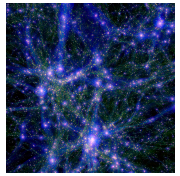




Extracting Lyα spectra

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 pixels)

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

dl **: physical cell size**

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

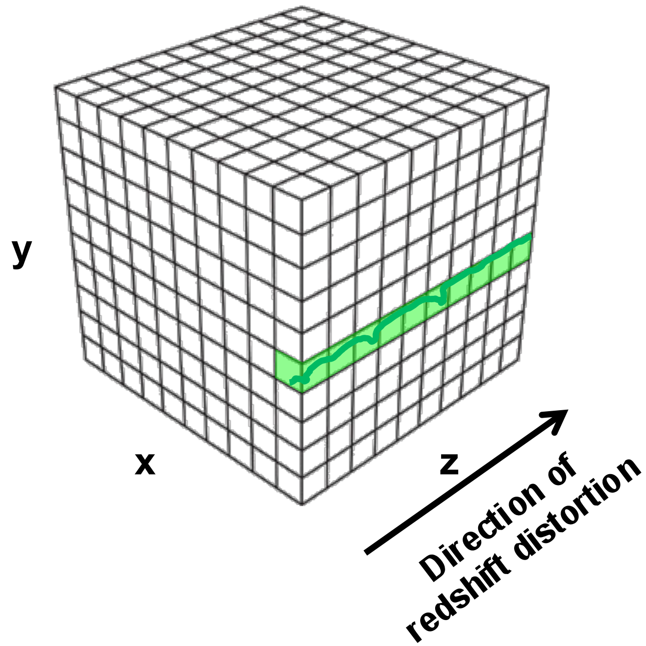
$$\sigma(\upsilon_{obs}) = f_{12}\frac{\pi e^2}{m_e c}\times\frac{H(a,x)}{\sqrt{\pi}\Delta\nu_D}$$

$f_{12} = 0.4162$ **: 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**



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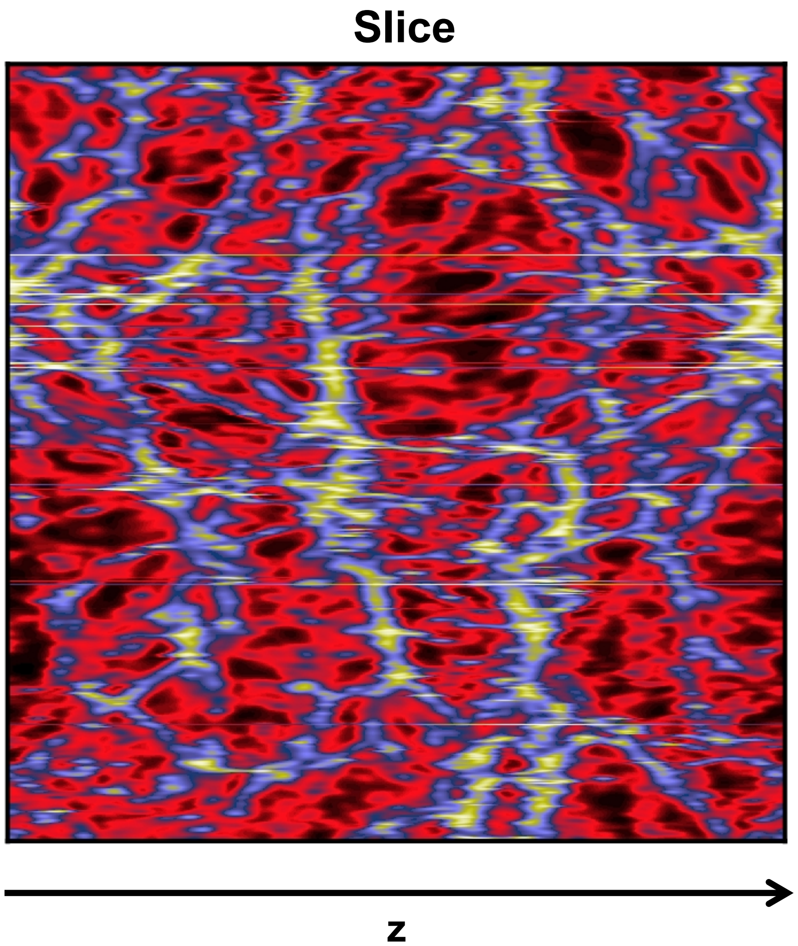
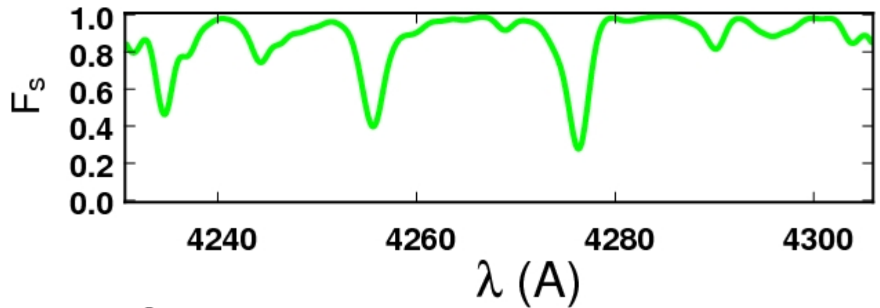
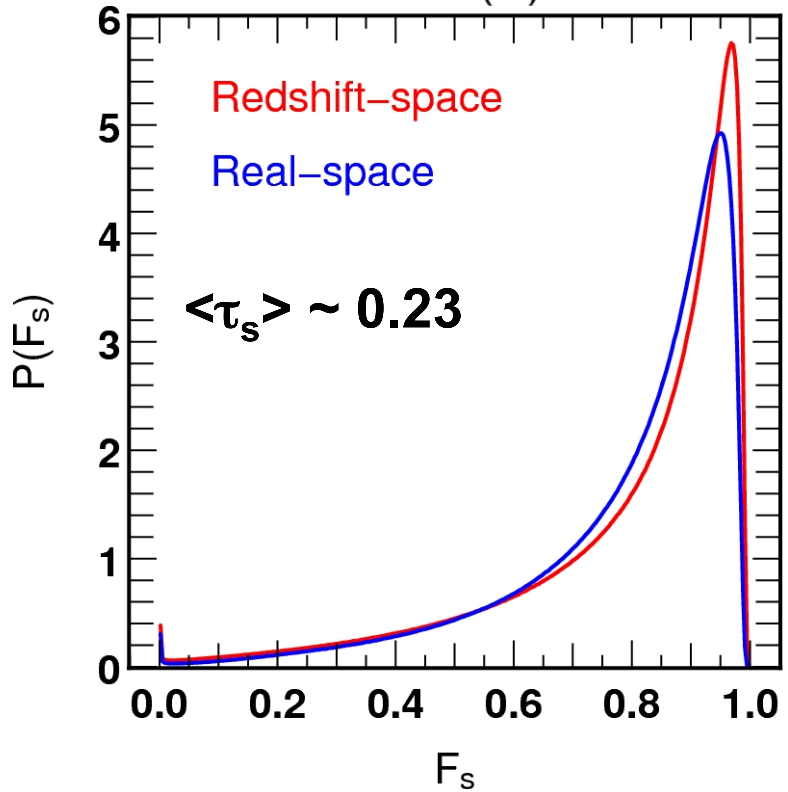


1-d smoothed at the BOSS resolution



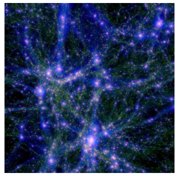


Extracting Dark matter skewers

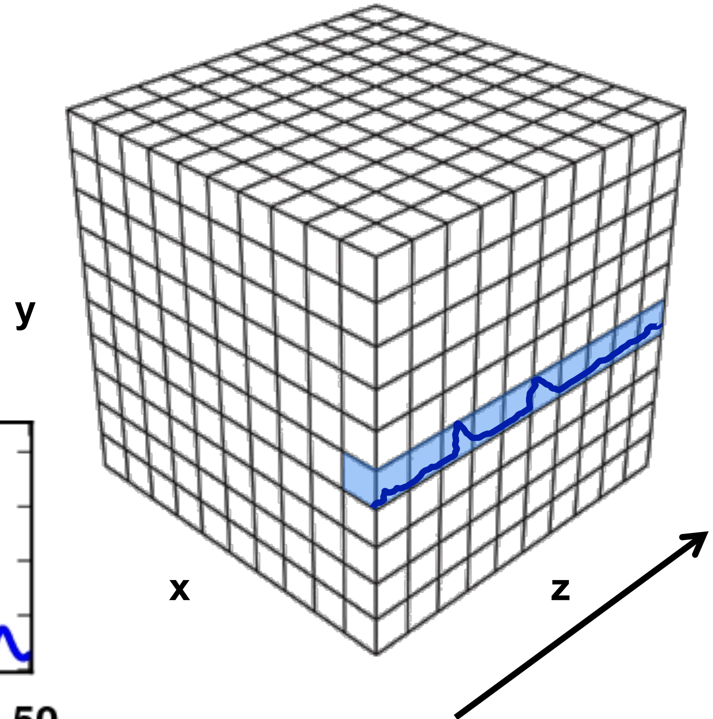
1. Adaptive interpolation of the DM particle distribution on a high resolution grid.

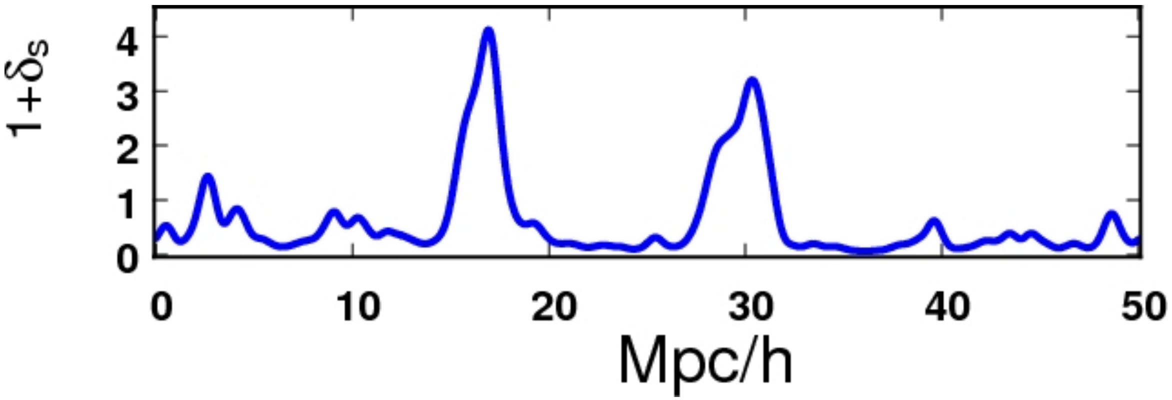
2. Smoothing with a Gaussian window in Fourier space

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



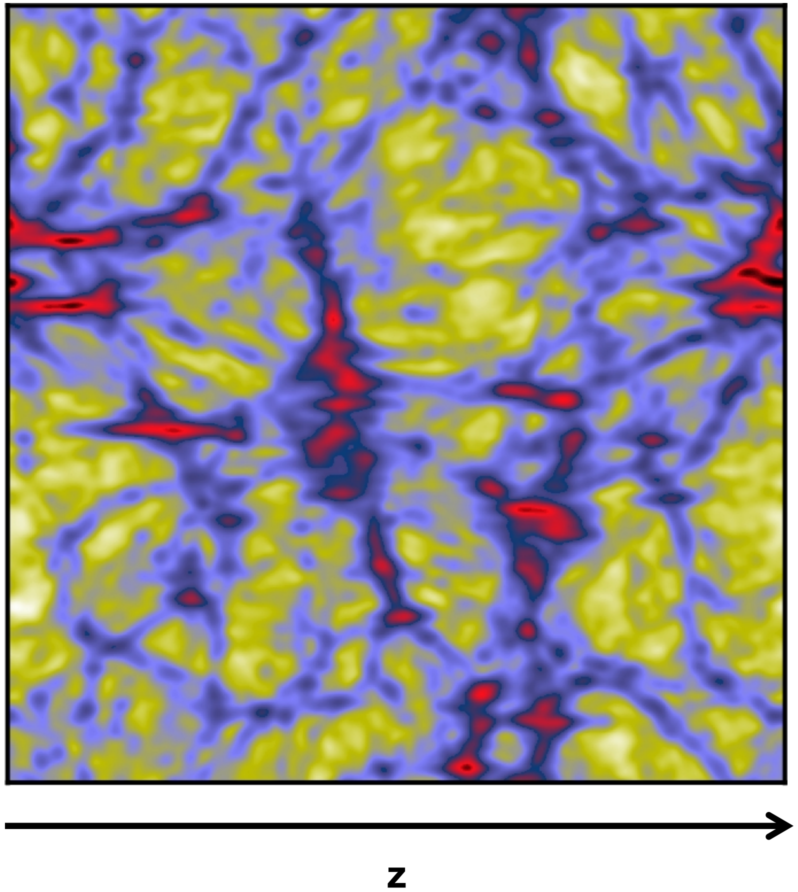
Grid of density field 1+δ (1024^3 pixels)



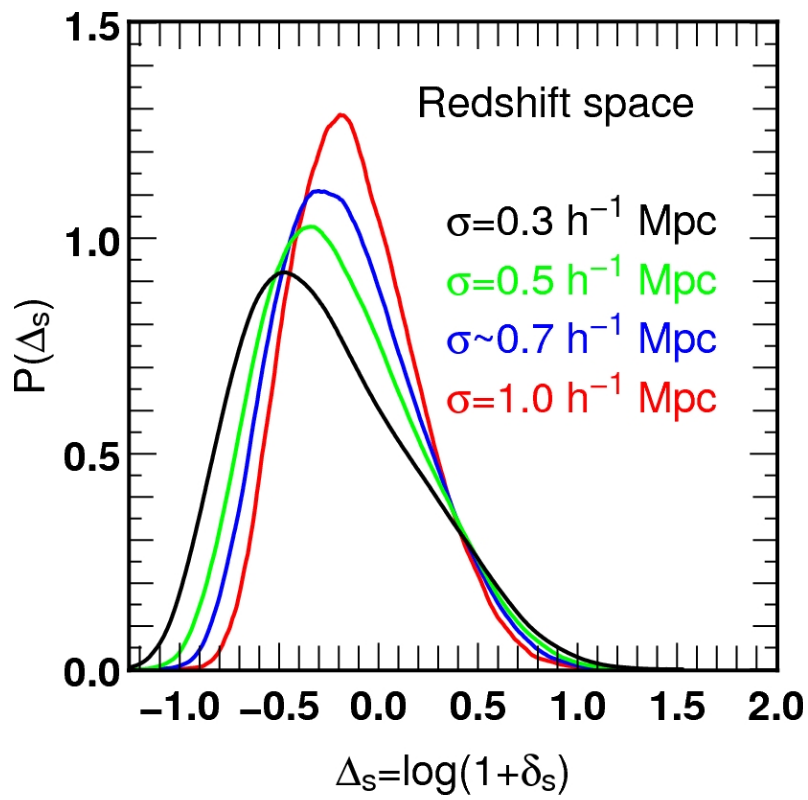


Extracting Dark matter skewers

Slice

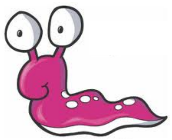


PDF



3-d smoothed at different scales

Plan



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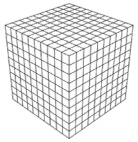
Deterministic mapping

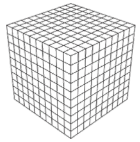
1. Construction of an "optimal" deterministic relation: $F_s = f(1+\delta_s)$

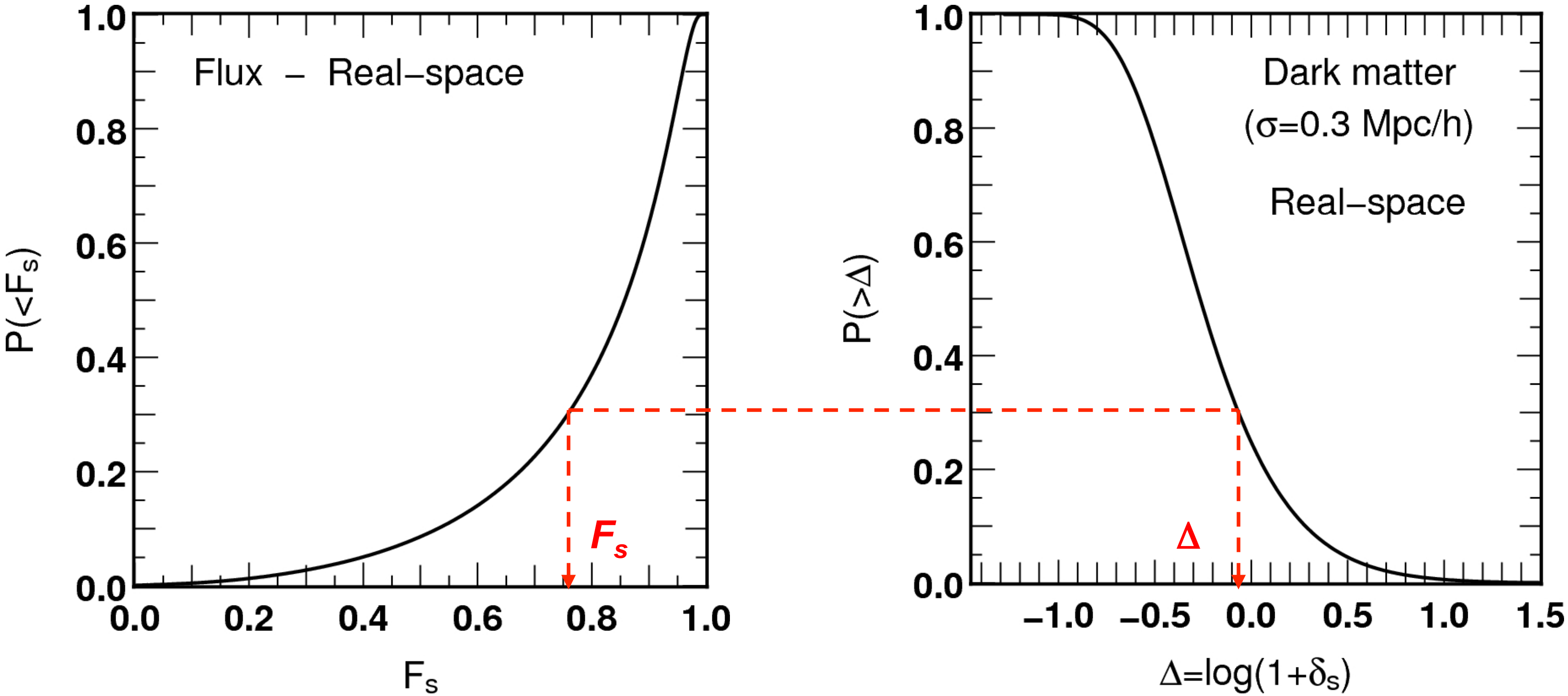
$$\int_0^{F_S} P(F_S')\, dF_S' = \int_{\delta_S}^{\infty} P(\delta_S')\, d\delta_S'$$

Grid of transmitted flux F_s



Grid of DM density contrast $1+\delta_s$

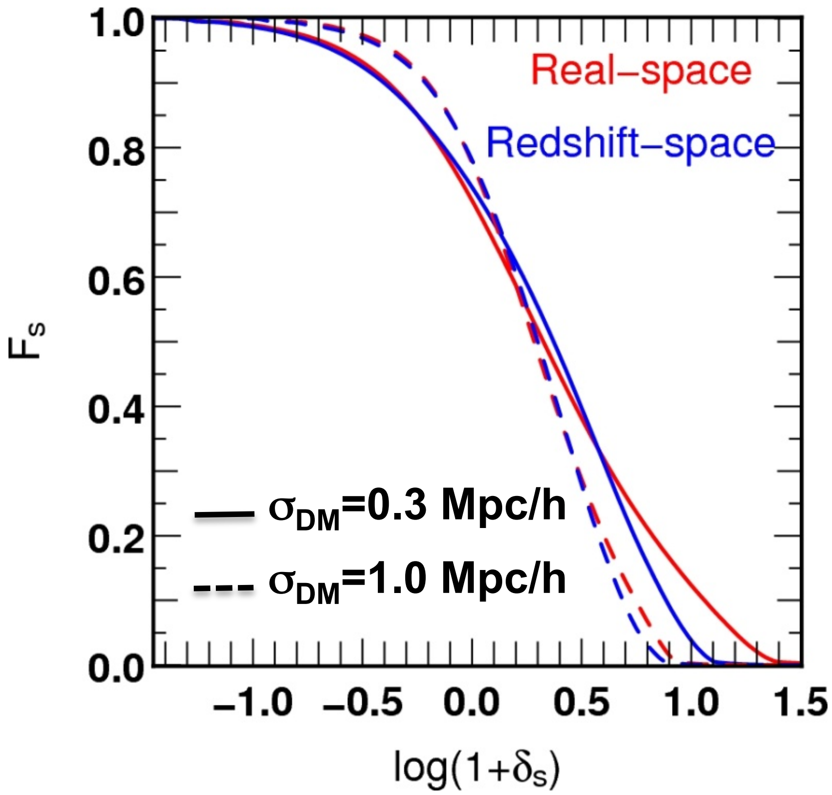


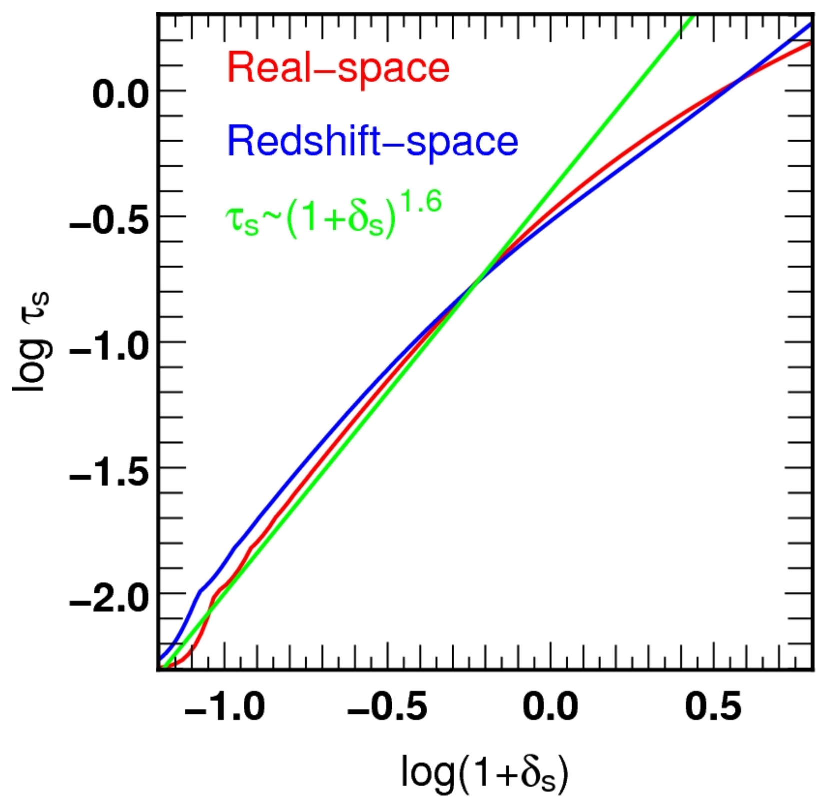


Deterministic mapping

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

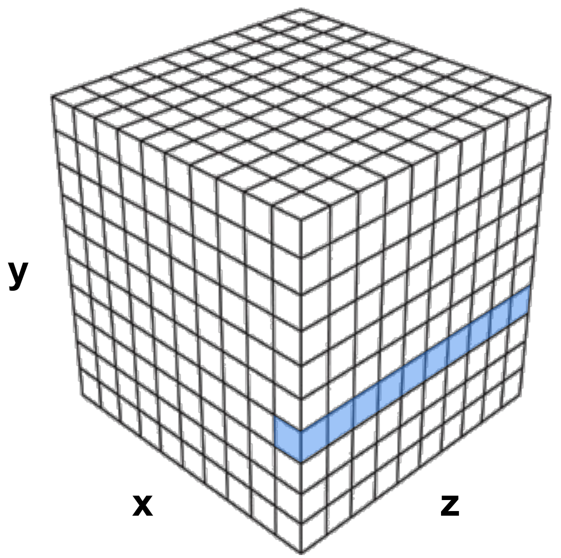
Optical depth: $\tau_s = -\ln F_s$

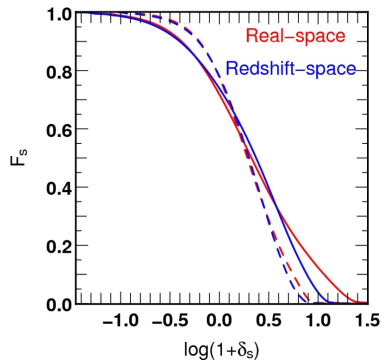




Deterministic mapping

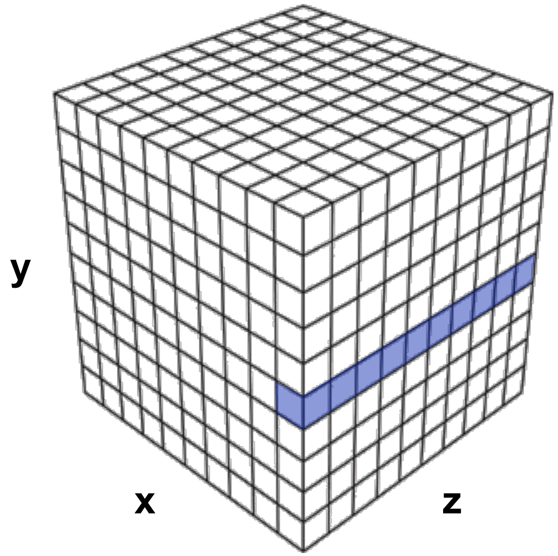
Grid of density contrast $1+\delta_s$
1024^3 pixels

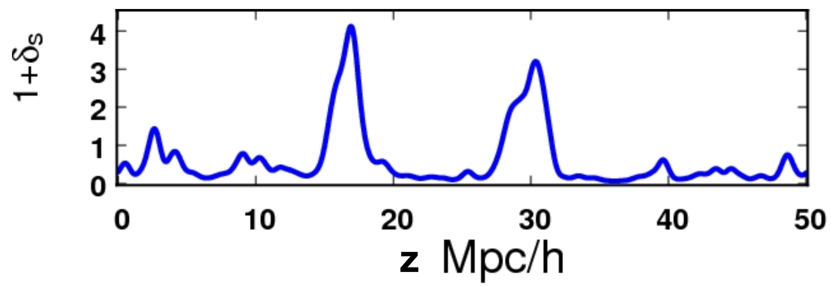


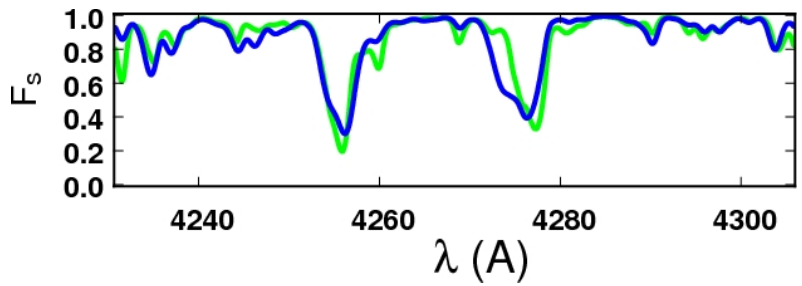


$$F_s = f(1+\delta_s)$$

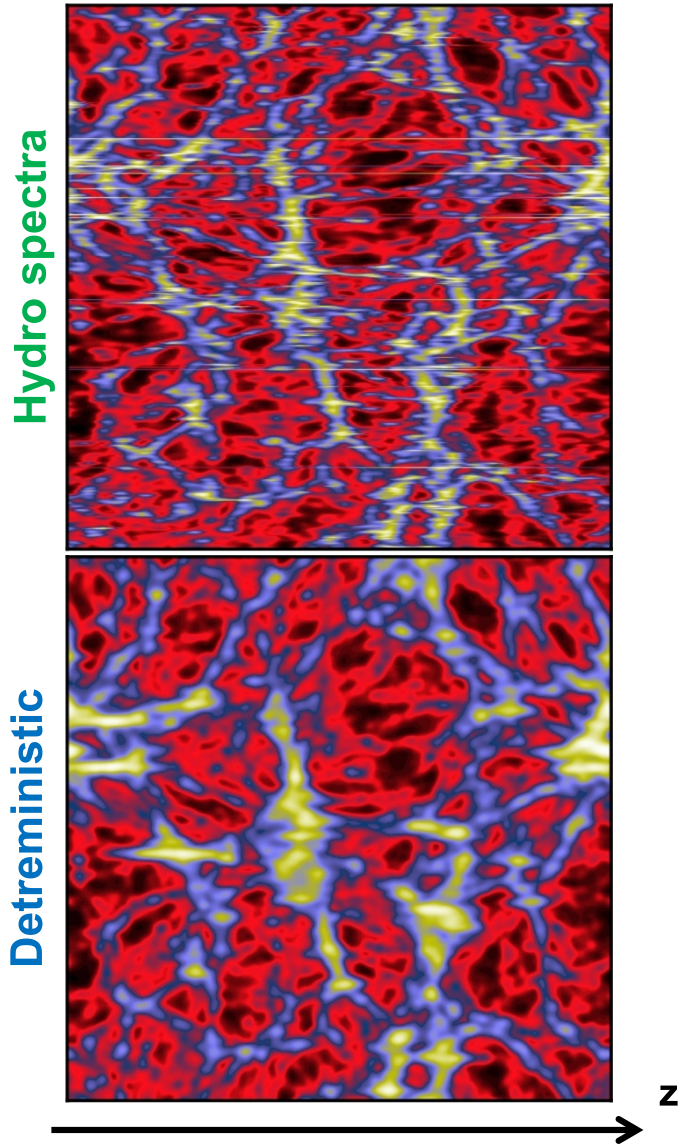
Grid of predicted transmitted flux F_s
1024^3 pixels

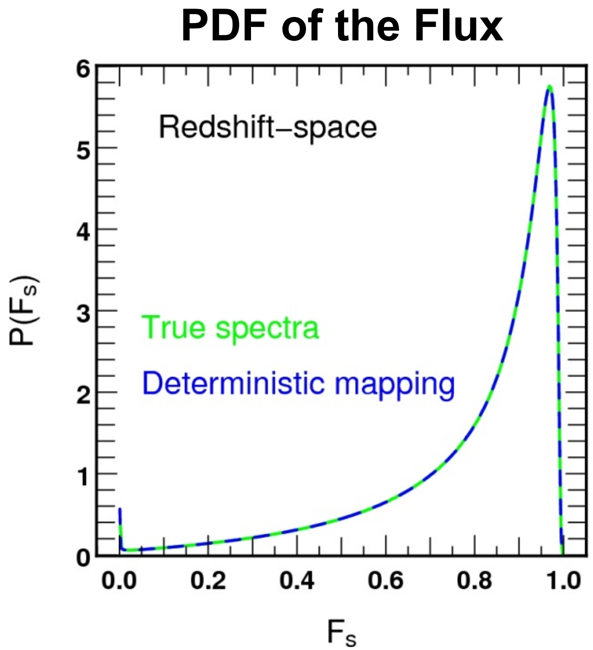


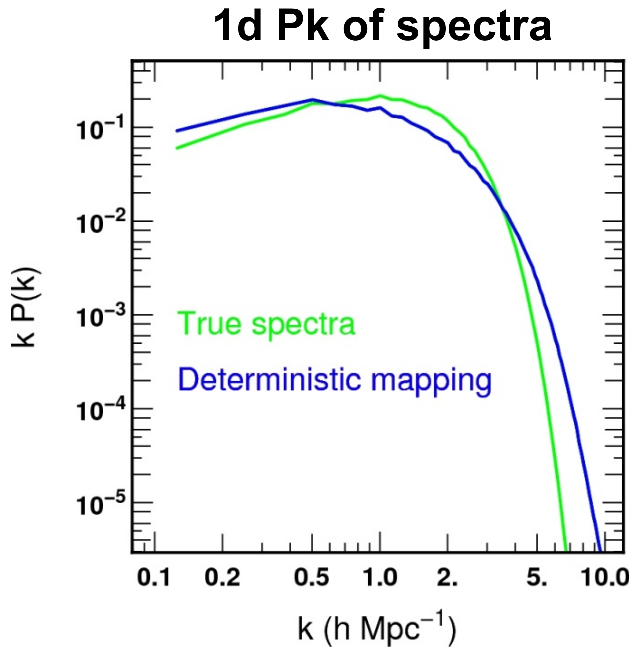


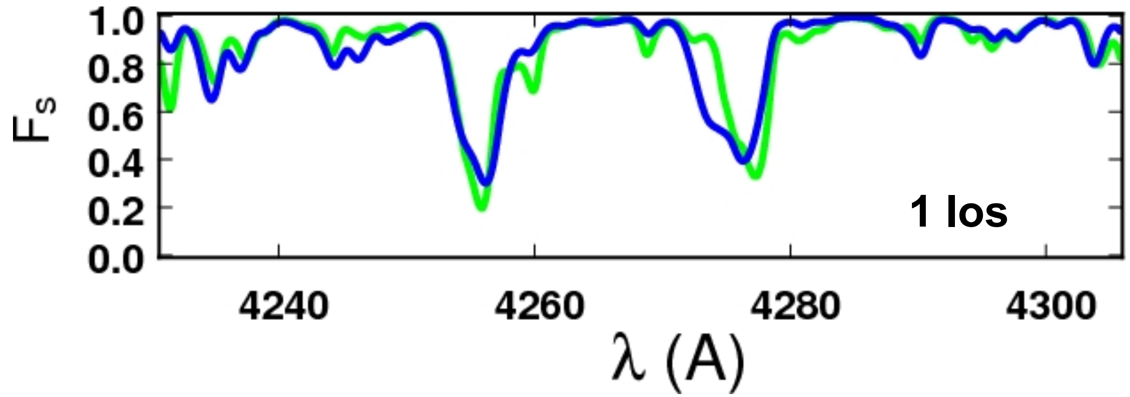


Deterministic mapping

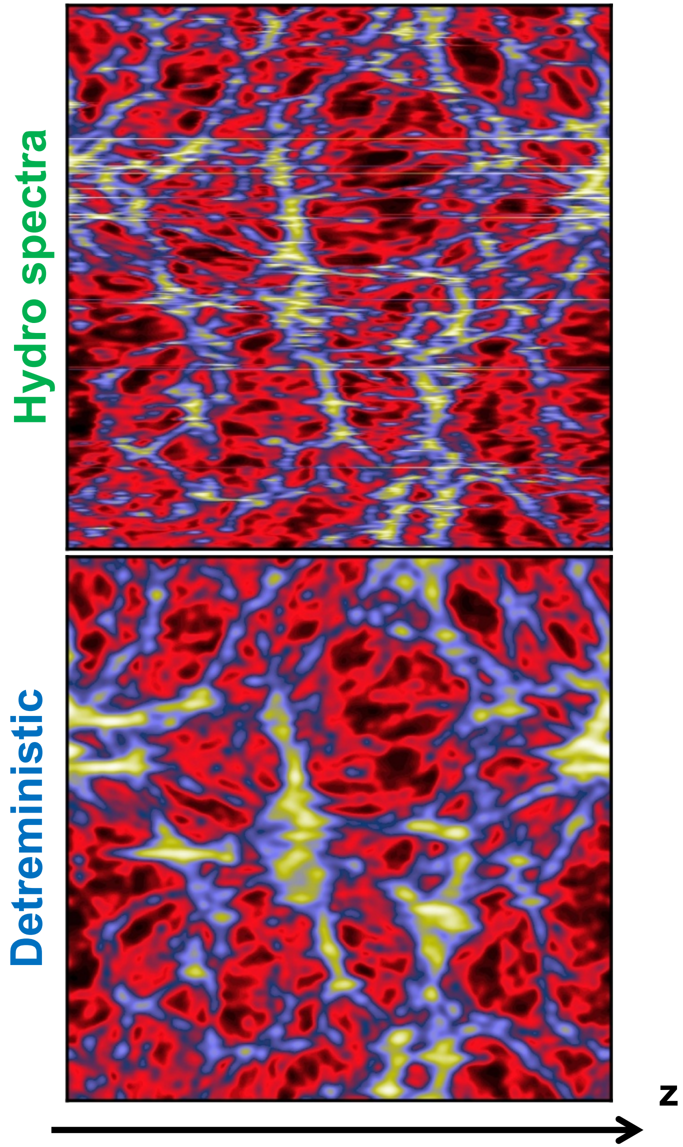


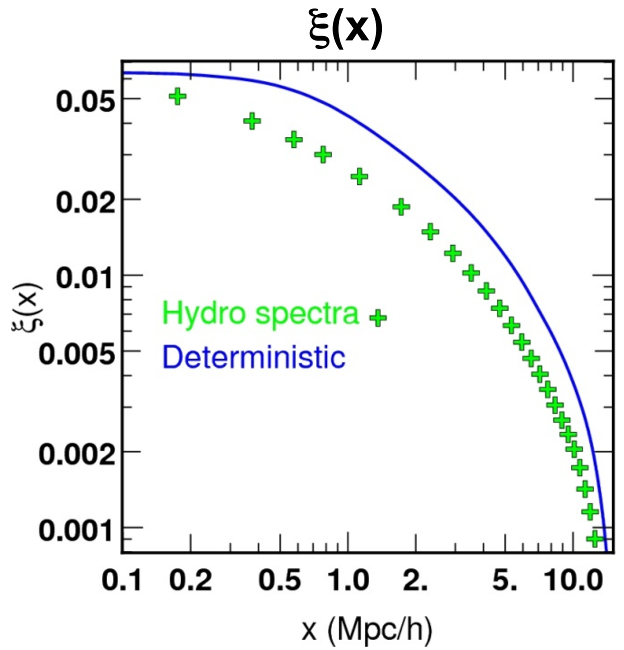


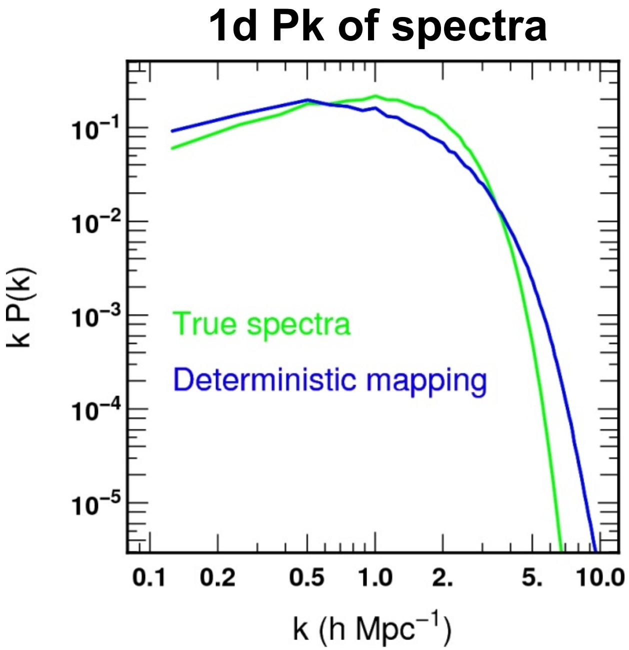


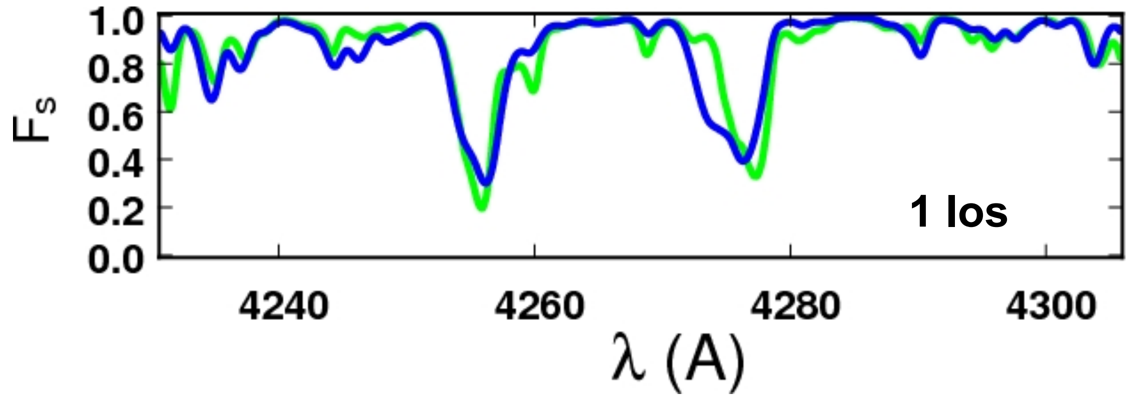


Deterministic mapping

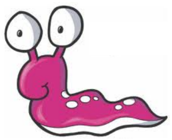








Plan



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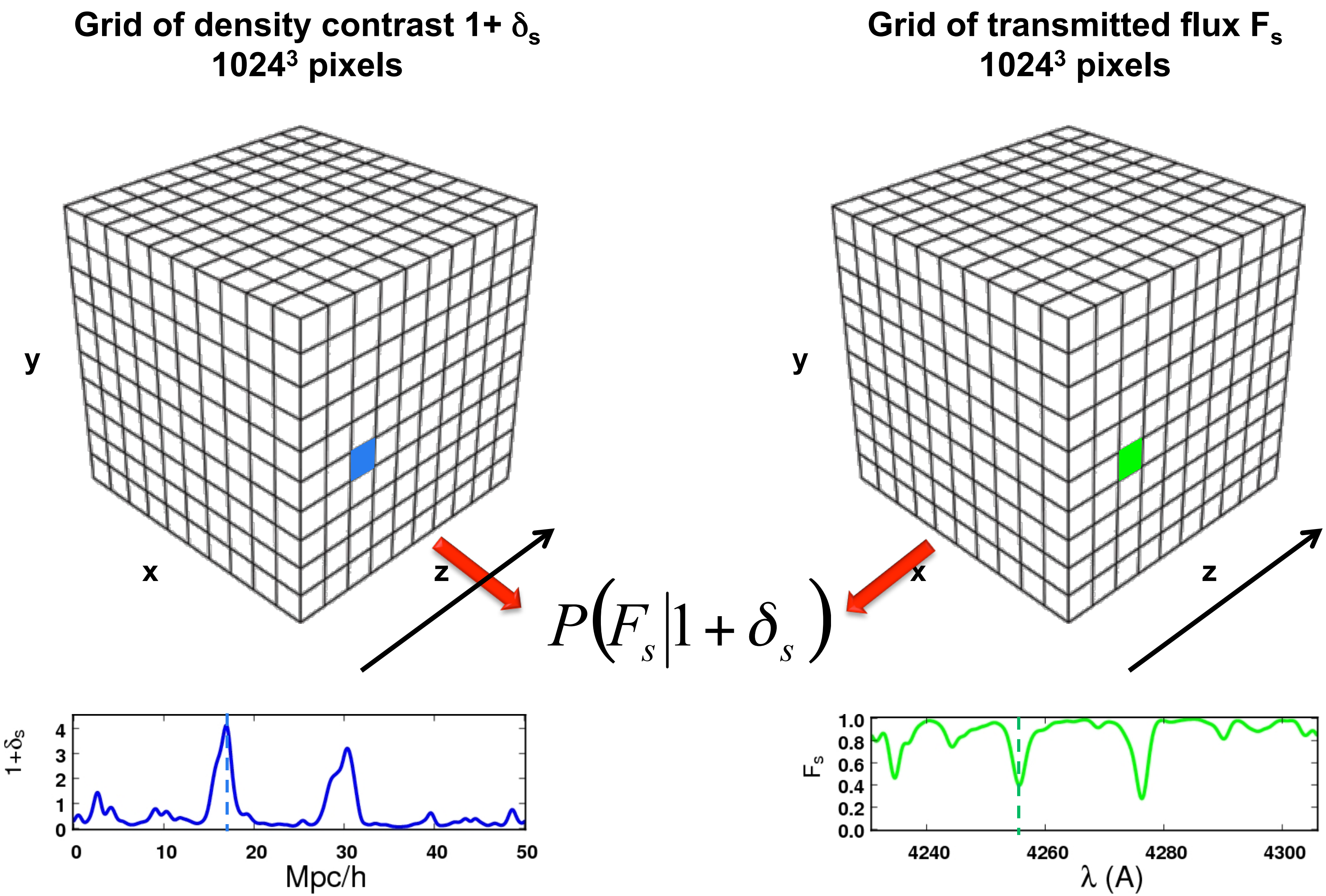
Predicting conditional Flux distributions



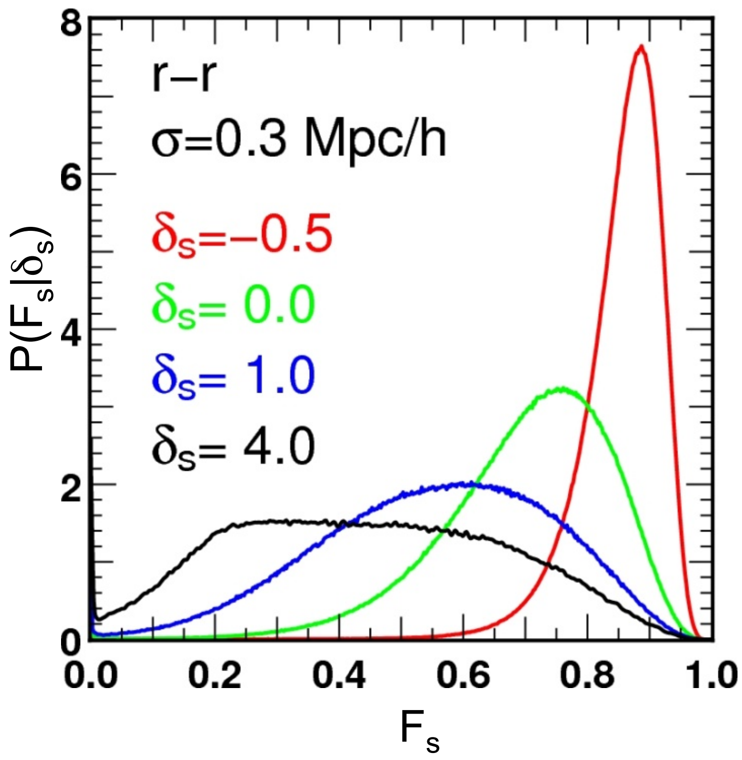
Predicting conditional Flux distributions

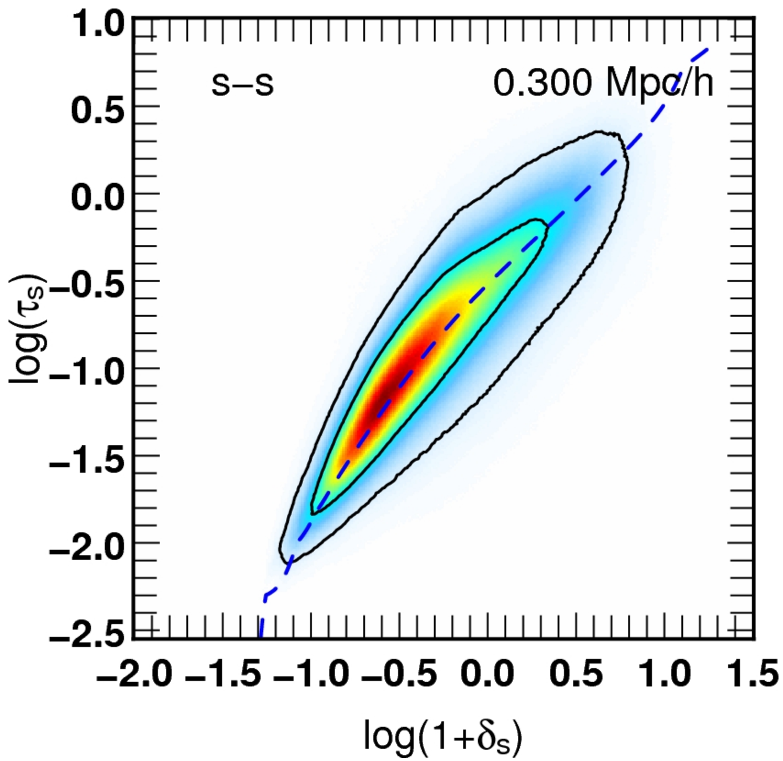
$$P\left(F_s \middle| 1+\delta_s\right)$$

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

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

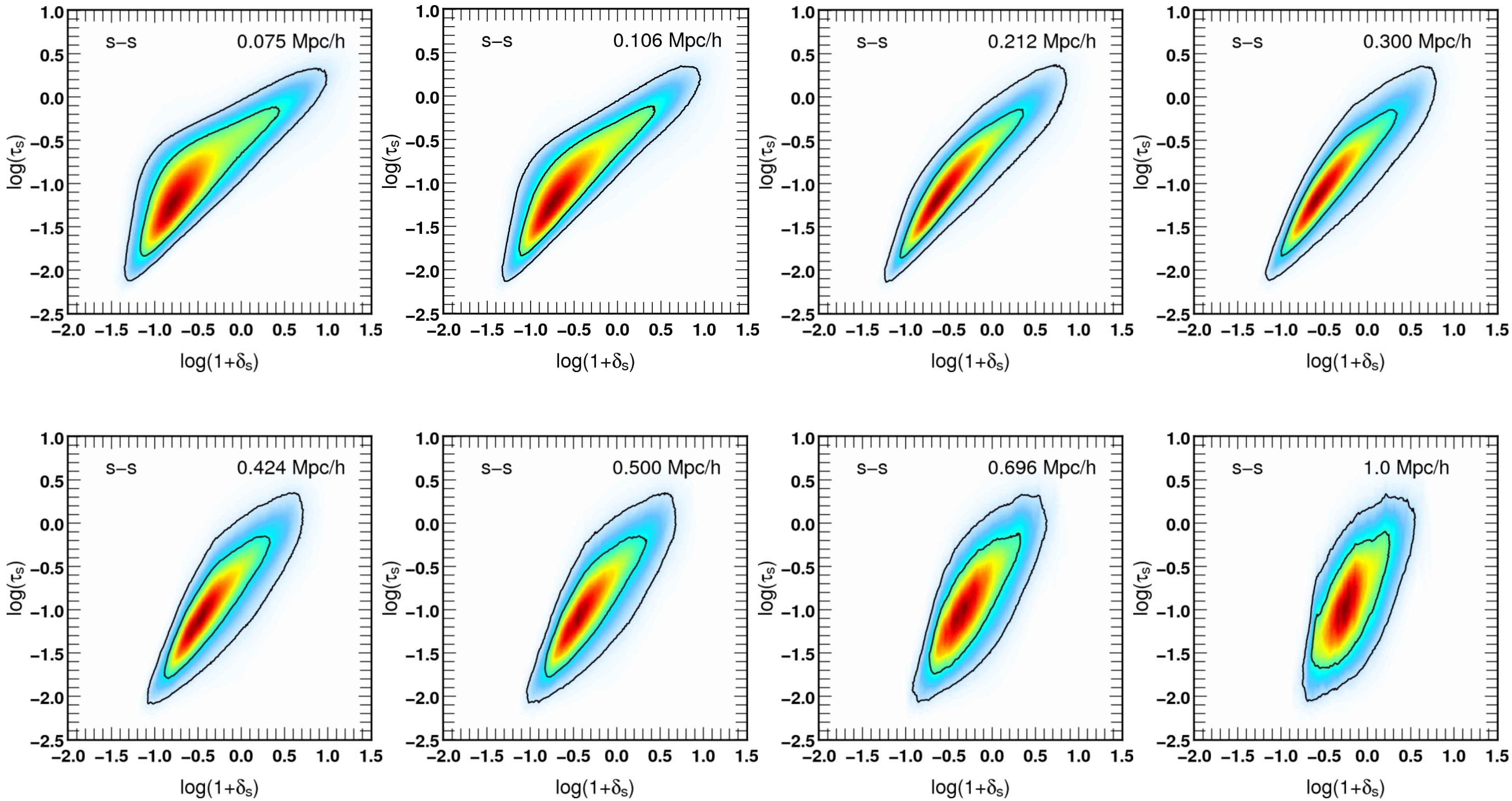
Ex:



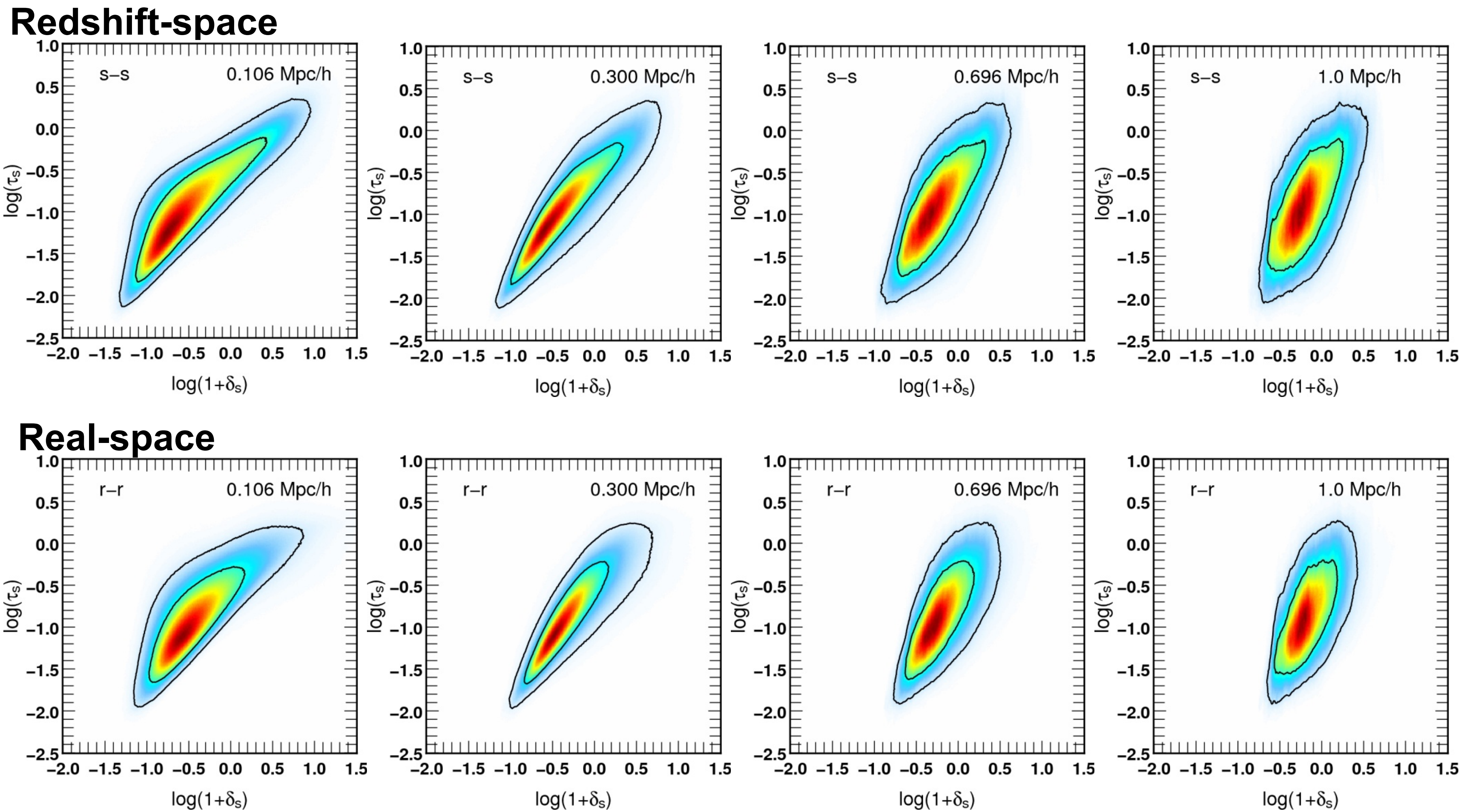


Predicting conditional Flux distributions

Redshift-space

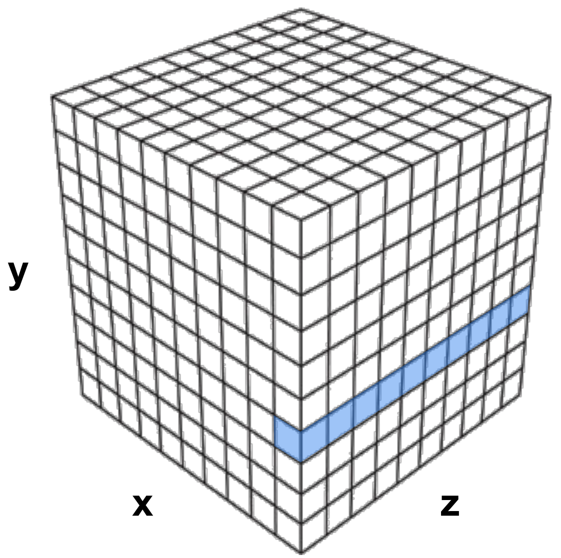


Predicting conditional Flux distributions

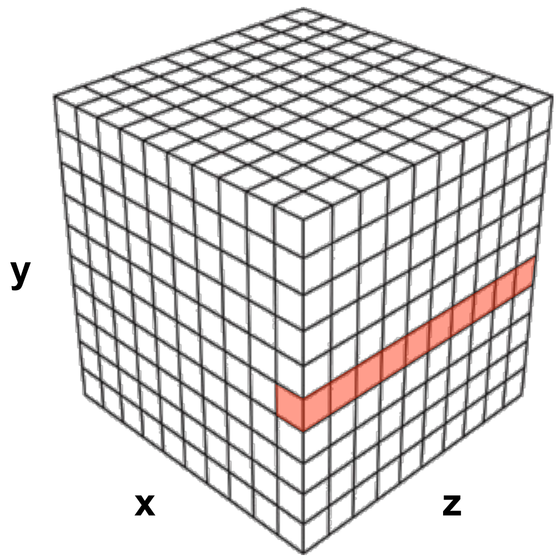


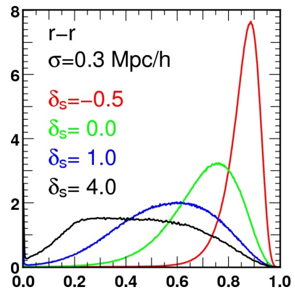
Probabilistic mapping

Grid of DM density contrast 1+ δ_s
1024^3 pixels

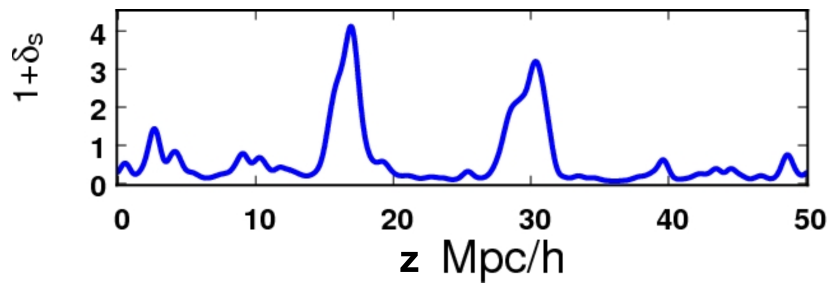


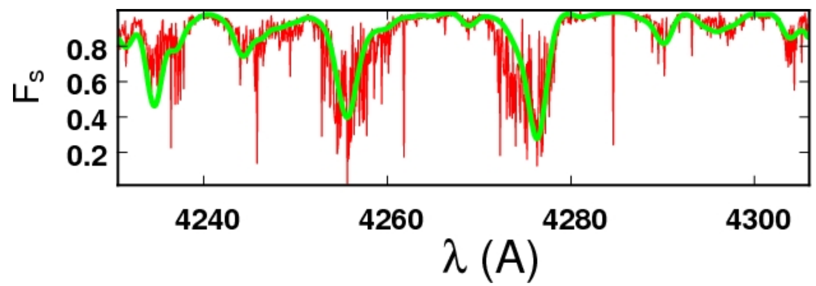
Grid of predicted transmitted flux F_s
1024^3 pixels



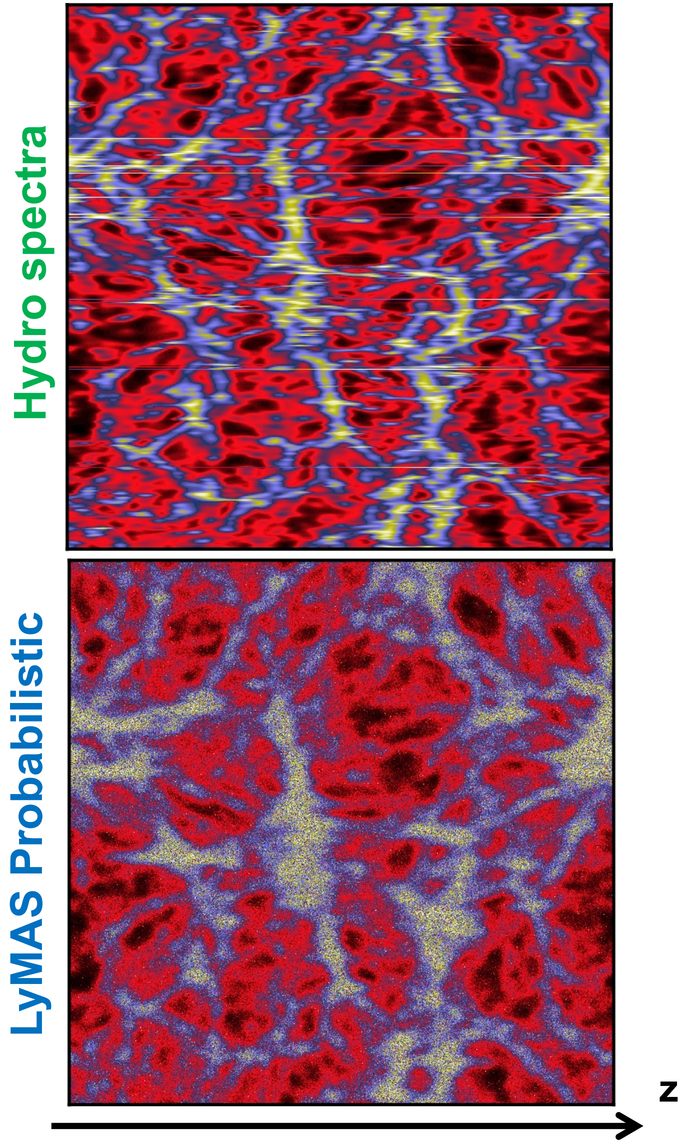


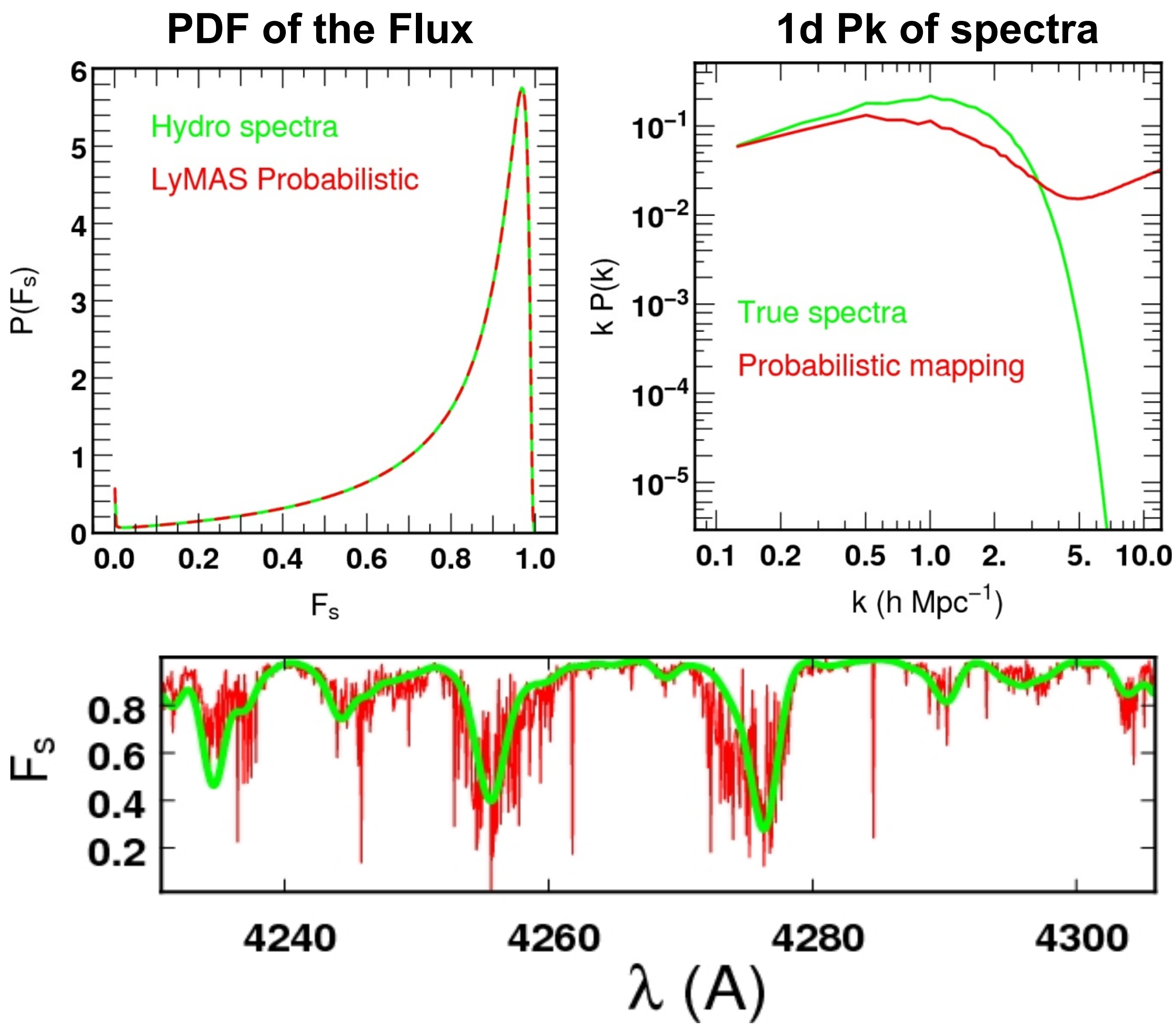
$$P\left(F_s \middle| 1+\delta_s\right)$$



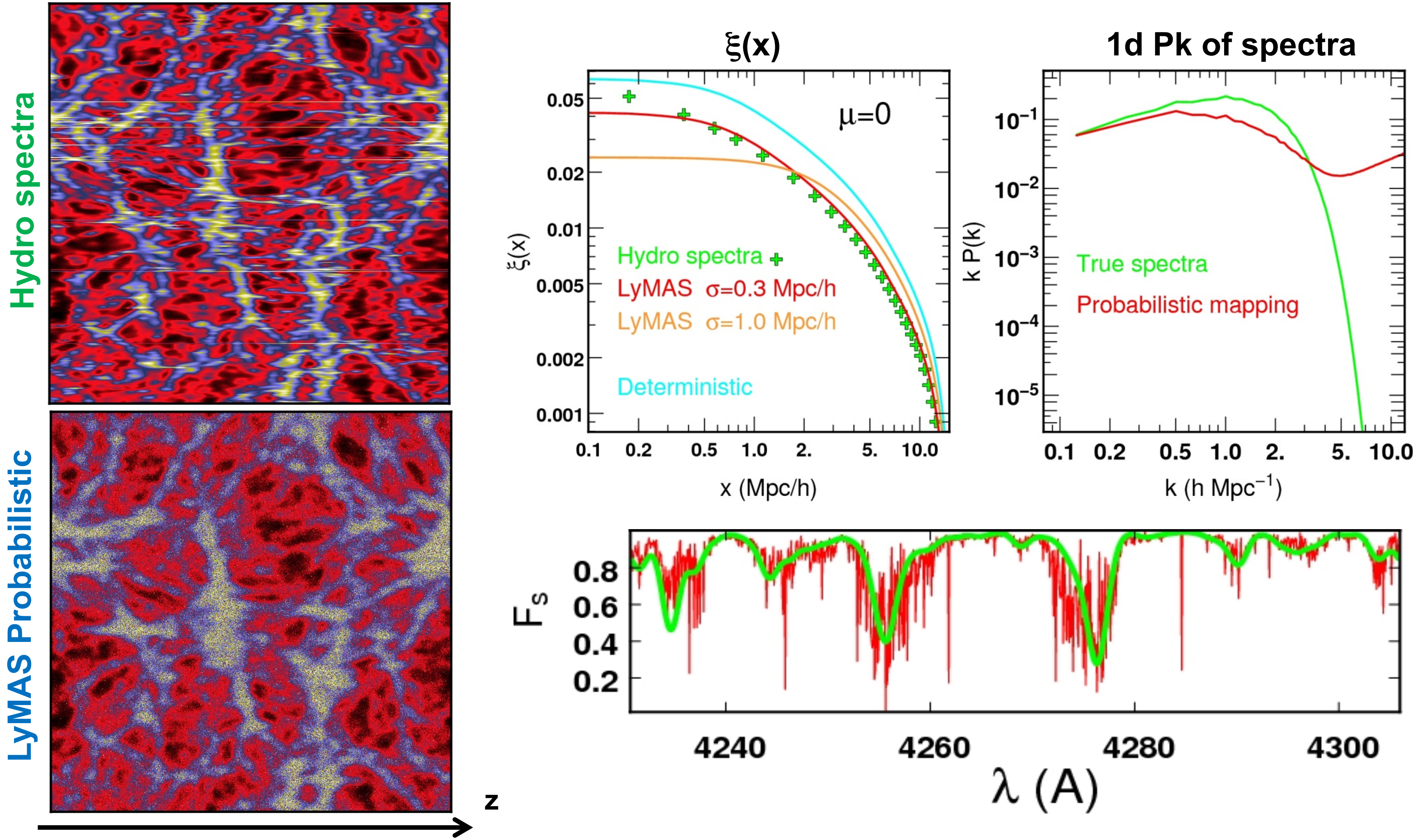


Probabilistic mapping





Probabilistic mapping



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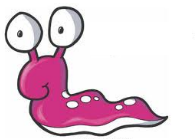

5. LyMAS Coherent mapping
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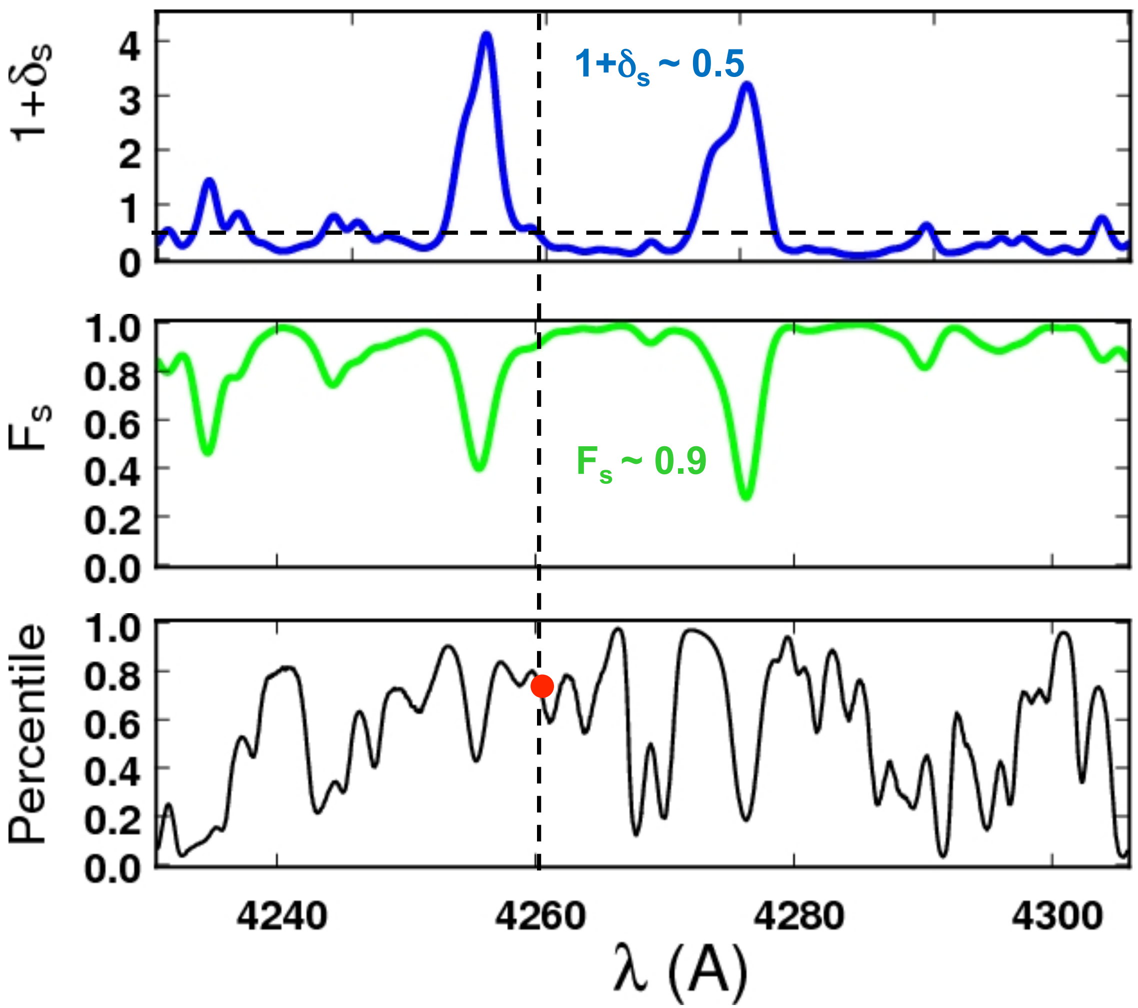
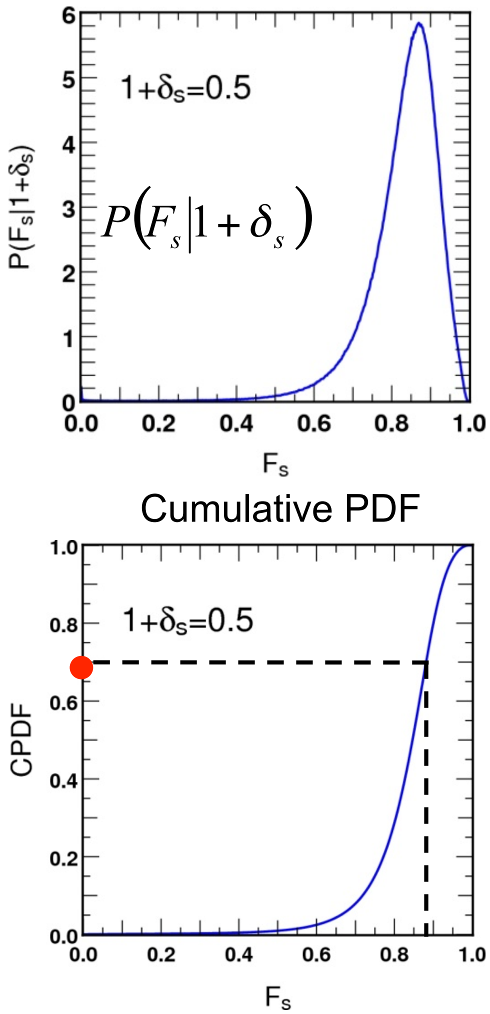
Coherent mapping

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

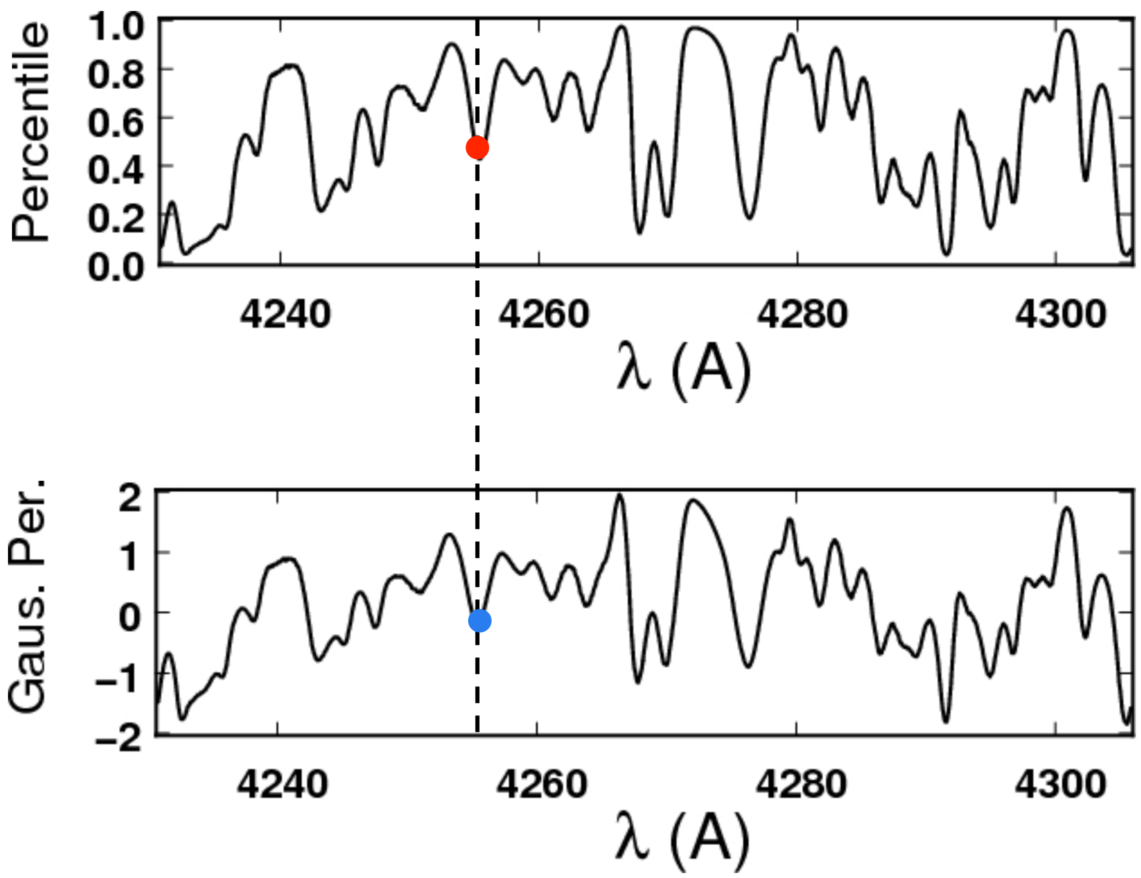




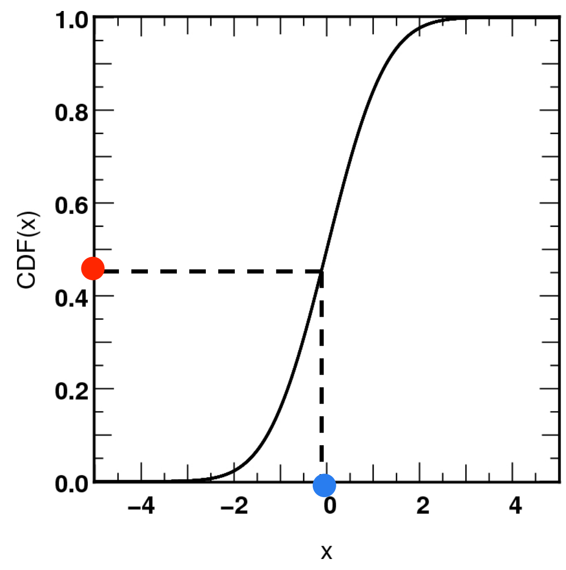
Coherent mapping

2. Construction of “Gaussianized” percentile spectra:

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



Cumulative PDF of Gaussian function



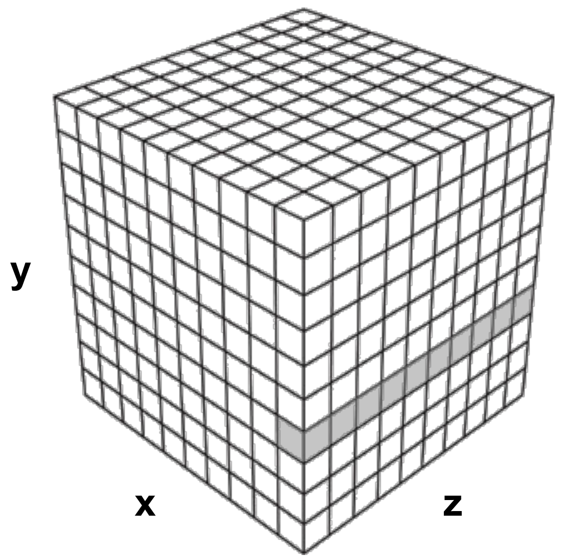
$$CDM(x) = \frac{1}{2}\left[1 + erf\left(\frac{x-\mu}{\sqrt{2\sigma^2}}\right)\right]$$

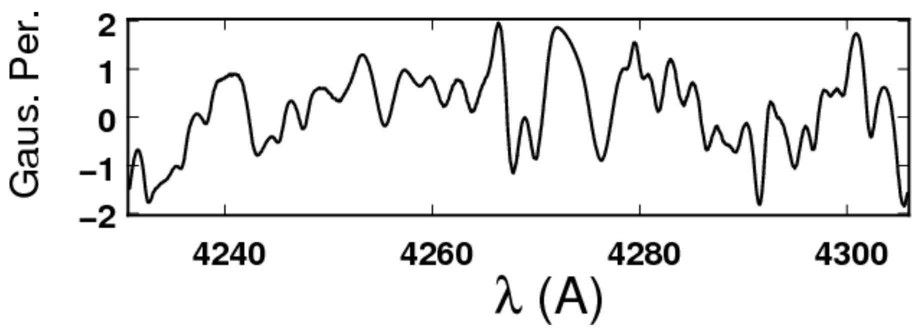
$$\mu = 0$$

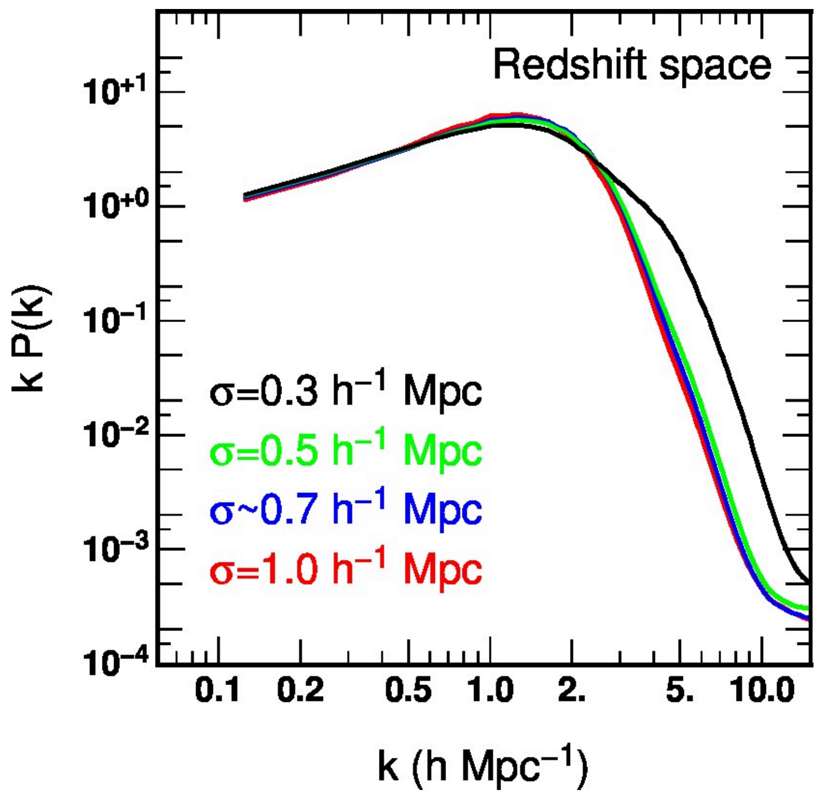
$$\sigma^2 = 1$$

Coherent mapping

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

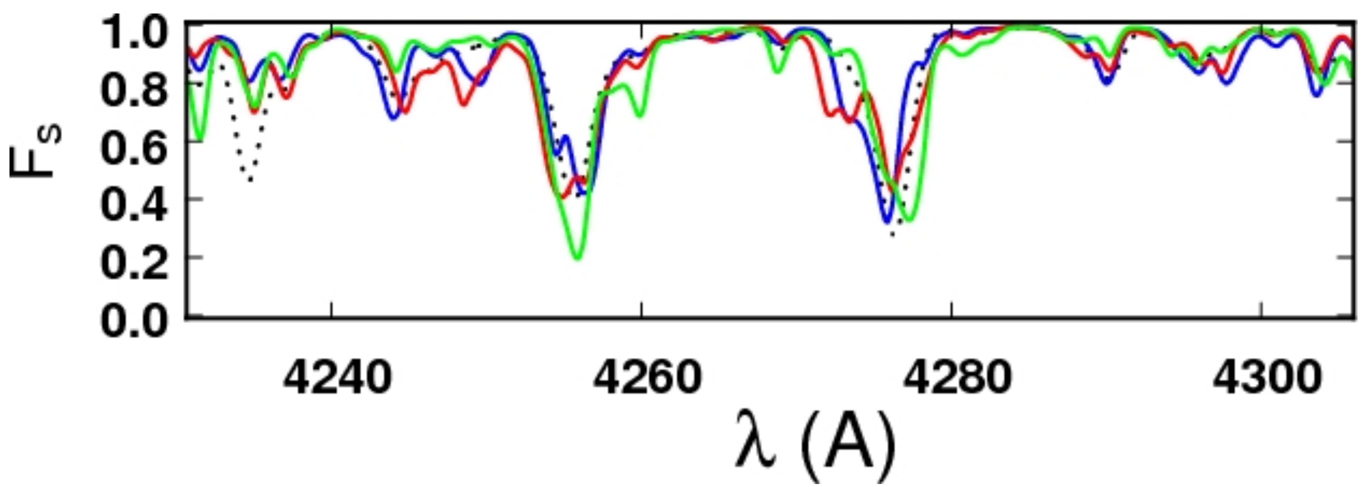






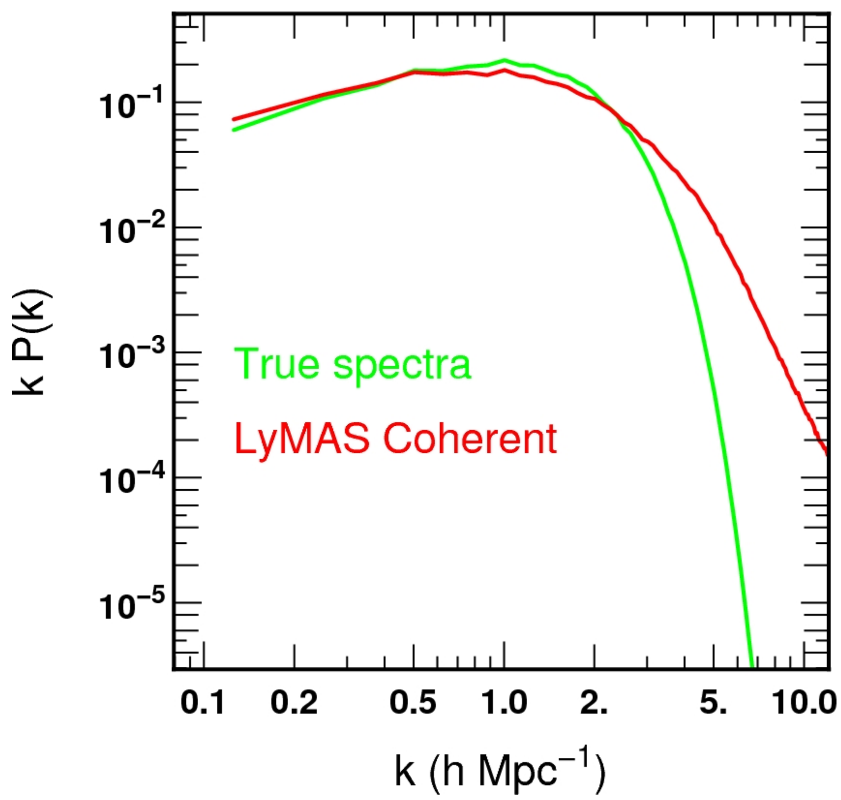
Coherent mapping

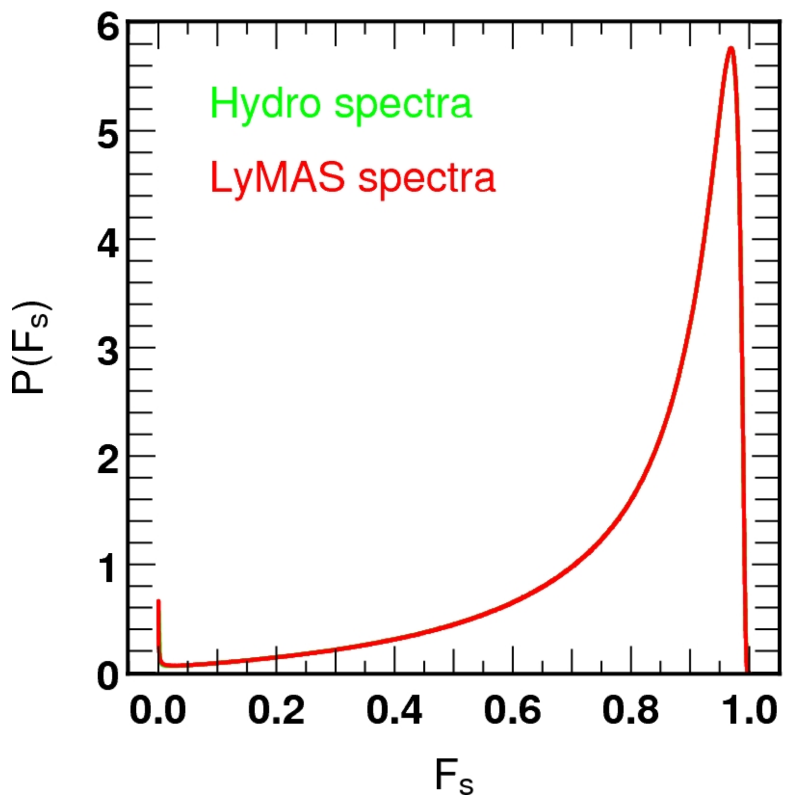
1. For each DM skewer, create a realization of G.Per(x) of the 1-d gaussian field
2. Get a realization of Per(F) by “degaussianization”
3. Get the flux field by drawing the flux at each pixel from the location of in $P(F_s|1+\delta_s)$ implied by the value of Per(F)



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

Coherent mapping

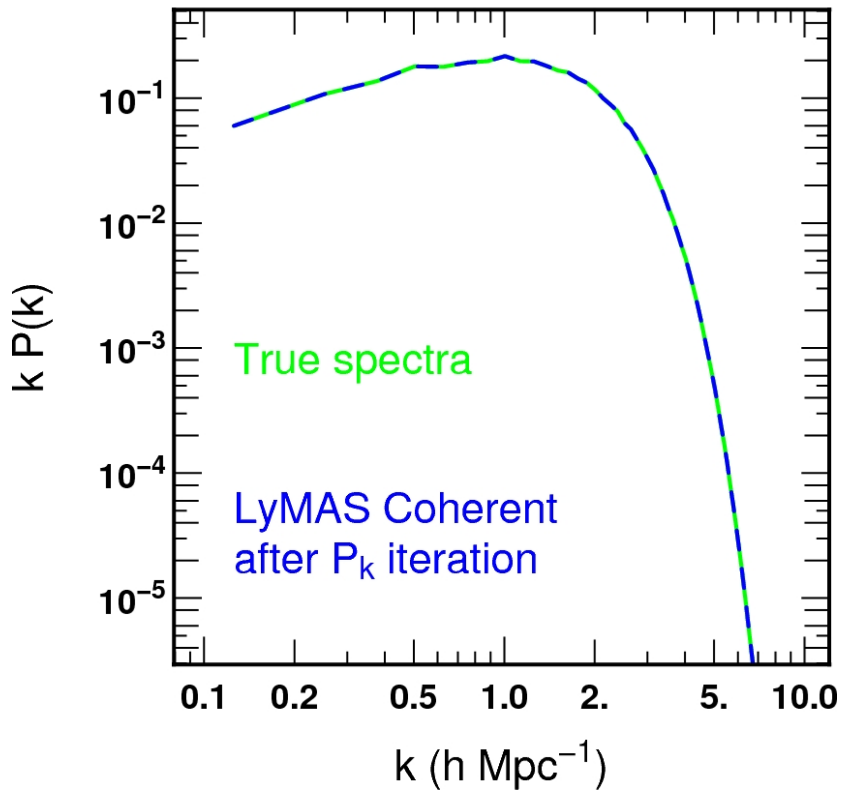


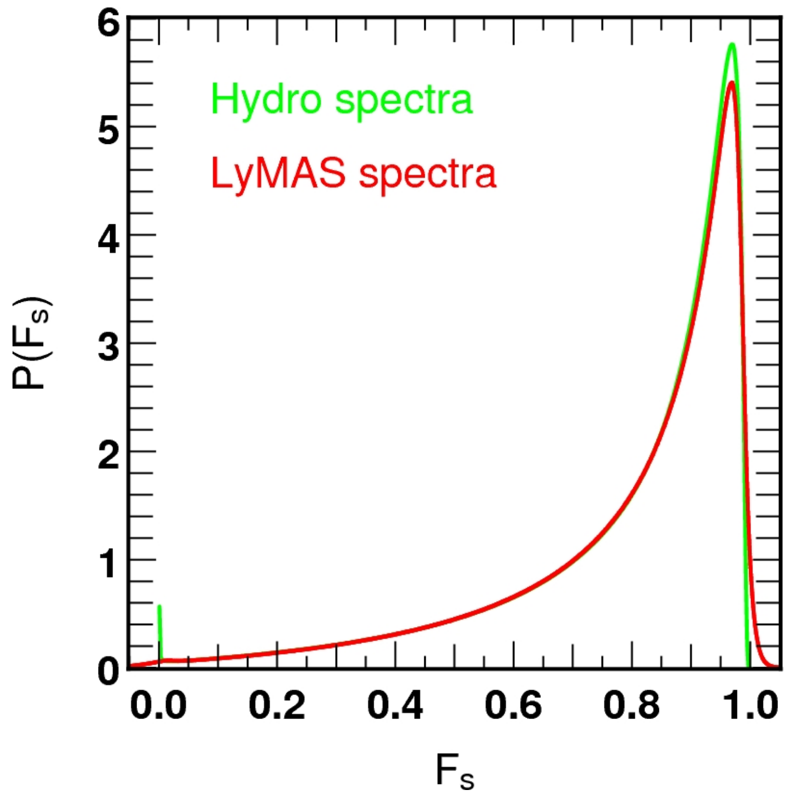


Coherent mapping

4. Iteration on Pk:

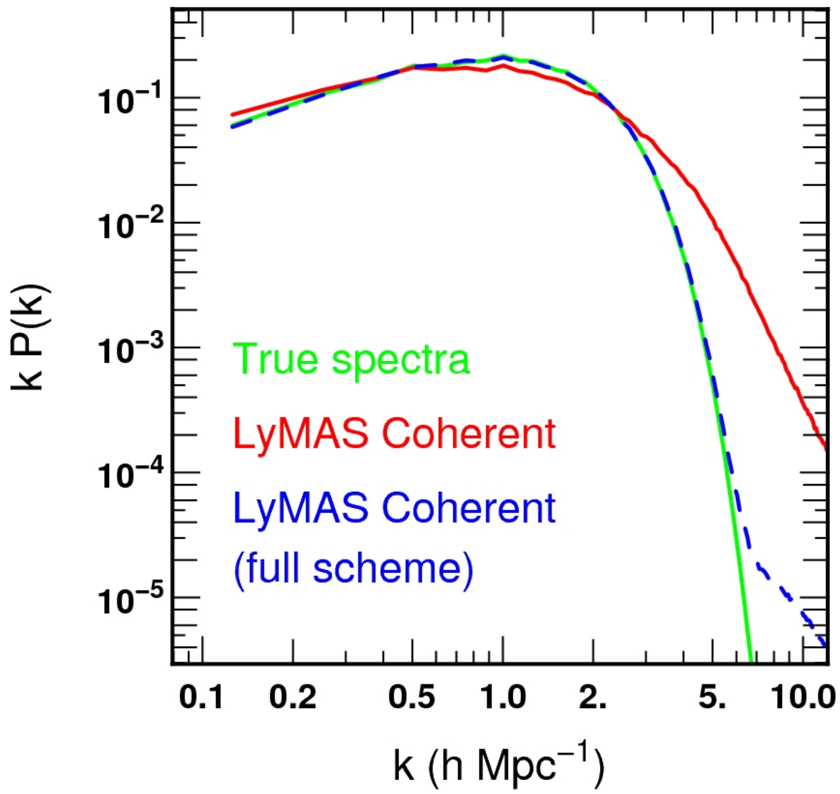
(multiply each Fourier components by the ratio $[P_F(k)/P_{PS}(k)]^2$)

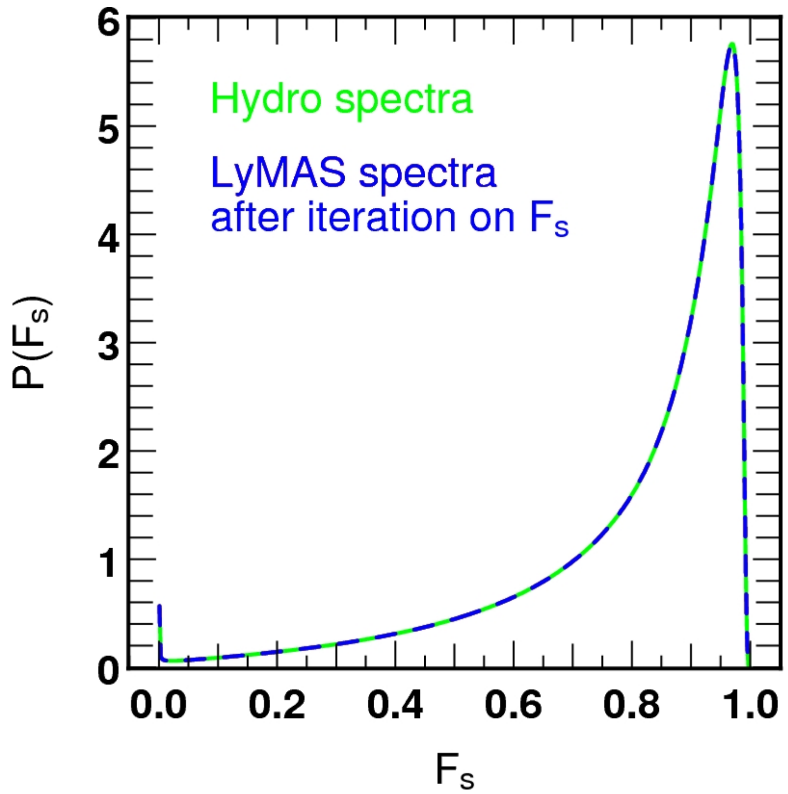




Coherent mapping

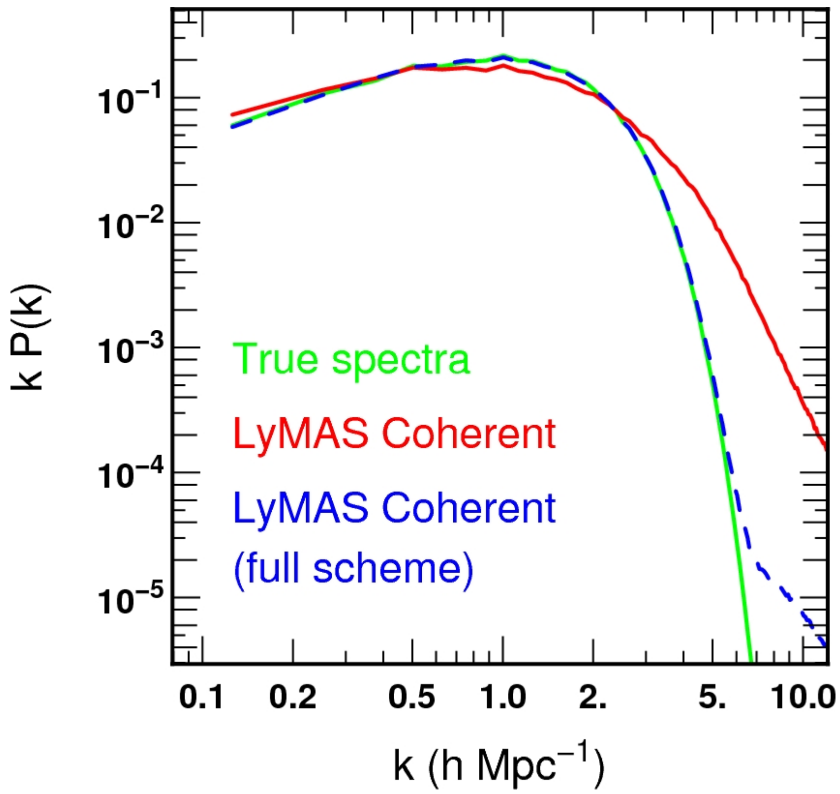
4. Iteration on F_s:

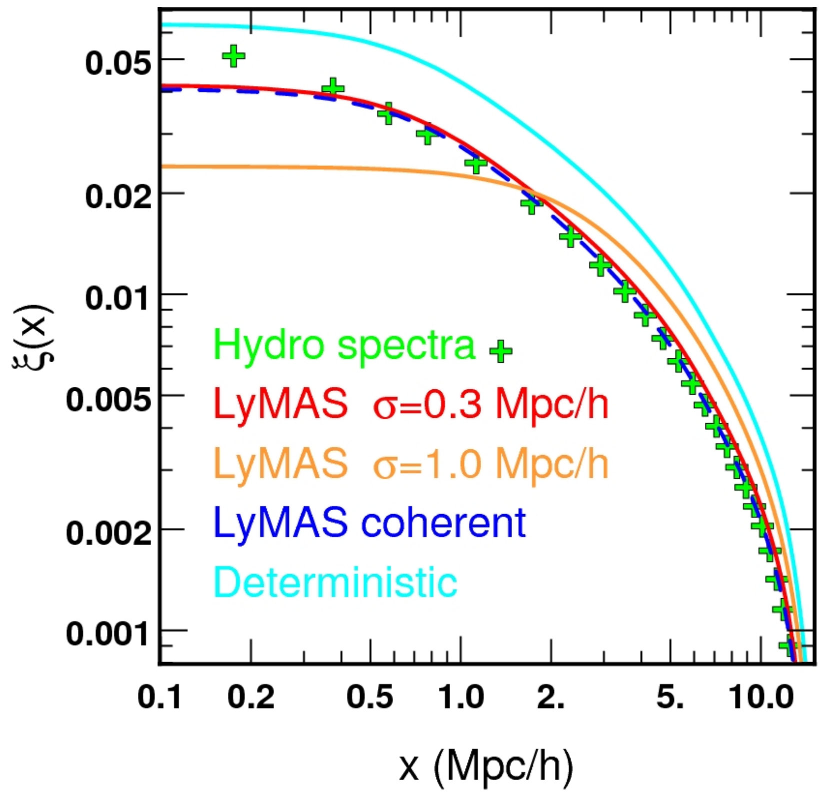




Coherent mapping

4. Iteration on F_s:





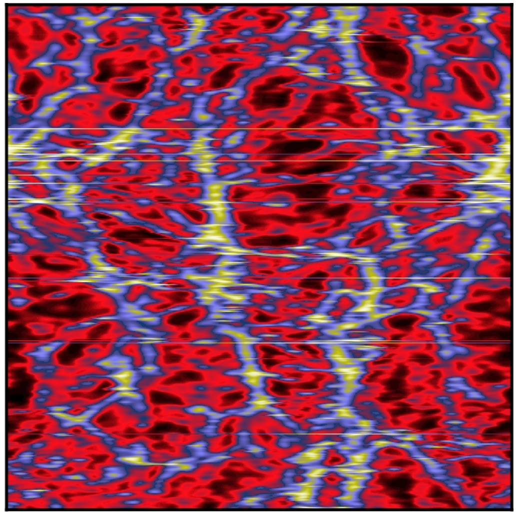
Mapping

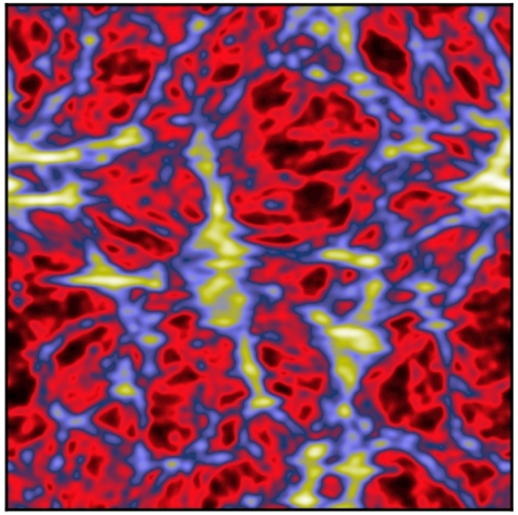
Hydro Spectra F_s

1d P_k

PDF(F_s)

$\xi(x)$





Deterministic mapping

~~1d P_k~~

PDF(F_s)

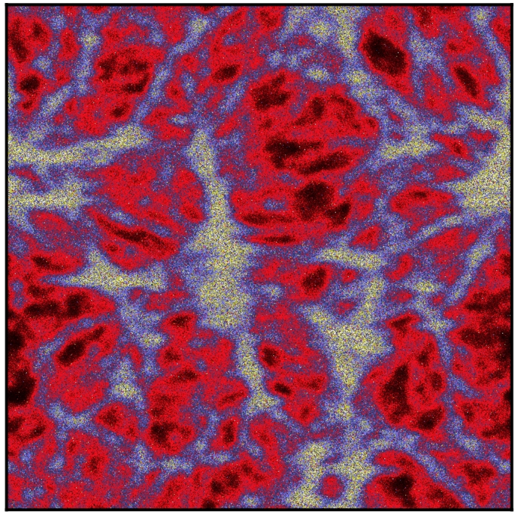
~~$\xi(x)$~~

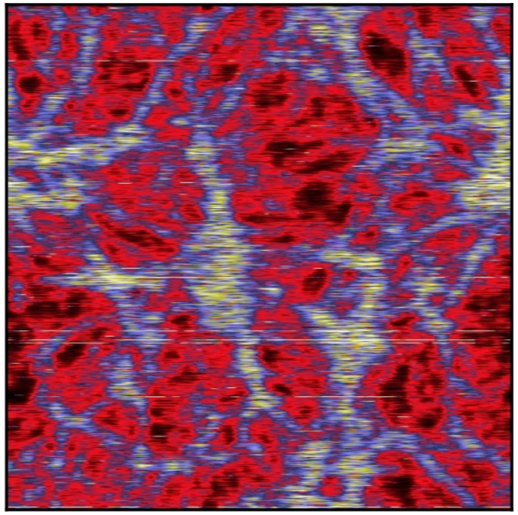
LyMAS probabilistics

~~1d P_k~~

PDF(F_s)

$\xi(x)$





LyMAS coherent

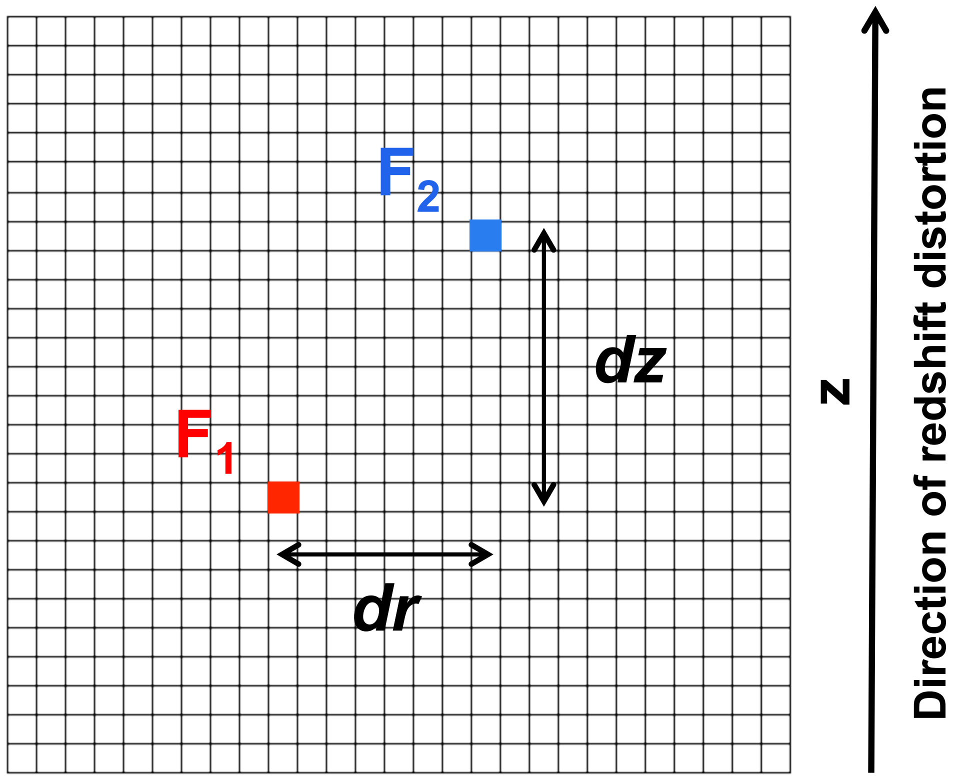
1d P_k

PDF(F_s)

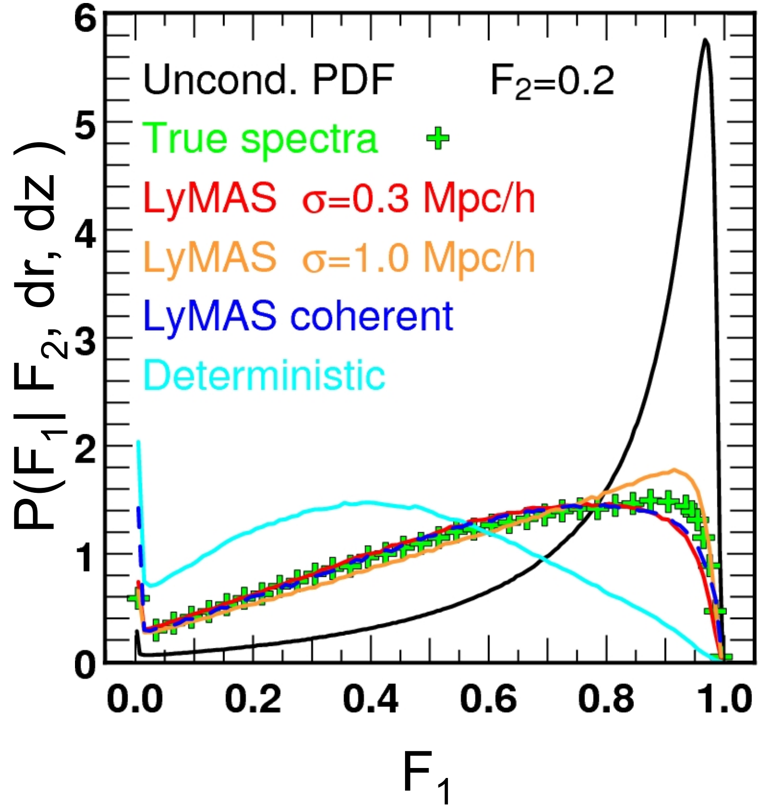
$\xi(x)$

Two-point conditional flux PDF

$$P\left(F_1 \middle| F_2, dr, dz\right)$$

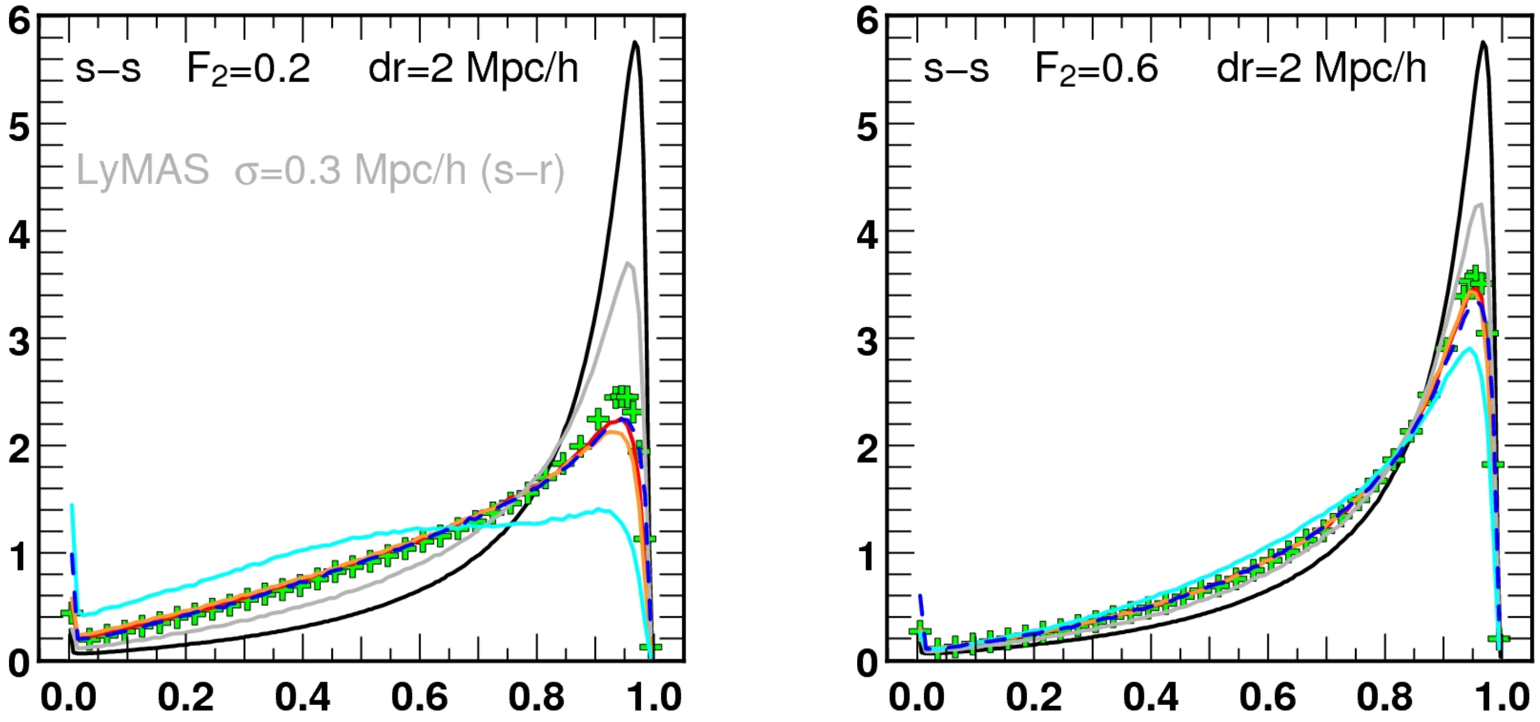


Ex: F2 = 0.2
dr = 1Mpc/h
dz = 0 Mpc

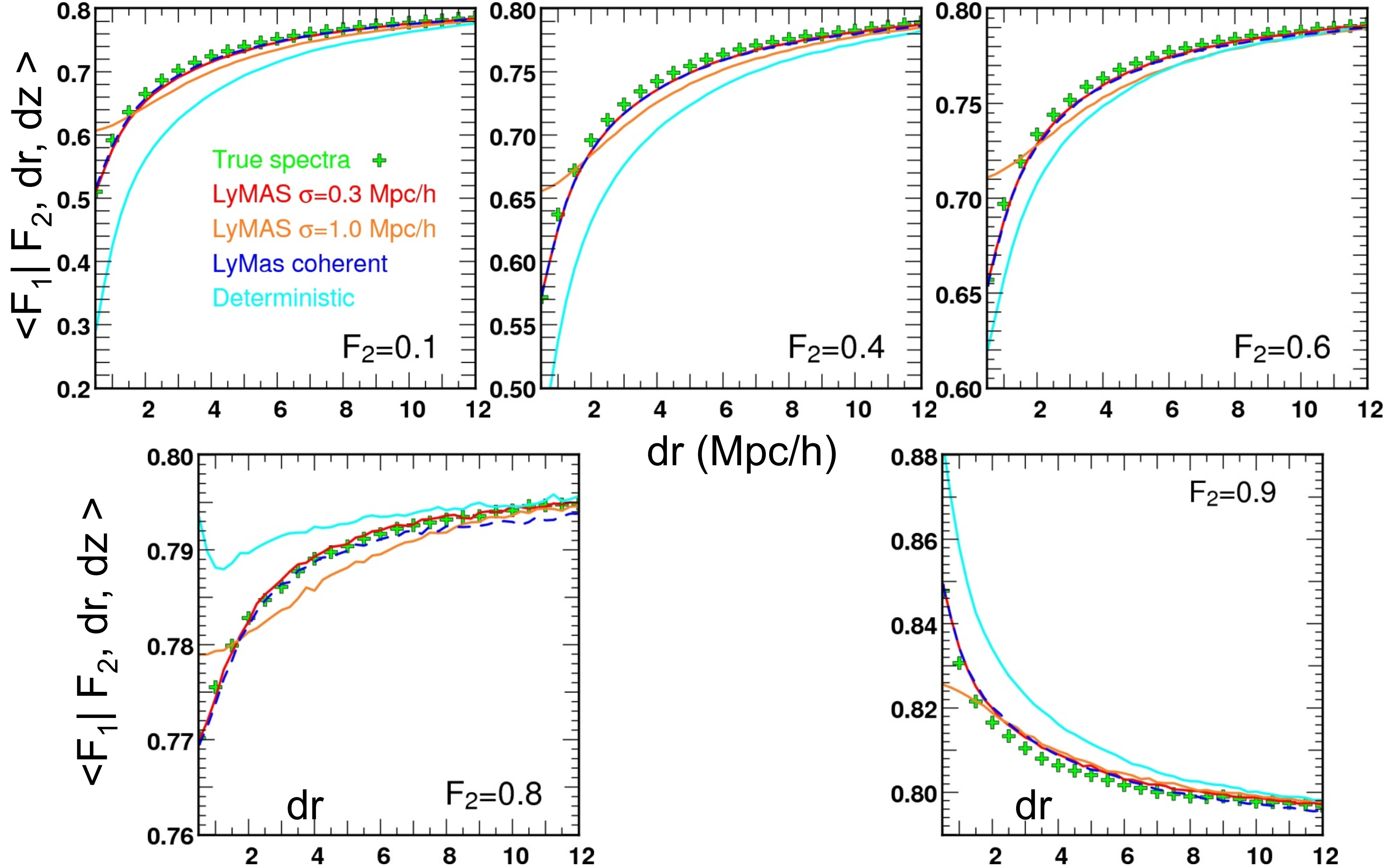


Two-point conditional flux PDF

$$P\left(F_1 \middle| F_2, dr, dz\right)$$

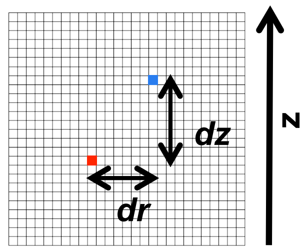


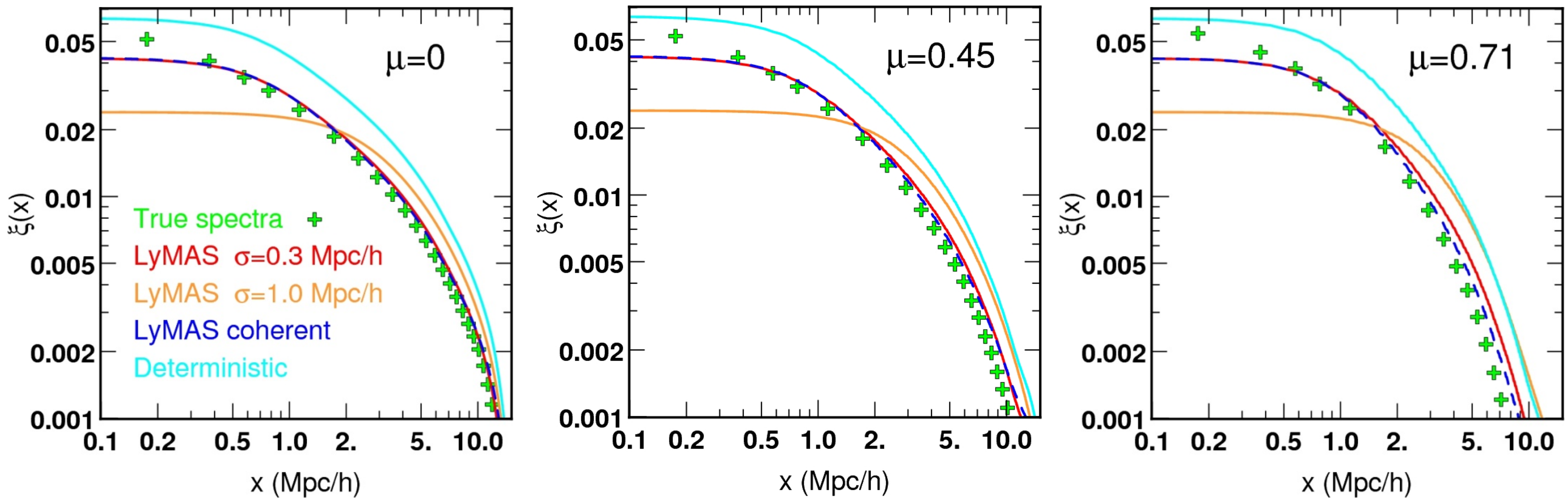
Conditional mean flux $<F_1|F_2,dr,dz>$



Correlation function

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





$dz = 0$ $\quad$ $dr = 0.5dz$ $\quad$ $dr = dz$

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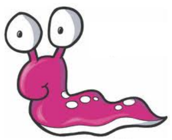

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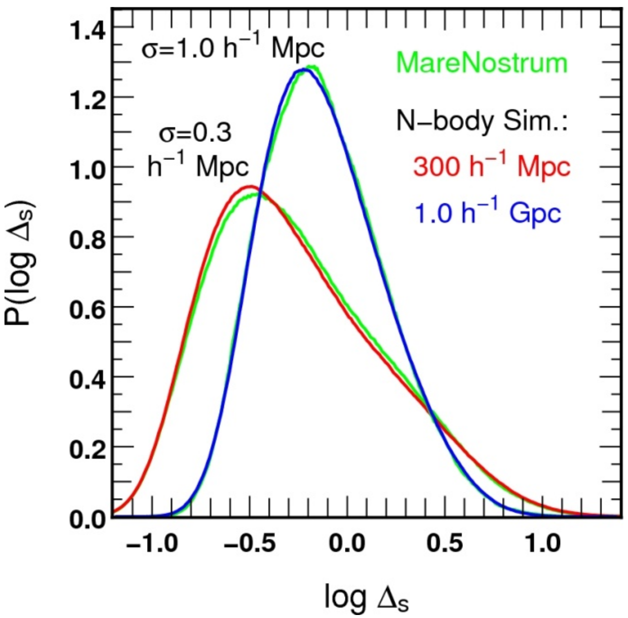
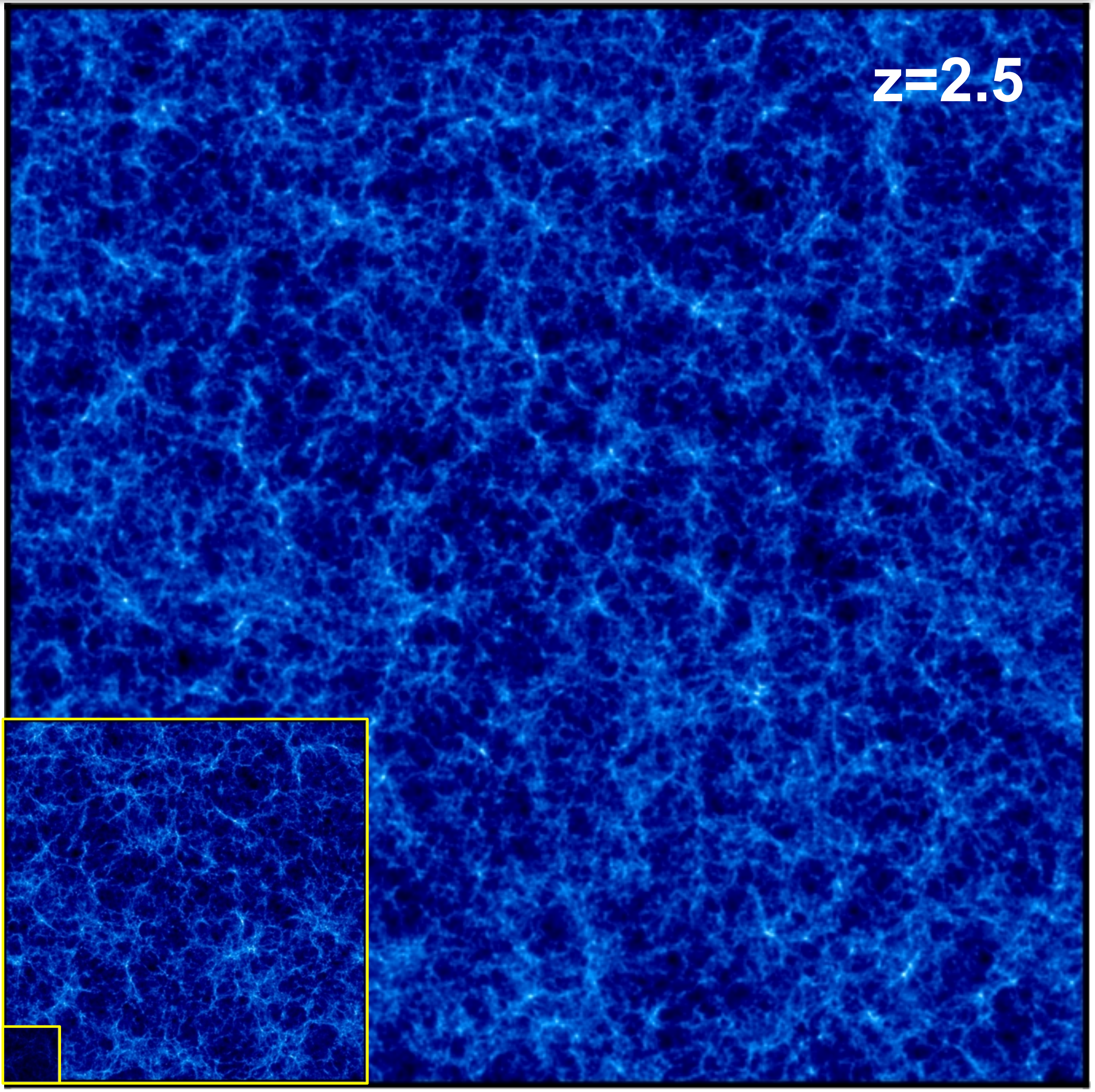
Application to large cosmological DM simulations

Gadget2 (Springel 2005)

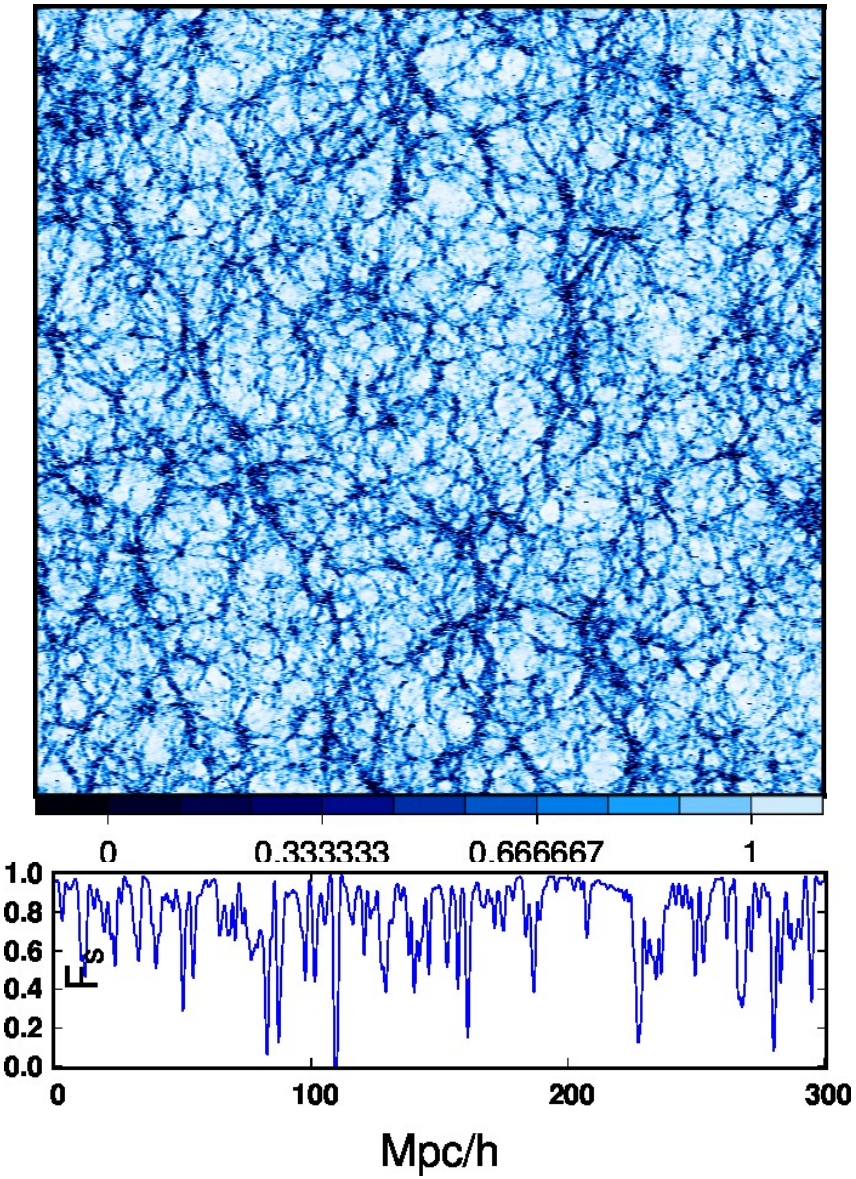
300 Mpc/h - 1024^3 particles - WMAP1 cosmology σ_{DM}=0.3 Mpc/h

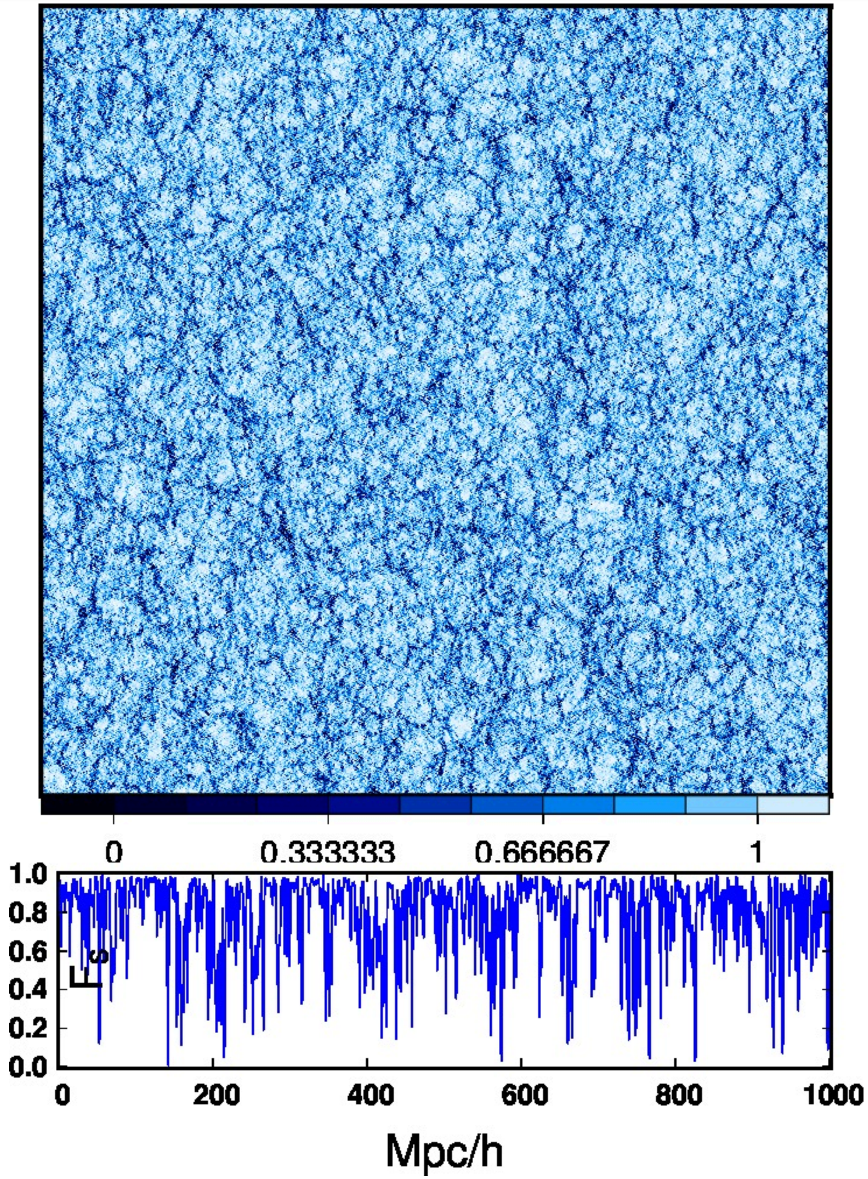
1.0 Gpc/h - 1024^3 particles - WMAP1 cosmology σ_{DM}=1.0 Mpc/h





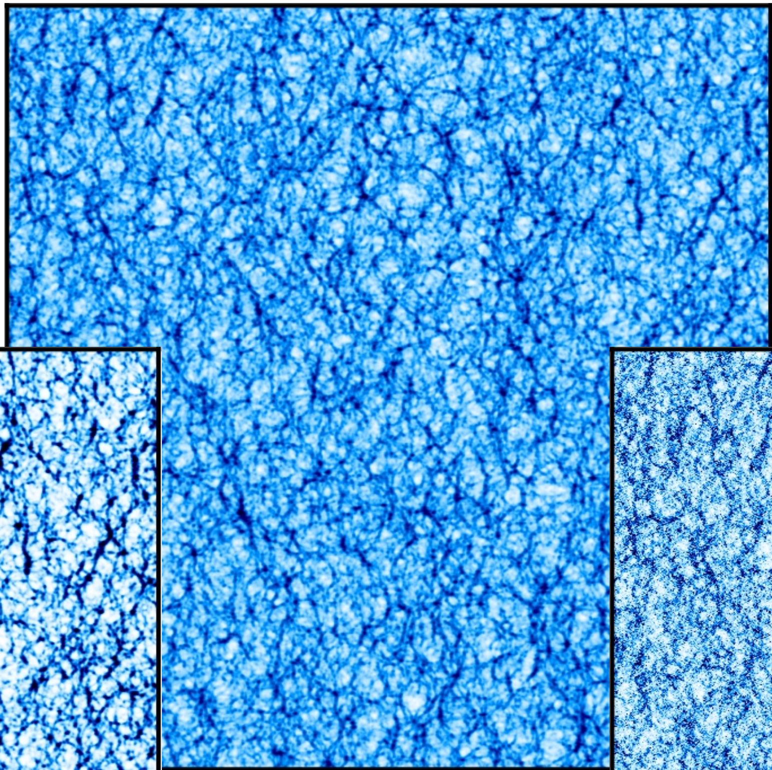
Application to large cosmological DM simulations





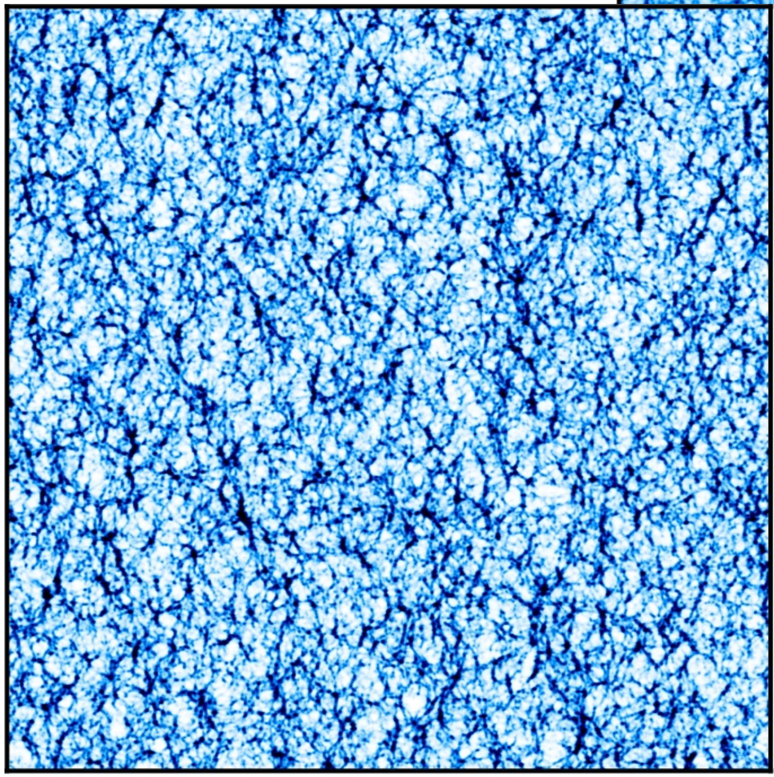
Application to large cosmological DM simulations

1 Gpc/h

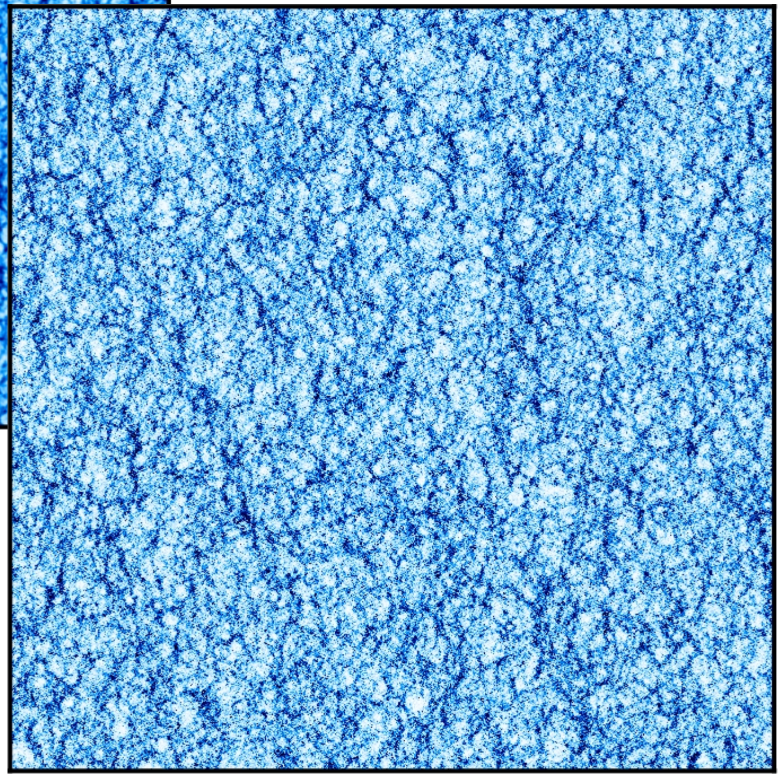


DM

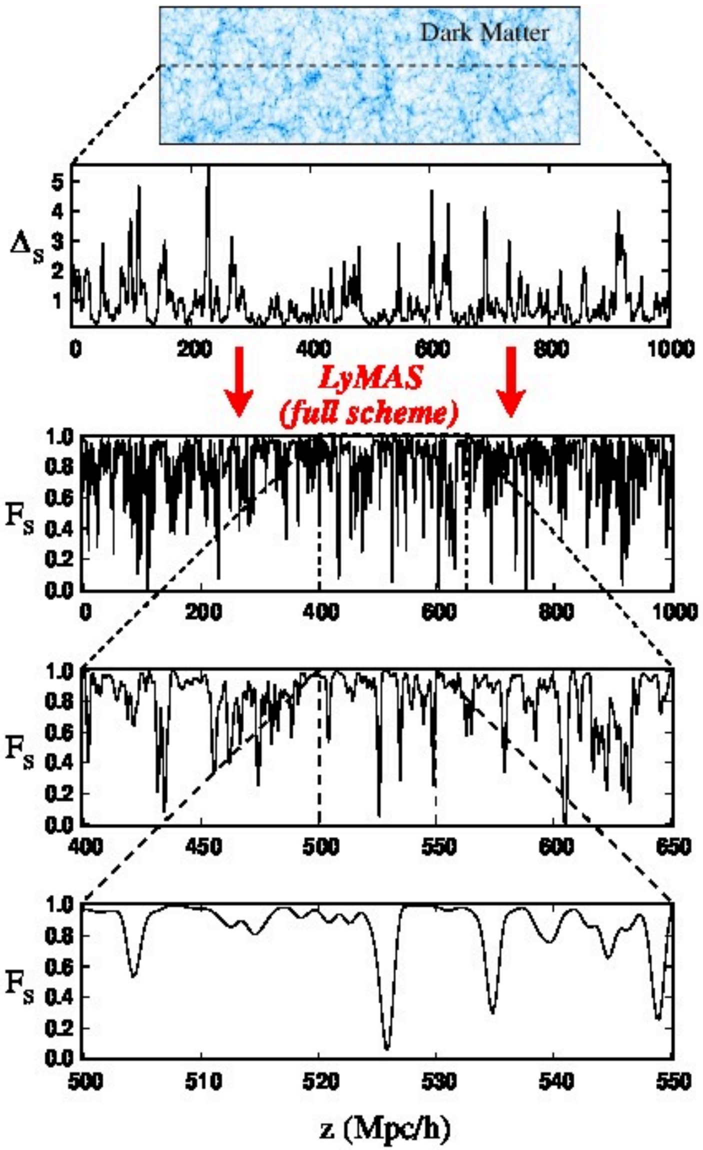
Deterministic

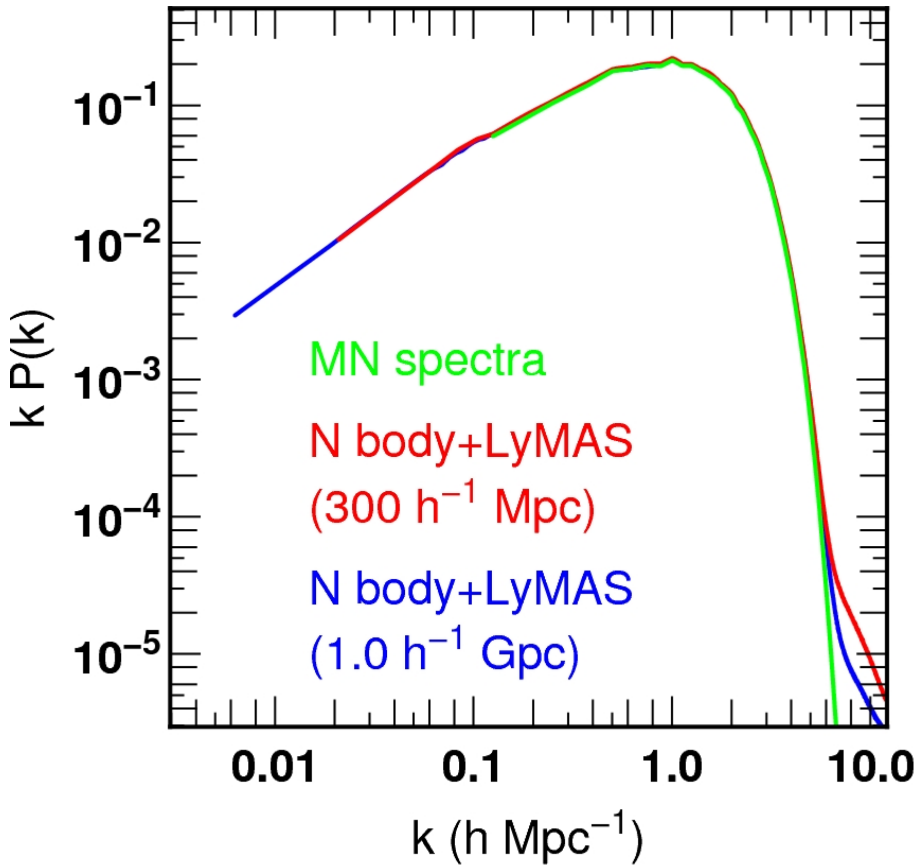


LyMAS

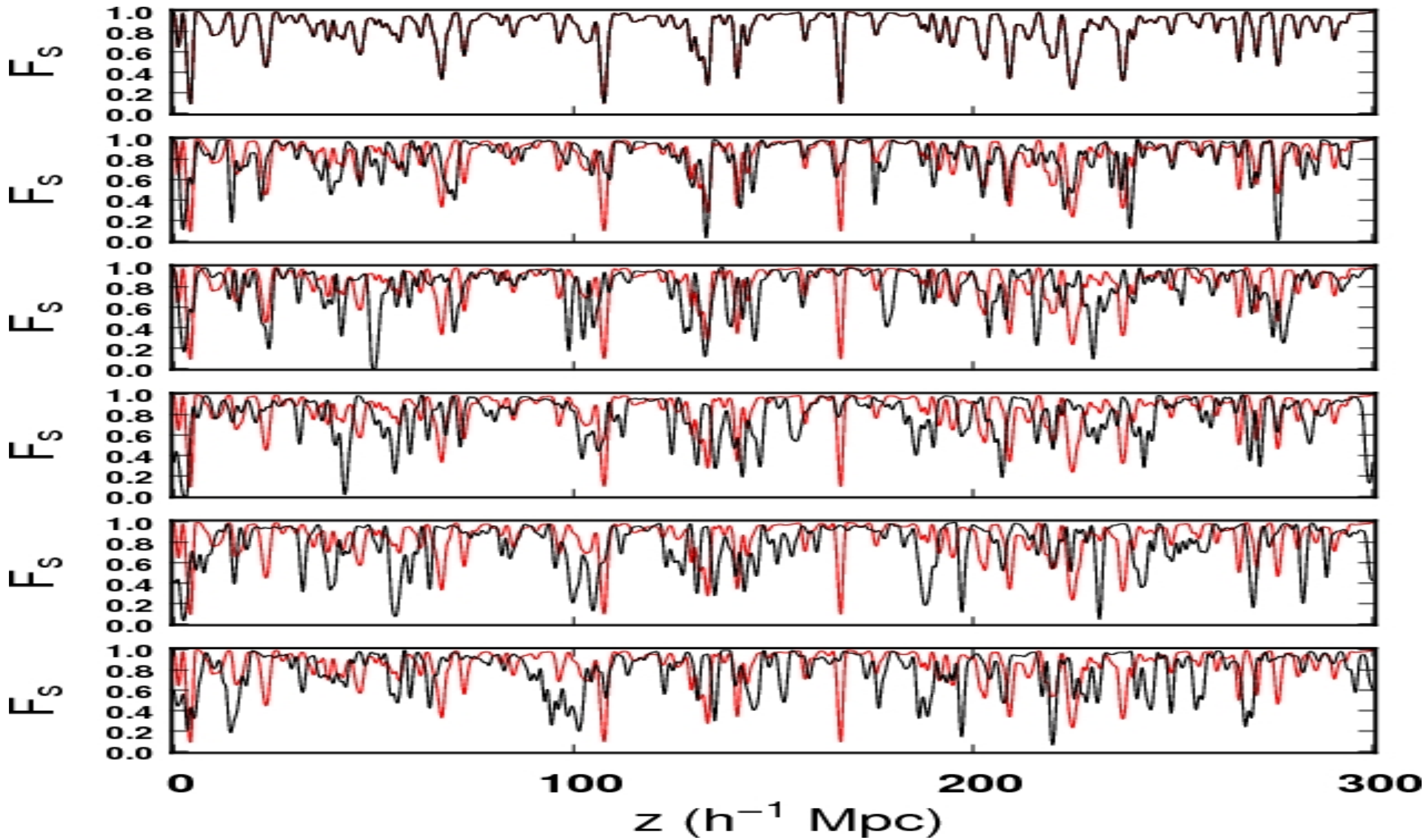


Application to large cosmological DM simulations



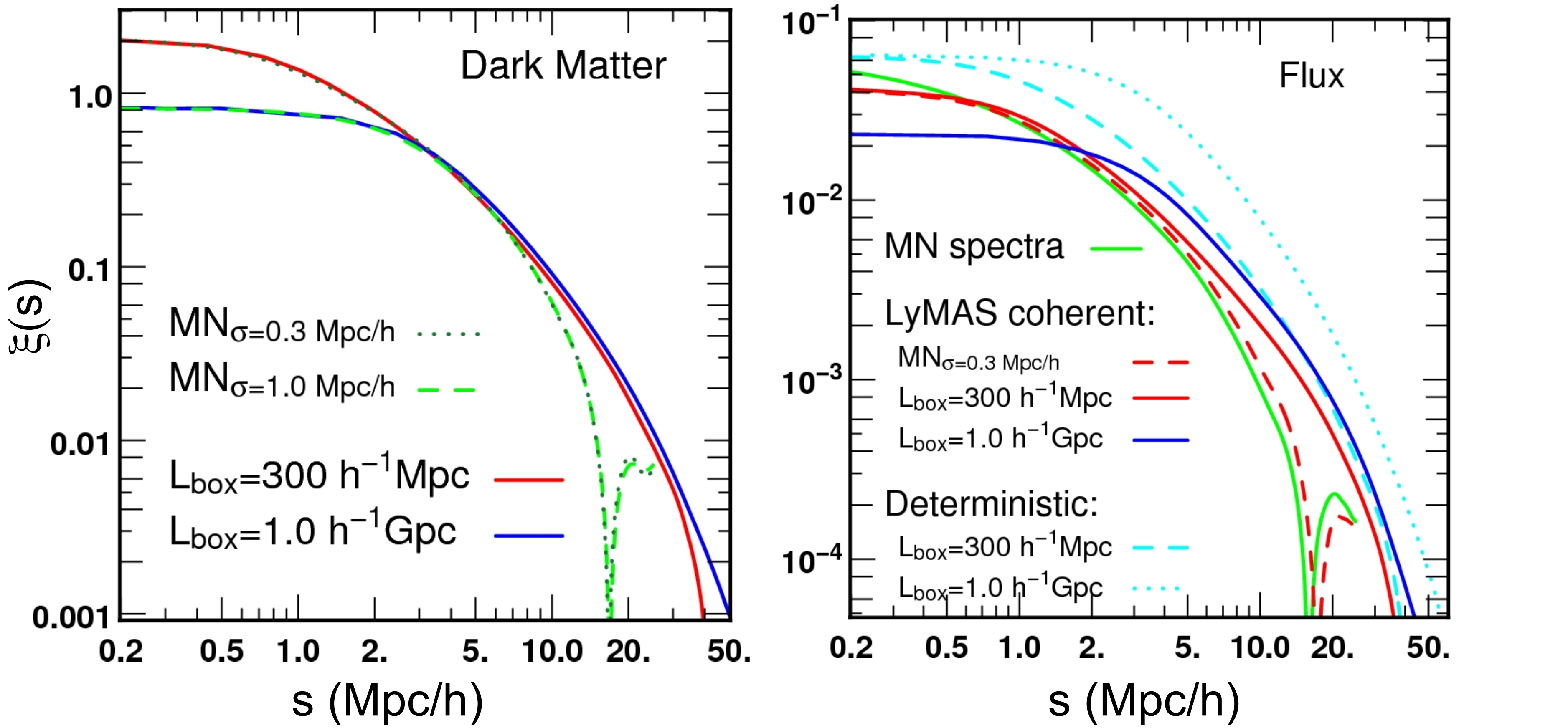


Application to large cosmological DM simulations



Application to large cosmological DM simulations

Correlation function:

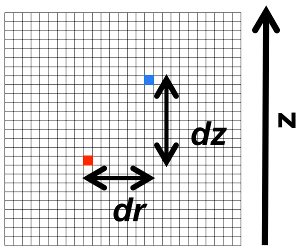


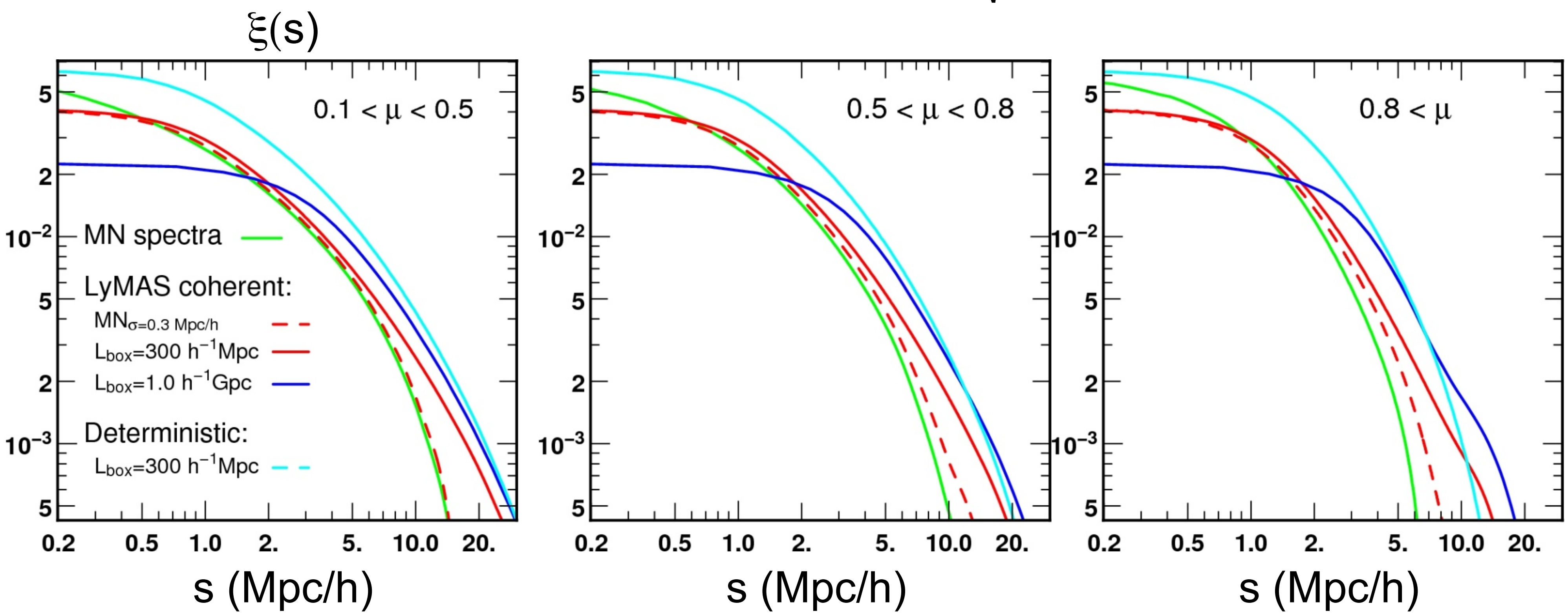
Application to large cosmological DM simulations

Correlation function:

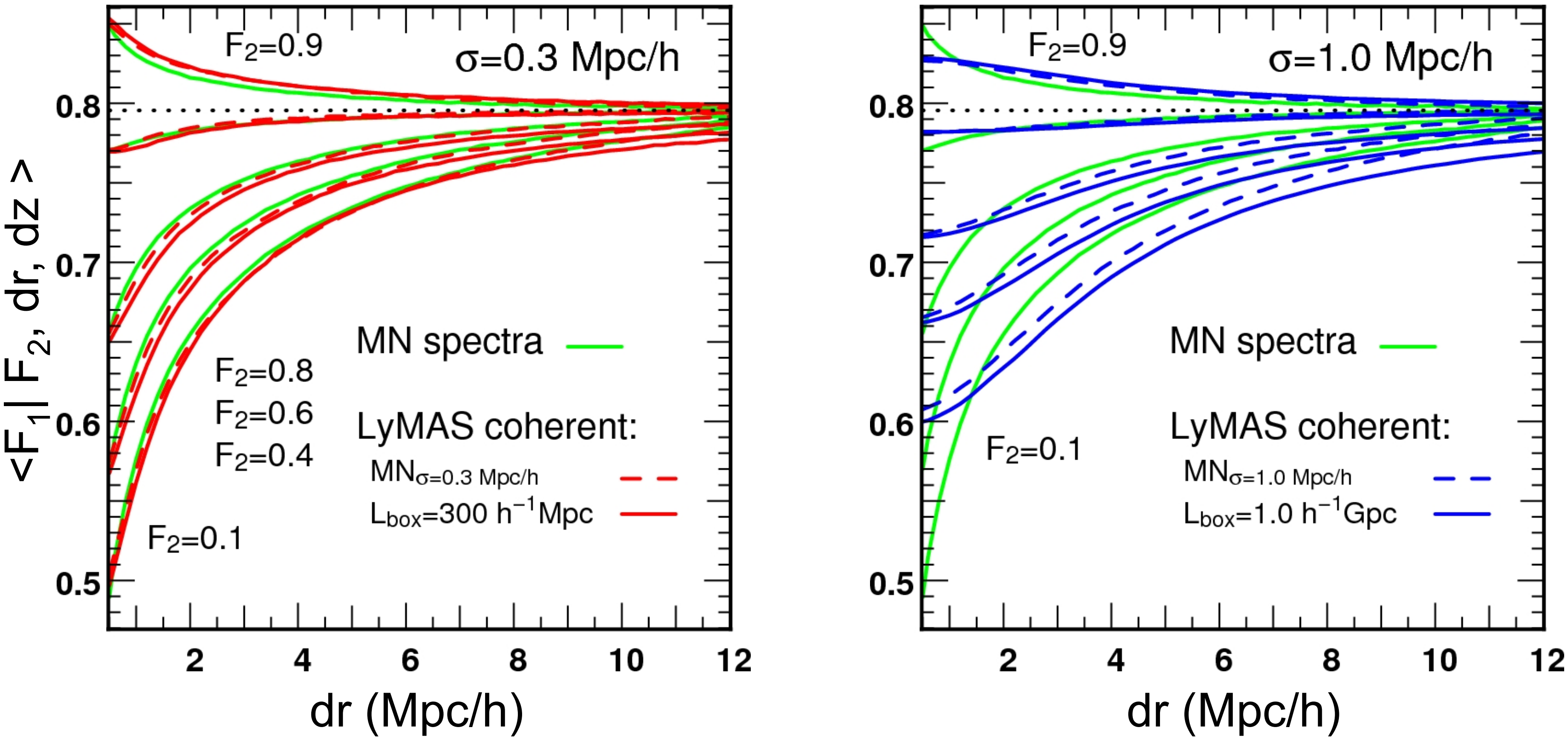
$$\mu = \frac{dz}{\sqrt{dr^2 + dz^2}}$$

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

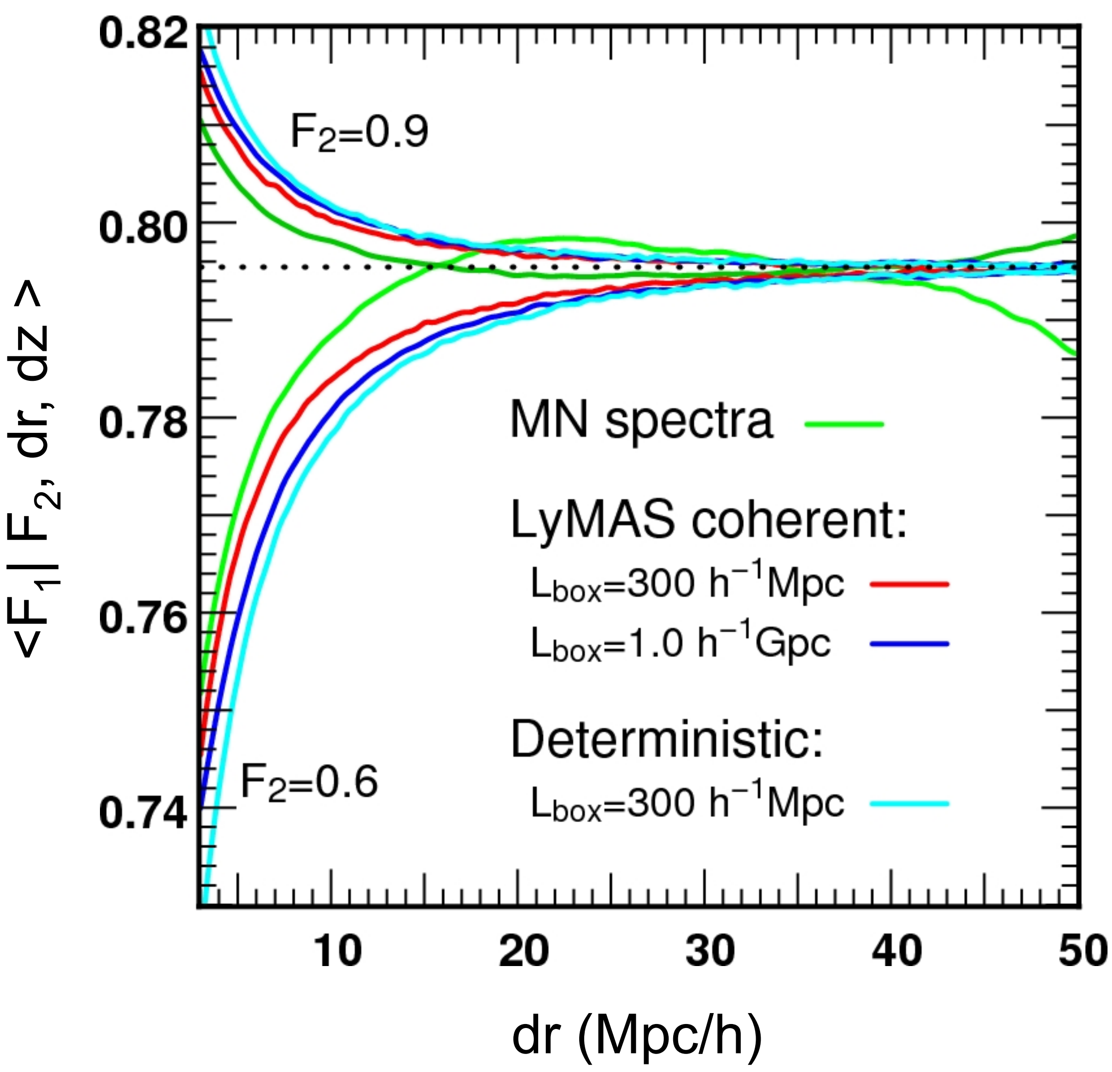




Application to large cosmological DM simulations

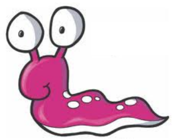


Application to large cosmological DM simulations



Plan

1. Introduction
2. Hydro simulations and hydro spectra
3. Deterministic mapping
4. LyMAS Probabilistic mapping
5. LyMAS Coherent mapping
6. Application to large N-body simulations



7. Next

Numerical modeling improvements

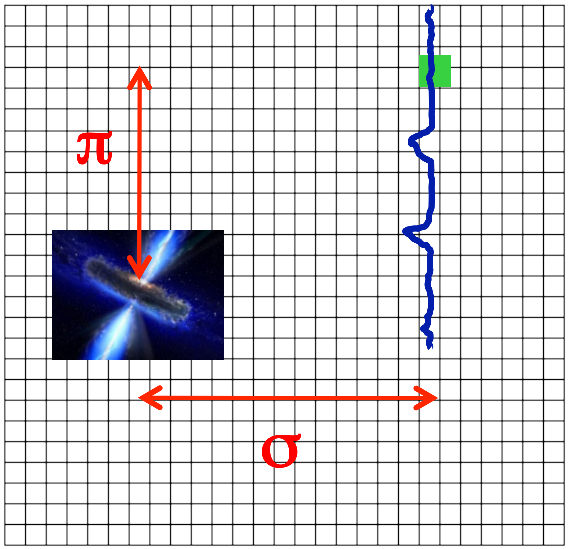
1. Algorithms
   - QSO continuum
   - Redshift evolution
   - Noises
   - Non constant spectral resolution
   - Etc…

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

Cross correlation quasar Lyα in BOSS survey

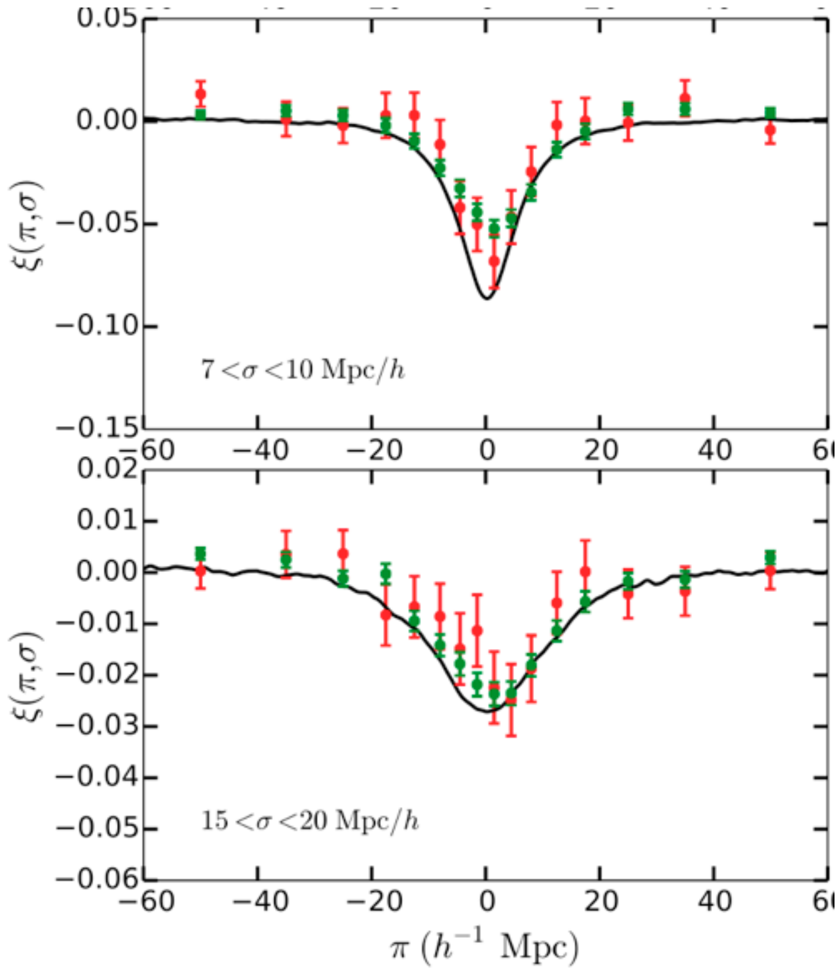
Font-Ribera et al. (2013)

(SDSS DR9)



LyMAS mocks: WMAP7 – 1 Gpc/h –

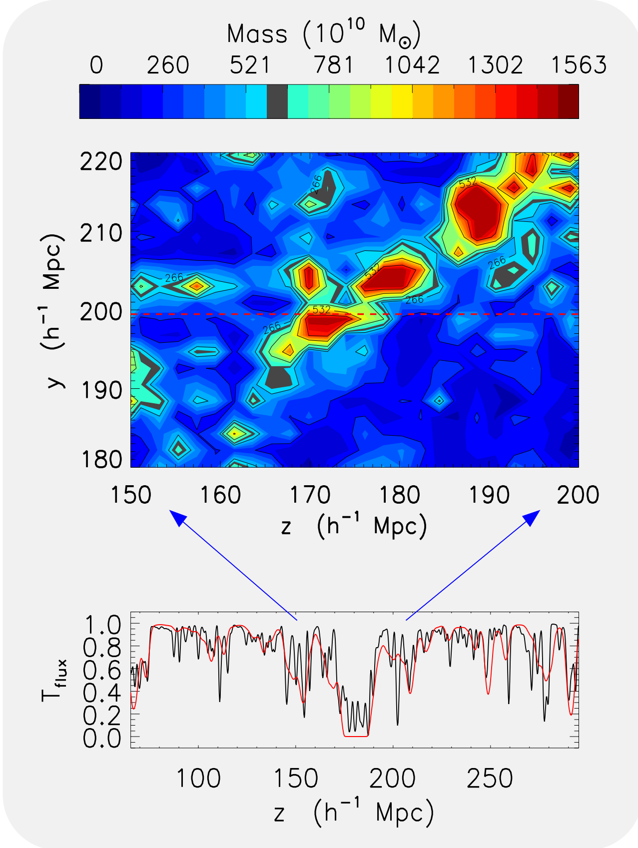
2048^3 particles – AGN and noAGN



"Modelling the Lya forest cross correlation with LyMAS" Lochhass, Weinberg, Peirani et al., to be submitted

MAMMOTH + LyMAS

MApping the Most Massive Overdensity Through Hydrogen



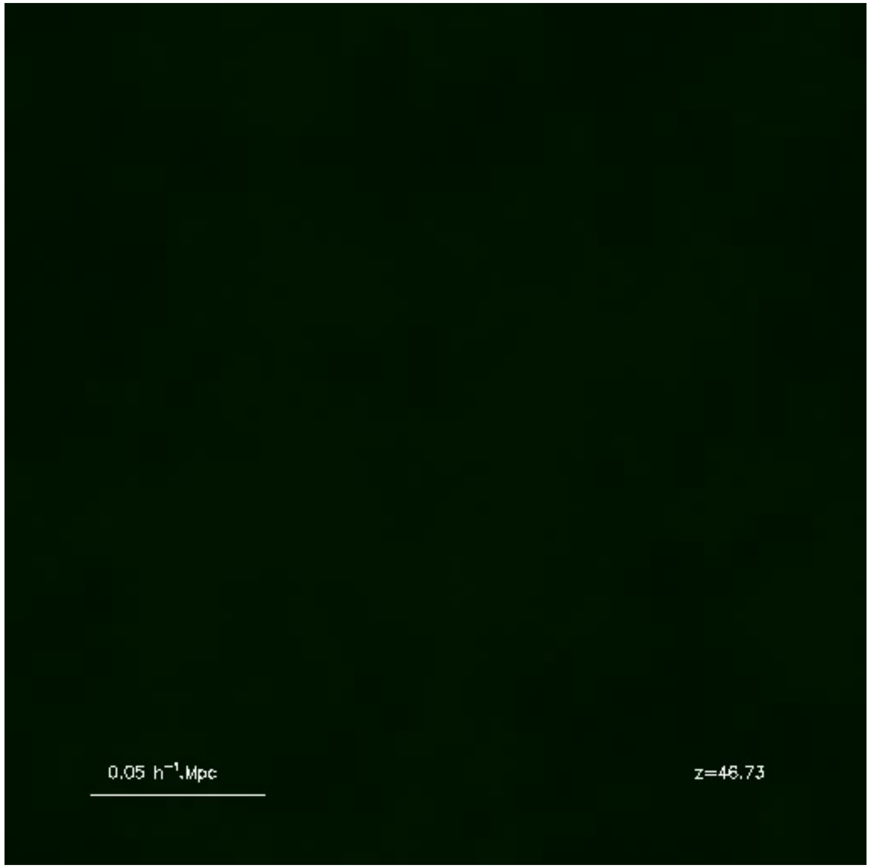
“MApping the Most Massive Overdensity Through Hydrogen (MAMMOTH): I – Cai, Fan, Bian, Peirani, Frye, McGreer, White & Ho, to be submitted

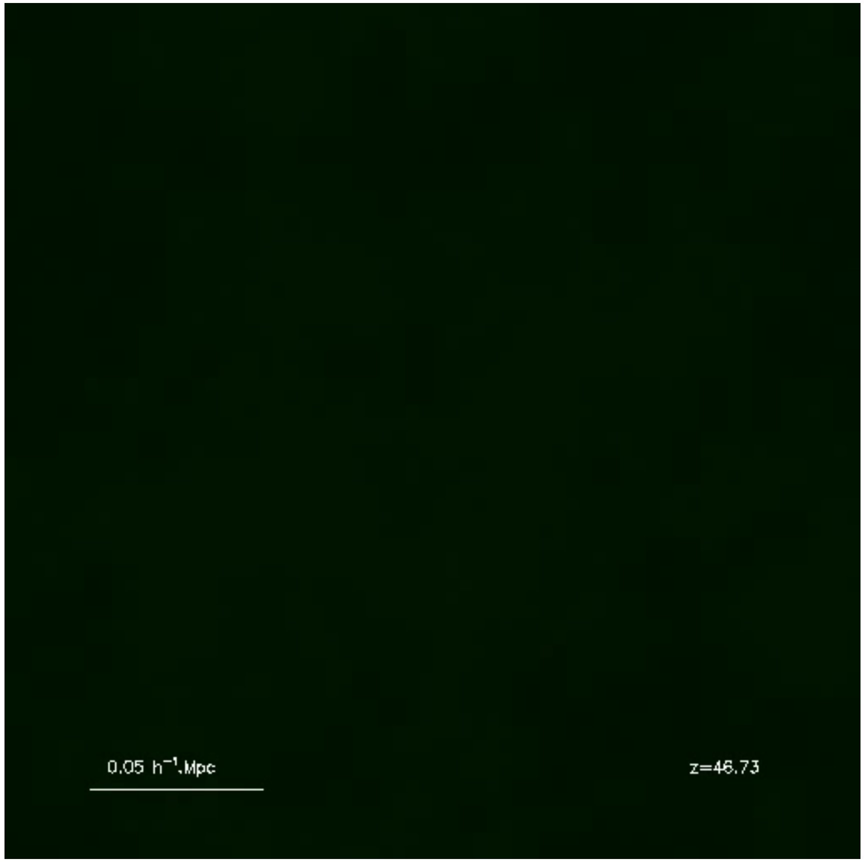
Effect of AGN feedback

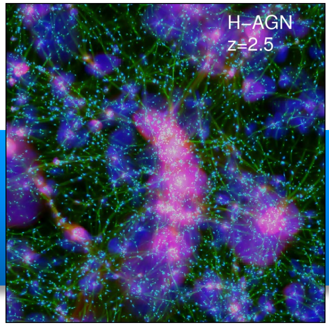
Studying how large-scale Lya clustering depends on cosmological and IGM parameters and on redshift

Ex: Effects of AGN feddback? (Peirani et al. in prep)

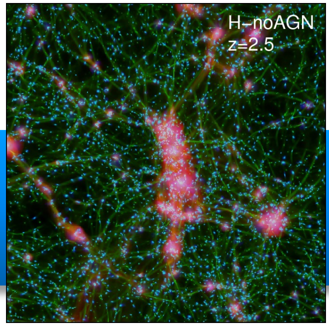
Red = gas temperature / Green = gas density / Blue = gas metallicity

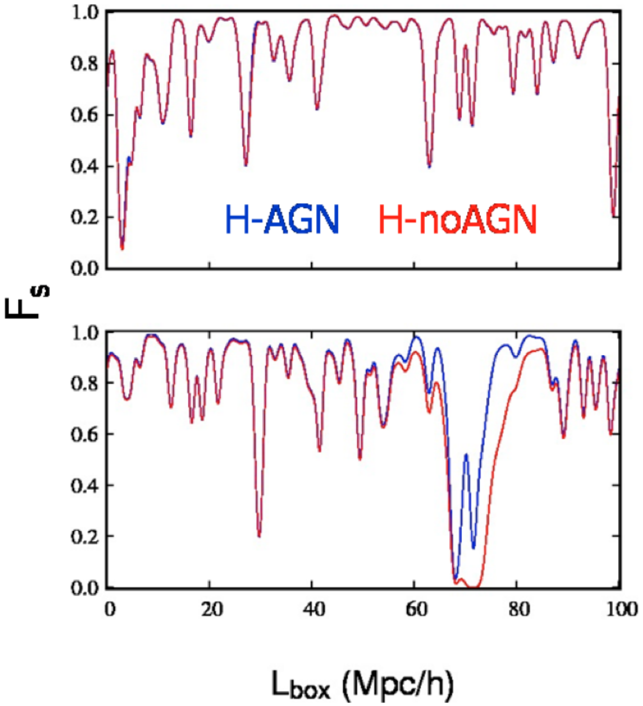


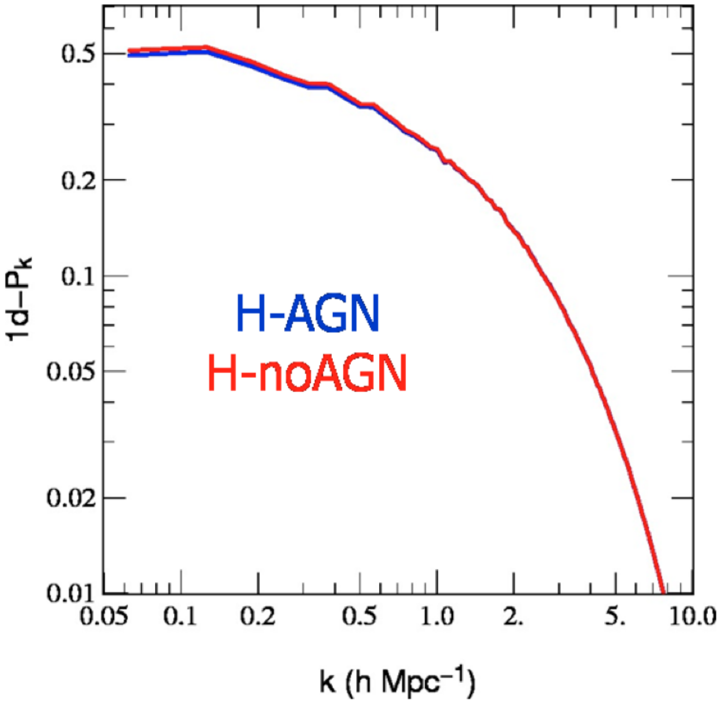




AGN vs noAGN







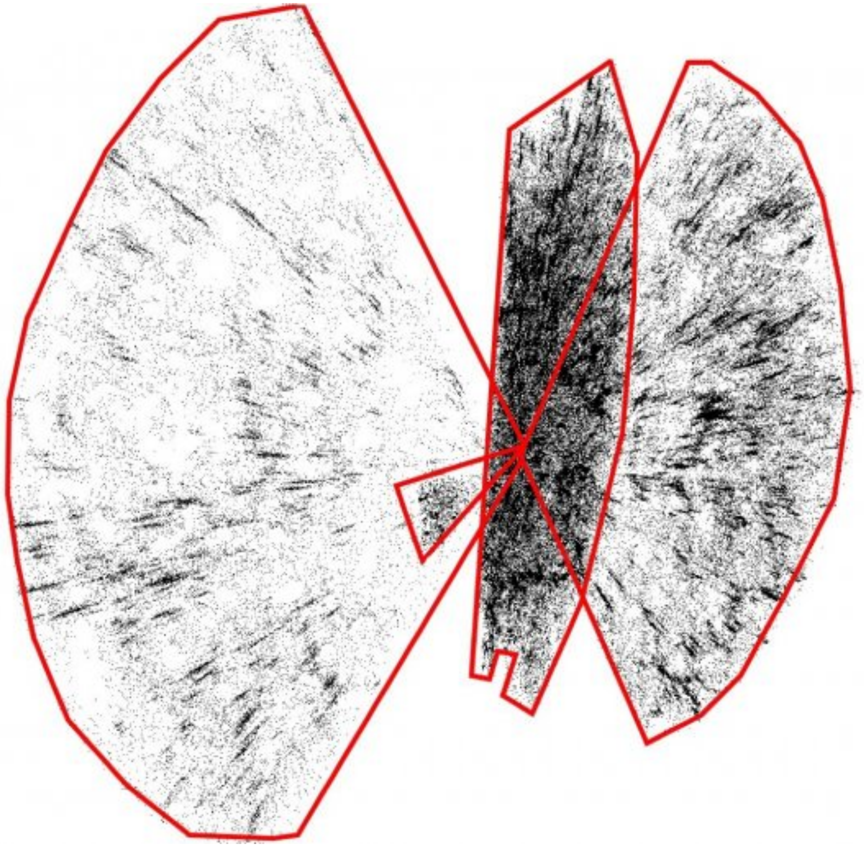
"The effect of AGN feedback on the Lya forest clustering"
Peirani et al., in prep

Mock catalogs of galaxies

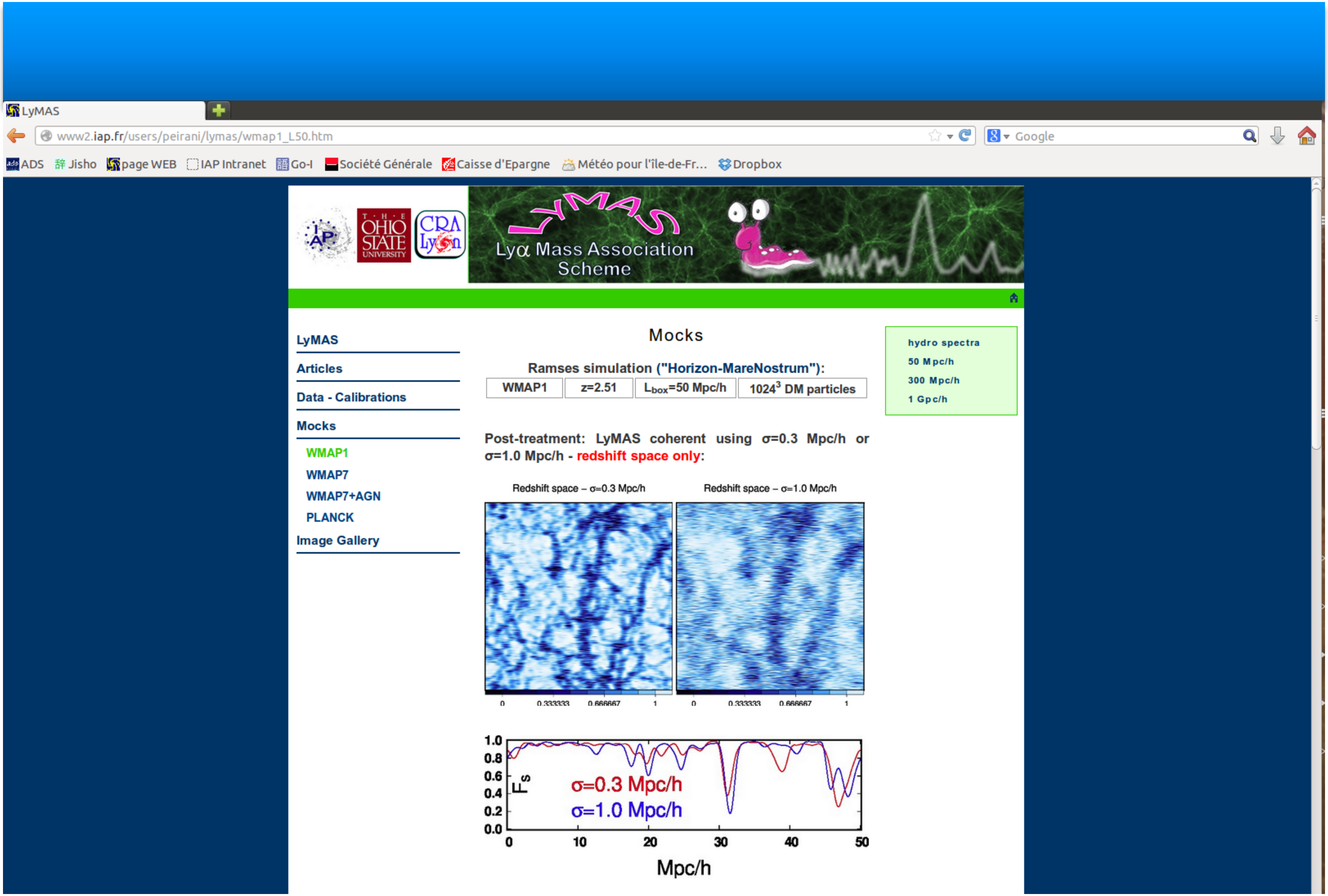
“MoLUSC: a MOck Local Universe Survey Constructor”

2008, ApJ, 678, 569

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



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




ありがとう　ございます！