The Lyman-alpha forest and dark matter

Eric Armengaud - CEA Saclay

News from the Dark - Montpellier 2018

Dark matter

Lyman-alpha forest : data

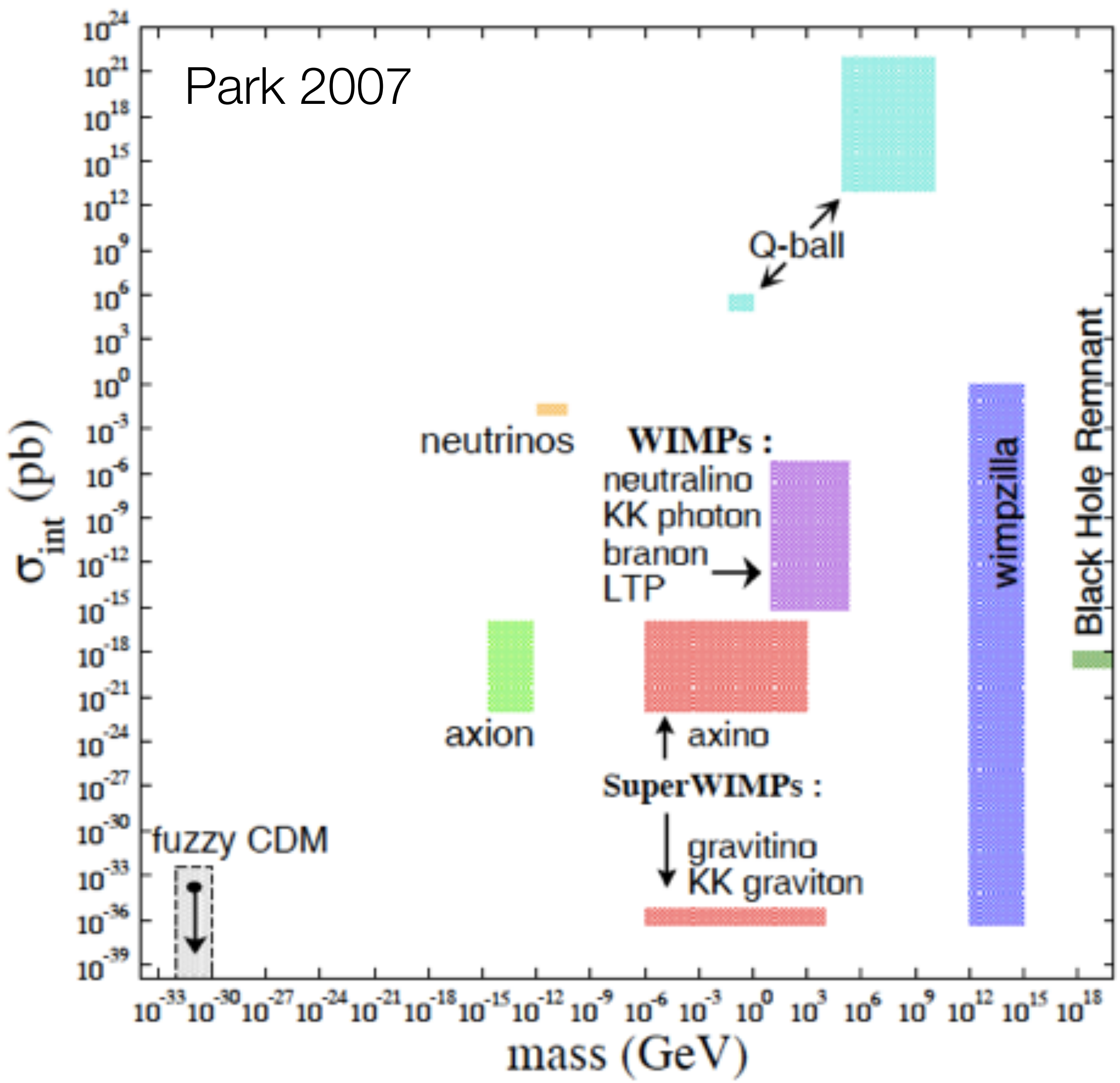
Modeling the Lyman-alpha forest

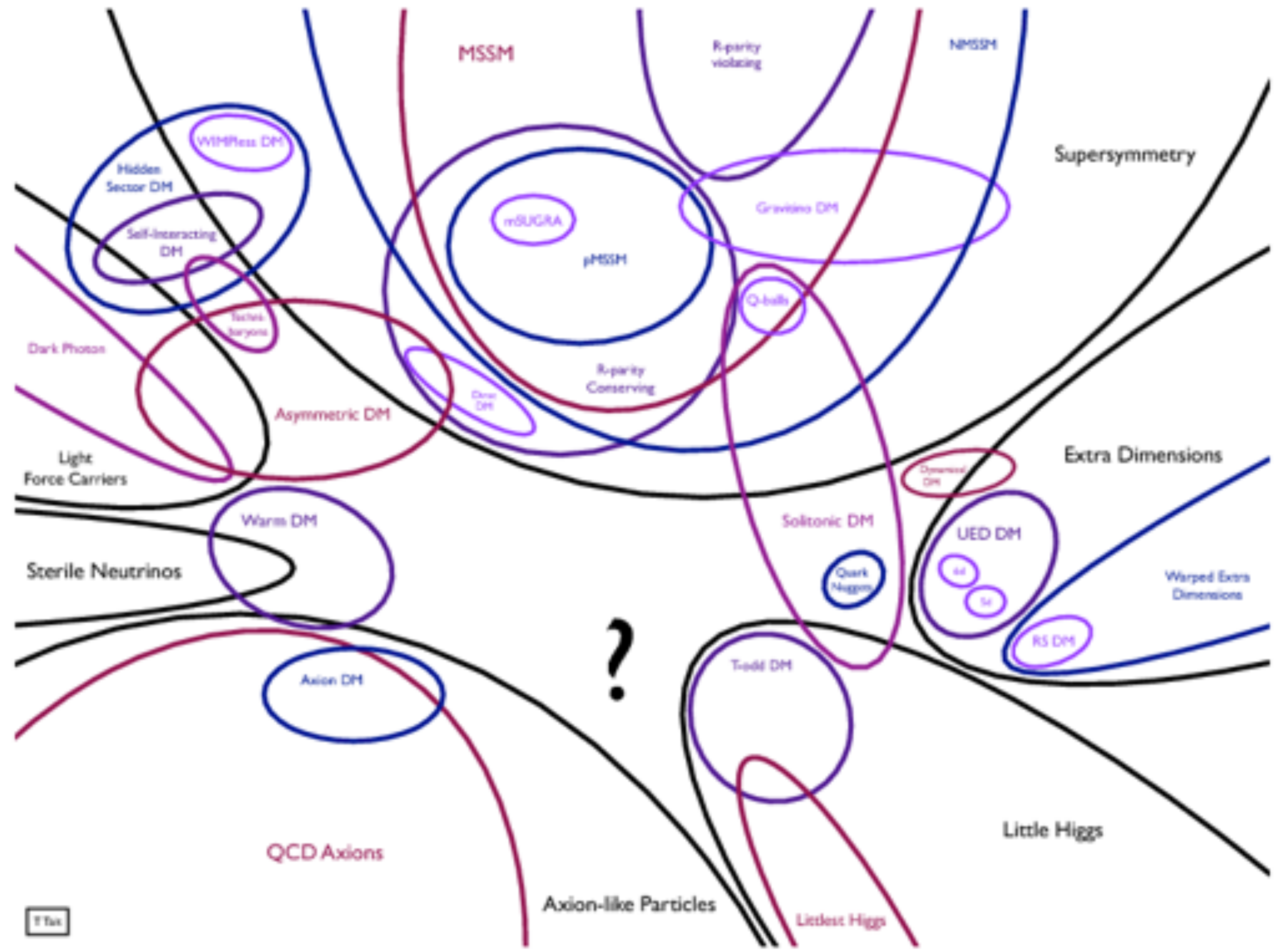
Constraining DM models with Lyman-alpha

What is Dark Matter ??

assuming a particle with QFT…

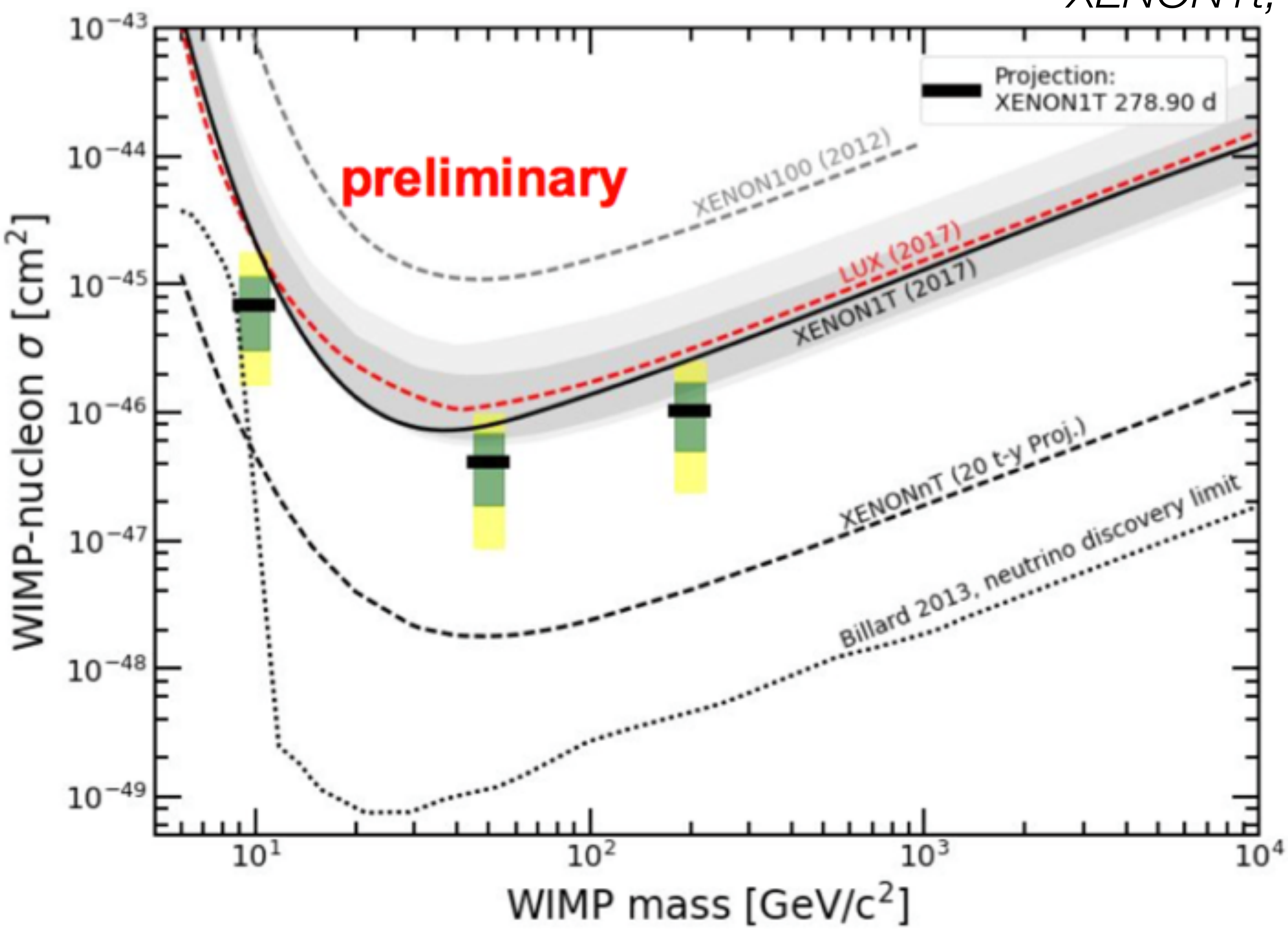
Tait 2013



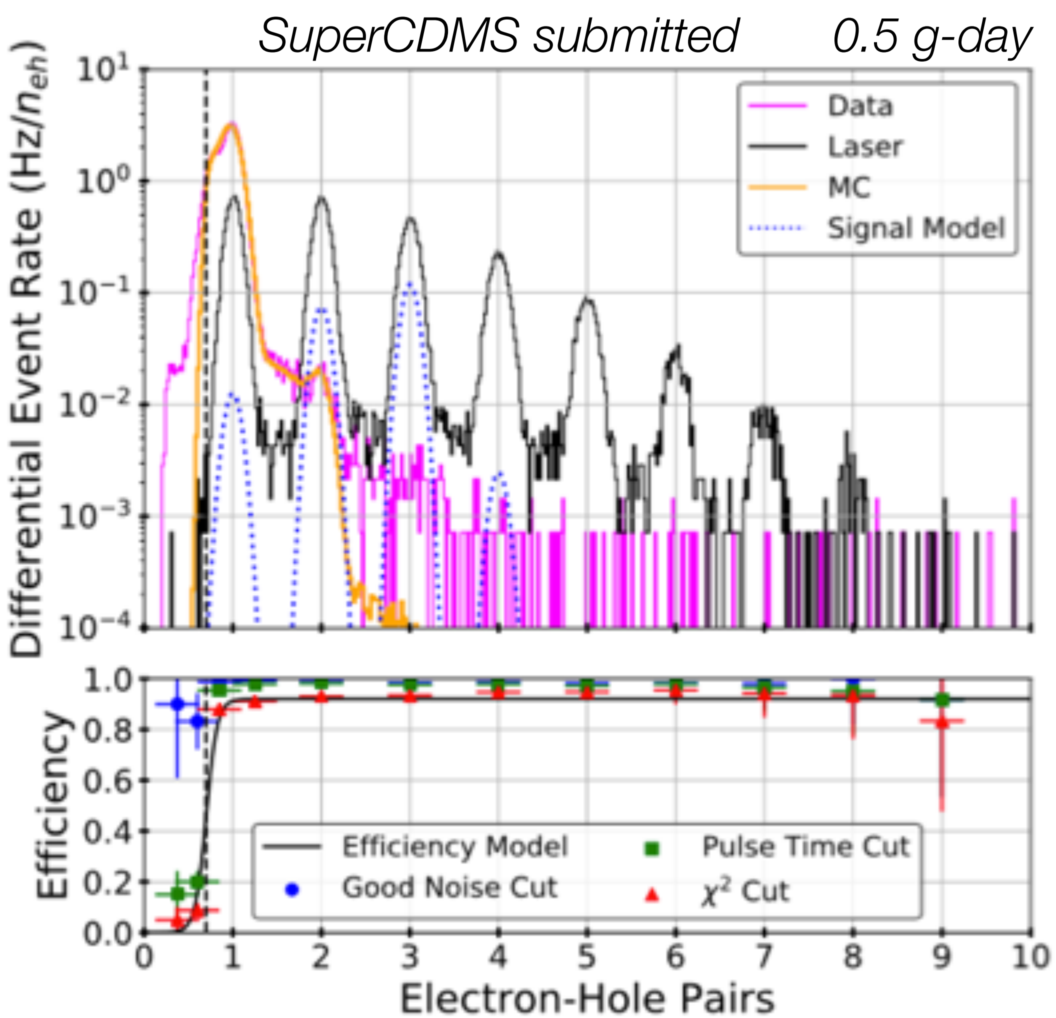


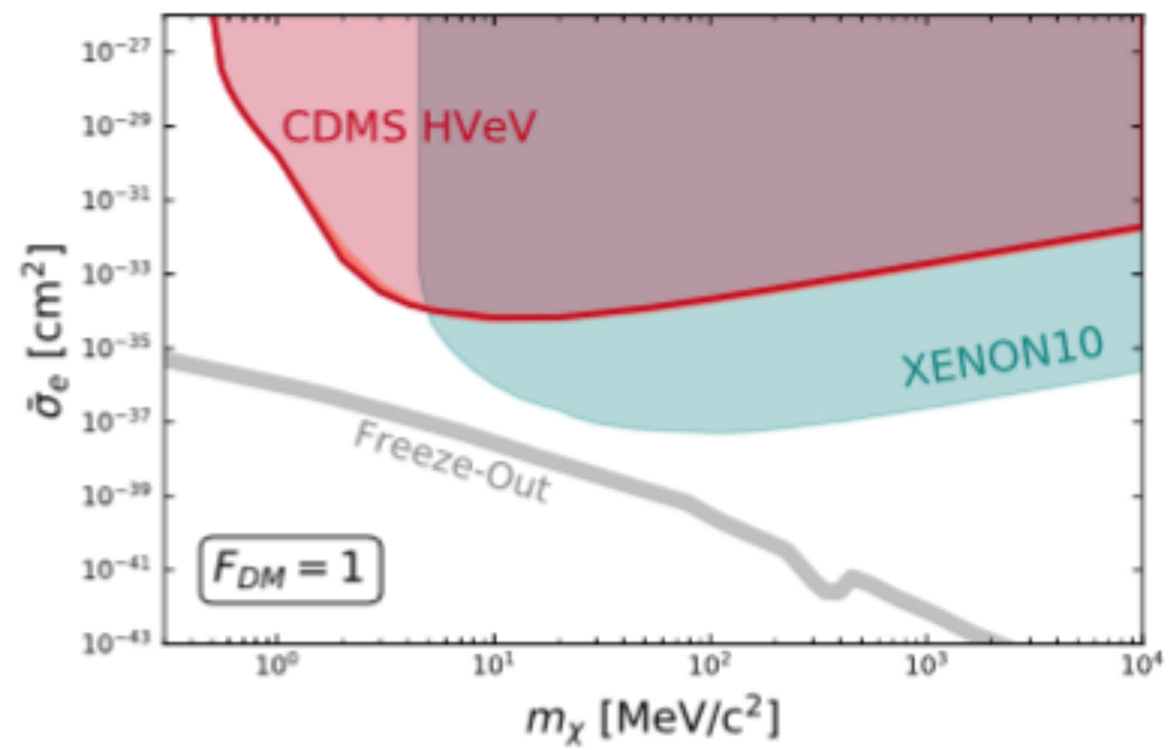
WIMPs ?

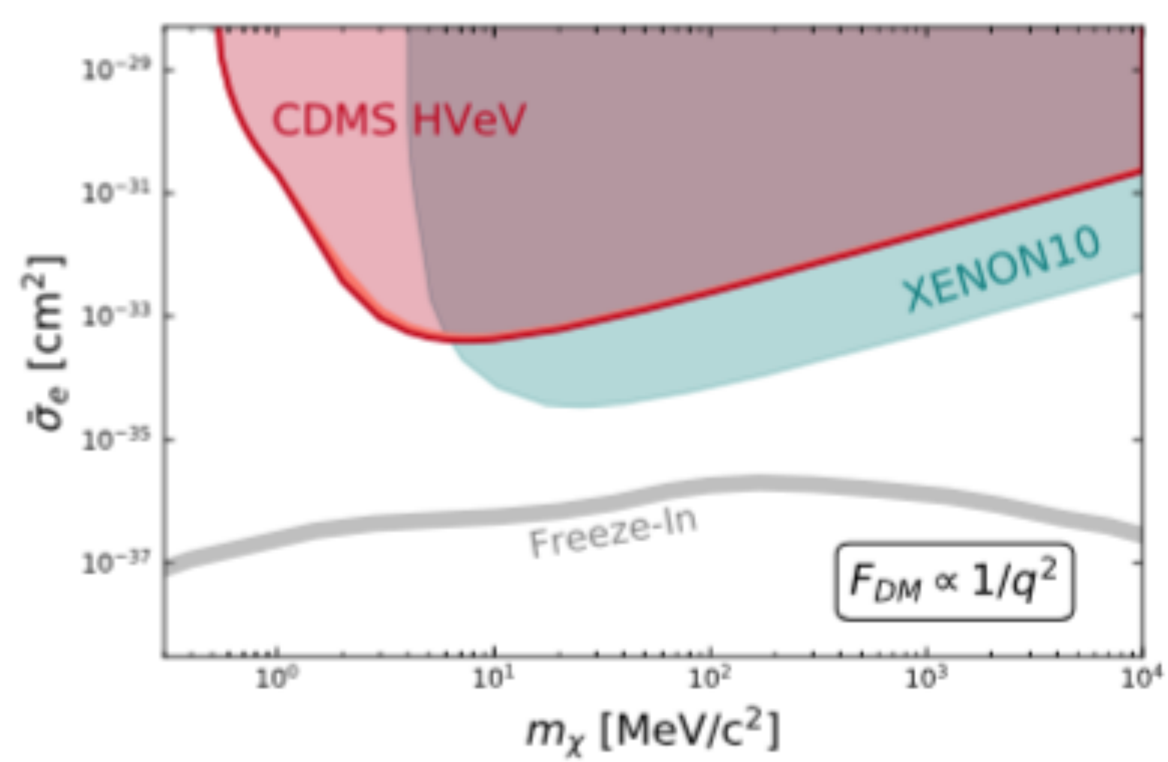
XENON1t, Moriond



Exploring more mass ranges …







MeV DM

- Direct search through DM-e scattering

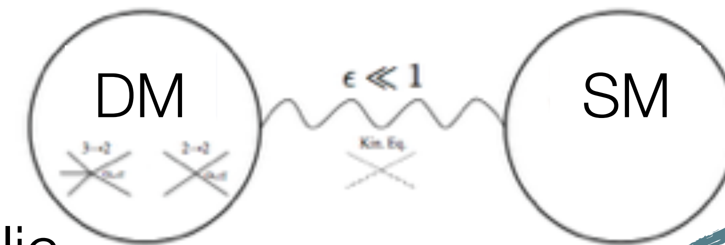
Complementary with astro/ cosmo signals/constraints

DM solutions to the small-scale « issues »

Strongly-Interacting DM (SIDM)

σ/m ~ 0.1-1 cm2/g
best solve cusp-core

eg. sub-GeV thermal relic with 3➝2 annihilation [Hochberg+ PRL 2014]



Fuzzy Dark Matter (FDM)

m~10^{-22} eV
de Broglie wavelength

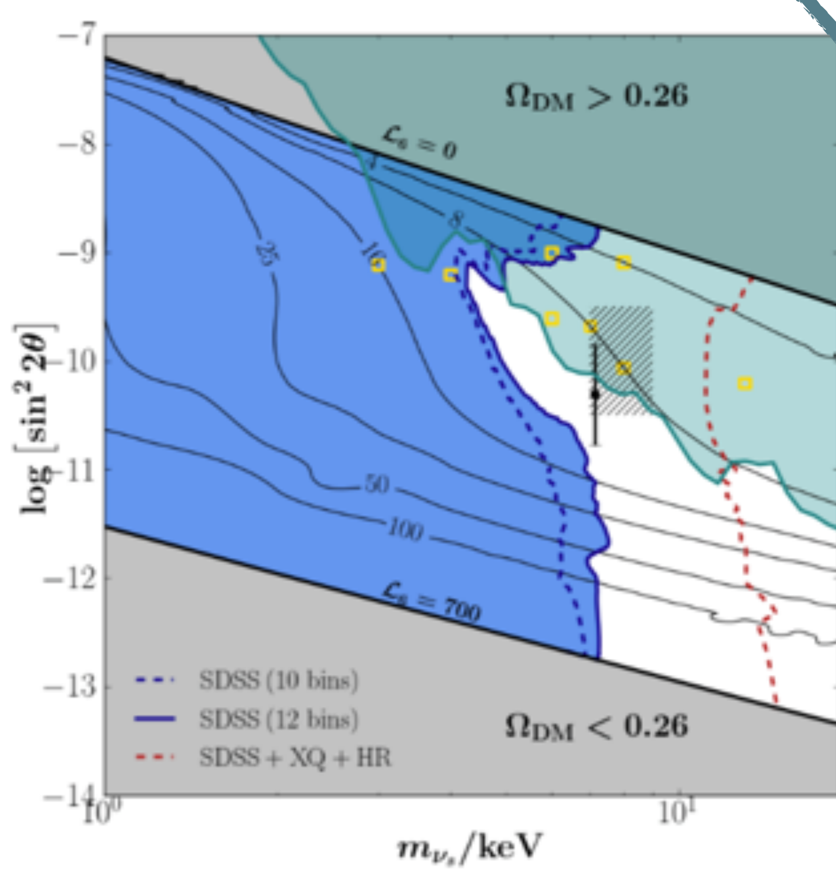
« no Catch 22 problem » - could solve both halo statistics & core profile ??

keV-scale relic (WDM)

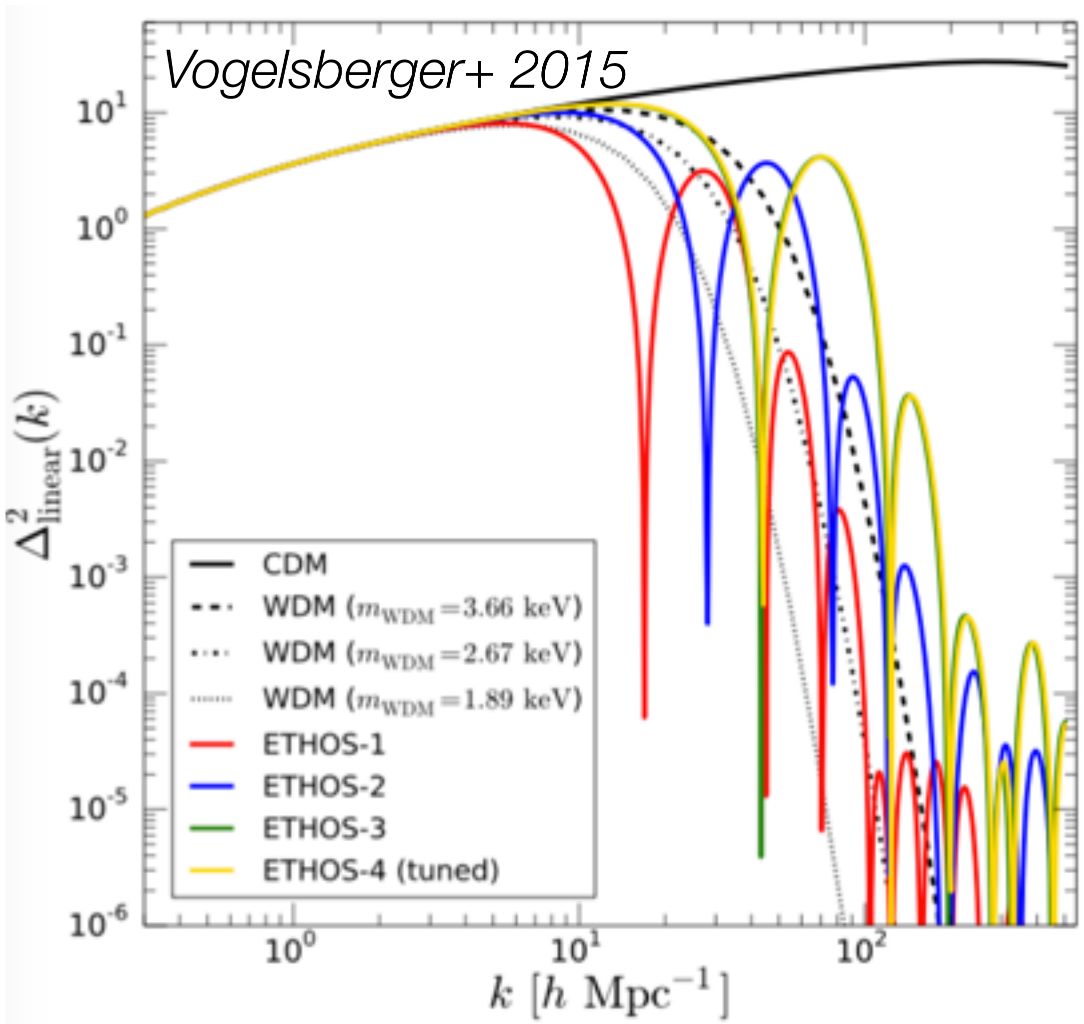
free-streaming
best solve missing satellites

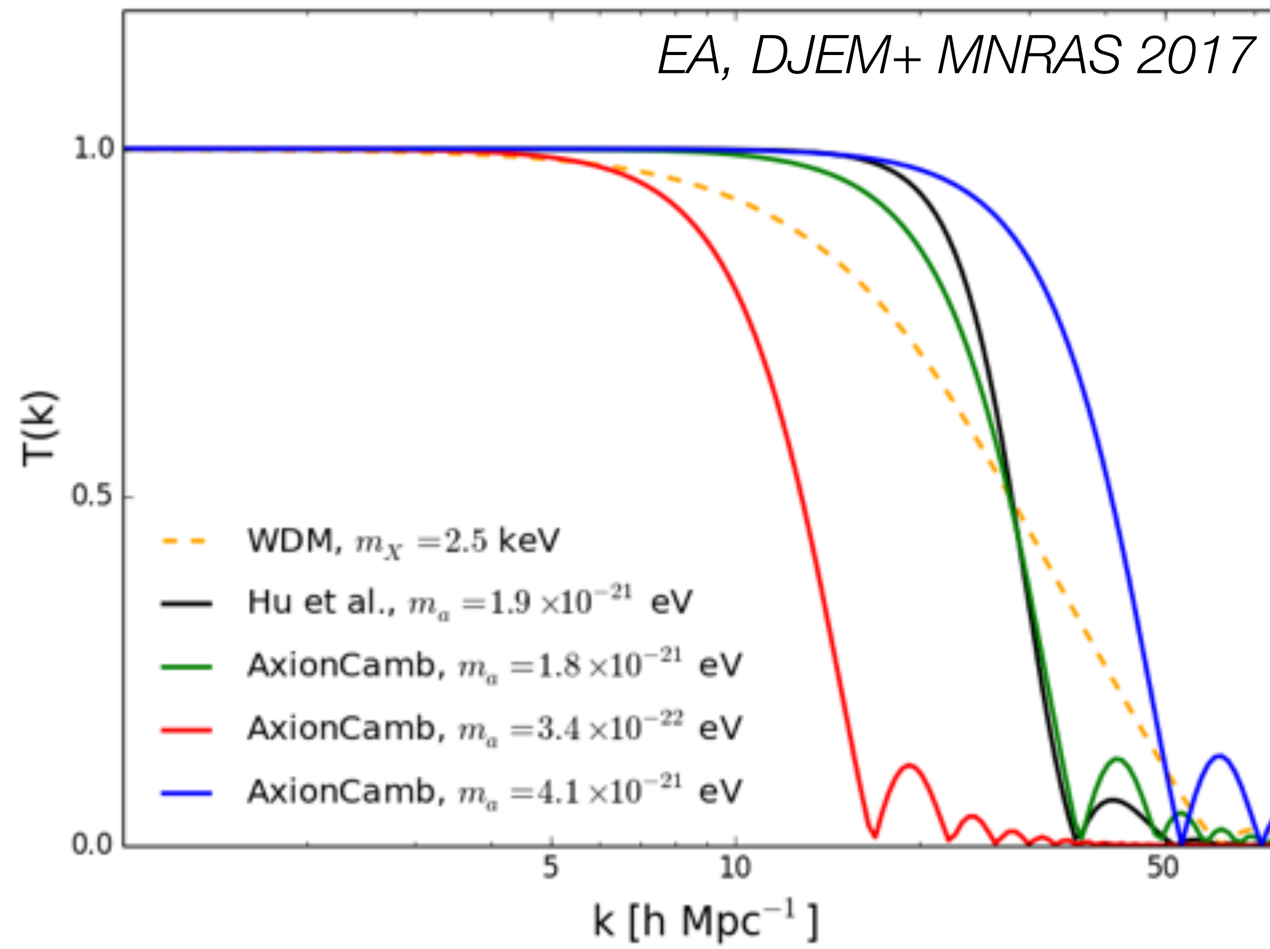
eg. sterile neutrino [Shaposhnikov+ PLB 2005]

3.5 keV line signal ?



Linear P(k) in W/SI/FDM

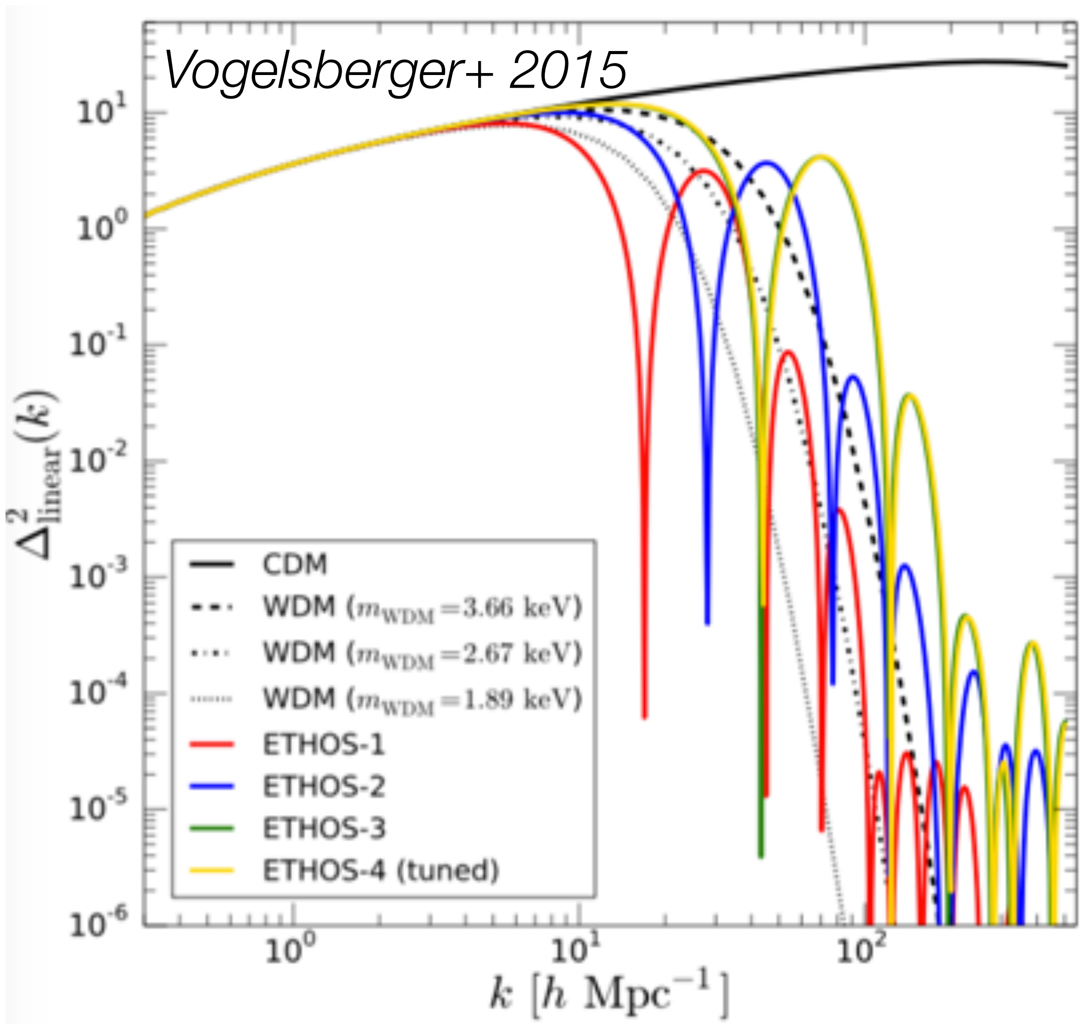


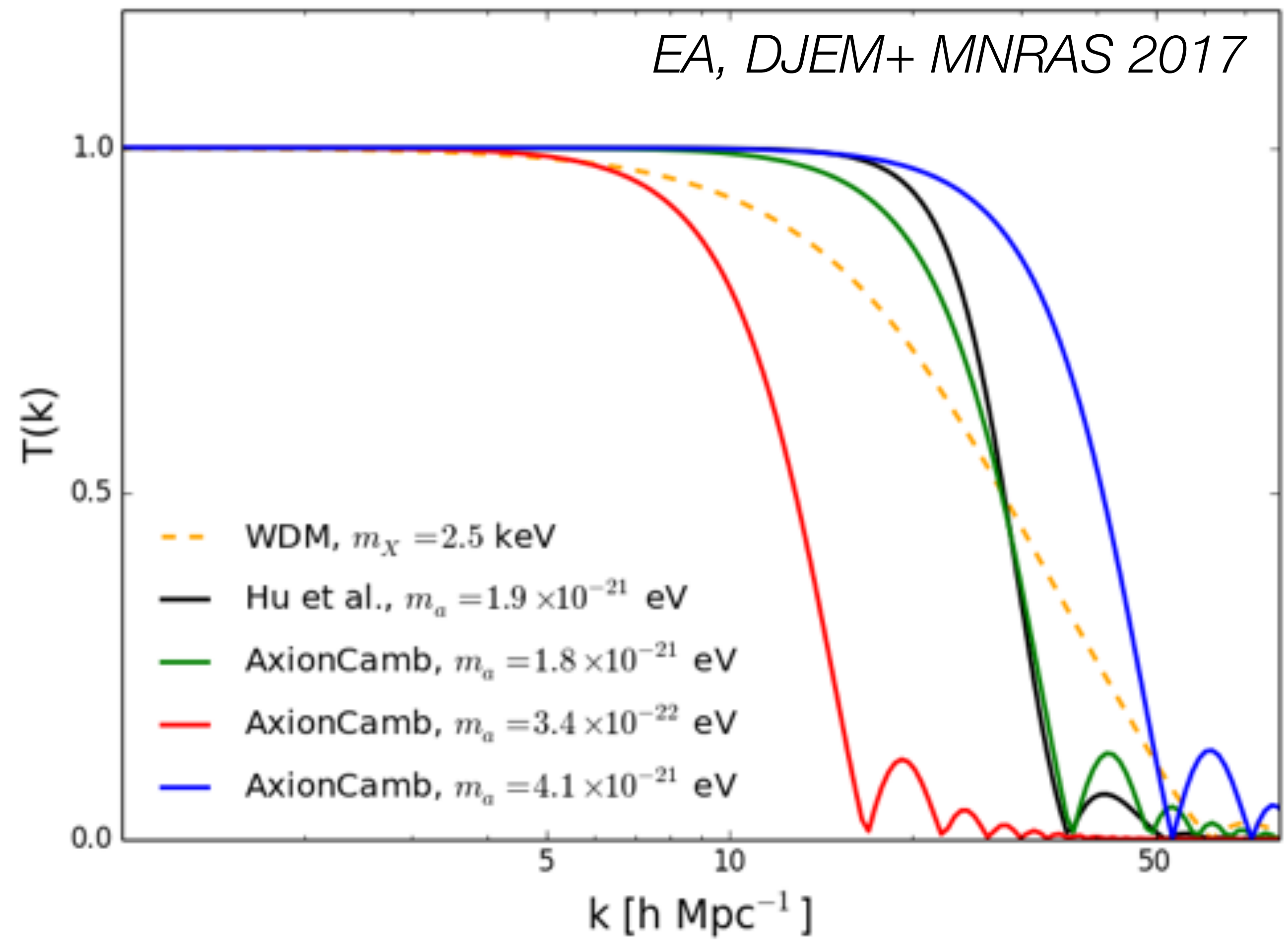


Small-scale cutoff @ high z => truncation in HMF

- High-z galaxy counts
- Delayed reionization
- Lyman-alpha spectrum cutoff

Linear P(k) in W/SI/FDM





Small-scale cutoff @ high z => truncation in HMF

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- Delayed reionization
- **Lyman-alpha spectrum cutoff**

Dark matter

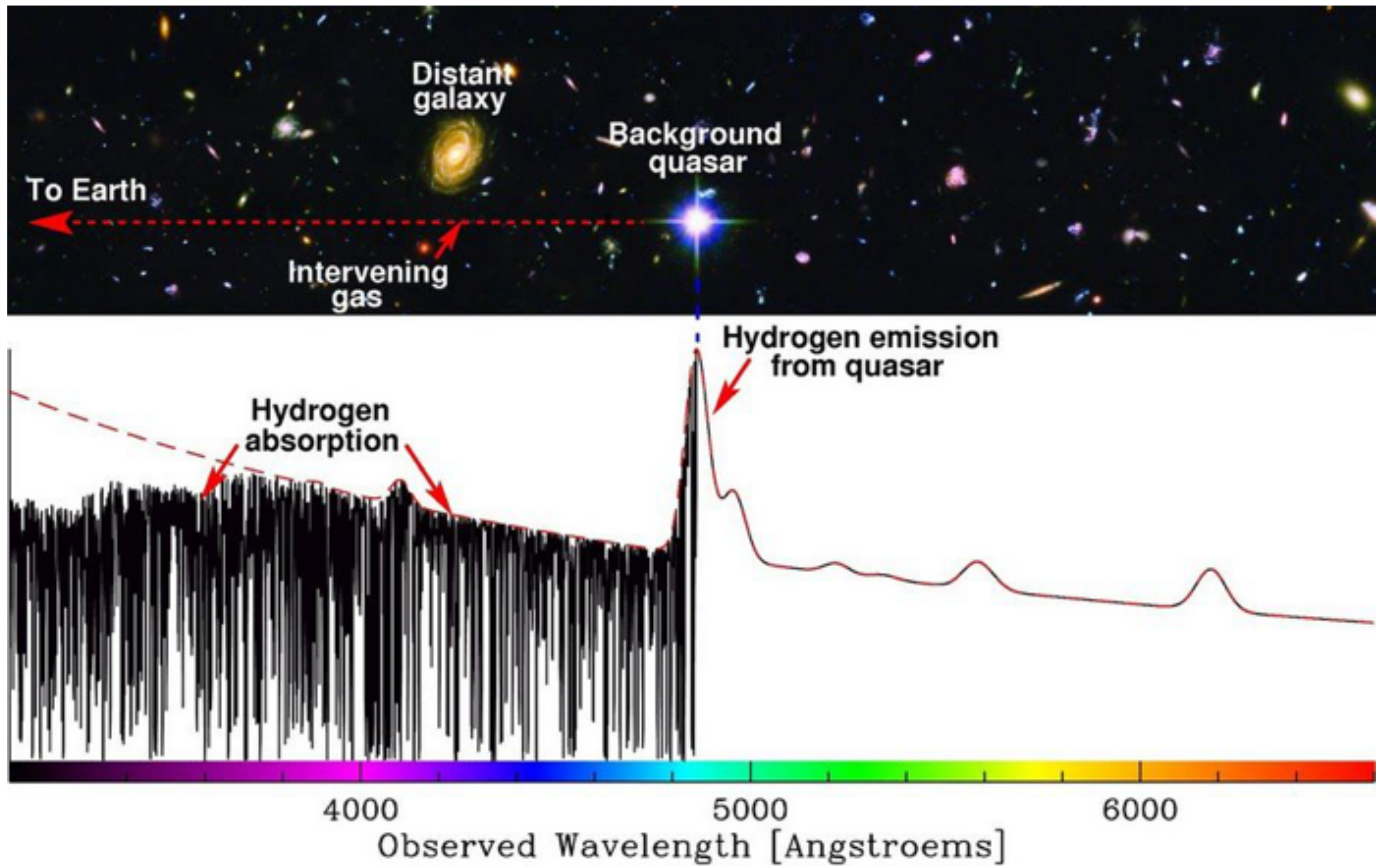
Lyman-alpha forest : data

Modeling the Lyman-alpha forest

Constraining DM models with Lyman-alpha

The Lyman-α forest

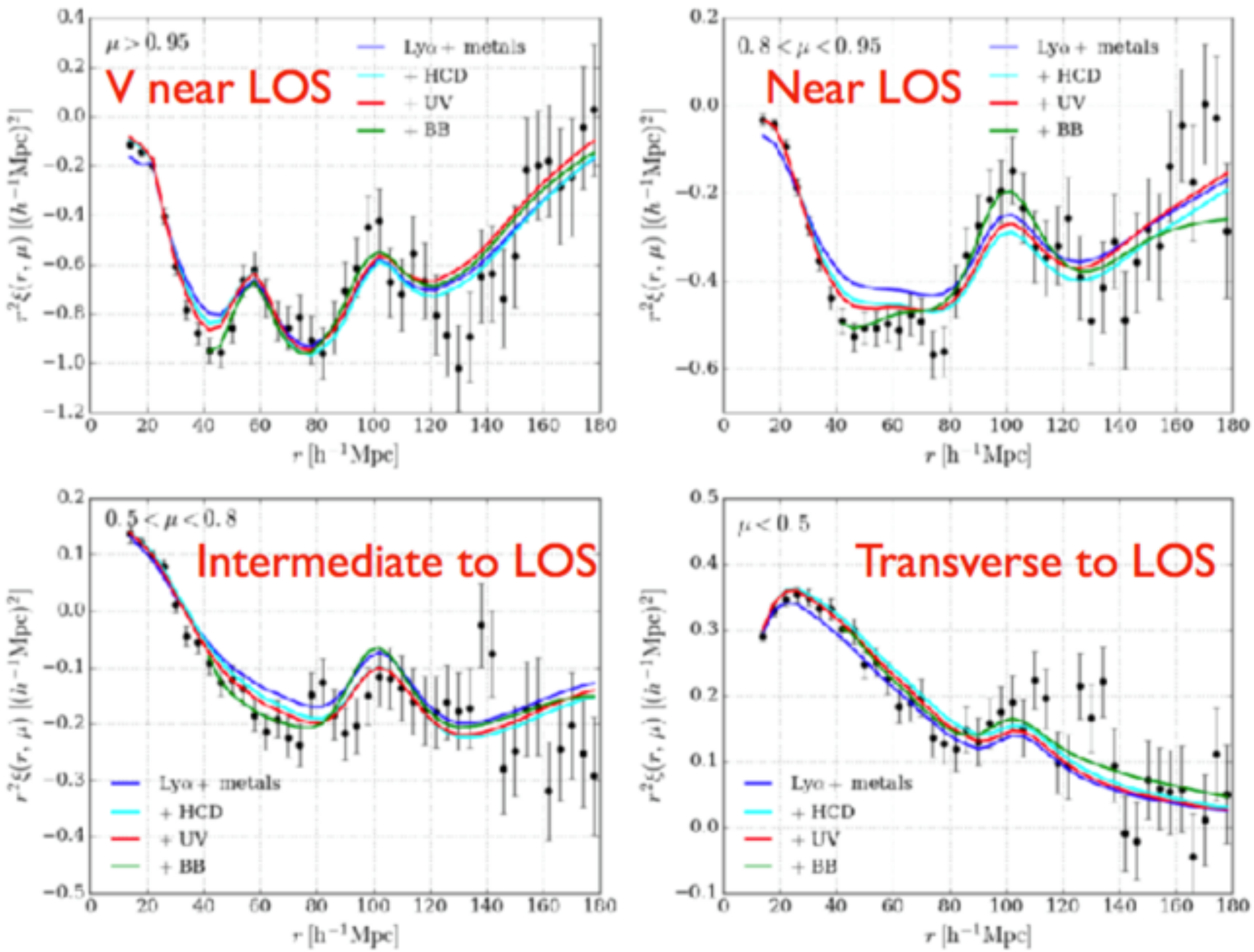
Measure fluctuations of Lyman-α flux transmitted by the neutral intergalactic medium



Closely related to the small-scale matter power spectrum - however through :

- non-linear structure growth
- IGM physics

Lyman-alpha forest @ large scale : BOSS



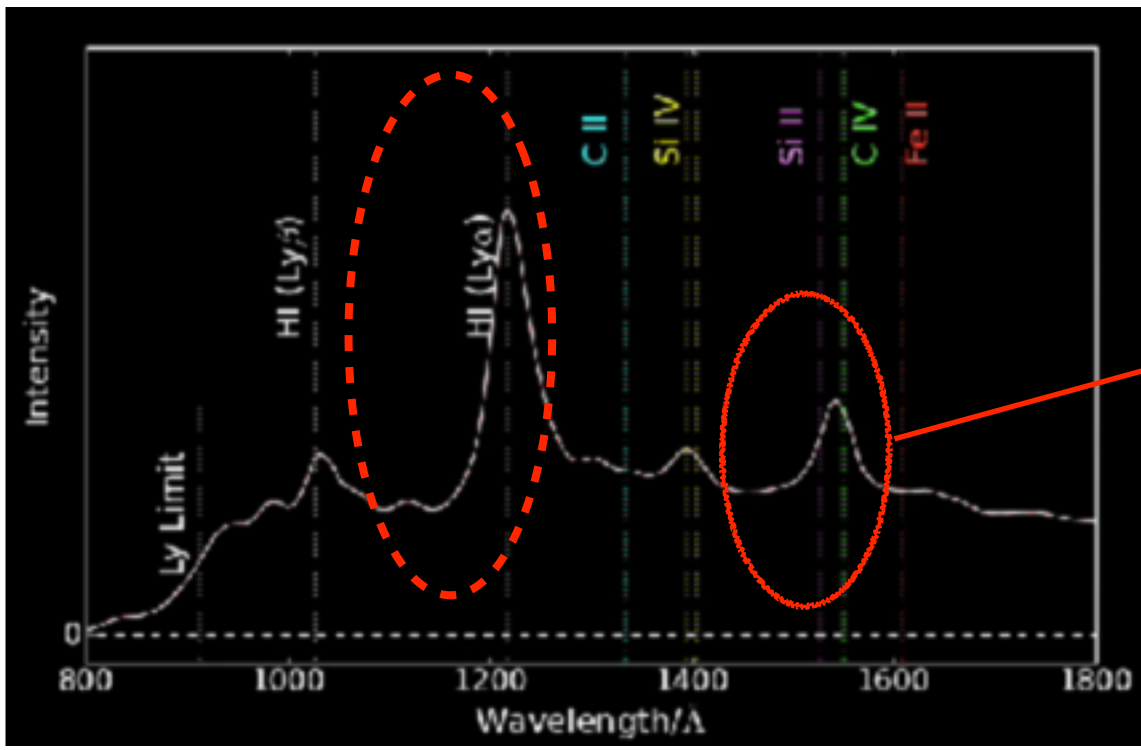
3-D measurement
Bautista+ 2017 - DR12

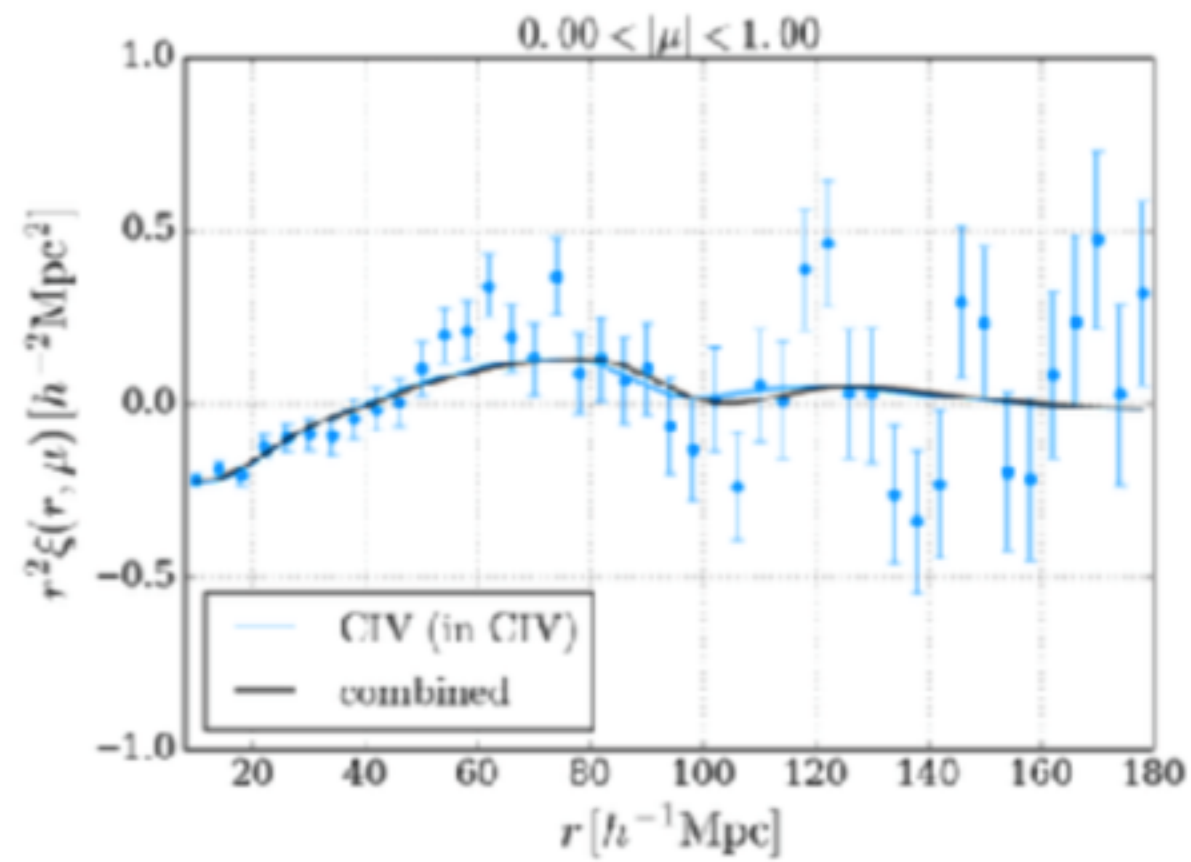
Correlation function
between pixels

Models :
CDM N-body mocks +
gaz prescriptions

eBOSS : even @ lower z

Low-z quasar survey (z~1.5) primarily for QSO clustering (BAO, RSD)
Cannot measure Ly-alpha forest … but :

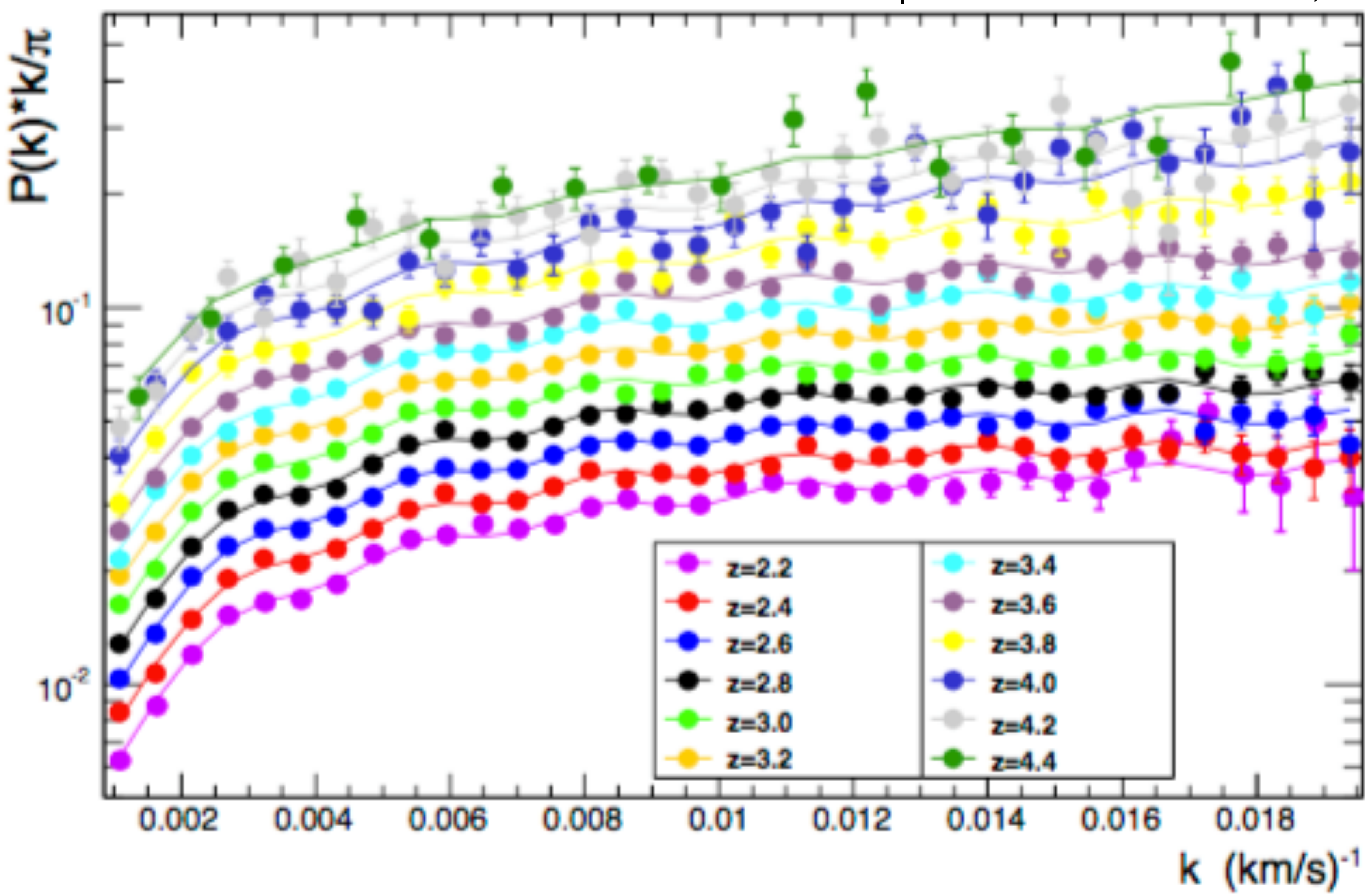




CIV forest measurement (Blomqvist+ 2018)
1.7 sig BAO detection
final eBOSS expect ~7% precision

Small-scale, 1D power spectrum : BOSS

Palanque-Delabrouille et al., A&A 2013

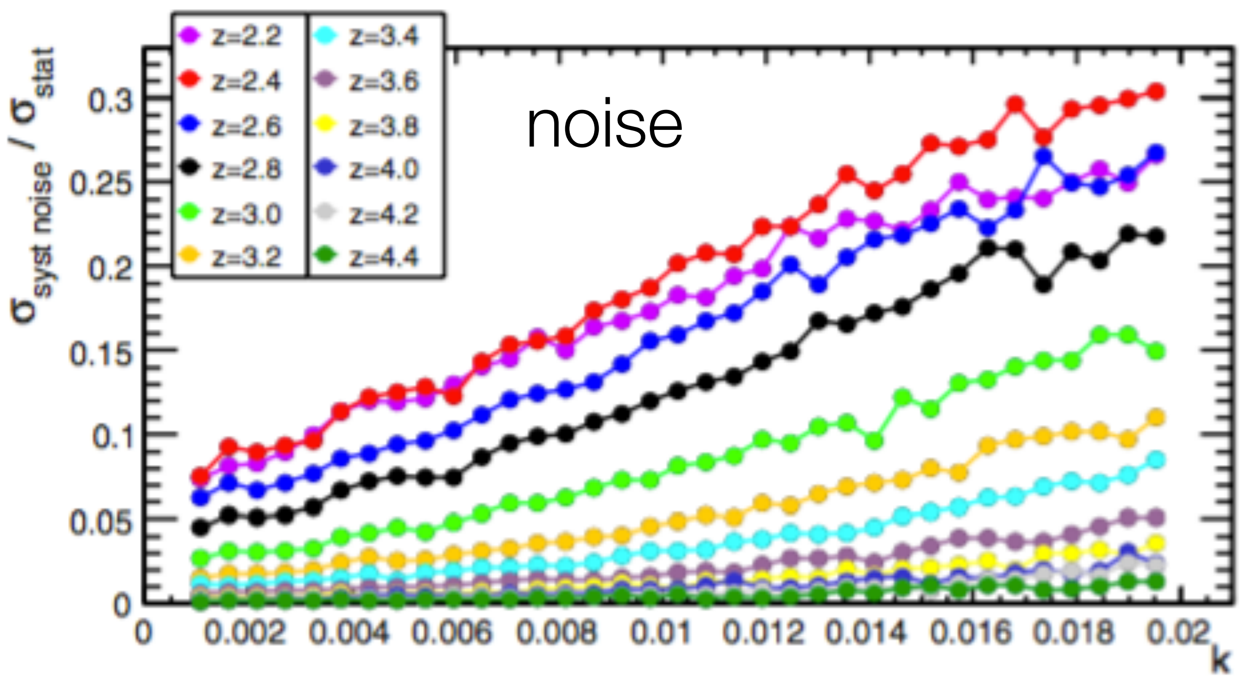


SDSS DR9 catalog : 60000 quasar spectra

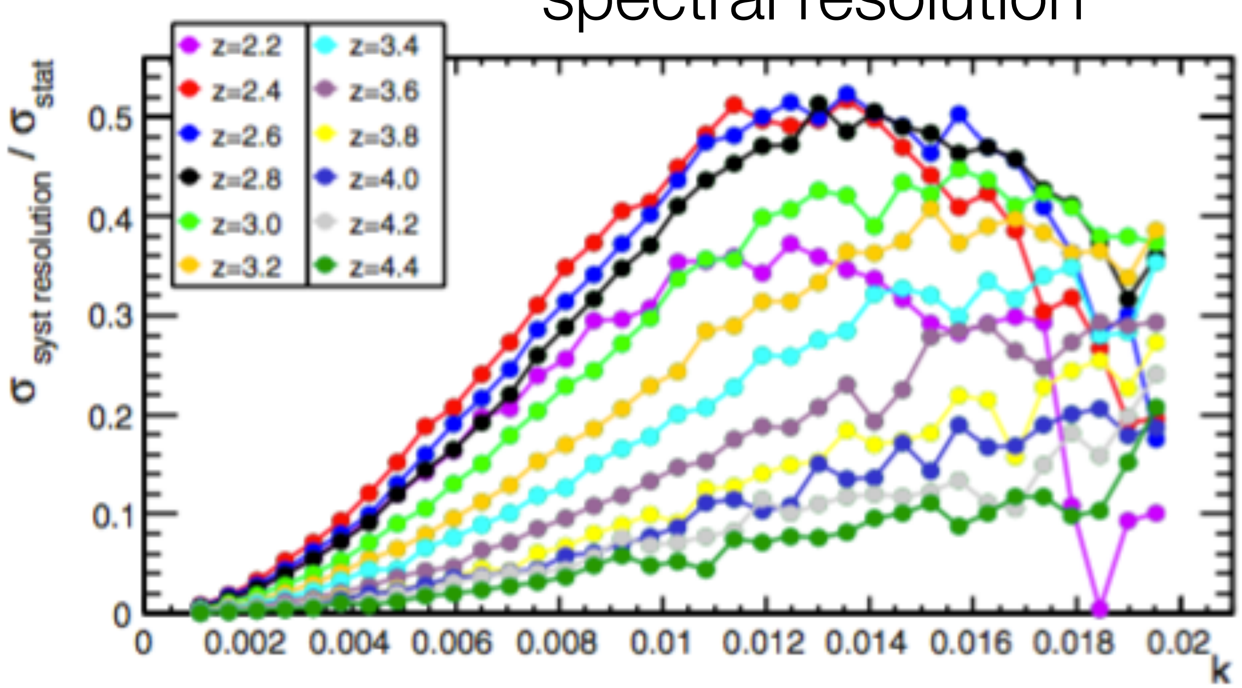
⟹ **flux power spectra with near-% precision**

- z=2.4-4.2
- *scales down to ~ Mpc*

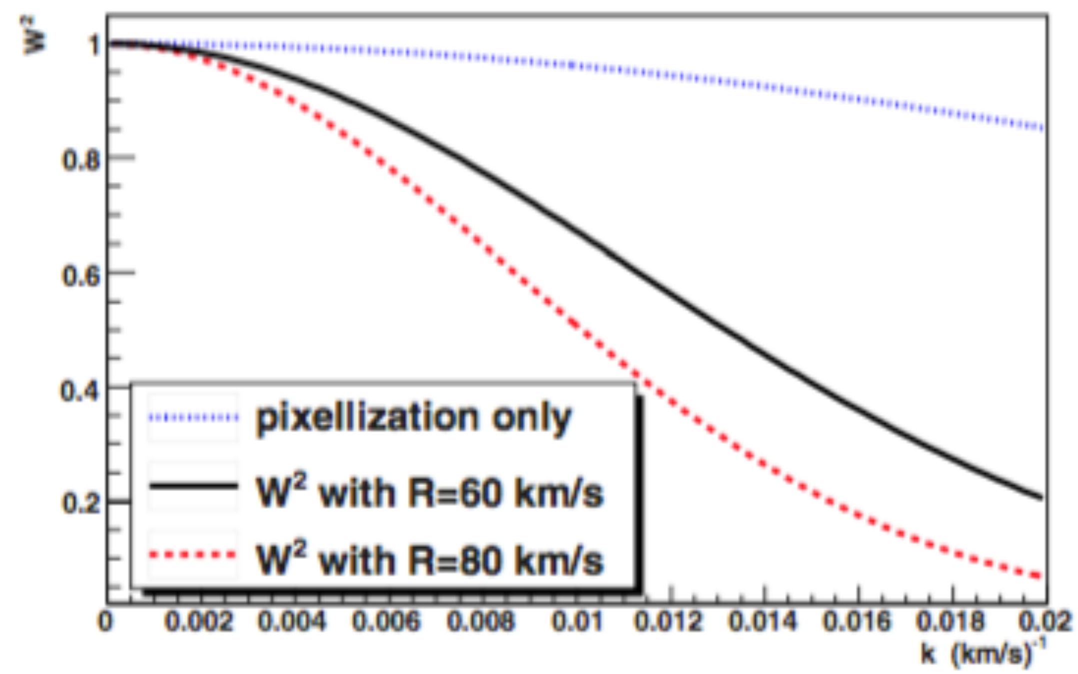
BOSS power spectrum measurement



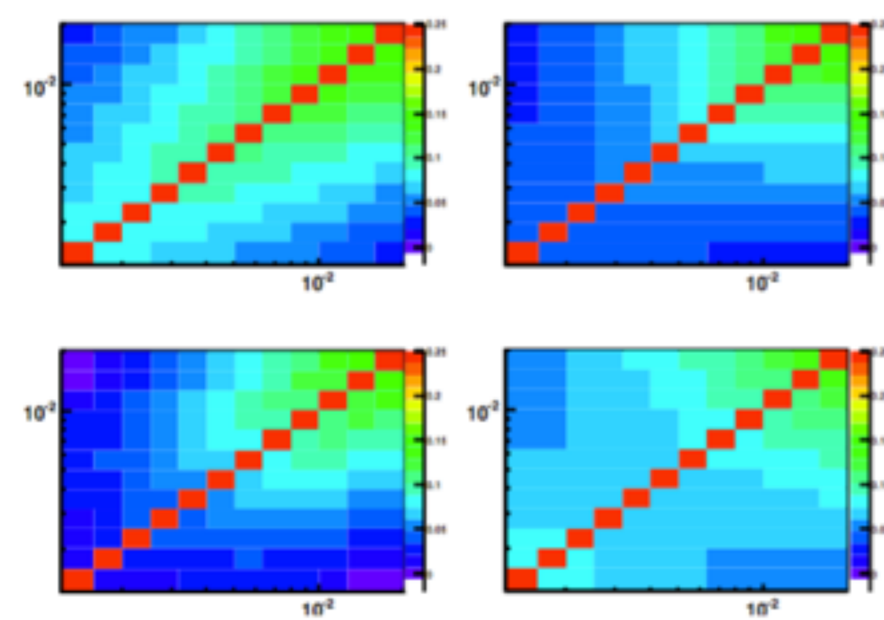
spectral resolution



resolution kernel

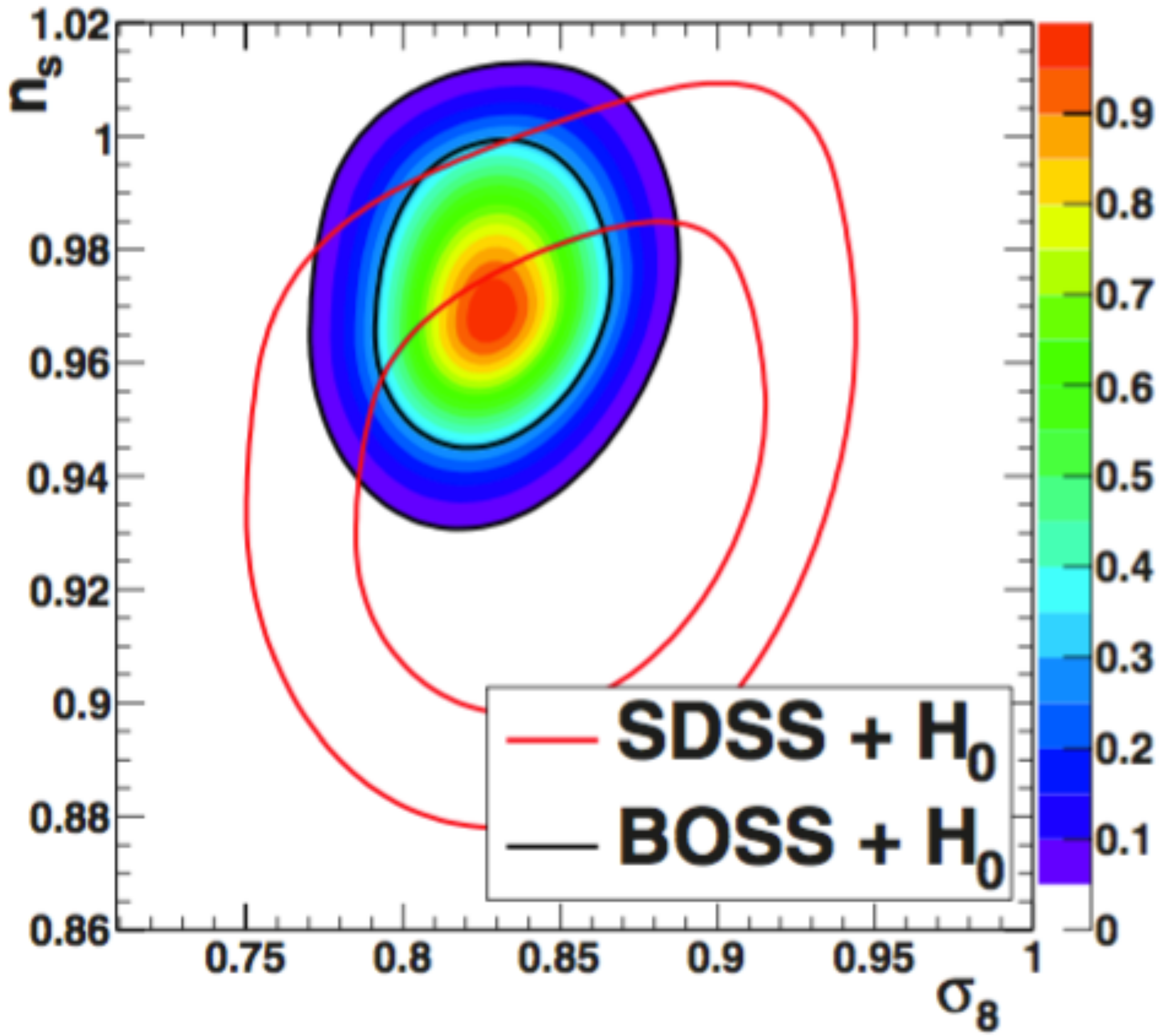


correlation matrix



E. Armengaud - CEA Saclay

SDSS ==> BOSS



Next :

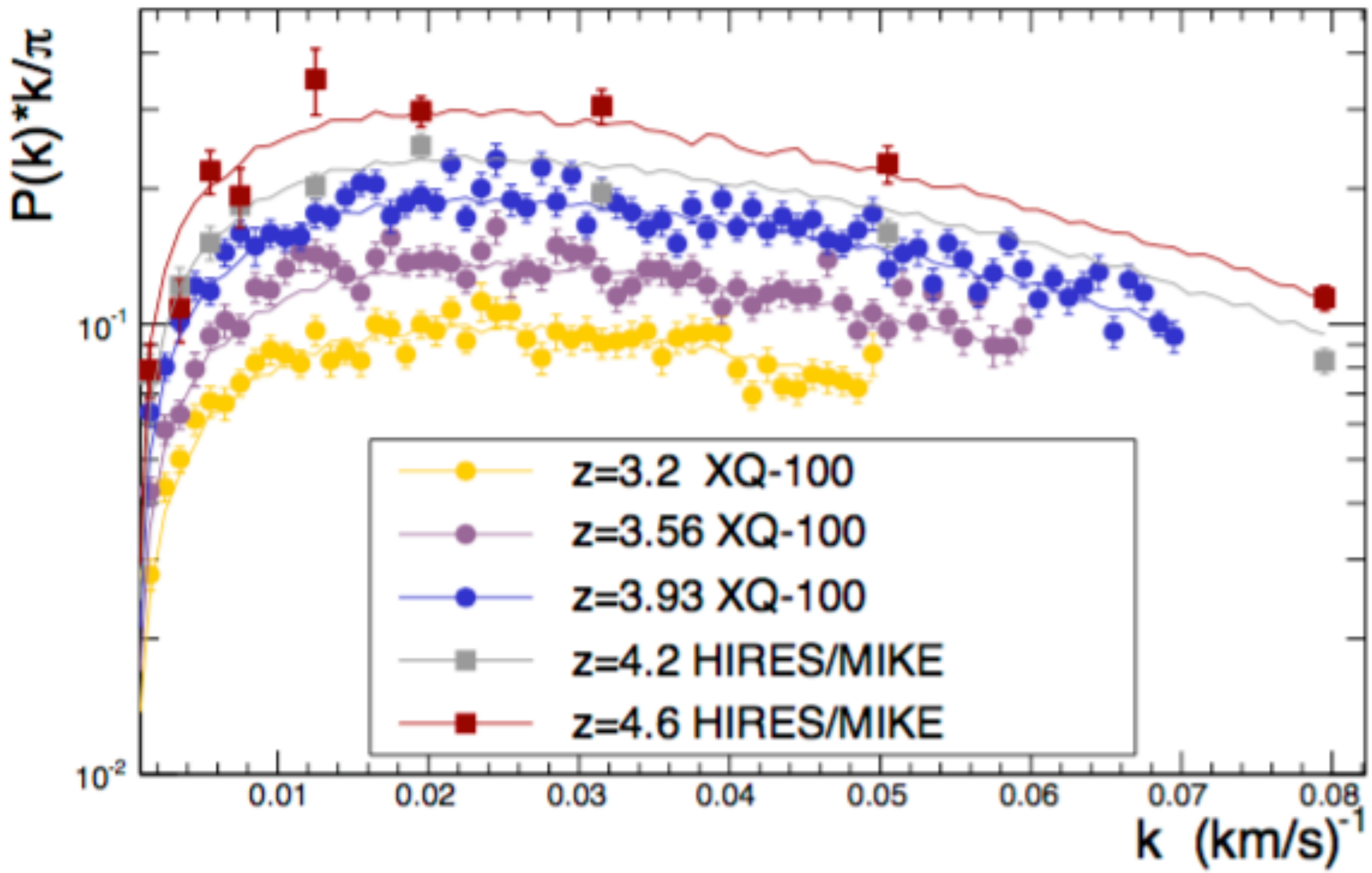
SDSS - DR14 (eBOSS)
  small improvements

DESI
  700,000 Ly-alpha forest quasars
  Commissionning 2019
  Science survey 2020

High-resolution Lyman-alpha

High resolution spectra
(VLT/X-SHOOTER, Magellan/MIKE, Keck/HIRES))
Smaller scales, higher z

Yèche et al. JCAP2017
Irsic+ 2017



observe Jeans smoothing

Dark matter

Lyman-alpha forest : data

Modeling the Lyman-alpha forest

Constraining DM models with Lyman-alpha

Predicted forest flux

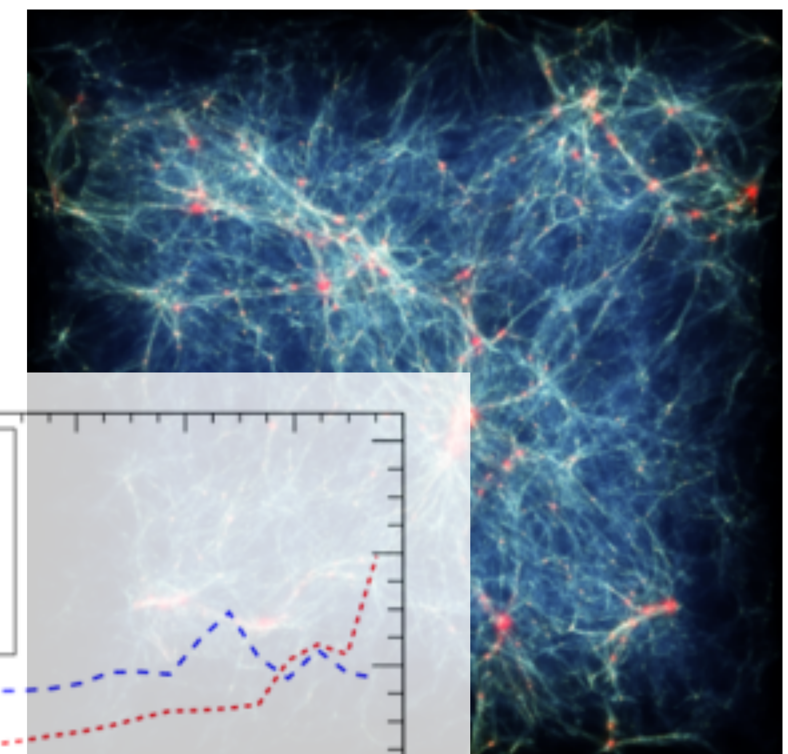
$$\tau_{\rm IGM}(z_{\rm a}) \approx 2[1+\delta(z_{\rm a})]^2 \frac{\alpha_{\rm rec}(T)}{\Gamma}\left(\frac{1+z_{\rm a}}{4}\right)^{4.5}$$

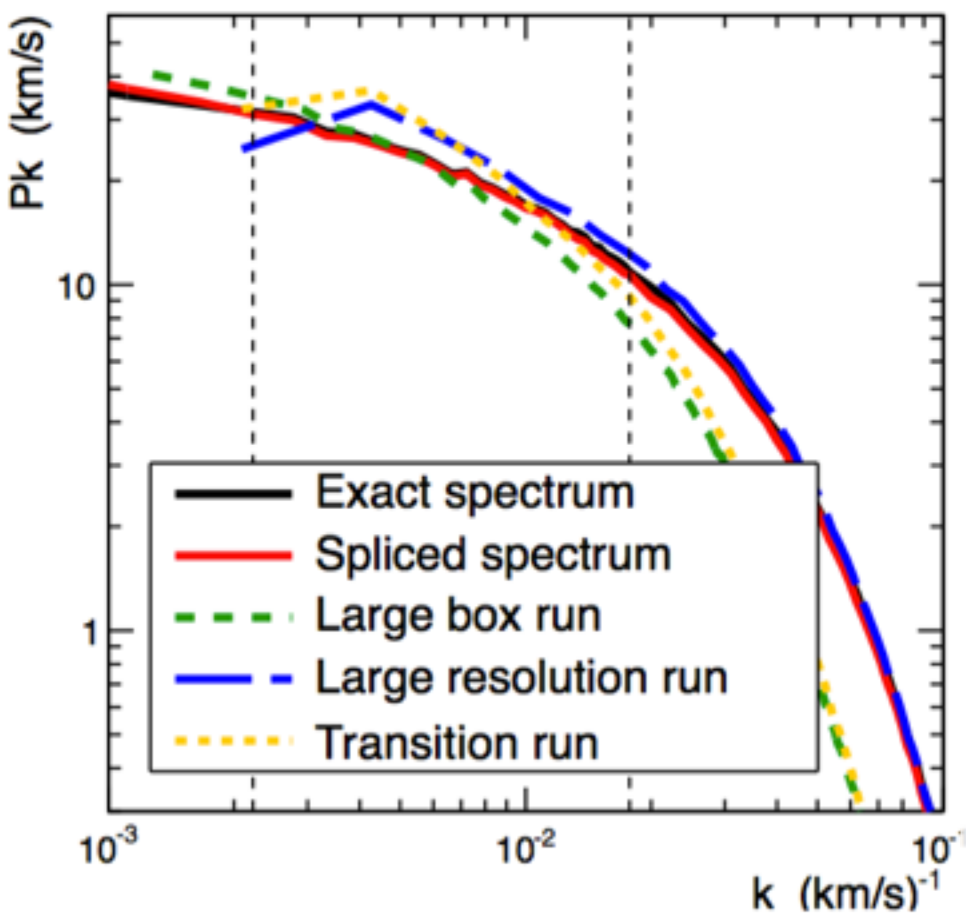
(fluctuating Gunn-Peterson approx.)

Non-linear evolution + hydrodynamics : Gadget simulations

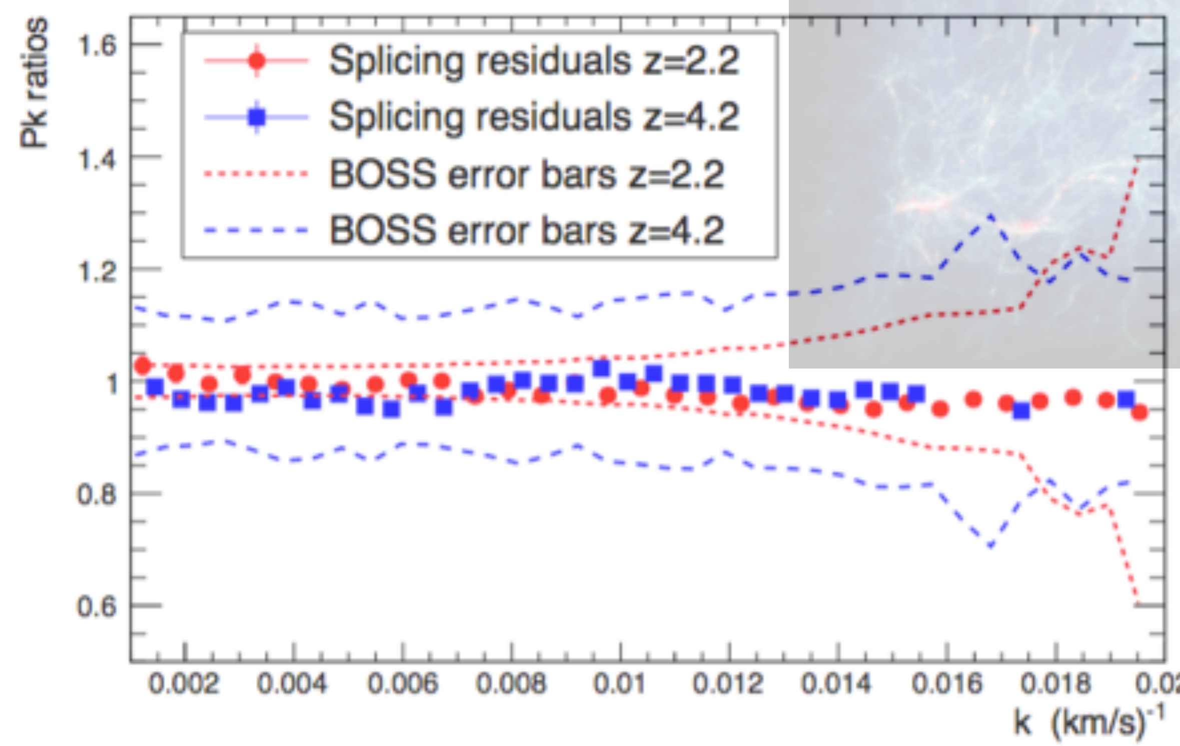
Draw « lines of sight » and predict flux spectrum $P_{1D}(k)$

Borde+ JCAP2014





splicing method for P(k) reconstruction



IGM physics, and others

IGM parameters included in hydro simulation

temperature vs z (T_0,γ) : heating params

$$T(\rho, z) = T_0(z)\ (1+\delta)^{\gamma(z)-1}$$

average optical depth $\tau_{\mathrm{eff}} = A^{\tau} \times (1+z)^{\eta^{\tau}}$

Other IGM fluctuations : simple corrections

reionization redshift (prior z = 9+/-1.5)

discrete ionizing sources (UV fluctuations)

feedback (AGN & galactic outflows)

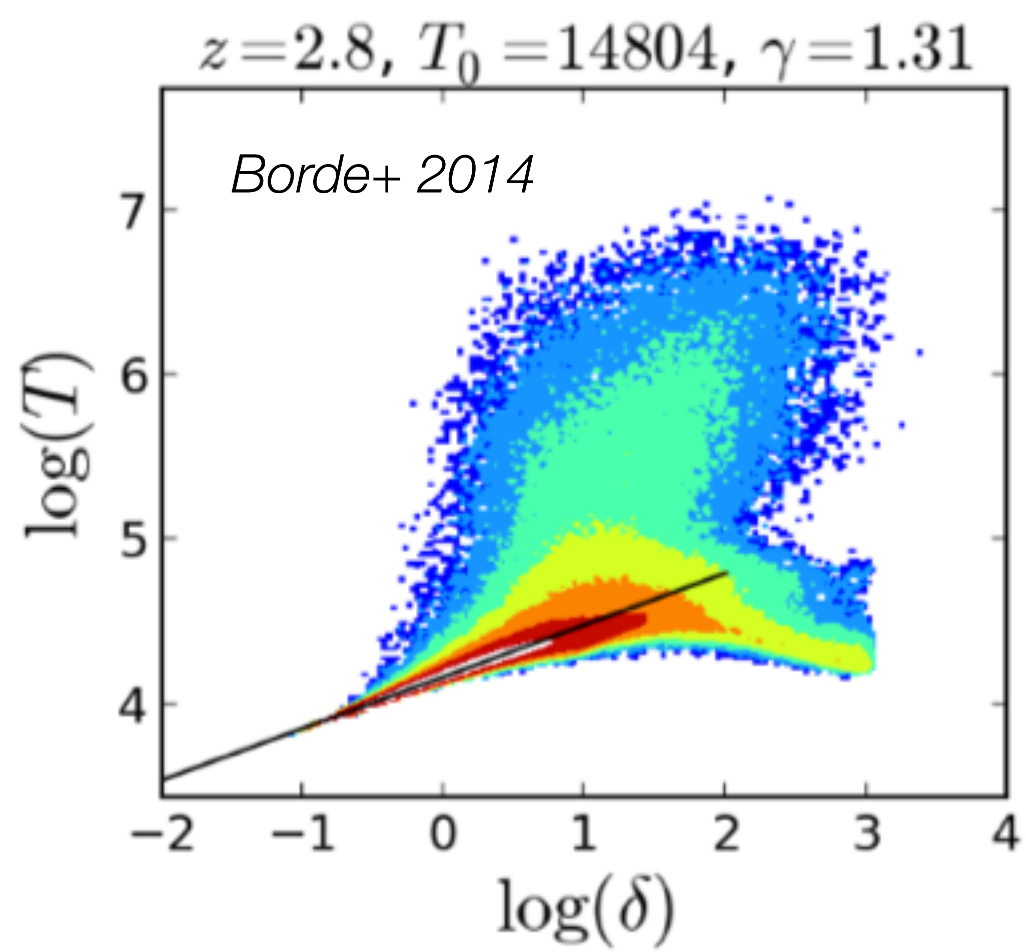
<u>**Non-IGM systematics**</u>

missed DLA, Si contamination

splicing artifacts

spectrometer resolution, noise

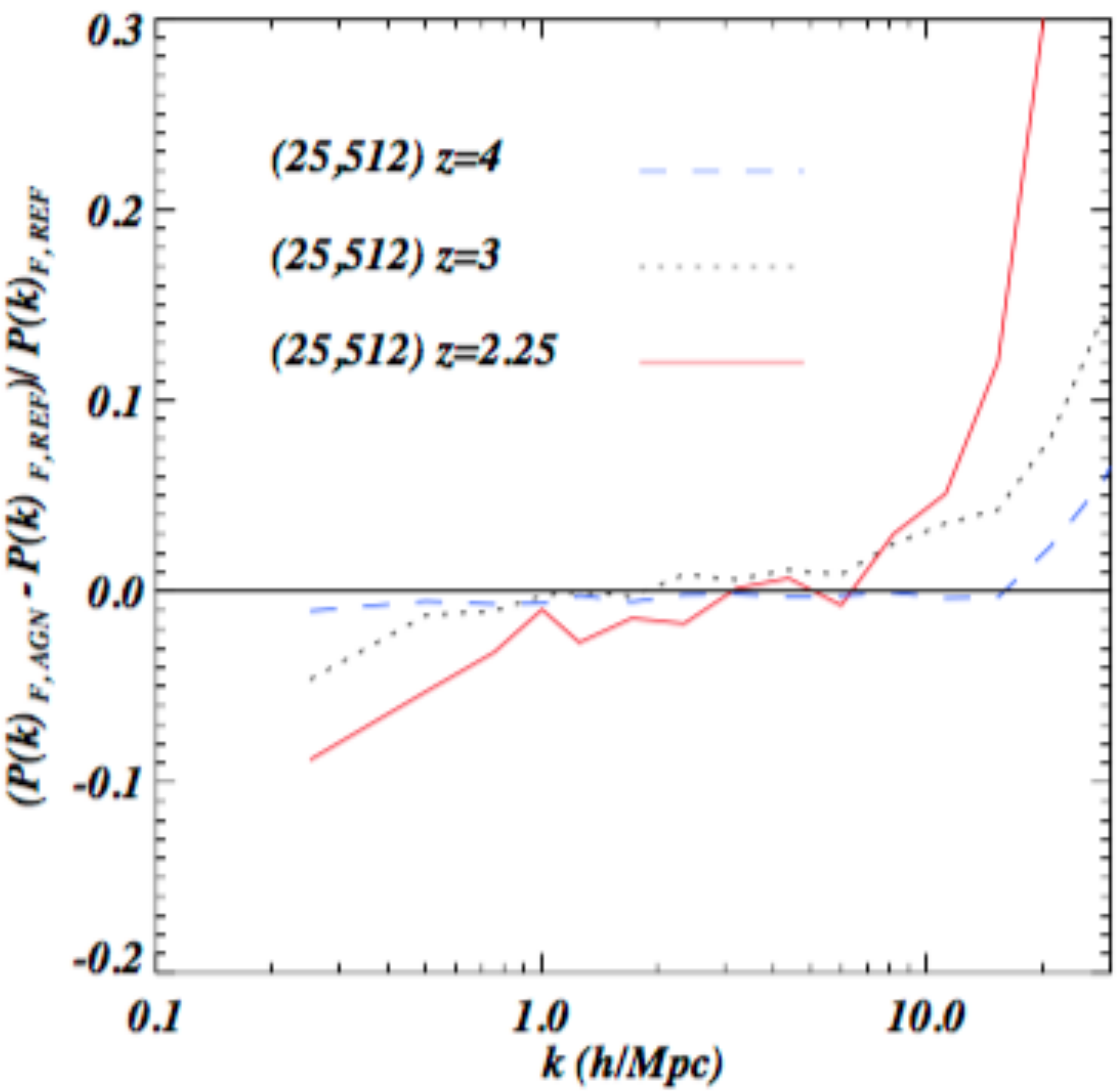
$$\mathcal{C}_{\mathrm{reso}} = e^{-(\alpha_{\mathrm{reso}}+\beta_{\mathrm{reso}}(z-3))\times k^2}$$

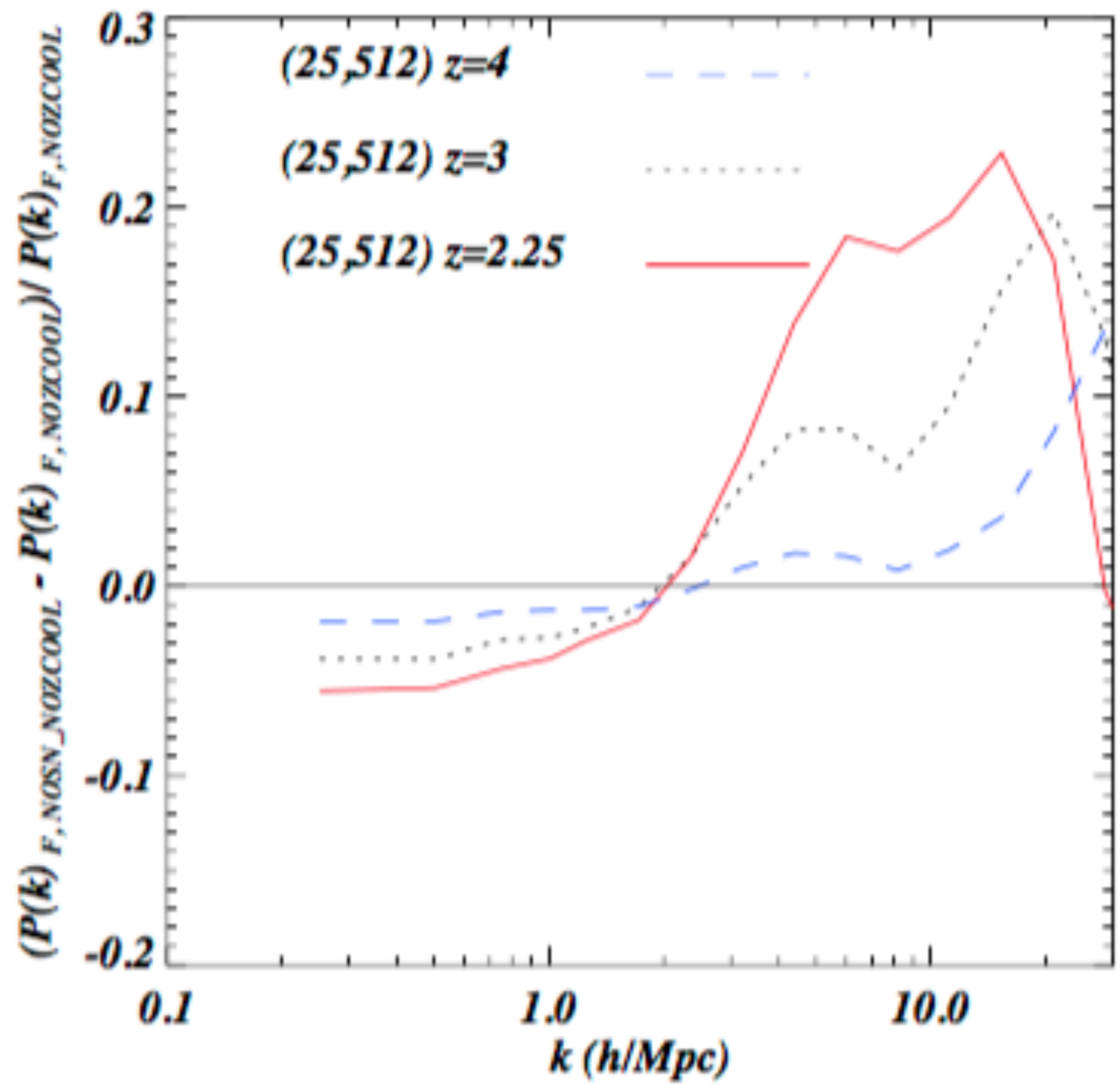


SN+AGN feedback

Viel+ MNRAS 429:1734–1746, 2013

$$\mathcal{C}^{\text{feedback}}_{\text{AGN}}(k) = (\alpha_{\text{AGN}}(z) + \beta_{\text{AGN}}(z) \times k) \times \alpha^{\text{feedback}}_{\text{AGN}}$$
$$\mathcal{C}^{\text{feedback}}_{\text{SN}}(k) = (\alpha_{\text{SN}}(z) + \beta_{\text{SN}}(z) \times k) \times \alpha^{\text{feedback}}_{\text{SN}}$$

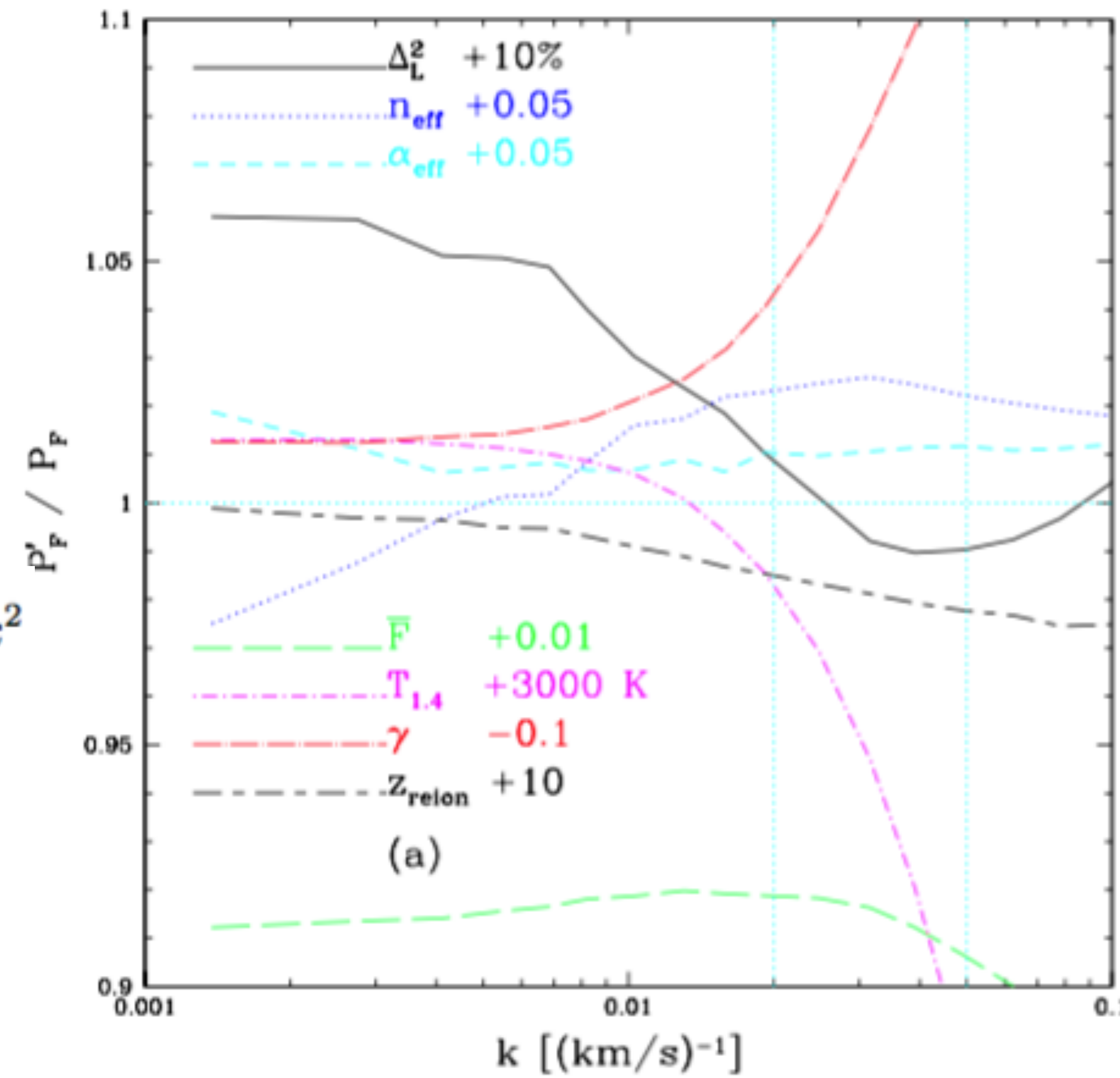




Reionization

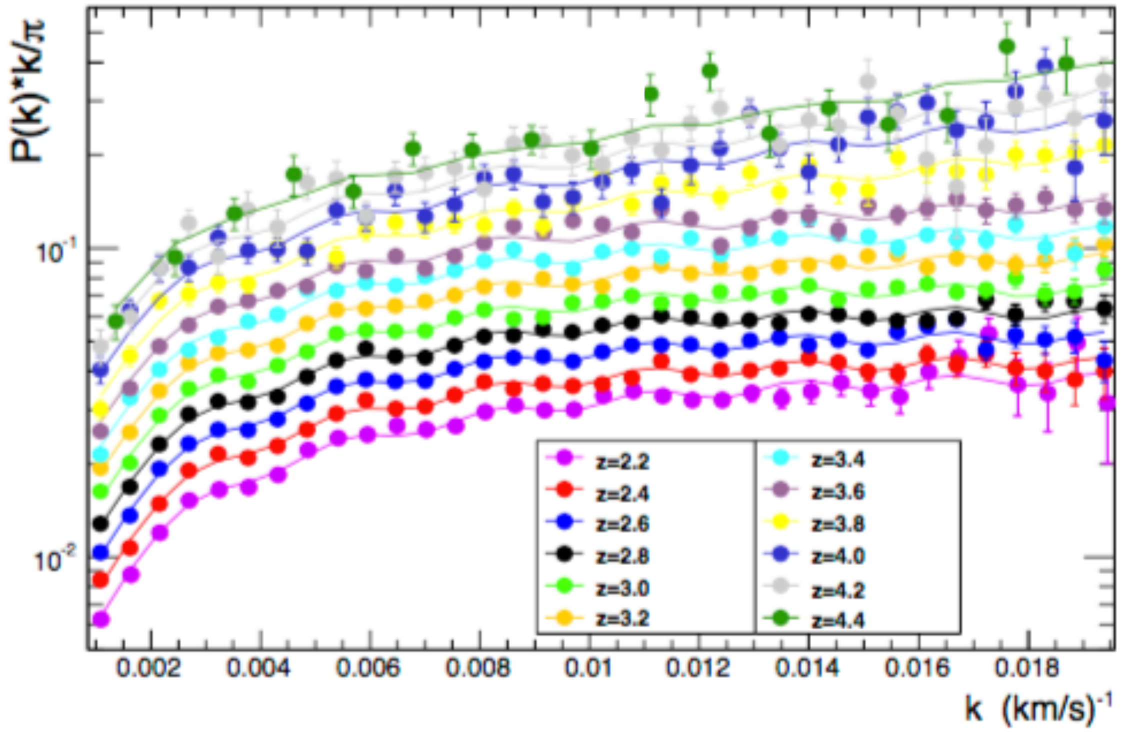
McDonald+ 2005

$$\mathcal{C}_\star(k) = \alpha_\star(z) + \beta_\star(z)k + \gamma_\star(z)k^2$$

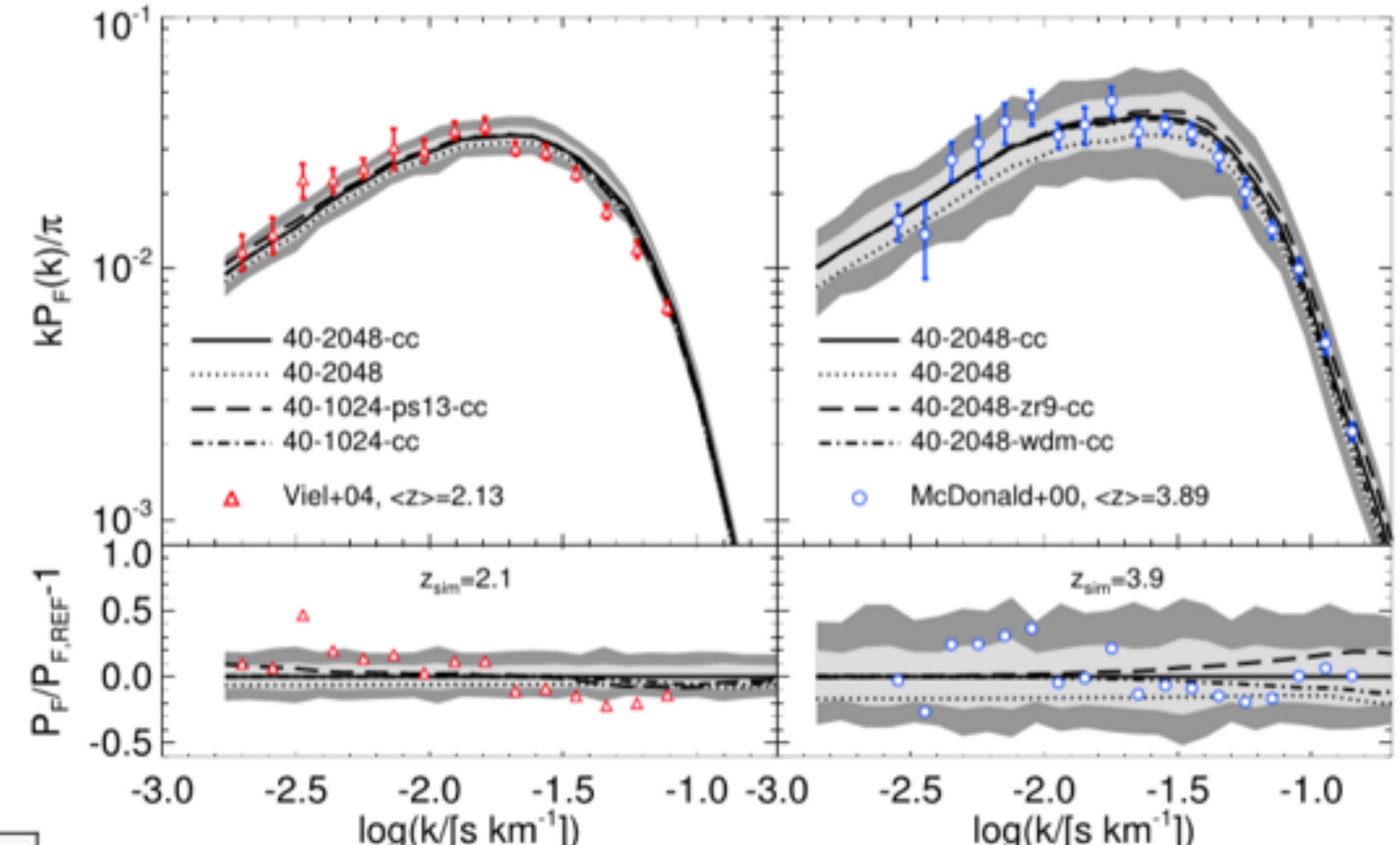


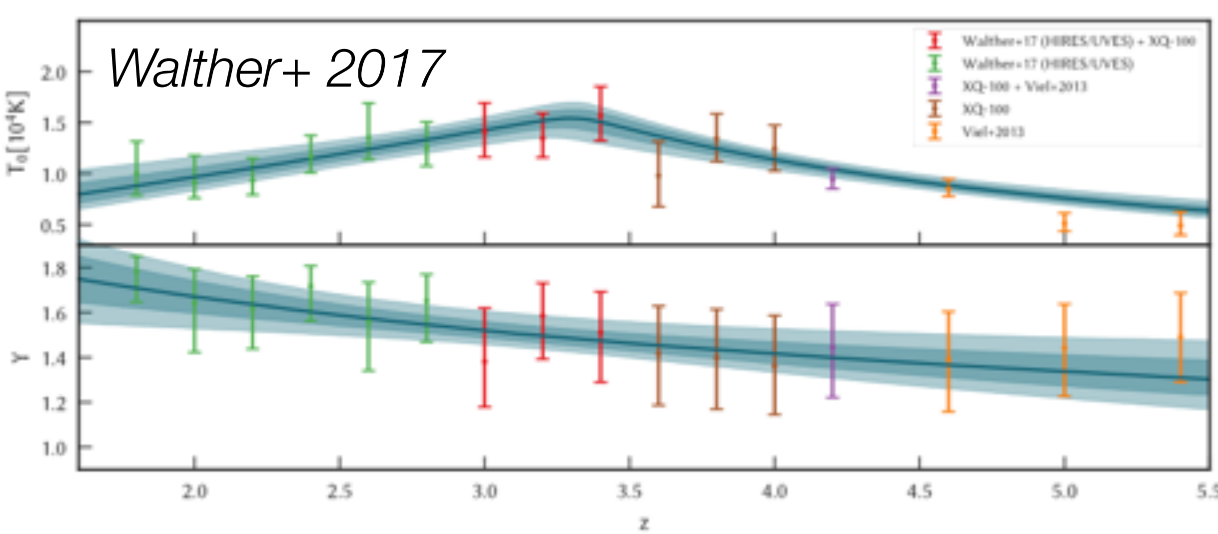
CDM fit

Palanque-Delabrouille+ A&A 2013



Bolton+, SHERWOOD simulation, MNRAS 2017





Overall good agreement with simplest CDM scenario

No apparent need at this stage for additionnal ingredients (feedback, UV fluctuations, patchy reionization…)

Dark matter

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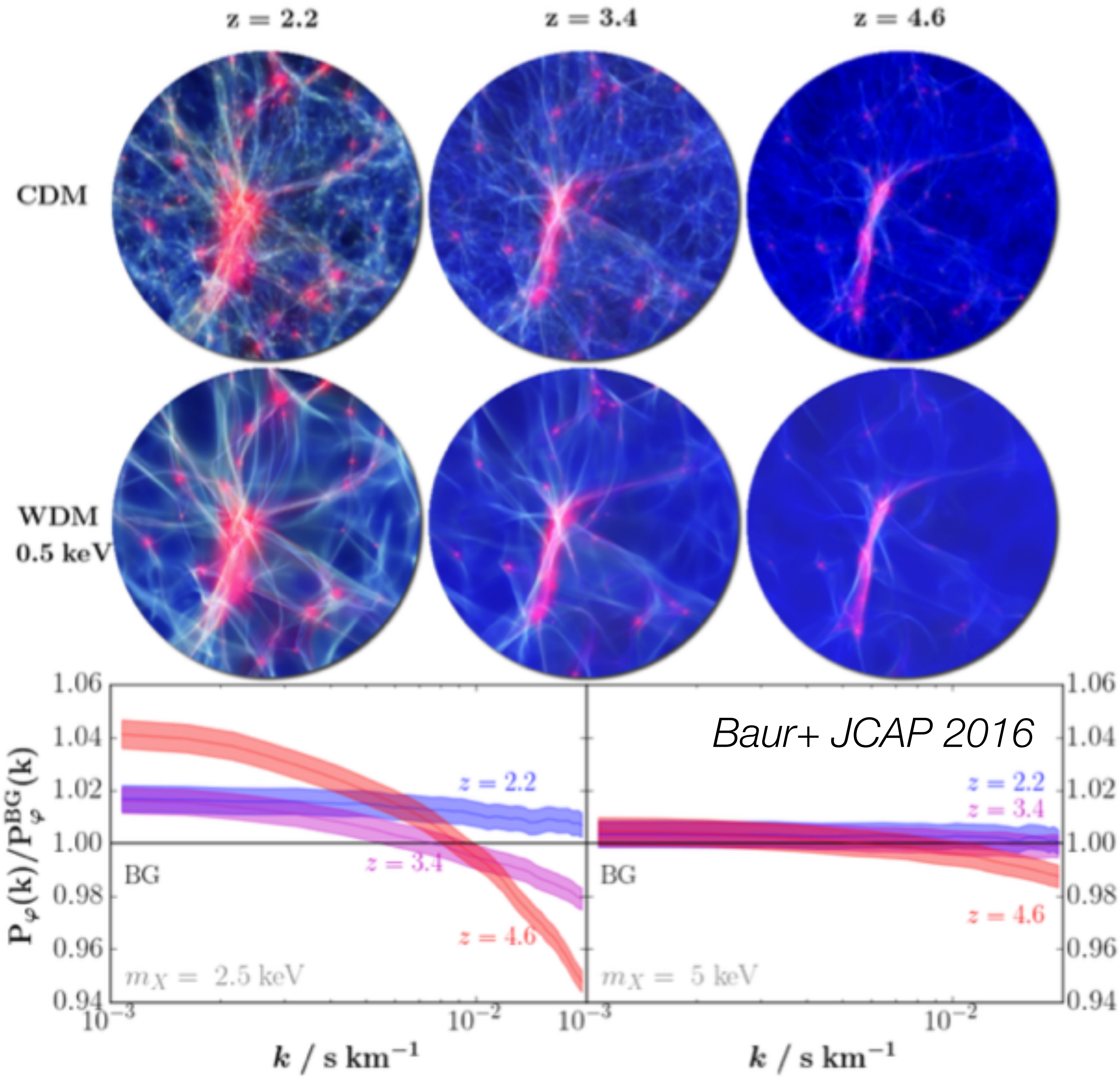
Lyman-alpha in WDM scenarios (1)



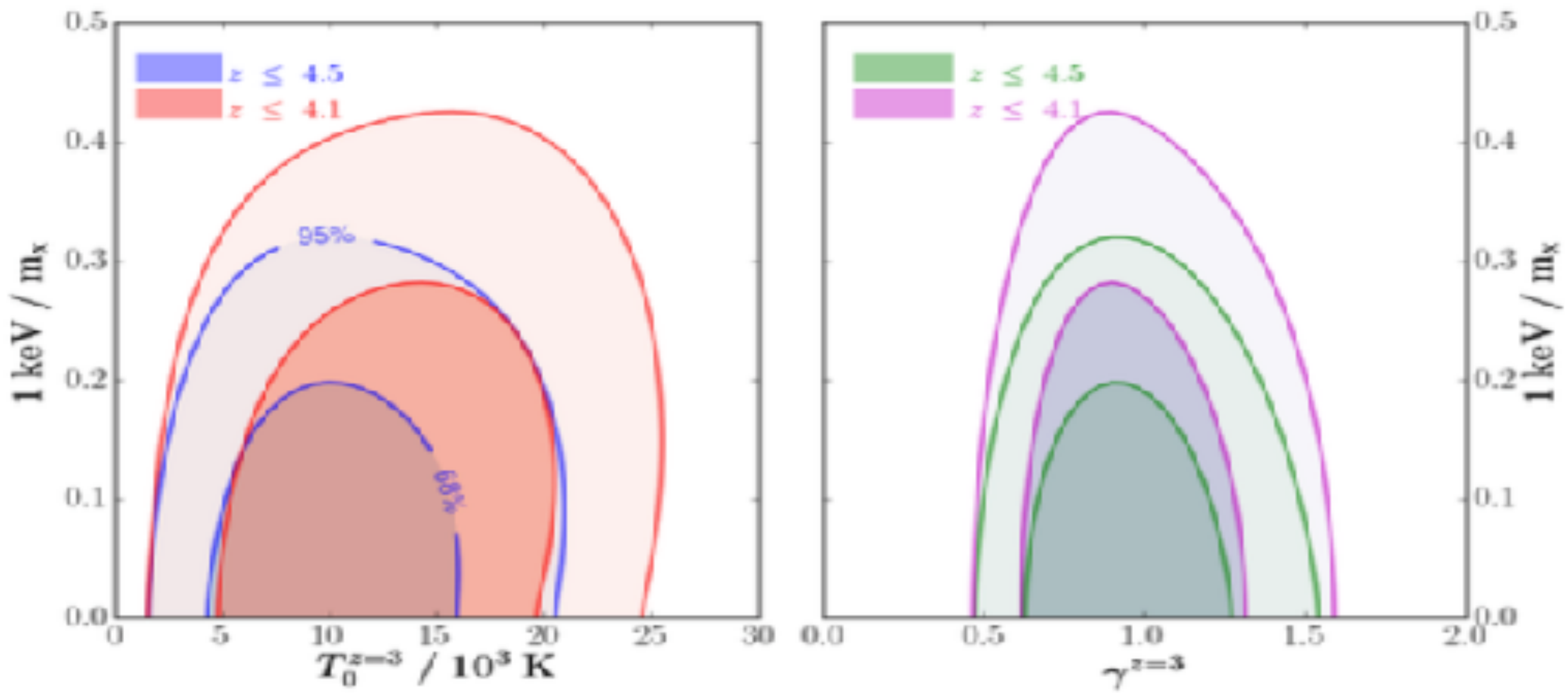
non resonantly produced sterile neutrinos (quasi-thermal distribution)

Scan over Ω_M, σ_8, n_s, h, T_0, γ, **1/m_X** **:** interpolate grid of simulations

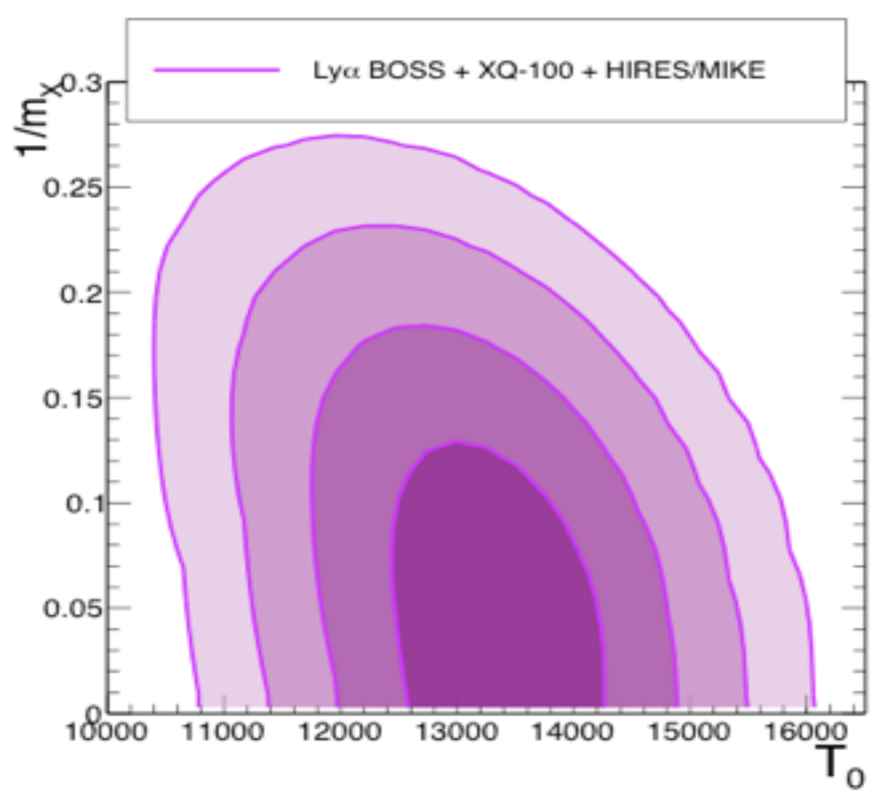
Frequentist fit including other nuisance parameters

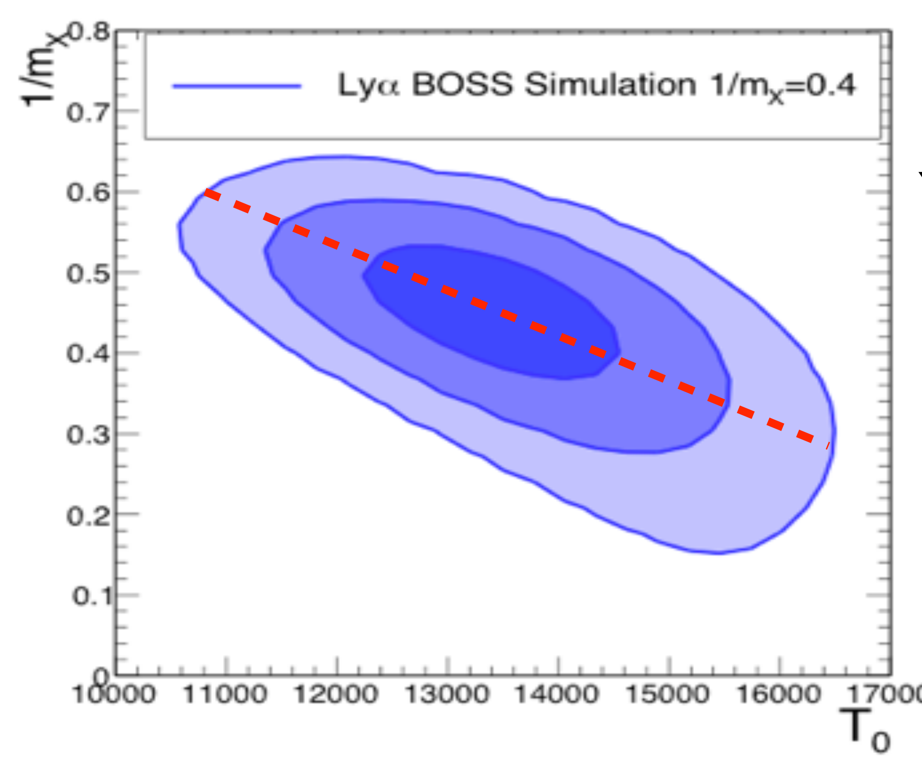
SDSS constraint :
$m_X \gtrsim$ 4keV

Cutoff-related parameters



Baur+ 2016
SDSS-only





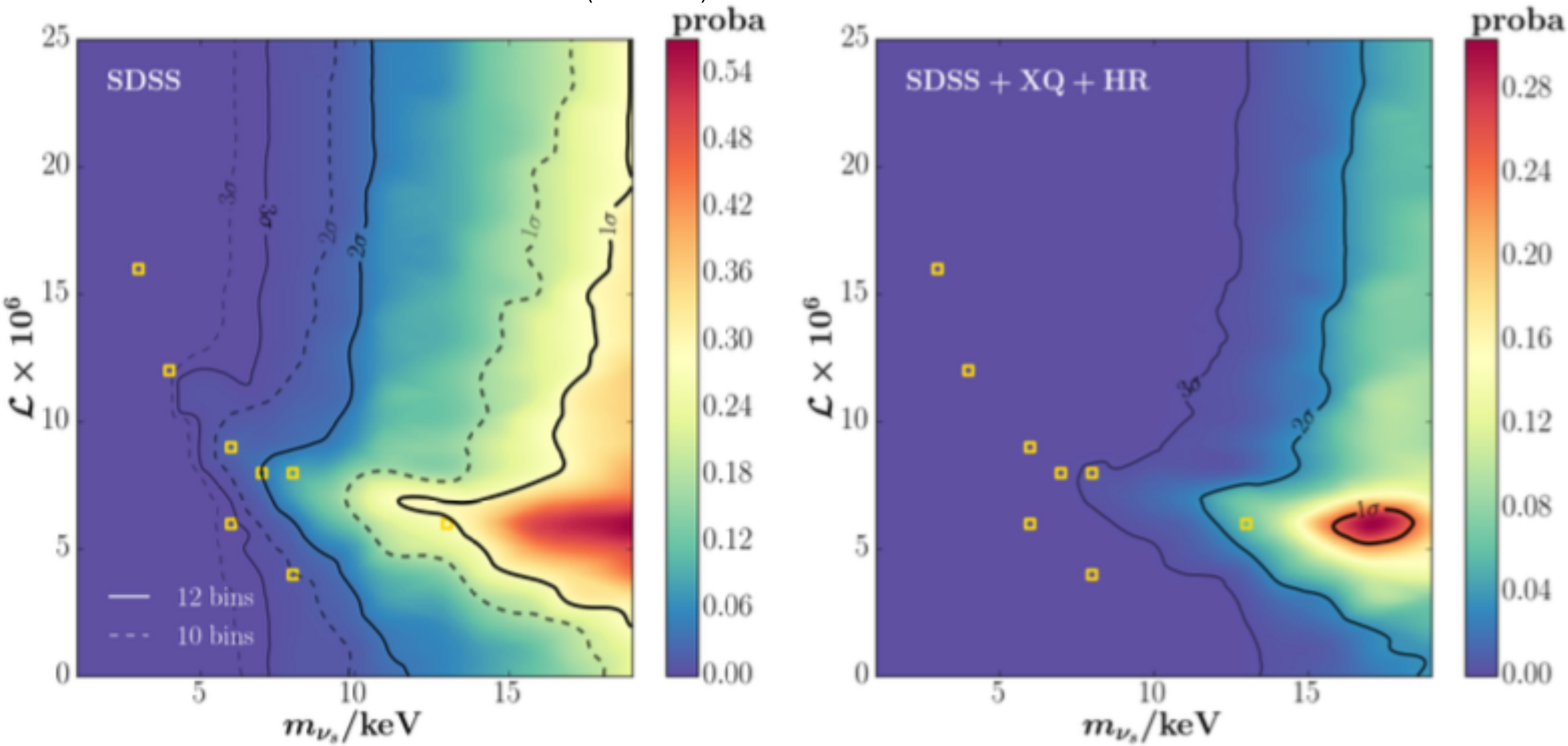
Yèche+ 2017
incl. high-resolution

Lyman-alpha in WDM scenarios (2)

Baur+ 2017

Resonantly produced sterile neutrinos (non-thermal distribution)

Can be matched to mixed CDM+ (thermal) WDM model



Lyman-alpha in WDM scenarios (2)

Baur+ 2017

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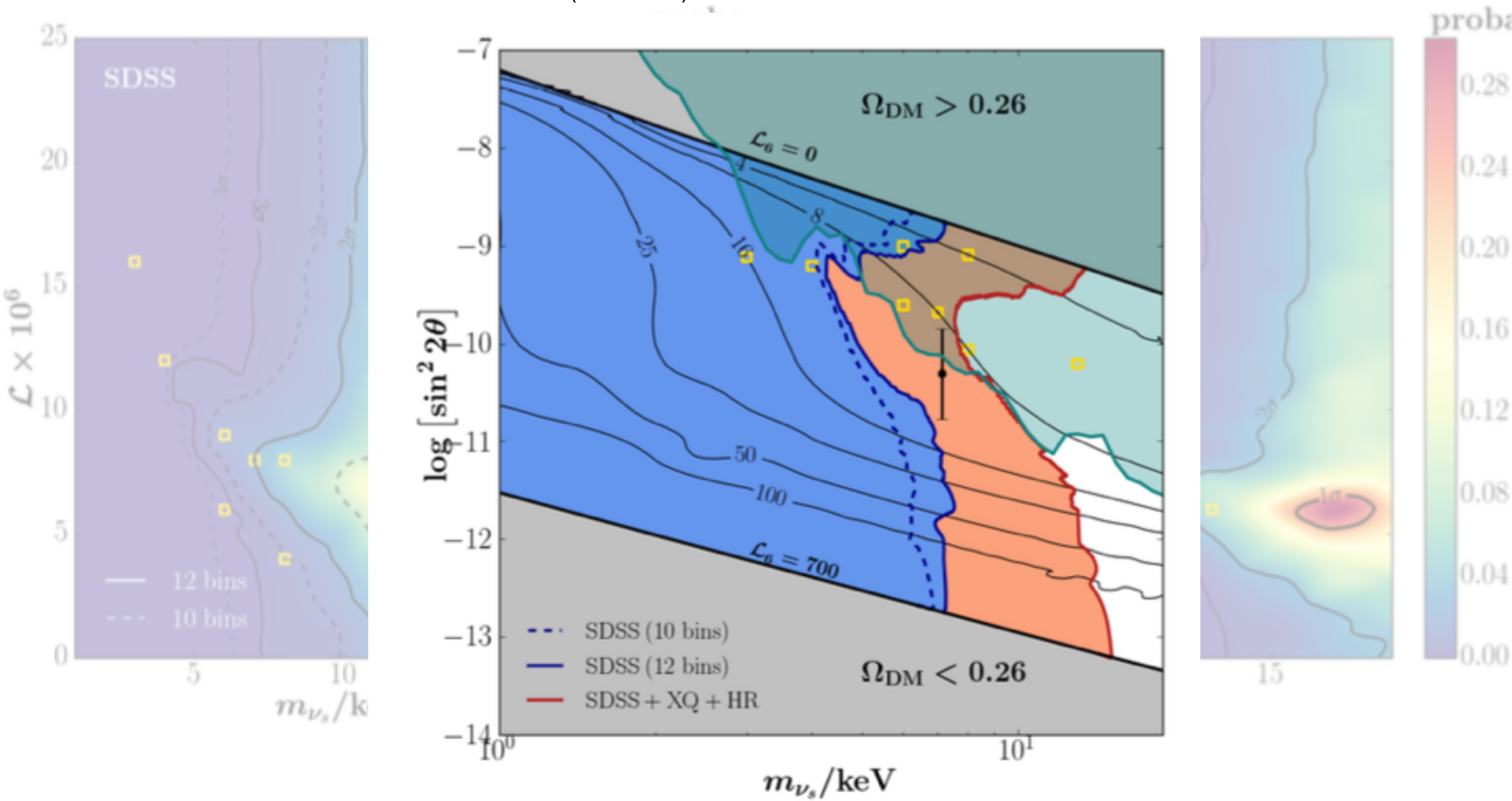
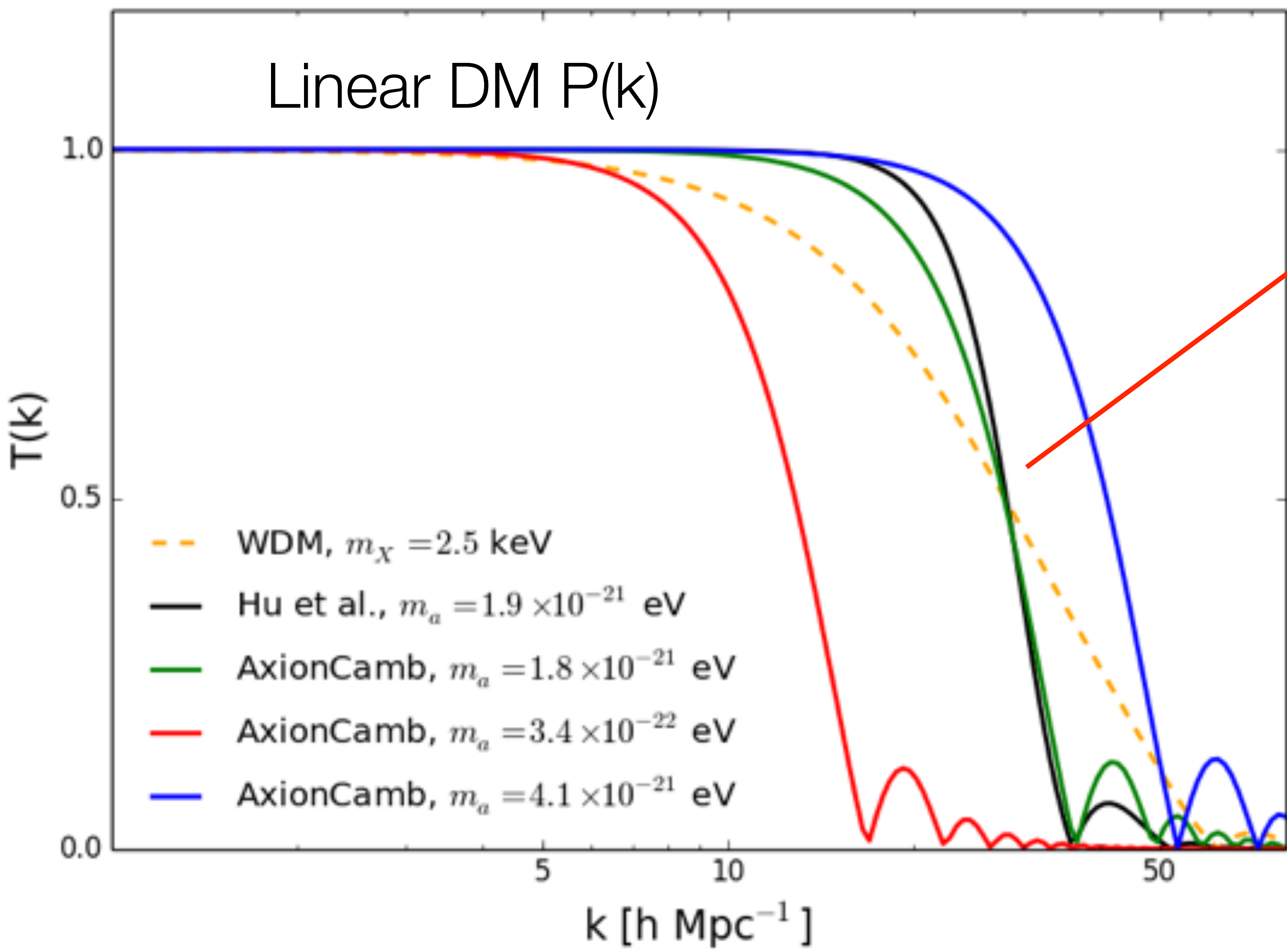


Lyman-α in FDM scenarios

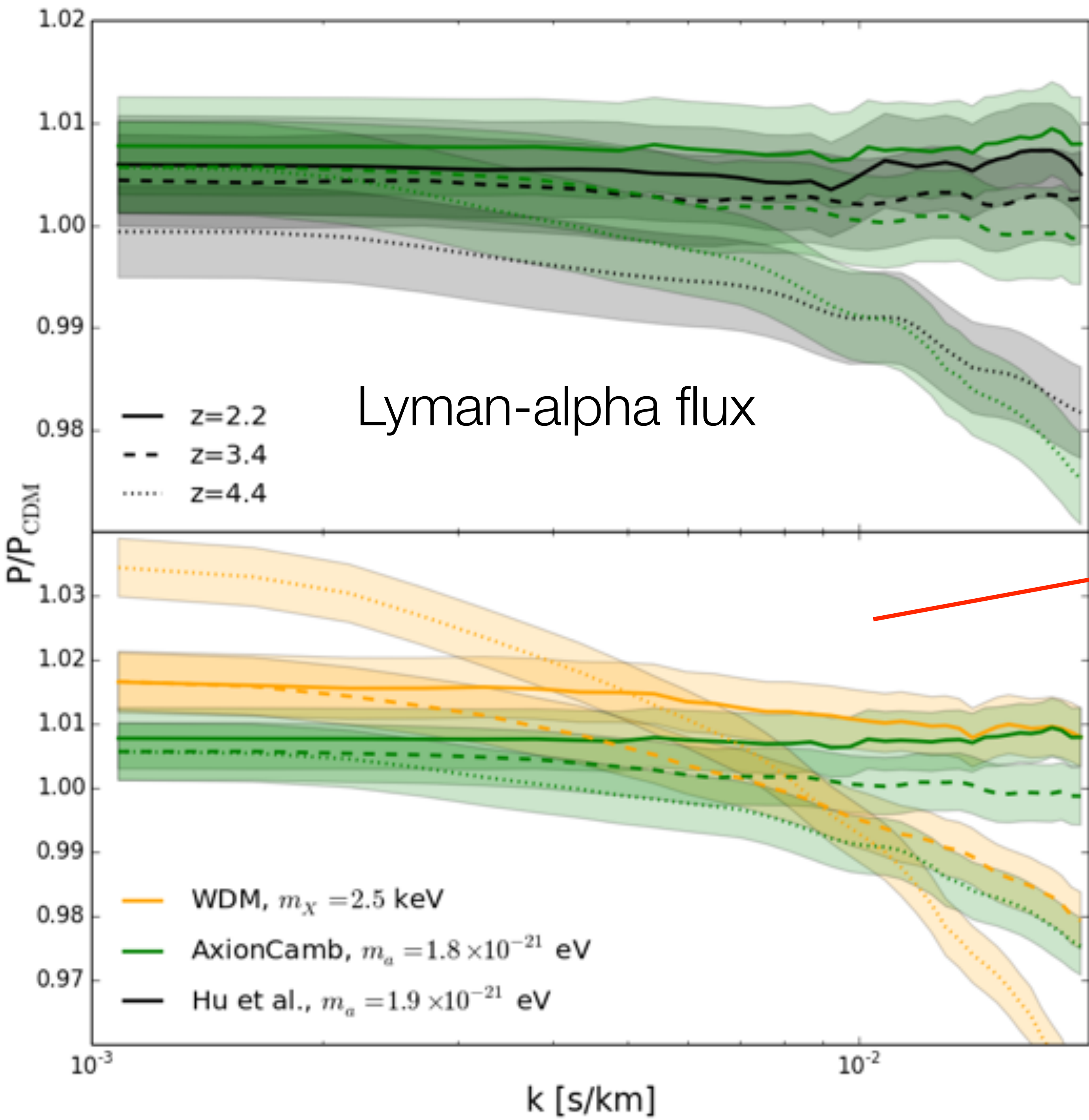
EA,DJEM+ MNRAS 2017
Irsic+ PRL2017



WDM - FDM mass scaling to match cutoff in linear P(k) :

$$m_X = 0.79 \left(\frac{m_a}{10^{-22}\,\mathrm{eV}} \right)^{0.42} \mathrm{keV}$$

Lyman-α in FDM scenarios



WDM - FDM mass scaling to match cutoff in linear P(k) :

$$m_X = 0.79 \left(\frac{m_a}{10^{-22}\,\mathrm{eV}}\right)^{0.42} \mathrm{keV}$$

Best match for the related Lyman-alpha flux spectrum :

$$\boldsymbol{m_X = 0.715 \times \left(\frac{m_a}{10^{-22}\,\mathrm{eV}}\right)^{0.558} \mathrm{keV}}$$

Use either :

- simulations with FDM initial conditions
- WDM simulations (more complete) + scaling law

$\mathbf{m_a \gtrsim 2\text{-}3 \times 10^{-21}\ eV}$

Include quantum pressure in cosmo. simulations ?

Schrödinger equation ⇒ Madelung equation

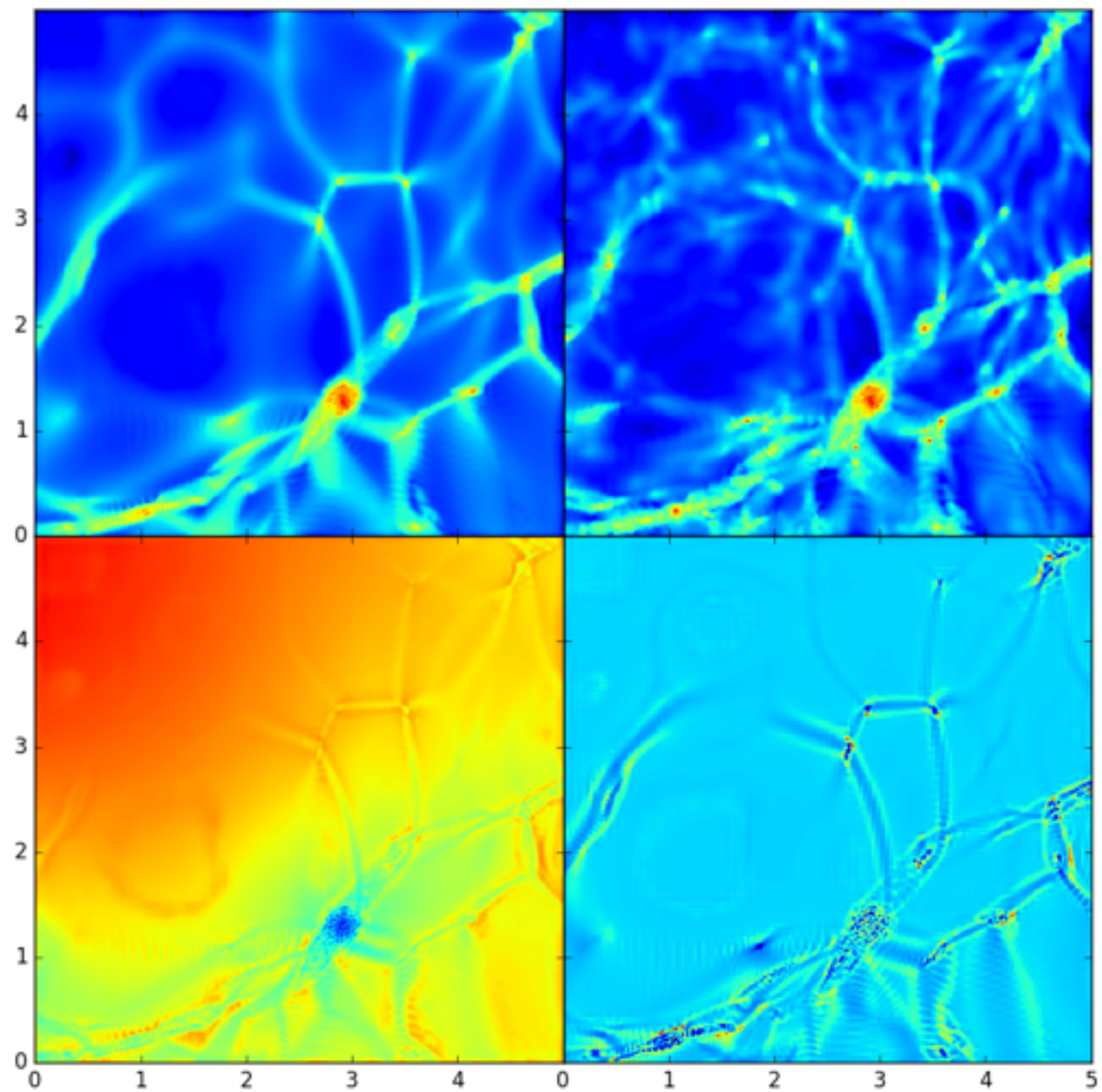
$$\partial_t \vec{v} + H\,\vec{v} + \frac{1}{a}(\vec{v}\cdot\nabla)\vec{v} = -\frac{1}{a}\nabla\left[\phi - \frac{\hbar^2}{2m_a^2\,a^2}\left(\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)\right]$$

∇Q hard to compute (small scale variations)

Use standard N-body ⟺ neglect ∇Q wrt gravitation force ∇ϕ

Density (FDM initial cond.)

Density (CDM initial cond.)

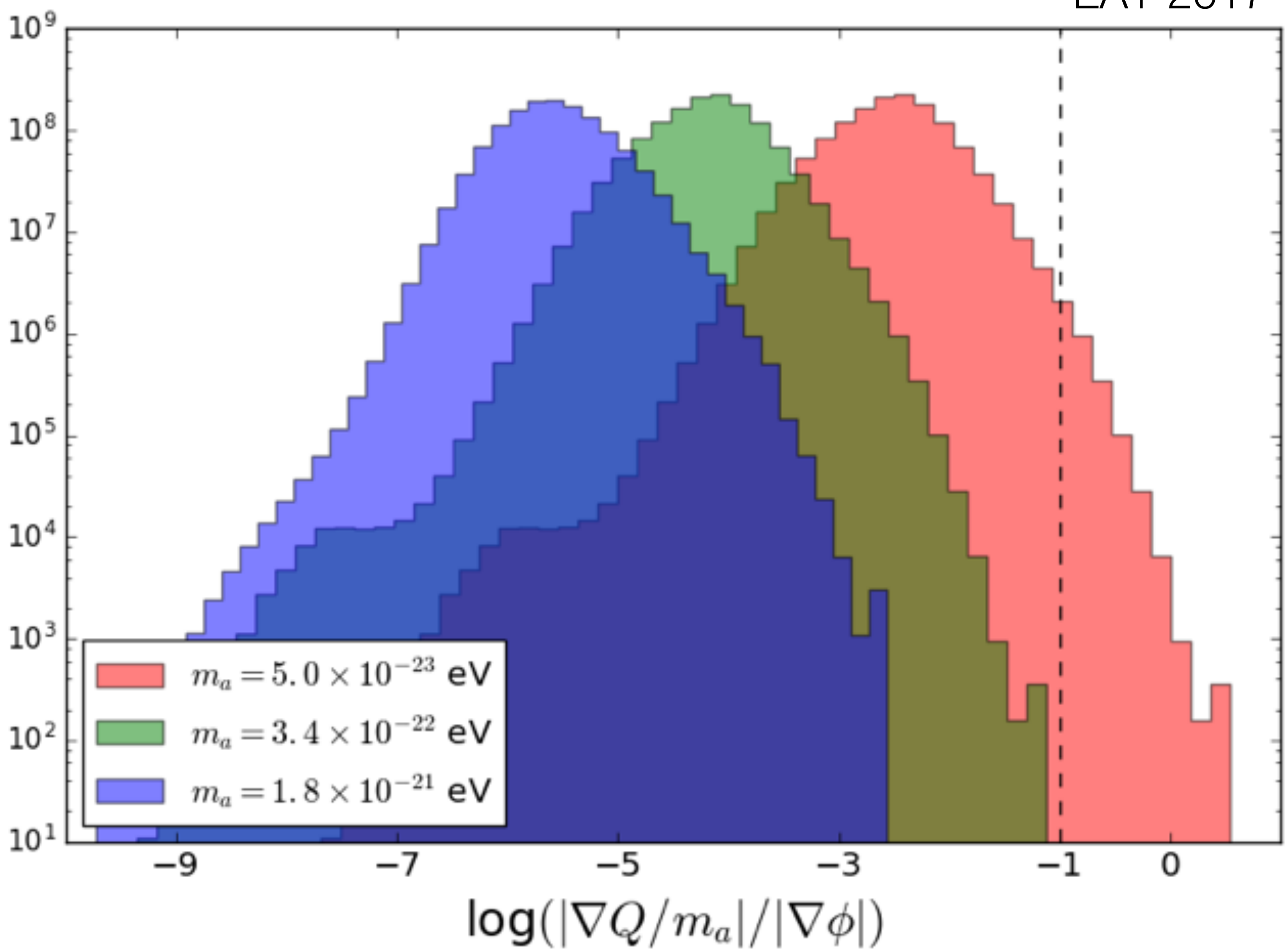


Gravitational potential

Quantum pressure

FDM : « Quantum force » vs gravitational force

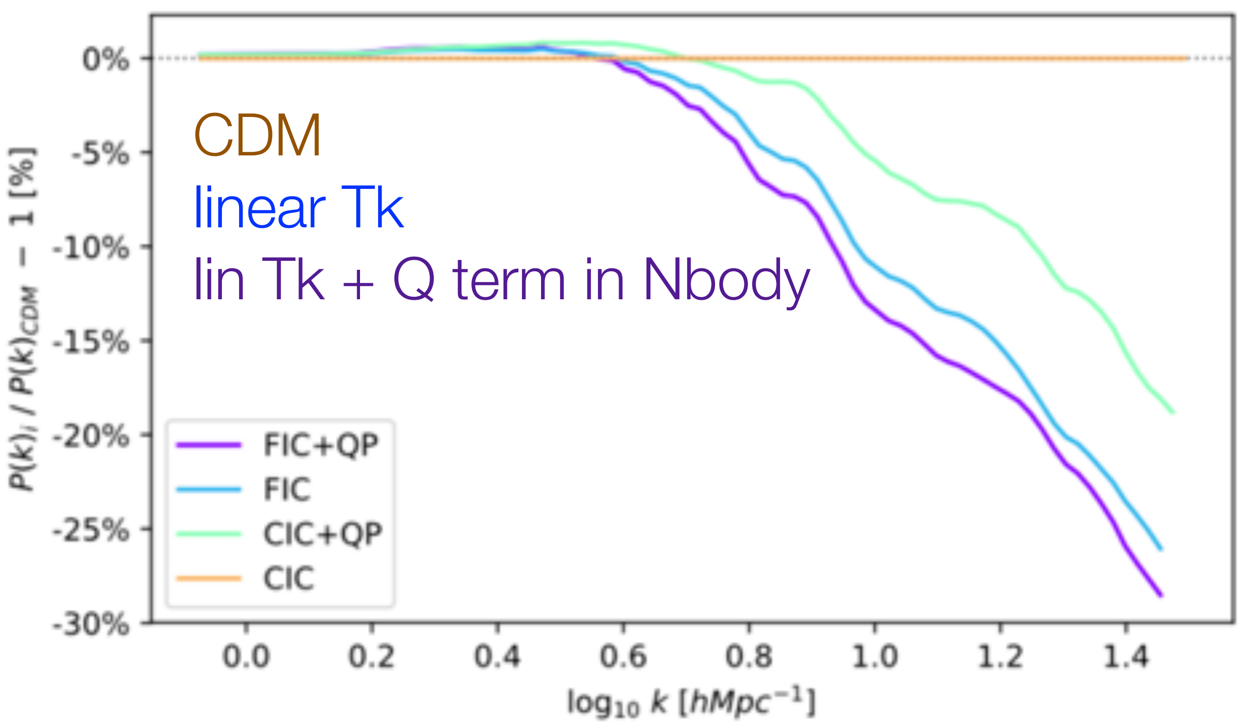
EA+ 2017



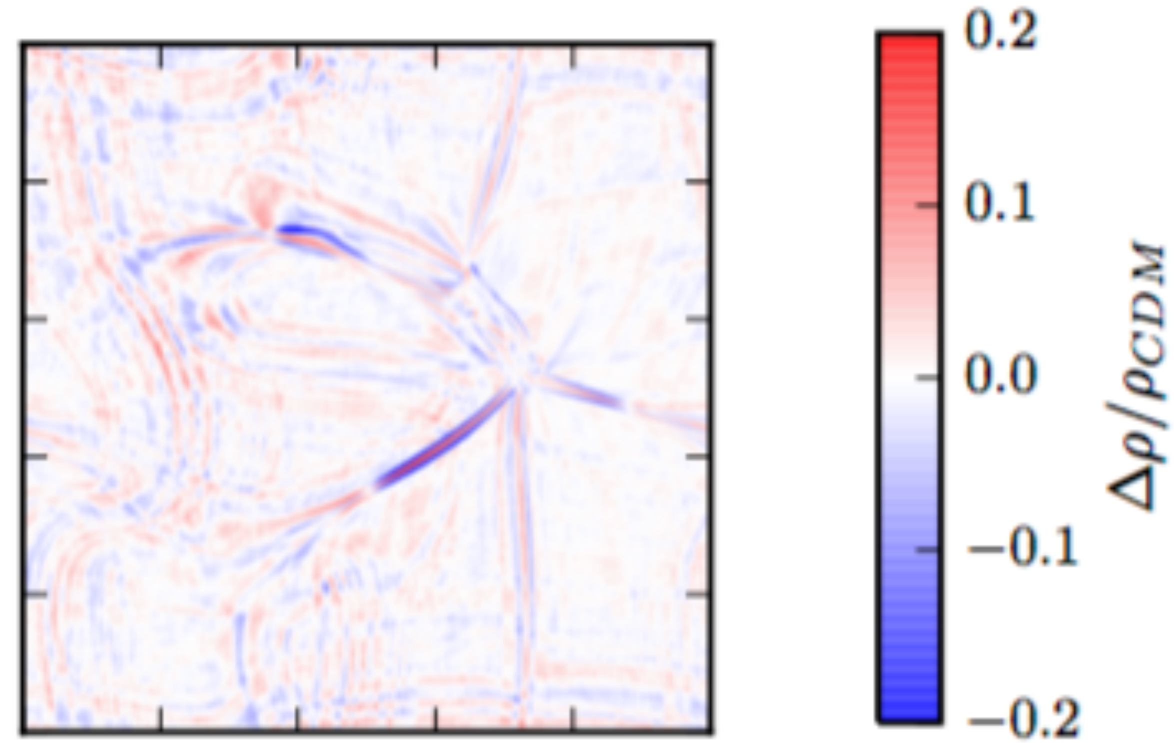
Usual N-body ok *at the scales considered here* at least for $\mathbf{m_a \gtrsim 10^{-22}}$ **eV**

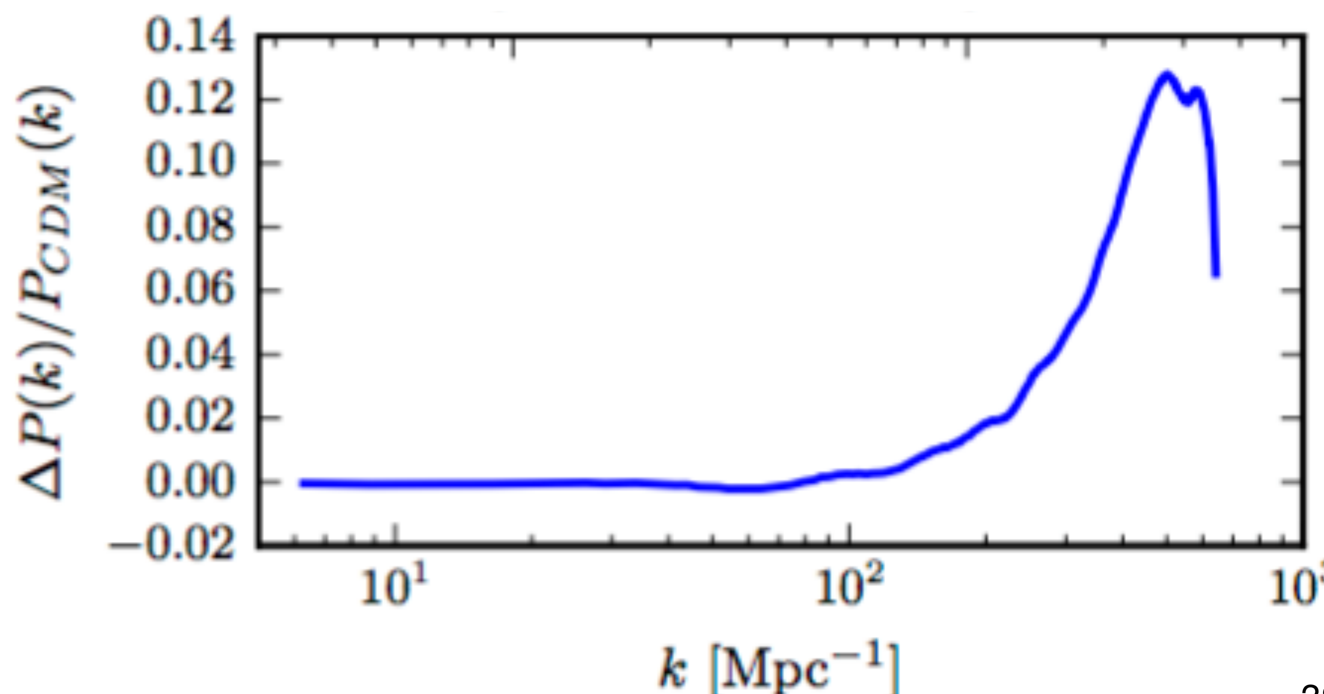
Full FDM simulations

Nori+Baldi, AX-GADGET 1801.08144



See also Zhang+ 1708.04389





Veltmaat +Niemeyer
PRD94 (2016) 12, 123523
Nyx-based

Summary

Lyman-alpha interesting probe of DM properties
potential for improvements (both measurements and IGM physics)
21-cm complementary

Fits CDM + simple[st] IGM model well at this stage
=> Contraints on W/FDM
m_X > few keV
m_a > few 10^{-21} eV

Those 95% CL bounds should be taken with a grain of salt given the sources of uncertainties