Properties of dark matter with the Lyman-alpha forest

Eric Armengaud - CEA Saclay

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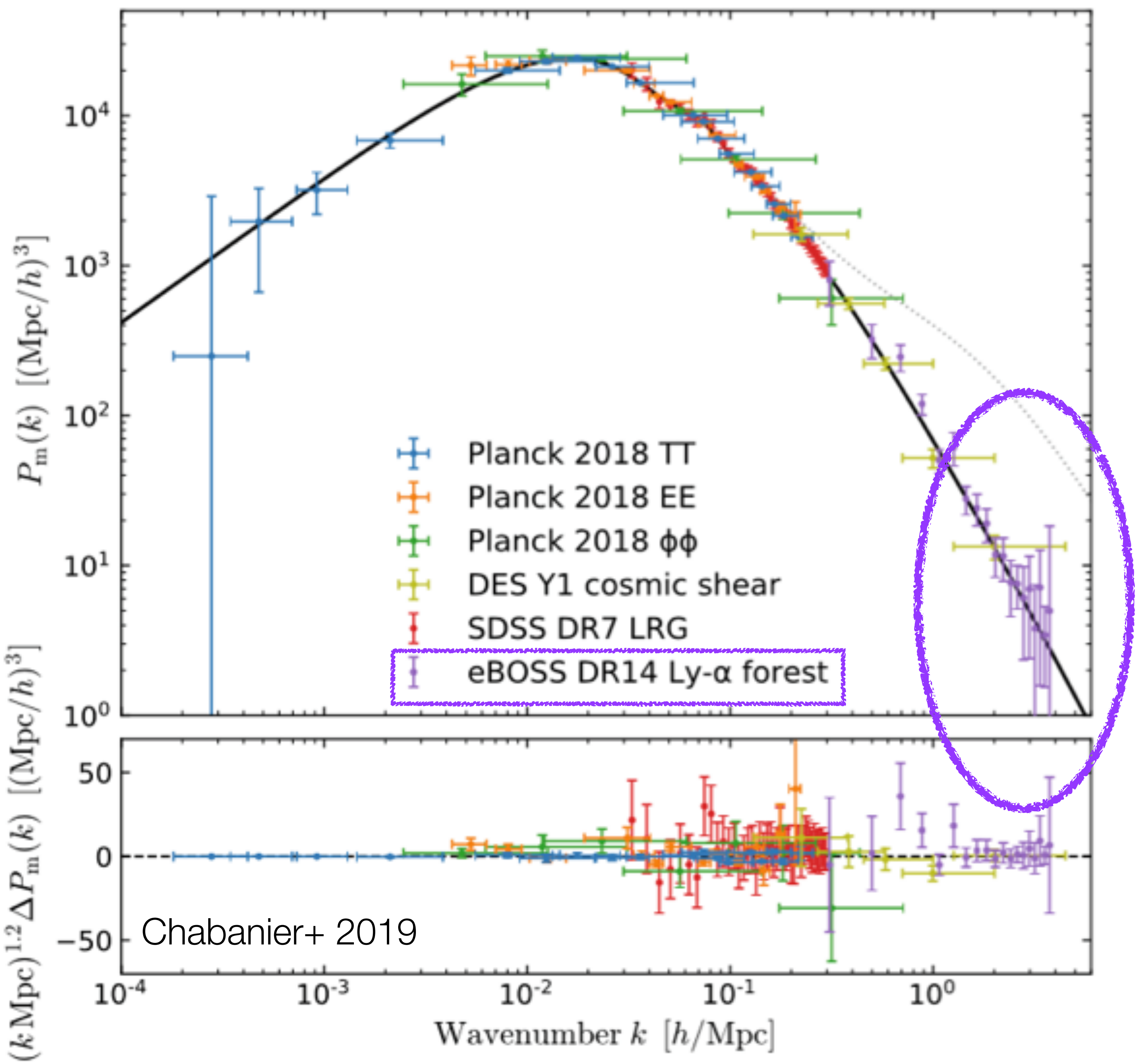
IAP - 09/12/2019

The Lyman-alpha forest in cosmology :

probes small scales k ~ h/Mpc
@ z ~ 2 - 5, mildly non-linear regime
Uses HI in IGM as a tracer of matter



- IGM science
- Matter power spectrum :
- BAO
- amplitude / slope of matter fluctuations at small scales and late time wrt CMB : running, m_ν
- **DM properties**

A few dark matter scenarios
among many others

Impact cosmological structures at large k

Fuzzy DM

Sterile neutrinos

WIMPs

Primordial black holes

10^{-22} eV — **μeV** — **keV** — **MeV** — **GeV** — **TeV** — **M_{Pl}** — **50 $M_{\odot}$**

QCD axions

Asymmetric DM

Self-interacting DM

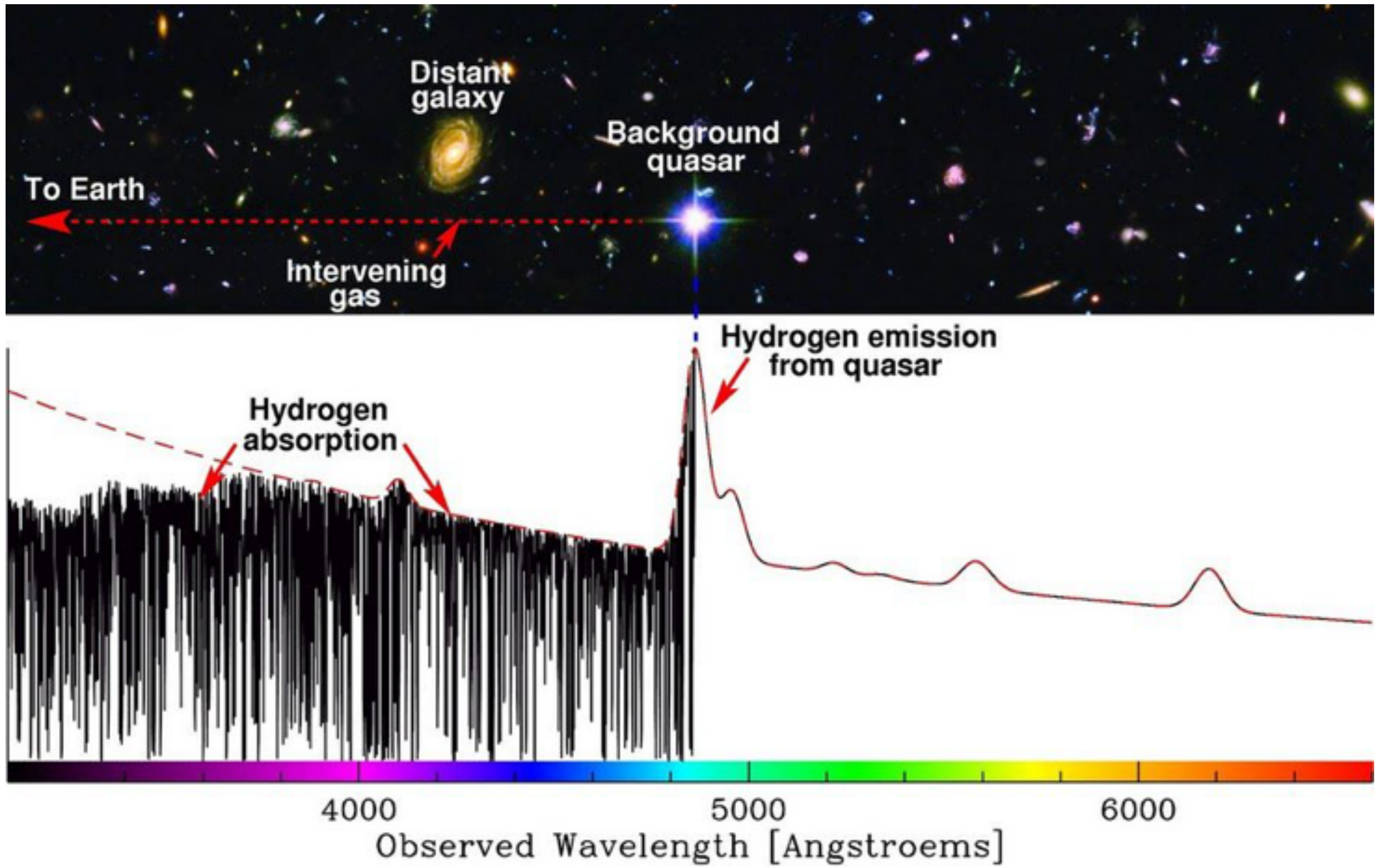
WIMPzillas

uncertainty principle
large-k fluctuations reduced
Lyman-alpha : $m \gtrsim$ few 10^{-21} eV
EA+ 2017, Irsic+ 2017

DM « granularity »
large-k fluctuations enhanced
Lyman-alpha : $m \lesssim 100\ M_{\odot}$
Murgia+ 2019

The Lyman-alpha forest

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



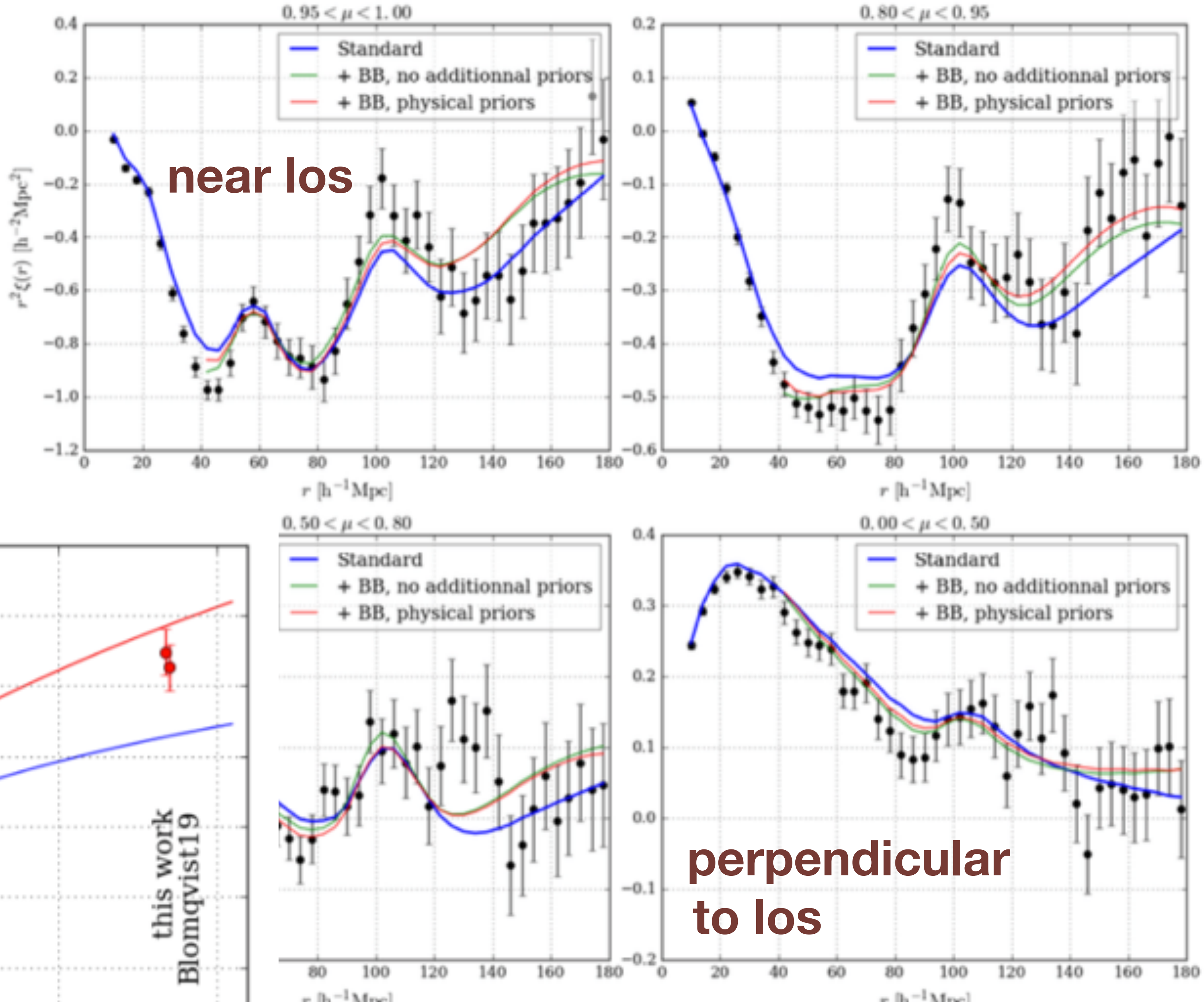
Connection to the matter power spectrum, however needs knowledge of :

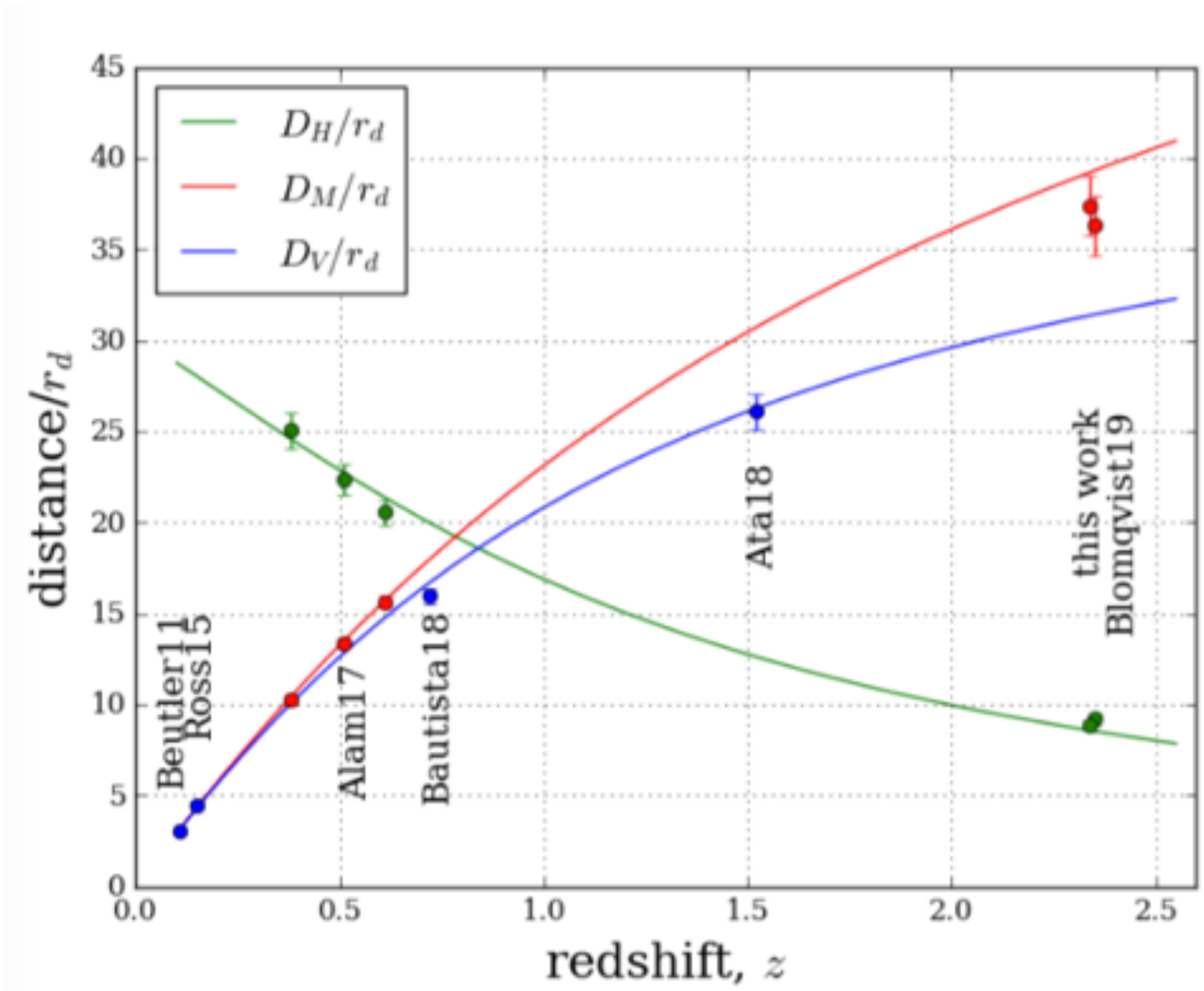
- non-linear structure growth
- intrinsic source (quasar) emission
- IGM physics
- instrumental response

Large-scale correlations in the Ly-alpha forest

BAO peak, parallel and perp. to line of sight

also cross-corr with quasars [Blomqvist+ 2019]

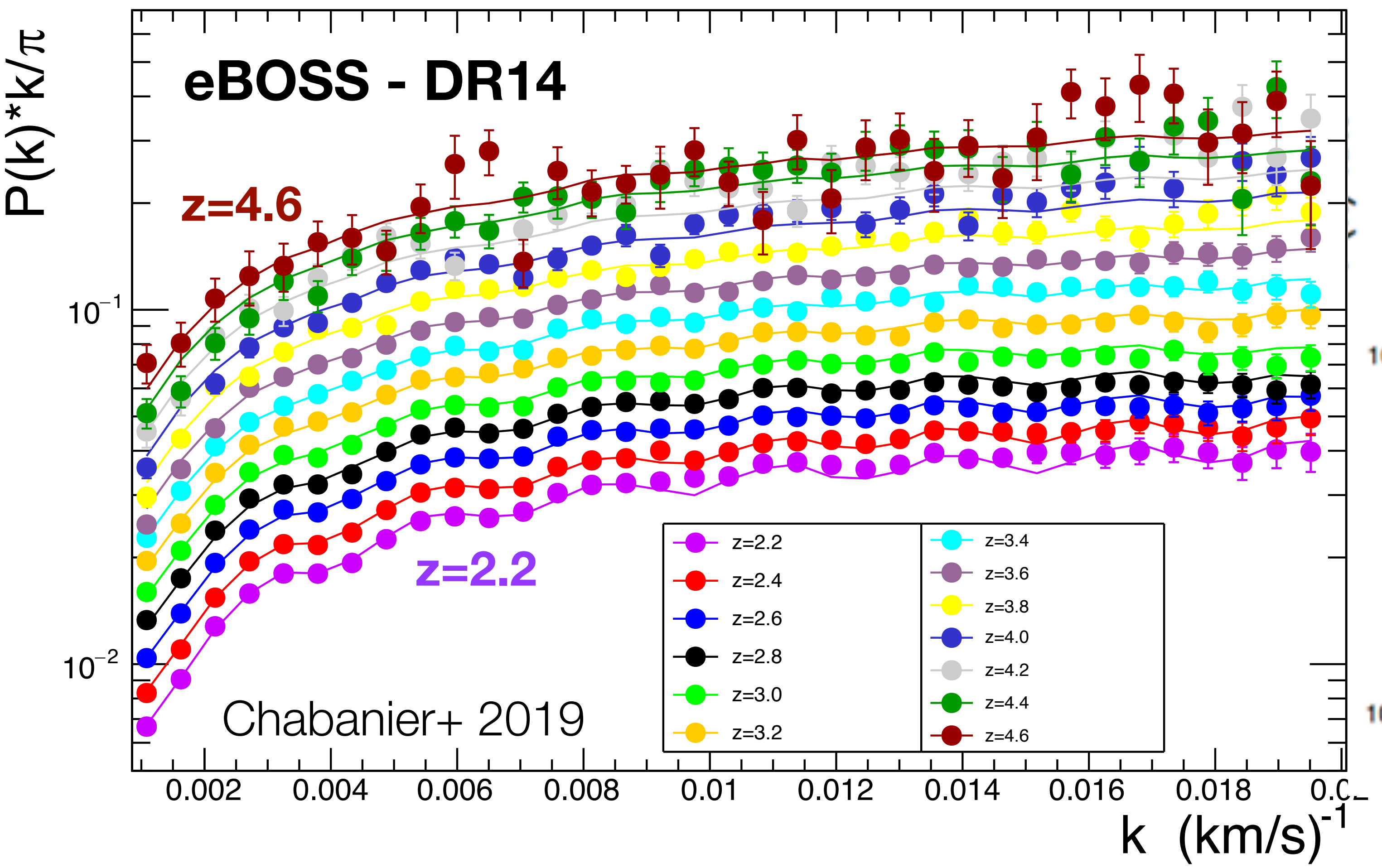


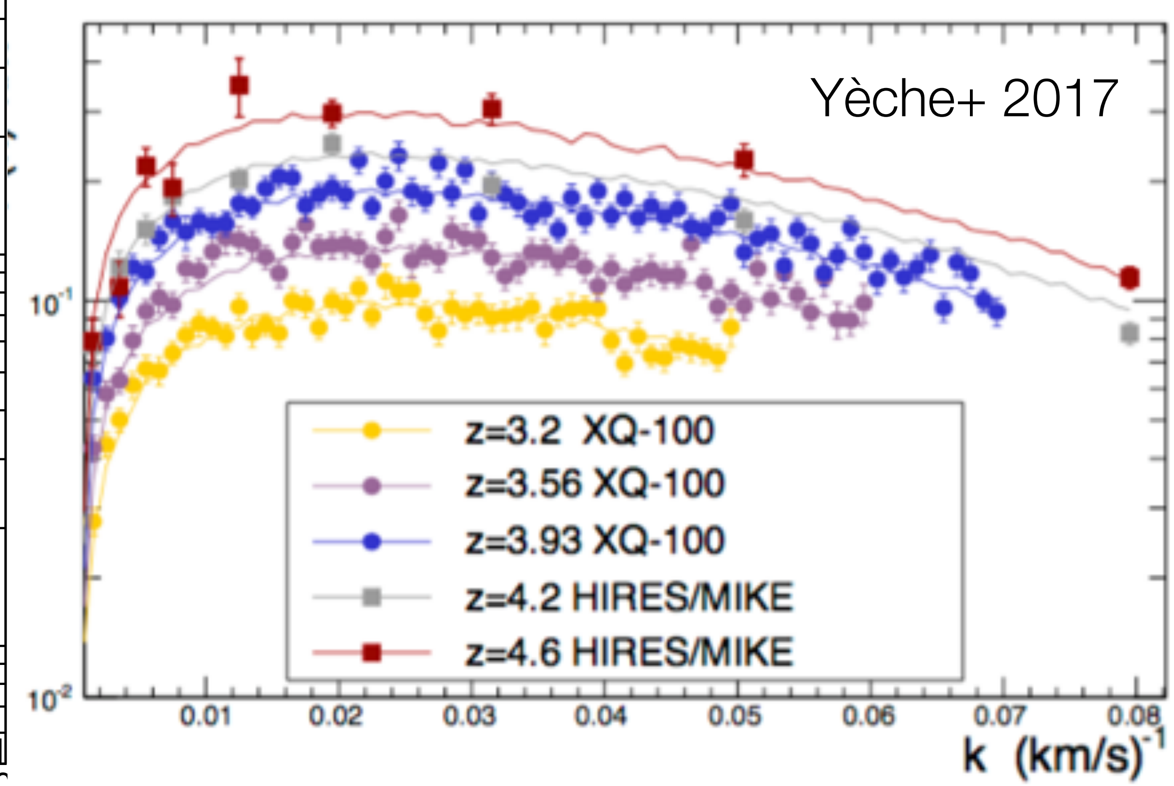


eBOSS DR14
de Sainte Agathe+ 2019

Small-scale correlations in the Ly-alpha forest

separation between lines of sight » Mpc (BOSS)
=> 1-D power spectrum (correlation within each line of sight)

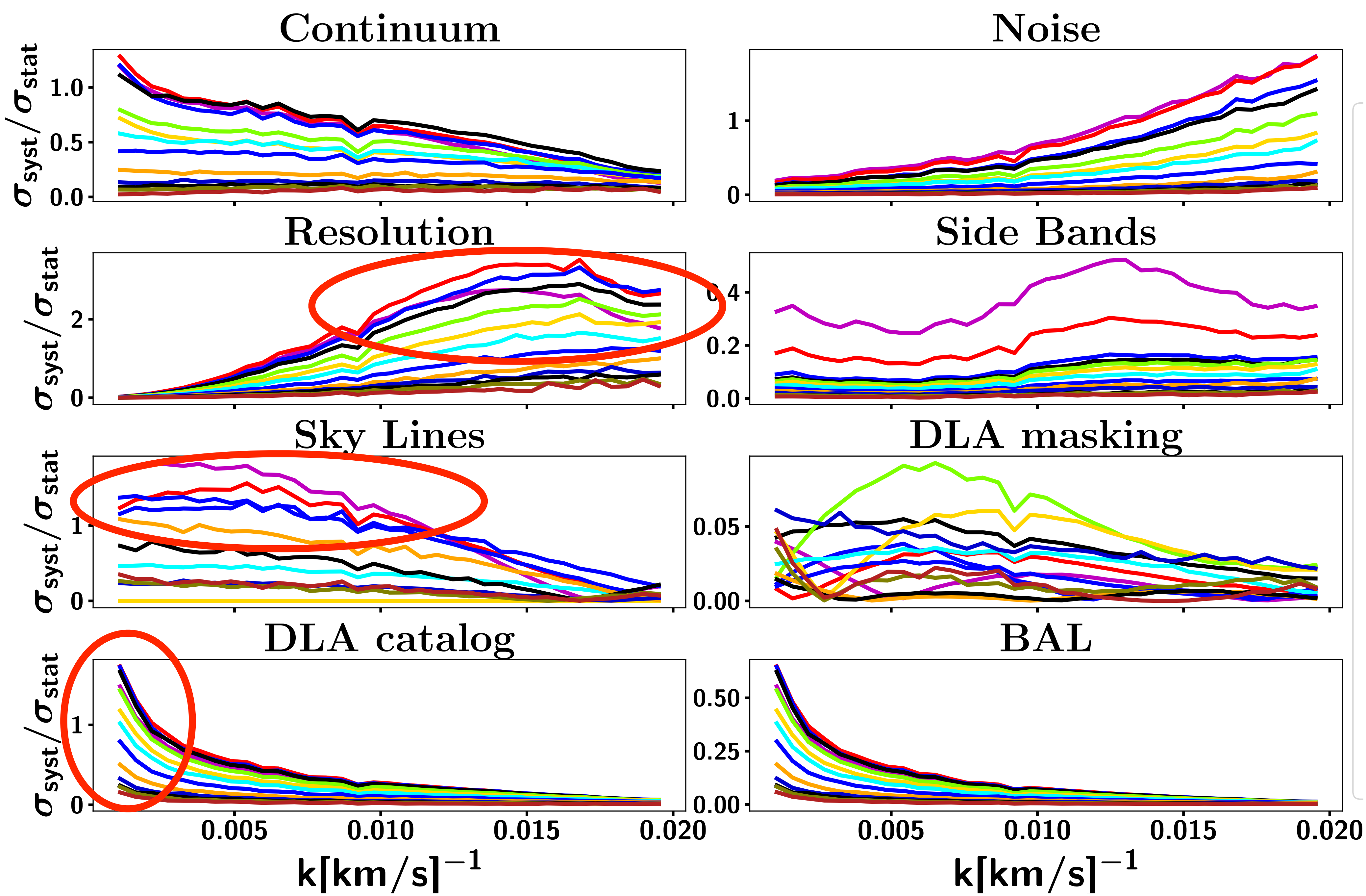




large statistics from wide field surveys (eg. BOSS 60000 spectra)

higher resolution & S/N (X-SHOOTER, MIKE, HIRES) : Jeans smoothing dominated

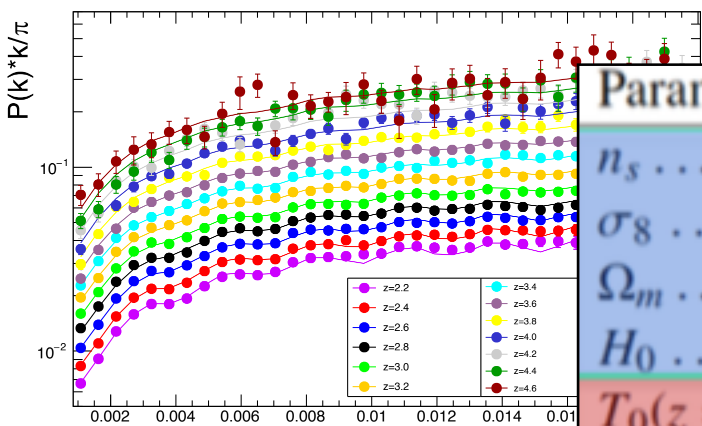
Uncertainties in the (e)BOSS 1D Lya power spectrum



Chabanier+ 2019

error bars near %-level
latest measurement mostly systematics limited, except at high z

Modelling the small-scale Lya forest within ΛCDM



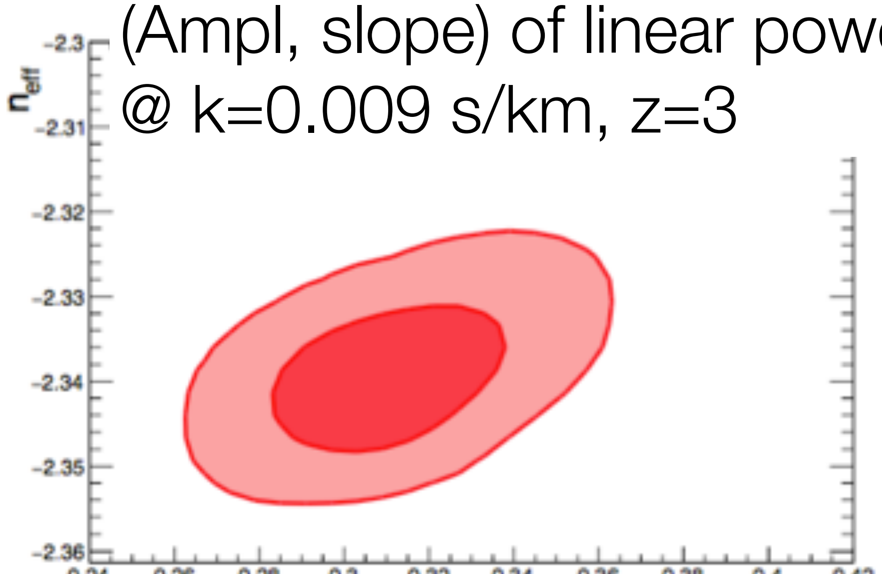
Parameter	Central value	Range
n_s	0.96	± 0.05
σ_8	0.83	± 0.05
Ω_m	0.31	± 0.05
H_0	67.5	± 5
$T_0(z=3)$	14000	± 7000
$\gamma(z=3)$..	1.3	± 0.3
A^τ	0.0025	± 0.0020
η^τ	3.7	± 0.4

Requires a heating model of the IGM =>
$T = T_0 (1+\delta)^{\gamma-1}$

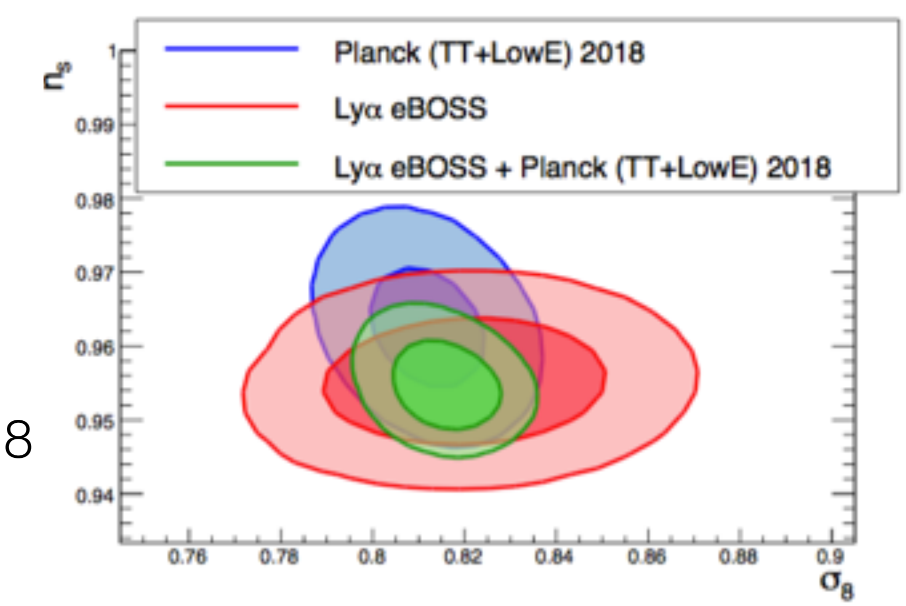
Inference based on a grid of Gadget hydro simulations
- Uses splicing technique to cover range of scales
- Taylor-based interpolation in parameter space

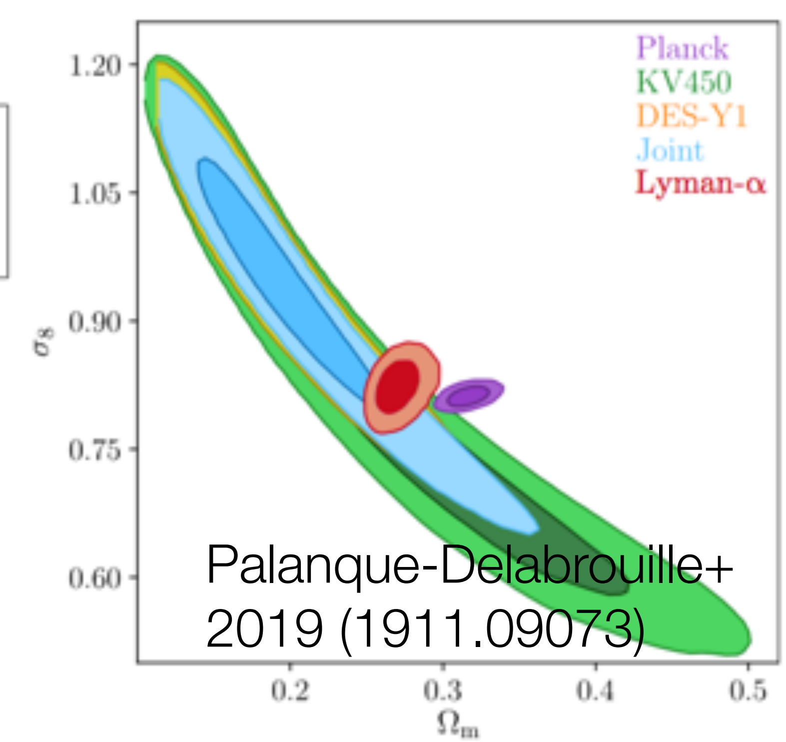
Likelihood includes observational + modelling nuisance parameters

(Ampl, slope) of linear power
@ k=0.009 s/km, z=3



Chabanier+ 2018





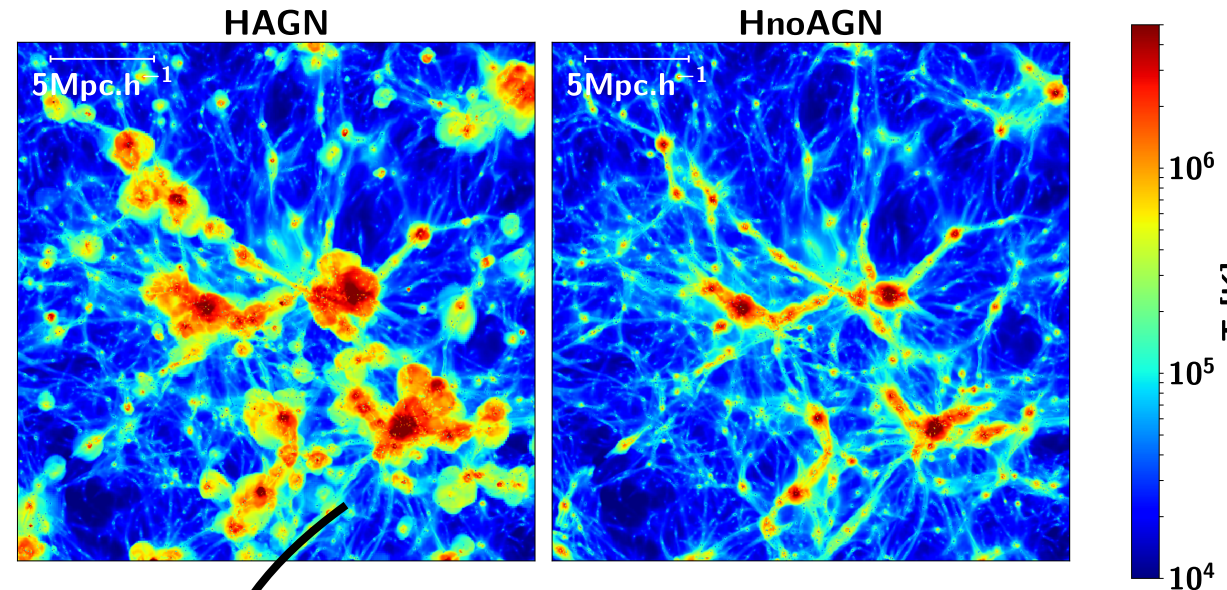
Palanque-Delabrouille+ 2019 (1911.09073)

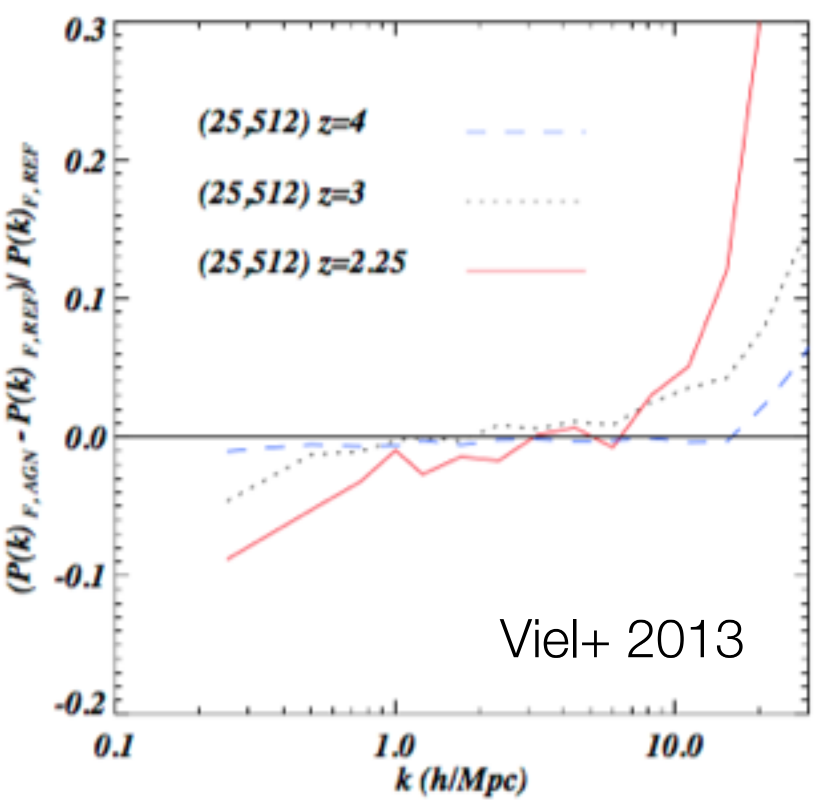
Uncertainties in Lya modelling - example of AGN feedback

Need dedicated high-resolution simulations

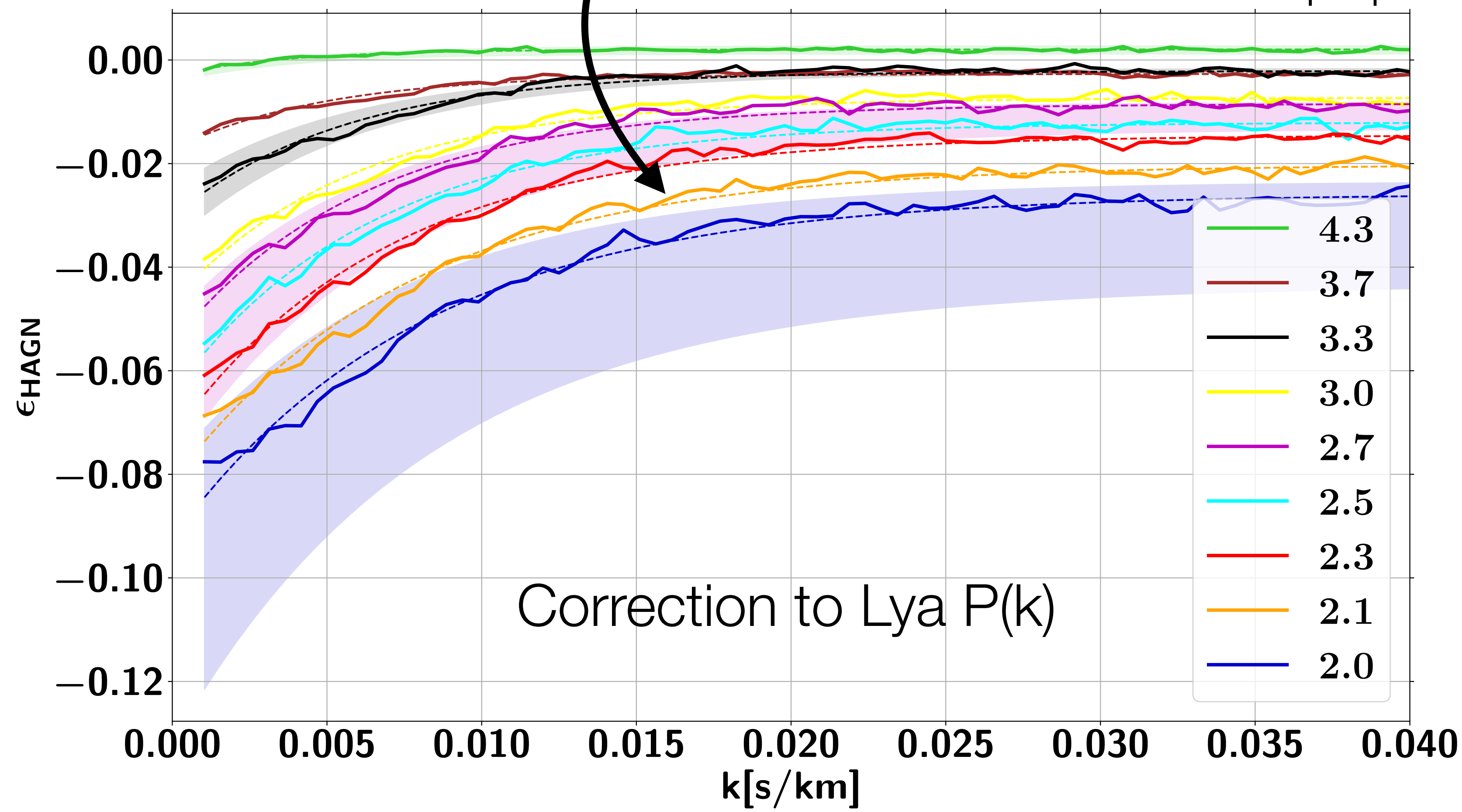
eg. compare HorizonAGN (RAMSES) with HnoAGN to estimate relative correction to the Lya flux

AGN feedback : heating and mass redistribution in the IGM

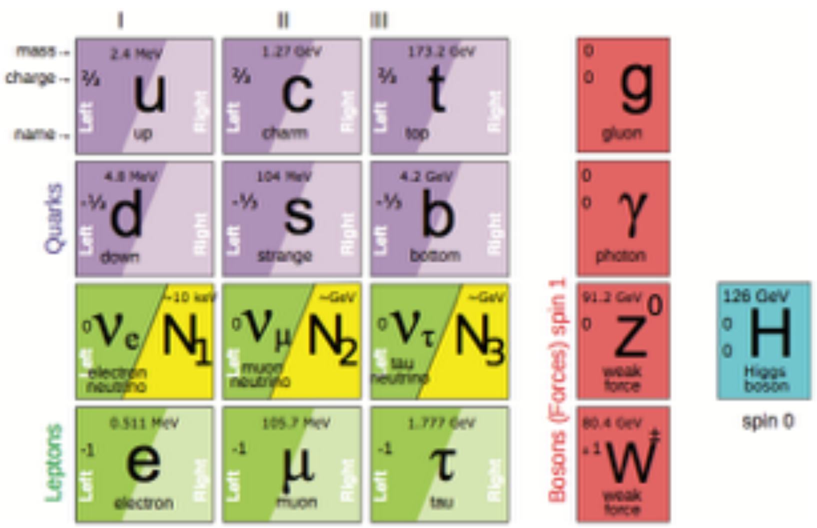




Chabanier et al. - in prep.



keV sterile neutrinos

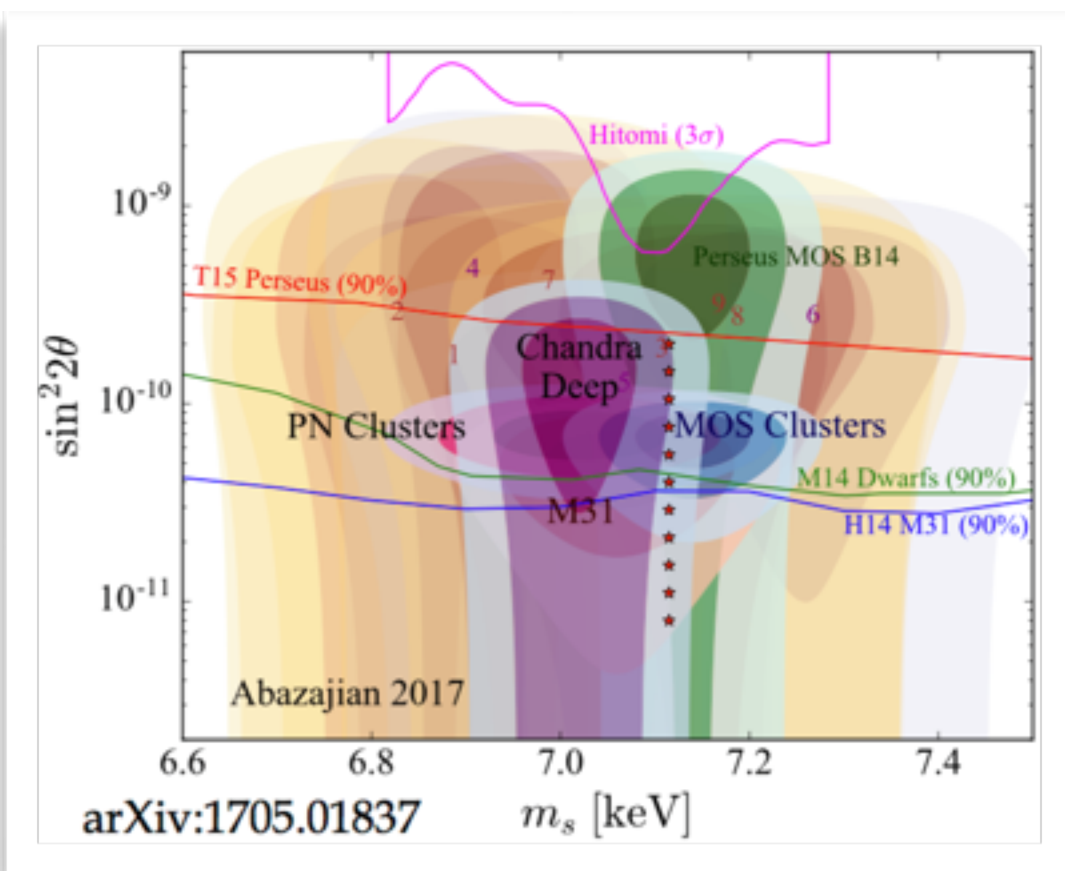


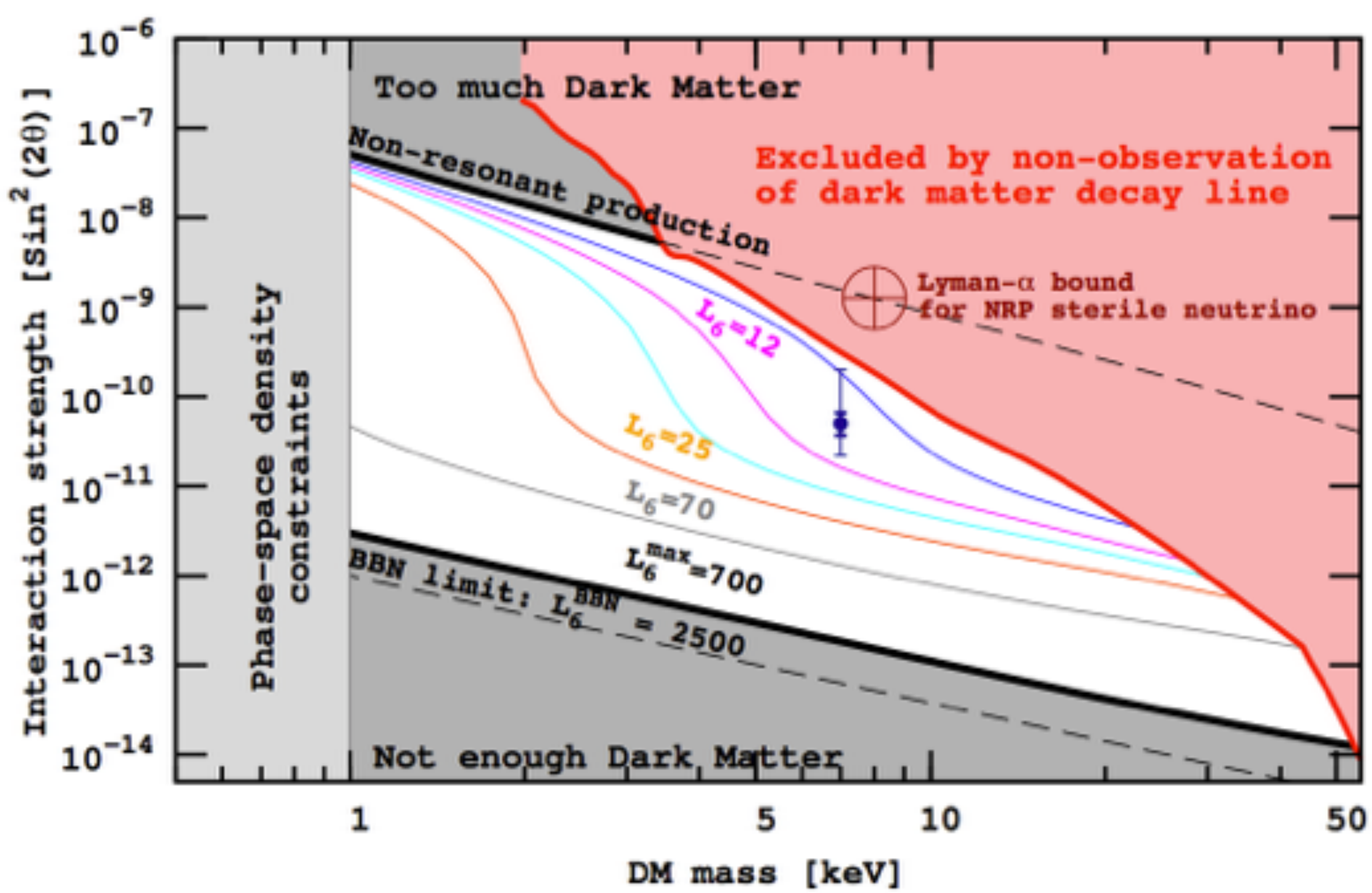
νMSM (and variants) [Shaposhnikov+ 2005]

2 heavy (> GeV) neutral leptons N_2, N_3

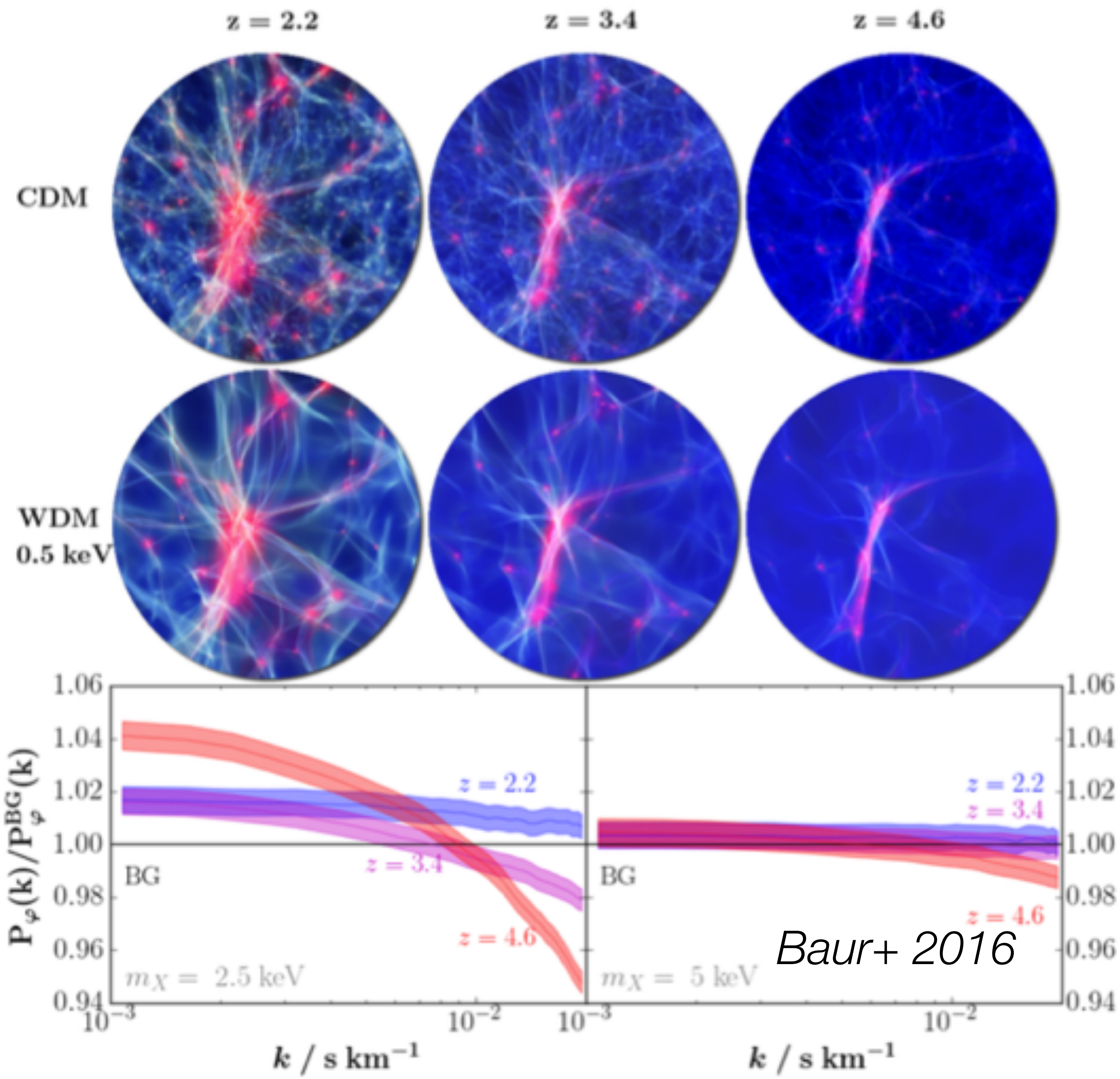
If $M(N_1)$ ~ keV : possible DM window

- Production by mixing with active ν
- Hints of indirect detection by X-ray line $N_1 \rightarrow \nu\gamma$

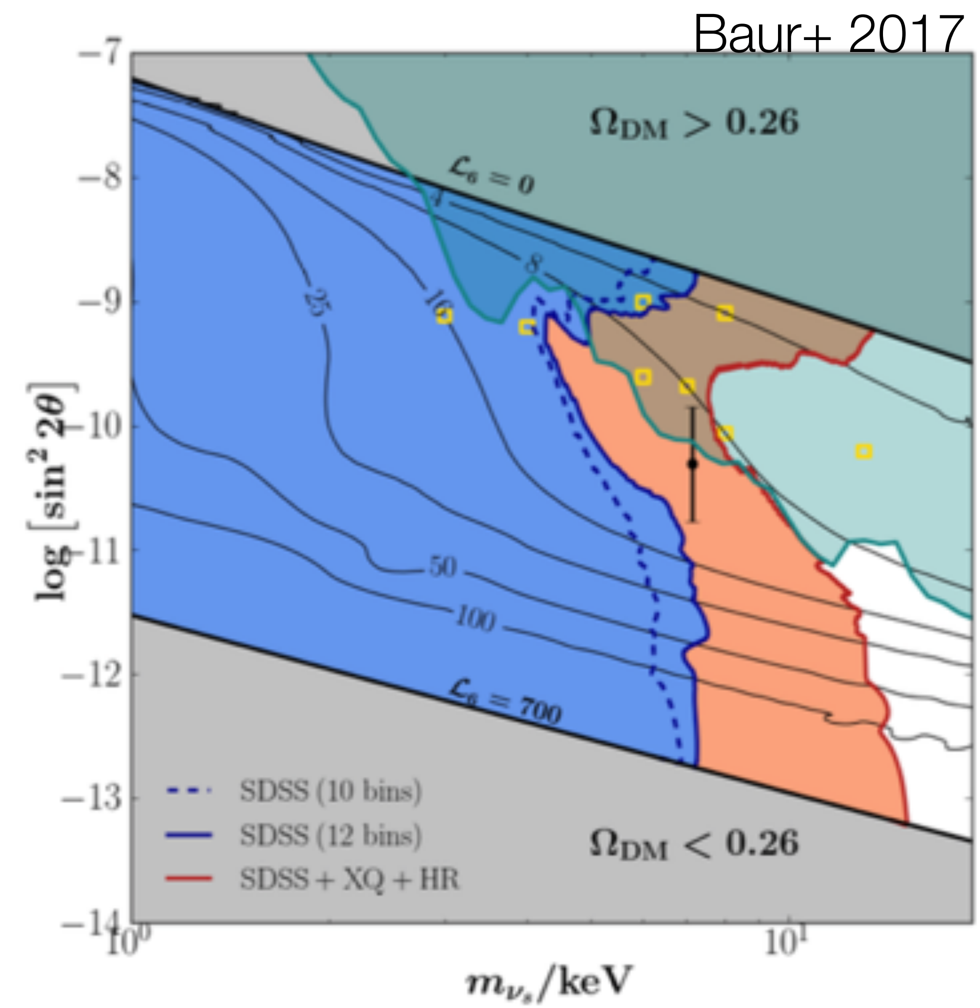




Lyman-alpha constraints on keV sterile neutrinos



- Velocity distribution smoothes structures (free streaming) : cut-off in linear P(k)
- For Lya : effect in competition, but not fully degenerate with Jeans smoothing



- non resonantly produced sterile neutrinos : quasi-thermal distribution
- resonant production : matched to mixed CDM + (thermal) warm DM scenario

Bound could be relaxed assuming specific IGM thermal history (Garzilli+ 2015)

Fuzzy dark matter (FDM)

m ~ 10^{-22} eV - lower bound on the mass of DM
quantum wave effects smooth density fluctuations on scales relevant to structure formation or DM halo dynamics

$$\frac{\lambda_{\rm dB}}{2\,{\rm kpc}} \sim \left(\frac{10^{-22}\,{\rm eV}}{m}\right)\left(\frac{10\,{\rm km/s}}{v}\right)$$

- Archetype : axion-like particles ==> misalignement mechanism

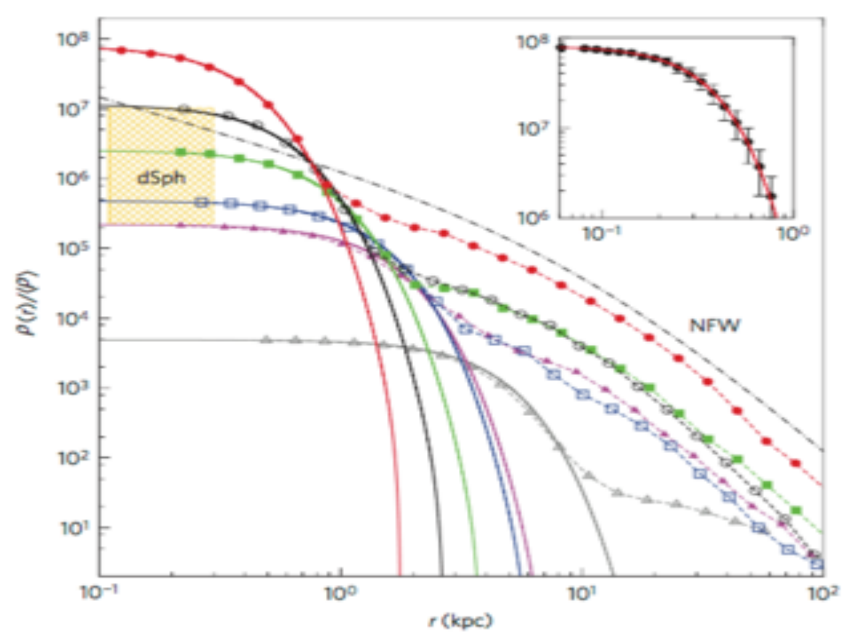
$$\phi = F \times a$$

high-energy scale   angle

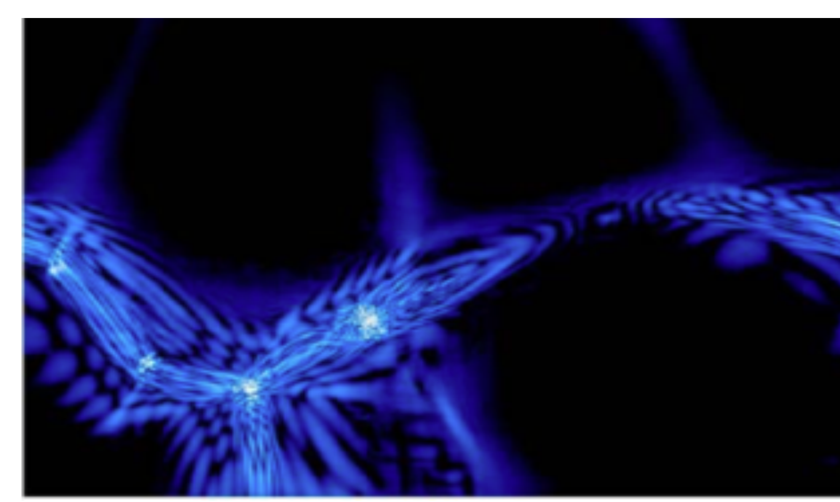
$$\Omega_a = \frac{m^{1/2}\,F^2\,T_{\rm CMB}^3}{\rho_c\,M_{\rm Pl}^{3/2}} \sim 0.1\left(\frac{F}{10^{17}\,{\rm GeV}}\right)^2\left(\frac{m}{10^{-22}\,{\rm eV}}\right)^{1/2}$$

Hui+ 2017

Physics strongly modified at halo scale (solitons)



Schive+ 2014



FDM and cosmological structures

Linear perturbations : FDM ~ fluid with effective speed of sound

$$c_s^2 = \frac{k^2/4m_a^2a^2}{1+k^2/4m_a^2a^2}$$

Related Jeans scale :

$$k_J = 67\, a^{1/4} \left(\frac{\Omega_a h^2}{0.12}\right)^{1/4} \left(\frac{m_a}{10^{-22}\,\mathrm{eV}}\right)^{1/2} \mathrm{Mpc}^{-1}$$

Cut-off in linear matter power spectrum for scales smaller than Jeans scale at equality

- Linear cosmology (~CMB) excludes FDM masses < 10^{-24} eV

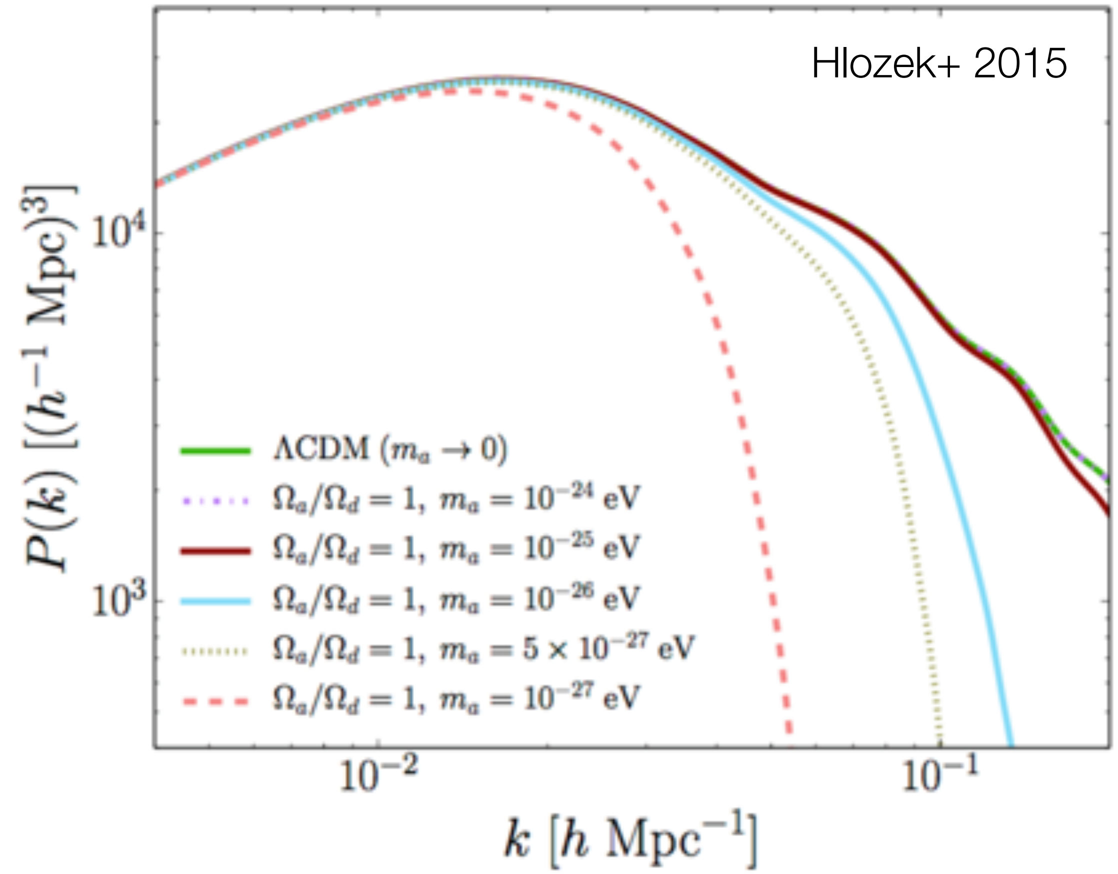
- Non-linear probes : truncation in HMF

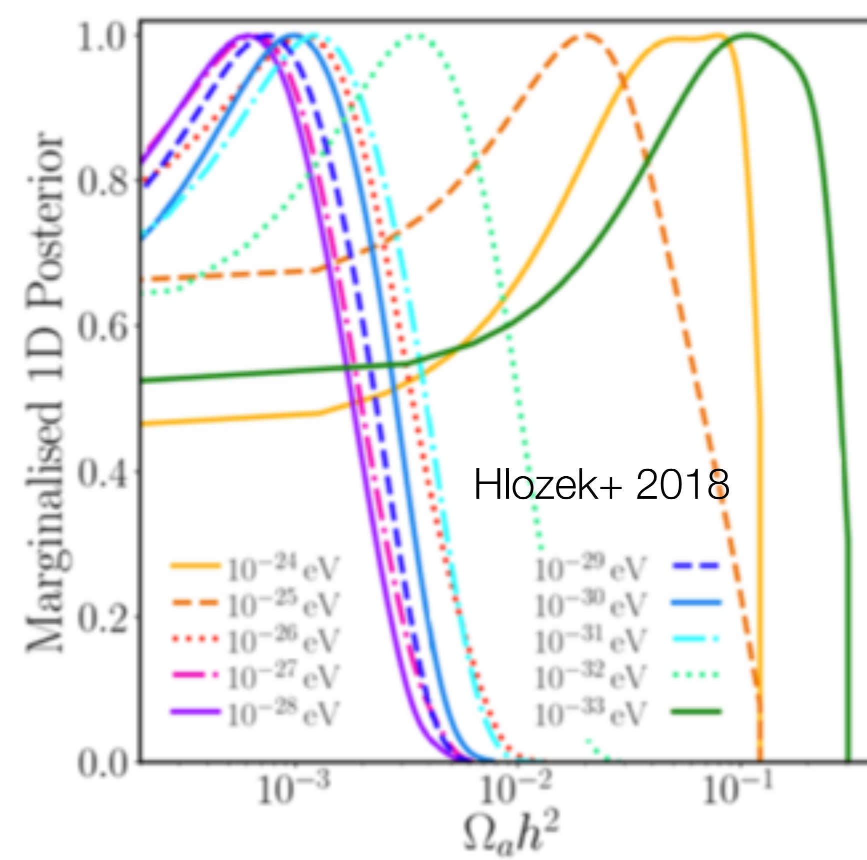
  High-z galaxy counts

  Delayed reionization

  Lyman-alpha [/21cm / ..] spectrum cutoff

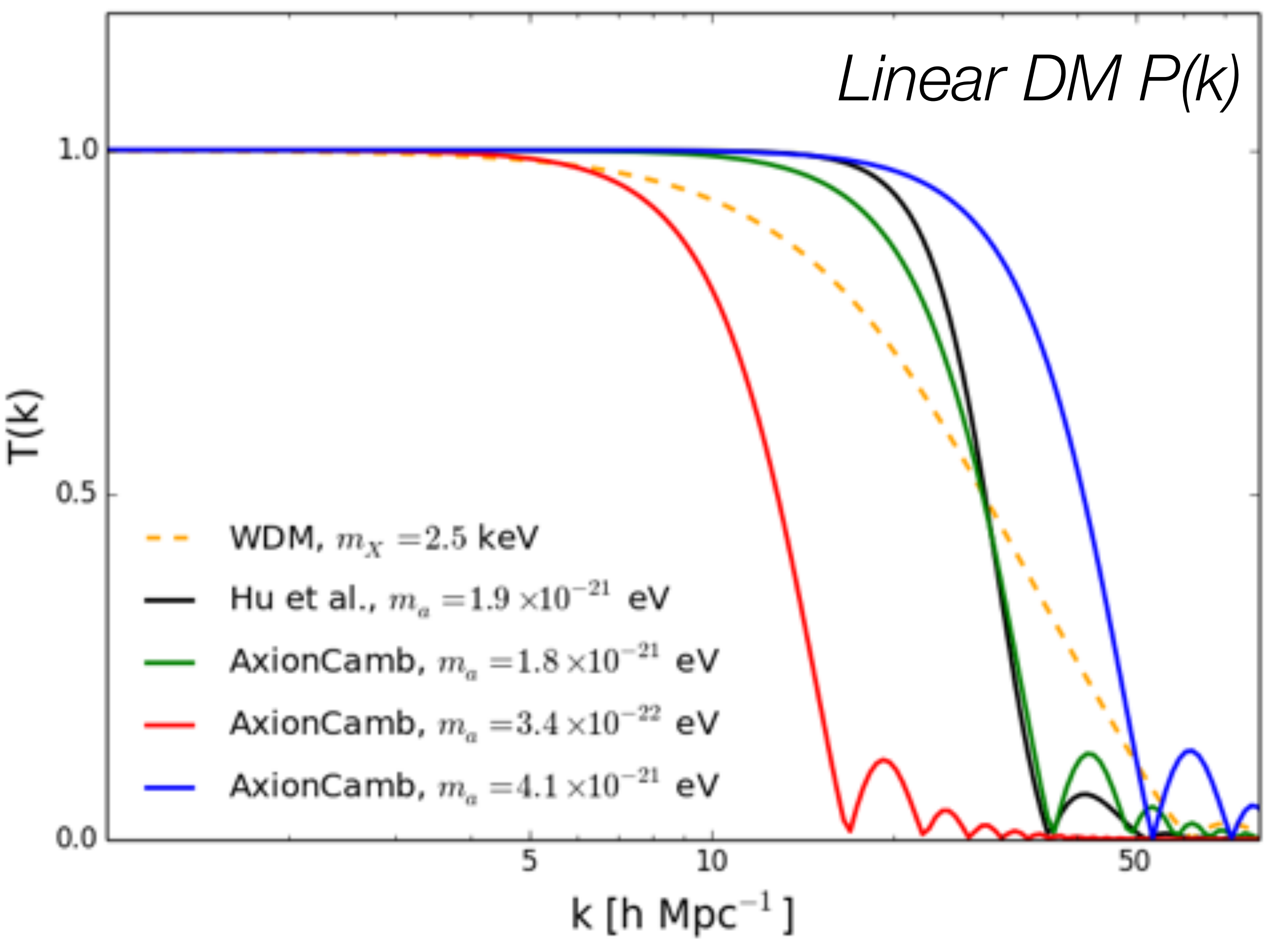
Constraints up to ~10^{-21} eV

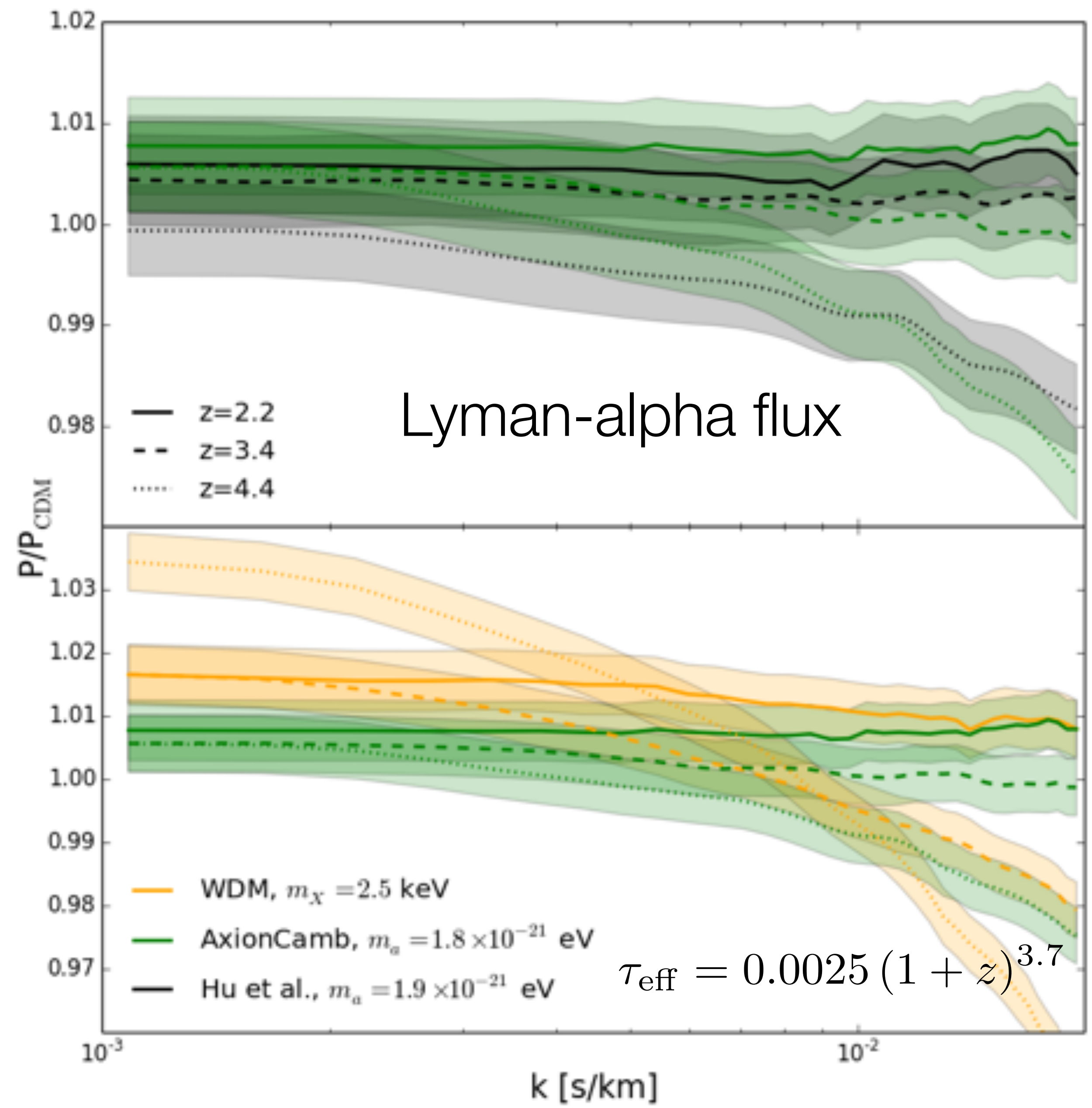




Lyman-alpha constraint on FDM

EA+ 2017, Irsic+ 2017





Fair to use WDM - FDM mass scaling :

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

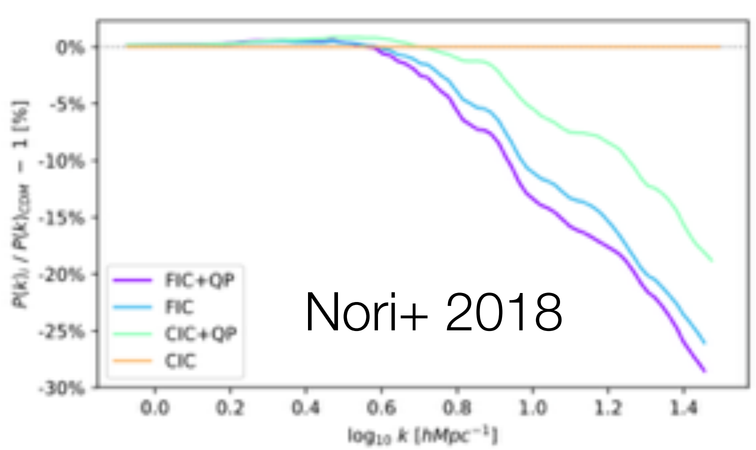
$m_a \gtrsim$ 2-3 x 10^{-21} eV

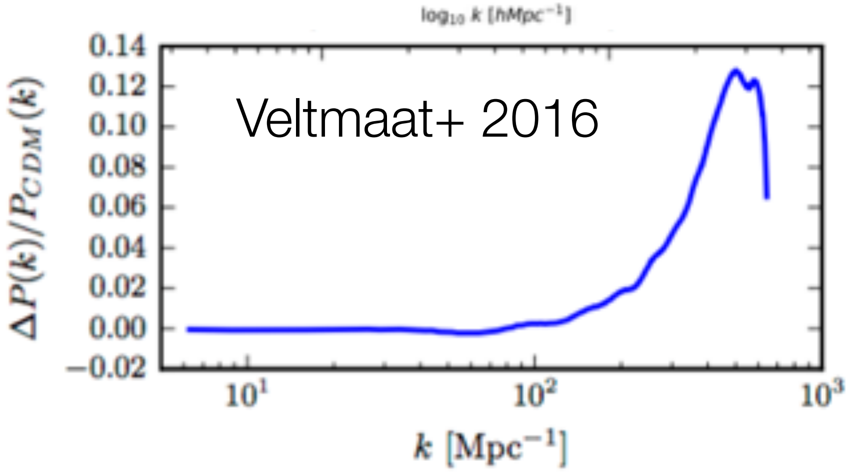
Quantum effects in NL structure formation

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

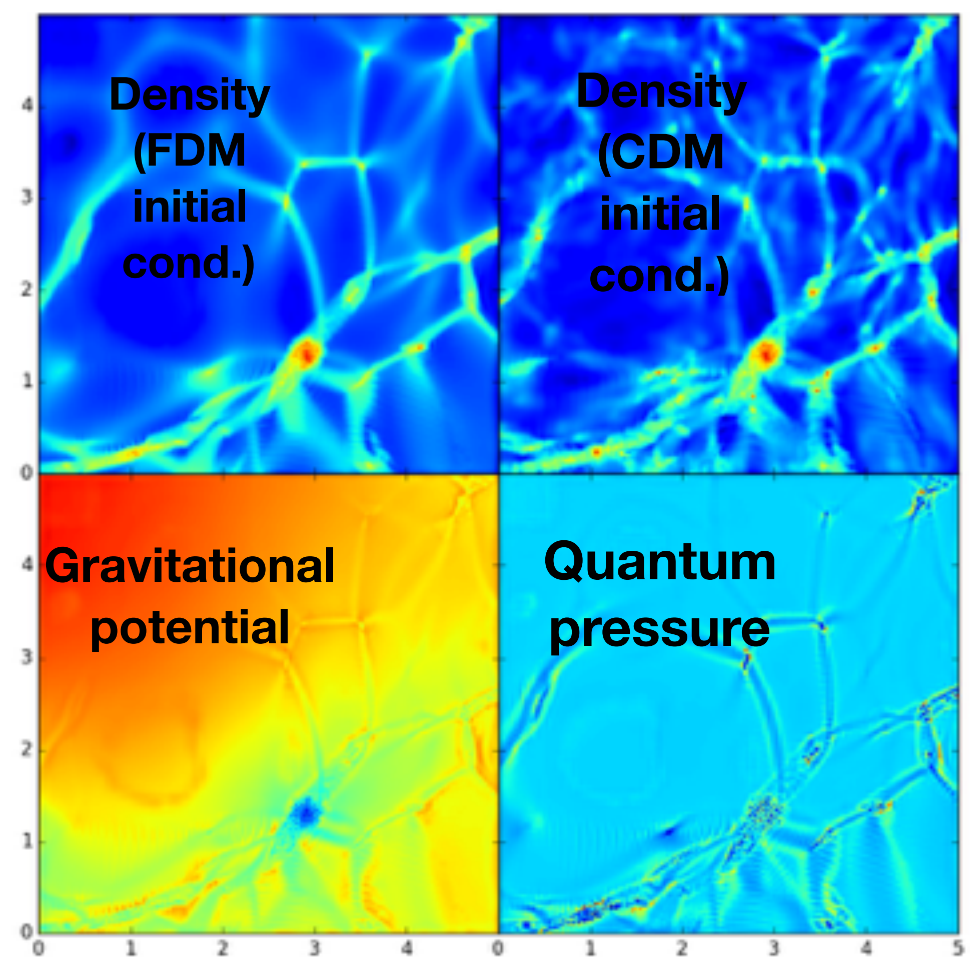
Use standard N-body ⟺ neglect ∇Q
wrt gravitation force ∇ϕ

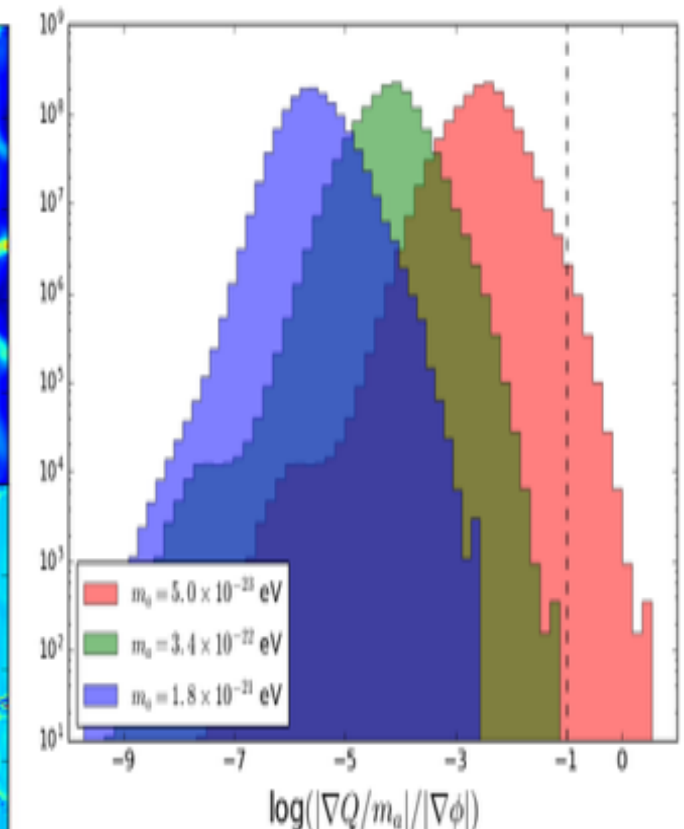
DM-only simulations with Q





EA+ 2017 - standard hydro simulations





=> Ly-alpha simulations expected
to be safe a least for $m_a > 10^{-22}$ eV

Summary

The Lyman-alpha forest is/remains a major cosmological probe

- As of now the main « 3D » observable for LSS @ z ~ 2 - 5 (BAO etc..)
- Complementarity with 21cm, lensing…
- Stats & sytematics will improve with new DESI + high-resolution, together with new-generation numerical predictions

Impact on DM models

- Provides significant constraints on keV sterile neutrino and fuzzy DM scenarios
- Taken at face value, these scenarios are quasi-excluded. However the robustness of Ly-alpha bounds relies on understanding IGM physics, quantum pressure…
- Also interacting DM and PBH bounds