Properties of dark matter with the Lyman-alpha forest

The example of fuzzy dark matter

Eric Armengaud - CEA Saclay

Paris - Tokyo Dark Matter seminar
online - 29/11/2021
https://granite.phys.s.u-tokyo.ac.jp/ja/?SYRTE-UTokyoDMSeminar

Dark matter in cosmological observation

Dynamics of large, gravitationally bound systems
Galaxies, clusters

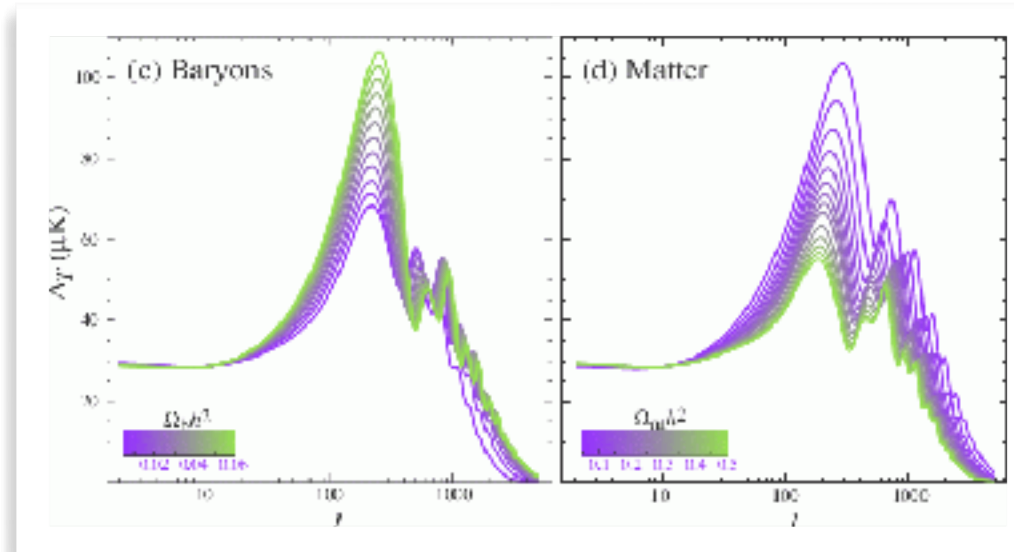
Complex "baryonic" phenomena

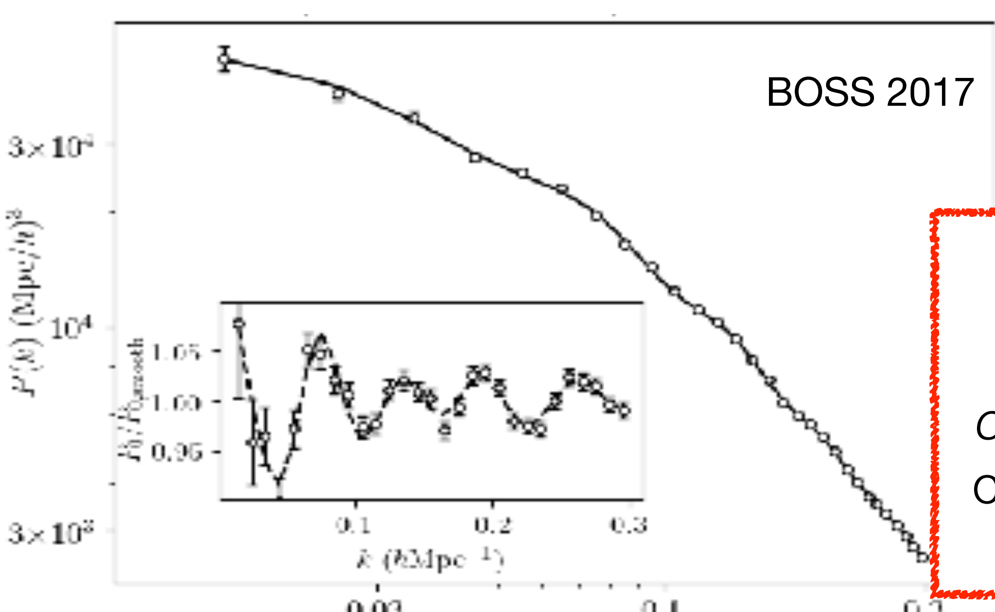
Dark matter in cosmological observation

Dynamics of large, gravitationally bound systems
Galaxies, clusters

Distance ladders + BBN
$\Omega_M = 0.25 \quad \neq \quad \Omega_B = 0.04$

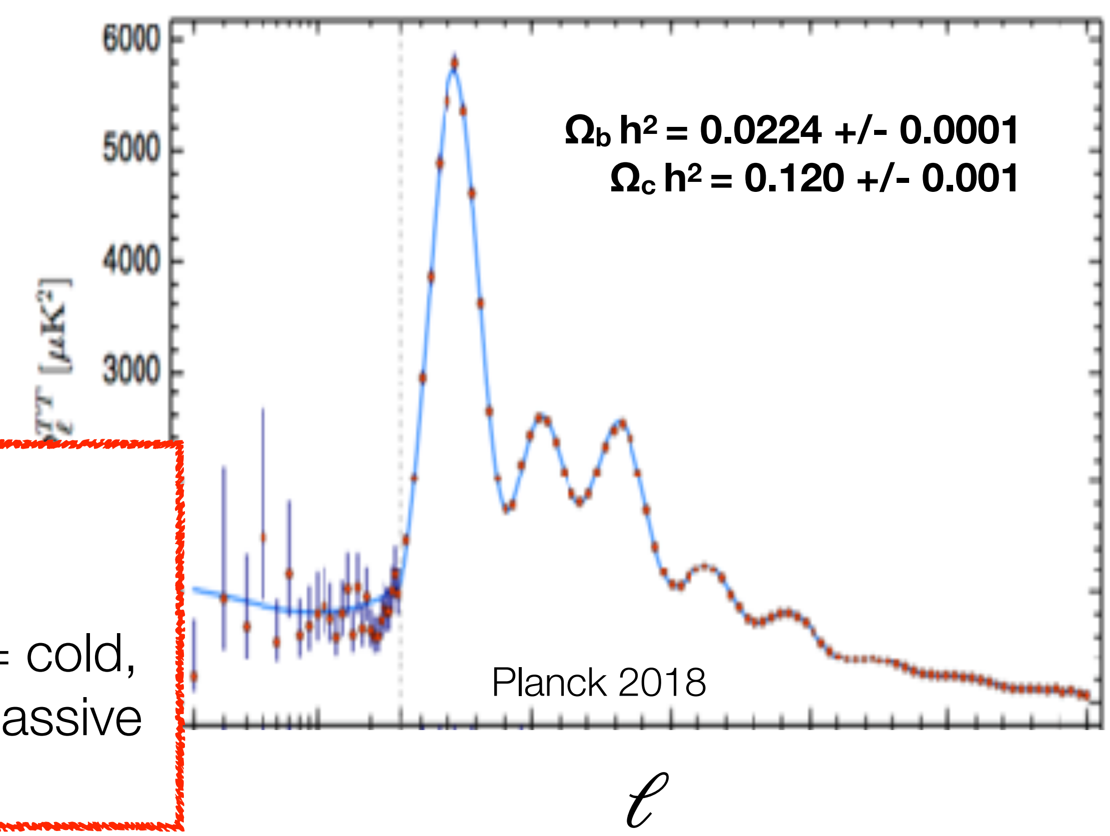
Large-scale matter fluctuations, BAO
"Simple" physics, linear regime: precise predictions





Robust

on large scales: DM = cold, collisionless fluid of massive particles



** 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

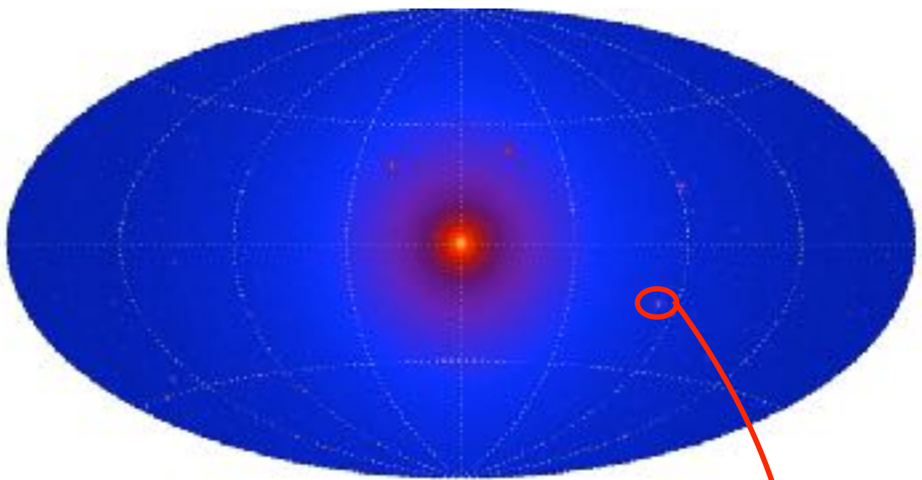
DM « granularity »
large-k fluctuations enhanced
Lyman-alpha : m $\lesssim$ 100 $M_{\odot}$
Murgia+ 2019

Microphysical DM properties from cosmology ?

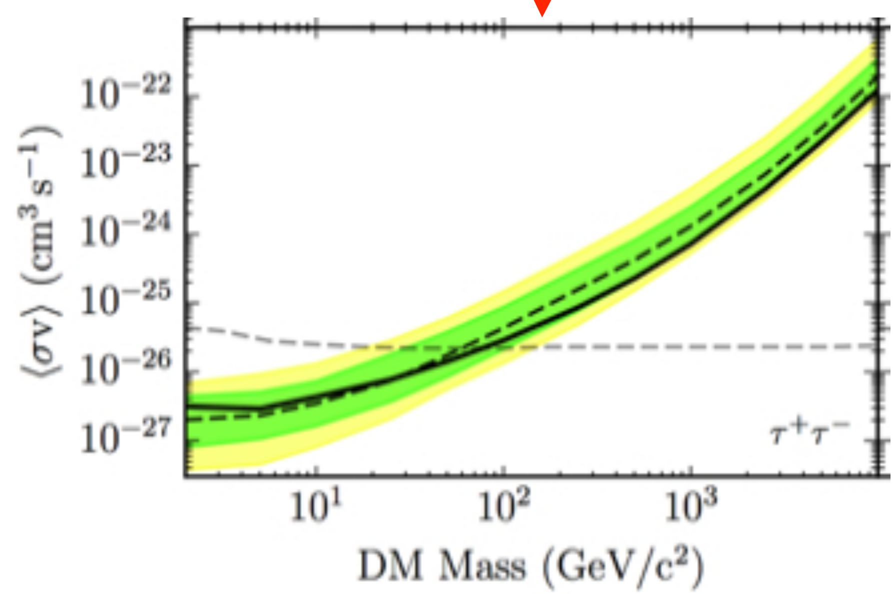
Small scales: optimise the impact of "microphysics" vs gravitational effects

But: **must mitigate baryon physics**

- Ex: search for high-energy photon fluxes, use dwarf galaxies



FERMI-Lat, WIMP search



In this talk: search for statistical modifications of the matter distribution at small cosmological scales wrt CDM

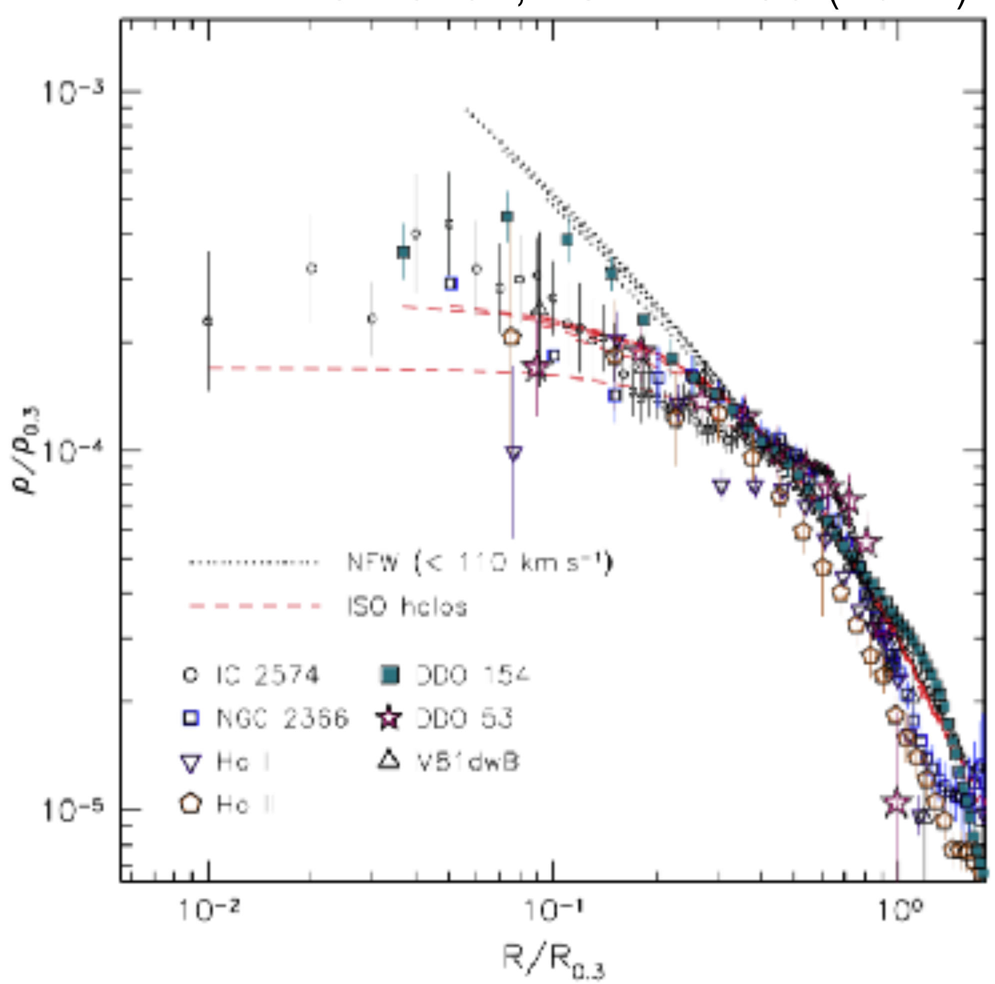
- Lyman-alpha forest an efficient probe

The CDM « small-scale crisis »

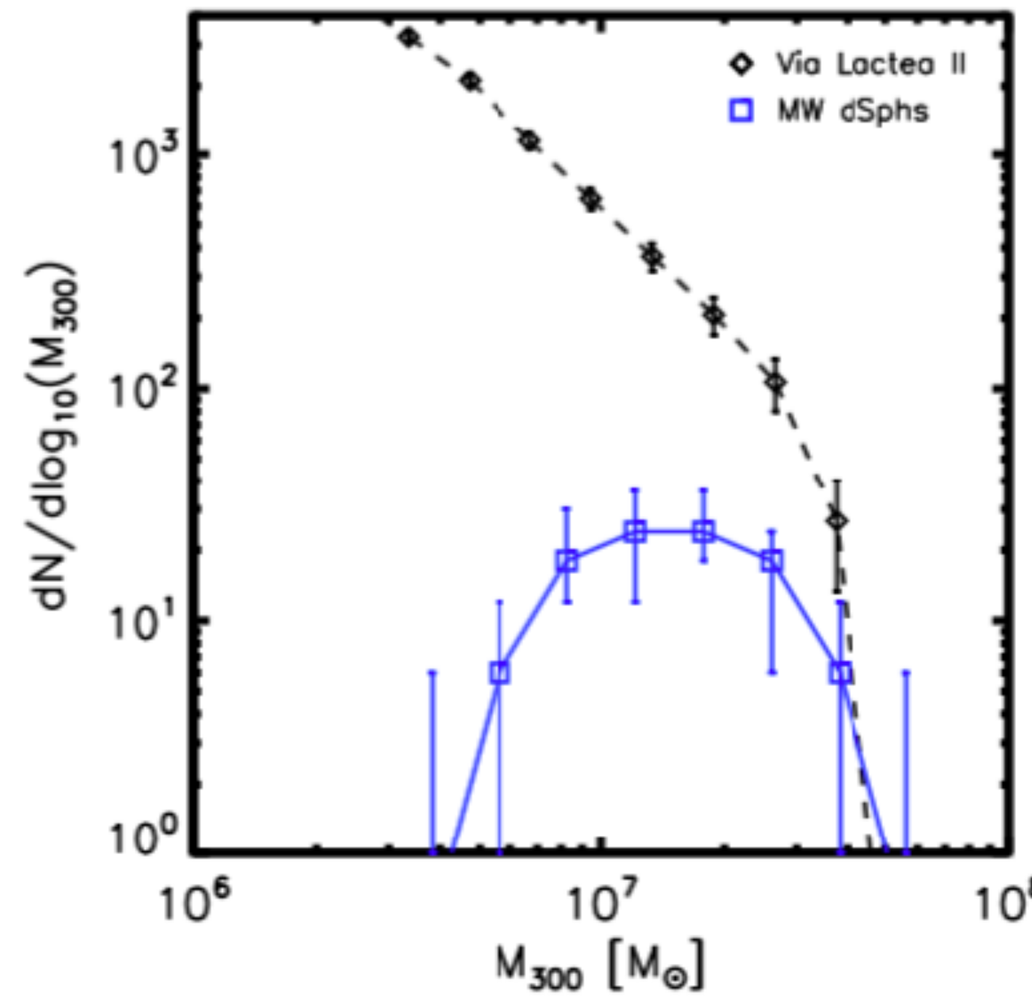
Since end of ‘90s

Several ~kpc-scale features of matter distribution cannot be reproduced by CDM-only LSS simulations

cusp vs core profiles
Oh et al., AJ 141:193 (2011)



missing satellites
Bullock, arxiv:1009.4505



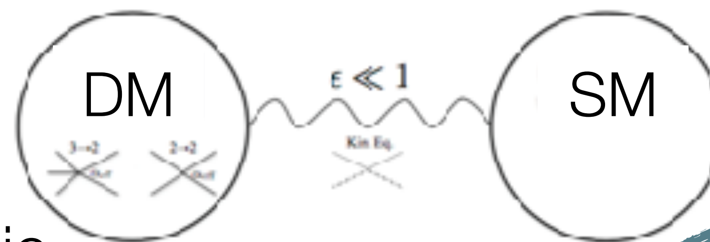
- Baryon physics (feedback)
- Dark matter properties ??

DM solutions to the « small-scale issues »

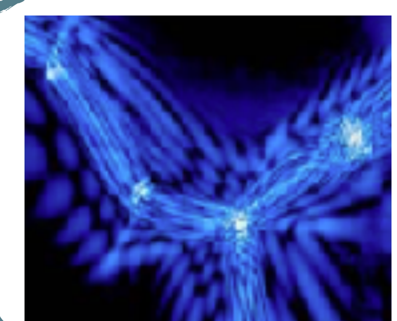
Strongly-Interacting DM (SIDM)

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

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



Fuzzy Dark Matter (FDM)



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

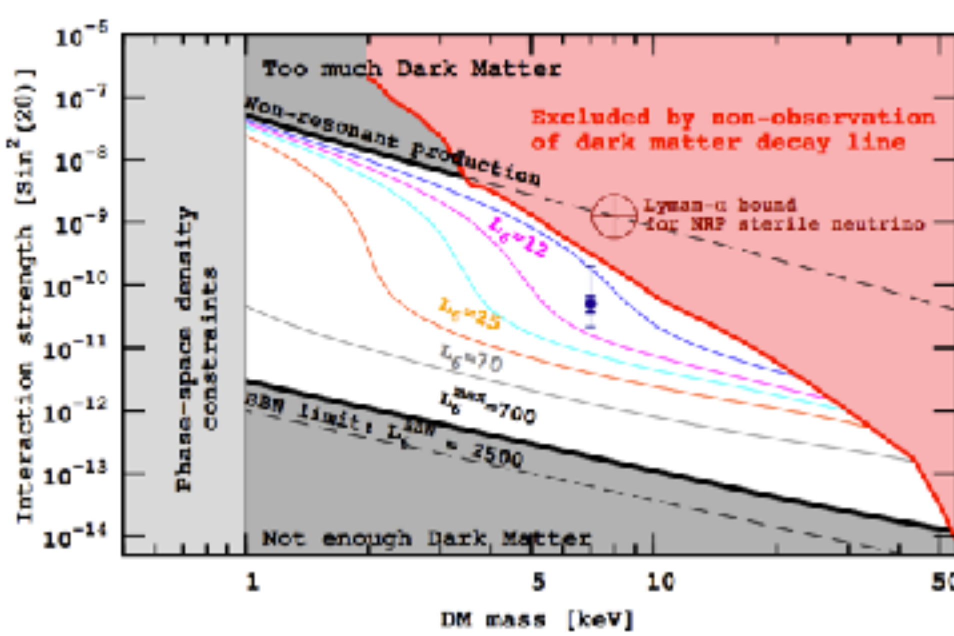
« no Catch 22
problem » -
could solve both
halo statistics &
core profile ?

Warm Dark Matter (WDM)

free-streaming
best solve missing
satellites

eg. sterile neutrino

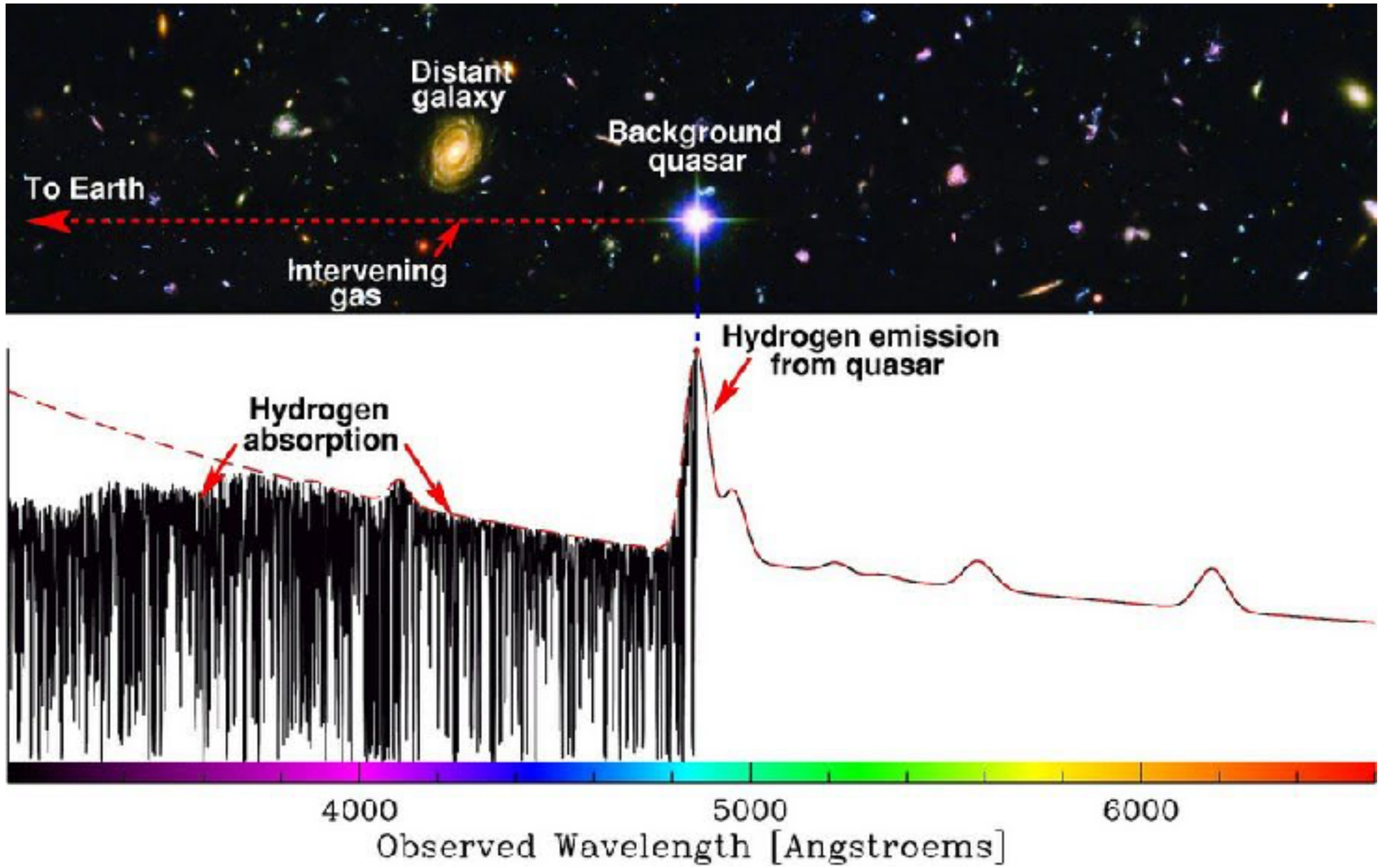
3.5 keV line signal ?



The Lyman-alpha forest

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

wavelength in visible
⇒ z > 2



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

HI fraction ~ 10^{-5}

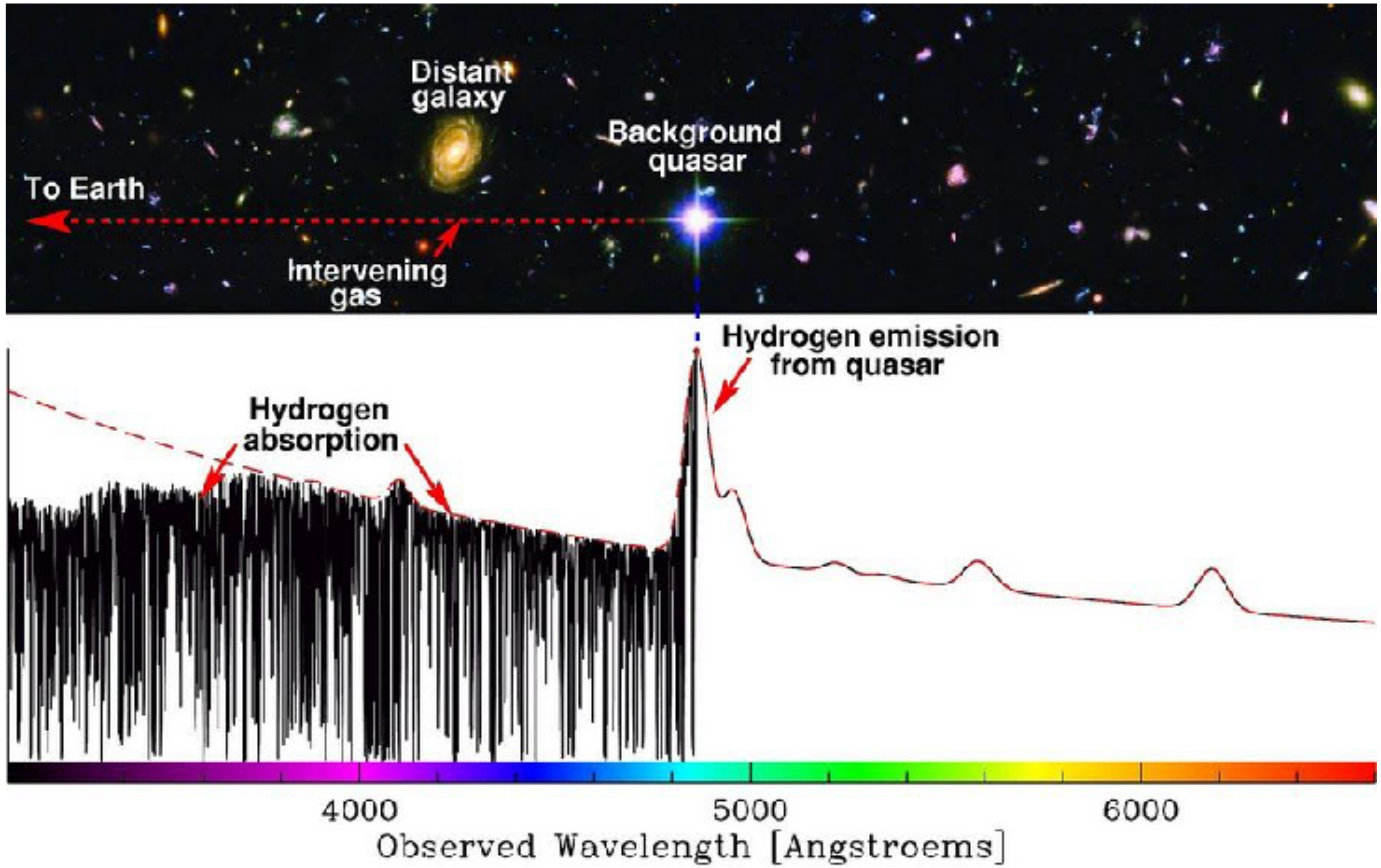
τ ~ 1 for mild (~linear) density fluctuations: a miracle !

- sensitive to **small-scale** matter density fluctuations
- does not probe "dense" objects (DLAs)

The Lyman-alpha forest

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

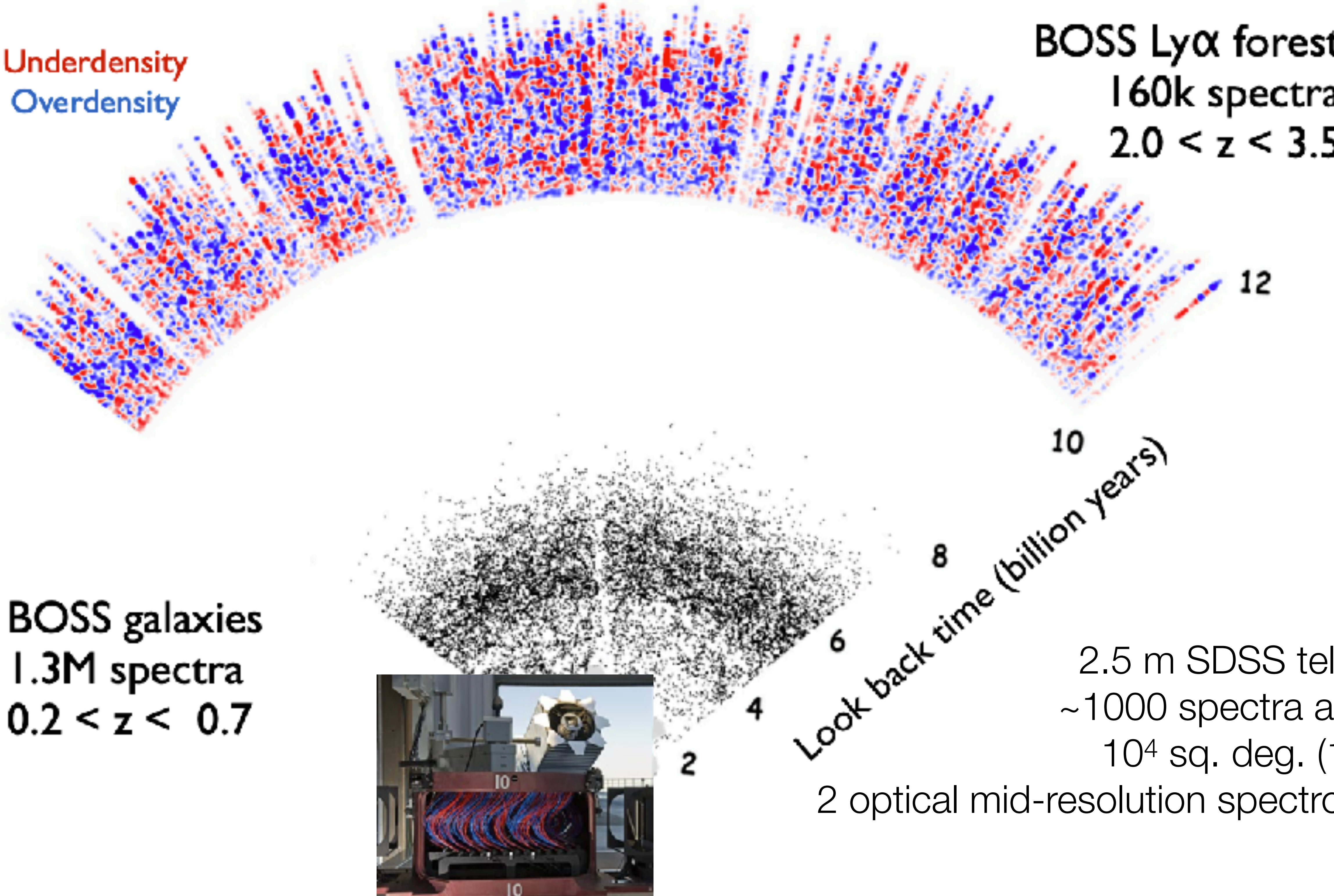
wavelength in visible
⇒ $z > 2$



In order to precisely connect to matter power spectrum, need knowledge of :

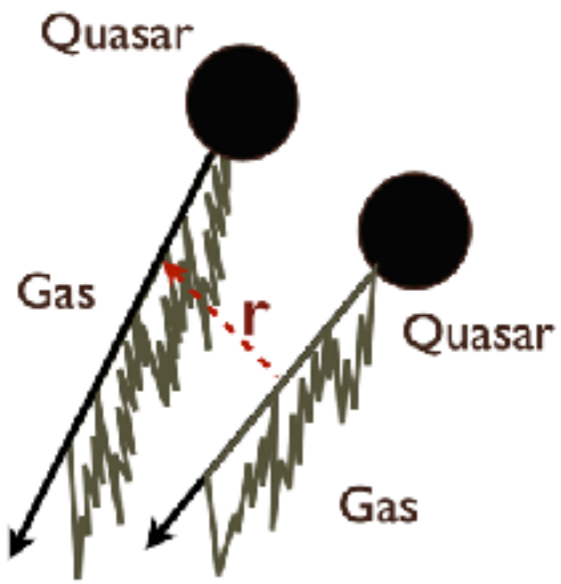
- non-linear structure growth
- intrinsic source (quasar) emission
- IGM physics
- instrumental response

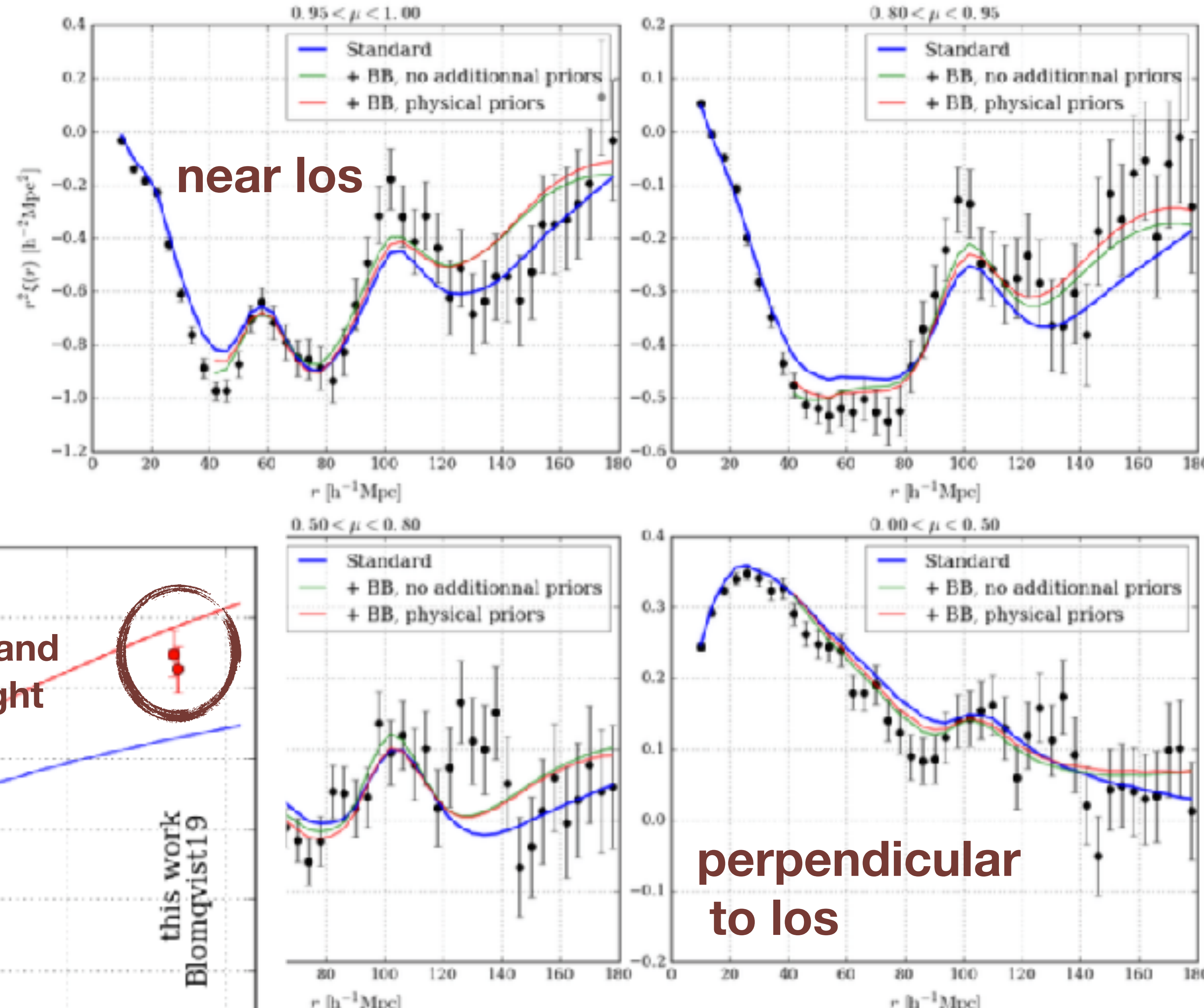
The SDSS - BOSS redshift survey

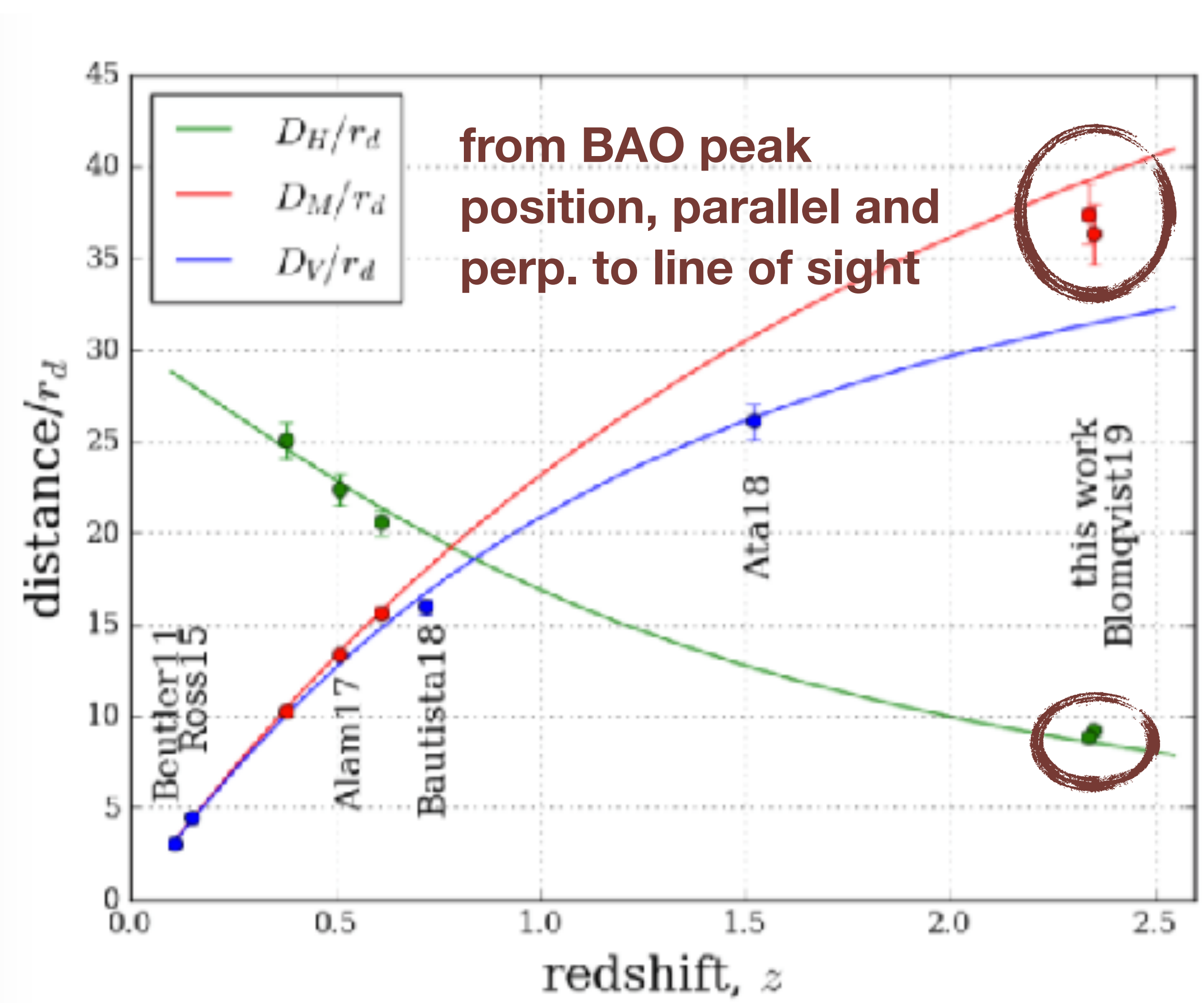


2.5 m SDSS telescope
~1000 spectra at a time
10^4 sq. deg. (1/4 sky)
2 optical mid-resolution spectrographs

Large-scale correlations in the Ly-alpha forest

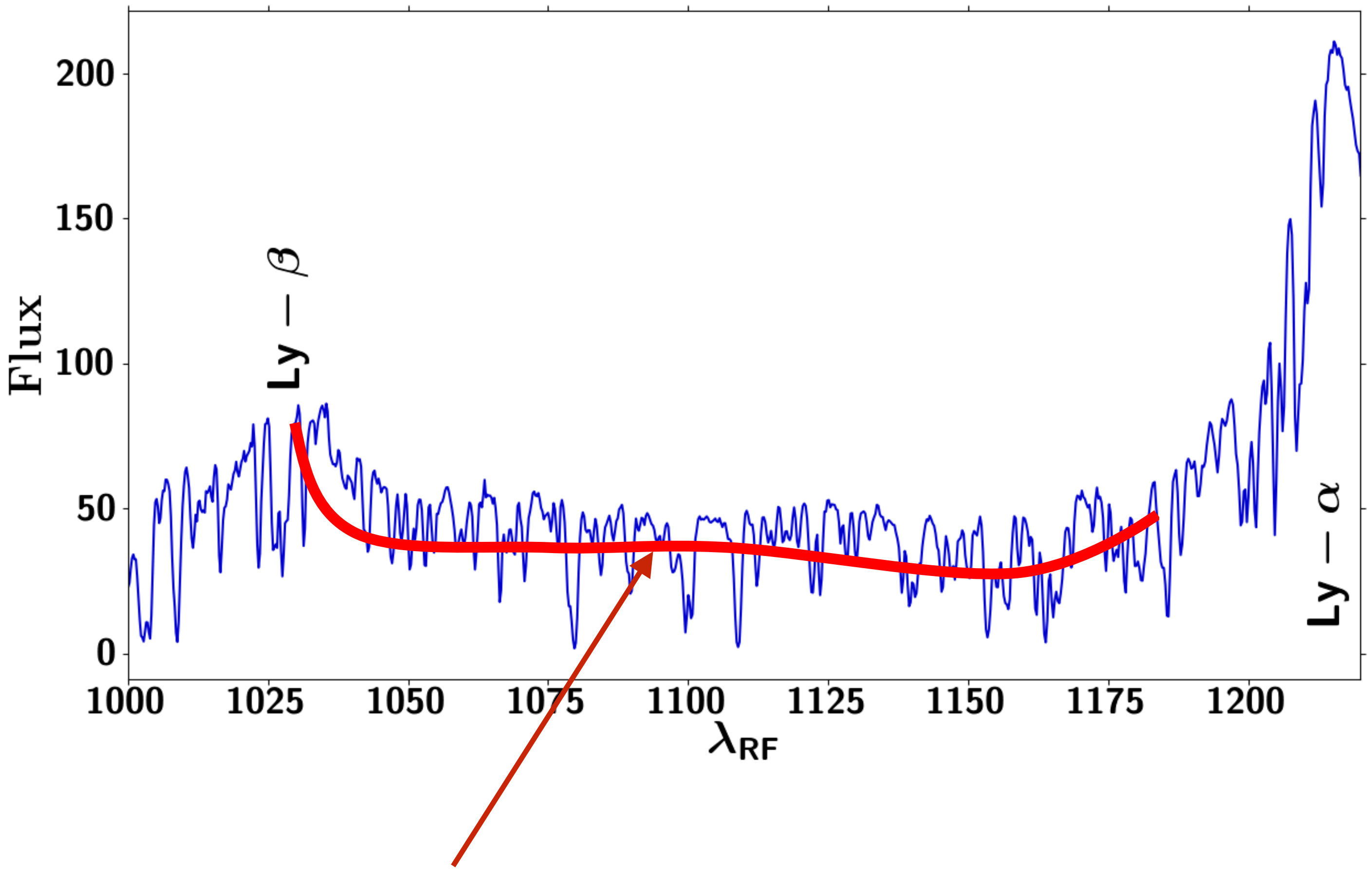






eBOSS DR14
de Sainte Agathe+ 2019

Lyman-alpha forest: small-scale, 1D power spectrum



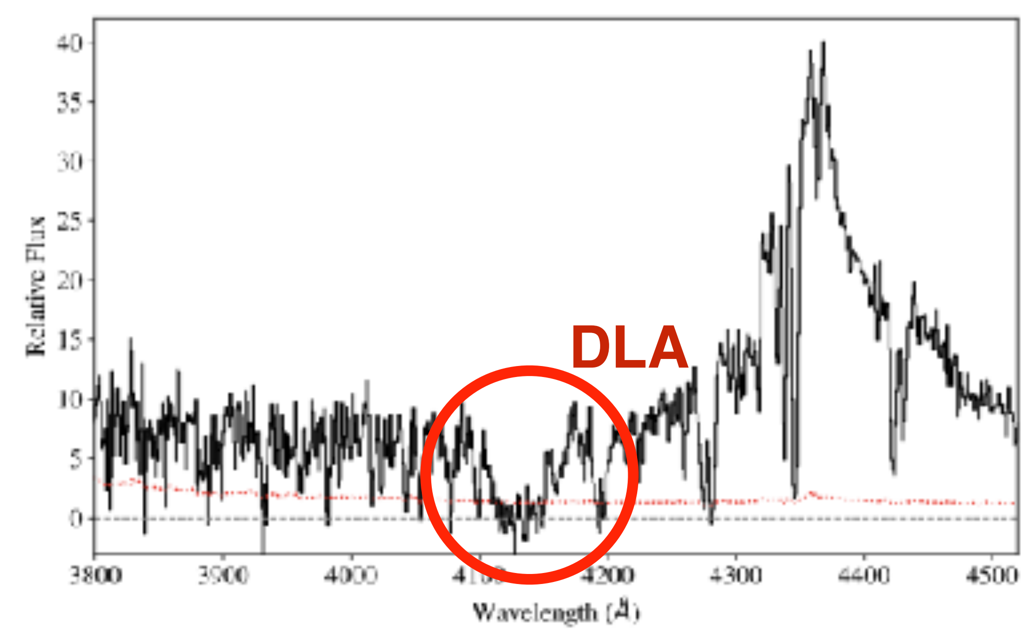
(Quasar continuum) x (mean transmission)

$$\delta(\lambda) = \frac{f(\lambda)}{C_q(\lambda)\bar{f}(z)} - 1$$

$P_{1D}(k) = < (\mathrm{FFT}(\delta))^2 >$

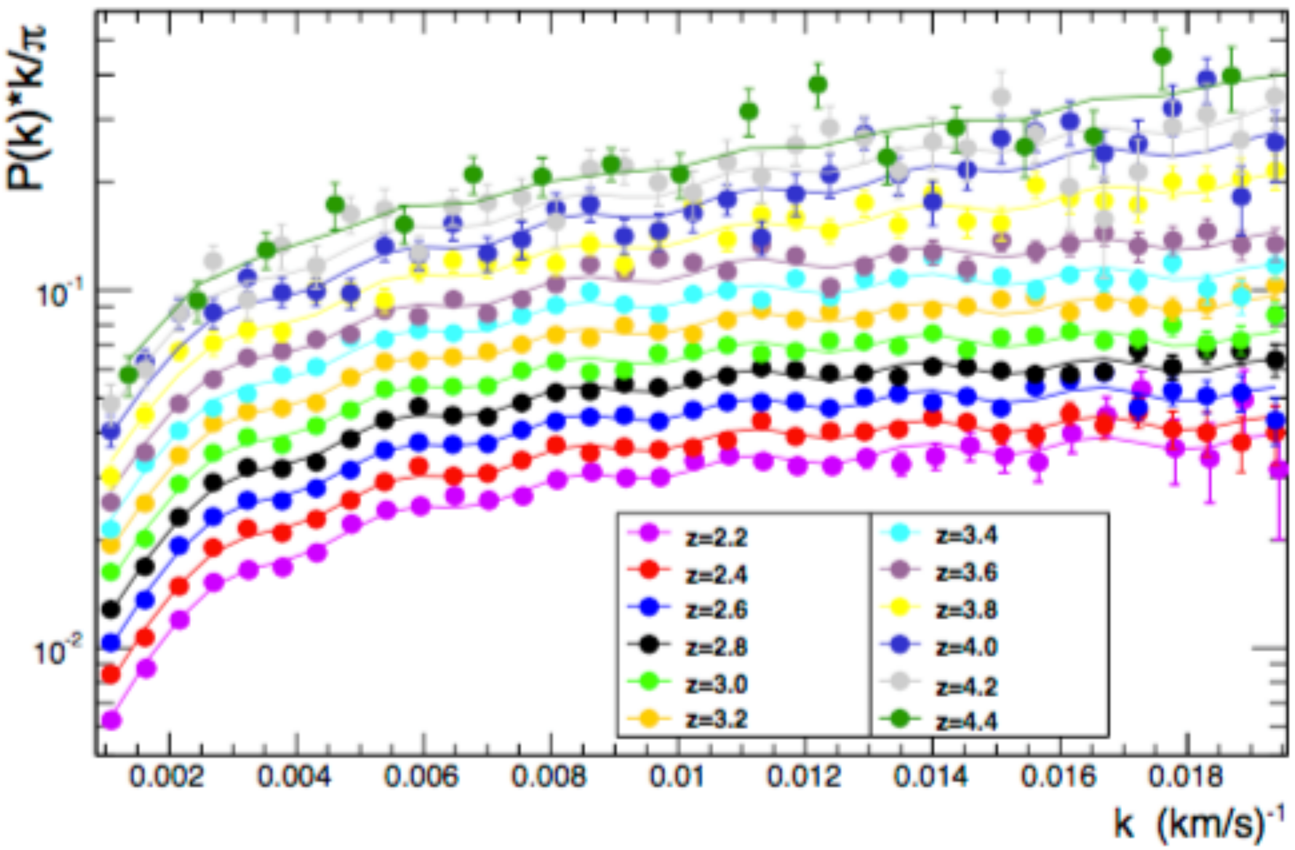
related to 3D matter P(k)

eBOSS DR14: 43,000 spectra out of 190,000
- select SNR, resolution
- remove high density absorbers

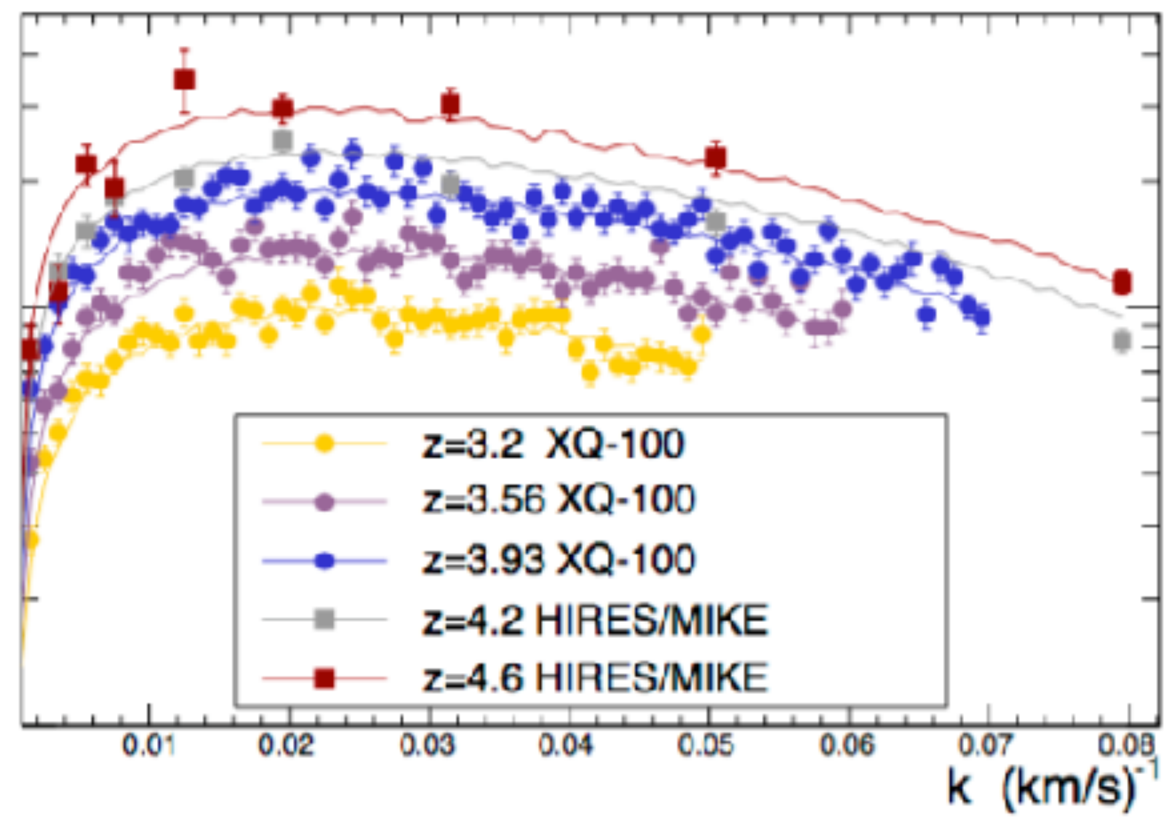


Lyman-α : P1D measurement

Palanque-Delabrouille et al., A&A 2013



Yèche et al. JCAP2017



SDSS catalog

⟹ flux power spectra with near-% precision

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

High resolution spectra

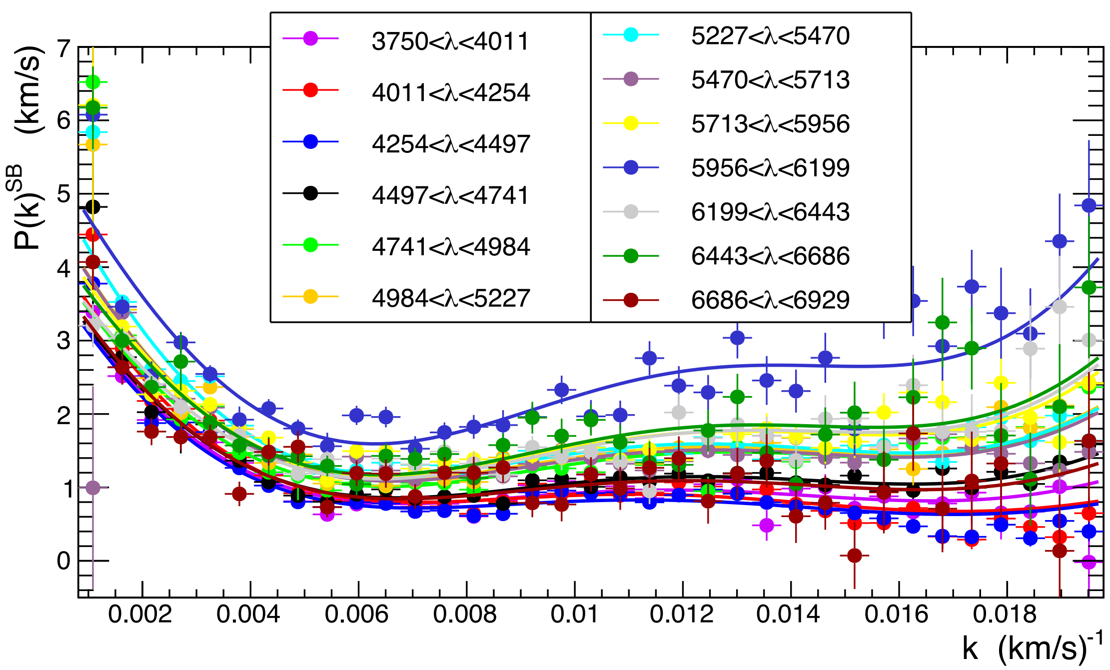
(VLT/X-SHOOTER, Magellan/MIKE, Keck/HIRES))

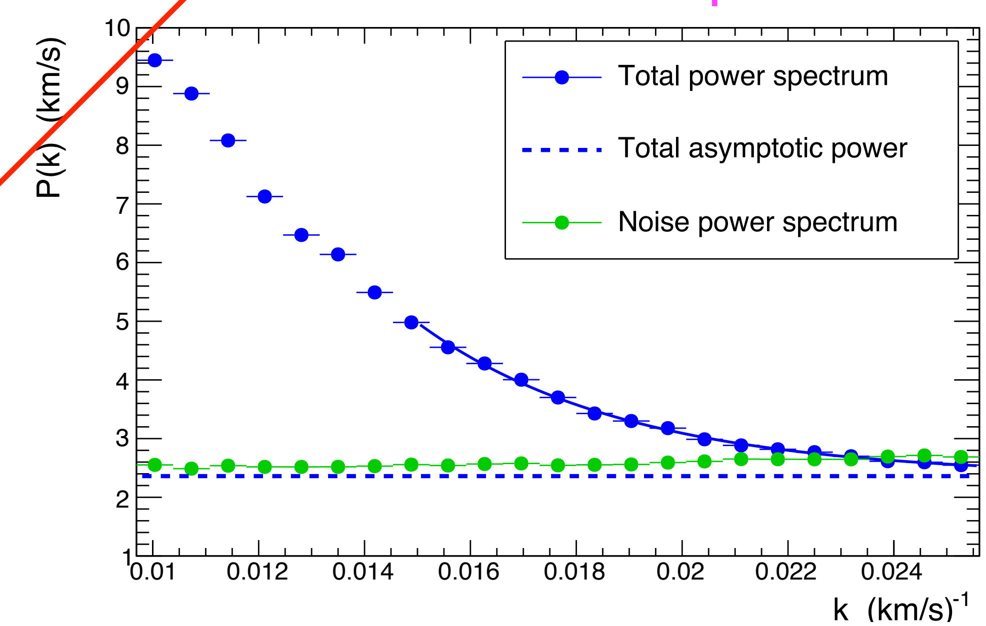
Smaller scales, higher z

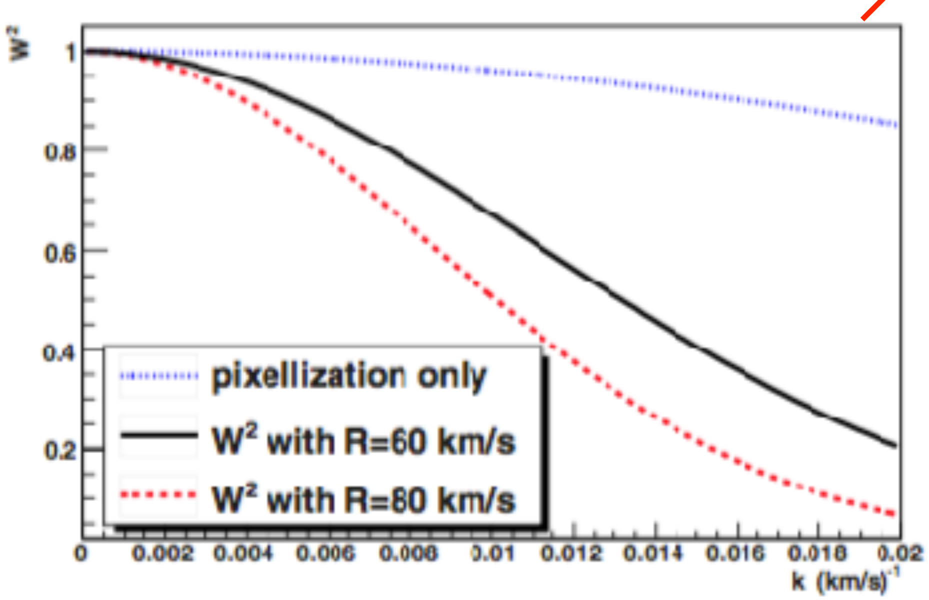
P1D measurement

(eBOSS)

$$P_{raw}(k) = [P_{Ly\alpha}(k) + P_{HI-Si3}(k) + P_{metals}(k)].W^2(k) + P_{noise}(k)$$

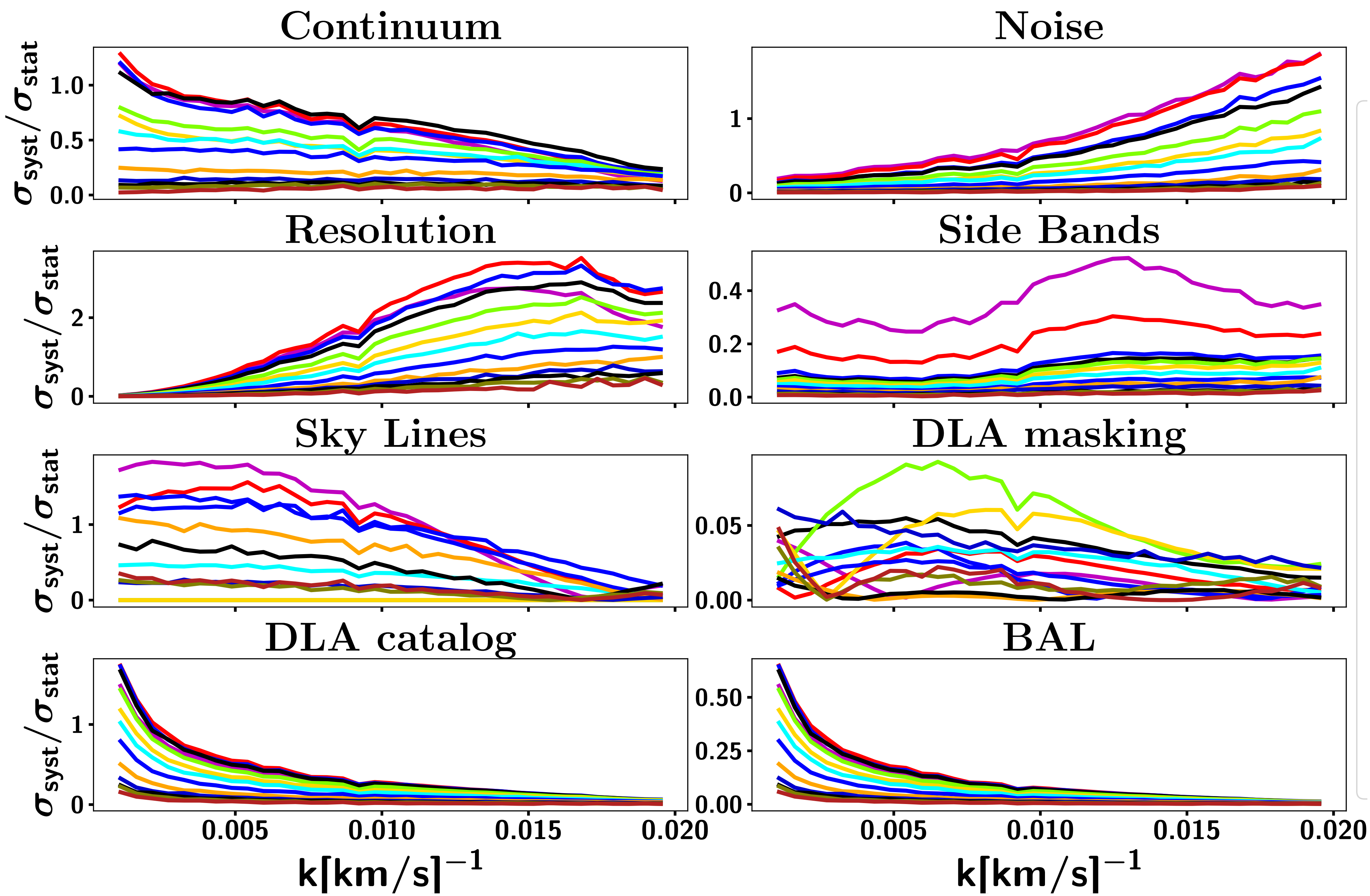






Strong impact on high k
(small scales)

Uncertainties in the eBOSS 1D Lya power spectrum



Chabanier+ 2019

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

Modelling the small-scale Lyman-alpha forest

1) Linear matter power spectrum

Boltzmann solver [A_S, n_S, Ω_M...]

2) Non-linear gravitational evolution + hydrodynamics :

cosmo-hydro simulation (GADGET, NYX, ...)

gaz from SPH or grid method

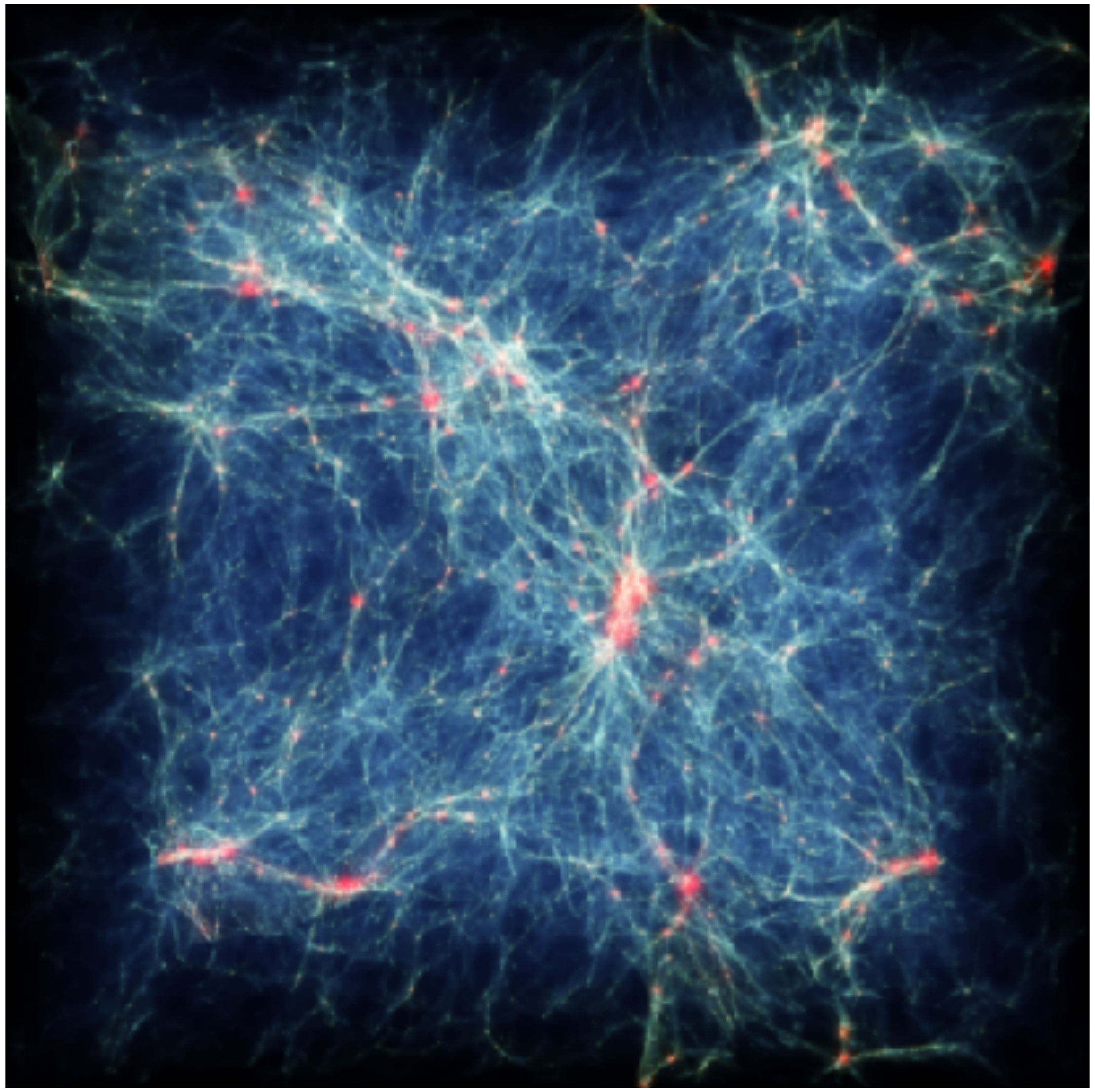
includes explicit model for gaz thermodynamics (heating rates) [T_0, γ]

3) Model Lya forest:

Draw « lines of sight », compute absorption

Compute $P_{1D}(k)$

Borde+ JCAP 2014



- Full computation for a few models
- Interpolate between models in parameter space (Taylor grid, bayesian emulator)

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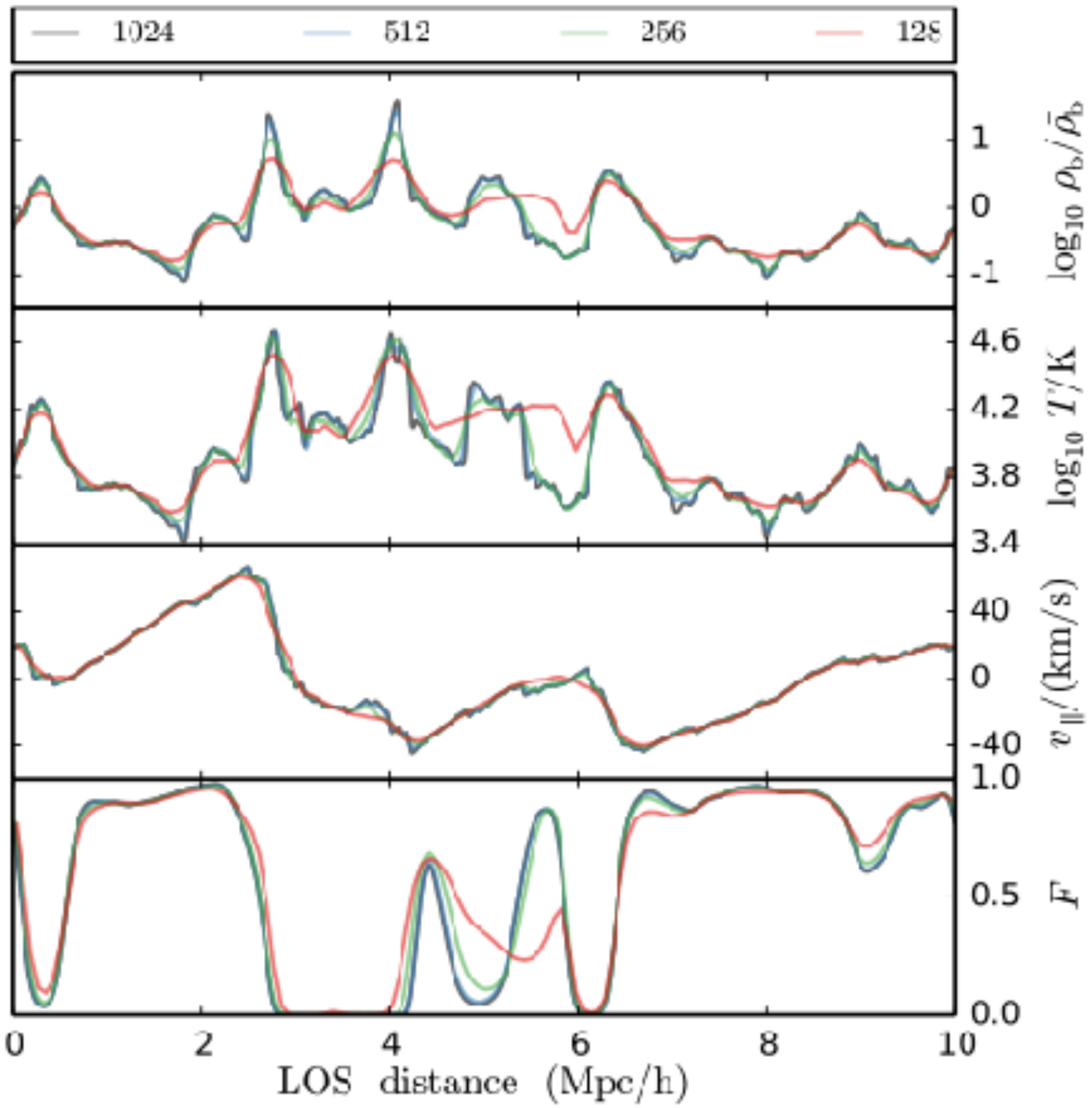
Lukic+ MNRAS 2015



- Full computation for a few models
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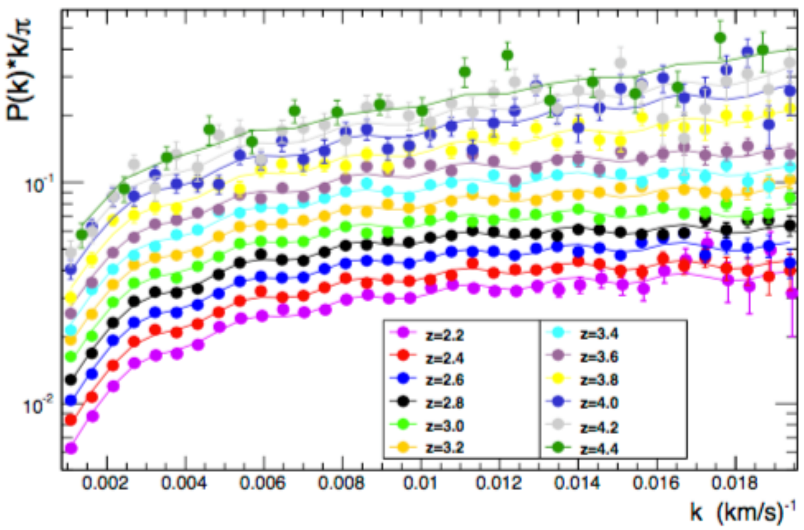
Modelling the small-scale Lya forest: BOSS, ΛCDM

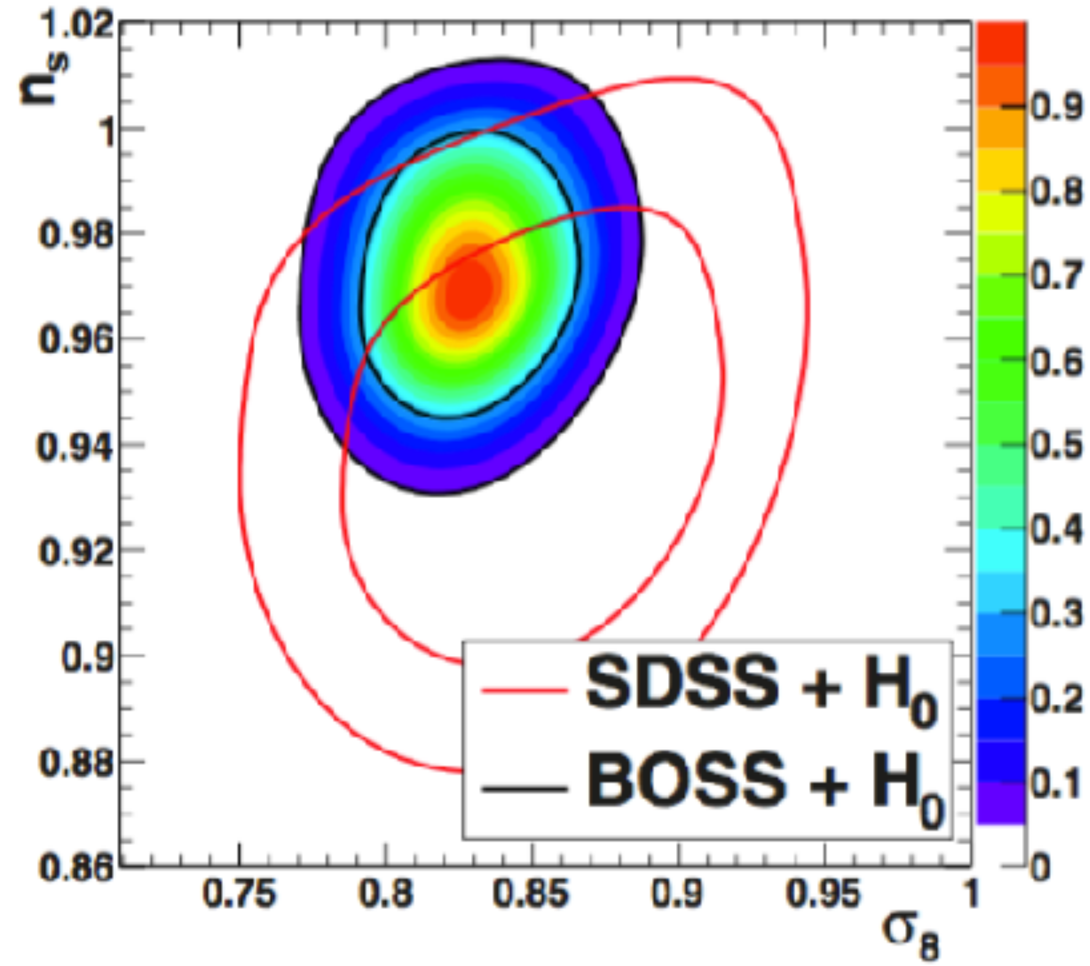
Parameter	Central value	Range
n_s	0.96	± 0.05
σ_8	0.83	± 0.05
Ω_m	0.31	± 0.05
H_0	67.5	± 5
$T_0(z=3)$	14000	± 7000
$\gamma(z=3)$..	1.3	± 0.3
A^{τ}	0.0025	± 0.0020
η^{τ}	3.7	± 0.4

Inference based on a GADGET grid
4 "cosmology" + 4 "IGM" parameters

Likelihood includes several other "nuisance" parameters (observational + modelling)



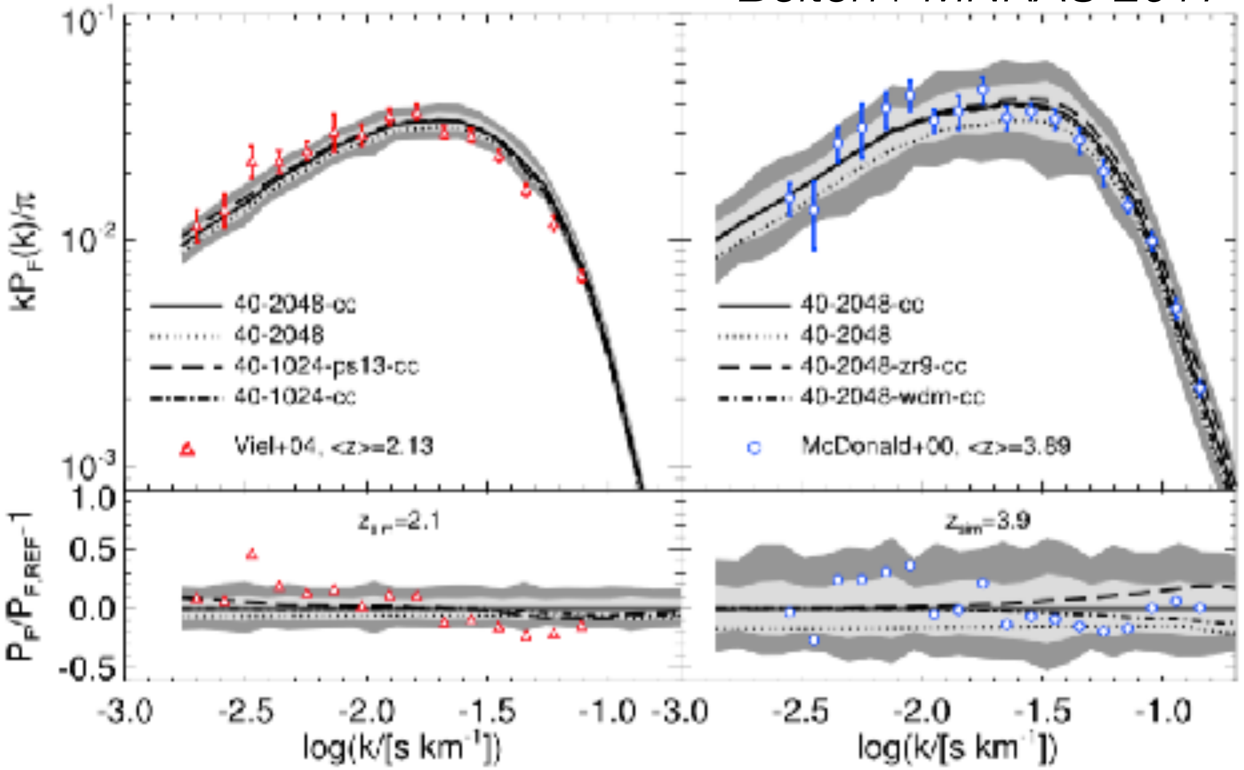
Palanque-Delabrouille+
JCAP 2020



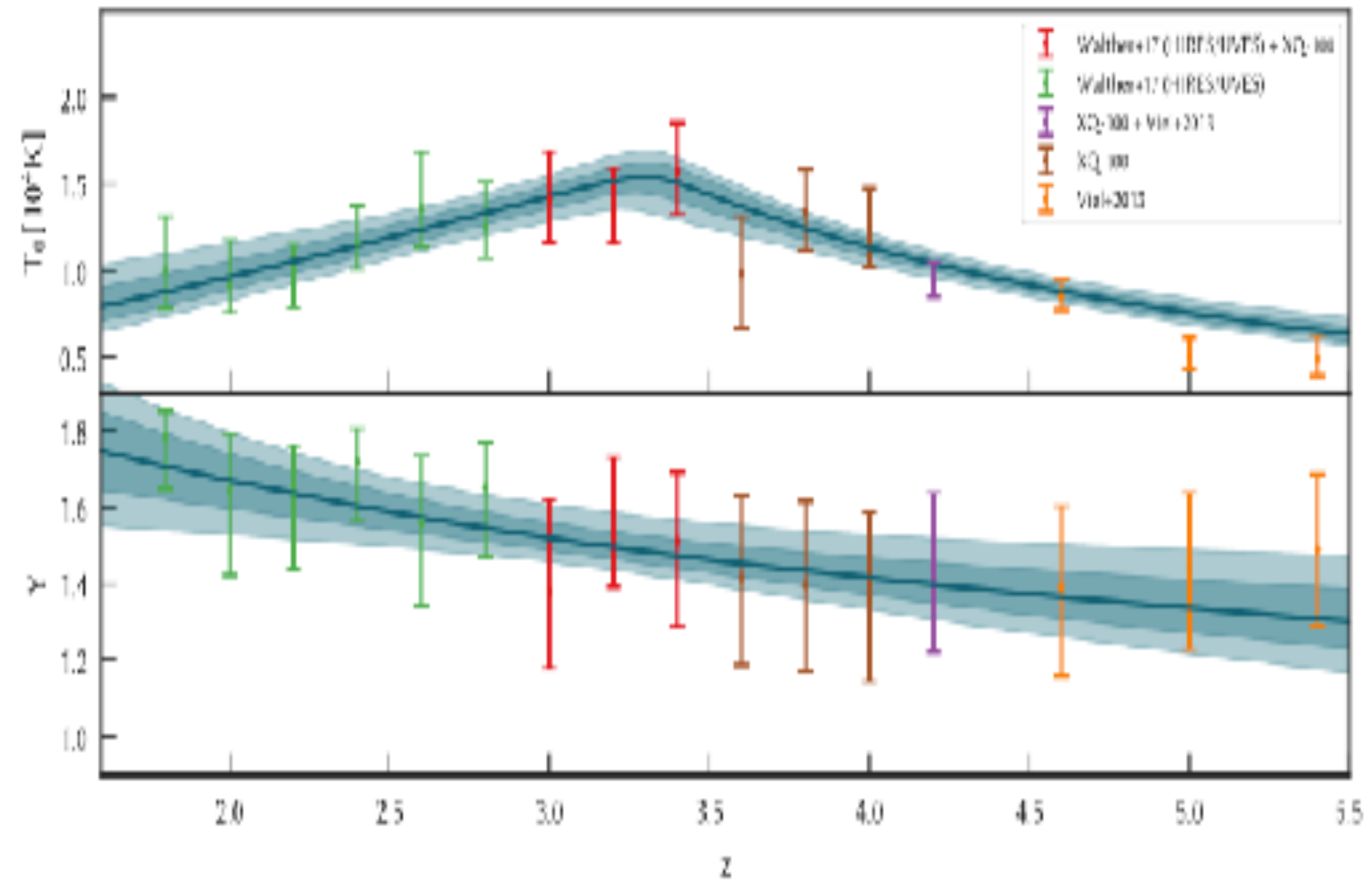
Overall good agreement with simplest CDM scenario

IGM effects

Bolton+ MNRAS 2017



Walther+ 2017



Cutoff @ high k: thermal broadening + Jeans smoothing

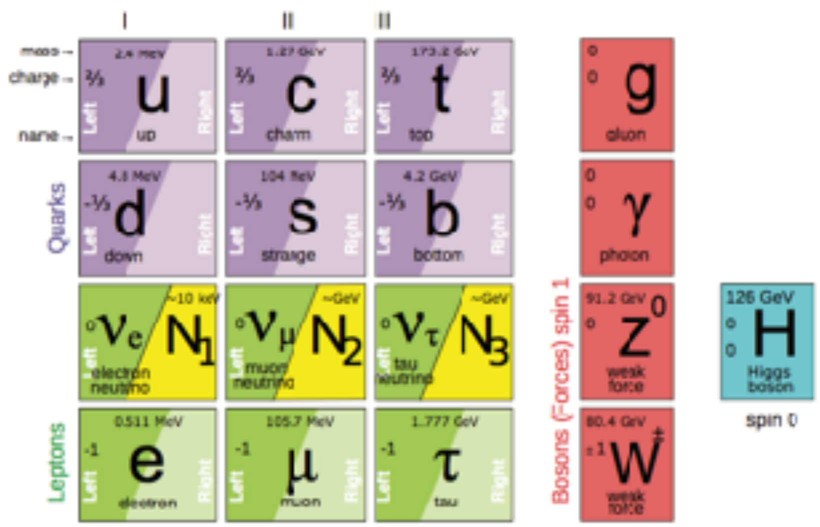
Description depends on thermal model for IGM [T_0, ɣ]

Other possible IGM effects not included in simulation grids:

- AGN / SN feedback
- Reionization (@ high z)
- Spatial fluctuations of the UV background

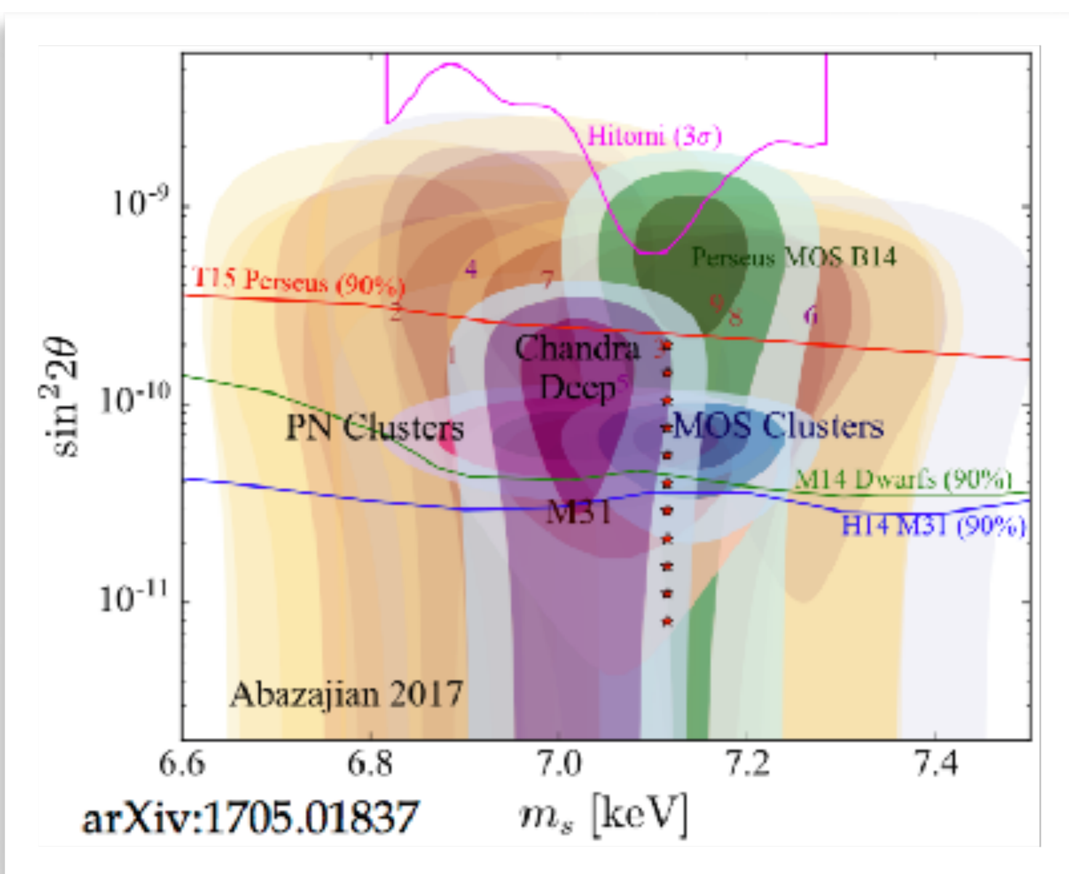
=> *Impact estimated with dedicated simulations*

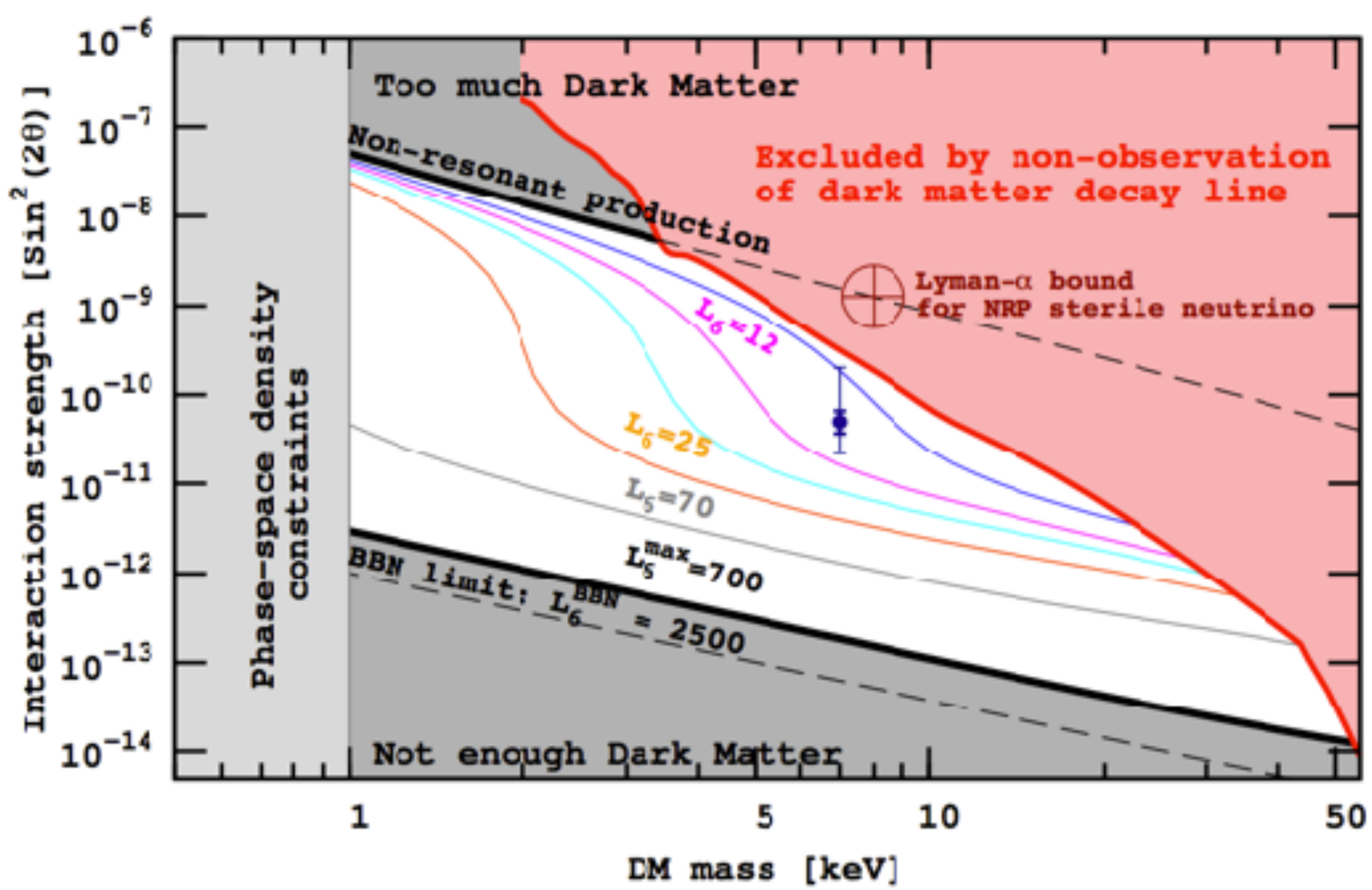
keV sterile neutrinos



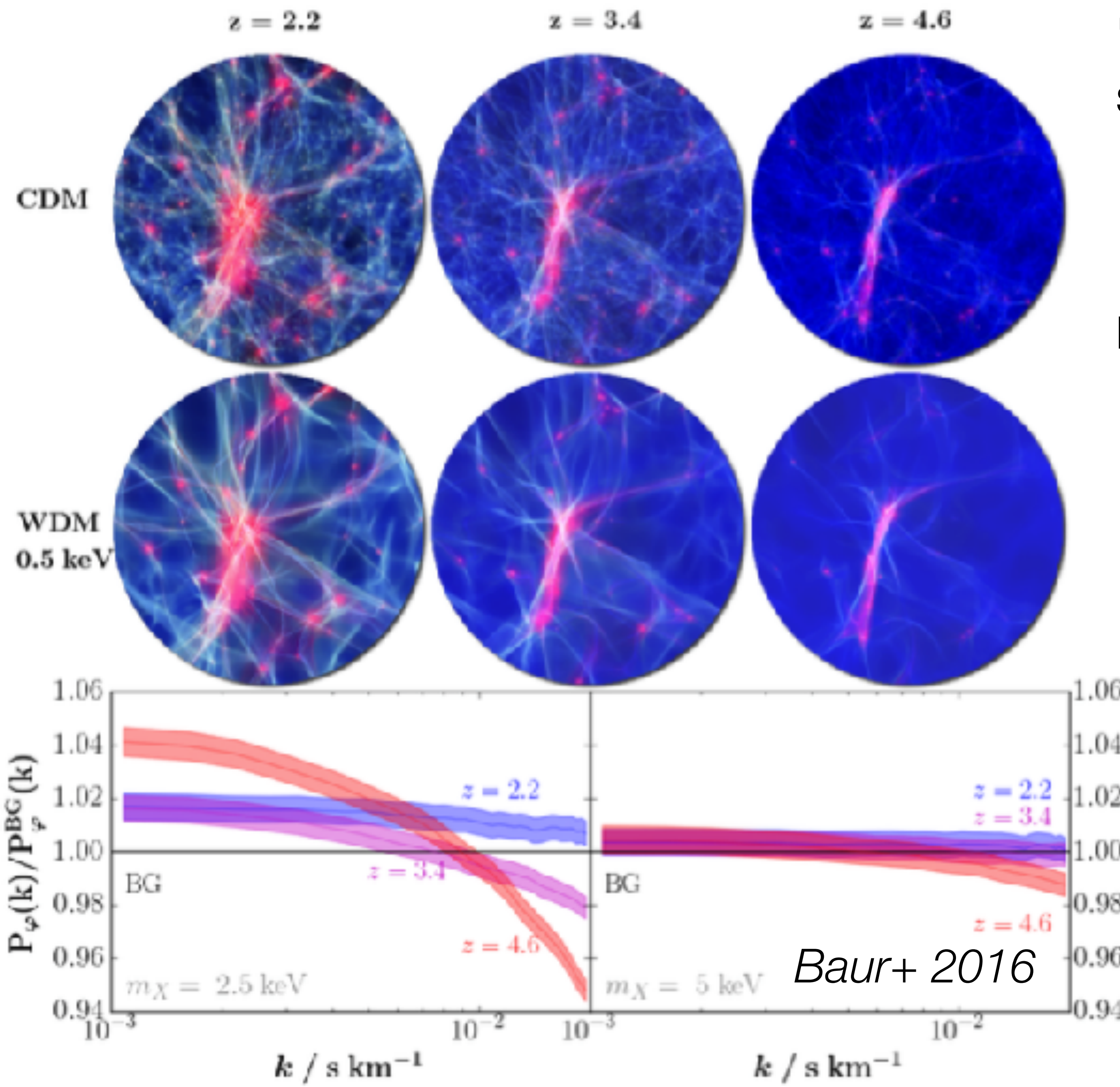
νMSM (and variants) [Shaposhnikov+ 2005]
If $M(N_1)$ ~ keV : possible DM window

Production by mixing with active ν
X-ray line $N_1 \to \nu\gamma$





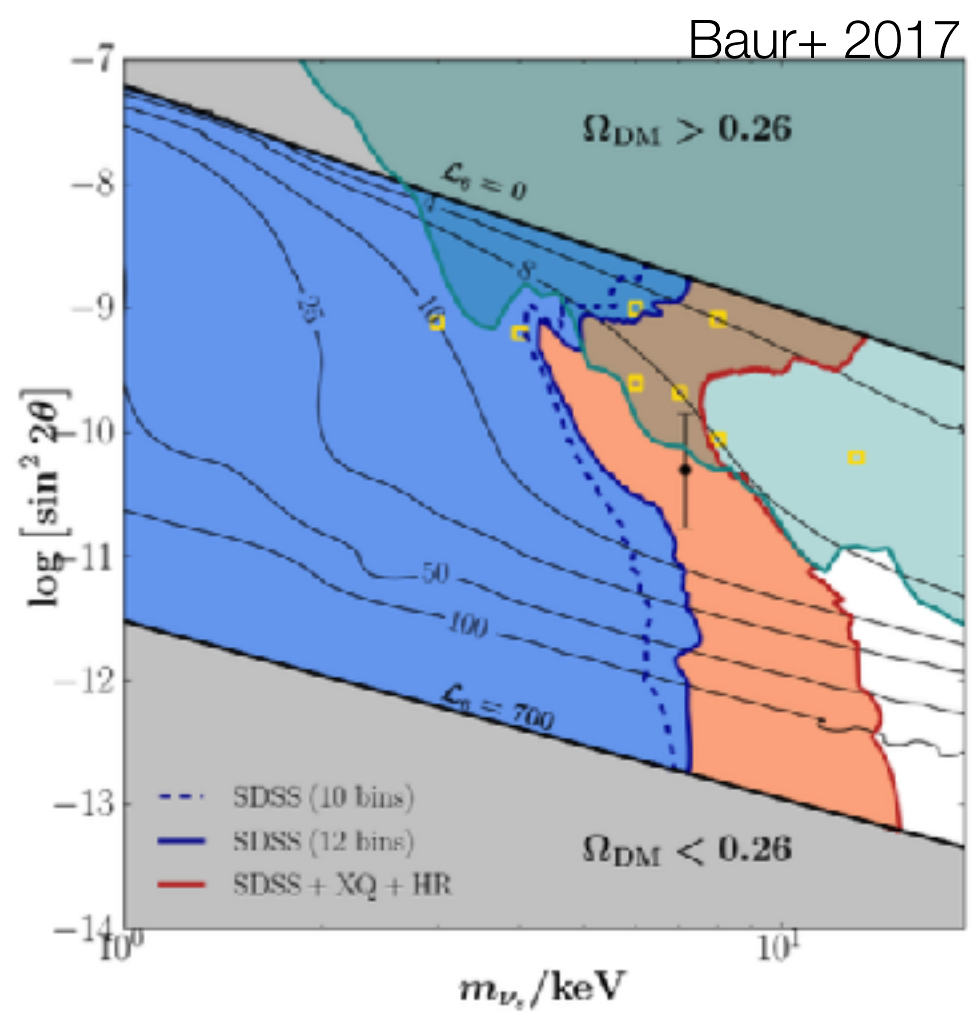
Lyman-alpha constraints on keV sterile neutrinos



"Warm" dark matter: velocity distribution smoothes structures (free streaming)

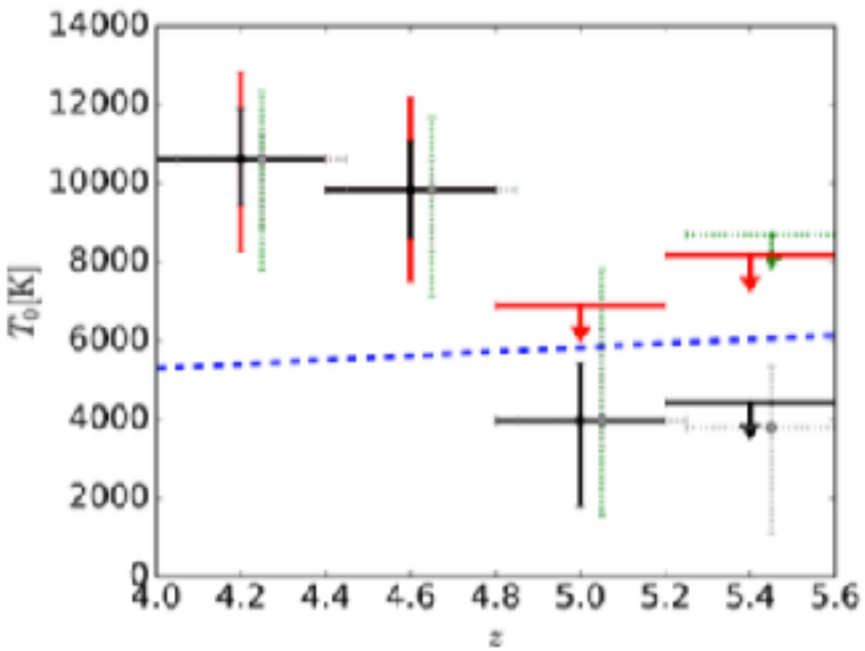
→ Cut-off in linear P(k)

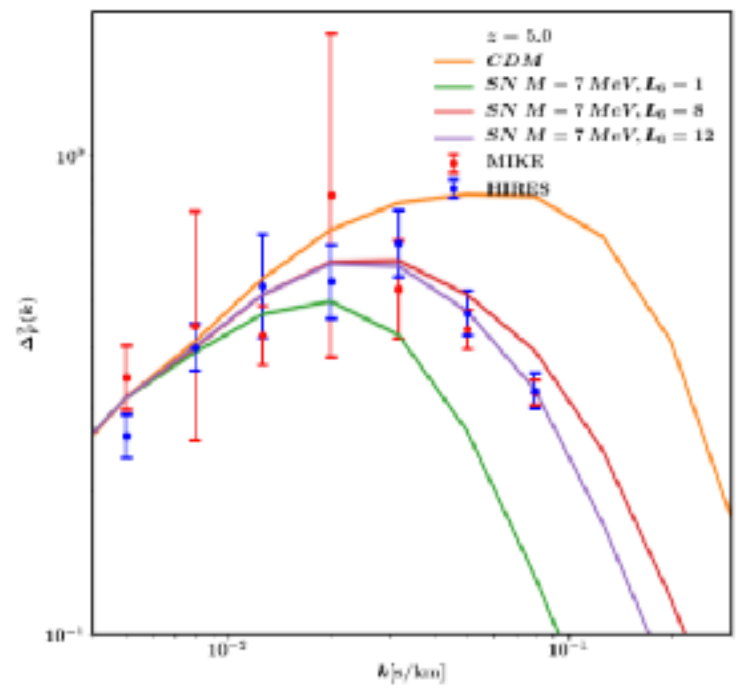
Impacts Lyman-alpha P1d @ high z, high k



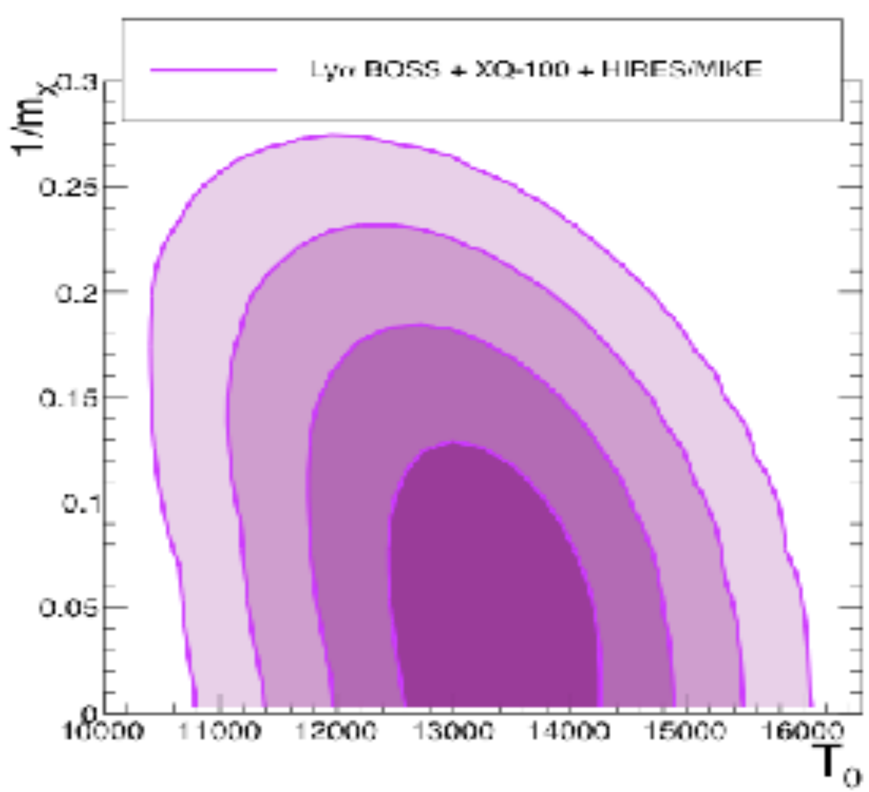
7 keV scenario (marginally) disfavored by Lyman-alpha

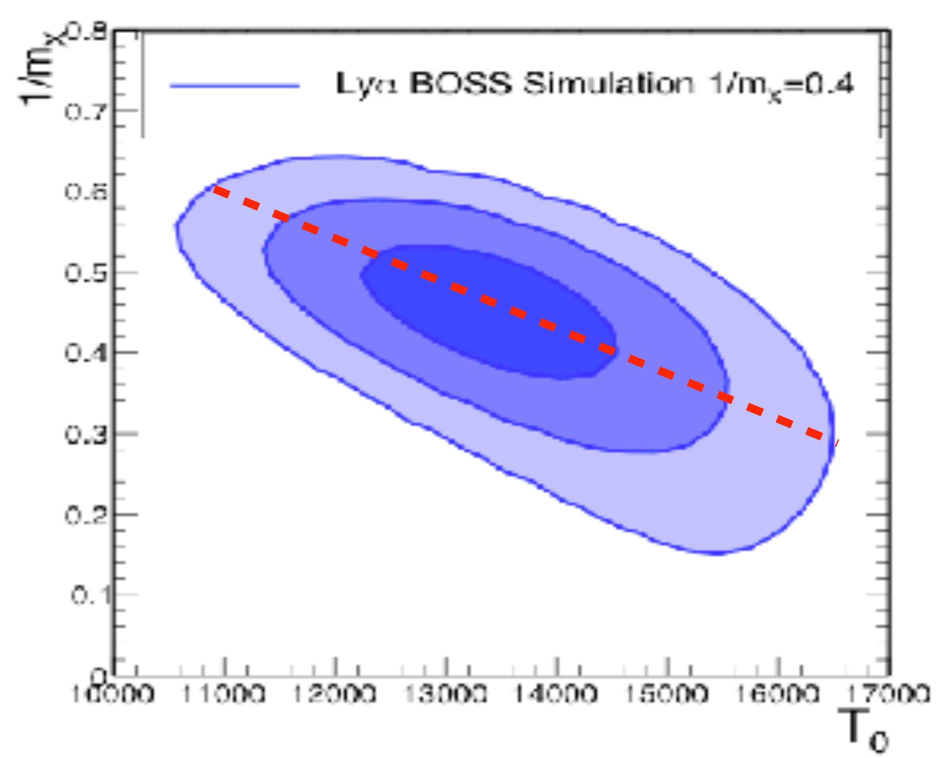
Not fully settled yet: impact of IGM thermal modelling





Garzilli+ 2015
Specific toy model for IGM temperature may still fit sterile neutrino scenario

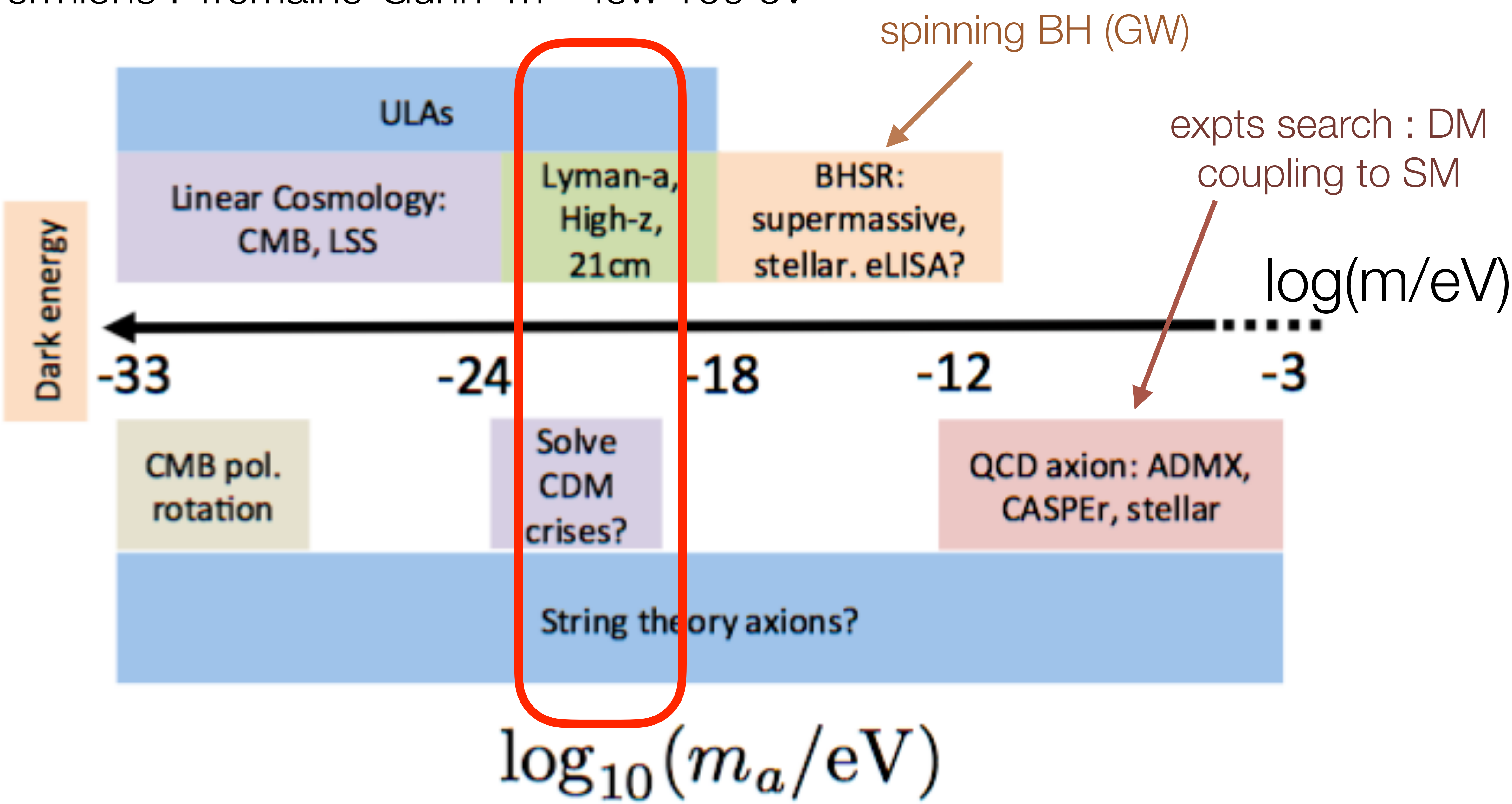




Yèche+ 2017

Probes of very light DM bosons

Fermions : Tremaine-Gunn m ≳ few 100 eV



D. Marsh, Phys. Rep. 2016

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

$$\mathcal{L} \sim \sqrt{g}\left[\frac{1}{2}F^2 g^{\mu\nu}\partial_\mu a\,\partial_\nu a - \mu^4(1-\cos a)\right]$$

effective potential from non-perturbative effects
mass $m=\mu^2/F$

H > m_a : DE regime

H < m_a : DM regime

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

Hui+ 2017

Structure formation in FDM

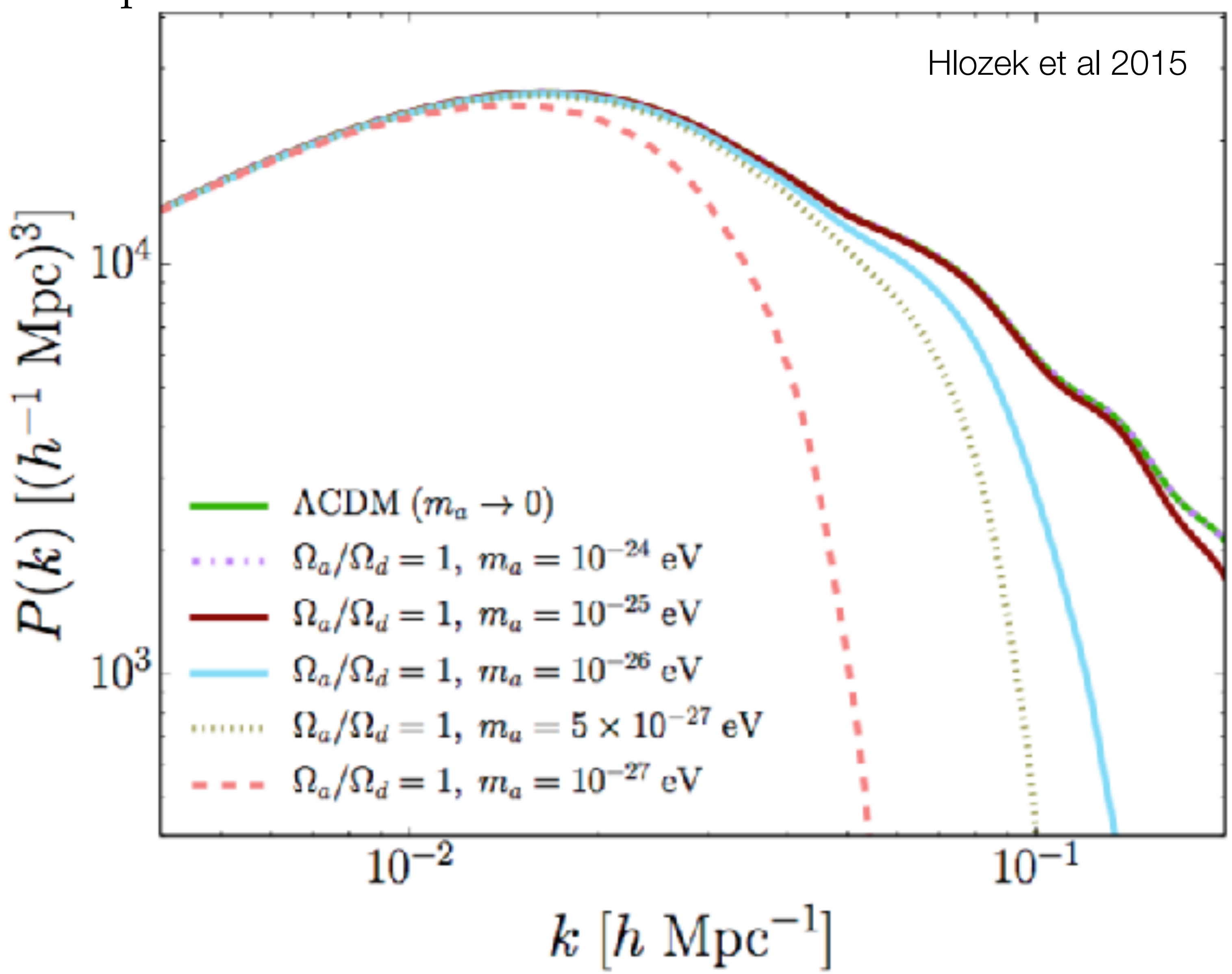
Linear perturbations : FDM ~ fluid with effective speed of sound $$c_s^2 = \frac{k^2/4m_a^2a^2}{1+k^2/4m_a^2a^2}$$

Related "Jeans" scale :

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

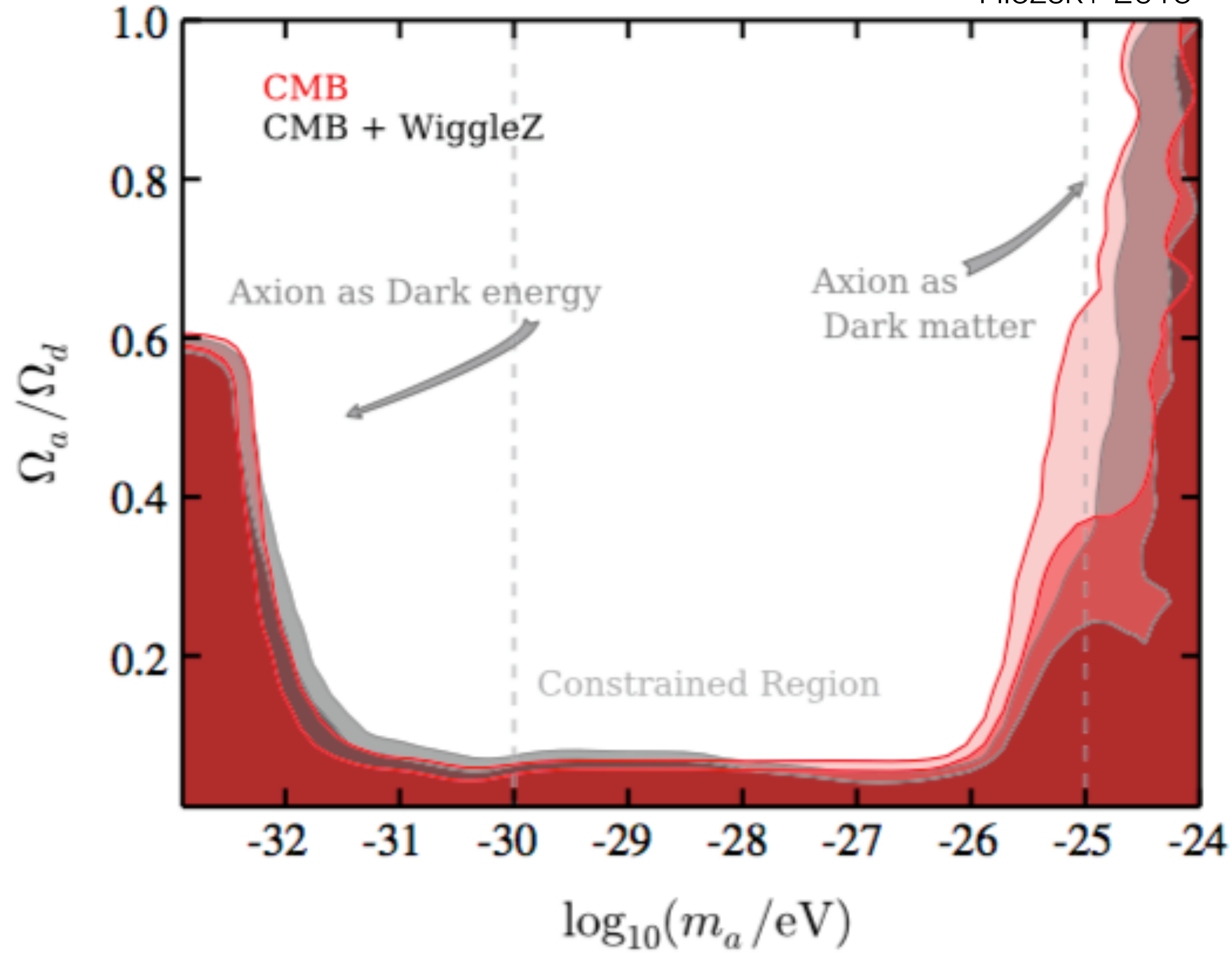
Cut-off in linear matter power spectrum

for scales smaller than Jeans scale at the time of equality



Constraints on FDM : linear perturbations

Hlozek+ 2015



- Linear cosmology excludes $m_a \sim 10^{-24}$ eV

- Larger masses ~ 10^{-22} eV probed by eg. galaxy luminosity function, reionization, strong gravitational lensing, **Lyman-α forest**

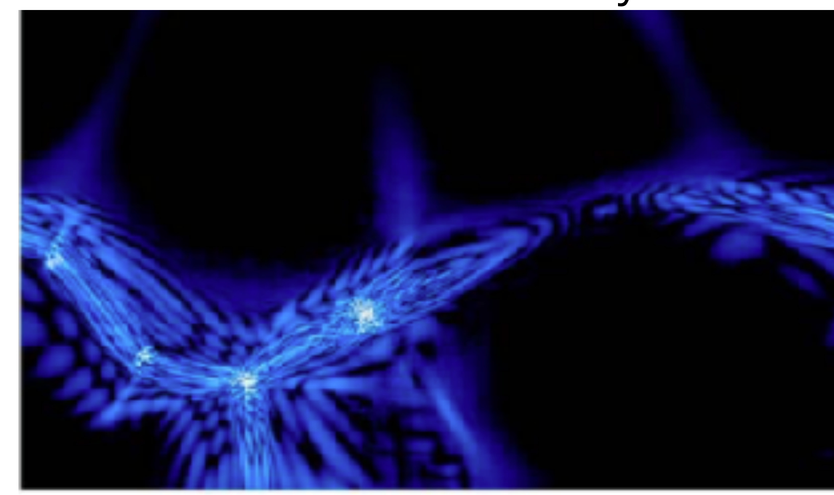
FDM phenomenology: halos

Non-linear, non-relativistic : Schrödinger-Poisson system

$$\left[i\frac{\partial}{\partial\tau}+\frac{\nabla^2}{2}-aV\right]\psi=0$$

$$\nabla^2 V=|\psi|^2-1,$$

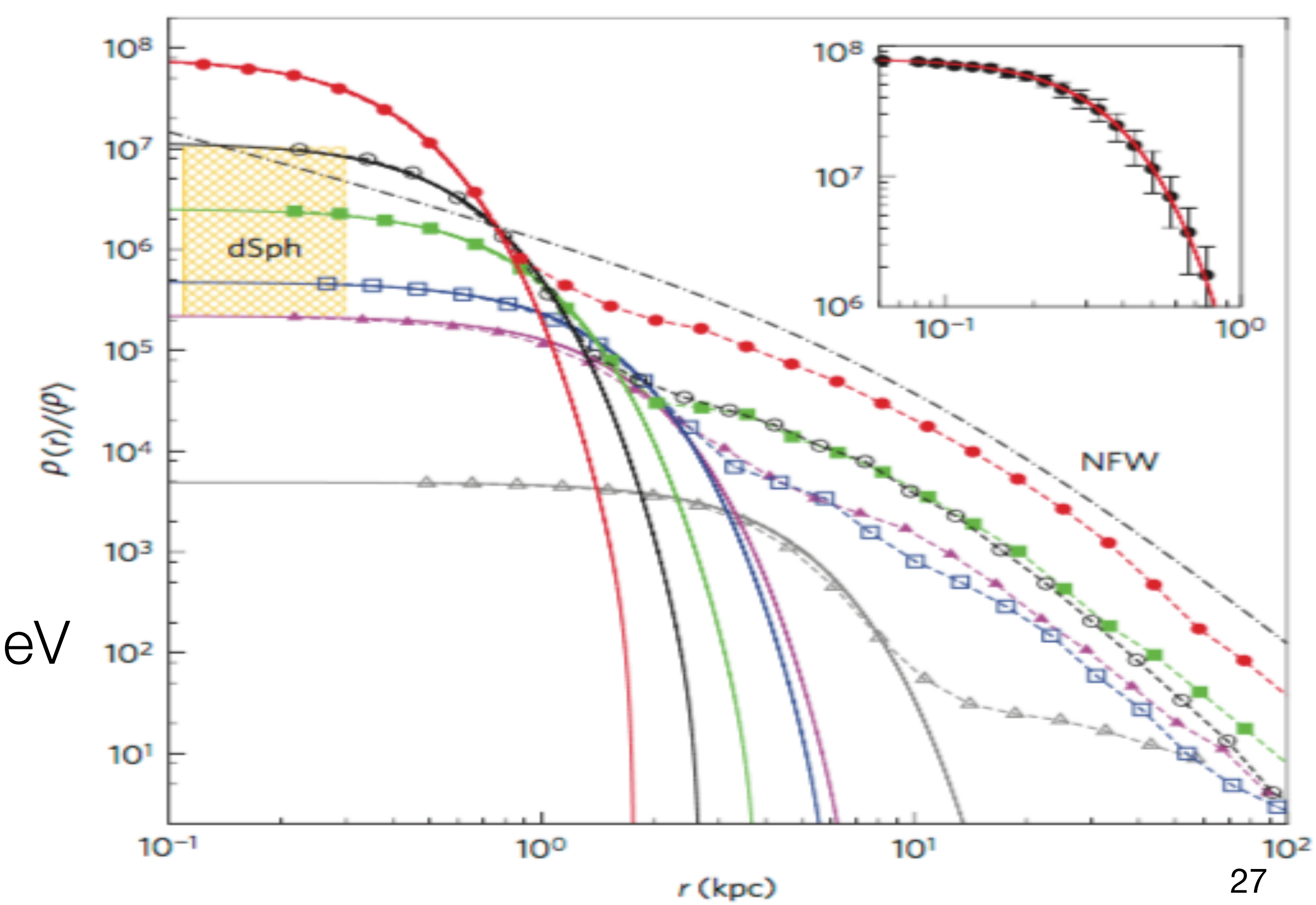
Schive et al. Nature Phys. 2014



Dedicated simulations

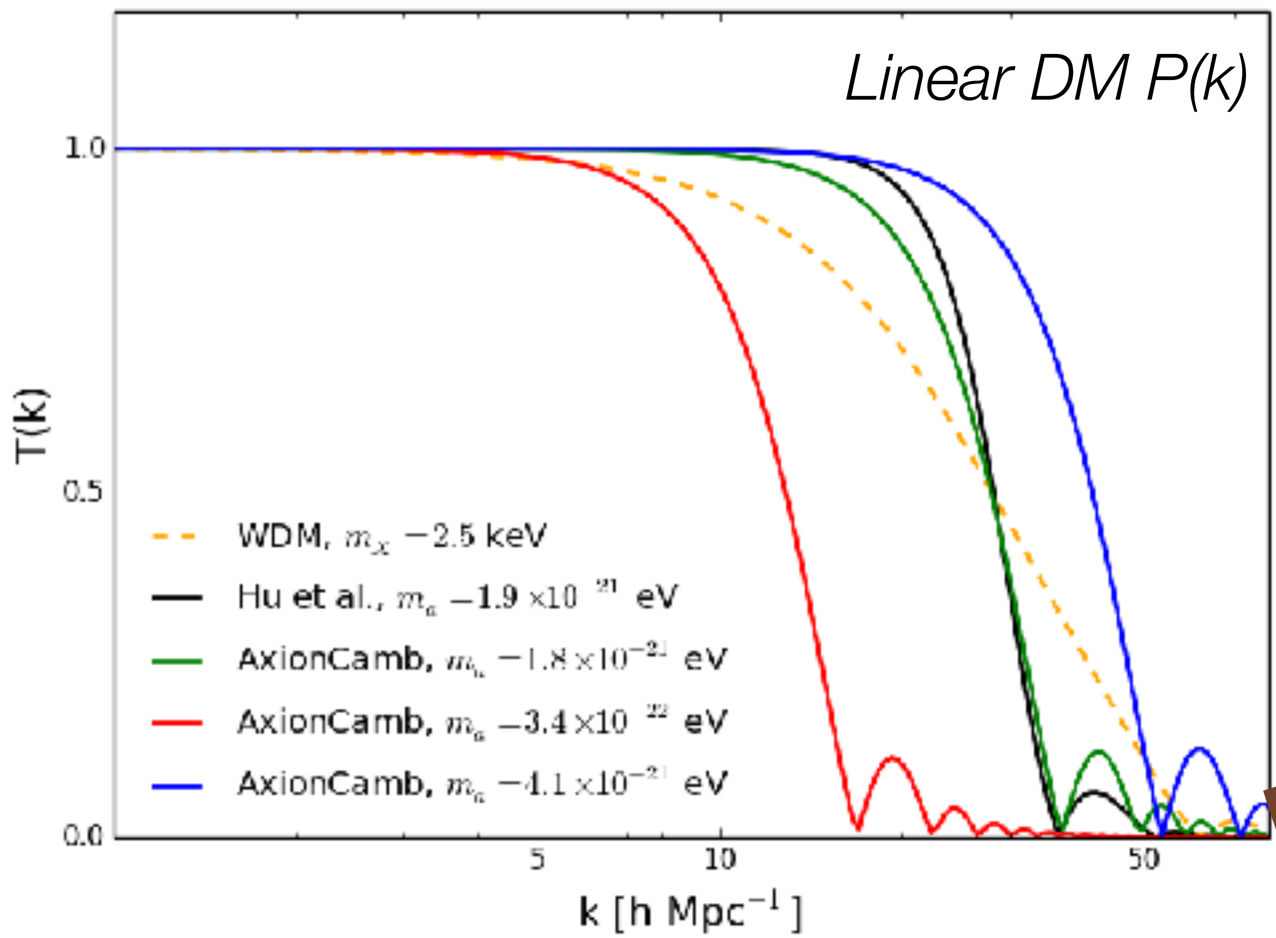
Key prediction: **solitonic core**

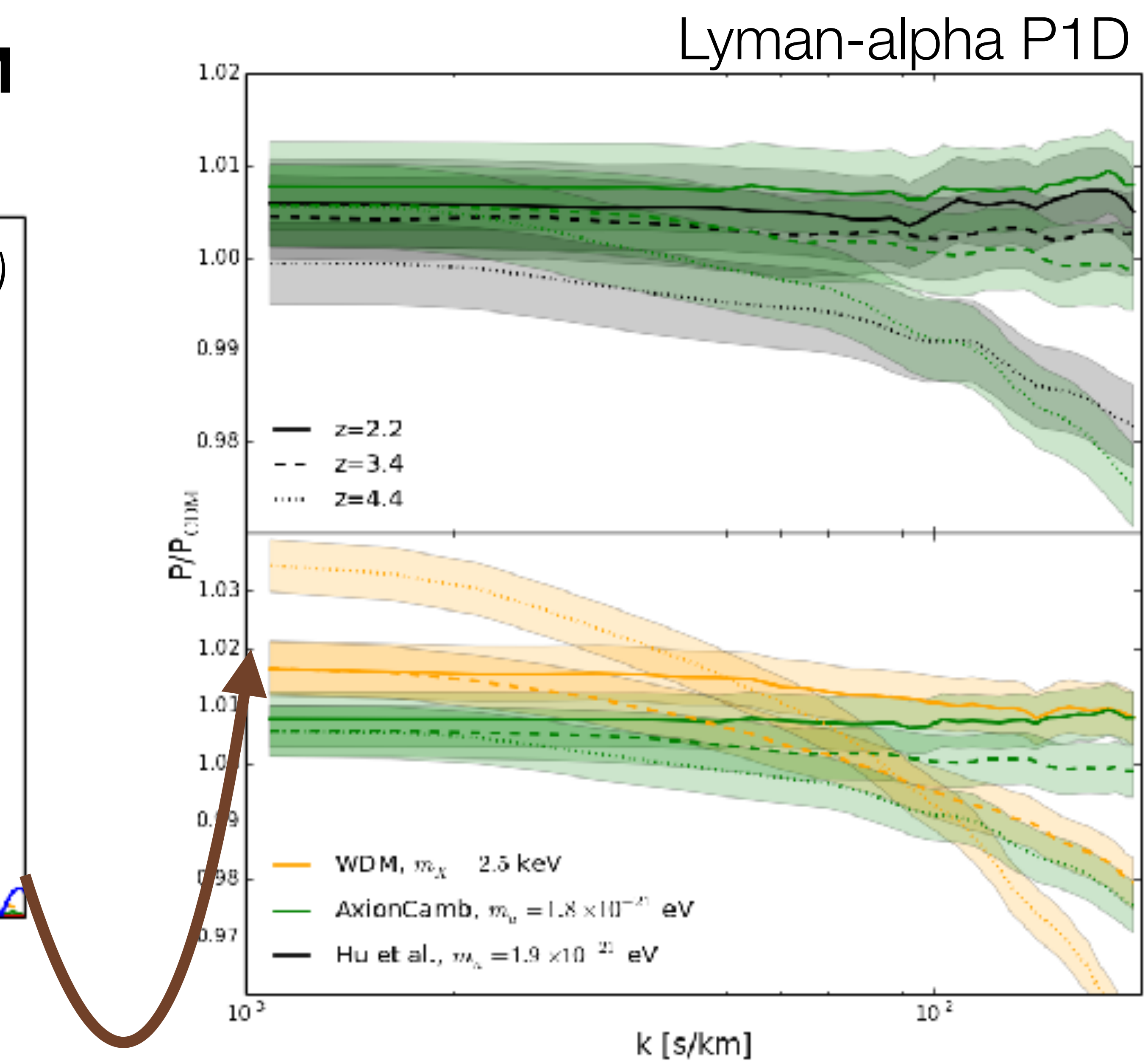
May fit dwarf kinematics with m_a~10^{-22} eV



Lyman-alpha constraint on FDM

EA+ 2017





Combine grid of CDM simulations + few simulations with FDM initial conditions

Fair to use WDM - FDM mass scaling :

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

$m_a > 2.0 \times 10^{-21}$ - 2.9×10^{-21} eV

Also Irsic+ 2017 **$m_a > 2.0\mathrm{x}10^{-21}$ - $3.7\mathrm{x}10^{-21}$ eV**

Rogers+ 2020 **$m_a > 2\mathrm{x}10^{-20}$**

Quantum pressure in cosmological simulations

Schrödinger ⇒

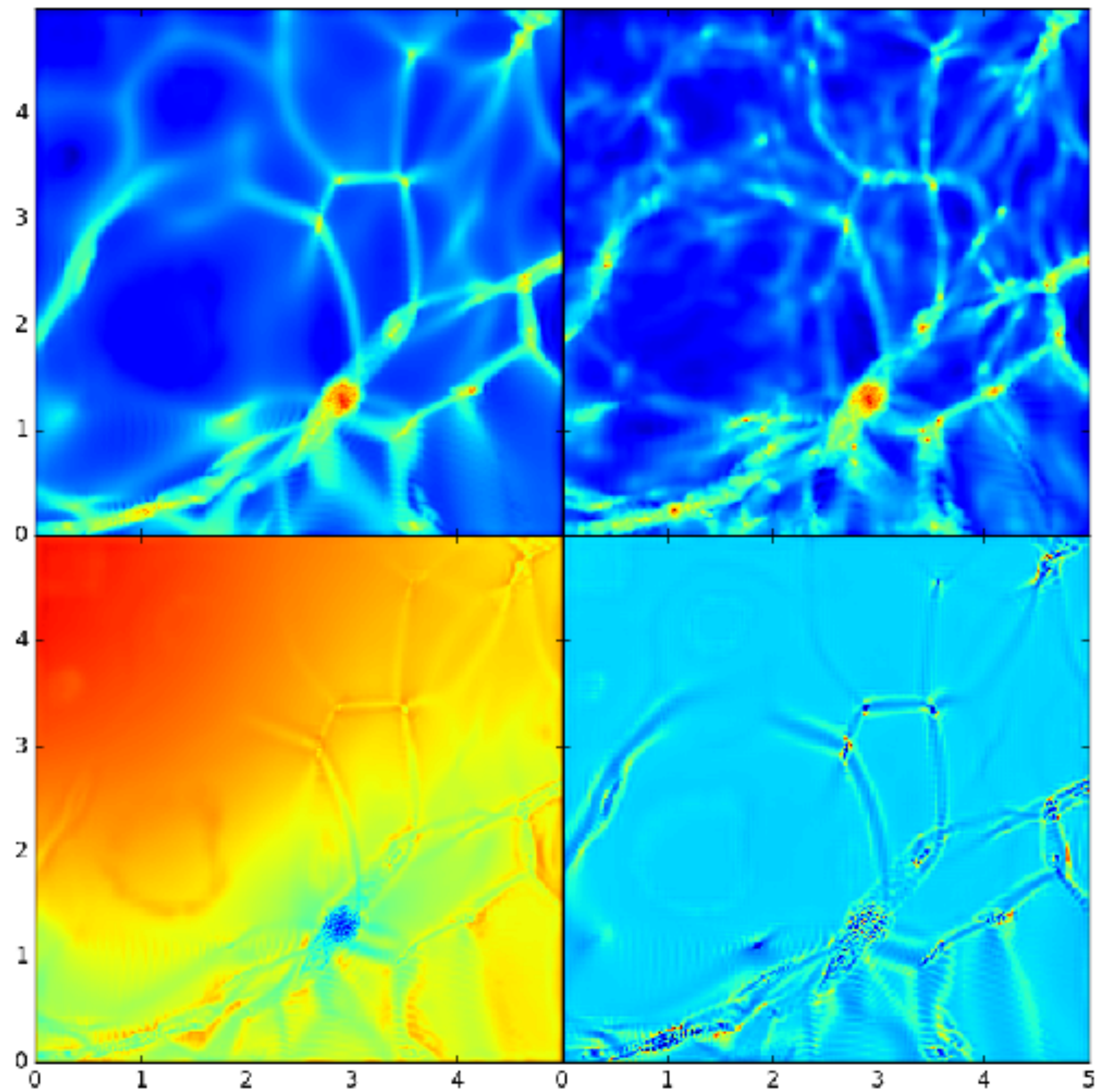
Madelung equation

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

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

Density (FDM initial cond.)

Density (CDM initial cond.)



Gravitational potential

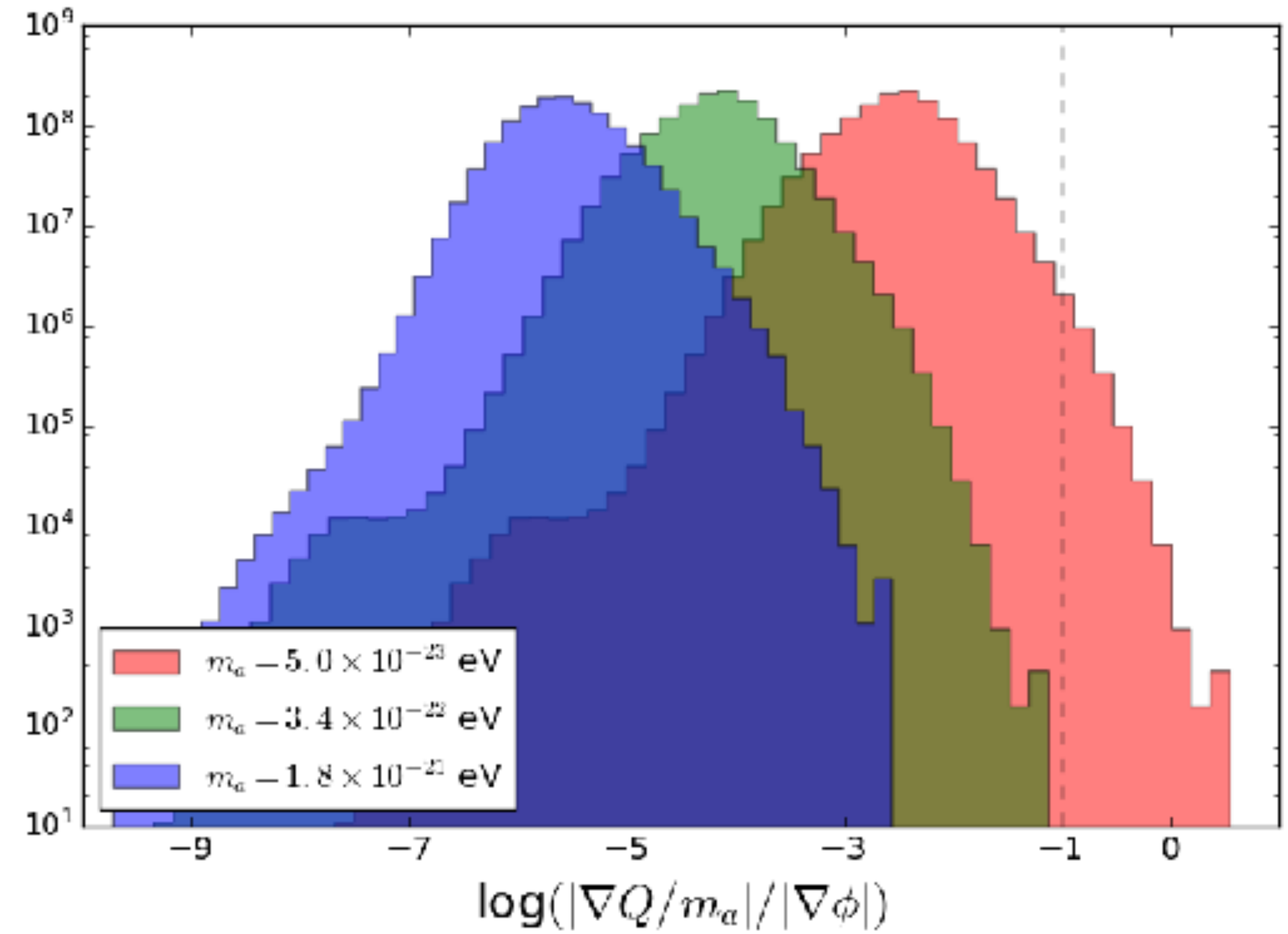
Quantum pressure

Quantum pressure in cosmological simulations

Schrödinger ⇒

Madelung equation

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

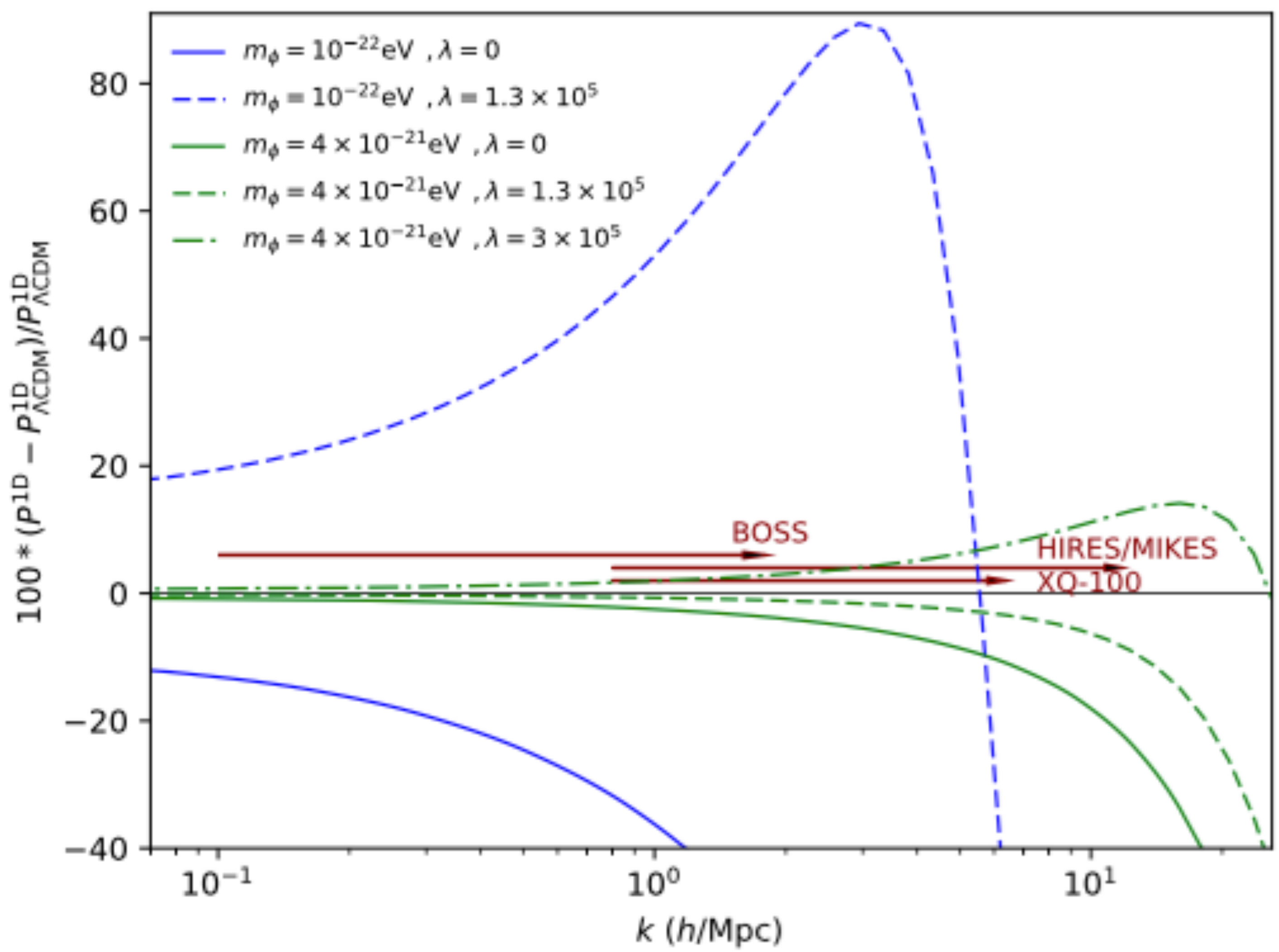


Use standard N-body ⟺ neglect ∇Q wrt gravitation force ∇ϕ

→ "Usual" simulations expected to be ok for Lyman-alpha at least for $m_a > 10^{-22}$ eV

Fuzzy Dark Matter with self-interactions

Linares Cedeño et al. PRD 2017



Rich landscape of models

Self-interactions may completely change the phenomenology

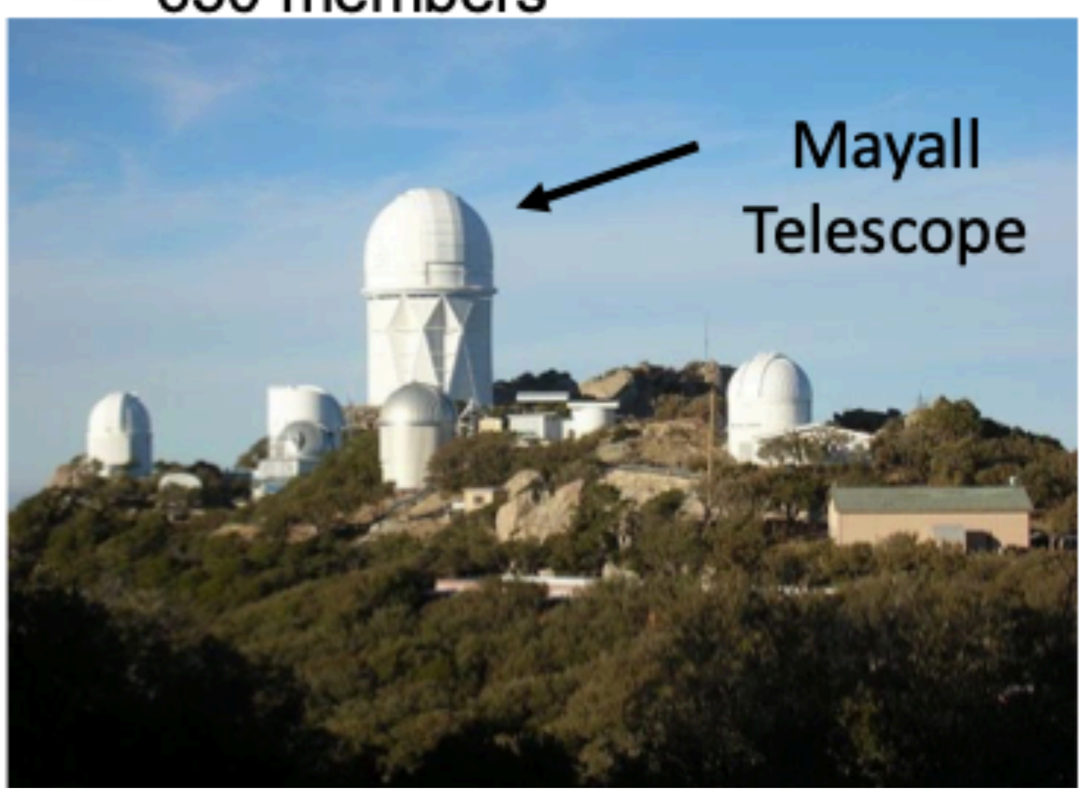
"Bump" in P(k):

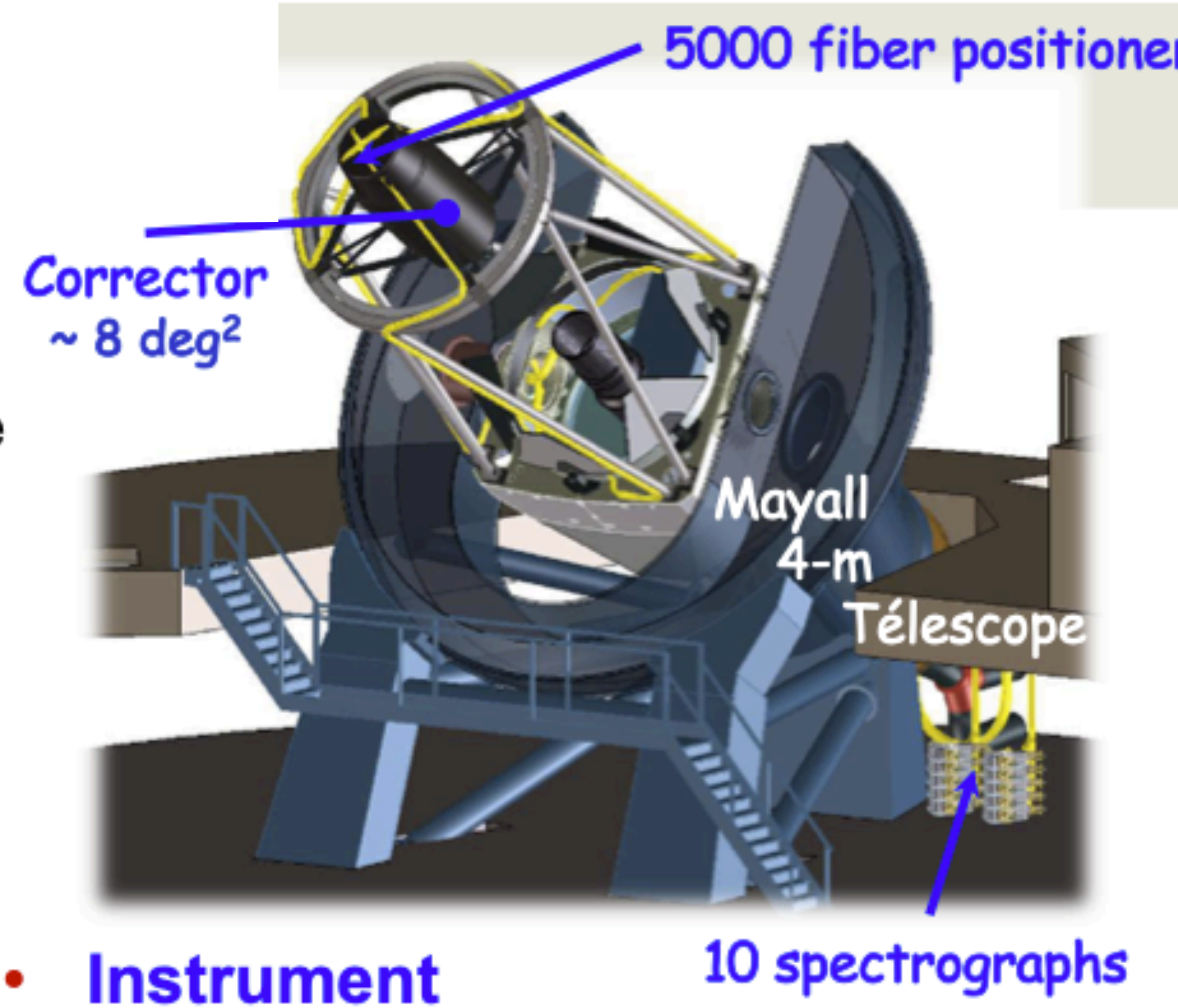
existing Lya bounds not valid

feature similar to that of ~ 100 $M_\odot$ PBH

The ~~future~~ **present : DESI survey**

- **Scientific project**
  - 14000 deg^2 survey for 0<z<3.7
  - Main scientific goals : Large Scale Structures (RSD and BAO)
  - International collaboration
  - 74 institutions (46 non-US)
  - 650 members



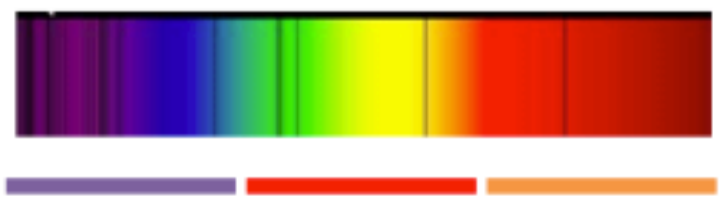


- **Instrument**
  - 4-m telescope at Kitt Peak (Arizona)
  - Wide FoV (~ 8 deg^2)
  - Robotic positioner with 5000 fibers
  - 10 spectrographs x 3 bands (blue, visible, red-NIR) →360-1020 nm

DESI main survey started Spring 2021

Ten 3-channel spectrographs

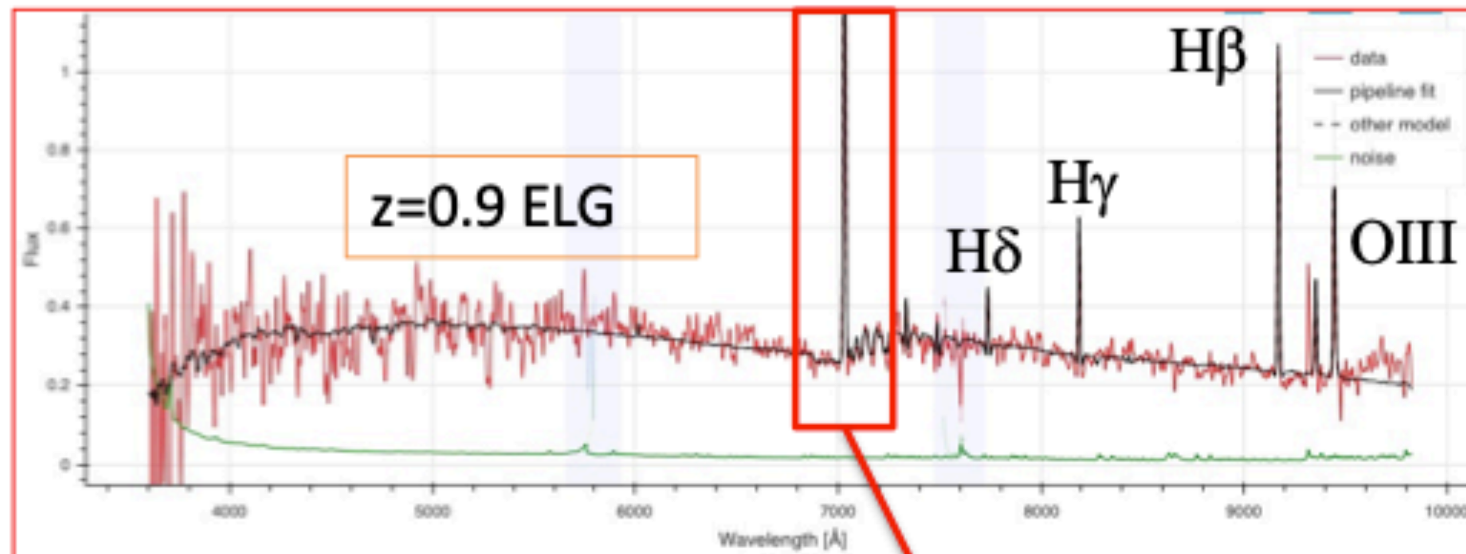
λ = 360 nm to 980 nm



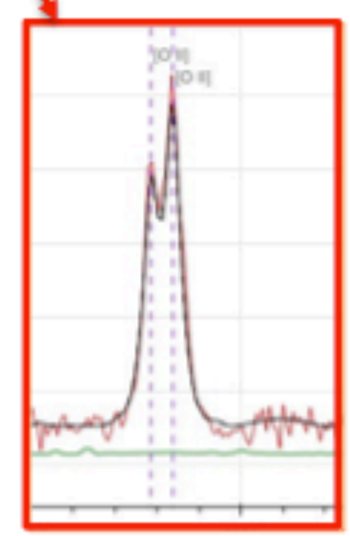
$$z = \frac{\lambda - \lambda_0}{\lambda_0}$$

[OII] 373 nm
up to z = 1.6

Emission line galaxies

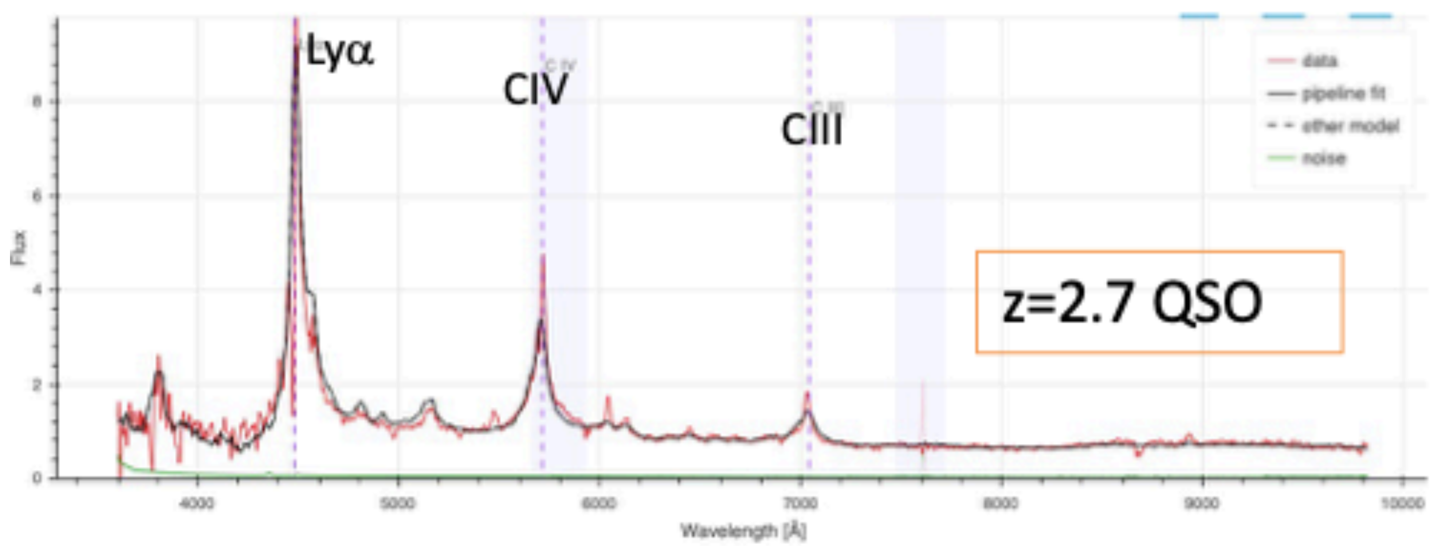


[OII] doublet



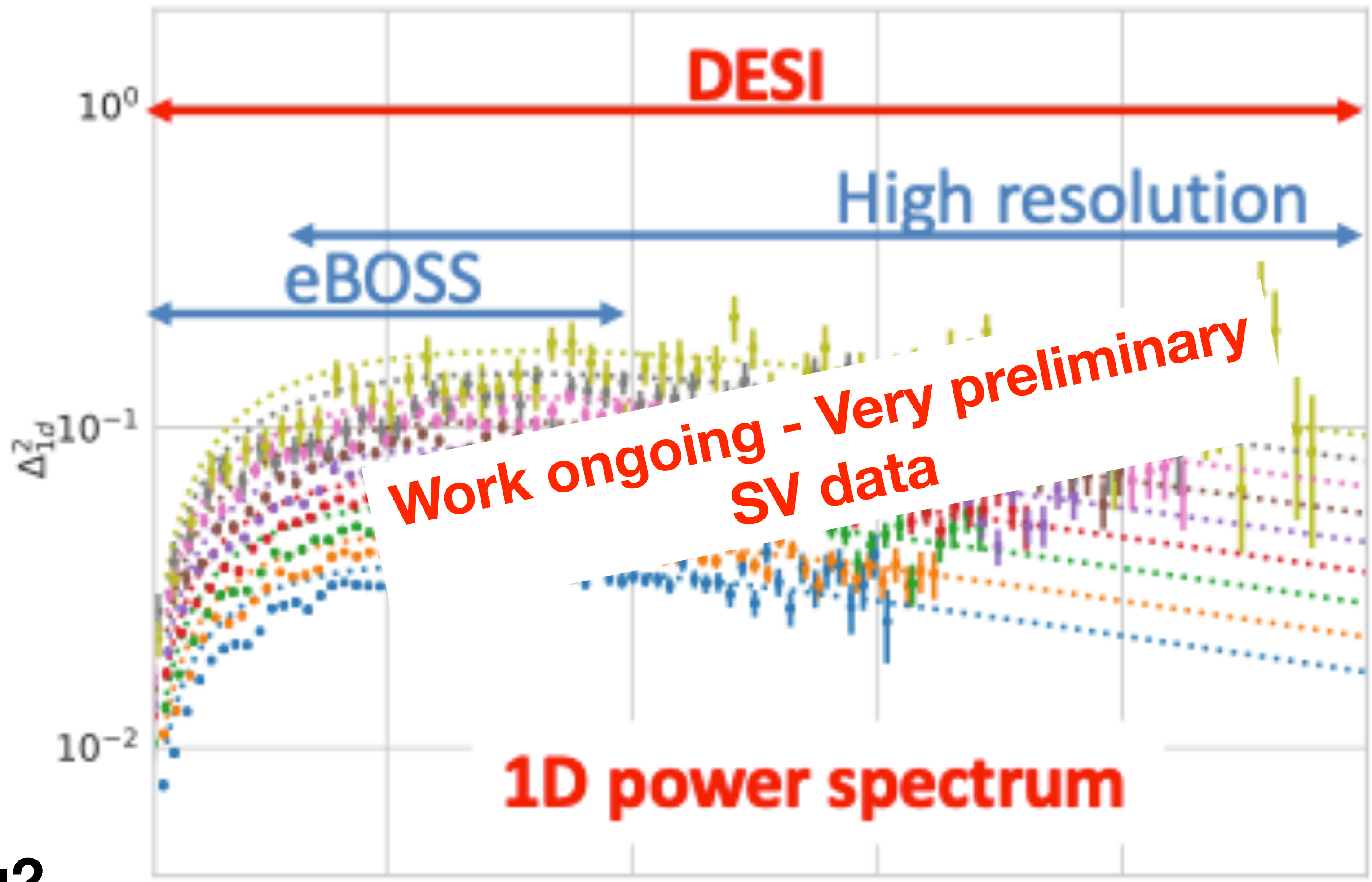
Quasars

Ly-α 121.6 nm
down to z = 2.0



DESI: expected impact for small-scale Lya / DM models

- **Resolution R~4000**
bridge the gap in "k" between SDSS and high-resolution observations



- **60 forest / deg2**
dense set of lines of sight => measure P3D
=> break degeneracies in IGM thermal model

Summary

Fuzzy Dark Matter

a possible solution to the "small scale CDM issues"

remarkable phenomenology interesting in itself (solitons, etc.)

Lya forest a major tool for observational cosmology:

- As of now a unique way to observe LSS (BAO, etc.) at z~ 2-5
- Unique probe of "small" scale primordial matter fluctuation
- **Fits CDM + simple IGM model well => constraints several DM models**

    m_X > few keV

    m_a > ~ 10^{-21} eV

    also: PBH, self-interacting DM (MeV - GeV)

Exact bounds should be taken with a grain of salt (many uncertainties...) !!

Future:

new-generation simulations and inference tools

DESI + high-resolution data

other probes: strong lensing, 21cm, high-redshift galaxy counts (JWST)