FUNDAMENTAL PHYSICS WITH LARGE/MEDIUM/SMALL SCALE STRUCTURES

LECTURE 2

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2022 Winter School
Tenerife (Spain)

Euclid Flagship Simulation

SISSA

PLAN

INTRO

FUNDAMENTAL PHYSICAL TESTS "BEFORE" GALAXIES ARE FORMED IN THE POST-REIONIZATION UNIVERSE

INTENSITY MAPPING
INTERGALACTIC MEDIUM (IGM)

GALAXY CLUSTERING: DYNAMICAL AND GEOMETRICAL PROBE

GALAXY CLUSTERS

WEAK LENSING

CONNECTIONS

FABIO FINELLI: CMB x LSS

KFIR BLUM: SMALLER SCALES PROPERTIES OF GALAXIES

LUCA AMENDOLA: MODIFICATION OF GRAVITY/DARK ENERGY

OLGA MENA: NEUTRINOS

TRACY SLATYER: DARK MATTER

IGM

du Mas des Bourboux, H., et al. (2020)

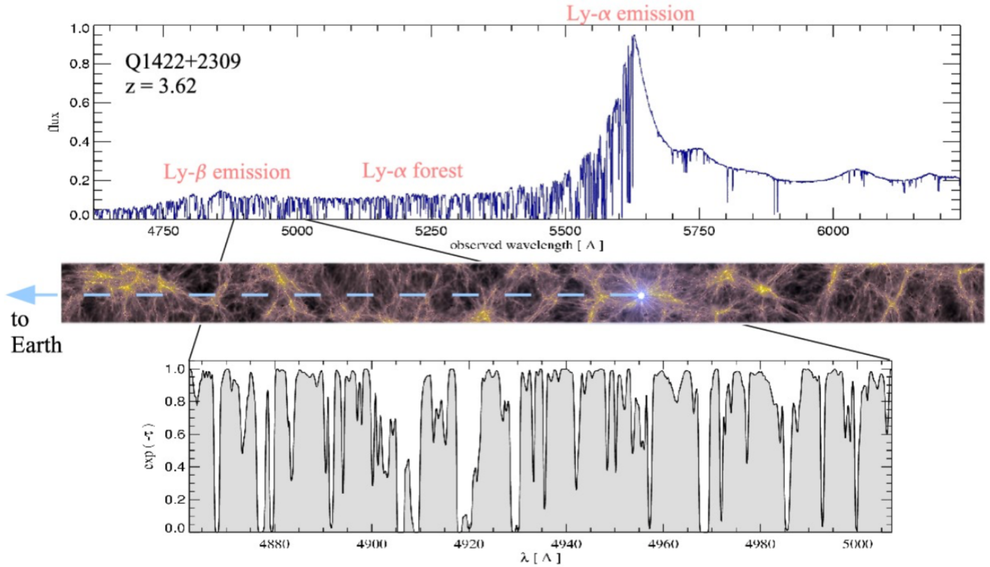
Font-Ribera, A., et al. (2014a)

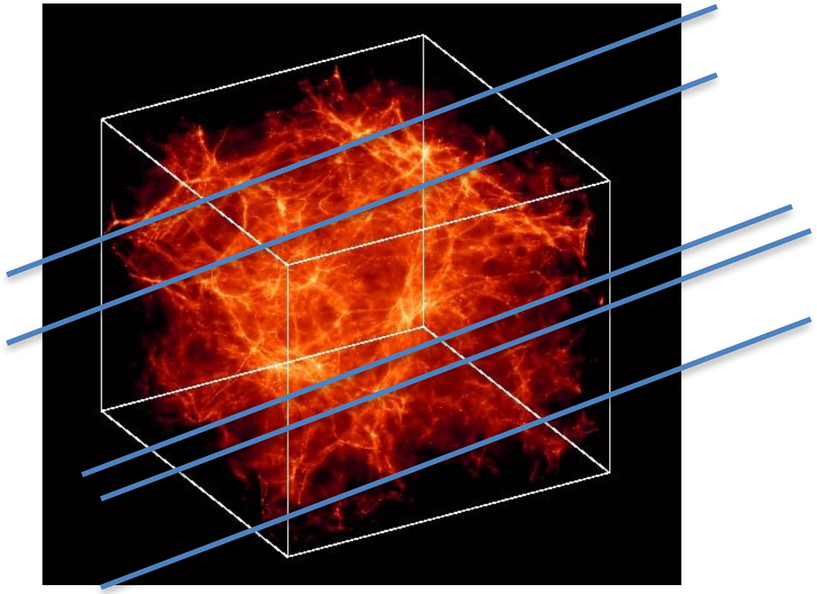
Chabanier, S., et al. (2019)
Viel et al. 2005

Irsic+17

DESI Collaboration (2016b), arXiv:1611.00037

The Lyman-alpha forest





- **Intergalactic medium:** filaments at low density (outside galaxies) - distances spanned 0.1-100 Mpc/h
- Lyman-alpha forest its the main manifestation of the IGM
- High redshift observable, 1D projected power (but also 3D)

Semi-analytical models for the Ly-a forest

(Bi 1993, Bi & Davidsen 1997, Hui & Gnedin 1998, Matarrese & Mohayaee 2002)

$$k_J^{-1}(z) \equiv H_0^{-1}\left[\frac{2\gamma k_B T_m(z)}{3\mu m_p \Omega_{0m}(1+z)}\right]^{1/2}$$

Jeans length

$$\delta_0^{\rm IGM}(\mathbf{k},z) = \frac{\delta_0^{\rm DM}(\mathbf{k},z)}{1+k^2/k_J^2(z)} \equiv W_{\rm IGM}(k,z) D_+(z)\delta_0^{\rm DM}(\mathbf{k})$$

Filtering of linear DM density field

$$\mathbf{v}^{\rm IGM}(\mathbf{k},z) = E_+(z)\frac{i\mathbf{k}}{k^2}W_{\rm IGM}(k,z)\delta_0^{\rm DM}(\mathbf{k})$$

Peculiar velocity

$$n_{\rm IGM}(\mathbf{x},z) = \overline{n}_{\rm IGM}(z)\exp\left[\delta_0^{\rm IGM}(\mathbf{x},z) - \frac{\langle(\delta_0^{\rm IGM})^2\rangle D_+^2(z)}{2}\right]$$

Non linear density field

$$T(\mathbf{x},z) = T_0(z)\left(1+\delta^{\rm IGM}(\mathbf{x},z)\right)^{\gamma(z)-1}$$

'Equation-of-state'

$$\alpha(z,T(z))\, n_p n_e = J(z) n_{\rm HI} \ ,$$

Neutral hydrogen ionization equilibrium equation

$$\tau(u) = \frac{\sigma_{0,\alpha}\, c}{H(z)}\int_{-\infty}^{\infty} dy\, n_{\rm HI}(y)\, \mathcal{V}\left[u - y - v_{\parallel}^{\rm IGM}(y),\, b(y)\right]$$

Optical depth

Density Velocity Temperature

Linear fields:
density, velocity

Non linear fields

+

Temperature

Spectra:
Flux=exp(-τ)

MV, Matarrese S., Mo HJ., Haehnelt M., Theuns T., 2002a, MNRAS, 329, 848

Modelling 3D flux power

Arino-i-Prats, Miralda-Escude', MV, Cen (2015) - McDonald (2003)

$$\delta_F = \frac{F}{\bar{F}(z)} - 1 \qquad \eta = -\frac{1}{aH}\frac{\partial v_p}{\partial x_p}$$

$$\beta = \frac{b_{F\eta}\, f(\Omega)}{b_{F\delta}} \qquad b_{F\delta} = \frac{\partial \delta_F}{\partial \delta} \qquad b_{F\eta} = \frac{\partial \delta_F}{\partial \eta}$$

$$\delta_F = b_{F\delta}\delta + b_{F\eta}\eta$$

3D flux power

$$P_F(k,\mu) = b_{F\delta}^2\,(1+\beta\mu^2)^2\; P_L(k)\, D(k,\mu)$$

$$D\;(k,\mu) = \exp\left\{ \left[q_1\Delta^2(k) + q_2\Delta^4(k)\right] \left[1 - \left(\frac{k}{k_v}\right)^{a_v} \mu^{b_v}\right] - \left(\frac{k}{k_p}\right)^2 \right\}$$

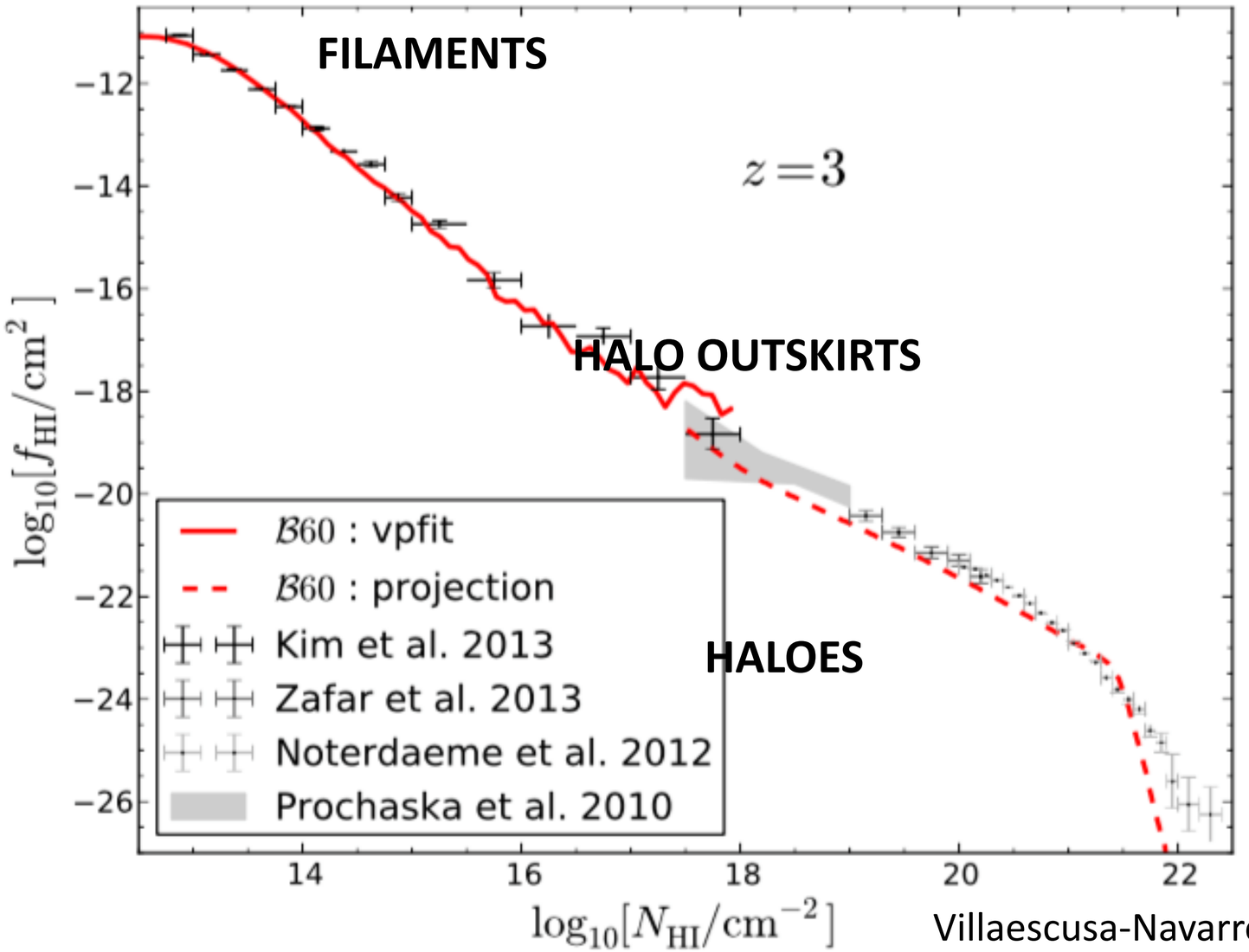
non-linear matter power — thermal broadening — pressure smoothing

1D flux power

$$P_{1\mathrm{D}}(k_\parallel, z) = \frac{1}{2\pi}\int_{k_\parallel} P_F(k, k_\parallel, z)\, k\, dk$$

Towards a consistent model

$$\delta = -1 \rightarrow \delta \sim 30 \rightarrow \delta \sim 100$$



Villaescusa-Navarro,MV+14

Some key questions

- Is there a consistent model of HI evolution from z=1100 to z=0?

  what are the observables we *cannot* fit?

- To what extent HI traces the underlying structure formation process?

  scale dependent bias? HI halo model? Shot noise?

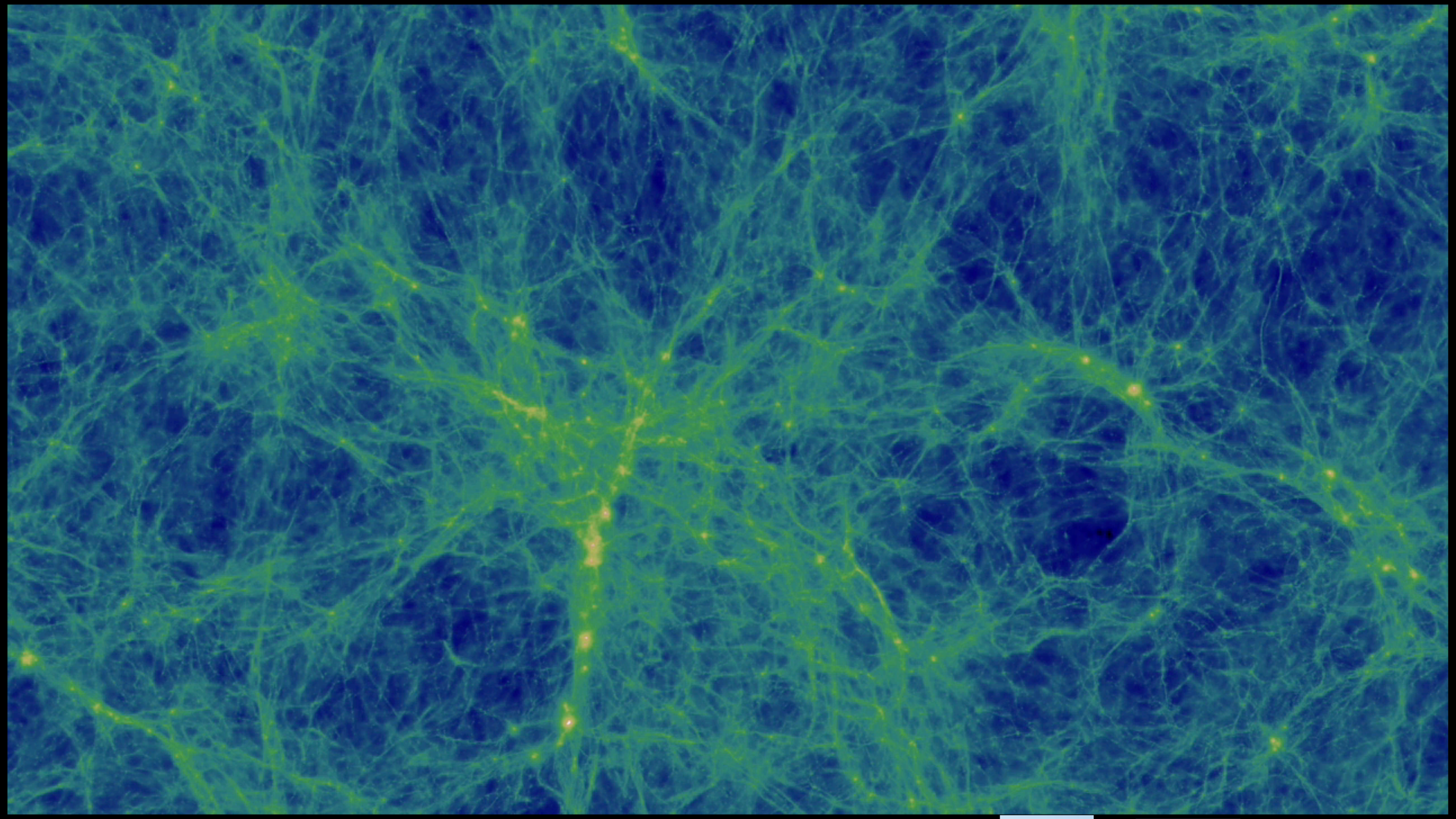
- To what extent HI evolution is influenced by galaxy formation?

- Can we constrain feedback models?

- Is there evidence of new physics?

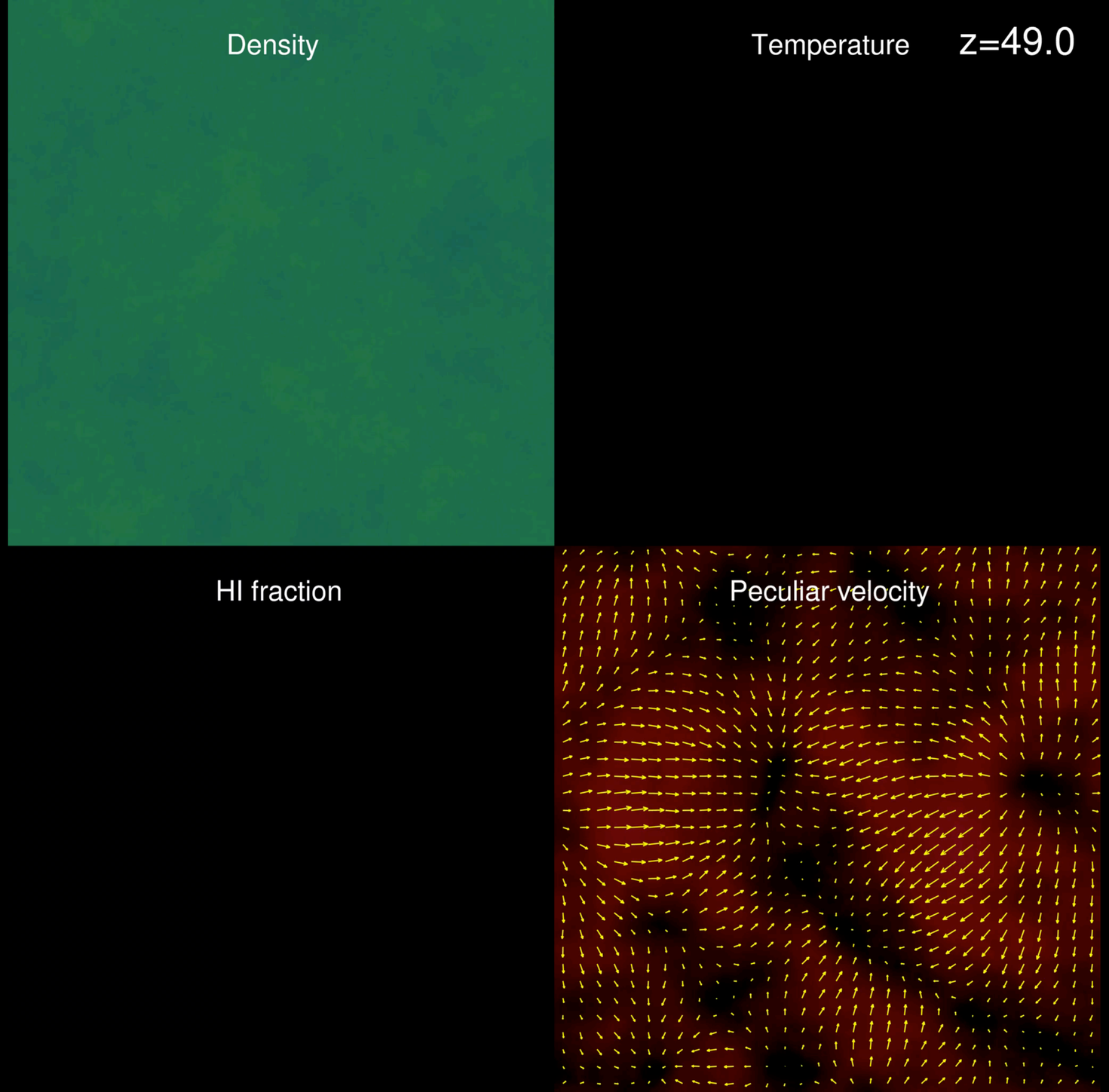
NEUTRINO MASSES, GEOMETRY OF THE UNIVERSE, DARK MATTER NATURE?

IGM SIMULATIONS



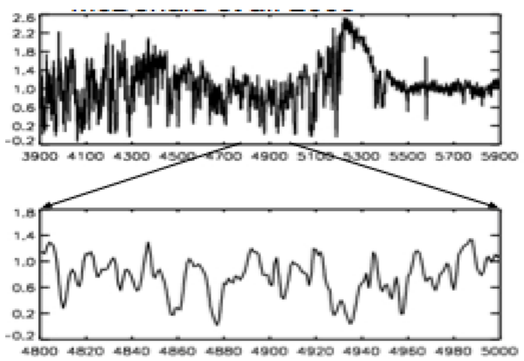
Bolton+17, Sherwood simulation suite (PRACE call: 15 CPU Mhrs)
Puchwen+19, New simulations (PRACE call: 23 CPU Mhrs)

New
PRACE runs
down to
M_gas=10^4 M_sun



COSMOLOGY WITH QSOs

BOSS/SDSS-III



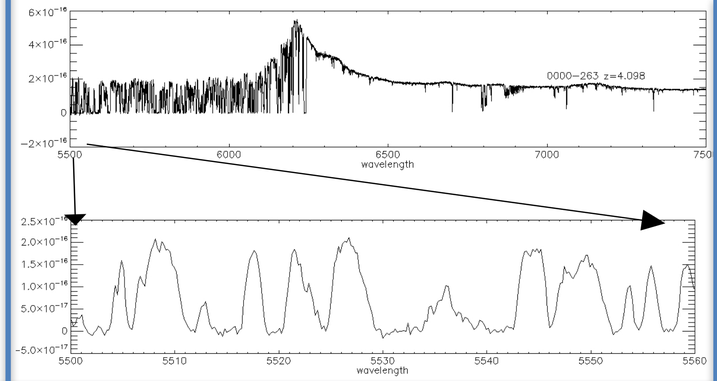
Low resolution BOSS and SDSS-III spectra S/N~2-3 - 160,000 spectra

Used to detect BAOs at z=2.3 and correlations in the transverse direction

Used to place stringent constraints on neutrino masses <0.12 eV

Busca+13, Slosar+14, Font-Ribera+14
Palanque-Delabrouille+15
Seljak+06, Baur+16, Yeche+17 etc.

XQ-100



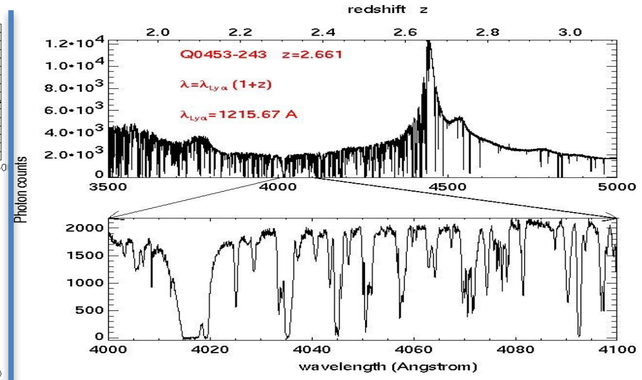
Medium resolution X-Shooter VLT spectra S/N ~ 30

100 spectra at z>3.5

Used to place stringent constraints on Warm Dark Matter in combination with high res. spectra

Irsic, MV+ 17a,17b
Lopez+16, Irsic+16

HIRES/MIKE



High resolution VLT or Keck spectra S/N ~100 - ~hundreds of spectra

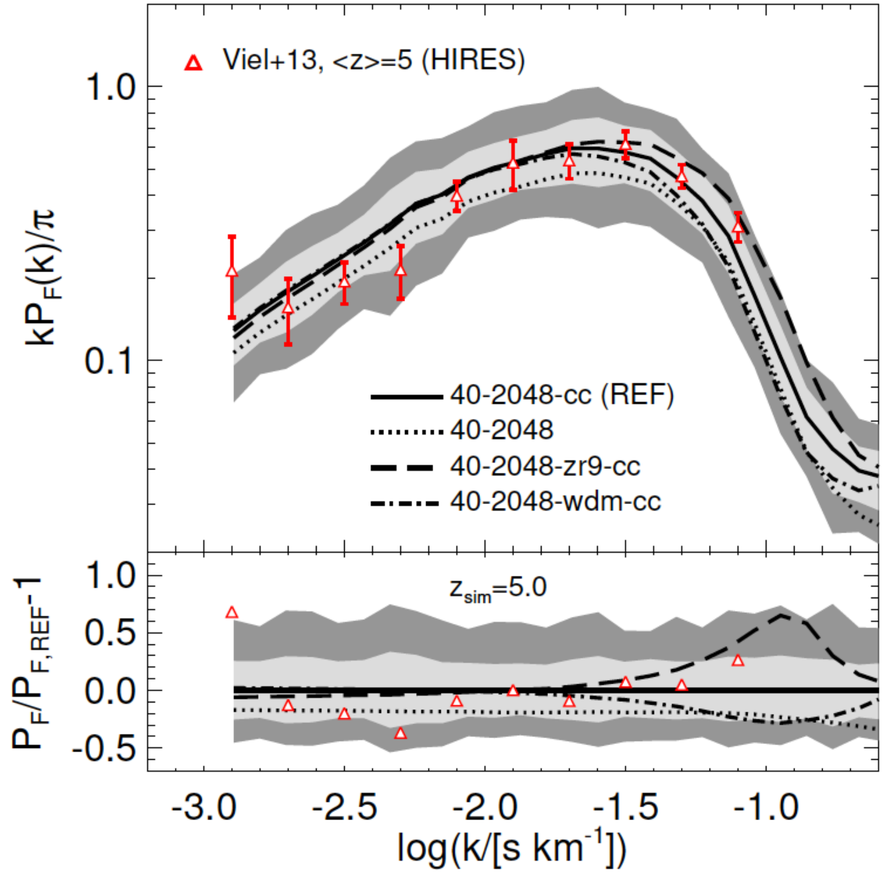
Used for WDM, astrophysics of the IGM and galaxy formation, variation of fundamental constants

*MV+05,08,13, **Becker**+11*
Yeche+17, Garzilli+18 ,
Bosman+18

High vs low-z Lyman-alpha flux power

High redshift:
constraining reionization

Statistical error usually comparable or larger than known systematic errors



Lyman-alpha forest open issues

Overall broad consistency between LCDM model and Lyman-alpha flux statistics.

Several different groups running hydro sims for quantitative cosmological ana
forest data (Lukic, Onorbe, Palanque-Delabrouille, Theuns, etc.).

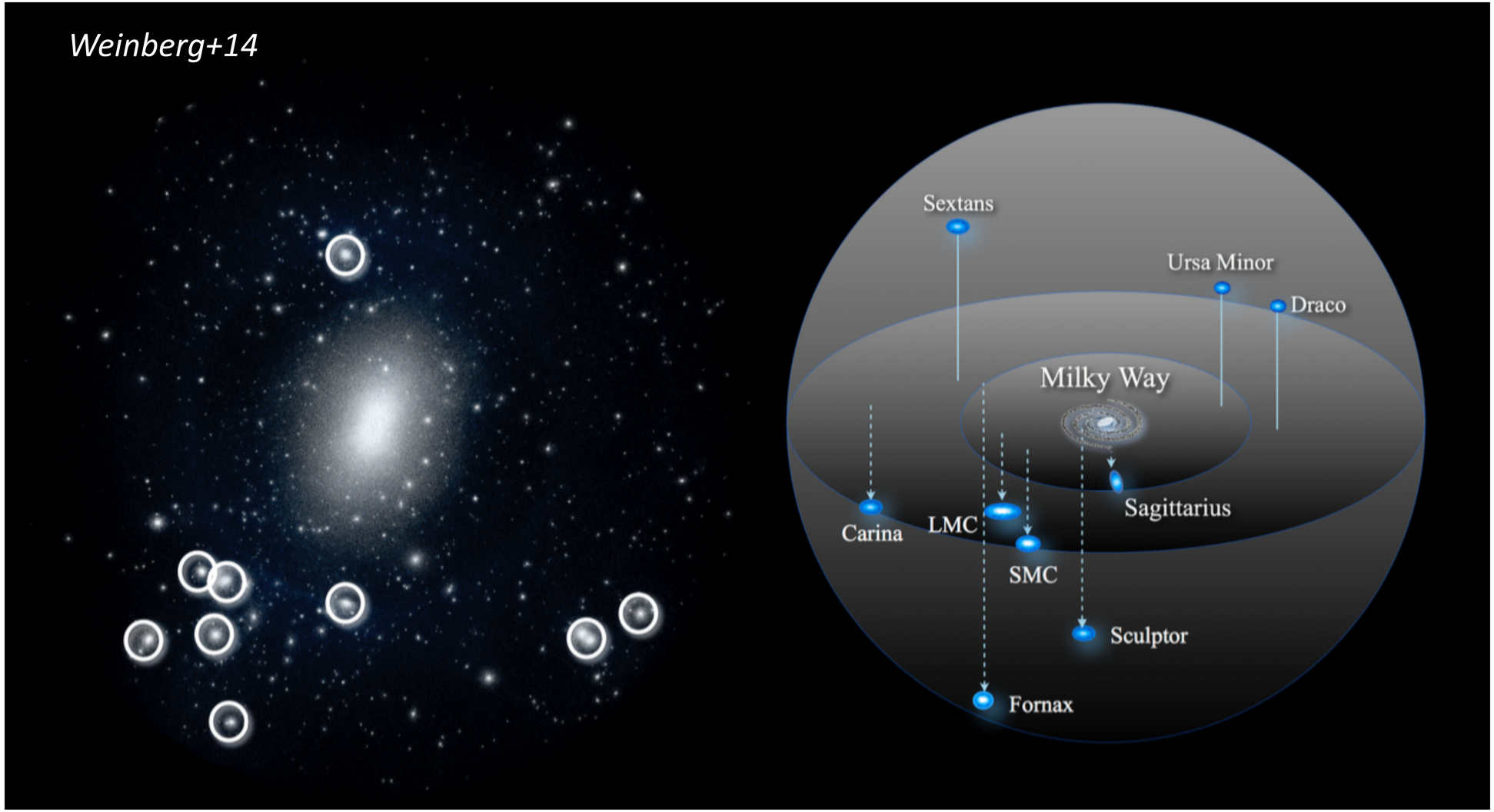
Critical areas for modelling/simulations:

1) high-redshift regime: UV/temperature fluctuations.
2) low and intermediate redshifts: galactic feedback, HeII reionization.
3) modelling several statistics at once (PDF, 1D, 3D, bispectrum) - self-consistent model of 3D and 1D flux power not addressed.
4) resolution under control @ k=0.1 s/km roughly scales of k ~ 10-20 h/Mpc @ z=2-6?

COLDNESS OF COLD DARK MATTER

- Prompted around 2000 by small scale problems of LCDM: missing satellites, cusp/core, too-big to fail.
- Prompted also more recently by detection of unidentified line at 3.55 keV (Boyarsky+, Bulbul+)
- Problems still present, maybe solved by astrophysics only (feedback?). Numerics still tricky.
- On the observational side progress driven by IGM and dwarf galaxies (SDSS, DES etc.)
- **Investigation of these issues is interesting even without addressing the tensions with data: measure dark matter free streaming at scales larger than those of any SUSY model.**
- General models advocate particles with non-zero thermal velocities (i.e. pressure) that produce a suppression of power (more abrupt and at smaller scales than neutrinos).
- Next frontier: more high-z QSOs for IGM, tidal streams in the MW, substructures with lensing.

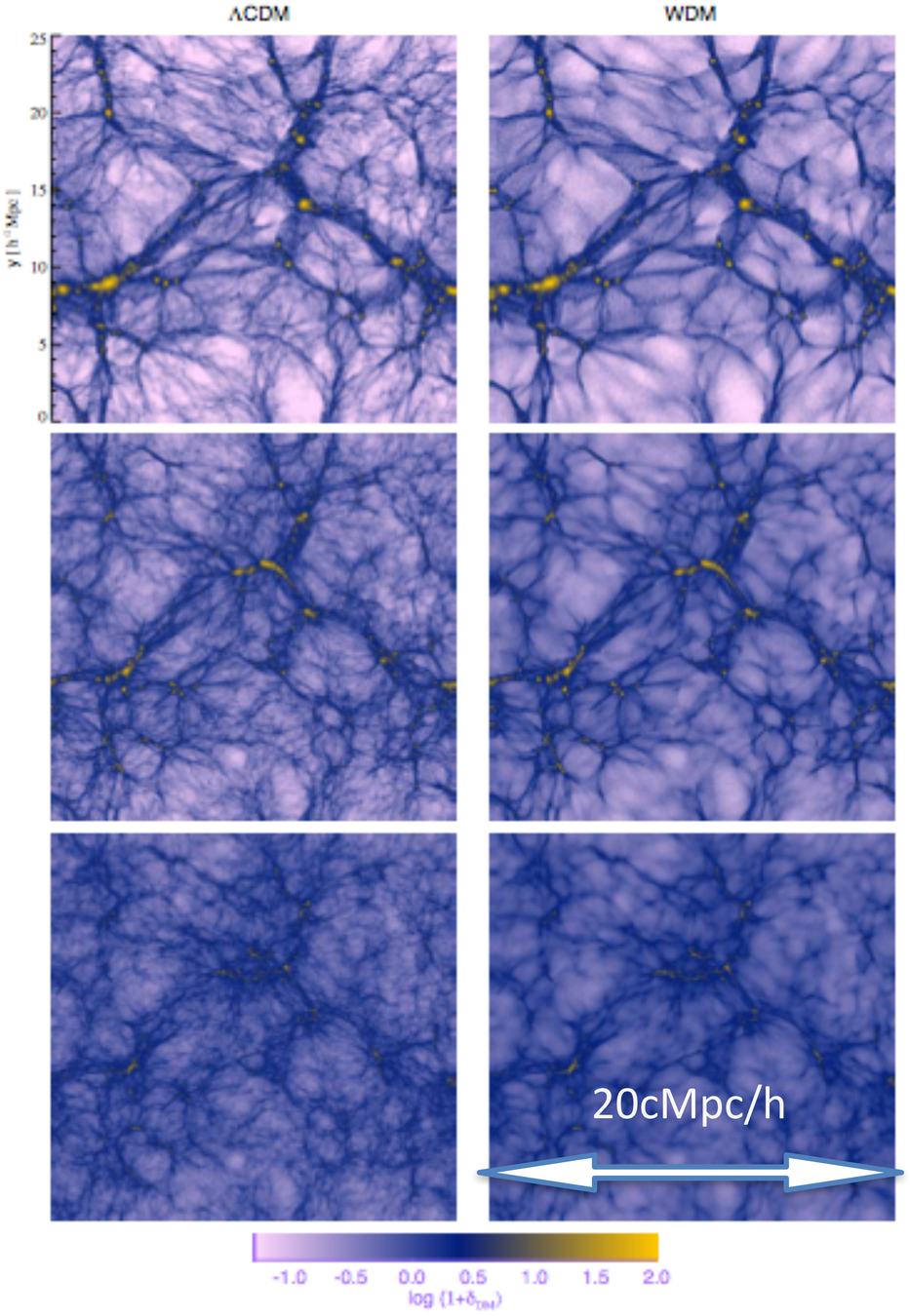
ΛCDM model: small scales problems?



1) Too big to fail problem
2) Missing satellite problem
3) Cusp-core problem

Note that baryonic physics (e.g. galactic feedback) could also solve the tension. Contrived to have DM perfectly mimicking baryons (different z-evolution?)

THE COSMIC WEB in WDM/LCDM scenarios



z=0

$$\frac{T_x}{T_\nu} = \left(\frac{10.75}{g_*(T_D)}\right)^{1/3} < 1$$

$$k_{\rm FS} = \frac{2\pi}{\lambda_{\rm FS}} \sim 5\,{\rm Mpc}^{-1}\left(\frac{m_x}{1\,{\rm keV}}\right)\left(\frac{T_\nu}{T_x}\right)$$

$$\omega_x = \Omega_x h^2 = \beta\left(\frac{m_x}{94\,{\rm eV}}\right)$$

$$\beta = (T_x/T_\nu)^3$$

z=2

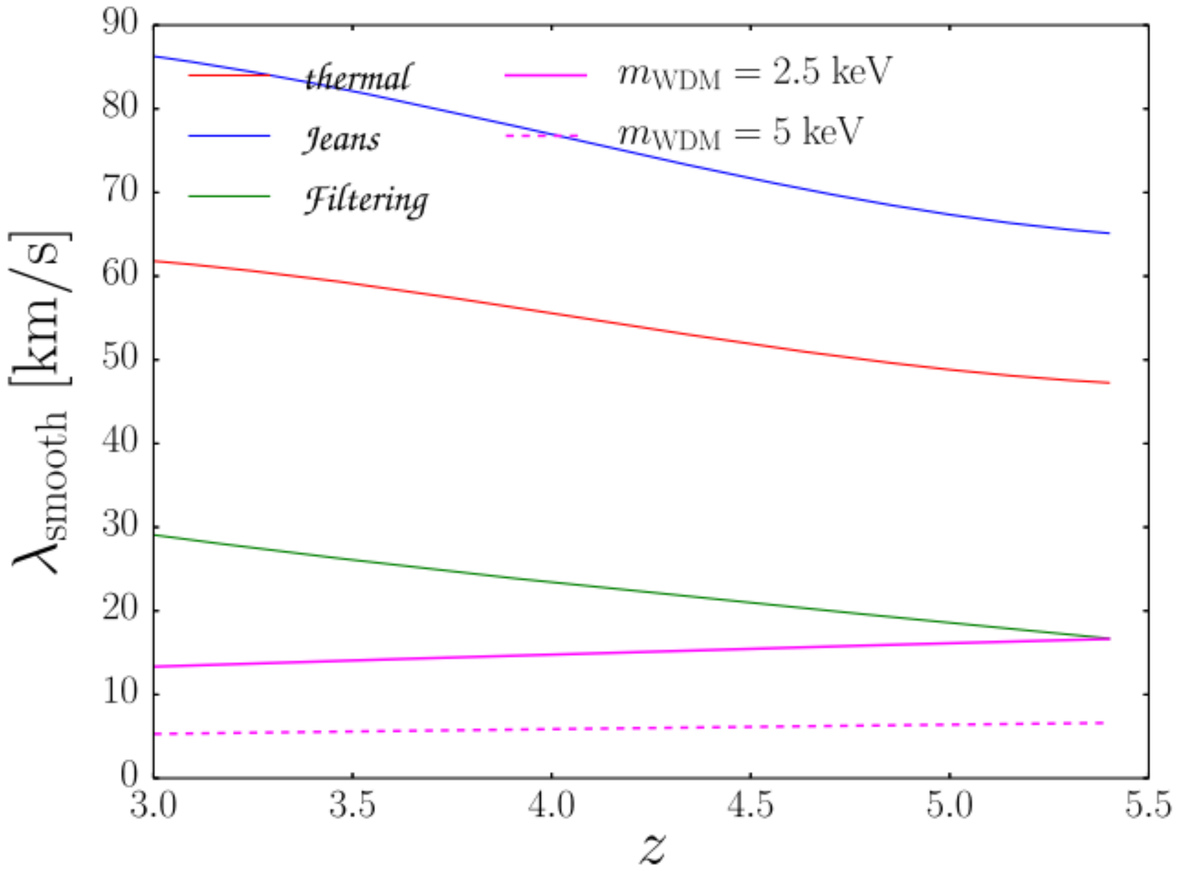
$$k_{\rm FS} \sim 15.6\frac{h}{\rm Mpc}\left(\frac{m_{\rm WDM}}{1{\rm keV}}\right)^{4/3}\left(\frac{0.12}{\Omega_{\rm DM}h^2}\right)^{1/3}$$

z=5

WARNING:
Numerical fragmentation is less of an issue for the Lyman-alpha forest flux, but still reaching convergence especially at high-z is demanding (voids contribute).

MV, Markovic, Baldi & Weller 2013
Markovic & MV, 2014

Smoothing scales

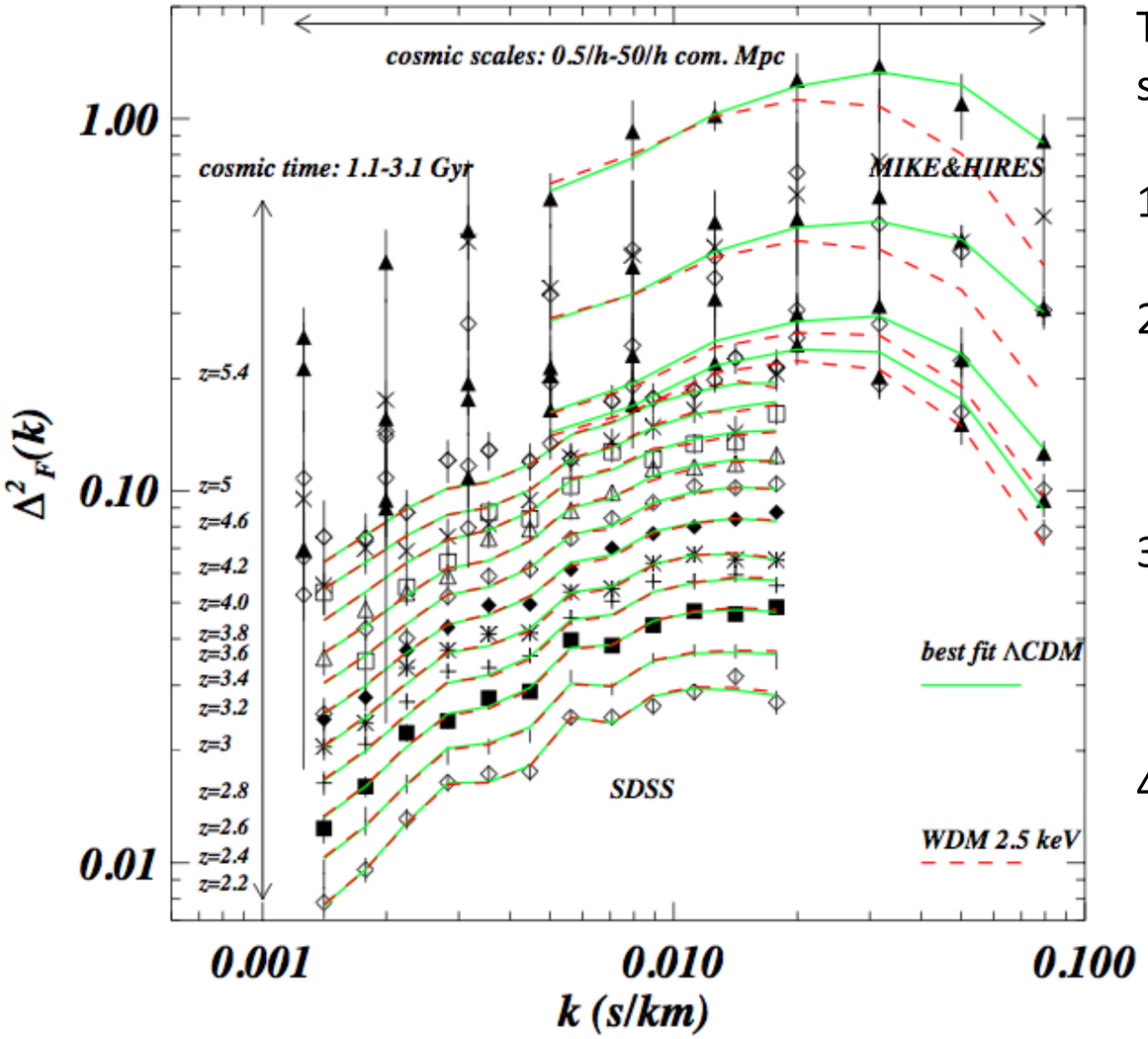


Irsic,MV+17

- Different physical scales (on top of instrumental resolution) affect the power spectrum cutoff:
- thermal: instantaneous temperature at that redshift);
- Jeans: scale due to gas pressure;
- filtering scale: depends on all the previous thermal history;
- WDM cutoffs are basically redshift independent
- Constraints are obtained from a full shape of the 1D fux power.

STATUS in 2013

$M_{\text{thermal WDM}} > 3.3$ keV (2σ C.L.)



This lower limit is derived under some assumptions

1) Bayesian analysis

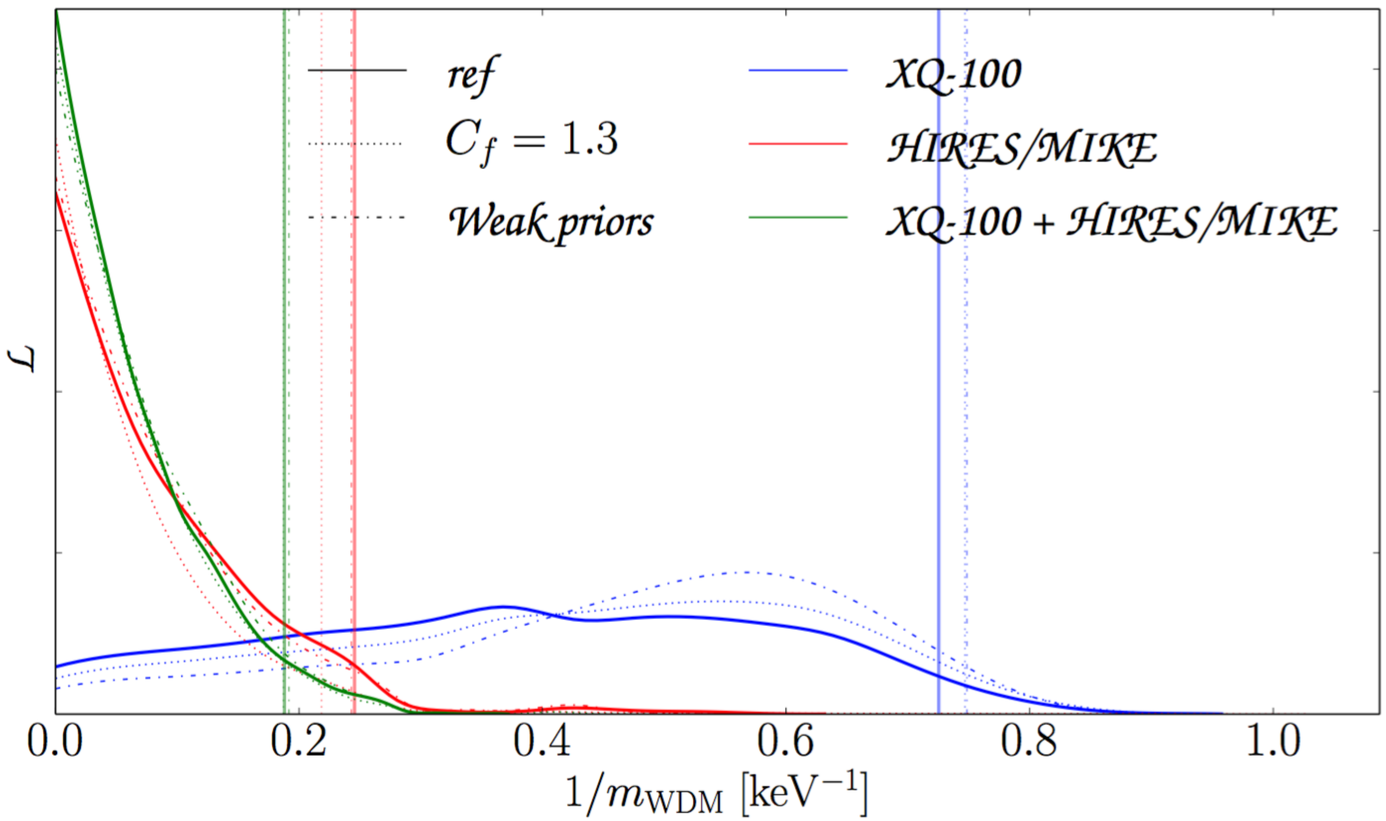
2) Bootstrap-derived covariance matrix from mock QSO sample with entries multiplied by 1.3

3) resolution corrections performed and particularly important at high-z & small-scales

4) limited exploration of z_reio Jeans smoothing

2017/18 status: the X-Shooter sample and new results for WDM (thermal)

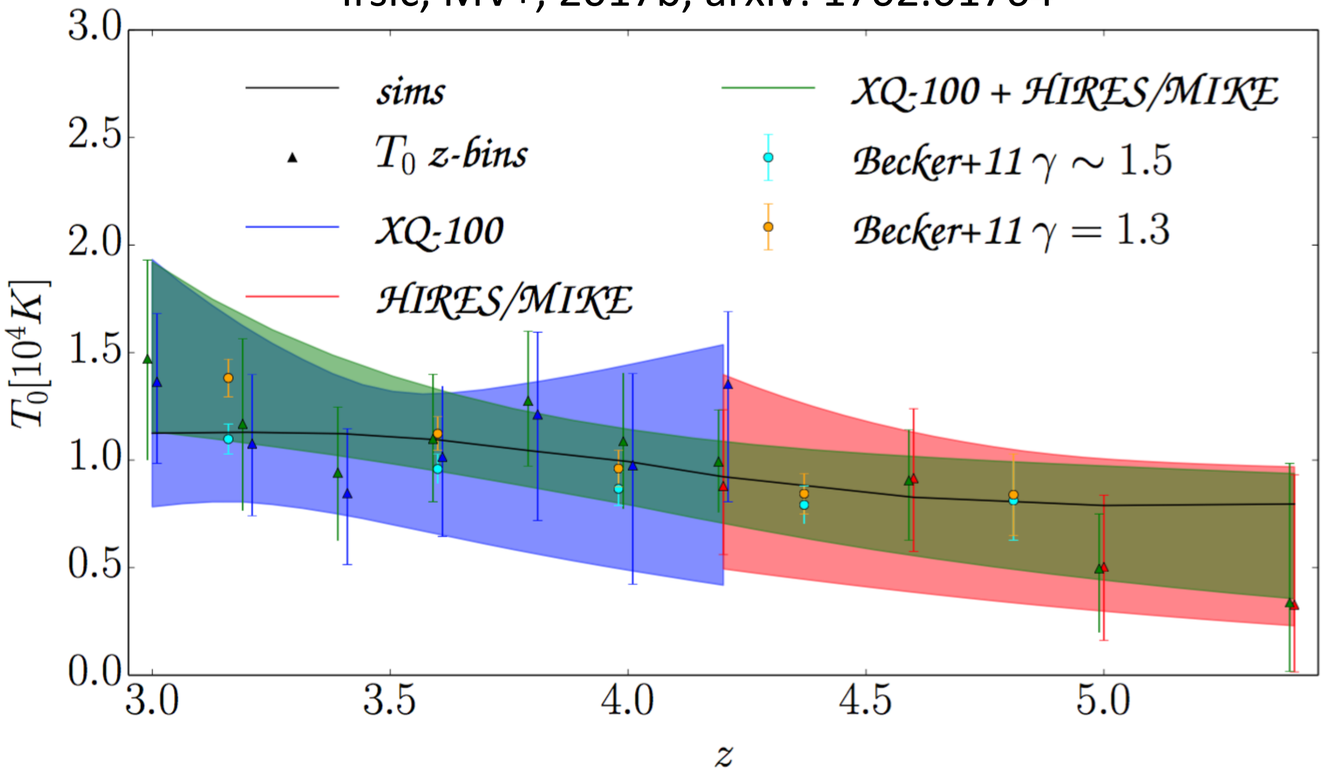
Irsic, MV+, 2017b, arxiv: 1702.01764



- Likelihood greatly improves (shrinks) when combined with HIRES, pushing towards LCDM (cold).
- **Increasing covariance matrix by 1.3 (for XQ-100) or applying weak priors on cosmo parameters does not impact (this is good)**.
- Limits are then: > 1.4, > 4.1, > 5.3 keV for the reference cases for XQ-100 (medium res.), HIRES/Keck (high res.) and combined, respectively.

X-Shooter sample: IGM thermal priors

Irsic, MV+, 2017b, arxiv: 1702.01764



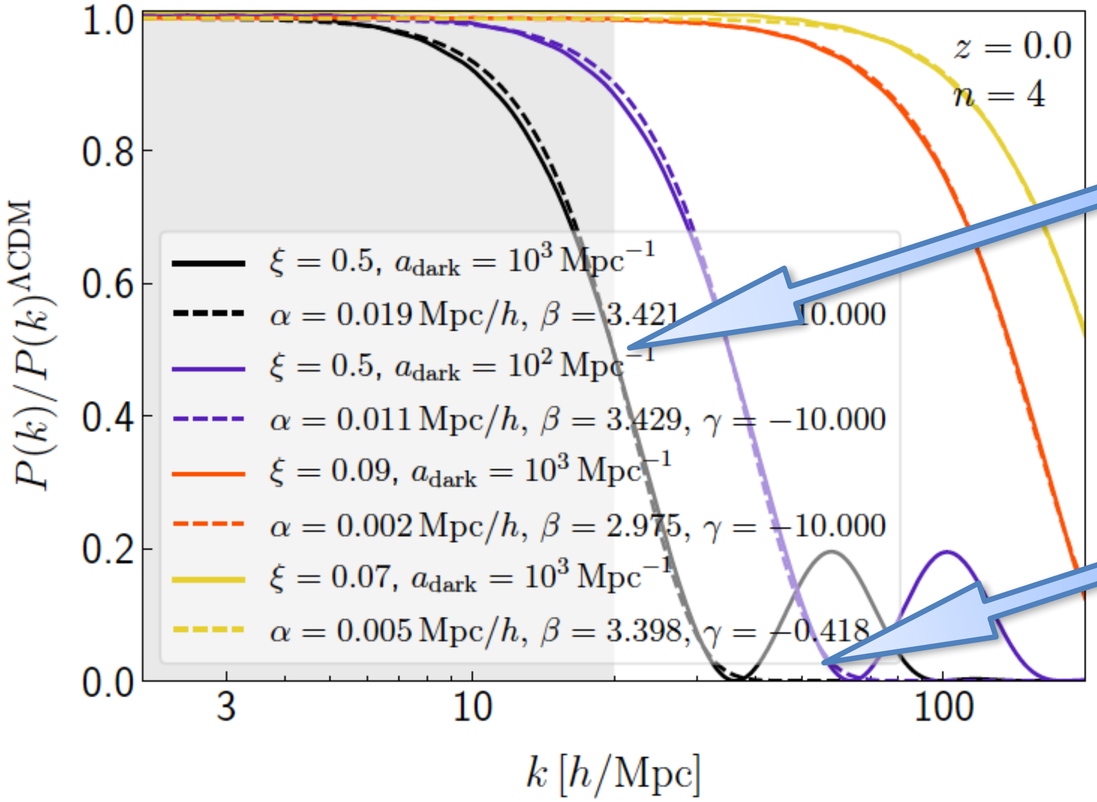
- Thermal history is the main nuisance. It is marginalized over but still quite sensitive to priors.
- For reference case $T_{IGM}(z)$ assumed to be a power-law (motivated by IGM physics), having this assumption lifted weakens the combined constrained to 3.5 keV.
- Key-aspect here: wide redshift range that allows to break degeneracies between WDM cutoff, Jeans pressure, filtering scale (all suppress power but differently in z).

Non-Cold Dark Matter: DM-Dark radiation interactions

Non relativistic DM scattering off (extra) relativistic radiation
n=0,2,4 are the models usually explored

$$\Gamma_{\mathrm{DR-DM}} \propto a_{\mathrm{dark}} T^n$$

$$\xi = T_{\mathrm{DR}}/T_\gamma$$



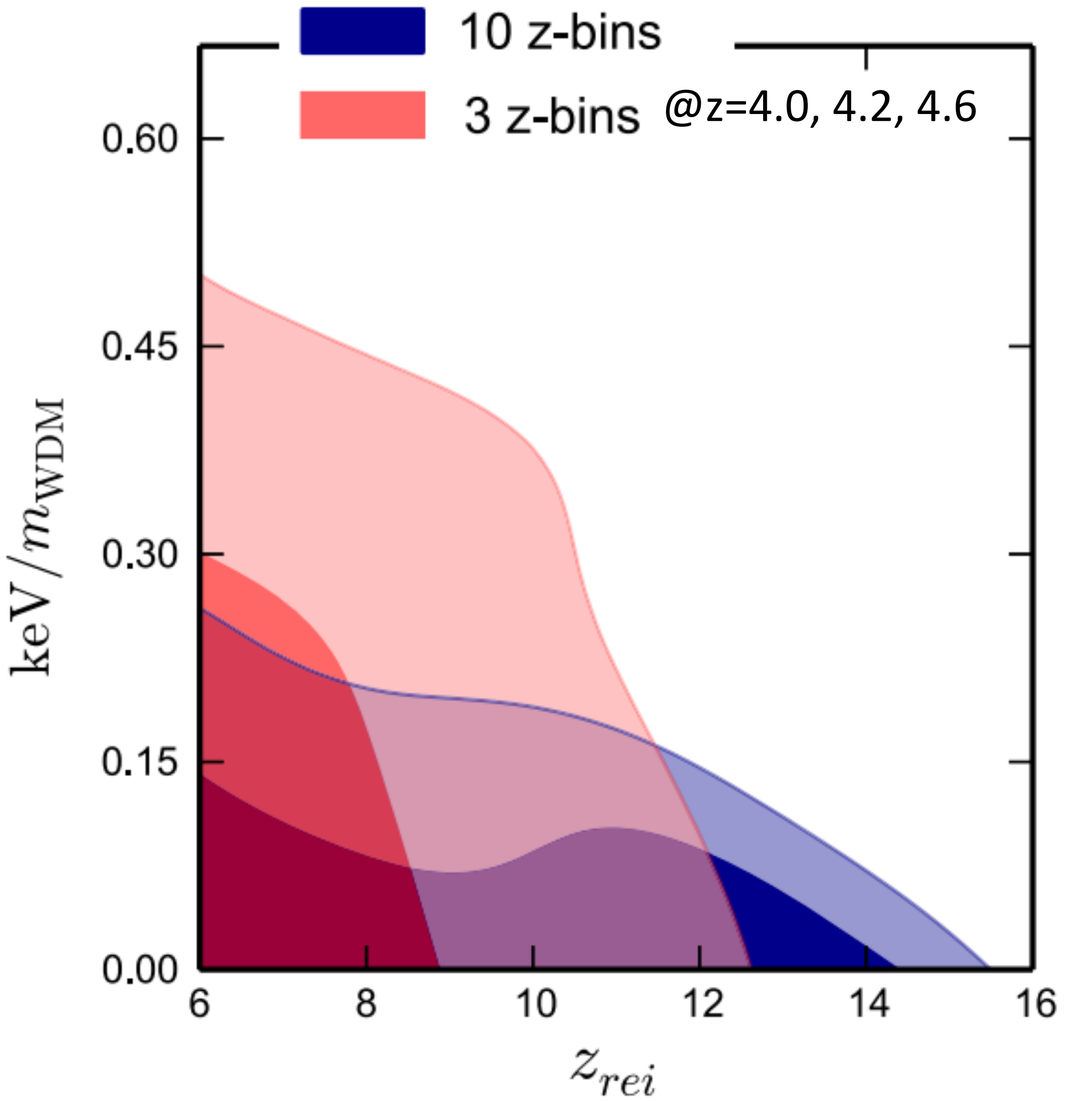
Late kinetic decoupling induced by DM-DR produces collisional damping (cutoff in P(k))

DM clustering and DR pressure produce DAOs at small scales

Archidiacono, Hooper, Murgia, Bohr, Lesgourgues, MV 2019

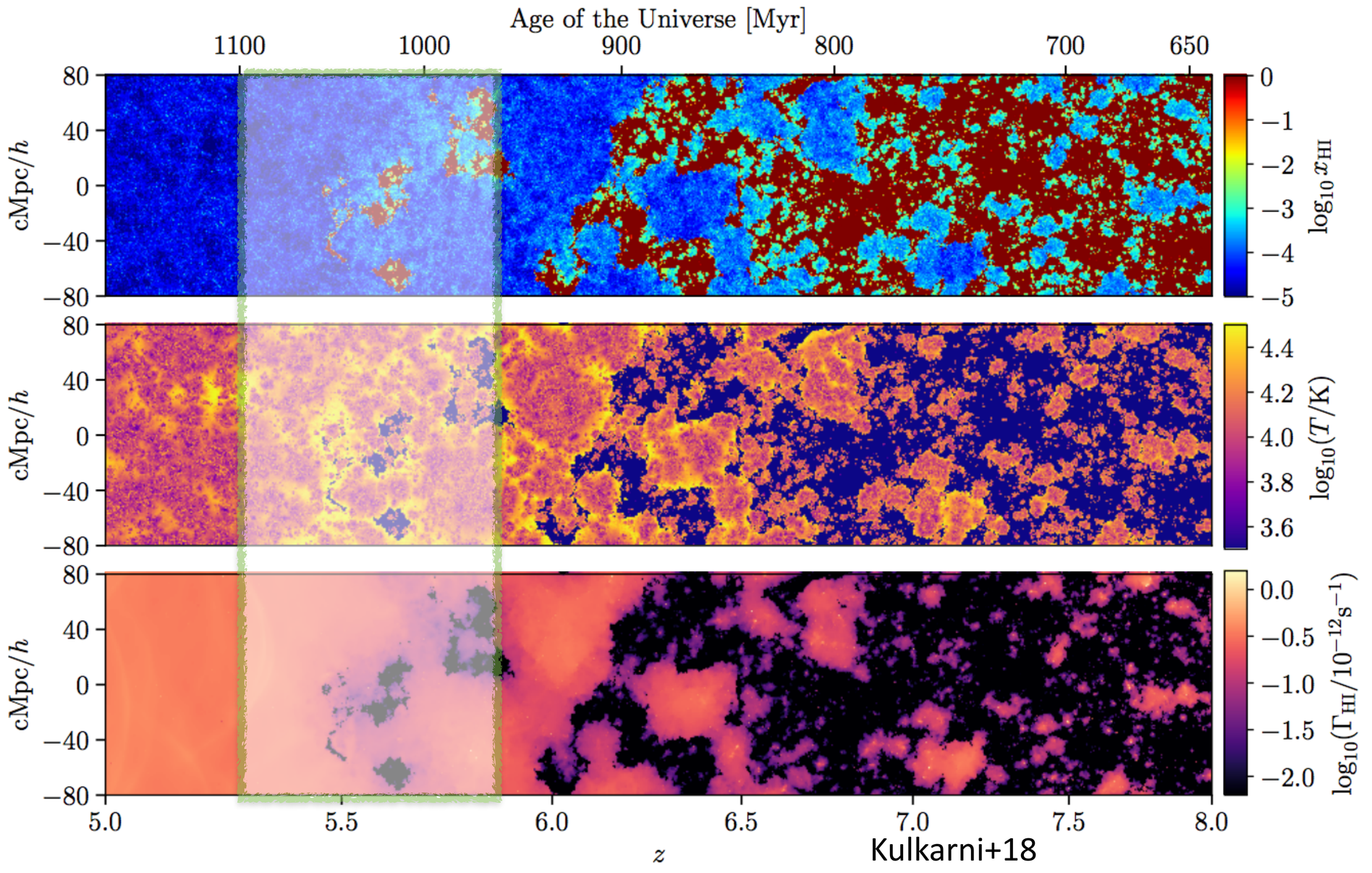
Redshift coverage is important

Since it allows to break degeneracies



Irsic,MV+17

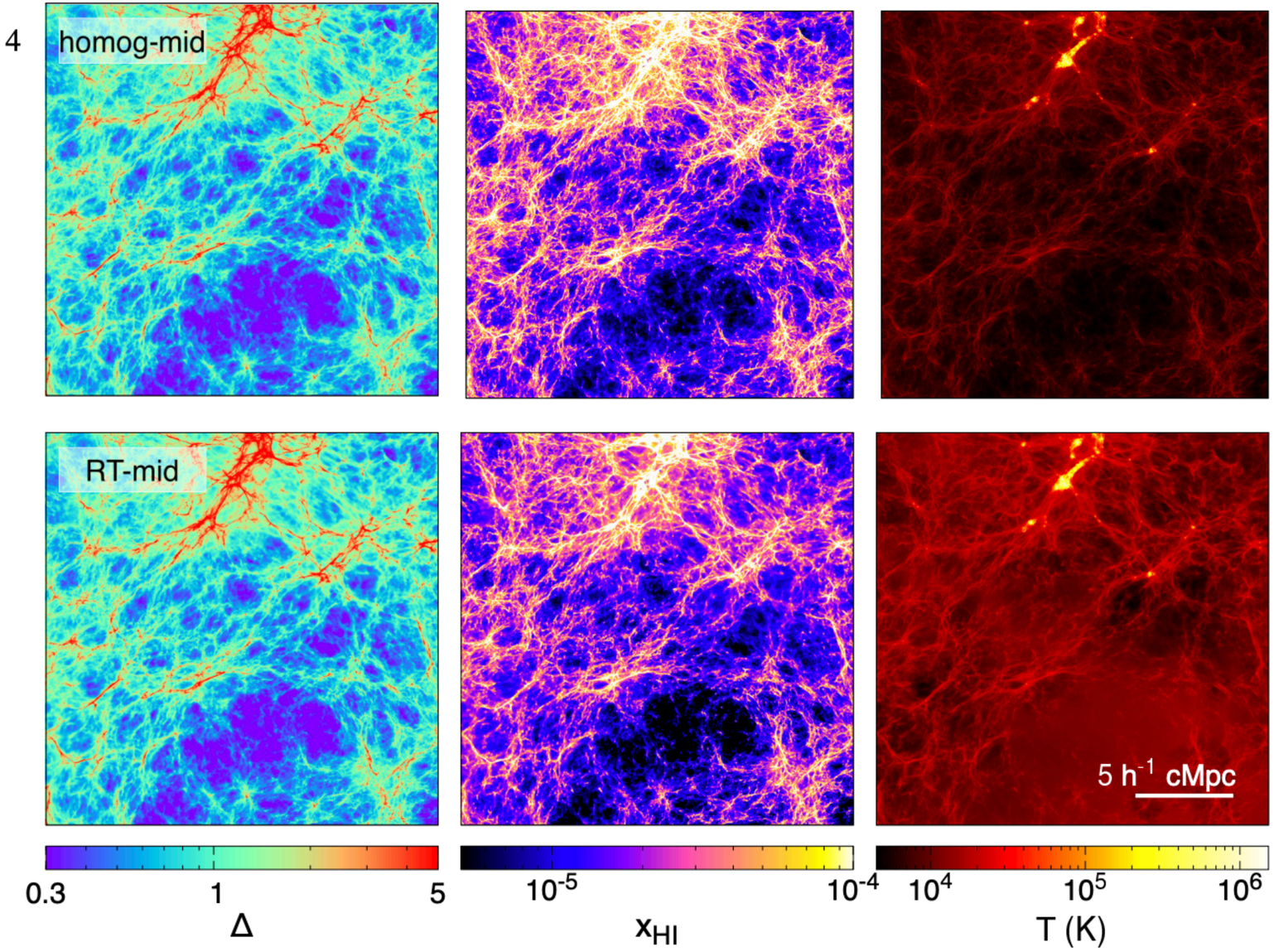
Reionization - I: islands of neutral hydrogen surviving?



Kulkarni+18

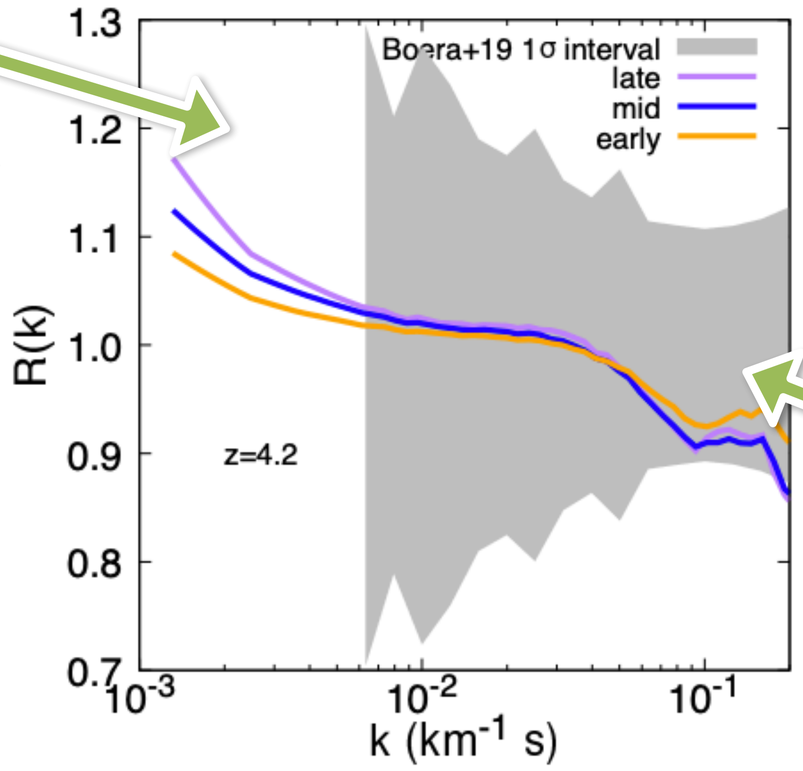
Reionization - II: islands of neutral hydrogen surviving?

Molaro,Irsic+21 arxiv:2109.06897



Reionization - III: flux power

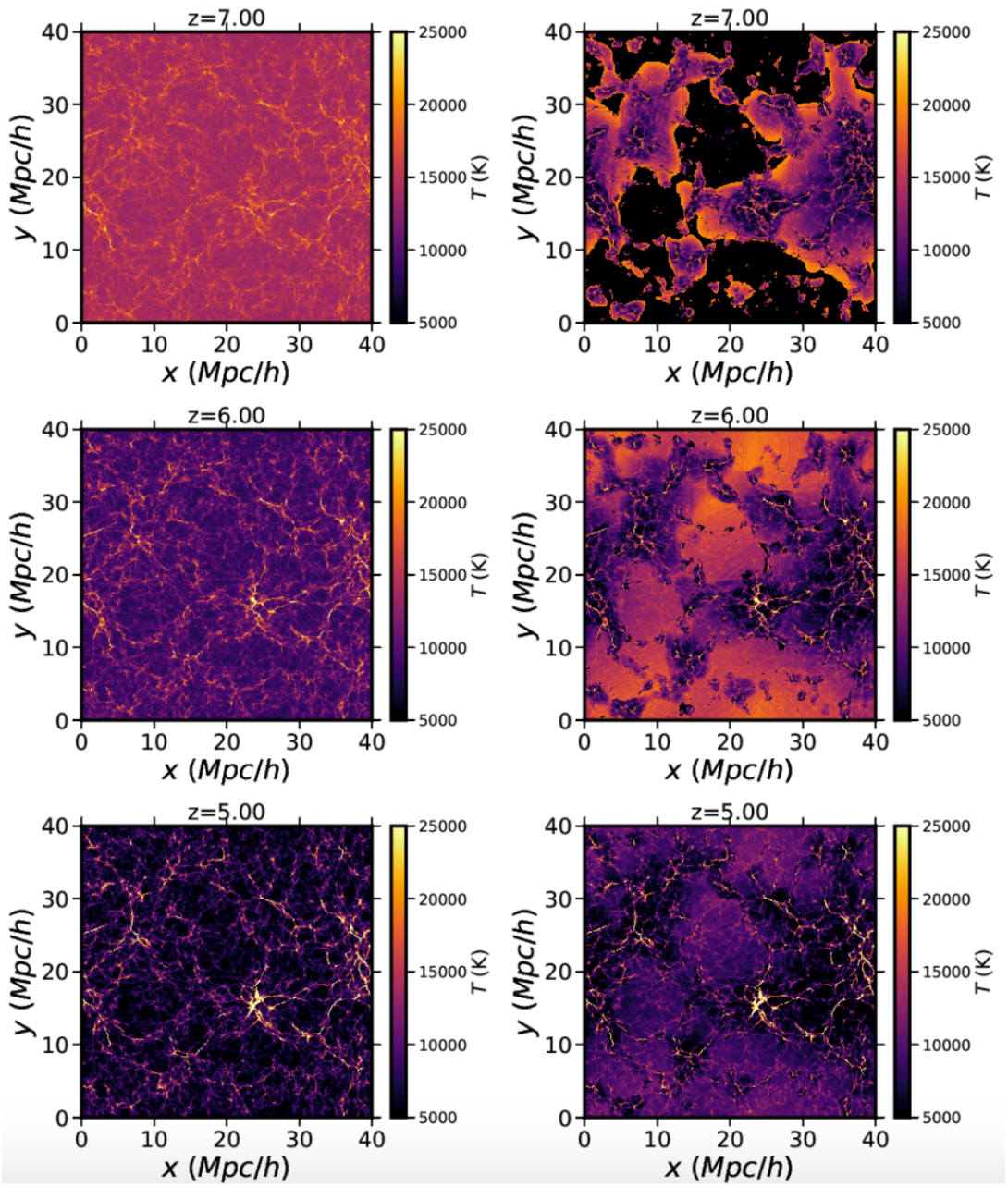
Boost
due to variation in neutral fraction from large scale temperature fluctuations



Suppression
due to thermal broadening of recently ionised regions

Molaro,Irsic+21 arxiv:2109.06897

Reionization - IV: temperature fluctations

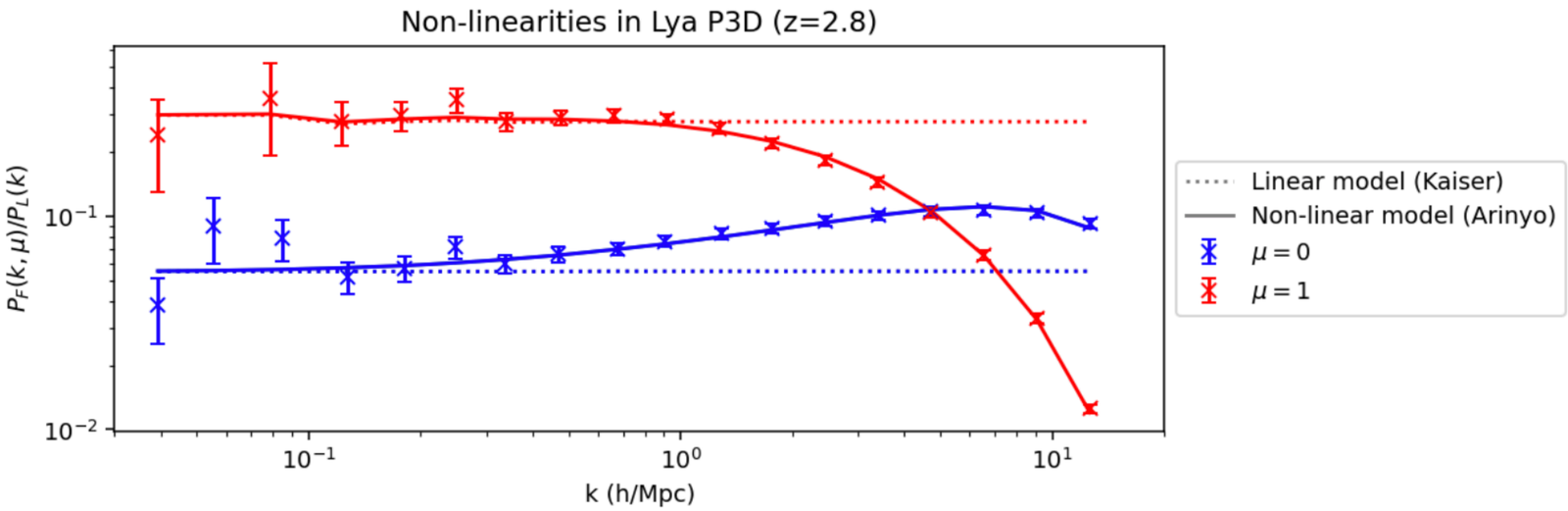


Onorbe+18: homogenous (left) vs. patchy reionization (right) with temperature fluctuations

UVB fluctuations decrease opacity in overdense regions with more sources of ionizing photons, and increase the opacity in underdense regions that are distant from sources.

Temperature fluctuations: overdense regions reionize early and are cold and opaque, while underdense regions reionize late and are hot and transparent.

A closer look at 3D flux power



Scalar Dark Matter - I

$$\nabla_\mu \nabla^\mu \phi = m^2 \phi, \quad G_{\mu\nu} = 8\pi G T_{\mu\nu},$$

KG and Einstein equations

$$T^\phi_{\mu\nu} = g_{\mu\nu}\left(-\frac{1}{2}\partial_\rho\phi\partial^\rho\phi - \frac{1}{2}m^2\phi^2\right) + \partial_\mu\phi\partial_\nu\phi.$$

Energy momentum tensor for the scalar field

$$ds^2 = -(1+2\Phi)dt^2 + a(t)^2(1-2\Phi)d\boldsymbol{x}^2$$

Metric

$$\phi = \frac{1}{\sqrt{2m}}\left(\varphi e^{-imt} + \varphi^* e^{imt}\right)$$

Oscillating field

$$i\left(\dot{\varphi} + \frac{3}{2}H\varphi\right) = -\frac{\partial^2\varphi}{2a^2 m} + m\Phi\varphi,$$

Dropping higher order and averaging over one oscillating period: Schrodinger type eq.

$$\rho_\phi \equiv m\varphi\varphi^*, \quad v_i \equiv \frac{\partial_i\{\arg(\varphi)\}}{am} = -\frac{i}{2am}\left(\frac{\partial_i\varphi}{\varphi} - \frac{\partial_i\varphi^*}{\varphi^*}\right)$$

Defining density and velocities of the fluid

$$\dot{v}_i + Hv_i + \frac{v_j\partial_j v_i}{a} = -\frac{\partial_i\Phi}{a} + \boxed{\frac{1}{2a^3m^2}\partial_i\left(\frac{\partial^2\sqrt{\rho_\phi}}{\sqrt{\rho_\phi}}\right)}$$

Euler eq. NOTE the pressure term

$$\dot{\rho}_\phi + 3H\rho_\phi + \frac{\partial_i(\rho_\phi v_i)}{a} = 0.$$

Continuity

Hui+16 for a review, Mocz & Succi 15 for SPH implementation, Marsh+15, Nori&Baldi 18

Scalar Dark Matter - II

$$\delta_{\rm m} = F\delta_\phi + (1-F)\delta_{\rm c}$$

$$\ddot{\delta}_{\phi\boldsymbol{k}} + 2H\dot{\delta}_{\phi\boldsymbol{k}} + \frac{c_s^2 k^2}{a^2}\delta_{\phi\boldsymbol{k}} - \frac{3}{2}H^2\delta_{{\rm m}\boldsymbol{k}} = 0,$$

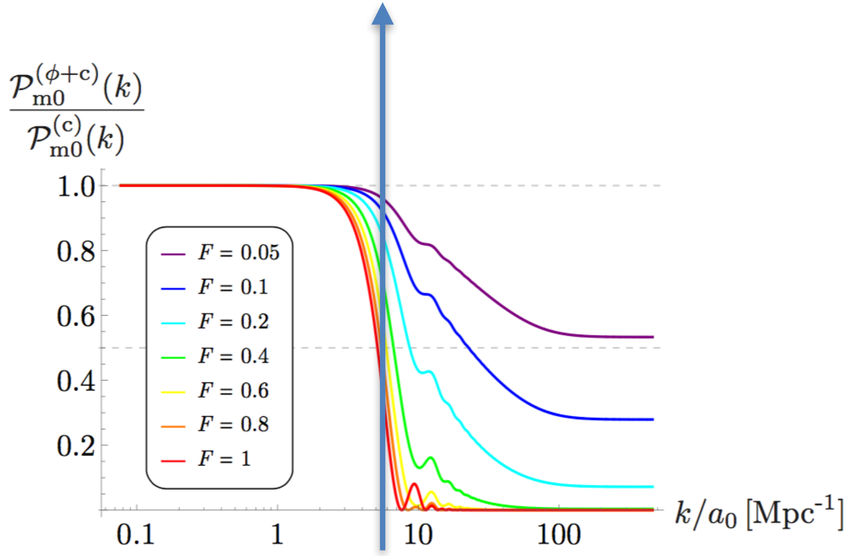
$$\ddot{\delta}_{{\rm c}\boldsymbol{k}} + 2H\dot{\delta}_{{\rm c}\boldsymbol{k}} - \frac{3}{2}H^2\delta_{{\rm m}\boldsymbol{k}} = 0.$$

$$c_s^2 \equiv \frac{k^2}{4a^2m^2}, \qquad \frac{k_{\rm J}}{a} = \sqrt{Hm},$$

Linear perturbation theory in CDM+scalar field model

$$\frac{k_{\rm Jeq}}{a_0} = \frac{a_{\rm eq}}{a_0}\sqrt{H_{\rm eq}m} \approx 7\,{\rm Mpc}^{-1}\left(\frac{m}{10^{-22}\,{\rm eV}}\right)^{1/2}$$

Sound speed of scalar DM and Jeans scale definition

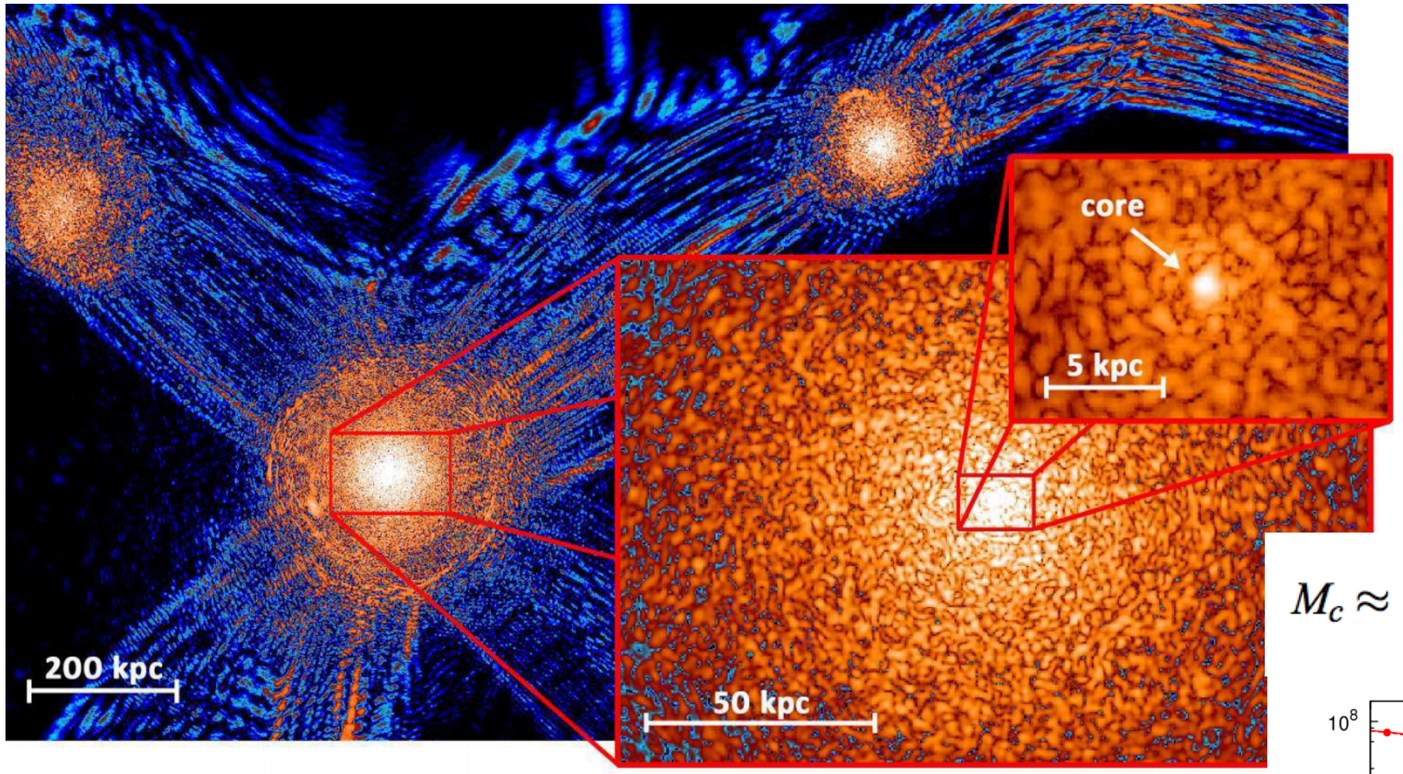


At $k<k_J$ no pressure
At $k>k_J$ pressure and oscillations
no growth
Comoving Jeans $k_J \sim a^{1/4}$ in MD
Important quantity is k_J at equival.

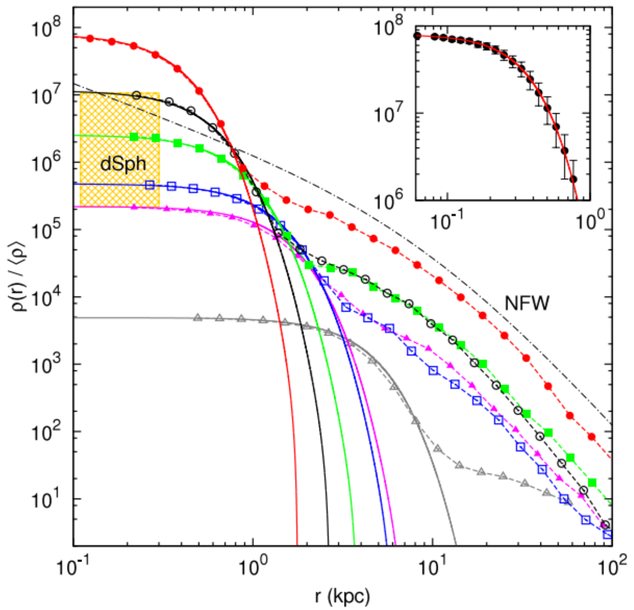
Plateau is set by FDM fraction
Cutoff scale set by FDM mass

Simulating Scalar Dark Matter

Schive+ 14



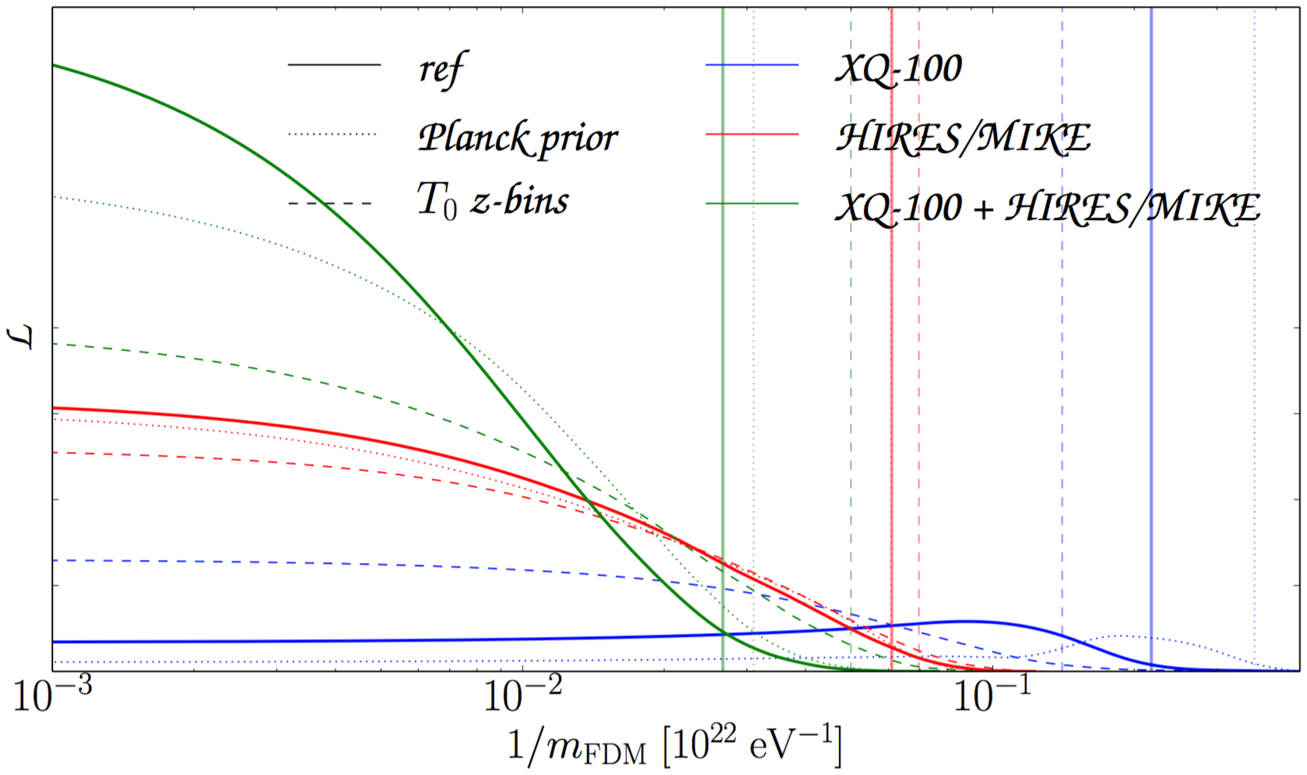
$$M_c \approx \frac{5.5 \times 10^9}{(m_B/10^{-23}\ \mathrm{eV})^2 (r_c/\mathrm{kpc})} M_\odot$$



- Very **distintictive prediction: solitonic core** (steep jump in density) with a simple numerical solution (e.g. Mocz+17, Schive+17, Marsh+15).
- Stability of the core over cosmological times still an open issue.
- Size of the core $M_{core} \sim M_{galaxy}^{1/3}$.
- Claimed detection at 10^{-22} eV from Phornax.
- Searched in galaxies but not seen, however baryon might be an issue (Blum+17).

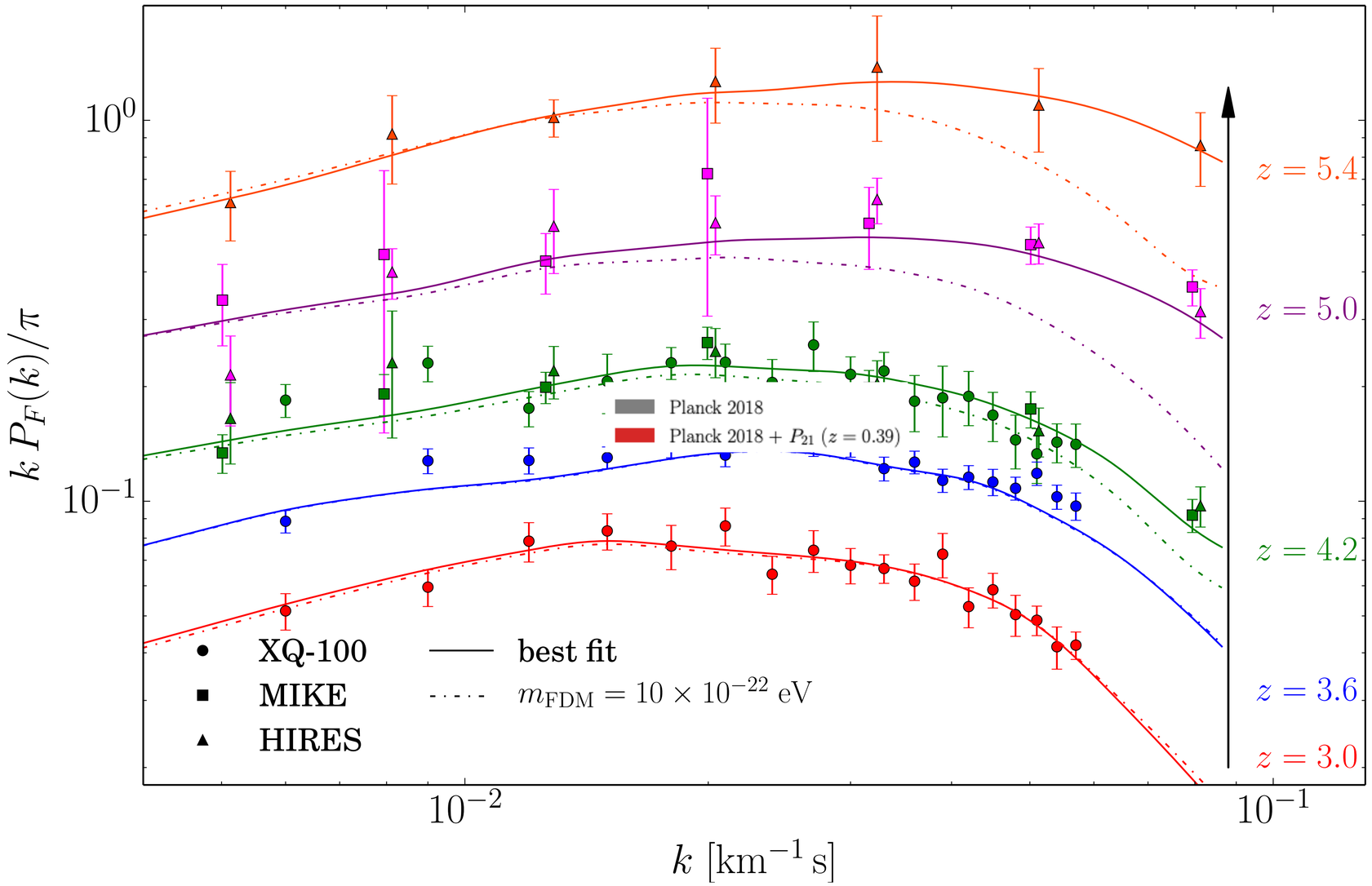
X-Shooter sample + HIRES/MIKE: constraints on ultra-light axions (Fuzzy Dark Matter)

Irsic, MV+, 2017c, arxiv: 1703.04683

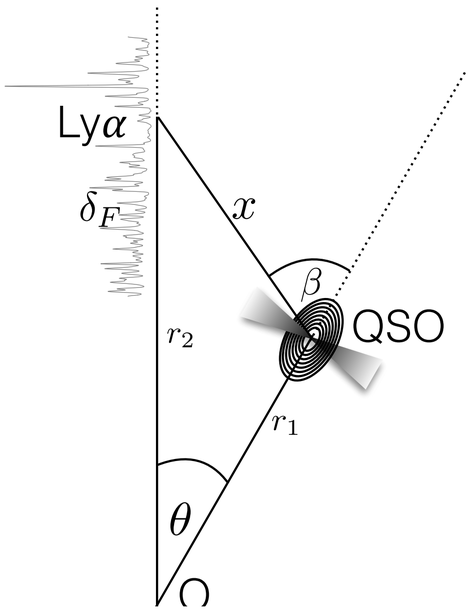


- New interest in FDM models. **VERY RICH IMPLICATIONS.**
- WDM thermal IGM constraints translated into FDM constraints by mapping $k_{1/2}$: poor approximation for large axion masses > 1.e-21.
- IGM constraints are **>2-4 x 10^{-21} eV** - ruling out the window range **0.1-1 x 10^{-21} eV** typically chosen to solve (putative) small scale LCDM crisis.

X-Shooter sample+HIRES/MIKE: constraints on ultra-light axions (Fuzzy Dark Matter)



Cross-correlation of QSOs and Lyman-alpha to probe relativistic effects



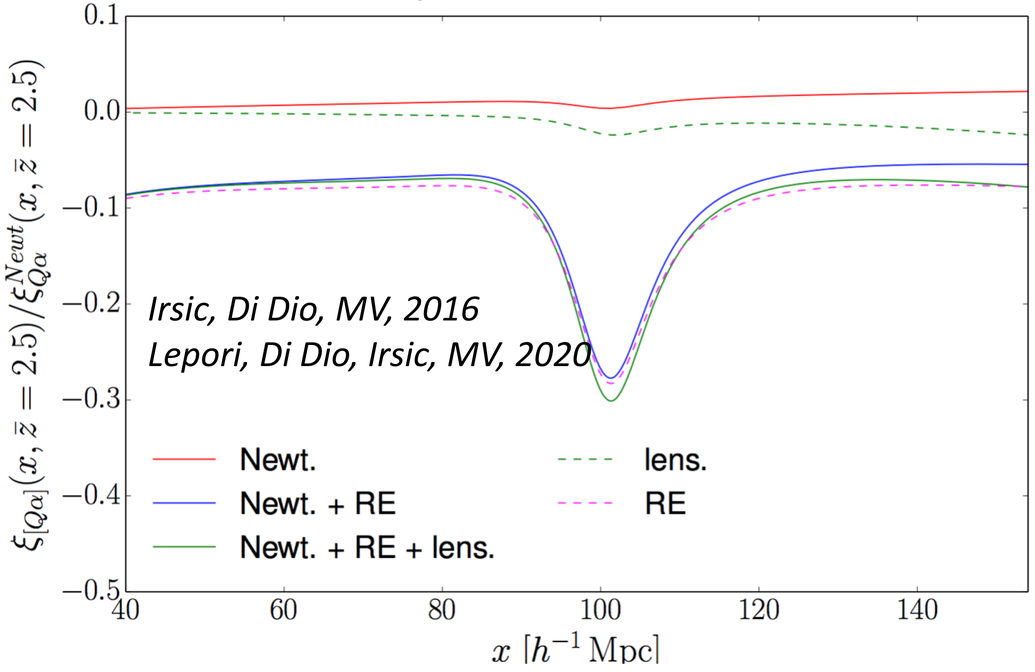
$$\xi_{Q\alpha} = \xi_{Q\alpha}^{\text{newt}} + \xi_{Q\alpha}^{\text{magnification}} + \xi_{Q\alpha}^{\text{relativistic}}$$

$$\xi_{Q\alpha}(z_1, z_2, \theta) \equiv \langle \Delta_Q(\mathbf{n}_1, z_1)\, \delta_F(\mathbf{n}_2, z_2) \rangle$$

$$\xi_{\alpha Q}(z_1, z_2, \theta) \equiv \langle \delta_F(\mathbf{n}_1, z_1)\, \Delta_Q(\mathbf{n}_2, z_2) \rangle.$$

Leading term for multi tracer Doppler term is of the order of $\mathcal{H}/k$

Amplitude of effect



- Antisymmetric part of the cross-correlation function.
- Large bias difference b_{QSOs}=3.6 $b_{Lyalpha}$=-0.15.
- Multi tracer amplifies effects.
- Relativistic effects nearly constant at scales > 40 com. Mpc/h at the level of 10% or more.
- S/N ratio of the effect for SDSS/BOSS is 1, but for DESI will be 7.

Non-cold Dark Matter at small scales - I: a new and more general approach

Standard approach

$$T(k) = [1 + (\alpha k)^{2\nu}]^{-5/\nu}$$

Applies to thermal WDM
(Fermi Dirac distribution)

$$\nu = 1.12\ ;$$

$$\alpha = 0.049 \left(\frac{m_x}{1\ \mathrm{keV}}\right)^{-1.11} \left(\frac{\Omega_x}{0.25}\right)^{0.11} \left(\frac{h}{0.7}\right)^{1.22} h^{-1}\mathrm{Mpc}$$

$\Rightarrow$

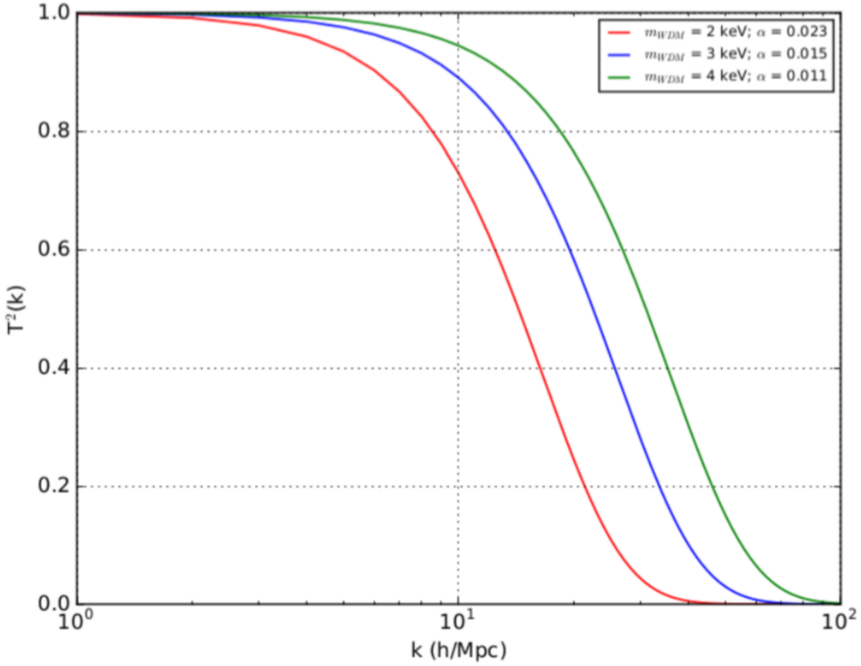
New general approach

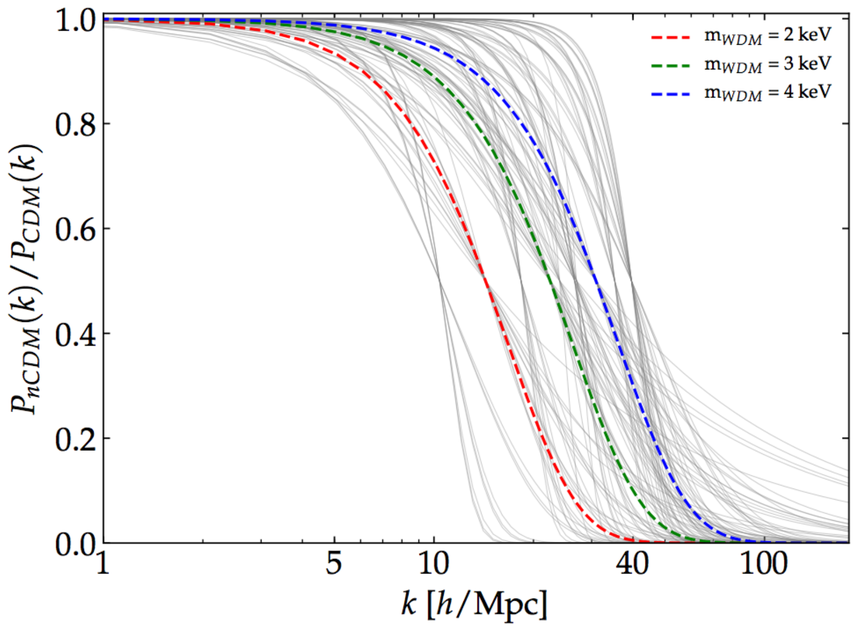
$$T(k) = [1 + (\alpha k)^{\beta}]^{\gamma}$$

Applies to ?

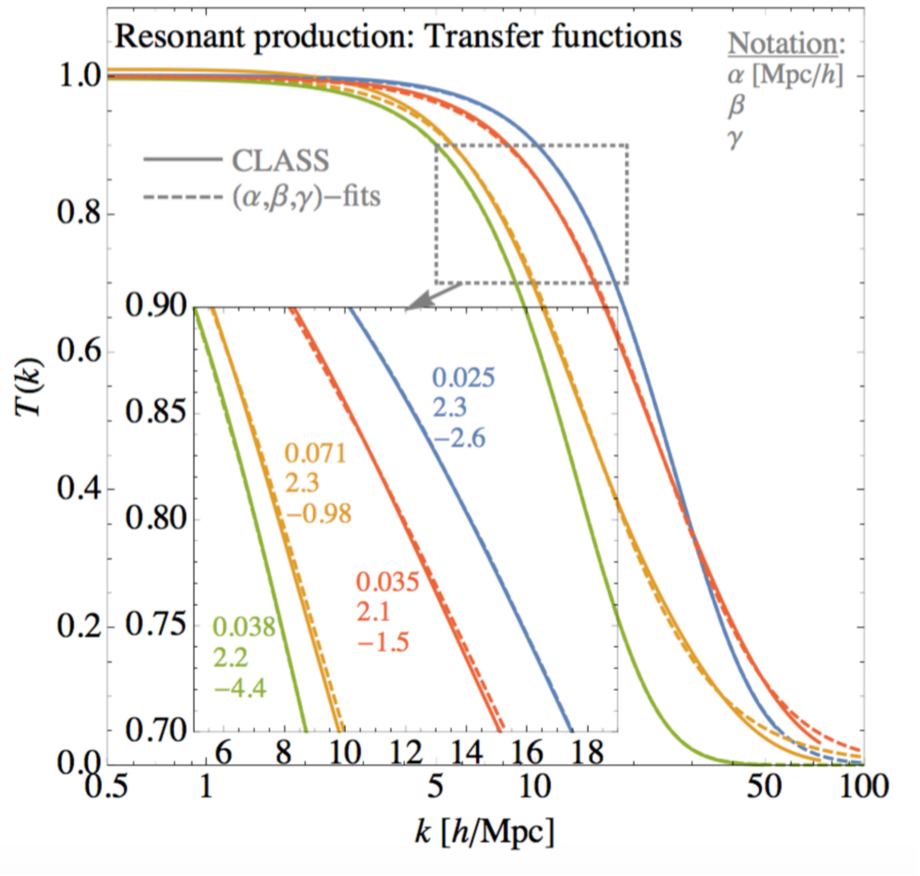
The larger is beta, the flatter is the shape for k < $k_{1/2}$; the larger is gamma, the steeper is the small-scale cutoff
.

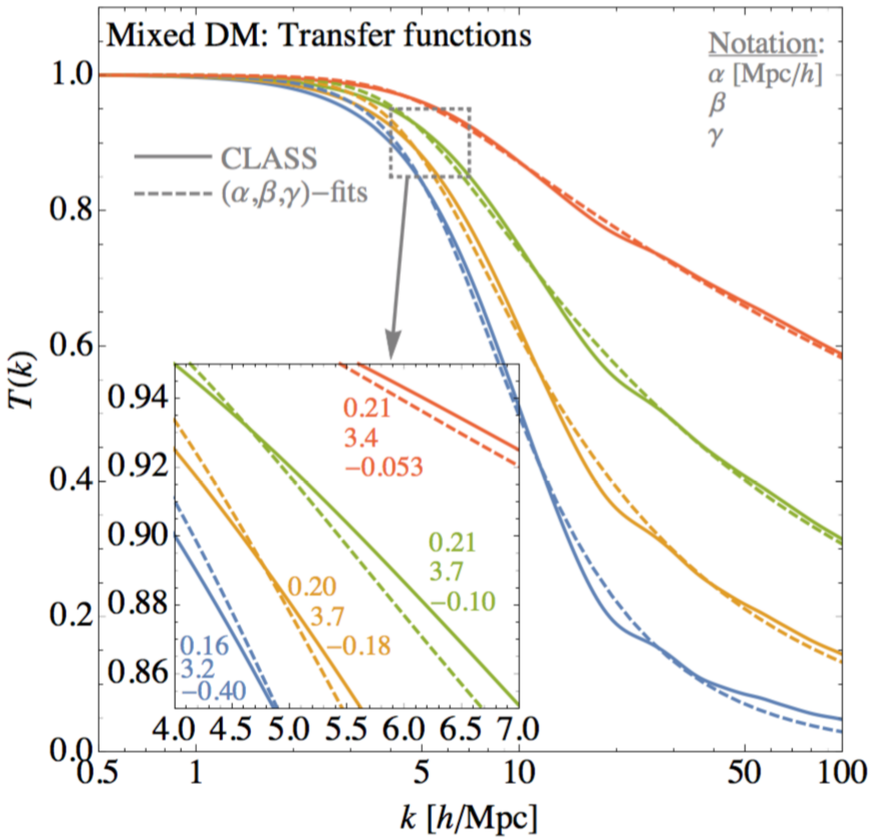
Murgia, Merle, MV +17





Non-cold Dark Matter at small scales - II: particle physics models

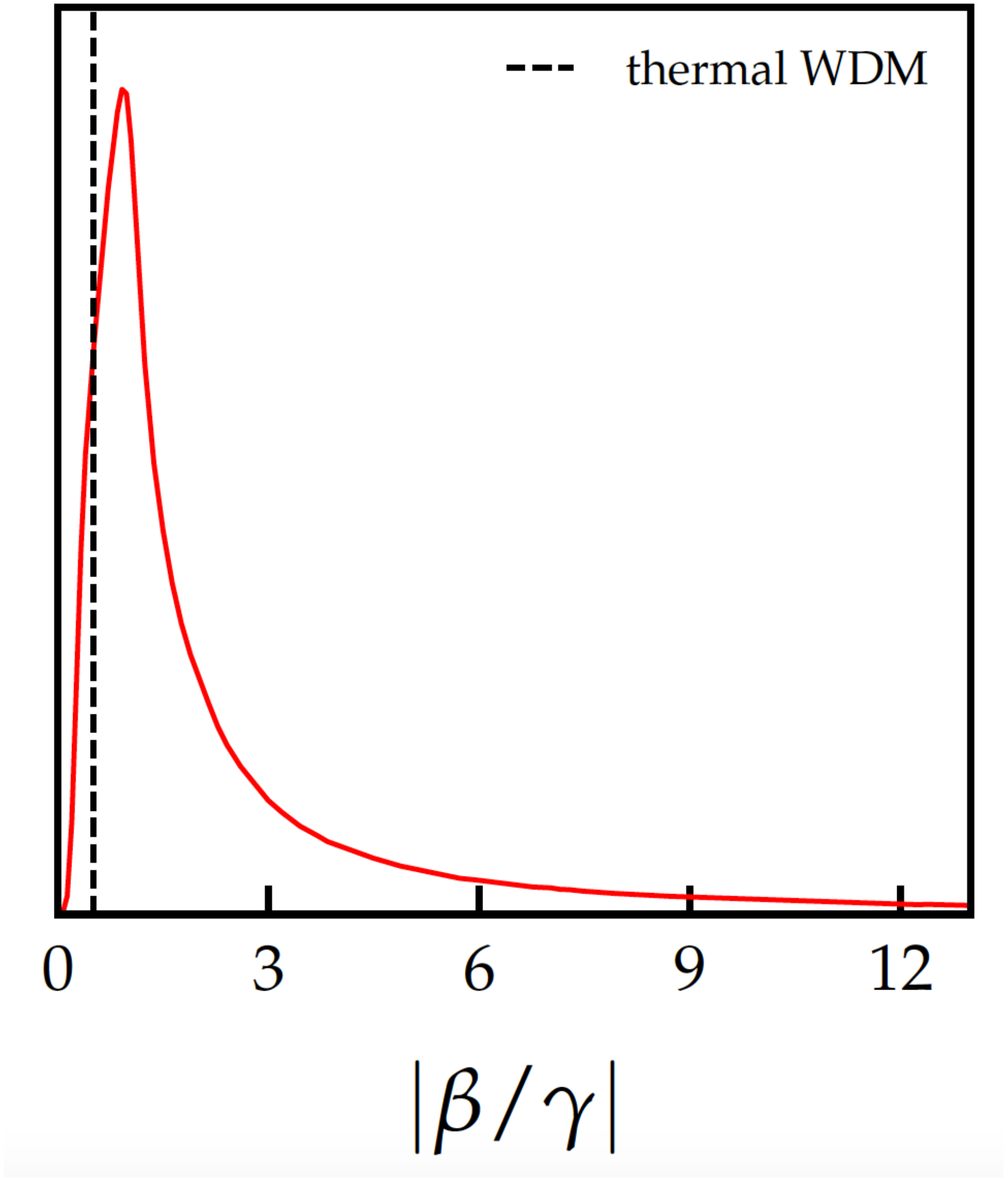




Simple parameterization proposed works well for:

- sterile neutrinos from scalar decays
- sterile neutrinos resonantly produced
- mixed cold+warm models
- fuzzy dark matter
- ETHOS models

Non-Cold Dark Matter and constraints on the SHAPE of the cutoff - II

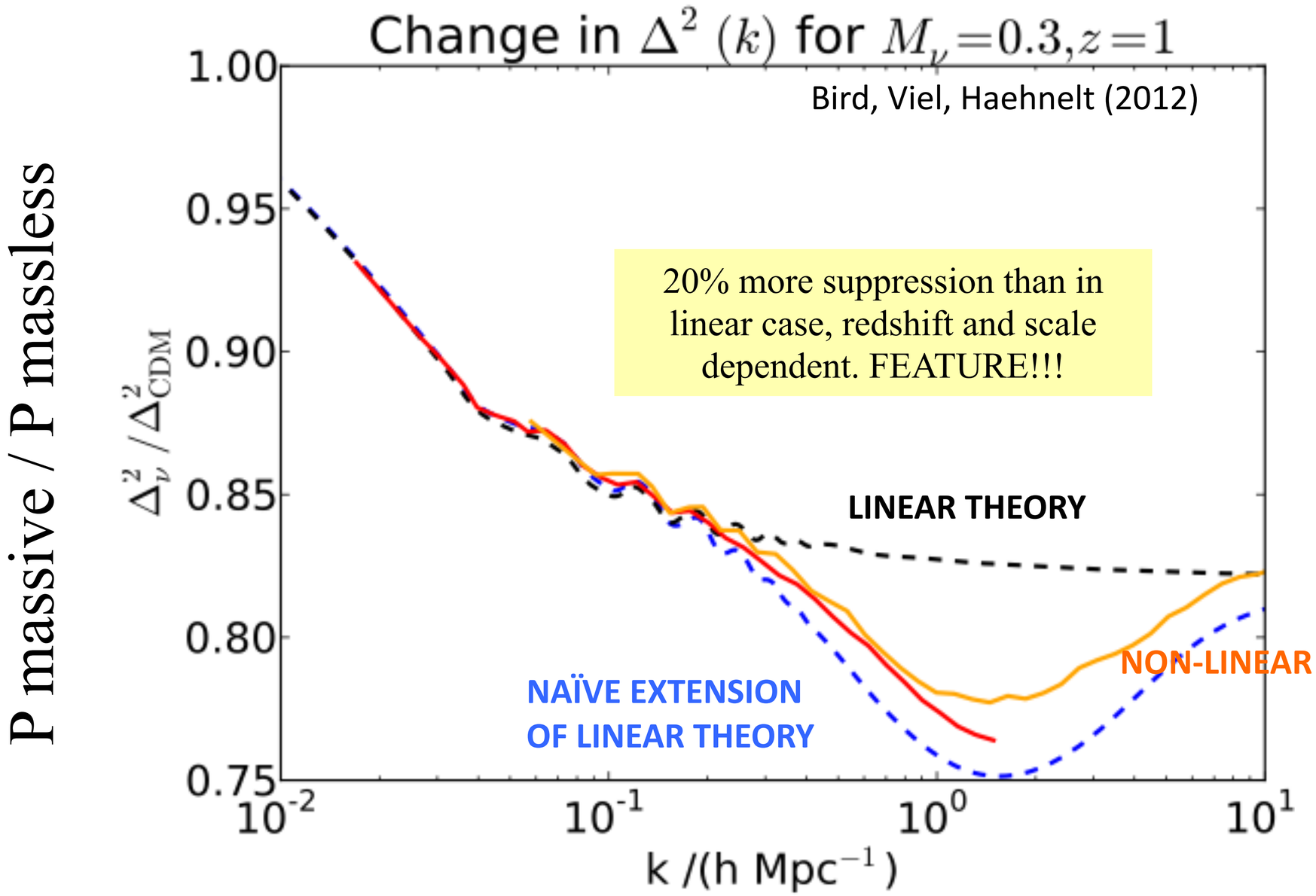


$$\alpha < 0.03\ \mathrm{Mpc}/h\ (2\sigma)$$

$$|\beta/\gamma| < 14$$

Murgia, Irsic, MV, 2018.
arXiv: 1806.08371

COSMOLOGICAL NEUTRINOS : NON-LINEAR MATTER POWER

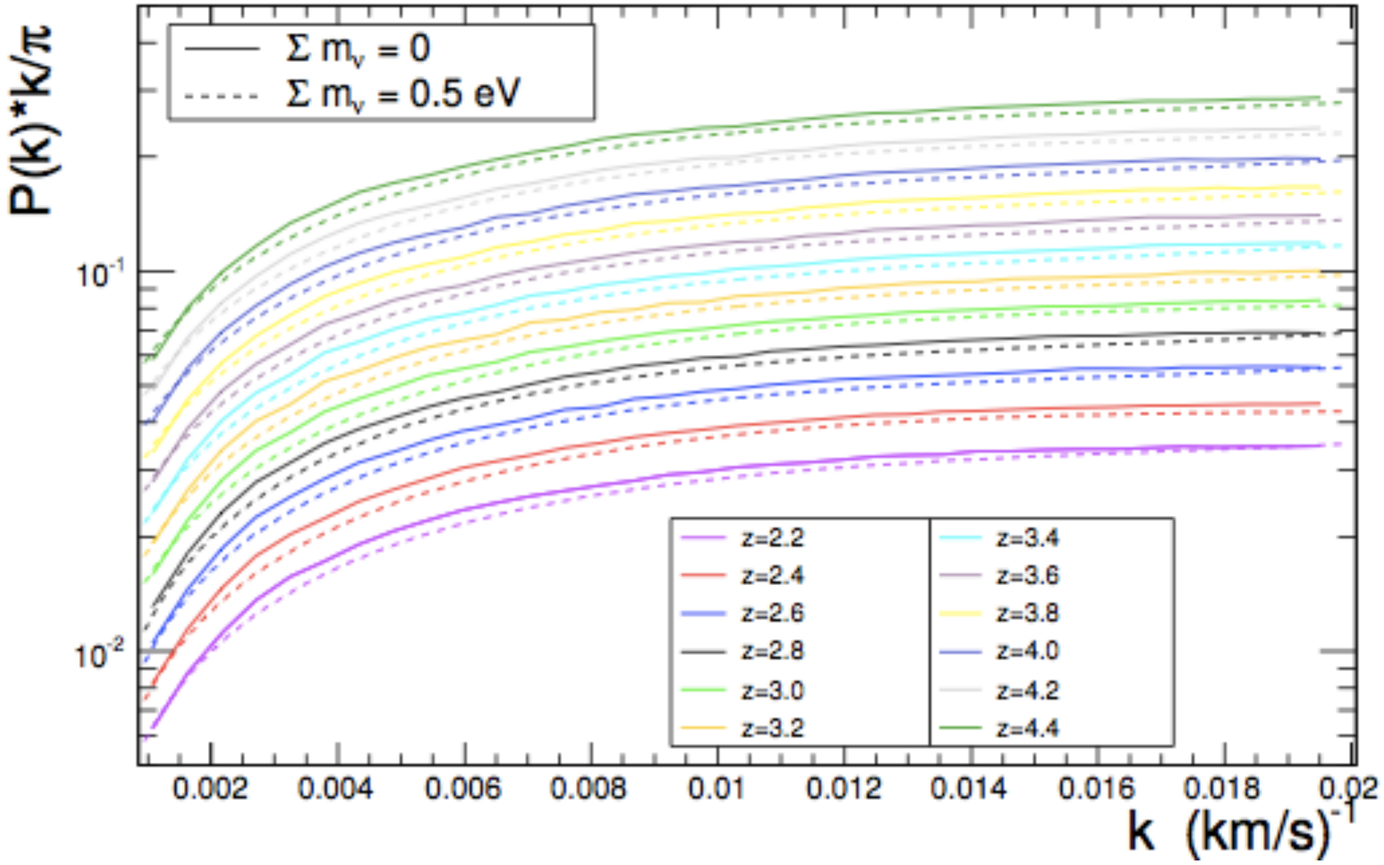


P massive / P massless

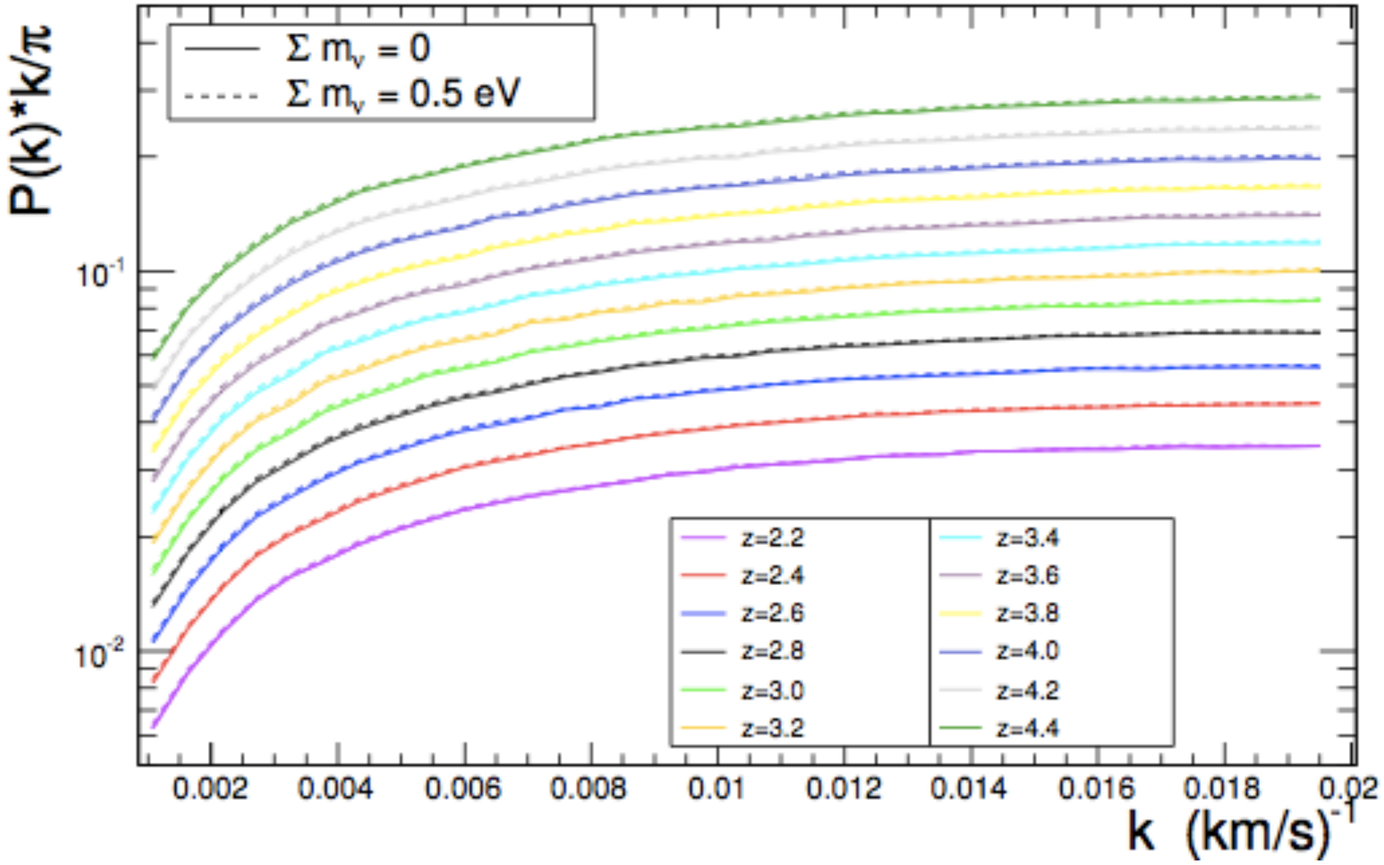
Cosmic Scale

http://www.sns.ias.edu/~spb/index.php?p=code

NEUTRINO IMPACT - I



NEUTRINO IMPACT - II

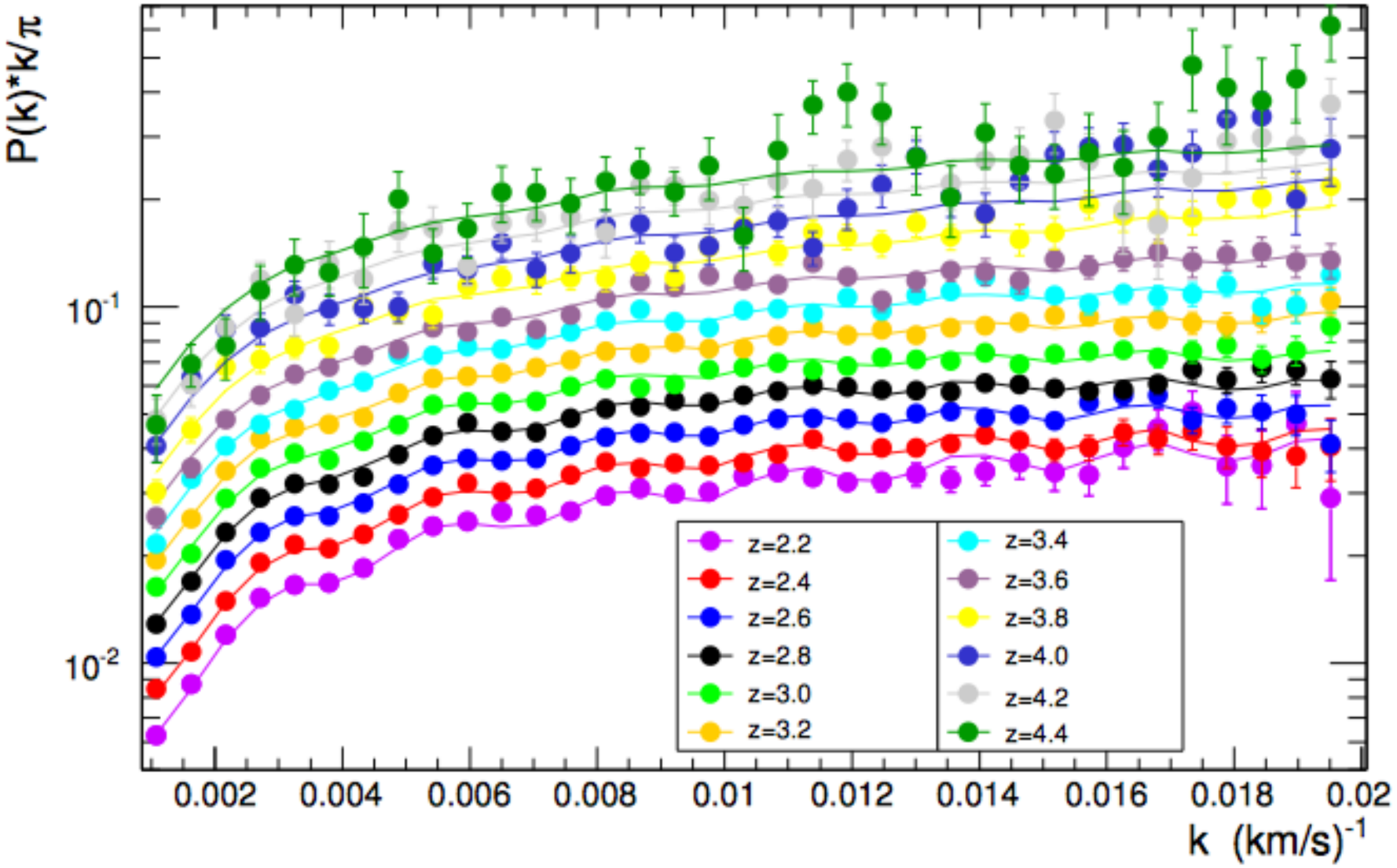


GROWTH OF STRUCTURES AT HIGH REDSHIFT

Constraint on neutrino masses from SDSS-III/BOSS Lyα forest and other cosmological probes

Nathalie Palanque-Delabrouille,[a,b] Christophe Yèche,[a] Julien Lesgourgues,[c,d,e] Graziano Rossi,[a,f] Arnaud Borde,[a] Matteo Viel,[g,h] Eric Aubourg,[i] David Kirkby,[j] Jean-Marc LeGoff,[a] James Rich,[a] Natalie Roe,[b] Nicholas P. Ross,[k] Donald P. Schneider,[l,m] David Weinberg[n]

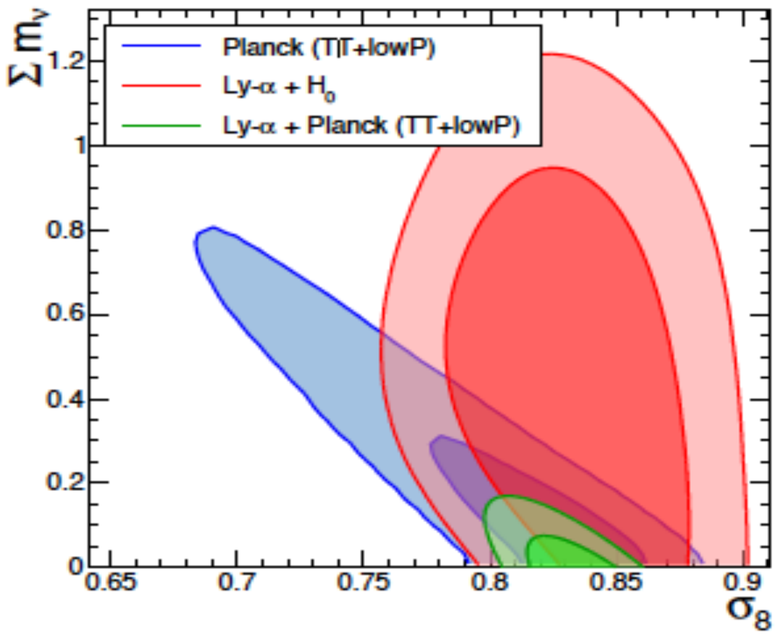
1D Flux power spectrum evolution



UPDATE using Planck 15

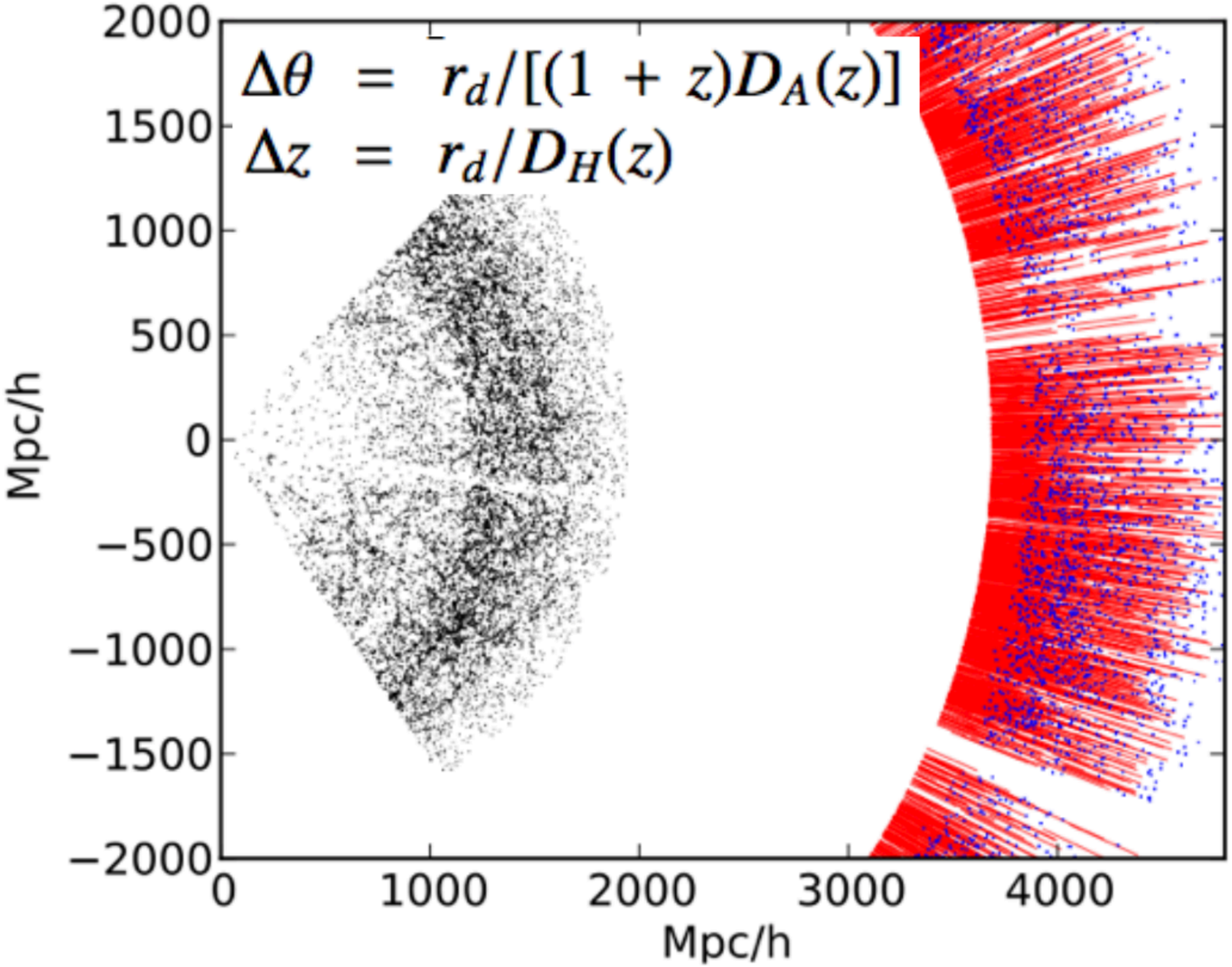
Palanque-Delabrouille+ 2015

Parameter	(1) Lyα + H_0^{Gaussian} ($H_0 = 67.3 \pm 1.0$)	(2) Lyα + Planck TT+lowP	(3) Lyα + Planck TT+lowP + BAO	(4) Lyα + Planck TT+TE+EE+lowP + BAO
σ_8	0.831 ± 0.031	0.833 ± 0.011	0.845 ± 0.010	0.842 ± 0.014
n_s	0.938 ± 0.010	0.960 ± 0.005	0.959 ± 0.004	0.960 ± 0.004
Ω_m	0.293 ± 0.014	0.302 ± 0.014	0.311 ± 0.014	0.311 ± 0.007
H_0 (km s^{-1} Mpc^{-1})	67.3 ± 1.0	68.1 ± 0.9	67.7 ± 1.1	67.7 ± 0.6
$\sum m_\nu$ (eV)	< 1.1 (95% CL)	< 0.12 (95% CL)	< 0.13 (95% CL)	< 0.12 (95% CL)
Reduced χ^2	0.99	1.04	1.05	1.05



SDSS- I

New regime to be probed with Lyman-α forest in 3D



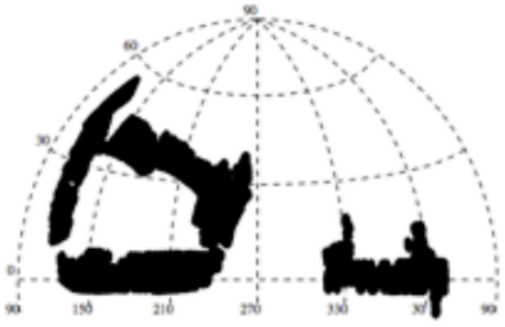
Slosar et al. 11
Busca et al. 13
Slosar et al. 13

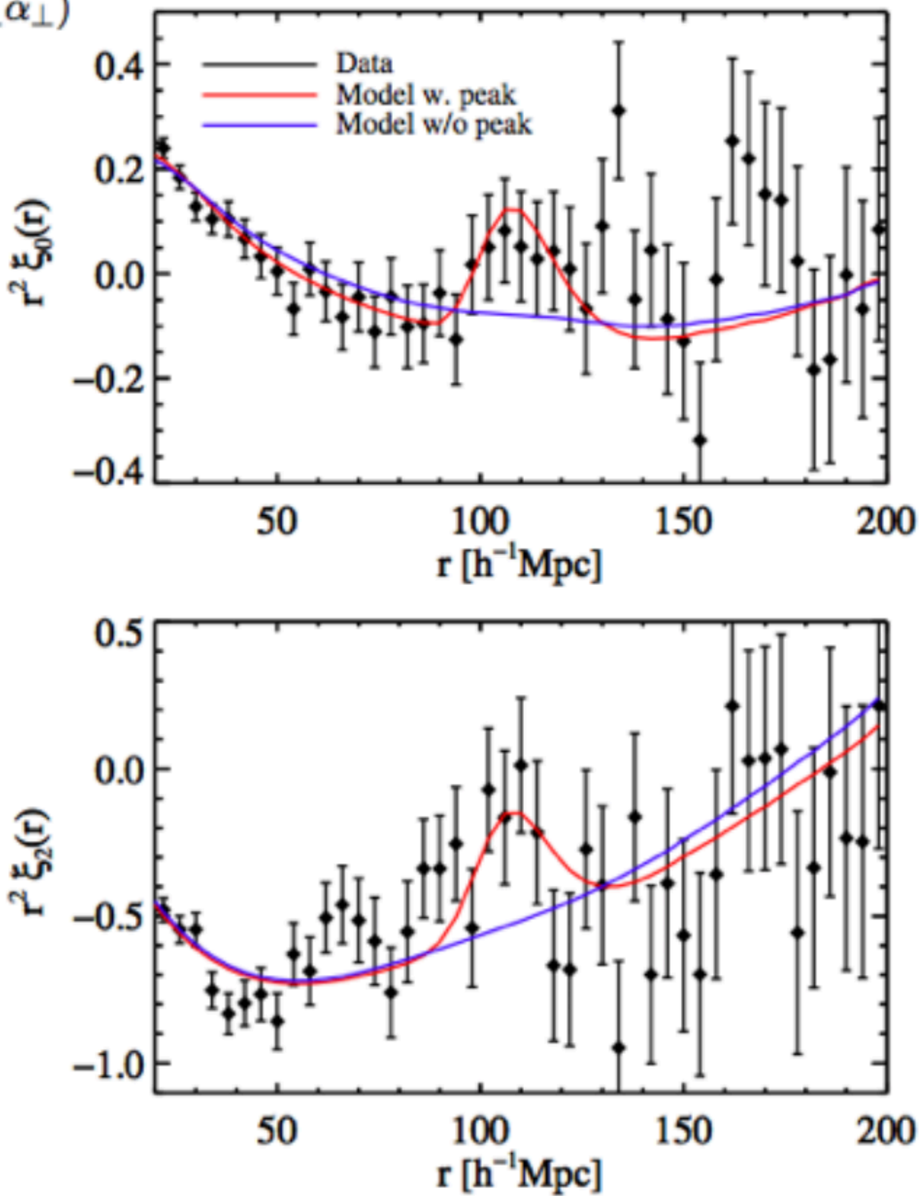
SDSS- II

Busca et al. 13

$$\xi_{\rm cosmo}(r_\parallel, r_\perp) = \xi_{\rm smooth}(r_\parallel, r_\perp) + a_{\rm peak} \cdot \xi_{\rm peak}(r_\parallel \alpha_\parallel, r_\perp \alpha_\perp)$$

$$\xi(r_\parallel, r_\perp) = \xi_{\rm cosmo}(r_\parallel, r_\perp, \alpha_\parallel, \alpha_\perp) + \xi_{\rm bb}(r_\parallel, r_\perp)$$





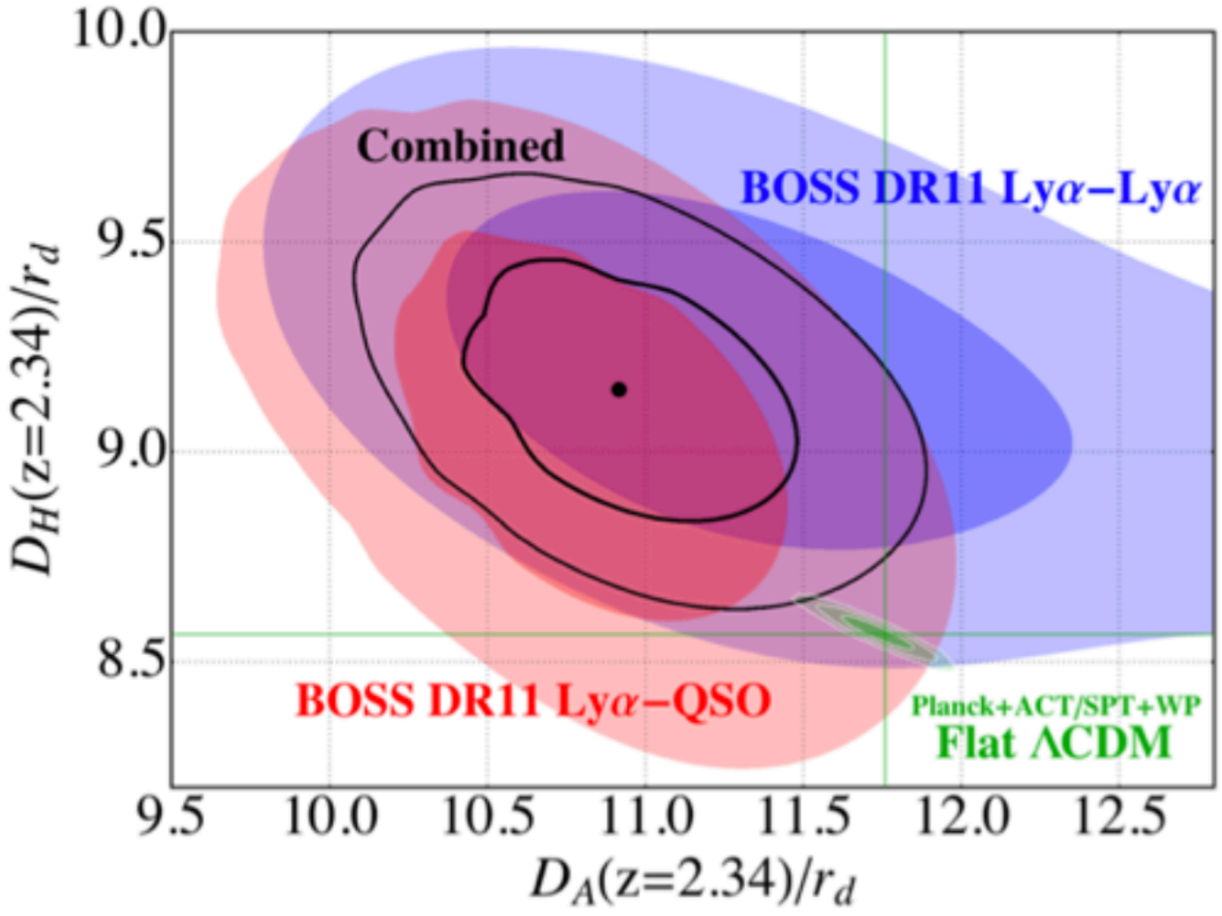
BAO feature detected at z=2.3
From 3000 deg^2, using 50000 QSOs
Significance of the detection at around 3σ

SDSS-III

$$P_{qF}(\mathbf{k}) = b_q \left[1 + \beta_q \mu_k^2\right] b_F \left[1 + \beta_F \mu_k^2\right] \; P(k)$$

6% precision measurement of D_A/r_d

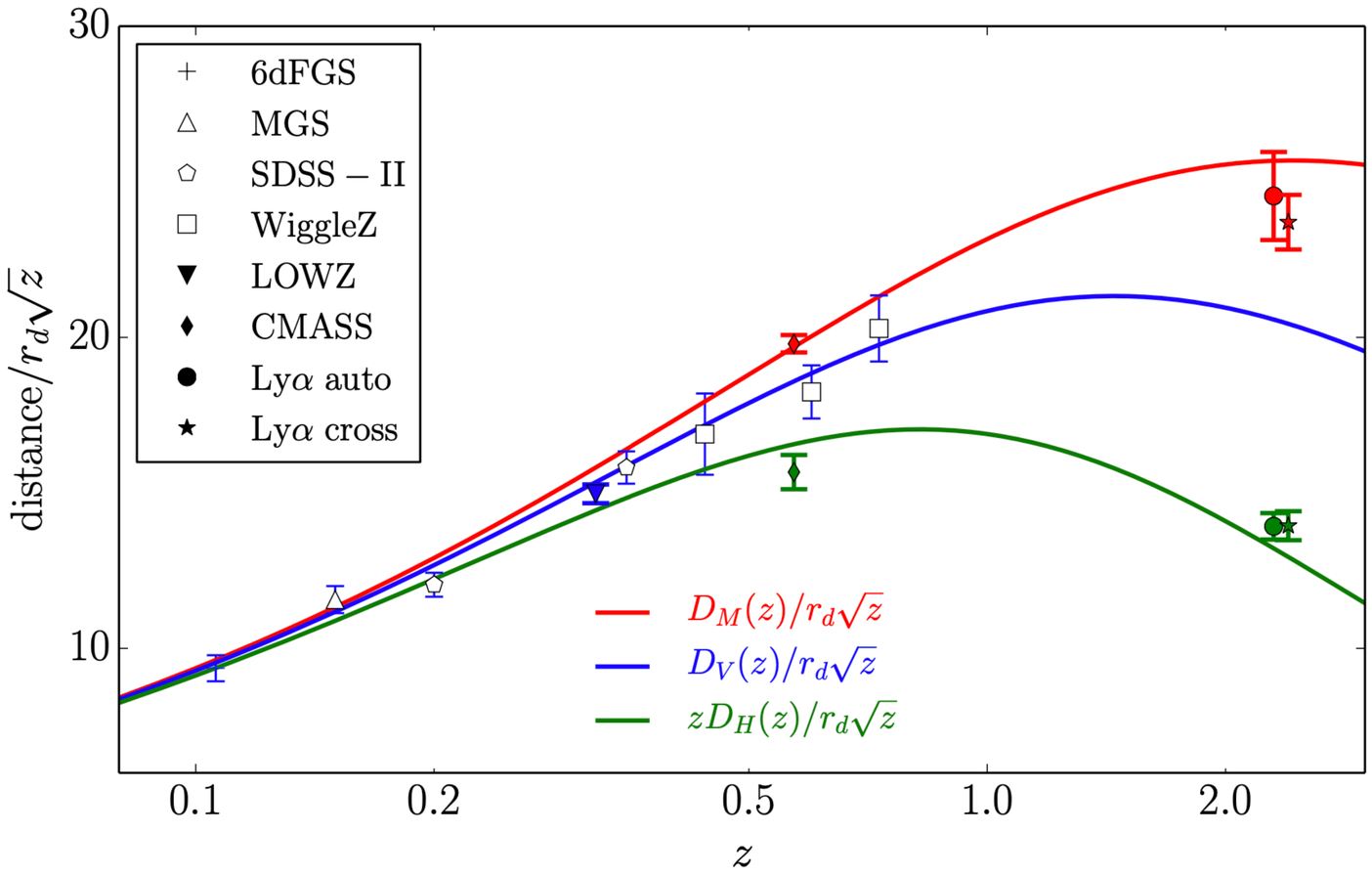
3% precision measurement of D_H/r_d



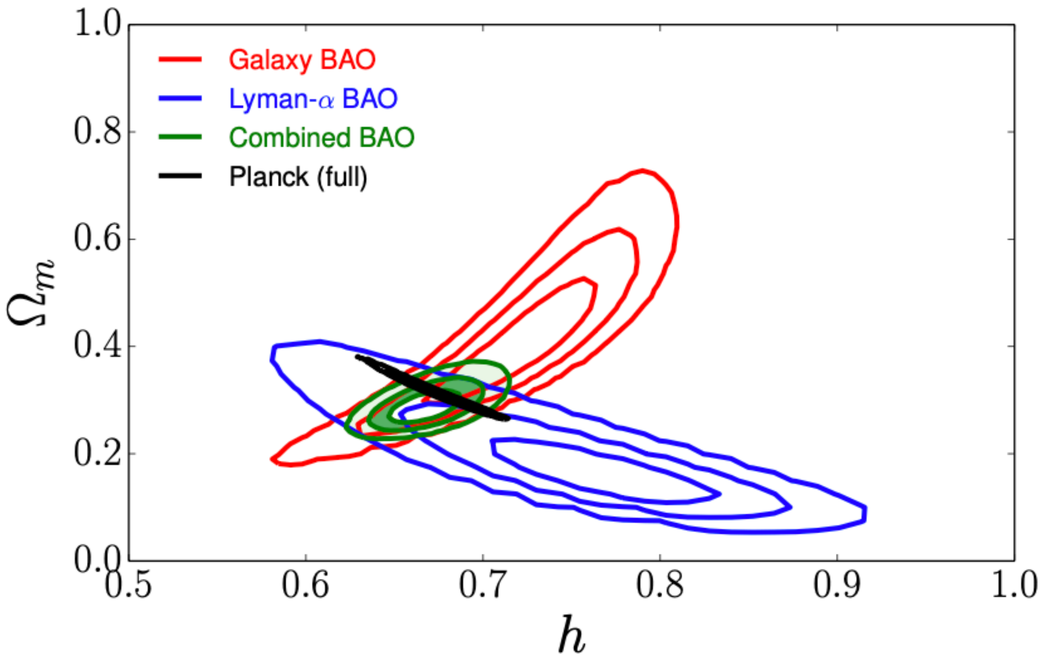
Delubac et al. 14

BAOs

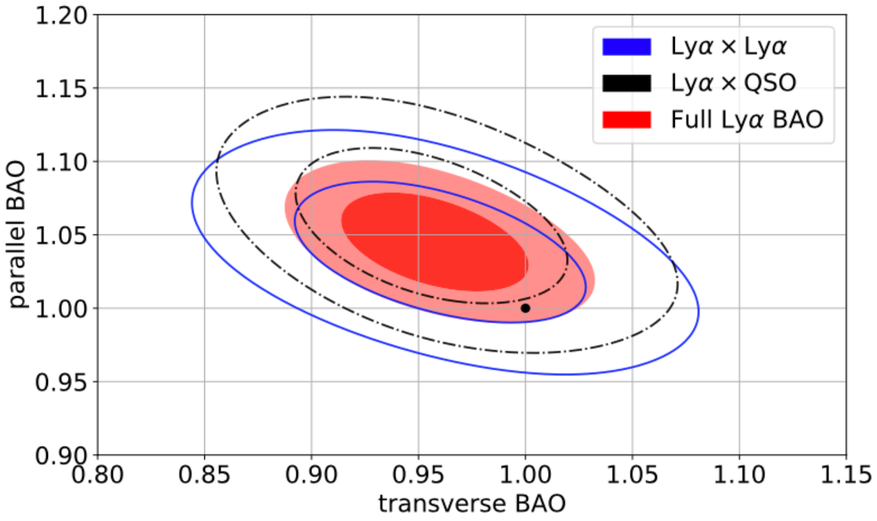
Aubourg+15

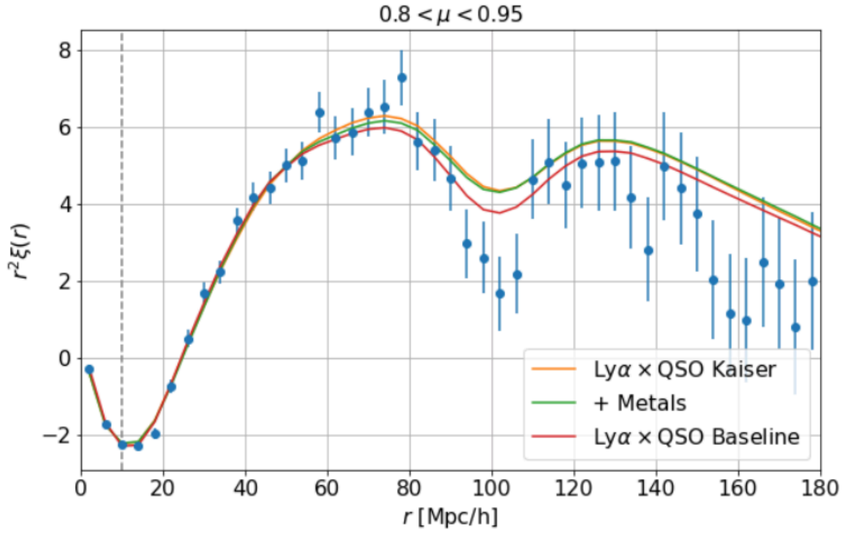


BAOs constraining power



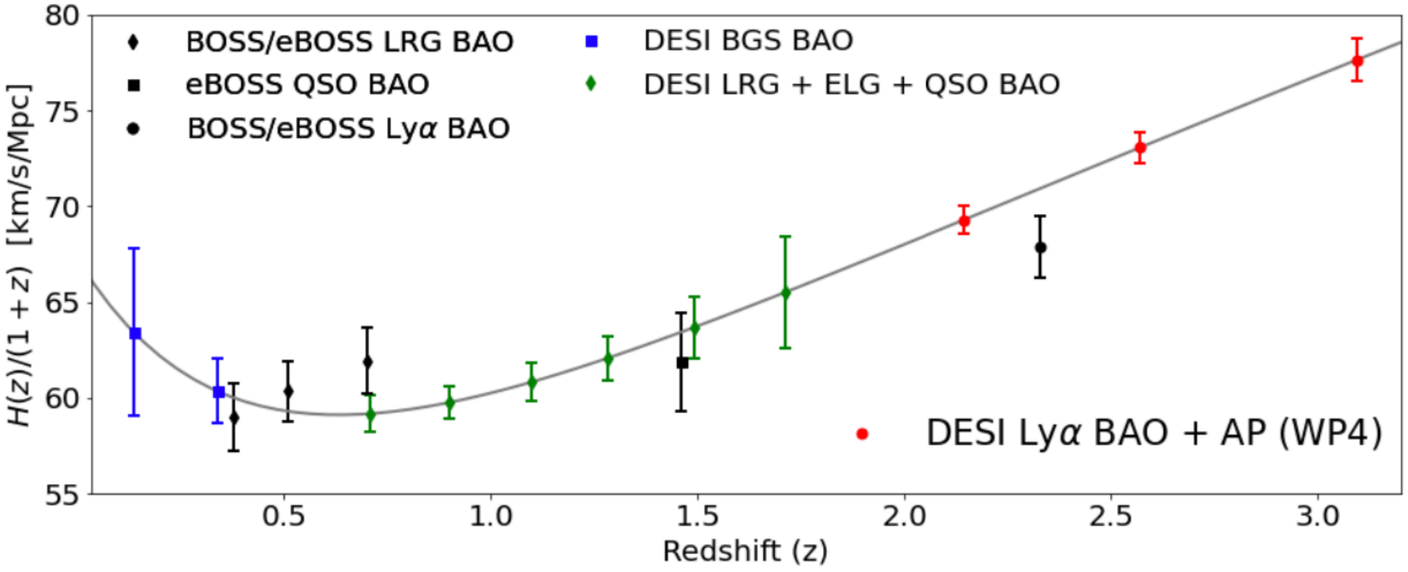
Lyman-alpha BAO





Du burboux+21

DESI forecasts: real data coming soon (2023 YR data release)



SUMMARY

- HI important cosmic tracer to perform **quantitative cosmology** especially at high redshift.
- HI in absorption as seen from the Lyman-alpha forest - main IGM manifestation ---> probe of the small scale structure
- But also ~100 Mpc scale in 3D --> BAO feature detected 10yrs ago in auto correlation and crosss with QSO
- IGM established probe of the dynamical and geometrical state of the Universe at high-z
- Wide set of scientific questions like DM nature, neutrinos, BAO, early dark energy models etc.
- No support for new physics
- Exciting times ahead with DESI, WEAVE and (more in the future) ANDES or other spectroscopic "Stage V" facilitie