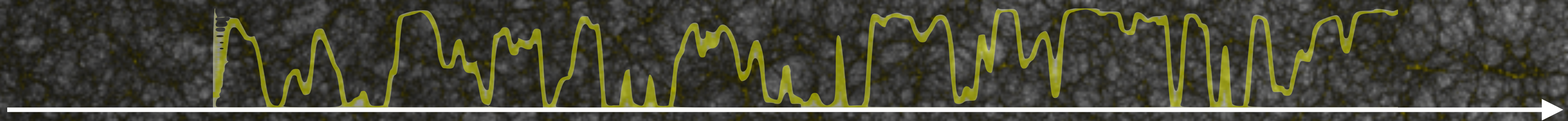
Fundamental Physics with the Intergalactic Medium



Matteo Viel – SISSA (Trieste)

03/07/2018 – SCIENCE WITH THE E-ELTs

Euclid Flagship simulation

OUTLINE

- Overview of data and simulations
- Recent results from BOSS/SDSS-III on BAO (geometry)
- Neutrinos
- Dark matter at small scales: Fuzzy dark matter constraints
- A more general approach to constrain DM properties

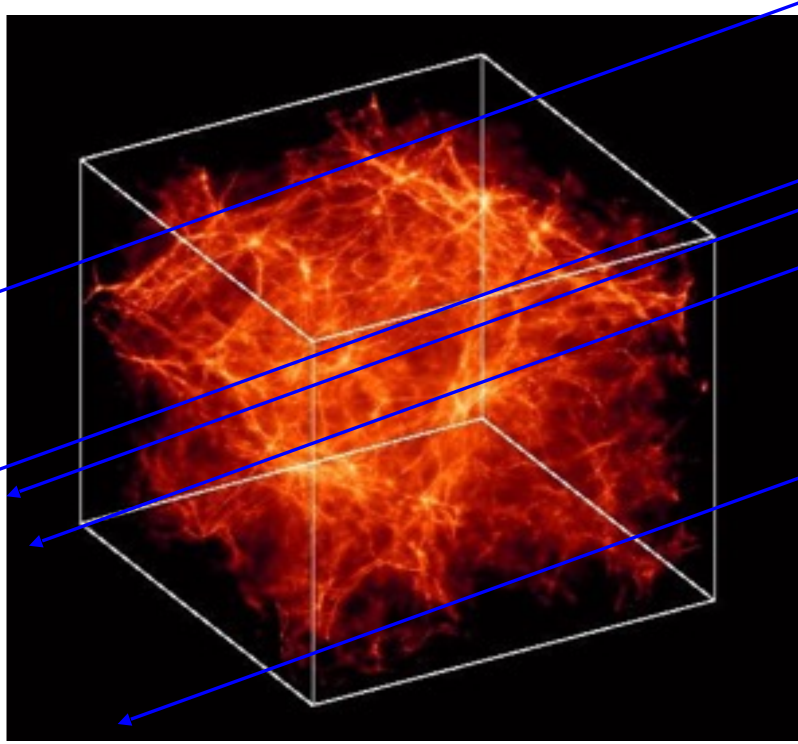
QUANTITATIVE IGM COSMOLOGY

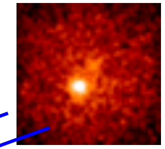
1) It probes the dynamical growth at the **smallest scales** (LCDM crisis? LCDM extensions?)

2) …but also **large scales** via BAO geometrical measurements (Lya-Lya or cross correlations Quasar-Lya)

3) IGM sink and reservoir of baryons test bed for **galaxy formation** feedback models

The Intergalactic Medium: Theory vs. Observations





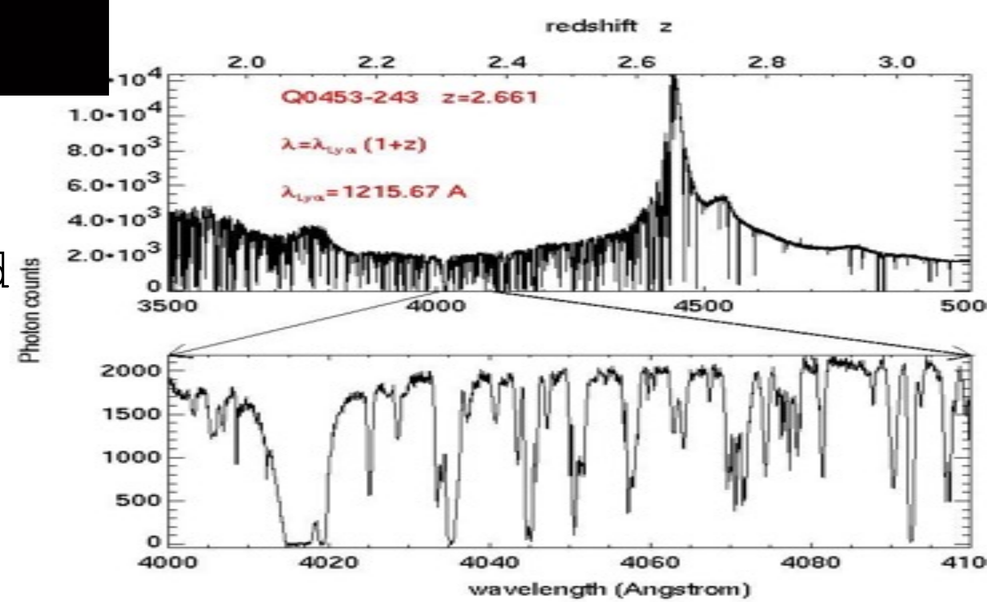
80% of the baryons at z=3 are in the **Lyman-α forest**

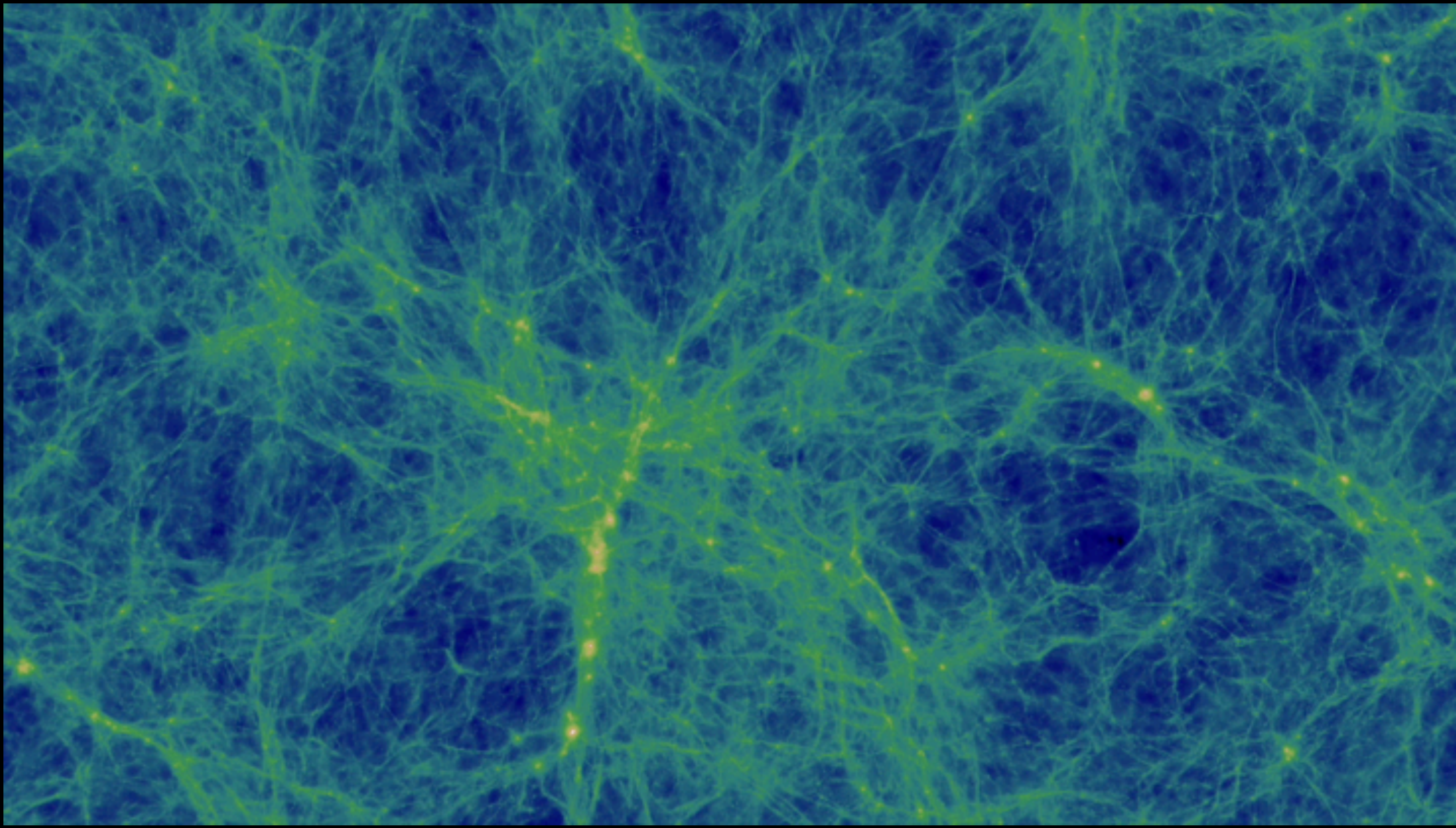
Bi & Davidsen (1997), Rauch (1998)
Review by Meiksin (2009), McQuinn (2015)

baryons as tracer of the dark matter density field

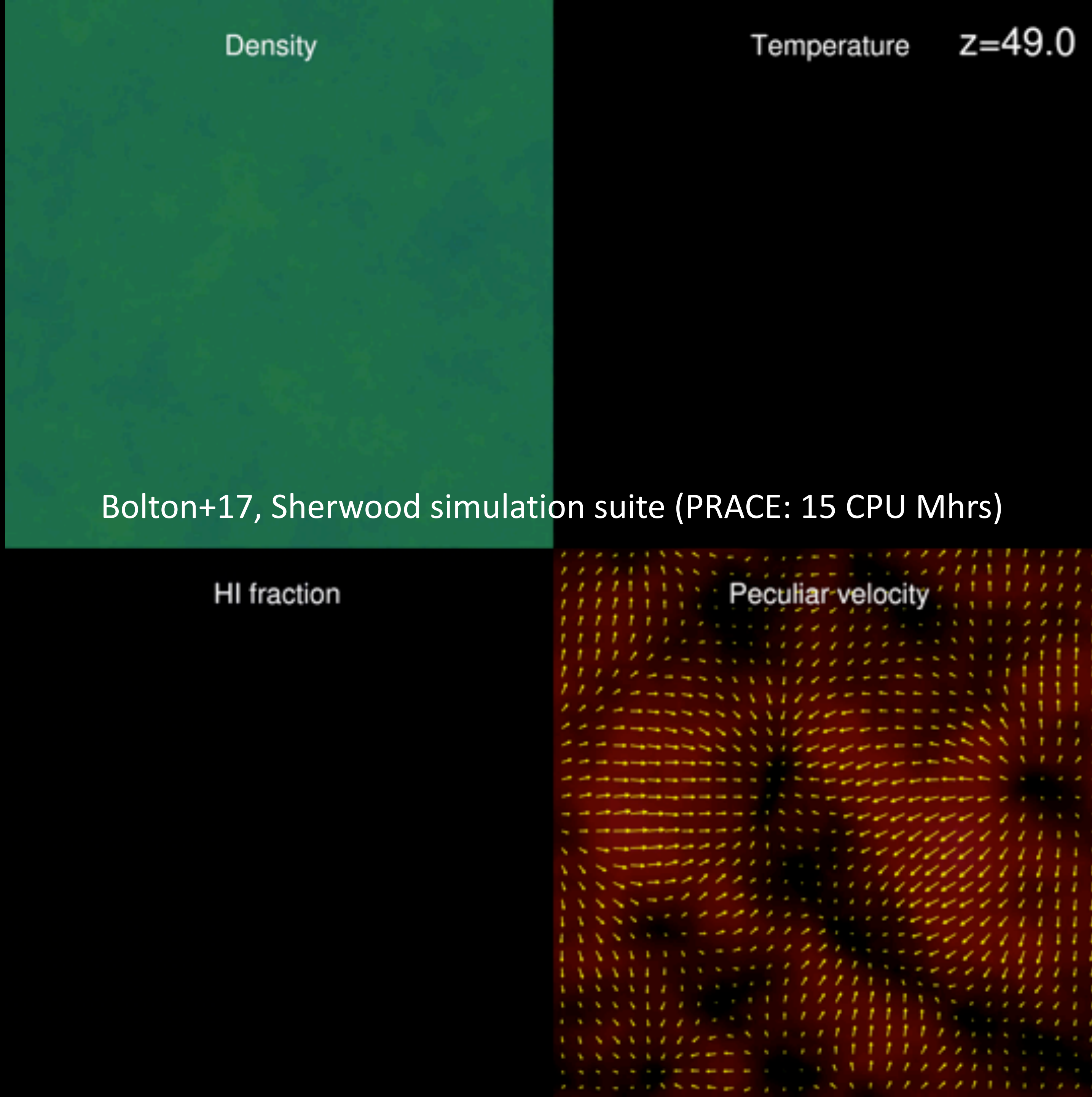
$\delta_{IGM} \sim \delta_{DM}$

Croft+ 99,02
MV+ 04
McDonald+ 01,03





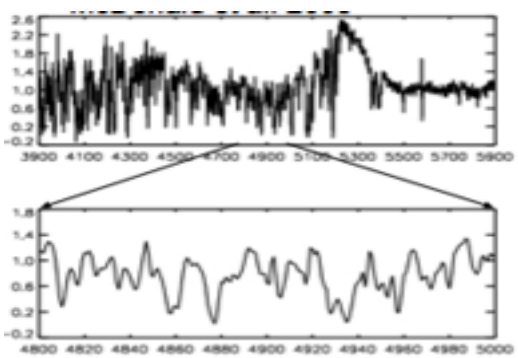
Bolton+17, Sherwood simulation suite (PRACE: 15 CPU Mhrs)



Bolton+17, Sherwood simulation suite (PRACE: 15 CPU Mhrs)

COSMOLOGY WITH QSO SPECTRA

BOSS/SDSS-III



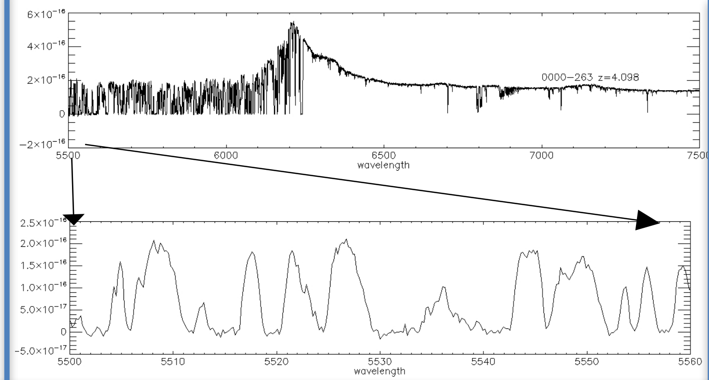
Low resolution BOSS and SDSS-III spectra S/N~2-3 – 160,000 spectra

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
Palanque-Delabrouille+15
Seljak+06, Baur+16, Yeche+17

XQ-100



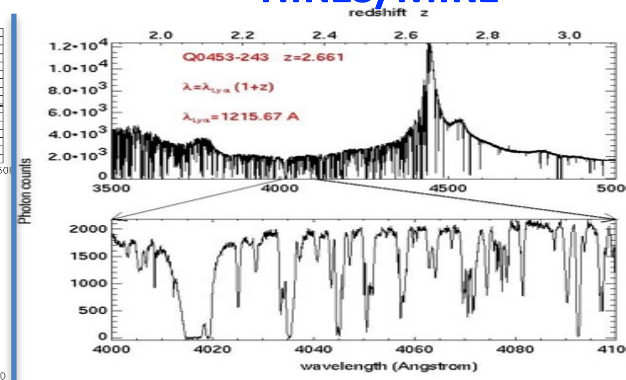
Medium resolution X-Shooter VLT spectra S/N ~ 30

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

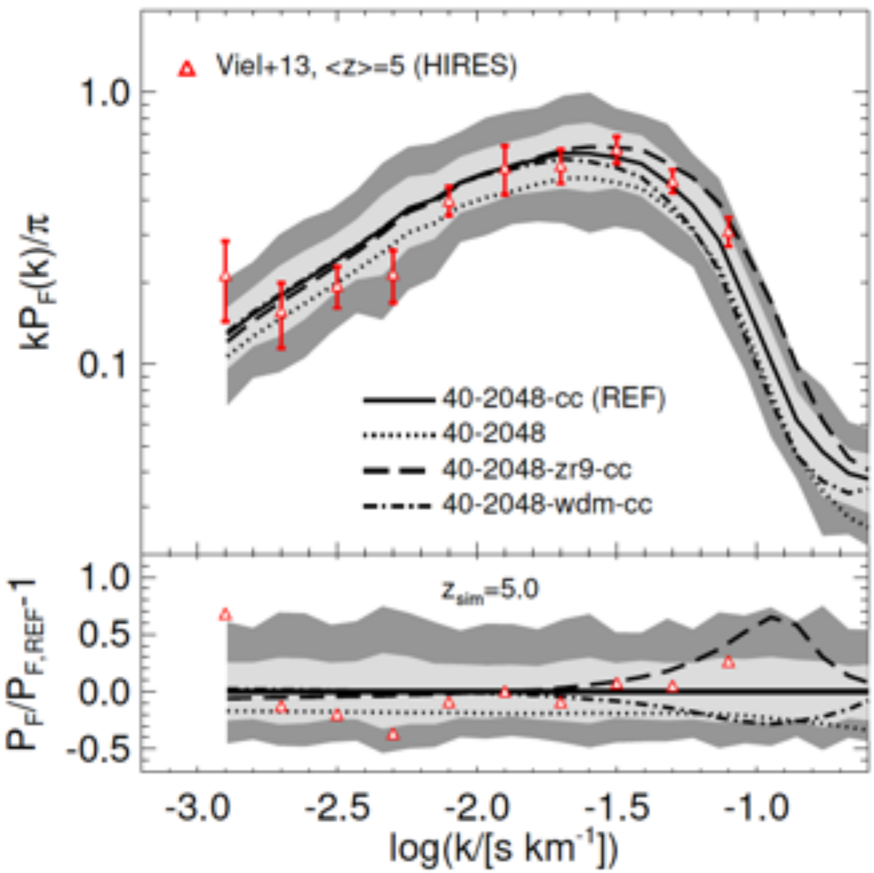
Two scientific cases for future spectrographs

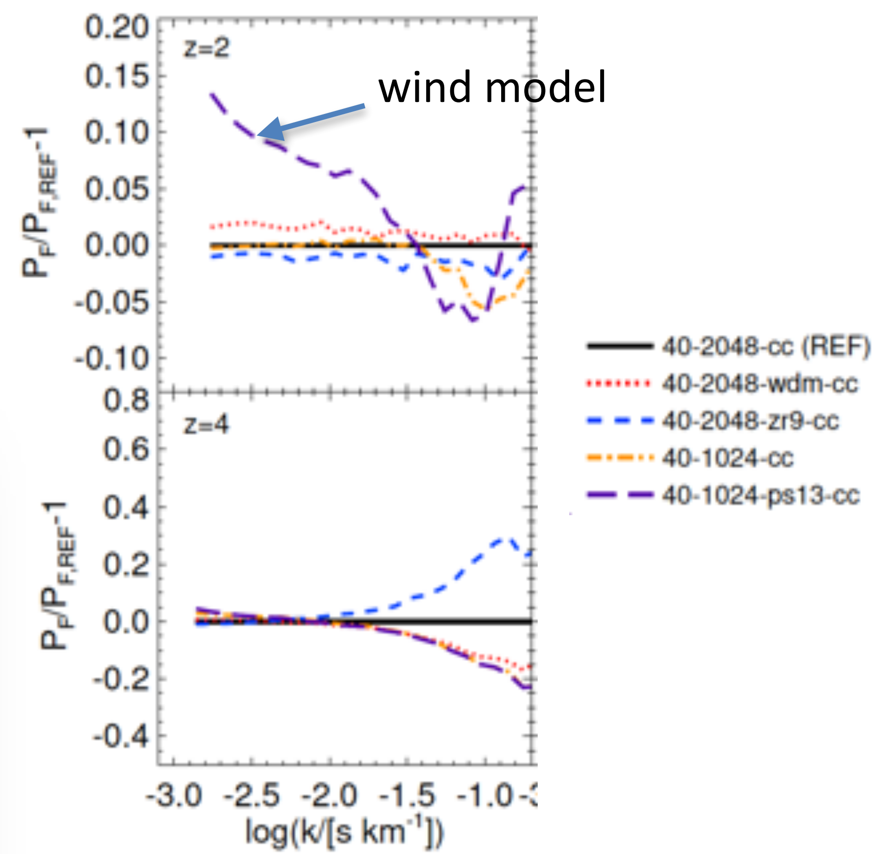
High redshift:
constraining reionization

error dominated by statistics

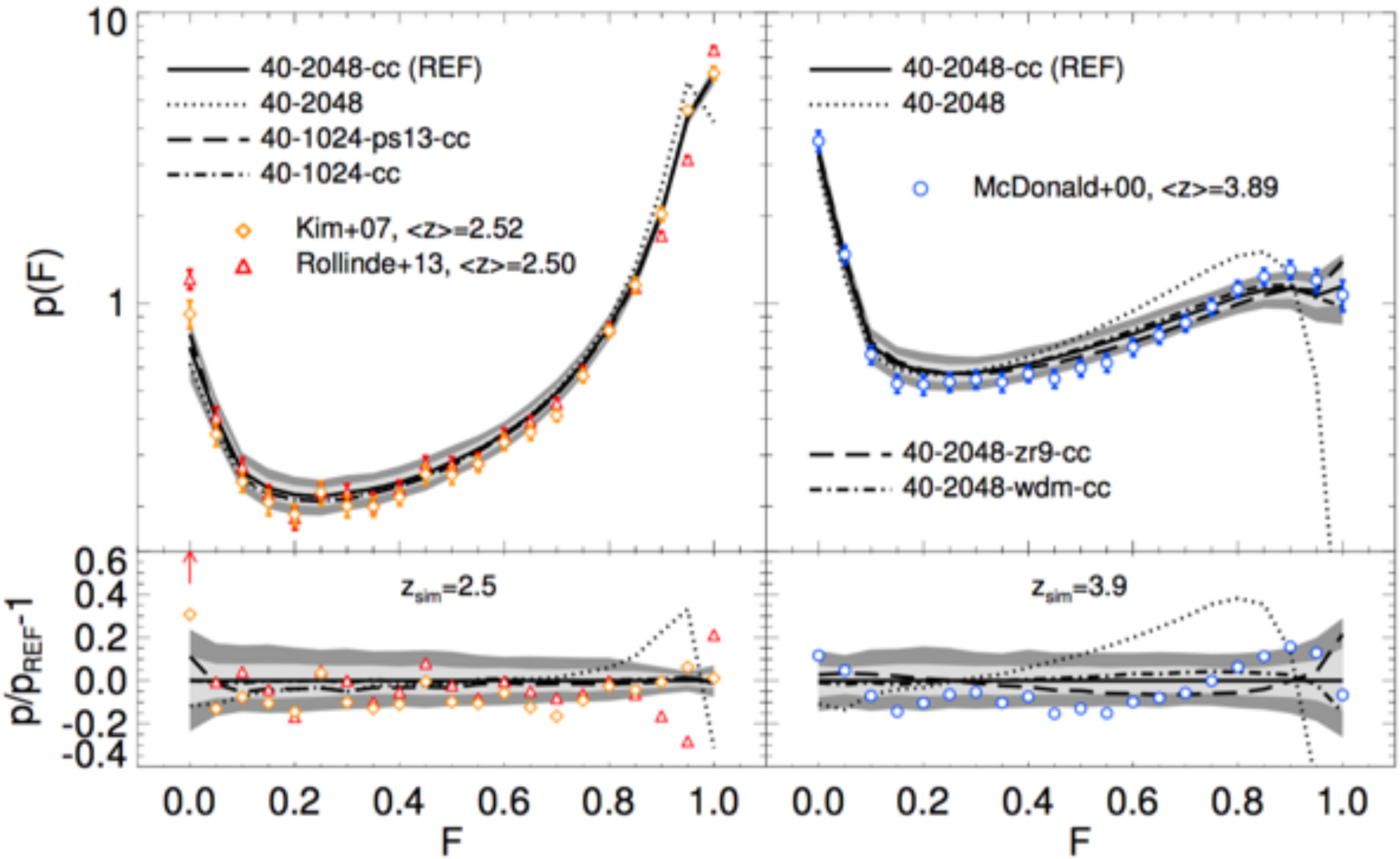
Low redshift:
constraining feedback

error dominated by systematics





Things that do not work perfectly: flux pdf



Flux one point distribution function quite difficult to fit for some known reason (continuum fitting poorly modelled) and some other effect (T-rho diagram more complex than expected?)

Better estimate of the continuum from HIRES @ E-ELT QSO spectra?

Two key *unique* aspects

$$P_{1D}(k) = \frac{1}{2\pi}\int_k^\infty P_{3D}(x)xdx$$

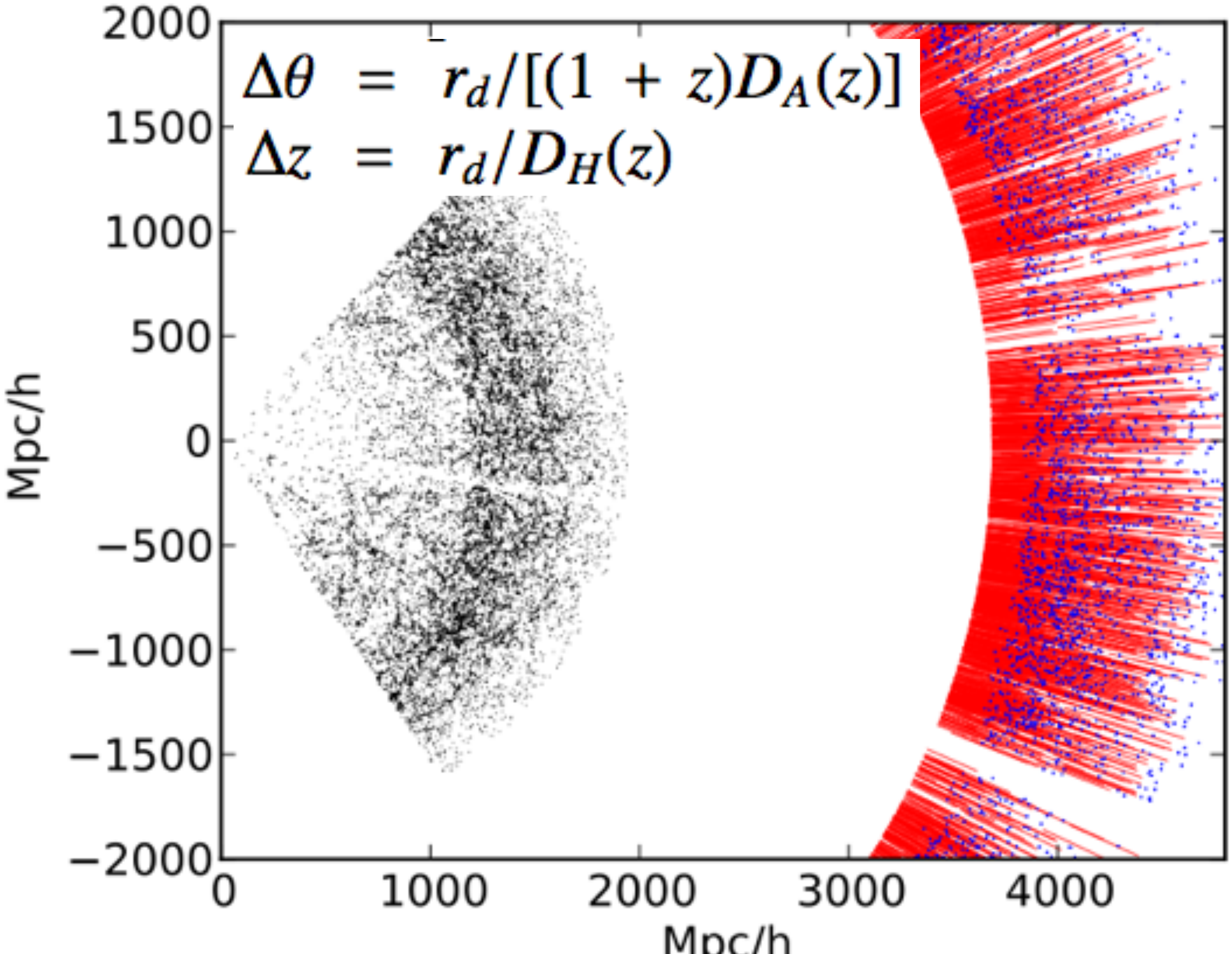
High redshift (and small scales):
possibly closer to linear behaviour

RESULTS FROM BOSS/SDSS-III

BAOs at z=2.3

SDSS/BOSS - I

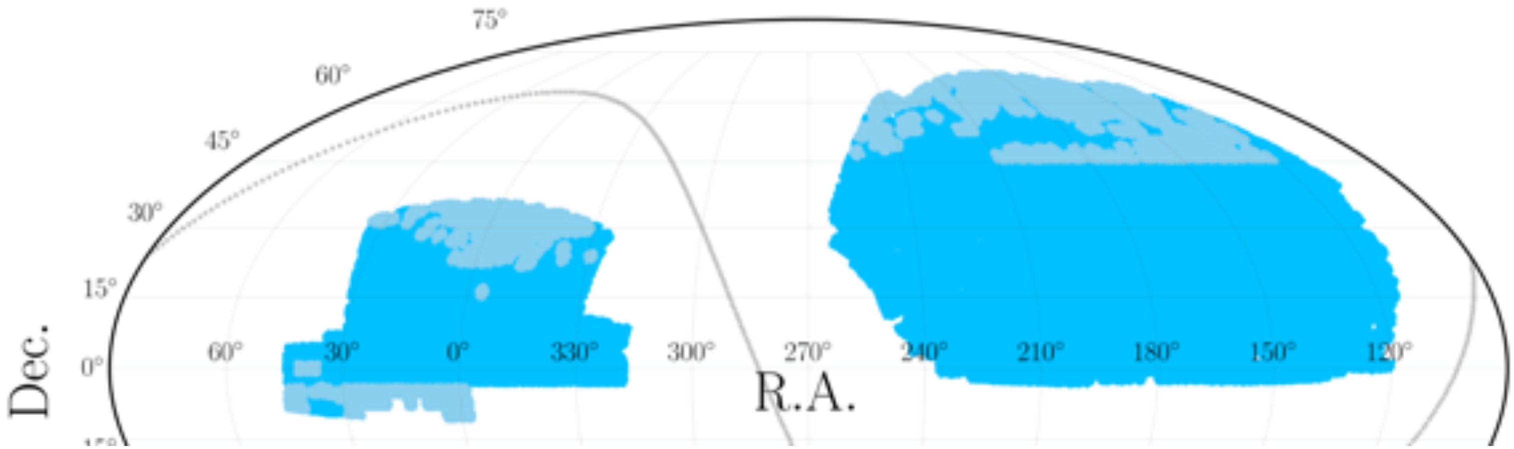
New regime to be probed with Lyman-α forest in 3D

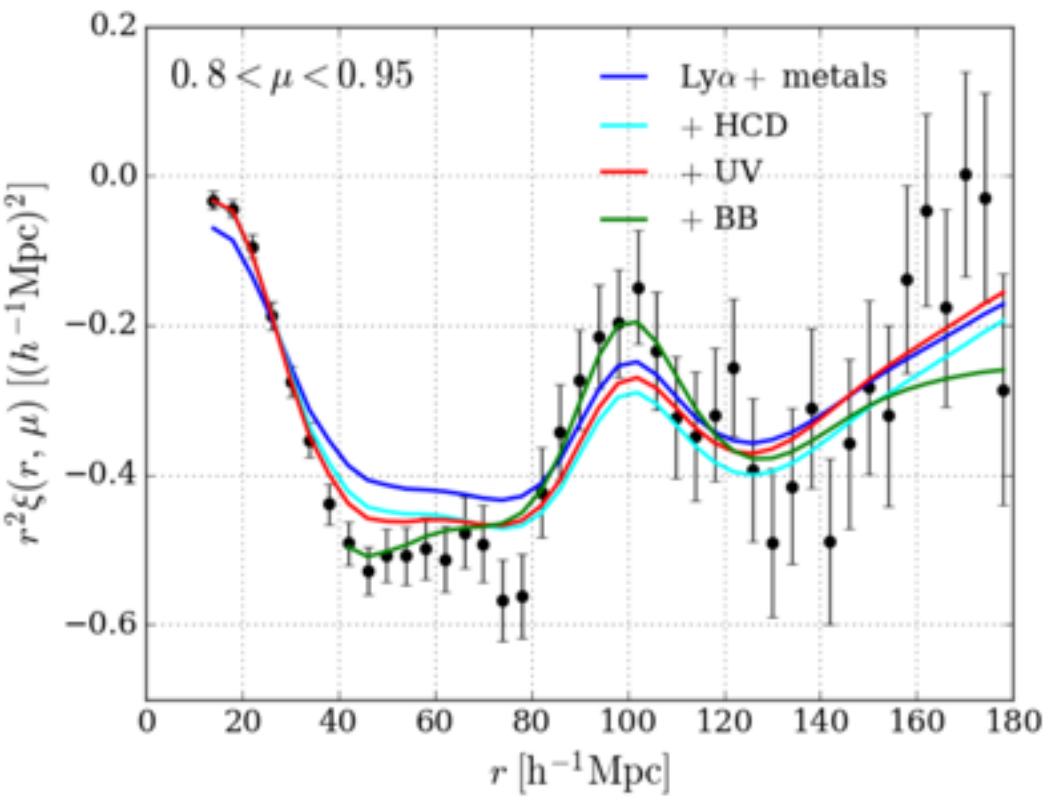


Slosar et al. 11
Busca et al. 13
Slosar et al. 13

SDSS/BOSS-II: final data release

Bautista+ 17, arXiv: 1702.00176





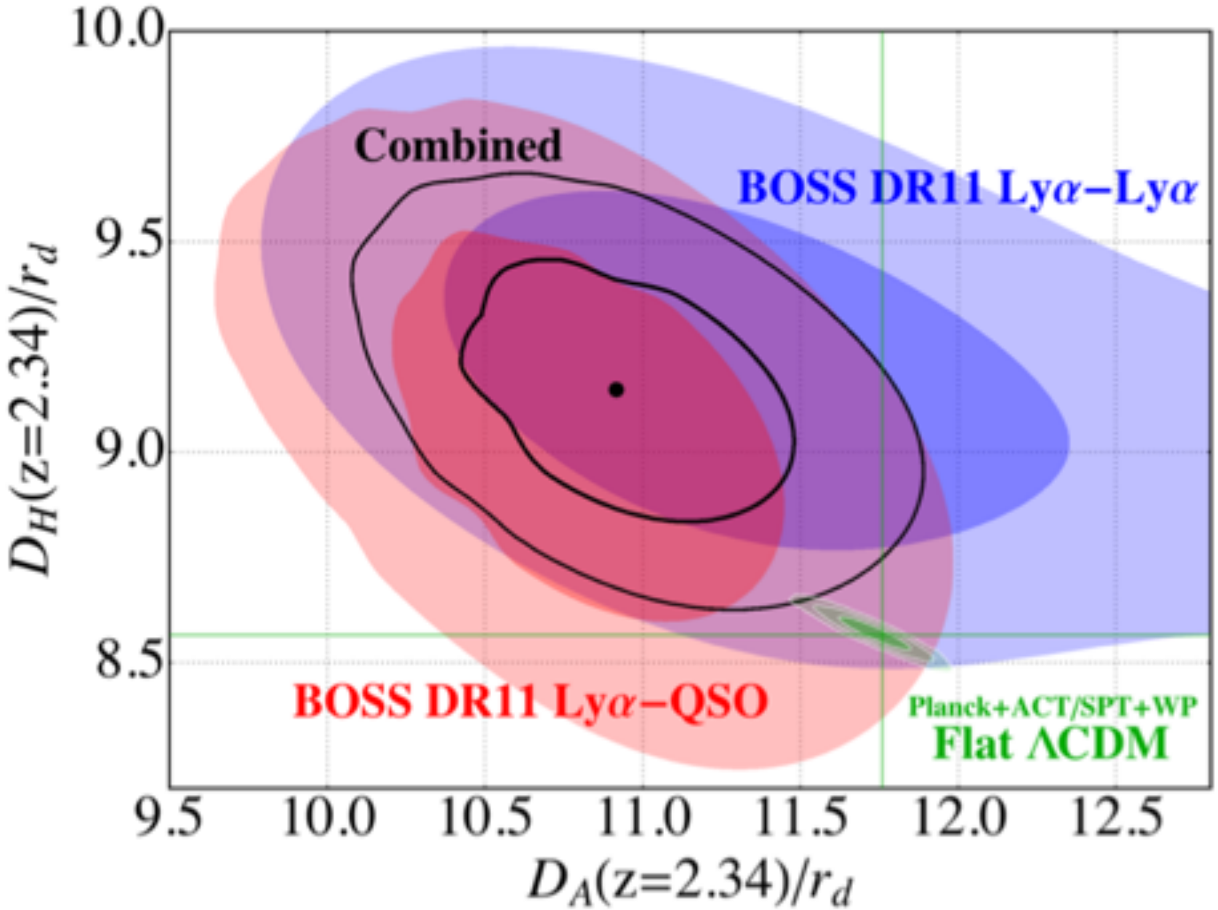
Flux correlation function in mu bin (nearly parallel to line-of-sight)

SDSS/BOSS-III: cross-correlation with QSOs

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

6% precision measurement of D_A/r_d

3% precision measurement of D_H/r_d

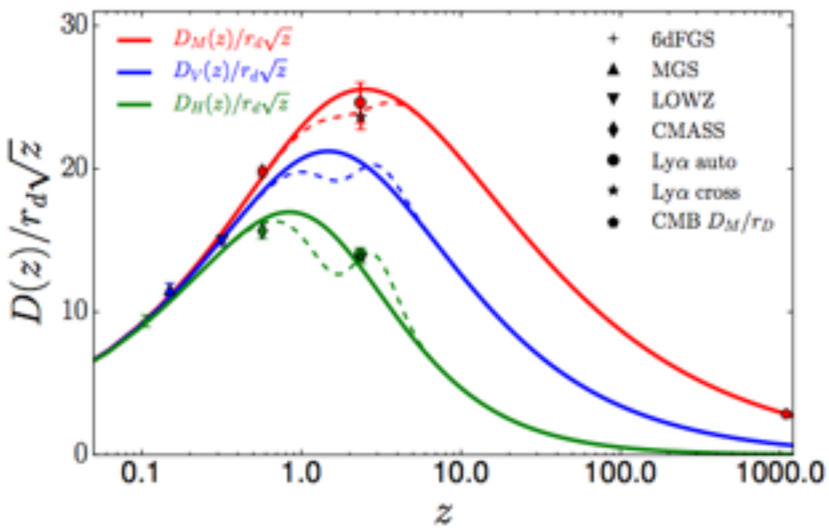


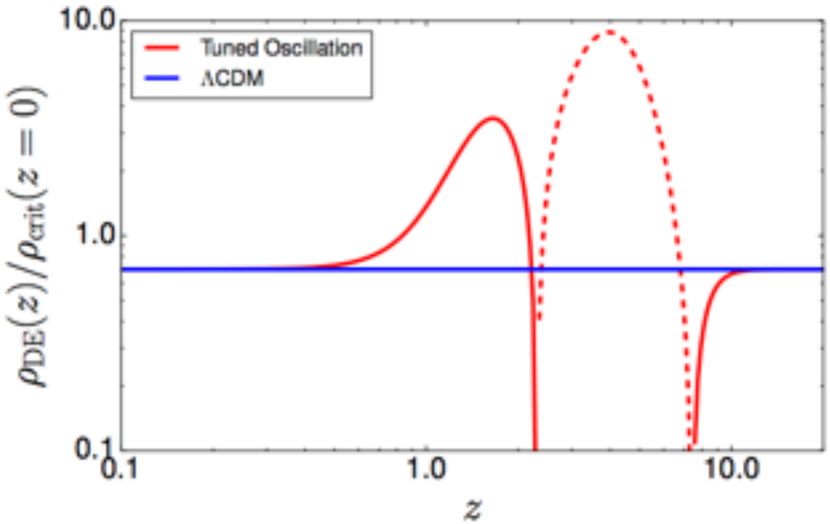
Delubac et al. 14

Lyman-alpha BAO: a tuned oscillation?

$\Delta\chi^2$=-6.6 with 3 d.o.f. for this model

Aubourg+15

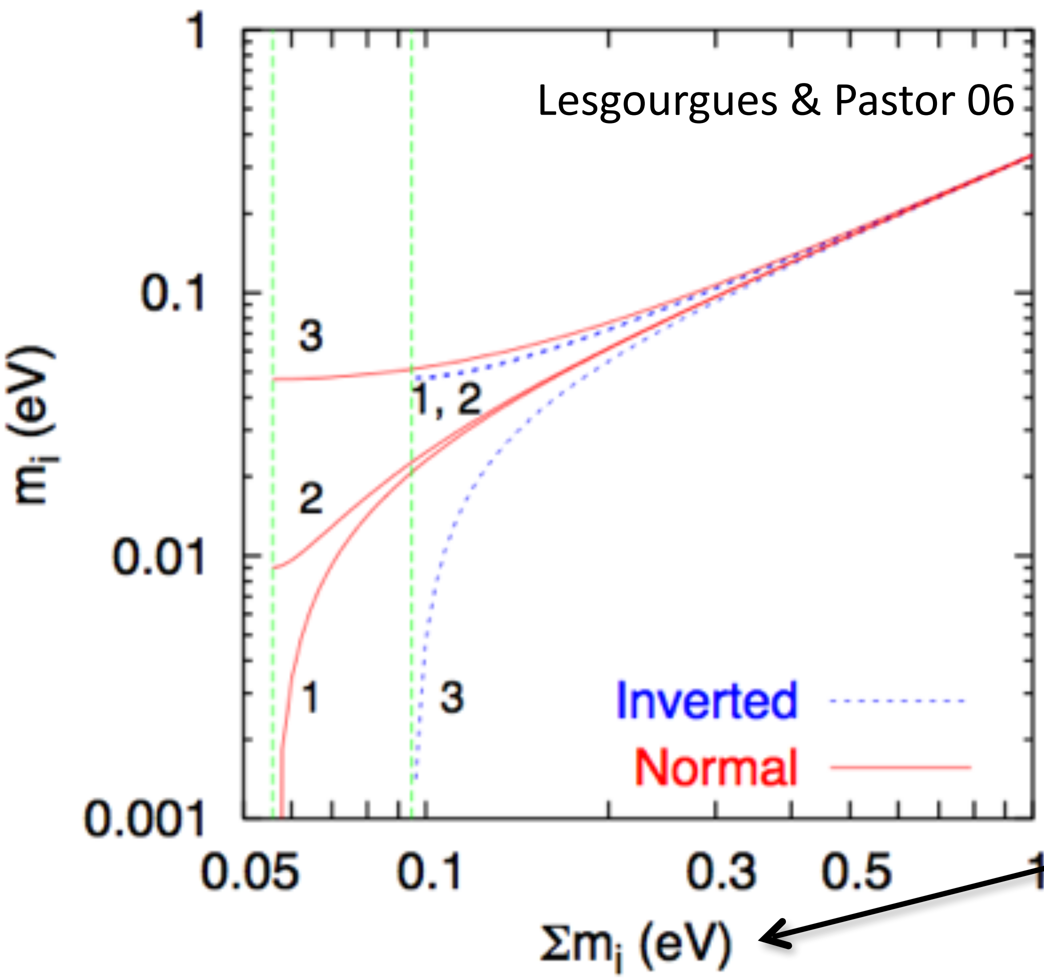




Anze Slosar

NEUTRINOS

COSMOLOGICAL NEUTRINOS - I: STARTING POINT



COSMOLOGY

constraints on the sum of the neutrino masses

$$0.056\,(0.095)\ \text{eV} \lesssim \sum_i m_i \lesssim 6\ \text{eV}$$

COSMOLOGICAL NEUTRINOS - II: FREE-STREAMING SCALE

Neutrino thermal velocity

$$v_{\rm th} \equiv \frac{\langle p \rangle}{m} \simeq \frac{3T_\nu}{m} = \frac{3T_\nu^0}{m}\left(\frac{a_0}{a}\right) \simeq 150(1+z)\left(\frac{1\,{\rm eV}}{m}\right)\,{\rm km\,s^{-1}}$$

Neutrino free-streaming scale

$$k_{FS}(t) = \left(\frac{4\pi G\bar{\rho}(t)a^2(t)}{v_{\rm th}^2(t)}\right)^{1/2}$$

Scale of non-relativistic transition

$$k_{\rm nr} \simeq 0.018\;\Omega_{\rm m}^{1/2}\left(\frac{m}{1\,{\rm eV}}\right)^{1/2} h\,{\rm Mpc}^{-1}$$

THREE COSMIC EPOCHS

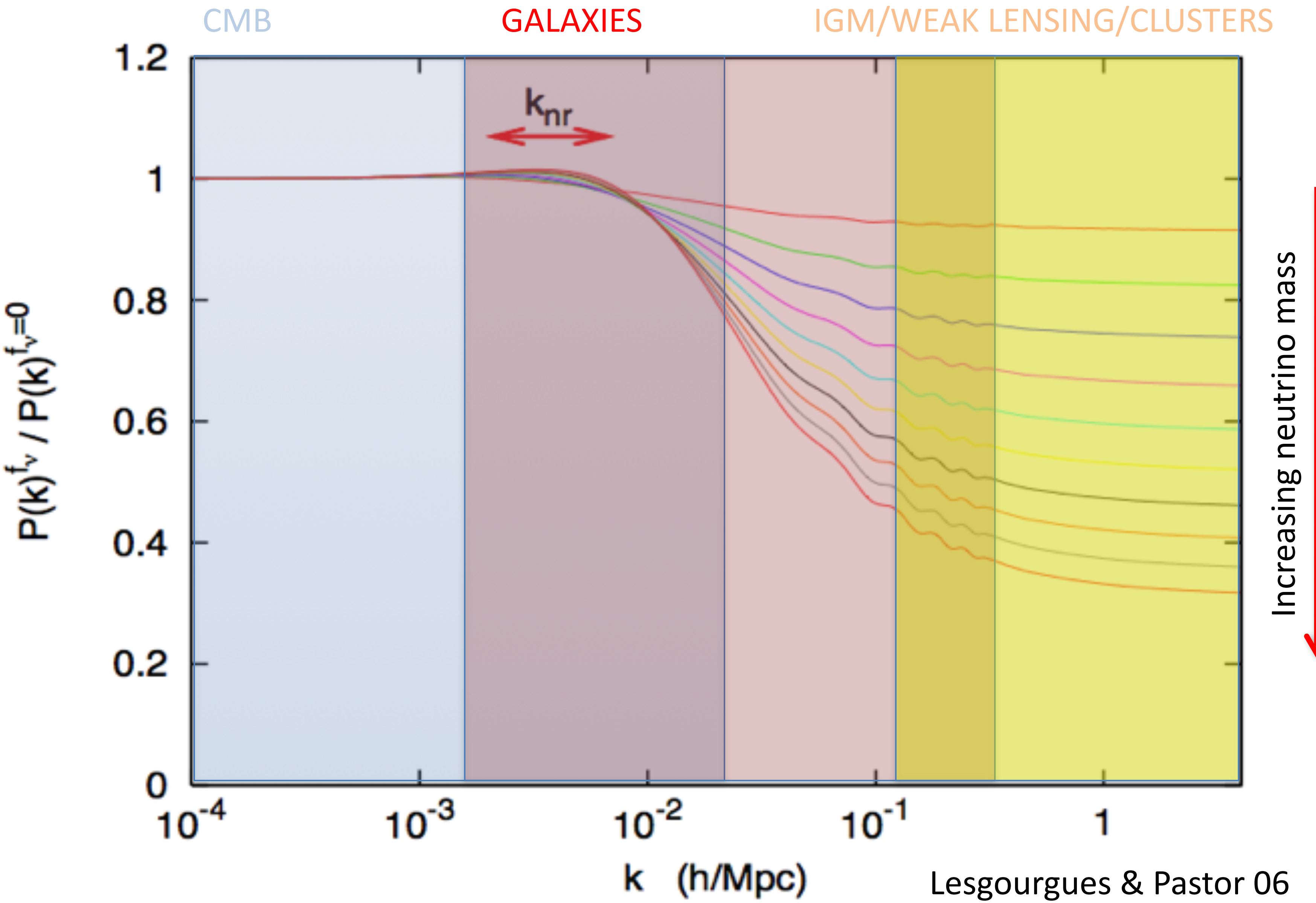
RADIATION ERA z>3400

MATTER RADIATION z<3400

NON-RELATIVISTIC TRANSITION z ~ 500

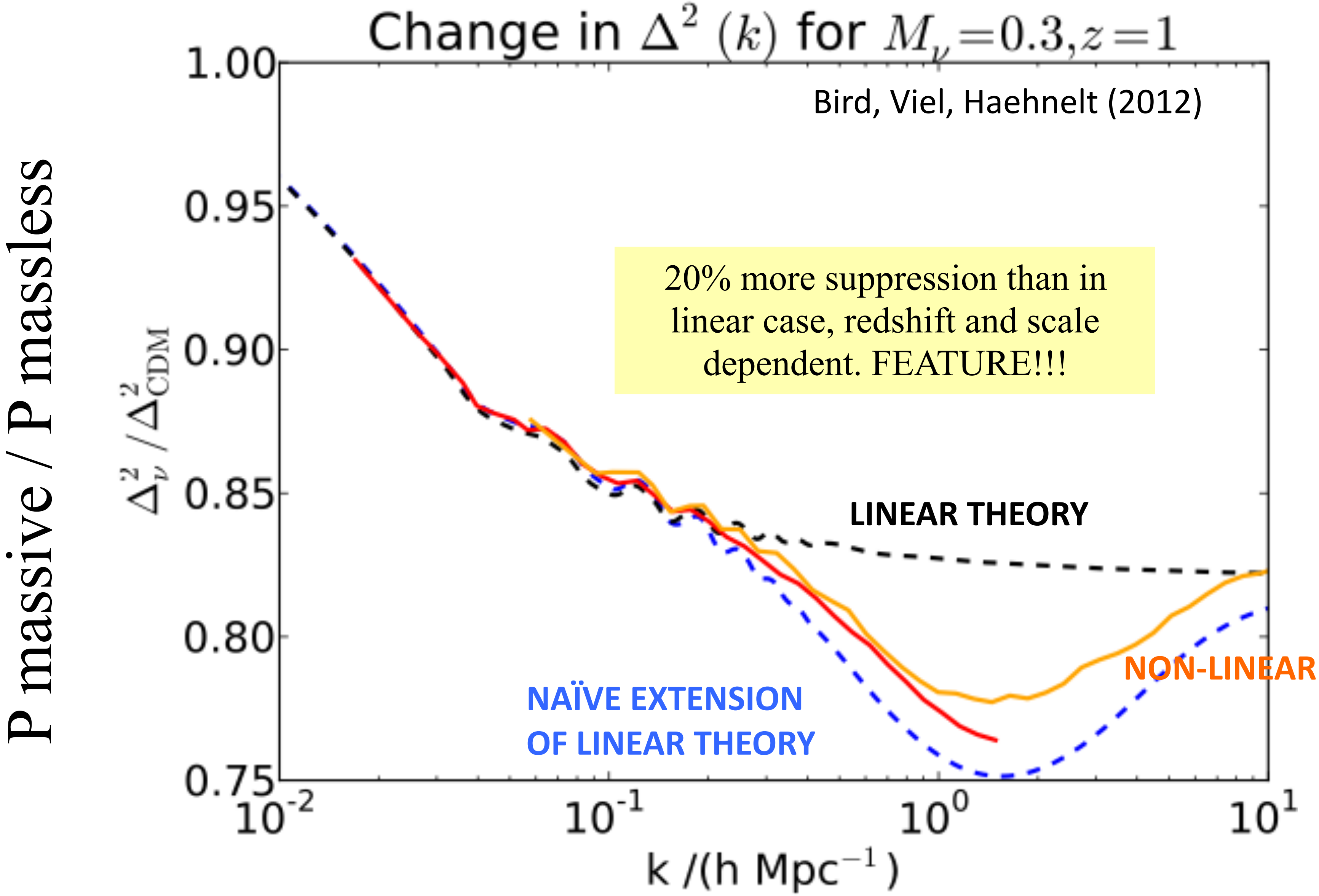
Below k_{nr} there is suppression in power at scales that are cosmologically important

COSMOLOGICAL NEUTRINOS - III: LINEAR MATTER POWER



Lesgourgues & Pastor 06

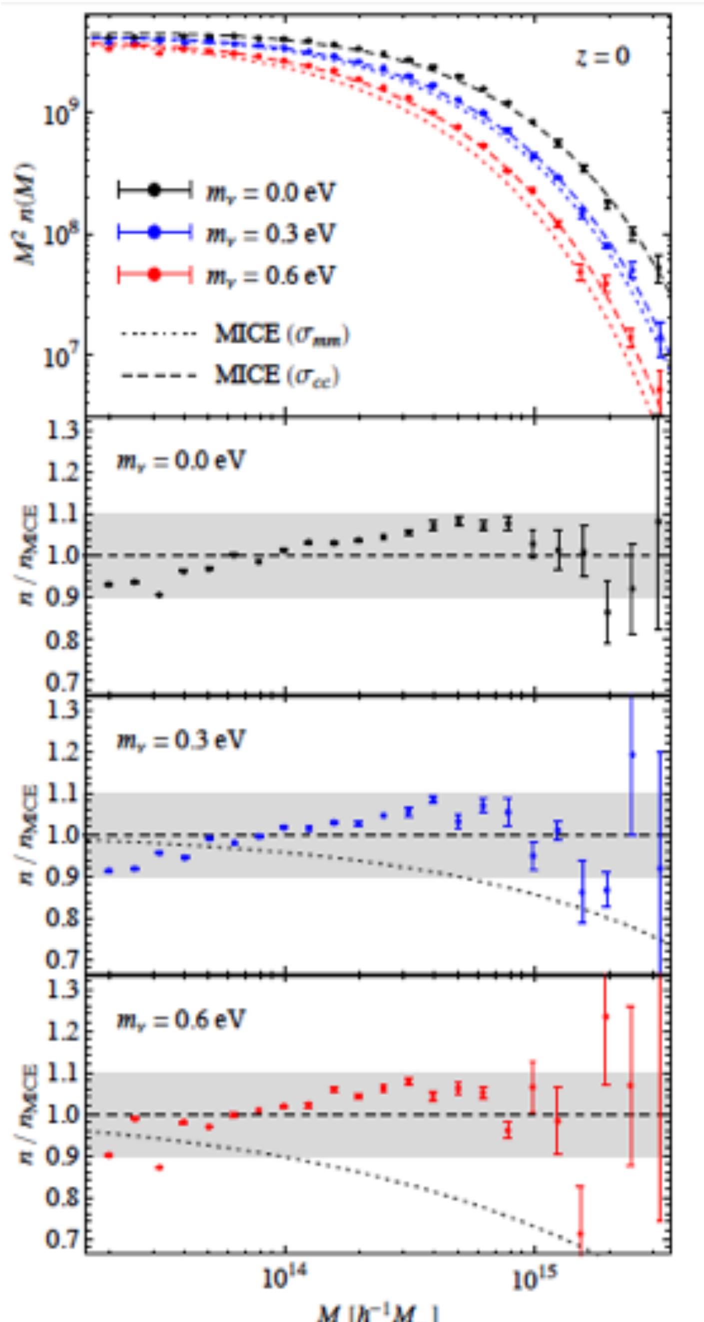
COSMOLOGICAL NEUTRINOS : NON-LINEAR MATTER POWER



Cosmic Scale

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

COSMOLOGICAL NEUTRINOS: MASS FUNCTION

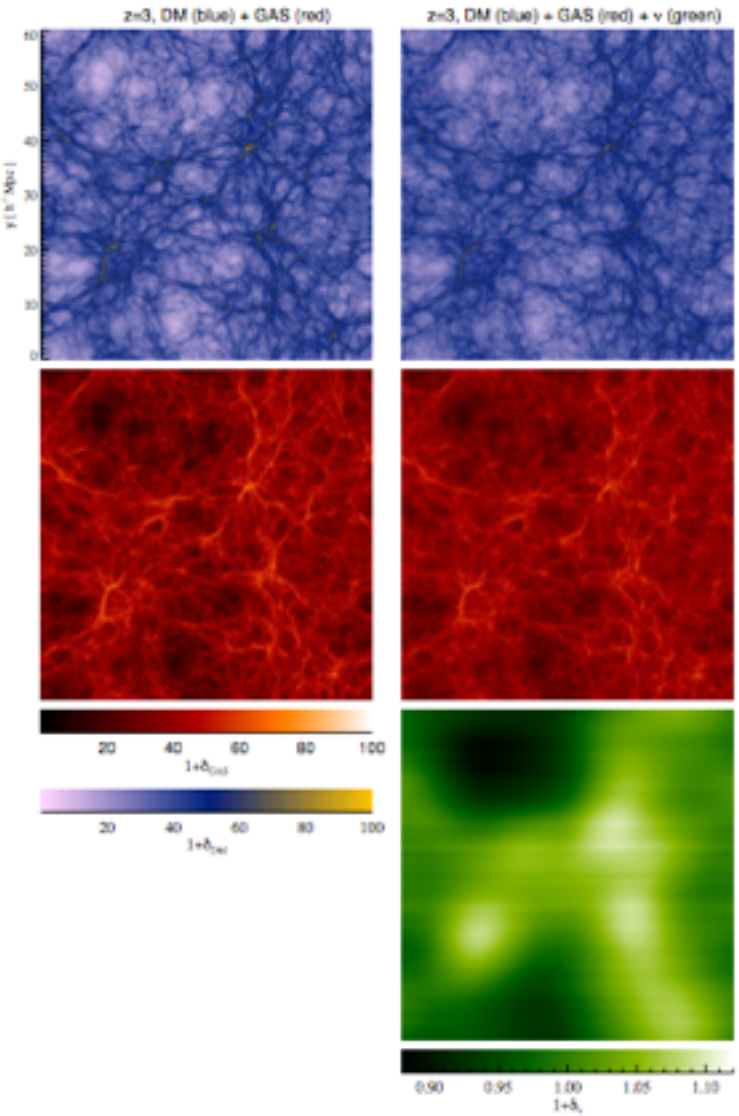


Halo mass function in massive neutrino cosmologies is better described by the CDM field rather than the matter field. It becomes universal and bias becomes scale independent if CDM is used.

Non trivial consequences for precision cosmology (bias

Castorina+14
Costanzi+14

NEUTRINOS IN THE IGM



N-body + hydro sims

Neutrino induced non-linear suppression understood and reproduced also with simple halo modelling (**Massara+ 15**)

Degeneracies with s8 are present

Neutrino induced effects on RSD (Marulli+11), BAOs (Peloso+15), mass functions and bias (Castorina+14) investigated

FROM IGM ONLY:

$\Sigma m_{\nu} < 0.9$ eV(2σ)

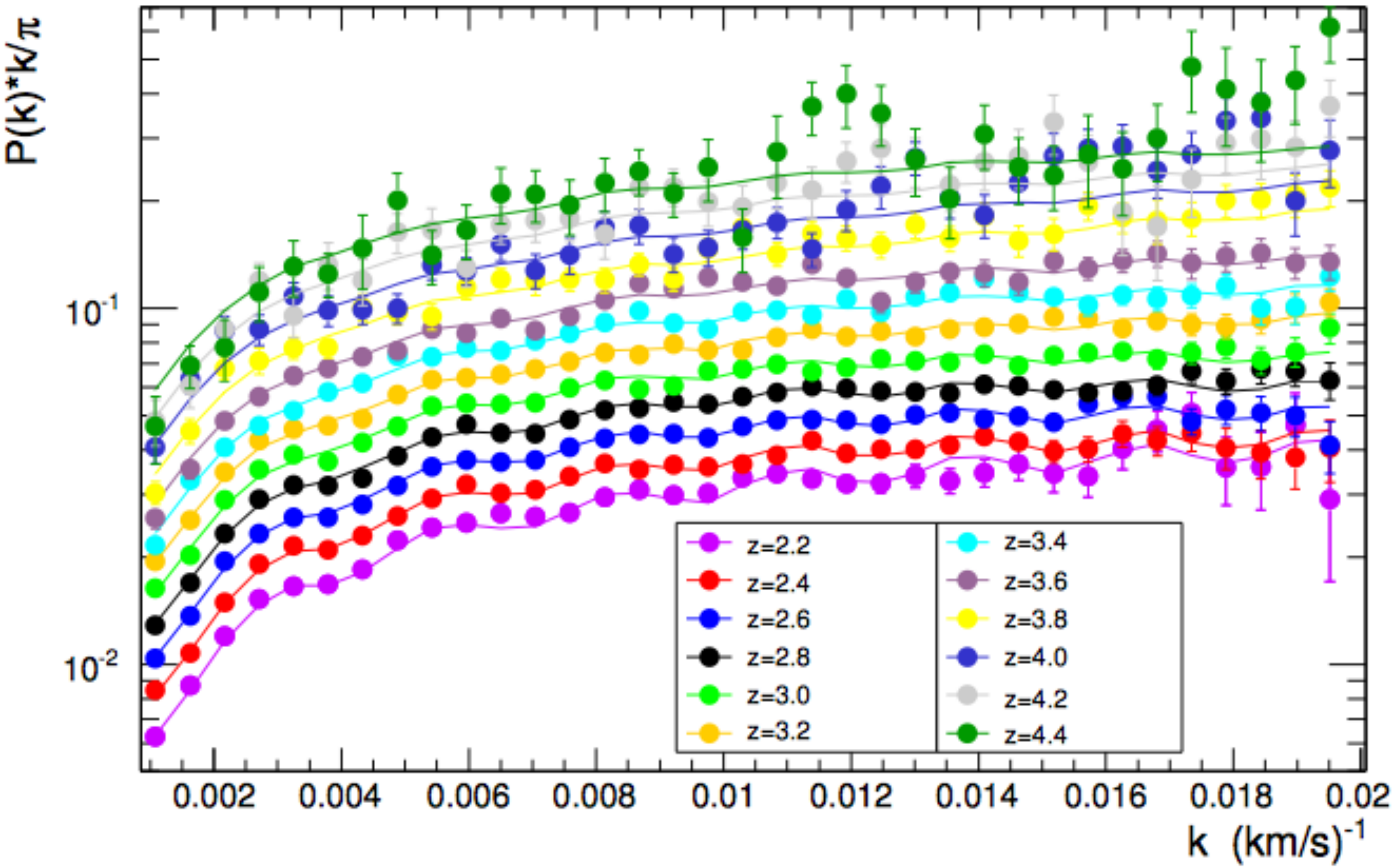
Viel, Haehnelt, Springel 2010
Rossi+ 14, Villaescusa-Navarro+14

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]

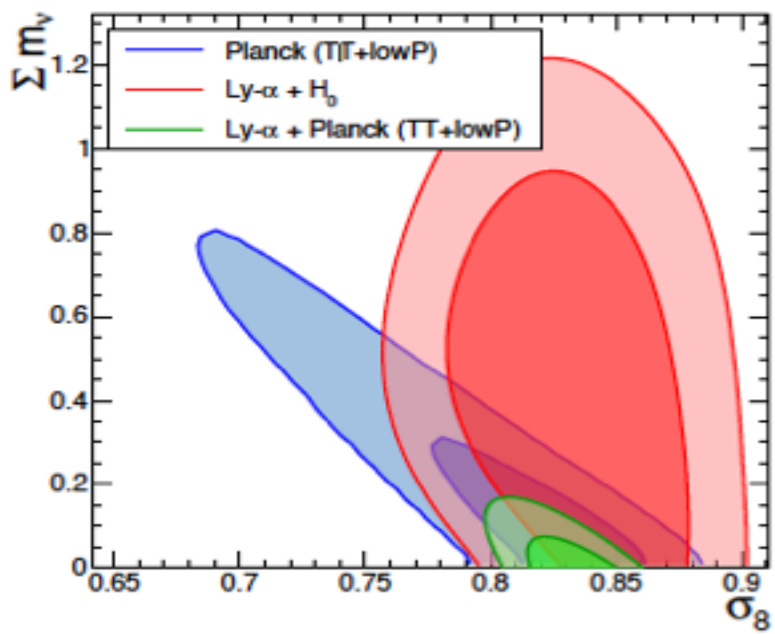
1D Flux power spectrum evolution



UPDATE using Planck 15

Palanque-Delabrouille+ 2015

Parameter	(1) Lyα + $H_0^{\rm Gaussian}$ ($H_0 = 67.3 \pm 1.0$)	(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



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.

- Problems still present, maybe solved by astrophysics only (feedback?). Numerics still tricky (Maccio', Schneider, etc.).

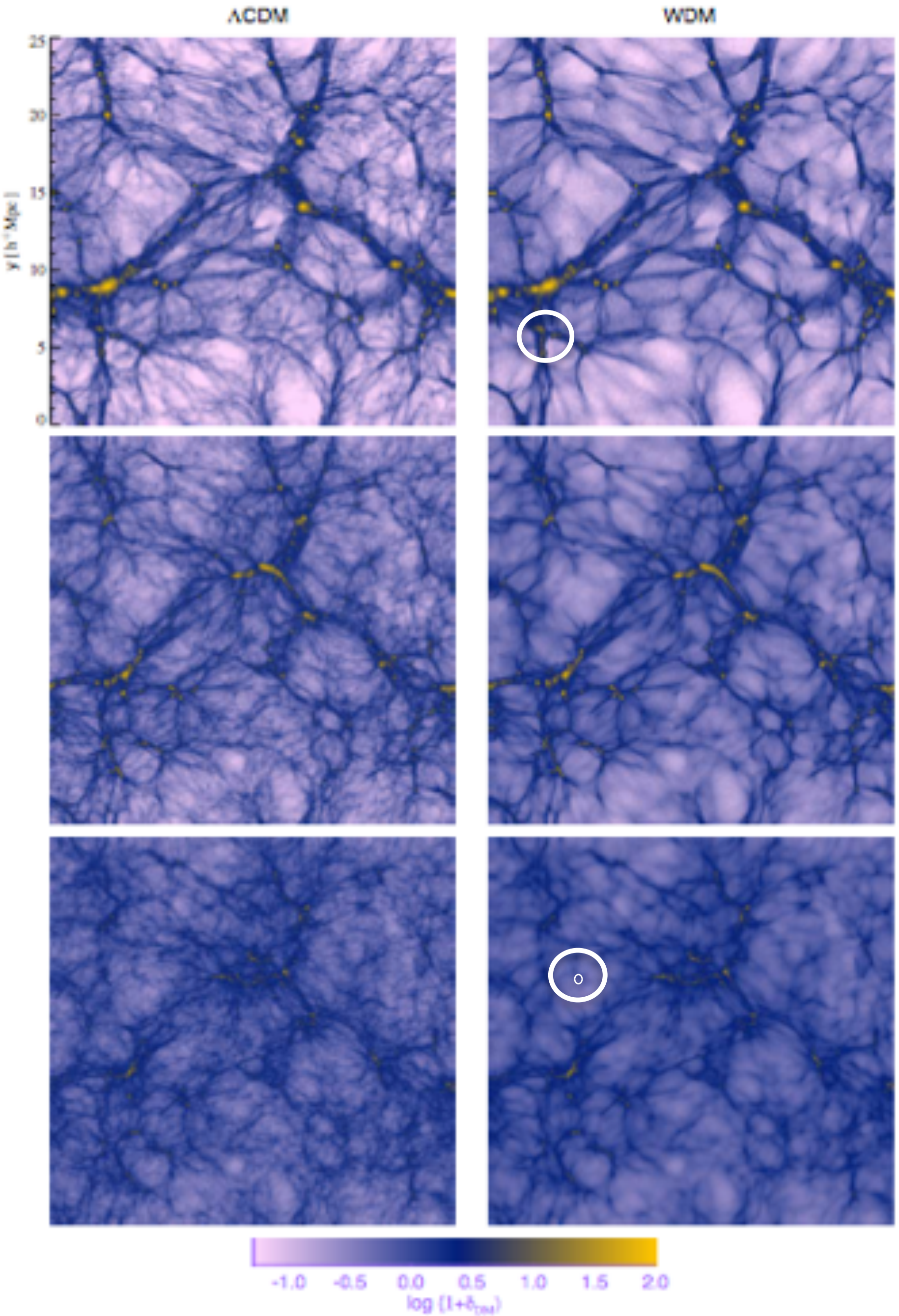
- On the observational side progress driven by IGM and dwarf galaxies (SDSS, DES etc.)

- Investigation of these issues is interesting even a-priori, without bringing in 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.

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

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

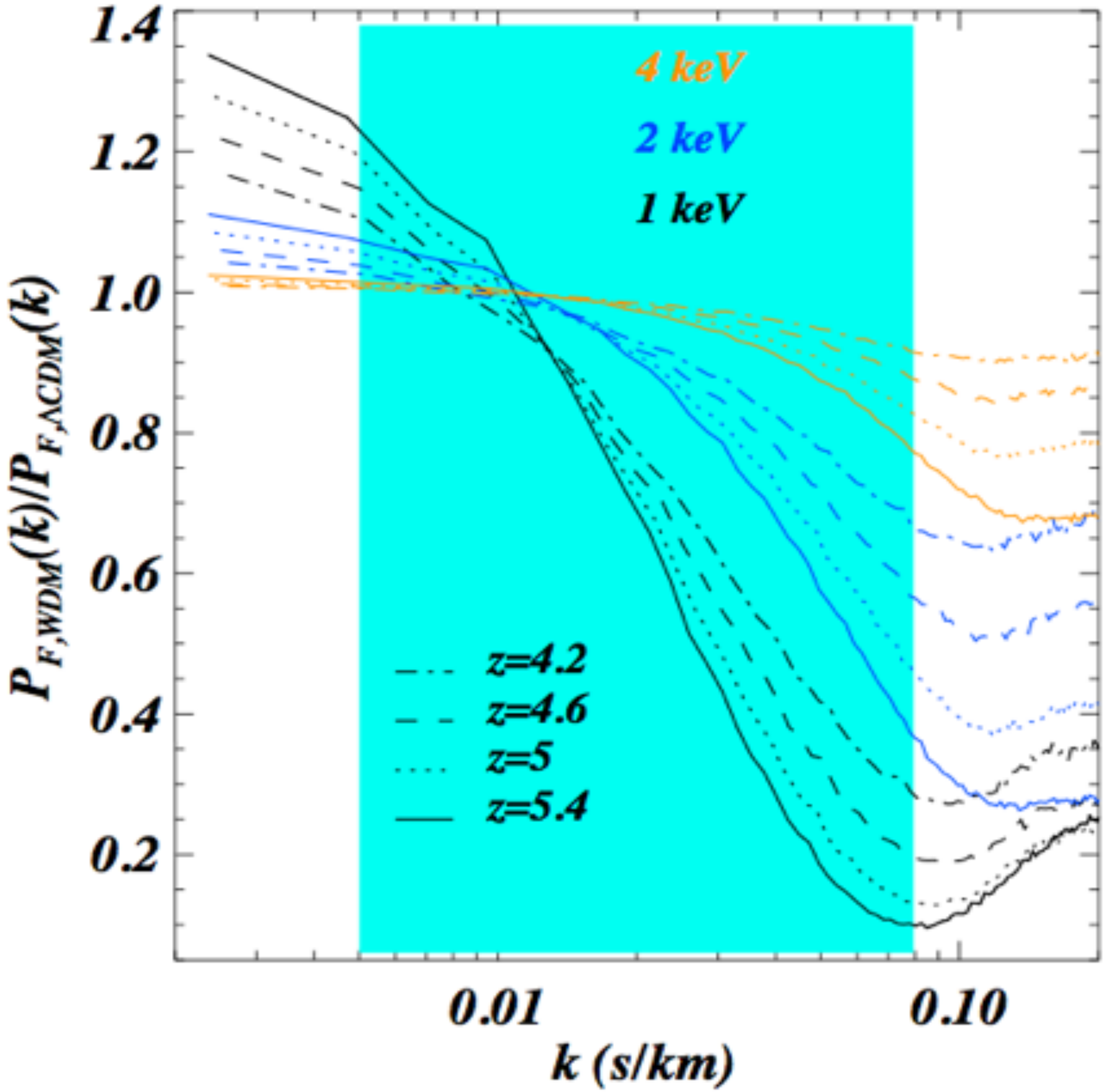
z=5

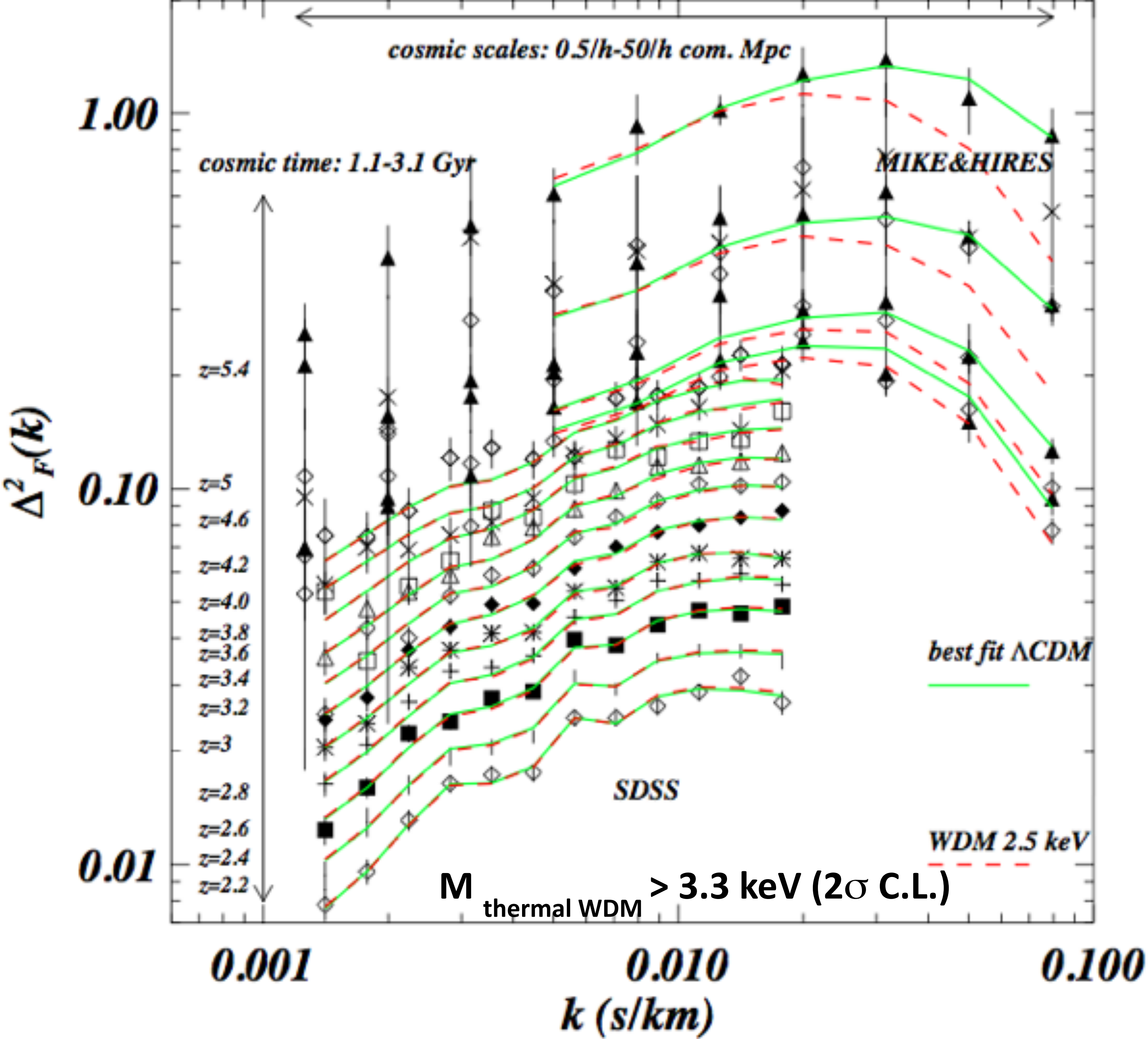
MV, Markovic, Baldi & Weller 2013

Markovic & MV, 2014

THE HIGH REDSHIFT WDM CUTOFF

$\delta_F = F/\langle F \rangle - 1$

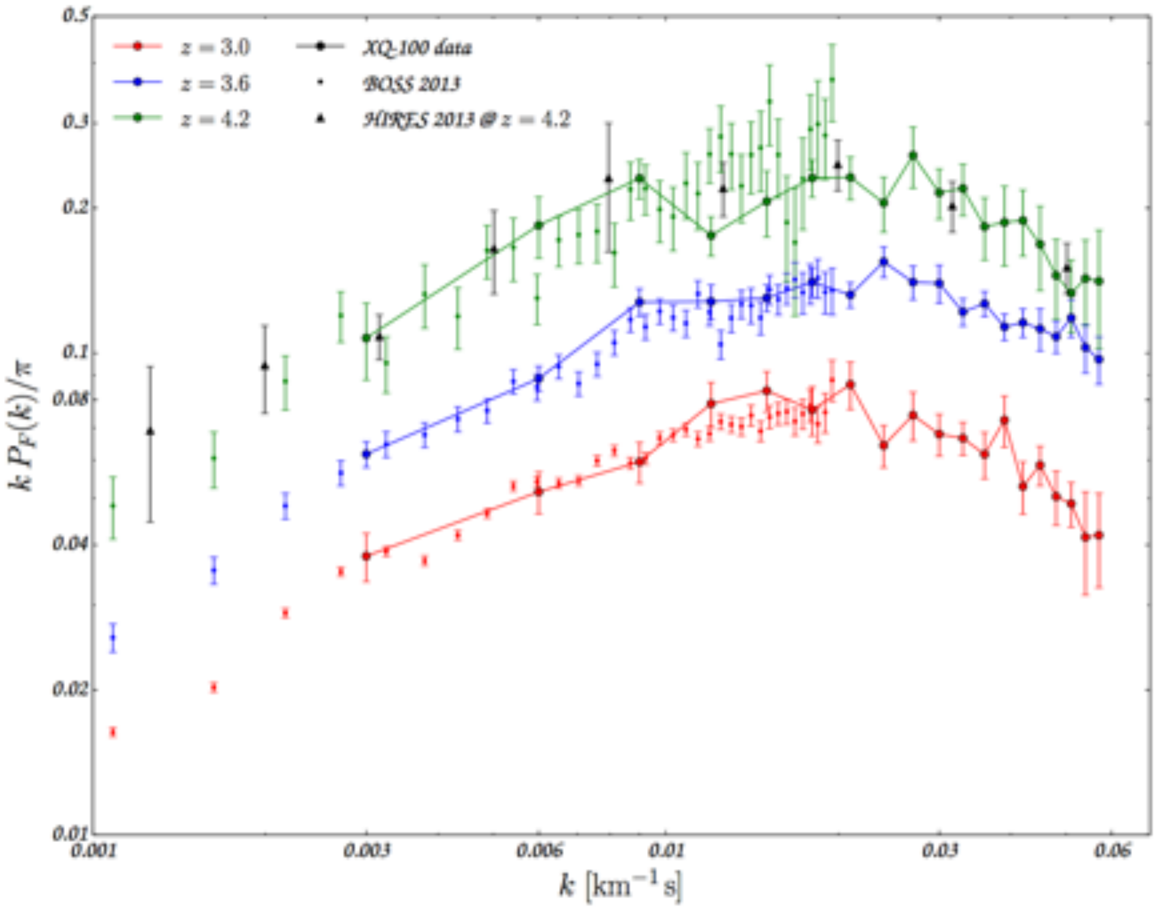




$M_{\text{thermal WDM}} > 3.3$ keV (2σ C.L.)

X-Shooter sample: bridging the gap between low-res and high-res

Irsic, MV+, 2017a, MNRAS, 466, 4332

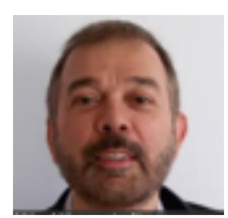


- Sample of 100 QSOs at z>3.5 (ESO Large Programme, PI: Lopez).
- Medium resolution 30-50: different systematics involved.
- Down to relatively small scales 0.06 s/km —> 5-10 com. Mpc/h.
- Power spectrum extraction tested on mock spectra built using PRACE simulations.
- Sample is not very constraining by itself but becomes constraining when complemented by other redshifts (like SDSS or HIRES).

Vid Irsic

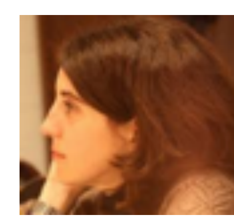
X-Shooter TS team

Cristiani



Cupani

D'Odorico



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

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

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

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

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 for sims.

Scalar Dark Matter - II

$$\delta_m = F\delta_\phi + (1-F)\delta_c.$$

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

$$\ddot{\delta}_{ck} + 2H\dot{\delta}_{ck} - \frac{3}{2}H^2\delta_{mk} = 0.$$

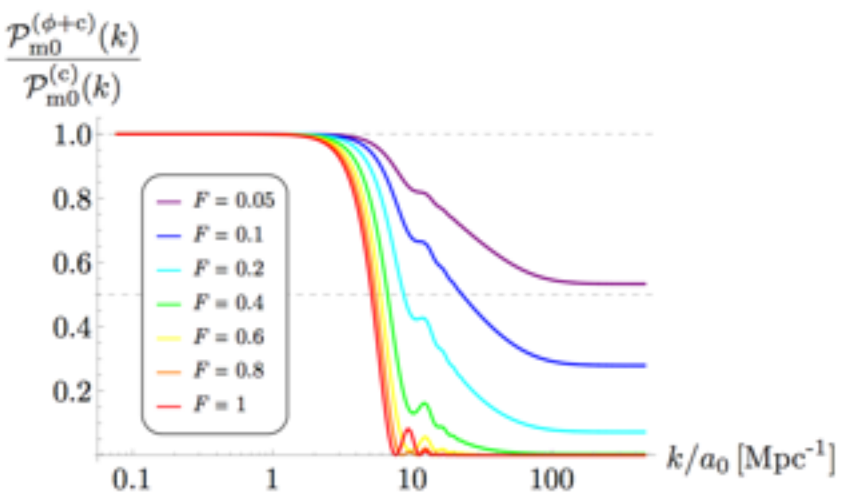
Linear perturbation theory
in CDM+scalar field model

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

Sound speed of scalar DM and Jeans
scale definition

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

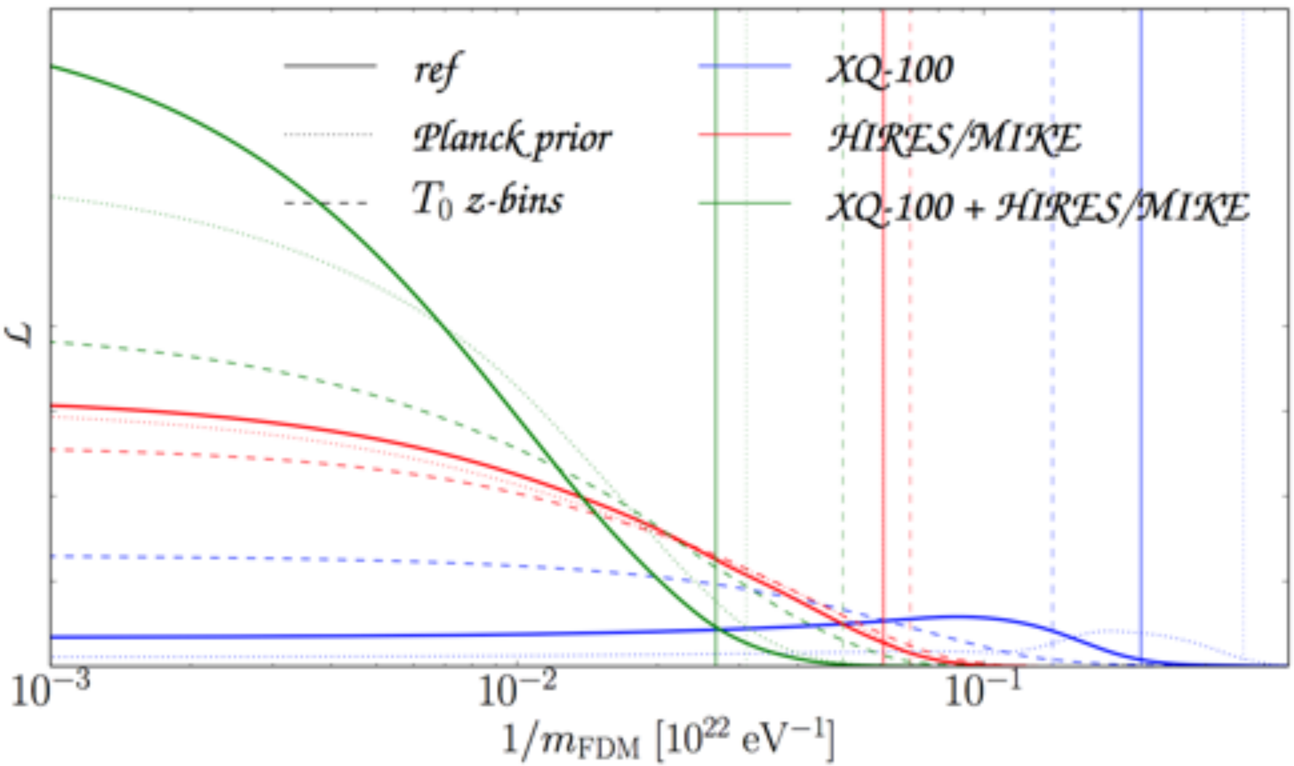
At $k<k_J$ no pressure
At $k>k_J$ pressure and oscillations
no growth
Comoving Jeans $k_J \sim a^{1/4}$ in MD
Important quantity is k_J at equival.



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

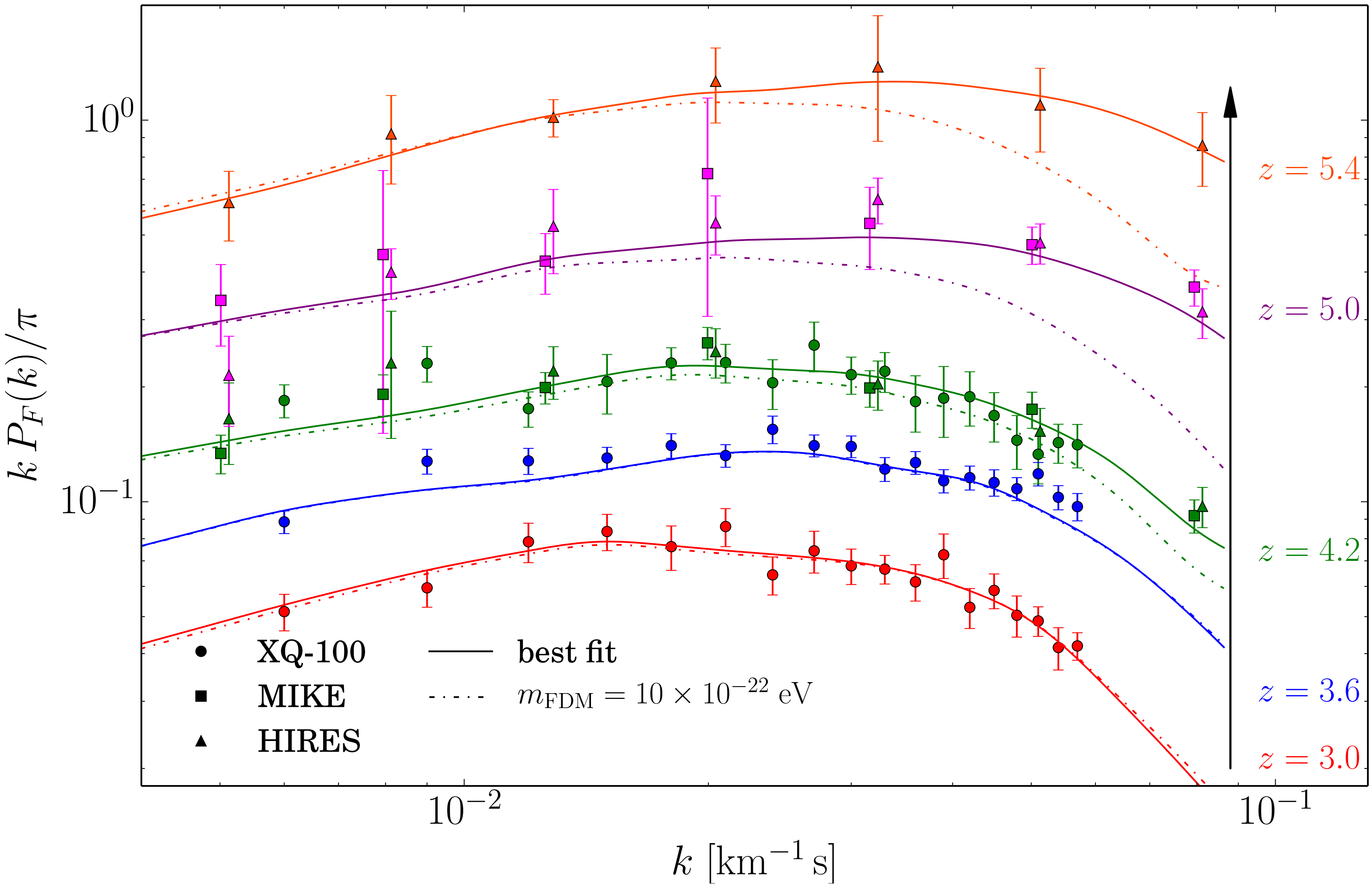
X-Shooter sample + HIRES/MIKE: constraints on ultra-light axions (Fuzzy Dark Matter)

Irsic, MV+, 2017c, arxiv: 1703.04683

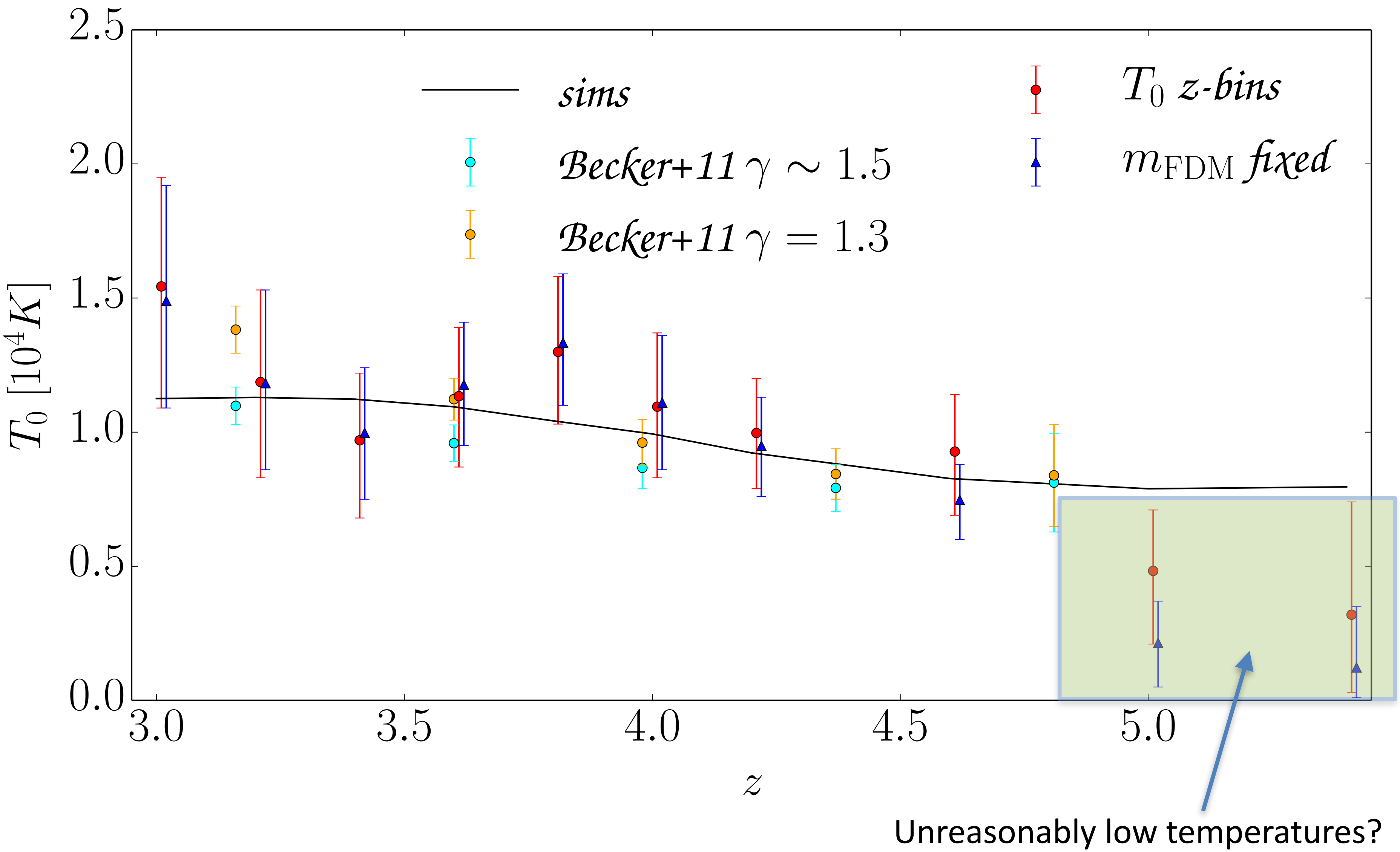


- New interest in FDM models. **VERY RICH IMPLICATIONS (e.g. Blum's talk later).**
- WDM thermal IGM constraints translated into FDM constraints by mapping $k_{1/2}$: poor approximation for large axion masses > 1.e-21.
- IGM constraints are **>2-4 x 10^{-21} eV** - ruling out the window range **0.1-1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

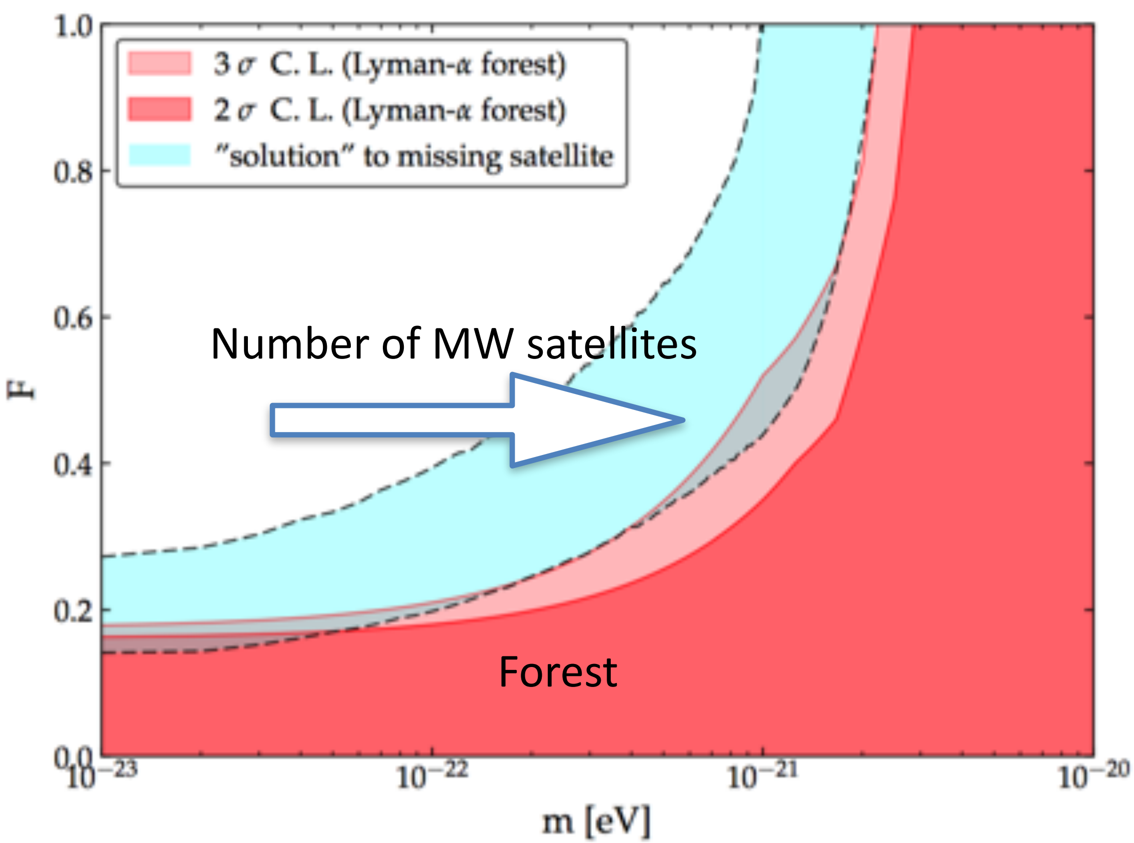
X-Shooter sample+HIRES/MIKE: constraints on ultra-light axions (Fuzzy Dark Matter)



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



Scalar Dark Matter as a fluid: implications for the number of MW satellites



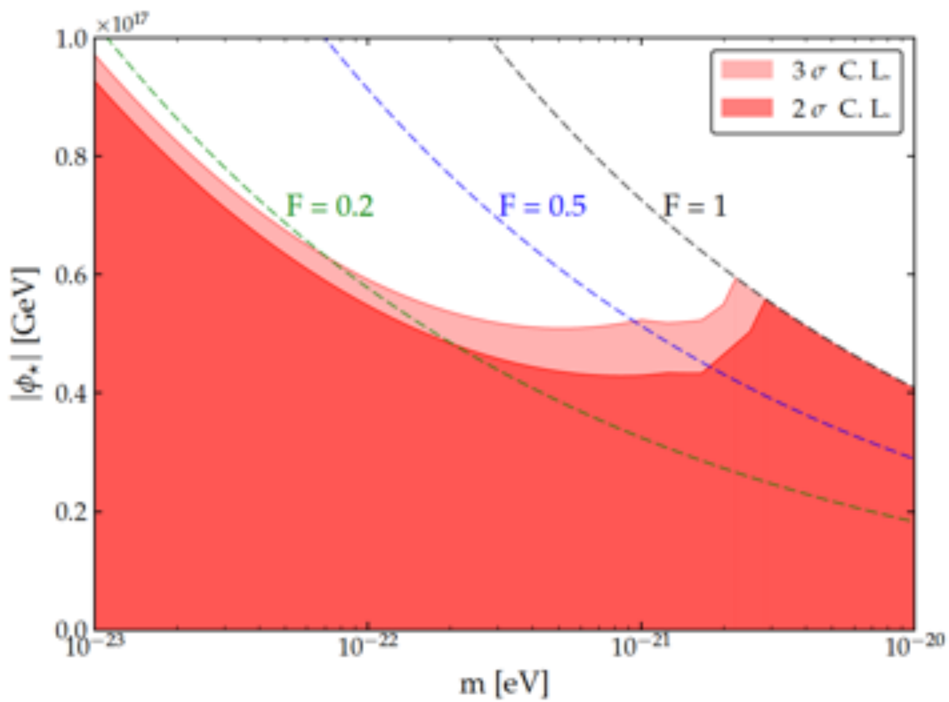
- Use of the mass function to reproduce a number of satellites in the range [20,60] for a MW halo in agreement with observations
- Forest constraints obtained from the so-called "area criterion" thus they are approximated especially for low F values.
- **Linear P(k)** only input for obtaining both these constraints
- Little room to solve the "small scale crisis" unless F~0.2 and mass 1.e-23,1.e-22

Kobayashi, Murgia +17

Scalar Dark Matter as a fluid: implications for the very early Universe

Kobayashi, Murgia + 17

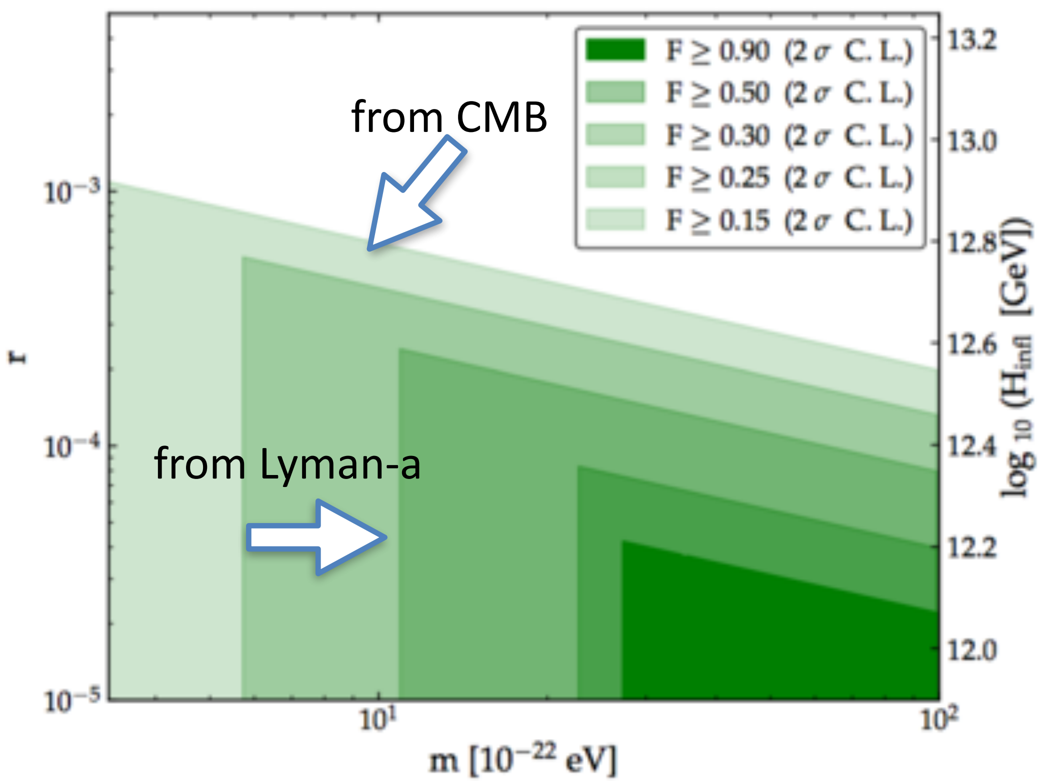
$$F \equiv \frac{\Omega_\phi}{\Omega_c} \approx 0.6 \left(\frac{g_{*\mathrm{osc}}}{3.36}\right)^{3/4} \left(\frac{g_{s*\mathrm{osc}}}{3.91}\right)^{-1} \left(\frac{\phi_\star}{10^{17}\,\mathrm{GeV}}\right)^2 \left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^{1/2}.$$



- Scalar fields with small masses motivated by string theory. Could be the DM.
- Scalar behaves like CDM except at scales smaller than its De Broglie wavelength —> suppression.
- Klein Gordon equation describes the field evolution: scalar stays frozen at its initial value at H>>m and behaves as pressureless matter at H<<m.
- Scalar starts oscillating in the radiation era.
- **FDM fraction could be casted as a function of mass and initial value of the scalar field**

Scalar Dark Matter as a fluid: implications for tensor to scalar ratio

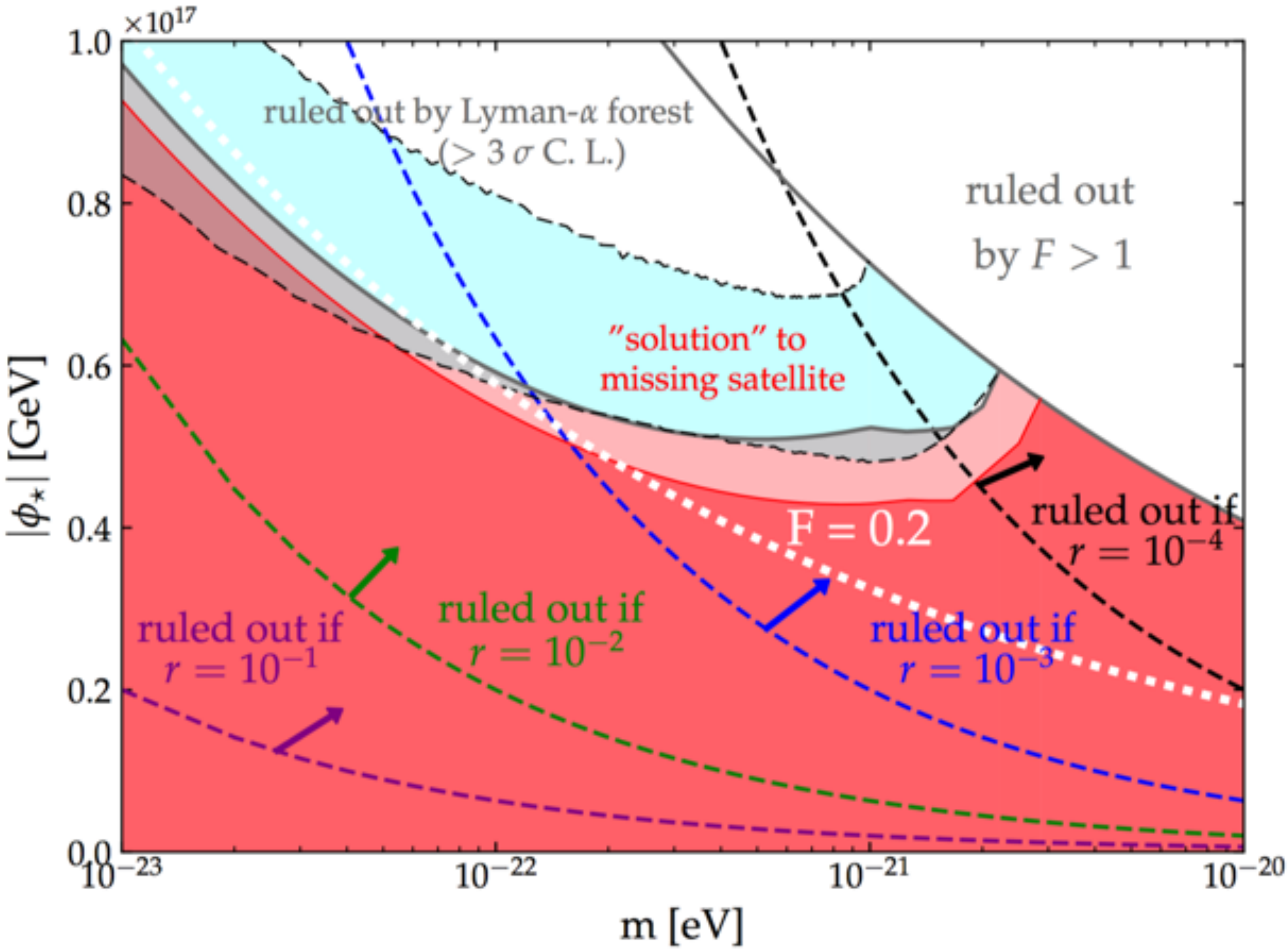
$$r(k_{\rm piv}) < 4\times 10^{-4}\left(\frac{g_{\star\rm osc}}{3.36}\right)^{-3/2}\left(\frac{g_{s\star\rm osc}}{3.91}\right)^{2}\left(\frac{m}{10^{-22}\,\rm eV}\right)^{-1}\left(\frac{\phi_\star}{10^{17}\,\rm GeV}\right)^{-2}$$



Kobayashi, Murgia + 17

- Scalar field will have super horizon fluctuations **during inflation** which will depend on the initial field value.
- Isocurvature perturbations will be produced (constrained by Planck upper bound). This will set a limit on the inflation scale, a limit on the **Hubble rate** when k=0.05/Mpc leaves the horizon and a **limit on tensor to scalar ratio.**

Scalar Dark Matter: summary plot



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)

$$\nu = 1.12\ ;$$

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

$\Rightarrow$

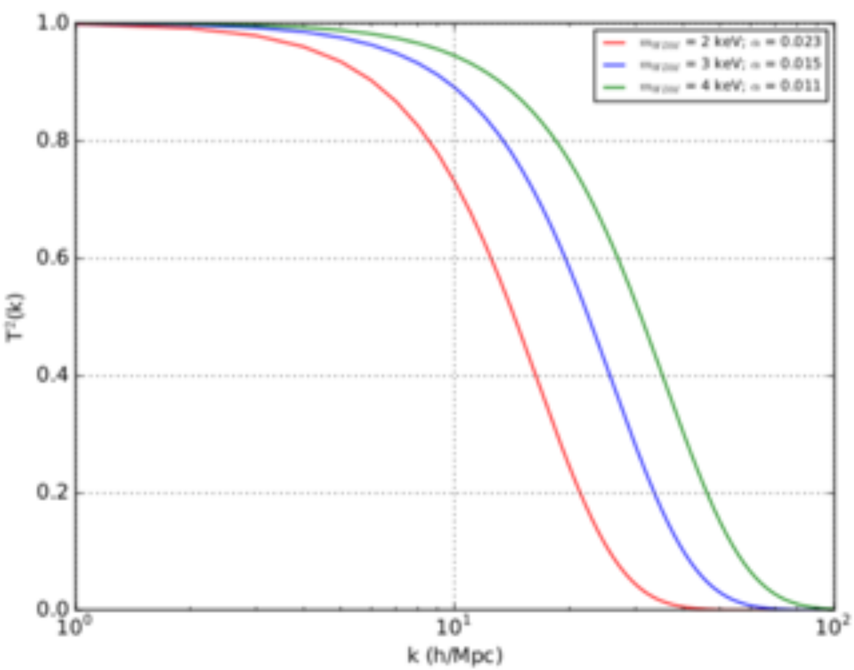
New general approach

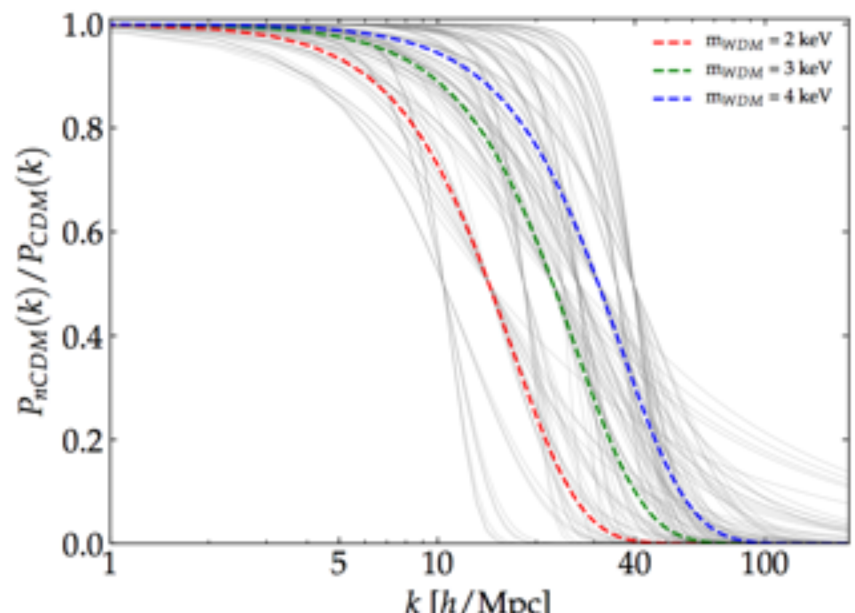
$$T(k) = [1 + (\alpha k)^{\beta}]^{\gamma}$$

Applies to ?

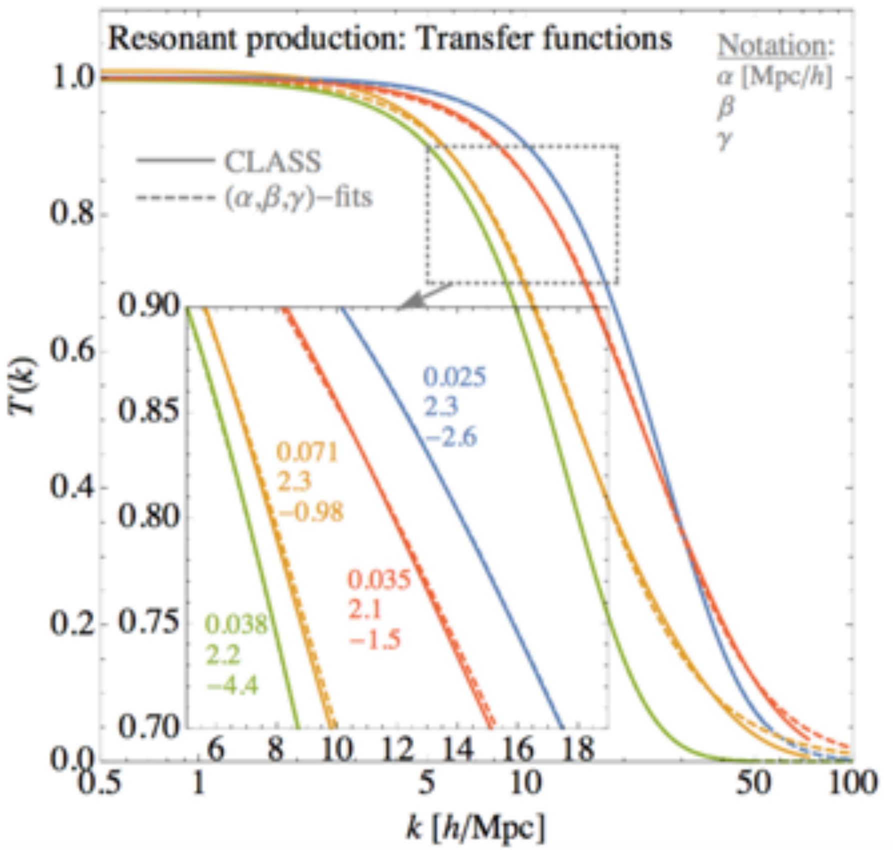
The larger is beta, the flatter is the shape for k < $k_{1/2}$; the larger is gamma, the steeper is the small-scale cutoff
.

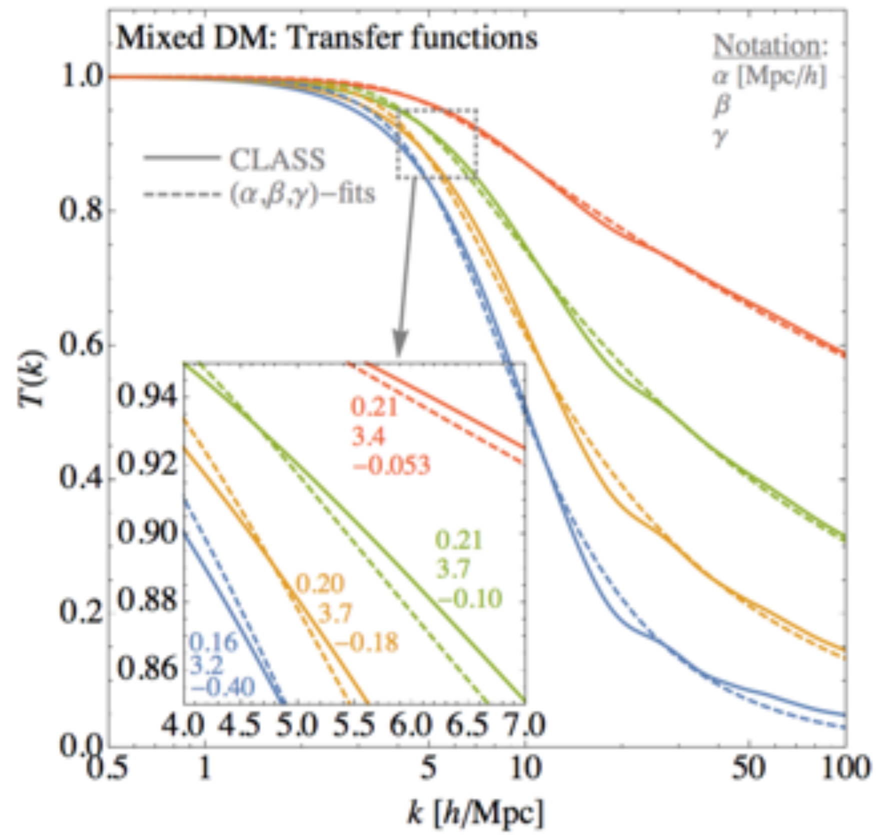
Murgia, Merle, MV +17





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





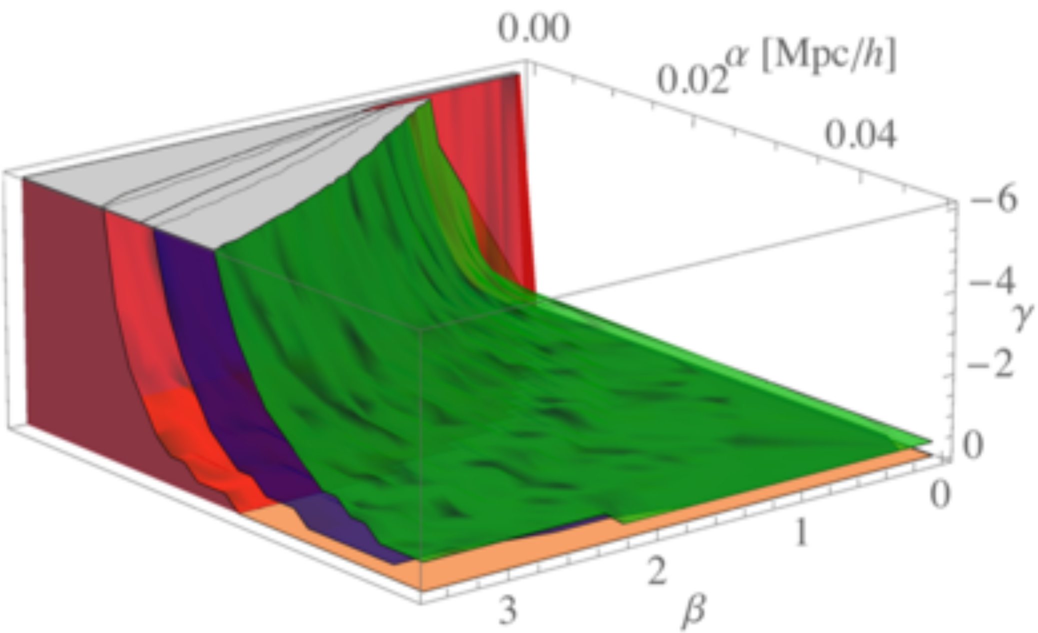
Simple parametrization proposed works well for:

- sterile neutrinos from scalar decays
- sterile neutrinos resonantly produced
- mixex models
- fuzzy dark matter
- ETHOS models

Non-cold Dark Matter at small scales - IV: approximate IGM constraints

"Conservative" case (95% C.L. limit)

$$m_{\rm WDM} = 3.5 \text{ keV} \Rightarrow \delta A_{\rm REF} = 0.38$$



$$\alpha \leq 0.058 \text{ Mpc}/h \quad (95\% \text{ C.L.})$$

The Area Criterion

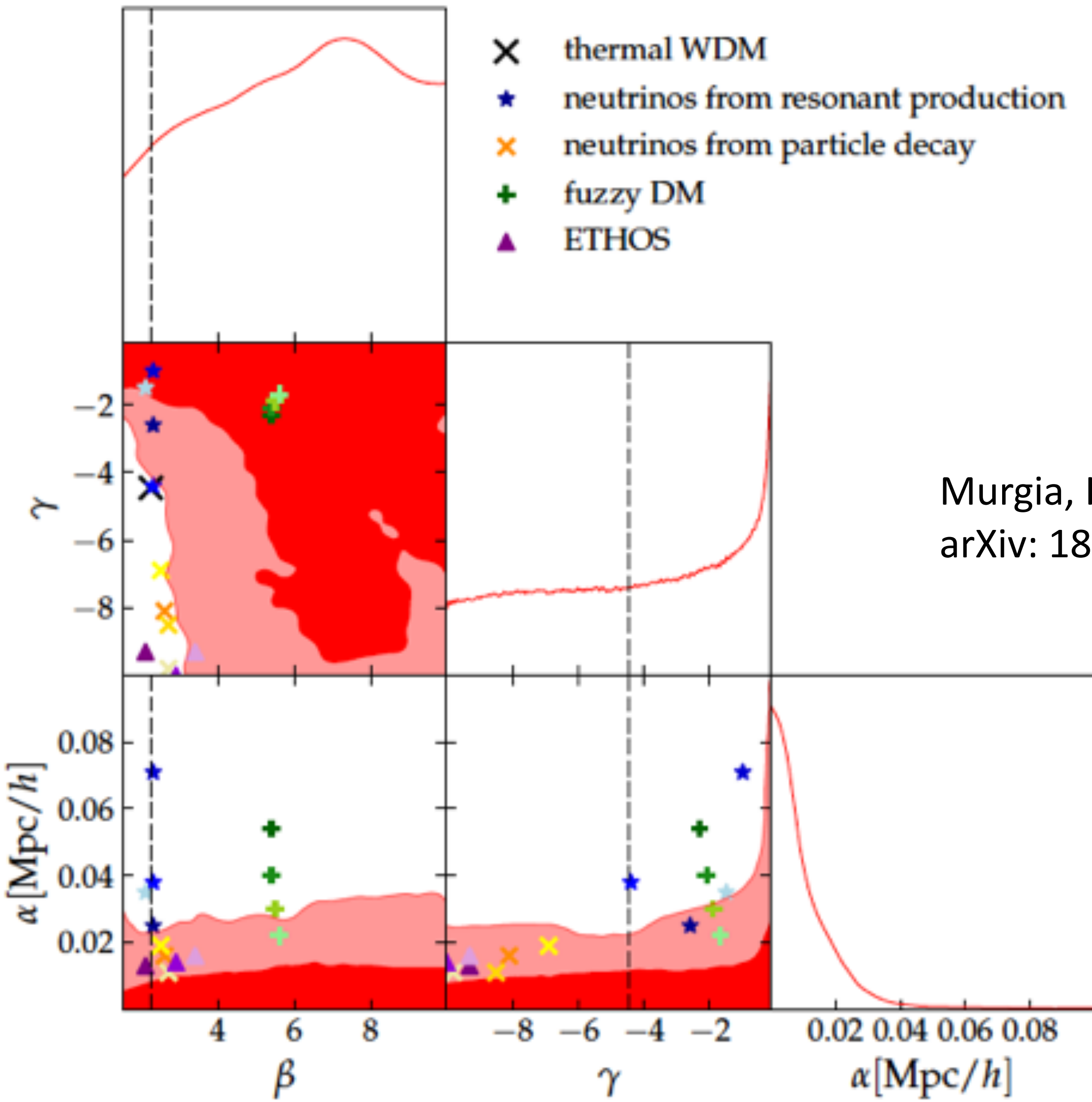
$$r(k) = \frac{P_{\rm 1D}^{\rm noncold}(k)}{P_{\rm 1D}^{\Lambda{\rm CDM}}(k)} \approx \frac{P_{\rm F}^{\rm noncold}(k)}{P_{\rm F}^{\Lambda{\rm CDM}}(k)}$$

$$\delta A = \frac{A_{\Lambda{\rm CDM}} - A}{A_{\Lambda{\rm CDM}}} \quad \text{with} \quad A = \int_{k_{\rm min}}^{k_{\rm max}} r(k)dk$$

$$\delta A > \delta A_{\rm REF}$$

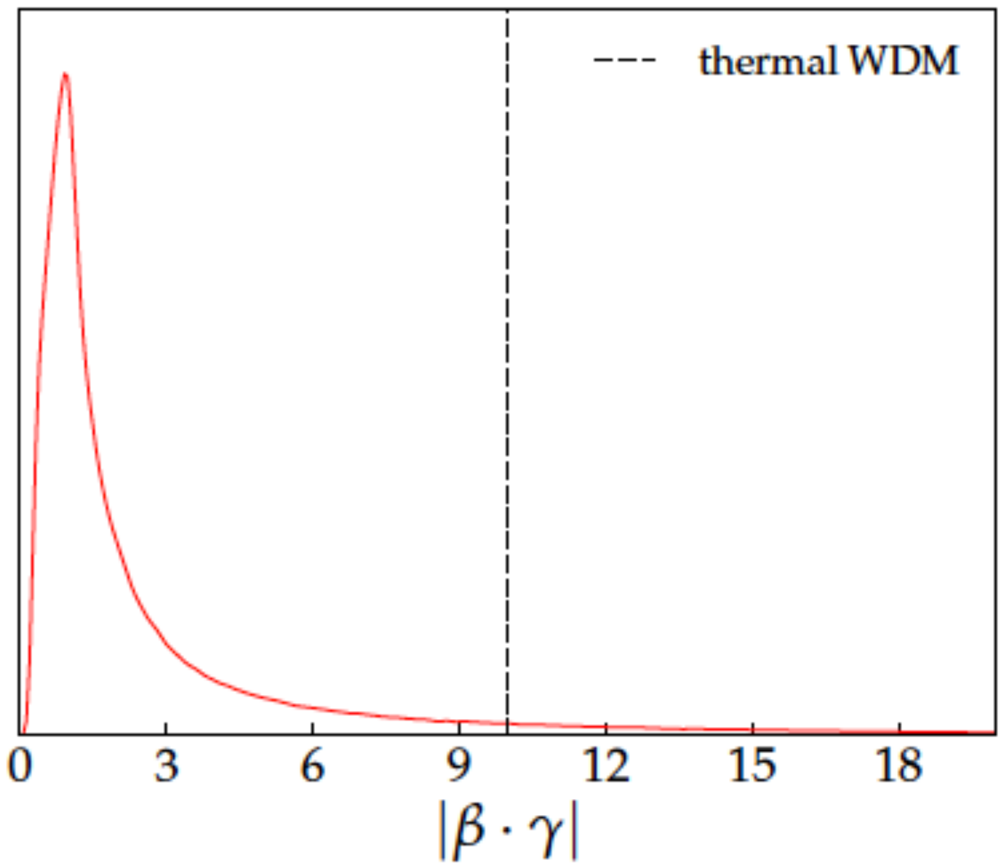
If Area is larger than
ref value (calculated for WDM
standard analysis)
then a model is rejected

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



Murgia, Irsic, MV, 2018.
arXiv: 1806.08371

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

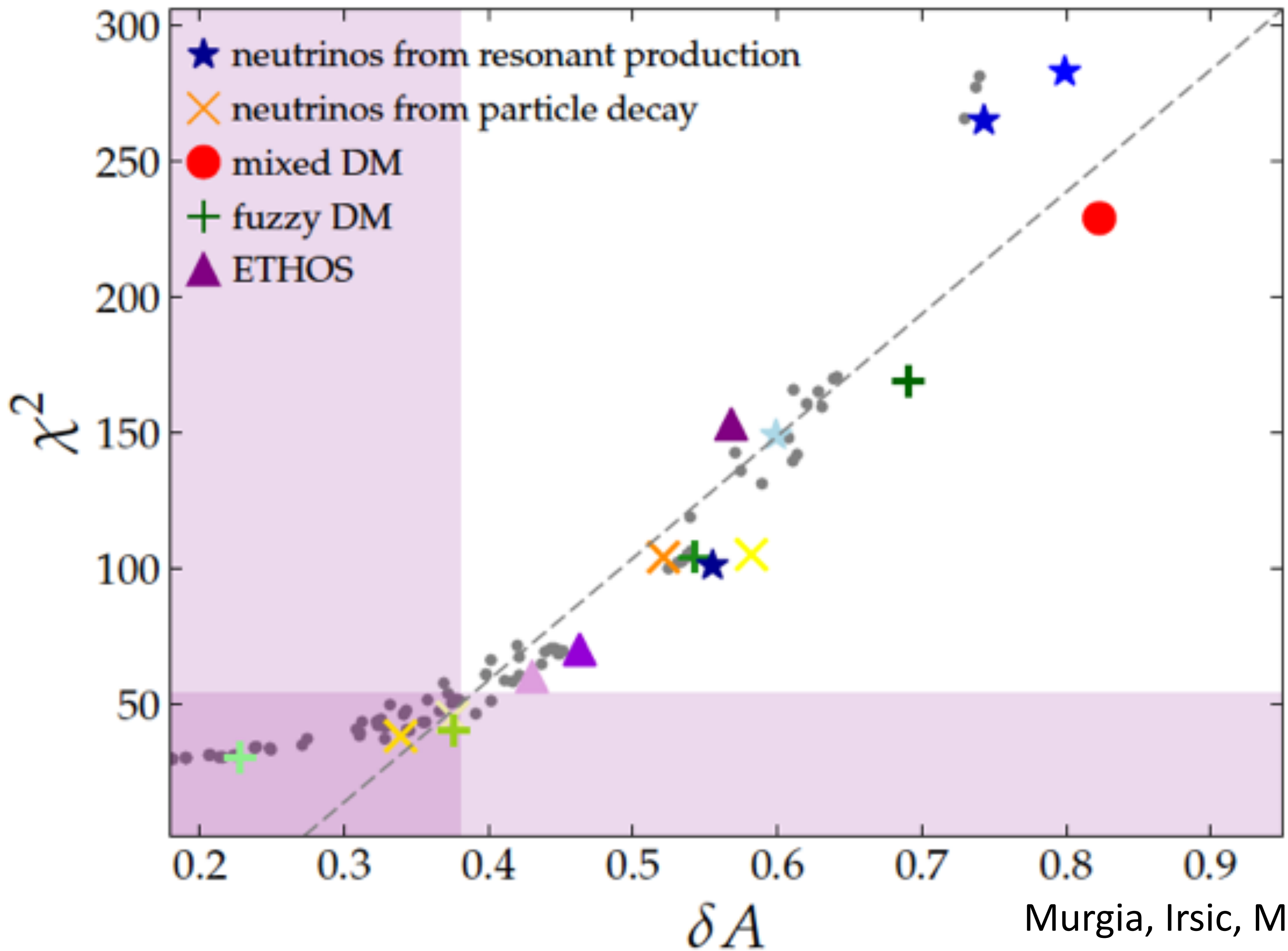


$$\alpha < 0.03 \ \mathrm{Mpc}/h \ (2\sigma)$$

$$|\beta \cdot \gamma| < 14$$

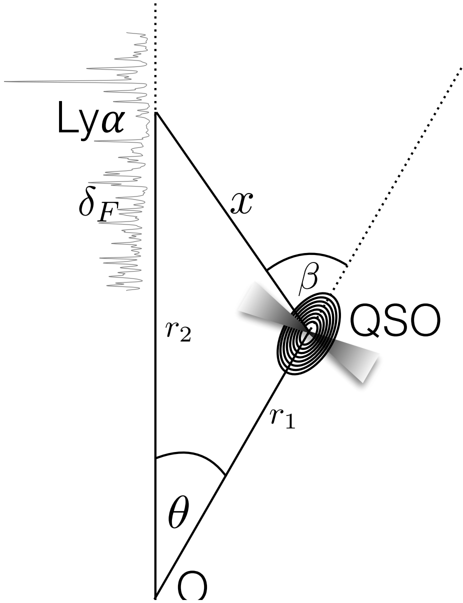
Murgia, Irsic, MV, 2018.
arXiv: 1806.08371

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



Murgia, Irsic, MV, 2018.
arXiv: 1806.08371

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



also Yann Rasera's talk

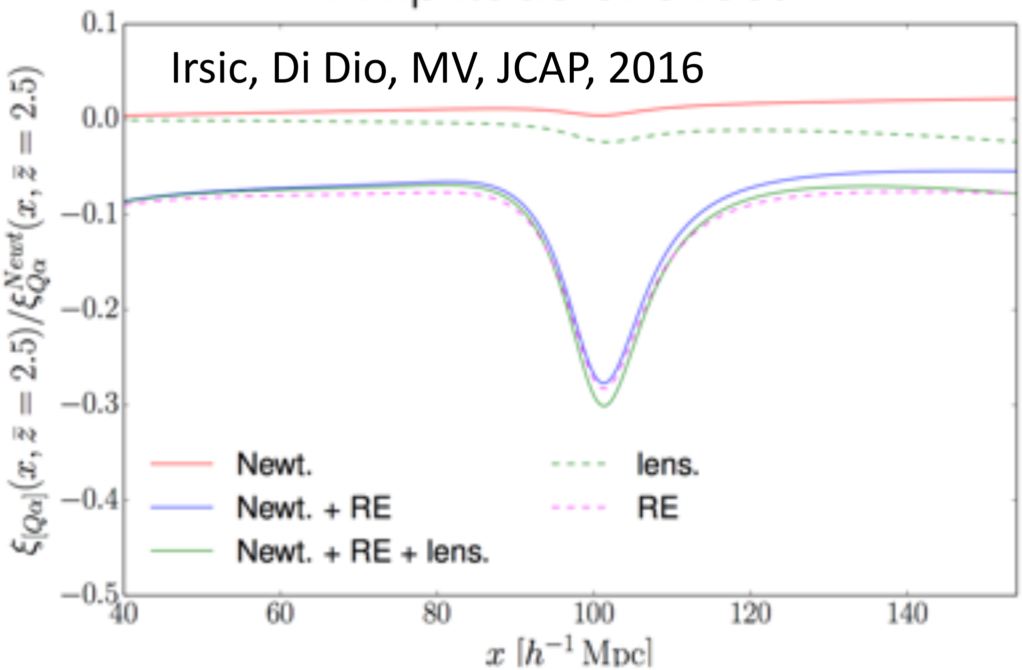
$$\xi_{Q\alpha} = \xi_{Q\alpha}^{\rm newt} + \xi_{Q\alpha}^{\rm magnification} + \xi_{Q\alpha}^{\rm relativistic}$$

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

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

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.

CONCLUSIONS

- BAOs: clear detection, sytematics under control, tension with Planck smaller.

- NEUTRINOS: no support for non zero neutrino masses from IGM data total neutrino mass <0.12 eV 2σ C.L. Neutrino non-linearities crucial for future surveys.

- WDM: consistency with cold dark matter > 3.5-5.3 keV relics 2σ C.L.

- FDM: constraints > 2.e-21 eV, ruling out the parameter space advocated for solving small scale LCDM crisis.

- More general simple model presented, more accurate results soon.