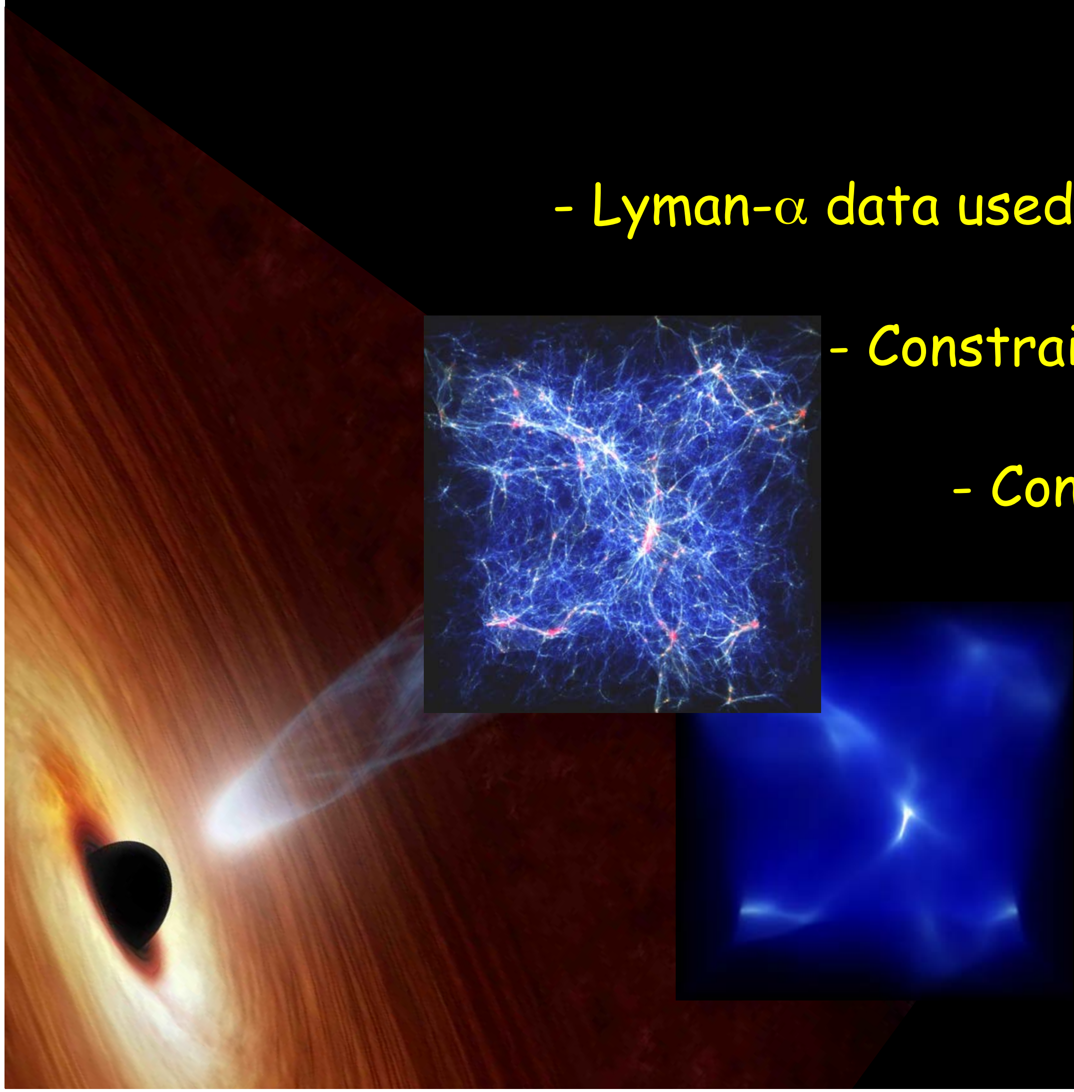
Measuring small-scale structure in the IGM to constrain cosmology

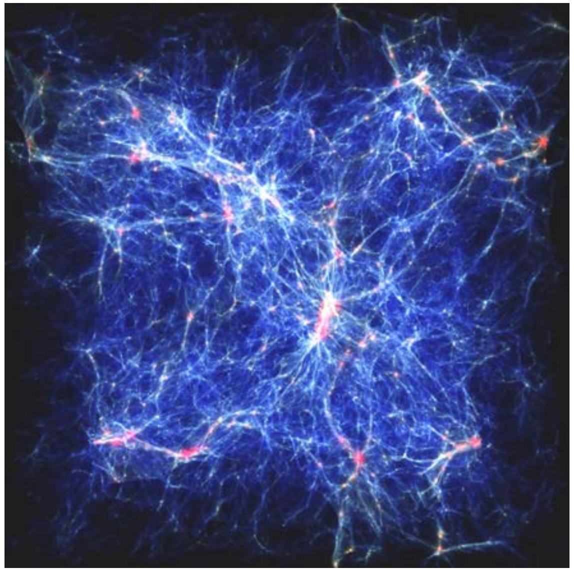
- Lyman-α data used
- Constraint on ν mass
- Constraint on warm dark matter

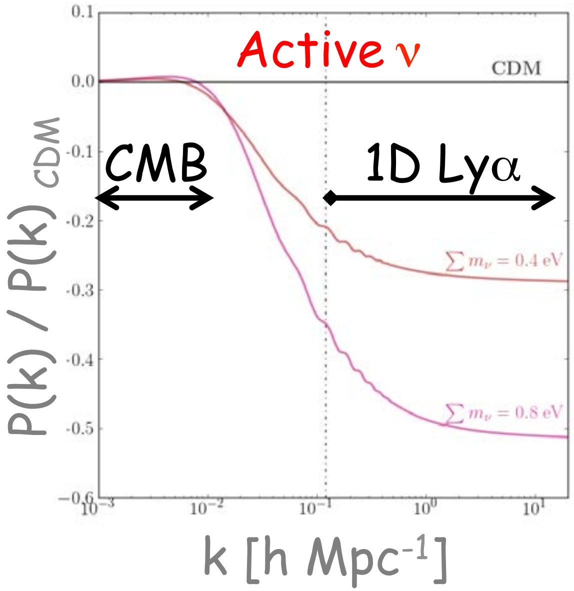


N. Palanque-Delabrouille
CEA-Saclay

Intergalactic interconnections
Marseille, July 2018

Lyman-α forest and cosmology

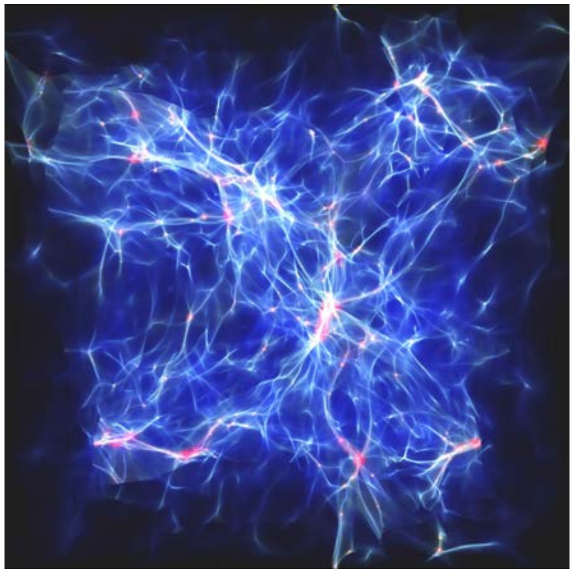


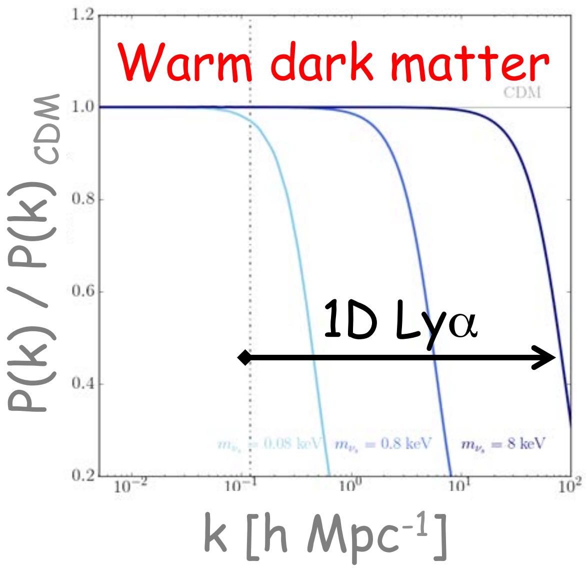


Active neutrinos

- CMB vs. Lyα P(k) comparison
- Greater impact as m_ν increases

⇒ **Upper limit on m_ν**



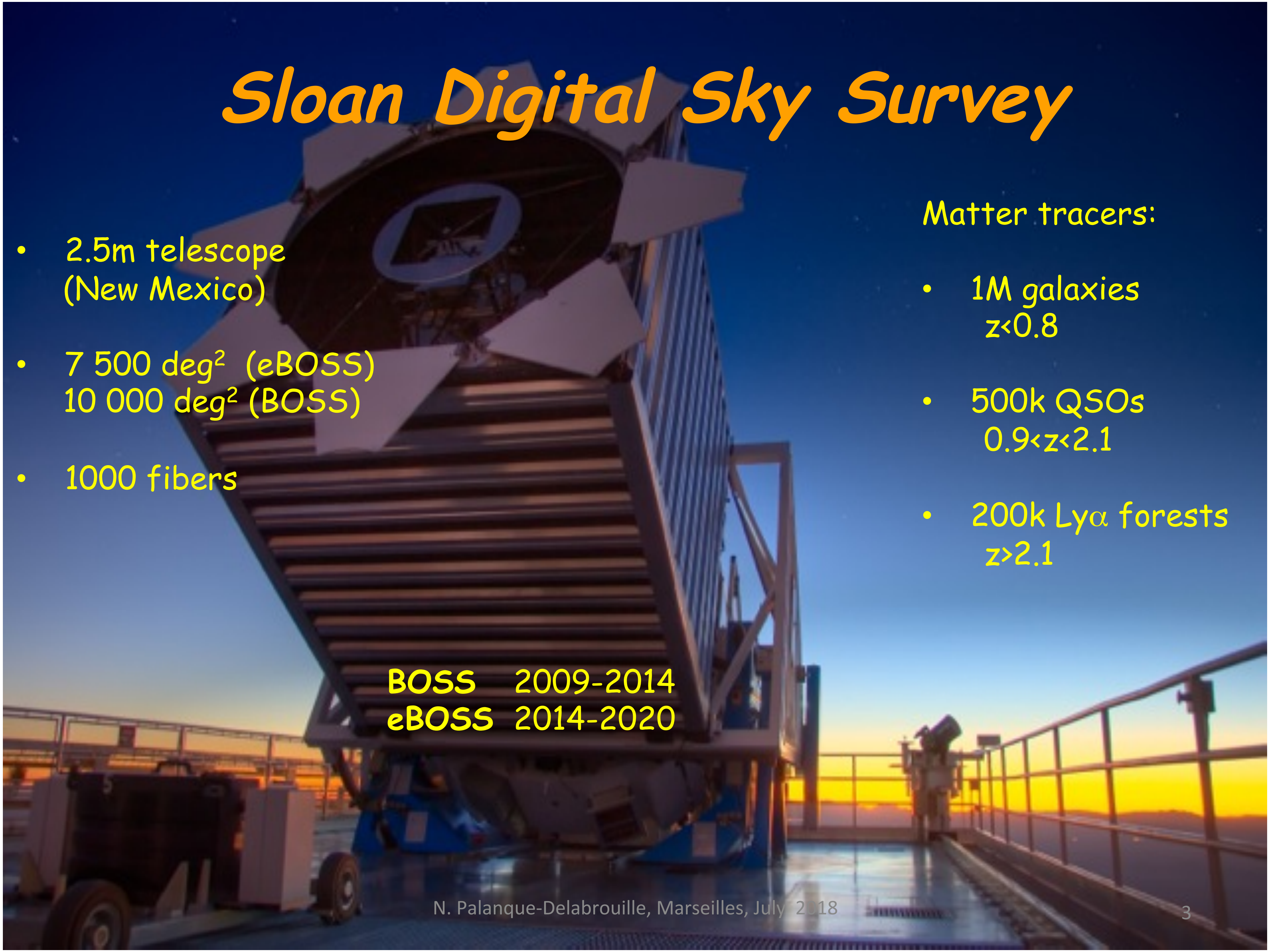


Warm dark matter

- Power cut-off on small scales
- Greater impact as m_{WDM} decreases

⇒ **Lower limit on m_{WDM}**

Sloan Digital Sky Survey



- 2.5m telescope
  (New Mexico)
- 7 500 deg^2 (eBOSS)
  10 000 deg^2 (BOSS)
- 1000 fibers

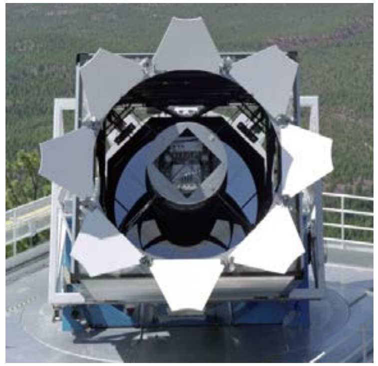
Matter tracers:

- 1M galaxies
  $z<0.8$
- 500k QSOs
  $0.9<z<2.1$
- 200k Lyα forests
  $z>2.1$

BOSS 2009-2014
eBOSS 2014-2020

Lyman-α forest 1D power spectrum

Selection of ~14 000 out of 60 000 z>2.1 BOSS QSOs

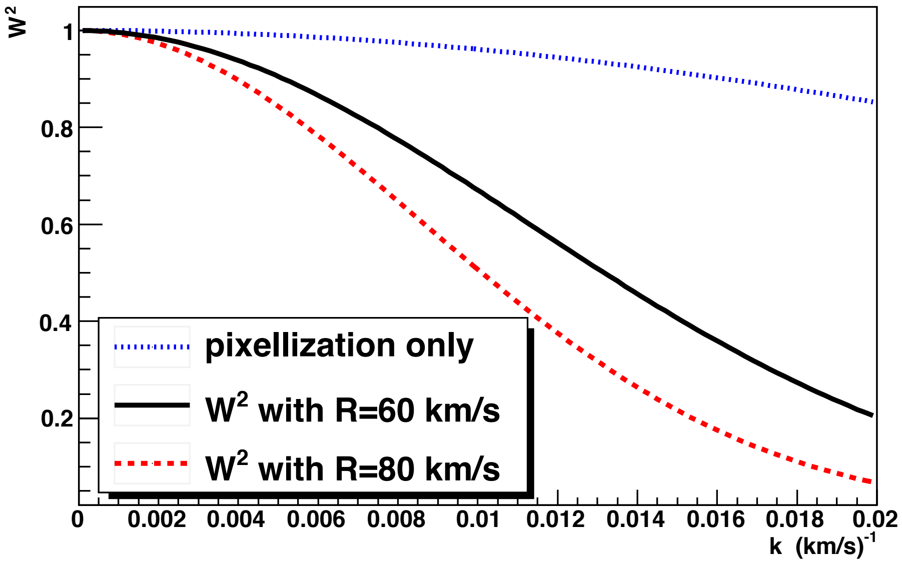


Detailed study of contributions from

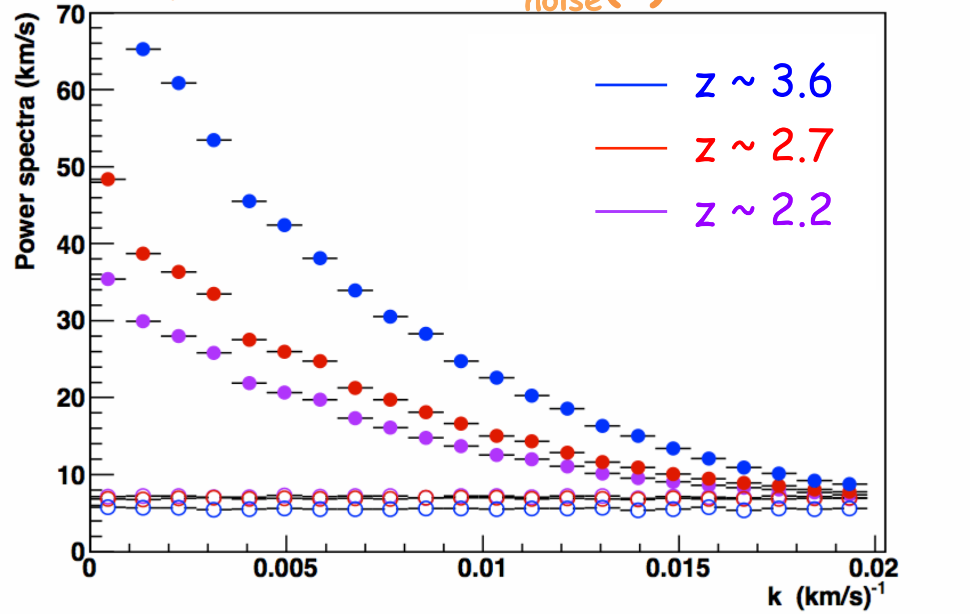
- **detector (spectrograph resolution, noise)**
- **astrophysics (sky lines, correlation with other absorbers)**

$$P_{Raw}(k) = [P_{Ly\alpha}(k) + P_{Ly\alpha\text{-}SiIII}(k) + P_{metals}(k)] \times W^2(k) + P_{Noise}(k)$$

Resolution = Window function W^2



White noise = $P_{noise}(k)$

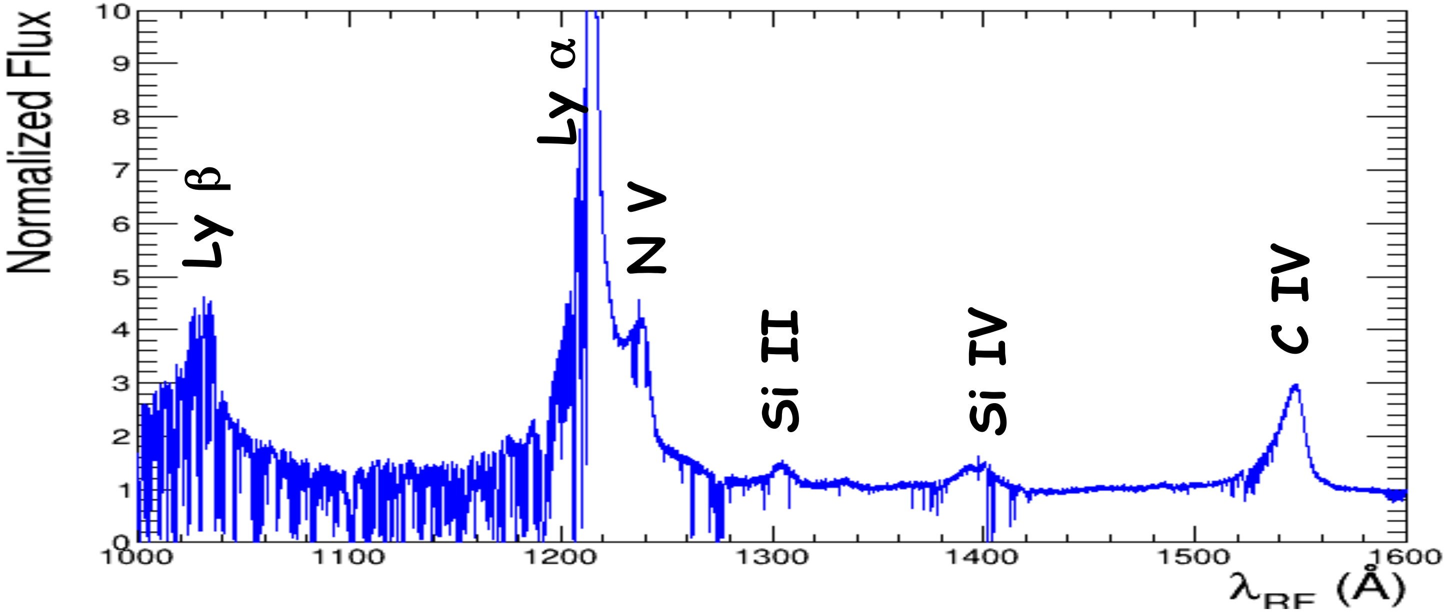


Lyman-α forest 1D power spectrum

X-Shooter on the VLT
XQ-100 program

100 QSOs at z ~ 3.5

SNR per pixel ~25 (vs. SDSS ~2)
Resolution ~15 km/s (vs. SDSS: ~75 km/s)

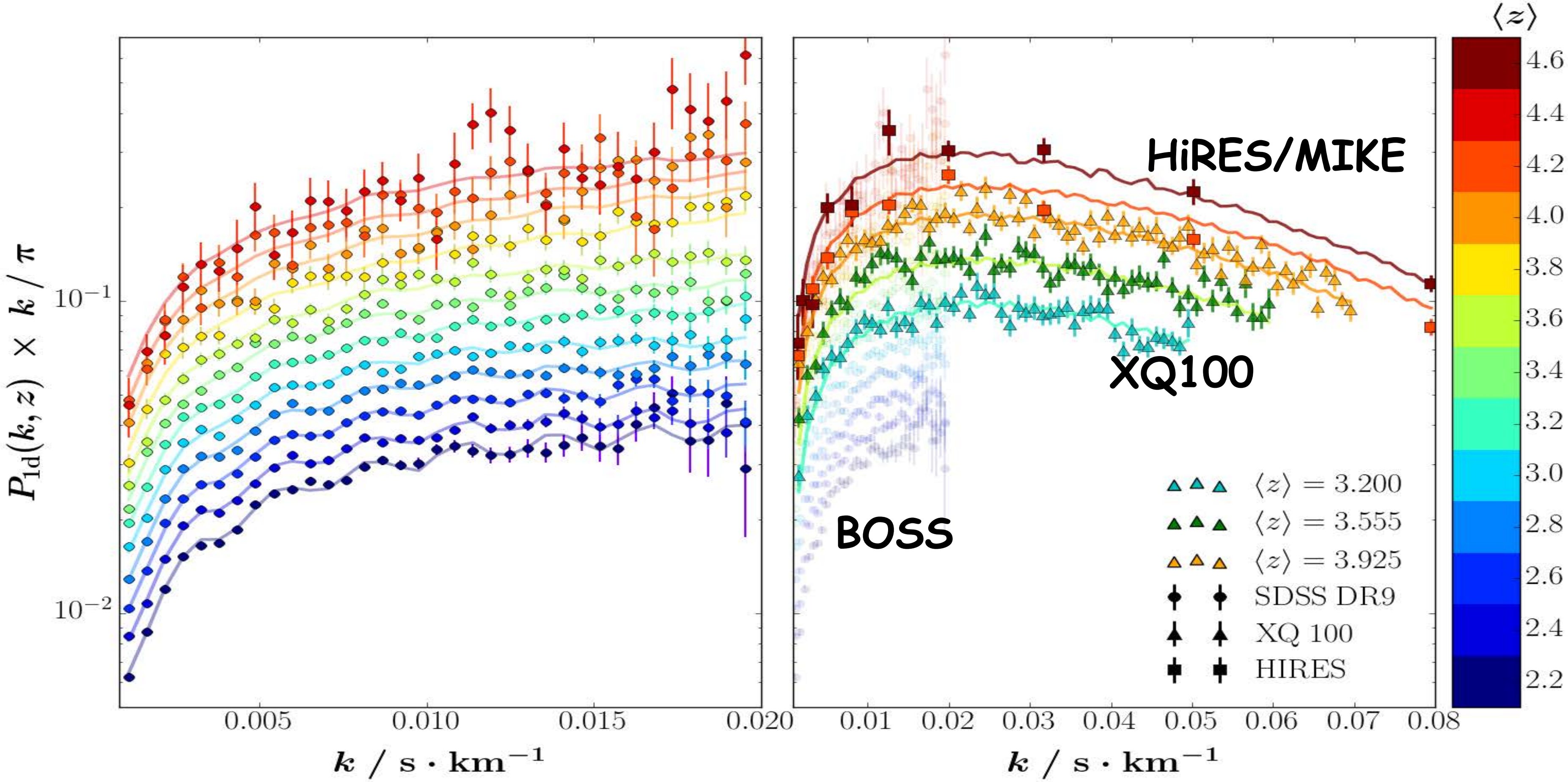


Lyman-α forest 1D power spectrum

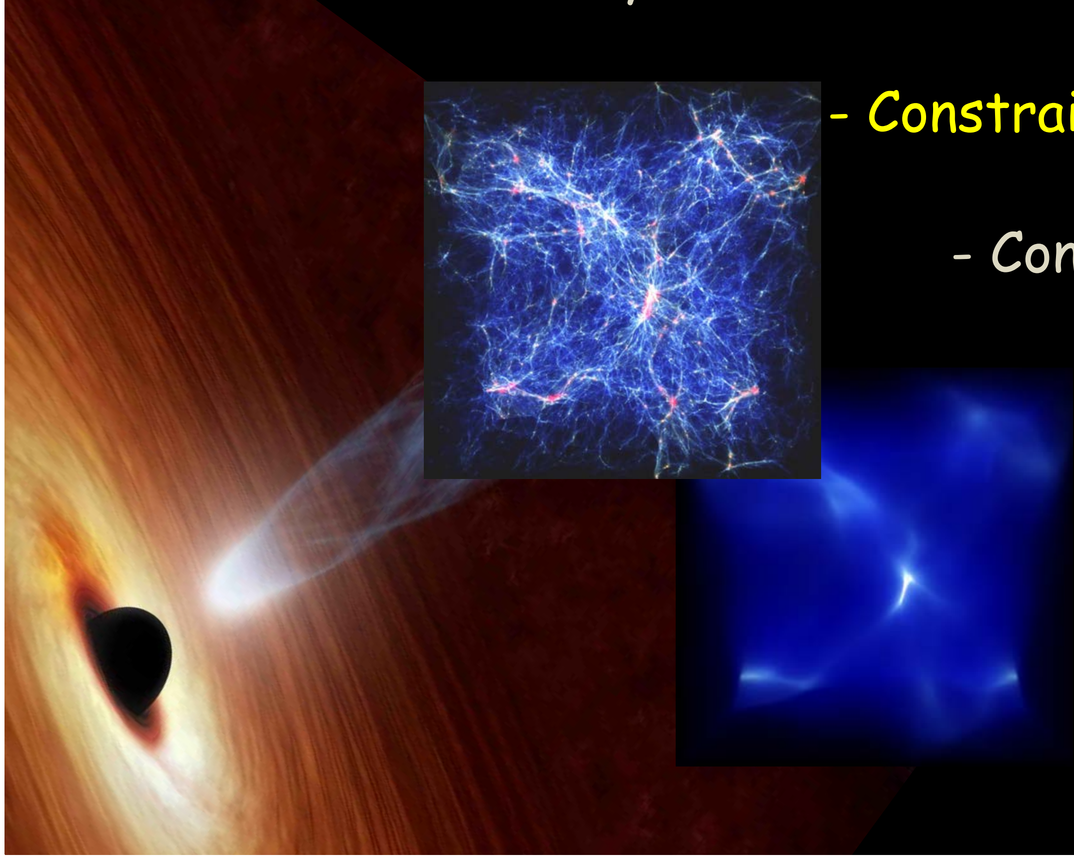
BOSS
NPD, Yeche+ (2013)
12 bins z=2.2 to 4.4

XQ100
Yeche, NPD+ (2017)
Irsic, Viel+ (2017)
z=3.2, 3.6, 3.9

HiRES/MIKE
Viel, Becker+ (2013)
z=4.2, 4.6, (5.4)



Measuring small-scale structure in the IGM to constrain cosmology



- Lyman-α data used

- Constraint on ν mass

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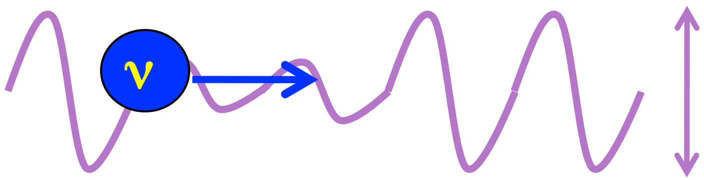
m_ν & large-scale structures

Neutrinos are relativistic early on
Neutrinos "free stream" at v=c until t_{nr} (actually once they have decoupled)

⇒ Destroy perturbations of wavelength $\lambda < ct_{nr}$
although normal clustering on scales $\lambda > ct_{nr}$

- Heavy neutrinos (t_{nr} early)

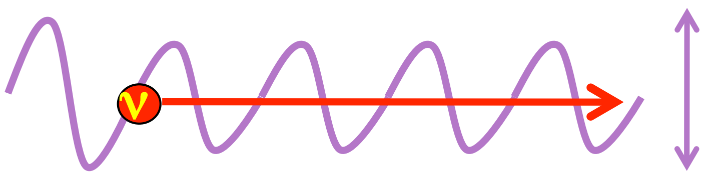
  Strong suppression over short range



m_ν ~ keV ⇒ size of dwarf galaxy perturbations smoothed out

- Light neutrinos (t_{nr} late)

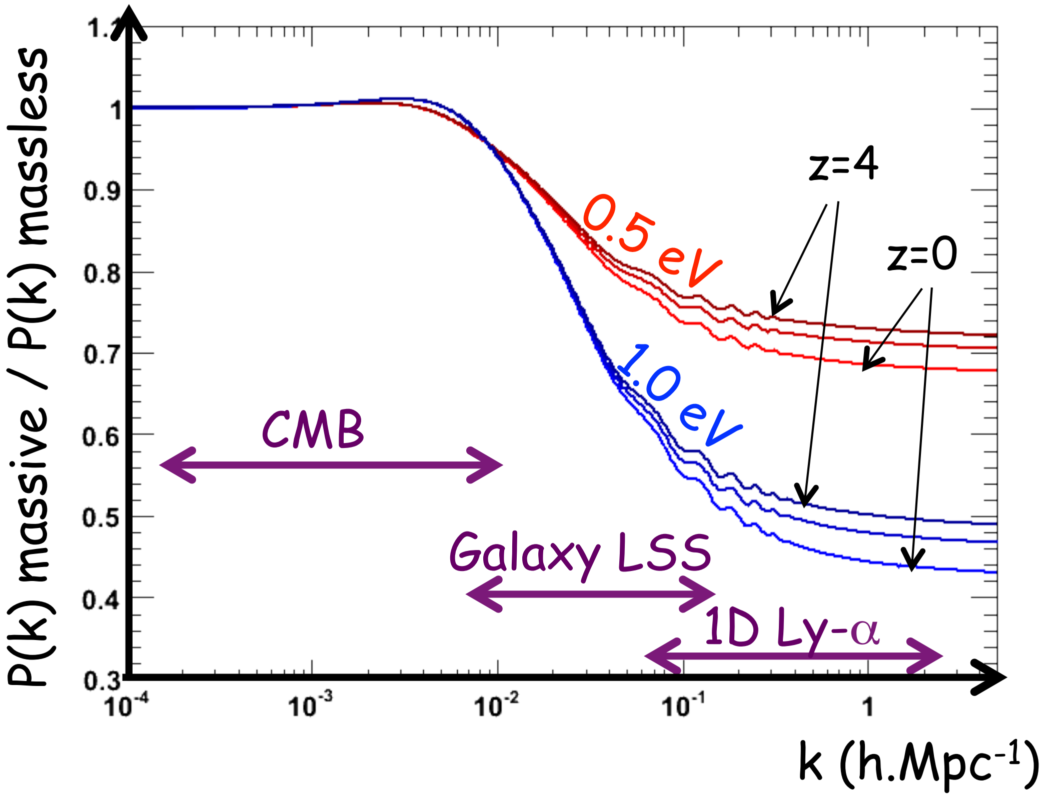
  Weak suppression over long range



m_ν ~ eV ⇒ size of galaxy cluster perturbations smoothed out

m_ν & large-scale structures

Different probes ⇔ different scales



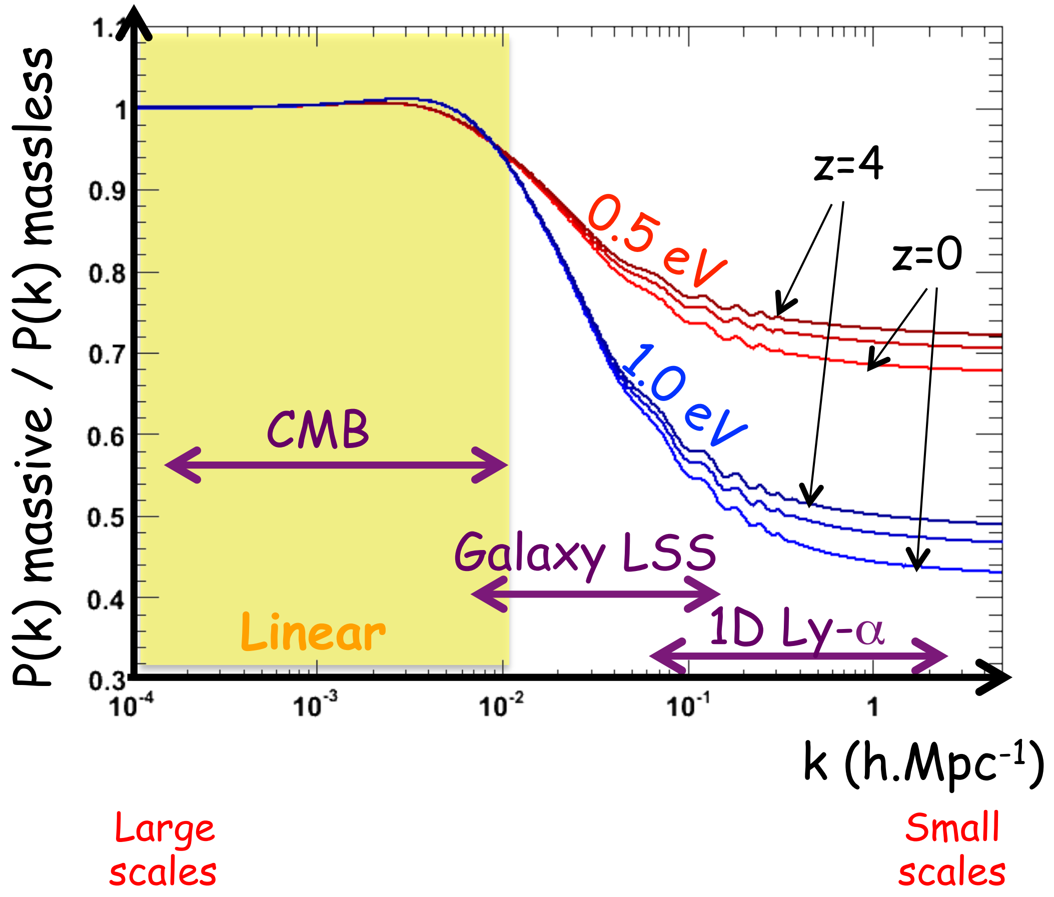
Large scales

Small scales

- Suppression factor ⇔ Σmν
- Suppression is z-dependent
- Ly-α
  - Small scales, max effect ✚
  - Large z-range [2.1 ; 4.5] ✚

m_ν & large-scale structures

Different probes ⇔ different scales



- Suppression factor ⇔ Σmν
- Suppression is z-dependent
- Ly-α
  - Small scales, max effect +
  - Large z-range [2.1 ; 4.5] +
  - Non-linear regime, flux (not mass) P(k) ⇒ Hydro simulations −

Hydrodynamical simulations

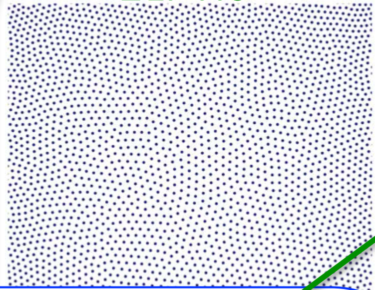
$(100\ h^{-1}\mathrm{Mpc})^3$ with *3072^3* particles/species

McDonald (2003) splicing approach

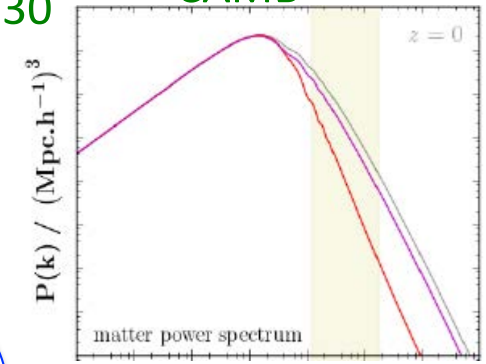
- dark matter
- baryons
- (degenerate-mass) neutrinos

2LPTic

z=30

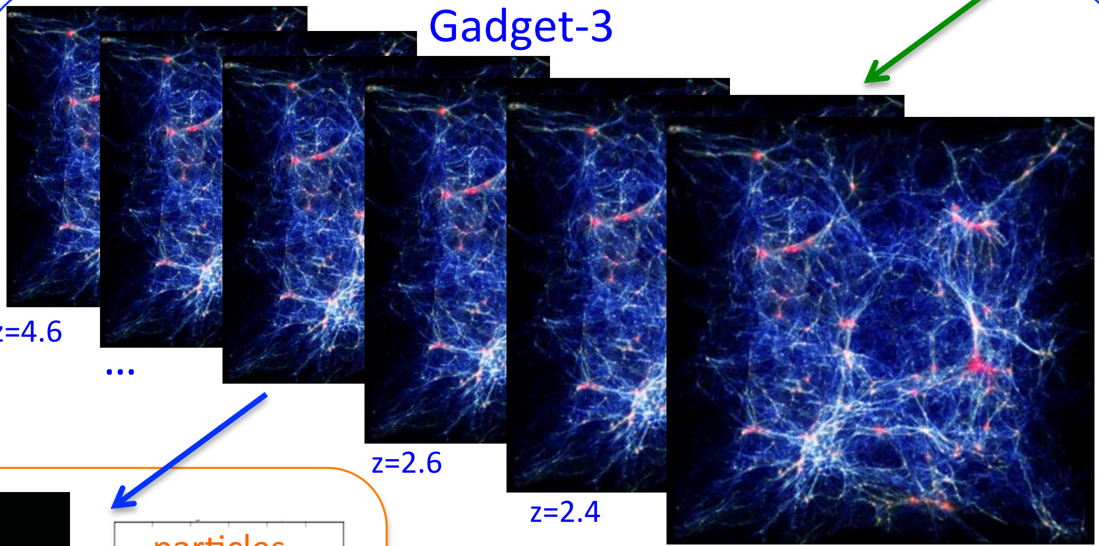


CAMB

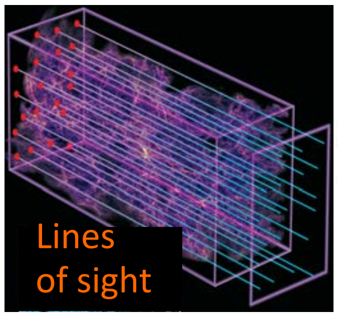


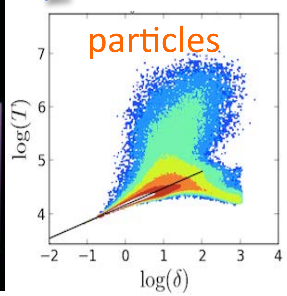
Initial conditions

Gadget-3



N-body + SPH simulation





Ly-α power spectrum

Borde, NPD et al. (2014)

Rossi, NPD et al. (2014)

Hydrodynamical simulations

Grid of simulations

→ 2nd-order Taylor expansion for cosmo & astro parameters centered on Planck (2013)

$$f(\mathbf{x}+\Delta\mathbf{x}) = f(\mathbf{x}) + \sum_i \frac{\partial f}{\partial x_i}(\mathbf{x})\Delta x_i + \frac{1}{2}\sum_i\sum_j \frac{\partial^2 f}{\partial x_i \partial x_j}(\mathbf{x})\Delta x_i \Delta x_j$$

TGCC Bruyères-le-châtel

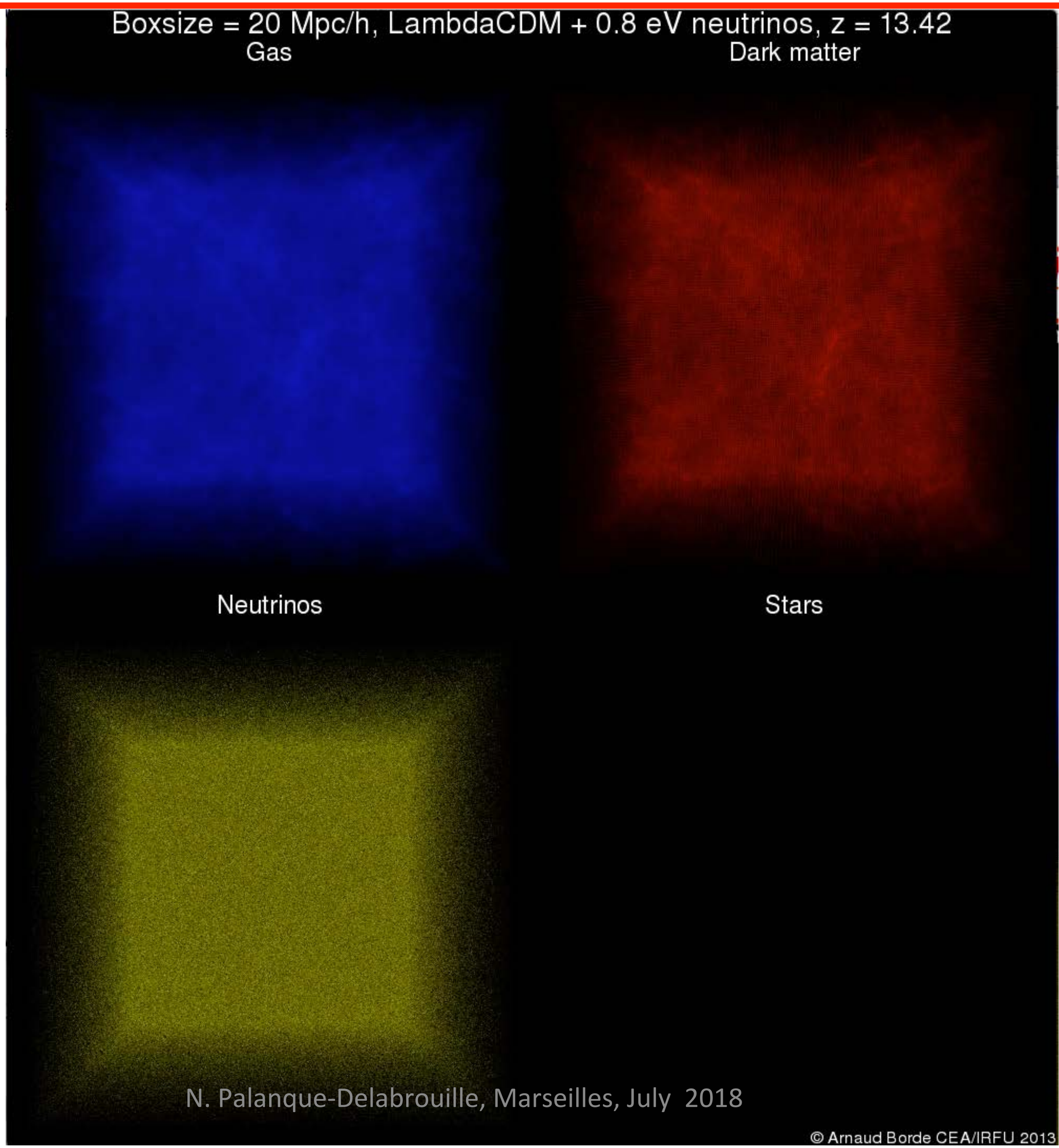
	parameter	*central*	*range*
Cosmology	keV / m_X	0.0	+0.2 +0.4
	$\Sigma m_\nu / eV$	0.0	+0.4 +0.8
	h	0.675	±0.05
	Ω_M	0.31	±0.05
	σ_8	0.83	±0.05
	n_s	0.96	±0.05
	$dn_s / d\ln k$	0.00	±0.04
	z_{reio}	12	±4
	N_{eff}	3.046	±1
Intergalactic Medium	$T_0^{z=3} / K$	14,000	±7,000
	$\gamma^{z=3}$	1.3	±0.3
Optical Depth	A^τ	0.0025	±0.0020
	η^τ	3.7	±0.4

Hydrodynamical simulations

z = 15 → 0

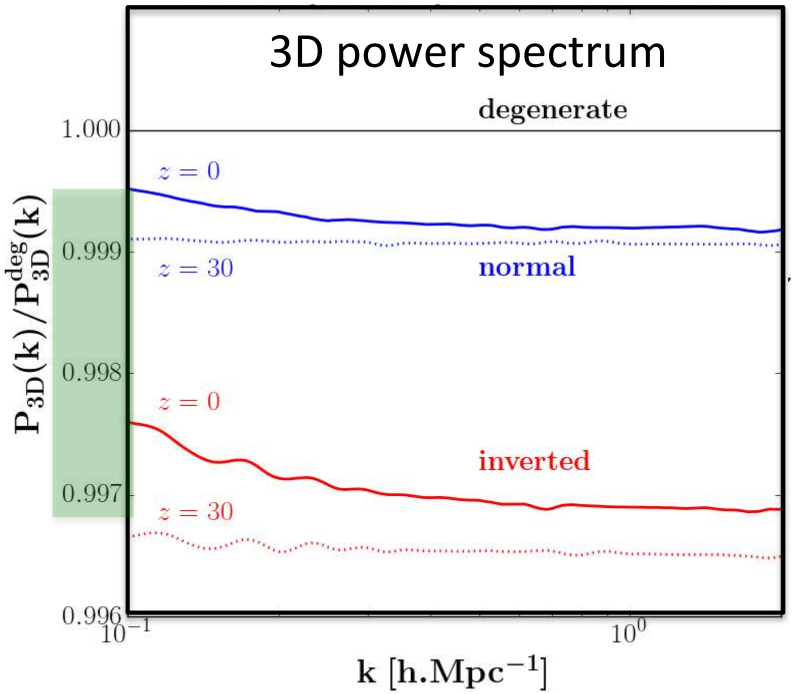
3 species
- Baryons
- Dark matter
- Neutrinos

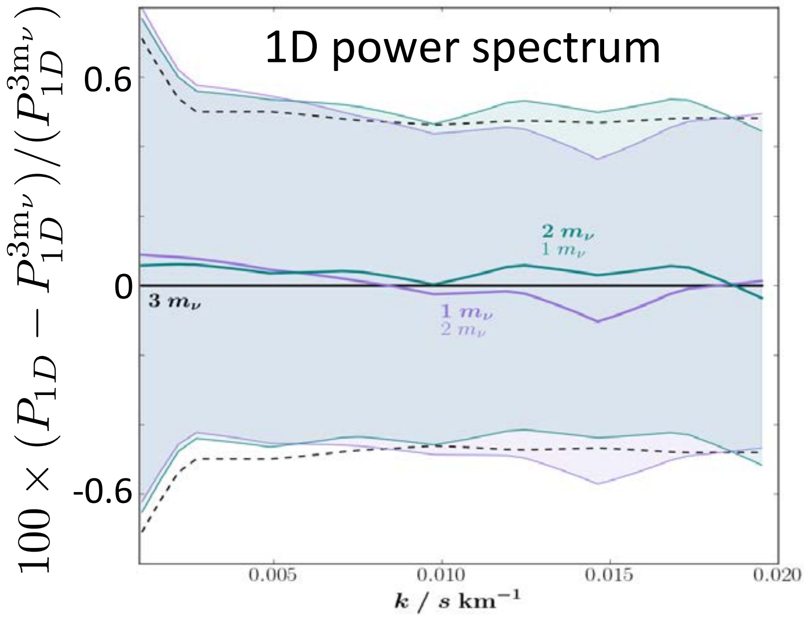
Stars formed from baryons



@ A. Borde (CEA-Saclay)

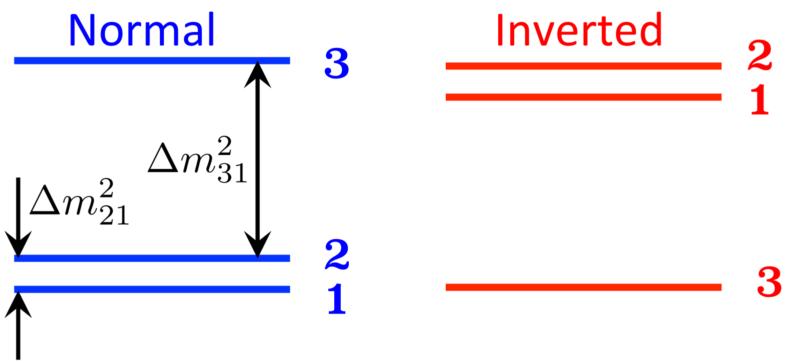
Neutrino mass (Σm) or masses (m_i)?





Hierarchy	m_1	m_2	m_3
Degenerate	0.033	0.033	0.033
Normal	0.022	0.024	0.055
Inverted	0.0007	0.049	0.050

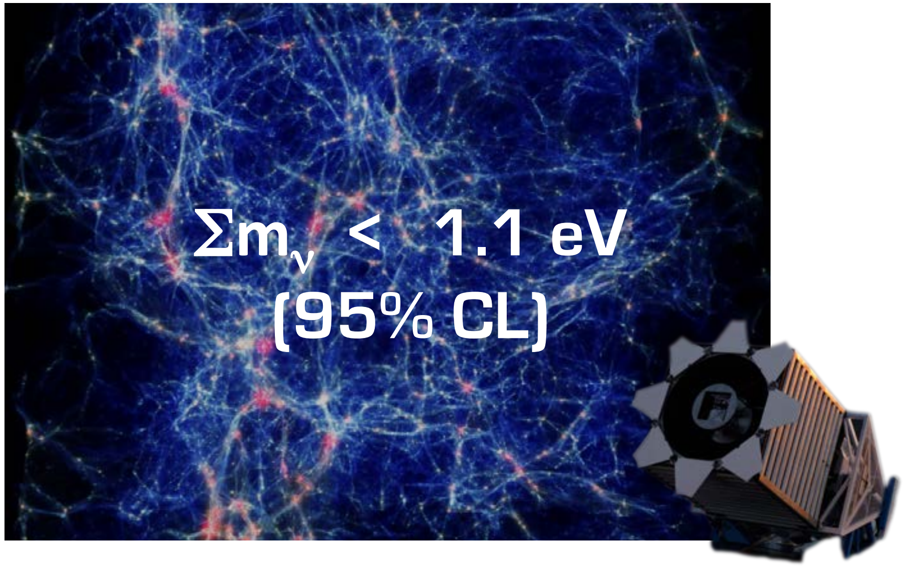
Σm = 0.10 eV



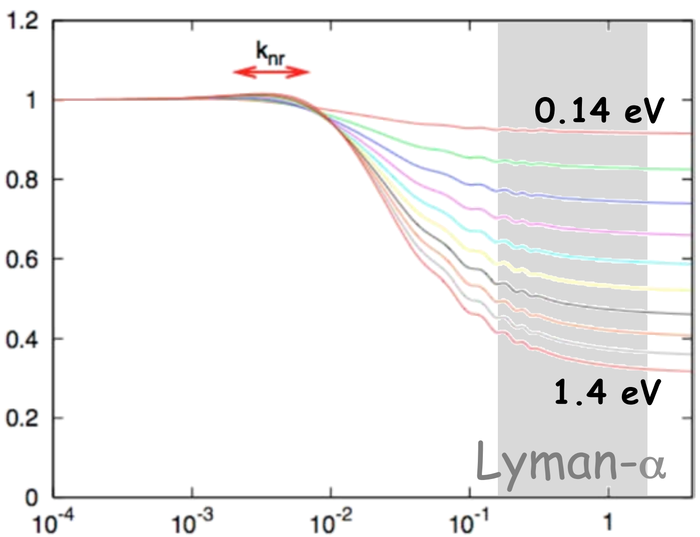
NPD, Yeche, Baur+ (2015)

'Exclusively' a Σm effect

M_ν constraint

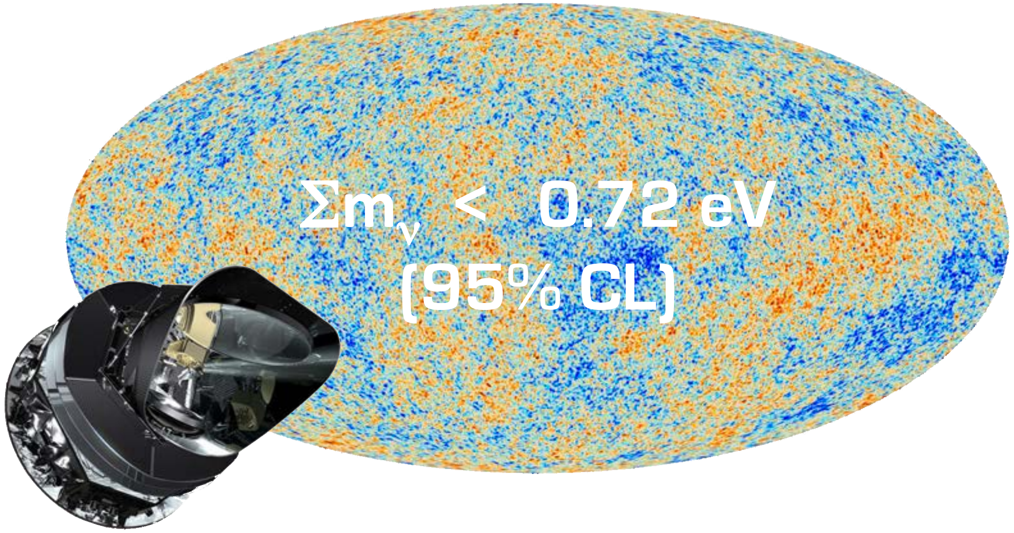


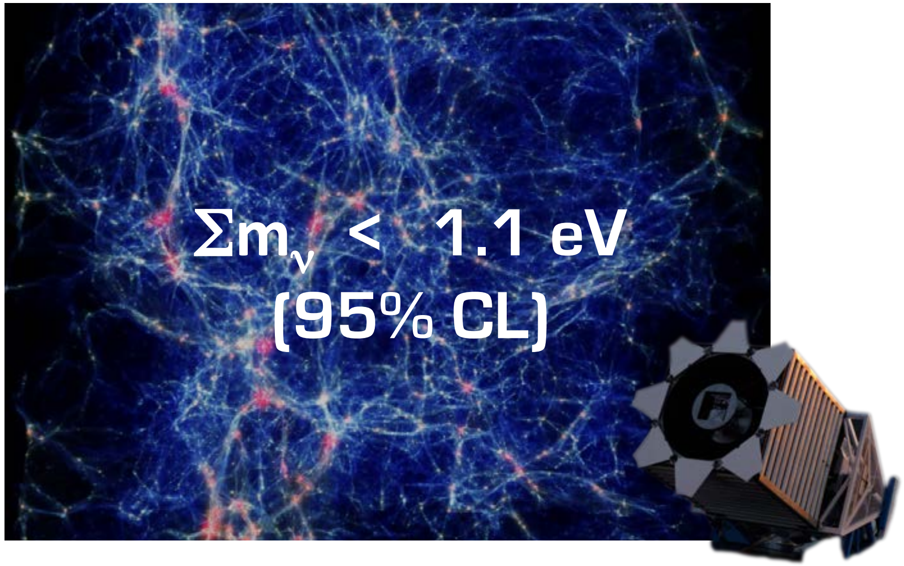
P(k) massive / P(k) massless

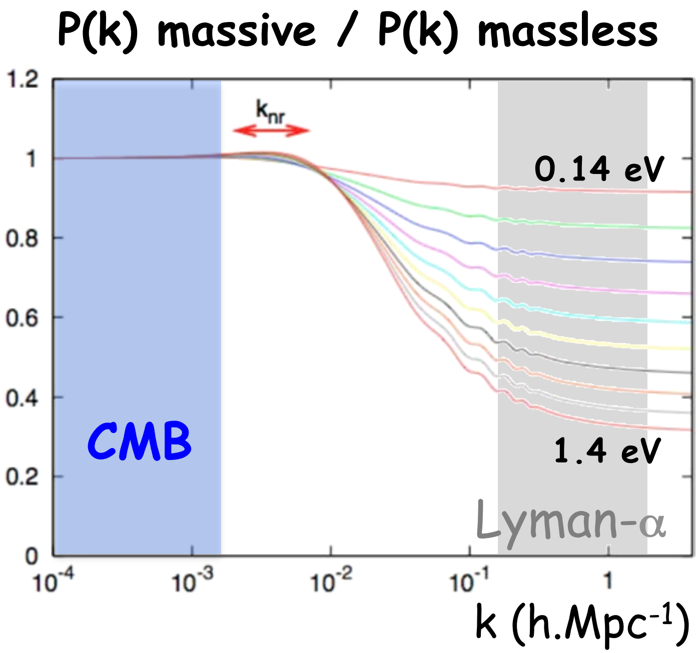


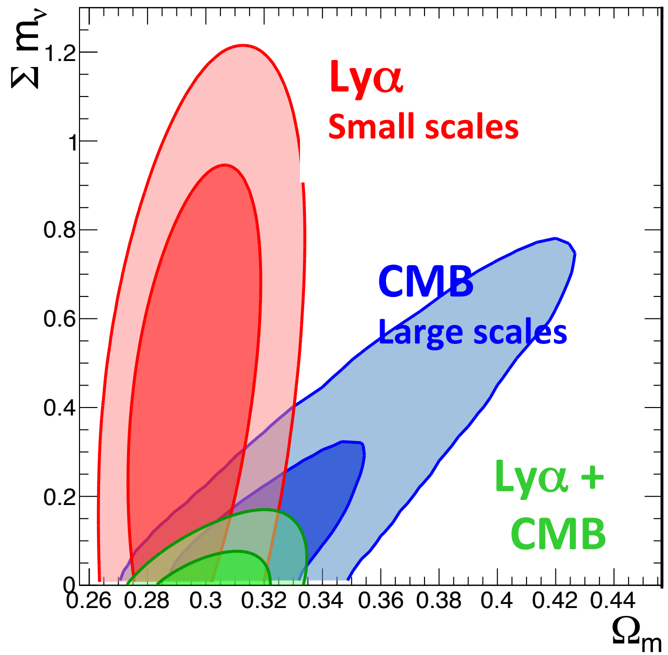
k (h.Mpc^{-1})

Mν constraint





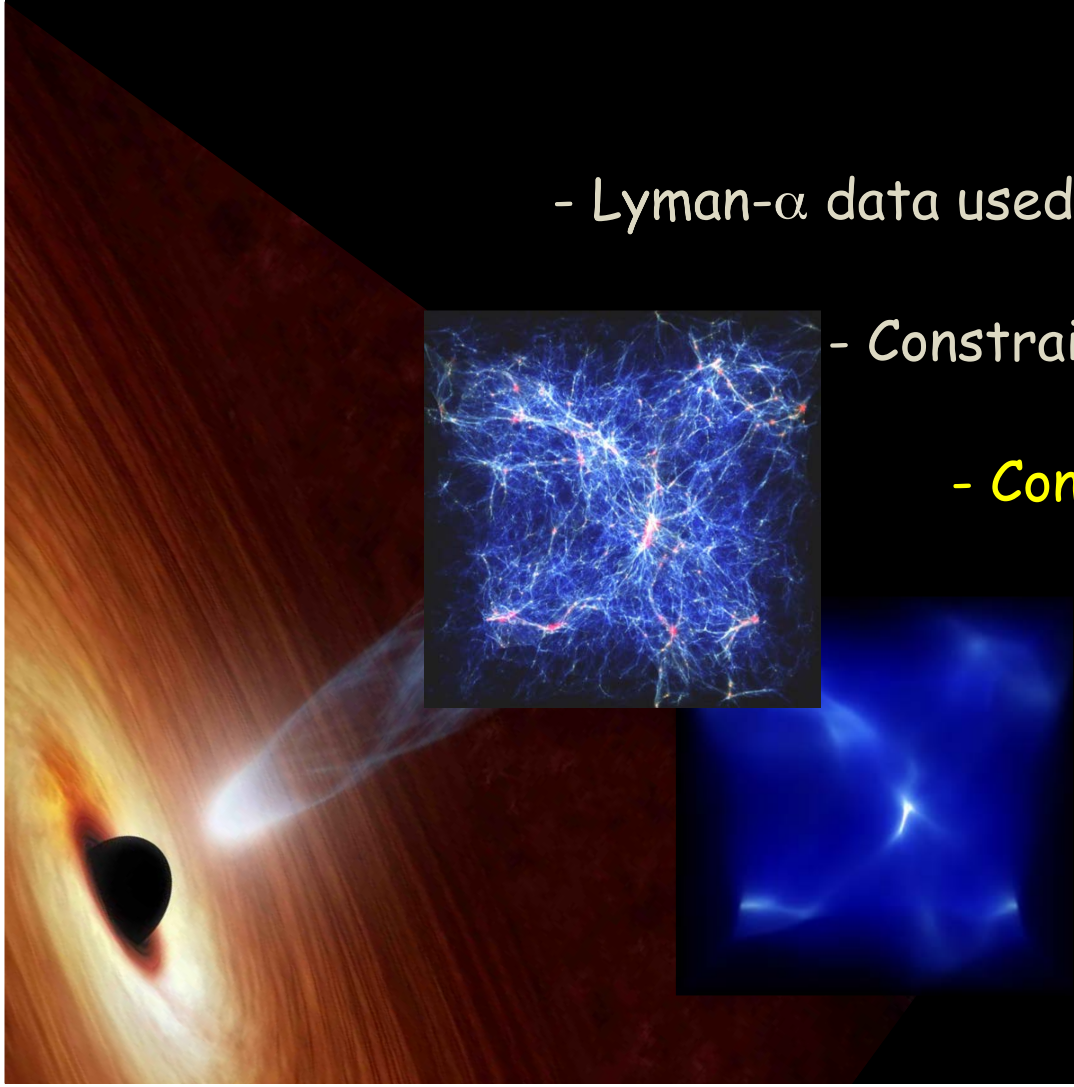




$\Sigma m_\nu < 0.12$ eV

NPD, Yèche, Borde et al. (2015)
NPD, Yèche, Baur, et al. (2015)

Measuring small-scale structure in the IGM to constrain cosmology



- Lyman-α data used

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- Constraint on warm dark matter

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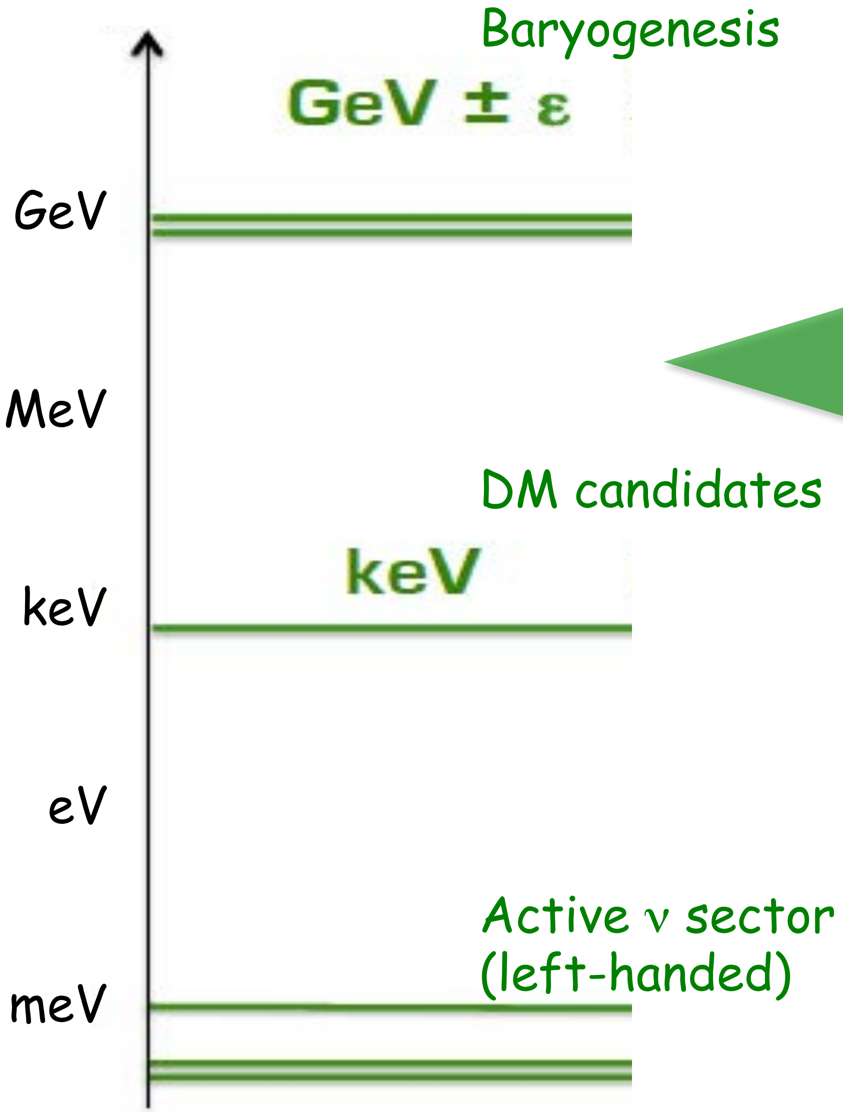
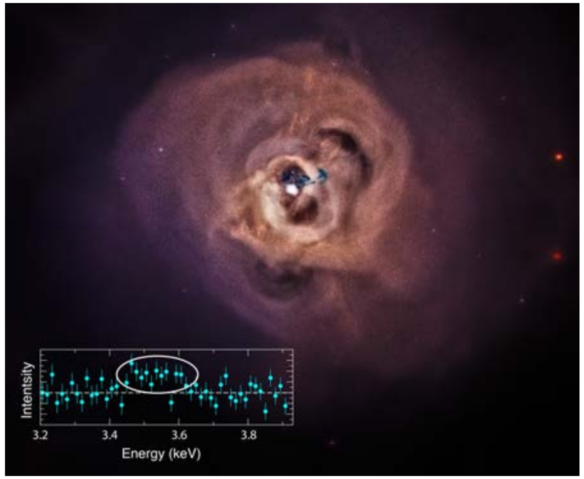
Marseille, July 2018

Sterile neutrino sector



Sterile ν sector
(right-handed)
ν Minimal Extension

Preseus cluster
Andromeda galaxy
XMM clusters



3.5 keV line (XMM): decay of 7 keV ν_s ?

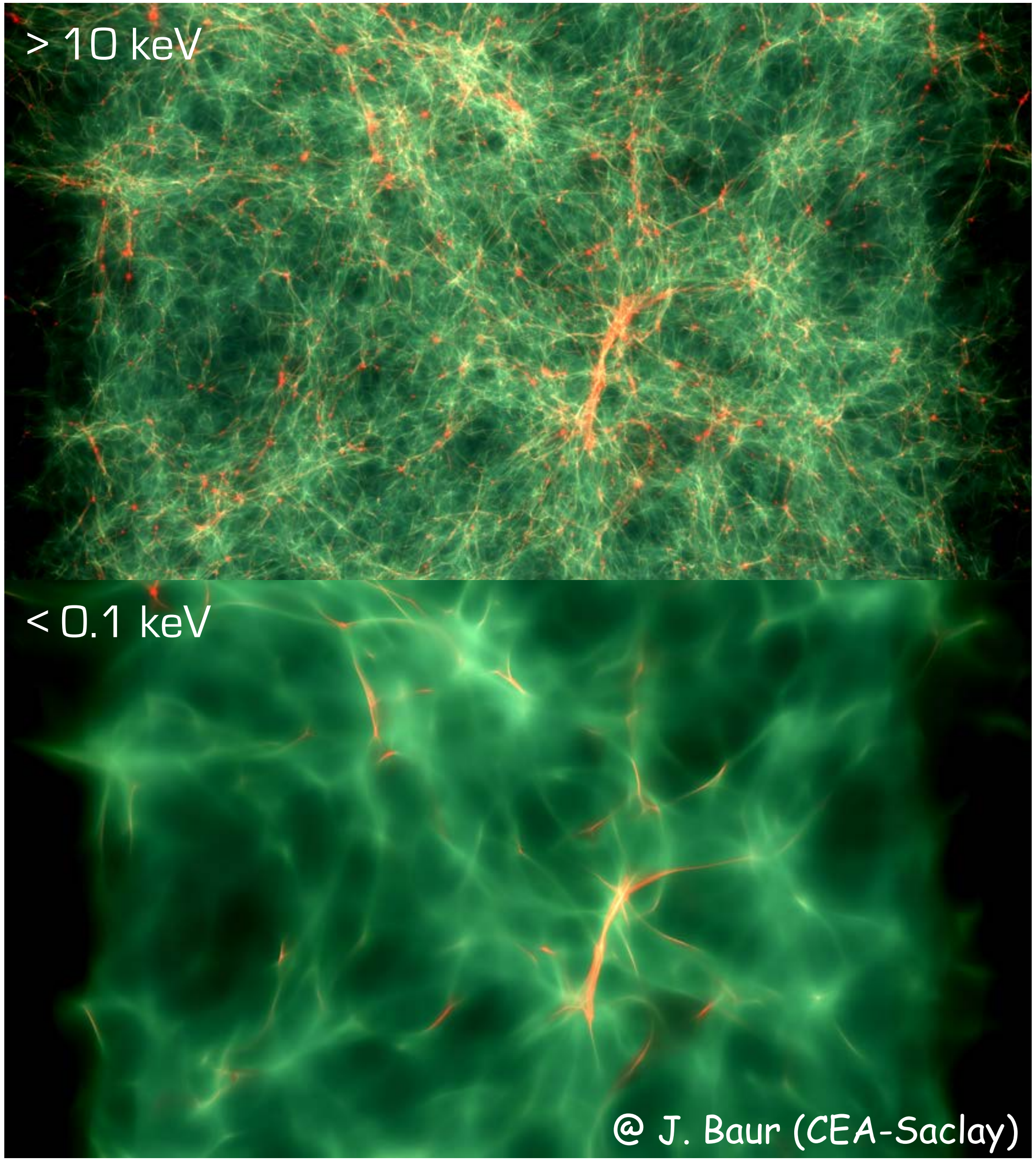
Bulbul++ 2014, Boyarsky++ 2014, Cappelluti++ 2017

Warm Dark Matter

If all
dark matter
were

Cold Dark Matter

Hot Dark Matter



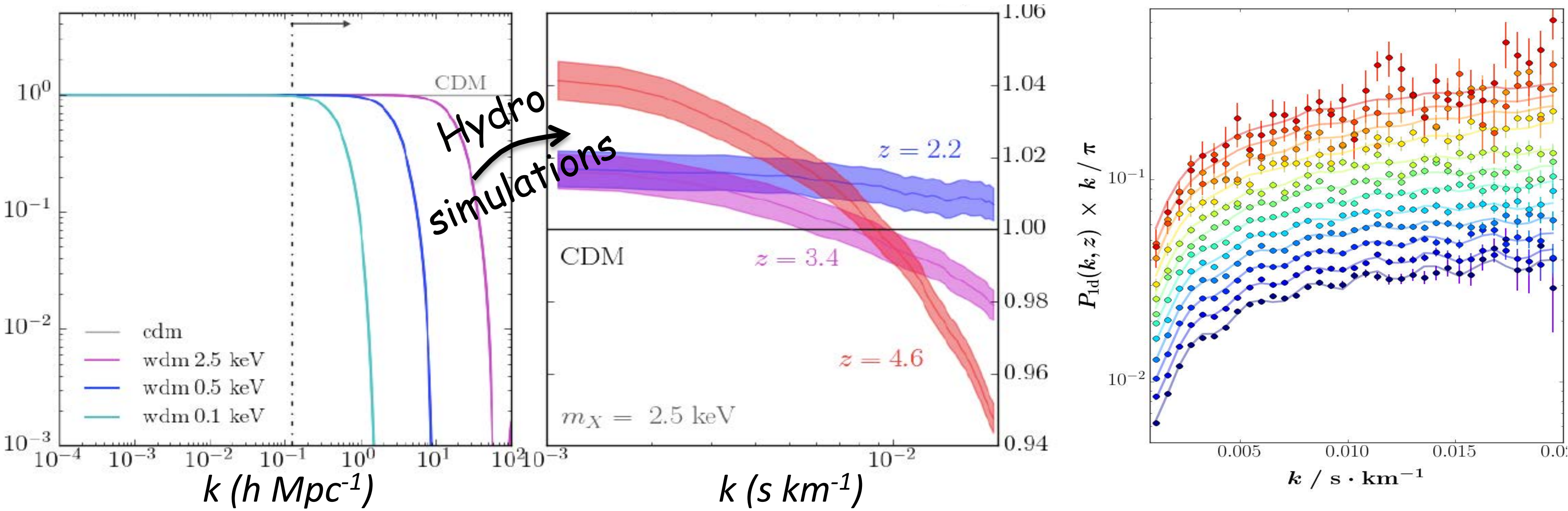
Free Streaming Horizon

$$\lambda^0_{\rm FSH} = \int_0^{t_0} \frac{\langle v \rangle}{a}\, dt$$

Ly-α forest & WDM

$P_{WDM}(k) / P_{CDM}(k)$ $P_{Ly\alpha}(k) . k / \pi$

Matter power spectrum Lyα flux power spectrum Fit on data



High-z and high-k bins most constraining
(more sensitive to linear regime cutoff)

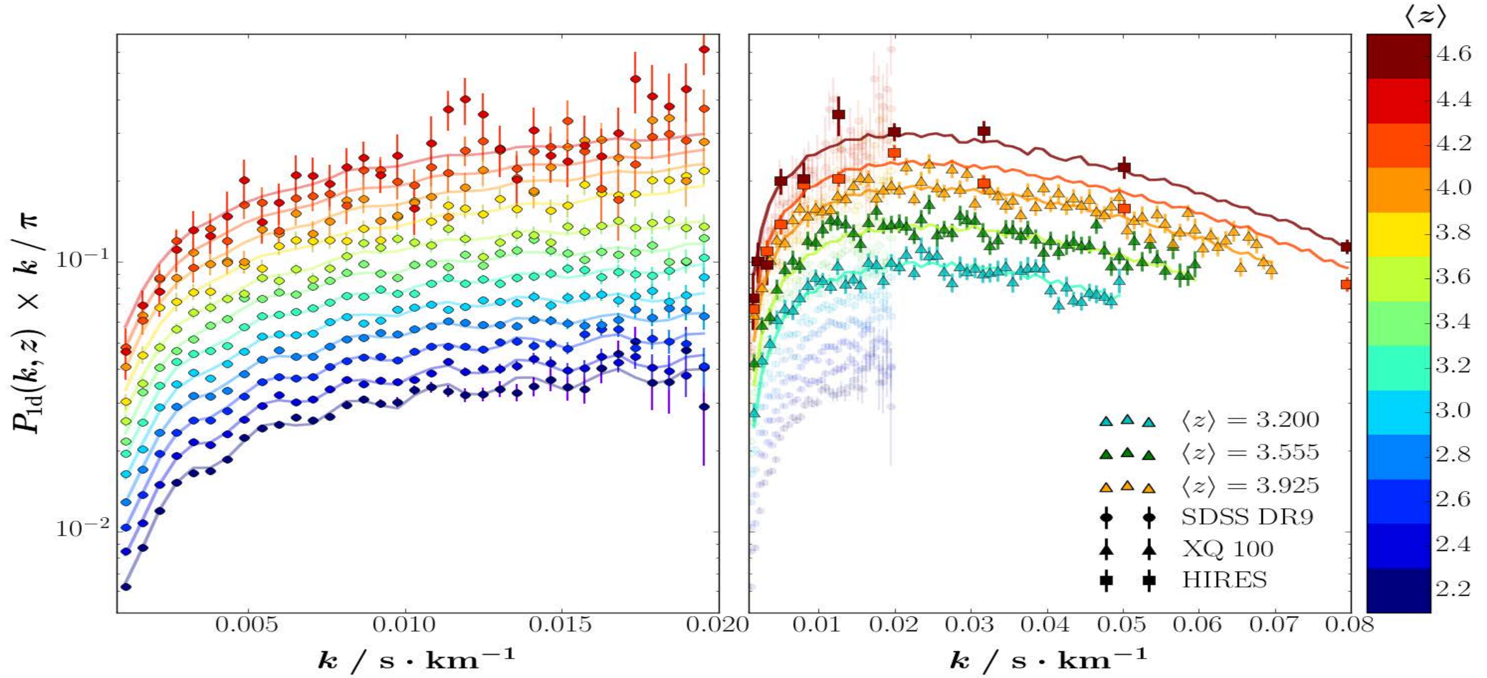
Warm Dark Matter: thermal relic & NRP ν_s

High-z and high-resolution bins have large constraining power
(closer to linear case, more sensitive to sharp cutoff)

Data Set	BOSS z<4.1	BOSS z<4.5	BOSS + XQ100 + HIRES/MIKE
Lower bound on m_X (keV)	2.97	4.1	4.65 (z≤4.6) [1] / 5.3 (z≤5.4) [2]
Lower bound on m_s (keV)	16.1	24.4	28.8 (z≤4.6) [1] / 34.1 (z≤5.4) [2]

$$m_{\nu_s} = \kappa \; m_x^{\mu} / \omega_{\rm wdm}^{1/3}$$

[1] Yèche, NPD+ (2017)
[2] Irsic, Viel+ (2017)



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More conservative

More prone to systematics
e.g. thermal history of IGM
Garzilli+ (2017)

Here broken power-law T(z)
assumed, with break at z=3

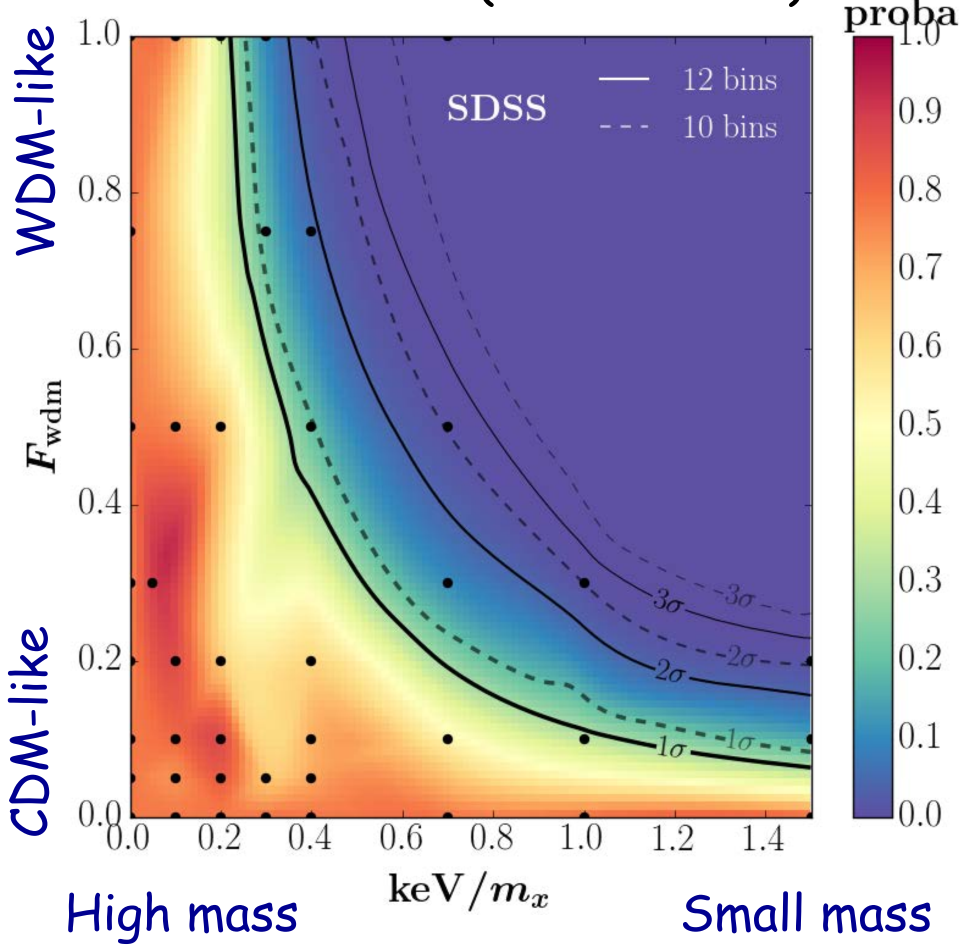
Among the strongest bounds to date

[1] Yèche, NPD+ (2017)
[2] Irsic, Viel+ (2017)

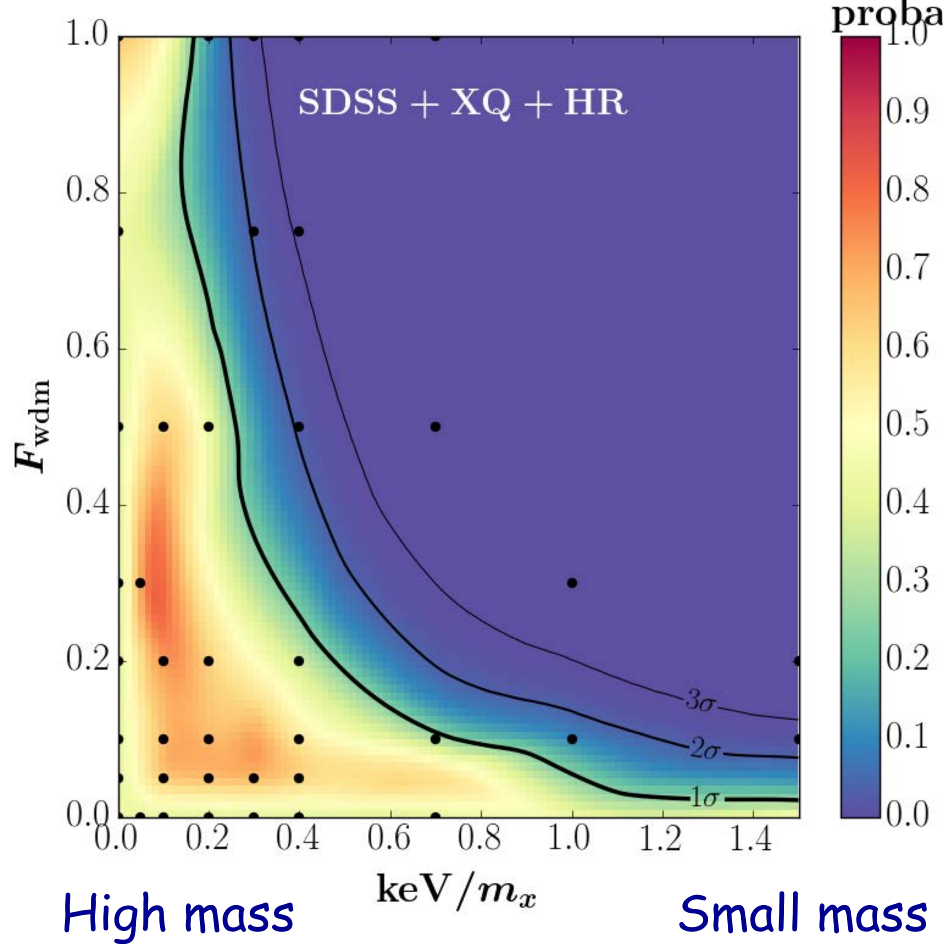
In combination with X-ray data (m_S < 4 keV),
excludes non-resonantly-produced sterile neutrinos

Cold+Warm Dark Matter

BOSS data (conservative)



BOSS + Hires/MIKE



Mixes with high-mass WDM or low WDM fraction are favored
(more CDM-like)

Baur, NPD+ (2017)

Sterile neutrinos: more general scenario

Resonantly produced sterile neutrinos (Shi & Fuller, 1999)

Lepton asymmetry

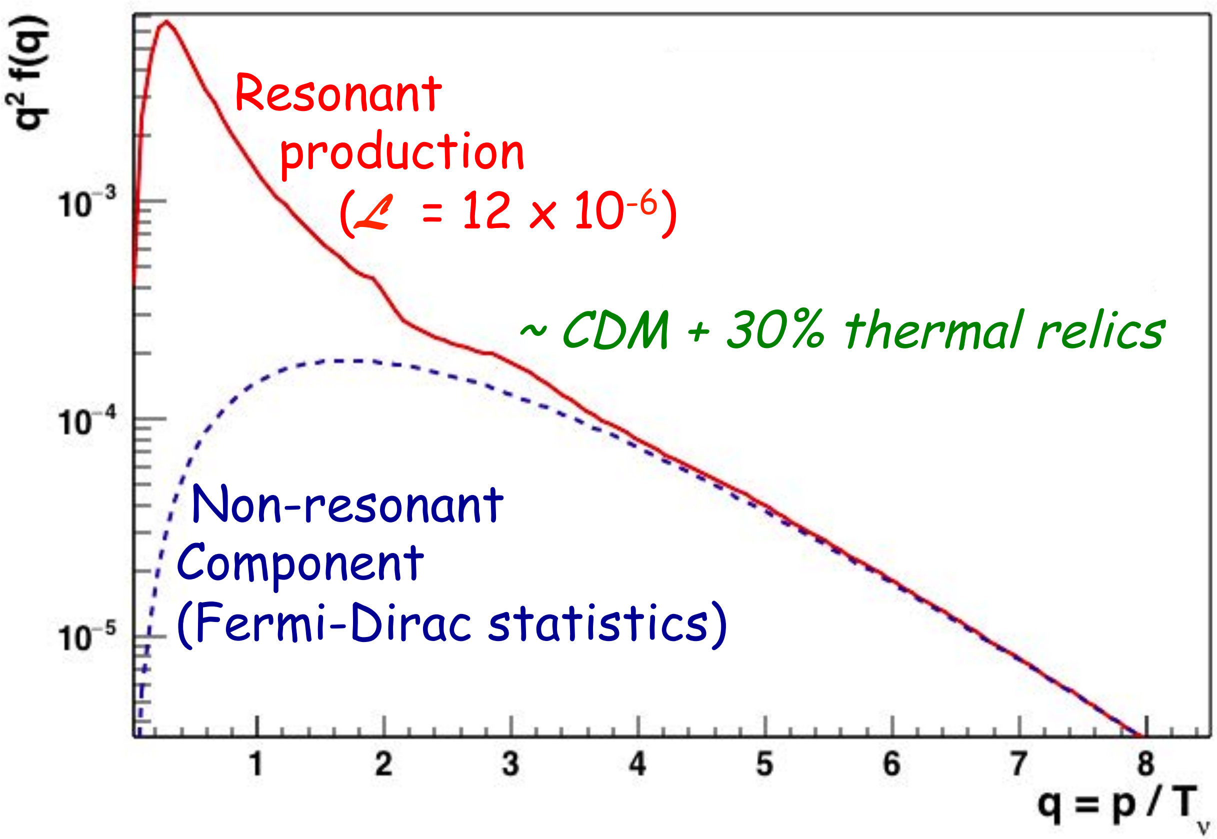
$$\mathcal{L} = \frac{|n_\nu - n_{\bar{\nu}}|}{s}$$

Enhanced oscillations

$$\nu_{e,\mu,\tau} \longleftrightarrow \nu_s$$

Non-thermal distribution
<u>Colder dark matter than non-resonant production</u>

m_s=4keV Phase-space Distribution

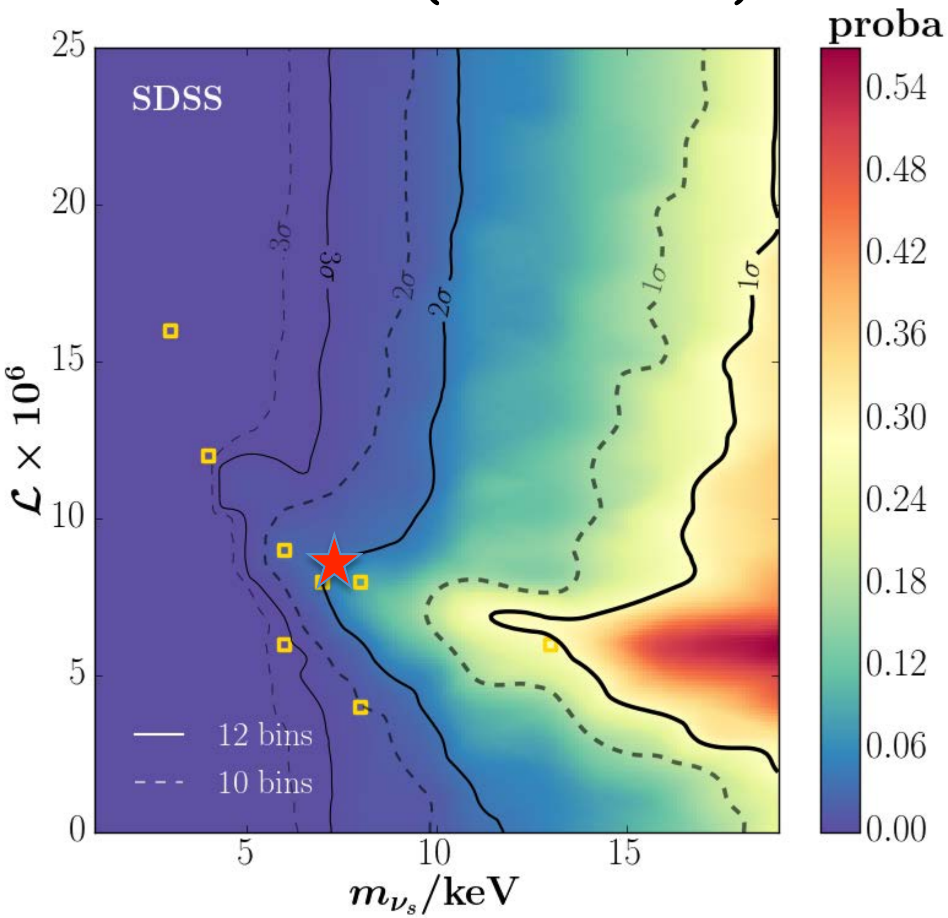


← Cold Warm →

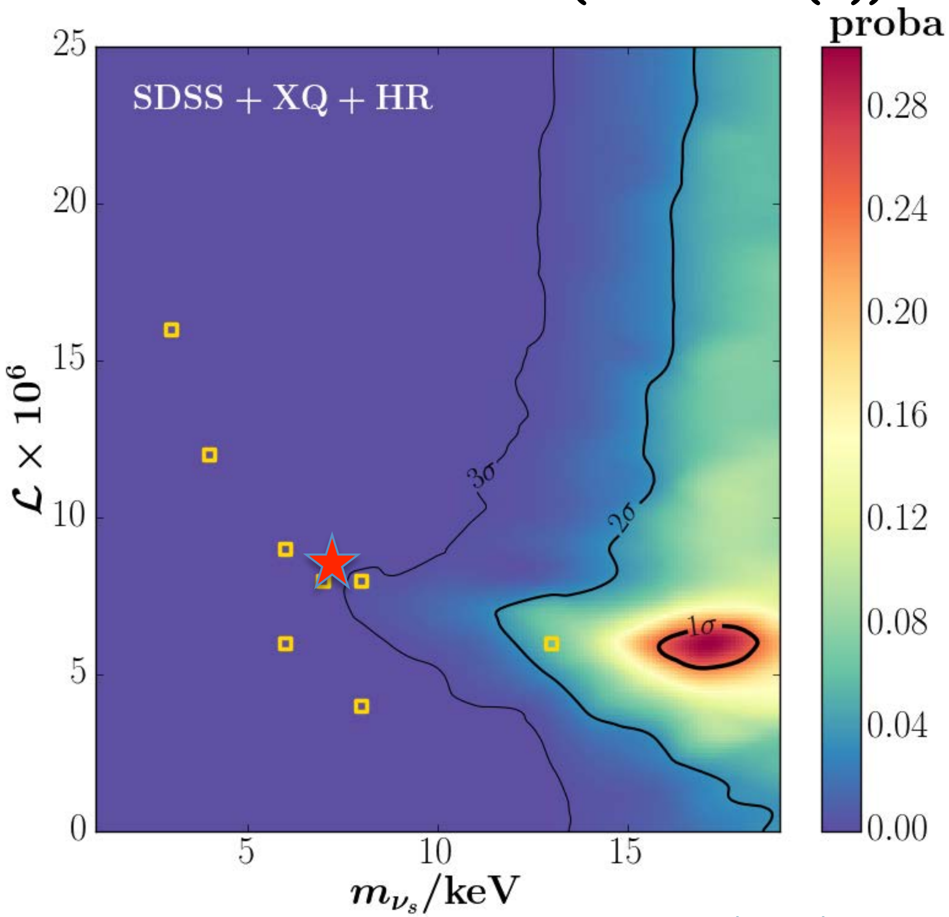
Resonantly-produced sterile neutrinos

Using C+WDM → non-resonant ν_s mapping at T_{1D} level
+ 8 hydro simulations near coldest models for validation

BOSS data (conservative)

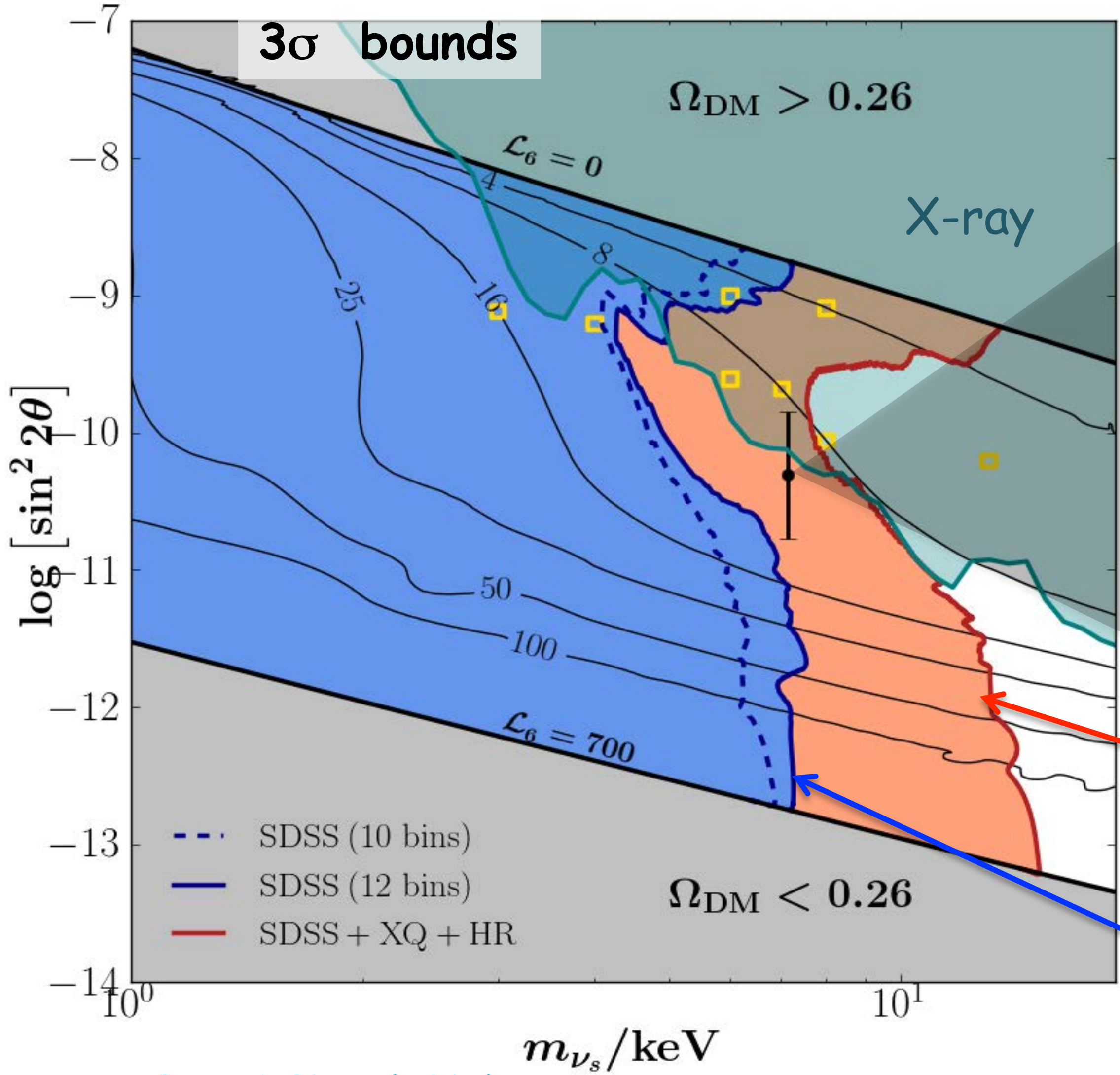


BOSS + Hires/MIKE (smooth T(z))



Baur, NPD+ (2017)

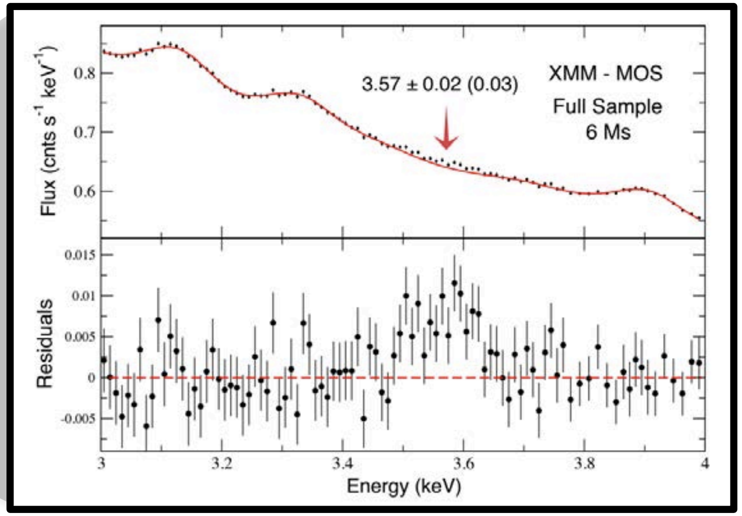
Resonantly-produced sterile neutrinos



Baur, NPD++ (2017)

Bulbul et al. 2014, ApJ 789 13

Boyarsky et al. 2014, PRL 113, 251301



Assuming broken power law T(z) to z=4.6 (3σ high-res. bounds)

Conservative (3σ mid-res. z<=4.2 bounds)

Conclusions

- **Lyα is a powerful probe for cosmology**

- **Constraint on mass of active neutrinos**
  - **Sum of neutrino masses Σm_ν < 0.12 eV** (95% CL) **from Lyα+CMB**

- **Constraint on warm dark matter & sterile neutrinos** (conservative BOSS only)
  - **m_{WDM} > 4.1 keV** (95% CL) **for thermal relic**
  - **$m_{sterile}$ > 24 keV** (95% CL) **for non-resonant production (NRP)**
    NRP sterile neutrinos excluded by Lyα + X-ray
  - **Interpretation of 3.5 keV X-ray line as ν_s**
    at odds with $m_{sterile}$(RP) Lyα constraints

- **Prospects**
  - **Improved mid-resolution data (full SDSS/BOSS in prep.)**
  - **Planck + DESI Lyα** $\sigma(\Sigma m_\nu)$ = 0.039 eV
  - **Planck + DESI Galaxy** $\sigma(\Sigma m_\nu)$ = 0.024 eV