

Irfu D-Days, Juillet 2016

Irfu / SPP – CEA

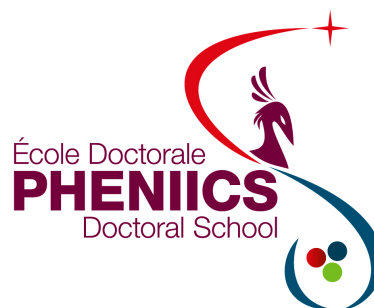


Determining Neutrino Masses with the Lyman-alpha Forest

Julien Baur

PhD student

Nathalie Palanque-Delabrouille & Christophe Yèche



10⁻³² seconds

1 second

100 seconds

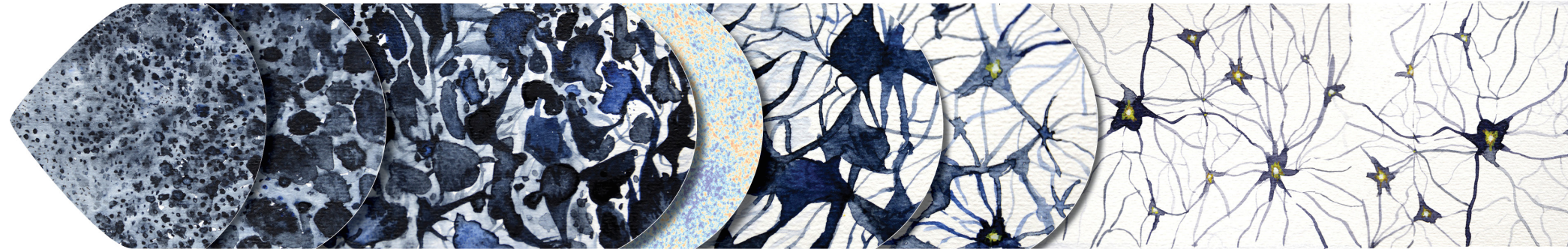
380 000 years

300–500 million years

Billions of years

13.8 billion years

Beginning
of the
Universe



Inflation

Accelerated expansion
of the Universe

Formation of light and matter

Light and matter are coupled

Dark matter evolves
independently: it starts
clumping and forming
a web of structures

Light and matter separate

- Protons and electrons
form atoms
- Light starts travelling
freely: it will become the
Cosmic Microwave
Background (CMB)

Dark ages

Atoms start feeling
the gravity of the
cosmic web of dark
matter

First stars

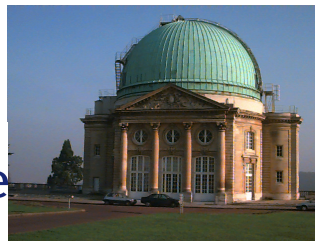
The first stars and
galaxies form in the
densest knots of the
cosmic web

Galaxy evolution

The present Universe

credit: Planck

l'Observatoire
de Paris



$$T = T_0 + 2.678 \cdot 10^{-14} \text{ eV}$$

start PhD

$$T_0 = 0.235 \text{ meV}$$

now

$T \sim 1 \text{ MeV}$
 $\nu_{e,\mu,\tau}$ decouple

10^{-32} seconds

1 second

100 seconds

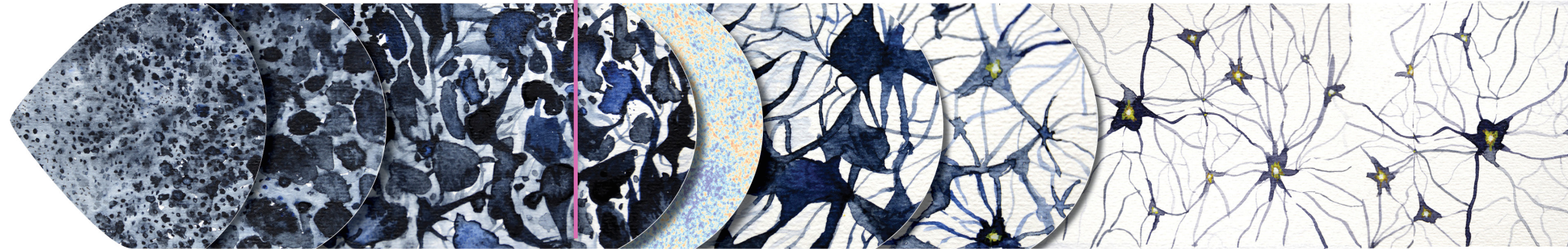
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$T < \sim \text{eV}$
 ν non-relativistic

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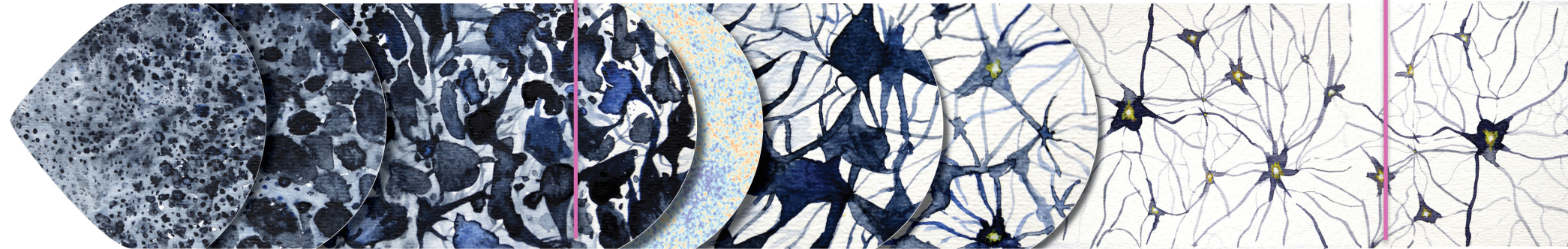
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$T \sim 1 \text{ MeV}$
 $\nu_{e,\mu,\tau}$ decouple

$1 \text{ MeV} < T < \sim \text{eV}$
 ν free-stream

$T < \sim \text{eV}$
 ν non-relativistic

10^{-32} seconds

1 second

100 seconds

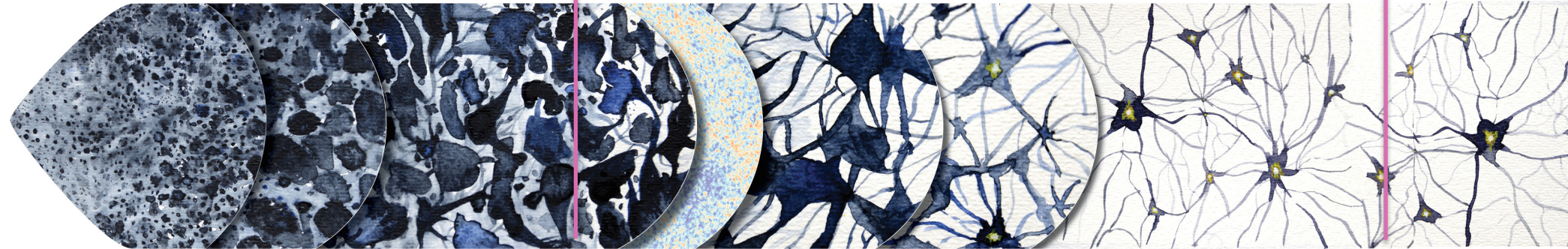
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 Accelerated expansion
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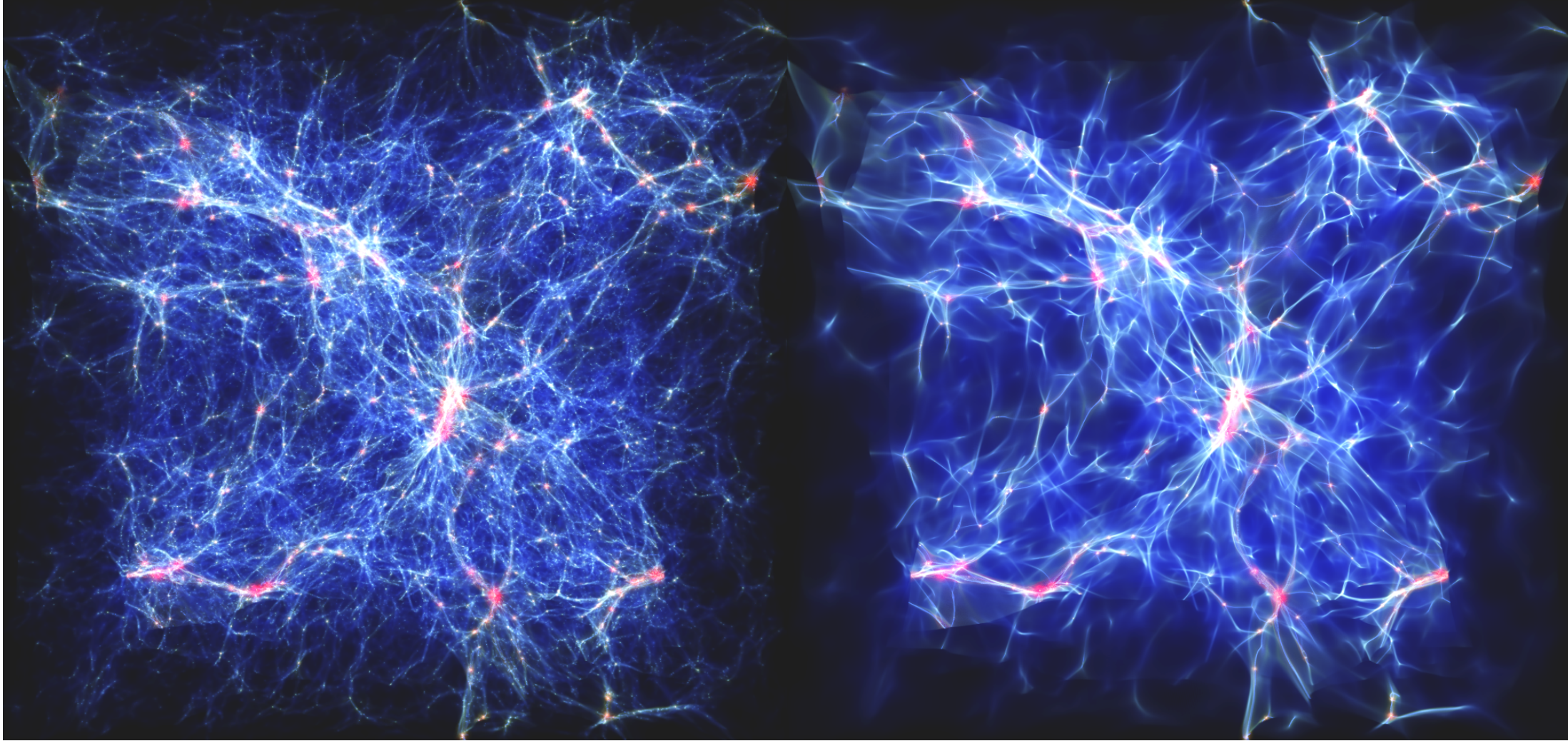


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 now

Free Streaming

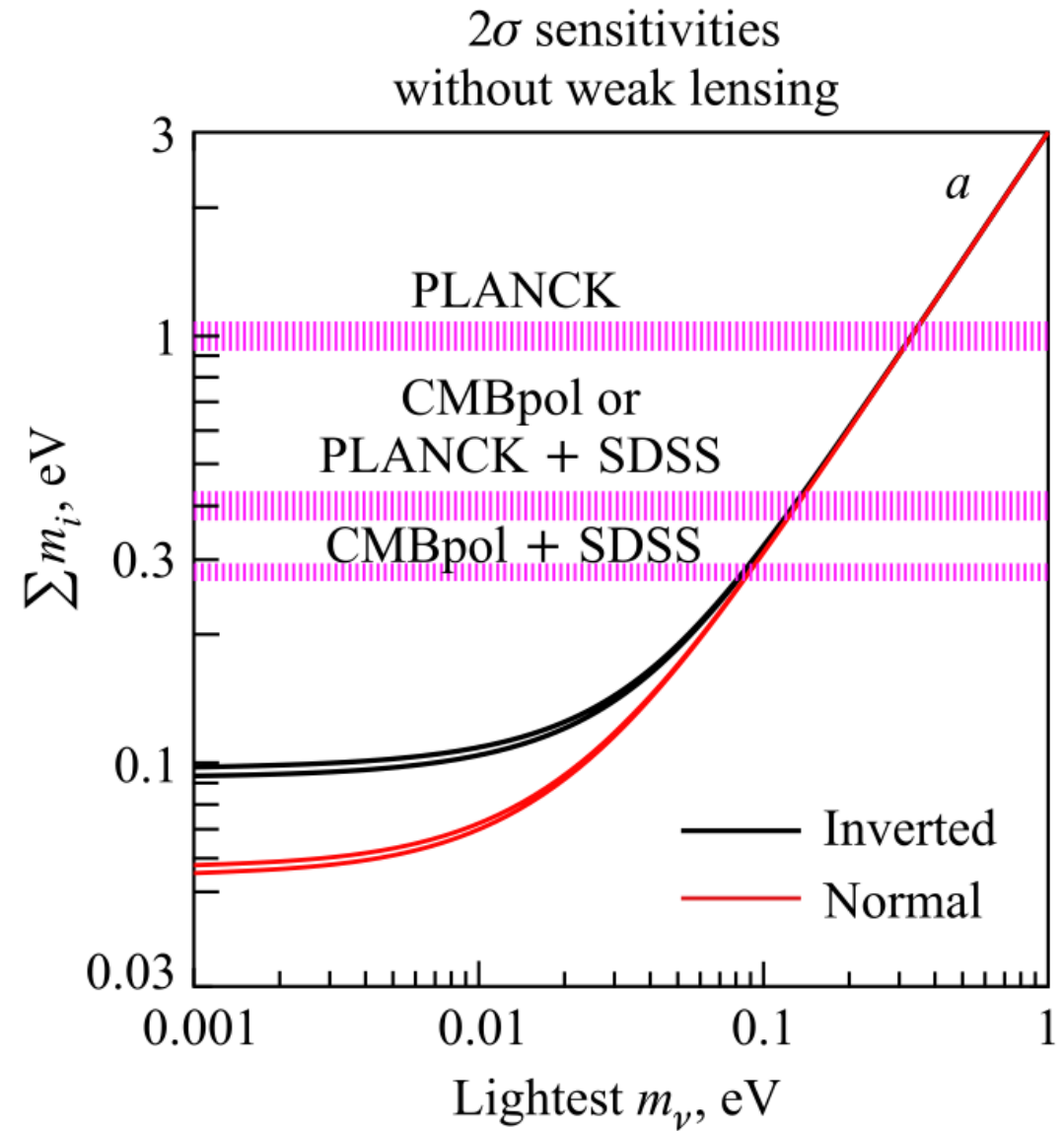
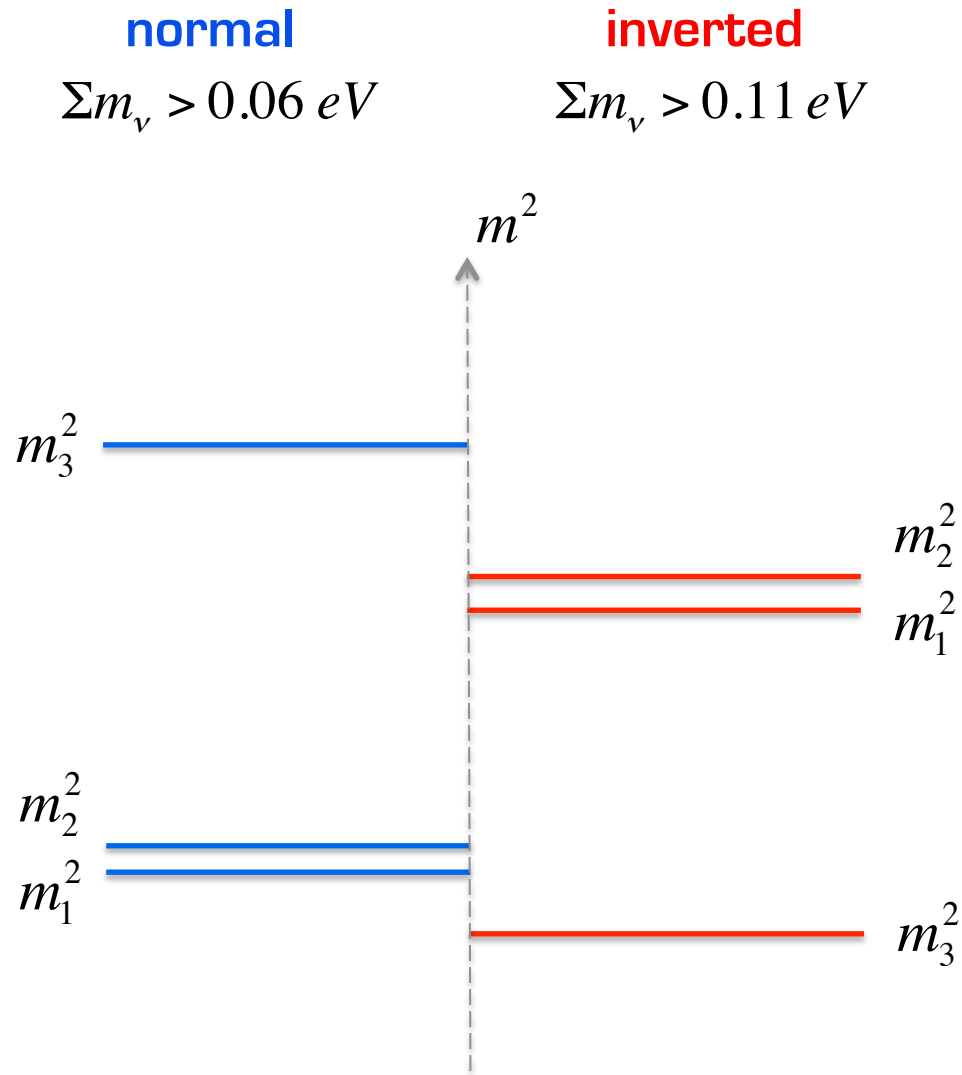
$$\lambda_{\text{FSH}}^0 = \int_0^{t_0} \frac{\langle v \rangle}{a} dt = \int_0^1 \frac{\langle v \rangle}{a^2 H} da$$



Cold Dark Matter

Warm Dark Matter

Mass Ordering

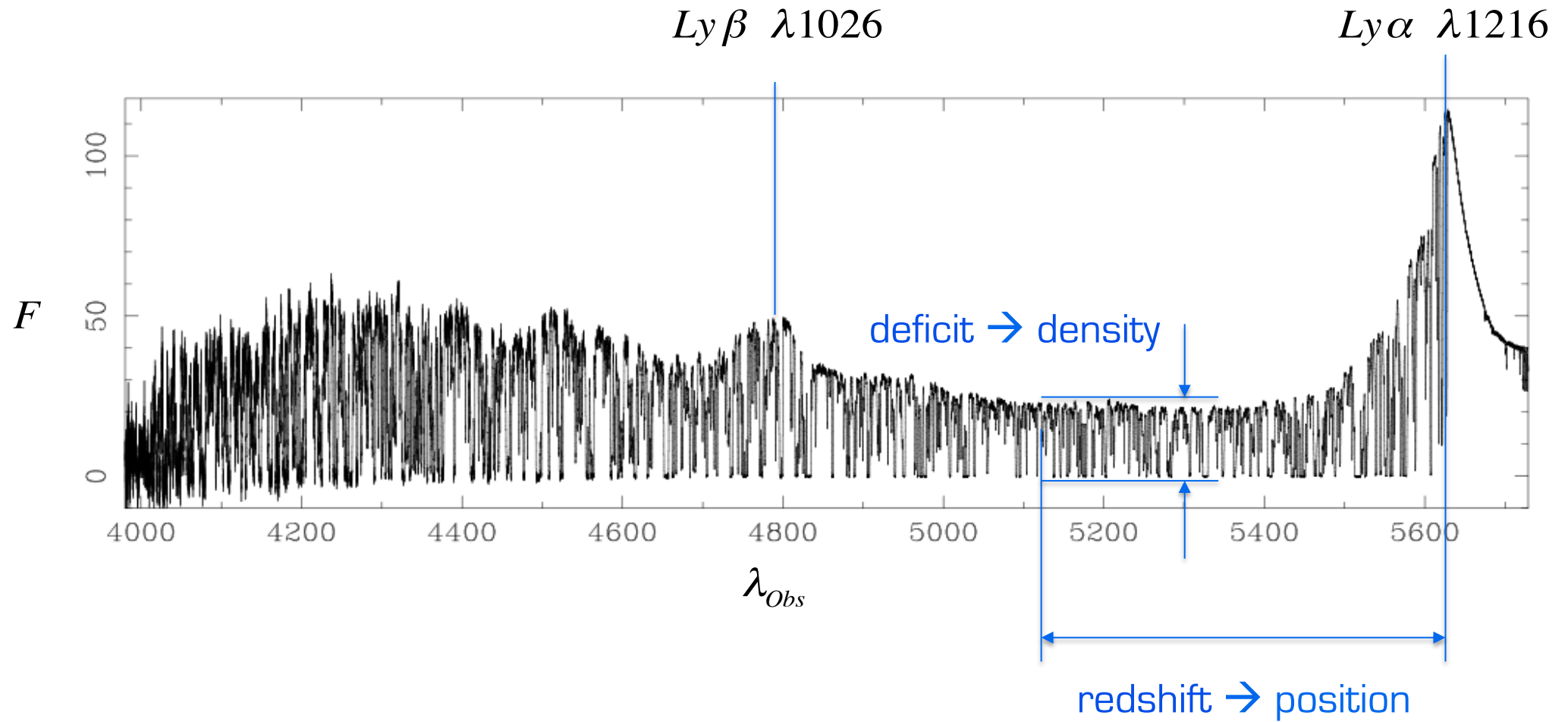


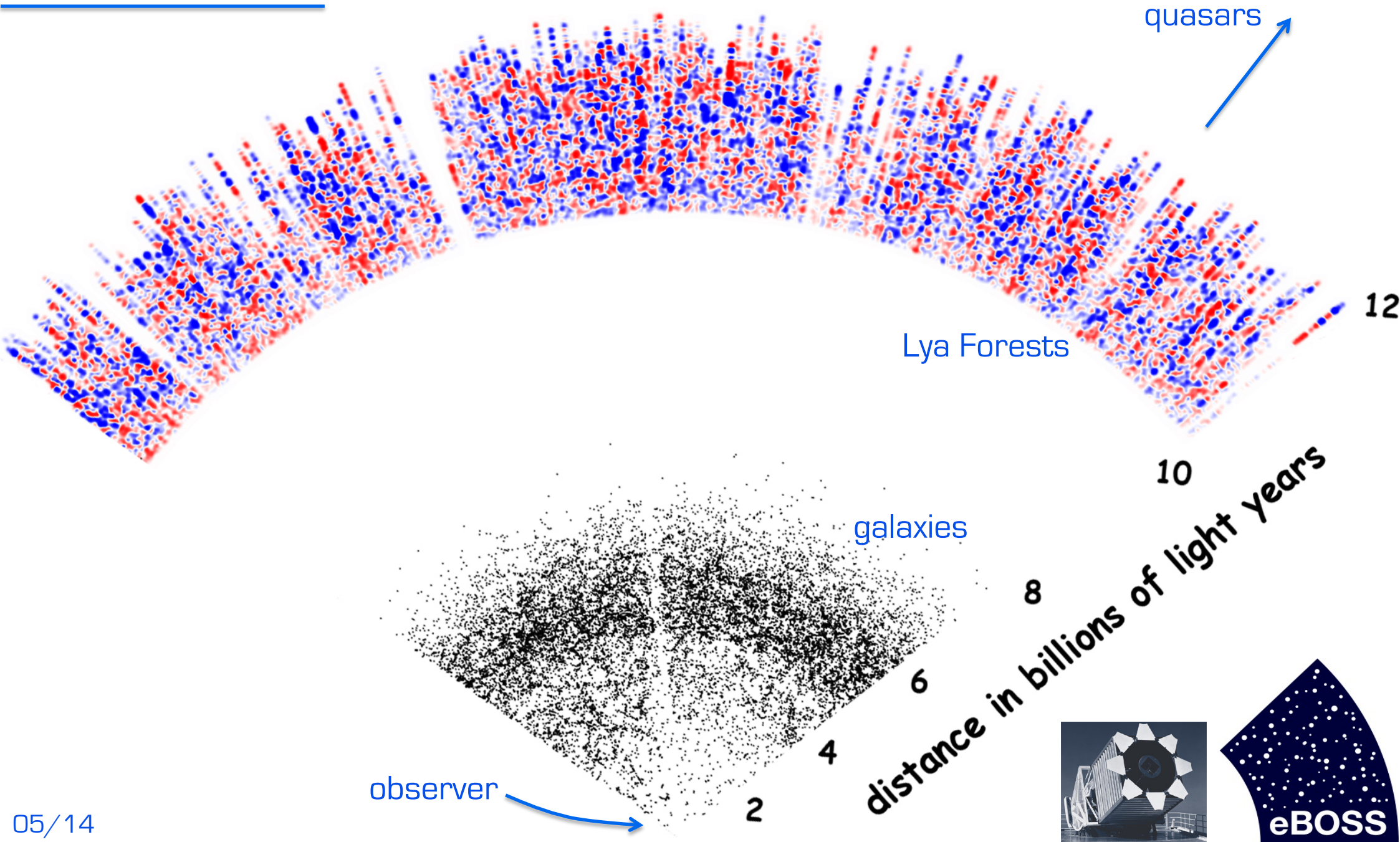
Lesgourgues & Pastor

Roadmap

- ◆ part 1 : Neutrinos in Cosmology
- ◆ part 2 : Lyman-alpha Forest
 - ◆ data from SDSS
 - ◆ constructed from simu

Lyman-alpha Forest

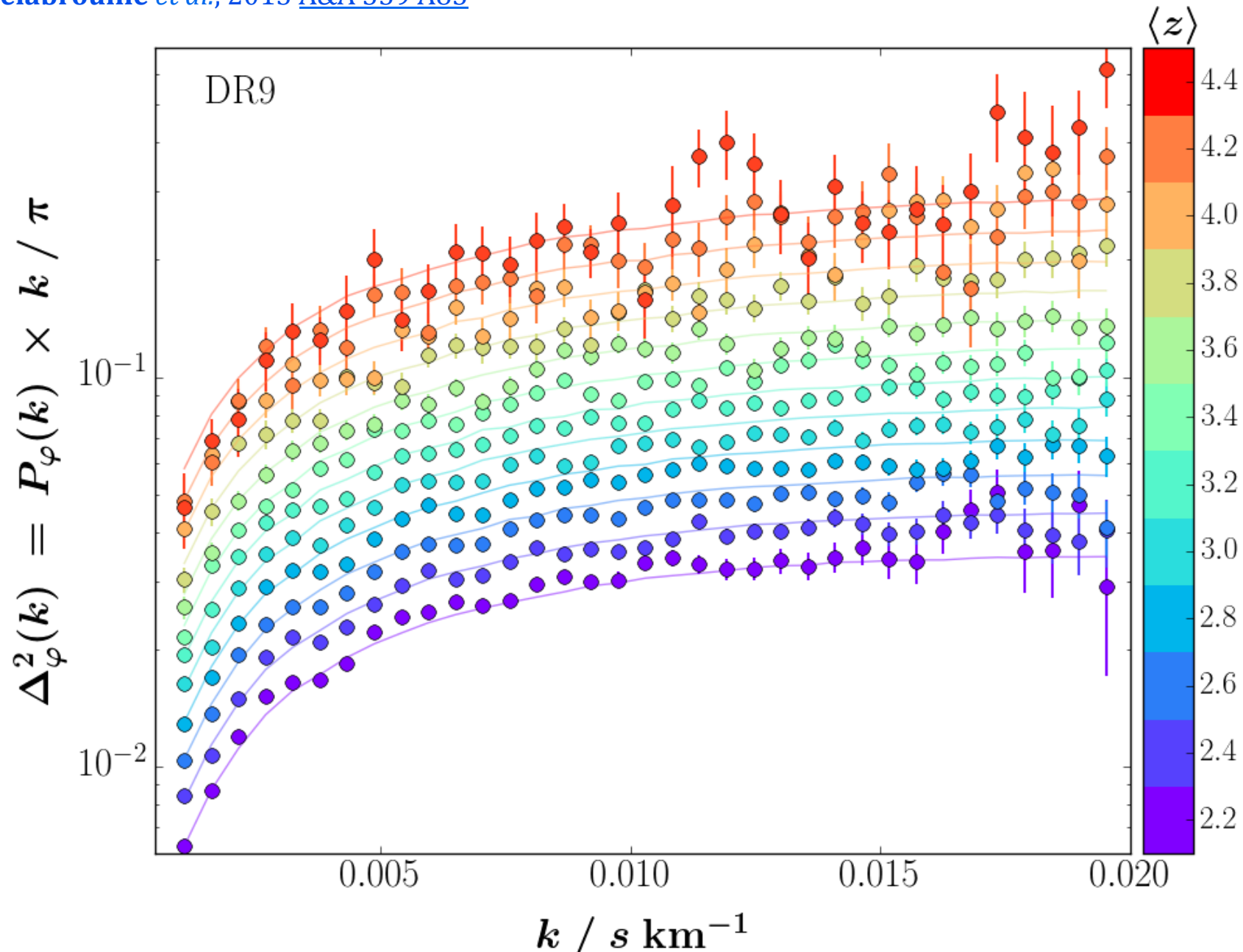




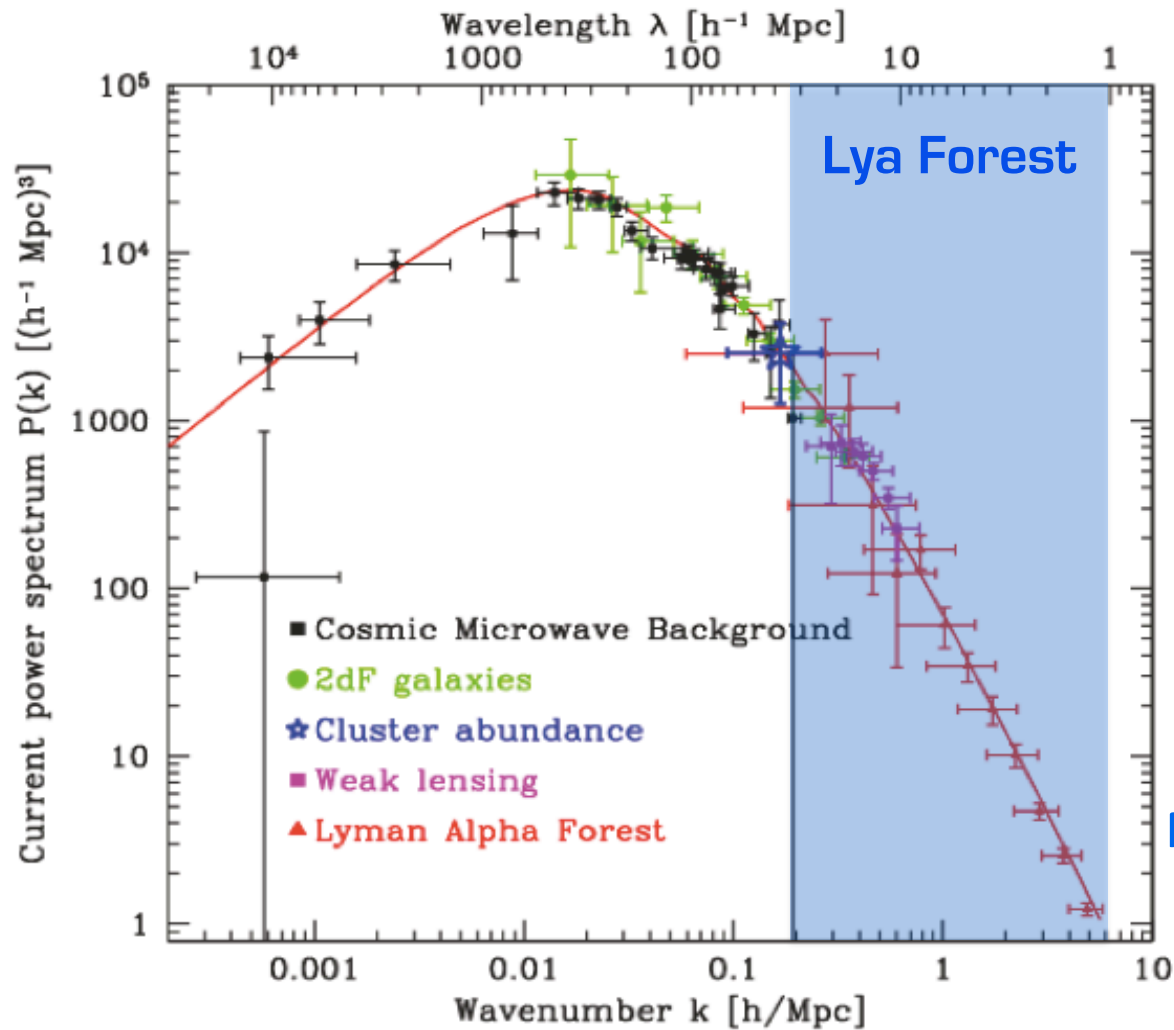
Flux Power Spectrum

$$P_{\phi}(k) = \left\langle \left| \tilde{\delta}_{\phi}(k) \right|^2 \right\rangle$$

Palanque-Delabrouille *et al.*, 2013 [A&A 559 A85](#)



from Flux PS to Matter PS



Tegmark & Zaldarriaga, 2002

$$P_{1D}(k_{\parallel}) = \frac{1}{2\pi} \int_{k_{\parallel}}^{\infty} k P_{3D}(k) dk$$

- ◆ unidimensional probe
- ◆ non-linear regime

Numerical Approach Required

Simulations

$(100 \text{ h}^{-1} \text{ Mpc})^3$ cube containing:

3072^3 baryonic gas particles \rightarrow Hydrodynamics

3072^3 dark matter particles \rightarrow N-body

3072^3 collisionless neutrinos \rightarrow N-body

$z = 4.6$

$z = 3.4$

$z = 2.2$

Rossi *et al.*, 2014, [A&A 567A 79R](#)

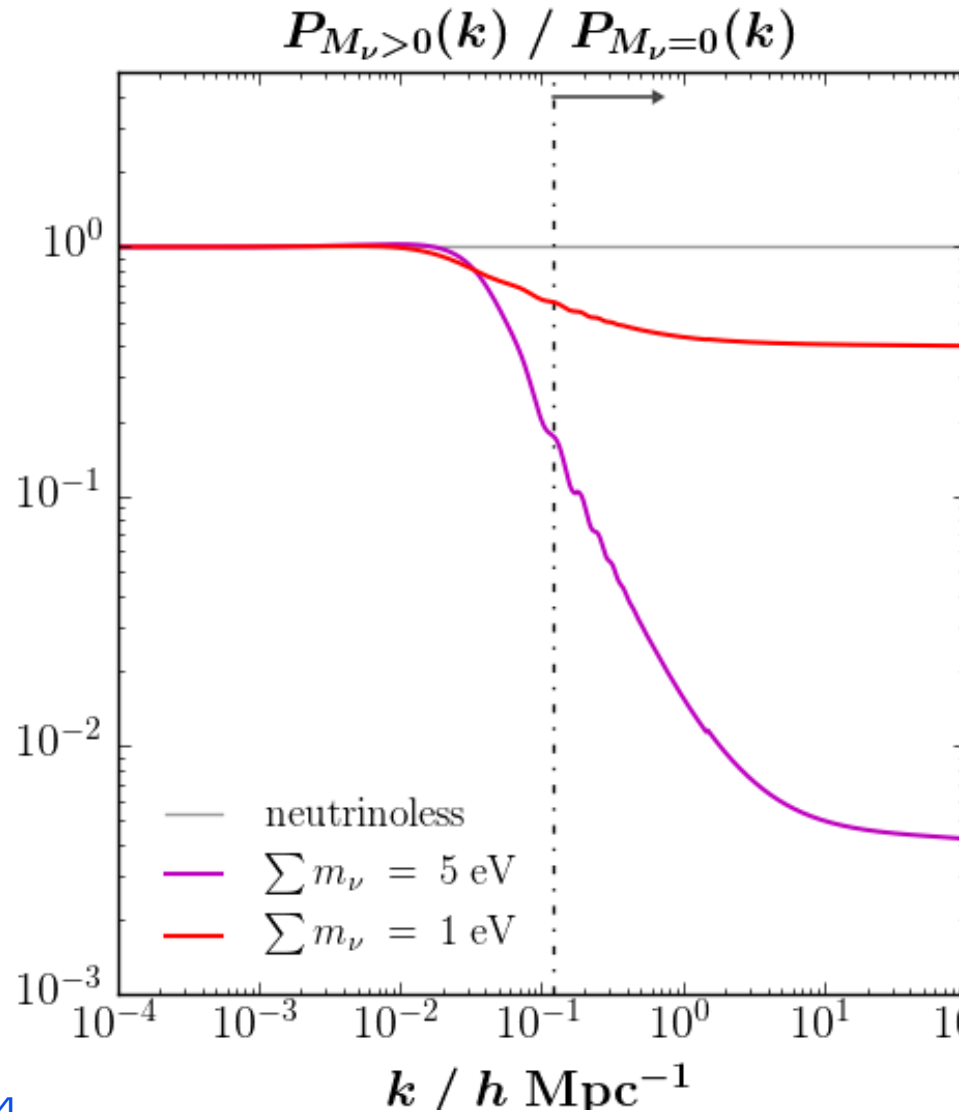
Borde *et al.*, 2014, [JCAP 07 005B](#)

Gadget-III

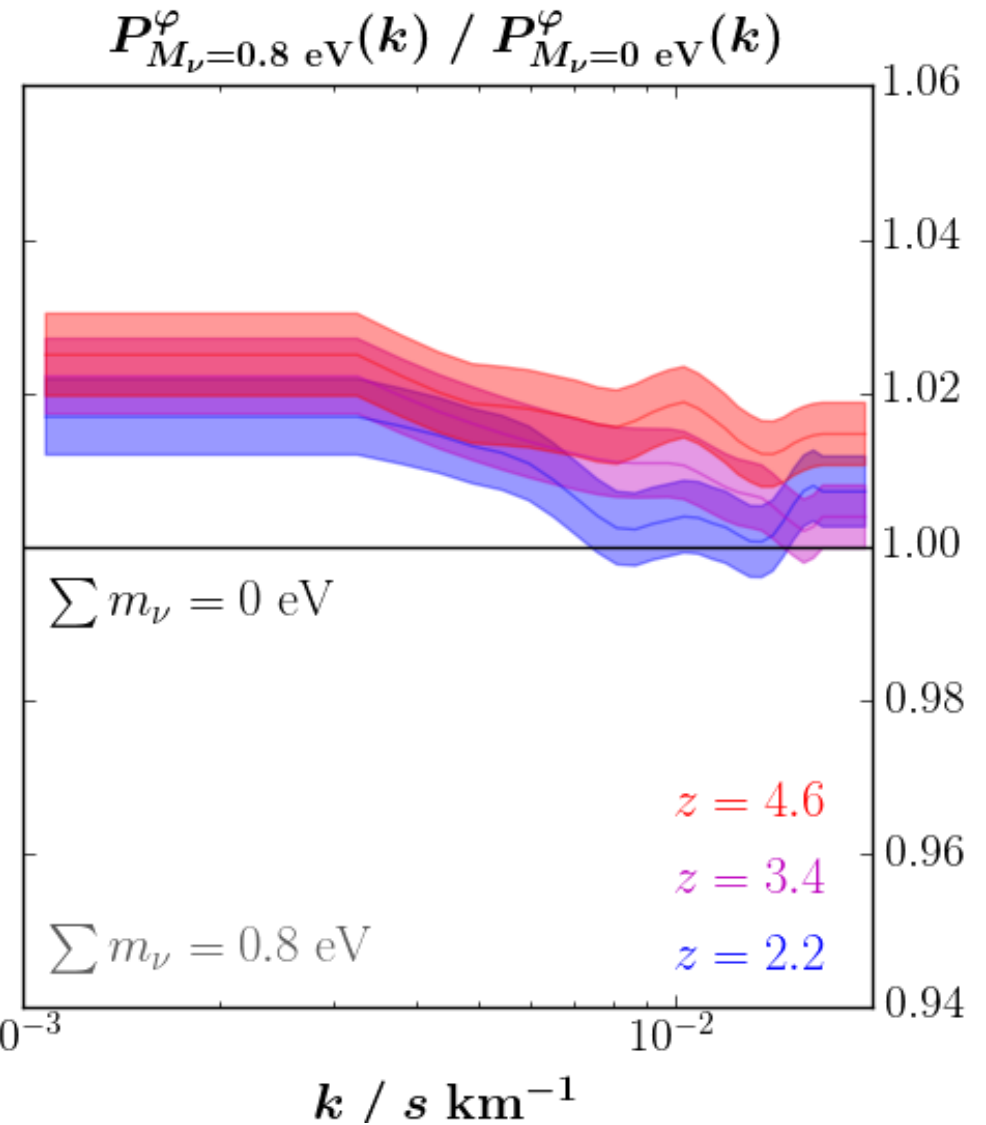
Roadmap

- ◆ part 1 : Neutrinos in Cosmology
- ◆ part 2 : Lyman-alpha Forest
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- ◆ part 3 : Constraints on Neutrino Masses
 - ◆ Λ -CDM ν
 - ◆ Λ -WDM

matter 3D PS

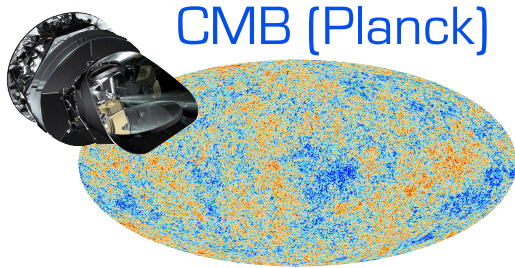


flux 1D PS



Constraints on Neutrino Masses

Ly- α (SDSS/BOSS)

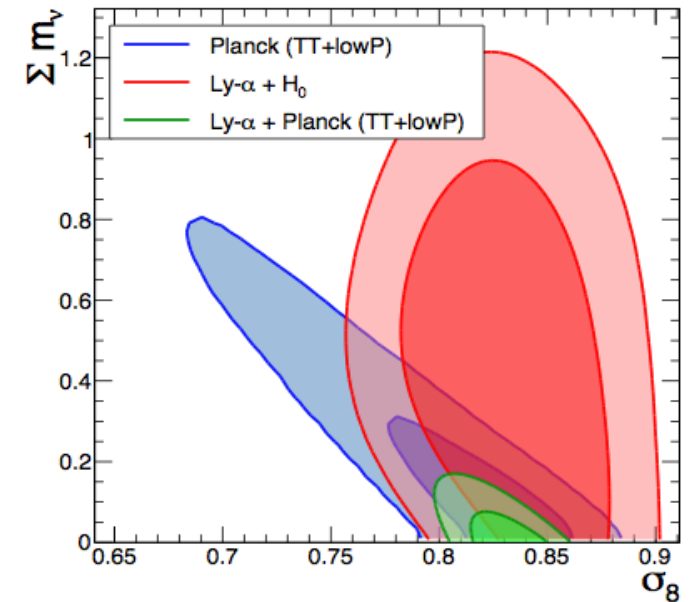
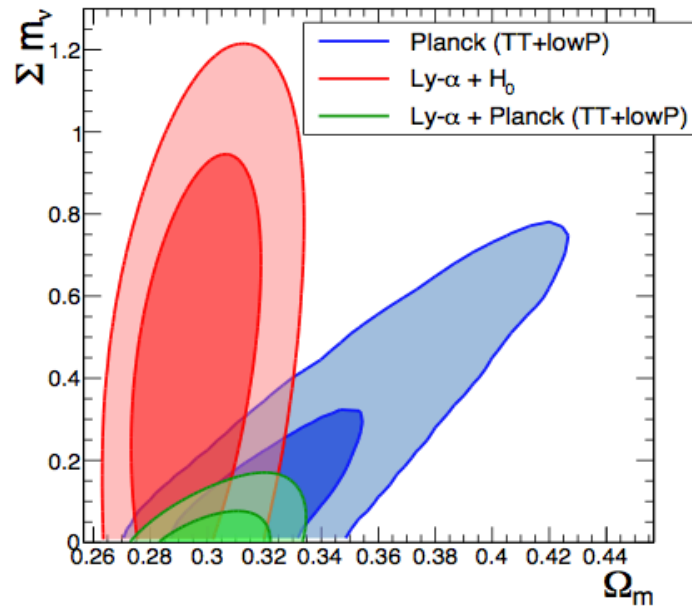
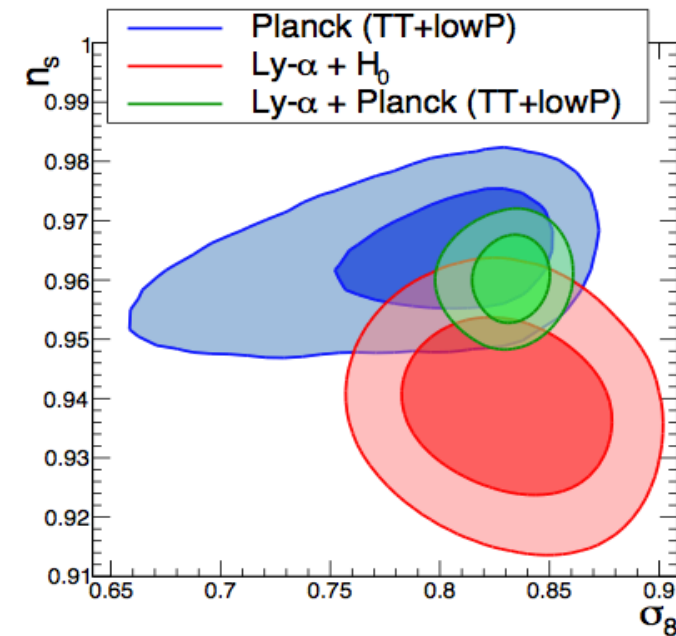
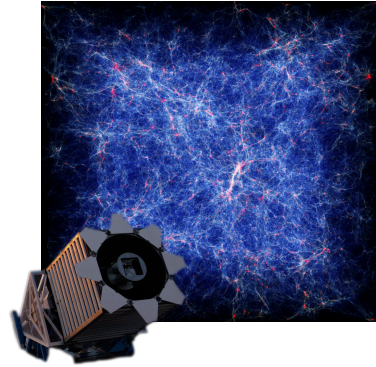


CMB (Planck)

Planck only : $\Sigma m_\nu < 0.72 \text{ eV}$ [95% CL]

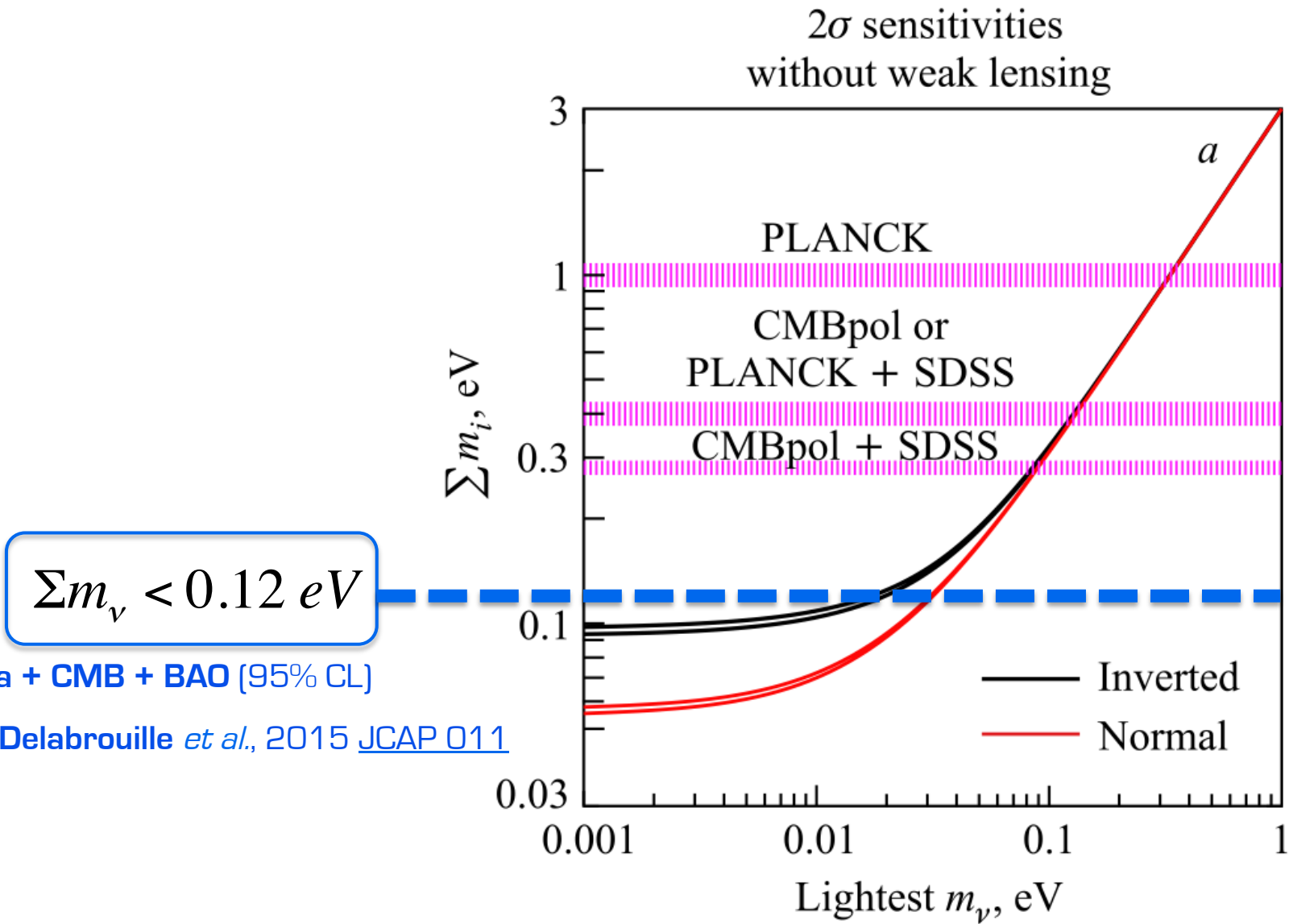
BOSS only : $\Sigma m_\nu < 1.1 \text{ eV}$ [95% CL]

Ly- α + Planck (TT+lowP) : $\Sigma m_\nu < \mathbf{0.12 \text{ eV}}$ [95% CL]



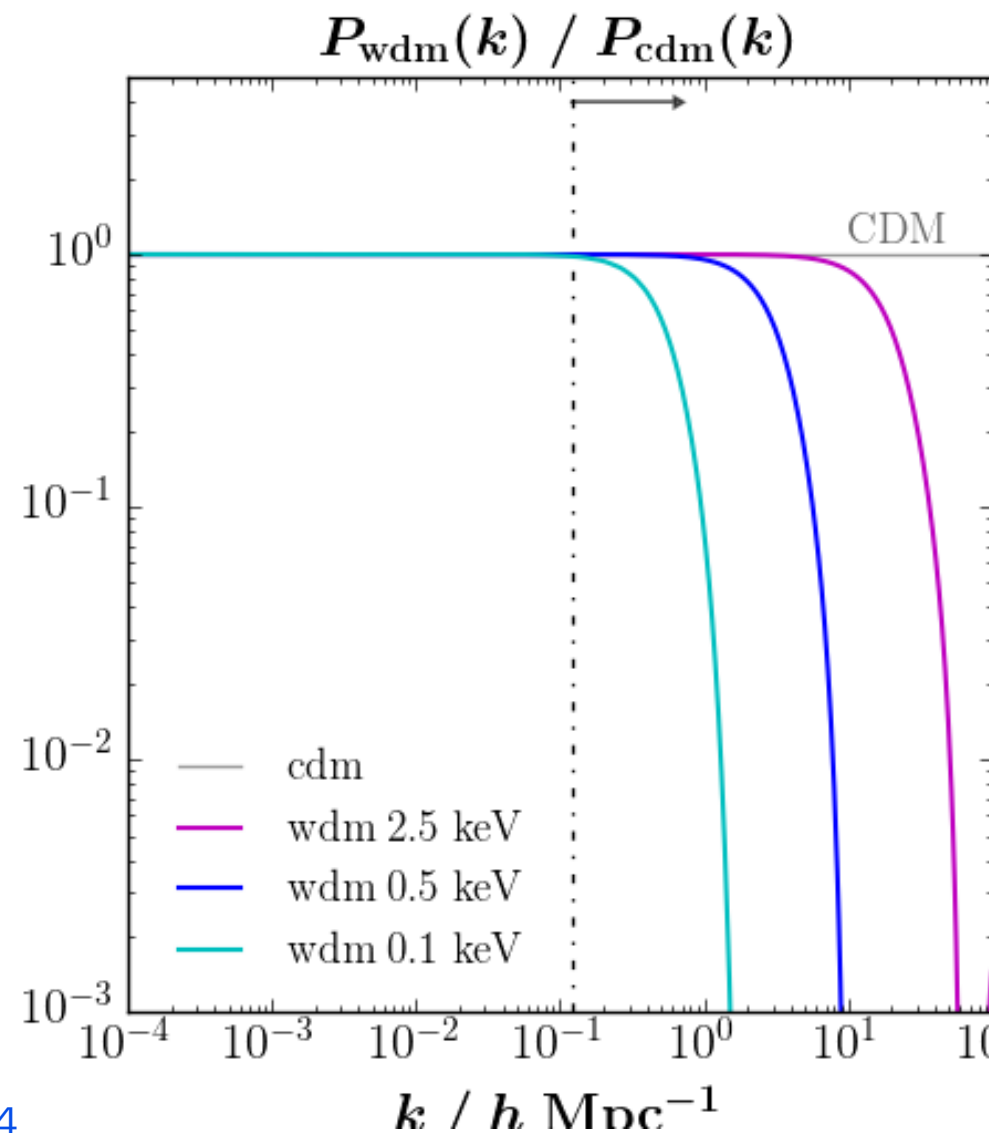
N.Palanque-Delabrouille *et al.*, 2015 [JCAP 011](#)

Results: Λ -CDM ν

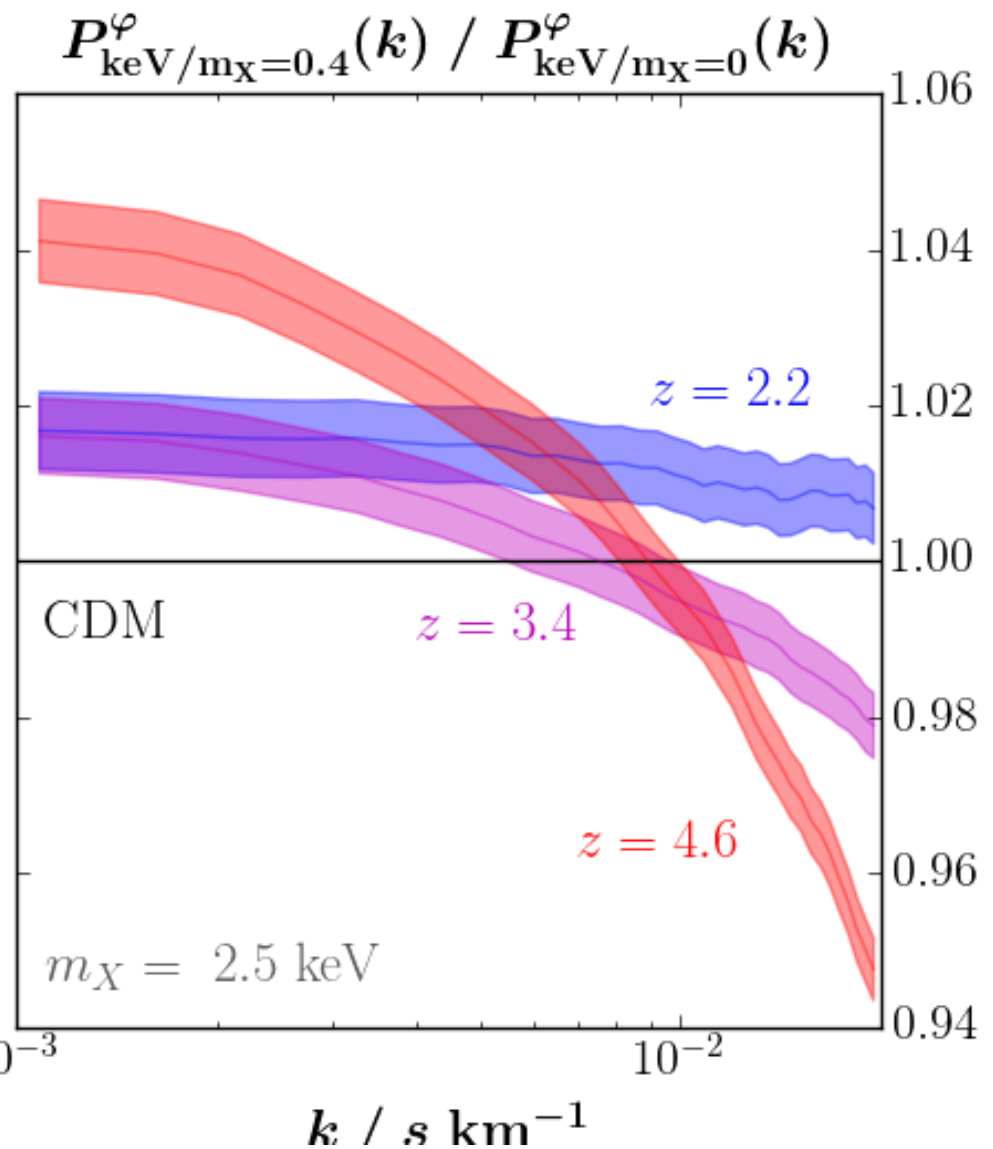


Lesgourgues & Pastor

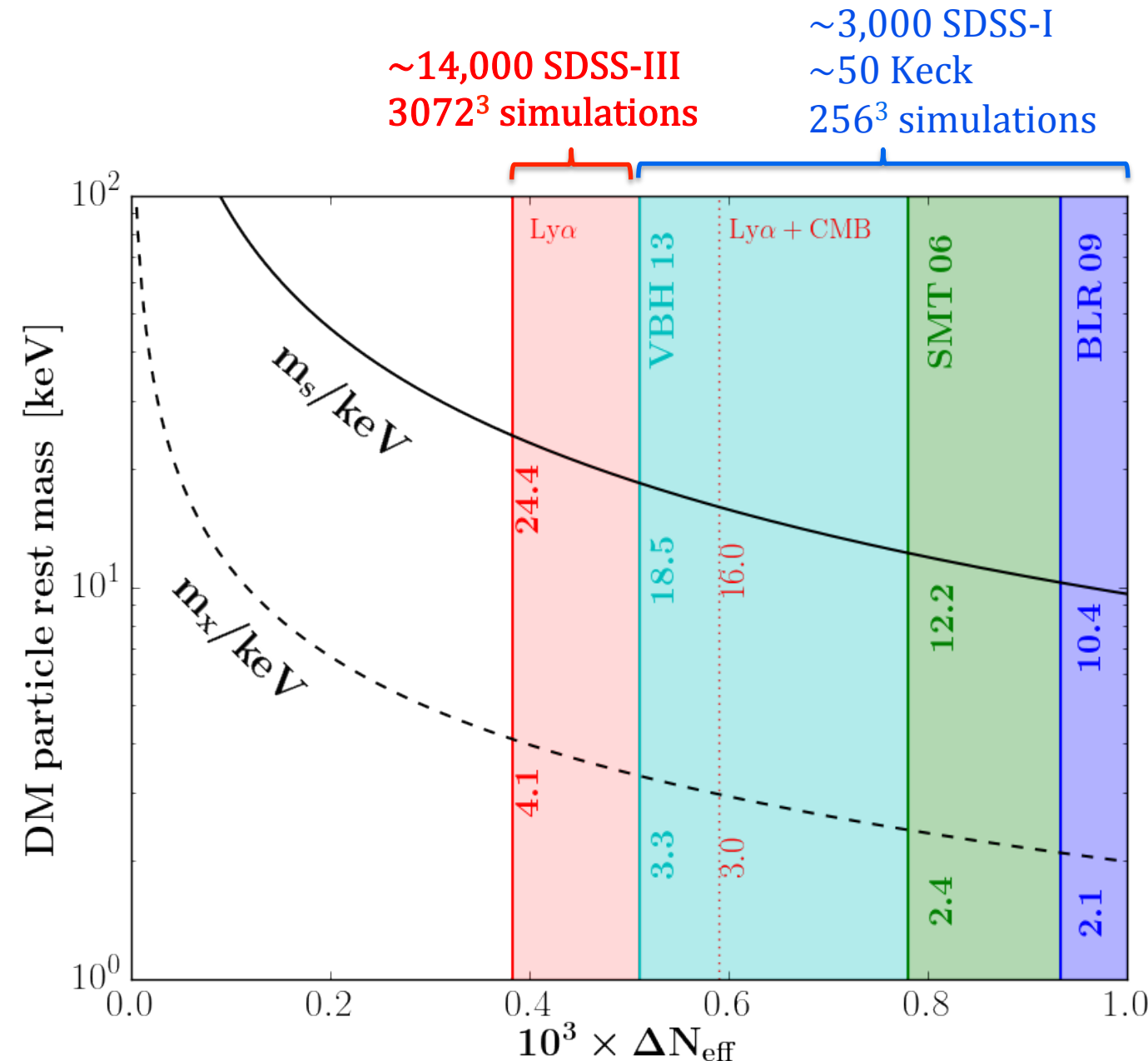
matter 3D PS



flux 1D PS



Constraints on WDM mass



Ly α **4.09 keV**

Ly α +CMB 2.96 keV

Ly α +CMB+BAO 2.93 keV

Running on spectral index

Ly α +CMB **4.26 keV**

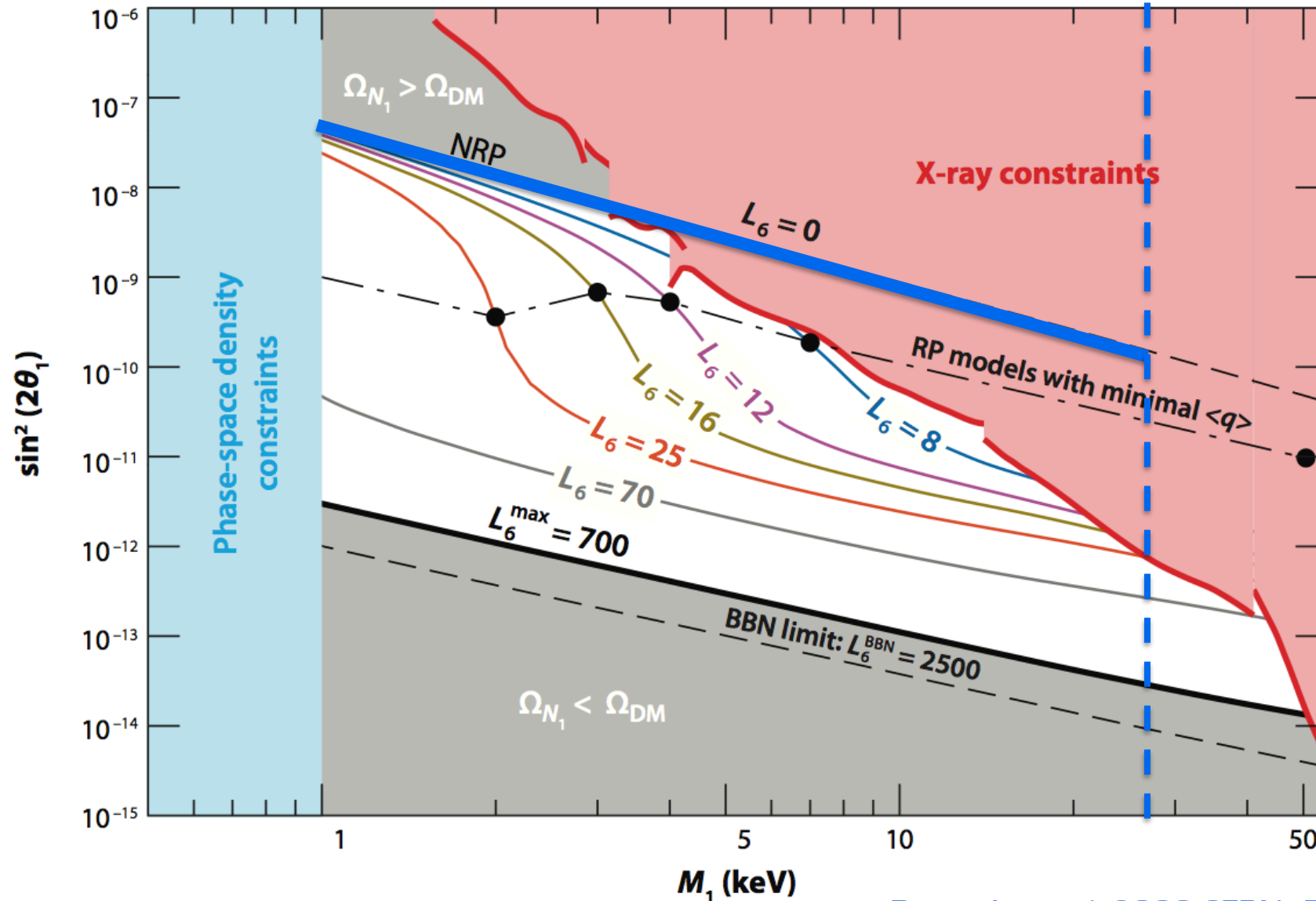
Ly α +CMB+BAO **4.12 keV**

Baur *et al.*, 2015 [arXiv:1512.01981](https://arxiv.org/abs/1512.01981)

Conclusion: Λ -WDM

Baur *et al.*, 2015 [arXiv:1512.01981](https://arxiv.org/abs/1512.01981)

$$m_{\nu}^{NRP} > 24.4 \text{ keV} \quad \text{Lya [95\% CL]}$$



Boyarsky *et al.*, 2008 [CERN-PH-TH 2008 234](https://arxiv.org/abs/0804.2633)

CONCLUSION

$$\Sigma m_\nu < 0.12 \text{ eV (95\% CL) } \text{ Lya + CMB}$$

$$m_x > 4.1 \text{ } 3.0 \text{ keV (95\% CL) } \text{ Lya (+CMB)}$$

SDSS (DR9)

SPH simulations

CONCLUSION

$$\Sigma m_\nu < 0.12 \text{ eV (95\% CL) Ly}\alpha + \text{CMB}$$
$$m_x > 4.1 \text{ } 3.0 \text{ keV (95\% CL) Ly}\alpha (+\text{CMB})$$

SDSS (DR12)

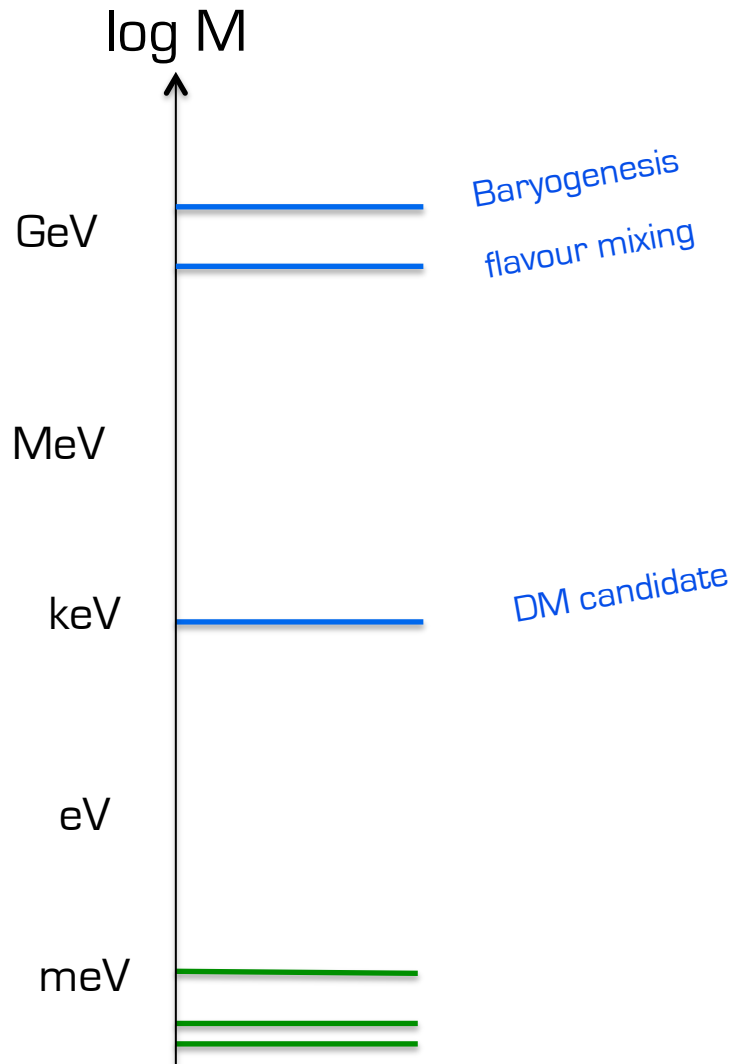
SPH simulations

XQ-100

UPCOMING

resonantly produced ν_s

BACKUP



sterile sector
right-handed SU[2] \times U[1] singlets

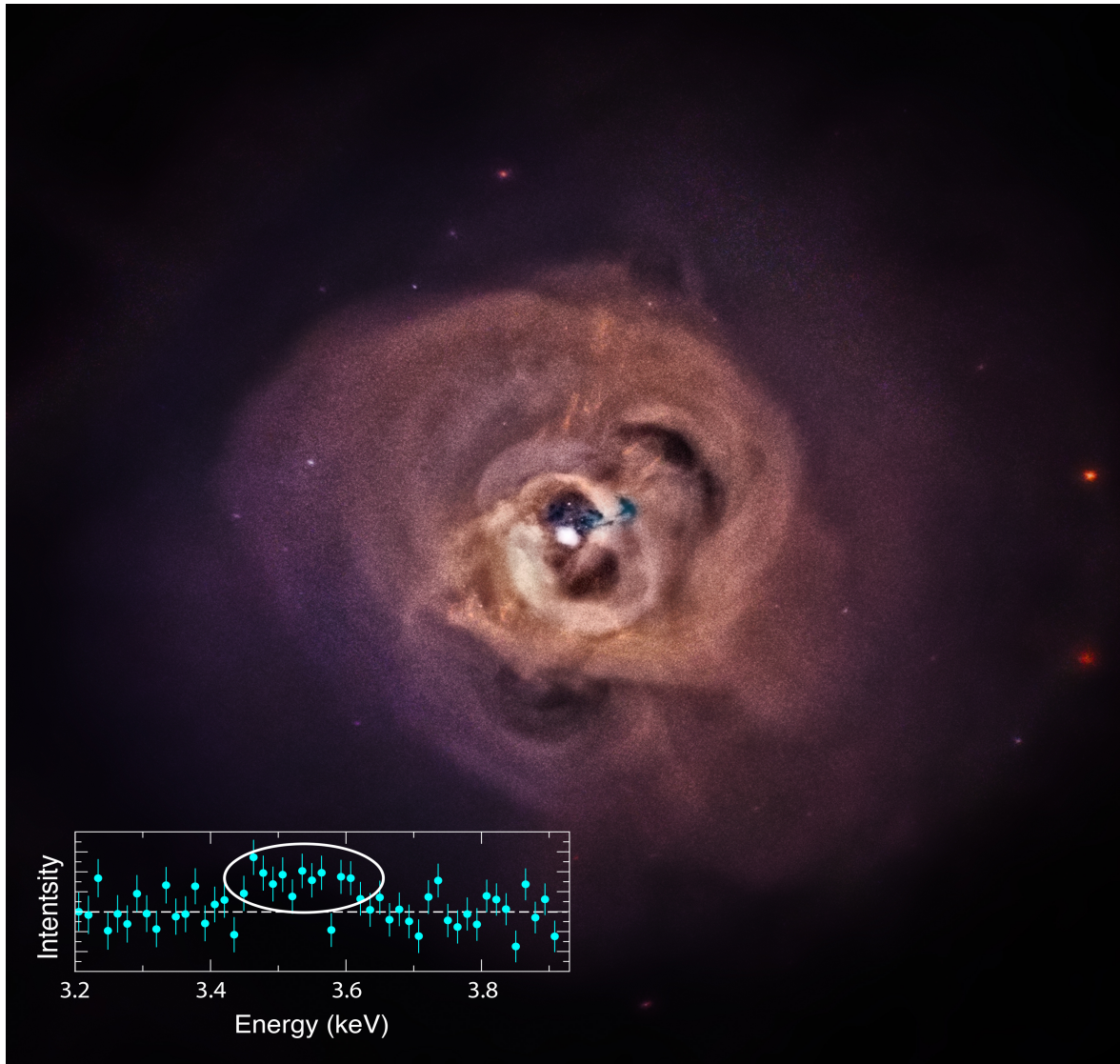
ν MSM

$$\begin{pmatrix} |\nu_A\rangle \\ |\nu_S\rangle \end{pmatrix} = \begin{pmatrix} \cos(\theta_M) & \sin(\theta_M) \\ -\sin(\theta_M) & \cos(\theta_M) \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \end{pmatrix}$$

active sector
left-handed SU[2] \times U[1] doublets

BSM

Hints of Sterile ν ?



Perseus cluster
Chandra, XMM-Newton

3.55 keV line

Decay channel

$$X \rightarrow \gamma\gamma \quad \text{or} \quad X \rightarrow \nu\gamma$$

Bulbul *et al.* 2014, [ApJ 789 13](#)

73 stacked XMM-N spectra
246 citations

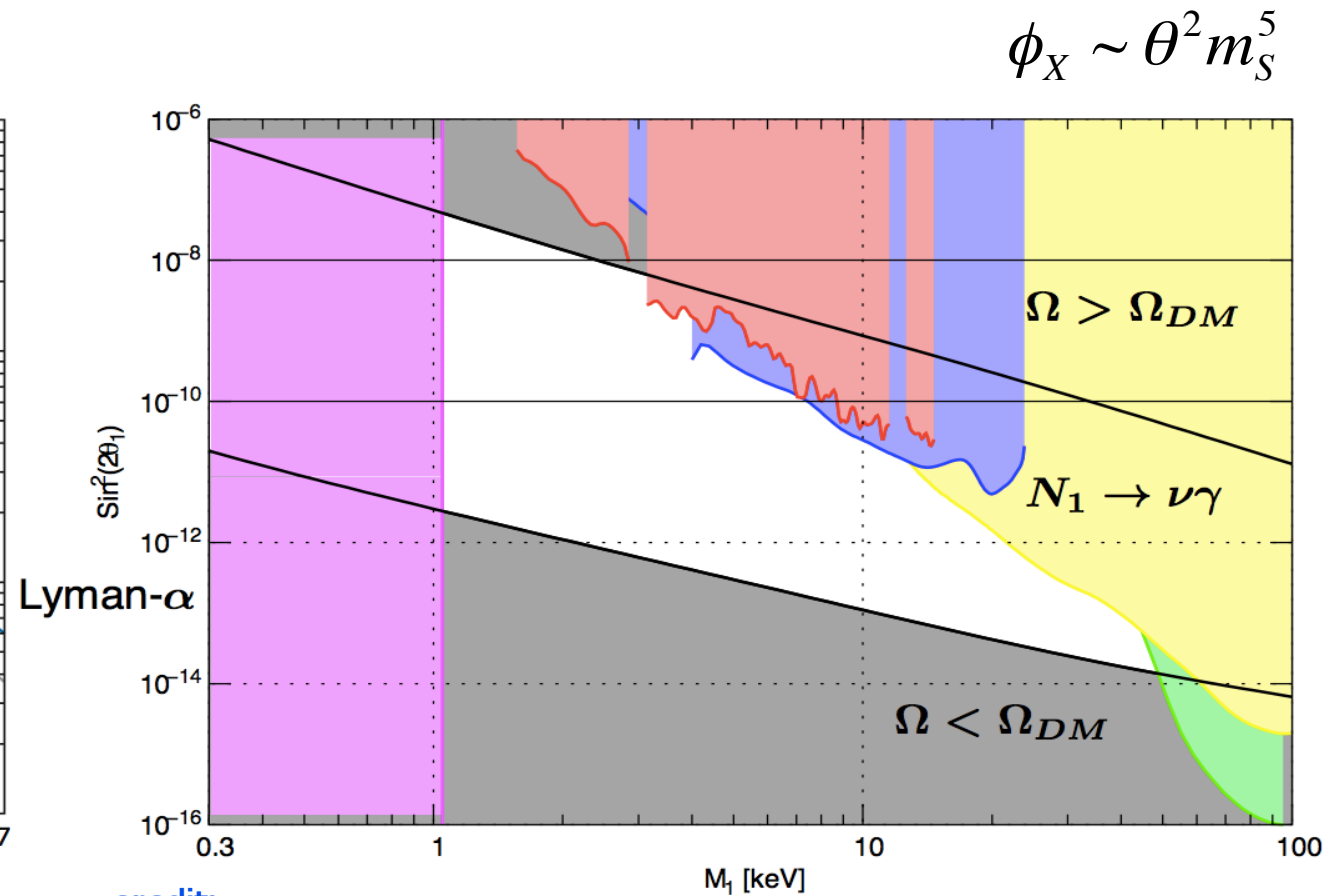
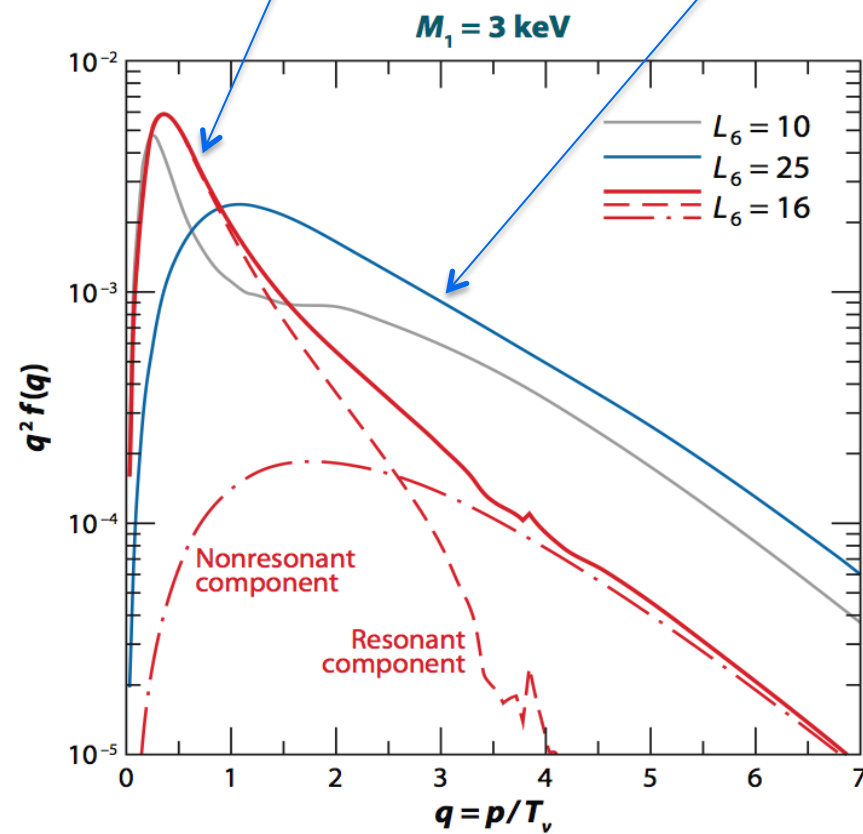
Boyarsky *et al.* 2014, [PRL 113, 251301](#)

Andromeda & Perseus clusters
235 citations

Parameter Space

« non-thermal » RP

« thermal » NRP

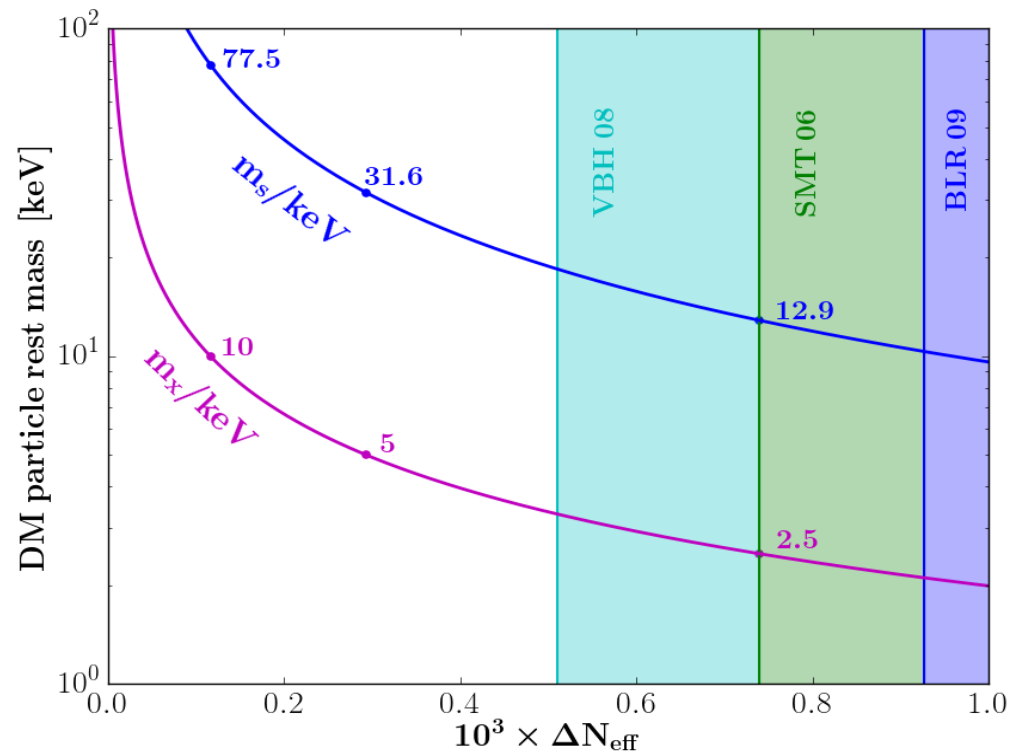


credit:

Boyarsky, Ruchayskiy, Shaposhnikov

Oscillations with active sector

Dodelson & Widrow '94



- ◆ Efficient active–sterile oscillations at

$$T \sim 150 \text{ MeV} \left(\frac{m_s}{\text{keV}} \right)^{-1/3}$$

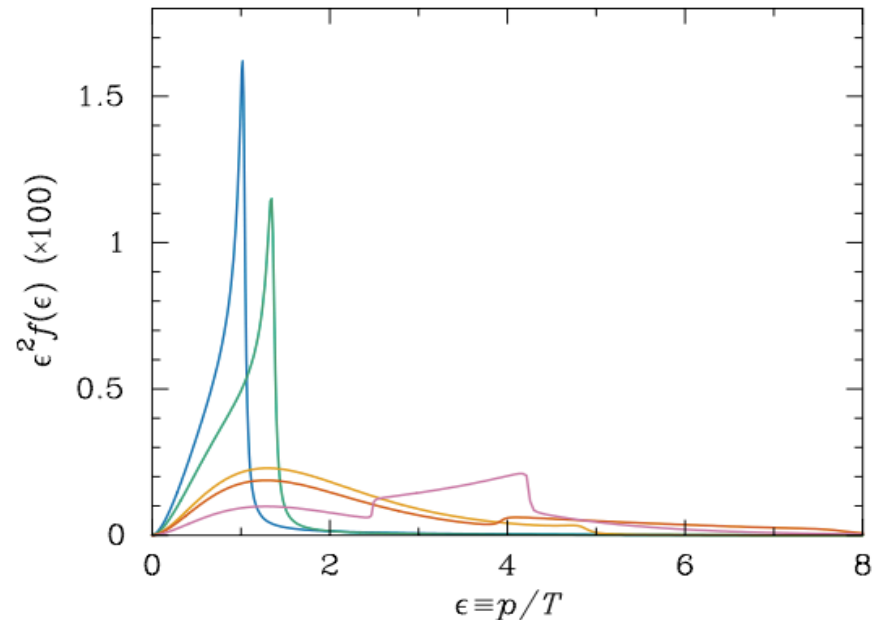
- ◆ Never reach thermal equilibrium, but ...

- ◆ Quasi–thermal PSD

$$f(p) = \frac{\sin^2 2\theta}{1 + \exp[p/T]}$$

MSW-type Resonance

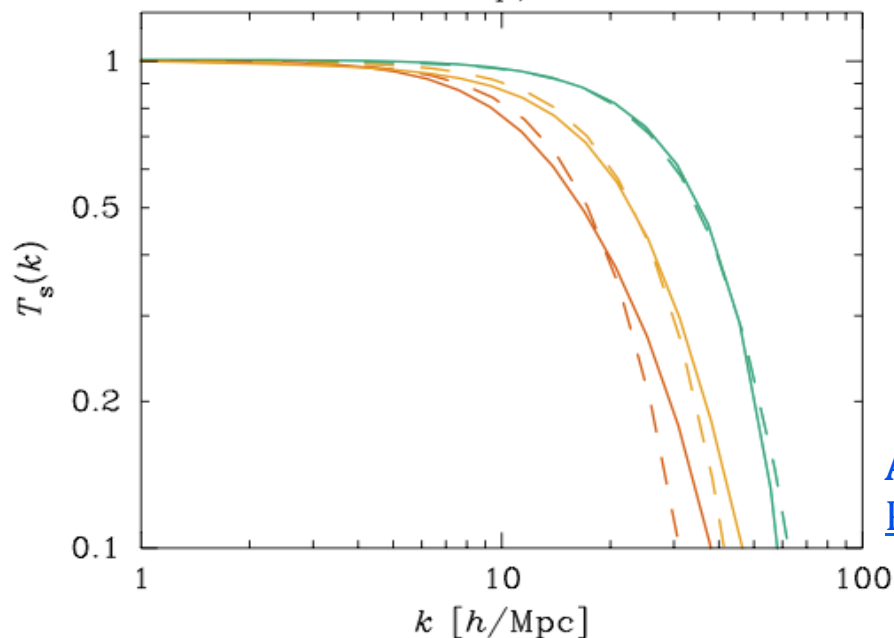
Shi & Fuller '99



- ♦ active-sterile resonance at

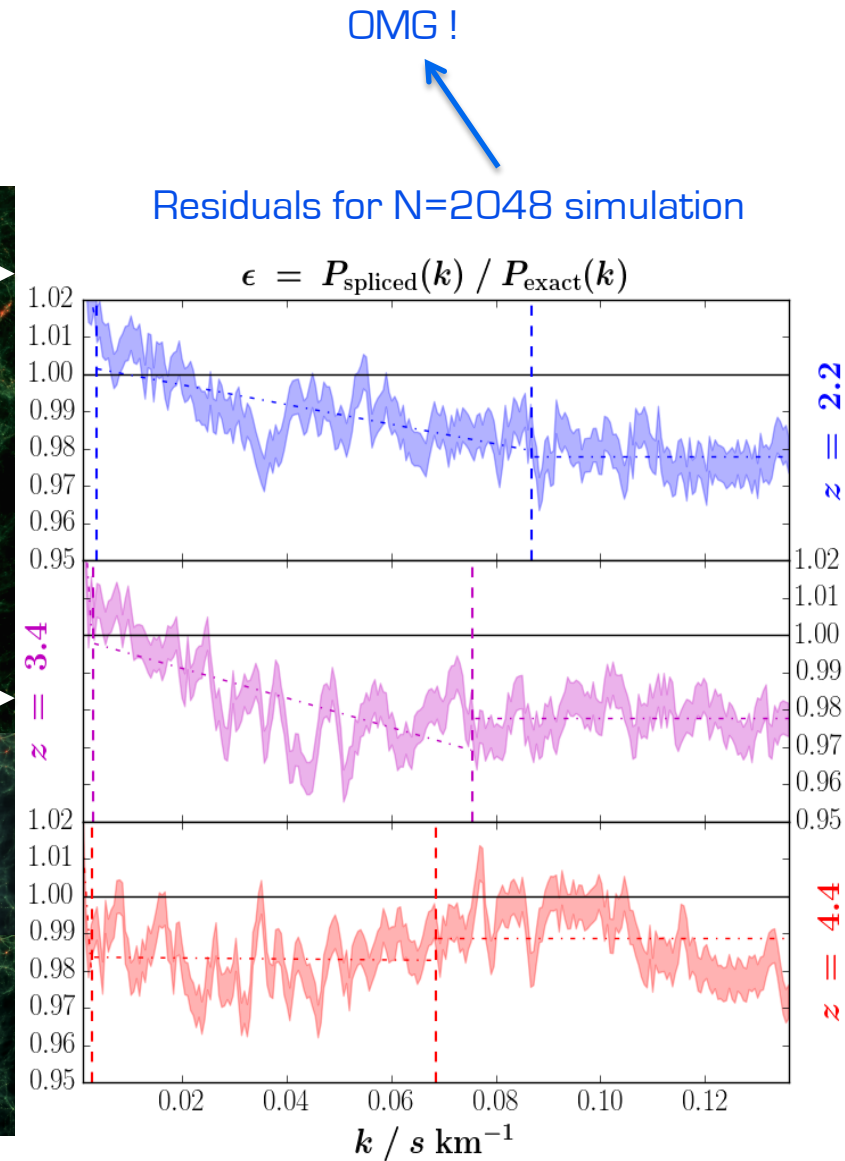
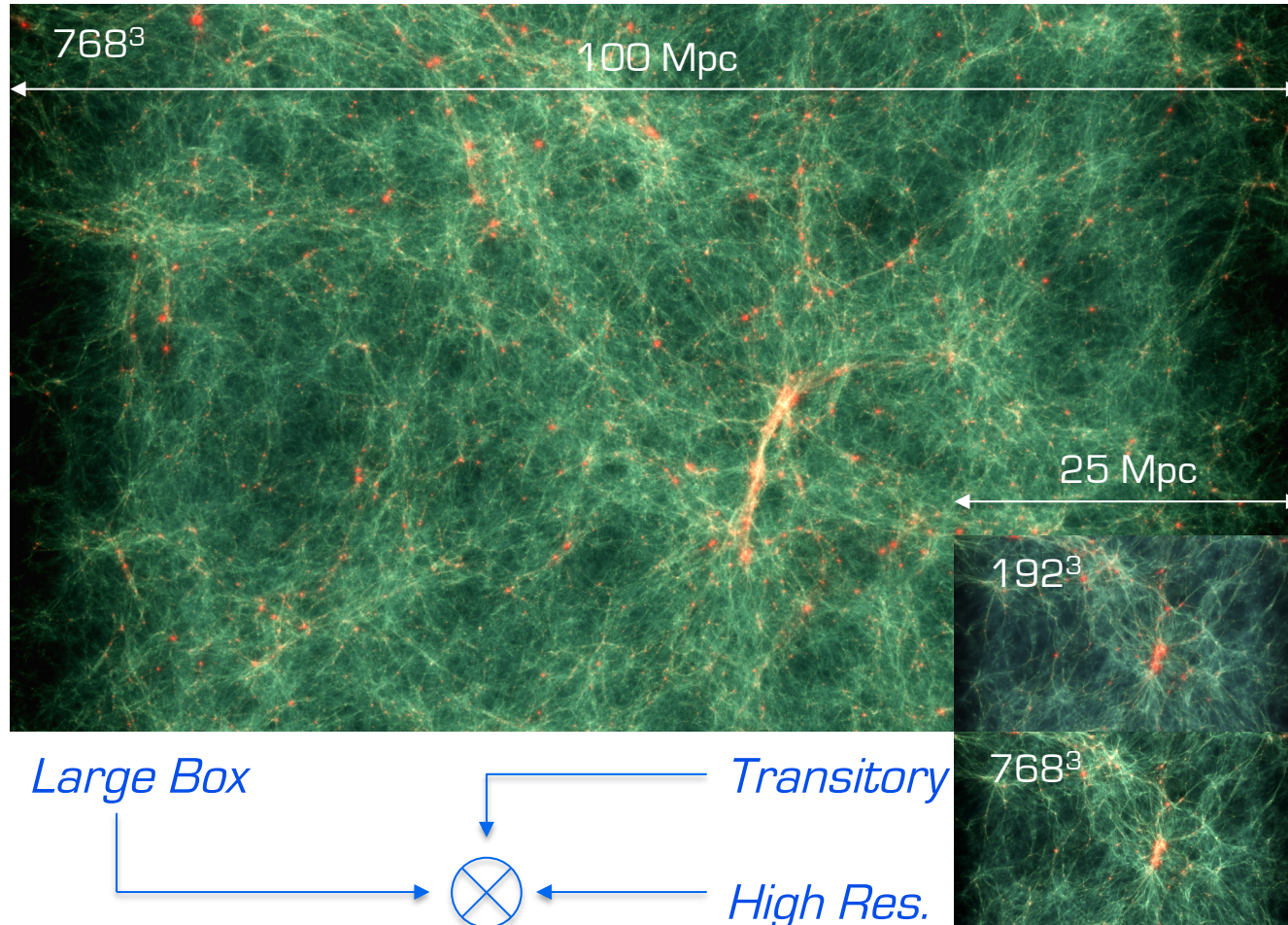
$$\left. \frac{p}{T} \right|_{res} \propto \frac{\delta m^2 \cos 2\theta}{T^4 L}$$

- ♦ Never reach thermal equilibrium
- ♦ PSD requires full Boltzmann treatment



Abazajian, 2014
[PRL 112, 161303](#)

Splicing Method



3072³ particles per species
in [100 Mpc]³ box

Simulation Parameters

<i>parameter</i>	<i>central</i>	<i>range</i>
$1\text{keV} / m_x$	0.0	+0.2 +0.4
n_s	0.96	± 0.05
Ω_M	0.31	± 0.05
σ_8	0.83	± 0.05
H_0	67.5	± 5.0
$T_0(z=3)$	14k	$\pm 7k$
$\gamma(z=3)$	1.3	± 0.3
A^τ	0.0025	± 0.0020
η^τ	3.7	± 0.4

Neutrino mass

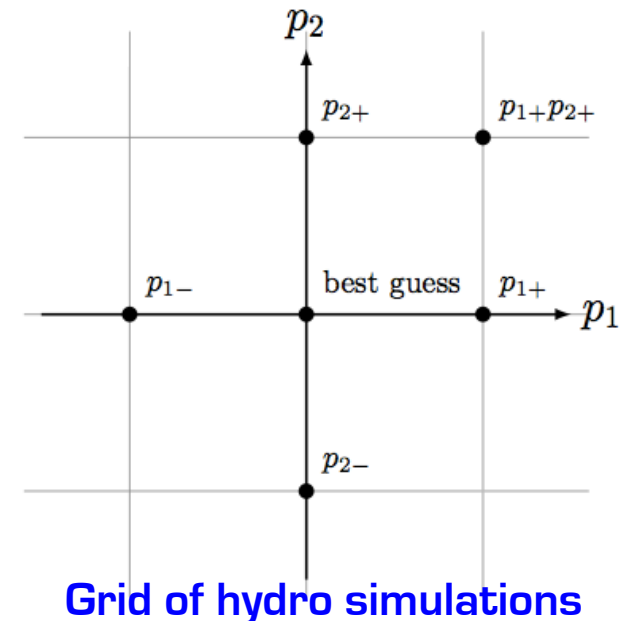
Cosmology

Intergalactic Medium

Optical Depth (UV)

Nuisance Parameters

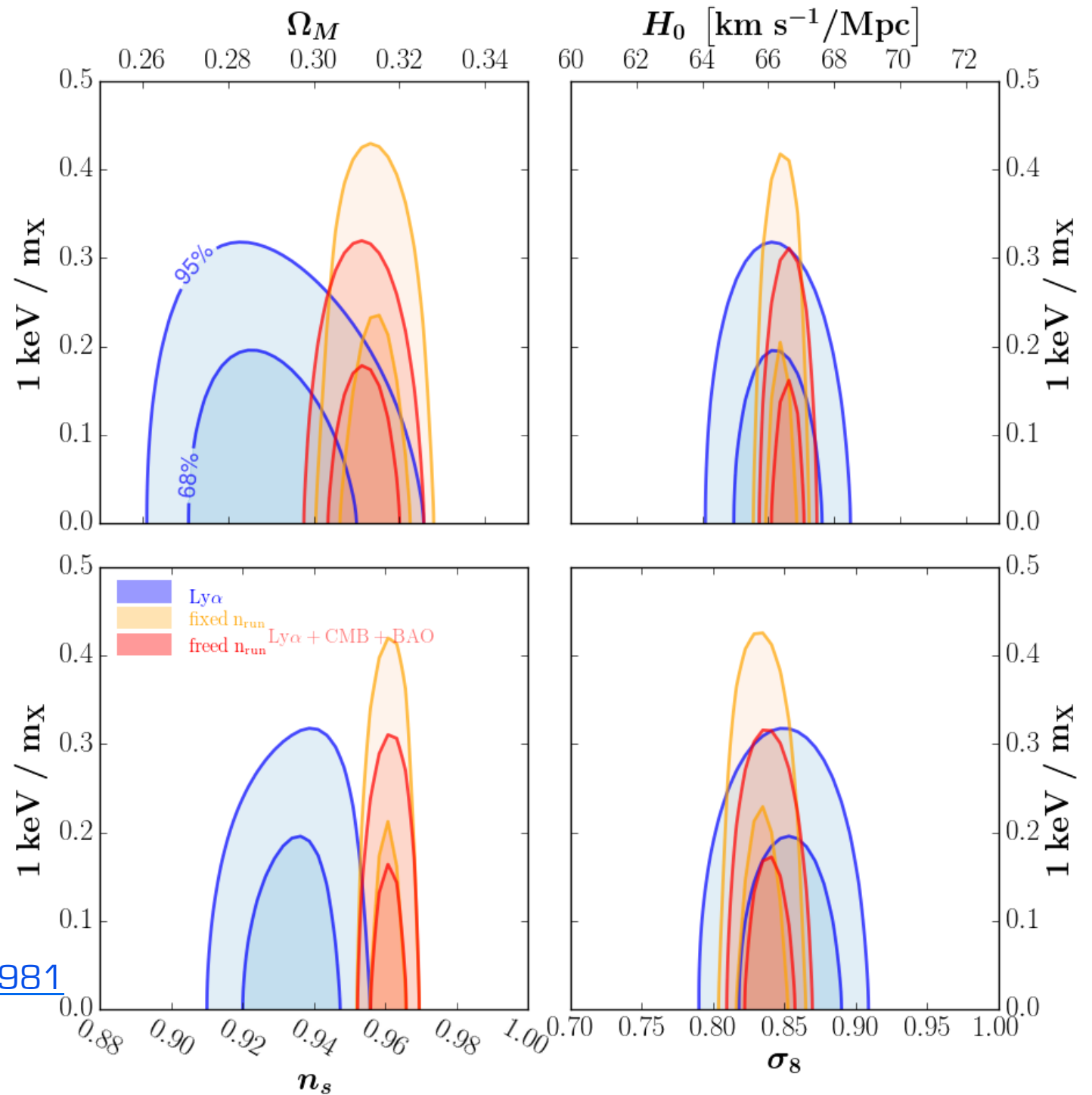
Re-ionization Redshift	1
IGM thermal state	3
Ionizing UV background	1
Feedback Processes	5
running of the spectral index	1
Simulations Uncertainty	2
Spectrograph Resolution	2
Data Noise	12



55 for Σm_ν
55 for keV/m_x

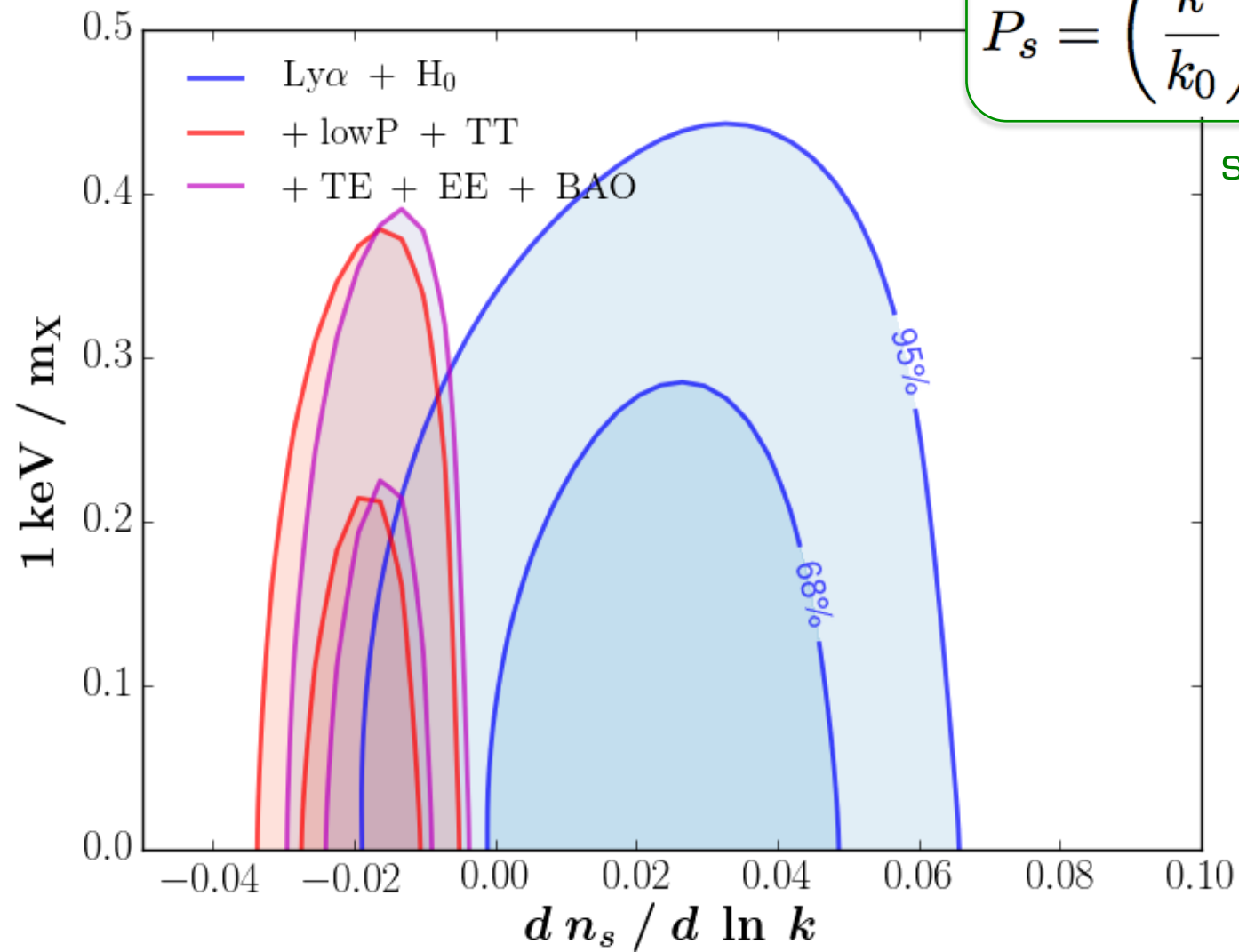
Fit in our likelihood computation

Degeneracies



Baur *et al.*, 2015 [arXiv:1512.01981](https://arxiv.org/abs/1512.01981)

Spectral Index Running

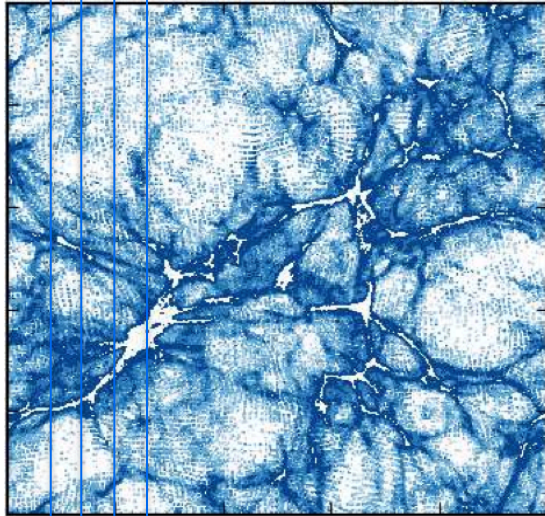


$$P_s = \left(\frac{k}{k_0} \right)^{n_s - 1 + \frac{1}{2} \frac{dn_s}{d \ln k} \ln(k/k_0)}$$

scalar power spectrum

Constructing the simulated Ly α PS

Gadget snapshot



100,000 l.o.s.
1,000,000 particles

12 z-bins in Ly α forest range

Thermal history of IGM

$$T(\rho, z) = T_0(z) (1 + \delta)^{\gamma(z)-1}$$

Optical Depth

$$\tau_{\text{eff}} = A^\tau \times (1 + z)^{\eta^\tau}$$

Cosmology

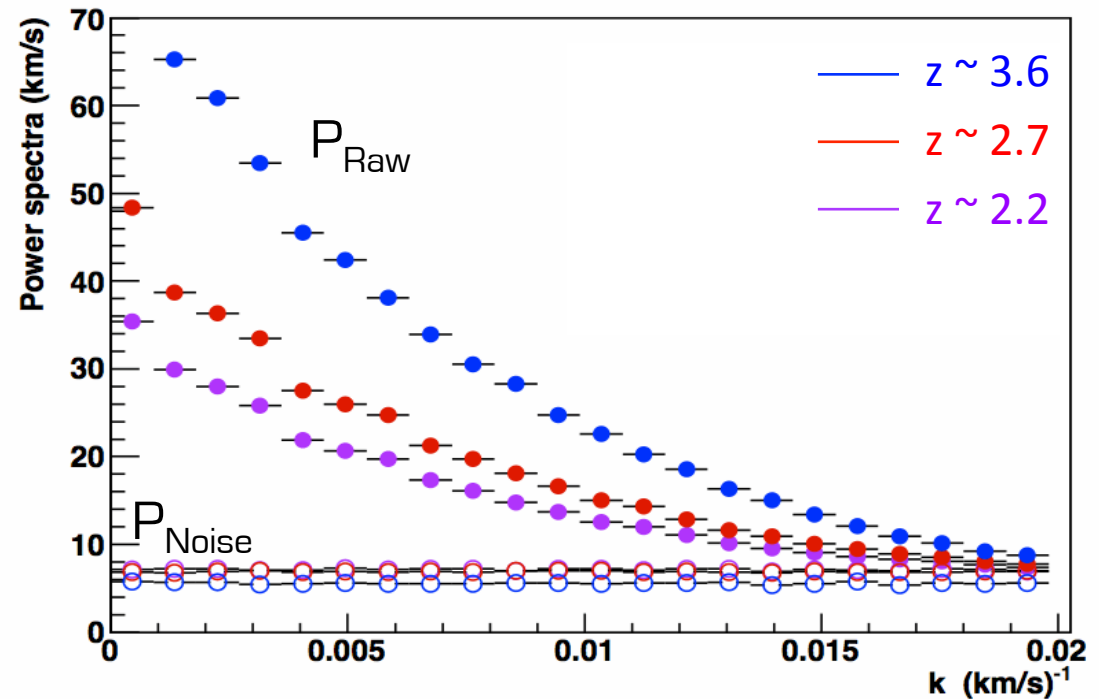
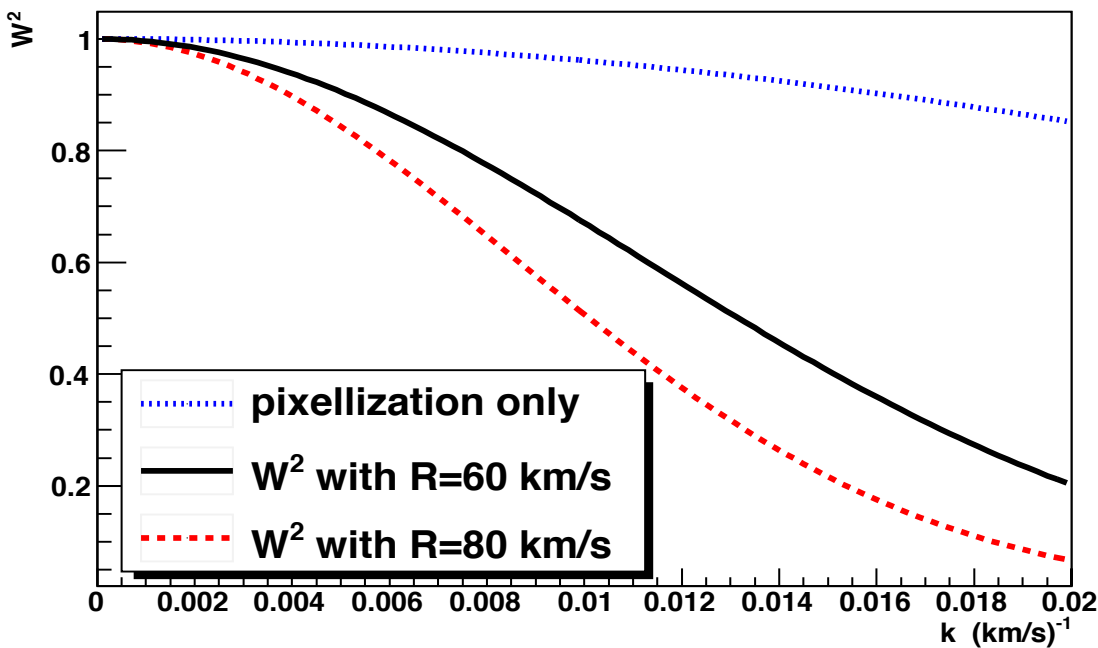
Parameter	(1) Ly α + H_0^{Gaussian} ($H_0 = 67.3 \pm 1.0$)	(2) Ly α + Planck TT+lowP	(3) Ly α + Planck TT+lowP + BAO	(4) Ly α + Planck TT+TE+EE+lowP + BAO
σ_8	0.831 ± 0.031	0.833 ± 0.011	0.845 ± 0.010	0.842 ± 0.014
n_s	0.938 ± 0.010	0.960 ± 0.005	0.959 ± 0.004	0.960 ± 0.004
Ω_m	0.293 ± 0.014	0.302 ± 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

[N.Palanque-Delabrouille *et al.*, 2015 JCAP 011](#)

Lya Power Spectrum

$$P_{\text{Raw}}[k] = [P_{\text{Lya}}[k] + P_{\text{Lya-SIII}}[k] + P_{\text{metals}}[k]] \times W^2[k] + P_{\text{Noise}}[k]$$

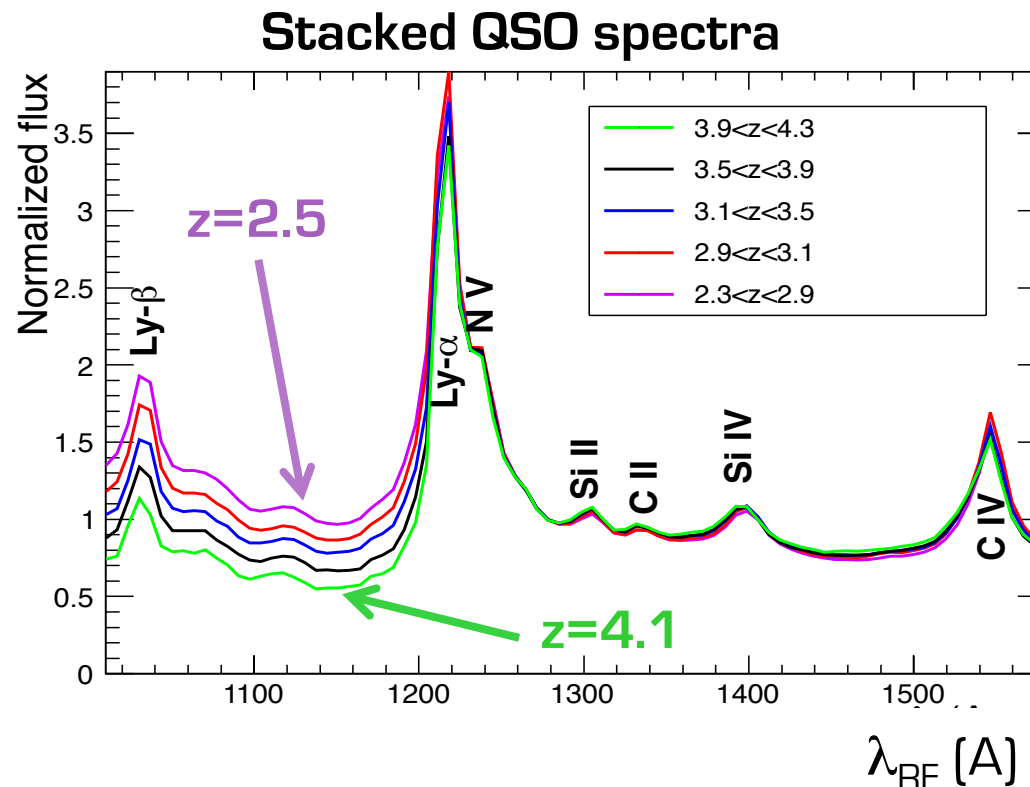
what we measure \nearrow $P_{\text{Raw}}[k]$ \nwarrow $P_{\text{Lya}}[k]$ what we want
 correlated SIII-Lya absorption \nearrow $P_{\text{Lya-SIII}}[k]$
 metals background \nearrow $P_{\text{metals}}[k]$
 window function \nearrow $W^2[k]$
 white noise \nearrow $P_{\text{Noise}}[k]$



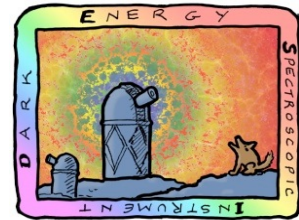
Sample

Palanque-Delabrouille *et al.*, 2013 [A&A 559 A85](#)

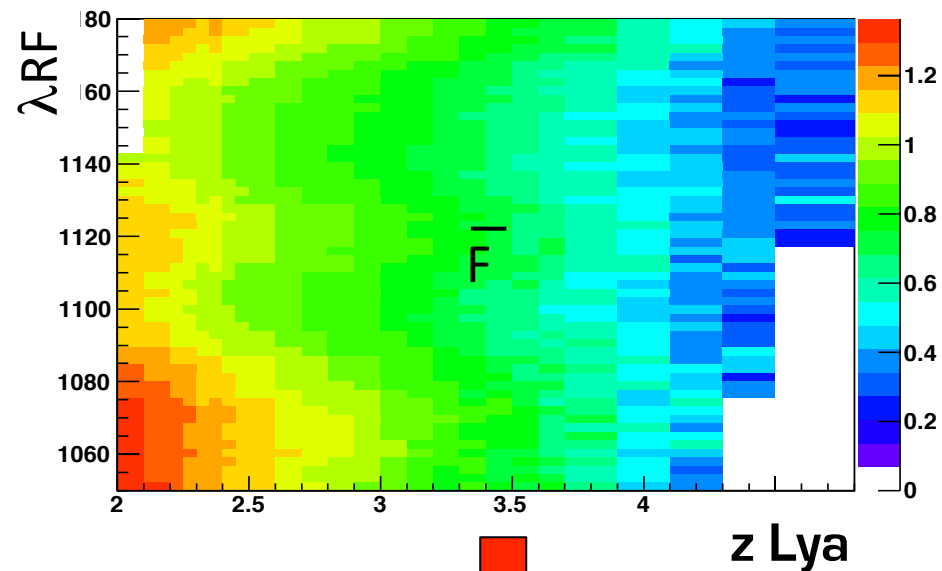
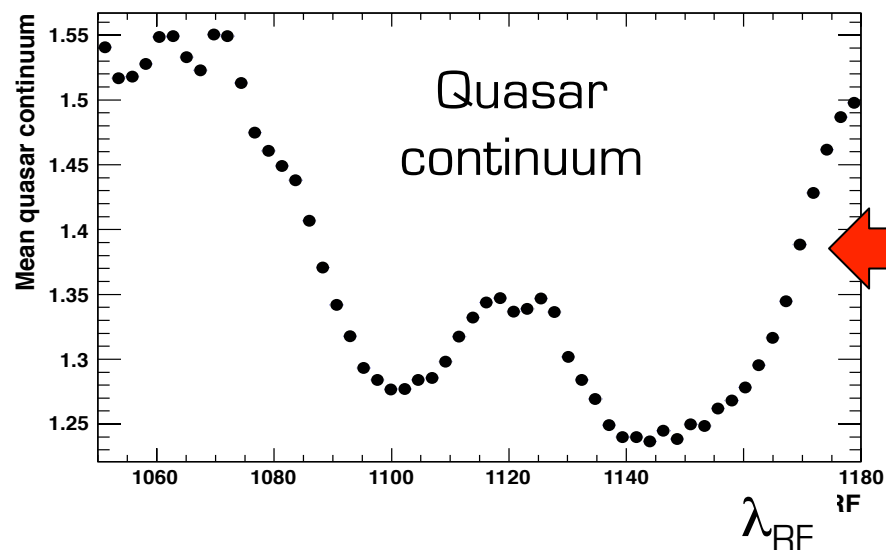
- 14,000 DR9 QSOs out of 60,000
 - Selected for:
 - ◆ quality (no flagged pixels, no high density absorbers)
 - ◆ SNR > 2
 - ◆ resolution < 85 km/s
- } to obtain $\sigma_{\text{syst}} \sim \sigma_{\text{stat}}$



1D Power Spectrum



$$P_{raw}(k) = |FT(\delta)|^2 \quad \text{where} \quad \delta = \frac{F}{\overline{F}} - 1$$



δ : normalized transmitted flux fraction

