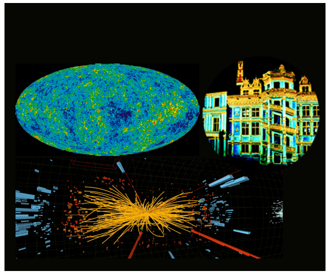
28th Rencontres de Blois on Particle Physics and Cosmology (2016)

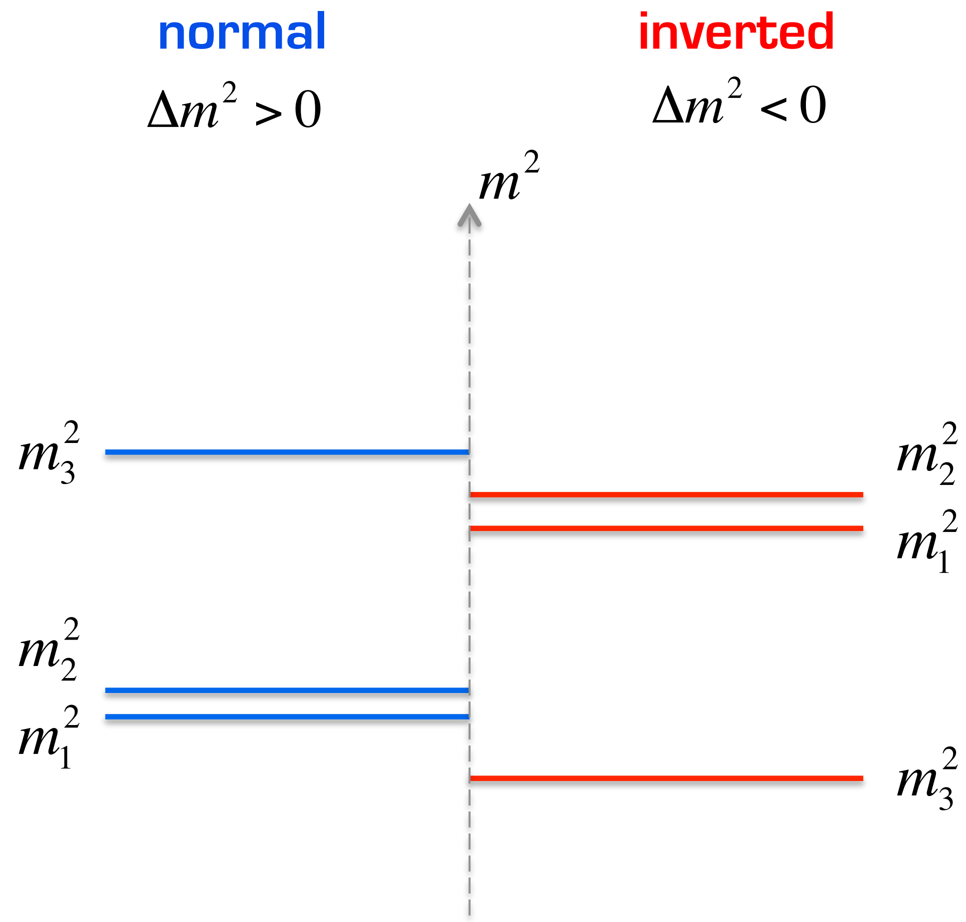


Constraints on Neutrino Mass from the Lyman-alpha Forest

Julien Baur
PhD student
Nathalie Palanque-Delabrouille & Christophe Yèche

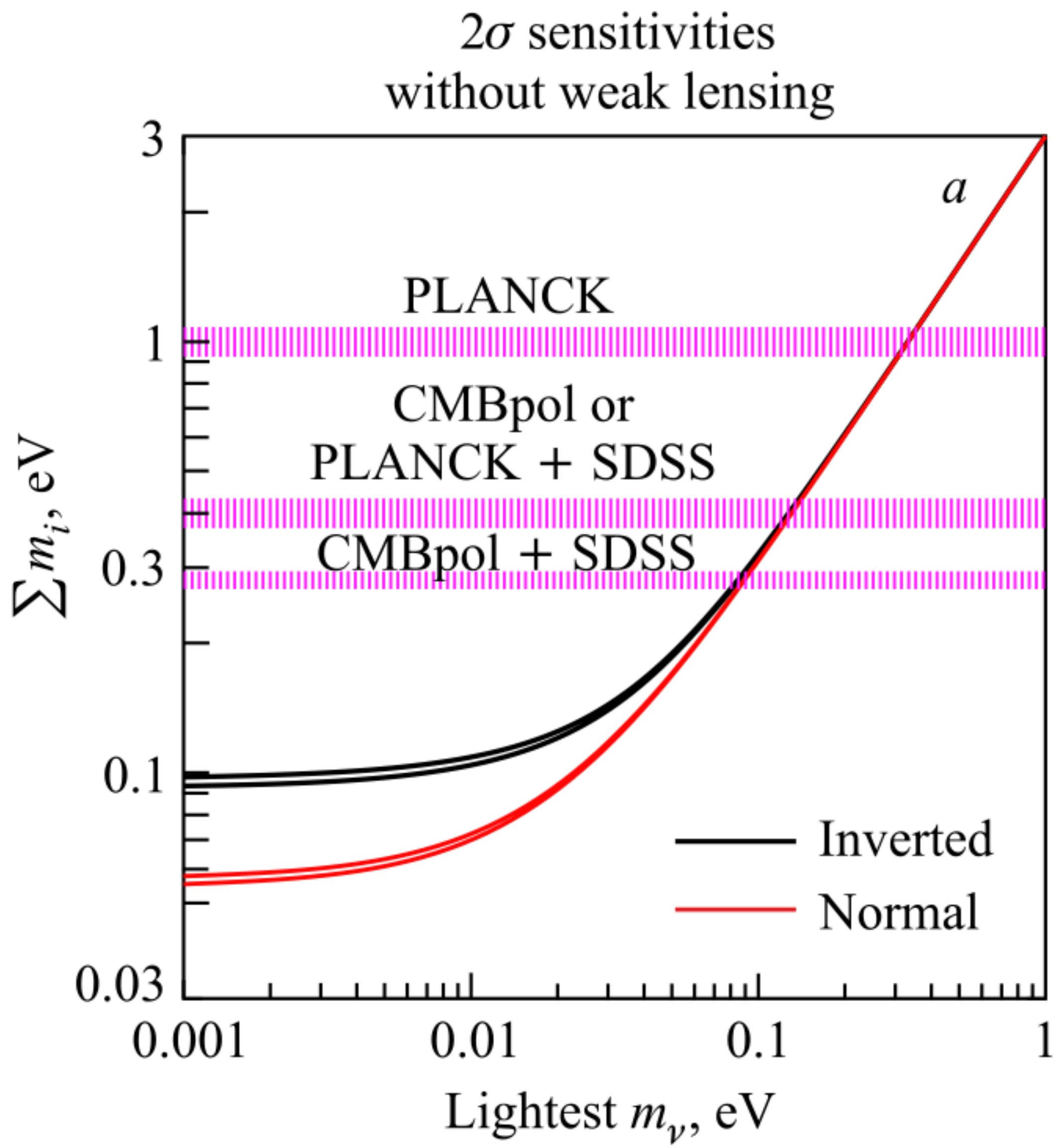
Irfu / SPP – CEA

Mass Ordering



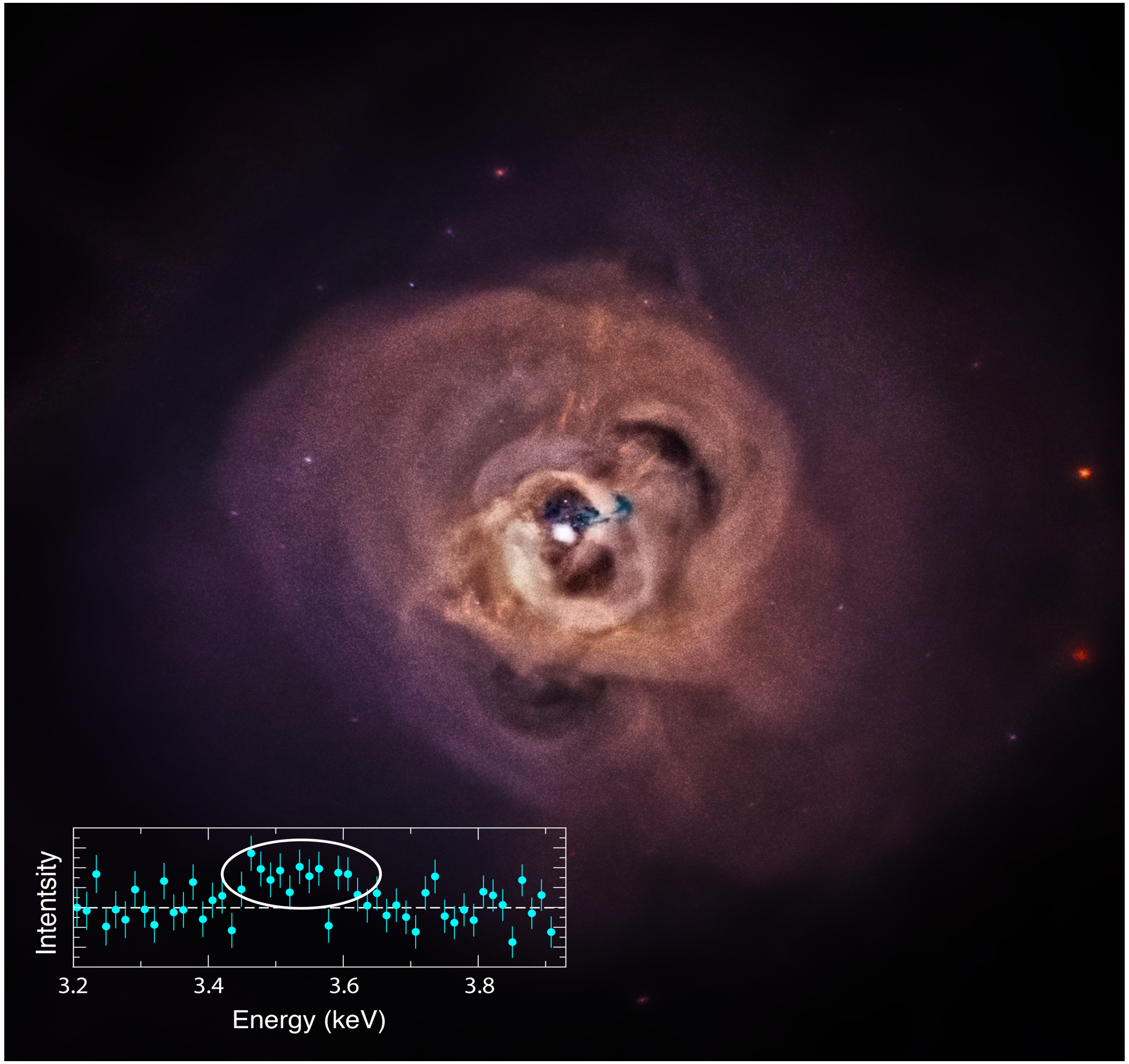
$\Sigma m_\nu > 0.06\, eV$

$\Sigma m_\nu > 0.11\, eV$



Lesgourgues & Pastor

Hints of Sterile ν ?



Perseus cluster
Chandra, XMM−Newton

3.55 keV line

Decay channel

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

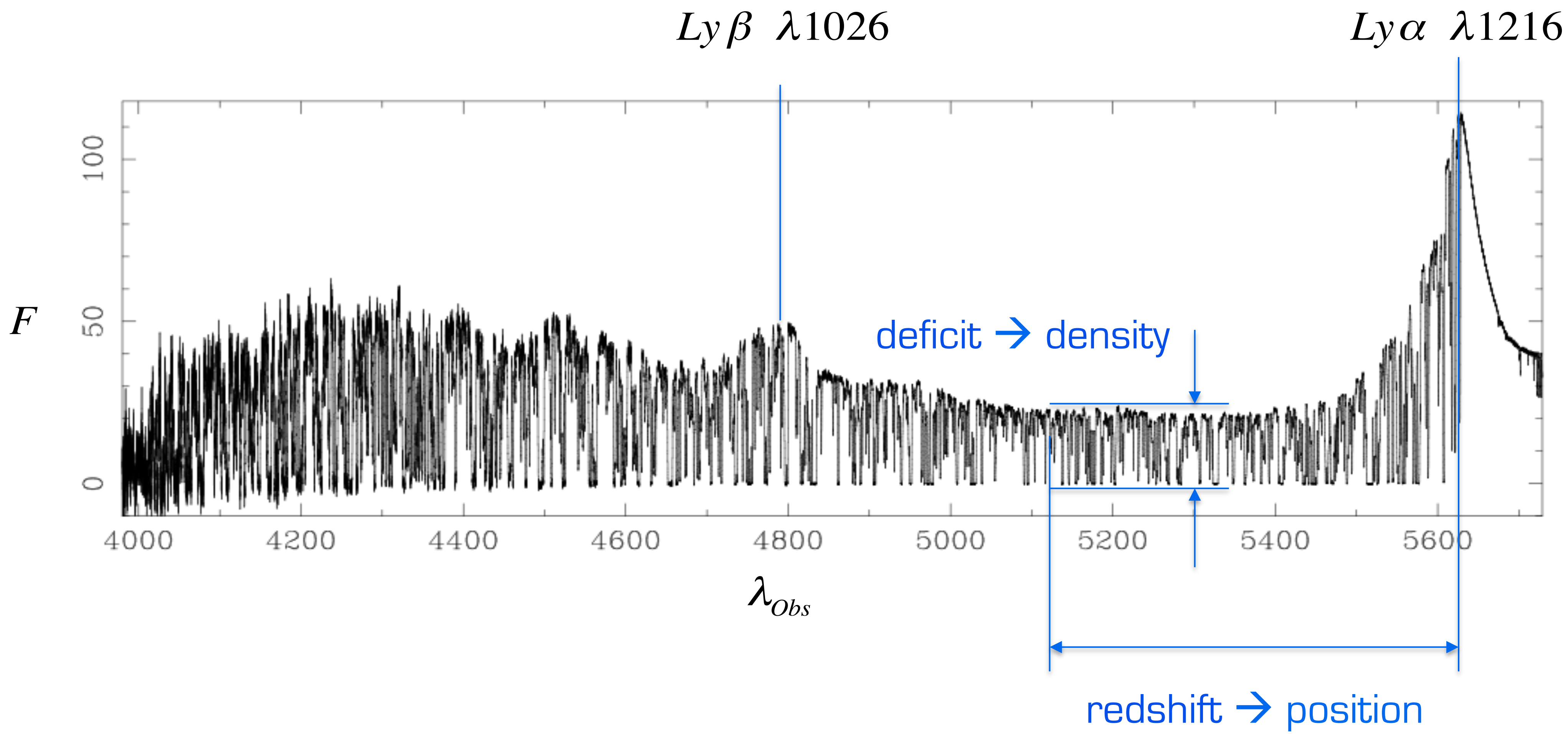
Bulbul *et al.* 2014, ApJ 789 13

73 stacked XMM-N spectra
246 citations

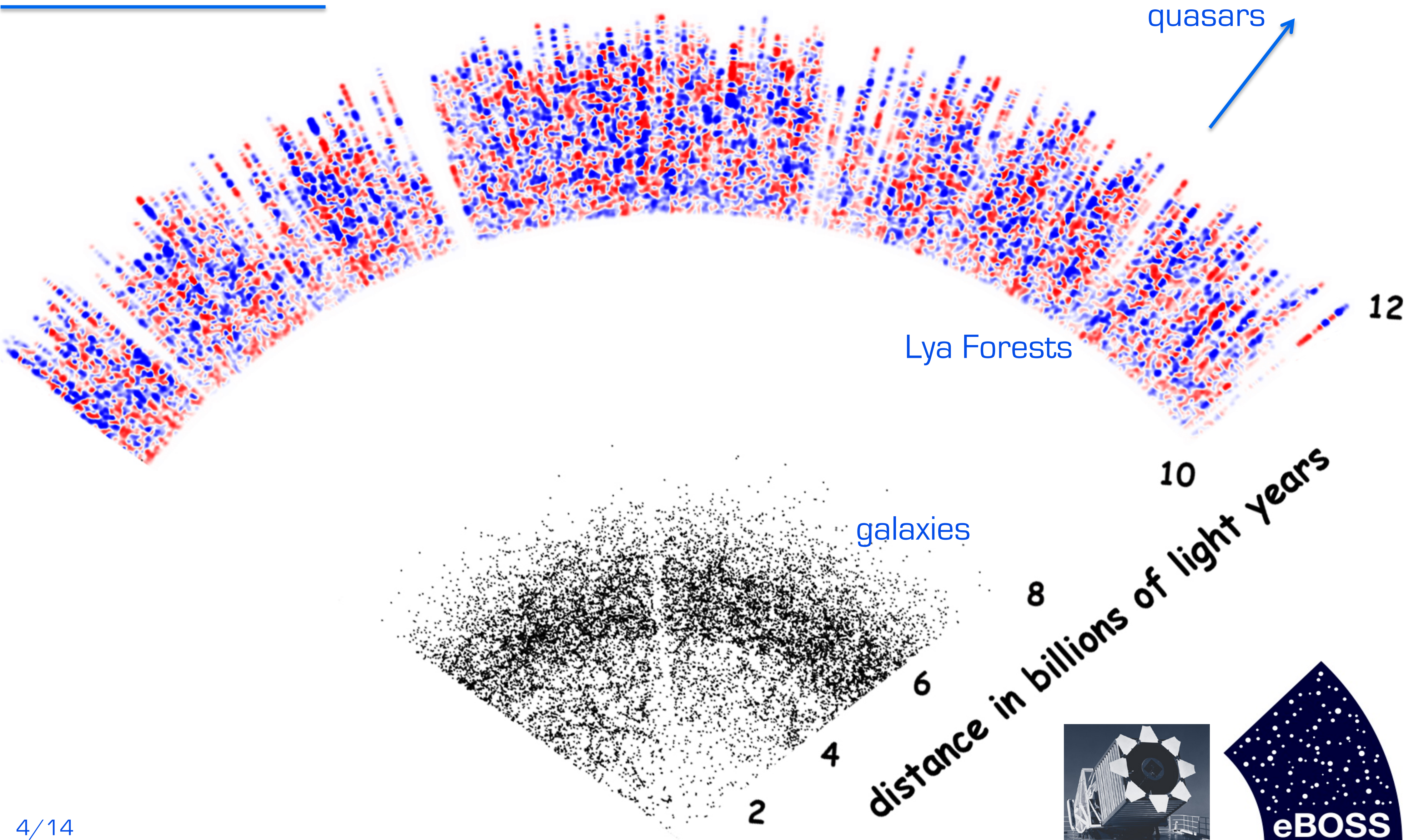
Boyarsky *et al.* 2014, PRL 113, 251301

Andromeda & Perseus clusters
235 citations

Lyman-alpha Forest



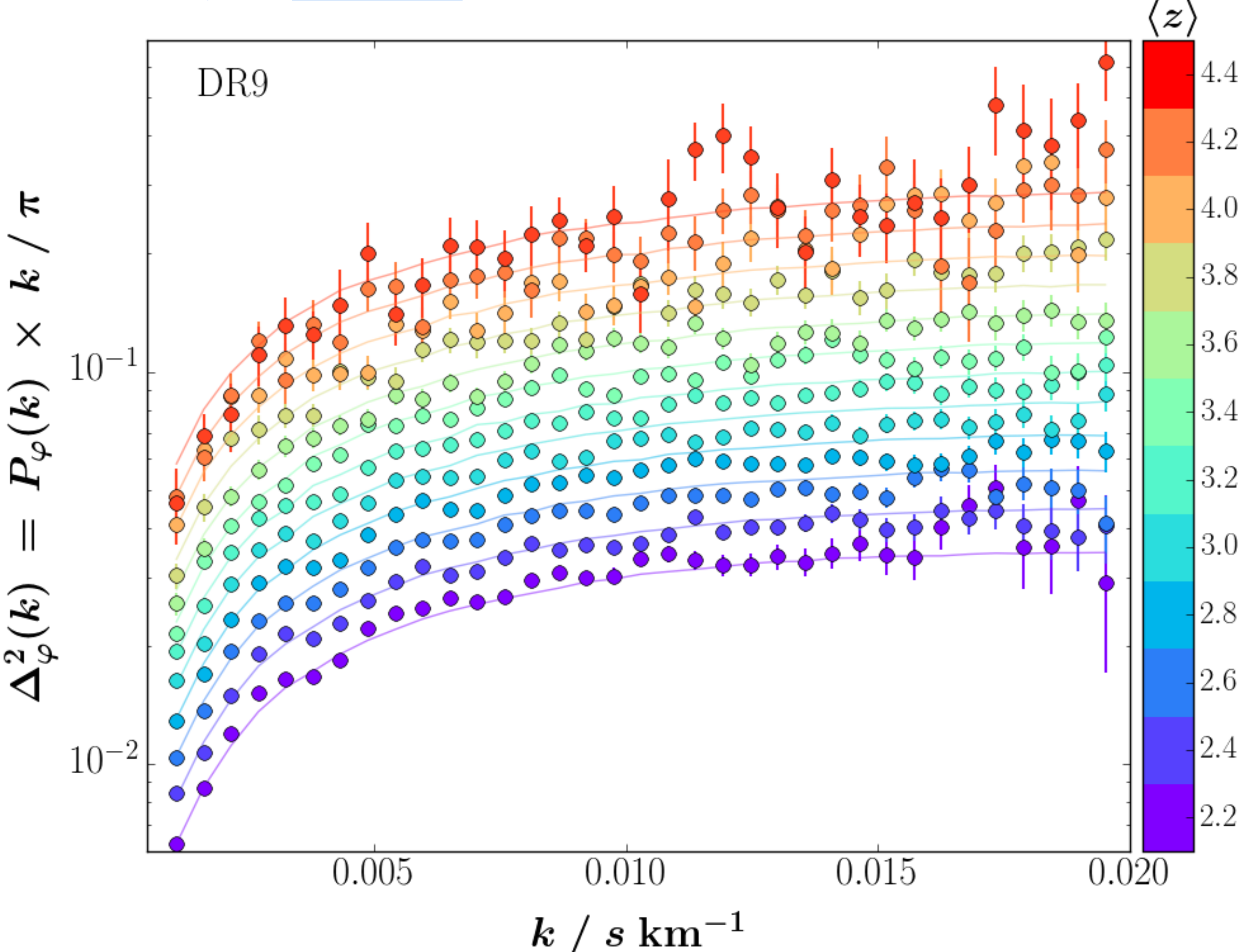
SDSS – BOSS


quasars
Lya Forests
galaxies
12
10
8
6
4
2
distance in billions of light years

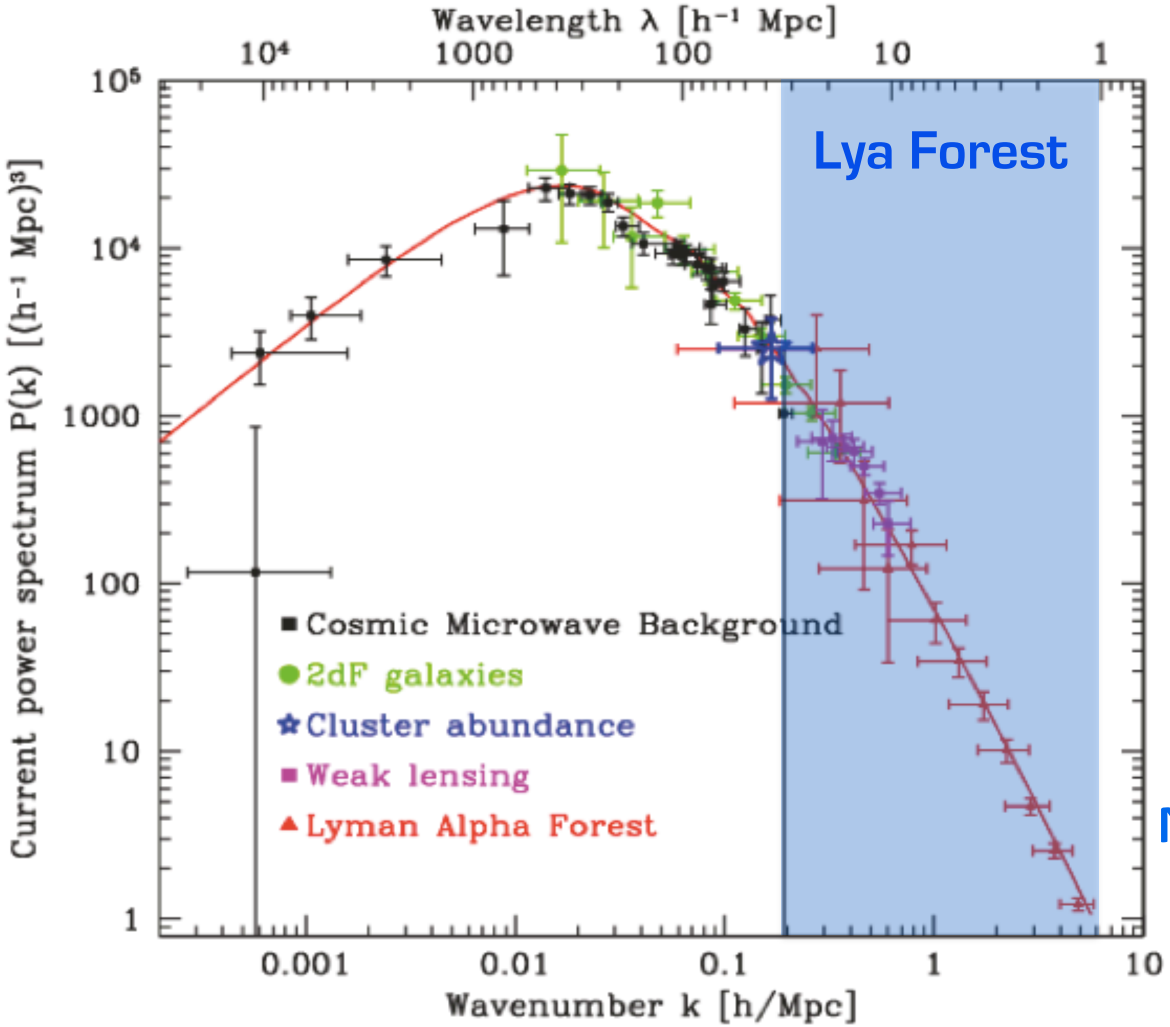
Flux Power Spectrum

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

Palanque-Delabrouille *et al.*, 2013 A&A 559 A85



from Flux PS to Matter PS



Tegmark & Zaldarriaga, 2002

$$P_{1D}(k_{\|}) = \frac{1}{2\pi} \int_{k_{\|}}^{\infty} k P_{3D}(k) \mathrm{d}k$$

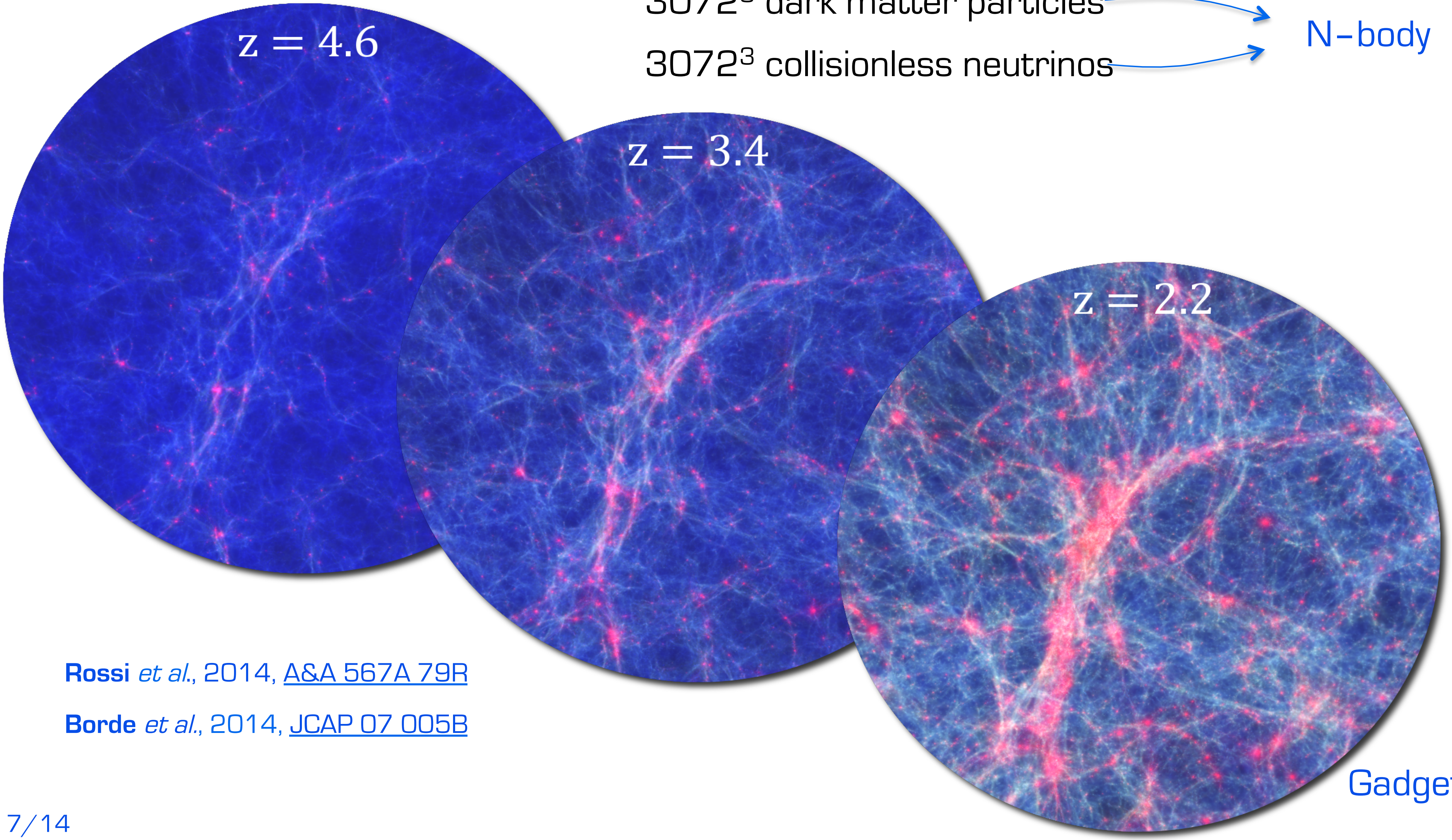
- unidimensional probe
- non–linear regime

Numerical Approach Required

Simulations

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

- 3072^3 baryonic gas particles → Hydrodynamics
- 3072^3 dark matter particles → N-body
- 3072^3 collisionless neutrinos → N-body



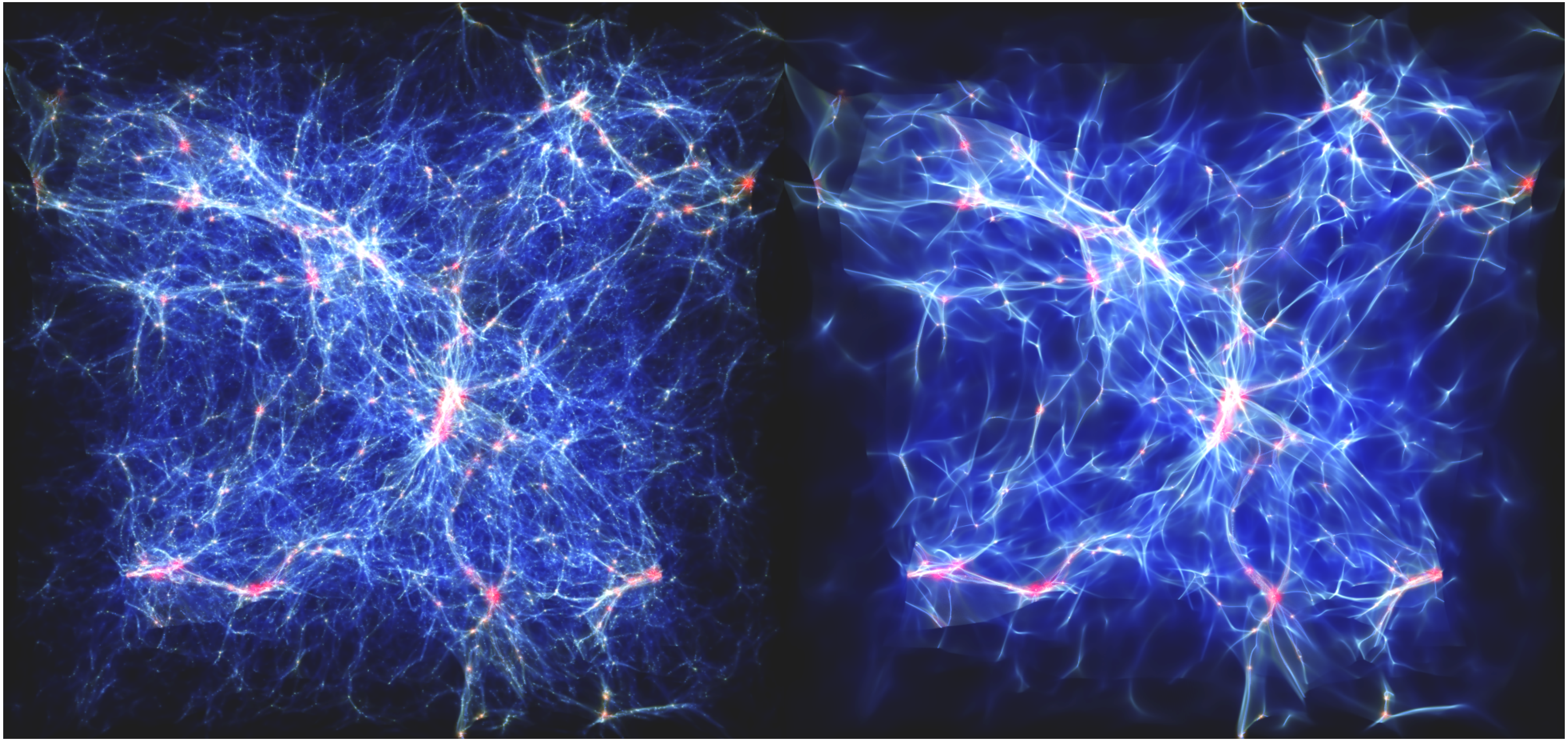
Gadget-III

Rossi *et al.*, 2014, A&A 567A 79R

Borde *et al.*, 2014, JCAP 07 005B

Free Streaming

$$\lambda^0_{\mathrm{FSH}} = \int_0^{t_0} \frac{\langle v \rangle}{a}\, dt = \int_0^1 \frac{\langle v \rangle}{a^2 H}\, da$$



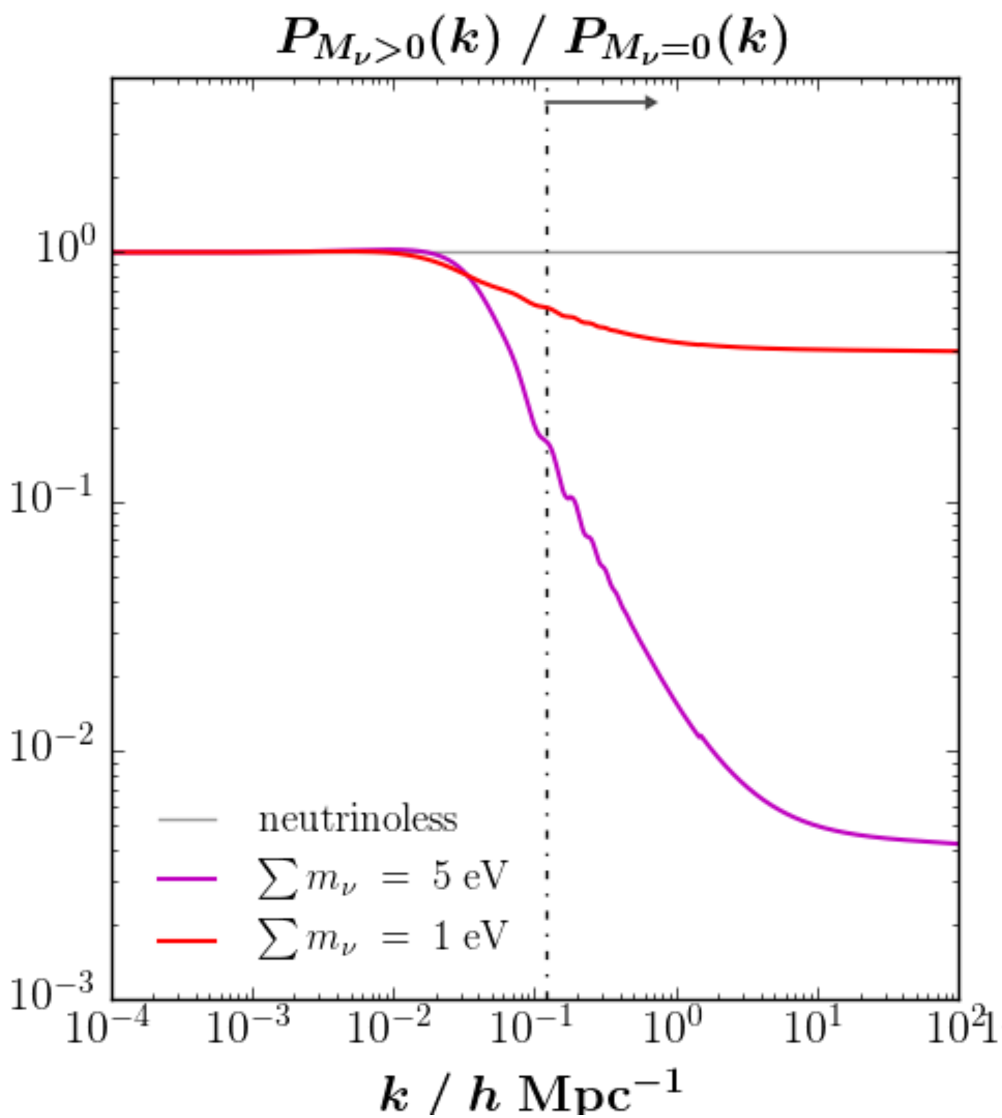
Cold Dark Matter **Warm** Dark Matter

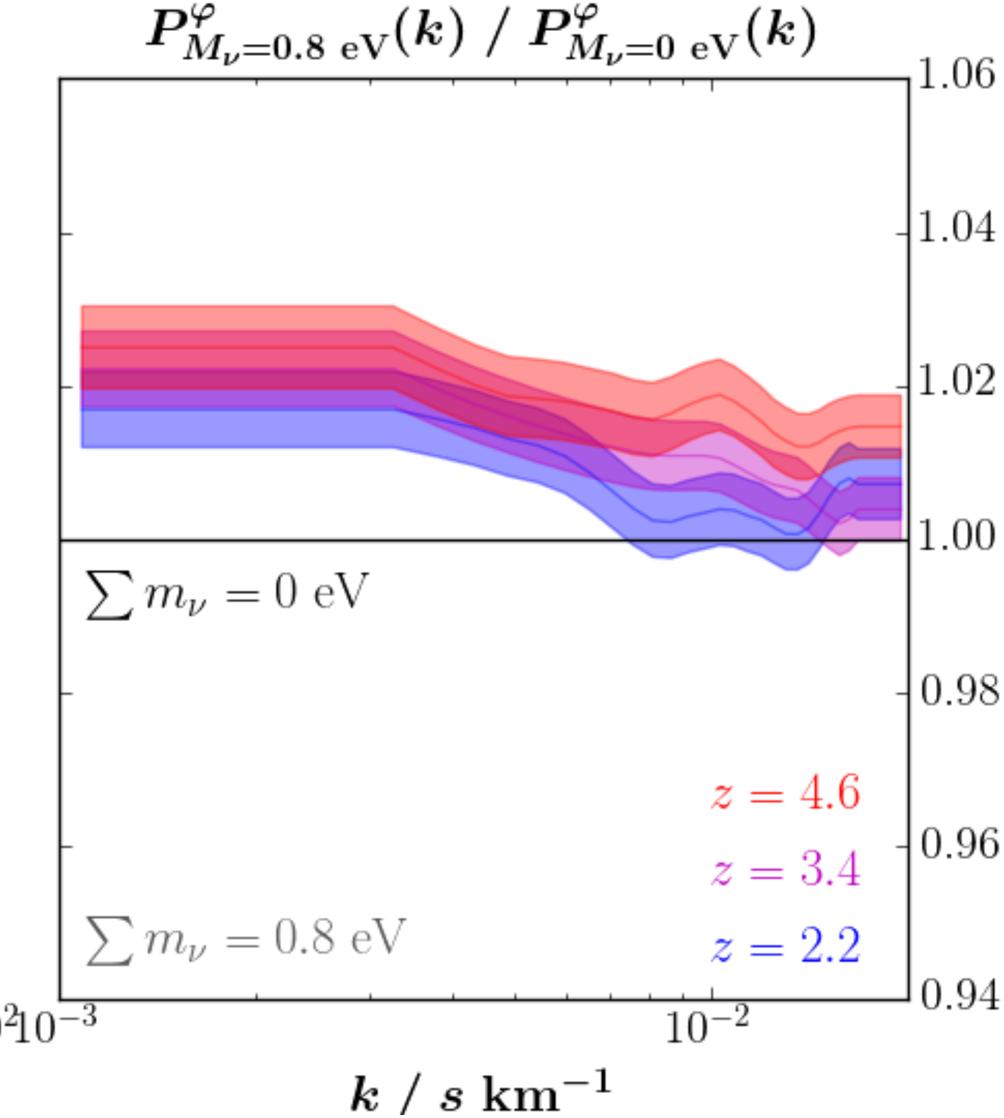
Impact on Power Spectrum

Λ-CDMν

matter 3D PS

flux 1D PS

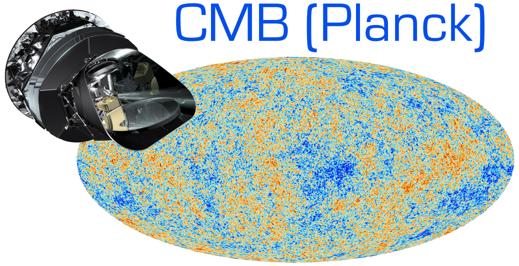


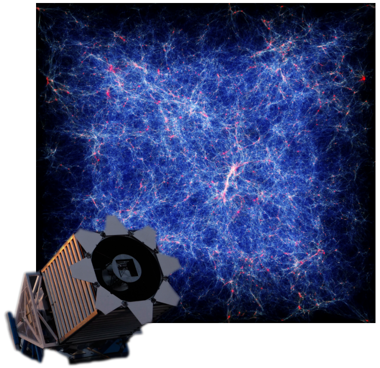


Constraints on Neutrino Masses

Ly-a (SDSS/BOSS)

CMB (Planck)

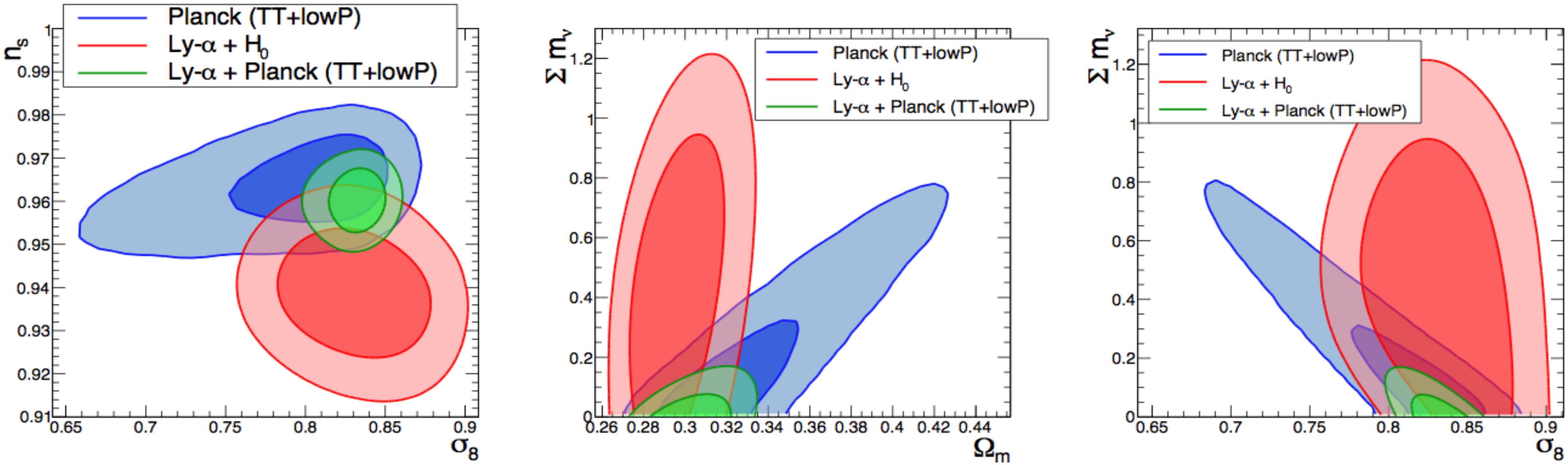




Planck only : $\Sigma m_\nu < 0.72$ eV (95% CL)

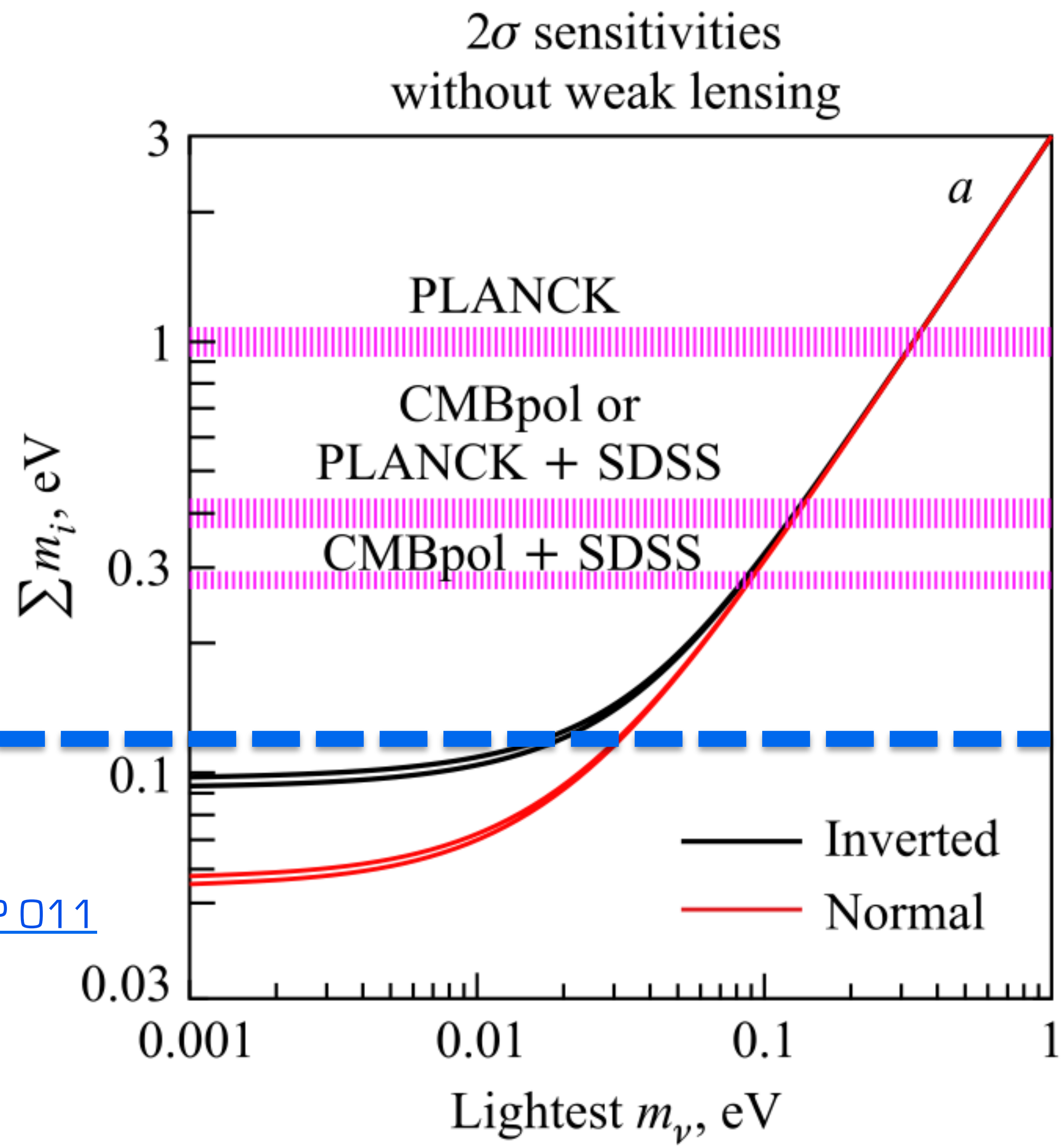
BOSS only : $\Sigma m_\nu < 1.1$ eV (95% CL)

Lya + Planck (TT+lowP) : $\Sigma m_\nu < 0.12$ eV (95% CL)



N.Palanque-Delabrouille *et al.*, 2015 JCAP 011

Results: Λ-CDMν



$$\Sigma m_\nu < 0.12\ eV$$

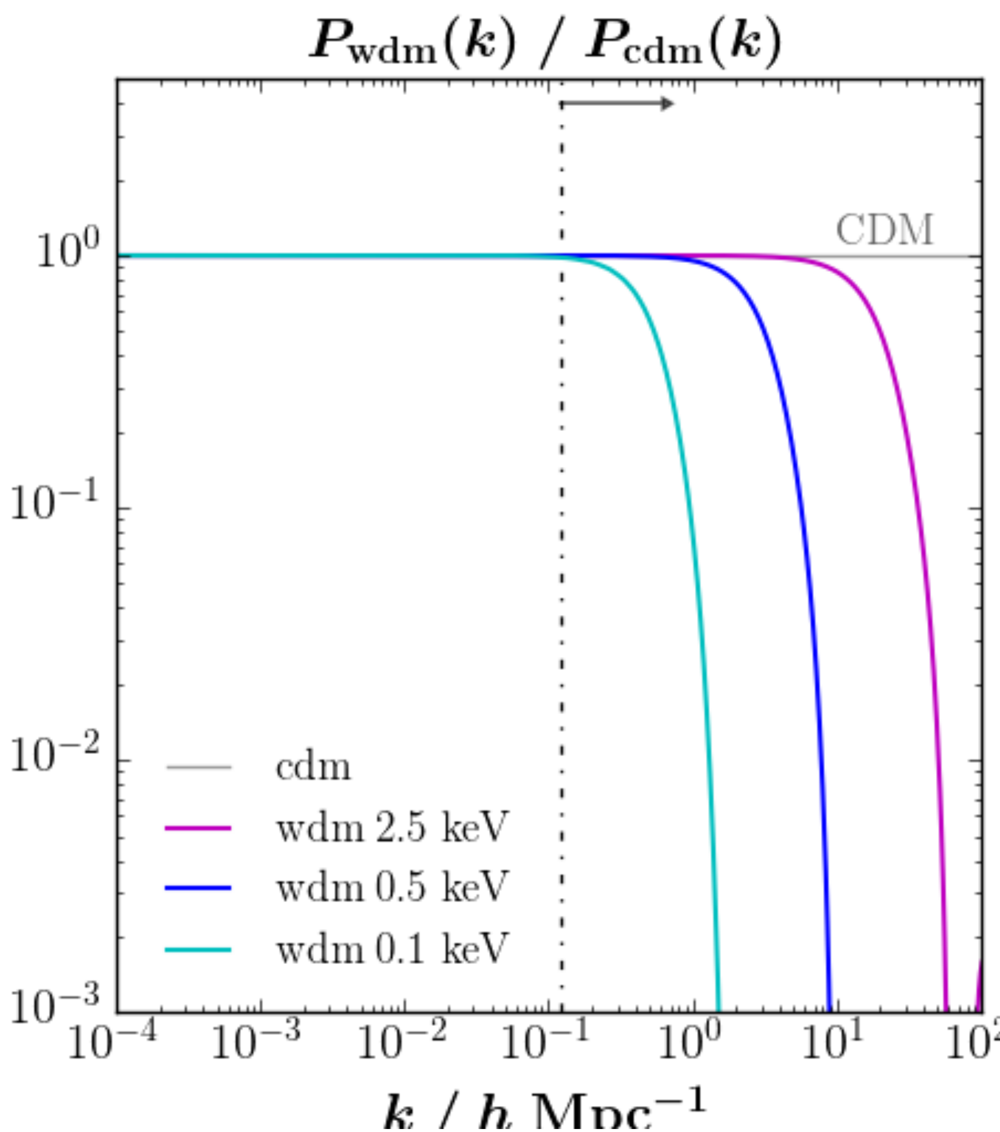
Lya + CMB + BAO (95% CL)

N.Palanque-Delabrouille *et al.*, 2015 JCAP 011

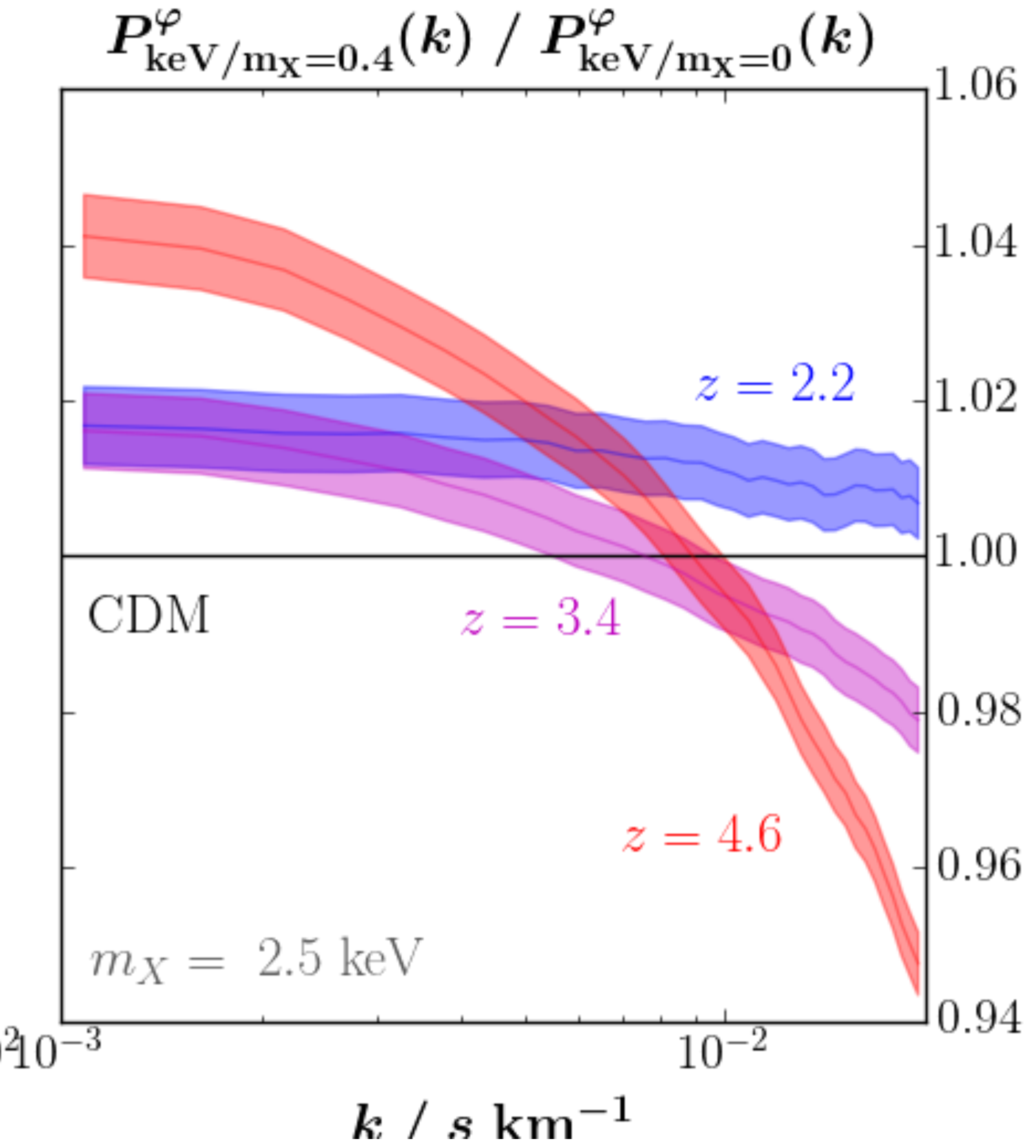
Lesgourgues & Pastor

Impact on Power Spectrum

matter 3D PS



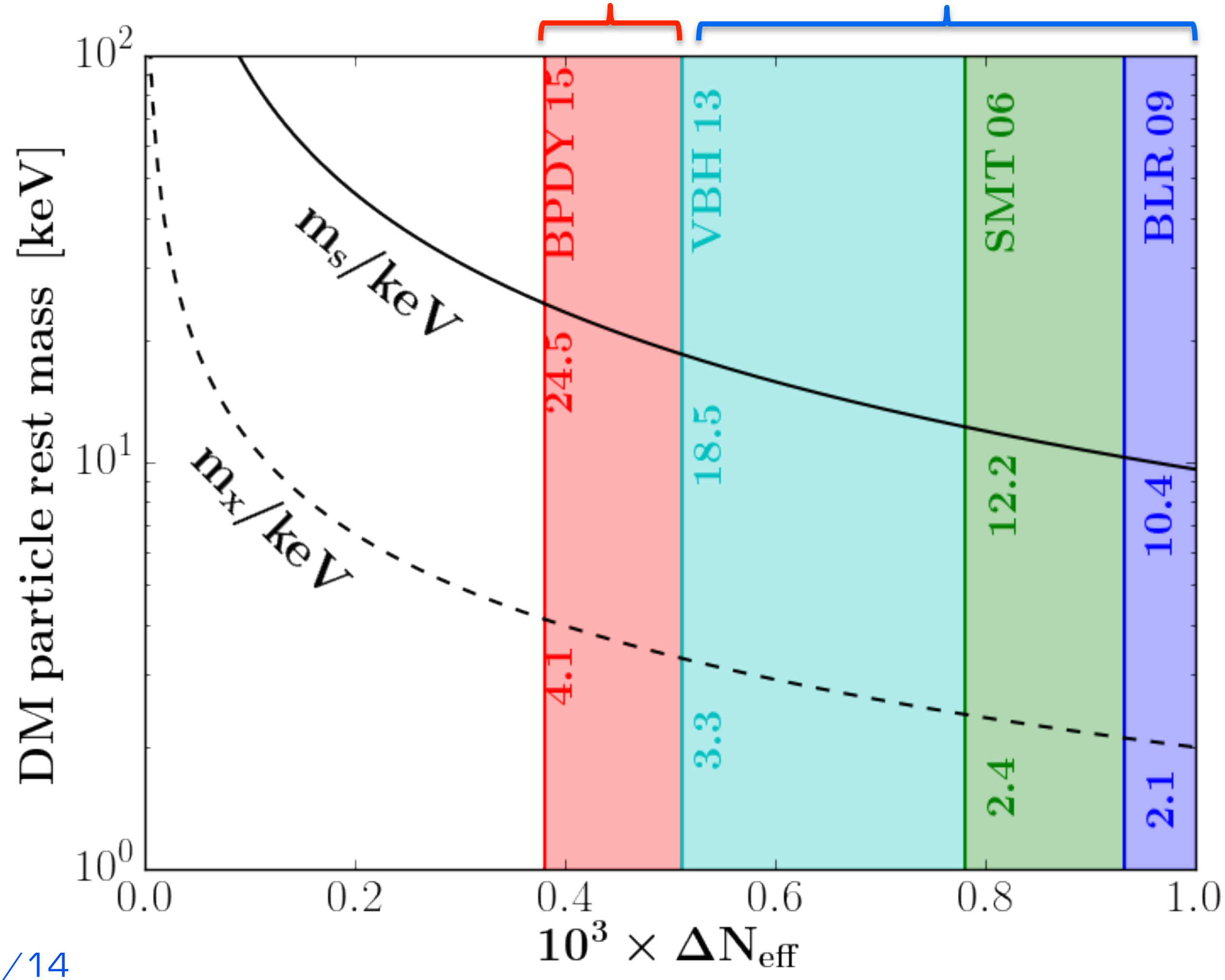
flux 1D PS



Constraints on WDM mass

~14,000 SDSS-III
3072^3 simulations

~3,000 SDSS-I
~50 Keck
256^3 simulations



Lya	**4.11 keV**
Lya+CMB	3.02 keV
Lya+CMB+BAO	2.98 keV
Running on spectral index	
Lya+CMB	**4.30 keV**
Lya+CMB+BAO	**4.17 keV**

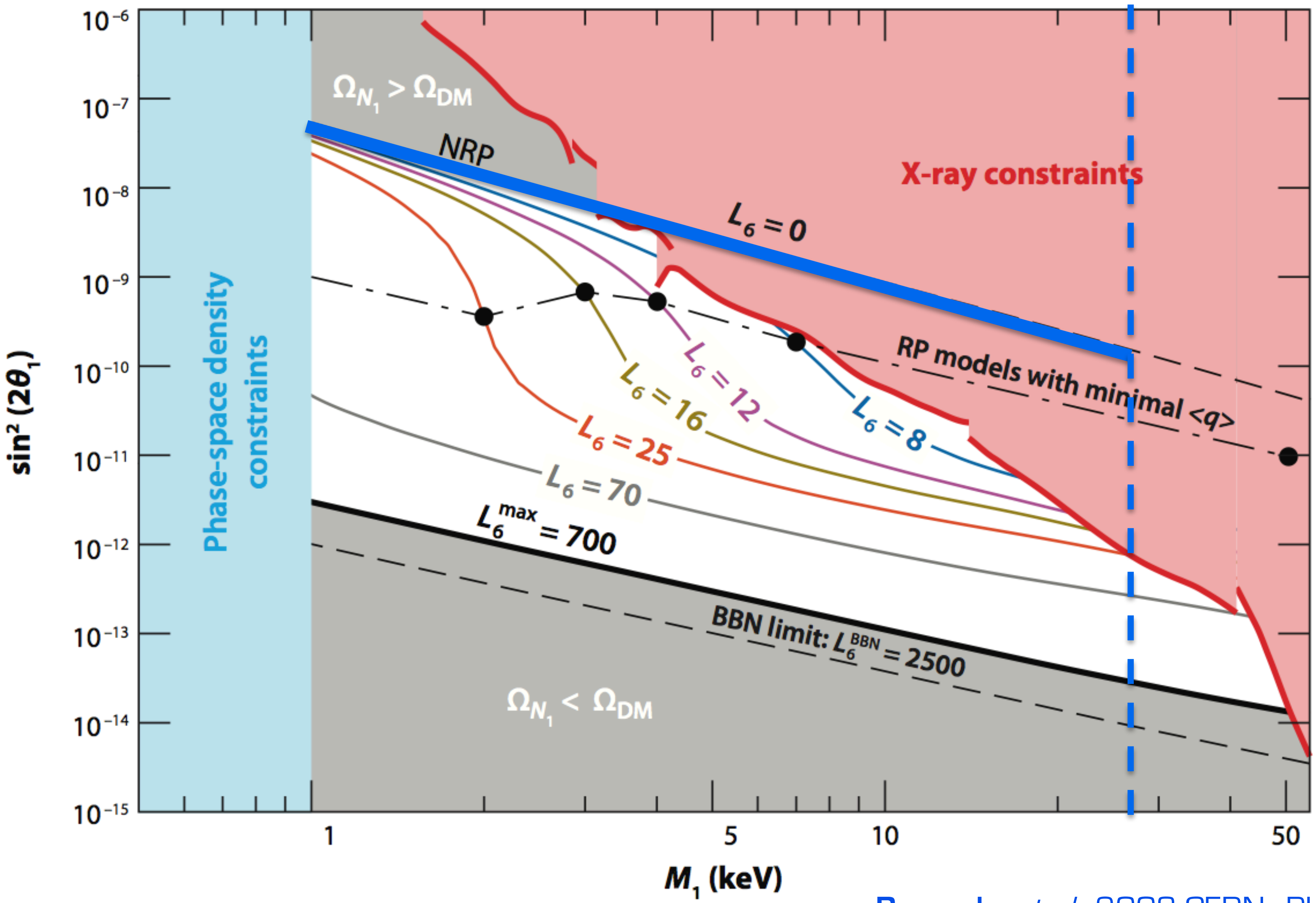
Baur *et al.*, 2015 arXiv:1512.01981

Conclusion: Λ−WDM

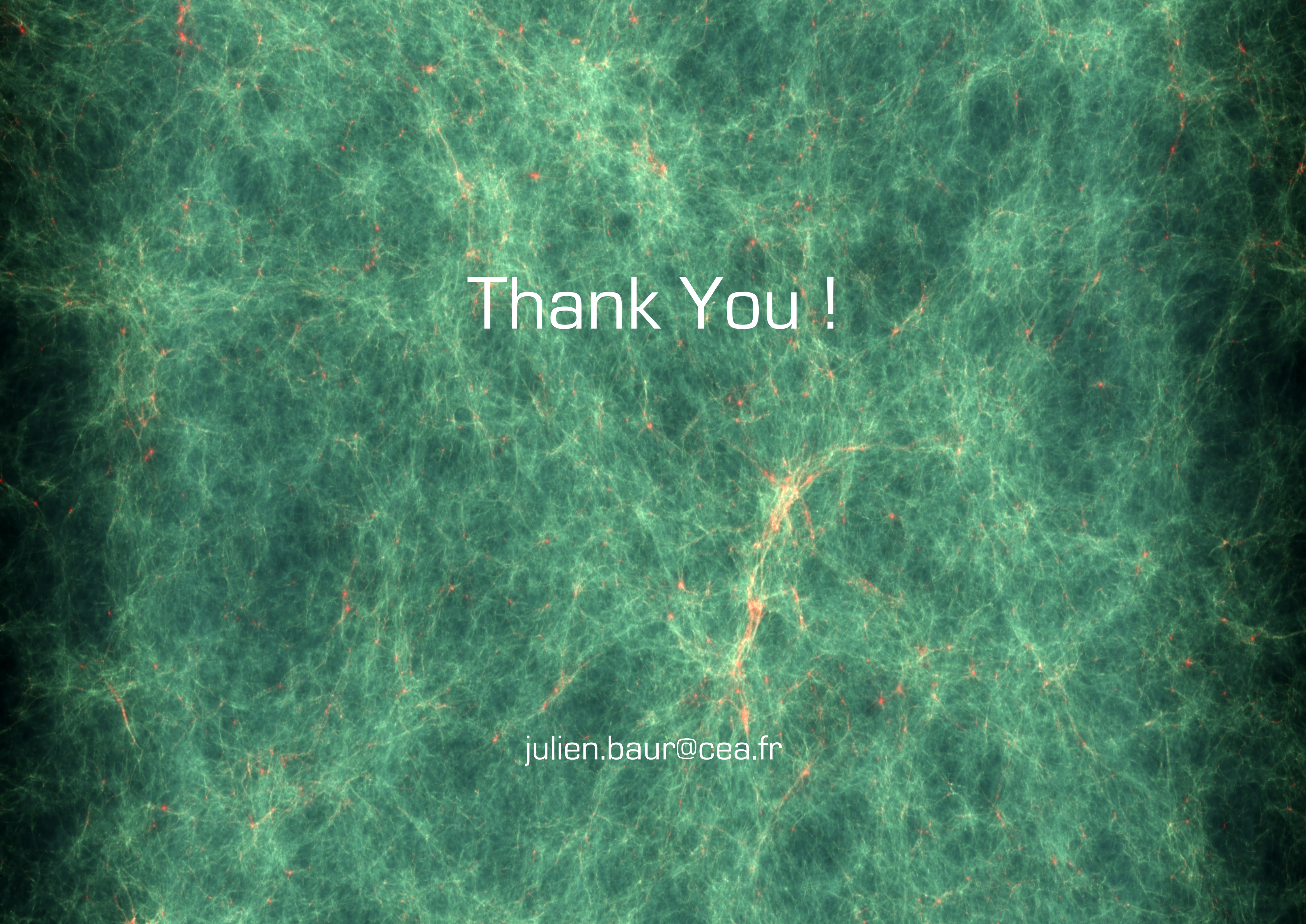
Baur *et al.*, 2015 arXiv:1512.01981

$$m_\nu^{NRP} > 24.5\ keV$$

Lya (95% CL)



Boyarsky *et al.*, 2008 CERN−PH−TH 2008 234



Thank You !

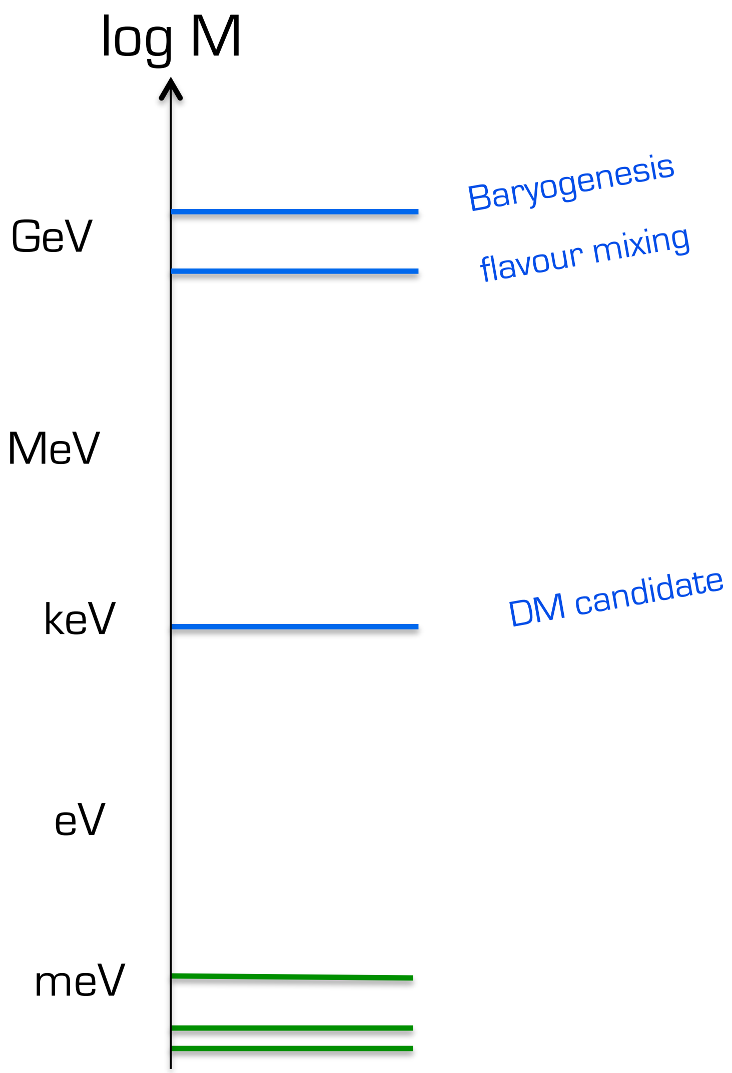
julien.baur@cea.fr

BACKUP

νMSM Framework

Asaka, Blanchet & Shaposhnikov '05

(keV, GeV±ε)



sterile sector

right-handed SU(2)×U(1) singlets

νMSM

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

active sector

left-handed SU(2)×U(1) doublets

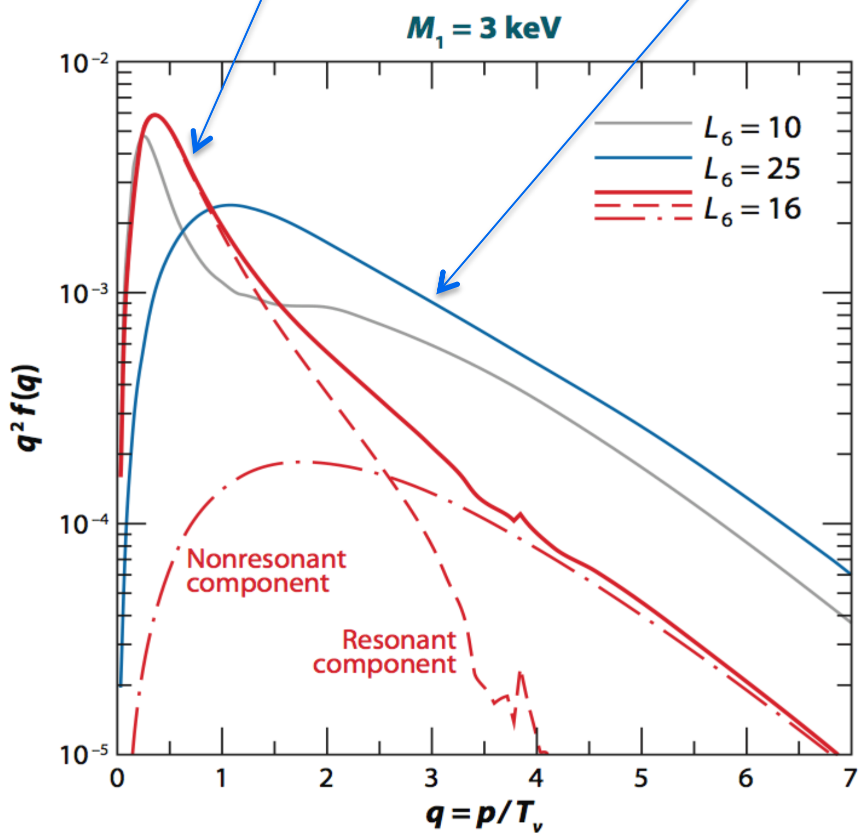
BSM

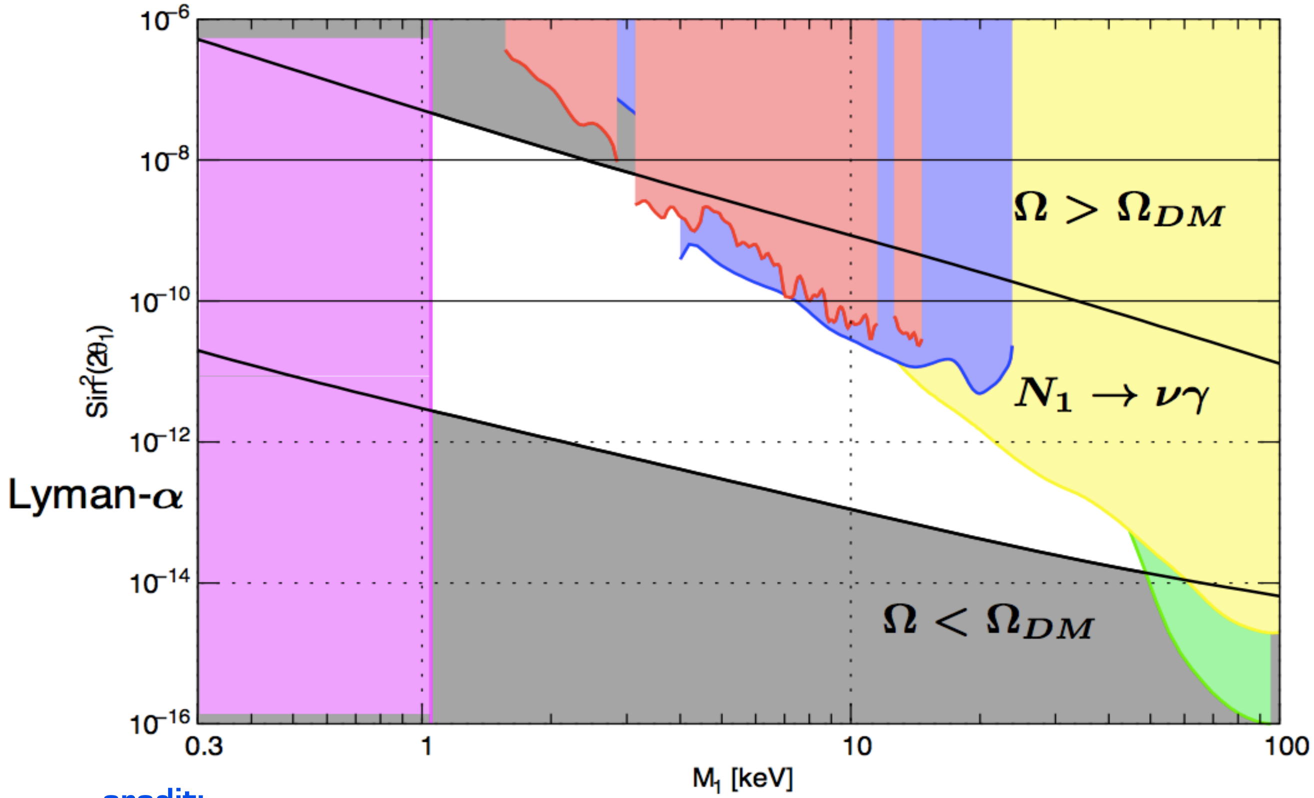
Parameter Space

« non-thermal » RP

« thermal » NRP

$$\phi_X \sim \theta^2 m_S^5$$

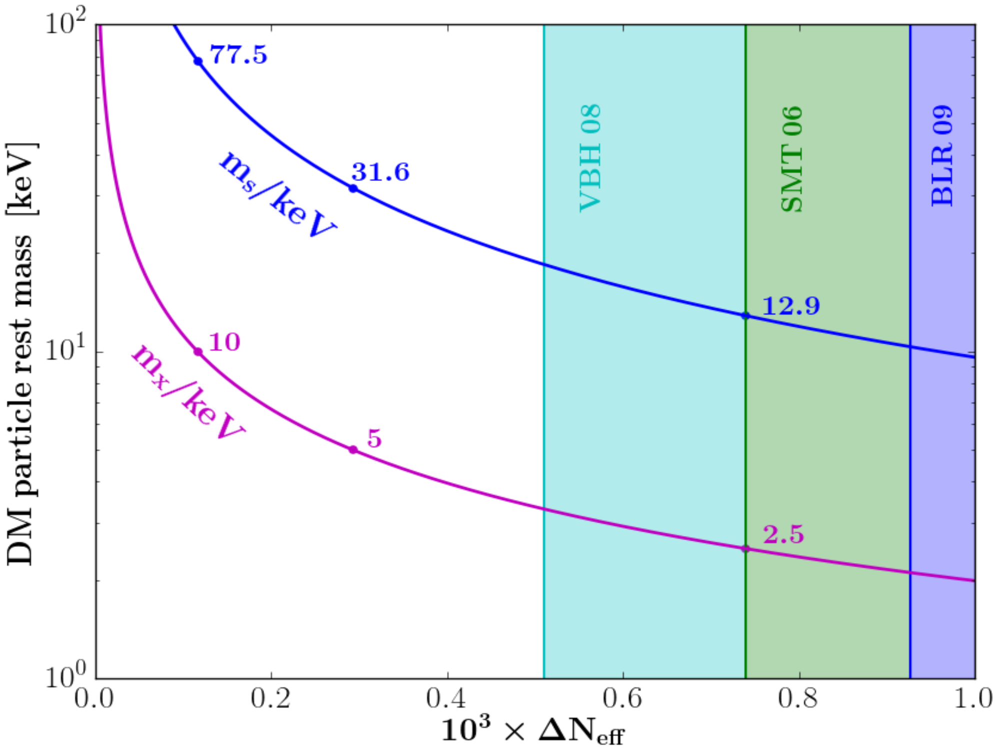




credit:
Boyarsky, Ruchayskiy, Shaposhnikov

Oscillations with active sector

Dodelson & Widrow '94



- Efficient active–sterile oscillations at

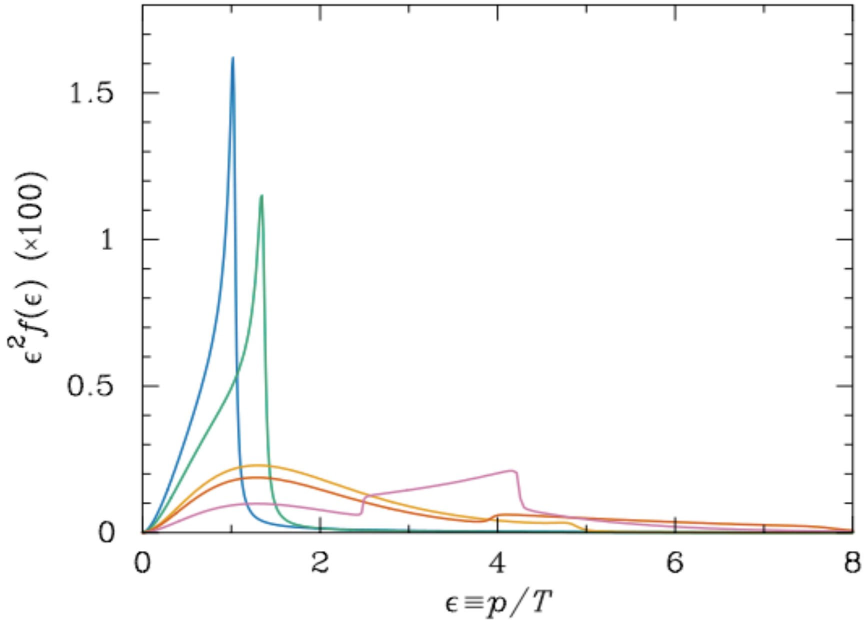
$$T \sim 150\ MeV \left(\frac{m_S}{keV}\right)^{-1/3}$$

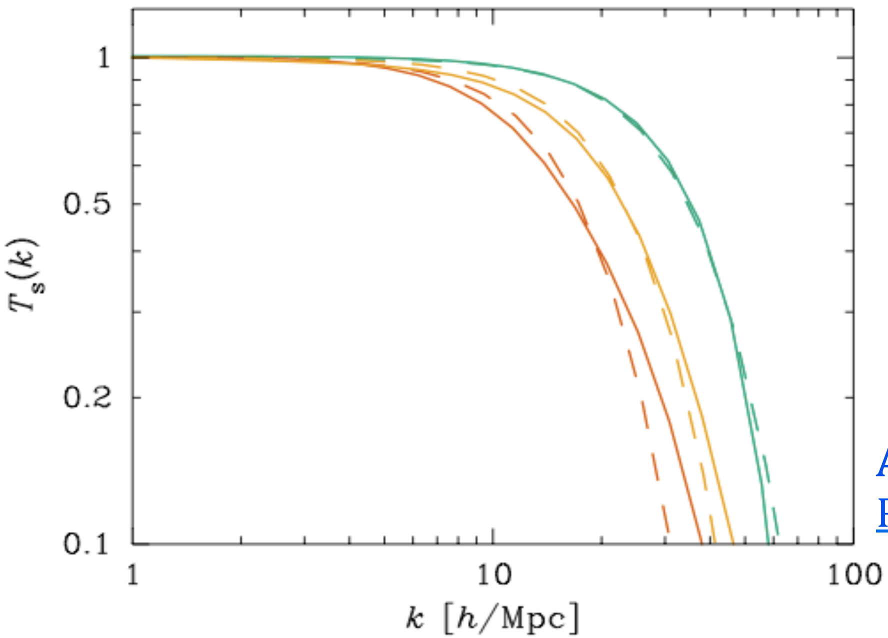
- Never reach thermal equilibrium, but …

- Quasi–thermal PSD

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

MSW-type Resonance





Shi & Fuller '99

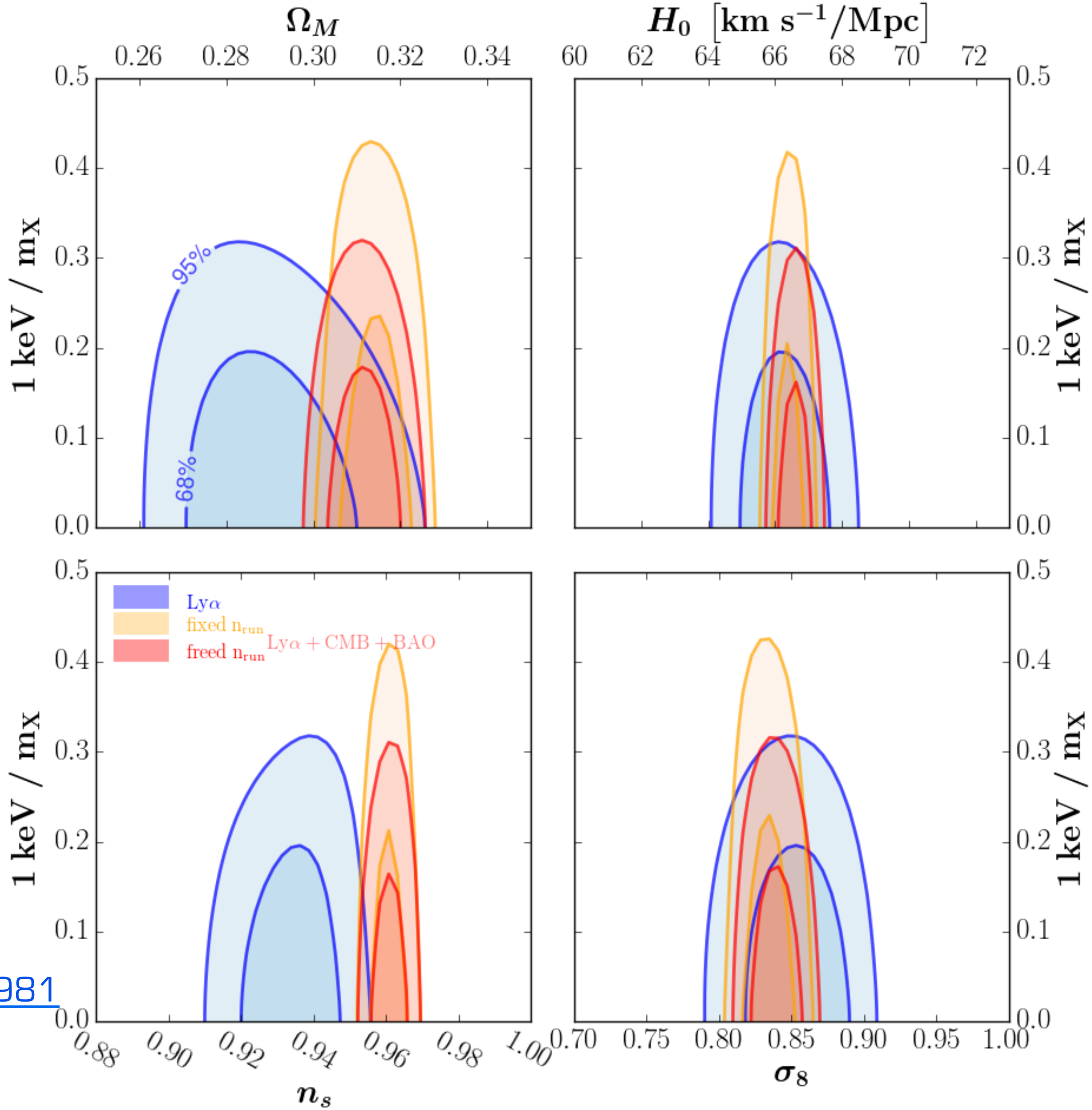
- active-sterile resonance at

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

- Never reach thermal equilibrium
- PSD requires full Boltzmann treatment

Abazajian, 2014
PRL 112, 161303

Degeneracies

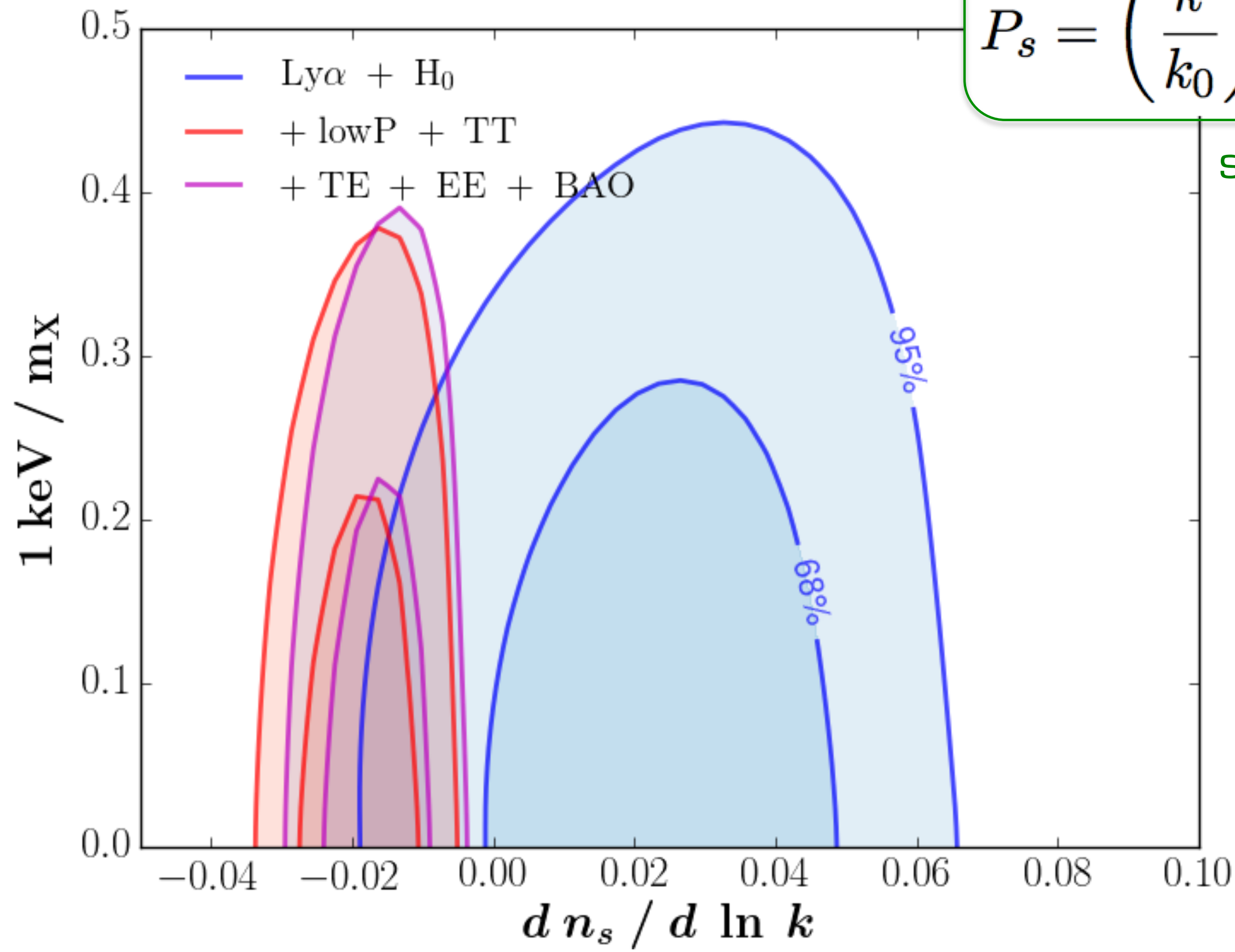


Baur *et al.*, 2015 arXiv:1512.01981

Spectral Index Running

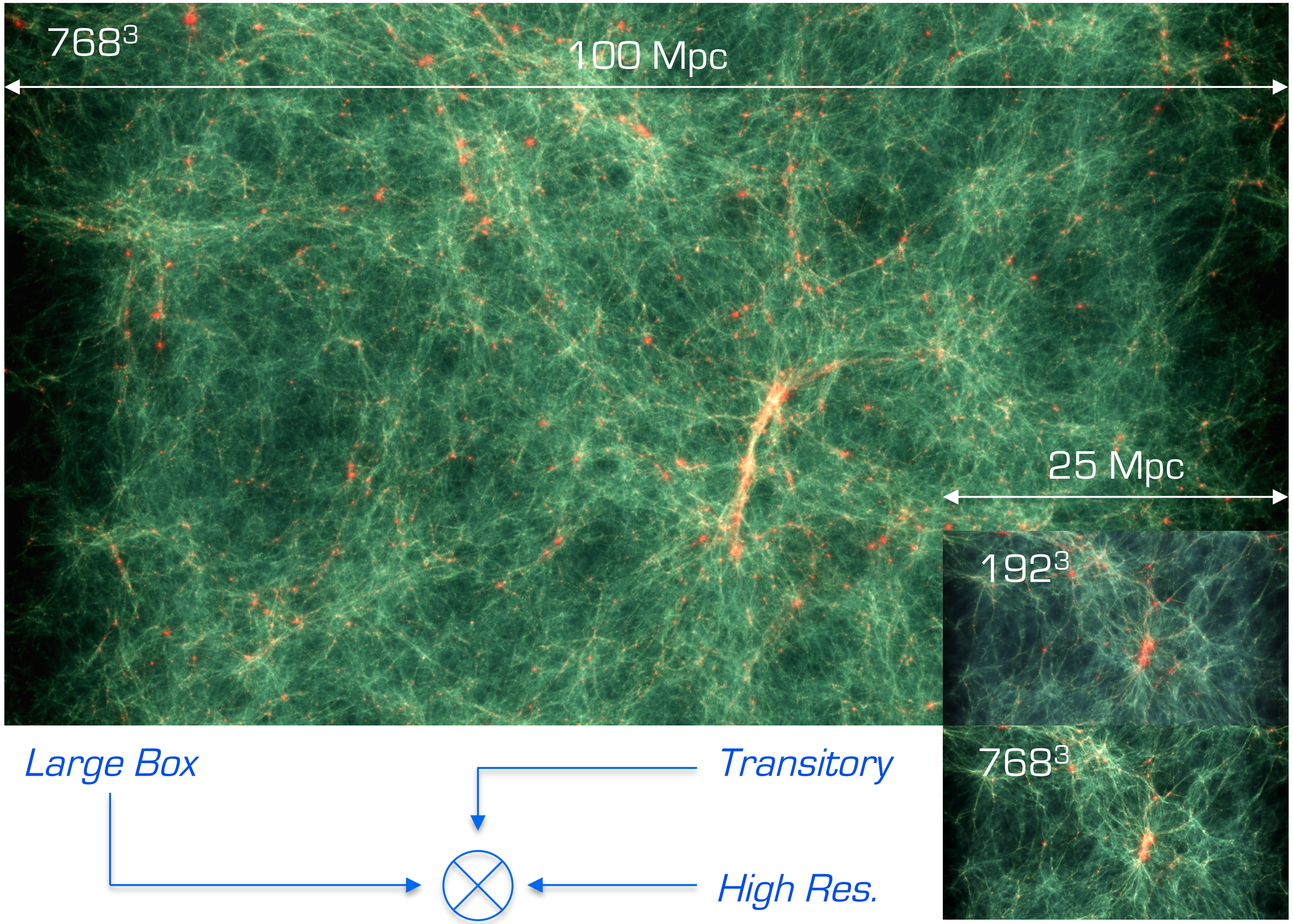
$$P_s = \left(\frac{k}{k_0}\right)^{n_s - 1 + \frac{1}{2} dn_s/d\ln k \ln(k/k_0)}$$

scalar power spectrum



Splicing Method

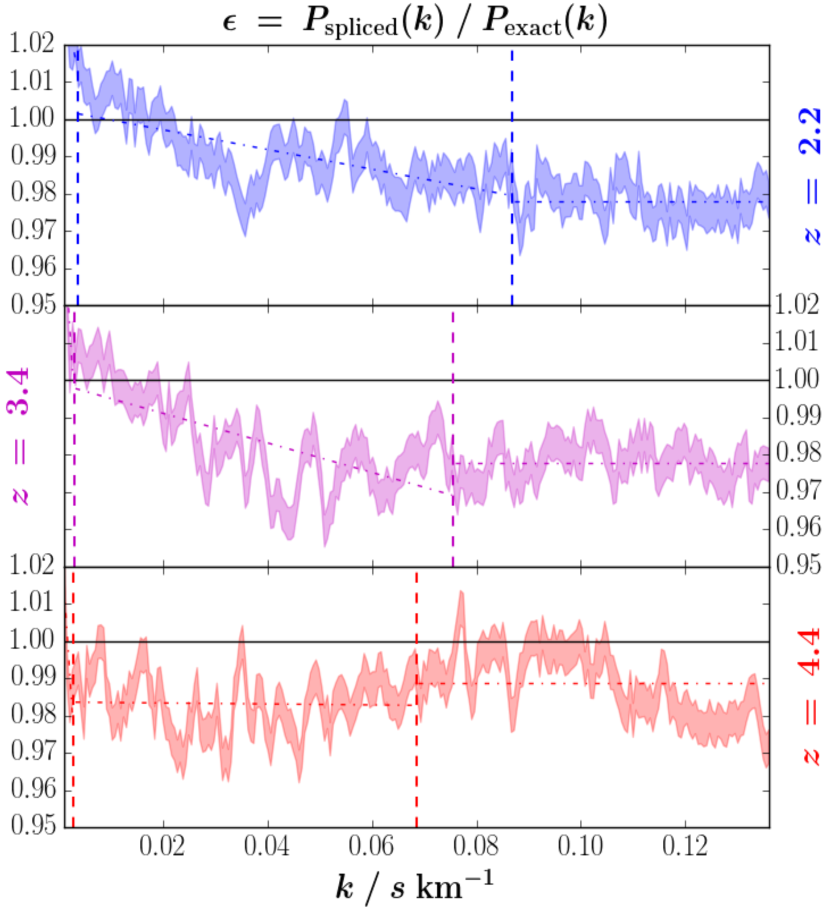
OMG !



Large Box — *Transitory* — *High Res.*

3072^3 particles per species
in $(100\ \text{Mpc})^3$ box

Residuals for N=2048 simulation



Simulation Parameters

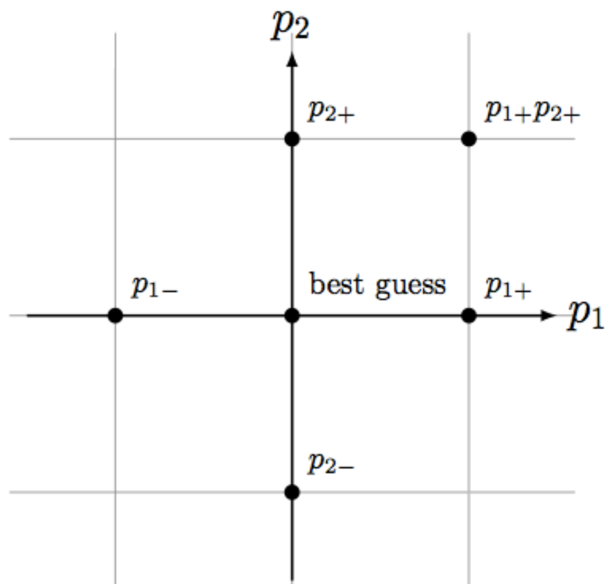
parameter	central	range
$1keV / m_X$	0.0	+0.2 +0.4
n_s	0.96	±0.05
Ω_M	0.31	±0.05
σ_8	0.83	±0.05
H_0	67.5	±5.0
$T_0(z=3)$	$14k$	$\pm 7k$
$\gamma(z=3)$	1.3	±0.3
A^τ	0.0025	±0.0020
η^τ	3.7	±0.4

Neutrino mass

Cosmology

Intergalactic Medium

Optical Depth (UV)



Grid of hydro simulations

55 for $\Sigma\, m_\nu$
55 for keV/m_x

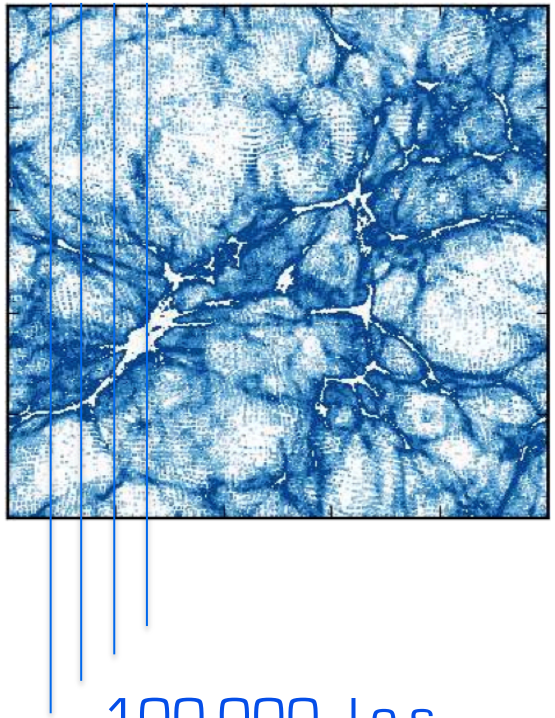
Nuisance Parameters

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

Fit in our likelihood computation

Constructing the simulated Lya PS

Gadget snapshot



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

12 z-bins in Lya 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) 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

N.Palanque-Delabrouille *et al.*, 2015 JCAP 011

Lya Power Spectrum

correlated SiIII−Lya absorption

window function

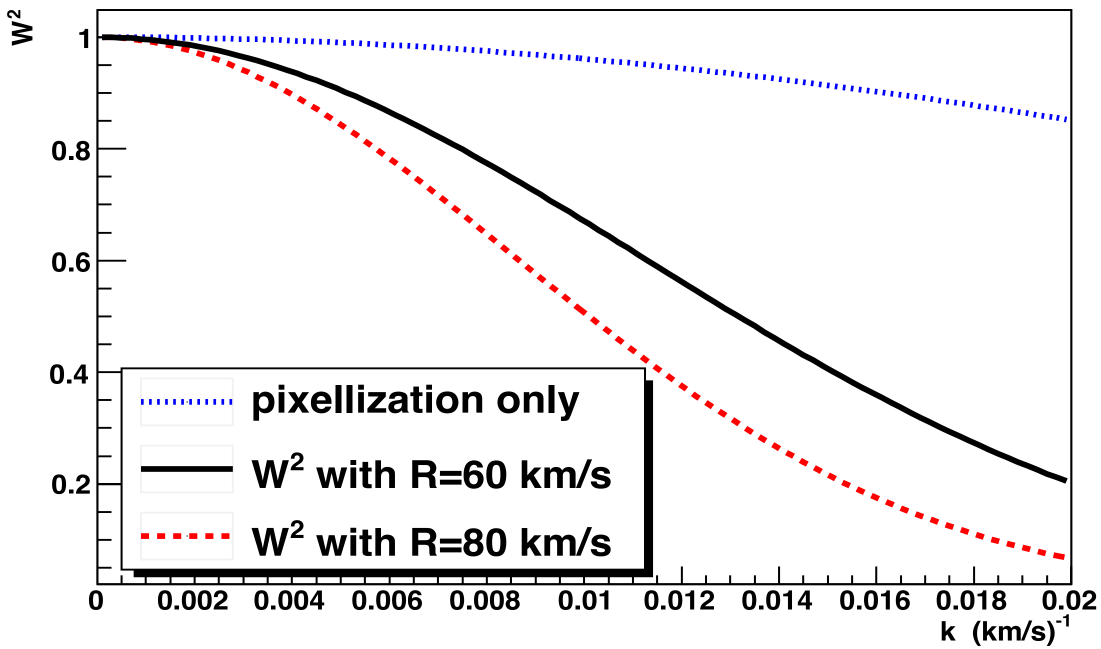
metals background

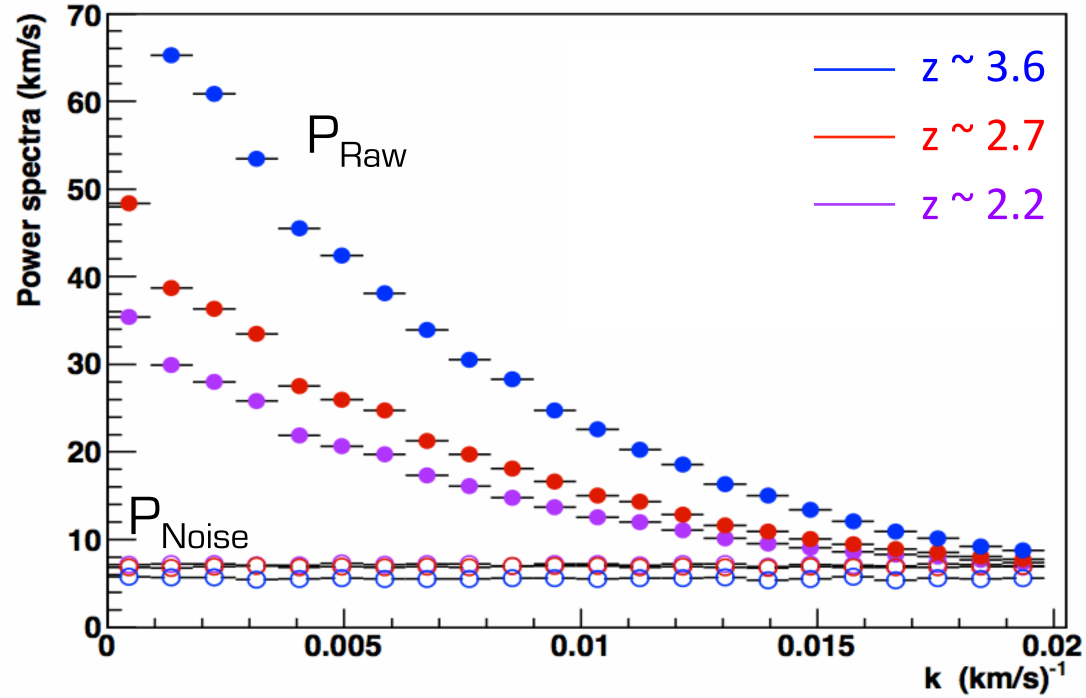
white noise

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

what we measure

what we want



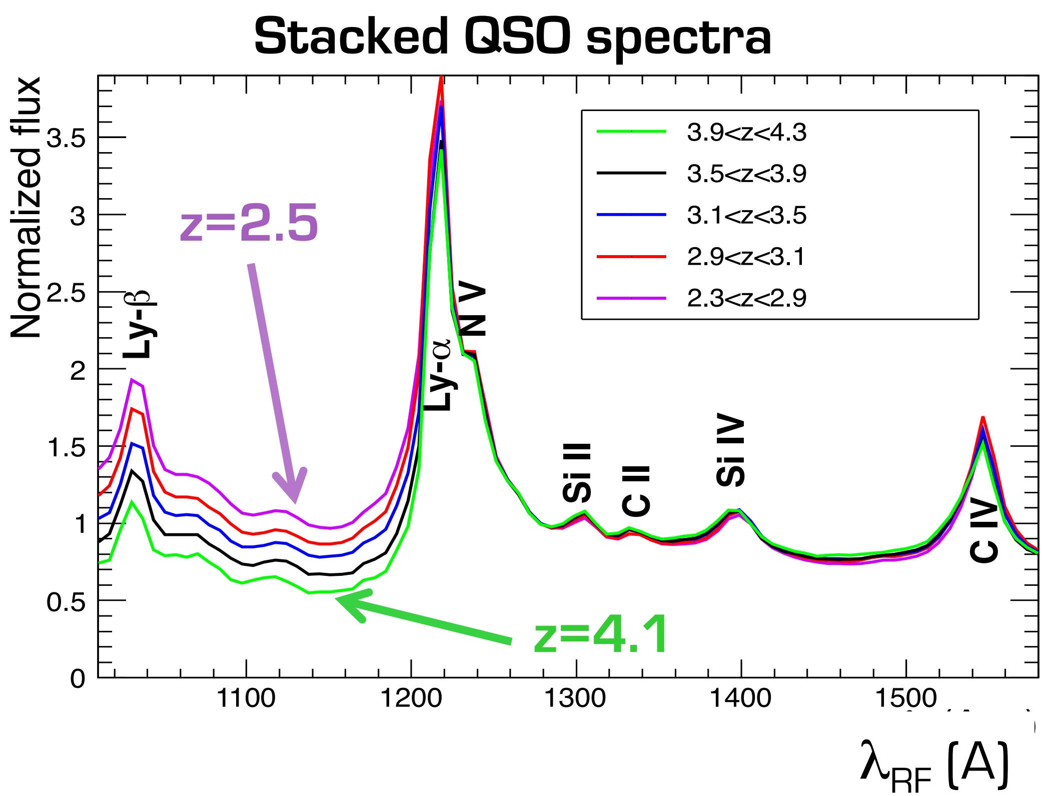


Sample

Palanque-Delabrouille *et al.*, 2013 A&A 559 A85

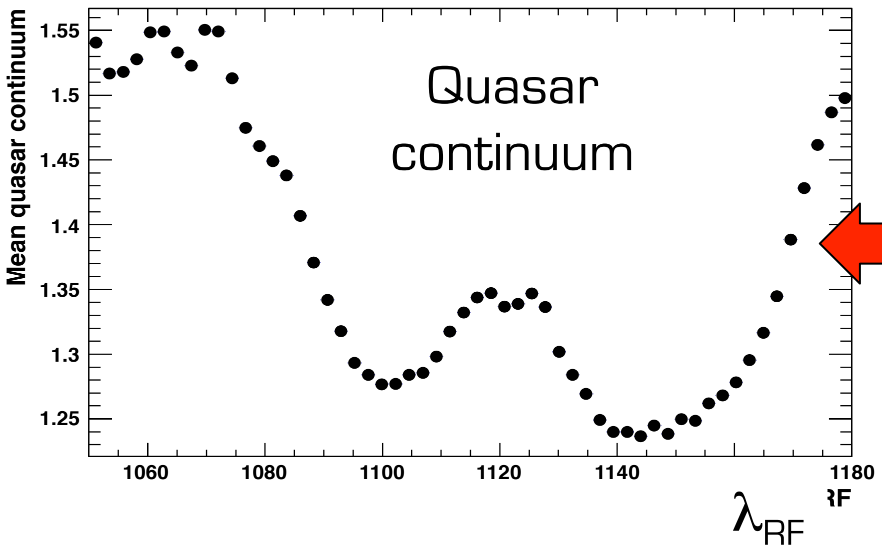
- 14,000 DR9 QSOs out of 60,000
- Selected for:
  - quality (no flagged pixels, no high density absorbers)
  - SNR > 2
  - resolution < 85 km/s

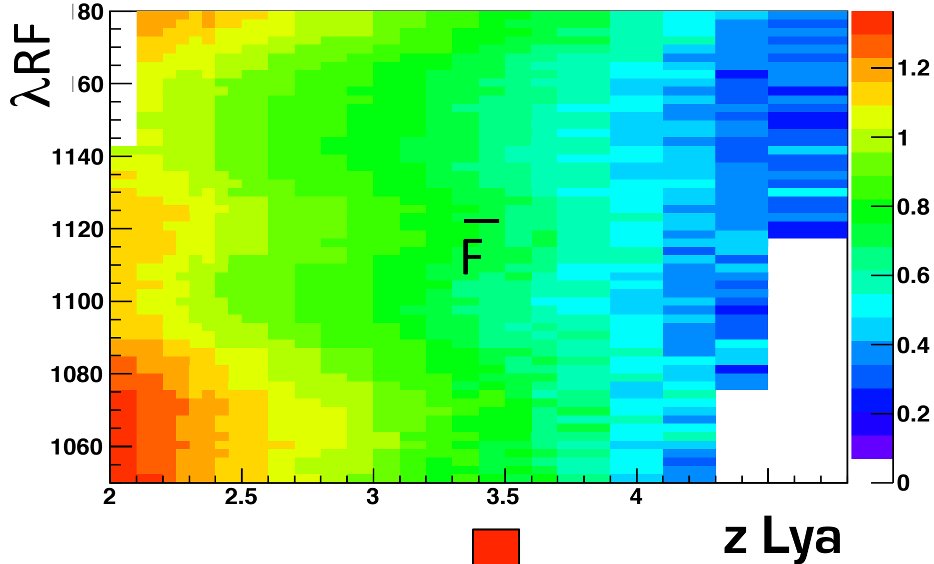
} to obtain $\sigma_{syst} \sim \sigma_{stat}$

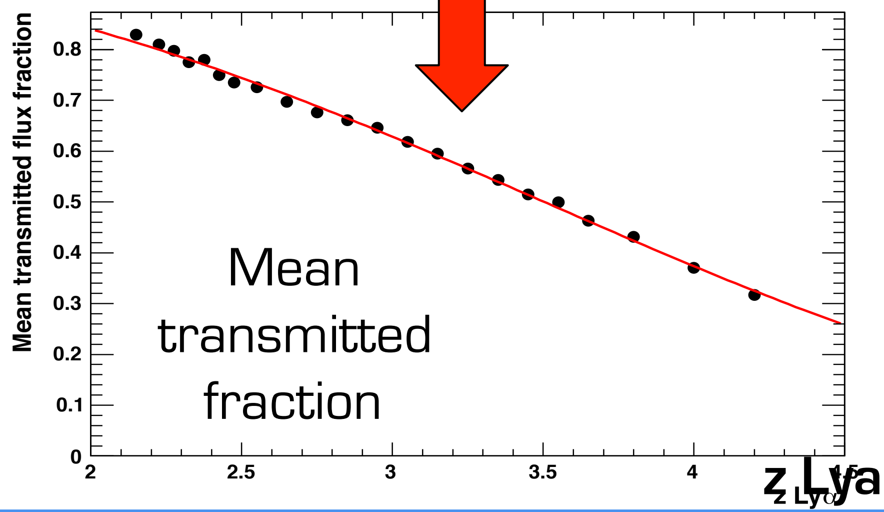


1D Power Spectrum

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







δ: normalized transmitted flux fraction