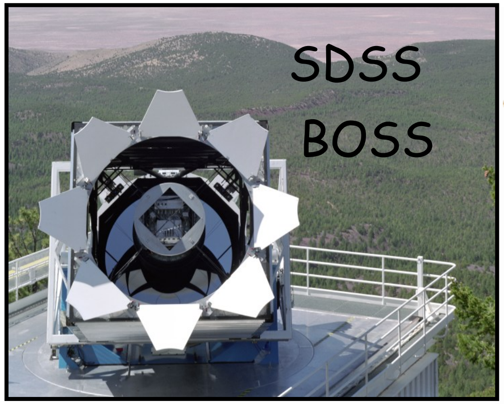
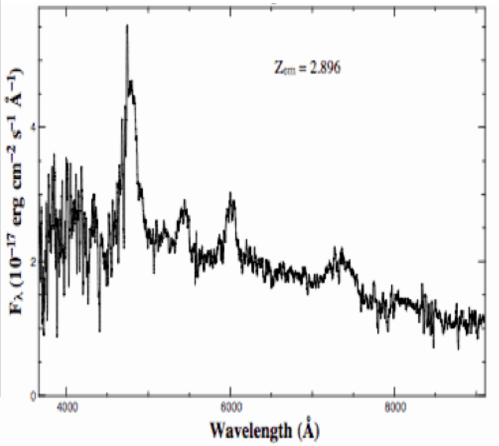
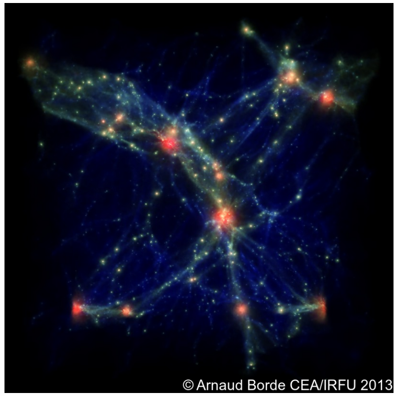
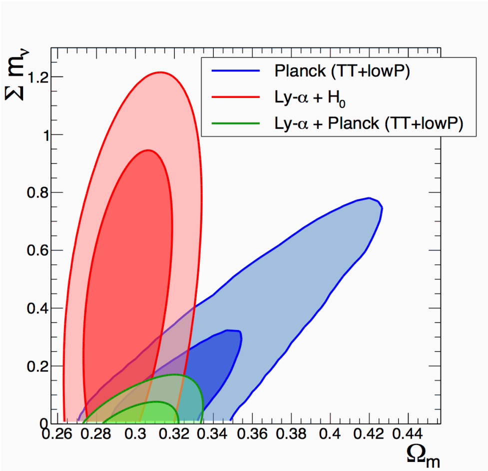
Neutrino mass and cosmology with Ly-α forests





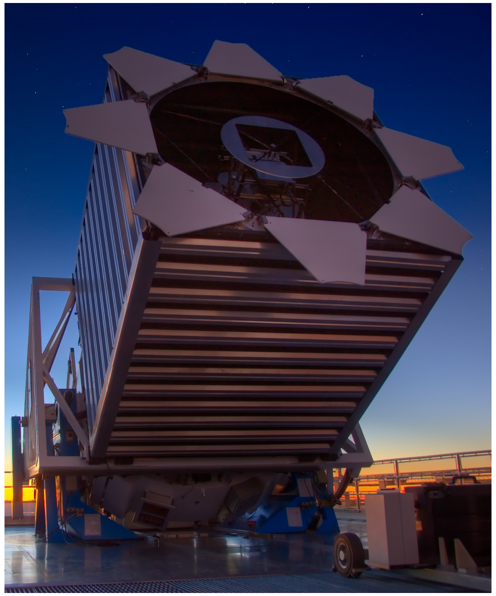




Christophe Yèche
CEA-Saclay Ifu

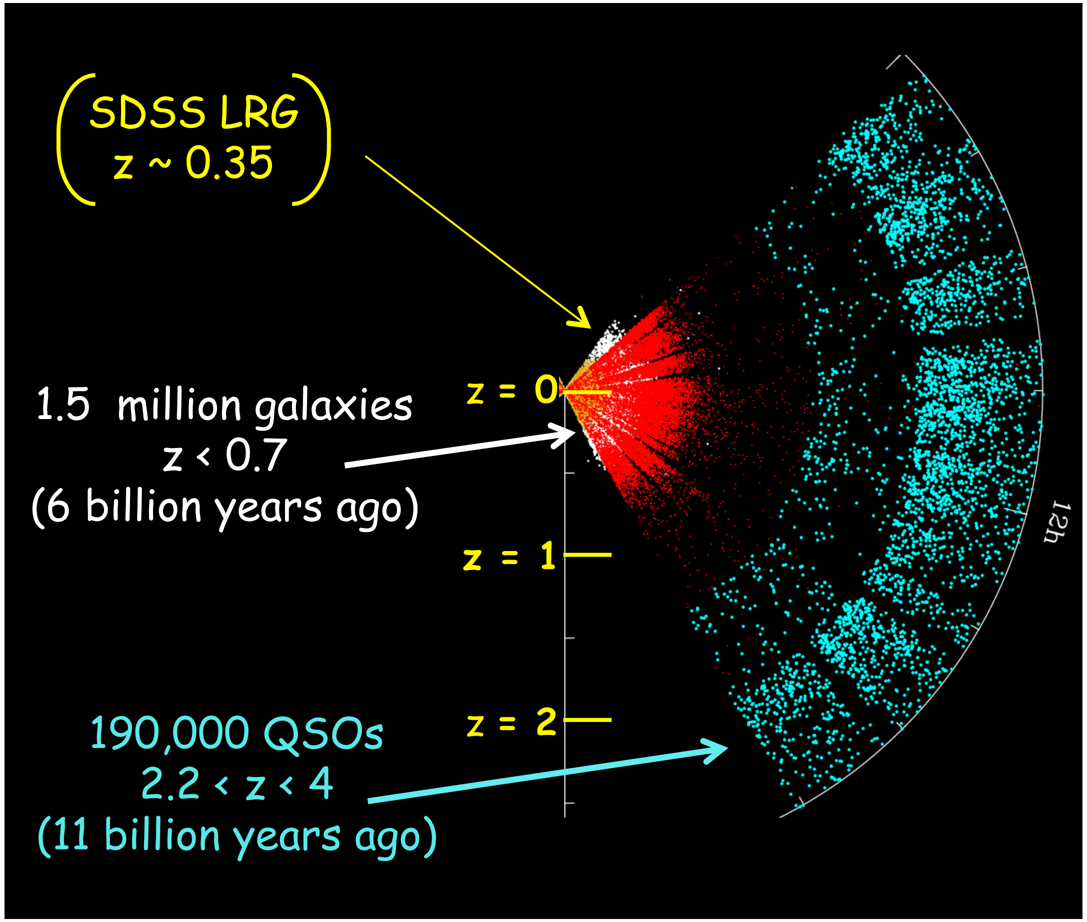
Texas Symposium, Geneva, December 15, 2015

SDSS BOSS/eBOSS



BOSS
2009-2014

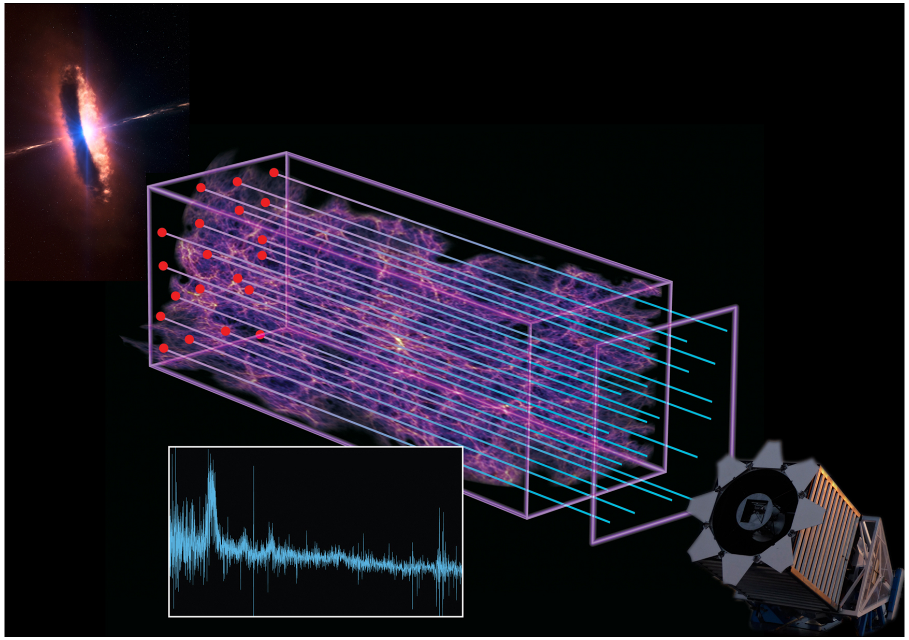
eBOSS
2014-2020



SDSS spectroscopic survey

- 2.5 m Sloan telescope (New Mexico)
- Survey area: 10,000 deg^2
- Redshifts: 1000 fibers

Ly-α forests, matter tracers

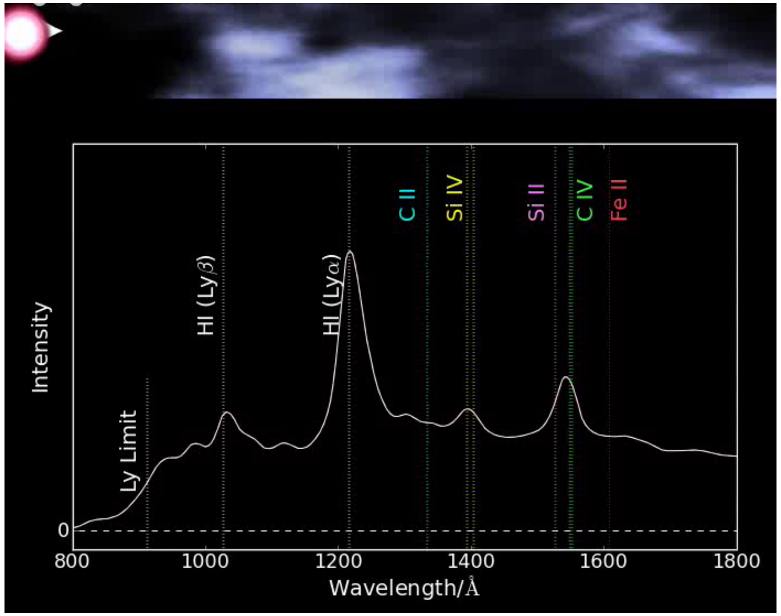


Principles

➢ Use Ly-α forests of quasars (2.2<z<4)

➢ HI absorption in IGM along the line of sight of QSOs

➢ We expect low density gas (IGM) to follow the dark matter density

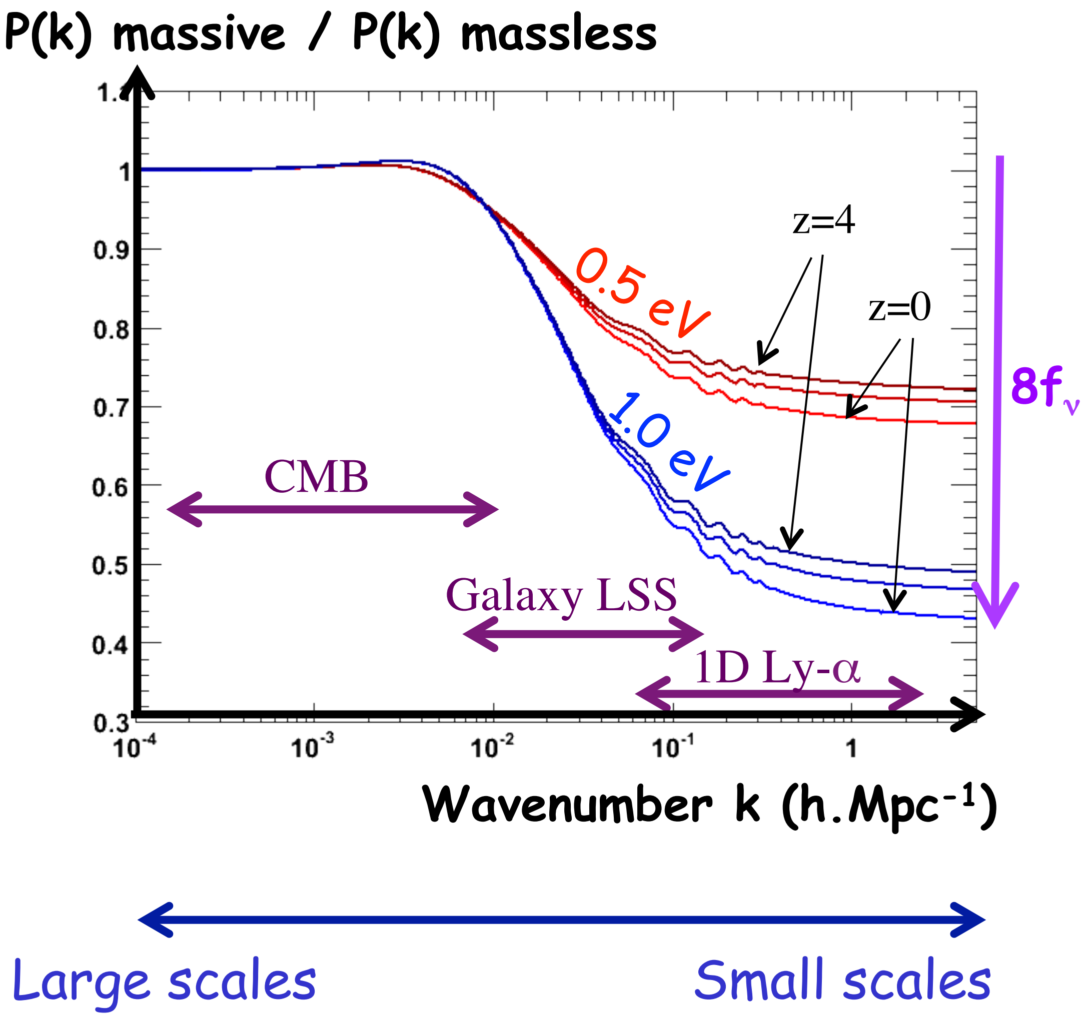


1D power spectrum

➢ Correlation between the pixels of a line of sight

➢ Proxy of the matter down to scale 1 Mpc

Impact of neutrino masses



- Free-streaming ⇒ suppression of small scales
- Suppression factor ⇔ Σm_ν
- Independent measurements (CMB, Galaxies, 1D Ly-α)
- Suppression is z-dependent

Ly-α:
- Access to small scales (max effect) +
- Large z-range [2.1 ; 4.5] +
- Caveat: non-linear regime and power spectrum of flux (not mass density) —

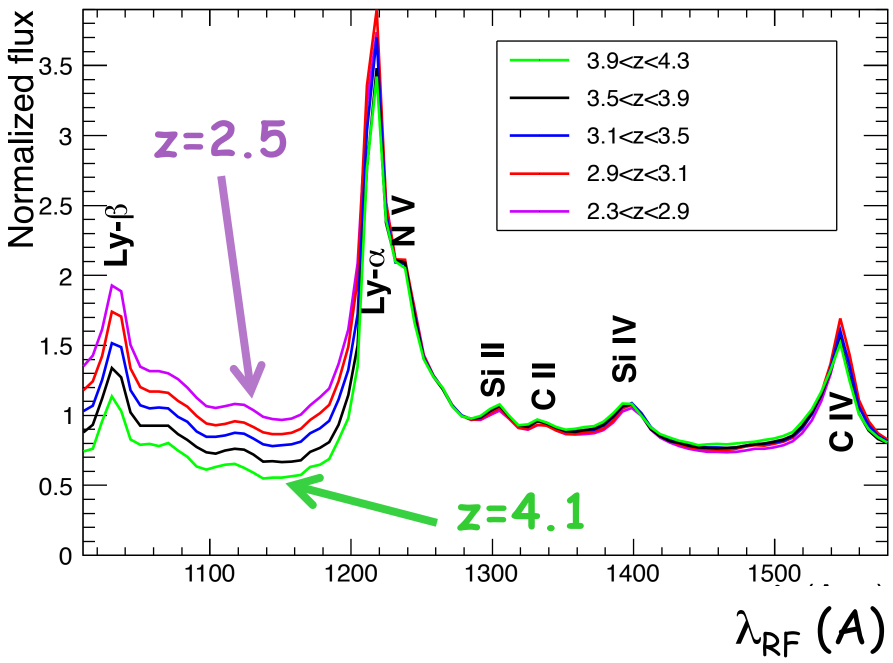
⇒ **Hydro/N body simulations**

Ly-α forests in BOSS

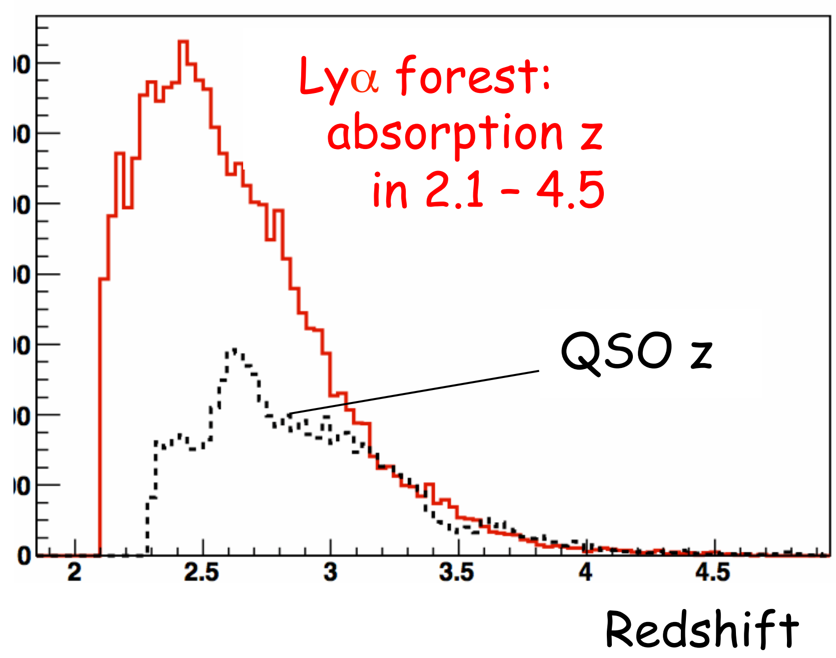
- 14000 DR9 QSOs out of 60000
- Selected for
  - quality (no flagged pixels, no high density absorbers)
  - SNR > 2
  - resolution < 85 km/s

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

Stacked QSO spectra



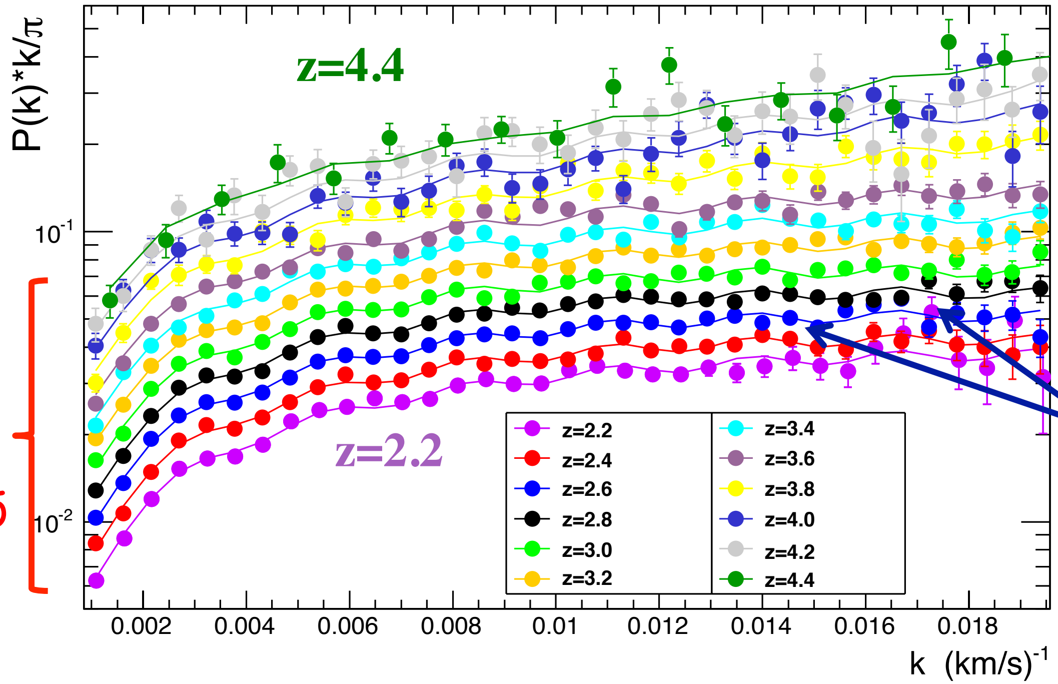
Redshift distribution



Palanque-Delabrouille., Yèche, Borde et al. (2013)

1D Power Spectrum

12 slices in redshift from 2.1 to 4.5



Wiggles: Lya-SiIII correlations

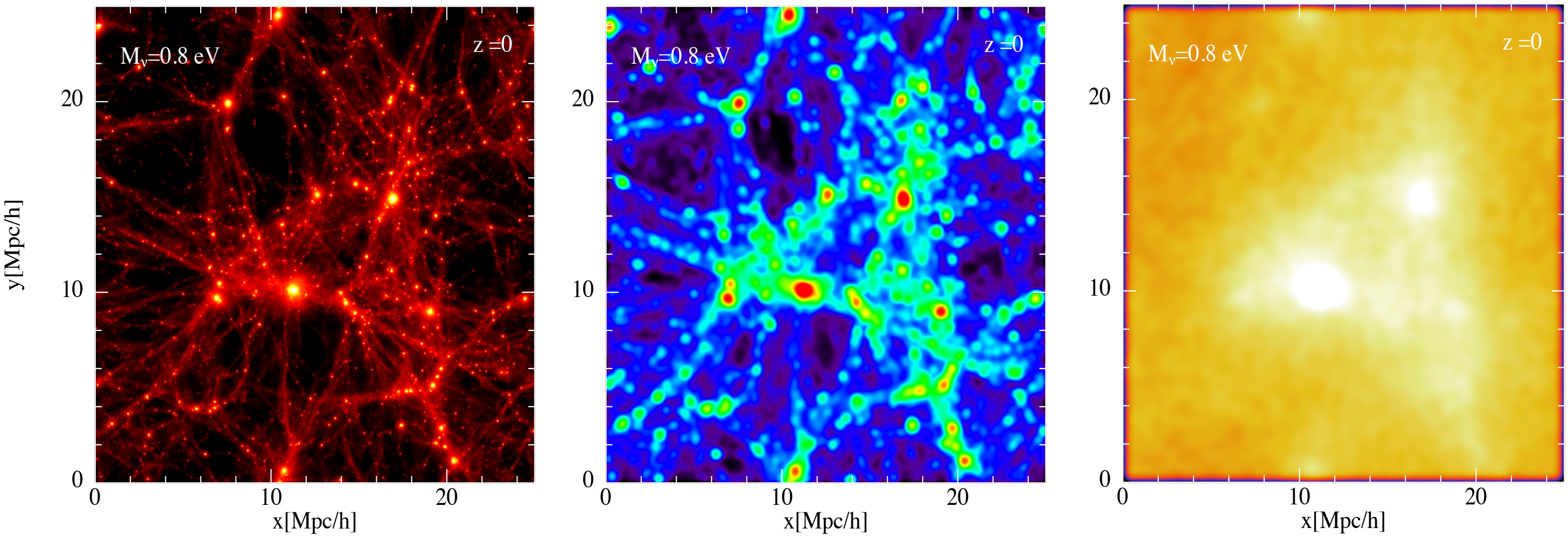
- Detailed study of spectrograph resolution, noise, lines of sky, correlation with other absorbers…

- Need simulations to come back to linear matter power spectrum

Hydro-dynamical simulations

- **3 Species:** dark matter + baryons + 3 degenerate-mass neutrinos
- **Methodology:**
  - Linear (CAMB) to z=30
  - Simulations from z=30 to z=2.0
  - Hydro/N-body simulations

Baryons **Dark matter** **Neutrinos**



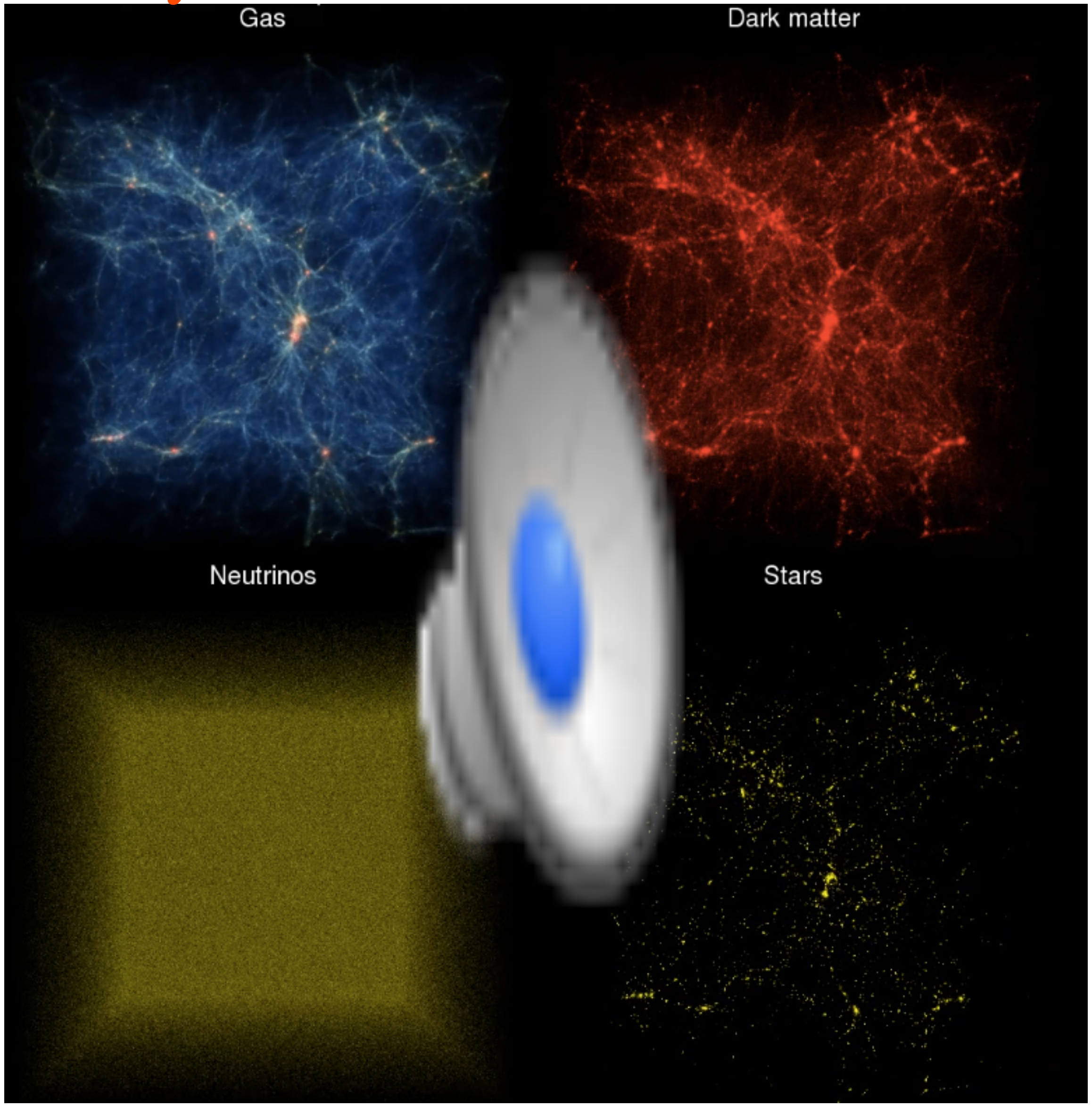
@ G. Rossi

Hydro-dynamical simulations

$z = 15 \rightarrow 0$

3 species
- Baryons
- Dark matter
- Neutrinos

Stars formed from baryons



Borde et al. (2014)
Rossi et al. (2014)

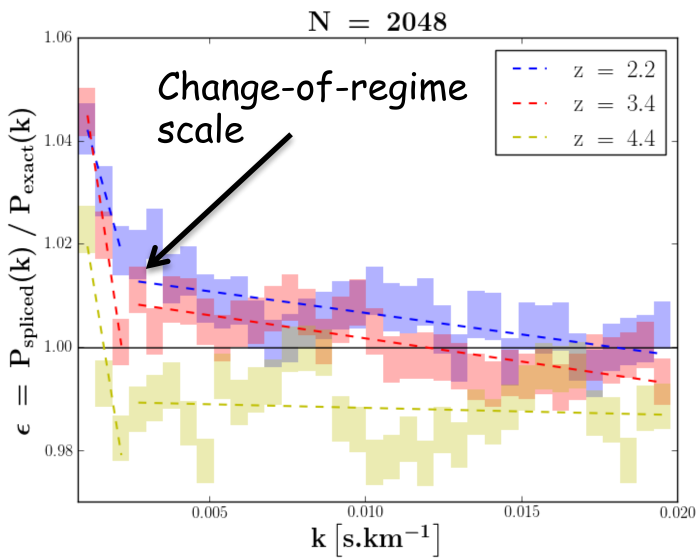
Splicing technique

(McDonald, 2003)

Combine large box & high resolution (using a transition simulation)

(100 Mpc.h^{-1}, 768^3) (25 Mpc.h^{-1}, 768^3) (25 Mpc.h^{-1}, 192^3)

⇔ equivalent to **100 Mpc.h^{-1}** with **3072^3** particles per species



- Comparison with high resolution simulation
  ~1% agreement
- Broken-line model with 2 free nuisance parameters

Grid parameter space

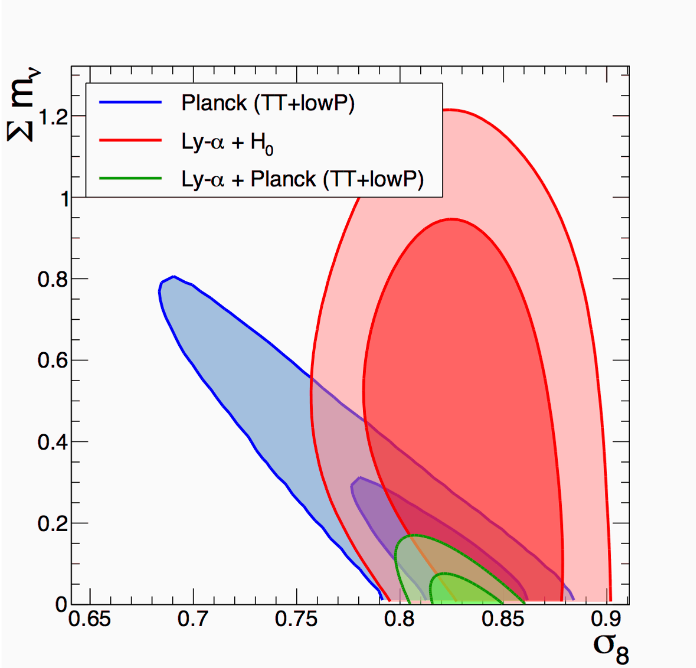
- **Grid of simulations**
  → 2nd-order Taylor expansion for cosmo & astro parameters centered on Planck (2013)

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

Parameter	Central value	Range	
n_s	0.96	± 0.05	Cosmology
σ_8	0.83	± 0.05	Cosmology
Ω_m	0.31	± 0.05	Cosmology
H_0	67.5	± 5	Cosmology
$T_0(z=3)$	14000	± 7000	IGM
$\gamma(z=3)$..	1.3	± 0.3	IGM
A^τ	0.0025	± 0.0020	Optical depth
η^τ	3.7	± 0.4	Optical depth
$\sum m_\nu$ (eV)	0.0	0.4, 0.8	Neutrino

- 36 simulations + 3 normalizations (+ numerous sanity checks)
- **>4Mhrs CPU** at TGCC CURIE supercomputer
- **23 nuisance parameters** (Resolution, Noise, UV fluctuations, AGN or SN feedback, DLA and splicing)

Constraint on Σm_ν



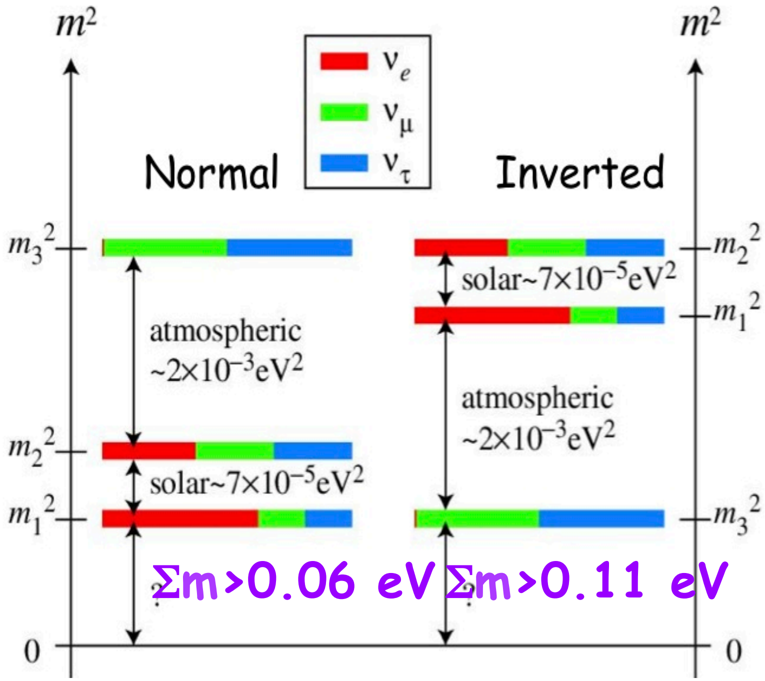
Limits:

- With Ly-α alone:
  Σm_ν < 1.1 eV @95%CL
- With Planck 2015 alone:
  Σm_ν < 0.72 eV @95%CL
- Combined with CMB (Planck 2015)
  Σm_ν <0.12 eV @95%CL

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

Palanque-Delabrouille , Yèche, Lesgourgues et al. (2014) and (2015)

Neutrino mass hierarchy

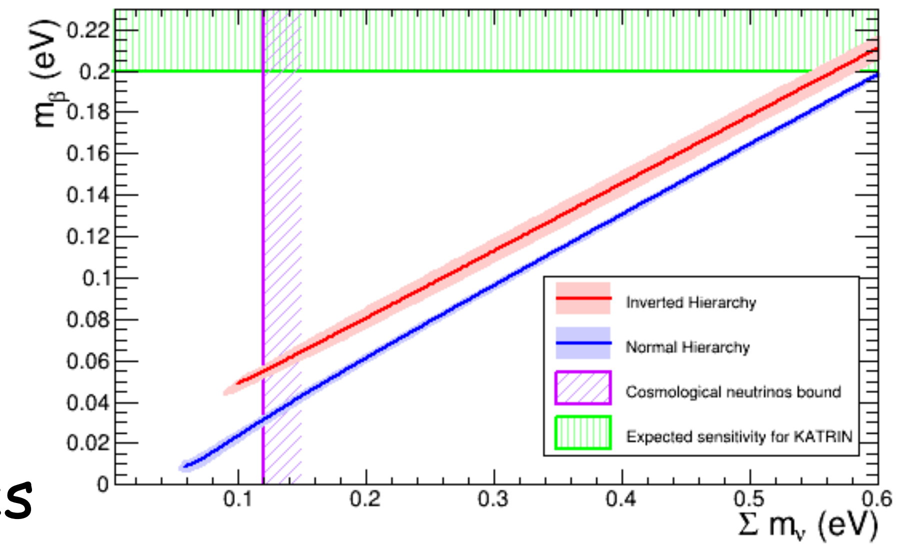


- Direct measurement with tritium β-decays: $^3H \longrightarrow {}^3He + e^- + \nu_e$

  → Current limits m_β <2eV
  → Sensitivity of 0.2 eV in near future (KATRIN experiment)

- Complementary with cosmology

With Σm_ν < 0.12 eV @95%CL



- NH is "favored"
- If disagreement with KATRIN experiment

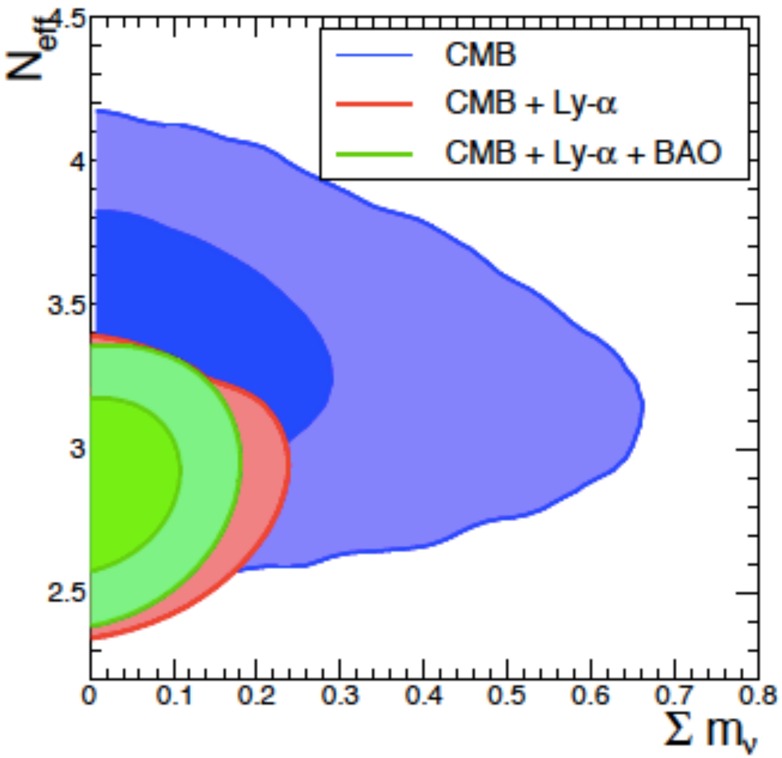
⟹ Indication of new physics

Dark radiation - N_{eff}

$$\rho_{\rm R} = \rho_\gamma + \rho_\nu = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

Sensitivity to the number of neutrino species

- Full degeneracy in Ly-α data alone
- Constraint when combining Ly-α and CMB (Planck 2013)



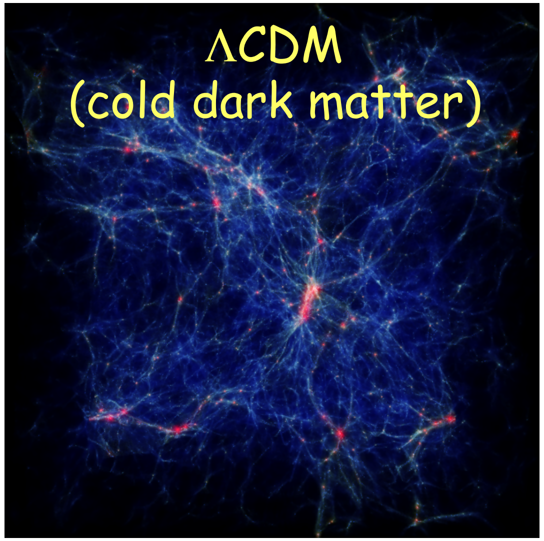
$N_{eff} = 2.91\ ^{+0.21}_{-0.22}$ (95% CL)

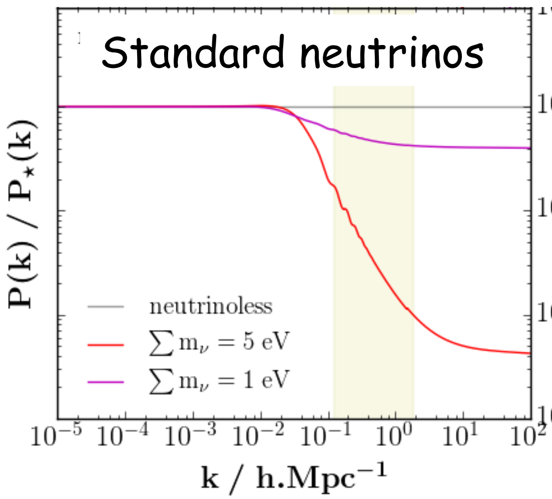
$\Sigma m_\nu < 0.15$ eV (95% CL)

$\Rightarrow N_{eff} = 4$ excluded at $> 5\sigma$

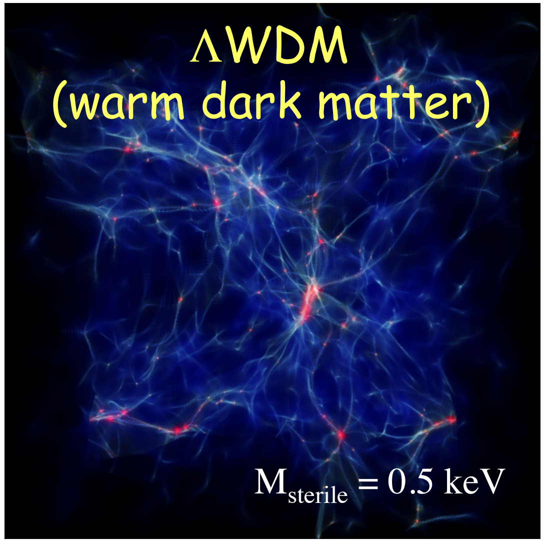
Rossi , Yèche, et al. (2015)

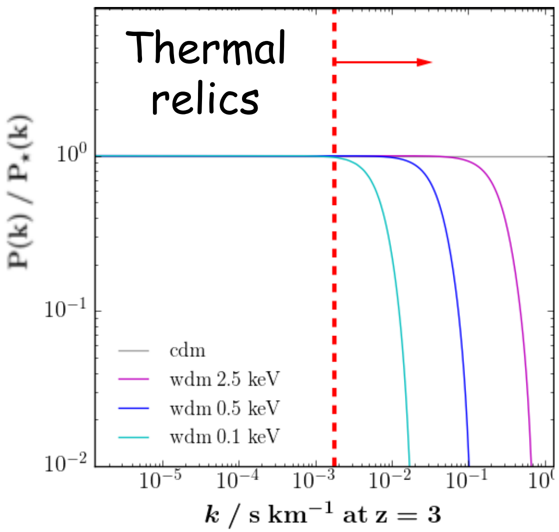
WDM: Thermal relics





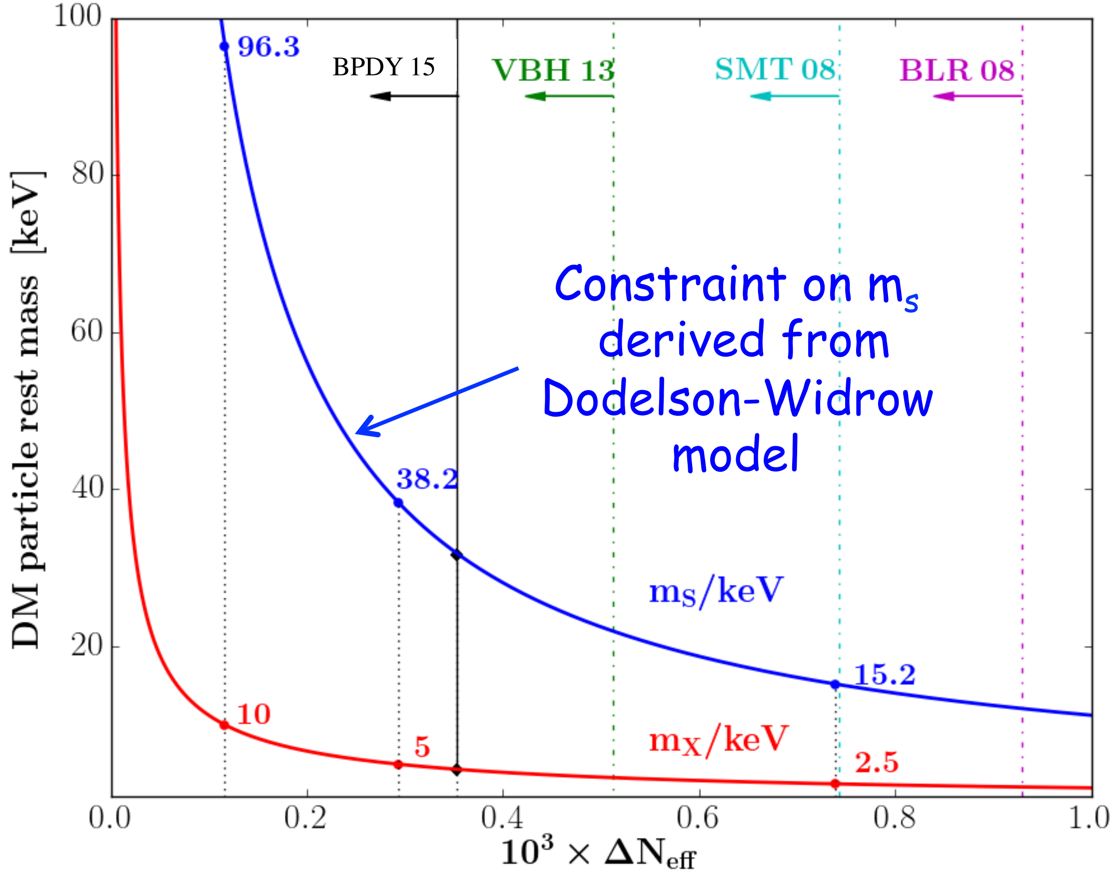
- All dark matter is WARM
- Add sterile neutrinos in hydro simulation grid





- Lack of power on small scales
- Detectable in BOSS if significant effect, i.e., if m_x small

Sterile Neutrino?



(Baur, Palanque-Delabrouille, Yèche et al. (2015))

95% CL from BOSS Lya

$m_X \geq 4.35$ keV

$m_s \geq 31.7$ keV

Boyarsky, Lesgourgues, Ruchayskiy
$m_s \geq 12.1$ keV
(WMAP-5 &SDSS)

Seljak, Makarov, Trac
$m_X \geq 2.5$ keV
(SDSS Ly-a)

Viel, Bolton, Haenelt
$m_X \geq 4.0$ keV
(HIRES & SDSS)

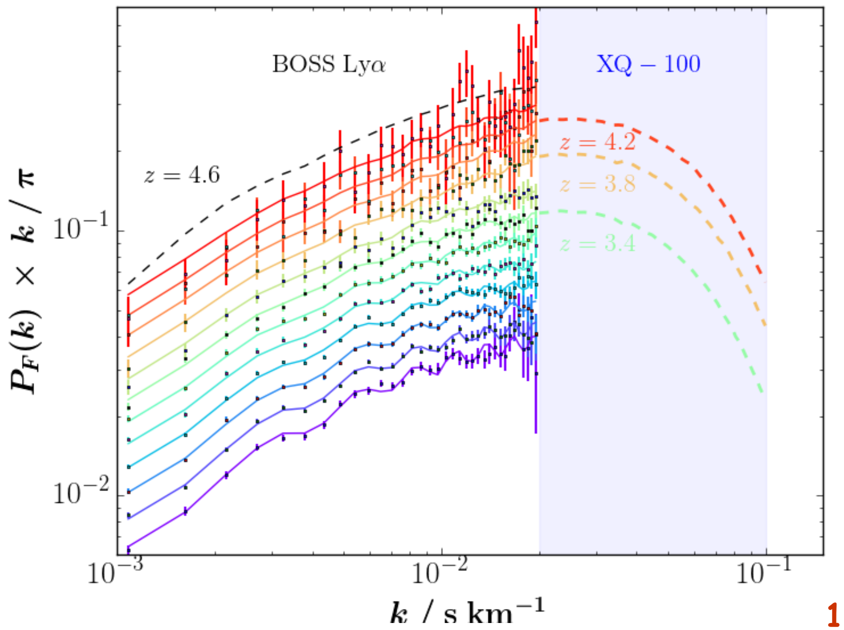
Strong limit on pure WDM model
in case of non-resonantly produced neutrinos

Conclusions

- High potential of Lyα forest on (n_s, σ_8, Ω_m, H_0, Σm_ν)
  - Sum of neutrino masses $\Sigma m_\nu < 0.12$ eV (95% CL) from Lyα+CMB

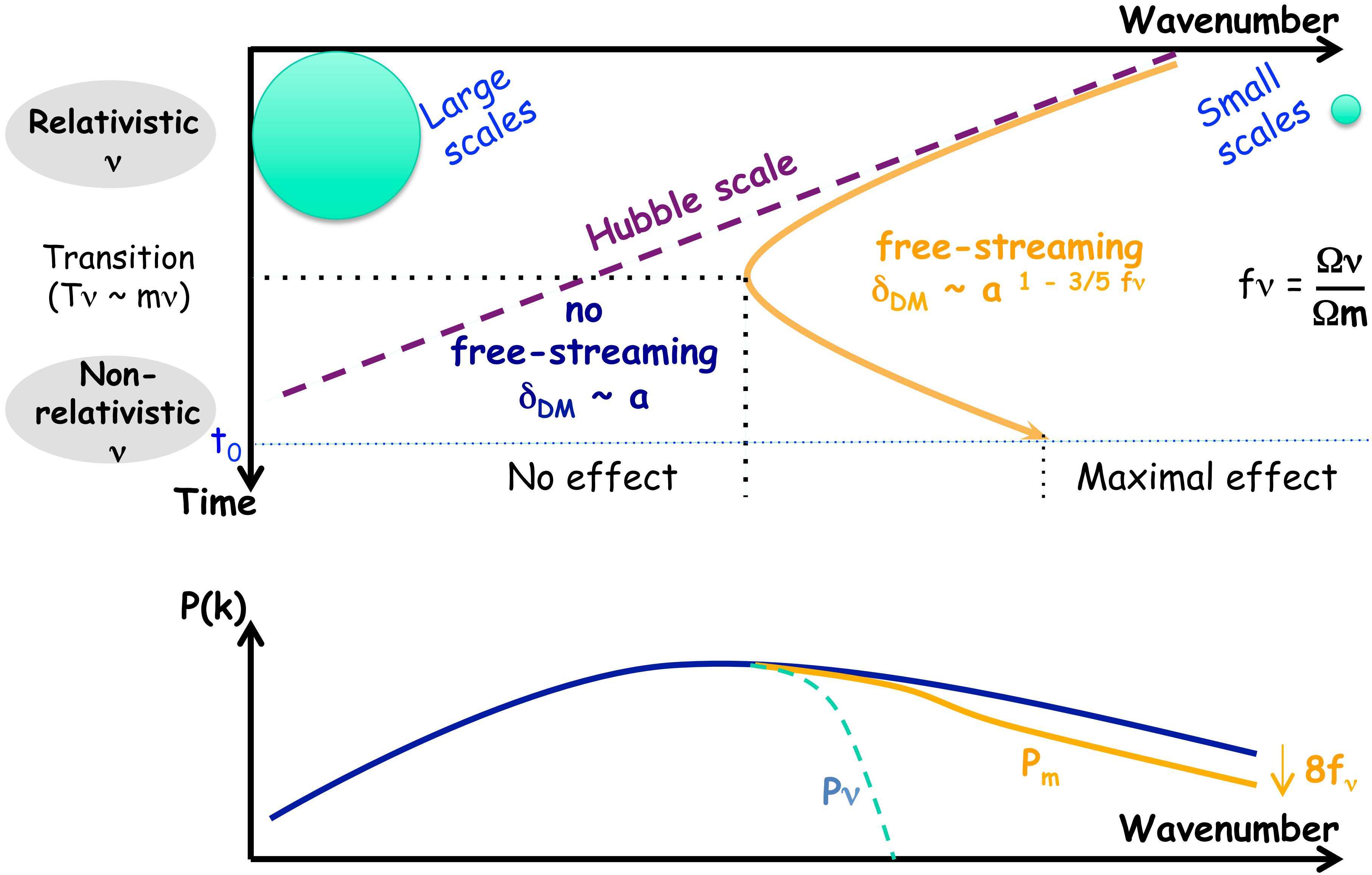
- Constraint on sterile neutrinos from Lyα
  - $m_{sterile} > 31.7$ keV (95% CL) in case of non-resonantly produced neutrinos with Dodelson-Widrow model

- Prospects
  - Lower statistical uncertainties (high z): BOSS DR12 + eBOSS
  - High resolution spectra VLT (X-shooter) XQ100

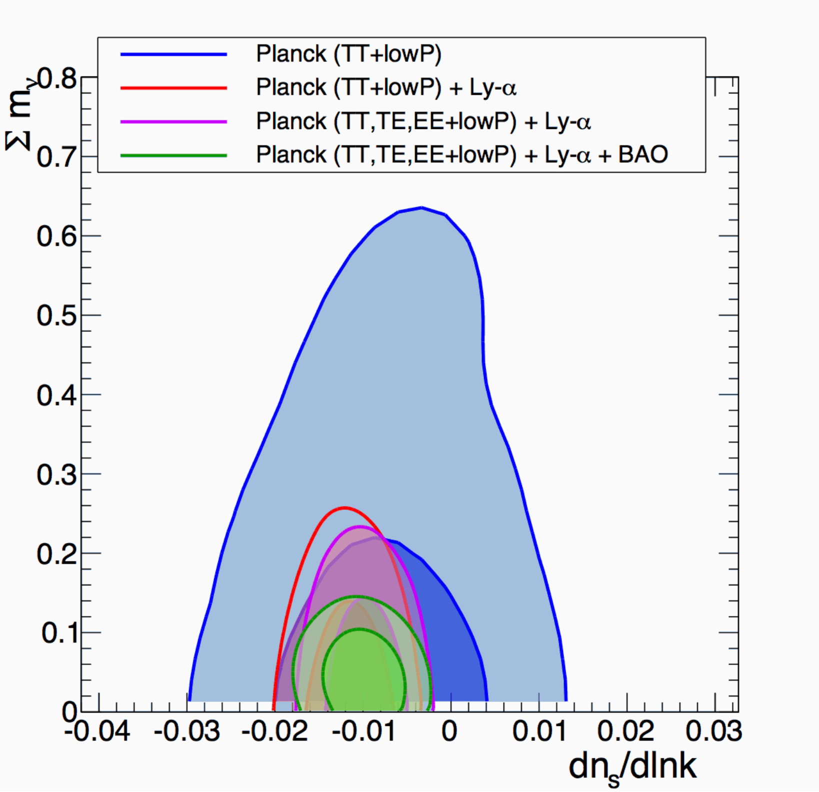


Additional Slides

Neutrino mass and large-scale structures



Relaxing the tilt of the primordial spectrum



Running of n_s ($dn_s/d\ln k$)

Similar value of running for Planck & for Planck + Lyα

Similar constraints on Σm_ν letting running of n_s free

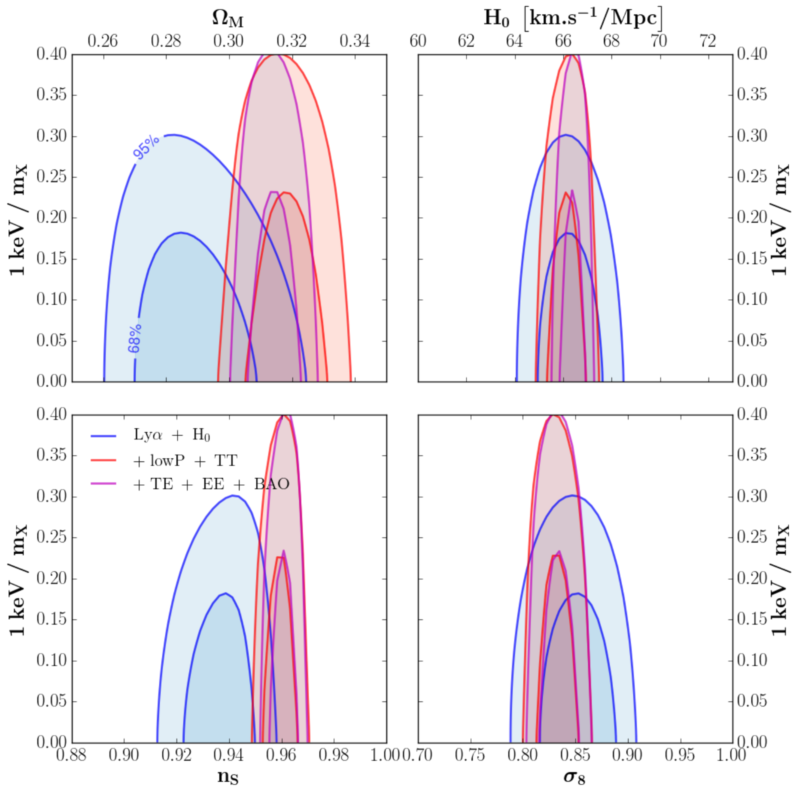
$\Rightarrow$ Negligible impact on Σm_ν of tension on n_s and improvement of χ^2 by ~11

Σm_ν < 0.20 eV 95%CL (TT+lowP + Lyα)

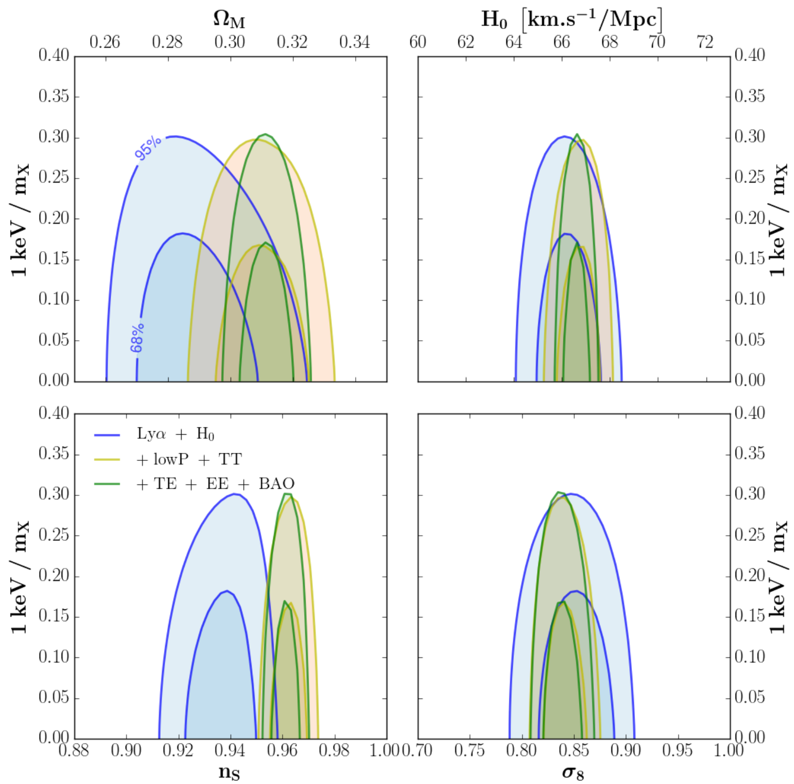
Σm_ν < 0.12 eV 95%CL (TT+lowP + Lyα +BAO + EE+TE)

Sterile neutrinos

Data set	Lower bound on $\frac{m_X}{keV}$ $\left(\frac{m_s}{keV}\right)$	
Ly-α + H_0 ($z < 4.5$)	4.35 (31.7)	
Ly-α + H_0 ($z < 4.1$)	3.10 (20.2)	
	no running	with running
Ly-α + Planck (TT + lowP)	3.27 (21.7)	4.55 (33.7)
Ly-α + Planck (TT + lowP+ TE + EE) + BAO	3.18 (21.0)	4.42 (32.5)



Without running of n_s



With running of n_s