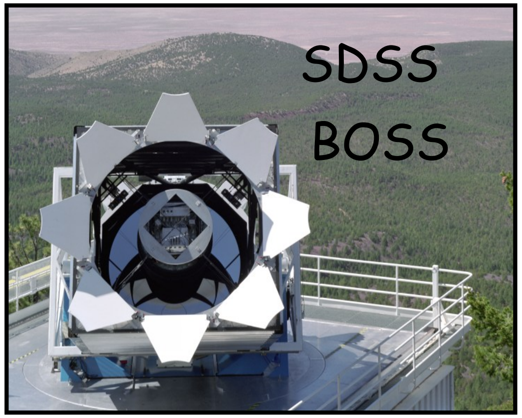
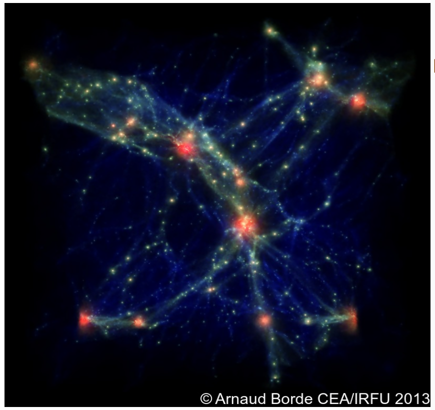
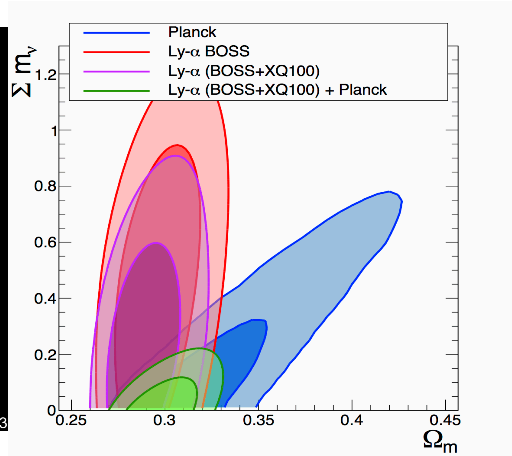
Neutrino mass and Warm Dark Matter in cosmology





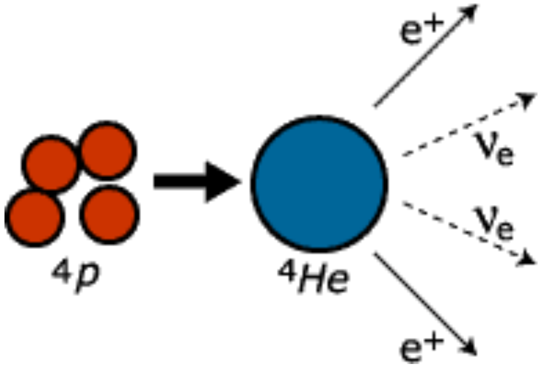


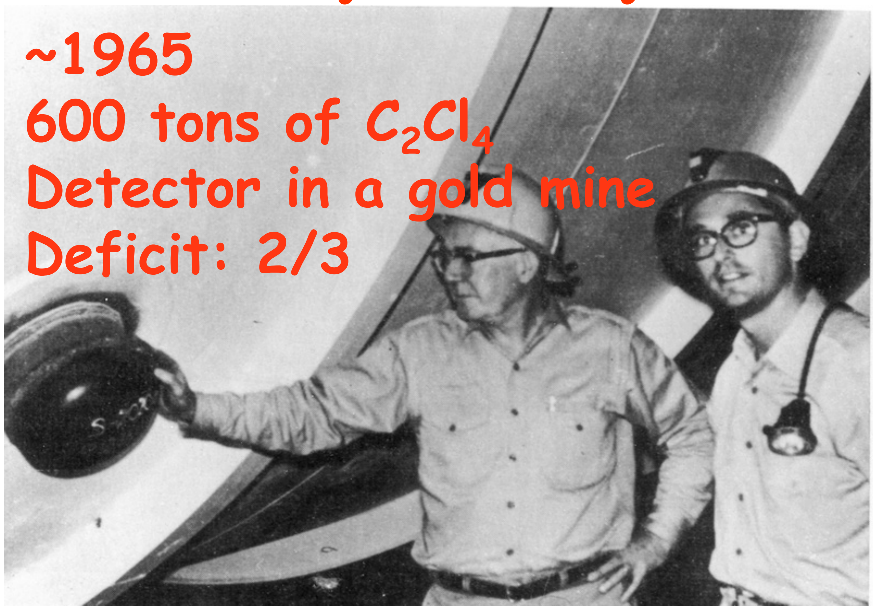
Christophe Yèche
CEA-Saclay Irfu

Séminaire IHPC, November 10, 2017

Brief introduction on neutrino mass

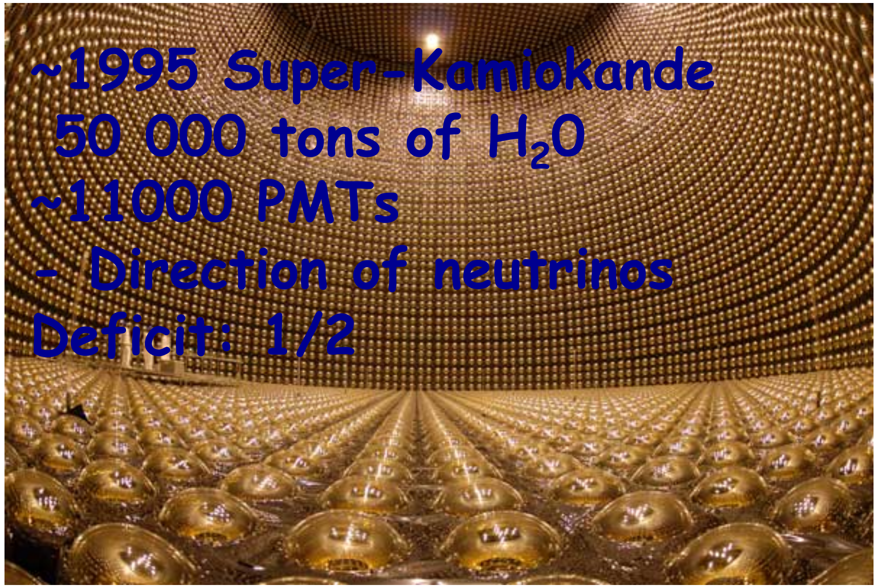
Solar neutrinos - Mystery



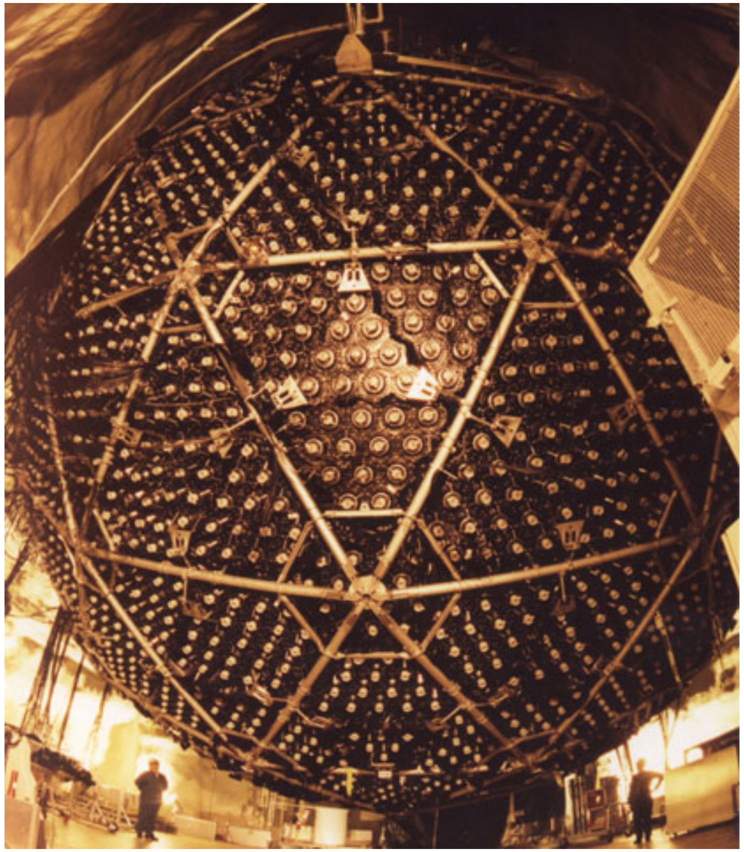


Fusion reaction:

- Sun: Astrophysical source
- Well constrained by models proposed by J. Bahcall
- Discrepancy between theory and experiment for ~35 years



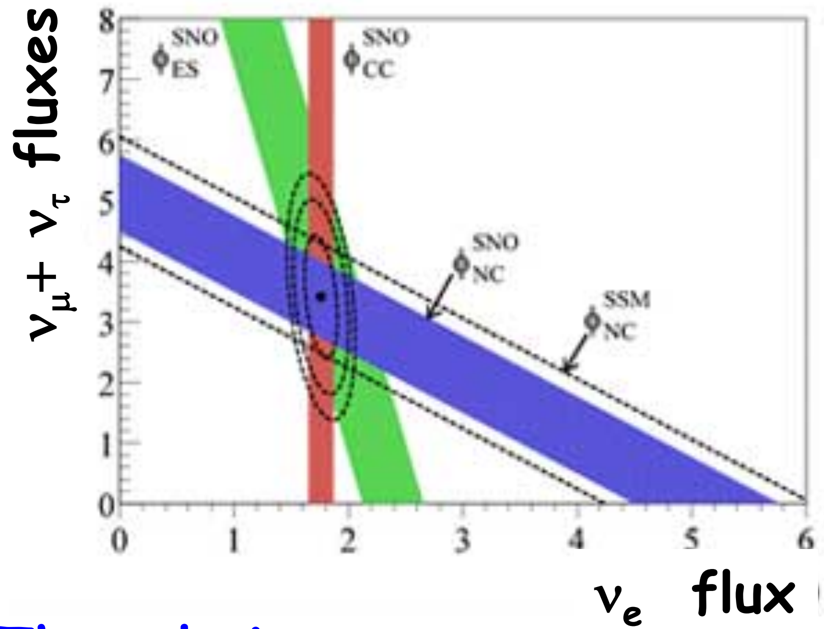
Solar neutrinos- the solution



2001 SNO
1000 tons of D_2O
10000 PMTs

SNO sensitive to the 3 species of neutrinos

→ Confirmation of the deficit
→ Only 1/3 of the ν_e arrive on earth
→ Observe two other species



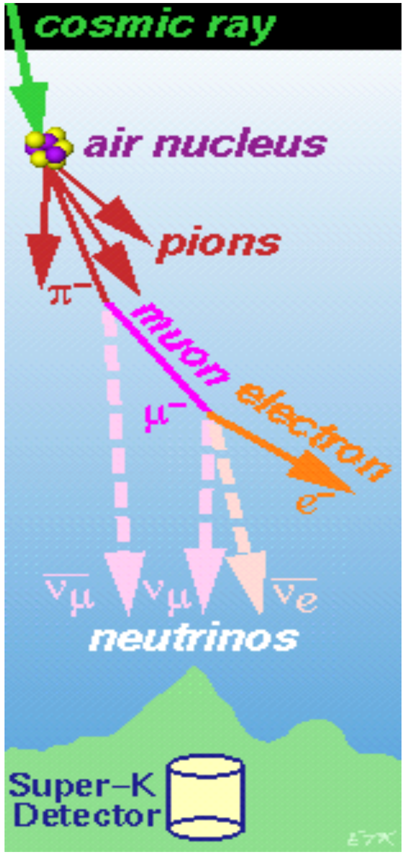
The solution

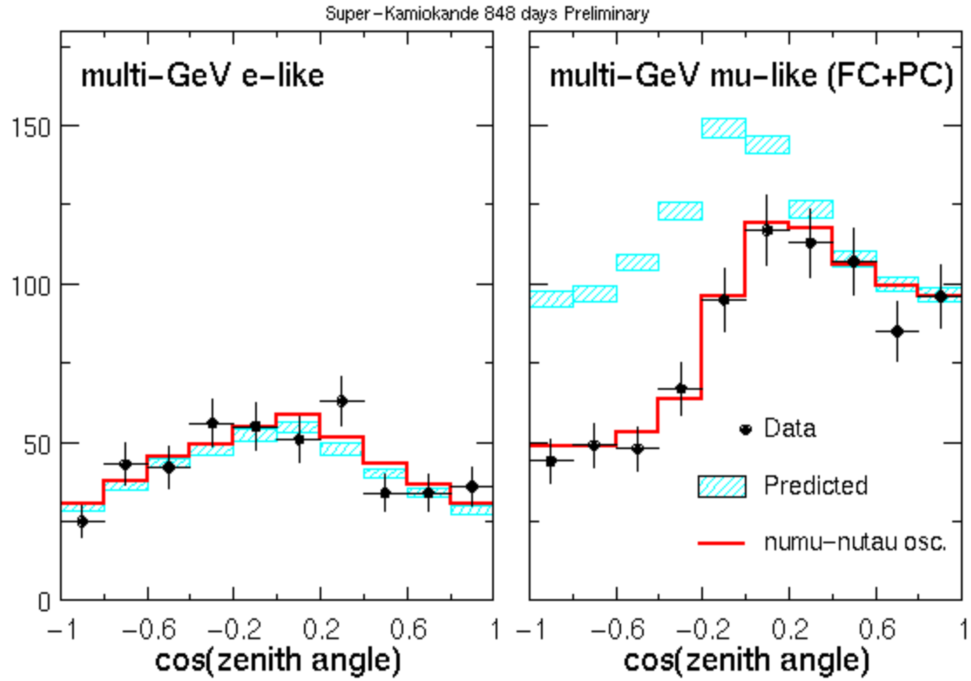
→ Neutrinos oscillations $\nu_e \longrightarrow \nu_\tau$, $\nu_e \longrightarrow \nu_\mu$
→ the solar model works!

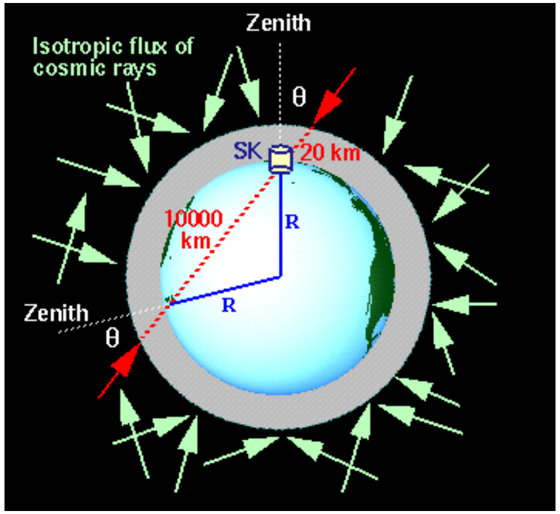
Consequence

→ The neutrinos have a mass!!!

Atmospheric neutrinos







In 1998 new discovery of Super-Kamiokande

- Deficit of ν_μ compared to model
- Longer is the ν_μ flight larger is the effect
- The solution: neutrino oscillations

$$\nu_\mu \longrightarrow \nu_\tau$$

Neutrino masses

Neutrino oscillations

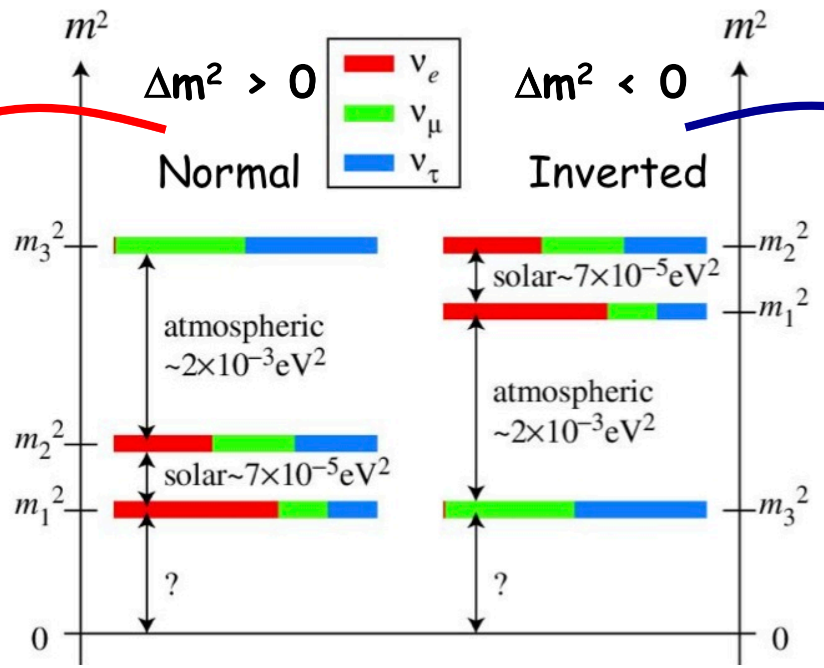
Mass eigenstates $m_{1,2,3}$ and flavor eigenstates $m_{e,\mu,\tau}$

Solar	$\delta m^2 = m_2^2 - m_1^2$	$\sim 7.5\ 10^{-5}\ eV^2$
Atmospheric	$\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$	$\sim 2.4\ 10^{-3}\ eV^2$

→ No constraint on absolute masses

→ 2 schemes (sign of Δm^2)

$\Sigma m > 0.06$ eV



$\Sigma m > 0.10$ eV

An answer with the cosmological neutrinos?

Neutrinos in cosmology

Cosmic neutrino background

At early times ($T_\nu \gg m_\nu$), neutrinos contribute as **radiation** $\rho_\nu \propto T_\nu^4$

At late times ($T_\nu \ll m_\nu$), neutrinos contribute as **matter** $\rho_\nu = m_\nu n_\nu$

Non-relativistic transition

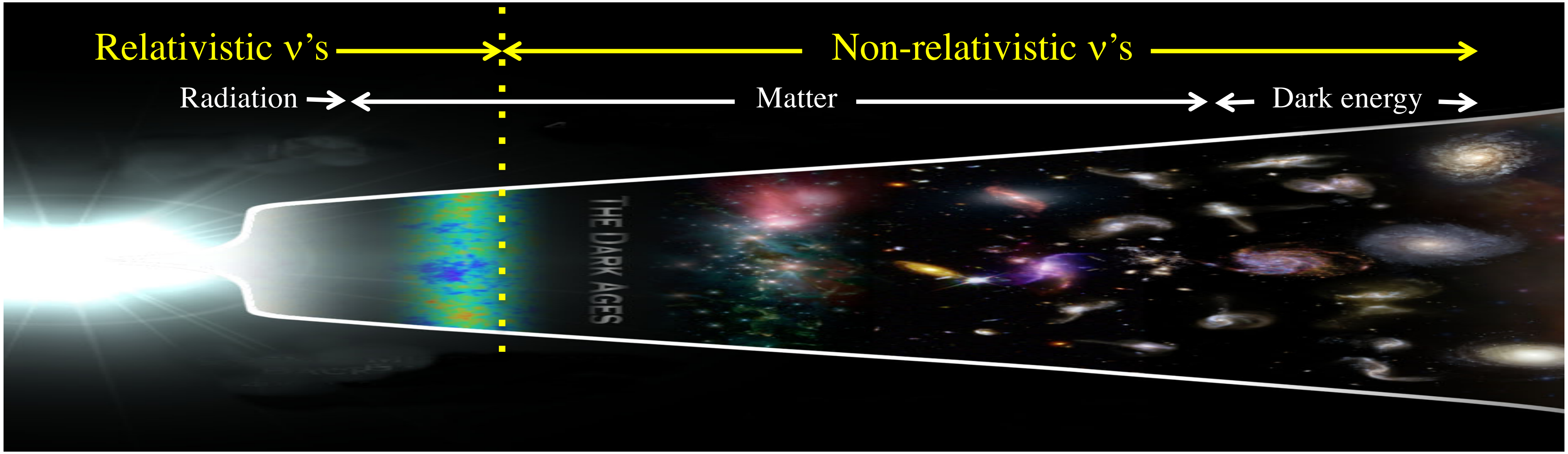
$$m_\nu \sim \langle p \rangle = \frac{\int p f(p) d^3p}{\int f(p) d^3p} = 3.15\, T_\nu \quad \text{with} \quad f(p) = \frac{1}{e^{p/T_\nu}+1}$$

$$z_{nr} \sim 1900 \, \frac{m_\nu}{1\,\mathrm{eV}} \longrightarrow$$

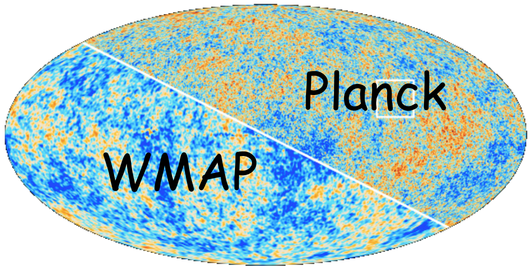
At recombination

m_ν < 0.6 eV (Σm_ν <1.7) : relativistic

m_ν > 0.6 eV (Σm_ν >1.7) : matter-like



Impact on CMB



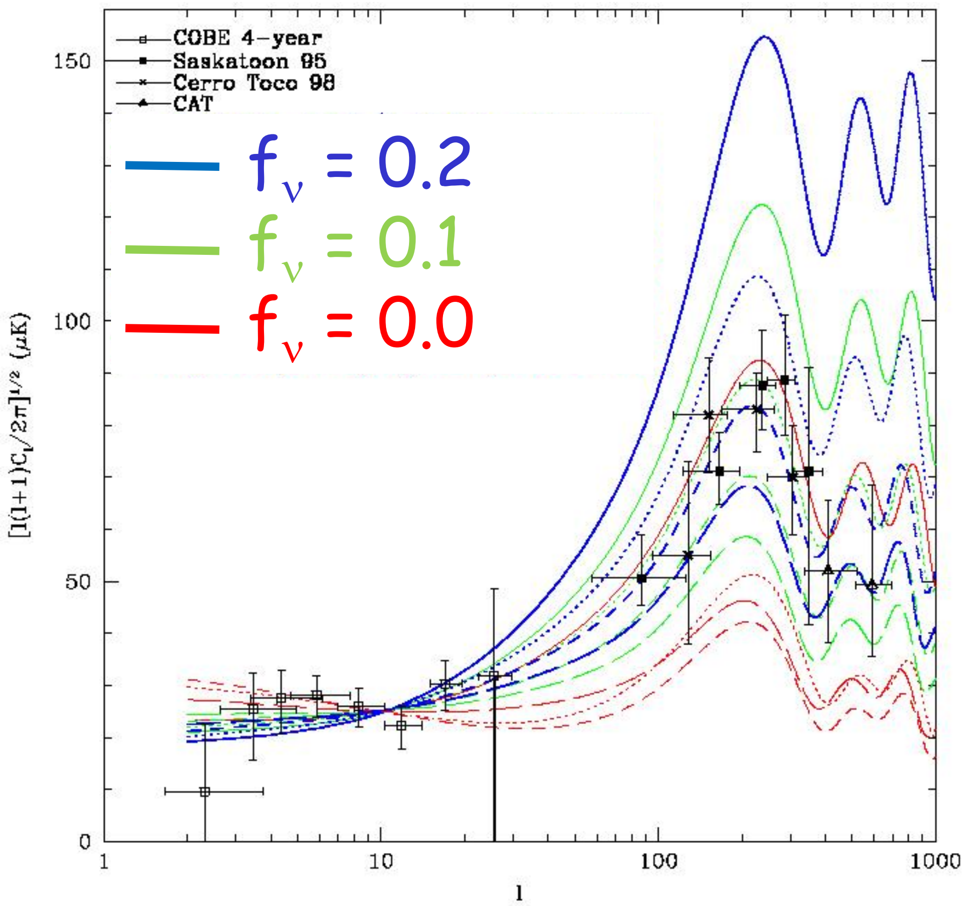
- m_ν > 0.6 eV (Σm_ν > 1.7 eV)
  - Non relativistic at CMB
  - Hot Dark Matter (HDM)

⇒ Direct impact on CMB power spectrum:

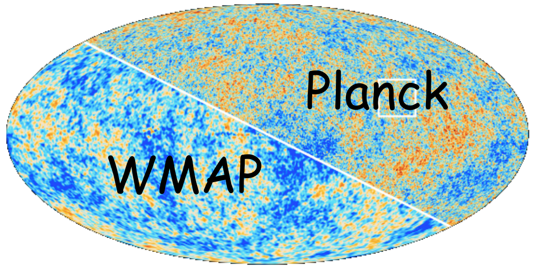
⇒ Even with pre-WMAP (COBE…), **in late 90s**, the damping of C_ℓ on intermediate scales (100<l<1000) cannot be explained without relativistic neutrinos

⇒ Fully excluded with WMAP including HCDM models (10% of HDM)

⇒ $f_\nu = \Omega_\nu / \Omega_m$
Fraction of neutrinos in Matter



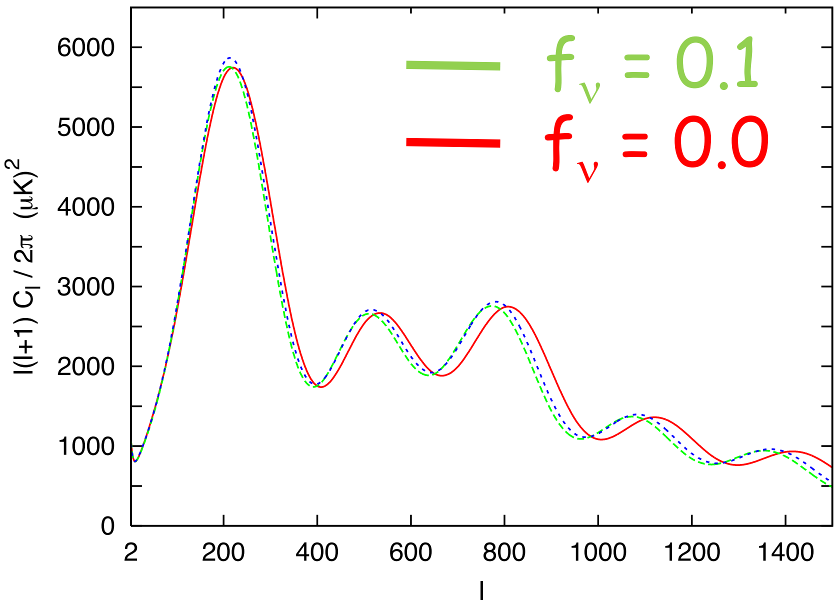
Impact on CMB



- m_ν < 0.6 eV (Σm_ν < 1.7 eV) - relativistic at CMB

$\Rightarrow$ "No" impact on baryon-photon plasma, and thus on primary CMB
$\Rightarrow$ Subtle changes in peak position & amplitude
$\Rightarrow$ Postponing of matter-radiation equivalence z_{eq},
OR, z_{eq} being well measured by CMB, Ω_m – Σm_ν degeneracy

$$1+z_{eq} = \frac{\Omega_b + \Omega_{cdm}}{\Omega_\gamma \left[1+\frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right]} = \frac{\Omega_m - \Omega_\nu}{\Omega_\gamma \left[1+\frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right]} \quad \textbf{with} \quad \Omega_\nu = \frac{\Sigma m_\nu}{93.1 eV}$$



- CMB alone not sufficient for neutrinos masses sub-eV
- Add information directly from **the matter distribution**

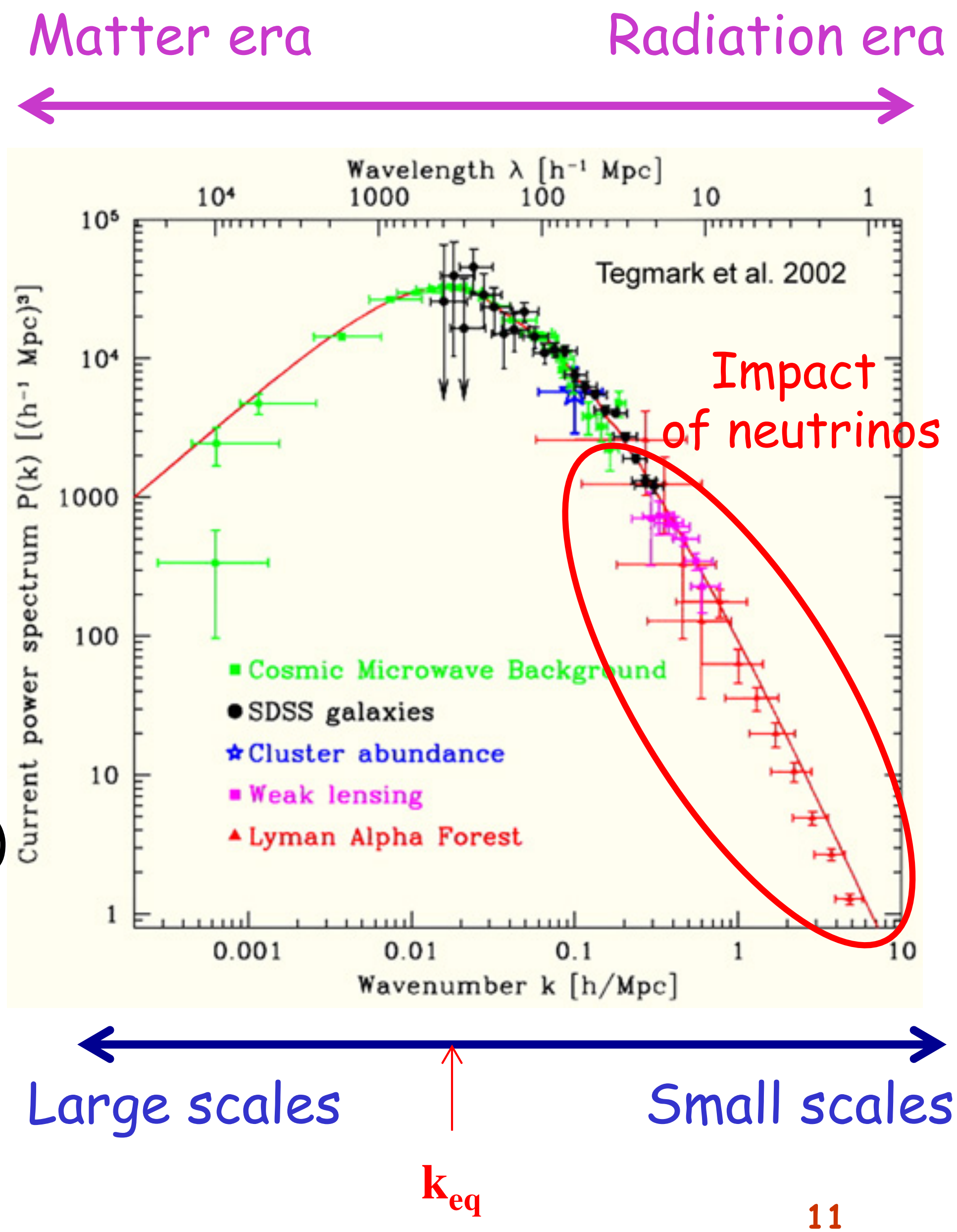
Matter power spectrum

Matter power spectrum

- Analogy with sound: higher at certain frequencies
- Real space ⟹ k-space (Mpc^{-1})
- First observation of "total" power spectrum with different tracers of the matter

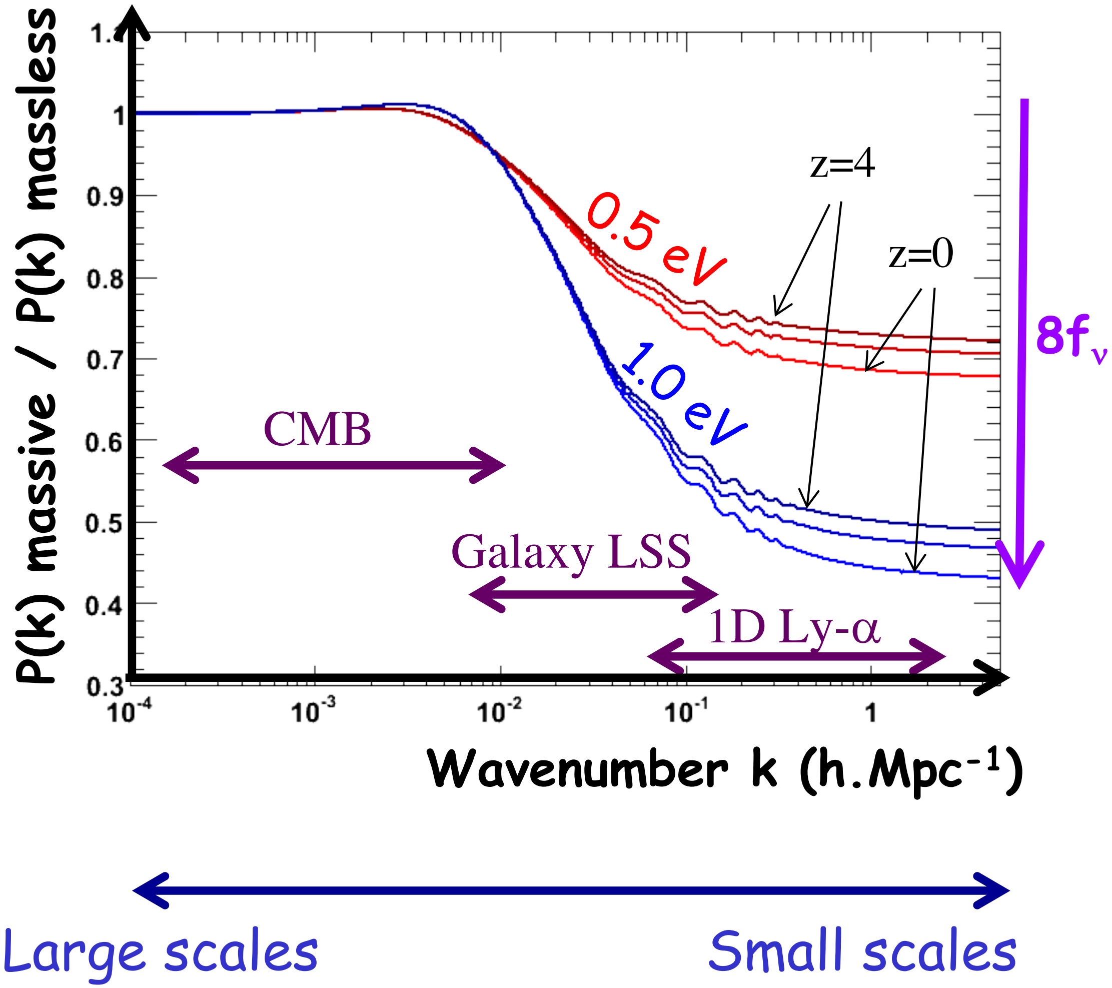
Finite velocity of light

- Causality "horizon" (↗ with time)
- Small scales enter horizon early
  Large scales enter horizon late
- Relativistic neutrinos will affect small scales



Impact on matter power spectrum

- Impact in CMB-alone only for non-relativist neutrinos ⇒ ~1-2 eV limit



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

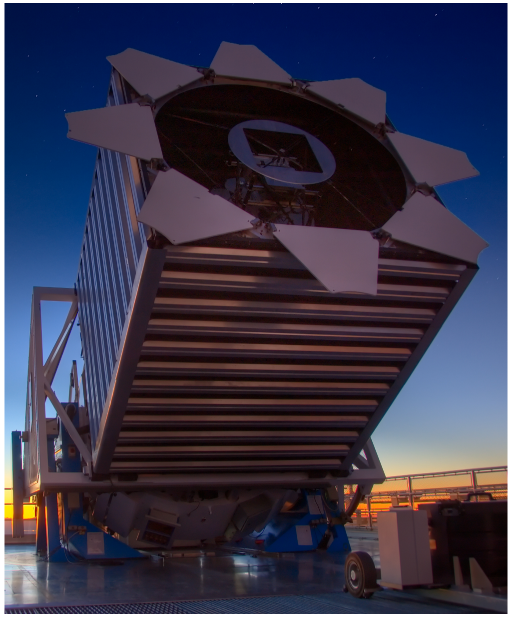
Ly-α:

- 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) −

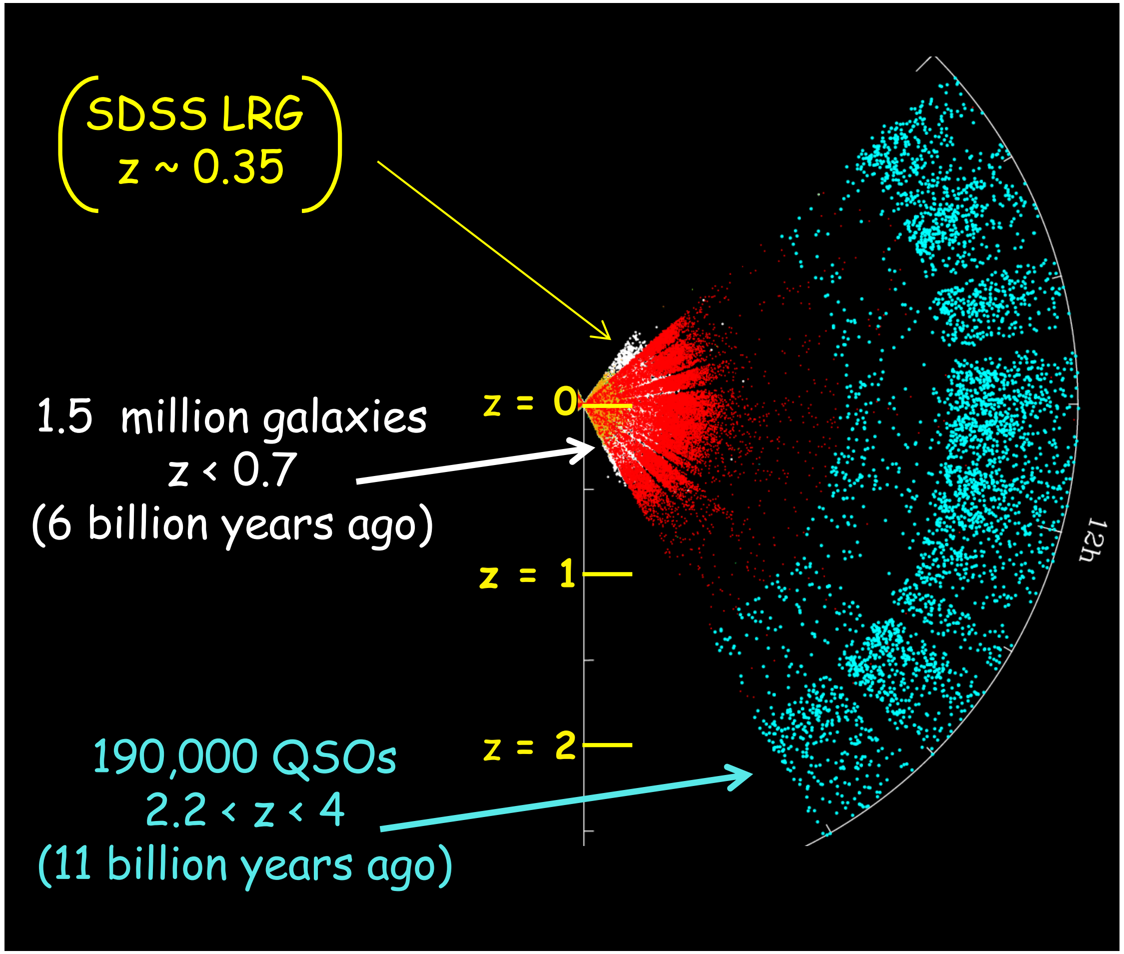
⇒ **Hydro/N body simulations**

Ly-α forests with BOSS and XQ-100

SDSS BOSS



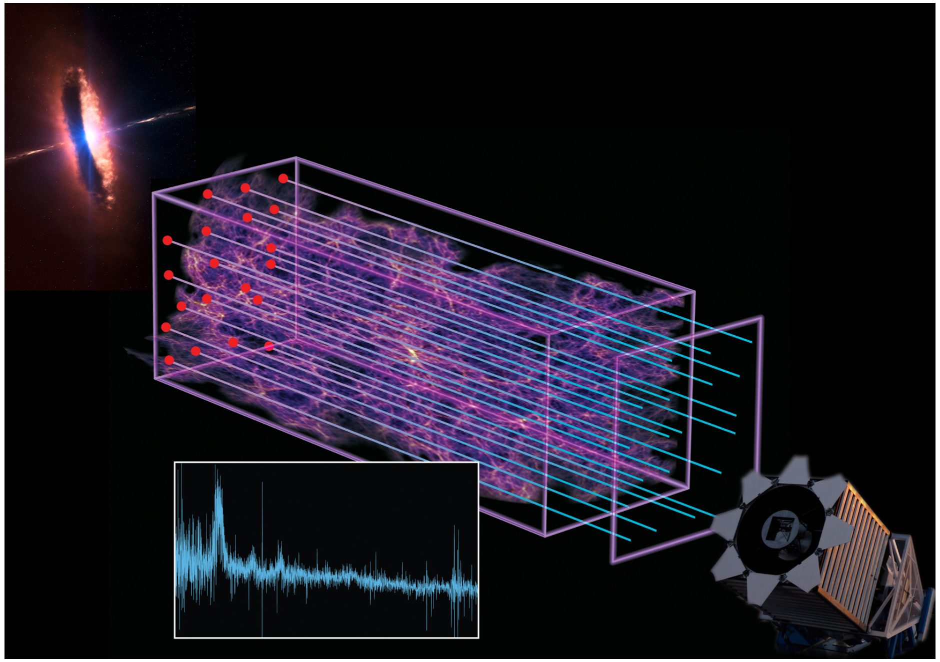
BOSS
2009-2014



SDSS spectroscopic survey

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

Ly-α forests, matter tracers

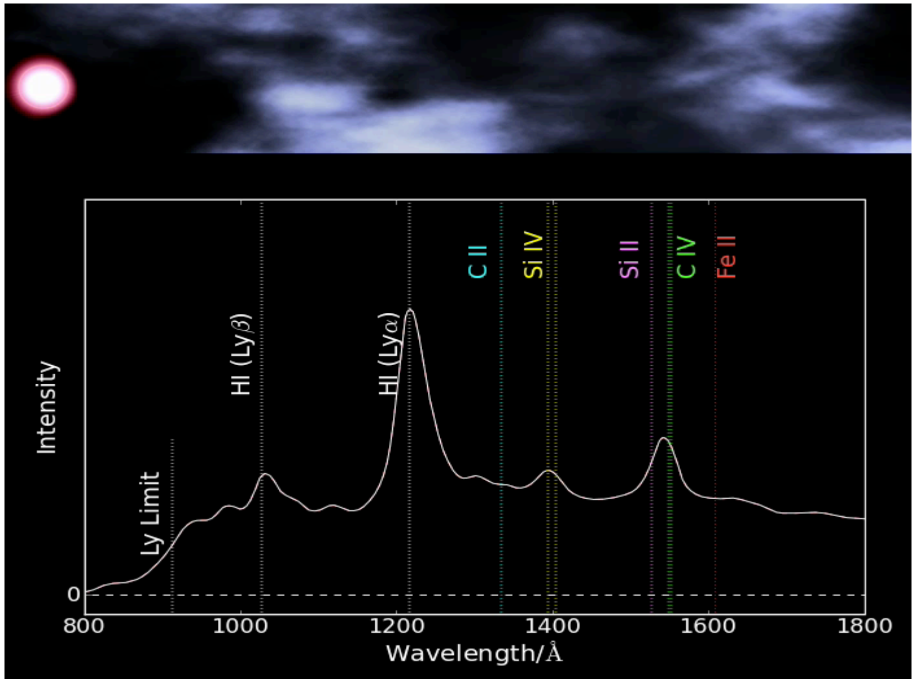


Principles

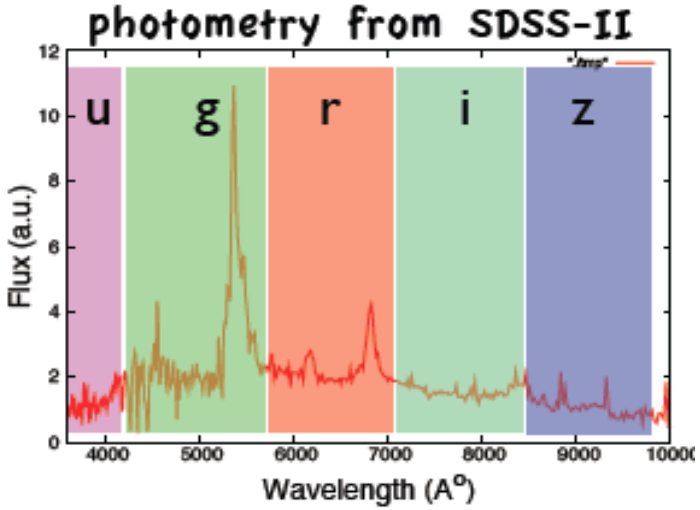
- Use Ly-α forests of quasars (2.2<z<4)
- HI absorption in IGM along the line of sight of QSOs
- We expect low density gas (IGM) to follow the dark matter density

1D power spectrum

- Correlation between the pixels of a line of sight
- Proxy of the matter down to scale 1 Mpc

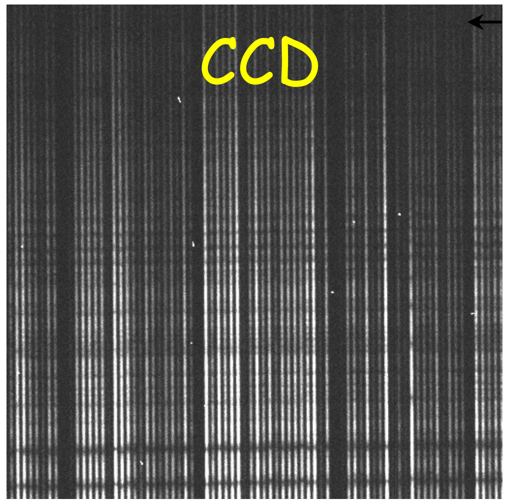


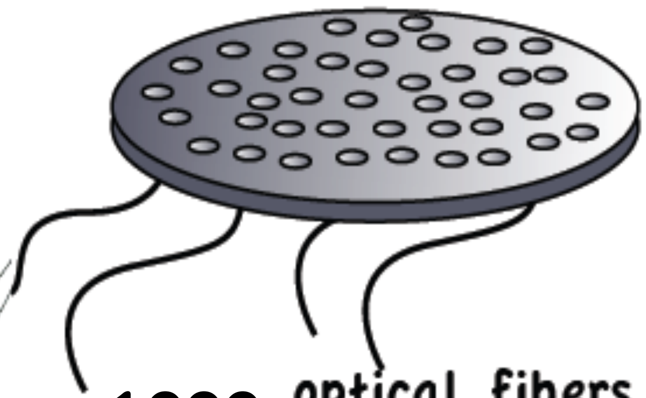
BOSS Observation Strategy



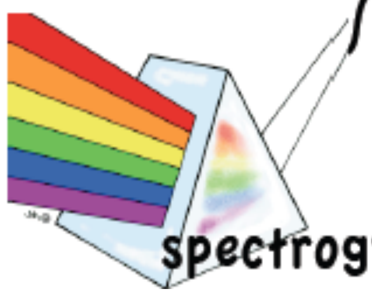
List of targets

SDSS J112253.51+005329.8
SDSSp J120441.73-002149.6
SDSSp J130348.94+002010.4
SDSSp J141205.78-010152.6
SDSSp J141315.36+000032.1
....



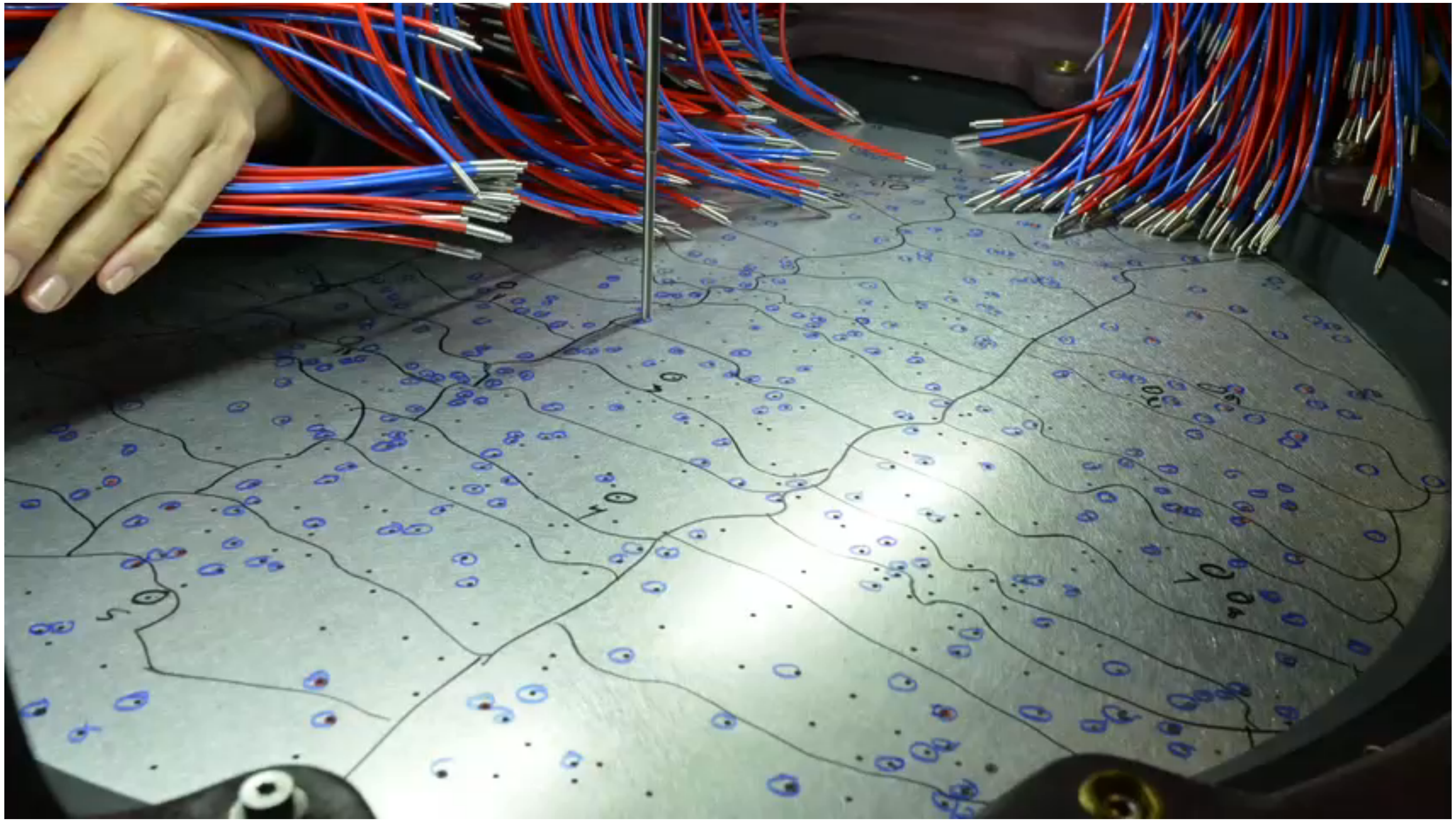


1000 optical fibers



spectrograph

Plug and Observe



Several steps (~3 months)

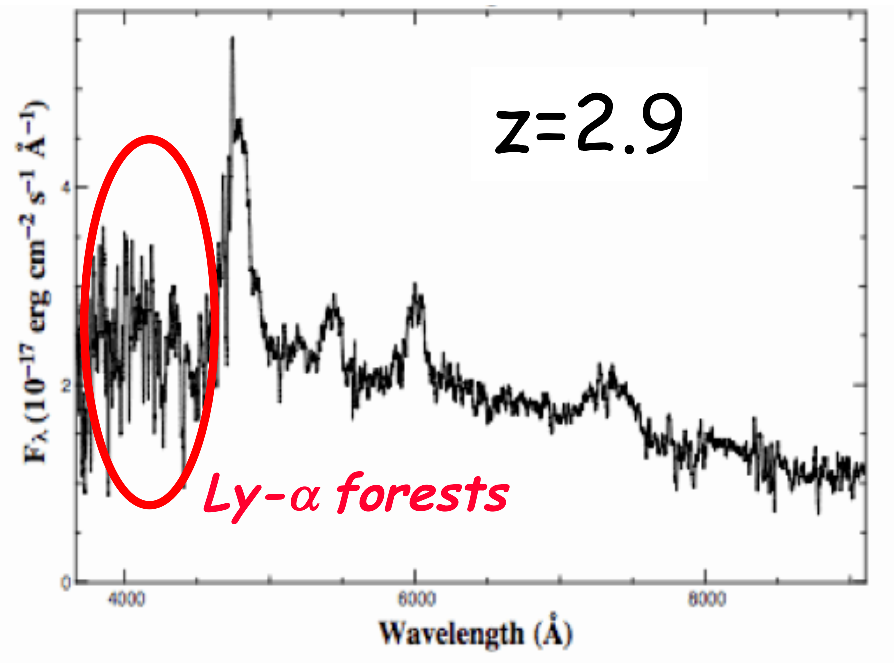
- Target selections (~40 QSOs deg^{-2} and ~150 galaxies deg^{-2})
- Drill plates (1000 holes per plate)
- Plug plates on cartridges during day

Ly-α forests in BOSS

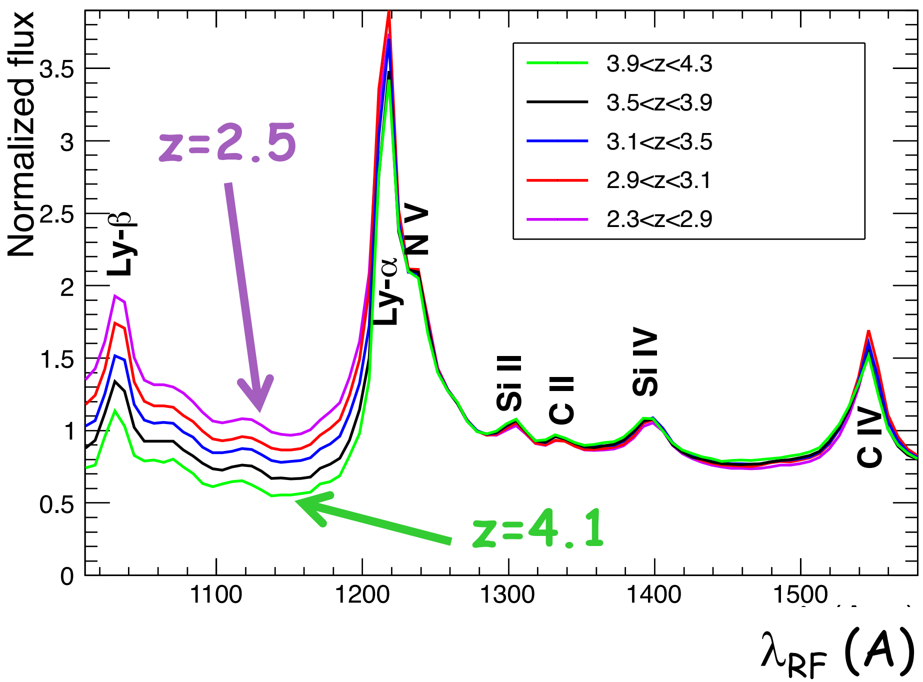
- 14000 DR9 QSOs out of 60000
- Selected for
  - quality (no flagged pixels, no high density absorbers)
  - SNR > 2
  - resolution < 85 km/s

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

One QSO spectrum



Stacked QSO spectra



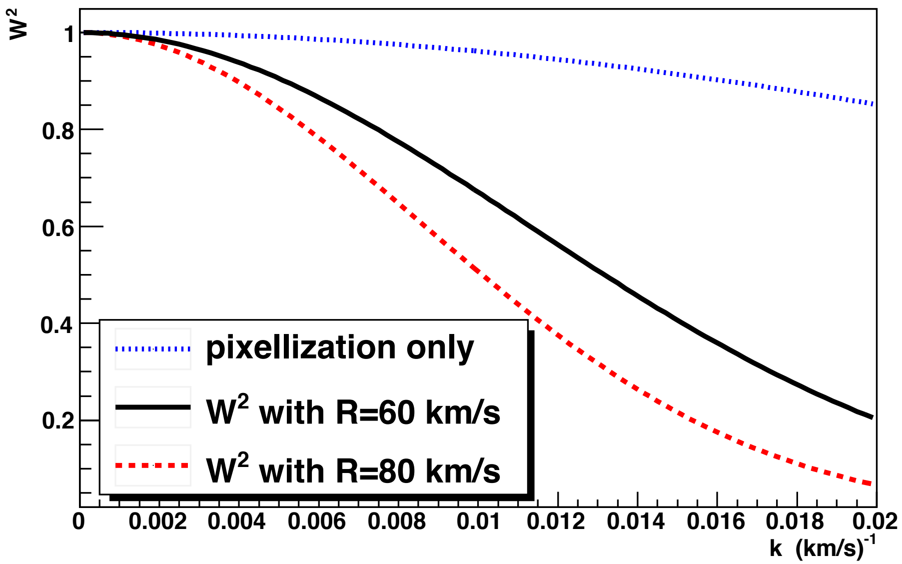
Palanque-Delabrouille., Yèche, Borde et al. (2013)

1D Power Spectrum analysis a tough analysis!

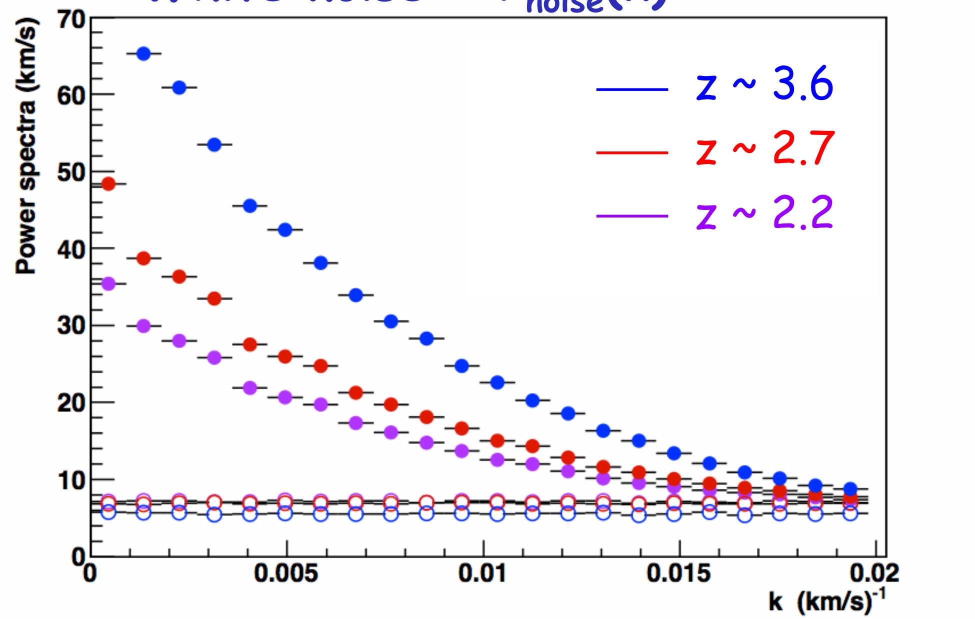
- Detailed study of spectrograph resolution, noise, lines of sky, correlation with other absorbers…
- **Largest correction** at small scales (high k)

$$P_{Raw}(k) = (P_{HI}(k) + P_{HI-SiIII}(k) + P_{metals}(k)).W^2(k) + P_{Noise}(k)$$

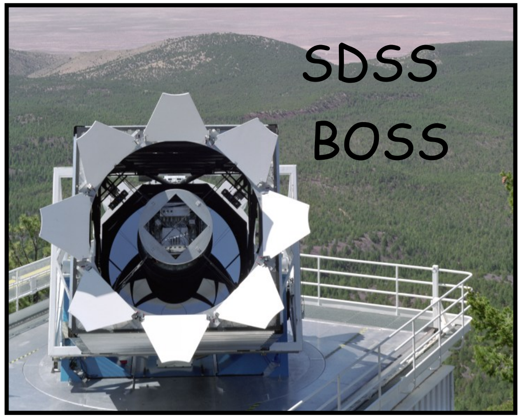
Resolution = Window function W^2



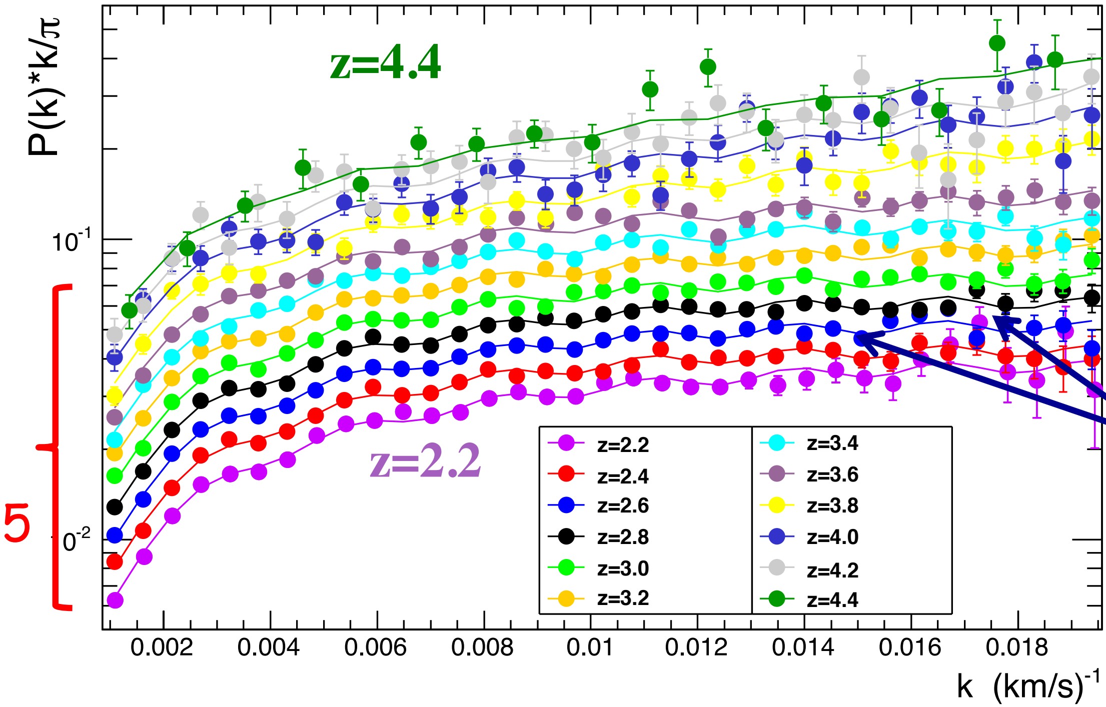
White noise = $P_{noise}(k)$



1D Power Spectrum



12 slices
in redshift
from 2.1 to 4.5

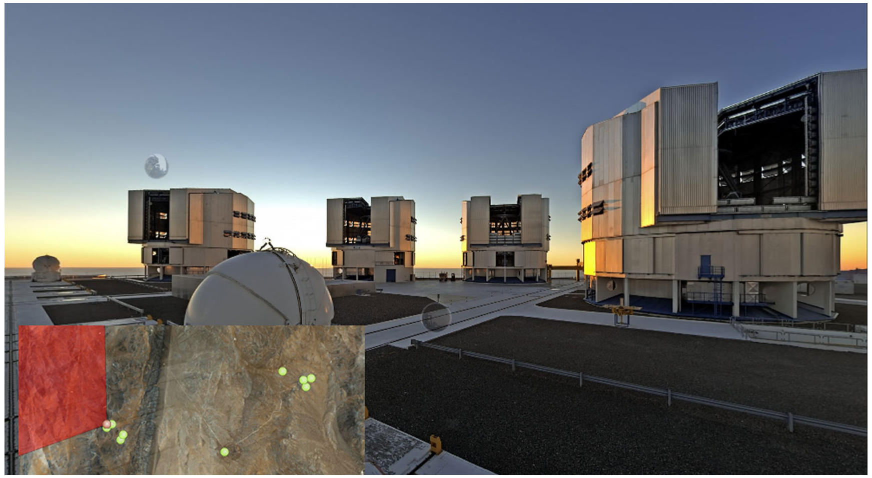


Wiggles: Lya-SiIII
correlations

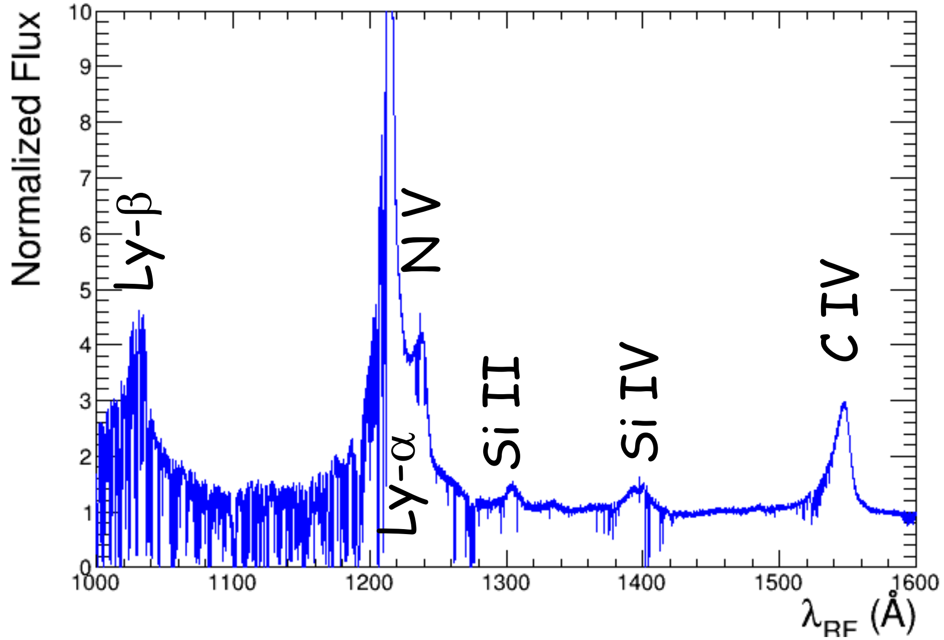
Palanque-Delabrouille., Yèche, Borde et al. (2013)

- Improve small scales (see next slides)
- Need simulations to come back to linear matter power spectrum (see next slides)

Ly-α forests in XQ100



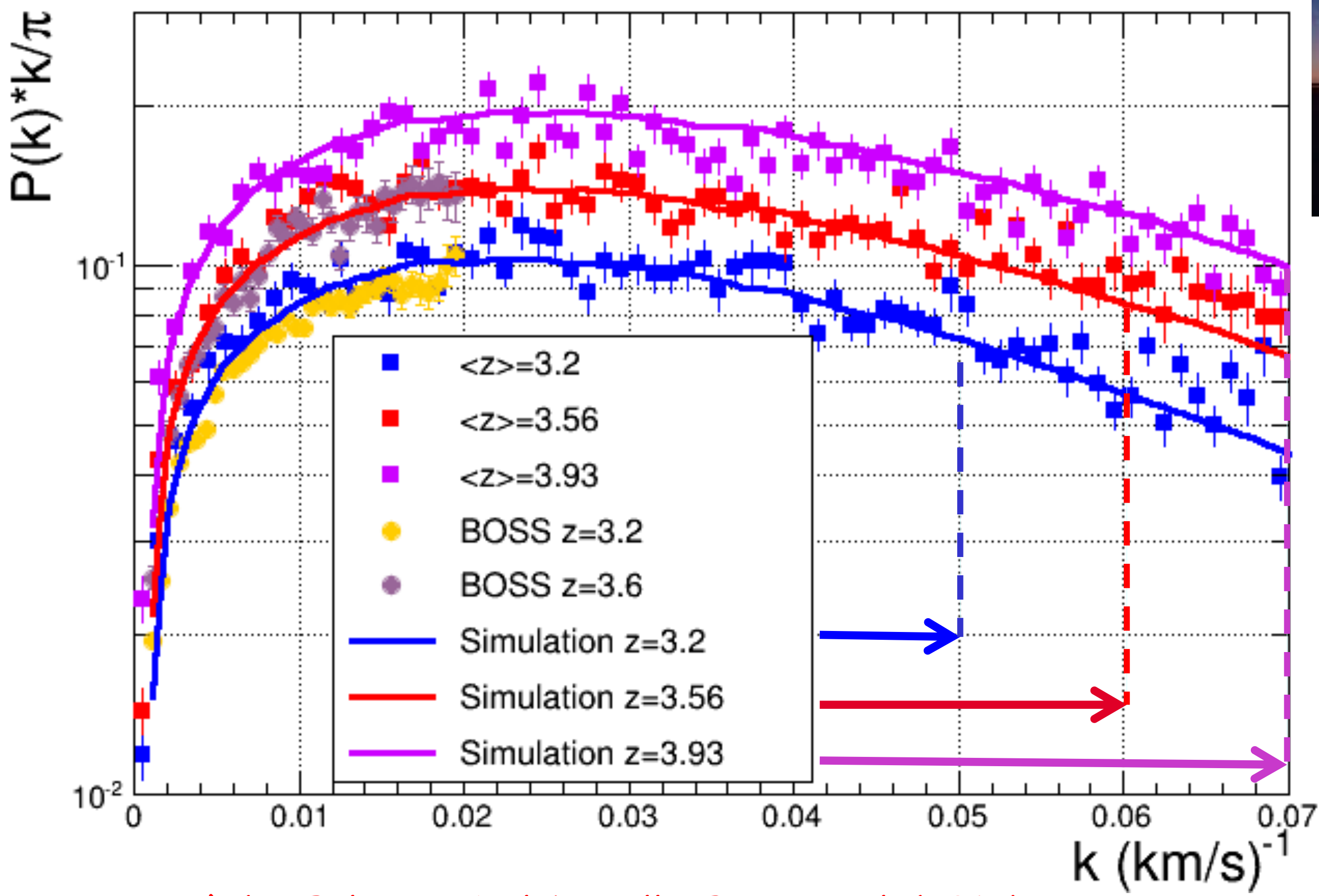
One QSO spectrum



100 QSOs observed with VLT/X-shooter, z ~ 3.5 - 4.5

- **XQ100 Vs BOSS**: 700 for BOSS with same z
- SNR per pixel in Ly-α forest 5-60, on average ~25
- **XQ100 Vs BOSS**: SNR per pixel 10-20 times better
- Resolution (UVB arm: ~18km/s, VIS arm: ~12km/s)
- **XQ100 Vs BOSS**: Resolution 3-5 times better

1D Power Spectrum



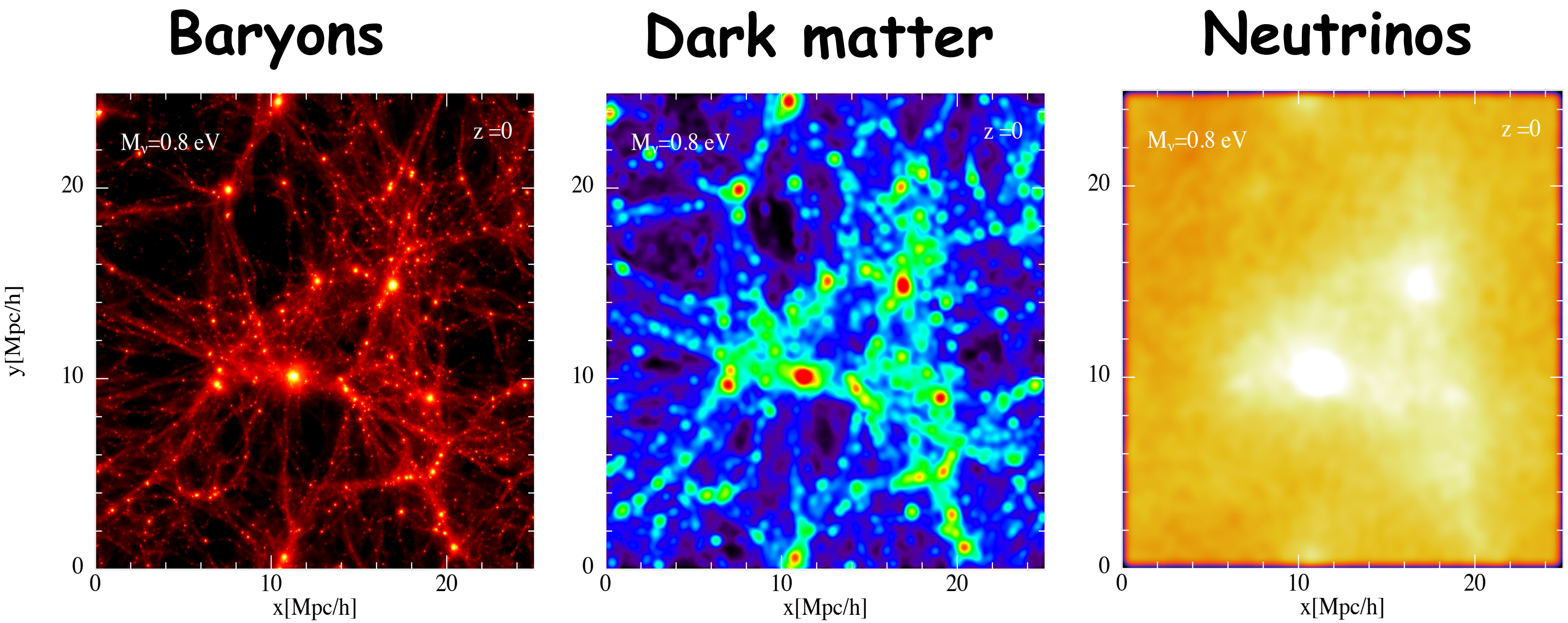
Yèche, Palanque-Delabrouille, Baur et al. (2017)

- Three bins in redshifts with different k-range
- Excellent agreement with BOSS
- Common likelihood based on the same hydro simulations (BOSS: 12 redshift bins, XQ-100: 3 redshift bins).

Neutrinos masses

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



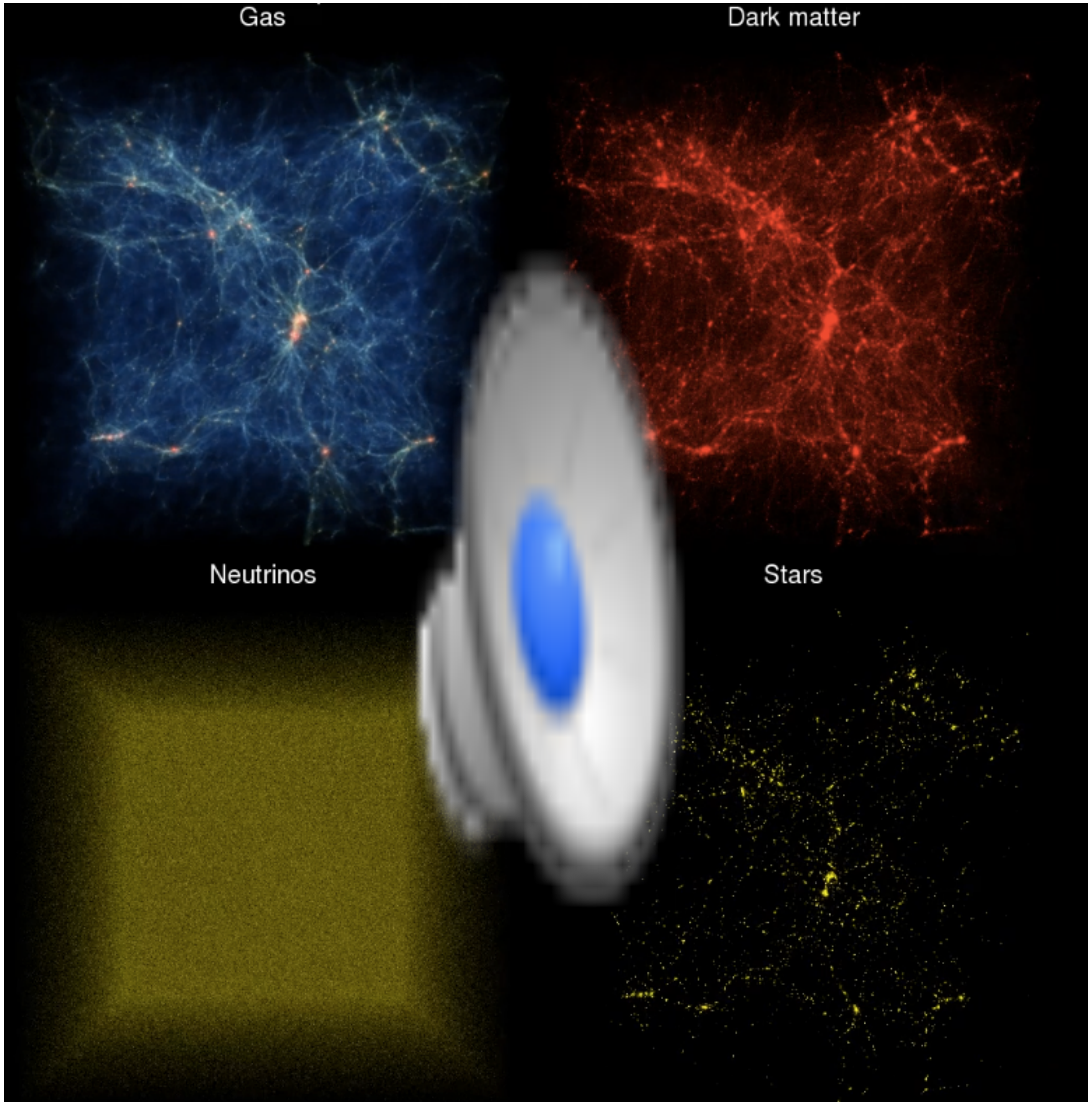
@ G. Rossi

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)

Grid parameter space

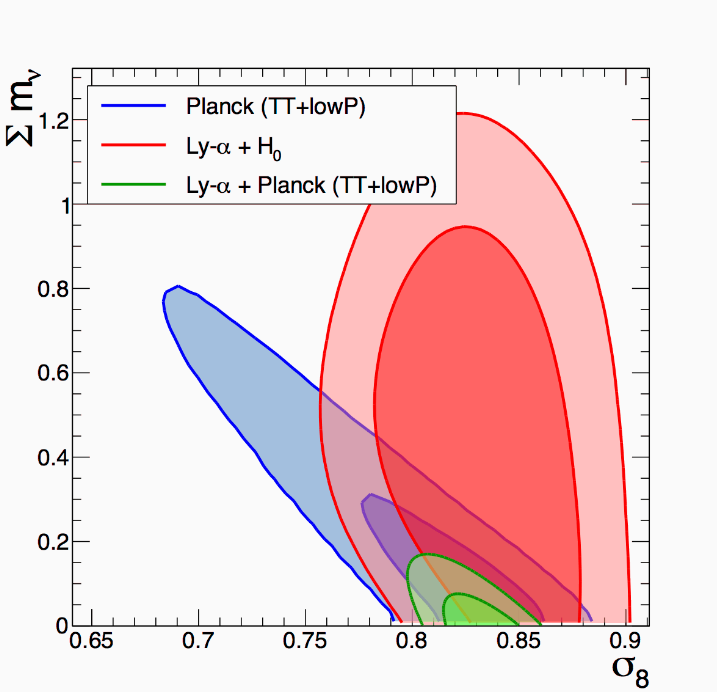
- **Grid of simulations**
  → 2nd-order Taylor expansion for cosmo & astro parameters centered on Planck (2013)

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

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



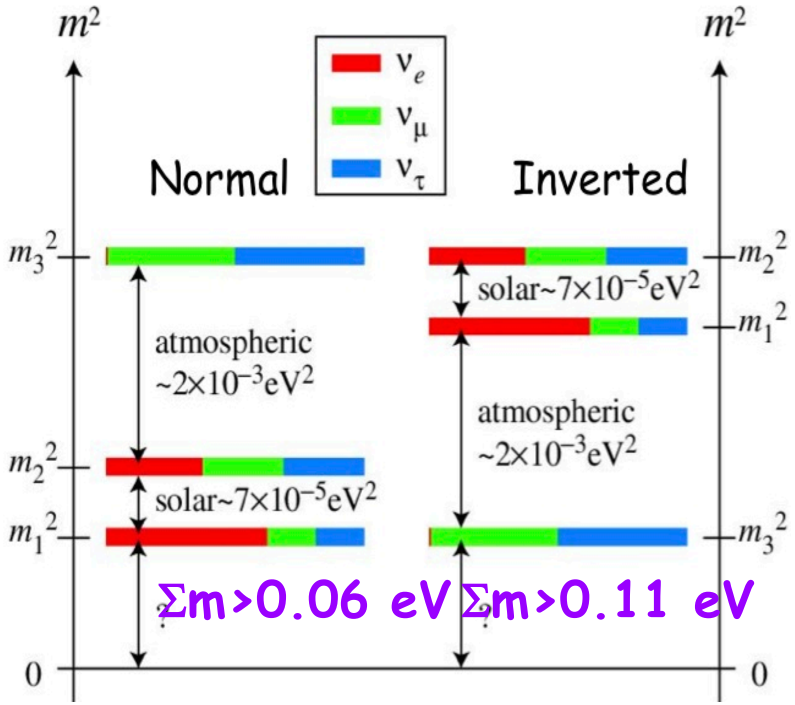
Limits:

- 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: $^3H \longrightarrow {}^3He + e^- + \nu_e$

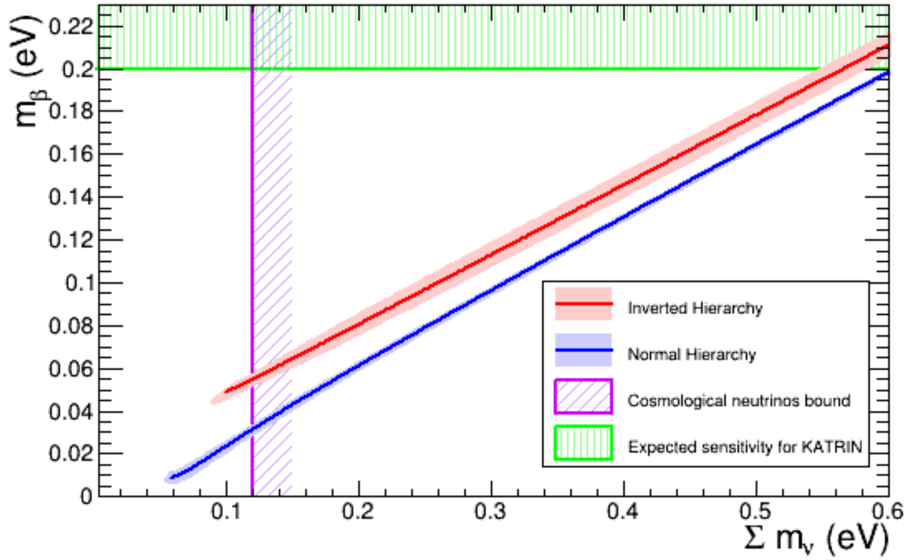
  $\longrightarrow$ Current limits m_β <2eV
  $\longrightarrow$ Sensitivity of 0.2 eV in near future (KATRIN experiment)

- Complementary with cosmology

With Σm_ν < 0.12 eV @95%CL

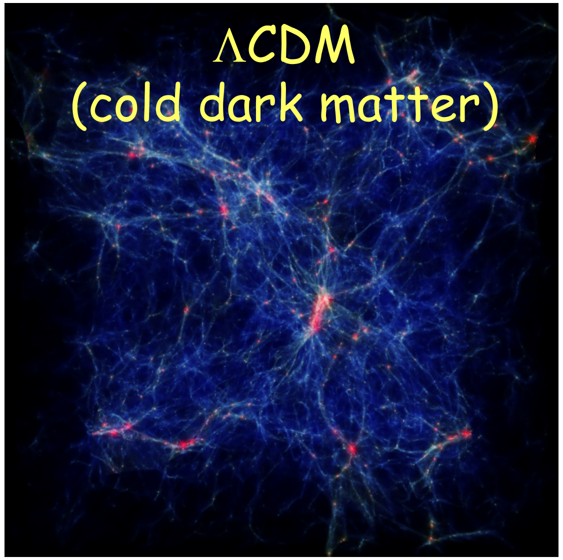
- NH is "favored"
- If disagreement with KATRIN experiment

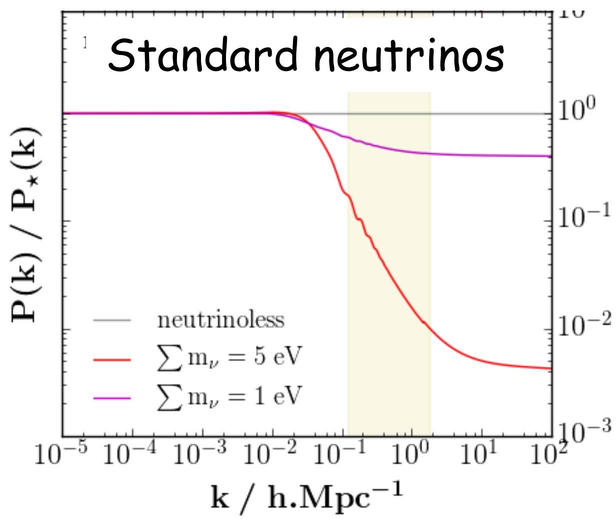
$\Longrightarrow$ Indication of new physics



Warm Dark Matter
and
Sterile neutrinos

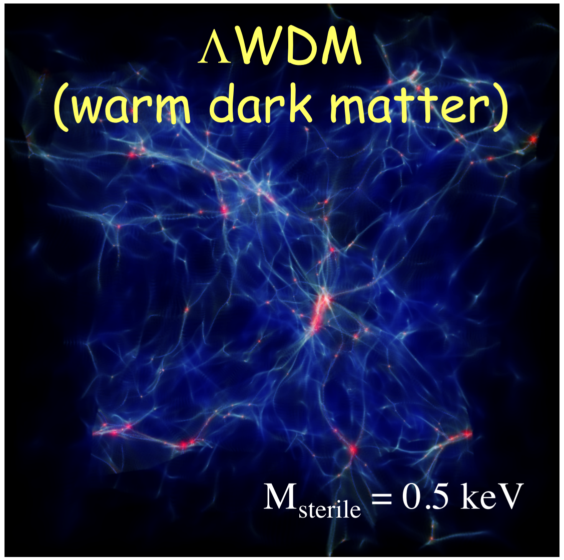
WDM: Thermal relics

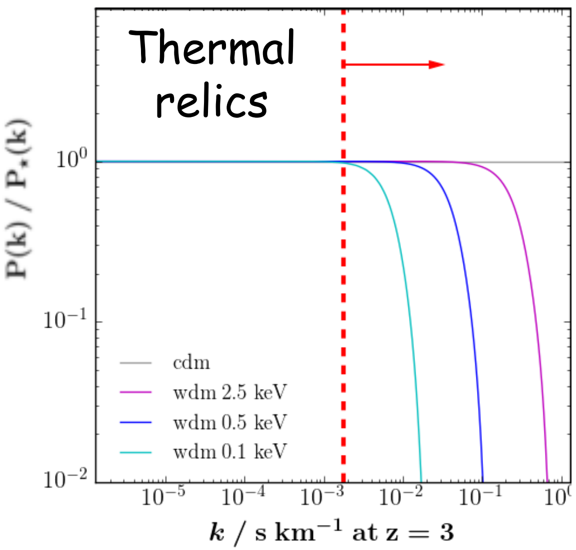




Standard neutrinos

- Constraint given by comparing CMB and Ly-a
- **Upper limit on ν mass**

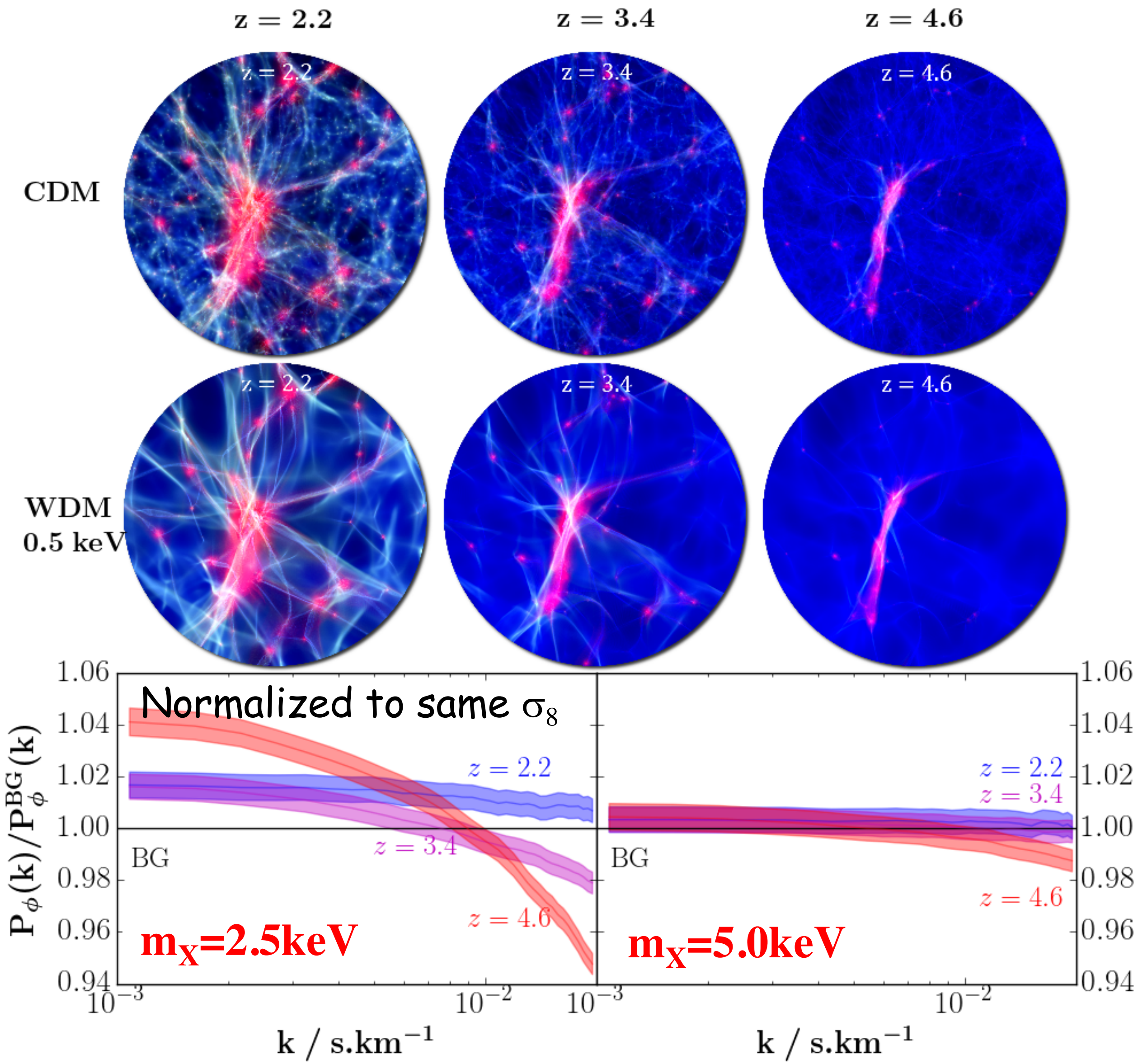




Thermal relics – Sterile neutrinos:

- cut-off: Lack of power on small scales
- Detectable in BOSS/XQ100, if significant effect, i.e., if m_x small
- **Lower limit on ν mass**

Sterile neutrinos and Ly-α

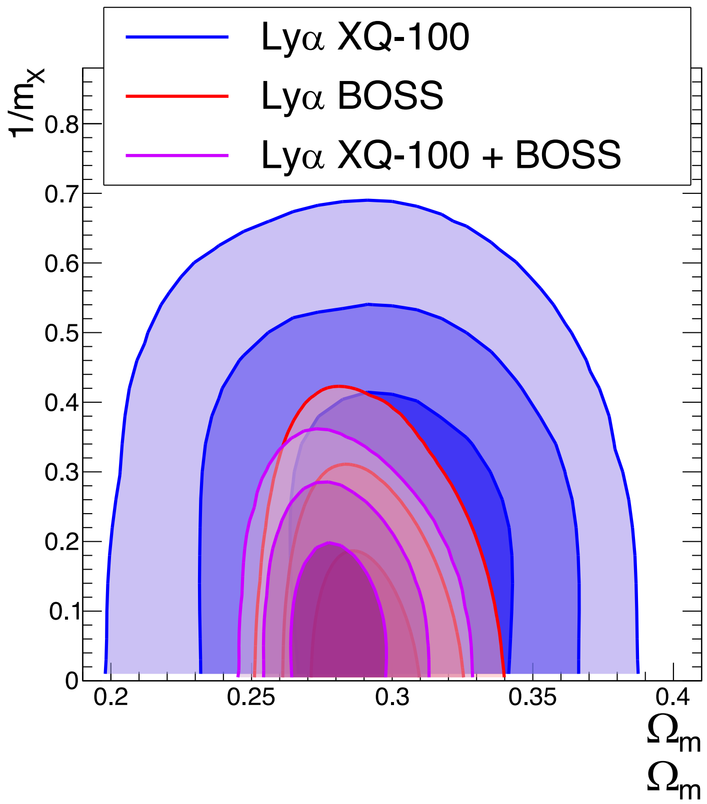


- More sensitive to high z
- More sensitive to lower mass

- Need high z and high k to get the best limit

- **Extraction of a lower mass limit**

Thermal relics

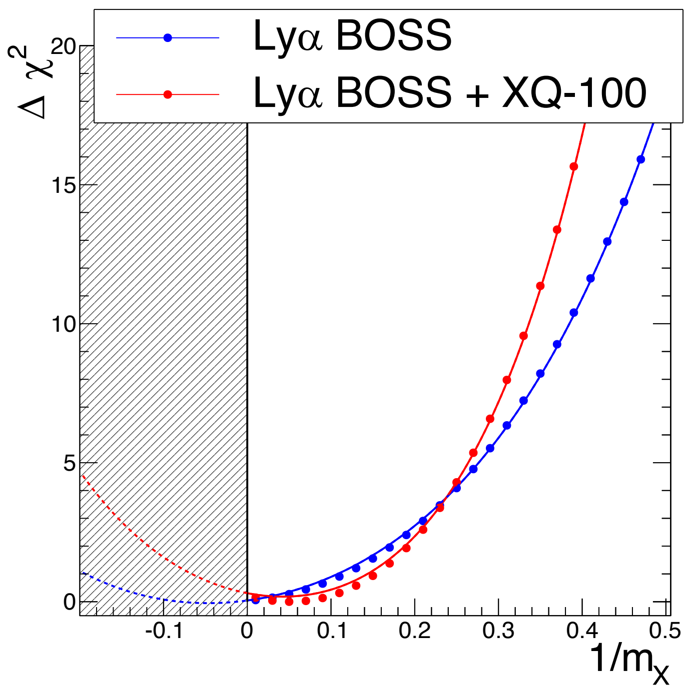


Limits:

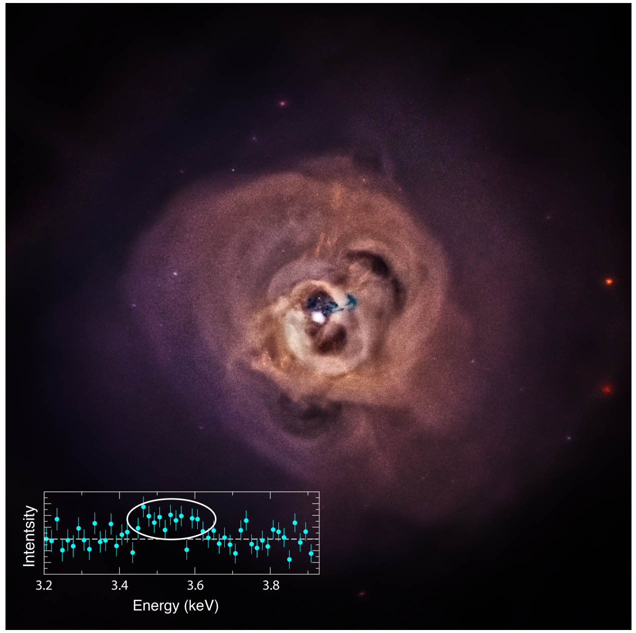
- With Ly-α XQ100 alone:
  Relics: m_x>2.23 keV @95%CL
- With Ly-α BOSS alone:
  Relics: m_x>4.09 keV @95%CL
- With Ly-α (BOSS+XQ100+HIRES) :
  Relics: m_x>4.65 keV @95%CL

Adding XQ100 to BOSS:

- Marginal gain at 95% C.L
- Significant gain at 3σ
- 10% improvement on the parabolic profile of χ^2

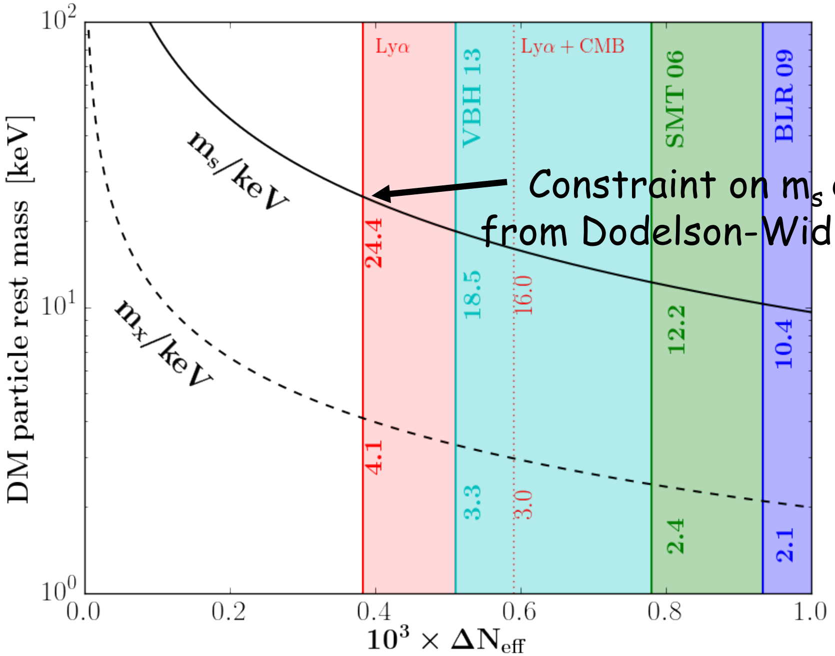


Sterile Neutrino



- Observation of a 3.5 KeV X-ray line with XMM by Boyarski's & Bulbul's from galaxy clusters (Perseus, Centaurus…) or Andromeda galaxy

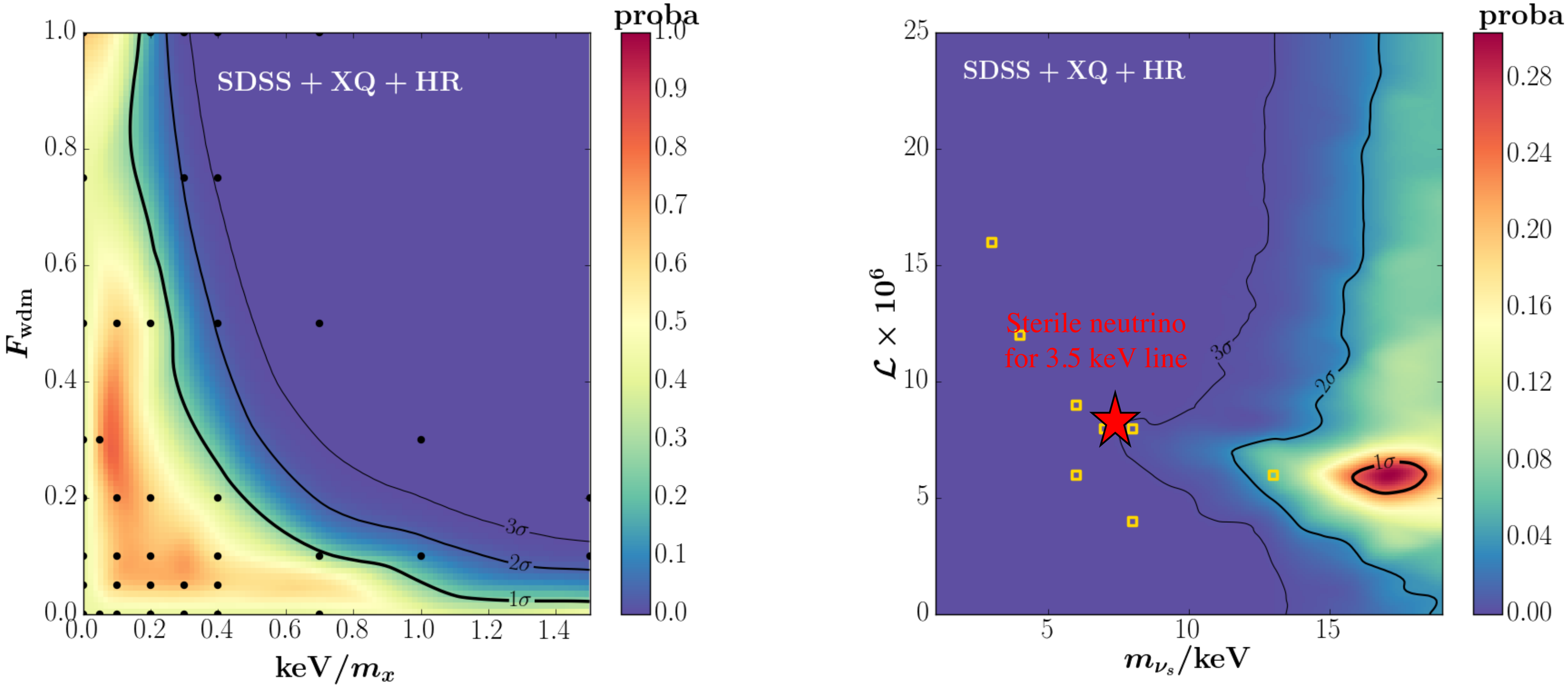
A possible interpretation: Decays of 7 keV sterile neutrinos



- Strong limit on WDM model in case of non-resonantly produced neutrinos
- Rule out 7 keV sterile neutrinos of 3.5 keV line

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

Sterile Neutrino: Generic models



CDM + WDM mixtures → Neutrinos resonantly-produced

(Baur, Palanque-Delabrouille, Yèche et al. (2017))

→ Sterile neutrinos for 3.5 keV lines excluded at ~3σ in case of resonant production

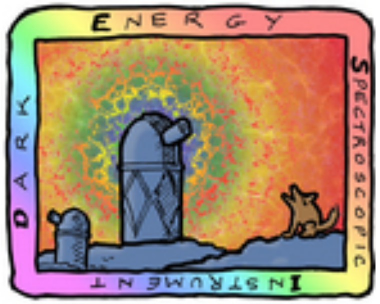
Conclusions

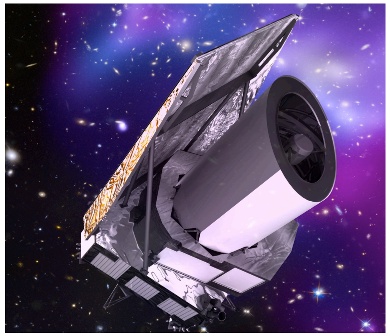
Conclusions

- 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

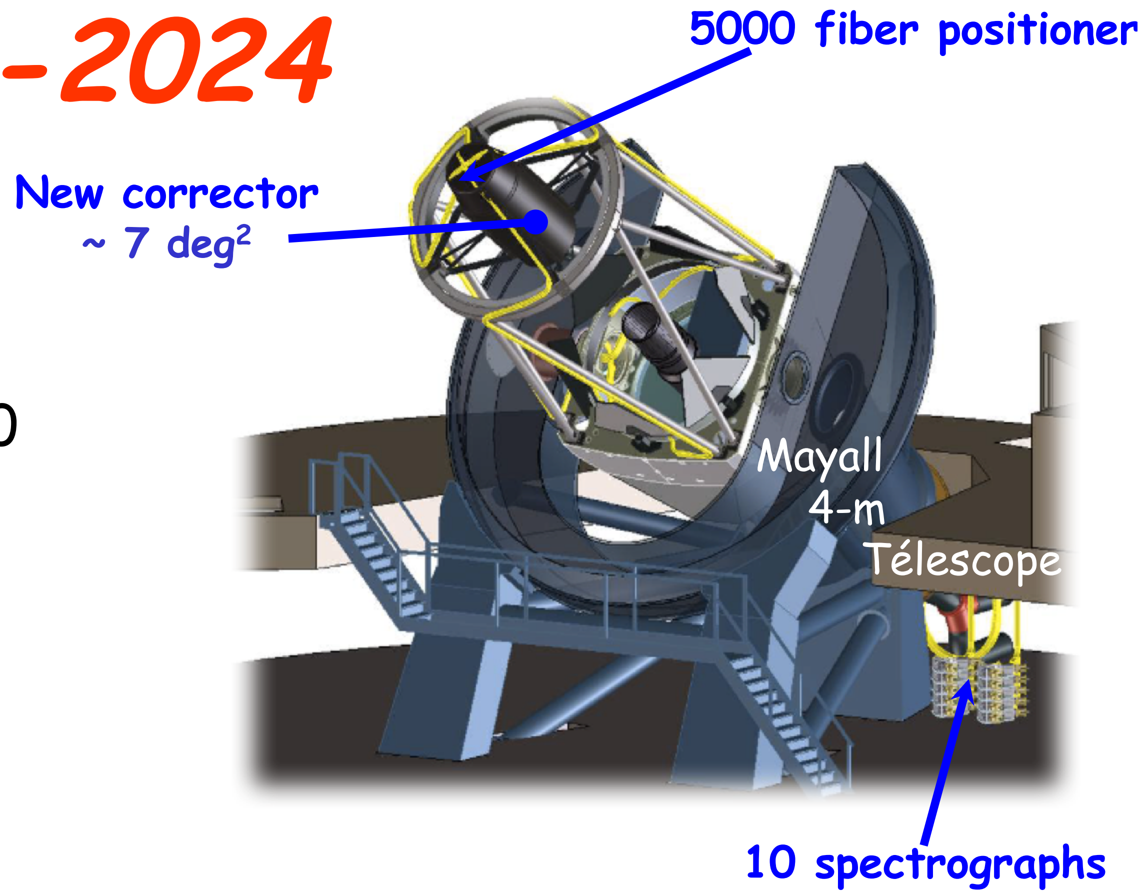
- Constraint on sterile neutrinos from Lyα forest
  - $m_{sterile} > 28.8$ keV (95% CL) in case of non-resonantly produced neutrinos with Dodelson-Widrow model
  - Sterile neutrinos (~7 keV) explaining 3.5 keV line ruled out at ~3σ for all the production modes

- Prospects
  - Lower statistical uncertainties (high z): BOSS DR12 + eBOSS
  - Future projects: DESI,
  - DESI, Euclid





DESI 2019-2024



Instrument

- 4m.telescope at Kitt Peak
- Wide FoV (~ 7 deg^2)
- Robotic positioner with 5000 fibers
- 10 spectrographs x 3 bands (blue, visible, red-NIR)
  →360-1020 nm

Scientific Project

- International Collaboration steered par Berkeley (DOE)
- 14000 deg^2 survey for 0.3<z<4.5
- 20M galaxies and quasars (R~4000)

Constraints on neutrino mass

- Ly-α $\sigma(\Sigma m_\nu) = 0.041$ eV
- All $\sigma(\Sigma m_\nu) = 0.020$ eV

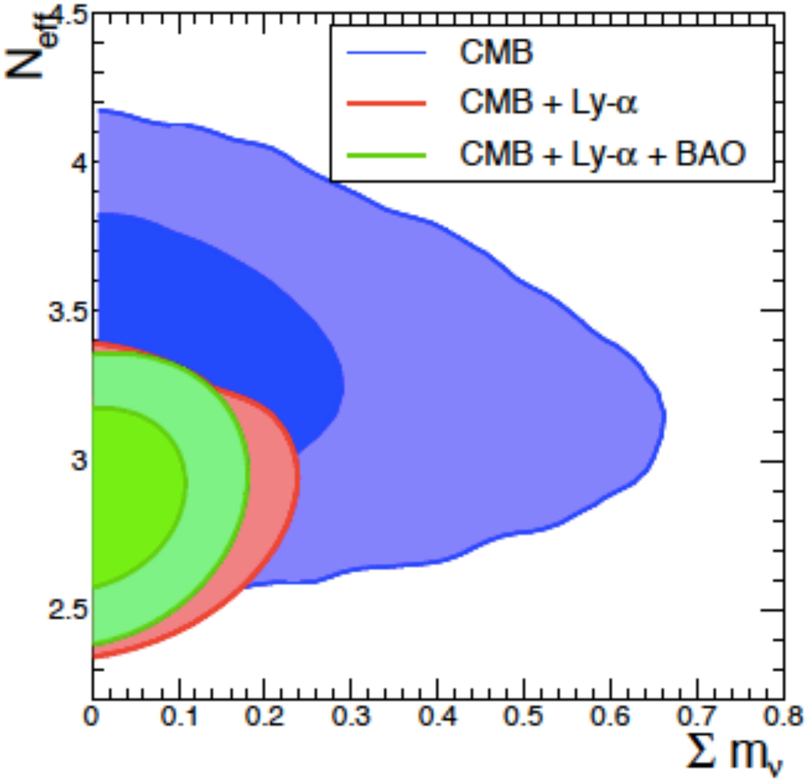
Additional slides

Dark radiation - N_{eff}

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

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)

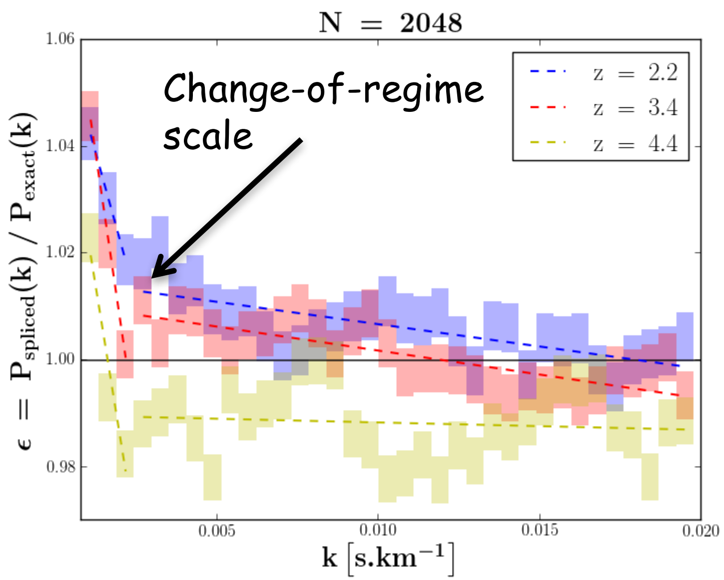
Splicing technique

(McDonald, 2003)

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

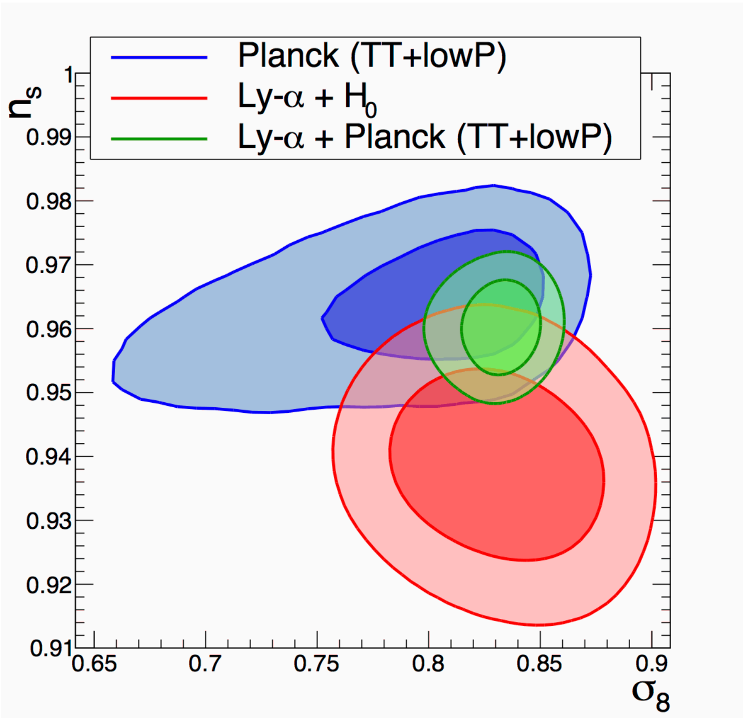
(100 Mpc.h^{-1}, 768^3) (25 Mpc.h^{-1}, 768^3) (25 Mpc.h^{-1}, 192^3)

$\Leftrightarrow$ 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

A mystery : running of n_s



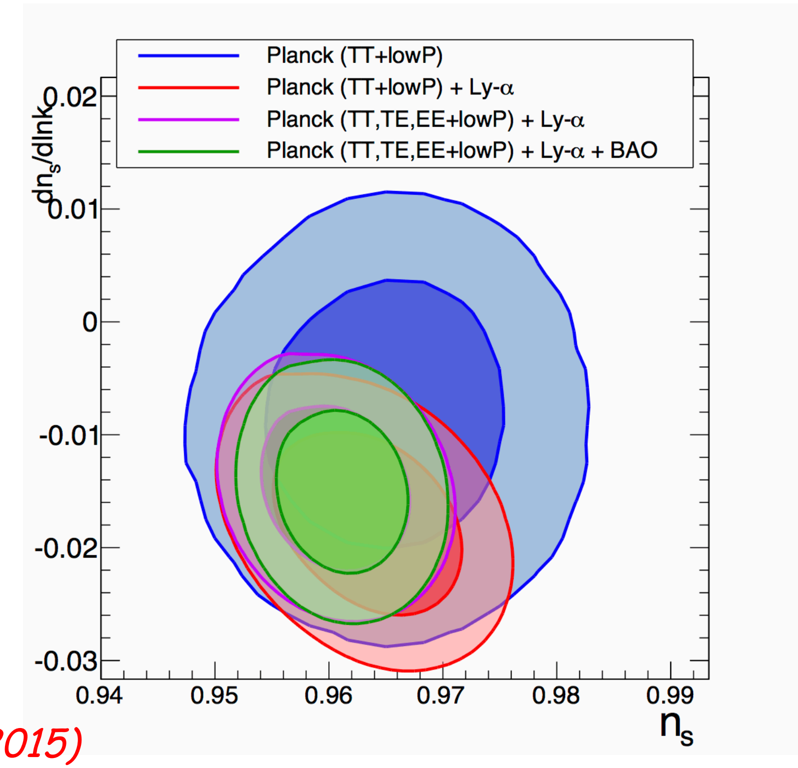
- Small tension (2.3σ) on n_s between Planck and Ly-α
- Tension can be accommodated by running n_s

- "Historical" trends to negative value for $dn_s/d\ln k$

SPT: -0.024 ± 0.011

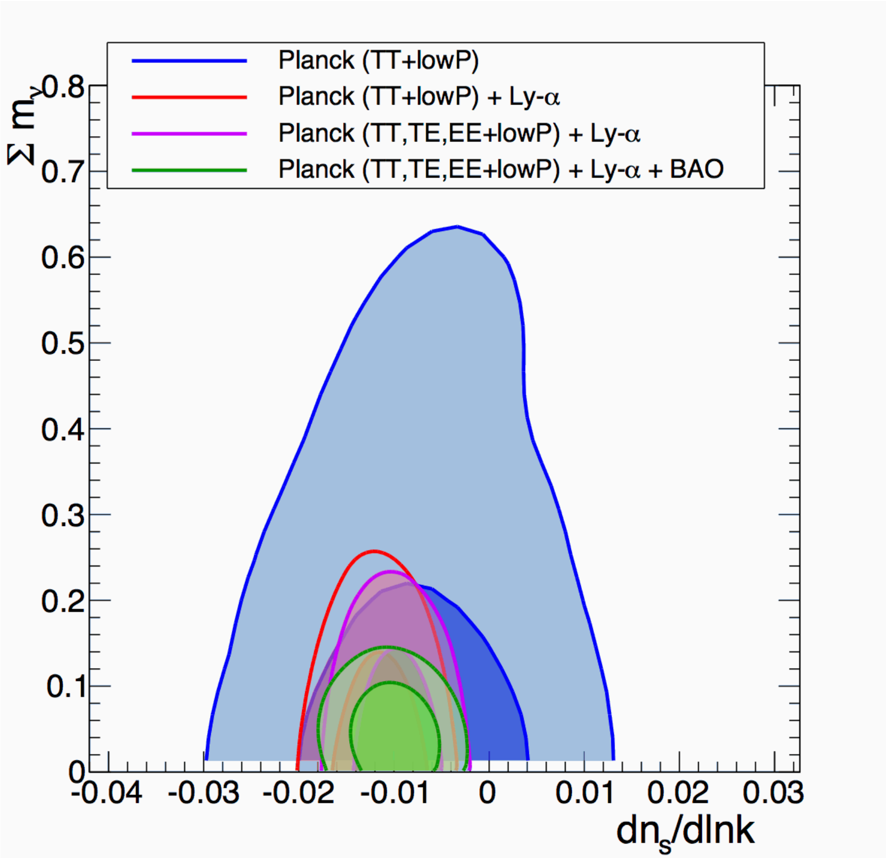
WMAP+SPT+ACT: -0.022± 0.012

- Confirmation with Ly-a ???



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

Impact of n_s running on Σm_ν



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

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)