Séminaire LPC Clermont–Ferrand

Lyman-alpha Forests:
Neutrino Masses & Warmth of Dark Matter

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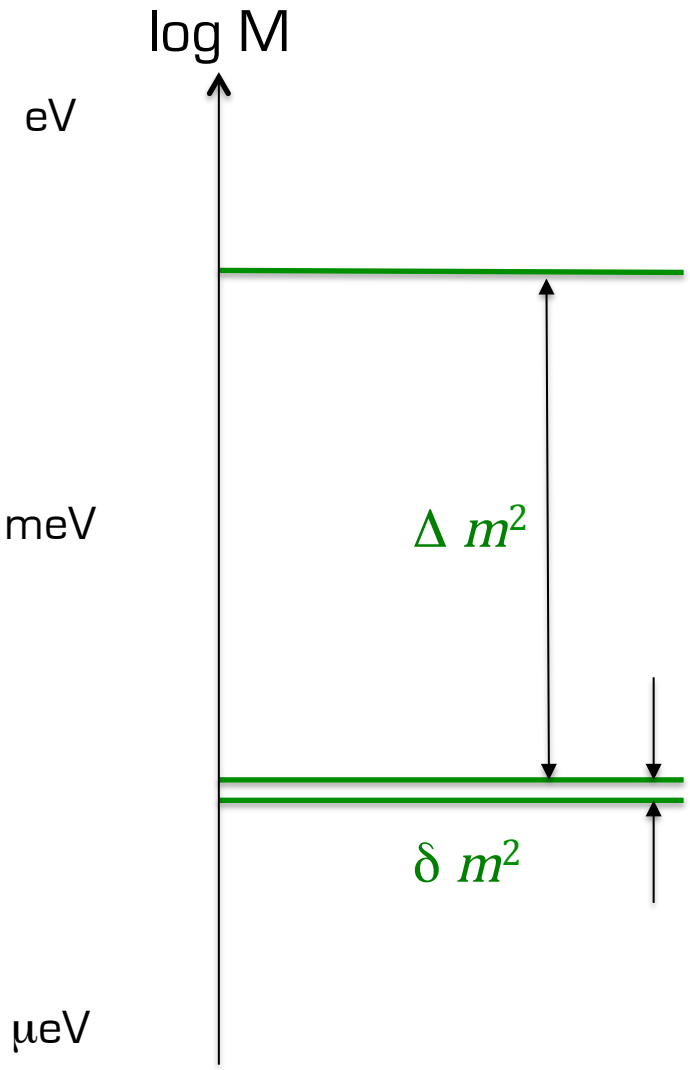
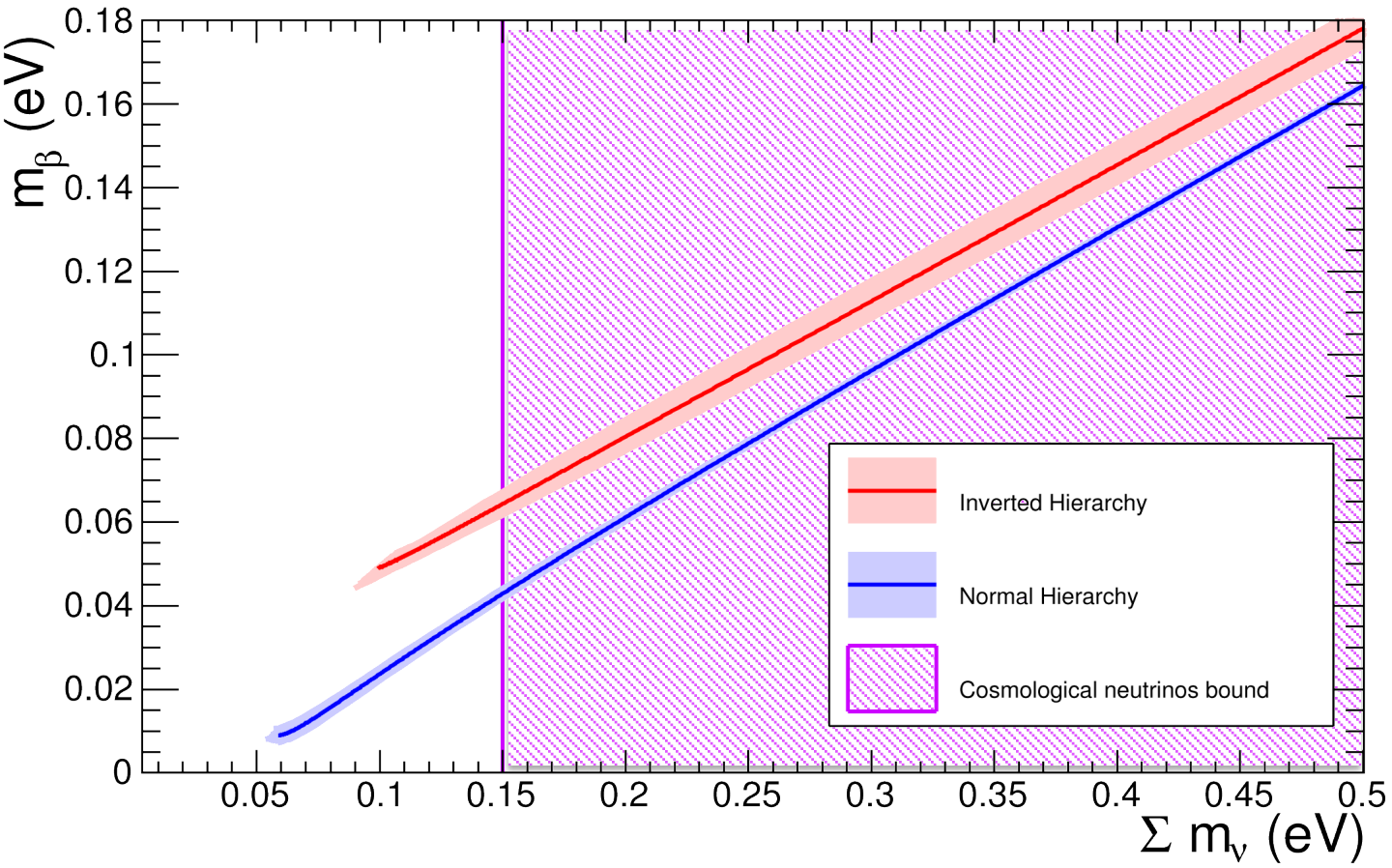
Irfu / SPP – CEA

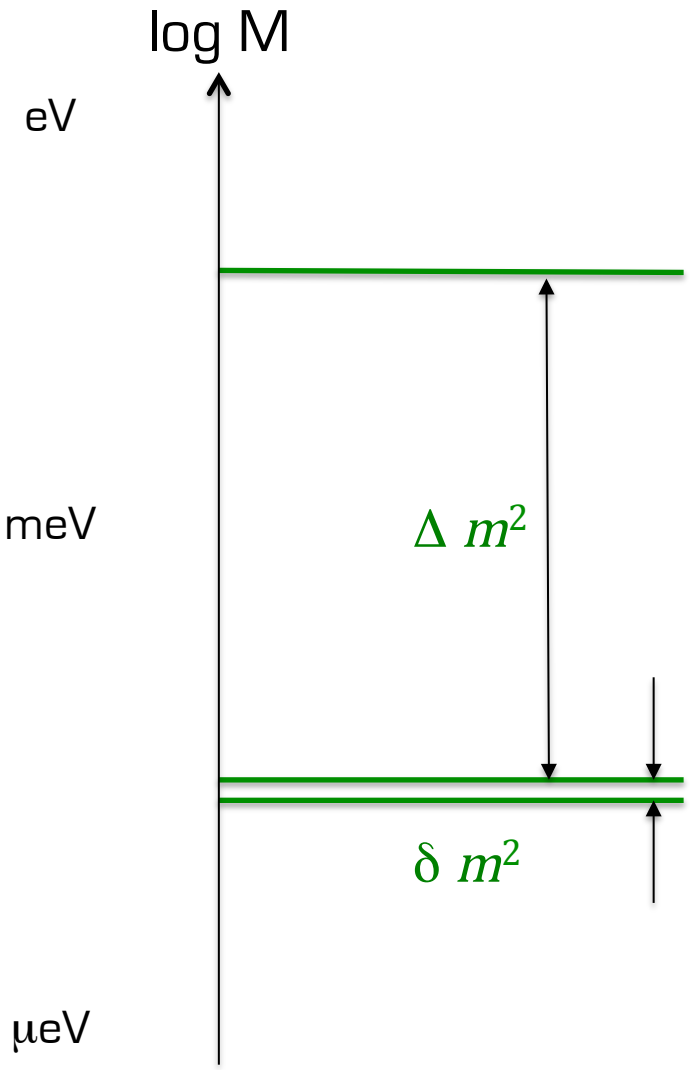
Neutrino Masses

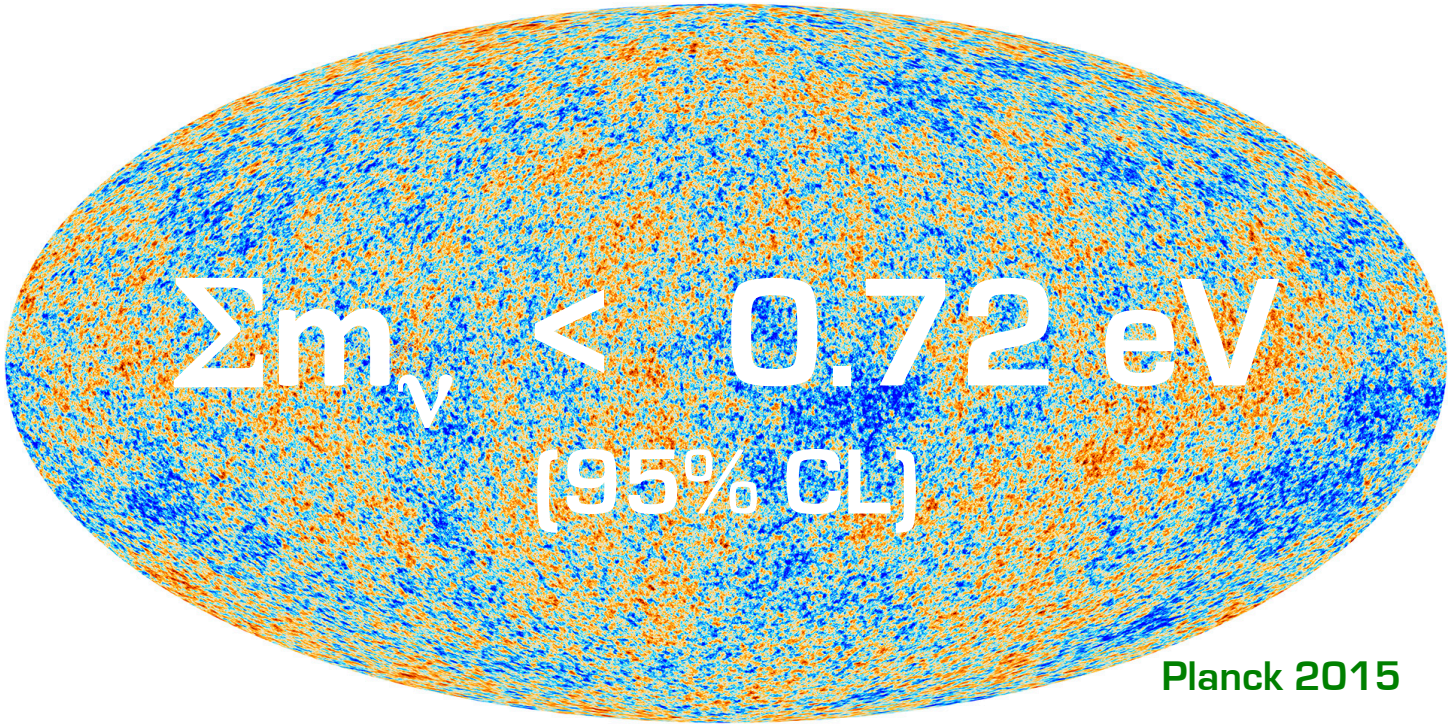


KATRIN neutrinoless beta decay



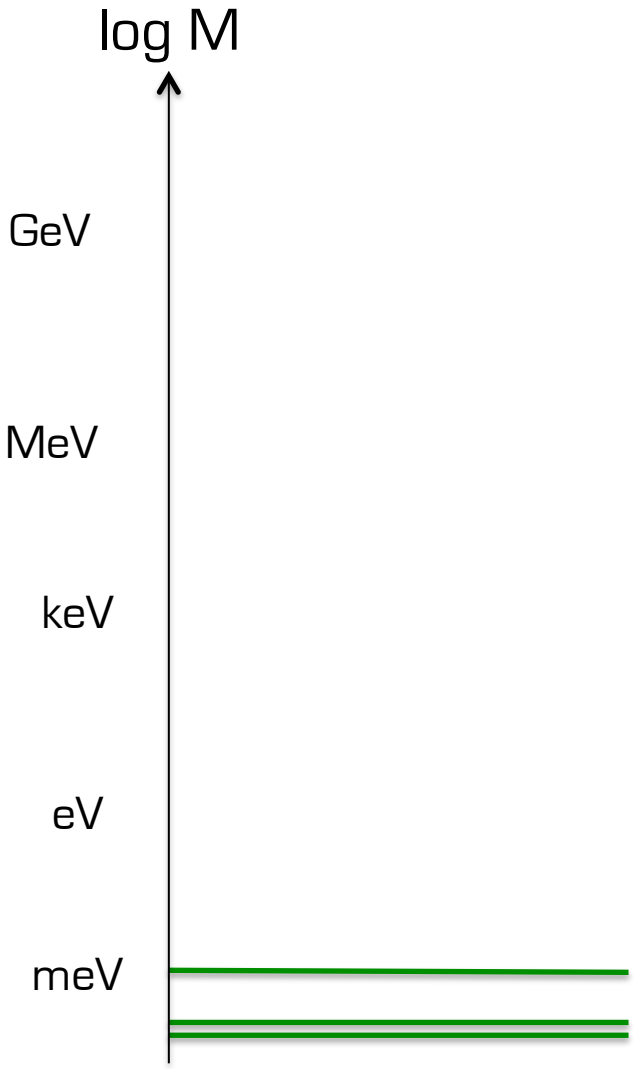
Cosmic Microwave Background





Planck 2015

Neutrino Masses

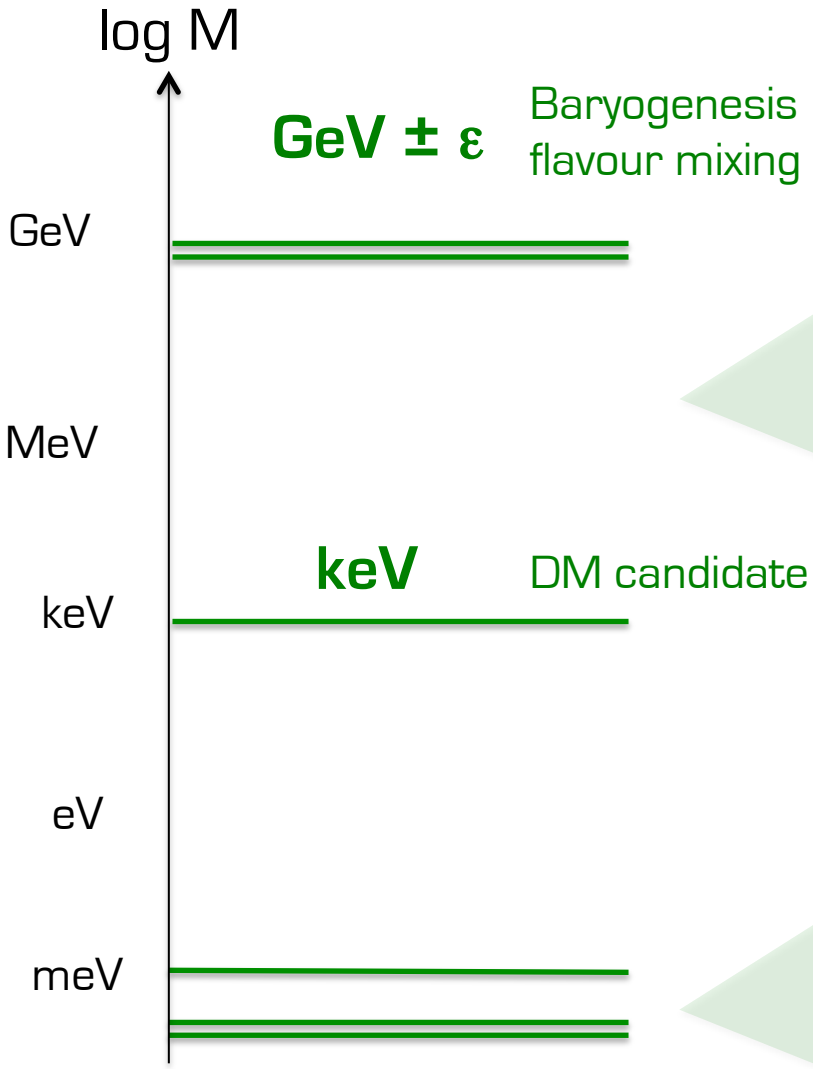


active sector

left-handed SU(2)×U(1) doublets

Standard Model

Sterile Neutrino DM



sterile sector

right-handed SU(2)×U(1) singlets

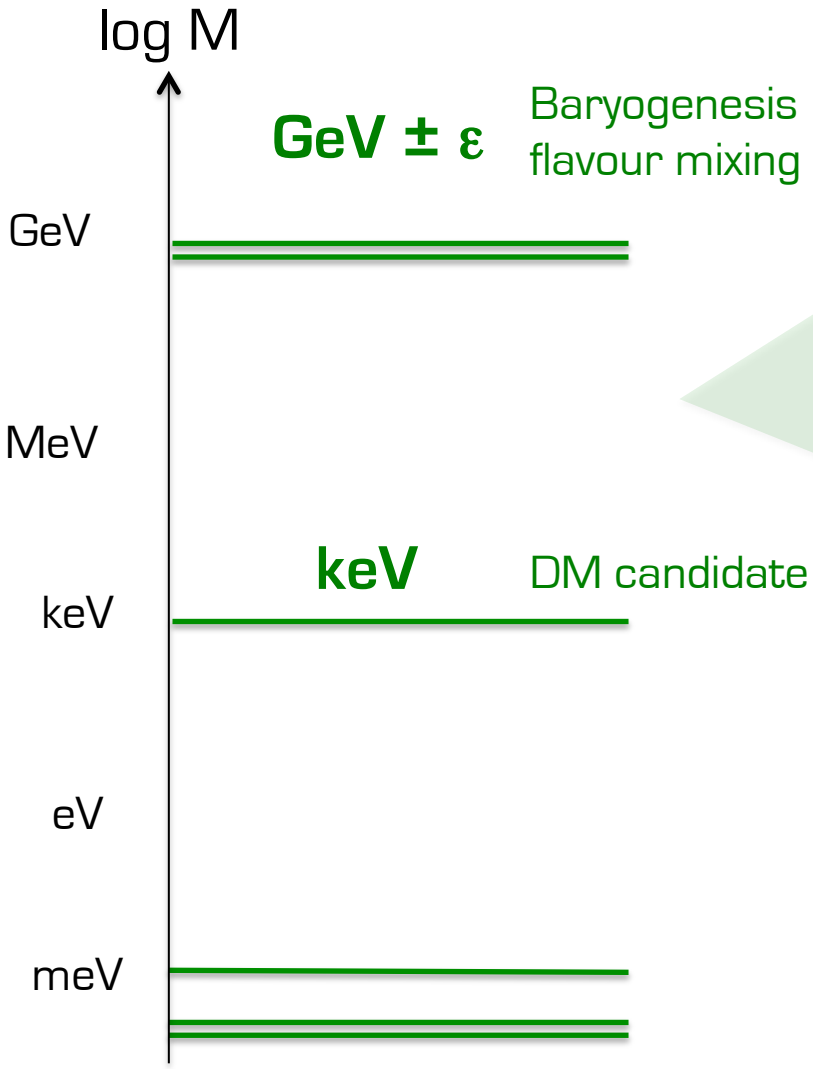
ν Minimal Extension

active sector

left-handed SU(2)×U(1) doublets

Standard Model

Sterile Neutrino DM



sterile sector

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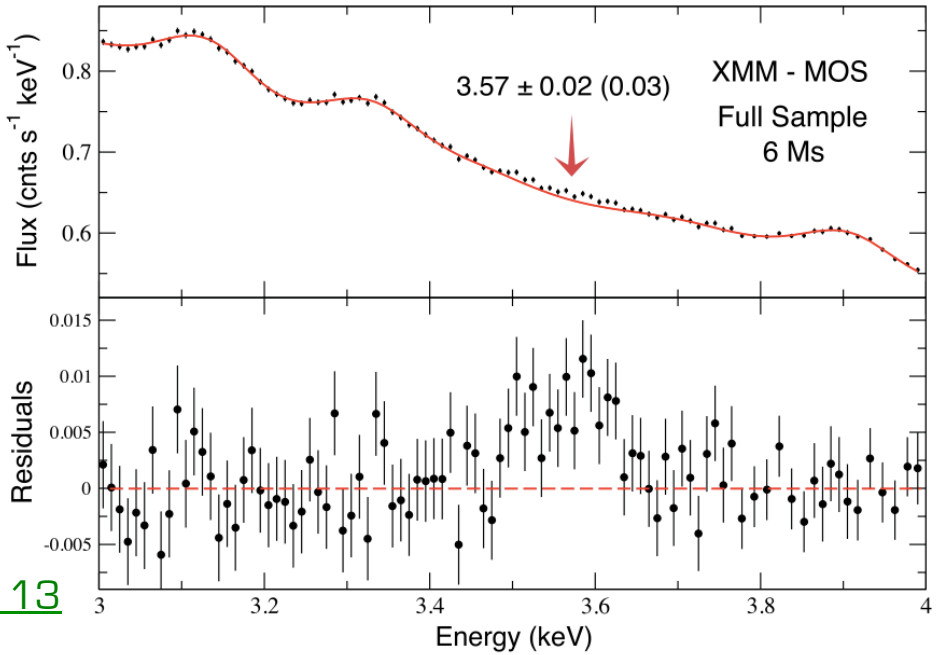
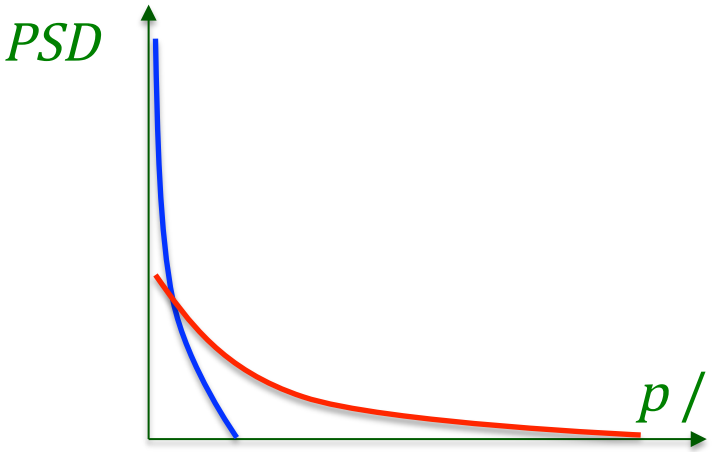
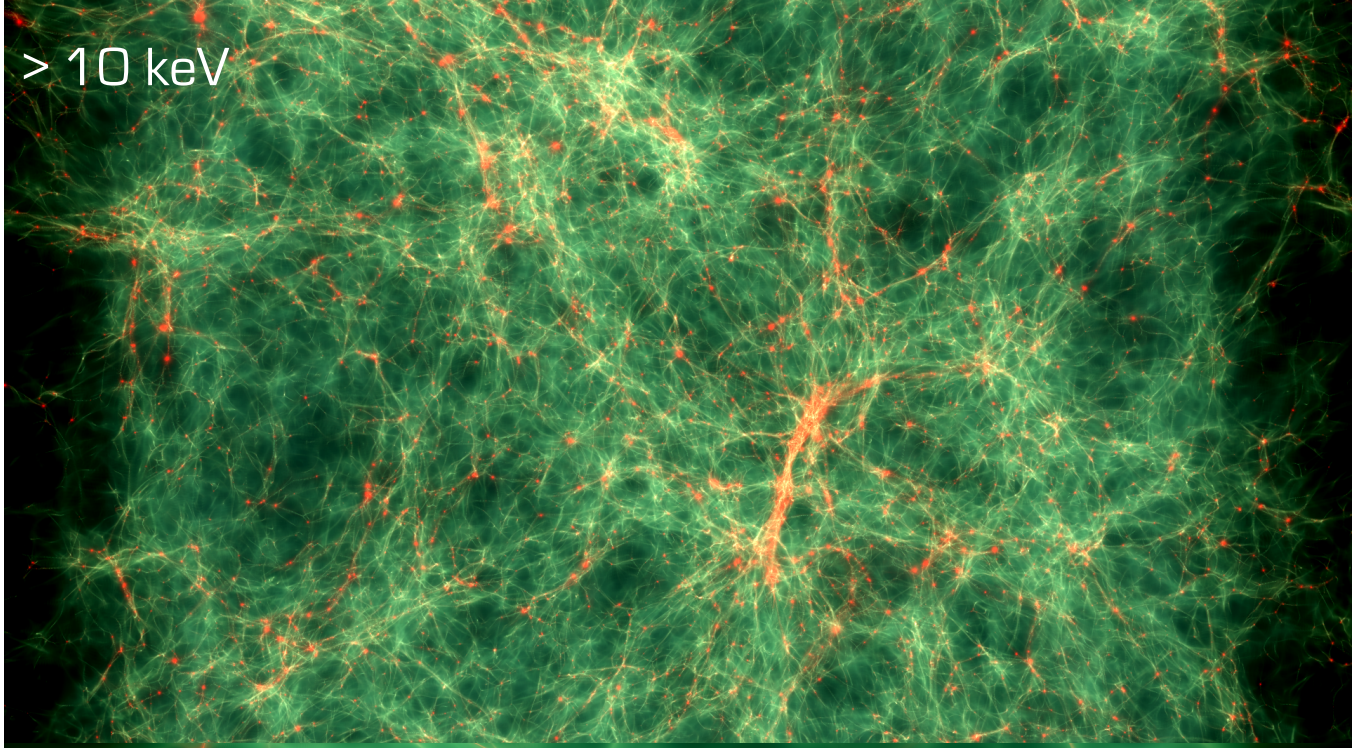


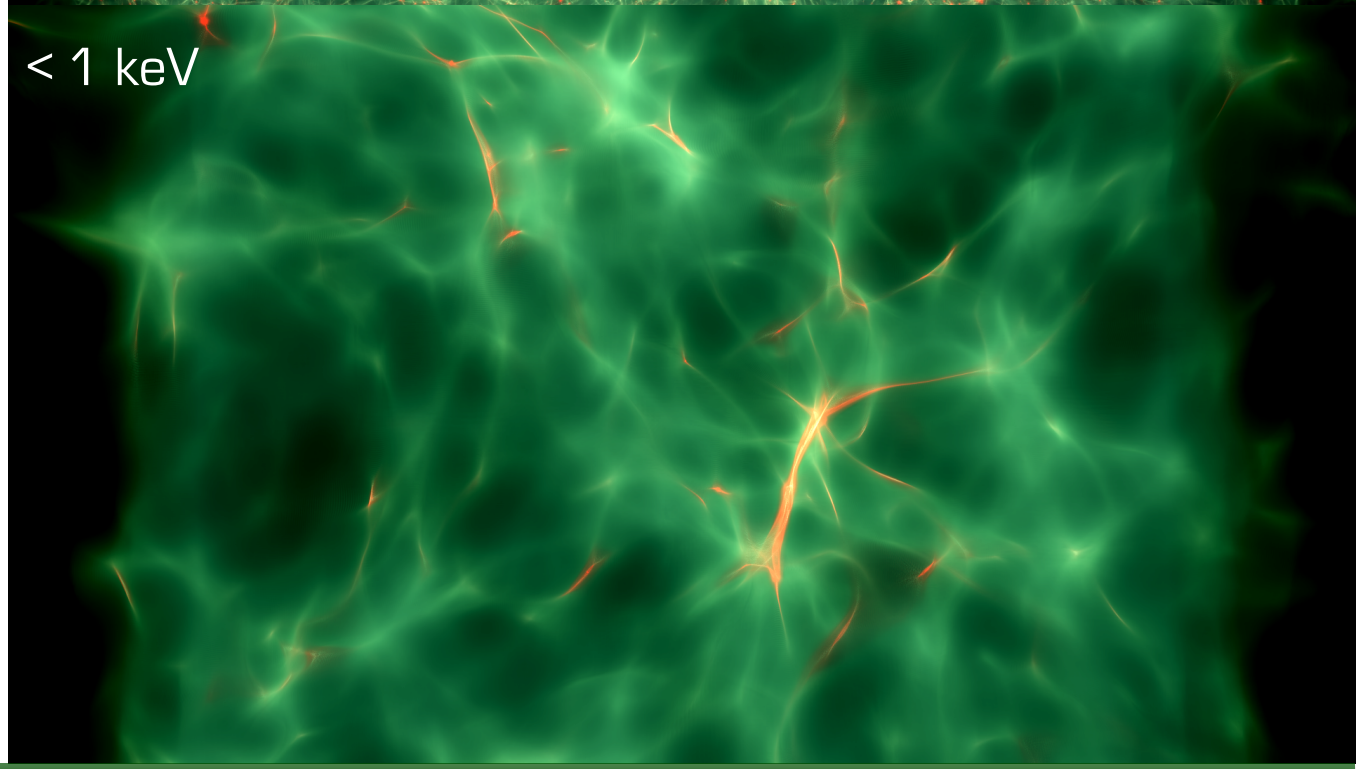
Bulbul *et al.*, 2014 ApJ 789 13

Cold Dark Matter





Hot Dark Matter

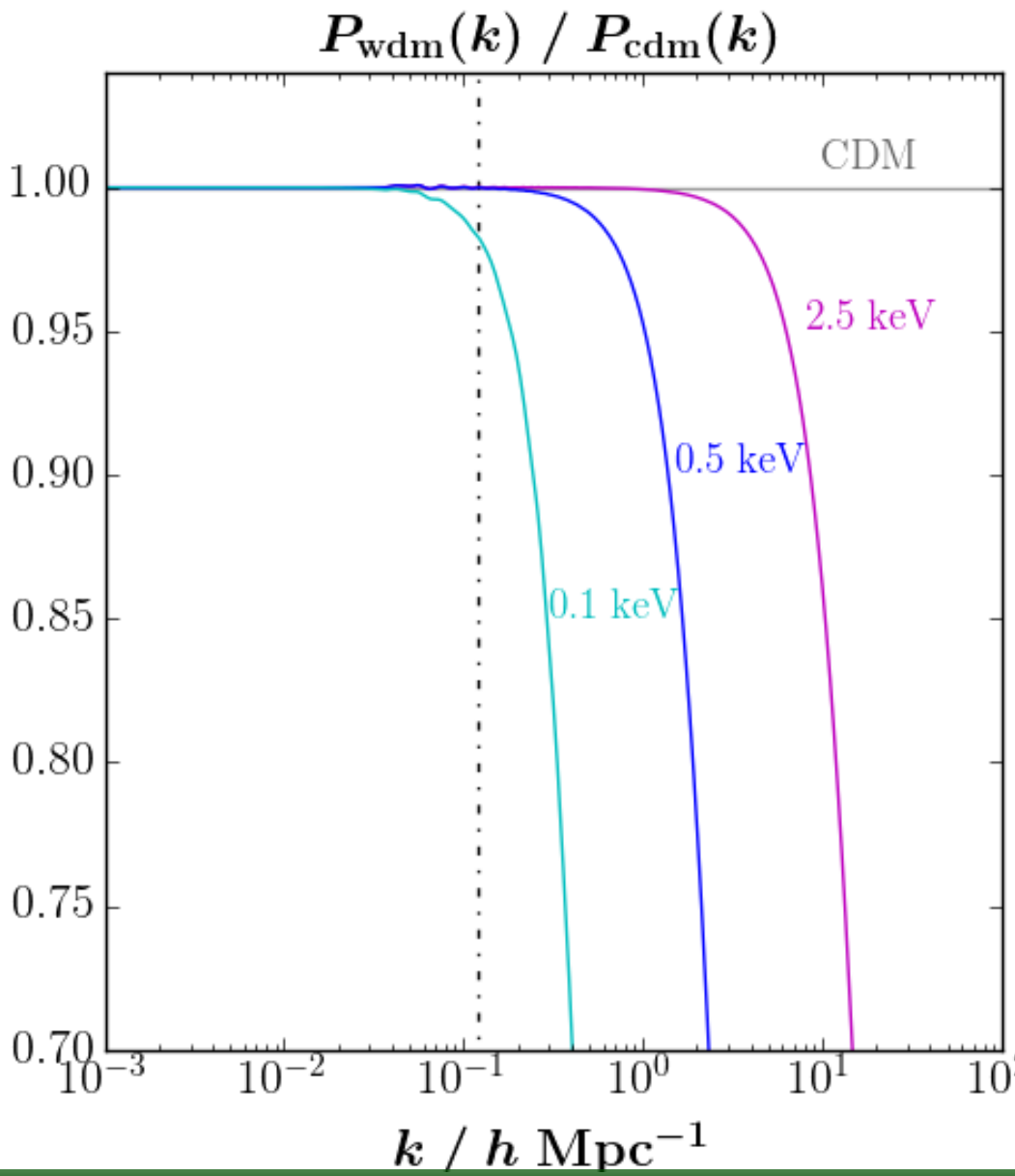


Free Streaming Horizon

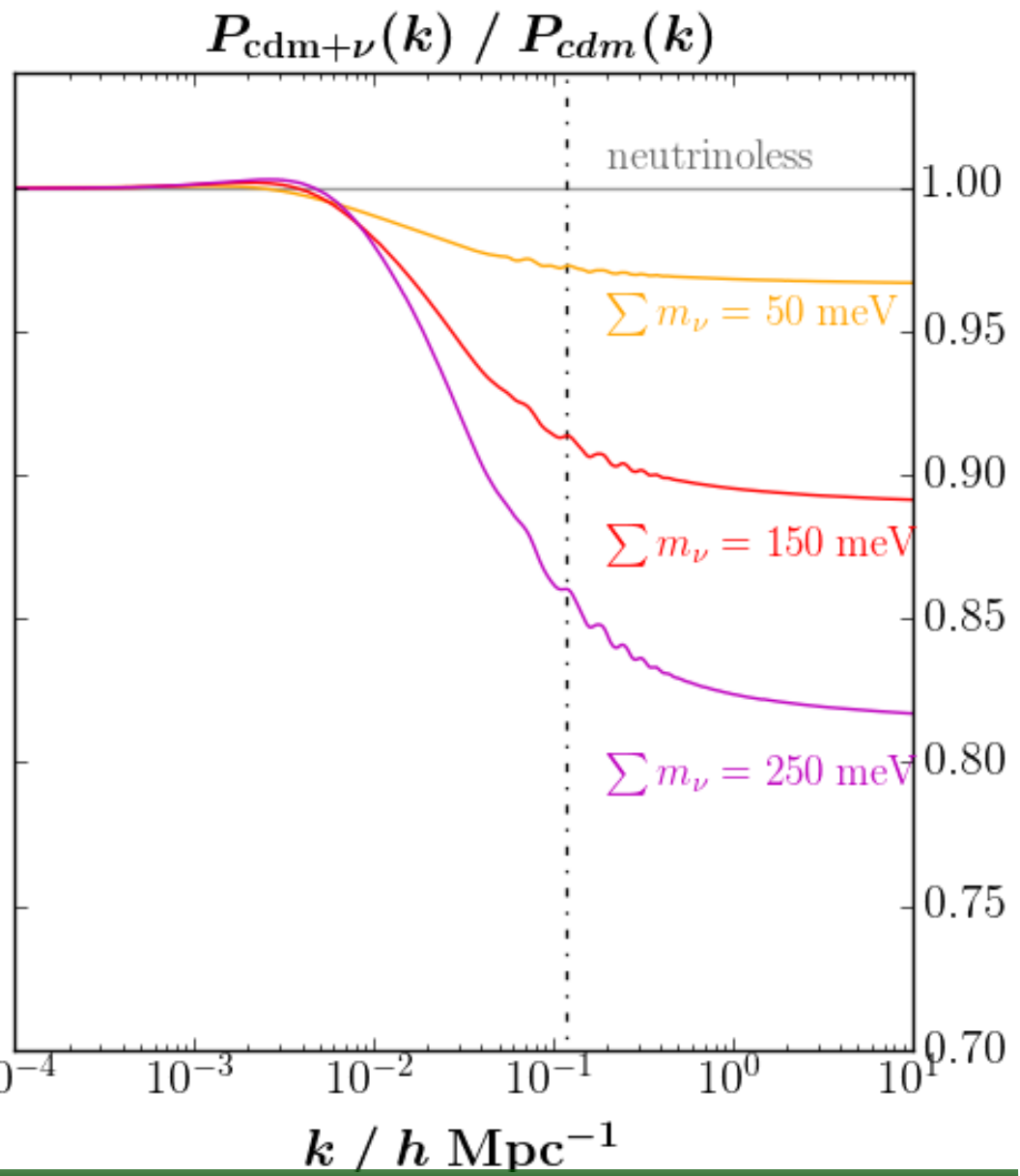
$$\lambda_{\mathrm{FSH}}^{0} = \int_{0}^{t_0} \frac{\langle v \rangle}{a}\, dt$$

Matter Power Spectrum (3D)

Λ-WDM

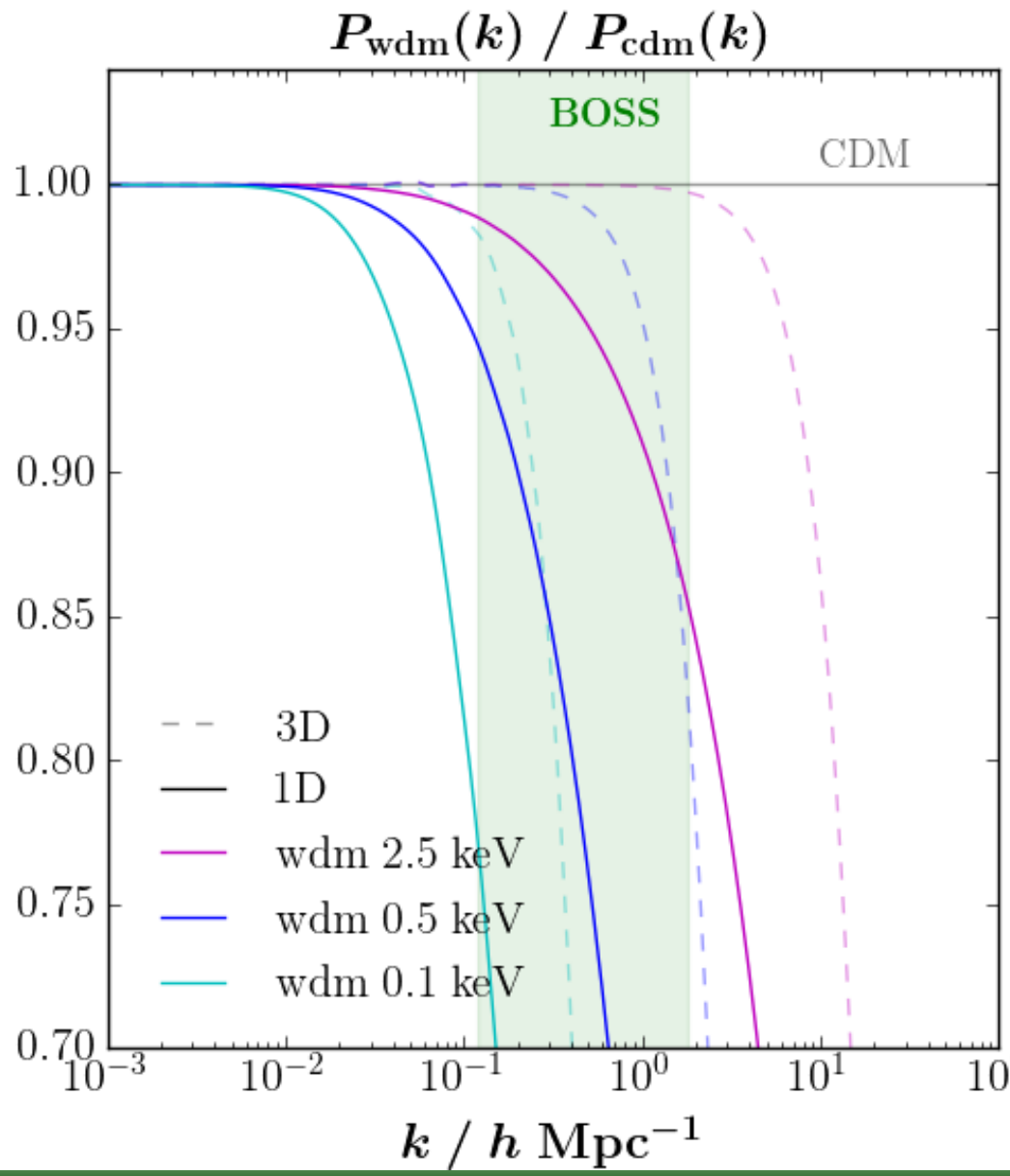


Λ-CDMν

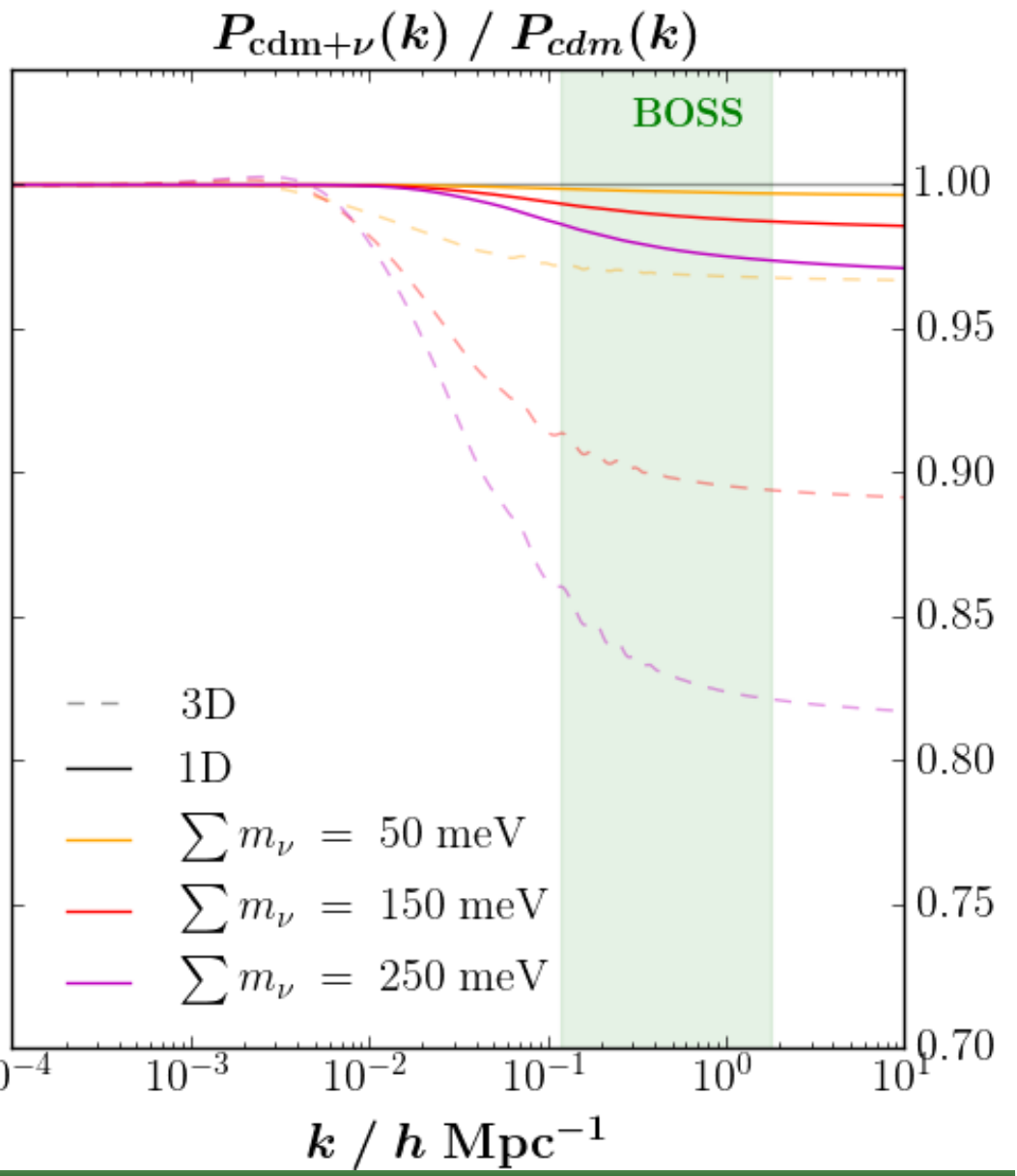


Matter Power Spectrum (1D)

Λ-WDM



Λ-CDMν



Roadmap

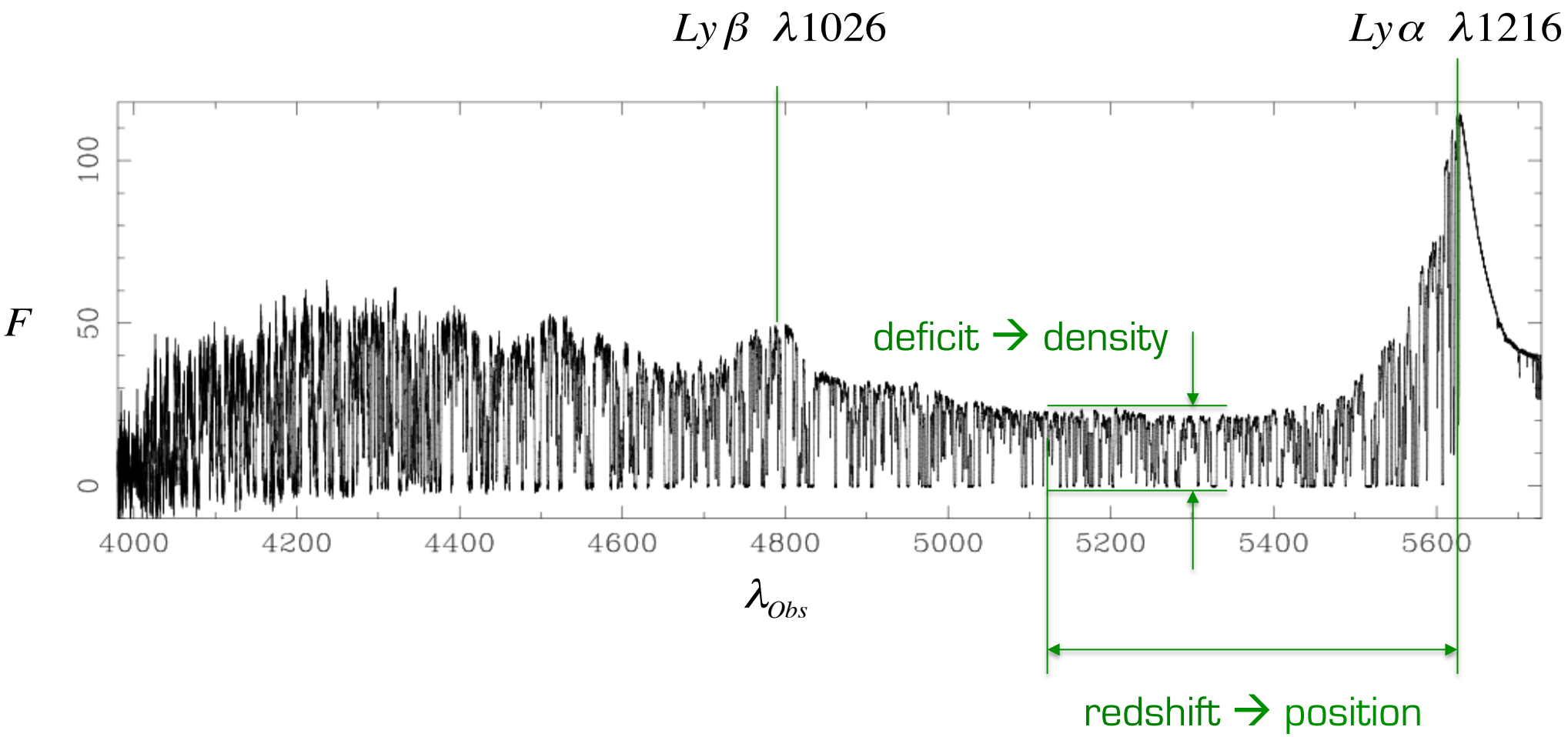
1 Neutrino Masses in Cosmology

2 The Ly-α Forest Observable

3 Hydrodynamics Simulations

4 Some Interesting Results ...

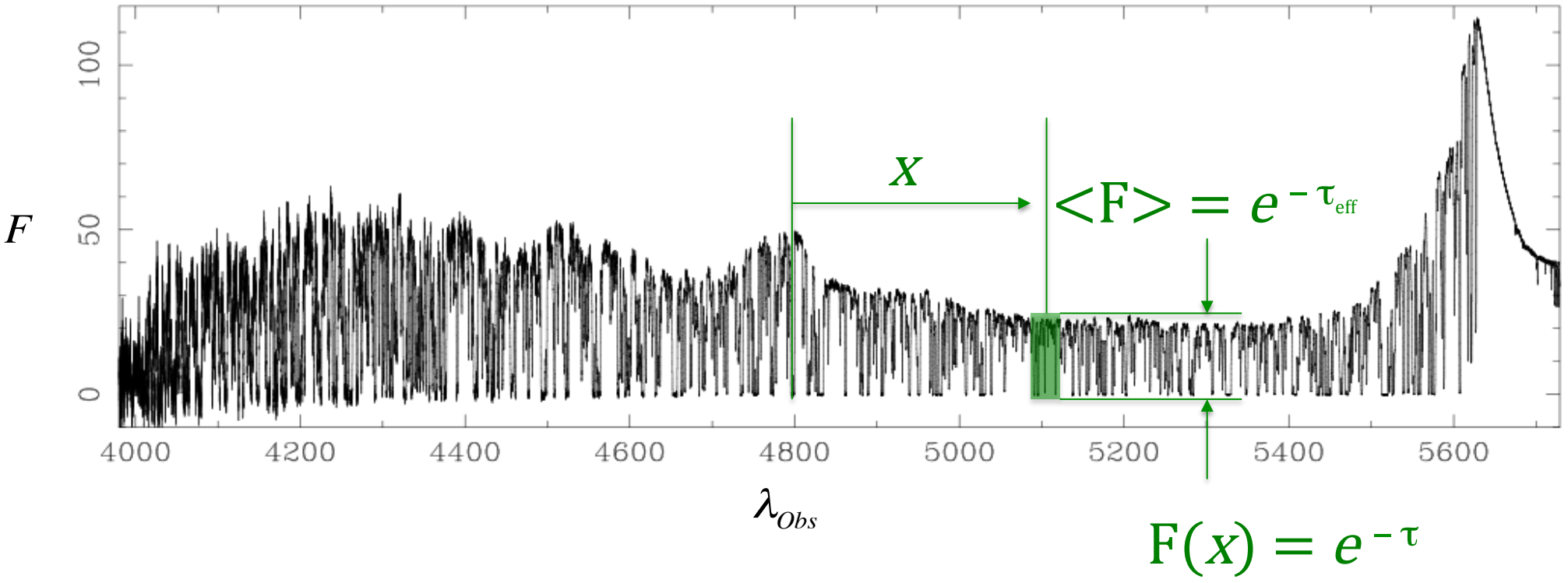
Lyman-alpha Forest



Lyman-alpha Forest

$$\delta(x) = \frac{F(x) - \langle F \rangle}{\langle F \rangle}$$

normalised transmitted flux fraction



Lyman-alpha Forest

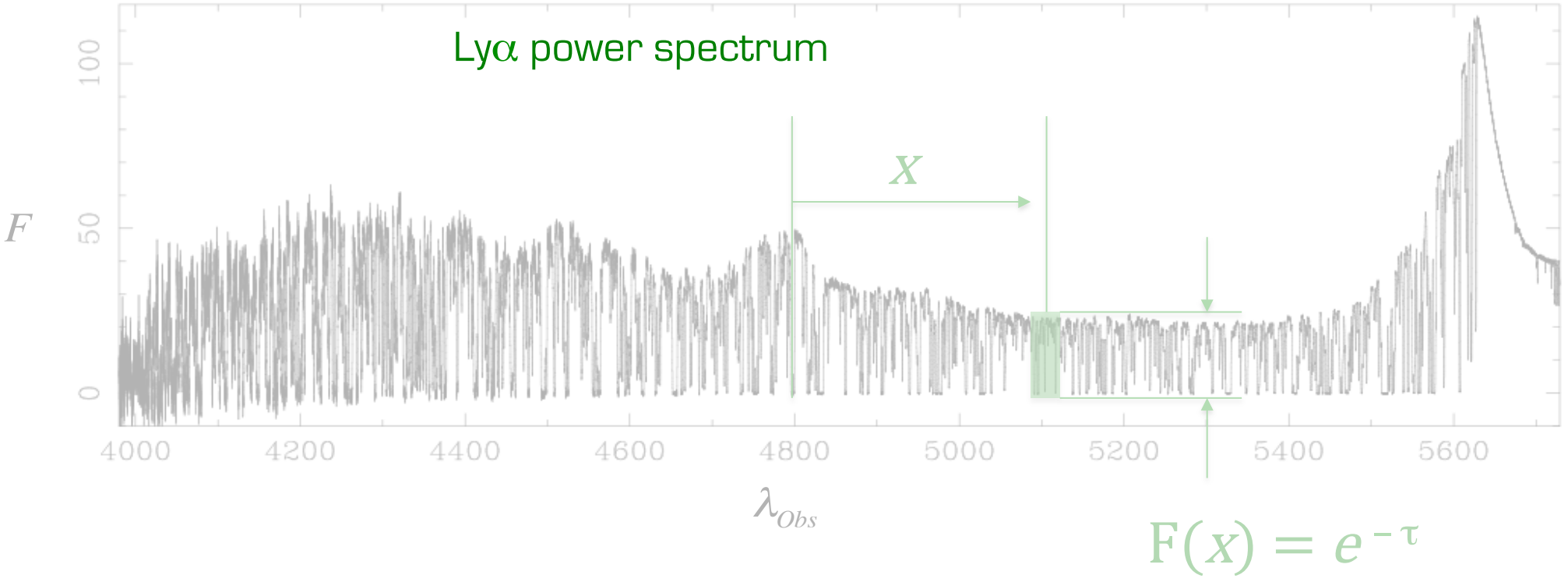
$$\delta(x) = \frac{F(x) - \langle F \rangle}{\langle F \rangle}$$

normalised transmitted flux fraction

Fourier Transform

$$\| \delta(k) \|^2 = \left(P_{Ly\alpha}(k) + P_{nuis}(k) \right) \times W^2(k) + P_{noise}(k)$$

Lyα power spectrum



Lyman-alpha Forest

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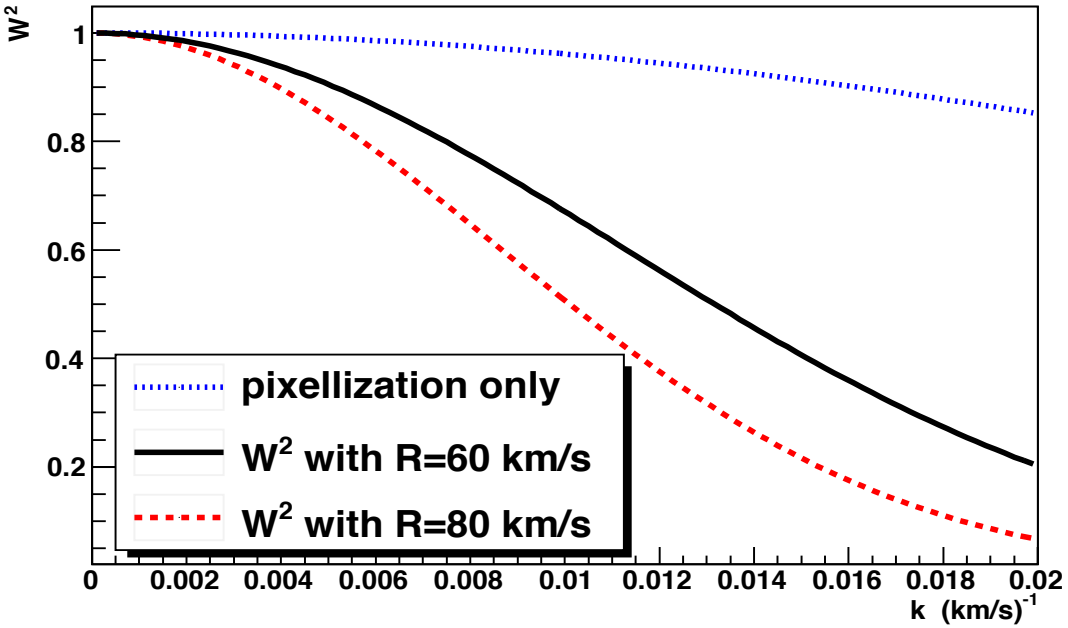
Window function



$$W(k, R, \Delta v) = \exp\left[\frac{-(kR)^2}{2}\right] \times \frac{\sin k\Delta v/2}{k\Delta v/2}$$

$\Delta v = 69$ km/s pixel size

R = 60–80 km/s resolution

$\sigma_{syst} \sim 3\%$ (high k)

Lyman-alpha Forest

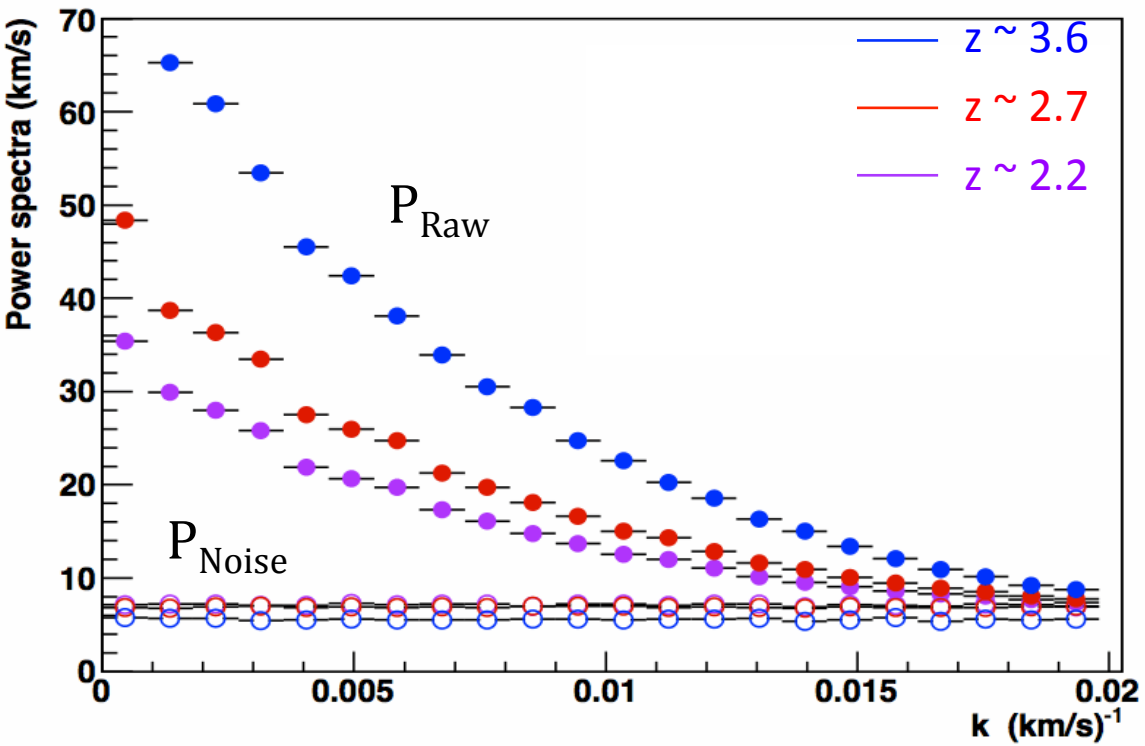
$$\delta(x) = \frac{F(x) - \langle F \rangle}{\langle F \rangle}$$

normalised transmitted flux fraction

Fourier Transform

$$\| \delta(k) \|^2 = \left(P_{Ly\alpha}(k) + P_{nuis}(k) \right) \times W^2(k) + P_{noise}(k)$$

white noise



estimated by subtracting different exposures of same quasar

$\sigma_{syst} \sim 2\%$ (high k, low z)

Lyman-alpha Forest

$$\delta(x) = \frac{F(x) - \langle F \rangle}{\langle F \rangle}$$

normalised transmitted flux fraction

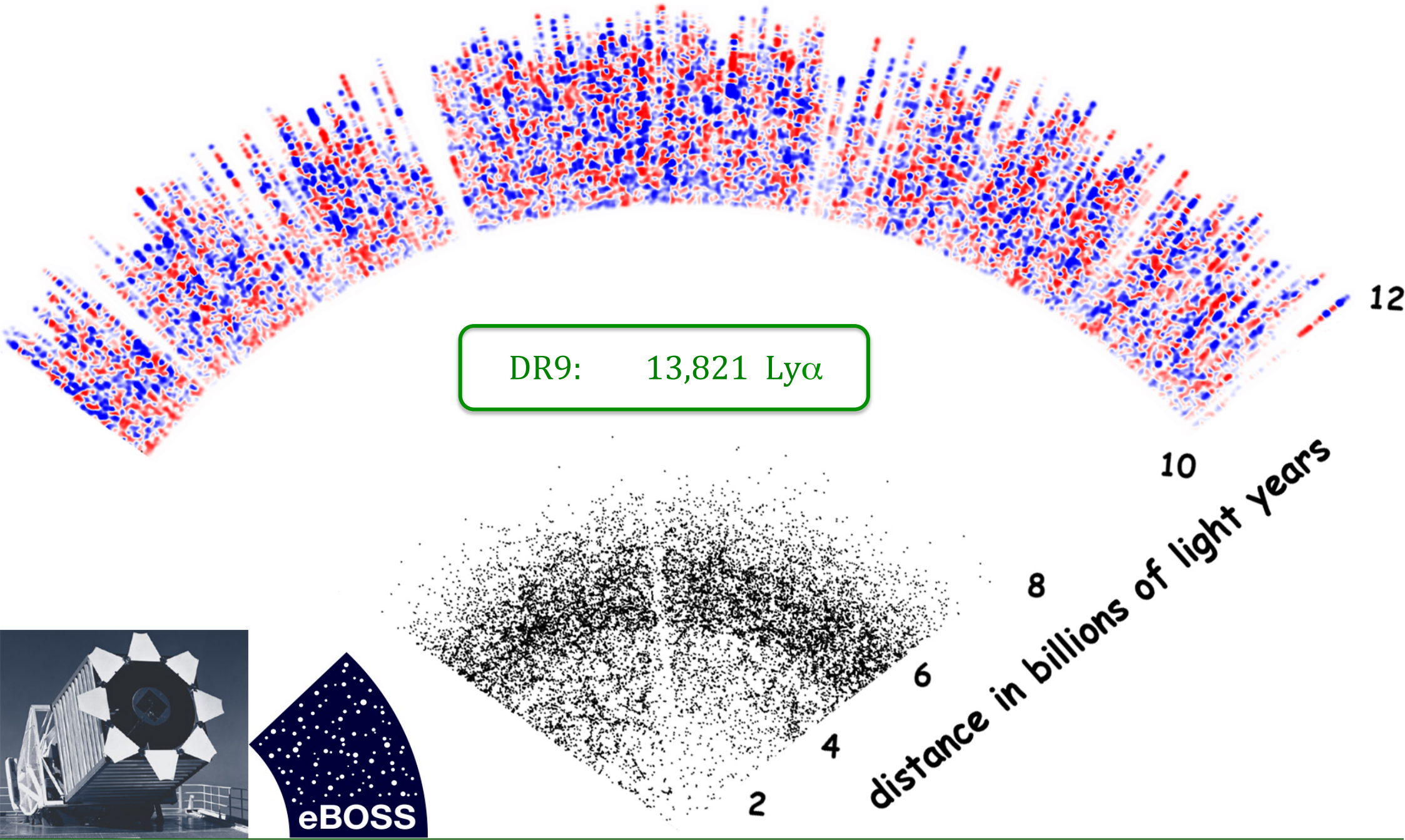
Fourier Transform

$$\| \delta(k) \|^2 = \left(P_{Ly\alpha}(k) + P_{nuis}(k) \right) \times W^2(k) + P_{noise}(k)$$

Lyα power spectrum

$$P_{Ly\alpha}(k) = \left\langle \frac{|\delta(k)|^2 - P_{noise}(k)}{W^2(k)} \right\rangle$$

Baryon Oscillation Spectroscopic Survey

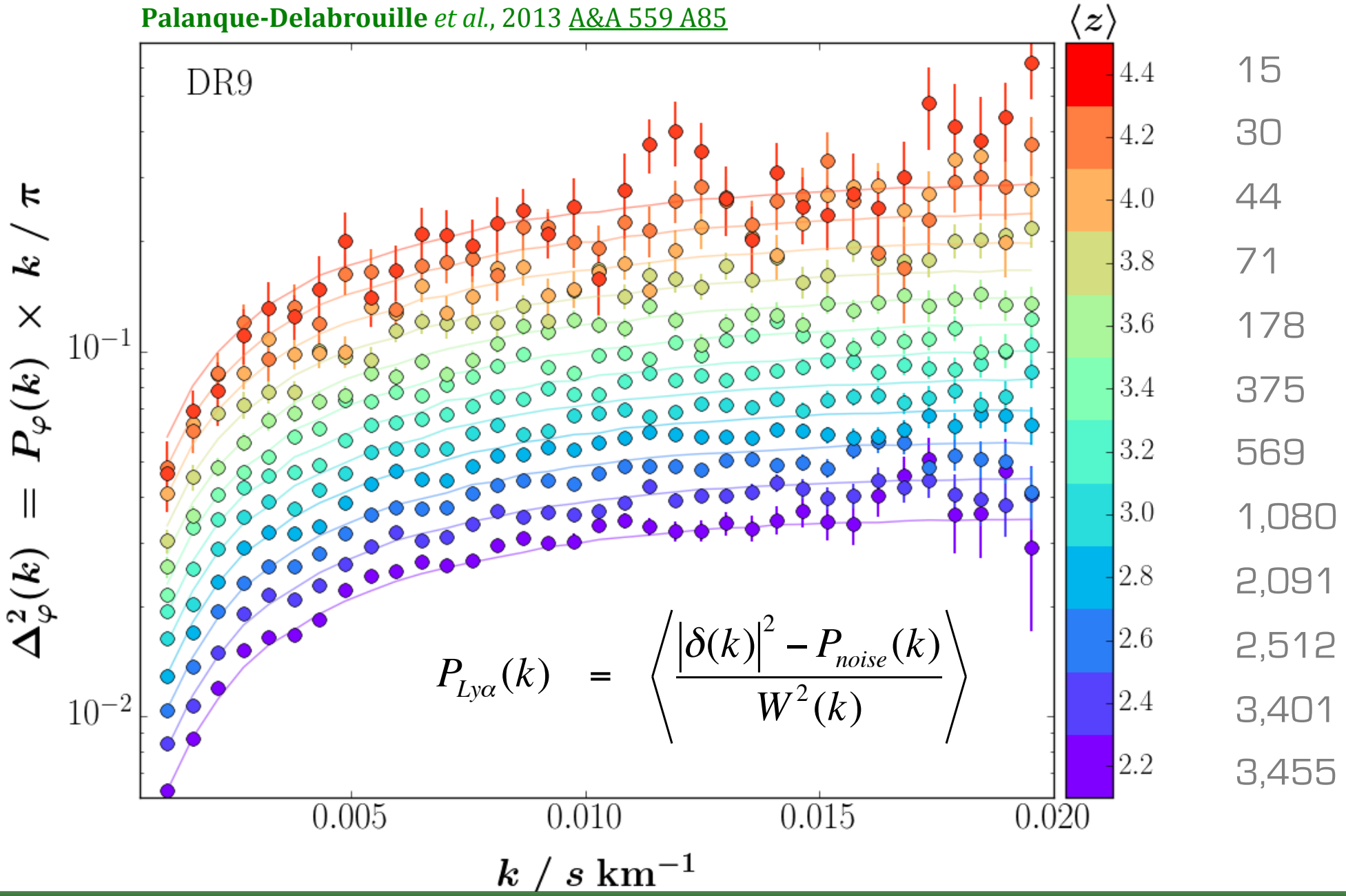


DR9: 13,821 Lyα

eBOSS

Flux Power Spectrum

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



Roadmap

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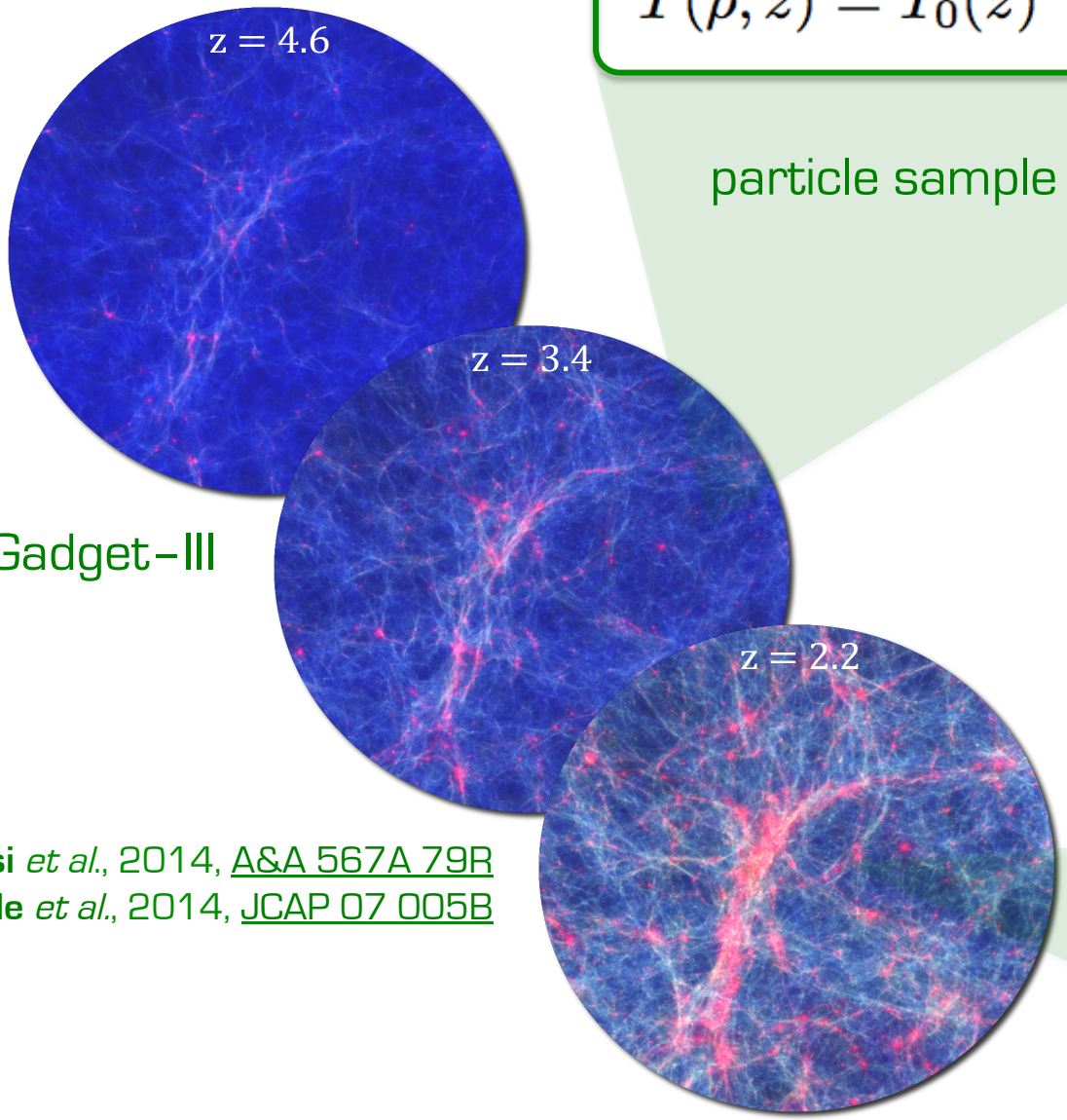
Hydro Simulations

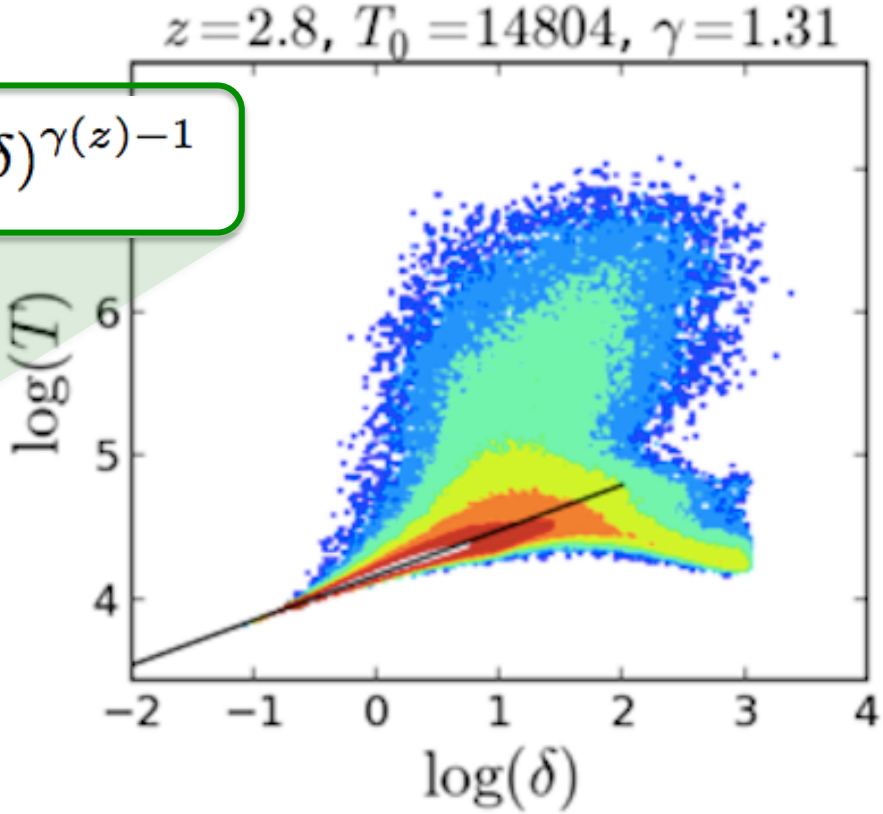


Gadget-III

Rossi *et al.*, 2014, A&A 567A 79R
Borde *et al.*, 2014, JCAP 07 005B

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

particle sample



L.O.S. sample

$$\tau \propto \int dv_{\parallel}\ \frac{n_H^2 \sqrt{T}}{\nabla v_{\parallel}\ n_{\gamma}} f(z)$$

$$F(r_{\parallel}) = e^{-\tau}$$

Parameters

parameter	*central*	*range*
$\Sigma m_\nu \,/\, eV$	ν *less*	$+0.4\,+0.8$
$keV \,/\, m_X$	0.0	$+0.2\,+0.4$
h	0.675	± 0.05
Ω_M	0.31	± 0.05
σ_8	0.83	± 0.05
n_s	0.96	± 0.05
z_{reio}	12	± 4
$T_0^{z=3} \,/\, K$	14,000	$\pm 7{,}000$
$\gamma^{z=3}$	1.3	± 0.3
A^τ	0.0025	± 0.0020
η^τ	3.7	± 0.4

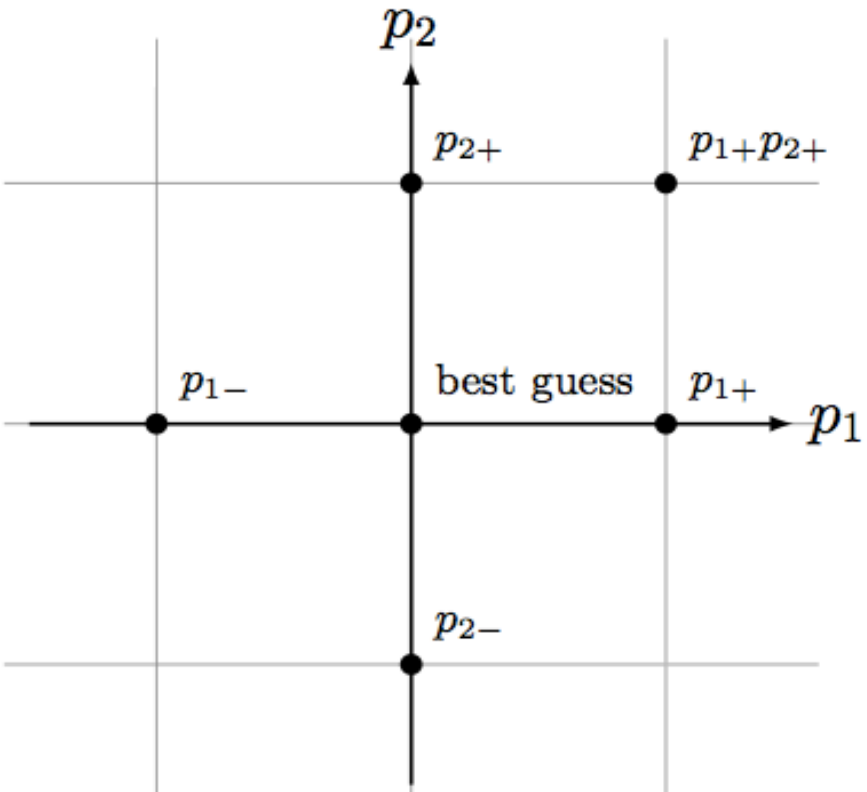
Λ–CDMν only

Λ–WDM only

Cosmology

Intergalactic Medium

Optical Depth



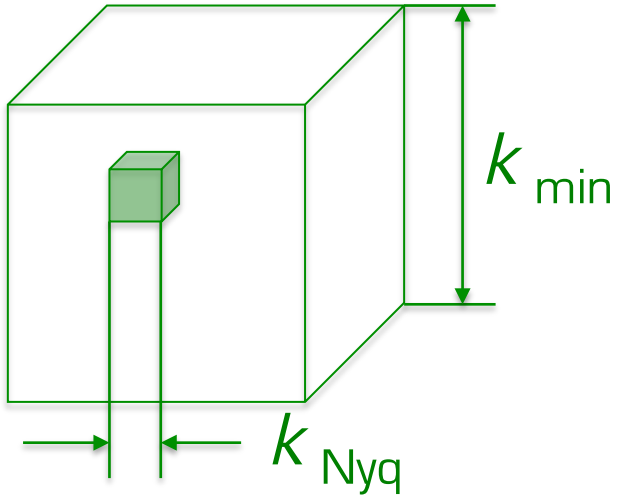
2nd order Taylor expansion

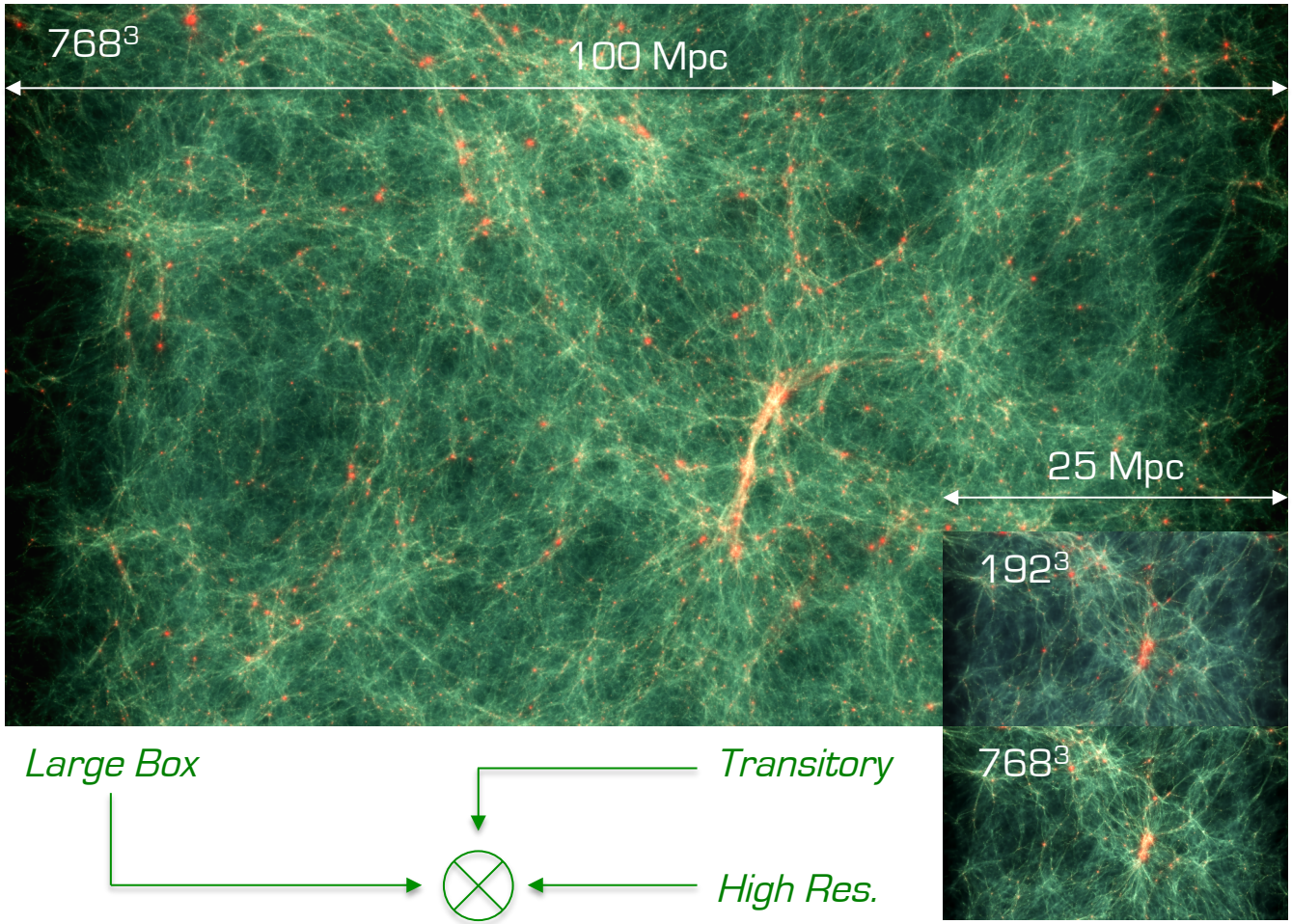
$$\langle F \rangle = e^{-\tau_{eff}}$$

fixing UV photoionization rate

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

Splicing the Power Spectrum



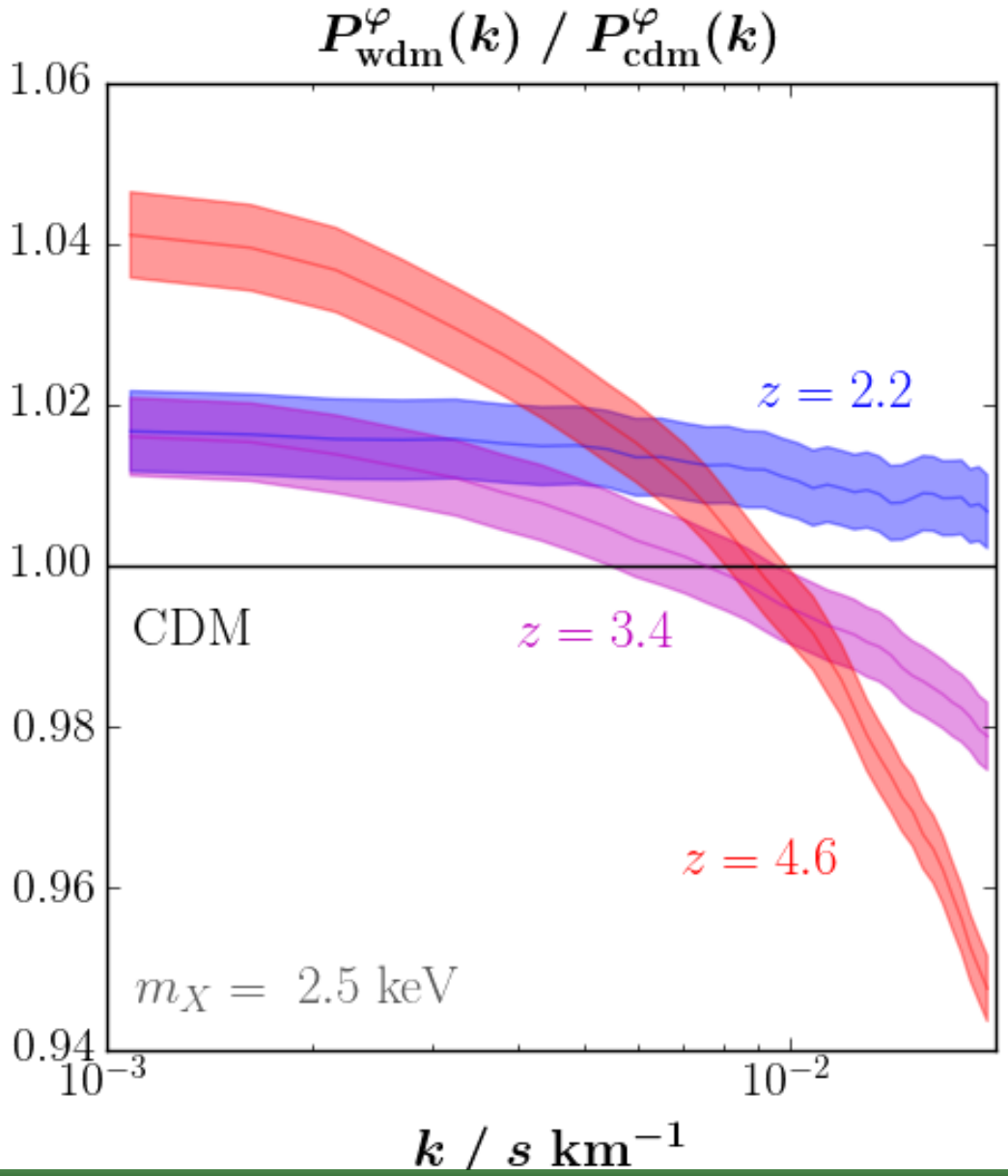


$\sigma_{syst} \sim 3\%$
(high k, high z)

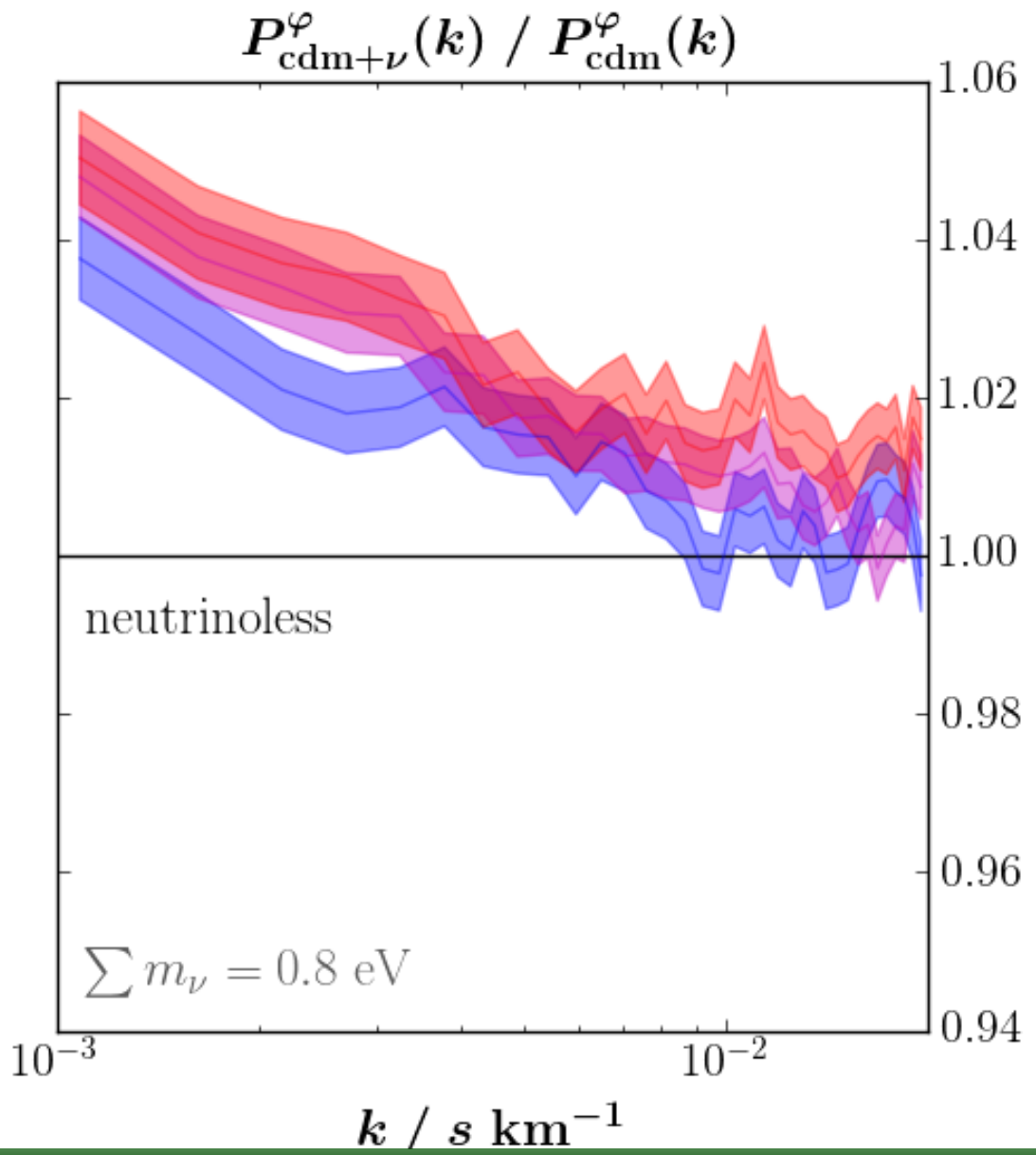
3072^3 particles per species in $(100\ \text{Mpc})^3$ box

Lyα Power Spectrum (1D)

Λ-WDM



Λ-CDMν



Roadmap

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3. Hydrodynamics Simulations
4. Some Interesting Results ...

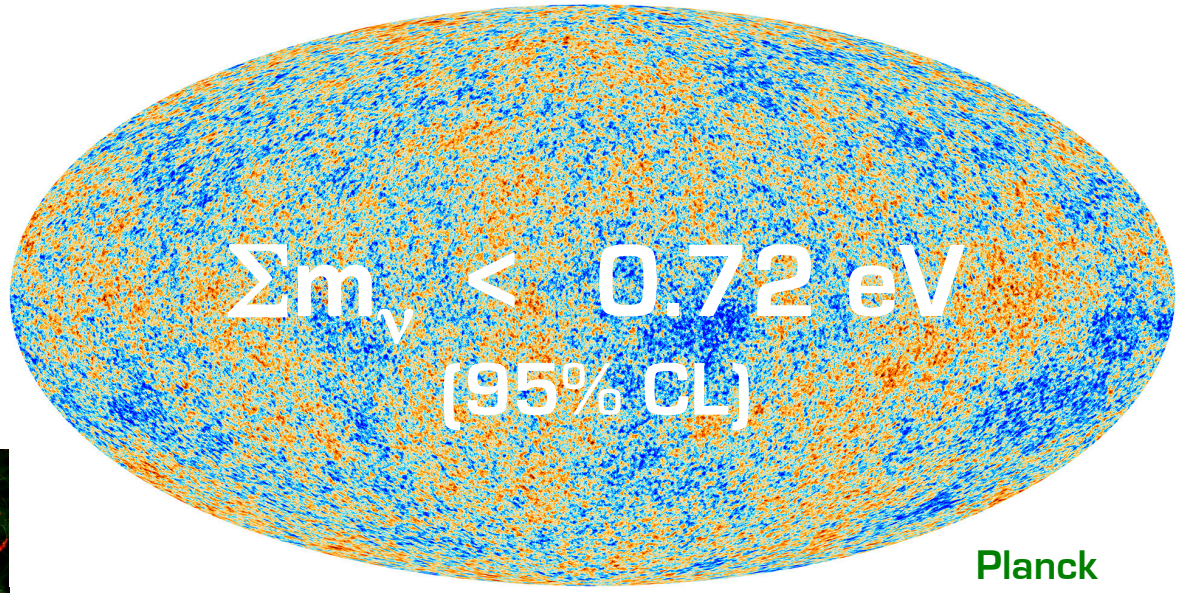
Nuissance Parameters

Palanque-Delabrouille *et al.*, 2015 JCAP 02 045

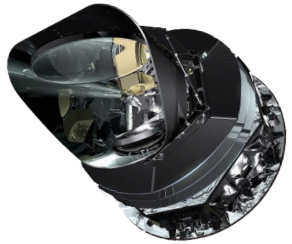
Reference (Lyα+CMB) : $\Sigma m_\nu < 0.15$ eV (95% CL)

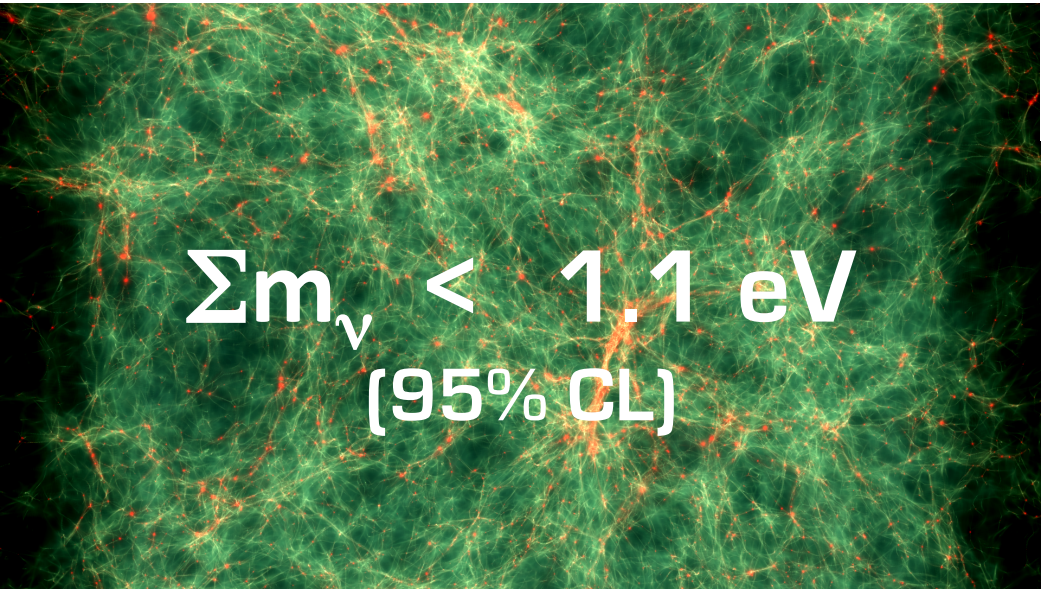
		σ_8	n_s	Σm_ν
Technical:	Simulation Splicing	$\pm$0.001	$\pm$0.002	$\pm$0.03
	Spectrograph Resolution	+0.000	+0.000	+0.00
Astrophysical:	IGM state	+0.000	–0.001	+0.02
	AGN feedback	–0.001	+0.001	+0.02
	SN feedback	+0.001	–0.001	–0.01
	UV fluctuations	+0.001	–0.002	–0.03
	Damped Lya Absorbers	+0.000	+0.002	+0.03

Constraints on Neutrino Masses



Planck



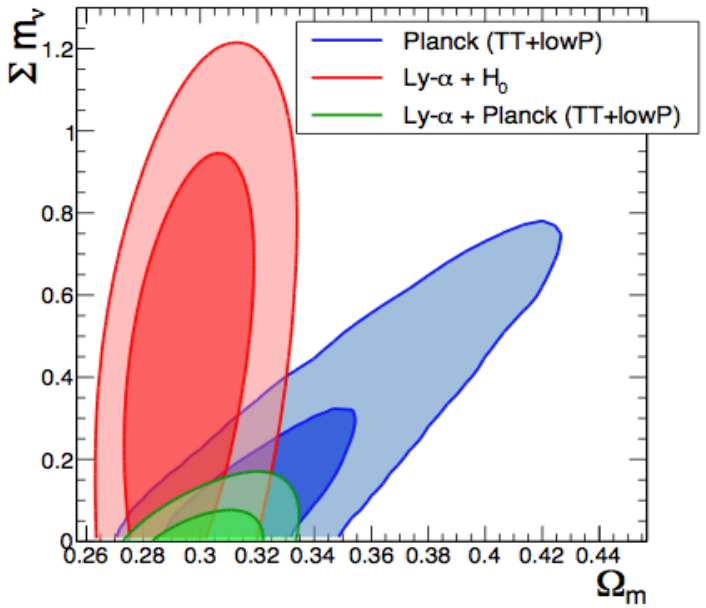


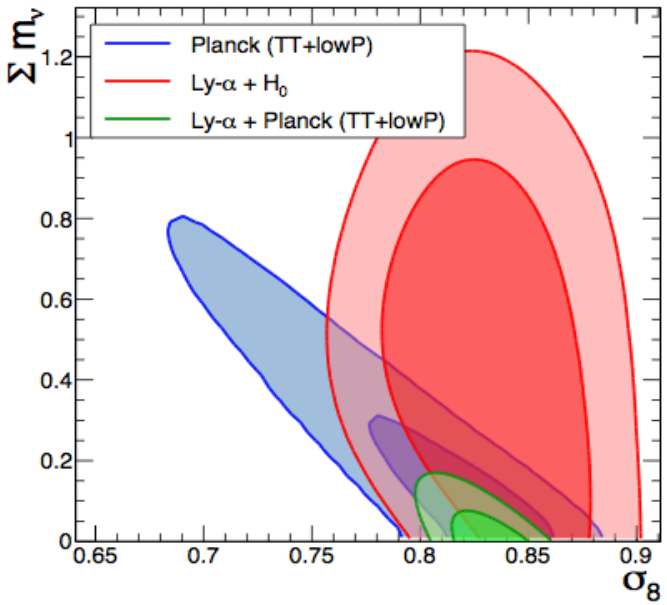
BOSS

Constraints on Neutrino Masses

Palanque-Delabrouille *et al.*, 2015 JCAP 11 011

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





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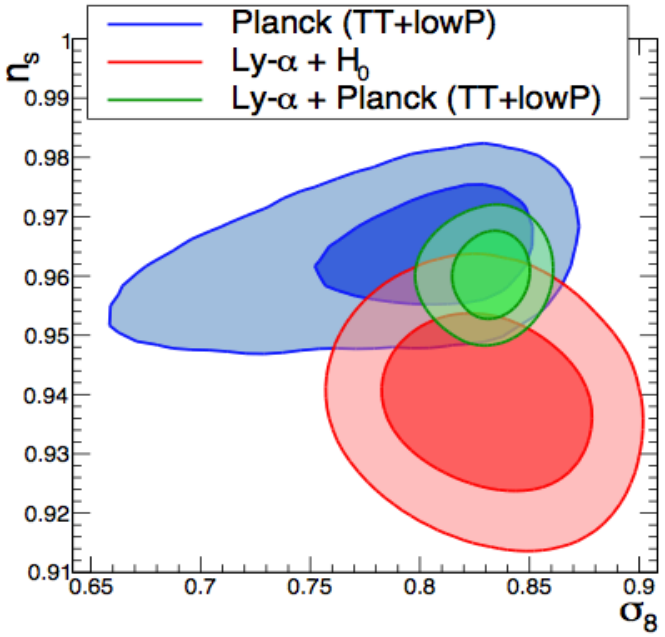


Limit is unchanged when freeing the running on n_s

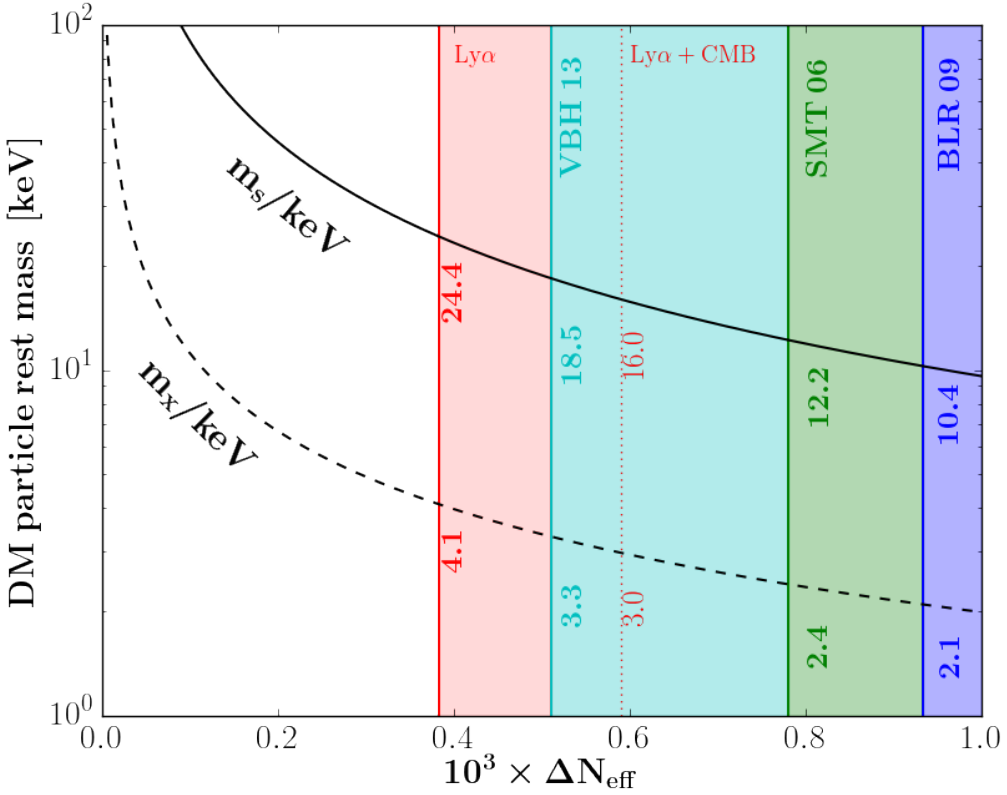
$$P_s = \left(\frac{k}{k_0}\right)^{n_s - 1 + \frac{1}{2}\mathrm{d}n_s/\mathrm{d}\ln k \ln(k/k_0)}$$

Constraints on WDM

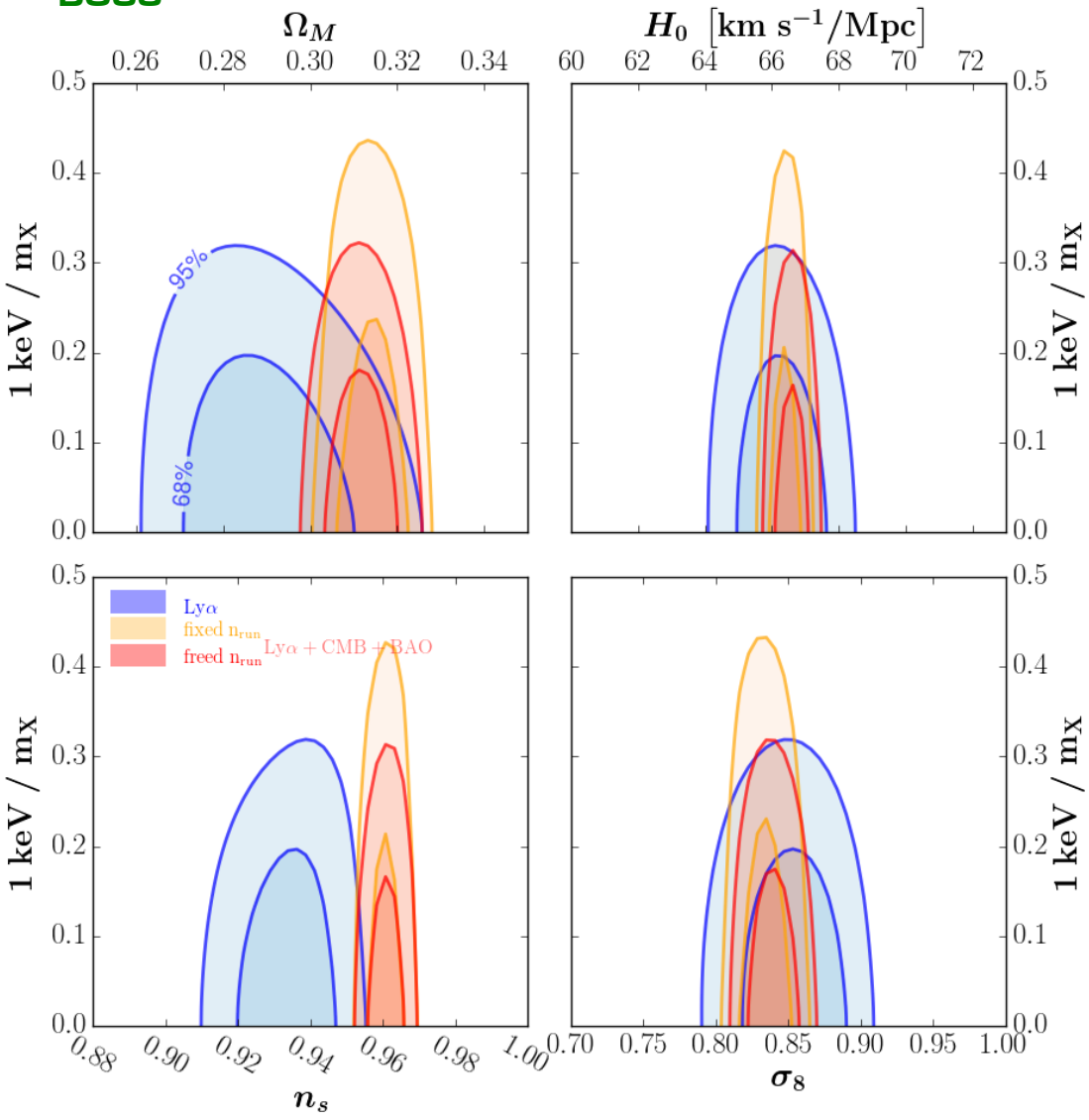
Baur *et al.*, 2016 JCAP 08 012

BOSS only : $m_{wdm} > 4.1$ keV (95% CL)

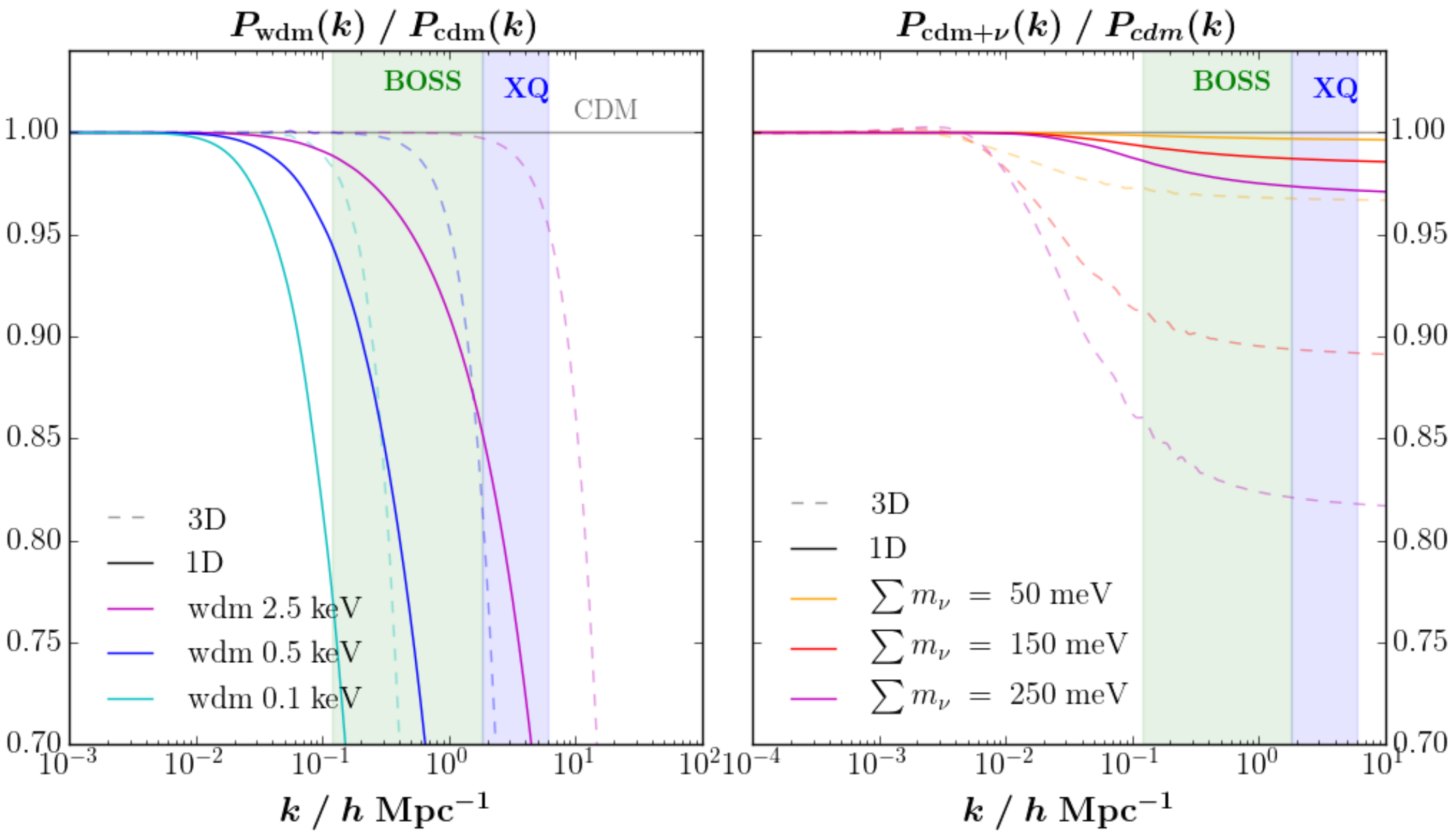
Planck + BOSS : $m_{wdm} > 3.0$ keV (95% CL)



BOSS



Upcoming: higher k with *XQ-100*



Takeaway

– Lyα forests probe Mpc scales <==> ν free streaming scale

– Complementary probe to CMB, WL, galaxy clustering

– ~14,000 med-res QSO sample and most resolute hydro simulations

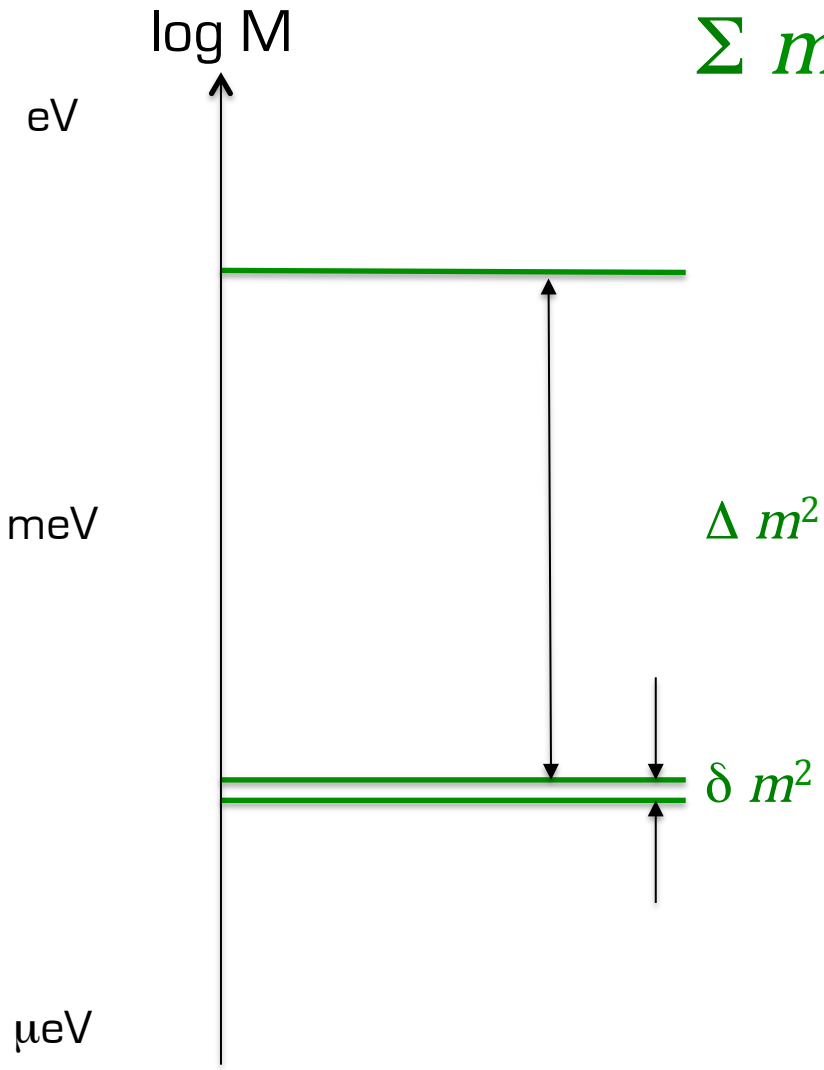
– 11 simu + 13 nuissance + 12 noise parameters marginalised over

– BOSS DR9: $\Sigma m_\nu < 0.12$ eV (95%CL) and $m_{wdm} > 4.1$ keV (95%CL)

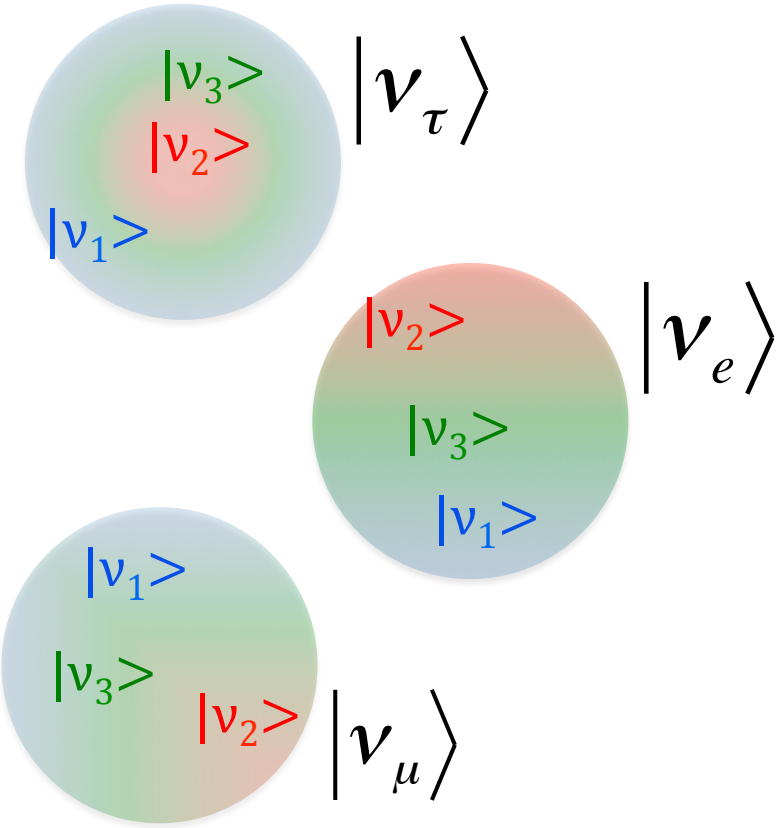
Thank You !

julien.baur@cea.fr

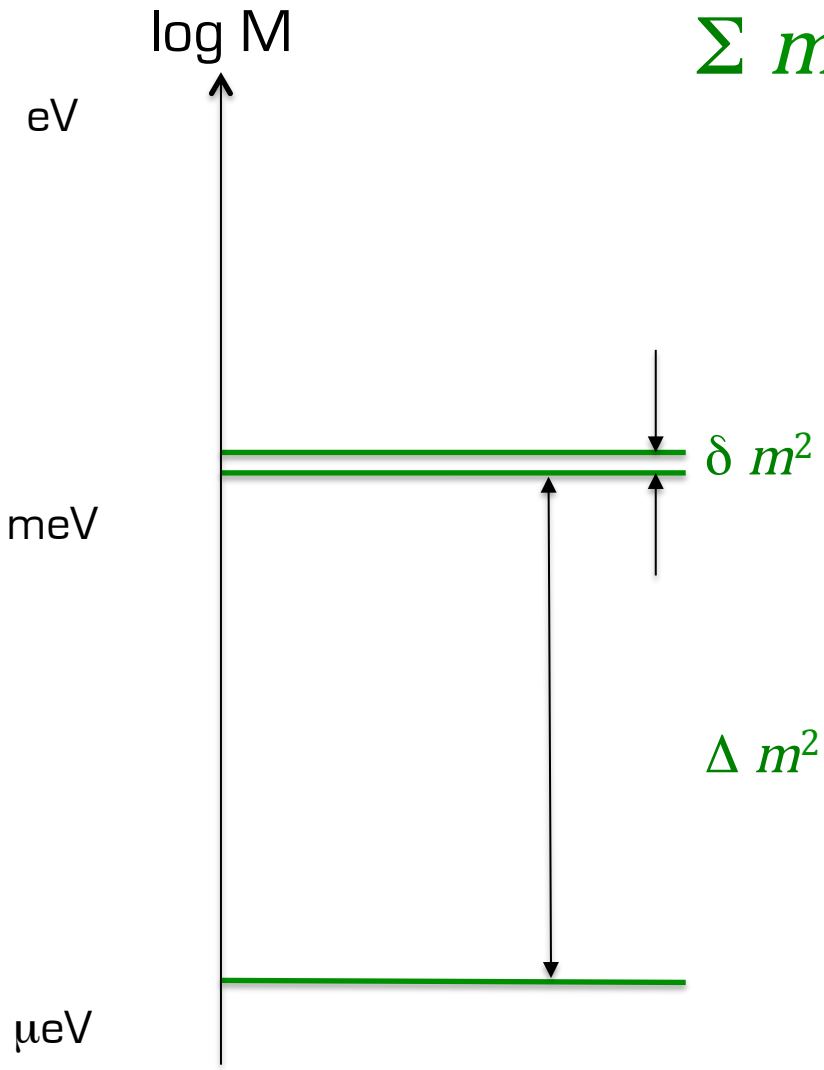
Normal Ordering



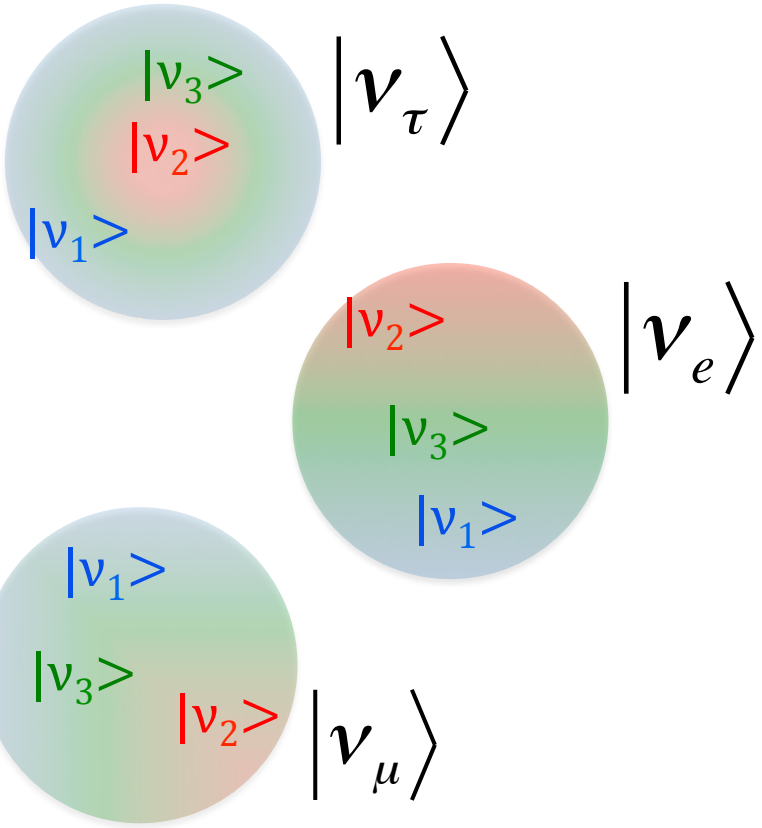
$$\Sigma\, m_\nu \;\geq\; 0.06\ \text{eV}$$

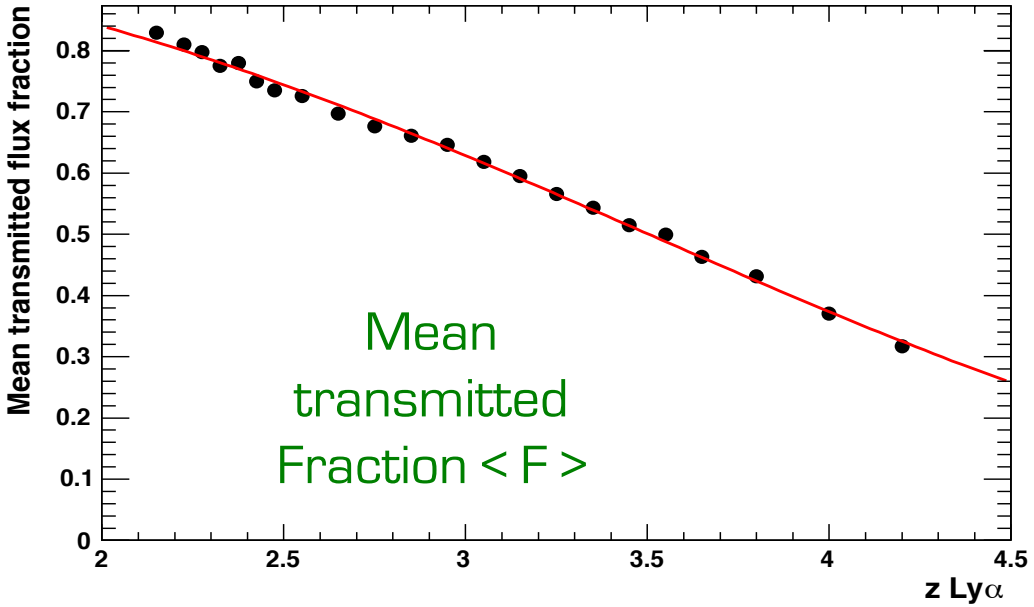


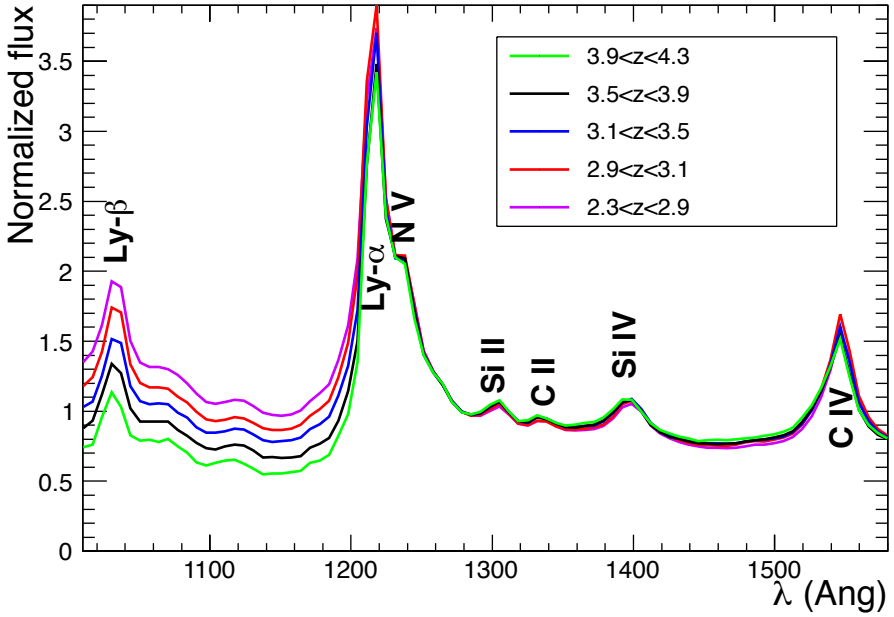
Inverted Ordering

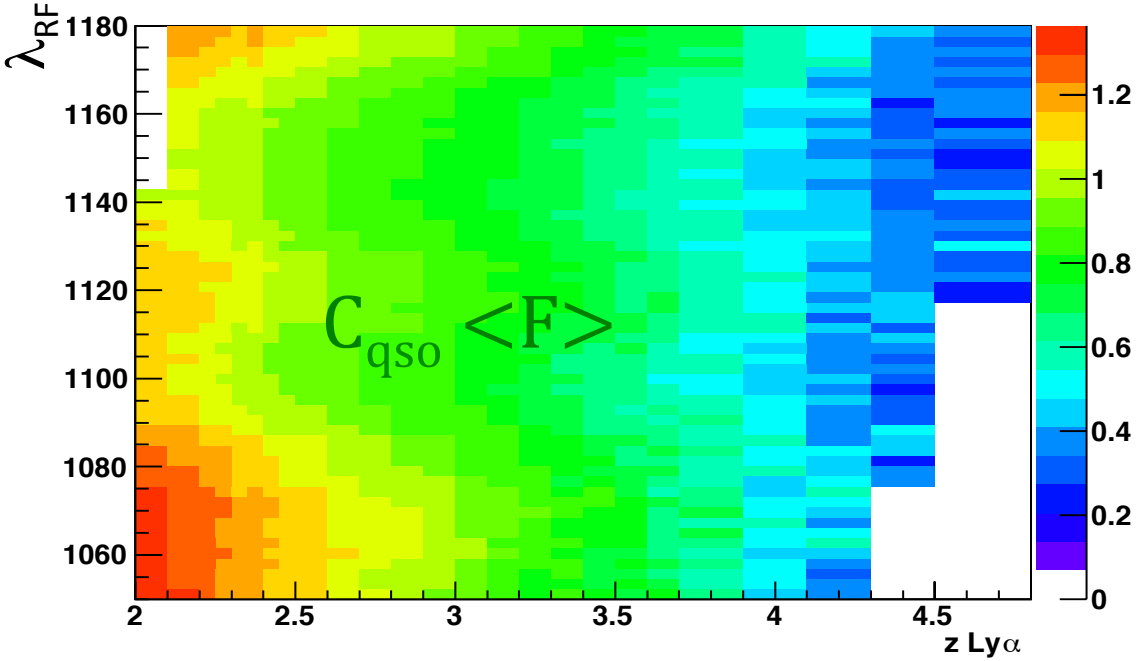


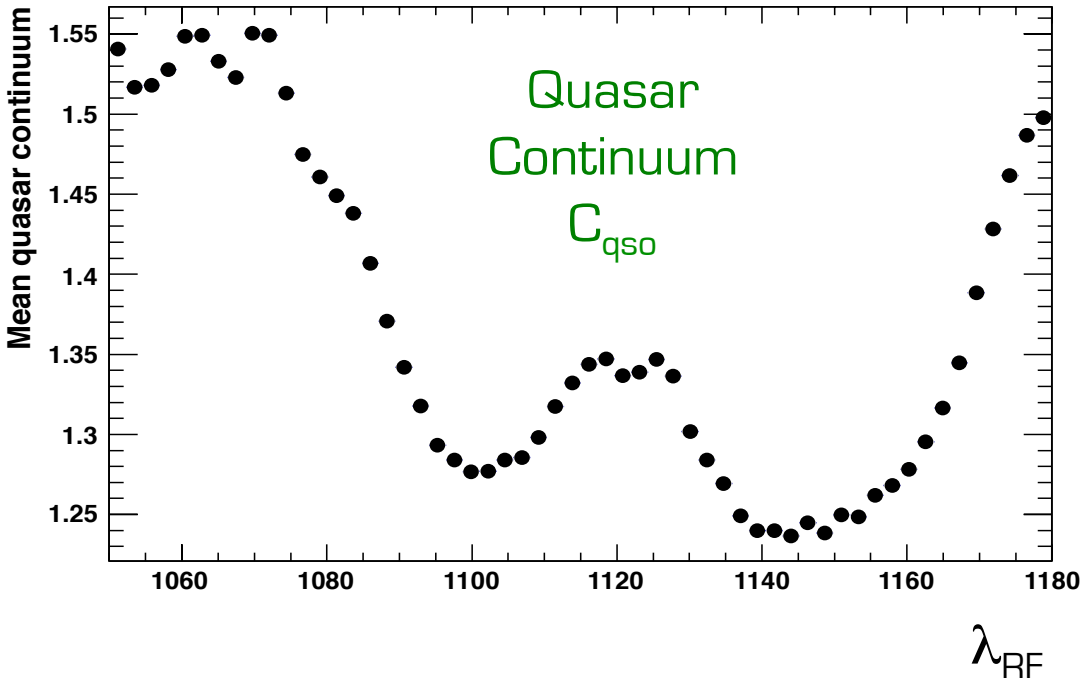
$$\Sigma\, m_\nu \;\geq\; 0.11\ \text{eV}$$

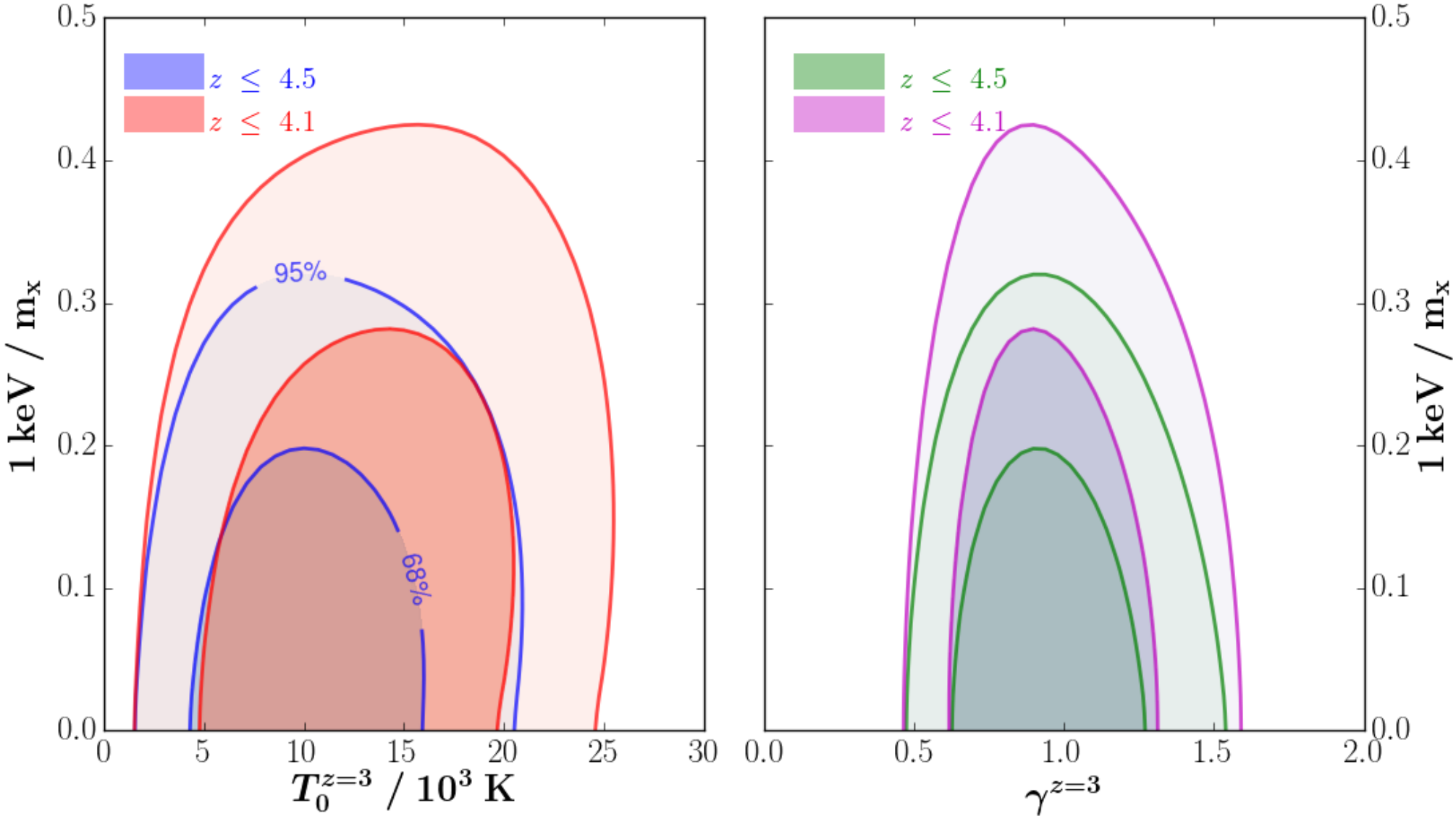



Mean transmitted flux fraction
z Lyα
Mean
transmitted
Fraction < F >

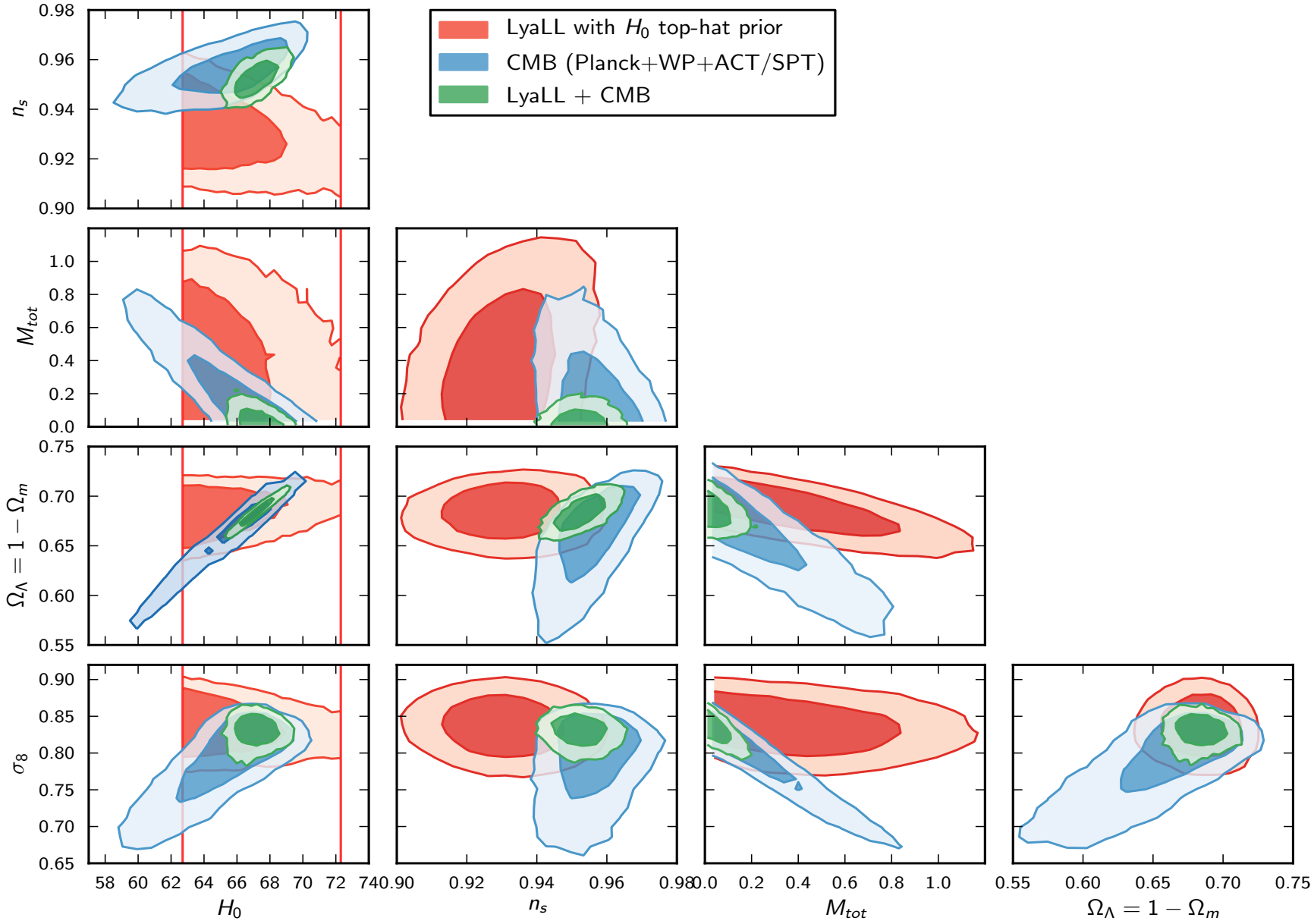

Normalized flux
λ (Ang)
3.9<z<4.3
3.5<z<3.9
3.1<z<3.5
2.9<z<3.1
2.3<z<2.9
Ly-β
Ly-α
N V
Si II
C II
Si IV
C IV


λRF
z Lyα
Cqso <F>

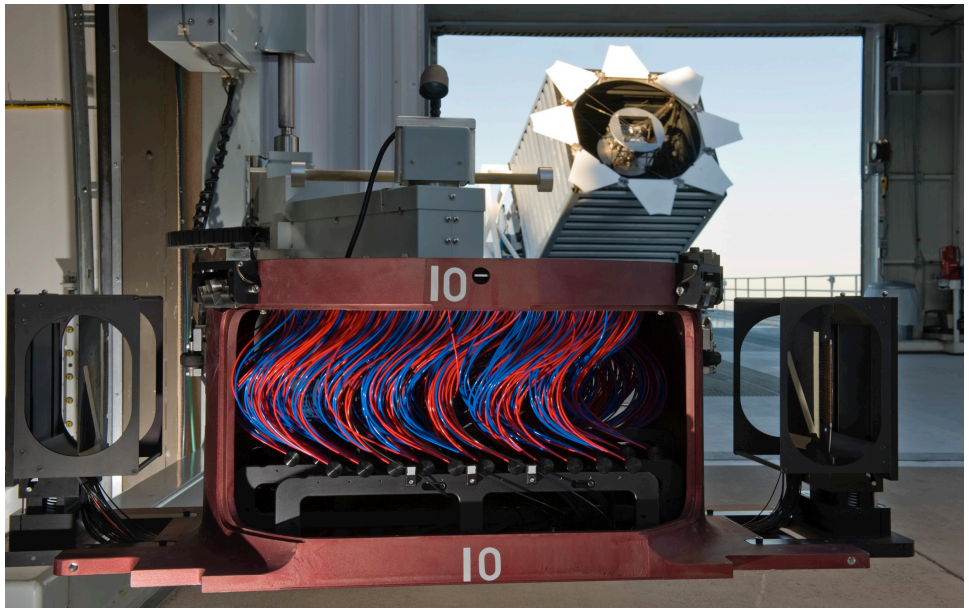

Mean quasar continuum
λRF
Quasar
Continuum
Cqso


$z \leq 4.5$
$z \leq 4.1$
95%
68%
$1\ \mathrm{keV}\ /\ \mathrm{m_x}$
$T_0^{z=3}\ /\ 10^3\ \mathrm{K}$
$\gamma^{z=3}$

Fit results


LyaLL with H_0 top-hat prior
CMB (Planck+WP+ACT/SPT)
LyaLL + CMB
n_s
M_{tot}
$\Omega_\Lambda = 1 - \Omega_m$
σ_8
H_0
n_s
M_{tot}
$\Omega_\Lambda = 1 - \Omega_m$

Baryon Oscillations Spectroscopic Survey



SDSS : wide f.o.v. (7 deg^2) telescope

~10,000 deg^2 celestial coverage

5 filter CCD cameras (u g r i z)

BOSS: photometry

target selection (~180,000 quasars)

drill plate (coordinates)

spectrograph (1,000 spectra / hr)

probes $z \in [2.1, 4.5]$ range (Ly–α)