

Soutenance de Doctorat

Laboratoire de l'Accélérateur Linéaire, Orsay



Détermination de la masse des neutrinos cosmologiques avec les forêts Ly α

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sous la direction de

Nathalie Palanque-Delabrouille

Irfu / DPhP – CEA



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les neutrinos en cosmologie

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4a neutrinos leptoniques et matière noire mixte

4b neutrinos stériles et matière noire pure

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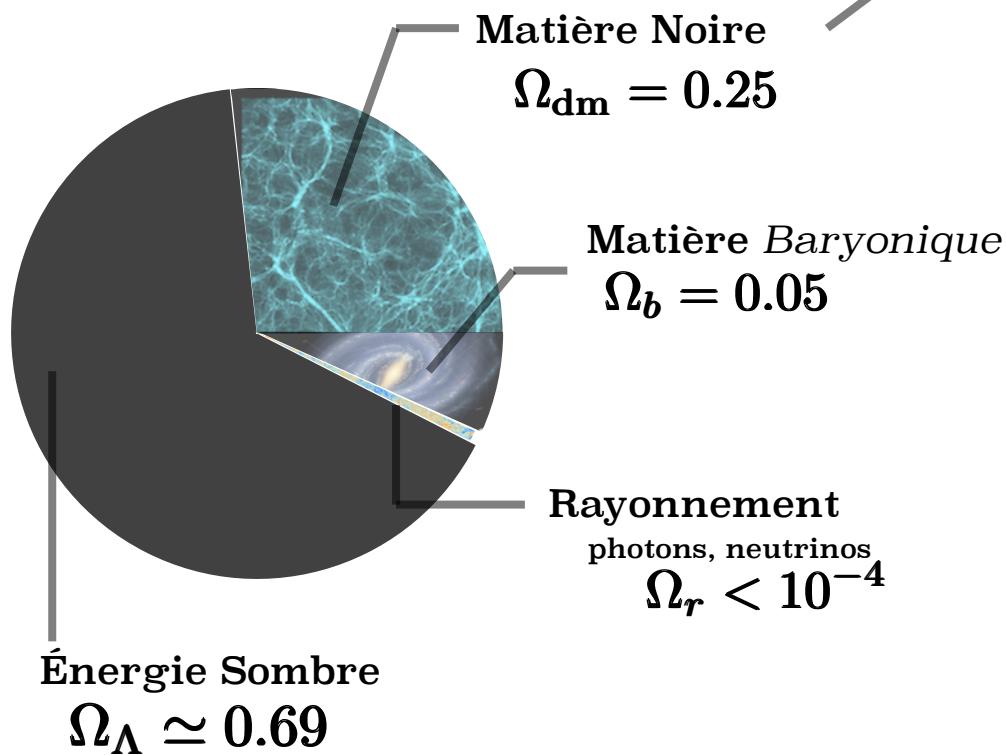
4

Modèles: neutrinos candidats matière noire

4a neutrinos leptoniques et matière noire mixte

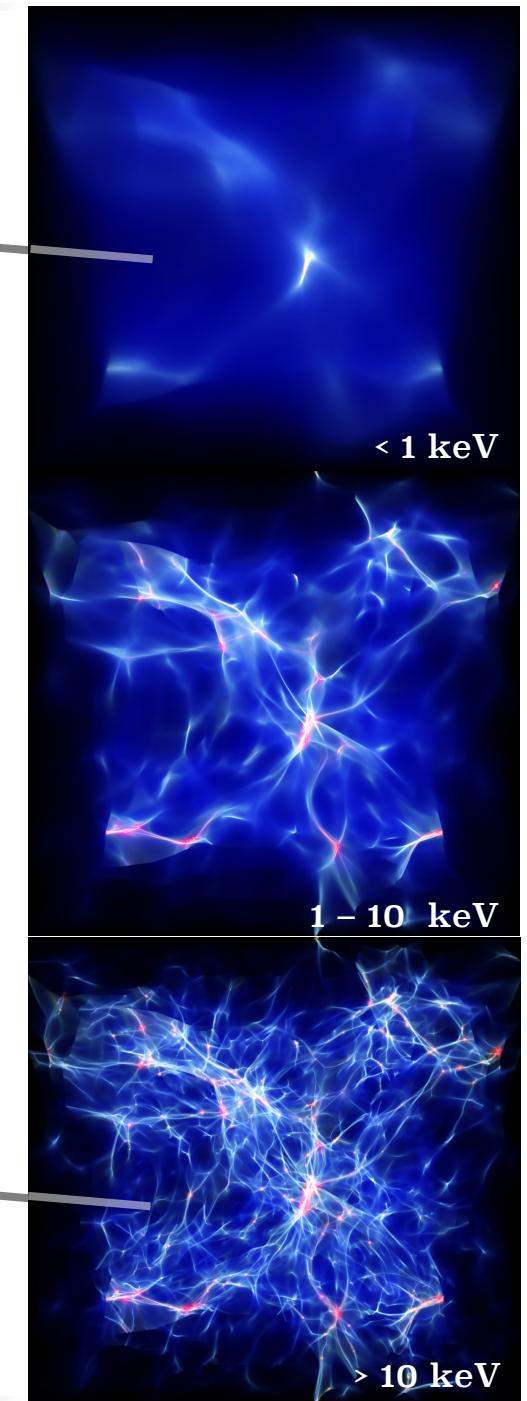
4b neutrinos stériles et matière noire pure

Matière Noire



matière noire chaude

- fragmentation de structures
- formation des galaxies tardive
- galaxies satellites sous-abondantes



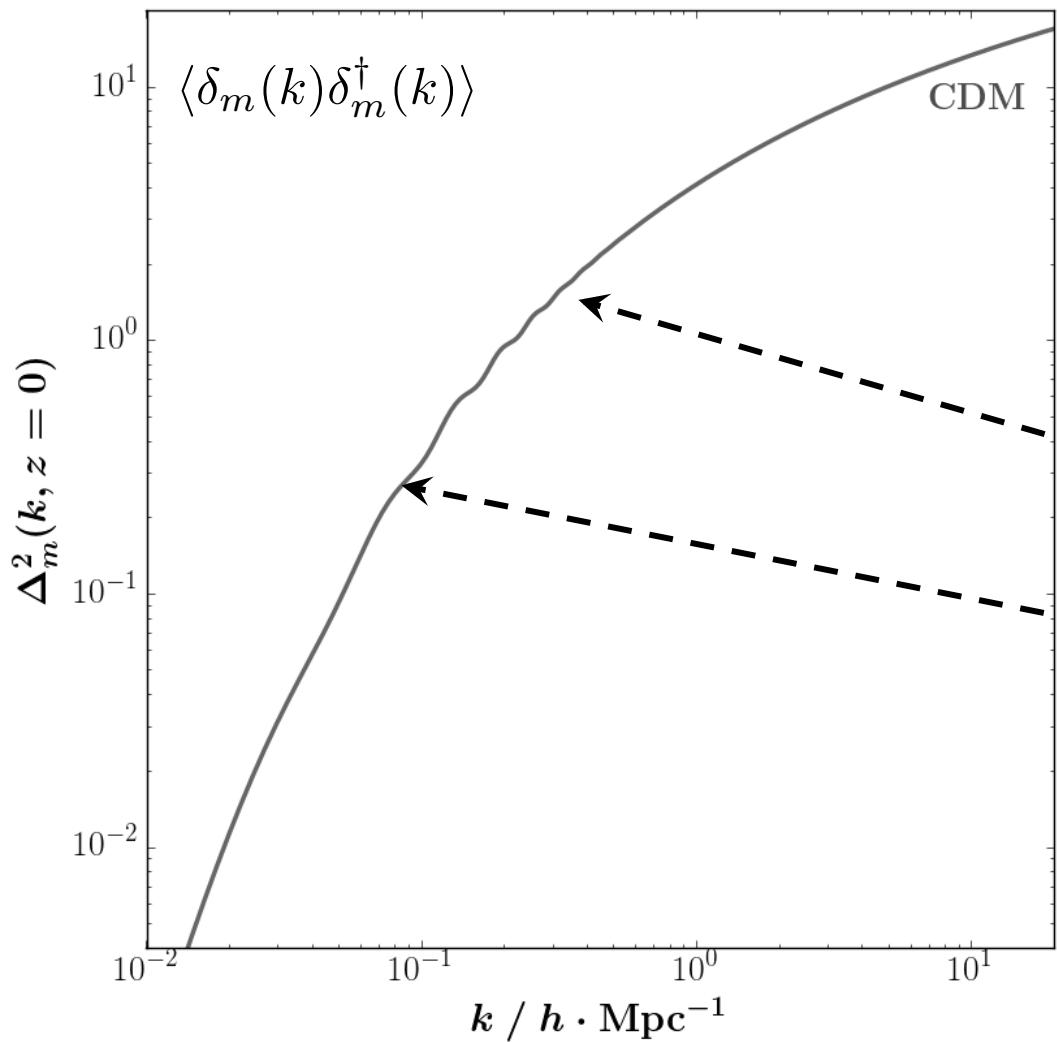
matière noire tiède

matière noire froide

- cœurs des amas piqués
- galaxies satellites surabondantes

Spectre de Puissance

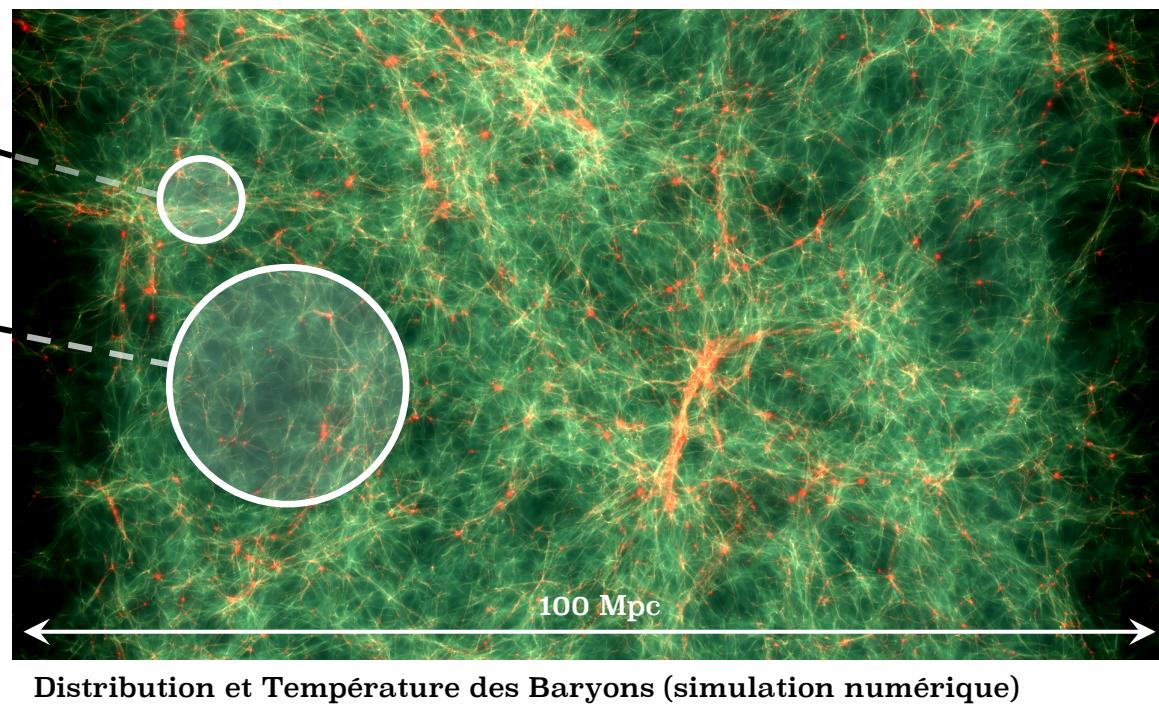
Variance (par échelle)



Densité de matière

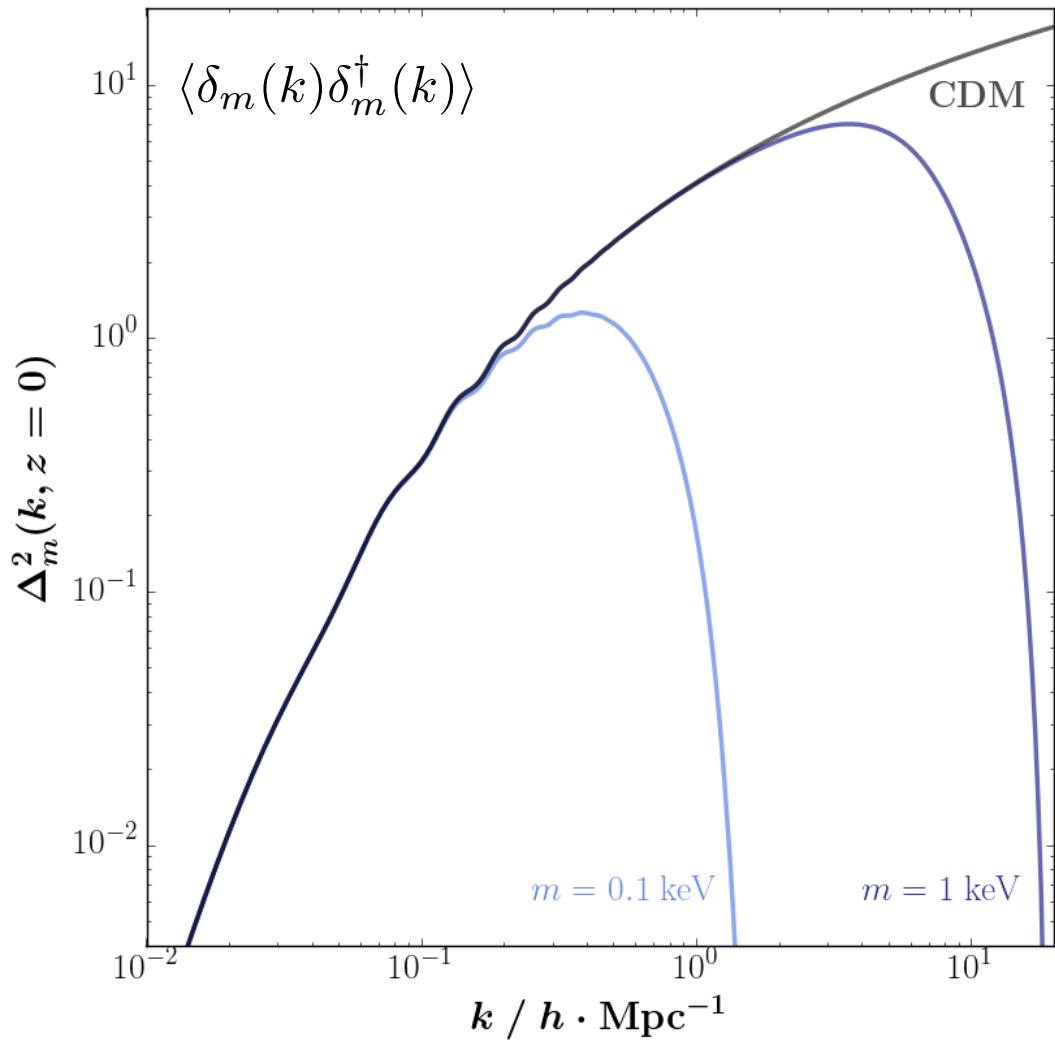
$$\delta_m = \delta_b + \delta_{\text{dm}}$$

$$\rho(\vec{r}) = \bar{\rho} (1 + \delta(\vec{r}))$$



Spectre de Puissance

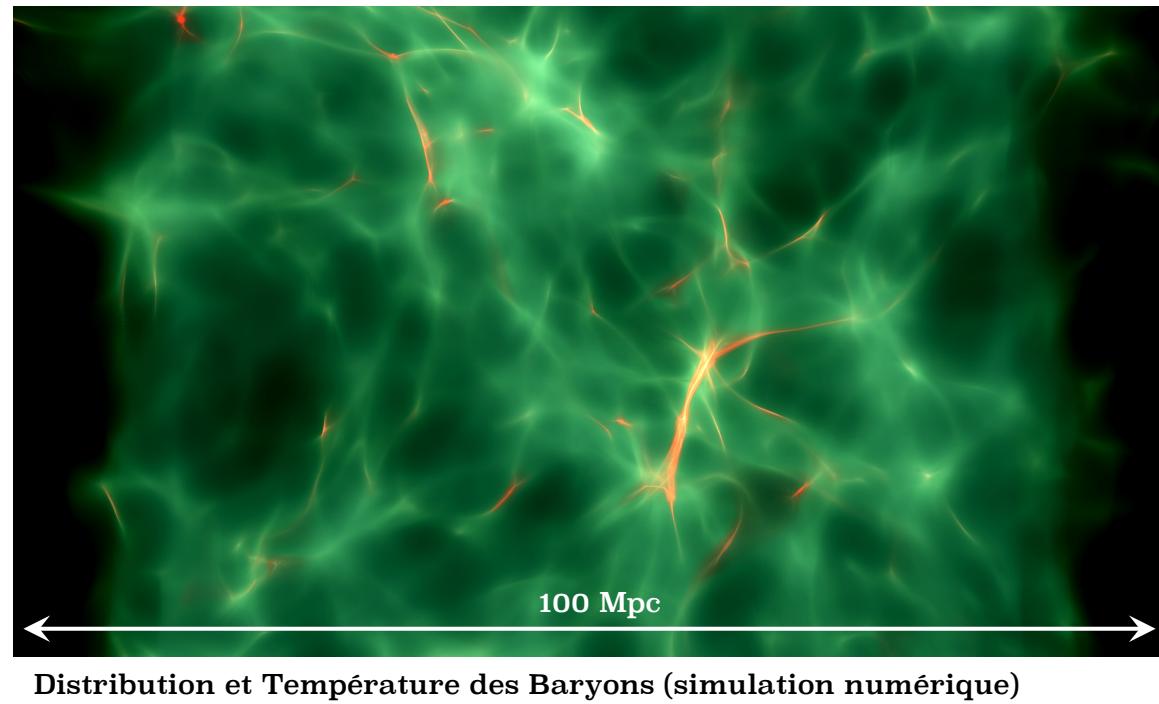
Variance (par échelle)



Densité de matière

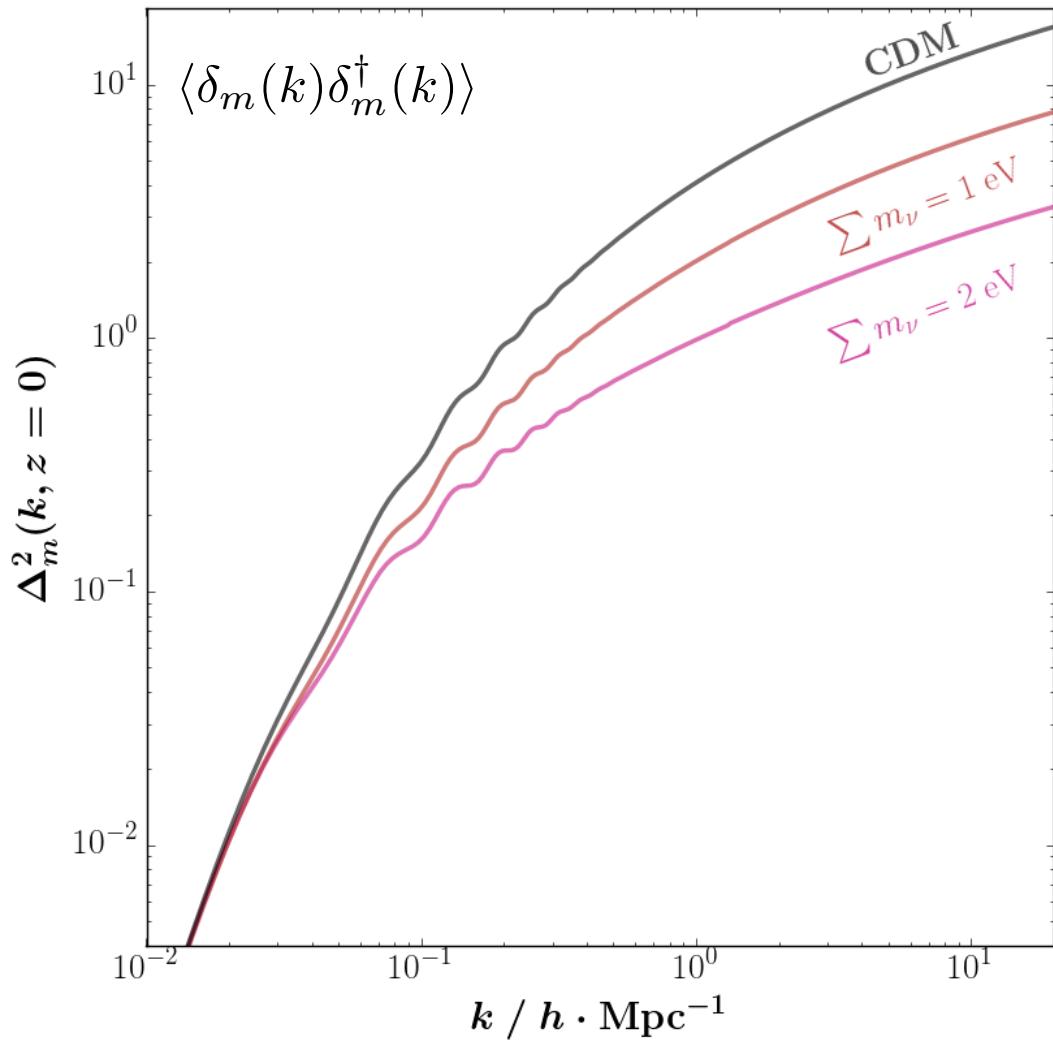
tiède ou chaude

$$\delta_m = \delta_b + \delta_{dm}$$



Spectre de Puissance

Variance (par échelle)



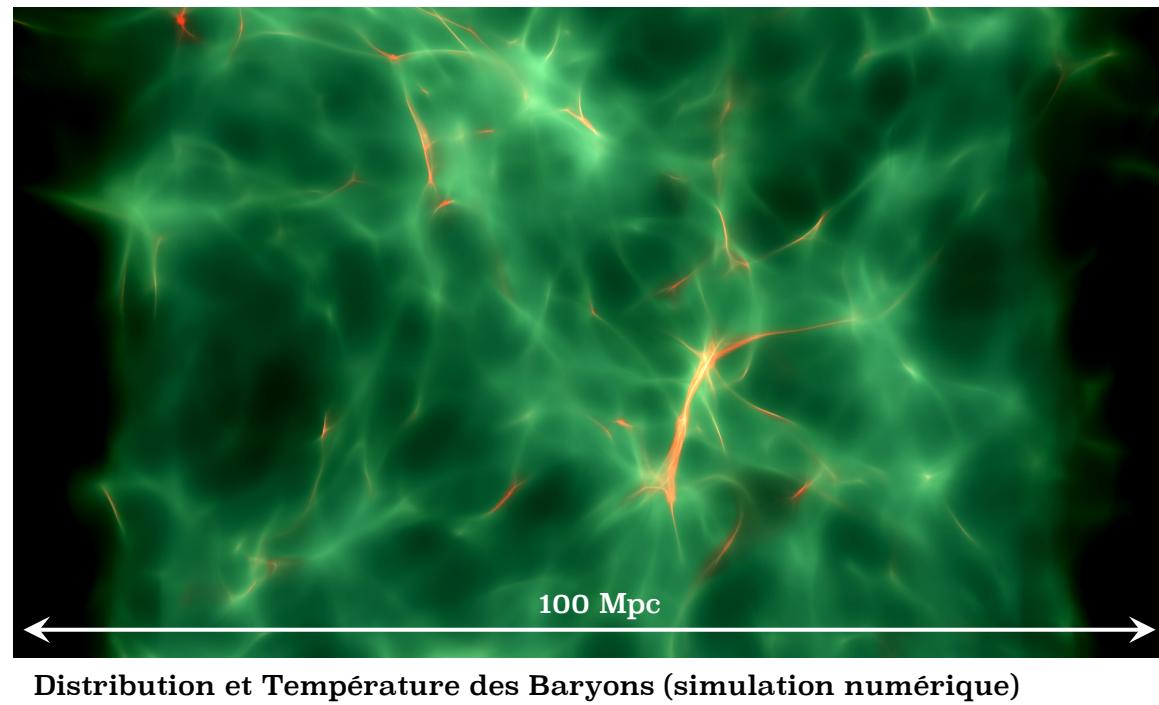
Densité de matière

froide et chaude

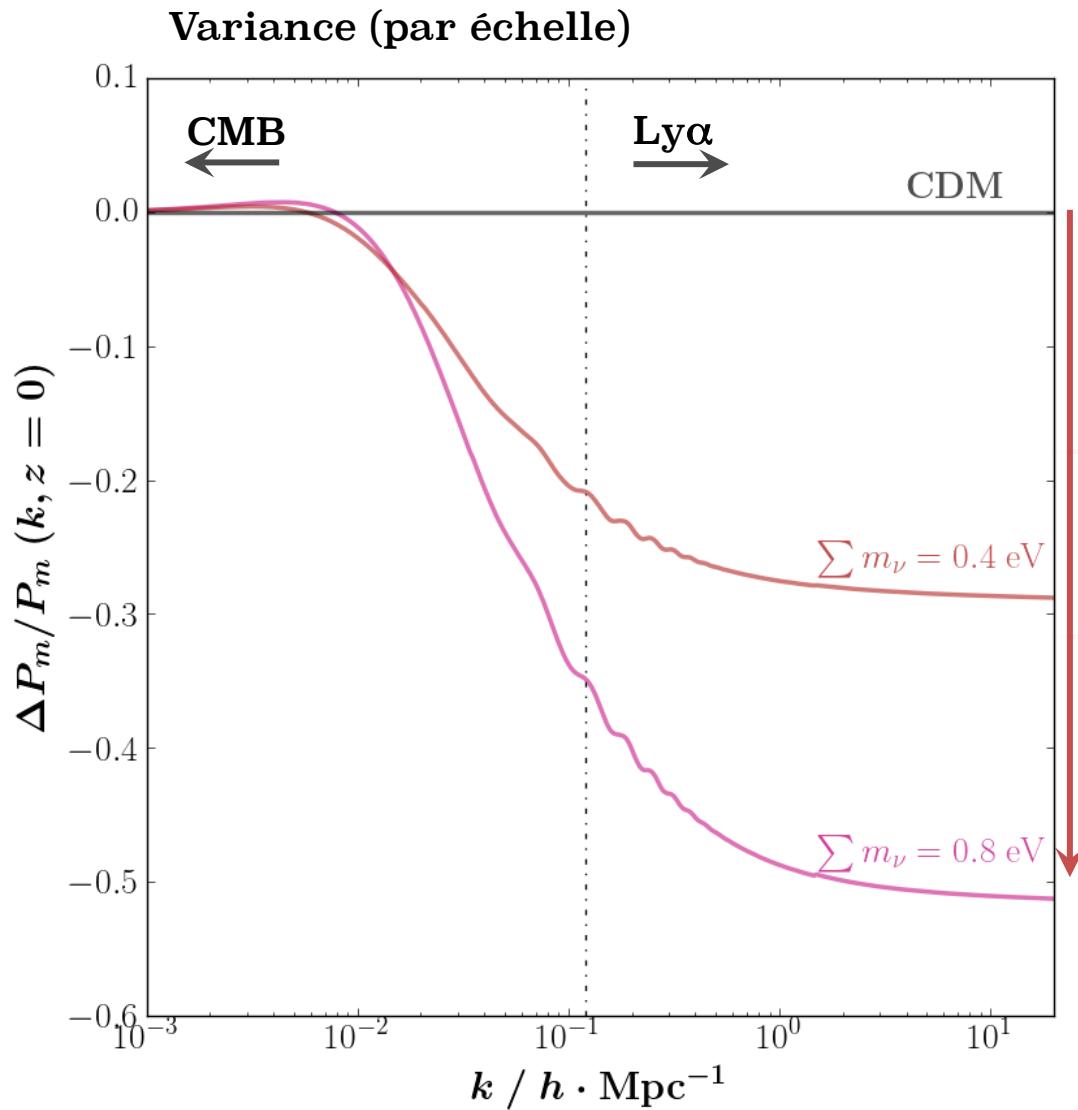
$$\delta_m = \delta_b + \delta_{\text{dm}}$$

$$\delta_{\text{cdm}} + \delta_{\text{hdm}}$$

$$\delta_\nu$$



Spectre de Puissance



Densité de matière

$$\delta_m = \delta_b + \delta_{\text{dm}}$$

froide et chaude

$$\delta_{\text{cdm}} + \delta_{\text{hdm}} \quad \delta_\nu$$

$$f_\nu = \frac{\Omega_\nu}{\Omega_b + \Omega_{\text{cdm}} + \Omega_\nu}$$

Densité des neutrinos $\Omega_\nu h^2 = \frac{\sum m_\nu}{93.14 \text{ eV}}$

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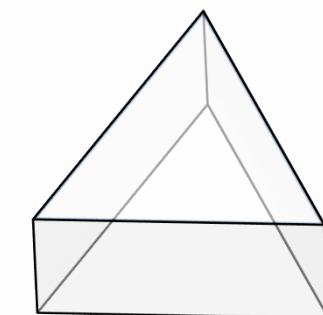
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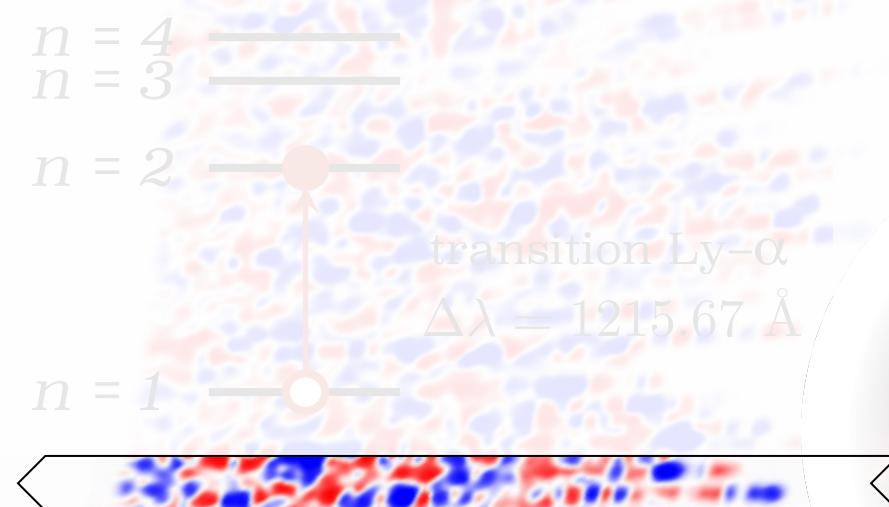
Modèles: neutrinos candidats matière noire

- 4a neutrinos leptoniques et matière noire mixte
- 4b neutrinos stériles et matière noire pure

Forêt Lyman-Alpha



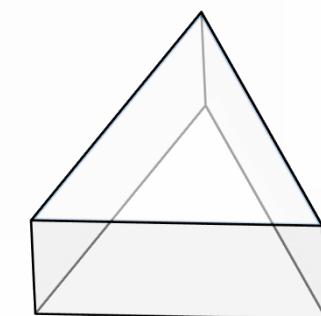
spectrographe



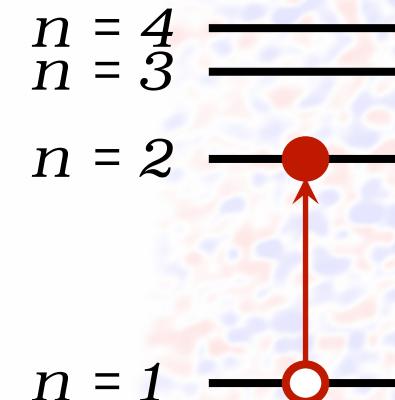
Milieu Diffusif (MIG)

Source (QSO)

Forêt Lyman-Alpha

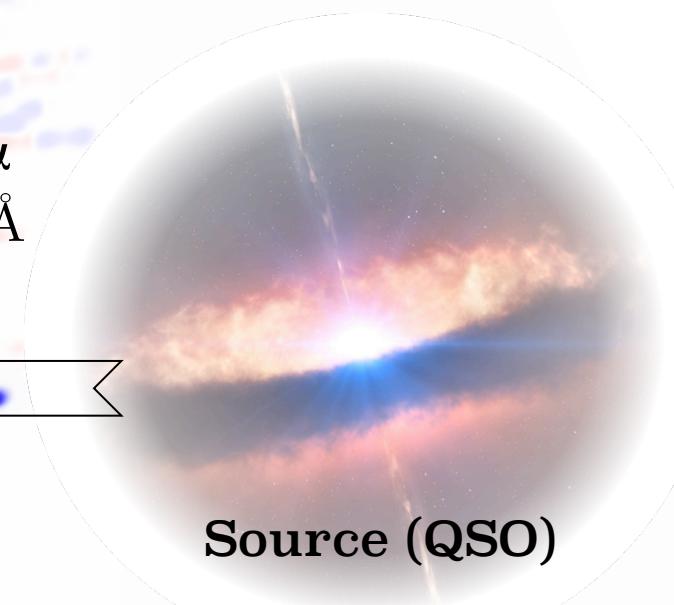


spectrographe



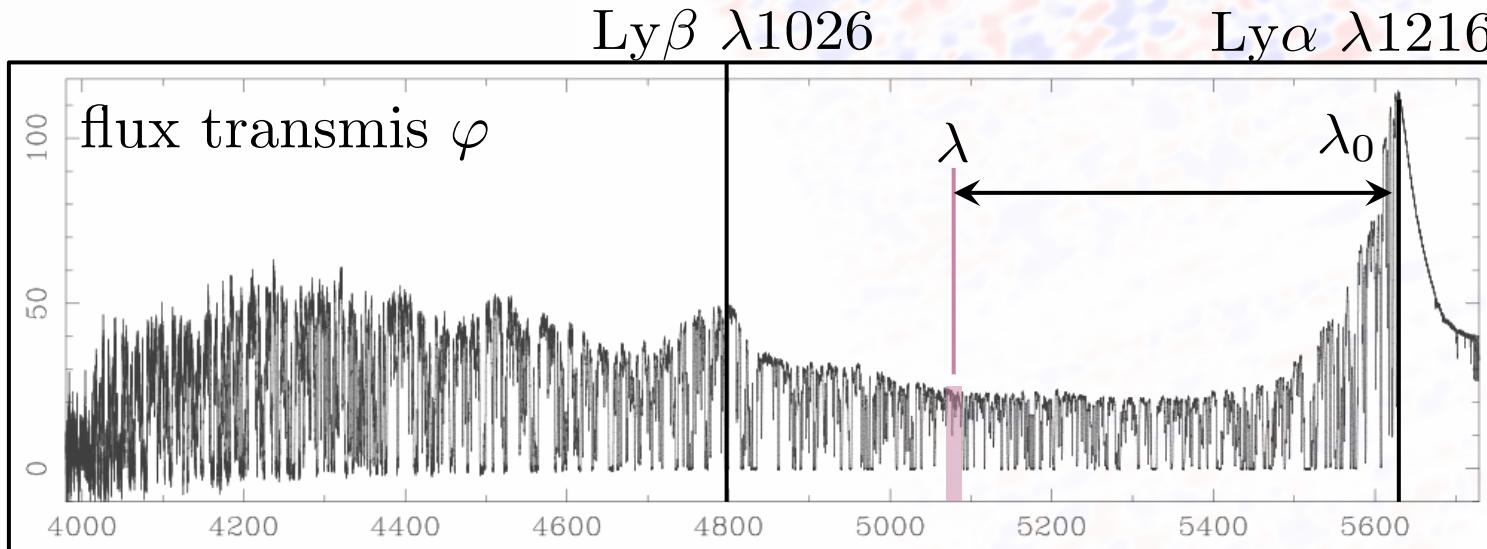
transition Ly- α
 $\Delta\lambda = 1215.67 \text{ \AA}$

Milieu Diffusif (MIG)



Source (QSO)

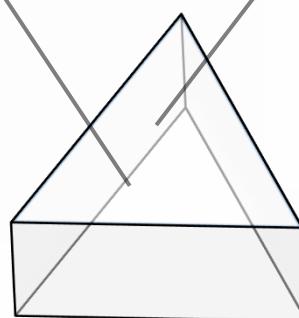
Forêt Lyman-Alpha



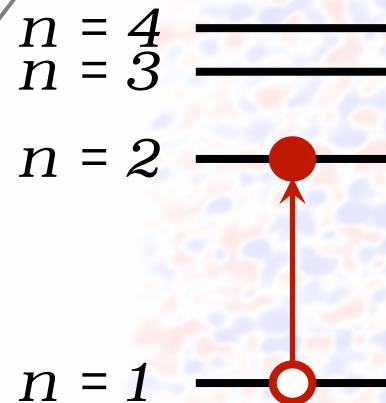
décalage spectral
 \implies
position

$$1 + z = \frac{\lambda}{\lambda_0} = \frac{a_0}{a(t)}$$

$\lambda / \text{\AA}$

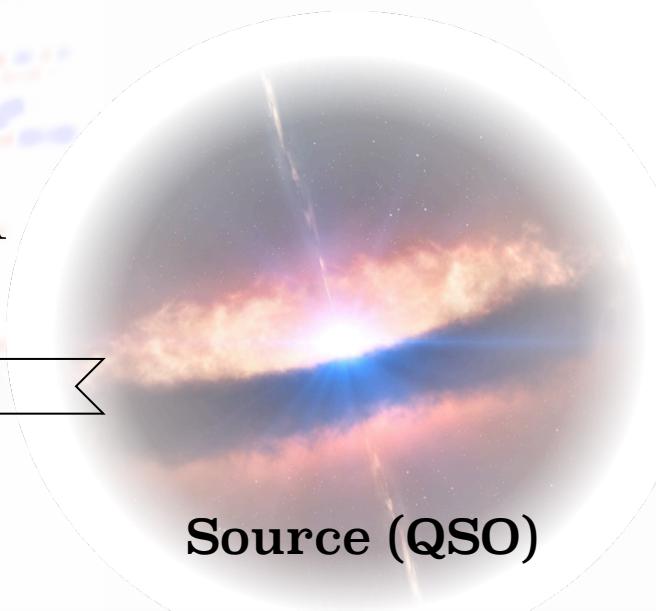


spectrographe



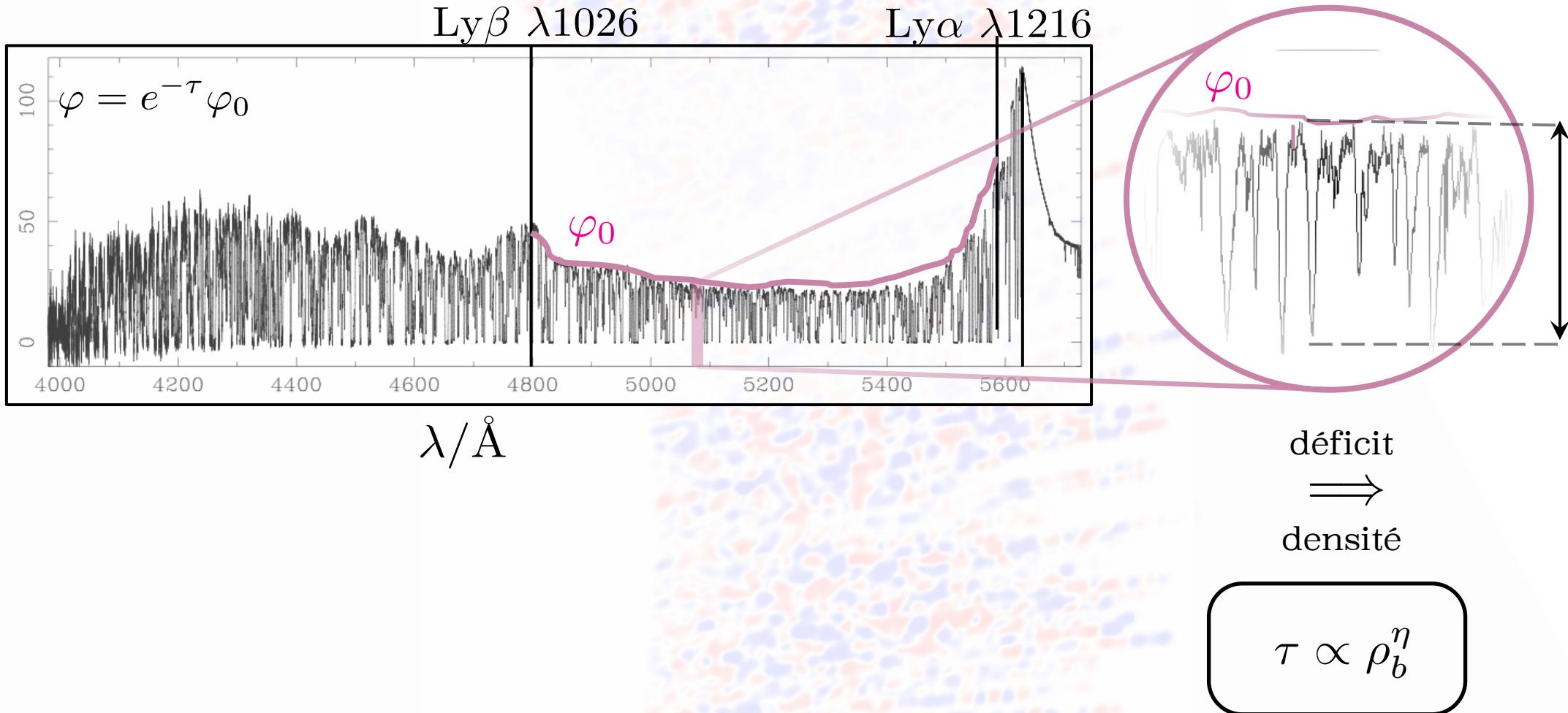
transition Ly- α
 $\Delta\lambda = 1215.67 \text{ \AA}$

Milieu Diffusif (MIG)

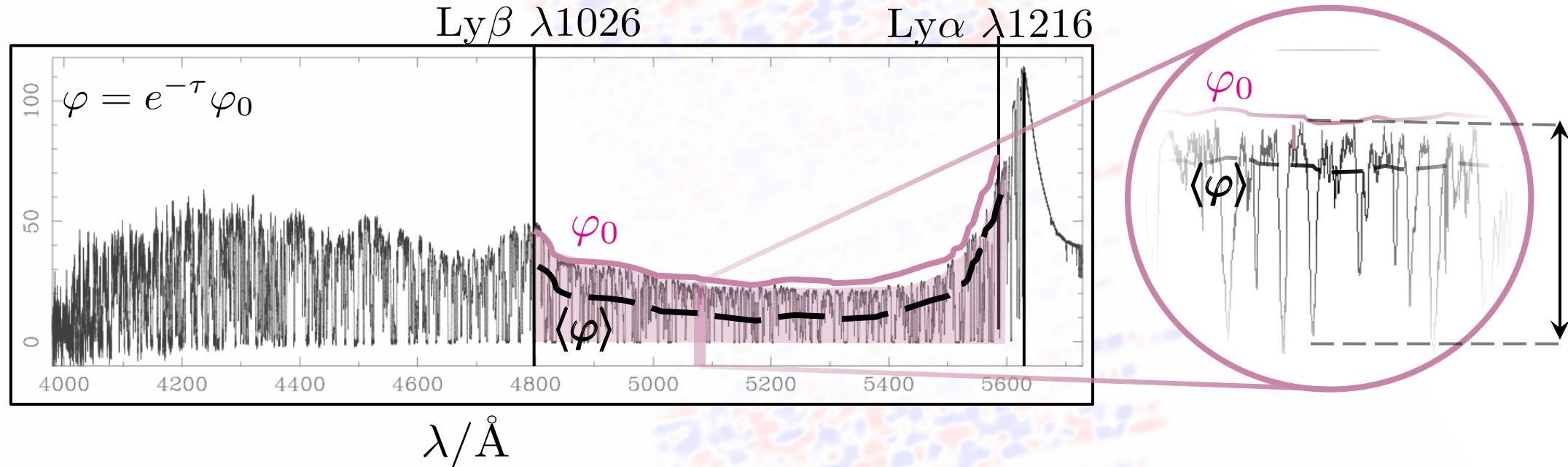


Source (QSO)

Forêt Lyman-Alpha



Forêt Lyman-Alpha

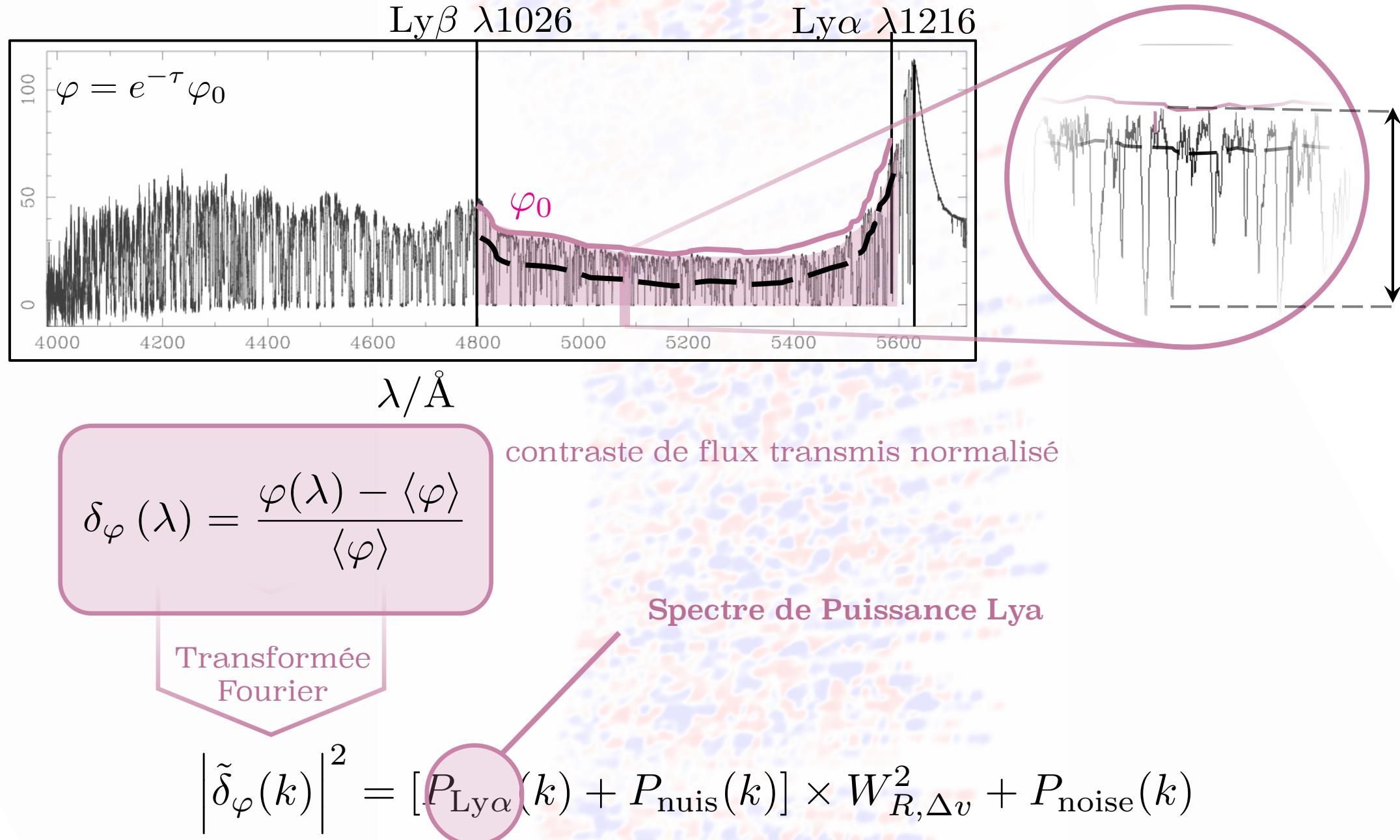


$$\delta_\varphi(\lambda) = \frac{\varphi(\lambda) - \langle \varphi \rangle}{\langle \varphi \rangle}$$

contraste de flux transmis
normalisé

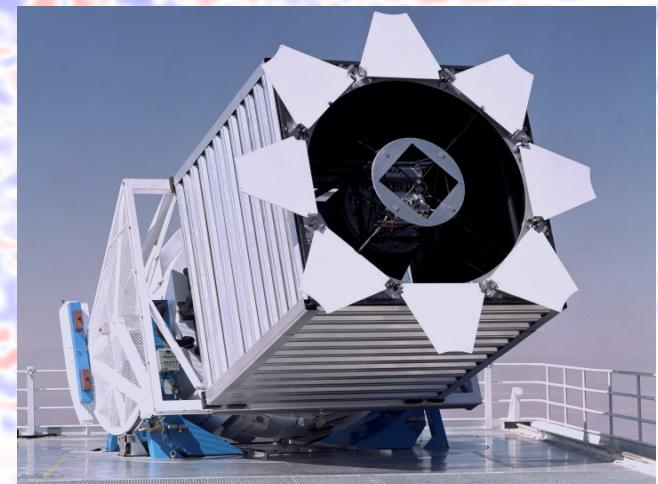
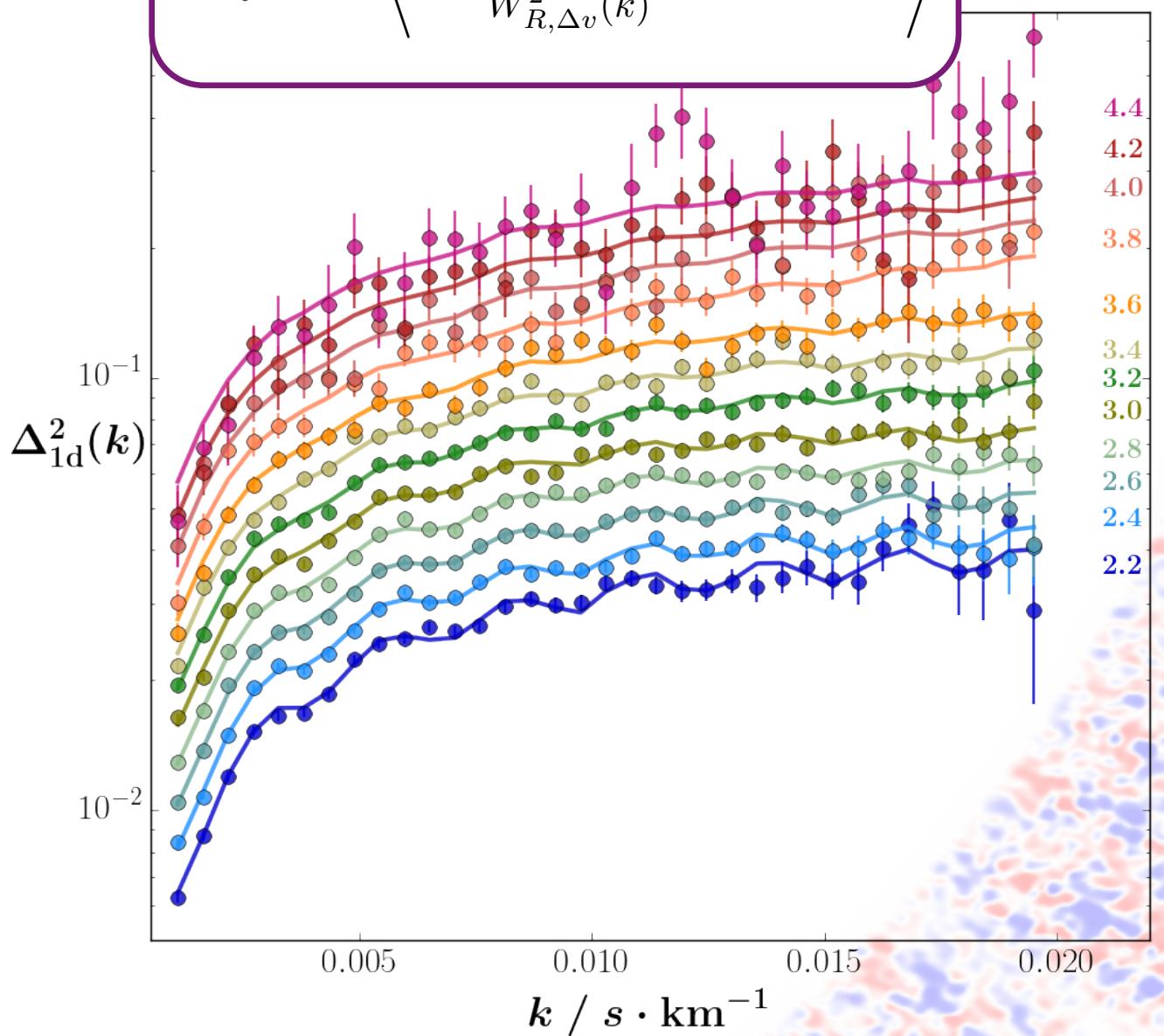
flux transmis moyen
 $\langle \varphi \rangle = e^{-\tau_{\text{eff}}}$

Forêt Lyman-Alpha



Spectre de Puissance Ly α

$$P_{\text{Ly}\alpha}(k) = \left\langle \frac{|\tilde{\delta}(k)|^2 - P_{\text{noise}}(k)}{W_{R,\Delta v}^2(k)} - P_{\text{nuis}}(k) \right\rangle$$



Télescope 2.5m au Apache Point Observatory
Crédit: SDSS

DR9 Baryon
Oscillations
Spectroscopic
Survey

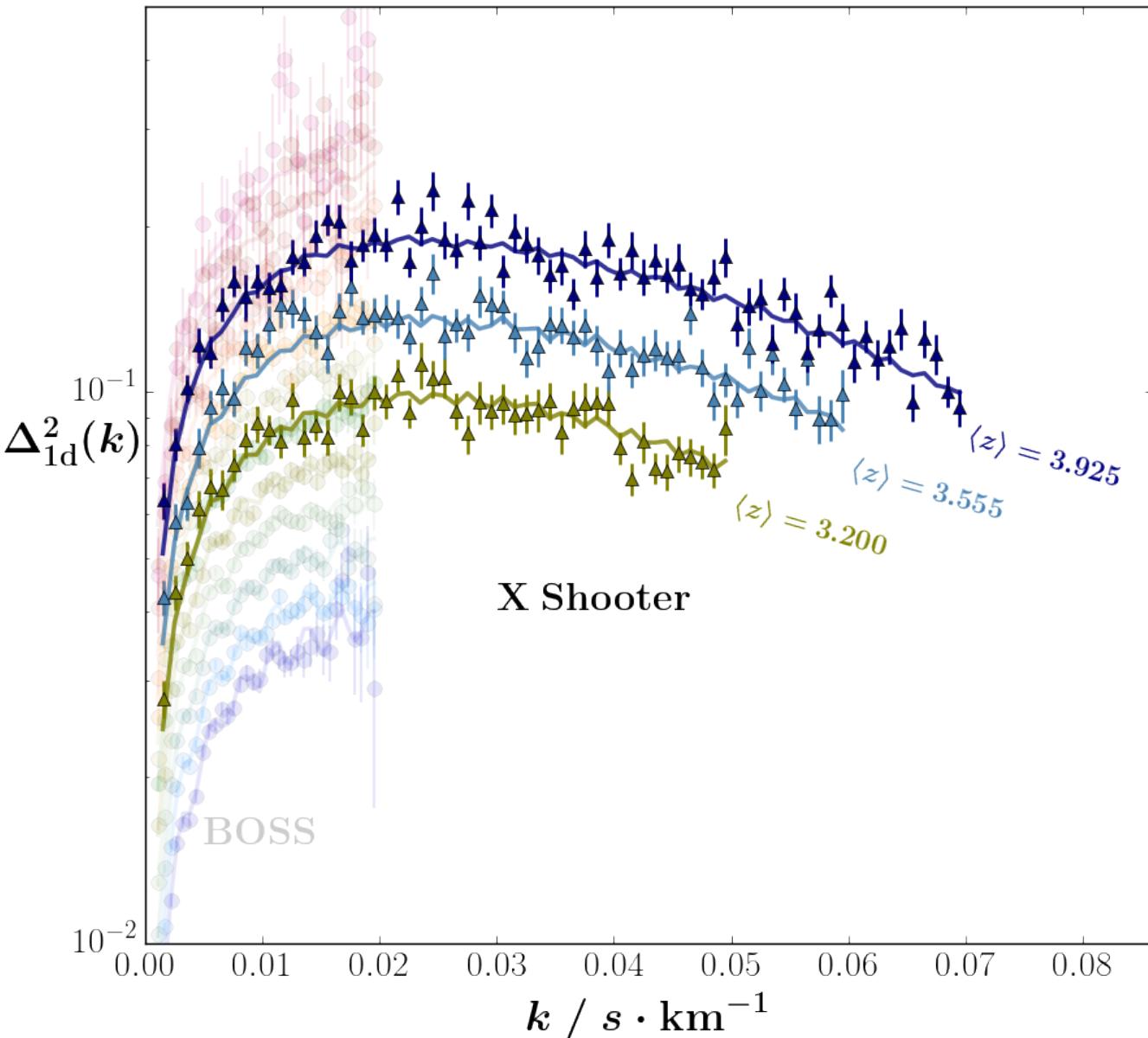
13,821 forêts Ly α

35 bins k

12 bins z

Données Moyenne Résolution

Yèche, Palanque-Delabrouille, **Baur** et al.,
JCAP 06 (2017) 047



Les 4 télescope principaux de 8.2m du VLT
Crédit: ESO

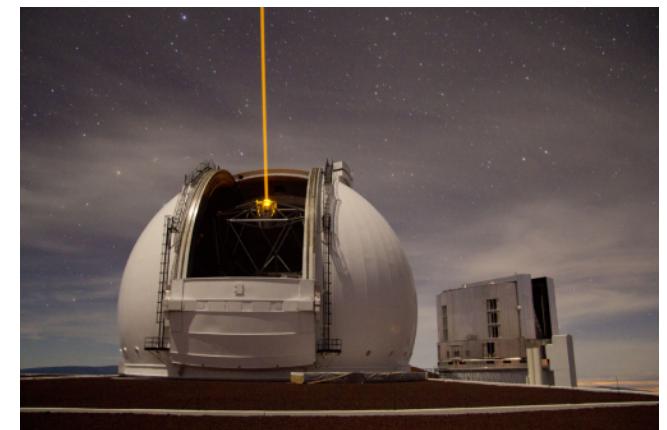
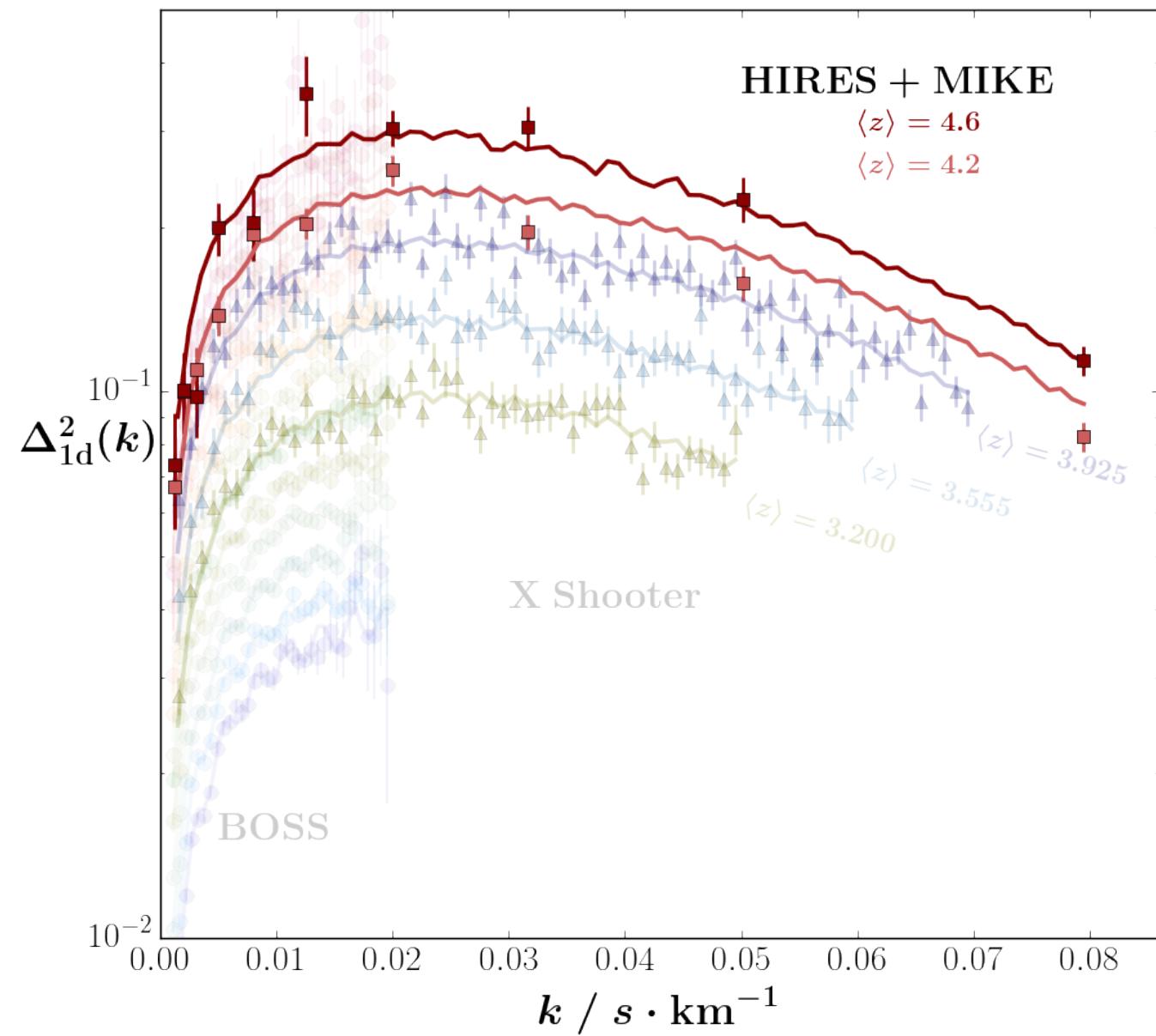
XSHOOTER
XQ-100

100 forêts Lyα

3 bins z

50, 60, 70 bins k

Données Haute Résolution



Télescope de 10m du WMKO
Crédit: Andrew Cooper

Magellan
Inamori
Kyocera
Echelle

High
Resolution
Echelle
Spectrometer

< 100 forêts Ly α
4 bins z
9 bins k

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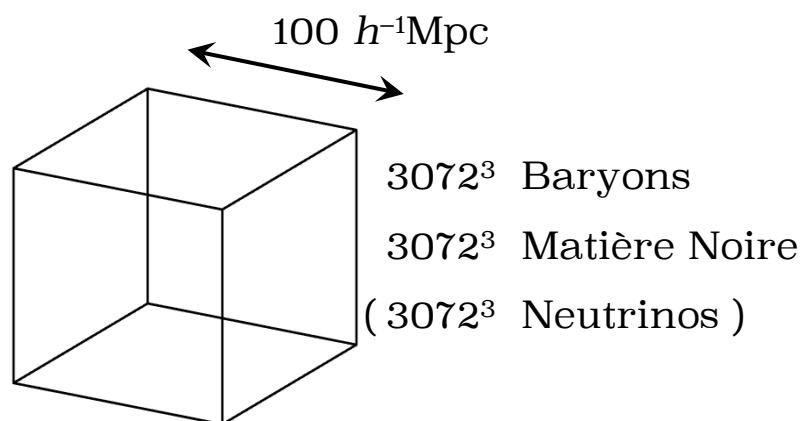
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Modèles: neutrinos candidats matière noire

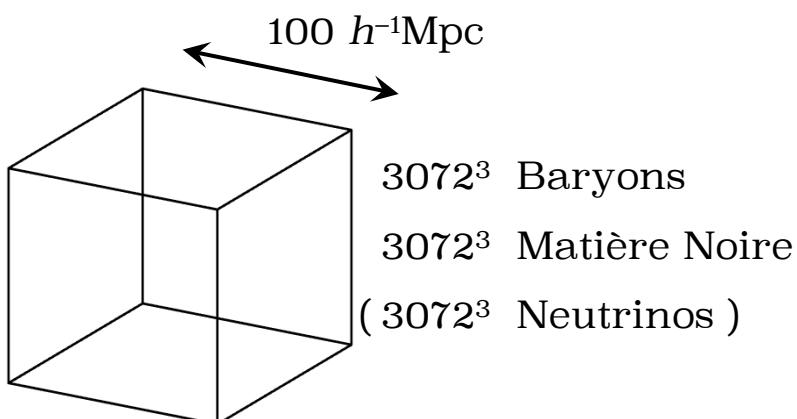
- 4a** neutrinos leptoniques et matière noire mixte
- 4b** neutrinos stériles et matière noire pure

Simulations Hydrodynamiques



- Conditions Initiales
- Calcul Non-Linéaire
- Construction de l'Observable

Simulations Hydrodynamiques



■ Conditions Initiales

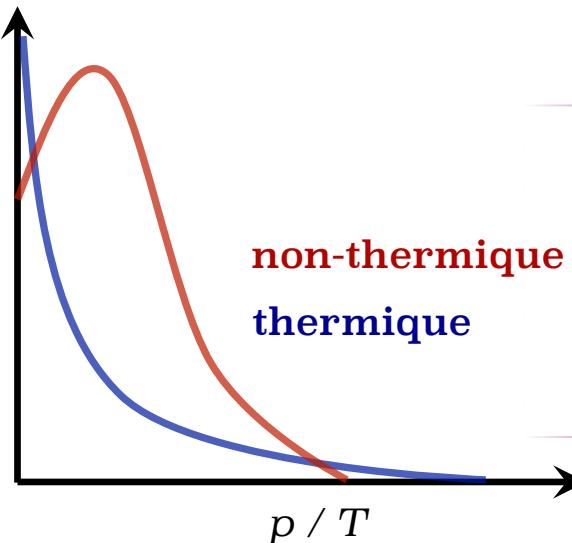
■ Calcul Non-Linéaire

■ Construction de l'Observable

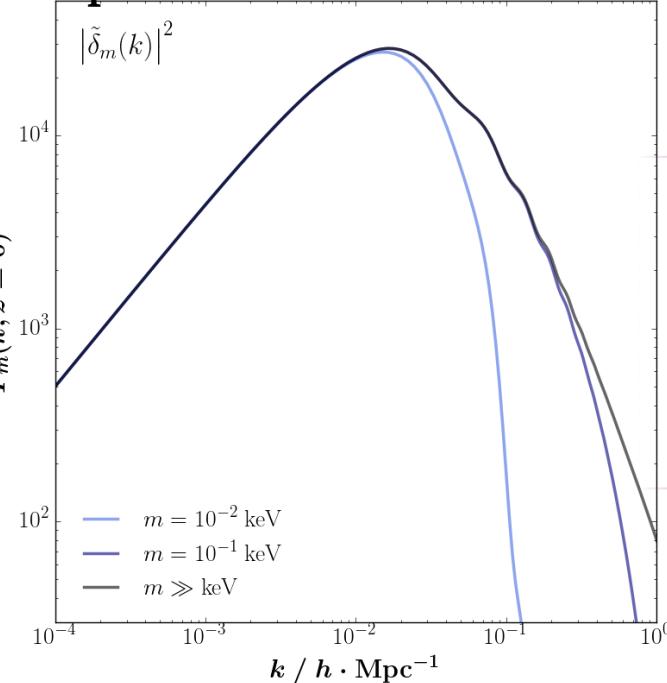
Code for Anisotropies in the Microwave Background
Antony Lewis & Anthony Challinor

Cosmic Linear Anisotropy Solving System
Julien Lesgourgues

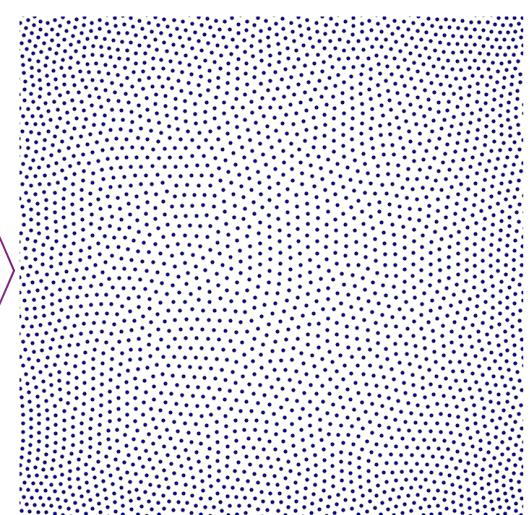
Distribution des vitesses



Spectre de Puissance

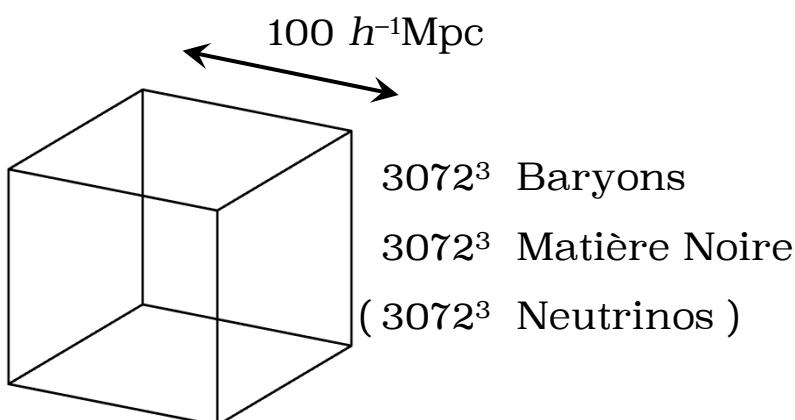


$z = 30$



Simulations Hydrodynamiques

- Conditions Initiales
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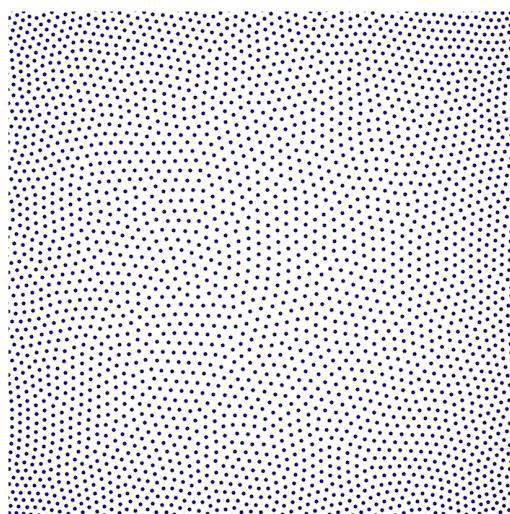


Calcul N-corps & Hydrodynamique (Tree PM)

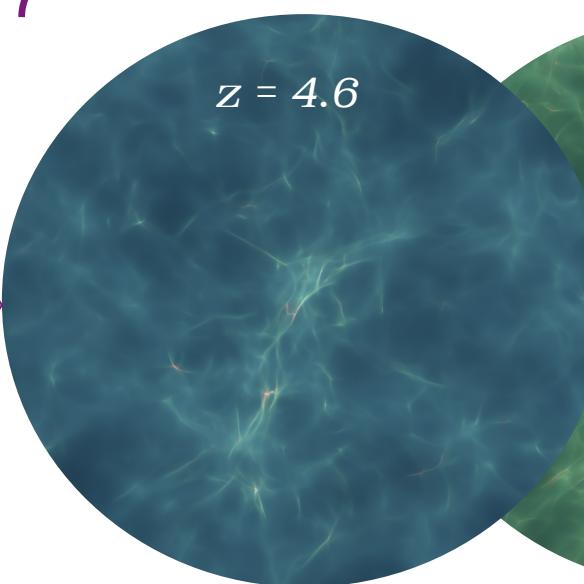
GAlaxies with Dark matter & Gas intEracT
Volker Springel

$$z = 2.2, 2.4, 2.6, \dots 4.6$$

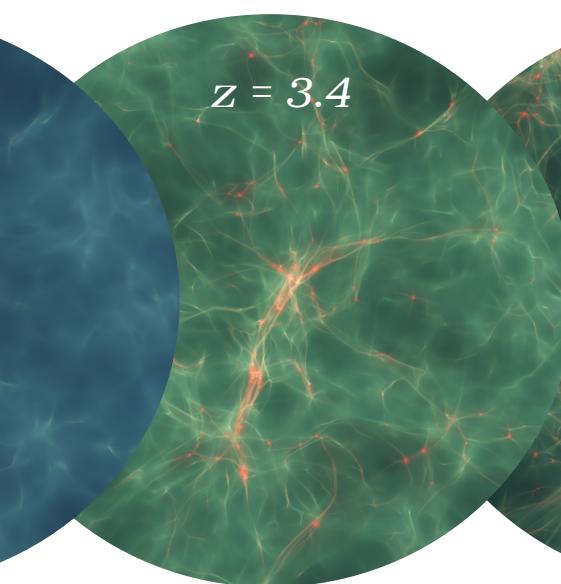
$z = 30$



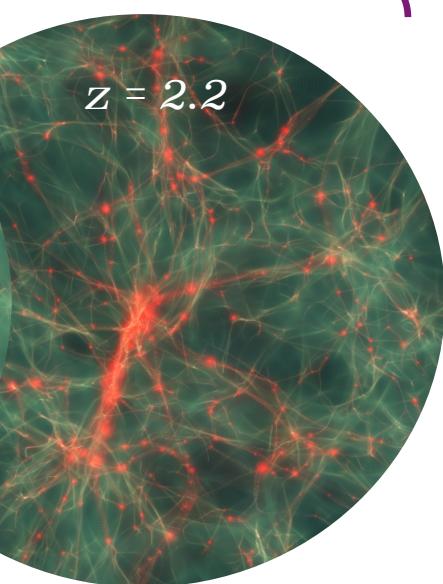
$z = 4.6$



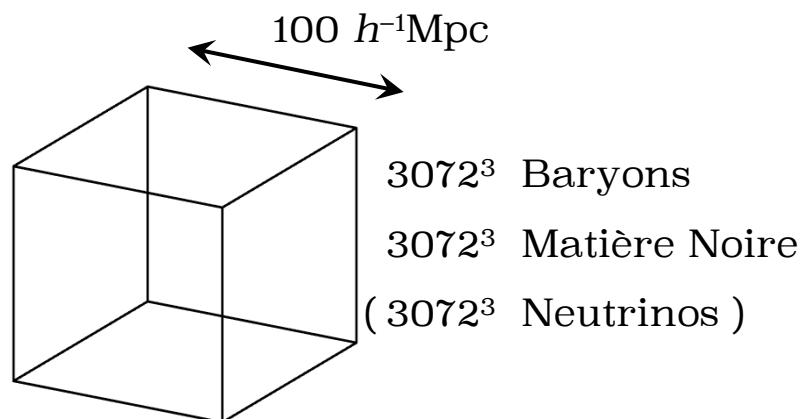
$z = 3.4$



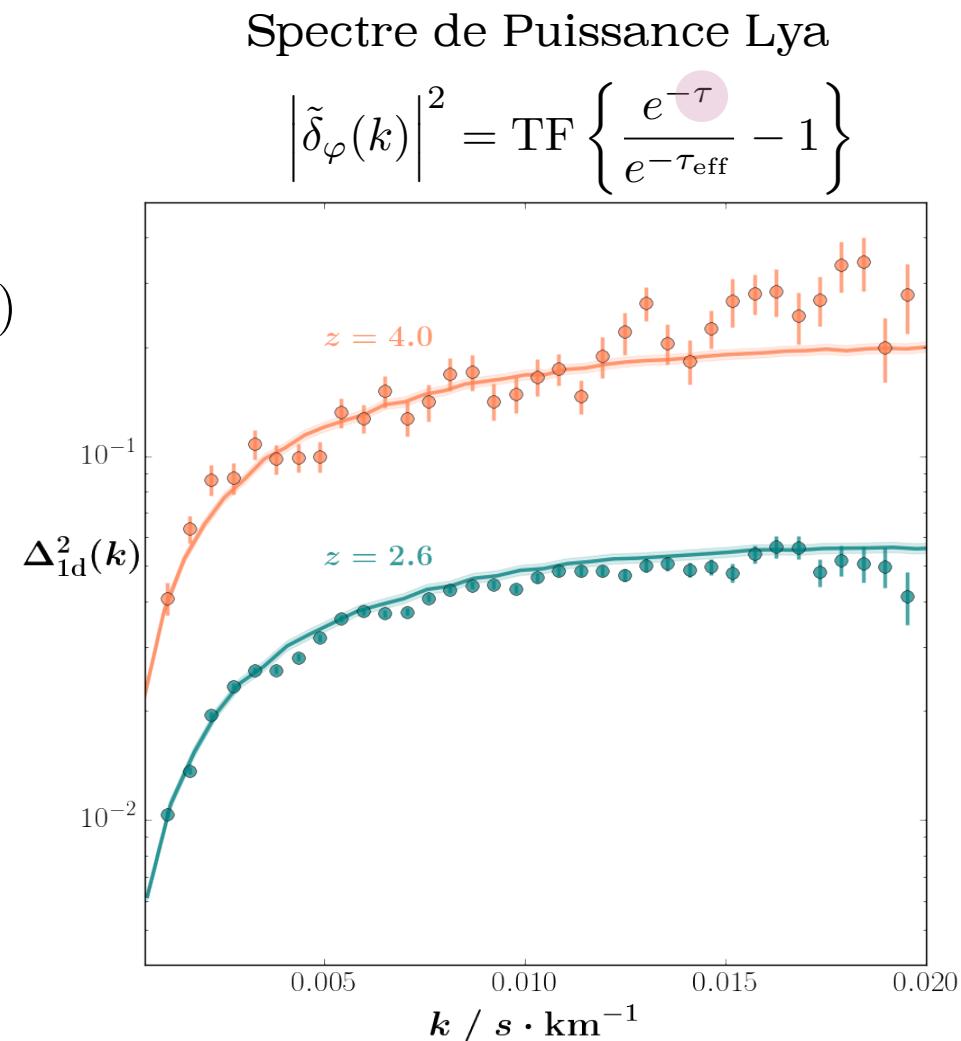
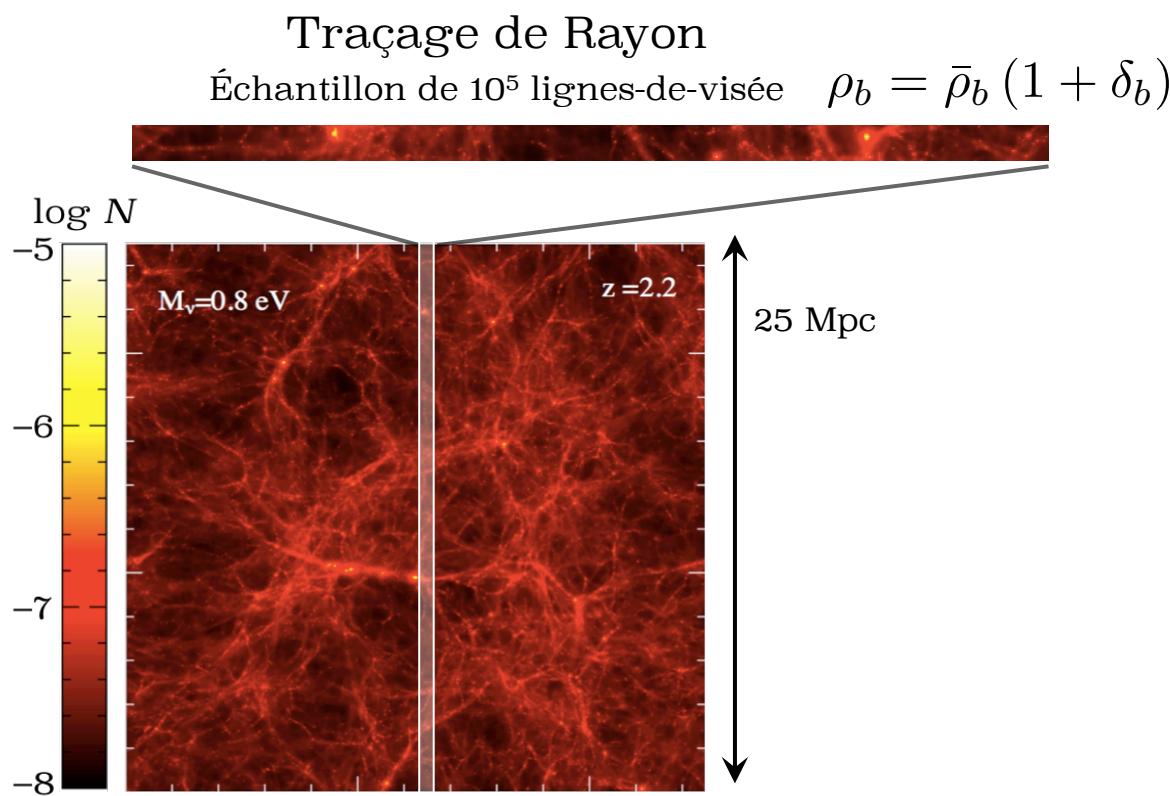
$z = 2.2$



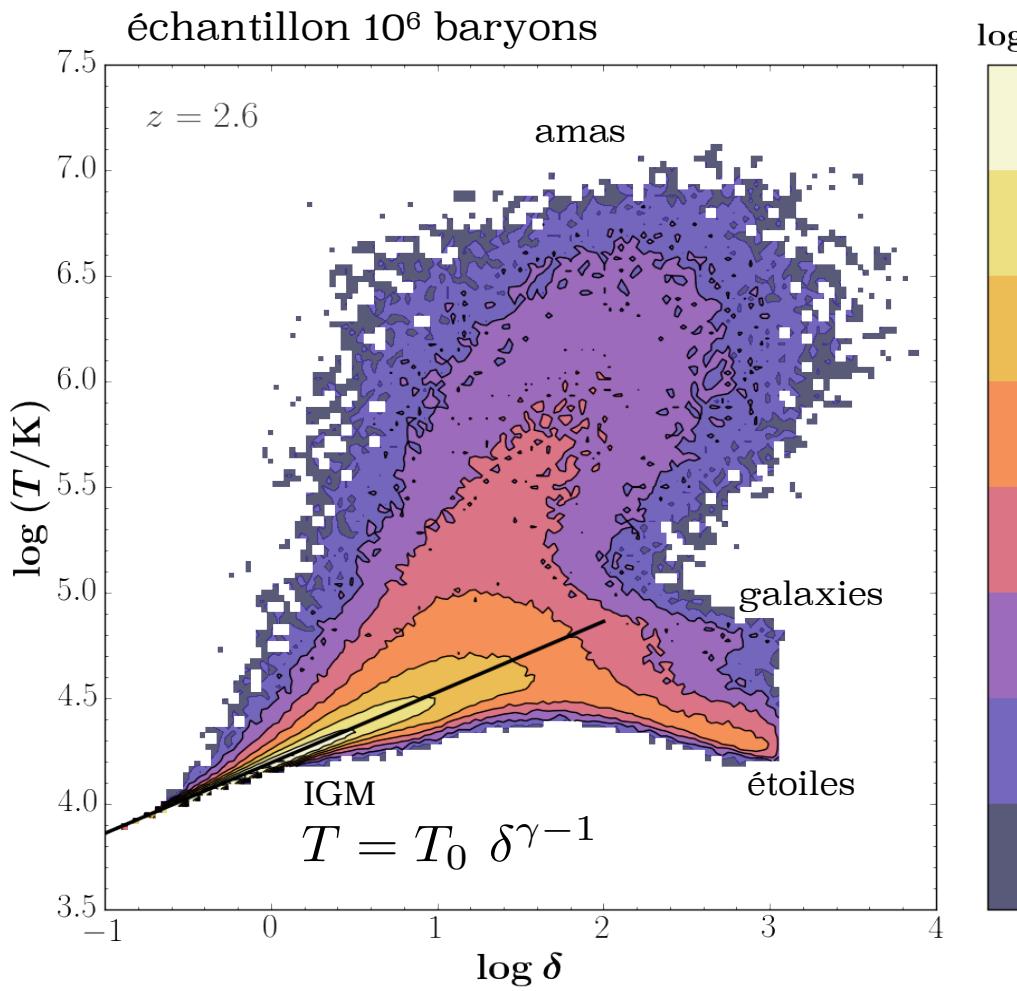
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Grille de Paramètres



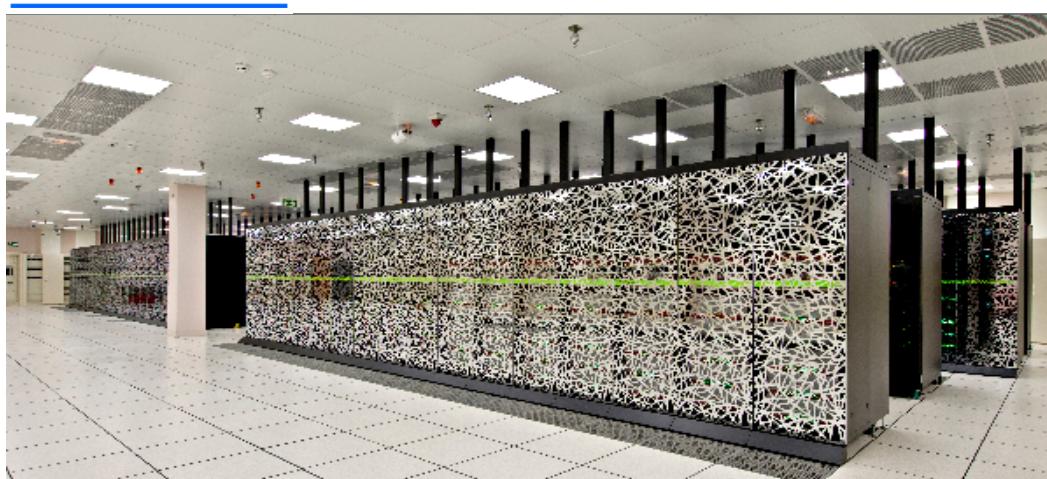
modèle de référence

parameter	$x_{0,i}$	Δx_i
cosmological		
h	= 0.675	± 0.05
Ω_m	= 0.31	± 0.05
σ_8	= 0.83	± 0.05
n_s	= 0.96	± 0.05
non-ΛCDM / neutrino		
$dn_s/d\ln k$	= 0.00	± 0.02
N_{eff}	= 3.046	± 1.000
$\sum m_\nu/\text{eV}$	= 0.0	$+ 0.4, 0.8$
keV/m_x	= 0.0	$+ 0.2, 0.4$
astrophysical		
$T_0^{z=3}/10^3\text{K}$	= 14.0	± 7.0
$\gamma^{z=3}$	= 1.3	± 0.3
$A^\tau/10^{-3}$	= 2.5	± 2.0
η^τ	= 3.7	± 0.4
z_*	= 12.0	± 4.0

Grille de Paramètres

1 simulation = 50 khrs

PRACE	Regular Access	2371	8.0 Mhrs CPU
	Preparatory Access	2777	0.2 Mhrs CPU
GENCI	Regular Access	7706	3.7 Mhrs CPU



parameter	$x_{0,i}$	Δx_i
cosmological		
h	= 0.675 ± 0.05	
Ω_m	= 0.31 ± 0.05	
σ_8	= 0.83 ± 0.05	
n_s	= 0.96 ± 0.05	
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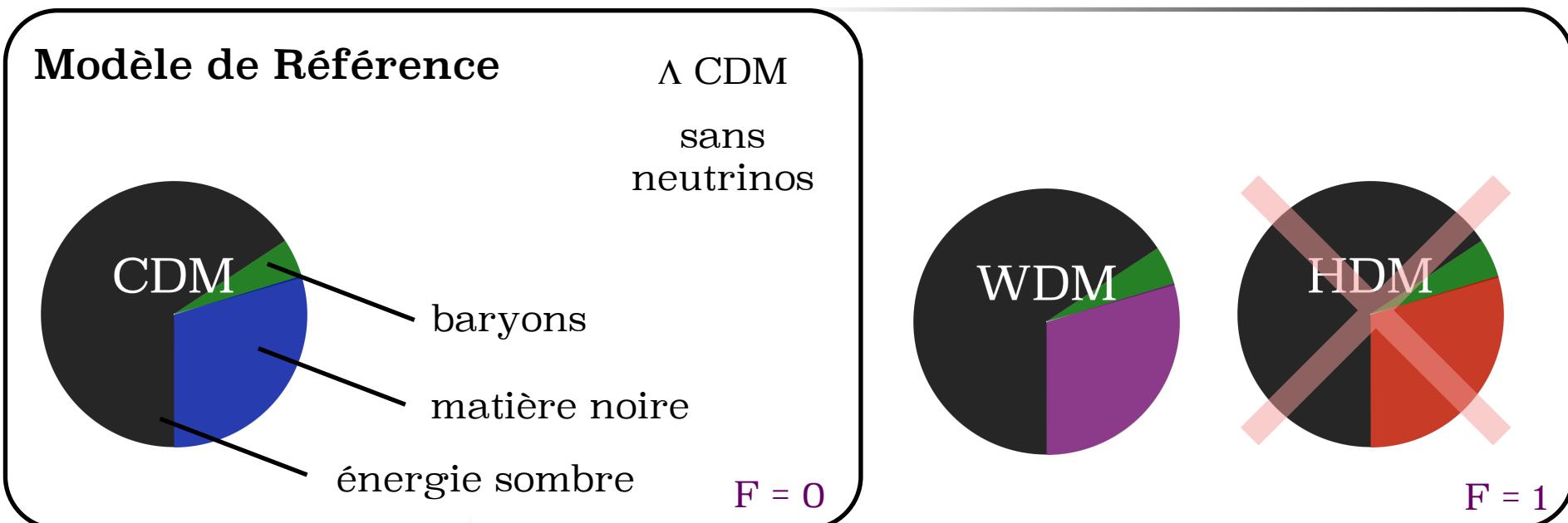
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4a neutrinos leptoniques et matière noire mixte

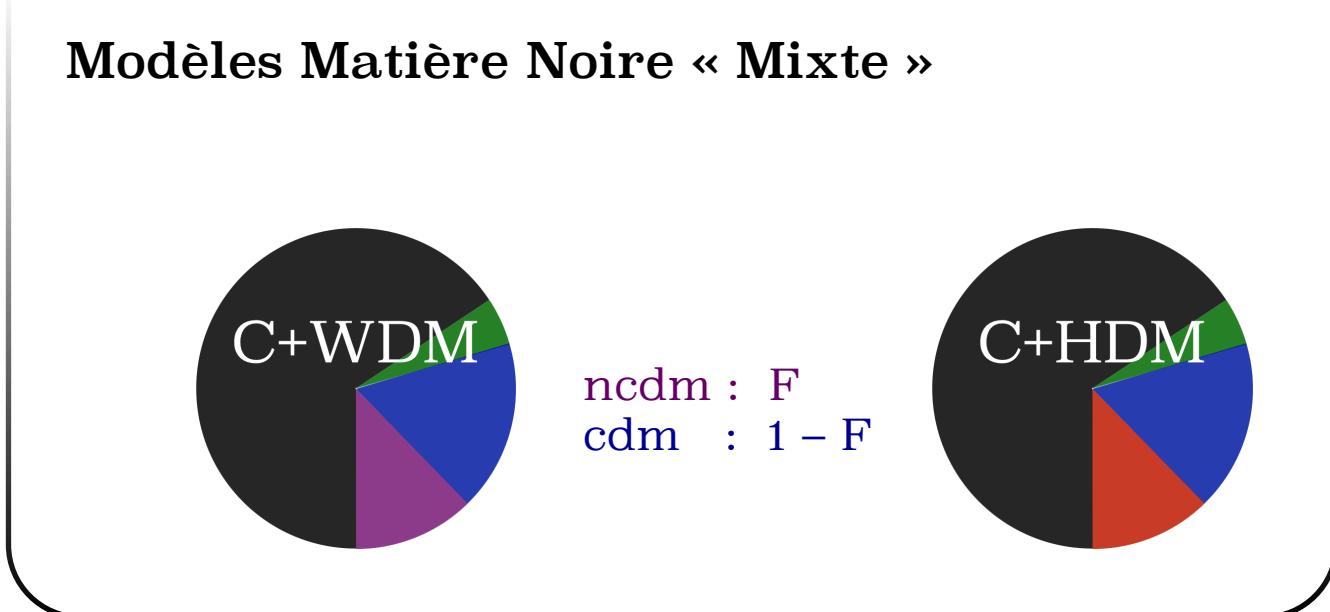
4b neutrinos stériles et matière noire pure

Modèles

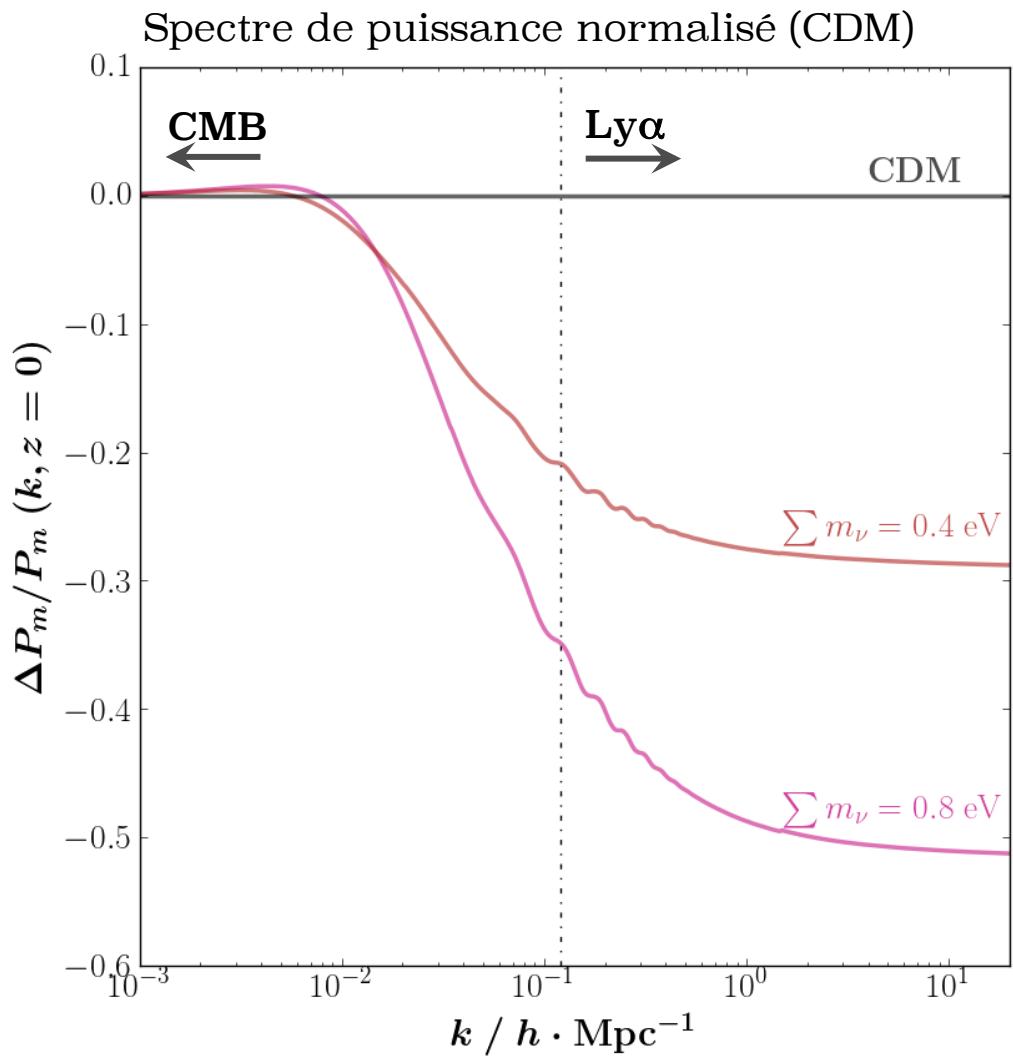
Modèles Matière Noire « Pure »



Modèles Matière Noire « Mixte »

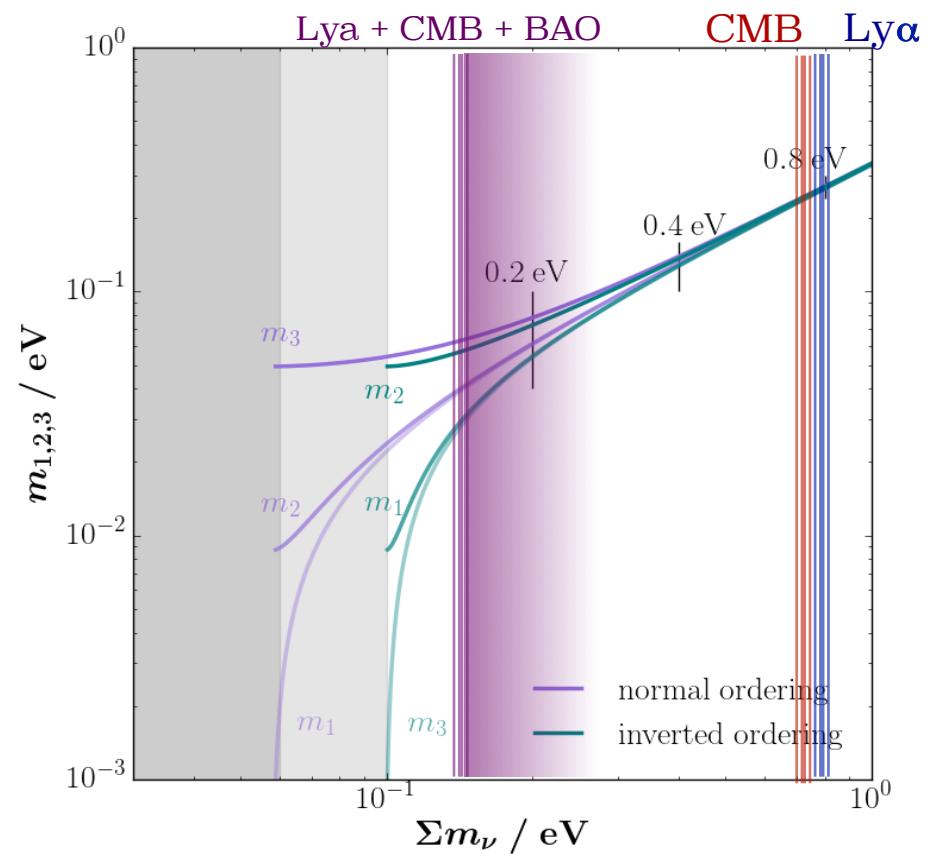


Limites sur $\sum m_\nu$



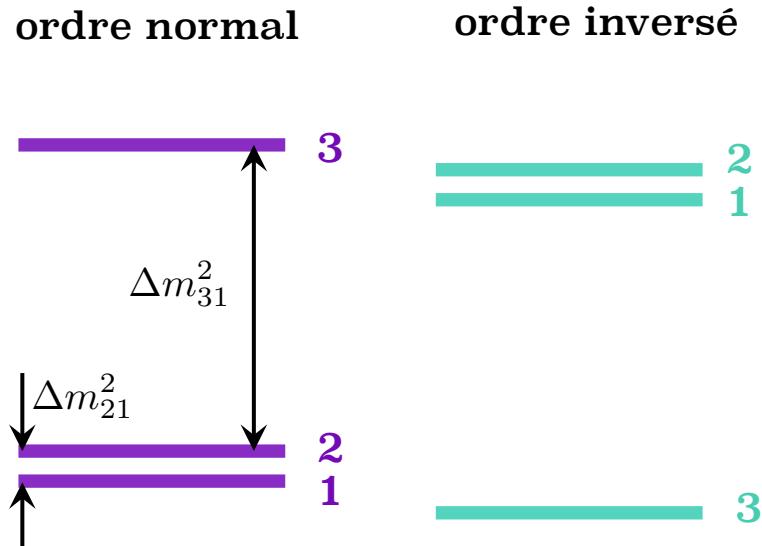
95 % C.L.

Data set	Ly- α + H_0	+ CMB	+BAO
BOSS DR9	1.1	0.12	0.12
BOSS DR9 + XQ-100	0.8	0.14	0.14



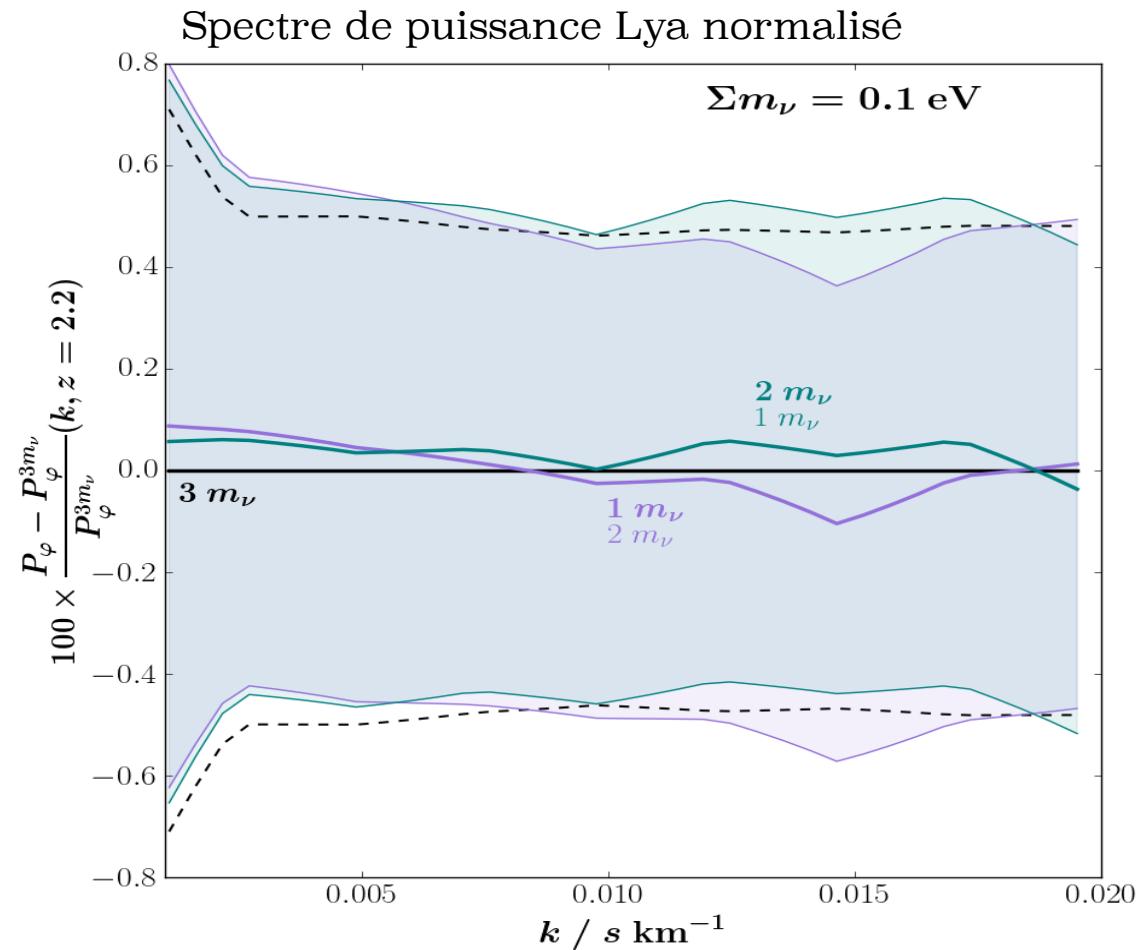
Ordre des masses

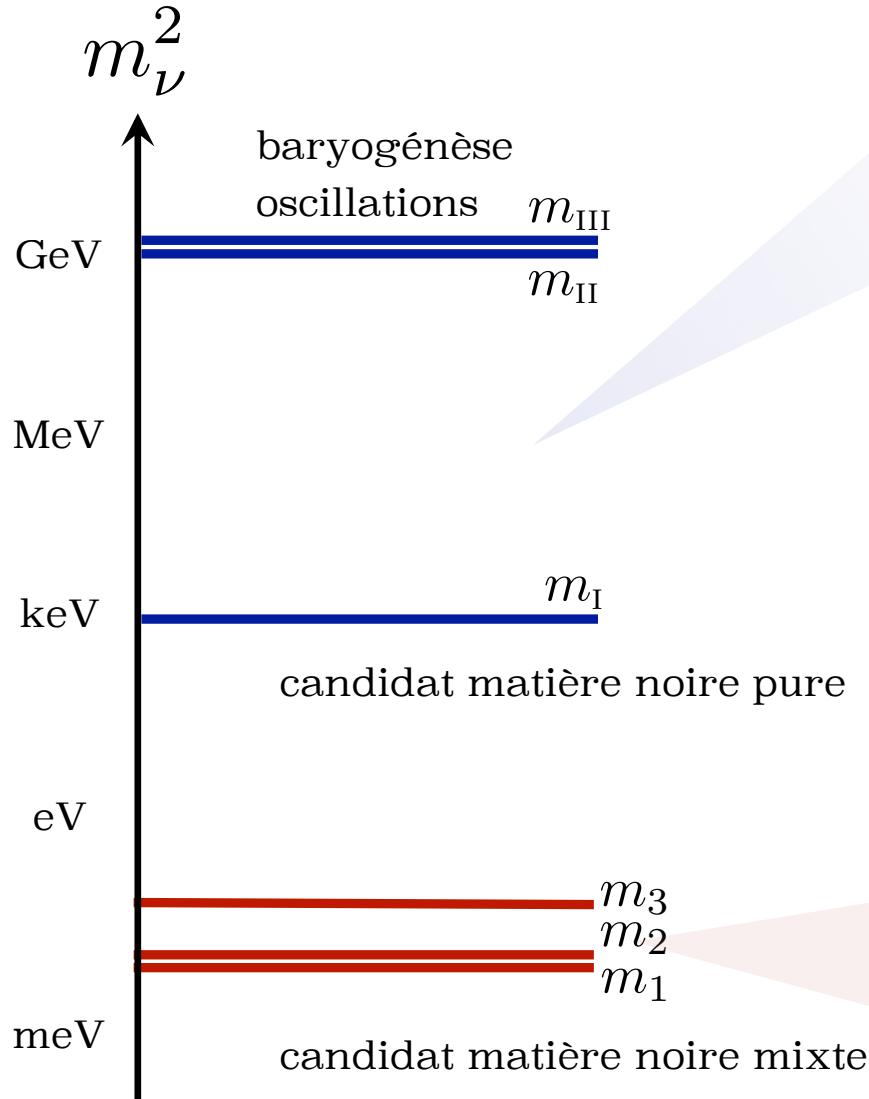
Palanque-Delabrouille, Yèche, **Baur** et al., JCAP 11 (2015) 011



configuration	m_1/meV	m_2/meV	m_3/meV
solo	100	0	0
inverted	50	49	1
normal	54	24	22
degenerate	33	33	33

$$\sum m_\nu = 0.1 \text{ eV}$$

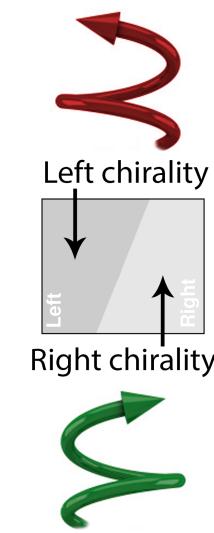




Neutrinos Stériles

hélicité droite

2.4 MeV $\frac{2}{3}$ Left up	1.27 GeV $\frac{2}{3}$ Left charm	171.2 GeV $\frac{2}{3}$ Left top
4.8 MeV $-\frac{1}{3}$ Left down	104 MeV $-\frac{1}{3}$ Left strange	4.2 GeV $-\frac{1}{3}$ Left bottom
$<0.0001 \text{ eV}$ 0 Left electron neutrino	$\sim \text{keV}$ 0 Left sterile neutrino	$\sim 0.01 \text{ eV}$ 0 Left muon neutrino
0 Left electron neutrino	$\sim \text{GeV}$ 0 Left sterile neutrino	$\sim \text{GeV}$ 0 Left tau neutrino
0.511 MeV -1 Left electron	105.7 MeV -1 Left muon	1.777 GeV -1 Left tau



Neutrinos Leptoniques

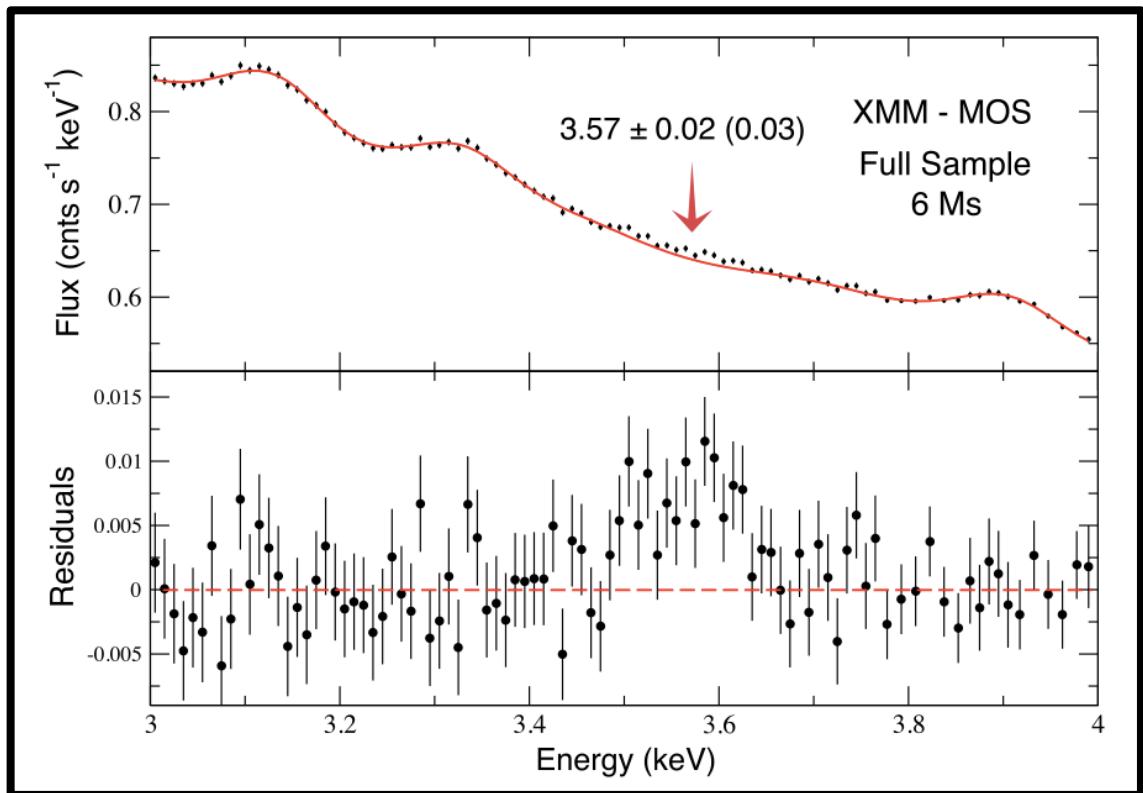
hélicité gauche

Neutrinos Stériles

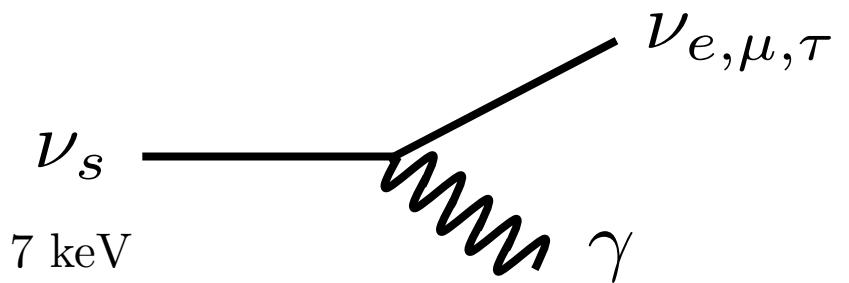


Bulbul *et al.* 2014, ApJ 789 13

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



canal de désintégration



Production par Oscillations



nombre effectif de neutrinos thermalisés

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

CMB (Planck) TT+TE+EE+lowP

$$N_{\text{eff}} = 2.99 \pm 0.30$$

Dodelson & Widrow (1994)

oscillations $\nu_{e,\mu,\tau} \longleftrightarrow \nu_s$

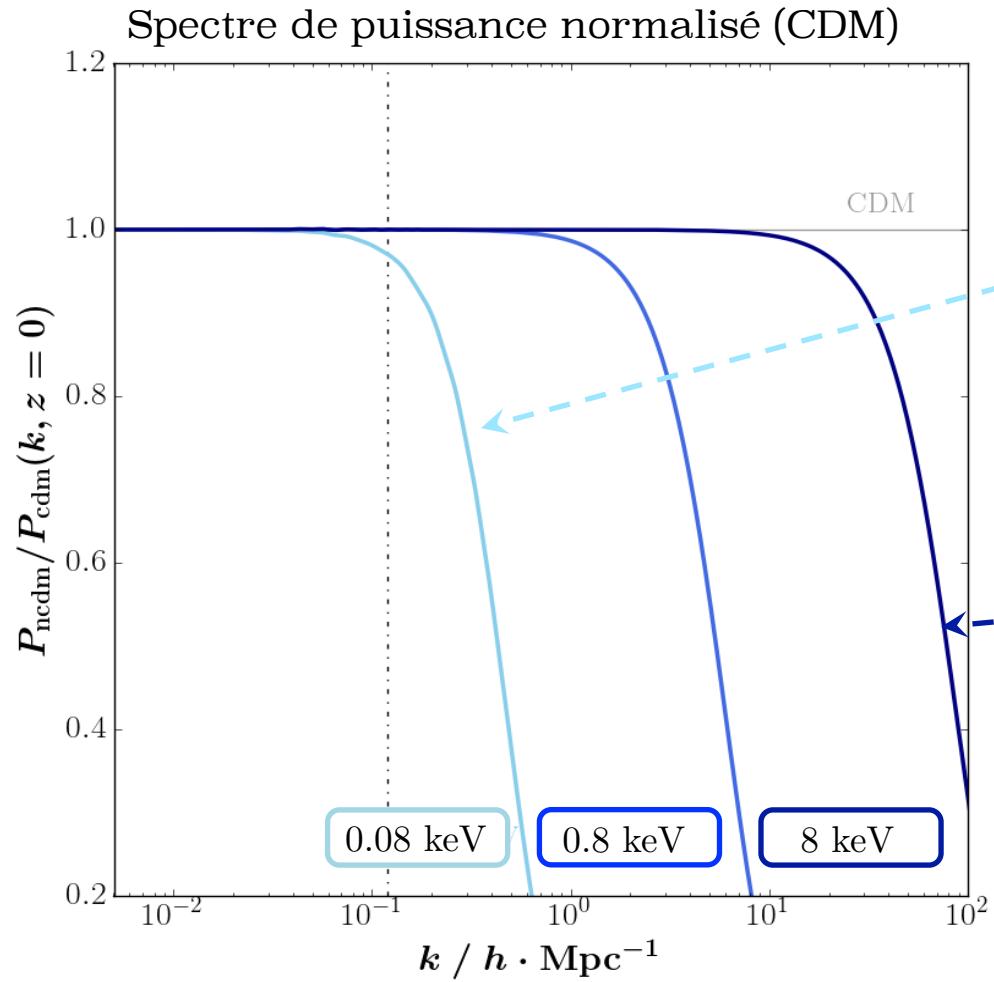
taux de production maximal

$$\frac{m_{\nu_s}}{\text{keV}} \left(\frac{T_\nu}{150 \text{ MeV}} \right)^3 \sim 1$$

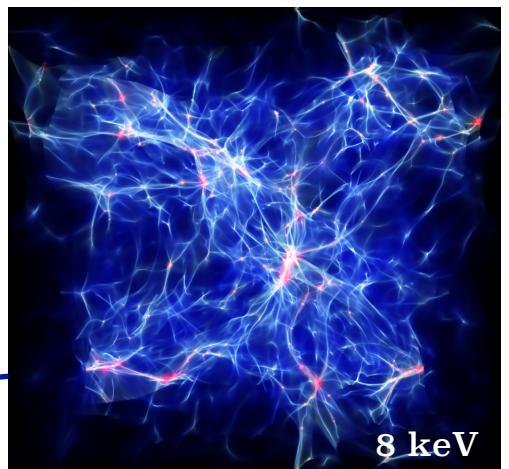
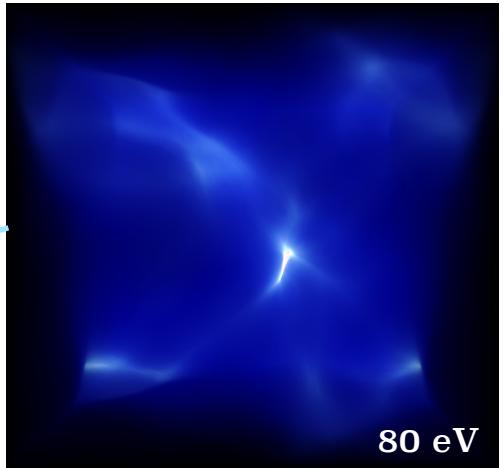
fonction de distribution

$$f_s(p) = \frac{\sin^2 2\theta}{1 + e^{p/T}}$$

Limites sur m_{ν_s}



visualisation simulation numériques



correspondance de masse

$$m_{\nu_s} = \kappa m_x^\mu / \omega_{\text{wdm}}^{1/3}$$

stérile
générique
(thermalisée)

Limites sur m_{ν_s}



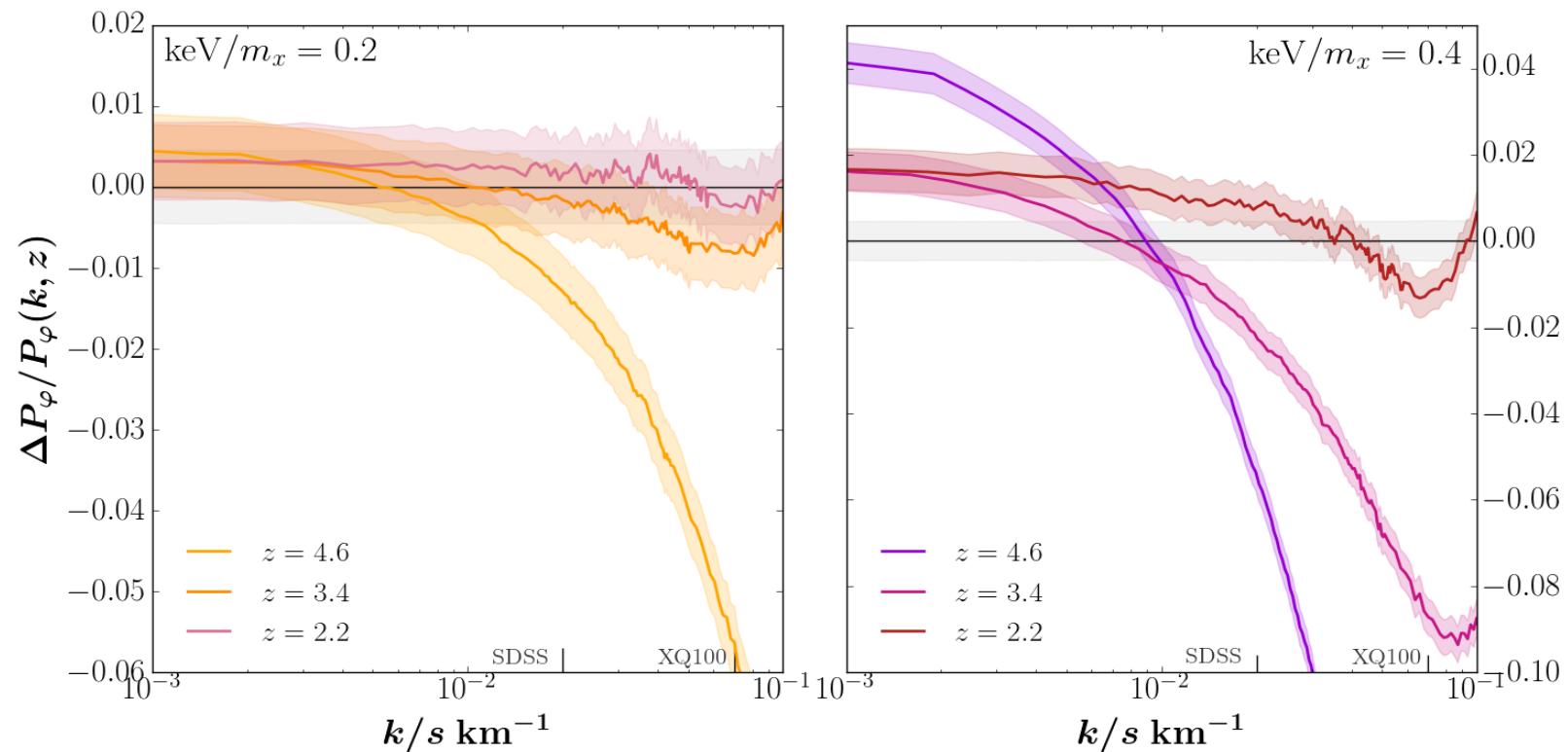
Baur et al., JCAP 08 (2016) 012

48 citations

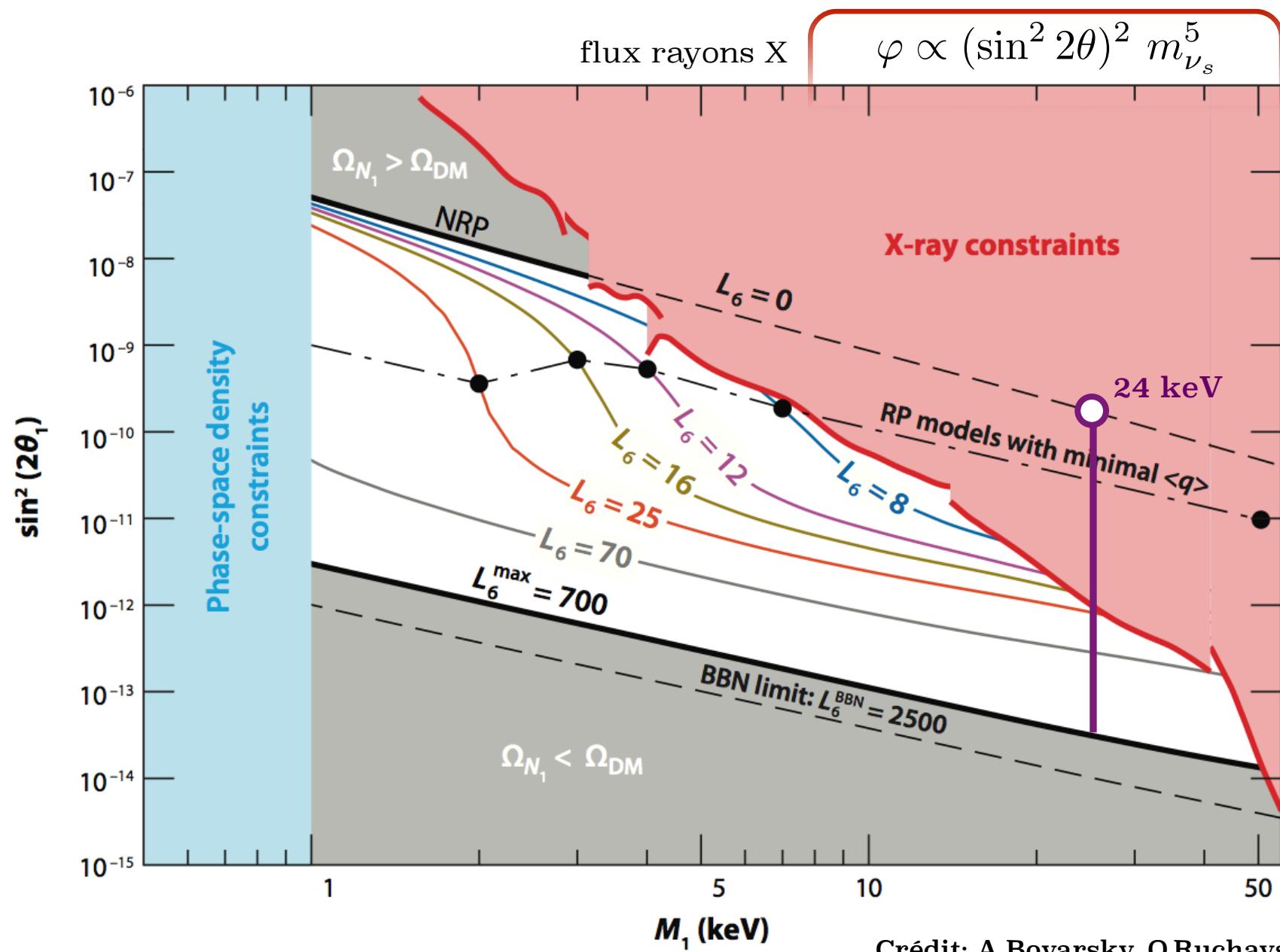
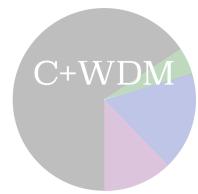
95 % C.L.

Data set	SDSS/BOSS	XQ-100	SDSS+XQ	SDSS+XQ+HR
m_x/keV	4.09	2.08	4.17	4.65
$m_{\nu_s}^{\text{nrp}}/\text{keV}$	24.4	10.2	25.0	28.8

Yèche, Palanque-Delabrouille, Baur et al.,
JCAP 06 (2017) 047



Limites sur m_{ν_s}



Crédit: A.Boyarsky, O.Ruchayskiy, J.Lesgourgues

Production Résonante



oscillations $\nu_{e,\mu,\tau} \longleftrightarrow \nu_s$

Shi & Fuller (1999)

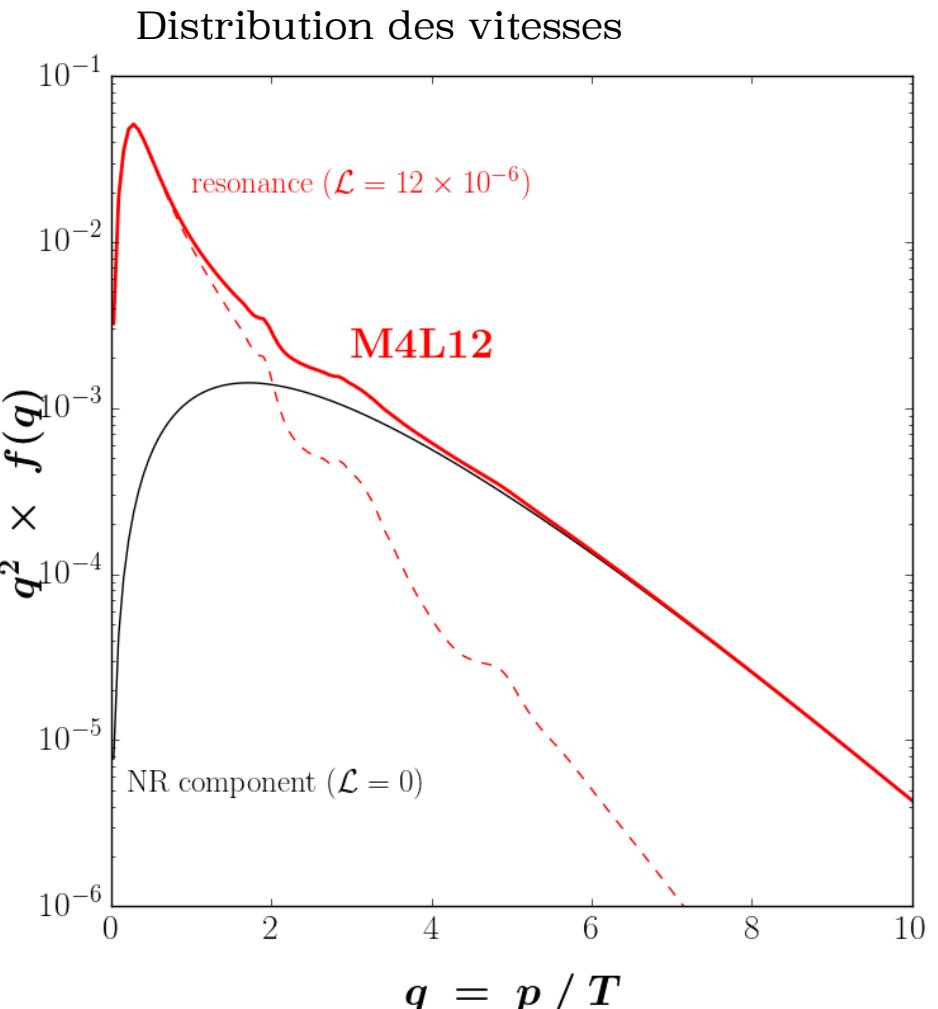
asymétrie leptונית

$$\mathcal{L} = \frac{|n_\nu - n_{\bar{\nu}}|}{s}$$

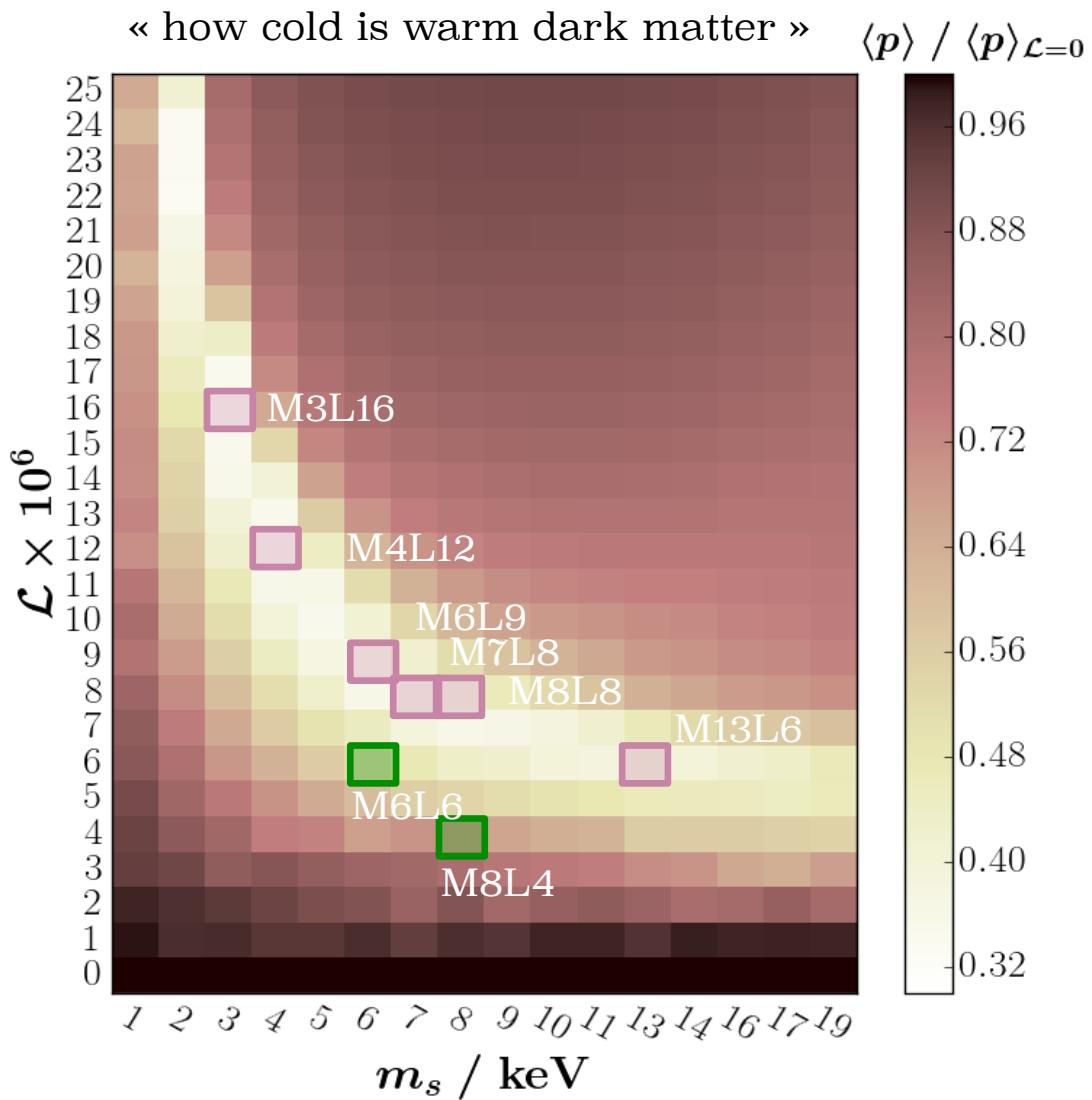
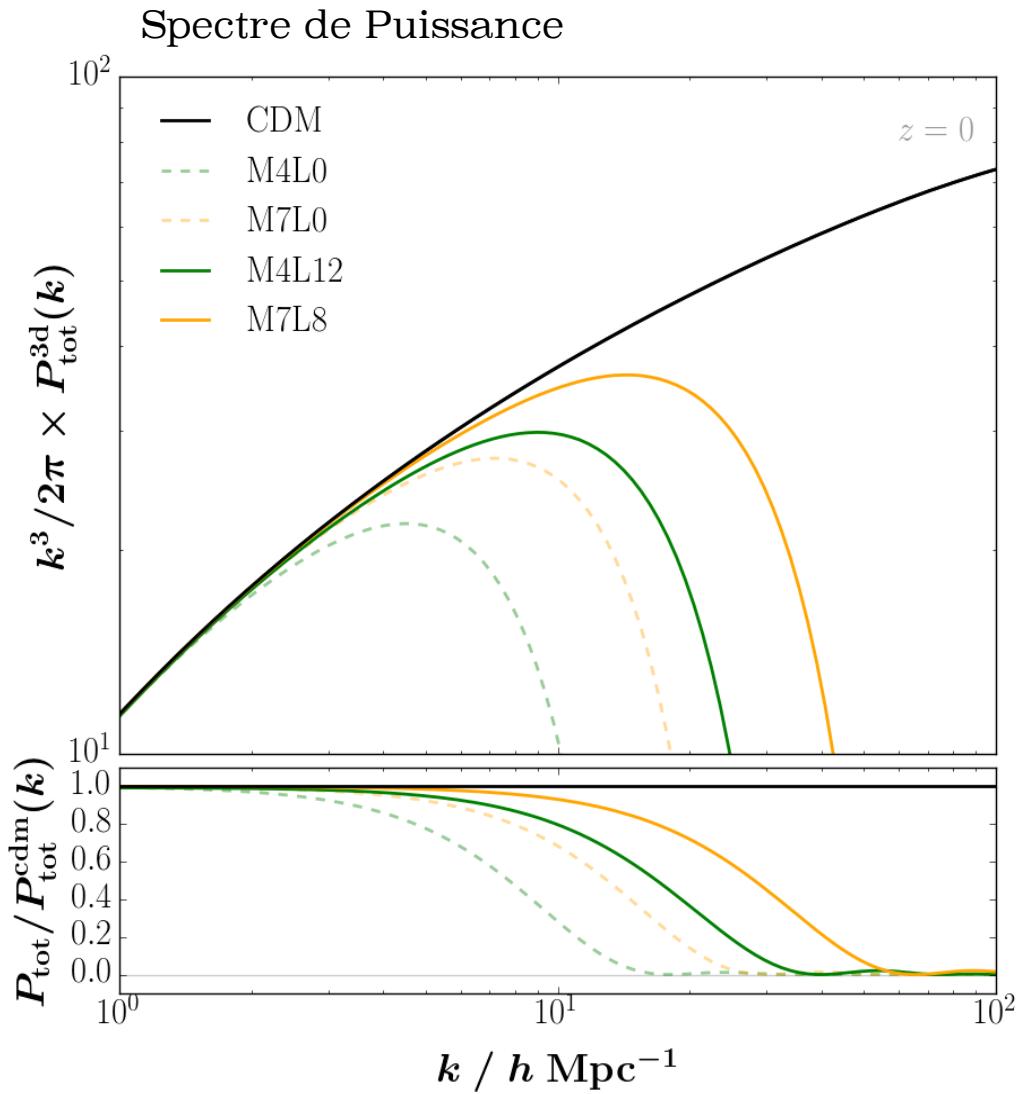
taux d'oscillations accentué

fonction de distribution
non-thermique

longueur de diffusion afaiblie

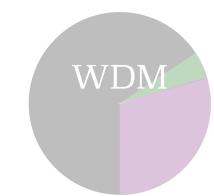


Résonance

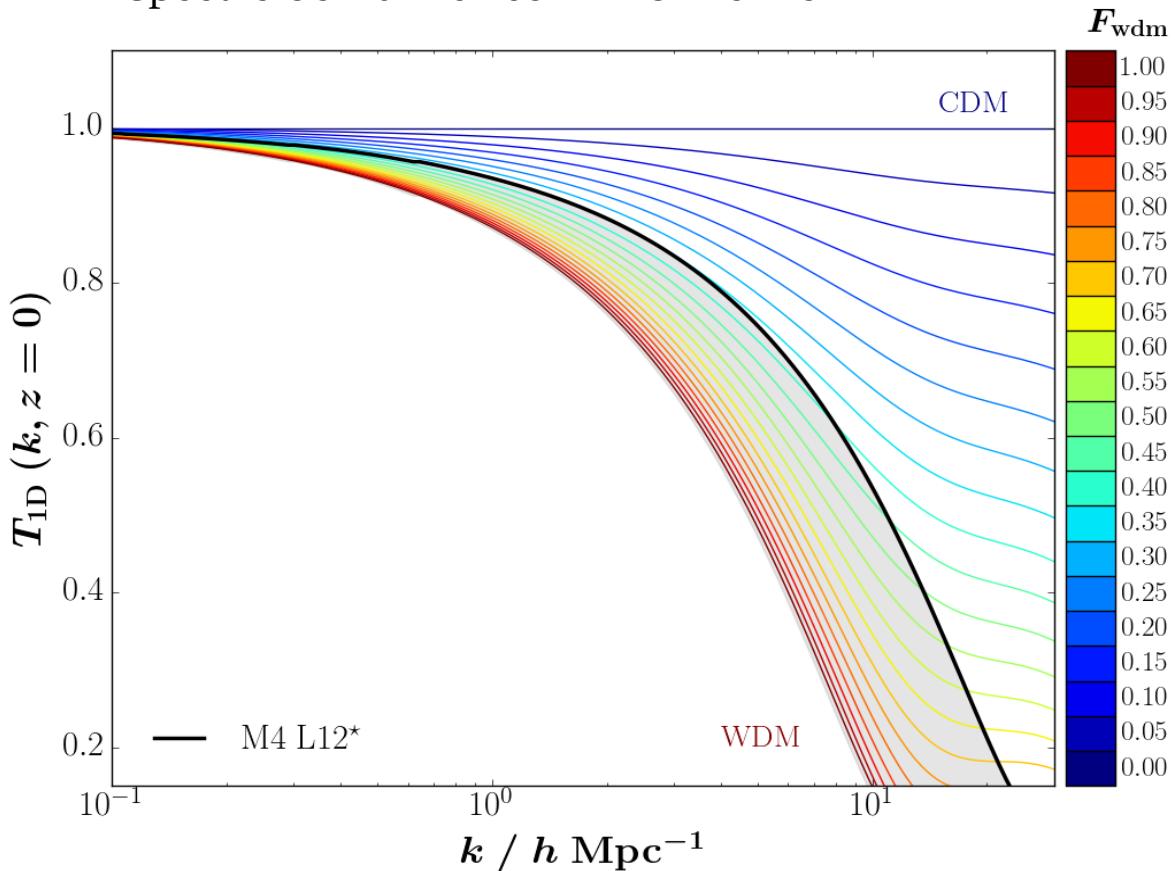


Cartographie

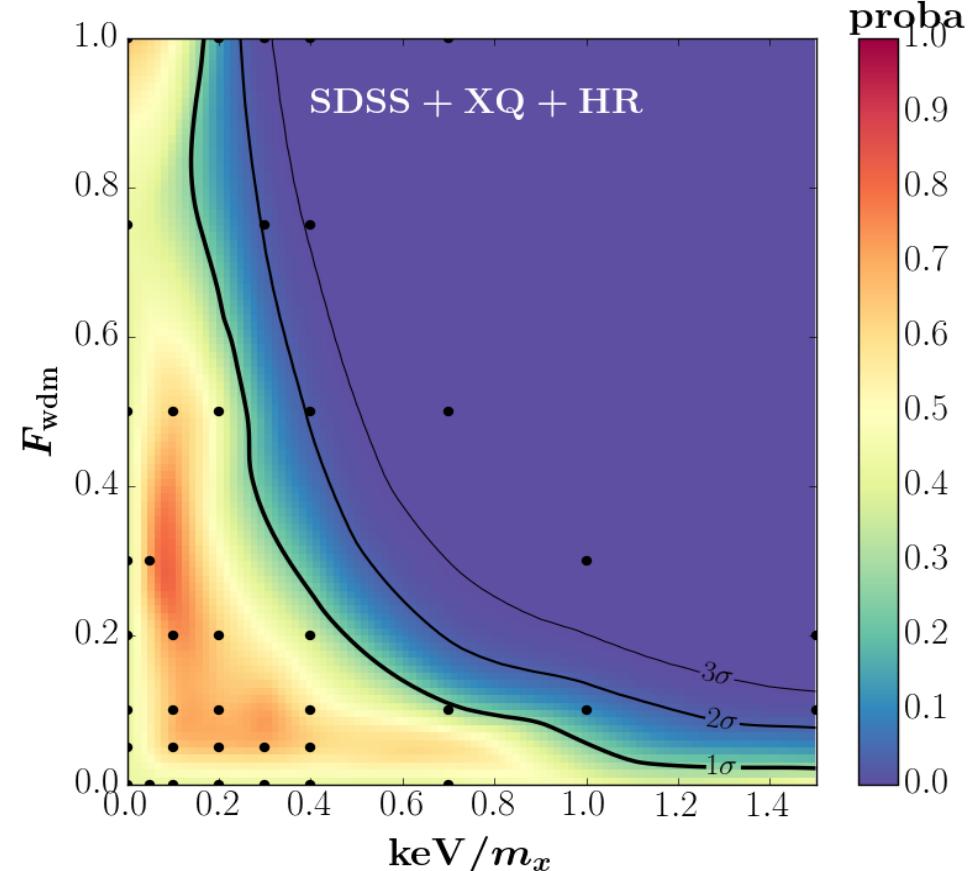
Baur et al. 2017, arXiv:1706.03118



Spectre de Puissance 1D normalisé



Contraintes C+WDM



Cartographie

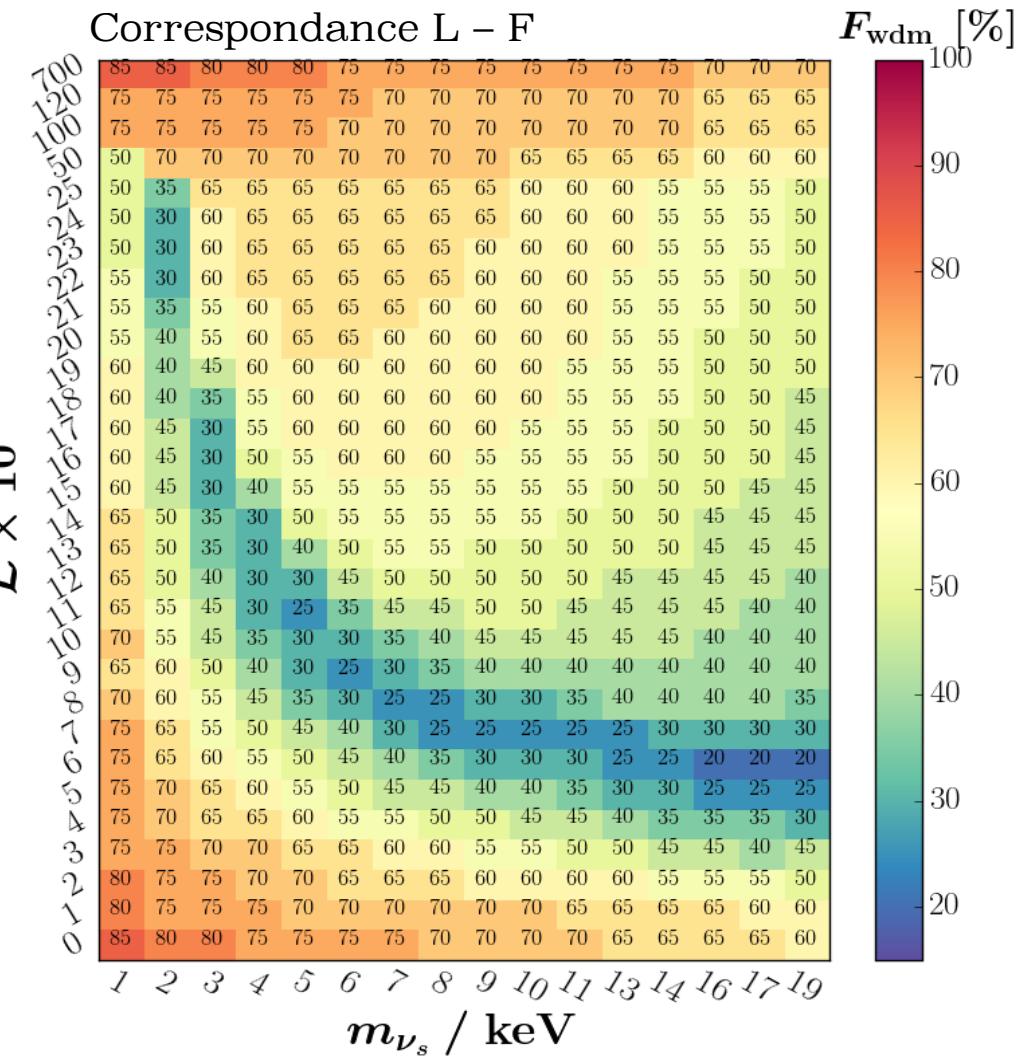


Interpolation des contours 2D
dans le plan (m, F)

Ajustement $T_{1D}(m, F) \longleftrightarrow T_{1D}(m, L)$

Ajout des simulations RPSN

Contours 2D dans le plan (m, L)

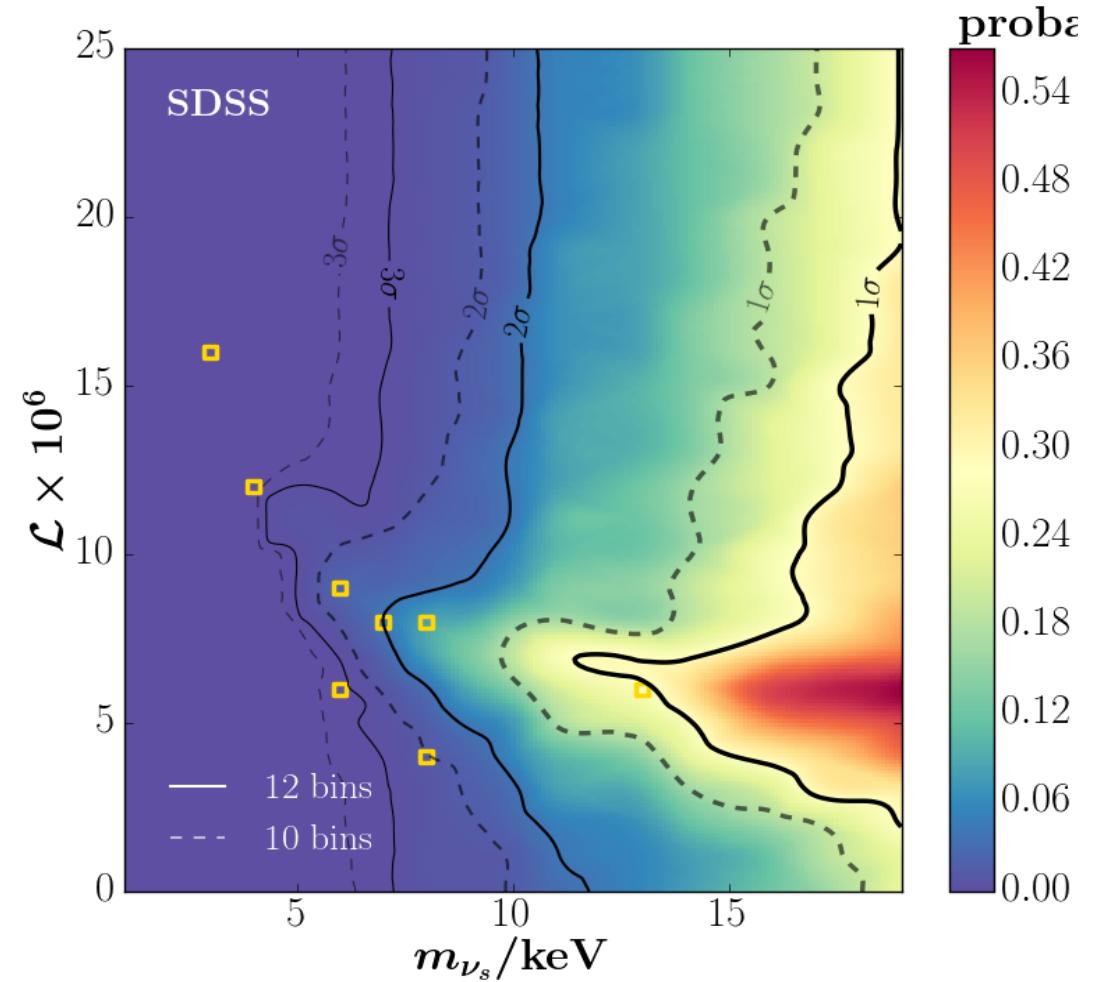


Résultats

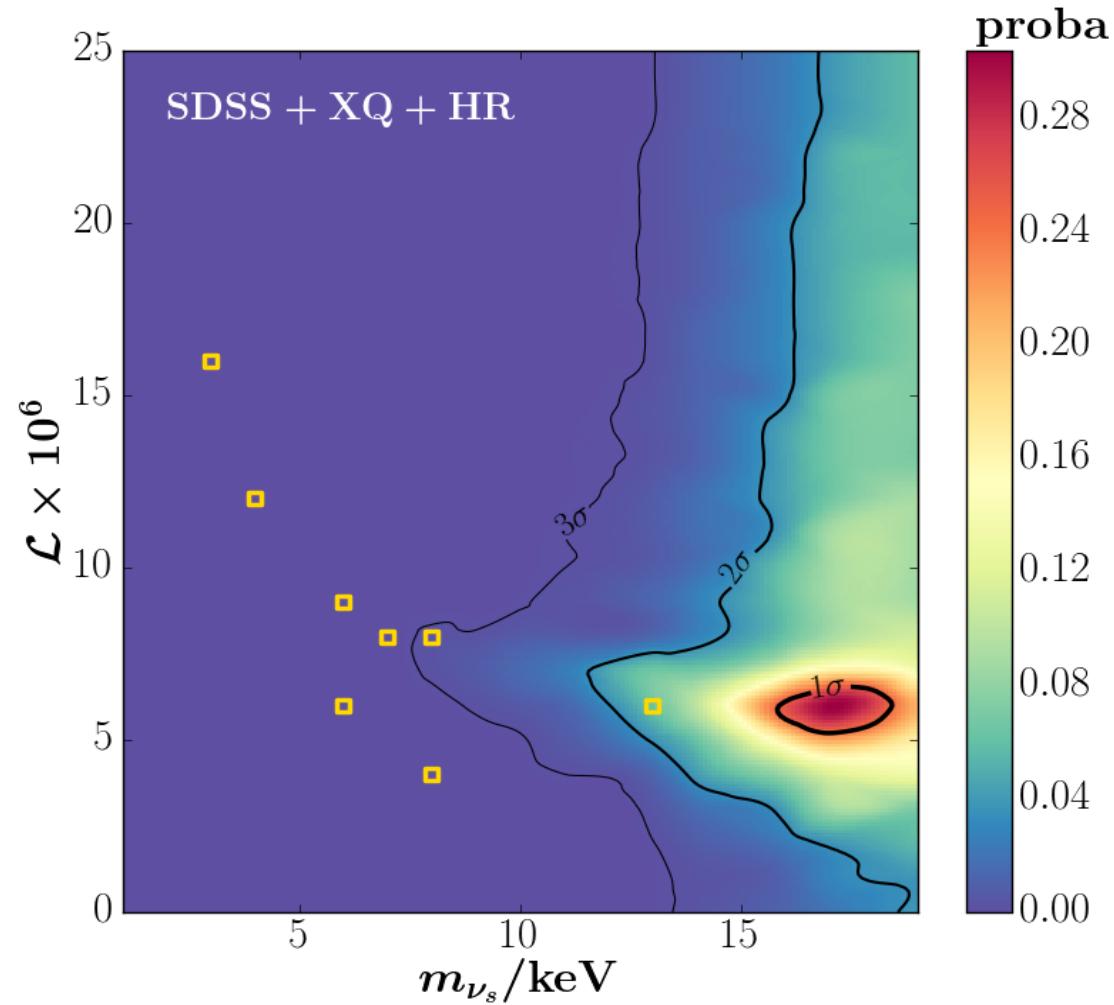
Baur et al. 2017, arXiv:1706.03118



Données basse résolution ($k < 0.02 \text{ s/km}$)

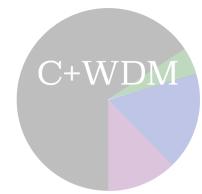
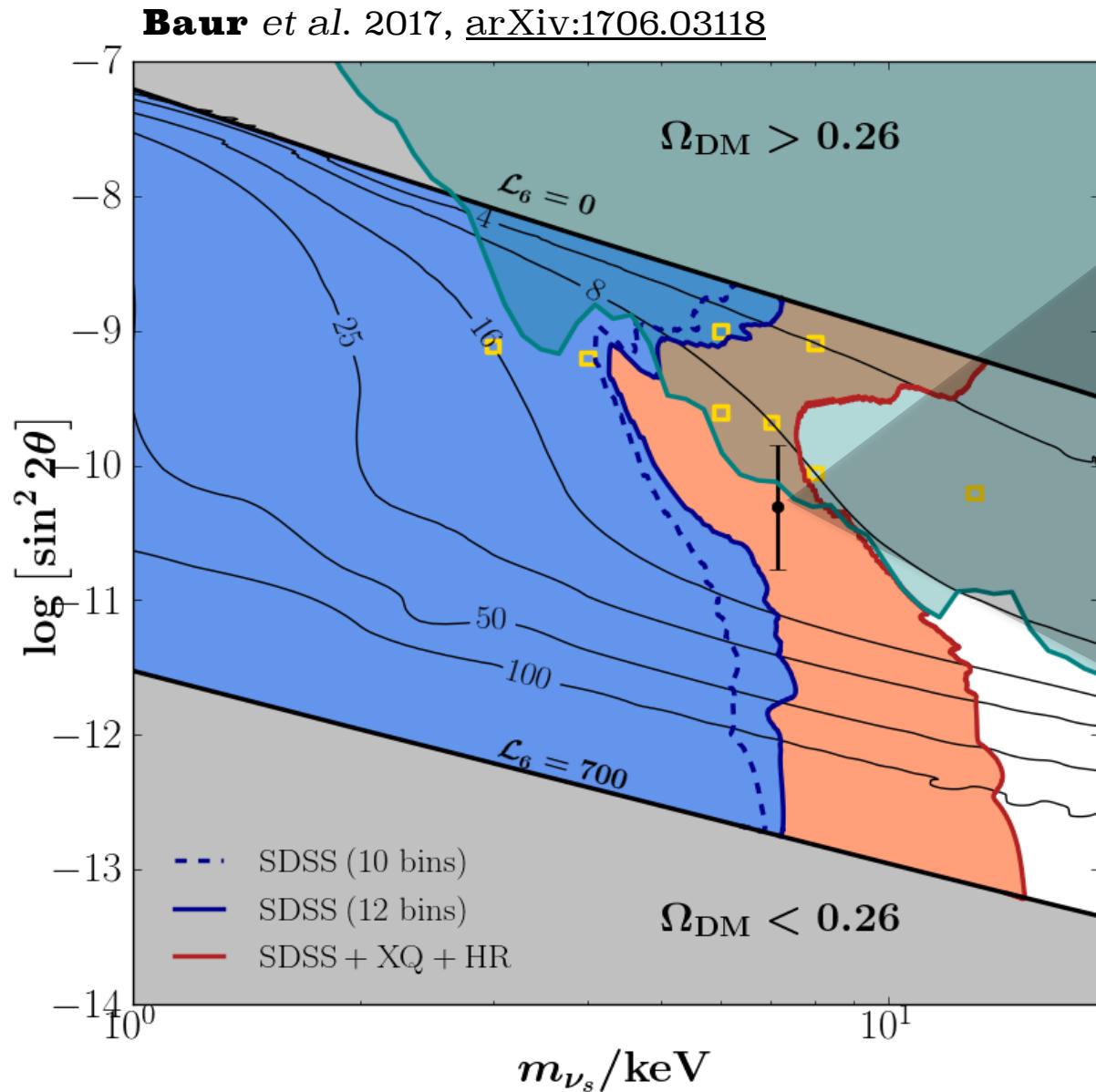


Données haute résolution ($k < 0.07 \text{ s/km}$)

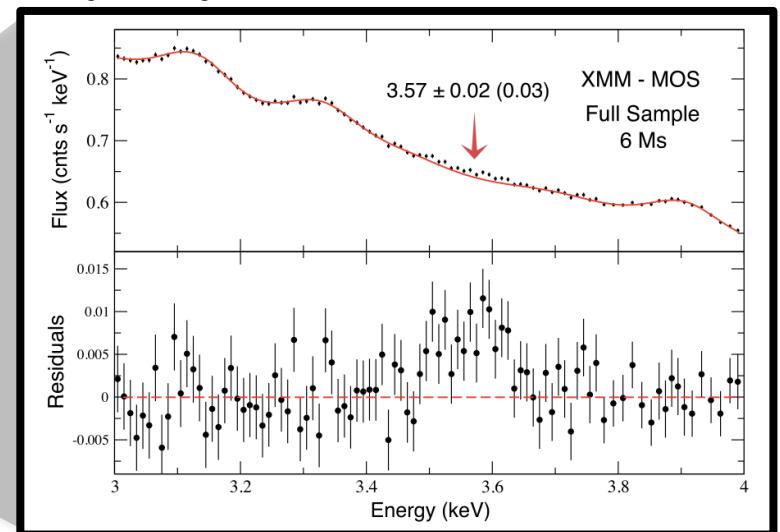


Résultats

Contours à 3σ



Bulbul et al. 2014, [ApJ 789 13](#)
Boyarsky et al. 2014, [PRL 113, 251301](#)



Conclusion



Simulations numériques modulables

- matière noire pure, mixte, « fuzzy » etc
- mécanisme de production



Limites sur la masse des neutrinos *leptoniques*

$$\sum m_\nu \leqslant 0.14 \text{ eV}$$

95% C.L.



Limites sur la masse des neutrinos *stériles*

$$m_{\nu_s} \geqslant 24 \text{ keV}$$

M7L8 exclu à 3.1 σ

Perspectives

Modélisation de l'IGM

- Redshift de ré-ionisation
- Effets baryoniques
- IGM tiède