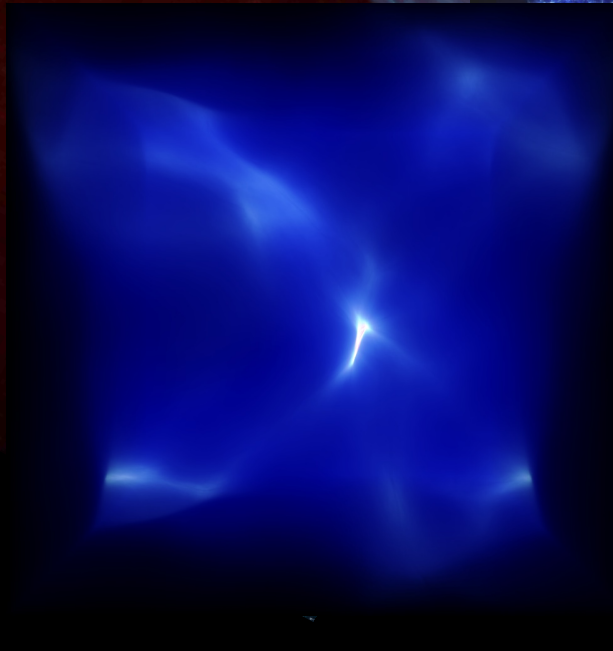
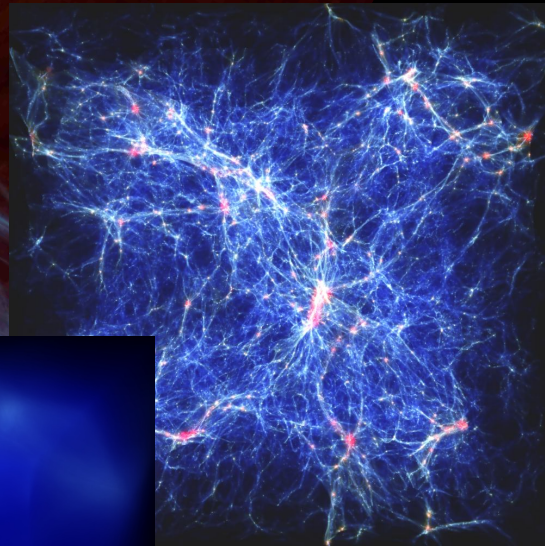


What Lyman- α surveys tell us about neutrinos

N. Palanque-Delabrouille,
CEA-Saclay,
(visitor at Berkeley)

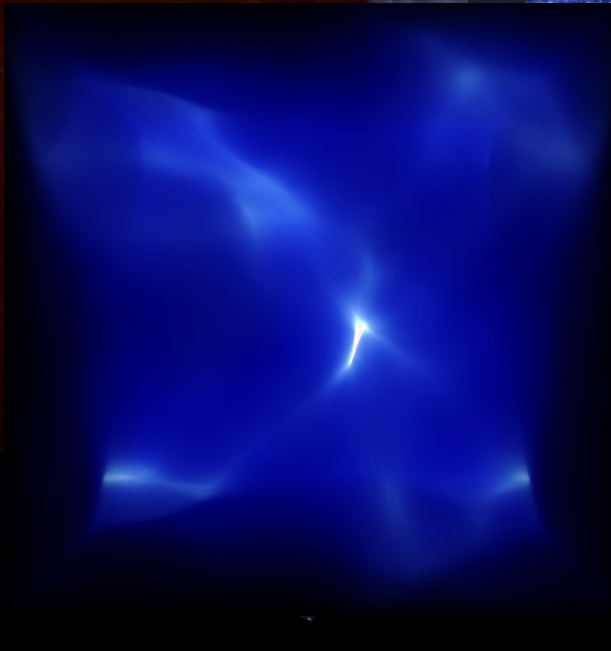
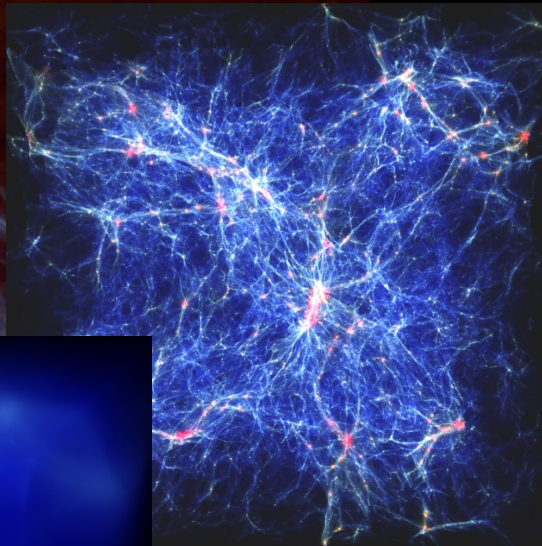
1. Massive neutrinos and large-scale structures
2. BOSS quasar survey
3. Results on Σm_ν
4. What about sterile neutrinos?



What Lyman- α surveys tell us about neutrinos

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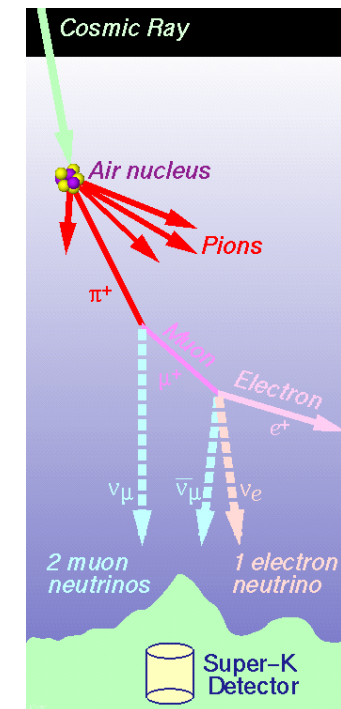
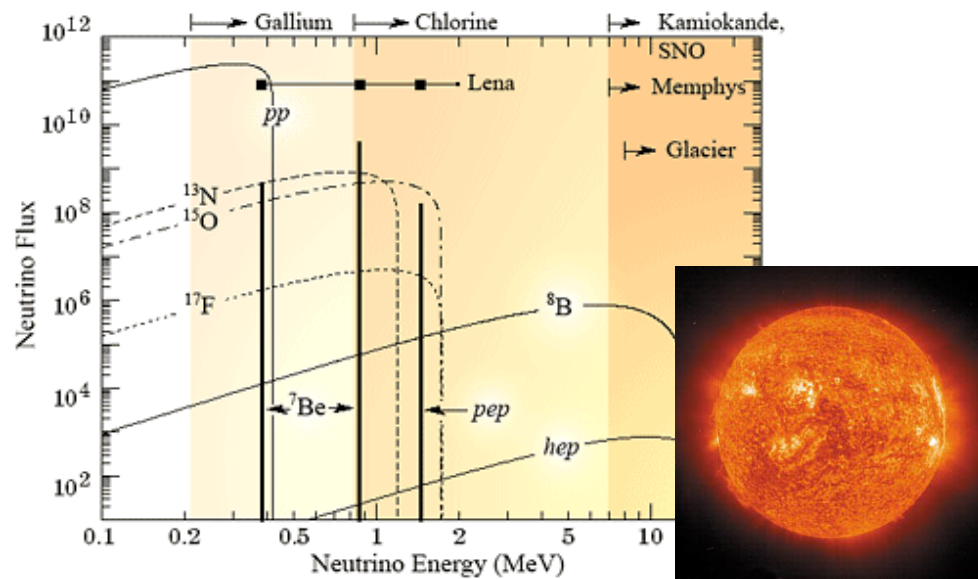
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Neutrino masses

● Neutrino oscillations

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



→ No constraint on absolute masses

Capozzi et al. (2014)

Neutrino masses

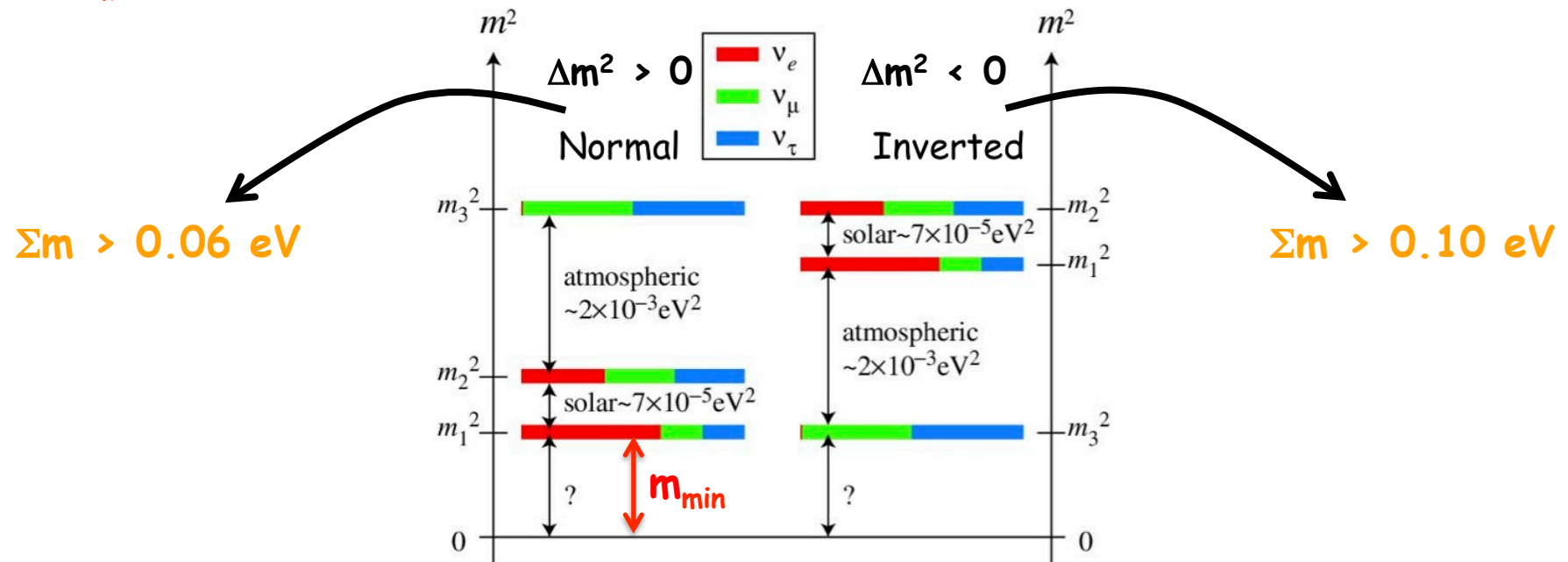
- **Neutrino oscillations**

Solar $\delta m^2 = m_2^2 - m_1^2 \quad \sim 7.5 \cdot 10^{-5} \text{ eV}^2$

Atmospheric $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2 \quad \sim 2.4 \cdot 10^{-3} \text{ eV}^2$

- **→ 2 possible mass patterns (sign of Δm^2)**

$m_{\min} > 0 \Rightarrow$



Neutrino masses

- **Neutrino oscillations**

Solar $\delta m^2 = m_2^2 - m_1^2 \quad \sim 7.5 \cdot 10^{-5} \text{ eV}^2$

Atmospheric $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2 \quad \sim 2.4 \cdot 10^{-3} \text{ eV}^2$

- $\rightarrow$ At least two neutrino mass eigenstates with $m_i > 0.01 \text{ eV}$ & $m_j > 0.05 \text{ eV}$

Cosmological implications?

- Thermal neutrino background decouples at $T \sim 1 \text{ MeV}$
(fixed by weak interactions)

- Present temperature: $T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma = 1.95K \sim 10^{-4} \text{ eV}$

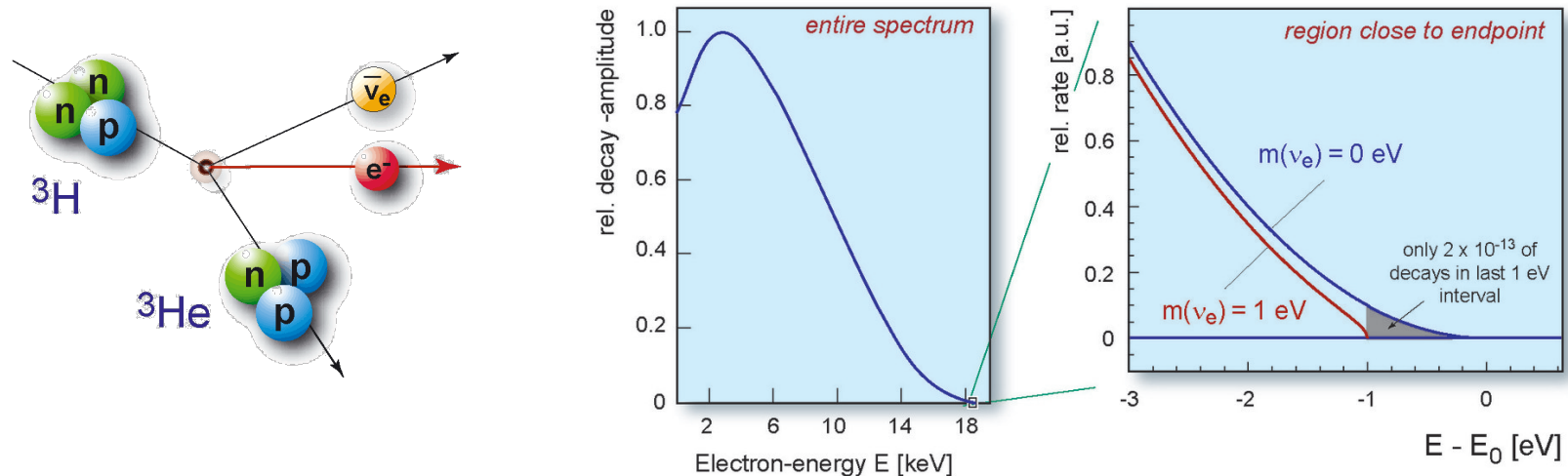
- **At least two relic neutrinos are non-relativistic today**

$\rightarrow$ Present-day energy density: $\Omega_\nu = \frac{m_\nu n_\nu}{\rho_c} = \frac{m_\nu}{93h^2 \text{ eV}} > 0.1\%$

$\rightarrow$ Contribute to DM

Neutrino masses

- Direct mass measurement from Tritium β decay:



Sensitivity to $m_\beta = (\sum |U_i|^2 m_i^2)^{1/2}$

Currently in degenerate-mass regime so $m_\beta \sim m_{\min}$

→ $m_{\min} < 2$ eV (current limits) $\max \Omega_\nu \sim 15\%$

→ sensitivity of 0.2 eV in near future (KATRIN experiment)

*Lobashev [Troitsk] 2003;
Krauss et al. [Mainz] 2005*

Neutrino masses

- Particle-physics bounds on neutrino masses: $0.06 < \Sigma m < 6 \text{ eV}$

- Major role to play for cosmology for $\Sigma m \sim \text{eV}$

→ Non-relativistic today

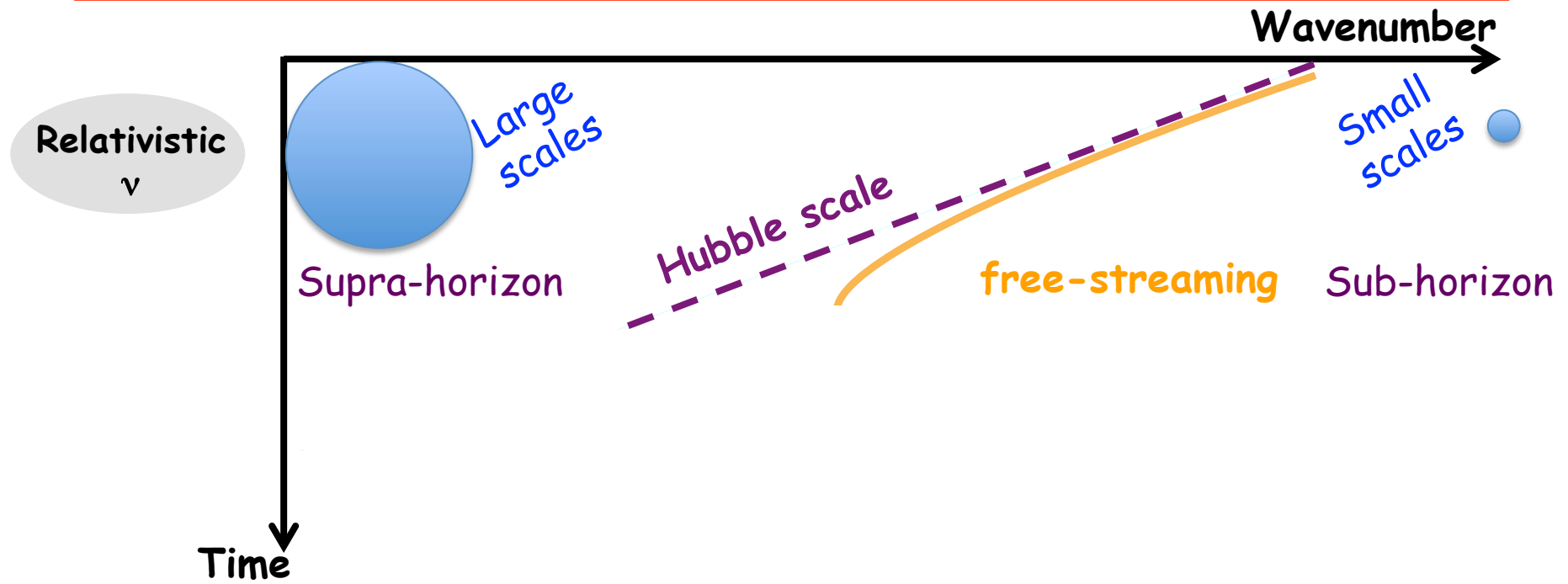
Contribute to DM

→ Relativistic till late

Free-stream

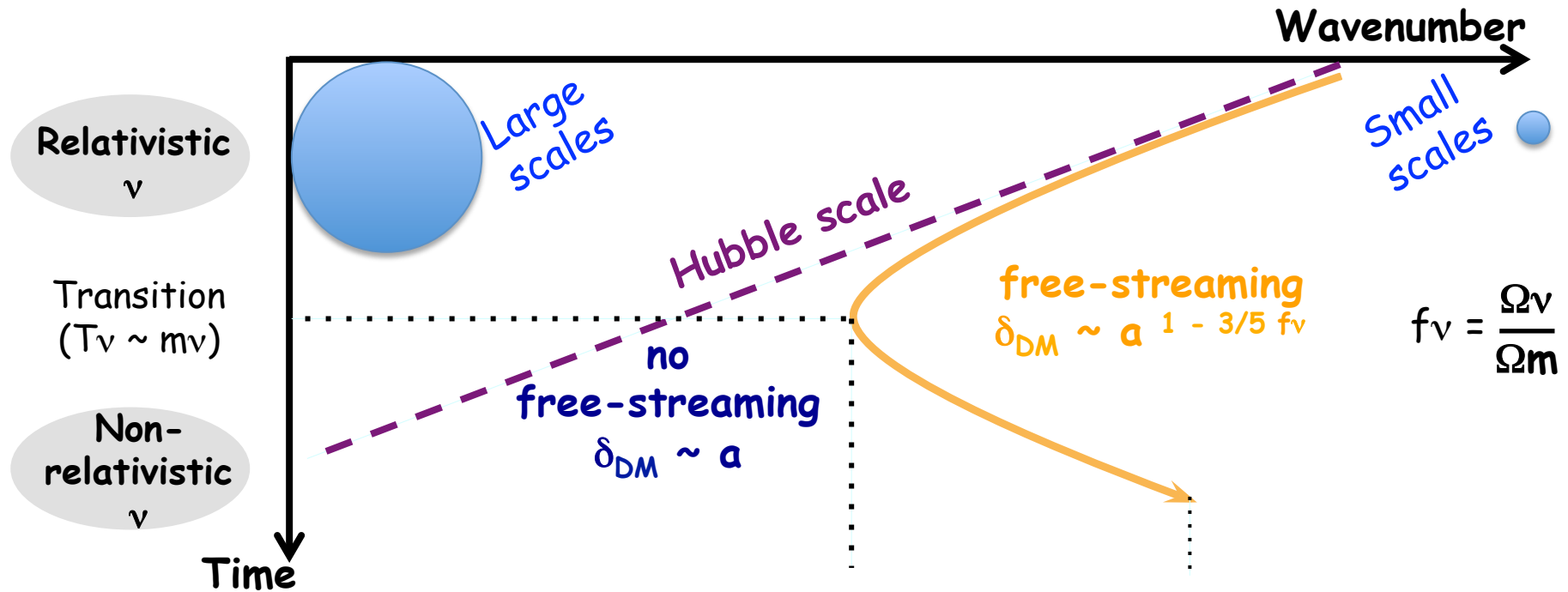
Wipe-out of sub-horizon scales (causality)

Neutrino mass & large-scale structures



Relativistic ν : $\lambda_{\text{FS}} \sim d_H = c/H(z) \sim t$

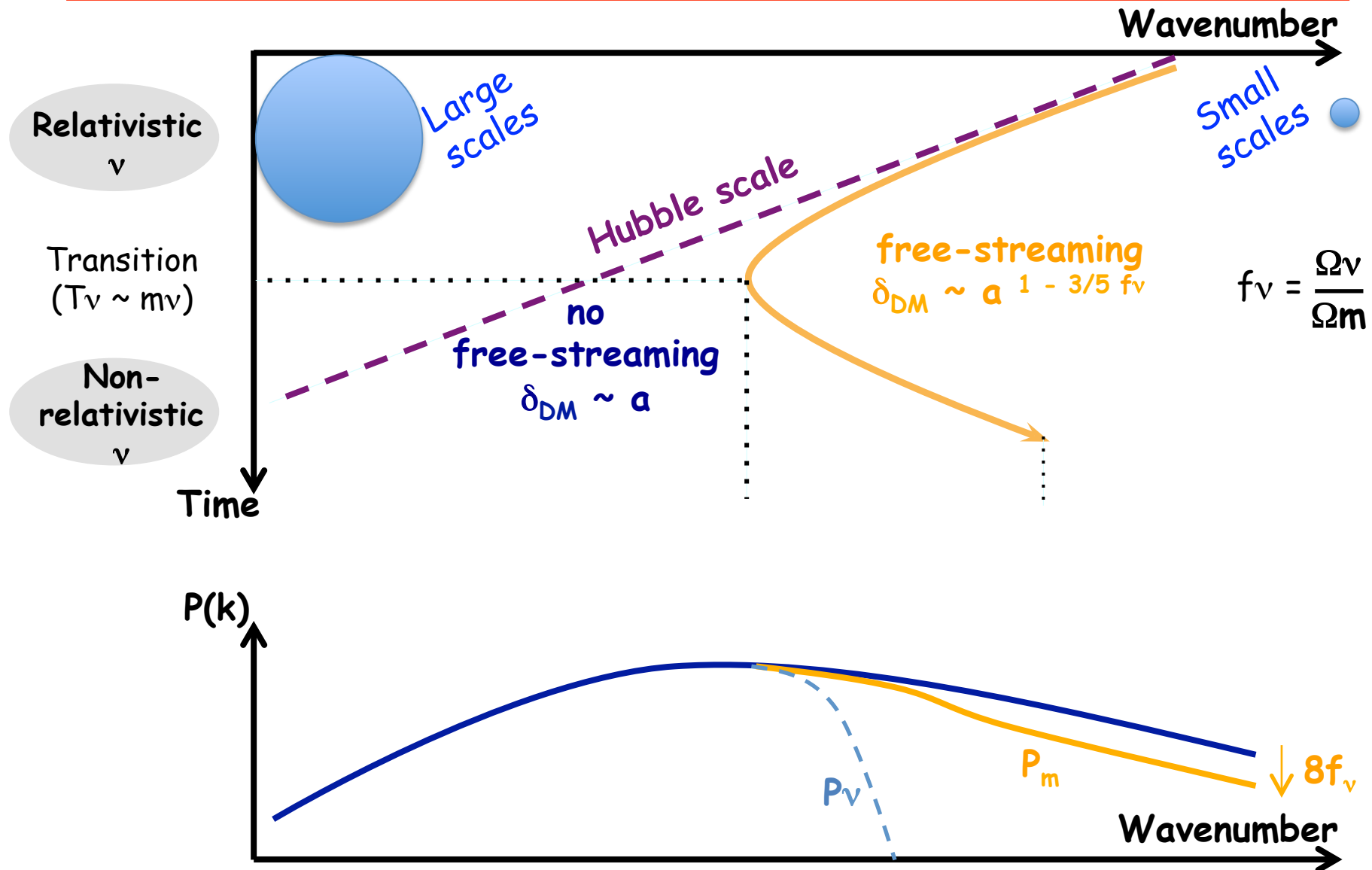
Neutrino mass & large-scale structures



Relativistic ν : $\lambda_{FS} \sim d_H = c/H(z) \sim t$

Non-relativistic ν : $\lambda_{FS} \sim v(z)/H(z)$ where $v(z) \sim T(z) \sim T_0 (1+z) = T_0 / a$
 $\Rightarrow \lambda_{FS} \sim 1/[aH(z)]$
 $\Rightarrow \lambda_{FS} \sim t^{1/3}$ since $a \sim t^{2/3}$ in matter dominated Universe
 $\Rightarrow \lambda_{FS}/a \sim t^{-1/3}$ (comoving coordinates)

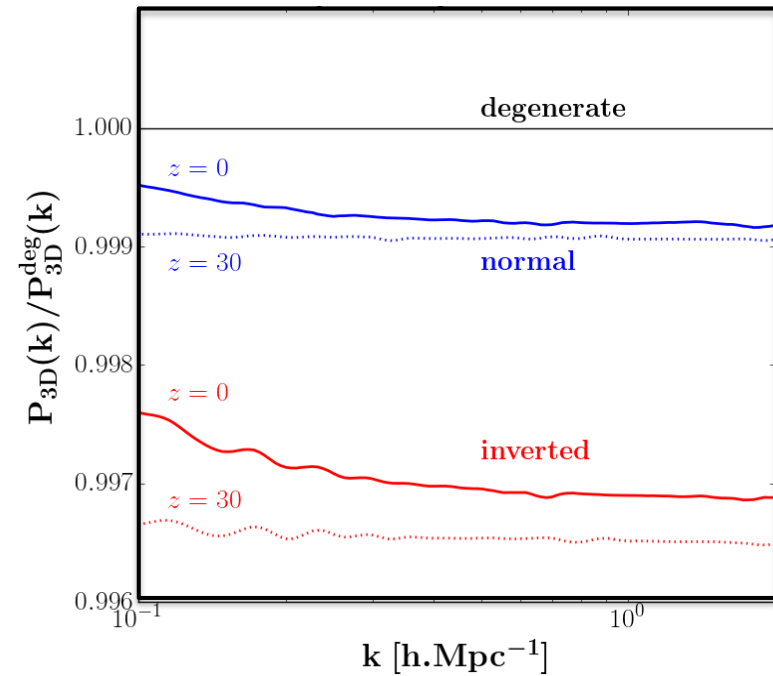
Neutrino mass & large-scale structures



Neutrino mass (Σm) or masses (m_i)?

$$\Sigma m = 0.10 \text{ eV}$$

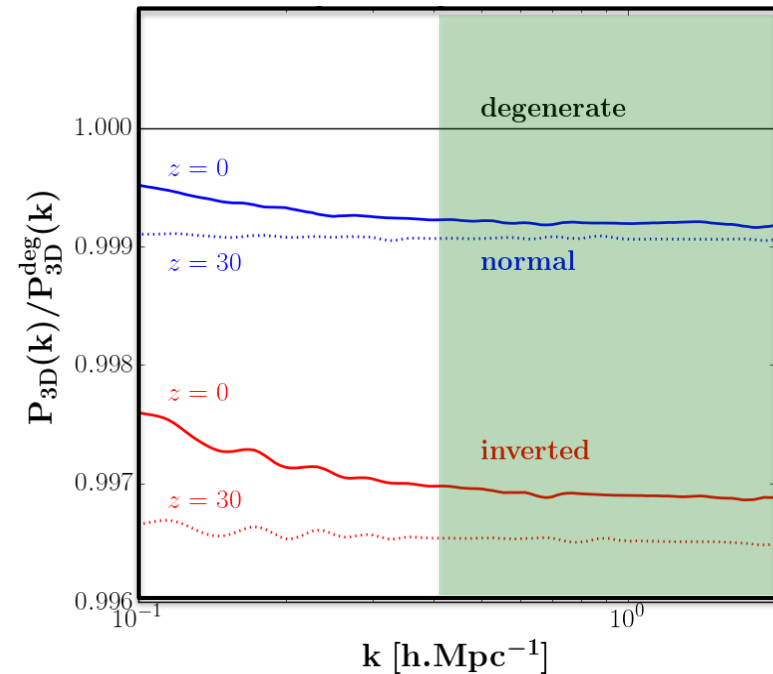
Hierarchy	m_1	m_2	m_3
Degenerate	0.033	0.033	0.033
Normal	0.022	0.024	0.055
Inverted	0.0007	0.049	0.050



Neutrino mass (Σm) or masses (m_i)?

$$\Sigma m = 0.10 \text{ eV}$$

Hierarchy	m_1	m_2	m_3
Degenerate	0.033	0.033	0.033
Normal	0.022	0.024	0.055
Inverted	0.0007	0.049	0.050



- $z_{\text{NR}} \sim 3$ for $m_1 = 0.007 \text{ eV}$

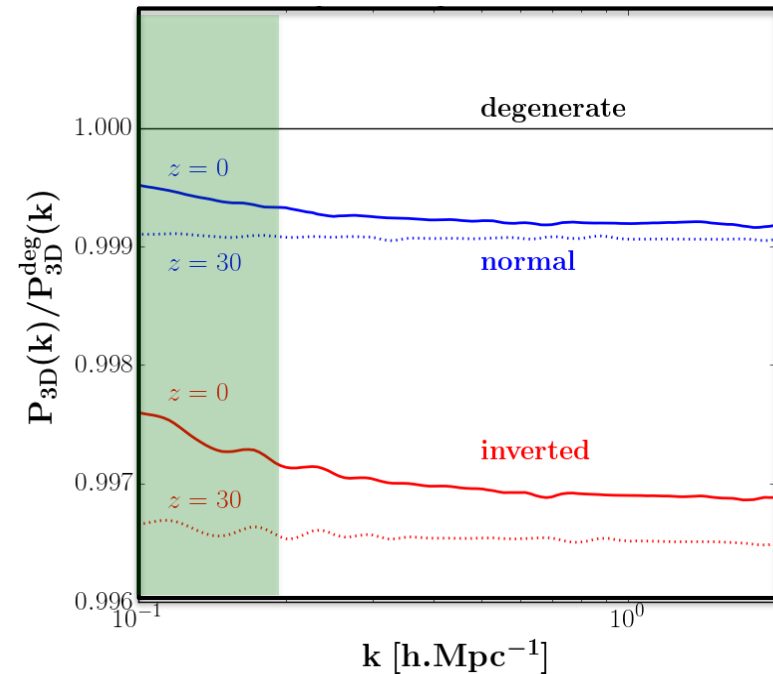
→ Longer contribution to background density

→ Stronger power suppression

Neutrino mass (Σm) or masses (m_i)?

$$\Sigma m = 0.10 \text{ eV}$$

Hierarchy	m_1	m_2	m_3
Degenerate	0.033	0.033	0.033
Normal	0.022	0.024	0.055
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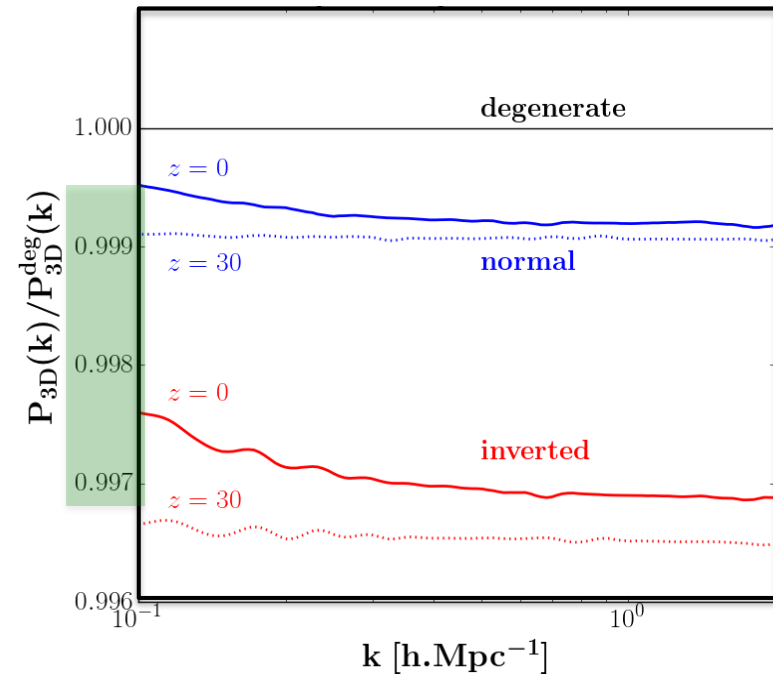
- Larger m_2, m_3
 - Earlier non-relativistic transition
 - Damping restricted to smaller scales
 - Excess of power on larger ($\sim 10^{-2} \text{ h Mpc}^{-1}$) scales

Neutrino mass (Σm) or masses (m_i)?

$$\Sigma m = 0.10 \text{ eV}$$

Hierarchy	m_1	m_2	m_3
Degenerate	0.033	0.033	0.033
Normal	0.022	0.024	0.055
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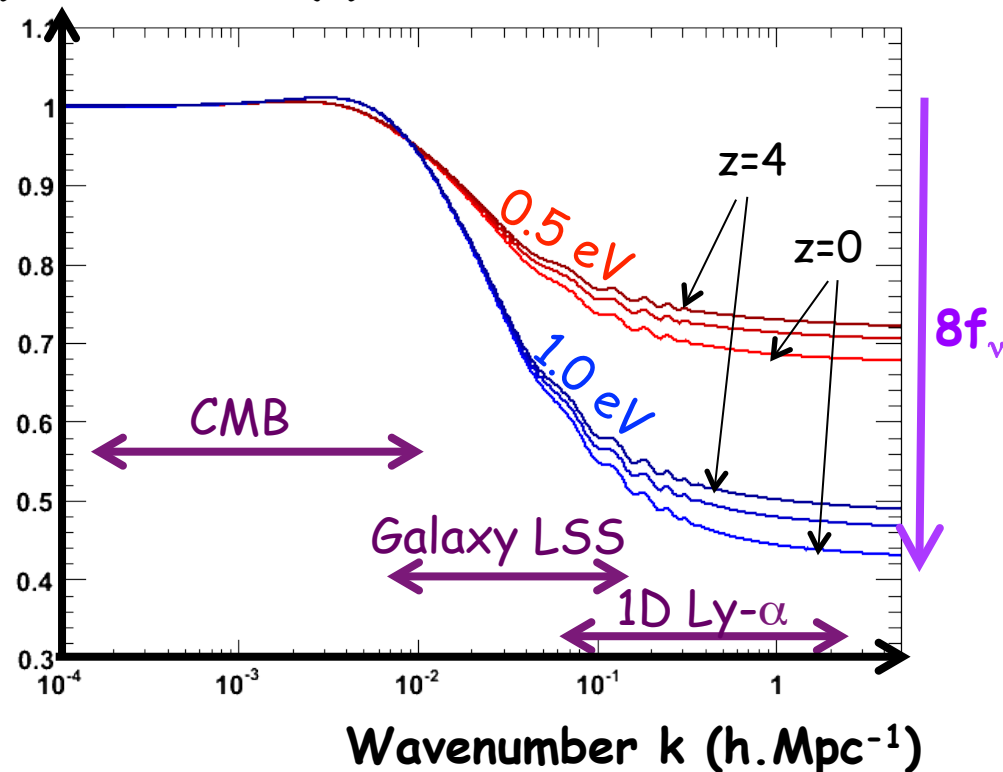
- **Sub-percent effect**
on 3D matter power spectrum
- **< Sub-percent effect**
on 1D flux power spectrum



**'Exclusively'
a Σm effect**

Neutrino mass & large-scale structures

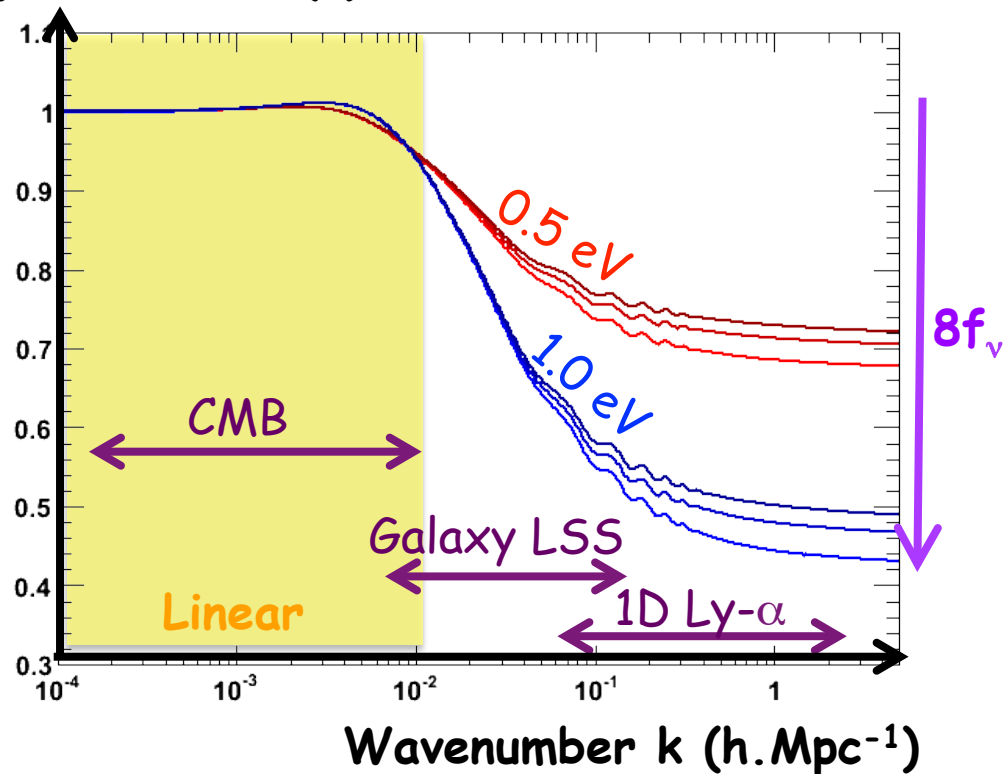
$P(k)$ massive / $P(k)$ massless



- Suppression factor $\Leftrightarrow \Sigma m\nu$
- 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] 

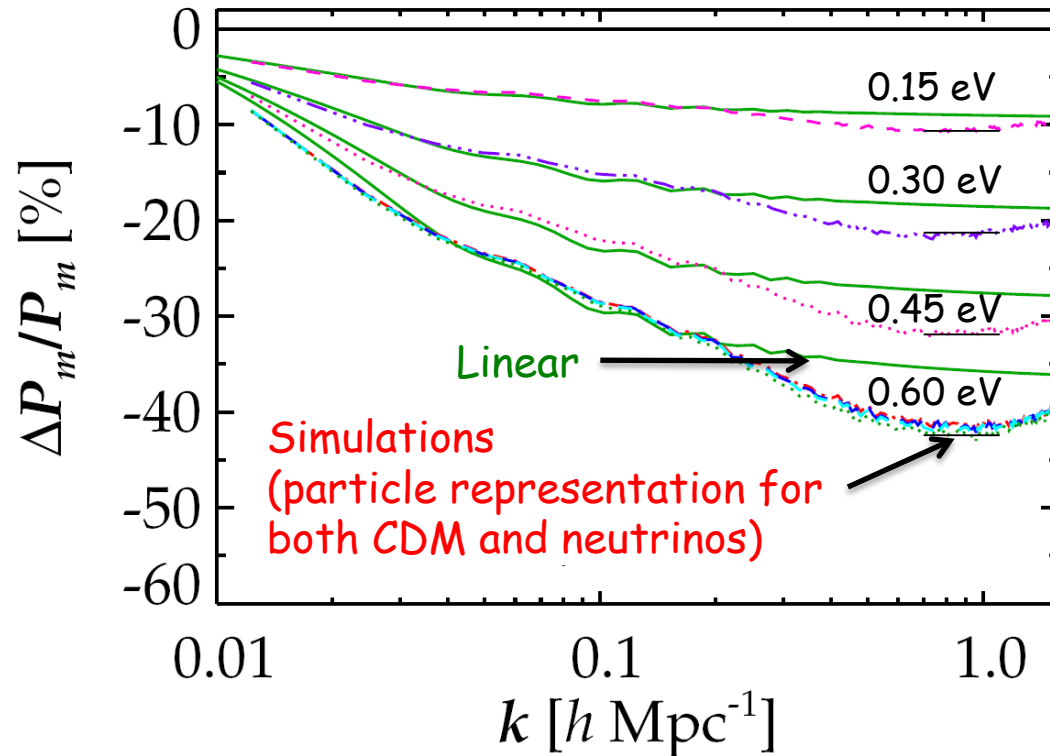
Neutrino mass & large-scale structures

$P(k)$ massive / $P(k)$ massless



- Suppression factor $\Leftrightarrow \Sigma m_\nu$
- 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] +
 - Non-linear regime and flux power spectrum (not mass density)
 $\Rightarrow$ Hydro simulations -

Neutrino mass & large-scale structures



Linear perturbation theory:

$$\frac{\Delta P_m}{P_m} \sim 8 \frac{\Omega_\nu}{\Omega_m}$$

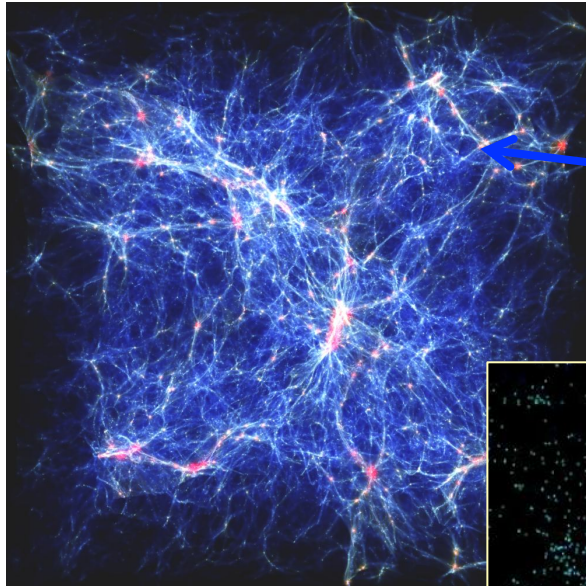
With nonlinear corrections:

$$\frac{\Delta P_m}{P_m} \sim 9.8 \frac{\Omega_\nu}{\Omega_m}$$

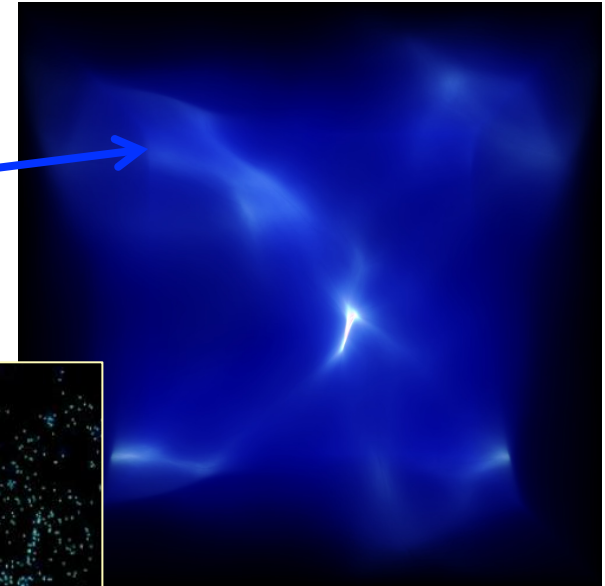
*Brandbyge, Harnestad, Haugbolle & Thomsen 2008;
Viel, Haenelt & Springel 2010; Bird, Viel & Haenelt 2012;
Brandbyge & Hannestad 2009, 2010;
Ali-Hamoud & Bird 2012*

Neutrino masses & large-scale structures

Λ CDM

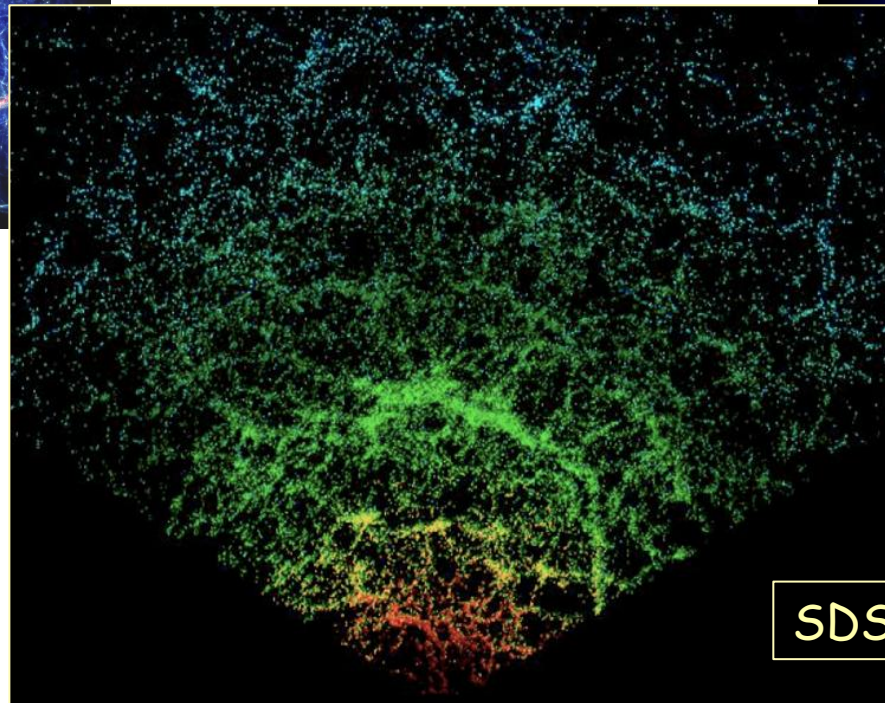


HDM (3×30 eV neutrinos)



Simulations

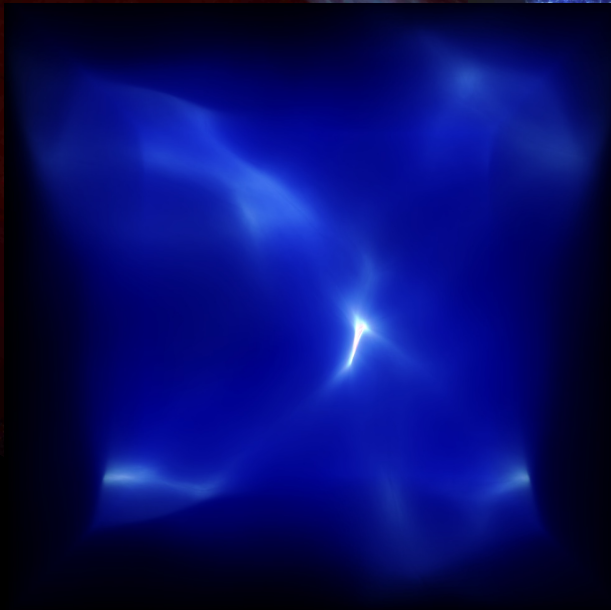
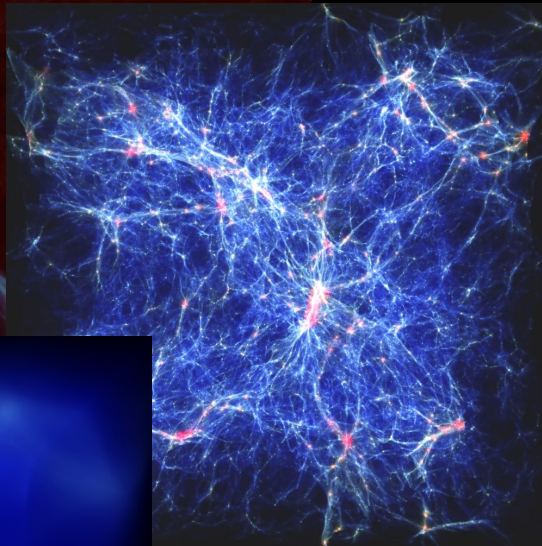
25 Mpc/h boxes
768³ particles per species



SDSS

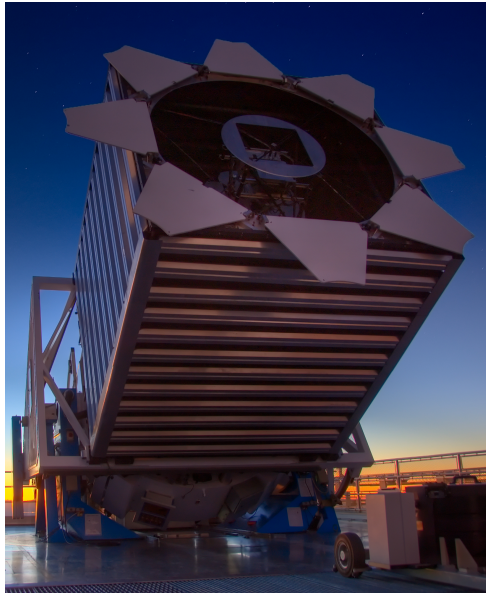
What Lyman- α surveys tell us about neutrinos

N. Palanque-Delabrouille,
CEA-Saclay



1. Massive neutrinos and large-scale structures
2. **BOSS quasar survey**
3. Results on Σm_ν
4. What about sterile neutrinos?

SDSS BOSS/eBOSS

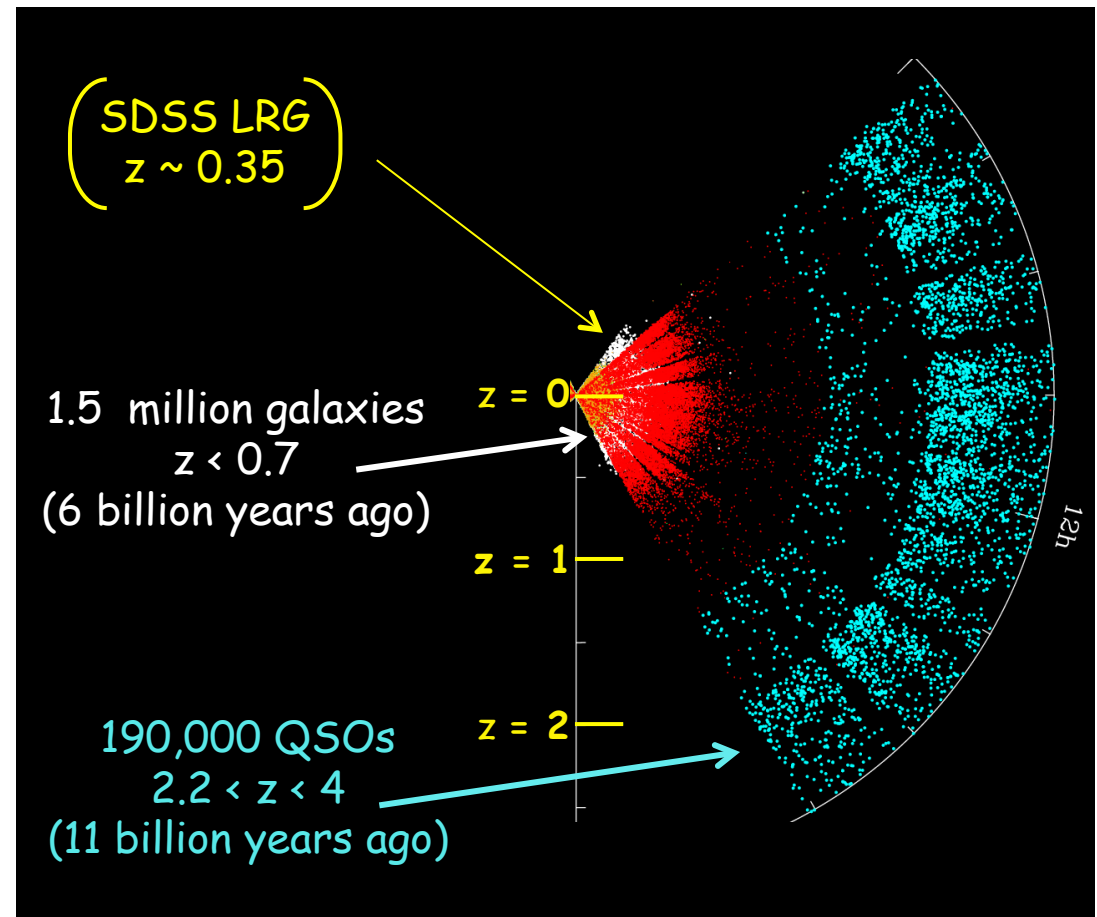


BOSS
2009-2014

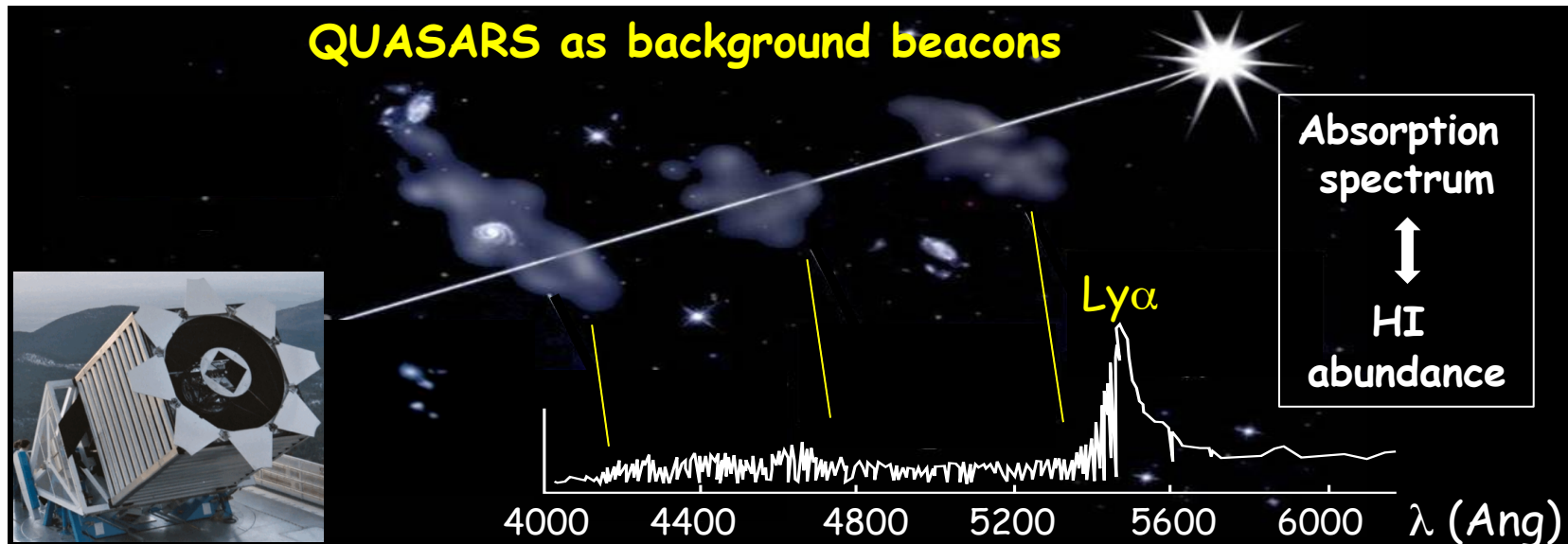
eBOSS
2014-2020

SDSS spectroscopic survey

- 2.5 m Sloan telescope (New Mexico)
- Survey area: **10,000 deg²**
- Redshifts: **1000 fibers**

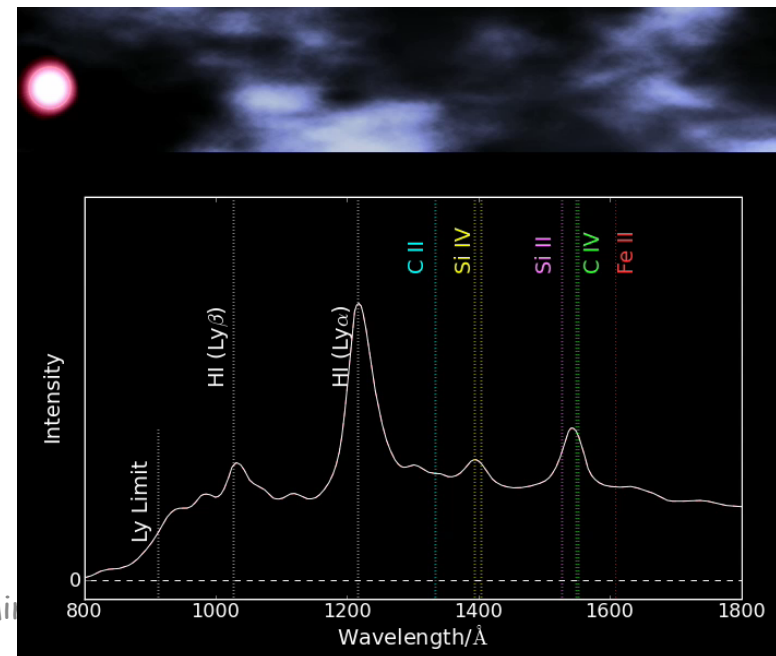


BOSS quasar survey

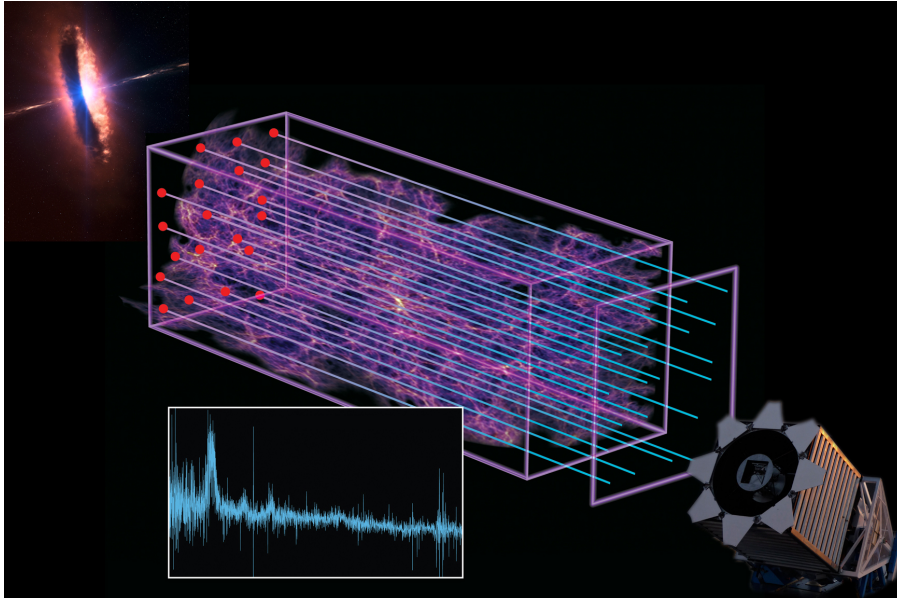


Principles

- Quasars **visible to high z** ($z > 5$)
- Absorption along line of sight from neutral H in IGM
- Low density gas (IGM) as proxy of **dark matter density**

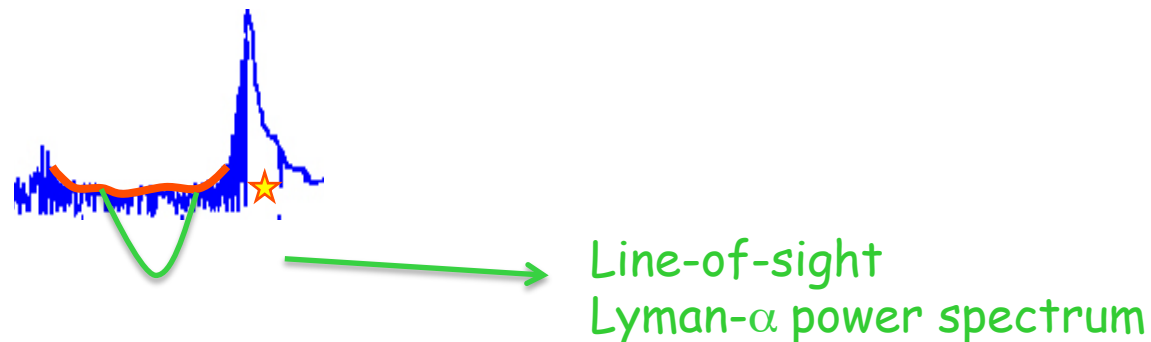


Lyman- α forest in 1D



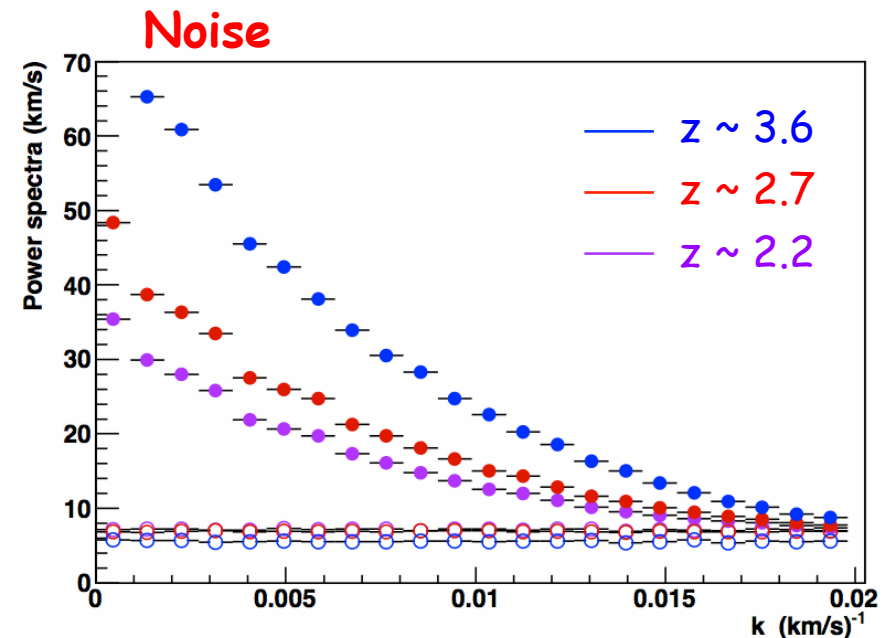
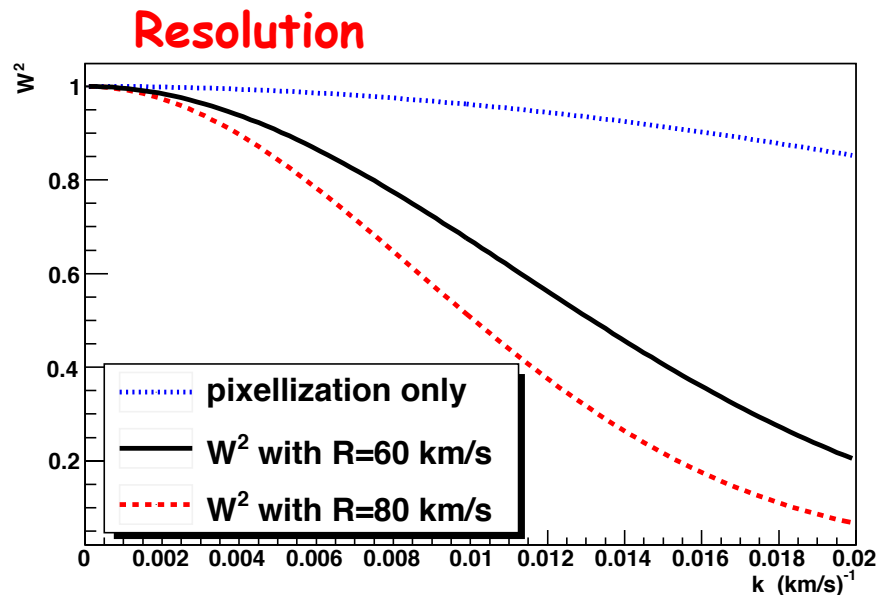
1D power spectrum

- Fourier transform of correlation between line-of-sight pixels
- Matter distribution down to **small scales** (~ 1 Mpc)
- Sensitive to **neutrino masses**



Lyman- α forest in 1D

- 14.000 DR9 QSOs out of 60000
- Selected for
 - quality (no flagged pixels, no high density absorbers)
 - SNR > 2
 - resolution < 85 km/sto obtain $\sigma_{\text{syst}} \sim \sigma_{\text{stat}}$

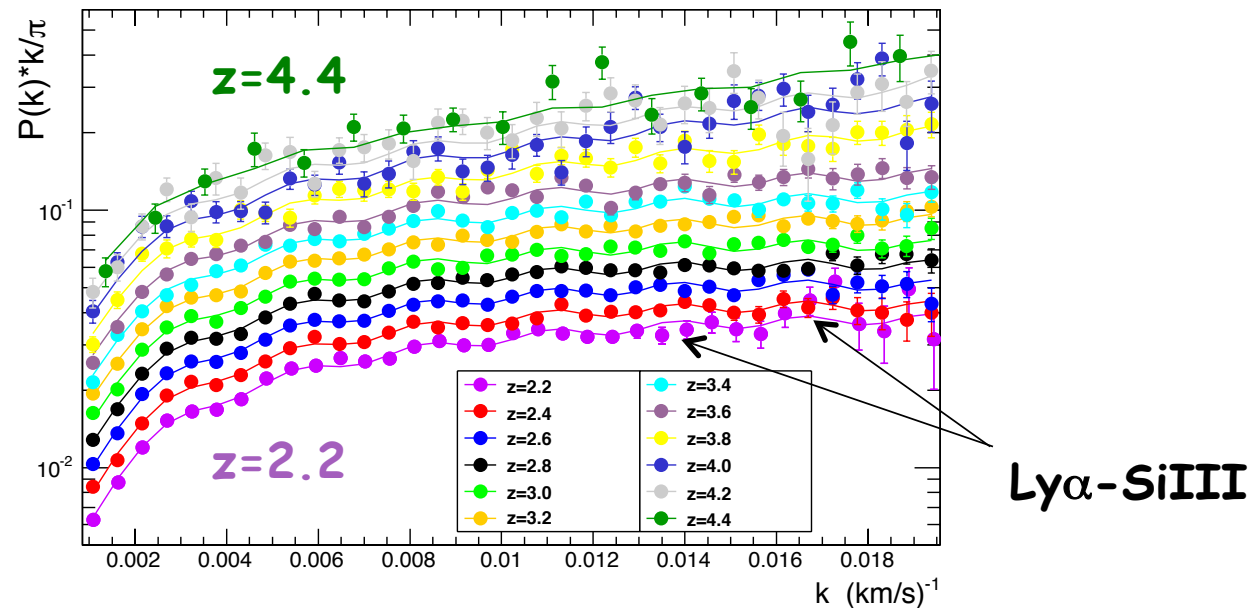


Large effect at high k

Lyman- α forest in 1D

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

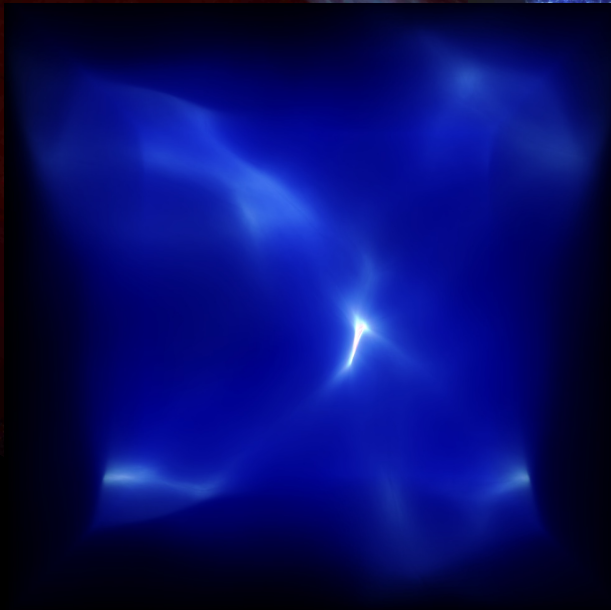
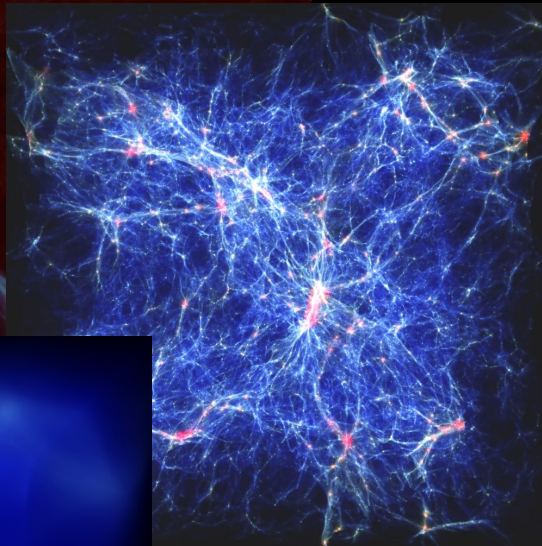
N P-D, Yèche, Borde
et al. (2013)



- Two independent methods** to compute $P(k) \rightarrow$ good agreement
- Fourier transform of δ_F
 - Likelihood fit of $P(k)$

What Lyman- α surveys tell us about neutrinos

N. Palanque-Delabrouille,
CEA-Saclay



1. Massive neutrinos and large-scale structures
2. BOSS quasar survey
3. 1D Lyman- α forest
Results on Σm
4. What about sterile neutrinos?

Hydrodynamical simulations

$(100 h^{-1}\text{Mpc})^3$ with each 3072^3 particles

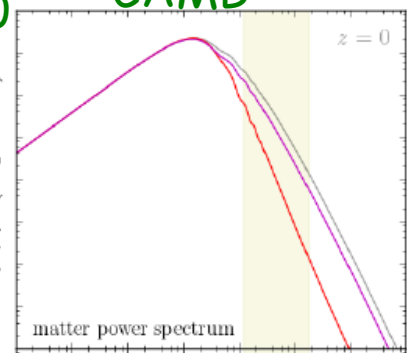
- dark matter
- baryons
- degenerate-mass neutrinos

2LPTic

$z=30$

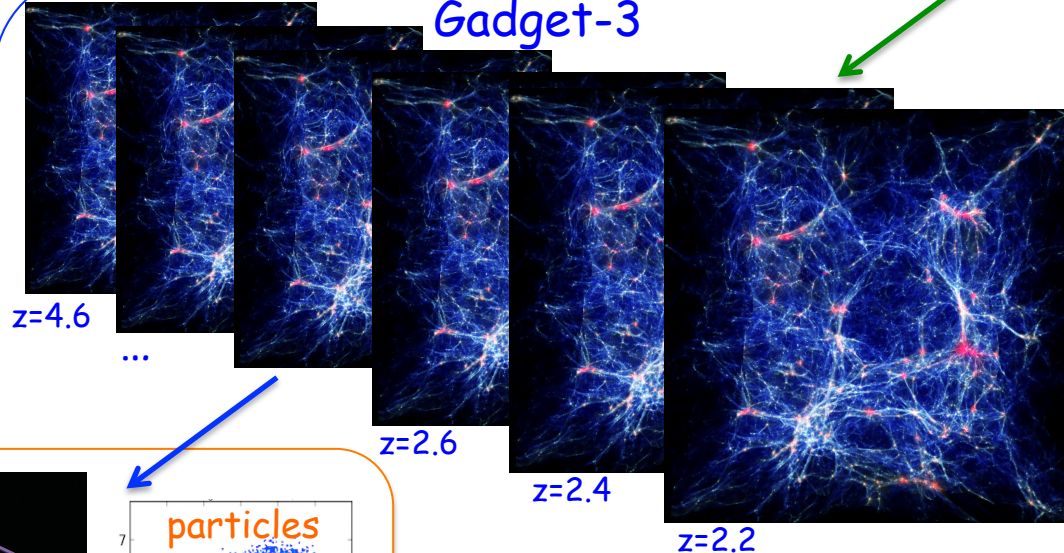
CAMB

$P(k) / (\text{Mpc} \cdot h^{-1})^3$

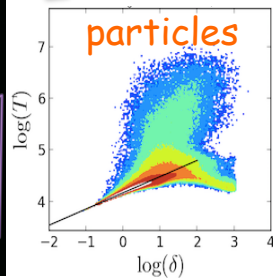
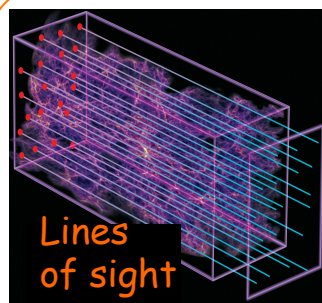


Initial conditions

Gadget-3

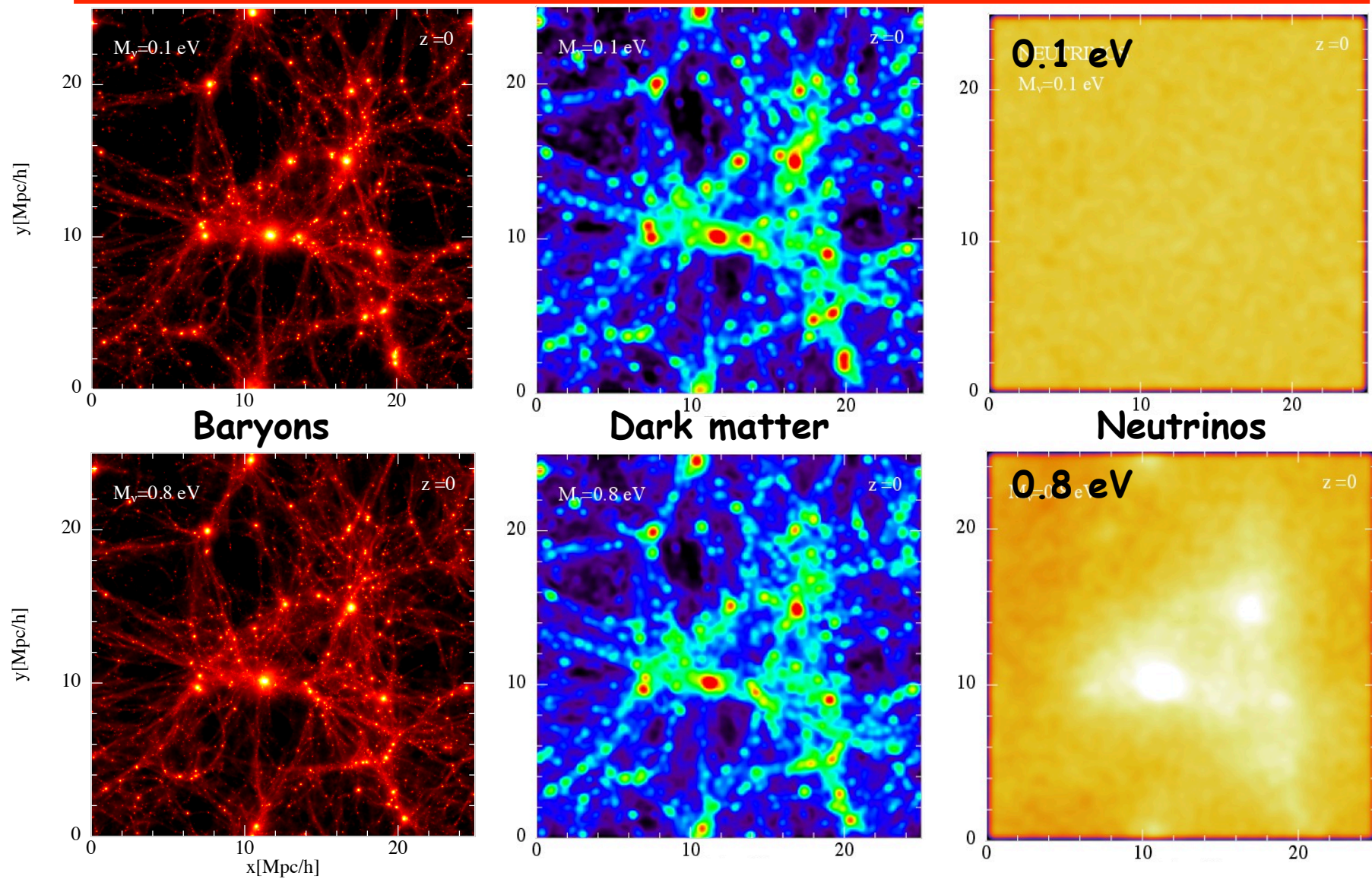


N-body + SPH simulation



Ly- α
power spectrum

$z = 0$, impact of Σm



© G. Rossi

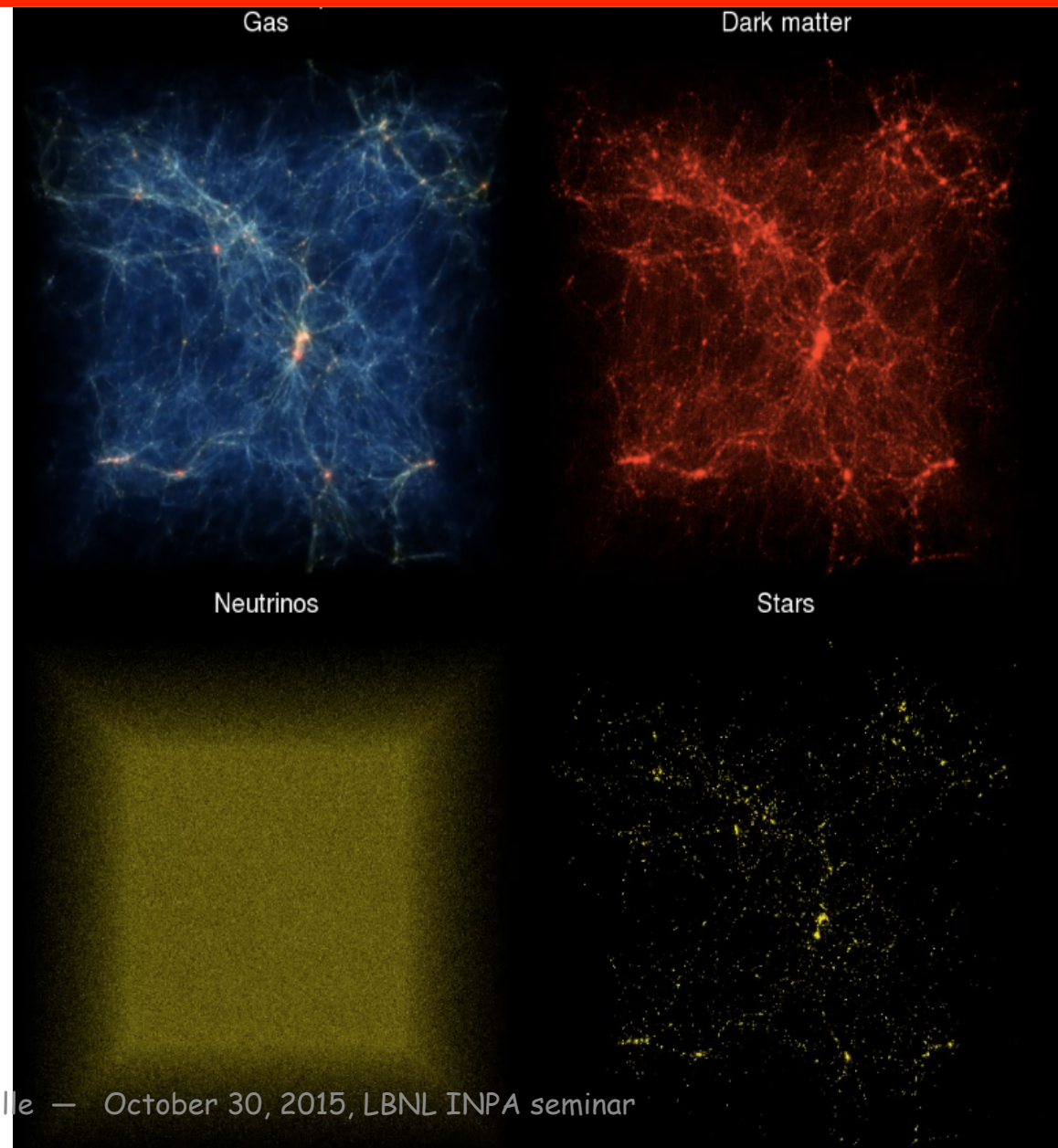
Hydrodynamical simulations

$z = 15 \rightarrow 0$

3 species

- Baryons
- Dark matter
- Neutrinos

Stars formed
from baryons
($T < 10^5 \text{K}$ & $\delta > 10^3$)



Hydrodynamical simulations

- **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
σ_8	0.83	± 0.05
Ω_m	0.31	± 0.05
H_0	67.5	± 5
$T_0(z=3)$	14000	± 7000
$\gamma(z=3)_{..}$	1.3	± 0.3
A^τ	0.0025	± 0.0020
η^τ	3.7	± 0.4
$\sum m_\nu$ (eV)	0.0	0.4, 0.8

Cosmology

IGM

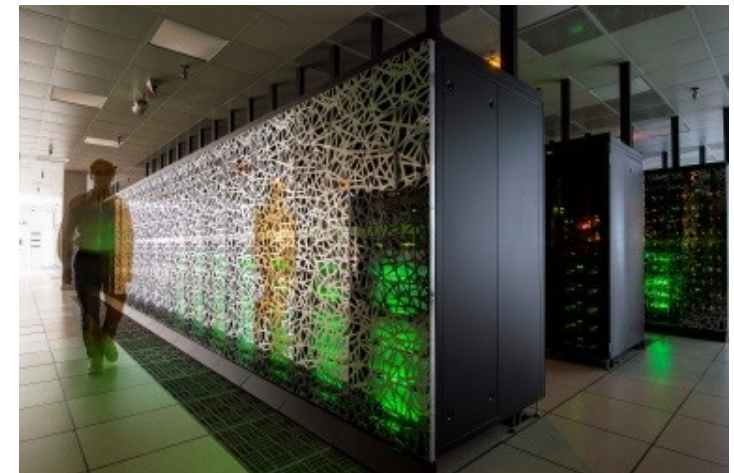
Optical depth

Neutrino

Borde et al. (2014)

Rossi et al. (2014)

- **36 simulations + 3 normalizations**
(+ numerous sanity checks)
- **>4Mhrs CPU** at TGCC
CURIE supercomputer



Fit nuisance parameters

- Simulation splicing

(McDonald, 2003)

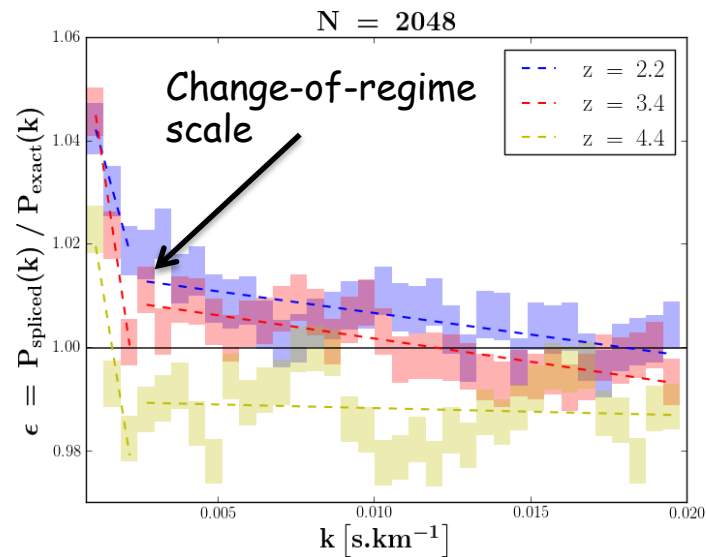
Combine **large box** & **high resolution** (using a **transition** simulation)

(100 Mpc.h⁻¹, 768³)

(25 Mpc.h⁻¹, 768³)

(25 Mpc.h⁻¹, 192³)

⇔ equivalent to 100 Mpc.h⁻¹ with 3072³ particles per species



Broken-line model
2 free nuisance parameters

Fit nuisance parameters

- Technical*
- Simulation splicing
 - Spectrograph resolution



2 nuisance parameters
(correction factor + redshift-dependence)

- Spectra noise



12 nuisance parameters
(1 per redshift bin)

Fit nuisance parameters

Technical

- Simulation splicing
- Spectrograph resolution
- Spectra noise

- SN or AGN feedbacks
- UV fluctuations
- Residual contribution of high-density absorbers (DLA)

Astrophysical



4 nuisance parameters (1 per effect)

- Modeling of T_{IGM}



5 parameters:

- $T_0(z=3)$ & $\gamma(z=3)$, where $T = T_0(1+\delta)^\gamma$
- Free slopes for redshift-dependence $\eta^{T_0}(z<3)$, $\eta^{T_0}(z>3)$, η^γ

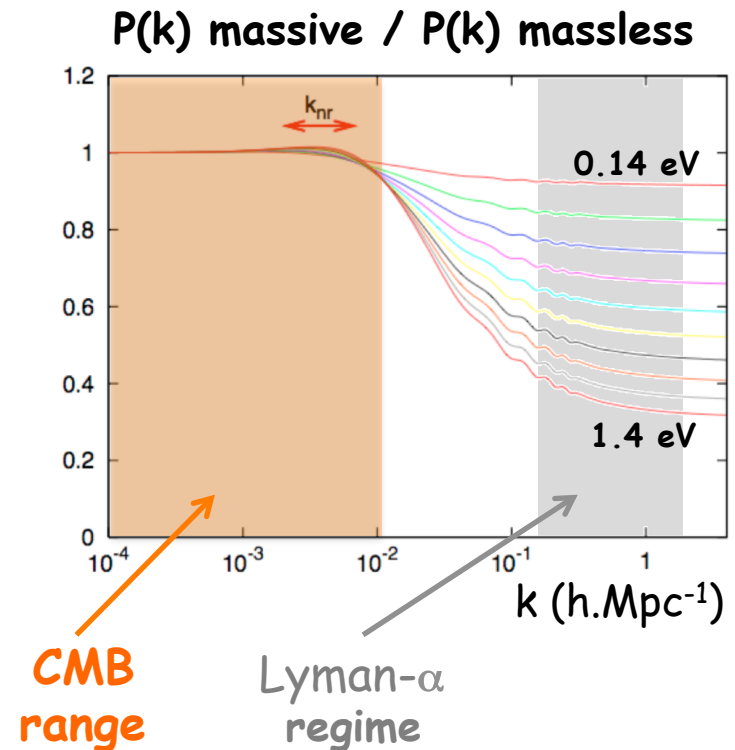
Fit to data

- Large degeneracies when Ly α alone (-70% correlation $\Sigma m - \sigma_8$)

Small sensitivity to tiny k and z -dependence of $P(k)$ suppression

- Improved sensitivity when combined to CMB:

+ Sensitivity to amplitude of suppression



Fit results

- Ly- α (-70% correlation $\Sigma m - \sigma_8$)

$$\Sigma m_\nu < 1.1 \text{ eV} @ 95\%CL$$

- CMB (Planck 2015 TT+lowP)

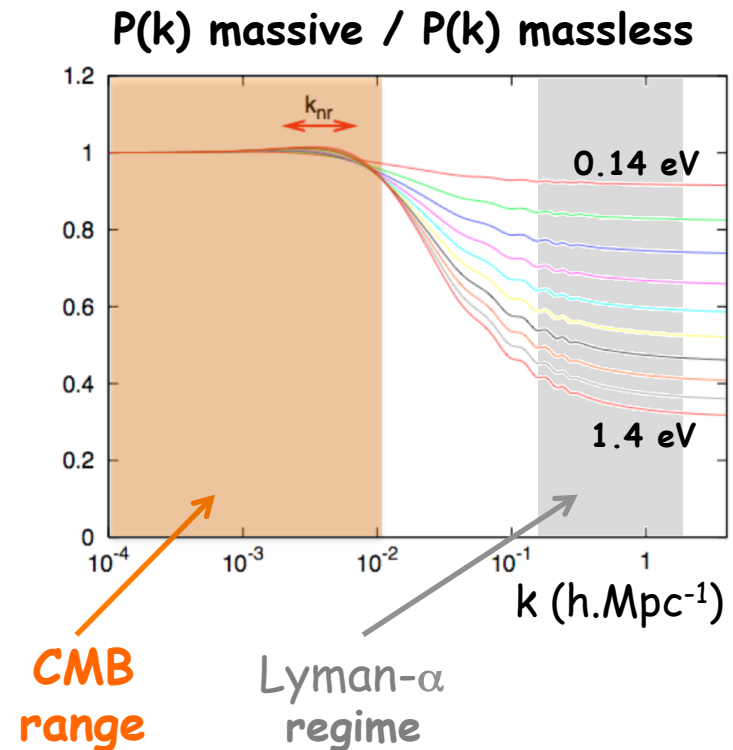
$$\Sigma m_\nu < 0.72 \text{ eV} @ 95\%CL$$

- Ly- α + CMB

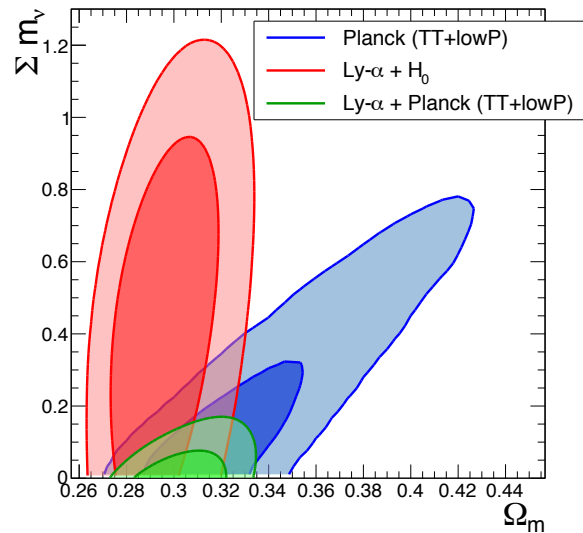
$$\Sigma m_\nu < 0.12 \text{ eV} @ 95\%CL$$

N. P.-D., Yèche, Lesgourgues et al. (2015)

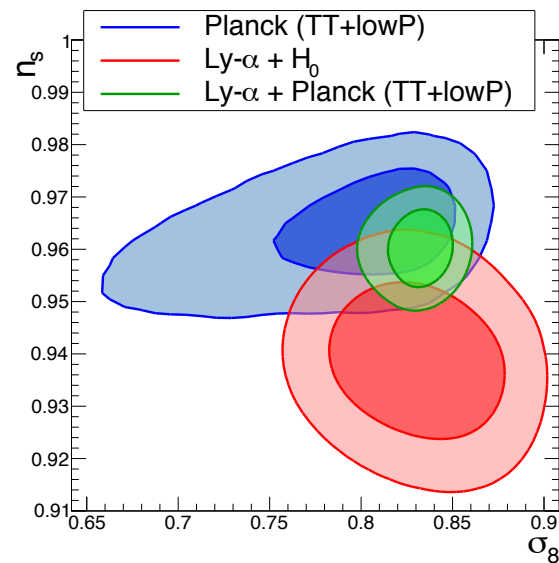
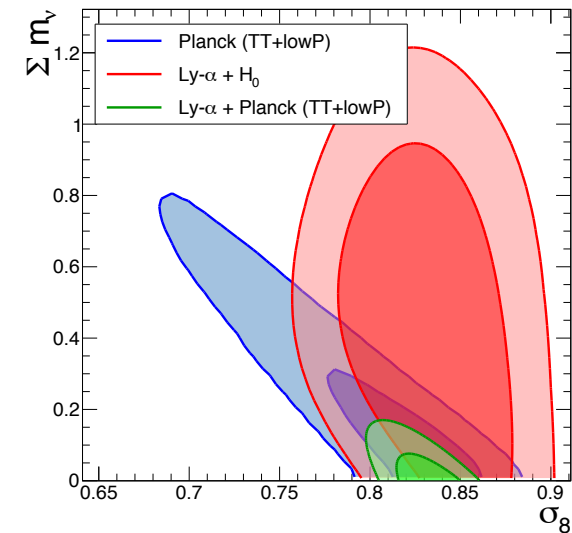
N. P.-D., Yèche, Baur, et al. (2015)



Updated results



- Planck 2015 ($\Sigma m_\nu < 0.72$ eV)
- Ly- α $z < 4.5$
- Cosmic variance
- Splicing
- IGM modeling
- Marginalization over systematics

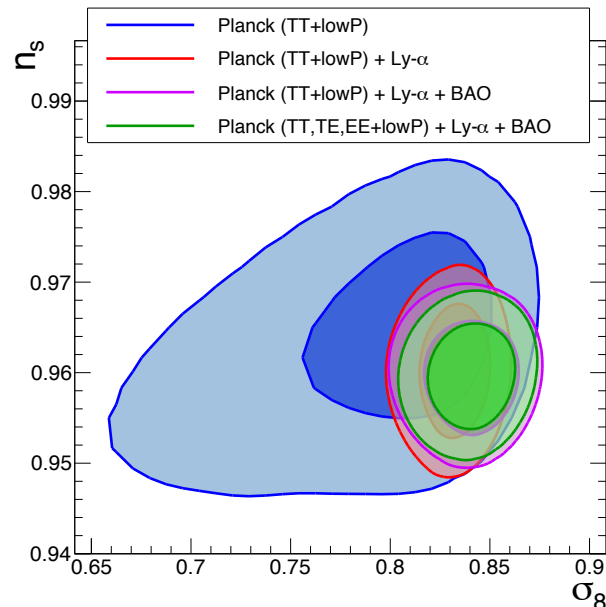
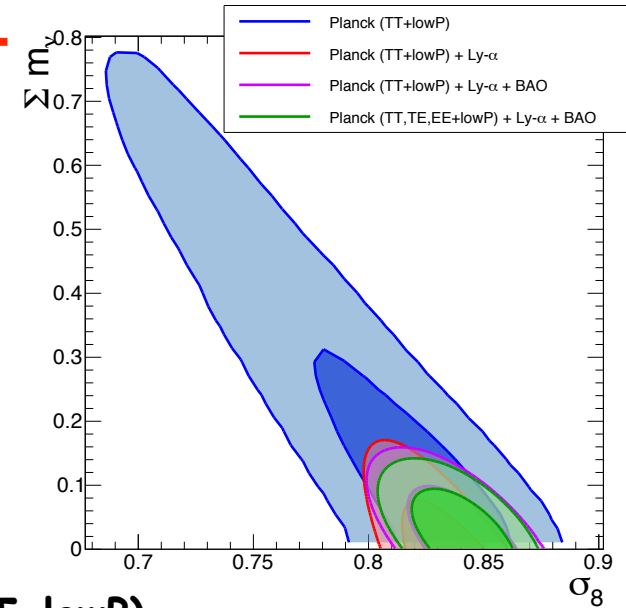
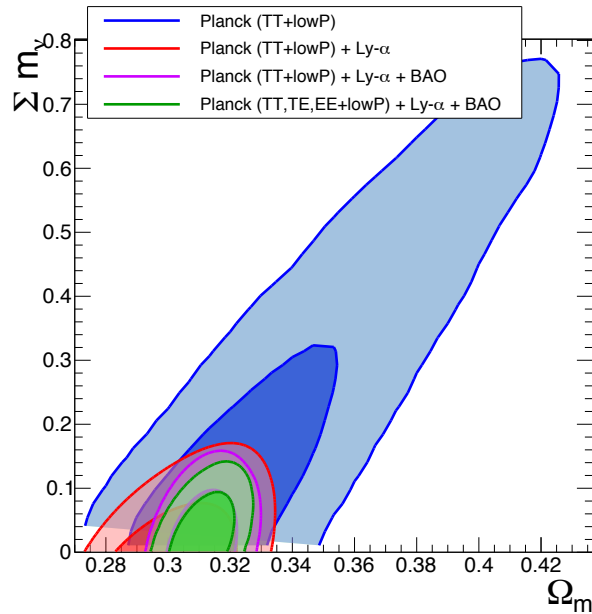


Parameter	[1] Ly α + H_0^{Gaussian} ($H_0 = 67.3 \pm 1.0$)	[2] Ly α + Planck TT+lowP
σ_8	0.831 ± 0.031	0.833 ± 0.011
n_s	0.938 ± 0.010	0.960 ± 0.005
Ω_m	0.293 ± 0.014	0.302 ± 0.014
H_0 (km s $^{-1}$ Mpc $^{-1}$)	67.3 ± 1.0	68.1 ± 0.9
Σm_ν (eV)	< 1.1 (95% CL)	< 0.12 (95% CL)

N. P-D, Yèche, Baur, et al. (2015)

Updated results

Adding probes



Planck 2015:

$\Sigma m_\nu < 0.72 \text{ eV}$ 95%CL (TT+lowP)

$\Sigma m_\nu < 0.21 \text{ eV}$ 95%CL (TT+lowP +BAO)

$\Sigma m_\nu < 0.17 \text{ eV}$ 95%CL (TT+lowP +BAO + EE+TE)

Planck 2015 + Ly α :

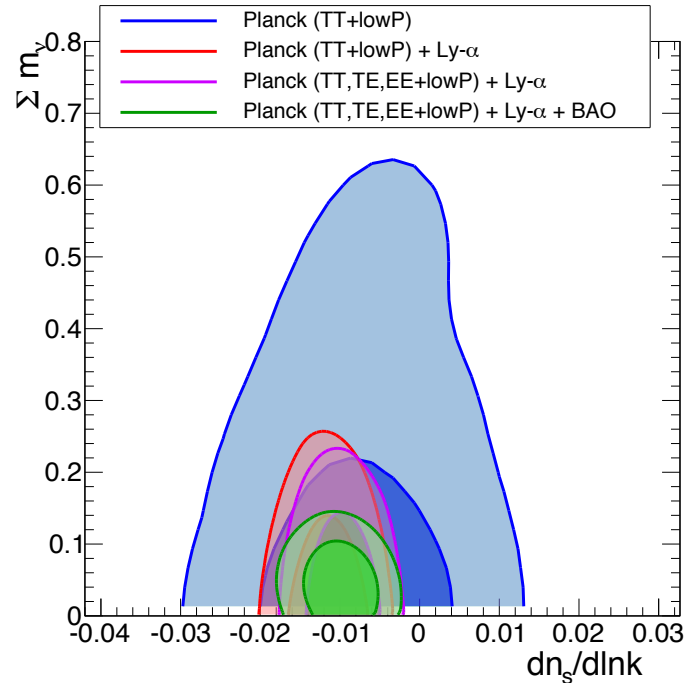
$\Sigma m_\nu < 0.12 \text{ eV}$ 95%CL (TT+lowP + Ly α)

$\Sigma m_\nu < 0.13 \text{ eV}$ 95%CL (TT+lowP + Ly α +BAO)

$\Sigma m_\nu < 0.12 \text{ eV}$ 95%CL (TT+lowP + Ly α +BAO + EE+TE)

N. P-D, Yèche, Baur, et al. (2015)

Updated results



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

Similar value of running ($\sim 10^{-2}$) for

- Planck alone (within CMB k -range)
- Planck + $\text{Ly}\alpha$ ($\neq n_s$ at k_{CMB} & $k_{\text{Ly}\alpha}$)

Similar constraints on Σm_ν letting running of n_s free

$\Rightarrow$ Negligible impact on Σm_ν of tension on n_s

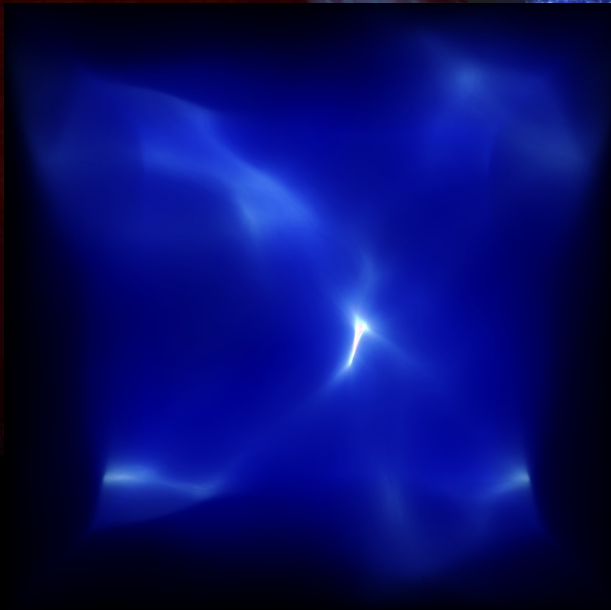
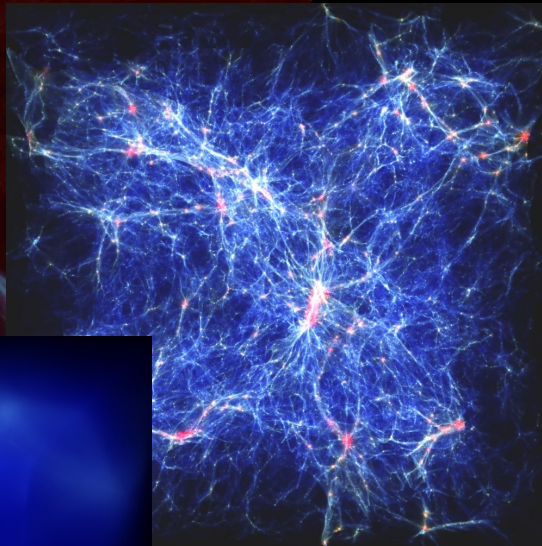
$$\Sigma m_\nu < 0.19 \text{ eV} \quad 95\% \text{CL (TT+lowP + Ly}\alpha\text{)}$$

$$\Sigma m_\nu < 0.12 \text{ eV} \quad 95\% \text{CL (TT+lowP + Ly}\alpha\text{ + BAO + EE+TE)}$$

N. P-D, Yèche, Baur, et al. (2015)

What Lyman- α surveys tell us about neutrinos

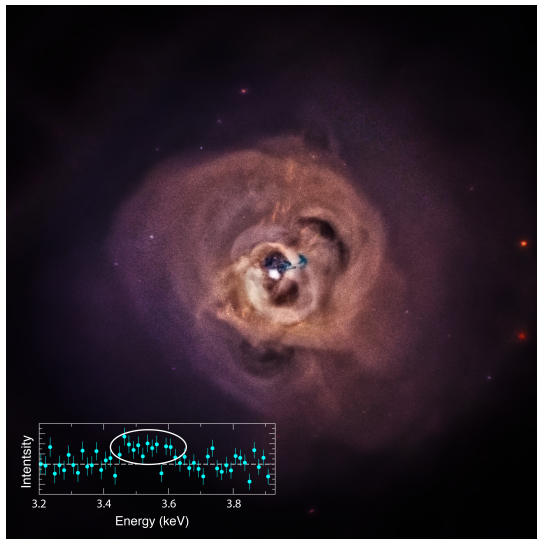
N. Palanque-Delabrouille,
CEA-Saclay



1. Massive neutrinos and large-scale structures
2. BOSS quasar survey
3. 1D Lyman- α forest
Results on Σm_ν
4. What about sterile neutrinos?

Sterile neutrinos?

- CDM drawbacks
 - Excess of satellites
 - Cuspy galaxy cores
- Unidentified 3.5 keV line in stacked X-ray spectra (Andromeda galaxy, Perseus clusters, XMM clusters)



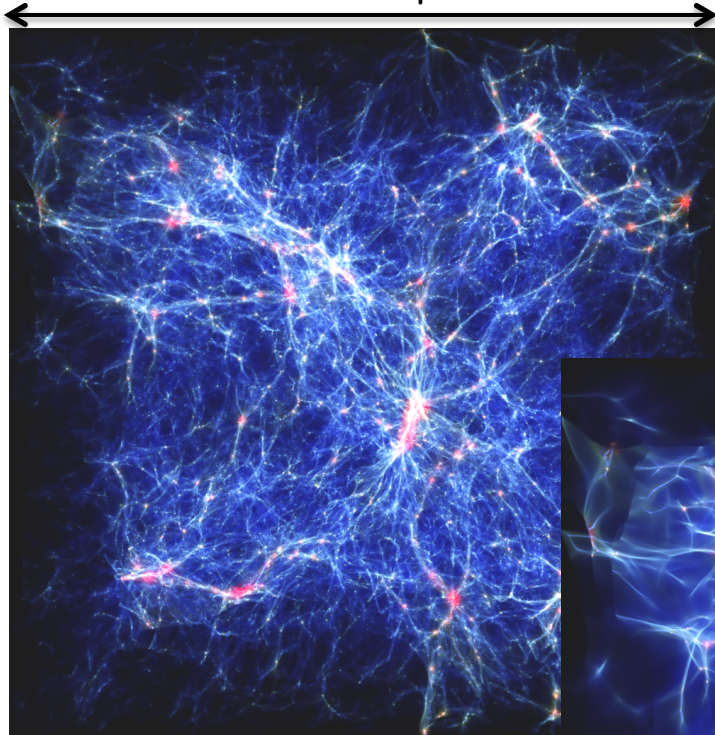
→ 7 keV sterile neutrino?

→ Warm dark matter?

Sterile neutrinos?

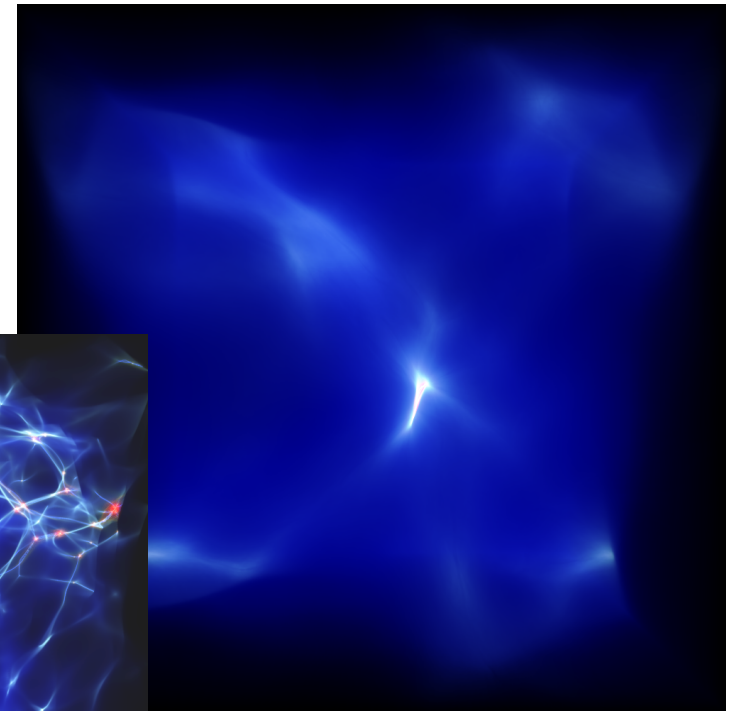
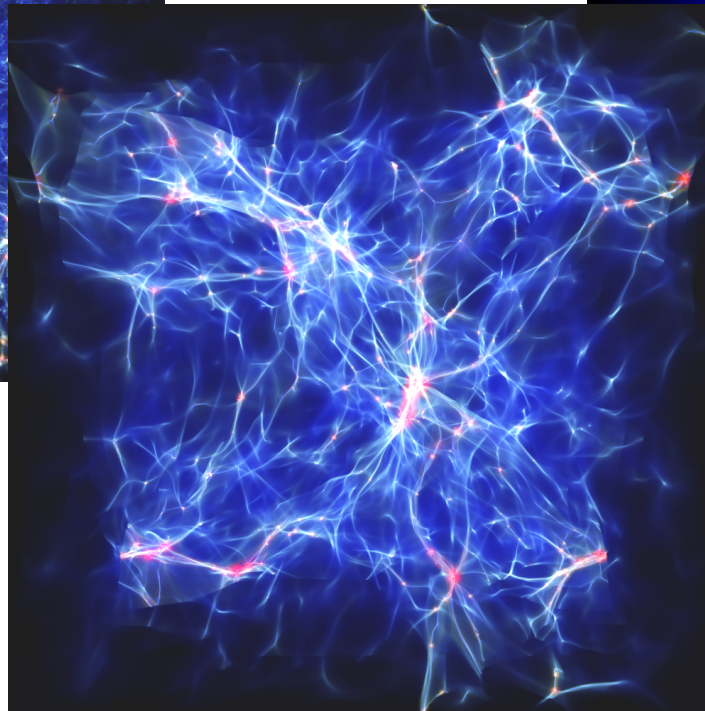
2×768^3 particles (gas+DM)
 $25 \text{ h}^{-1} \text{ Mpc}$

Assuming all DM is ...



Cold DM
 $\geq \text{keV}$

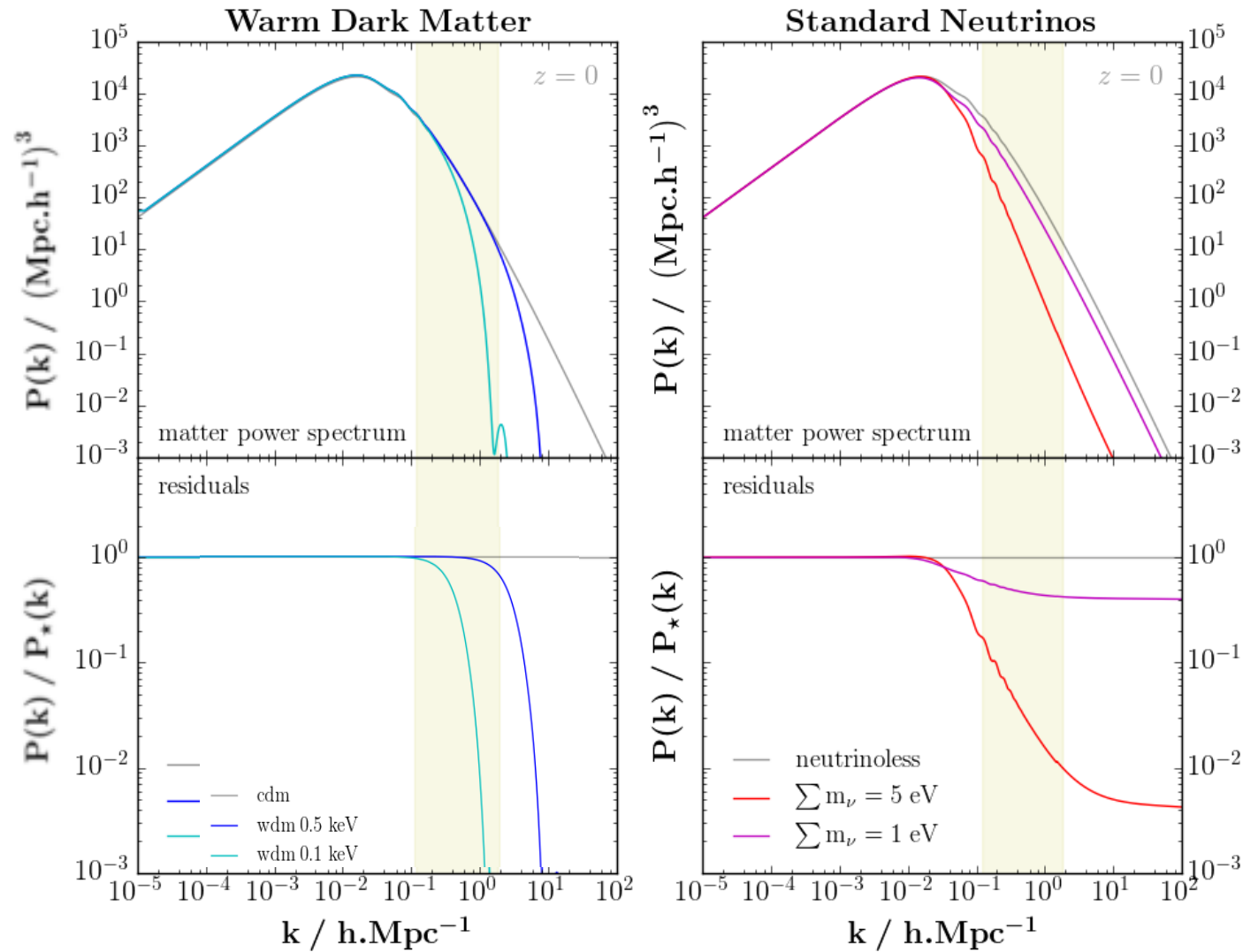
Warm DM
500 eV



Hot DM
100 eV

@ J. Baur (IRFU/SPP)

Sterile neutrinos?



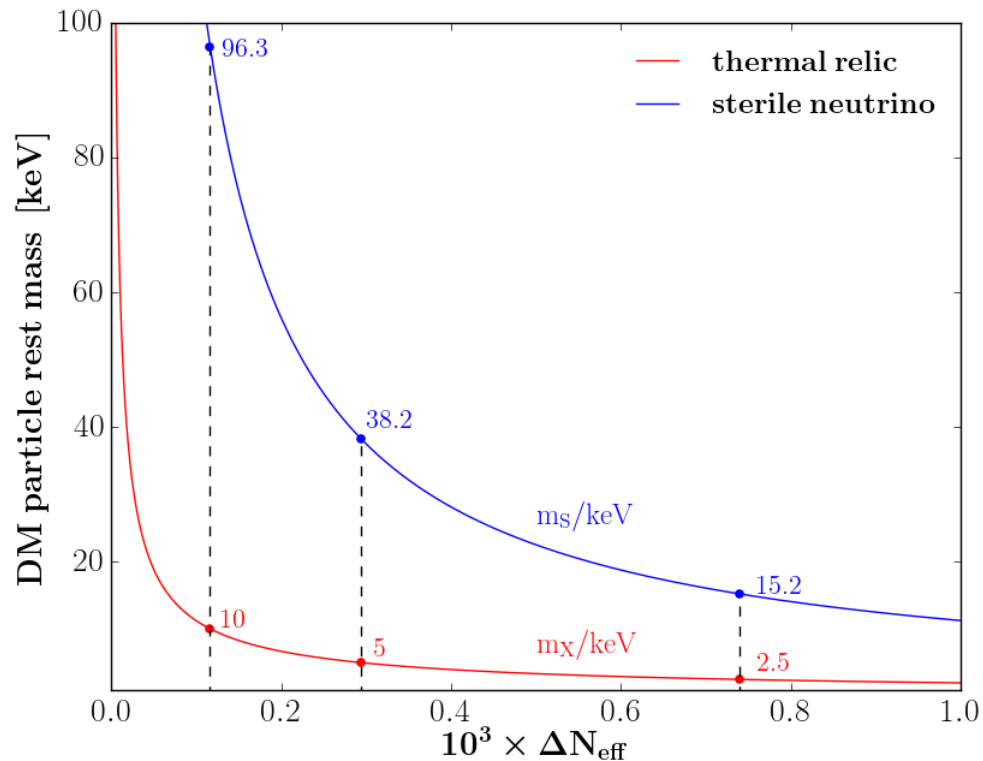
Sterile neutrinos?

$$\Omega_{DM} h^2 = \chi \left(\frac{T}{T_\nu} \right)^3 \left(\frac{m}{93 \text{ eV}} \right)$$

$$N_{eff} = 3.046 + \Delta N_{eff}$$

$$(\Delta N_{eff})^{1/4}$$

Colombi, Dodelson, Widrow (1996)
Lewis CAMB notes



$$\Omega_{DM} h^2 \propto m_s^3 \propto m_{th}^4$$

Sterile neutrinos

Thermal relics

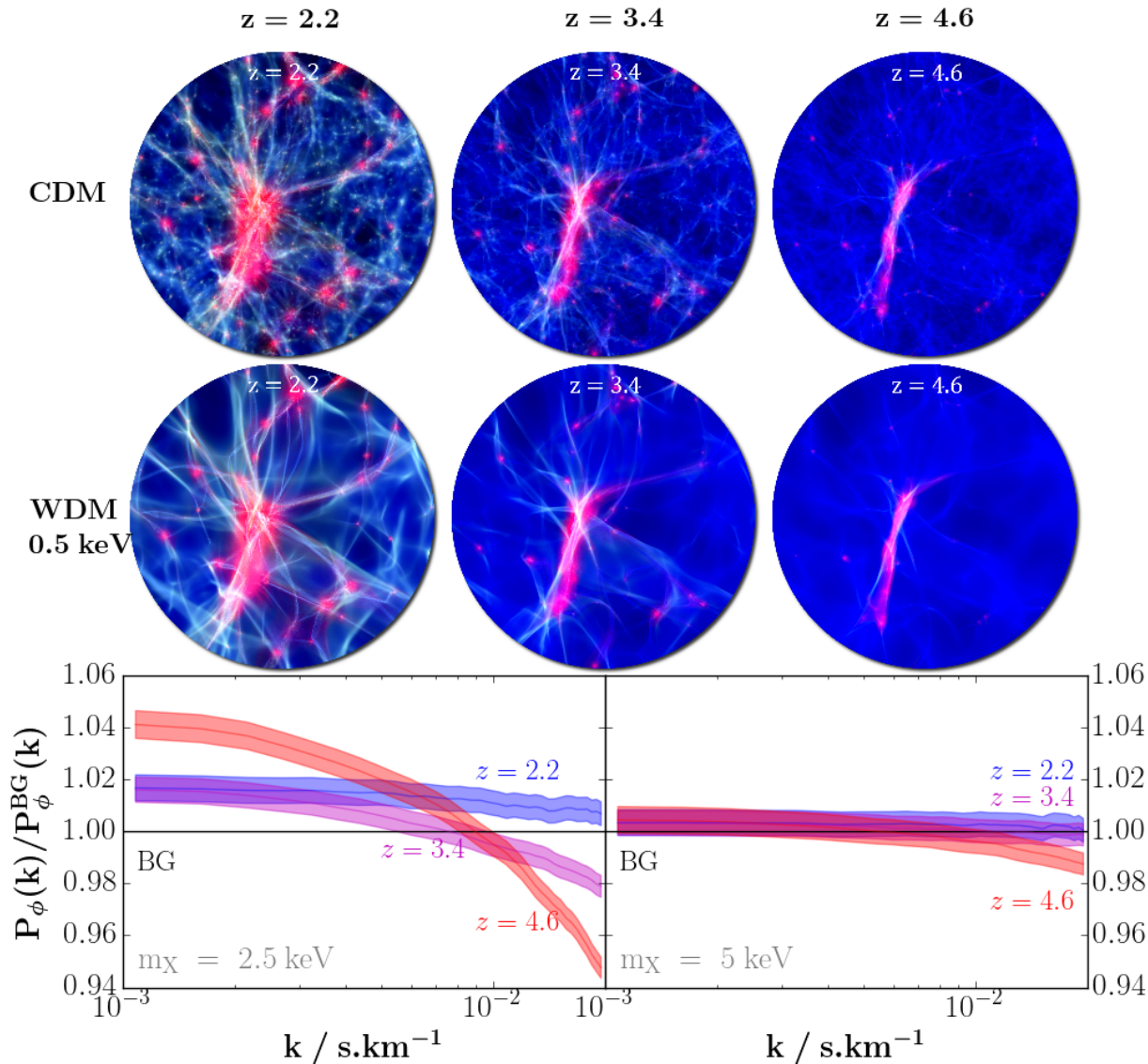
$$\begin{aligned} T_s &= T_\nu \\ \chi_s &\neq 1 \end{aligned}$$

$$\begin{aligned} T_{th} &\neq T_\nu \\ \chi_{th} &= 1 \end{aligned}$$



Simulate thermal relics only

Sterile neutrinos?



Normalized
to same σ_8



High z
High k

Sterile neutrinos?

Ly- α alone

data set	lower bound on $\frac{m_X}{\text{keV}} \left(\frac{m_s}{\text{keV}} \right)$
Ly- α + H_0 ($z < 4.5$)	4.35 (31.7)
Ly- α + H_0 ($z < 4.1$)	3.10 (20.2)

Preliminary

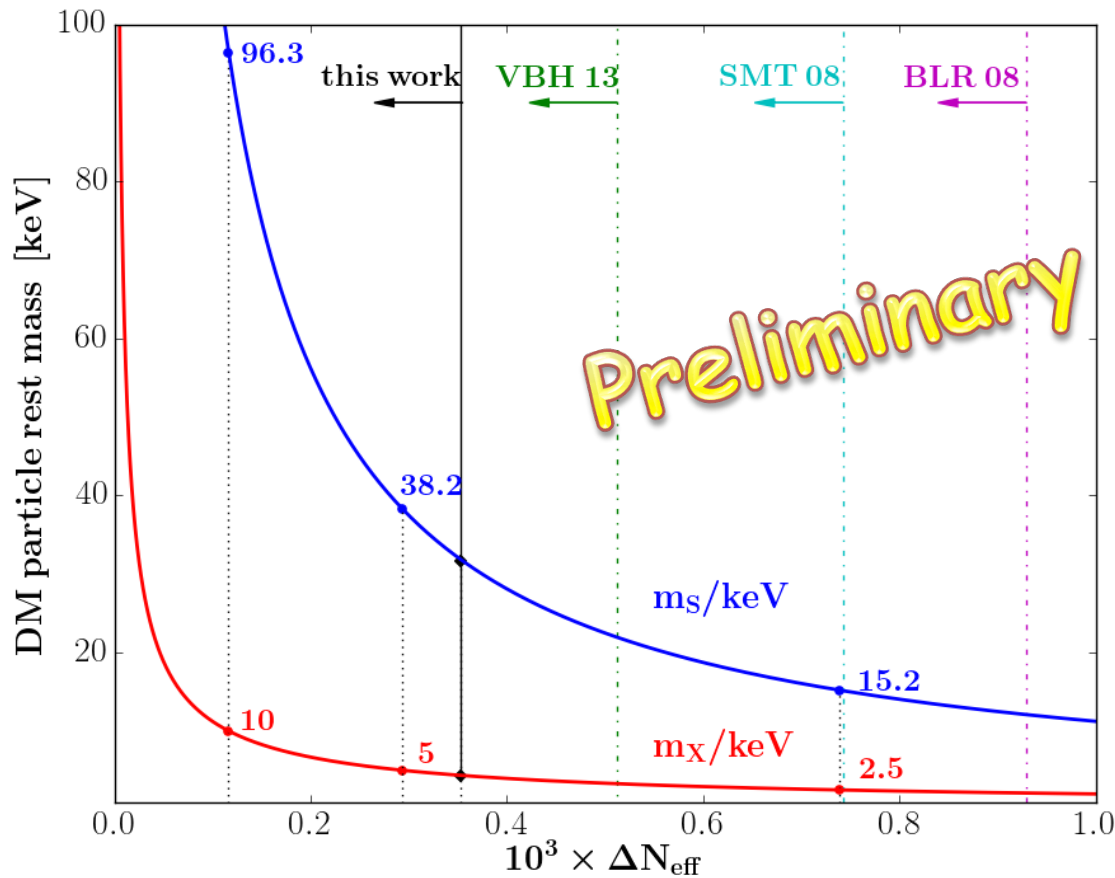
Thermal relics

Sterile ν 's

(Dodelson-Widrow
Mechanism)

Baur et al. (in prep)

Sterile neutrinos?



95% CL from BOSS Ly α

$$m_X \geq 4.35 \text{ keV}$$

$$m_s \geq 31.7 \text{ keV}$$

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

Seljak, Makarov, Trac
 $m_X \geq 2.5 \text{ keV}$
 (SDSS Ly- α)

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

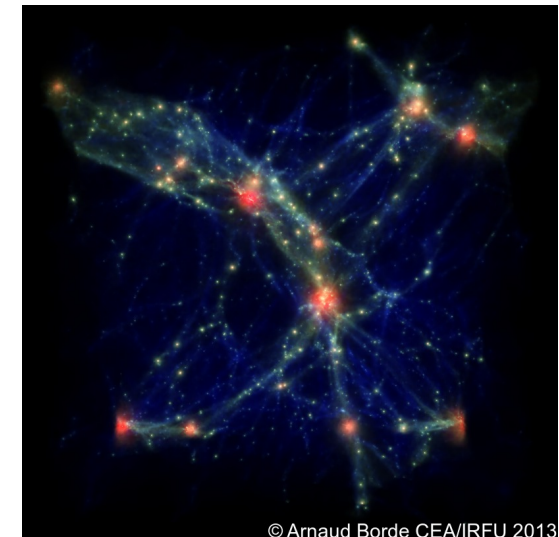
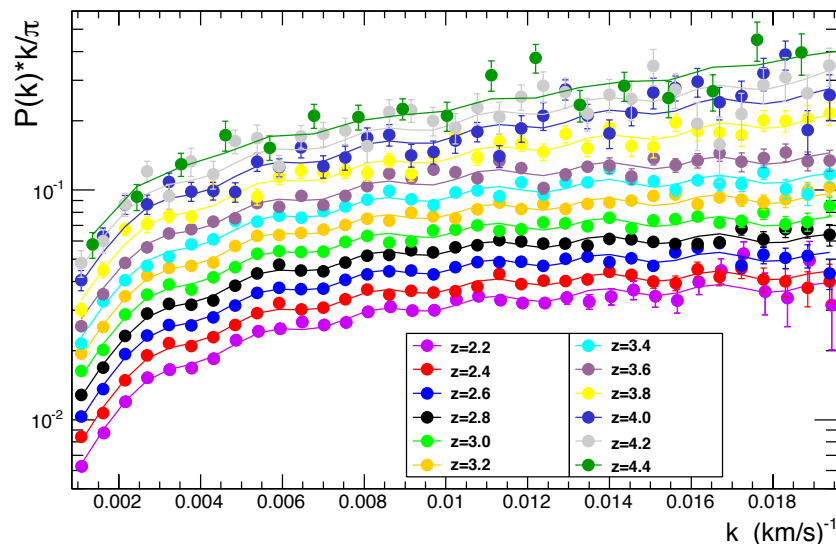


At odds with 7keV sterile neutrino **IF** pure WDM

Conclusions

- **High potential of Ly α forest** (expansion, growth, Σm_ν , m_s)
 - Sum of neutrino masses $\Sigma m_\nu < 0.12$ eV (95% CL) from Ly α +CMB
 - $m_x > 4.4$ keV (95% CL) if all DM in thermal relics
- **Prospects**
 - Lower statistical uncertainties (high z): BOSS DR12 + eBOSS
 - Add high-z data (X-Shooter?)
 - DESI !

Projected 24 meV sensitivity on Σm_ν (from galaxy clustering)



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