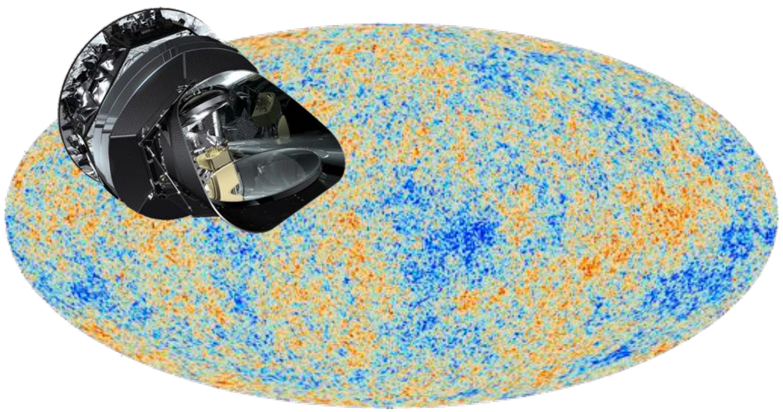
Neutrino mass from cosmology

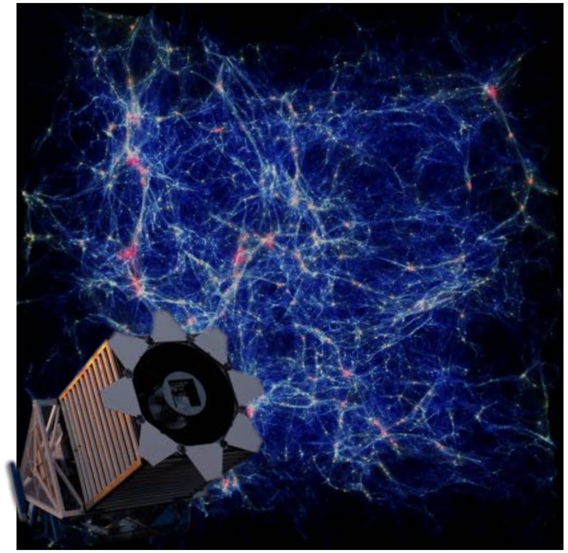
N. Palanque-Delabrouille (CEA-Saclay)

- Introduction to neutrino mass in cosmology

- Constraints from
  Cosmic Microwave Background (Planck)
  & Large-scale structures (BOSS)

- Cosmology & sterile neutrinos





SFP — December 2, 2016

Neutrino masses

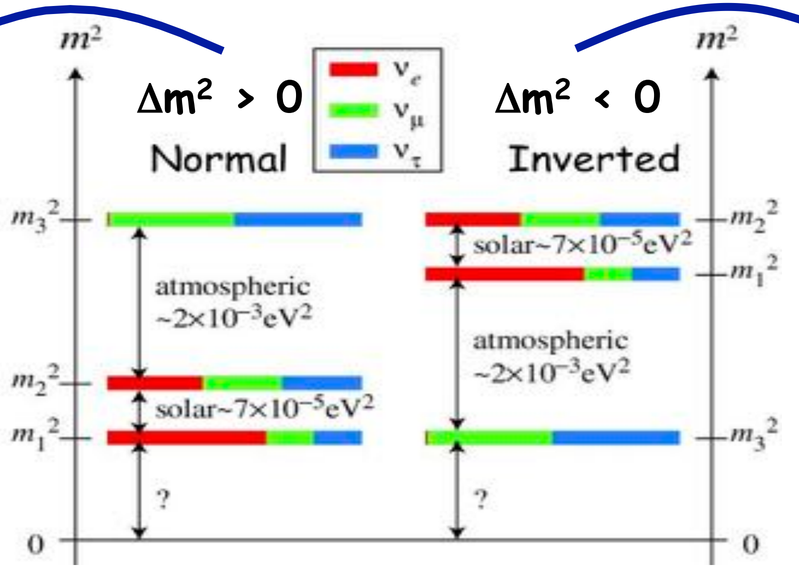
Neutrino oscillations

Solar $\delta m^2 = m_2^2 - m_1^2$ ~ $7.5\ 10^{-5}\ eV^2$

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

At least one neutrino with mass $m > \sqrt{\Delta m^2}$ ie. $m > 0.05$ eV

$\Sigma m > 0.06$ eV



$\Sigma m > 0.10$ eV

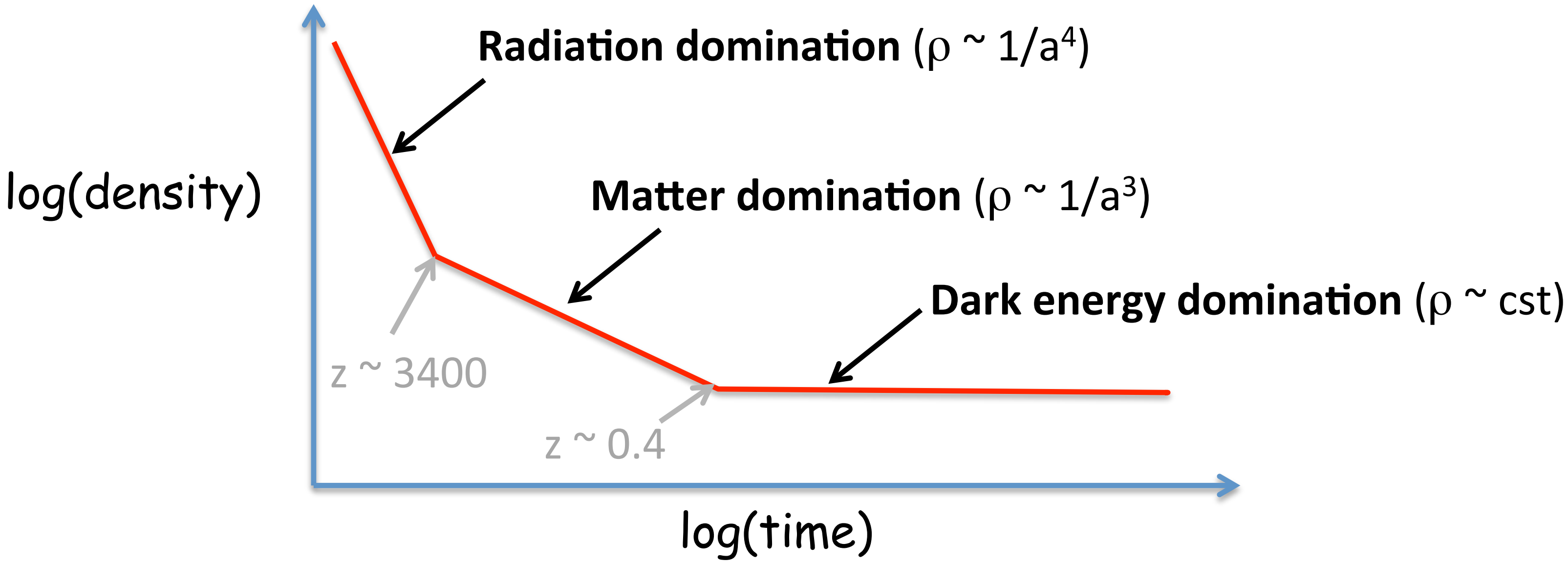
Tritium β decay $m_{min} < 2$ eV $\Rightarrow$ $0.06\ eV < \Sigma m < 6.00\ eV$

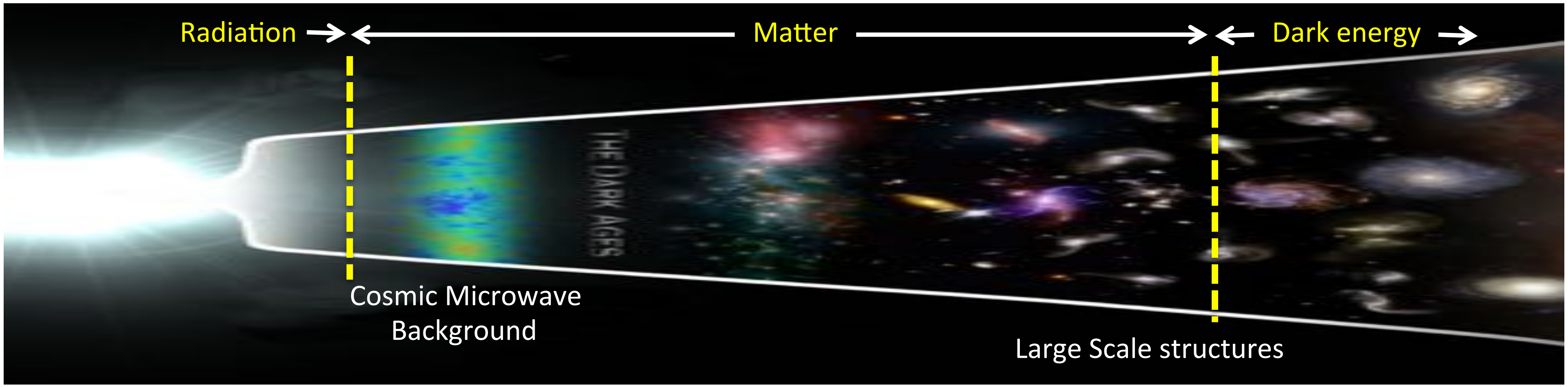
(Cosmology only sensitive to Σm_ν)

Thermal history of Universe

Universe expands ($a = 1/(1+z)$ ↗)

Density and temperature decrease with time





Cosmic neutrino background

Neutrinos "decouple" (= do not interact any longer) at T ~ 1MeV

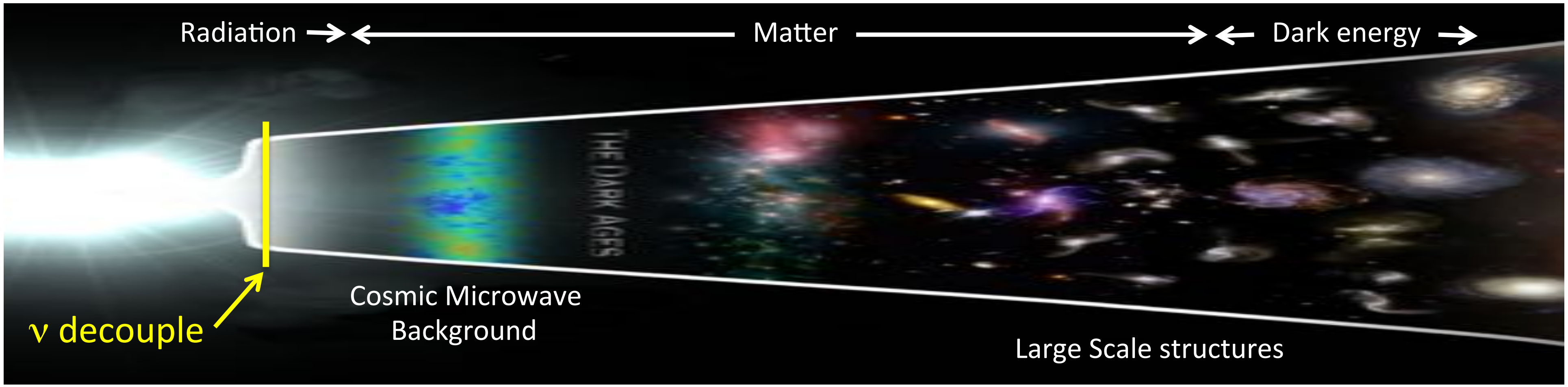
→ Cosmic Neutrino Background (like CMB for photons)
with $T_\nu \propto 1/a = 1+z$

Temperature from entropy conservation at e± annihilation

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \sim 1.95\,K \times (a_0/a)$$

Number density (Fermi-Dirac for ν vs. Bose-Einstein for γ statistics)

$$n_\nu = \frac{3}{11} n_\gamma \sim 113\,\mathrm{cm}^{-3} \times (a_0/a)^3$$ **per flavor**



Cosmic neutrino background

At early times ($T_\nu \gg m_\nu$)

Neutrinos contribute as **radiation**: $\rho_\nu \propto T_\nu^4$

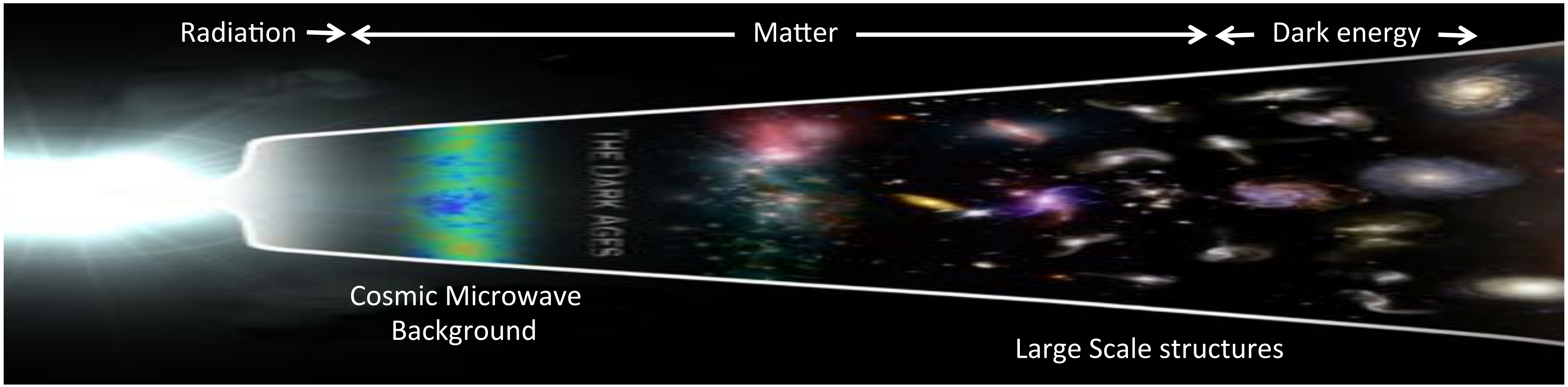
At late times ($T_\nu \ll m_\nu$)

Neutrinos contribute as **matter**: $\rho_\nu = m_\nu n_\nu$

Non-relativistic transition

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

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



Cosmic neutrino background

Non-relativistic transition

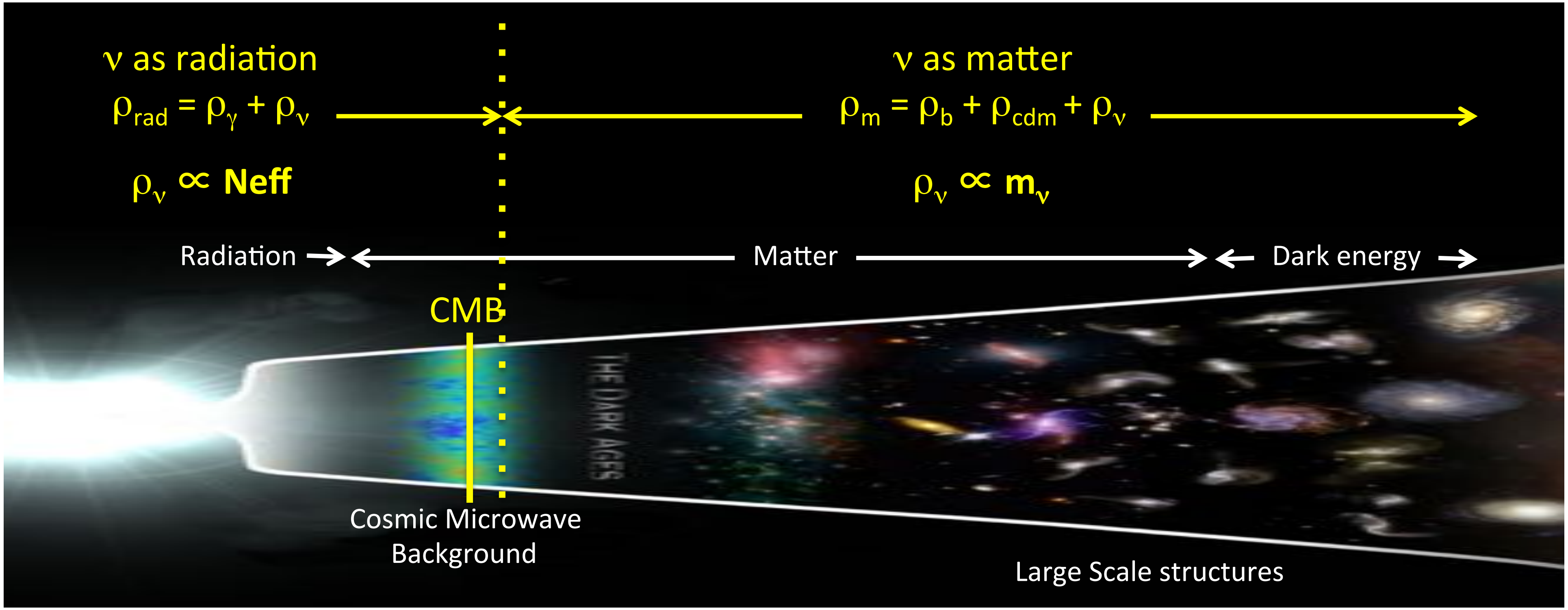
$$z_{nr} \sim 1900 \frac{m_\nu}{1\,\mathrm{eV}}$$

Photon recombination (CMB)

$$z_{\mathrm{CMB}} \sim 1080$$

ν's at CMB emission
m_ν < 0.6 eV : relativistic
m_ν > 0.6 eV : matter-like

m_ν > 0.05 eV, T_ν(today) ~ 0.0002 eV
so at least 1 non-relativistic ν today



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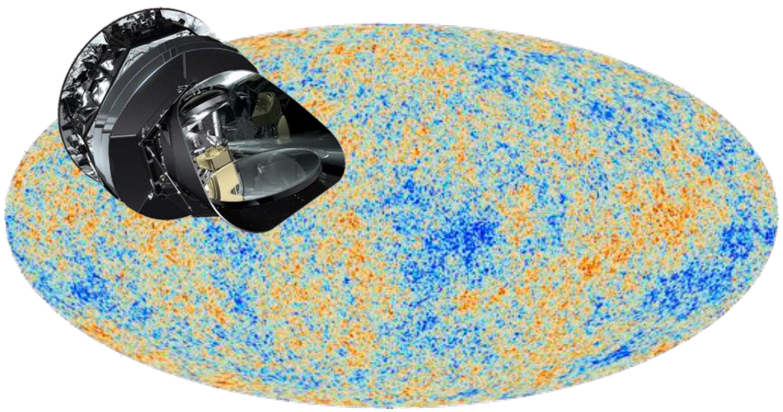
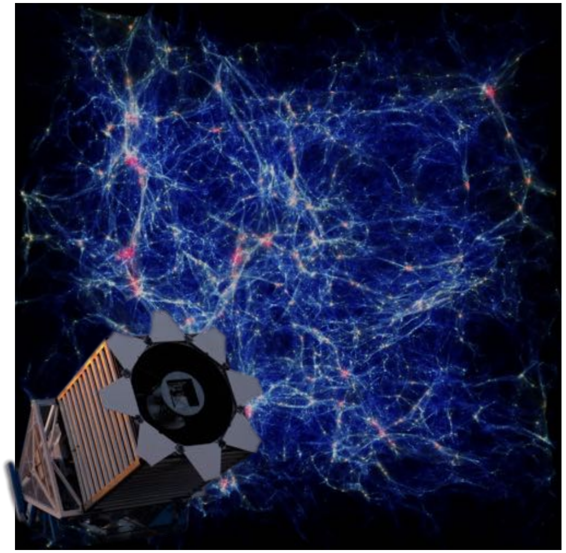




Neutrino mass and CMB

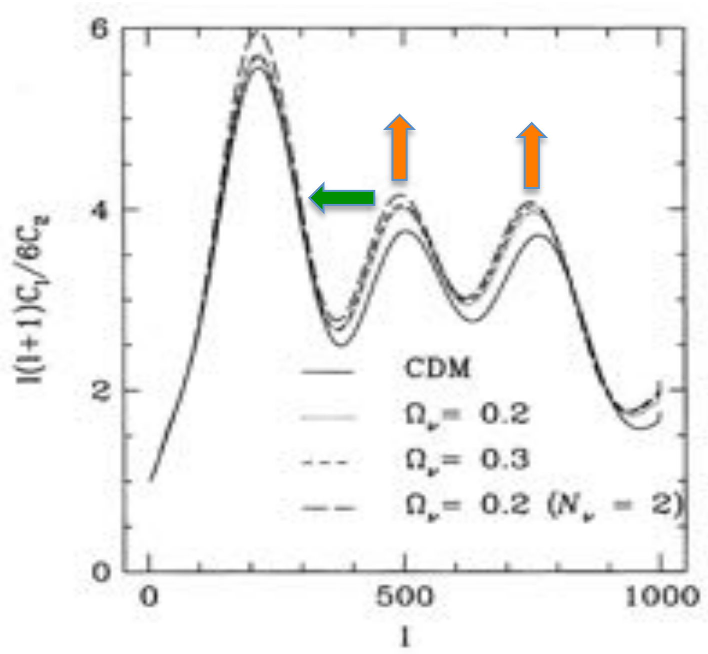
m_ν > 0.6 eV (Σm_ν > 1.7 eV)

⇒ ν's non-relativistic at CMB
⇒ Direct impact on CMB power spectrum (damping of C_ℓ on small scales)

m_ν < 0.6 eV (Σm_ν < 1.7 eV)

⇒ ν's relativistic at CMB
no impact on baryon-photon plasma
⇒ Postponed t_{EQ}
⇒ Subtle impact on peak position & amplitude

WMAP 7 alone	Σm_ν < 1.3 eV
WMAP 7 +BAO + SN	Σm_ν < 0.71 eV
WMAP 7 +BAO + H_0	Σm_ν < 0.58 eV

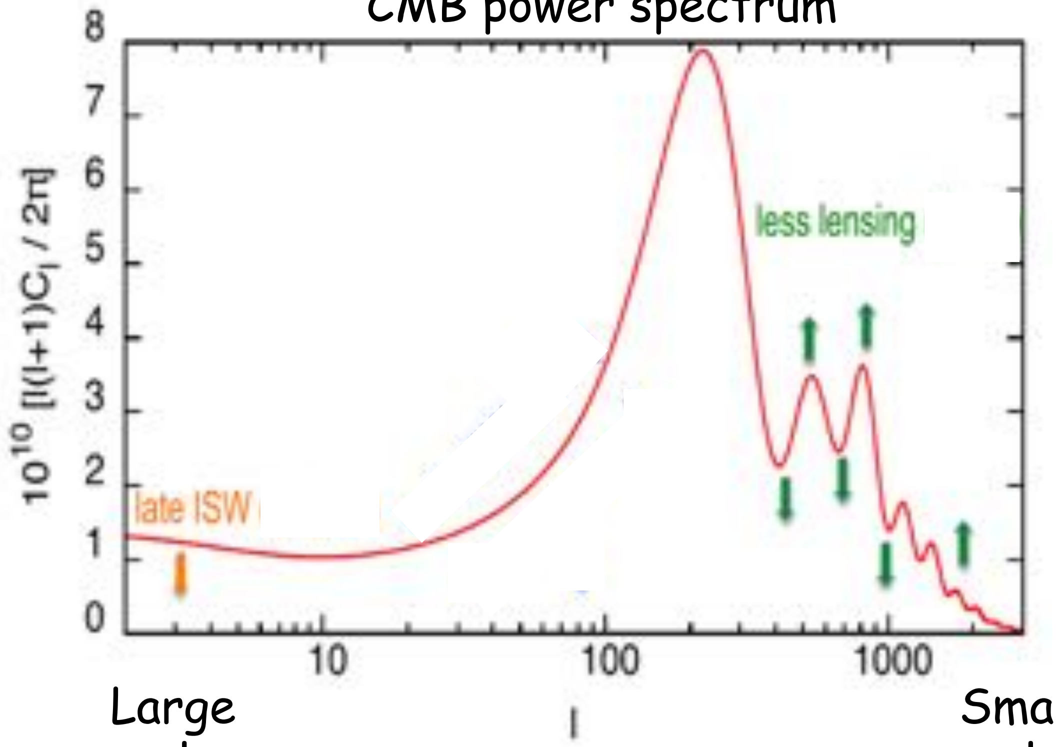


Neutrino mass and CMB

m_ν < 0.6 eV (Σm_ν < 1.7 eV)

Major effects of Σm_ν are indirect ones (secondary anisotropies)

CMB power spectrum



Large scales

Small scales

Indirect effects if Σm_ν ↗

- **Late ISW***
  Duration of DE era
  (decay of potentials)
  Hidden by cosmic variance

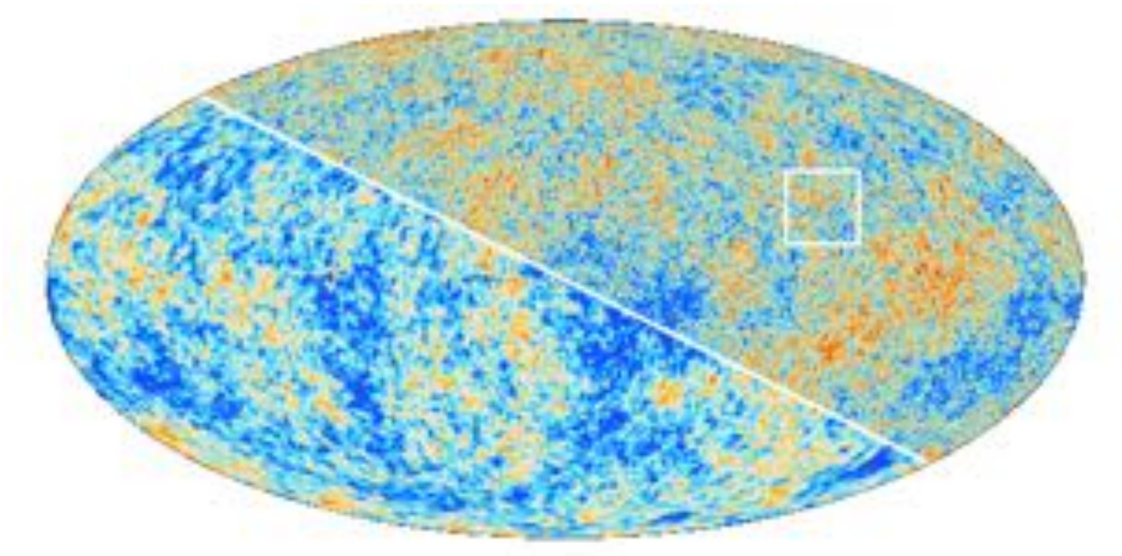
- **Lensing by structures**
  Damping of small scales
  Signal in polarization

*Integrated Sachs-Wolfe effect

Neutrino mass and CMB

m_ν < 0.6 eV (Σm_ν < 1.7 eV)

Major effects of Σm_ν are indirect ones (secondary anisotropies)



ndirect effects if Σm_ν ↗

Late ISW*
Duration of DE era
(decay of potentials)
Hidden by cosmic variance

Lensing by structures
Damping of small scales

Small scales & Polarization measurement
This is why Planck is important !

*Integrated Sachs-Wolfe effect

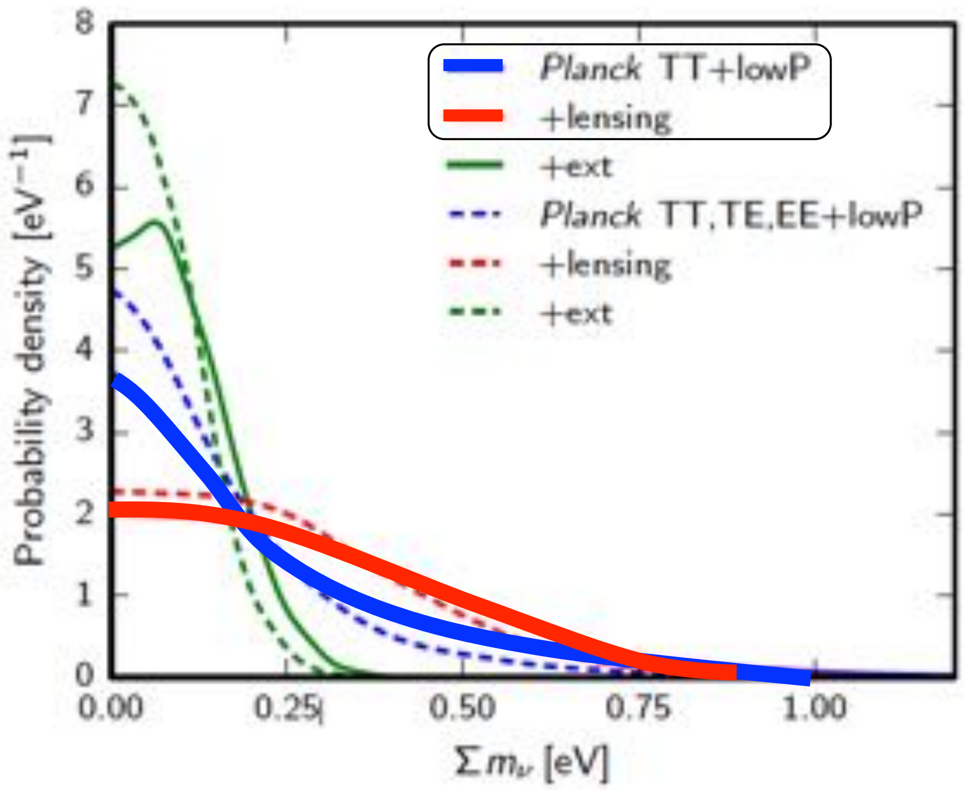
Neutrino mass and CMB

Planck 2015

$\Sigma m < 0.72$ eV (95% CL)
Planck TT+lowP
(broad tail to high mass)

$\Sigma m < 0.68$ eV (95% CL)
Planck TT+lowP+lensing
(preference for $\Sigma m \neq 0$)

$\Sigma m < 0.23$ eV
Planck TT+lowP+BAO+SN+H0



Neutrinos & large-scale structures

m_ν (non-relativistic ν) modifies matter density at late time

⇒ Modified expansion rate

⇒ Slower clustering (H ↗) when m_ν ↗

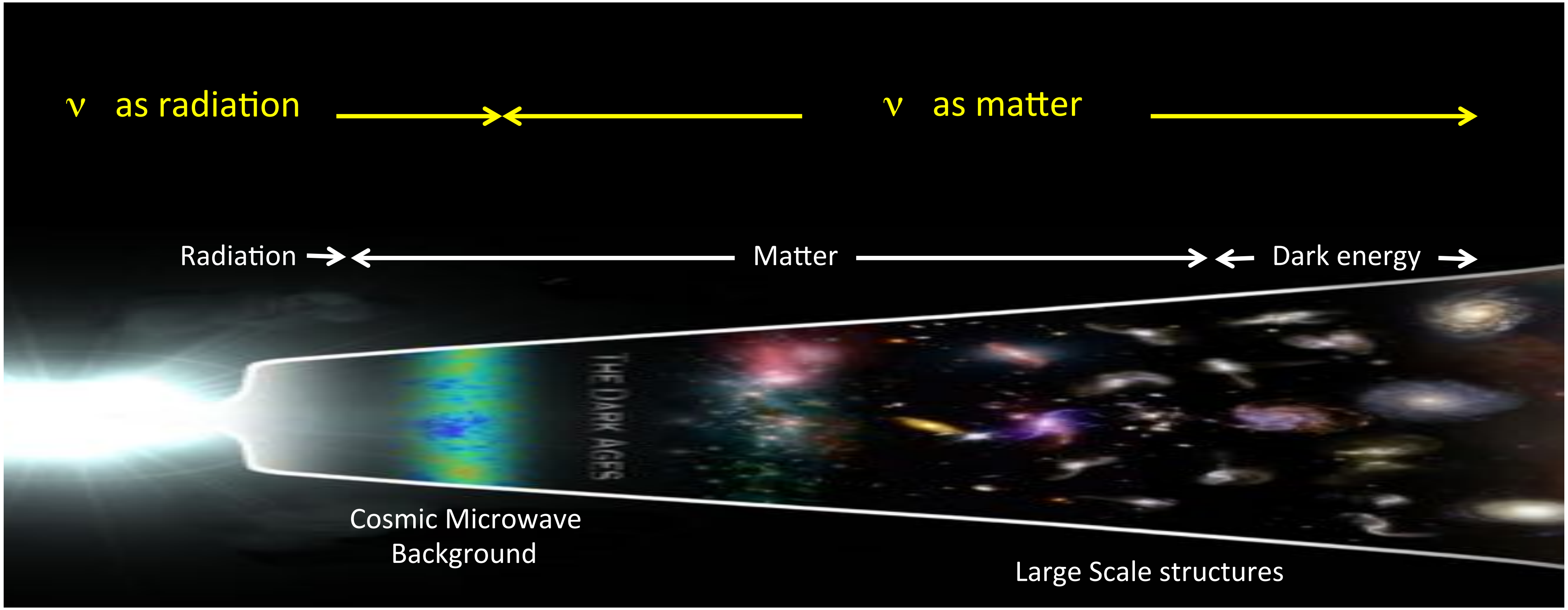
$$H^2 = \frac{8\pi G}{3}(\rho_r + \rho_\Lambda + \rho_{\rm cdm} + \rho_b + \rho_\nu)$$

But neutrinos relativistic at early time

⇒ Neutrinos "free-stream"

⇒ Less clustering when m_ν ↗

$$\frac{\partial\rho_m}{\rho_m} = (1 - f_\nu)\frac{\partial\rho_{\rm cdm}}{\rho_{\rm cdm}}$$



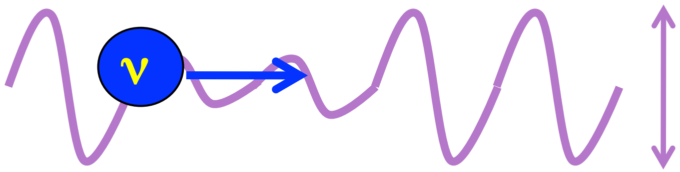
Neutrino free-streaming

neutrinos "free stream" at v=c until t_{nr} (actually once they have decoupled)

$\Rightarrow$ **Destroy perturbations of wavelength $\lambda < ct_{nr}$**
although normal clustering on scales $\lambda > ct_{nr}$

- **Heavy neutrinos (t_{nr} early)**

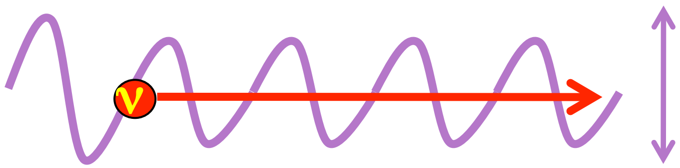
  Strong suppression over short range

  m_ν = 4 keV $\Rightarrow$ size of dwarf galaxy perturbations smoothed out

- **Light neutrinos (t_{nr} late)**

  Weak suppression over long range

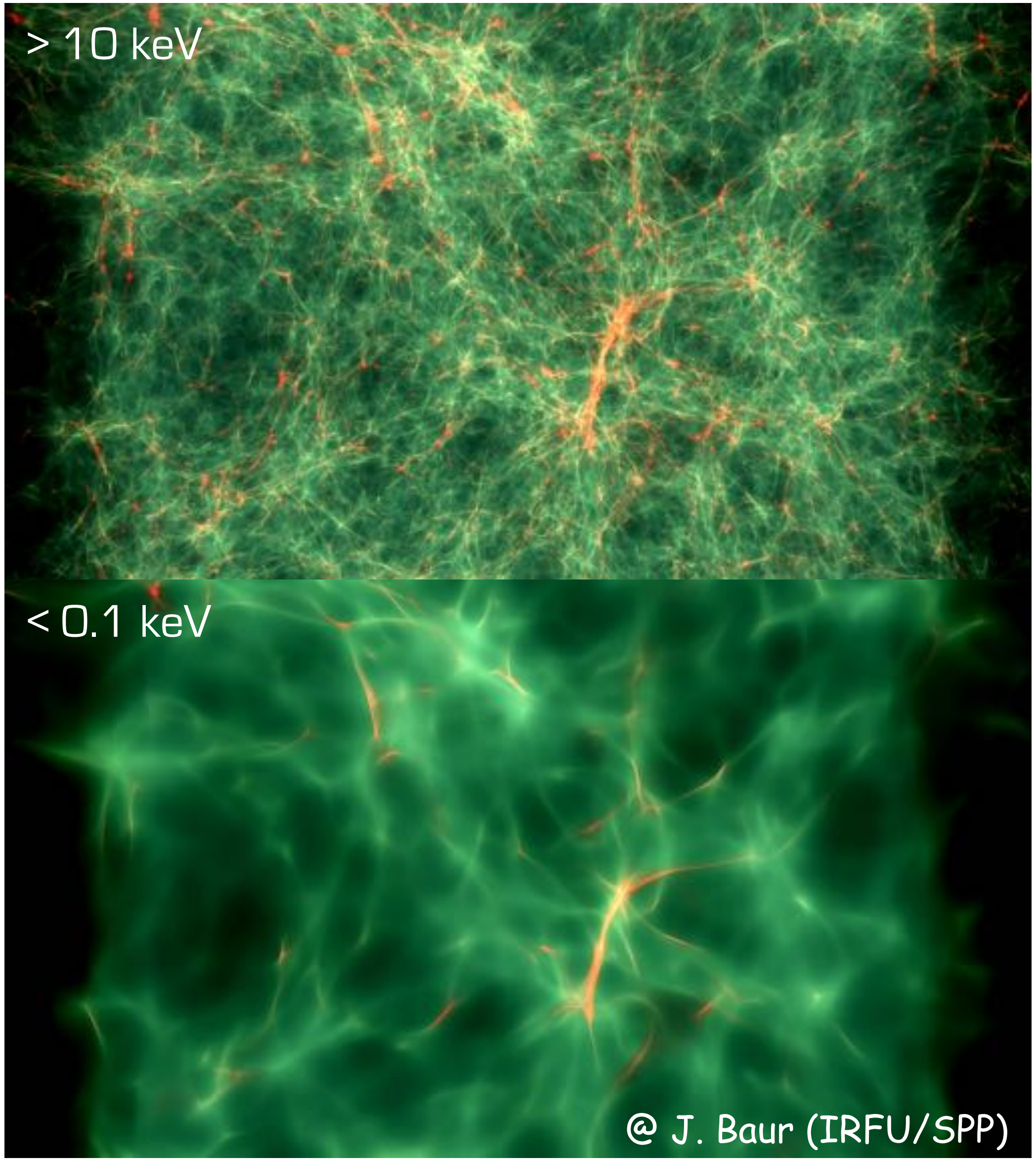
  m_ν = 1 eV $\Rightarrow$ size of galaxy cluster perturbations smoothed out

Neutrinos & large-scale structures

If all
dark matter
were

Cold Dark Matter

Hot Dark Matter

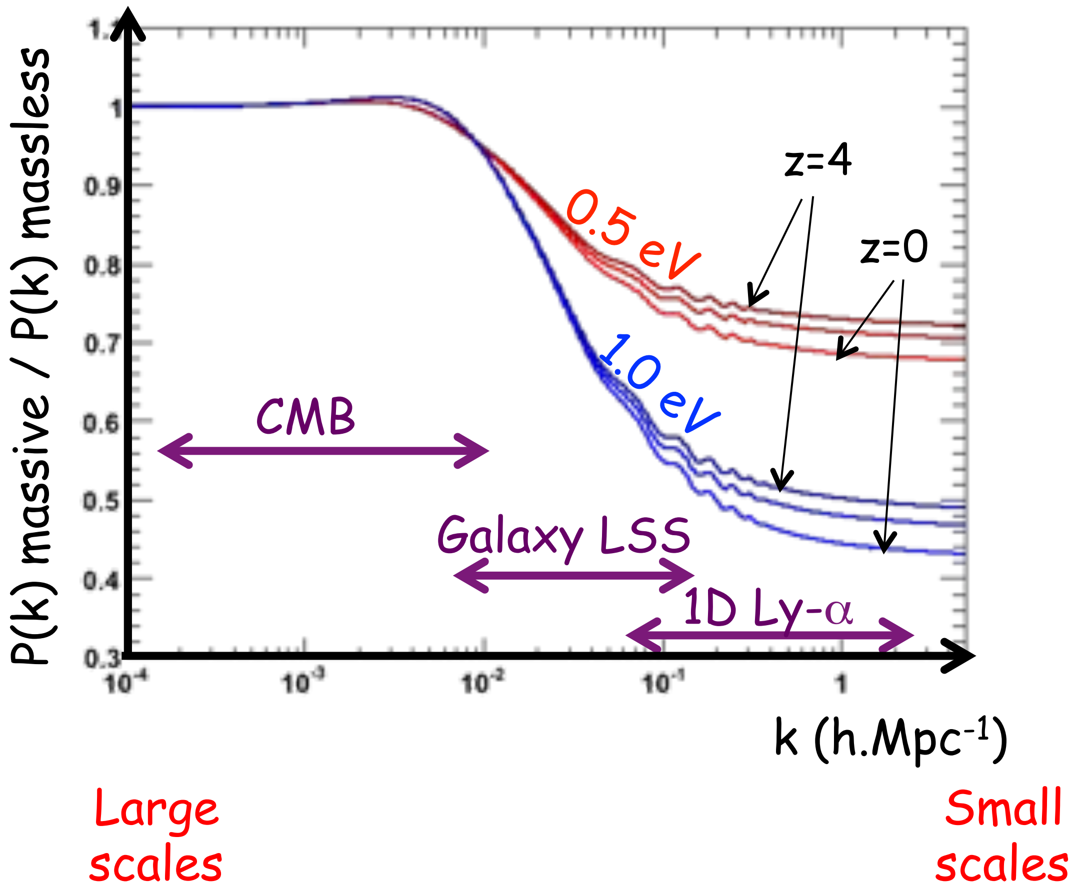


Free Streaming Horizon

$$\lambda^0_{\rm FSH} = \int_0^{t_0} \frac{\langle v \rangle}{a} \, dt$$

Neutrinos and large-scale structures

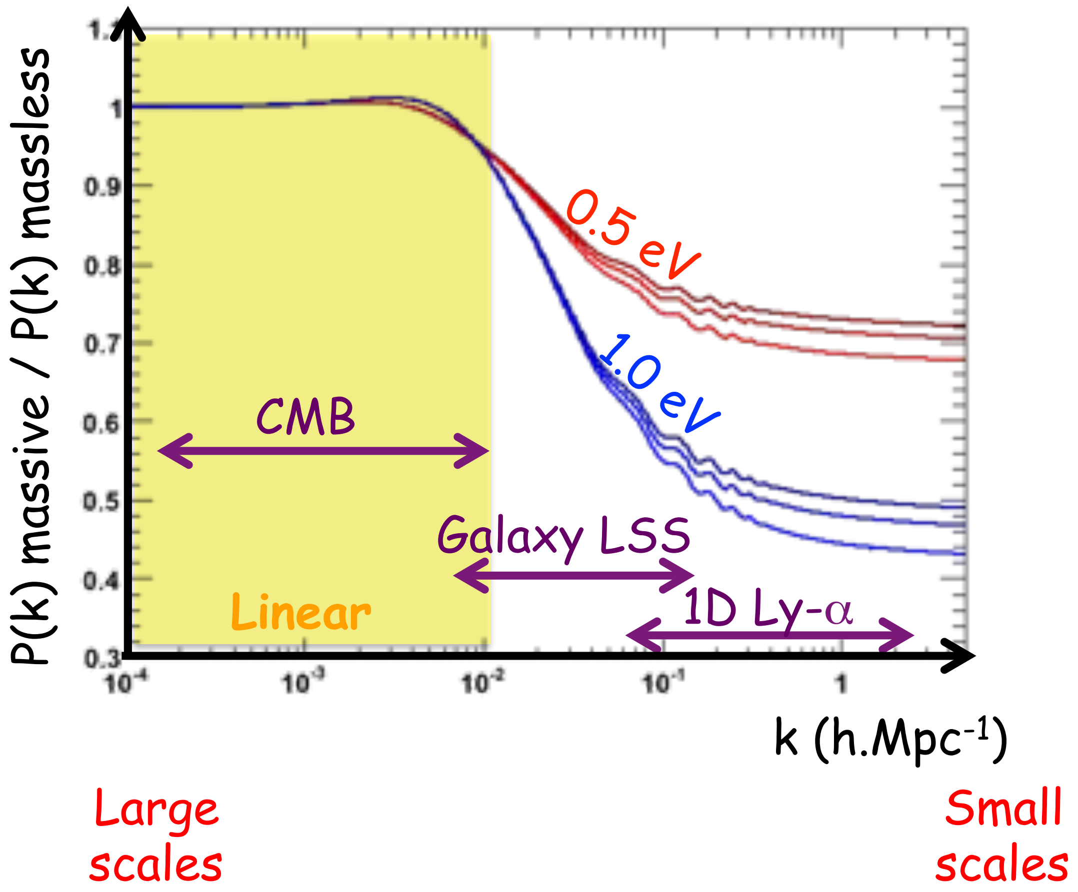
Different probes ⇔ different scales



- Suppression factor ⇔ Σmν
- Suppression is z-dependent
- Ly-α
  - Small scales, max effect ✚
  - Large z-range [2.1 ; 4.5] ✚

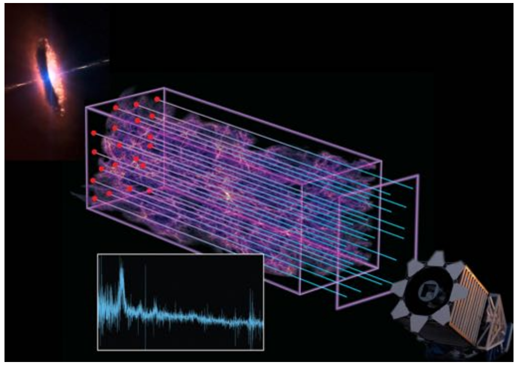
Neutrinos and large-scale structures

Different probes ⇔ different scales



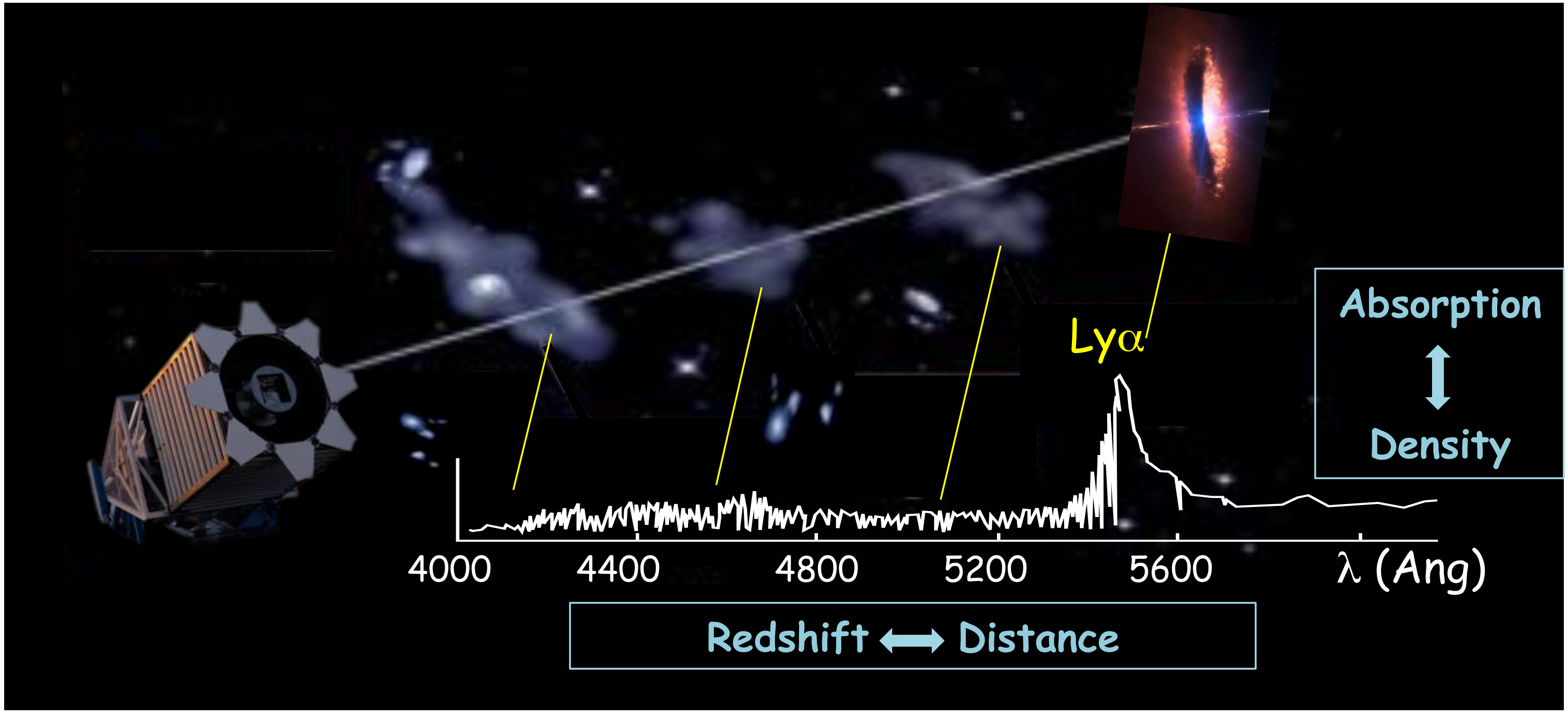
- Suppression factor ⇔ Σmν
- Suppression is z-dependent
- Ly-α
  - Small scales, max effect +
  - Large z-range [2.1 ; 4.5] +
  - Non-linear regime, flux (not mass) P(k) ⇒ Hydro simulations −

Ly-α forest *(BOSS)*



Method

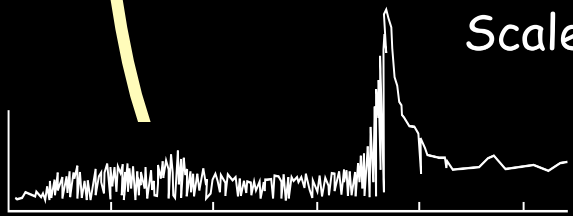
- Quasars visible to high redshift (>5)
- Absorption by neutral H (IGM) along line-of-sight
- IGM probes matter density
- Matter distribution on small scales (ν, ν_s)



Ly-α forest

Spatial correlation of
absorption features
(power spectrum)

Scales ~ 1 to 100 Mpc

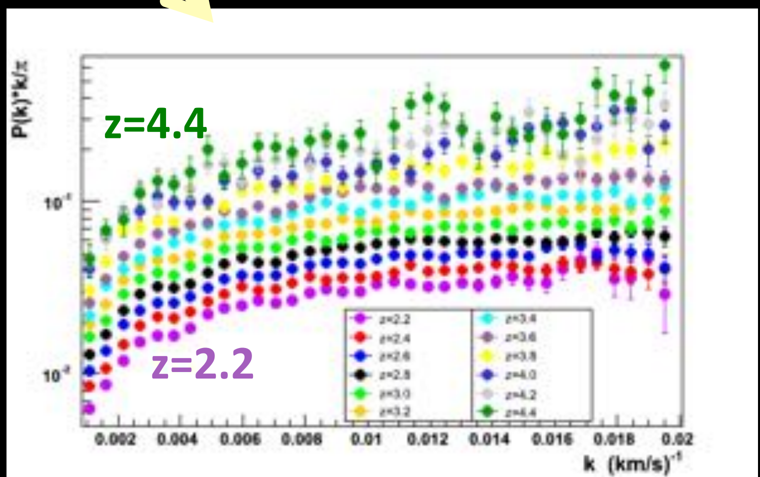


cosmology

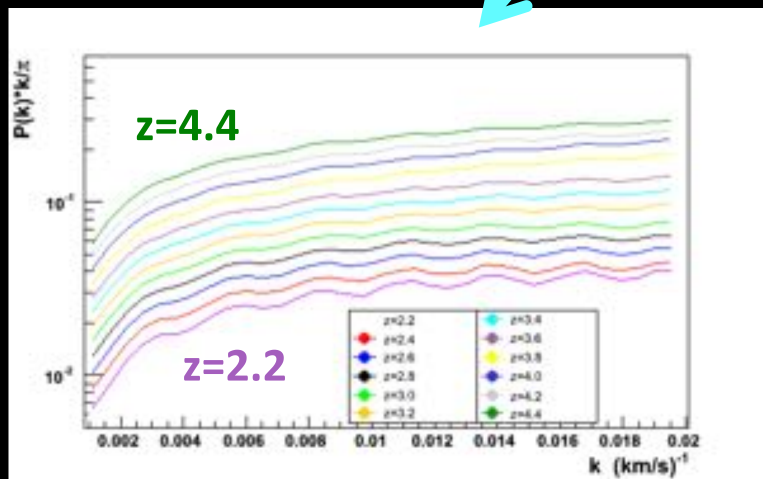
ν

ν_s

Data



Simulations

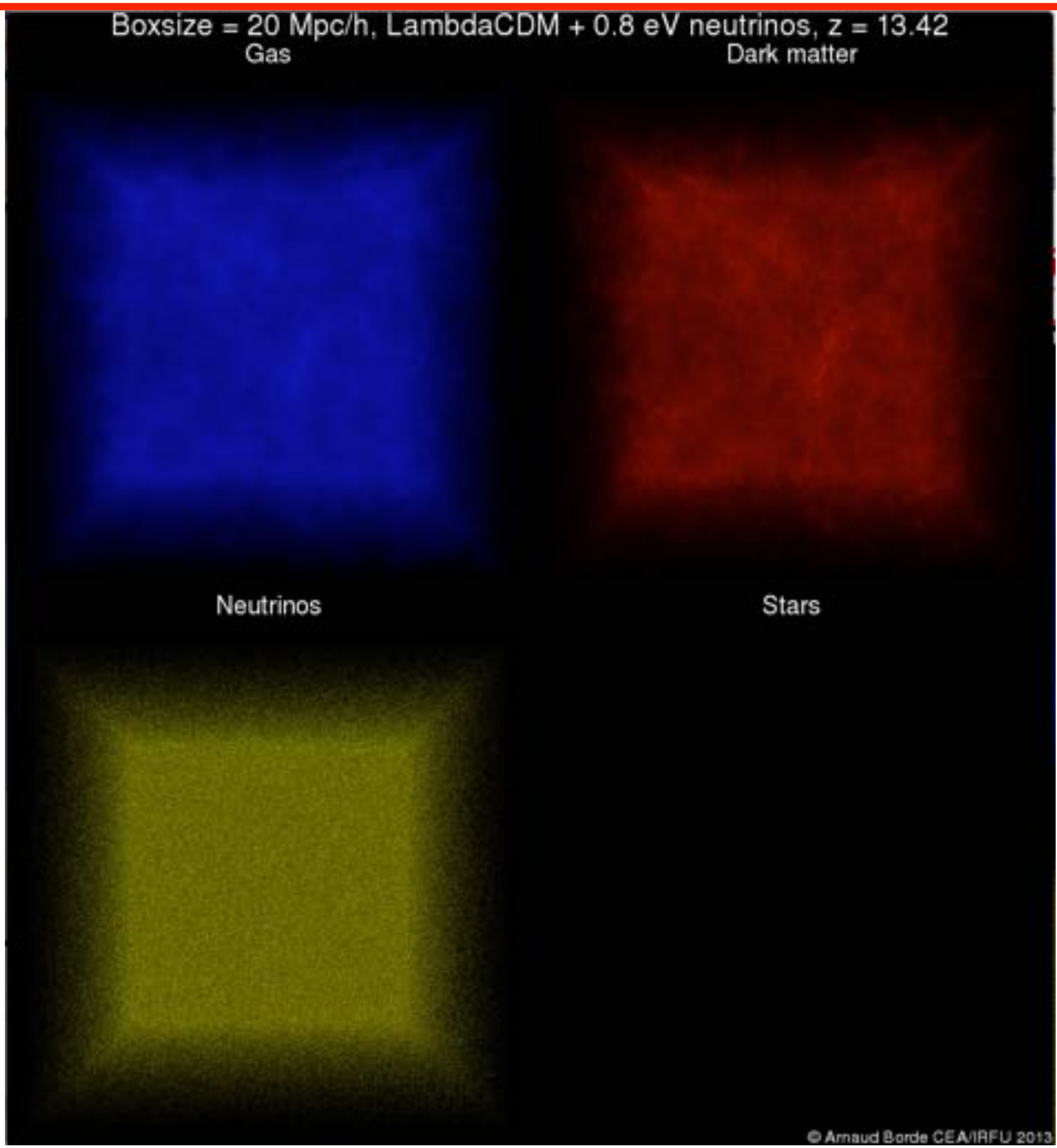


Hydrodynamical simulations

z = 15 → 0

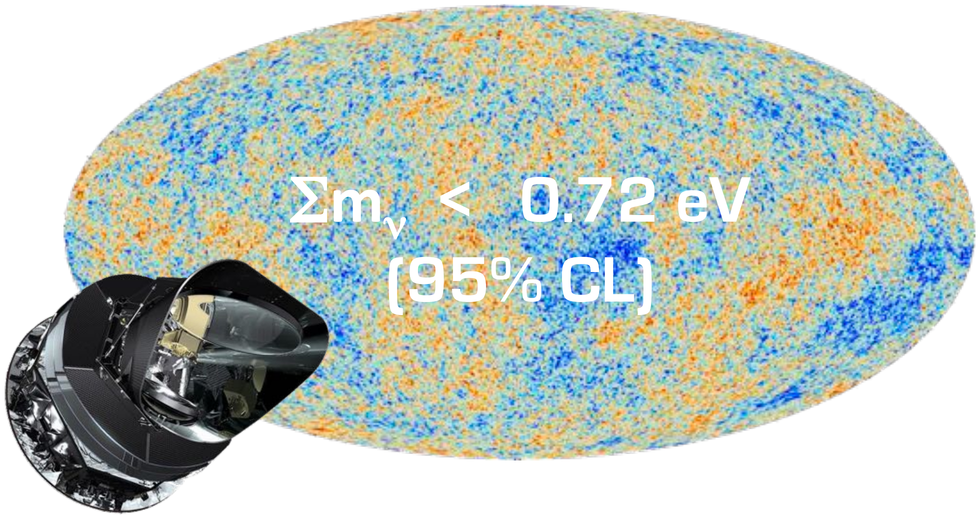
3 species
- Baryons
- Dark matter
- Neutrinos

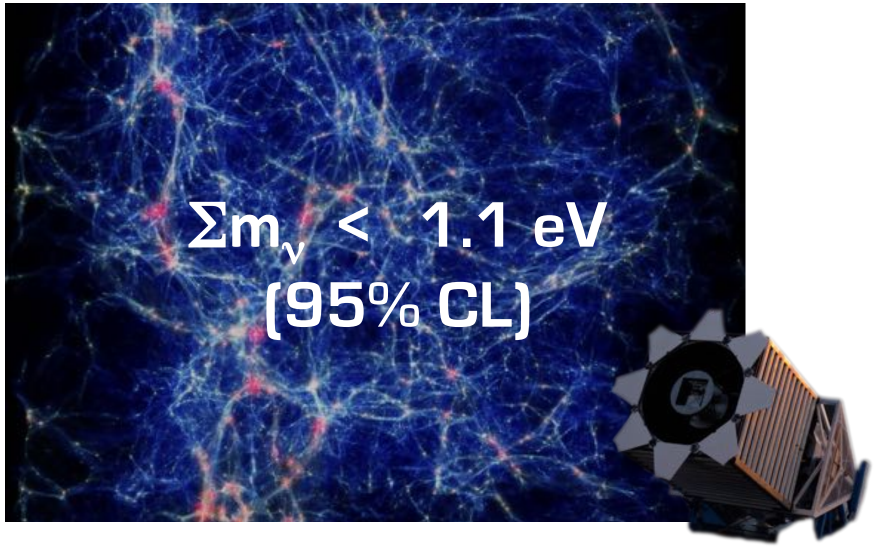
Stars formed
from baryons



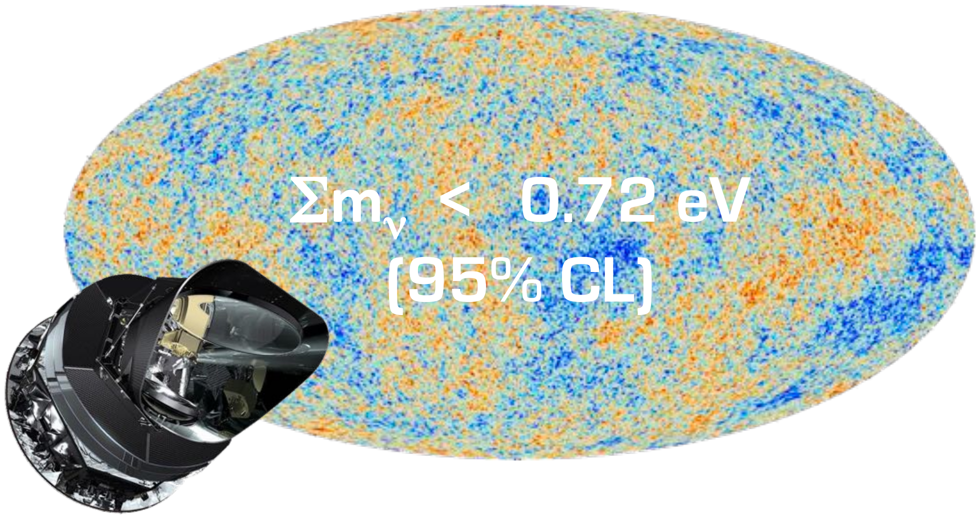
@ A. Borde
(IRFU/SPP)

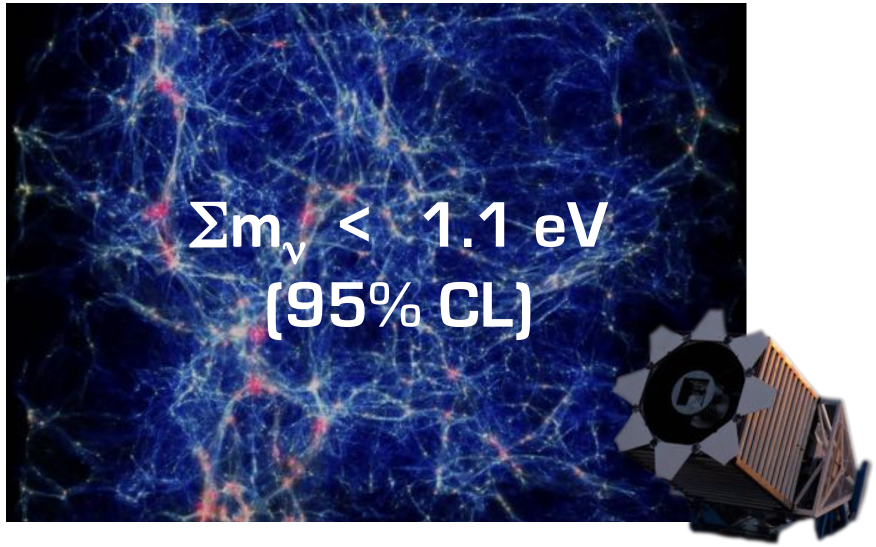
Ly-α forest (BOSS)

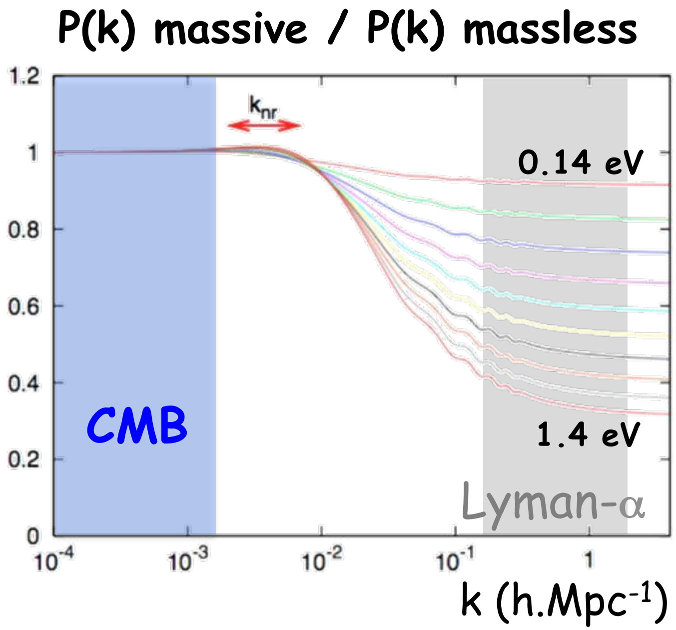


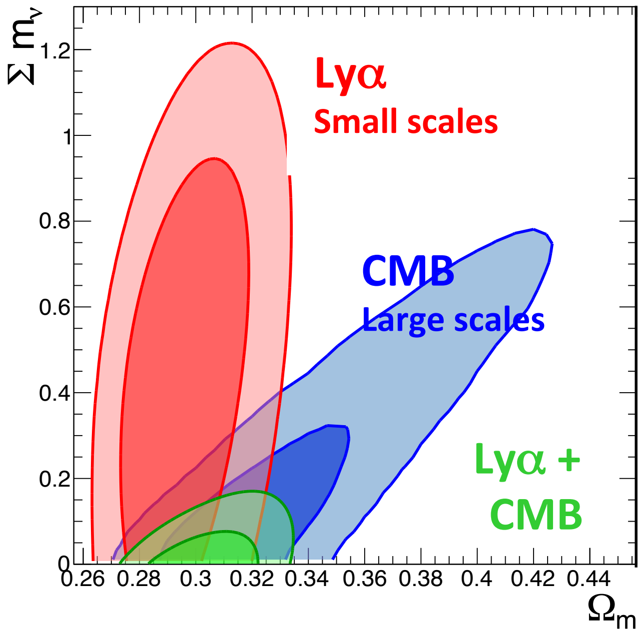


Ly-α forest *(BOSS)*









Σm_ν < 0.12 eV

P.-D., Yèche, Baur, et al.
(arXiv:1506.05976)

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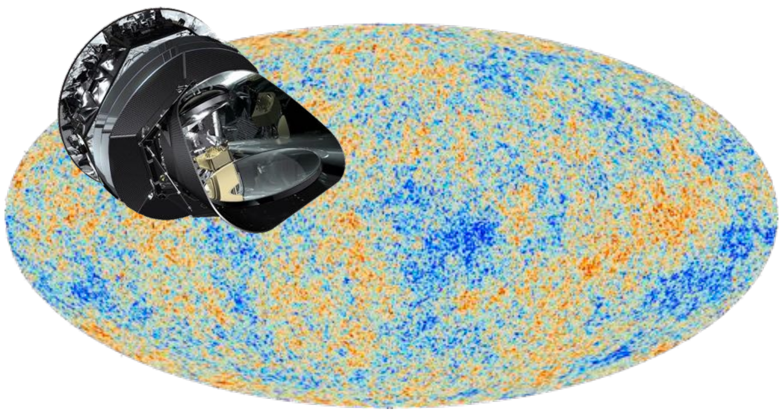
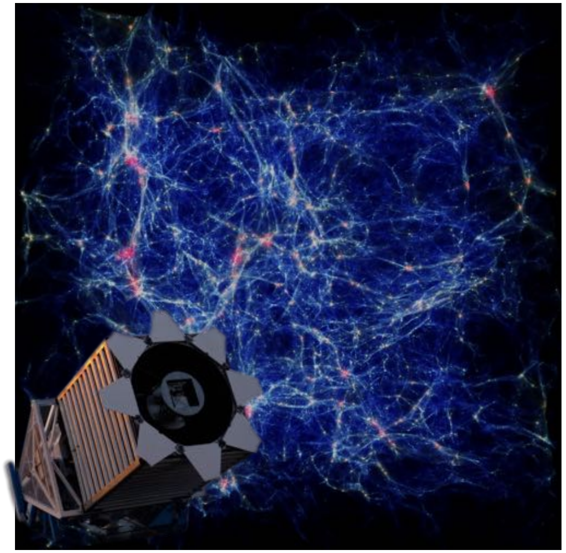
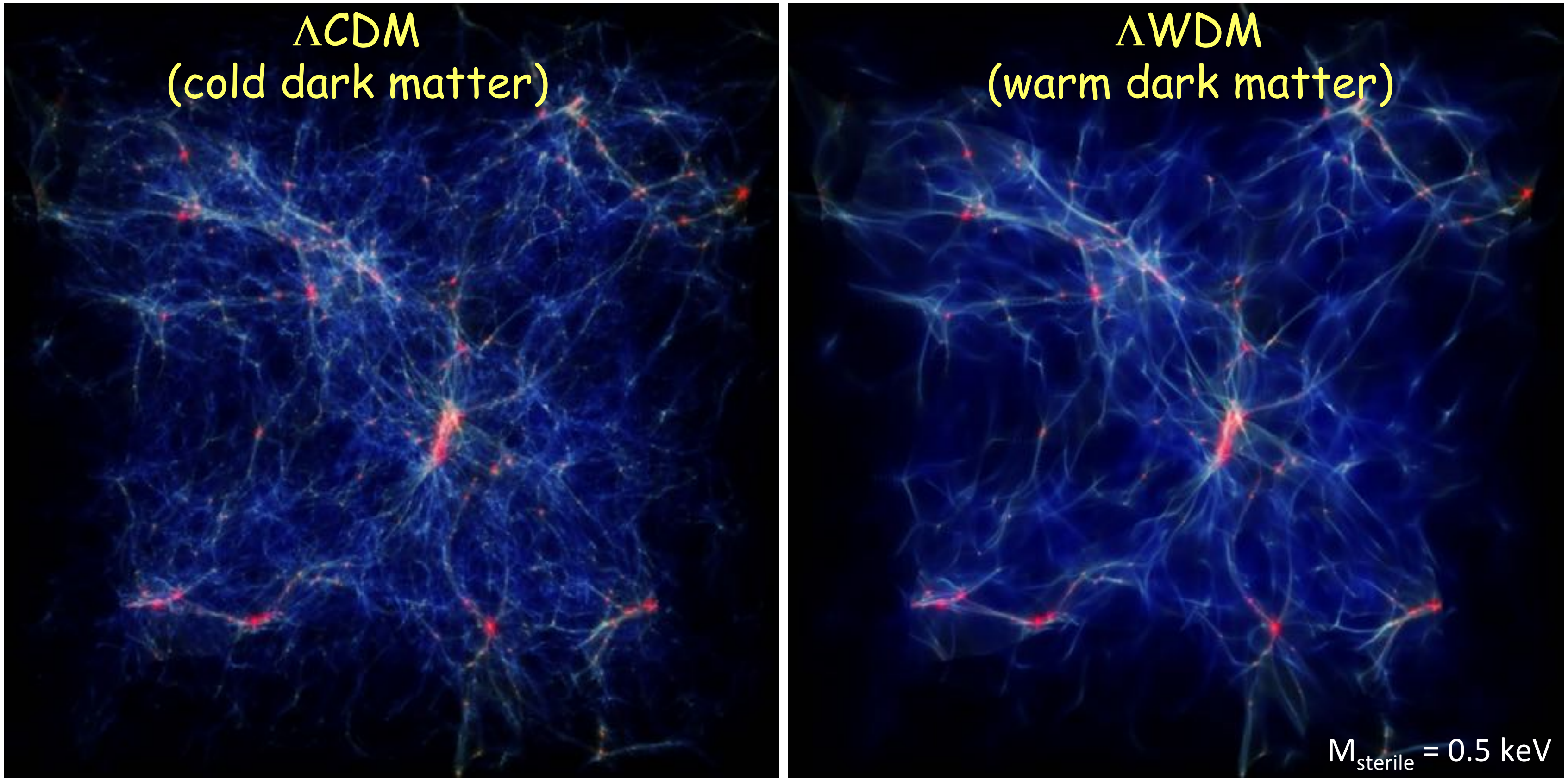




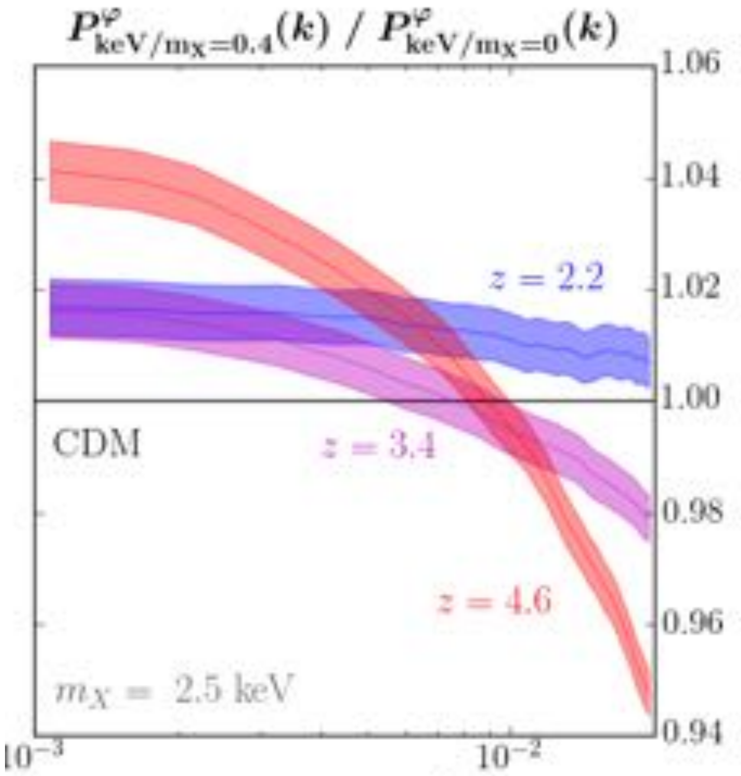
keV sterile neutrinos?

@ J. Baur (IRFU/SPP)



If ALL dark matter is WARM (keV-range sterile neutrinos)
Replace CDM by WDM in hydro simulations
→ Lack of power on small scales
→ Detectable if $m_{sterile}$ small enough

keV sterile neutrinos?

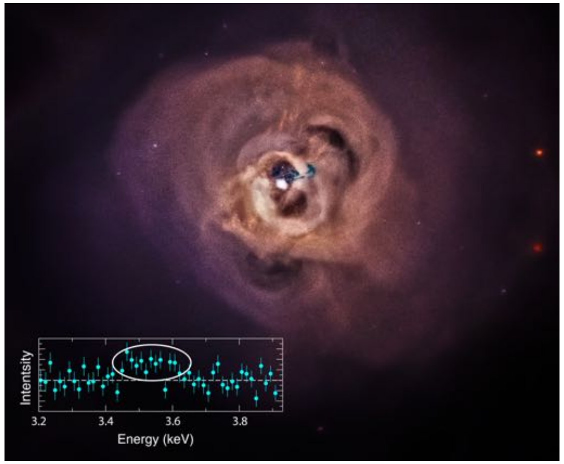


Ly-α from SDSS/BOSS

⟹ m_{WDM} > 4.1 keV (95% CL)

$m_{sterile}$ > 24.4 keV (95% CL)

(Baur, P.D. et al., arXiv:1512.01981)



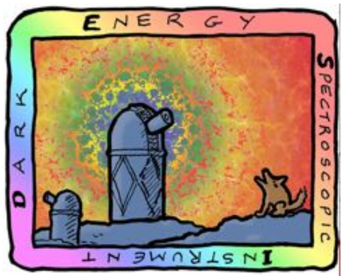
3.5 keV line (XMM) as decay of non-resonantly produced 7 keV ν_s ?

→ excluded

→ resonant production?

Conclusions

- Particle physics bounds on neutrino masses: $0.06 < \Sigma m < 6$ eV
- Major role of neutrinos in cosmology
  - Impact on matter clustering
  - Probed by CMB lensing or large-scale structures
  - Sum of neutrino masses $\Sigma m_\nu < 0.12$ eV (95% CL) from Lyα+CMB
- Constraint on sterile neutrinos from Lyα
  - $m_{sterile} > 24$ keV (95% CL) for non-resonant production (NRP)
  - In conflict with 3.5 keV X-ray line (for NRP sterile ν)
- Prospects
  - More realistic sterile ν models
  - More Lyα (BOSS, eBOSS, high-resolution VLT)
  - Planck + DESI Galaxy $\sigma(\Sigma m_\nu) = 0.024$ eV
    Planck + DESI Lyα $\sigma(\Sigma m_\nu) = 0.039$ eV
  - CORE + Euclid $\sigma(\Sigma m_\nu) = 0.003$ eV*



*no theoretical uncertainty