Neutrinos & Warm Dark Matter from a cosmology perspective

SDSS: a clustering saga

Lyman-α survey

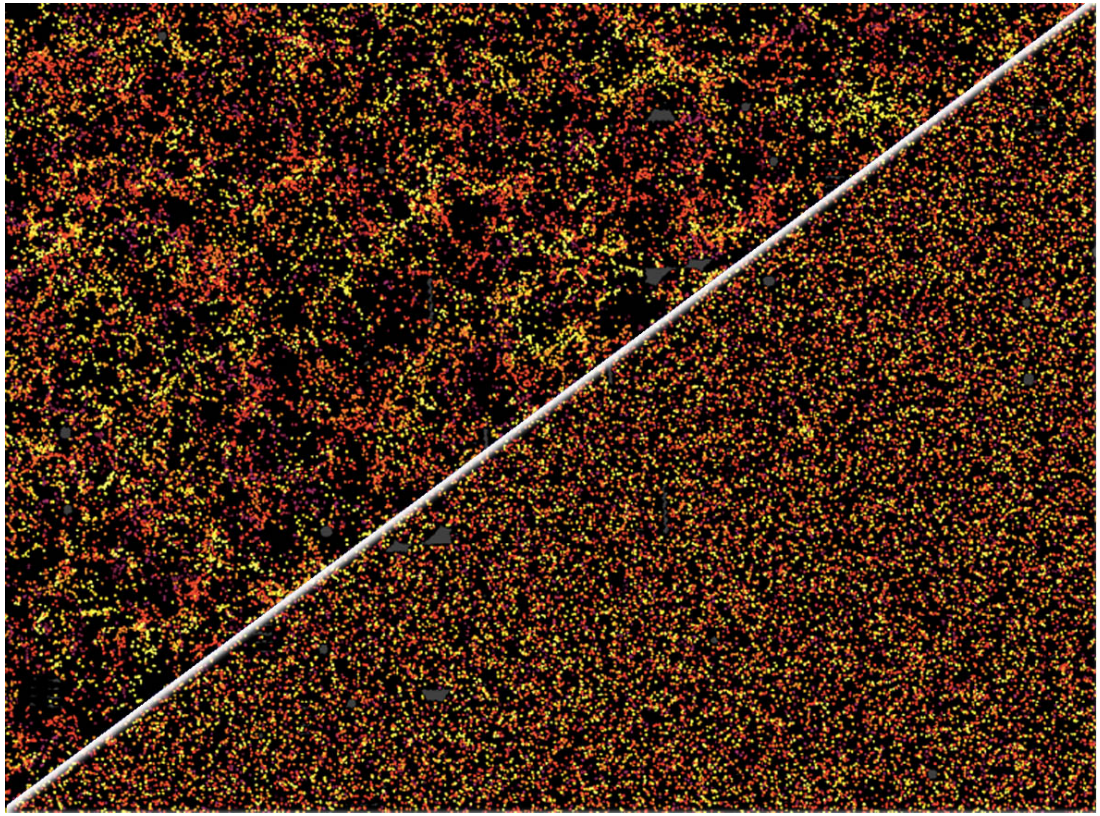
Constraining Σm_ν

Nature of dark matter

N. Palanque-Delabrouille
CEA-Saclay

Clustering in the Universe

500 deg^2 BOSS galaxies (0.50<z<0.55)



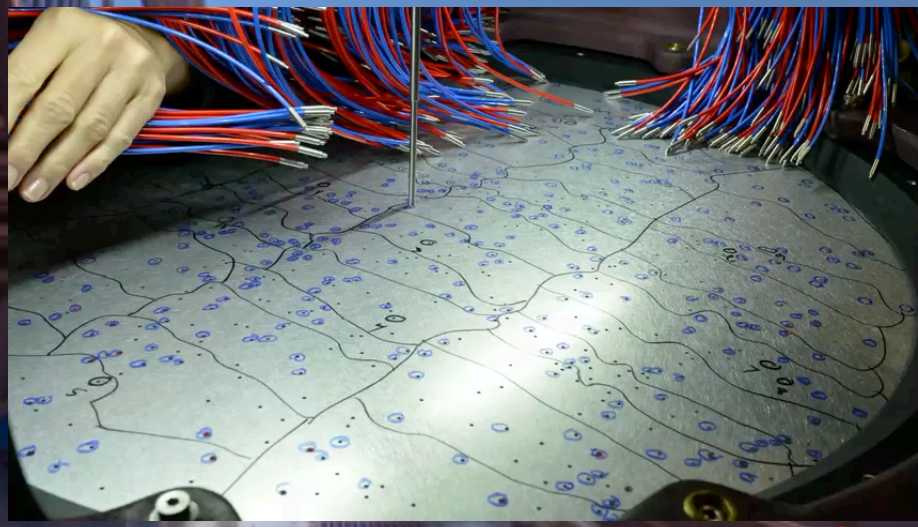
500 deg^2 random (0.50<z<0.55)

Sloan Digital Sky Survey

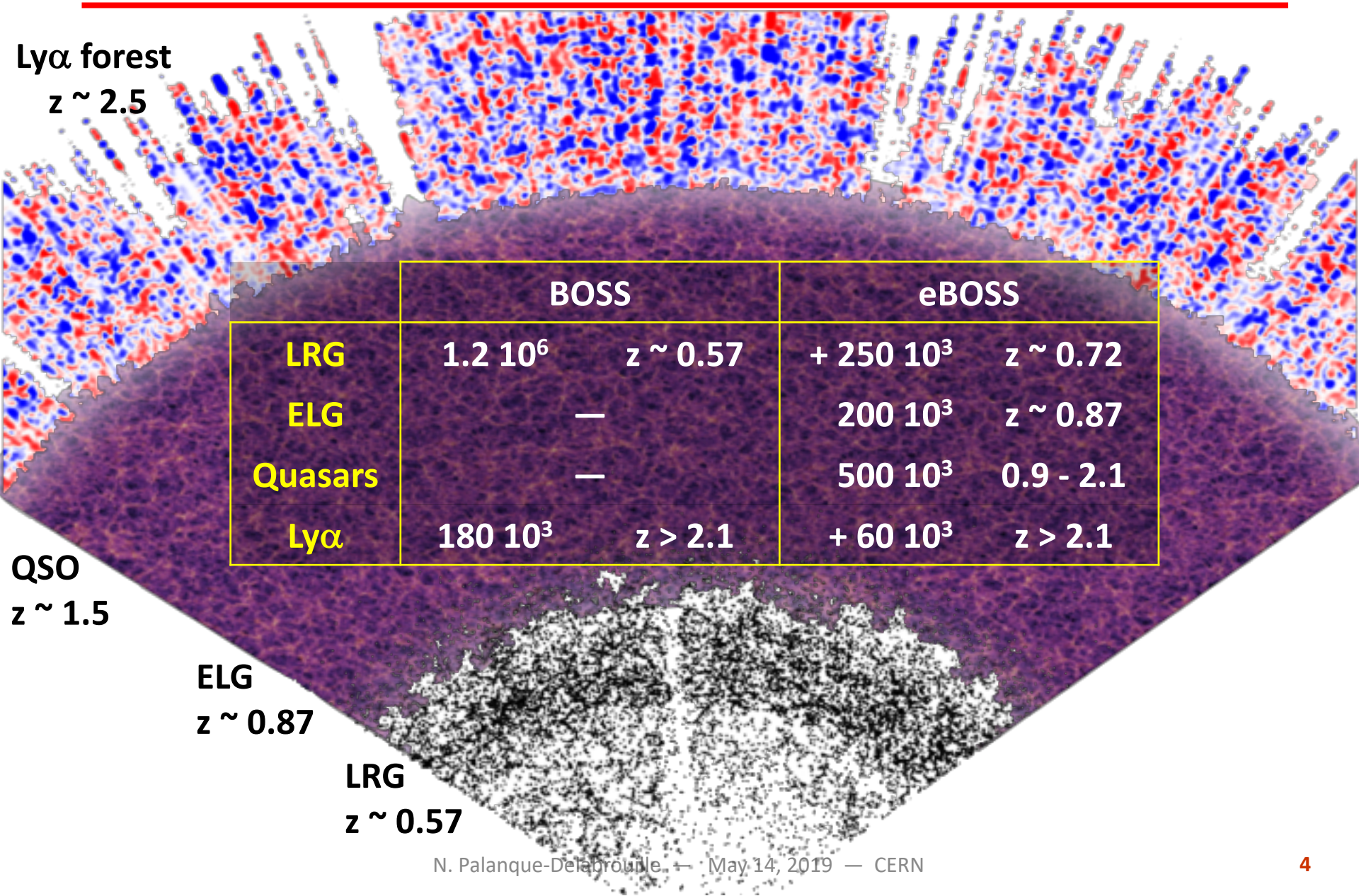
- **2.5m telescope**
  (New Mexico)

- **3D map of structures**
  - **(α,δ) from**
    - **BOSS: 10 000 deg^2**
    - **eBOSS: 7 500 deg^2**
  - **z from 1000 fibers**

BOSS 2009-2014
eBOSS 2014-2020

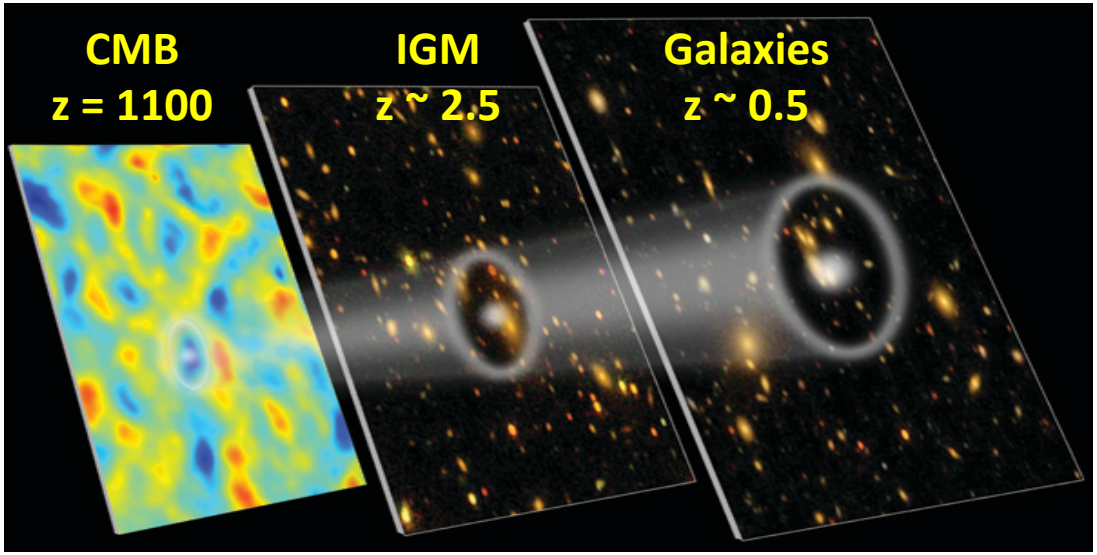


SDSS BOSS and eBOSS



	BOSS		eBOSS	
LRG	$1.2\ 10^6$	z ~ 0.57	$+\ 250\ 10^3$	z ~ 0.72
ELG	—		$200\ 10^3$	z ~ 0.87
Quasars	—		$500\ 10^3$	0.9 - 2.1
Lyα	$180\ 10^3$	z > 2.1	$+\ 60\ 10^3$	z > 2.1

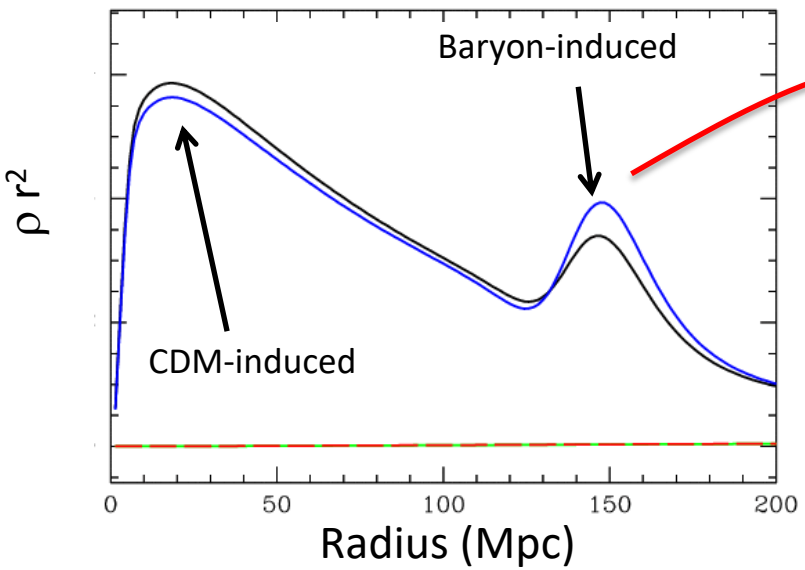
Baryon Acoustic Oscillations (BAO)

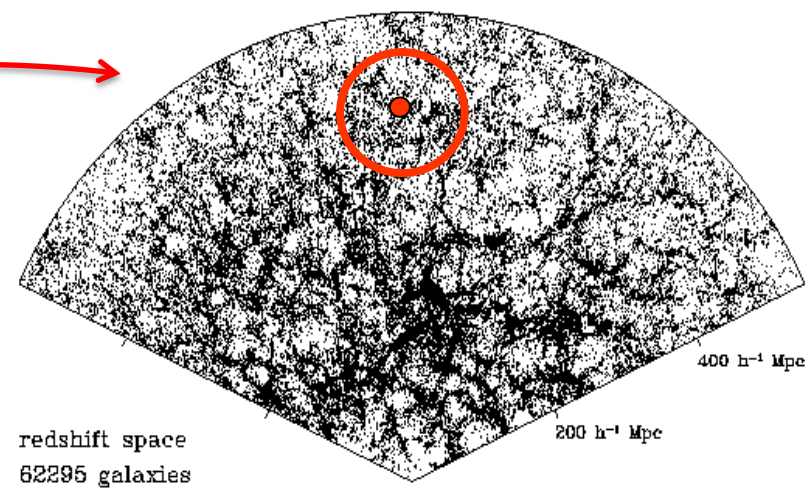


Propagation of baryon-photon overdensity wave in plasma

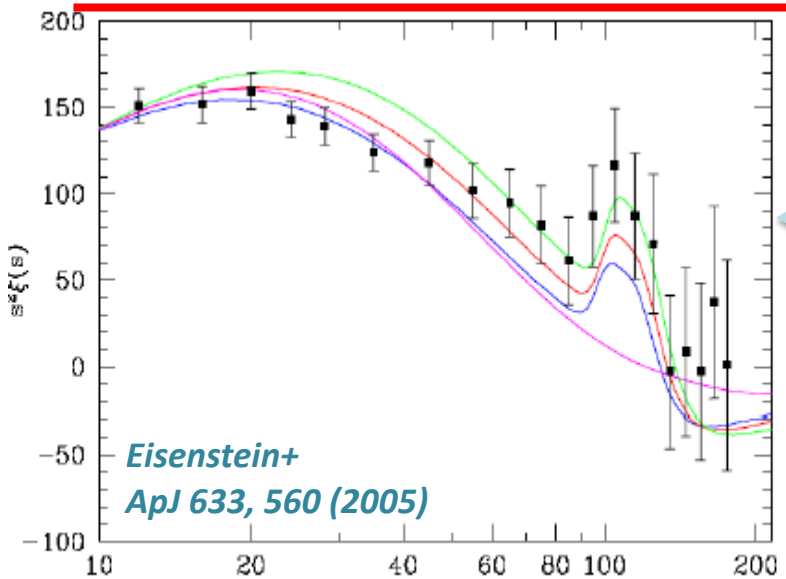
Wave frozen at recombination, at comoving r_s ~ 150 Mpc

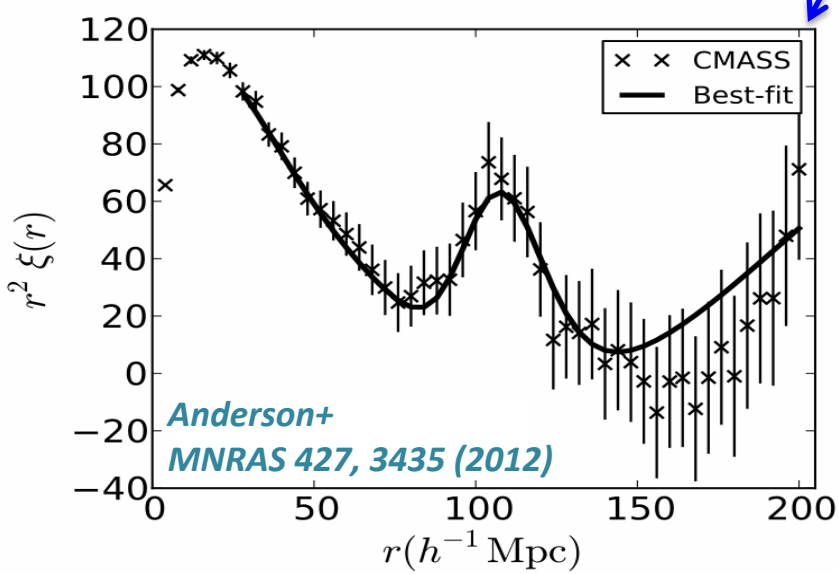
A preferred 3D scale
Standard ruler in LSS





Baryon Acoustic Oscillations (BAO)





Observations

2005: First detection of BAO peak

2012: 5σ confirmation by BOSS

Baryon Acoustic Oscillations (BAO)

Observations

2005: First detection of BAO peak
2012: 5σ confirmation by BOSS
2014: First 3D measurements of BAO

Transverse direction

$\Delta\theta = r_s / [(1+z)\, D_A(z)]$

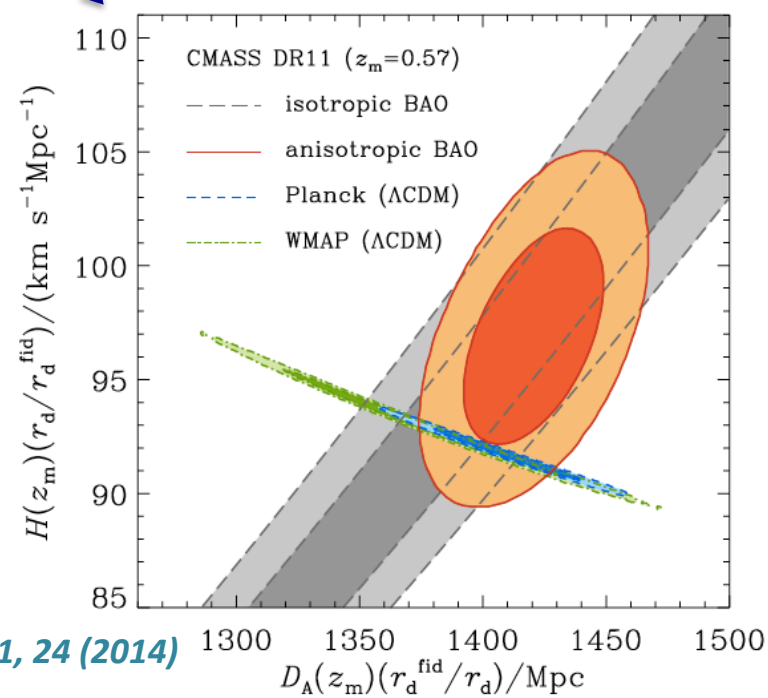
$\Rightarrow$ Angular distance $D_A(z)$

as SNIa: $D_L(z) = (1+z)^2\, D_A(z)$

Radial direction (along line of sight)

$\Delta z = r_s\, H(z) / c$

$\Rightarrow$ Hubble parameter $H(z)$

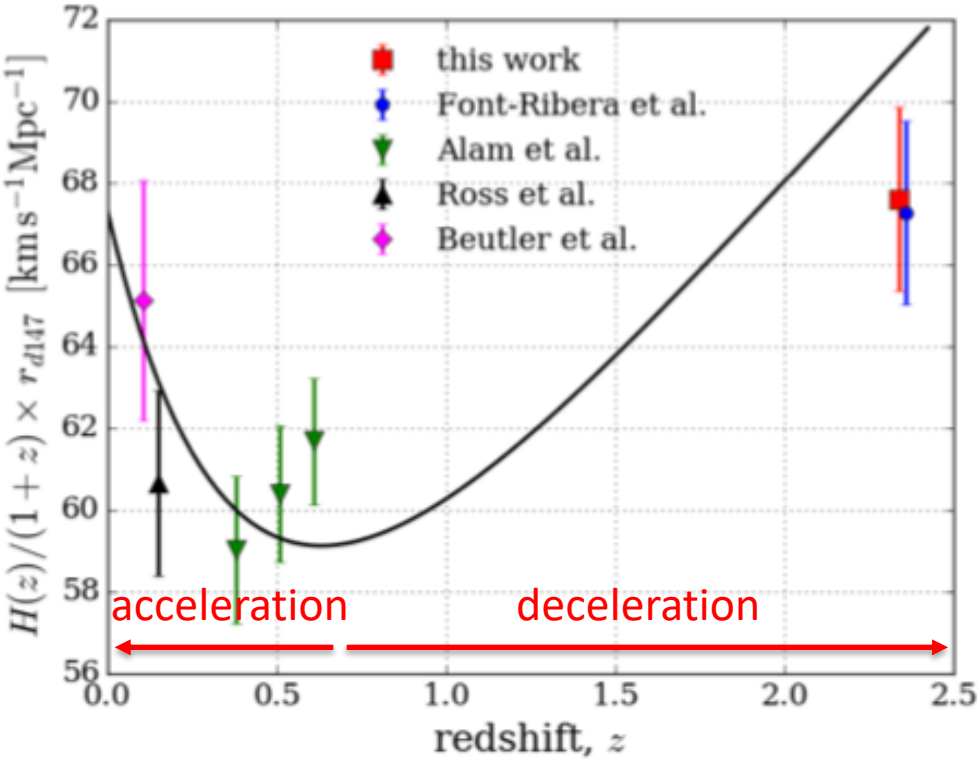


Anderson+
MNRAS 441, 24 (2014)

Baryon Acoustic Oscillations (BAO)

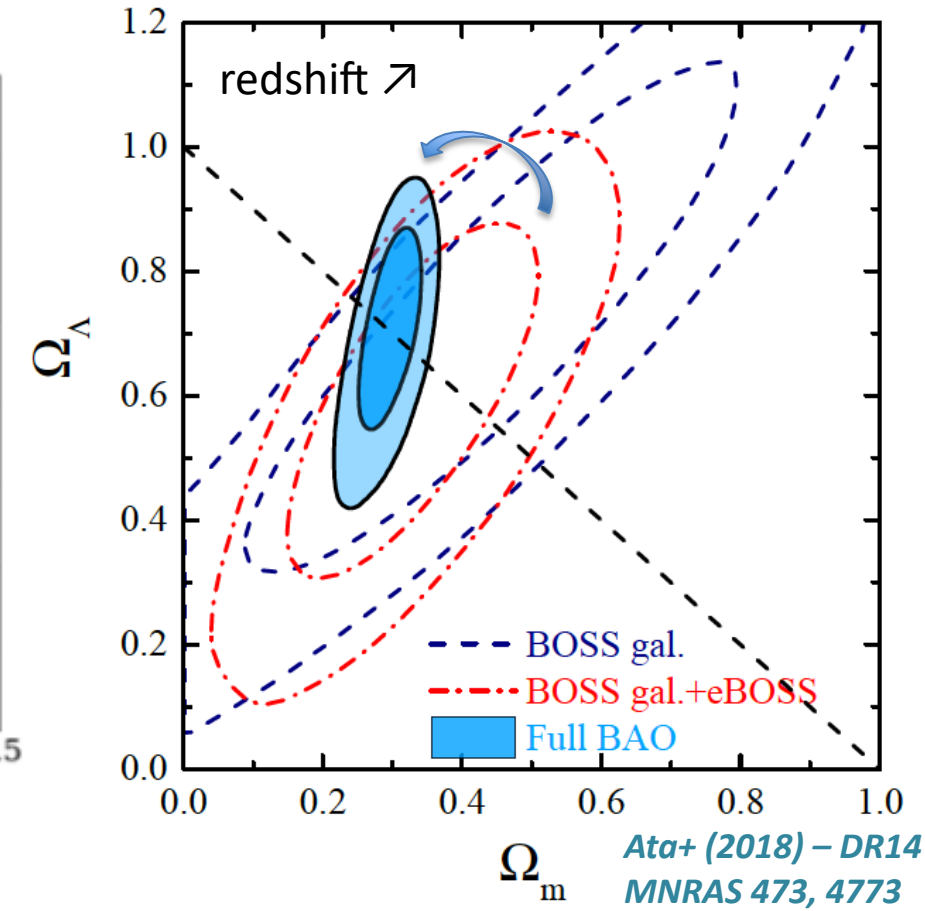
Large redshift-range from galaxies to Lyα

Evidence for phase of deceleration prior to present acceleration



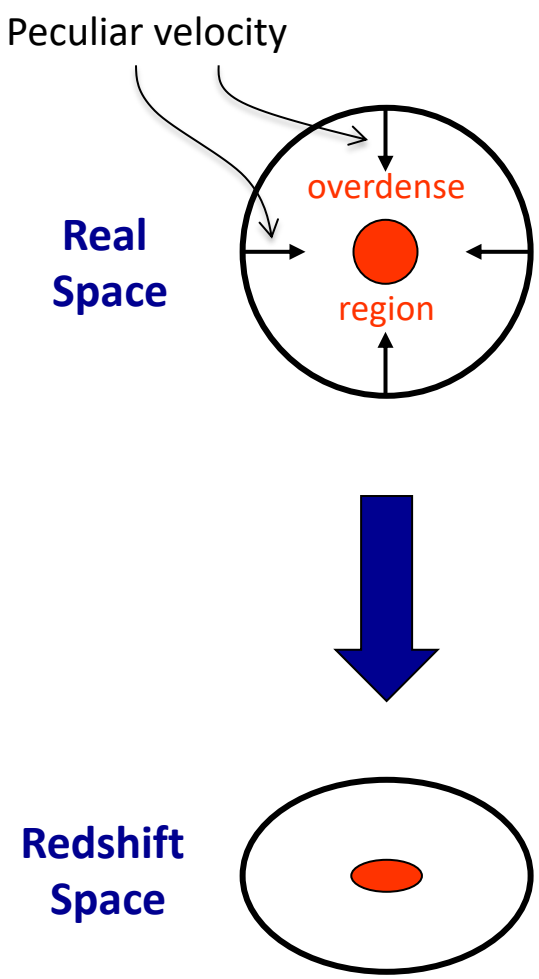
Bautista+ (2017)
BOSS DR12

Evidence for spatial flatness independently of CMB



Ata+ (2018) – DR14
MNRAS 473, 4773

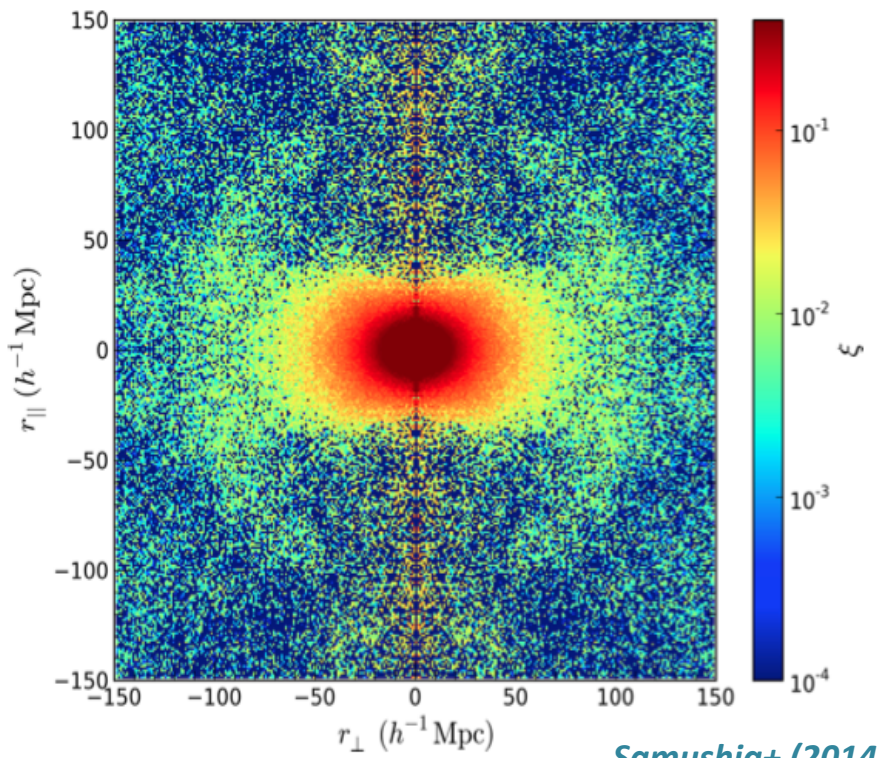
Redshift Space Distortion



Measure of gravitational growth

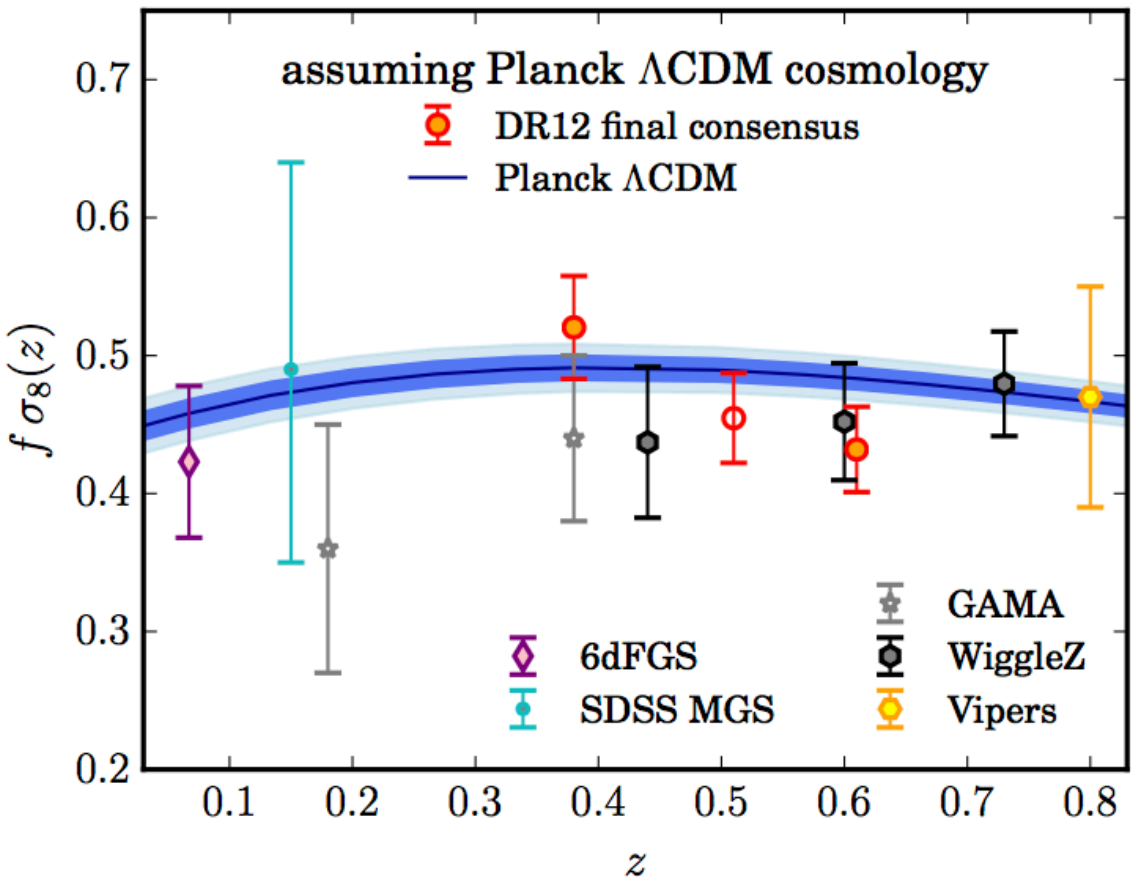
$$P_F(k) = b_F^2 \times \left[1 + \beta \cos(\theta)^2\right]^2 \times P_L(k)$$

$$\beta \rightarrow f\sigma_8$$



Samushia+ (2014)

Redshift Space Distortion



Alam+ (2016)
BOSS DR12

Amplitude of flattening depends on

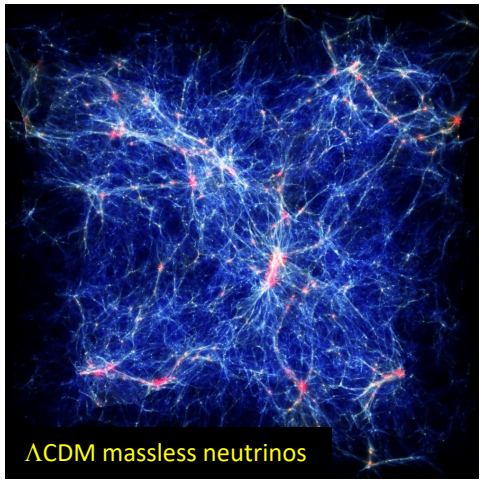
$f(z)\sigma_8(z) \propto dG/d\ln(a)$

with G linear growth rate

Test deviation from GR: $f\sigma_8 \rightarrow f\sigma_8\,[A_{f\sigma 8}+B_{f\sigma 8}.(z-z_p)]$

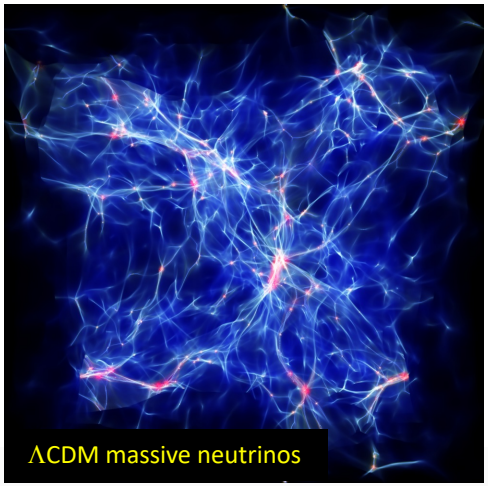
$A_{f\sigma 8} = 0.96 \pm 0.06$ and $B_{f\sigma 8} = -0.62 \pm 0.40$

Small-scale clustering and free streaming



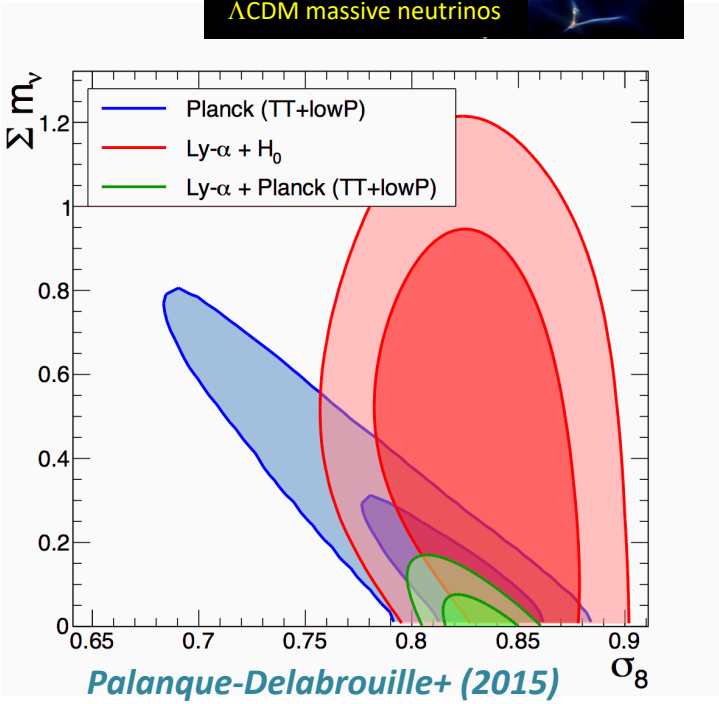
Free streaming of relativistic particles (hydrodynamical simulations)

Suppression of small scales



Suppression depends on particle mass

Constraint on Σmν
Constraint on mass of warm dark matter



Palanque-Delabrouille+ (2015)

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Nature of dark matter

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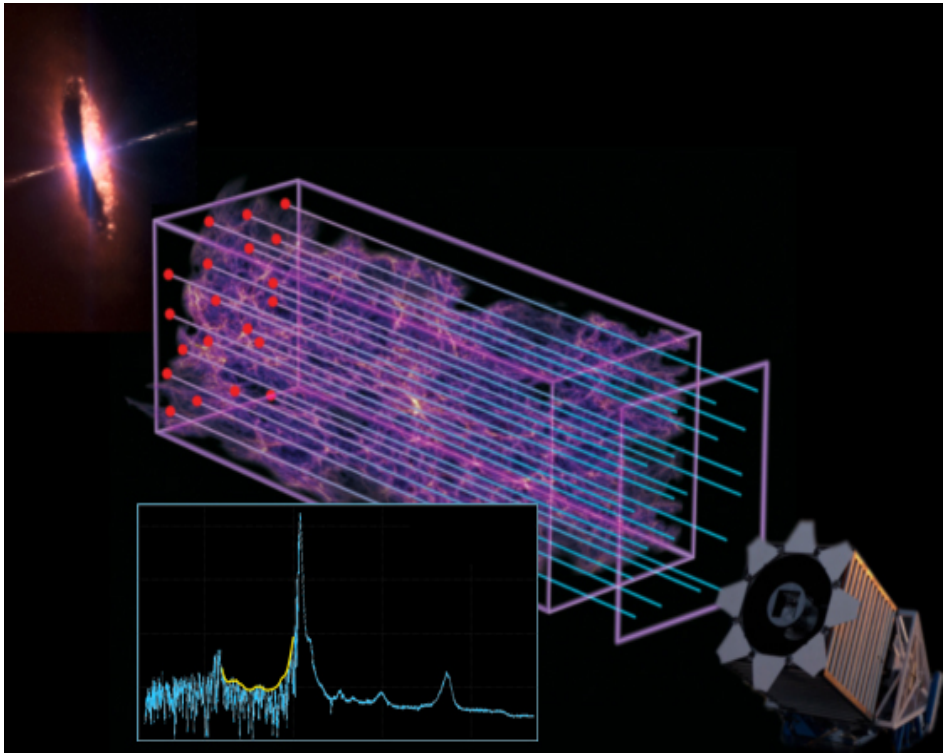
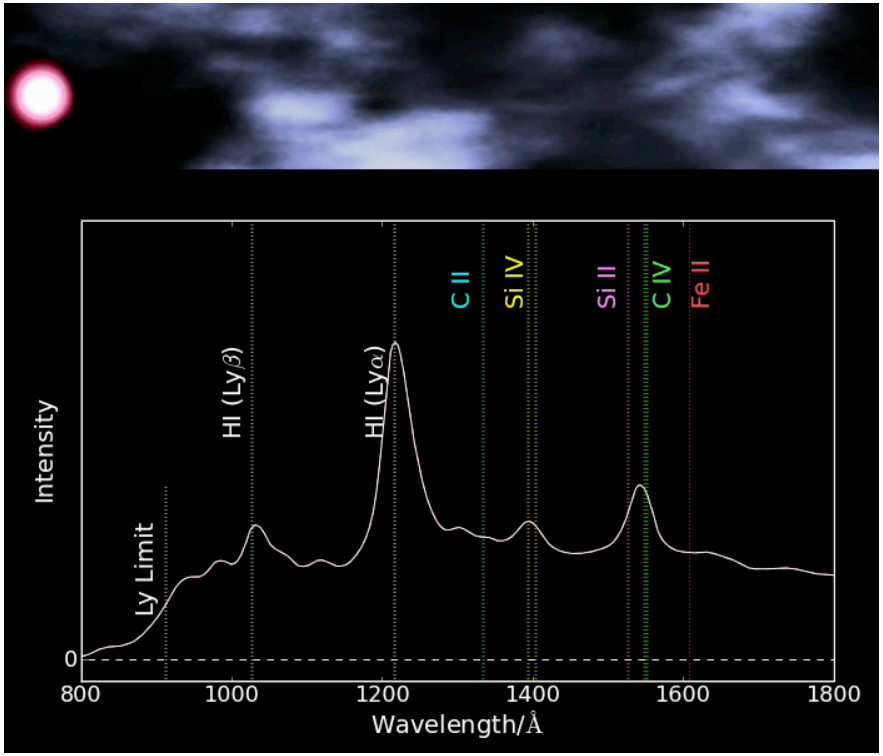
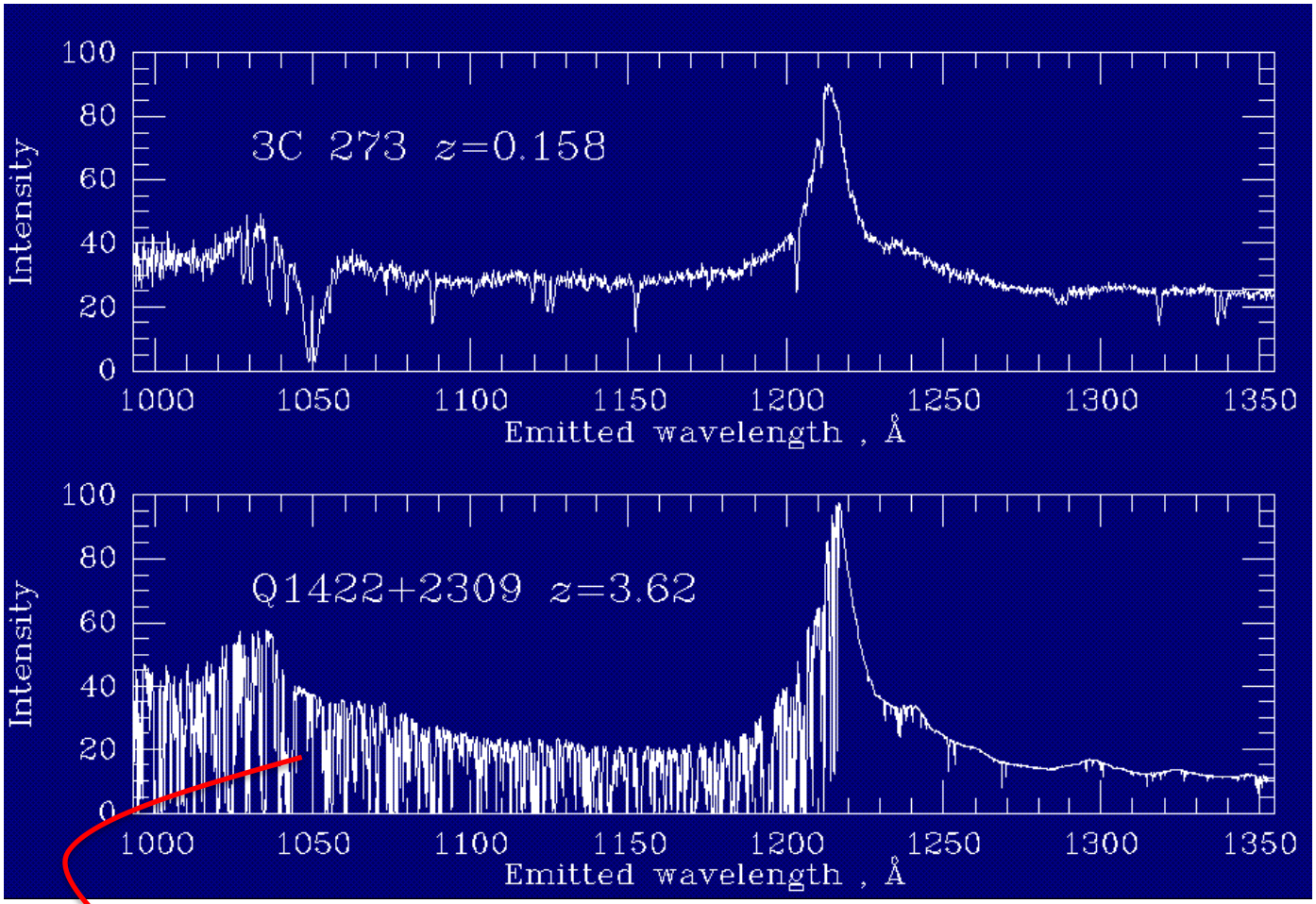
Lyα forest





- **Quasars visible to high redshift (z ~ 5)**
- **Absorption by neutral H (IGM) on light path**
- **IGM probes matter density**
- **Matter distribution on small scales (ν, ν_s)**
- **1D Power spectrum (along line of sight)**

Lyα forest



Small density of neutral H in local Universe (~fully ionized)

Higher density of neutral H in distant Universe (higher neutral H Density)

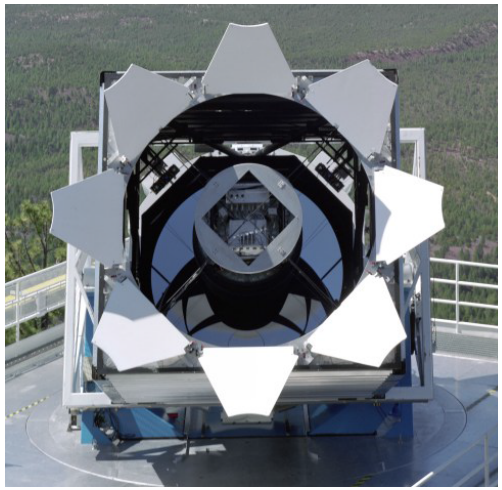
Transmitted flux fraction: $\delta = \frac{f - \langle f \rangle}{\langle f \rangle}$

Lyα forest 1D power spectrum

Selection of ~14 000 out of 60 000 z>2.1 BOSS QSOs

Detailed study of contributions from

- **detector (spectrograph resolution, noise)**
- **astrophysics (sky lines, correlation with other absorbers)**



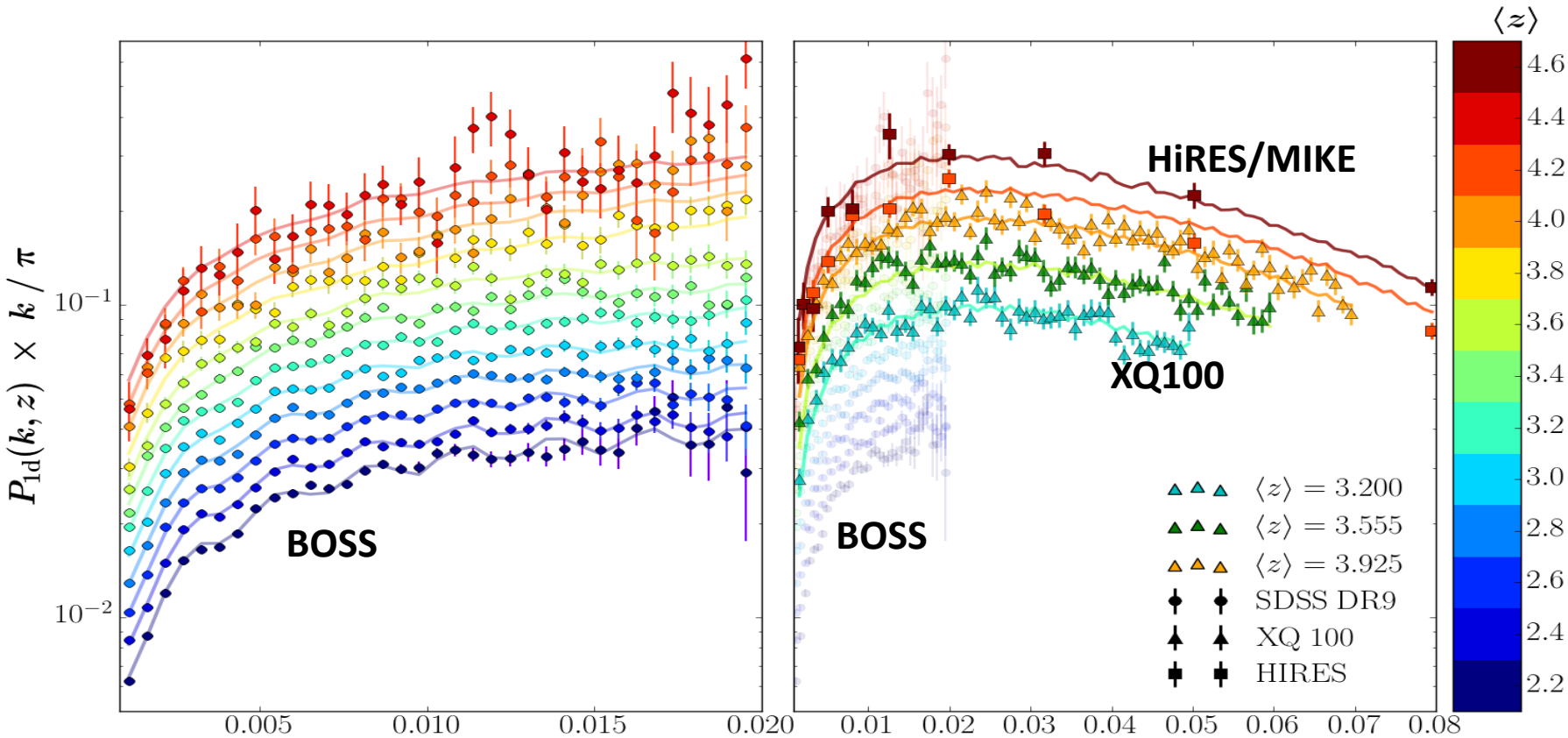
$$P_{Raw}(k) = [P_{Ly\alpha}(k) + P_{Lya\text{-}SiIII}(k) + P_{metals}(k)] \times W^2(k) + P_{Noise}(k)$$

Lyα forest 1D power spectrum

BOSS
NPD, Yeche+ (2013)
12 bins z=2.2 to 4.4

XQ100
Yeche, NPD+ (2017)
Irsic, Viel+ (2017)
z=3.2, 3.6, 3.9

HiRES/MIKE
Viel, Becker+ (2013)
z=4.2, 4.6, (5.4)



Large scales Small scales

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Why ν's have mass

Neutrino oscillations ⇒ ν's are massive

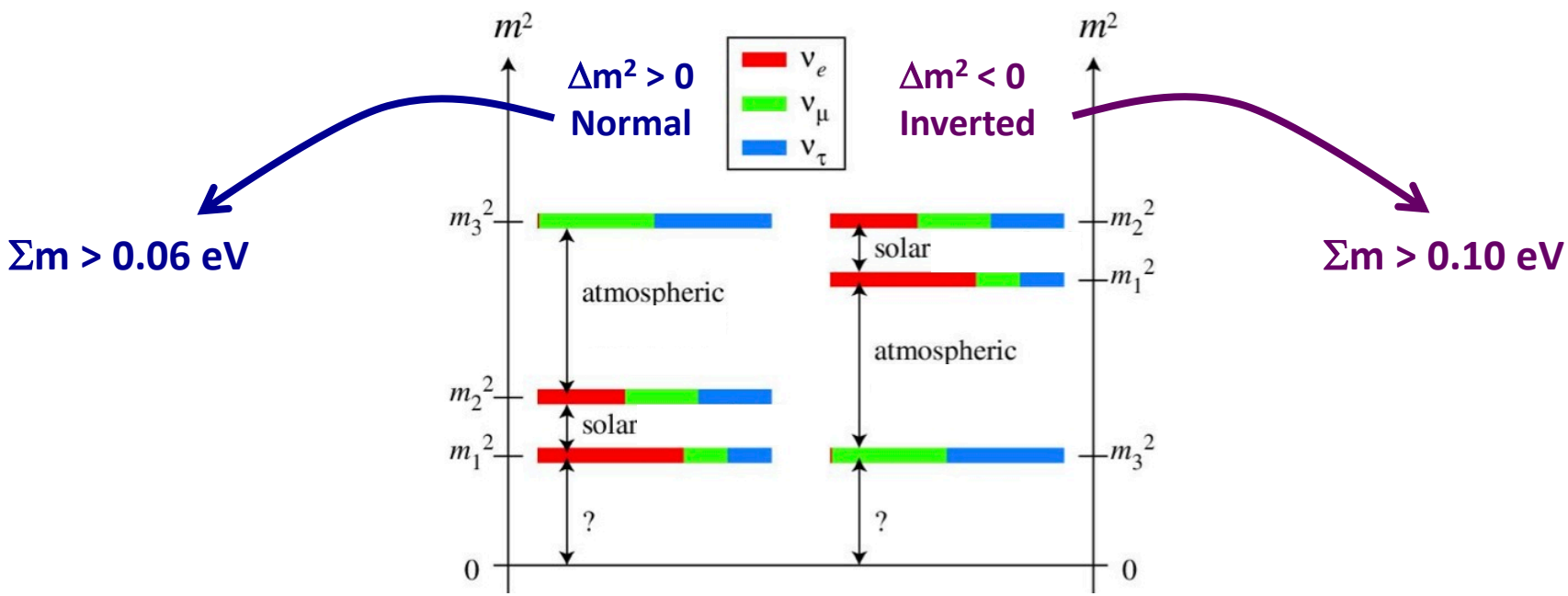
Solar $\delta m^2 \sim 7.5\ 10^{-5}\ eV^2$

Atmospheric $\Delta m^2 \sim 2.4\ 10^{-3}\ eV^2$

Direct m_ν detection from Tritium β decay

$m_e < 2$ eV

→ $0.06\ eV < \Sigma m_\nu < 6\ eV$



Why ν's have mass

primordial
thermal history

Big Bang
nucleosynthesis

In Universe, $\Sigma n_\nu \sim n_\gamma \sim 2.\ 10^9\ n_p$ (considering all 3 neutrino specie

$\Longrightarrow$ even for $m_\nu \sim 0.5$ eV $= 5.\ 10^{-10}\ m_p$

total ν mass ($\Sigma n_\nu m_\nu$) of order of total stellar mass ($n_p m_p$) !

$\Longrightarrow$ **Can cosmology help?**

m_ν & large-scale structures

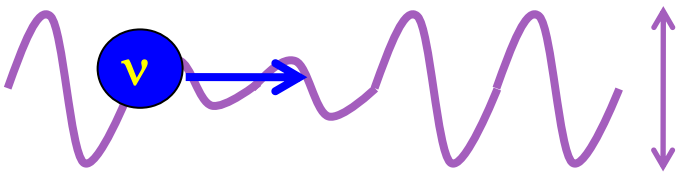
Neutrinos are relativistic early on
Neutrinos "free stream" at v=c until t_{nr} (actually once they have decoupled)

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

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

  Strong suppression over **short** range

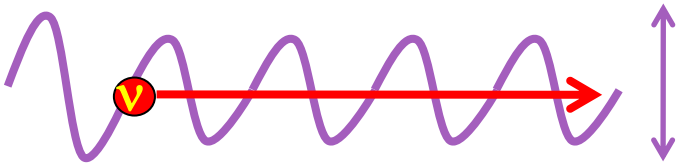
  $m_\nu \sim$ keV $\Longrightarrow$ size of dwarf galaxy perturbations smoothed out



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

  Weak suppression over **long** range

  $m_\nu \sim$ eV $\Longrightarrow$ size of galaxy cluster perturbations smoothed out



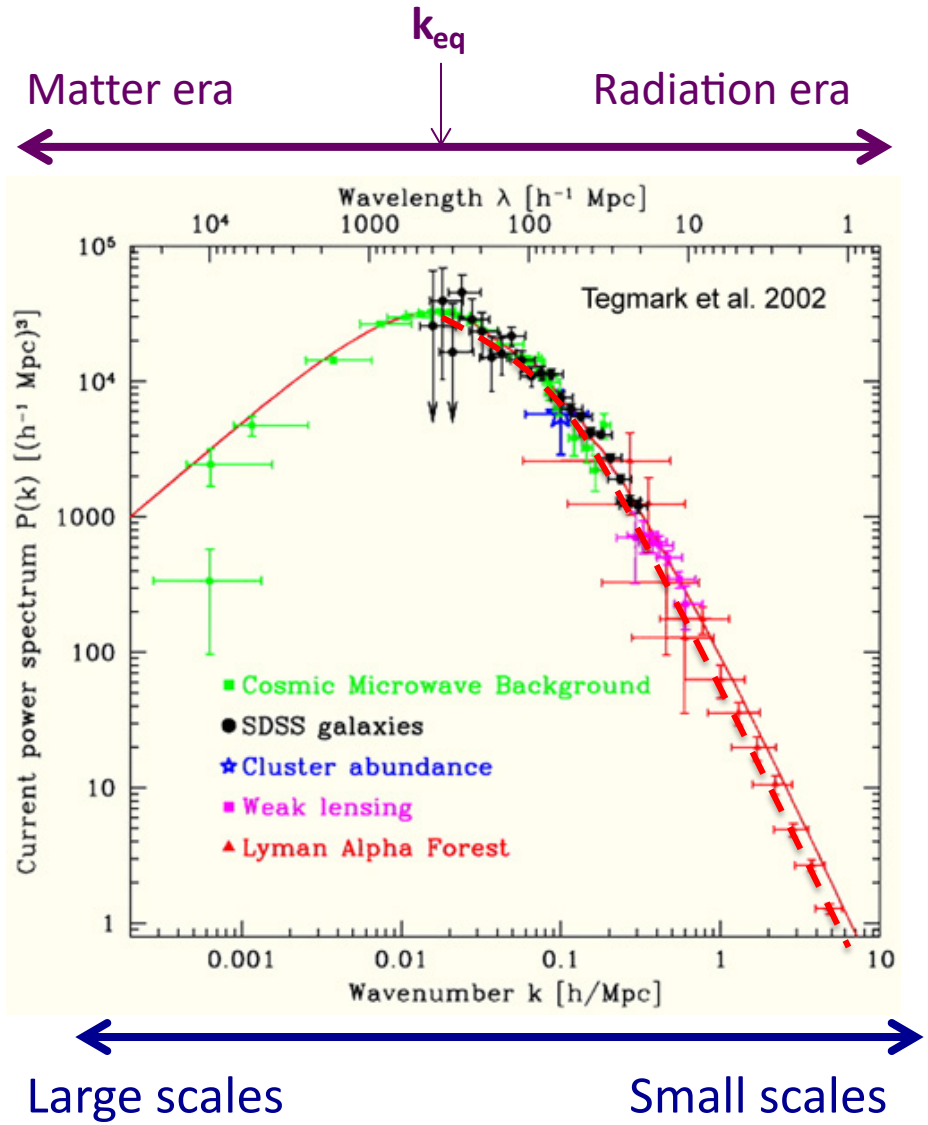
Impact of m_ν on large-scale structures

Matter power spectrum

Real-space (Mpc) ⟷ k-space (Mpc^{-1})

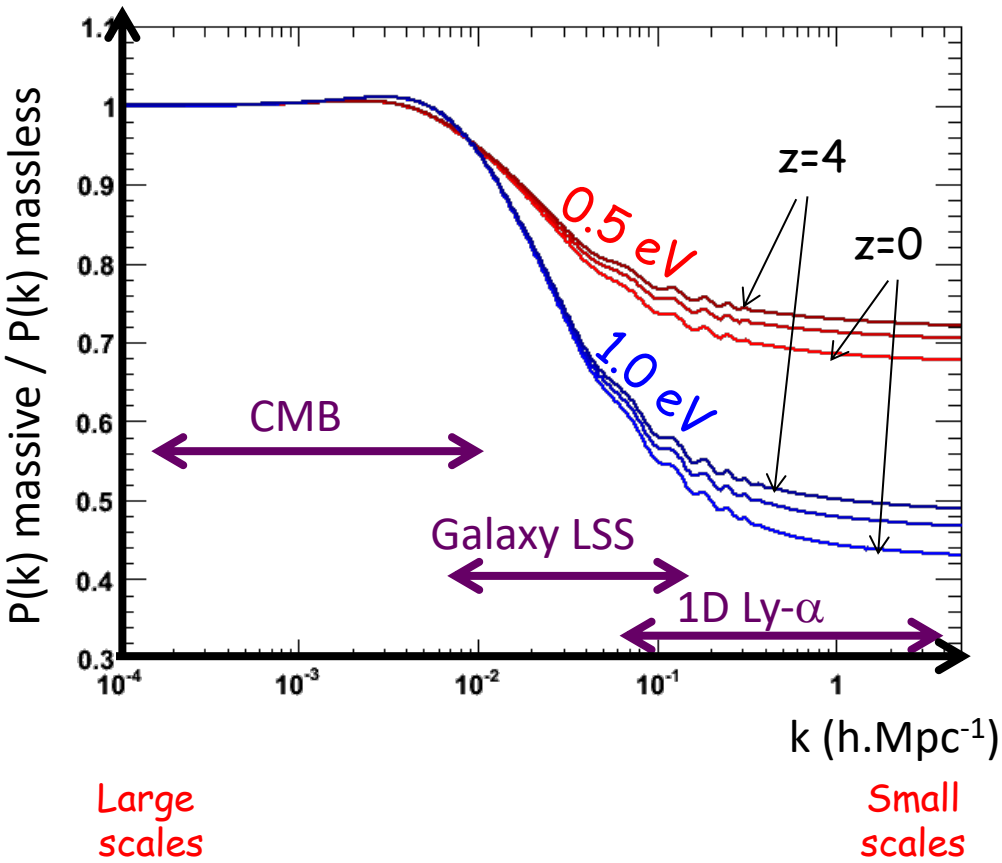
Causality horizon ↗ with time
- Early events ⟷ small scales
- Late events ⟷ large scales

Free-streaming
of relativistic ν's further
suppresses power on small scales



Neutrinos and large-scale structures

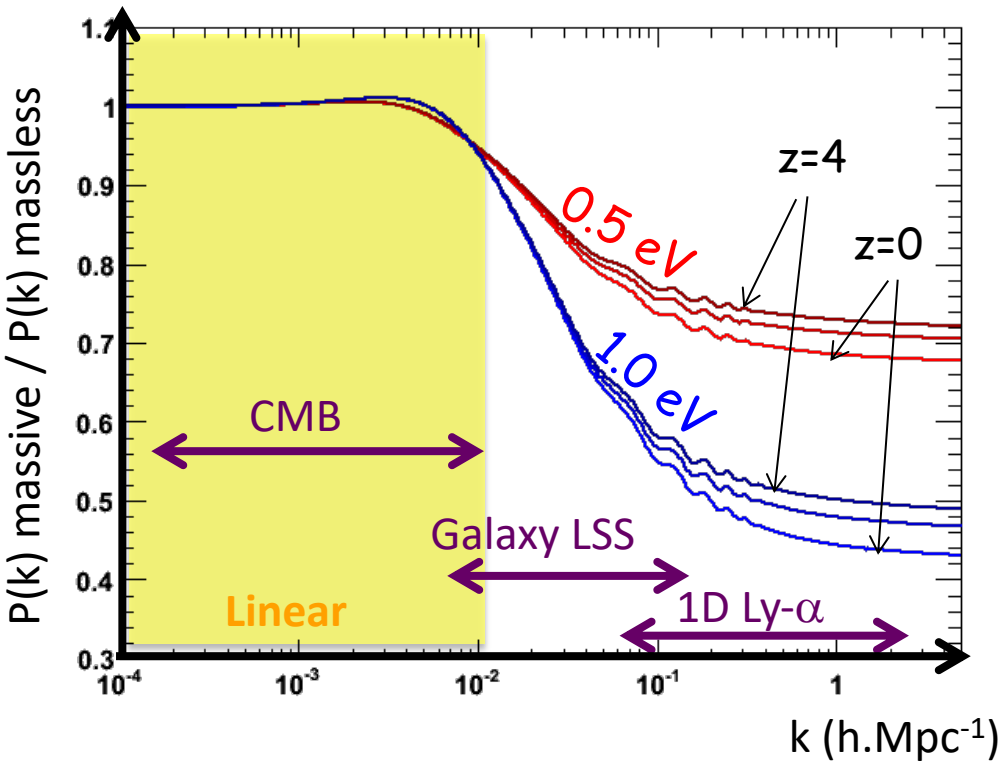
Different probes ⟺ different scales



- Suppression factor ⟺ $\Sigma m\nu$
- 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



Large scales

Small scales

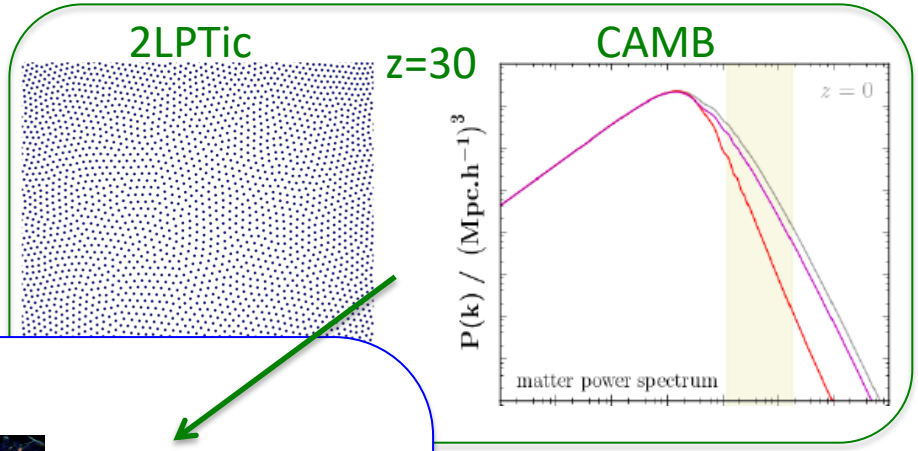
- Suppression factor ⇔ $\Sigma m\nu$
- Suppression is z-dependent
- **Ly-α**
  - Small scales, max effect ➕
  - Large z-range [2.1 ; 4.5] ➕
  - Non-linear regime, flux (not mass) P(k) ⇒ Hydro simulations ➖

Hydrodynamical simulations

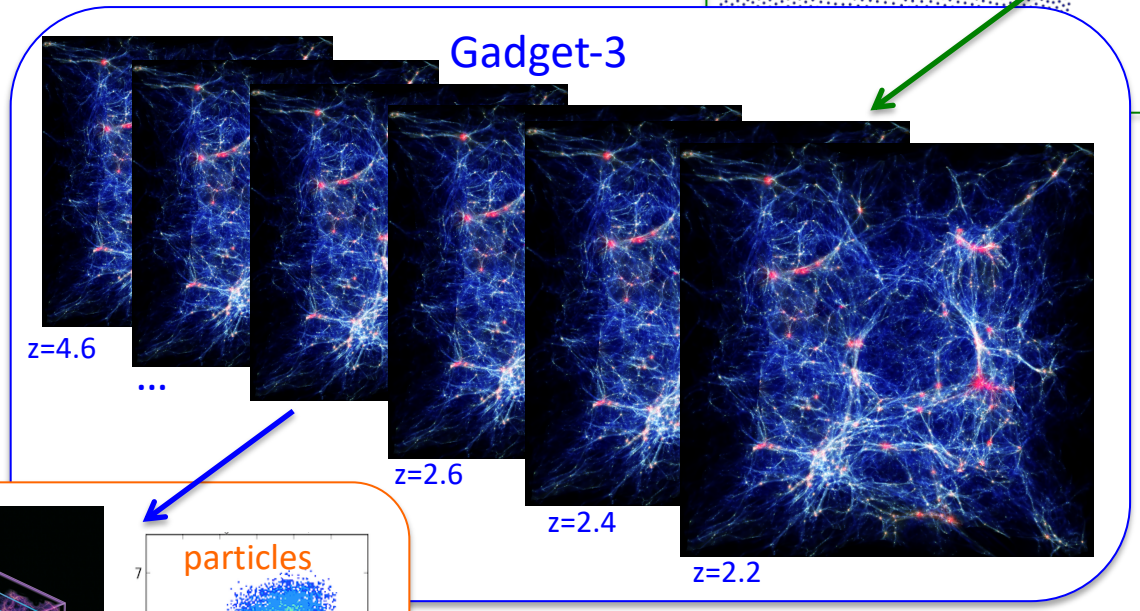
(100 h^{-1}Mpc)^3 with *3072*^{3} particles/species

McDonald (2003) splicing approach

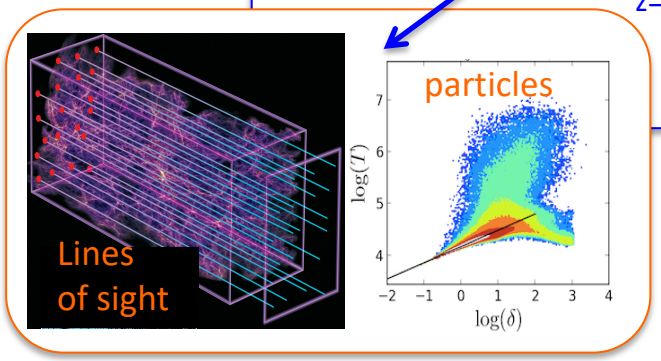
- dark matter
- baryons
- (degenerate-mass) neutrinos



Initial conditions



N-body + SPH simulation



Ly-α power spectrum

Borde, NPD et al. (2014)

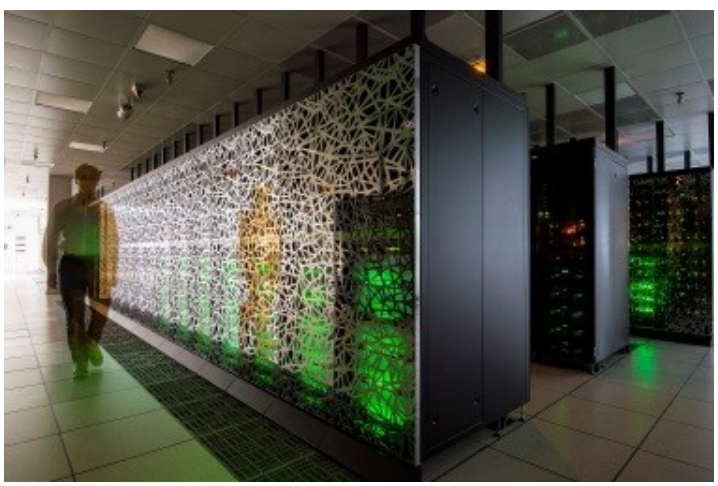
Rossi, NPD et al. (2014)

Hydrodynamical simulations

Grid of simulations

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

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



TGCC Bruyères-le-châtel

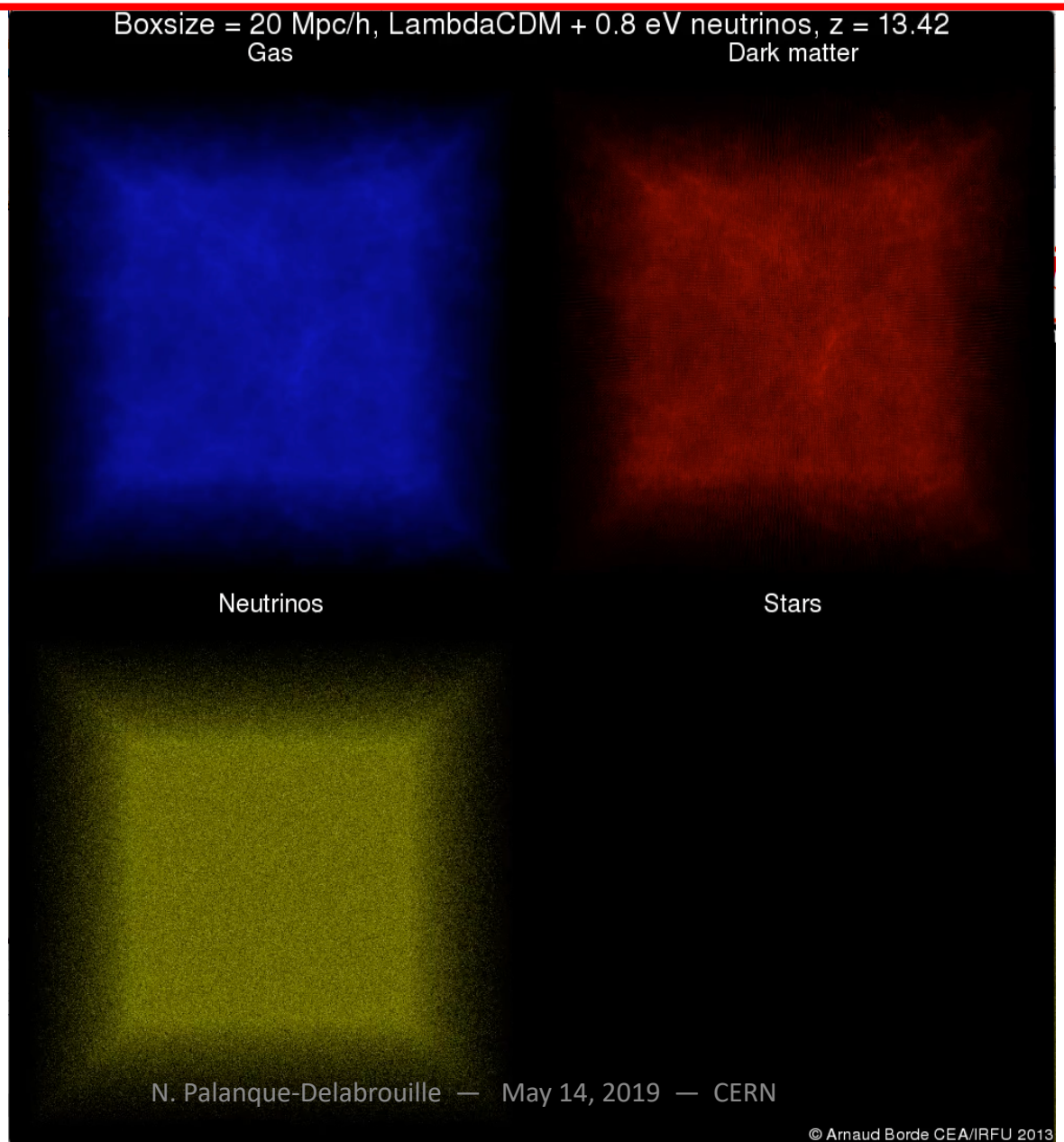
	parameter	central	range
Cosmology	keV / m_X	0.0	+0.2 +0.4
	$\Sigma m_\nu / eV$	0.0	+0.4 +0.8
	h	0.675	±0.05
	Ω_M	0.31	±0.05
	σ_8	0.83	±0.05
	n_s	0.96	±0.05
	$dn_s / d\ln k$	0.00	±0.04
	z_{reio}	12	±4
	N_{eff}	3.046	±1
Intergalactic Medium	$T_0^{z=3} / K$	14,000	±7,000
	$\gamma^{z=3}$	1.3	±0.3
Optical Depth	A^τ	0.0025	±0.0020
	η^τ	3.7	±0.4

Hydrodynamical simulations

z = 15 → 0

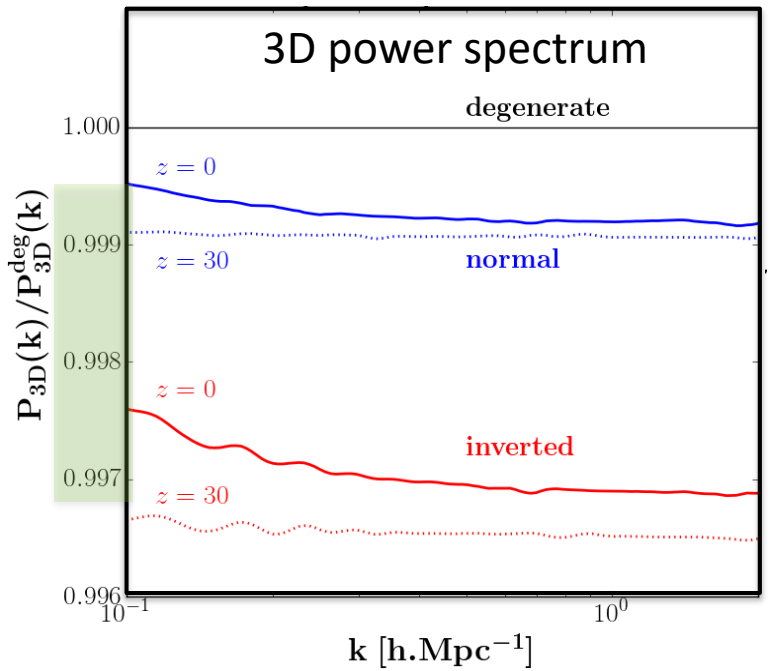
3 species
- Baryons
- Dark matter
- Neutrinos

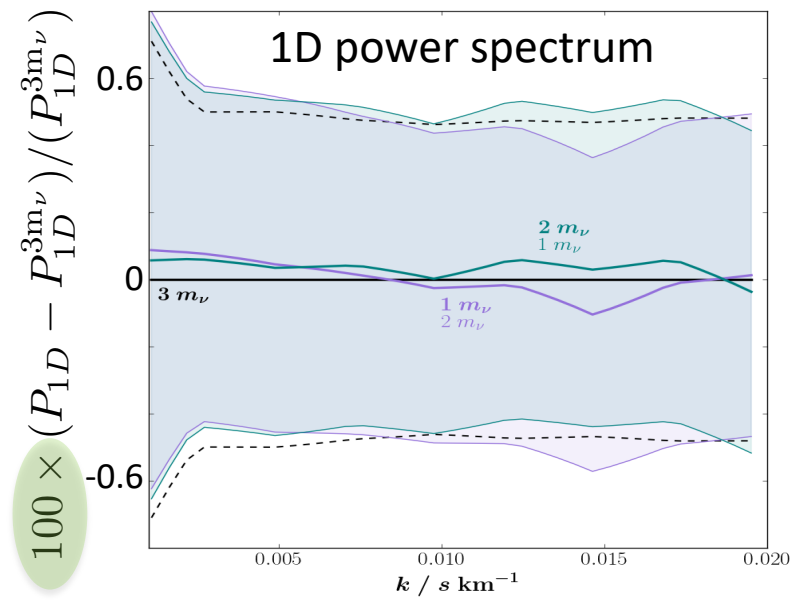
Stars formed from baryons



@ A. Borde (CEA-Saclay)

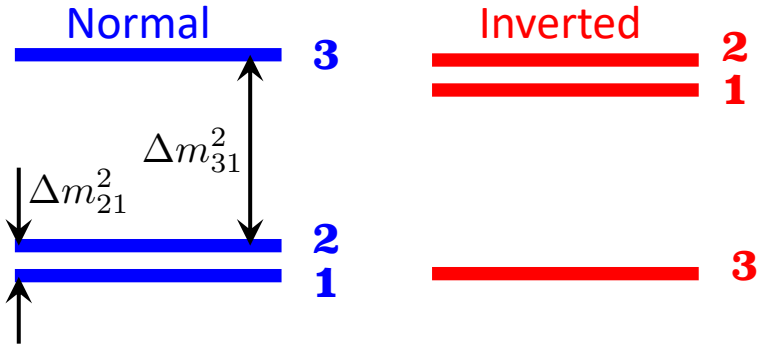
Neutrino mass (Σm) or masses (m_i)?





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

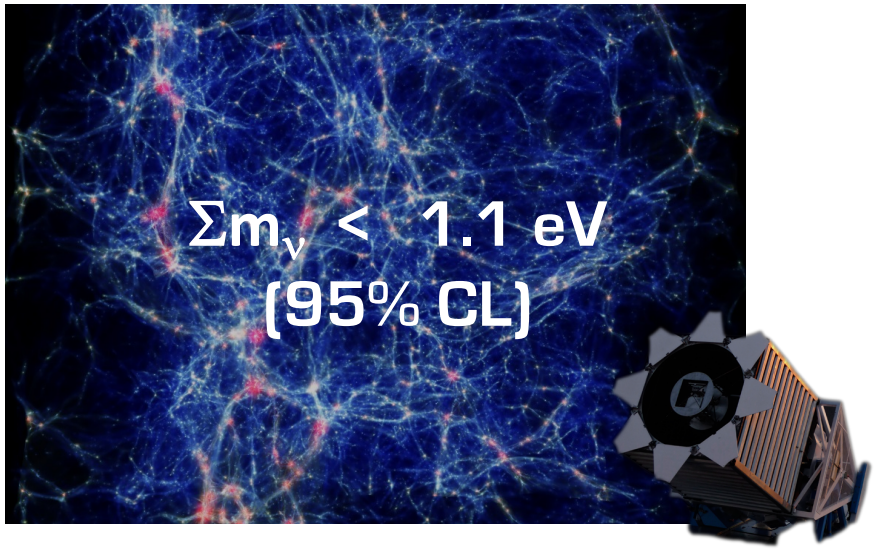
Σm = 0.10 eV



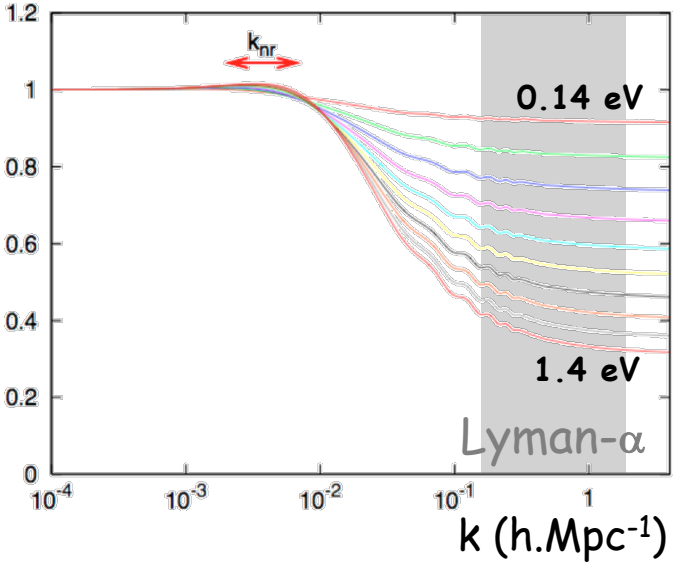
NPD, Yeche, Baur+ (2015)

'Exclusively' a Σm effect

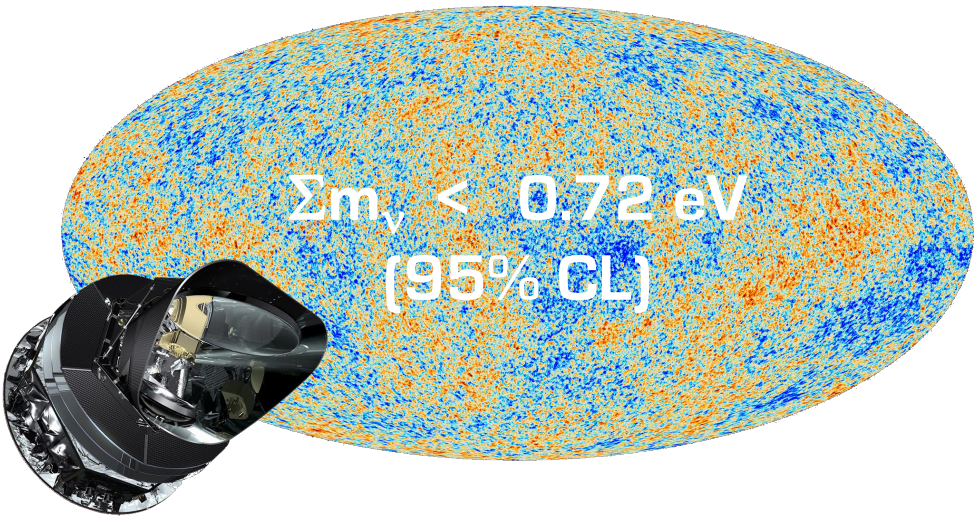
M_ν constraint

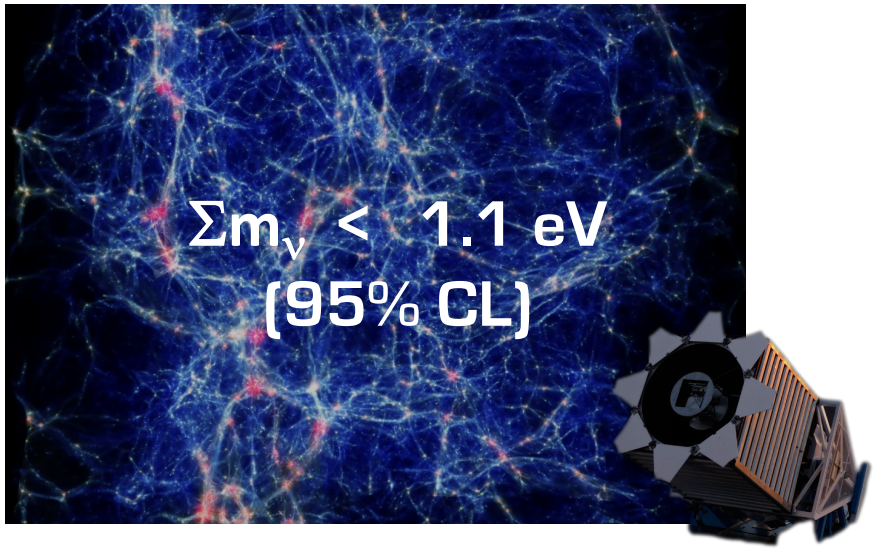


P(k) massive / P(k) massless

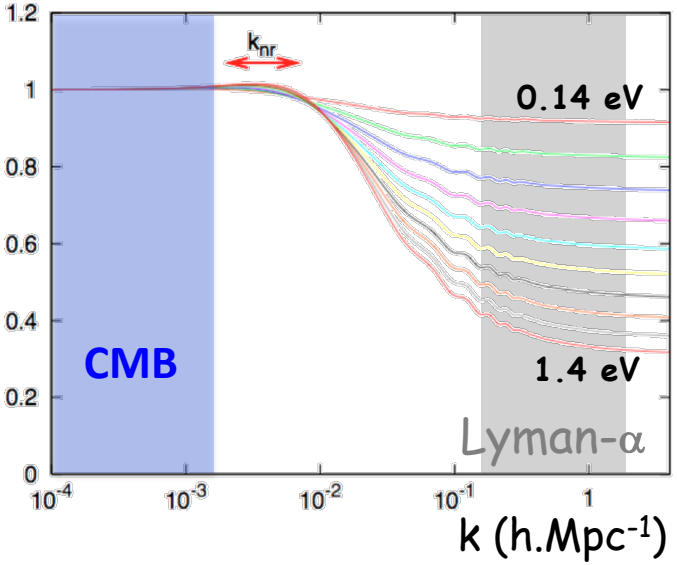


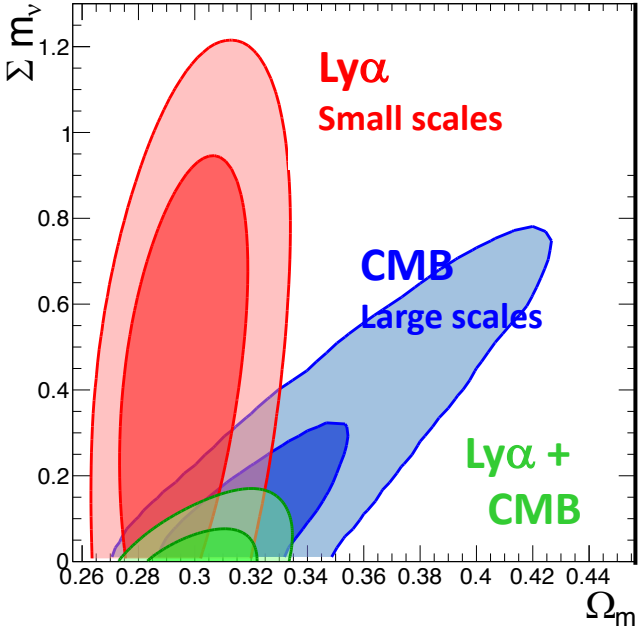
$M\nu$ constraint





P(k) massive / P(k) massless





$\Sigma m_\nu < 0.12$ eV

NPD, Yèche, Borde et al. (2015)
NPD, Yèche, Baur, et al. (2015)

Neutrinos & Warm Dark Matter from a cosmology perspective

SDSS: a clustering saga

BOSS & Lyman-α

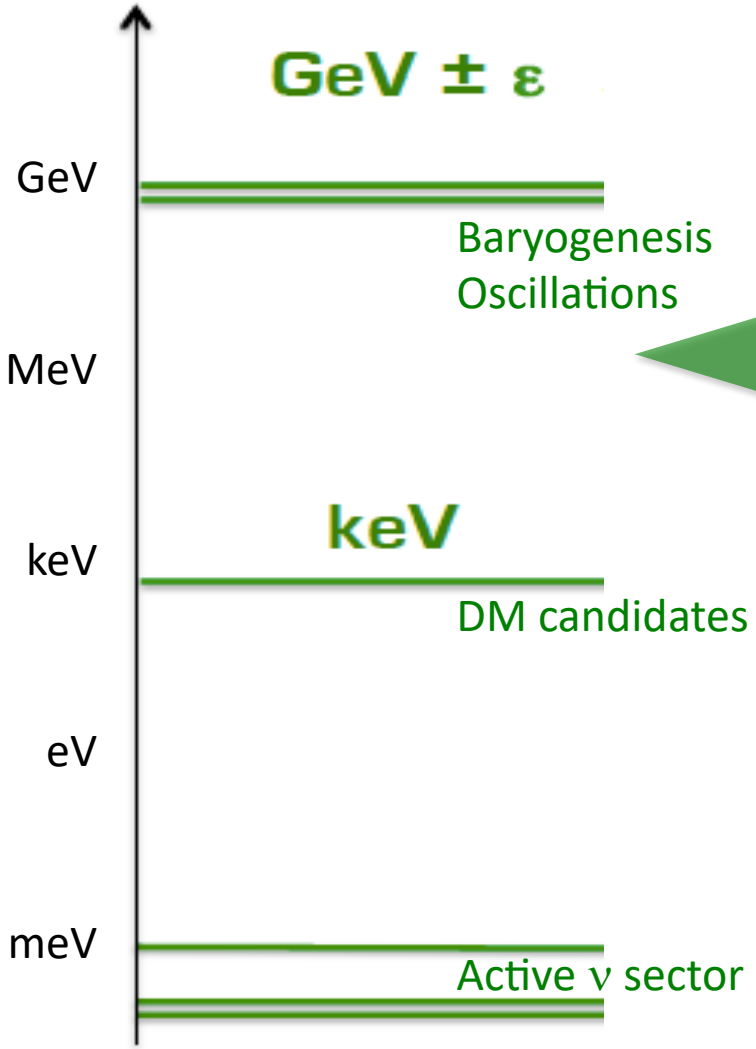
Constraining Σm_ν

Nature of dark matter

N. Palanque-Delabrouille
CEA-Saclay

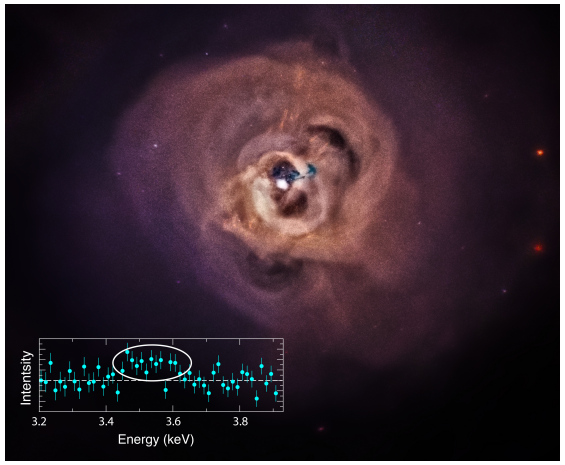
Sterile neutrino sector

Beyond the Standard Model to explain m_ν



Sterile ν sector
ν Minimal Extension (νMSM)
Laine & Shaposhnikov

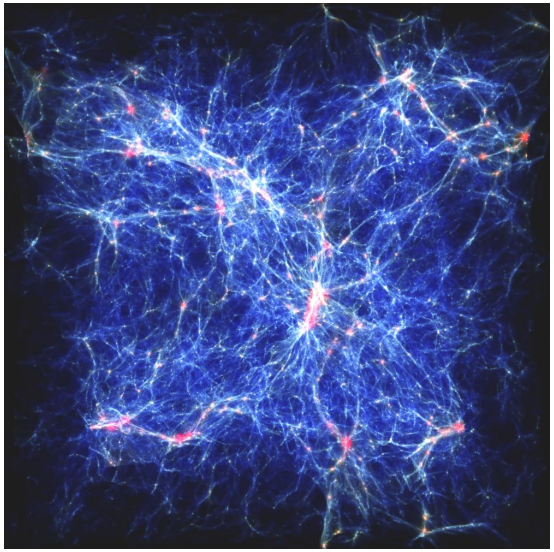
Perseus cluster
Andromeda galaxy
XMM clusters

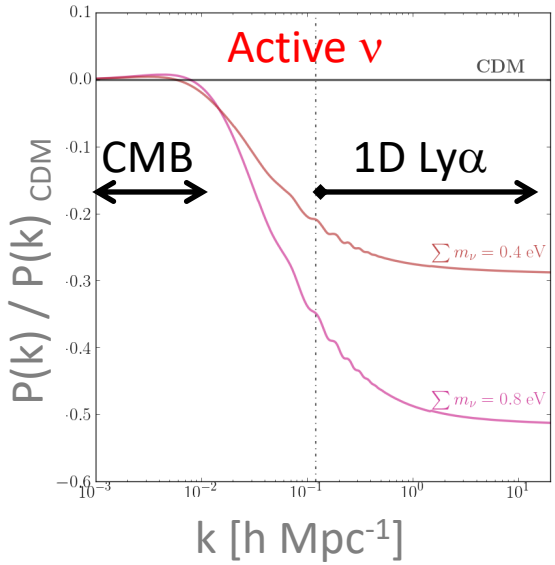


3.5 keV line (XMM): decay of 7 keV ν_s ?

Bulbul++ 2014, Boyarsky++ 2014, Cappelluti++ 2017

Lyman-α forest and cosmology

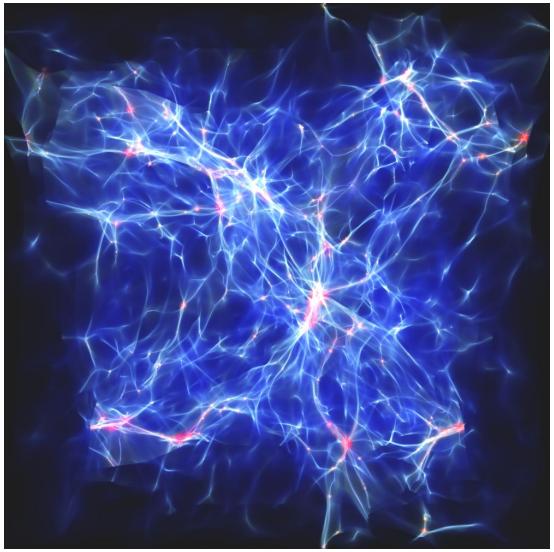


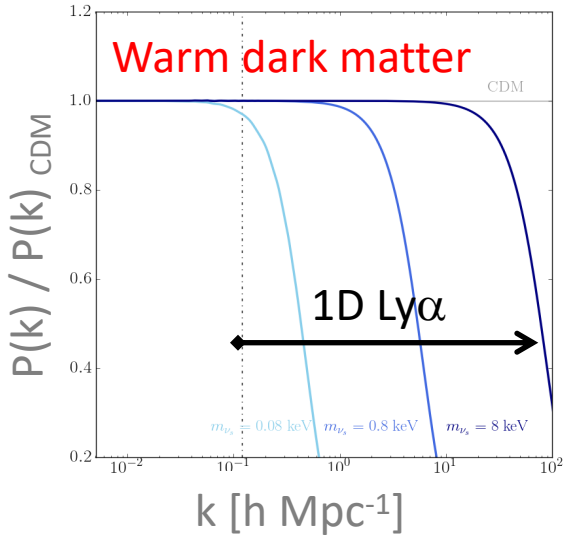


Active neutrinos

- CMB vs. Lyα P(k) comparison
- Greater impact as m_ν increases

⟹ Upper limit on m_ν





Warm dark matter

- Power cut-off on small scales
- Greater impact as m_{WDM} decreases

⟹ Lower limit on m_{WDM}

Ly-α forest & WDM

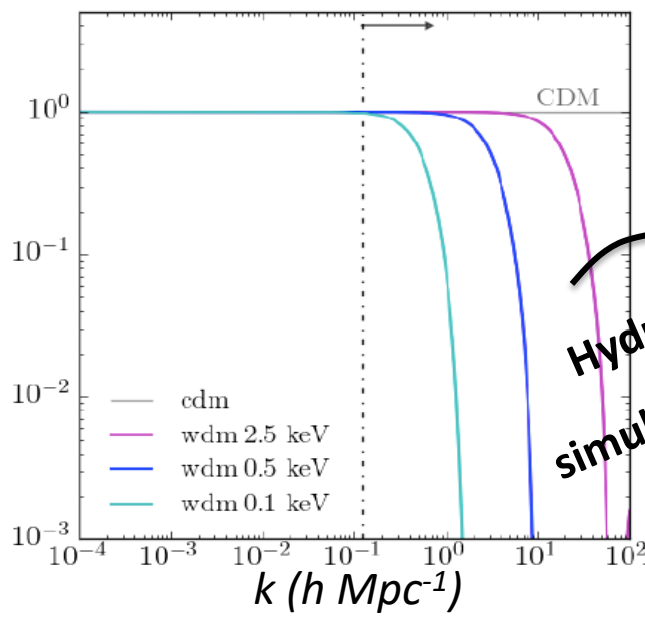
$P_{WDM}(k) / P_{CDM}(k)$

$P_{Ly\alpha}(k) \,.\, k / \pi$

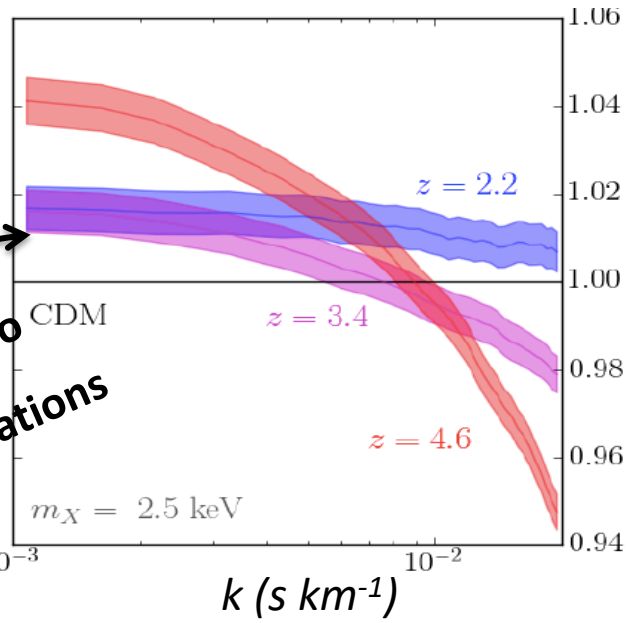
Matter power spectrum

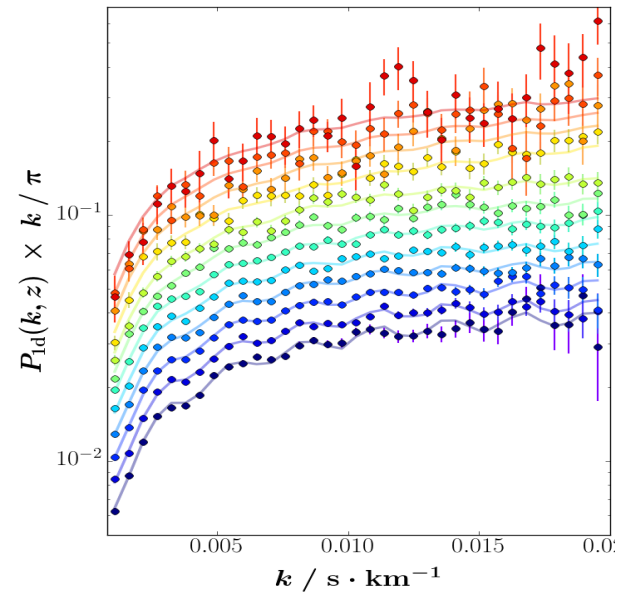
Lyα flux power spectrum

Fit on data



Hydro simulations





High-z and high-k bins most constraining
(more sensitive to linear regime cutoff)

Warm Dark Matter: thermal relic & NRP ν_s

High-z and high-resolution bins have large constraining power
(closer to linear case, more sensitive to sharp cutoff)

Data Set	BOSS z<4.1	BOSS z<4.5	BOSS + XQ100 + HIRES/MIKE
Lower bound on m_X (keV)	2.97	4.1	4.65 (z≤4.6) [1] / 5.3 (z≤5.4) [2]
Lower bound on m_s (keV)	16.1	**24.4**	28.8 (z≤4.6) [1] / 34.1 (z≤5.4) [2]

Baur, NPD+ (2016)

[1] **Yèche, NPD+ (2017)**
[2] **Irsic, Viel+ (2017)**

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Baur, NPD+ (2016)

More conservative

More prone to systematics
(thermal history of IGM)

Among the strongest bound to date

In combination with X-ray data (m_s < 4 keV),
excludes non-resonantly-produced sterile neutrinos

[1] **Yèche, NPD+ (2017)**
[2] **Irsic, Viel+ (2017)**

Sterile neutrinos: a more general scenario

Resonantly produced sterile neutrinos *(Shi & Fuller, 1999)*

Lepton asymmetry

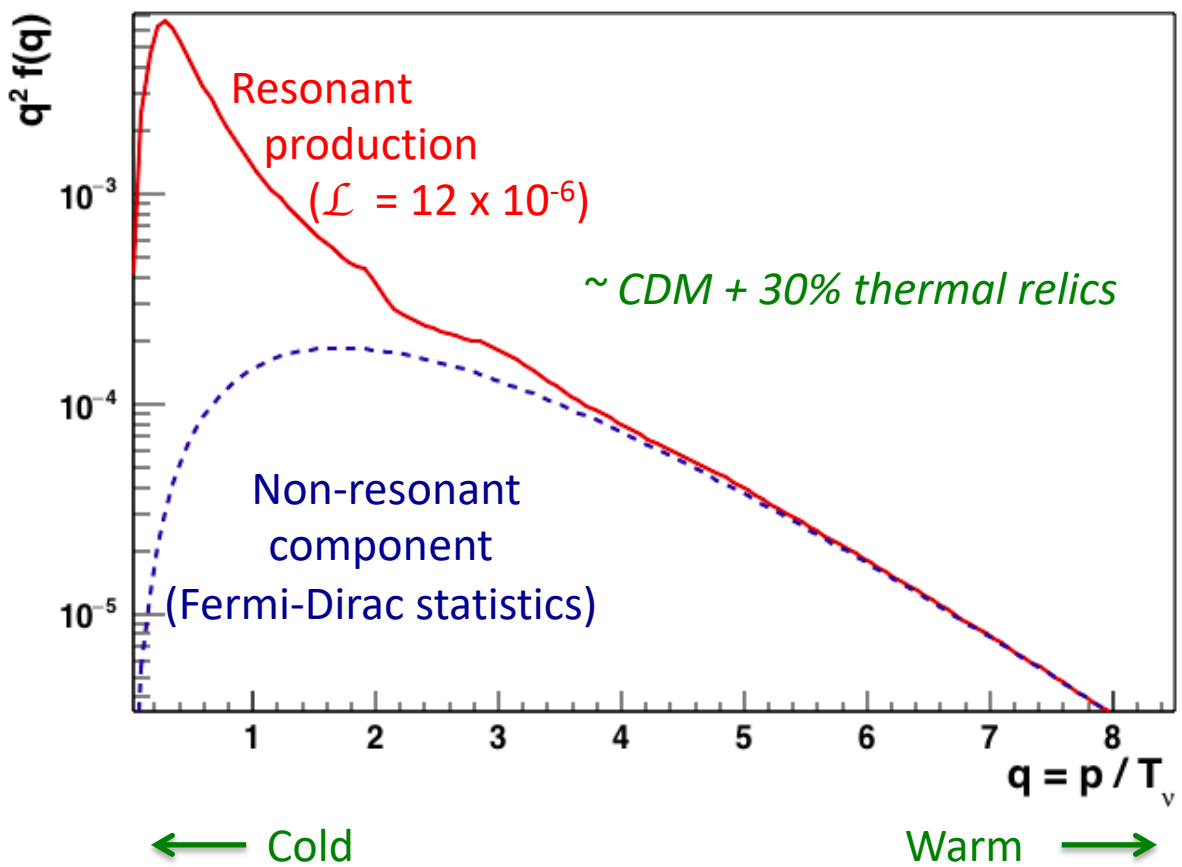
$$\mathcal{L} = \frac{|n_\nu - n_{\bar{\nu}}|}{s}$$

Enhanced oscillations

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

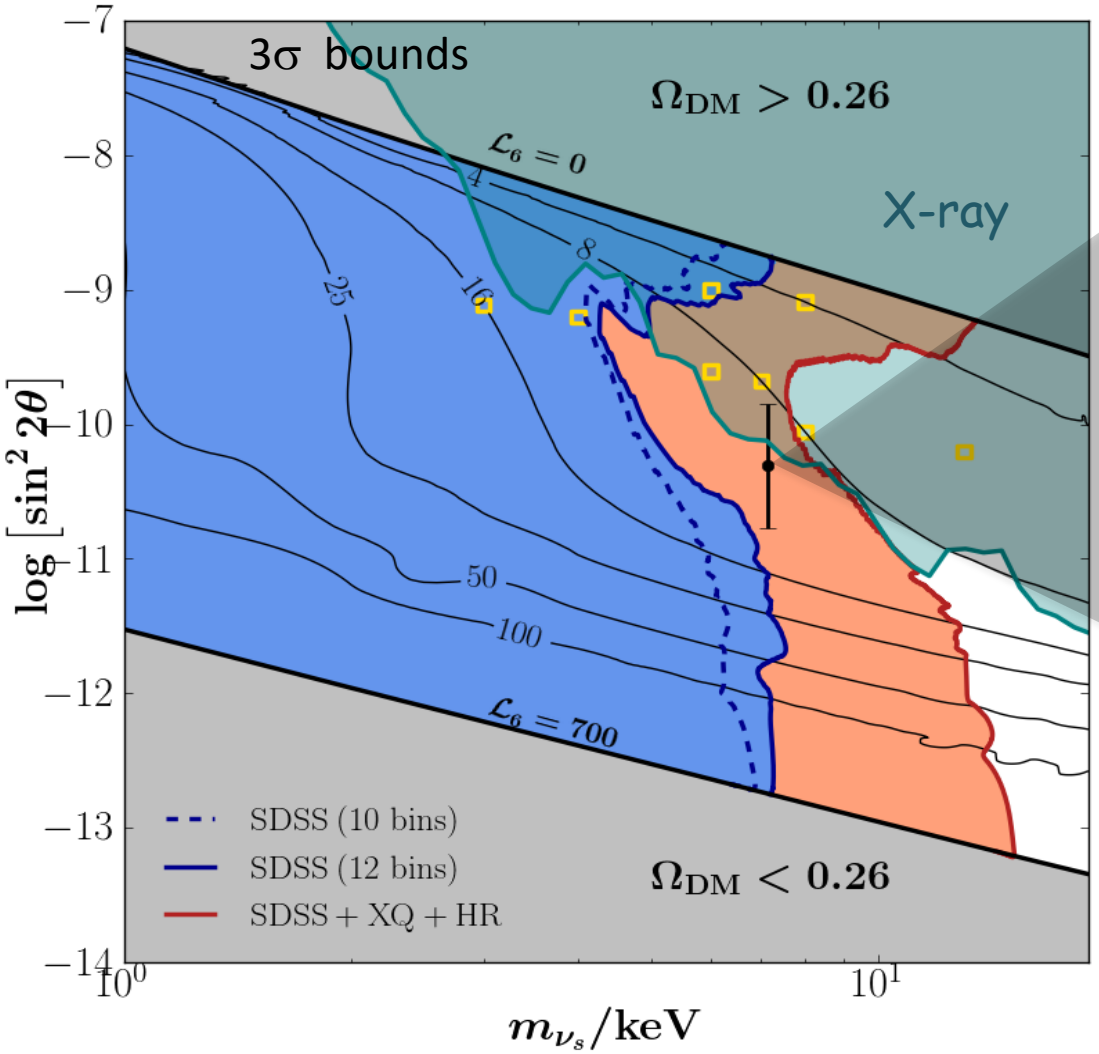
Non-thermal distribution
<u>Colder dark matter than non-resonant production</u>

m_s = 4 keV Phase-space Distribution



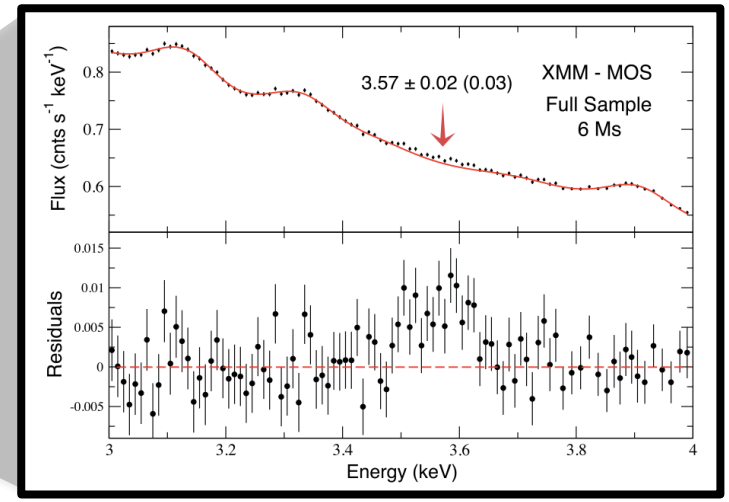
← Cold Warm →

Resonantly-produced sterile neutrinos



Bulbul et al. 2014, ApJ 789 13

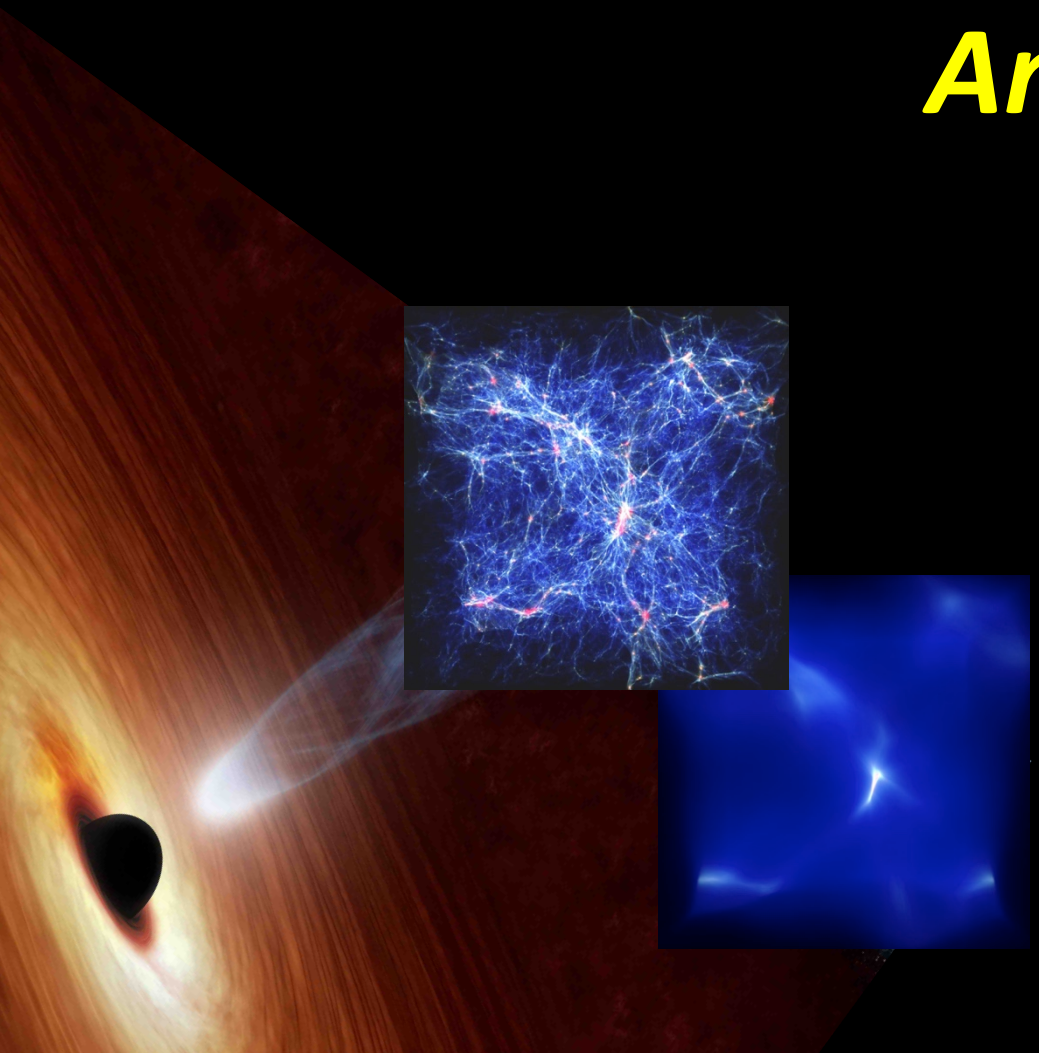
Boyarsky et al. 2014, PRL 113, 251301



Baur, NPD+ (2017)

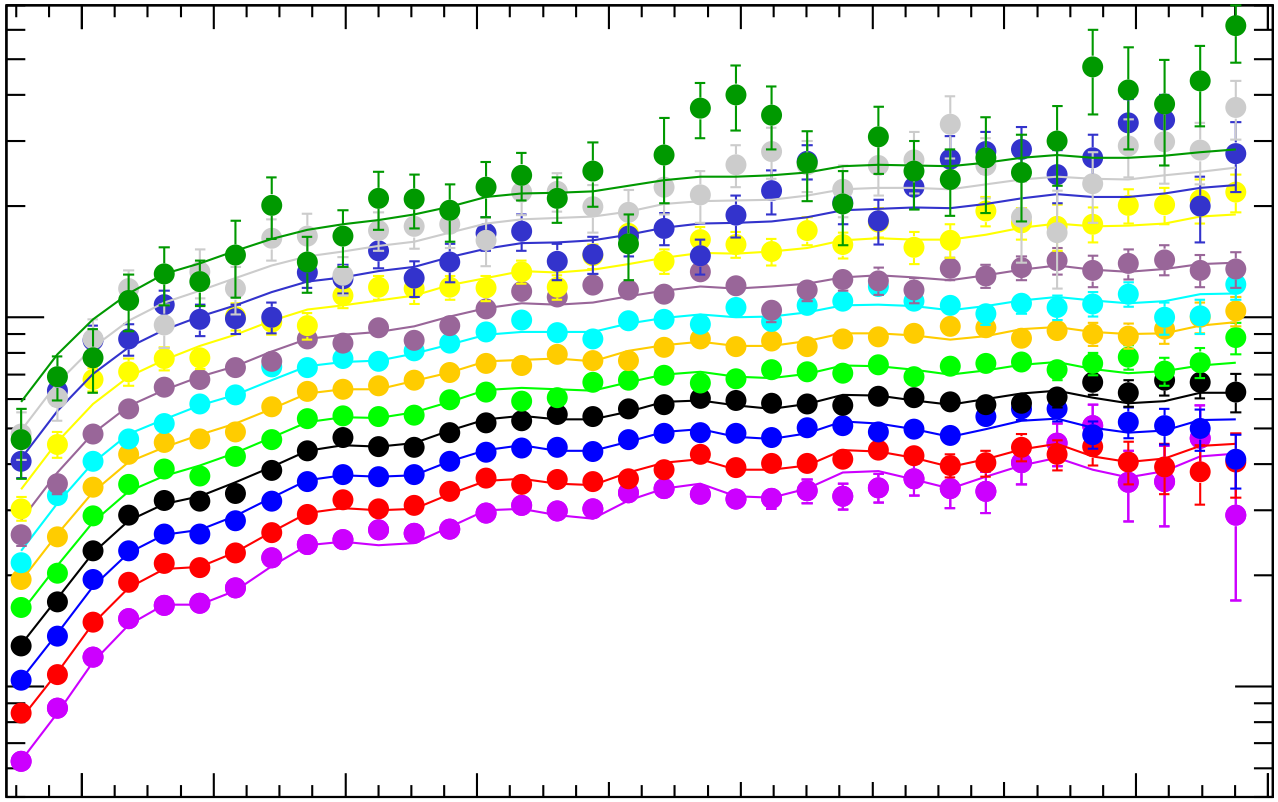
Lyman-α data in tension with 7 keV sterile ν (X-ray data)

And beyond?



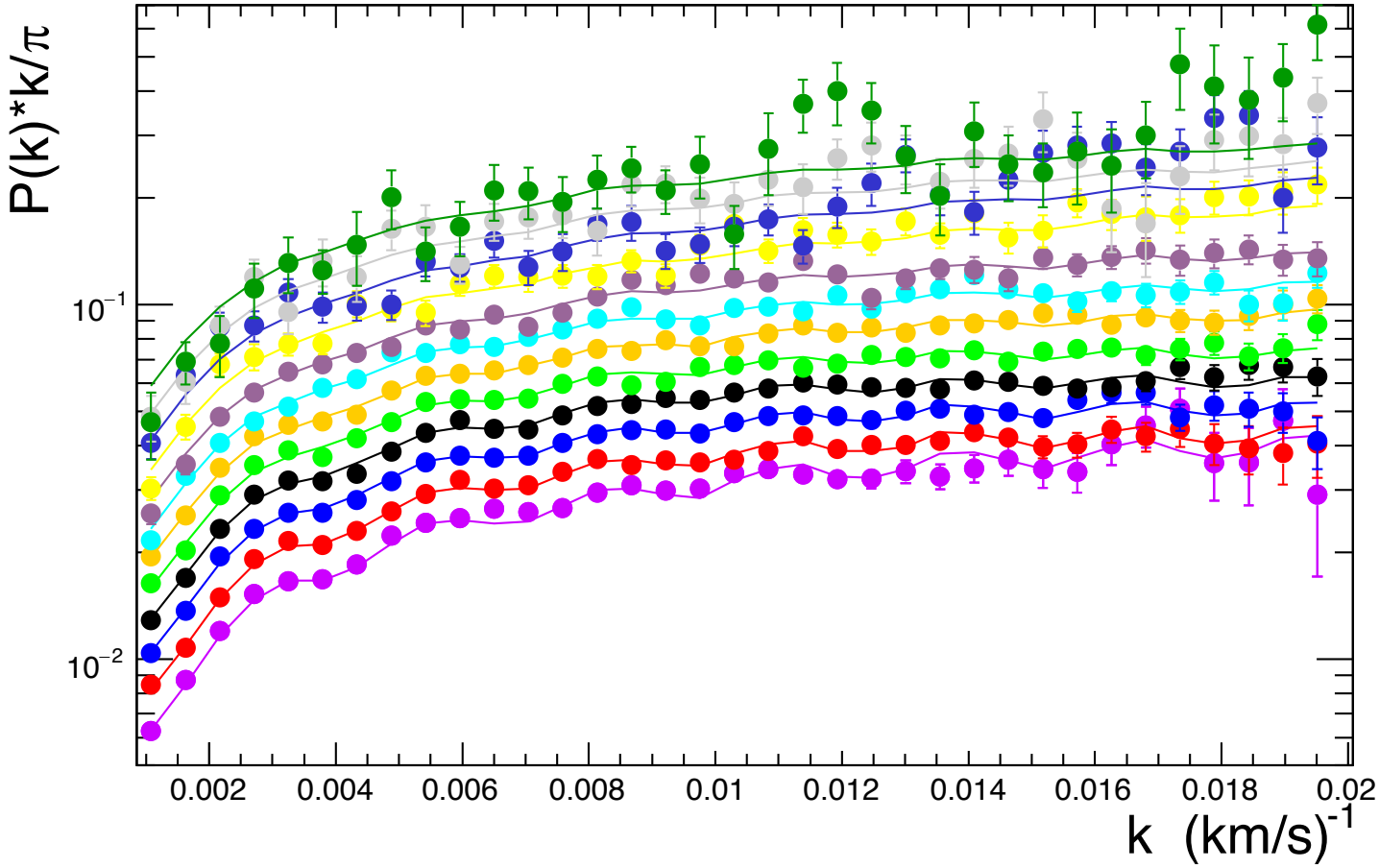
BOSS

First year BOSS: Using best 13k out of 60k quasars



BOSS + eBOSS

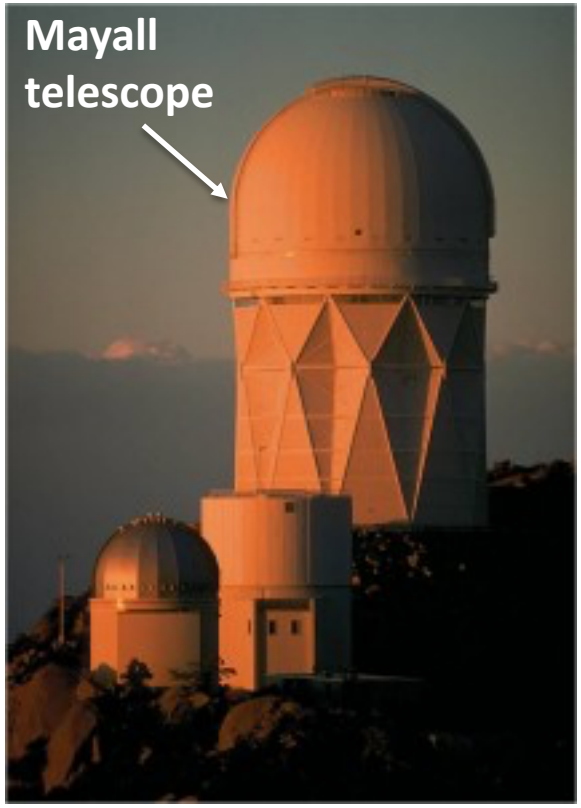
Full BOSS + first year eBOSS: Using best 44k out of 200k quasars

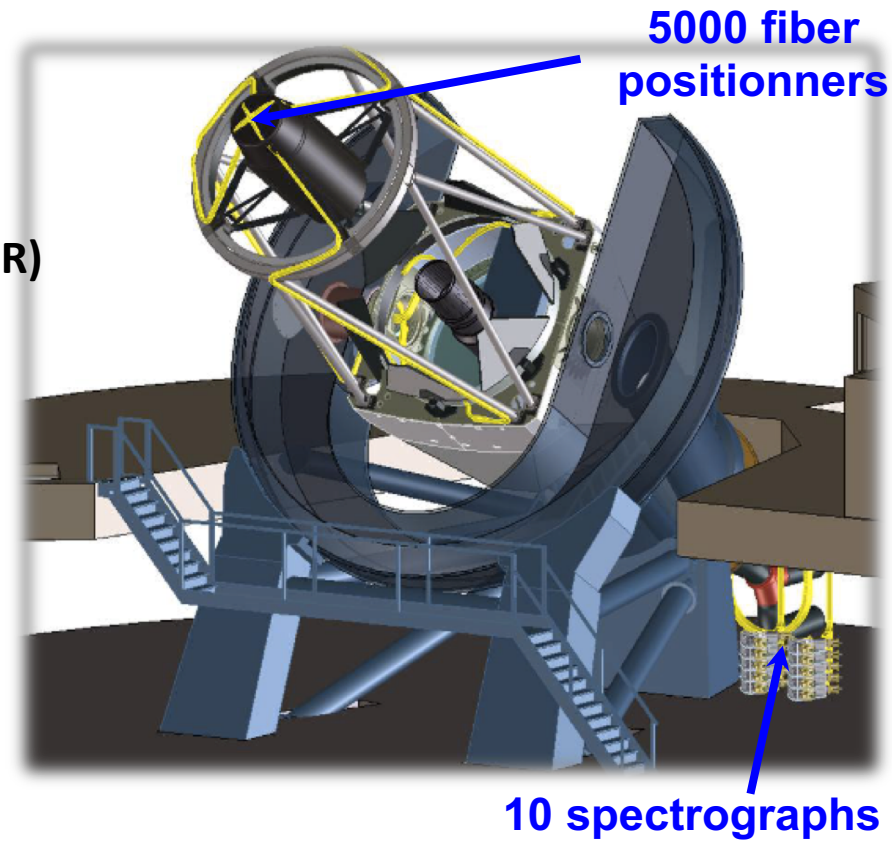


DESI (2020-2025)

DESI instrument

- 4m telescope in Arizona
- 5000 robotic fiber positioners
- 10 spectrographs x 3 bands (B, V, IR)





DESI survey

- 14,000 deg^2 spectroscopic survey $0 < z < 4.5$ for BAO & RSD
- International collaboration (74 institutes, 46 non-US)
- > 600 members, 40 French engineers & physicists

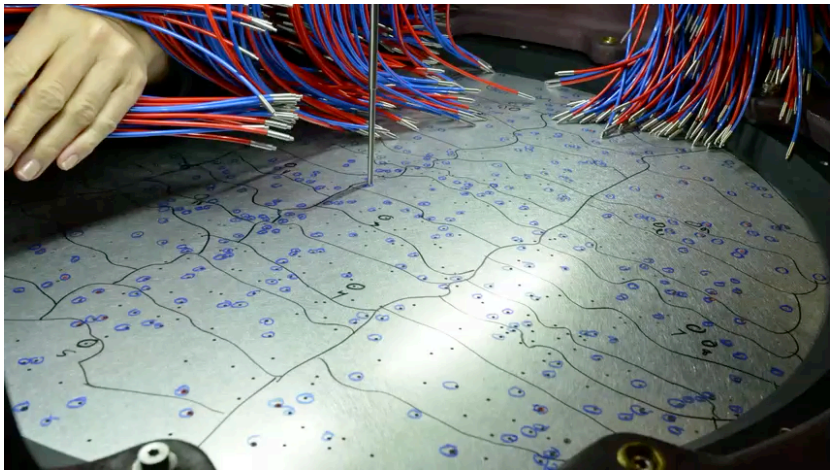
DESI (2020-2025)

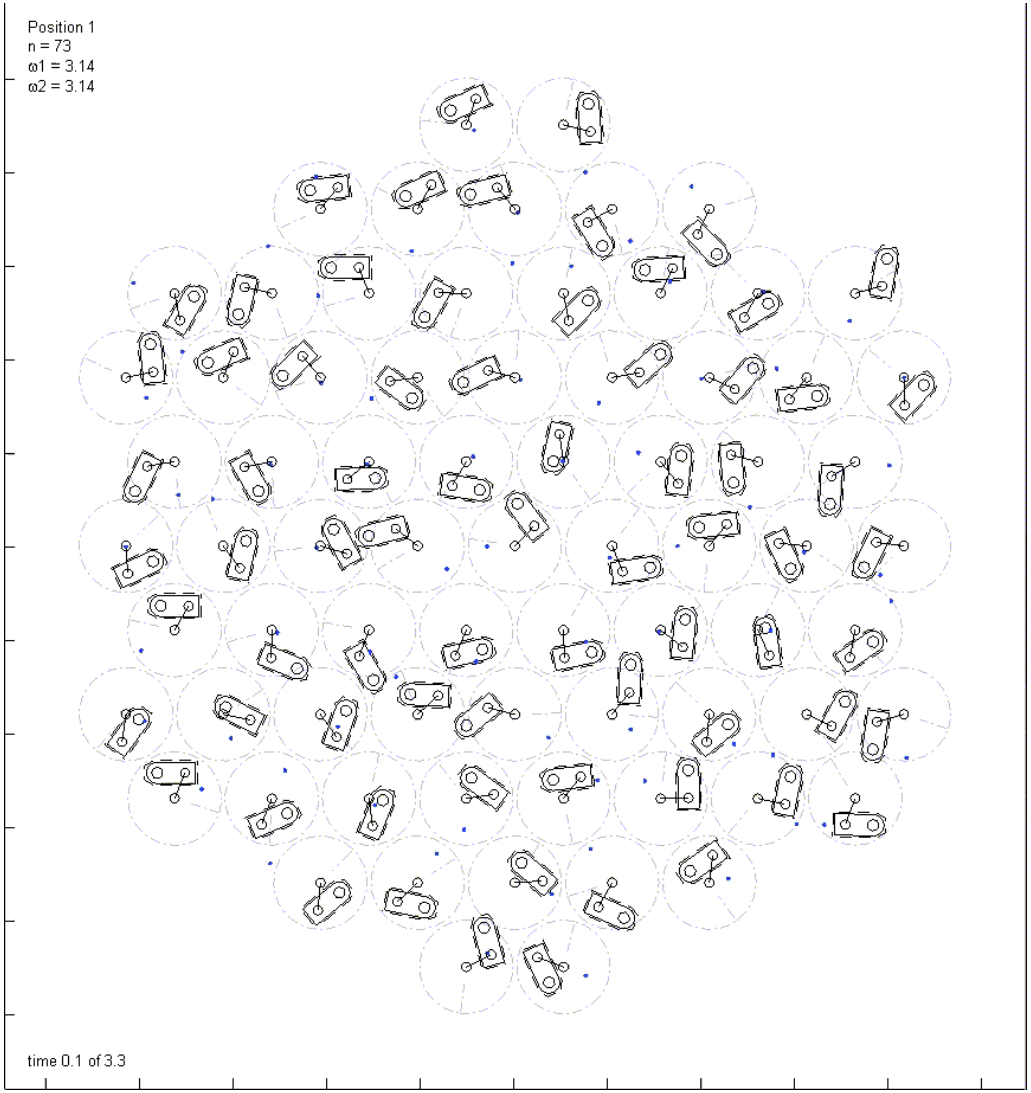
DESI
2020-2025

Fibers positioned
in 2 minutes

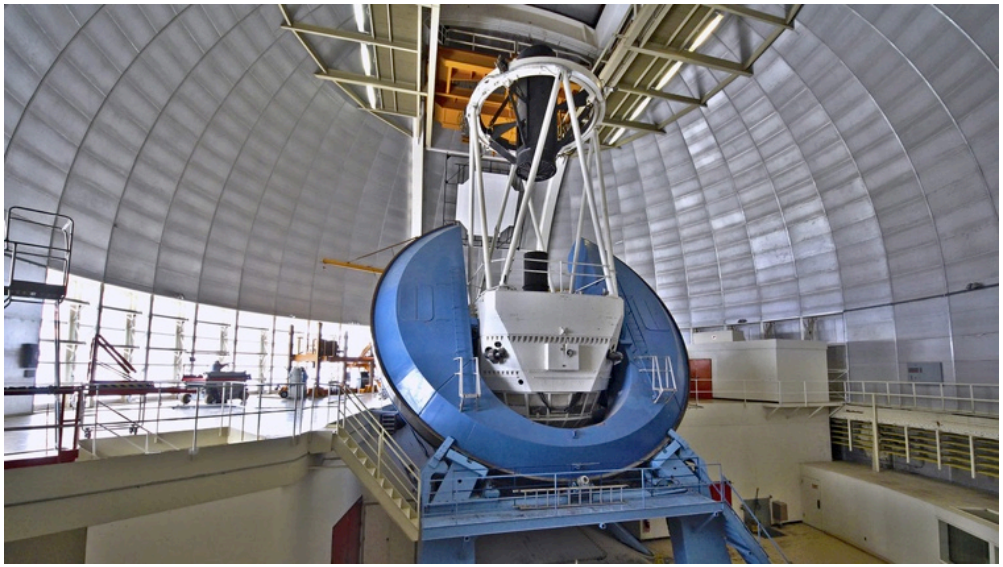
SDSS
2009-2020

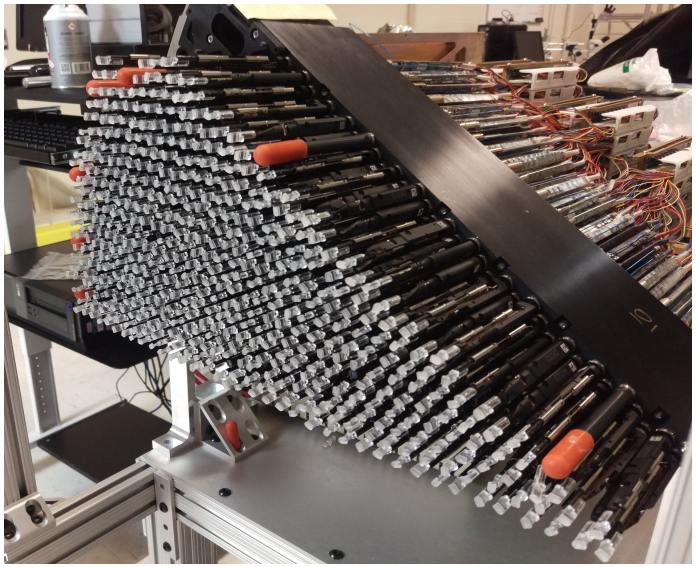
~1 hour per plate

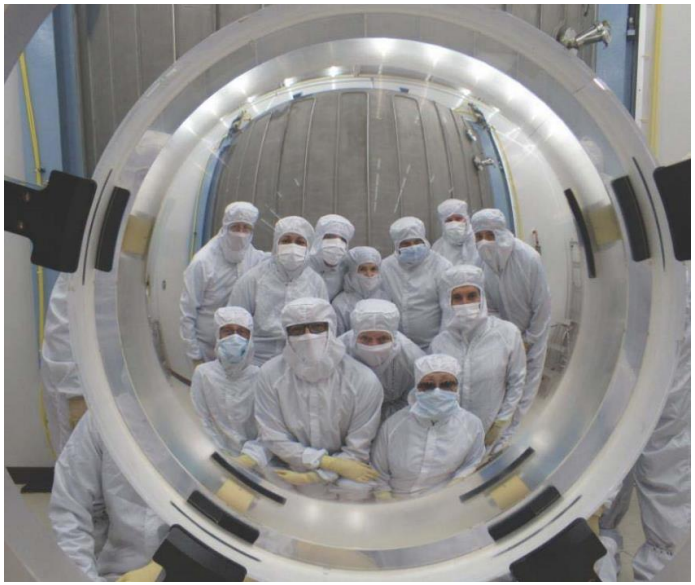


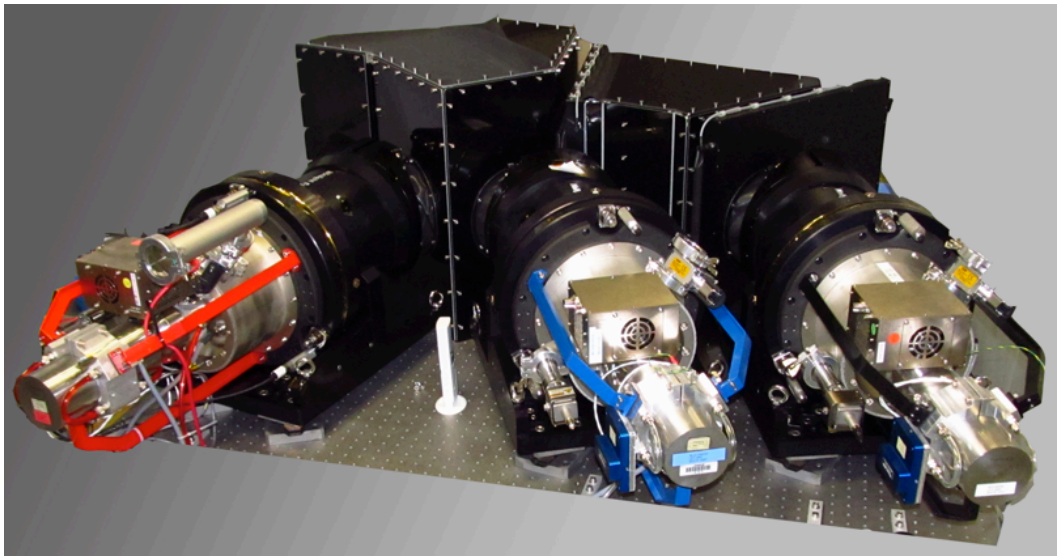


DESI (2020-2025)





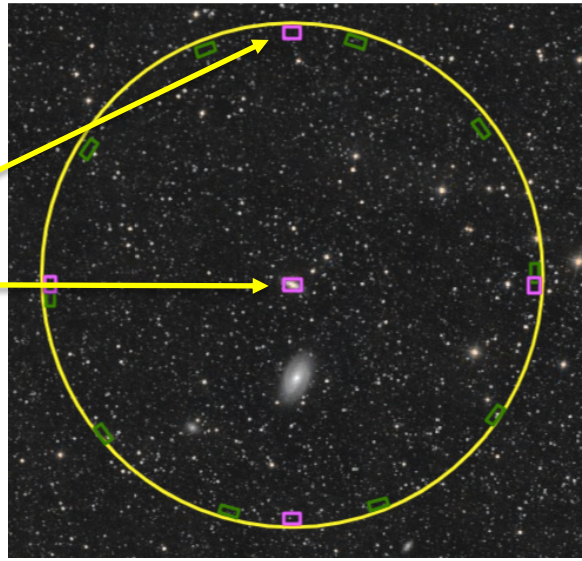




DESI (2020-2025)

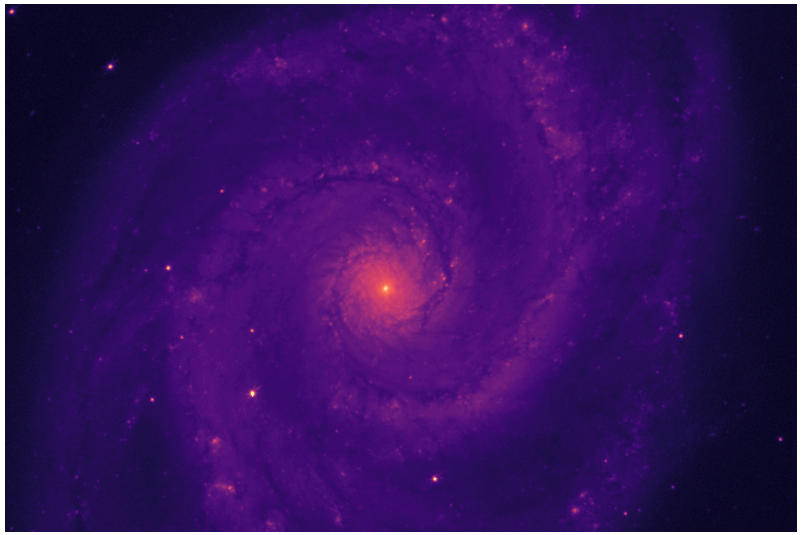
Commissioning Instrument on corrector

4 off-axis cameras
1 on-axis camera
22 illuminated fiducials



Corrector looks good
→ delivering sub-arcsec images simultaneously across FOV

Was one of the major sources of risk!



DESI (2020-2025)

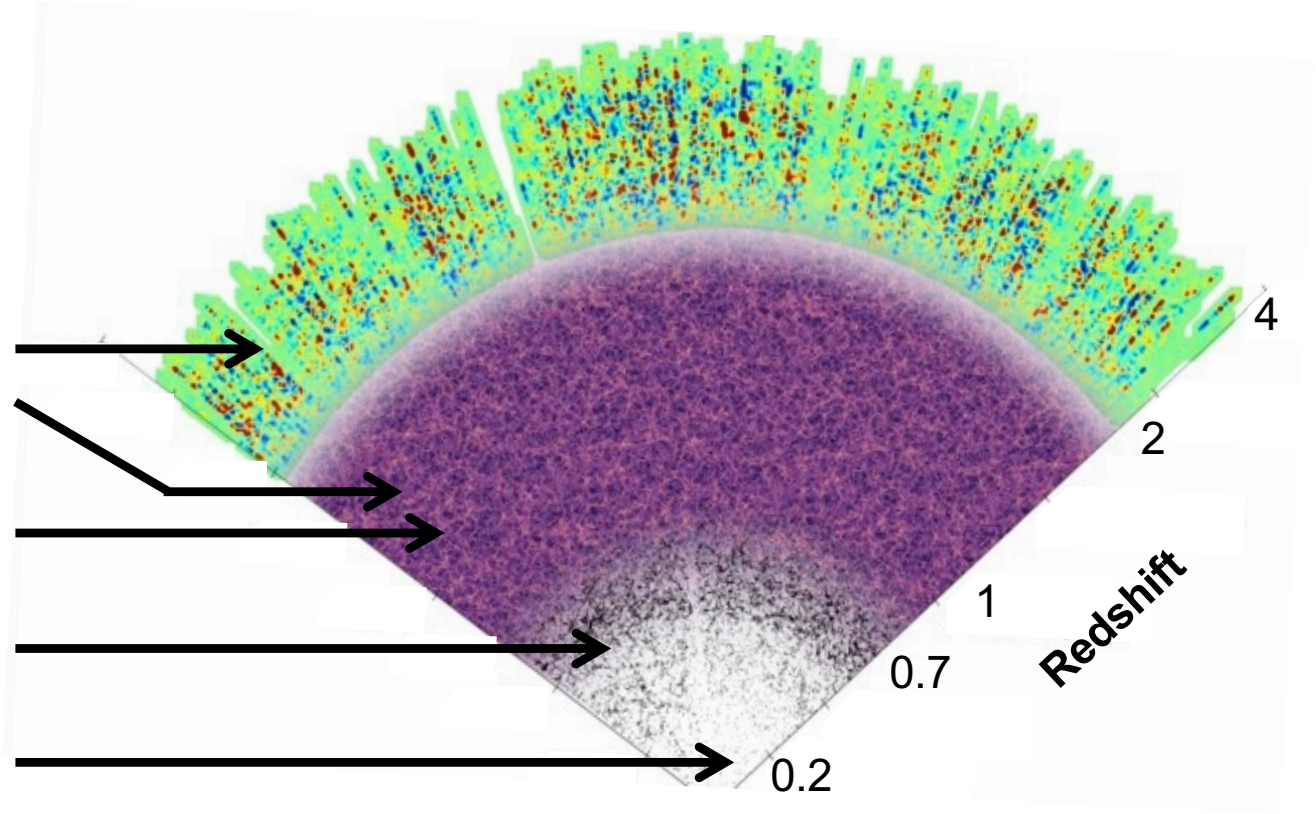
- **Five target classes spanning redshifts z=0.05 → 4.5**
- **35 million redshifts over 14,000 sq. degrees in five years**
- **x30 larger volume than the SDSS map**

2.4 million QSOs
Lyα z > 2.1
Tracers 1.0 < z < 2.1

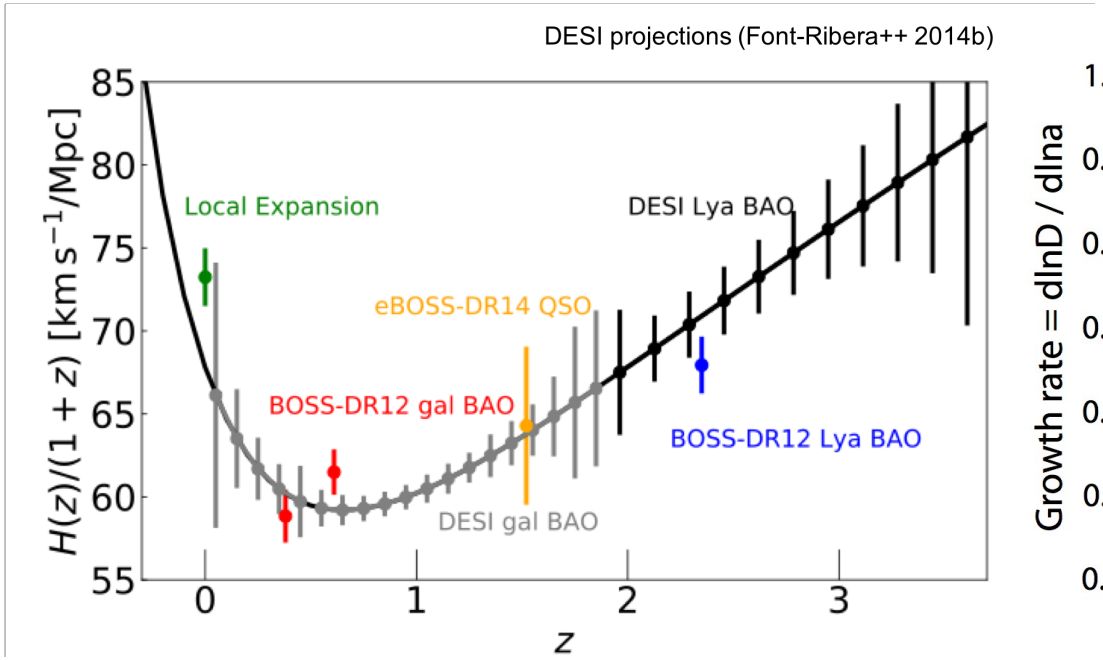
17 million ELGs
0.6 < z < 1.6

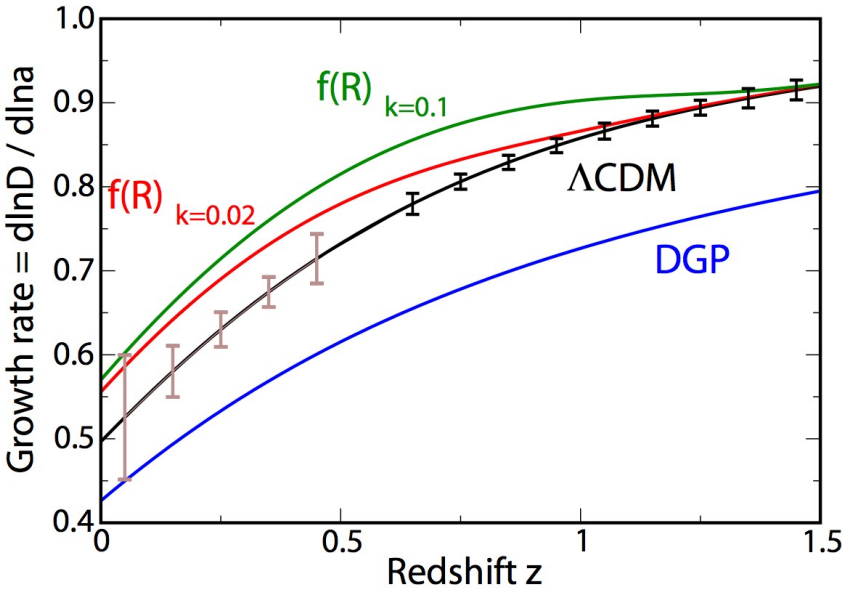
6 million LRGs
0.4 < z < 1.0

10 million brightest galaxies
0.05 < z < 0.4



DESI (2020-2025)





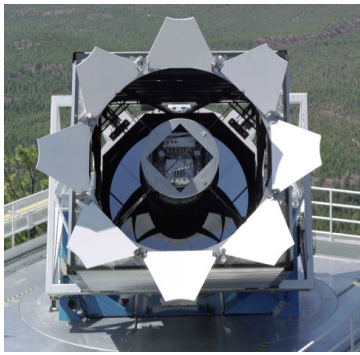
Improvements compared to SDSS

- **BAO:** 1 order of magnitude better $\sigma(a) \sim 0.1\%$
- **RSD:** better than 1% over the full redshift range
- **Neutrino masses:** precision ~20-25 meV on Σm_ν
- **Non-gaussianity (inflation):** $\sigma(f_{NL}) \sim 5$ (DESI-only)

Conclusions

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

- **Constraint on mass of active neutrinos**
  - **Sum of neutrino masses $\Sigma m_\nu < 0.12$ eV** (95% CL) **from Lyα+CMB**



- **Constraint on warm dark matter & sterile neutrinos**
  - **m_s (non-resonantly produced) excluded**
  - **m_s (resonantly produced) in conflict**
    with sterile ν interpretation of 3.5 keV X-ray line
  - **(constraints on fuzzy dark-matter)**

- **Prospects**
  - **Update with full SDSS BOSS + eBOSS**
  - **Planck + DESI Lyα $\sigma(\Sigma m_\nu) = 0.039$ eV**
  - **Planck + DESI Galaxy $\sigma(\Sigma m_\nu) = 0.024$ eV**