Neutrino and dark matter cosmology with the Lya forest:

the interplay between large-scale evolution and small-scale baryonic physics

Solène Chabanier

(Lawrence Berkeley National Lab, previously CEA Saclay)

Collaborators: Zarija Lukic, Nathalie Palanque-Delabrouille, Christophe Yèche, Frédéric Bournaud, Yohan Dubois ..

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1- Open issues in the Standard Cosmological model

2- Measurements of the Lya forest 1D power spectrum

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4- Cosmological results

Massive neutrinos in the Standard Cosmological model

Neutrino oscillation → Evidences for physics beyond the standard model

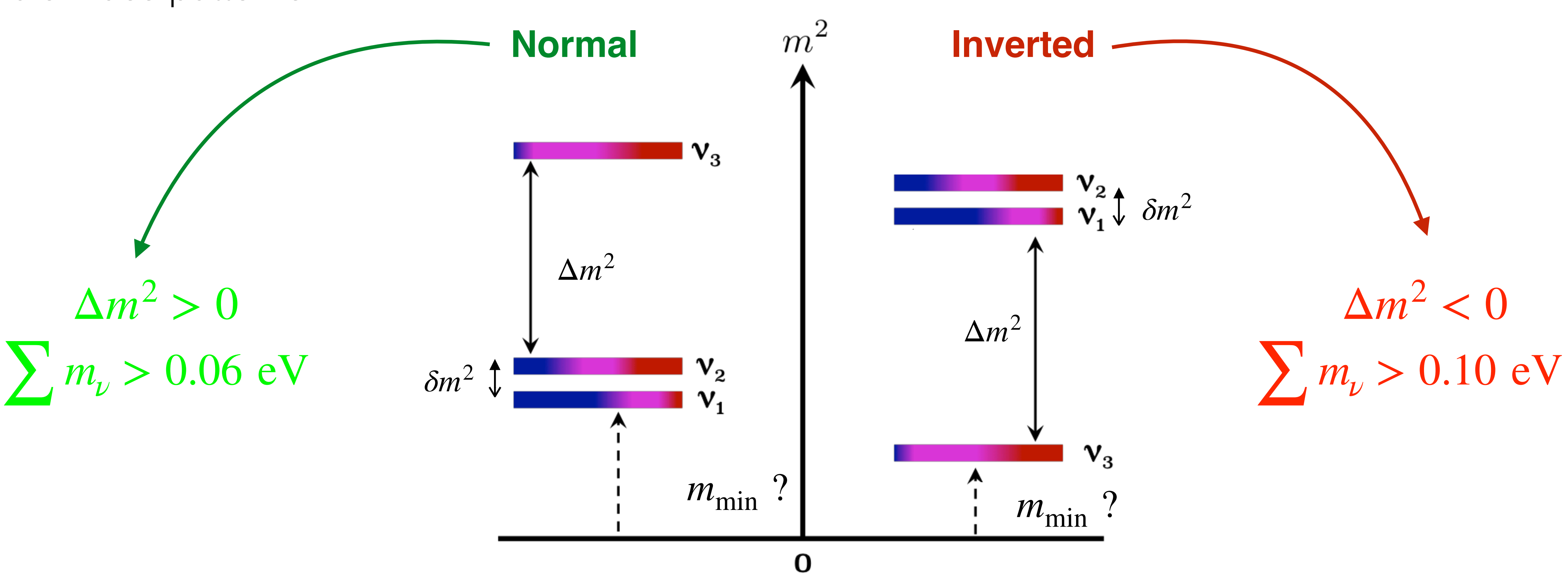
- Mass eigenstates $m_{1,2,3}$ and flavor eigenstates $m_{e,\mu,\tau}$

Solar neutrinos: $\delta m^2 = m_2^2 - m_1^2 \sim 7.5 \cdot 10^{-5}\ \mathrm{eV}^2$

Atmospheric neutrinos: $|\Delta m^2| = |m_3^2 - \left(\frac{m_1 + m_2}{2}\right)^2| \sim 2.4 \cdot 10^{-3}\ \mathrm{eV}^2$

ν_e ν_μ ν_τ

- Two possible mass patterns:



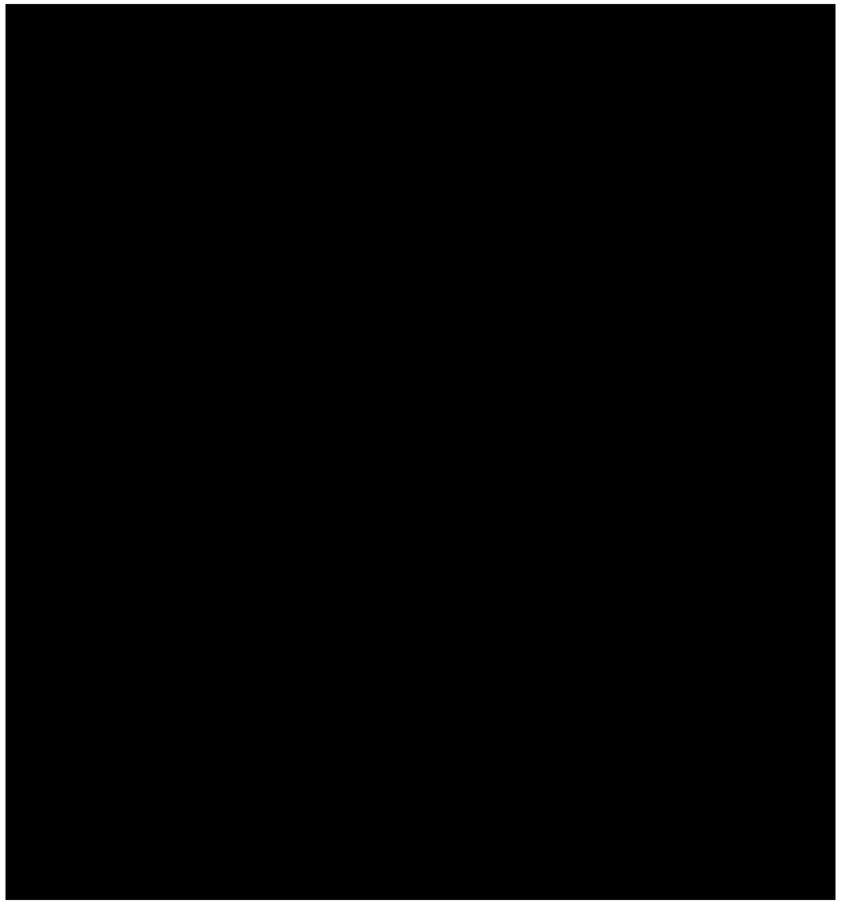
Massive neutrinos in the Standard Cosmological model

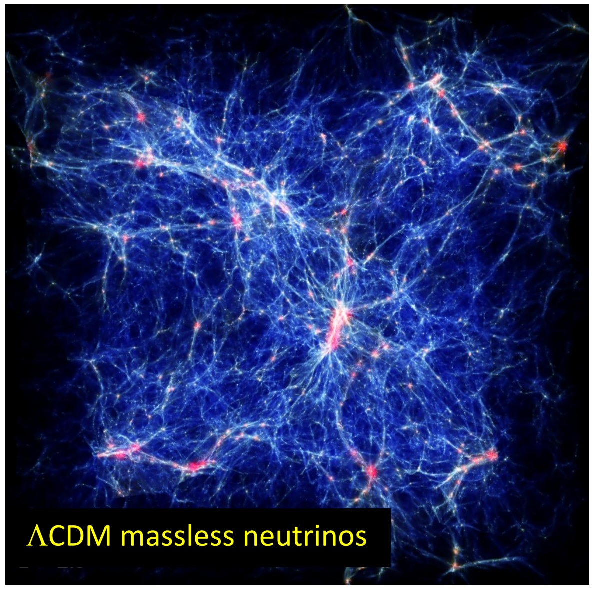
Cosmological implications

ν are the most abundant particles after γ

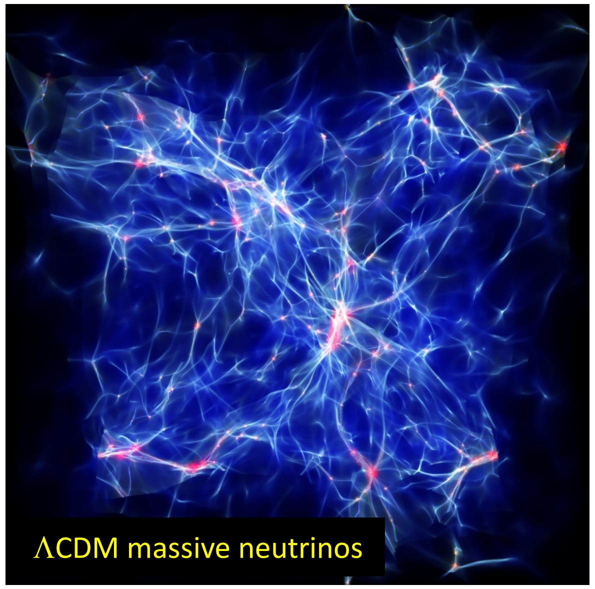
- Particle-physics bounds on neutrino masses: $0.06\ \mathrm{eV} < \sum m_\nu < 3\mathrm{eV}$ → $0.15\,\% < \Omega_\nu < 15\,\%$
- Relativistic up to $z_{NR} \gg z_{rec}$ $\quad \nu \sim \gamma$
- Non-relativistic today: $\nu \sim$ dark matter with large velocity dispersion

→ **free-stream and smooth-out small scale fluctuations**



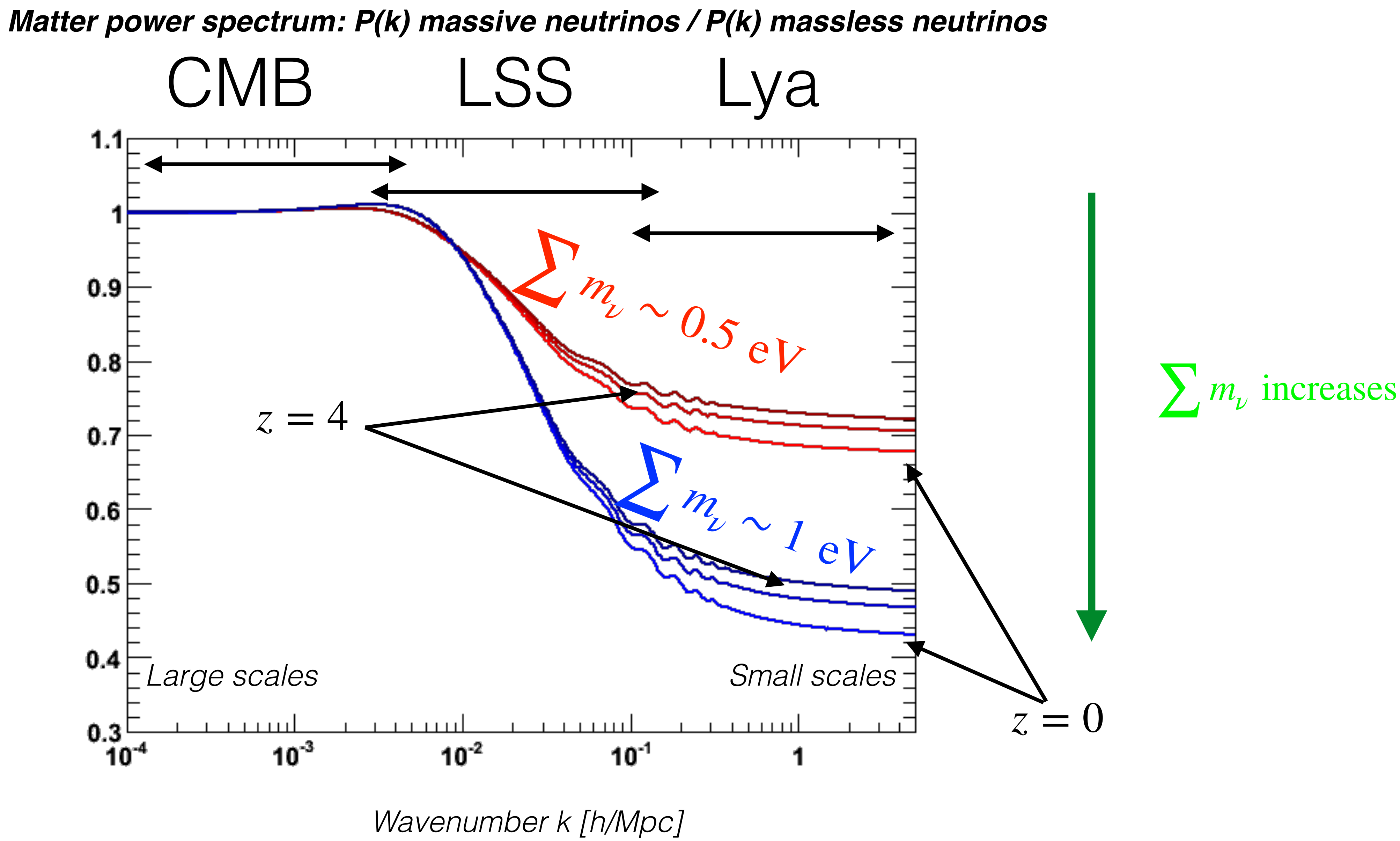


Suppression of small scales



Massive neutrinos in the Standard Cosmological model

Cosmological implications



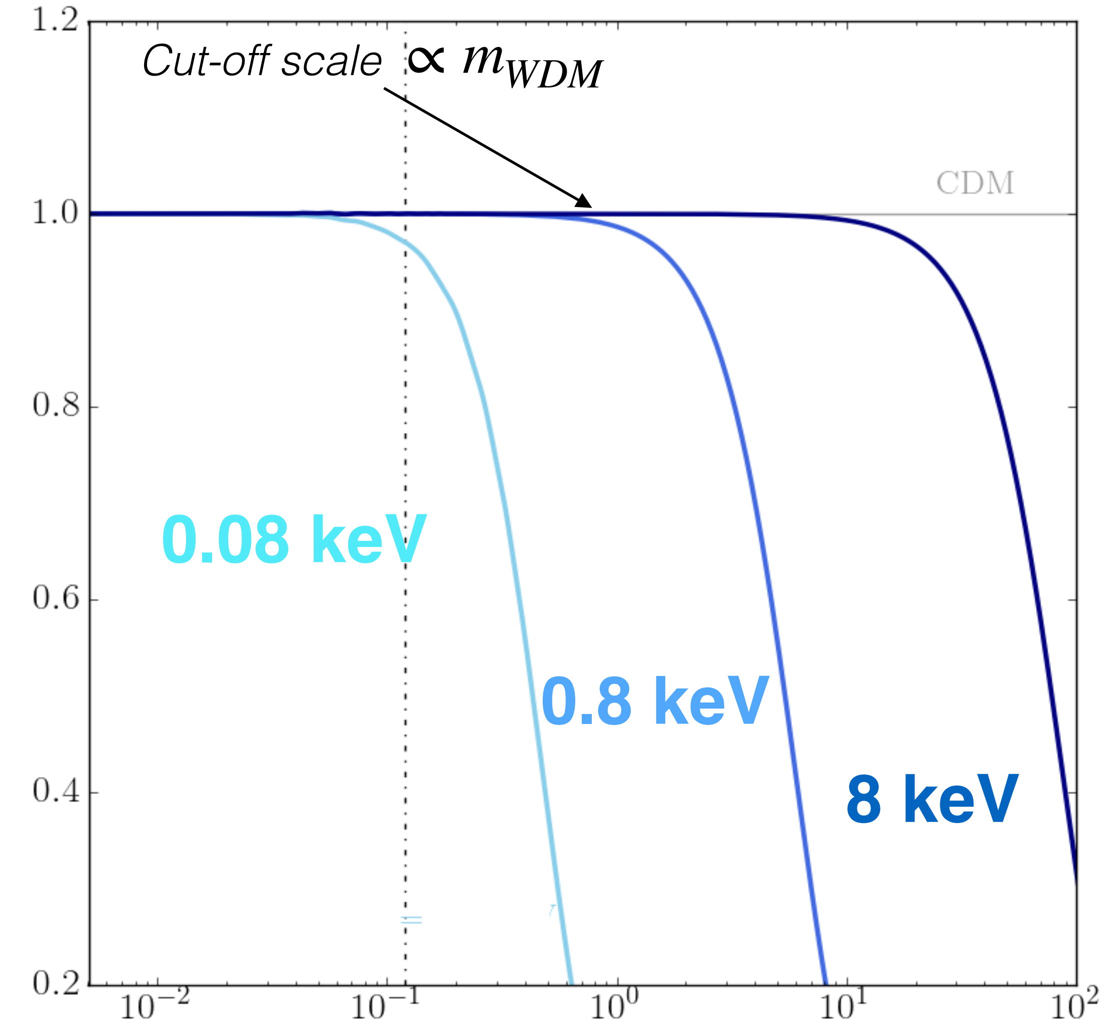
The Lya forest is sensitive to: - the maximal suppression
- the redshift dependence

Warm dark matter

- **Small-scale challenges** of the **cold** dark matter model
  - *The Missing Satellite problem*
  - *The Cusp-Core problem*
  - *The Too-Big-to-Fail problem*

- Exotic model: the **warm dark matte**r model
  → *Non-negligible velocity dispersion*
  → *Free-streaming length ~ galaxy scale*
  → *Suppress small-scale fluctuation while keeping large-scale CDM predictions*

Matter power spectrum:
P(k) [WDM]/ P(k) [CDM]



Large scales ***Small scales***

Wavenumber k [h/Mpc]

Warm dark matter particle induce a power cut-off in the matter power spectrum

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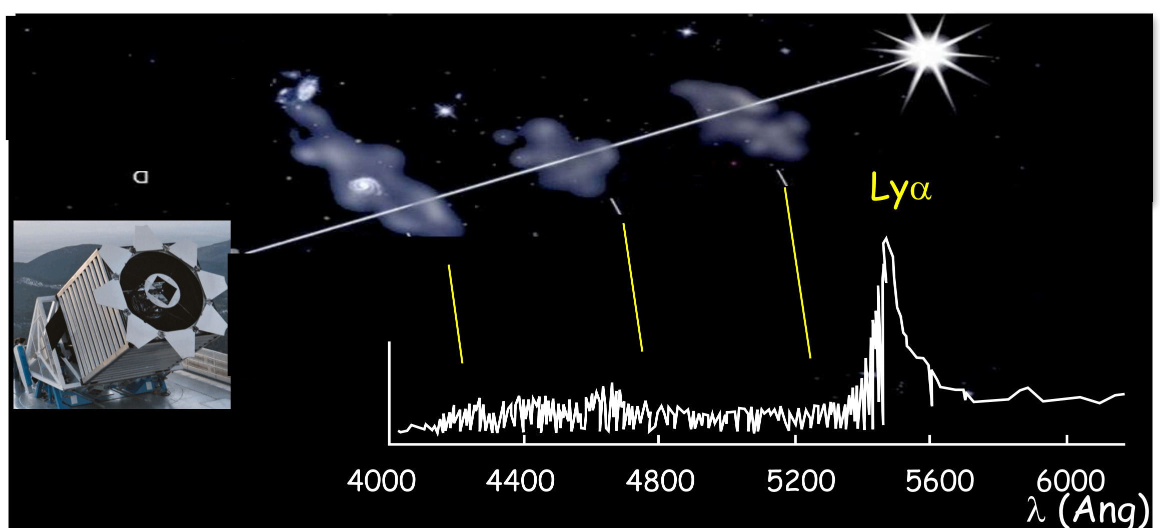
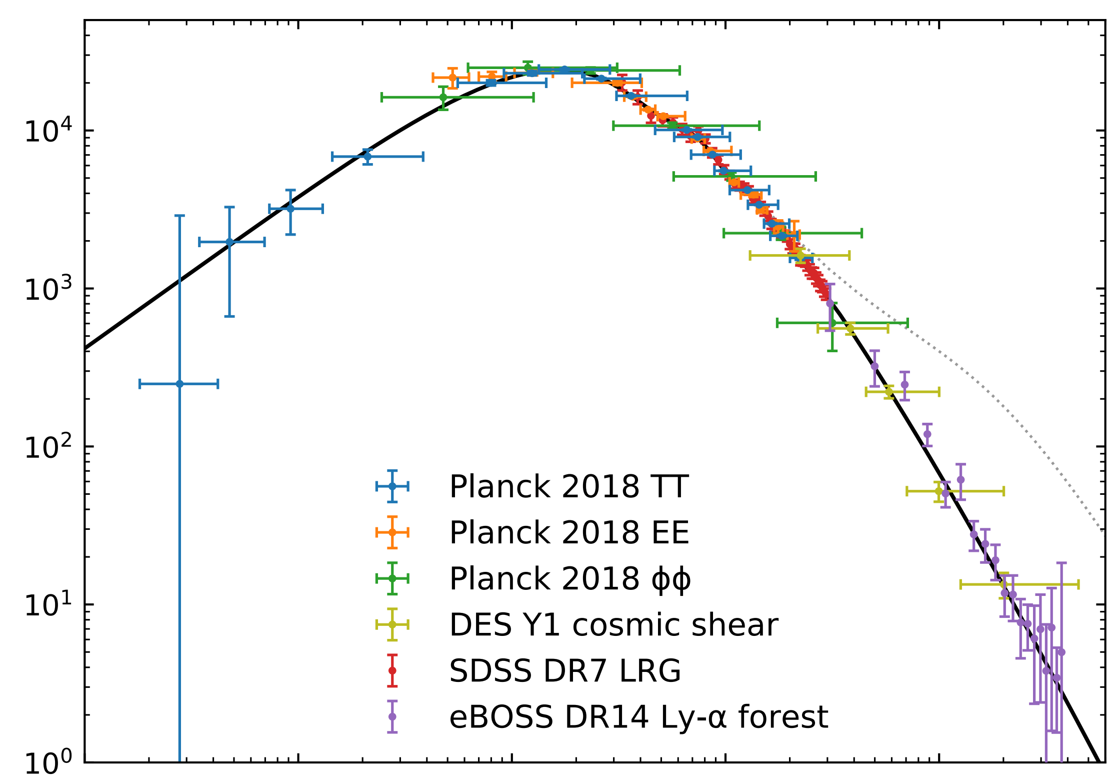
The Lya forest

- Neutral hydrogen **absorptions in the IGM** along the line of sight of high redshift quasars
- Low density IGM acts as a **proxy of dark matter density at small scales**



Matter power spectrum at z = 0

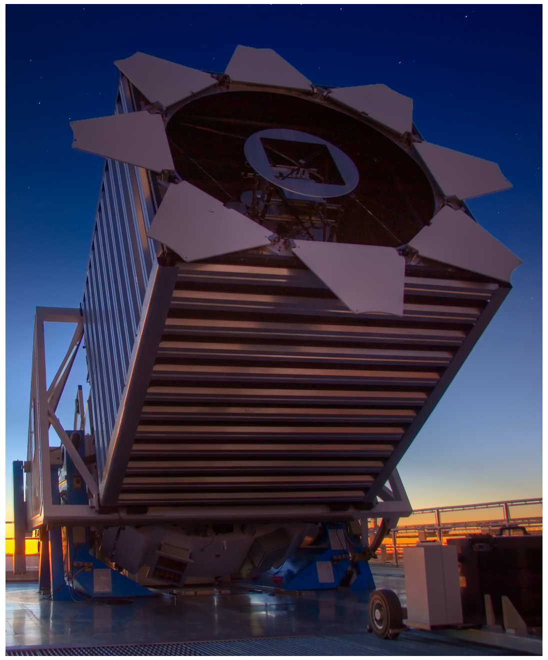


Large scales *Small scales*

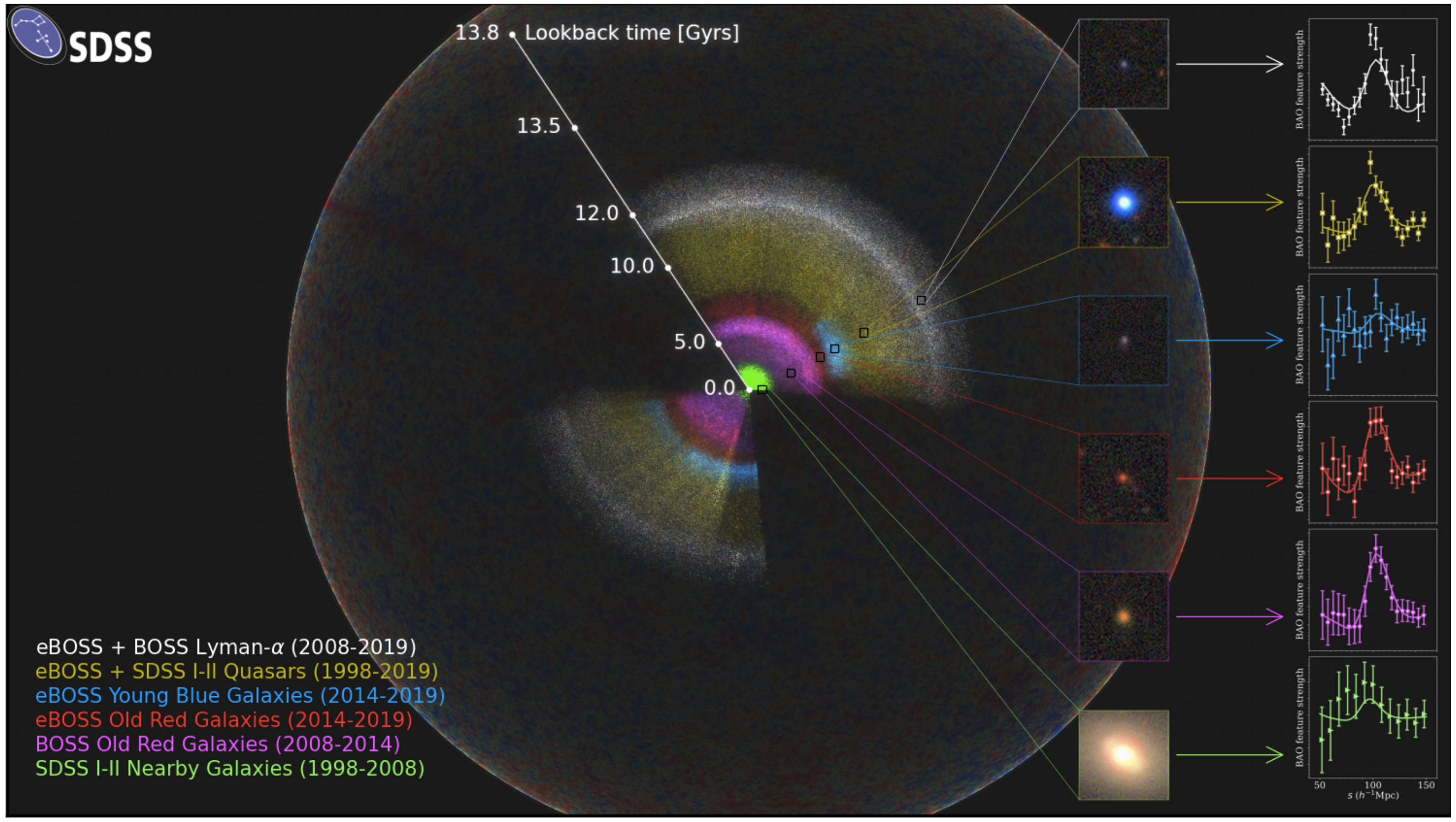
Chabanier et al. 2019b

The BOSS/eBOSS spectroscopic surveys

The SDSS telescope



Redshift distribution of eBOSS tracers



Credits: A. Raichoor

- (extended)-Baryonic Oscillation Spectroscopic survey
- 2.5m Sloan telescope (New Mexico)
- Survey area: 10,000 deg^2
- Redshifts: 1,000 fibers
- Four tracers of matter: blue galaxies, red galaxies, low-z QSOs and high-z QSOs (for Lya forest)

⟶ 3D map of ~2 million galaxies and quasars covering 11 billion years of cosmic time

1D Lya power spectra data analysis

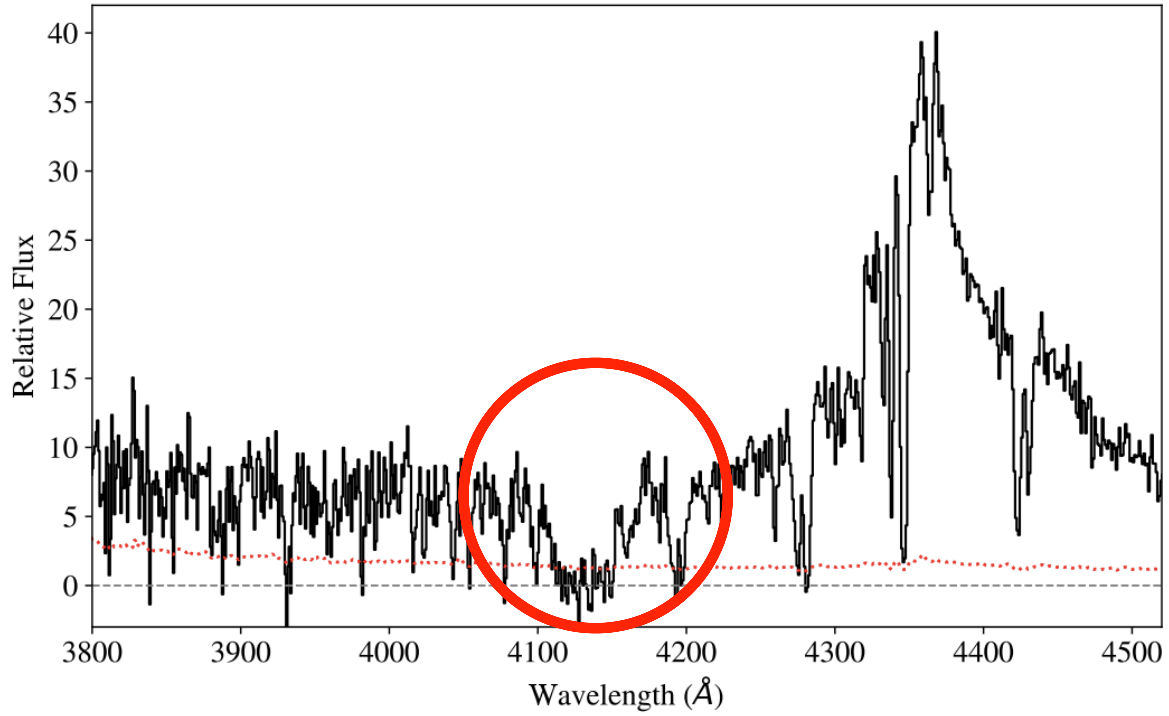
Data selection

- ~43,000 quasar spectra out of 200,000 in **DR14** with $2.1 \leq z_{Ly\alpha} \leq 4.7$
- Selection based over
  - Noise (SNR > 2)
  - Resolution (< 85 km/s) probe small-scale fluctuations
  - Quality (no high-density absorbers)

→ **Increase precision of measurements**

SDSS Lya spectra with high-density absorbers (DLA)

Damped Lya systems



1D Lya power spectra data analysis

Analysis method

based on McDonald+06

- Transmitted flux fraction $$\delta_F = \frac{f(\lambda)}{C_q(\lambda)} - 1$$

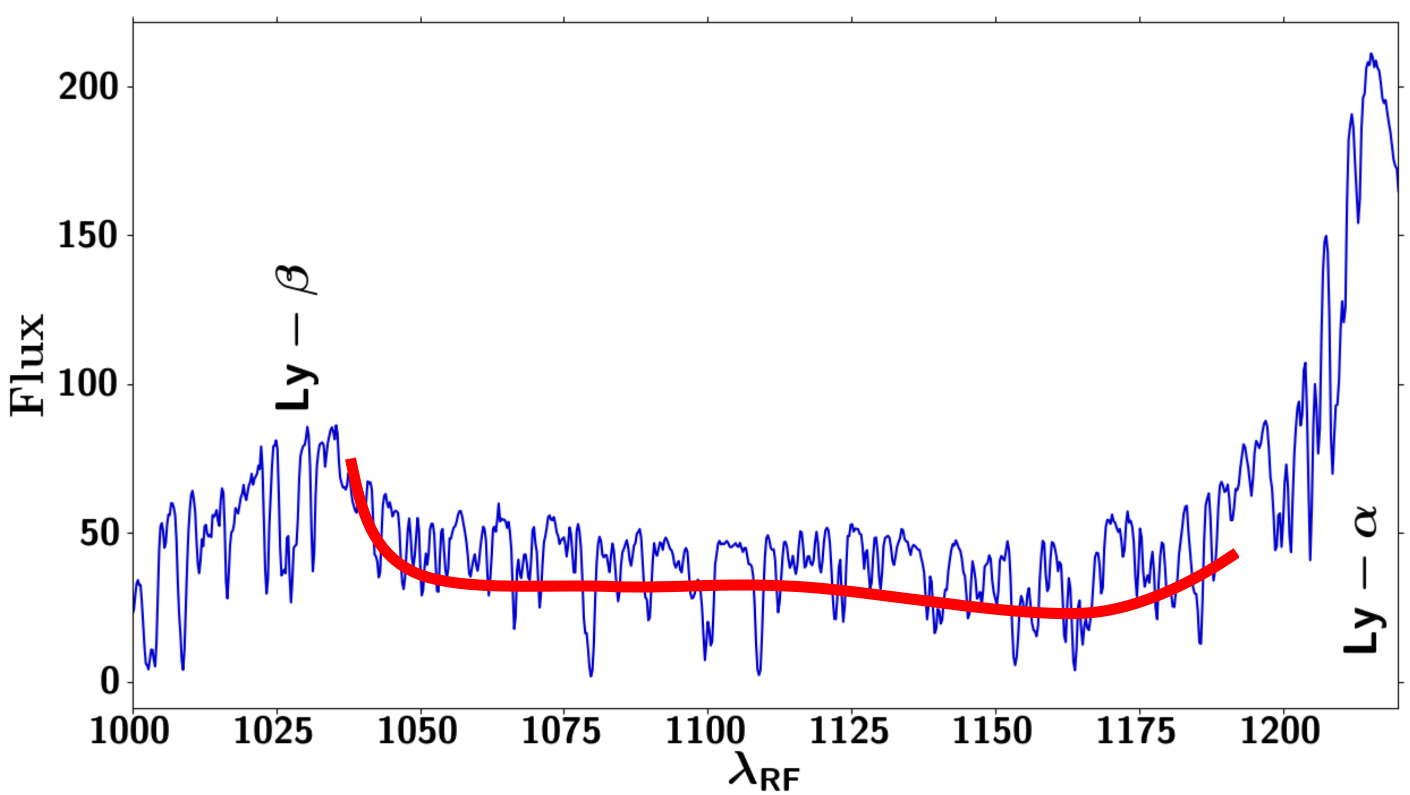
Absorbed spectrum

Unabsorbed spectrum

Bautista+17, du Mas des Bourboux+17

- Flux power spectrum $$P_F = FFT^2(\delta_F) = FFT(\xi_F)$$

Palanque-Delabrouille+13, Chabanier+19

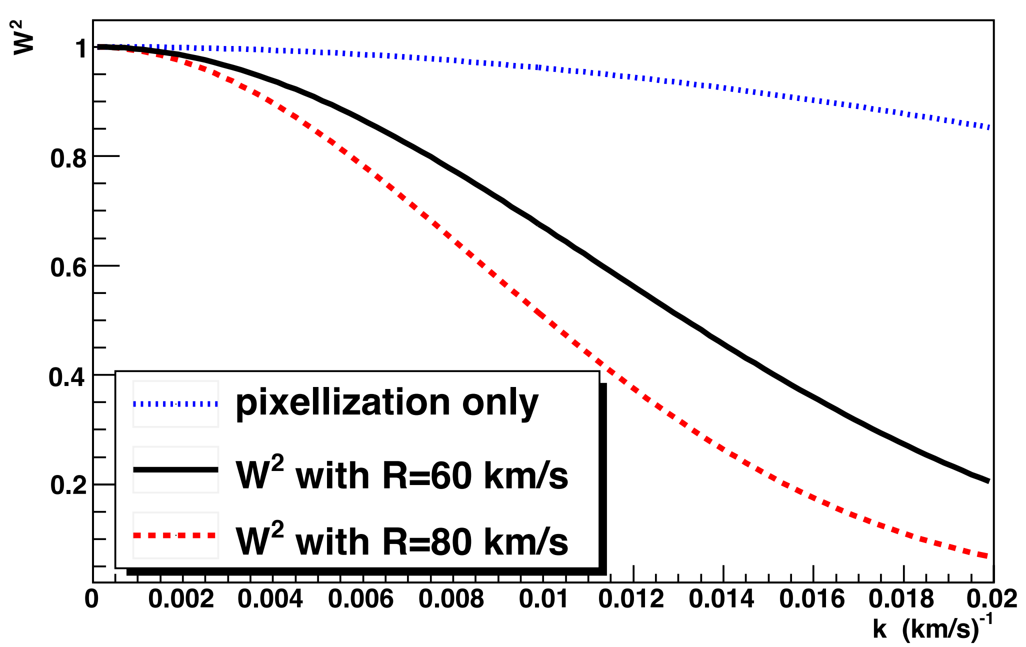


1D Lya power spectra data analysis

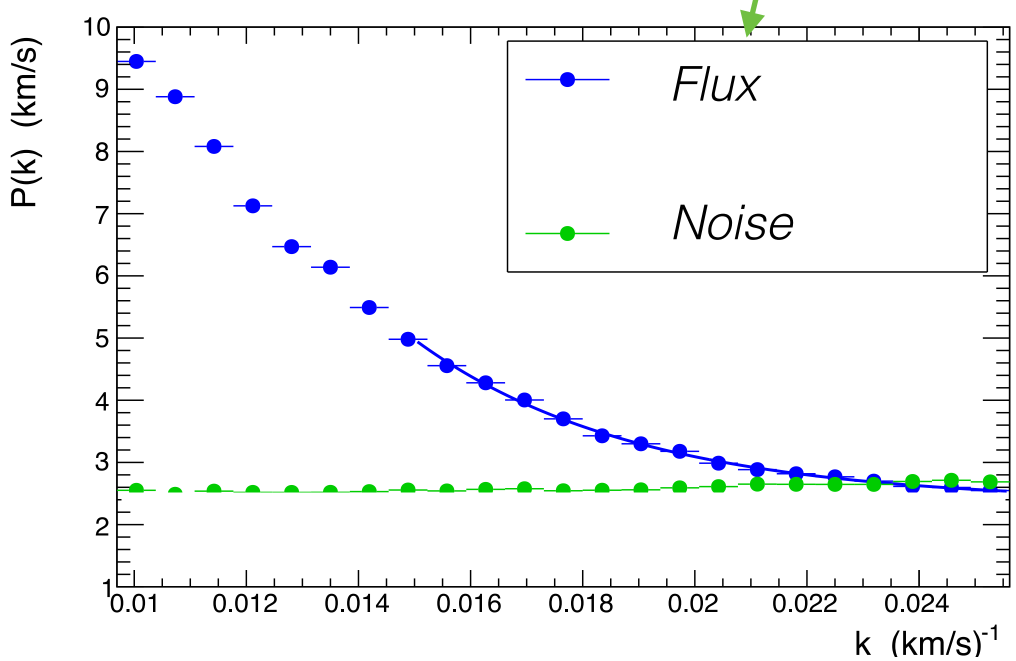
Analysis method

$$P_F(k) = [P_{Ly\alpha}(k) + P_{correlated}(k) + P_{uncorrelated}(k)] \cdot W^2(k) + P_{noise}(k)$$

W = resolution + pixellisation



Large scales *Small scales*



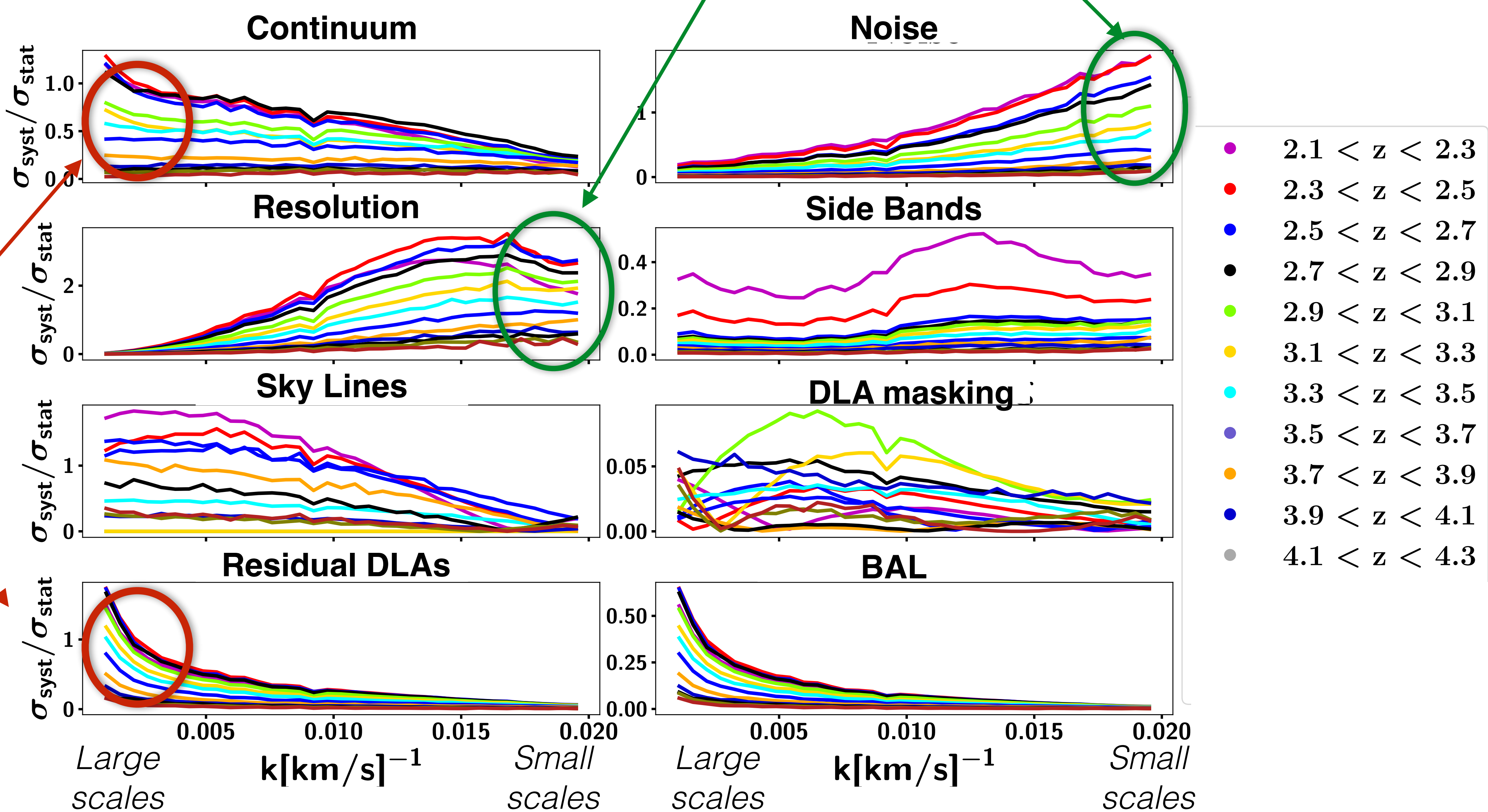
Large scales *Small scales*

1D Lya power spectra data analysis

Systematics uncertainties

$\sum m_\nu,\ m_{WDM}$
(small scales)

n_s, σ_8, α_s
(Large scales)

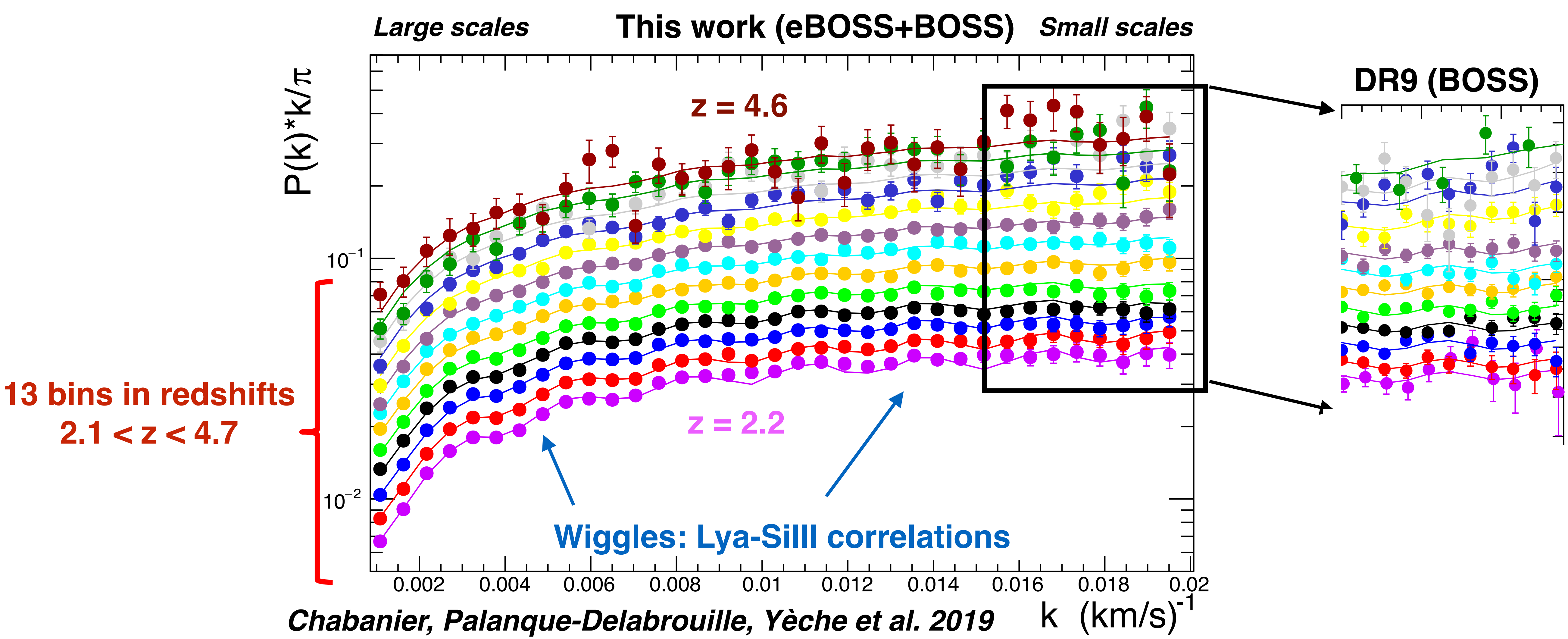


Ratio of systematics / statistical uncertainties

if > 1: systematics dominate

1D Lya power spectra data analysis

Final measurements of eBOSS $\mathrm{P}_{\mathrm{Ly}\alpha}$



Chabanier, Palanque-Delabrouille, Yèche et al. 2019

- **Unprecedented level of precision** *(<1% at low z)*:
    - statistics: QSOs x 3 and optimization of data selection
    - systematics: careful investigation of systematic biases and their sources

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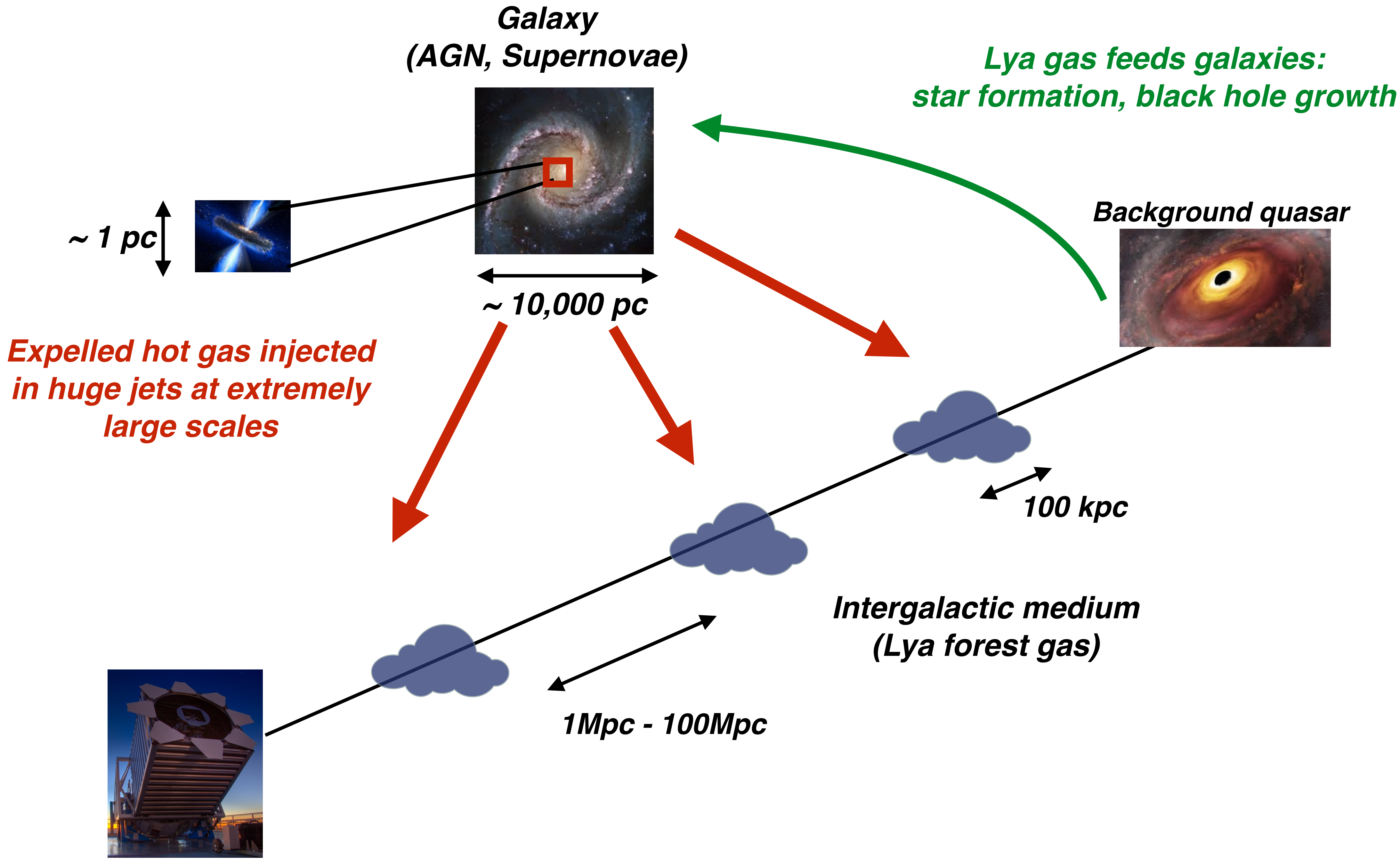
AGN feedback in cosmology

Supermassive black holes and supernovae **expel large amount of gas and energy** from the center of galaxies

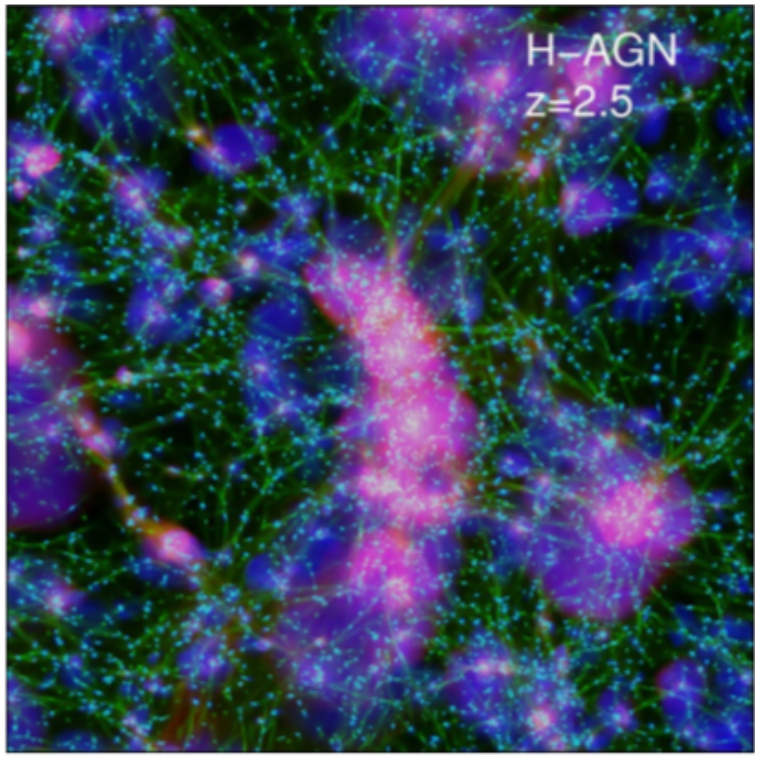


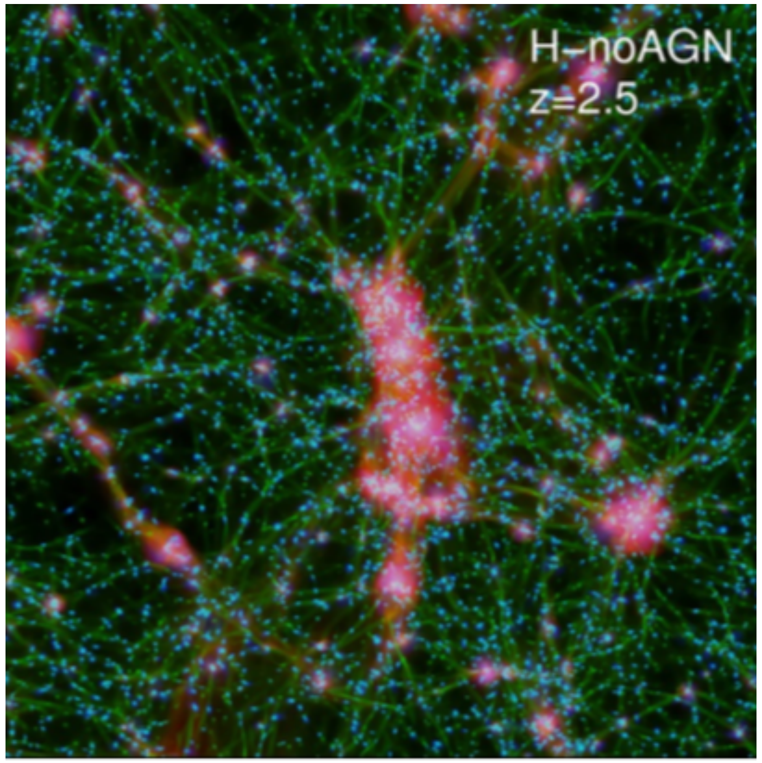
The Horizon-AGN suite of simulations

The fiducial Horizon-AGN simulation

- Cosmological hydrodynamical simulation run with the Adaptative Mesh Refinement (AMR) code RAMSES *(Teyssier 2002)*
- Box size: $L_{box} = 100\ Mpc/h$
- Cell size: from $100\ \mathrm{kpc/h}$ to $1\ \mathrm{kpc/h}$
- Included physics: - Gas cooling with contribution from metals
  - Heating from a uniform UV background
  - Stellar formation
  - Stellar feedback: release mass, energy and metals
  - AGN feedback

- Companion simulation Horizon-noAGN





gas density
temperature
gas metallicity

The Horizon-AGN suite of simulations

AGN feedback implementation

- Black hole are sink particles which can accrete gas at the Bondi-Hoyle accretion rate:

$$\boxed{\dot{M}_{BH} = \frac{4\Pi\alpha G^2 M_{BH}^2 \bar{\rho}}{(\bar{c}_s^2 + \bar{u}^2)^{3/2}}}$$

α boost factor, accounts for not resolving the accretion disk

$$\begin{cases} (\rho / \rho_0)^2 & \text{if} \quad \rho > \rho_0 \\ 1 & \text{otherwhise} \end{cases}$$

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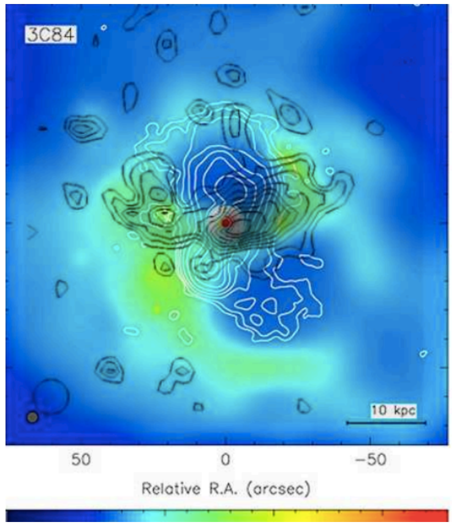
- AGN feedback proceeds in two modes:
  - *Quasar mode:* high-z universe, emit large amount of radiations, photo-ionize and heat gas

    → Injection of **thermal energy**

  - *Radio mode:* low-z universe, creation of inflated cavities with strong magnetic fields

    → Injection of **kinetic energy**



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    $\longrightarrow$ Injection of **thermal energy**

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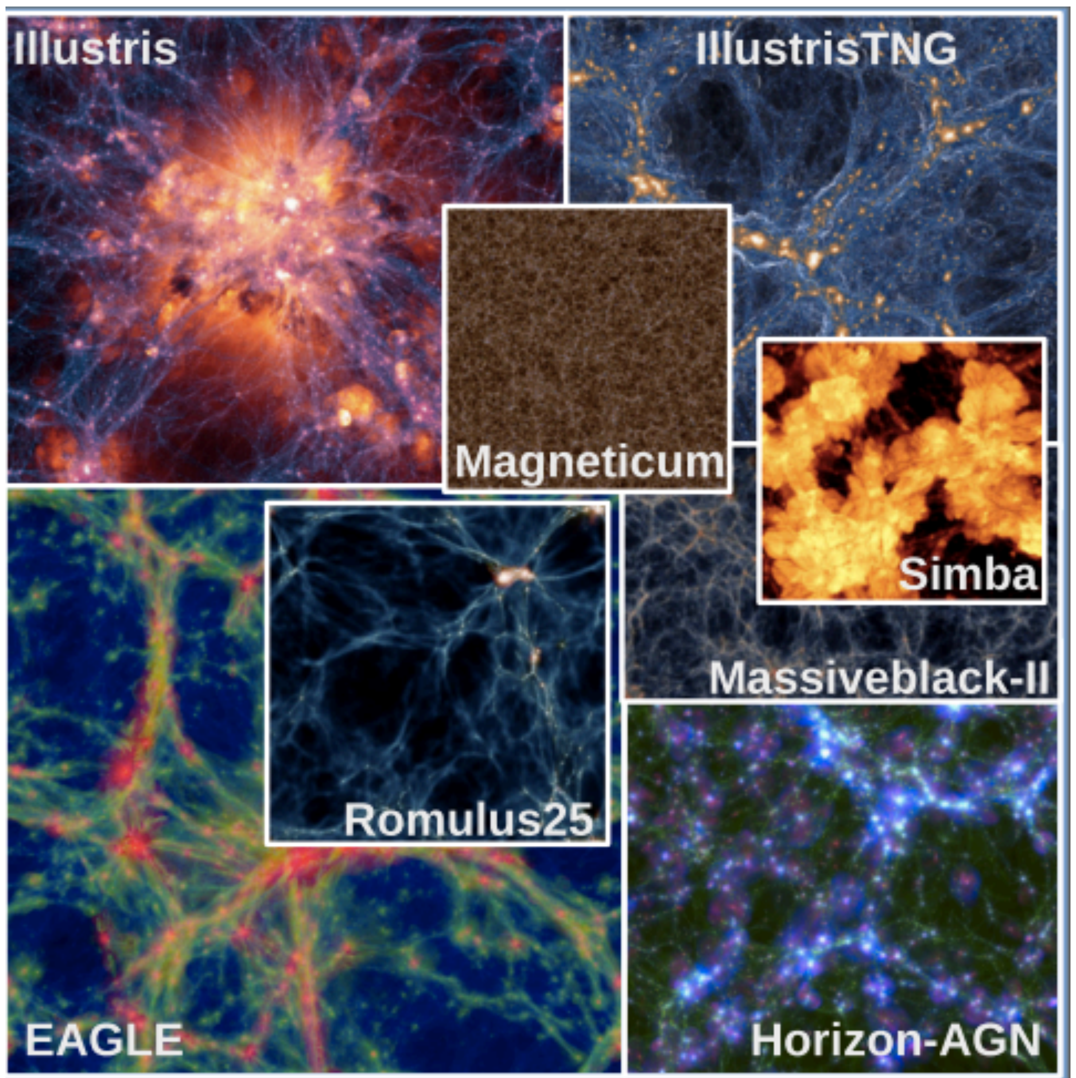
    $\longrightarrow$ Injection of **kinetic energy**

- A fraction ϵ_f of the radiated energy L_r is injected to the medium

$$\boxed{\Delta E_{IGM} = \epsilon_f L_r}$$

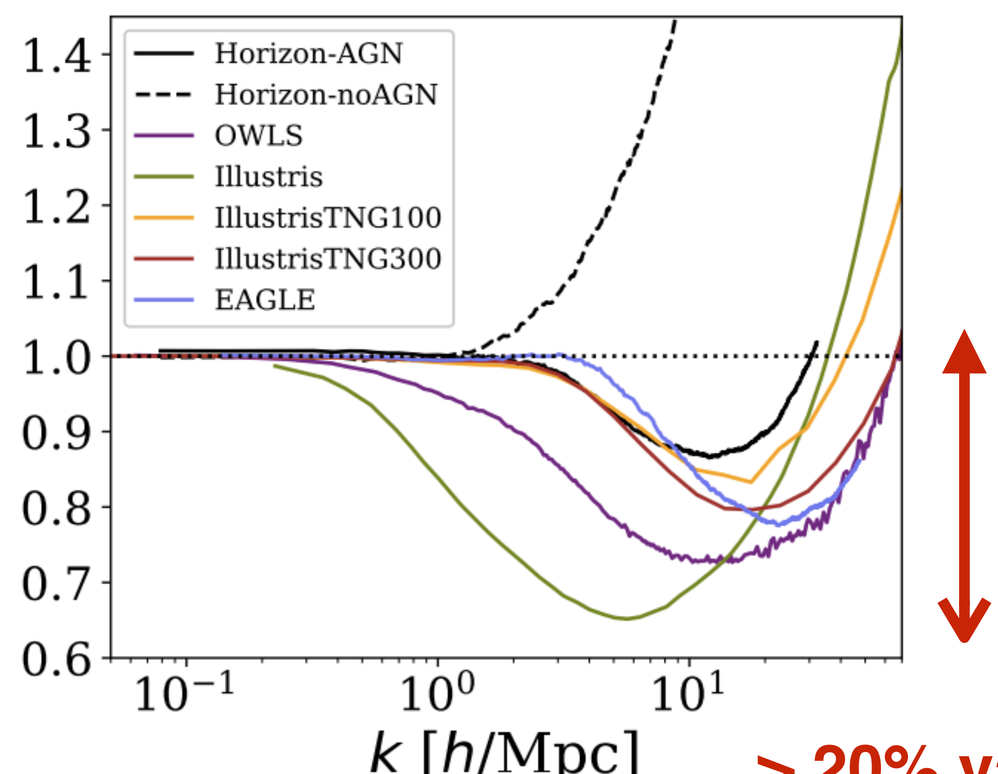
The Horizon-AGN suite of simulations

AGN feedback implementation and calibration: a source of large variability



Vogelsberger et al. 2019

P_{matter}[baryonic processes]/P_{matter}[no baryonic processes]



Chisari et al. 2018

Recall: data precision ~1%

The Horizon-AGN suite of simulations

- Construction of a set of simulations exploring a large range plausible range of feedback models
- **Variation of feeding and feedback parameters**

→ chosen to span the observable uncertainties of galaxy properties

(1) The Maggorian relation $M_{BH} - M_*$

(2) The mean fraction of gas in galaxies

Stochasticity in the accretion rate

$$\dot{M}_{BH} = \frac{4\Pi\alpha G^2 M_{BH}^2 \bar{\rho}}{(\bar{c}_s^2 + \bar{u}^2)^{3/2}}$$

Radius of energy deposition

Amount of injected energy

$$\Delta E_{IGM} = \epsilon_f L_r$$

Simulation	α	r_{AGN}	ϵ_f
HAGN	$\begin{cases} (\rho/\rho_0)^2 & \text{if } \rho > \rho_0 \\ 1 & \text{otherwhise} \end{cases}$	Δx	$\begin{cases} 0.1 & \text{if radio} \\ 0.15 & \text{if quasar} \end{cases}$
HAGNclp10	10% of the time: $10\alpha_{HAGN}$	$r_{AGN,HAGN}$	$\epsilon_{f,HAGN}$
HAGNclp100	1% of the time: $100\alpha_{HAGN}$	$r_{AGN,HAGN}$	$\epsilon_{f,HAGN}$
HAGNr+	α_{HAGN}	$2\Delta x$	$\epsilon_{f,HAGN}$
HAGNr−	α_{HAGN}	$0.5\Delta x$	$\epsilon_{f,HAGN}$
HAGNϵ+	α_{HAGN}	$r_{AGN,HAGN}$	$\begin{cases} 3 & \text{if radio} \\ 0.45 & \text{if quasar} \end{cases}$
HAGNϵ−	α_{HAGN}	$r_{AGN,HAGN}$	$\begin{cases} 0.33 & \text{if radio} \\ 0.05 & \text{if quasar} \end{cases}$

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- Construction of a set of simulations exploring a large range plausible range of feedback models
- Variation of feeding and feedback parameters

→ chosen to **span the observable uncertainties of galaxy properties**

(1) The Maggorian relation $M_{BH} - M_*$

(2) The mean fraction of gas in galaxies

	$\Delta\sigma_{\mathrm{f_{gas}}}$	$\Delta\sigma_{\mathrm{M_{BH}-M_*}}$
HAGN	0	0
HAGN_clp10	$< \sigma_{\mathrm{f_{gas}}}$	$\sigma_{\mathrm{M_{BH}-M_*}}$
HAGN_clp100	$\sigma_{\mathrm{f_{gas}}}$	$\sigma_{\mathrm{M_{BH}-M_*}}$
HAGN_R+	$3\sigma_{\mathrm{f_{gas}}}$	$2\sigma_{\mathrm{M_{BH}-M_*}}$
HAGN_R-	$2.7\sigma_{\mathrm{f_{gas}}}$	$3.3\sigma_{\mathrm{M_{BH}-M_*}}$
HAGN_E+	$2.3\sigma_{\mathrm{f_{gas}}}$	$3.5\sigma_{\mathrm{M_{BH}-M_*}}$
HAGN_E-	$2.5\sigma_{\mathrm{f_{gas}}}$	$3.5\sigma_{\mathrm{M_{BH}-M_*}}$

Range of feedback model covered is at the limit of realistic galaxy observables

The Horizon-AGN suite of simulations

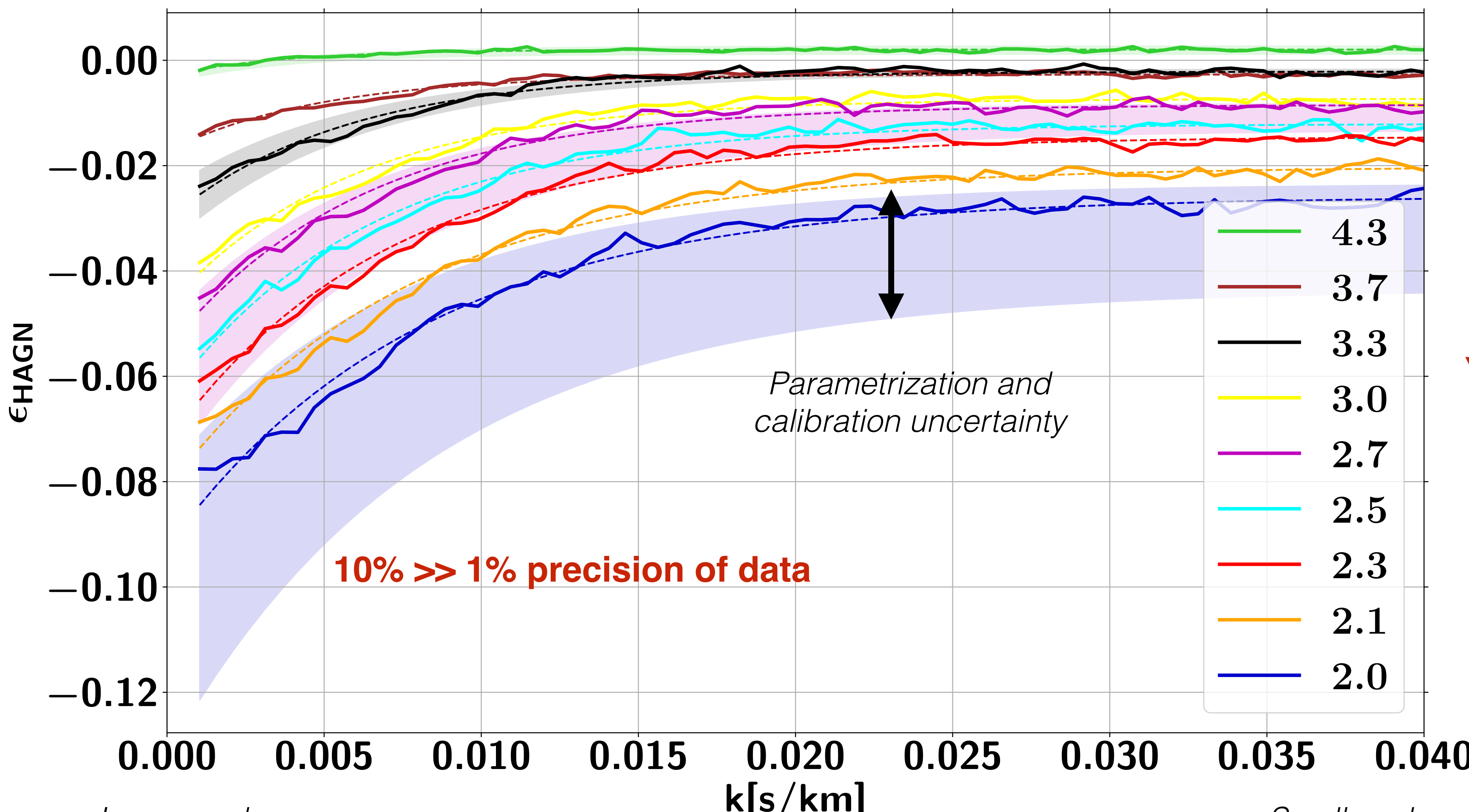
Impact of AGN feedback on $\mathbf{P_{Ly\alpha}}$

Suppression increases with..

$$\epsilon_{HAGN} = \frac{P_{Ly\alpha}[HAGN]}{P_{Ly\alpha}[HnoAGN]} - 1$$

.. increasing scales

.. decreasing redshift



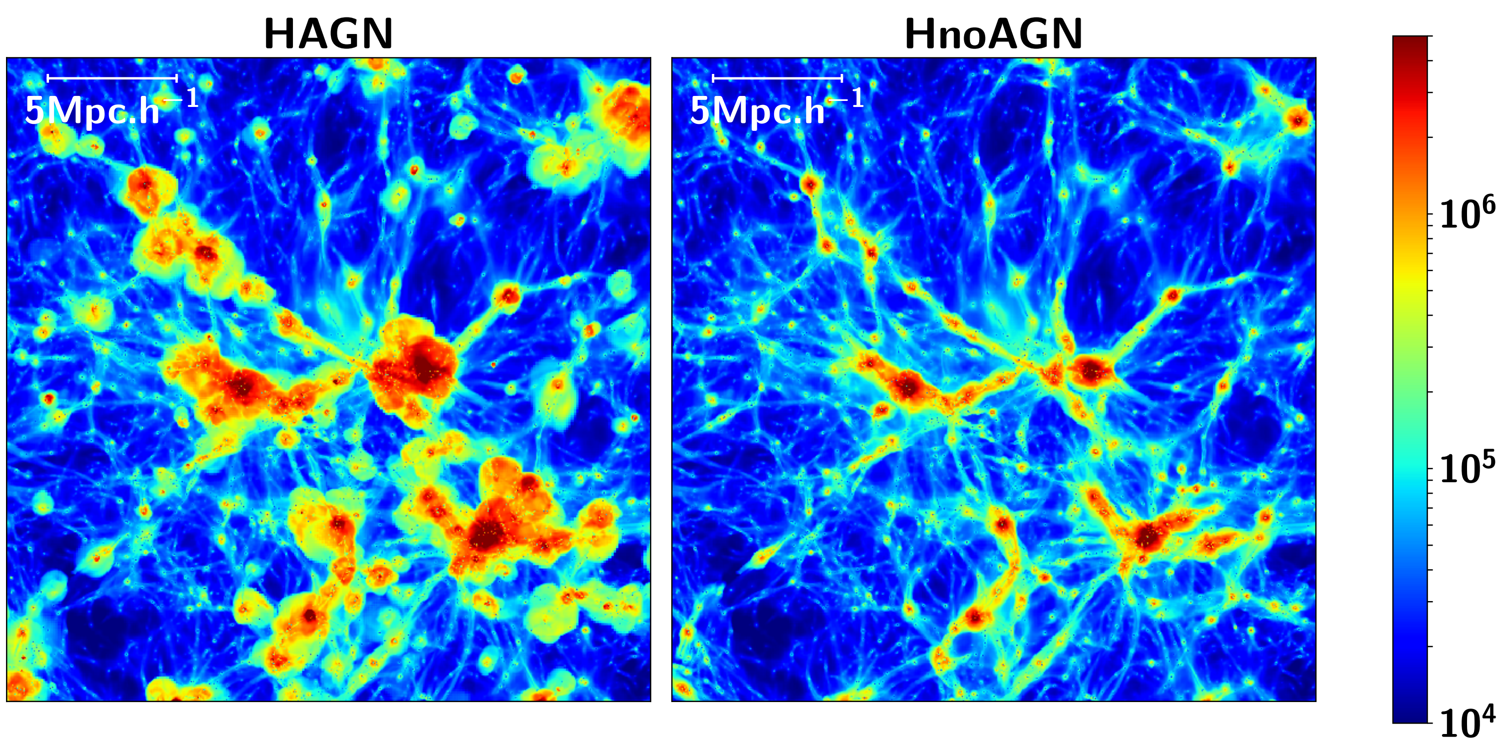
Large scales *Small scales*

Chabanier et al. 2020a

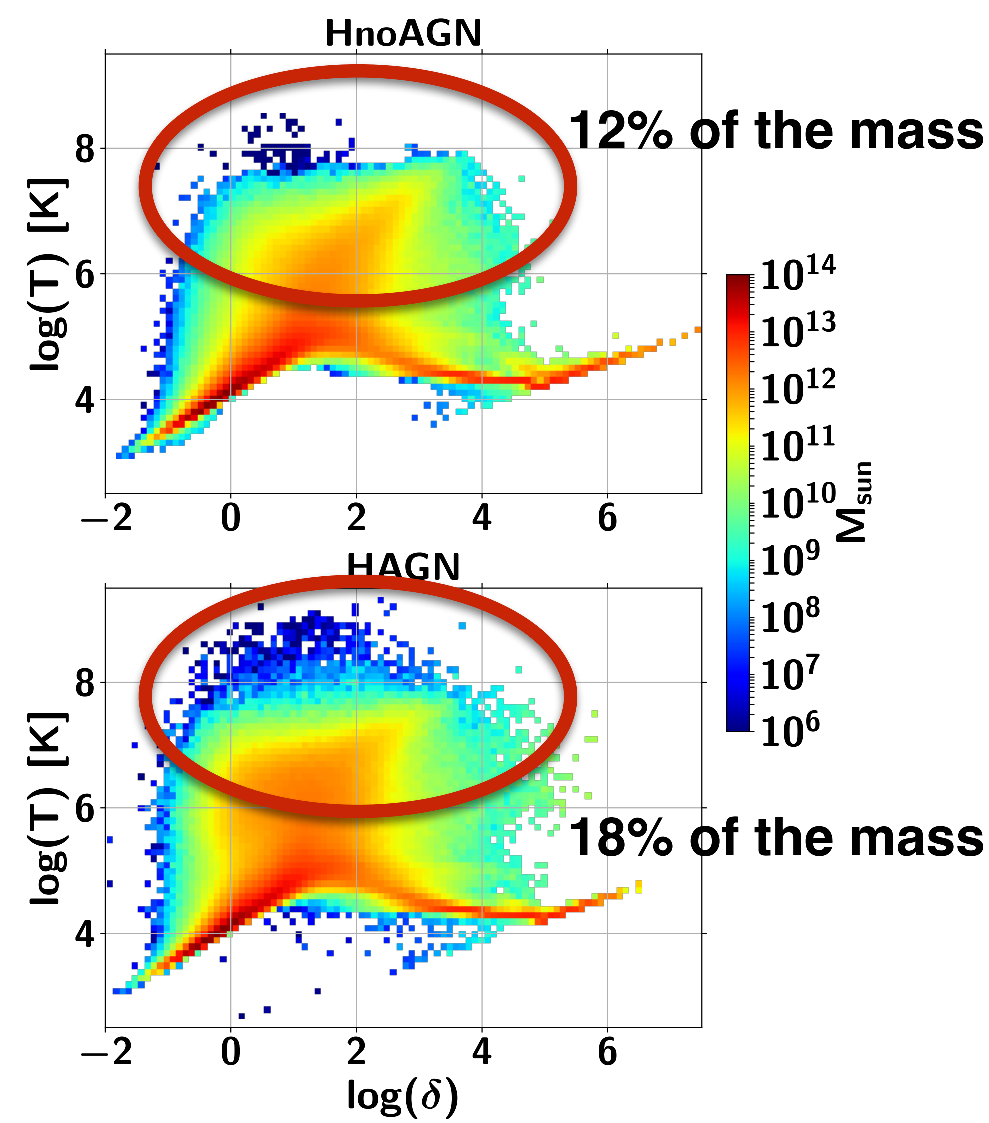
The Horizon-AGN suite of simulations

Impact of AGN feedback on $\mathrm{P}_{\mathrm{Ly}\alpha}$: suppression of power ? → **Efficient heating**

Temperature maps



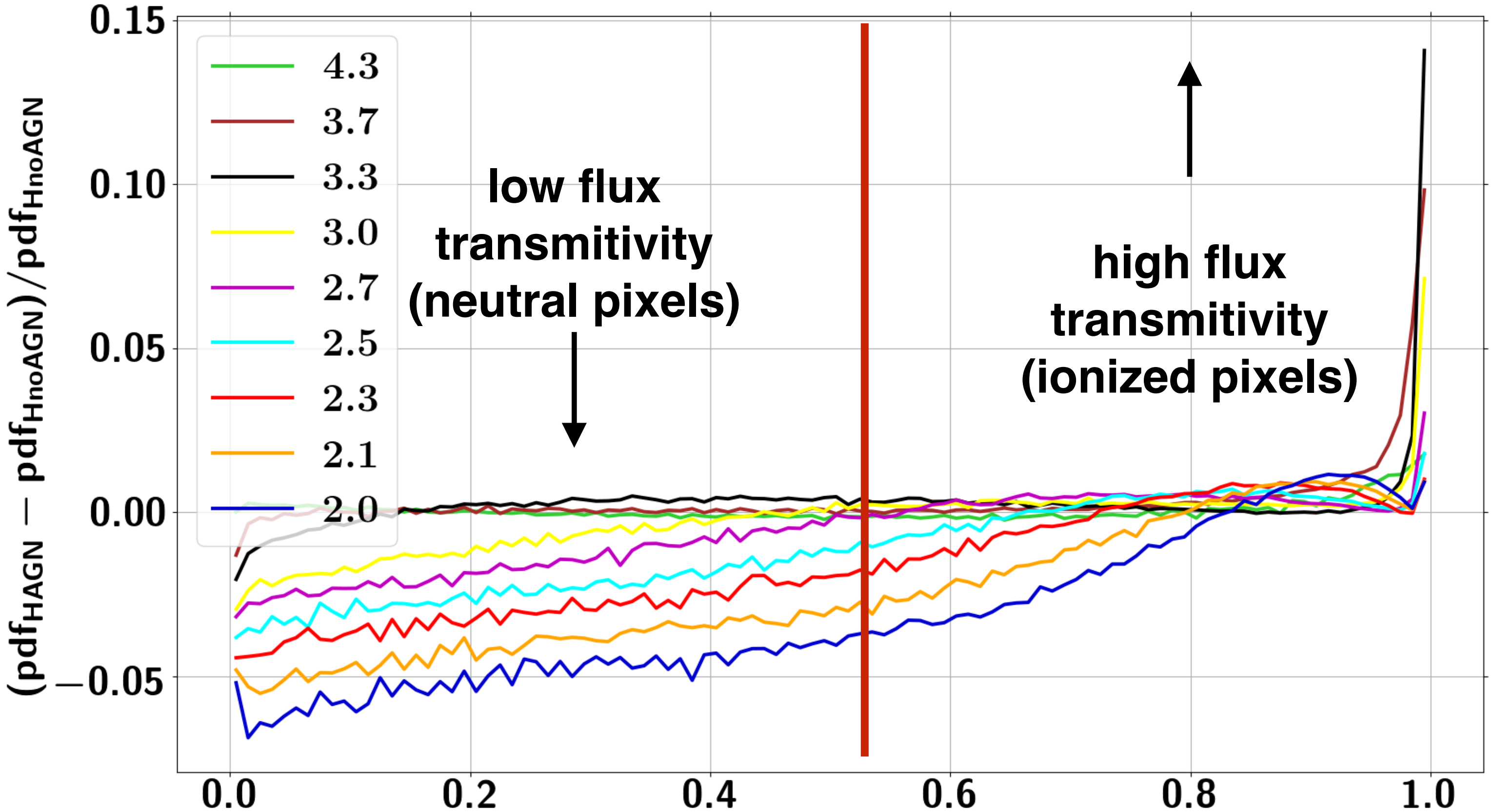
Temperature-density distribution



The Horizon-AGN suite of simulations

Impact of AGN feedback on $P_{Ly\alpha}$: suppression of power ? → **Efficient heating**

Differences in the flux probability distribution function



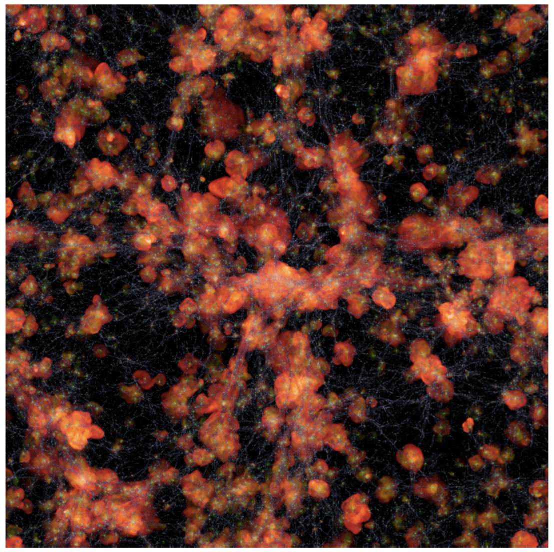
Heating → **ionization** → **suppression of power**

Resolution dependent

Thermal effects dominate over gas re-distribution effects

→ **Coupling between IGM resolution and AGN feedback correction ?**

The Extreme-Horizon simulation



- **Goal**: push resolution in the diffuse IGM (~90% of the simulation volume)
  → test systematic effects on the AGN feedback correction

- Proposed the Extreme-Horizon as a « **Grand Challenge** » on the brand new AMD partition of TGCC/Joliot-Curie

<u>Horizon-AGN simulation</u>
L = 100 Mpc/h
Number of resolution elements: **~ 4 billion**
4,096 CPUs
4 Mh

→ ***Doubling resolution everywhere*** *except inside galaxies where the resolution is kept unchanged*

<u>Extreme-Horizon simulation</u>
L = 50 Mpc/h
Number of resolution elements: **~ 18 billion**
25,000 CPUs
50 Mh

- Control simulation Standard-Horizon: at the HAGN resolution in EH volume

Minimal resolution SH/HAGN ↘ (48.8)
Minimal resolution EH ↙ (24.4)

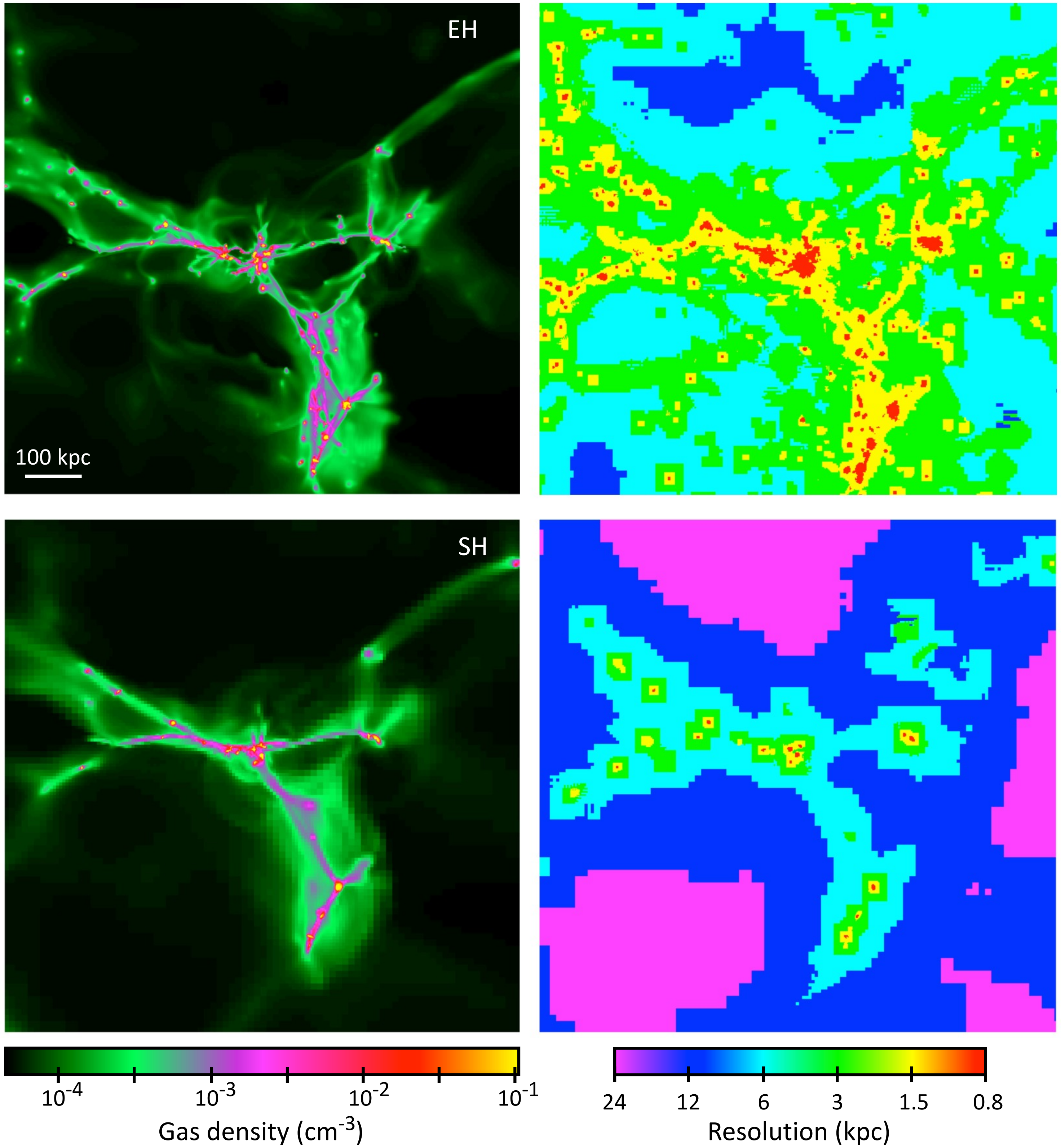
comoving grid resolution [kpc/h]	97.6	48.8	24.4	12.2	6.1	3.05	1.52	0.76
physical grid resolution [kpc]	47	23.5	11.7	5.8	2.9	1.5	0.7	0.3
volume fraction (EH) (z = 2)	–	45%	43%	10%	1%	0.04%	$z < 2$	$z < 2$
volume fraction (SH) (z = 2)	80%	17%	2%	0.17 %	0.013%	5×10^{-4}%	$z < 2$	$z < 2$
volume fraction (HAGN) (z = 2)	77%	19%	2%	0.2 %	0.01%	6×10^{-4}%	$z < 2$	$z < 2$

The Extreme-Horizon simulation

Chabanier et al. 2020b

Extreme-Horizon z ~ 3

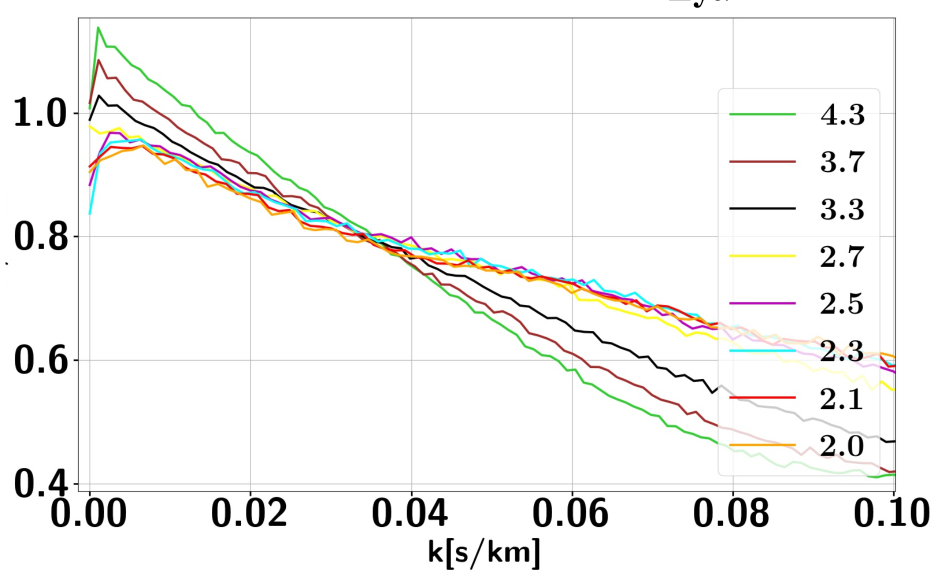
Standard-Horizon z ~ 3



The Extreme-Horizon simulation

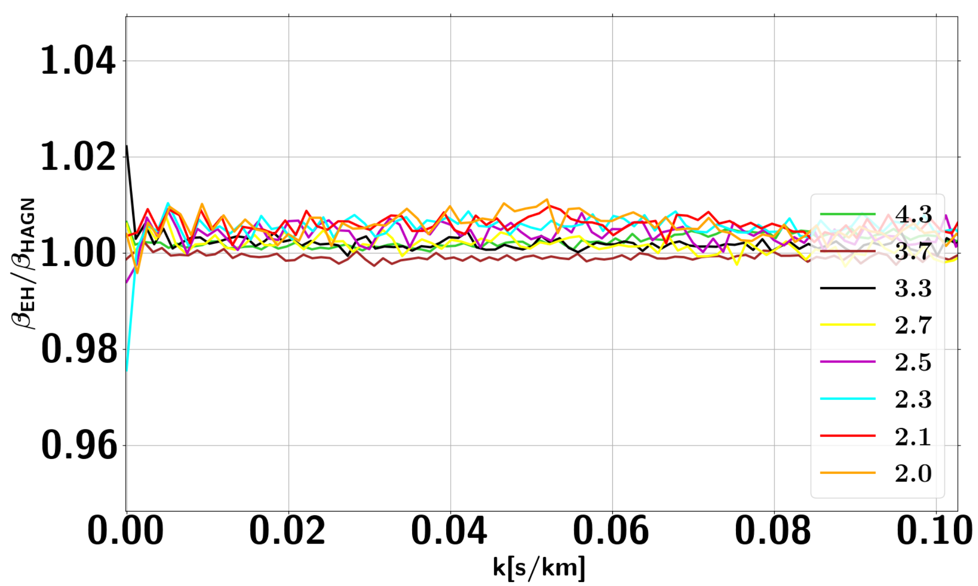
Resolution effects

Resolution effects on $\mathbf{P_{Ly\alpha}}$



Large effects, especially at small scales
→ $P_{Ly\alpha}$ are not converged in absolute

Resolution effects on AGN feedback correction



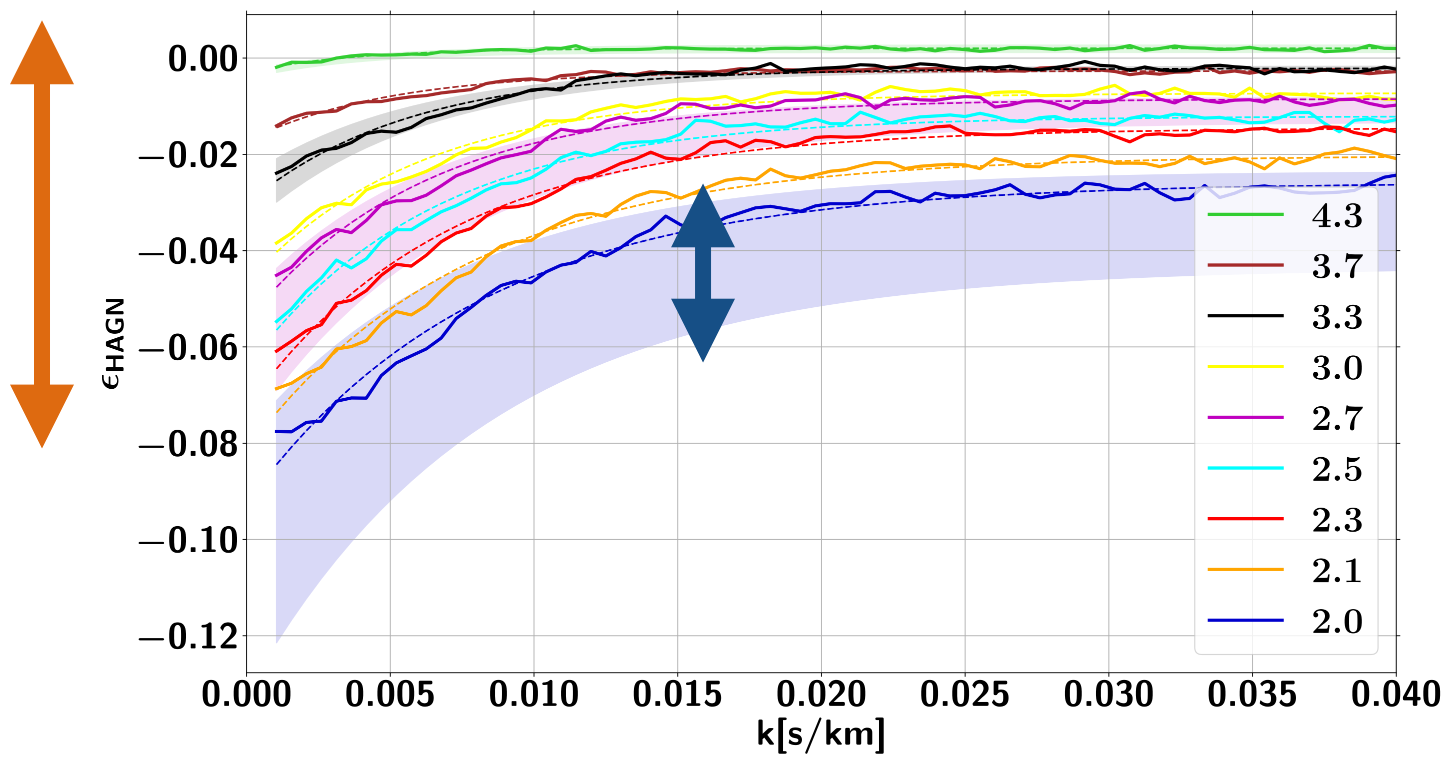
Differences well below the percent level
→ **AGN feedback corrections are converged**

The Horizon-AGN suite of simulations

Impact on cosmological parameters

AGN feedback bias

Feedback calibration and modeling uncertainty



$$\frac{\Delta n_s}{n_s} \sim 2\sigma_{n_s,eBOSS} \pm 0.8\sigma_{n_s,eBOSS}$$

$$\frac{\Delta \sigma_8}{\sigma_8} = 1\sigma_{\sigma_8,eBOSS} \pm 0.25\sigma_{\sigma_8,eBOSS}$$

AGN feedback are not negligible given the level of precision reached by Lya data

$$\sigma_{DESI} \ll \sigma_{eBOSS}$$

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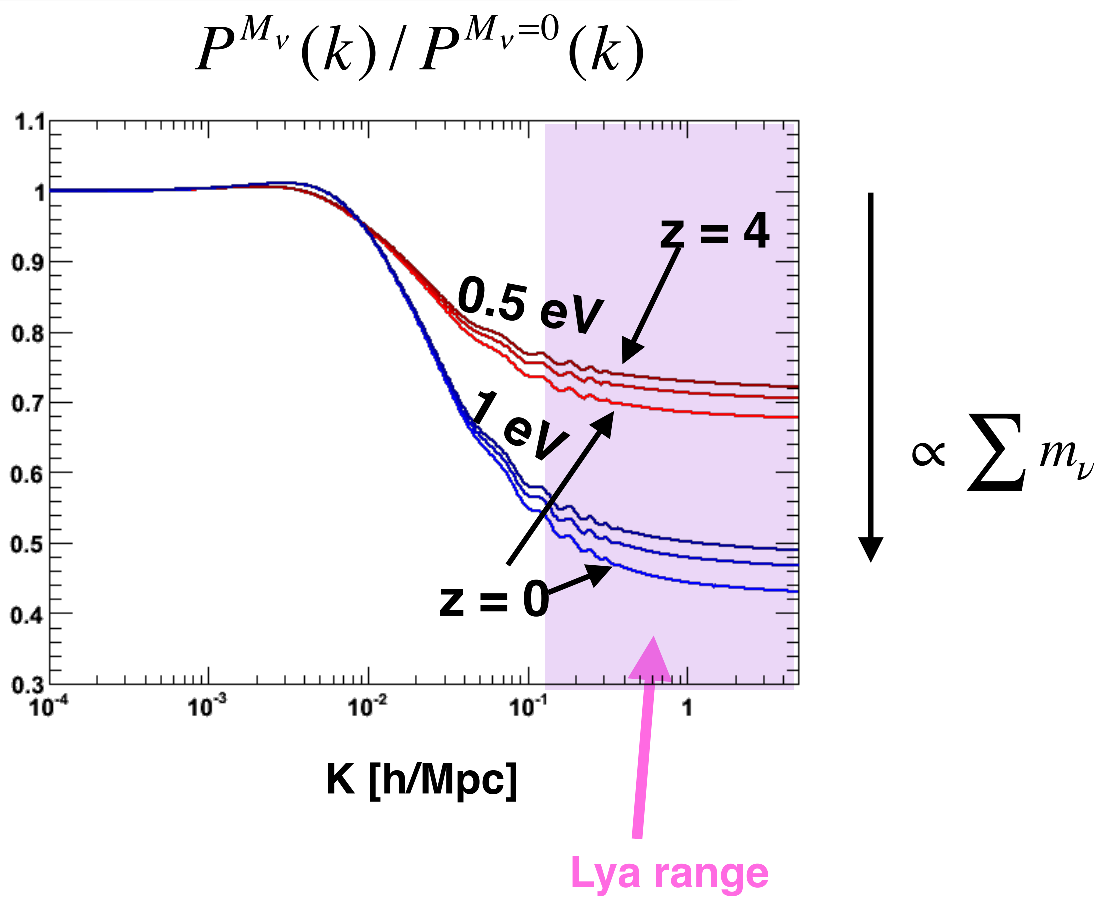
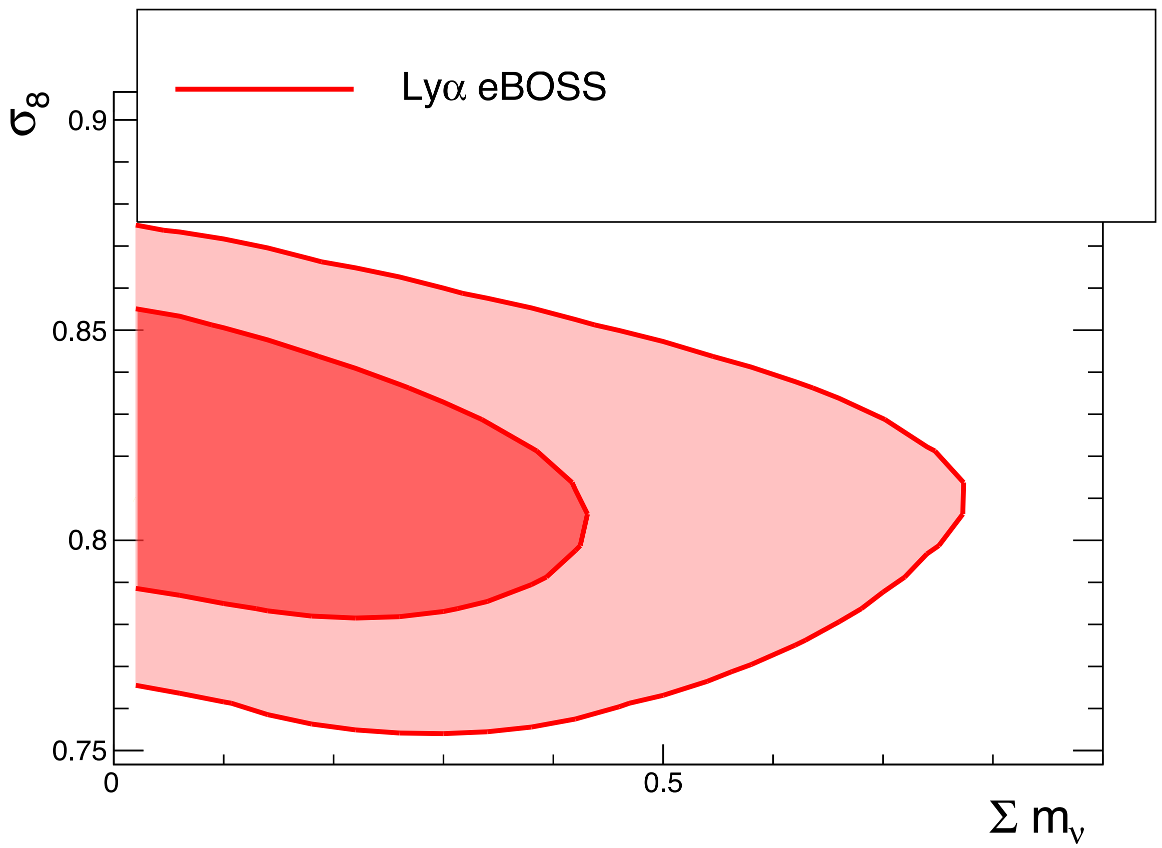
Sum of neutrino masses



Palanque-Delabrouille et al. 2020

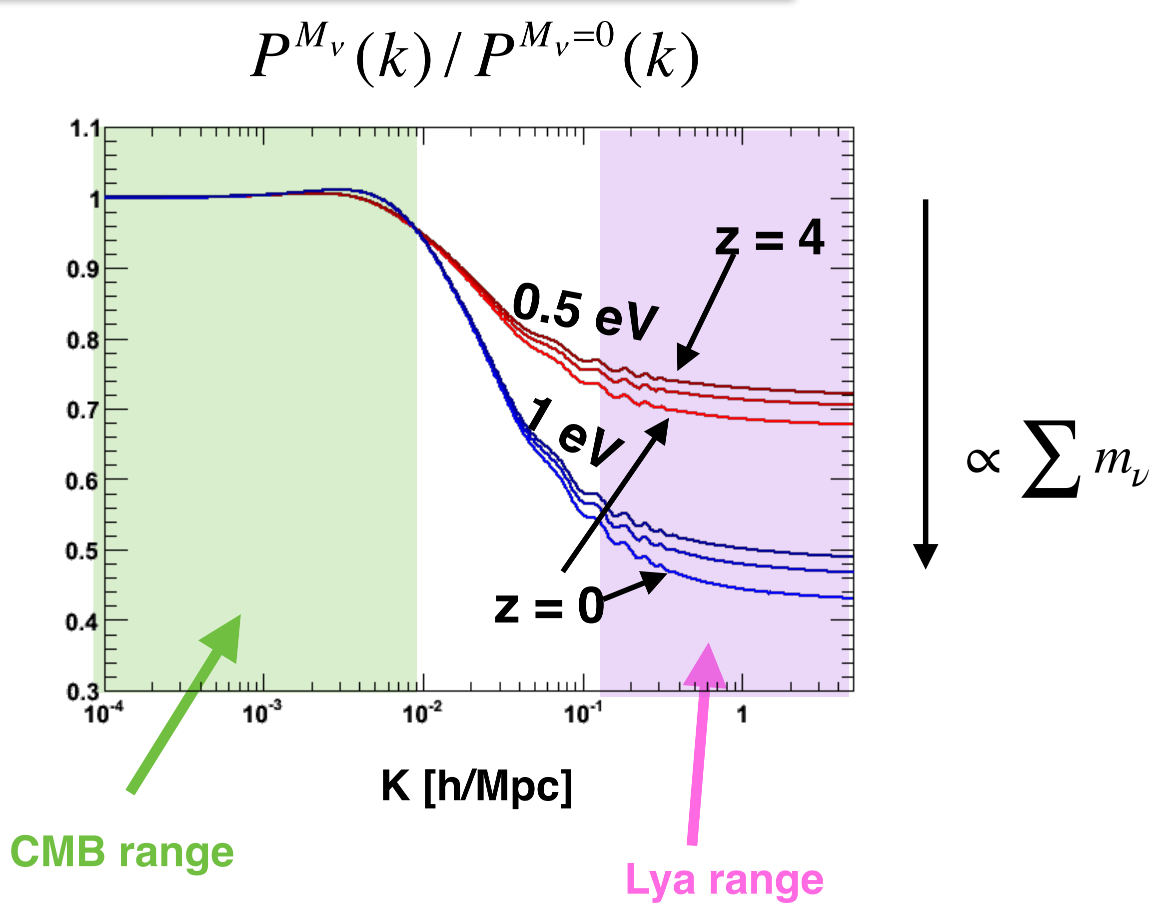


- Lya alone: power suppression + z-dependence ⟶ $\sum m_\nu < 0.58$ eV @ 95% CL

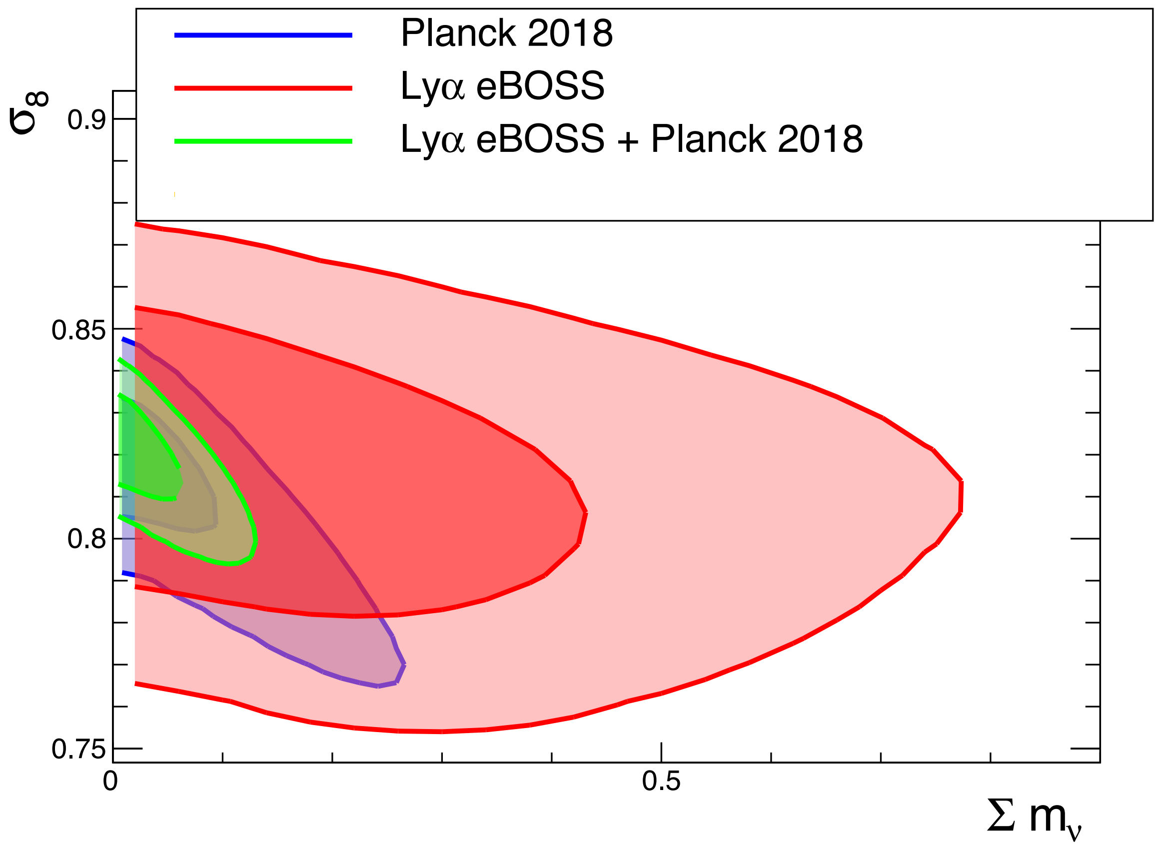
⟶ **factor 2 improvement compared to BOSS**

but **large degeneracy** $\sigma_8 - \sum m_\nu$

Sum of neutrino masses



Palanque-Delabrouille et al. 2020



- Lya alone: power suppression + z-dependence → $\sum m_\nu < 0.58$ eV @ 95% CL

→ factor 2 improvement compared to BOSS

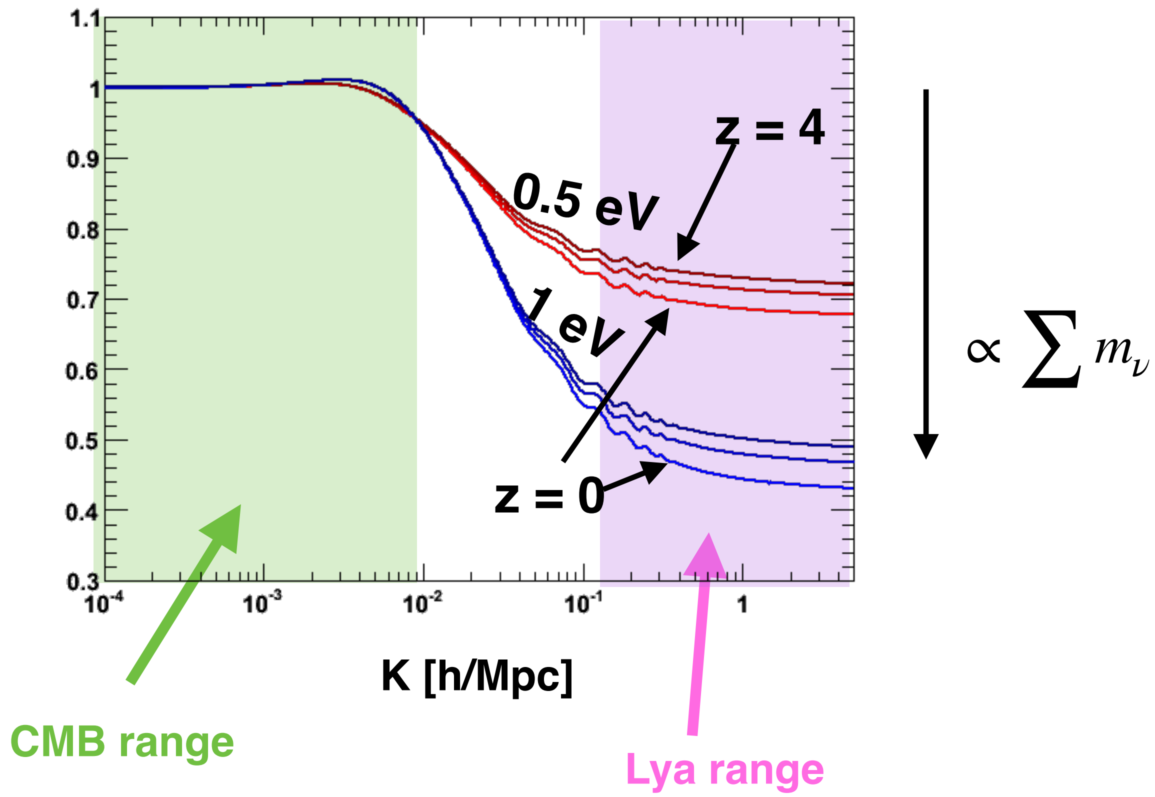
but **large degeneracy** $\sigma_8 - \sum m_\nu$

- Lya + CMB: sensitive to amplitude suppression → $\sum m_\nu < 0.105$ eV @ 95% CL

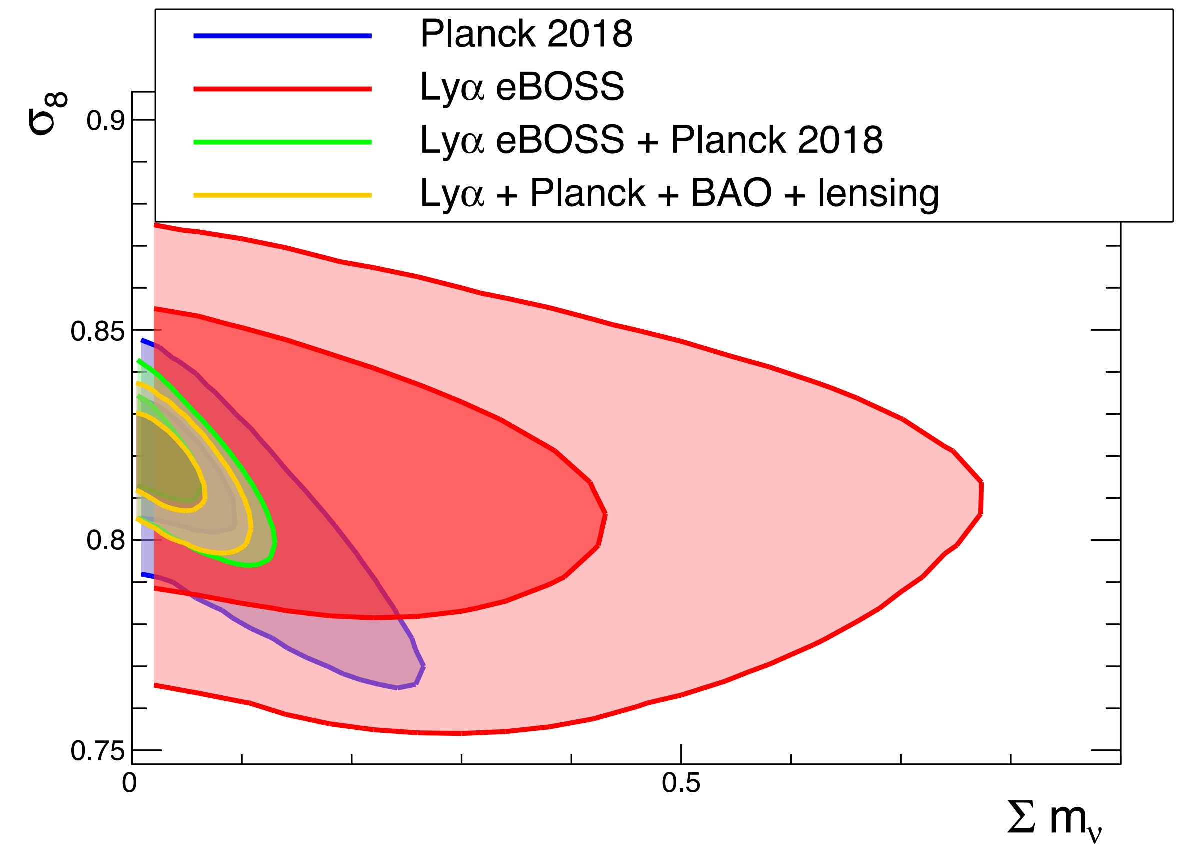
→ **Combination breaks degeneracy** and significantly tightens the constraint

Sum of neutrino masses

$$P^{M_\nu}(k) / P^{M_\nu=0}(k)$$



Palanque-Delabrouille et al. 2020



- Lya alone: power suppression + z-dependence ⟶ $\sum m_\nu < 0.58$ eV @ 95% CL

  ⟶ factor 2 improvement compared to BOSS

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- Lya + CMB: sensitive to amplitude suppression ⟶ $\sum m_\nu < 0.105$ eV @ 95% CL

  ⟶ Combination breaks degeneracy and significantly tightens the constraint

- Lya + CMB + BAO + lensing: ⟶ $\sum m_\nu < 0.089$ eV @ 95% CL

  ⟶ **Among the strongest constraints to date**
  marginal tensions on the inverted neutrino mass hierarchy $\left(\sum m_{\nu,min} = 0.095 \text{ eV}\right)$

Warm Dark Matter

- **Early decoupled thermal relics:**
  - Initially in thermal equilibrium
  - Additional contribution to the effective number of radiative species $\rho_{\mathrm{rad}} \propto (\mathrm{N_{eff}} + \Delta\mathrm{N_{eff}})\rho_\gamma$
  - Decoupled during the radiation era $\mathrm{T_{dec}} \gg 100\ \mathrm{GeV}$ while **relativistic**

  → suppress power below free-streaming scale $\lambda_{\mathrm{FS}} \propto m_X^\alpha \Delta N_{eff}^\beta$

- **Sterile neutrinos**
  - Insensitive to all fundamental interactions except gravity
  - Generic production mechanism: through oscillation with standard neutrinos

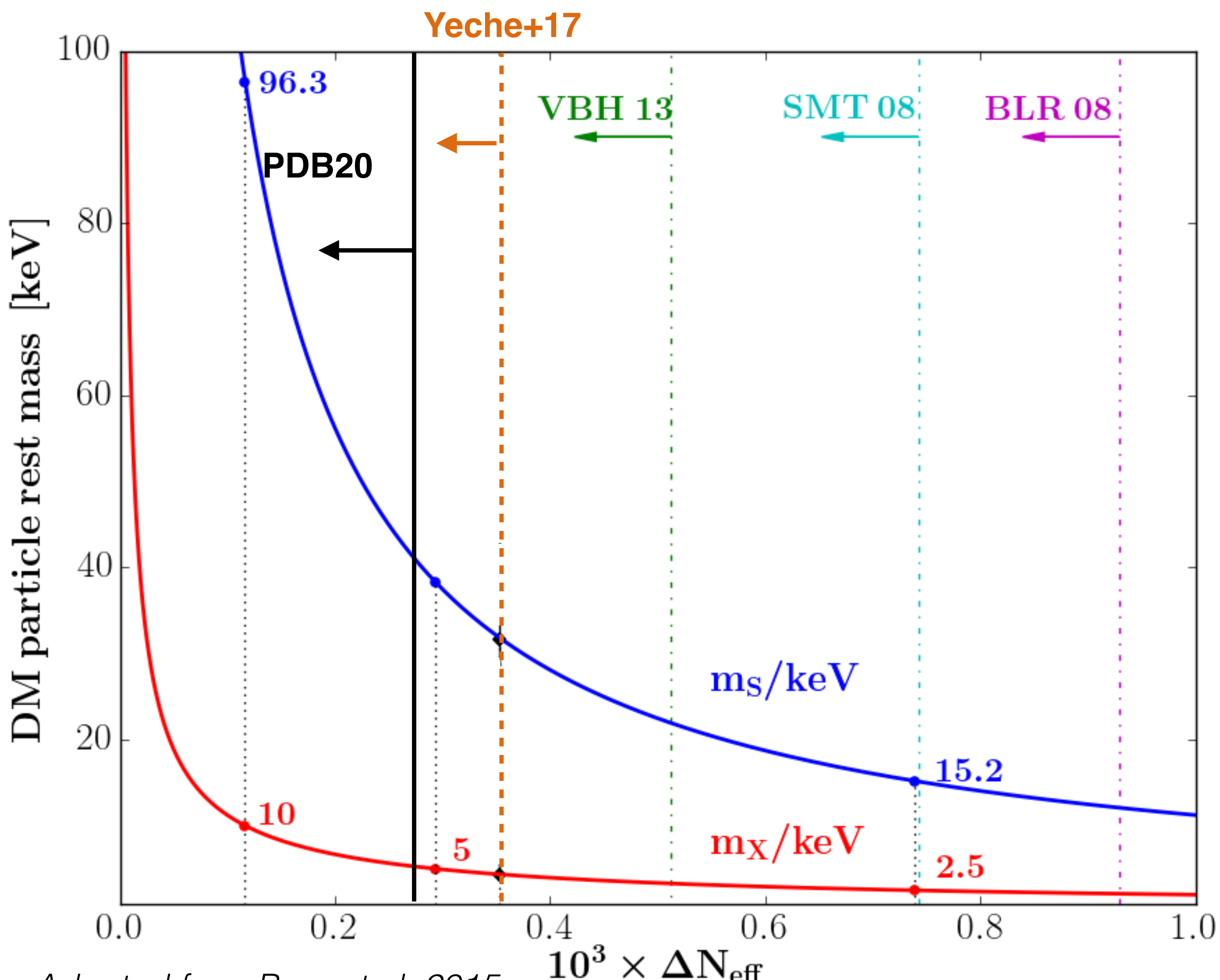
- Direct mapping between the two models: *(non-resonant production)*

$$\Omega_{\mathrm{DM}} \cdot m_{\nu_s}^3 \propto m_X^4$$

Sterile neutrino mass *Thermal relics mass*

Warm Dark Matter

Authorized parameter space $\mathrm{m_{WDM} - N_{eff}}$



Adapted from Baur et al. 2015

100 high-resolution quasar spectra (resolution 3-5 times better than SDSS)

- eBOSS Lya + XQ-100 (high-res)
  Palanque-Delabrouille et al.20

$$m_X > 5.3\ \mathrm{keV}$$

$$m_{\nu_s} > 34\ \mathrm{keV}$$

- X-rays observations give
  Boyarsky et al. 2007

$$m_{\nu_s} < 4\ \mathrm{keV}$$

Sterile neutrinos

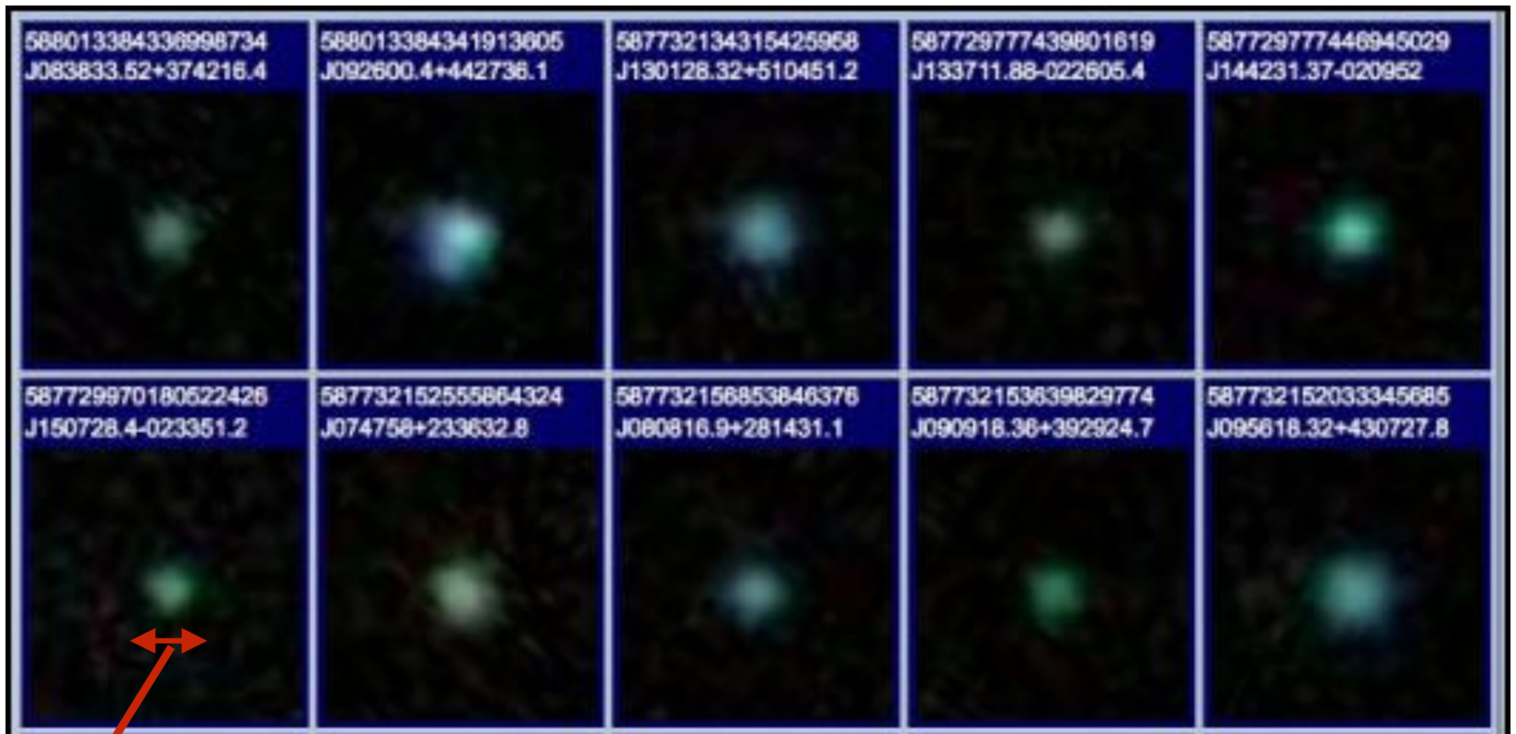
Thermal relics

→ **Strongest limits** on warm dark matter models

Non-resonantly produced sterile neutrinos excluded as pure warm dark matter

Unexpected results: Massive compact galaxies

Massive compact and star forming galaxies with the Hubble Space Telescope



Cardamone et al. 2009

Effective radius: 1-2 kpc while 10 kpc for the Milky Way

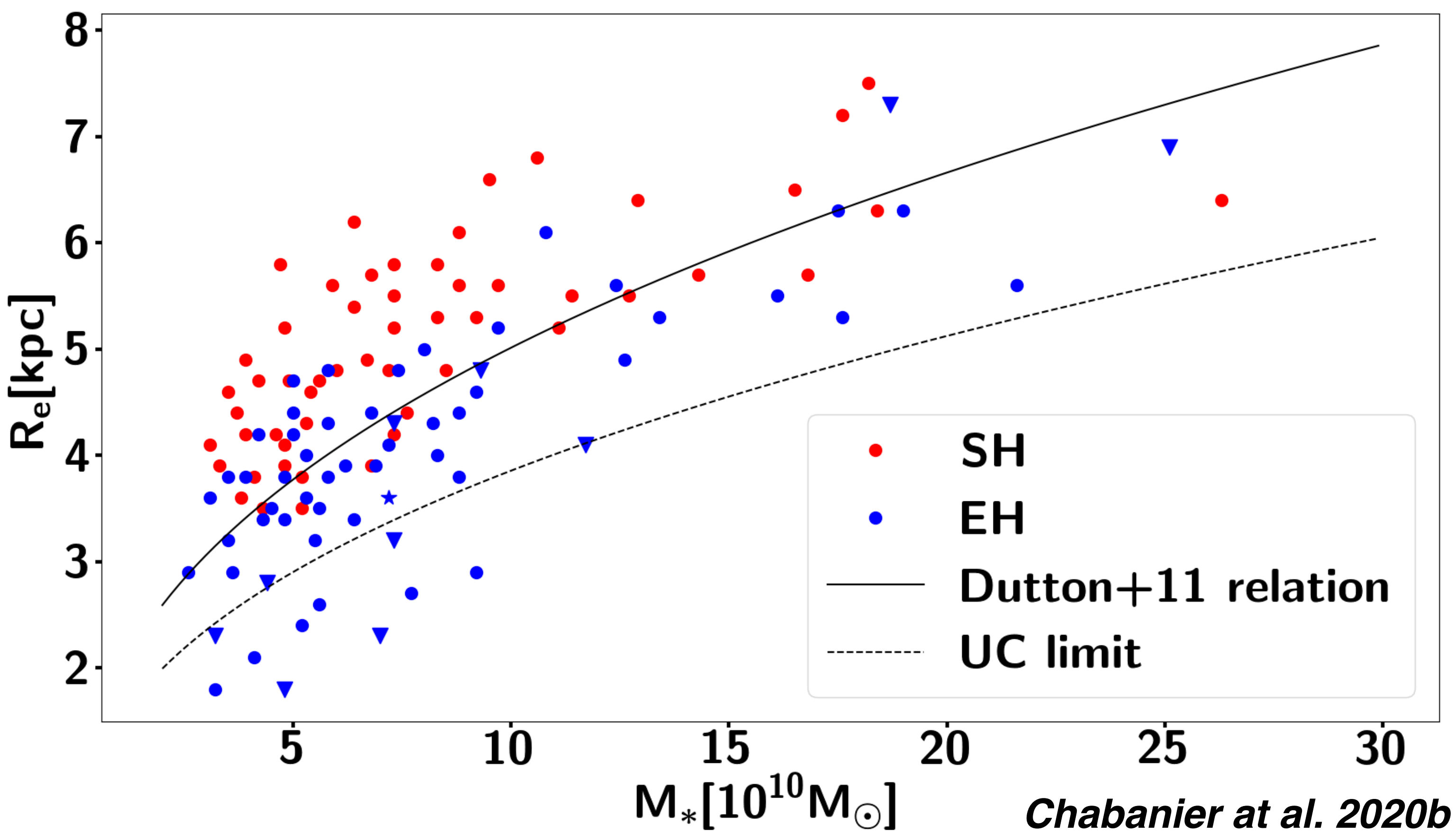
- High redshift galaxies are **more compact** than low-redshift galaxies
  Daddi et al. 2005, Kriek et al. 2009, Dutton et al. 2011, Elbaz et al. 2018

- Population of **very compact star-forming** galaxies at z=2 : « blue nuggets »
  Barro et al. 2013, Williams et al 2014

→ Compaction mechanism still highly debated

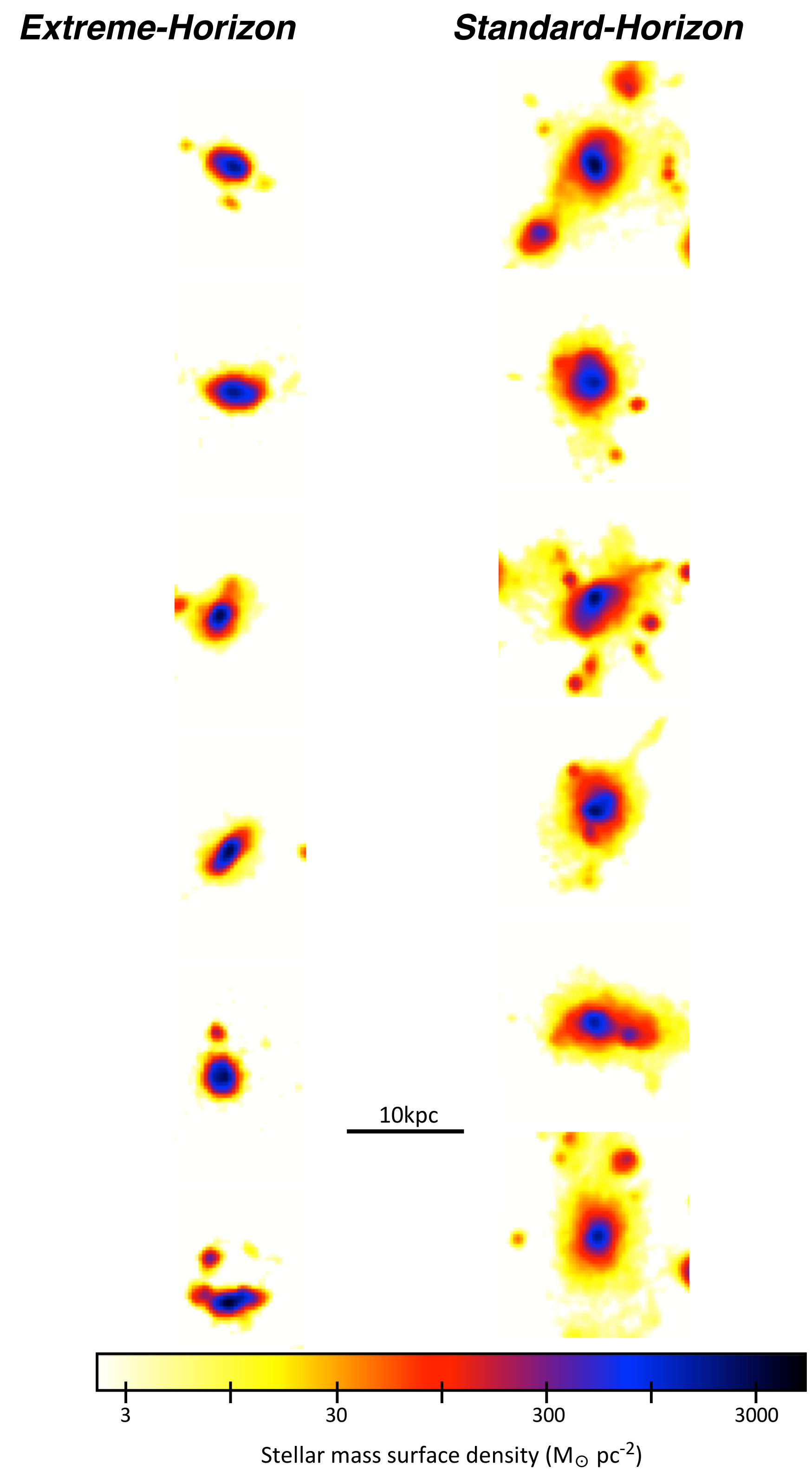
Unexpected results: Massive compact galaxies

Size - Mass relation of massive galaxies



Chabanier at al. 2020b

Stellar mass surface density of a sample of massive galaxies



At z = 2 in the Extreme-Horizon simulation:

1) More compact massive galaxies

2) Population of ultra-compact galaxies

Unexpected results: Massive compact galaxies

Compaction mechanism: improved modeling of cold gas flows accretion

Difference in size of 10-20%

Difference in size of a few %

Difference in specific angular momentum of inflowing gas of massive galaxies

Galaxy samples	Mean difference in $\mathcal{L}_{in}$
EH vs. SH	13% lower
EH-NUC vs. SH	10% lower
EH vs. SH at $M_* < 10^{11}$ M$_\odot$	12% lower
EH-UC vs. EH-NUC at $M_* < 10^{11}$ M$_\odot$	3% lower

utra-compact

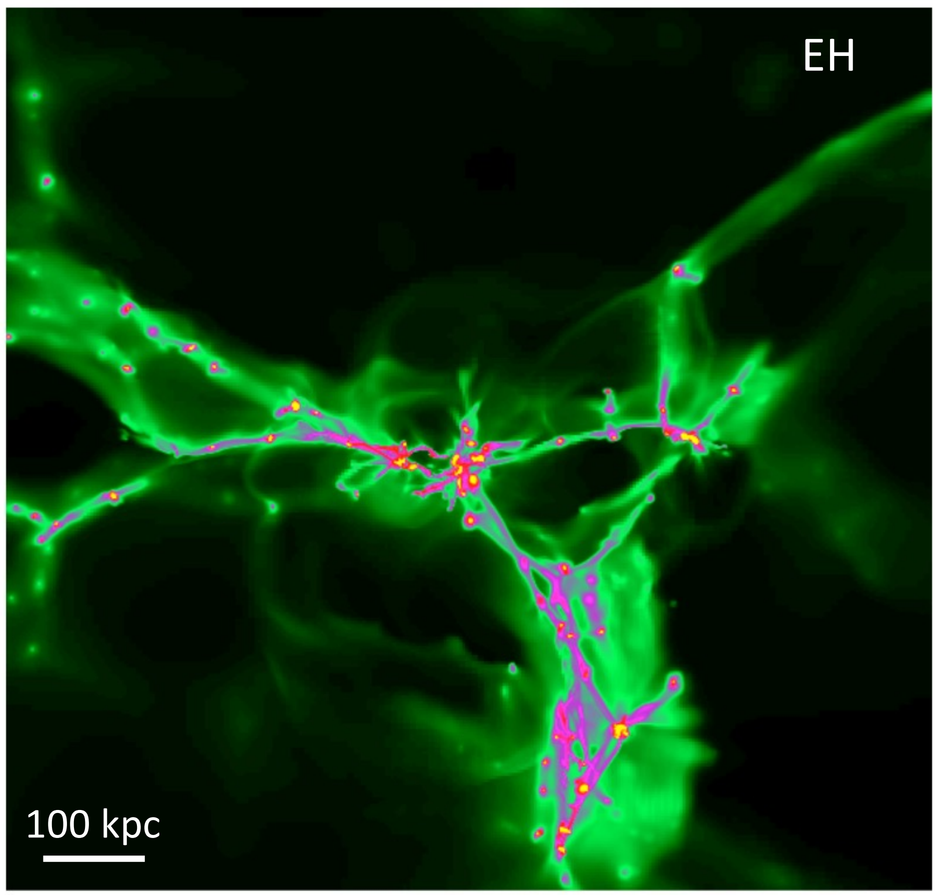
non utra-compact

Improved resolution of inflowing gas results in lower angular momentum:

- Accounts for smaller size of massive galaxies in EH
- But is not sufficient to explain Ultra-Compact galaxies

Unexpected results: Massive compact galaxies

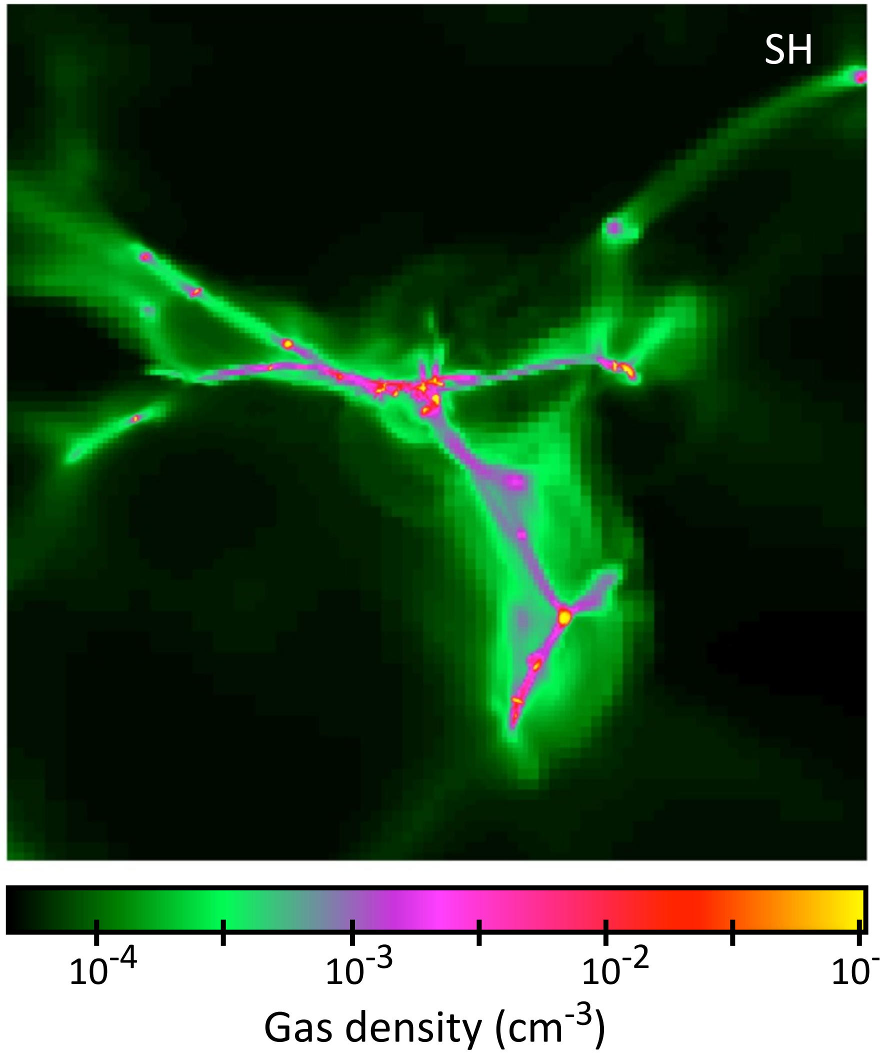
Extreme-Horizon z ~ 3



Chabanier at al. 2020b

EH forms earlier low-mass galaxies

Standard-Horizon z ~ 3



ultra-compact: repeated major mergers of low-mass progenitors

→ independently of feedback mechanisms

Conclusion and prospectives

- The Lya forest is a powerful probe for cosmology

  → *Neutrino masses, warm dark matter, expansion, growth*

- **Unprecedented level of precision** of the Lya power spectrum with eBOSS data (1% at low redshifts)

- Major **improvement of theoretical predictions** with hydrodynamical simulations

- Constraints on

  - Neutrino masses: $\sum m_\nu < 0.105 \text{ eV}$ from Lya + CMB among the better constraints to date

  - Sterile neutrinos: $m_{\nu_s} > 34 \text{ keV}$ outreach previous constraints

- Formation of ultra-compact galaxies in EH

- Prospects:
  - Lya power spectrum with DESI data
  - Numerical modeling of the Lya forest
    construction of grid, 3D power spectrum parametrization, convergence between hydro codes
  - Galaxy formation and evolution models: Can EH help alleviating issues in early-quenching of galaxies (and possibly formation of barred galaxies) ?