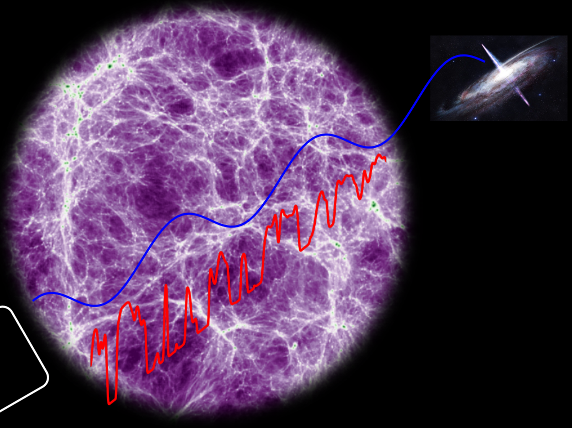
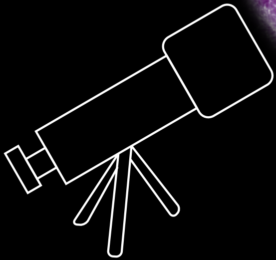
What Lyman-α data tell us about Dark Matter



Vid Iršič

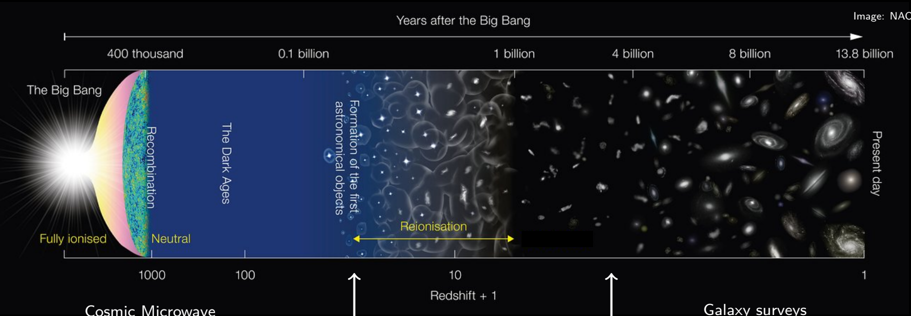
University of Hertfordshire



News from the Dark 10

Montpellier September, 2025

Cosmic Epochs



Cosmic Microwave Background

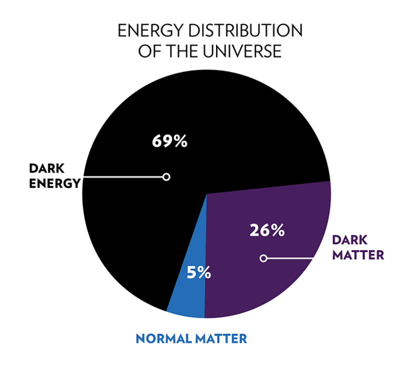
First stars & galaxies

Peak of the star-formation

Galaxy surveys

Big Open Questions

- Nature of Dark Matter
- Nature of Dark Energy
- Inflation / Initial Conditions



Big Open Questions

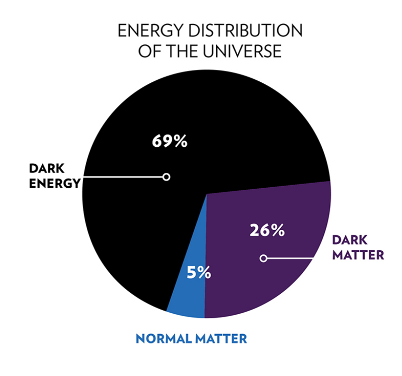
- Nature of Dark Matter

What can we learn from Ly-α data about Dark Matter?

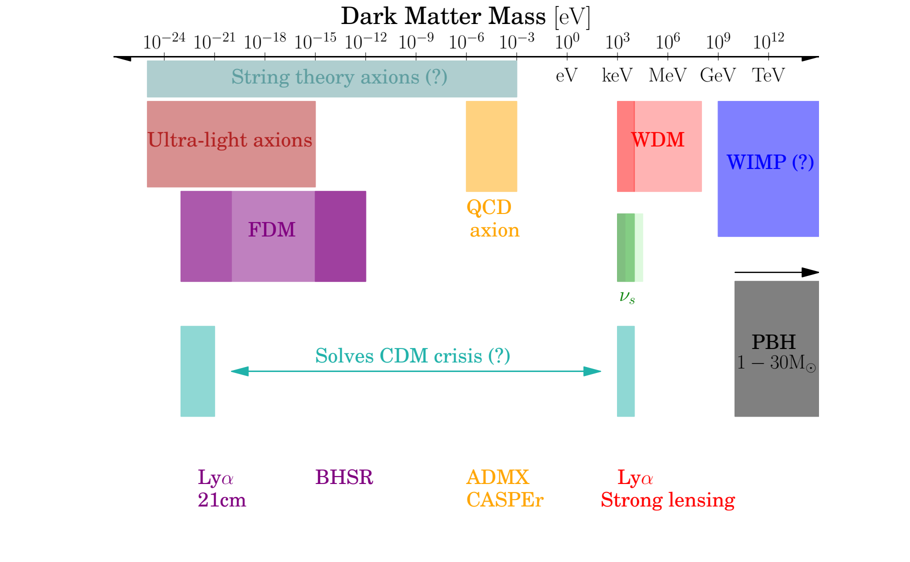
How is it affecting formation of structures in the Universe?

Can we differentiate between different Dark Matter models?

What is the outlook for the future?

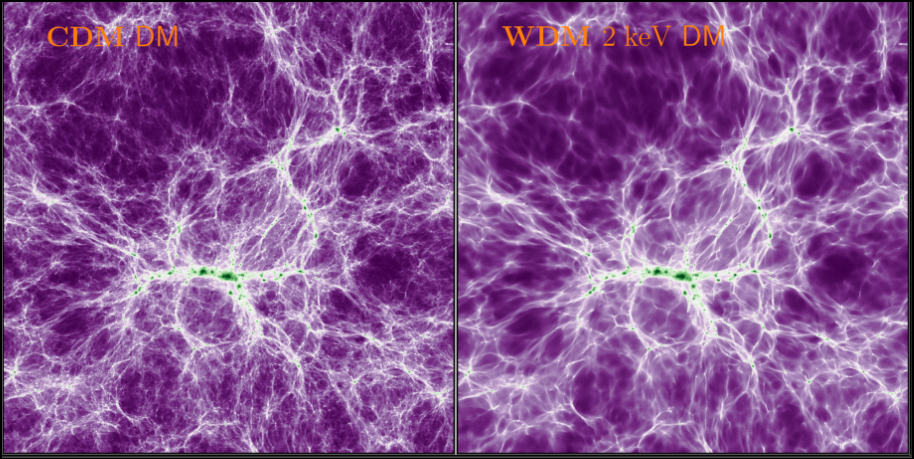


Where to look for DM?



- Mass range of theoretical models is very large
- composite/mixed DM, self-interaction, decay rate, SM interaction, production channels, ...

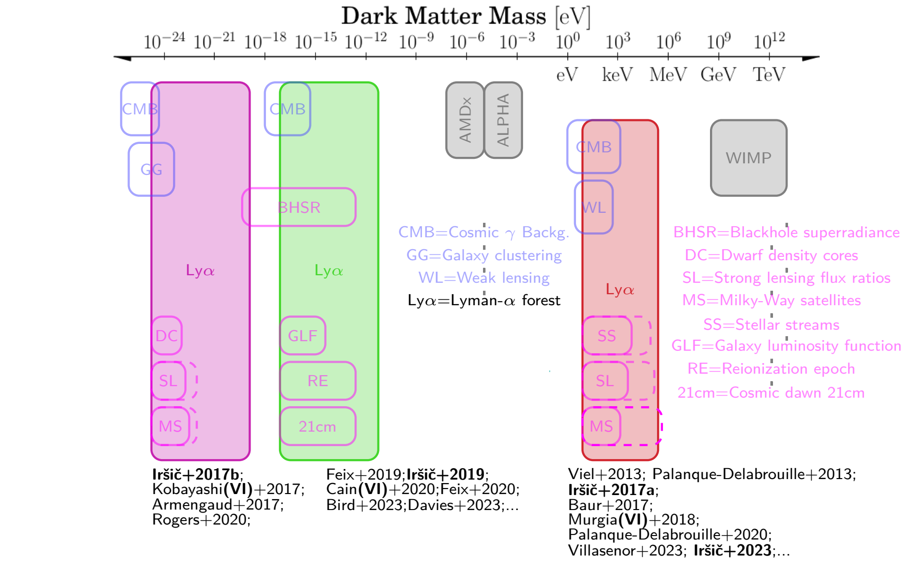
non-CDM erases small scale structure



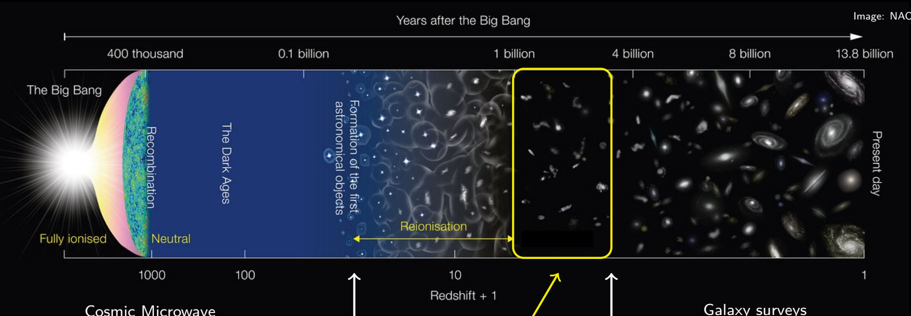
Cold Dark Matter (CDM):
Lots of small-scale structure

Warm Dark Matter (WDM):
Free-streaming of DM particles
(From the time they decouple
until they become non-relativistic)

Astrophysical Laboratories



High-z Cosmic Web



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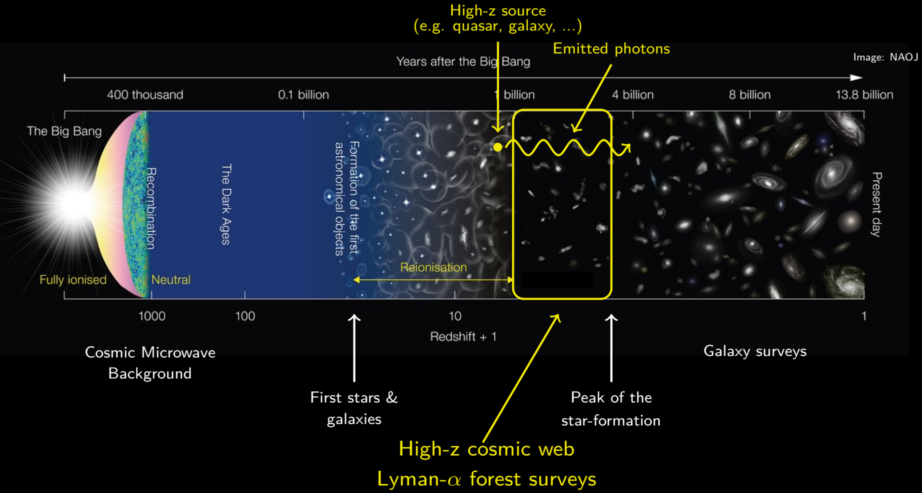
High-z Cosmic Web



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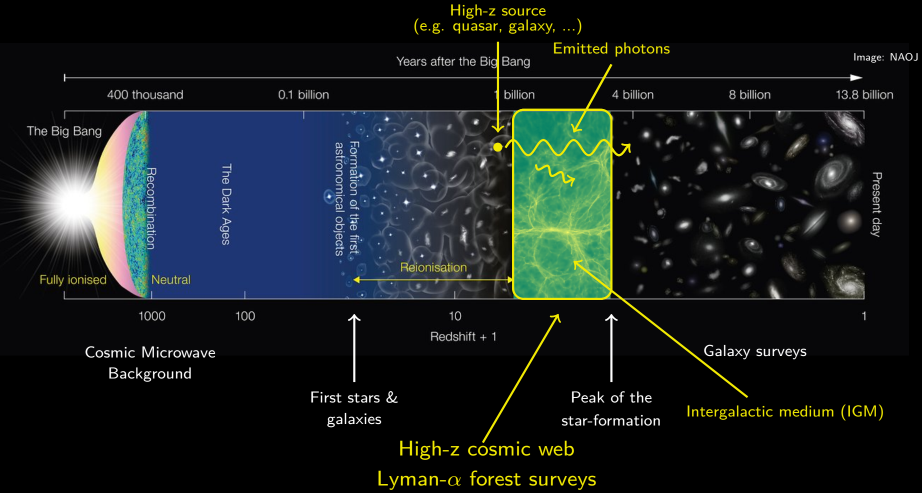
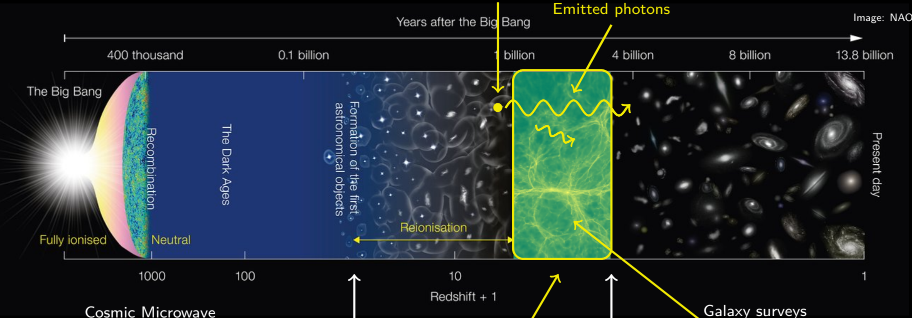


High-z Cosmic Web

High-z source
(e.g. quasar, galaxy, ...)

Emitted photons

Image: NAOJ



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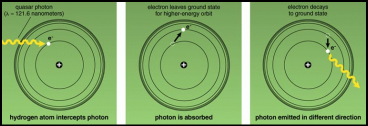
Intergalactic medium (IGM)

Ly-α scattering $(\gamma + e^-)$
$n = 1 \rightarrow 2$ in neutral hydrogen

High-z cosmic web

Lyman-α forest surveys



High-z Cosmic Web

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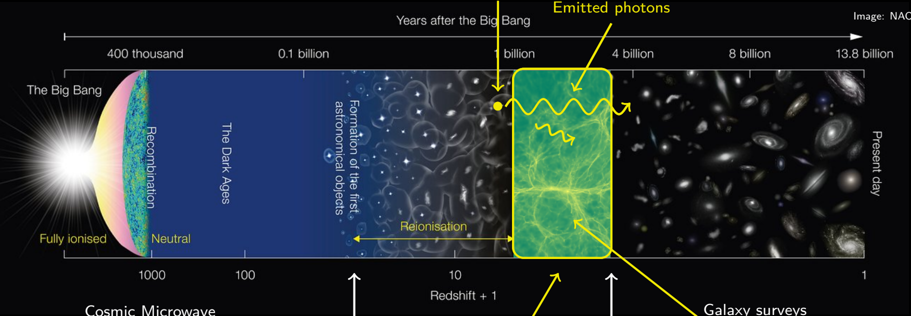

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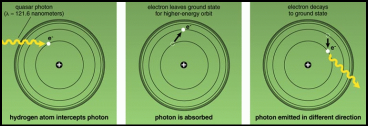
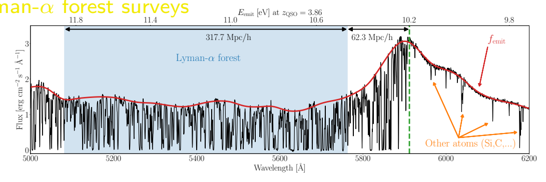
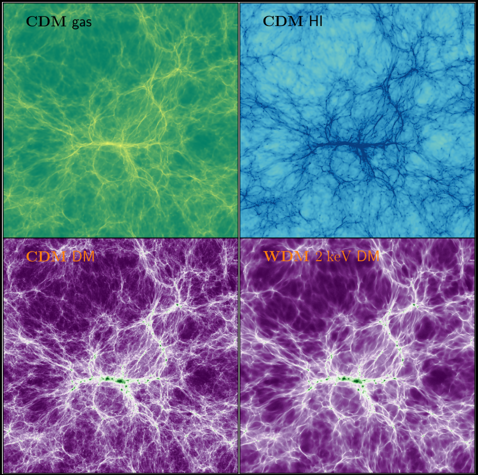




Lyman-α forest



Transmission = exp(- optical depth)

Optical depth:

$$\tau = \int n_{\mathrm{HI}}\, \sigma_\alpha(\nu)\, ds$$

Lyα $\propto \delta_{\mathrm{gas}} \propto \delta_{\mathrm{dm}}$

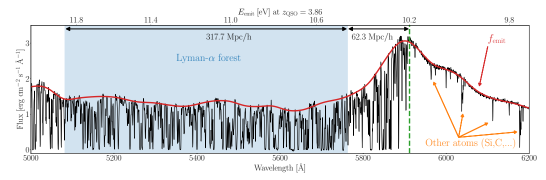
- Volume weighted
- Sensitivity to $1 + \delta_{\mathrm{gas}} \sim 0.5 - 5$

Astrophysics can be modelled!

heating and cooling of gas

+ H,He ionization

+ gravity



Lyman-α as a tracer of matter

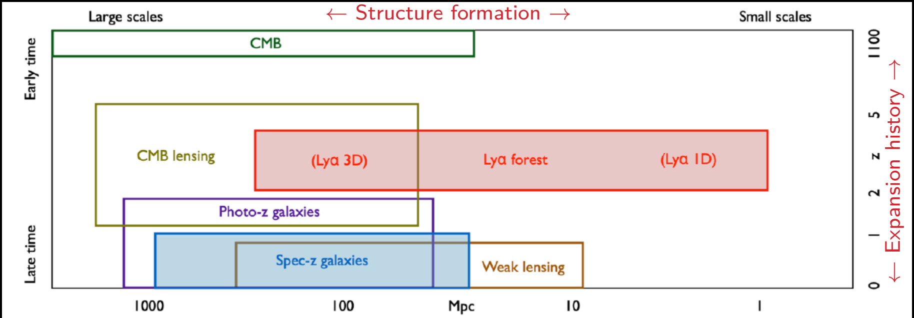


Image: A. Font-Ribera

Lyman-α forest:

- High-redshift tracer of matter
- Sensitive to mostly mean density $\Delta = \rho/\bar{\rho} \sim 0.5 - 5$
- Access to a wide range of scales (~ 0.07 Mpc to ~ 700 Mpc)
- Astrophysics can be simulated or modelled

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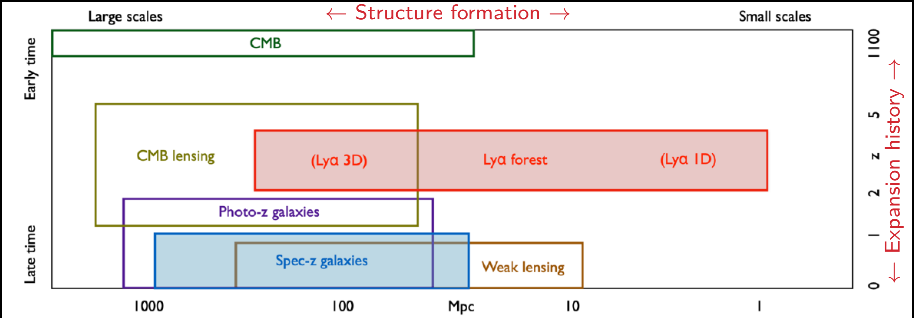

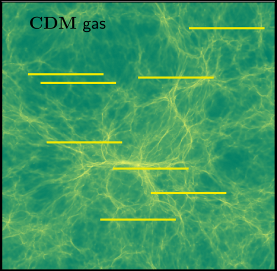

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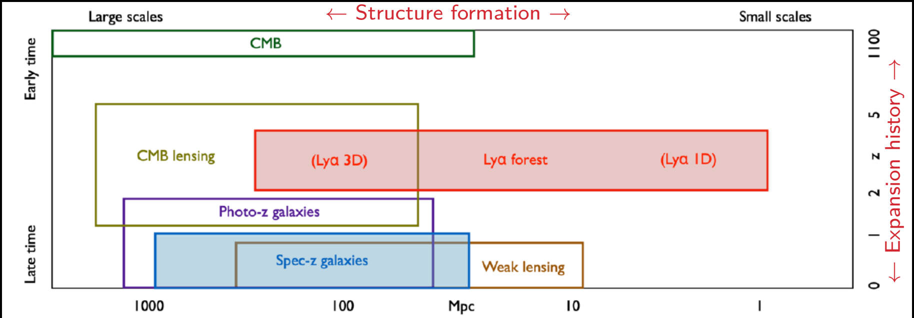

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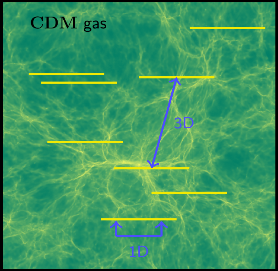

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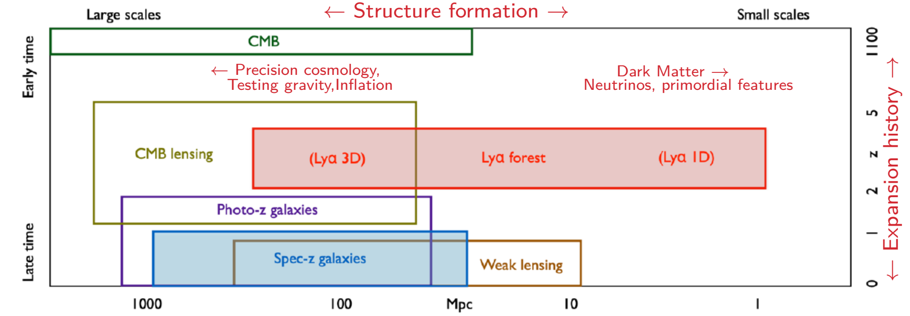

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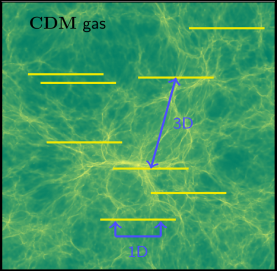
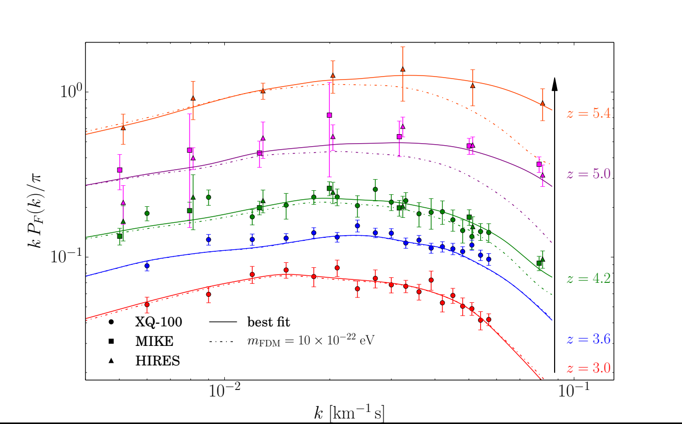


1D Lyman-α forest surveys



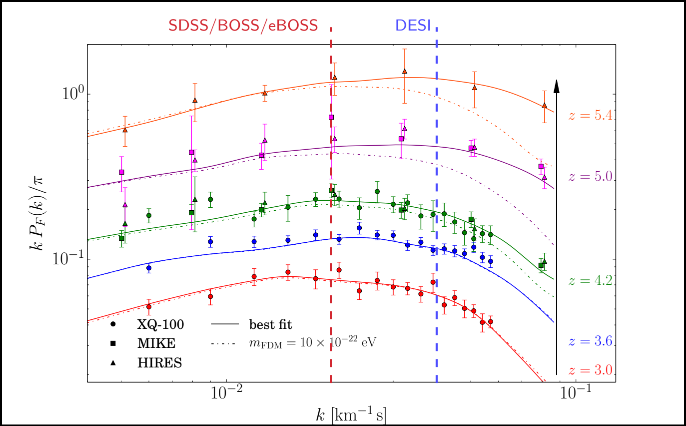
1D Lyman-α forest:

- High-redshift tracer of matter $(2 < z < 5.5)$
- Sensitive to mostly mean density $\Delta = \rho/\bar{\rho} \sim 0.5 - 5$
- Projected tracer $(k_{\parallel})$

1D Lyman-α forest surveys

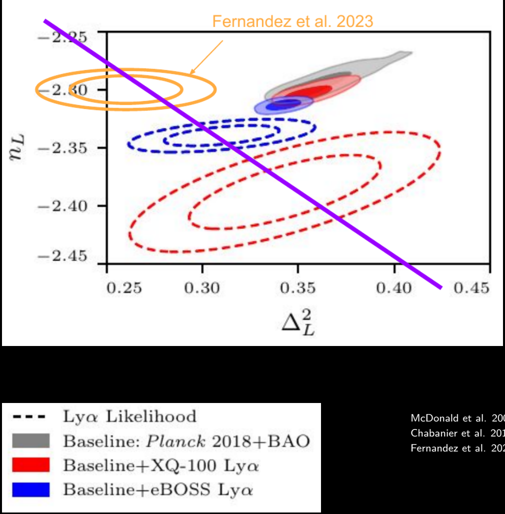
- BOSS, eBOSS, DESI, ... > 1 Mpc/h

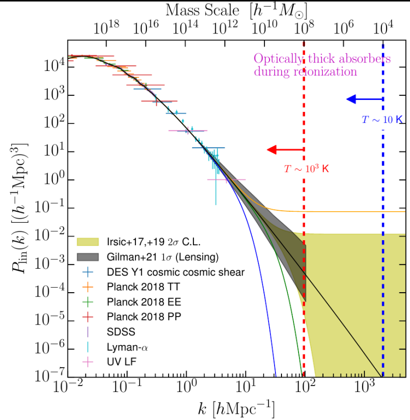
$\rightarrow$ Limited by resolution of the instrument



1D Lyman-α forest surveys

- BOSS, eBOSS, DESI, ... > 1 Mpc/h





McDonald et al. 2005; **Irsic** et al. 2017b; Yeche et al. 2017; Pedersen et al. 2023; Esposito, **VI** et al. 2022
Chabanier et al. 2019; Palanque-Delabrouille et al. 2020; Goldstein, **VI** et al. 2023; Rogers & Poulin 2024
Fernandez et al. 2024; Walther et al. 2025

1D Lyman-α forest surveys

- BOSS, eBOSS, DESI, ... > 1 Mpc/h

- High-resolution instruments

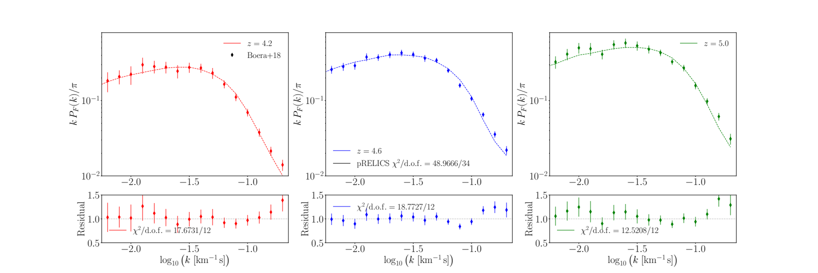
→ UVES, HIRES, XSHOOTER,

ESPRESSO, ELT/ANDES, ...

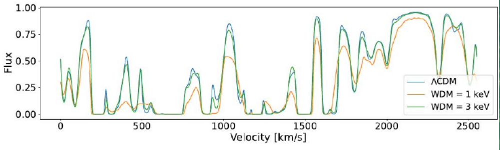
→ Limited by the statistics

(e.g. $\sim 10 - 100$ spectra)

Viel et al. 2013; Baur et al. 2015
Irsic et al. 2017ab; Armengaud et al. 2017; Kobayashi, **VI** et al. 2017; Murgia, **VI** et al. 2018;
Murgia et al. 2019; **Irsic** et al. 2020; Hooper et al. 2022; Garny et al. 2022; Fuß et al. 2022;
Garzilli et al. 2019; Rogers et al. 2020; Villasenor et al. 2023;
Irsic et al. 2024; Garcia-Galego, **VI** et al. 2025



Nature of Dark Matter



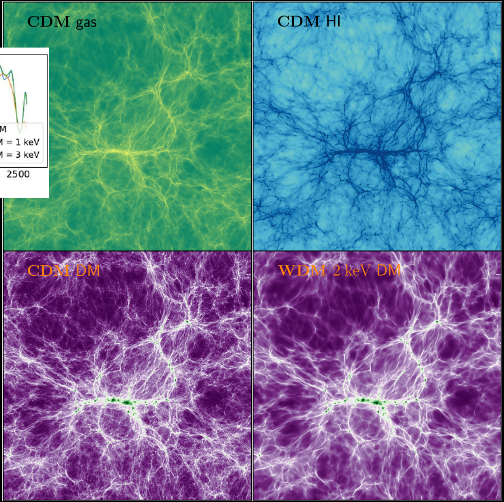
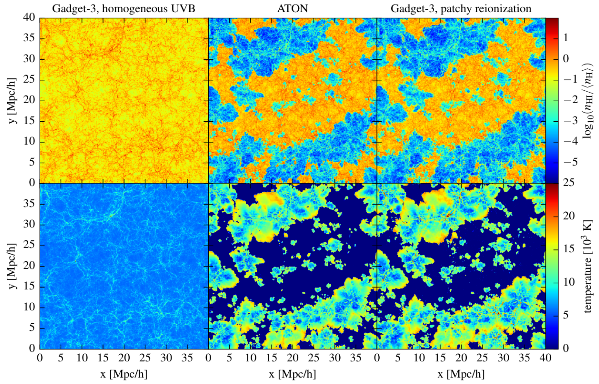
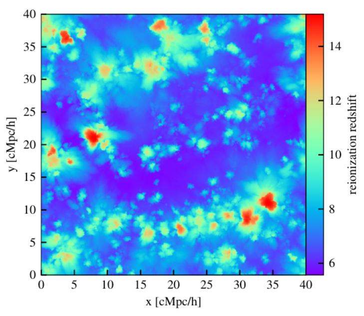


Image: Simulated Universe $20^3\ (\mathrm{Mpc/h})^3$, 2×1024^3 DM+gas particles

Cosmological simulations





Sherwood-Relics simulation suite

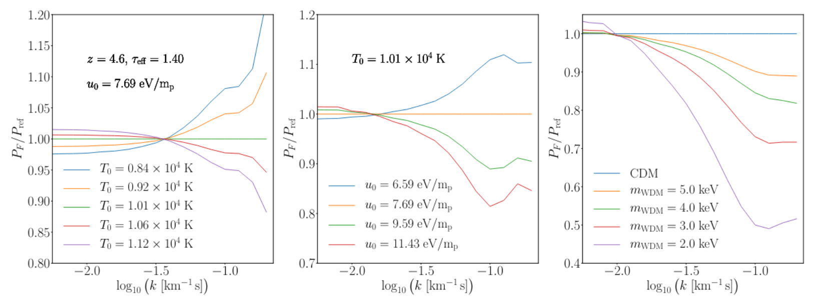
- Simulations tuned to high-redshift intergalactic medium
- varying thermal history, thermal state, inhomogenous reionizaton + beyond CDM models

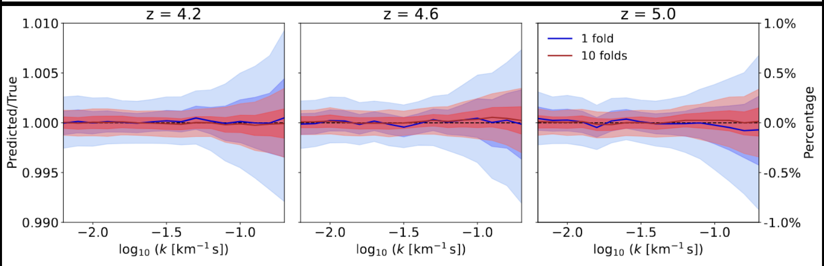
Molaro, **VI** et al. 2020, 2022; Puchwein, **VI** et al. 2023; **Iršič** et al. 2024

Kulkarni et al. 2016; Keating et al. 2017; Onorbe et al. 2016; Wu et al. 2020; Montero-Camacho et al. 2020; Cain et al. 2022, 2024;

Bolton et al. 2016; Lukić et al. 2015; Villasenor et al. 2020, 2022; Doughty et al. 2023; Chabanier et al. 2024; Khan et al. 2024; Bird et al. 2024;

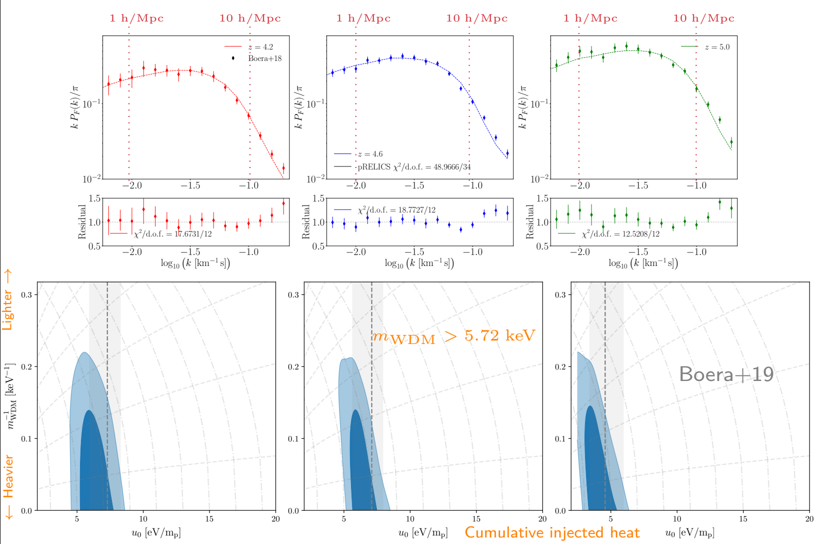
Likelihood emulator





McDonald et al. 2005; Viel et al. 2013; **Iršič** et al. 2017; Walther et al. 2017; Rogers et al. 2020;
Molaro, **VI** et al. 2022; Cabayol-Garcia et al. 2023; Fernandez et al. 2024; Walther et al. 2025; Garcia-Galego, **VI** et al. 2025;

Bayesian Likelihood Analysis



m_{WDM} limits

Viel+05: > 2.0 keV

Seljak+05: > 2.1 keV

Viel+13: > 3.5 keV

Baur+15: > 4.1 keV

Garzilli+15: > 1.9 keV

VI+17: > 5.3 keV

Yeche+17: > 4.6 keV

Palanque+20: > 5.3 keV

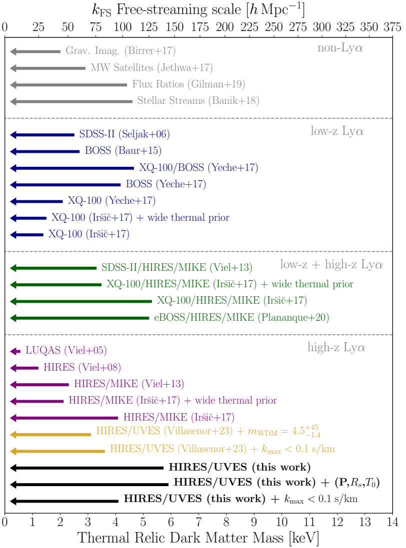
Villasenor+22: > 3.1 keV

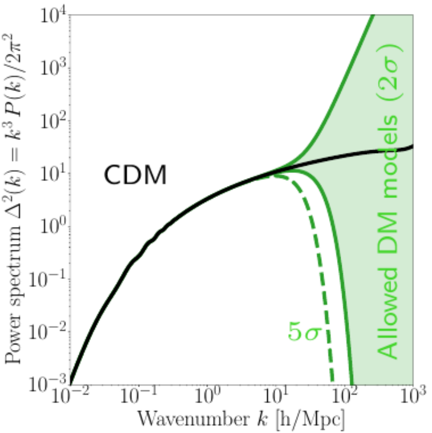
VI+24: > 5.7 keV

Irsic et al. 2024

- New WDM bound: $m_{\mathrm{WDM}} > 5.7$ keV
- Improved modelling ($\mathbf{P}$, R_s, T_0): $m_{\mathrm{WDM}} > 5.9$ keV
- Conservative $k_{\mathrm{max}} < 10$ h/Mpc: $m_{\mathrm{WDM}} > 4.1$ keV → 2x better than in 2017

Searching for New Physics at Small Scales



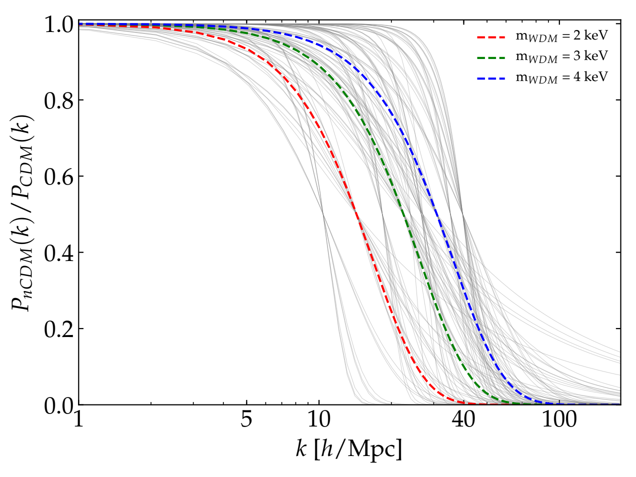


Cain, VI et al. 2022; Garcia-Gallego, VI et al. 2025

General non-CDM models

General transfer function for DM: $T(k) = \sqrt{\frac{P_{\rm nCDM}}{P_{\rm CDM}}} = \left[1 + (\alpha k)^{\beta}\right]^{\gamma},$

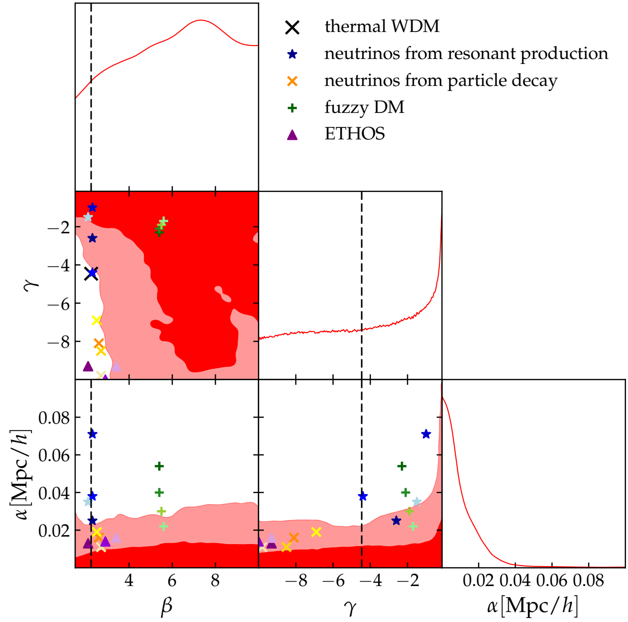
E.g. for thermal WDM: $\beta = 2.24,\ \gamma = -4.46,\ \alpha \propto 0.049 \left(\frac{m_{\rm WDM}}{1\ {\rm keV}}\right)^{-1.11} h^{-1}\ {\rm Mpc}$



with R. Murgia (1806.08371)

Murgia et al. 2017; Murgia, **VI** et al. 2018
Archidiacono et al. 2019; Hooper et al. 2022

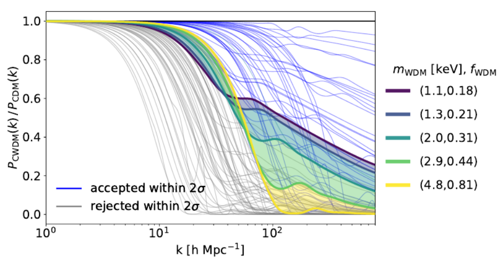
Constraints on the shape of the nCDM $T(k)$

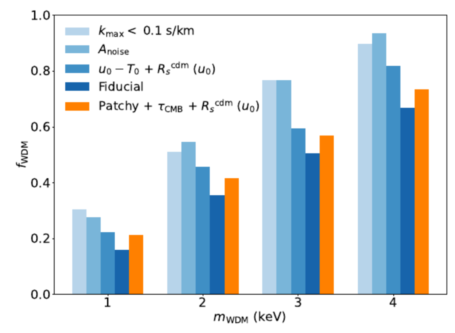


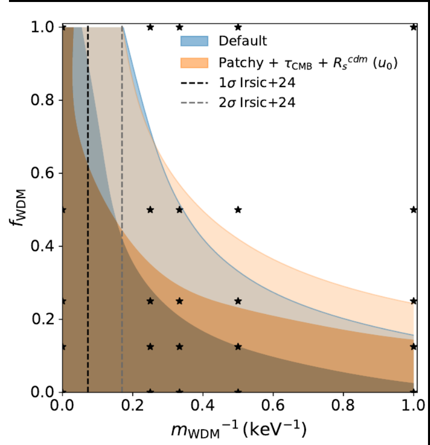
	α [Mpc/h]	β	γ
Neutrinos from resonant production	0.025	2.3	−2.6
	0.071	2.3	−1.0
	0.038	2.3	−4.4
	0.035	2.1	−1.5
Neutrinos from particle decay	0.016	2.6	−8.1
	0.011	**2.7**	**-8.5**
	0.019	2.5	−6.9
	0.011	**2.7**	**-9.8**
Mixed models	0.16	3.2	−0.4
	0.20	3.7	−0.18
	0.21	3.7	−0.1
	0.21	3.4	−0.053
Fuzzy DM	0.054	5.4	−2.3
	0.040	5.4	−2.1
	0.030	**5.5**	**-1.9**
	0.022	**5.6**	**-1.7**
ETHOS models	0.0072	1.1	−9.9
	0.013	2.1	−9.3
	0.014	2.9	−10.0
	0.016	3.4	−9.3

Mixed Warm Dark Matter

Olga Garcia-Galego, IoA



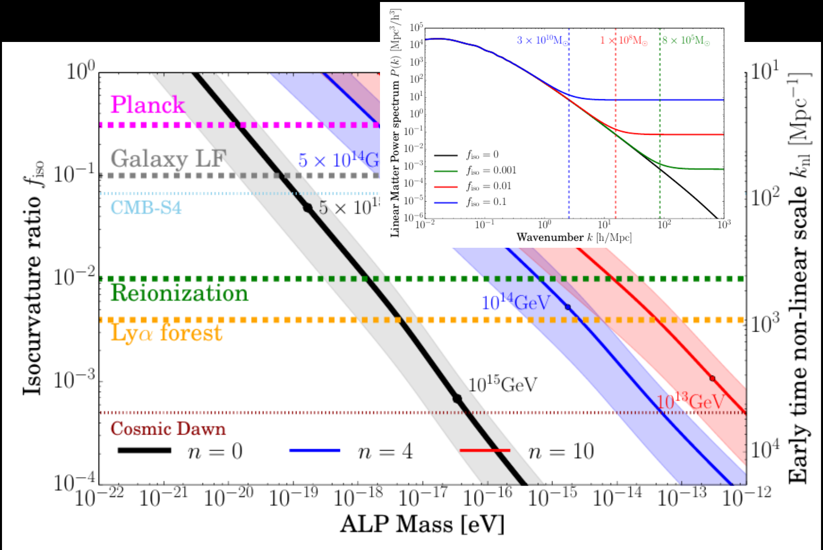




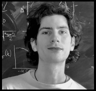
Garcia-Gallego, **VI** et al. 2025 (2504.06367) ;Kobayashi, **VI** et al. 2017 (mixed FDM) ;
Palazzo et al. 2007; Boyarsky et al. 2009; Baur et al. 2017; Diamanti et al. 2017; Parimbelli et al. 2021

Axion-like particle DM with PQ breaking after inflation

Irsic et al. 2020; Murgia et al. 2019; Ivanov & Trifinopoulos 2025

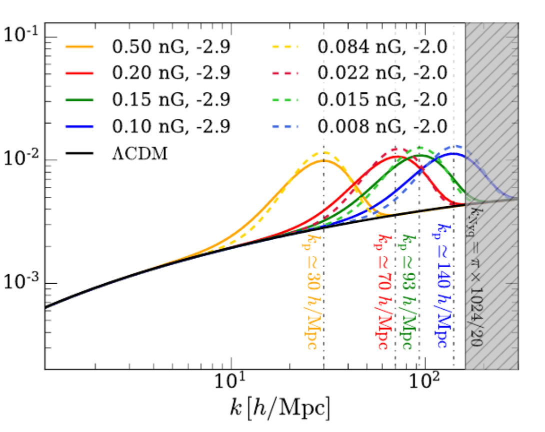


Models that enhance structure formation



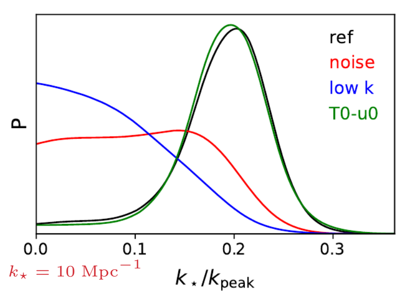
Mak Pavicevic, SISSA

Primordial Magnetic Fields

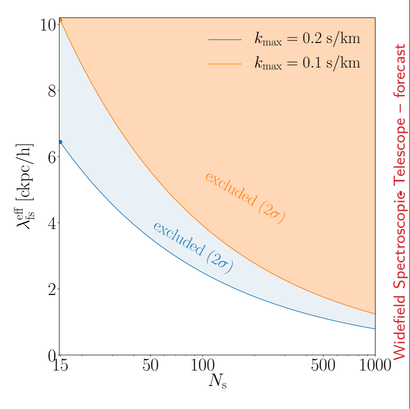


Pavicevic, **VI** et al. 2025 (2501.06299)

$$\frac{k_\star}{k_{\rm peak}} \sim \left(\frac{B_{\rm 1Mpc}}{nG}\right), \text{ for } n_B = -2.9$$



What next?



Improvements for the future:

- Improve statistics
  (EQUALS (PI: T.Berg), Gemini/GHOST (PI: S.Bosman),
- Better instrument modelling
  (or increase SNR for observations)
- Keep improving theory models
  (Radiative transfer, small-scale peculiar velocity, ...)

Can we rule out large ranges in DM particle mass?

Motivation: resonant sterile neutrino (3.5 keV),
excluding ultra-light axions with $m_{\rm a} > 10^{-14}$ eV

Can we distinguish between DM models?

Motivation: information on production mechanism

Big Open Questions

- Nature of Dark Matter

  What can we learn from Ly-α data about Dark Matter?

  How is it affecting formation of structures in the Universe?

  Can we differentiate between different Dark Matter models?

  What is the outlook for the future?

Big Open Questions

- Nature of Dark Matter

  What can we learn from Ly-α data
  about Dark Matter?
  Mass of DM, production mechanism, ...

  How is it affecting formation of
  structures in the Universe?
  Smoother clustering, suppressed structure formation, dynamics

  Can we differentiate between
  different Dark Matter models?
  Is the glass half full or half empty?

  What is the outlook for the future?
  Dominated by low statistics!

Conclusions

- Dark Matter with Lyman-α forest
- Ly-α forest as a unique probe of the matter distribution (redshift range, scales coverage)
- 1D clustering on small-scales $(1\ \mathrm{Mpc/h})$
- Constraints on DM models: particle mass!
- Constraining production mechanisms, Mixed Dark Matter models, isocurvature models, ...
- Much scope for improvement – statistics dominated!