DESI first year cosmological results

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on behalf of the DESI collaboration

24 Mai 2024 - LPCA Seminar

LPC Particules pLasmas Univers applicationS
Laboratoire de Physique de Clermont

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1. Cosmological context
2. The Dark Energy Spectroscopic Instrument
3. The Lyman-α forest
4. DESI first year BAO cosmological results
5. Other Lyman-α forest studies

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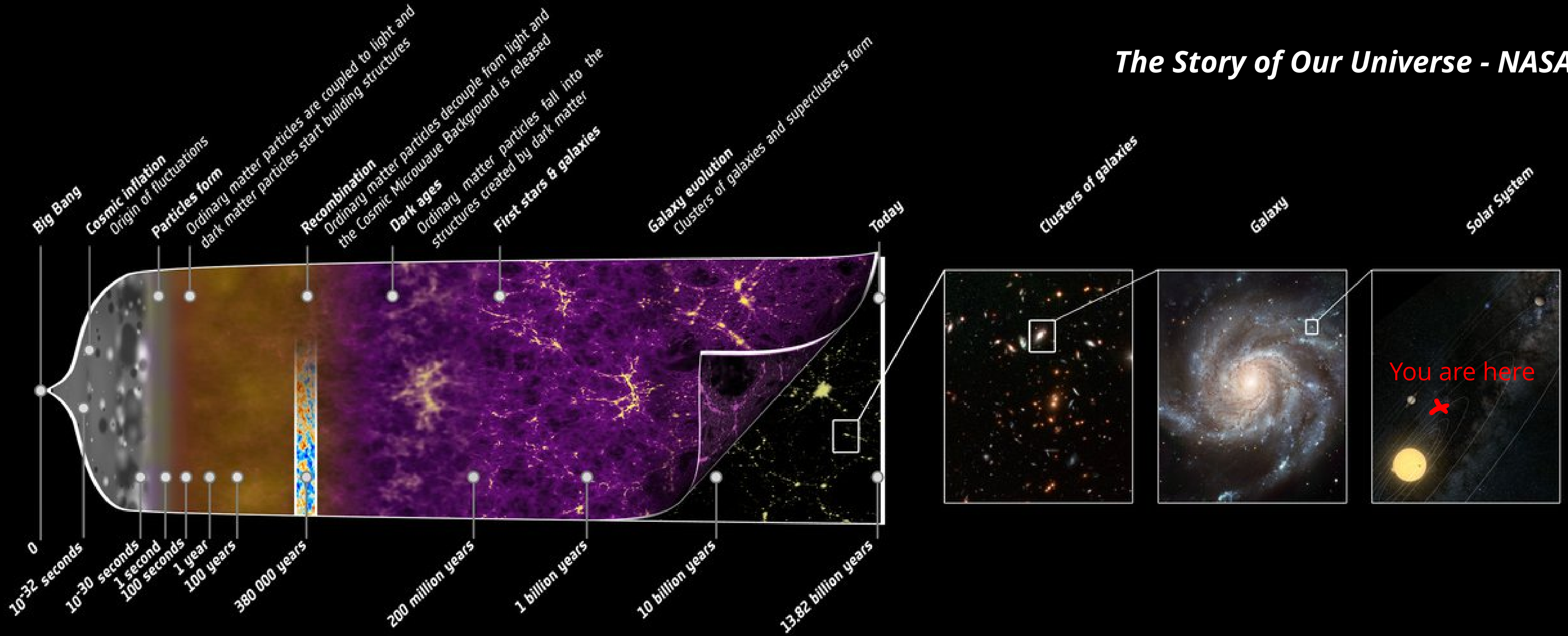
Cosmological context

The Story of Our Universe - NASA



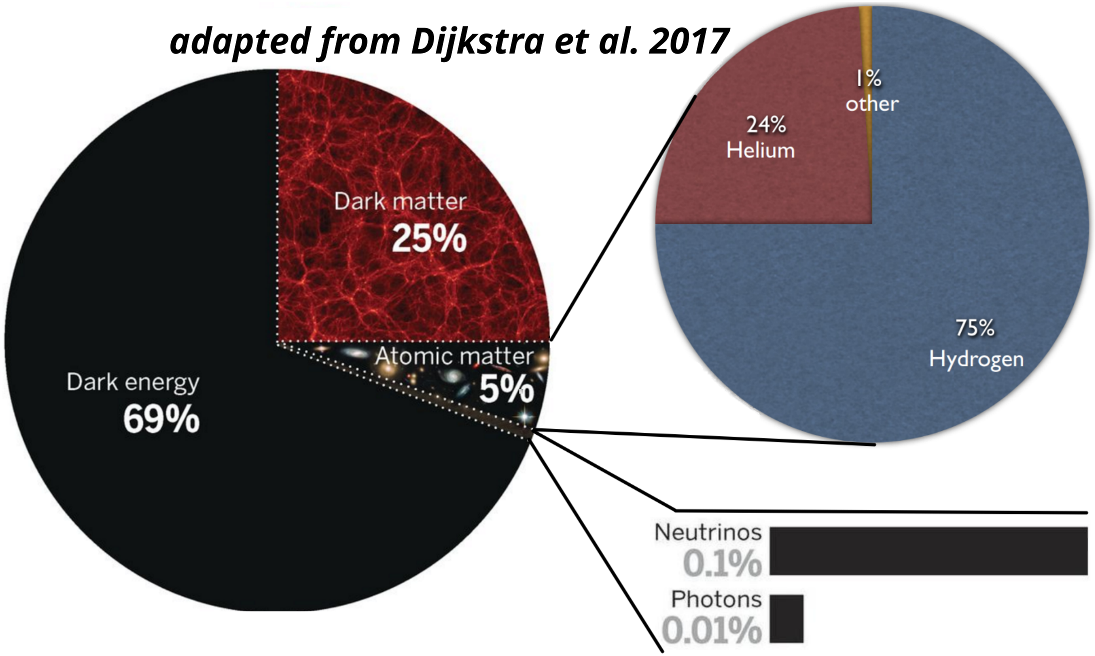
How did the Universe evolve to its current state?
What are the fundamental constituents of our Universe?
How is matter distributed in the Universe?

Global content of our Universe

- Evolution of the Universe described by the ΛCDM model

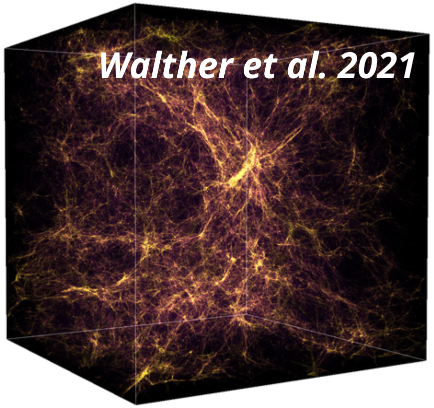
- Composition today:
  - Only 5 % of its content is known
  - Properties of components constrained by observations

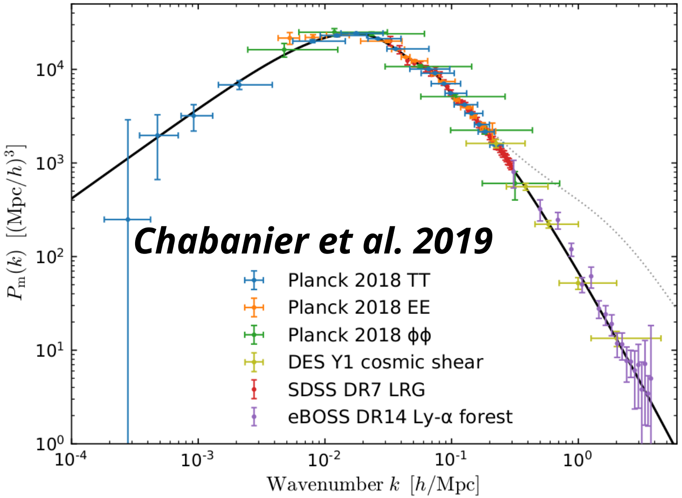
adapted from Dijkstra et al. 2017



What is the nature of dark energy and dark matter?

Large scale structures

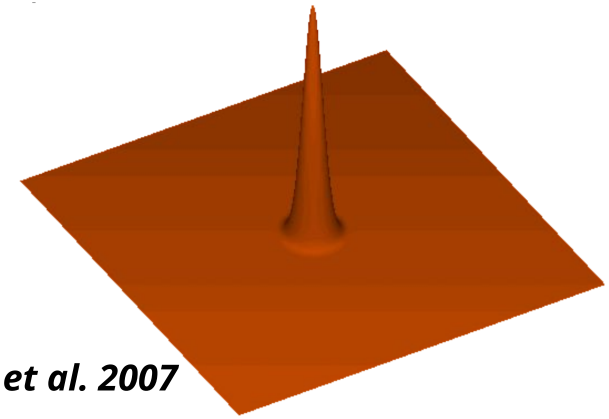




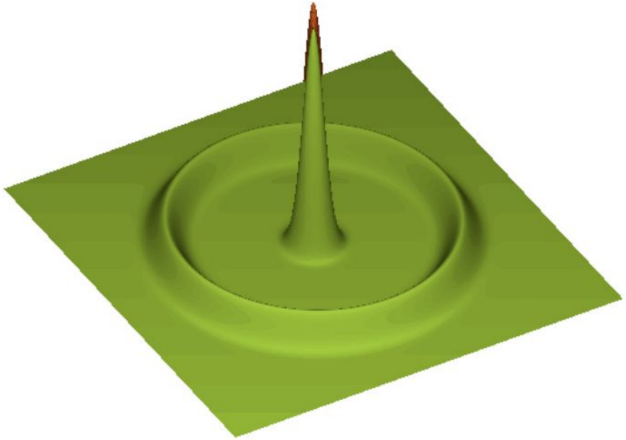
- Initial density perturbations in the primordial Universe.
- Perturbations grows to form the cosmic web: halos, filaments, walls and voids
- Large-scale distribution of matter characterized by the linear power spectrum

How can we probe the cosmic web?
What can we learn from it?

Baryon acoustic oscillations



Eisenstein et al. 2007



- Sound wave created by an overdensity of baryons and dark matter in the primordial plasma

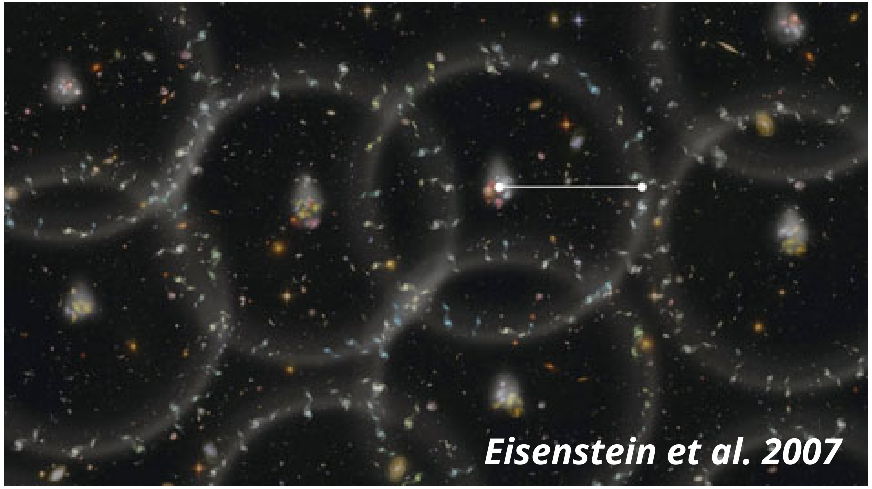
Baryon Acoustic Oscillations (BAO):

- **Sound waves in the primordial Universe ...**

Baryon acoustic oscillations

- At recombination (z~1100)
  - Baryon/photon decouples
  - Sound waves froze at sound horizon scale:

$$\boxed{r_{\mathrm{d}} \simeq 150\mathrm{Mpc}}$$



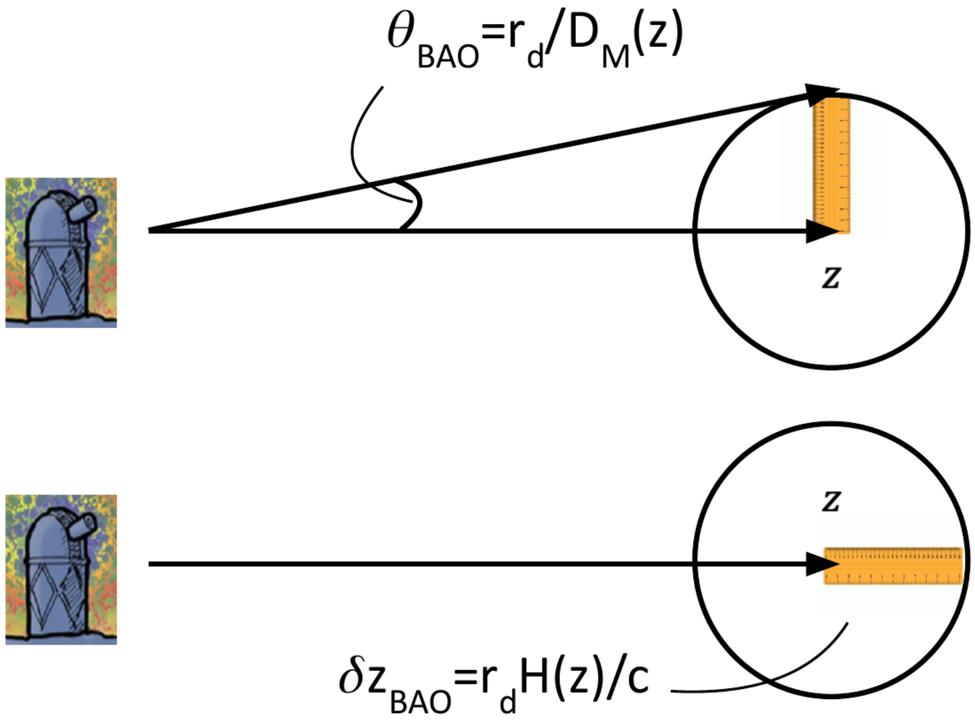
- Effect of all overdensities in the primordial plasma:
  - Statistical BAO signal in the matter distribution

Baryon Acoustic Oscillations (BAO):

- **Sound waves in the primordial Universe ...**
- **... imprint a characteristic scale in the density distribution**

Baryon acoustic oscillations

- **BAO = Standard ruler**
  - Measurement of distance at a given redshift
  - Expansion history from different redshift measurements (encoded in $D_{\mathrm{M}}(z)$ and $H(z)$)



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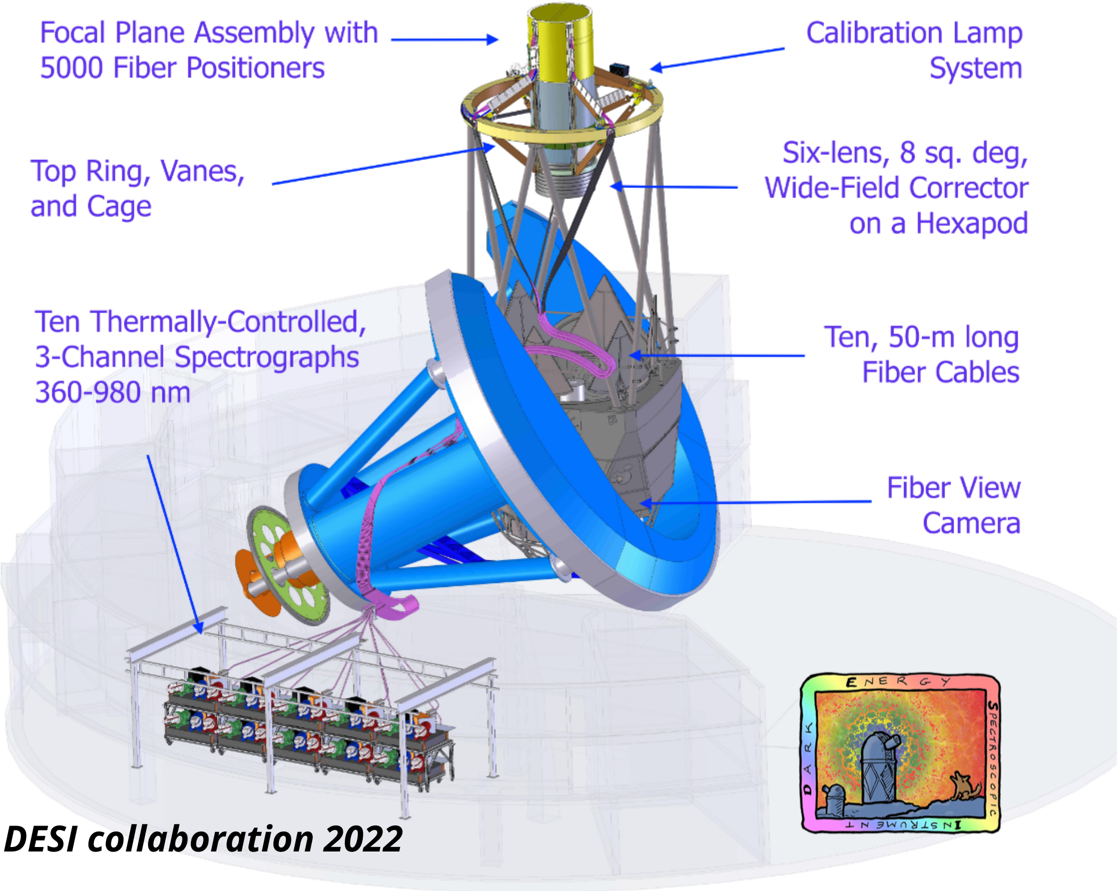
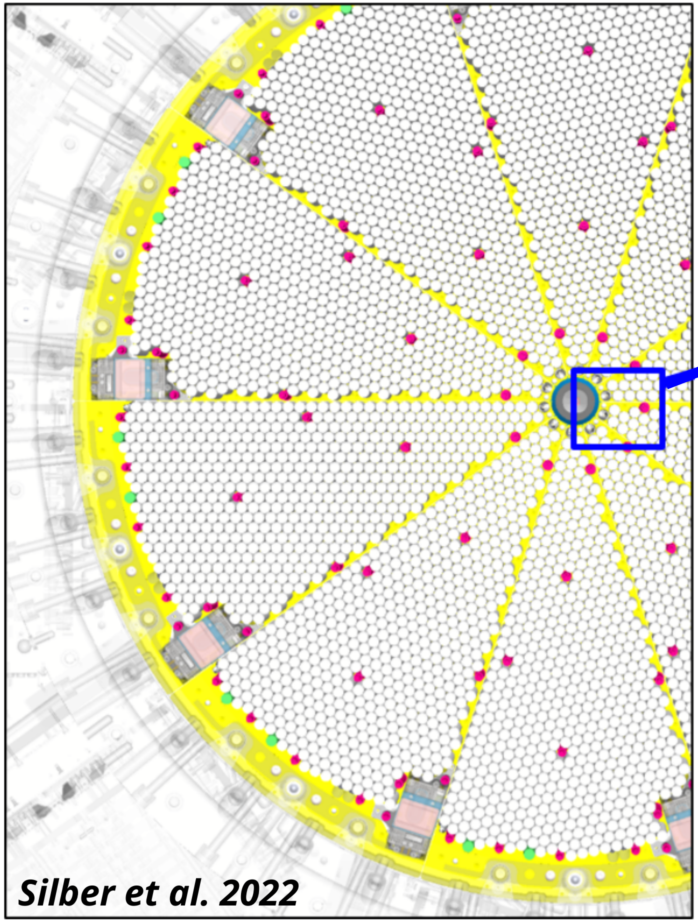
DESI instrument

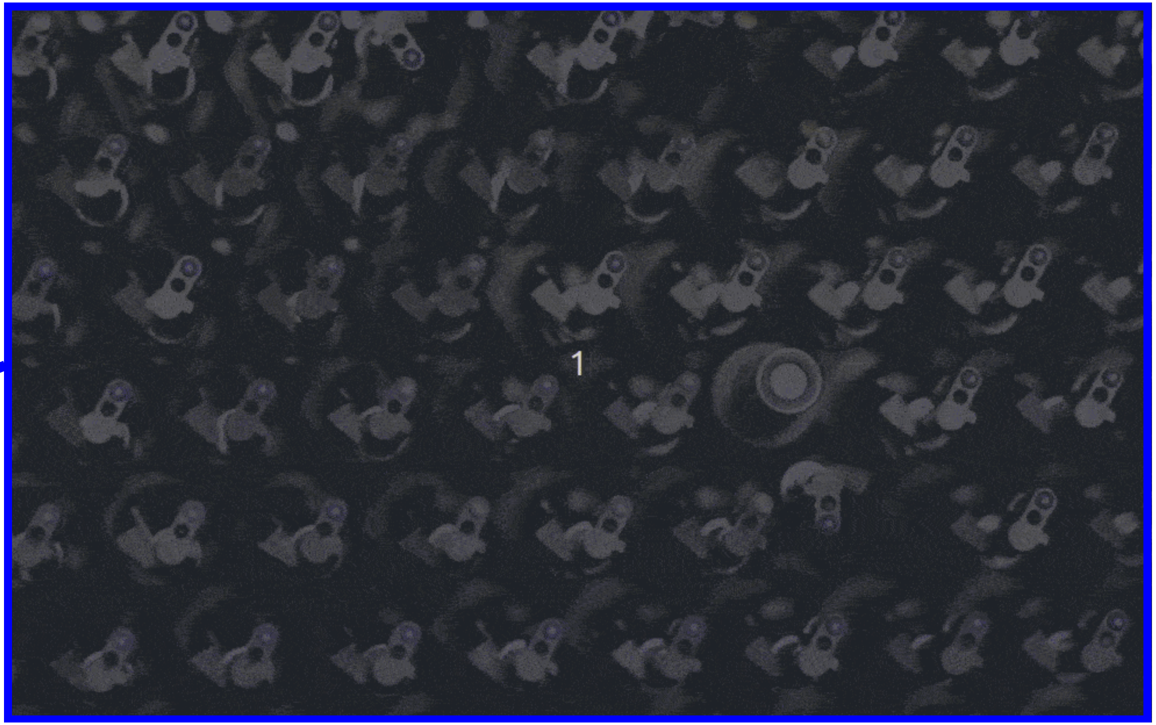
- 4 m telescope at Kitt Peak Observatory



DESI collaboration 2022

DESI focal plane



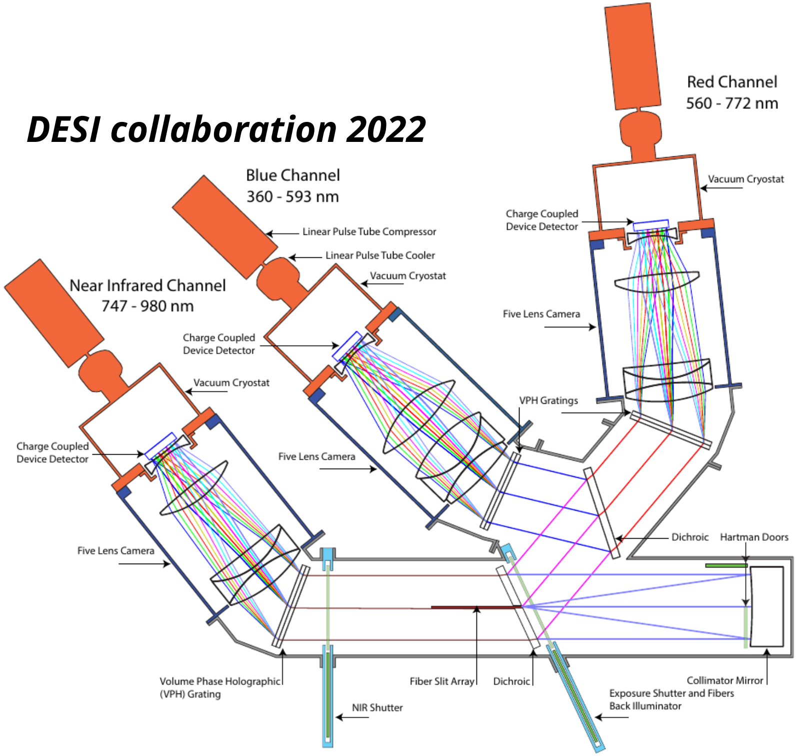


- 5 μm positioning in few sec. for **5000 targets**
- All fibers connected to the spectrographs

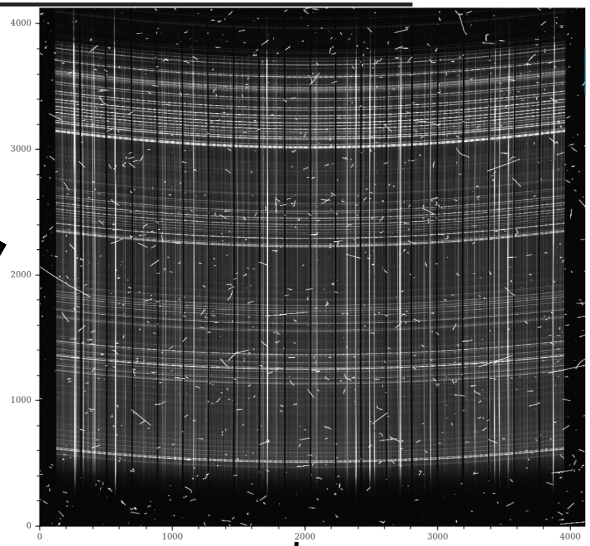
DESI spectrographs

- 10 Spectrograph modules containing 3 CCD each

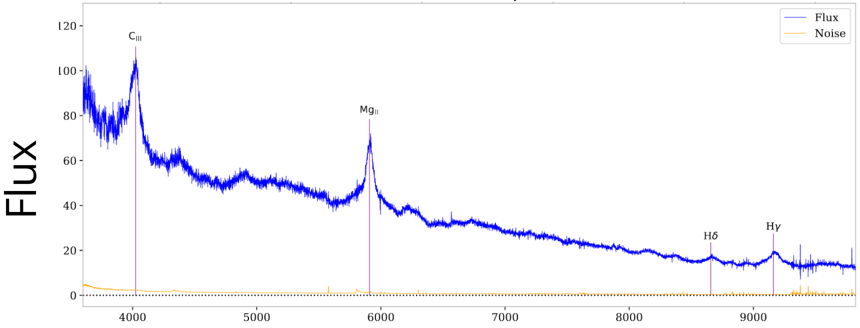
DESI collaboration 2022



CCD Image



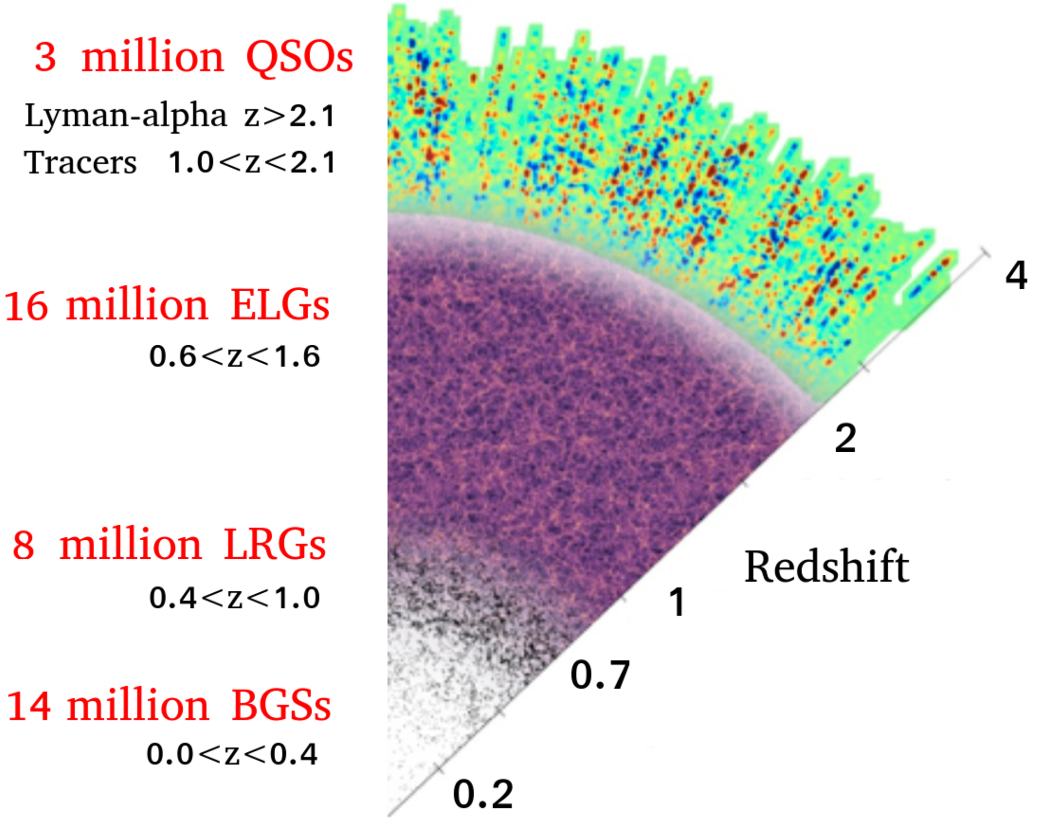
Spectrum



Targets of the cosmological survey

- **BGS**: Bright Galaxy Survey
- **LRG**: Luminous Red Galaxy
- **ELG**: Emission Line Galaxy
- **QSO**: Quasar
    - $z > 2.1$: with a Lyman-α forest
    - $z < 2.1$: as tracers

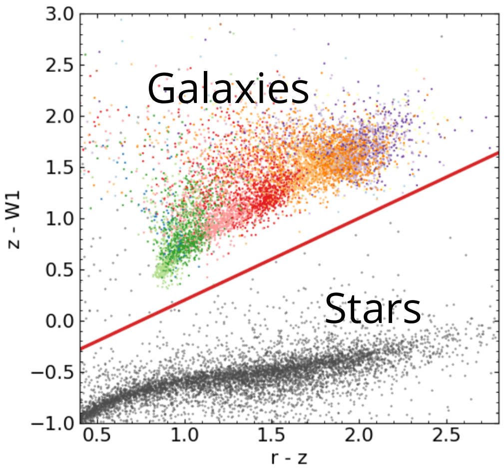
40 million redshifts in 5 years



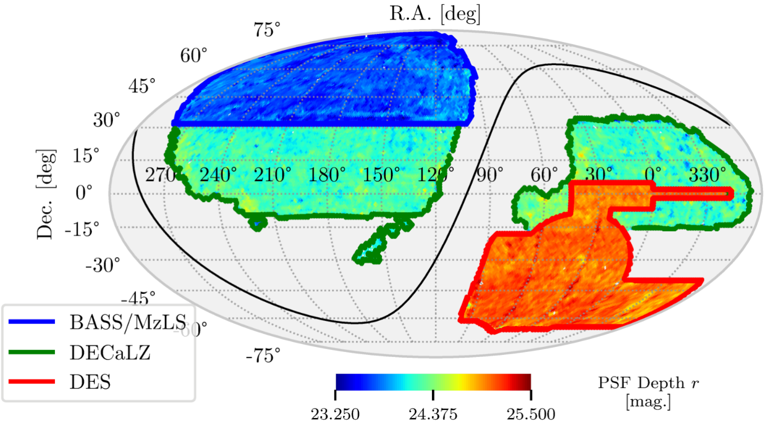
DESI in a nutshell

Target Selection (BGS, LRG, ELG, QSO)

Zhou et al. 2022

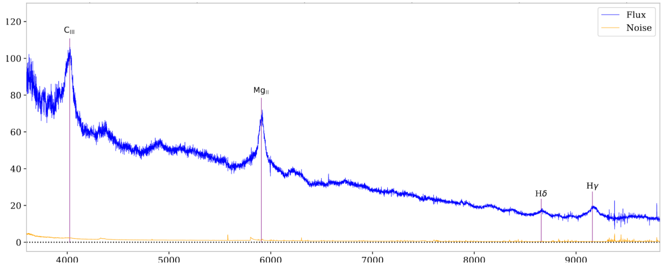


Chaussidon et al. 2022



Photometry

Observing (5000 spectra simultaneously)

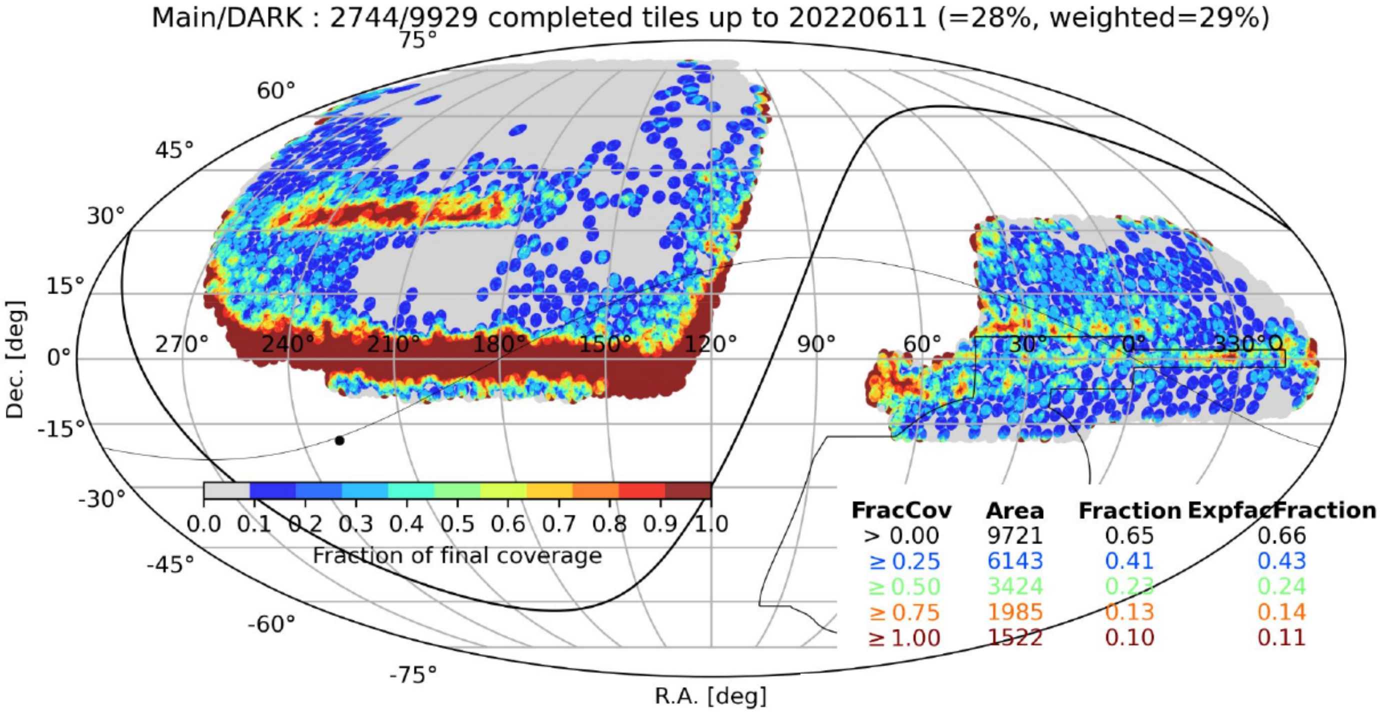


Catalog of spectra and redshifts

Survey progress

Y1 completion

- Full coverage: **14,000 deg²**
- Y1 data set used in the results presented here



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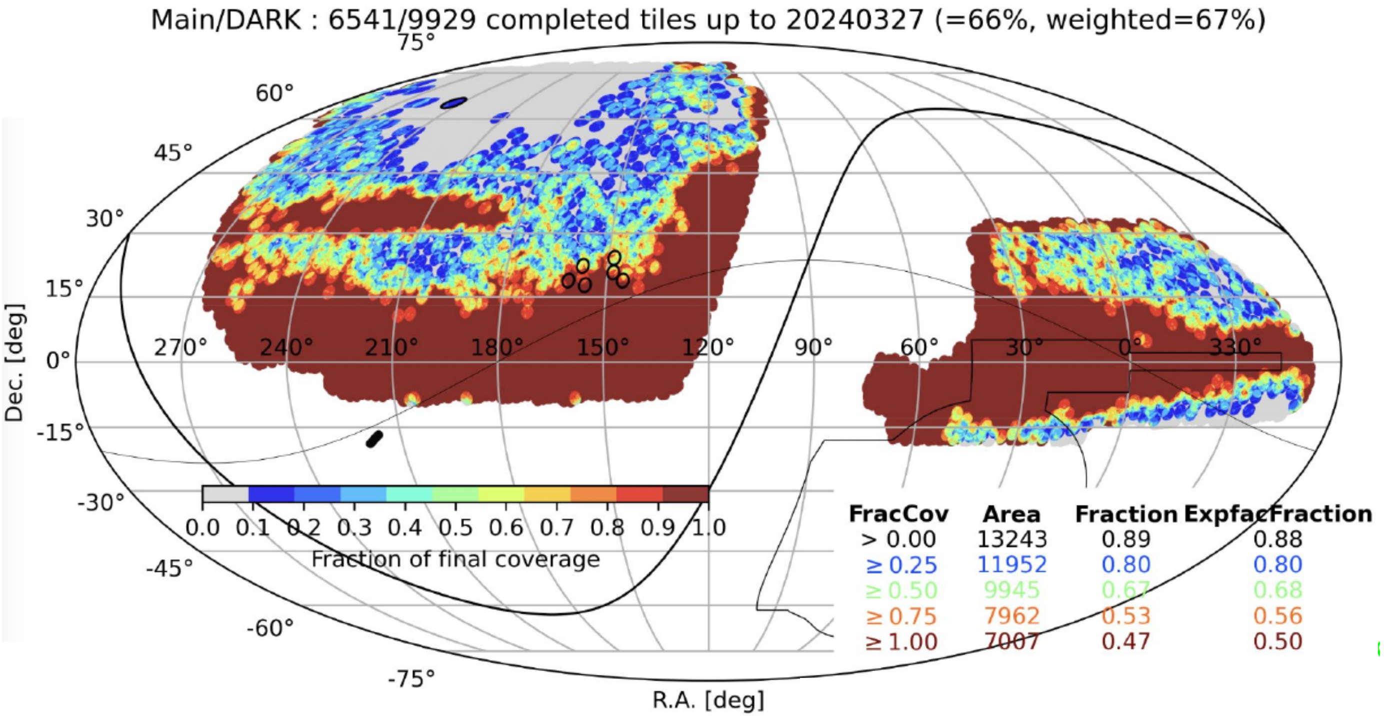
Survey progress

Y3 completion

- Full coverage: **14,000 deg²**
- Y1 data set used in the results presented here
- Y3 data set secured



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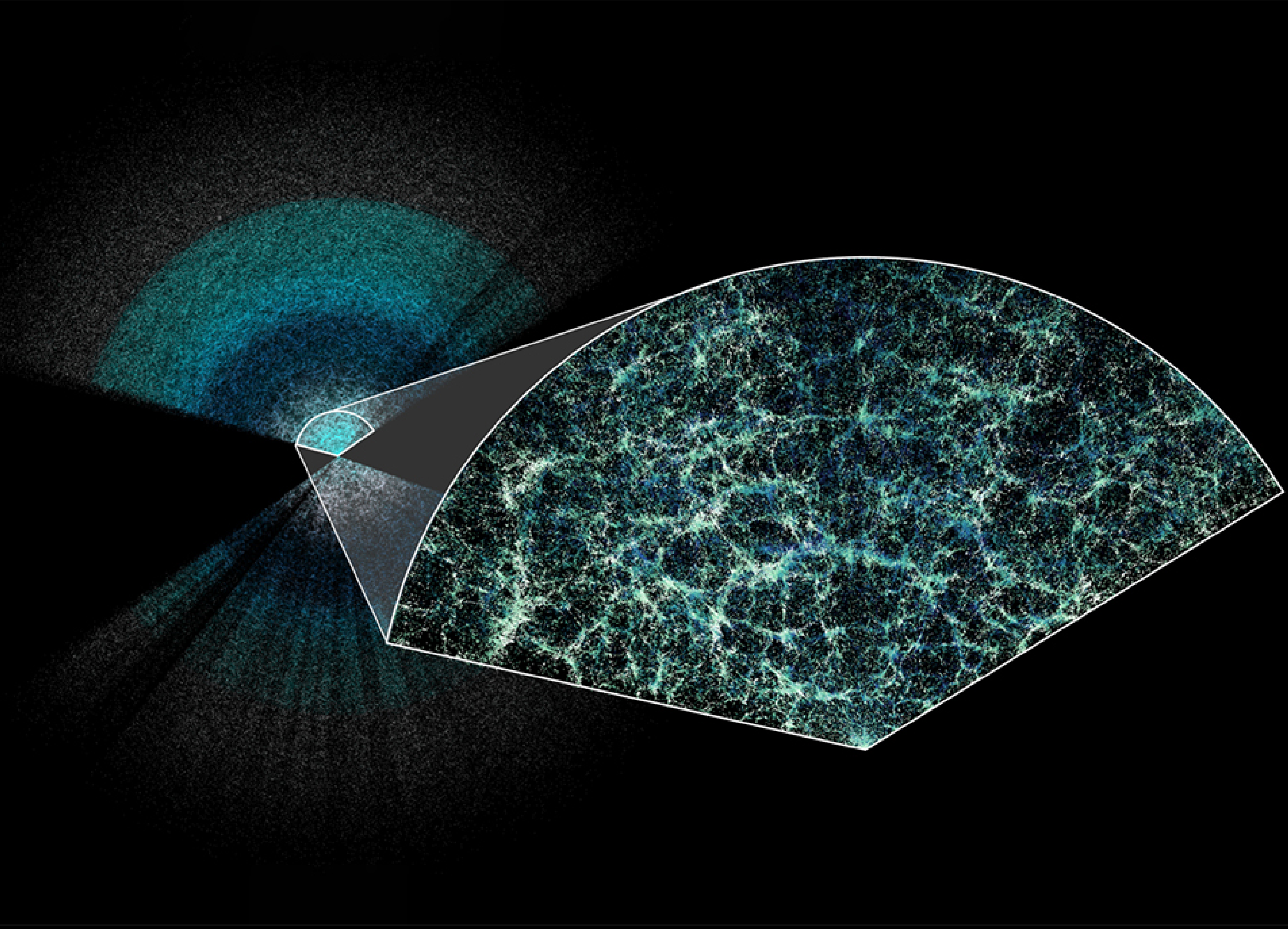
DESI science goals:

- Galaxy and quasar clustering
- Lyman-α forest
- Clusters and cross-correlations
- Galaxy and quasar physics
- Milky way Survey
- Transients and low-z



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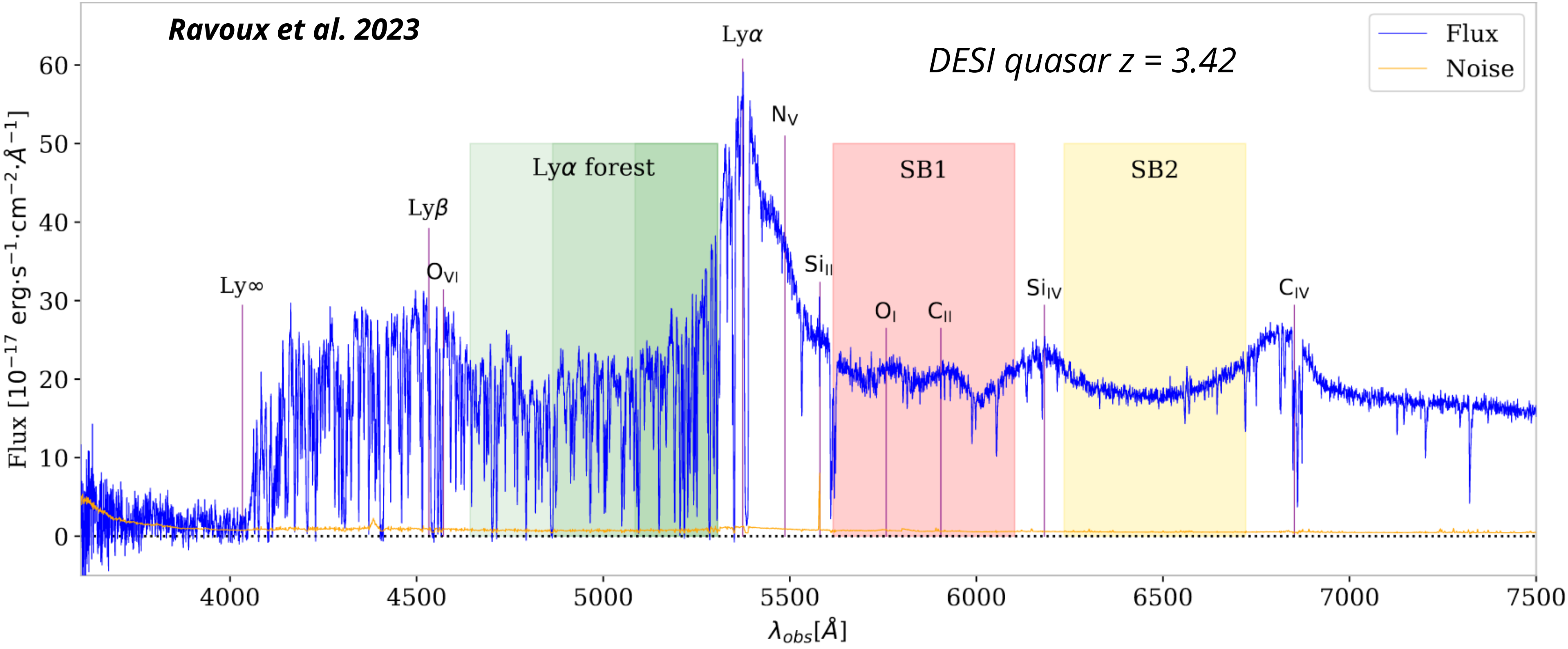
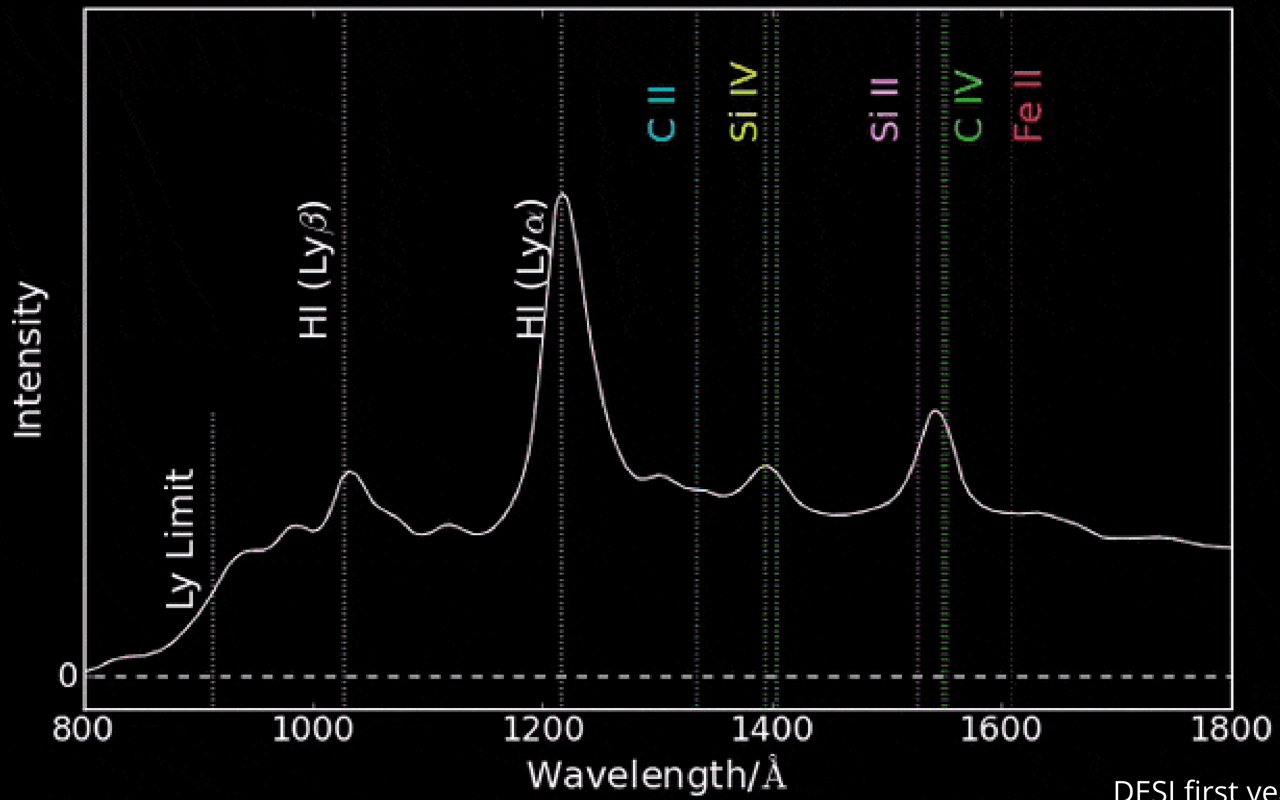
The Lyman-α forest

- Lines in quasar spectra at $\lambda_{\rm obs} = (1 + z_{\rm abs})\, \lambda_{\rm Ly\alpha}$ caused by absorbers in the intergalactic medium (IGM) at $z_{\rm abs}$





Intensity
Ly Limit
HI (Lyβ)
HI (Lyα)
C II
Si IV
Si II
C IV
Fe II
0
800
1000
1200
1400
1600
1800
Wavelength/Å

Lyman-α physics

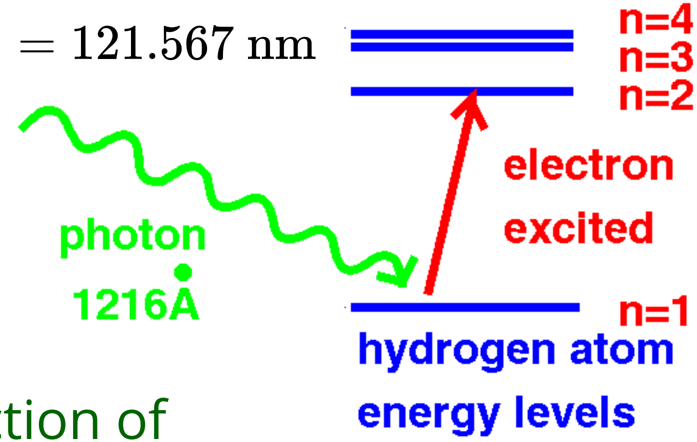
- Optical depth (degree of transparency of the medium):

$$\tau_\alpha(r) = \int \boxed{n_{\mathrm{HI}}(r)}\boxed{\sigma_\alpha(r)}dr$$

Density of neutral hydrogen

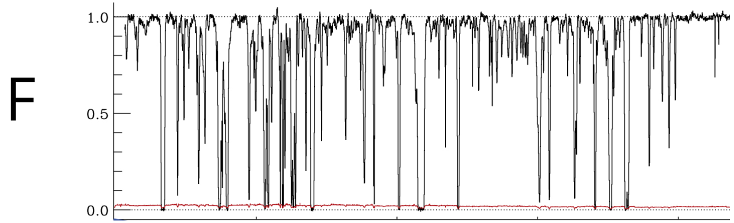
Cross section of Lyman-α transition

$$\lambda_\alpha = 121.567\ \mathrm{nm}$$



- Fraction of transmitted flux:

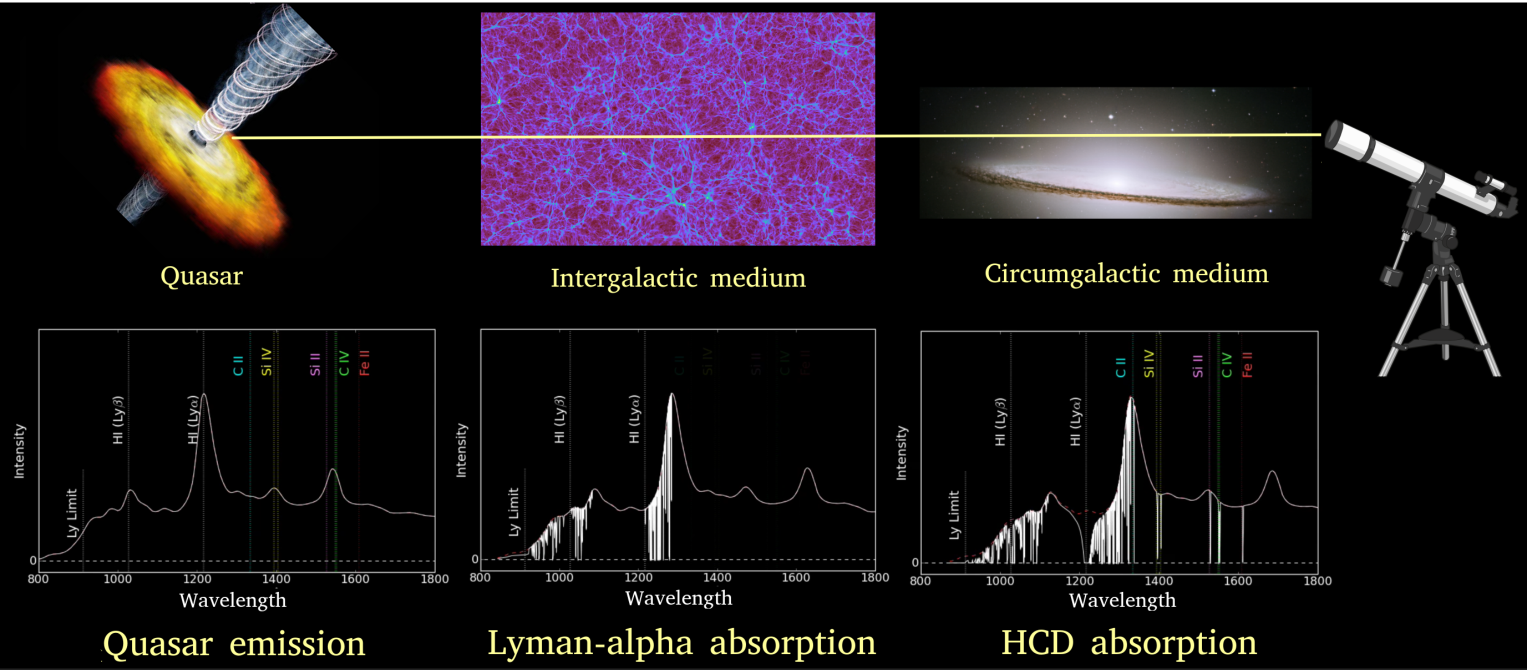
$$\mathrm{F(r)} = \exp\left(-\tau_\alpha(r)\right)$$



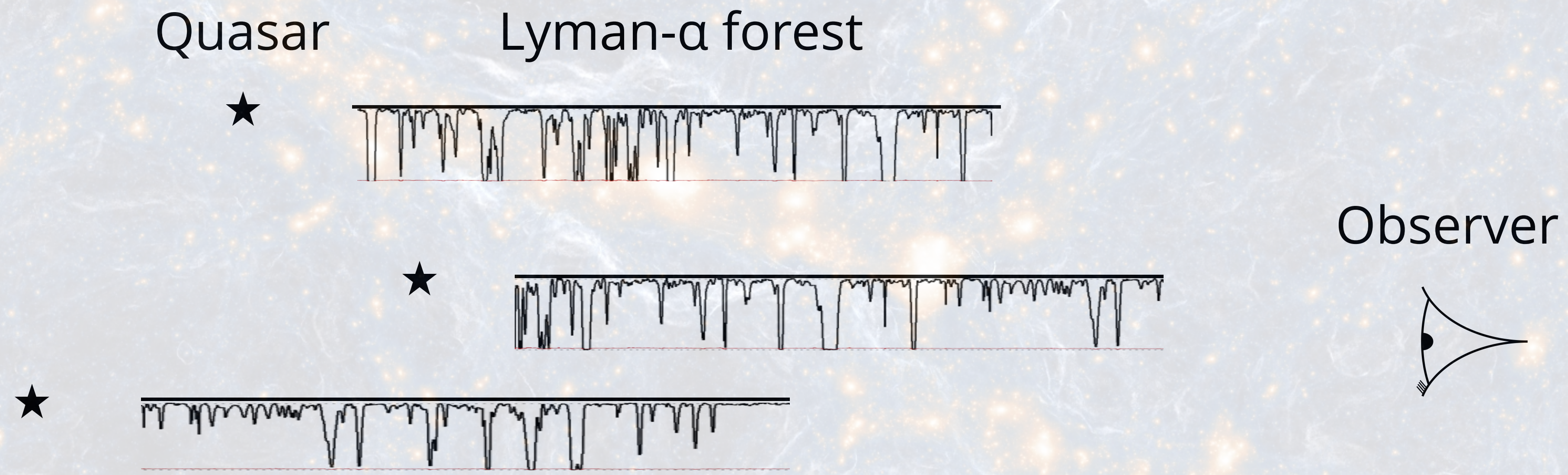
Lyman-α forest = non-linear tracer of neutral hydrogen in the intergalactic medium

Contaminants

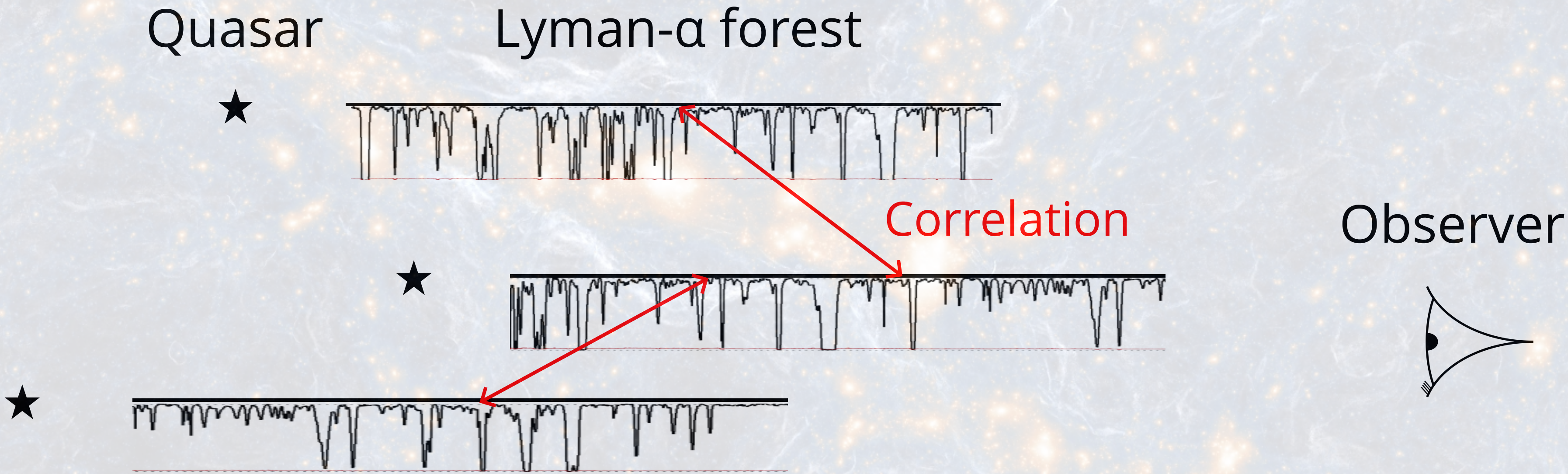
- Near the quasar:
  - Intrinsic continuum
  - Broad absorption line quasars (BAL)
- Along the line-of-sight:
  - Metal absorptions (C, Si, O, N...)
  - Damped Lyman-α systems (DLA)
- Near the telescope:
  - Atmospheric absorption and emission
  - Instrument noise
  - Spectrograph resolution



Lyman-α clustering



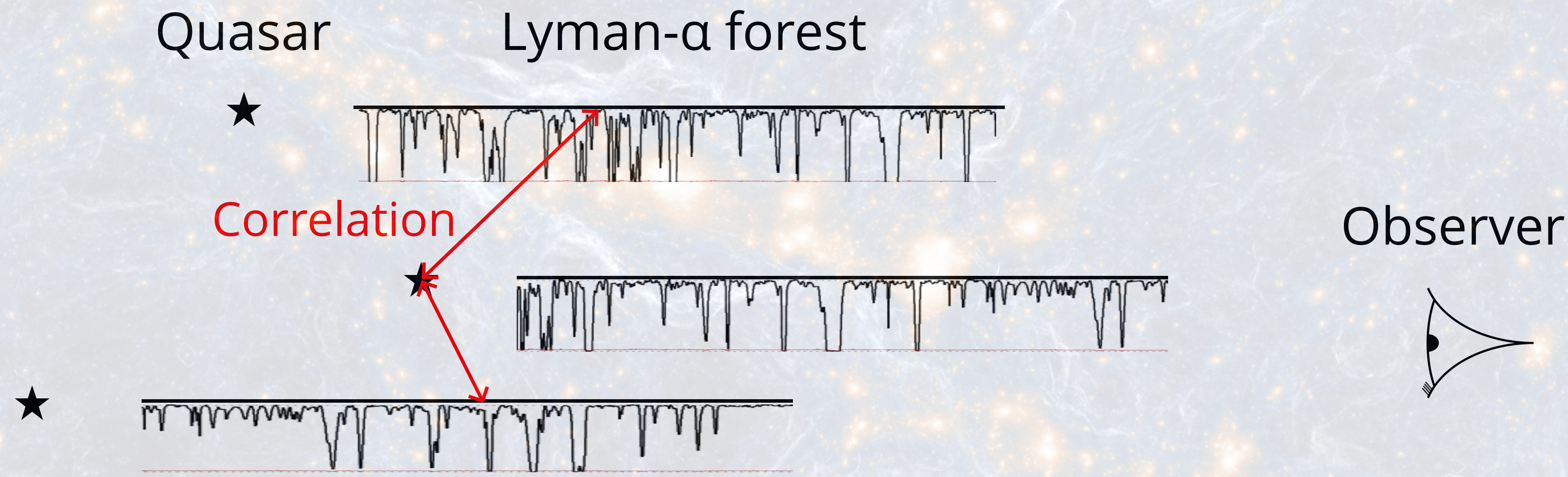
Lyman-α clustering



F = Fraction of transmitted flux $\rightarrow$ $\delta_F = \frac{F}{\langle F \rangle} - 1$ $\rightarrow$ 3D auto correlation

$$\xi_\alpha(\vec{r}) = < \delta_F(\vec{x})\delta_F(\vec{x}+\vec{r}) >_x$$

Lyman-α clustering



F = Fraction of transmitted flux $\longrightarrow$ $\delta_F = \dfrac{F}{\langle F \rangle} - 1$ $\longrightarrow$ 3D cross correlation with quasars

$$\xi_{\alpha q}(\vec{r}) = < \delta_F(\vec{x})\delta_{\mathrm{qso}}(\vec{x}+\vec{r}) >_x$$

Lyman-α BAO Y1

3D auto correlation

3D cross correlation with quasars

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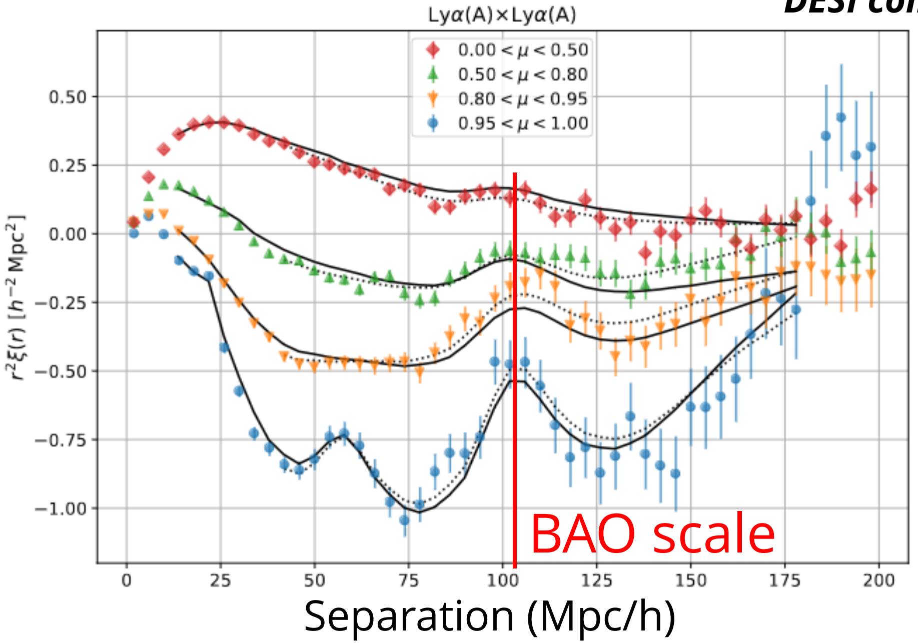
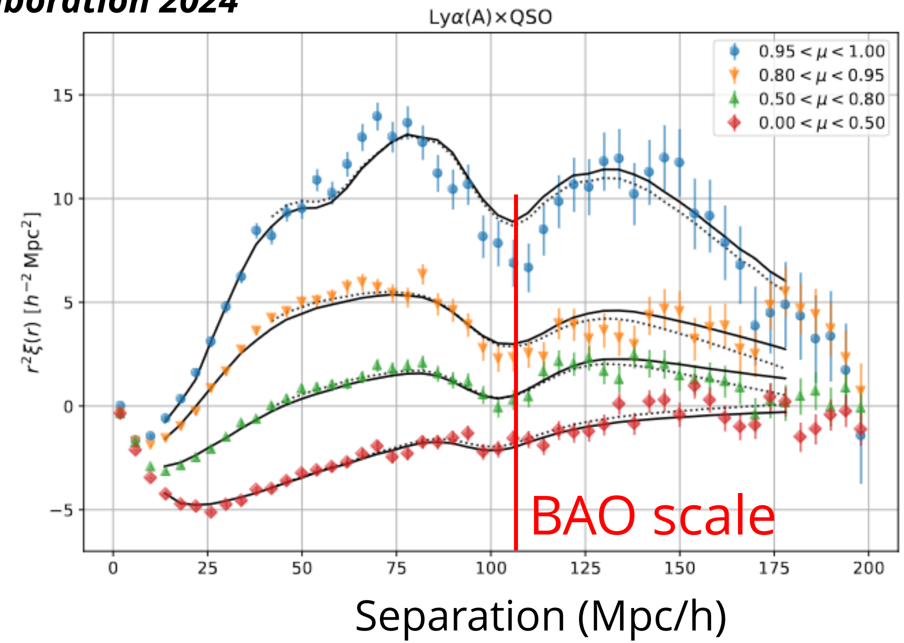
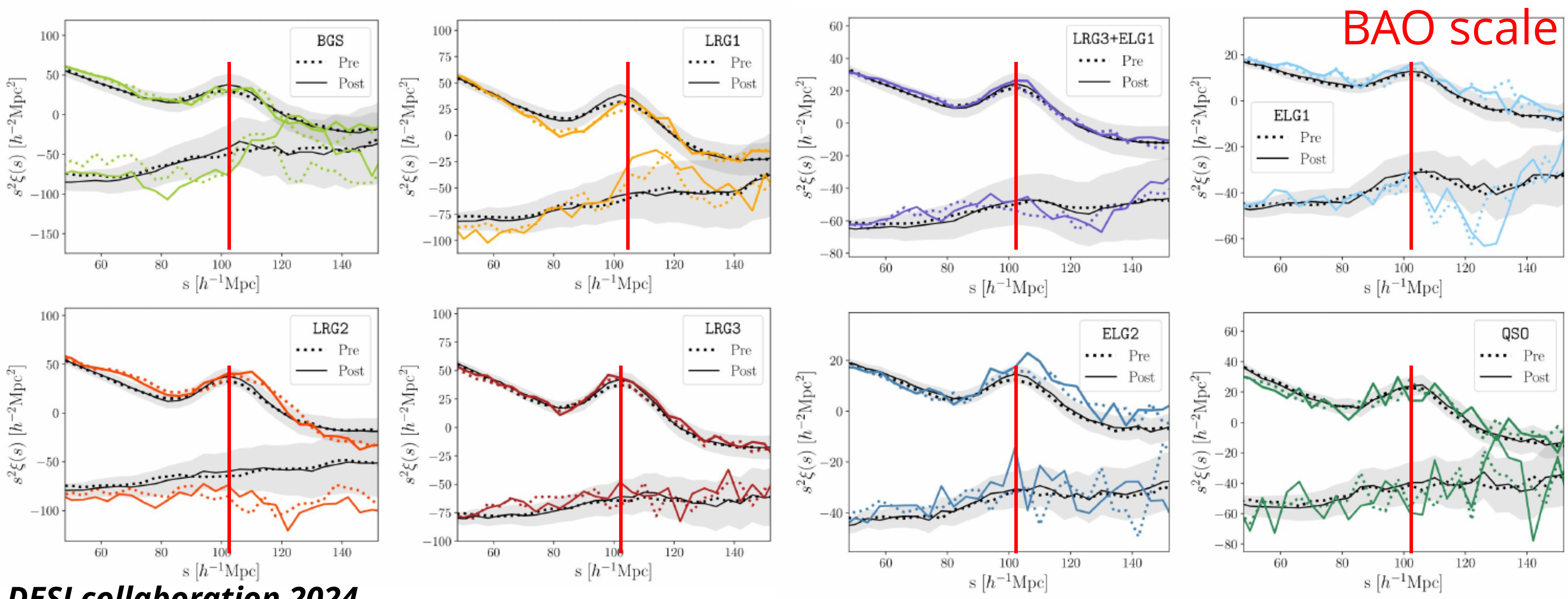




Measurement of the BAO scale with the Y1 data of DESI

BAO Y1 signal on galaxies

- 3D auto-correlation of galaxies for BGS, LRG, ELG and QSO as tracers
- BAO scale measured over different redshifts



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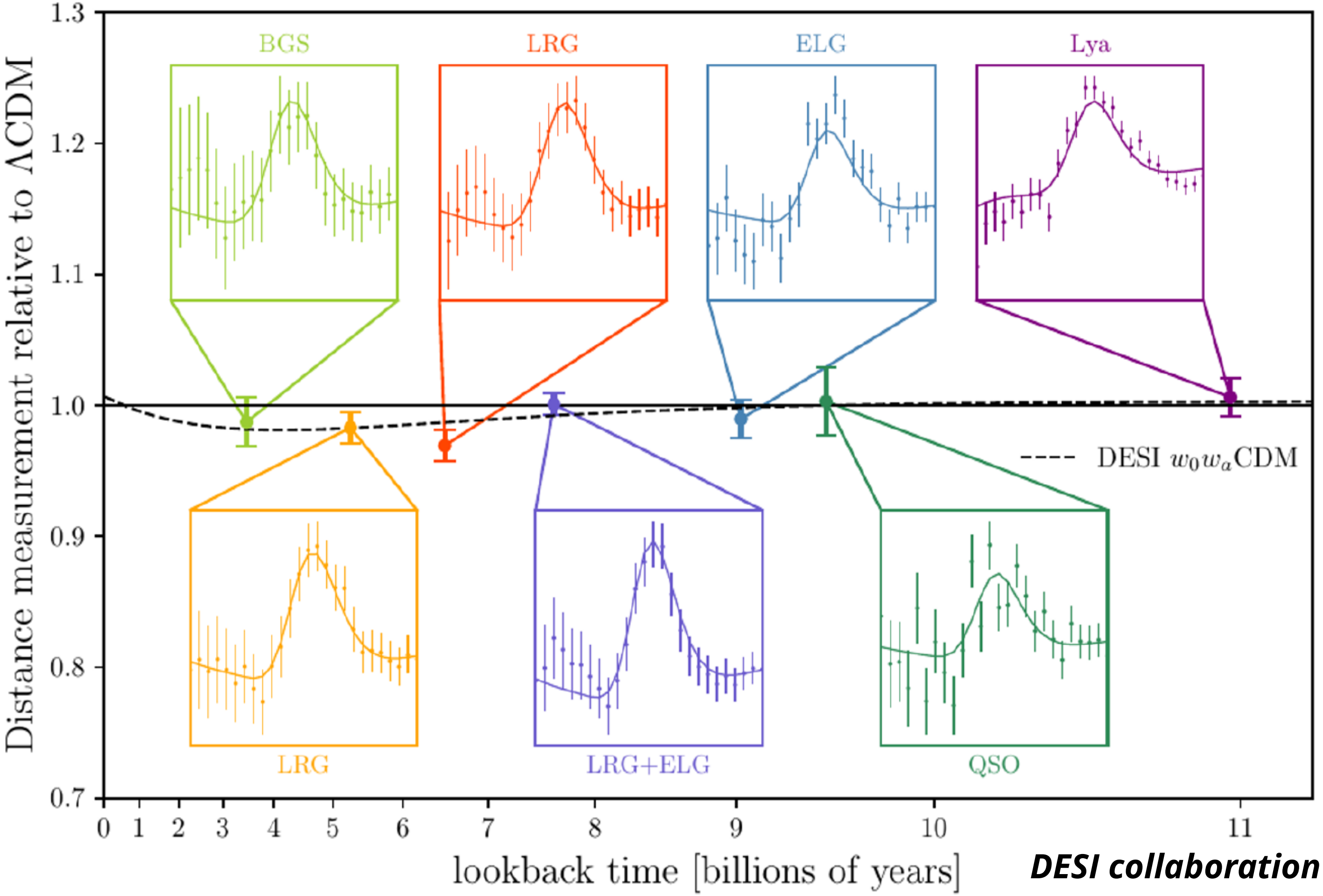
All BAO signals from DESI Y1



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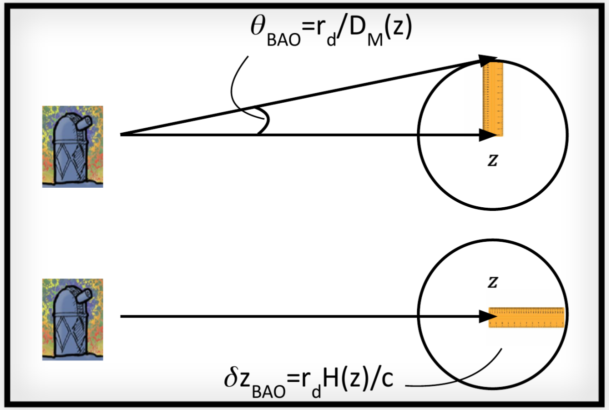
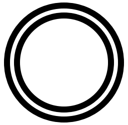
Cosmological constraints



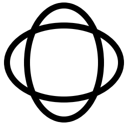
- Overall BAO scale:

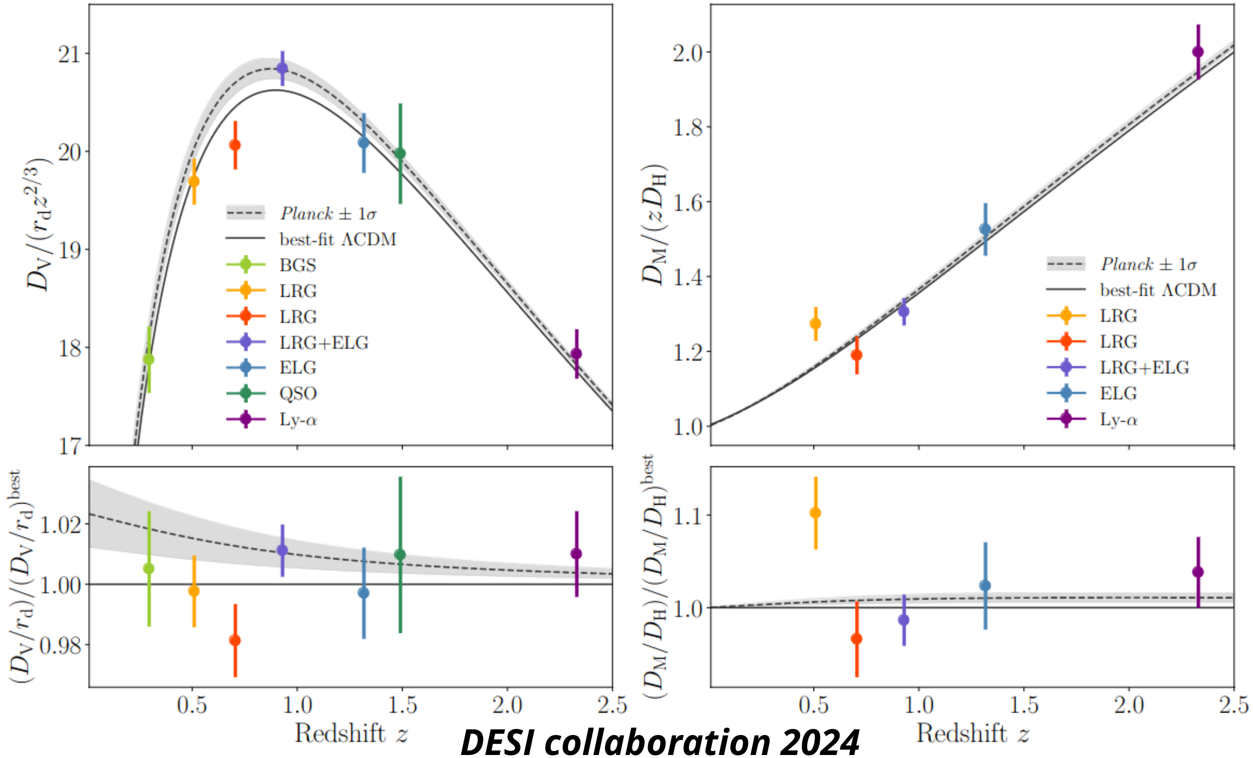
$$\frac{D_V(z)}{r_d} = \frac{1}{r_d}\left(\frac{zD_M^2(z)c}{H(z)}\right)^{1/3}$$



- BAO anisotropy:

$$\frac{c}{D_M(z)H(z)}$$





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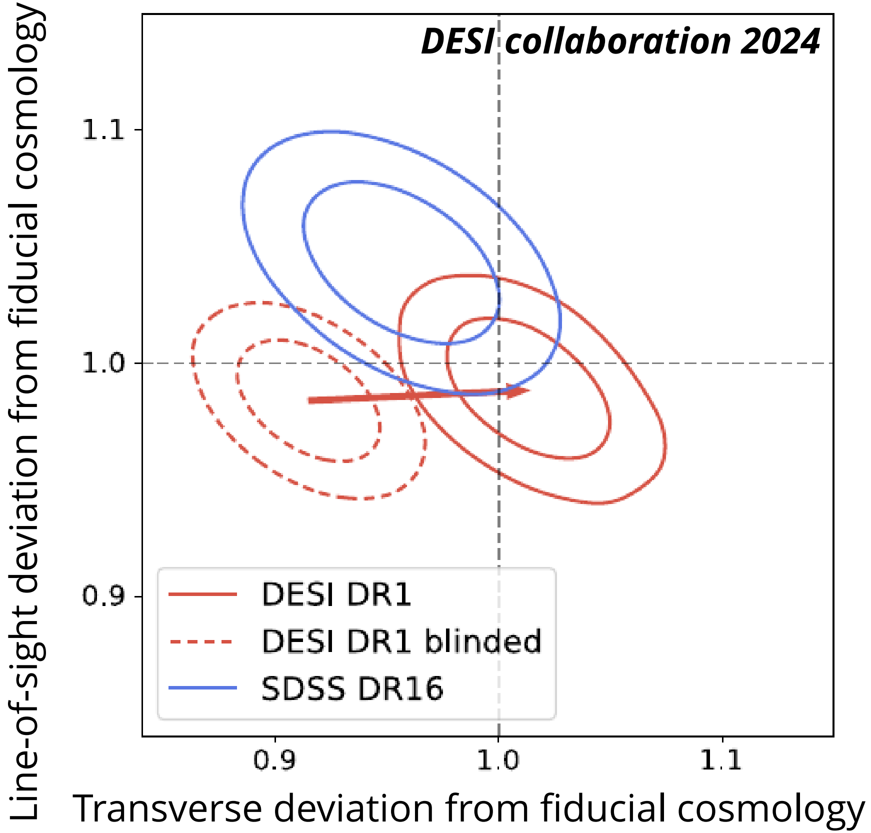
A word on blinding

- Blinded analysis to avoid confirmation bias:
  - **For galaxies**: shift of all redshifts based on a random ΛCDM model
  - **For Lyman-α forest**: unknown shift of the BAO peak
- Unblinding after passing an extending list of tests

Example for Lyman-α forest:



Hubble constant

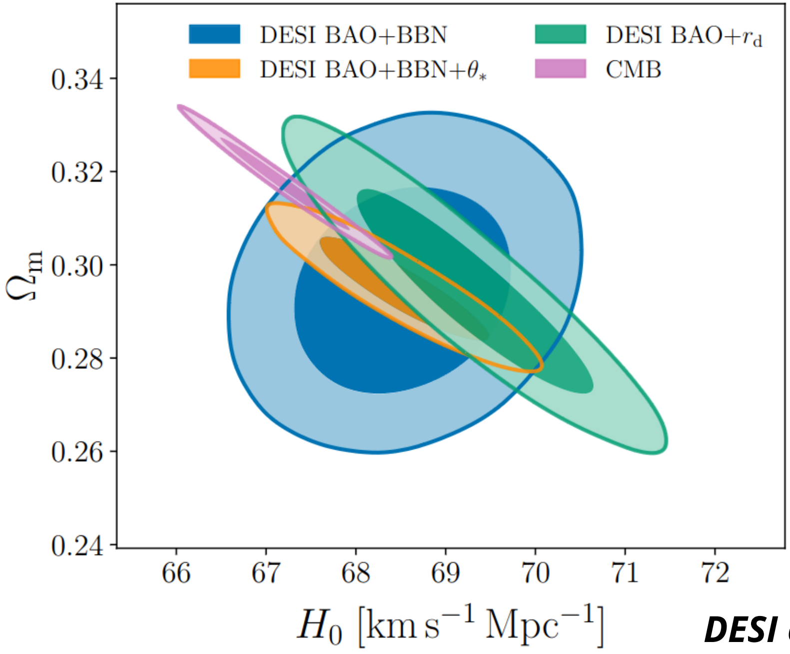
ΛCDM model with baryon information from BBN

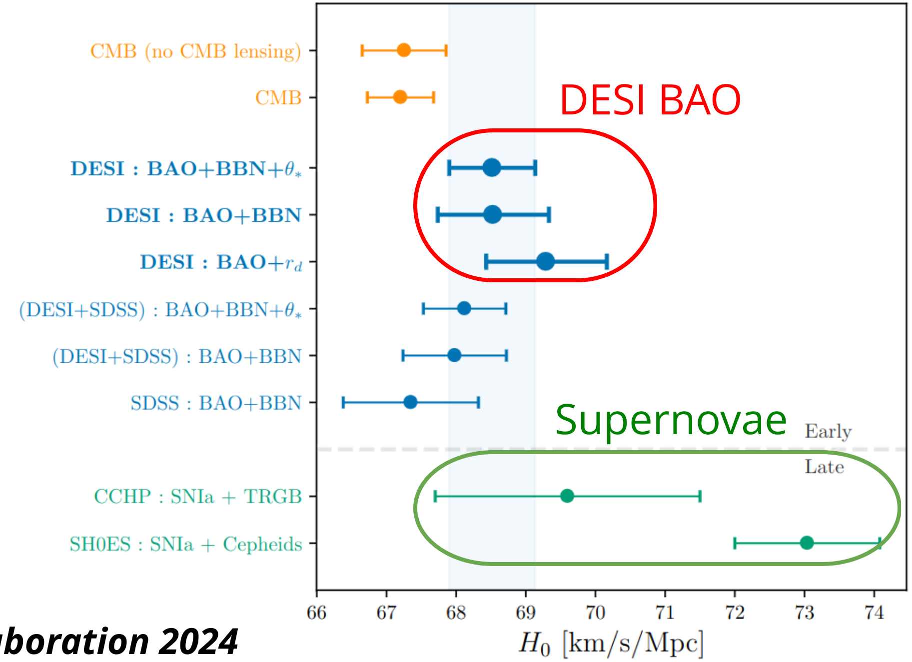
r_d Sound horizon scale

θ_* CMB angular acoustic scale

$$\boxed{H_0 = (68.52 \pm 0.62)\mathrm{km s^{-1} Mpc^{-1}}}$$

DESI + BBN





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In tension with late time measurements (Supernovae)

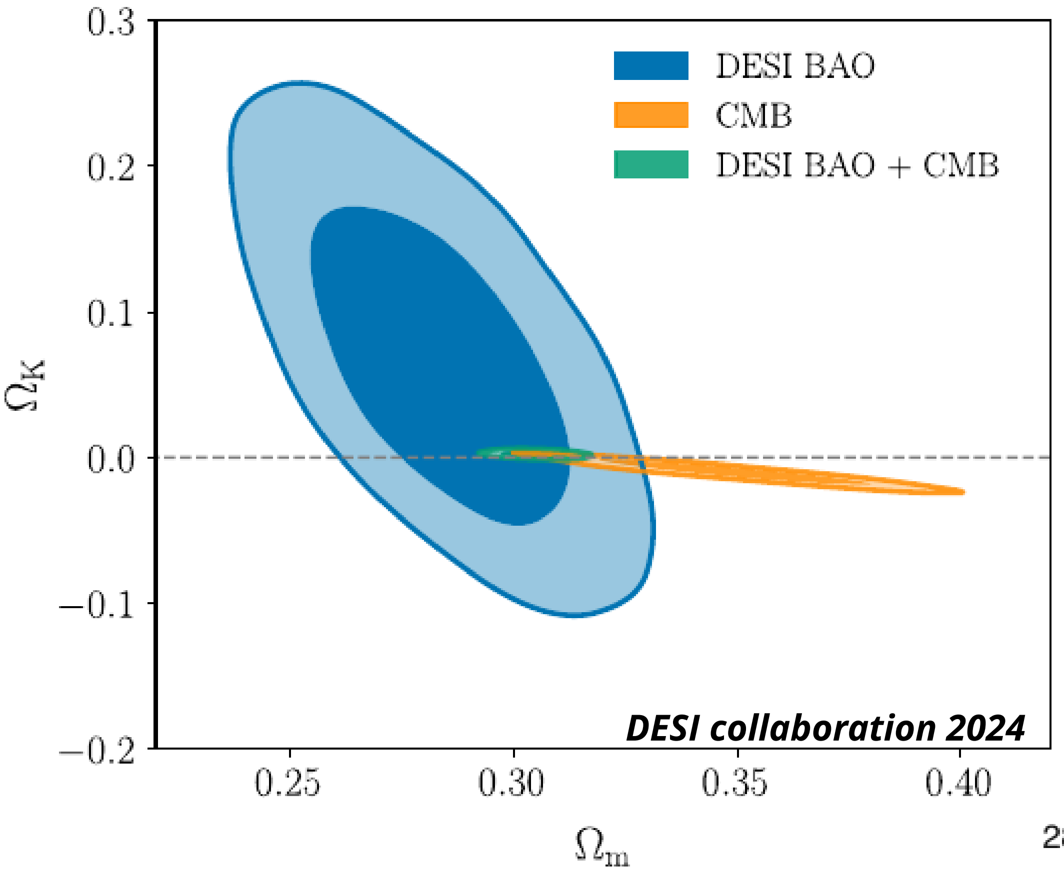
Curvature

ΛCDM model with free spatial curvature (K)

$$\boxed{\Omega_K = 0.0024 \pm 0.0016}$$

DESI + CMB

In favor of a flat Universe



28

Dark energy

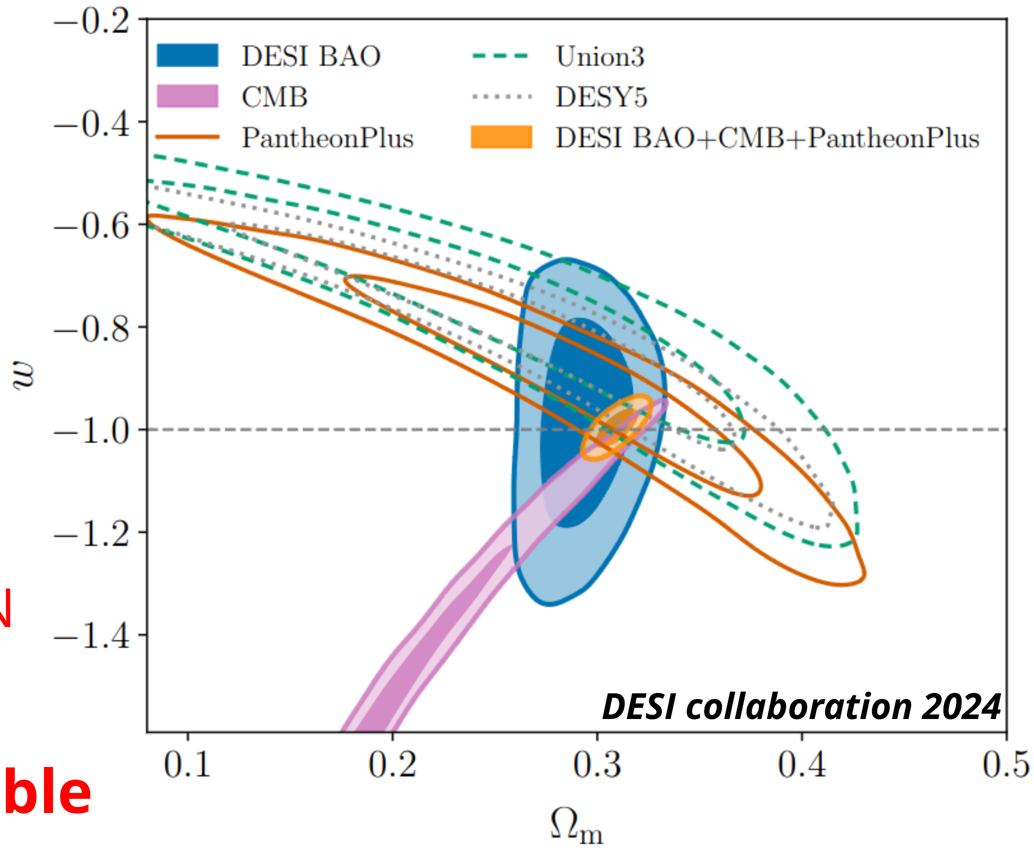
- Dark Energy equation of state (-1 for ΛCDM):

$$w = P/\rho$$

- *w*CDM model:

$\boxed{w = -0.99^{+0.15}_{-0.13}}$ DESI

$\boxed{w = -0.997 \pm 0.025}$ DESI + CMB + SN



Assuming constant EoS, compatible with a cosmological constant

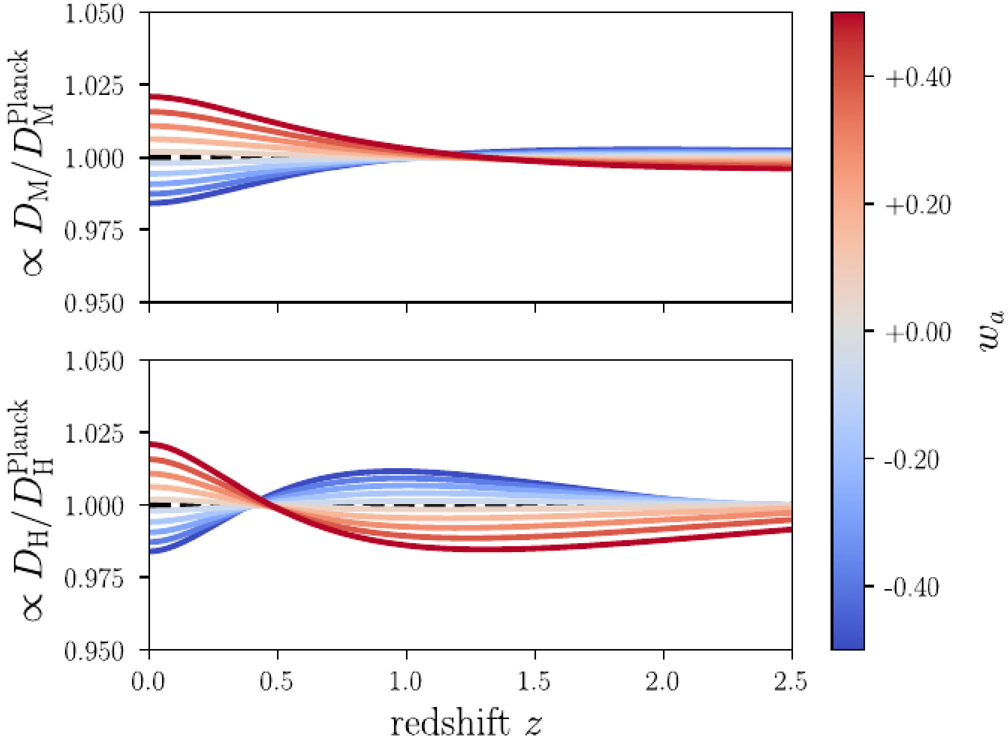
Dark energy

- Varying equation of state (CPL):

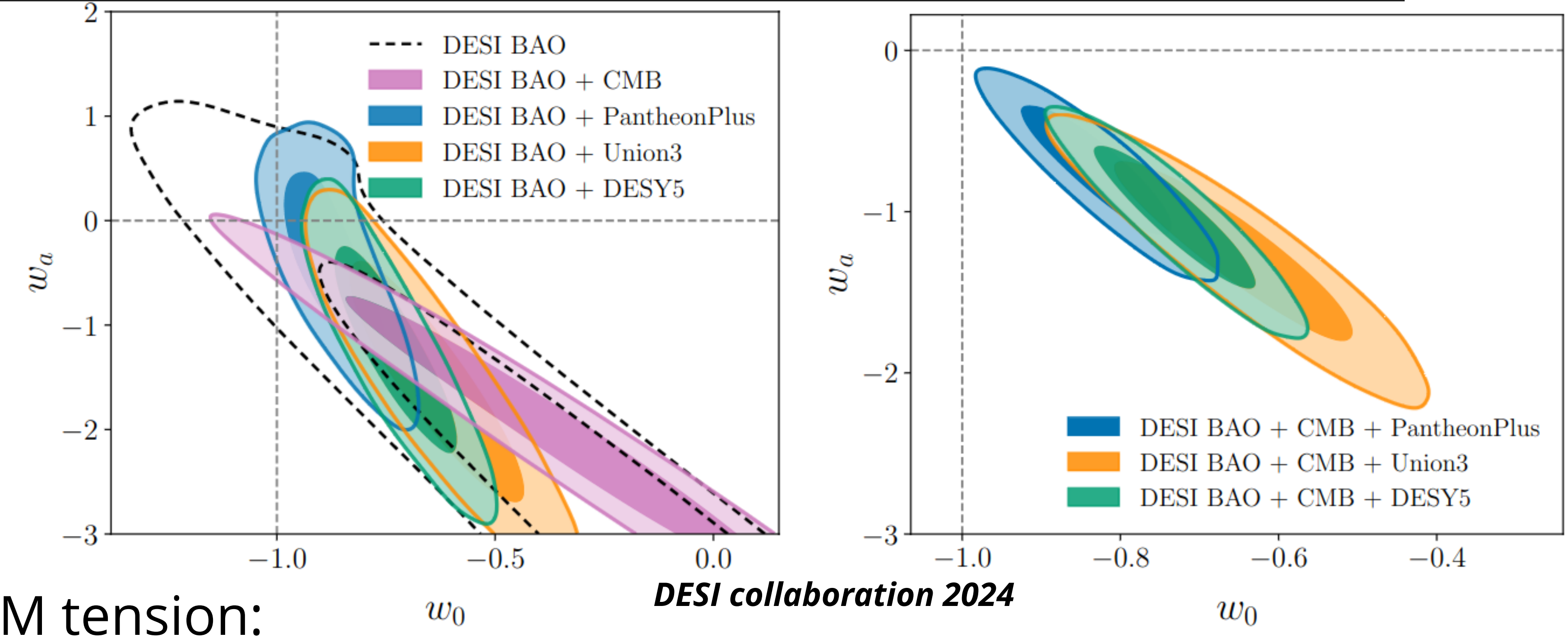
$$w(a) = w_0 + (1-a)w_a$$

- Can mimic wide range of viable cosmological models (phase transition, scalar field, modified gravity)
- ΛCDM:

$$w_0 = -1 \quad w_a = 0$$



Dark energy



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ΛCDM tension:

DESI + CMB + Pantheon+:	2.5σ
DESI + CMB + Union3:	3.5σ
DESI + CMB + DESY5:	2.5σ

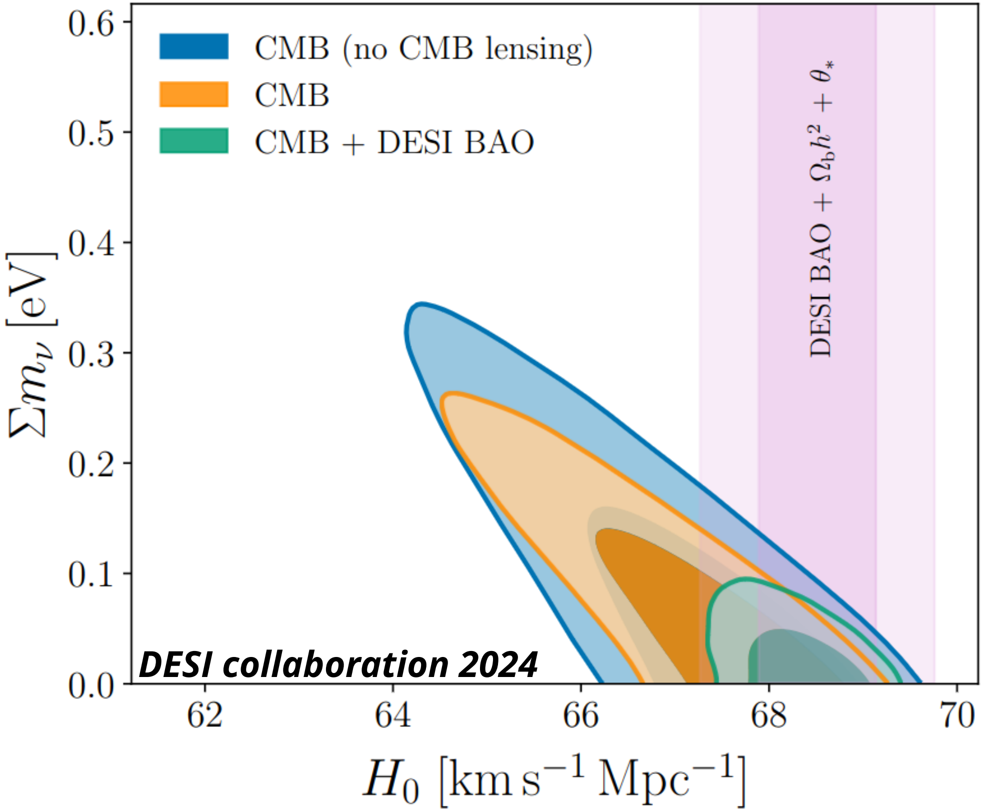
First hint of varying dark energy equation of state

Neutrino mass

- Neutrino mass impacts cosmology
- CMB degeneracies broken by BAO, through Hubble constant measurement

$$\boxed{\sum m_\nu < 0.072\text{eV}}$$ DESI + CMB

$$\boxed{\sum m_\nu < 0.195\text{eV}}$$ DESI + CMB with (w_0, w_a)



Strong constraint on neutrino mass

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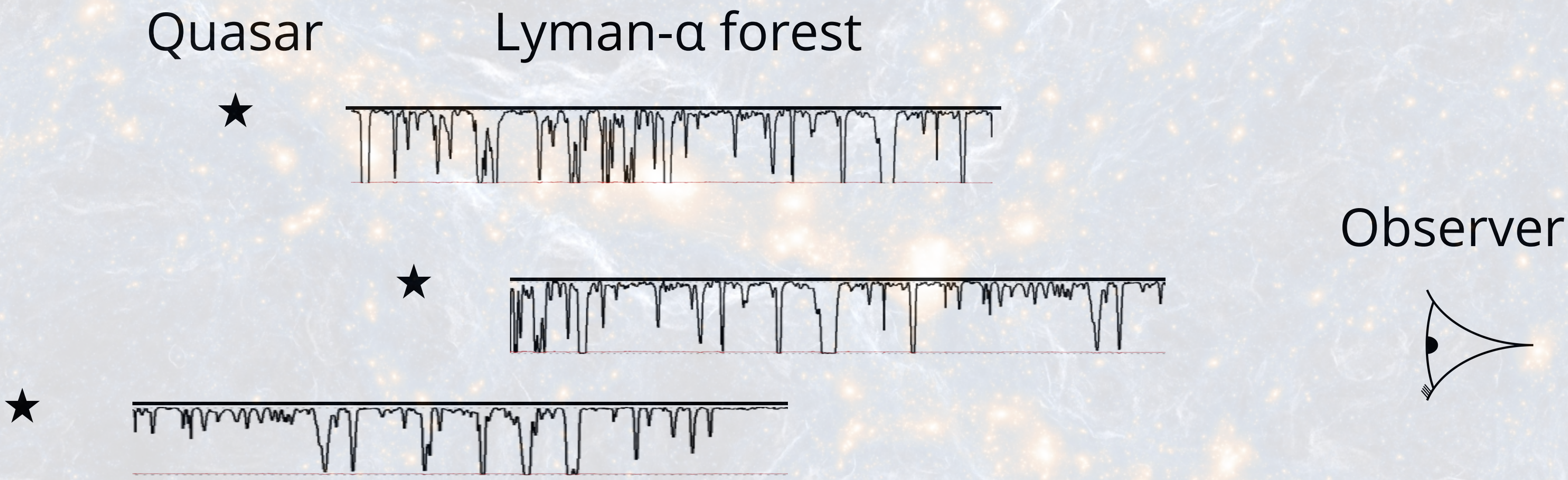
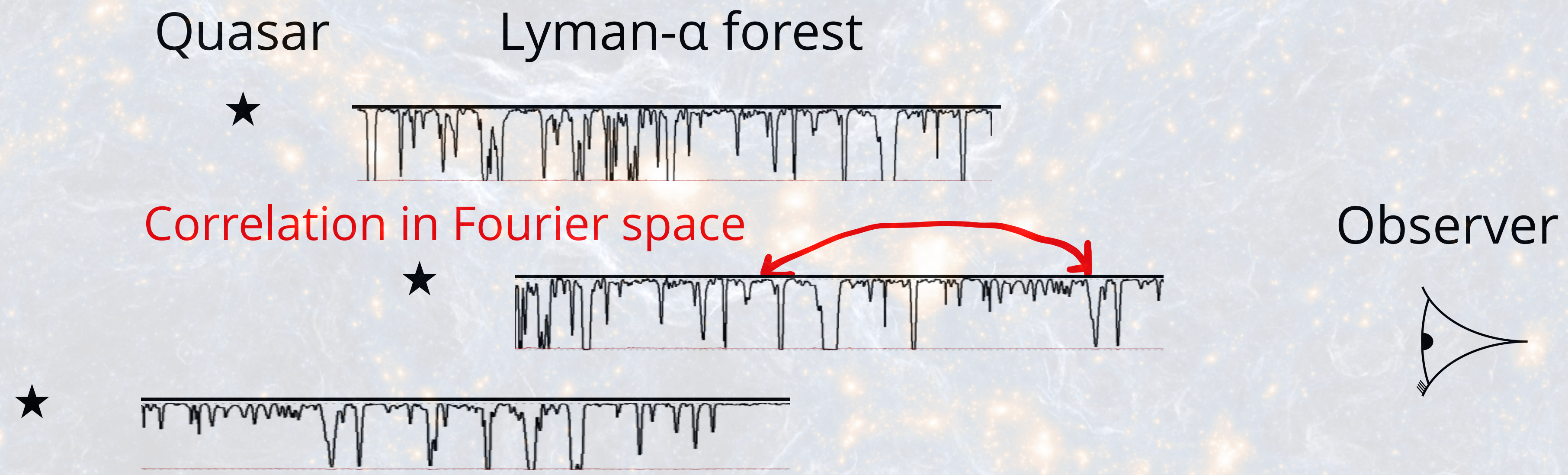
Lyman-α clustering



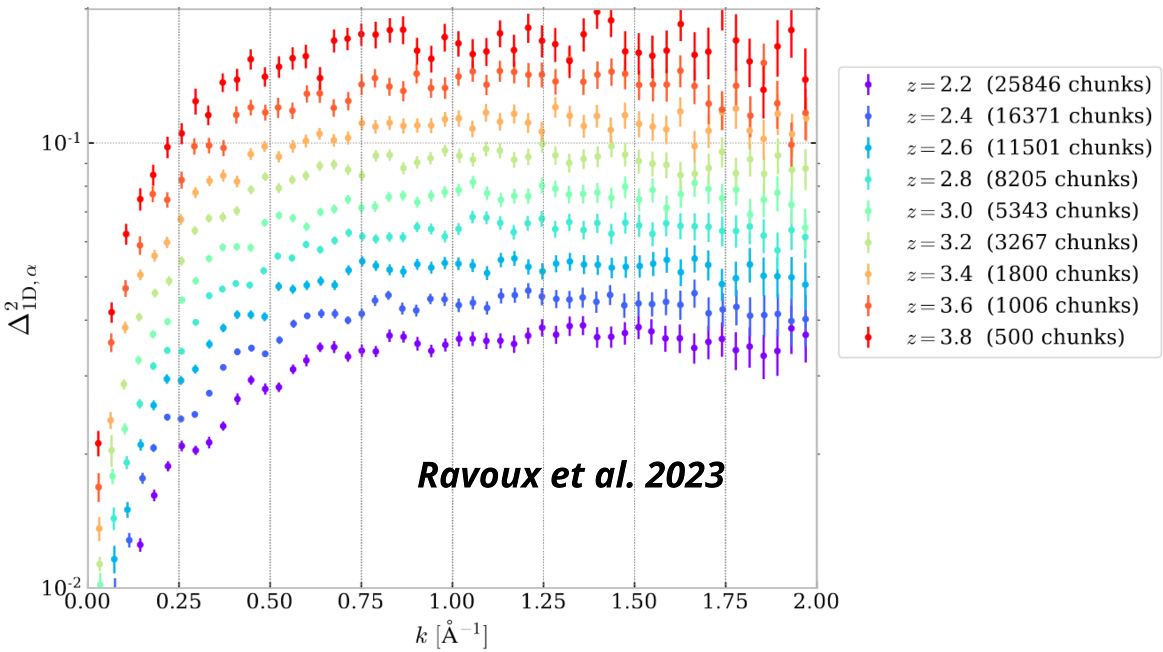
Lyman-α clustering



F = Fraction of transmitted flux $\rightarrow$ $\delta_F = \frac{F}{\langle F \rangle} - 1$ $\rightarrow$ $\boxed{P_{1\mathrm{D}} = \langle |\delta_F(k)|^2 \rangle_{\mathrm{forests}}}$

One dimensional power spectrum

- Correlations along individual lines-of-sight in Fourier Space
- Sensitive to small-scale matter clustering and IGM thermal state
- Unique probe to constrain neutrino masses and dark matter properties (WDM, FDM...)



DESI EDR FFT measurement

Lyman-α clustering

F = Fraction of transmitted flux $\rightarrow$ $\delta_F = \frac{F}{\langle F \rangle} - 1$ $\rightarrow$ $\delta_{F\mathrm{map}}$

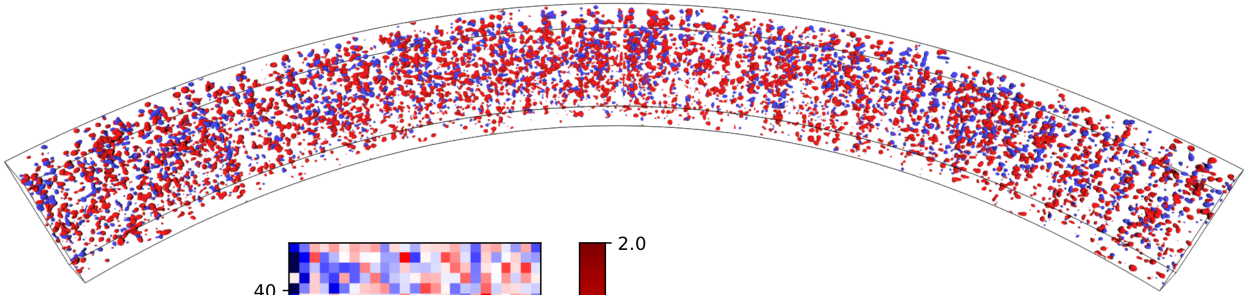
3D tomographic map of Lyman-α absorption

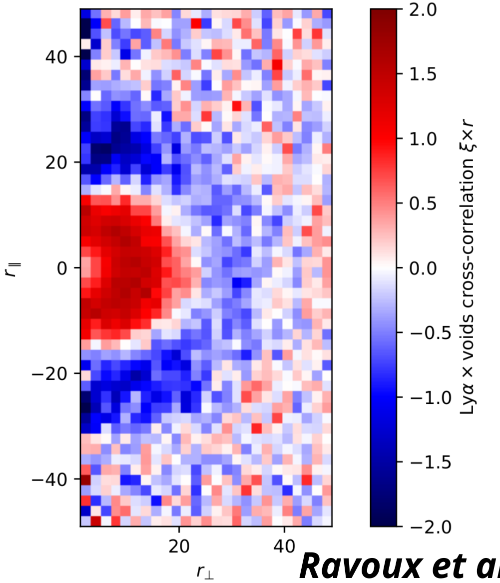
Tomographic map

- Gives a 3D map tracing matter at redshift z > 2

- **Applications:**
  - Identification of proto-cluster candidates
  - Cross-correlations with cosmic voids, tracer of velocity flows in the cosmic web

Ravoux et al. 2020





Ravoux et al. 2022

eBOSS DR16 measurement

Conclusion

- Hint of varying dark energy from DESI Y1 BAO data
- Strong constraints on ΛCDM and neutrino mass
- Lyman-α forest yields a lot of applications

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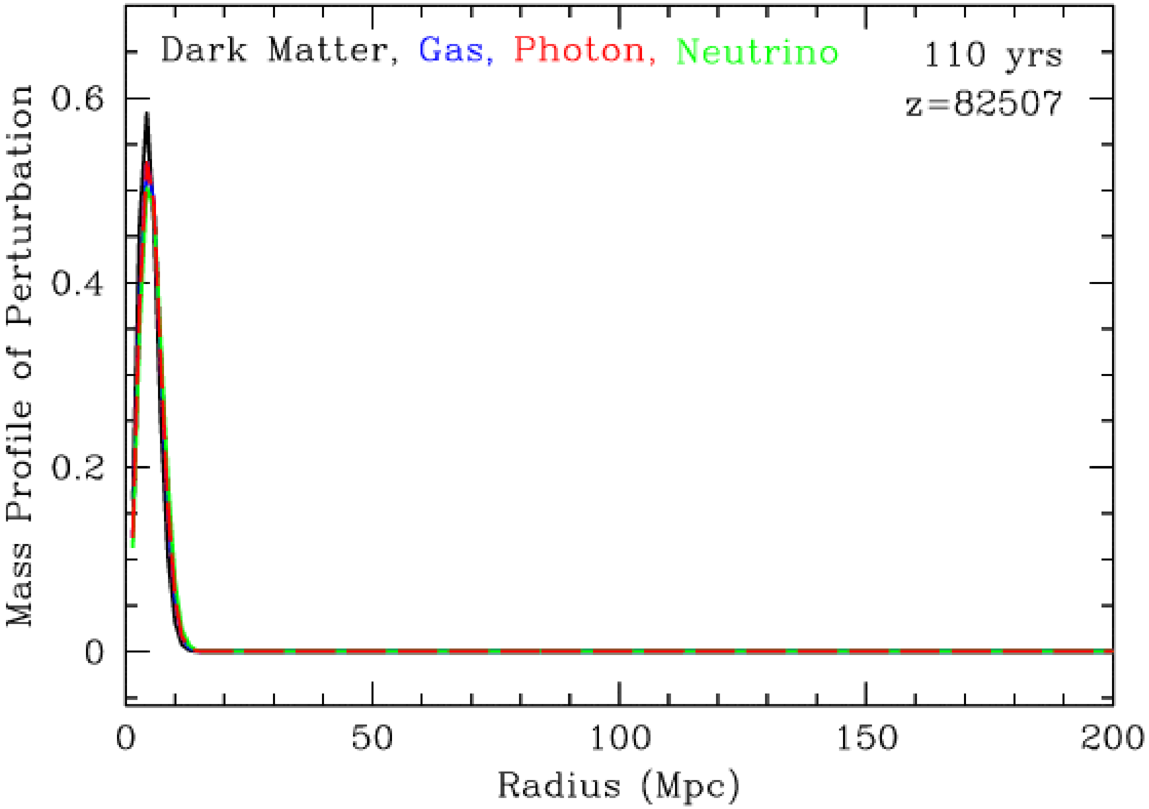
U.S. Department of Energy Office of Science

BAO for different species

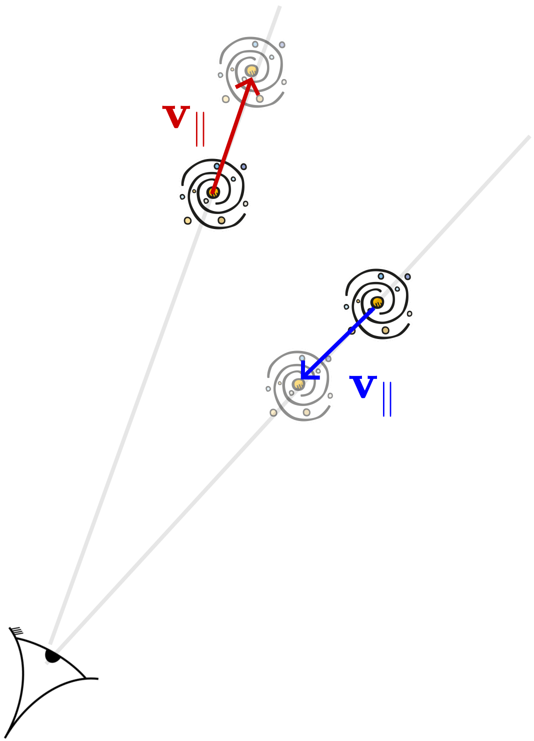
Interplay between different species in the primordial plasma and after recombination



Cosmological probes: RSD

- Redshifts precisely measured by spectroscopic surveys:
  - Universe expansion + peculiar velocity
  - Position shifted by the line-of-sight peculiar velocity

$$(1 + z_{\rm obs}) = (1 + z_{\rm cosmo})(1 + z_{\rm peculiar})$$

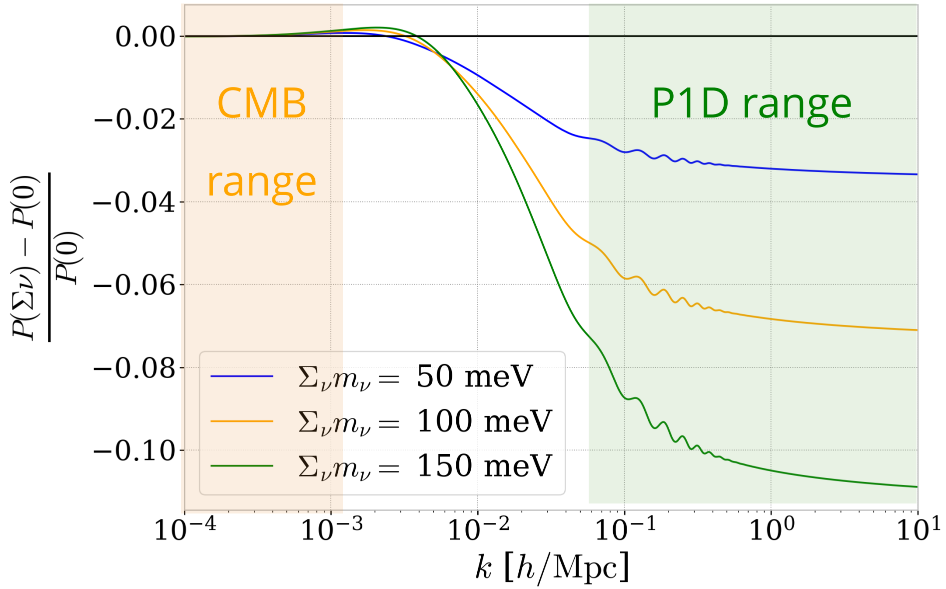


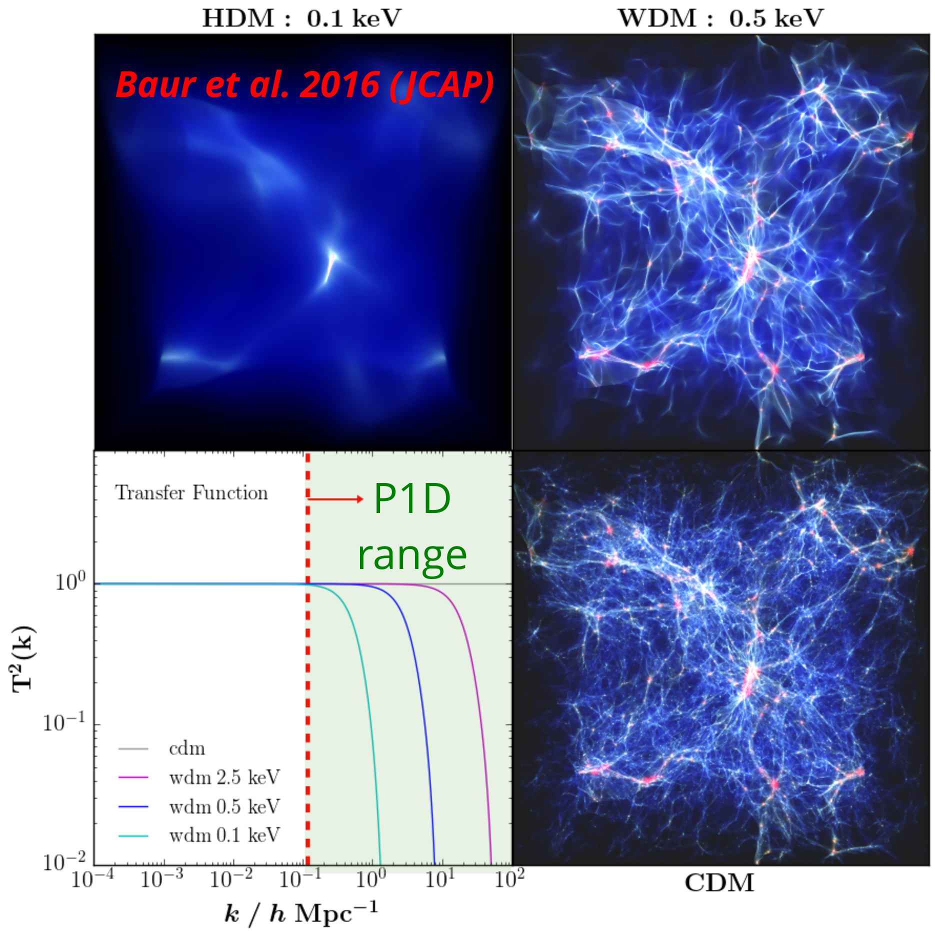
- **Redshift Space Distortions (RSD)**: Distortion of cosmological observable due to peculiar velocities

Neutrinos in cosmology

- Matter power spectrum impacted by:
  - Sum of neutrino masses $\sum m_\nu$
  - Dark matter model (e.g. warm dark matter)

Unique probe to constrain neutrino masses and dark matter properties





Latest constraints with eBOSS

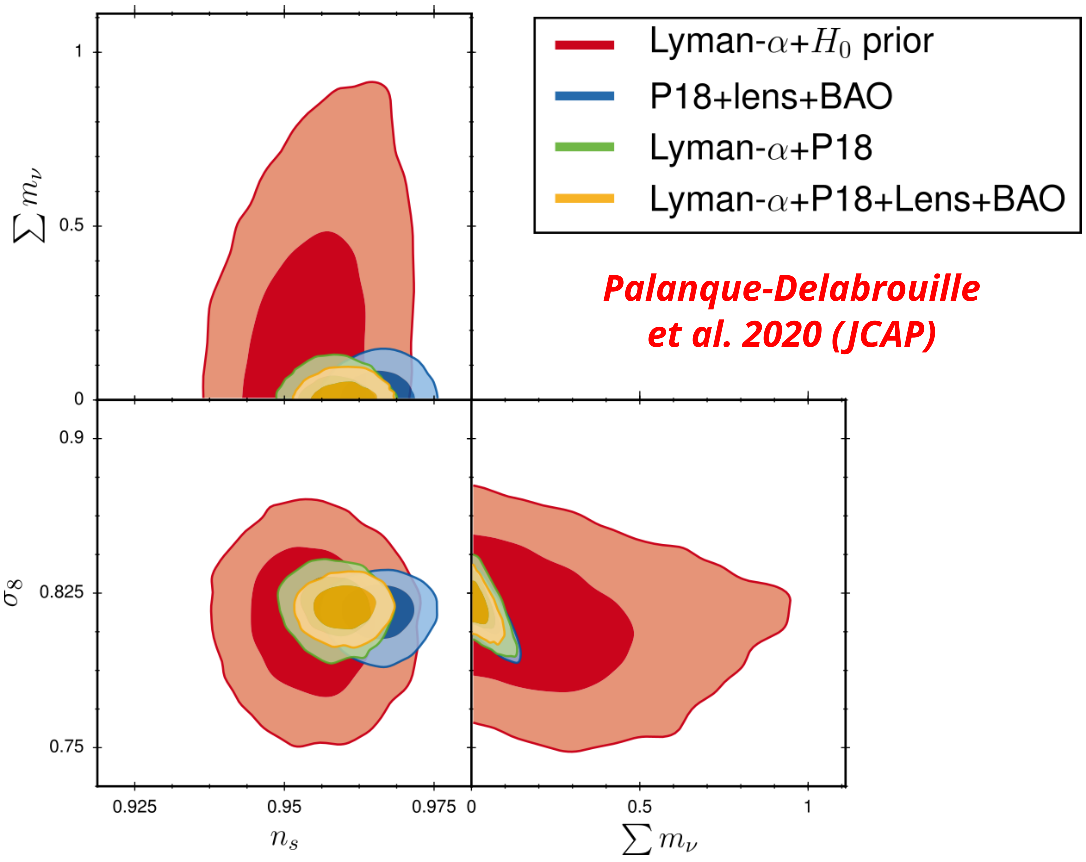
- Neutrino mass (P1D +CMB):

$$\boxed{\sum m_\nu < 0.11\ \text{eV}}$$ at 95% C.L.

- Warm dark matter model:

$$\boxed{m_X > 5.3\ \text{keV}}$$ at 95% C.L.

- Other constraints: Fuzzy dark matter, sterile neutrinos, running of the primordial power spectrum

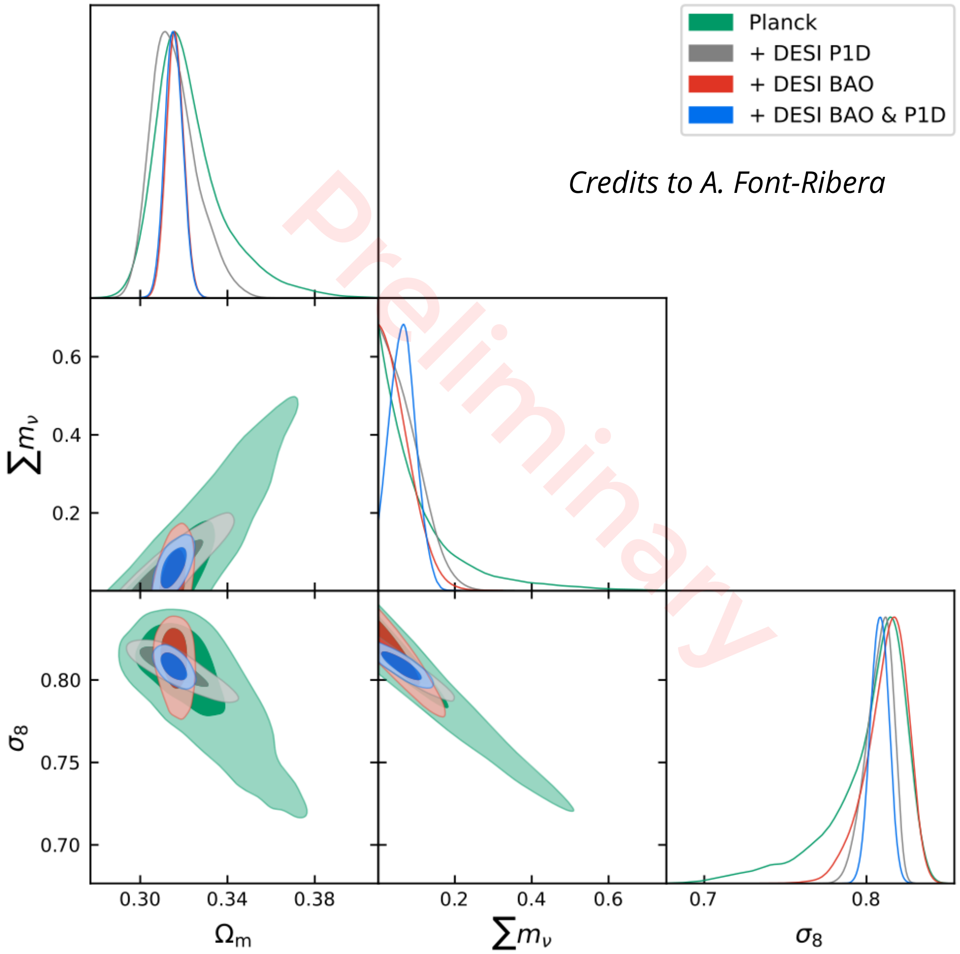


Palanque-Delabrouille et al. 2020 (JCAP)

Forecasts for DESI

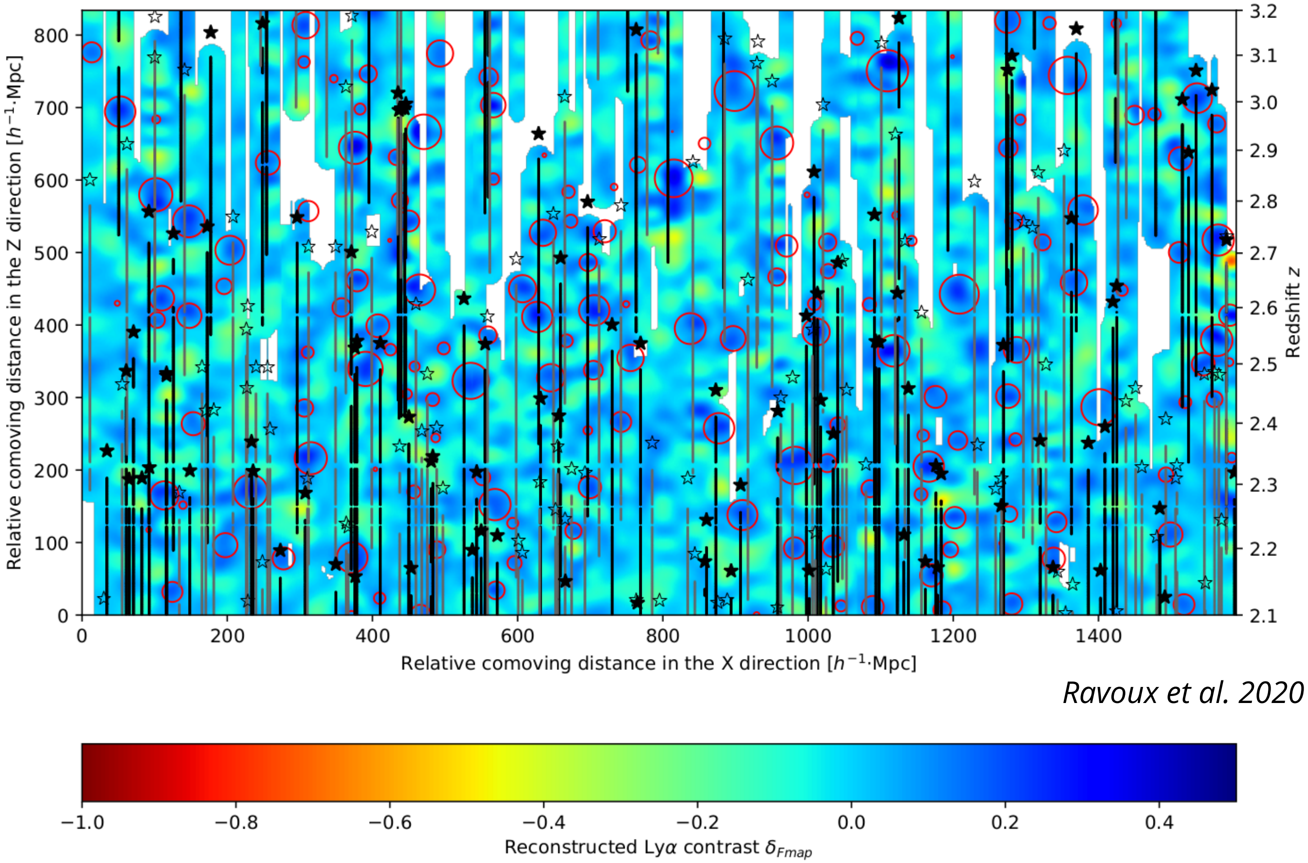
- Constraints on WDM improved by a factor 1.6 ***Valluri et al. 2022***
- IGM thermal parameters by a factor 2.
- Neutrino mass, in association with BAO and CMB:

$$\sigma\left(\sum m_\nu\right) = 0.03\ \mathrm{eV}$$

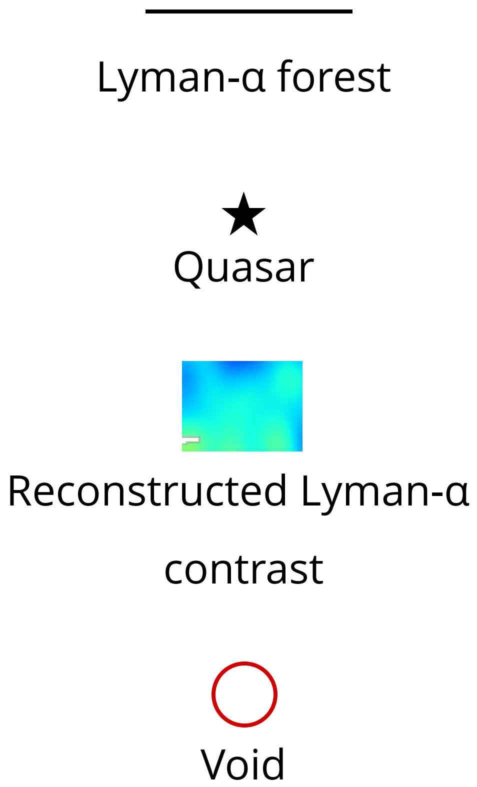


Credits to A. Font-Ribera

Wiener filter map on eBOSS data

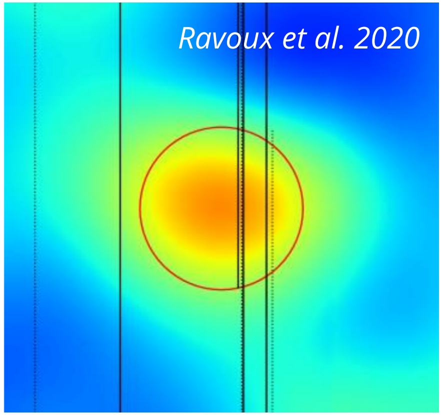


Ravoux et al. 2020



Applications

- Identification of proto-cluster candidates:
  - Densest regions of the map with density threshold
  - Criteria on the number of crossed lines-of-sight



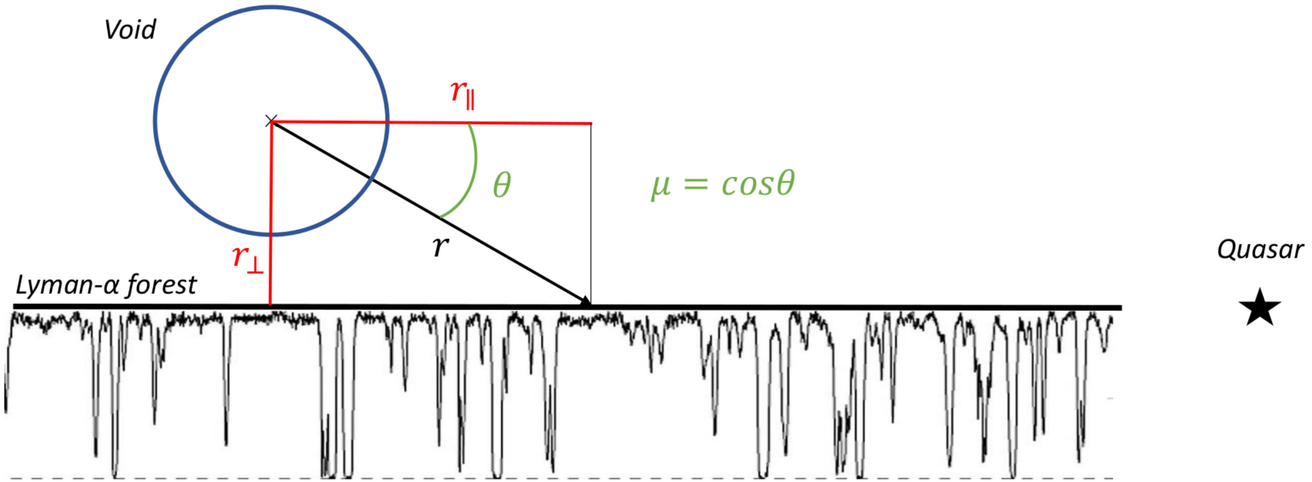
Ravoux et al. 2020

- High redshift cosmic voids:
  - 3D spherical void finder
  - Void can be used to probe the dynamic of the cosmic web

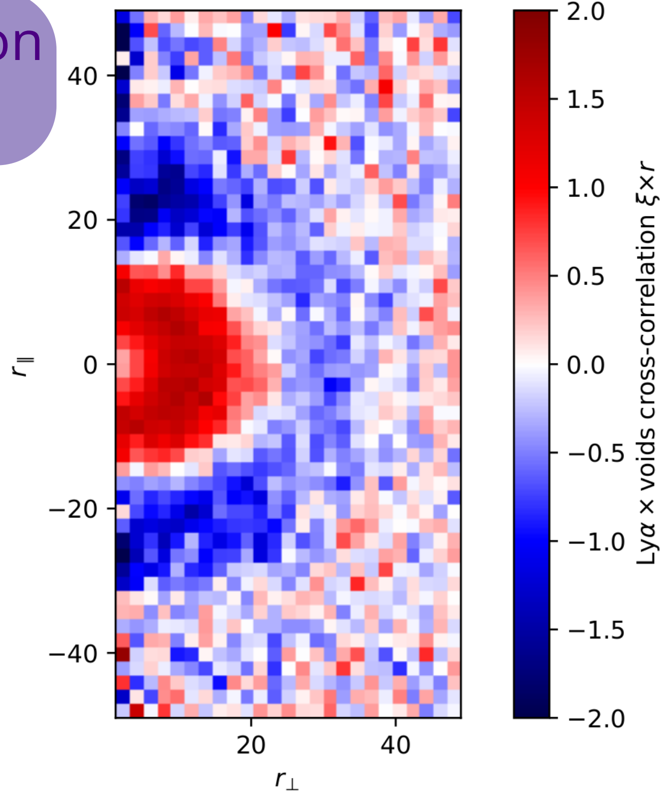
Lyman-α / Void cross correlation

- Distance between void centers and Lyman-α flux contrast:

3D cross correlation with voids



Ravoux et al. 2022



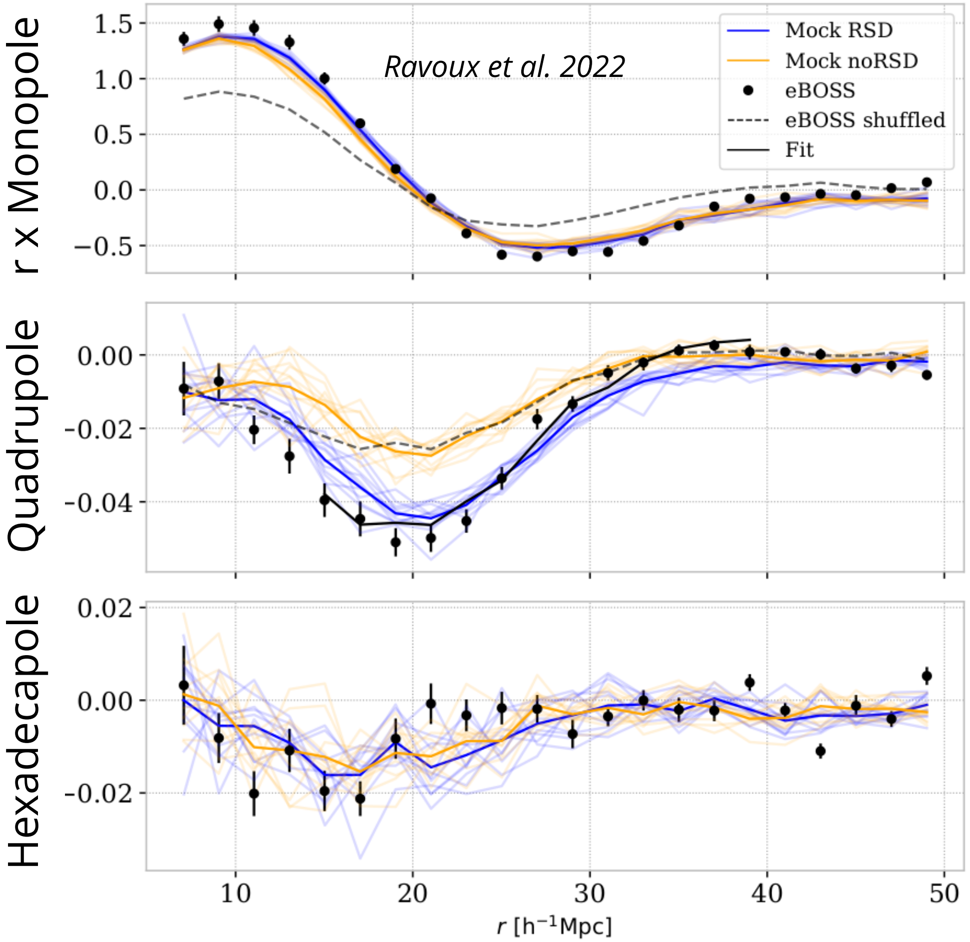
eBOSS measurement

Multipole expansion

- Use of a spherical decomposition to measure deformation of voids
- Effect of velocities seen in eBOSS data

$$\beta = \frac{b_\eta f}{b} = 0.52 \pm 0.05$$

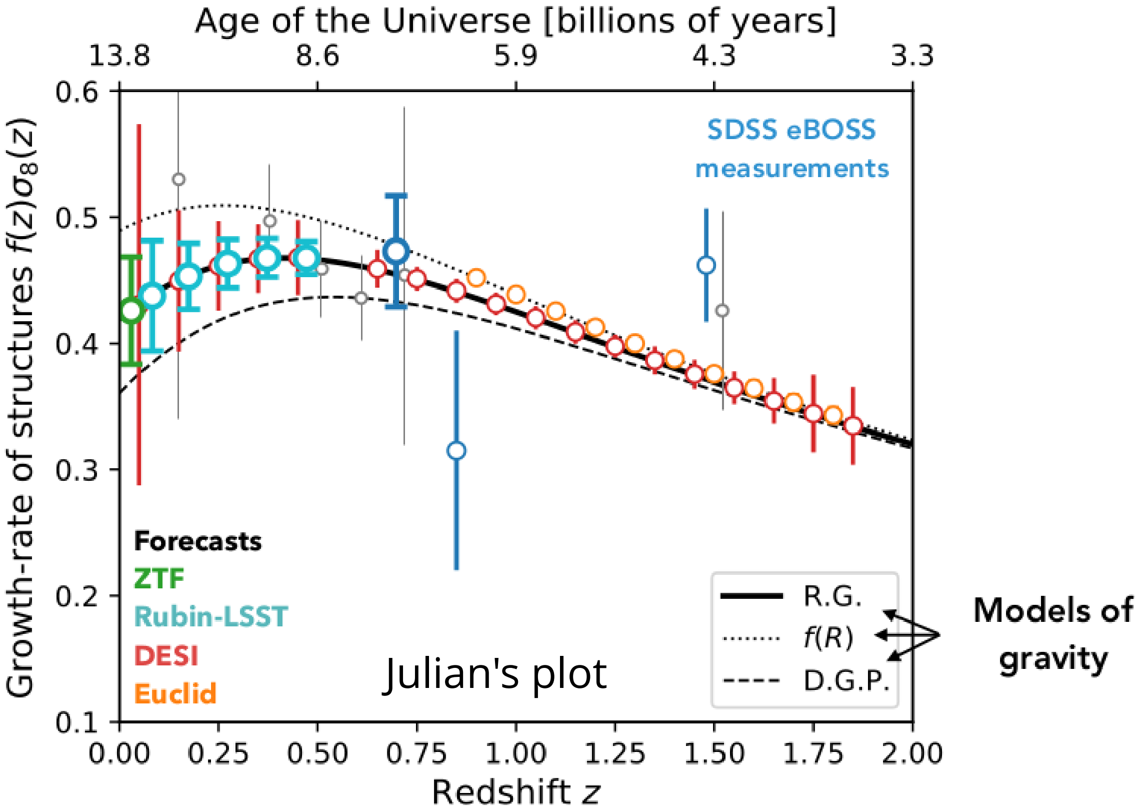
View of velocity flow around voids at z > 2



Growth rate forecasts

- **RSD** very effective for high-z
- **Peculiar velocities** for low-z

- Constraint improvement with combination of methods



Methods

- Growth rate measurement methods with peculiar velocities:

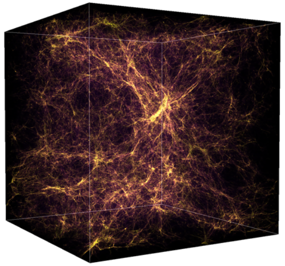
Density/momentum power spectra

$$\langle\delta_{\rm g}(k)\delta_{\rm g}(k)\rangle \ \langle\delta_{\rm g}(k)\mathbf{v}(k)\rangle \ \langle\mathbf{v}(k)\mathbf{v}(k)\rangle$$

Density-velocity comparison

$$\mathbf{v}_{\rm measured} \longleftrightarrow \nabla\cdot\mathbf{v}_{\rm pred} \propto -aHf\delta$$

Forward modeling

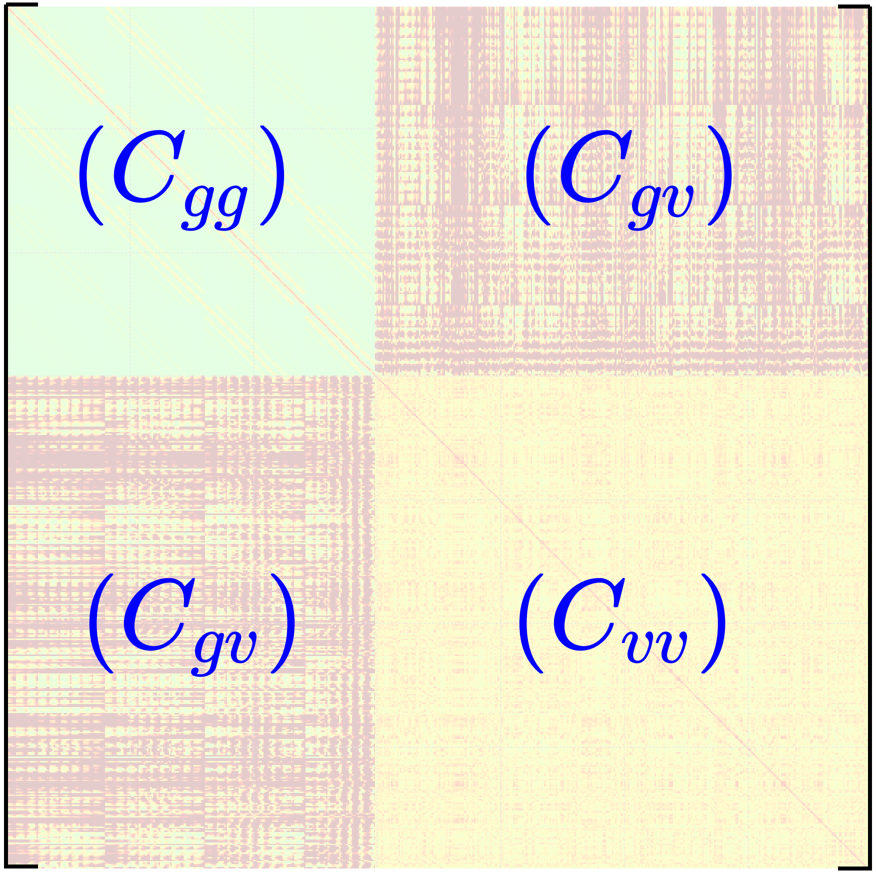


$$\longrightarrow (\delta_{\rm g}, \mathbf{v})$$

Maximum likelihood

Covariance matrix

$$\mathcal{L}(p) \propto \exp\left[-\frac{1}{2} \begin{bmatrix} \delta \\ v \end{bmatrix}^T \begin{bmatrix} (C_{gg}) & (C_{gv}) \\ (C_{gv}) & (C_{vv}) \end{bmatrix}^{-1} \begin{bmatrix} \delta \\ v \end{bmatrix} \right]$$



Density field from galaxy surveys (DESI, Euclid)

Velocities from SNIa (ZTF, LSST)

Covariance matrice computed from theory and coordinates