Lyman-α data as a probe of dark matter interactions

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Based on 1907.01496 and 2110.04024

SOTU, TIFR

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Overview

1. DM paradigm revisited

- Small-scale crisis
- Tensions

2. Lyman-α data

- What is Lyman-α data
- How to use Lyman-α data

3. DM - DR interactions

- Why this model
- Bounds from Lyman-α

4. DM - neutrino interactions

- Model and pipeline
- Hints of interactions

The CDM paradigm

The dark matter paradigm

- ~85% of the matter content in the universe is invisible (see intro slide of every dark matter talk)
- Current dark matter paradigm: cold, collisionless, non-baryonic matter that interacts gravitationally
- "Cold dark matter" = velocity dispersion is so small that the corresponding free-streaming length $\lambda_{\rm fs}$ is negligible for cosmological structure formation
- Most likely candidate: WIMPs → particles interacting weakly, produced via freeze-out at $T_{\rm fo} \sim m_\chi/20$

Cosmological failings of CDM

A crisis on the smallest scales: mismatch between simulations and observations of structures in our local neighbourhood

- Missing satellite problem: we observe fewer satellites than expected from simulations
- Too-big-to-fail problem: most massive sub-halos that should be big enough have not ignited
- Core-cusp problem: we see cored flat profiles, simulations predict cuspy profiles peaked at the centre
- Diversity problem: we see too many different galaxy profiles

Cosmological failings of ΛCDM

- Expansion rate of the universe, H_0, can be measured different ways
- ~5σ tension between early and late measurements
- Systematic errors have been rigorously checked. CMB measurements assume ΛCDM

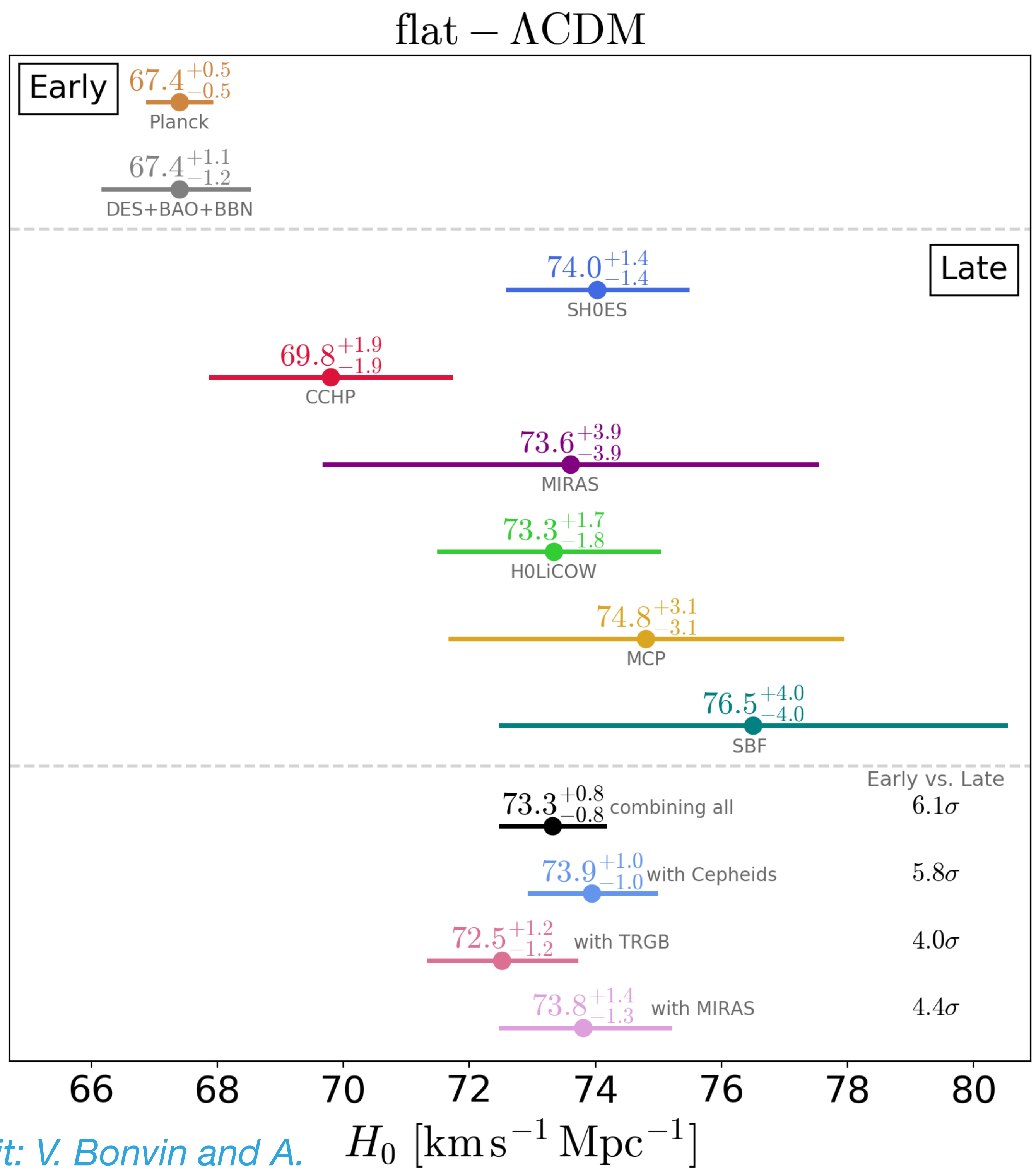
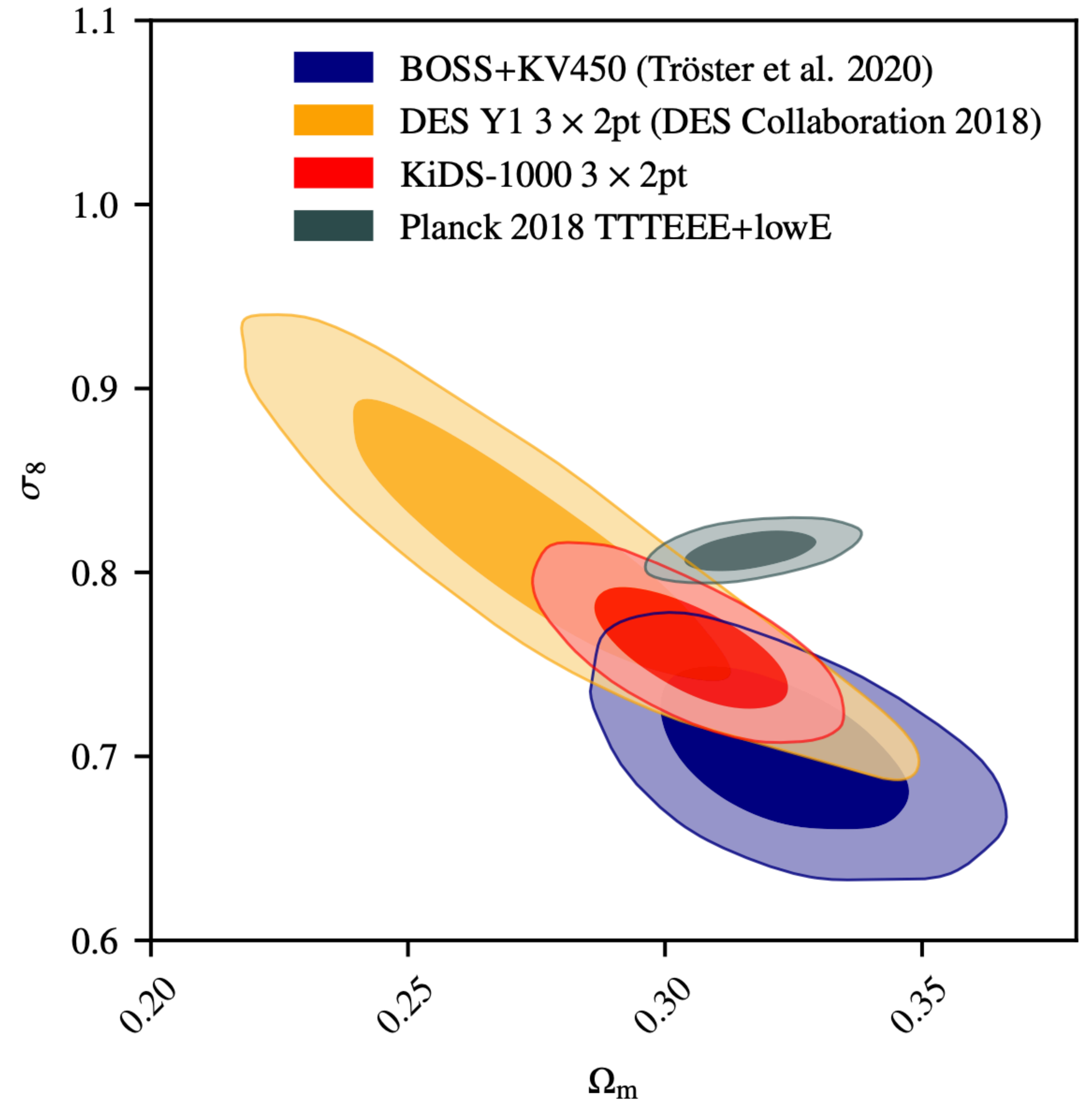


Figure credit: V. Bonvin and A. Shahib, available at 1907.10625

Cosmological failings of ΛCDM

- Clustering parameter σ_8 measures amplitude of the power spectrum on scales of 8 Mpc/h
- There is a ~2.5σ tension between weak lensing and CMB measurements
- CMB measurements assume ΛCDM. Weak lensing data requires extensive cleaning and processing



Di Valentino et al. 2008.11285

Lyman-α data

Lyman-α data

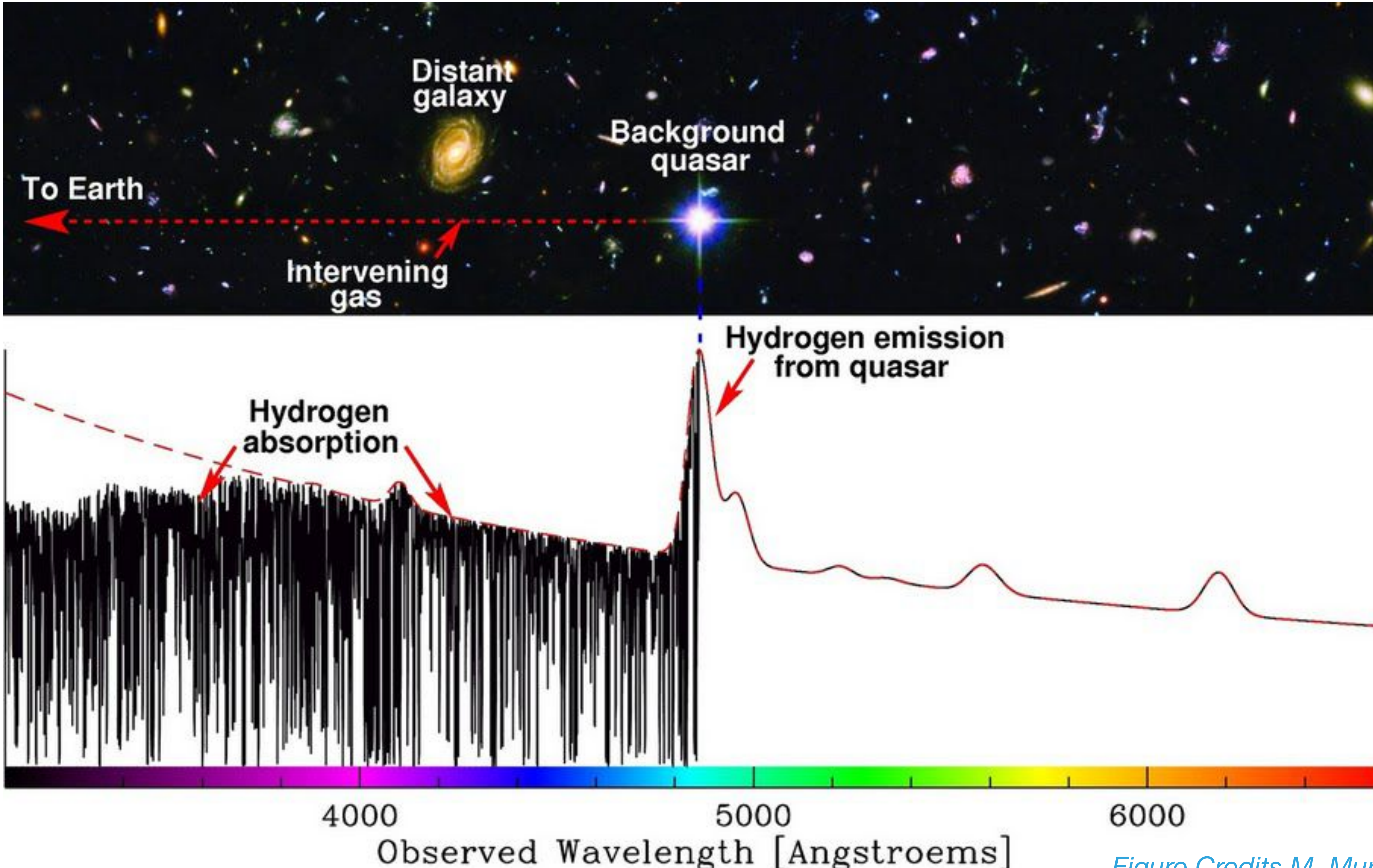
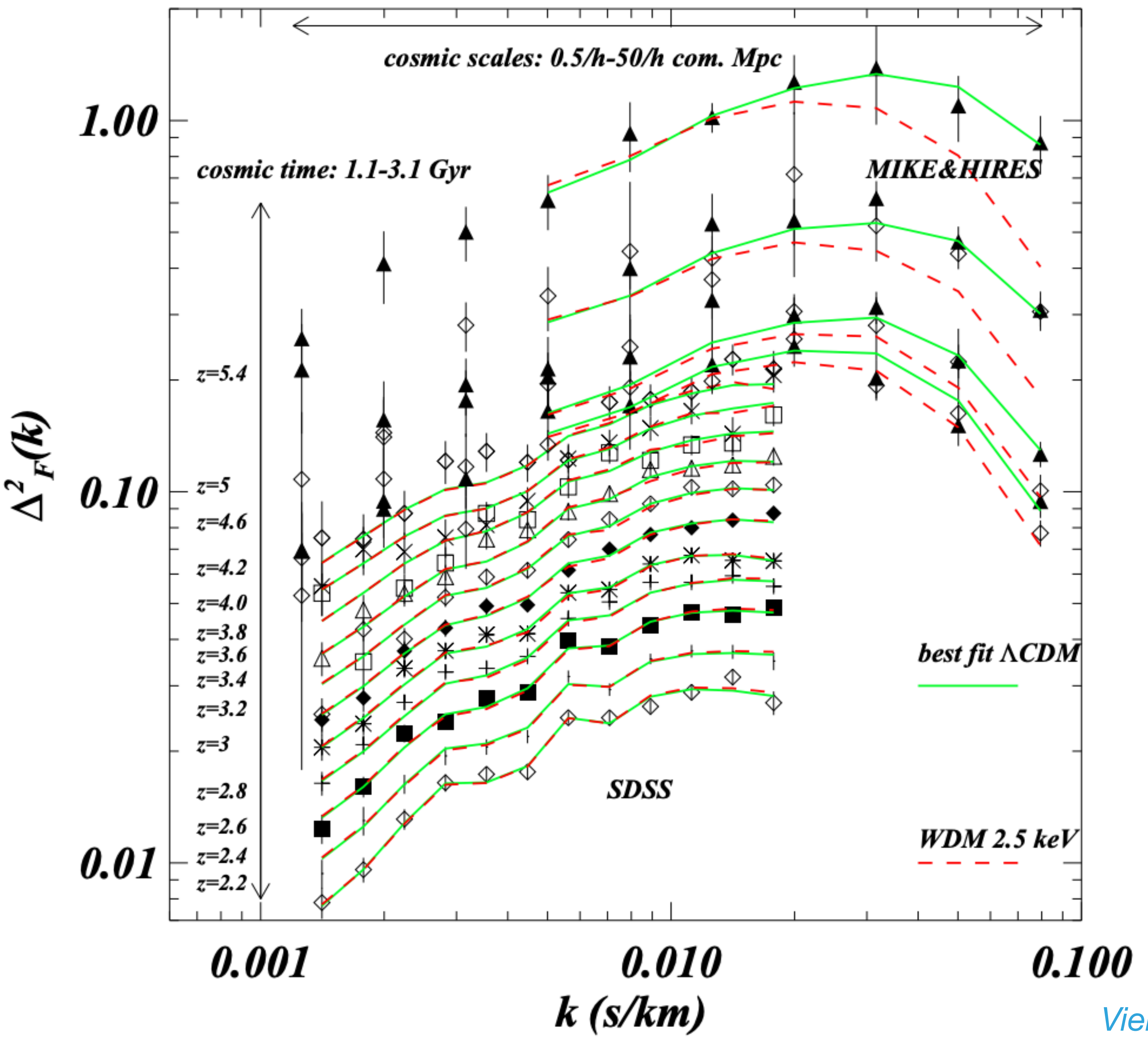


Figure Credits M. Murphy

Lyman-α data

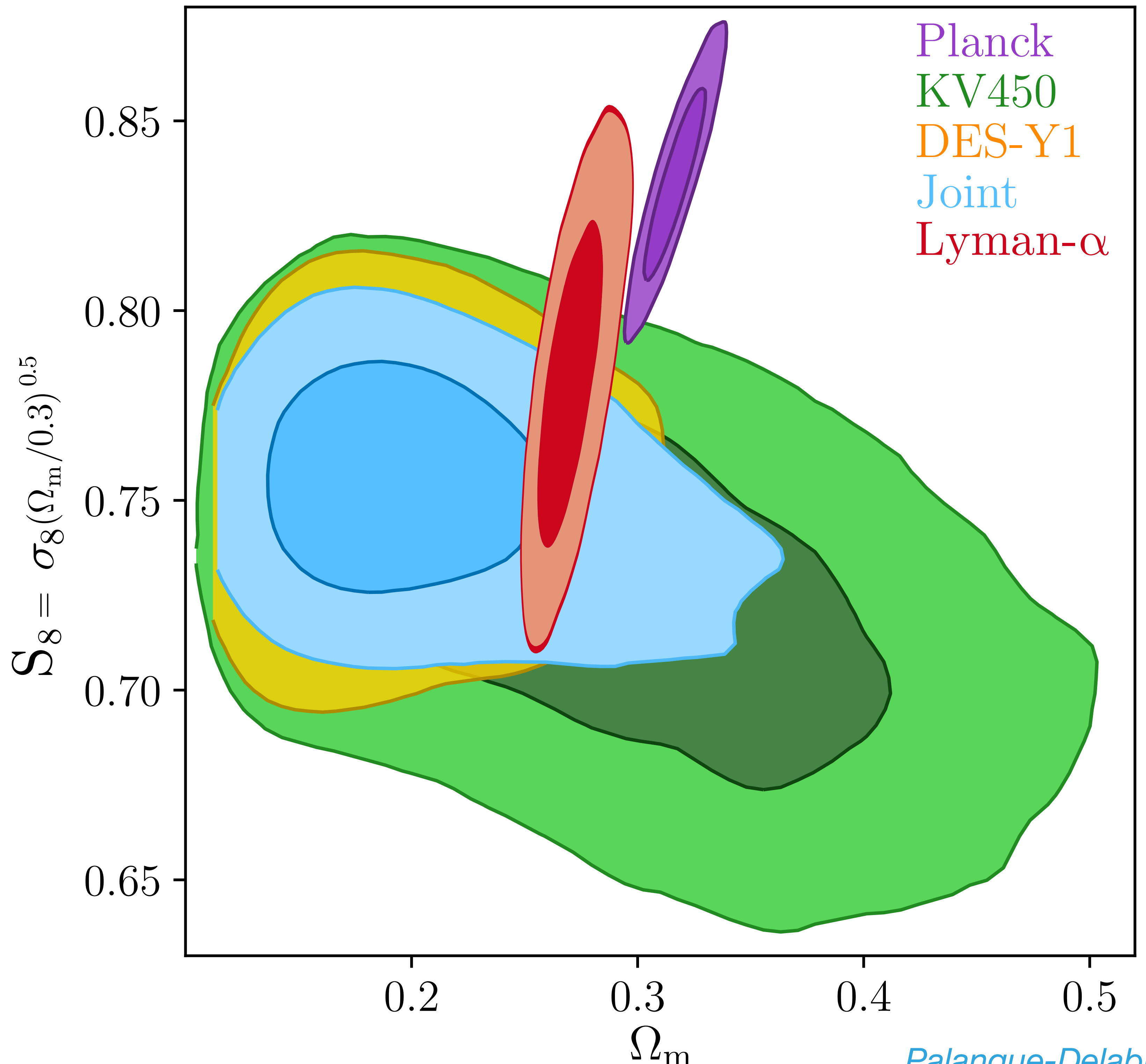
- Absorption lines produced by the inhomogeneous IGM along different line of sights to distant quasars
- Allows us to trace hydrogen clouds → smallest structures
- Provides a tracer of the matter power spectrum at high redshifts ($2 \lesssim z \lesssim 5$) and small scales ($0.5\,h/\mathrm{Mpc} \lesssim k \lesssim 20\,h/\mathrm{Mpc}$)
- Can constrain models that affect small scale structure formation
- IGM filament modelling requires nonlinear evolution: this needs hydrodynamical simulations → parameter scans are not feasible

Lyman-α data and ΛCDM



Viel et al. 1306.2314

Lyman-α data and ΛCDM



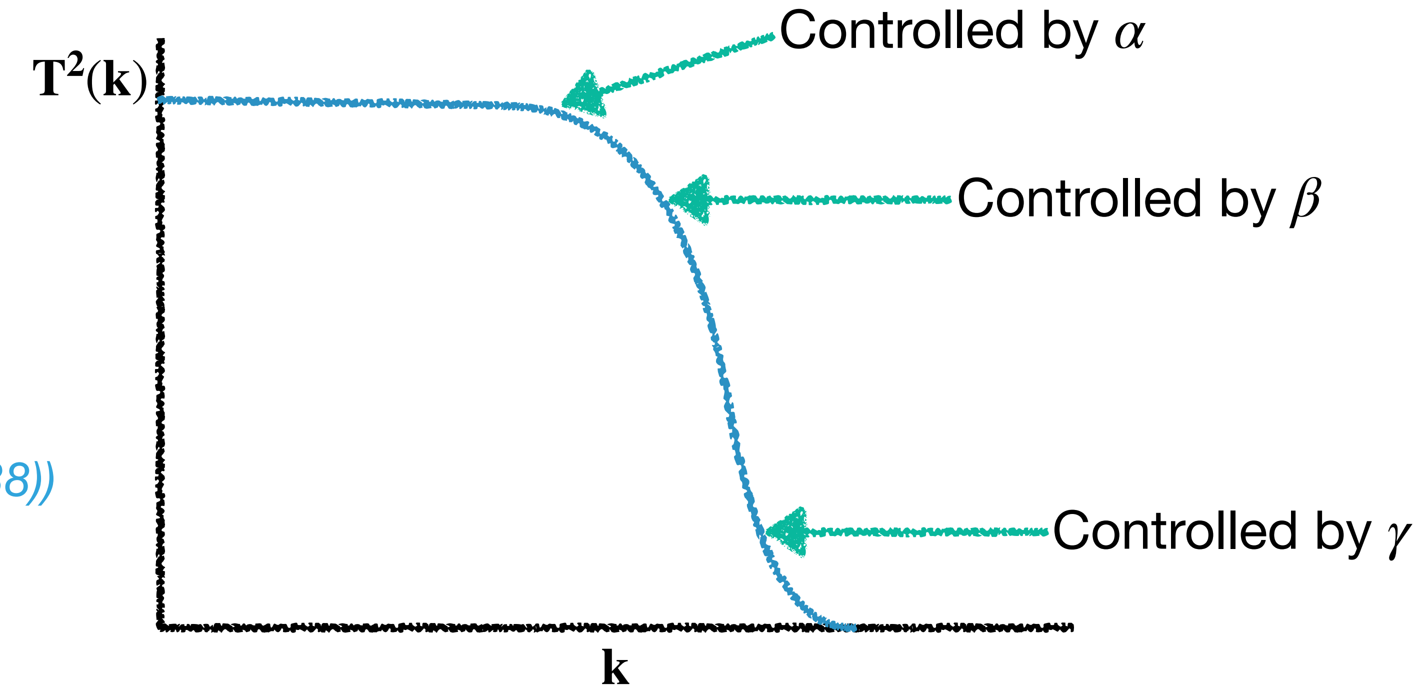
Palanque-Delabrouille et al. 1911.09073

How to use Lyman-α data

- MontePython likelihood for Lyman-α data
- Inspired by WDM: focus on the *shape* of the suppression caused by NCDM models

$$T^2(k) = \frac{P(k)_{\rm nCDM}}{P(k)_{\rm CDM}} = \left[1 + (\alpha k)^\beta\right]^{2\gamma}$$

(initially proposed in Murgia et al. (1704.07838))

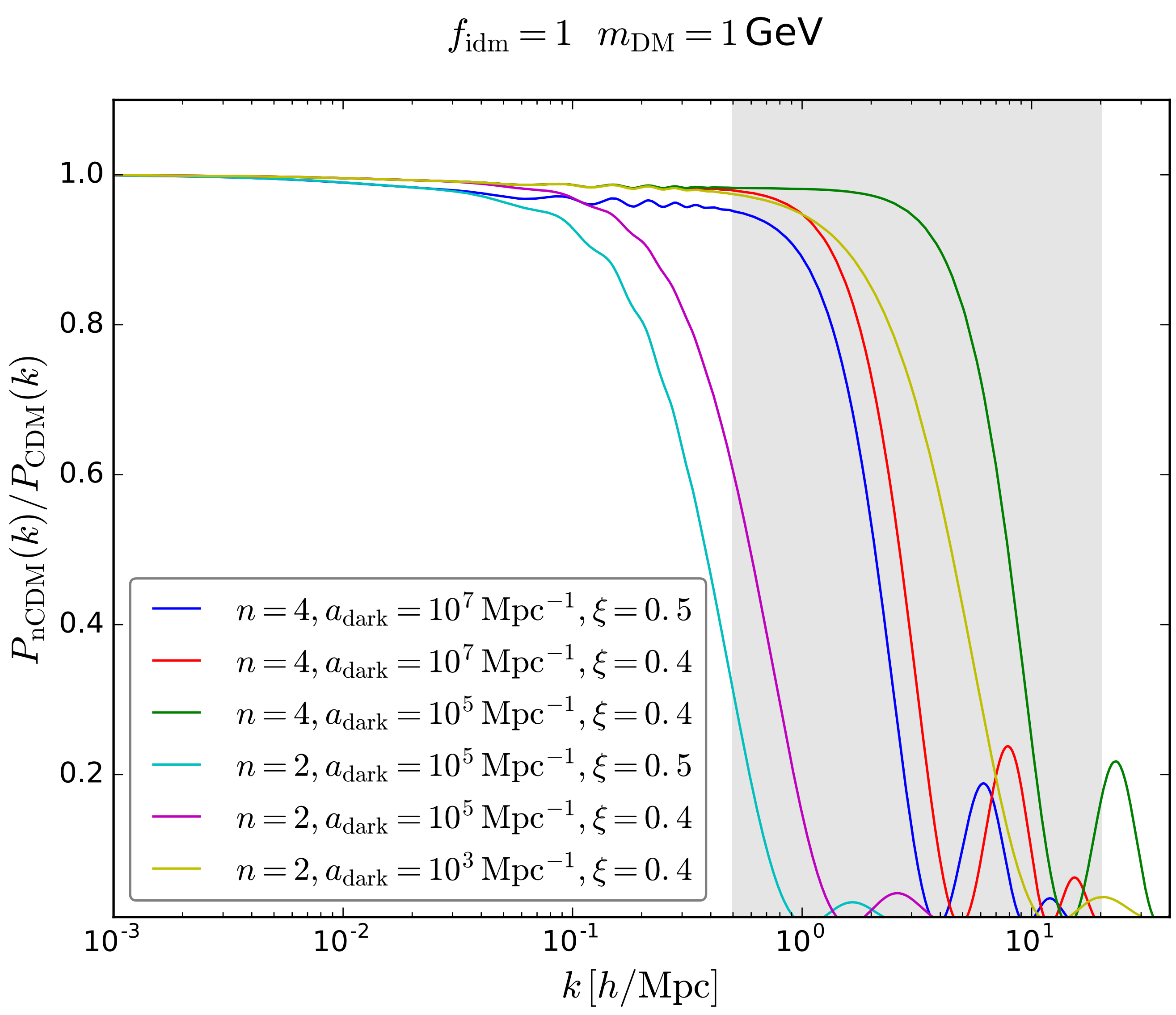


- Use a grid of hydro sims for over 100 different benchmark $\alpha\beta\gamma$, with a corresponding χ^2 given by Lyman-α data (MIKE/HIRES)
- Interpolate in grid to obtain a χ^2 from Lyman-α data for any NCDM model that can be described by $\alpha\beta\gamma$

DM - DR interactions

DM-DR model

*Archidiacono, **DCH**, Murgia, Bohr, Lesgourgues, Viel 1907.01496*



- Dark Matter - Dark Radiation interactions induce a suppression of the matter power spectrum on small scales
- For general interactions, we use ETHOS formalism (Cyr-Racine et al. 1512.05344)
- We consider only the process $\chi\tilde{\gamma} \leftrightarrow \chi\tilde{\gamma}$, with no DM or DR self-interactions
- Relevant parameters: amplitude of scattering rate $a_{\rm dark}$, amount of dark radiation $\xi = T_{\rm dr}/T_\gamma$, temperature dependence of scattering rate n, dark matter mass $m_{\rm DM}$, and fraction of interacting dark matter $f_{\rm idm}$

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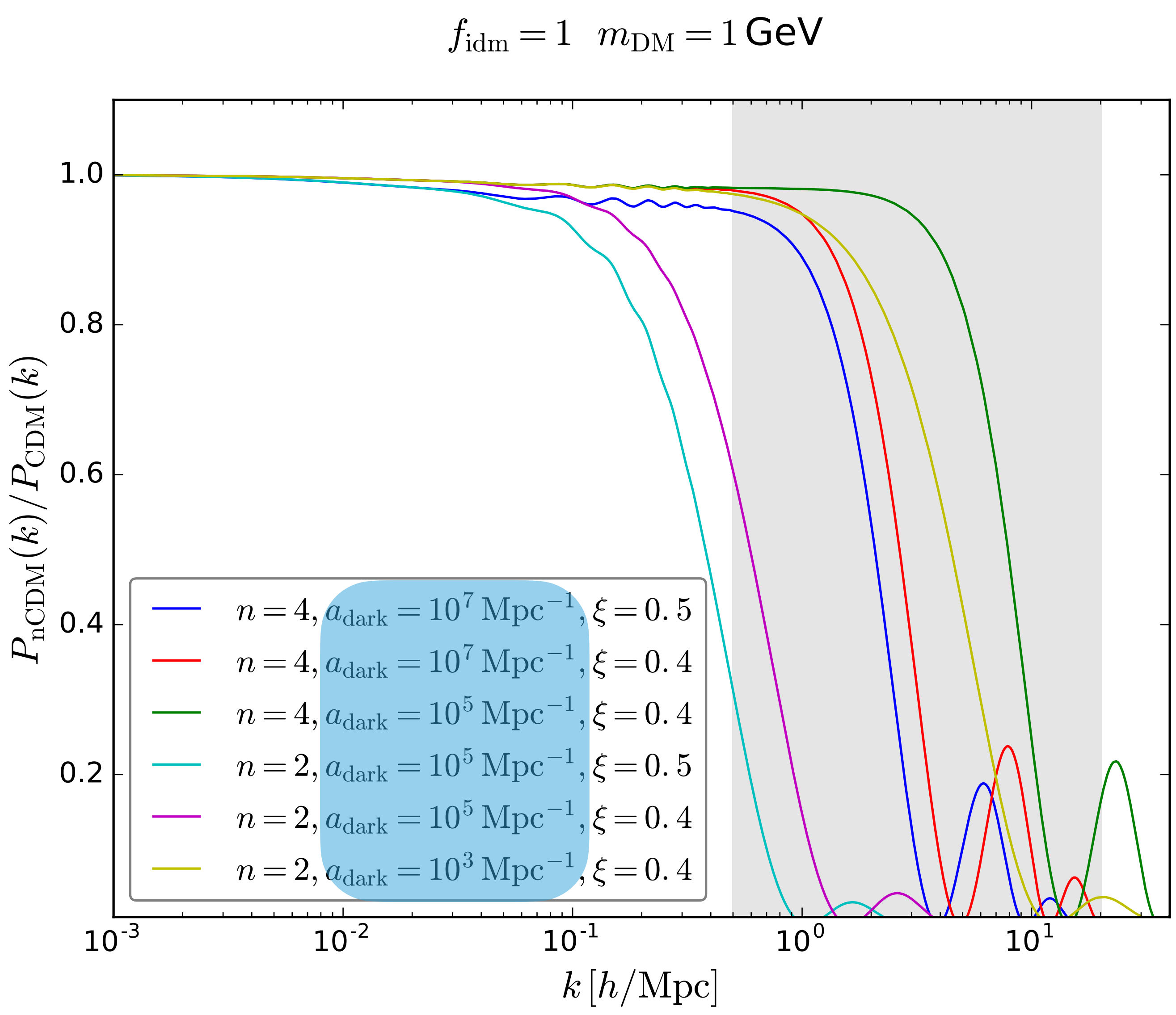

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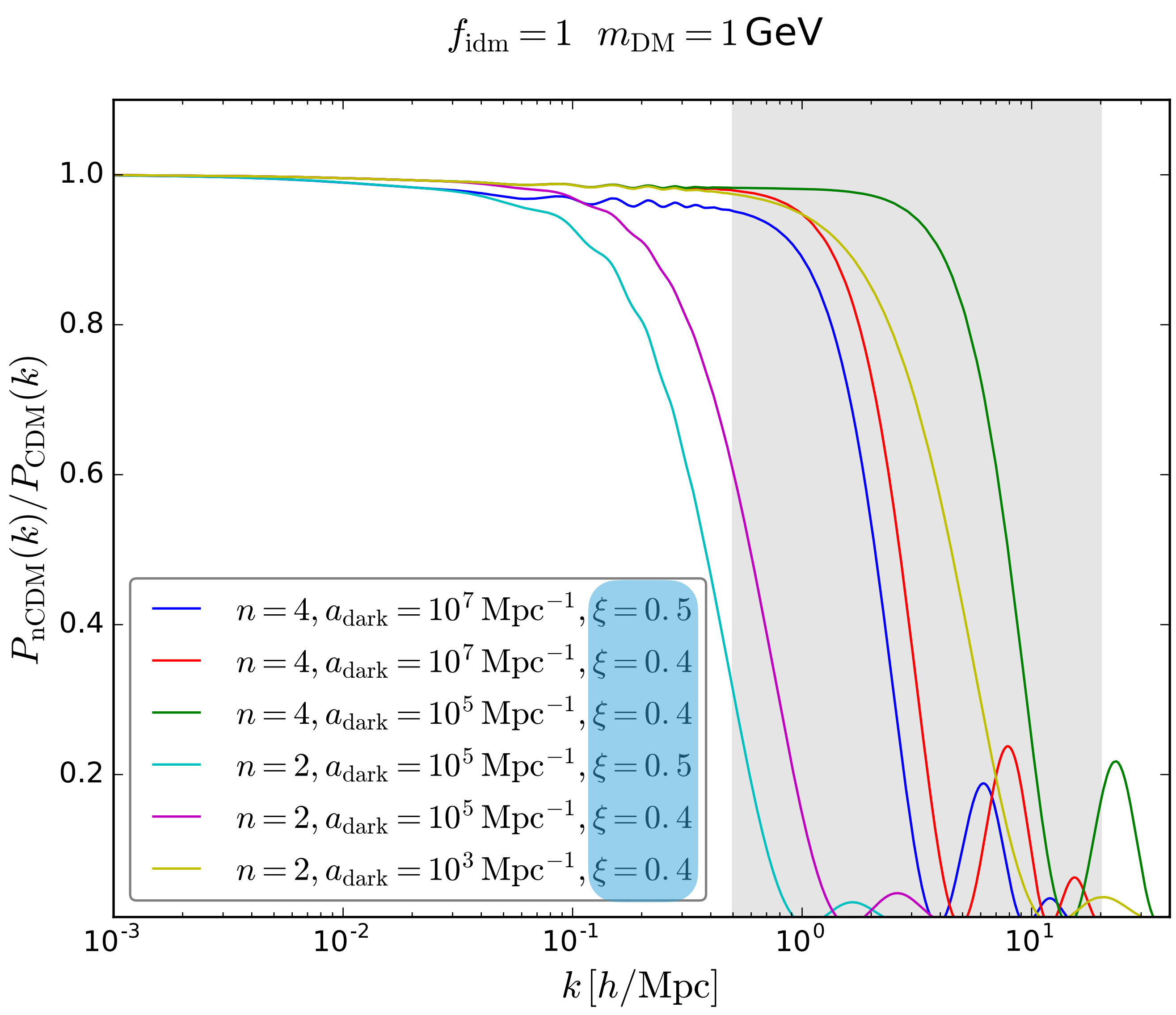

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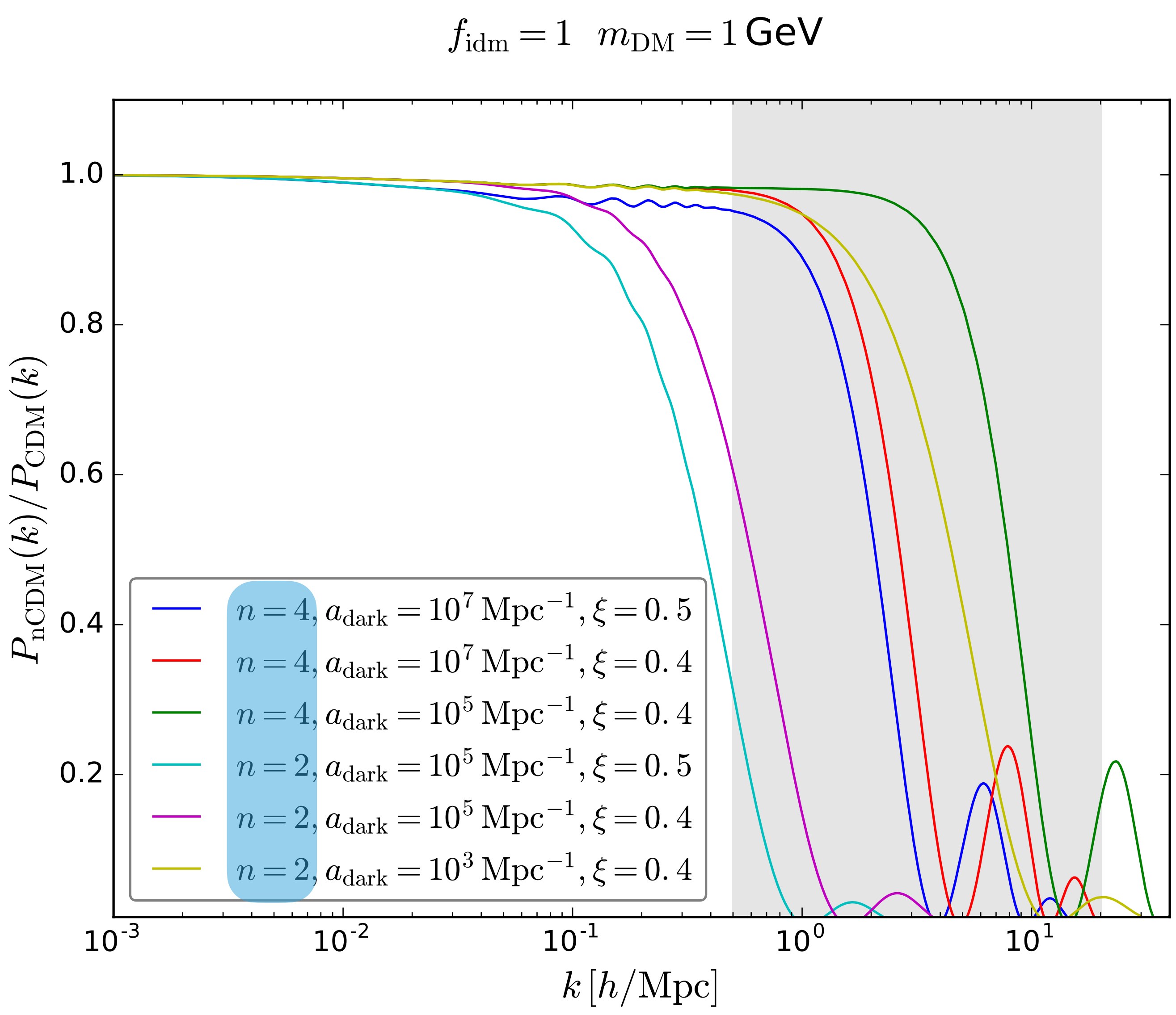

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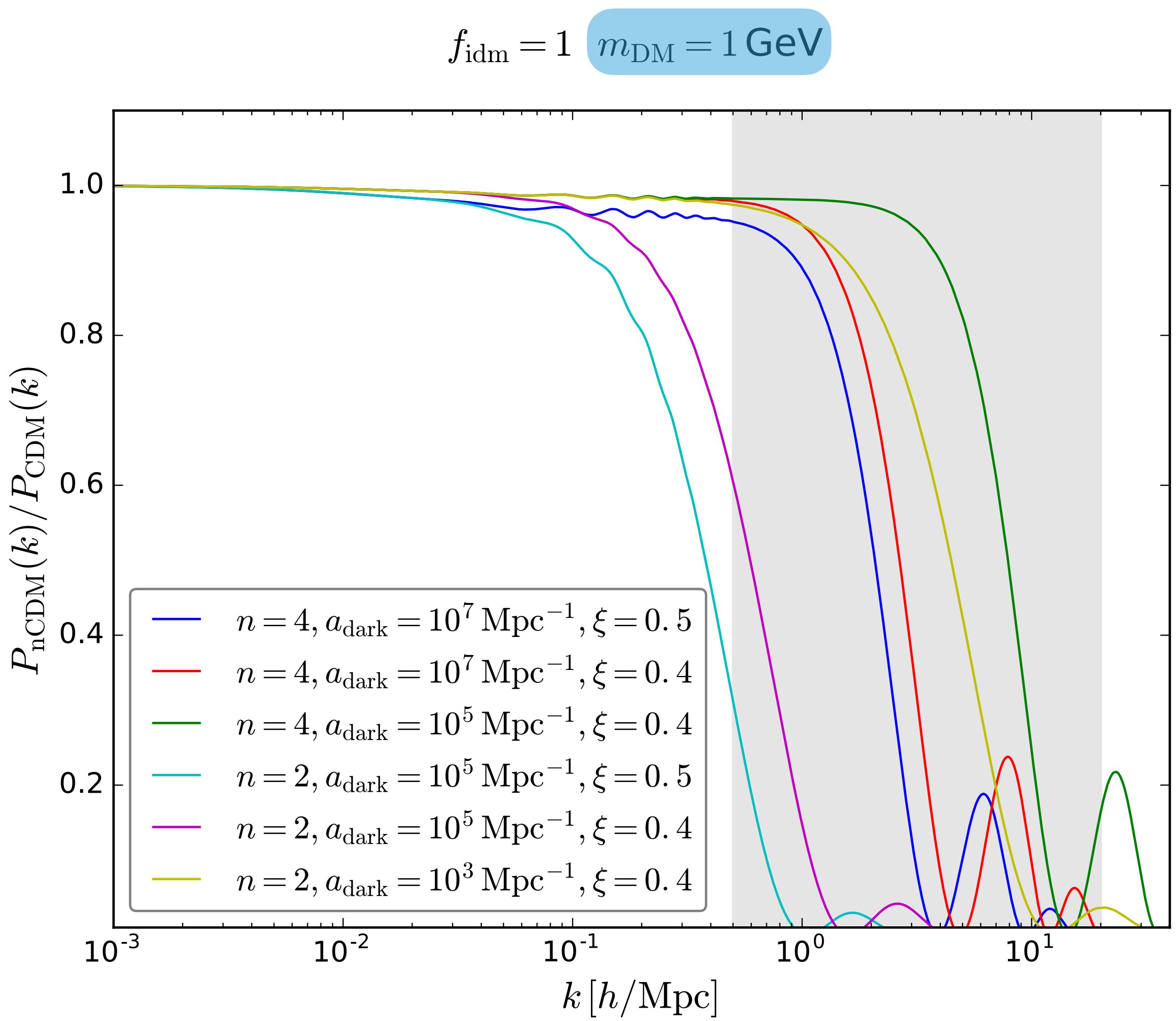

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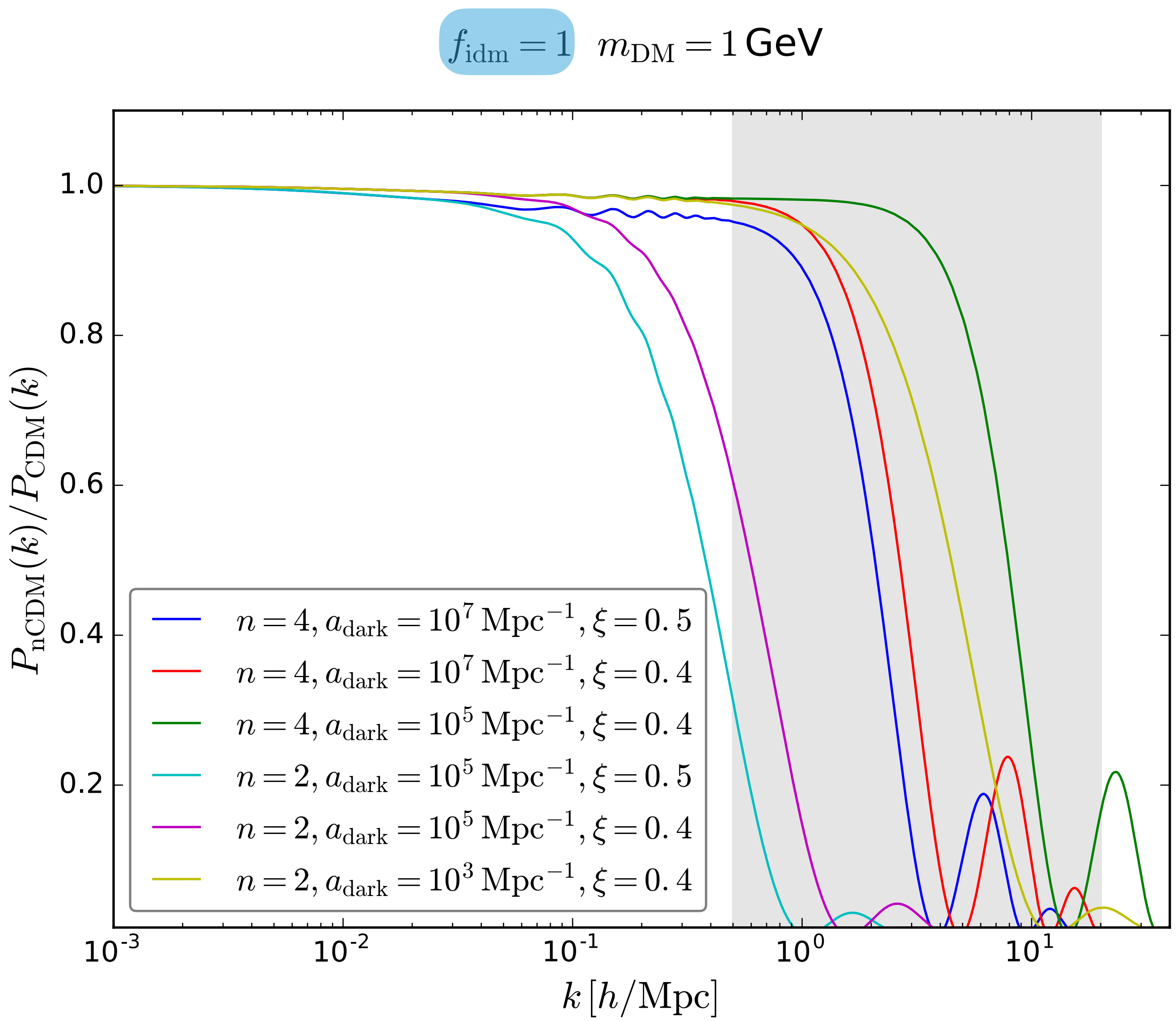

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Solving the tensions

- Case of $n = 4$ can explain missing satellites *(Archidiacono et al. 1706.06870)*
- Later kinetic decoupling results in the matter power spectrum being suppressed on small scales → number of satellites is reduced
- Case of $n = 0$ may solve H_0 and S_8 tensions *(e.g. Buen-Abad et al. 1505.03542)*
- DR acts like extra N_{eff} → H_0 increases to maintain z_{eq}, collisional damping with DR suppresses DM growth, leading to a small scale matter power suppression → lower S_8
- The combination of relativistic particles and the DM-DR coupled fluid allows us to avoid constraints that kill other solutions to these tensions (extra Silk damping, added lensing, …) *(See Becker, **DCH**, et al. 2010.04074)*

Testing the set-up

- Pipeline:

CLASS (cosmology) → MontePython (parameter inference) ← Lyman-α $(\alpha\beta\gamma)$ (data)

- We will run MCMCs for the cases of $n = 4$ and $n = 0$ using Planck, BAO, and Lyman-α data

- Several checks in the likelihood to see if method is applicable $\rightarrow$ "no-data" runs

DM-DR new constraints

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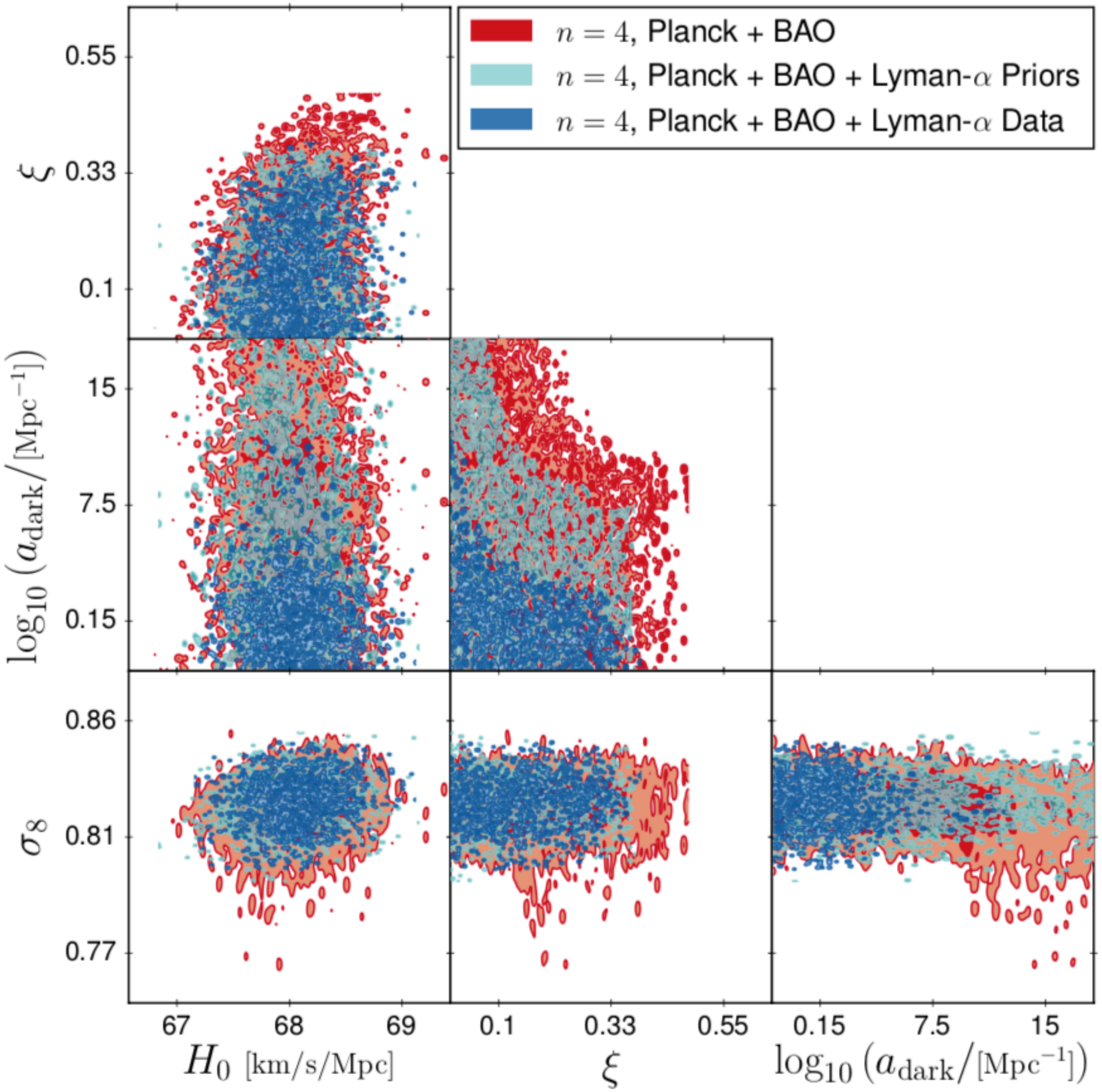

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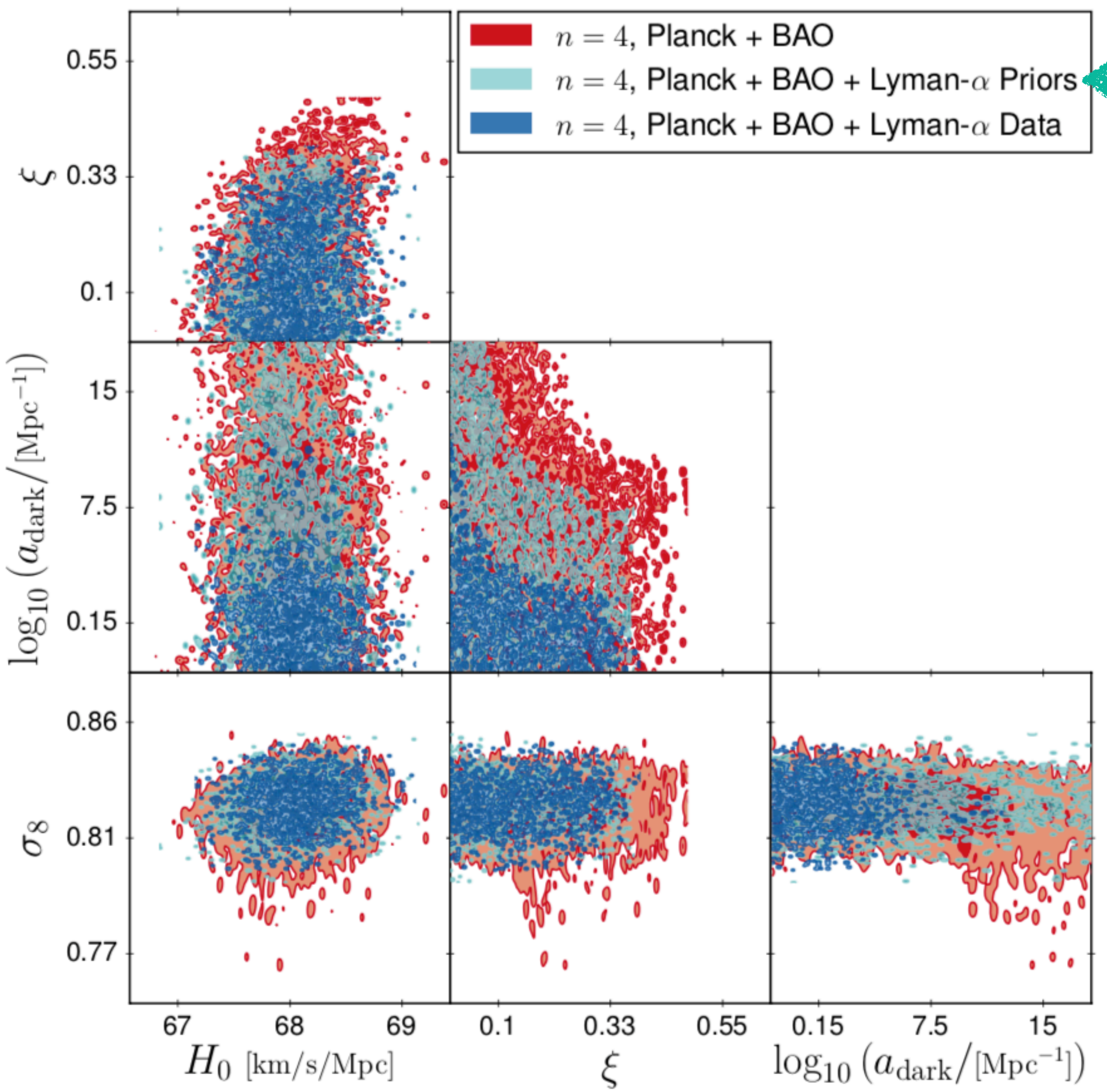

Region where our method works

DM-DR new constraints

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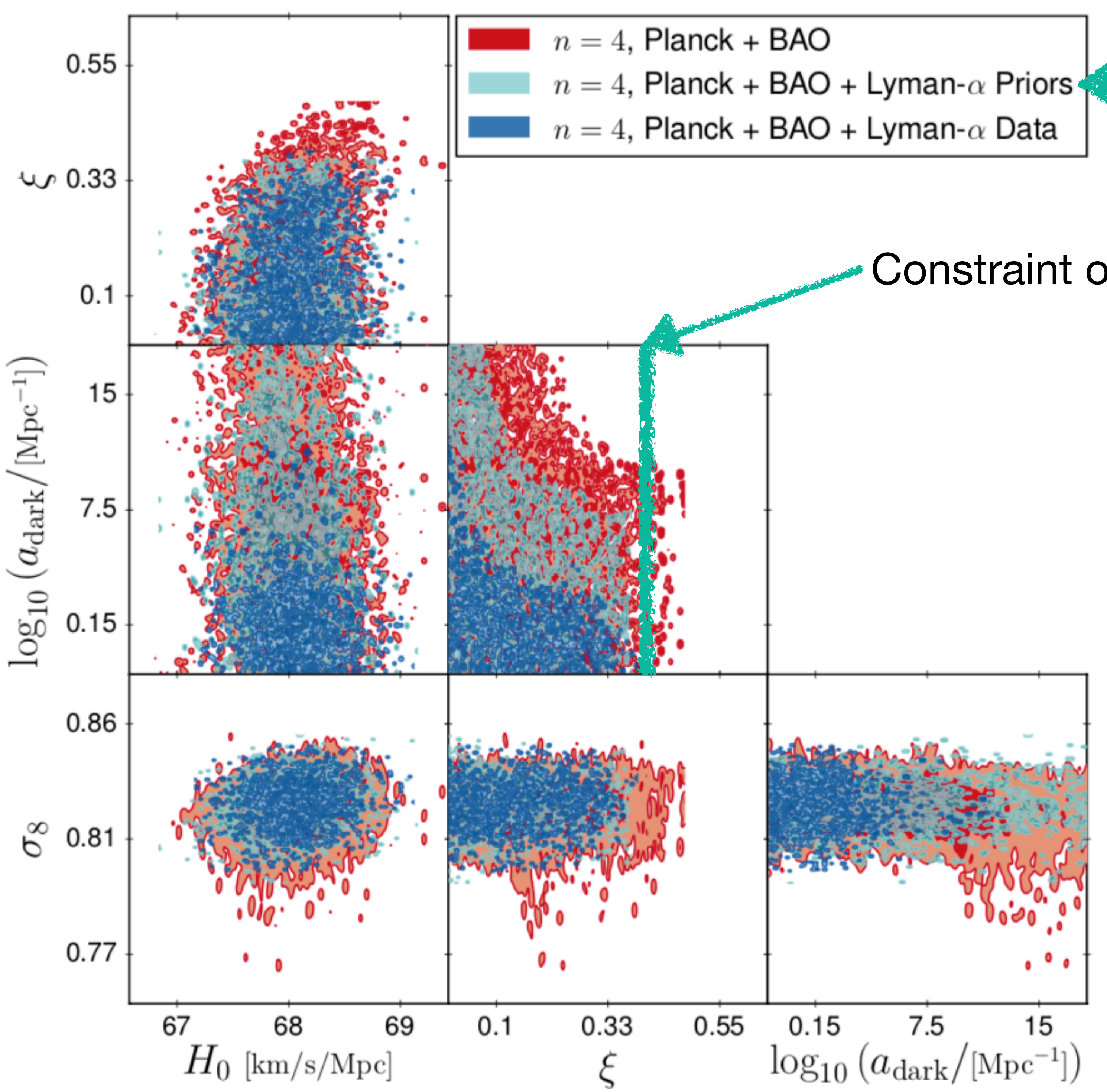

Region where our method works

Constraint on extra dark radiation

DM-DR new constraints

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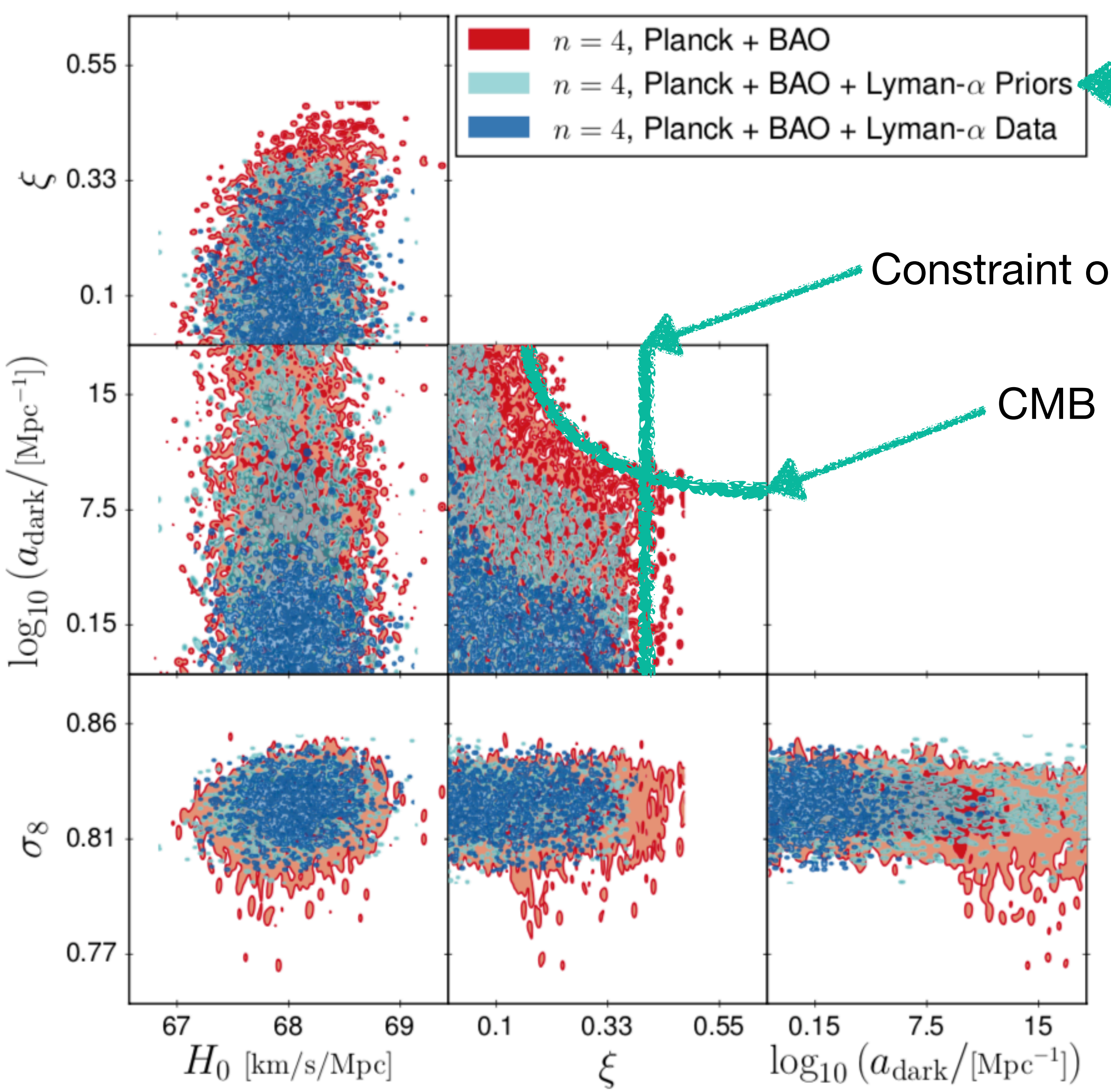

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Constraint on extra dark radiation

CMB bound on DM-DR interactions

DM-DR new constraints

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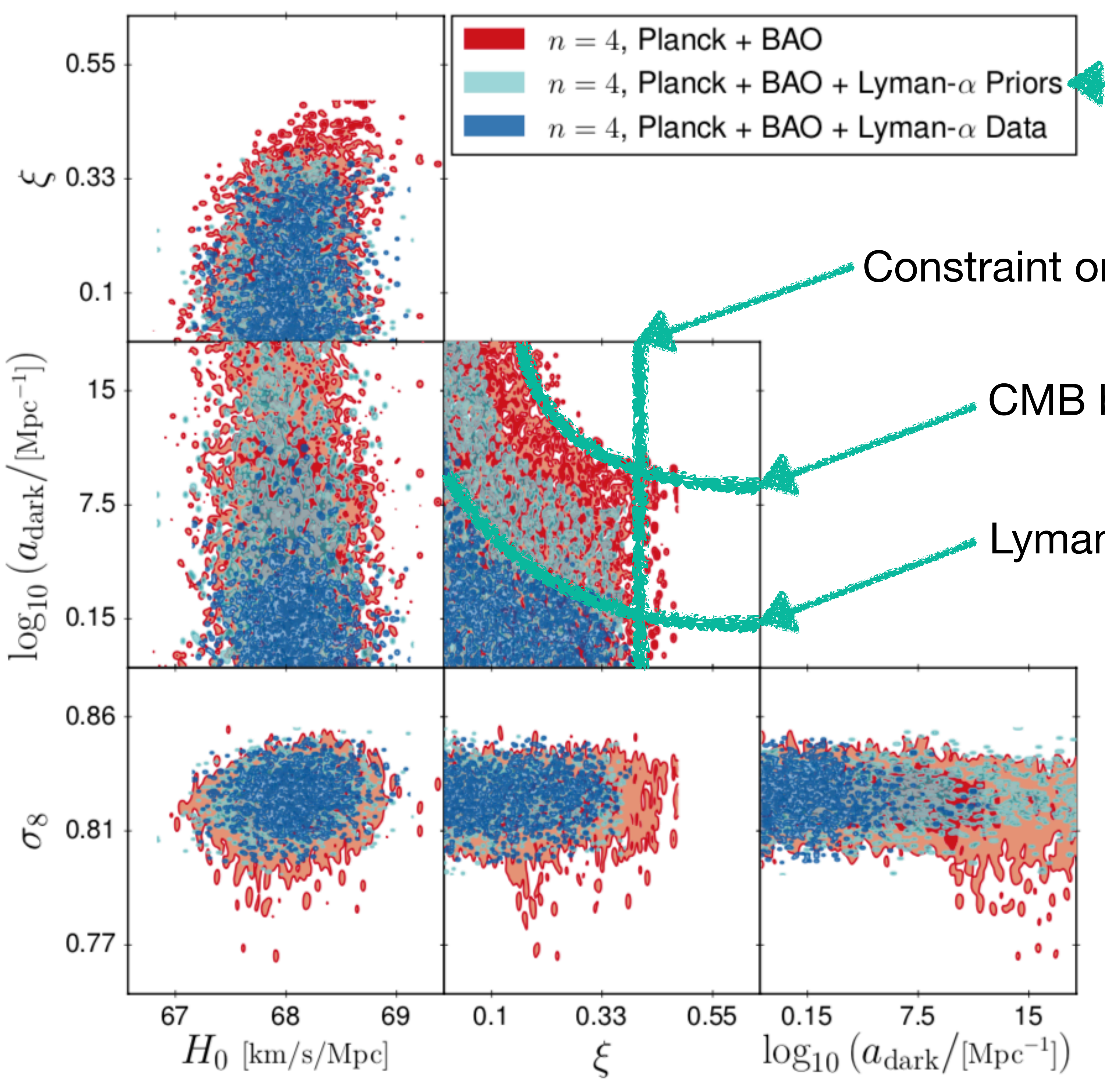

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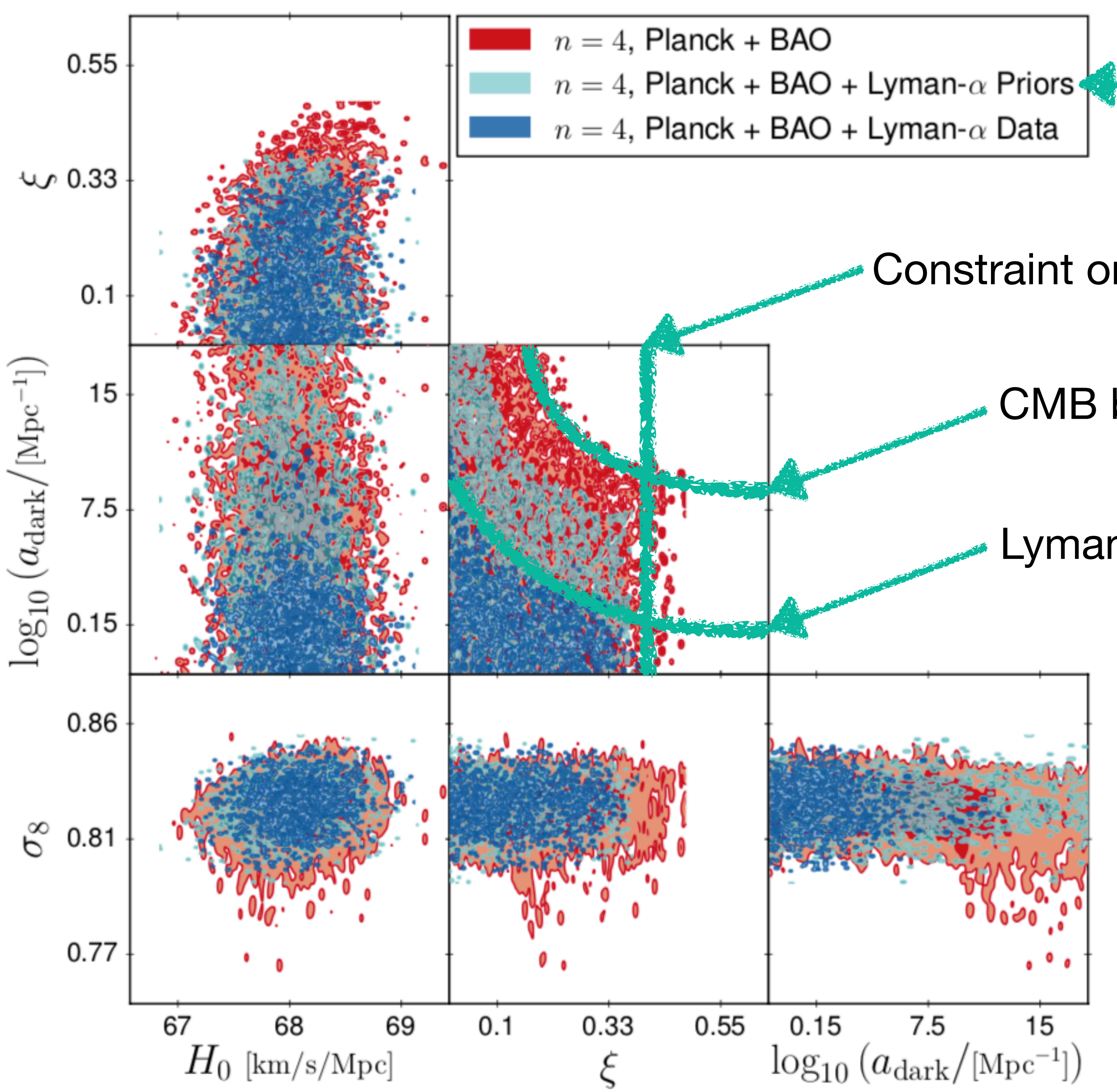

Region where our method works

Constraint on extra dark radiation

CMB bound on DM-DR interactions

Lyman-α bound on DM-DR interactions

Final bounds on physical parameters:

$$\Delta N_{\rm eff} < 0.23$$

$$a_{\rm dark}\xi^4 < 30\,{\rm Mpc}^{-1}$$

DM-DR new constraints

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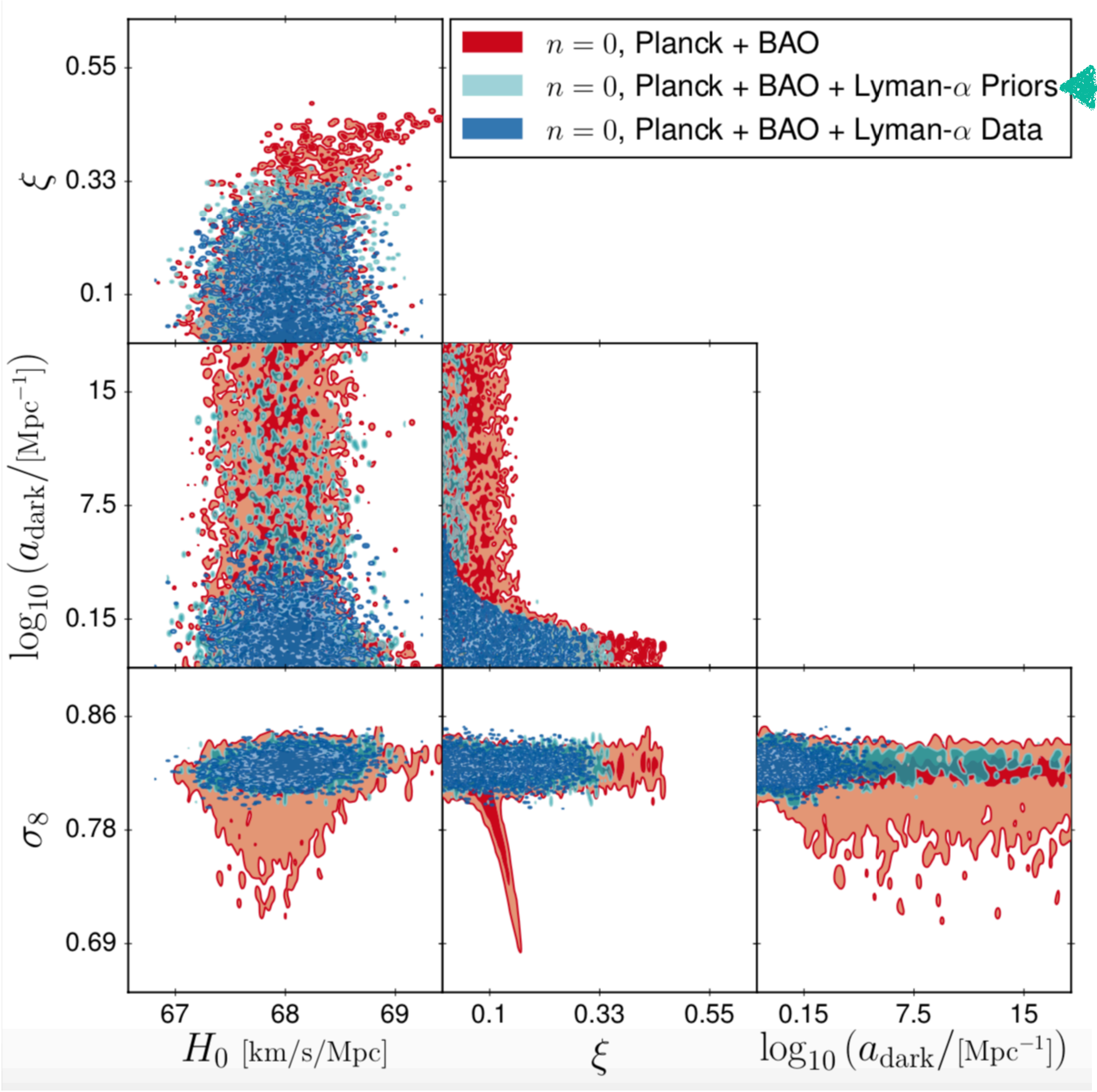

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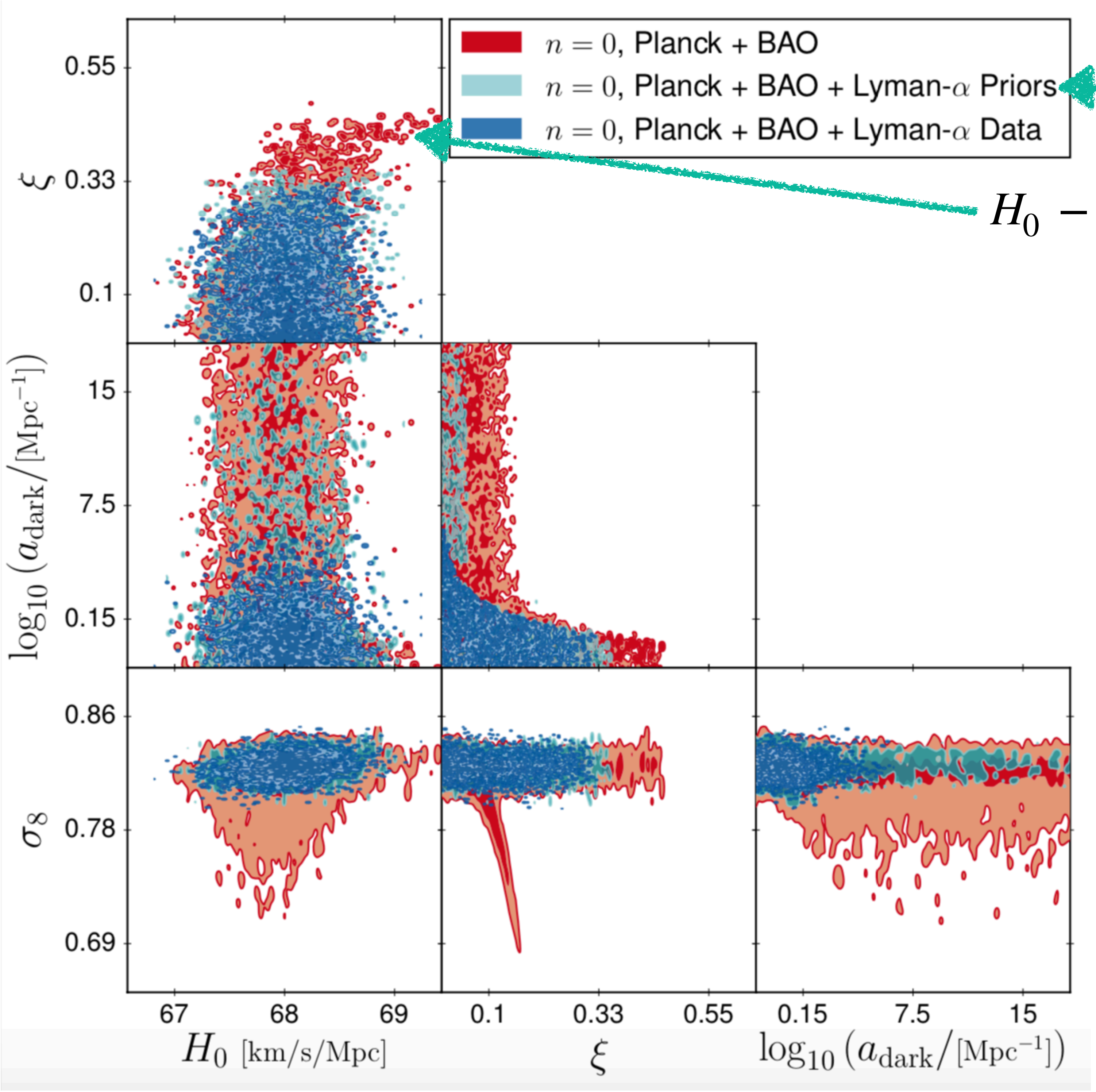

Region where our method works

$H_0 - \xi$ degeneracy: more dark radiation leads to higher H_0 values

DM-DR new constraints

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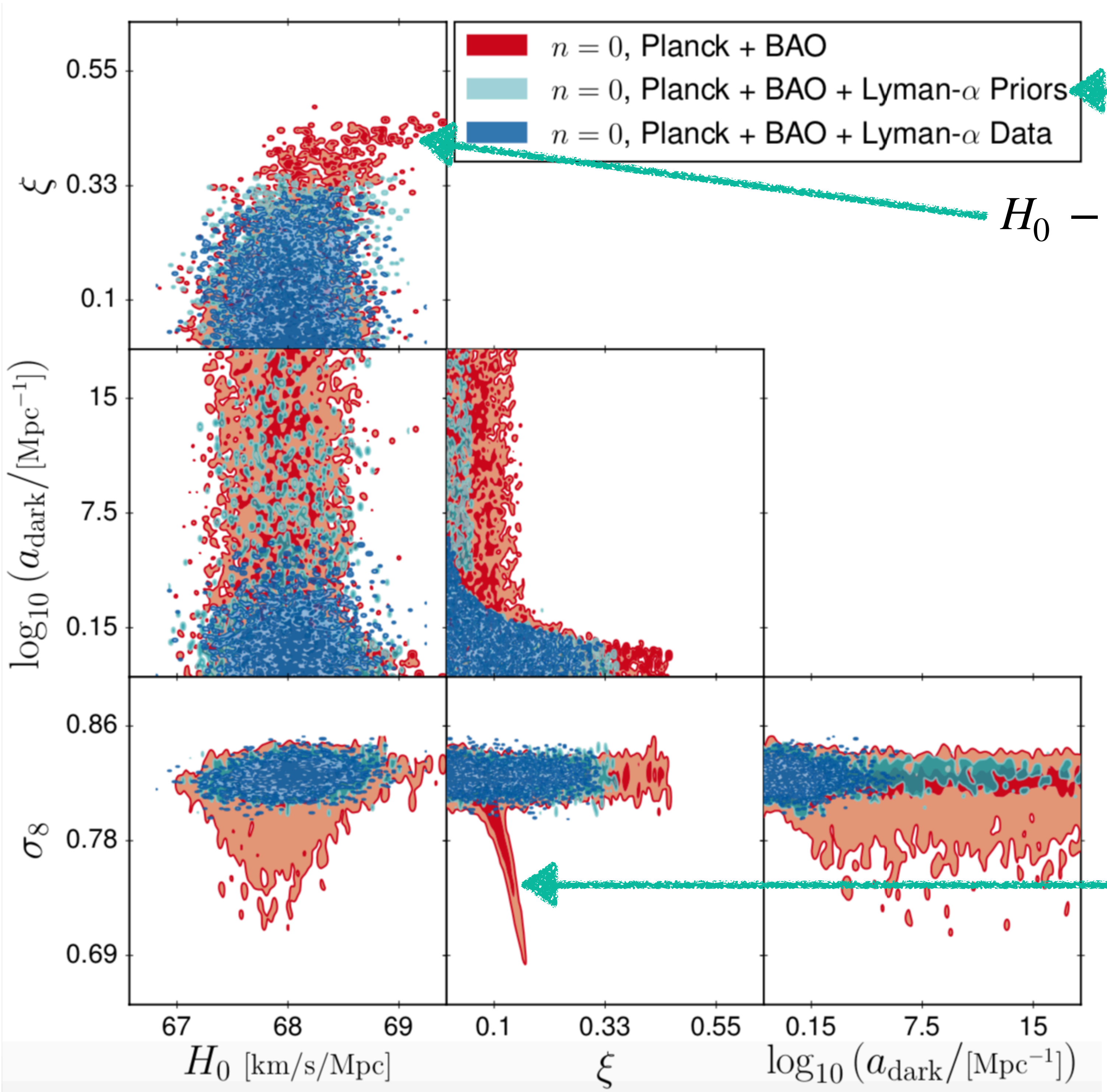

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$\sigma_8 - \xi$ degeneracy: with the right amount of dark radiation, we can get lower σ_8 values

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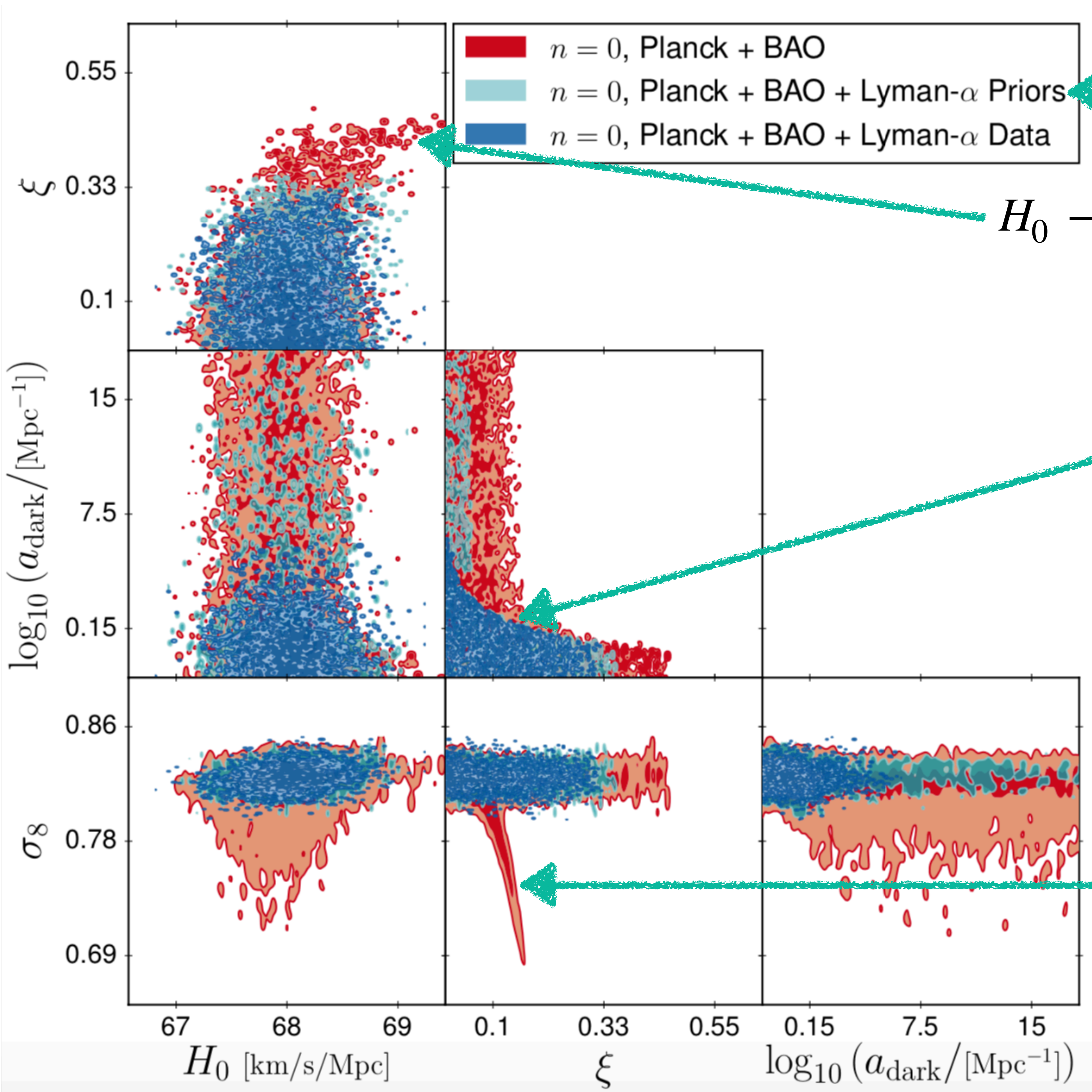

Region where our method works

$H_0 - \xi$ degeneracy: more dark radiation leads to higher H_0 values

Problem: our method and our Lyman-α constraints overlap: method can not be fully trusted in this regime

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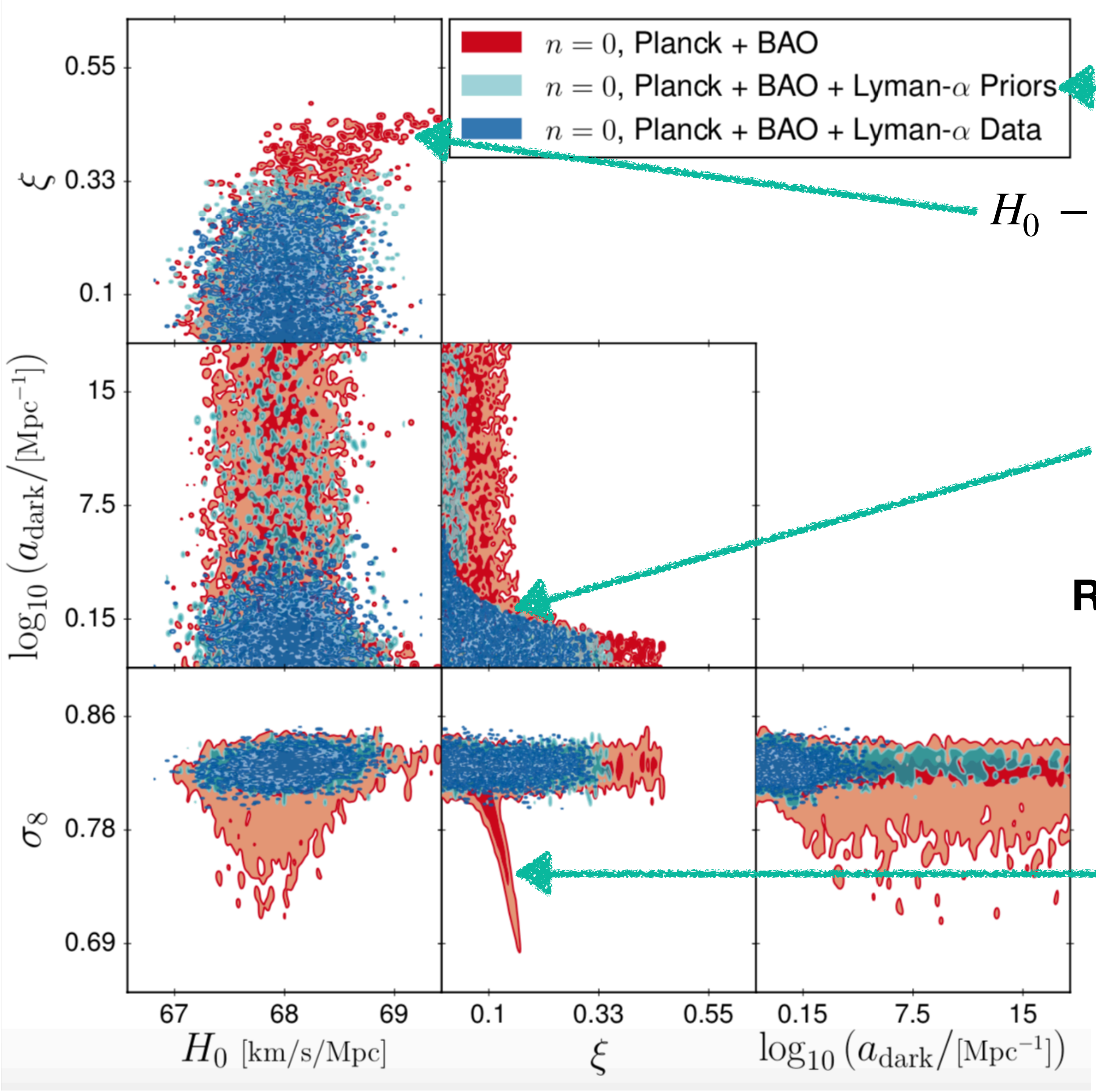

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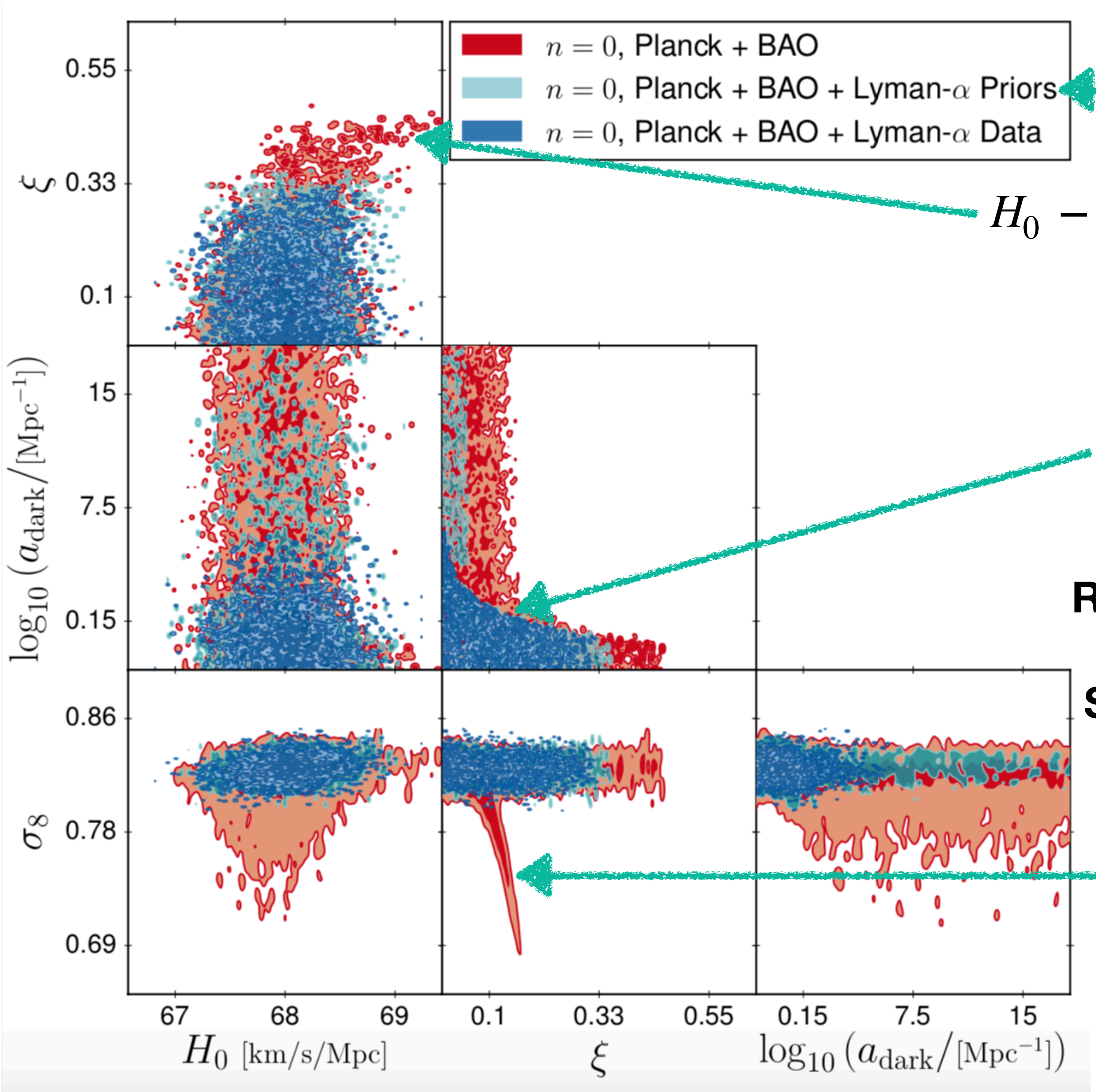

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Solution: expand our grid of simulations!

$\sigma_8 - \xi$ degeneracy: with the right amount of dark radiation, we can get lower σ_8 values

DM - neutrino interactions

Dark matter - neutrino interactions

- Massive neutrinos interacting with DM through a constant scattering term (similar to Thomson scattering)

$$u_{\mathrm{iDM}\nu} = \frac{\sigma_0}{\sigma_{\mathrm{Th}}} \left(\frac{m_\chi}{100\mathrm{GeV}} \right)^{-1}$$

- We remain agnostic on the underlying particle physics model

- Additional drag between the two species erases structures on small scales → can suppress matter power spectrum

- Can potentially solve the S_8 tension

Set-up

- Recently Mosbech et al. (2011.04206) implemented this model in the cosmology code `CLASS`
- This model was only constrained using Planck + BAO data
- A full analysis using Lyman-α data has never been done for this model
- We will test if Lyman-α data constrain and potentially favour these interactions
- Check if this model is still a potential solution to the S_8 tension

Testing the set-up

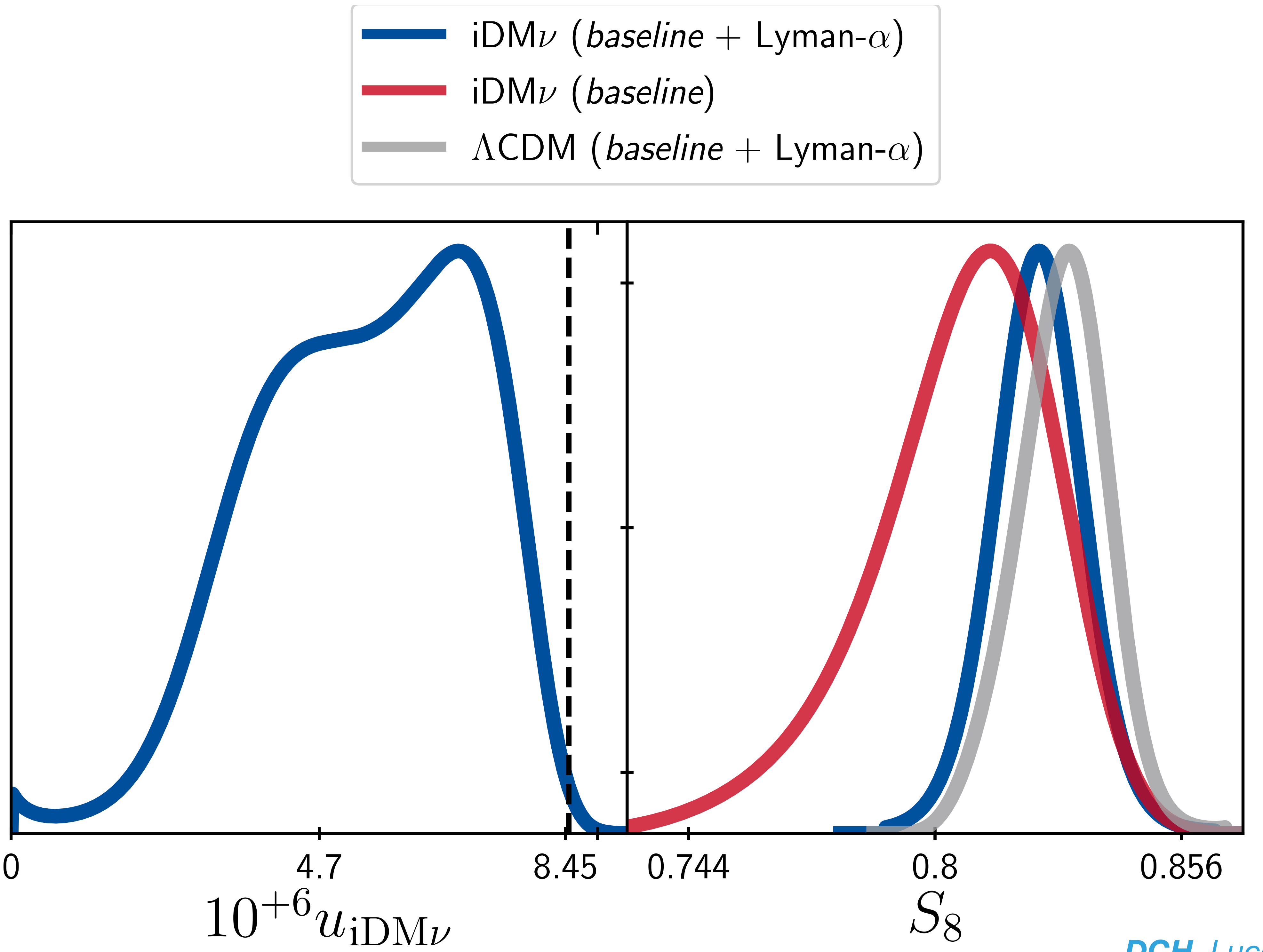
- Pipeline:

CLASS (cosmology) → MontePython (parameter inference) ← Lyman-α $(\alpha\beta\gamma)$ (data)

- To test the cosmology code we reproduced the results for interacting DM-neutrinos using Planck and BAO data

- To test the likelihood we ran the case of massive non-interacting neutrinos, obtain consistent upper bound on sum of neutrino masses

Hints of interactions



DCH, *Lucca 2110.04024*

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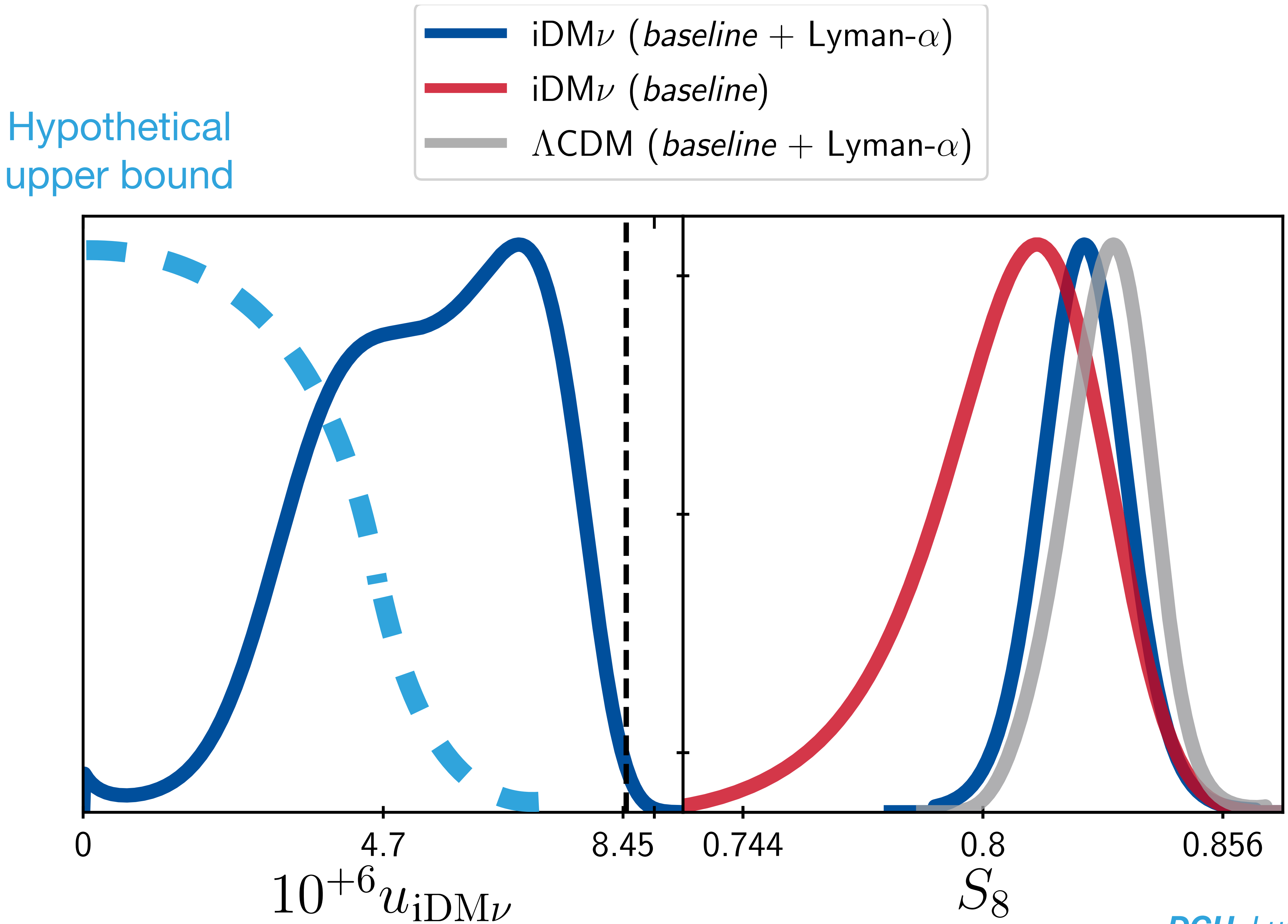

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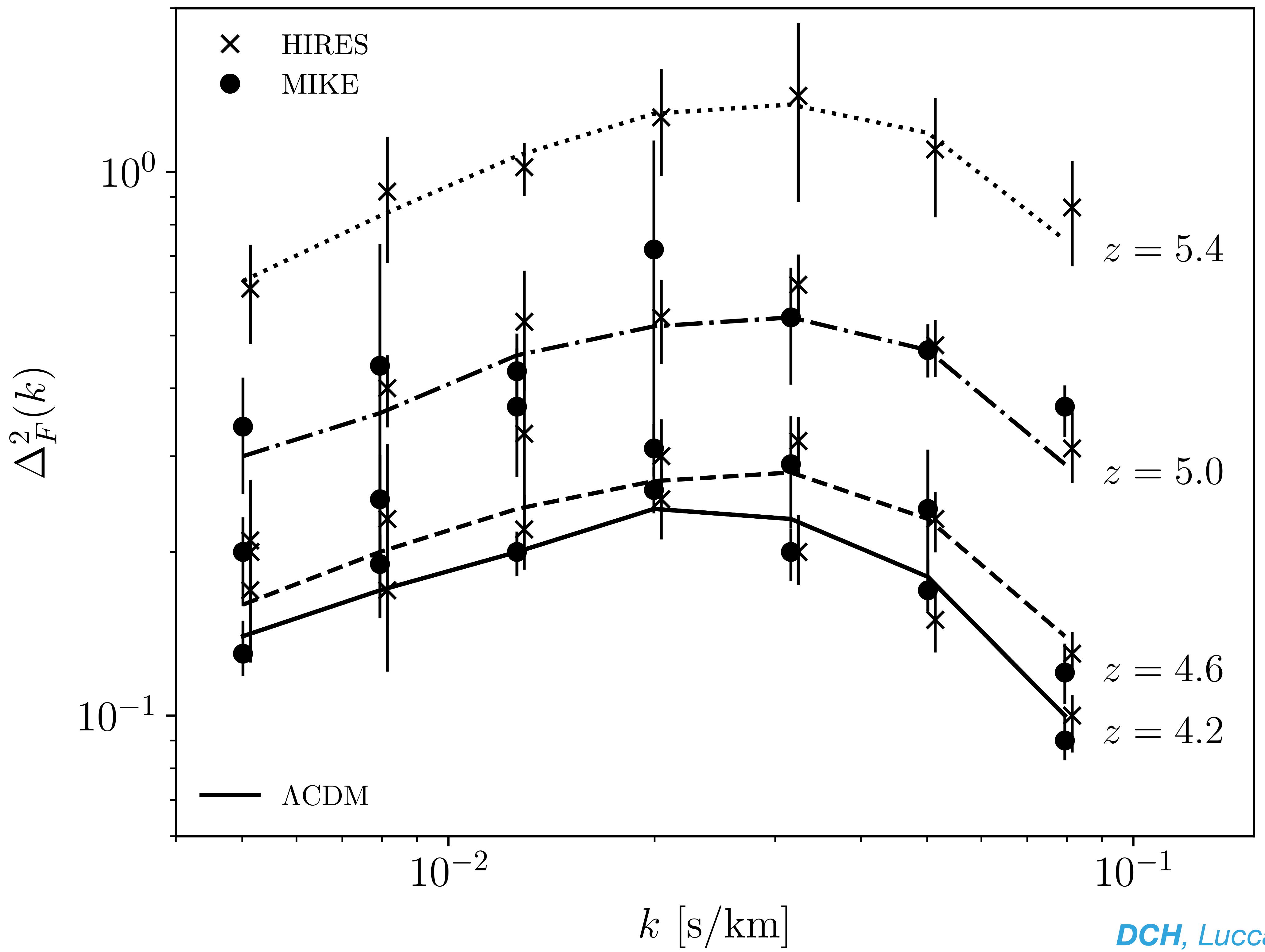

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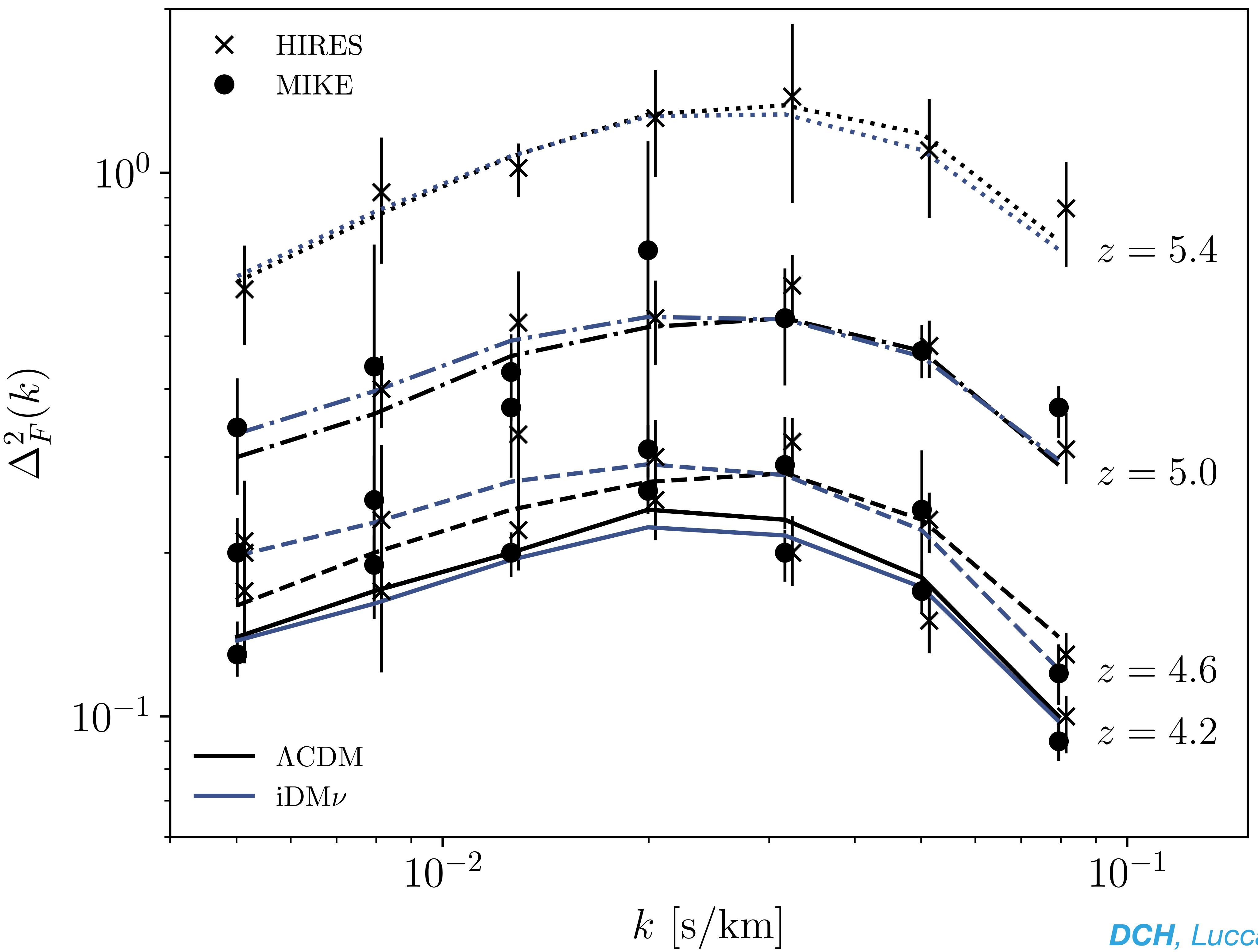

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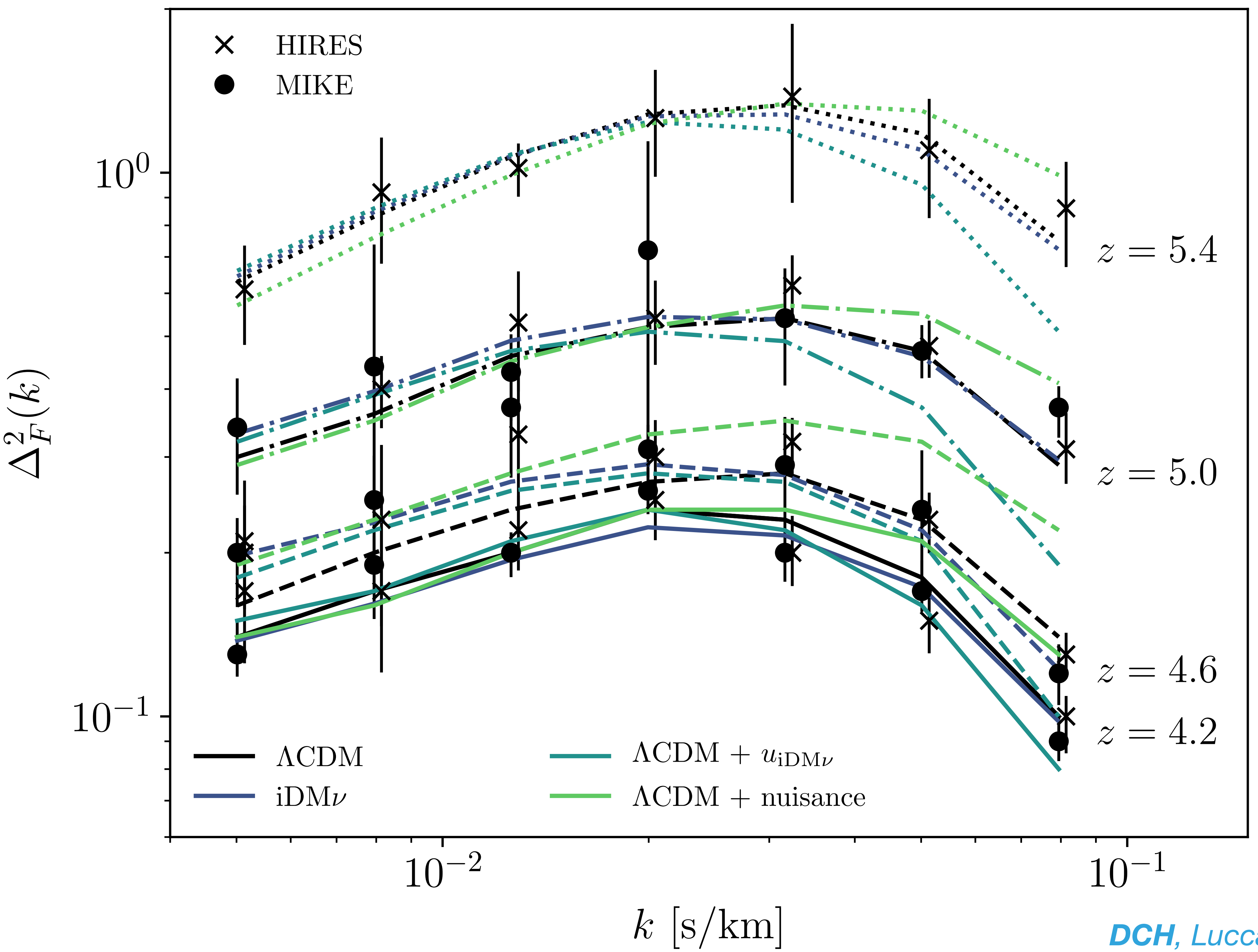

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Beware: potential issues

- The slope of the Lyman-α flux ($n_{\rm eff}$) appears in the grid parameters
- Grid constructed for $n_{\rm eff}$ in the range $[-2.3474, -2.2674]$ and only extrapolated to the range $[-2.6, -2.0]$
- Our best-fit gives $n_{\rm eff} = -2.507^{+0.038}_{-0.087}$ → border case
- Need dedicated simulations to test if $(\alpha\beta\gamma)$ method works for these $n_{\rm eff}$ values

Beware: potential issues

- The IGM temperature appears as an astrophysical/ nuisance parameter
- In our best-fit we have a lower temperature than expected
- But the expected values were derived from Lyman-α data assuming ΛCDM and might not be applicable in the interacting model
- Detailed hydro sims varying the IGM temperature will clarify this

What next?

- Expand grid of simulations to models with plateaus (e.g. DM - baryons, mixed models)
- Check if boundaries of grid are well-described
- Include broader range of temperature variations
- Refine interpolator to include XQ-100 data as well

Summary

- Cracks in the standard CDM paradigm call for new models
- NCDM models have a significant impact on small scales observables, making Lyman-α data crucial to constrain them
- We obtained state-of-the-art constraints on DM-DR interactions
- We showed that Lyman-α data prefer non-zero interactions between DM and massive neutrinos at 3σ
- Grid needs expanding for more models, further checks needed on astrophysical parameters
- The preference for a non-ΛCDM flux is independent of the numerical details and of the specific model

Thank you for your attention