



# Searching for Dilaton Fields in the Ly $\alpha$ Forest

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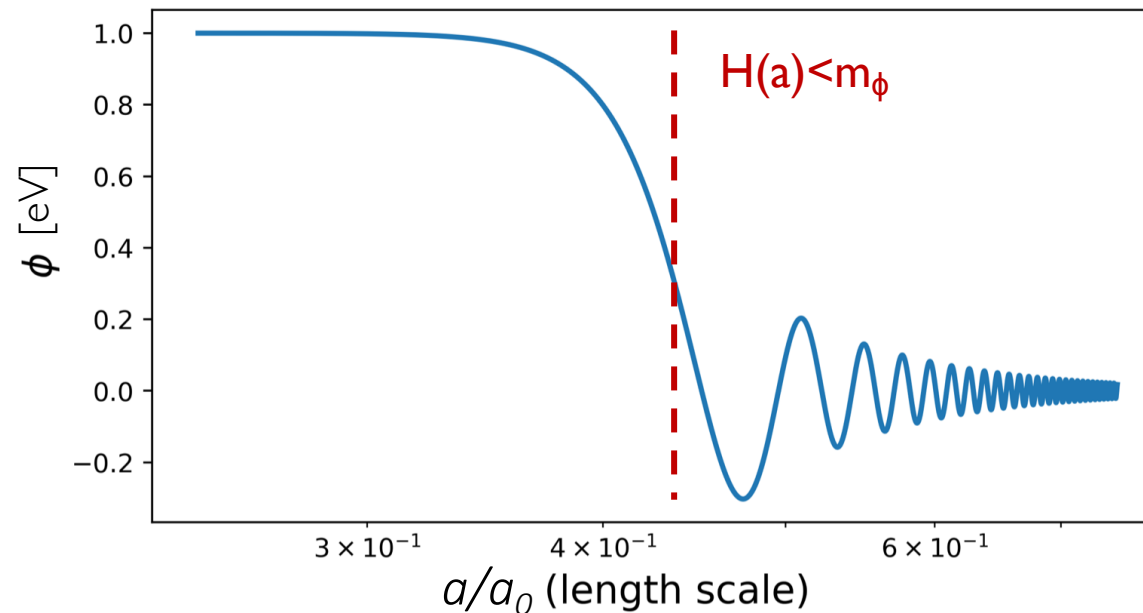
Louis Hamaide – Planck 06/22

# Introduction to dilatons (1/2)

- Dilatons & other scalar degrees of freedom are generic features of extra dimensional theories
- They can be produced non-thermally through the misalignment mechanism

Klein-Gordon equation

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2\phi = 0$$



Can produce  
massive,  
pressureless,  
ultralight cold  
DM for  $\Lambda$ CDM

Late time solution:

$$\phi(\mathbf{x}, t) = \sum_k \phi_{0,k} \cos(\omega_\phi t + \mathbf{k} \cdot \mathbf{x} + \varphi_k)$$



$$\rho_{\phi,k} = \frac{1}{2} m_\phi^2 \phi_{0,k}^2$$

# Introduction to dilatons (2/2)

- Dilatons can couple to many Lagrangian terms in the Standard Model (through dimensionful couplings):

$$S = \int d^4x \sqrt{|g|} \left\{ \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi) + \mathcal{L}_{\text{SM}} + \mathcal{L}_\phi^{\text{int}} \right\}$$

$$\mathcal{L}_\phi^{\text{int}} = \kappa \phi \left[ + \frac{d_e}{4e^2} F_{\mu\nu} F^{\mu\nu} - \frac{d_g \beta_3}{2g_3} G_{\mu\nu}^A G^{A\mu\nu} - d_{m_e} m_e \bar{e} e - \sum_{i \neq u, d} (d_{m_i} + \gamma_{m_i} d_g) m_i \bar{\psi}_i \psi_i \right], \quad (2)$$

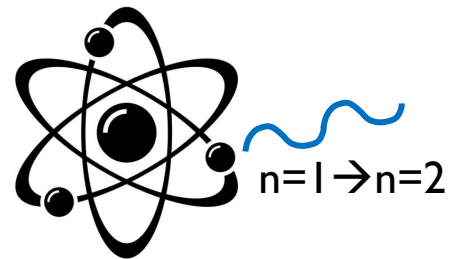
$$\Delta E_{\text{Ly}\alpha} = \frac{3}{4} \text{Rydberg} = \frac{3m_e \alpha^2}{8}$$

- This leads to variations of "constants" of nature such as the fine structure constant or fermion masses:

$$\mathcal{L}_{EM} = -\frac{1 - d_e \kappa \phi}{4e^2} F_{\mu\nu} F^{\mu\nu} \simeq -\frac{1}{4(1 + d_e \kappa \phi) e^2} F_{\mu\nu} F^{\mu\nu}$$

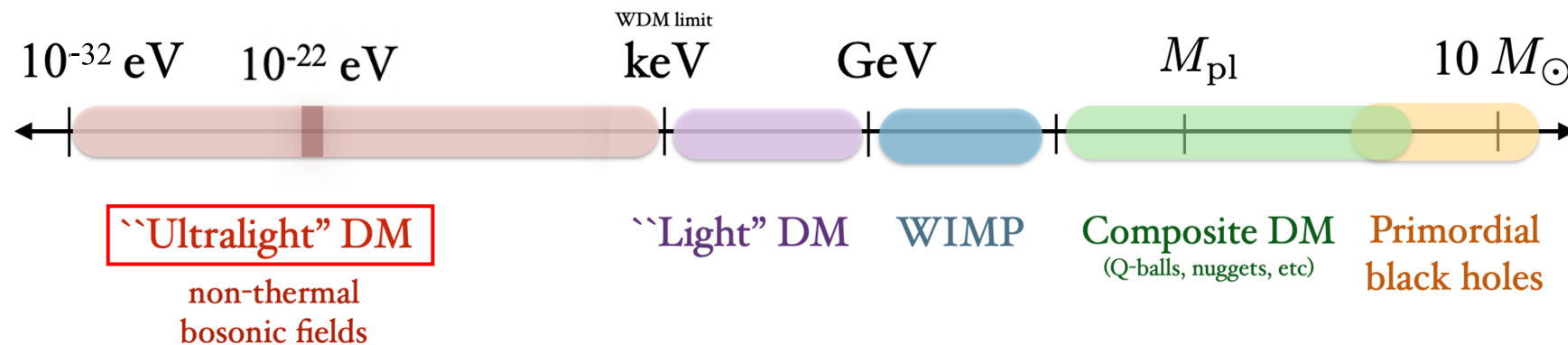
$$\alpha(\phi) = (1 + d_e \kappa \phi) \alpha = (1 + d_e \varphi) \alpha.$$

$$m_i(\phi) = (1 + d_{m_i} \kappa \phi) m_i = (1 + d_{m_i} \varphi) m_i, \quad (i = e, u, d).$$

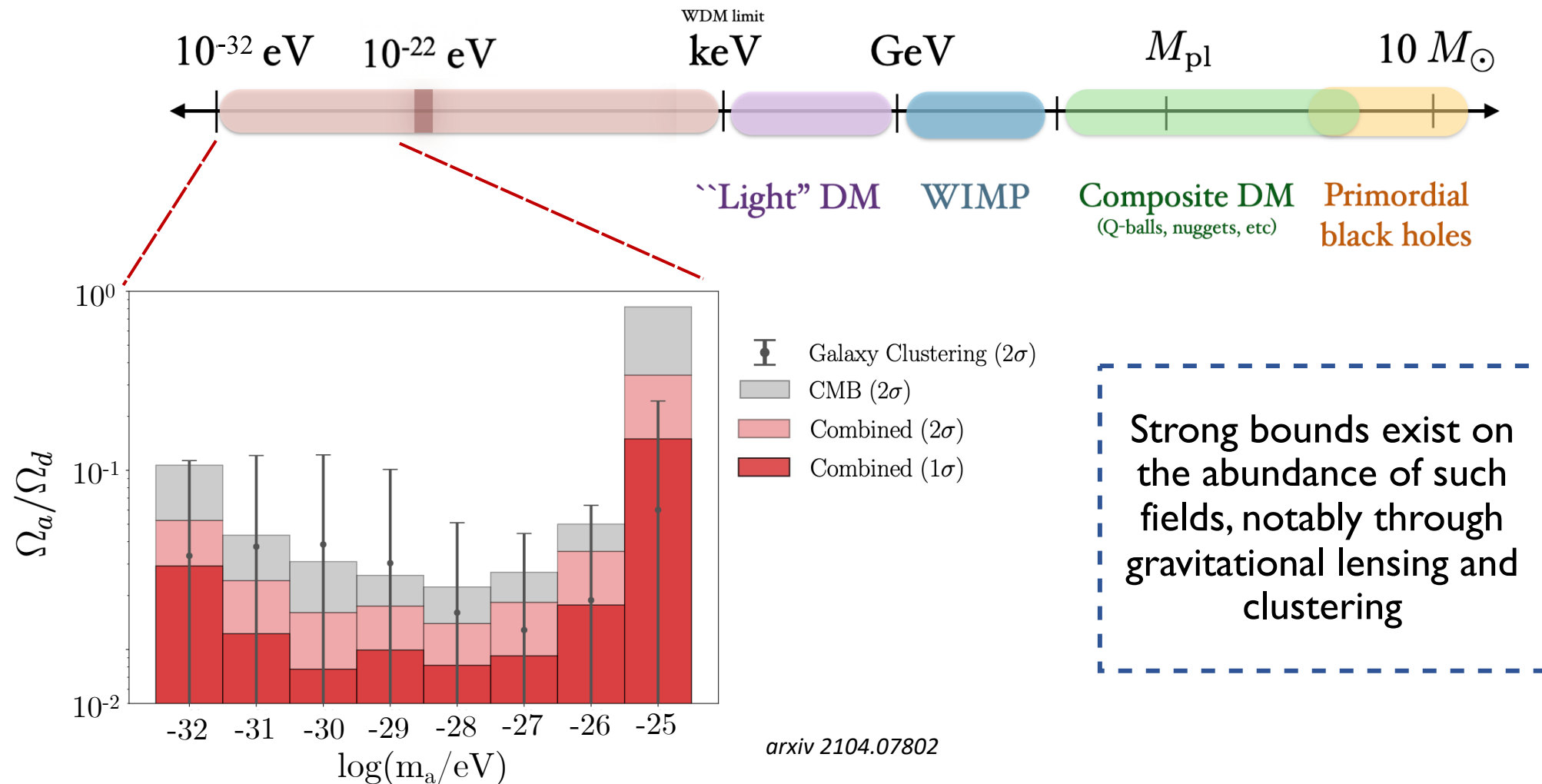


# Motivation For Ultra-Ultralight Fields (1/2)

- Many theoretical + observational motivations for dark matter (DM): rotation curves of galaxies, bullet clusters, neutrino oscillations, strong CP problem and more!
- Large mass range available to explore experiments and theory
- At lowest masses phenomenology benefits from  $\rho_{\phi,k} = \frac{1}{2}m_{\phi}^2\phi_{0,k}^2$  scaling of dilaton amplitude

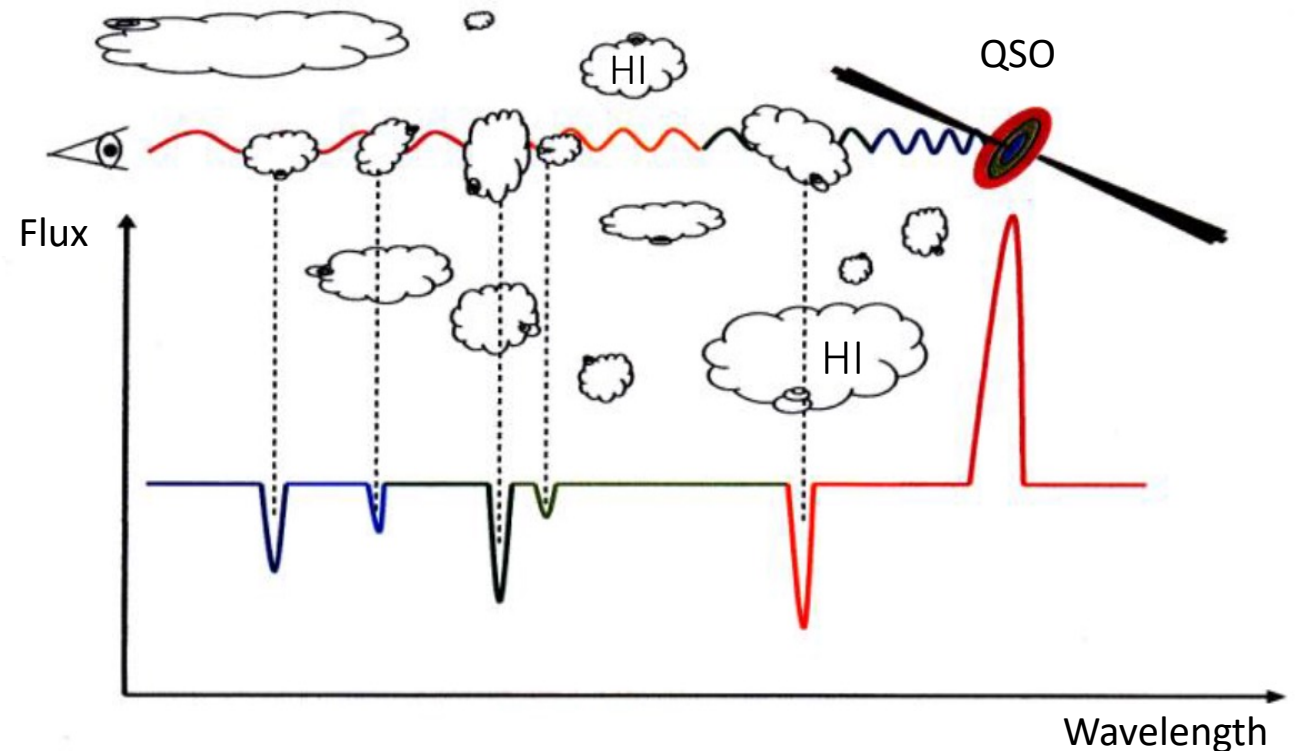


# Motivation For Ultra-Ultralight Fields (2/2)



# Ly- $\alpha$ forest intro (1/2)

- A quasar ( $z \sim 5$ ) emits a relatively smooth spectrum of radiation
- Ly- $\alpha$  frequency ( $n=1 \rightarrow n=2$ ) photons are absorbed by ground state hydrogen at different wavelengths (redshifts) along the LOS: this is the Lyman- $\alpha$  forest, which is well understood and measured
- Lyman- $\alpha$  forest can probe distribution of hydrogen
- We now expect a dilaton field (and  $\alpha$ ) to be oscillating and varying  $\alpha$  in each cloud: what effect is there on absorption profiles?



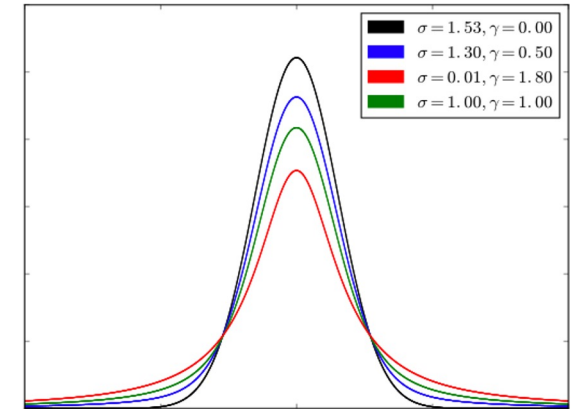
# Ly- $\alpha$ forest intro (2/2)

- Absorption profiles are modelled using Voigt profiles
- The Gaussian and Lorentzian distributions model temperature and “natural” broadening respectively

$$\tau = V(T, \beta, n_{\text{HI}}) * n_{\text{HI}}$$

$$\mathcal{V}(v_H(x, z), b_T(x, z), \gamma) = \frac{\gamma}{\pi^{3/2} b_T} \int_{-\infty}^{\infty} \frac{e^{-\frac{v'^2}{b_T}}}{\gamma^2 + (v_H(x, z) - v')^2} dv'$$

$$b_T(x, z) = \sqrt{\frac{2k_B T(x, z)}{m_p}}, \quad \gamma = \frac{\lambda_0}{2\pi\tau_{\text{Ly}\alpha}}$$



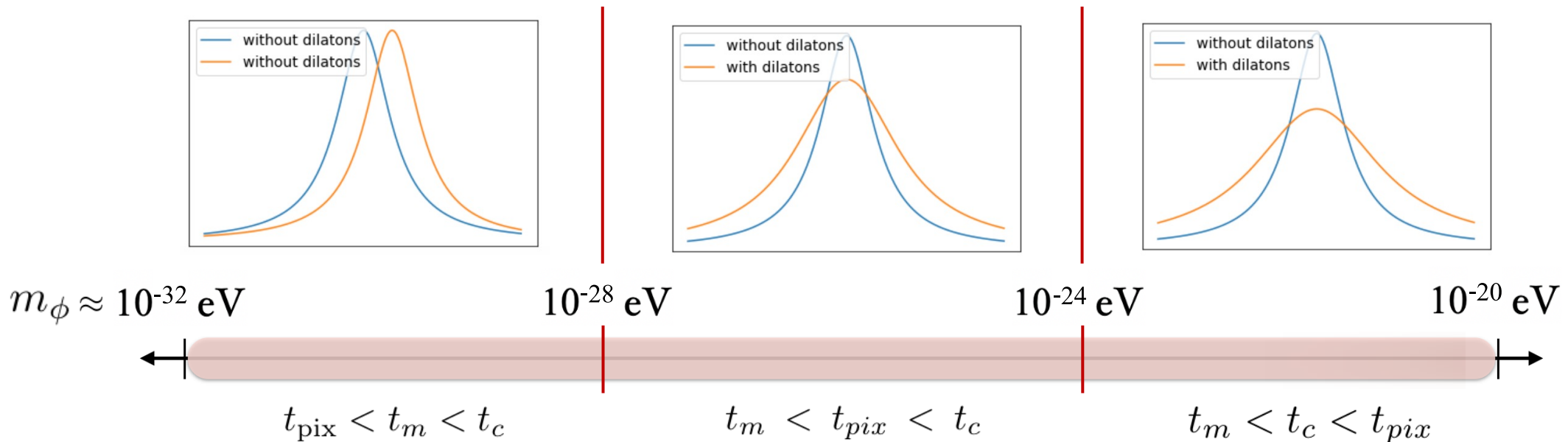
- Accounting for oscillating variation of the absorption wavelength requires another convolution. Final convolution comes from averaging over Rayleigh distribution (models decoherence):

$$\mathcal{V}(v_H(x, z), b_T(x, z), \gamma) = \frac{\gamma}{\pi^{5/2} b_T} \int_{-1}^1 \int_0^{\infty} \int_{-\infty}^{\infty} \frac{e^{-\frac{v'^2}{b_T}} \left( \frac{2\phi_r}{\langle \phi_r \rangle} e^{-\frac{\phi_r^2}{\langle \phi_r \rangle^2}} \right)}{(\gamma^2 + (v_H(x, z) - v' - 2ckd_i \phi_r \phi_m)^2) \sqrt{1 - \phi_m^2}} d\phi_m d\phi_r dv'$$

# Dilaton Effect on Ly- $\alpha$

- Effect depends on time it takes photons to cross a pixel, which we know from the evolution of redshift along the LOS (typically  $O(10\text{kPc})$ )
- Two time scales matter: the dilaton coherence time  $t_c$  and the oscillation (Compton) time  $t_m$  :

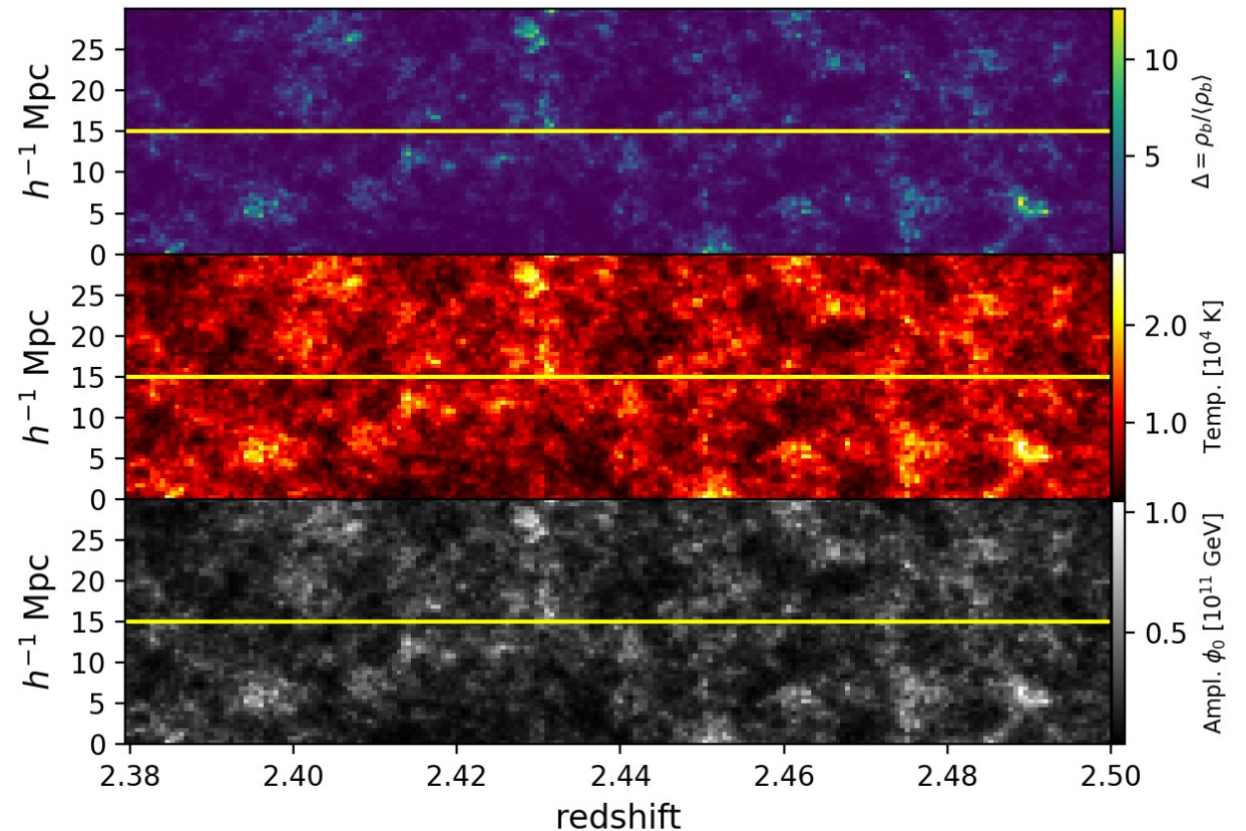
$$t_c \approx \frac{\lambda_{\text{dB}}}{v_\phi} = \frac{2\pi}{m_\phi v_\phi^2} \quad t_m \approx m_\phi^{-1}$$



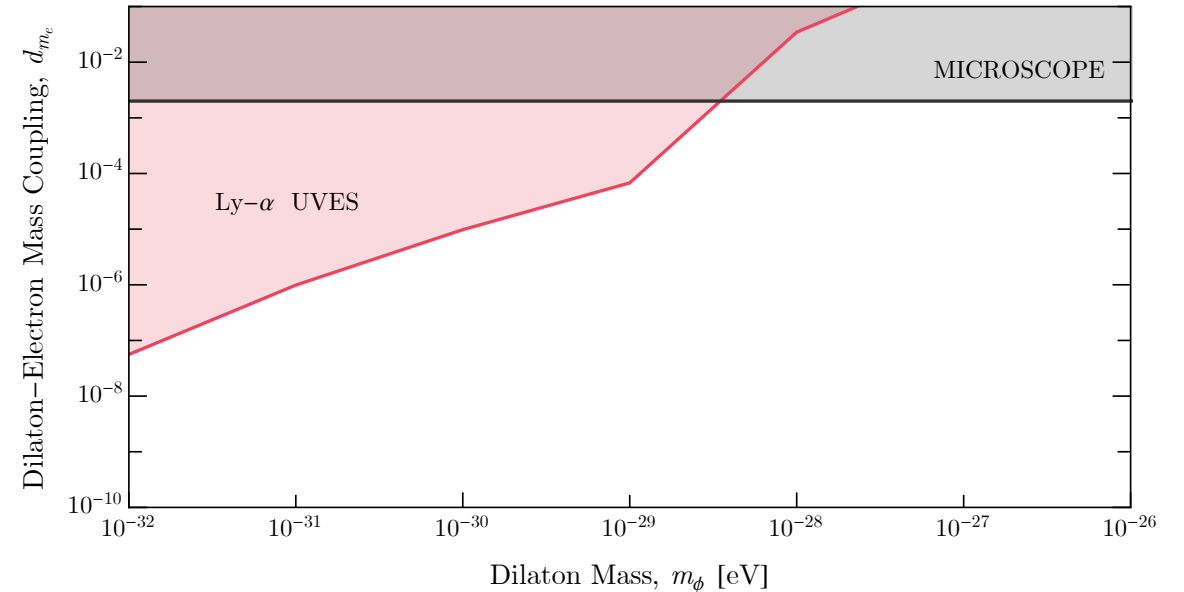
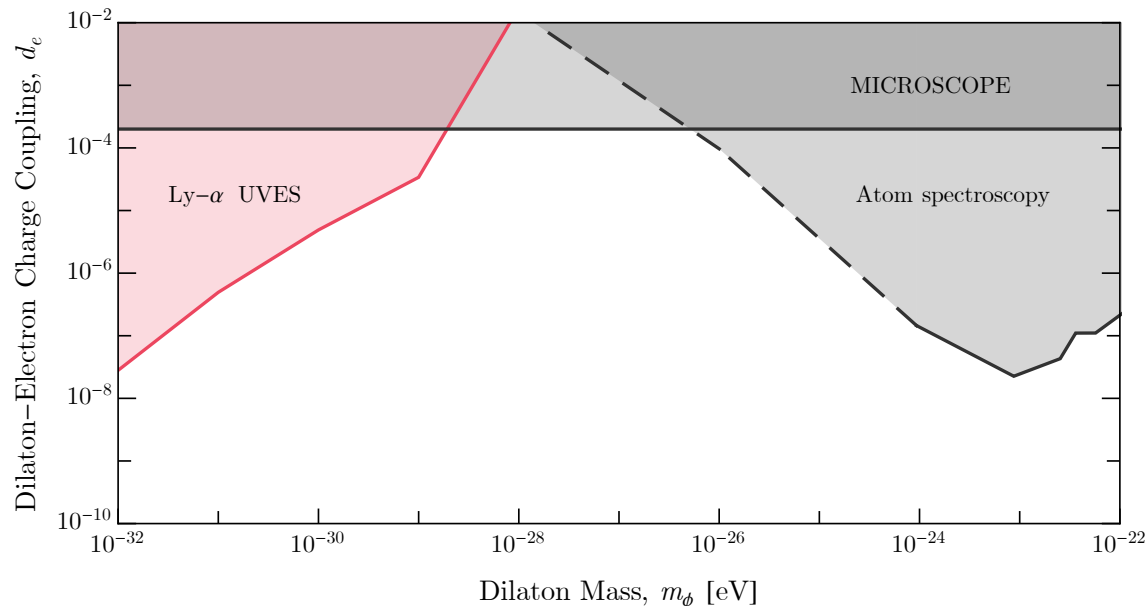


# Synthetic data

- We assume a  $\Lambda$ CDM cosmology fitted by 2018 Planck data
- We generate 3D synthetic UVES SQUAD data at each dilaton mass
- Use axionCAMB for structure formation: structure suppressed at smallest dilaton masses
- We compare reconstructed optical depths with/without dilaton effect
- Future work should be done to study more carefully degeneracies (i.e. use a more comprehensive autocorrelation matrix) with temperature modelling, cosmological parameters, peculiar velocities...



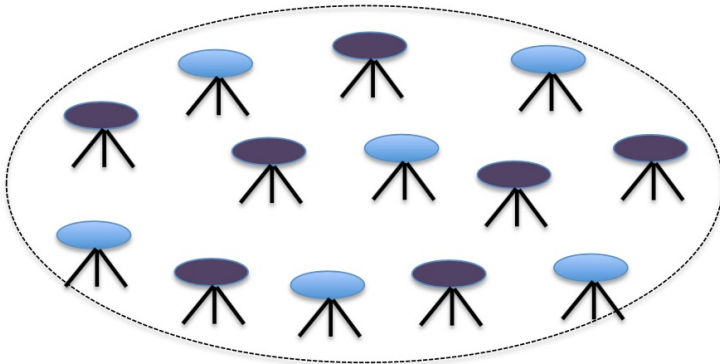
# Ly $\alpha$ Results



- UVES SQUAD data can significantly improve bounds ( $\sim 500$  QSOs,  $10^6$  spectral resolution)
- Competing bounds limited by integration time (e.g. atomic clocks, equivalence principle tests)
- Results scale differently for  $t_{\text{pix}} < t_m < t_c$

# Extending to 21cm (1/2)

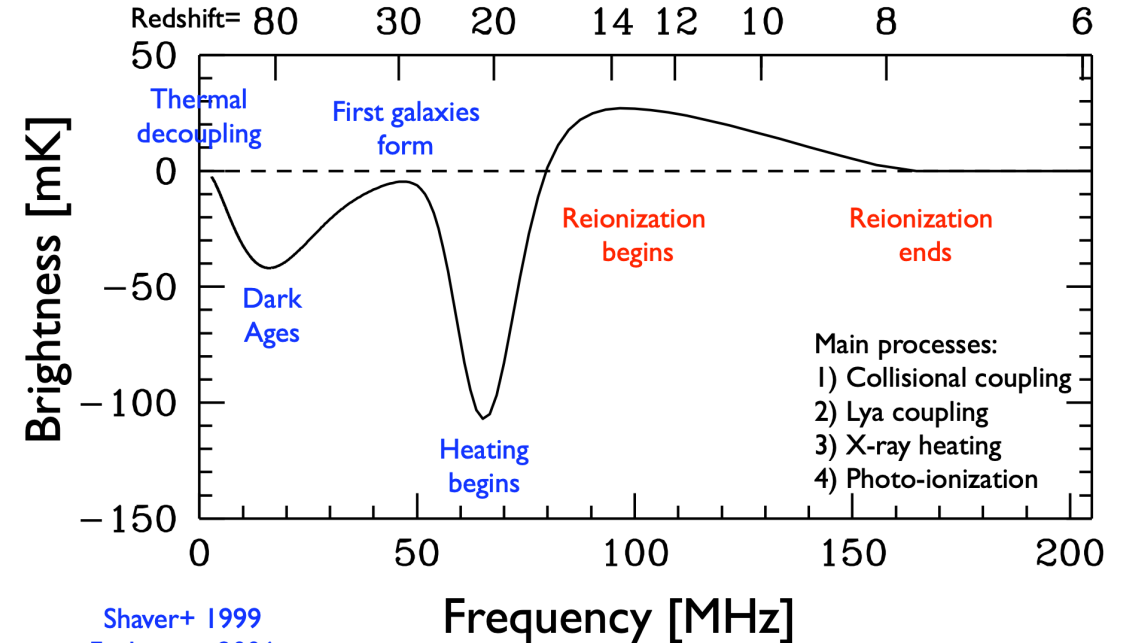
- 21cm surveys are effectively high resolution cameras of the distribution of neutral hydrogen. Looking for broadening is analogous to Ly $\alpha$  (but sometimes in emission): simply replace the SNR and number of pixels
- We use largest angular scales to maximise SNR<sup>1</sup> and data:
  - 21cm signal faint but SKA provides SNR similar to Ly $\alpha$
  - Number of voxels (data points) still 100x UVES SQUAD



$$\text{SNR} = \frac{T_{21\text{cm}}}{T_{\text{sys}}} \sqrt{\Delta\nu t_p N_b}$$

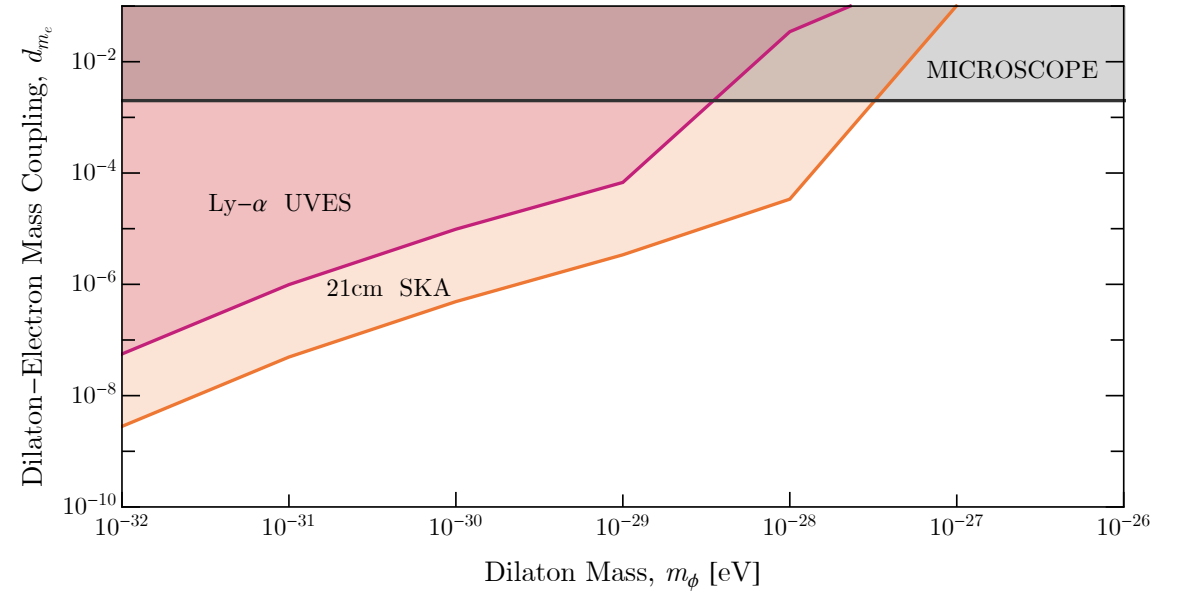
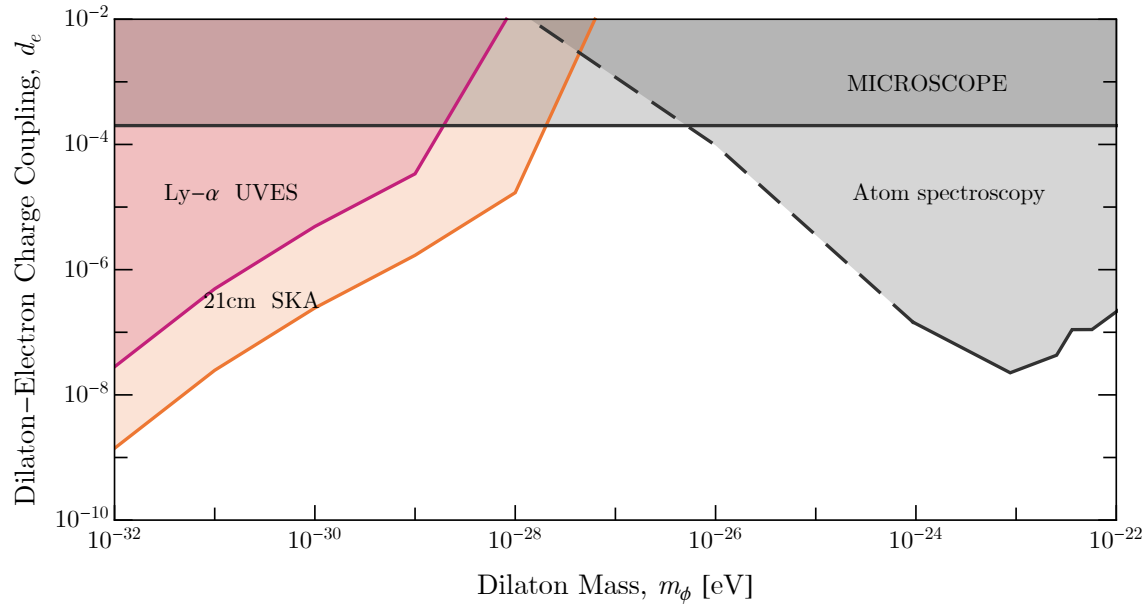
$$\Delta\theta^2 = \lambda_{21\text{cm}}^2 / D_{\text{dish}}^2$$

## Brief 21cm cosmology primer



<sup>1</sup> Bounds scale as (# voxels)<sup>1/4</sup>SNR<sup>1/2</sup> at larger mass and (# voxels)<sup>1/2</sup>SNR at lower mass

# Extending to 21cm (2/2)



- SKA-like experiment data can further improve bounds (assuming  $\sim 25000 \text{deg}^2$ , 1 GHz bandwidth, 100kHz spectral resolution, 12500h integration time)
- 21cm bounds can be extended to bounds on quark mass couplings and gluon coupling:

$$\Delta E_{21\text{cm}} = \frac{4}{3} g_e g_p \alpha^2 \frac{m_e}{m_p} \text{Ry}$$

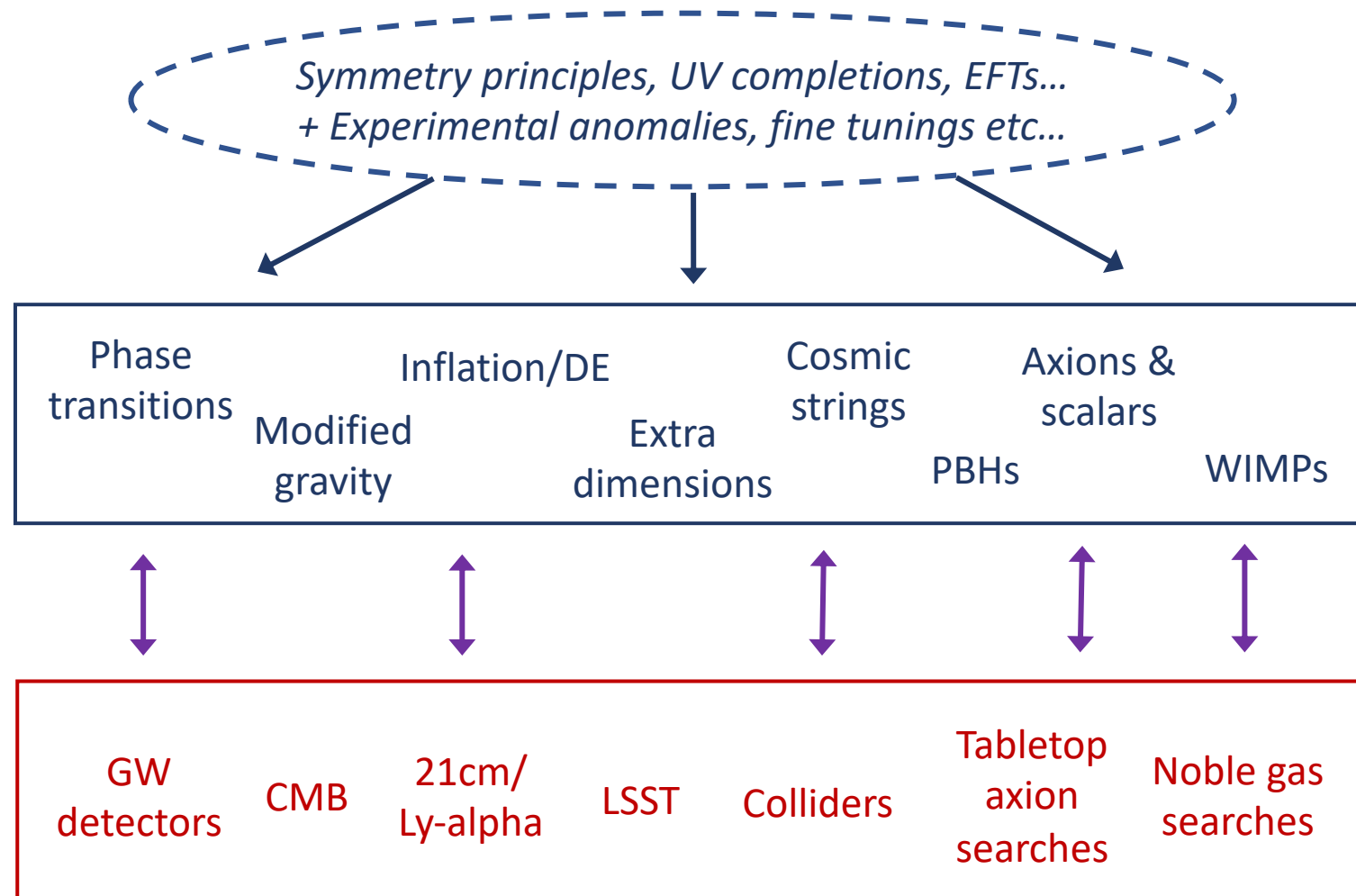
# Outlook & Conclusion

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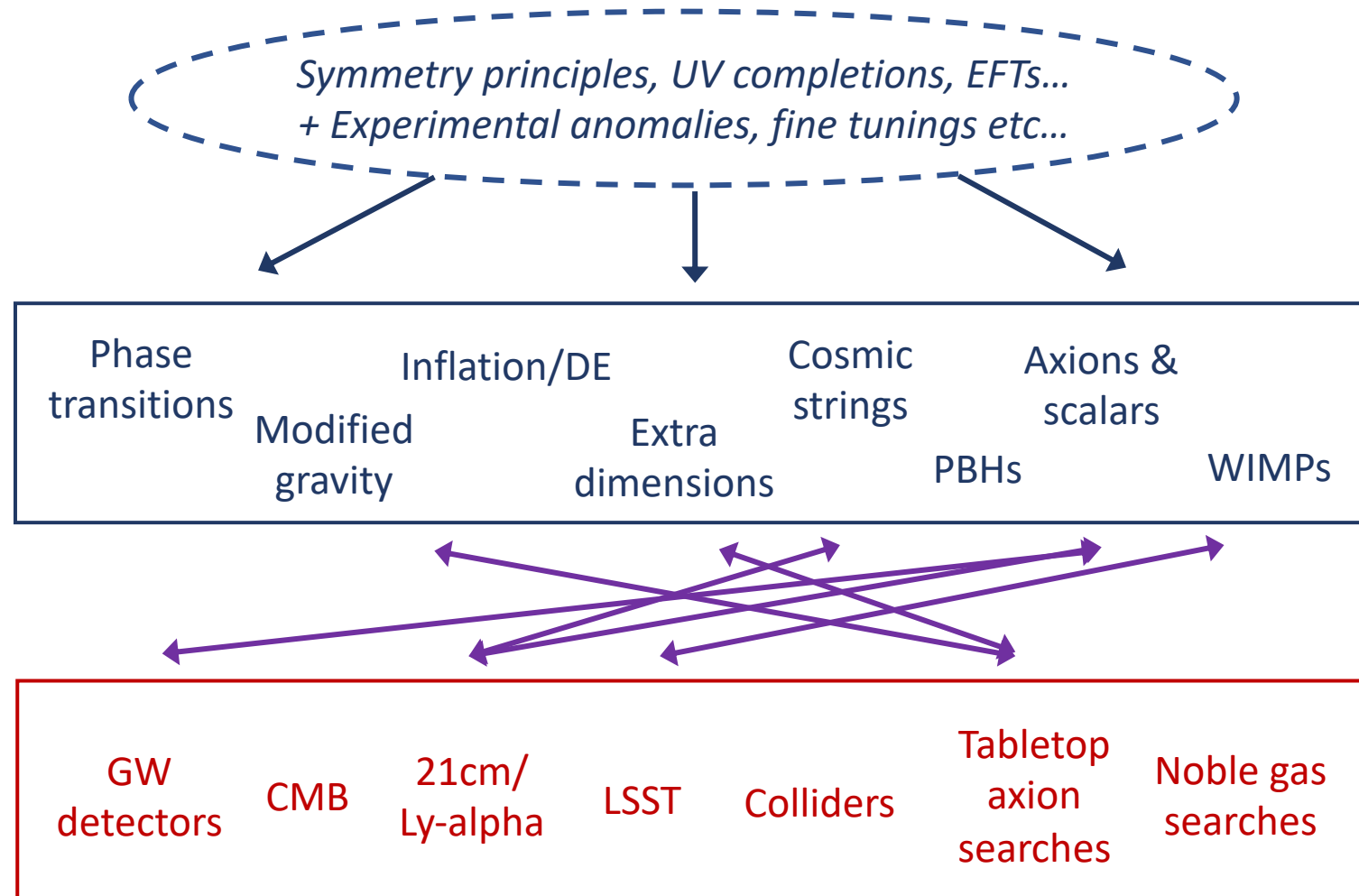
- Dilaton fields are well motivated ultralight DM candidates even below  $10^{-20}$  eV
- New physics can modify the Voigt profile used in cosmic survey, which needs to be carefully modelled
- We can follow similar methods for Ly $\alpha$  and 21 cm surveys, assuming fixed cosmology
- Ly $\alpha$  and 21 cm can competitively constrain couplings of dilatons and other scalar components of DM at ultra low masses: bounds on Ly $\alpha$  need running on real data set. 21 cm construction approved August 2021
- We harness a core strength of cosmological surveys: cosmic integration time / large DM column density
- Can expect improvements from further generations of surveys (HETDEX, ELT, SKA Phase II)
- Under review by PRD - Expect paper on arxiv soon!

**Thank you!**

# Landscape of Constraints

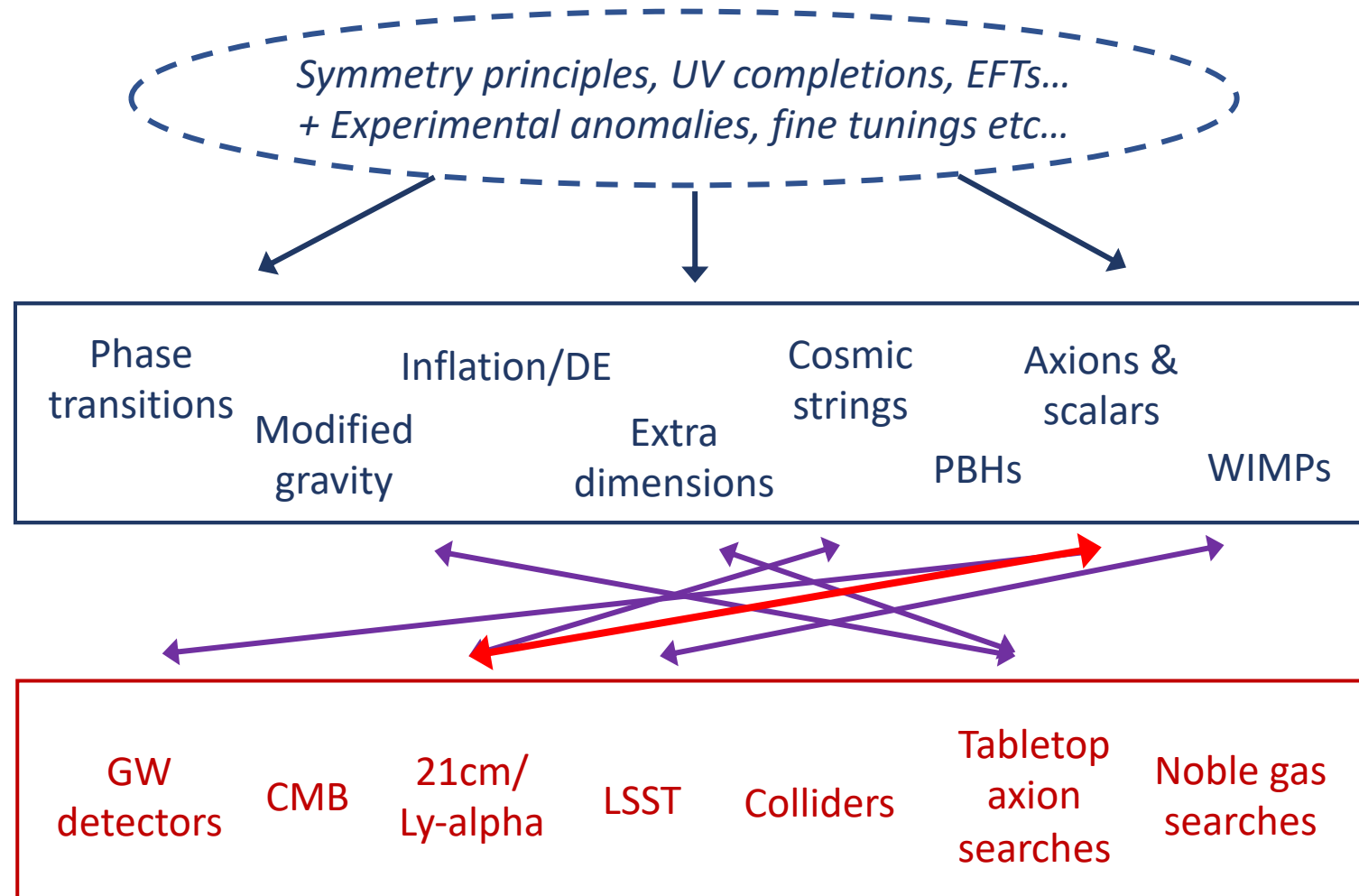


# Landscape of Constraints



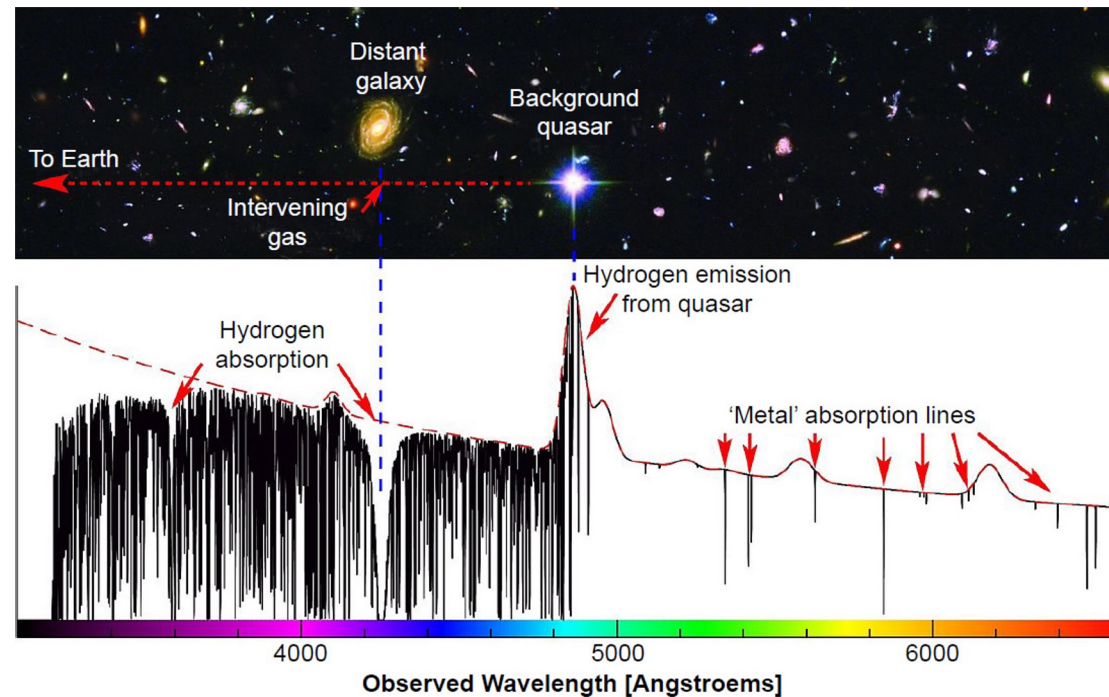


# Landscape of Constraints



# Foregrounds and Ly- $\alpha$ data

- A real spectrum will need to account for galactic foreground removal and pollution from other absorption lines (eg Ly $\beta$  and metal lines)

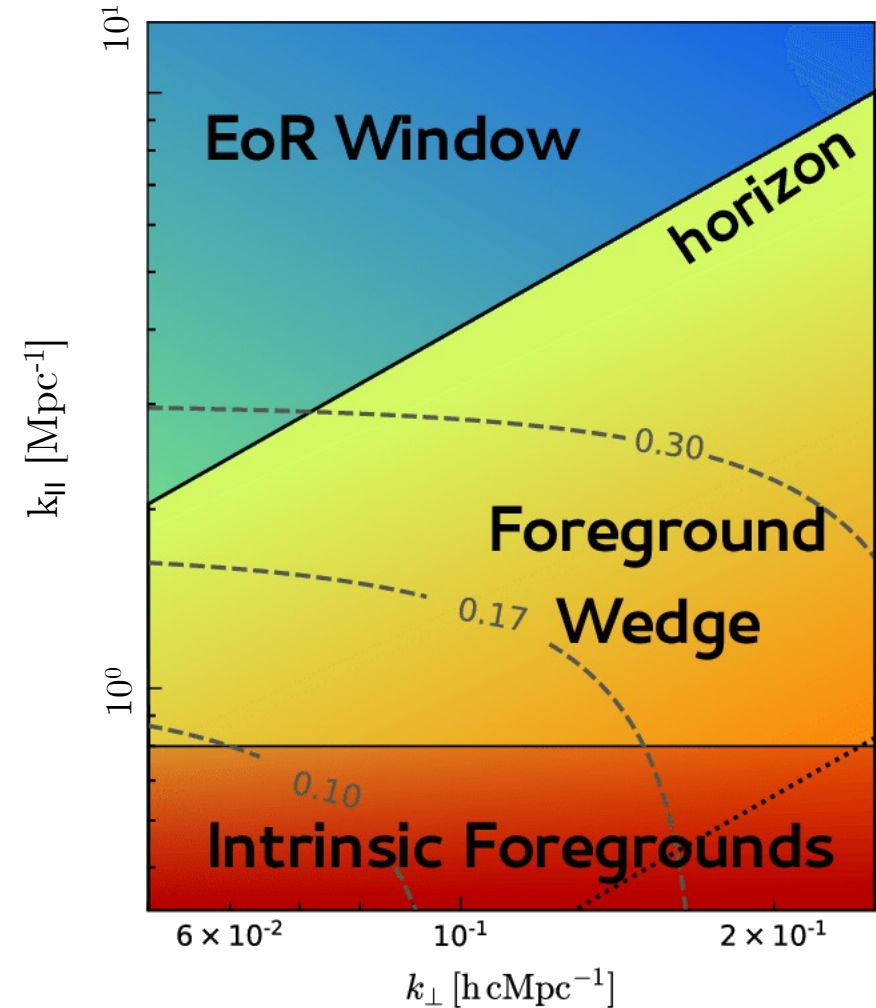


# SNR and treatment of 21 cm data

- Instrumental (red) and galactic (orange) foregrounds are important sources of noise. Here we ignored the latter, which mainly create noise in in the parallel component of frequency space, due to smooth spectral emission features, rather than in the transverse component. However reducing the observation angle reduces the SNR, as we see here. Taking a large angle and the best spectral resolution possible guarantees our results are independent of galactic foregrounds
- We show the full form of the SNR for radio interferometers:

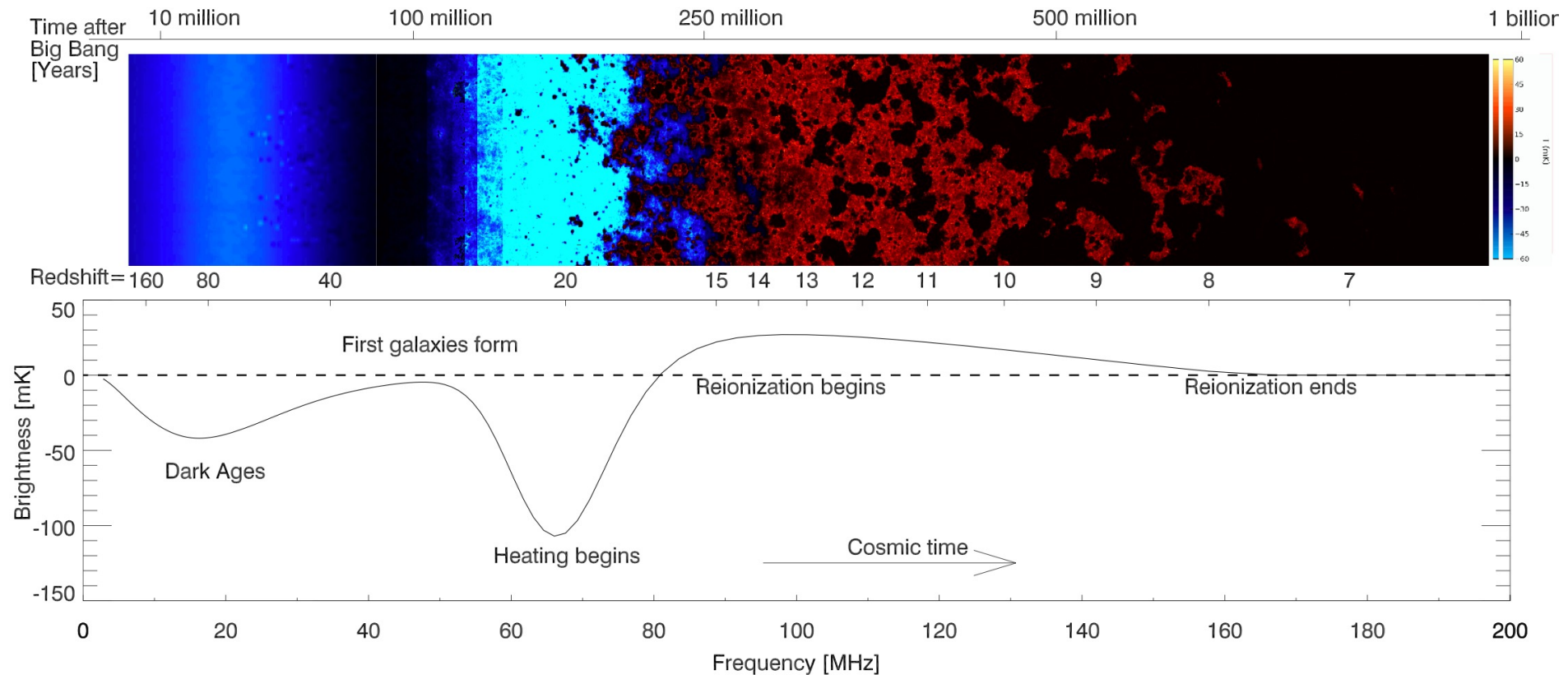
$$\sigma_T(\mathbf{u}, \nu) = \frac{\lambda^2 T_{\text{sys}}}{A_e \sqrt{2\delta\nu n(\mathbf{u})} (\Delta u)^2 t_p},$$

$$\theta_B^2 \sim \lambda^2 / D^2 \quad n(u) = \frac{N_a(N_a - 1)\lambda^2}{2\pi(D_{\text{max}}^2 - D_{\text{min}}^2)}.$$



# 21 cm signal before EoR

- A 21 cm signal varies widely over redshifts  $z \sim 5-20$ , which requires careful modelling as an underlying assumption, similarly to our work with Ly-alpha



# Context

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## Other approaches

- Webb et al (2012,2020) have posited difference in telescope measurements of  $\alpha$  comes from dipole variation (over scale of the universe)
- Could be due to scalar field coupling to  $F^2$
- Experiments look for spatial variation of alpha (with 5th force)
- Oscillation time should be faster than coherence time if dynamical field, which we assume...

## Our approach

- Assuming a primordial PS to this field (same as baryons), we can find the evolution of the PS today (see Bauer et al 2019)
- We can now think of the effect on  $\alpha$  as dependent on space and time
- Field can be as light as we want ( $>10^{-32}$ eV, and not major DM component  $<10^{-23}$ )

# Survey comparison

- UVES\_SQUAD (UVES+HIRES):
  - Spectral resolution: 3 km/s
  - Redshift 2.5
  - # LOS: 467
  - Median SNR: 20
- Ly-alpha forest interval: ~ 200 Angstrom restframe wavelength (Ly-beta → Ly-α)
- BOSS:
  - Up to 200.000 spectra (already observed), but lower quality (resolution, SNR)
- 21 cm:
  - $10^{11}$  pixels
  - SNR~20 at largest scales
- Future: SKA Phase II? ELT? HETDEX?

- Scaling at smallest masses (broadening):

$$\chi^2 \propto nr. \text{ of pixels}$$

$$\chi^2 \propto d_i^4$$

$$\chi^2 \propto SNR^2$$

- Scaling at larger masses (peak displacement):

$$\chi^2 \propto nr. \text{ of pixels}$$

$$\chi^2 \propto d_i^2$$

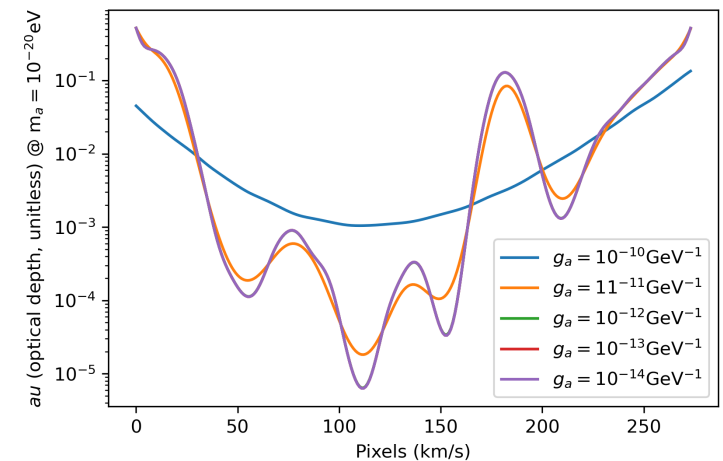
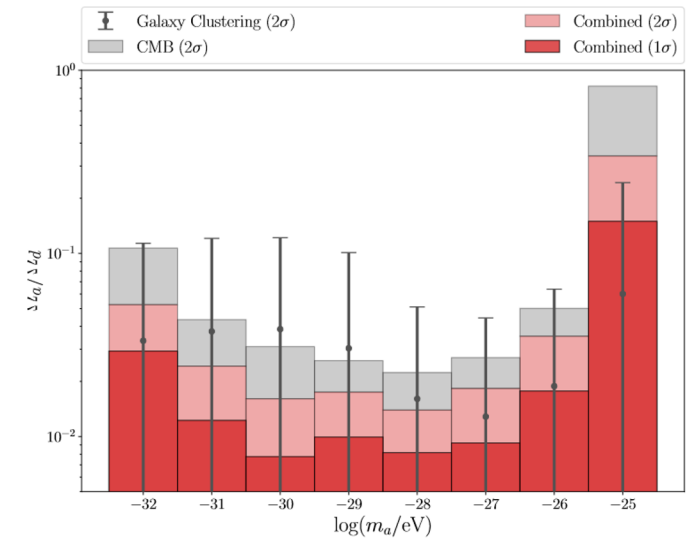
$$\chi^2 \propto SNR^2$$

→ To increase the constraints by one order of magnitude we have to increase the amount of data by four orders of magnitude

# Synthetic data & analysis

## Steps

1. Background model: No coupling ( $g_a=0$ ) & LCDM
2. Axion power spectra (transfer functions) by AxionCamb
3. Fractions corresponding to CMB bounds:  
Masses:  $10^{-20}$  eV,  $10^{-22}$  eV, ...,  $10^{-32}$  eV  
Fractions: 1, 0.2, ..., 0.06
4. We use nbodykit/reglyman (forward convolution with Voigt profile with specified IGM evolution: our last paper (consistent))  
→ Now on Github: Axionlyman
5. Compute spectra from same density while varying  $m_\phi$ ,  $g_\phi$



# Larger View Of Results

