Searching for Dilaton Fields in the Lyα Forest

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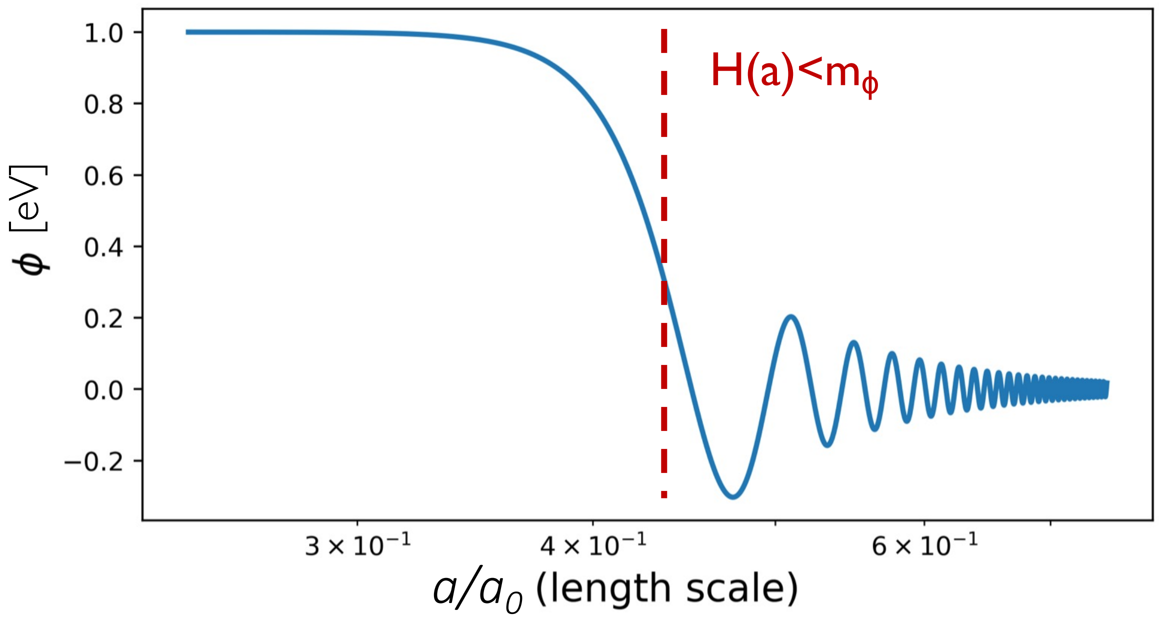
Introduction to dilatons (1/2)

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

Klein-Gordon equation

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



Can produce massive, pressureless, ultralight cold DM for ΛCDM

Late time solution:

$$\phi(\mathbf{x},t) = \sum_k \phi_{0,k}\cos(\omega_\phi t + \mathbf{k}\cdot\mathbf{x} + \varphi_k) \longrightarrow \rho_{\phi,k} = \frac{1}{2}m_\phi^2\phi_{0,k}^2$$

Introduction to dilatons (2/2)

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

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

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

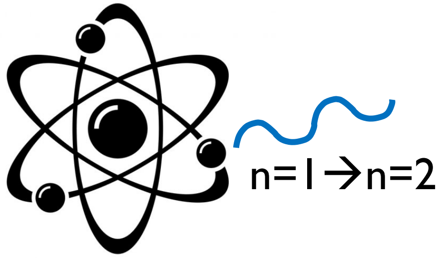
$$\Delta E_{\mathrm{Ly}\alpha} = \frac{3}{4}\mathrm{Rydberg} = \frac{3m_e\alpha^2}{8}$$

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

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

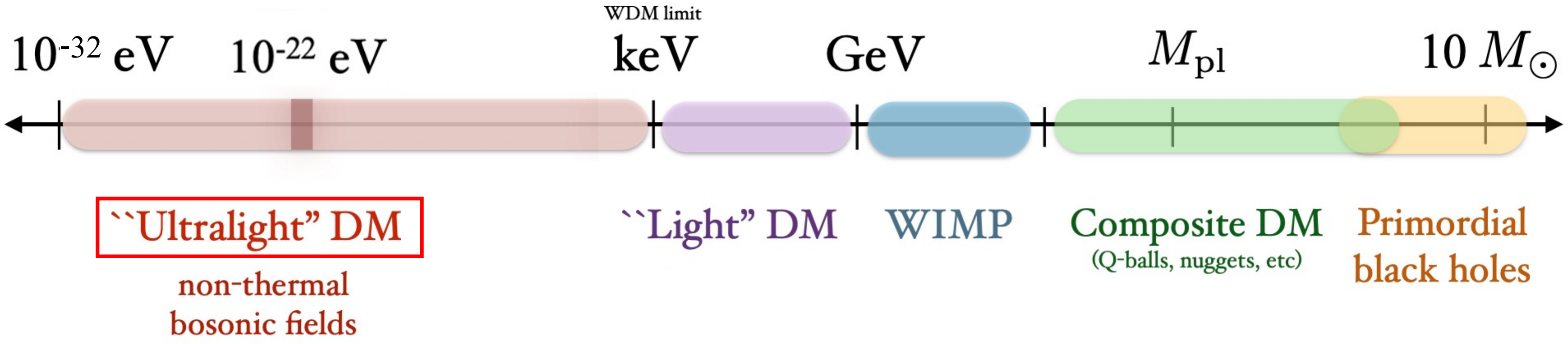
$$\alpha(\phi) = (1 + d_e\kappa\phi)\alpha = (1 + d_e\varphi)\alpha.$$

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

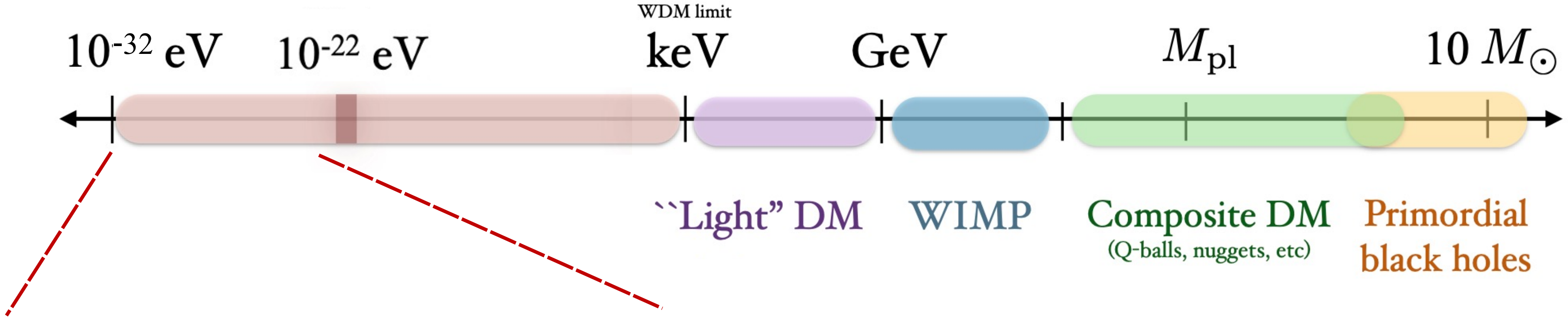


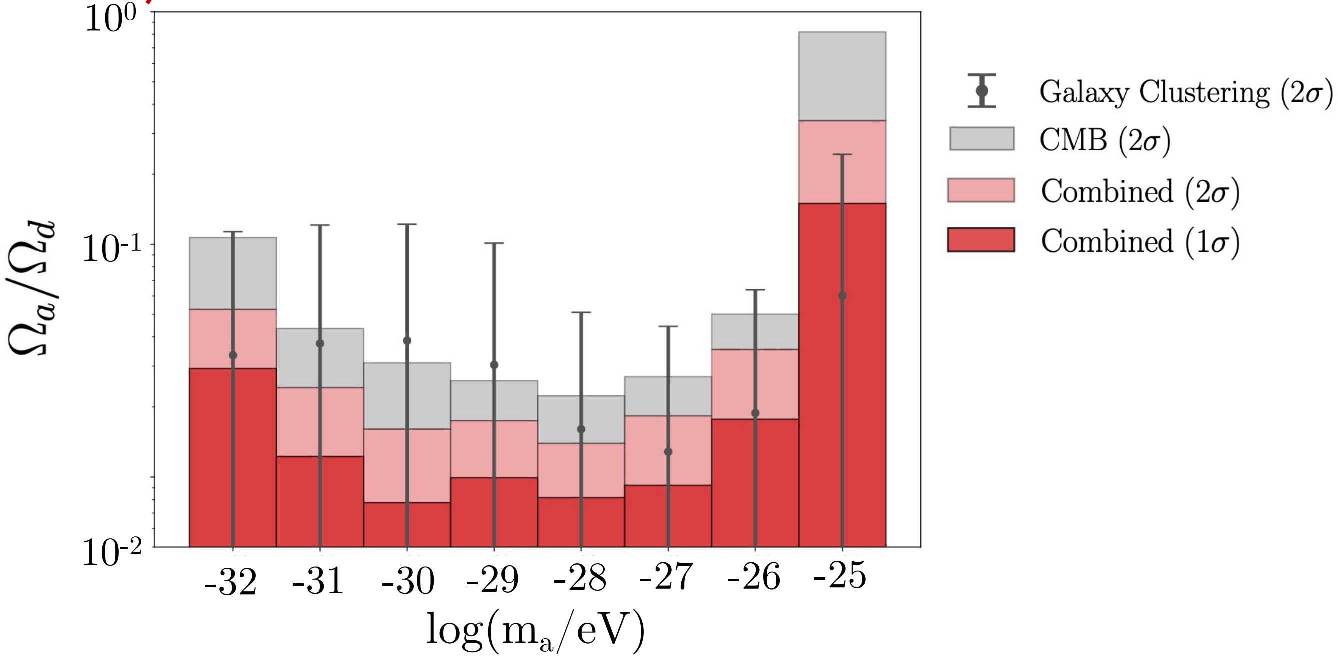
Motivation For Ultra-Ultralight Fields (1/2)

- 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)

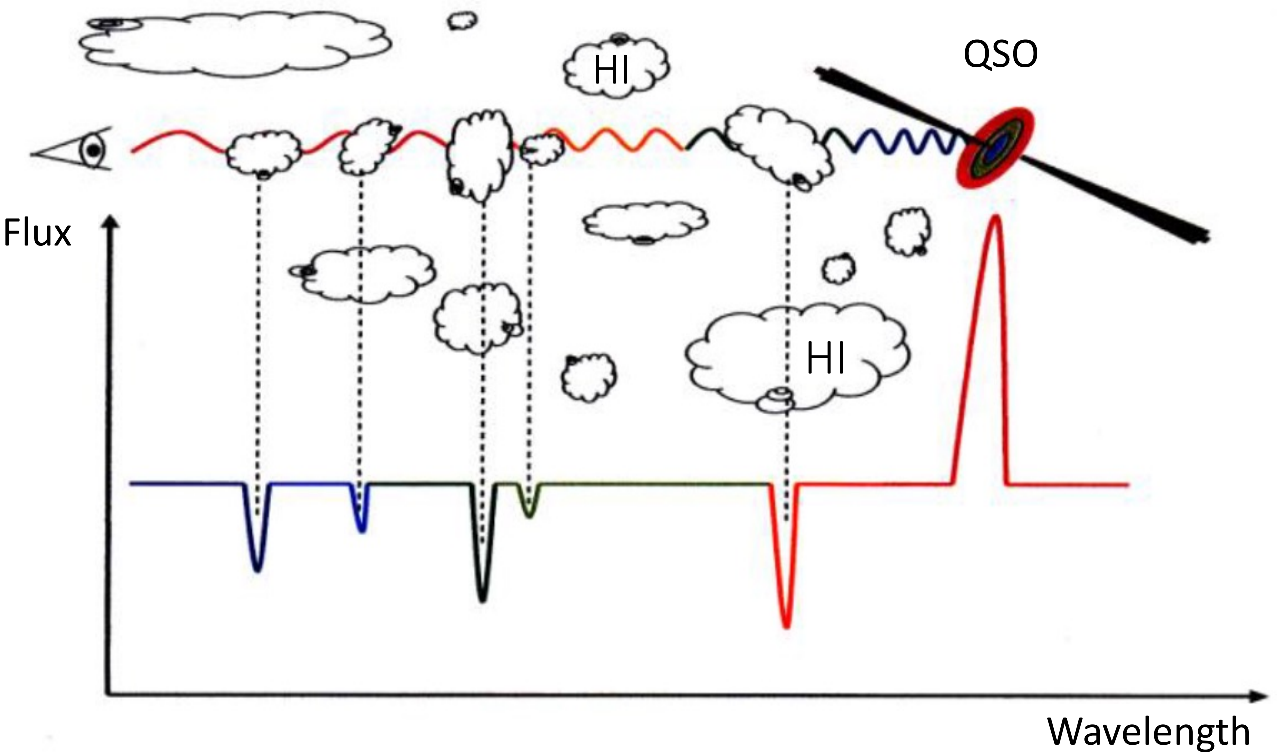




Strong bounds exist on the abundance of such fields, notably through gravitational lensing and clustering

Ly-α forest intro (1/2)

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



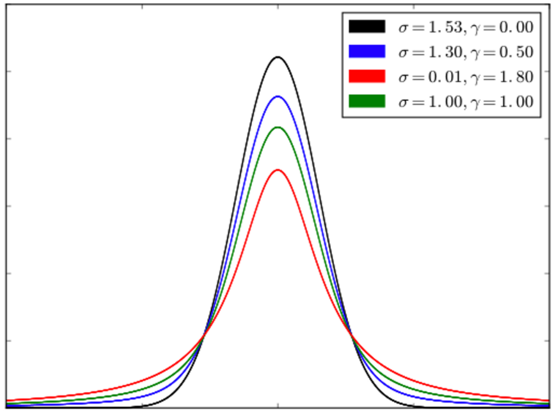
Ly-α forest intro (2/2)

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

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

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

$$b_T(x,z) = \sqrt{\frac{2k_{\mathrm{B}}T(x,z)}{m_{\mathrm{p}}}}, \qquad \gamma = \frac{\lambda_0}{2\pi\tau_{\mathrm{Ly}\alpha}}$$



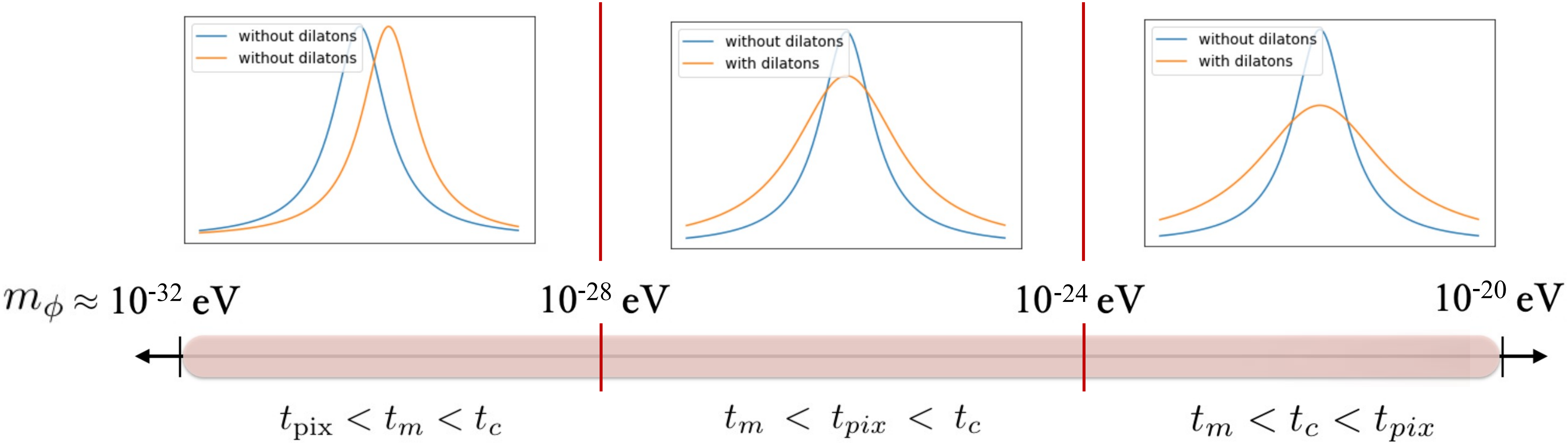
- Accounting for oscillating variation of the absorption wavelength requires another convolution. Final convolution comes from averaging over Rayleigh distribution (models decoherence):

$$\mathcal{V}(v_H(x,z), b_T(x,z), \gamma) = \frac{\gamma}{\pi^{5/2} b_T} \int_{-1}^{1} \int_{0}^{\infty} \int_{-\infty}^{\infty} \frac{e^{-\frac{v'^2}{b_T}} \left(\frac{2\phi_r}{\langle \phi_r \rangle} e^{-\frac{\phi_r^2}{\langle \phi_r \rangle^2}} \right)}{(\gamma^2 + (v_H(x,z) - v' - 2c\kappa d_i \phi_r \phi_m)^2)\sqrt{1 - \phi_m^2}} d\phi_m d\phi_r dv'$$

Dilaton Effect on Ly-α

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

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

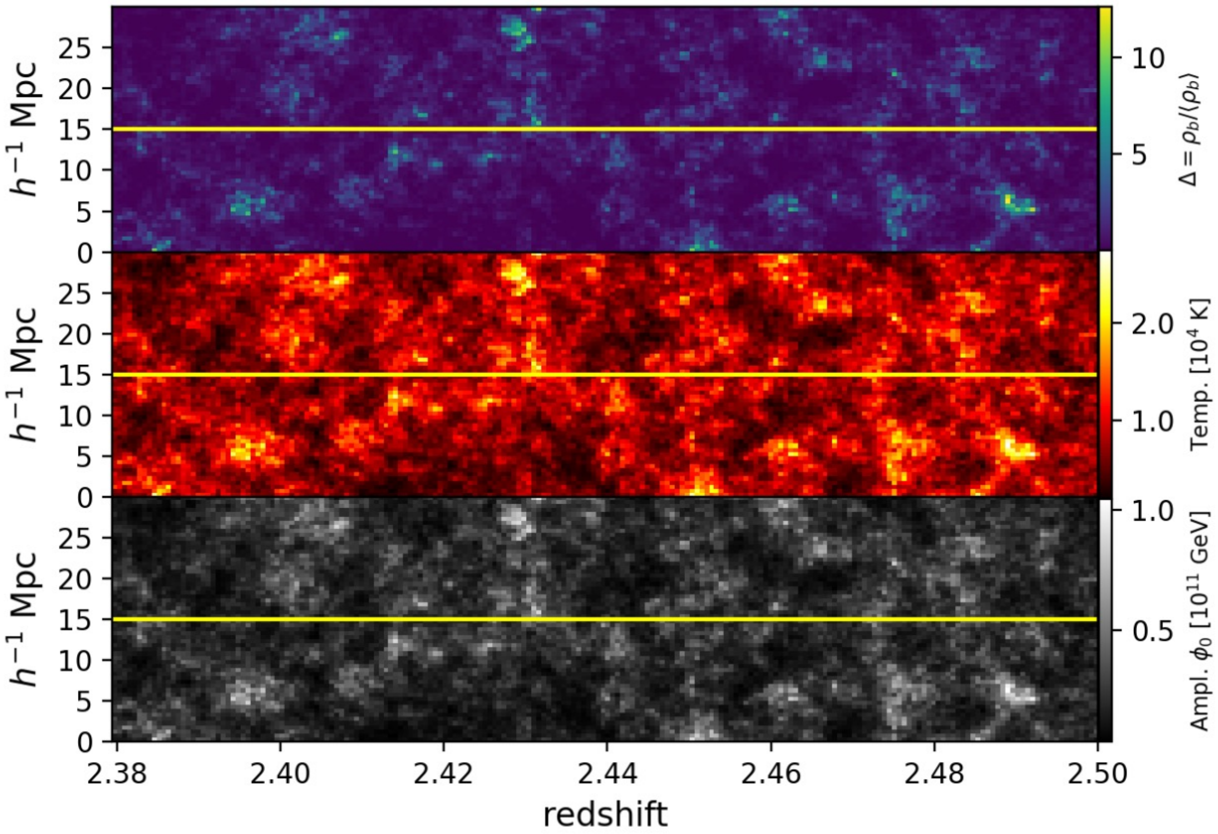


$m_\phi \approx 10^{-32}$ eV $\quad 10^{-28}$ eV $\quad 10^{-24}$ eV $\quad 10^{-20}$ eV

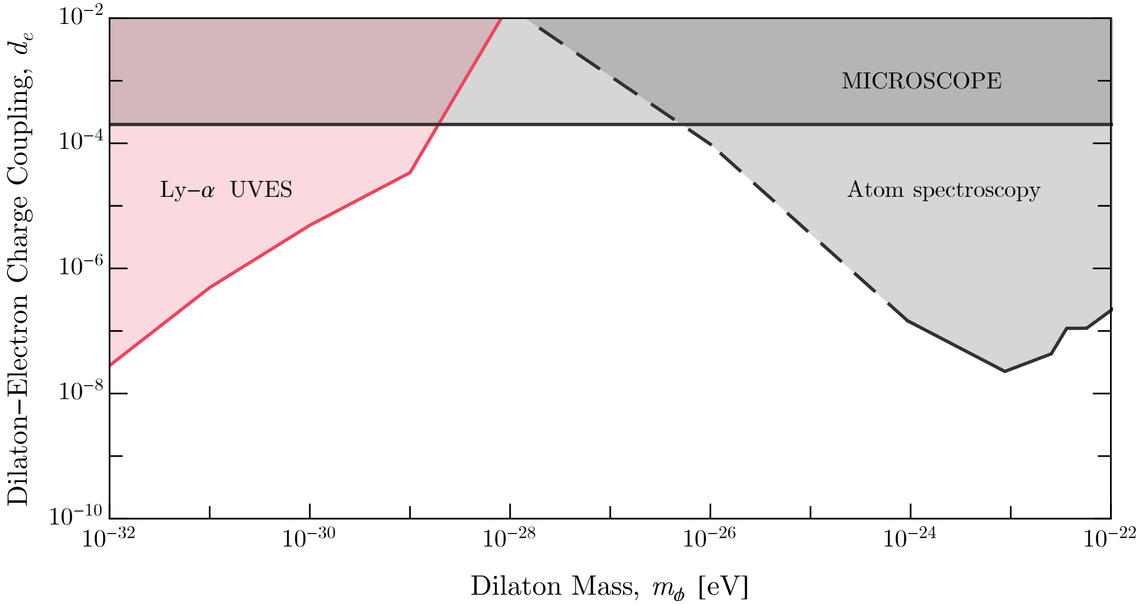
$t_{\mathrm{pix}} < t_m < t_c \quad t_m < t_{pix} < t_c \quad t_m < t_c < t_{pix}$

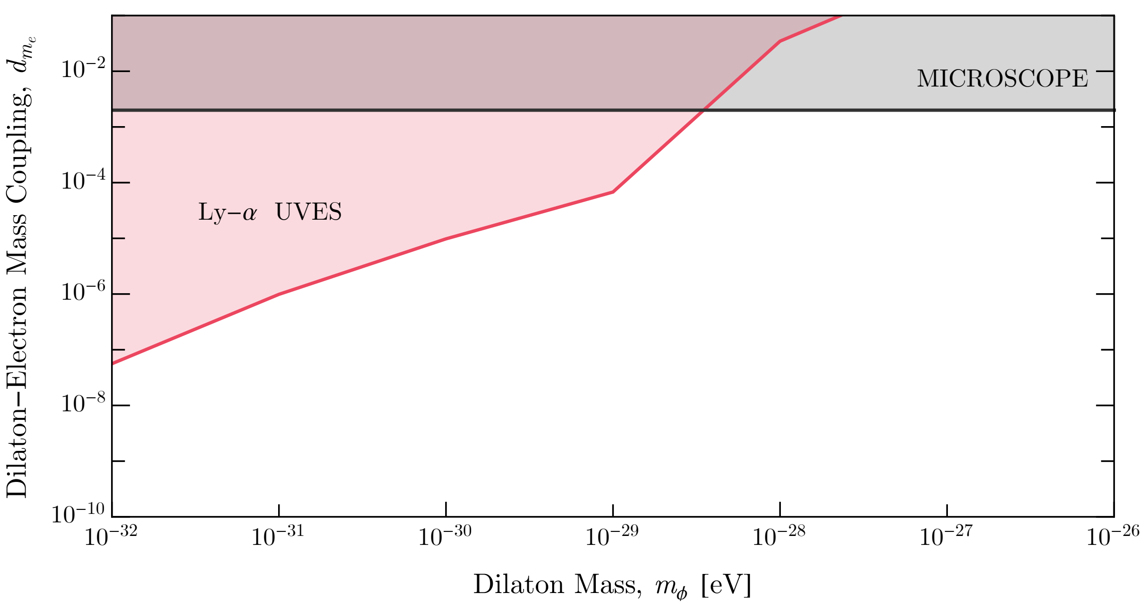
Synthetic data

- We assume a LCDM cosmology fitted by 2018 Planck data
- We generate 3D synthetic UVES SQUAD data at each dilaton mass
- Use axionCAMB for structure formation: structure surpressed at smallest dilaton masses
- We compare reconstructued opticals 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…



Lyα Results

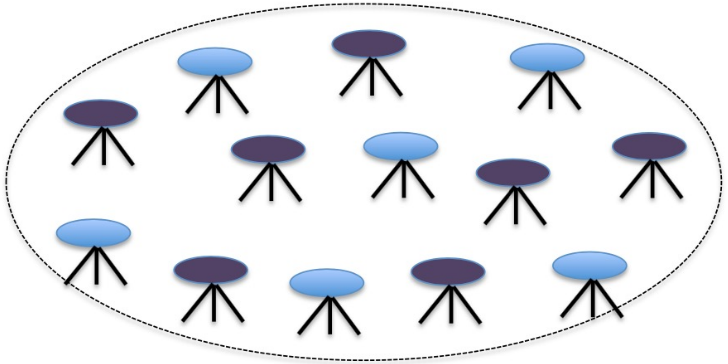




- UVES SQUAD data can significantly improve bounds (~500 QSOs, 10^6 spectral resolution)
- Competing bounds limited by integration time (e.g. atomic clocks, equivalence principle tests)
- Results scale differently for $t_{\rm pix} < t_m < t_c$

Extending to 21cm (1/2)

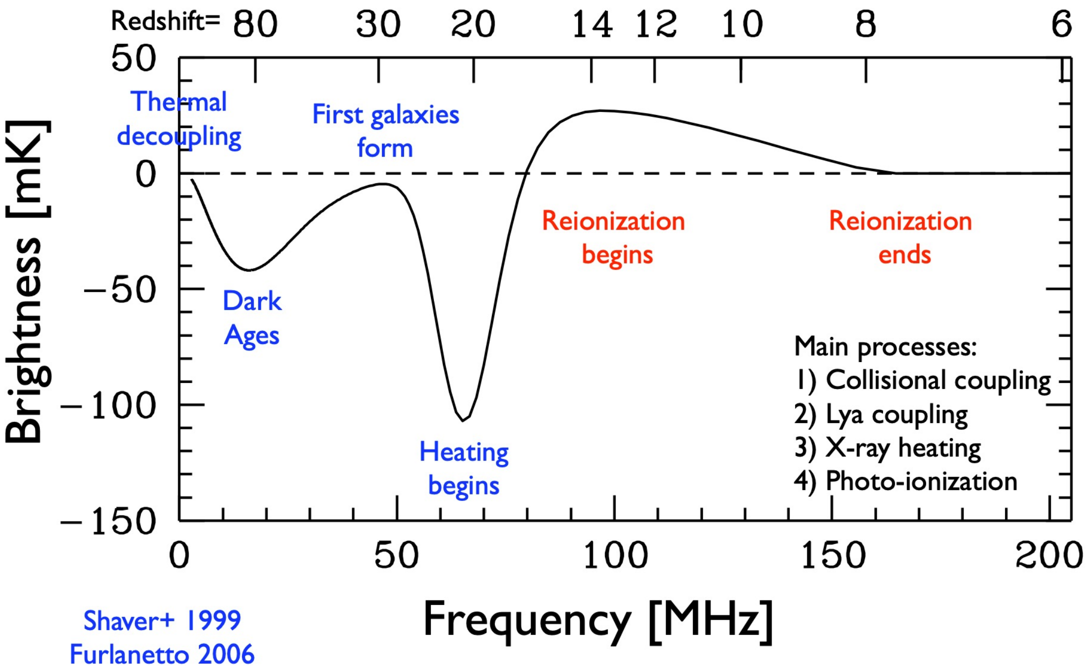
- 21cm surveys are effectively high resolution cameras of the distribution of neutral hydrogen. Looking for broadening is analogous to Lyα (but sometimes in emission): simply replace the SNR and number of pixels
- We use largest angular scales to maximise SNR[1] and data:
  - 21cm signal faint but SKA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



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

$$\Delta\theta^2 = \lambda^2_{21\mathrm{cm}}/D^2_{\mathrm{dish}}$$

Brief 21cm cosmology primer



Shaver+ 1999
Furlanetto 2006

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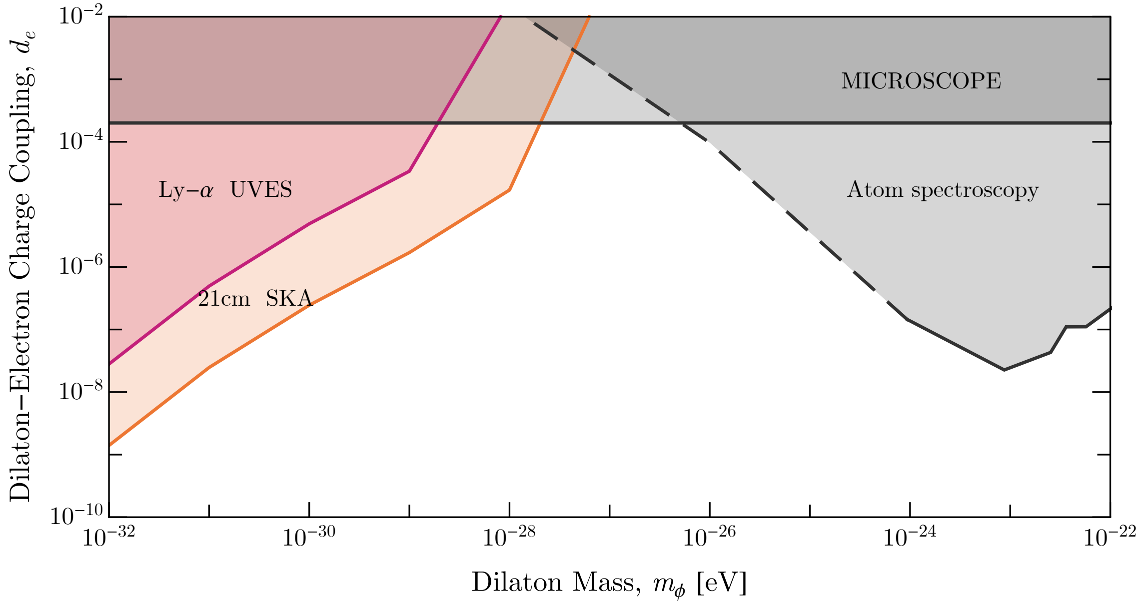
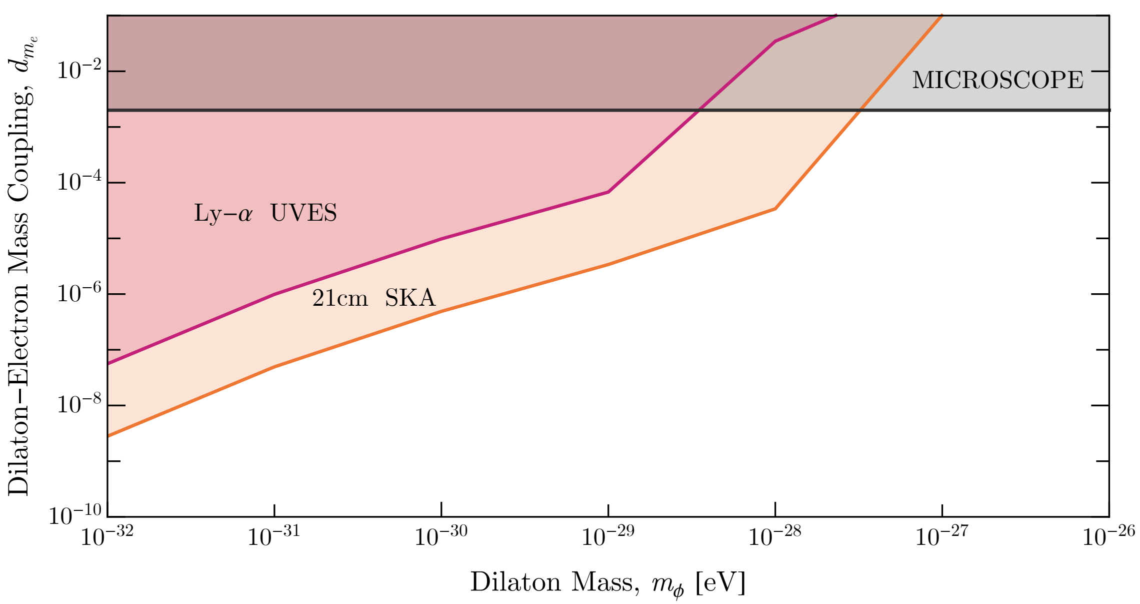
[1] Bounds scale as $(\#\ \mathrm{voxels})^{1/4}\mathrm{SNR}^{1/2}$ at larger mass and $(\#\ \mathrm{voxels})^{1/2}\mathrm{SNR}$ at lower mass

Extending to 21cm (2/2)





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

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

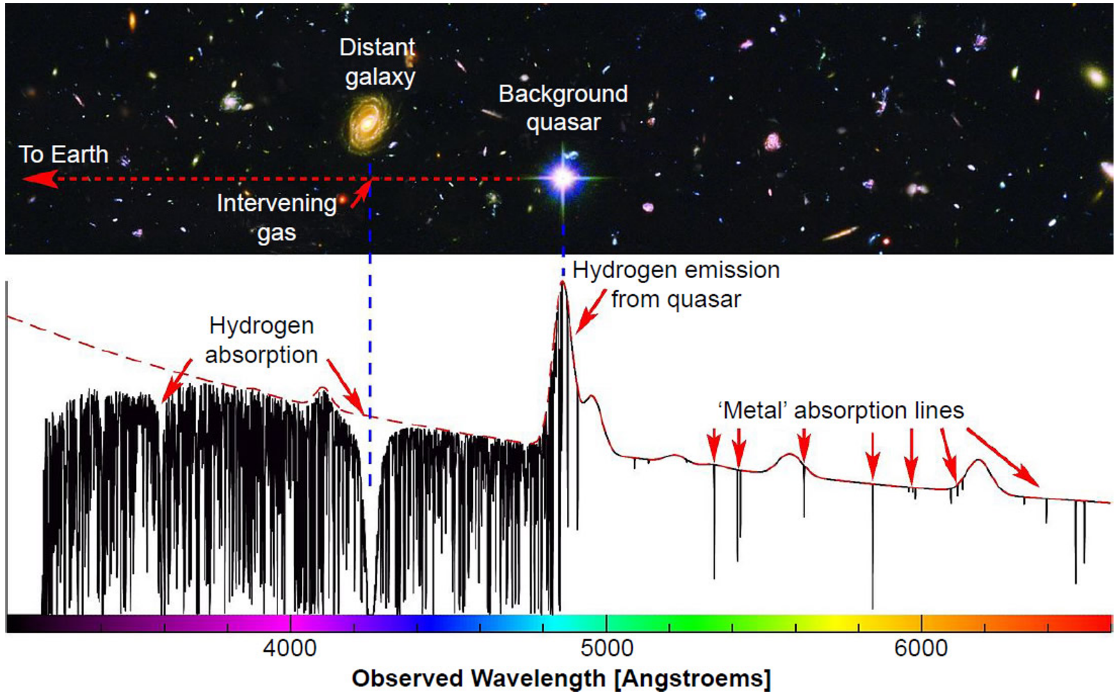
Outlook & Conclusion

- 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 Lyα and 21cm surveys, assuming fixed cosmology
- Lyα and 21cm can competitively constrain couplings of dilatons and other scalar components of DM at ultra low masses: bounds on Lyα need running on real data set. 21cm 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)
- Expect paper on arxiv soon!

Thank you!

Foregrounds and Ly-α data

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

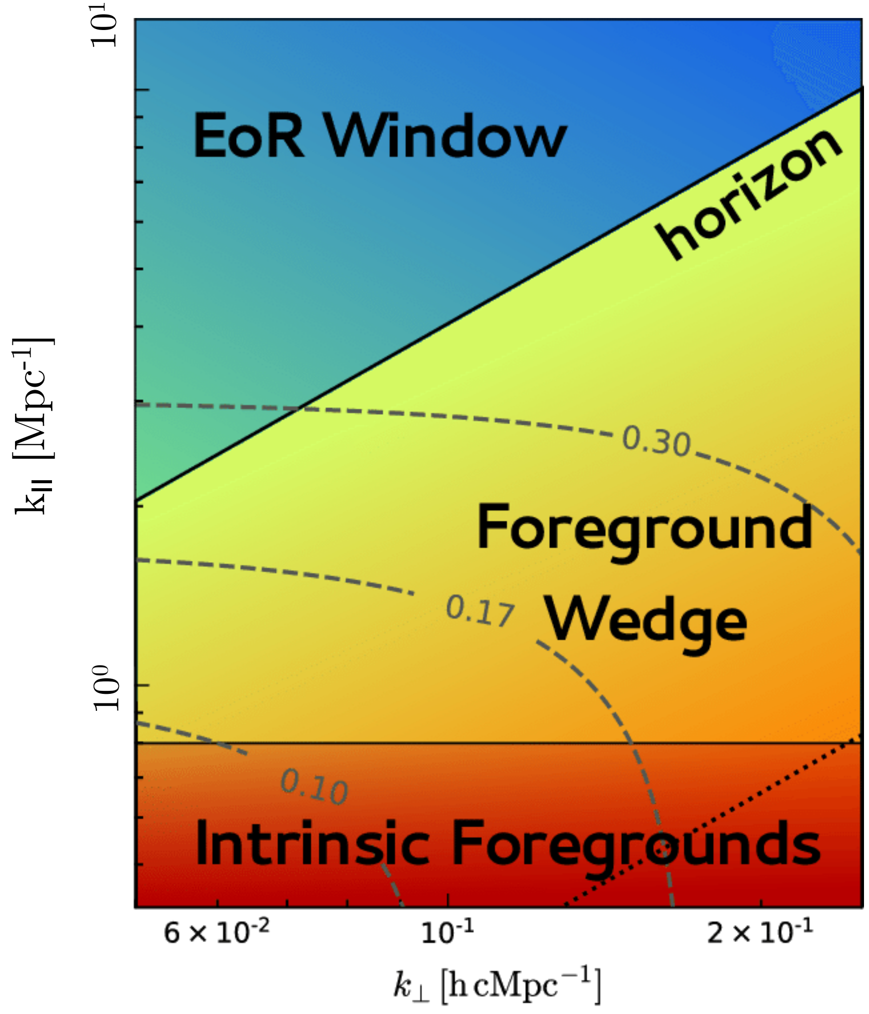


SNR and treatment of 21cm data

- 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:

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

$$\theta_{\rm B}^2 \sim \lambda^2/D^2 \qquad n(u) = \frac{N_a(N_a-1)\lambda^2}{2\pi(D_{\rm max}^2 - D_{\rm min}^2)}.$$



Context

Other approaches

- Webb et al (2012,2020) have posited difference in telescope measurements of α 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 α 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 Angstroem 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):

$$\chi^2 \propto nr.of pixels$$

$$\boxed{\chi^2 \propto d_i^4}$$

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

- Scaling at larger masses (peak displacement):

$$\chi^2 \propto nr.of pixels$$

$$\boxed{\chi^2 \propto d_i^2}$$

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

→ 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

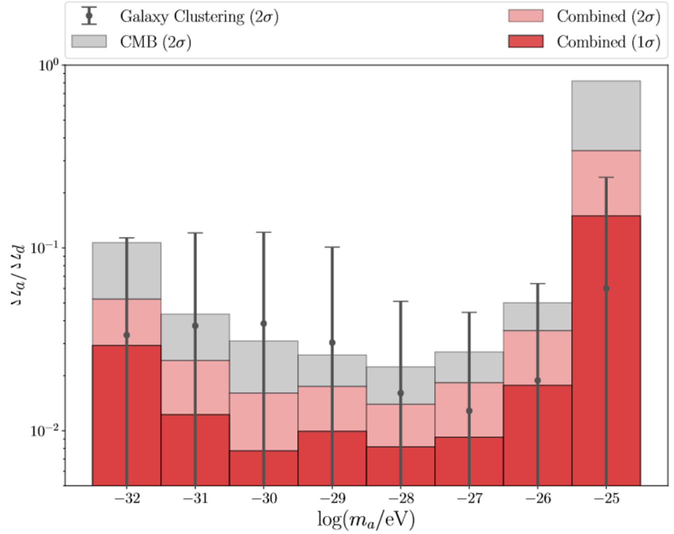
Steps

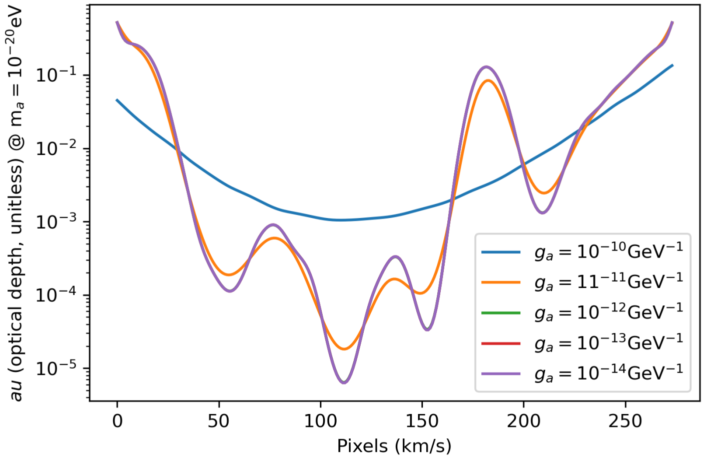
1. Background model: No coupling (ga=0) & LCDM
2. Axion power spectra (transfer functions) by AxionCamb
3. Fractions corresponding to CMB bounds:

    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_ϕ , g_ϕ





Larger View Of Results