TOWARDS A DIRECT MEASUREMENT OF COSMIC DYNAMICS

KICC 10th Anniversary Symposium

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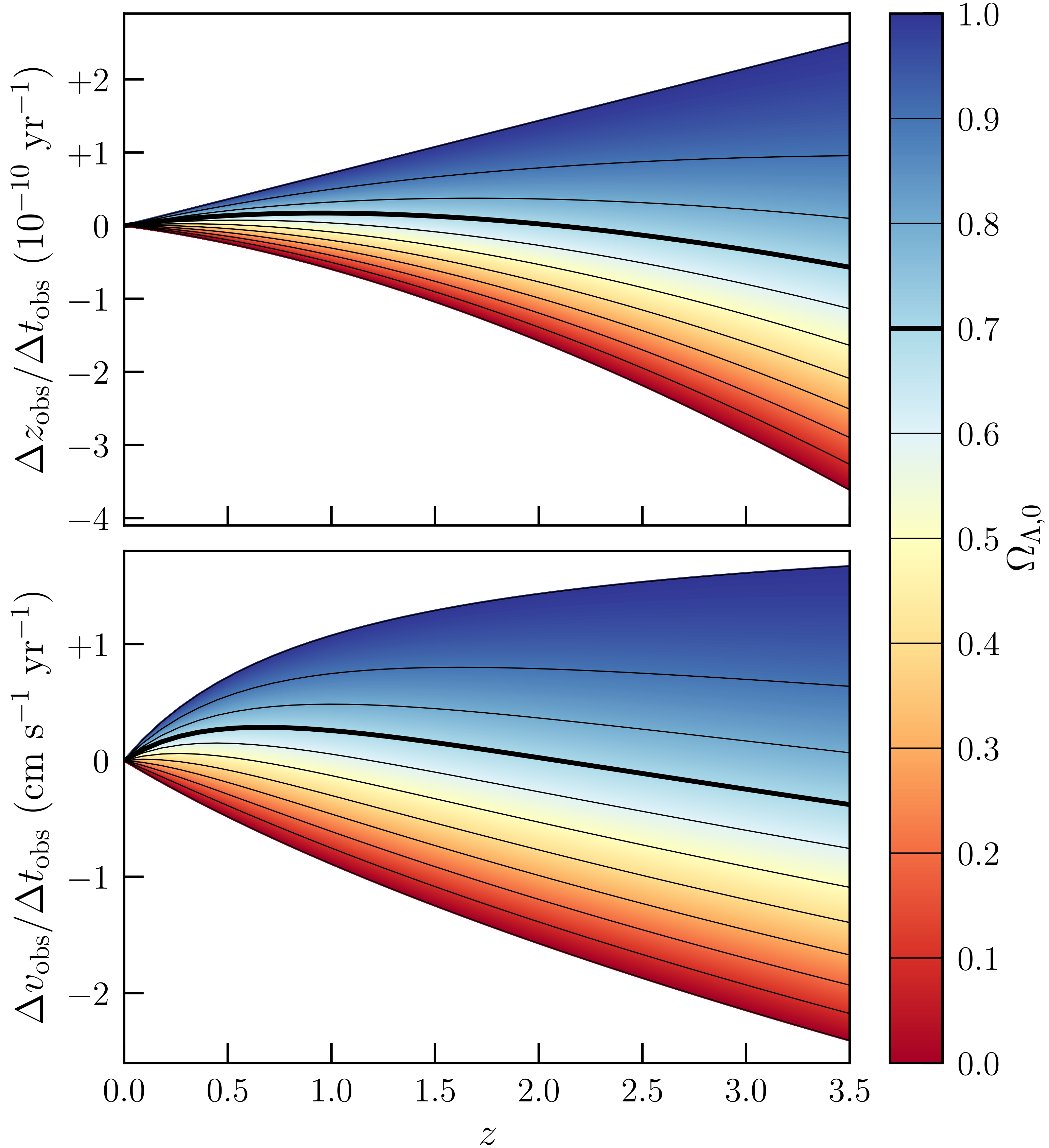
The Sandage Test

- **Watch the Universe expand in real time.**
- The expansion of the Universe causes the redshift and apparent brightness of a cosmological object to change with time.
- **For the concordant ΛCDM model, the expected signal is tiny, ~few mm/s/year**
- The signal gets bigger with time!



Sandage (1962)

(see also, McVittie 1962)

Proposed Experiments

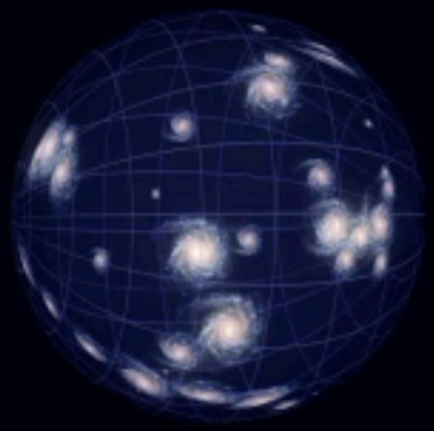
- **Lyα Forest - *'Sandage-Loeb test'* (Loeb 1998, Liske et al. 2008)**
  - Goal of current and future facilities (VLT+ESPRESSO, ELT+HIRES)
  - Instrumental systematics dominant
  - Source peculiar acceleration is sub-dominant

- **H I 21cm absorption (Darling 2012)**
  - Current best limit on the redshift drift $\Delta v/\Delta t < 10$ m/s/year, 2σ limit
  - Instrumental systematics sub-dominant
  - Limited by source peculiar acceleration

- **H I 21cm emission (Kloeckner et al. 2015)**
  - May be possible with future facilities (SKA)
  - Requires a change to SKA baseline specs

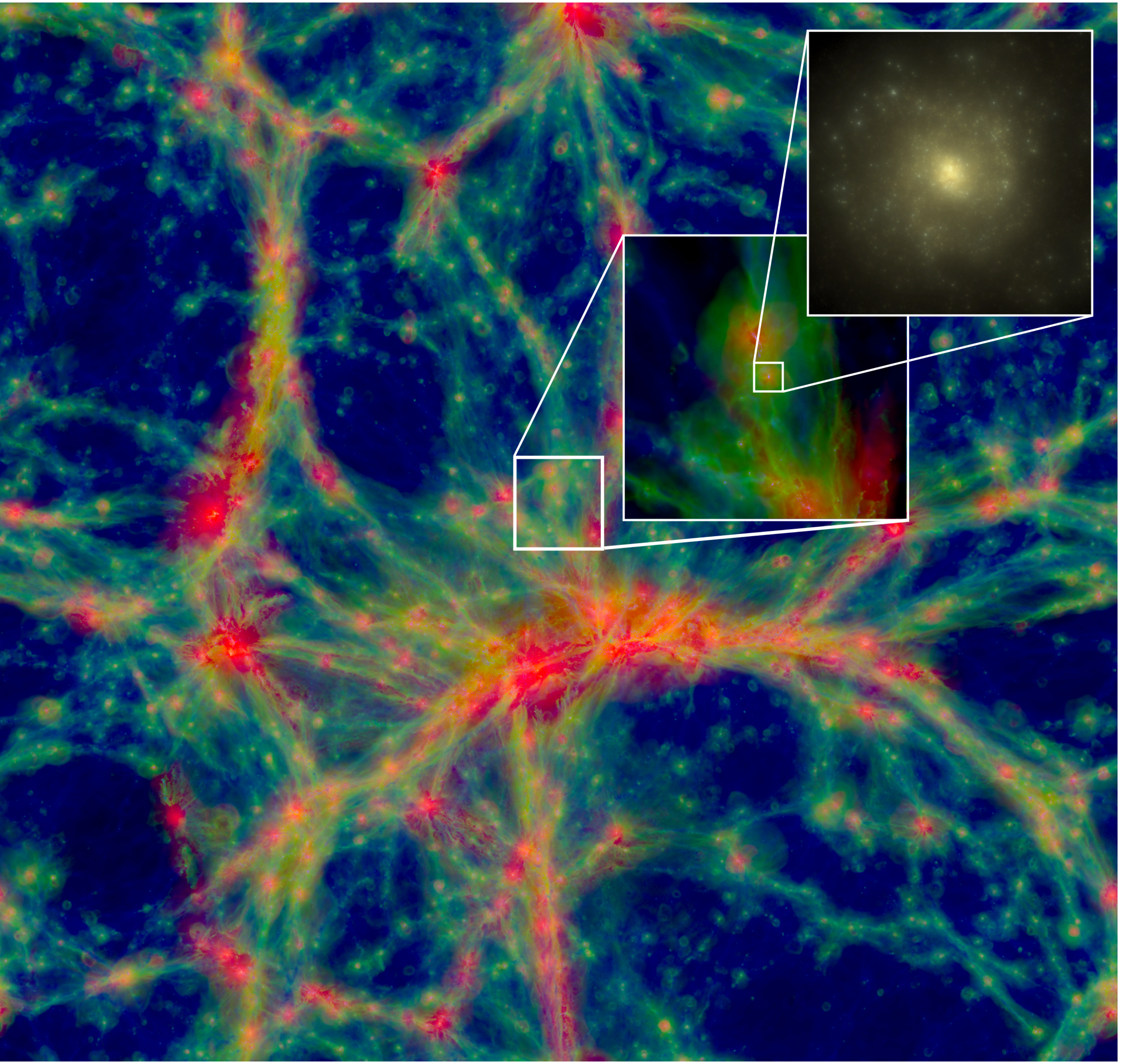
- **Sub-mm molecular absorption lines (Liske et al. 2008)**
  - Possible with current facilities (ALMA)
  - Instrumental systematics sub-dominant
  - Limited by source peculiar acceleration

Astro2020 Decadal Survey Science White Papers:
1903.05656, 1904.00217, 1907.08271



credit: ESA

EAGLE simulations



- **Ref-L100N1504 box**
  100 cMpc box
  1504^3 CDM particles
  $m_{dm} = 9.7 \times 10^6\ M_\odot$
  $H_0 = 67.77$ km s^{-1} Mpc^{-1}
  $\Omega_{\Lambda,0} = 0.693$
  $\Omega_{B,0}\ h^2 = 0.02216$

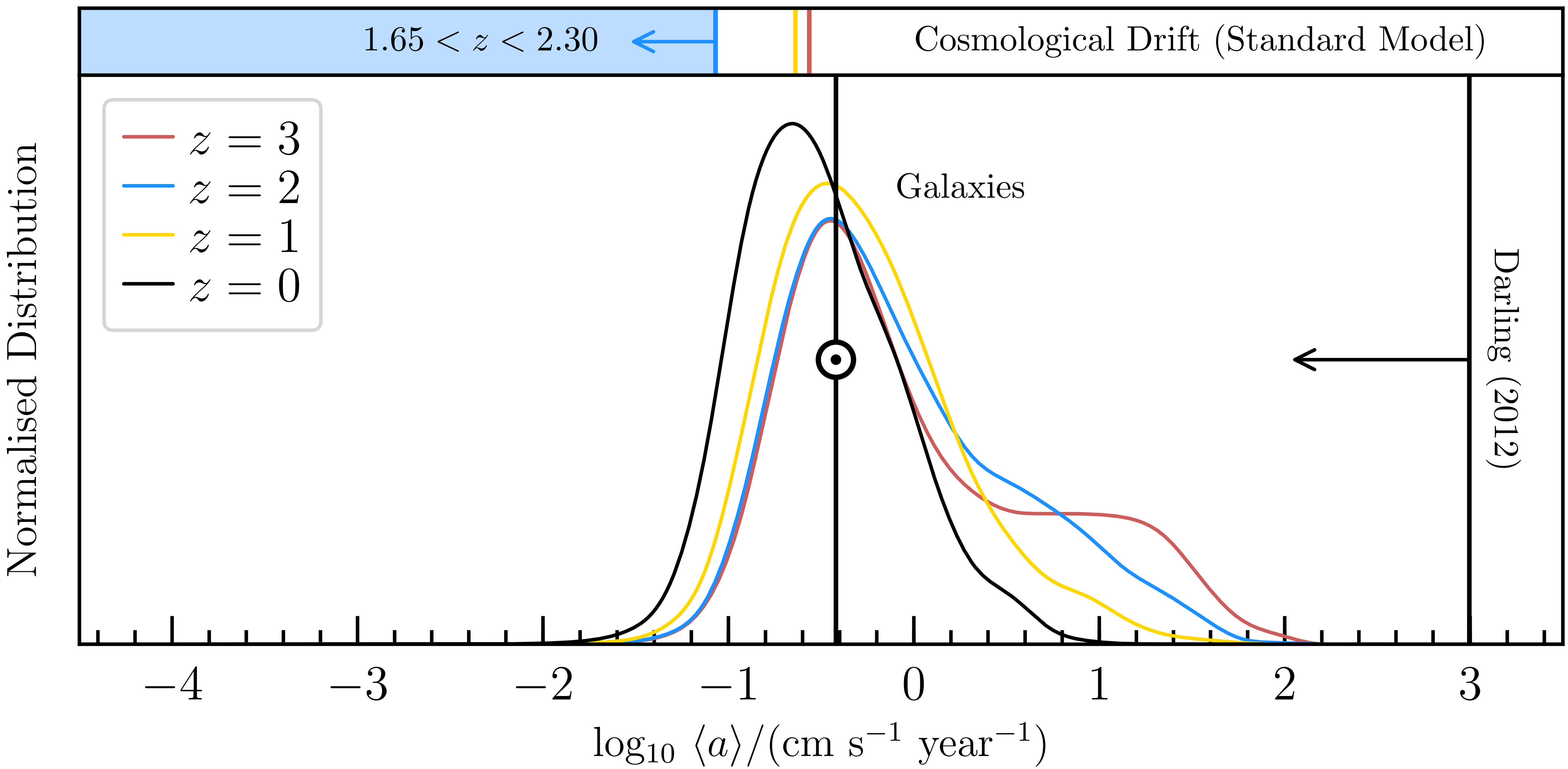
- **Cold/Molecular gas:**
  Identify gas particles that are about to turn into a star particle.

- **Lyα Forest:**
  Use the Schaye (2001) parameterisation to convert density to column density.

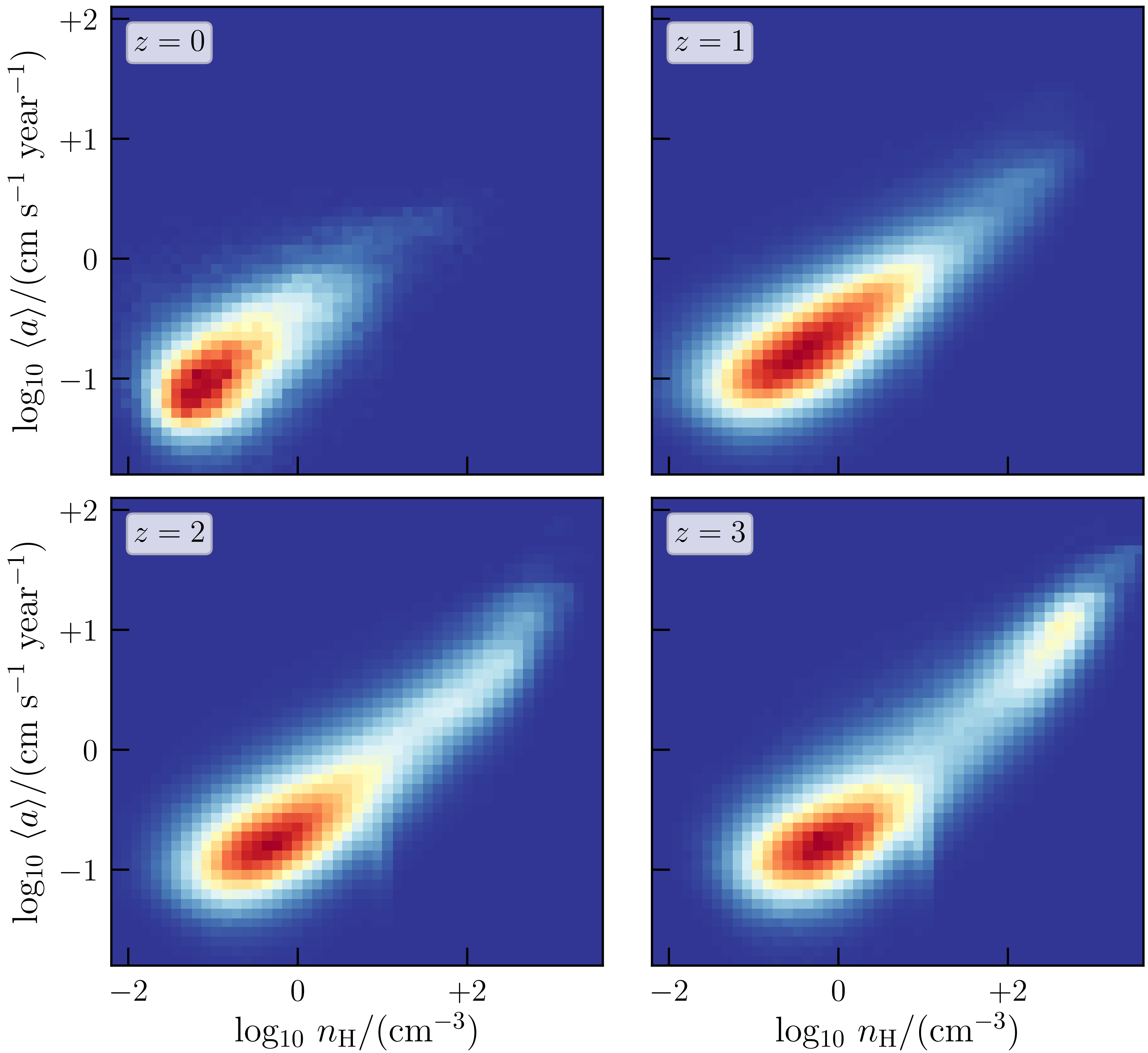
- **Peculiar acceleration:**
  Measure gravitational field strength around test particle.

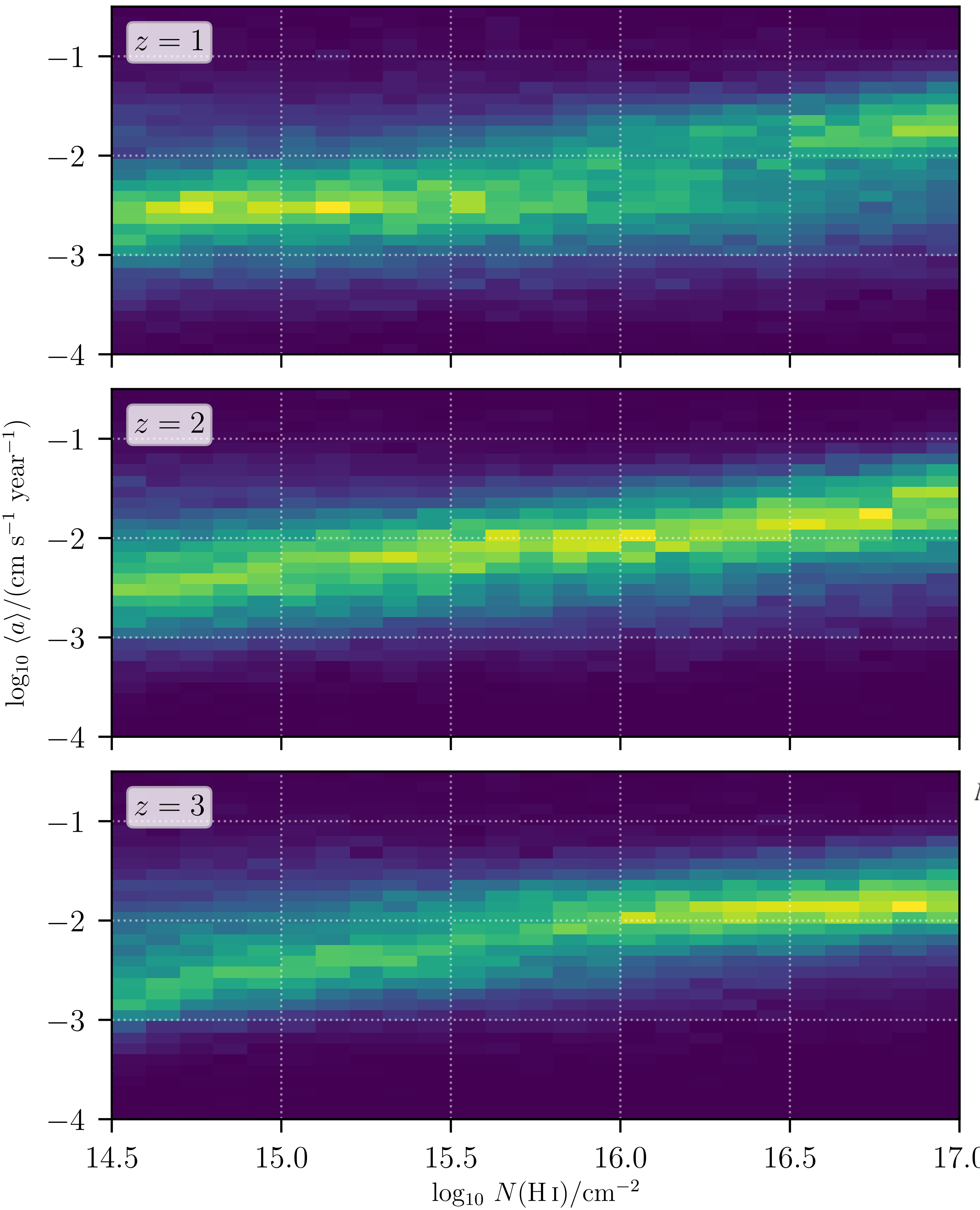
Summary of current status

(Cooke 2019, MNRAS submitted)



Acceleration of star forming gas in EAGLE





The EAGLE Lyα Forest

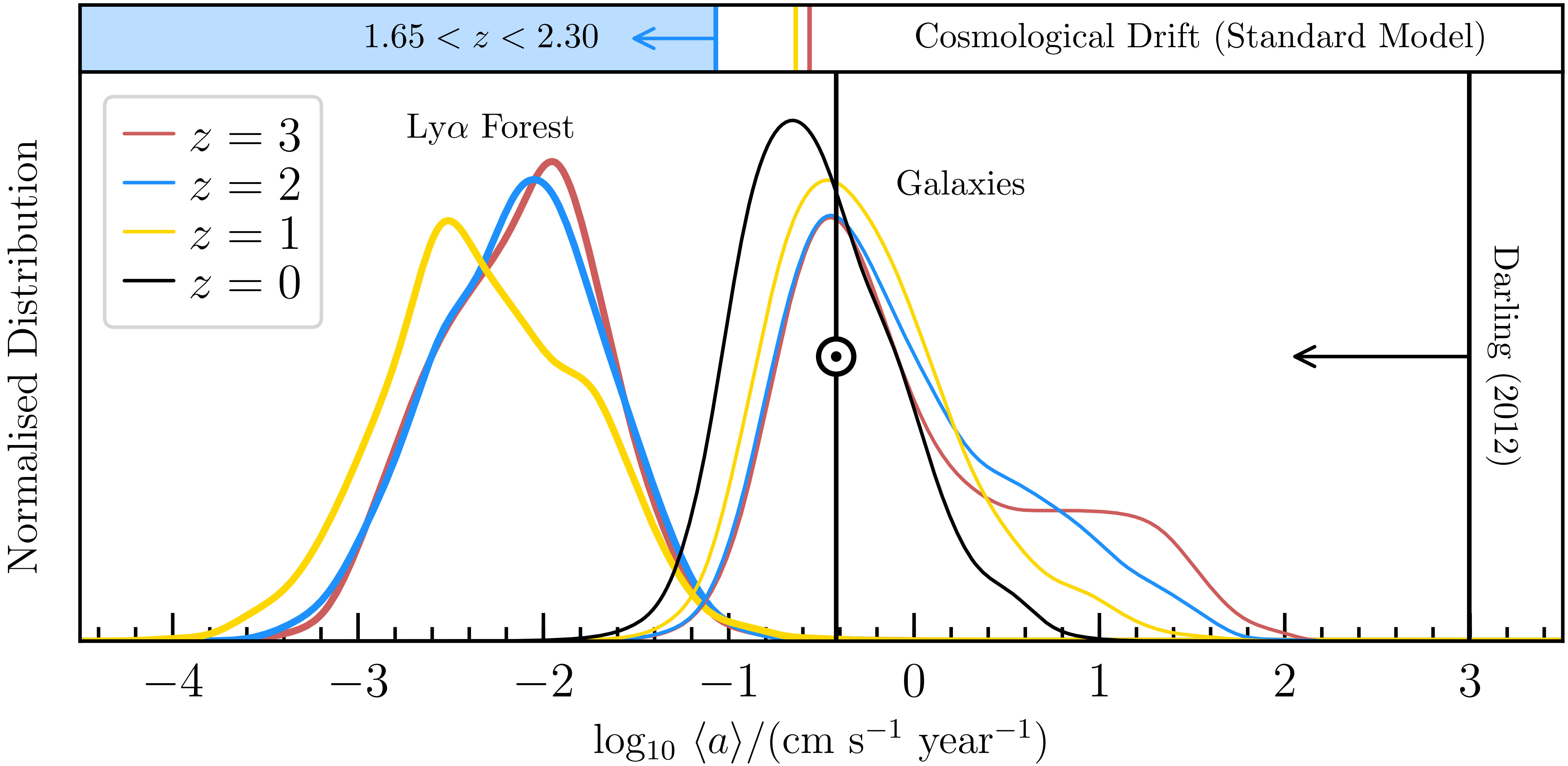
- **Expect peculiar acceleration to be low.** Lyman-α forest is expected to be far from galaxies.
- **Low *N*(H I) absorbers trace the large scale structure. Their motions are dominated by the Hubble flow (Rauch et al. 2005).**
- **Identify absorbers:** Use the Schaye (2001) model to convert density to column density:

$$N(\mathrm{H\,I}) = \frac{2.3 \times 10^{13}}{\Gamma_{\mathrm{H\,I}}} \left(\frac{n_{\mathrm{H}}}{10^{-5}\ \mathrm{cm^{-3}}} \right)^{1.5} \left(\frac{T}{10^4\ \mathrm{K}} \right)^{-0.26} \left(\frac{f_{\mathrm{b}}}{0.17} \right)^{0.5}$$

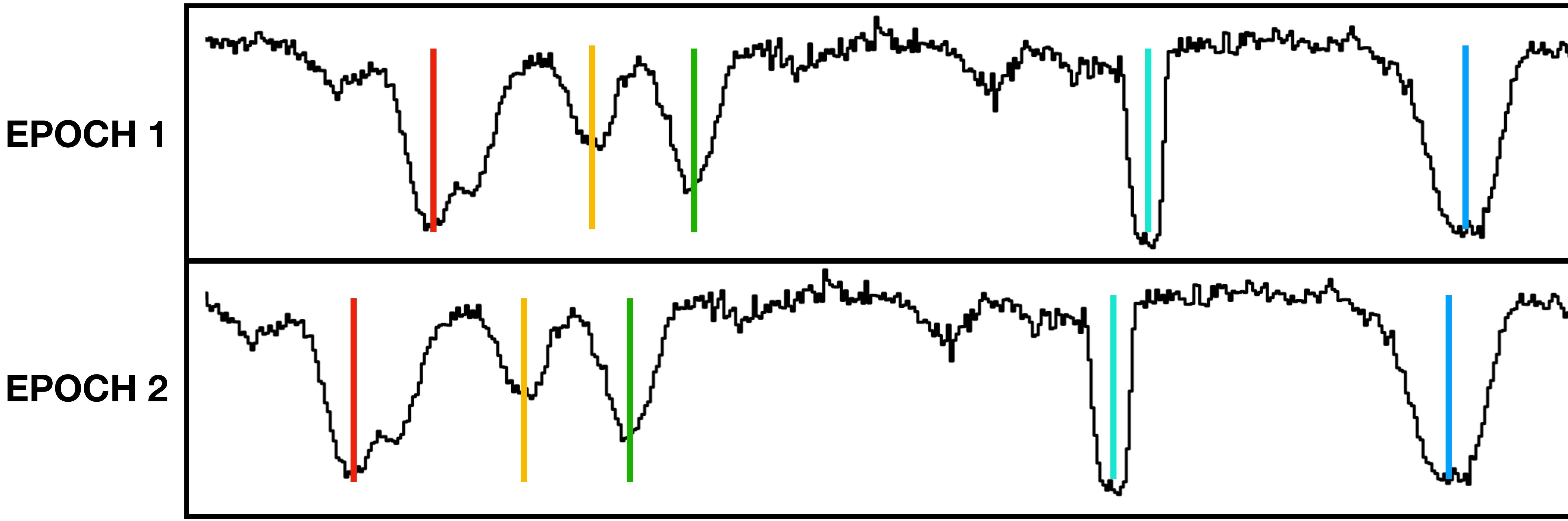
- This is a good approximation for the Lyman-α forest at redshift z > 1 (see Davé et al. 2010).
- **Lower *N*(H I) absorbers have lower peculiar acceleration.**

Summary of current status

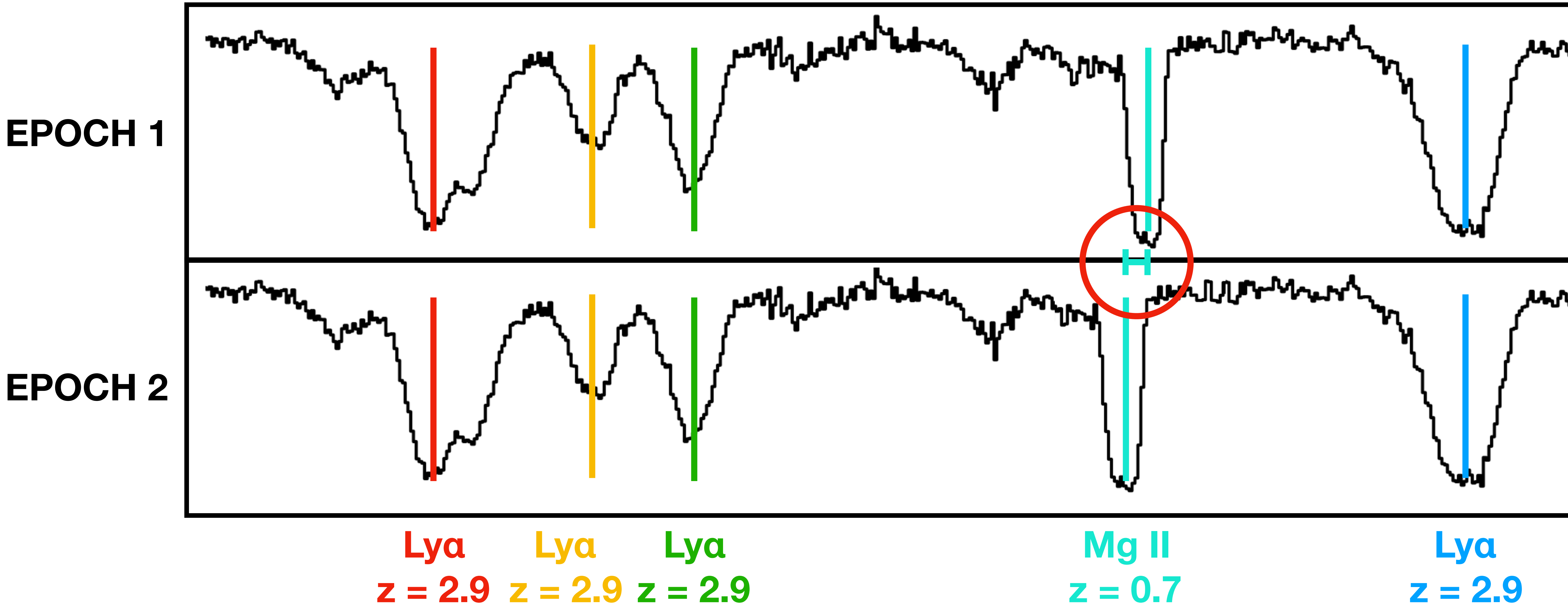
(Cooke 2019, MNRAS submitted)



Instrument Calibration Systematics



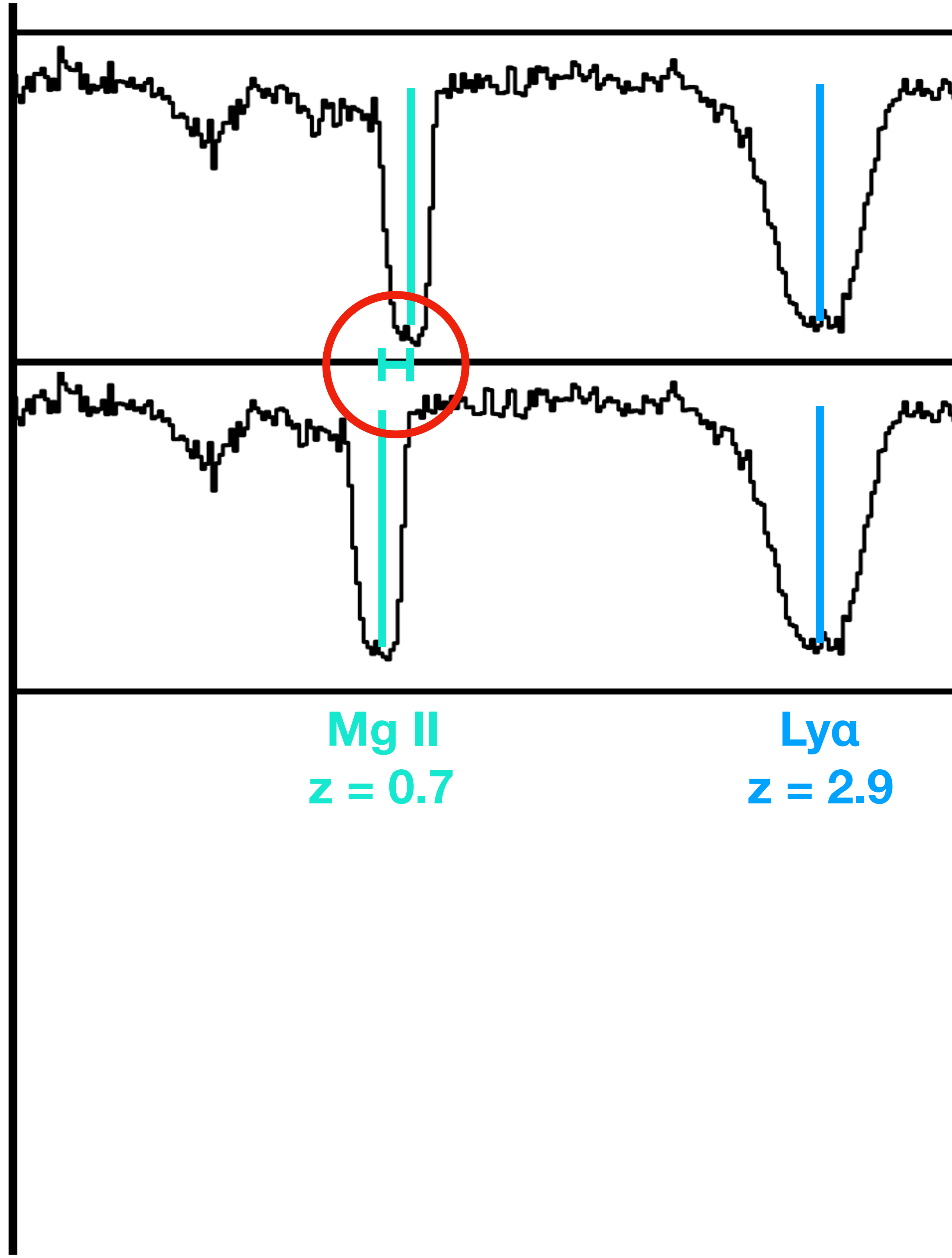
A relative measurement of cosmic dynamics



A relative measurement of cosmic dynamics

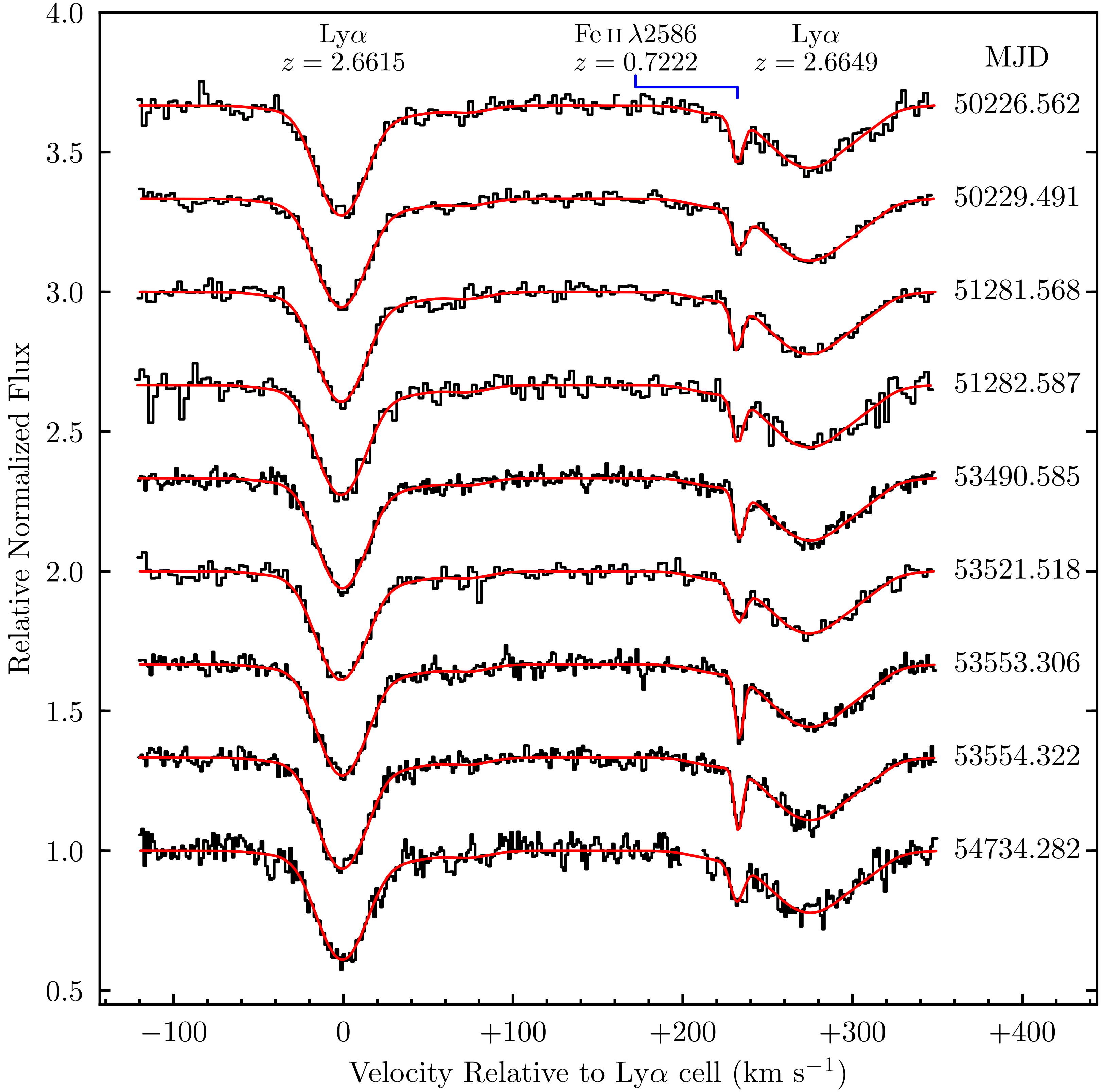
<u>Advantages of this approach</u>

- **The absolute wavelength calibration does not need to be known - just the relative calibration**
- **For favourable redshift combinations, the cosmological signal is doubled**
- **The peculiar acceleration of the observer (i.e. the Sun) cancels.**
- **The relative barycentric velocity correction is minimised.**



Relative Lyα forest experiment

(Cooke 2019, MNRAS submitted)

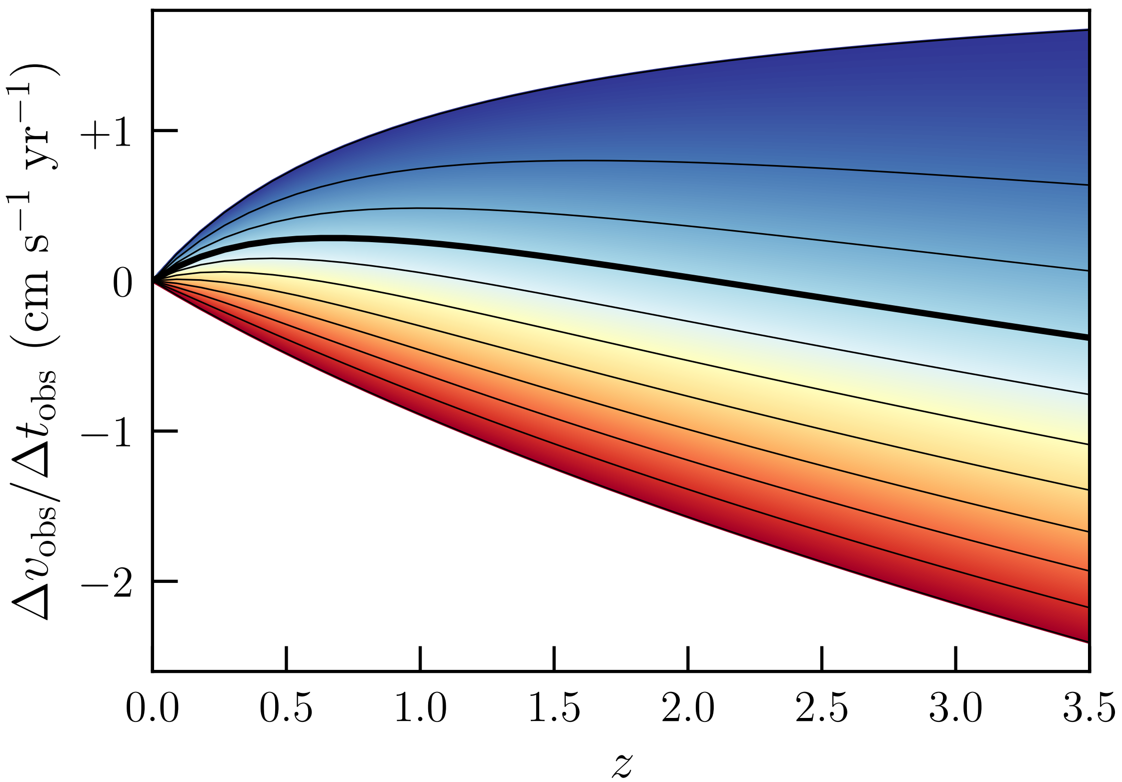


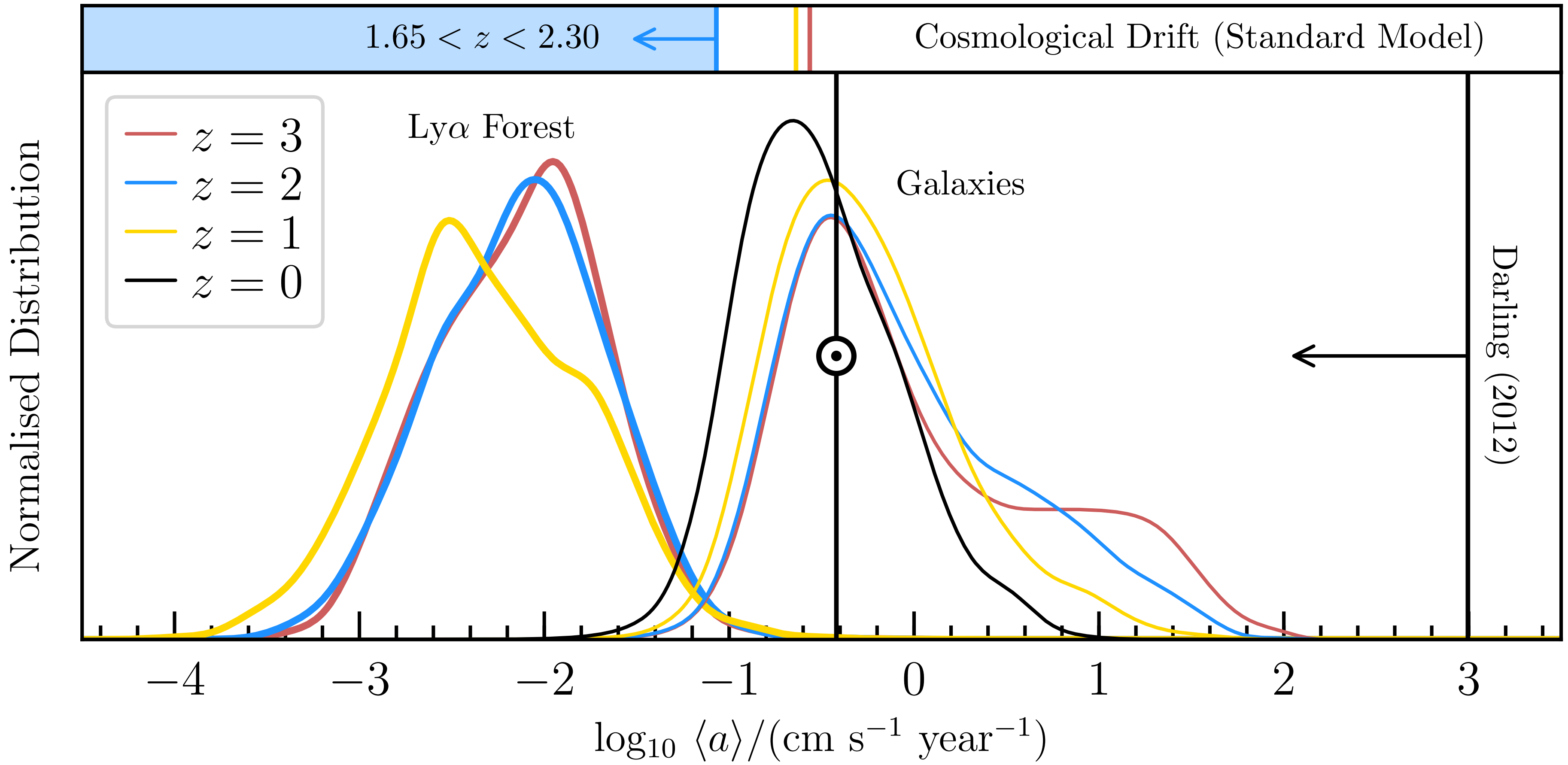
Test case: HS 1700+6416

- Bright QSO observed for over 12 years (1996 - 2008).
- All absorbers along this line-of-sight have: $N(\mathrm{H\ I}) < 10^{17}$ cm^{-2}
- Well-characterised line-of-sight. Can rule out metal contamination affecting the absorption lines.
- **Result, based on 4 systems: $\Delta v/\Delta t$ < 65 m/s/year (2σ limit)**
- Using current data, this could be reduced to ~30 cm/s/year

Conclusions

- Confirmed with simulations that the Lyα forest is well-suited to measuring the cosmic redshift drift.
- I propose that a relative measurement might help beat down systematics, and increase the strength of the signal.
- Current data are insufficient. Most likely, this experiment will require a dedicated facility observing quasars over decade-long timescales.





Acceleration measurements with ALMA

- **The frequency calibration of ALMA is accurate to at least 5 mm/s over a 7 year baseline.** Residual scatter appears to be random.
- **Can (at least in principle) measure the acceleration in the Milky Way with ALMA!** Note, the solar acceleration is ~7.6 mm/s/year
- **Currently less than 10 extragalactic molecular absorbers**
    - Intrinsic to quasar
    - Gravitationally lensed
    - Associated with galaxies (i.e. high peculiar acceleration)
- **Heterodyne technology also used in radio regime**
    - Can a decent sample of H I 21cm absorbers be used?