Atelier HIRES France - 12/11/2020

Working Group
Cosmology and Fundamental Physics

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(Many slides taken/adpted from J. Liske)

Cosmology and Fundamental Physics

Four main science cases:

A) Variability of physical "constants" (**α**, **μ**)

B) Evolution of the black-body temperature of the CMB (**$T_{CMB}(z)$**)

C) Abundance of deuterium (**D/H**) and the baryonic density of the Universe (**Ω_b**)

D) Redshift drift and the expansion history of the Universe (**dz/dt(z)**)

Confirm standard physics (reject alternative scenarios) or reveal new physics

→ *These probes are independent but intimately related by the underlying physics*

→ *All can be constrained using **electronic absorption lines (UV rest-frame)** in the distant Universe*

A: Variability of fundamental constants

Science

- Why fundamental ?:

  Not explained by theory. $\alpha = e^2/\hbar c$ and $\mu = m_p/m_e$ are parameters of the Standard Model and signify its incompleteness.

- Why constants ? :

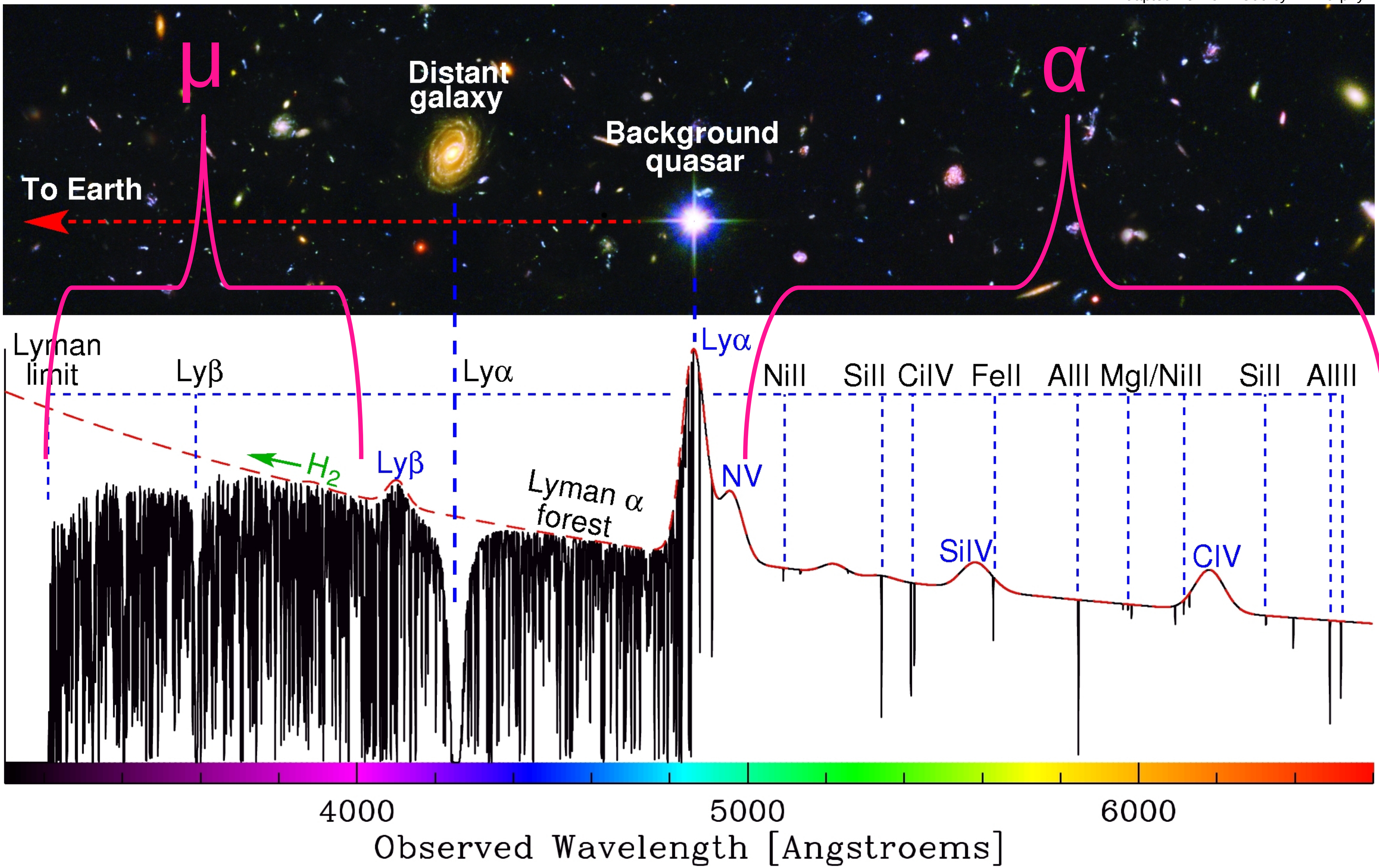
  Observed to be. α is stable to 10^{-17} yr^{-1} based only on Earth-bound experiments. But no theoretical reason at all.

- Modern unified theories (e.g. String/M-theory)
  - (3+1)-D constants related to size of extra dimensions.
  - Difficult to keep sizes constant in time.
- Scalar field theories ("string-inspired")
  - Bekenstein's (1982) varying-e theory:
    Scalar field couples to electromagnetism, driving e-variation.
  - Varying-c theories:
- Scalar fields appear to be real!
  - Higgs field confirmed.
- Grand unified schemes link constants
  - Most (not all) have μ varying more than α.

A: Variability of physical constants

How does it work ?

Adapted from J. Webb by M. Murphy



A: Variability of physical constants

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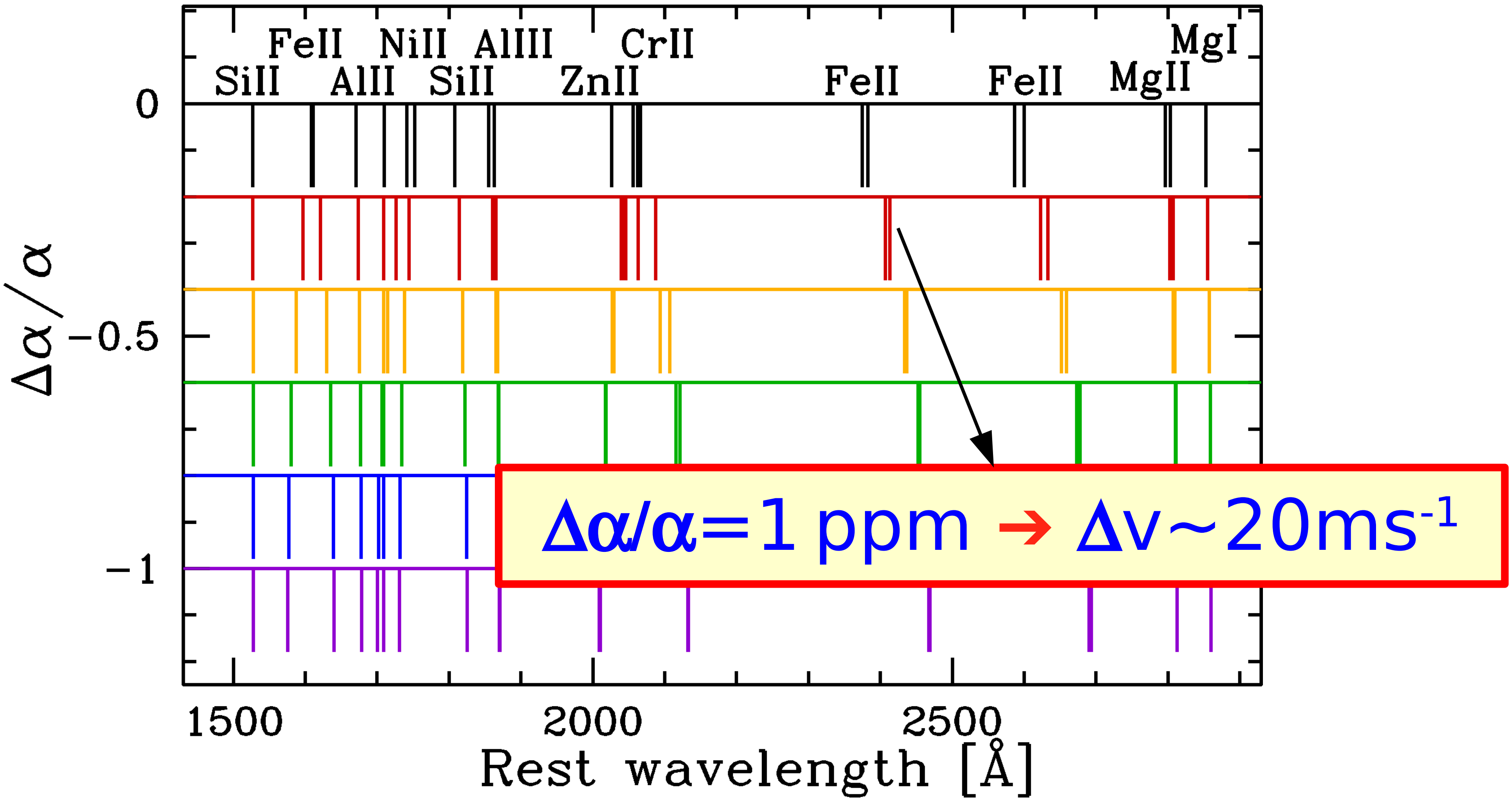
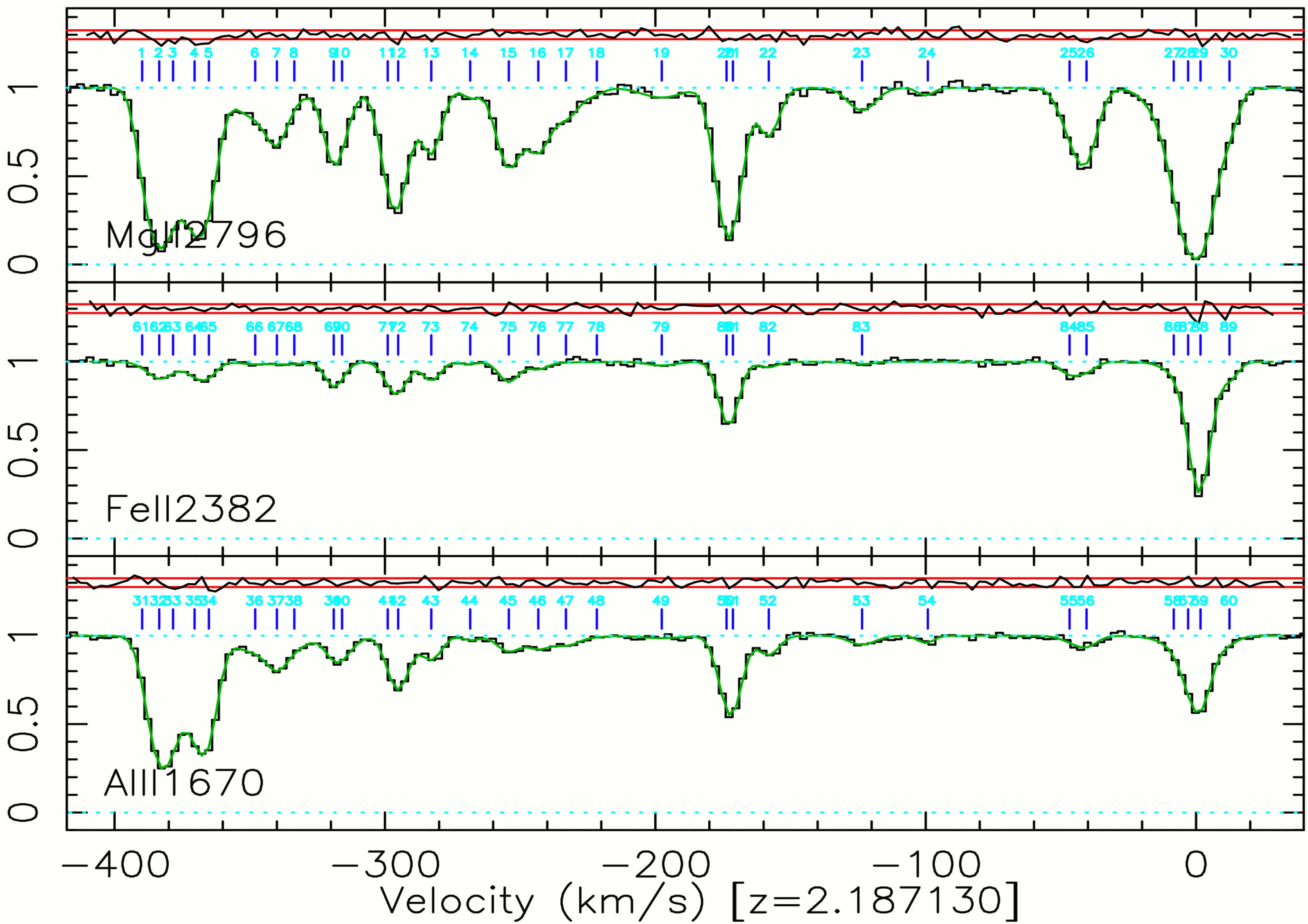
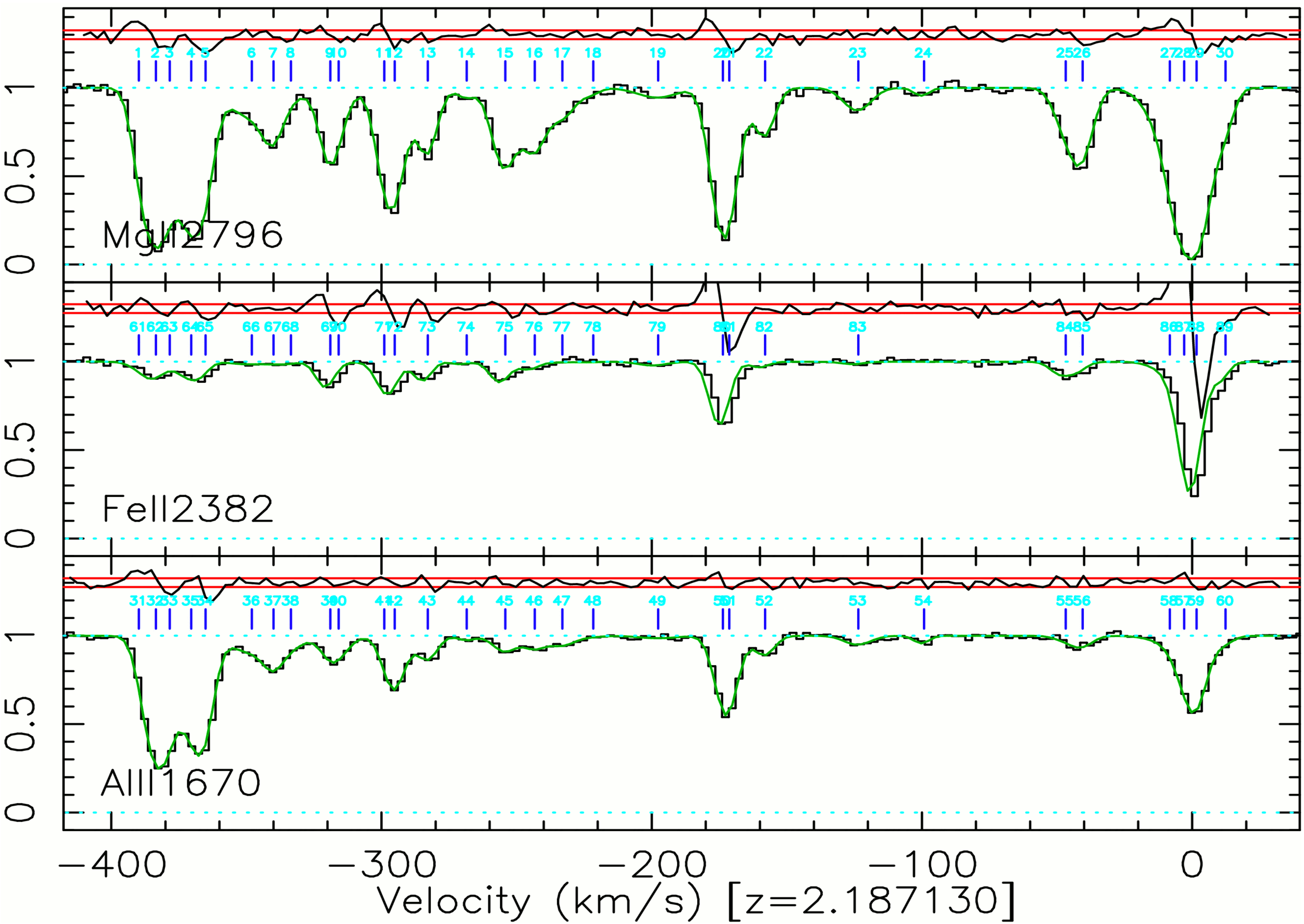


A: Variability of physical constants



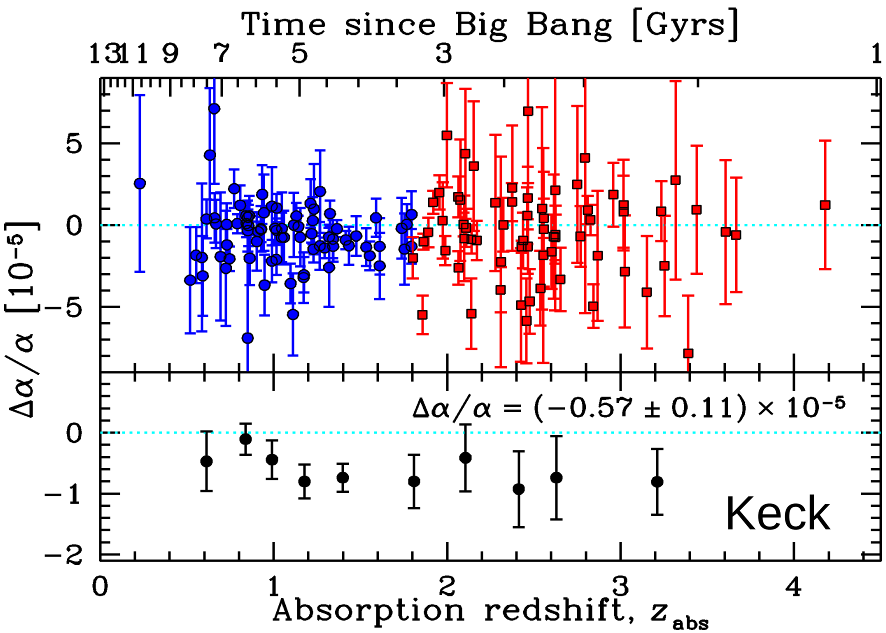
A: Variability of physical constants

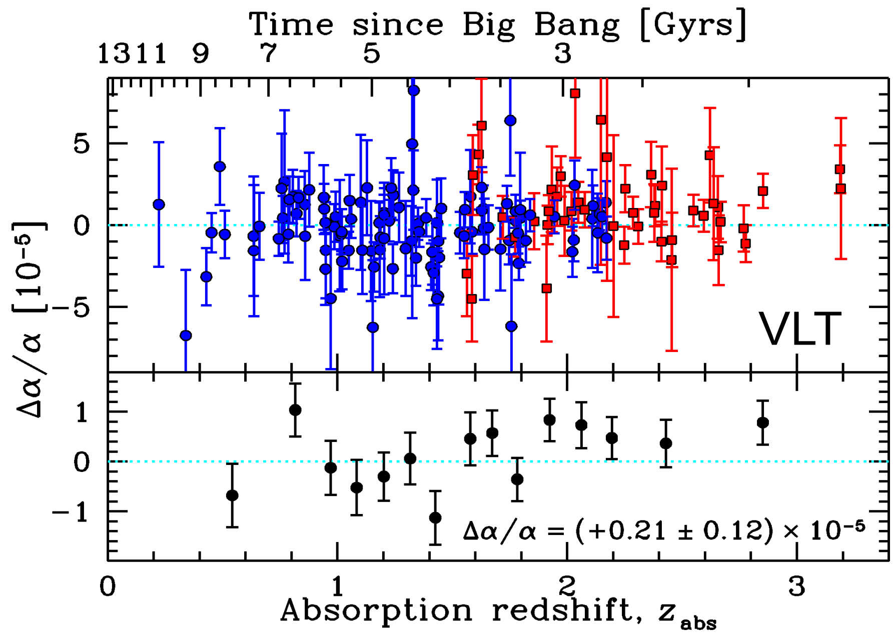
Change α by 10^{-4}



<u>**A:** Variability of physical constants</u>

Current status (α)



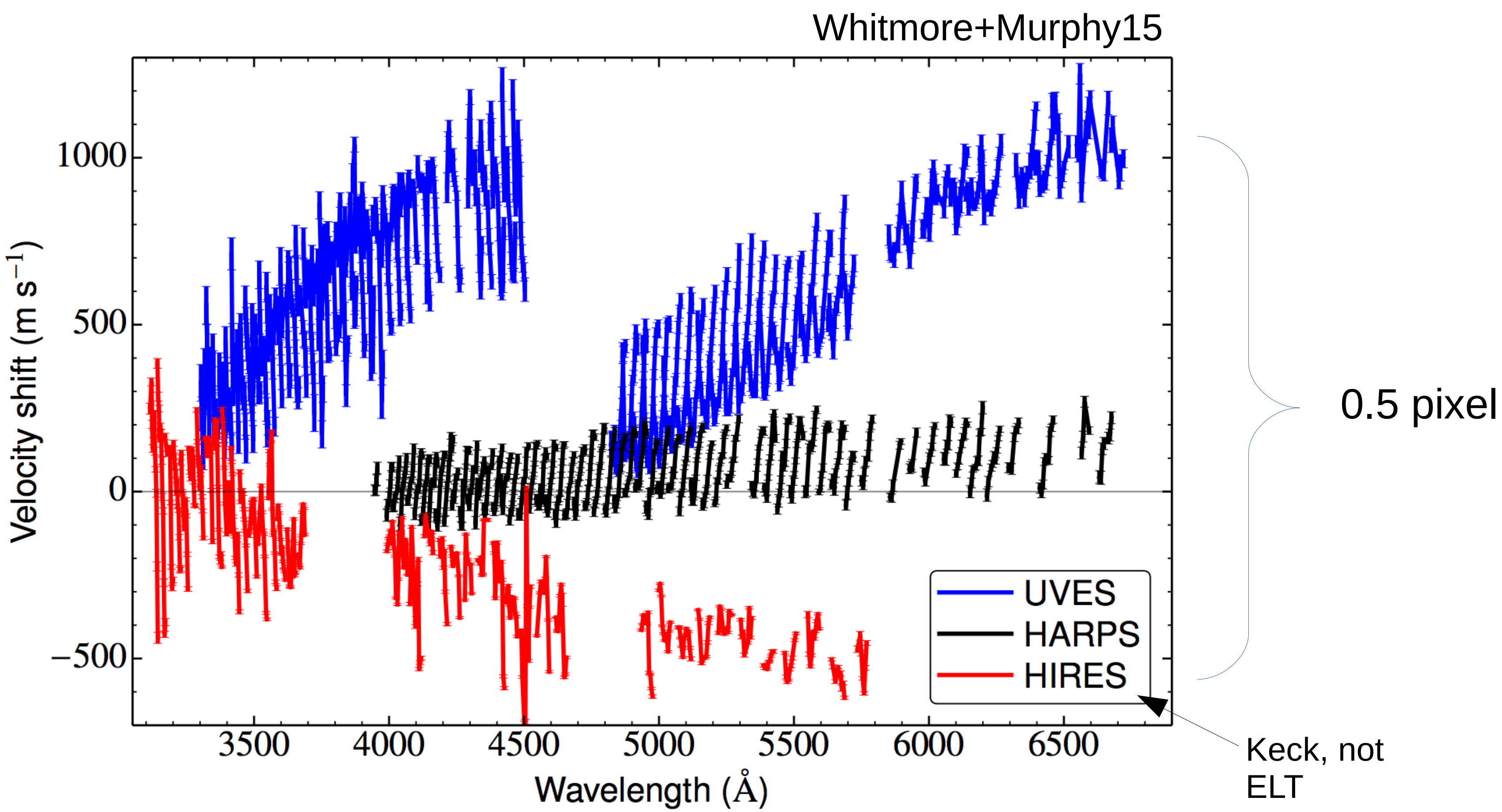


Murphy et al. (2004), King et al. (2012)

1ppm is far from precision reached on Earth... **BUT** $z \sim 2 \rightarrow \Delta t \sim 10$ Gyr

A: Variability of physical constants

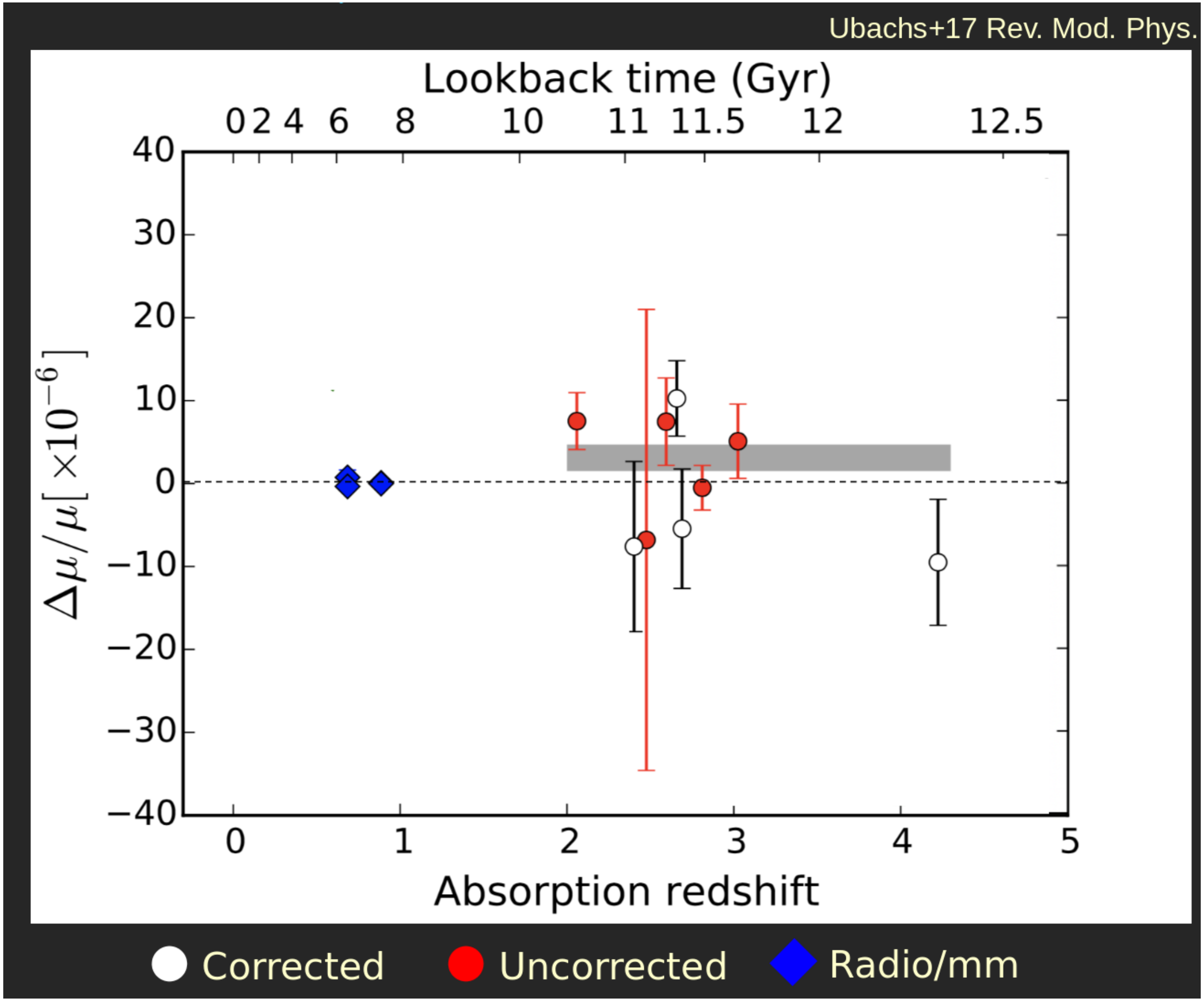
Current status



Slit spectrographs suffer from long-range distortions

A: Variability of physical constants

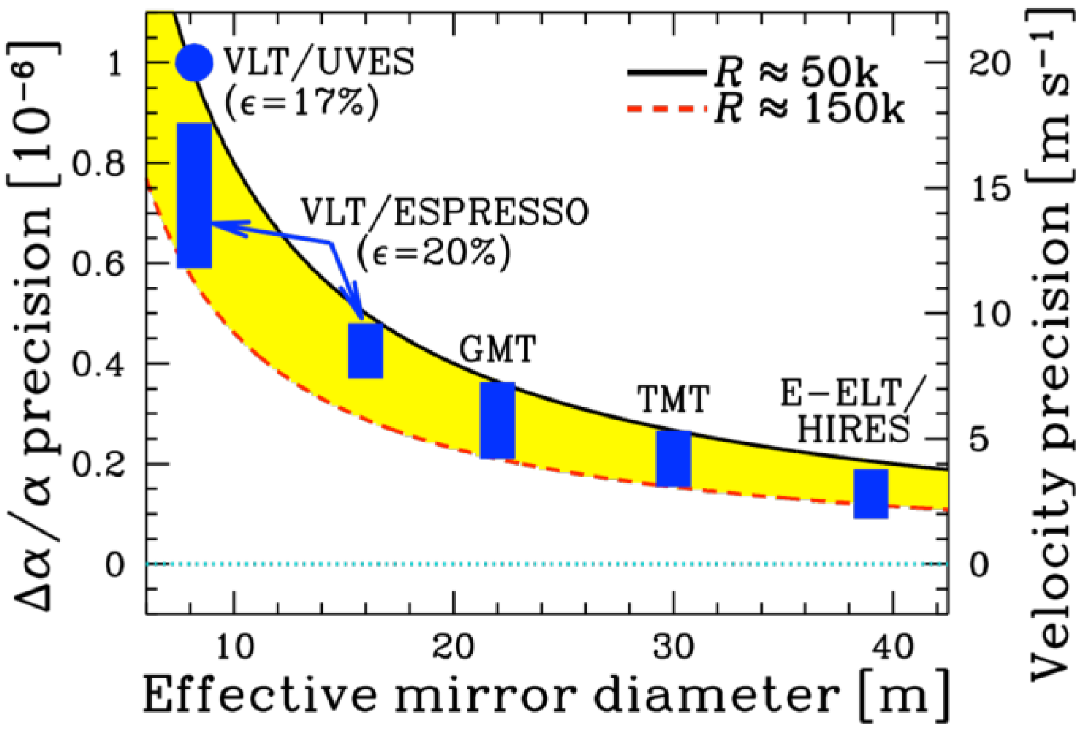
Current status (μ)



A: Variability of physical constants

What HIRES will bring

- New data free of long-range distortions.
- Improved S/N and resolution.
- Factor of ~5 increased precision



For the fundamental constants science case, the wavelengths of different transitions must be compared with 2 m/s accuracy (Top Level Requirement; goal is 1 m/s).
A complication <u>for alpha</u> <u>with the 3 arms design</u> is that this comparison must be made between transitions falling in the UVB and RIZ arms and these will have different wavelength calibrations.
*→ **This requires the use of an absolute wavelength calibrator which spans both arms and is delivered from a single source, like a laser frequency comb.***
In any case, on balance, the trade-off between gaining 50 nm at the blue end and (potentially) losing 40-70 nm at the red end is decided in favour of the former.

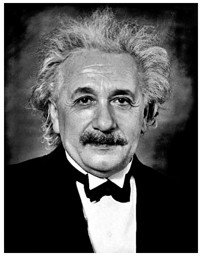
B: Evolution of T_{CMB}

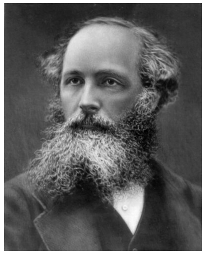
Science

- In the present Universe we measure $T_{CMB,0} = (2.7260 \pm 0.0013)$ K.

- The evolution of T_{CMB}, $T_{CMB}(z) = T_{CMB,0}\,(1+z)$, is a robust prediction of an adiabatically expanding Universe.

- Any departure from this relation implies either a violation of the equivalence principle or that the number of CMB photons is not conserved.





- A departure from the standard $T_{CMB}(z)$ relation is expected in many scenarios beyond the standard model, including many varying-α and dynamical DE models.

B: Evolution of T_{CMB}

How does it work?

- CMB populates rotational levels of molecules such as CO and fine-structure levels of atomic species such as CI.
- Measuring the populations of excited states provides T_{ex}.

$$\frac{N_1}{N_0} = \frac{g_1}{g_0} e^{-E_{01}/kT_{01}}$$

$$N_0\left(B_{01}I_\nu + \Gamma_{01} + \sum_j R^j_{01} n_j\right) = N_1\left(A_{10} + B_{10}I_\nu + \Gamma_{10} + \sum_j R^j_{10} n_j\right)$$

(De)-excitation by CMB

$$B_{01}I_\nu = 3B_{10}I_\nu = \frac{2.38\times 10^{-7}}{\exp(23.6\ \mathrm{K}/T_{\mathrm{CMB}})-1}\ \mathrm{s}^{-1}$$

Collisions → n_e, n_H, n_{H2} and T_k

$$R^j_{10} = \frac{1}{3} R^j_{01} \exp(23.6\ \mathrm{K}/T_{\mathrm{K}}). \quad (16)$$

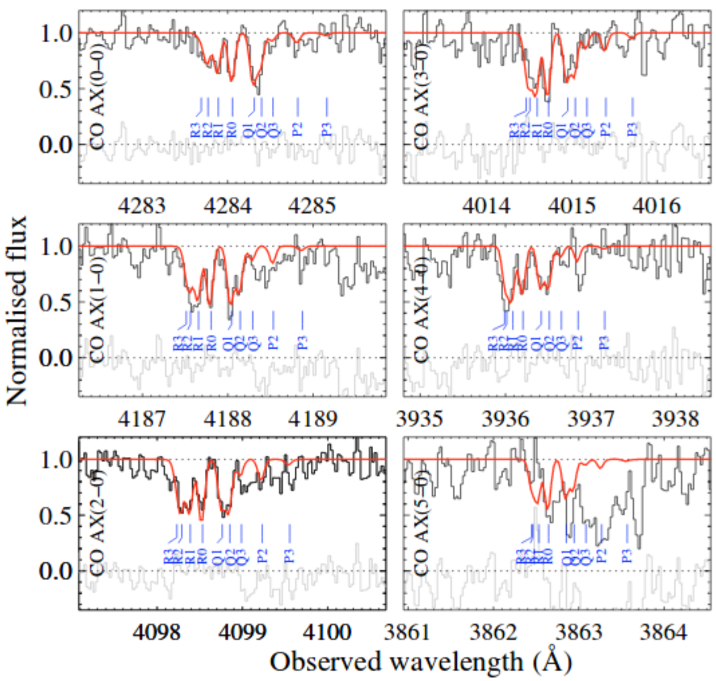
UV pumping

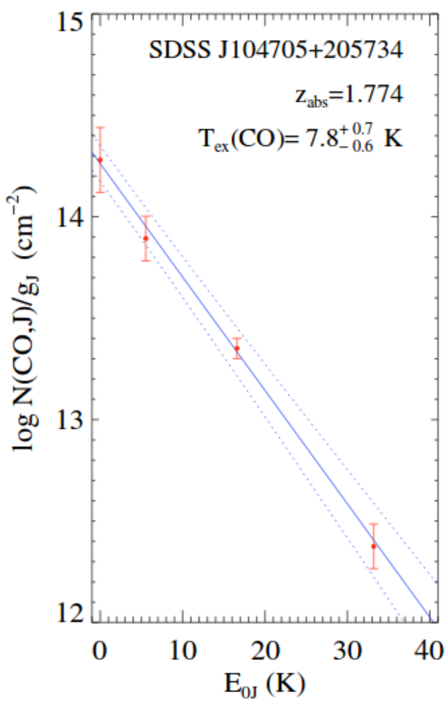
- Conversion to T_{CMB} requires knowledge of the physical conditions in the absorbing gas, in particular prevalence of collisional excitation.

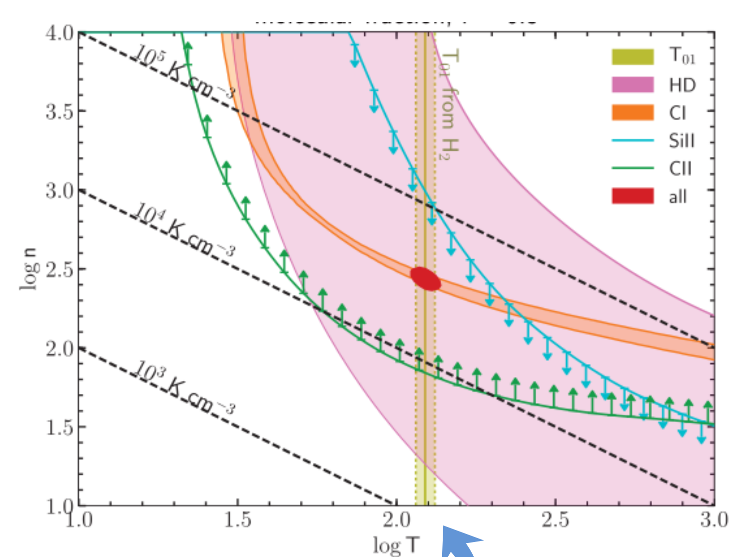
B: Evolution of T_{CMB}

How does it work?

TCMB = Tex(CO) – contribution from collisions





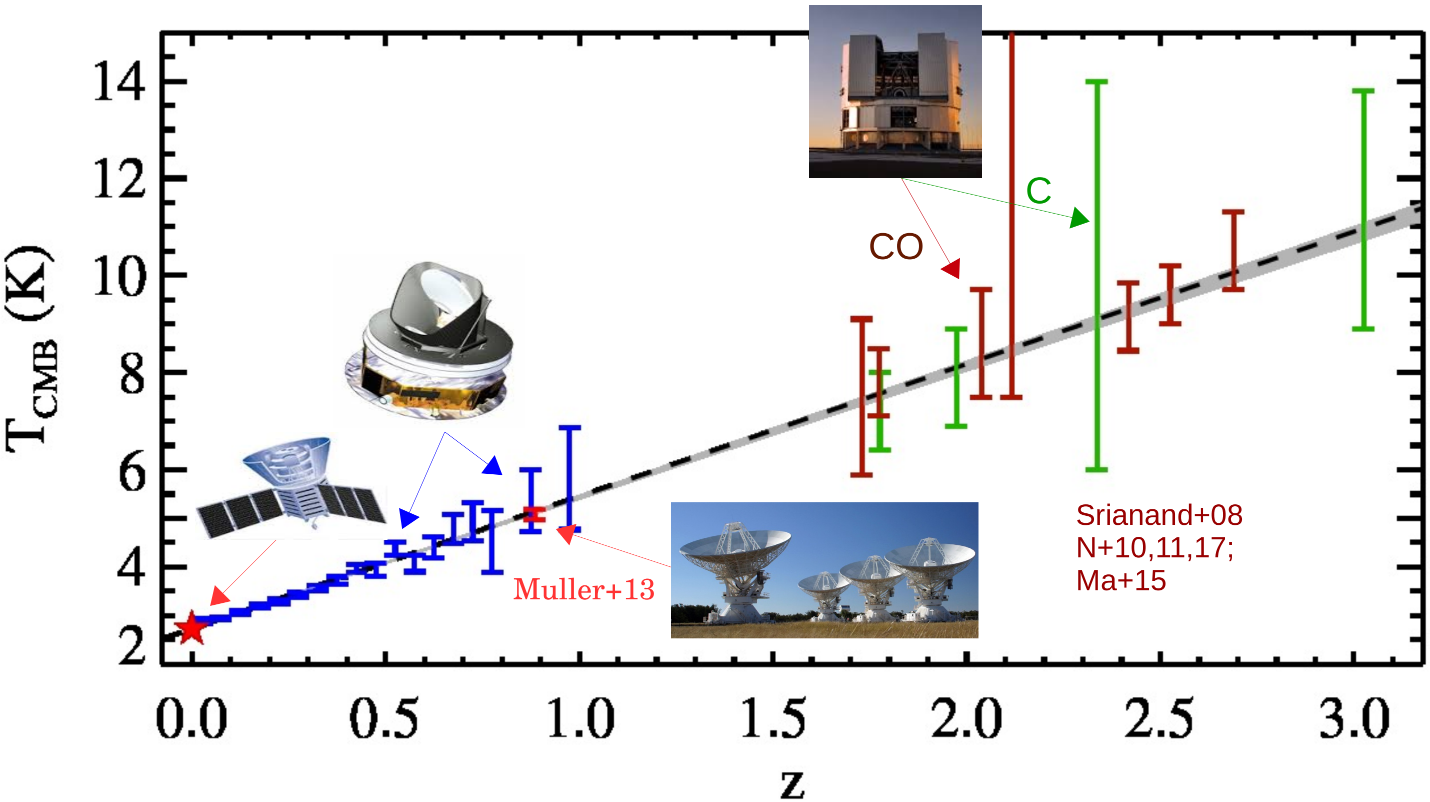


H_2 is essential
for further progress

B: Evolution of T_{CMB}

Current status

- CO provides best measurements at z>1.5 but only a few to date (Noterdaeme et al. 2011,2017)

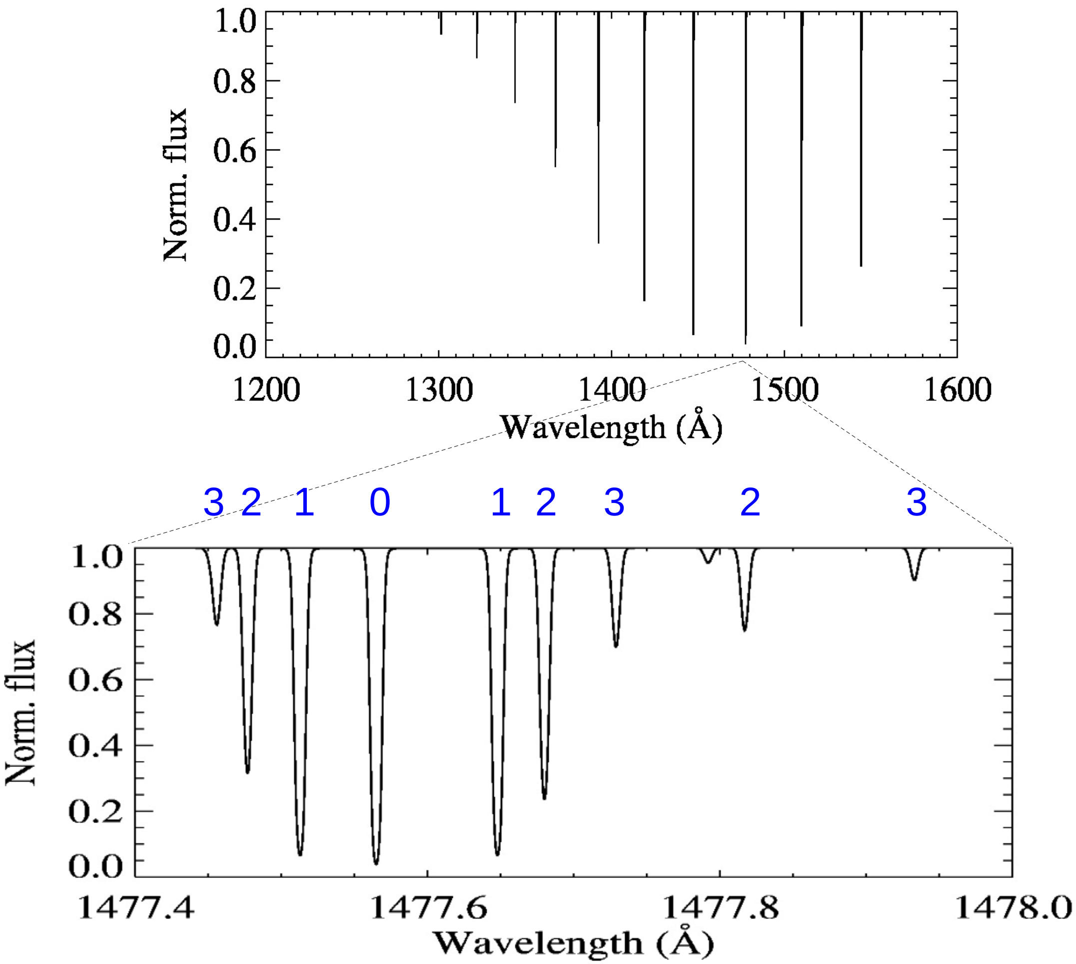


Lima et al. (2000) parametrization

$T_{CMB}(z) = T_{CMB}(0)\ (1+z)^{(1-\beta)} \rightarrow\ \beta=-0.001\ +/-\ 0.006$

B: Evolution of T_{CMB}

What HIRES will bring



Weak CO absorption lines with strongest bands at ~ 1350-1550 Å

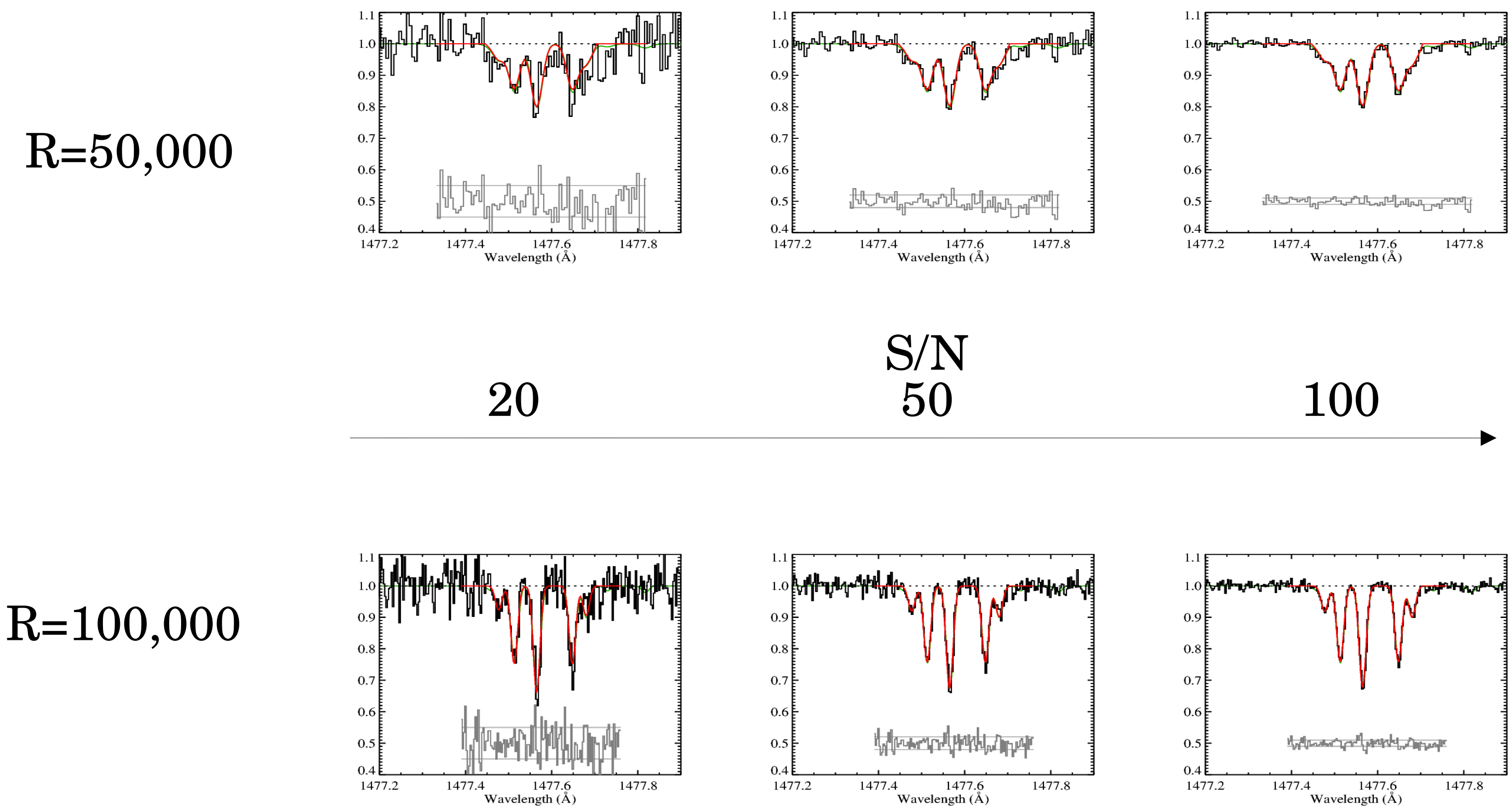
Doppler parameters b~1 km/s

Separation between lines from different rotational levels ~10 km/s

B: Evolution of T_{CMB}

What HIRES will bring

- Precision of T_{CMB} measurements scales with **S/N and resolution**
  - Improvement of measurements on existing sytems.
- Observations of new systems



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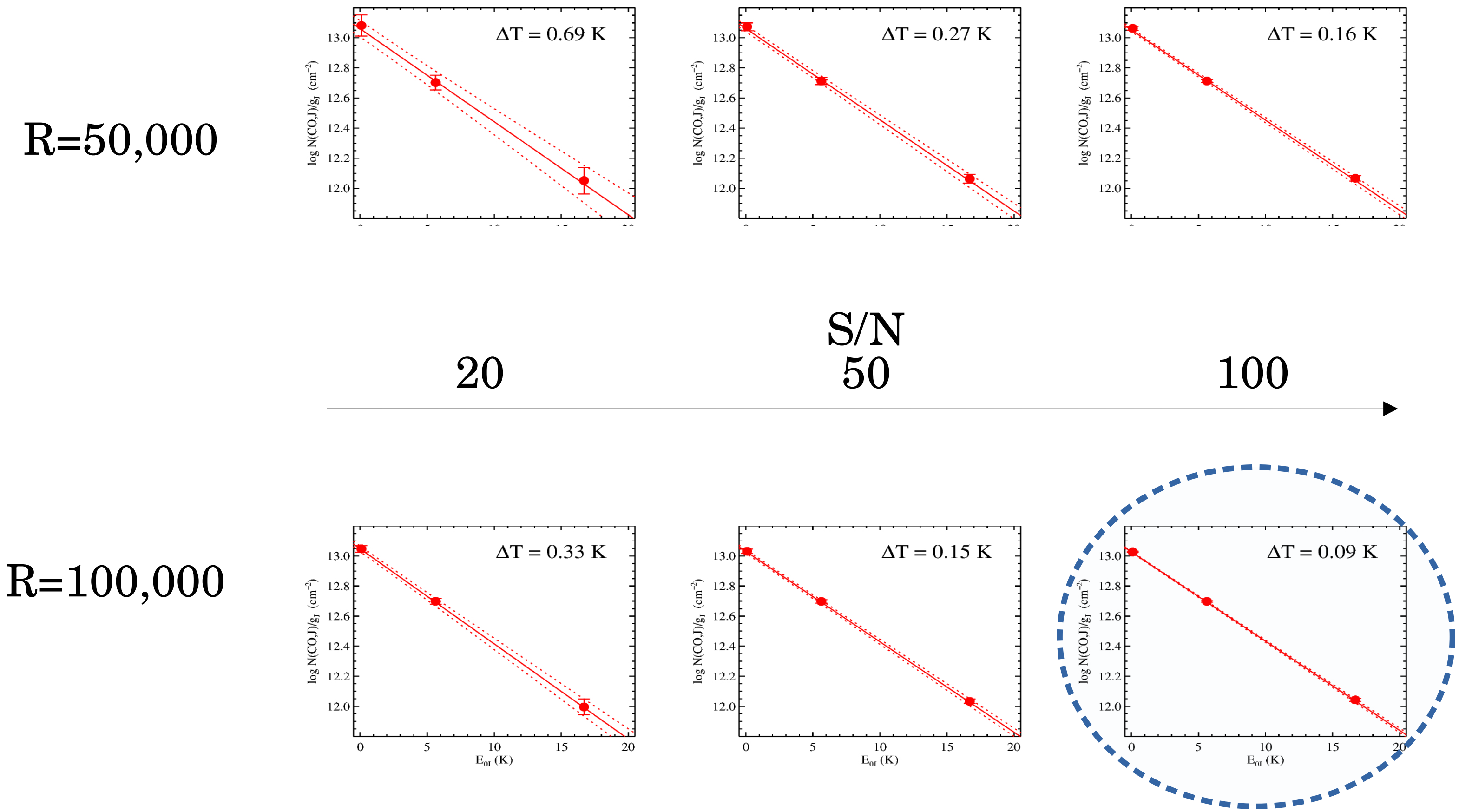
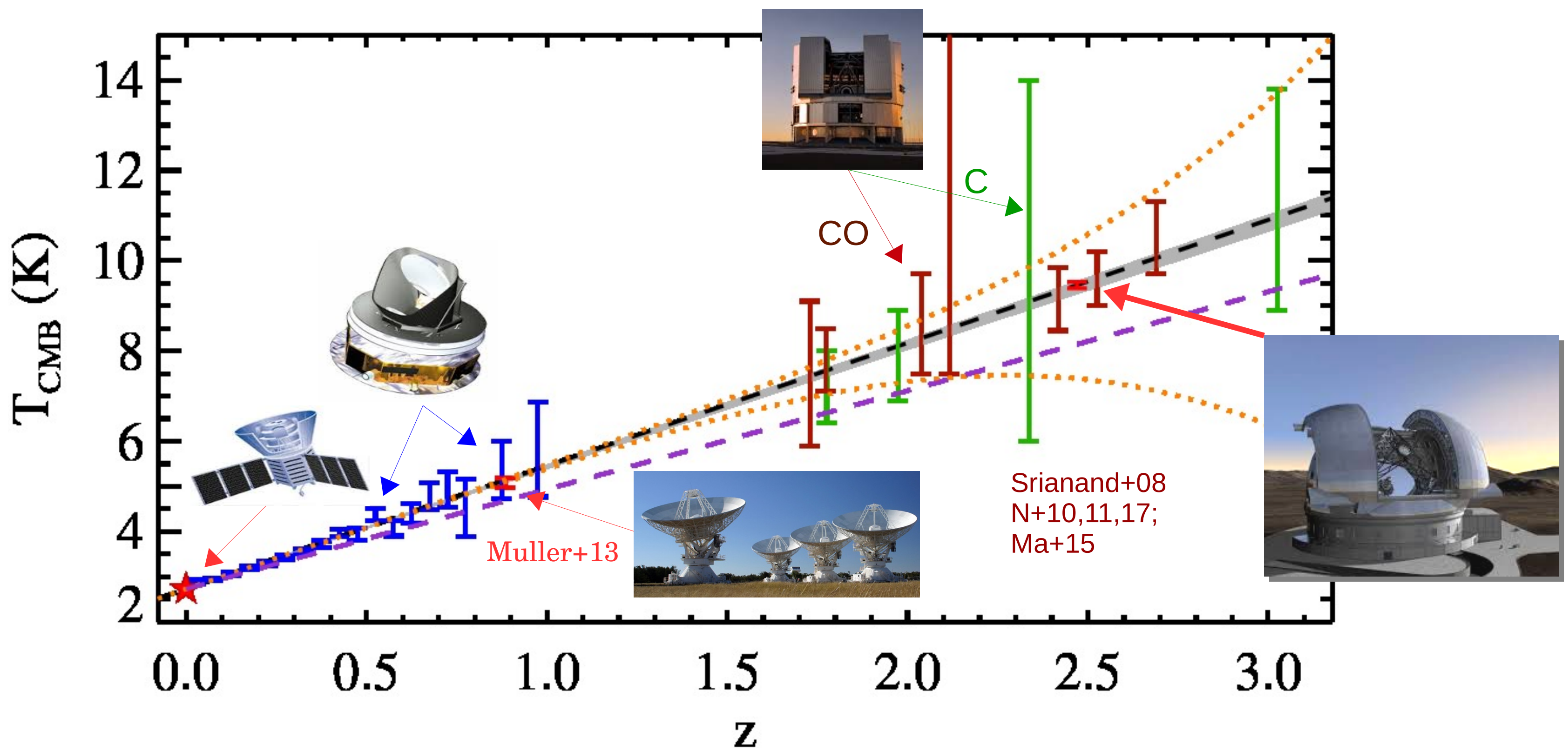


B: Evolution of T_{CMB}

Current status

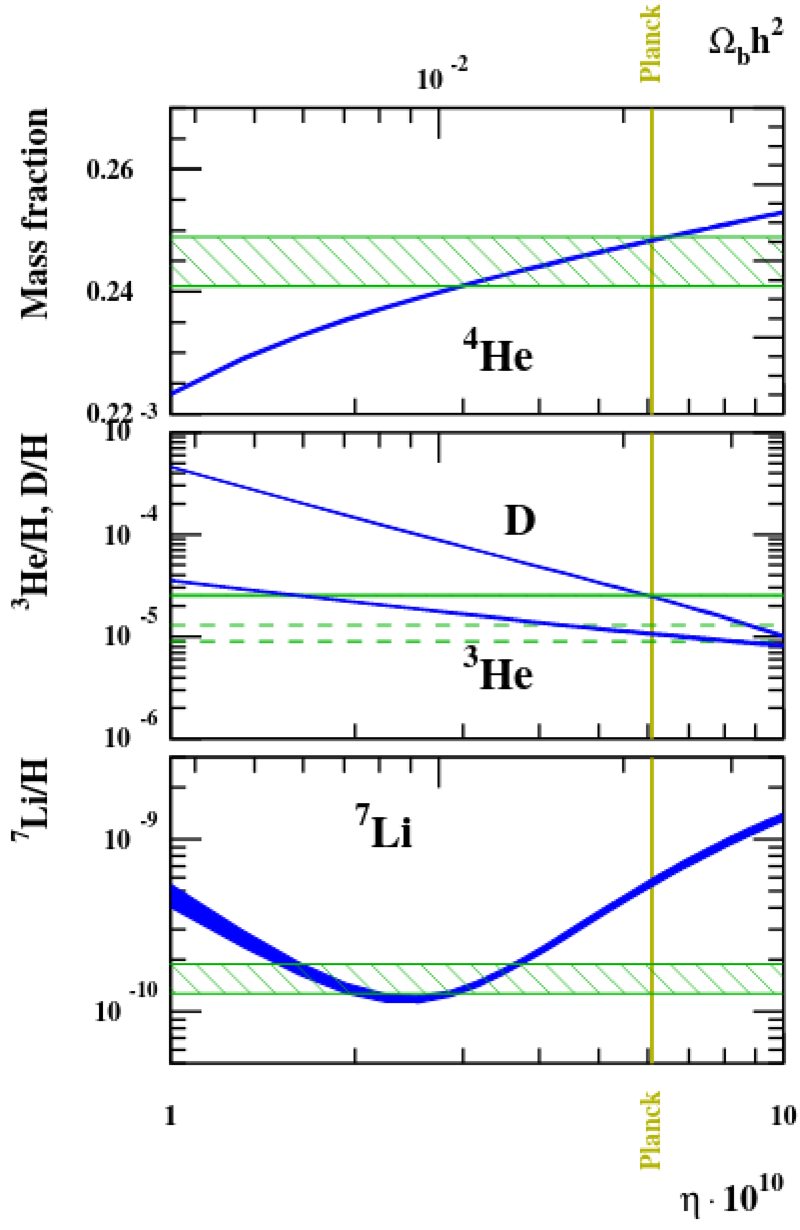


Other alternative theories with different parameterizations exist (e.g. Basset & Kunz 2004, Maeder 2017)

C: Primordial abundance of Deuterium

Science

- Big Bang nucleosynthesis (BBN) predicts the primordial abundance of deuterium as a function of the baryonic density of the Universe.
- D/H measurements, together with those of other light elements, constrain the physics of the Universe at age ~1 min.
- Comparison of Ω_b from D/H and from CMB → fundamental consistency test of cosmological model.
- Varying constants affect BBN.



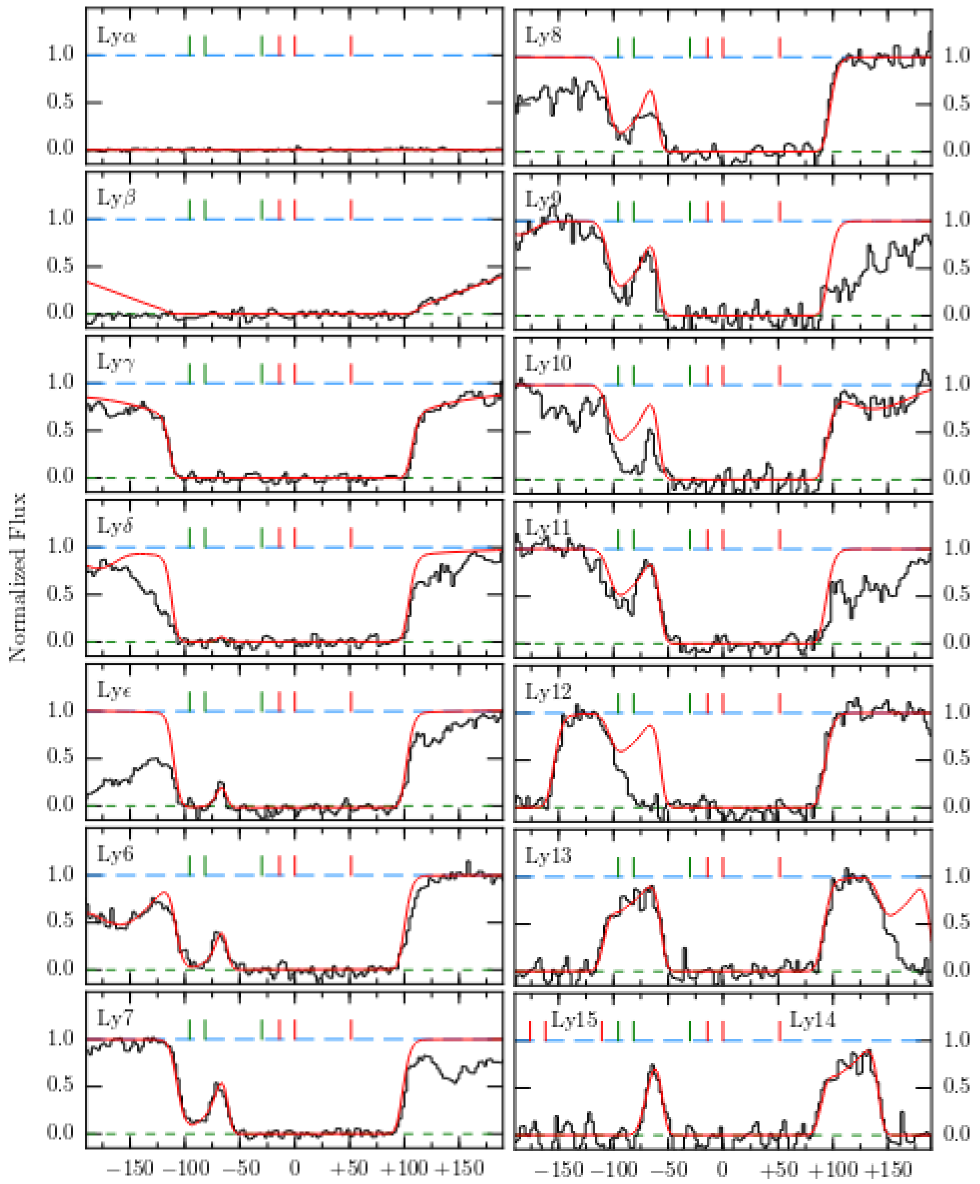
C: Primordial abundance of Deuterium

How does it work?

- Measure N(DI)/N(HI) from the Lyman series
- Need absorption systems with the simplest velocity structure.
- Select metal-poor systems:

  → Less number of components

  → Less affected by astration (destruction of D in stars)
- Difficulty in measuring simultaneously N(DI) and N(HI) since D/H ~ 10^{-5}



Δv = -81.6 km/s

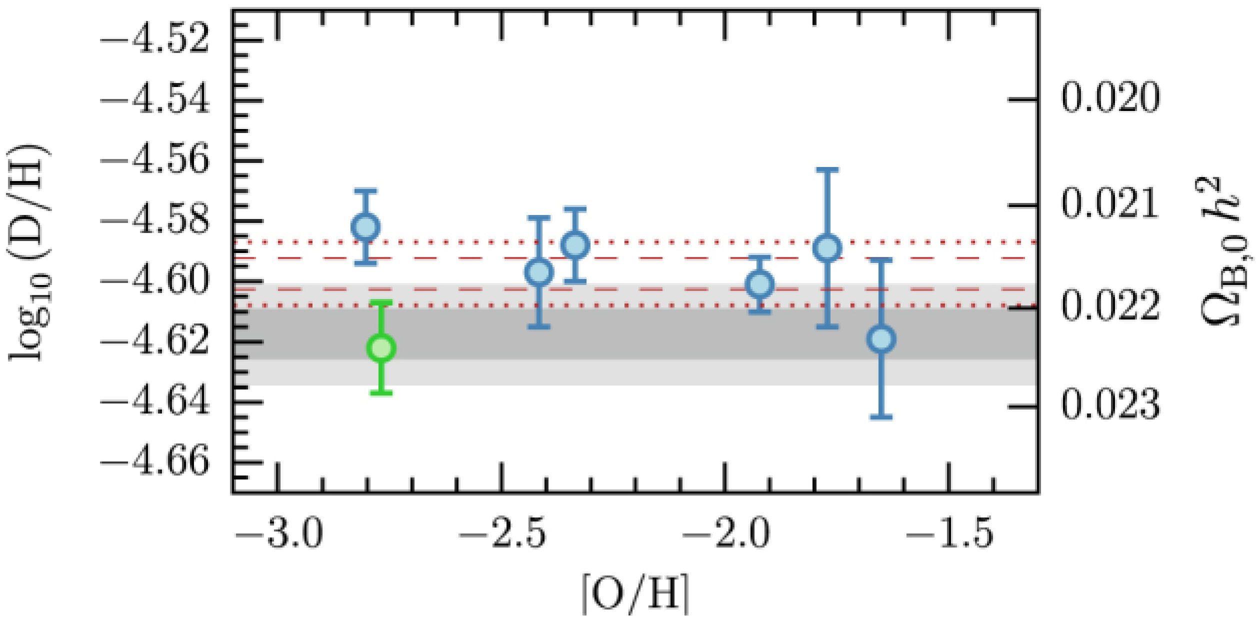
- More metal-rich systems to constrain (D/H) vs Z (and z).
- HD/H_2 ? Complex chemistry though.

C: Primordial abundance of Deuterium

Current status

- Only a few reliable measurements, in range 2.5 < z < 3.1.
- Some tension with Planck Ω_b : BBN calculations ?
- z>2.5 because drop in blue sensitivity
- z<3.1 because Lyman-alpha forest density (+ decreasing N_{QSO})

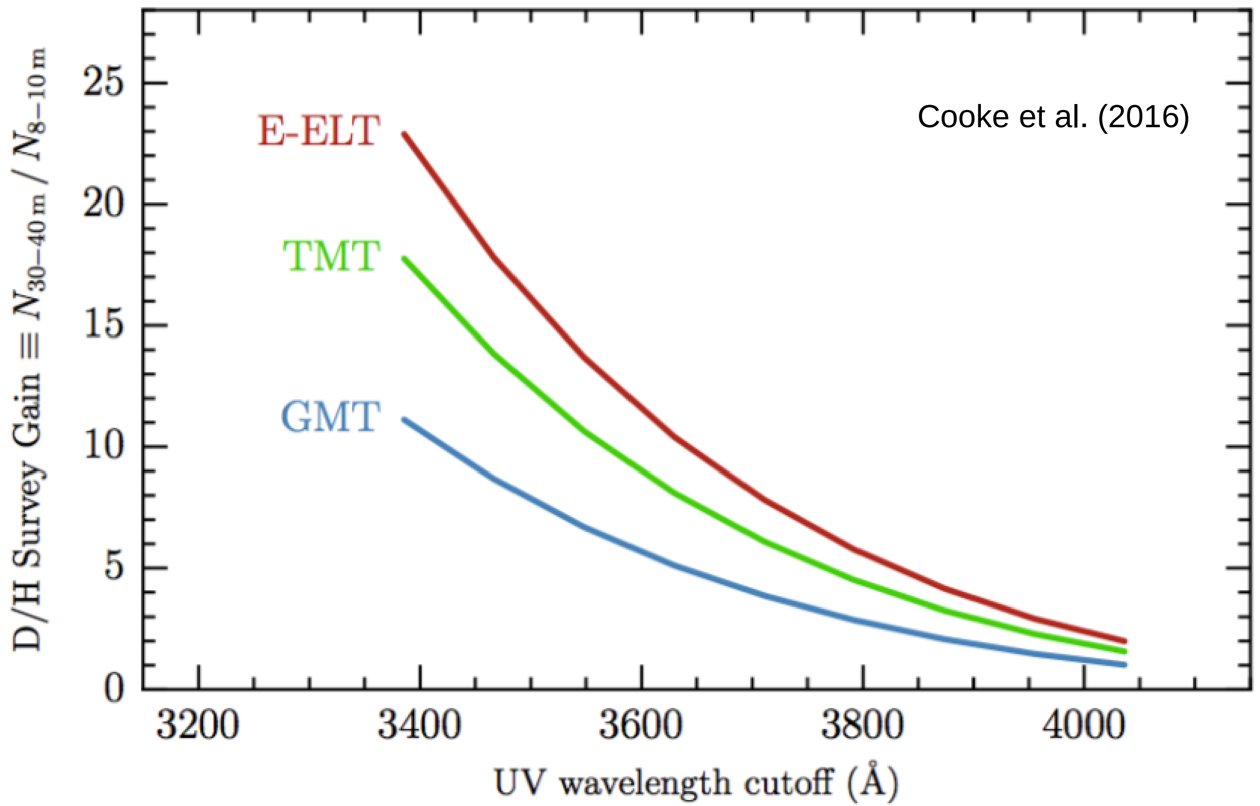
Cooke et al. (2018)



C: Primordial abundance of Deuterium

What HIRES will bring

- More targets!
- Gain compared to current samples (by going down the QSO luminosity function):



D: The redshift drift

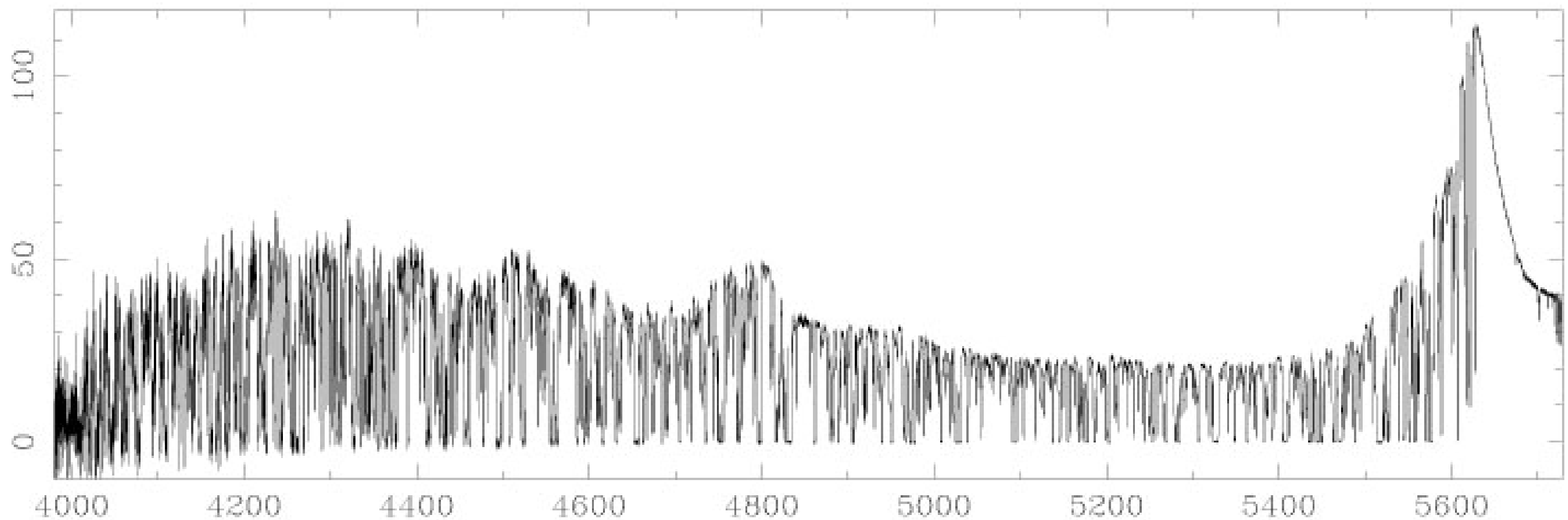
Science

- Observed accelerated expansion of the Universe !
- The redshift drift provides the only dynamical, i.e. non-geometric measurement of the expansion history.
- Completely model-independent.
- Completely independent of astrophysics.
- Provides constraints on expansion at high redshift
- Breaks degeneracies between cosmological parameters when combined with other cosmological data, esp. for non-standard models.

D: The redshift drift

How does it work?

- Long-term (~10 yr) monitoring campaign of the low-order Lyman forests of the brightest QSOs in the range $2 < z < 4$.
- Simultaneous modeling of a given absorption feature as a function of time provides $z(t) = z_0 + dz/dt(z_0)\ t$.
- Do this for many features at different z → dz/dt(z)



D: The redshift drift

Current status ✖

- Current facilities cannot collect enough photons !!!
- No instrument offers the required long-term stability (in wavelength space).

Current progress

- Bright, southern QSOs ($2 < z < 4$) → e.g. QUBRICS survey (Calderone et al. 2019)

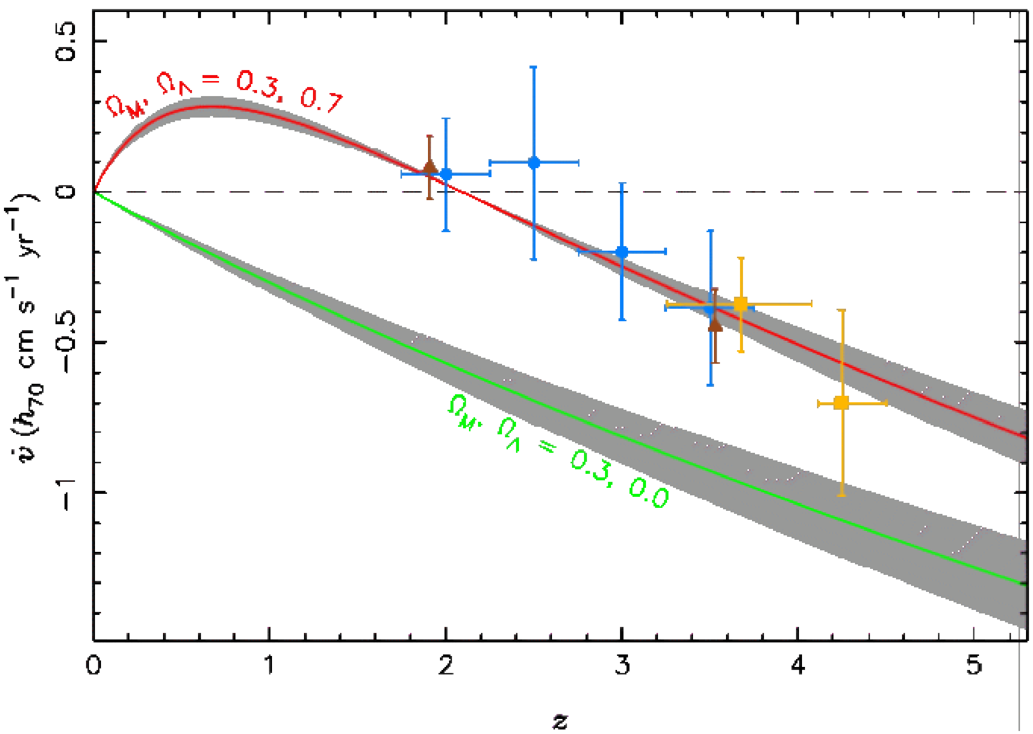
D: The redshift drift

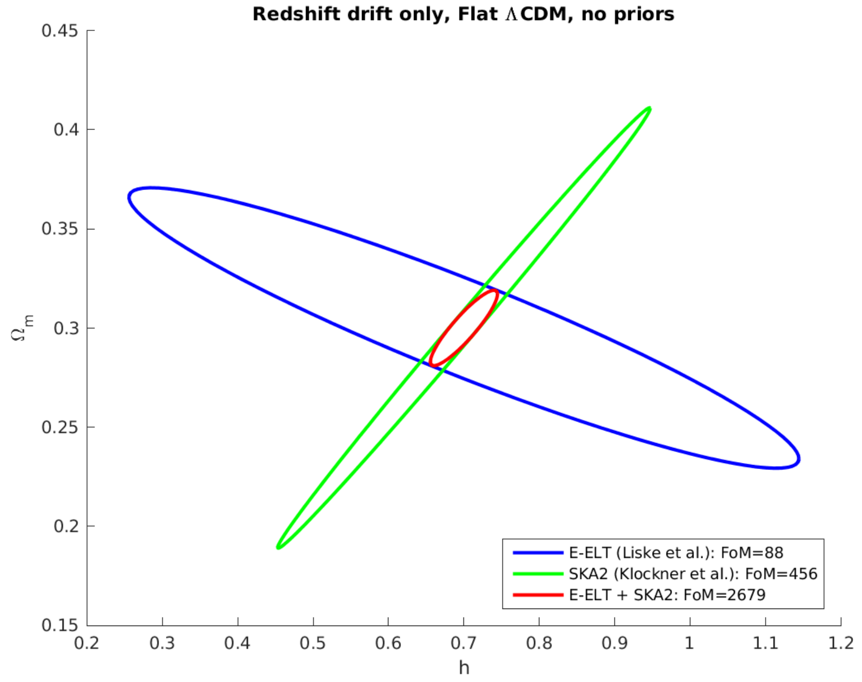
What ELT will bring

- Photons !!!

What HIRES must bring

- Long-term stability (in wavelength space).

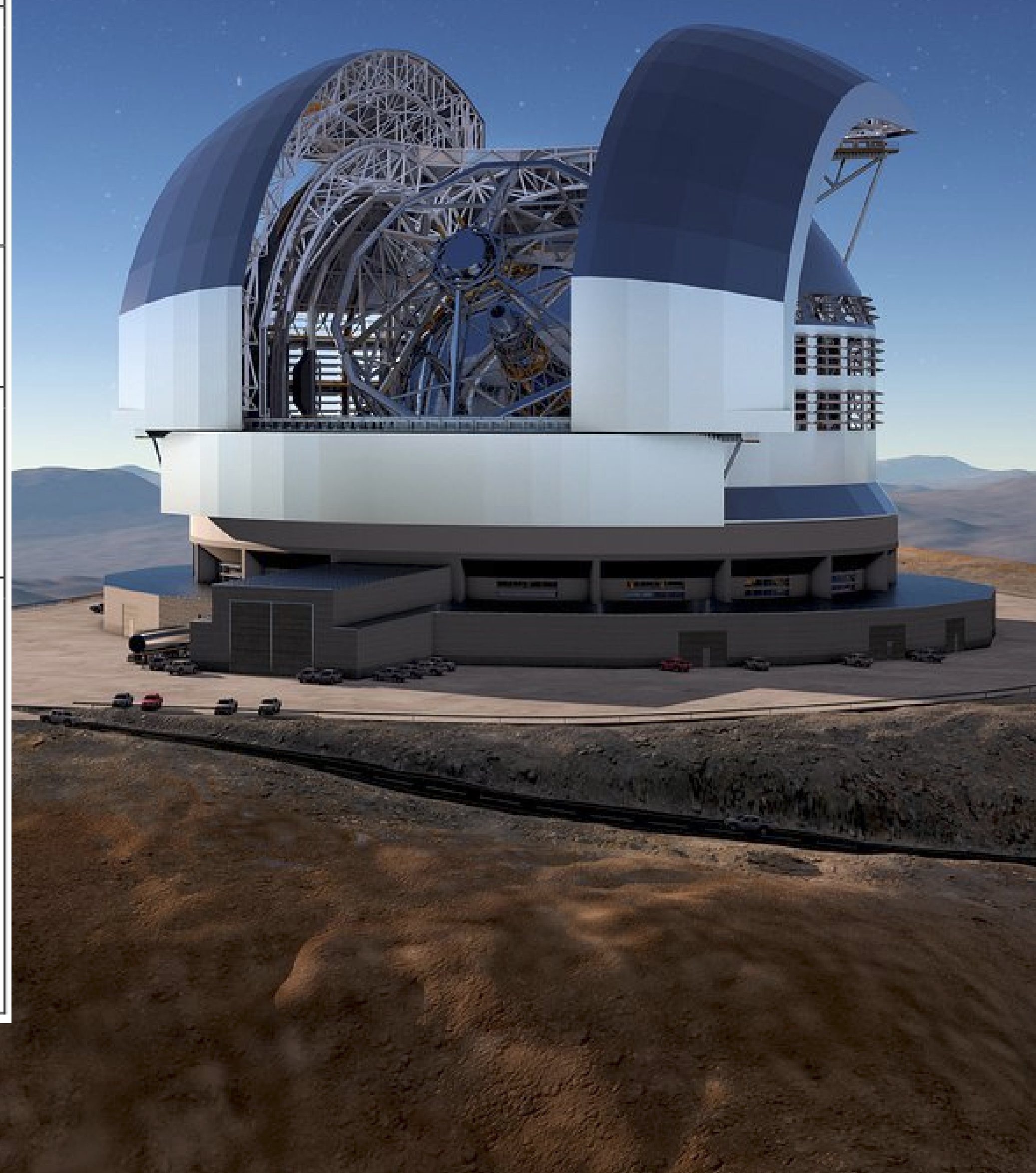




Liske et al. (2008)

REQUIREMENTS

Science case	Requirements (desirables in parentheses)
Constants	R: 80,000 (100,000) λ range: 370 (340) – 670 nm λ accuracy: 2 m/s Background subtraction: desirable
$T_{CMB}(z)$	R: 100,000 λ range: 370 (330) – 700 nm
D/H	R: 50,000 (100,000) λ range: 370 (340) – 590 nm Background subtraction: essential
Redshift drift	R: 100,000 λ range: 400 (380) – 670 (730) nm λ precision: 0.7 m/s Stability of λ accuracy: 2 cm/s over instrument lifetime Background subtraction: not yet known Instrument lifetime: 10 (20) years Throughput: 0.05 (0.2)



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FeII 161nm down to z=1.3 (moves opposite direction, grain x2 on α)

μ is based on **H_2** !

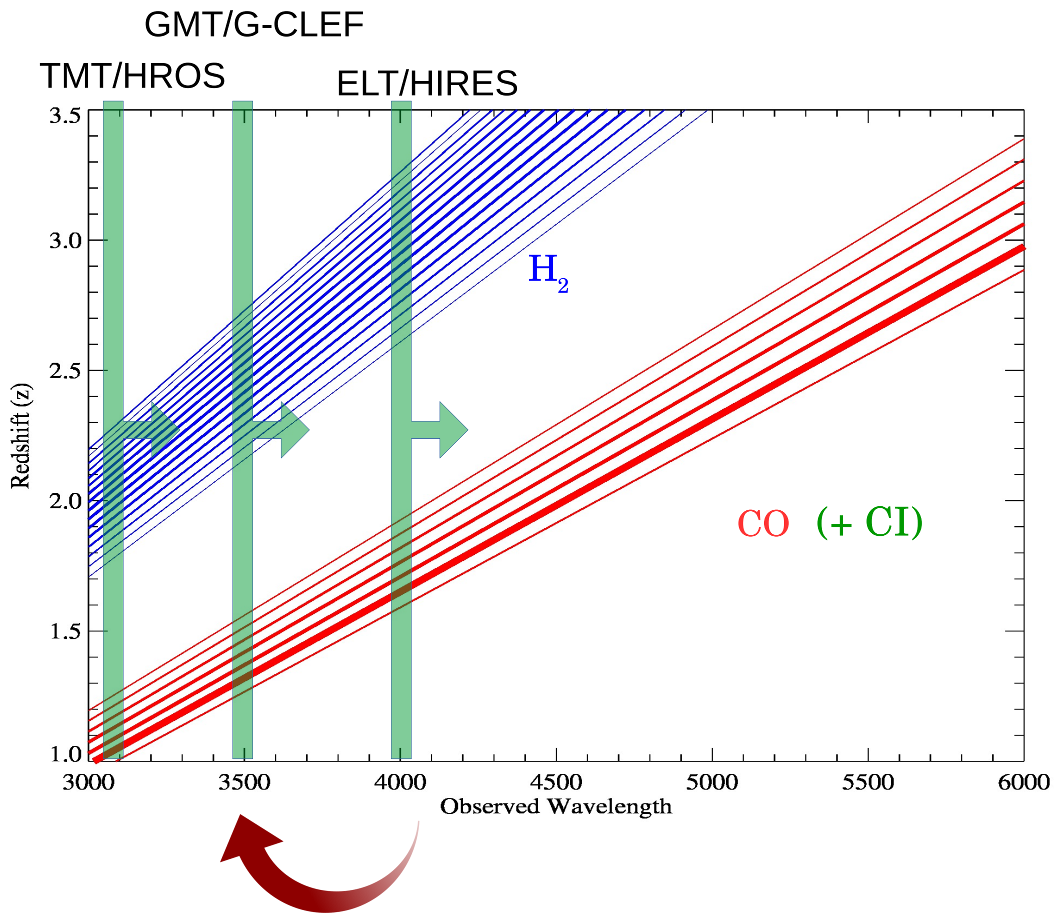
H_2 (95-105nm) @z=2-3 must be covered to convert T_{ex}(CO) → T_{cmb}

Lyman series (92-122nm) @ z=3 to be covered

Lyman-α (122nm) @ z=2 to see change in sign of z-drift signal

Blue is crucial for these science cases (but not only) :

Physics and chemistry in the gas (IGM, CGM, ISM) at high-z !!



GMT/G-CLEF
TMT/HROS
ELT/HIRES
3.5
3.0
2.5
2.0
1.5
1.0
Redshift (z)
H2
CO (+ CI)
3000
3500
4000
4500
5000
5500
6000
Observed Wavelength