Phi in the Sky: Astrophysical Probes of Fundamental Physics

Lecture 2

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Constants & Extra Dimensions

Unification of fundamental forces requires additional space-time dimensions; in such models, the true fundamental constants are defined in higher dimensions

  - (3+1)D constants are effective quantities, typically related to true ones via characteristic sizes of the extra dimensions

Expect space-time variation of such effective coupling constants

  - E.g., a varying α is unavoidable (at some level) in string theory

Many simple examples exist, e.g. in

- Kaluza-Klein models *[Chodos & Detweiler 1980, Marciano 1981]*
- Superstring theories *[Wu & Wang 1986]*
- Brane worlds *[Kiritsis 1999, Alexander 2000]*

The Role of Constants

Asymptotic states (pointing to emergence of new phenomena)?

- c: Limit velocity of massive particle in flat space-time
- G: Limit potential of mass not forming black hole in curved space-time
- h: Limit uncertainty (quantum of action)

Convenient conversion factors?

- Can't be pushed arbitrarily far: e=c=G=1 is ok, but e=c=h=1 is not

How many are fundamental?

    - The story so far: 3

Are they fixed by consistency conditions, or arbitrary?

Counterfactual Universes

- If α_{EM} were increased by 4% or α_S reduced by 0.4% the Carbon-12 resonance at 7.6 MeV (the Hoyle resonance) would not exist and the amount of carbon produced in stellar cores would be drastically reduced
  - Similarly, a 4% decrease in α_{EM} or a 0.4% increase in α_S would see stellar production of oxygen greatly reduced
- If α_S were larger by 4% or smaller by 10%, Helium-2 (i.e. diprotons) would be stable; this would speed up nuclear fusion and greatly reduce stellar lifetimes
  - Deuterium could not exist, so no carbon or oxygen would be produced at all
- If $\mu=m_p/m_e$ were much larger than its current value, no ordered molecular structures would exist

$\alpha(z)$, $\mu(z)$, $T(z)$ and Beyond

In theories where a dynamical scalar field yields varying α, other couplings are also expected to vary, including $\mu=m_p/m_e$

- In GUTs the variation of α is related to that of Λ_{QCD}, whence m_{nuc} varies when measured in energy scale independent of QCD
- Expect a varying, measured with H_2 *[Thompson 1975]* and other molecules
- Also will have violations of the $T(z)$ law, constrained to sub-percent level *[Avgoustidis et al. 2016, …]*
- and the distance duality (a.k.a. Etherington) relation

Molecular observations measure the inertial masses (not the gravitational ones) and they may or may not be probing μ...

- H_2 measurements do probe m_p/m_e; more complicated molecules probe $m_{nuc}/m_e \sim$ few m_p/m_e: but beware composition-dependent forces
- The ELT or ALMA may ultimately constrain these forces (H_2 vs HD vs CO vs…)

So What's Your Point?

Wide range of possible α-μ-T relations makes such measurements a unique discriminating tool between competing models

- Sensitive probe of unification scenarios *[Coc et al. 2007, Luo et al. 2011, Ferreira et al. 2012, Ferreira et al. 2013, …]*

$$\frac{\Delta\mu}{\mu} = [0.8R - 0.3(1+S)]\frac{\Delta\alpha}{\alpha}$$

$$\frac{\Delta g_p}{g_p} = [0.10R - 0.04(1+S)]\frac{\Delta\alpha}{\alpha}$$

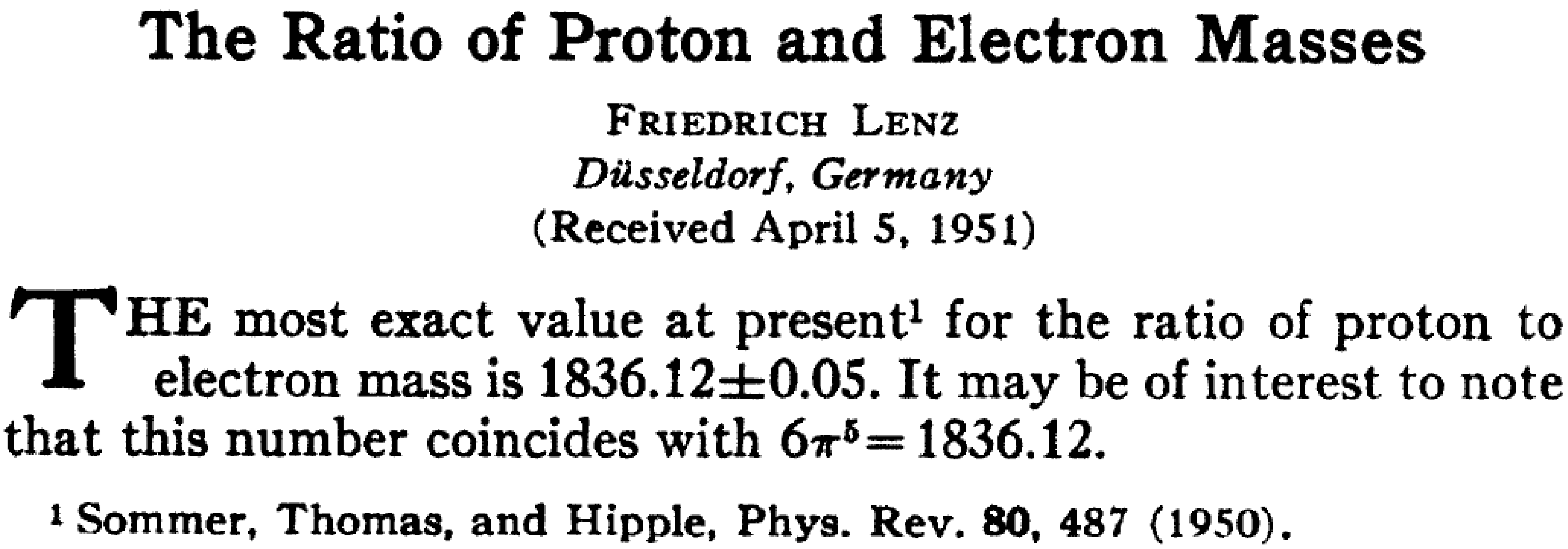
$$\frac{\Delta g_n}{g_n} = [0.12R - 0.05(1+S)]\frac{\Delta\alpha}{\alpha}$$

Theoretically, not all targets are equally useful – must actively search for ideal ones (for the ELT, ALMA, etc), where

- Several parameters can be measured simultaneously (e.g., μ+T relatively common both in optical/UV and radio/mm)
- Occasionally can measure α, μ and g_p (or T) in the same system
- One or more parameters can be measured in several independent ways (e.g., μ measured from various molecules)

Numerology

Phys. Rev. 82, 554 (1951)



The Ratio of Proton and Electron Masses

FRIEDRICH LENZ
Düsseldorf, Germany

(Received April 5, 1951)

THE most exact value at present[1] for the ratio of proton to electron mass is 1836.12±0.05. It may be of interest to note that this number coincides with $6\pi^5 = 1836.12$.

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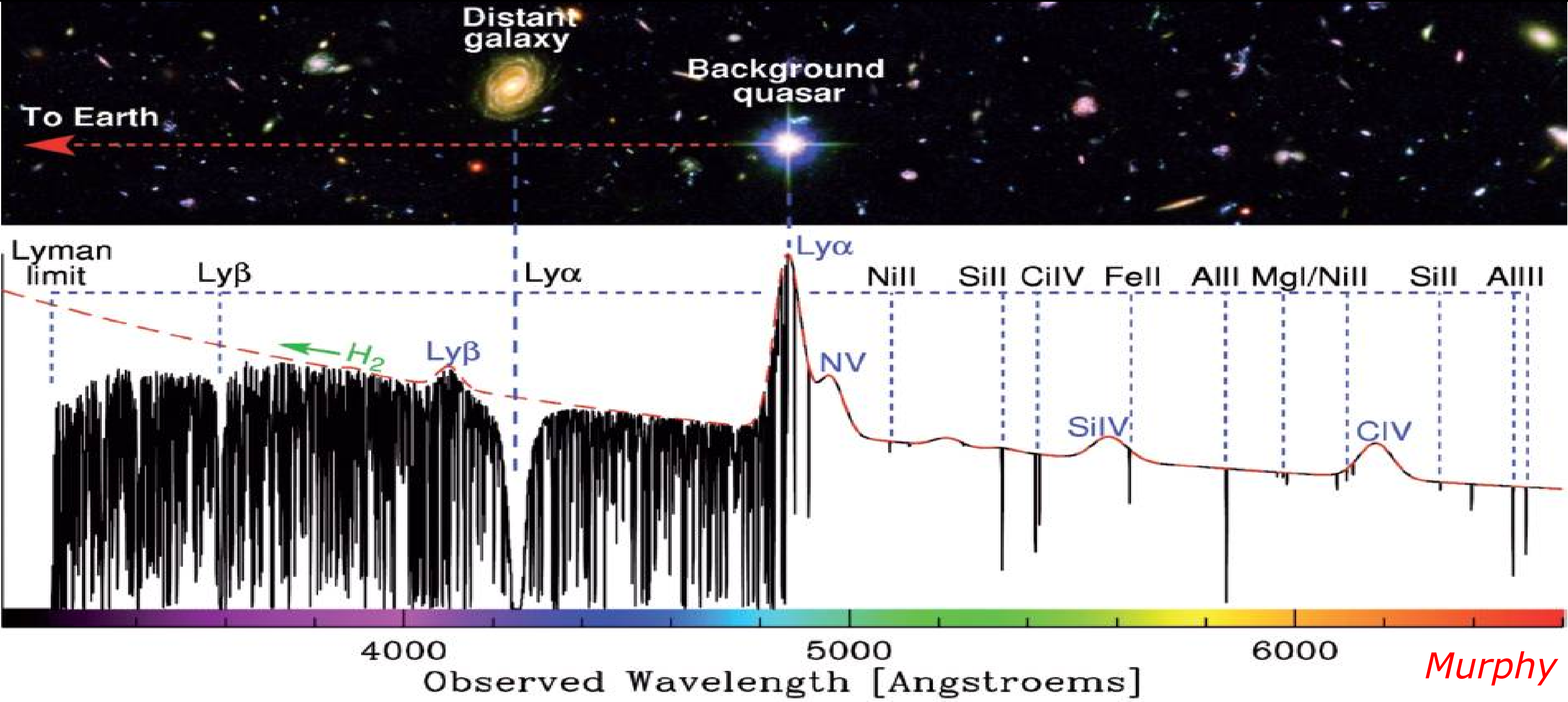
[1] Sommer, Thomas, and Hipple, Phys. Rev. **80**, 487 (1950).

Precision Spectroscopy in Astrophysics



Murphy

Examples of Spectroscopic Constraints

α_{em}: Fine-structure doublet

$\mu=m_p/m_e$: Molecular Rotational *vs.* Vibrational modes

$\alpha_{em}^2 g_p$: Rotational modes *vs.* Hyperfine H

$\alpha_{em} g_p \mu$: Hyperfine H *vs.* Fine-structure

$\alpha_{em}^2 g_p \mu$: Hyperfine H *vs.* Optical

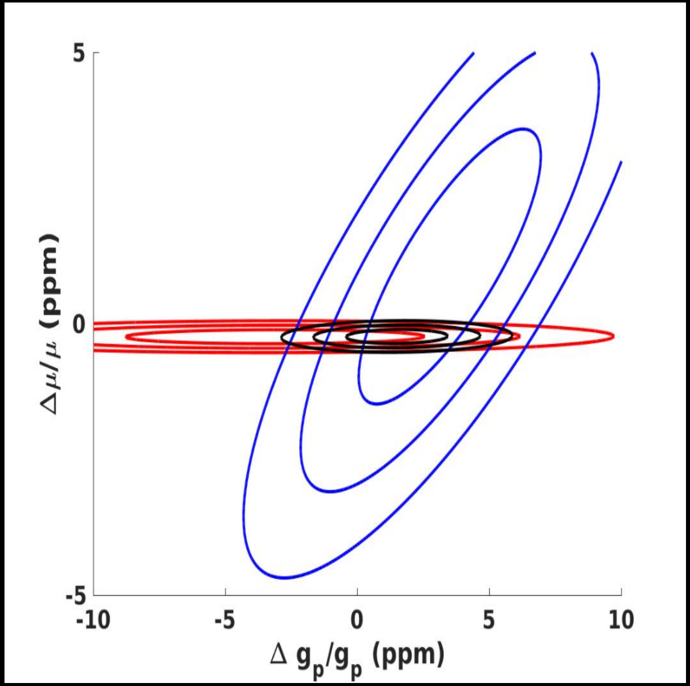
…

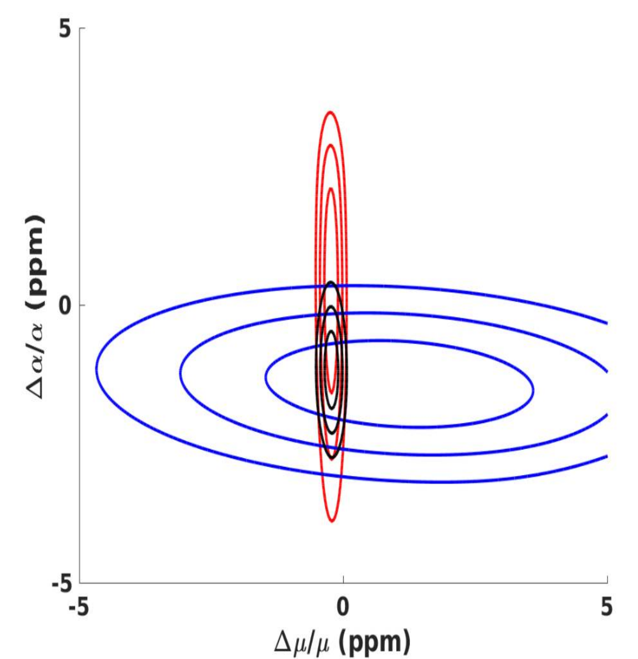
NB: Emission measurements are more straightforward than absorption ones, but much less sensitive *[Albareti et al. 2015]*; the available redshift range is similar *[Brinchmann et al. 2004, …]*

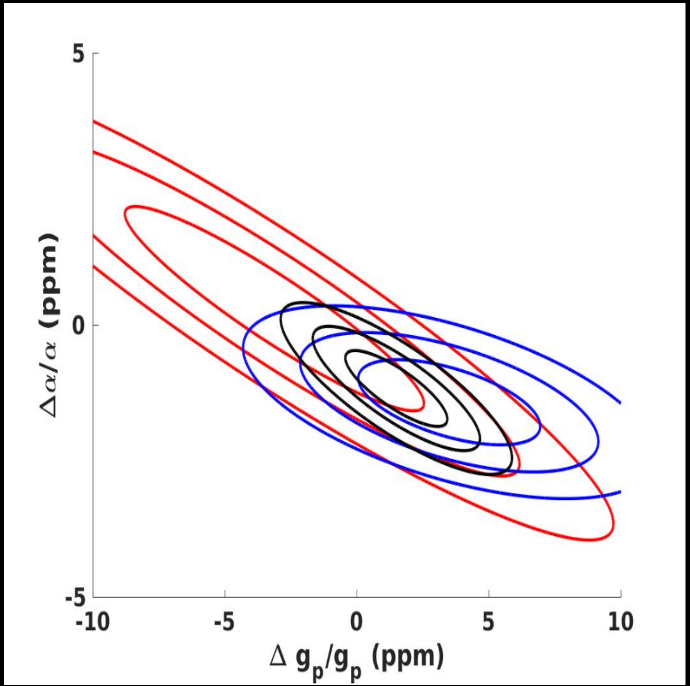
Before ESPRESSO: ca.375 QSO Measurements

Joint likelihood analysis of all data *[Martins & Vila Miñana 2019]*

- Two bins (Red: z<1 ; Blue: z>1 ; Black: All)
- 1-2 sigma detections, even without Webb *et al*. data
- … but systematics known to be at the 3 ppm level



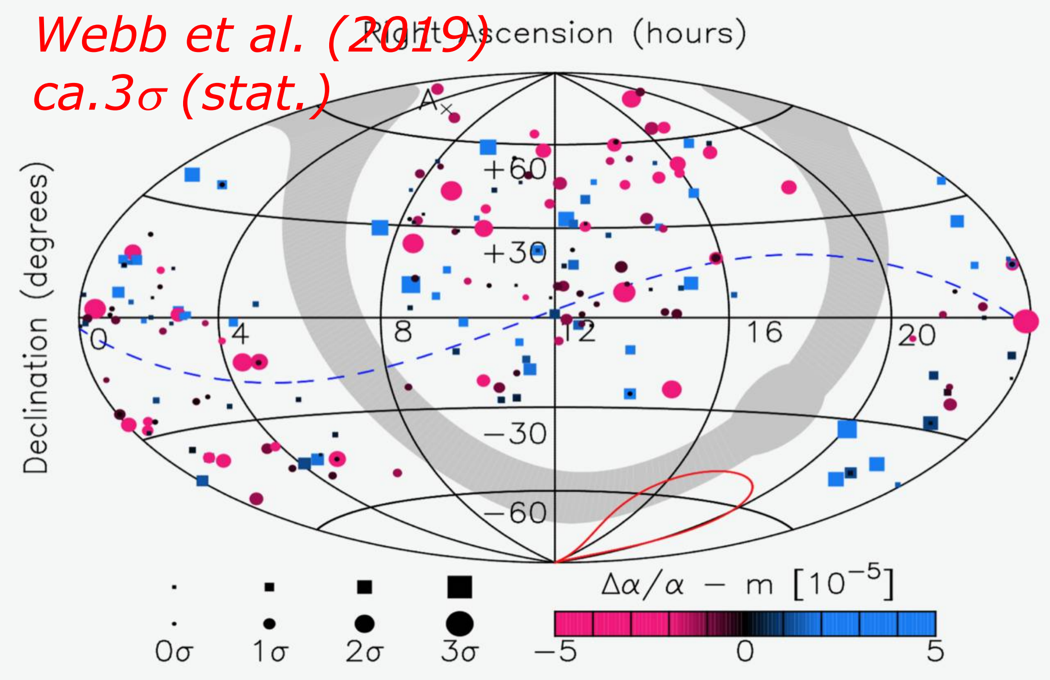


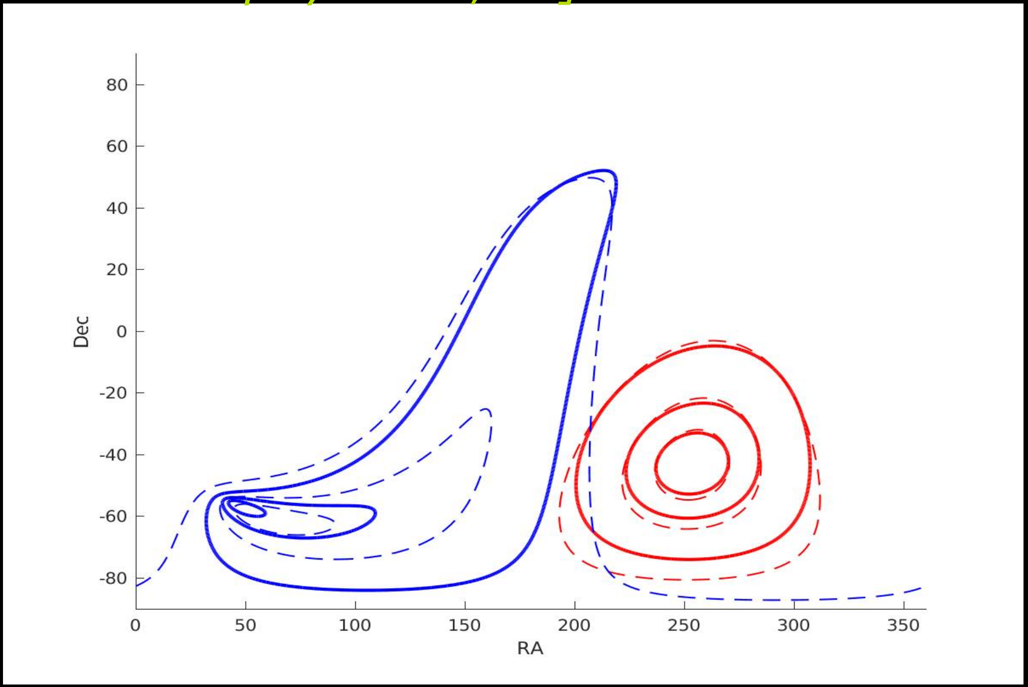


Spatial Variations: Dipoles?

Webb *et al.* (2011): 4.2 σ (stat) evidence for α dipole

- More recent analysis *[Martins & Pinho 2017]*: 2.3 σ, A = 5.6 ± 1.8 ppm
- For μ, A < 1.9 ppm (95.4% cl), also different preferred directions
- ...but beware systematics! *[Whitmore & Murphy 2015, ...]*


Webb et al. (2019)
ca.3σ (stat.)



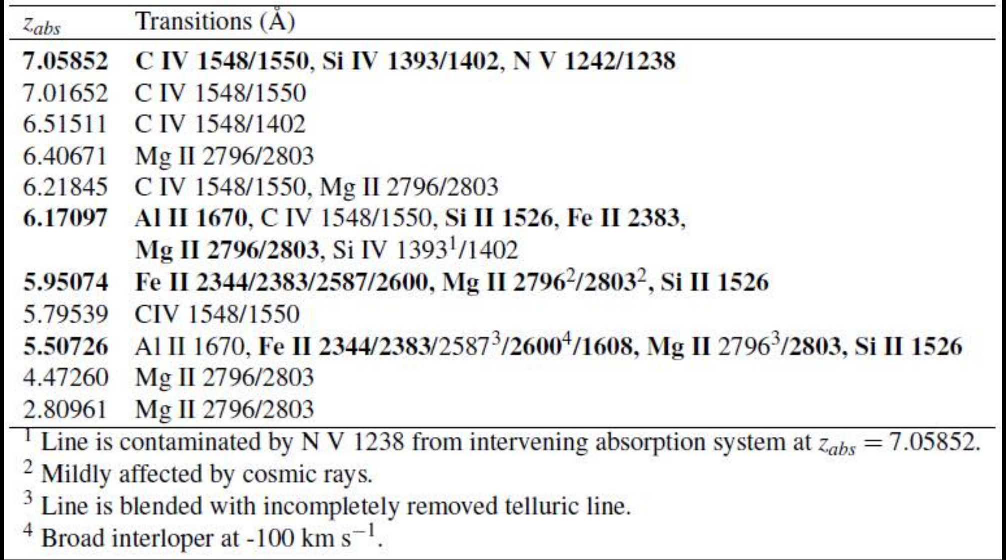
Aiming Higher

Observations of the z=7.09 quasar J1120+0641 *[Mortlock et al. 2011]* yield new direct measurements of α at z=5.51-7.06

- Previous highest-z direct α measurement: z = 4.18
- Look-back time 12.96 Gyr (for standard ΛCDM)

30h of X-SHOOTER data, first measurement in the IR

- R=7000-10000, new AI-based analysis method



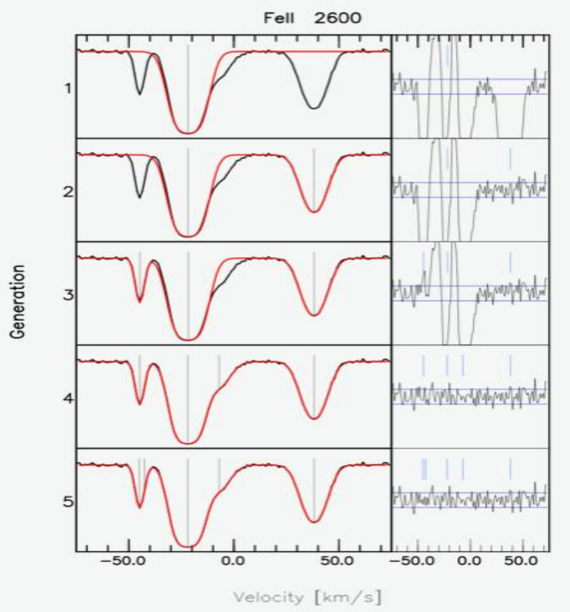
z_{abs}	Transitions (Å)
7.05852	**C IV 1548/1550, Si IV 1393/1402, N V 1242/1238**
7.01652	C IV 1548/1550
6.51511	C IV 1548/1402
6.40671	Mg II 2796/2803
6.21845	C IV 1548/1550, Mg II 2796/2803
6.17097	**Al II 1670**, C IV 1548/1550, **Si II 1526**, **Fe II 2383**, **Mg II 2796/2803**, Si IV 1393[1]/1402
5.95074	**Fe II 2344/2383/2587/2600**, Mg II 2796[2]/2803[2], **Si II 1526**
5.79539	CIV 1548/1550
5.50726	Al II 1670, **Fe II 2344/2383/**2587[3]**/2600[4]/1608**, **Mg II** 2796[3]**/2803**, **Si II 1526**
4.47260	Mg II 2796/2803
2.80961	Mg II 2796/2803

[1] Line is contaminated by N V 1238 from intervening absorption system at $z_{abs} = 7.05852$.

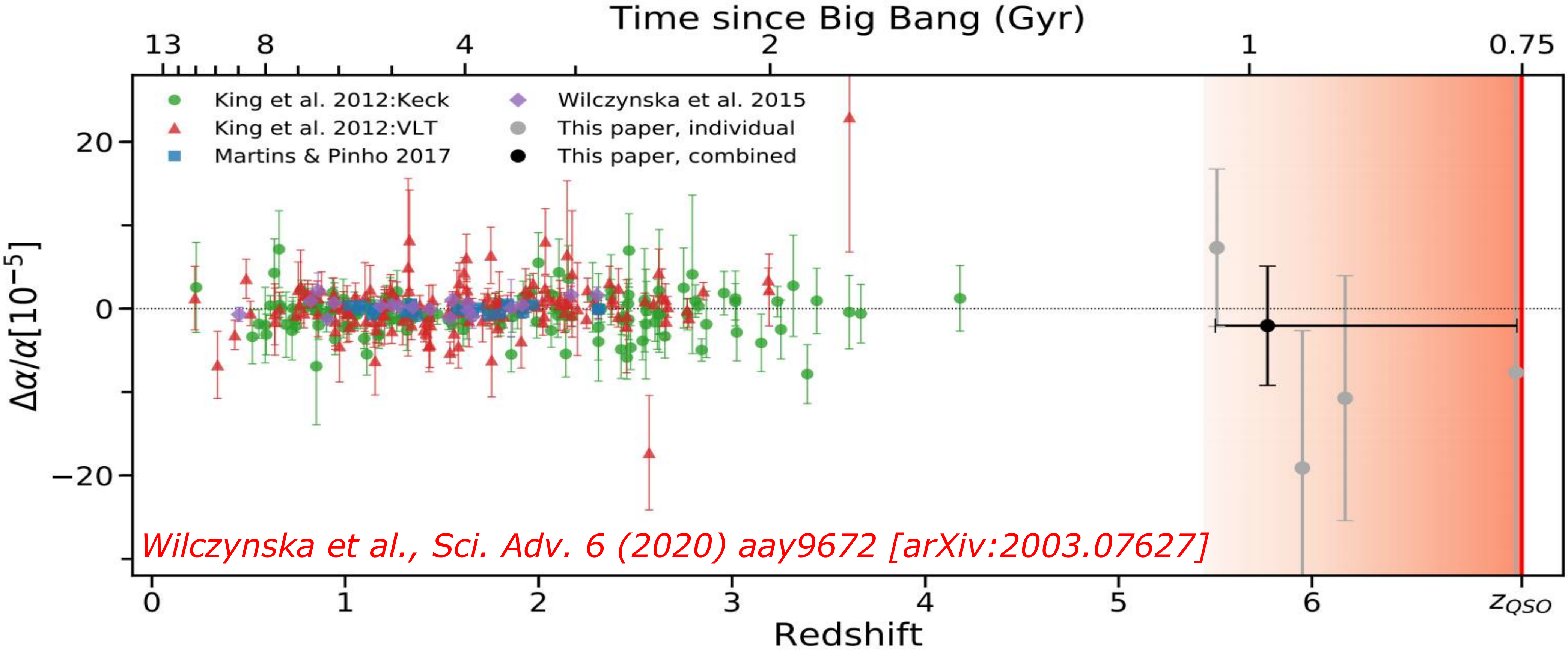
[2] Mildly affected by cosmic rays.

[3] Line is blended with incompletely removed telluric line.

[4] Broad interloper at -100 km s^{-1}.

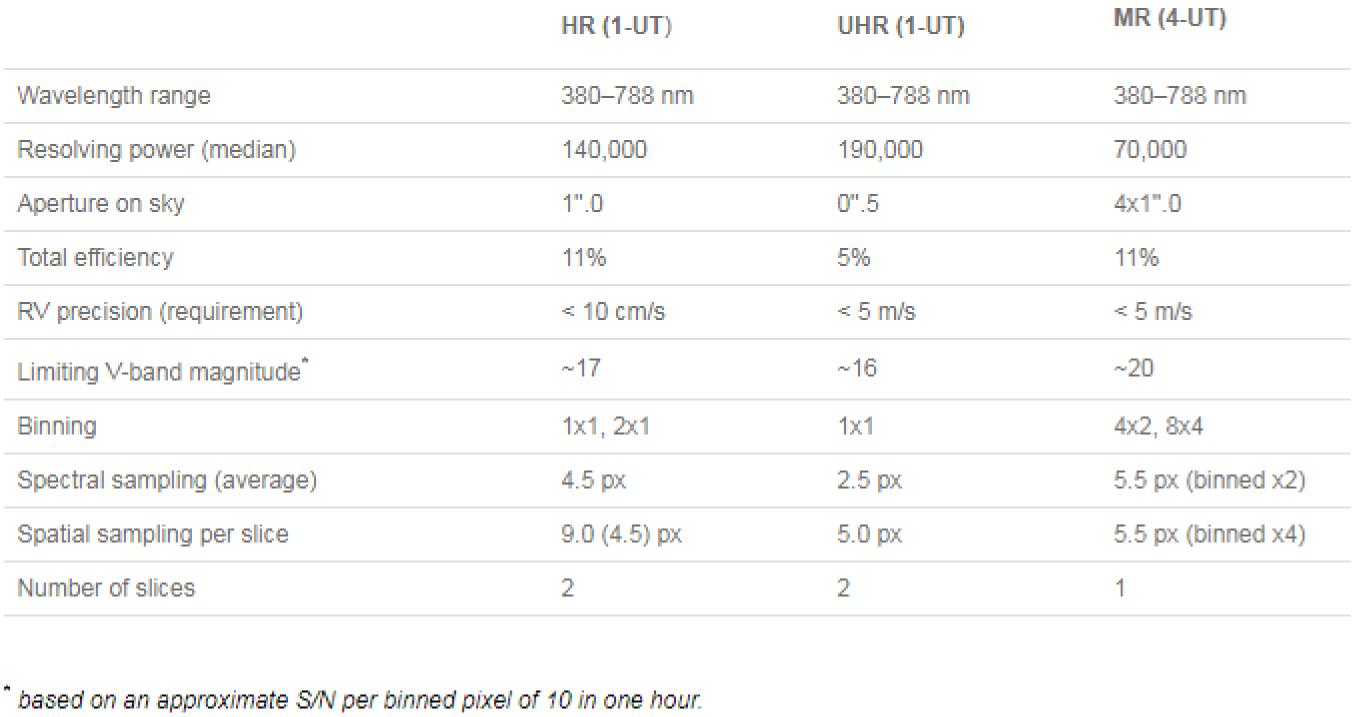


Pre-ESPRESSO Direct α Measurements



Wilczynska et al., Sci. Adv. 6 (2020) aay9672 [arXiv:2003.07627] espresso

ESPRESSO Instrument Configurations



	HR (1-UT)	UHR (1-UT)	MR (4-UT)
Wavelength range	380–788 nm	380–788 nm	380–788 nm
Resolving power (median)	140,000	190,000	70,000
Aperture on sky	1".0	0".5	4x1".0
Total efficiency	11%	5%	11%
RV precision (requirement)	< 10 cm/s	< 5 m/s	< 5 m/s
Limiting V-band magnitude*	~17	~16	~20
Binning	1x1, 2x1	1x1	4x2, 8x4
Spectral sampling (average)	4.5 px	2.5 px	5.5 px (binned x2)
Spatial sampling per slice	9.0 (4.5) px	5.0 px	5.5 px (binned x4)
Number of slices	2	2	1

* *based on an approximate S/N per binned pixel of 10 in one hour.*

ESPRESSO Fundamental Physics GTO Plans

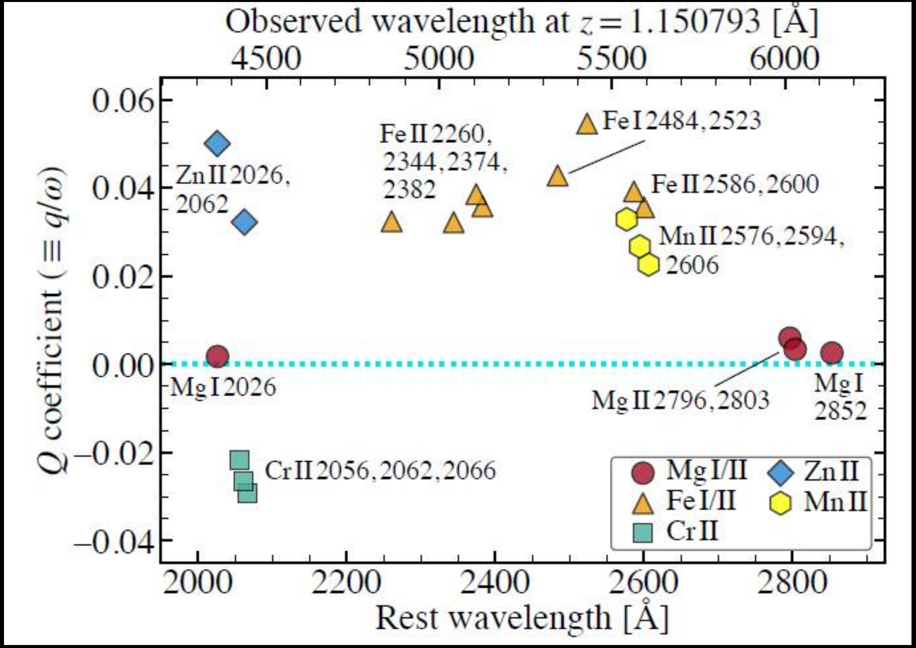
Science Goal:	**Possible targets**
Direct measurements of α (various ions)	14 QSOs
Direct measurements of μ (from H2, CO)	2 QSOs
Direct measurements of T_{CMB} (from CO, CI)	4 QSOs
Primordial Deuterium abundance	2 QSOs
Redshift drift	2 QSOs
Others (Deep spectrum, Lensed QSOs, 12C/13C, ...)	TBD

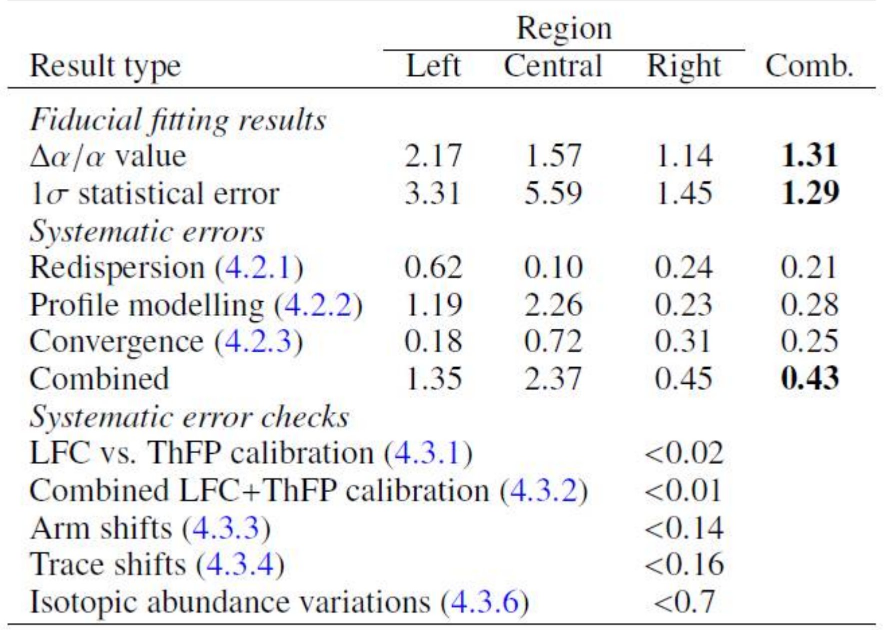
November 2018: First Data!

First ESPRESSO α Measurement

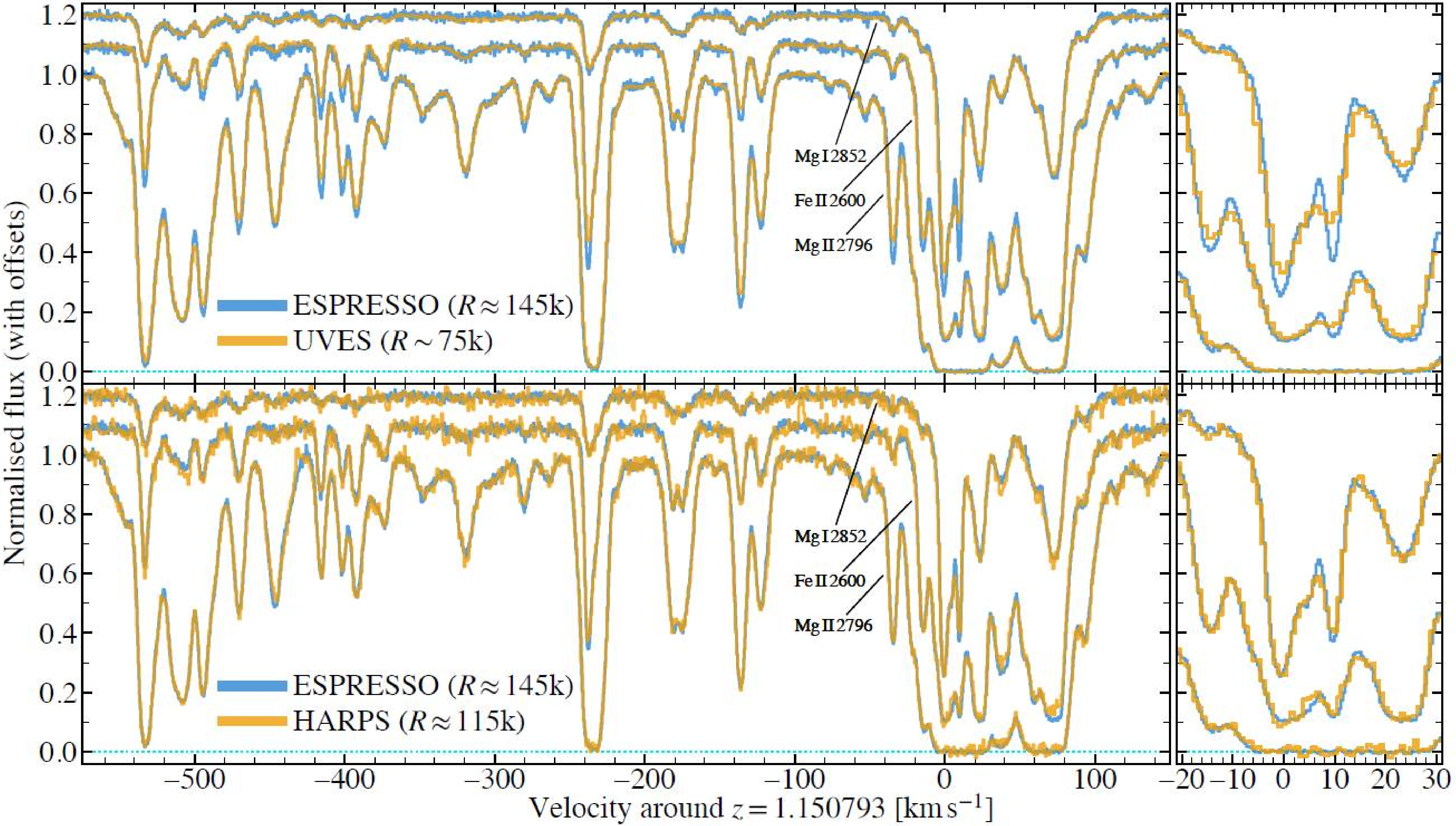
Detailed wavelength accuracy analysis in *Schmidt et al. (2021);* first constraint, at z=1.15, in *Murphy et al. (2022)*

- 16h of data on HE0515-44 (m_v=15.2)
- Blinded analysis yields $\Delta\alpha/\alpha = 1.3 \pm 1.3_{\rm stat} \pm 0.4_{\rm sys}$ ppm,
- Most accurate constraint (and one of the most precise) to date

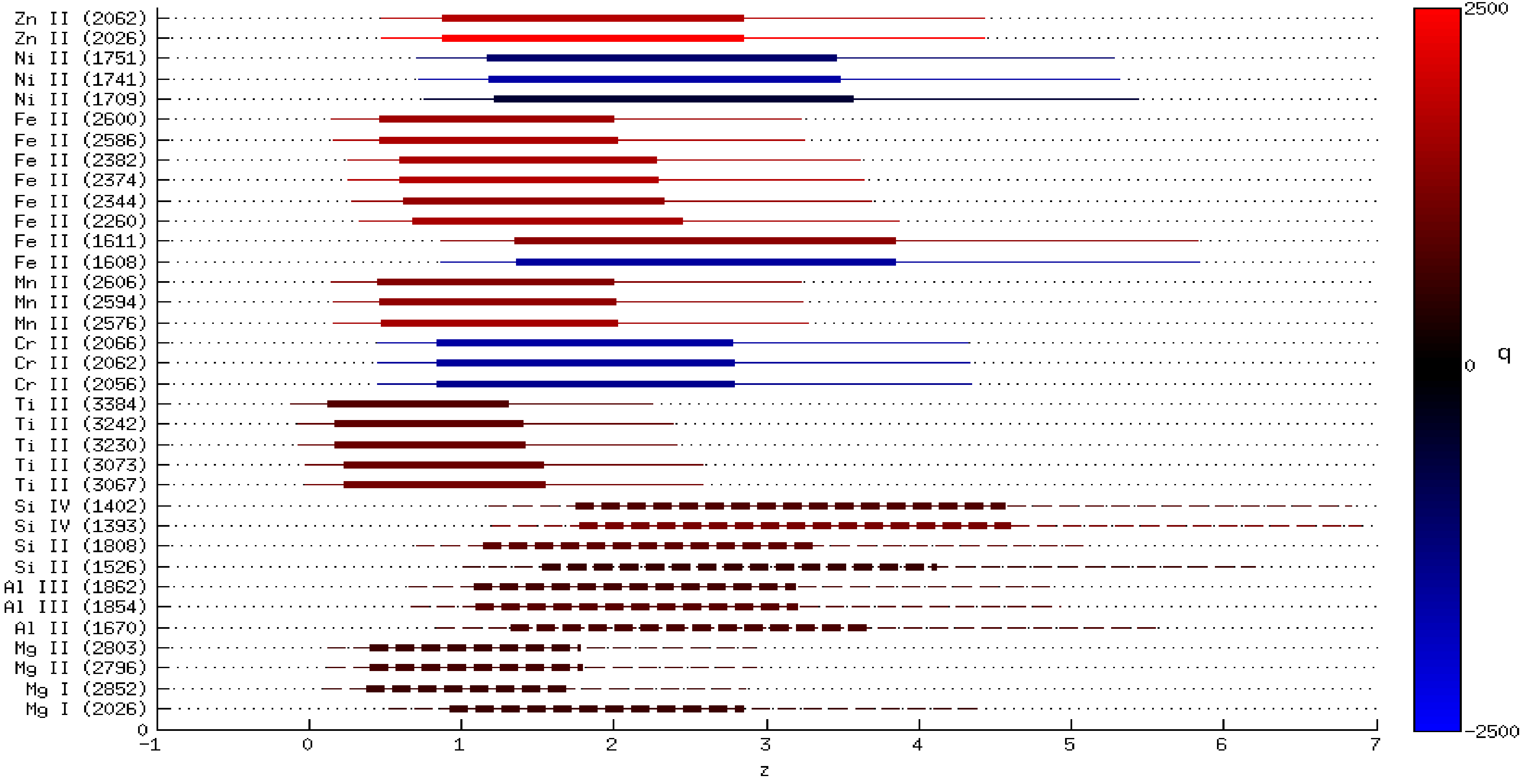




Result type	Region Left	 Central	 Right	Comb.
Fiducial fitting results				
$\Delta\alpha/\alpha$ value	2.17	1.57	1.14	**1.31**
1σ statistical error	3.31	5.59	1.45	**1.29**
Systematic errors				
Redispersion (4.2.1)	0.62	0.10	0.24	0.21
Profile modelling (4.2.2)	1.19	2.26	0.23	0.28
Convergence (4.2.3)	0.18	0.72	0.31	0.25
Combined	1.35	2.37	0.45	**0.43**
Systematic error checks				
LFC vs. ThFP calibration (4.3.1)			<0.02	
Combined LFC+ThFP calibration (4.3.2)			<0.01	
Arm shifts (4.3.3)			<0.14	
Trace shifts (4.3.4)			<0.16	
Isotopic abundance variations (4.3.6)			<0.7	


Normalised flux (with offsets)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Mg I 2852
Fe II 2600
Mg II 2796
ESPRESSO ($R \approx 145$k)
UVES ($R \sim 75$k)
ESPRESSO ($R \approx 145$k)
HARPS ($R \approx 115$k)
−500
−400
−300
−200
−100
0
100
−20
−10
0
10
20
30
Velocity around $z = 1.150793$ [km s^{-1}]

The ESPRESSO Bottleneck



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Other Constraints (Briefly)

Atomic clocks: very high sensitivity of fewx10^{-19}/yr *[Filzinger et al. 2023]*

- Future: molecular & nuclear clocks, 10^{-21}/yr likely achievable

Compact objects can constrain environmental dependencies to ca. 10^{-4} sensitivity; these are limited by nuclear physics uncertainties

- Pop. III stars *[Ekstrom et al. 2010]*, Solar-type stars *[Vieira et al. 2012]*, Neutron stars *[Pérez-García & Martins 2012]*, White dwarfs *[Magano et al. 2017]*
- White dwarf measurements do exist *[Berengut et al. 2013, Bagdonaite et al. 2014]*
- Solar twins constrain spatial variations in the Galaxy *[Murphy et al. 2022]*

Oklo (a natural nuclear reactor, 1.8 bn years ago, z~0.14): nominal sensitivity of fewx10^{-8} *[Davis et al. 2014, ...]*, but not a clean measurement

- Assumptions somewhat simplistic; effectively constrains α_s

Percent-level constraints obtained from SZ clusters *[de Martino et al. 2016, ...]*, the CMB *[Martins et al. 2002, Planck 2015, ...]* and BBN *[Martins et al. 2010, ...]*

- Tighter constraints can be obtained for specific model choices *[Coc et al. 2007, etc]*; e.g. Li problem might be solved in some GUT scenarios? *[Stern 2008]*

High-redshift Constraints: CMB & BBN

CMB: Changes ionization history, but weak bounds due to degeneracies

- Energy levels & binding energies are shifted
- Changes the Thomson cross-section, as α^2

BBN: Higher redshift, but model-dependent

- Changes Coulomb barrier, n-p mass difference, e.g. *[Gasser & Leutwyler 1988]*: $\Delta m = 2.05 - 0.76(1 + \Delta\alpha/\alpha)$ MeV
- NB: BBN counts photons, while the CMB weighs them