Varying fundamental constants may solve the H_0 tension

Latest constraints from HARPS and ESPRESSO

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In collaboration with the ESPRESSO Working Group on Fundamental Physics, John Webb, Chung-Chi Lee and others.

SISSA

Tensions in cosmology, Corfu, 9 Sep 2022

Fundamental constants are those "whose value we cannot calculate with precision in terms of more fundamental constants, not just because the calculation is too complicated (…) but because we do not know of anything more fundamental."

Steven Weinberg in "Overview of theoretical prospects for understanding the values of fundamental constants" RSPTA (1983) 310 249

Today's fundamental constants

are parameters of the Standard Cosmological Model

Based on Uzan 2011

General relativity **+** Standard model + dark matter + Λ **+** Copernican principle **+** Simply connected topology

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Dimensionful / Dimensionless

Constant	Symbol	Value
Speed of light in vacuum	c	$299\,792\,458\,\mathrm{m\,s^{-1}}$
Planck constant (reduced)	$\hbar$	$1.054\,571\,726(47) \times 10^{-34}\,\mathrm{J\,s}$
Newton constant	G	$6.673\,84(80) \times 10^{-11}\,\mathrm{m^2\,kg^{-1}\,s^{-2}}$
Weak coupling constant (at m_Z)	$g_2(m_Z)$	0.6520 ± 0.0001
Strong coupling constant (at m_Z)	$g_3(m_Z)$	1.221 ± 0.022
Weinberg angle		0.2229(3)
Electron Yukawa coupling	h_e	2.935×10^{-6}
Muon Yukawa coupling	h_μ	0.000607
Tauon Yukawa coupling	h_τ	0.0102057
Up Yukawa coupling	h_u	0.0000126 ± 0.000003
Down Yukawa coupling	h_d	0.000027 ± 0.000002
Charmed Yukawa coupling	h_c	0.00732 ± 0.00002
Strange Yukawa coupling	h_s	0.00055 ± 0.00003
Top Yukawa coupling	h_t	0.994 ± 0.002
Bottom Yukawa coupling	h_b	0.0240 ± 0.0002
Quark CKM matrix angle	$\sin\theta_{12}$	0.2244 ± 0.0014
	$\sin\theta_{23}$	0.04221 ± 0.0014
	$\sin\theta_{13}$	0.0249 ± 0.0005
Quark CKM matrix phase	δ_{CKM}	1.05 ± 0.24
Higgs potential quadratic coefficient	$\hat{\mu}^2$	$7835.02 \pm 20.03\ \mathrm{GeV}^2$
Higgs potential quartic coefficient	λ	0.1295 ± 0.021
QCD vacuum phase	θ_{QCD}	$< 10^{-9}$

Parametre	Symbol	Value
Reduced Hubble constant	h	0.73(3)
baryon-to-photon ratio	$\eta = n_{\mathrm{b}}/n_\gamma$	$6.12(19) \times 10^{-10}$
Photon density	$\Omega_\gamma h^2$	2.471×10^{-5}
Dark matter density	$\Omega_{\mathrm{CDM}} h^2$	0.105(8)
Cosmological constant	Ω_Λ	0.73(3)
Spatial curvature	Ω_K	0.011(12)
Scalar modes amplitude	Q	$(2.0 \pm 0.2) \times 10^{-5}$
Scalar spectral index	n_S	0.958(16)
Neutrino density	$\Omega_\nu h^2$	$(0.0005 - 0.023)$
Dark energy equation of state	w	$-0.97(7)$
Scalar running spectral index	α_S	-0.05 ± 0.03
Tensor-to-scalar ratio	T/S	< 0.36
Tensor spectral index	n_T	< 0.001
Tensor running spectral index	α_T	?
Baryon density	$\Omega_{\mathrm{b}} h^2$	0.0223(7)

Dimensionless quantities are easier to measure in terrestrial and astronomical settings

Quantity	Algebraic ratio	Numerical value	Related to
$\alpha_{\rm EM}$	$\dfrac{e^2}{4\pi\epsilon_0\hbar c}$	$1/137.03599976$	Strength of the electromagnetic force
$\alpha_{\rm W}$	$\dfrac{G_{\rm F}m_p^2c}{\hbar^3}$	1.03×10^{-5}	Strength of the weak force
$\alpha_{\rm S}(E)$	$\dfrac{g_s^2(E)}{\hbar c}$		Strength of the strong force
$\alpha_{\rm G}$	$\dfrac{Gm_p^2}{\hbar c}$	5×10^{-39}	Strength of the gravitational force
μ	$\dfrac{m_e}{m_p}$	5.44617×10^{-4}	
x	$g_p\alpha_{\rm EM}^2\mu$	1.62×10^{-7}	
y	$g_p\alpha_{\rm EM}^2$	2.977×10^{-4}	

Varying constants and the H_0 olympics

Model	$\Delta N_{\rm param}$	M_B	Gaussian Tension	$Q_{\rm DMAP}$ Tension		$\Delta\chi^2$	ΔAIC		One test passed
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	X	0.00	0.00	X	X
$\Delta N_{\rm ur}$	1	-19.395 ± 0.019	3.6σ	3.8σ	X	-6.10	-4.10	X	X
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	X	-9.57	-7.57	✓	✓
mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	X	-8.83	-4.83	X	X
DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	X	-8.92	-4.92	X	X
SIν+DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	X	-4.98	1.02	X	X
Majoron	3	$-19.380^{+0.027}_{-0.021}$	3.0σ	2.9σ	✓	-15.49	-9.49	✓	✓
primordial B	1	$-19.390^{+0.018}_{-0.024}$	3.5σ	3.5σ	X	-11.42	-9.42	✓	✓
varying m_e	1	-19.391 ± 0.034	2.9σ	2.9σ	✓	-12.27	-10.27	✓	✓
varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.9σ	✓	-17.26	-13.26	✓	✓
EDE	3	$-19.390^{+0.016}_{-0.035}$	3.6σ	1.6σ	✓	-21.98	-15.98	✓	✓
NEDE	3	$-19.380^{+0.023}_{-0.040}$	3.1σ	1.9σ	✓	-18.93	-12.93	✓	✓
EMG	3	$-19.397^{+0.017}_{-0.023}$	3.7σ	2.3σ	✓	-18.56	-12.56	✓	✓
CPL	2	-19.400 ± 0.020	3.7σ	4.1σ	X	-4.94	-0.94	X	X
PEDE	0	-19.349 ± 0.013	2.7σ	2.8σ	✓	2.24	2.24	X	X
GPEDE	1	-19.400 ± 0.022	3.6σ	4.6σ	X	-0.45	1.55	X	X
DM $\to$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	X	-0.19	3.81	X	X
DM $\to$ DR	2	-19.410 ± 0.011	4.3σ	4.5σ	X	-0.53	3.47	X	X

Schöneberg et al. 2022

Varying constants: winners of the H_0 olympics

Model	$\Delta N_{\rm param}$	M_B	Gaussian Tension	$Q_{\rm DMAP}$ Tension		$\Delta\chi^2$	ΔAIC		One test passed	
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	✗	0.00	0.00	✗	✗	
$\Delta N_{\rm ur}$	1	-19.395 ± 0.019	3.6σ	3.8σ	✗	-6.10	-4.10	✗	✗	
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	✗	-9.57	-7.57	✓	✓	3
mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	✗	-8.83	-4.83	✗	✗	
DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	✗	-8.92	-4.92	✗	✗	
SIν+DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	✗	-4.98	1.02	✗	✗	
Majoron	3	$-19.380^{+0.027}_{-0.021}$	3.0σ	2.9σ	✓	-15.49	-9.49	✓	✓	2
primordial B	1	$-19.390^{+0.018}_{-0.024}$	3.5σ	3.5σ	✗	-11.42	-9.42	✓	✓	3
varying m_e	1	-19.391 ± 0.034	2.9σ	2.9σ	✓	-12.27	-10.27	✓	✓	1
varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.9σ	✓	-17.26	-13.26	✓	✓	1
EDE	3	$-19.390^{+0.016}_{-0.035}$	3.6σ	1.6σ	✓	-21.98	-15.98	✓	✓	2
NEDE	3	$-19.380^{+0.023}_{-0.040}$	3.1σ	1.9σ	✓	-18.93	-12.93	✓	✓	2
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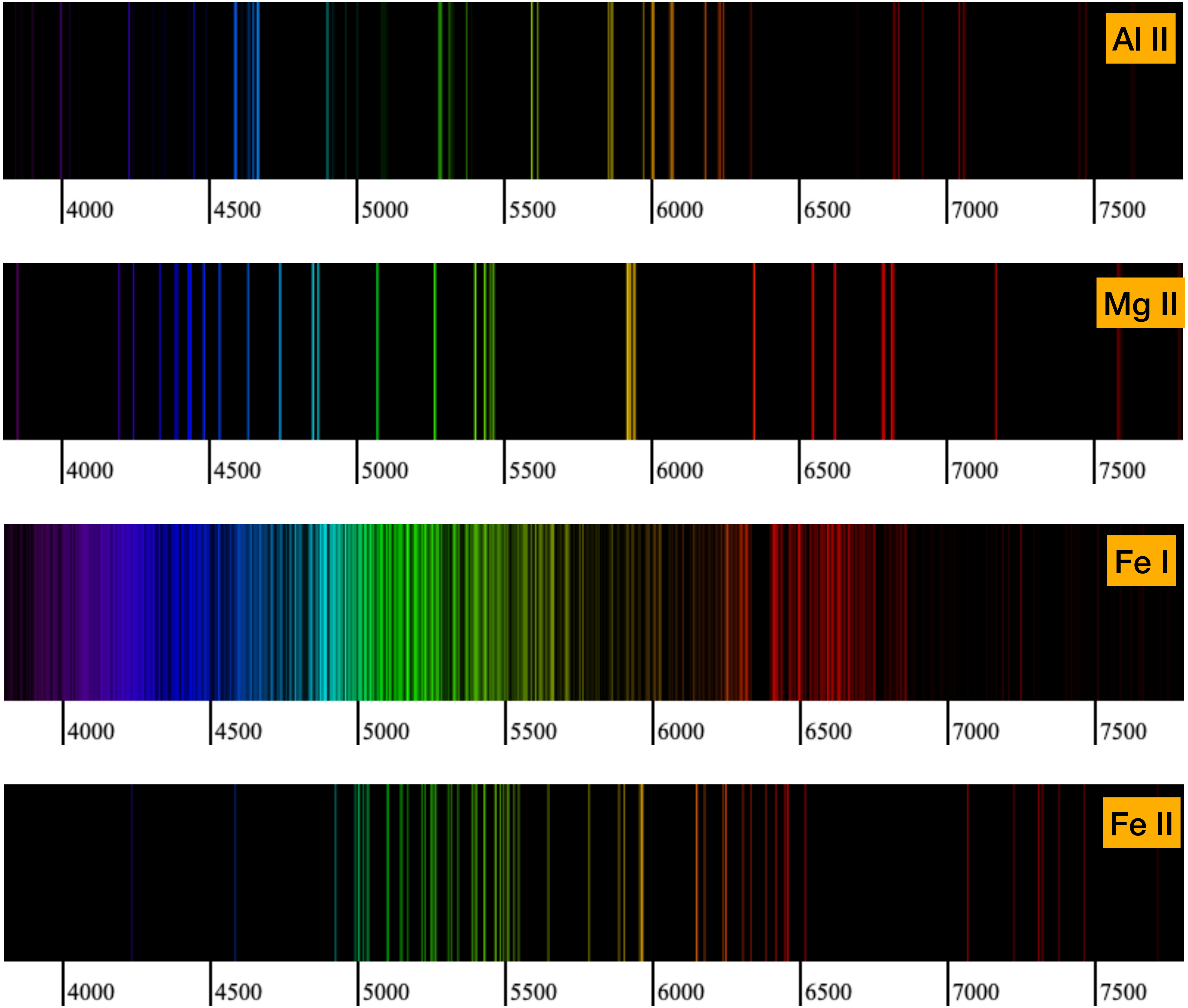
DM $\to$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	✗	-0.19	3.81	✗	✗	
DM $\to$ DR	2	-19.410 ± 0.011	4.3σ	4.5σ	✗	-0.53	3.47	✗	✗	

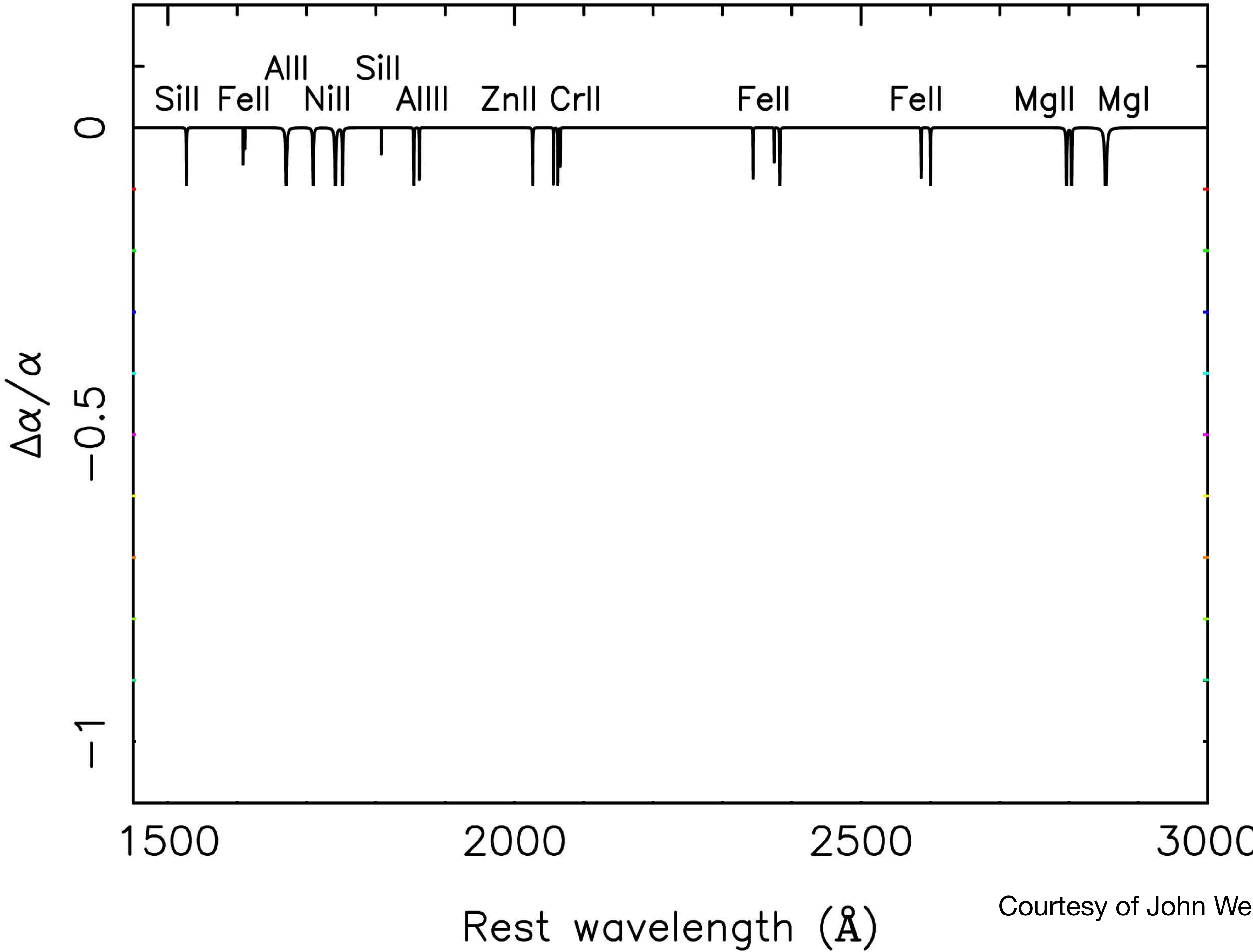
Schöneberg et al. 2022

Spectra from grotrian.nsu.ru



Observable: a pattern of velocity shifts between transitions

$$\frac{\Delta v}{c} \approx \frac{\Delta \alpha}{\alpha} \frac{2q}{\omega}$$



Courtesy of John Webb

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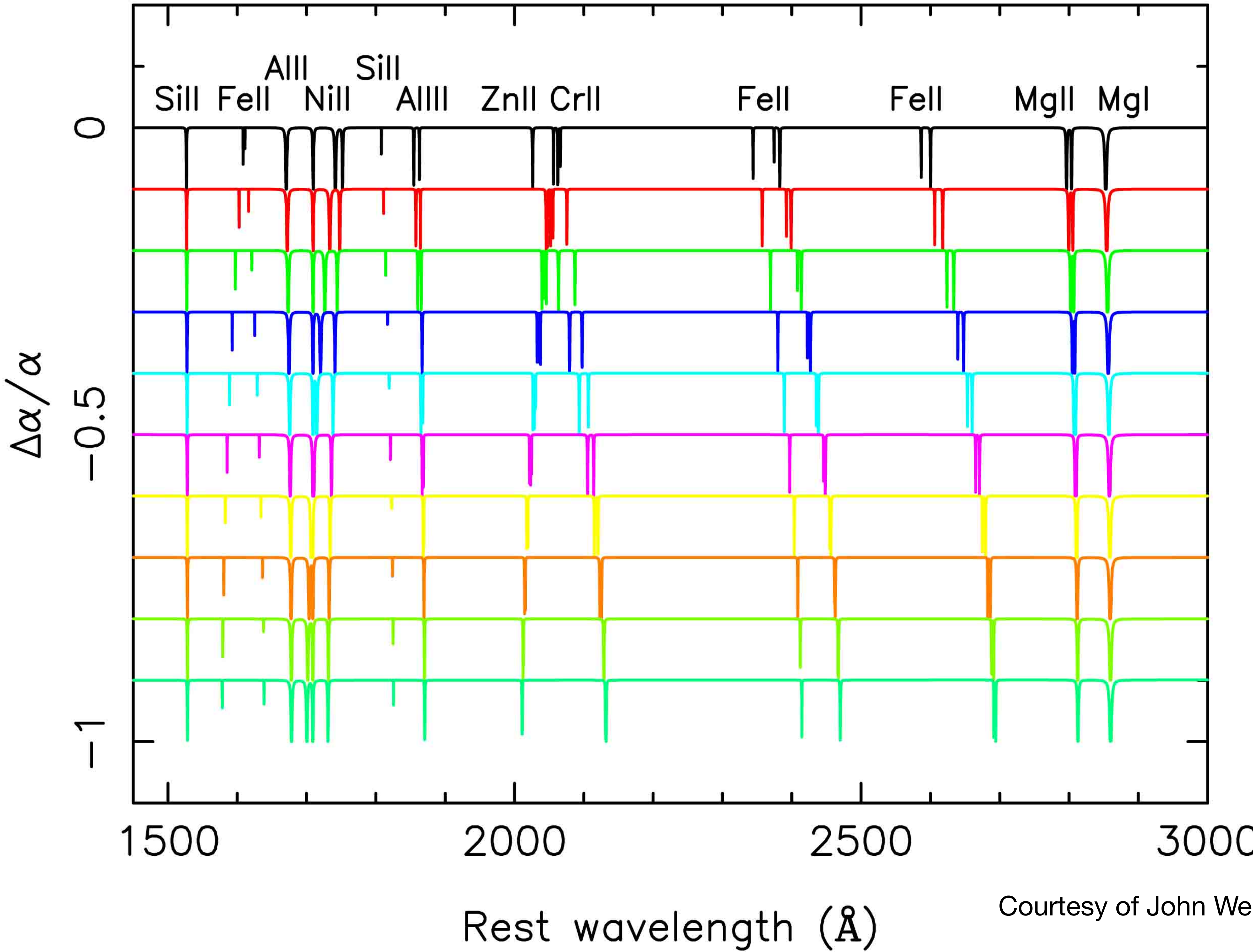
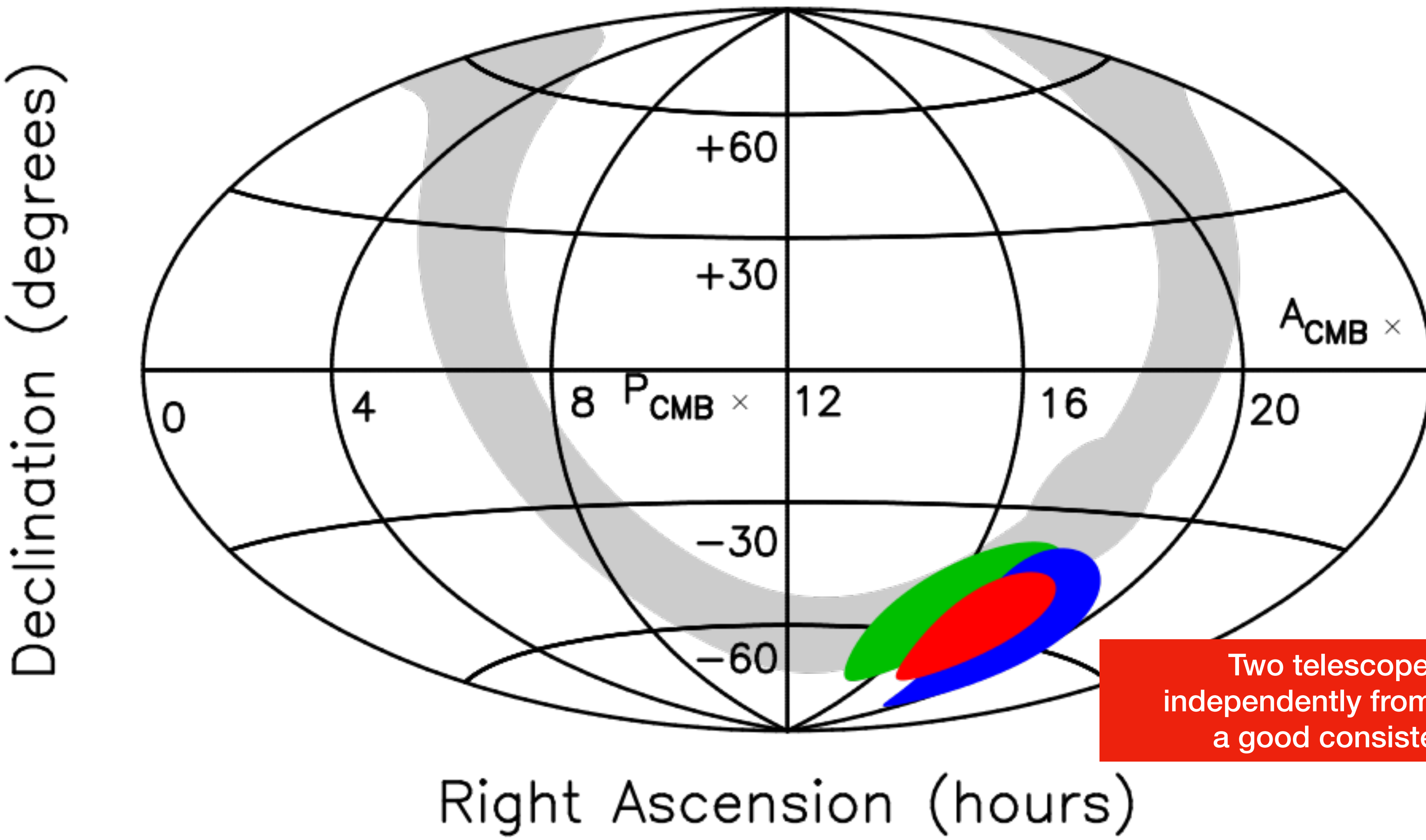


Courtesy of John Webb

154 VLT/UVES + 141 Keck/HIRES observations show evidence for a dipole on the sky, 4.2σ statistical

King et al. 2012
Webb et al. 2011



Two telescopes agree independently from each other, a good consistency test

VLT | Keck | Combined

Precision measurements require

1. **Bright quasars:**
   Sky surveys and dedicated searches (e.g. QUBRICS, Boutsia 2022)

2. **High resolution spectroscopy:**
   Echelle gratings

New!

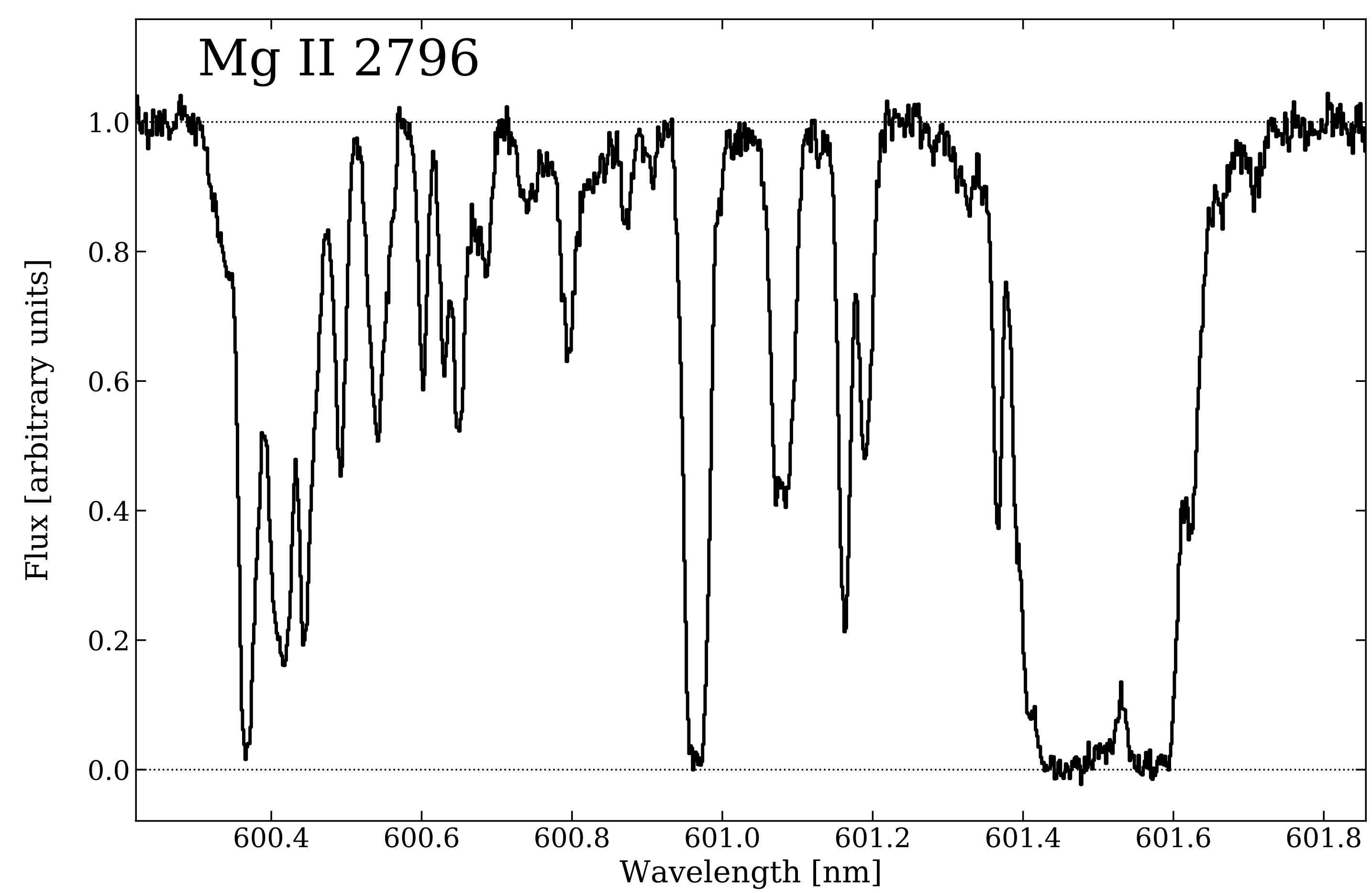
3. **Accurate wavelength calibration:**
   Laser Frequency Combs (Nobel prize for physics 2005)

4. **Robust analysis methods:**
   Artificial Intelligence Voigt Profile Fitting (AI-VPFIT, Lee et al. 2021)

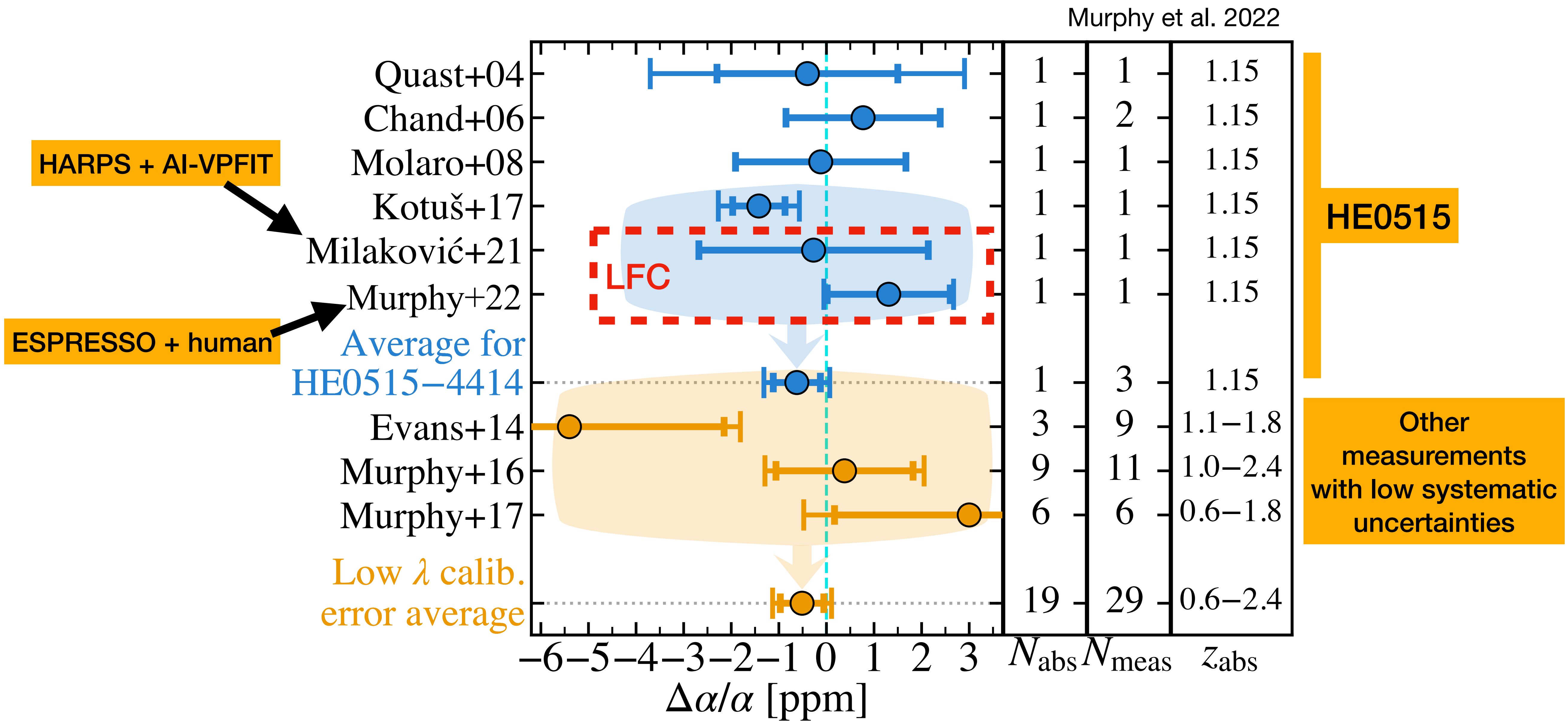
Artificial intelligence methods quickly produce objective and reproducible models

AI-VPFIT Lee, Webb, Carswell, Milaković (2021) MNRAS 504 1787
Lee, Webb, Milaković, Carswell (2021) MNRAS 507 27

- Genetic algorithms + Monte Carlo methods
- Information criterion as an **objective** criterion to choose the optimal model
- 100x increase in speed
- No human bias



HE 0515-4414: no evidence for variation but this is consistent with dipole predictions



Overall, no evidence for variation in any particular system

No evidence for time varying dark energy EoS

A scalar field would couple to the electromagnetic sector

Martins et al. 2022 (but see also de Fonseca et al. 2022)

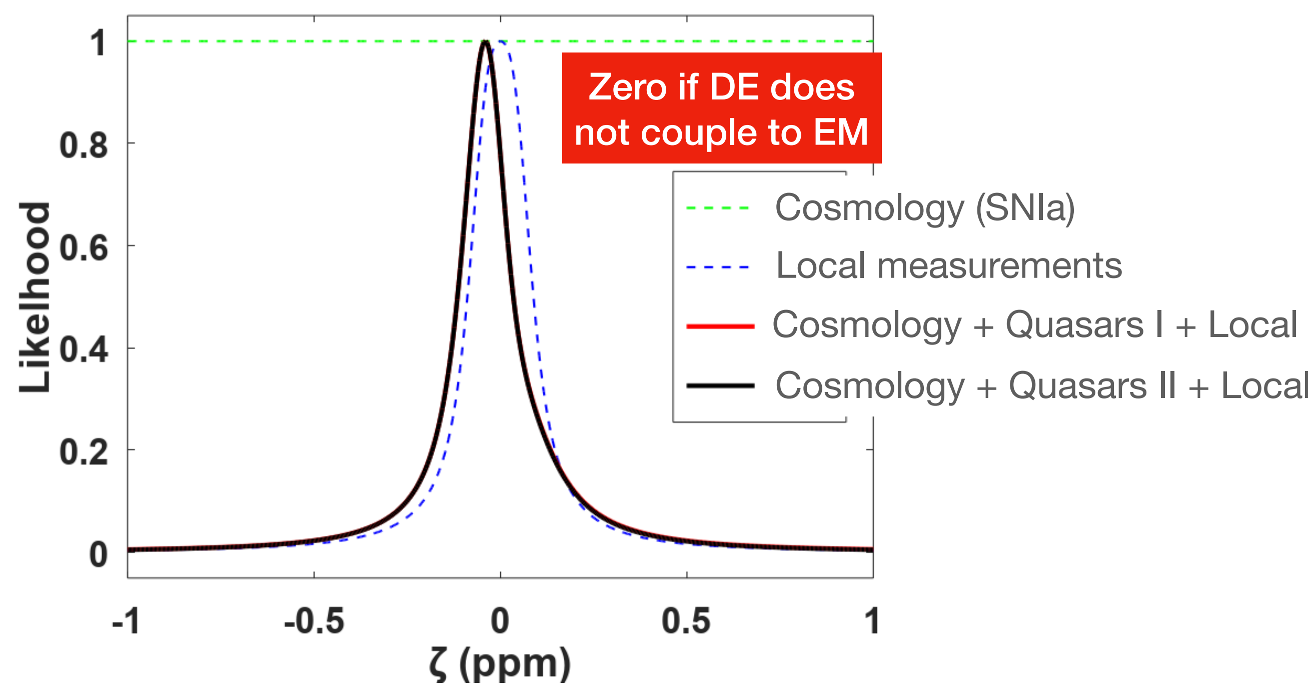
EM coupling — fractional DE density

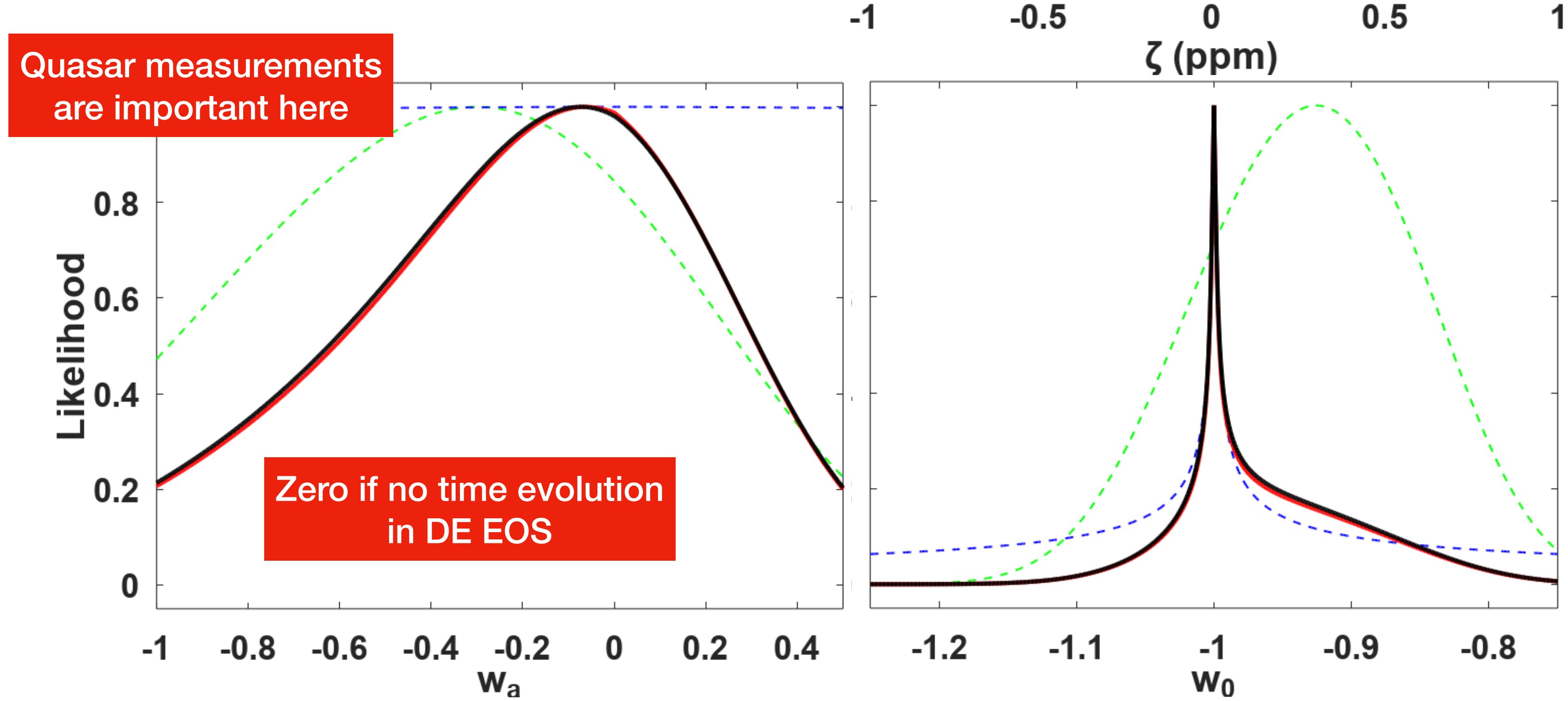
$$\frac{\Delta\alpha}{\alpha}(z) = \pm\zeta \int_0^z \sqrt{3\Omega_\psi(z')|1 + w_\psi(z')|}\,\frac{dz'}{1+z'}$$

+ for canonical fields
- for phantom fields

DE equation of state

$$w_\psi = w_0 + w_a \frac{z}{1+z}$$





Conclusions

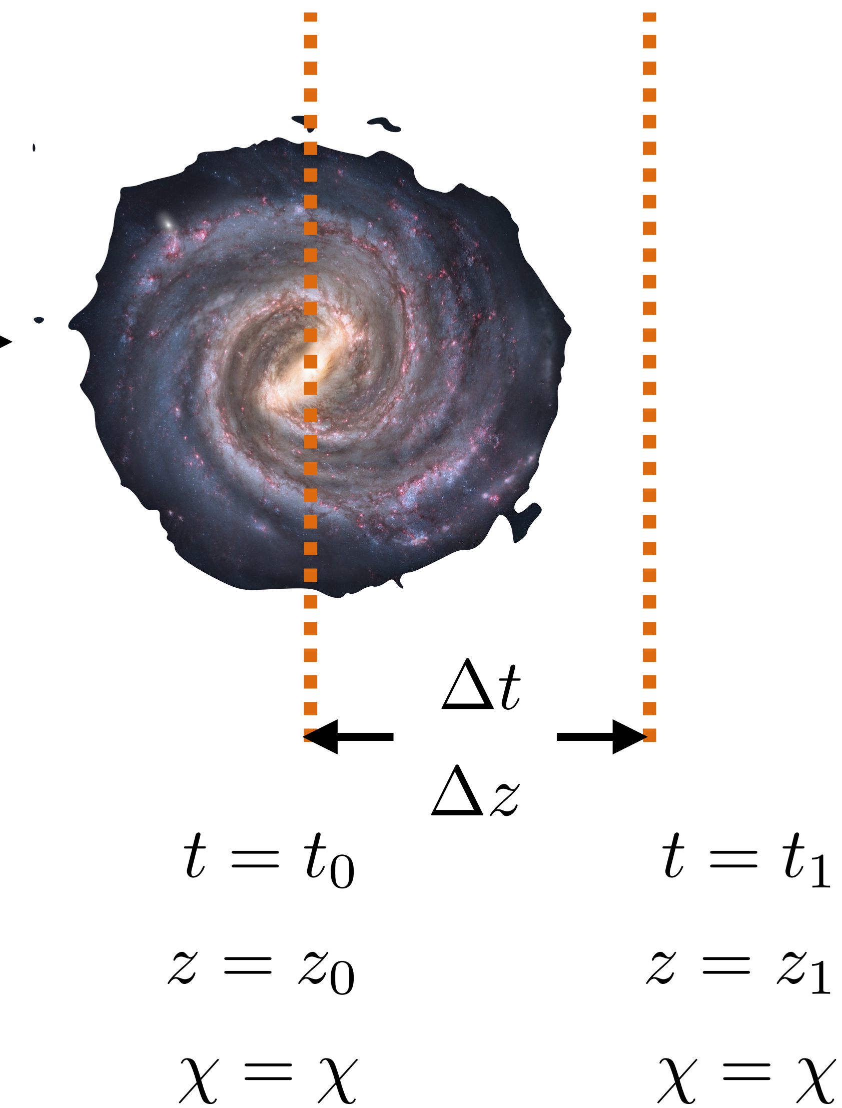
- Fundamental constants are expected to vary in many extensions of SM and ΛCDM (Uzan 2011; Martins 2017, many talks here)
- Existing measurements provide some evidence for a 4σ variation in α but are dominated by instrumental systematics (King et al. 2012; Whitmore & Murphy 2016)
- Measurements where this systematic is not present see no variation (Milaković et al. 2021; Murphy et al. 2022)
- High-quality data from ESPRESSO@VLT is becoming available, new measurements using AI-VPFIT (Webb et al. 2022, Lee et al. 2022) are coming soon
- This project is one of the science drivers for the ELT and ANDES

Do we need a model?
Direct measurement of the expansion <u>in real time</u>

In FLRW metric, redshifts of distant objects change with time

Similar to, but different from, cosmic chronometers (M. Moresco's talk)

DISTANCE χ



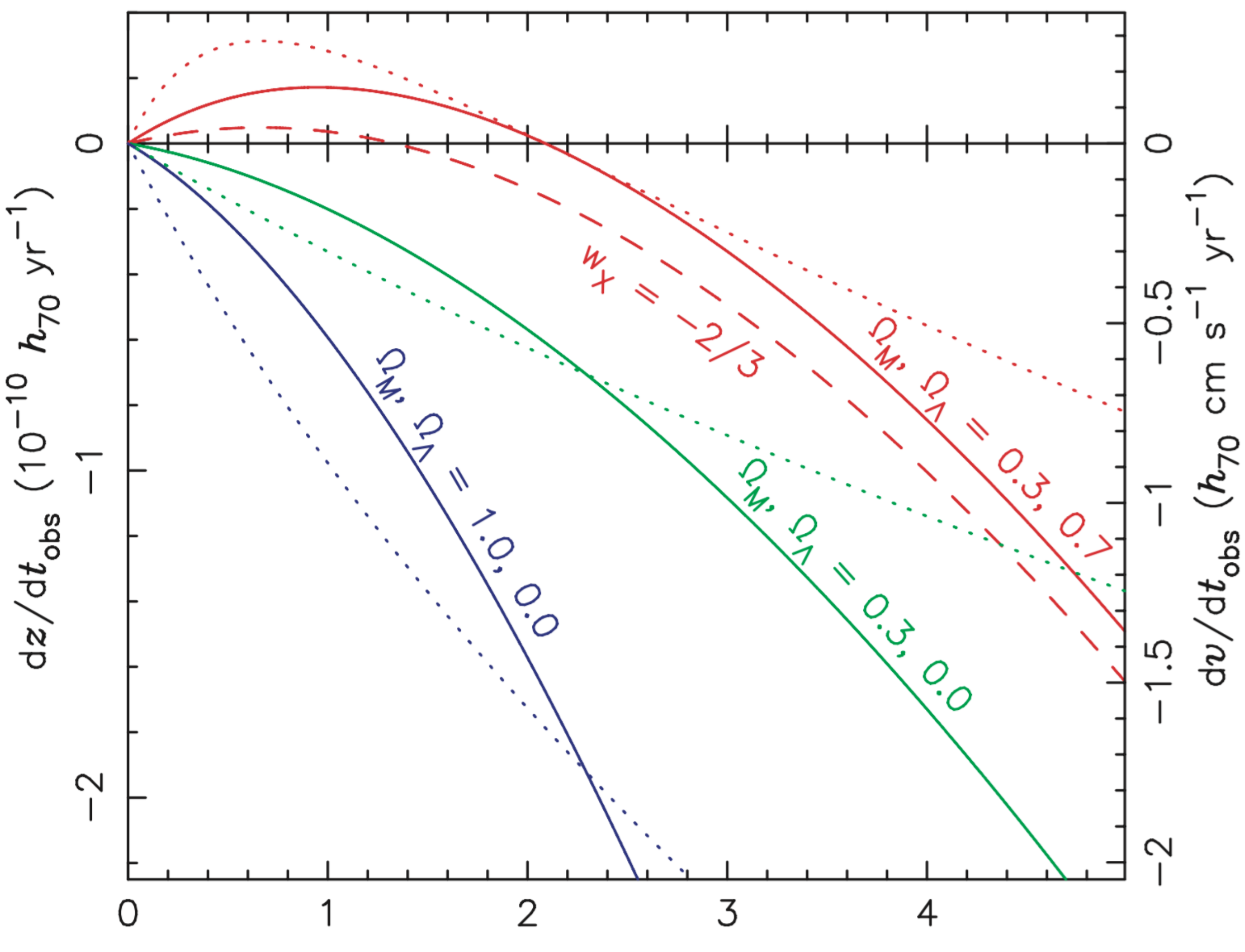
$$1 + z(t_{obs}, t_{em}) = \frac{a(t_{obs})}{a(t_{em})}$$

$$\frac{\mathrm{d}z_{|\chi}}{\mathrm{d}t_{obs}} = [1 + z_{|\chi}(t_{obs})]H(t_{obs}) - H(t_{em})$$

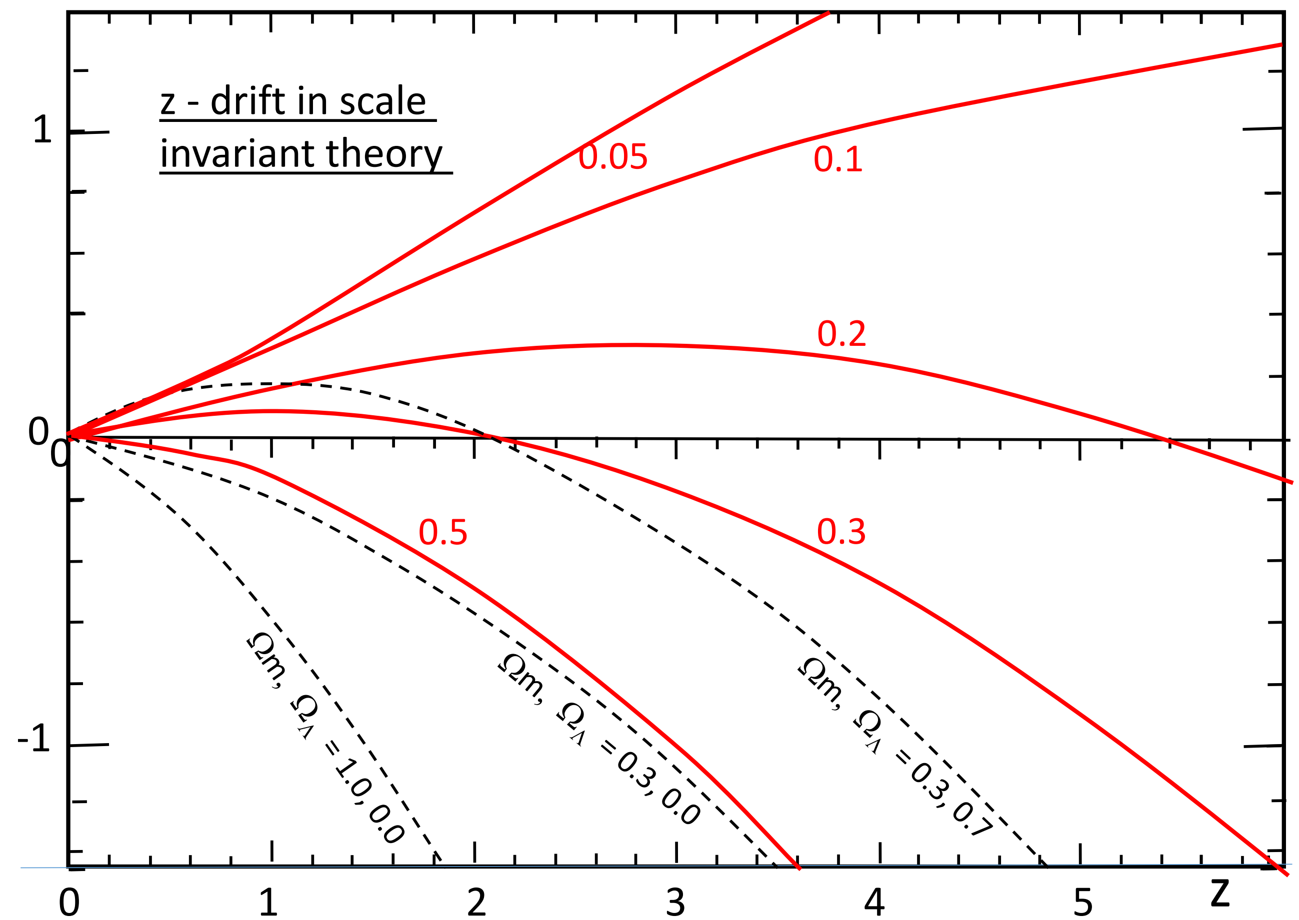
$$\frac{\mathrm{d}z_{|\chi}}{\mathrm{d}t_{obs}} \approx \frac{z_{|\chi}(t_{obs} + \Delta t_{obs}) - z_{|\chi}(t_{obs})}{\Delta t_{obs}}$$

10+ year project with the ELT and ANDES

Extremely difficult: line centre expected to shift by 0.01A on the detector in 10 years



Liske et al. 2008 z



Maeder, private communication

Ongoing project to observe two bright quasars
with ESPRESSO with a baseline of 1 year