Fundamental Physics and Cosmology in the ELT Era:
Theoretical Context (Part I)

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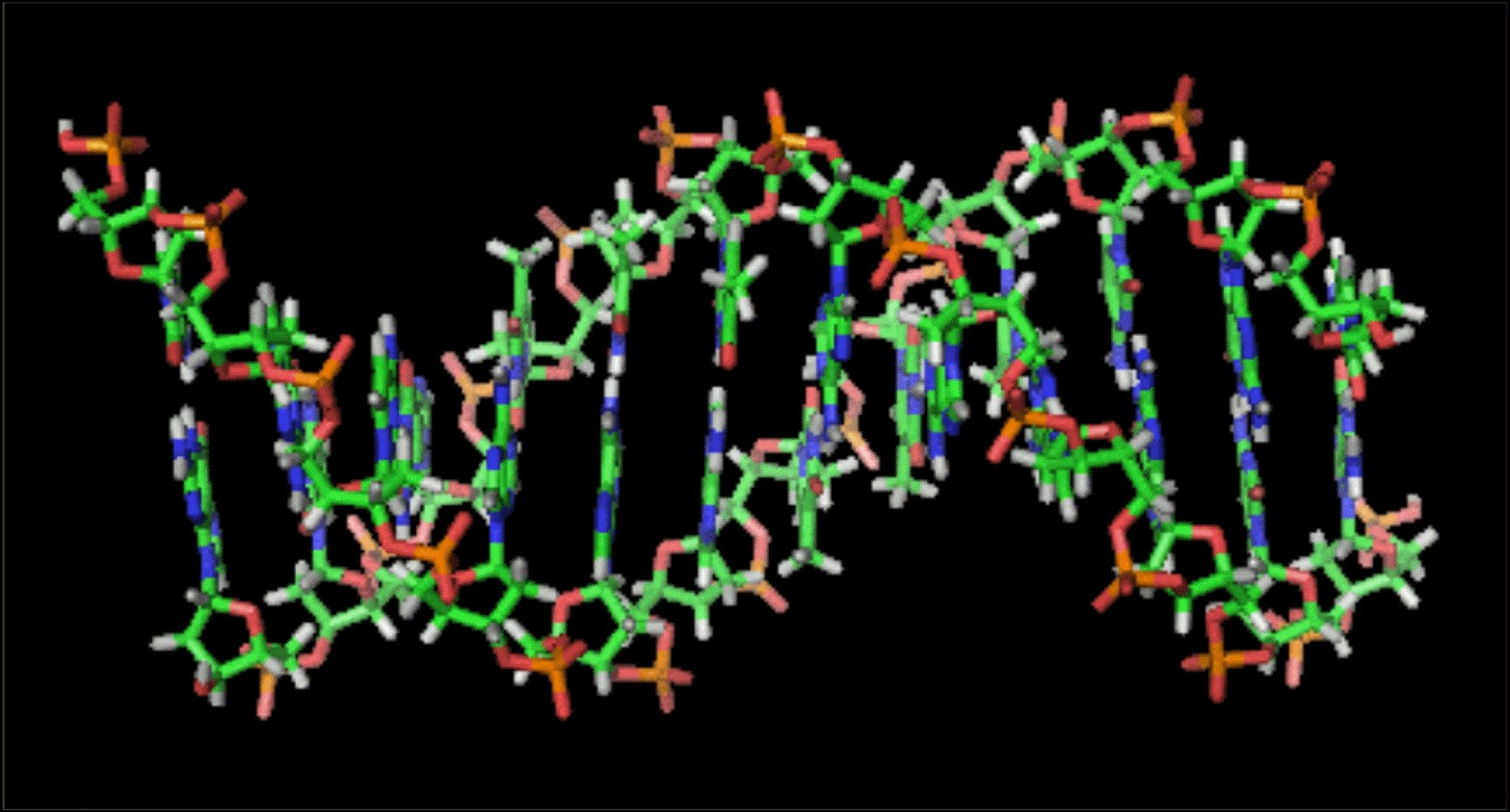
with Ana Catarina Leite, Ana Marta Pinho, Catarina Alves, Duarte Magano, Fernando Moucherek, João Vilas Boas, José Guilherme Matos, Tomás Silva and the rest of the CAUP Dark Side Team, plus Matteo Martinelli, Paolo Molaro and Stefano Cristiani

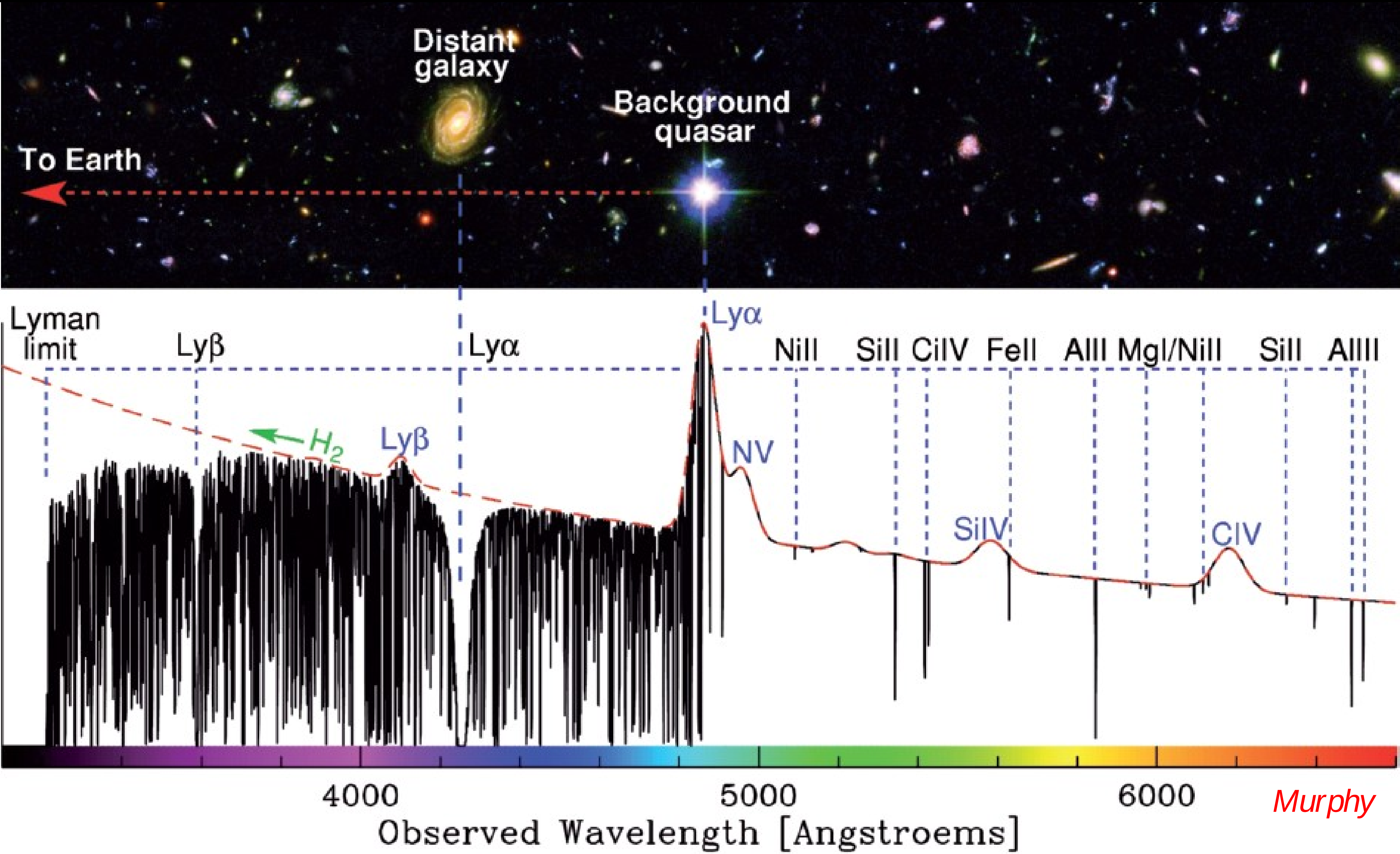
Is this a dog?

Is this a dog?

Precision Taxonomy



Precision Spectroscopy



So What's Your Point?

- Observational evidence for the acceleration of the universe shows that canonical theories of cosmology and particle physics are at least incomplete (and possibly incorrect)
- Is dark energy a cosmological constant (i.e. vacuum energy)?
  - If yes, it's 10^{many} times below Quantum Field Theory expectations
  - If no, the Einstein Equivalence Principle is violated
- New physics is out there, waiting to be discovered; the most pressing task for forthcoming astrophysical facilities is to search for, identify and characterize this new physics
- I will highlight the unique role of ESO facilities in this quest
  - I will mostly focus on ELT-HIRES science
  - ...but will also say a few words about ALMA, MICADO, HARMONI and synergies with other facilities
  - Full disclosure: I'm a member of the ELT PST, the ESPRESSO and ELT-HIRES Science Teams, plus Euclid and LISA

What is Fundamental Physics?

- Tests of fundamental laws/symmetries
  - Equivalence principle, Laws of Gravity, Spacetime structure and dimensionality, Foundations of quantum mechanics, etc.
- Search for/characterization of fundamental constituents
  - Scalar fields (Higgs, dark energy, …), new particles for dark matter, magnetic monopoles, fundamental strings, etc.
- Fundamental cosmology pursues these goals through astrophysical observations
- Fundamental theories (string theory, quantum gravity, extra dimensions, …) often lead to violations of standard principles
  - Space-time structure modified, violating Lorentz invariance
  - Fundamental couplings dynamical, violating Equivalence principle
  - Gravity laws modified at large and/or small scales

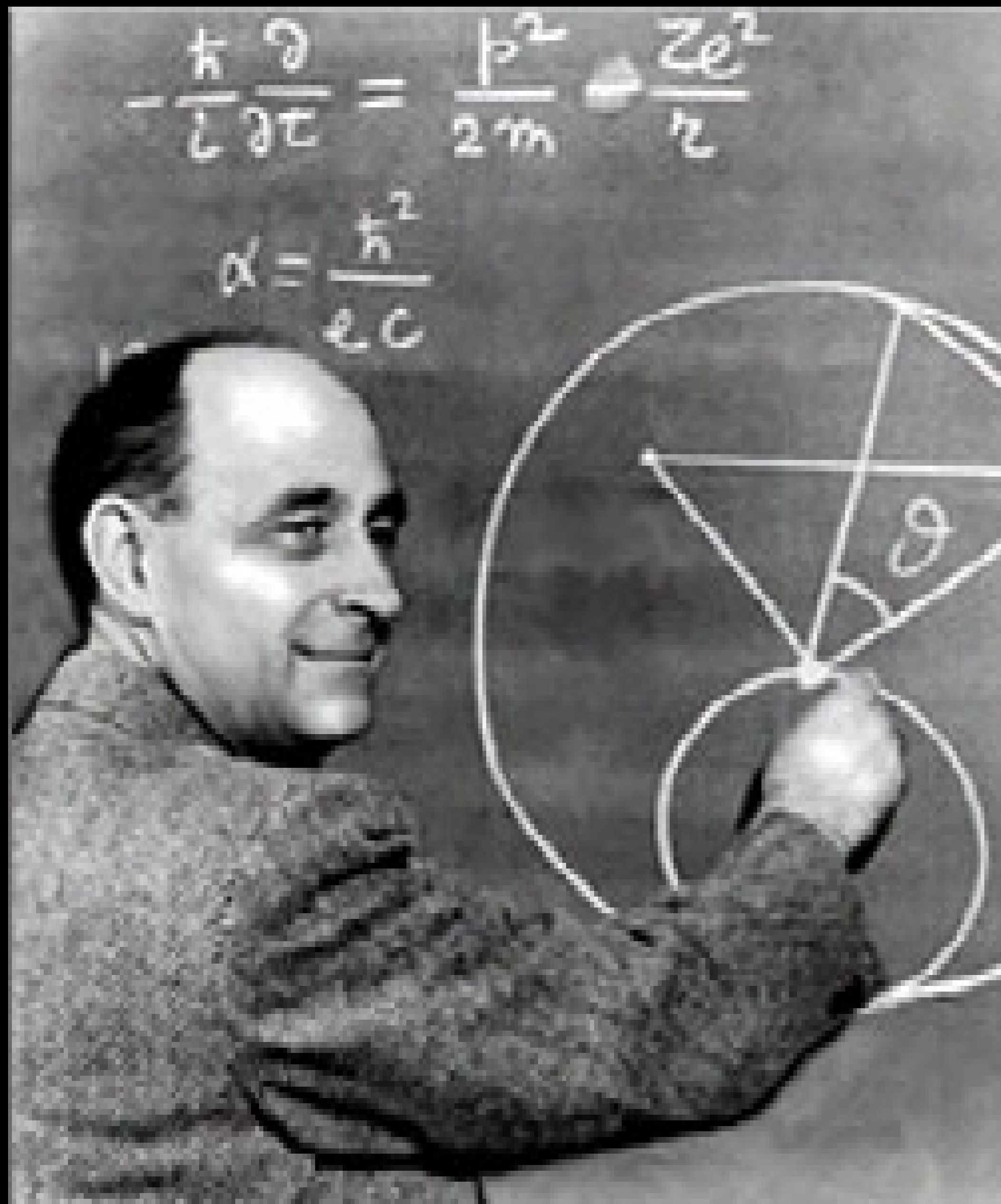
Hints of New Physics

- Three firmly established facts that the standard model of particle physics can't explain:
  - Neutrino masses: Key recent result in particle physics, needs new ad-hoc conservation law or phenomena beyond current framework
  - Dark matter: no Standard Model object can account for all the dark matter required by observations
  - Size of baryon asymmetry: A BAU mechanism does exist, but fails given the measured values of the parameters controlling it
- Our confidence in the standard model that leads us to the expectation that there must be new physics beyond it
    - All have obvious astrophysical and cosmological implications
- Progress in fundamental particle physics increasingly depends on progress in observational cosmology

Scalars, Because They're There

- We now know (from the LHC) that fundamental scalar fields are among Nature's building blocks
  - Does the Higgs have a cosmological counterpart?
  - Scalar fields are popular because they can take a VEV while preserving Lorentz invariance
  - Technical aside: Vector fields or fermions would break Lorentz Invariance and give you problems with Special Relativity
- Scalar fields play a key role in most paradigms of modern cosmology, yielding *inter alia*
  - Exponential expansion of the early universe (inflation)
  - Cosmological phase transitions & their relics (cosmic defects)
  - Dynamical dark energy powering current acceleration phase
  - Varying fundamental couplings
- More important than each of these is the fact that they don't occur alone: this allows key consistency tests

Varying Fundamental Couplings



Fundamental? Varying?

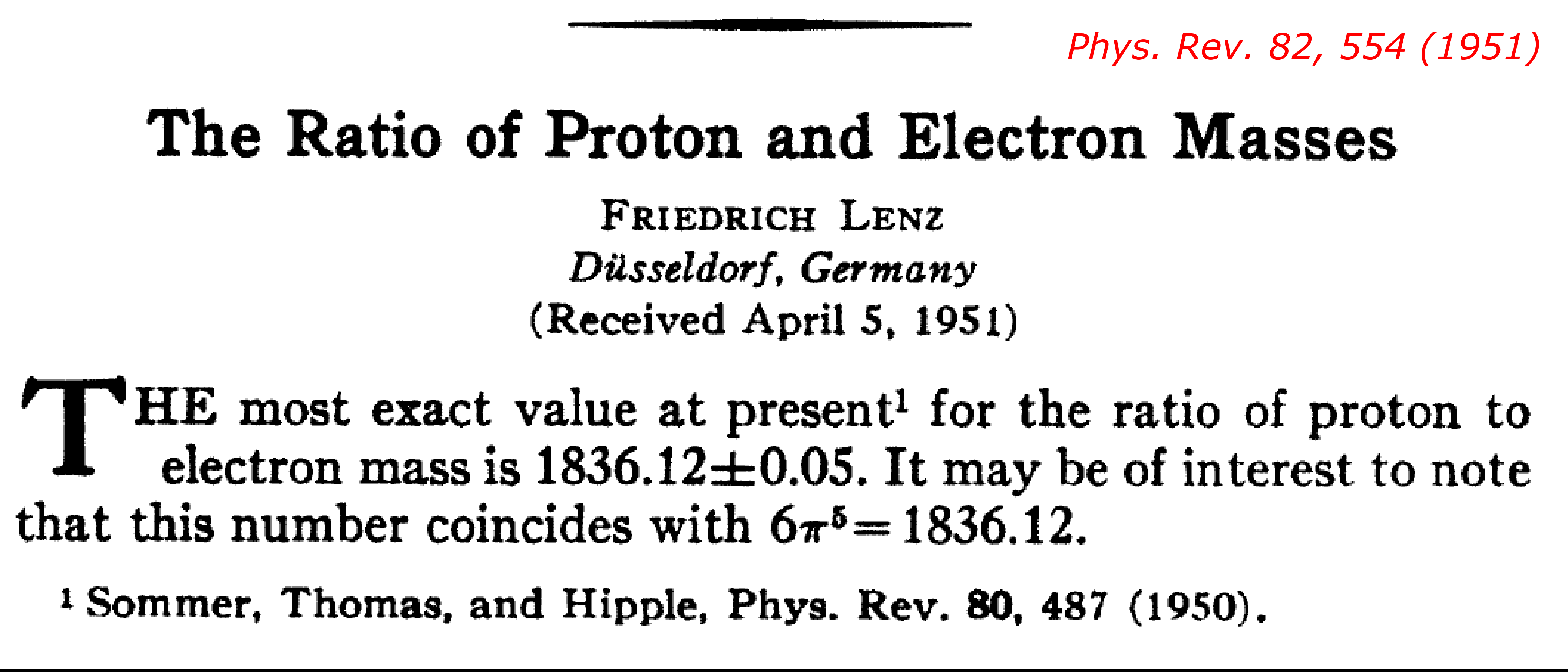
- Nature is characterized by some physical laws and dimensionless couplings, which historically we have assumed to be spacetime-invariant
  - For the former, this is a cornerstone of the scientific method
  - For latter, a simplifying assumption without further justification
- We have no 'theory of constants'
  - They determine properties of atoms, cells and the universe...
  - ...and if they vary, all the physics we know is incomplete
- Improved null results are important and very useful; a detection would be revolutionary
  - Natural scale for cosmological evolution would be Hubble time, but current bounds are 6 orders of magnitude stronger
  - Varying dimensionless physical constants imply a violation of the Einstein Equivalence Principle, a 5th force of nature, etc

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
- Hence expect space-time variation of such effective coupling constants.
    - For example, 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]*

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 $6\pi^5 = 1836.12$.

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

How Low Should One Go?

- Dark energy equation of state vs. Relative variation of α

  $(1+w_0)$ is naively *O*(1) — $(\Delta\alpha/\alpha)$ is naively *O*(1)

  Observationally $< 10^{-1}$ — Observationally $< 10^{-5}$

  - If not O(1), no 'natural' scale for variation: either fine-tuning...
  - ...or a new (currently unknown) symmetry forces it to be zero

- So is it worth pushing beyond ppm? Certainly yes!
  - Strong CP Problem in QCD: a parameter naively O(1) is known to be $<10^{-10}$, leading to postulate of Peccei-Quinn symmetry and axions
  - Sufficiently tight bound would indicate either no dynamical fields in cosmology...
  - ...or a new symmetry to suppress the couplings – whose existence would be as significant as that of the original field

$\alpha(z)$, $\mu(z)$, 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 $\mu=m_p/m_e$, which can be probed with H_2 *[Thompson 1975]* and other molecules
- Also, there will be violations of the T(z) law and the distance duality (Etherington) relation – on which more later
- 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…)

So What's Your Point?

- Wide range of possible α-μ-T relations makes this 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, …]*

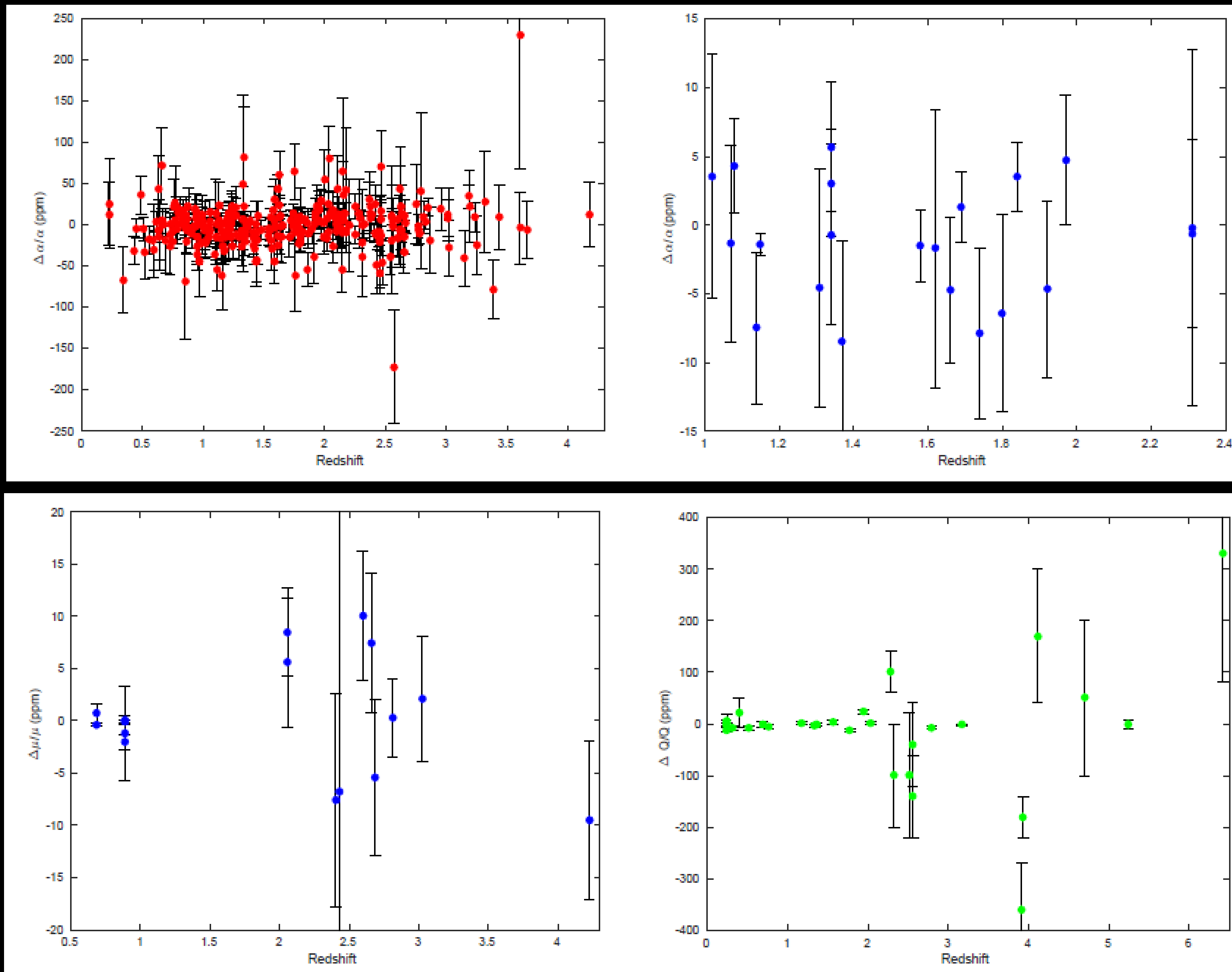
$$\frac{\Delta\mu}{\mu} = [0.8R - 0.3(1+S)]\frac{\Delta\alpha}{\alpha}$$

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

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

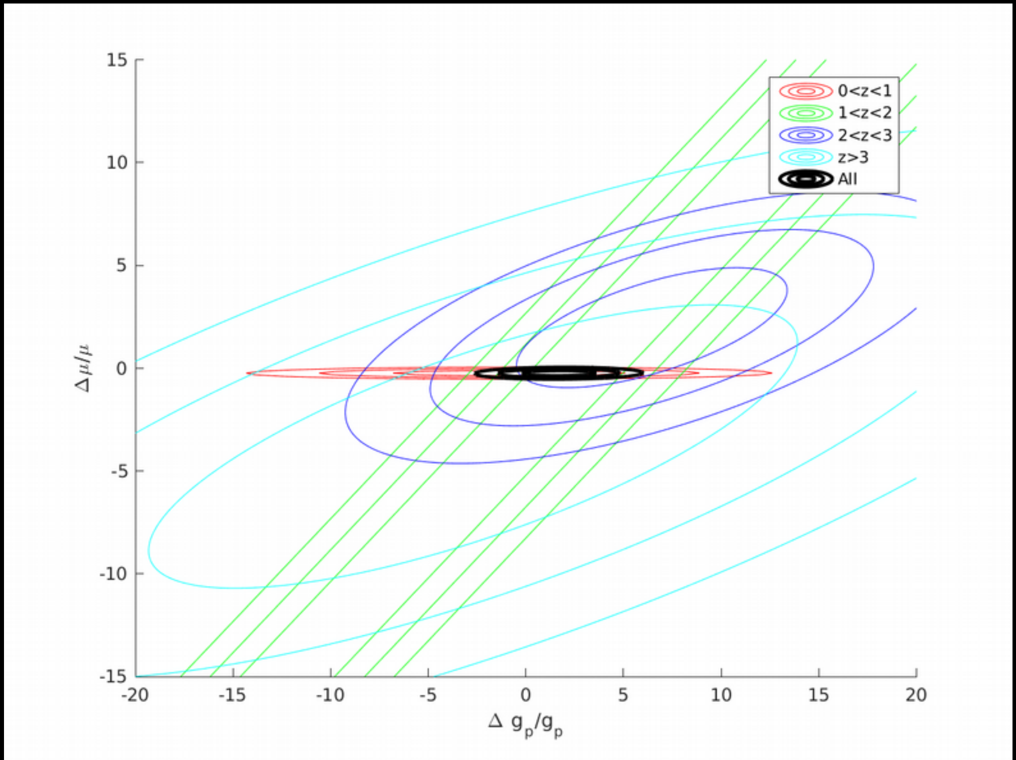
- Theoretically, not all targets are equally useful – must actively search for ideal ones (with ALMA, APEX, …), where
  - Several parameters can be measured simultaneously (e.g., μ+T relatively common both in optical/UV and radio/mm)
  - Occasionally can even measure α, μ and g_p in the same system
  - One or more parameters can be measured in several independent ways (e.g., μ measured from various molecules)

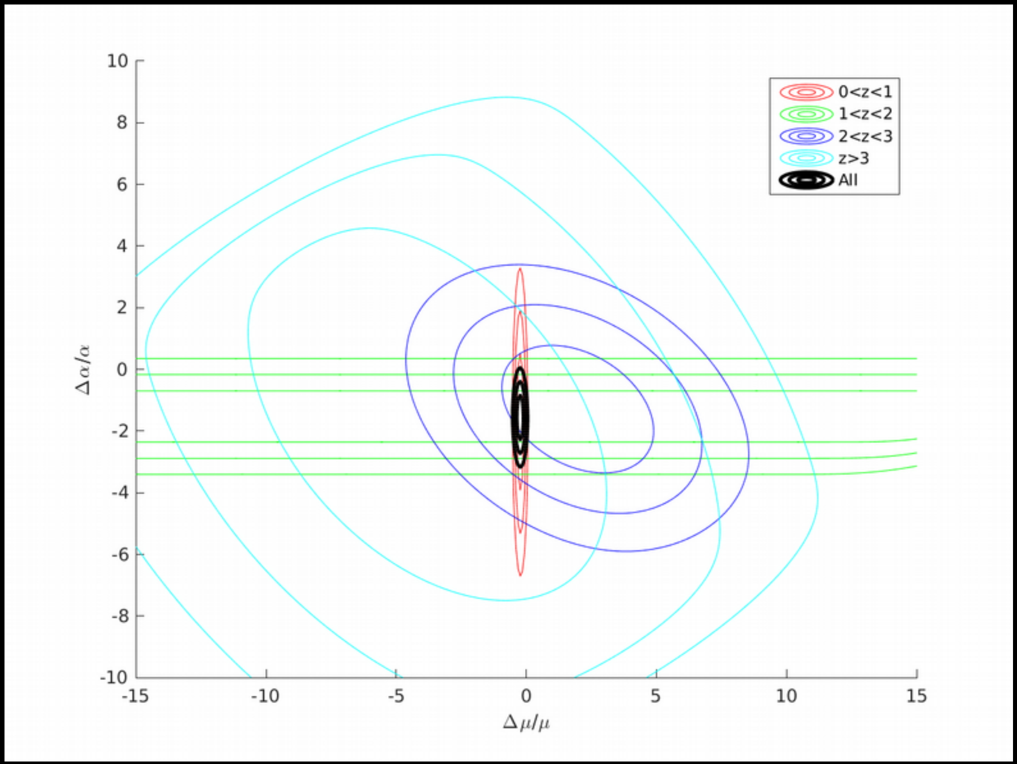
The 359 QSO Measurements So Far

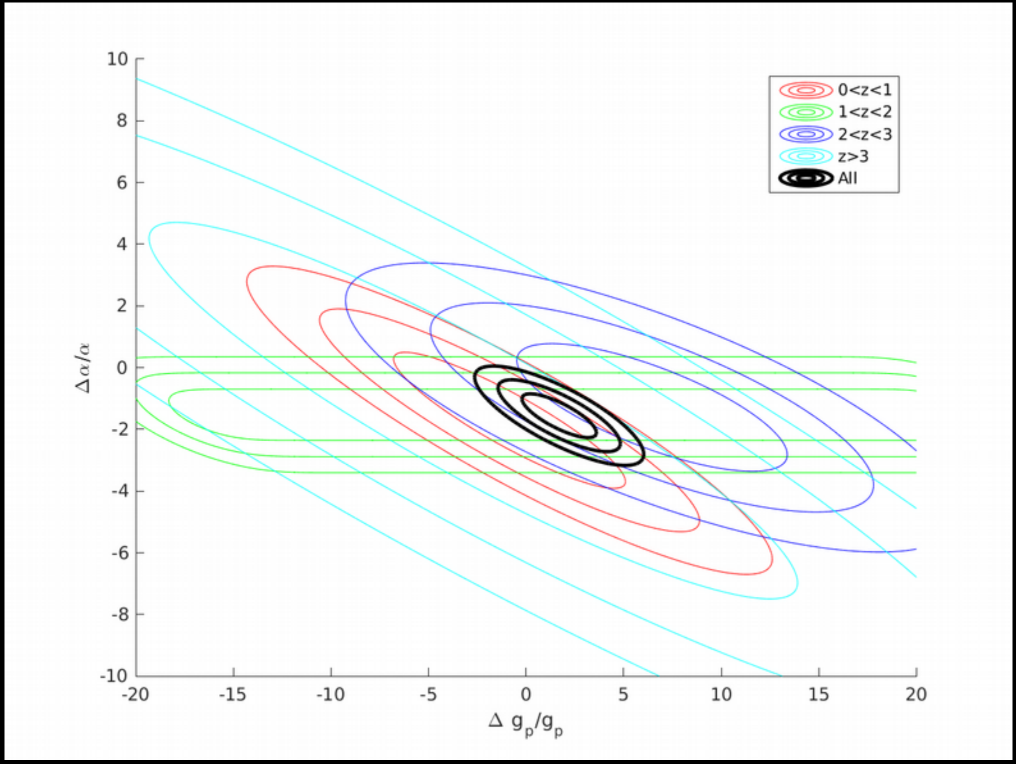


Global Analysis

- Joint analysis optical/UV and radio/mm data yields 1-2σ inconsistencies
  - Thus differences in matter and acceleration eras
  - To be clarified with APEX, ALMA and ESPRESSO

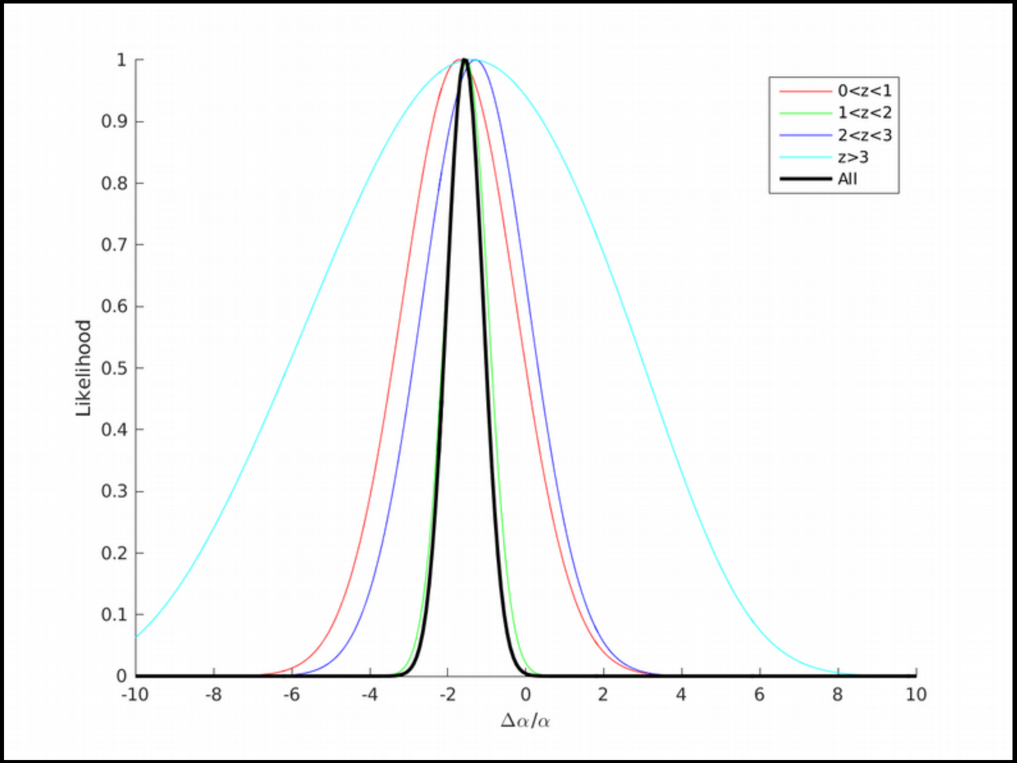


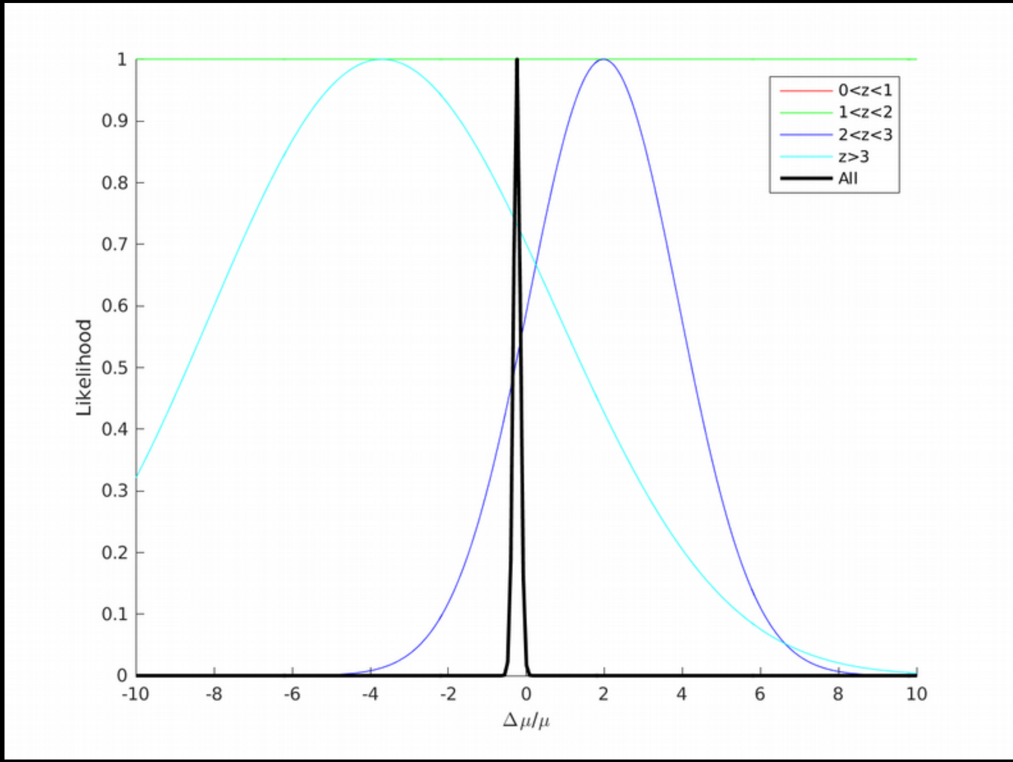


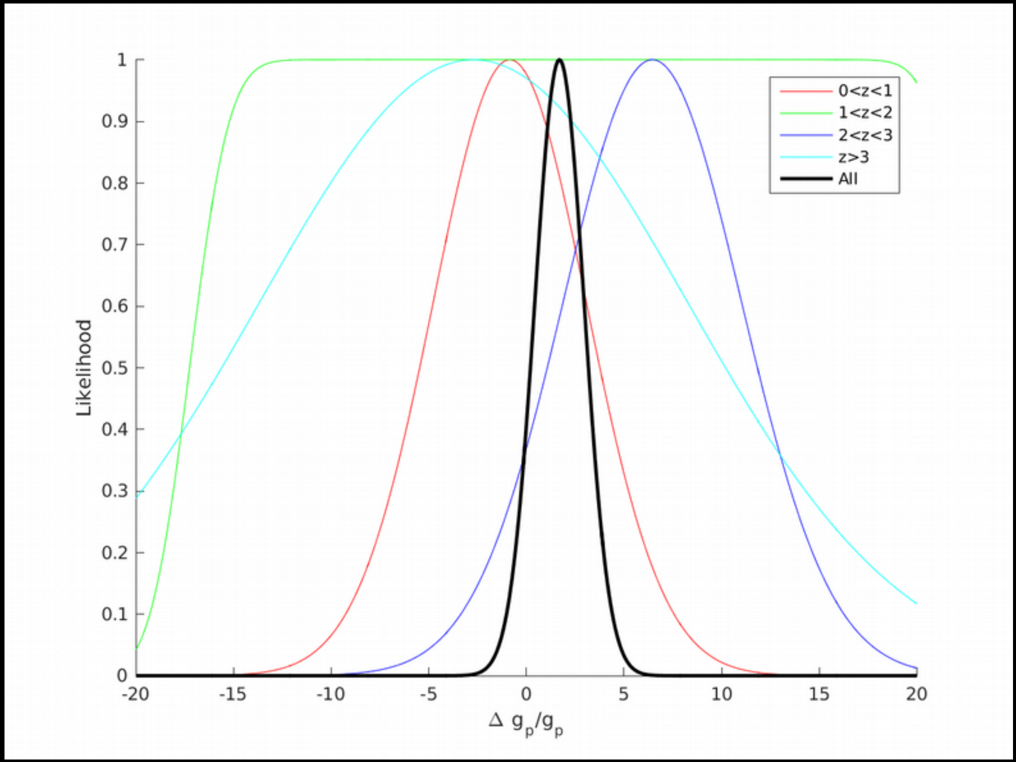


Global Analysis

- Very tight constraint on μ, but only at z<1
  - All-z best-fit 1σ values
    $\Delta\alpha/\alpha$ = -1.6±0.5 ppm
    $\Delta\mu/\mu$ = -0.2±0.1 ppm
    $\Delta g_p/g_p$ = 1.7±1.3 ppm

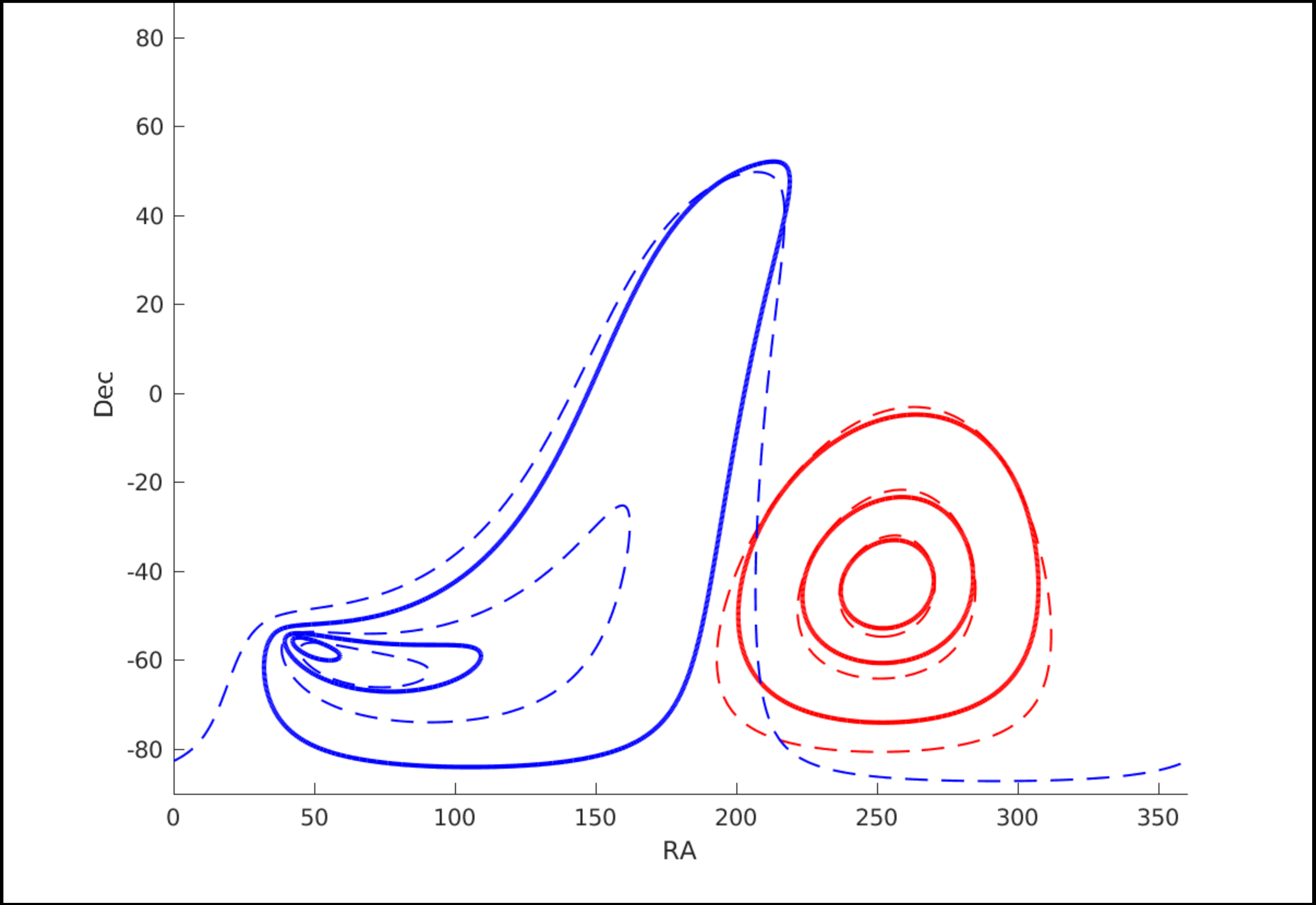






Spatial Variations: Dipoles?

- Webb *et al.* (2011): 4.2 σ statistical evidence for α dipole
  - Updated analysis: 2.3 σ, A = 5.6 ± 1.8 ppm
  - For μ, A < 1.9 ppm (95.4% cl), also different preferred directions



Other Constraints (Briefly)

- Atomic clocks: sensitivity of fewx10^{-17}/yr *[Rosenband et al. 2008]*
  - Future: molecular & nuclear clocks, 10^{-21}/yr achievable?
- Compact objects can constrain environmental dependencies to 10^{-4} sensitivity; limited by nuclear physics uncertainties
  - Solar-type stars *[Vieira et al. 2012],* Population III stars *[Ekstrom et al. 2010]*, Neutron stars *[Pérez-García & Martins 2012]*
  - White dwarf measurements now available *[Berengut et al. 2013, Bagdonaite et al. 2014]*
- Oklo (natural nuclear reactor, 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 *[Planck 2015]* and BBN *[Martins et al. 2010]*
  - Tighter constraints can be obtained for specific model choices
  - Li problem could be solved in some GUT scenarios? *[Stern 2008]*

Atomic Clocks & Unification

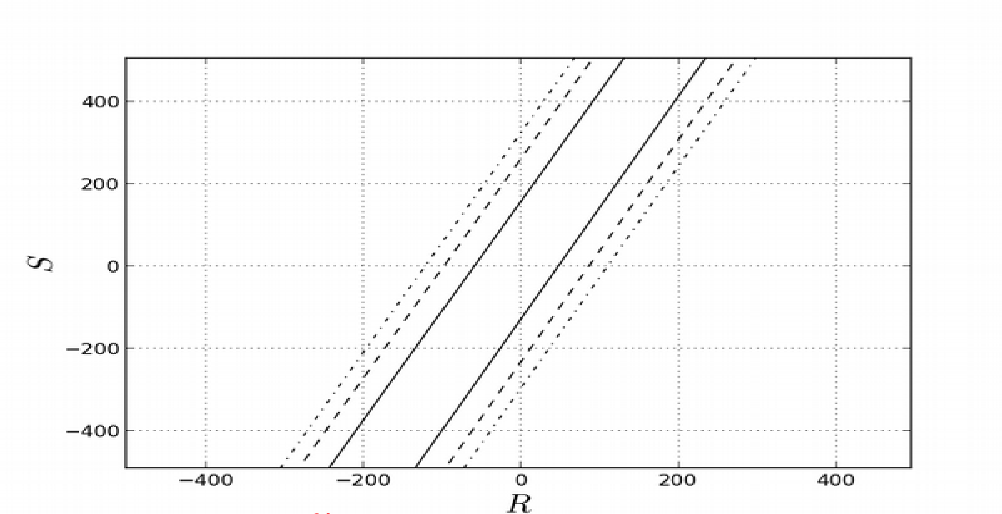
Clocks	$\dot{\nu}_{AB}/\nu_{AB}$ (yr^{-1})	λ_α	λ_μ	λ_g
Hg-Al	$(5.3 \pm 7.9) \times 10^{-17}$	-2.95	0.0	0.000
Dy162-Dy164	$(-5.8 \pm 6.9) \times 10^{-17}$	1.00	0.0	0.000
Cs-SF_6	$(-1.9 \pm 2.7) \times 10^{-14}$	2.83	0.5	-1.266
Cs-H	$(3.2 \pm 6.3) \times 10^{-15}$	2.83	1.0	-1.266
Cs-Sr	$(1.80 \pm 0.55) \times 10^{-16}$	2.77	1.0	-1.266
Cs-Hg	$(-3.7 \pm 3.9) \times 10^{-16}$	5.77	1.0	-1.266
Cs-Yb(E2)	$(-0.5 \pm 1.9) \times 10^{-16}$	1.83	1.0	-1.266
Cs-Yb(E3)	$(-0.2 \pm 4.1) \times 10^{-16}$	8.83	1.0	-1.266
Cs-Rb	$(1.07 \pm 0.49) \times 10^{-16}$	0.49	0.0	-2.000

$$\frac{d\ln\alpha}{dt} = (-2.2 \pm 2.4) \times 10^{-17}\,\mathrm{yr}^{-1}$$

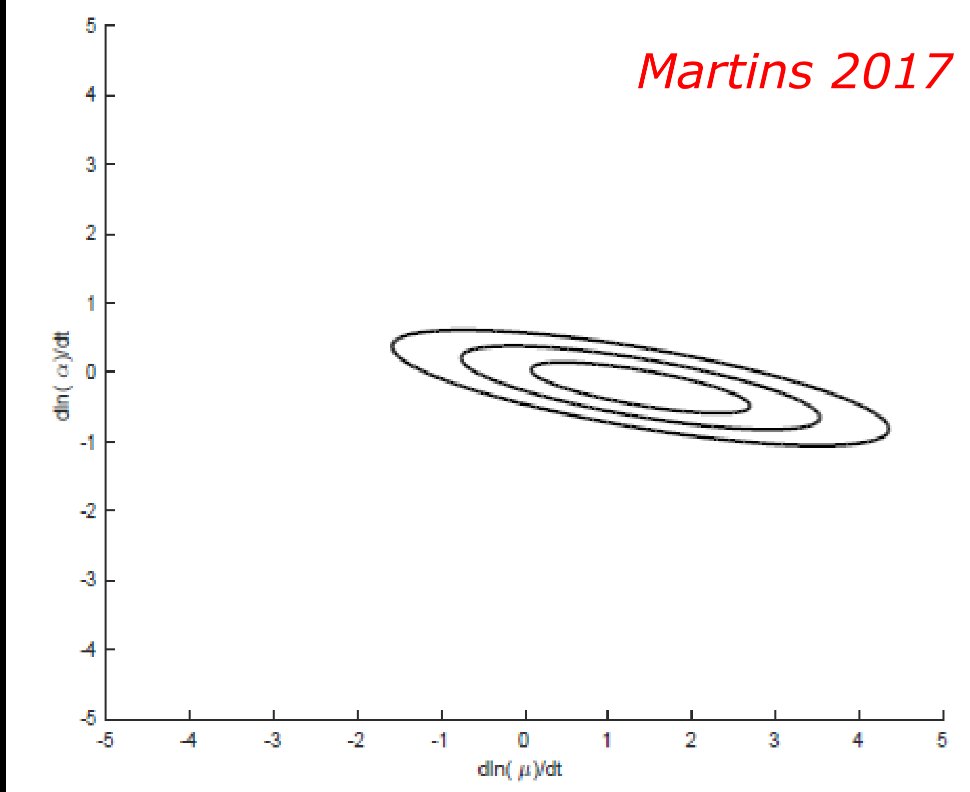
$$\frac{d\ln\mu}{dt} = (13.8 \pm 8.6) \times 10^{-17}\,\mathrm{yr}^{-1}$$

$$\frac{d\ln g_p}{dt} = (-5.8 \pm 2.5) \times 10^{-17}\,\mathrm{yr}^{-1}$$

- Tight constraints on present drifts, impacting cosmology
  - Also constraining unification



Ferreira, Julião, Martins & Monteiro 2012



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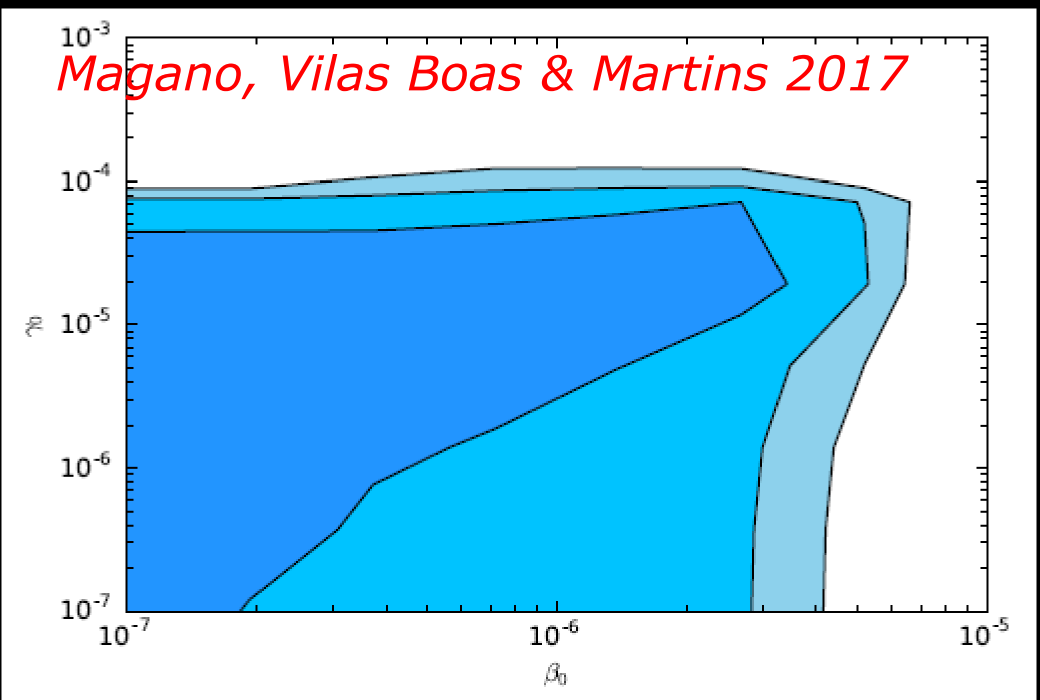
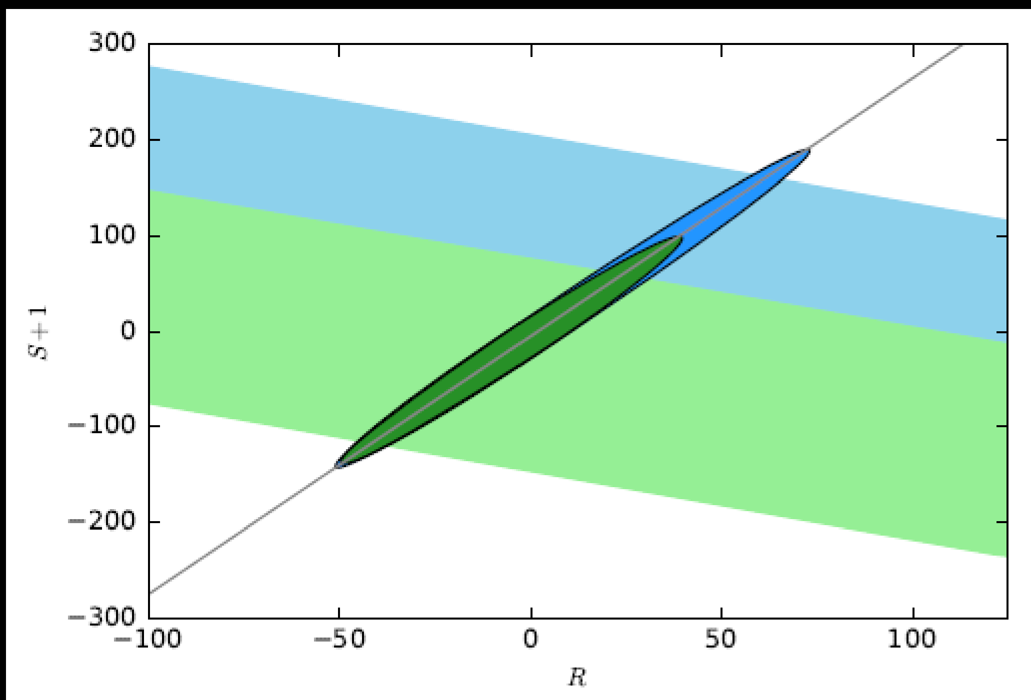
White Dwarfs & Unification

- The mass-radius relation for white dwarfs has an interesting dependence on α, R and S
  - Can constrain them if M and R are measured independently, though only 12 measurements exist *[Holberg et al. 2012]*
  - α (and also μ) directly measured on the surface of white dwarfs
- Combining the two yields complementary constrains on the R-S parameter space: opportunity for further GUT tests





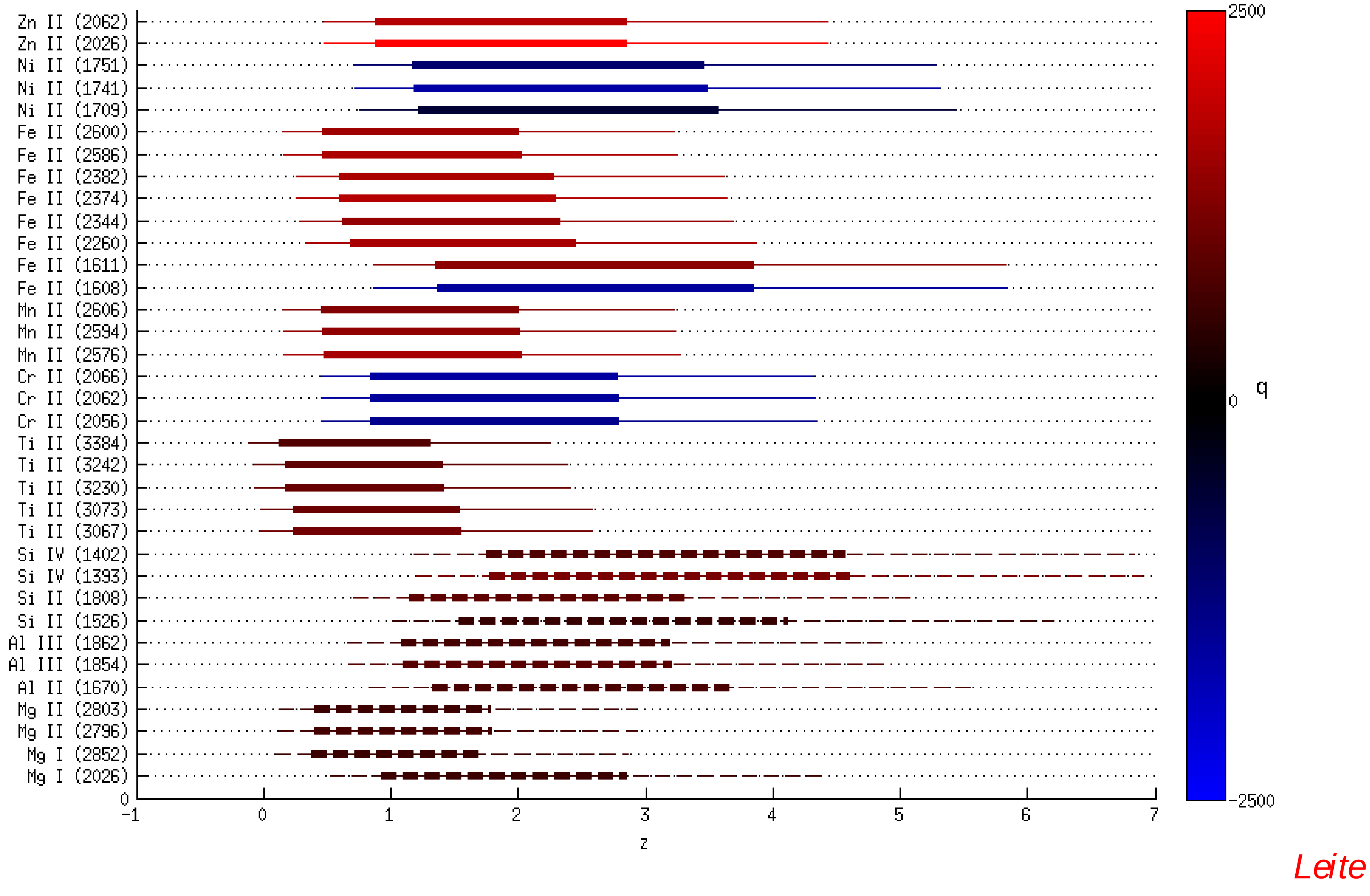
Would you like an ESPRESSO?

- ESPRESSO is...
  - A spectrograph on a 16m telescope (the largest until ELTs)
  - 380-780nm coverage in one shot
  - Wavelength calibration far more accurate than any other facility
  - Cleanest, best-quality spectra both at high and low SNR
  - Ultra-high resolution mode

Par./Mode	HR (1UT)	MR(4UTs)	UHR
Wave. range	380–780 nm	380–780 nm	380–780 nm
Resol. Power	134 000	59 000	≈ 200 000
Aper. on Sky	$1\farcs0$	$4'' \times 1''$	$0\farcs5$
Spec. Samp.	4.5 pix	11 pix	2.5 pix
Spat. Samp.	11×2 pix	22×2 pix	5×2 pix
Sim. Ref.	Yes (no sky)	Yes (no sky)	Yes (no sky)
Sky Sub.	Yes (no ref.)	Yes (no ref.)	Yes (no ref.)
Tot. Eff.	11 %	11 %	5 %

- 273 nights GTO: 80% exoplanets, 10% fundamental couplings
  - 10% still to be decided
  - External collaborators for specific projects possible
  - If you have any well-developed ideas, do get in touch (soon)

The ESPRESSO Bottleneck



Preliminary Targets

Name	z_{abs}	M	$\frac{\Delta\alpha}{\alpha}$ (10^{-6})	$\sigma_{\frac{\Delta\alpha}{\alpha}}(10^{-6})$	$\frac{\Delta\alpha}{\alpha}_{dip.}(10^{-6})$	Δq	# trans.	trans.	α syst	μ	T	Ref.
J034943-381031	3.02	17.3	-27.9	34.2	0.2	1350	2	SiII,FeII	1	x	x	[1]
J040718-441013	2.59	17.3	5.7	3.4*	0.9	2984	13	AlII,AlIII,SiII,CrII,FeII,FeII,NiII,ZnII	4	x'		[2]
J043037-485523	1.35	16.5	-4.0	2.3*	1.6	2990	17	MgI,AlII,SiII,CrII,MnII,FeII,NiII	1			[2]
J053007-250329	2.14	18.8	6.7	3.5*	-2.5	2990	7	AlII,CrII,FeII,FeII,NiII	1	x'		[2]
J110325-264515	1.84	15.9	6.1	3.9*	1.7	2890	4	SiII,FeII,FeII	4			[2]
J110325-264515	1.84	15.9	5.6	2.6	1.7	2760	3	FeII,FeII	4			[3]
J115944+011206	1.94	17.5	5.1	4.4*	-1.6	2990	12	SiII,CrII,MnII,FeII,FeII,NiII	3			[2]
J133335+164903	1.77	16.7	8.4	4.4	-1.9	2990	15	MgII,AlII,SiII,CrII,MnII,FeII,FeII,NiII,ZnII	4			[2]
HE1347-2457	1.43	16.3	-21.3	3.6	4.1	2790	3	FeII,FeII	1			[3]
J220852-194359	1.92	17.0	8.5	3.8	2.4	3879	16	AlII,SiII,CrII,MnII,FeII,FeII,NiII,ZnII	7			[2]
HE2217-2818	1.69	16.0	1.3	2.4	3.4	2890	6	AlIII,FeII,FeII	1			[4]
Q2230+0232	1.86	18.0	-9.9	4.9	-0.9	3879	14	SiII,CrII,FeII,FeII,NiII,ZnII	2			[1]
J233446-090812	2.15	18.0	5.2	4.3*	-0.5	3879	16	AlIII,CrII,FeII,FeII,NiII,ZnII	3			[2]
J233446-090812	2.28	18.0	7.5	3.7*	-0.5	2610	7	SiIV,CrII,FeII,FeII,NiII	3			[2]
Q2343+1232	2.43	17.5	-12.2	3.8*	-3.8	3879	11	AlII,SiII,CrII,FeII NiII,ZnII	4			[1]

* Measurements that lost transitions due to the wavelength range of ESPRESSO

' Measurements outside of the wavelength range of ESPRESSO

Leite, Martins, Molaro, Cristiani

References: [1] - Murphy's Ph.D. Thesis (2002), [2] - King's Ph.D. Thesis (2012), [3] - Molaro et al. (2008), [4] - Bonifacio et al. (2014)

- Only 2 (4?) targets for μ, 5 (6?) for T(z): a concern for HIRES