Three Tests of ΛCDM

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& the CAUP Dark Side Team

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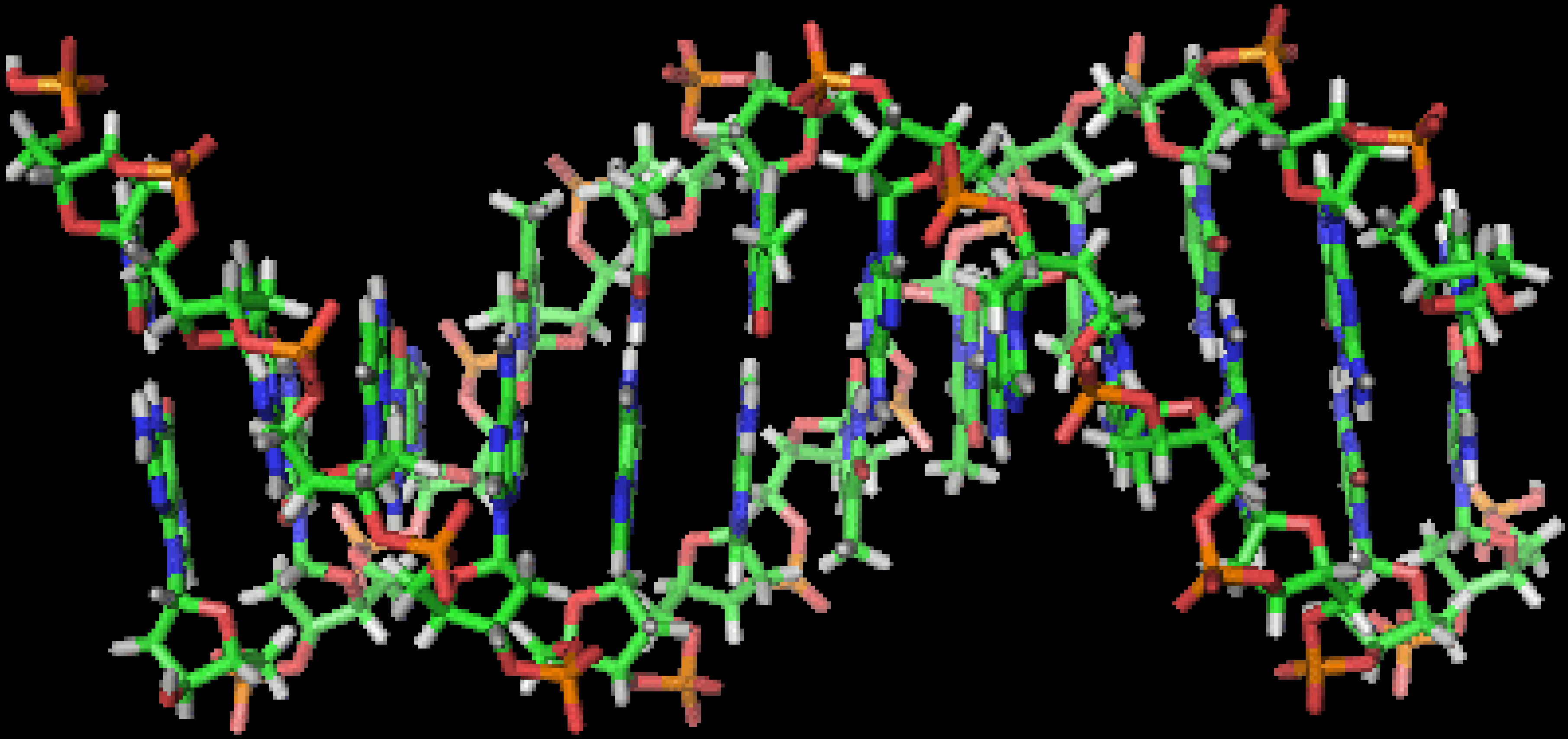
FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

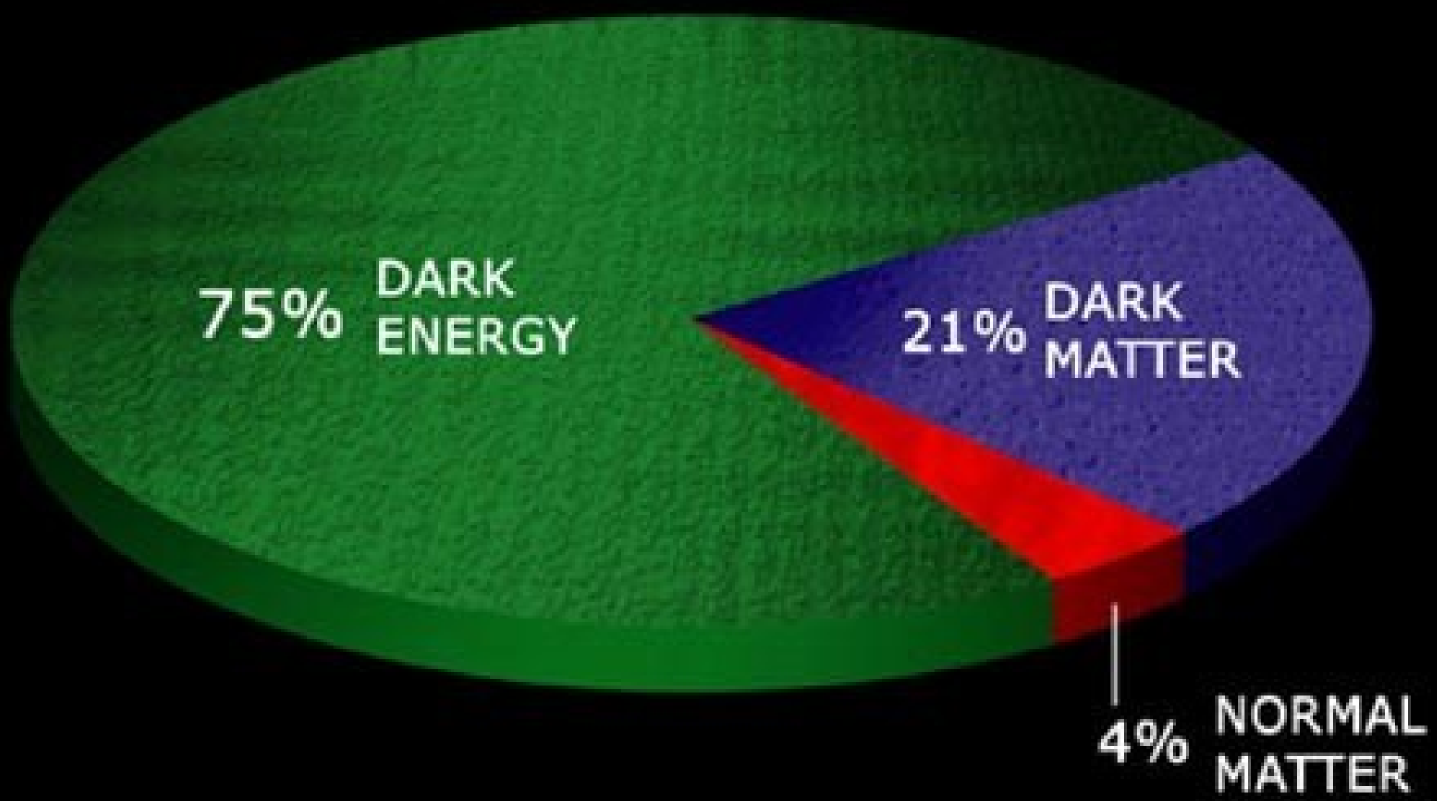
Is this a dog?

Is this a dog?

Precision Taxonomy



The Dark Universe: a new Neptune or a Vulcan?



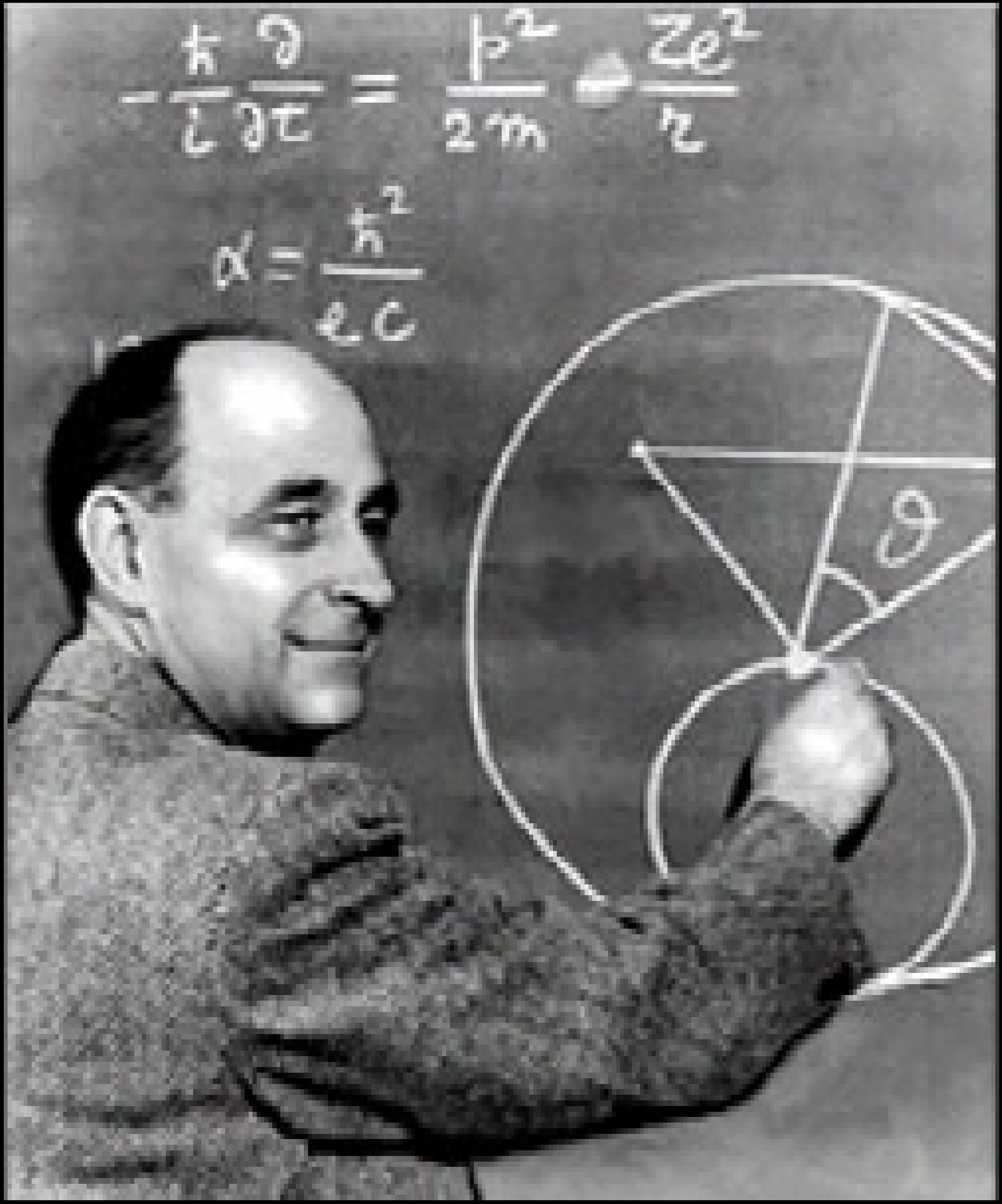
Hints of New Physics

- 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 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 cosmology.***

Scalar Fields in Cosmology

- 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
- ***Even more important than each of these paradigms is the fact that they don't occur alone: this will be crucial for future consistency tests!***

Varying Fundamental Constants



The Constants of Nature

- Nature is characterized by a set of physical laws and fundamental 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
- These couplings determine the properties of atoms, cells, planets and the universe as a whole.
  - If they vary, all the physics we know is incomplete
- Improved null results are important and 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 non-gravitational constants imply a violation of the Einstein Equivalence Principle, a 5th force of nature, etc

Classification

- A completely unsolved issue: no 'theory of constants' exists! *[Duff et al. 2002, Martins 2002]*
- A useful classification is in *[Lévy-Leblond 1979]*
  - Type A: Properties of particular physical objects, e.g. masses and moments of fundamental particles
  - Type B: Characteristics of classes of physical phenomena, e.g. coupling constants
  - Type C: Universal constants, e.g. speed of light, Planck constant
  - Type D: Invisible constants, e.g. isotropy of space, equivalence of inertial and gravitational mass
  - Type E: Constants indistinguishable from zero, e.g. mass of photon, neutrality of matter
- The classification of some constants changes with time, and may be different in different theories!

Phys. Rev. 82, 554 (1951)

The Ratio of Proton and Electron Masses

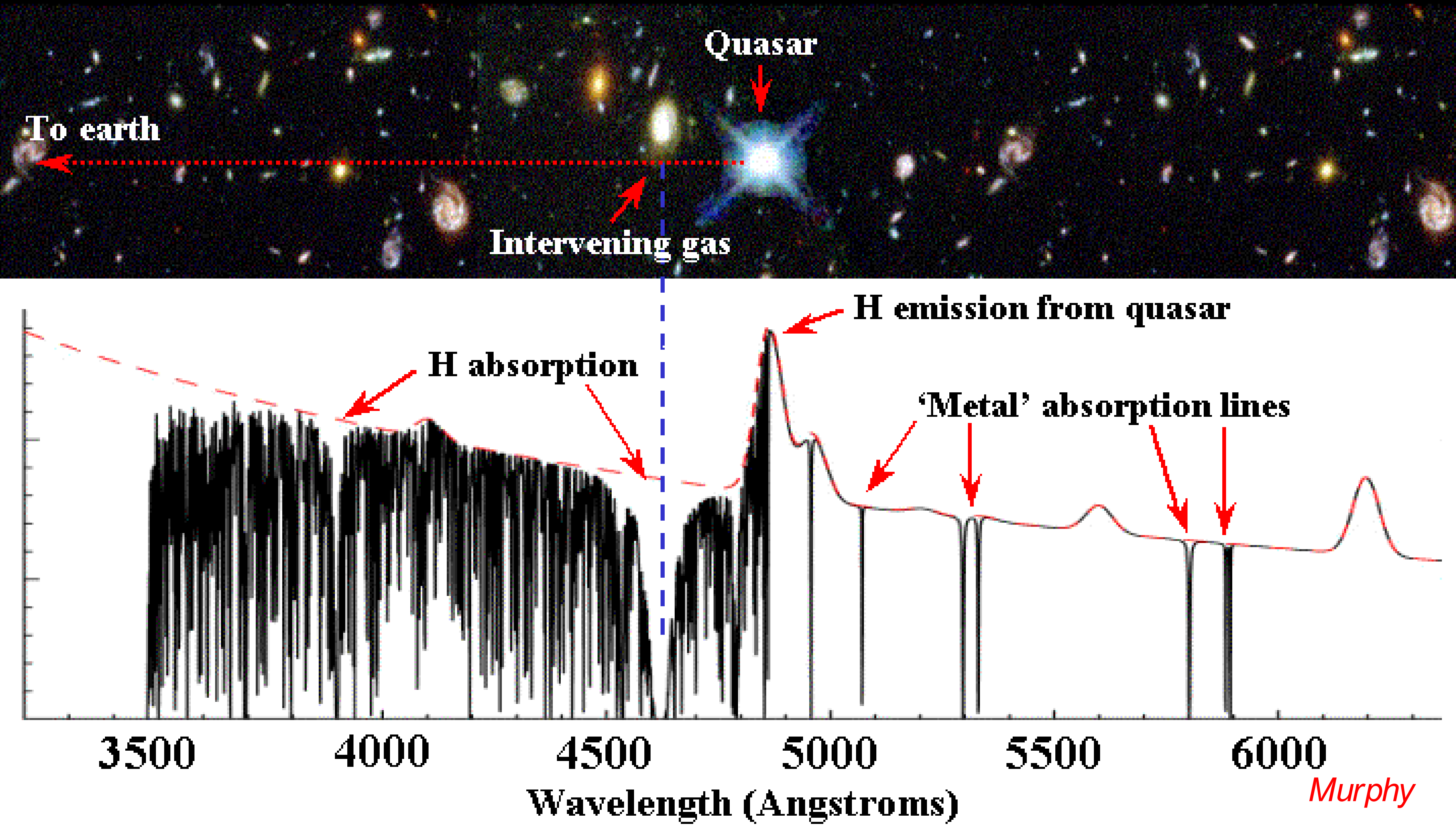
FRIEDRICH LENZ
Düsseldorf, Germany

(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 $6\pi^5 = 1836.12$.

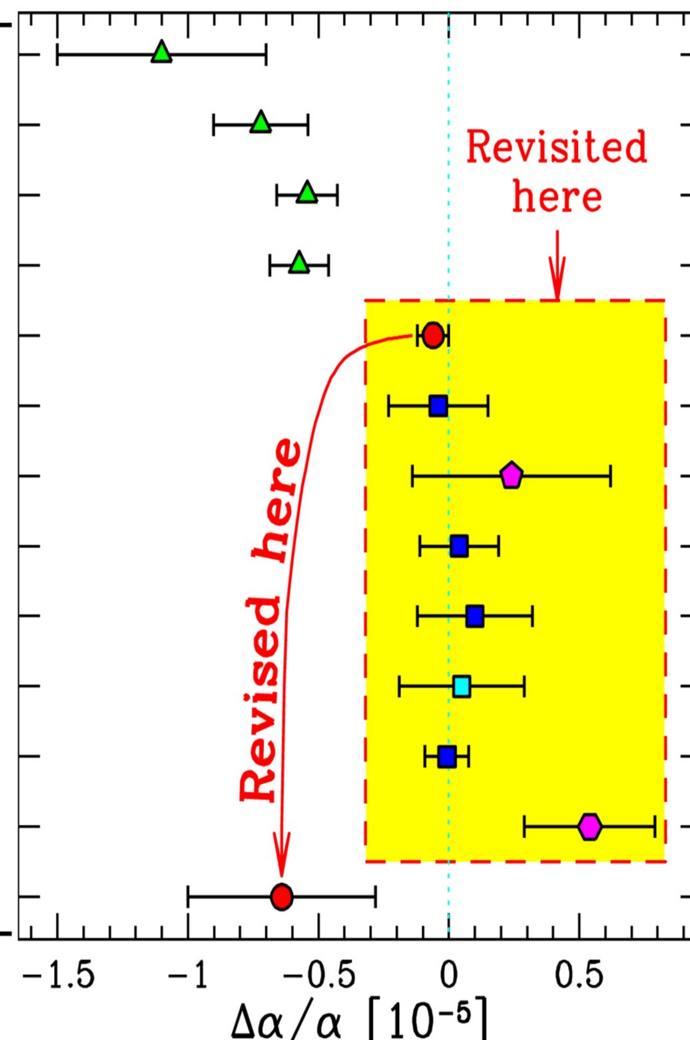
[1] Sommer, Thomas, and Hipple, Phys. Rev. **80**, 487 (1950).

Measuring α from Quasars



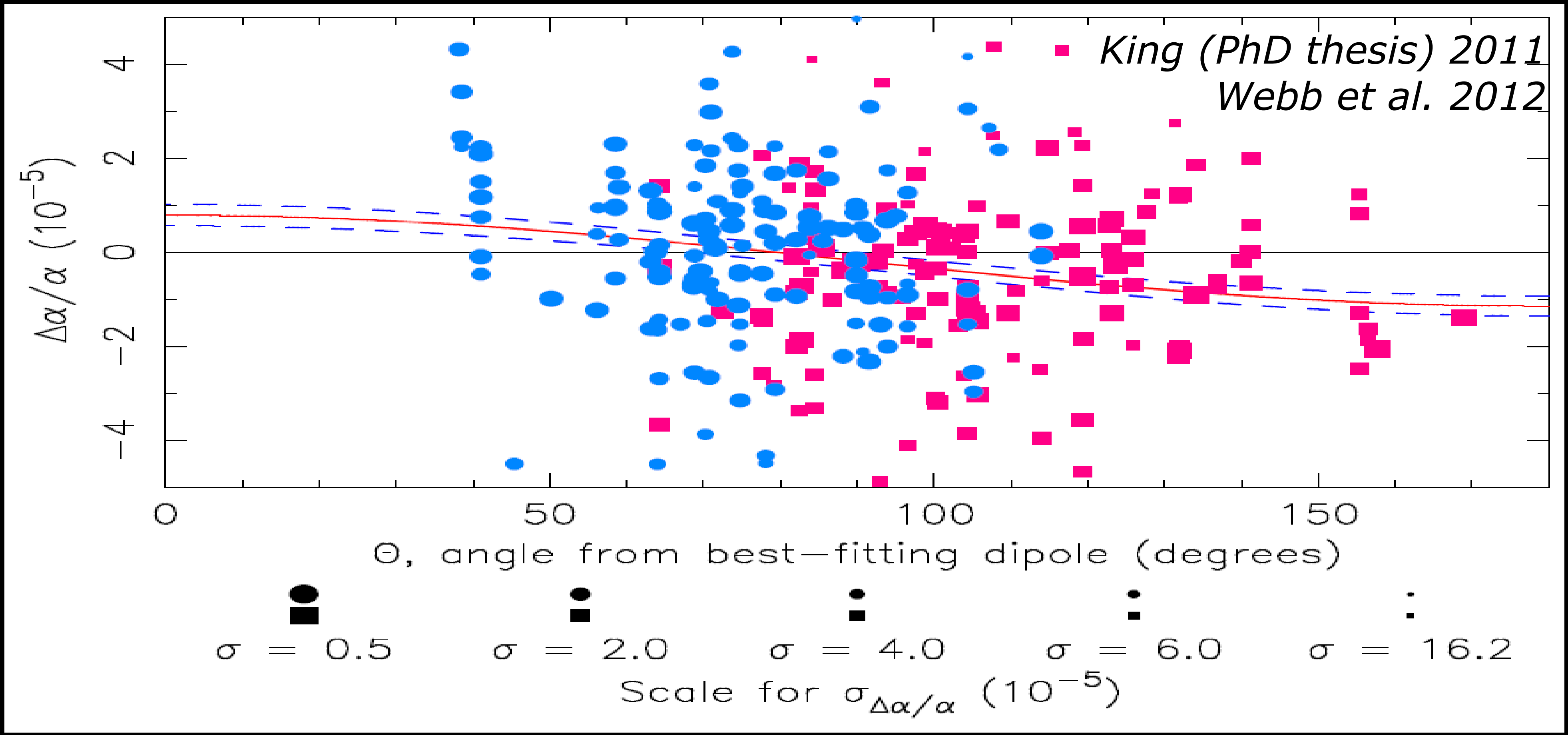
The Controversy Continues...

Instrument	N_{abs}	z_{abs}	$\Delta\alpha/\alpha$ [10^{-5}]	Reference
HIRES	30	0.5–1.6	−1.100 ± 0.400	Webb et al. (1999)
HIRES	49	0.5–3.5	−0.720 ± 0.180	Murphy et al. (2001a)
HIRES	128	0.2–3.7	−0.543 ± 0.116	Murphy et al. (2003)
HIRES	143	0.2–4.2	−0.573 ± 0.113	Murphy et al. (2004)
UVES	23	0.4–2.3	−0.060 ± 0.060	Chand et al. (2004)
UVES	1	1.151	−0.040 ± 0.190 ± 0.270	Quast et al. (2004)
UVES	1	1.839	+0.240 ± 0.380	Levshakov et al. (2005)
UVES	1	1.151	+0.040 ± 0.150	Levshakov et al. (2005)
UVES	1	1.151	+0.100 ± 0.220	Chand et al. (2006)
HARPS	1	1.151	+0.050 ± 0.240	Chand et al. (2006)
UVES	1	1.151	−0.007 ± 0.084 (± 0.100)	Levshakov et al. (2006)
UVES	1	1.839	+0.540 ± 0.250	Levshakov et al. (2007)
UVES	23	0.4–2.3	−0.640 ± 0.360	This work



Murphy et al.

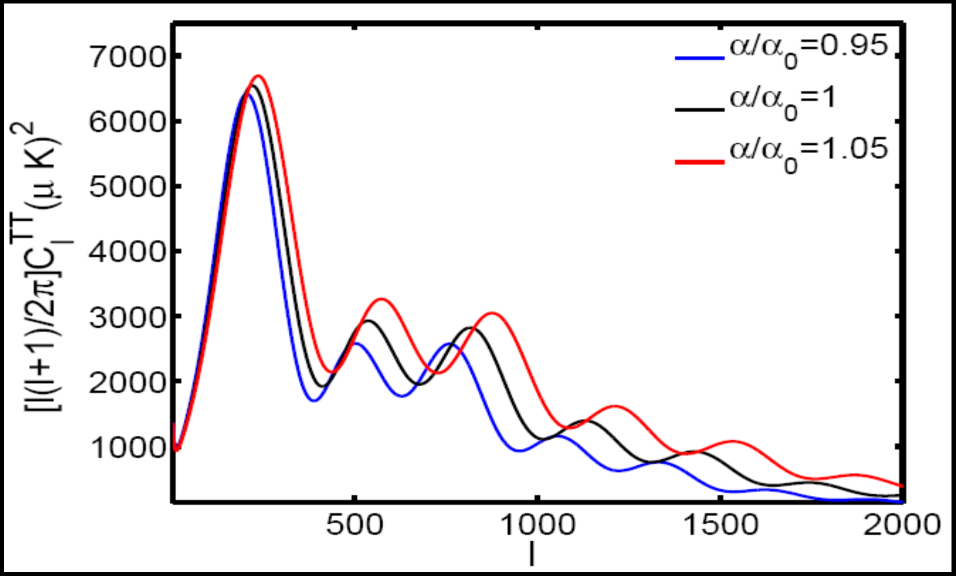
A Dipole on the Sky?

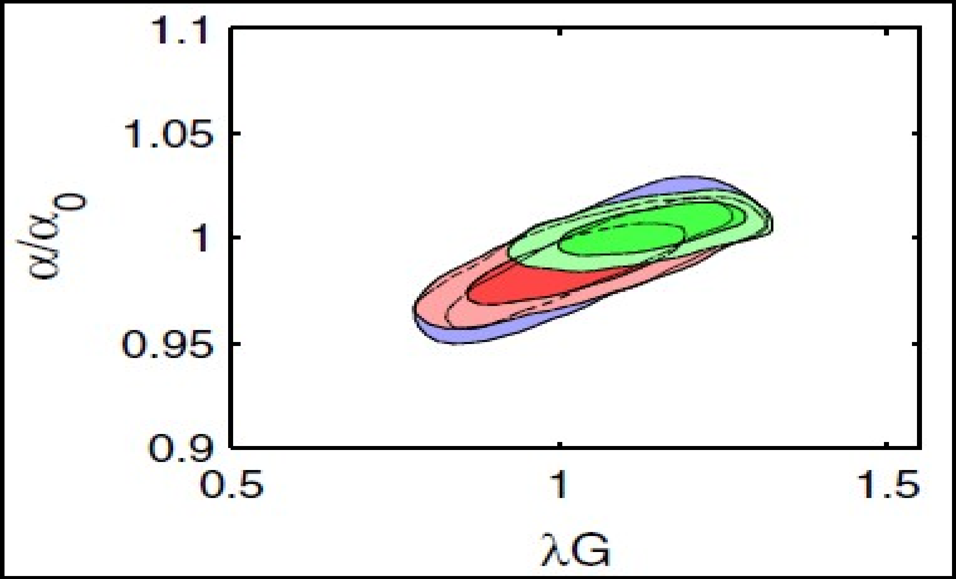


- New physics or systematics?
  - No known systematic can explain dipole
  - Existing data has been taken with other purposes
  - Need customized analysis pipelines *[Thompson et al. 2009, ...]*
  - UVES LP first results out soon *[Molaro et al. 2012, ...]*

Varying α and the CMB

- Changes ionization history
  - Energy levels & binding energies are shifted: changes z_{dec}
  - Changes the Thomson cross-section: effect goes as α^2
- Bounds relatively weak due to degeneracies
  - Percent barrier recently broken *[Menegoni et al. 2009]*
  - No evidence for variations
  - Can constrain joint variations, e.g. with G *[Martins et al. 2010]*





Early Dark Energy

- A cosmological constant is negligible at recombination, but a tracking scalar field can induce significant α variations.
  - All recent constraints on a have assumed Λ or constant w
  - There may be degeneracies
  - New data from ACT *[Dunkley et al. 2010]* and from H_0 measurements.
- Can use the EDE class of models *[Doran & Robbers 2006]*, linearly coupled to electromagnetism *[Nunes & Lidsey 2004].*

$$\Omega_{\rm de}(a) = \frac{\Omega_{\rm de}^0 - \Omega_{\rm e}\left(1 - a^{-3w_0}\right)}{\Omega_{\rm de}^0 + \Omega_m^0 a^{3w_0}} + \Omega_{\rm e}\left(1 - a^{-3w_0}\right)$$

$$w(a) = -\frac{1}{3[1 - \Omega_{\rm de}(a)]}\frac{d\ln\Omega_{\rm de}(a)}{d\ln a} + \frac{a_{eq}}{3(a + a_{eq})}$$

$$\alpha/\alpha_0(a) = 1 - \zeta\int_a^{a_0}\sqrt{3\Omega_{\rm de}(a)(1 + w(a))}\,d\ln a$$

$$\mathcal{L}_{\phi F} = -\frac{1}{4}B_F(\phi)F_{\mu\nu}F^{\mu\nu}$$

$$B_F(\phi) = 1 - \zeta\kappa(\phi - \phi_0)$$

$$\frac{\Delta\alpha}{\alpha} \equiv \frac{\alpha - \alpha_0}{\alpha_0} = \zeta\kappa(\phi - \phi_0)$$

$$w = -1 + \frac{(\kappa\phi')^2}{3\Omega_{\rm de}}$$

Varying α and Early Dark Energy

Datasets	α/α_0	Ω_e	ζ
WMAP7+HST	0.963 ± 0.044	< 0.064	< 0.047
WMAP7+HST2	0.960 ± 0.040	< 0.070	< 0.047
WMAP7+ACT+HST	0.975 ± 0.020	< 0.060	< 0.031
WMAP7+ACT+HST+BAO	0.986 ± 0.018	< 0.050	< 0.025
WMAP7+ACT+HST2+BAO	0.986 ± 0.016	< 0.050	< 0.021

TABLE I: Limits at 95% c.l. on α/α_0, Ω_e and the coupling ζ from the MCMC anlyses.

Experiment	σ_{α/α_0}	σ_{Ω_e}	σ_ζ
Planck	0.0012	0.0036	< 0.0012
CMBPol	0.00025	0.0015	< 0.00022

TABLE III: Fisher matrix errors at 68% c.l. on α/α_0 and Ω_e and upper bounds at 95% on coupling ζ from Planck and CMBPol.

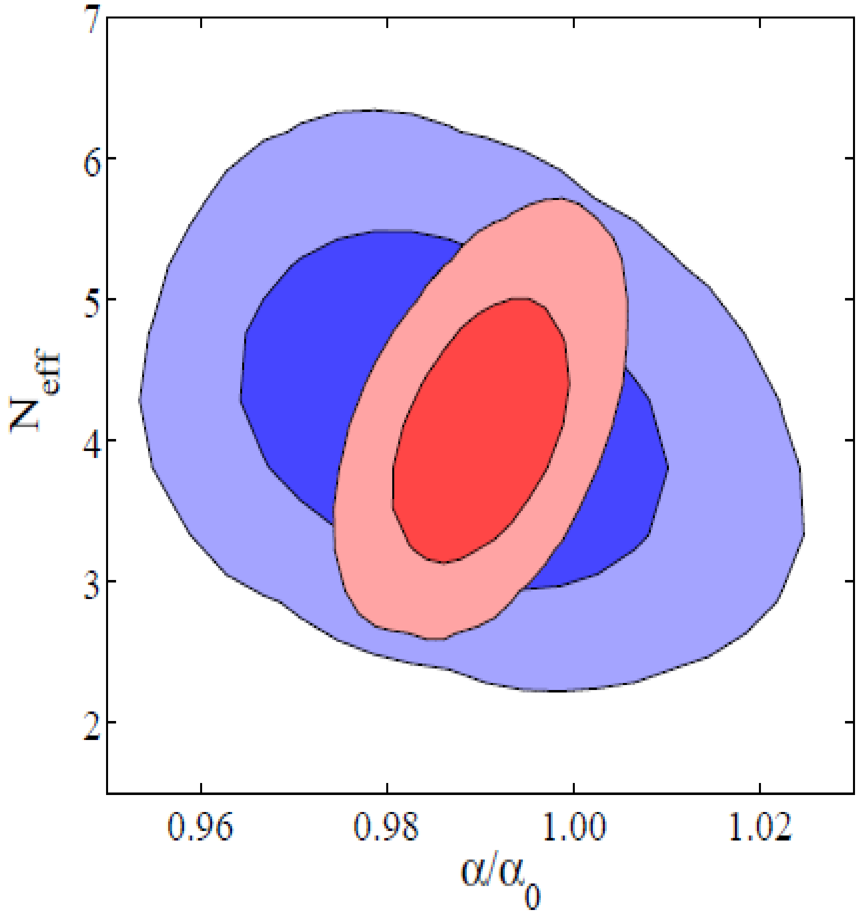
Calabrese et al.

- Standard MCMC analysis
  - ACT+BAO break H_0 degeneracy
  - No degeneracy between Ω_e and α
- Can independently constrain ζ:
  - $|\zeta_o|<10^{-3}$ *[Olive & Pospelov 2002]*
  - Our constraint only 20-40 times weaker, a testimony to the CMB sensitivity!
  - Cf. the Eddington parameter γ *[Schwab et al vs Bertotti et al]*
- Planck sensitivity on ζ comparable to current local bounds...
  - but μSCOPE and ACES will soon improve local bounds

The Fine Structure Constant and the CMB Damping Scale

Eloisa Menegoni[a], Maria Archidiacono[b], Erminia Calabrese[c],
Silvia Galli[d], C. J. A. P. Martins[e], and Alessandro Melchiorri[b]

Parameter	α/α_0	$\alpha/\alpha_0+N_{\rm eff}$	$\alpha/\alpha_0+N_{\rm eff}+Y_p$
$\Omega_b h^2$	0.0218 ± 0.0004	0.0224 ± 0.0005	0.0223 ± 0.0007
$\Omega_c h^2$	0.1144 ± 0.0034	0.1302 ± 0.0095	0.1303 ± 0.0094
τ	0.086 ± 0.014	0.088 ± 0.015	0.088 ± 0.016
H_0	68.9 ± 1.4	71.52 ± 2.0	71.8 ± 2.1
α/α_0	0.984 ± 0.005	0.990 ± 0.006	0.987 ± 0.014
n_s	0.976 ± 0.013	0.991 ± 0.015	0.992 ± 0.016
$log[10^{10} A_s]$	3.193 ± 0.037	3.169 ± 0.040	3.167 ± 0.042
A_{SZ}	< 2.00	< 2.00	< 2.00
A_C	< 16.0	< 15.8	< 14.8
A_P	< 24.7	< 24.9	< 22.4
Ω_Λ	0.7137 ± 0.0070	0.7020 ± 0.0094	0.704 ± 0.013
Age/Gyr	13.76 ± 0.24	13.18 ± 0.38	13.15 ± 0.37
Ω_m	0.2863 ± 0.0070	0.2980 ± 0.0094	0.296 ± 0.013
σ_8	0.836 ± 0.023	0.862 ± 0.028	0.859 ± 0.034
z_{re}	10.7 ± 1.2	11.0 ± 1.3	11.0 ± 1.3
$N_{\rm eff}$	–	$4.10^{+0.24}_{-0.29}$	$4.19^{+0.31}_{-0.35}$
Y_p	–	–	0.215 ± 0.096
χ^2_{min}	7600.2	7596.8	7596.5



arXiv:1202.1476

α, μ and beyond

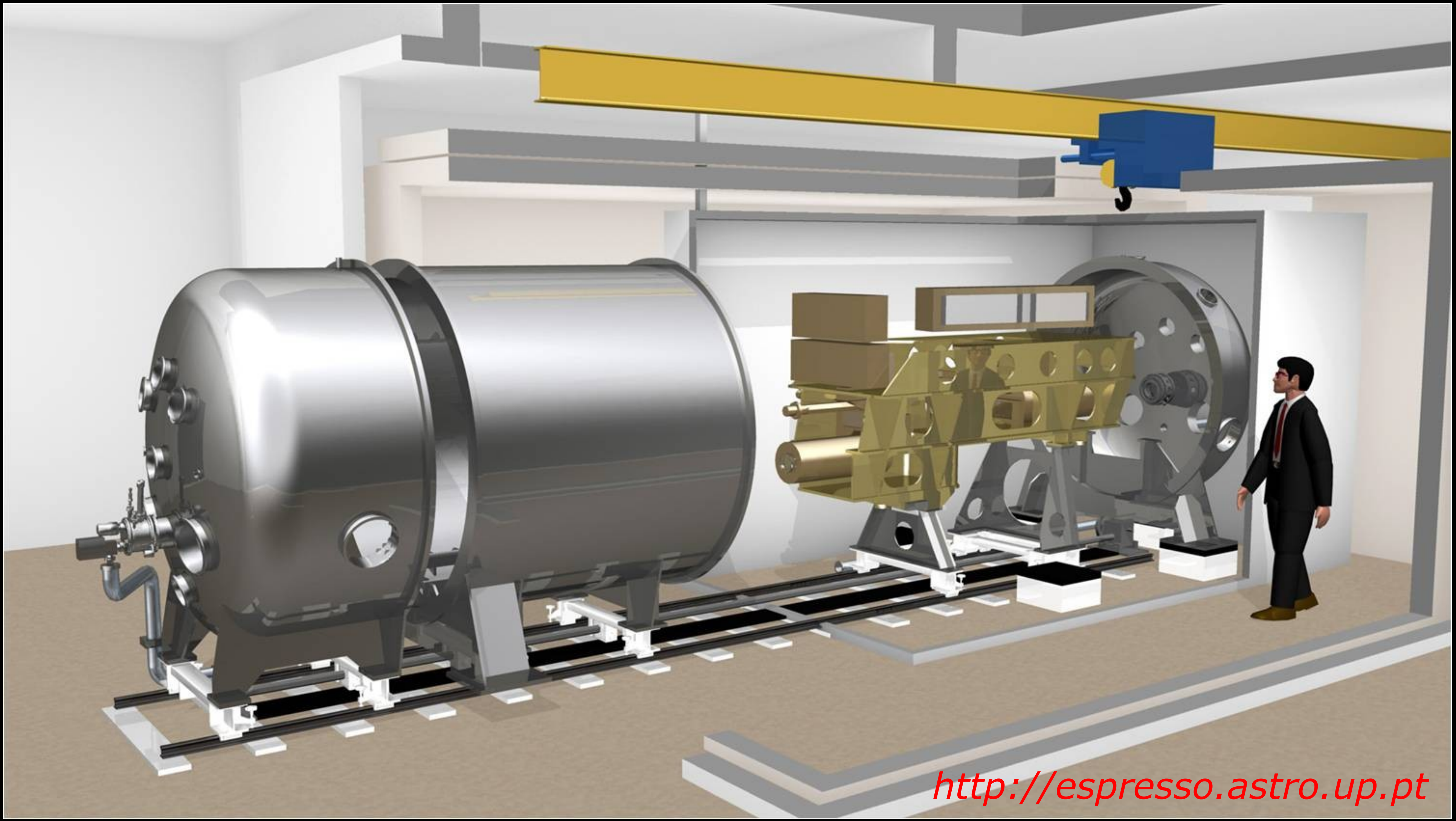
- In theories where a dynamical scalar field yields varying α, other gauge and Yukawa couplings are also expected to vary
  - In GUTs the variation of α is related to that of Λ_{QCD}, whence nucleon mass varies when measured in energy scale independent of QCD
  - Expect a varying $\mu=m_p/m_e$, which can be probed with H_2 *[Thompson 1975]* and other molecules.
- Wide range of possible α-μ relations makes this a unique discriminating tool between competing models.
- These 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
  - For more complicated molecules, $m_{nuc}/m_e \sim$ few m_p/m_e, but beware other effects such as composition-dependent forces!
  - Could ultimately constrain these couplings (H_2 vs HD vs ...).

Why is it so hard?

- Akin to finding exoplanets, except that only a few lines can be used and QSOs are much fainter than stellar sources!
- Measurement of fundamental constants requires observing procedures beyond what is done in standard observations.
  - Existing data has been taken with other purposes and does not have the necessary quality to fully exploit UVES capabilities.
- Need customized wavelength calibration procedures beyond those supplied by standard pipelines *[Thompson et al. 2009]*
  - Ultimately should calibrate with laser frequency combs, not ThAr lamps or I2 cells *[Li et al. 2008, Steinmetz et al. 2008]*.
  - In the meantime, one can do better with UVES (LP ongoing)!
- A new generation of high-resolution, ultra-stable spectrographs will be needed to resolve the issue:
  - Shortly: Maestro (R~90000) at MMT, PEPSI (R~300000) at LBT
  - Soon: ESPRESSO at the VLT, Later: CODEX at the E-ELT

Would You Like an ESPRESSO?

Would You Like an ESPRESSO?



Would you like an ESPRESSO?

- ESPRESSO is...
  - 380-800nm spectral coverage in one shot
  - Highest-resolution instrument on a 10m-class telescope
  - Wavelength calibration far more accurate than any other facility
  - Cleanest, best-quality spectra both at high and low SNR
  - A spectrograph on a 16m telescope (largest visible until ELTs)
  - Ultra-high resolution mode, far beyond existing facilities
- 273 nights GTO, over a few years:
  - 80% Rocky Planets, 10% Varying Constants
  - 10% to be decided: ToO + Exquisite Science + (Any ideas?)

Parameter	Standard 1-UT	4-UT	Ultra-High Res 1-UT
Wavelength range	380-800 nm	380-800 nm	380-800 nm
Resolving power	140’000	60’000	225’000
Aperture on sky	1.0 arcsec	4x1.0 arcsec	0.5 arcsec
Sampling (average)	3.3 pixels	4.0 pixels (binned x2)	2.1 pixels
Spatial sampling	6.9 pixels	4.0 pixels (binned x4)	3.5 pixels
Simultaneous reference	Yes (no sky)	Yes (no sky)	Yes (no sky)
Sky subtraction	Yes (no sim. ref.)	Yes (no sim. ref.)	Yes (no sim. ref.)
Total efficiency	10%	10%	TBD
Instrumental RV precision	< 10 cm s^{-1}	TBD	TBD

Was Einstein Right?

Dark Energy & Varying Couplings

- Universe dominated by component whose gravitational behavior is similar to that of a cosmological constant.
- Required cosmological constant value is so small that a dynamical scalar field is arguably more likely.
- Such a field must be slow-rolling (mandatory for $p<0$) and be dominating the dynamics around the present day.
- ***It follows [Carroll 1998] that couplings of this field lead to potentially observable long-range forces and time dependencies of the constants of nature.***

To Couple or Not To Couple

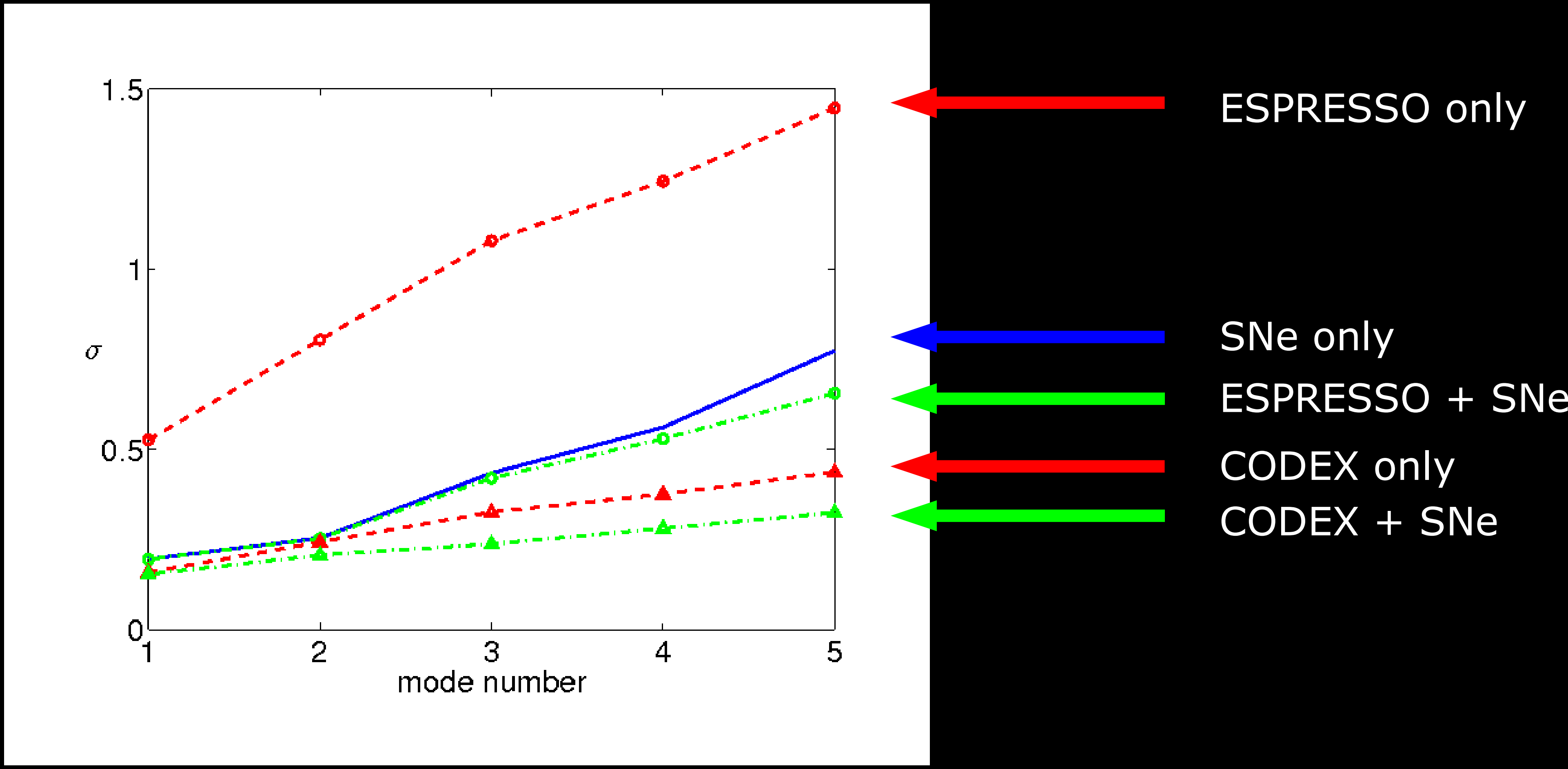
- Any scalar field couples to gravity.
- Couples to nothing else if a global symmetry $\phi \longrightarrow \phi + $ const. suppresses couplings to the rest of the Lagrangian.
  - If so, only derivatives and derivative couplings survive.
- Quantum gravity effects don't respect global symmetries, and there's no unbroken global symmetries in string theory.
- ***Scalars in the theory will couple to the rest of the world (in any manner not prevented by symmetry principles).***

Dynamical Dark Energy

- Standard methods (SNe, etc) are of limited use as dark energy probes *[Maor et al. 2001, Upadhye et al. 2005, etc]*
  - Clear detection of varying w(z) is key, since $w_0 \sim -1$
- Since the field is slow-rolling when dynamically important, a convincing detection of w(z) will be tough at low z.
- We must probe the deep matter era regime, where the dynamics of the hypothetical scalar field is fastest.
  - Varying fundamental couplings are ideal for probing scalar field dynamics beyond the domination regime *[Nunes & Lidsey 2004]*

Variation of fundamental parameters and dark energy. A principal component approach

L. Amendola,[1,*] A.C.O. Leite,[2,3,†] C.J.A.P. Martins,[3,‡] N.J. Nunes,[1,§] P.O.J. Pedrosa,[2,3,¶] and A. Seganti[4]



- CODEX can constrain dark energy better than SNe
  - Key advantage is huge redshift lever arm
  - ESPRESSO is no slouch either...

arXiv:1109.6793

To Couple or Not To Couple

- Reconstruction using varying fundamental constants requires an assumption on the field coupling...
  - … but coupling can be measured and compared to local constraints *[Calabrese et al. 2011]*
  - Inconsistent assumptions can be identified and corrected
- Consistency test opportunities for Euclid+CODEX

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Probing dark energy beyond $z = 2$ with CODEX

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(Received 20 February 2012; published 4 April 2012)

Precision measurements of nature's fundamental couplings and a first measurement of the cosmological redshift drift are two of the key targets for future high-resolution ultrastable spectrographs such as CODEX. Being able to do both gives CODEX a unique advantage, allowing it to probe dynamical dark energy models (by measuring the behavior of their equation of state) deep in the matter era and thereby testing classes of models that would otherwise be difficult to distinguish from the standard lambda-cold dark matter paradigm. We illustrate this point with two simple case studies.

arXiv:1202.4364

Interlude

- Many astrophysical objects can be used to search for spacetime variations of fundamental couplings
  - Population III stars *[Ekstrom et al. 2010]*
  - Neutron stars *[Perez-Garcia & Martins 2012]*
  - Solar-type stars *[Vieira et al. 2012, arXiv:soon]*
  - *...*

Probing unification scenarios with neutron stars

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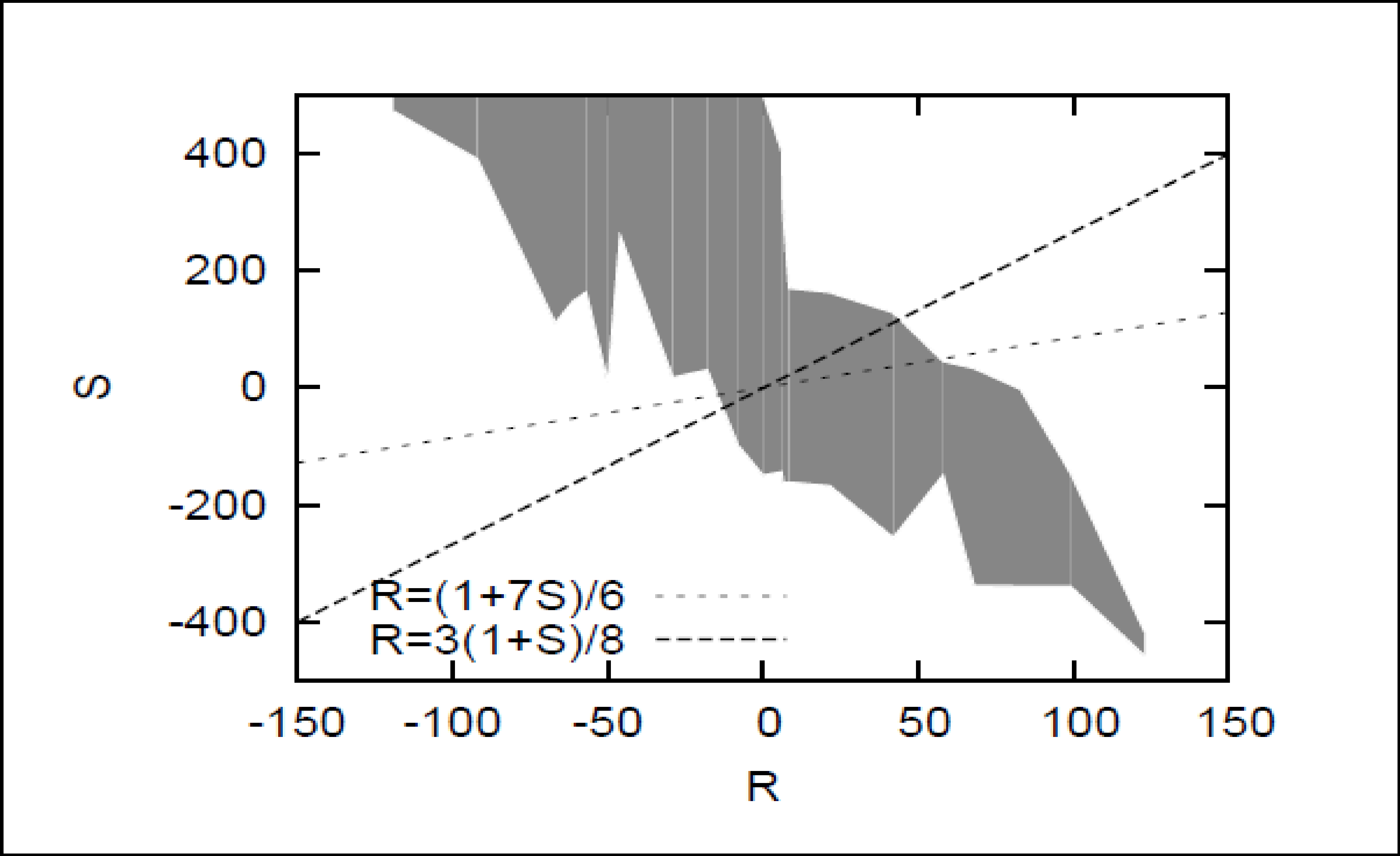
(Dated: March 5, 2012)

We discuss the sensitivity of the neutron star equation of state to combined variations of the gravitational, strong and electroweak coupling constants in the context of unification scenarios. We find that current knowledge of the neutron star mass-radius relationship and heavy ion collisions observable measurements constrain the equation of state as described by relativistic field models of interacting matter. In particular, there are unification scenarios that would be incompatible with the existence of these objects. This provides an additional independent constraint on the allowed range of variation of fundamental dimensionless constants.

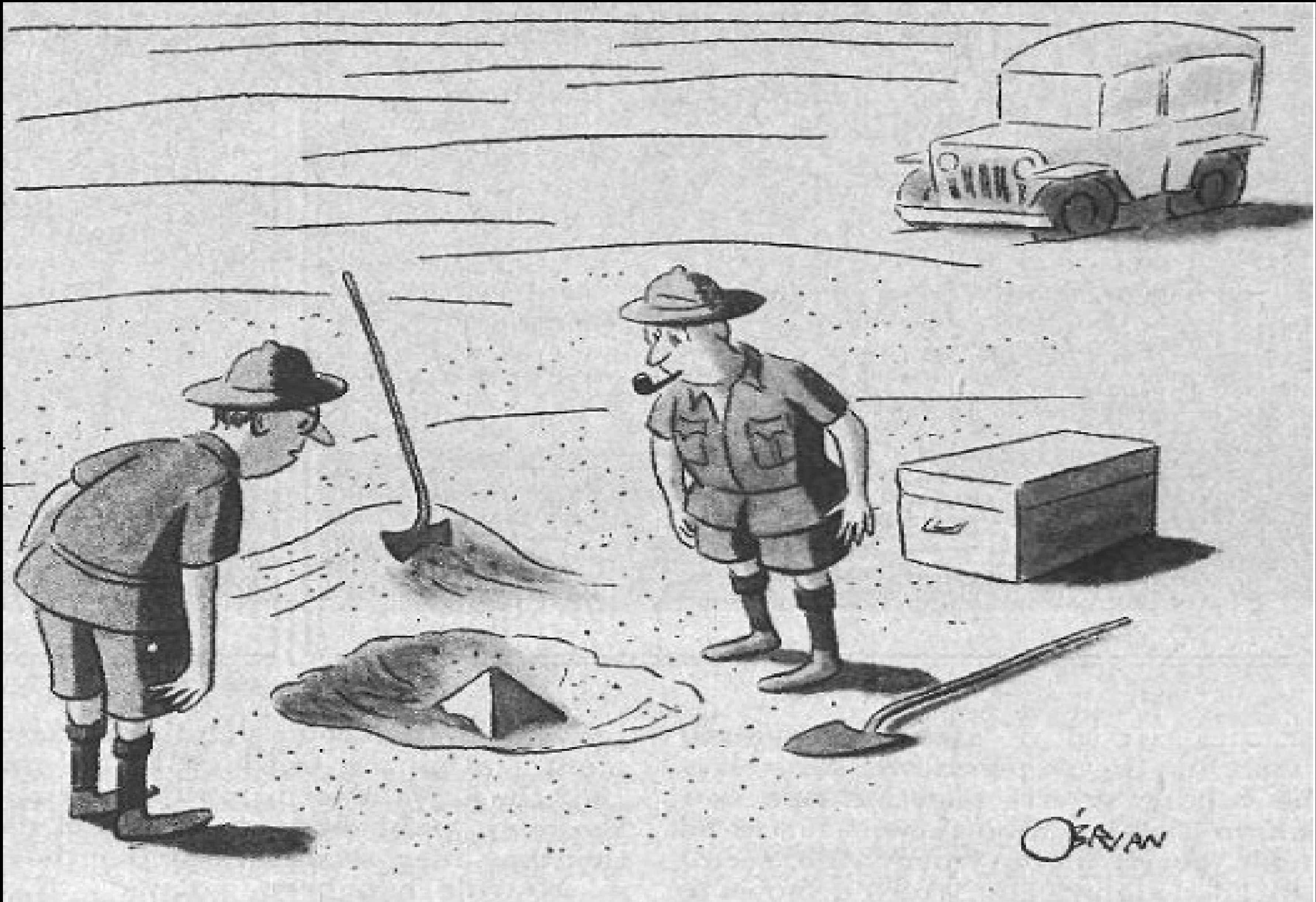
arXiv:1203.0399

Probing Fundamental Physics



arXiv:1203.0399

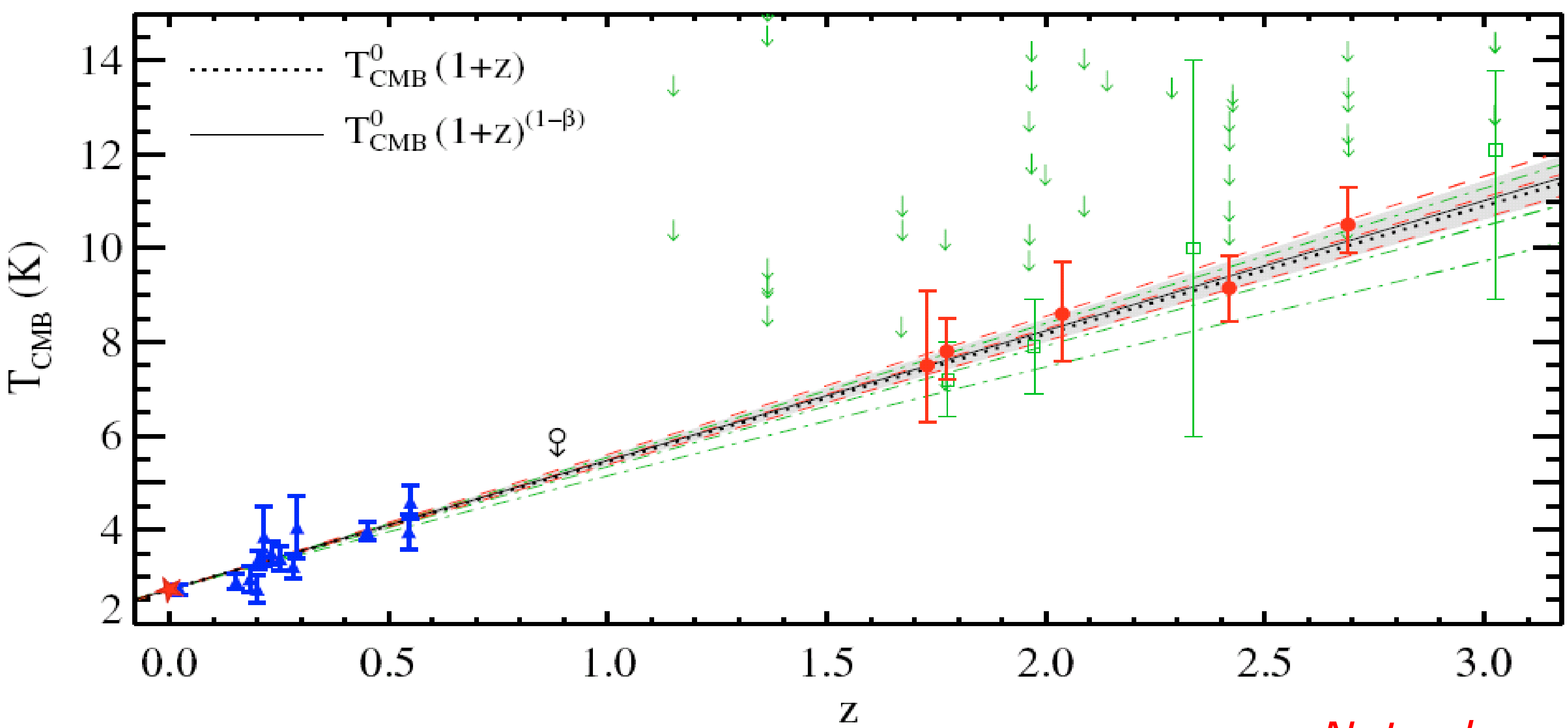
The Quest for Redundancy



"This could be the discovery of the century. Depending, of course, on how far down it goes."

The T(z) Relation

- $T(z)=T_0(1+z)$ is a robust prediction of standard cosmology
  - Adiabatic expansion, photon number conservation
  - Violated in many scenarios, e.g. string theory inspired ones
  - If $T(z)=T_0(1+z)^{1-\beta}$, find β=-0.01±0.03 *[Noterdaeme et al. 2011]*



Noterdaeme et al.

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  - If $T(z)=T_0(1+z)^{1-\beta}$, find $\beta=-0.01\pm0.03$ *[Noterdaeme et al. 2011]*

MEASURING THE REDSHIFT DEPENDENCE OF THE CMB MONOPOLE TEMPERATURE WITH PLANCK DATA.

I. de Martino[1], F. Atrio-Barandela[1], A. da Silva[2], H. Ebeling[3], A. Kashlinsky[4], D. Kocevski[5], C.J.A.P. Martins[2]

Draft version March 9, 2012

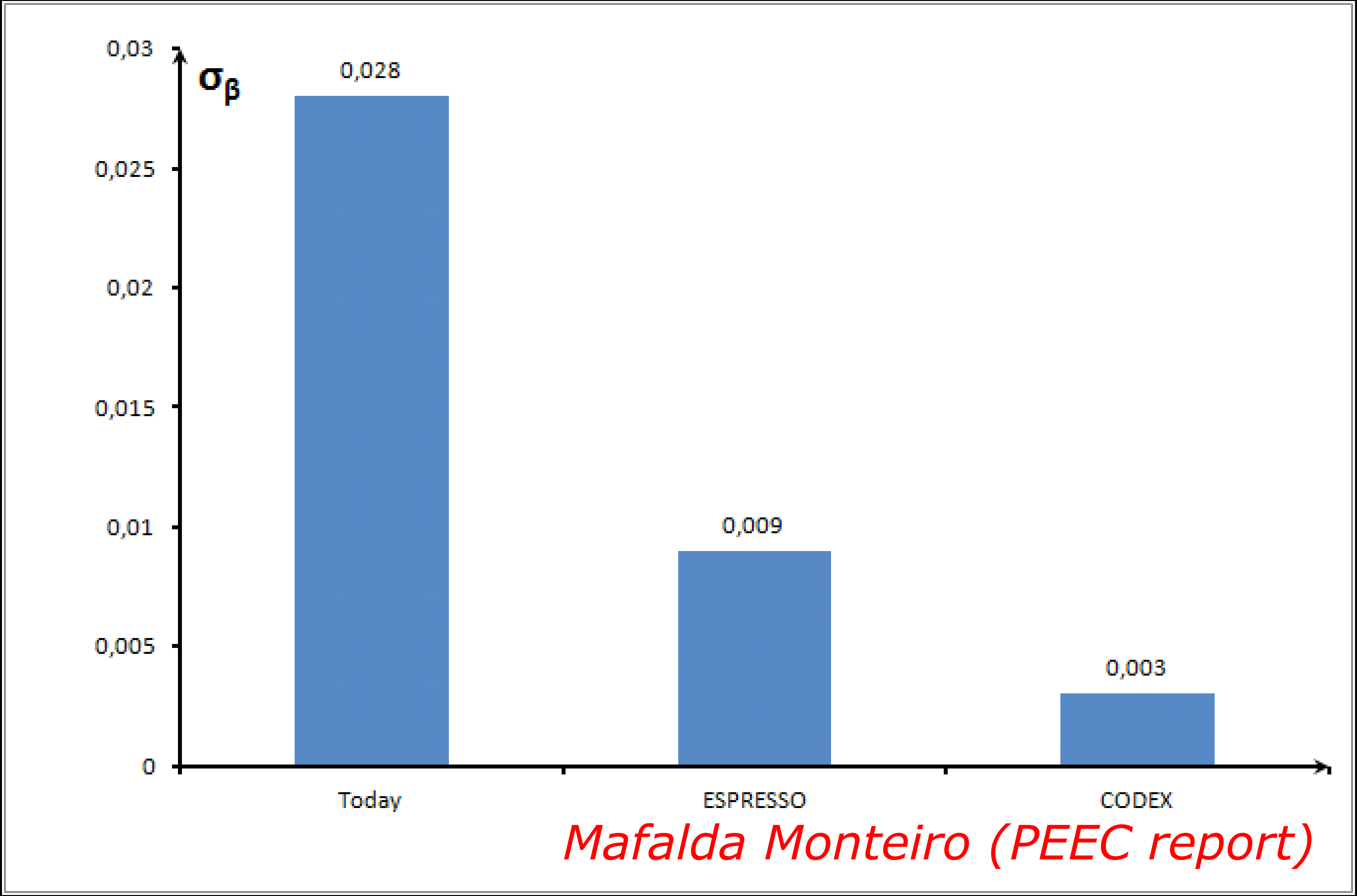
ABSTRACT

We study the power of PLANCK data to constrain deviations of the Cosmic Microwave Background black body temperature from adiabatic evolution using the thermal Sunyaev-Zeldovich anisotropy induced by clusters of galaxies. We consider two types of data sets: the cosmological signal is removed in the Time Ordered Information or is removed from the final maps; and two different statistical estimators, based on the ratio of temperature anisotropies at two different frequencies and on a fit to the spectral variation of the cluster signal with frequency. To test for systematics, we construct a template from clusters drawn from a hydro-simulation included in the pre-launch Planck Sky Model. We demonstrate that, using a proprietary catalog of X-ray selected clusters with measured redshifts, electron densities and X-ray temperatures, we can constrain deviations of adiabatic evolution, measured by the parameter α in the redshift scaling $T(z) = T_0(1+z)^{1-\alpha}$, with an accuracy of $\sigma_\alpha = 0.011$ in the most optimal case and with $\sigma_\alpha = 0.016$ for a less optimal case. These results represent a factor 2-3 improvement over similar measurements carried out using quasar spectral lines and a factor 6-20 with respect to earlier results using smaller cluster samples.

arXiv:1203.1825

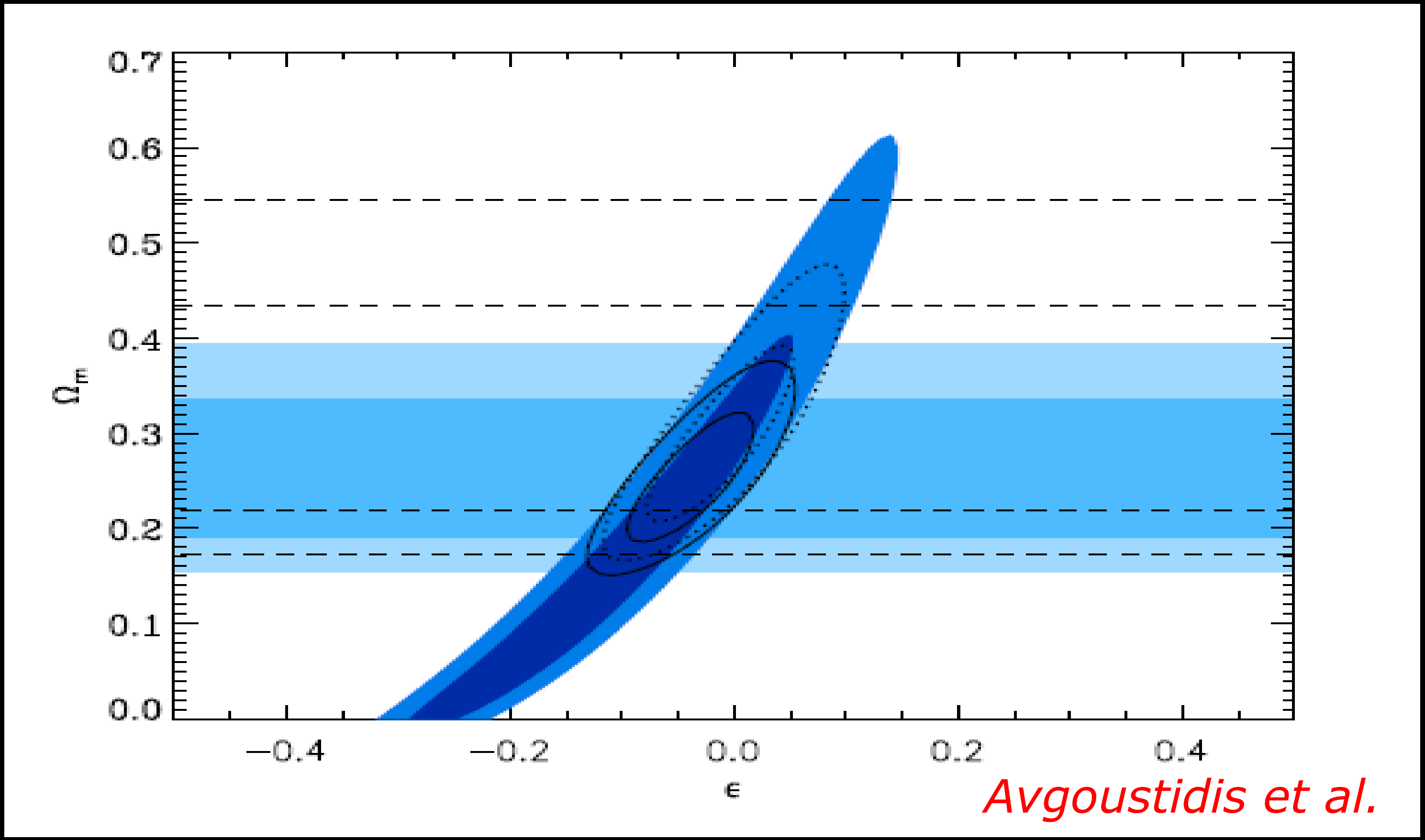
The T(z) Relation

- $T(z)=T_0(1+z)$ is a robust prediction of standard cosmology
  - Adiabatic expansion, photon number conservation
  - Violated in many scenarios, e.g. string theory inspired ones
  - If $T(z)=T_0(1+z)^{1-\beta}$, find β=-0.01$\pm$0.03 *[Noterdaeme et al. 2011]*



The Distance Duality Relation

- $d_L=(1+z)^2 d_A$ is a robust prediction of standard cosmology
  - Metric theory of gravity, photon number conservation
  - Violated if there's photon dimming, absorption or conversion
  - If $d_L=(1+z)^{2+\varepsilon} d_A$, find $\varepsilon=-0.04\pm0.08$ *[Avgoustidis et al. 2010, ...]*



A Consistency Test

- $T(z)=T_0(1+z)$ is a robust prediction of standard cosmology
  - Adiabatic expansion, photon number conservation
  - Violated in many scenarios, e.g. string theory inspired ones
  - If $T(z)=T_0(1+z)^{1-\beta}$, find $\beta=-0.01\pm0.03$ *[Noterdaeme et al. 2011]*
- $d_L=(1+z)^2 d_A$ is a robust prediction of standard cosmology
  - Metric theory of gravity, photon number conservation
  - Violated if there's photon dimming, absorption or conversion
  - If $d_L=(1+z)^{2+\epsilon} d_A$, find $\epsilon=-0.04\pm0.08$ *[Avgoustidis et al. 2010, ...]*
- In fact, in many models the two are not independent: $\beta=-2\epsilon/3$, so distance duality tests also constrain β
  - A generalized relation exists for any redshift dependence

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Constraints on the CMB temperature-redshift dependence from SZ and distance measurements

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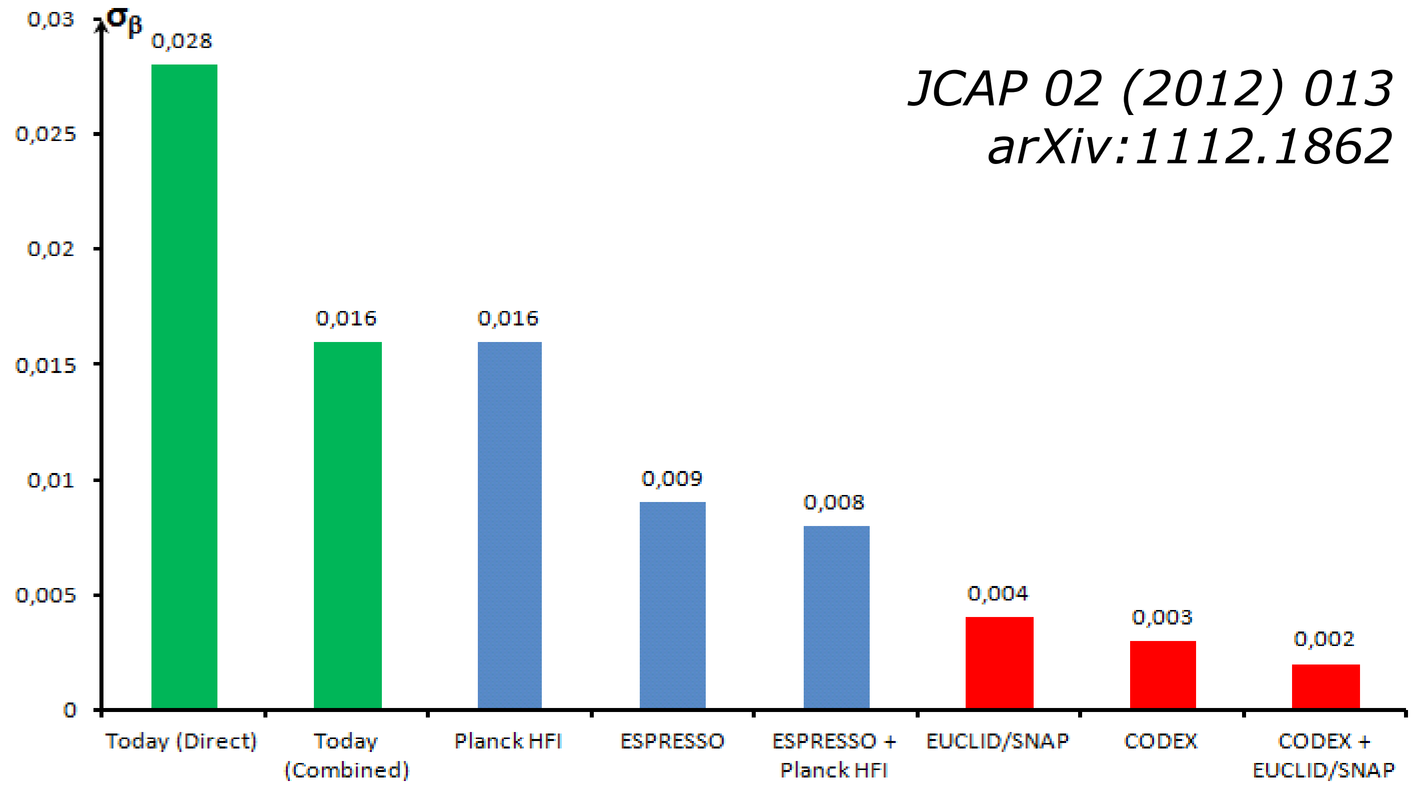

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arXiv:1112.1862

So What's Your Point?

- Observational evidence for the acceleration of the universe demonstrates that canonical theories of cosmology and particle physics are incomplete, if not incorrect
  - Several few-sigma hints: smoke but no smoking gun

- Forthcoming high-resolution ultra-stable spectrographs will enable new generation of precision consistency tests
  - Also: Equivalence Principle tests, Redshift drift
  - Interesting synergies with other facilities, including Euclid