Astrophysical Tests of the Stability of Fundamental Couplings

Carlos Martins* and the CAUP Dark Side Team

(with key contributions from Ana Catarina Leite, Ana Mafalda Monteiro, José Pedro Vieira, Mariana Julião, Marvin Silva, Miguel Ferreira, Pauline Vielzeuf and Pedro Pedrosa)

*FCT Research Professor
Disclaimer: I am a member of the E-ELT Project Science Team. E-ELT views expressed in this talk are my own, not those of ESO or the PST.
Fundamental Scalar Fields

- We now know that fundamental scalar fields are part of Nature's building blocks
  - Does the Higgs have a cosmological counterpart?
- 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
So What's Your Point?

- We all know that fundamental couplings run with energy

- Moreover, in many (or arguably most?) models they will equally naturally roll in time and ramble in space

- Therefore astrophysical (and local) tests of their stability provide us with optimal probes of fundamental cosmology
Varying Fundamental Couplings
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, yet we have no theory for them
- 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
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 \(1836.12 \pm 0.05\). 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 $\alpha$ from Quasars

![Diagram showing Measuring $\alpha$ from Quasars](image)

- **Quasar**: Emission from a distant galaxy
- **Intervening gas**: Absorption lines between the quasar and Earth
- **H absorption**: Hydrogen absorption lines
- **H emission from quasar**: Emission lines from the quasar
- **‘Metal’ absorption lines**: Absorption lines from elements other than hydrogen

*Wavelength (Angstroms)*

3500 4000 4500 5000 5500 6000

*Murphy*
Constraints from Absorption Lines

- $\alpha_{em}$: 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
- ...
A Dipole on the Sky?

King (PhD thesis) 2011
Webb et al. 2012
A Dipole on the Sky?

- >4 sigma evidence for a dipole; new physics or systematics?
  - Unclear if pure spatial dipole or dependent on lookback time
  - No known systematic can explain dipole, but difficult to model
  - A concern: archival data, taken for other purposes

- Key driver for ESPRESSO (VLT) and the ELT-HIRES
  - Better precision, and much better control of systematics

![Graph showing the relationship between velocity precision and effective mirror diameter for different telescopes, including VLT/UVES, VLT/ESPRESSO, GMT, TMT, and E-ELT/HIRES.](image)
Varying $\alpha$ from Symmetrons

[see Marvin Silva's poster, and Silva et al. 2014]
In theories where a dynamical scalar field yields varying $\alpha$, other gauge and Yukawa couplings are also expected to vary

- In GUTs the variation of $\alpha$ is related to that of $\Lambda_{QCD}$, whence $m_{\text{nuc}}$ 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

Wide range of possible $\alpha$-$\mu$ relations makes this a unique discriminating tool between competing models

- Find systems where various constants can be simultaneously measured, or where one can be measured in various ways

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

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

\[
\frac{\Delta g_n}{g_n} = [0.12R - 0.05(1 + S)] \frac{\Delta \alpha}{\alpha}
\]
The UVES Large Program for Testing Fundamental Physics

ESO 185.A-0745 UT2-Kueyen

LP Plan & Goals

- Only large program dedicated to varying constants, optimized sample & methodology, ca. 40 nights in 2010-13
  - Calibration lamps attached to science exposures (in same OB): don't reset x-disperser encoding position for each exposure
  - Observe bright (mag 9-11) asteroids at twilight, to monitor radial velocity accuracy of UVES and the optical alignments
  - Sample: Multiple absorption systems, brightness (S/N), high redshift (FeII 1608), simplicity, narrow components at sensitive wavelengths, no line broadening/saturation

- R~60000, S/N~100; potential accuracy is 1-2ppm/system, where photon noise and calibration errors are comparable
  - Our goal: 2ppm per system, 0.5ppm for full sample
  - All 3 active observational groups involved
  - Also compare/check/optimize different analysis pipelines
  - Introduce blind analysis techniques
Selected before alpha dipole was known [Bonifacio et al. 2014]

- 13 targets for $\alpha$, 2 targets for $\mu=\text{mp/me}$ (QSO 0405-443, HE 0027-1836)
- Already out: first results on HE2217-2818 and HE0027-1836
- Most raw data already in the ESO public archive, and reduced data products will also be made public – have fun!
First Results

- **HE2217-2818, \(z_{\text{abs}} \sim 1.69\):**
  \[ \Delta \alpha/\alpha = 1.3 \pm 2.4 \text{ sta} \pm 1.0 \text{ sys} \text{ ppm} \]
  - Dipole fit: \((3.2–5.4)\pm1.7 \text{ ppm}\) depending on model; our measurement does not confirm this, but is not inconsistent with it either

- **HE0027-1836, \(z_{\text{abs}} \sim 2.40\):**
  \[ \Delta \mu/\mu = -7.6 \pm 8.1 \text{ sta} \pm 6.3 \text{ sys} \text{ ppm} \]
  - Identified wavelength-dependent velocity drift (corrected with bright asteroid data)

- **Bottleneck: intra-order distortions (\sim 200m/s) & long-range distortions on UVES, discussion in Paper III [Whitmore et al.]**
  - Also identified in HARPS and Keck-HIRES
Current Dedicated Measurements

- Direct measurements of $\alpha$ and $\mu$ can be obtained in the UV/optical; in the radio band one can measure combinations
  - Parts per million sensitivity is nominally much easier to reach in the radio, though at significantly lower redshifts

<table>
<thead>
<tr>
<th>Object</th>
<th>$z$</th>
<th>$\Delta \mu/\mu$</th>
<th>Method</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>B0218+357</td>
<td>0.685</td>
<td>$0.74 \pm 0.89$</td>
<td>$NH_3/HCO^+/HCN$</td>
<td>[47]</td>
</tr>
<tr>
<td>B0218+357</td>
<td>0.685</td>
<td>$-0.35 \pm 0.12$</td>
<td>$NH_3/CS/H_2CO$</td>
<td>[48]</td>
</tr>
<tr>
<td>PKS1830–211</td>
<td>0.886</td>
<td>$0.08 \pm 0.47$</td>
<td>$NH_3/HC_3N$</td>
<td>[49]</td>
</tr>
<tr>
<td>PKS1830–211</td>
<td>0.886</td>
<td>$-1.2 \pm 4.5$</td>
<td>$CH_3NH_2$</td>
<td>[50]</td>
</tr>
<tr>
<td>PKS1830–211</td>
<td>0.886</td>
<td>$-2.04 \pm 0.74$</td>
<td>$NH_3$</td>
<td>[51]</td>
</tr>
<tr>
<td>PKS1830–211</td>
<td>0.886</td>
<td>$-0.001 \pm 0.103$</td>
<td>$CH_3OH$</td>
<td>[52]</td>
</tr>
<tr>
<td>J2123–005</td>
<td>2.059</td>
<td>$8.5 \pm 4.2$</td>
<td>$H_2/HD$ (VLT)</td>
<td>[53]</td>
</tr>
<tr>
<td>J2123–005</td>
<td>2.059</td>
<td>$5.6 \pm 6.2$</td>
<td>$H_2/HD$ (Keck)</td>
<td>[54]</td>
</tr>
<tr>
<td>HE0027–1836</td>
<td>2.402</td>
<td>$-7.6 \pm 10.2$</td>
<td>$H_2$</td>
<td>[56]</td>
</tr>
<tr>
<td>Q1101–264</td>
<td>1.84</td>
<td>$5.7 \pm 2.7$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q2348–011</td>
<td>2.426</td>
<td>$-6.8 \pm 27.8$</td>
<td>$H_2$</td>
<td>[55]</td>
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<tr>
<td>Q0405–443</td>
<td>2.597</td>
<td>$10.1 \pm 6.2$</td>
<td>$H_2$</td>
<td>[56]</td>
</tr>
<tr>
<td>J0643–504</td>
<td>2.659</td>
<td>$7.4 \pm 6.7$</td>
<td>$H_2$</td>
<td>[56]</td>
</tr>
<tr>
<td>Q0528–250</td>
<td>2.811</td>
<td>$0.3 \pm 3.7$</td>
<td>$H_2/HD$</td>
<td>[57]</td>
</tr>
<tr>
<td>Q0347–383</td>
<td>3.025</td>
<td>$2.1 \pm 6.0$</td>
<td>$H_2$</td>
<td>[58]</td>
</tr>
</tbody>
</table>

Data compilation from Ferreira, Frigola, Martins, Monteiro & Solà, to appear
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<table>
<thead>
<tr>
<th>Object</th>
<th>$z$</th>
<th>$Q_{AB}$</th>
<th>$\Delta Q_{AB}/Q_{AB}$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PKS1413+135</td>
<td>0.247</td>
<td>$\alpha^{2\times1.85}g_p\mu^{1.85}$</td>
<td>$-11.8 \pm 4.6$</td>
<td>[35]</td>
</tr>
<tr>
<td>PKS1413+135</td>
<td>0.247</td>
<td>$\alpha^{2\times1.57}g_p\mu^{1.57}$</td>
<td>$5.1 \pm 12.6$</td>
<td>[36]</td>
</tr>
<tr>
<td>PKS1413+135</td>
<td>0.247</td>
<td>$\alpha^2g_p$</td>
<td>$-2.0 \pm 4.4$</td>
<td>[37]</td>
</tr>
<tr>
<td>B0218+357</td>
<td>0.685</td>
<td>$\alpha^2g_p$</td>
<td>$-1.6 \pm 5.4$</td>
<td>[37]</td>
</tr>
<tr>
<td>J0134–0931</td>
<td>0.765</td>
<td>$\alpha^{2\times1.57}g_p\mu^{1.57}$</td>
<td>$-5.2 \pm 4.3$</td>
<td>[38]</td>
</tr>
<tr>
<td>J2358–1020</td>
<td>1.173</td>
<td>$\alpha^2g_p/\mu$</td>
<td>$1.8 \pm 2.7$</td>
<td>[39]</td>
</tr>
<tr>
<td>J1623+0718</td>
<td>1.336</td>
<td>$\alpha^2g_p/\mu$</td>
<td>$-3.7 \pm 3.4$</td>
<td>[39]</td>
</tr>
<tr>
<td>J2340–0053</td>
<td>1.361</td>
<td>$\alpha^2g_p/\mu$</td>
<td>$-1.3 \pm 2.0$</td>
<td>[39]</td>
</tr>
<tr>
<td>J0501–0159</td>
<td>1.561</td>
<td>$\alpha^2g_p/\mu$</td>
<td>$3.0 \pm 3.1$</td>
<td>[39]</td>
</tr>
<tr>
<td>J0911+0551</td>
<td>2.796</td>
<td>$\alpha^2\mu$</td>
<td>$-6.9 \pm 3.7$</td>
<td>[40]</td>
</tr>
<tr>
<td>J1337+3152</td>
<td>3.174</td>
<td>$\alpha^2g_p/\mu$</td>
<td>$-1.7 \pm 1.7$</td>
<td>[41]</td>
</tr>
<tr>
<td>BR1202–0725</td>
<td>4.695</td>
<td>$\alpha^2\mu$</td>
<td>$50 \pm 150$</td>
<td>[42]</td>
</tr>
<tr>
<td>J0918+5142</td>
<td>5.245</td>
<td>$\alpha^2\mu$</td>
<td>$-1.7 \pm 8.5$</td>
<td>[43]</td>
</tr>
<tr>
<td>J1148+5251</td>
<td>6.420</td>
<td>$\alpha^2\mu$</td>
<td>$330 \pm 250$</td>
<td>[42]</td>
</tr>
</tbody>
</table>

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  - Parts per million sensitivity is nominally much easier to reach in the radio, though at significantly lower redshifts

- Joint analysis of all the available data suggests some inconsistencies
  - Cf. Miguel Ferreira's poster; paper on the arXiv soon

- Radio band sensitivity is even better within the Galaxy ($z=0$), where one can search for environmental dependencies
  - No variation seen at the 0.1 ppm level for $\alpha$ [Truppe et al. 2013]
  - No variation seen at 0.05 ppm level for $\mu$ [Levshakov et al. 2013]
Why is it so hard?

• Akin to finding exoplanets, except much harder!
  – Much fainter sources, only a few lines clean

• Measurements of fundamental constants require observing procedures – and instruments – beyond current facilities
  – Need customized data reduction pipelines, including careful wavelength calibration procedures [Thompson et al. 2009]
  – Must calibrate with laser frequency combs, not ThAr lamps or I2 cells [Li et al. 2008, Steinmetz et al. 2008]

• A new generation of high-resolution, ultra-stable spectrographs will have these measurements as key driver
  – Shortly: PEPSI at LBT, 2016: ESPRESSO at VLT, Later: ELT-HIRES
Low-redshift Constraints

- Atomic clocks: sensitivity of few $10^{-17}$/yr [Rosenband et al. 2008]
  - Future: molecular & nuclear clocks, $10^{-21}$/yr achievable?

<table>
<thead>
<tr>
<th>Clock</th>
<th>$\nu_{AB}$</th>
<th>$\dot{\nu}<em>{AB}/\nu</em>{AB}$ (yr$^{-1}$)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hg-Al</td>
<td>$\alpha^{-3.208}$</td>
<td>$(5.3 \pm 7.9) \times 10^{-17}$</td>
<td>[22]</td>
</tr>
<tr>
<td>Cs-SF$_6$</td>
<td>$g_{Cs}\mu^{1/2}\alpha^{2.83}$</td>
<td>$(-1.9 \pm 0.12_{sta} \pm 2.7_{sys}) \times 10^{-14}$</td>
<td>[23]</td>
</tr>
<tr>
<td>Cs-H</td>
<td>$g_{Cs}\mu\alpha^{2.83}$</td>
<td>$(3.2 \pm 6.3) \times 10^{-15}$</td>
<td>[24]</td>
</tr>
<tr>
<td>Cs-Sr</td>
<td>$g_{Cs}\mu\alpha^{2.77}$</td>
<td>$(1.0 \pm 1.8) \times 10^{-15}$</td>
<td>[25]</td>
</tr>
<tr>
<td>Cs-Hg</td>
<td>$g_{Cs}\mu\alpha^{6.03}$</td>
<td>$(-3.7 \pm 3.9) \times 10^{-16}$</td>
<td>[26]</td>
</tr>
<tr>
<td>Cs-Yb</td>
<td>$g_{Cs}\mu\alpha^{1.93}$</td>
<td>$(0.78 \pm 1.40) \times 10^{-15}$</td>
<td>[27]</td>
</tr>
<tr>
<td>Cs-Rb</td>
<td>$(g_{Cs}/g_{Rb})\alpha^{0.49}$</td>
<td>$(0.5 \pm 5.3) \times 10^{-16}$</td>
<td>[28]</td>
</tr>
<tr>
<td>Cs-Yb</td>
<td>$g_{Cs}\mu\alpha^{1.93}$</td>
<td>$(0.49 \pm 0.41) \times 10^{-15}$</td>
<td>[29]</td>
</tr>
<tr>
<td>Cs-Rb</td>
<td>$(g_{Cs}/g_{Rb})\alpha^{0.49}$</td>
<td>$(1.39 \pm 0.91) \times 10^{-16}$</td>
<td>[30]</td>
</tr>
</tbody>
</table>

Data compilation from Ferreira, Julião, Martins & Monteiro 2013
Low-redshift Constraints

- **Atomic clocks**: sensitivity of fewx10^{-17}/yr \[\text{[Rosenband et al. 2008]}\]
  - Future: molecular & nuclear clocks, 10^{-21}/yr achievable?

- **Compact objects** used to constrain environmental dependencies; limiting factor usually comes from nuclear physics uncertainties
  - Population III stars \[\text{[Ekstrom et al. 2010]}\], sensitivity \(\sim\) fewx10^{-5}
  - Neutron stars \[\text{[Pérez-García & Martins 2012]}\], sensitivity \(\sim\) 10^{-4}
  - Solar-type stars \[\text{[Vieira et al. 2012]}\], sensitivity \(\sim\) 10^{-4} or better?
  - White dwarfs \[\text{[Berengut et al. 2013]}\], sensitivity \(\sim\) 10^{-4} or better?

- **Oklo** (natural nuclear reactor, \(z\sim0.14\)): nominal sensitivity of fewx10^{-8} \[\text{[Gould et al. 2006]}\], but not a 'clean' measurement
  - Assumptions somewhat simplistic; effectively constrains \(\alpha_s\)

- **Clusters of galaxies** (\(z<1\)): compare SZ and X-ray observations: 0.8% sensitivity \[\text{[Galli 2013]}\]
  - Promising with larger numbers of clusters
High-redshift Constraints

- Ionization history (and hence the cosmic microwave background) affected by varying constants
  - Clean probe, but relatively weak bounds due to degeneracies
  - Current $\alpha$-only bound [Planck 2013, paper XVI] is 0.4%
- More realistic approach: allow both $\alpha$ and particle masses to vary, in generic unification scenarios [Galli & Martins, 2014]
  - Constraints on unification can be combined with low-z ones
High-redshift Constraints

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  - Constraints on unification can be combined with low-z ones

- At higher redshifts constraints can be obtained from Big Bang nucleosynthesis, but they will necessarily be model-dependent
  - Current constraints are at around the 1% level, for relatively generic models [Martins et al. 2010]
  - Tighter constraints can be obtained for more specific choices of model [Coc et al. 2007, etc.]
  - Lithium problem might be removed in some GUT scenarios [Stern (PhD thesis) 2008], but in-depth analysis remains to be done
Was Einstein Right?

GR plus a cosmological constant is great!
Dark Energy & Varying Couplings

- Universe dominated by component whose gravitational behavior is similar to that of a cosmological constant
  - 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
- Couplings of this field lead to potentially observable long-range forces and varying constants [Carroll 1998]
  - These measurements (whether they are detections of null results) will constrain fundamental physics and cosmology
  - This ensures a 'minimum guaranteed science'
Taxonomy: Class I

- If the same degree of freedom is responsible for dark energy and varying $\alpha$, the latter's evolution is parametrically determined.
Going Further

- Standard methods (SNe, etc) are of limited use as dark energy probes [Maor et al. 2001, Upadhye et al. 2005, etc]
  - 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
  - Fundamental couplings ideally probe scalar field dynamics beyond the domination regime [Nunes & Lidsey 2004]

- ALMA, ESPRESSO and ELT-HIRES will map dark energy out to $z>4$ [Amendola et al. 2012]
  - Key synergies with redshift drift and with other E-ELT instruments (e.g., high-z supernovas from ELT-IFU)
  - More details in Ana Catarina Leite's talk on Friday
The Redshift Drift

- Direct probe of dynamics of the universe \cite{Sandage1962}
  - No assumptions on gravity, geometry, or clustering
  - Crucial for consistency tests \cite{Vielzeuf2012}, breaks CMB degeneracies \cite{Martinelli2012}

- Key ELT-HIRES driver (probing 2<z<5) \cite{Liske2008}
  - Uses Ly-\(\alpha\) forest, plus various metal absorption lines
  - Also within the reach of PEPSI?

- SKA may do it with HI (at z<1 in emission, z>8 in absorption), possibly also intensity mapping experiments?
  - Several recent claims \cite{Darling2012, Kloeckner2013, Yu2013}
  - More detailed studies ongoing
Euclid & Varying $\alpha$

- The weak lensing shear power spectrum (a Euclid primary probe) + Type Ia Supernovas can constrain Class I models
  - ...with external datasets
- Example for a CPL fiducial
  - Euclid WL
  - Euclid SN Ia (Astier et al.)
  - ELT Redshift drift & $\alpha$ data
  - + atomic clock bound
- Key synergy between Euclid and the E-ELT
  - Redshift drift & QSO data are crucial for breaking degeneracies [Vielzeuf & Martins 2012]
"This could be the discovery of the century. Depending, of course, on how far down it goes."
Equivalence Principle Tests

Variations of $\alpha$ at few ppm level naturally lead to Weak Equivalence Principle violations within 1 order of magnitude of current bound on the Eotvos parameter [Damour 2003].

- E.g., MICROSCOPE satellite should detect violations
A Consistency Test

- $T(z) = T_0(1+z)$ is a robust prediction of standard cosmology
  - Adiabatic expansion, photon number conservation
  - If $T(z) = T_0(1+z)^{1-\beta}$, find $\beta = -0.01 \pm 0.03$ [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
  - If $d_L = (1+z)^{2+\varepsilon} d_A$, find $\varepsilon = -0.04 \pm 0.08$ [Avgoustidis et al. 2010]

- In such models $\beta = -2\varepsilon/3$, but the $T-d_L$ relation is more generic: distance duality also constrains $\beta$
Taxonomy: Class II

- Models where the degree of freedom responsible for varying $\alpha$ does not provide (all of) the dark energy can be identified through consistency tests [Vielzeuf & Martins 2012]

- String-inspired runaway dilaton models [Damour et al. 2002]
  - Cf. Pauline Vielzeuf's poster; paper on the arXiv soon
Taxonomy: Class II

- Models where the degree of freedom responsible for varying $\alpha$ does not provide (all of) the dark energy can be identified through consistency tests [Vielzeuf & Martins 2012]

- String-inspired runaway dilaton models [Damour et al. 2002]

- In phenomenological Bekenstein-type models one has

\[
\frac{T(z)}{T_0} = (1 + z) \left( \frac{\alpha(z)}{\alpha_0} \right)^{1/4} \sim (1 + z) \left( 1 + \frac{1}{4} \frac{\Delta \alpha}{\alpha} \right)
\]

Avgoustidis, Martins, Monteiro, Vielzeuf & Luzzi 2013

\[
d_L(z) = d_A(z)(1 + z)^2 \left( \frac{\alpha(z)}{\alpha_0} \right)^{3/8} \sim d_A(z)(1 + z)^2 \left( 1 + \frac{3}{8} \frac{\Delta \alpha}{\alpha} \right)
\]

...which may be relevant for Planck data analysis

- Also true for disformal couplings, but not for chameleons

- Even if this degree of freedom does not dominate at low $z$, it can still bias cosmological parameter estimations
Euclid & Scalar-Photon Couplings

- Photon number non-conservation will change $T(z)$, the distance duality relation, etc. How do these models weaken constraints on cosmological parameters?

- Euclid can (even on its own, if it does a SN survey) constrain dark energy while allowing for photon number non-conservation [Avgoustidis et al. 2013]
  - Stronger constraints in combination with other probes

- $T(z)$ measurements are crucial for breaking degeneracies: they can be obtained with ALMA, ESPRESSO & ELT-HIRES
  - Also Planck clusters now – and hopefully COre/PRISM later…
Fundamental Cosmology in the E-ELT Era
The E-ELT Vision

Enabling discovery is achieved by opening parameter space

The E-ELT excels
- in collecting power
- in spatial resolution

These should not be compromised; they should be pushed into a range unattained previously

The E-ELT is not a survey telescope, indeed it's not a 'classical' telescope at all: it's an exquisite science experiment
Relevant E-ELT Instruments

- **Diffraction-limited NIR camera**
  - **ELT-CAM (PI Davies)** cf. MICADO+MAORY
    - First strong gravity tests around the galactic black hole (possibly others too)
    - Dynamical measurements of gravitational potential near event horizon
    - Direct (astrometric) test of no-hair 'theorem' *Will 2008*

- **Single-field wideband IFU NIR spectrometer**
  - **ELT-IFU (PI Thatte)**, cf. HARMONI+ATLAS
    - Spectroscopic characterization of Type Ia supernovas in $1<z<5$ *Hook 2012*
    - JWST (through NIRcam imaging) should find them and measure light curves

- **High-resolution, ultra-stable Optical/IR spectrograph**
    - Redshift drift: watching the universe expand in real time
    - Fundamental couplings: mapping the dark universe
    - The CMB temperature: mapping the bright universe
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
  - Fundamental coupling stability is optimal probe of new physics
- The story so far: nothing is varying at $\sim 10^{-5}$ level, already a very significant constraint (stronger than the Cassini bound)
  - At $10^{-6}$ level things are less clear – exponential growth in activity
  - 2-3 orders of magnitude improvement in sensitivity is coming...
  - ...but doing things properly is tough (so be patient)
- Dedicated instruments are coming, leading to a new generation of precision consistency tests
  - Redshift drift, T(z), Distance Duality, Equivalence Principle, ...
  - Synergies with other facilities, including ALMA, Euclid & SKA