Varying Couplings and Dark Energy: A Meta-Analysis

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with Ana Catarina Leite, Ana Marta Pinho, Catarina Alves, Fernando Moucherek, Tomás Silva and the rest of the CAUP Dark Side Team, plus Matteo Martinelli, Paolo Molaro and Stefano Cristiani

Scalars, Because They're There

- We know (from the LHC) that fundamental scalar fields are among Nature's building blocks
  - ...and that fundamental couplings run with energy
- These fields will naturally couple to the rest of the model
  - (unless there is an unknown principle to suppress them)
  - Couplings can therefore roll in time and ramble in space
- These couplings will lead to potentially observable long-range forces and varying couplings *[Carroll 1998, ...]*
  - These measurements (whether they are detections or null results) constrain fundamental physics and cosmology
  - This ensures a 'minimum guaranteed science'
  - Varying dimensionless physical constants imply a violation of the Einstein Equivalence Principle, a 5th force of nature, etc
  - There will also be violations of the T(z) law and the distance duality relation, which ptovide key consistency tests

How Low Should One Go?

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

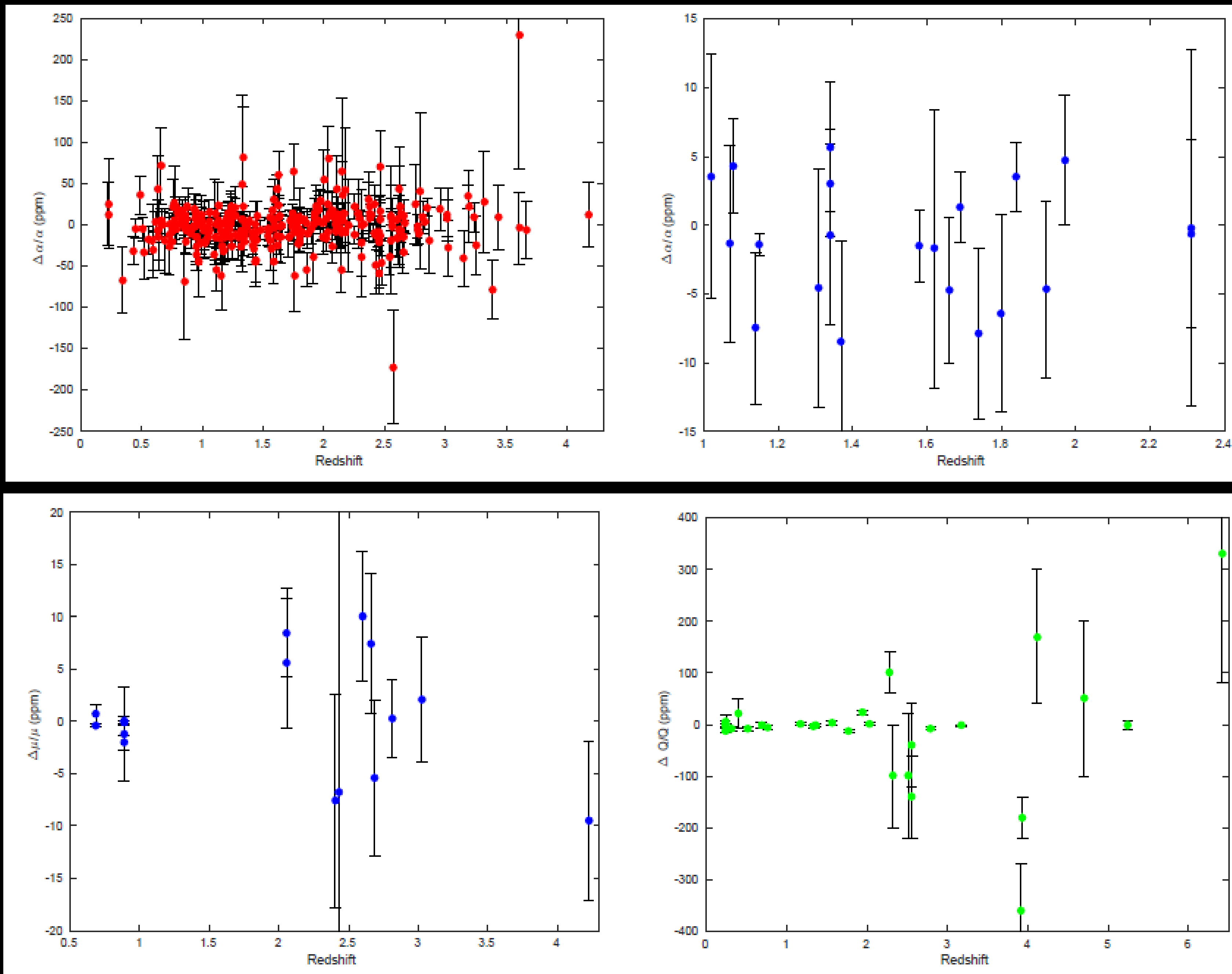
  $(1+w_0)$ is naively $O(1)$ — $(\Delta\alpha/\alpha)$ is naively $O(1)$

  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

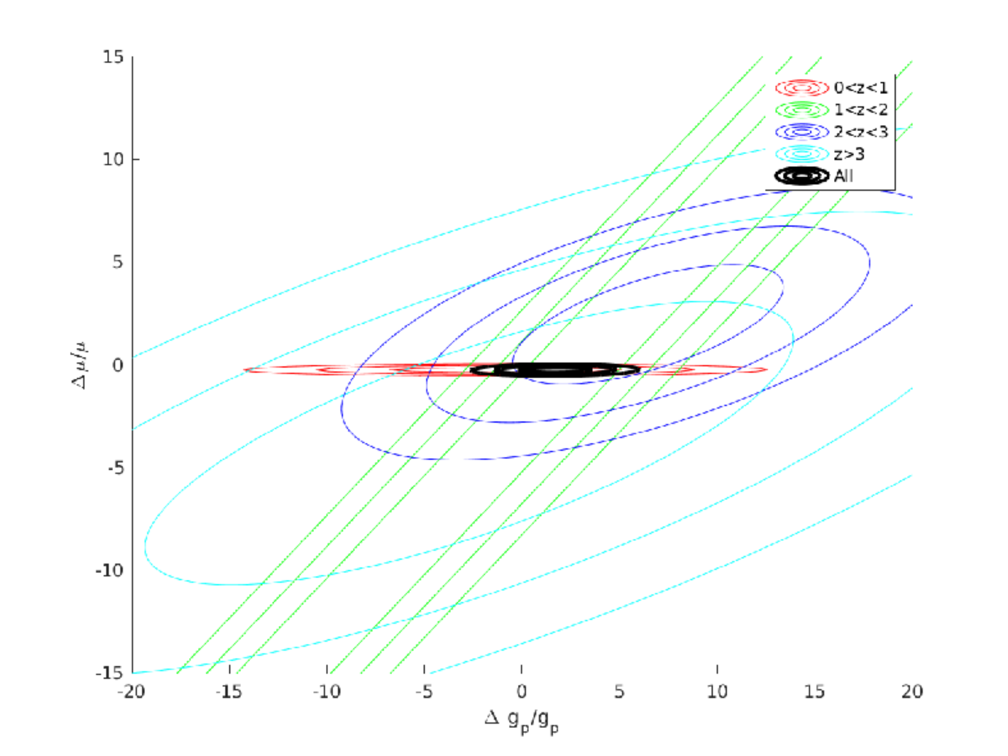
- So is it worth pushing beyond ppm? Certainly yes!
  - Strong CP Problem in QCD: a parameter naively O(1) is known to be $<10^{-10}$, leading to postulate of Peccei-Quinn symmetry and axions
  - Sufficiently tight bound would indicate either no dynamical fields in cosmology...
  - ...or a new symmetry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

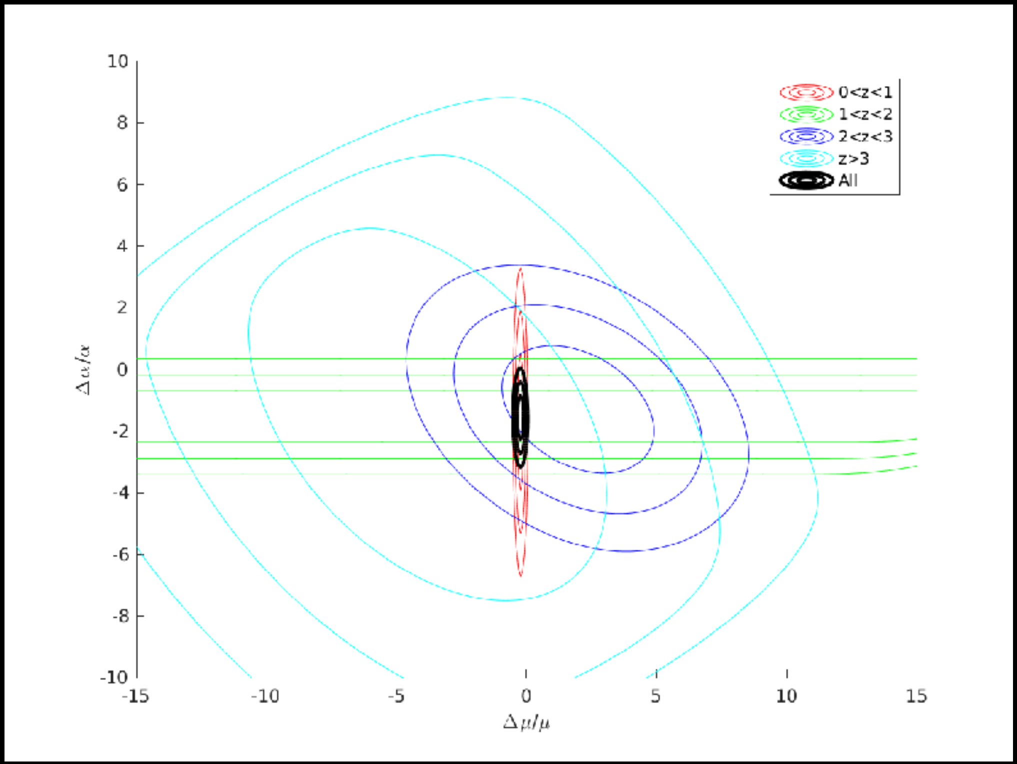
The 359 QSO Measurements So Far

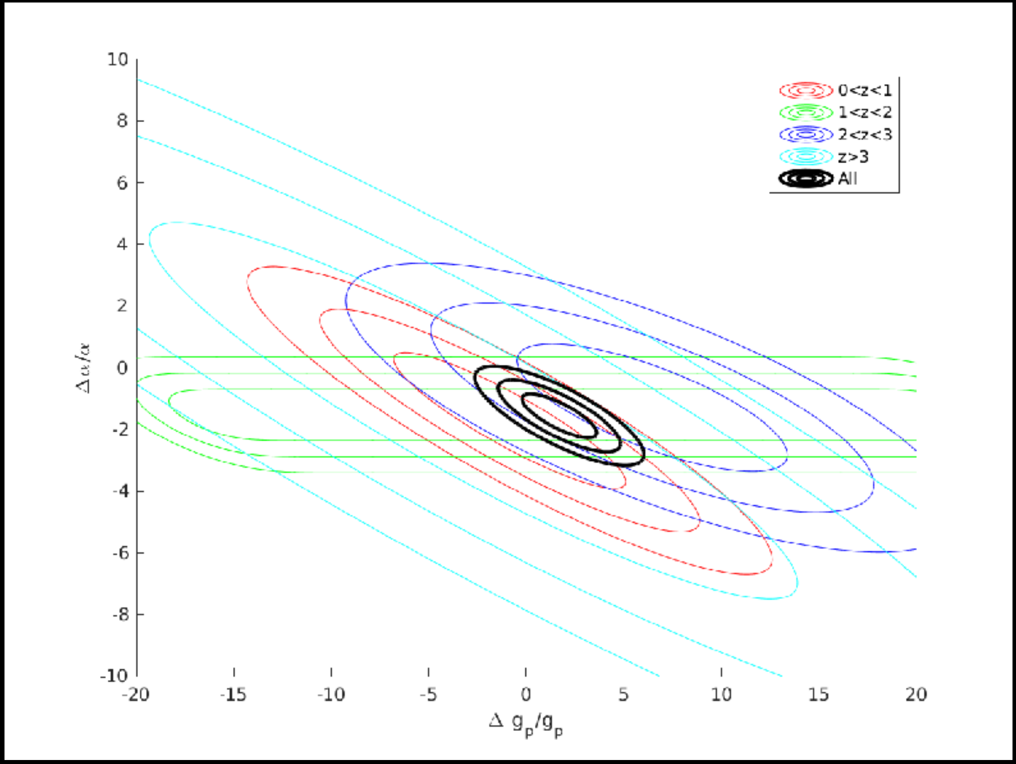


Global Analysis

- 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

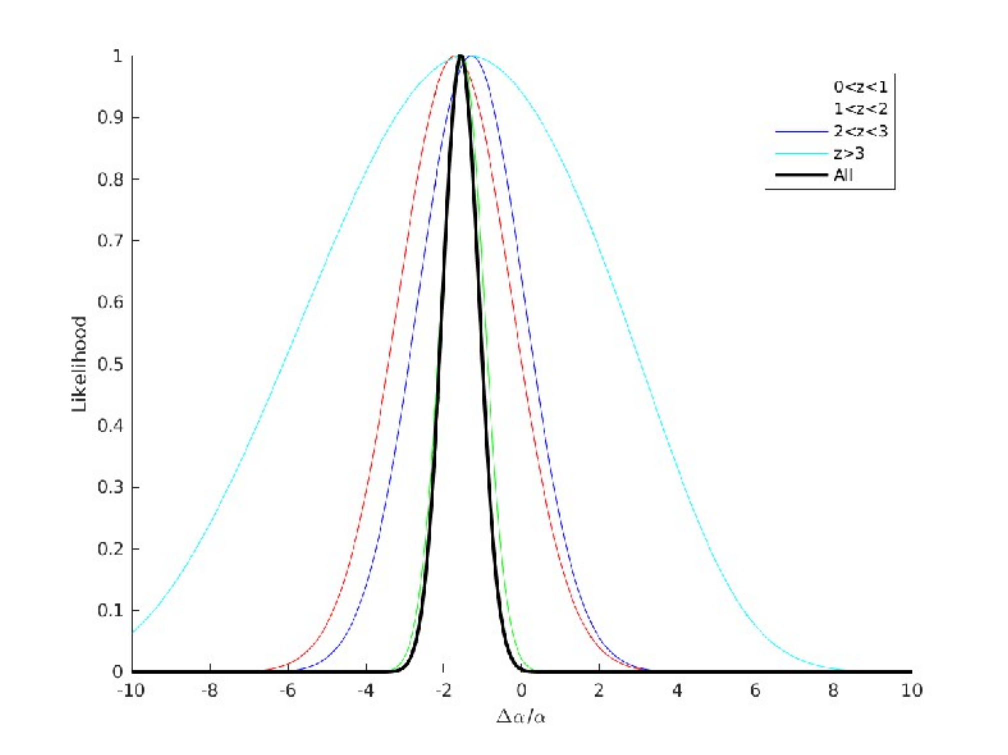


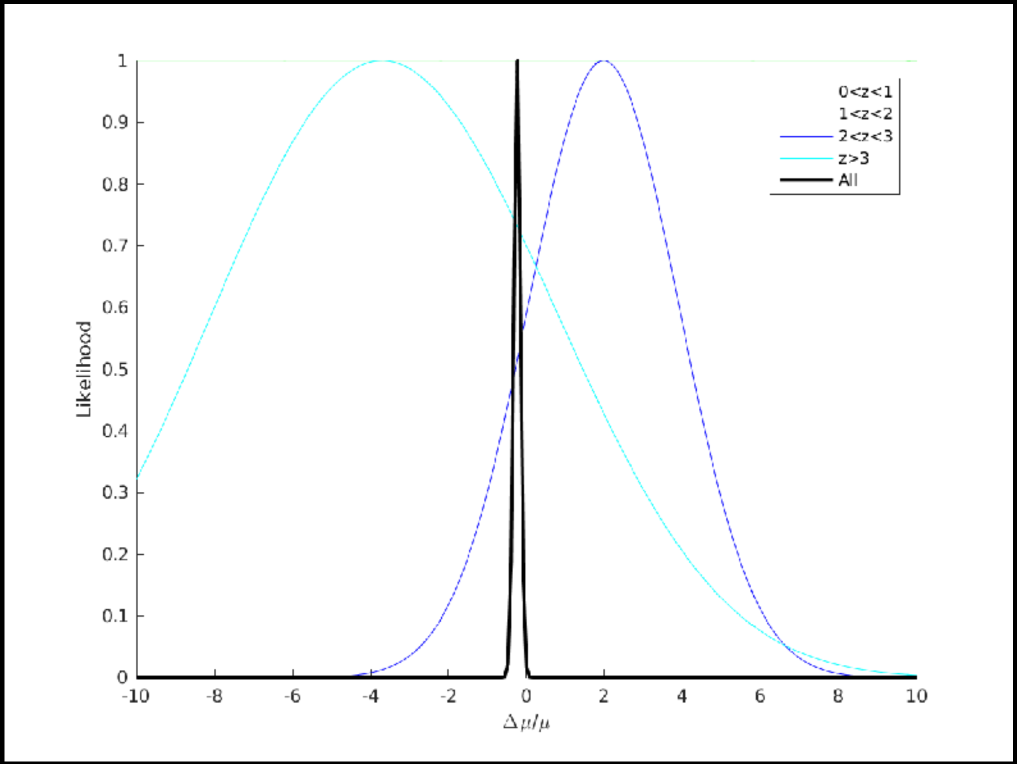


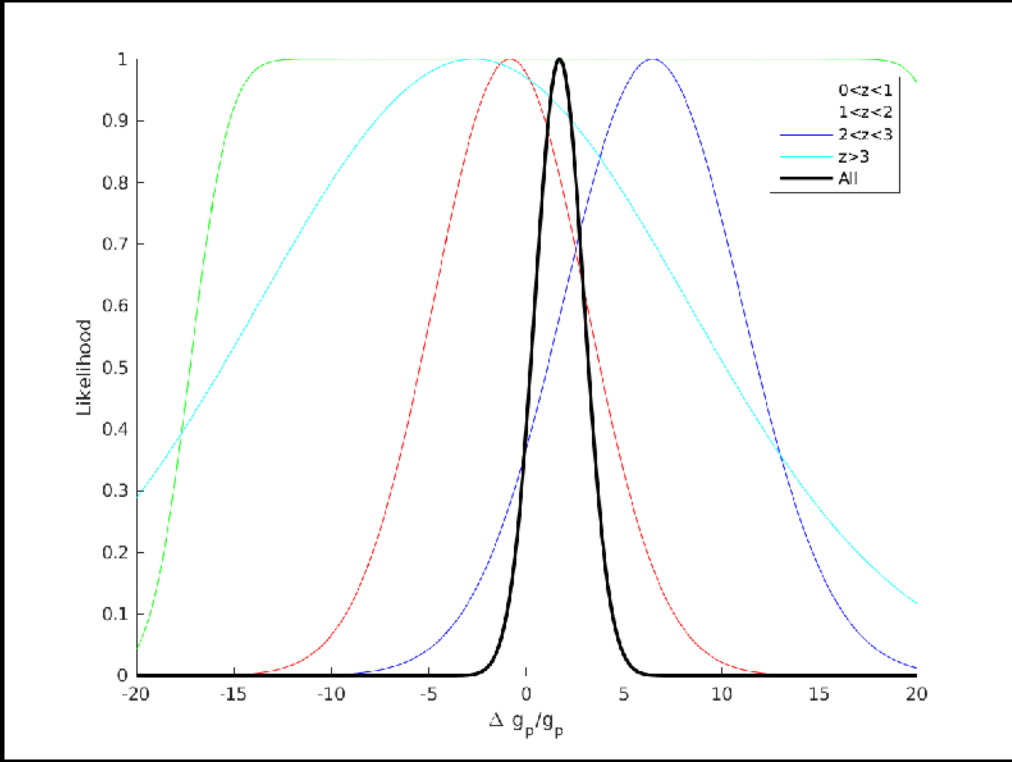


Global Analysis

- 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

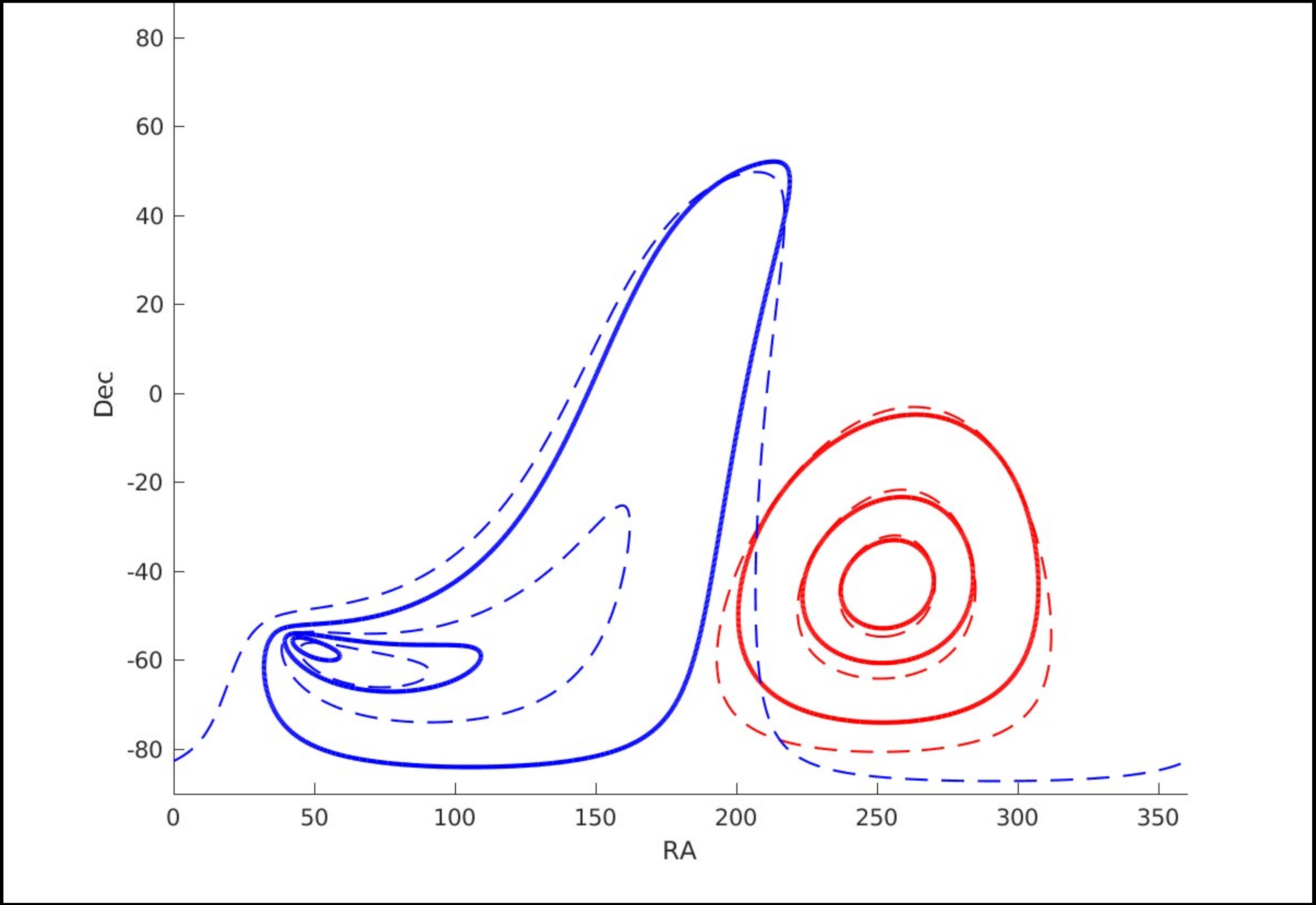






Spatial Variations: Dipoles?

- 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



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.″0	4″×1″	0.″5
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% to be decided: Target of Opportunity and/or Exquisite Science
  - External collaborators for specific projects possible (in principle)
  - If you have any well-developed ideas, do get in touch (soon)

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 will lead to potentially observable long-range forces and varying 'constants' *[Carroll 1998, Wetterich 1998, Damour 2004, ...]*
  - Current measurements already provide competitive constraints on fundamental physics and cosmology
  - Flagship science cases (and design drivers) for forthcoming ESO facilities, including ESPRESSO and the E-ELT

Quintessence-type Models

- If the same degree of freedom is responsible for dark energy and varying α, the latter's evolution is parametrically determined

$$\frac{\Delta\alpha}{\alpha}(z) = \zeta \int_0^z \sqrt{3\Omega_\phi(z')[1+w_\phi(z')]}\frac{dz'}{1+z'}$$

- Current QSO + Clocks + Cosmo 1D marginalized constraints for these models are *[Martins et al. 2015, 2016]*

$|\zeta| < 4\mathrm{x}10^{-6}$ (2 sigma)

- ESPRESSO GTO should improve this bound by a factor ~10, assuming null results *[Alves et al. 2016]*
  - More details in Ana Catarina Leite's talk (Wednesday)

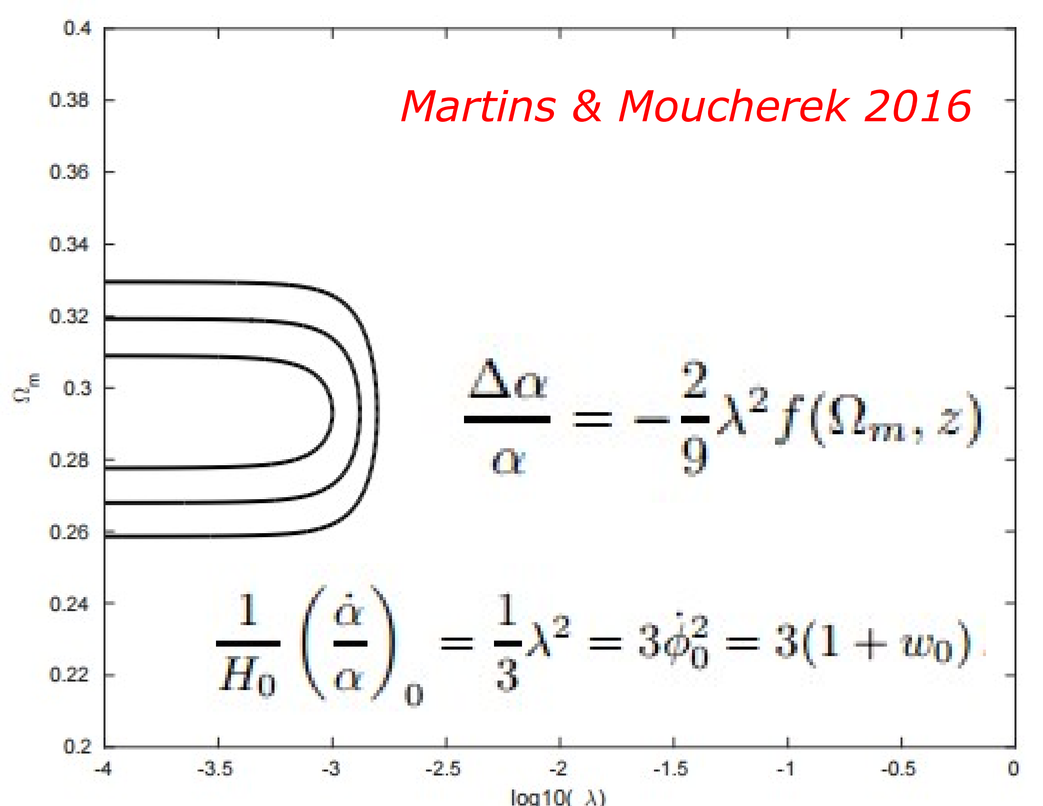
Strong Constraints on the Weak EP

- In these models the scalar field will inevitably couple to nucleons (through the α dependence of their masses) and therefore lead to violations of the Weak Equivalence Principle
  - Cf. *[Dvali & Zaldarriaga 2002, Chiba & Kohri 2002, Damour & Donoghue 2010, Uzan 2011, …]*
- Measurements of α constrain Eotvos parameter: current 2σ bound for these models $\eta < 1.6\times10^{-14}$ *[Martins et al. 2016]*
  - > 10x tighter than current direct bounds
  - ...but testable by MICROSCOPE (very soon)
  - For Bekenstein-type models, $\eta < 1.3\times10^{-14}$ at 3σ
- Forthcoming high-resolution ultra-stable spectrographs will keep providing competitive constraints
  - ESPRESSO GTO can reach $\sim2\times10^{-16}$ (5x better than MICROSCOPE)
  - ELT-HIRES sensitivity few$\times10^{-18}$, similar to that of proposed STEP

Rolling Tachyons

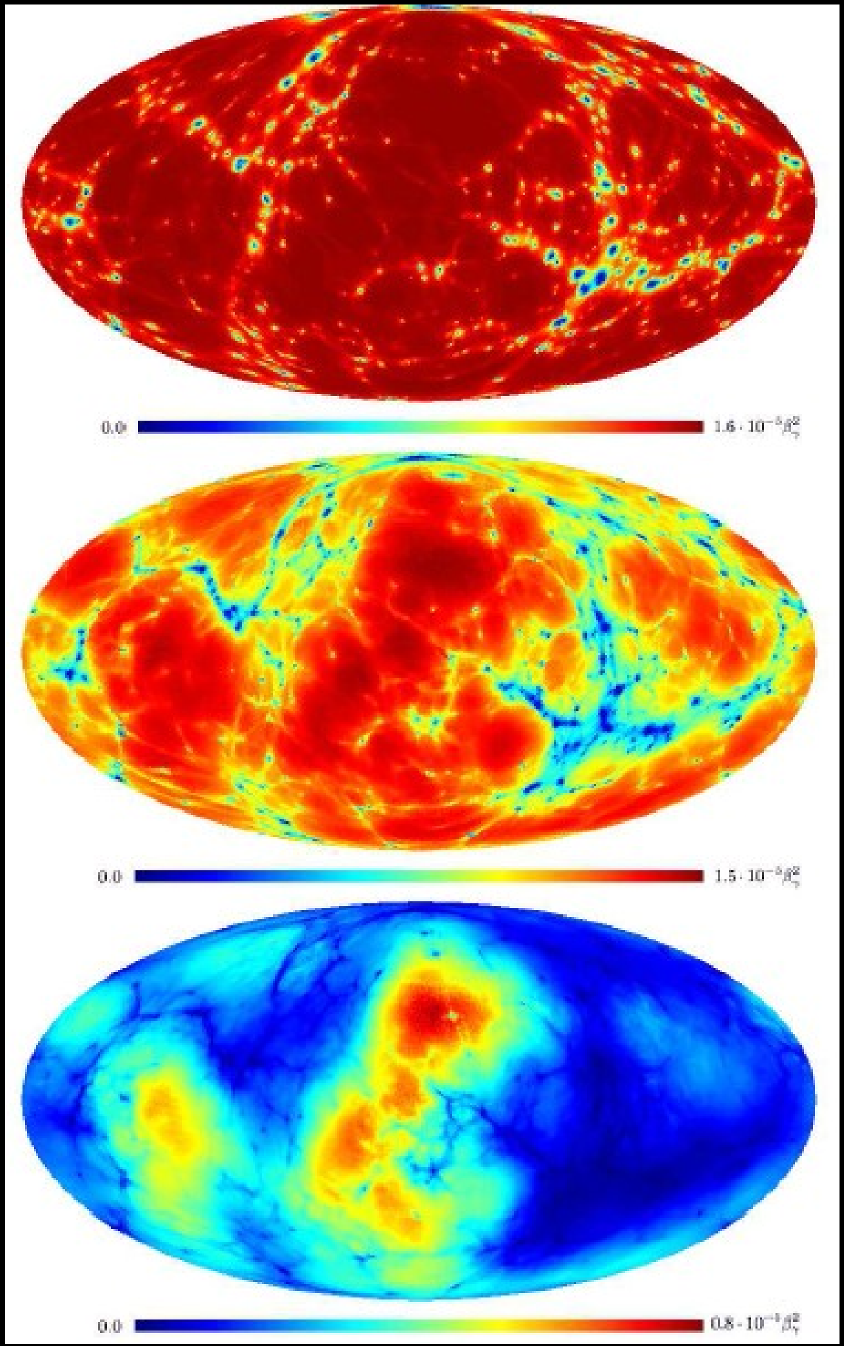
- A rolling tachyon is a Born-Infeld scalar: motivated in string theory *[Sen 2002]*, naturally yields coupling to gauge fields
  - Tachyon Lagrangian generalizes the one for a relativistic particle, like quintessence one generalizes that of a non-relativistic one
  - Quintessence couplings not fixed in Standard Model, here they come from an effective D-brane action (a DBI type action)
- Potential slope determines both w and α: thawing models with $\Delta\alpha/\alpha<0$, tight constraint

$$(1+w_0) < 2.4 \times 10^{-7}, \quad 99.7\% C.L.$$



- Background cosmology probes can't distinguish these from ΛCDM, but α data can
  - Also applies to other models

Spatial Variations: Symmetrons



[Silva et al., PRD89 (2014) 024025]

- Analytic calculations plus N-body simulations: 3D α power spectrum
  - Parameters: symmetry breaking scale factor, 5th force between particles $(F_\phi/F_{grav})=2\beta^2(\phi_{local}/\phi_0)^2$

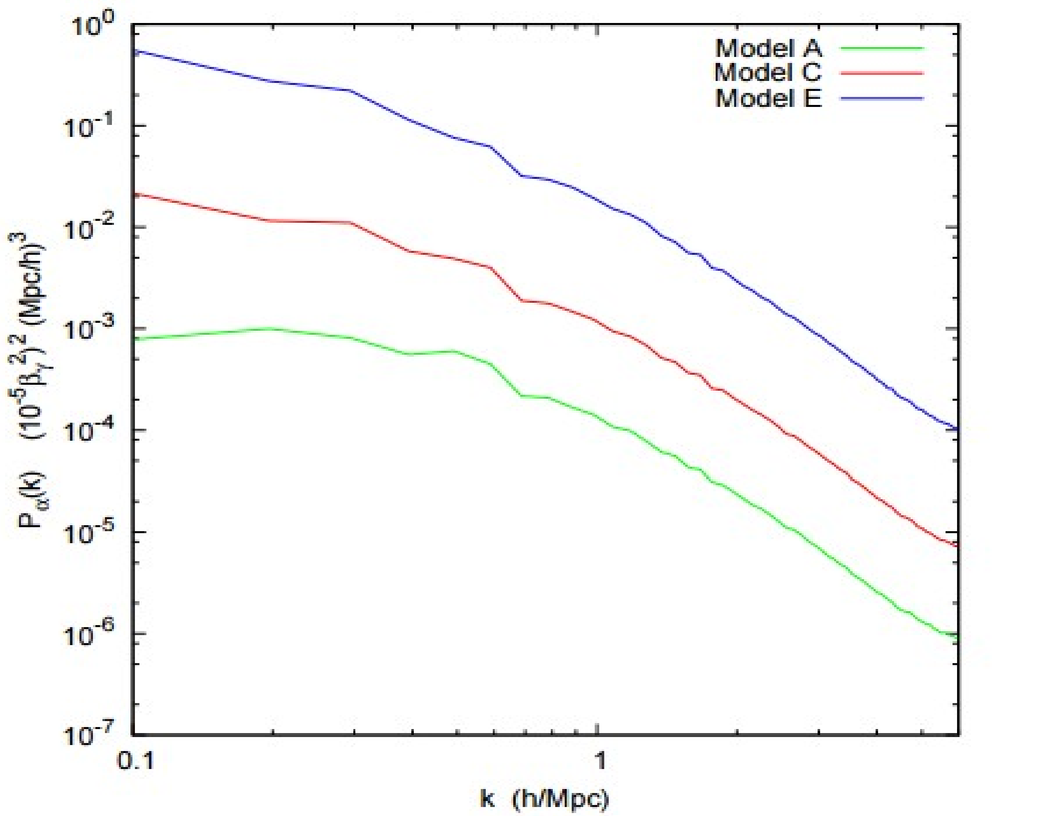
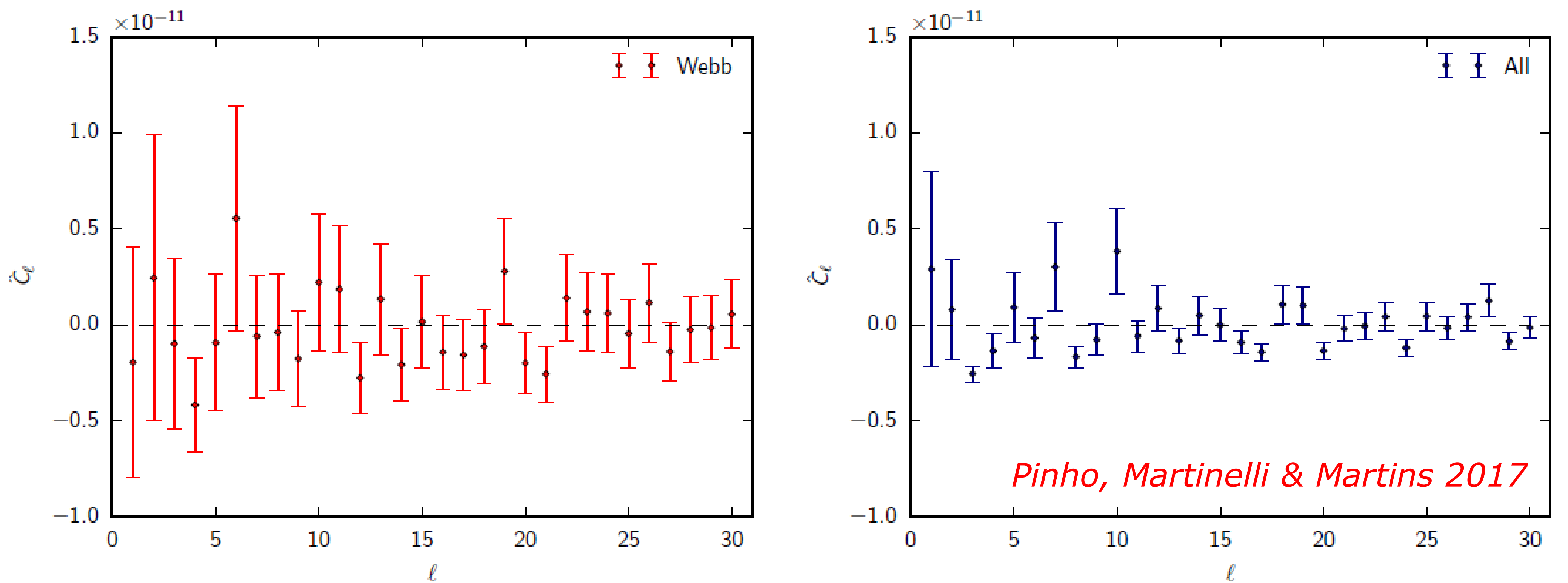


FIG. 9. The $(\alpha-\alpha_0)$ power-spectrum at $z=0$ for the models A, C and E (solid).

Spatial Variations: Symmetrons

- Use current data to calculate 2D angular power spectrum (Cl)
  - Beware number density of sources, sky coverage, ...
  - Note that the recent measurements have a significant impact
  - No statistically significant evidence for variations is found

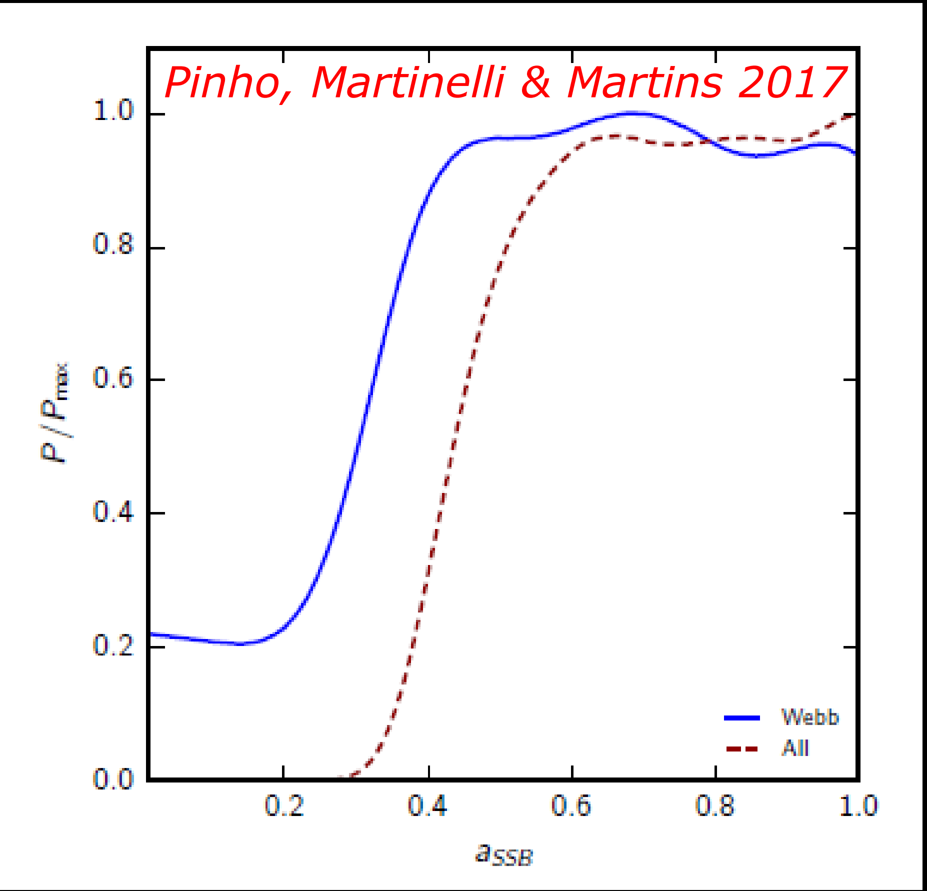


Spatial Variations: Symmetrons

- Use current data to calculate 2D angular power spectrum (Cl)
  - Beware number density of sources, sky coverage
  - Convert Pα(k) to Cl (with Limber approximation or other methods)
  - Finally, MCMC and constrain (also, repeat for other models...)

- Current data sensitive enough to provide some constraints (but not yet to scan the full parameter space)
  - E.g., constraints on strength of fifth force, log(β^2), and epoch of phase transition, for fixed cosmology

	$a_{SSB} = 0.33$	$a_{SSB} = 0.50$	$a_{SSB} = 0.66$
Webb	< -0.5	< 0.2	< 1.2
All	< -0.9	< -0.2	< 0.7



So What's Your Point?

- Precision spectroscopy is a direct, competitive probe of the (unknown) new physics behind the universe's acceleration
    - E.g., it provides best current WEP constraints
- ESPRESSO is coming soon – and will be a game changer
    - Consistency test of MICROSCOPE results
    - Competitive 'guaranteed science' implications for dark energy and fundamental physics
- In the 2020's the E-ELT will be the flagship tool in a new generation of precision consistency tests
    - Unique value of complementarity, redundancy, and synergies with other facilities, including ALMA, Euclid and the SKA

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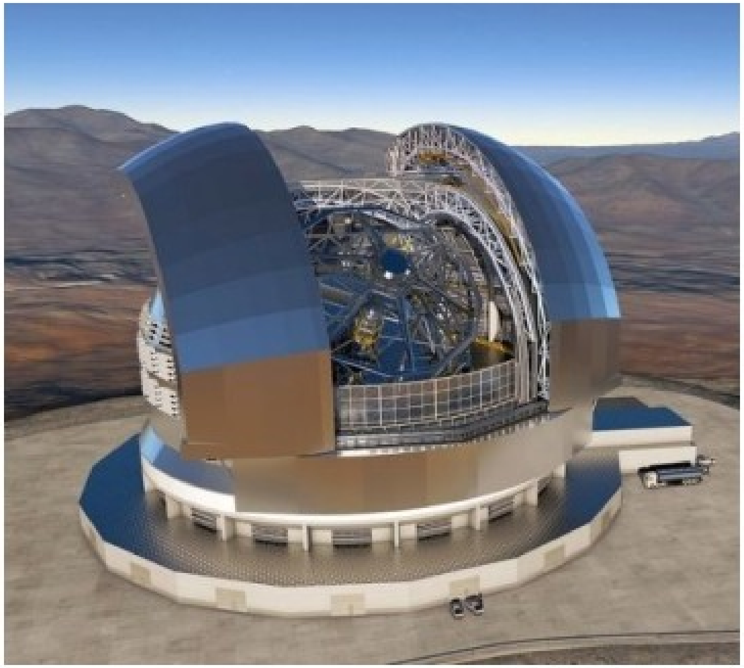
Cosmology and Fundamental Physics with Current and Future ESO Facilities

Published: 16 Jan 2017



3rd Azores School on Observational Cosmology
5th Azores International Advanced School in Space Sciences
Angra do Heroísmo, Azores, Portugal, 27 August – 2 September 2017

In the coming years a range of ground- and space-based facilities will gather an unprecedented amount of high-quality data in observational astrophysics and cosmology. These will allow open cosmological problems, e.g., nature of dark matter, dark energy, inflation and neutrino masses, to be tackled, all of which require new physics. In order to fully exploit these datasets, the interplay of a broad range of expertise, encompassing theory, phenomenology, high performance computing, data analysis and instrumentation, is required.

The aim of the school is to prepare the next generation of astrophysicists for this exciting quest, in the context of current and forthcoming ESO facilities, in particular the E-ELT. In addition to a range of lectures and hands-on tutorials, the students will have an opportunity to present their own work and discuss it with world experts in the field. Attendance will be limited to 40 students, who must apply by **31 March 2017**.

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Lecturers

A preliminary list of lecturers and the topics they will cover is as follows:

Giuseppe Bono (Roma): H0 and age of the universe, Cosmic distance ladder
Elisabetta Caffau (Paris): BBN, Population III stars
Michele Cirasuolo (ESO): ESO facilities, The E-ELT
Richard Ellis (ESO): End of dark ages, reionization
Paulo Freire (Bonn): Strong gravity tests
Bruno Leibundgut (ESO): Supernovas as cosmology probes
Joe Liske (Hamburg): Galaxy evolution, Redshift drift
Carlos Martins: (Porto): Theoretical context
Paolo Molaro (Trieste, TBC): ESPRESSO, CMB temperature measurements
Matteo Viel (Trieste): IGM tomography & galaxy formation, Dark matter and neutrinos
John Webb (UNSW/Cambridge): Stability of fundamental constants

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