JENAM 2010

Joint European and National Astronomy Meeting

LISBON PORTUGAL
Faculdade de Ciências
Universidade de Lisboa

SEP 6-10. 2010

THE EUROPEAN WEEK OF ASTRONOMY AND SPACE SCIENCE

SYMPOSIUM

SEP MON+TUE 6+7. 2010

FROM VARYING COUPLINGS TO FUNDAMENTAL PHYSICS

The first international meeting devoted to this topic was held during JENAM2002. This had a strong impact on subsequent developments. After eight years the field has considerably matured and it is time for a new assessment in the European countries. We will bring together the most active researchers in this area to discuss the latest developments, explore ways to leverage the unique capabilities of the various groups and create synergies with European facilities such as ESO's VLT (and the future E-ELT), ESA's Planck and Herschel spacecrafts, as well as ALMA and the LBT, in which Europe is actively involved.

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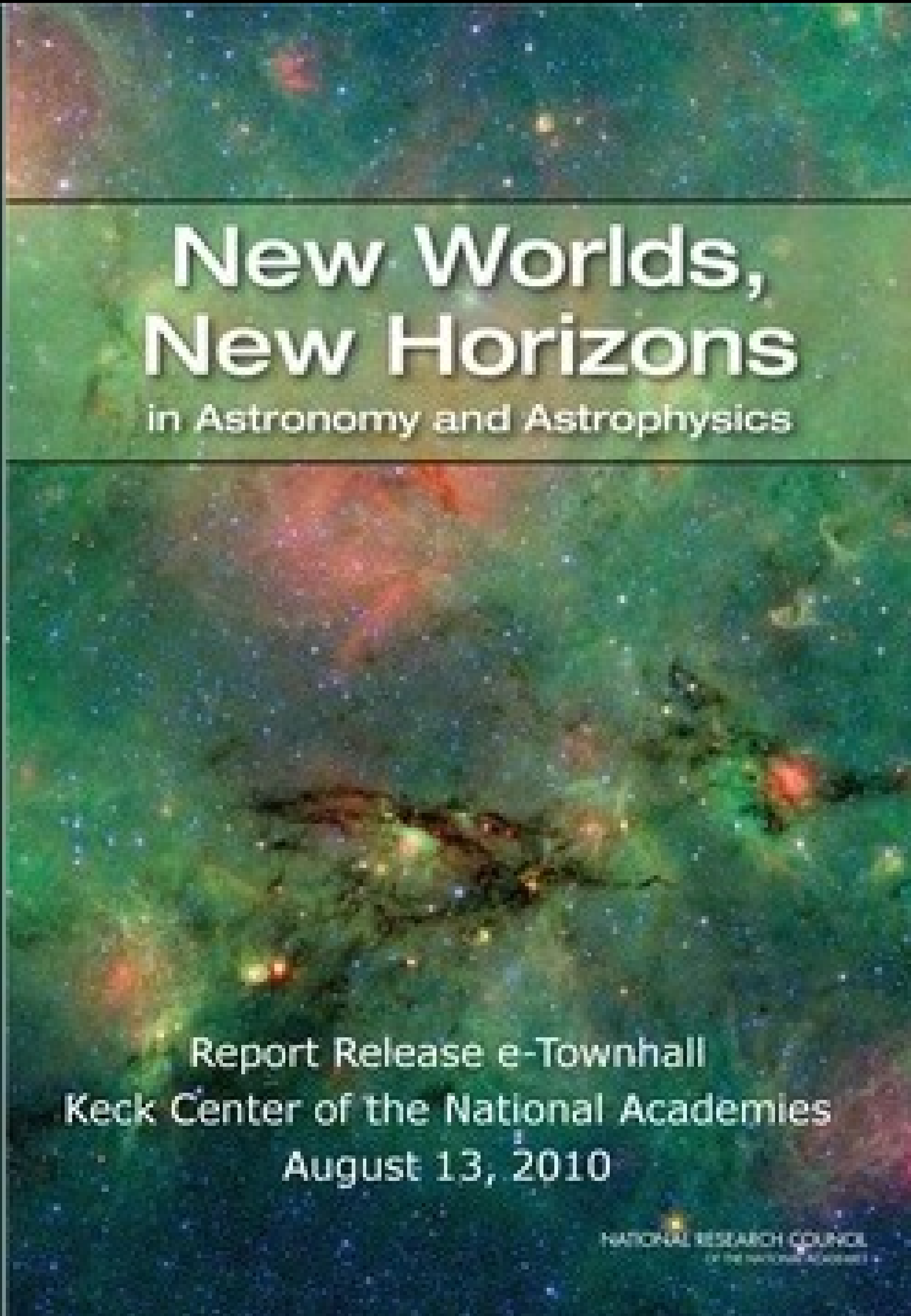


**A Roadmap for
Fundamental Physics in Space**

Prepared by the ESA-appointed
Fundamental Physics Roadmap Advisory Team (FPR-AT)

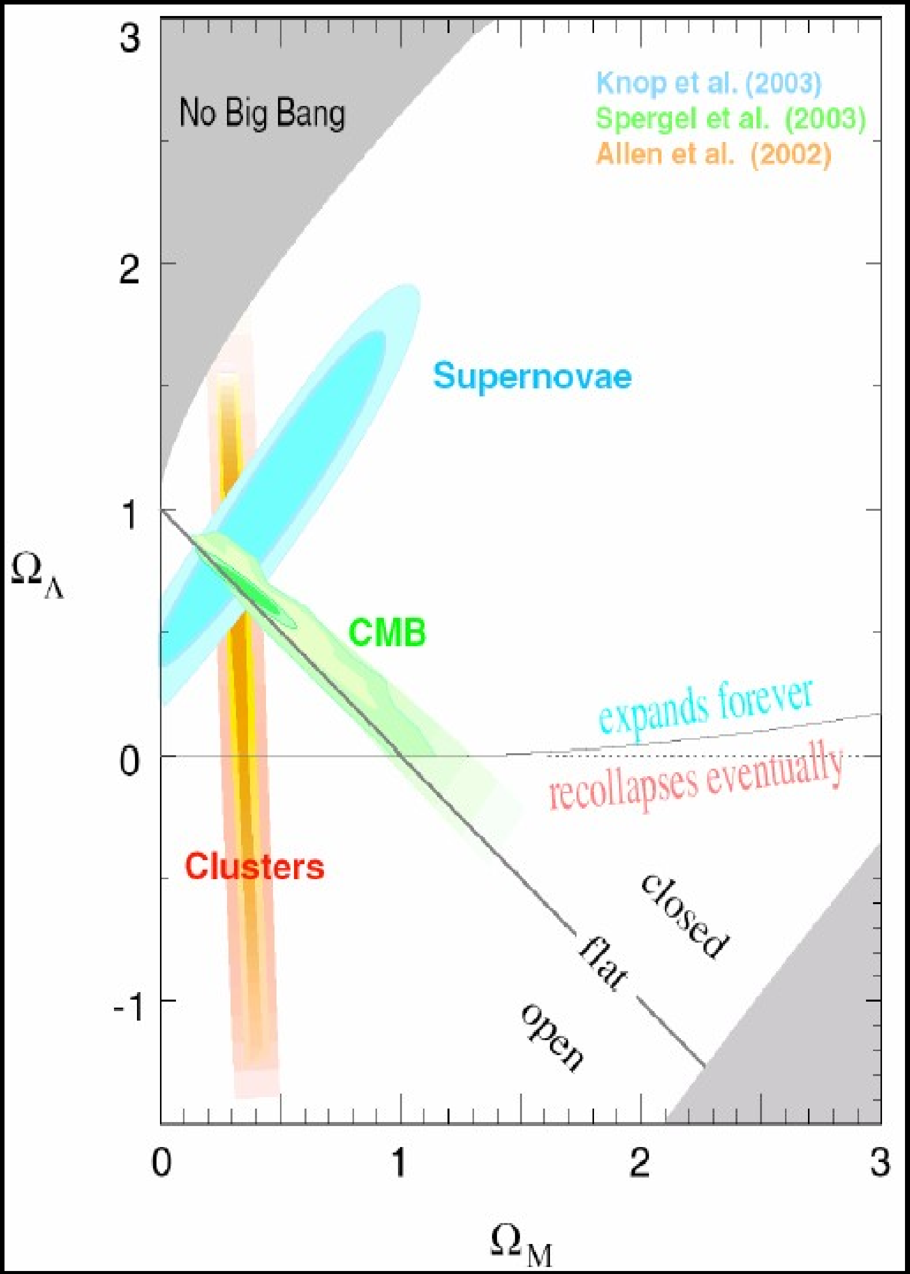
26 July 2010

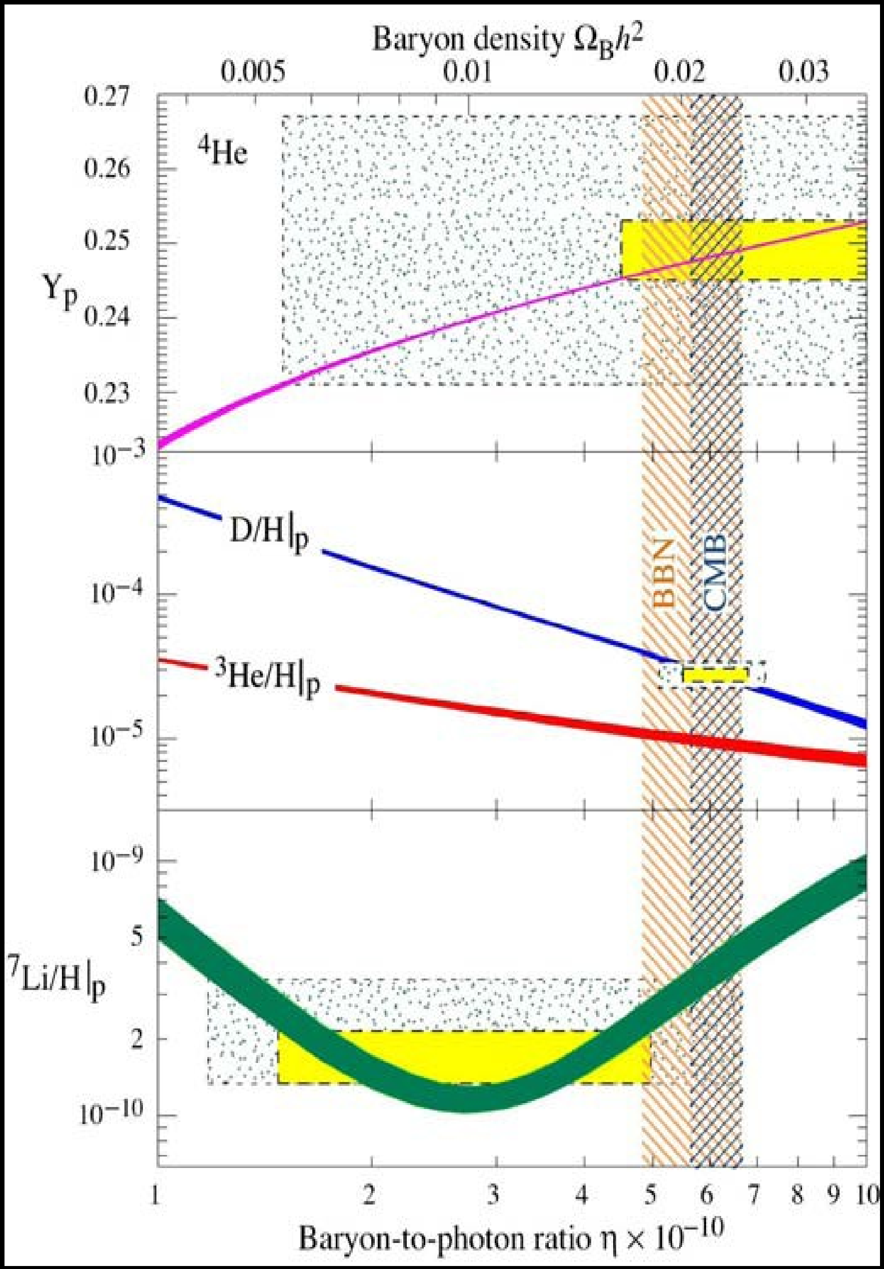
The Quest for Scalar Fields

- The fields of Nature:
  - Observed particles are described by Fermi spinors
  - Gauge forces are described by boson vector fields
  - Einstein gravity uses only a 2-tensor (the metric)
  - Is there anything else (such as fundamental scalar fields)?
- Scalar fields have long been part of the standard model of particle physics (cf. the Higgs particle).
- Recent developments suggest that they could be equally important in astrophysics and cosmology.
- ***Yet neither side has so far produced definitive experimental or observational evidence for them…***


via
della Fisica
viale
dell'Astronomia

The Concordance Model





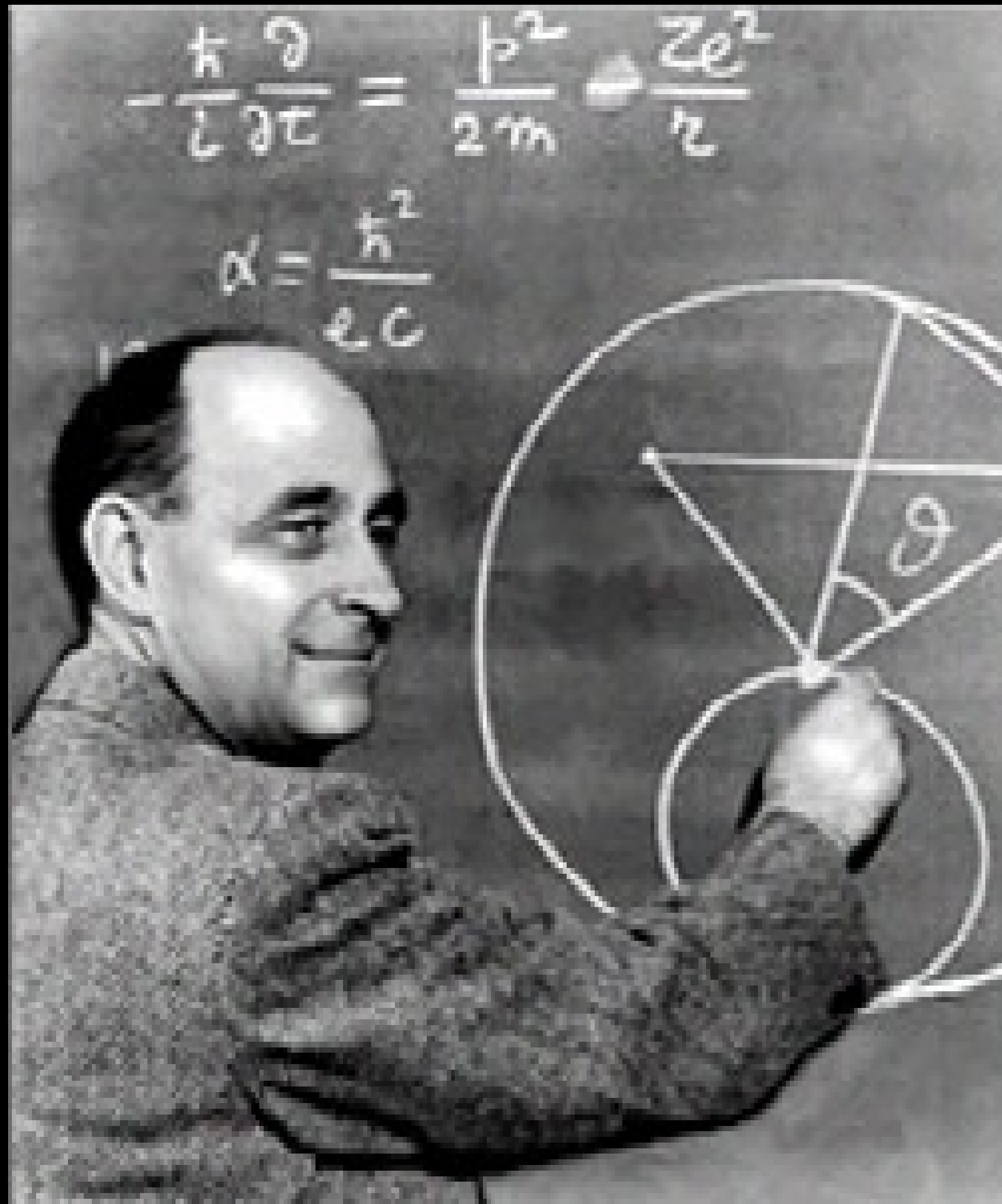
Hints of New Physics

- Three firmly established facts that the standard model of particle physics can't explain:
  - Neutrino masses
  - Dark matter
  - Size of baryon asymmetry
- 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 usually 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

The Role of Constants

- A completely unsolved issue: no 'theory of constants' exists! *[Duff et al. 2002, Martins 2002]*
- Asymptotic states?
  - c: Limit velocity of massive particle in flat space-time
  - G: Limit potential for mass not forming black hole in curved space-time
  - h: Limit uncertainty (quantum of action)
- Convenient conversion factors?
  - Can't be pushed arbitrarily far...
- Pointers to the emergence of new phenomena
- **How many are fundamental? *(The story so far: 3)* Will they be fixed by consistency conditions, or remain arbitrary?**

Constants & Extra Dimensions

- Unification of fundamental forces requires additional space-time dimensions; in such models, true fundamental constants are defined in higher dimensions
- (3+1)D constants are effective quantities, typically related to the true constants via characteristic sizes of the extra dimensions
- Hence expect space-time variation of such effective coupling constants.
    - Inter alia, a varying α is unavoidable 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]*

The Strong Sector, α & μ

- In theories where a dynamical scalar field is responsible for varying α, the other gauge and Yukawa couplings are also expected to vary.
- In GUTs there's a relation between the variation of α and that of Λ_{QCD}, implying that nucleon mass will vary when measured in units of an energy scale independent of QCD.
- ***Expect variations of $\mu=m_p/m_e$, which can be measured, e.g. using H_2 [Thompson 1975].***
- Wide range of possible α-μ relations implies that simultaneous measurements of both are a key discriminating tool between competing models.

An Example

- For the MSSM embedded on a GUT

$$(d \ln \mu / dt) \sim R \, (d \ln \alpha / dt)$$

- If α varies due to a varying unified coupling, R>0 (typically 40); if due to varying unification scale, R<0 (typically -50)
- Can build say SU(5) models with any value of -500<R<600 *[Calmet & Fritzsch 2002]*. |R| typically large: fine-tuning needed for |R|<1
- Large numbers arise simply because the strong coupling and the Higgs VEV run (exponentially) faster than α
- *By probing $\alpha(z)$ and $\mu(z)$ we can test GUT scenarios without needing to detect any GUT model particles at accelerators!*

Was Einstein Right?

Dynamical Dark Energy

- 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.
- Slow-roll (mandatory for $p<0$) and present-day domination imply *[Carroll 1998]* that couplings of this field lead to observable long-range forces and time dependence of the constants of nature.
- Standard methods (SNe, Lensing, etc) are of limited use as dark energy probes *[Maor et al. 2001, Upadhye et al. 2005].*
  - Clear detection of varying $w(z)$ is key to convincing result, since $w_0 \sim -1$
- ***Since the field is slow-rolling when dynamically important, a convincing detection of w(z) is very unlikely even with EUCLID or JDEM***

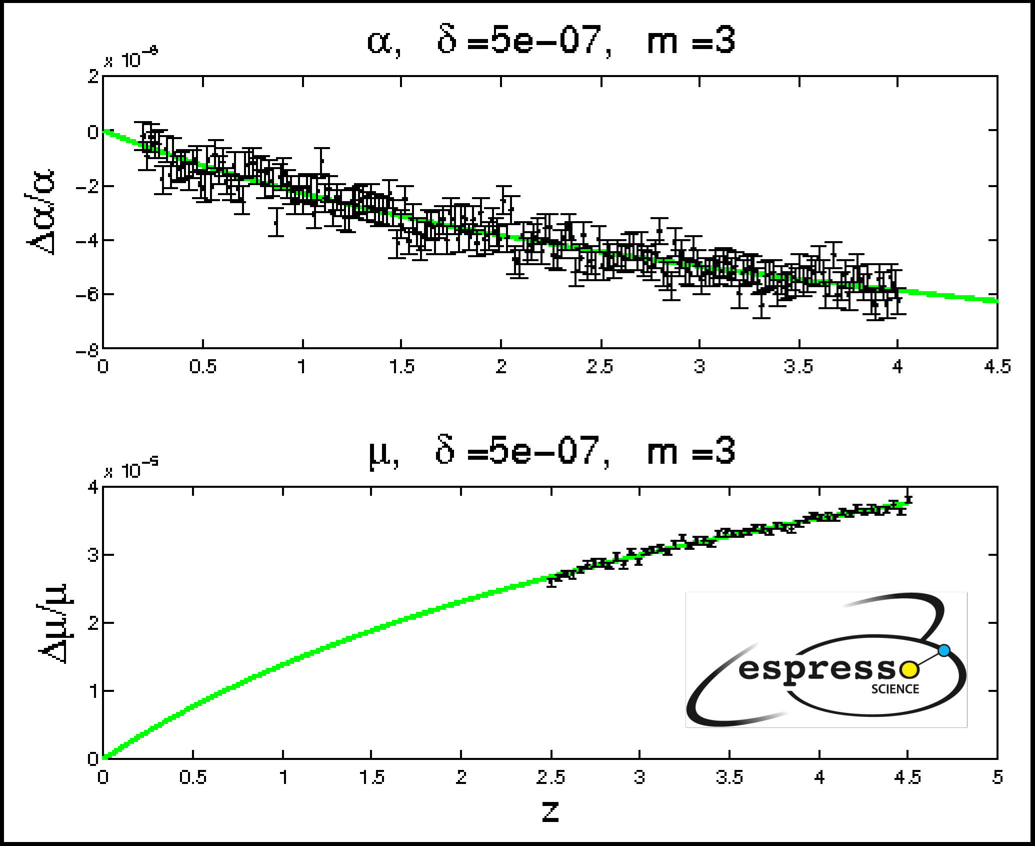
From $\alpha(z)$ - and $\mu(z)$ - to $w(z)$

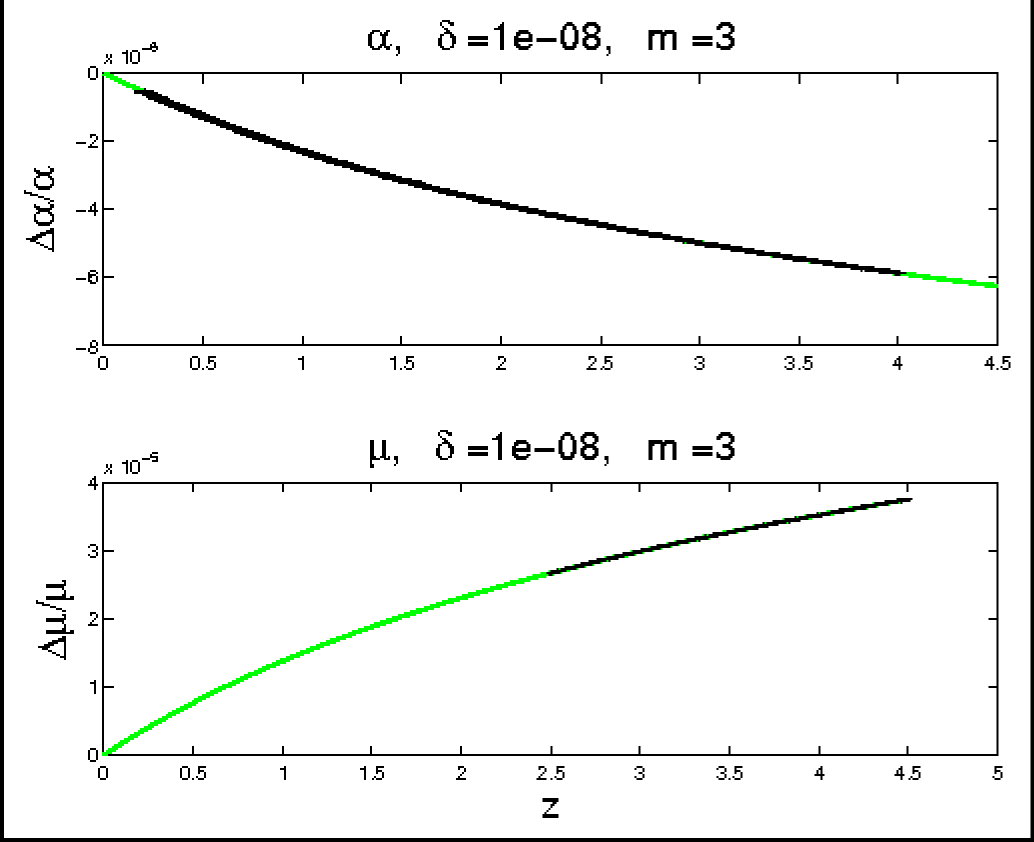
[More in Nelson Nunes' talk]

- Scalar field yielding dark energy must give varying couplings. They can be used to reconstruct w(z) *[Nunes & Lidsey 2004].*
  - Analogous to reconstructing the 1D potential for the classical motion of a particle, given its trajectory
- Will complement and extend traditional methods.
- Key Advantages:
  - ***Direct probe of Grand Unification and fundamental physics***
  - ***Directly distinguishes Λ from a dynamical field (no false positives)***
  - ***Huge z lever arm, probes otherwise inaccessible z range where field dynamics is expected to be fastest (deep matter era)***
  - ***Low-cost, ground-based (~100 good nights on VLT, Keck, LBT)***
  - ***We can start now!***

In Practice: ESPRESSO & CODEX

[More in Paolo Molaro's talk]





In Practice: ESPRESSO & CODEX

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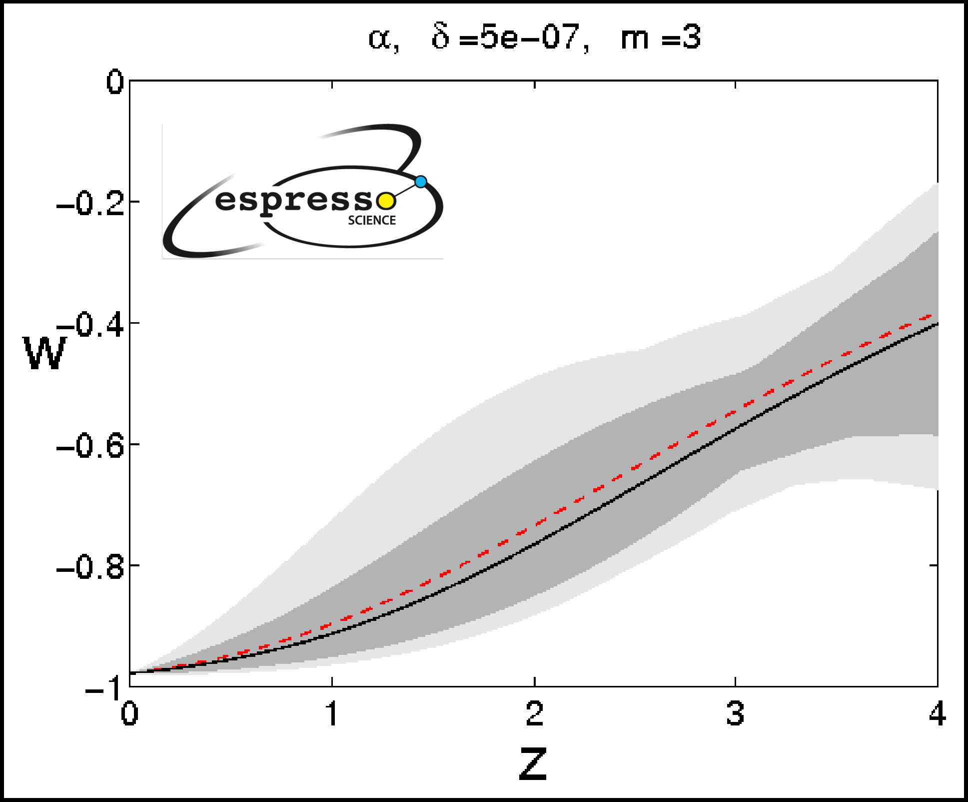
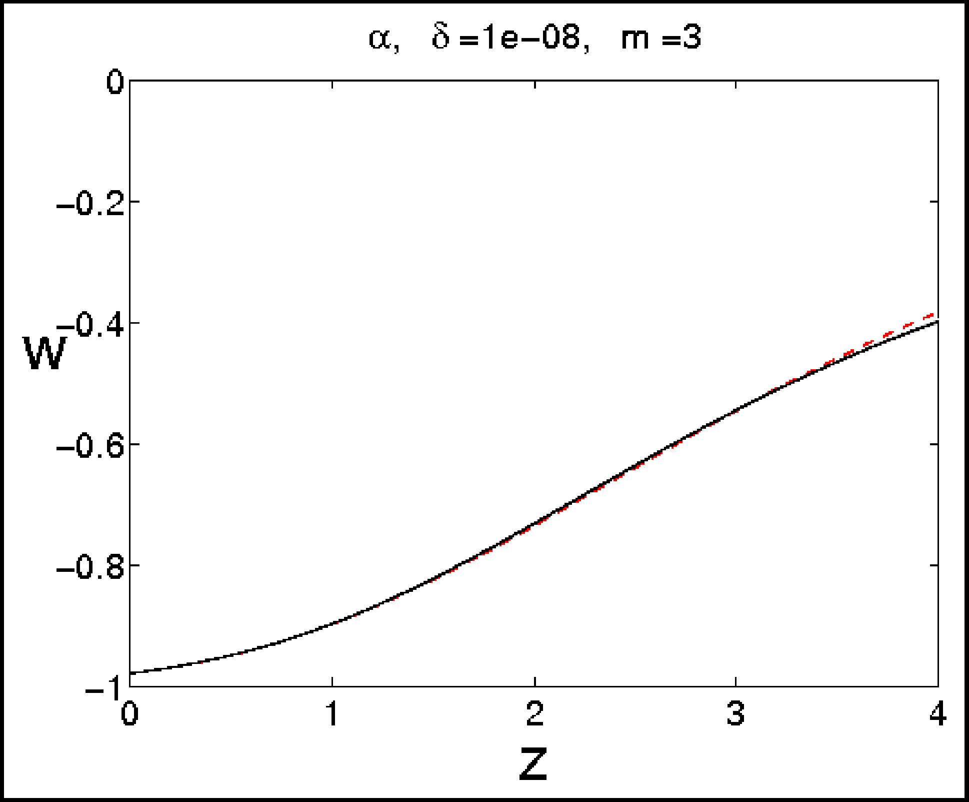
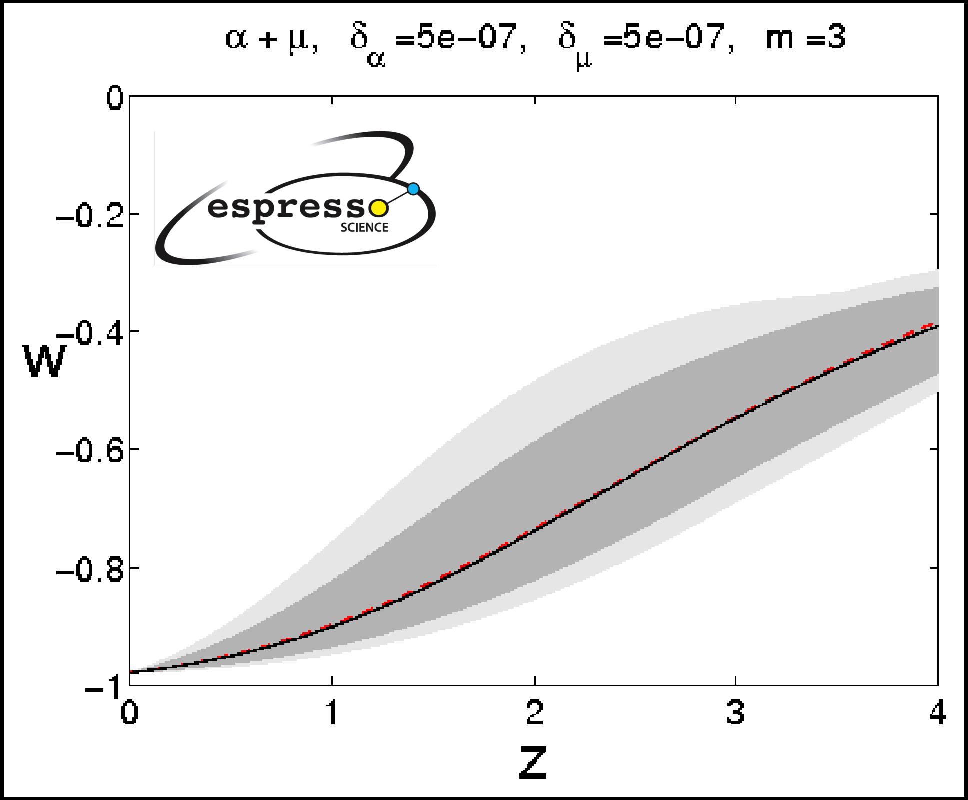
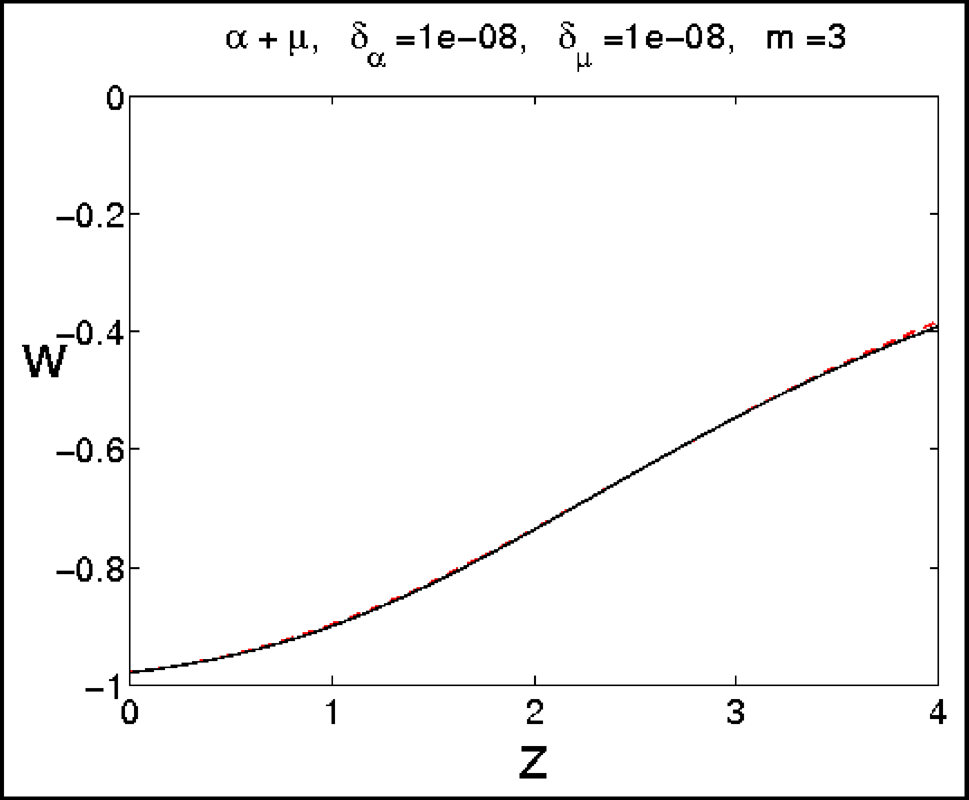




In Practice: ESPRESSO & CODEX

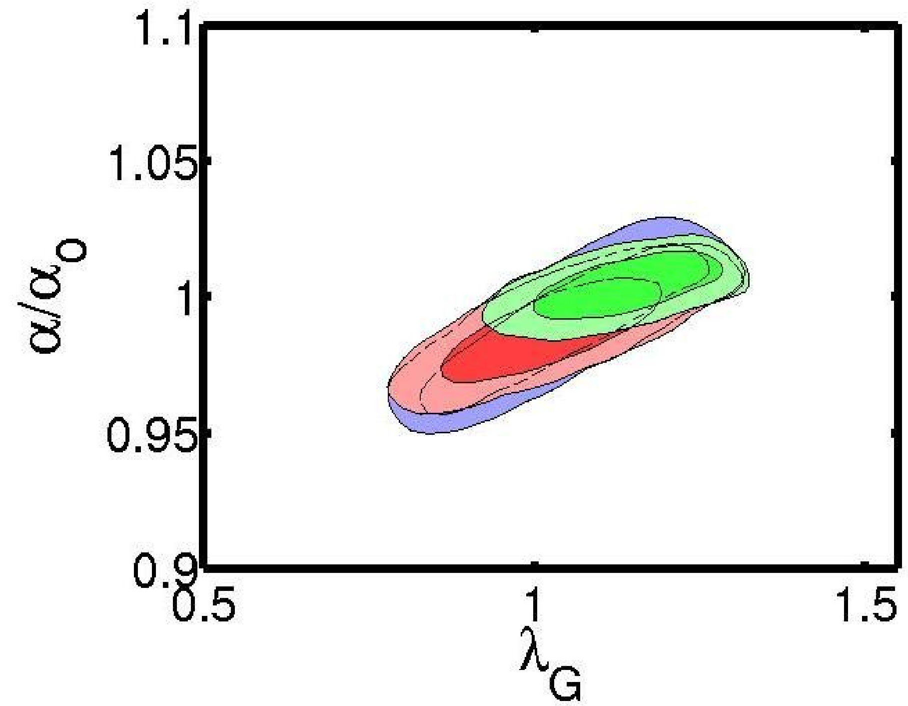
[More in Paolo Molaro's talk]



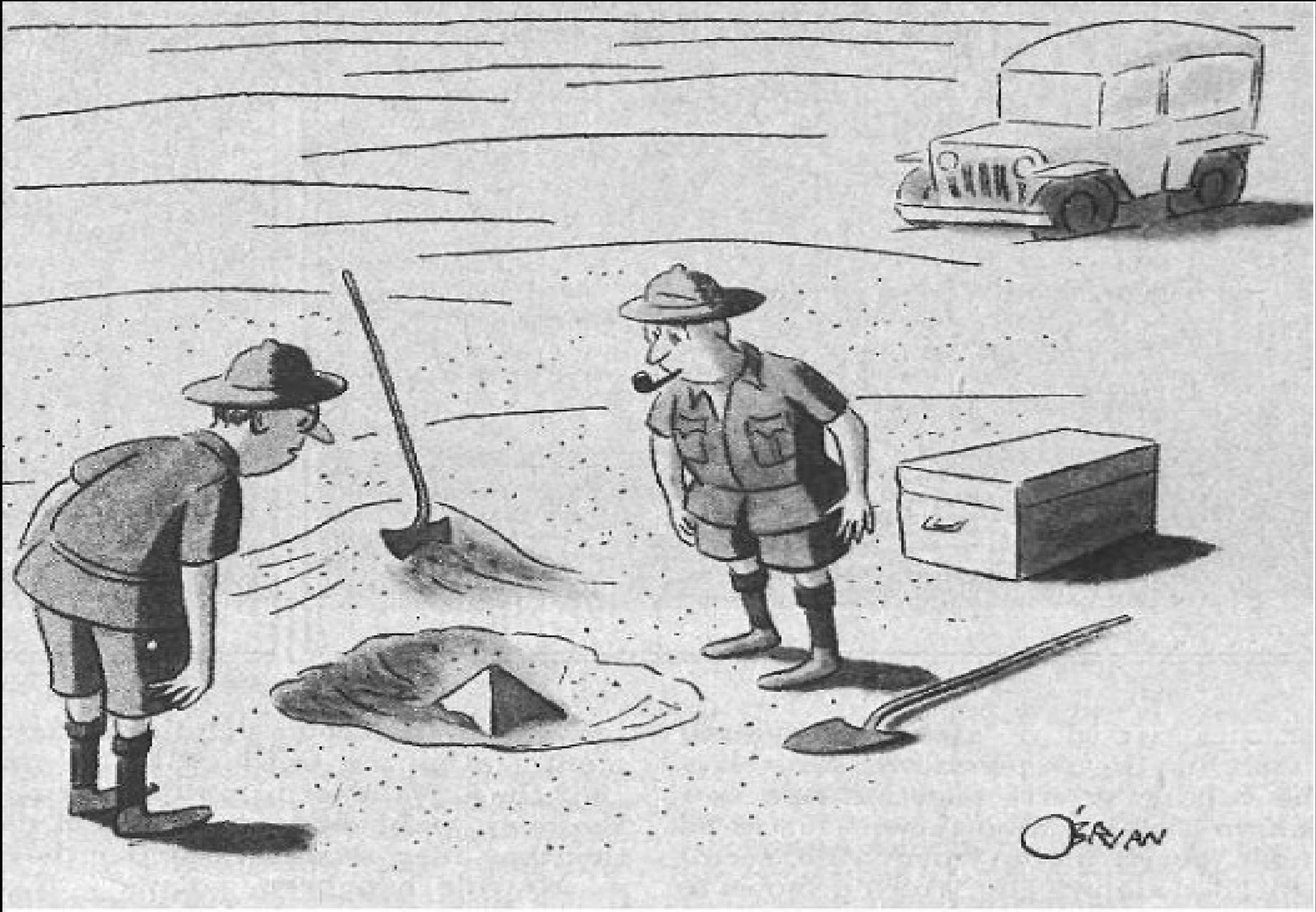


The Quest for Redundancy (in alphabetic order)

- Atomic clocks
- BBN
- Clusters
- CMB
- Geophysics
- Helioseismology
- Spectroscopy
- Strong Gravity
- ...
- plus other tests: Equivalence Principle, T(z), etc



[More in Silvia Galli's talk]



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