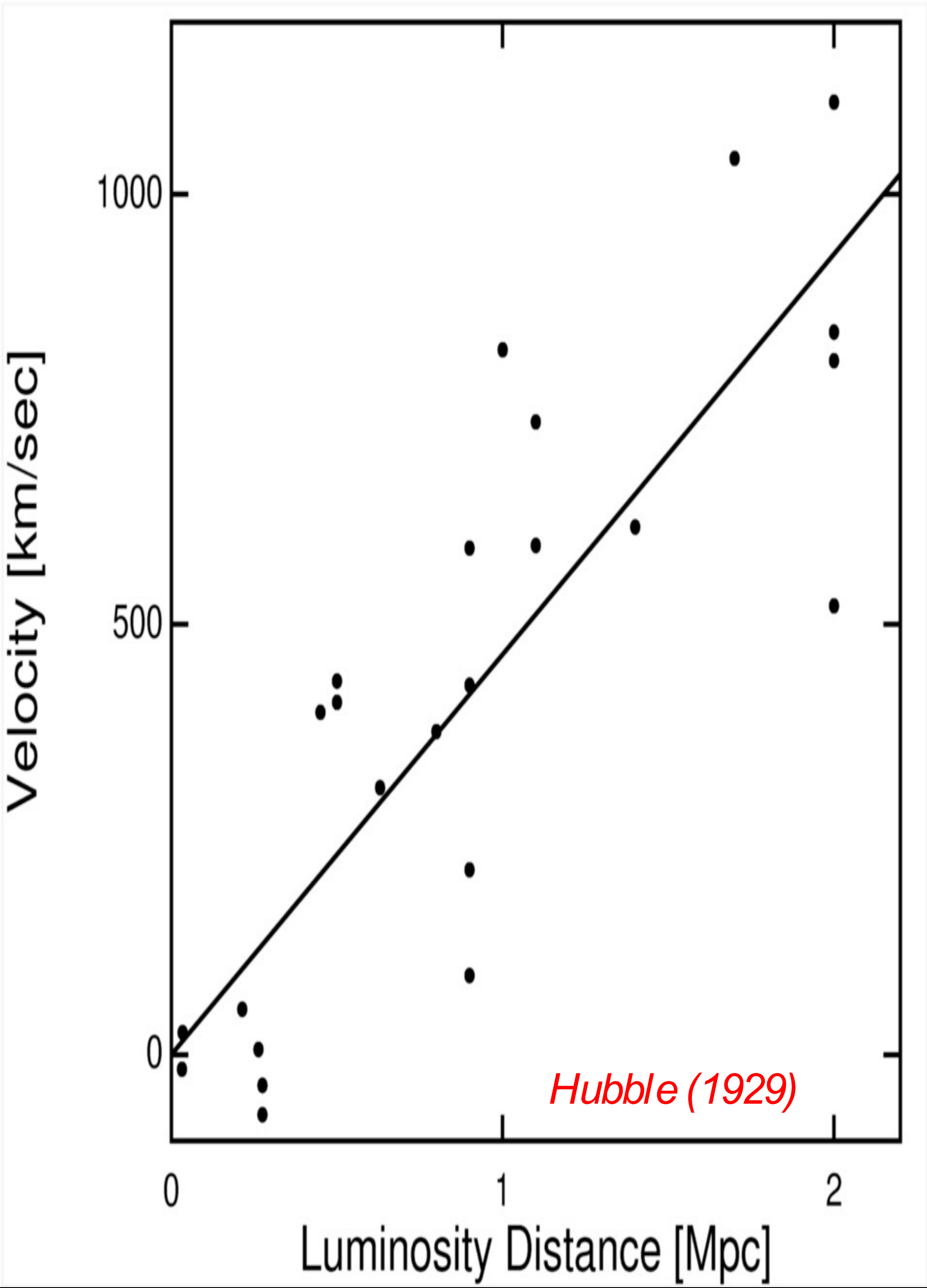
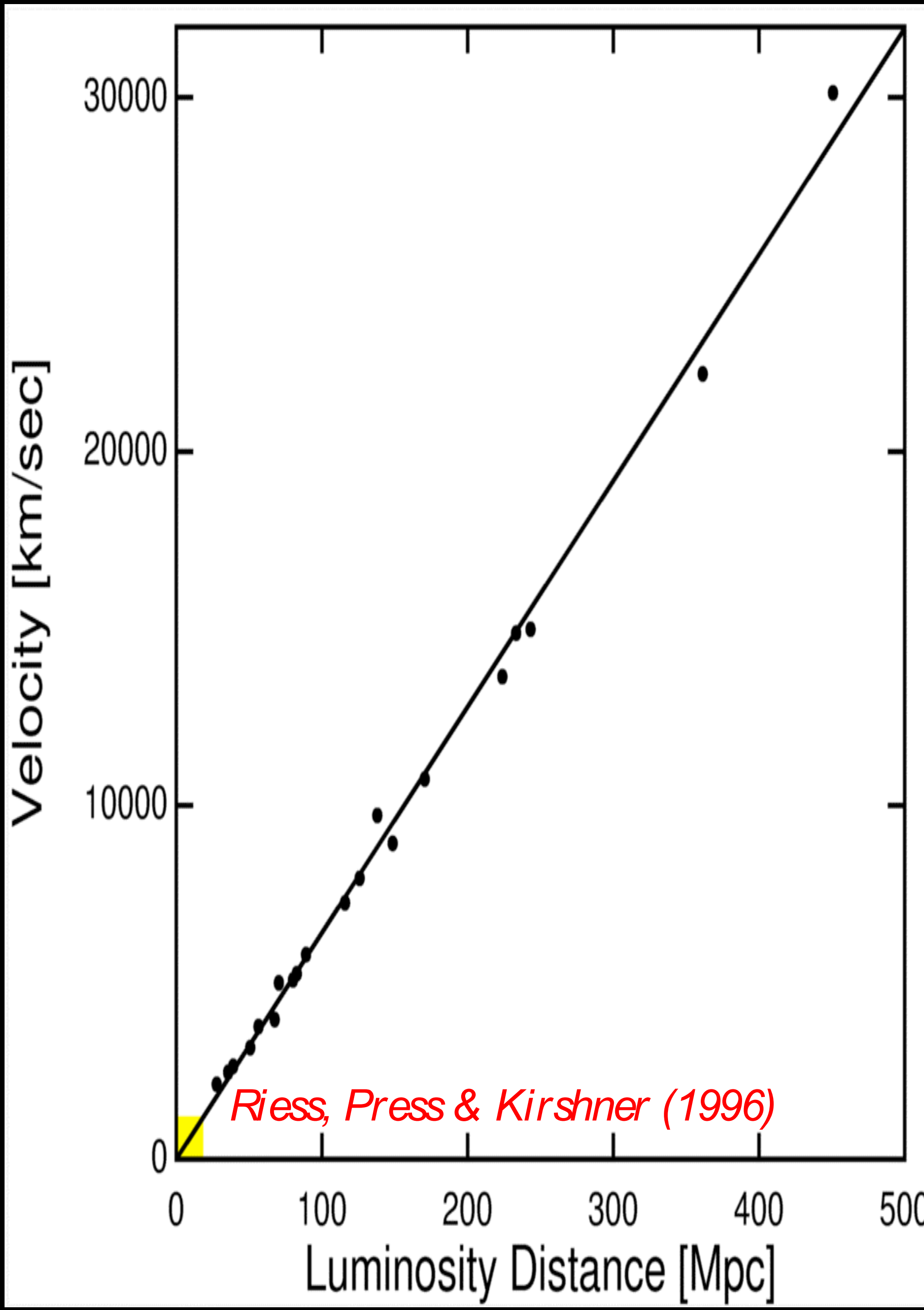
Looking for New Physics in the Early Universe

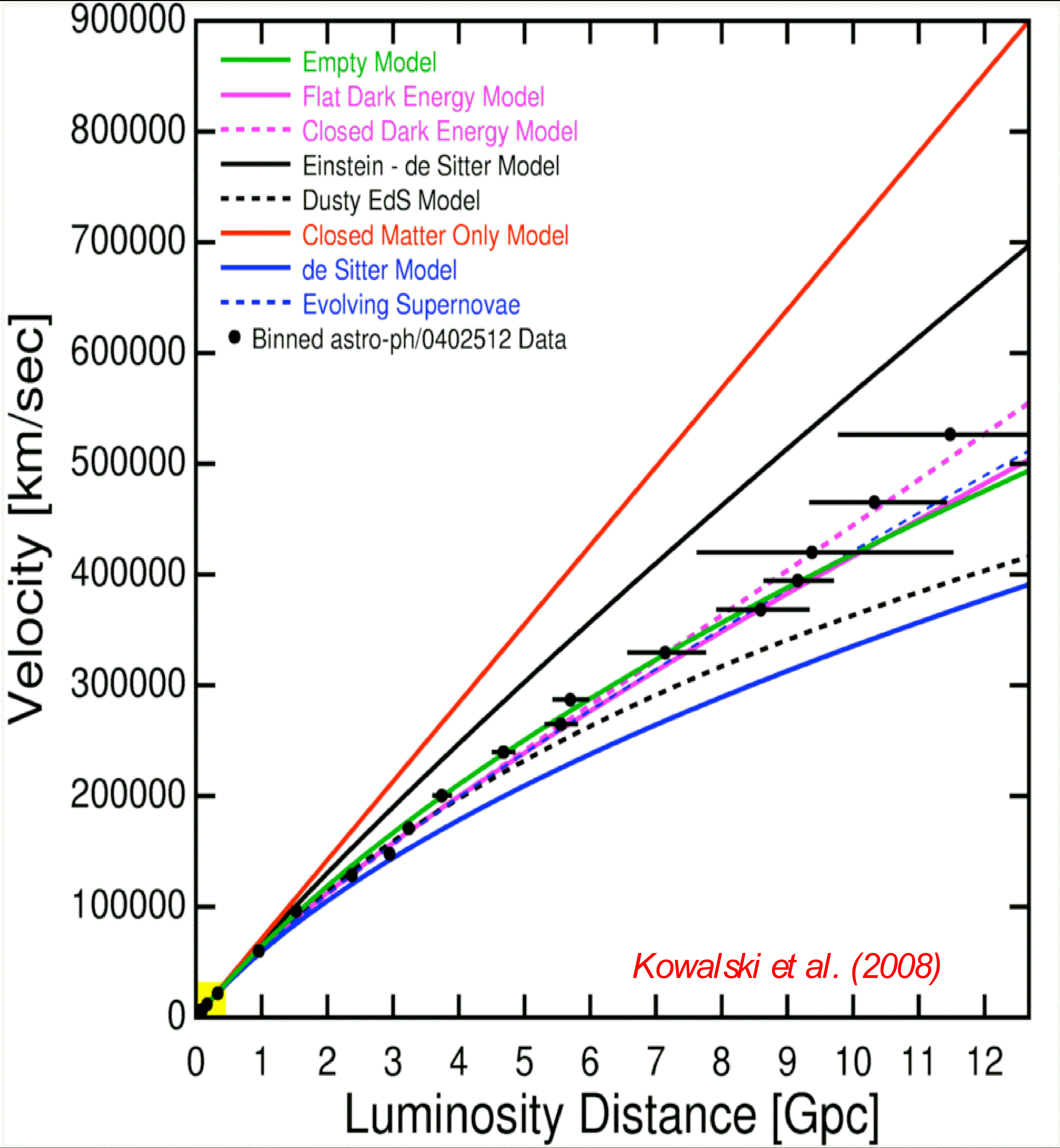
Carlos.Martins@astro.up.pt



Velocity [km/sec]
1000
500
0
0
1
2
Luminosity Distance [Mpc]
Hubble (1929)

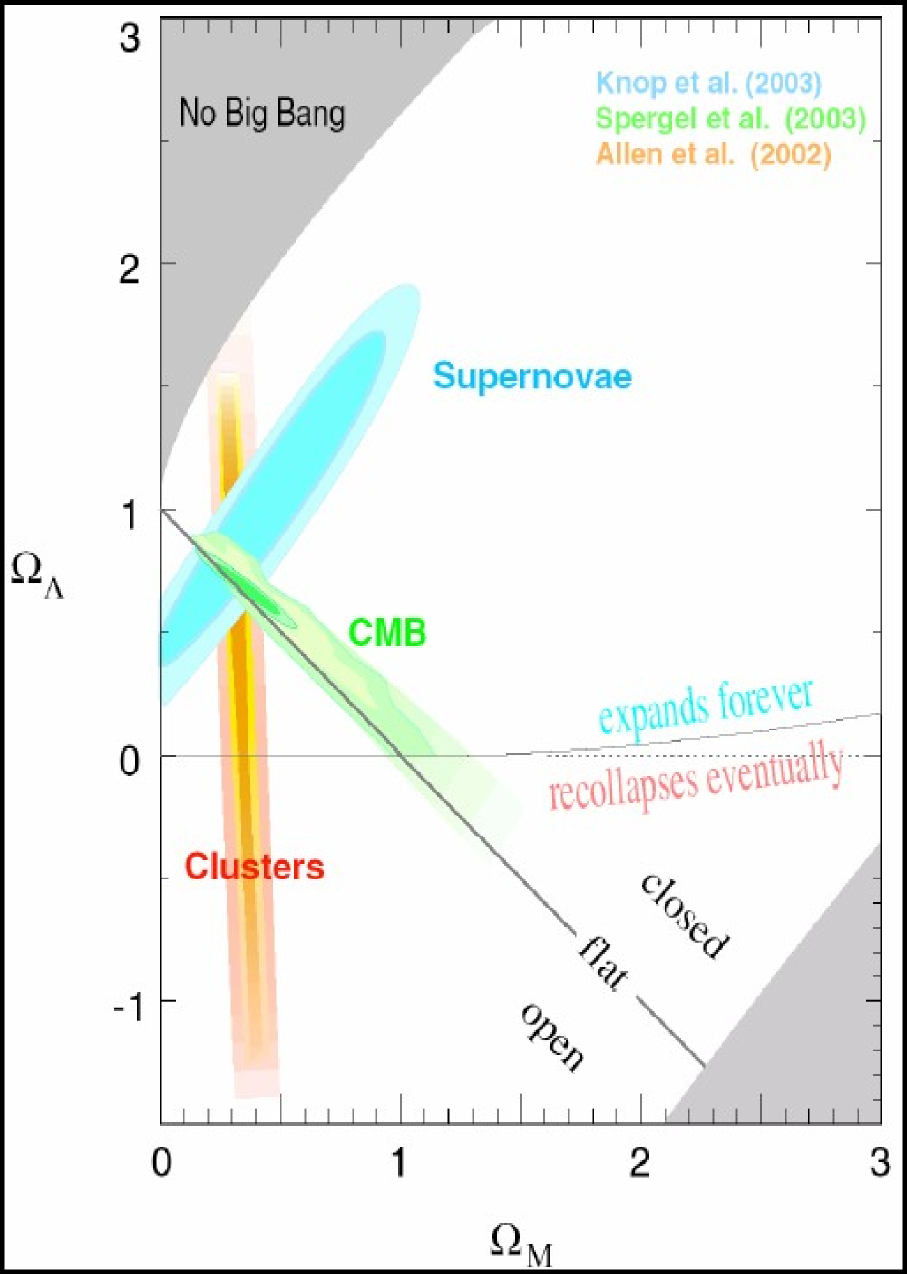


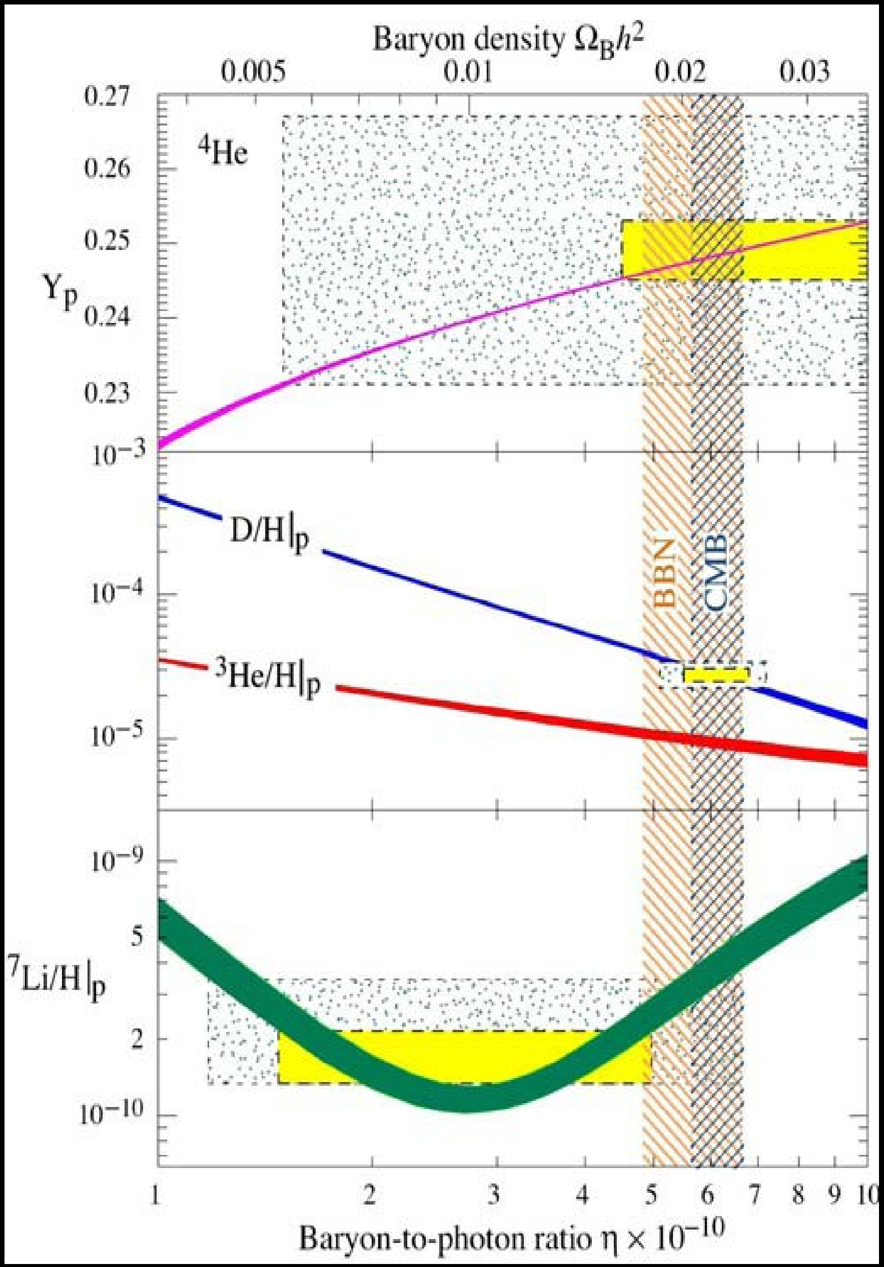
Velocity [km/sec]
30000
20000
10000
0
0
100
200
300
400
500
Luminosity Distance [Mpc]
Riess, Press & Kirshner (1996)



Empty Model
Flat Dark Energy Model
Closed Dark Energy Model
Einstein - de Sitter Model
Dusty EdS Model
Closed Matter Only Model
de Sitter Model
Evolving Supernovae
Binned astro-ph/0402512 Data
Kowalski et al. (2008)
Velocity [km/sec]
Luminosity Distance [Gpc]
0
100000
200000
300000
400000
500000
600000
700000
800000
900000
0 1 2 3 4 5 6 7 8 9 10 11 12

The Concordance Model





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...***


viale
dell'Astronomia
via
della Fisica

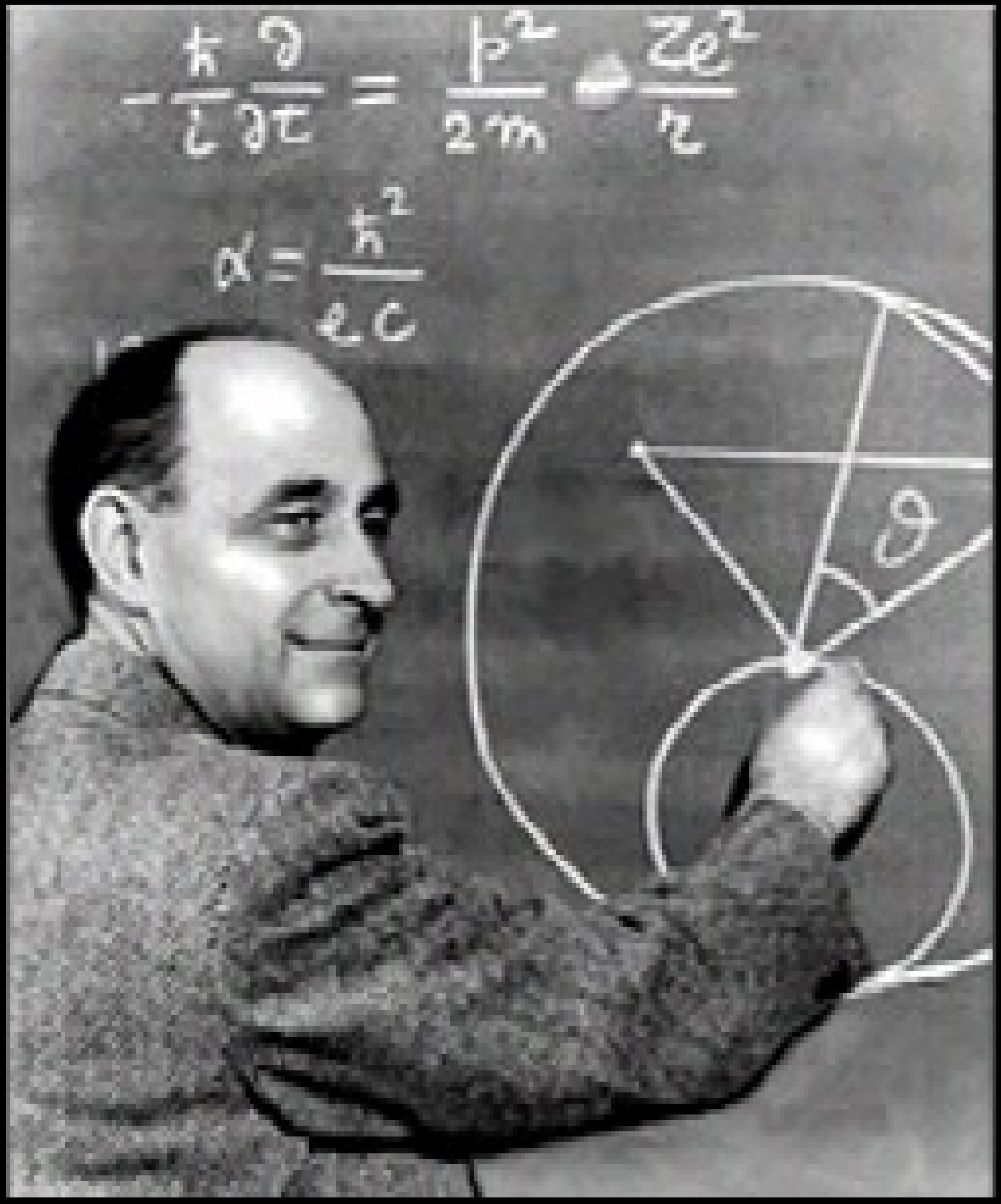
Hints of New Physics

- 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 SM object can account for the dark matter required by observations (baryons or massive neutrinos can't do it).
  - 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 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!

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)***
- **Are they fixed by consistency conditions, or arbitrary?**

Constants & Extra Dimensions

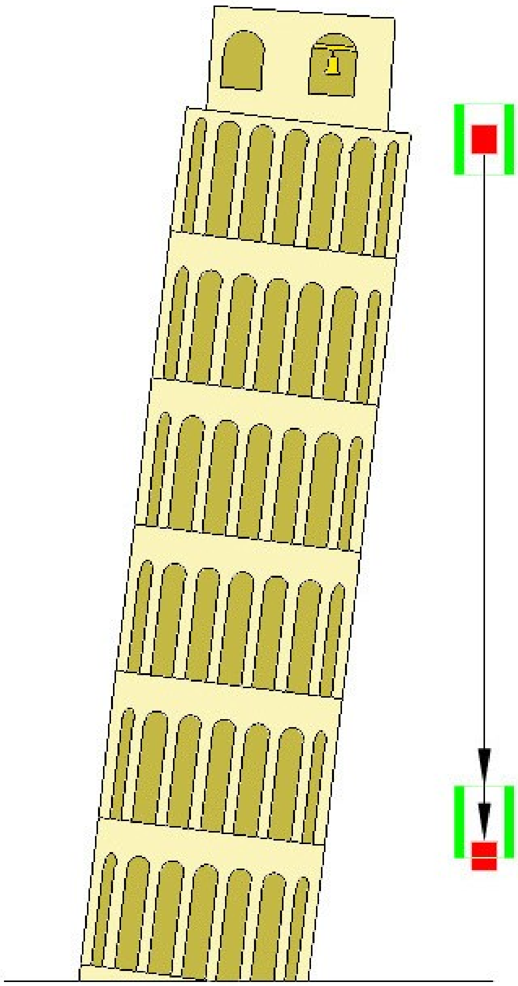
- Unification of fundamental forces requires additional space-time dimensions; in such models, true fundamental constants are defined in higher dimensions
- (3+1)D constants are effective quantities, typically related to the true constants via characteristic sizes of the extra dimensions
- Hence expect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

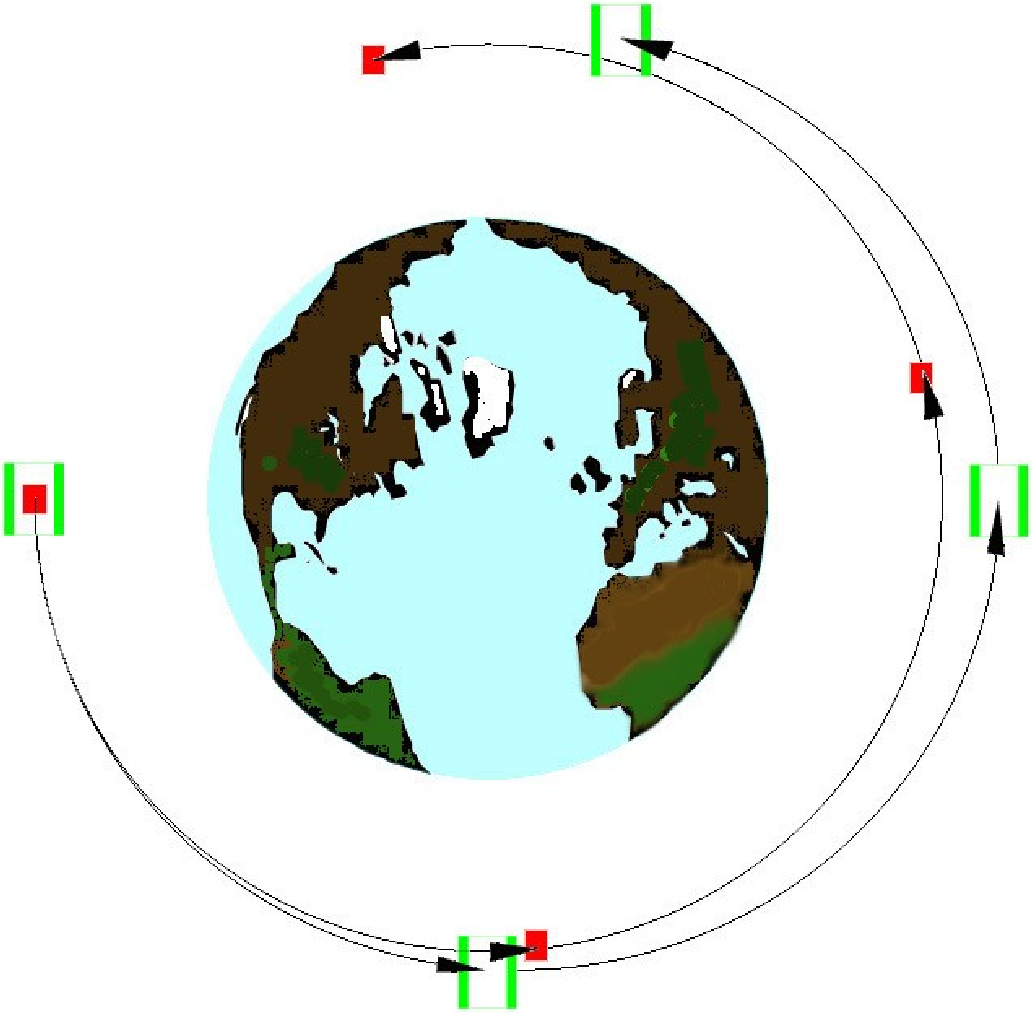
Dark Energy & Varying Couplings

- 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 $\phi \longrightarrow \phi + \text{const.}$ 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).***





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).

Counterfactual Universes

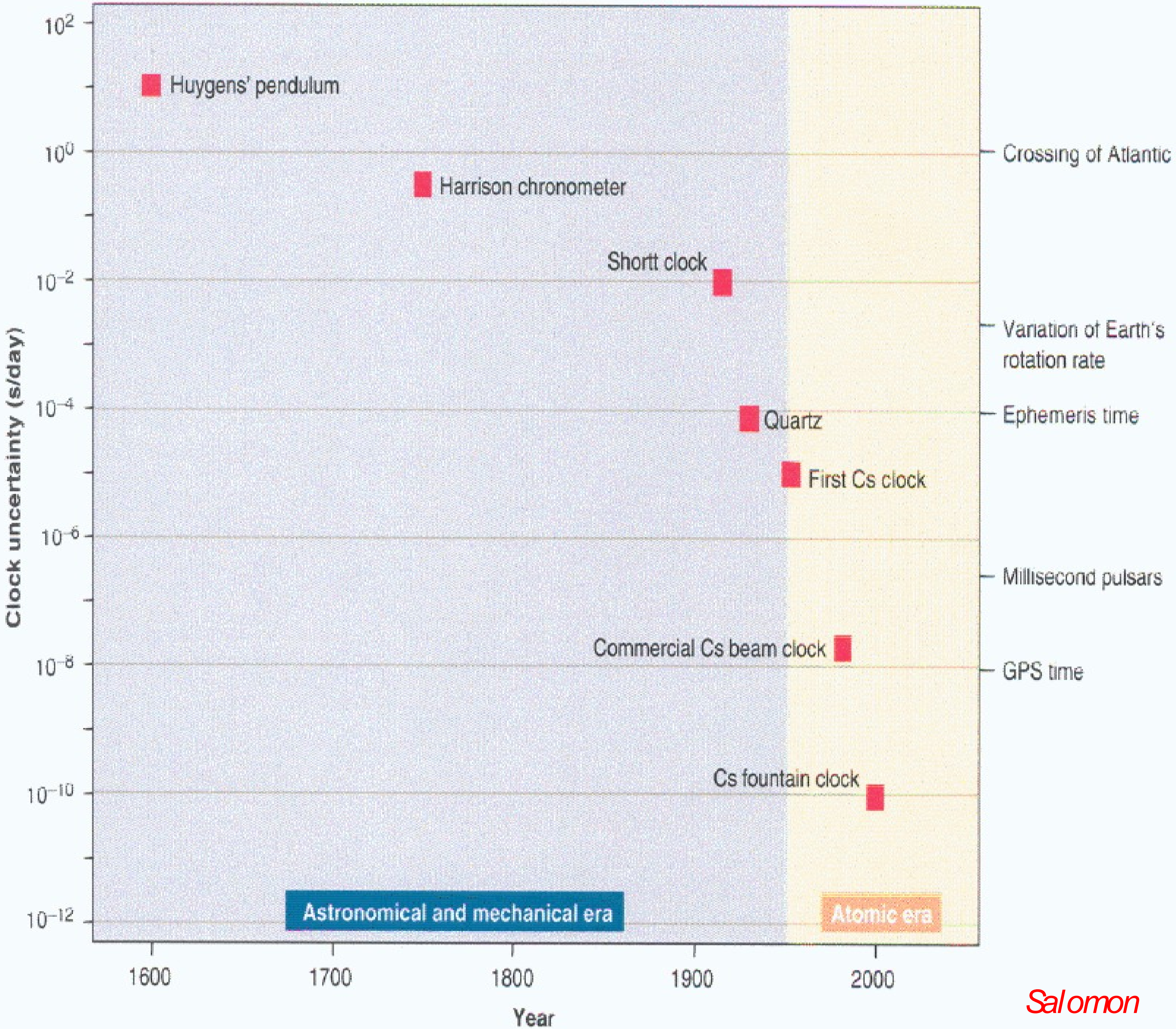
- If α_{EM} were increased by 4% or α_S reduced by 0.4% the carbon-12 resonance at 7.6 MeV (the Hoyle resonance) would not exist and the amount of carbon produced in stellar cores would be drastically reduced
    - Similarly, a 4% decrease in α_{EM} or a 0.4% increase in α_S would see stellar production of oxygen greatly reduced
- If α_S where larger by 4% or smaller by 10%, Helium-2 (i.e. diprotons) would be stable; this would speed up nuclear fusion and greatly reduce stellar lifetimes
    - Deuterium could not exist and therefore no carbon or oxygen would be produced at all
- If μ where much larger than its current value, no ordered molecular structures would exist

Constants from A to (almost) Z

- Atomic Clocks (also molecular, soon nuclear?)
- Big Bang Nucleosynthesis
- Clusters (soon at arXiv)
- Cosmic Microwave Background (cf. Eloisa's talk)
- Geophysics (Oklo, meteorites)
- New Methods (watch this space)
- Spectroscopy (cf. Paolo's talk)
- Strong Gravity (white dwarfs, neutron stars)
- ...and Various Consistency Tests

Atomic Clock Basics

- Clock = Oscillator + Counter
- In an atomic clock, ticker is quantum-mechanical: a photon is absorbed by an atom's last electron, causing it to flip its spin and magnetic field
- Key ongoing developments include:
  - Laser-cooled, atomic fountain clocks
  - Clocks based on a single atom (as opposed to an ensemble)
  - Optical clocks (THz, as opposed to GHz – microwave)
  - Micro-gravity (use dedicated satellites or the ISS)
  - Nuclear (^{229}Th) clocks?



Huygens' pendulum
Harrison chronometer
Shortt clock
Quartz
First Cs clock
Commercial Cs beam clock
Cs fountain clock
Crossing of Atlantic
Variation of Earth's rotation rate
Ephemeris time
Millisecond pulsars
GPS time
Astronomical and mechanical era
Atomic era
Clock uncertainty (s/day)
Year
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
1600
1700
1800
1900
2000

Salomon

Local Constraints & Expectations

- Direct constraint by the NIST group *[Rosenband et al. 2008]* comparing single-atom Al+ and Hg+ optical clocks over a period of a year yields

  $d/dt\ (\ln \alpha) = (-1.6 \pm 2.3) \times 10^{-17}/yr$

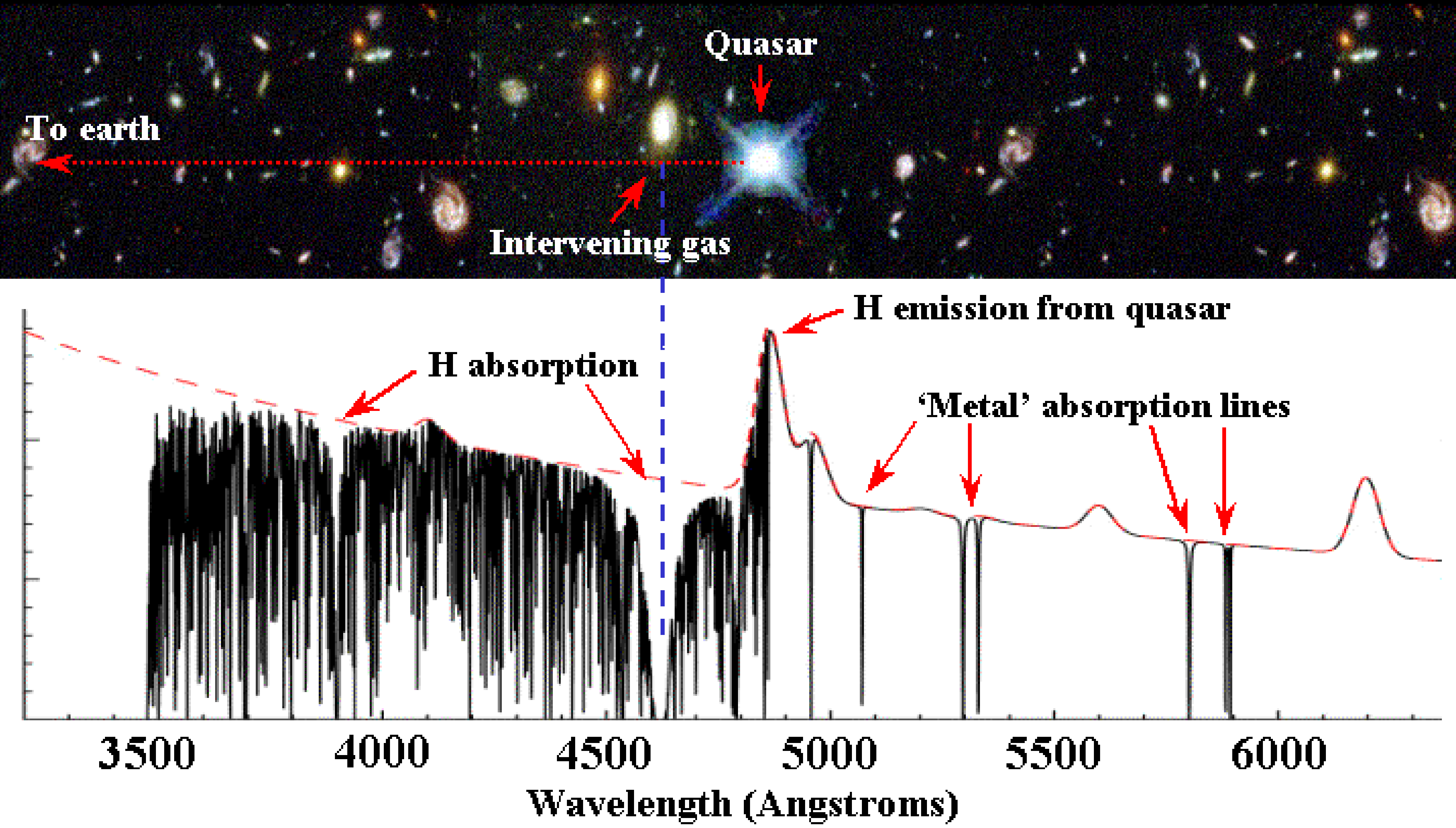
- Direct local constraints on m are significantly weaker: *[Shelkovnikov et al. 2008]* comparing molecular and Cs clocks over 2 years, find $d/dt\ (\ln \mu) = (-3.8 \pm 5.6) \times 10^{-14}/yr$

- Key future experiments and expected improvements in orders of magnitude (note integration times small):
  - ACES (French-Swiss project, at the ISS, 2013): 1 o.m.
  - μSCOPE (mostly a CNES satellite, 2012): 2 o.m.
  - GG (Italian, ?): 3 o.m.?
  - STEP (a joint ESA-[NASA] cryo-satellite, ?): 5 o.m.
- These apply both to various aspects of the EEP and (indirectly) to α

The Oklo Reactor

- Natural nuclear reactor in Gabon, went off about 1.8 bn years ago (z~0.14); ran for 10^5 years in few-second bursts.
- Observable: Samarium abundance depletion (0.9->0.02), sensitive to neutron cross sections: resonance E~97.3meV, well below scale of nuclear physics.
- First MCNP analysis *[Petrov et al. At. Energy 98:296, 2005, PRC74: 064610,2006]* highlights shortcomings of previous studies, finds $\Delta\alpha/\alpha=(0.6+6.2)\text{x}10^{-8}$
- Independent analysis *[Gould et al. PRC74: 024607,2006]* finds $\Delta\alpha/\alpha=(0.7+1.8)\text{x}10^{-8}$
- Measurement not 'clean', naive assumptions on other quantities
- Effectively it's a constraint on α_S

Measuring α from Quasars



Murphy

Measuring α from the CMB

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; 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 ...).

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.
- 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 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 tough at low z (even with EUCLID or WFIRST).

Dark Energy from Varying Constants
(or: I can tell you, but it will cost you 1M€)

with L. Amendola, A.C. Leite, N. Nunes, P. Pedrosa, G. Robbers

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

- Scalar field yielding dark energy gives varying couplings which 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

$$\gamma_x = \frac{\Delta x}{x} = \sum_{i=1}^{m} g_{xi} (\ln a)^i = \zeta_x \kappa \delta\phi$$

$$w(\ln a) = -1 + \frac{1}{3}\left(\frac{g_x{}'}{\zeta_x}\right)^2 \left(1 + \frac{1}{\sigma a^3}\right)$$

- Will complement and extend traditional methods.
- Key Advantages:
  - Distinguishes Λ from a dynamical field without 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!

Finding ζ

- From 1st derivatives of the data plus $\Omega_{\phi 0}$ and w_0 from a different experiment (but uncertainty large near w~-1)

$$\zeta_x^2 = \frac{1}{3}\frac{(\Delta x/x)'^2}{\Omega_\phi(1+w)}$$

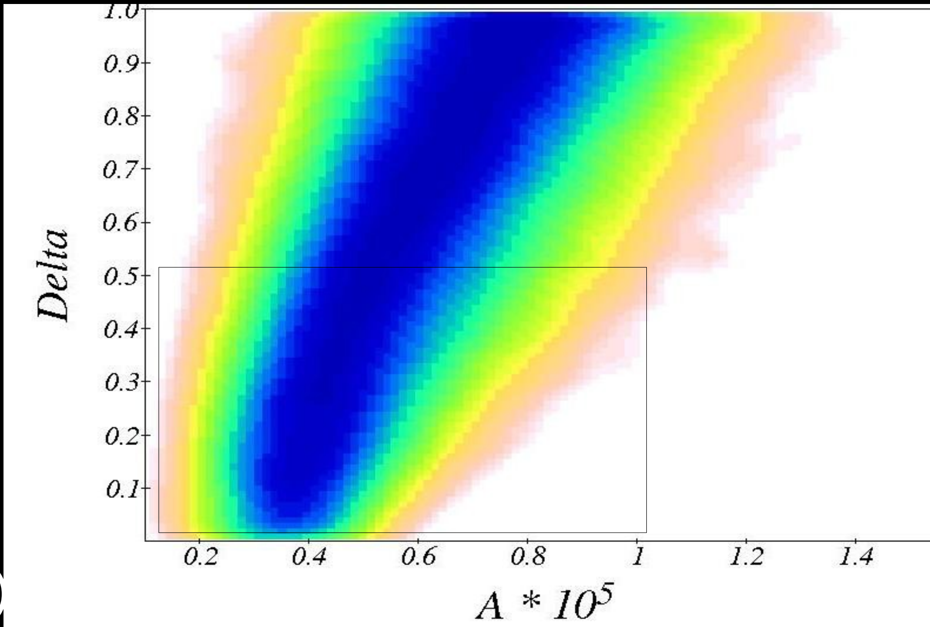
- Can use next equation in the hierarchy, so 2nd derivatives of the data must be calculated (will only work if not too noisy)

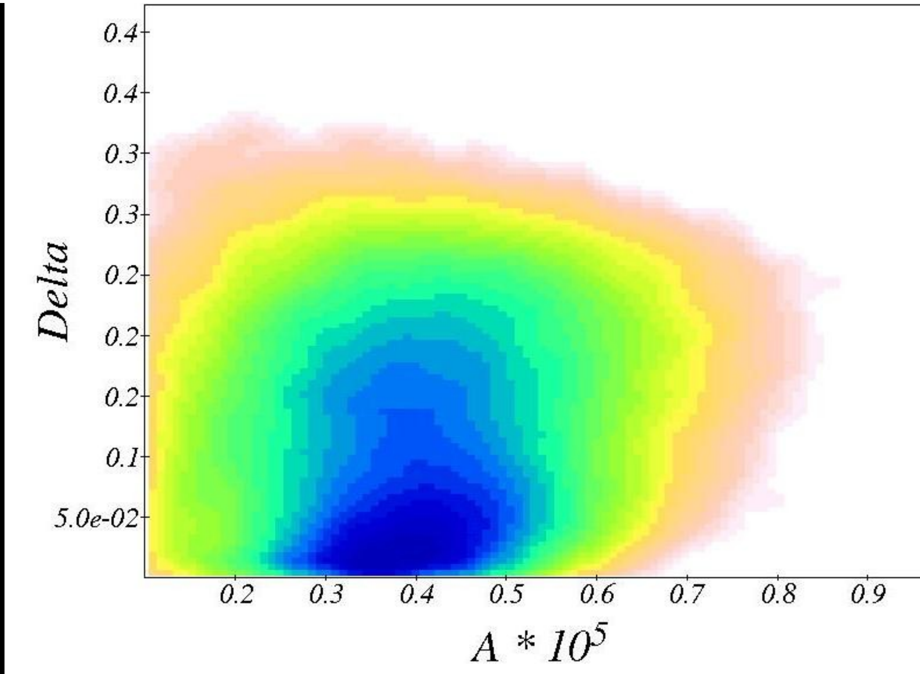
$$\zeta_x^2 = \frac{(\Delta x/x)'^2}{w'}\frac{\Omega_m}{\Omega_\phi}\left(w + \frac{2}{3\Omega_m}\frac{(\Delta x/x)''}{(\Delta x/x)'}\right)$$

- Equivalence Principle tests provide an upper bound (may soon provide a measurement); slow-roll yields lower bound
- We can simply assume a value motivated by some theory
- Comparing $w_\alpha(z)$ and $w_{sn}(z)$ will allow low-z reconstruction of $B_F(\phi)$ (testing the ansatz being used) and measuring ζ

Current Data & Local Tests

- Is the Webb result compatible with atomic clock bounds?
  - Comparison is model-dependent
- Adopt toy-model parametrization of the evolution to z~4
  - Function of N = ln (a) = -ln(1+z)
- Sharp transition required at z~1
  - Related to onset of dark energy domination?
  - May leave little other imprints *[Mortonson et al. 2009]*
- Atomic clocks bound is crucial!



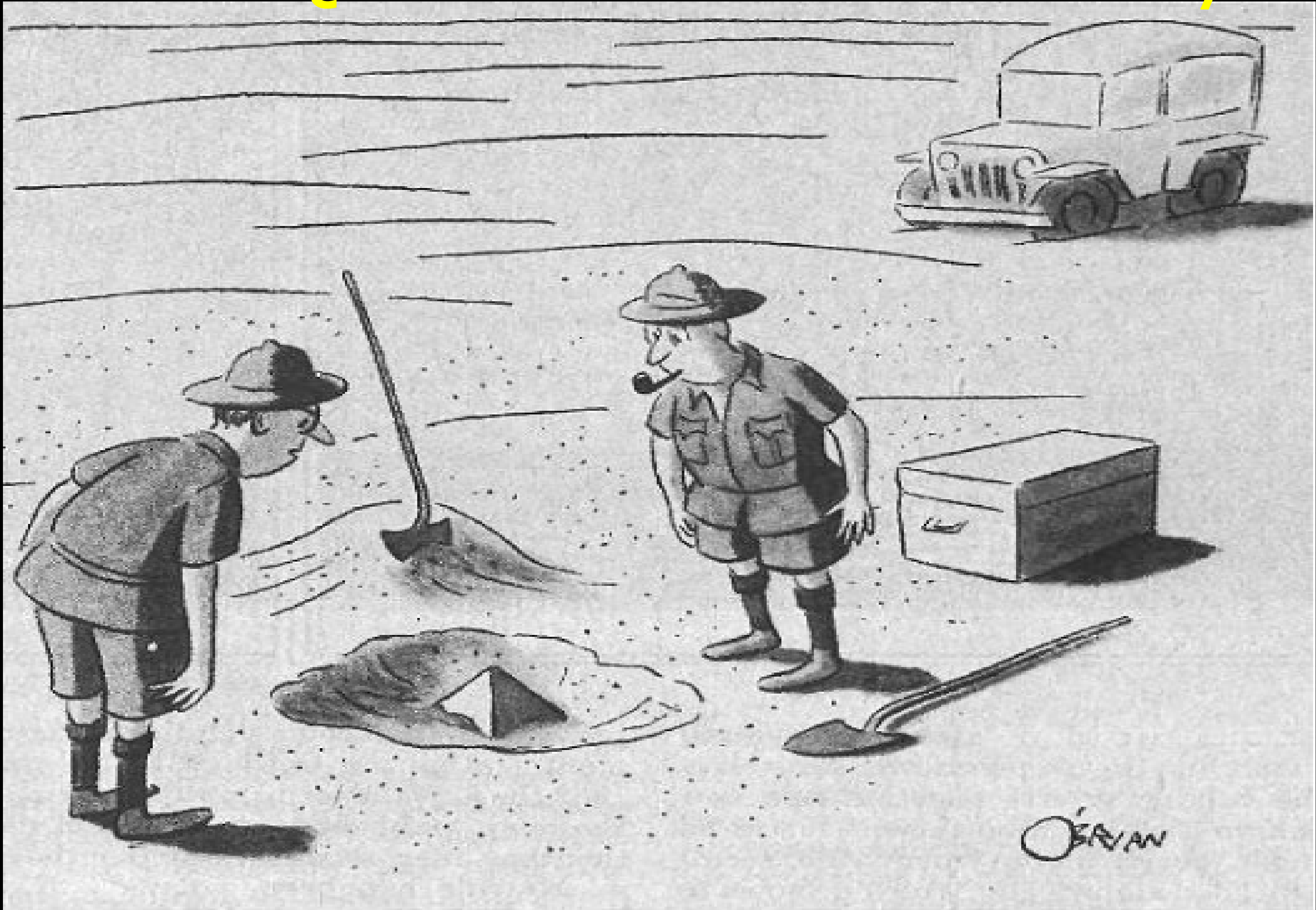


A worked example

- Using PCA techniques *[Huterer & Starkman 2003]*, and combining supernova & constants data.
- Two alternatives for deciding number of components
  - Minimizing risk = bias^2 + variance
  - Error normalization *a la* JDEM FoMSWG *[Albrecht et al. 2009]*
- Various scenarios for ESPRESSO & CODEX:
  - Baseline: 30 (100) absorber measurements, each with an uncertainty of 6×10^{-7} (1×10^{-7})
  - Ideal: 100 (150) absorber measurements, each with an uncertainty of 2×10^{-7} (3×10^{-8})
  - Control: Normal distribution of the uncertainties
  - For supernovas, we assume 3000 measurements, each with an uncertainty of 0.11 in the magnitude, up to z=1.7

This and the following 6 slides contain unpublished results, and will be made available later.

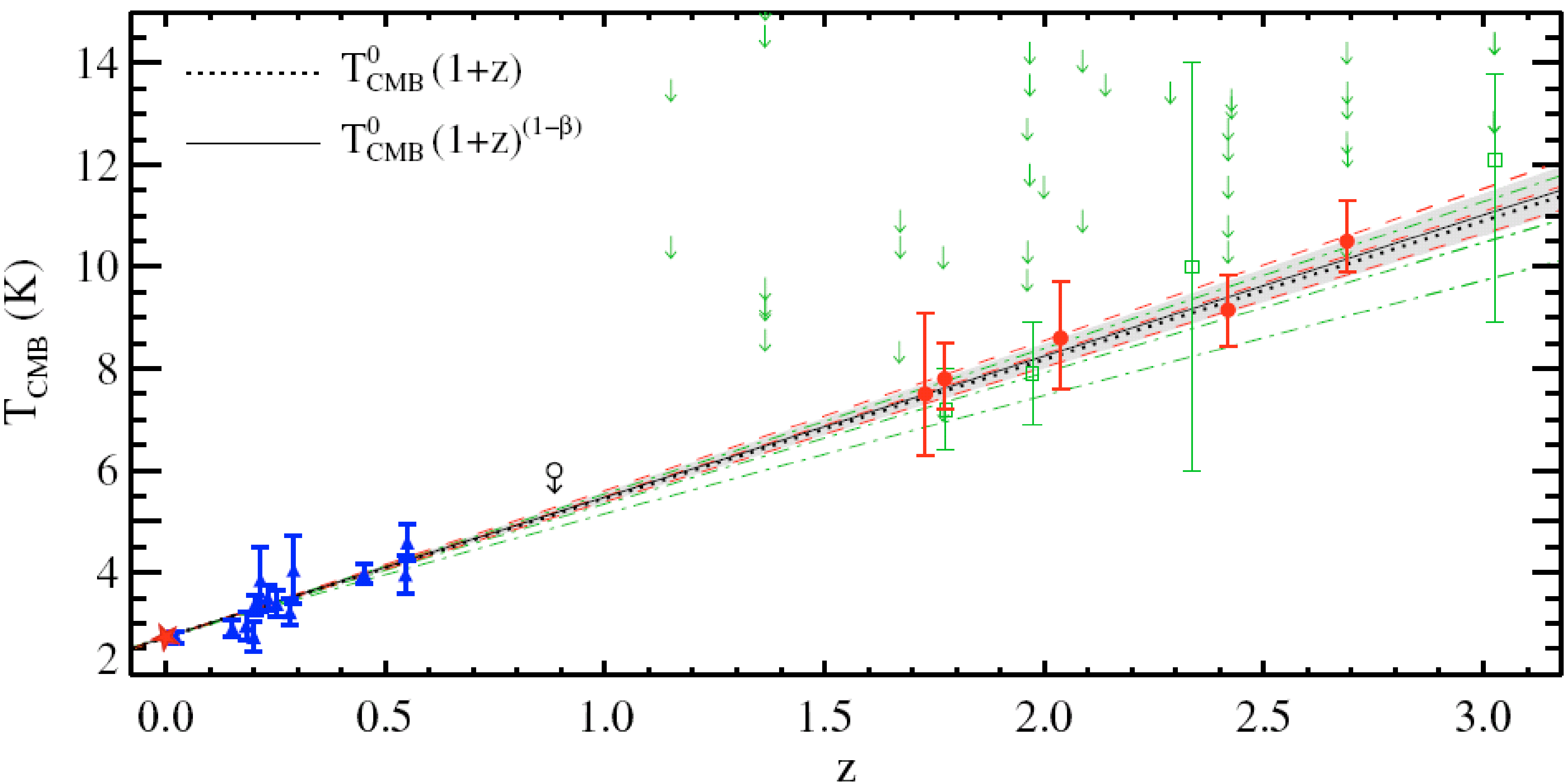
The Quest for Redundancy



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

The CMB Temperature

- $T(z)=T_0(1+z)^{1-\beta}$, $\beta=0$ in standard model. Currently $\beta<0.03$



Noterdaeme et al.

This slide contains unpublished results, and will be made available later.

So What's Your Point?

- Nothing is varying at $\sim 10^{-5}$ level; this is already a very significant constraint (cf. the Cassini bound).
- The coming years will bring big gains in sensitivity and also dedicated experiments - but doing things right is tough!
  - We'll get to 10^{-6} soon (PEPSI, ESPRESSO) and to 10^{-7} later
  - Need customized observation procedures, laser frequency comb calibration, purpose-built data reduction pipelines, ...
  - Need further astrophysical probes
- Keep in mind the dark energy lesson: it's clear that a detection will only be believed when there's redundancy
  - Equivalence Principle tests
  - Laboratory measurements, T(z), opacity, etc
- Varying constants are a powerful, versatile and low-cost way to probe fundamental physics and dark energy.