Fundamental Physics and Cosmology in the ELT Era:

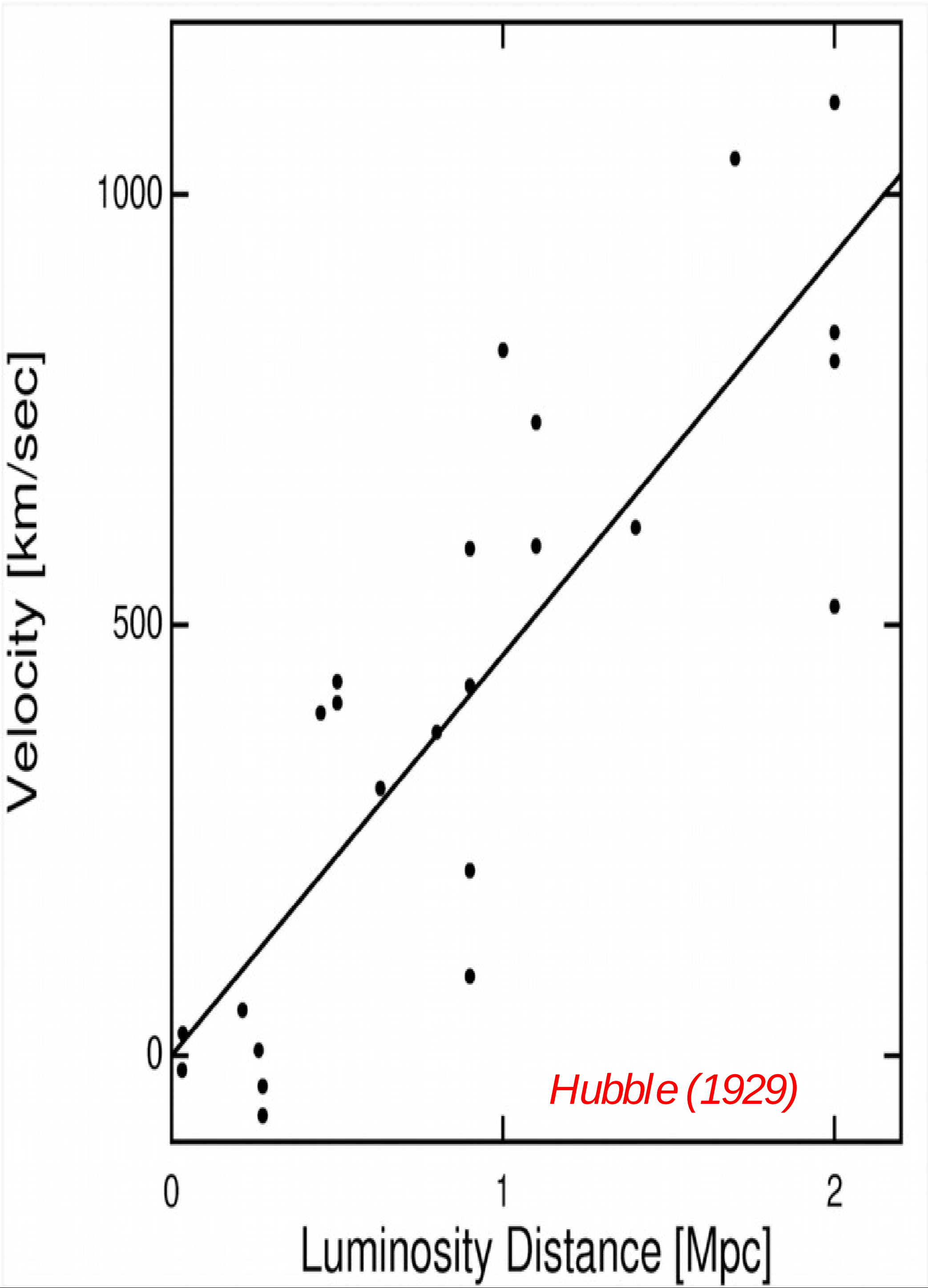
Theoretical Context (Part II)

Carlos.Martins@astro.up.pt

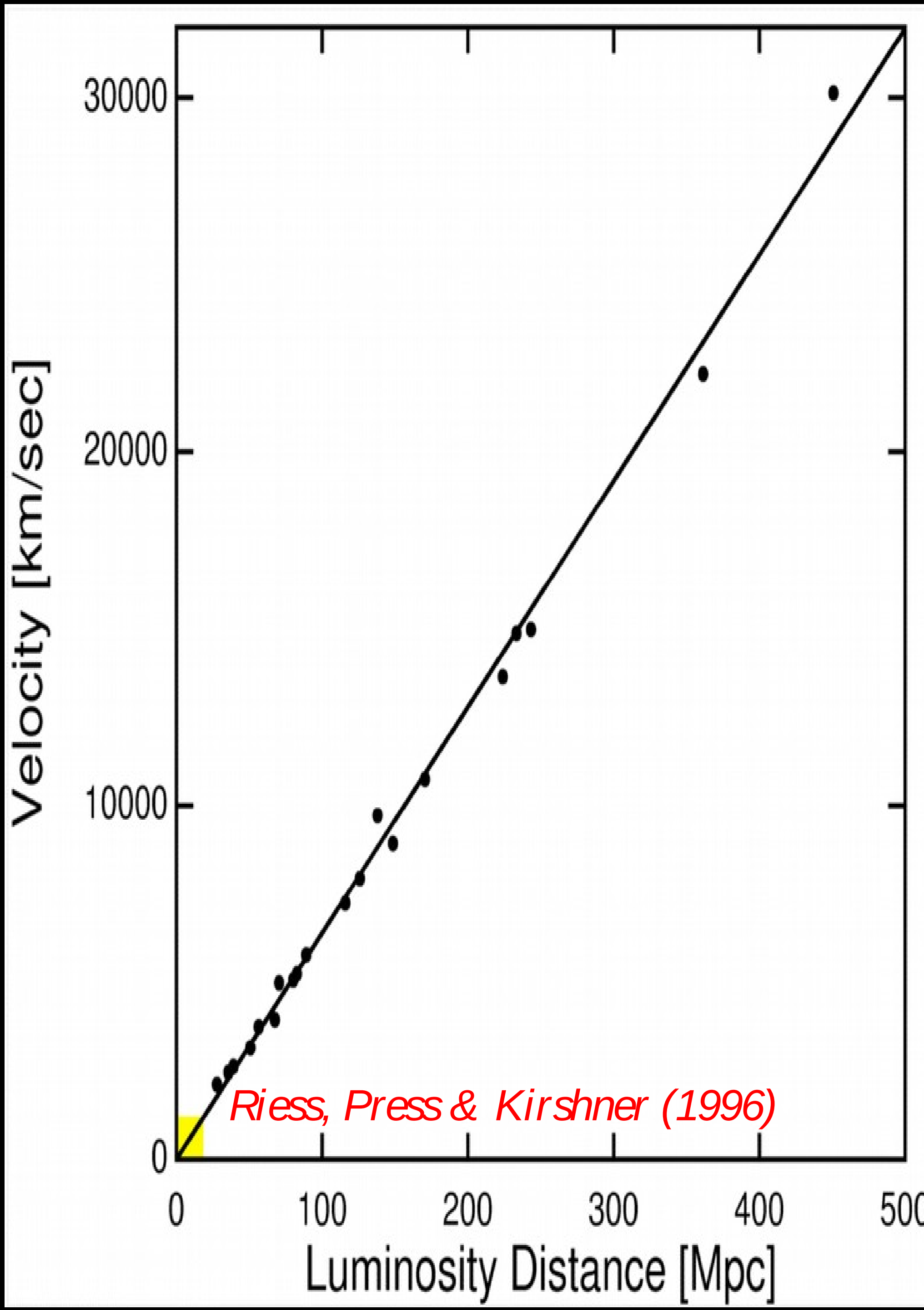
with Ana Catarina Leite, Ana Marta Pinho, Catarina Alves, Duarte Magano, Fernando Moucherek, João Vilas Boas, José Guilherme Matos, Tomás Silva and the rest of the CAUP Dark Side Team, plus Matteo Martinelli, Paolo Molaro and Stefano Cristiani

Matters of Gravity

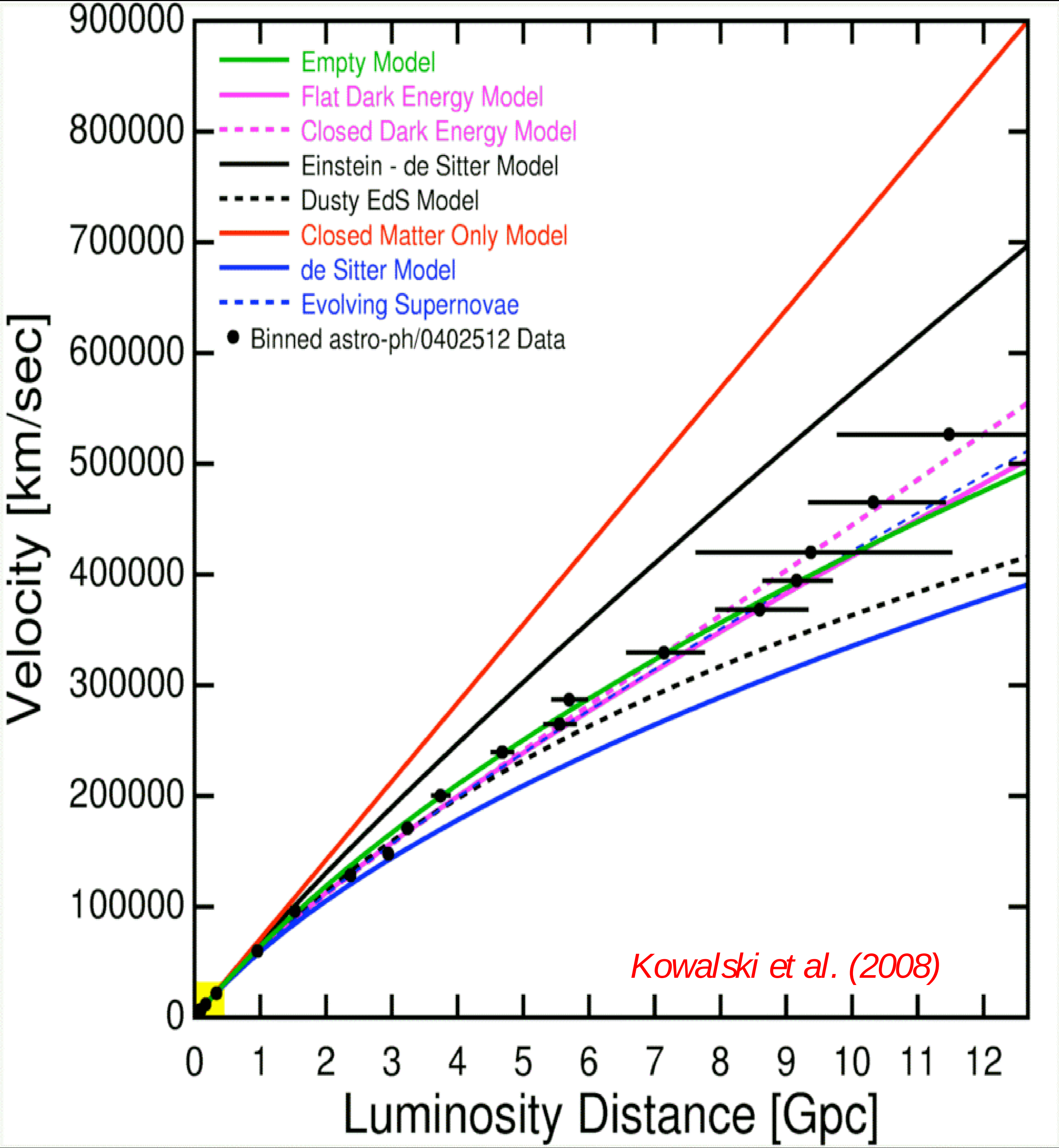
- ca. 300 BC: Gravity is always attractive; how do we avoid that the sky falls on our heads?
  - Aristotle's answer: A fifth element (a.k.a. aether)
- ca. 1692: Gravity is always attractive; how do we avoid that the stars fall on our heads?
  - Newton's answer: God's initial conditions
- ca. 1917: Gravity is always attractive; how do we avoid that the Universe falls on our heads?
  - Einstein's answer: A cosmological constant modifies GR and prevents collapse, making the universe (nominally) stable



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)

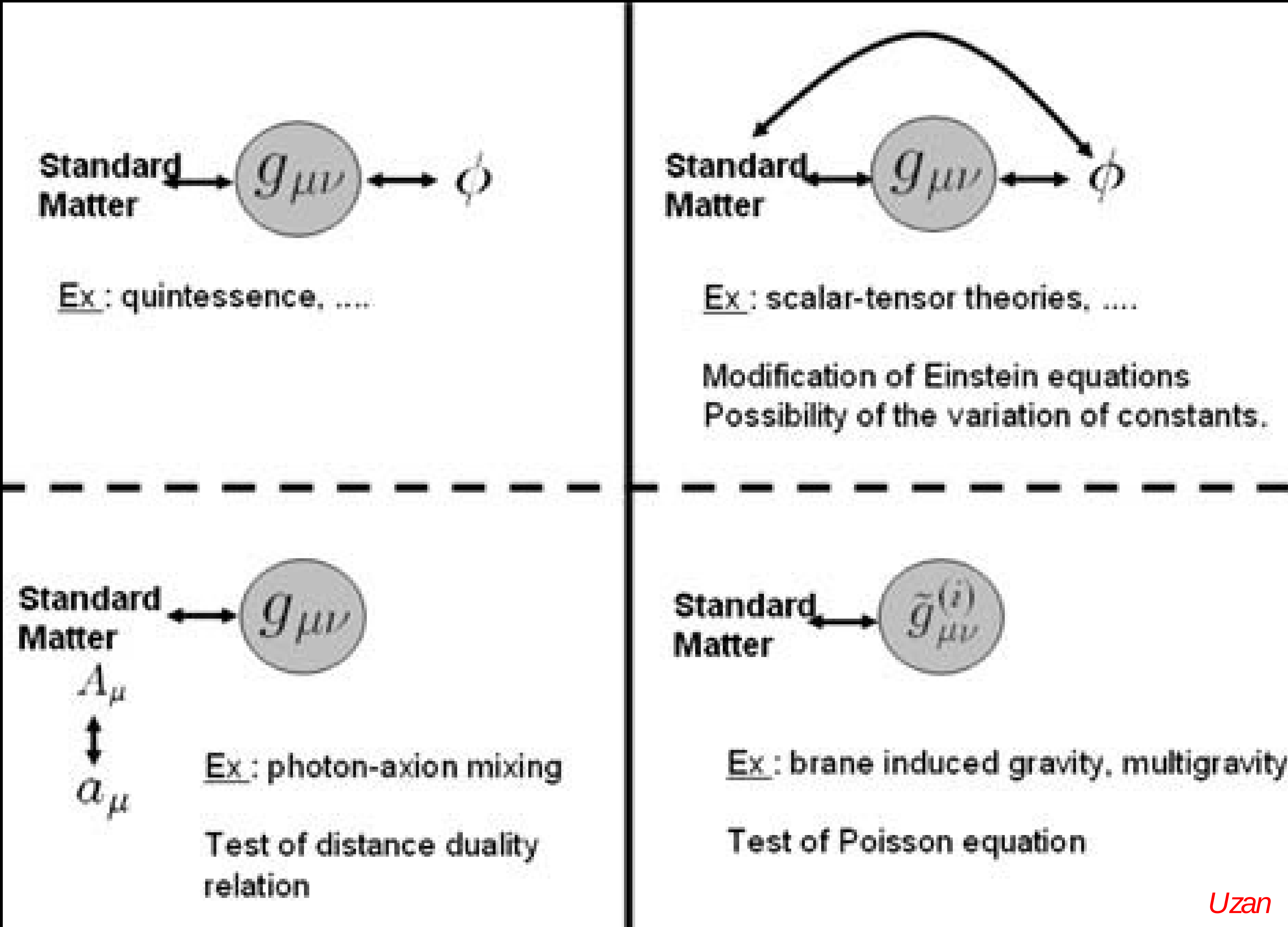


Empty Model
Flat Dark Energy Model
Closed Dark Energy Model
Einstein - de Sitter Model
Dusty EdS Model
Closed Matter Only Model
de Sitter Model
Evolving Supernovae
Binned astro-ph/0402512 Data
Kowalski et al. (2008)
Velocity [km/sec]
Luminosity Distance [Gpc]
0
100000
200000
300000
400000
500000
600000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

Was Einstein Right?

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, ...]*
  - All measurements (whether detections of null results) constrain fundamental cosmology: 'minimum guaranteed science'
  - 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 ELT


Standard Matter
$g_{\mu\nu}$
ϕ
Ex : quintessence, ...
Standard Matter
$g_{\mu\nu}$
ϕ
Ex : scalar-tensor theories, ...
Modification of Einstein equations
Possibility of the variation of constants.
Standard Matter
$g_{\mu\nu}$
A_μ
a_μ
Ex : photon-axion mixing
Test of distance duality relation
Standard Matter
$\tilde{g}^{(i)}_{\mu\nu}$
Ex : brane induced gravity, multigravity
Test of Poisson equation
Uzan

To Couple or Not To Couple

- Any scalar field couples to gravity; it couples to nothing else if a global symmetry $\phi \dashrightarrow \phi + \text{const.}$ suppresses couplings to the rest of the Lagrangian
  - If so, only derivatives and derivative couplings survive
- … however quantum gravity effects do not respect global symmetries, and there are no (unbroken) global symmetries in string theory
- Scalars in the theory will naturally couple to the rest of the world (in any manner not prevented by symmetry principles)

Quintessence-type Models

- If the same degree of freedom is responsible for dark energy and varying α, its 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]*

$|\zeta| < 4\times10^{-6}$ (2 sigma)

- ESPRESSO GTO should improve this bound by a factor ~10, assuming null results *[Alves et al. 2017]*
  - Or a >3 sigma detection for non-zero ζ saturating current bounds

Strong Constraints on the Weak EP

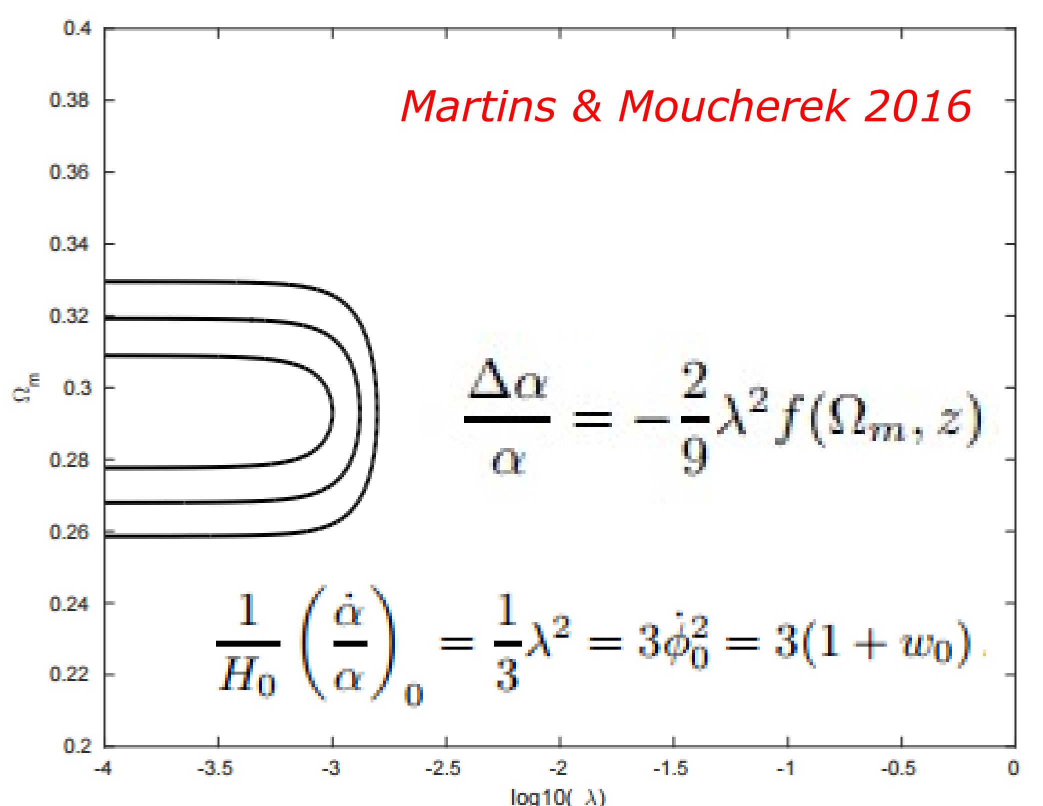
- In these models the scalar field will inevitably couple to nucleons (through the α dependence of their masses) and therefore lead to violations of the Weak Equivalence Principle
  - For detailed discussions see *[Dvali & Zaldarriaga 2002, Chiba & Kohri 2002, Damour & Donoghue 2010, Uzan 2011, …]*
- 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, and these are well motivated in string theory and naturally give rise to a coupling to gauge fields: the field dynamics itself leads to α variations
  - 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

$$(1+w_0) < 2.4\times10^{-7}\,, \quad 99.7\% C.L.$$

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



Aiming Higher (i.e., Deeper)

- 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 probe scalar field dynamics both more directly and beyond the domination regime
- ALMA, ESPRESSO & ELT-HIRES will map dark side to z~4 *[Amendola et al. 2012, Leite et al. 2014, 2016]*
  - Key synergies with redshift drift and high-z SNe from ELT-IFU (a.k.a. HARMONI)
  - ELT can do it better than low-z probes *[Leite & Martins 2015]*

Leite et al. 2014

Model	ESPRESSO	ELT-HIRES
Constant	649.8	19.5
Step	2231.6	66.9
Bump	1420.1	42.6

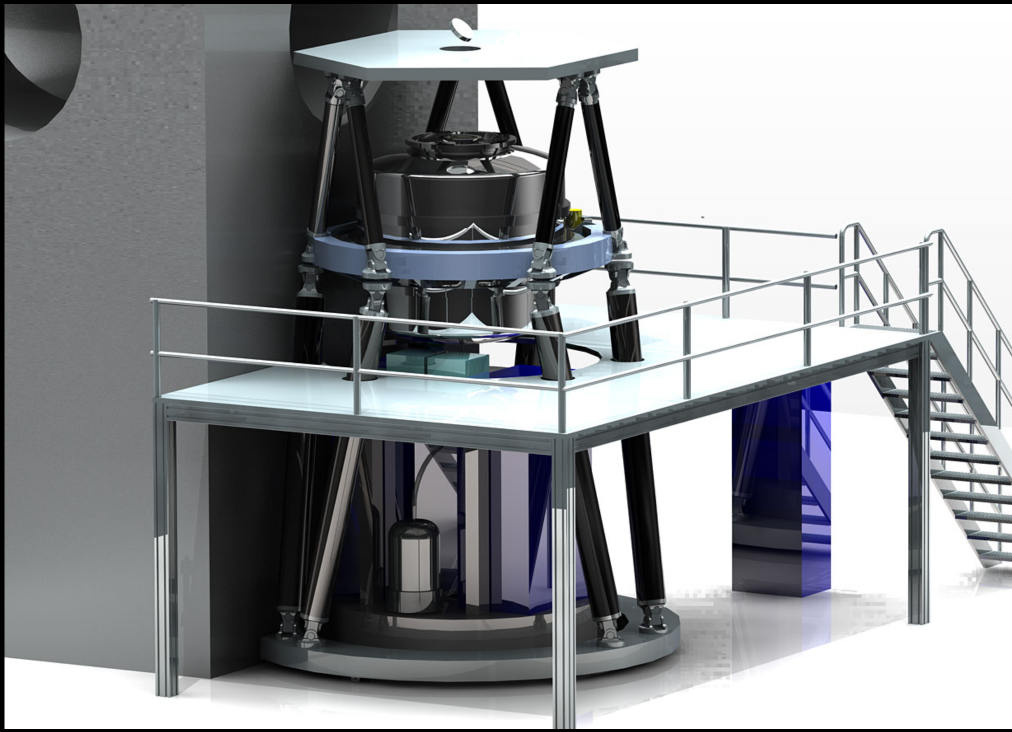
Strong Gravity

- GR well tested in weak field regime (table-top, solar system, pulsars), but two strong-field effects have no weak-field limit
  - Presence of a horizon around collapsed objects
  - No stable circular orbits near a black hole or neutron star
- Strong-field tests of gravity are crucial, and the Galactic Centre is an ideal environment in which to do it
  - Direct test of metric theories (e.g., Kerr black hole solution is not unique to General Relativity)
  - May provide further insight on the nature of spacetime (GR is classical, and may break down in this limit)
- In GR, post-Newtonian effects depend exclusively on distance from center; in alternative theories other factors play a role
  - The closer one gets to the center the stronger the constraints, and the higher the chances of identifying new physics
  - Horizon size of Schwarzschild $4x10^6 M_o$ black hole at GC is ~10 μas

Strong Gravity with MICADO

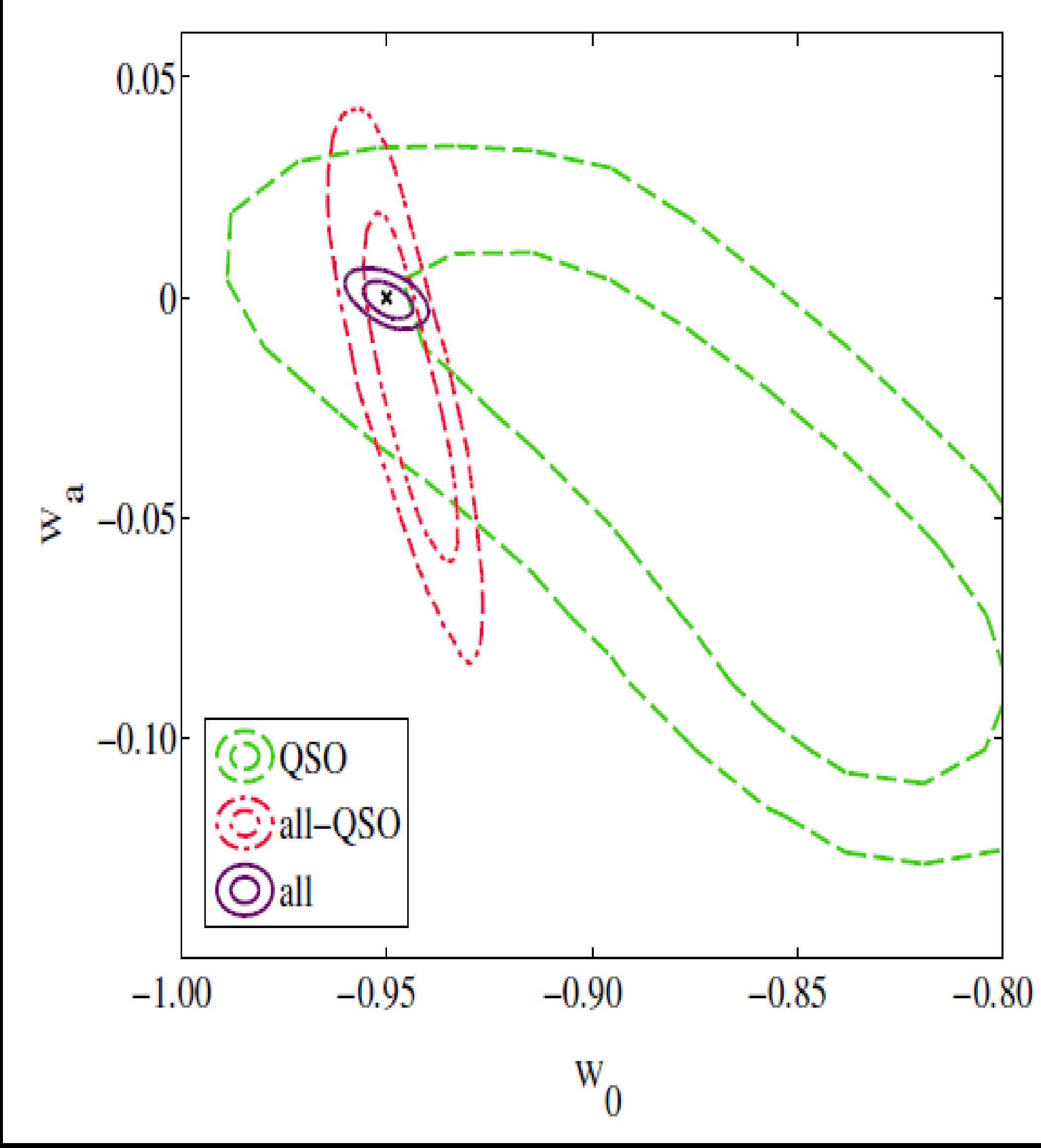
- Stars in highly eccentric orbits with periods of a few months will have detectable precession of their orbital planes
  - Up to 10 µas/year, assuming a black hole rotation rate of at least half the maximum allowed value *[Will 2008]*
- MICADO may directly test the so-called No-hair Theorem*, which would be a direct proof of the presence of a black hole
  - Astrometric observations of 2+ such stars provide a simultaneous measurement of angular momentum and quadrupole moment
  - In geometrized (c=G=1) units, $Q_2=-J^2/M$
  - ALMA may do this too

  * strictly, it's a conjecture

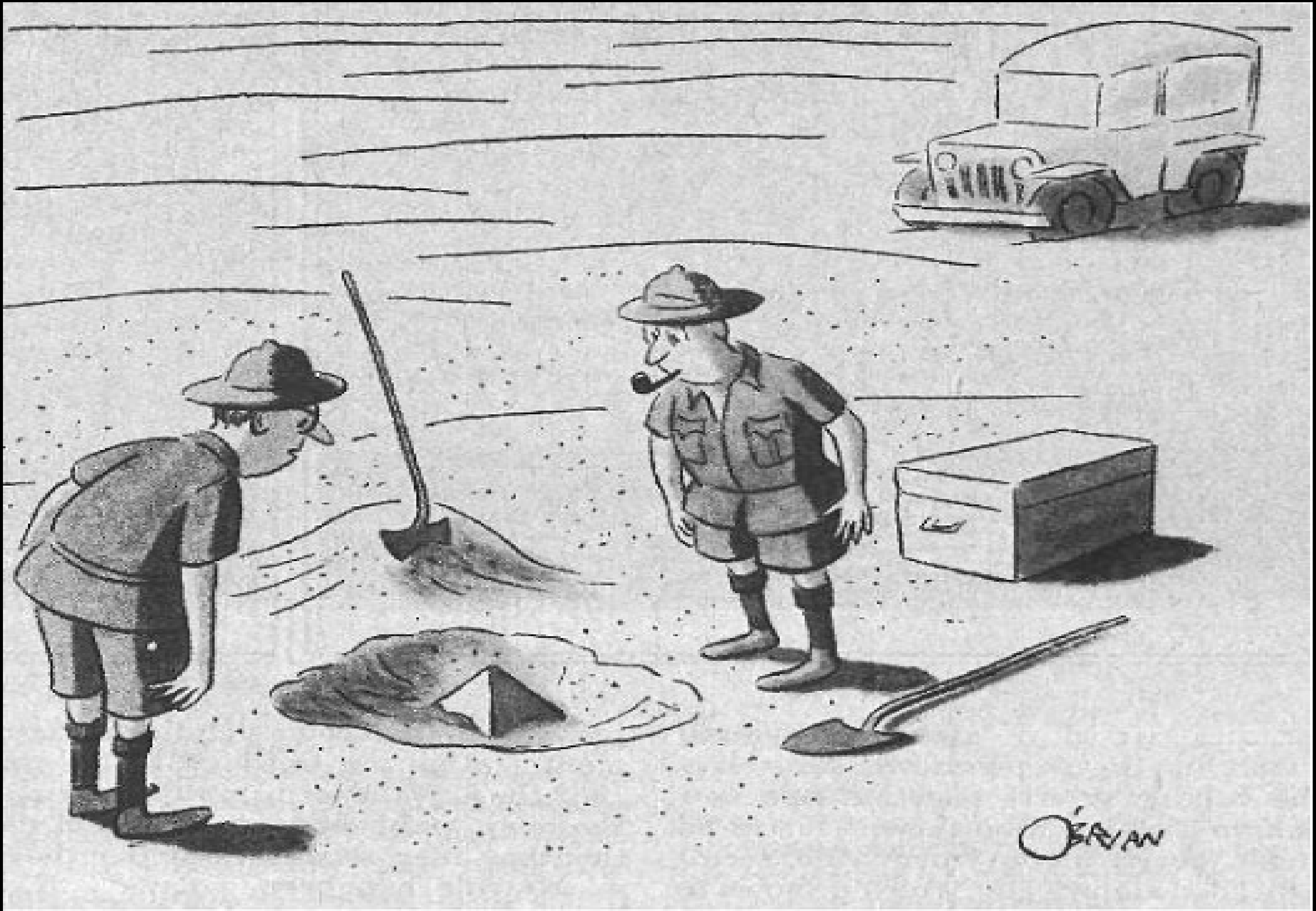


Euclid & Varying α

- The weak lensing shear power spectrum + Type Ia SNe can constrain these models
  - …with external datasets
- Example for a CPL fiducial
  - Euclid WL + DESIRE SN Ia data *[Astier et al. 2014]*
  - ELT spectroscopic data (+ atomic clock prior)
- For a full analysis see *[Calabrese et al. 2014]*
  - Further synergies between Euclid and the ELT are currently being studied
  - Cf. Euclid Theory Review v2 *[Amendola et al. 2016]*

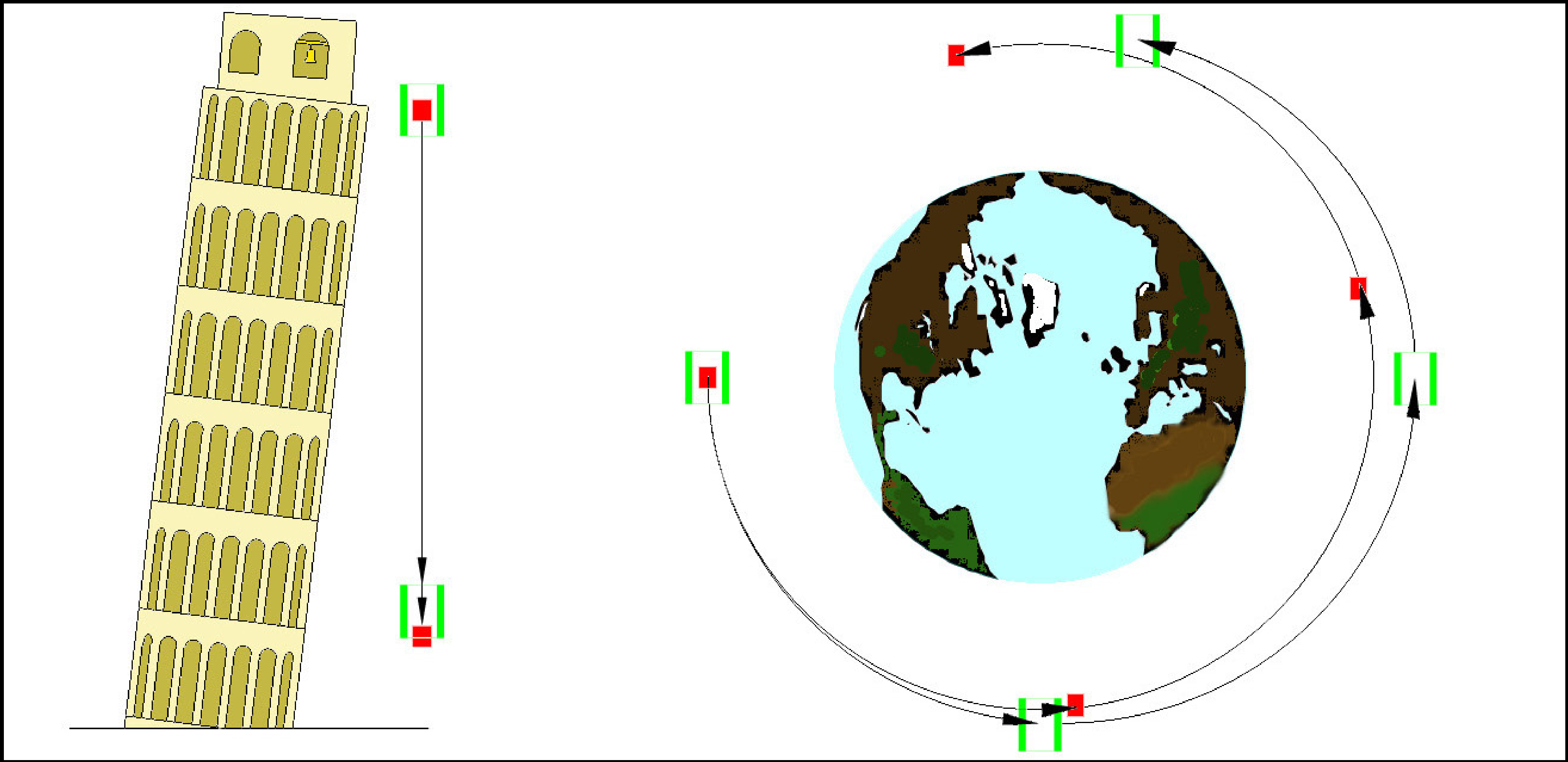


The Quest for Redundancy



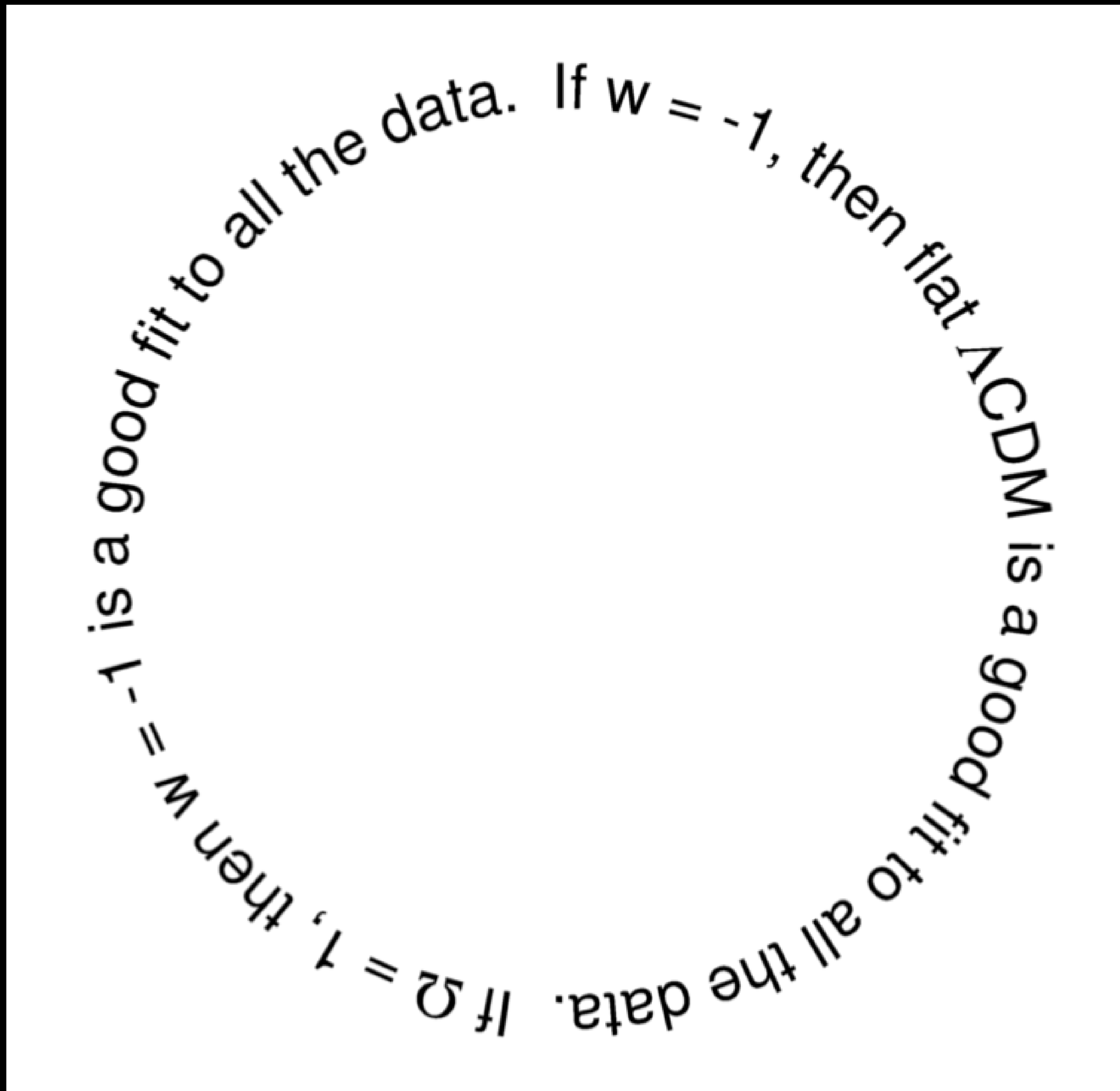
"This could be the discovery of the century. Depending, of course, on how far down it goes."

Equivalence Principle Tests



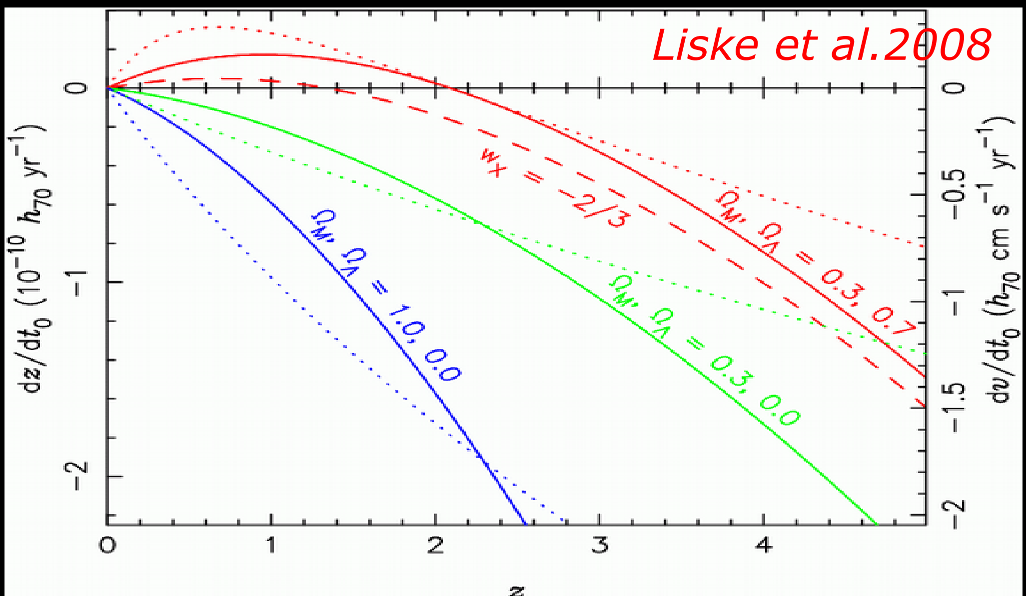
- Variations of α at few ppm level naturally lead to Weak Equivalence Principle violations within 1 order of magnitude of current bound on the Eotvos parameter *[Damour 2003]*
  - MICROSCOPE (launched 25 April 2016) should detect violations

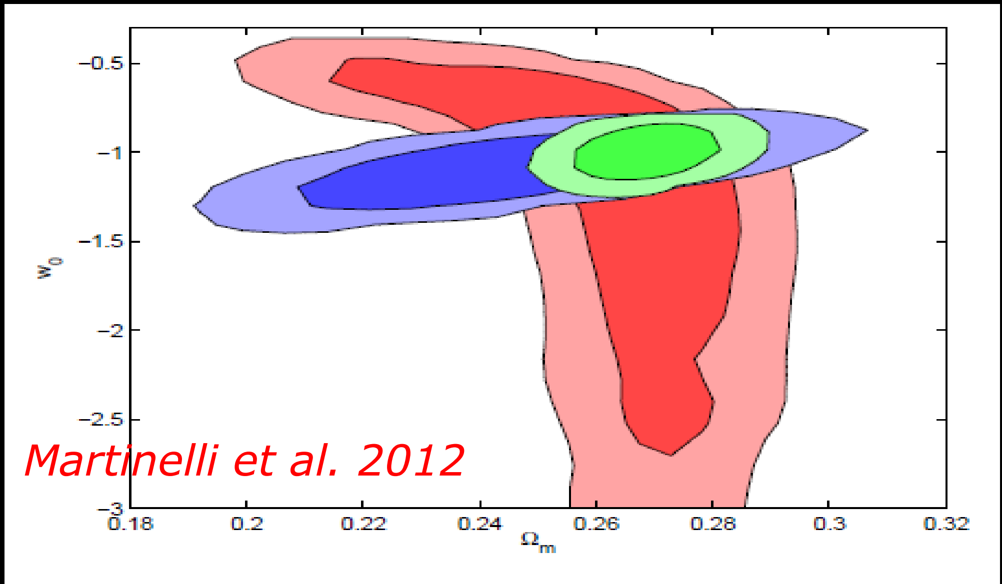
Mind Your (Cosmological) Priors



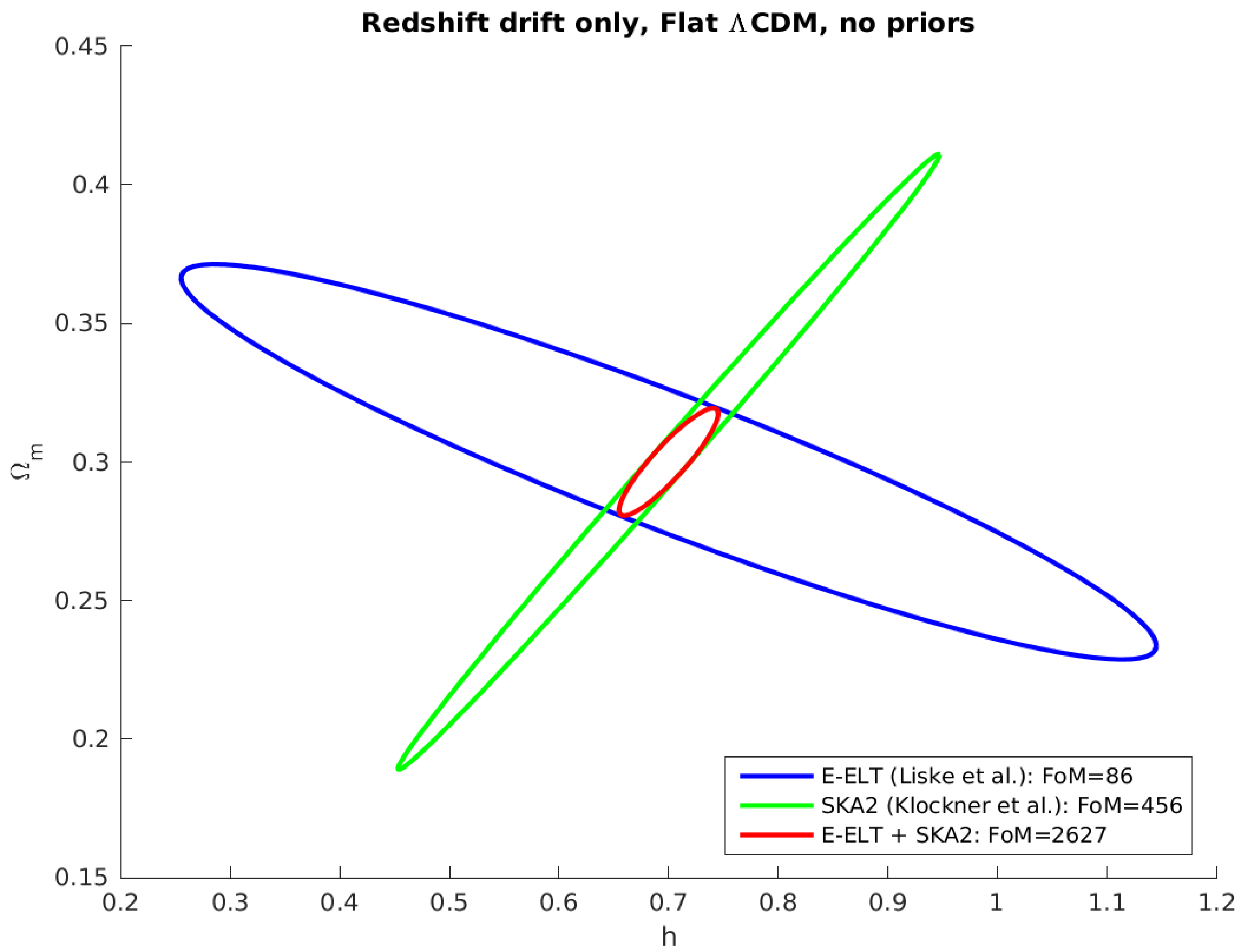
The Redshift Drift

- A direct non-geometric model-independent measurement of the universe's expansion history *[Sandage 1962]*
    - No assumptions on gravity, geometry or clustering
    - Rather than mapping our (present-day) past light-cone, it directly maps evolution by comparing past light-cones at different times
- Key ELT-HIRES driver (probing 2<z<5) *[Liske et al. 2008]*, unique tool to close consistency loop and break degeneracies
    - SKA may measure it at z<1 *[Darling 2012, Kloeckner et al. 2013]*, more detailed studies ongoing *[Martins et al. 2016, ...]*



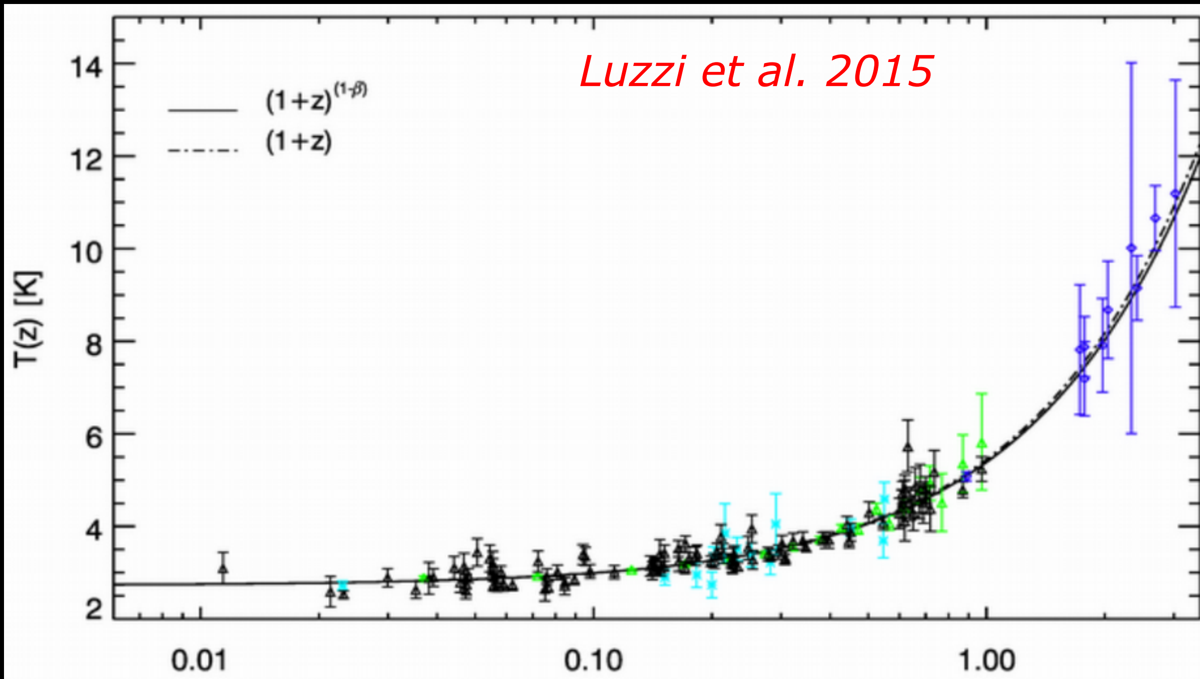


Redshift Drift Synergies



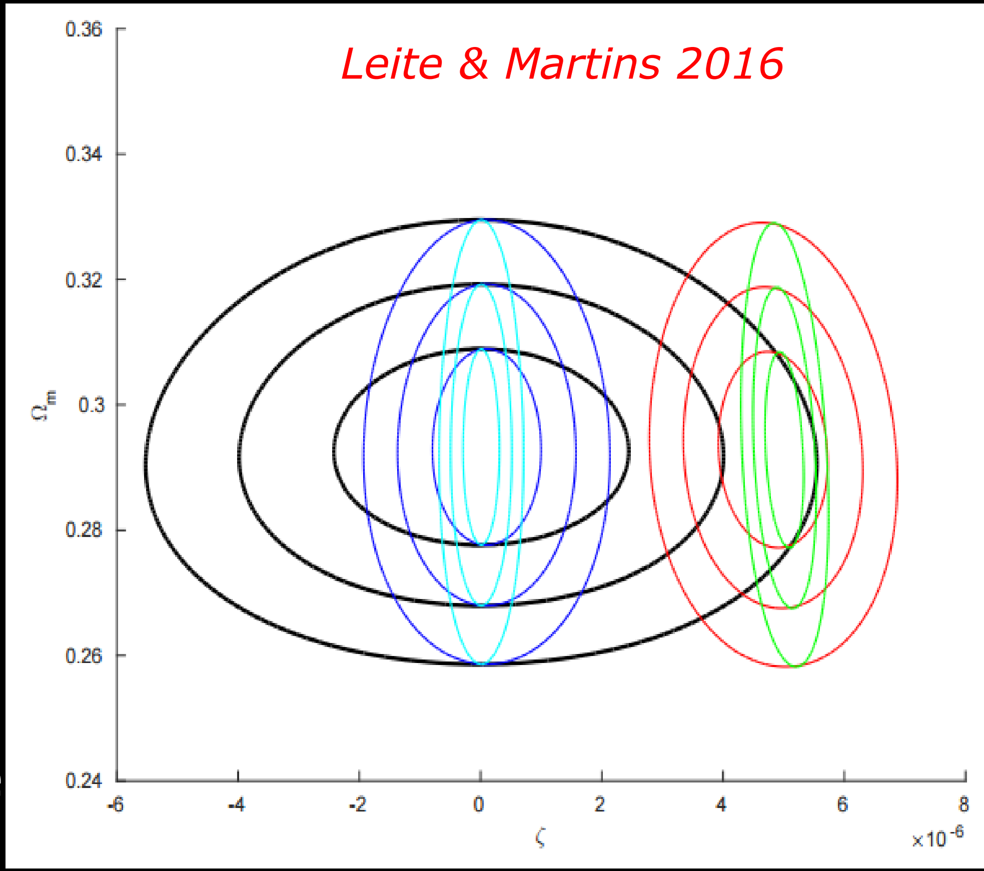
A Photon Consistency Test

- $T(z)=T_0(1+z)$ is a robust prediction of standard cosmology
  - Assumes adiabatic expansion and photon number conservation
  - If $T(z)=T_0(1+z)^{1-\beta}$, $\beta=-0.01\pm0.03$ *[Noterdaeme et al. 2011, …]*
  - Spectroscopic measurements with CO are S/N limited
- $d_L=(1+z)^2 d_A$ is a robust prediction of standard cosmology
  - Assumes metric theory of gravity, photon number conservation
  - If $d_L=(1+z)^{2+\varepsilon} d_A$, find $\varepsilon=-0.04\pm0.08$ *[Avgoustidis et al. 2010, …]*
- In many models $\beta=-2\varepsilon/3$: duality constrains β
  - Current constraint at 0.8% level, and will be improving…
  - Need more targets for ALMA, ESPRESSO and ELT-HIRES



Other Model Examples

- Models where α field does not provide all dark energy can be identified via consistency tests *[Vielzeuf & Martins 2012, …]*
  - Compare reconstructions, or use the redshift drift
  - Examples: Bekenstein models, Runaway dilaton scenarios *[Damour et al. 2002]*
  - Current α WEP bound for these is $\eta < 1\text{-}5\times10^{-14}$



- Even if the field does not dominate at low z, photon number nonconservation will bias parameter estimation
  - Studied for Euclid *[Calabrese et al. 2014, Avgoustidis et al. 2014]*
- ALMA, ESPRESSO & ELT-HIRES T(z) measurements crucial
  - Also SZ clusters at low z *[de Martino et al. 2015, Luzzi et al. 2015]*

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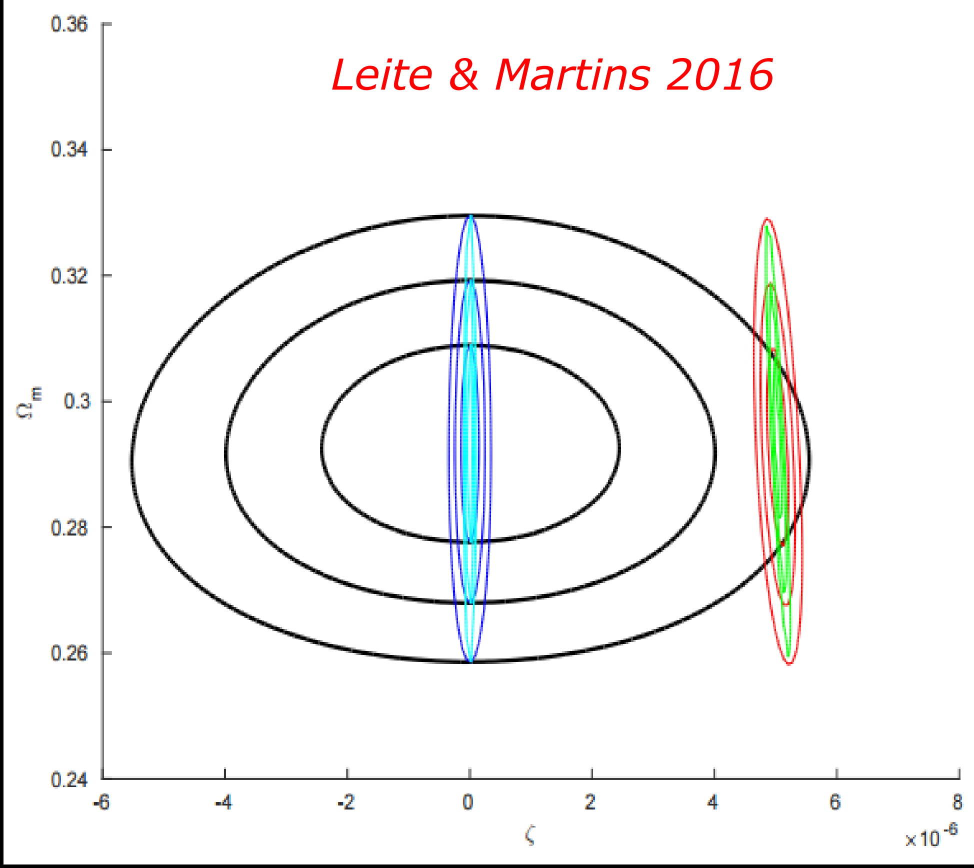

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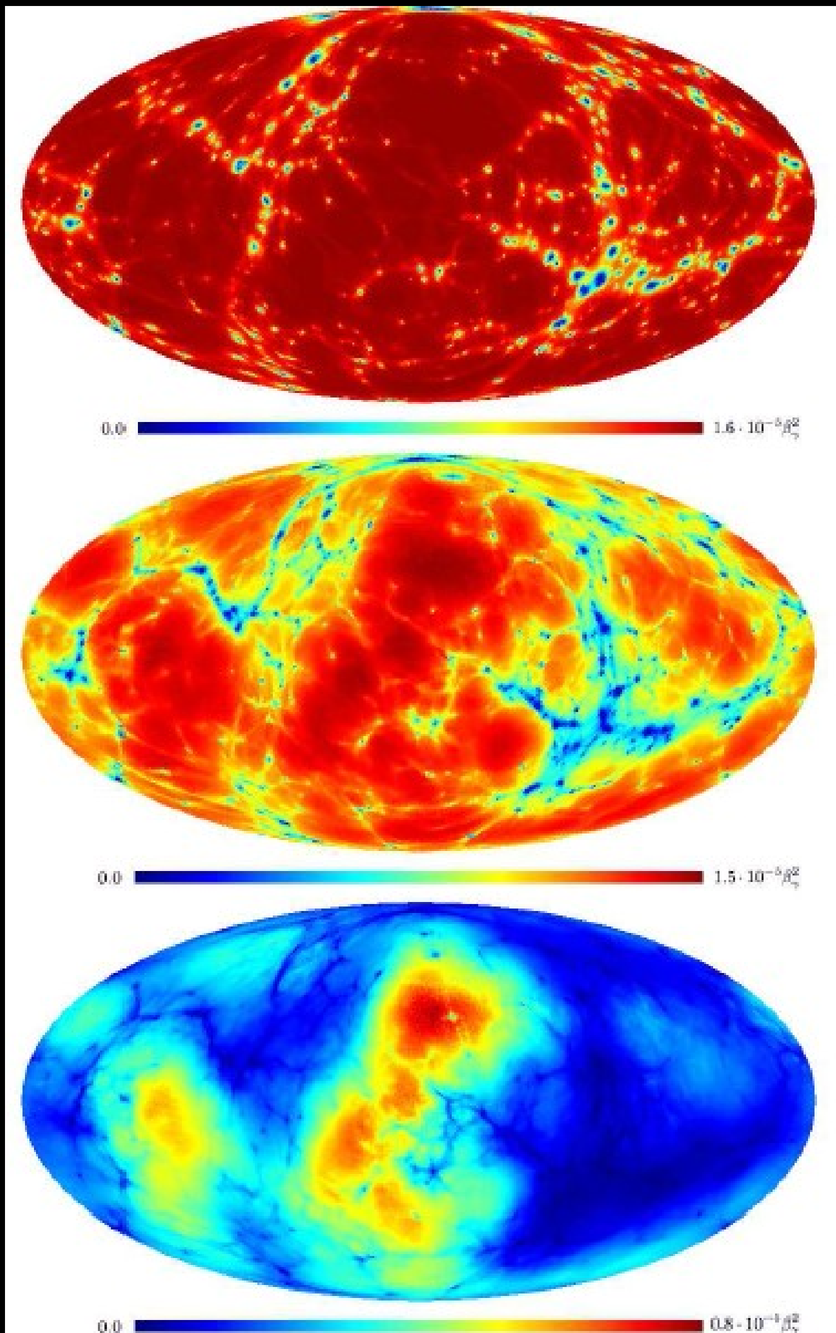
Spatial Variations: Symmetrons



[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 $(F_\phi/F_{grav})=2\beta^2(\phi_{local}/\phi_0)^2$

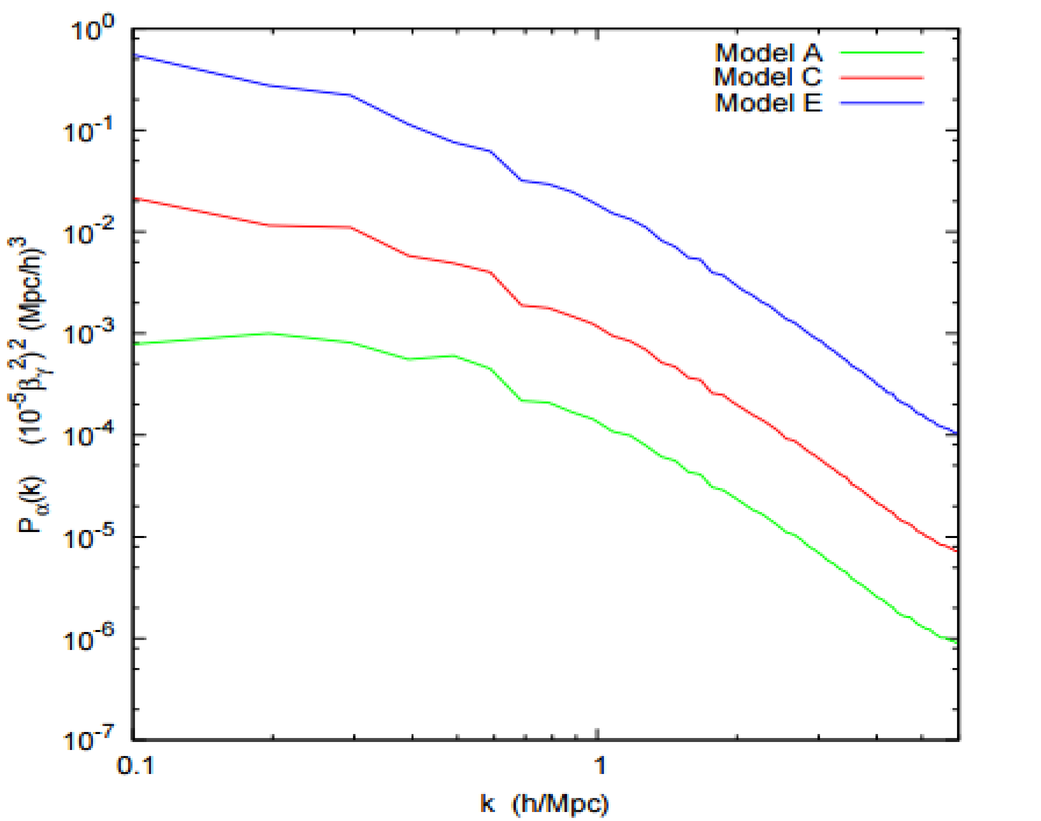
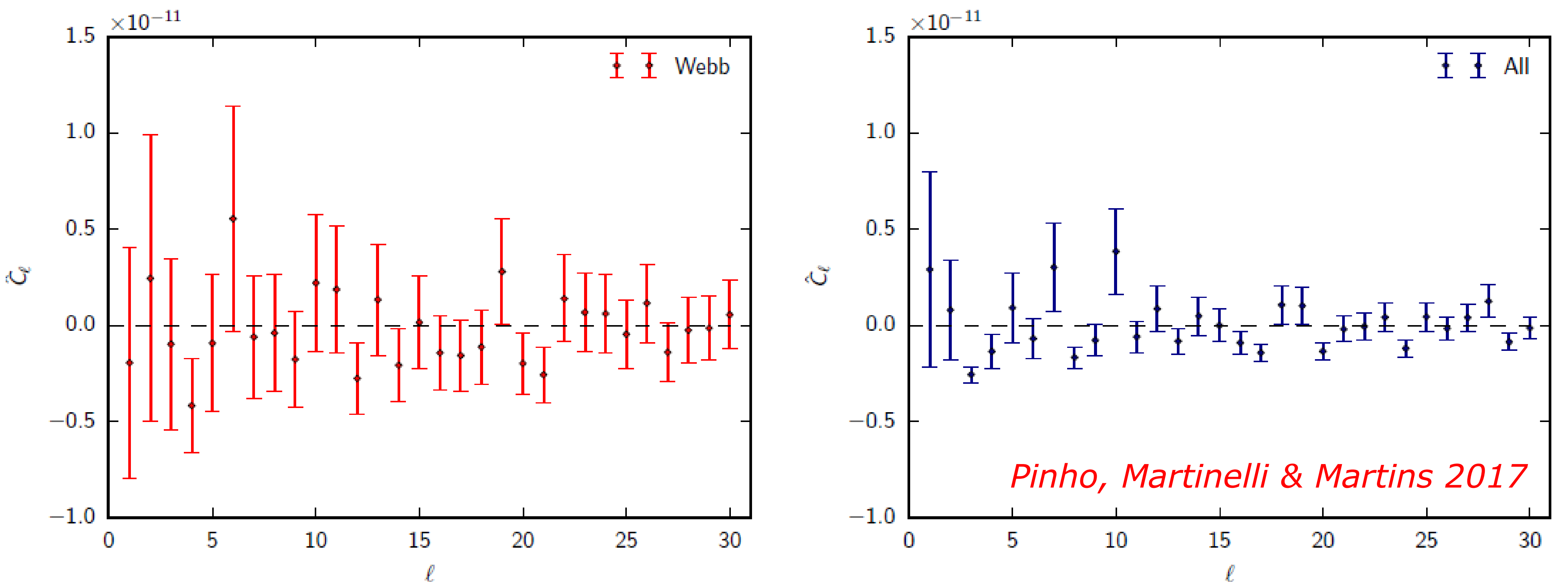


FIG. 9. The $(\alpha - \alpha_0)$ power-spectrum at $z = 0$ for the models A, C and E (solid).

Spatial Variations: Symmetrons

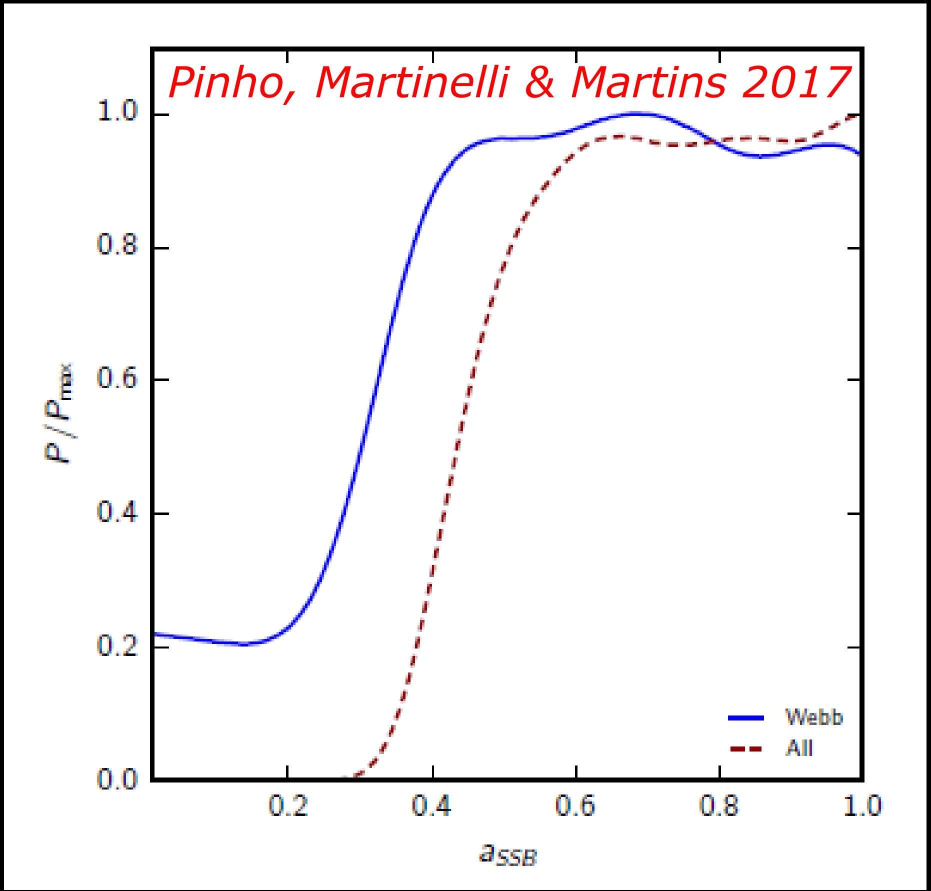
- Use current data to calculate 2D angular power spectrum (Cl)
  - Beware number density of sources, sky coverage, ...
  - Note that the recent measurements have a significant impact
  - No statistically significant evidence for variations is found



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

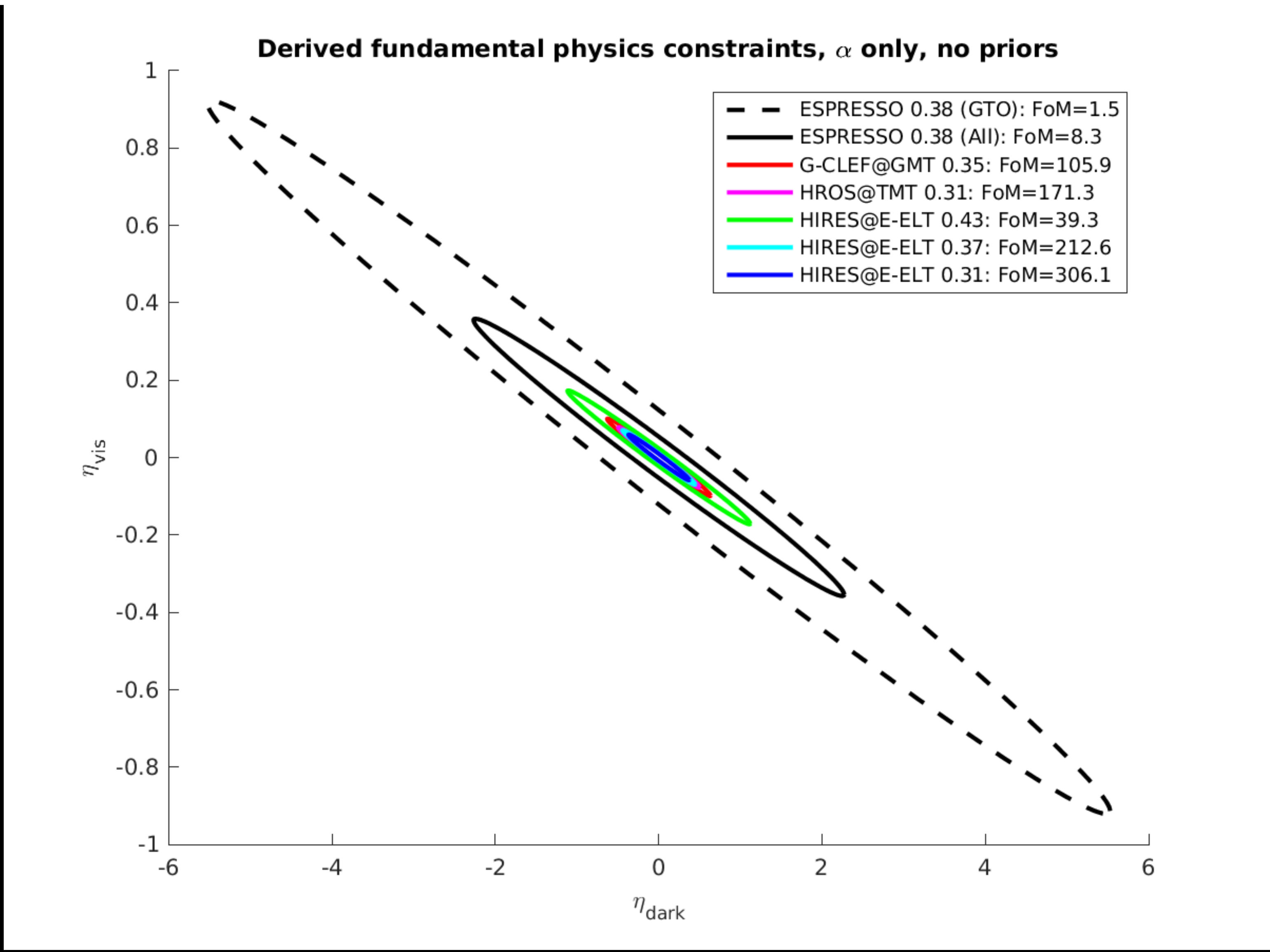
	$a_{SSB} = 0.33$	$a_{SSB} = 0.50$	$a_{SSB} = 0.66$
Webb	< -0.5	< 0.2	< 1.2
All	< -0.9	< -0.2	< 0.7



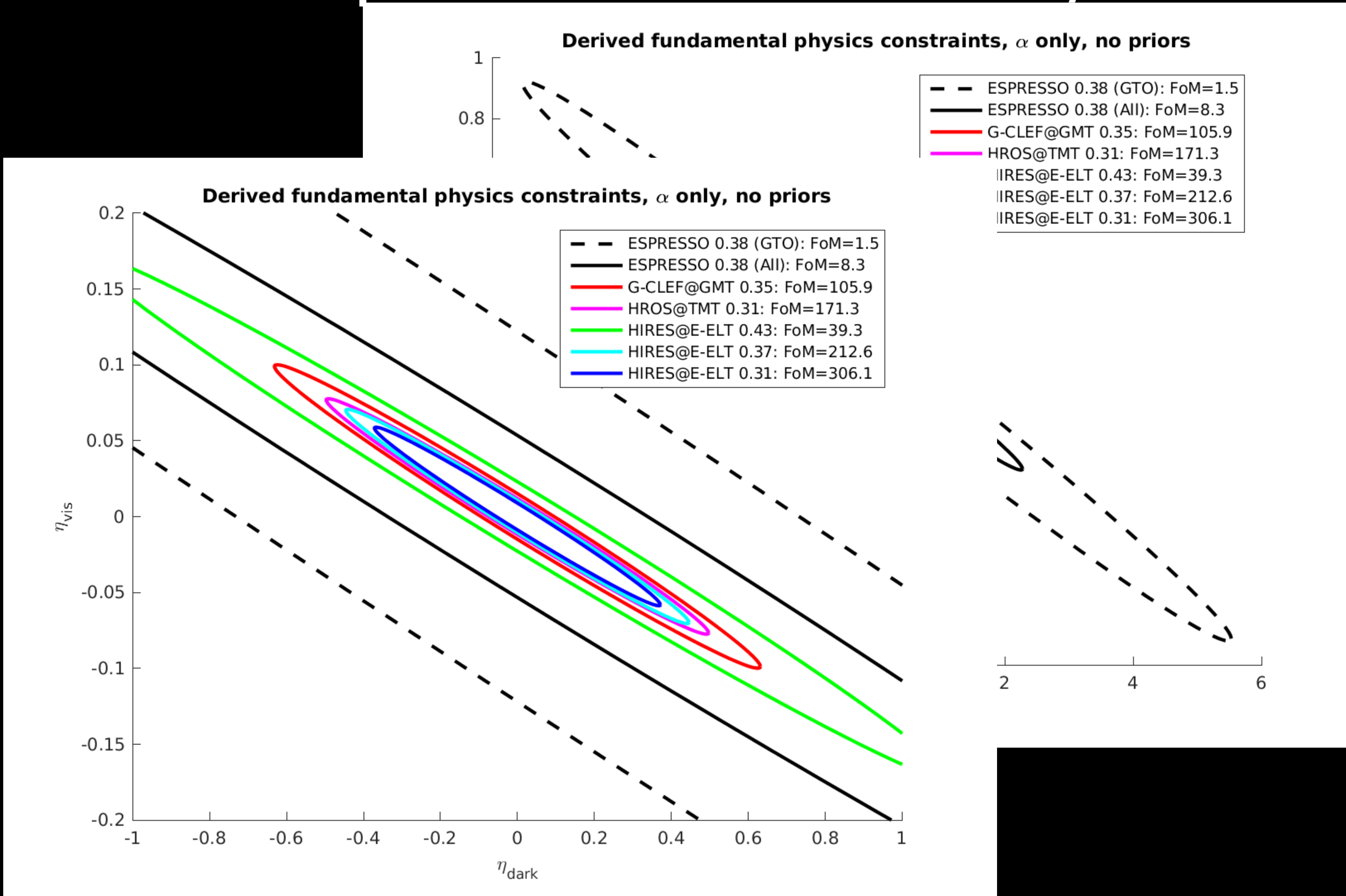
So What's Your Point?

- The ELT has the potential to be the most powerful gravity and fundamental cosmology probe in the next few decades
  - Weak Equivalence Principle tests (mostly from α data)
  - Composition-dependent force tests (mostly from μ data)
  - Strong-field tests, including 'No-hair Theorem' (from MICADO)
  - Mapping dark side from z=0 to z=4 (from HIRES & HARMONI)
  - Direct model-independent probe of the universe dynamics
  - Also weak acceleration 'MOND-like' regime in MW outskirts
- What is needed
  - 50-250 nights of telescope time (over the instruments' lifetime)
  - Identify further 'clean' targets (especially for μ & redshift drift)
  - Better lab wavelengths of most atomic/molecular transitions
  - Beyond z=4: go into IR or use lines below 1600 A
  - Adequate access to UV/blue wavelengths

The Importance of the UV/Blue



The Importance of the UV/Blue



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
  - Precision astrophysical spectroscopy provides a direct and competitive probe of the (still unknown) new physics
- Nothing varying at ~ few$\times10^{-6}$ level, already a tight bound (stronger than Cassini bound, best available WEP constraint)
  - ESPRESSO is coming soon, and will be a game changer
  - Important consistency test with MICROSCOPE
- The ELT will be the flagship tool in a new generation of precision consistency tests
  - Competitive 'guaranteed science' implications for dark energy and fundamental physics
  - Unique value of complementarity, redundancy, and synergies with other facilities (including ALMA, Euclid & SKA)


Let's do it!