Phi in the Sky: Astrophysical Probes of Fundamental Physics

Lecture 3

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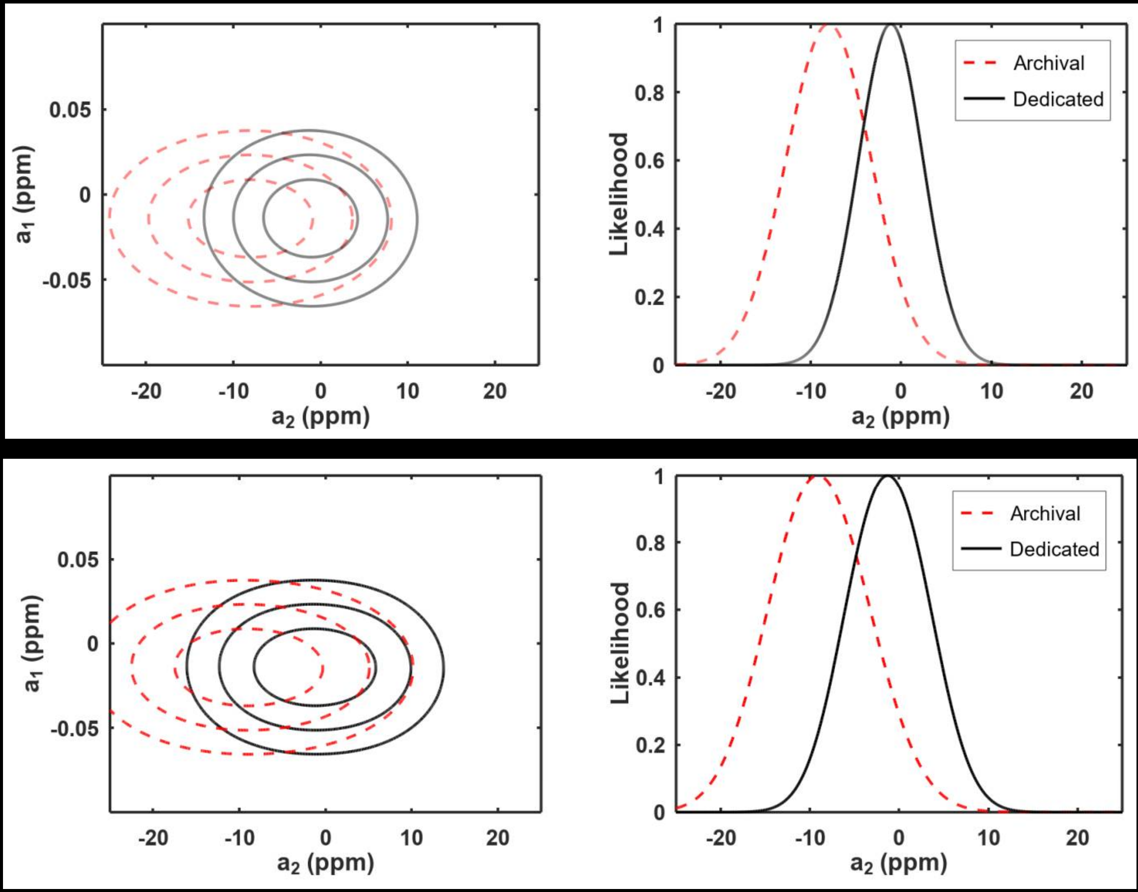
Varying α Cosmography

Model-independent approach: Taylor series expansion of possible redshift dependence of α
[Martins et al. 2022]

$$\frac{\Delta\alpha}{\alpha}(y) = \frac{1}{\alpha_0}\left(\frac{d\alpha}{dy}\right)_0 y + \frac{1}{2\alpha_0}\left(\frac{d^2\alpha}{dy^2}\right)_0 y^2 + + \frac{1}{6\alpha_0}\left(\frac{d^3\alpha}{dy^3}\right)_0 y^3$$

$$y \equiv \frac{z}{1+z}$$



Atomic clocks constrain linear term, astrophysics constrains higher-order ones

No statistically significant evidence for variations ($<2\sigma$ even for archival data)

Counting Photons

The COBE-FIRAS black-body intensity spectrum of the CMB is among the most precise cosmological measurements, and yields the well known $T_0 = 2.7260 \pm 0.0013$ *[Fixsen 2009]*

- This is confirmed by other measurements in the Galaxy
- However, this says nothing about the CMB temperature at non-zero redshift
- Such non-zero redshift measurements are scarce

In standard cosmology, assuming adiabatic expansion and photon number conservation, the CMB temperature obeys $T_{CMB}(z) = T_0(1+z)$

- However, there are many non-standard scenarios which violate this (including all those where α varies)
- Typically can be parameterised as $T_{CMB}(z) = T_0(1+z)^{1-\beta}$ *[Lima et al. 2000, ...]*
- Opportunity to test many non-standard models

QSO Absorption Lines and T_{CMB}

T_{CMB} determined from QSO absorption spectra with transitions between fine-structure levels partly populated by the CMB *[Bahcall & Wolf 1968]*

- McKellar (1941) identified Galactic CN 2.3 K transition excited by CMB with $T_0=2.729\pm0.027$K, the first (indirect) CMB detection
- CN is best known CMB thermometer, but so far not identified outside our Galaxy

C^0, C^+ and CO have UV transitions redshifted to optical at $z\sim1-3$ with fine-structure levels with T_{exc} close to the CMB

- C^0 has 3 fine-structure levels with T_{exc} of 23.6 K & 38.9 K: used since 1980s, latest $T_{CMB}(z=2.4)=10\pm4$K *[Srianand et al. 2000]*
- C^+ has 2 fine-structure levels with T~91.3 K, which have been used to obtain $T_{CMB}(z=3.0)=12.1^{+1.7}_{-3.2}$ K *[Molaro et al. 2002]*
- Both of these fine-structure levels can by populated by processes other than the CMB radiation, degrading the method's performance

Carbon Monoxide

CO effectively systematic-free, as competing excitation mechanisms are almost negligible: measurements can be considered S/N dominated

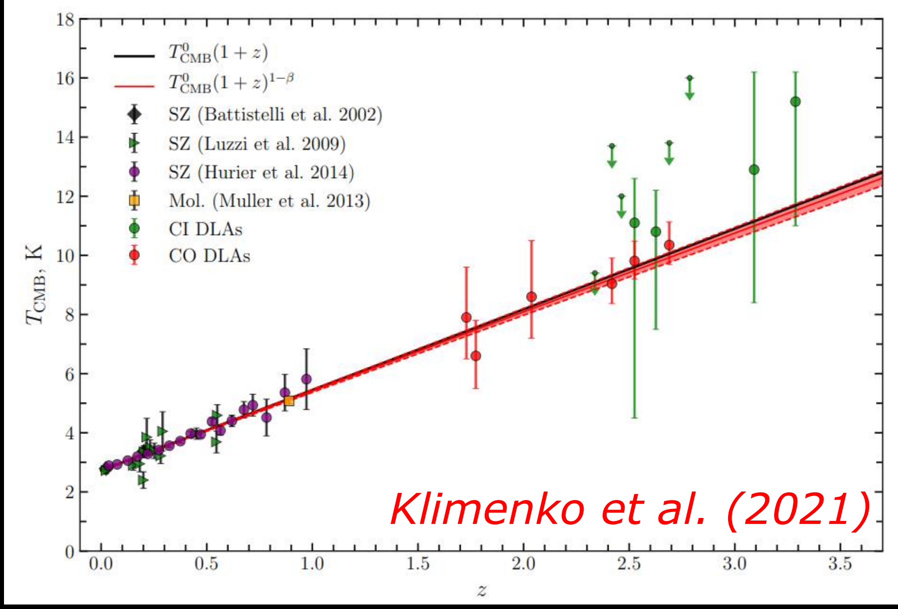
- Sobolev et al. (2015) estimated a small correction that should be applied for excitation by collisions with hydrogen atoms or molecules, but this is small
- Relies on electronic transition between A and X states at ~1544A, falling in the optical at z>1.5; other transitions between different rotational states also used

Only recently used, due to lack of high-z CO detections (hard due to the low dust opacity required to observe background source)

First detection *[Srianand et al. 2008]* $T_{z=2.4}$=9.15±0.72 K

[Noterdaeme et al. 2011] provided 5 measurements with 0.7-1.3 K errors, later a 6th, $T_{z=2.53}=9.6^{+0.7}_{-0.6}$ K

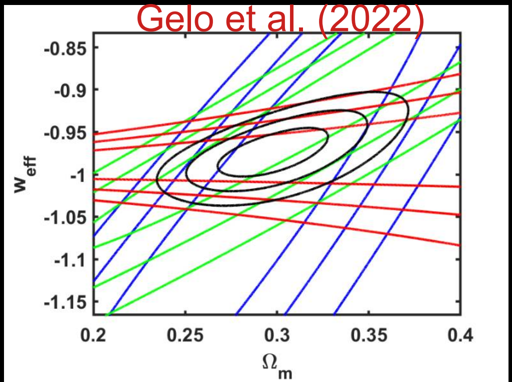
[Muller et al. (2013)] used mm-range absorptions in 13 different molecules to find $T_{z=0.9}$=5.08±0.10 K



A Photon Consistency Test

$T(z)=T_0(1+z)$ is a robust prediction of standard cosmology

- Assumes adiabatic expansion and photon number conservation
- $T(z)$ is a competitive cosmological probe *[Gelo et al. 2022]*
- A simple parametrization is $T(z)=T_0(1+z)^{1-\beta}$

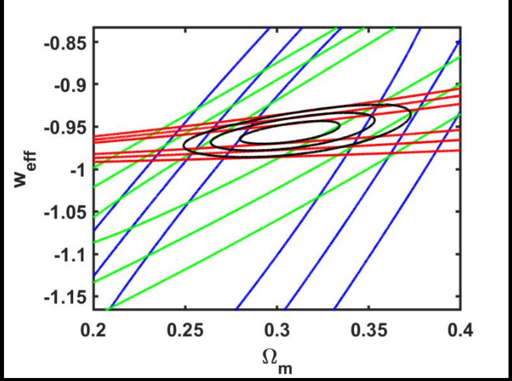


$d_L=(1+z)^2 d_A$ is a robust prediction of standard cosmology

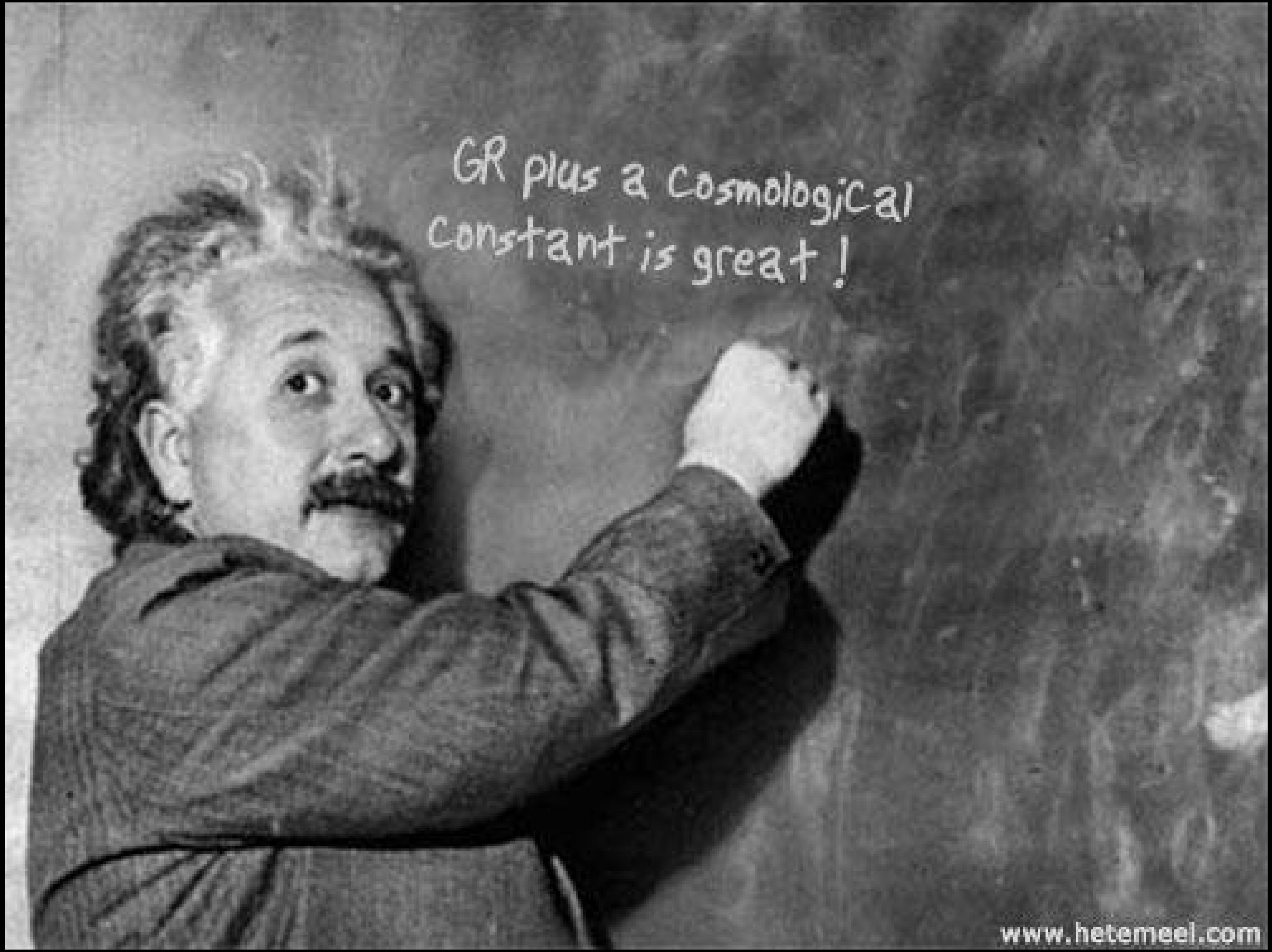
- Assumes metric theory of gravity, photon number conservation
- A simple parametrization is $d_L=(1+z)^{2+\varepsilon}d_A$

In many models, $\beta=-2\varepsilon/3$: distance duality tests also constrain β *[Avgoustidis et al. 2012]*

- Current constraint 0.8% *[Avgoustidis et al 2016, ...]*
- Important external data, e.g. for Euclid constraints on non-standard models *[Martinelli et al. 2020]*



Was Einstein Right?



Dark Energy & Varying Couplings

Universe dominated by unknown 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, ...]*

- These measurements (whether they are detections or null results) constrain fundamental physics and cosmology
- E.g., scalar field inevitably couples to nucleons, leading to WEP violations
- Current measurements already provide competitive constraints
- ESPRESSO provides significant improvements (and a testbed for the ELT)

How Low Should One Go?

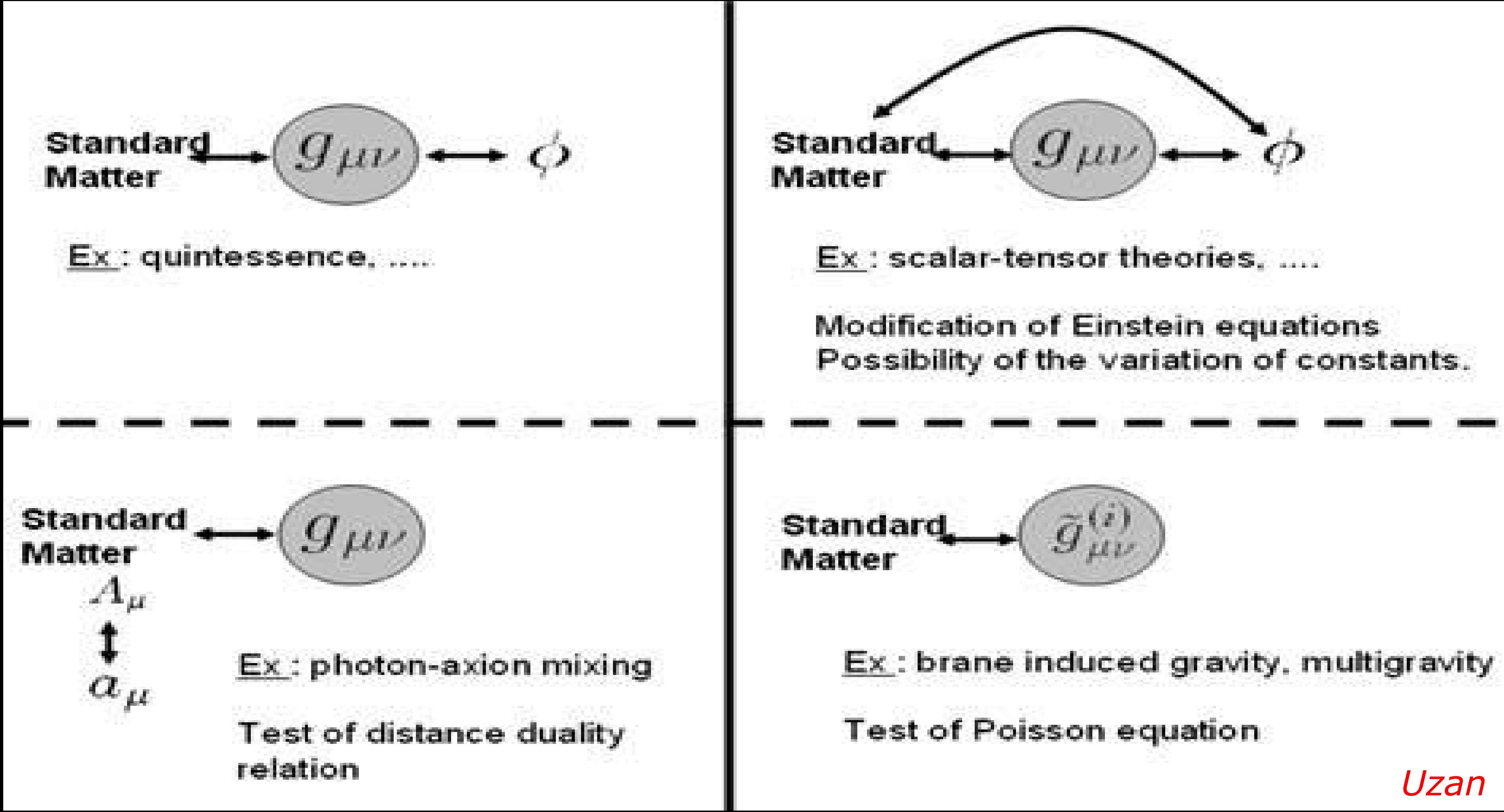
Dark energy equation of state vs. Relative variation of α

Dark energy equation of state	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? Obviously 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
- Tight bound implies either no dynamical cosmological fields or a new symmetry – whose existence would be even more significant
- Anyway, strong dynamical dark energy and Equivalence Principle constraints


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

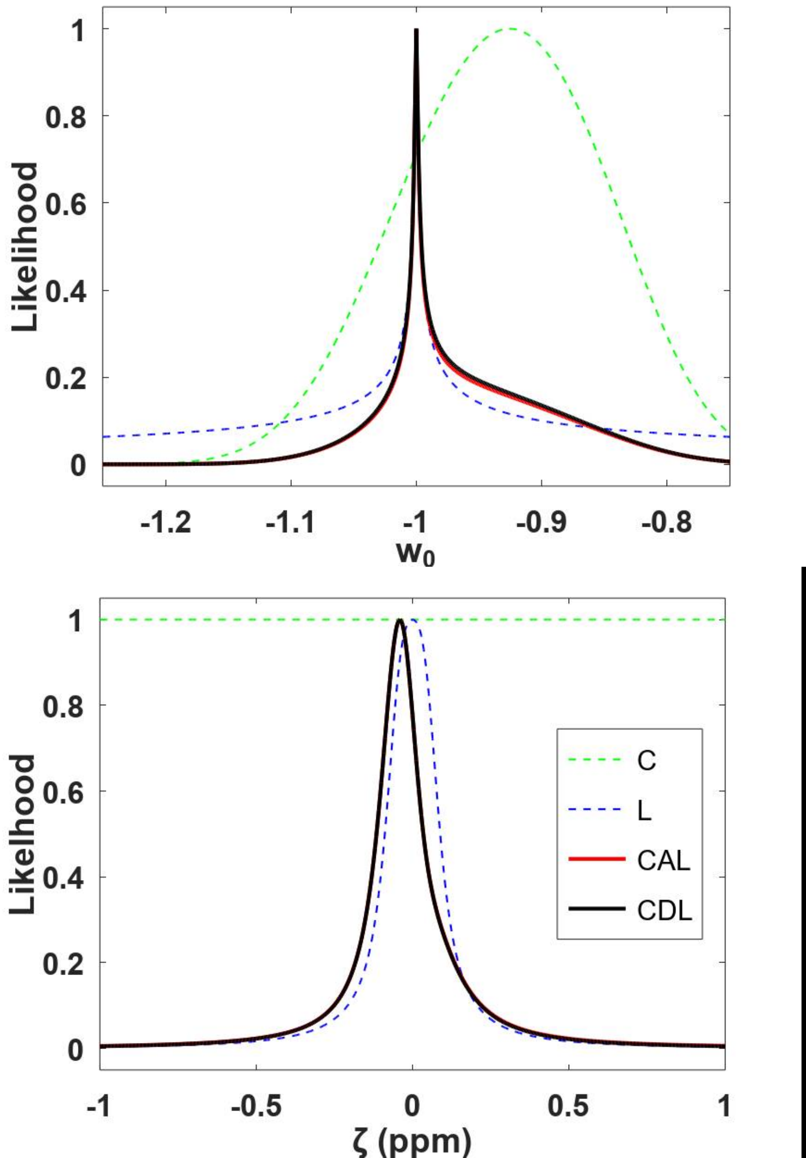
Two Model Classes

Class I: the same degree of freedom yields dynamical dark energy and α

- α evolution is parametrically determined, constrains dark energy equation of state

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

- Can distinguish freezing and thawing models *[Vilas Boas et al. 2020]*
- Example: CPL *[Martins et al. 2022]*, from ESPRESSO & other low-redshift data
- Local constraints (atomic clocks, WEP) dominate, but redshift lever arm relevant



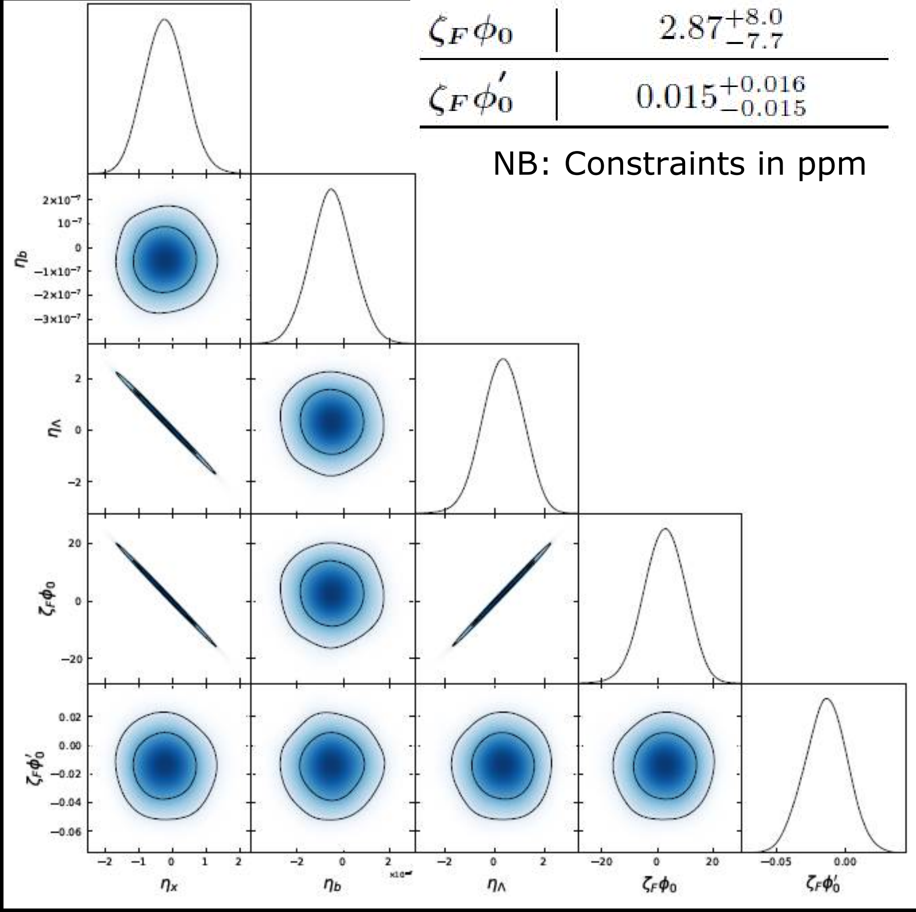
Two Model Classes

Param	68% C.L.
η_χ	$-0.24^{+0.63}_{-0.66}$
η_b	$\left(-0.54^{+0.93}_{-0.94}\right) \cdot 10^{-7}$
η_Λ	$0.34^{+0.88}_{-0.85}$
$\zeta_F \phi_0$	$2.87^{+8.0}_{-7.7}$
$\zeta_F \phi_0'$	$0.015^{+0.016}_{-0.015}$

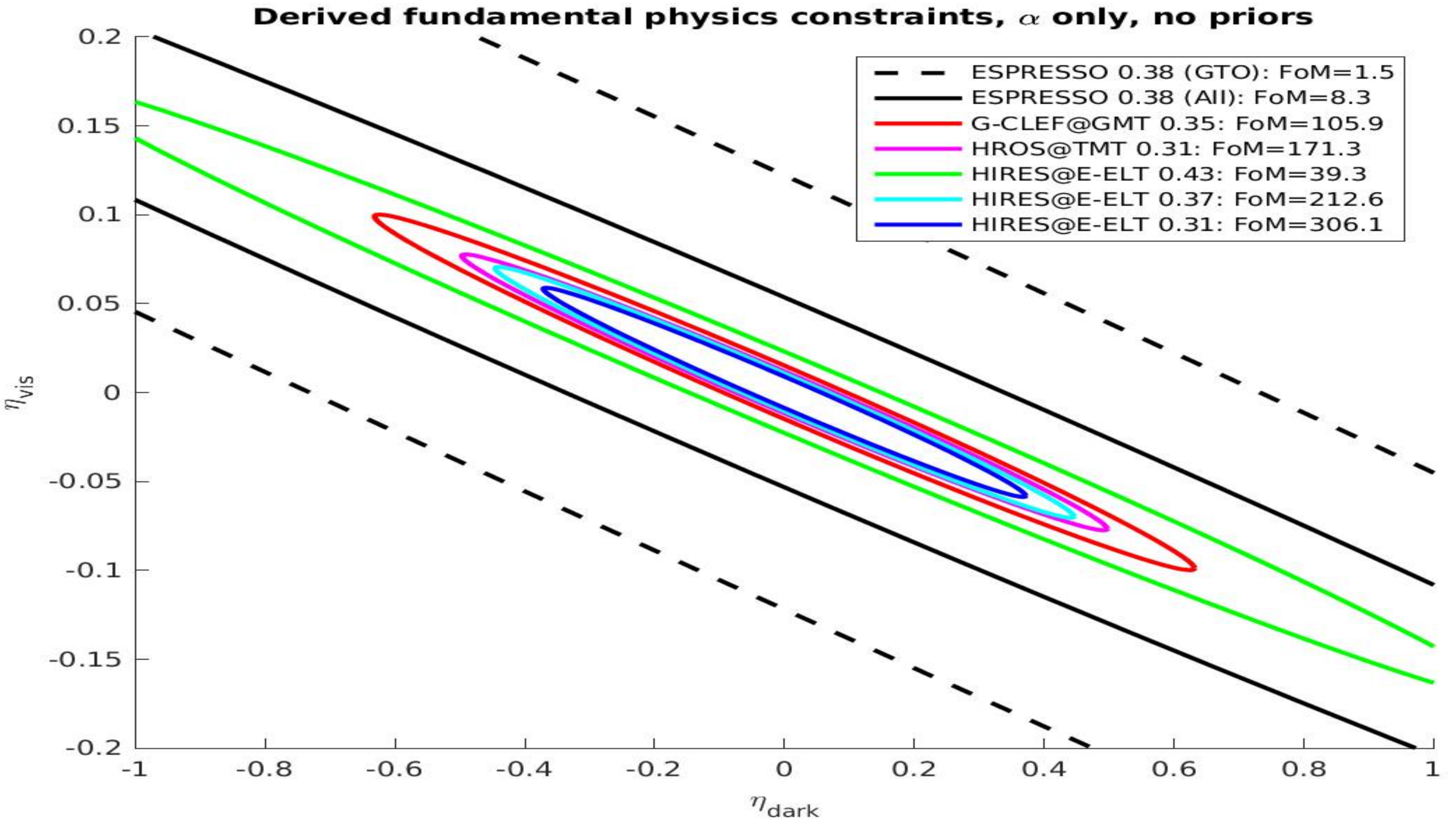
NB: Constraints in ppm

Class II: α dynamical d.o.f. only has subdominant effect on recent dynamics

- I.e., there is a cosmological constant providing (most of) the dark energy
- Identifiable through consistency tests, α still constrains model parameters
- Could be only non-ΛCDM fingerprint *[Tavares & Martins 2020]*
- Example: Bekenstein-type models, couplings constrained to sub-ppm
- Full analysis in *[Vacher et al. 2022]*



ELTs: Collecting Area vs. Blue Coverage



A Simple Case Study: Rolling Tachyons

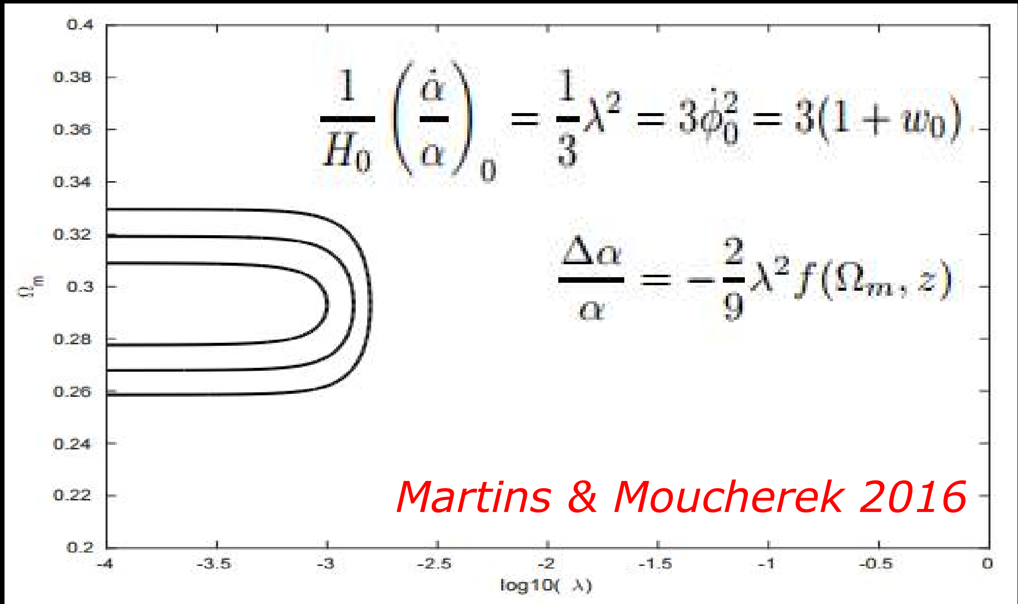
A rolling tachyon is a Born-Infeld scalar: well motivated in string theory, field dynamics unavoidably leads to α variations *[Sen 2002, …]*

- 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 (i.e., a DBI type action)

Potential slope determines w and α: thawing models with $\Delta\alpha/\alpha<0$, but extremely tightly constrained

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

Background cosmology data will never distinguish this from ΛCDM, only α data can do it

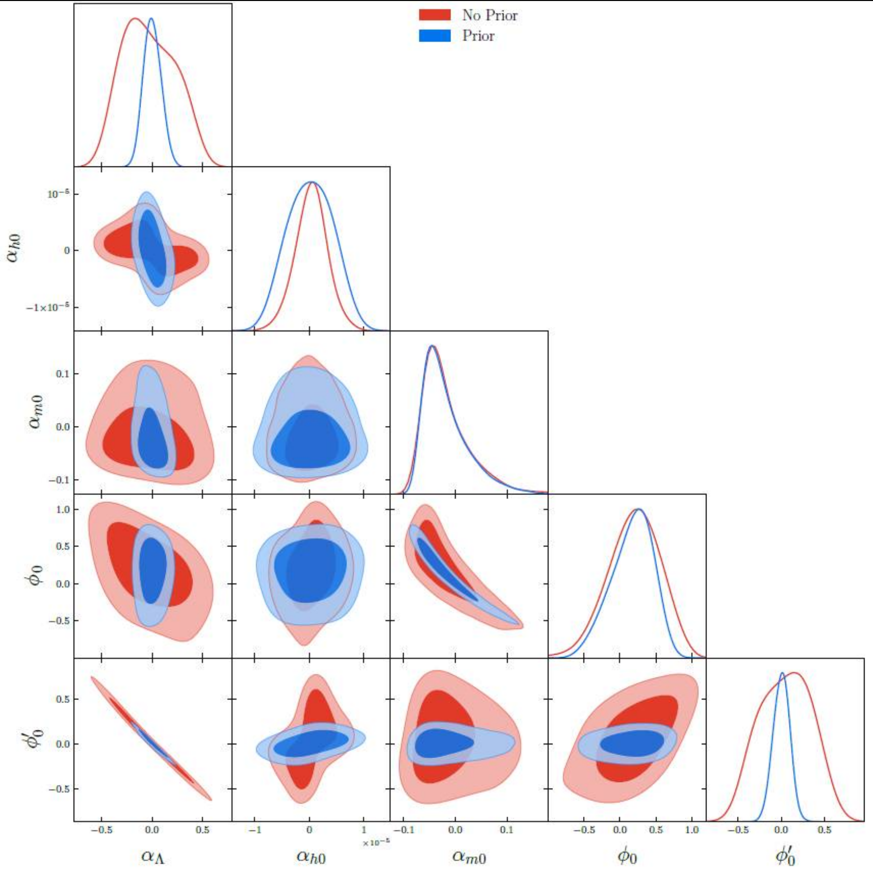


Constraining String Theory

- Runaway dilaton *[Damour et al. 2002]* is a string-inspired model reconciling massless dilaton with experimental data
  - Dilaton has couplings α_i with each component

$$\frac{2}{3-\phi'^2}\phi'' + \left(1-\frac{p}{\rho}\right)\phi' = -\sum_i \alpha_i(\phi)\frac{\rho_i - 3p_i}{\rho}$$

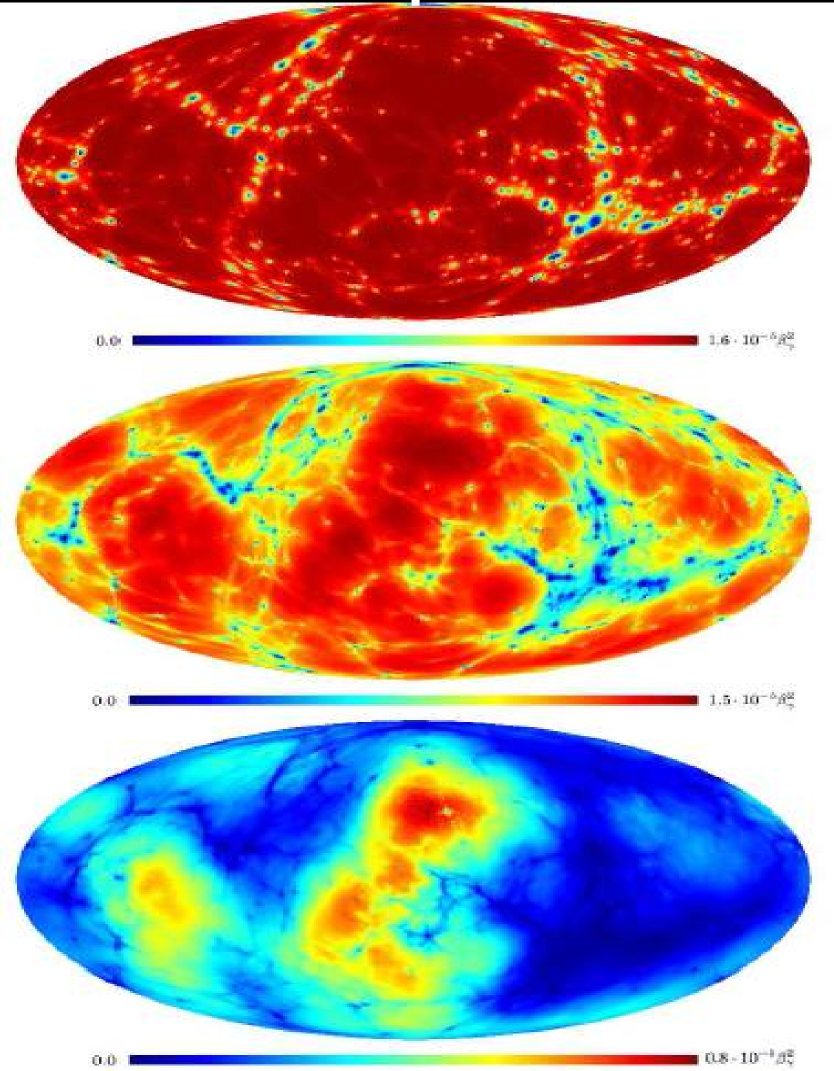
- Constrained by cosmology, α and local data cf. *[Vacher et al., Schoneberg et al. 2023]*
  - Order unity couplings are now ruled out
  - (Also tight limits for Swampland Conjecture)



Parameter	68 % C.L.
$\alpha_{h,0}$	$(0.01\,^{+4.22}_{-4.17}) \times 10^{-6}$
$\alpha_{m,0}$	$(-1.68\,^{+2.24}_{-5.78}) \times 10^{-2}$
α_V	$(0.04\,^{+1.12}_{-1.27}) \times 10^{-1}$
ϕ_0	$(1.64^{+3.82}_{-2.53}) \times 10^{-1}$
ϕ'_0	$(0.02\,^{+1.36}_{-1.26}) \times 10^{-1}$

Parameter	Prior on ϕ'_0	No prior on ϕ'_0
$\alpha_{h,0}$	$(-1.63\,^{+4.33}_{-4.71}) \times 10^{-6}$	$(0.21\,^{+2.97}_{-2.80}) \times 10^{-6}$
$\alpha_{m,0}$	$(-1.70\,^{+2.08}_{-5.71}) \times 10^{-2}$	$(-1.39\,^{+2.65}_{-6.03}) \times 10^{-2}$
α_Λ	$(0.50\,^{+8.94}_{-9.39}) \times 10^{-2}$	$(-0.16\,^{+2.34}_{-3.65}) \times 10^{-1}$
ϕ_0	$(16.7^{+3.68}_{-2.43}) \times 10^{-1}$	$(17.5^{+4.25}_{-3.23}) \times 10^{-1}$
ϕ'_0	$(0.20\,^{+9.97}_{-9.98}) \times 10^{-2}$	$(3.7\,^{+38.4}_{-31.0}) \times 10^{-2}$

Spatial Variations: Symmetrons



Analytic calculations plus N-body simulations: 3D α power spectrum

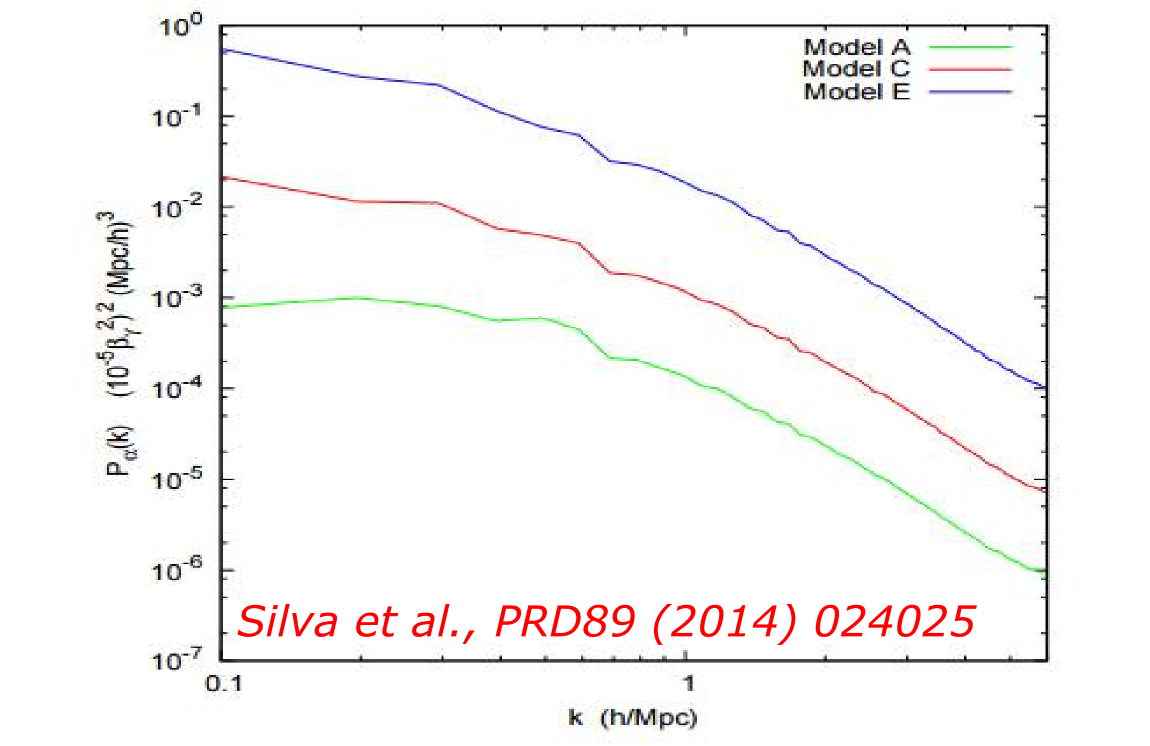
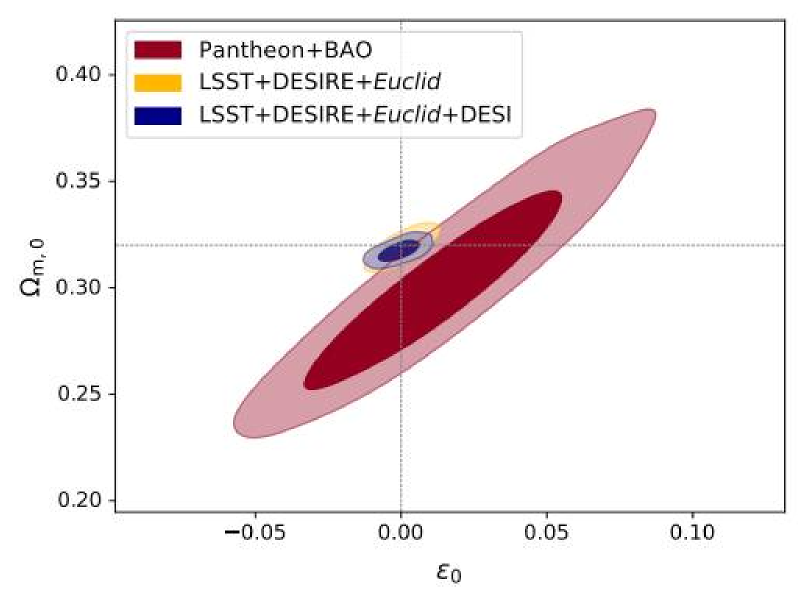


FIG. 9. The $(\alpha - \alpha_0)$ power-spectrum at $z = 0$ for the models A, C and E (solid).

Interlude: A Euclid Test

Euclid & other surveys probe Etherington relation (which holds for metric theories of gravity with photon number conservation)

- Improved previous constraints by factor 2.5 *[Martinelli et al. 2020]*
- Euclid improvement: 6x with parametric methods...
- ...or 3x with non-parametric methods (MLGA reconstruction)



Euclid: Forecast constraints on the cosmic distance duality relation with complementary external probes★

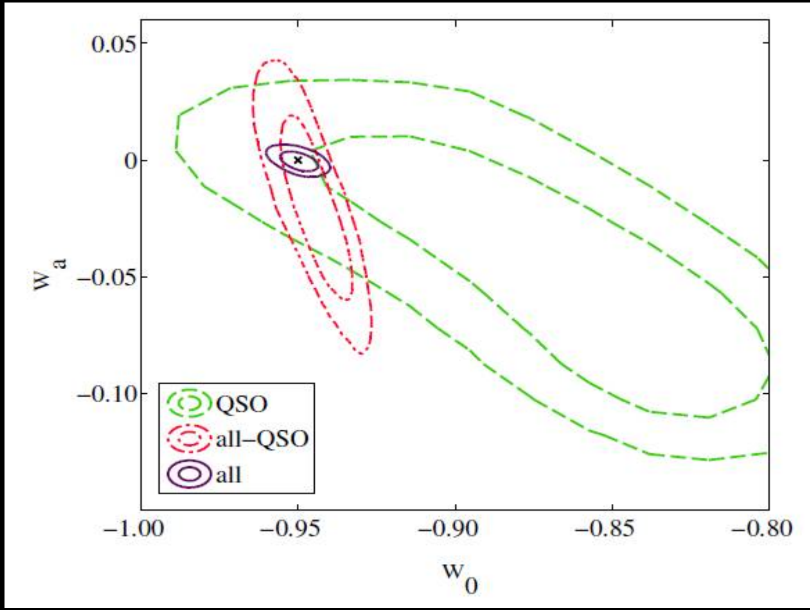
M. Martinelli[1]★★, C.J.A.P. Martins[2,3], S. Nesseris[1], D. Sapone[4], I. Tutusaus[5,6], A. Avgoustidis[7], S. Camera[8,9,10], C. Carbone[11], S. Casas[12], S. Ilić[13,14,15], Z. Sakr[15,16], V. Yankelevich[17], N. Auricchio[18], A. Balestra[19], C. Bodendorf[20], D. Bonino[10], E. Branchini[21,22,23], M. Brescia[24], J. Brinchmann[3], V. Capobianco[10], J. Carretero[25], M. Castellano[23], S. Cavuoti[24,26,27], R. Cledassou[28], G. Congedo[29], L. Conversi[30,31], L. Corcione[10], F. Dubath[32], A. Ealet[33], M. Frailis[34], E. Franceschi[18], M. Fumana[11], B. Garilli[11], B. Gillis[29], C. Giocoli[35,36,37], F. Grupp[20,38], S.V.H. Haugan[39], W. Holmes[40], F. Hormuth[41], K. Jahnke[42], S. Kermiche[43], M. Kilbinger[12], T.D. Kitching[44], B. Kubik[45], M. Kunz[46], H. Kurki-Suonio[47], S. Ligori[10], P.B. Lilje[39], I. Lloro[48], O. Marggraf[49], K. Markovic[40], R. Massey[50], S. Mei[51], M. Meneghetti[35,37], G. Meylan[52], L. Moscardini[18,36,53], S. Niemi[44], C. Padilla[54], S. Paltani[32], F. Pasian[34], V. Pettorino[12], S. Pires[12], G. Polenta[55], M. Poncet[28], L. Popa[56], L. Pozzetti[18], F. Raison[20], J. Rhodes[40], M. Roncarelli[18,36], R. Saglia[20,38], P. Schneider[49], A. Secroun[43], S. Serrano[5,6], C. Sirignano[57,58], G. Sirri[53], F. Sureau[12], A.N. Taylor[29], I. Tereno[59,60], R. Toledo-Moreo[61], L. Valenziano[18,53], T. Vassallo[38], Y. Wang[62], N. Welikala[29], J. Weller[20,38], A. Zacchei[34]

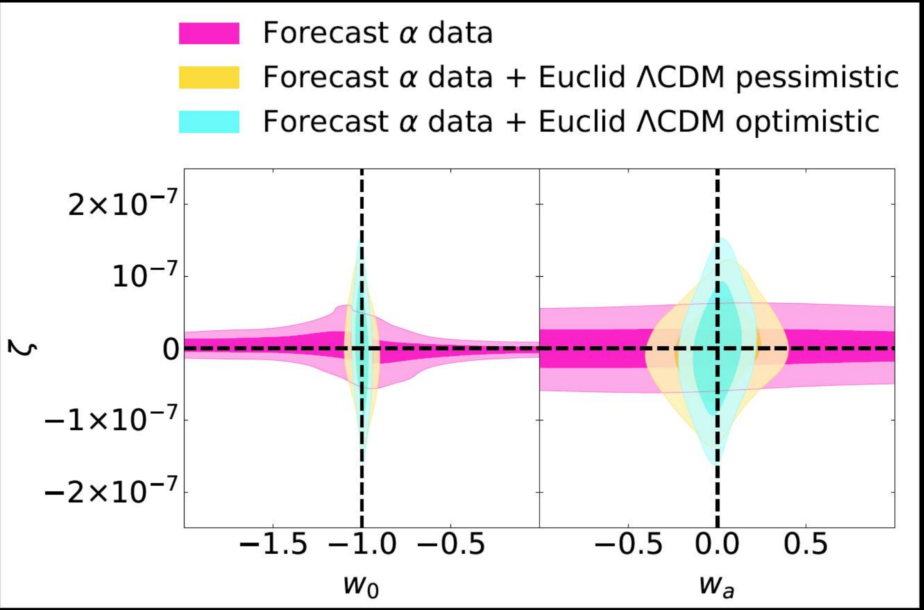
Interlude: Euclid & Varying α

Euclid forecast constraints on dark energy coupled to electromagnetism, with astrophysical and laboratory data *[Martinelli et al. 2021]*

- Improves Euclid dark energy FoM by between 8% and 26%, depending on the correct fiducial model (larger improvements in the null case)

Increasing redshift lever arm is crucial *[Calabrese et al. 2014]*





Interlude: 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 important too, and the Galactic Centre is an ideal environment in which to do it

- Direct test of metric theories (e.g., Kerr black hole solution not unique to GR)
- 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 $4 \times 10^6 M_\odot$ black hole at GC is ~10 μas

Mind Your Cosmological Priors