Phi in the Sky: Astrophysical Probes of Fundamental Physics

Lecture 4

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The Redshift Drift

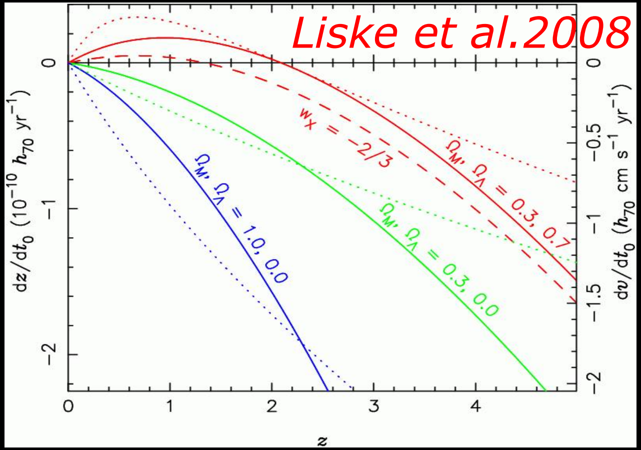
A direct non-geometric model-independent measurement of the universe's expansion history *[Sandage 1962]*

- Watching the universe expand in real time!
- Independent of gravity, geometry or clustering
- Not mapping (present-day) past light-cone, but directly comparing different past light-cones

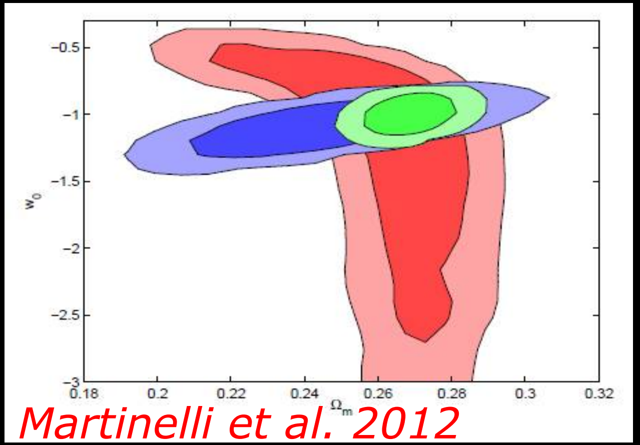
$$\dot{z} \equiv \frac{\mathrm{d}z}{\mathrm{d}t_{\mathrm{obs}}}(t_0) = (1+z)H_0 - H(z)$$

ELT flagship science driver (for z>2) *[Liske et al. 2008],* unique tool to close consistency loop and break parameter degeneracies

- SKAO can cover z<1 *[Klockner et al. 2015, …]*
- In practice, measure a spectroscopic velocity



Liske et al.2008



Martinelli et al. 2012

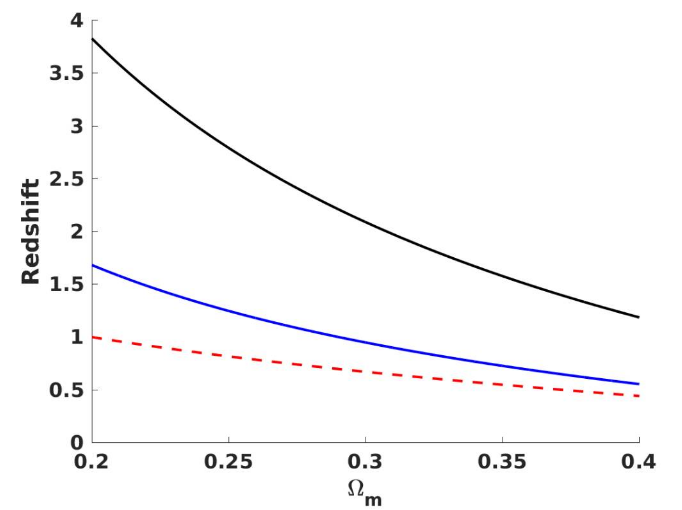
Redshift Drift vs Spectroscopic Velocity

In practice one measures a spectroscopic velocity; feasibility of LFC calibration being explored *[Probst et al. 2020, Milakovic et al. 2020]*

$$\frac{\Delta z}{\Delta t} = H_0\,[1+z-E(z)]$$

$$\Delta v = \frac{c\Delta z}{1+z} = (cH_0\Delta t)\left[1-\frac{E(z)}{1+z}\right]$$

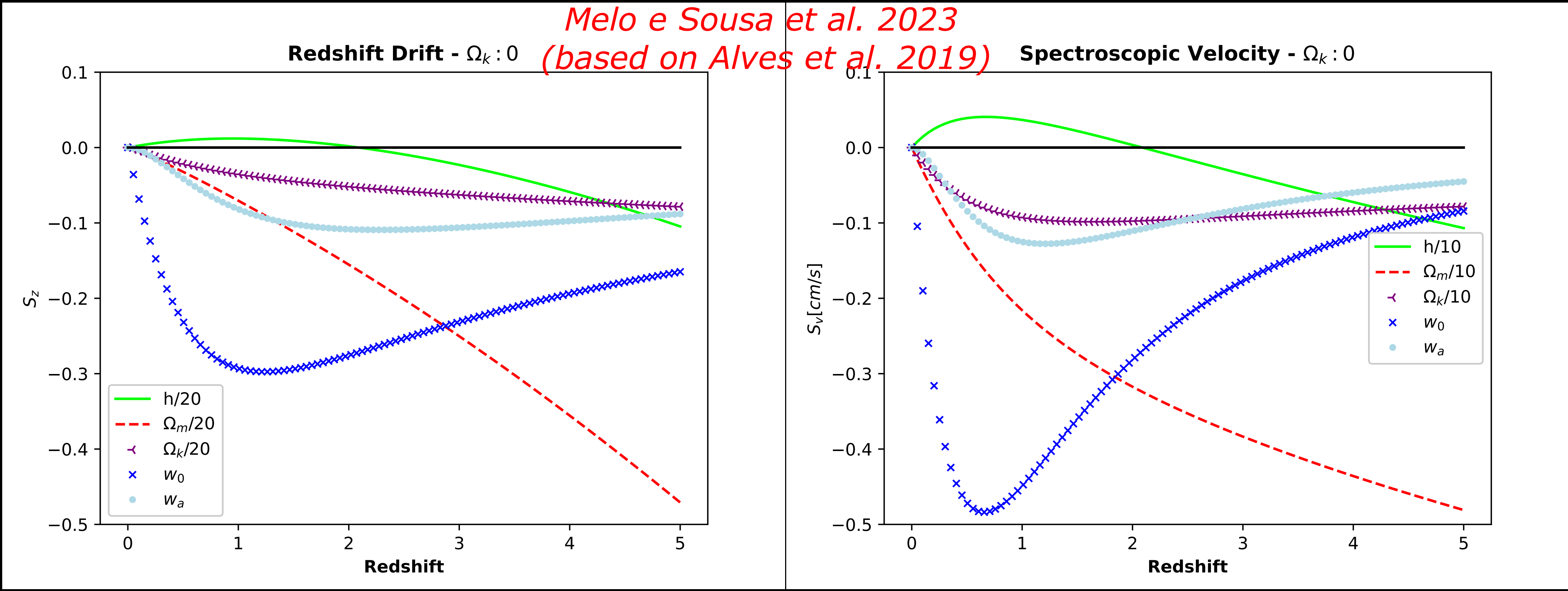
- The two have different redshift dependencies
- Cf. zero drift, maximal positive drift and maximal positive spectroscopic velocity for flat ΛCDM
- Unique feature: the signal grows linearly with the experiment time



Cosmological parameter sensitivities are redshift-dependent, and correlations can change sign; this will impact constraining power and lead to high-low redshift synergies *[Alves et al. 2019]*

Cosmological Parameter Sensitivity

(for a CPL fiducial model)



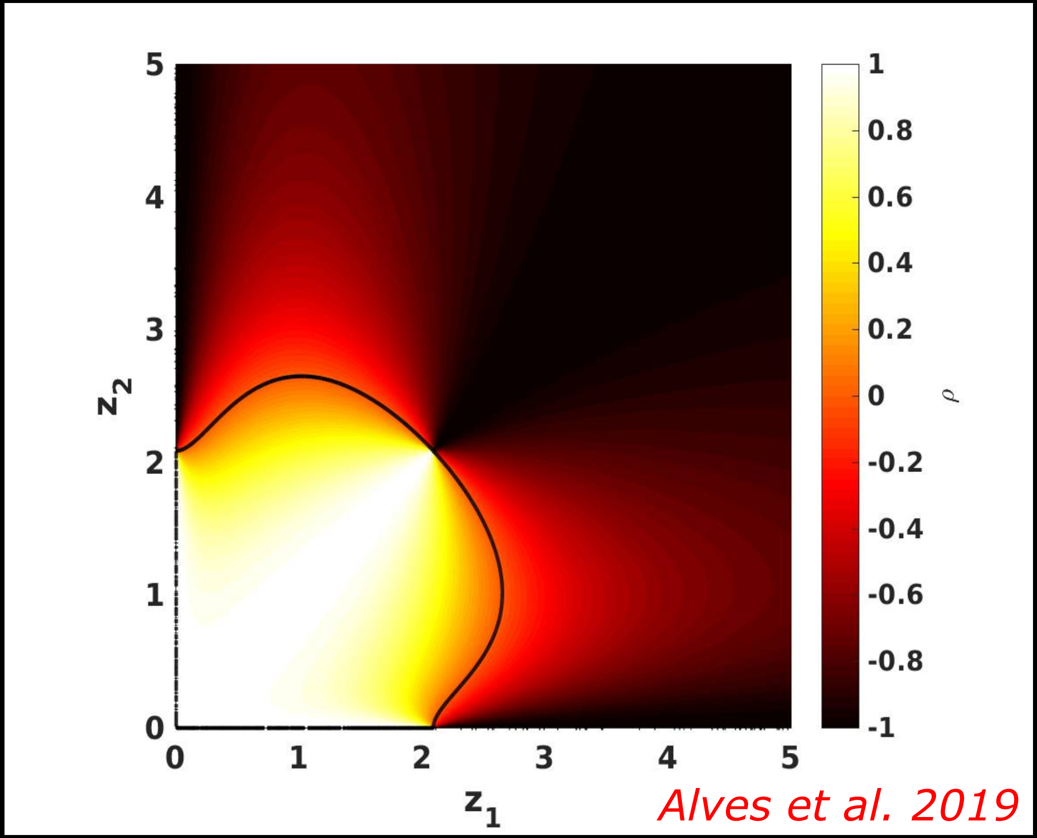
Melo e Sousa et al. 2023
(based on Alves et al. 2019)

Redshift Drift - $\Omega_k : 0$

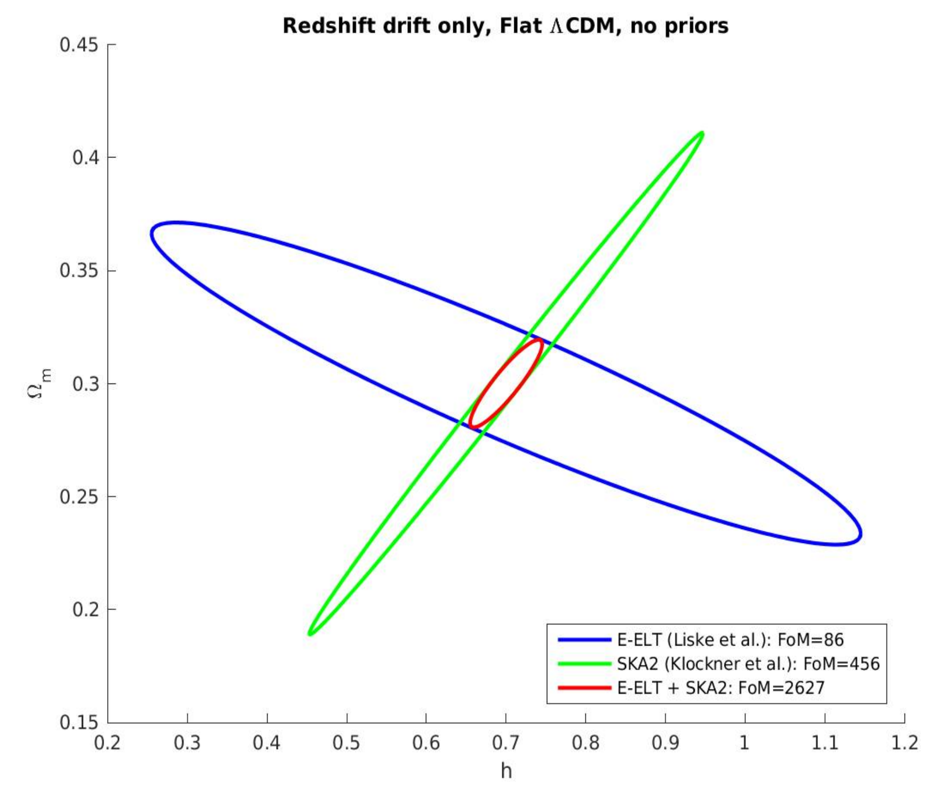
Spectroscopic Velocity - $\Omega_k : 0$

The Importance of a Redshift Lever Arm

(A flat LCDM example)



Alves et al. 2019



Canonical vs Differential Redshift Drift

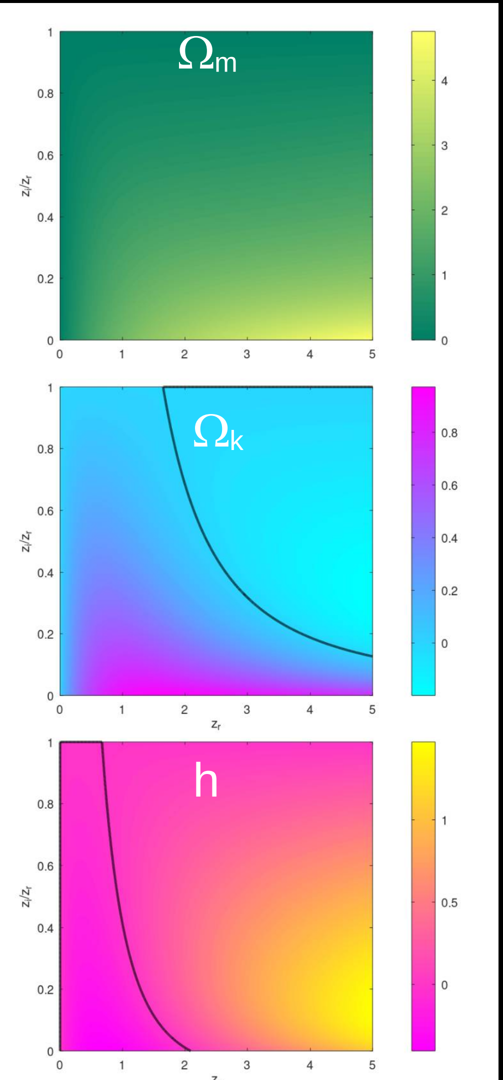
ELT differential redshift drift: measure drift between reference and intervening redshifts (rather than relative to z=0) *[Cooke 2020]*

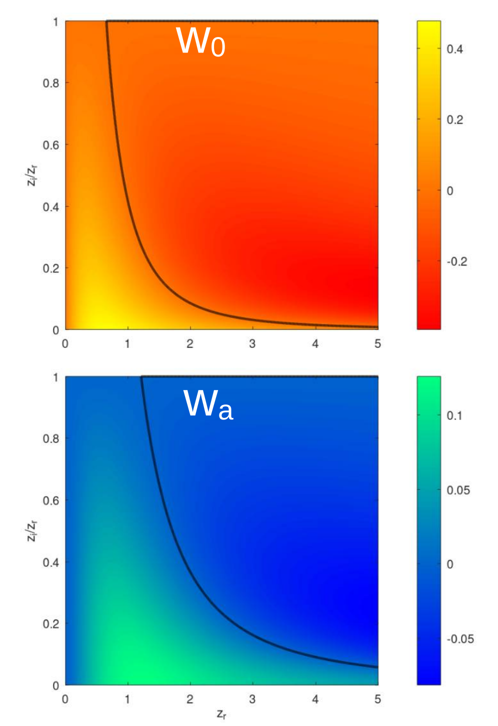
- For suitable redshift pairs, Δv can be larger (thus easier to detect)
- Measured quantity becomes $\Delta v_{ir} = (cH_0\Delta t)\left[\frac{E(z_r)}{1+z_r} - \frac{E(z_i)}{1+z_i}\right]$

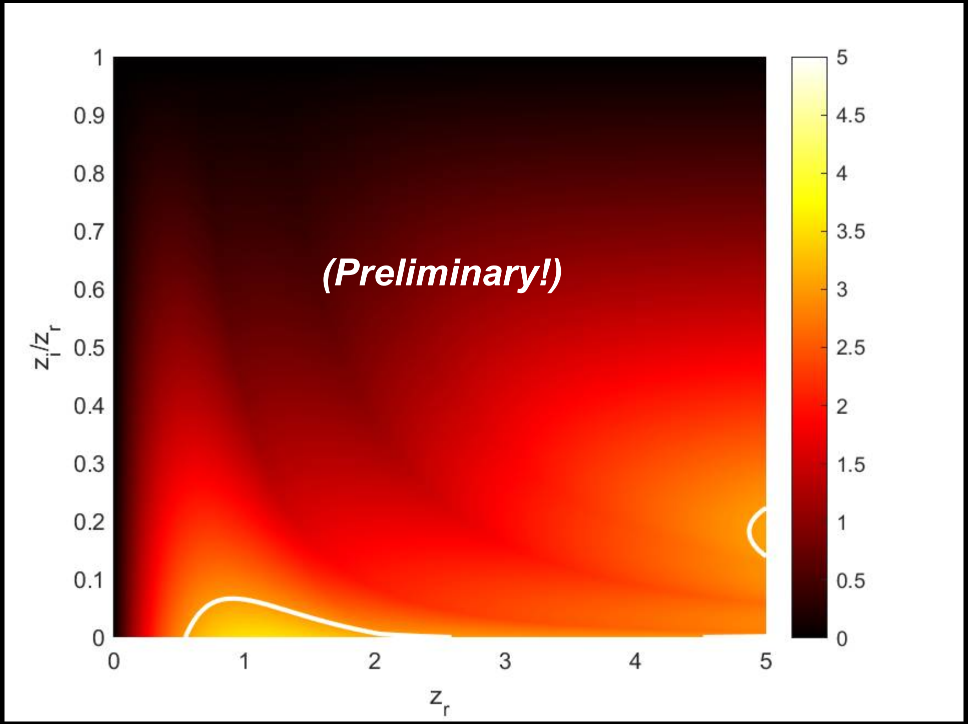
Amplifying the spectroscopic velocity signal does not necessarily improve constraints on specific parameters *[Esteves et al. 2021]*

- Nevertheless, if one’s goal is to improve cosmological constraints, suitable choices of redshifts can dramatically improve them
- Caveat: effectively treating reference and intervening redshifts as free parameters (in practice, we can only observe those we know...)

Cosmological Parameter Sensitivity (CPL)







For Ω_m, the canonical redshift drift is always the optimal strategy

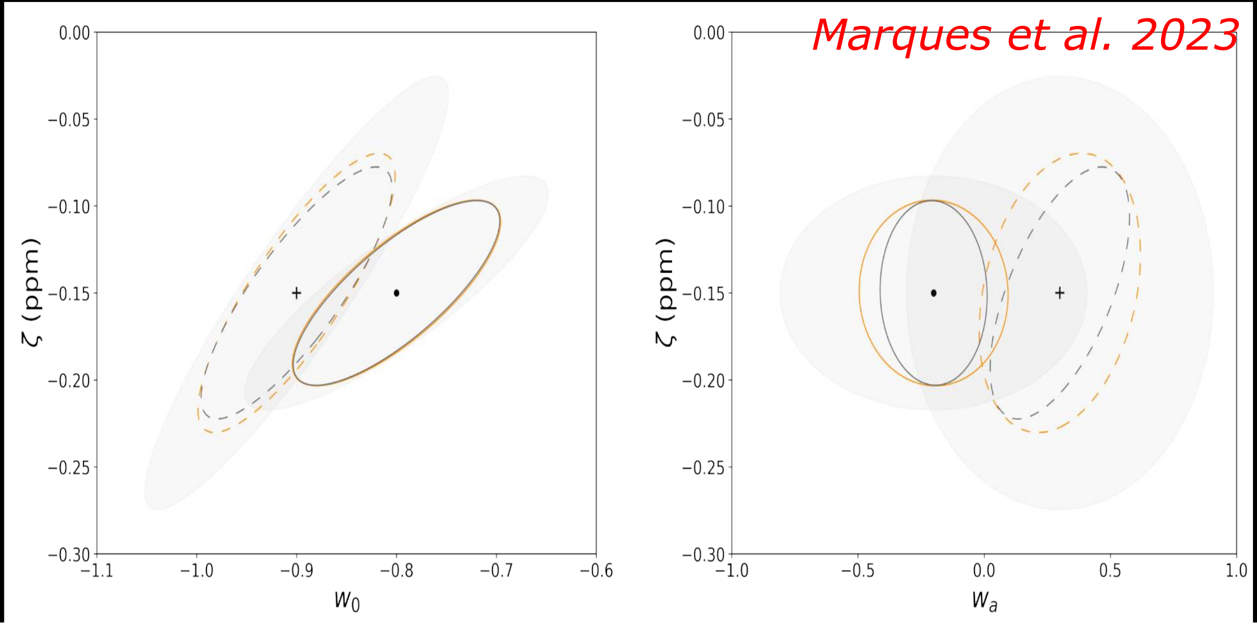
H_0: redshift arm is key; Dark energy and Ω_k: span the acceleration epoch

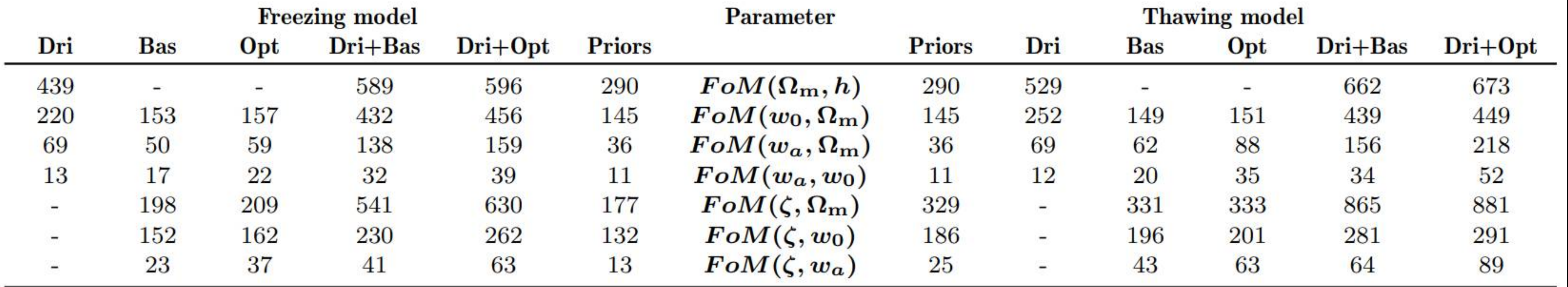
NB: Results can be model-dependent (and do not include instrument effects)

Synergies I: ANDES

Combining redshift drift and α data enables jointly constraining cosmological and fundamental physics model parameters

Fisher Matrix forecast code at
https://github.com/CatarinaMMarques/FisherCosmology


Marques et al. 2023



Freezing model						Parameter	Thawing model					
Dri	Bas	Opt	Dri+Bas	Dri+Opt	Priors		Priors	Dri	Bas	Opt	Dri+Bas	Dri+Opt
439	-	-	589	596	290	$FoM(\Omega_m, h)$	290	529	-	-	662	673
220	153	157	432	456	145	$FoM(w_0, \Omega_m)$	145	252	149	151	439	449
69	50	59	138	159	36	$FoM(w_a, \Omega_m)$	36	69	62	88	156	218
13	17	22	32	39	11	$FoM(w_a, w_0)$	11	12	20	35	34	52
-	198	209	541	630	177	$FoM(\zeta, \Omega_m)$	329	-	331	333	865	881
-	152	162	230	262	132	$FoM(\zeta, w_0)$	186	-	196	201	281	291
-	23	37	41	63	13	$FoM(\zeta, w_a)$	25	-	43	63	64	89

Real-time Cosmography

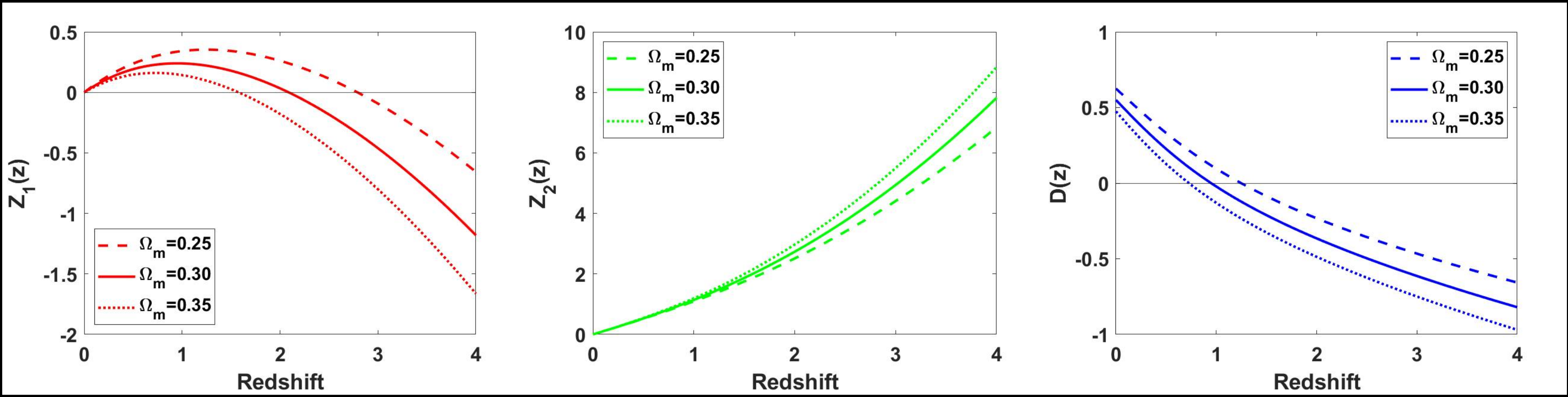
First and second redshift derivatives are powerful test of the ΛCDM paradigm; cosmographic approach useful here *[Martins et al. 2016]*

- The drift of the drift can be obtained numerically from a set of measurements of the drift at different redshifts, e.g. by the SKAO

$$Z_1(z) = \frac{1}{H_0}\frac{dz}{dt_0} = 1 + z - E(z)$$

$$Z_2(z) = \frac{1}{H_0^2}\frac{d^2z}{dt_0^2} = \frac{1+q(z)}{1+z}E^2(z) - E(z) - q_0(1+z)$$

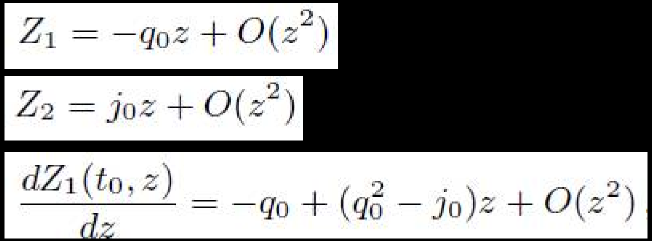
$$\frac{dZ_1(z)}{dz} = 1 - E(z)'$$



Real-time Cosmography with the SKAO

Low-redshift measurements provide direct constraints on the cosmographic coefficients *[Martins et al. 2016]*

- To linear order,



$$Z_1 = -q_0 z + O(z^2)$$

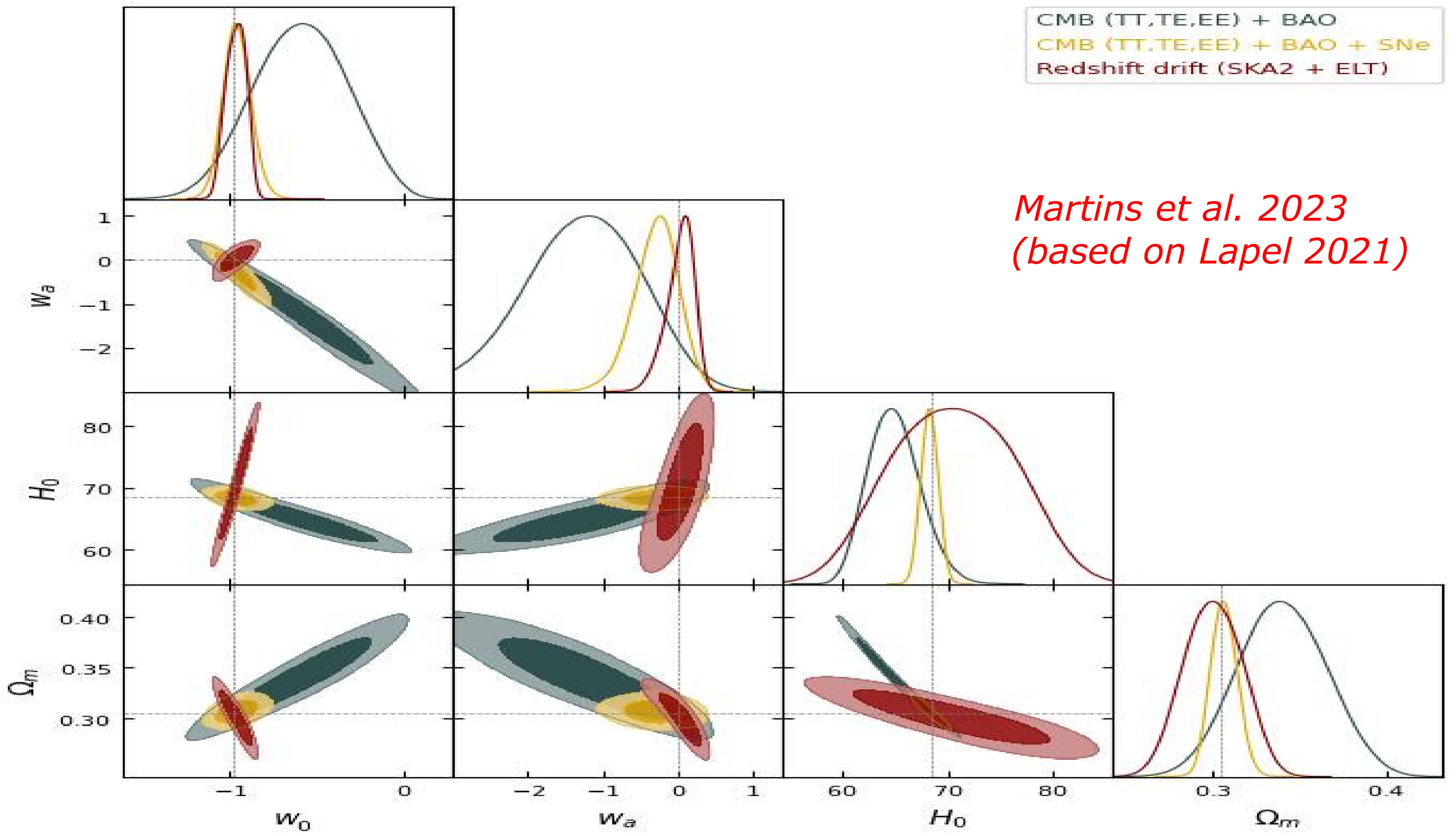
$$Z_2 = j_0 z + O(z^2)$$

$$\frac{dZ_1(t_0,z)}{dz} = -q_0 + (q_0^2 - j_0)z + O(z^2)$$

Asumming specs discussed in *[Klockner et al. 2015]*, SKAO redshift drift measurements can reach σ_{q0}~0.006 and σ_{j0}~0.13

- Optimal way to measure q_0 with both accuracy and precision, which is not possible with traditional distance indicators *[Neben & Turner 2013]*
- A key consistency test: j(z)=1 at all redshifts for a flat ΛCDM universe
- More broadly, a positive drift implies SEC violation, hence dark energy

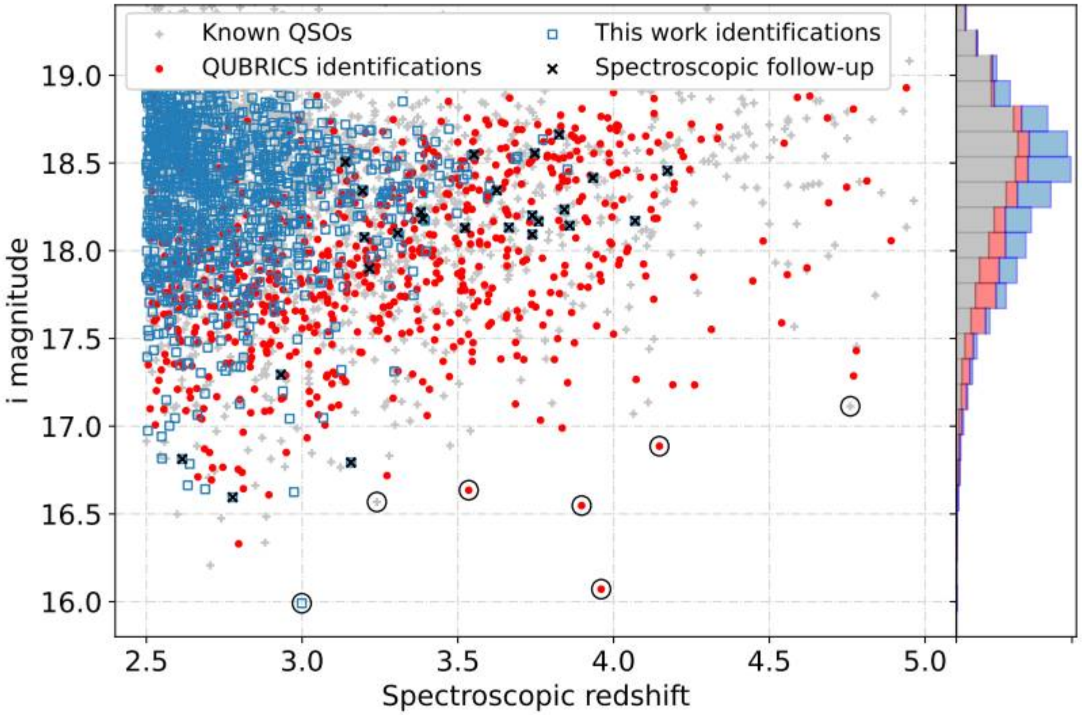
Synergies II: ELT + SKAO

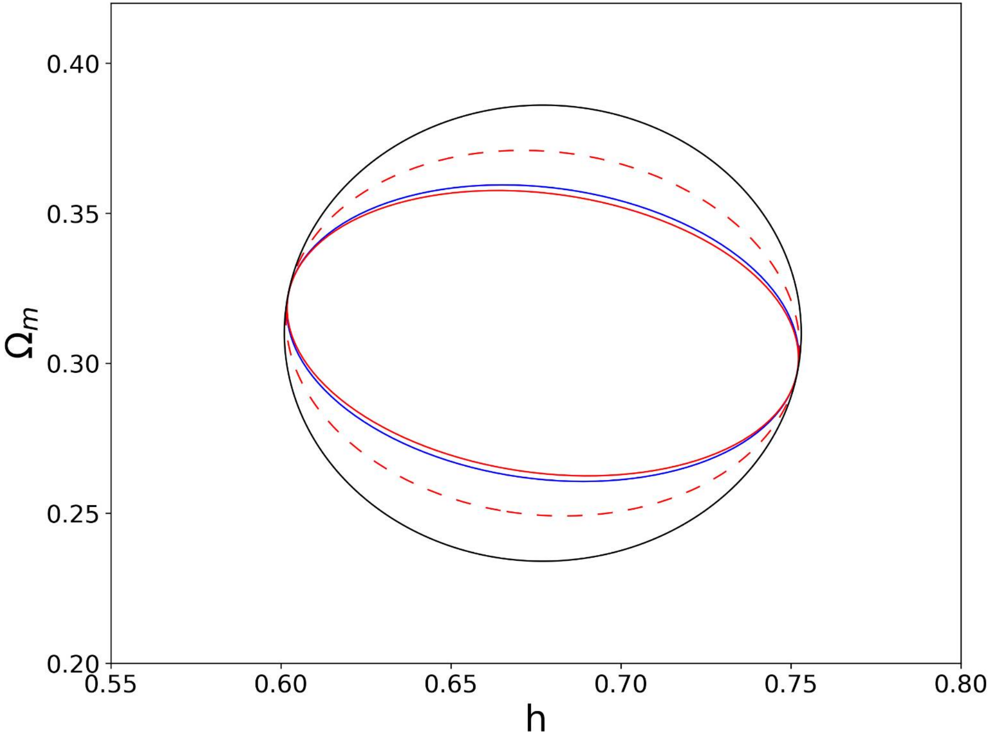


Martins et al. 2023
(based on Lapel 2021)

An ANDES Golden Sample

Recently discovered bright high-z QUBRICS QSOs significantly reduce observation time for the same return *[Cristiani et al. 2023]*





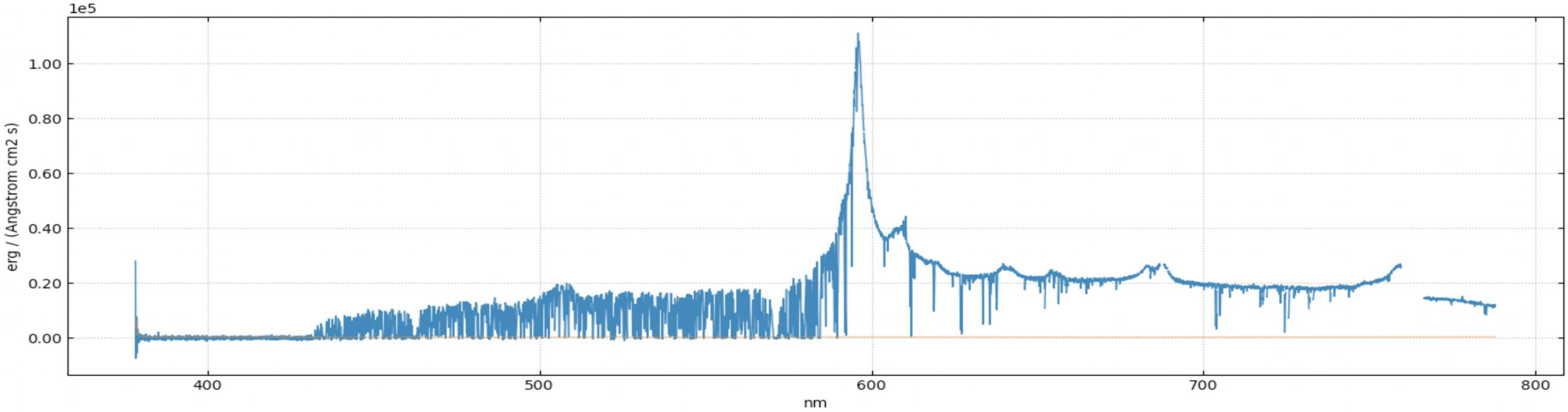
The ESPRESSO Redshift Drift Experiment

Current limits 1000x larger than expected signal, and systematics-dominated

- *[Darling 2012]* in the radio at $z<0.7$, *[Cooke 2020]* in the optical at $z>2$

ESPRESSO can improve this by a factor ~10 with an experiment time of 1 year and an observation time of 40h for 2 QUBRICS 'superbright' QSOs

- Test and optimise methodology with real data, test instrument stability
- Two independent experiments, also 'zeroth epoch' for ANDES (calibration permitting)



Stay tuned for the ANDES Science White Papers
(you will see them on the arXiv in a few weeks...)

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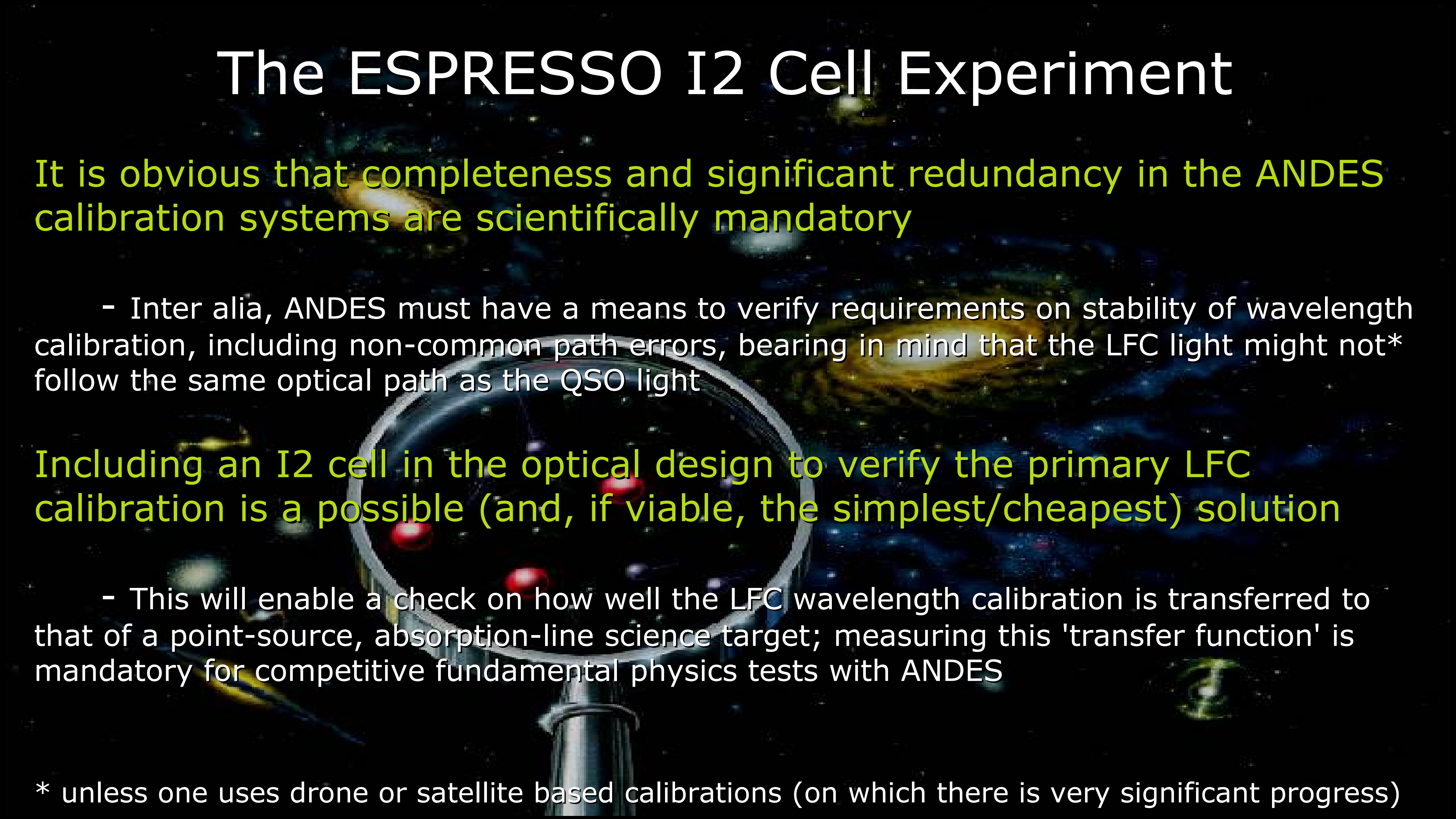
The ESPRESSO I2 Cell Experiment



It is obvious that completeness and significant redundancy in the ANDES calibration systems are scientifically mandatory

- Inter alia, ANDES must have a means to verify requirements on stability of wavelength calibration, including non-common path errors, bearing in mind that the LFC light might not* follow the same optical path as the QSO light

Including an I2 cell in the optical design to verify the primary LFC calibration is a possible (and, if viable, the simplest/cheapest) solution

- This will enable a check on how well the LFC wavelength calibration is transferred to that of a point-source, absorption-line science target; measuring this 'transfer function' is mandatory for competitive fundamental physics tests with ANDES

* unless one uses drone or satellite based calibrations (on which there is very significant progress)

An ELT Fundamental Physics Roadmap

The ELT can be a leading gravity/fundamental cosmology probe

- Direct model-independent probe of the universe dynamics
- Weak Equivalence Principle tests (mostly from α data)
- Composition-dependent force tests (mostly from μ data)
- Testing temperature redshift relation, distance duality, and BBN
- Strong-field tests, including 'No-hair Theorem' (MICADO, ...)
- Mapping dark side from $z=0$ to $z=4$ (ANDES, HARMONI, ...)
- Constraining dark sector couplings, and environmental dependencies
- Weak acceleration 'MOND-like' regime in Milky Way outskirts?

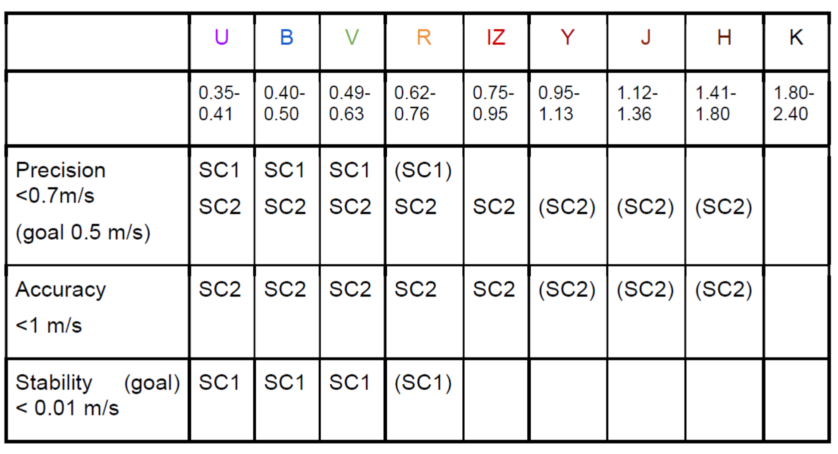
Most of these are ANDES science cases (and some are ELT flagship cases), but other ELT instruments can play a meaningful role too

Can We Be Competitive?

The core science cases are photon-starved but systematics-limited

For ANDES to be a competitive 2030s fundamental cosmology facility, it must significantly and cumulatively improve on the ESPRESSO

- Precision
- Accuracy
- Stability
- UV coverage



	U	B	V	R	IZ	Y	J	H	K
	0.35-0.41	0.40-0.50	0.49-0.63	0.62-0.76	0.75-0.95	0.95-1.13	1.12-1.36	1.41-1.80	1.80-2.40
Precision <0.7m/s (goal 0.5 m/s)	SC1 SC2	SC1 SC2	SC1 SC2	(SC1) SC2	SC2	(SC2)	(SC2)	(SC2)	
Accuracy <1 m/s	SC2	SC2	SC2	SC2	SC2	(SC2)	(SC2)	(SC2)	
Stability (goal) < 0.01 m/s	SC1	SC1	SC1	(SC1)					

Addittionally, one needs

- 50-250 nights of telescope time (over the telescope’s lifetime)
- Further 'optimal' targets (especially for μ)
- Better lab wavelengths of key transitions (mainly below 1600 A)

So What's Your Point Again?

The acceleration of the universe shows that canonical theories of cosmology & particle physics are incomplete, if not incorrect

- Precision astrophysical spectroscopy provides a direct and competitive probe of the (still unknown) new physics that must be out there

Nothing varies at ~ fewx10^{-6} level, a very tight bound (e.g. stronger than Cassini bound, and far stronger than w bounds)

- ESPRESSO is here, new and more robust measurements coming soon
- With MICROSCOPE and atomic clocks, stringent new tests possible

The ELT (mainly ANDES) can be the flagship tool for the 2030s generation of precision consistency tests of fundamental physics

- Competitive 'guaranteed science' implications for dark energy
- Unique synergies with other facilities (including Euclid & SKAO)

Let's do it!