Cosmology with the VLT in 2030

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The Very Large Telescope in 2030

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Introduction

The Brief

- What are the prospects for advances in cosmology and fundamental physics from astrophysical observations over the next decade?
- What contributions can the VLT make to cosmology at the start of the ELT era, *circa* 2030? How can the VLT assist the ELTs in the field of cosmology?

Terminology

- *'Cosmology'* is here shorthand for 'fundamental and cosmological physics' – i.e. the underlying model for, and physical parameters of, the universe
  - …so, Dark Matter and Dark Energy – *yes*; but Dark Ages – *no*
- *'2030'* is here shorthand for 'the start of the era of extremely large telescopes'
  - …so, the period when ELT, TMT and GMT are beginning serious science operations

Cosmology with the VLT – the story so far

VLT cosmology 1999

- What were the plans for cosmology with the VLT before it saw first light?
- **From Extrasolar Planets to Cosmology: The VLT Opening Symposium** (1999)
  - *Supernovae at high redshifts* – Leibundgut
  - *A Sunyaev-Zel'dovich Effect Survey for High Redshift Clusters* – Mohr
  - *Probing the Large-Scale Structure with the REFLEX Cluster Survey* – Böhringer
- Not comprehensive, of course, but still a rather modest set of goals in this field

VLT cosmology 2009

- After its first decade, what cosmology had the VLT done, and what were future plans?
- **Science with the VLT in the ELT era** (2009)
  - The *VLT Science Highlights* (retrospective) section has <u>no</u> papers on cosmology!
  - The *Future VLT science priorities* (prospective) section has…
    - *Baryonic Acoustic Oscillations* – Gavin Dalton
    - *Next Generation Deep Redshift Surveys with the VLT* – Olivier Lefèvre
    - *Probing Dark Energy with Cosmological Redshift Surveys at the VLT* – Luigi Guzzo

VLT cosmology 2009

- **Science with the VLT in the ELT era** (2009)
  - The *VLT Synergy with ELTs* section has…
    - *From ESPRESSO to CODEX* – Joe Liske et al.
    - *Observational Cosmology with the ELT and JWST* – Massimo Stiavelli
    - *GRB Afterglows in the ELT Era* – Kann & Klose
    - *The E-ELT: A Chance to Measure Cosmic Magnetic Fields* – Strassmeier & Ilyin
  - Again, a rather modest impact on cosmology (and here ‘cosmology’ is more broadly inclusive)

VLT cosmology 2009

- **Science with the VLT in the ELT era** (2009)
  - The *2nd Generation VLT and VLTI Instruments* section has…
    - *GRAVITY: Microarcsecond Astrometry and Deep Interferometric Imaging with VLT* – Eisenhauer++
    - *New Science Opportunities Offered by MUSE* – Bacon++
  - The *New Instrument Concepts and Operating Modes* section has…
    - *Wide Field Options on the VLT* – Todd
    - *Science with a 16m VLT: The Case for the Variability of Fundamental Constants* – Molaro
    - *Very Large Spectroscopic Surveys with the VLT* - Parry

Limitations on impact

- So, why has the VLT had relatively little impact on cosmology so far?
  - Most cosmology needs large surveys using wide fields and/or large time allocations
  - The VLT lacks a genuine wide field mode and high-multiplex spectrographs to exploit it
  - The VLT has not allocated large amounts of time to programs focussed on cosmology
- These limitations have been common to most 8m-class telescopes (except Subaru)

Limitations on impact

- These issues were clear in 2009: see Olivier Lefèvre's talk, **Next Generation Deep Redshift Surveys with the VLT…**
  - "There are two limiting factors for new surveys on the VLT."
  - Lack of wide-field spectrographs…
    - "One is the lack of a near-IR multi-object spectrograph with a large field and large multiplex… a simple and efficient instrument concept optimized for Y and J bands remains a front runner"
    - "…it is clearly time to develop … instrument concepts for very wide field ($\sim$1 deg^2), capable to obtain $\sim 10^4$ redshifts"
  - Support for really large surveys…
    - "A fundamental support to large surveys is the strong commitment … to carry out a few large programs over many years."
    - "In its current way of dealing with large programs, ESO is *de facto* preventing very large >100 nights, multi-year programs to get accepted or to get completed. The example of VIMOS is enlightening: it has not been possible to date to complete the highest ranked science program which was the main motivation to build VIMOS."
    - "For the VLT and ESO to remain competitive on large survey science will therefore require a change of paradigm to enable the large allocation of observing time required by deep redshift surveys."

Limitations on impact

- These issues were also addressed by Luigi Guzzo's talk, **Probing Dark Energy with Cosmological Redshift Surveys at the VLT…**
  - "The question is thus whether the ESO community will be willing, in the ELT era, to invest in having one 8-m 'redshift machine' out of the four VLT units. The lesson to be learned from the unique results obtained by the previous-generation 4-m AAT telescope when it was dedicated to surveys with the 2dF facility, is that such a decision would certainly turn out to be a breakthrough investment for cosmology in the next decade."
- *This is still a key question in deciding ESO's strategy for the VLT in the ELT era, although the landscape in which it must be answered has changed significantly*

The 2009 vision for the 2020s

- **A Twenty Year Science Vision for European Astronomy – Guy Monnet & Tim de Zeeuw**

  ‘Cosmology’-related topics [current facilities, *future facilities*]

  - Evolution of dark energy with cosmological epoch
    [Planck, *SKA, X-ray Survey, Wide-Field Space Telescope*]
  - Consistent picture of dark matter and dark energy
    [Planck, Dark Matter Detectors, *SKA, X-ray Survey, Wide-Field Space Telescope, ELT, CTA*]
  - Search for relic gravitational waves from CMB polarisation
    [*CMB Polarisation Satellite*]
  - Direct detection of gravitational waves in strong gravity regions
    [Ground Gravitational Detectors, *LISA*]
  - Direct studies near supermassive black-hole horizons
    [SWIFT, XMM, INTEGRAL, 8–10 m Telescopes, VLTI, HESS, *X-ray Observatory, Sub-mm VLBI*]
  - Understanding the astrophysics of compact objects
    [SWIFT, XMM, INTEGRAL, *X-ray Survey, ELT, X-ray Observatory*]
  - Understanding the origin of high-energy neutrinos & cosmic rays
    [HESS, AUGER, *CTA*]

Cosmology in the 2020s

Key questions in the 2020s

- As the 2020s start, the key questions in cosmology (for astrophysicists) are…
  - What is dark matter? (Is it particle physics or modified gravity?)
  - What is dark energy? (Is it the cosmological constant or something else?)
  - Is the apparent discrepancy between CMB and distance-ladder measurements of H_0 real? If so, is it cosmologically significant?
  - Probing other aspects of fundamental physics with astrophysical observations…

Key questions in the 2020s

- Possible astrophysical observations of fundamental physics include…
  - NS/WD (degenerate matter) equations of state
  - Gravitational wave sirens as distance estimators
  - Direct measures of the expansion rate (*dz/dt*)
  - Variation of fundamental constants (limits on)
  - Annihilating/interacting dark matter
  - Non-GR behaviour in the strong-field regime
  - ...and probably others!
- Green examples are certainly physical; orange examples are likely unphysical but worth exploring; *all are observationally challenging!*

High-impact facilities in the 2020s

- Types of facilities most likely to have impact on cosmology in the next decade include:
  - Large wide-field surveys (imaging for weak lensing & photometric redshifts; spectroscopy for precise redshifts & peculiar velocities)
    - E.g. TAIPAN, DESI, 4MOST, EUCLID, WFIRST, etc.
  - Dedicated time-domain facilities (transient detection through rapid large-area imaging; fast follow-up of transients with spectroscopy)
    - E.g. LSST, DREAMS, many 2m/4m telescopes, and some 8m telescopes
  - For ‘cosmology’ as defined here, JWST is unlikely to be a dominant facility (or available in 2030?)

Key cosmology facilities in the 2020s

- LSST – 8m survey telescope, starting 2020
  - Repeated optical imaging of the whole (southern) sky
  - 18,000 deg^2 in 6 filters, ~825 visits per field
  - Magnitude limits expected to be $r < 24.5$ in single images and $r < 27.8$ in the full stacked data
  - Cosmology (LSS+DM+DE) studied using weak lensing, supernovae and baryon acoustic oscillations
- DESI – 4m survey telescope, starting 2020
  - *Existing* 4m telescope with *new* wide-field (8 deg^2), high-multiplex (5000 fibres), medium-resolution (R>4000), 0.36–0.98μm spectrograph
  - Cosmology (LSS+DM+DE) from power spectrum, baryon acoustic oscillations, growth of structure

Key cosmology facilities in the 2020s

- VISTA + 4MOST – starting 2022
  - *Existing* 4.1m telescope with *new* wide-field (4 deg^2), high-multiplex (1624 fibres), medium-resolution (R>4000), 0.37–0.95μm spectrograph
- Subaru + PFS – starting 2022
  - *Existing* 8.2m telescope with wide-field (1.3 deg^2) O/IR imager and *new* high-multiplex (2400 fibres), medium-resolution (R>2400), 0.38–1.26μm spectrograph
- MaunaKea Spectroscopic Explorer (MSE)
  - *Proposed* 11.3m telescope with wide-field (1.5 deg^2), high-multiplex (4332 fibres), medium-resolution (R>2500), 0.36–1.3μm spectrograph

Redshift survey comparison

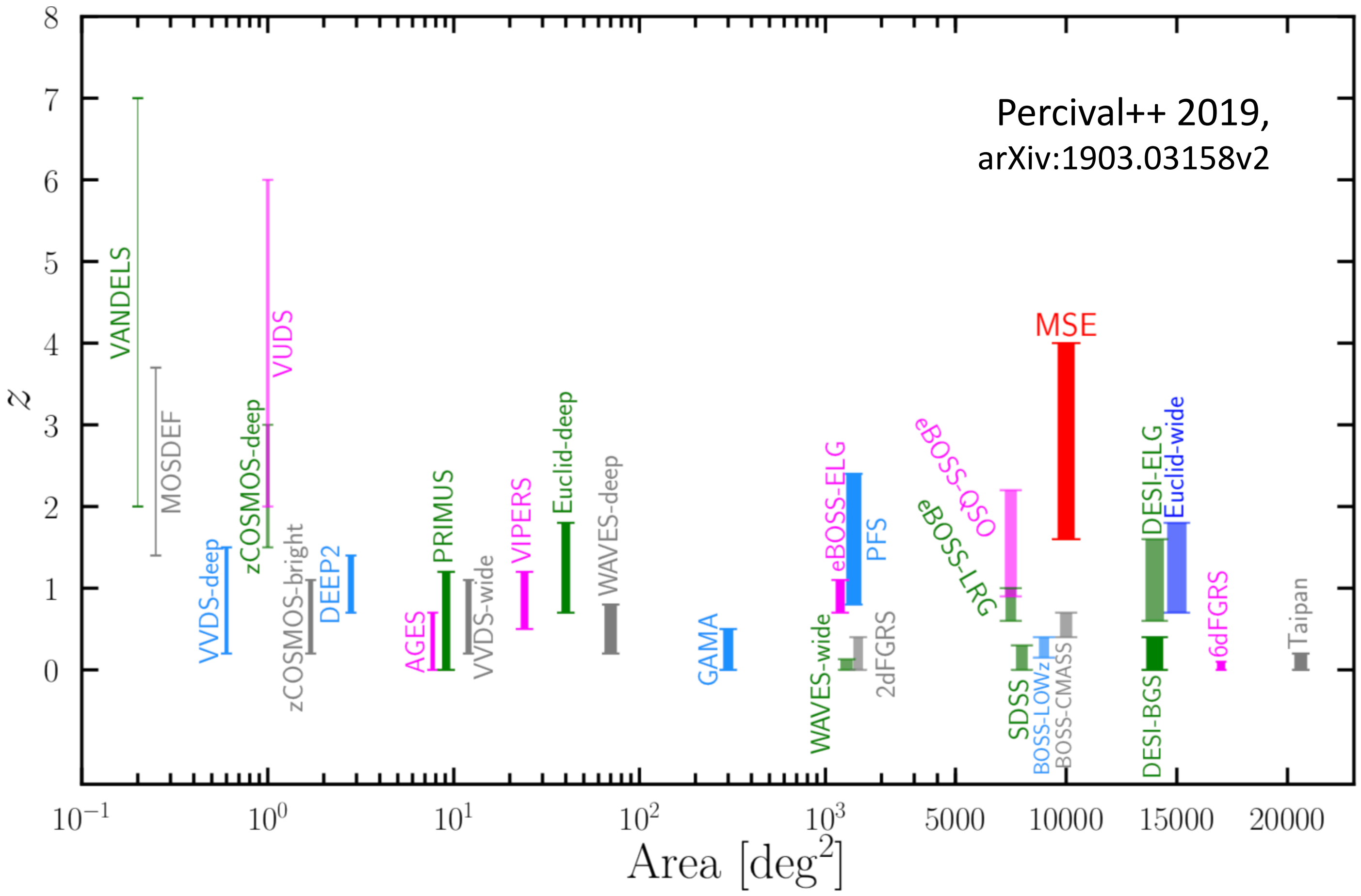

Figure 1. *Recent galaxy redshift surveys as a function of their area and redshift range, compared with the proposed MSE survey. The thickness of each bar is proportional to the total number of galaxies. Notice the transition from logarithmic to linear scale on x-axis at* 5000 deg^2.

Key cosmology facilities in the 2020s

- EUCLID – ESA 1.2m telescope; 2022 launch
  - Optical/IR imaging and low-resolution spectroscopy
  - Reach a dark energy *FoM* > 400 using only weak lensing (WL) and galaxy clustering (BAO) ⇒ w_p and w_a to 0.02 and 0.1 (1σ)
  - Measure γ, the growth factor exponent, to <0.02 (1σ), sufficient to distinguish GR from a variety of modified-gravity theories
  - Test the CDM paradigm for hierarchical structure formation; measure sum of neutrino masses to better than 0.03eV (1σ)
  - Constrain n_s, spectral index of the primordial power spectrum, to 1% precision (with Planck); probe inflation by measuring the non-Gaussianity of initial conditions (f_{NL}) to a 1σ precision of ~2
- WFIRST – NASA 2.4m telescope; mid-2020s
  - NIR imaging and (possibly) spectrocopy
  - Cosmology from WL, BAO and SNe using NIR imaging, photo-z's and (possibly) spectroscopic z's
  - Similar science goals to EUCLID

Combined power for cosmology

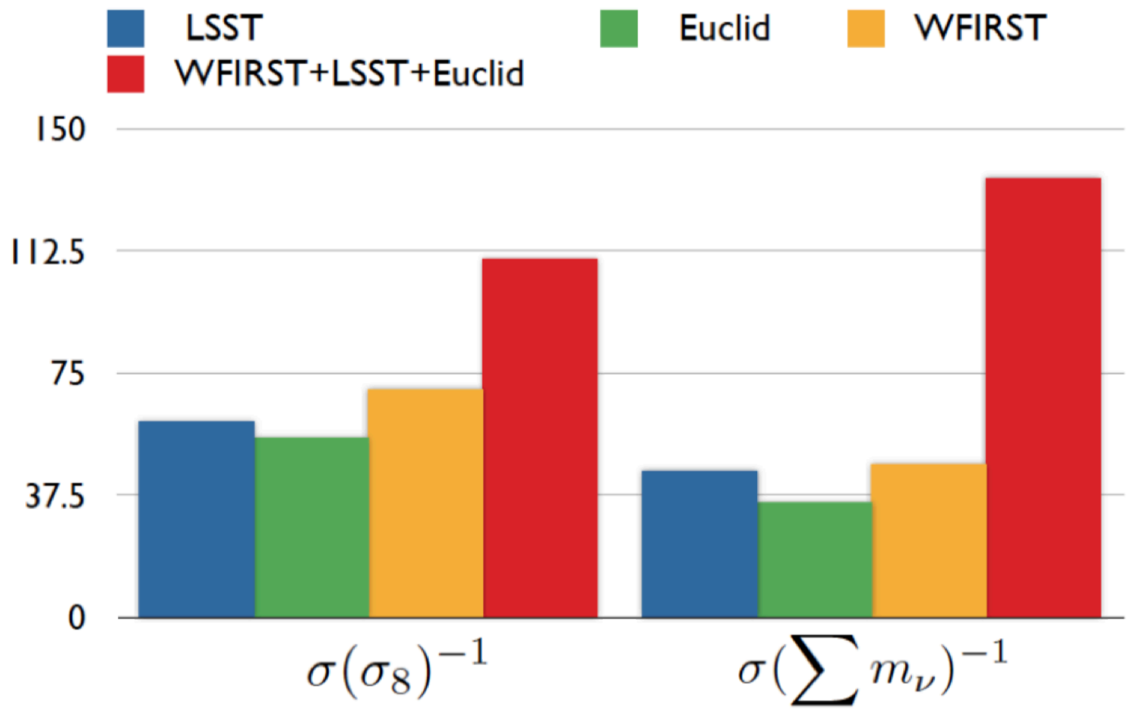

Figure 1: The chart shows how the complementarity of LSST, Euclid and WFIRST contributes to significant improvement in constraints on cosmological parameters. As described in the text, the improved constraints on σ_8 come from the mitigation of intrinsic alignment and other systematics in weak lensing; the improved constraints on the sum of neutrino masses $\sum m_\nu$ (in eV) comes from the combination of the weak lensing, CMB convergence maps, and galaxy clustering, in particular by reducing the multiplicative bias i[...] Time Machine [...]ent. Note that the space based surveys are assumed to have used ground based photometry to obtain photo-z's.

The status of cosmology in 2030

- 'Cosmology in 2030' is largely speculation…
  - …but some things we *might* have concluded and some things we *won't* have concluded
- We *likely will* have…
  - Resolved the H_0 controversy (my guess: a mild correction to the BAO scale and recalibration of the distance ladder; no conflict with ΛCDM)
  - Either detected small ($\sim$1%) deviations from a cosmological constant or constrained the allowed deviations to <1% over $0<z<1100$
  - Determined the NS/WD equations of state
  - Used GW sirens as distance estimators

The status of cosmology by 2030

- We *likely won't* have...
  - Observed variation of fundamental constants
  - Directly measured the expansion rate (*dz/dt*)
  - Observed non-GR behaviour in the strong-field regime (or weak-field regime, for that matter)

- But recall Arthur C. Clarke's (other) maxim!
  - *If an elderly but distinguished scientist says something is possible, he is almost certainly right; but if he says it is impossible, he is very probably wrong.*

  [elderly? distinguished??]

Cosmology in 2030

Key questions in 2030

- If the key questions in 2030 are not just more refined versions of the key questions in 2020, then they are hard to predict
  - E.g., if a clear deviation from LCDM ($w \neq -1$) or from GR ($\gamma \neq 0.55$) is detected, the nature of the deviation (and any interpretive theory) must guide future investigations
  - However, it is *likely* that such investigations will involve even more precise measurements of the same quantities (or more sophisticated variants) over the full accessible redshift range

Key questions in 2030

- On the other hand, if something *surprising* is detected, then having a wide range of capabilities may be desirable
  - Variation of fundamental constants might require UVES/HIRES-like capability to pursue
  - Non-GR behaviour in the strong-field regime might require GRAVITY-like capability
- So while big dedicated instruments/surveys are certainly going to be *important*, having broad and versatile capabilities might be *crucial* if the universe surprises us again

ELTs and cosmology

- ELTs do not have cosmology & fundamental physics as their strongest scientific drivers
  - The reasons that apply to 8m-class telescopes apply *a fortiori* to ELTs!
- Worse (from the *VLT in 2030* perspective) is that most cosmological applications using the VLT can be done better with an ELT
  - A counter-example is VLTI (e.g. GRAVITY for observations of strong-field non-GR behaviour)
  - Another potential advantage for the VLT is that it *could* offer larger time allocations than ELTs

ELTs and cosmology

- Worth remembering that it won't be just ELT by 2030, but very likely also GMT and TMT

Telescope + Instrument	Aperture (m^2)	Field ($arcmin^2$)	Relative AΩ
GMT+GMACS	368	50.0	0.16
TMT+WFOS	655	40.5	0.23
ELT+MOSAIC	978	40.0	0.34
GMT+MANIFEST	368	314.2	1.00

- MOSAIC will likely arrive considerably later
- GMT with the MANIFEST fibre system has a field of view similar to VLT, an aperture 7x larger and 'wide-field' optical spectrographs at both medium (GMACS) and high resolution (G-CLEF)

The VLT's role in cosmology in 2030

Cosmology with old & planned VLT instruments

- <u>Conclusion #1</u>: Existing and proposed VLT instruments can variously contribute to cosmological studies, but are *unlikely* to have a major impact (LSS/DM/DE etc.)
- <u>Conclusion #2</u>: However, they *might* have a major impact on fundamental physics *if* something unexpected turns up…
  - Variation in fundamental constants
  - Non-GR behaviour in the strong-field regime

Cosmology with MUSE & BlueMUSE

- MUSE needs no introduction; BlueMUSE will be presented in Johan Richard's talk on Wednesday
  - Blue-optimised (0.35-0.6μm), medium-resolution (R>3000), integral field (1.4'x1.4' @ 0.3") spectrograph
  - For cosmology purposes, BlueMUSE expands the redshift range accessible with MUSE
- MUSE/BlueMUSE enables a range of cosmological studies including…
  - Strong lensing around rich clusters
  - Tomography of the IGM/ICM
- However, the primary science cases for BlueMUSE do not include cosmology in the sense used here

Cosmology with MAVIS

- MAVIS is the Multi-object Adaptive-optics Visible Imager Spectrograph (*aka* VAOI) for the VLT, currently in Phase A
  - See talk by Richard McDermid for science and design
- The MAVIS white papers include several cosmological science cases, mostly galaxy-scale tests of dark matter…
  - *Dark matter in the smallest dwarf galaxies* – Ken Freeman
  - *Resolved Angular Momentum with MAVIS* – Sarah Sweet et al.
  - *Investigating the nature of dark matter through galaxy dynamics at $z \sim 1-2$ with MAVIS* – Andrea Grazian & Nicola Menci
  - *Testing CDM with Gravitational Lensing* – Colin Jacobs
  - *Exploiting strong lensing clusters with MAVIS* – P. Rosati et al.
  - *Spectroscopy of distant Cepheids with MAVIS* – L. Inno et al.
- A 'wide' field for MAVIS is possible through BATMAN, a MOS capability using MOEMS technology (likely as a future upgrade)

Upgrades & instruments – wide-field?

- Possibilities for upgrades & new instruments for the VLT/I will be explored in other talks…
- One obvious idea is to upgrade one of the UTs to have a wide field and equip it with a MOS
  - See Mark Casali's talk for how this might be done
- Equally obvious questions for such proposals…
  - Is it competitive with the many existing or planned wide-field facilities? (esp. as it would start later)
  - What about the impact of converting a UT to wide-field on the unique VLTI capabilities?
  - If 8-metre wide-field science is deemed critical for ESO, might not buying into a facility like Subaru PFS or MSE offer better value-for-money?

Other options for a wide-field 8-metre

- ESO could consider buying a share in a wide-field 8m-class system someone else is building
  - Savings in cost (in proportion to share purchased)
  - Savings in staff effort (and no loss of focus on ELT)
- Examples of *possible* facilities to buy into…
  - Subaru + PFS – starting 2022
    - *Existing* 8.2m telescope with wide-field (1.3 deg^2) O/IR imager and new high-multiplex (2400 fibres), medium-resolution (R>2400), 0.38–1.26μm spectrograph – *but fully subscribed?*
  - MaunaKea Spectroscopic Explorer (MSE)
    - *Proposed* 11.3m telescope with wide-field (1.5 deg^2), high-multiplex (4332 fibres), medium-resolution (R>2500), 0.36–1.3μm spectrograph – *not yet funded; northern hemisphere*

Other upgrades & instruments?

- Are there non-wide-field instruments one might build for the VLT with a science case that is primarily cosmology?
  - *Not obviously* – but happy to be proved wrong!
- Do other existing or upgraded instruments have potential cosmological applications?
  - *Yes* – but will generally need large time allocations
  - Example #1: a bigger survey with UVES to observe QSO spectra to look for variations in fundamental constants; *this is* a *high-risk/high-return program*
  - Example #2: a higher-multiplex feed for UVES that accesses the VLT's full ~25 arcmin FoV for baryon tomography; *would this program be competitive?*

Summary

Cosmology with the VLT in 2030

- Cosmology won't be a primary science driver for the VLT (or VLT instruments) in 2030…
- …unless a UT is converted to wide-field MOS
  - But it's likely *sufficient*, *cheaper* and *better for ELT* if ESO buys into another wide-field MOS facility
- …or unless something unexpected is revealed by current cosmological exploration
  - This is a (soft) argument for a broad and versatile set of existing/upgraded/new VLT instruments
- In *either* case, ESO likely needs to be willing to allocate <u>large</u> amounts of VLT time in order to have a major impact on cosmology