ESO's Wide Field Spectroscopic Telescope

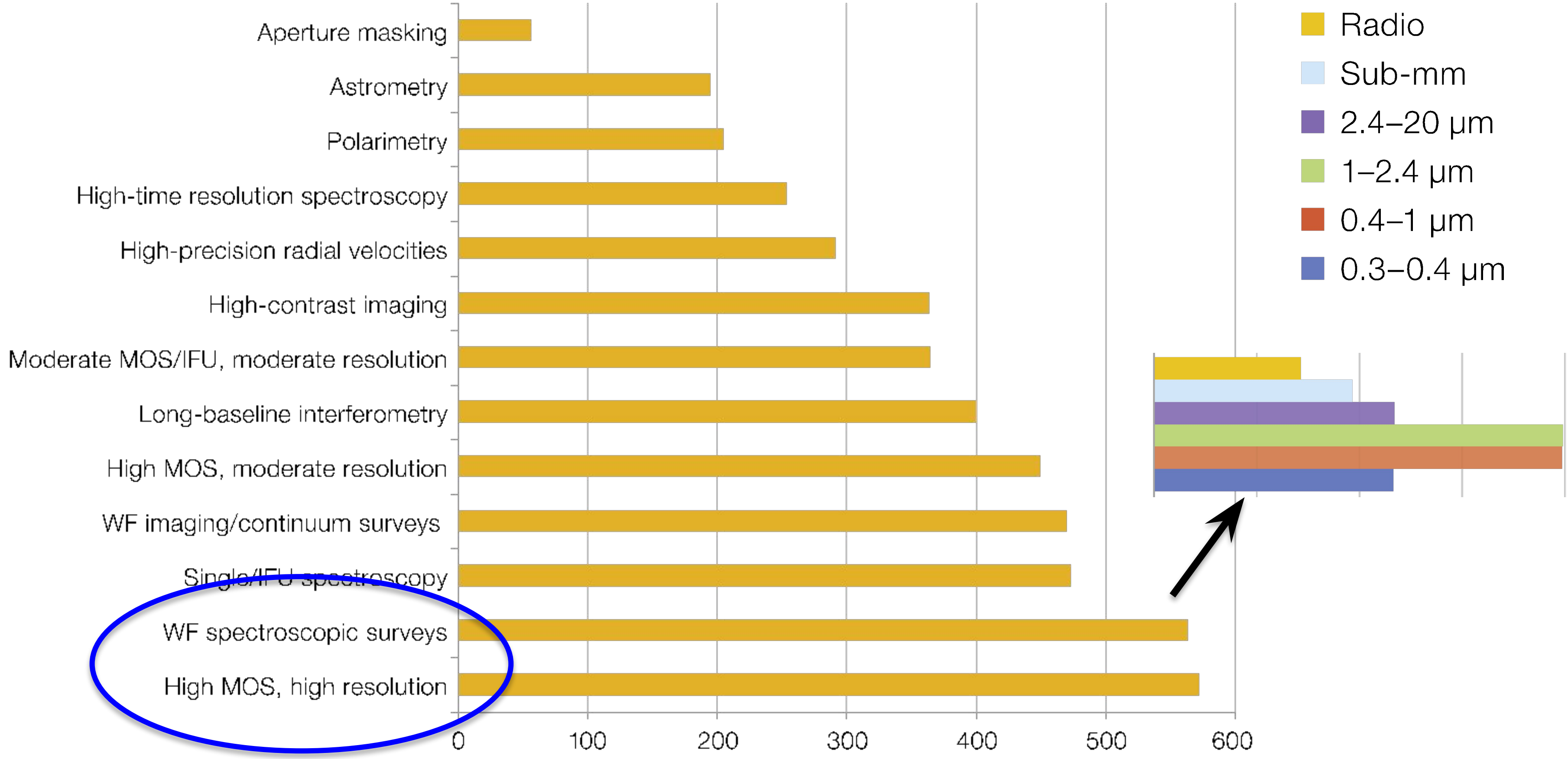
ESO Study of Need

- Richard Ellis (ESO, Coordinator)
- Malcolm Bremer (Bristol, UK)
- Eline Tolstoy (Groningen, NL)
- Hans-Walter Rix (Heidelberg, D)
- Jarle Brinchmann (Leiden, NL)
- Johan Richard (Lyon, F)
- Darach Watson (Copenhagen, DK)
- Luigi Guzzo (Milan, IT)
- Joss Bland-Hawthorn (Sydney, Australia)

ESO Science Priorities - I

Q: What is most important capability for your research in 2020-2030?

1775 overall responses out of 9350 polled (20%)

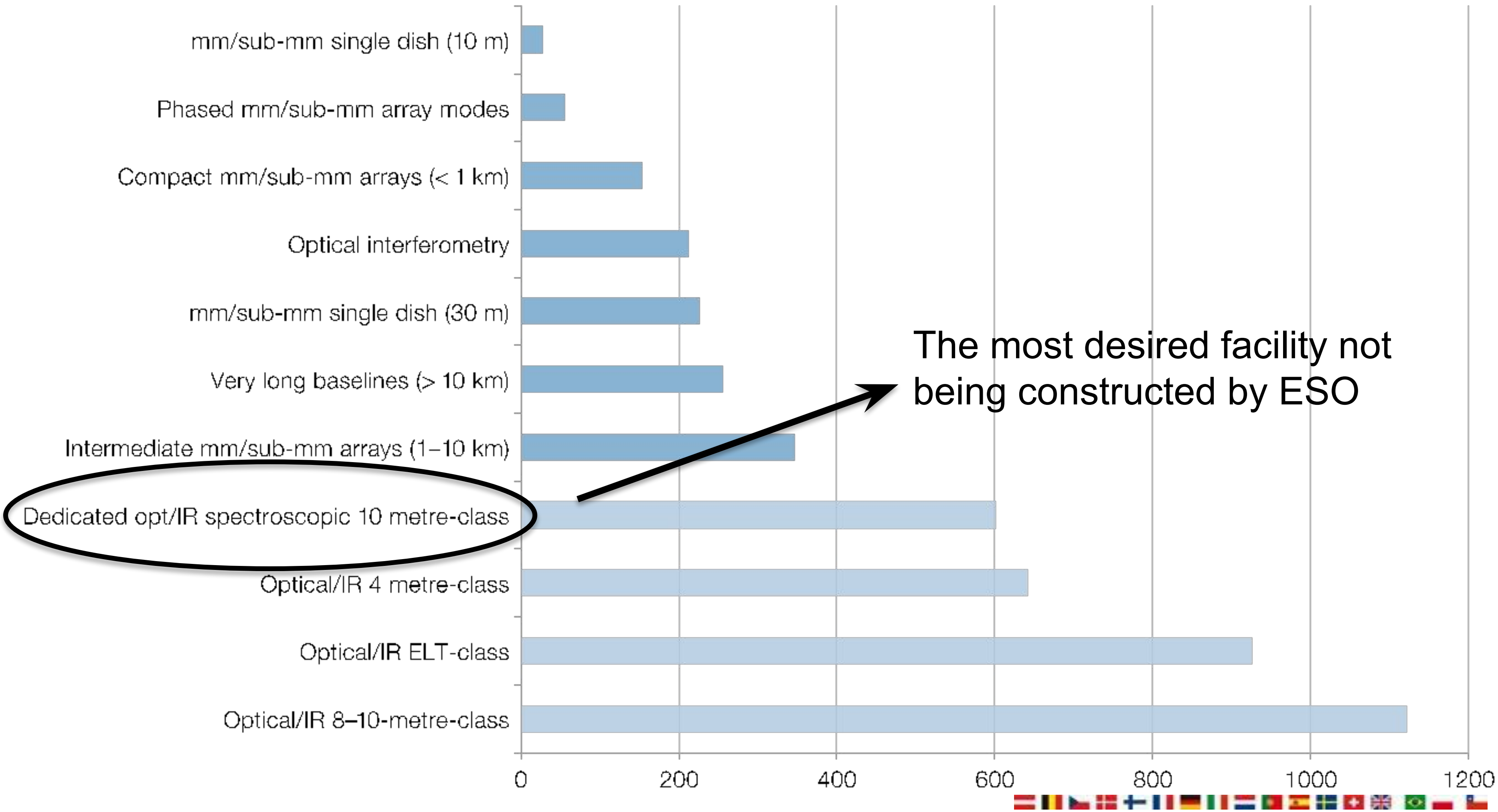


ESO Messenger #161 September 2015

ESO Science Priorities - II

Q: What facilities are most required for your research in 2020-2030?

4575 answers (avg. 3 per respondent)



Lessons from 2dF and SDSS

Originally designed for large scale structure surveys in the late 1990's, SDSS and AAT's 2dF continue to reinvent their basic infrastructure to do new spectroscopic science!

- AAT – WiggleZ, GAMA, HERMES-GALAH/Kepler K2, HECTOR
- SDSS: SEGUE-1/2, BOSS, MARVEL, APOGEE-1/2, EBOSS, MaNGA
- Now VISTA: Public imaging surveys: 4MOST spectroscopic surveys

A dedicated large aperture spectroscopic facility will be a sound investment provided it is designed with versatility in mind

Working Group Rationale

- What ambitious science questions will be driving the field in the 2020s that are beyond the capability of upcoming facilities (4MOST,WEAVE, PFS, DESI)?
- How do these relate to complementary facilities e.g. LSST/Euclid/WFIRST, JWST and ELT?
- Should an increased capability be in terms of depth, spectral resolution and/or survey size?
- What are the relevant technical issues: sky subtraction, deployable/panoramic IFUs, optics etc?
- Assemble the scientific case and define requirements

Report submitted to ESO and STC in October 2016

https://arxiv.org/abs/1701.01976

Current Status

- ESO has endorsed an ERC Infrastructure proposal to undertake a conceptual design study over the next 3-4 years
- It involves many of the original SpecTel players with a strong Australian involvement
- Only considering southern option
- Upon completion of the study, ESO would make a decision on whether to proceed with detailed design and costing and eventually construction
- Australia may join ESO fully on this timescale and this would increase likelihood of funding

Decadal White Paper

- https://ui.adsabs.harvard.edu/abs/2019BAAS...51g..45E/abstract
- enhanced cosmology case WRT SpecTel white paper
  - a sample of at least 20,000 galaxies to I~25.3 spanning the full color and magnitude range for photo-z
  - A sample of 20,000 galaxies/sqdeg; color-selected from LSST images to precisely-tuned comoving number densities to redshifts z<1.5
  - 3-D clustering of at least one hundred million galaxies over 1.5<z<4

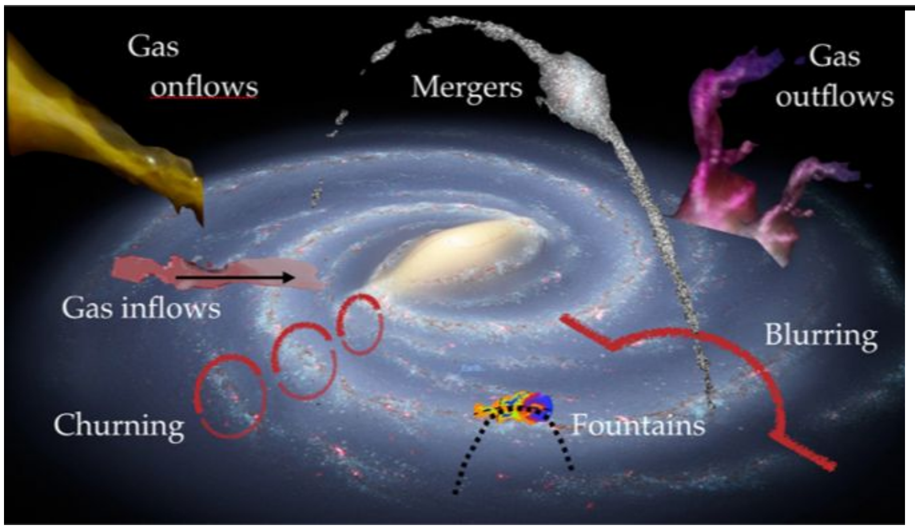
Design Focus

- The 1.43m diameter Cassegrain focal plane is as large as possible given current limits in the manufacture of corrective optics.
  - possible to duplicate DESI's fiber positioner design to produce a 15,000 fiber system
  - decreasing spacing to 6.5 mm (MegaMapper concept) leads to 40,000 fibers
  - Back of envelope: 5 mm spacing, 60,000 fibers, 400M galaxies, 10 years → 10% of LSST Gold Sample

Galactic Science

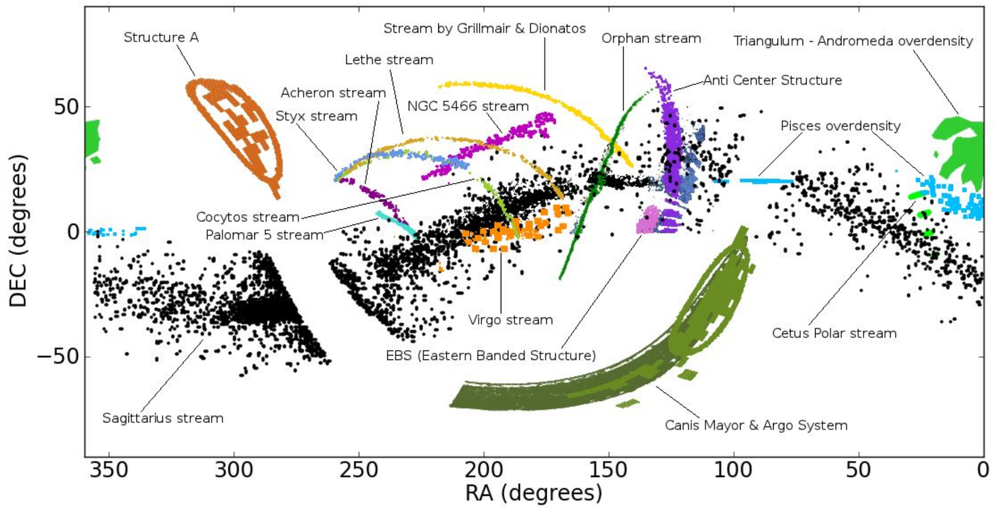
The Milky Way as a Model Organism

Stellar chemistry and kinematics as probes of physical processes for galaxy assembly



A. Recio-Blanco

Kinematics and ages of stars in Galactic streams as probe of the dark matter halo



P. Diez

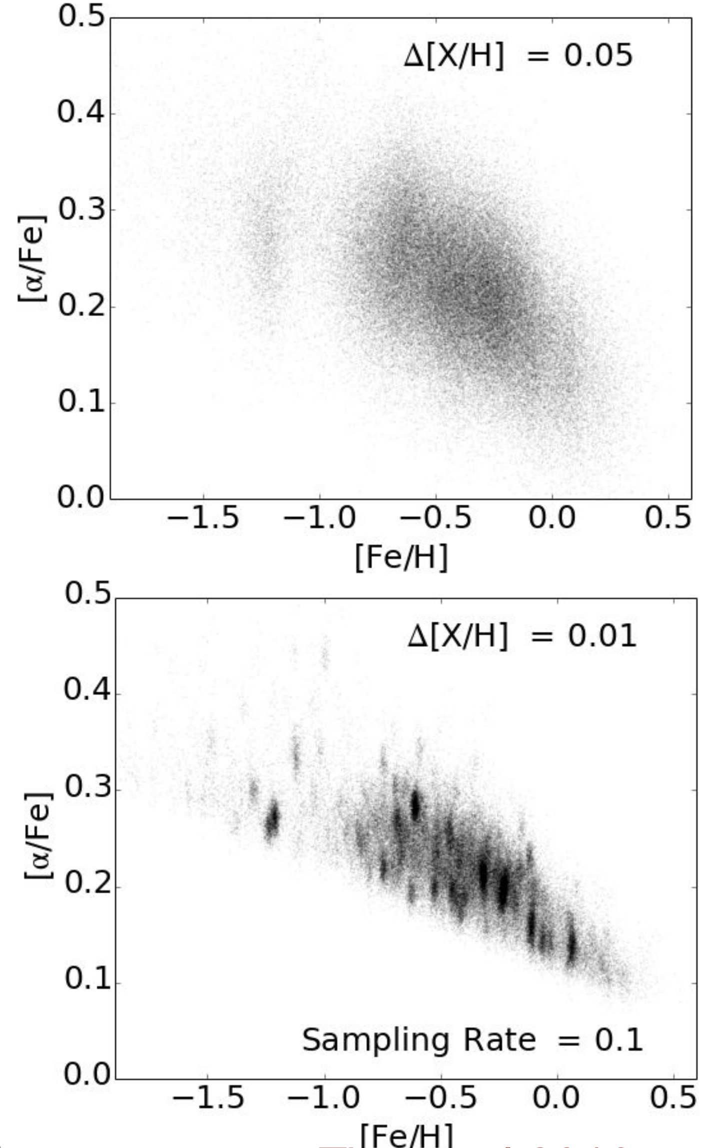
Ages, abundances & orbits of ~50-100 million stars throughout the Local Group

Four key questions

- Galactic gravitational potential and role of dark matter
  - 3D distribution of DM in Galaxy and its visible satellites
  - Evidence for low-mass dark halos (a key prediction of CDM)
- Assembly history of a prototypical large galaxy
  - Is this consistent with hierarchical cosmology?
  - `Chemical tagging' allows identification of widely-dispersed stars of common origin
- Stellar physics and origin of the chemical elements
  - Connecting nucleosynthetic yield with star formation history, gaseous inflow/outlows
  - Formation of heavy elements e.g. r-process
- Local group satellites as tests of low mass galaxy formation models
  - Connection to earliest sources in reionisation era

Chemical Tagging Statistics

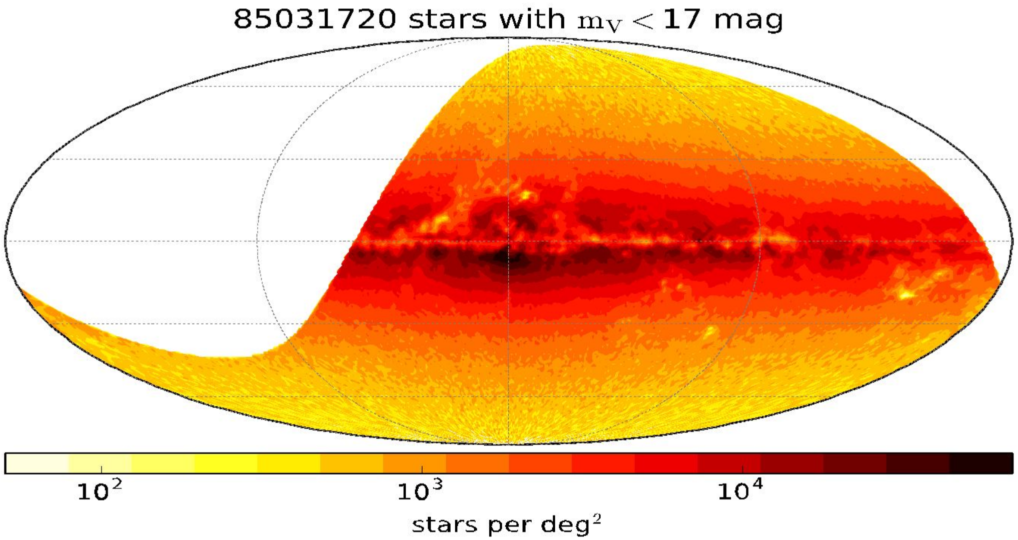
- High precision abundances essential for chemical tagging: δ[X/H] < 0.03
- Increasing the number of elements N is also advantageous: N >15
- Sample size M is likewise important: M ~40× 4MOST & MOONS (also probing further in distance)
- Gain c.f. 4MOST:
  - rare events scale as M: 40x
  - # of twins scales as M^2: 1600x
  - Tagging precision $δ[X/H]^N$: 1000x



Ting et al 2016

Illustrative Survey

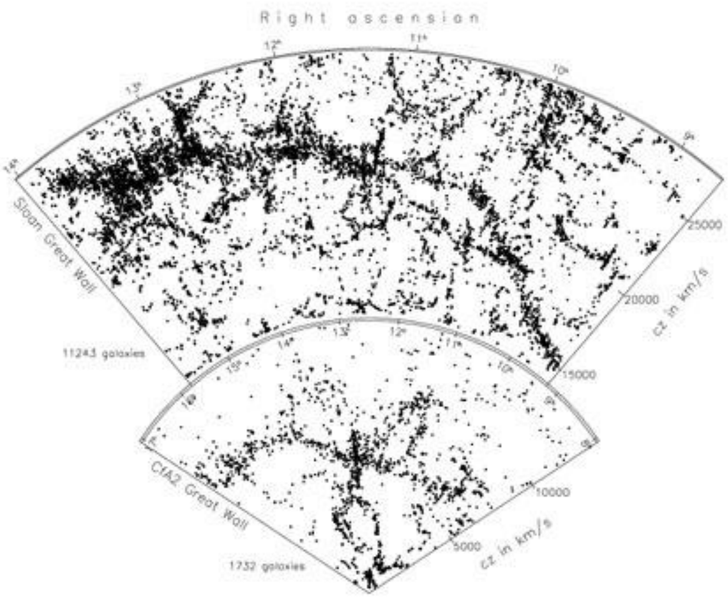
R~20,000-40,000 spectra of 85M stars with m_V<17



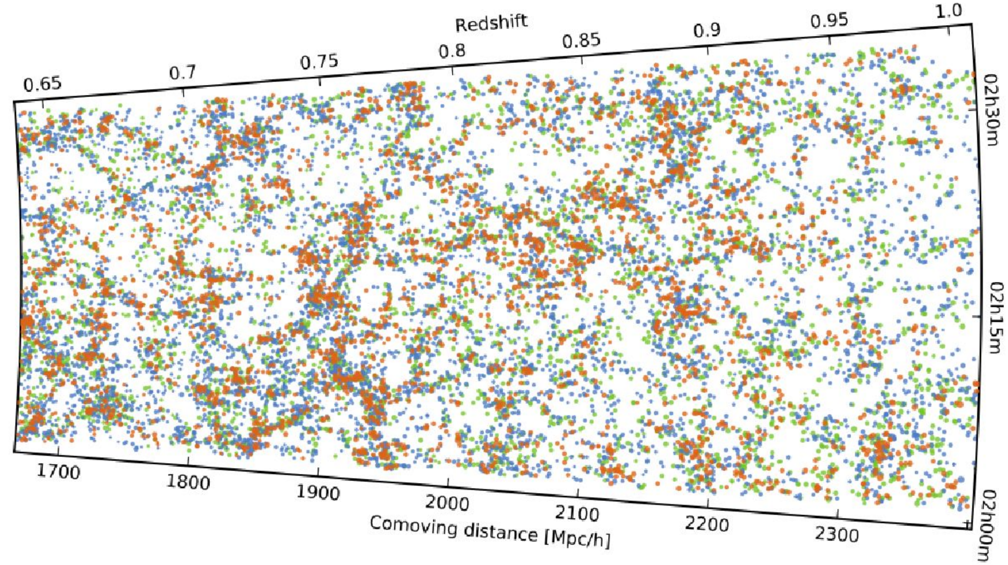
Sharma et al 2011

- Stellar target densities at V~17 range from 600 to 10,000 deg^{-2} necessitating a high multiplex requirement (N~5000)
- Kinematic data can be secured to fainter limits
- Exposure times for abundances will be 1-2 hours for a 10 m aperture
- Such an ambitious survey would take ~5 years – comparable to the investments made e.g. with SDSS/2dF
- Report discusses other Galactic science cases

Extragalactic Science



SDSS z < 0.1



VIPERS 0.5 < z < 1.2 : Guzzo et al

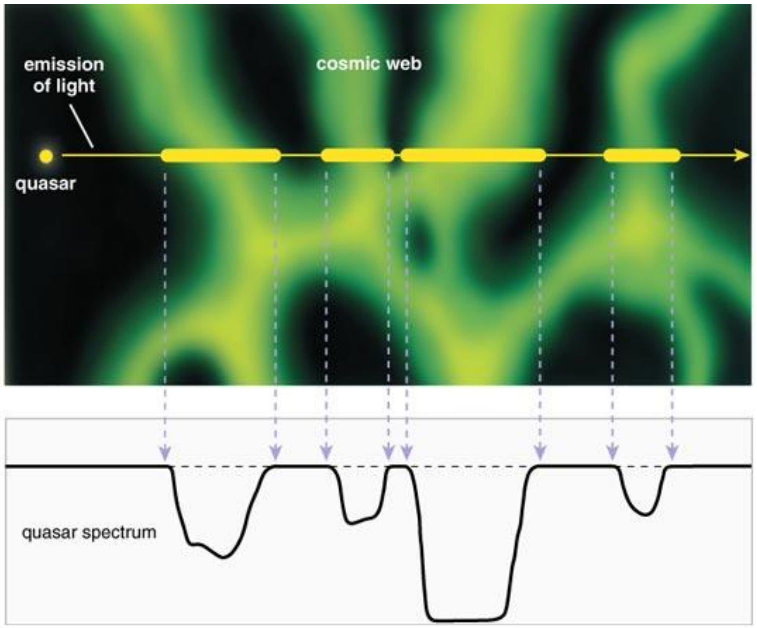
The major goal is to chart the evolving 3D structure of the cosmic web and link this to the assembly history and chemical enrichment of galaxies and their circumgalactic gas

But reaching beyond z~1 to the peak of SF activity is prohibitive with current facilities.

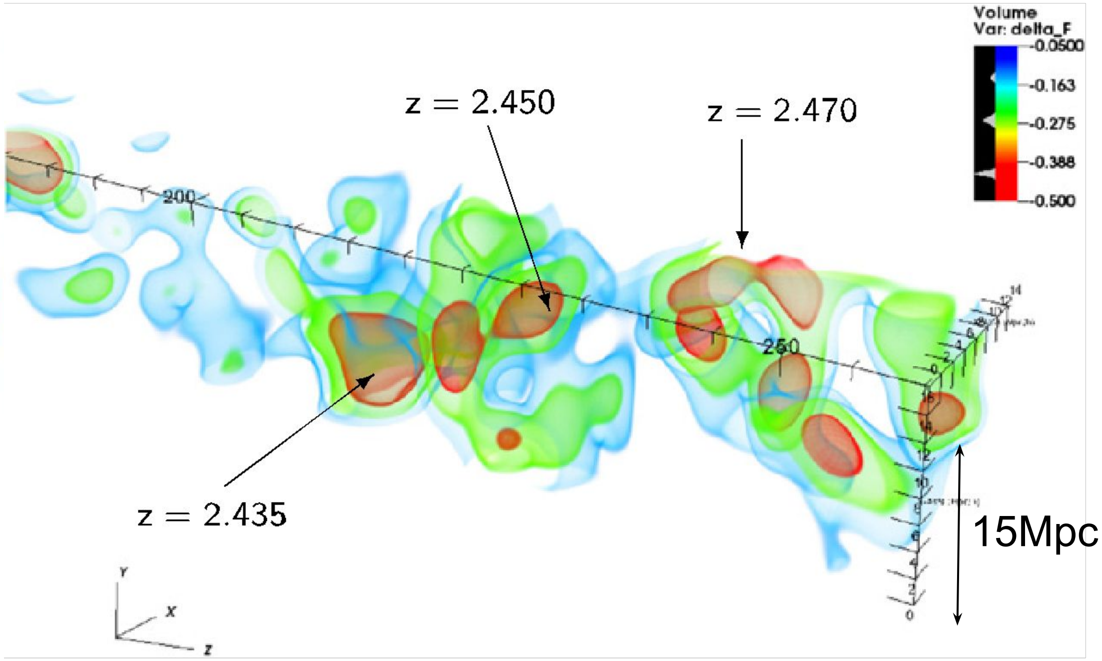
The Rationale

- Euclid and LSST imaging will enable precision photometric selection of faint galaxies over large areas (15,000 deg^2)
- JWST/ELTs will provide good spectra but over small areas
- Charting the cosmic web and its relationship to galaxies requires good sampling and adequate quality spectra over large volumes (~1 Gpc^3)
- Two simultaneous surveys of the cosmic web
  - Reconstruction of the evolving 3D density distribution with SDSS-like fidelity from spectra of 6. 10^6 redshift 1<z<4 galaxies – a legacy survey
  - Topology of the dark matter over large volumes from Lyman alpha forest seen in absorption line spectra of z~2.3-3 galaxies
- Higher resolution spectra to study the baryonic cycle via stellar/ISM features in the context of the local DM density field

Lyα Absorption & IGM Tomography



Simcoe (2016)



Lee et al (2016)

- Lyα absorption traces large scale structure in mildly overdense regime
- Originally exploited with QSOs but demonstrated via R~1000 Keck spectra of more numerous 2.3< z < 3 Lyman break galaxies (Lee et al 2014)
- Key advance will be mapping much larger volumes (~Gpc^3) with adequate sampling (~3 Mpc) in conjunction with the larger LSS survey

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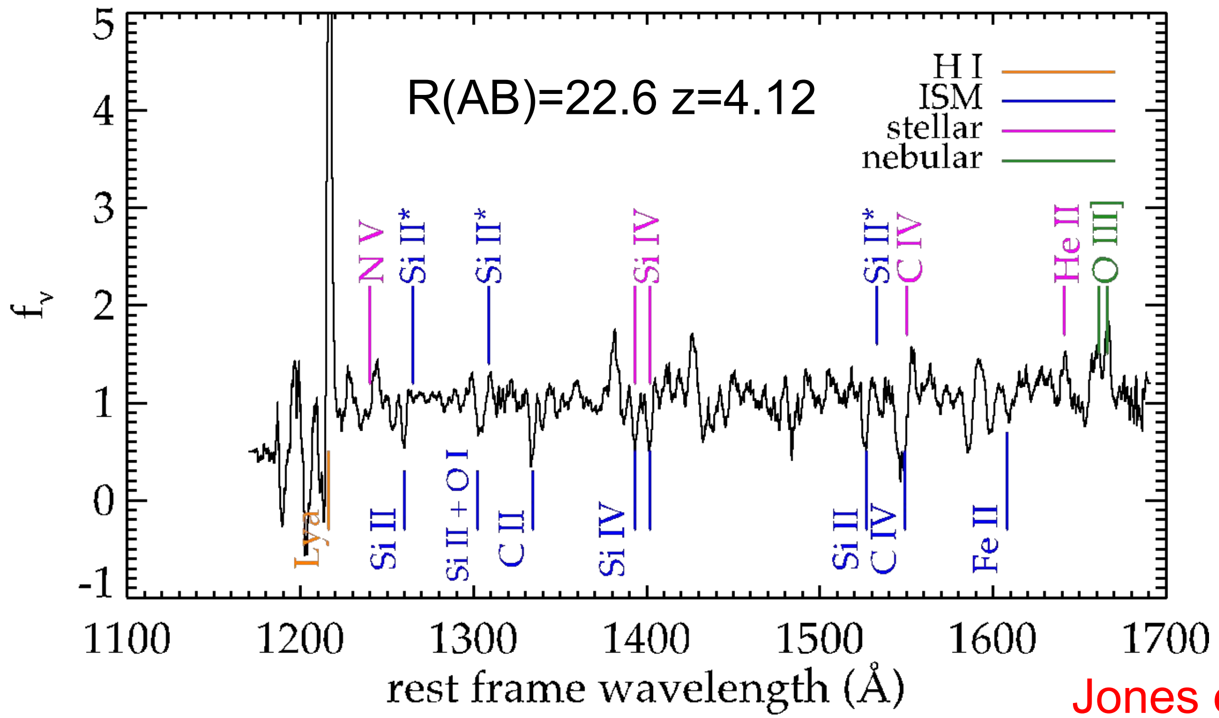
Stars/ISM & the Baryonic Cycle



Jones et al (2013)

- Deep R~3000 spectra of bright z ~2.5-4 galaxies will provide unique data on the ISM and stellar populations and the covering fraction of neutral gas
- This will provide richer data on the baryonic cycle of accretion and outflows as a function of the associated DM density field
- The key UV features will not be reached with JWST but there may be valuable synergies with nebular emission line studies with MOONS

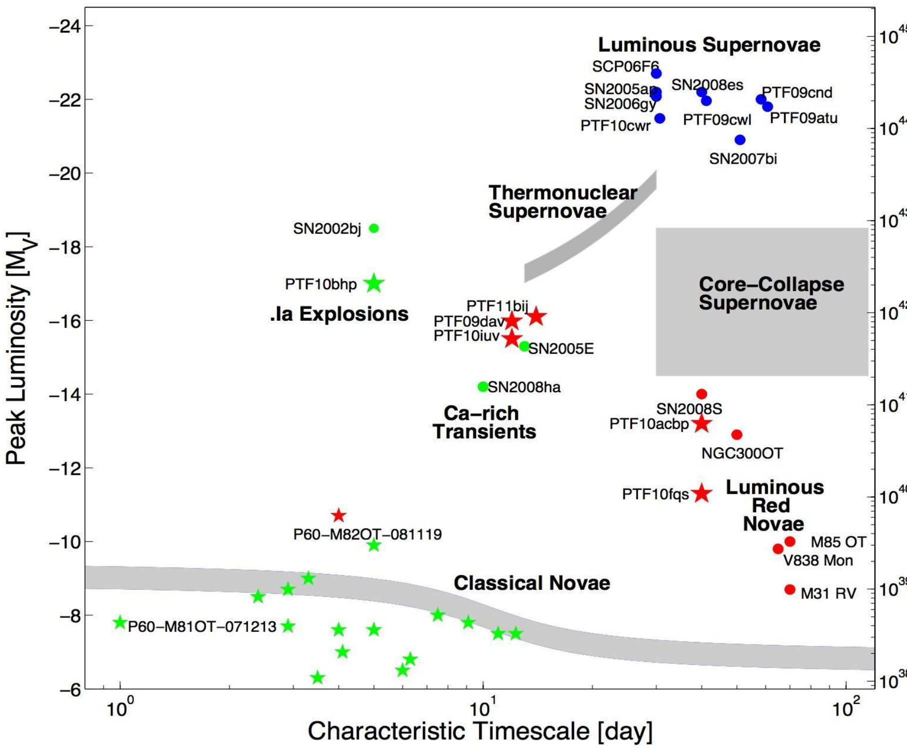
LSST and Transient Science

What is ESO's Response to LSST?

- LSST will transform searches for time-dependent phenomena, a major growth area in astrophysics
- WFIRST ~~will~~ may continue/extend the possibilities
- Science themes include:
  - Classical SNe – astrophysics and cosmology
  - Rarer events – SNe Ib/c, SLSNe, GW events, kilonovae, gap transients, tidal disruption events
  - AGN – reverberation mapping
- US study reports emphasize need for spectroscopic follow-up
- Distinguish between follow-up of rare *live events* and accumulated *transpired events* where host galaxy redshifts and local environment properties will be ascertained (c.f. OzDES)
- Report discusses various programmes of this nature

Illustration: SNe Follow-Up

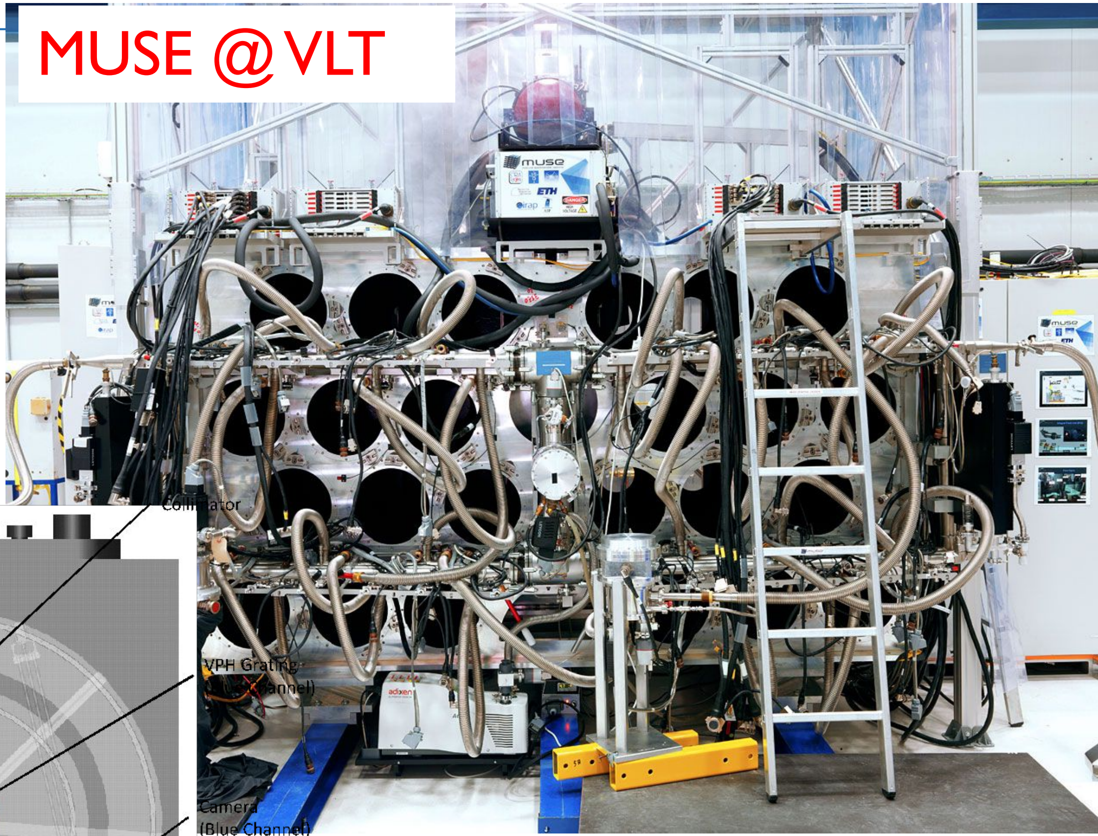
- LSST will generate 300,000 SNe/year (60% Ia, 35% II, 5% others)
- So ~40,000 *live events* at any time (~2-4 deg^{-2} or ~10-20 per FOV)
- After 5 years, accumulated *transpired events* ~80 deg^{-2} (~400 per FOV)
- SNe Ia photometric redshifts won't be accurate enough for cosmology so host galaxy data valuable (especially beyond 4MOST limit of z~0.8)
- Both *live* and *transpired* events can be followed-up by coordinating with R~1000 galaxy programme
- Estimate ~300,000 live spectra. Many thousands of spectra of unusual transients, e.g. gap transients, PI-SNe.

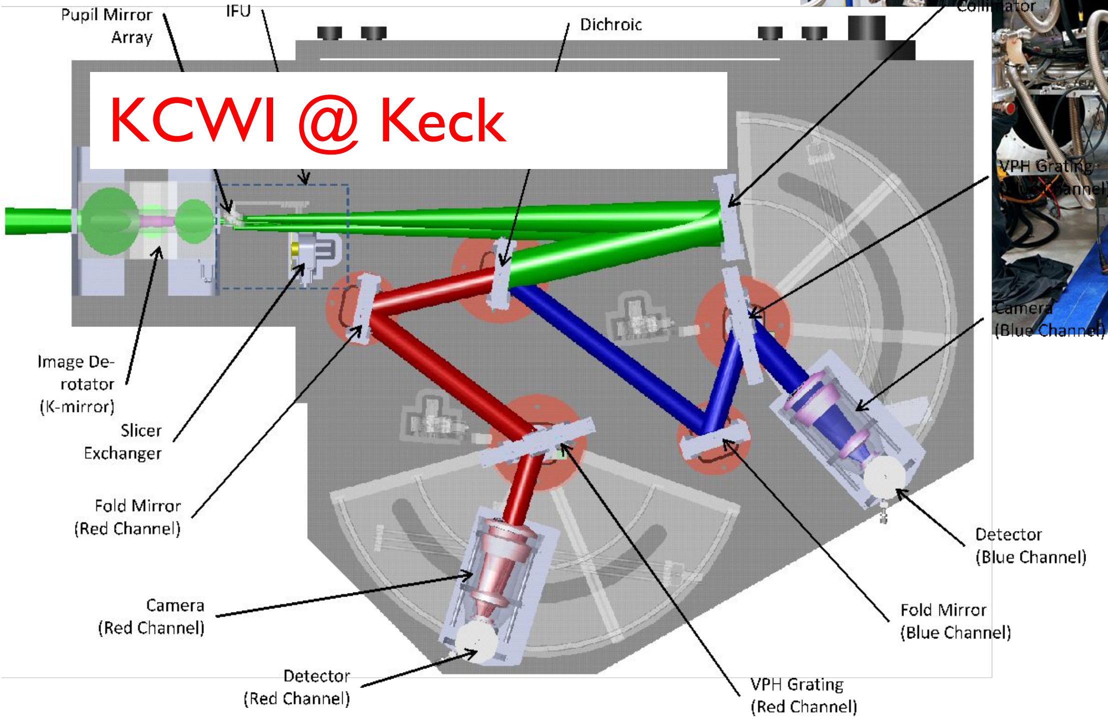


M Kasliwal

Integral Field Spectroscopy

Pixel by pixel spectra: not driven by photometric targets, currently popular, but is there a wide range of applications?

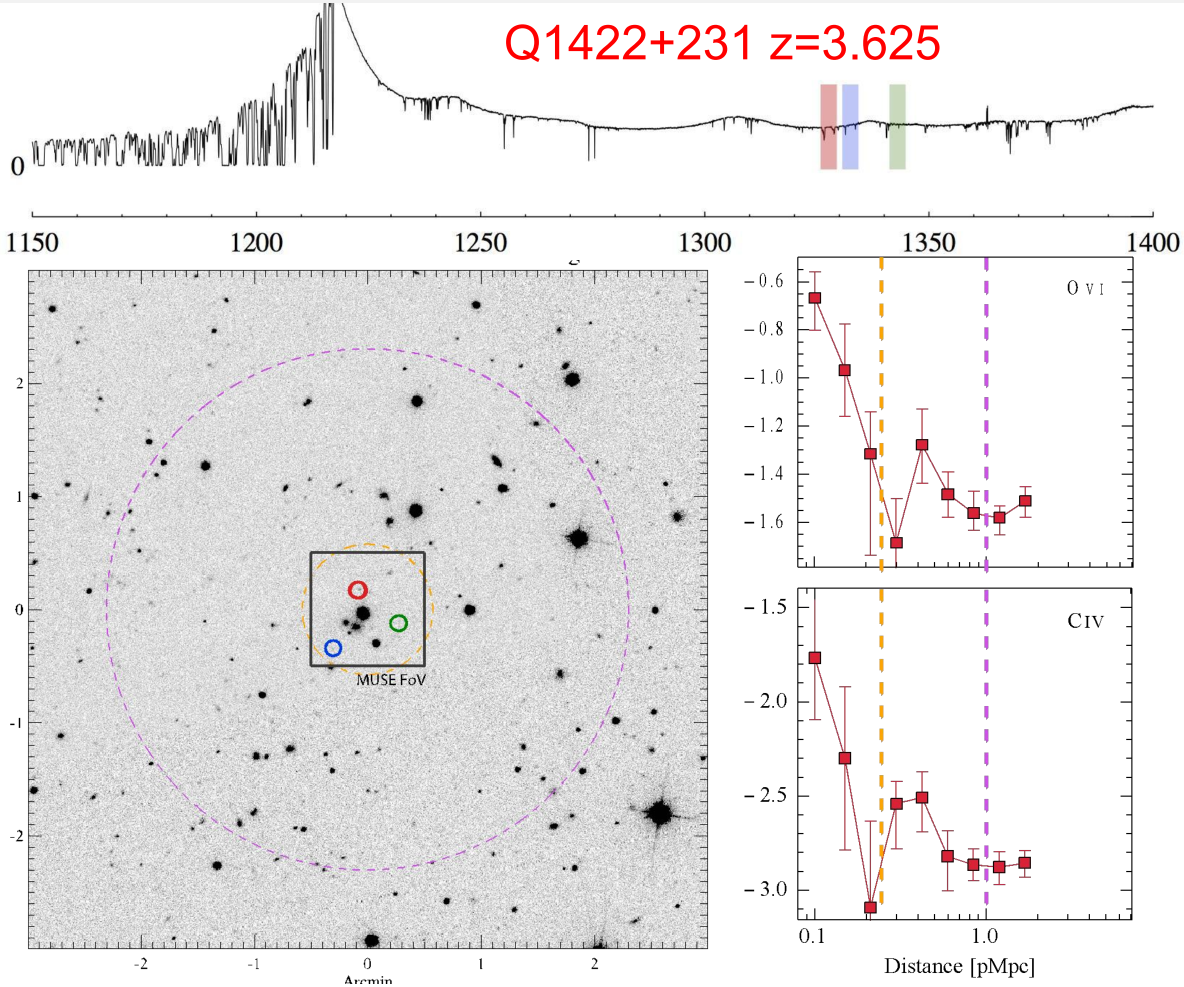




Case for a super-MUSE

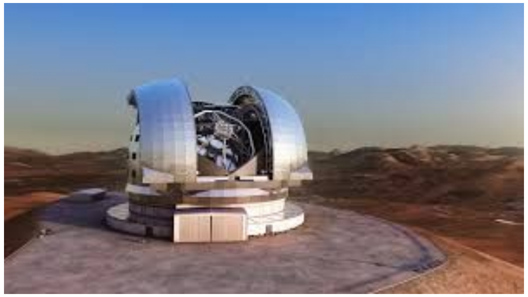
Pixel-by-pixel spectroscopy without photometric bias

- Enrichment of the IGM by galaxies can be studied by correlating metal line absorption in QSOs with the transverse distance to galaxies in the same cosmic volumes
- E-ELT HIRES will increase the number of accessible QSOs 10-fold
- A Super-MUSE with a 3x3 arcmin field will chart associated galaxies within 1 Mpc of the sightline



Straka et al 2016; Turner et al 2014

Important Synergies



- A well-sampled deep spectroscopic survey of $1<z<4$ galaxies over ~200+ deg^2 will provide legacy data for studies of sources located by a range of ground- and space-based observatories
- It will provide a quantitative measure of the local galaxy and DM environment for all sources in the survey area
- Specifically for the E-ELT there will be many synergies, e.g.
  - MOS on E-ELT would trace the DM in finer detail (~1 Mpc) in denser regions in coordination with the wide field telescope
  - HIRES will provide metallic absorption line spectra for 15-20 QSOs at z~2-3 per wide telescope FOV enabling the proposed facility to associate galaxies with the local IGM chemistry

Summary of Science Requirements

Report collates telescope & spectroscopic requirements for 3 science areas recognising they may present technical challenges (see later)

- **Telescope aperture**: 10-12m driven by R~40,000 spectra of V~17 stars & R~3000 spectra of AB~24 galaxies. Competitive with PFS/MSE.
- **Field of view**: 5 deg^2 driven by surface density of V~17 stars, LBGs and rarity of transients
- **Multiplex gain**: N~5000 driven by need to fully utilise FOV and complete science programmes on <5 year timescales
- **Spectral resolutions**: R~1000-3000 (galaxies, transients)
  R~20,000-40,000+ (stars)
- **Wavelength Range**: 360-1000nm: blue important for stars and Lya forest; IR extension optional (c.f. MOONS)
- **Super-MUSE?** exciting extragalactic applications, perhaps implemented as later upgrade with additional focal station

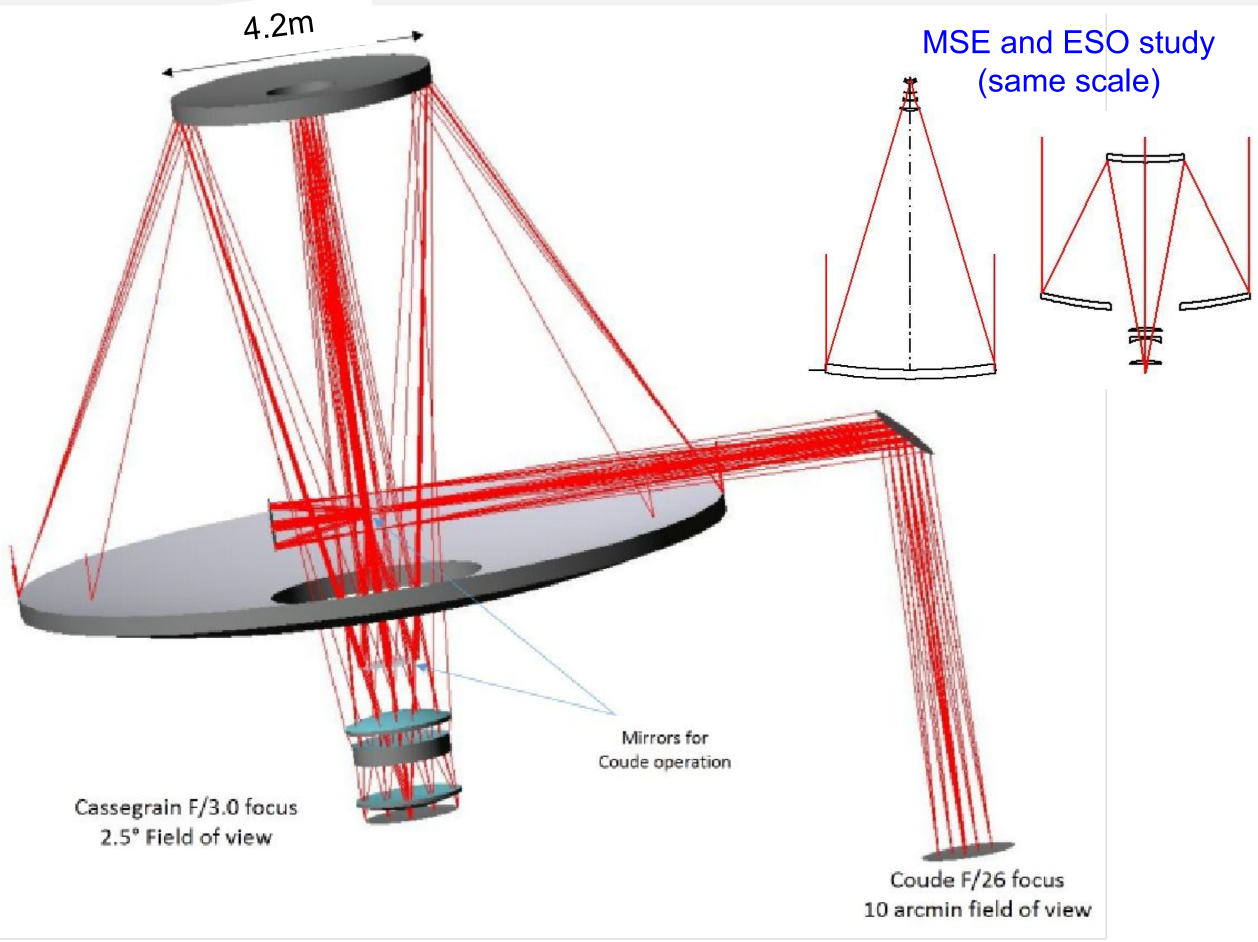
A Telescope Option

Is a 10-12m class telescope with a ~5 deg^2 FOV possible?

Cassegrain design is compact & flexible

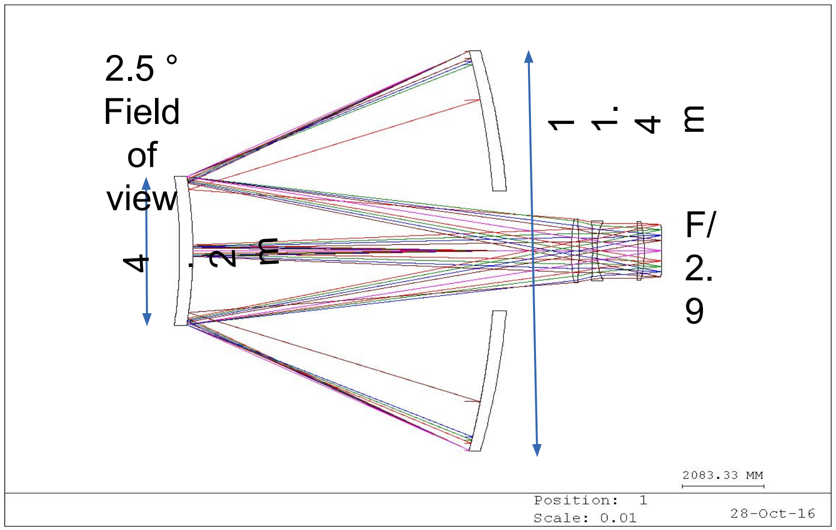
11.4m f/0.6 primary (78 ELT segments) with a 5 deg^2 f/2.9 field ideal for fibres with good images from 360-1300nm.

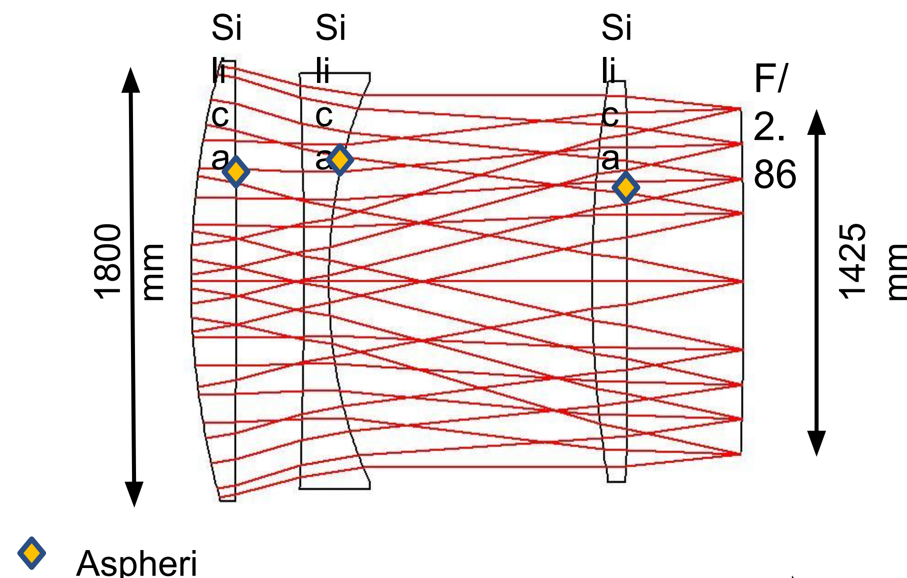
Gravity-invariant f/26 Coudé focus with 10 arcmin FOV suitable for a Super-MUSE



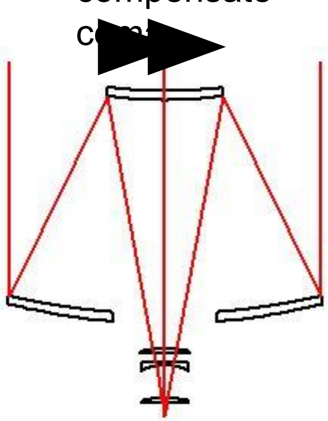
Pasquini et al arXiv 1606.06494, 1708.03561

Corrector with Innovative ADC

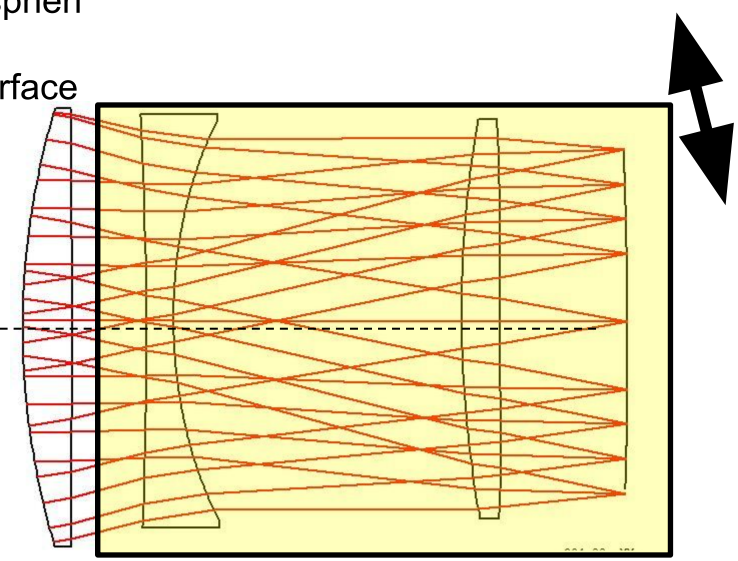




M2 translation to compensate co...

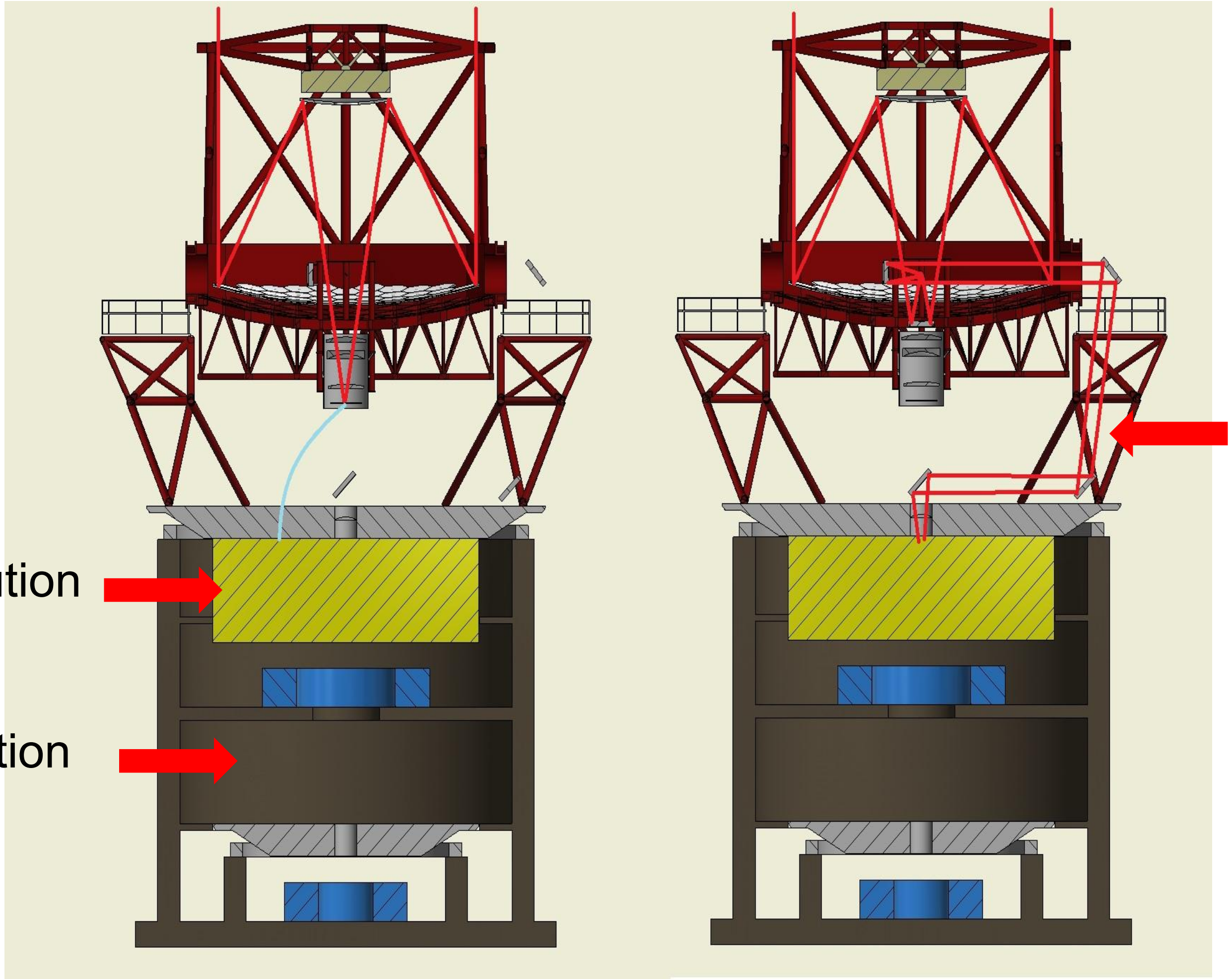


ADC operates over 360-1300nm via modest tilt (<0.3 deg) of portion of corrector and positioner around a point 5m in front



Current Status - Telescope

All spectrographs and Coudé focus in a compact enclosure (no extended Nasmyths)



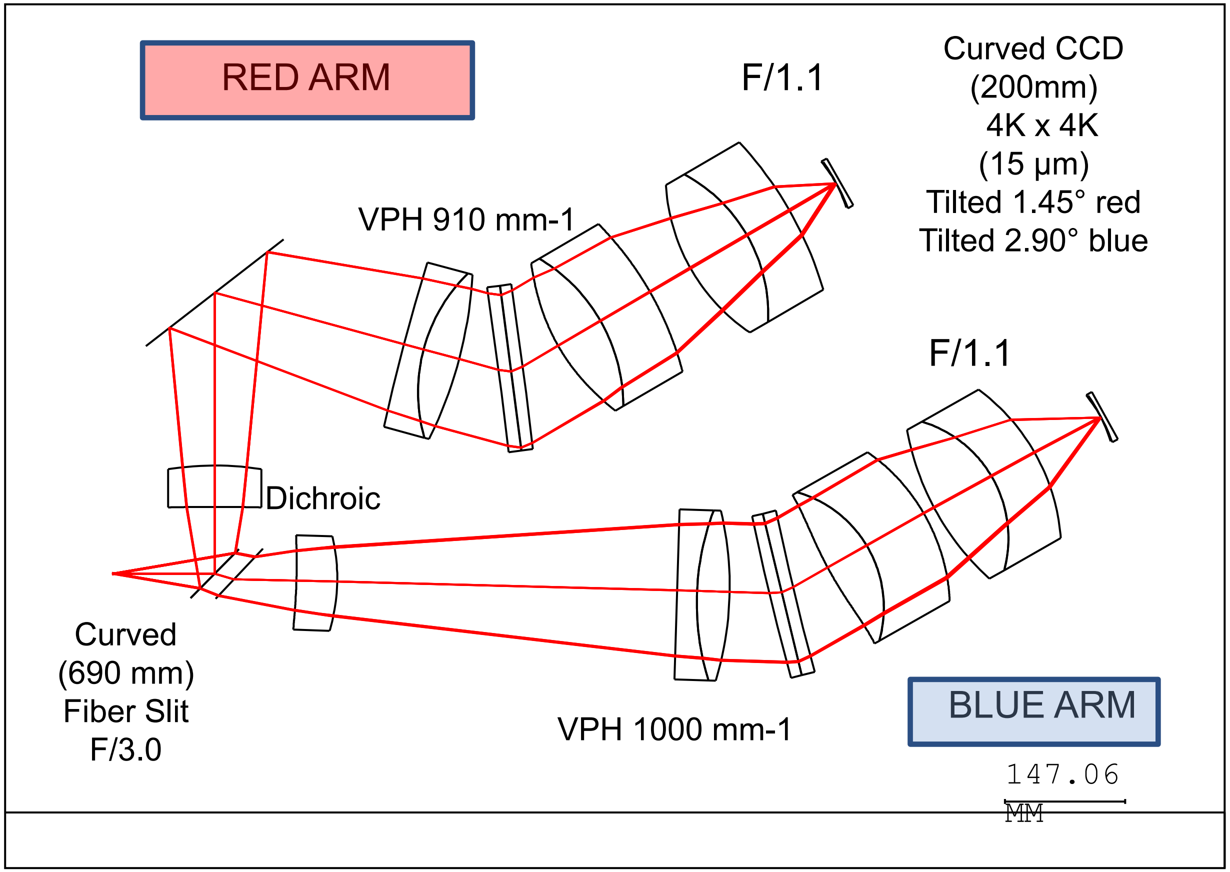
High Resolution

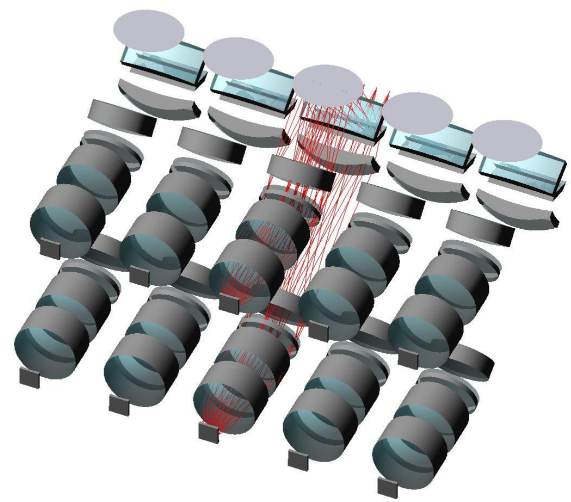
Low Resolution

Coudé train
10 arcmin FOV
(Super-MUSE)

Current Status – LR Spectrographs

Two-arm spectrograph design accommodating 650 fibers at R~2600
f/3.0 collimator with dichroic splitting λλ380-690nm and 680-1000nm
f/1.1 camera feeding two curved 4K CCDs



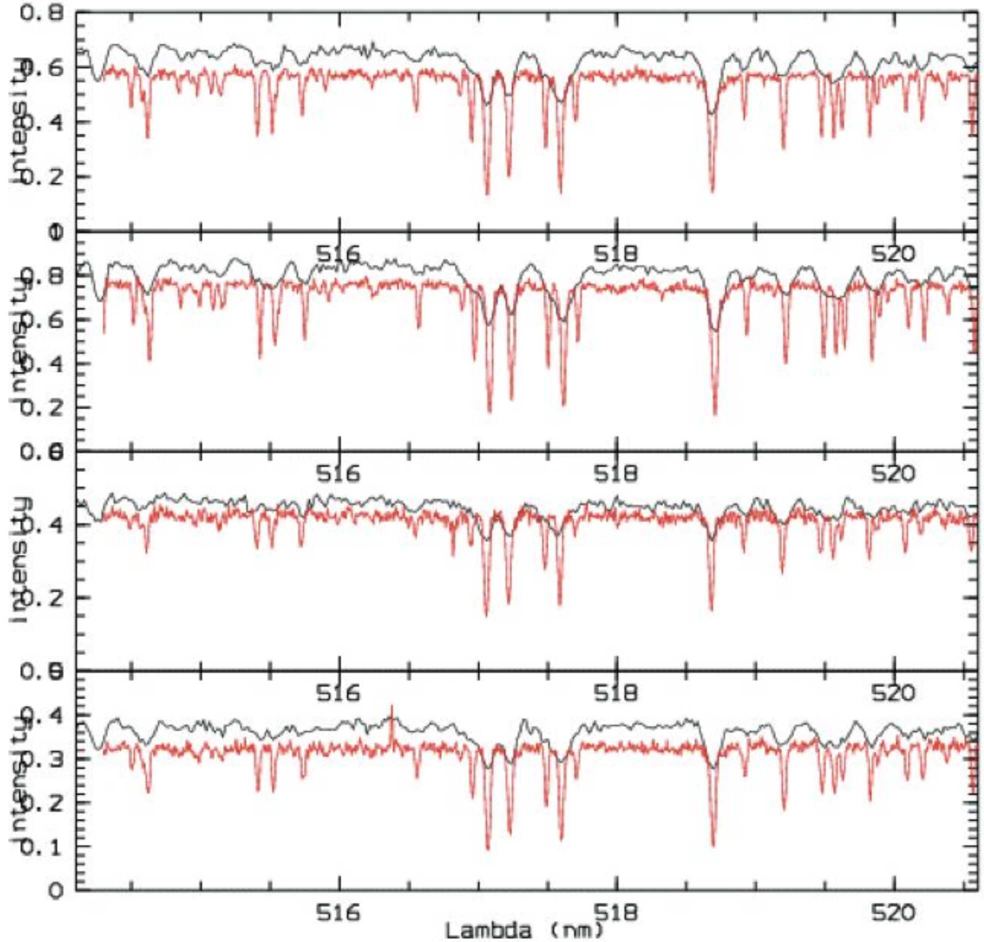


Module of 5 such spectrographs would accommodate 3250 fibres

Spectral Resolution

- For precision abundances (<0.03 dex), spectra with R~20,000-40,000 are required to avoid blending as well for reliable placement of the continuum
- A S/N>80 ensures the weakest lines (~5% continuum depth) can be measured

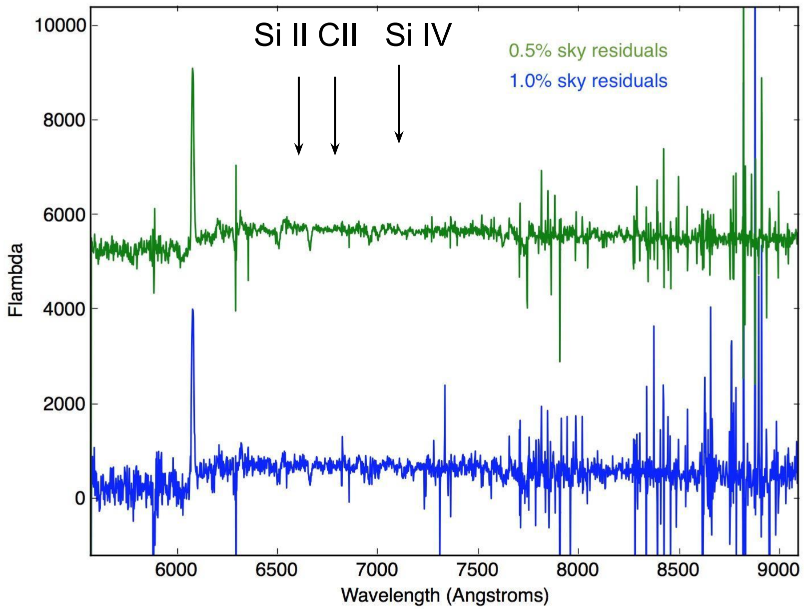
FLAMES R~6000 c.f. R~26000

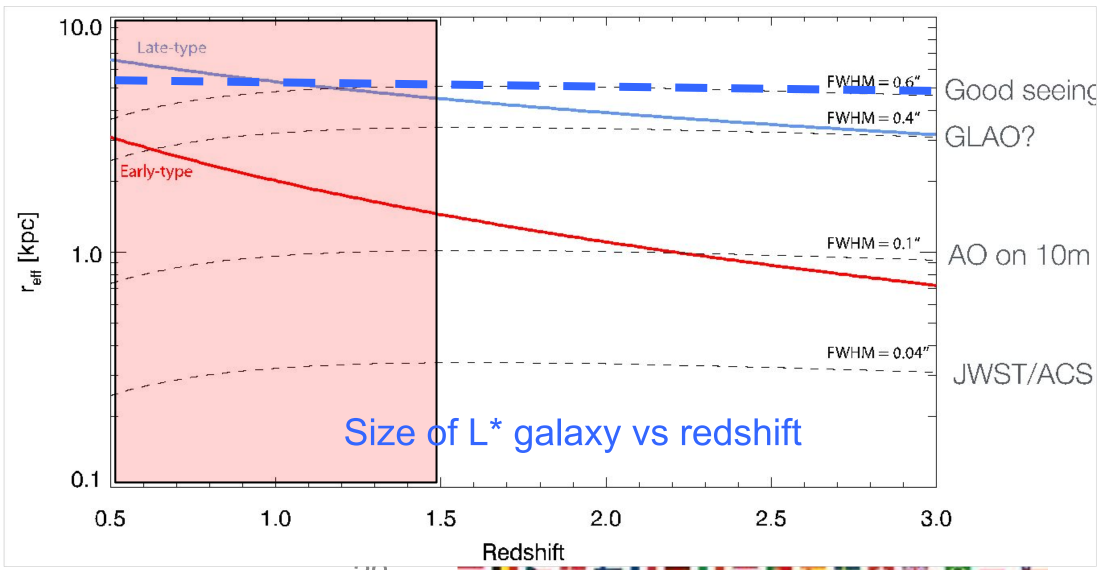


Pasquini et al ESO Messenger (2002)

Other Technical Issues

- Sky subtraction with fibres?
  - BOSS achieves 1%, FLAMES < 1%, PFS targets 0.5%
  - Simulations suggest AB~24 absorption line studies feasible
- Deployable IFUs?
  - Some advantages (resolved spectra, no aperture losses)
  - Significantly reduces multiplex gain and z > 1.5 sources unresolved





A Ω product (m^2 deg)

	Telescope Diameter	Central Obstr.	Aperture²	Ω (deg^2)	Product
ESO VLT (VIMOS)	8.0	0.97	48.75	0.043	2.08
ESO VLT (FLAMES)	8.0	0.97	48.75	0.136	6.63
ESO VISTA (4MOST)	3.7	0.89	9.57	4.00	38.3
ESO VLT (MOONS)	8.0	0.97	48.75	0.136	6.63
WEAVE	4.2	0.88	12.2	3.14	38.3
SUBARU (PFS)	8.0	0.97	48.75	1.33	64.7
MAYALL (DESI)	3.8	0.85		8.00	77

	Telescope Diameter	Central Obstr.	Aperture²	Ω (deg^2)	Product
LSST (imaging only)	8.2	0.63	33.27	9.62	320
MSE	11.2	0.97	96.0	1.50	144
ESO CONCEPT STUDY	11.2	0.86	84.6	4.91	415

Operational Considerations

How would it be operated and what would be ESO's role?

- PFS and 4MOST both have external teams funding and delivering instrument to a national/international observatory (NAOJ/ESO)
- Community access is monitored by observatory
- In this case instrument cost ≈ telescope cost? Conceivably both would be funded as a package (a la VISTA)
- Operational model depends on
  - How the components are funded
  - Who defines the science programme
  - Who executes the observations
  - Who produces and releases the data products
- A key issue is whether such a project is ESO-only

International Aspects

- Australian interest recognised by additional WG member (Joss Bland-Hawthorn); now joined ESO-lite…
- US initiative `*Maximizing Science in the Era of LSST*' co-chairs Najita/Willman (arXiv:1610.01661) recommends a wide field southern spectroscopic facility and identifies the ESO initiative
- Canadian/French involvement in *Mauna Kea Spectroscopic Explorer (MSE)* has done much valuable work and is currently in the vanguard in this area – partnership?
- Chinese interest in LAMOST-South
- Can more than one such facility can be funded in the ELT era?

Hopefully it will eventually happen!

Working Group Charge

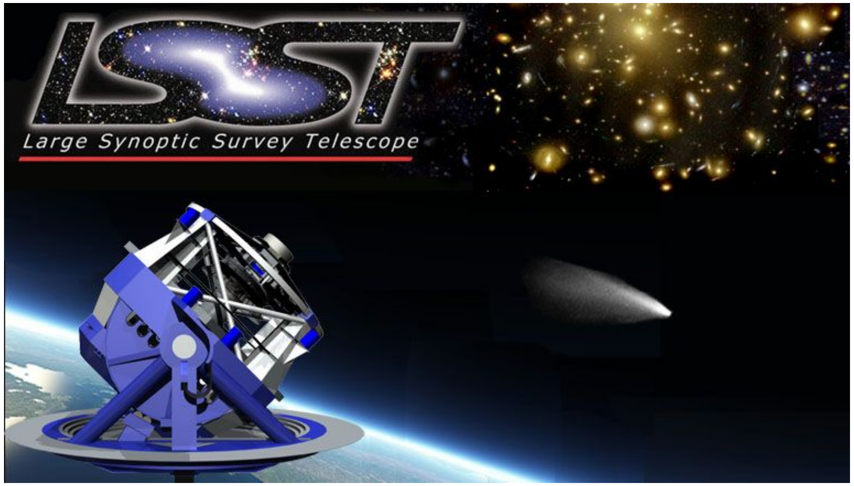
The Working Group will consider:

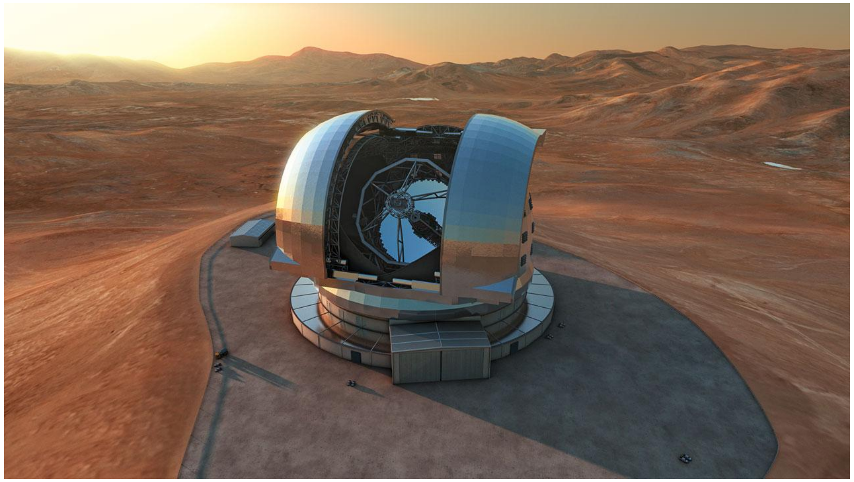
- The scientific case for highly-multiplexed ground-based spectroscopy in the era of LSST, E-ELT and space missions such as JWST, Euclid and WFIRST
- Examples of survey projects and specific synergies with the above facilities and how these affect the design parameters of a survey telescope
- The likely scientific outcomes from the current suite of 4 to 8 metre spectroscopic survey facilities (4MOST/WEAVE, MOONS, DESI/Subaru PFS) and how these propel the case for a more ambitious or complementary facility
- The unique scientific opportunities enabled by a wide-field integral field capability (a la MUSE)
- The mode of operations, data processing and other requirements that relate to disseminating the processed data to the ESO community.

Illustrative Surveys

- Evolution of the Cosmic Web $1 < z < 4$
  - 6×1 Gpc^3 redshift bins each containing 10^6 galaxies
  - Magnitude limit ranges from i_{AB}~23.1 (z~1) to 25.8 (z~4)
  - Emission line redshifts requires 2–7 hrs
  - Lyα absorption tomography @ z~2.3-3 also requires 2-7 hrs
  - Concurrent R~1000 surveys would take 400 nights (3-5 yrs)
  - Commensurate with e.g. investment made by PFS
- Baryonic cycle via stellar/ISM studies @ z~2.5-4
  - Higher s/n~10 per Å and R~3000 for absorption lines
  - Targetting i_{AB}~24 requires 20-50 hrs
  - Diverting 5% of fibres in parallel with Cosmic Web survey yields 2×10^5 high quality spectra (100 × VANDELS)

Long Term Synergies





What is ESO’s response to LSST?