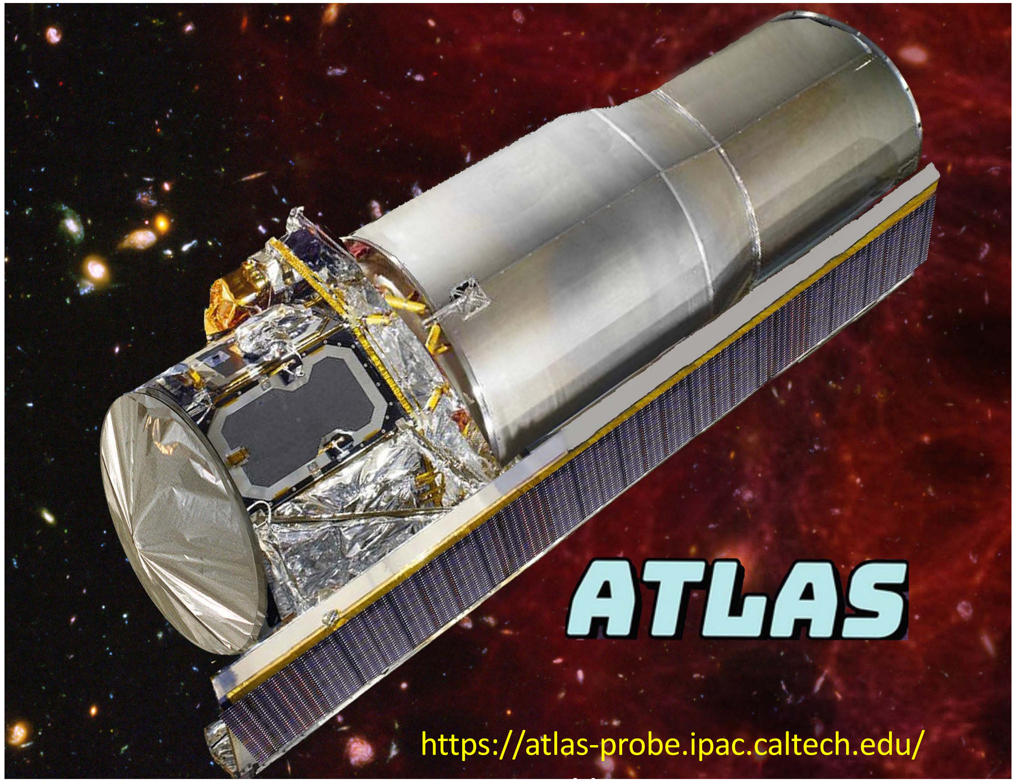
Massively-Multiplexed Spectroscopy in Space

Richard Ellis (University College London)



Why Spectroscopy?

Spectroscopy is the observational astronomer's most important tool

Extragalactic applications based upon redshifts and emission line measures

- Charting the 3D structure of the universe as function of SF activity
- Tracing expansion history via BAO studies
- Tracing the growth of structure via redshift space distortions (RSD)
- Selecting background populations for precision lensing measures of DM distribution over cosmic time

Other applications (dependent on aperture & instrumental resolution)

- Absorption line probes of intermediate redshift galaxies (outflows, CGM studies, stellar ages..)
- Stellar kinematics and abundance measures in Milky Way and nearby satellites
- Transient follow-up and classification
- Characterisation of trans-Neptunian objects

Why Now?

The next decade will see a huge investment in panoramic imaging

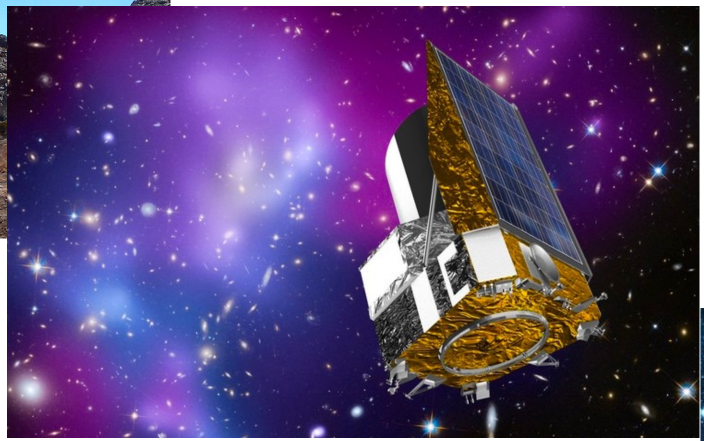
- To fully exploit the imaging facilities coming online, a comparable investment in spectroscopy is required
- Time and again, experience has shown the value of such synergies (e.g. APM/2dF, SDSS, HST/Keck, DES/OzDES..)
- Upcoming imaging surveys are **much deeper and over wider fields** than previously, placing impractical demands on presently-available spectroscopic facilities
- In recognition of the above, numerous 'white papers' and reports have cogently argued for new spectroscopic facilities (both on the ground and in space)

THIS TALK: Review the scientific landscape, compare & contrast the ground and space-based prospects

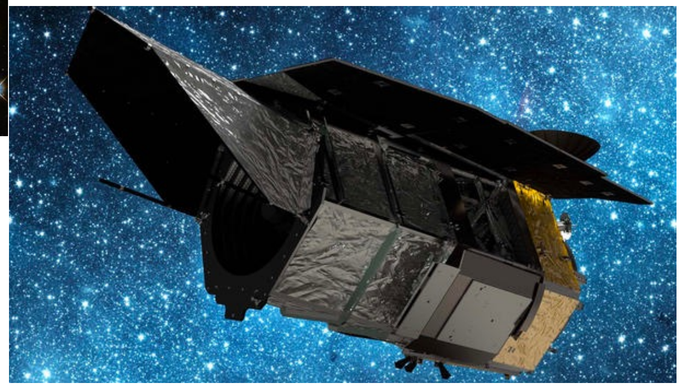
A Decade of Deep Wide Field Imaging

Significant investment in panoramic **DEEP** multi-color imaging in the 2020s

Vera C Rubin Observatory 6.5m (formerly LSST) 2022-2032:
ugrizy ~ 25-27 over 18000 deg^2 (wide-fast-deep survey)
ugrizy ~ 27-29 over ~38 deg^2 (4 deep drilling fields)



Euclid Space Tel 1.2m 2022-2029:
<riz> + YJH > 24 over 15000 deg^2
> 26 over 40 deg^2



Nancy G Roman Space Telescope (formerly WFIRST) 2026-2032:
YJH +F184 < 27 for 2000 deg^2 (wide field survey)
+ deep fields (strategy TBD following community input)

The Case for Investment in New Spectroscopic Facilities

Many comprehensive reports have emphasized the science case

Committee-based reports:

Optimizing the U.S. Ground-Based Optical and Infrared Astronomy System (2015):
Elmegreen et al (NRC) http://nap.edu/21722

Maximizing Science in the Era of LSST (2016): Najita, Willman et al (Kavli Foundation)
https://arxiv.org/pdf/1610.01661.pdf

Future of Multi-Object Spectroscopy (2016): Ellis et al (ESO) https://arxiv.org/pdf/1701.01976.pdf

Astro2020 White Papers (selection):

Towards a Spectroscopic Survey Roadmap for 2020s & Beyond (Bolton et al)

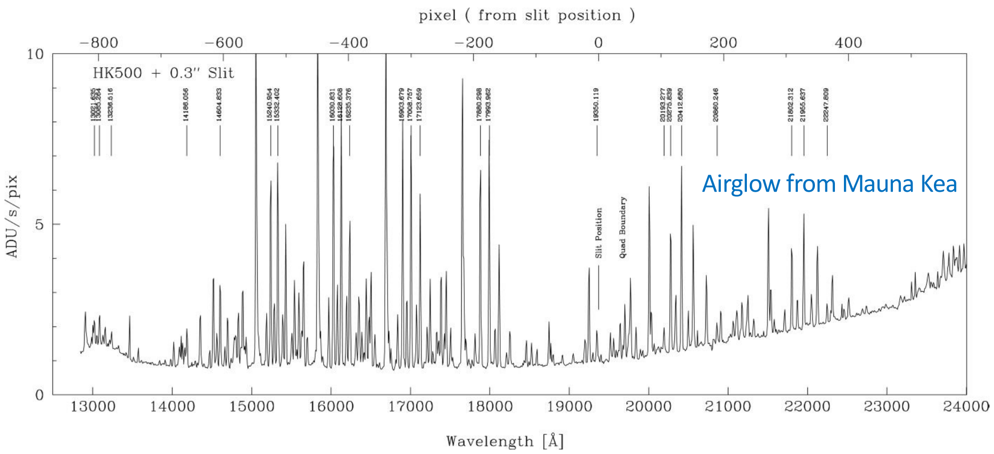
ATLAS Probe: Breakthrough Science of Galaxy Evolution, Cosmology, Milky Way & Solar System
Illuminating the dark universe with a very high density galaxy redshift survey over a wide area (Wang et al)
Observing Galaxy Evolution in the Context of Large-Scale Structure (Dickinson et al)
Empirically Constraining Galaxy Evolution (Behroozi et al)

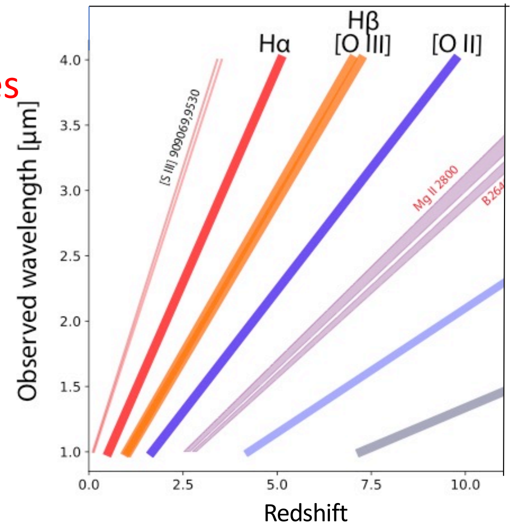
Ground-based Investment (Extant & Proposed)

	Instrument/Telescope	Collecting Area m^2	Field of view deg^2	Multiplex
4m class funded	4MOST	10.7	4.00	1400
	Mayall 4m / DESI	11.4	7.08	5000
	WHT / Weave	13.0	3.14	1000
8-10m class funded	Subaru / PFS	52.8	1.25	2400
	VLT / MOONS	52.8	0.14	500
	Keck / DEIMOS	76.0	0.015	150
	Megamapper	28.0	7.06	20,000
Proposed & unfunded	Keck / FOBOS	76.0	0.087	1800
	MSE @ CFHT	78.5	1.52	4000
	ESO Spectel	113.1	4.90	5000

Why Space?

Crucial gains for exploiting faint & high z targets located with new imaging facilities





<u>Access to the Near-infrared</u>

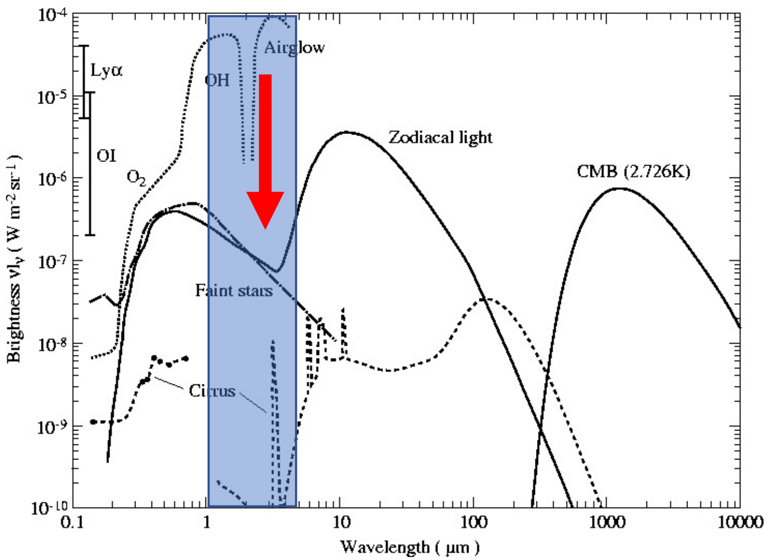
Use of redshifted optical diagnostics ([O II],[O II],Hα) beyond K band

Multiple line studies (metallicity, ionization state) unaffected by airglow

Lower background means greater performance & at lower spectral resolution

Stable instrument performance and improved image quality

24/7 operational efficiency



Science Frontiers with Massively-Multiplexed Facilities

Applications depend on spectral resolution, wavelength range and aperture

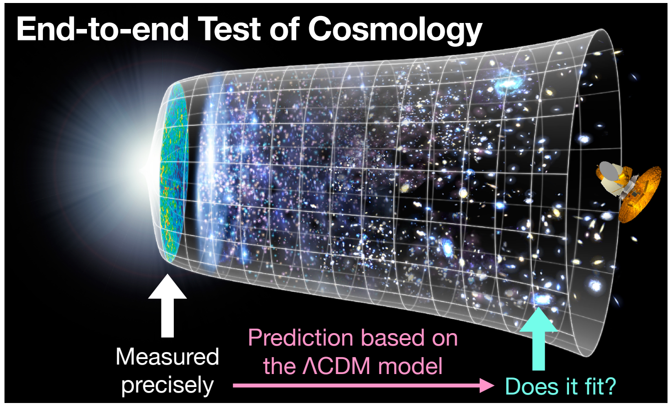
- Cosmology – end to end tests of the standard model, dark energy/modified GR, neutrino mass/hierarchy
- Galaxy evolution – environmental studies relating to cosmic web, baryon cycle studies
- Galactic archeology – kinematics for DM probes, chemical tagging for assembly histories
- Transient universe – classifications of SN types, exploring phase-space for new classes of variables
- Solar system – trans-Neptunian studies

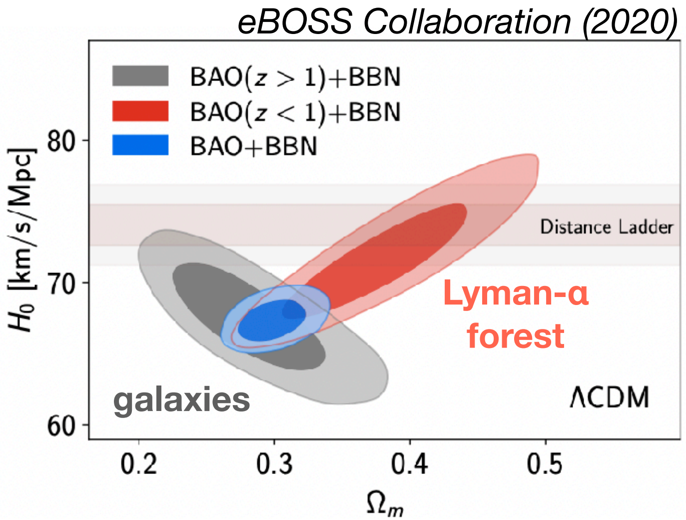
Aim here to discuss top-level science questions regardless of instrumental choices to indicate possible synergies between ground and space-based surveys

Cosmology - I

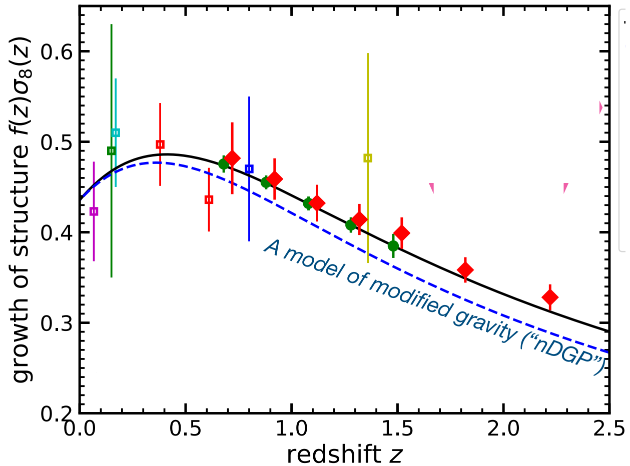
End to end tests of the standard model (ΛCDM) seem to be failing..

- Possible tensions in H_0 and S_8: what might they imply?
- Need to trace **distances** and **structure growth** over large redshift range
- **Ideally use a single spectroscopic tracer** ([O II]/Hα)
- Requires unrestricted access to near-infrared





So far, **BAO distance measures** come from different tracers: galaxies at low z, Lyman-α forest at high z



Growth of density fluctuations: **DESI z<1.5** **PFS z>1.5**

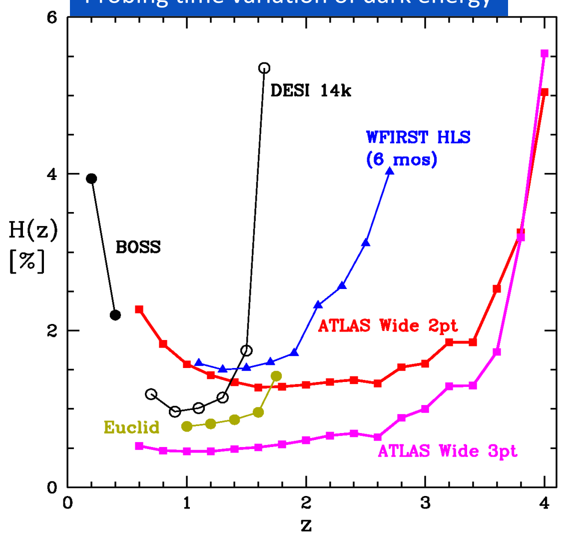
Cosmology - II

Focus of ATLAS lies primarily in **redshift range 1 < z < 4** complementing most ground-based surveys (z < 1.5) and, especially, in **sampling density**

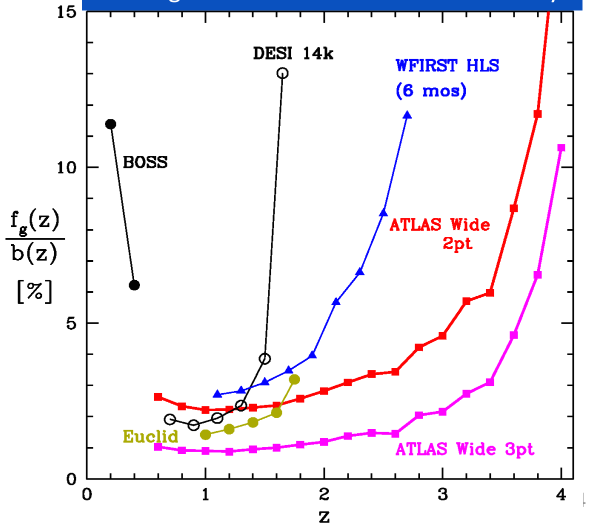
Whereas structure growth measures (f_g) benefit from a long z baseline, BAO distance measures beyond z~2 may be a bit of a "shot in the dark" in terms of learning about dark energy. What do we expect to find?

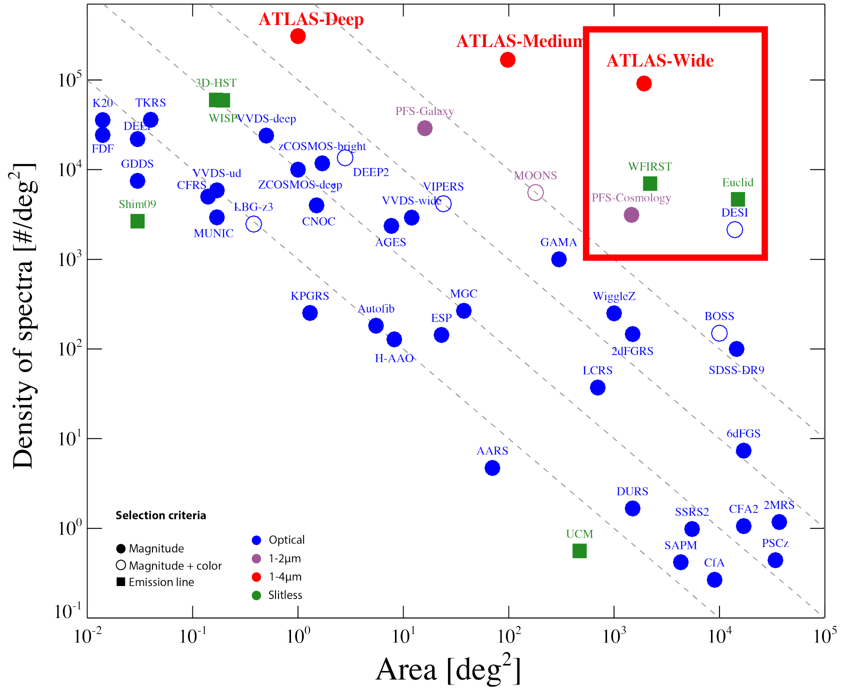
Will it be useful to review what comes out of PFS (0.6 < z < 2.4)?

Probing time variation of dark energy



Probing deviations from General Relativity



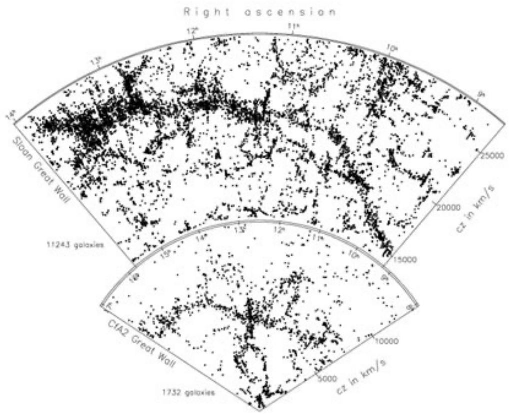


Synergies with lensing including improved background N(z) data

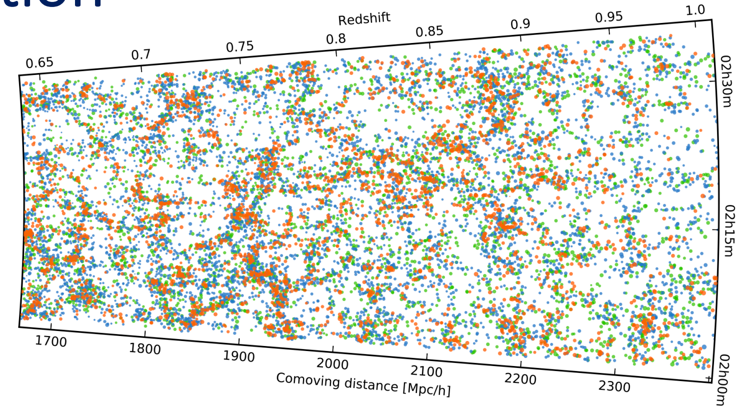
Neutrino mass constraints from scale and time-dependent suppression of matter power spectrum?

Wang et al (2019)

Galaxy Evolution



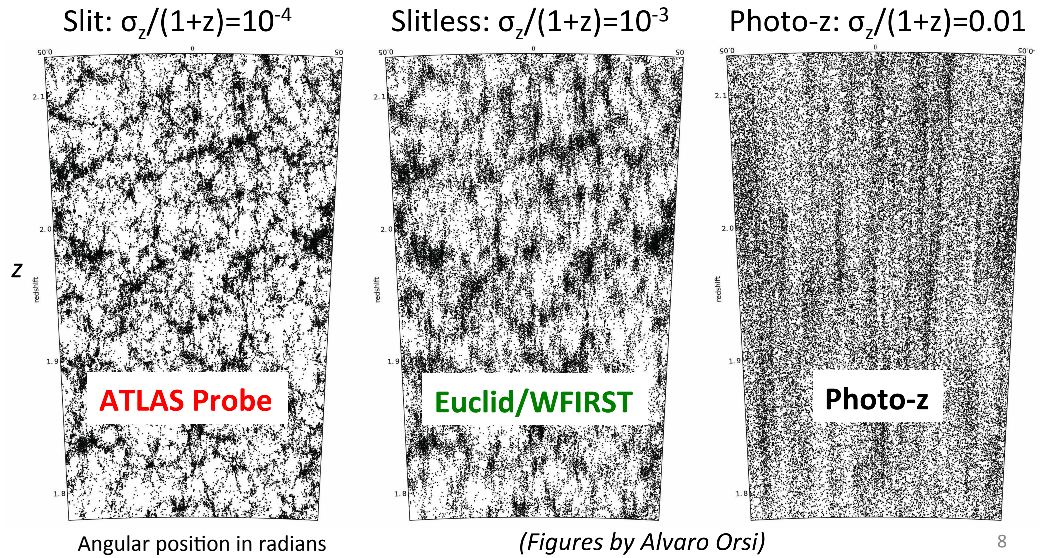
SDSS z < 0.1

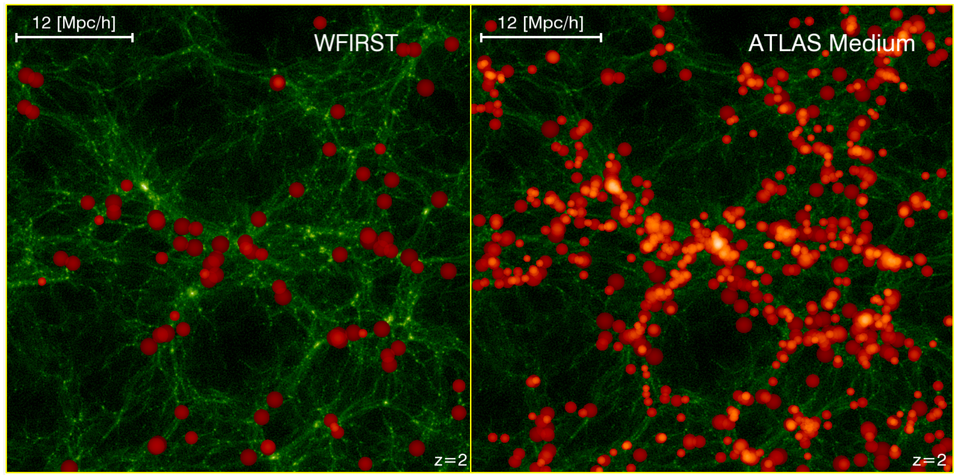


VIPERS 0.5 < z < 1.2 : Guzzo et al

- Charting the cosmic web in the context of galaxy assembly history and chemical enrichment requires good sampling and quality spectra over large cosmic volumes
- Probing beyond z~1 is prohibitive with current facilities
- Euclid & Rubin Obs will yield precision photometric selection of 2 < z < 4 galaxies over 15,000 deg^2

Highly-sampled slit spectroscopy in space

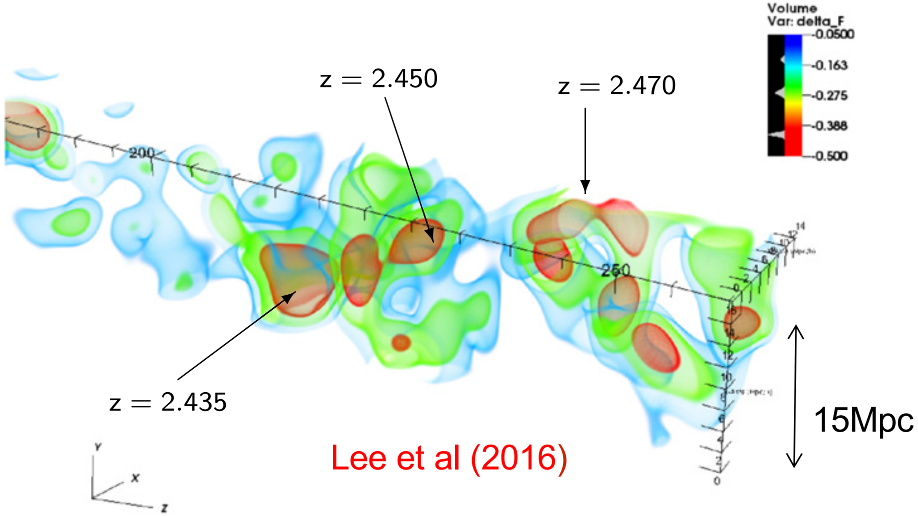




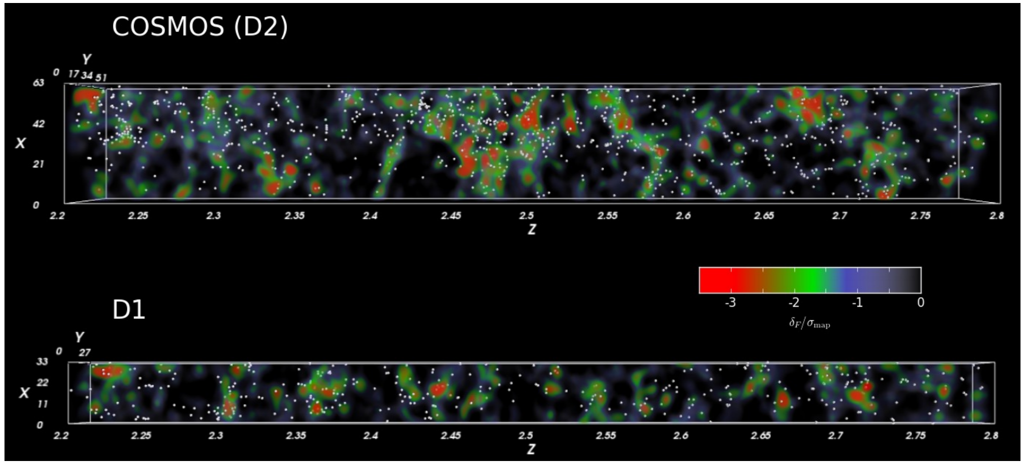
Provided it is technically reliable, DMD 'slit' spectroscopy targeting Hα offers greater precision and **more complete** sampling of the illuminated cosmic web than slitless grism spectra (Euclid/Roman) and photometric redshifts (Rubin)

Dickinson et al (2019)

IGM Tomography via Lyα absorption spectroscopy



Lee et al (2016)



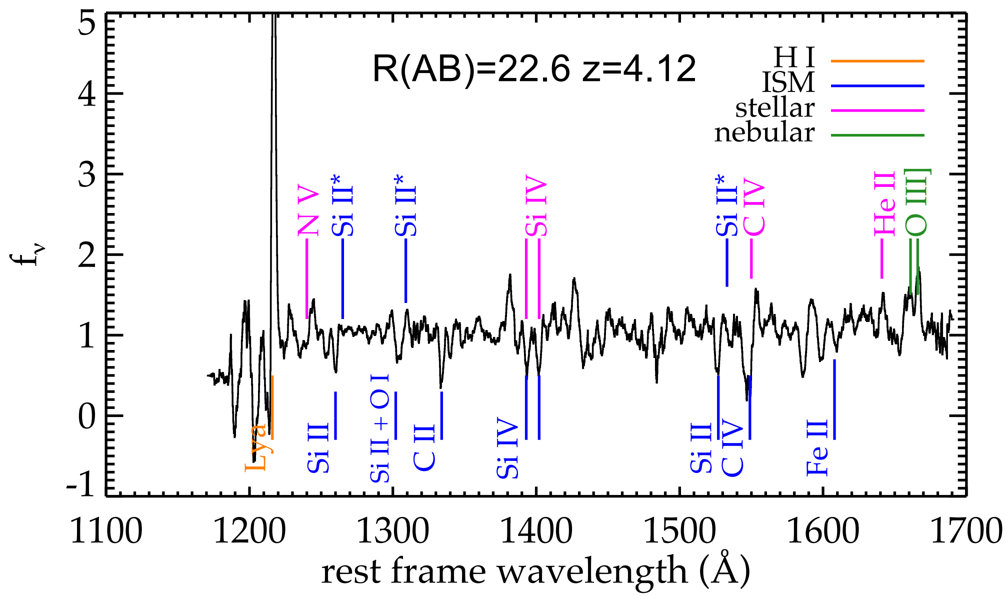
Newman et al (2020)

An equally powerful probe of the cosmic web in redshift range 2.3 < z < 3.5 is possible with large ground-based telescopes:

- Lyα absorption traces large scale structure in mildly overdense regime (i.e. DM)
- Now exploited via Keck and Magellan spectra of abundant Lyman break galaxies (Lee et al 2014, Newman et al 2020)
- Subaru's PFS will map much larger volumes (~ 6 Gpc^3) with adequate sampling (~3 Mpc)
- ELTs will offer coordinated mapping of smaller volumes at better sampling (~1 Mpc)
  & locate metal absorbers to study IGM chemistry in foreground halos

Close coordination between ground and space seems appropriate in this area

Stars/ISM & the Baryon Cycle



Jones et al (2013)
DEIMOS R~2100

- Deep R>2000 spectra of bright z ~2.5-4 galaxies can 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 accessible to JWST so will remain the province of 8-30m facilities

Nonetheless this raises the capability of ATLAS for <u>rest-frame optical absorption studies of high z galaxies</u>

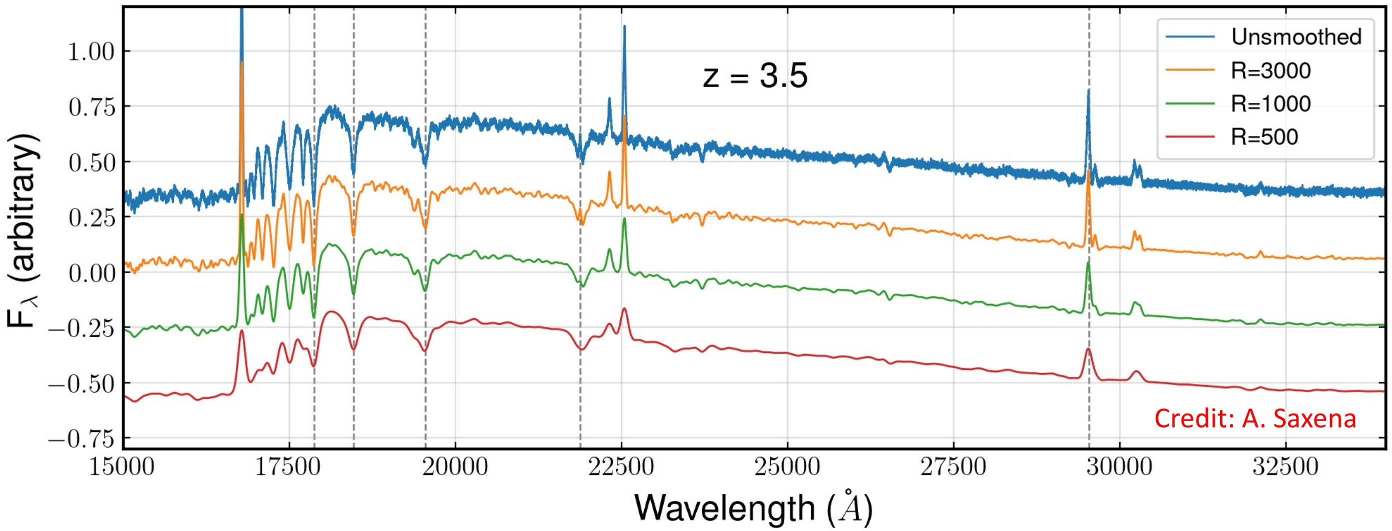
Optimal Spectral Resolution for Galaxy Evolution Studies?

Multi-object optical surveys

Survey	Telescope	Instrument	λλ (nm)	R (0.8”)
GDDS (Abraham)	Gemini	GMOS R150	550-920	600
KBSS (Steidel)	Keck	LRIS B400	300-680	800
VANDELS (Pentericci)	VLT	VIMOS MR	480-1000	720
PFS	*Subaru*	*Blue arm*	*380-650*	*2300*
		Red arm	*630-970*	*3000*

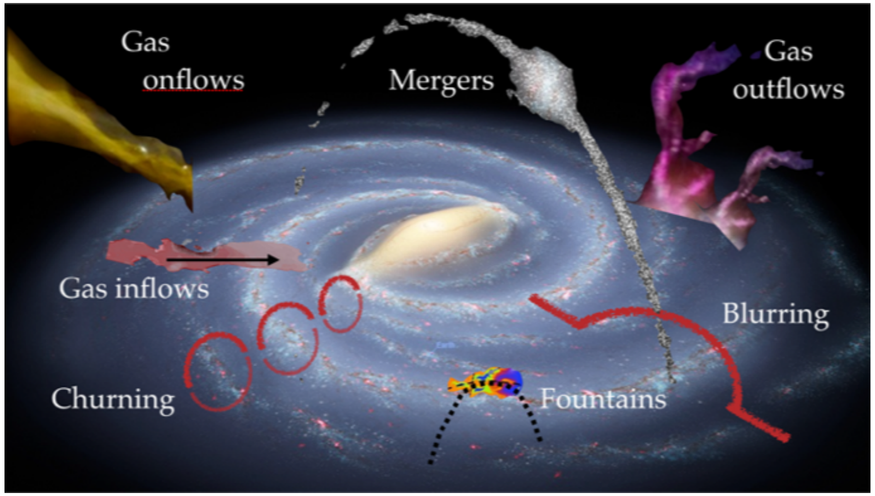
Near-IR instruments (ground/space)

Instrument	R
Keck MOSFIRE	3500
VLT X-shooter	5600
PFS (IR arm)	*4300*
VLT MOONS	*4300*
HST WFC3/G141	130
Euclid	380
Roman ST	460



Galactic Archeology

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



A. Recio-Blanco

Assembly history of the Milky Way, a prototypical large galaxy: it is consistent with hierarchical cosmology?

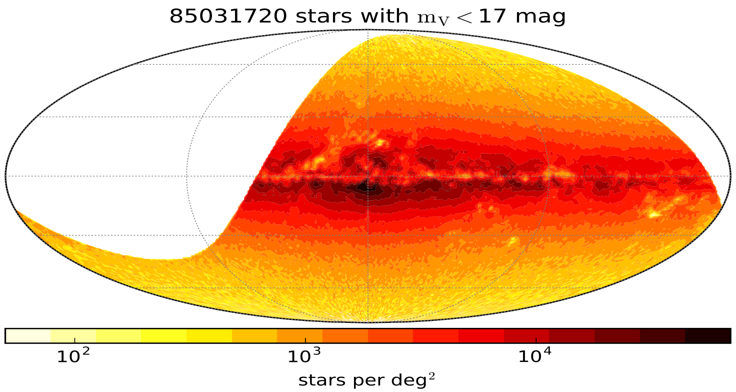
- Studies in the DM-dominated halo (3-D distribution, low mass dark halos, cores vs cusps in satellites)
- ‘Chemical tagging’ identifies widely-dispersed stars of common origin reconstructing merger histories
- Connecting nucleosynthetic yield with earlier SF histories; formation of heavy elements e.g. r-process
- Satellites as tests of low mass galaxy formation models and earliest sources in reionisation era

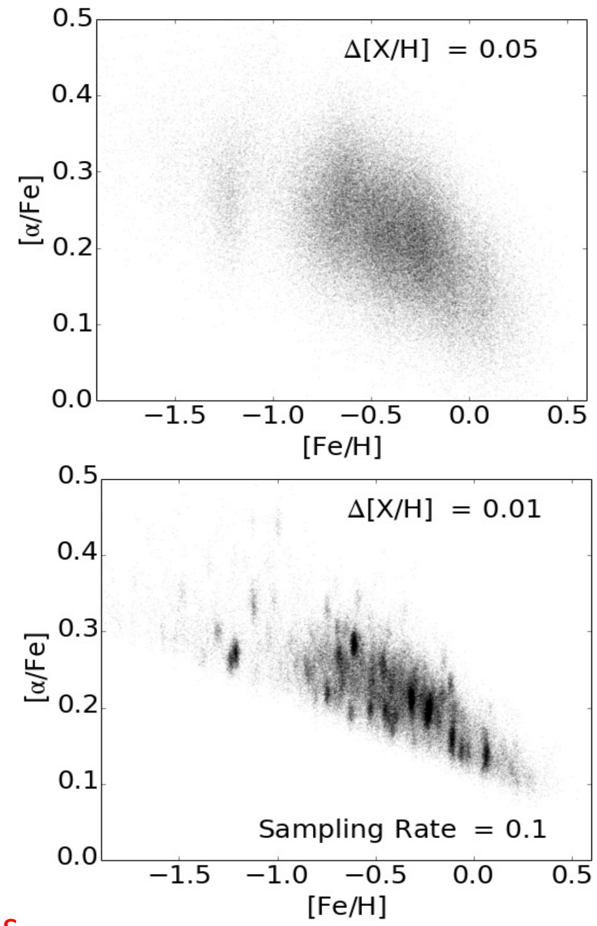
Chemical Tagging Statistics

Chemical tagging enables individual dispersed Galactic stars to be 'fingerprinted' and collated to identify their birth history. Although planned with various 4m spectroscopic facilities (e.g. 4MOST, WEAVE), gain of wide-field larger telescopes is significant (Megamapper, MSE, Spectel)

Illustrative survey: R~20,000 spectra of ~15M V<17 stars
Target densities ~ 600 to 10,000 deg^{-2}

- High precision abundances essential: d[X/H] < 0.03
- High number of elements N advantageous N >15
- Sample size M is important
- Probing further in distance
  - rare events scale as M
  - # of twins scales as M^2
  - Tagging precision d[X/H]^N

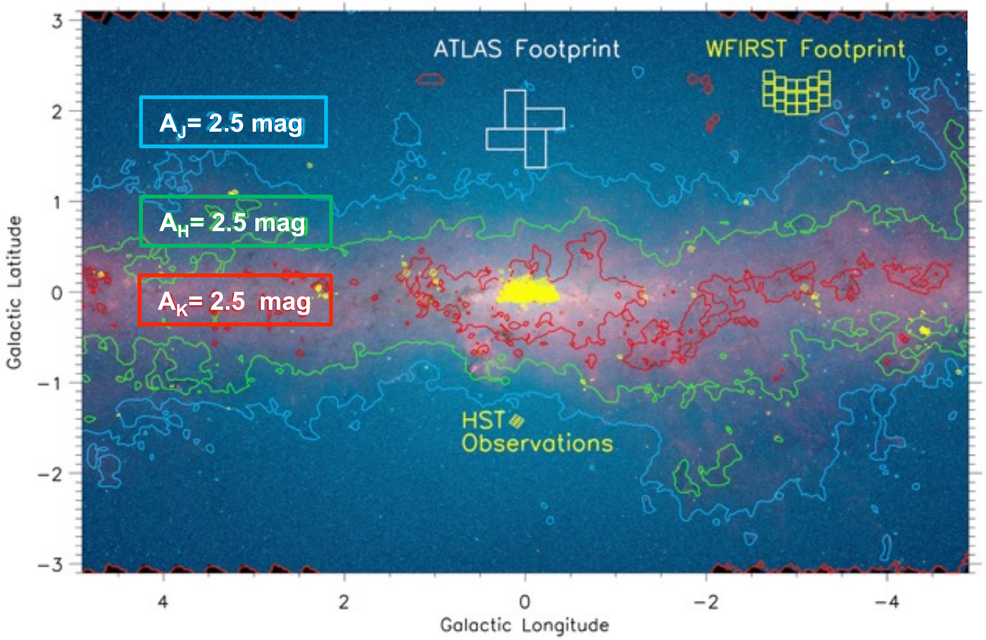


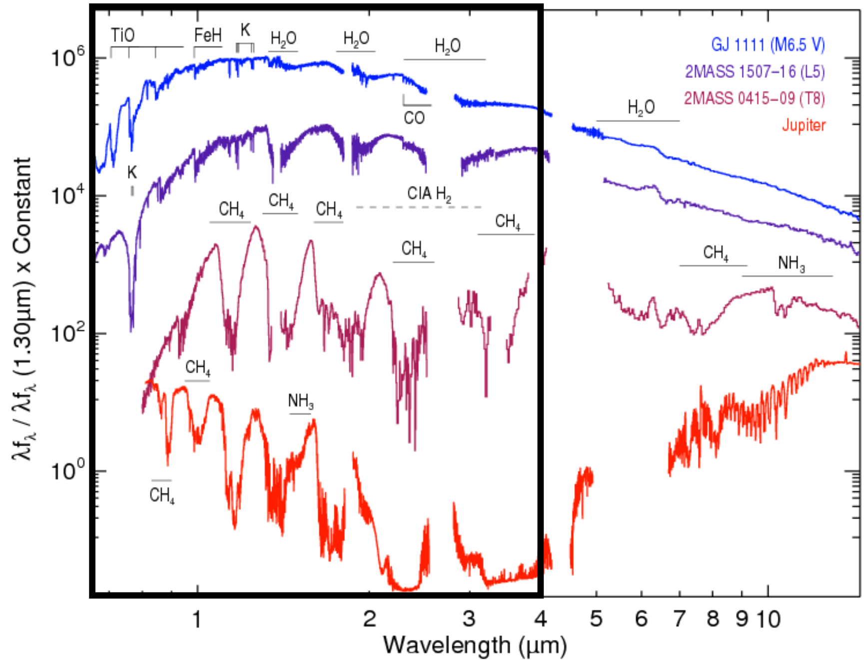


Exciting growth area for wide-field large aperture optical ground-based facilities

Ting et al 2016

Near infrared Galactic science



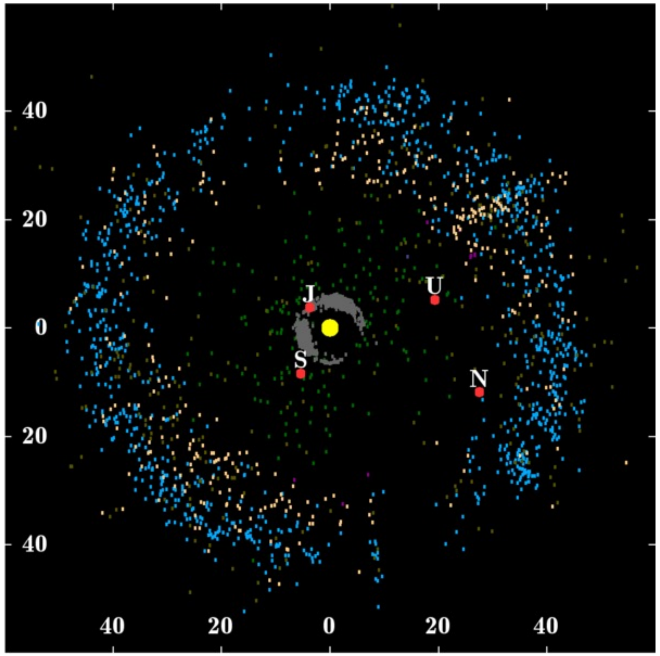


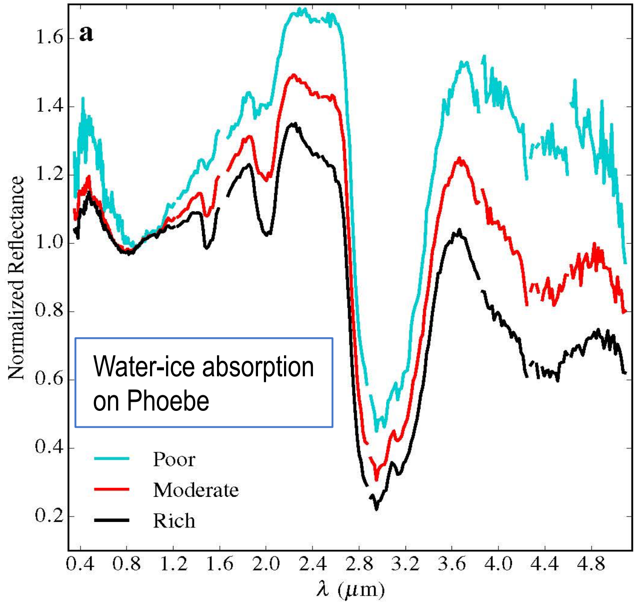
Space-borne near-infrared spectroscopy most effective in probing molecular bands, composition and effective temperatures of long-lived low mass stars in the crowded and dust-obscured Galactic plane

Improved 3D structure of Galactic disk in concert with Gaia proper motions and radial velocities

Key issue is ability to resolve individual stars in the most crowded regions (is 0.75 arcsec aperture optimal?)

Solar System Science





Near-infrared spectroscopy key to compositional studies of thousands of trans-Neptunian objects whose orbits are known

Many thousands more will soon be discovered and analysed with Rubin Observatory (total population 10^5 >100 km across!)

If non-sidereal sources can be efficiently tracked, this is an exciting growth area!

Transient Science

- Rubin Observatory will also transform searches for time-dependent phenomena:
  major growth area in astrophysics

- Roman Space Telescope will continue/extend the possibilities

- Spectra needed to confirm classifications and follow-up unexplored phase-space

  - Classical SNe – astrophysics and cosmology
  - Rarer events – SNe Ib/c, SLSNe, GW events, kilonovae, gap transients, tidal disruption events
  - AGN – reverberation mapping

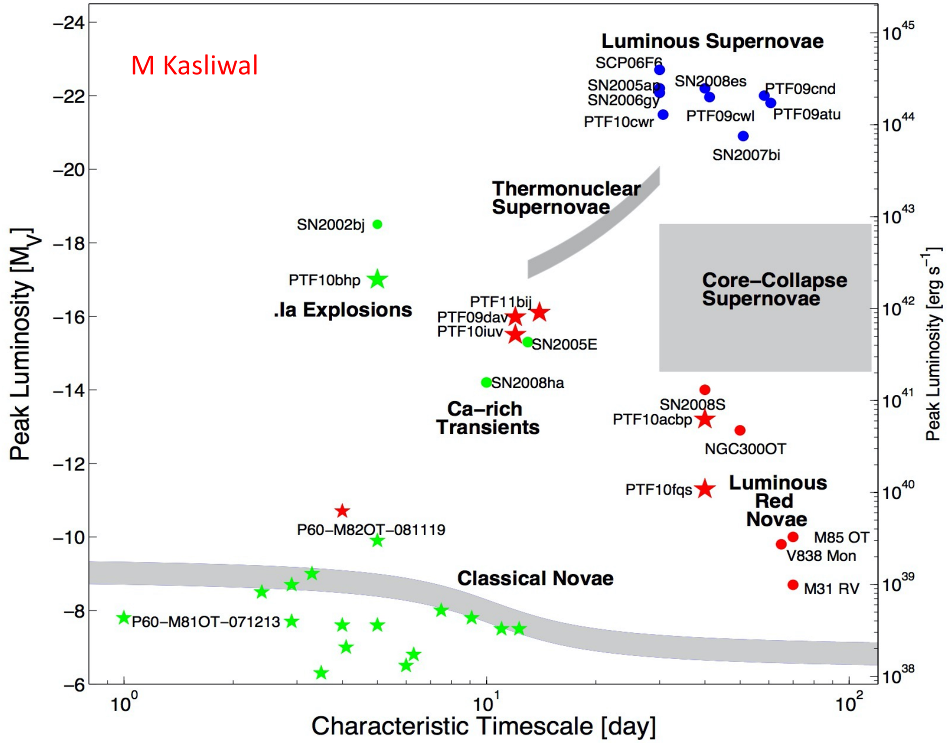
- Distinguish between follow-up of rare *live events* and accumulated *transpired events* where host galaxy redshifts and local environment properties will be ascertained (c.f. successful DES+OzDES model)

- Traditionally been done at optical wavelengths with rapid-response automated telescopes; but most transients found in the 2020s will be fainter and require more powerful facilities

- Is there a role for rapid-response near-infrared spectroscopy in space?

Illustration: SNe Follow-Up

- Rubin Observatory will generate 300,000 SNe/year (60% Ia, 35% II, 5% others)
- Expect ~40,000 *live events* at any time: 2-4 deg^{-2}
- Accumulated *transpired events over 5yrs:* ~80 deg^{-2}
- *Live spectra* calibrate photometric classifiers which, together with host galaxy spectra for *transpired events*, adequate for cosmology
  (4MOST z < 0.6, but can probe z>1 in near-IR)
- Over 5 year mission ~25,000 live spectra? Many hundreds of spectra of rare/unusual transients



Ellis et al arXiv 1701.01976

The Emerging Landscape – Space/Ground Partnership

- Massively-multiplexed spectroscopy will exploit the upcoming investment in deep panoramic imaging

- Science themes extend well beyond cosmological surveys
  - Galactic archeology as probe of near-field cosmology (DM tracers, assembly histories)
  - Galaxy evolution in relation to the cosmic web
  - Transient sources, trans-Neptunian bodies

- Significant push with ground-based facilities but largely focusing in the optical

- Unique science in the near-infrared where space has a big advantage
  - More complete coverage, free from OH obscuration
  - Reduced sky background and extension beyond 2.5 microns (high redshift)

- ATLAS has many advantages over other space facilities
  - Slit-based spectroscopy (if technical risk can be allayed)
  - Higher spectral resolution (is R~1000 optimal?)
  - Any options for an IFU – even if incompletely sampled?

Ultimately we will likely have both ground- and space-based facilities so synergies will be very important