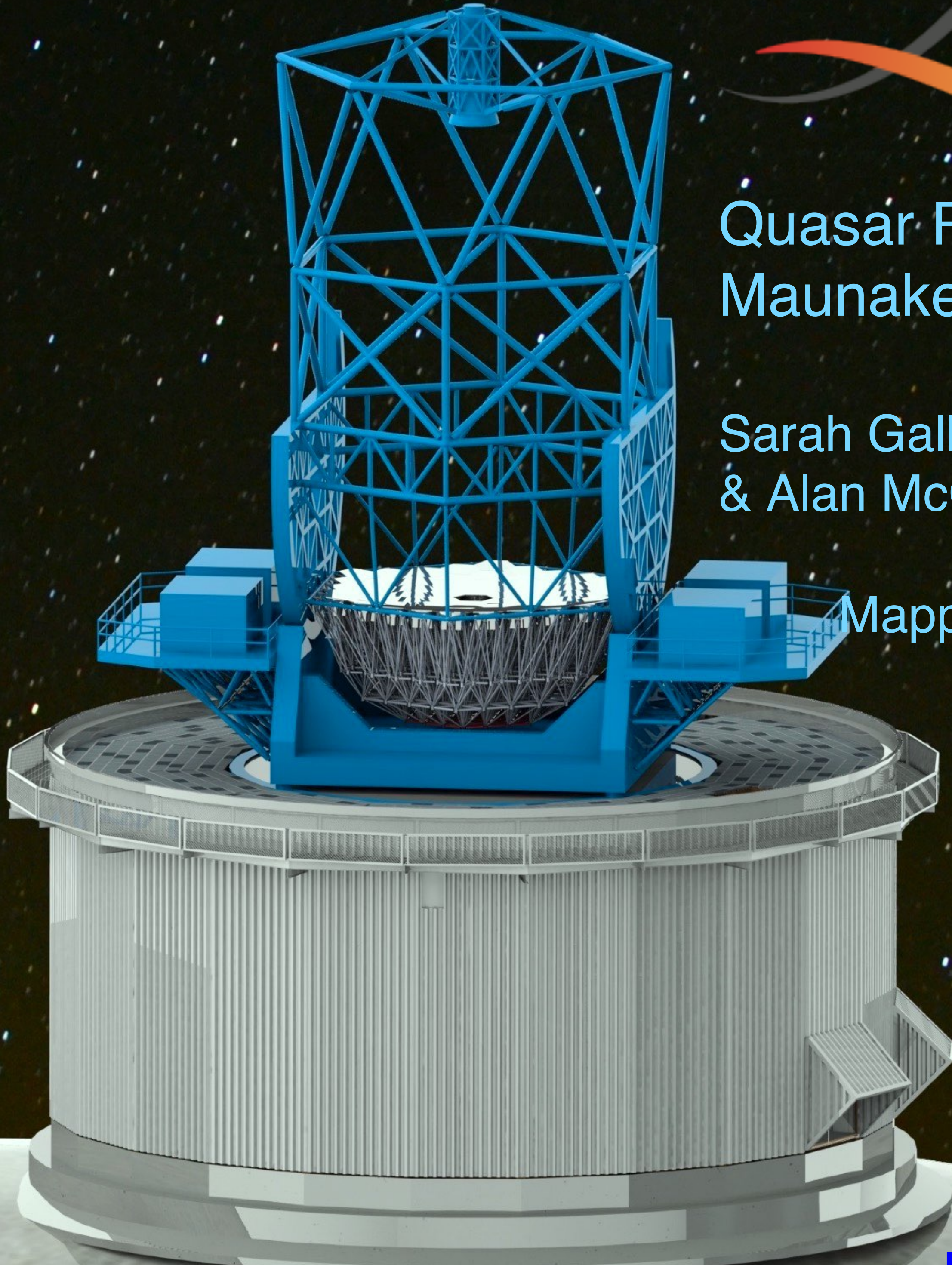


Quasar Reverberation Mapping with the Maunakea Spectroscopic Explorer

Sarah Gallagher

Western University · Canada

& Alan McConnachie (NRC-Herzberg, Canada)

Mapping the Inner Parsec of Quasars team:

Kelly Denney (Ohio State, USA)

Pat Hall (York U, Canada)

Keith Horne (St. Andrews, UK)

Anna Pancoast (CfA, USA)

Yue Shen (U of Illinois, USA)

Chris Willott (NRC-Herzberg, Canada)

http://mse.cfht.hawaii.edu

MSE = CFHT+SDSS on steroids

excellent site, way bigger & all spectra, all the time

spectroscopy monster

MSE = CFHT+SDSS on steroids

excellent site, way bigger & all spectra, all the time

coldown.deviantart.com/art/Rainbow-monster-360034942

spectroscopy monster

Motivation

- In the past year:
  - Australian Decadal Plan:

Building on Australia's world-leading expertise in optical multi-object spectroscopy, **development of an 8-metre class optical/IR wide-field spectroscopic survey telescope towards the end of the decade would complement Australian optical/IR astronomers' leading priority of access to a multi-purpose 8-metre class optical/IR observatory.** Such a facility, most likely constructed by an international partnership, would address several of the fundamental astronomical questions of the coming decade, including the nature of dark matter and dark energy, the formation and evolution of the Milky Way and how stars and galaxies process chemical elements. It would also provide follow-up spectra of objects identified by the SKA and imaging telescopes like the US-led Large Synoptic Survey Telescope (LSST). Involvement in the LSST, especially in combination with a large, wide-field optical/infrared spectroscopic survey facility, would provide excellent synergies with the next generation of radio facilities (ASKAP, MWA, SKA), and build on Australia's leadership in all-sky surveys.

Motivation

- In the past year:
  - Australian Decadal Plan
  - Canadian Mid-Term Review (of our Decadal Plan):

> "…The scientific and collaborative opportunities available to MSE partners are a direct indicator of the strategic relevance of MSE to the future astronomy landscape.
>
> The MTRP thus makes the following recommendation:
>
> Recommendation: The MTRP strongly recommends that Canada develop the MSE project, and supports the efforts of the project office to seek financial commitments from Canadian and partner institute sources."

Motivation

- In the past year:
  - Australian Decadal Plan
  - Canadian Mid-Term Review (of our Decadal Plan)
  - Establishment of ESO Working Group on Wide Field MOS:

> "Following the prioritisation of the ESO science programme for the 2020s and the envisaged importance of highly-multiplexed spectroscopy for numerous scientific applications in the future, the ESO Director for Science, Rob Ivison, has established a Working Group to investigate the scientific case, synergistic opportunities and practical requirements for a dedicated ground-based wide field spectroscopic survey telescope in the 2020s."

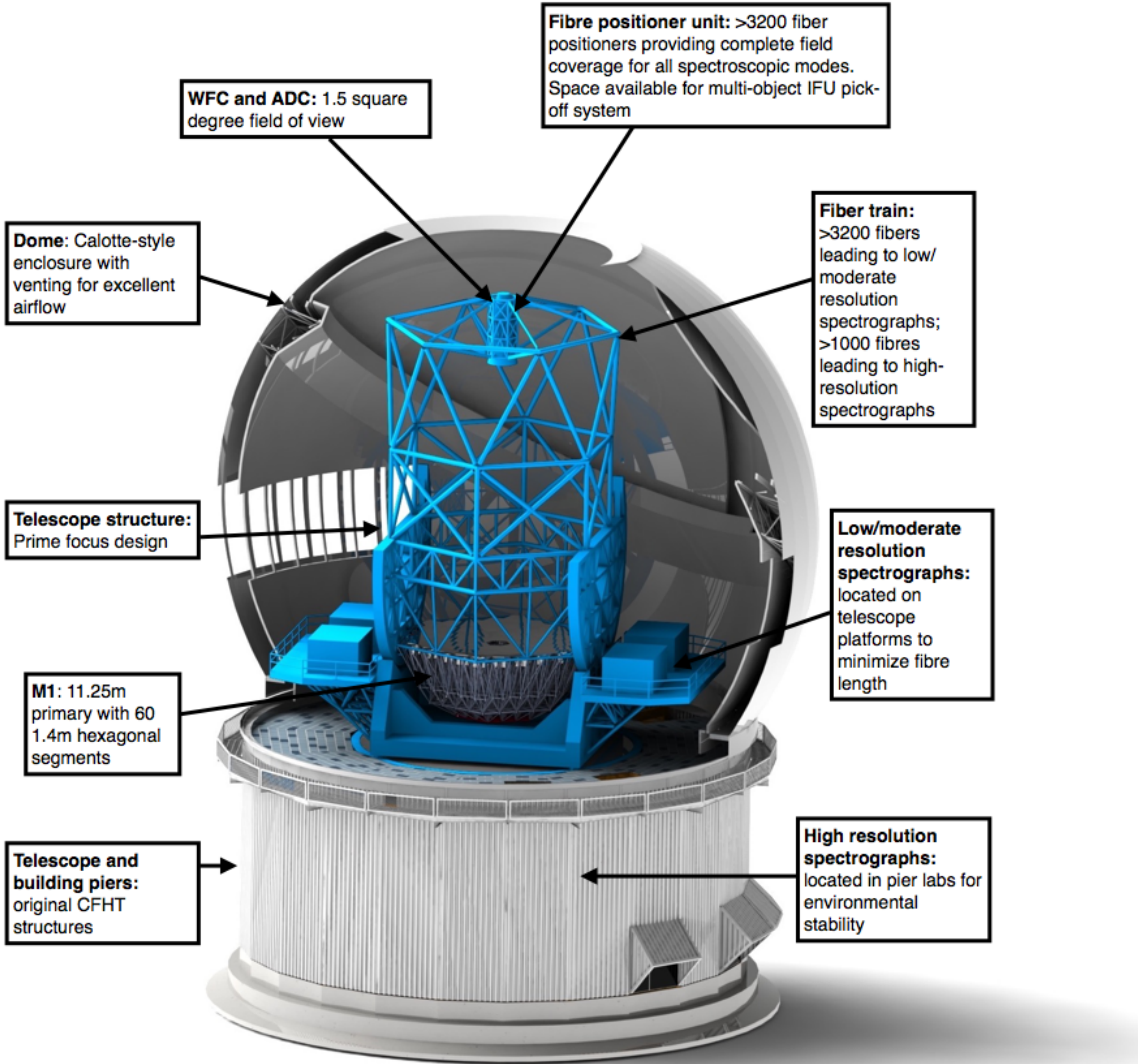
Advantages of CFHT → MSE

Legacy

3.6-m Canada-France-Hawaii Telescope
Existing infrastructure (institutional + structural)
Large dome + building pier
Best seeing on Maunakea (typically 0.6”)

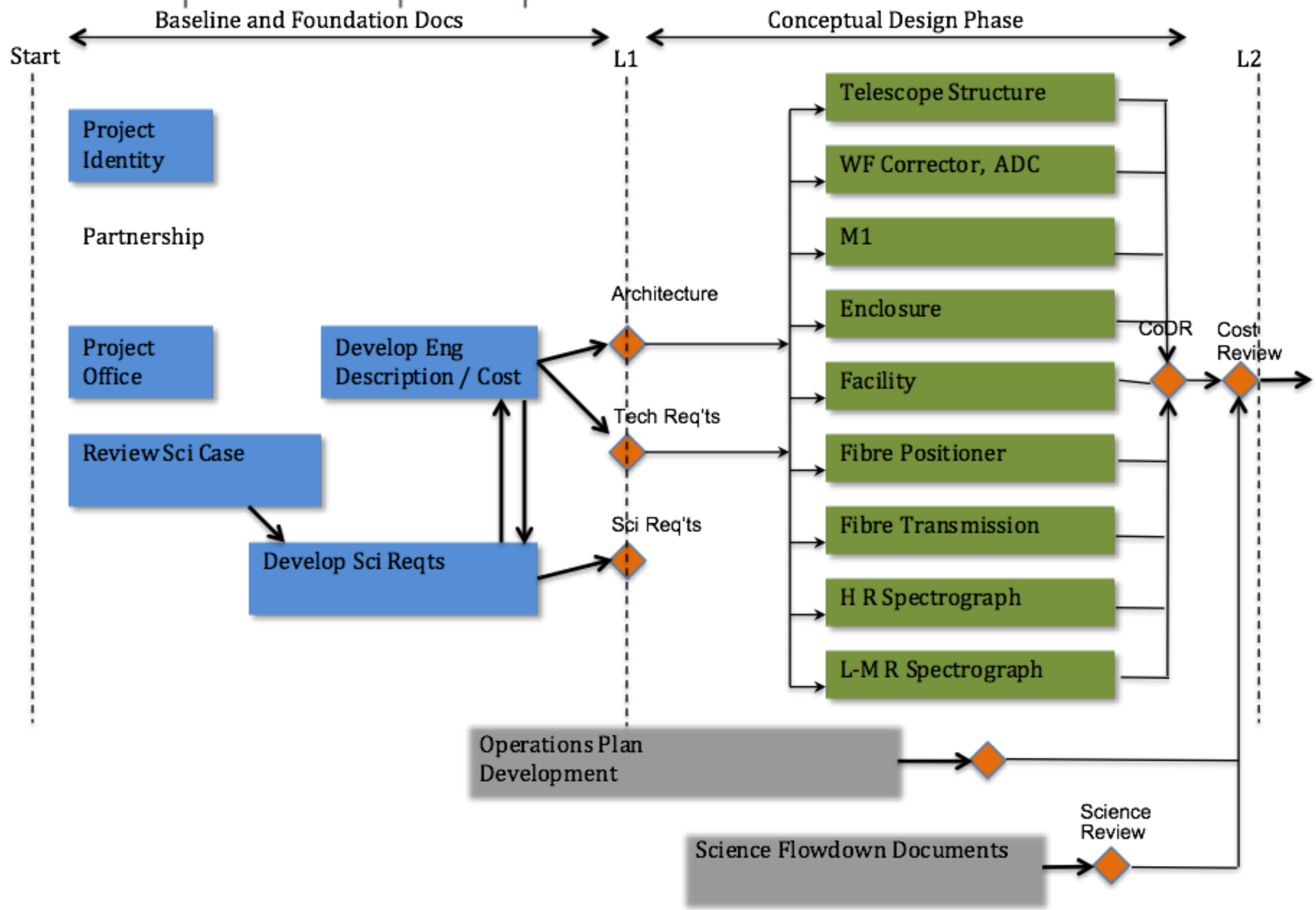
International Collaboration

- MSE Collaboration includes:
  - Canada, France, Hawaii (CFHT members)
  - Australia, China (USTC + NIAOT), India, Spain


Fibre positioner unit: >3200 fiber positioners providing complete field coverage for all spectroscopic modes. Space available for multi-object IFU pick-off system
WFC and ADC: 1.5 square degree field of view
Fiber train: >3200 fibers leading to low/ moderate resolution spectrographs; >1000 fibres leading to high-resolution spectrographs
Dome: Calotte-style enclosure with venting for excellent airflow
Telescope structure: Prime focus design
Low/moderate resolution spectrographs: located on telescope platforms to minimize fibre length
M1: 11.25m primary with 60 1.4m hexagonal segments
Telescope and building piers: original CFHT structures
High resolution spectrographs: located in pier labs for environmental stability

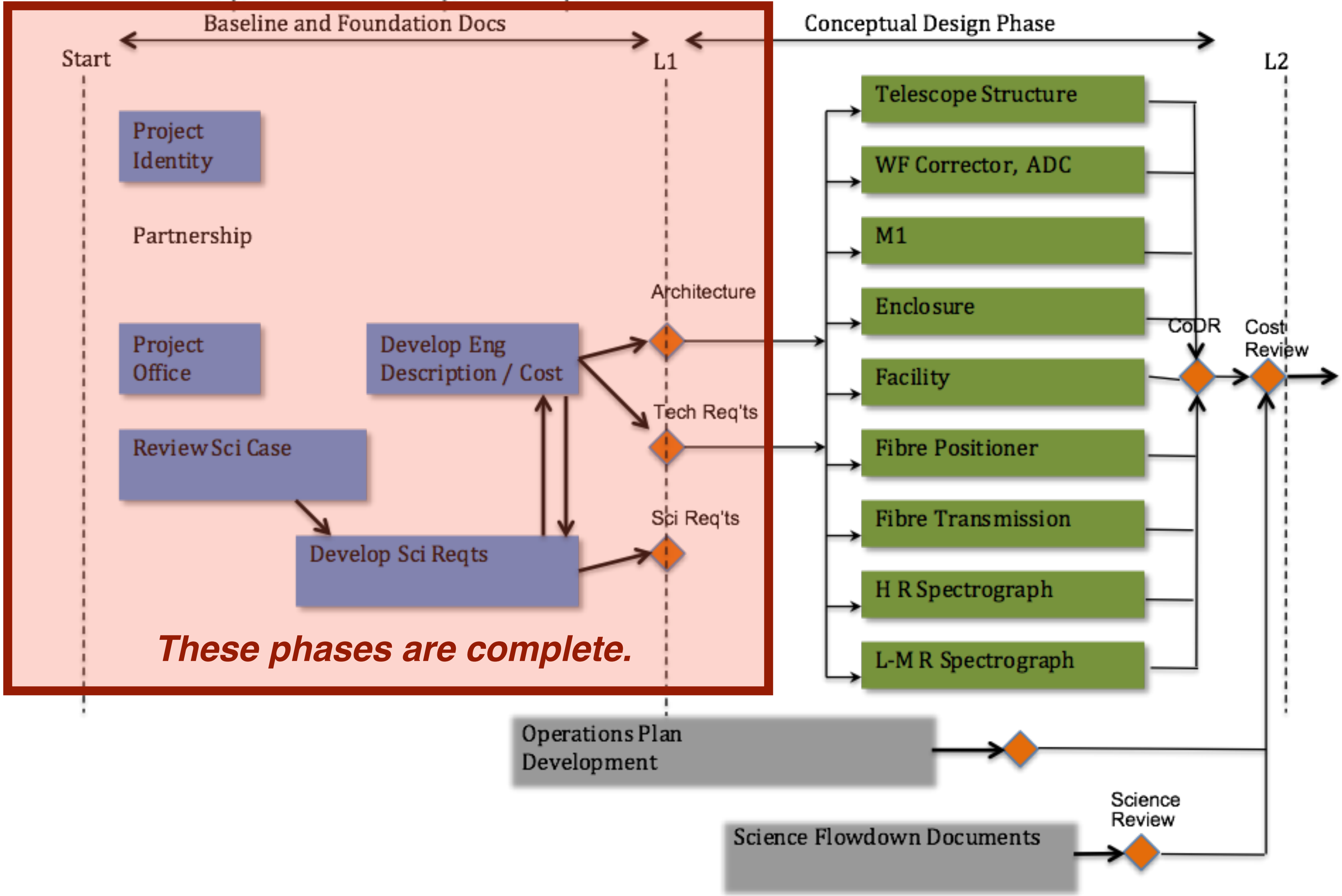
Maunakea Spectroscopic Explorer

Project Status



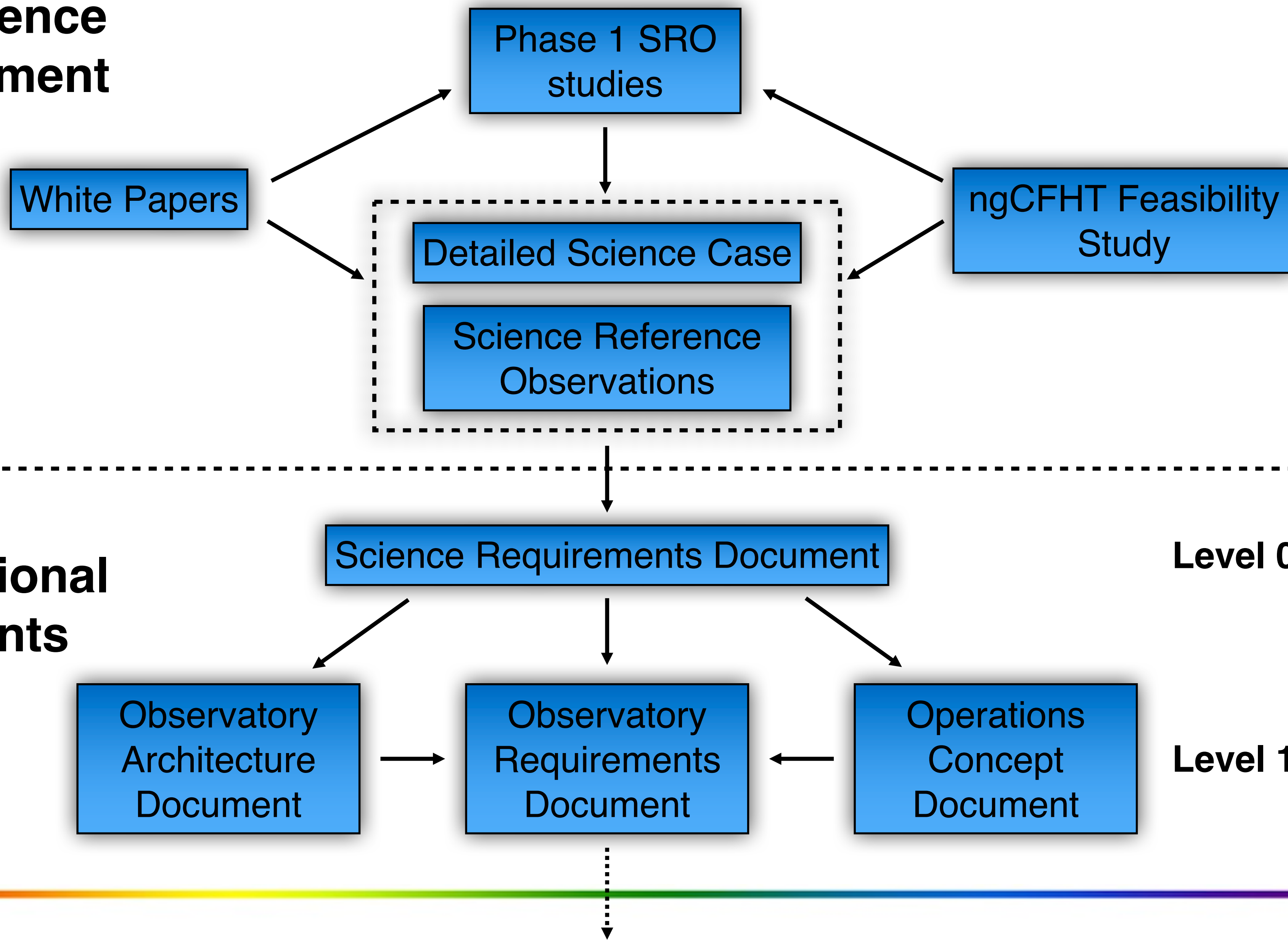
Maunakea Spectroscopic Explorer

Project Status



Science Development to Date

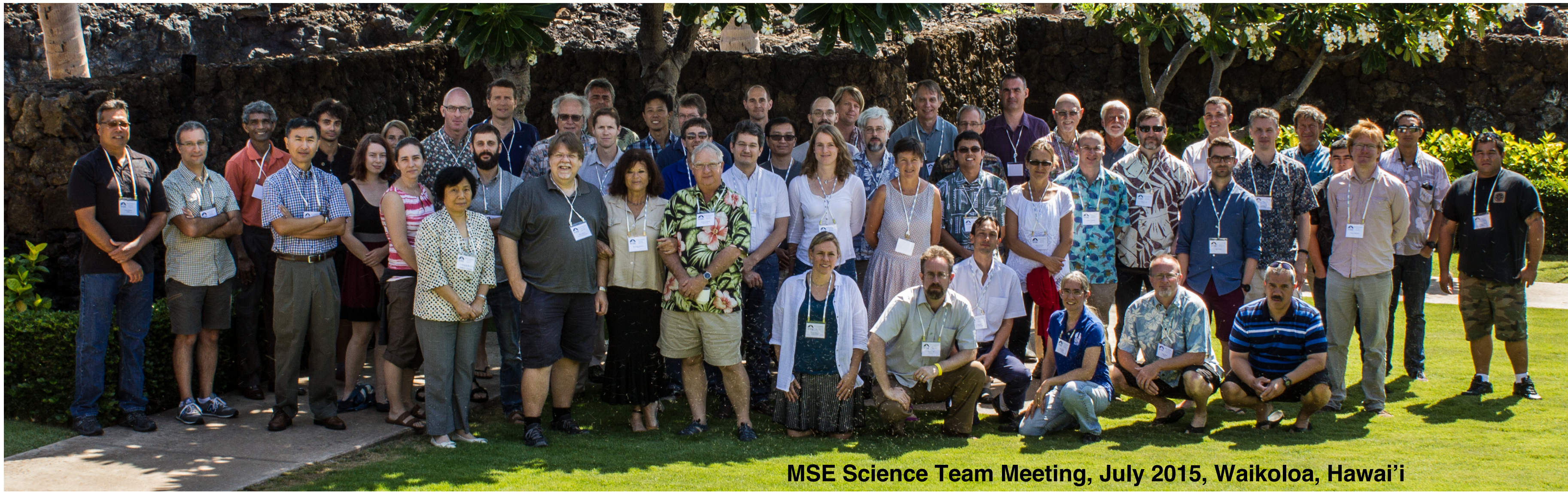
MSE Science Development Phase



MSE Foundational Documents

Maunakea Spectroscopic Explorer

The MSE Science Team



MSE Science Team Meeting, July 2015, Waikoloa, Hawai'i

- Project Scientist: Alan McConnachie
- Systems Scientist: Nicolas Flagey

- MSE Science Team (107 members):
  - Australia - 15; Canada - 15; China - 8; France - 22; India - 10; Spain - 8; Other - 19

Science Requirements

- **Science Requirements:** the science capabilities *required* to conduct the suite of science programs described by the Science Reference Observations (SROs): **high-impact science programs that are uniquely possible using MSE**

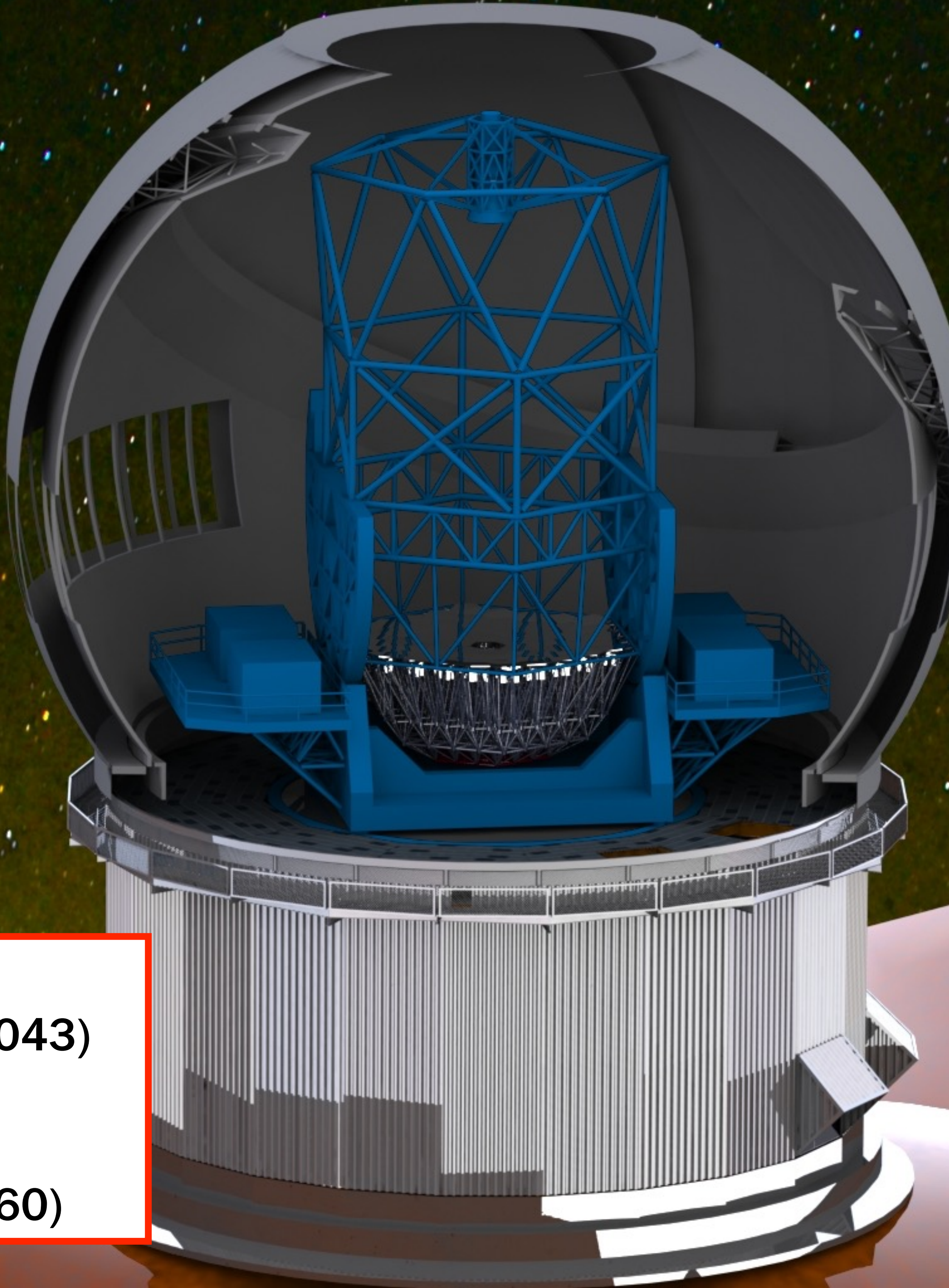
- Currently 24 science requirements define the capabilities of MSE. Board-level approval is needed to change these.

The composition and dynamics of the faint Universe

I. Deconstructing the Galaxy

II. Linking Galaxies to the Large Scale Structure of the Universe

III. Illuminating the Dark Universe

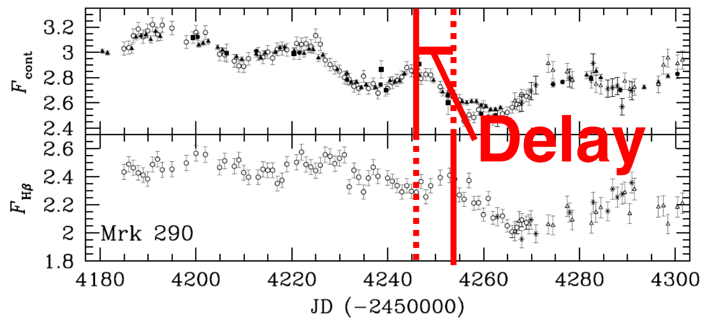


“Detailed Science Case”
(~200 pages; arxiv.org/abs/1606.00043)
&
“MSE: a concise summary”
(10 pages; arxiv.org/abs/1606.00060)

Maunakea Spectroscopic Explorer

Mapping the Inner Parsec of Quasars: program goals

Measure black holes masses for ~2500 quasars up to z~3.



Map the inner parsec of 100s of quasars.

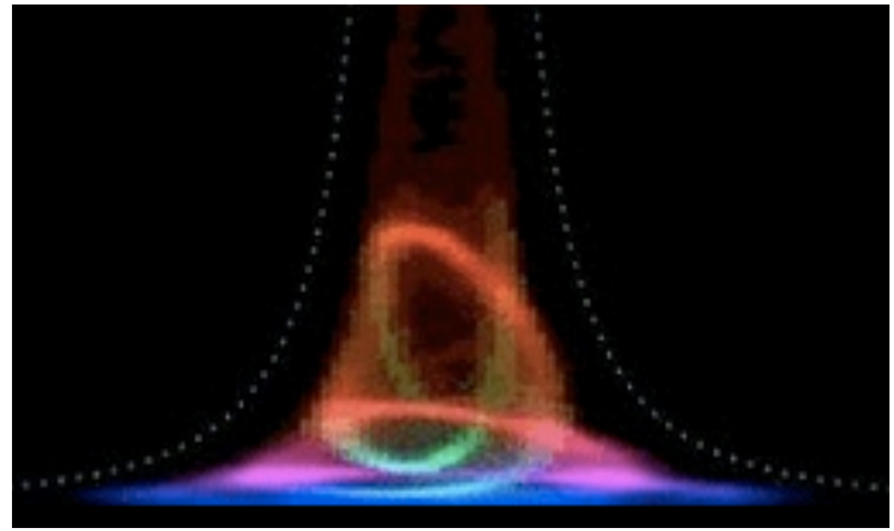
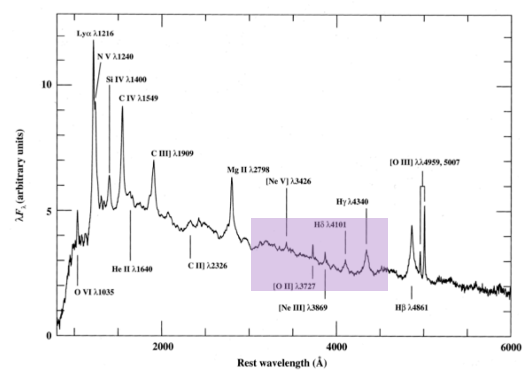


Image credit: Keith Horne

Obtain extremely high S/N rest-frame optical-UV spectra of ~5000 quasars.



BONUS: High-z Hubble diagram for cosmology

Specs for the MSE RM Quasar Program

5000 quasars:

→ *7 fields, ~700 quasars per 1.5 deg^2 field*

Repeat observations:

→ *100 epochs; cadence from days to months over ~5 yrs*

Sensitivity (1 hr exposure):

→ *S/N~30 (10) i=21.8 (23.25) @ CIV for z=2*

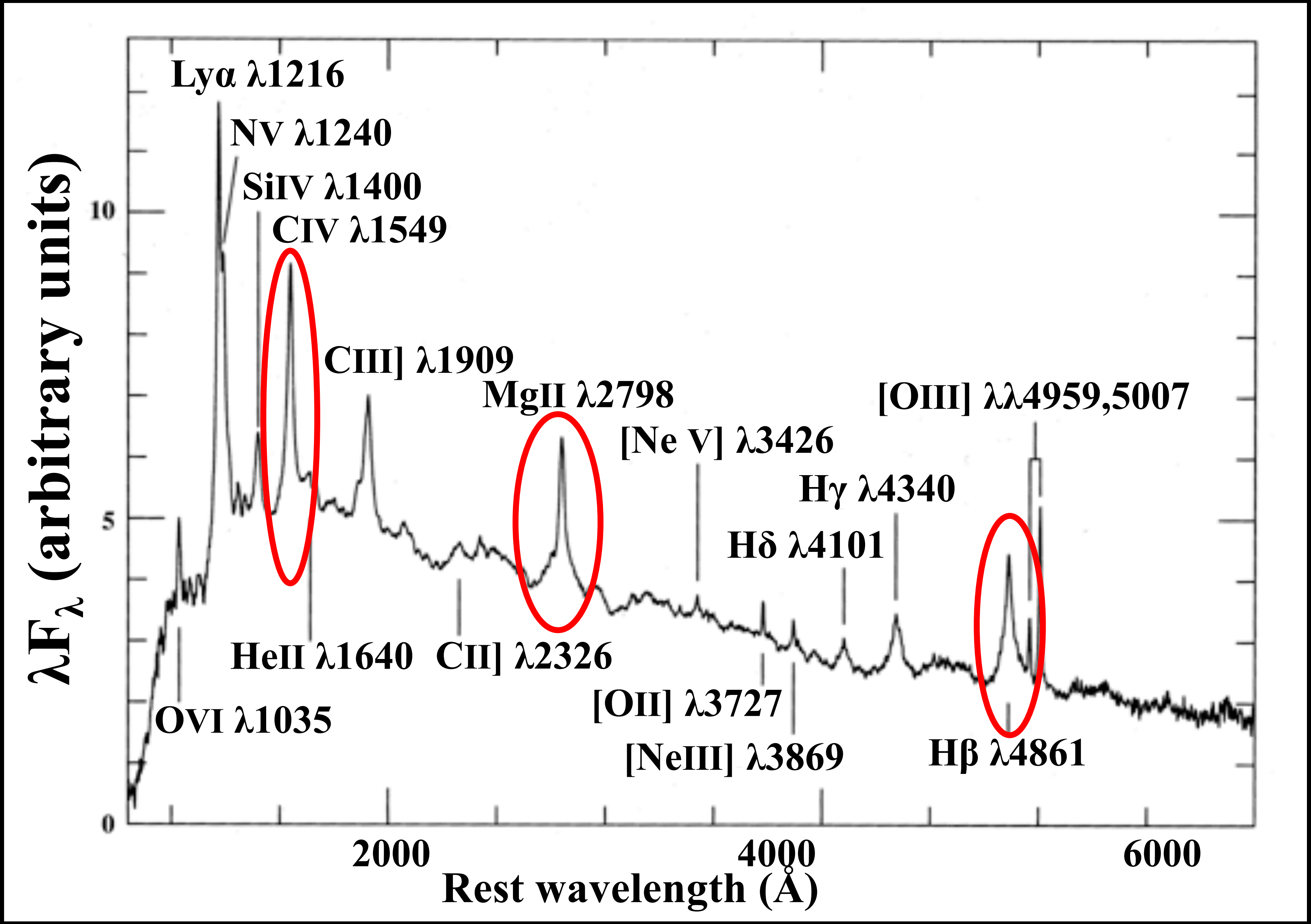
Wavelength coverage:

→ *400 nm to 1.8 μm to get CIV through Hβ*

Accurate spectrophotometry:

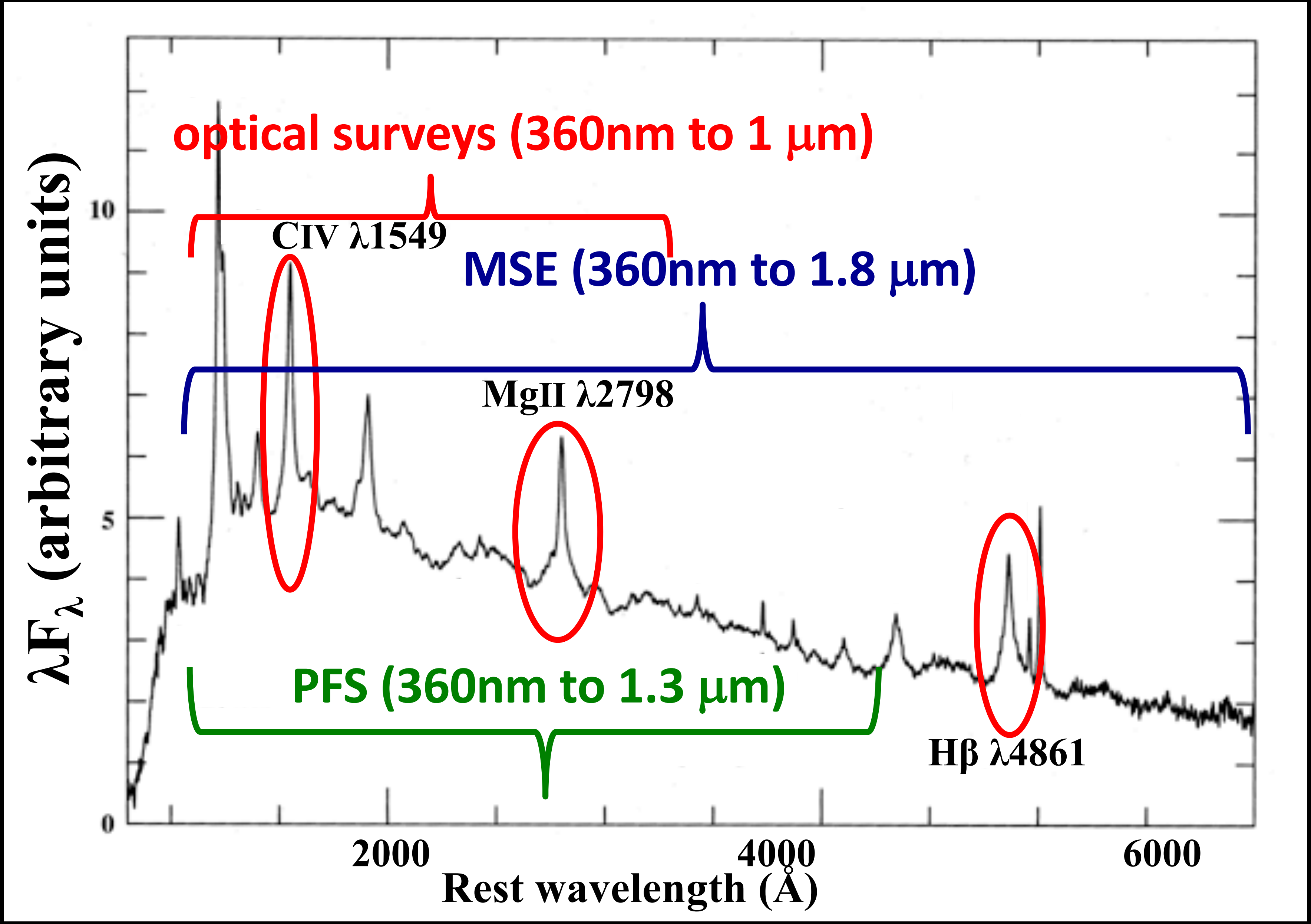
→ *3-4% (relative) accuracy across the bandpass*

Emission Lines Used for BH Masses



Composite from the Large Bright Quasar Survey (Francis et al. 1991)

Wavelength coverage at z=2



Composite from the Large Bright Quasar Survey (Francis et al. 1991)

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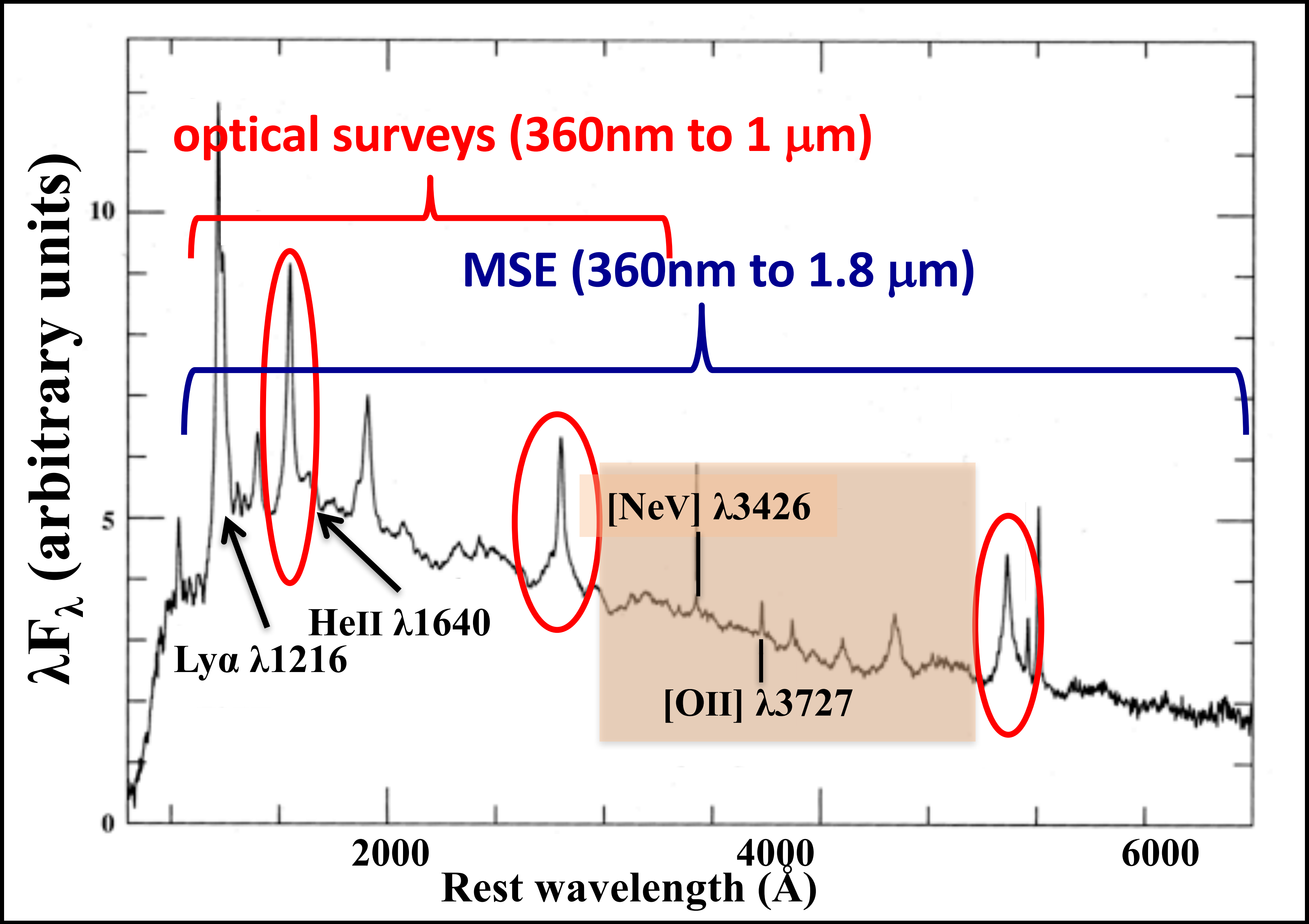


Composite from the Large Bright Quasar Survey (Francis et al. 1991)

Why H-band?

Peak of quasar epoch is z~2-3

→ *when black hole mass was built-up in massive galaxies*

→ *these host galaxies will be prime targets for ELTS*

Access to a range of emission lines

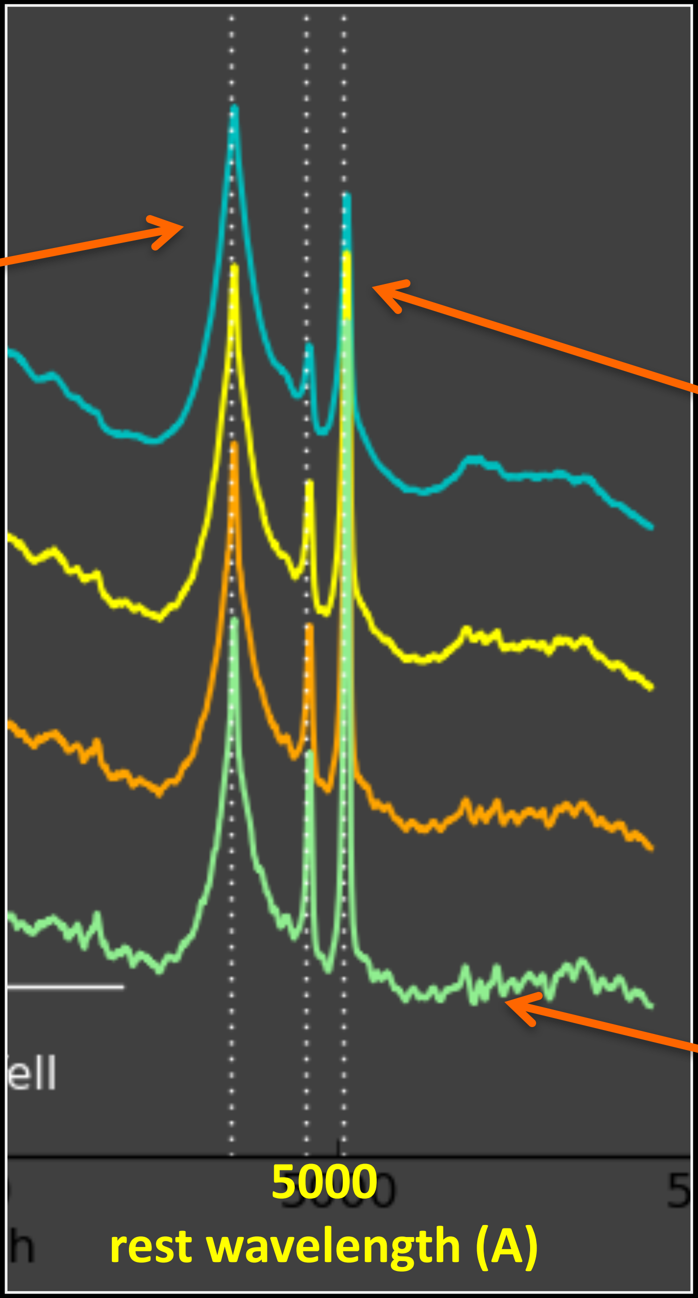
→ *CIV to Hβ probes the inner to the outer broad-line region*

→ *many more narrow-lines in rest-frame optical*

→ *many more host galaxy features in rest-frame optical*

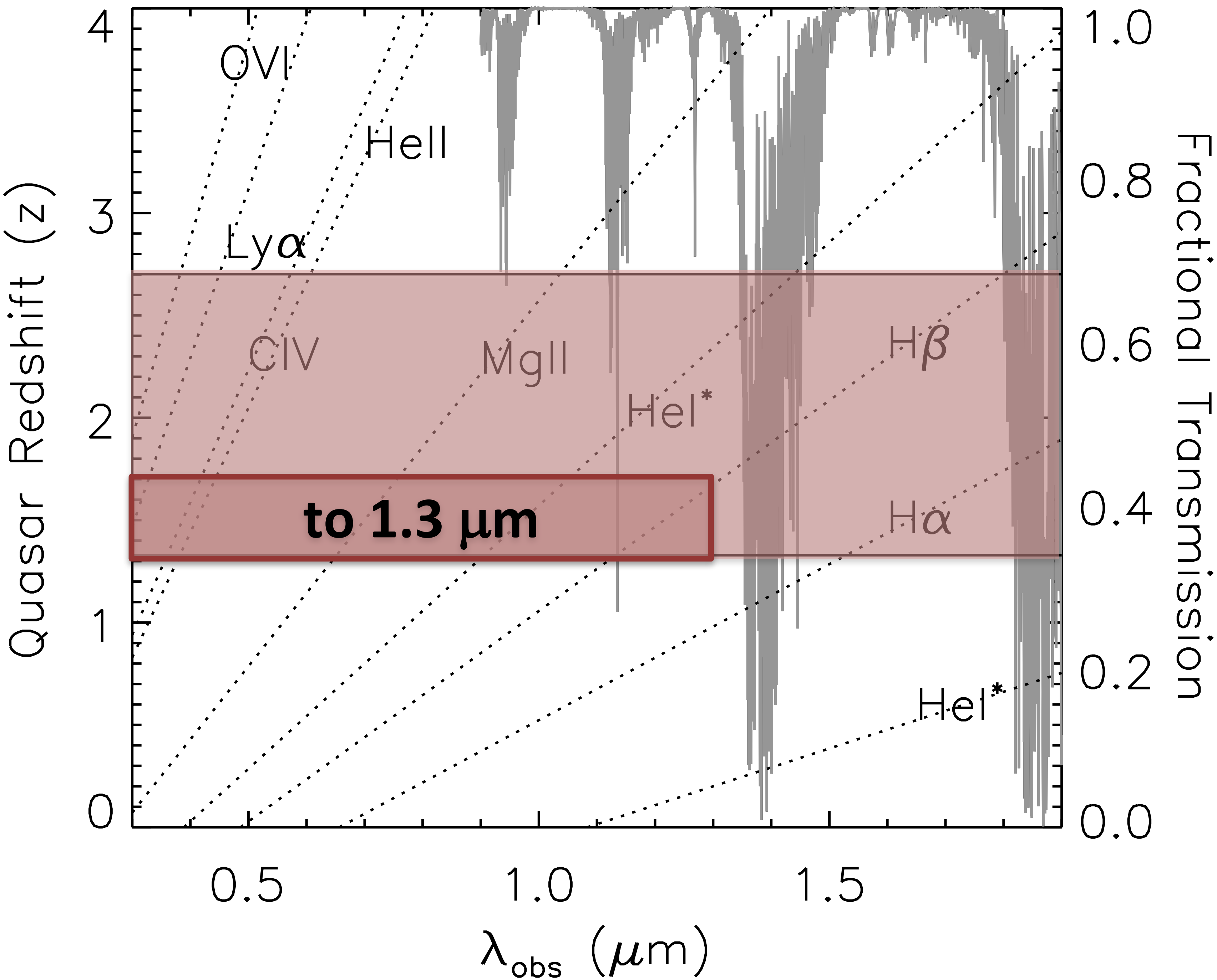
Hβ Region (H-band at z~2)

Hβ
reverberating
emission line



[OIII] doublet
narrow line emission
→ doesn't reverberate on short timescales
→ flux calibrator

local continuum



OVI
HeII
Lyα
CIV
MgII
HeI*
Hβ
Hα
HeI*
to 1.3 µm
Quasar Redshift (z)
Fractional Transmission
λobs (µm)
0.5
1.0
1.5
0
1
2
3
4
0.0
0.2
0.4
0.6
0.8
1.0

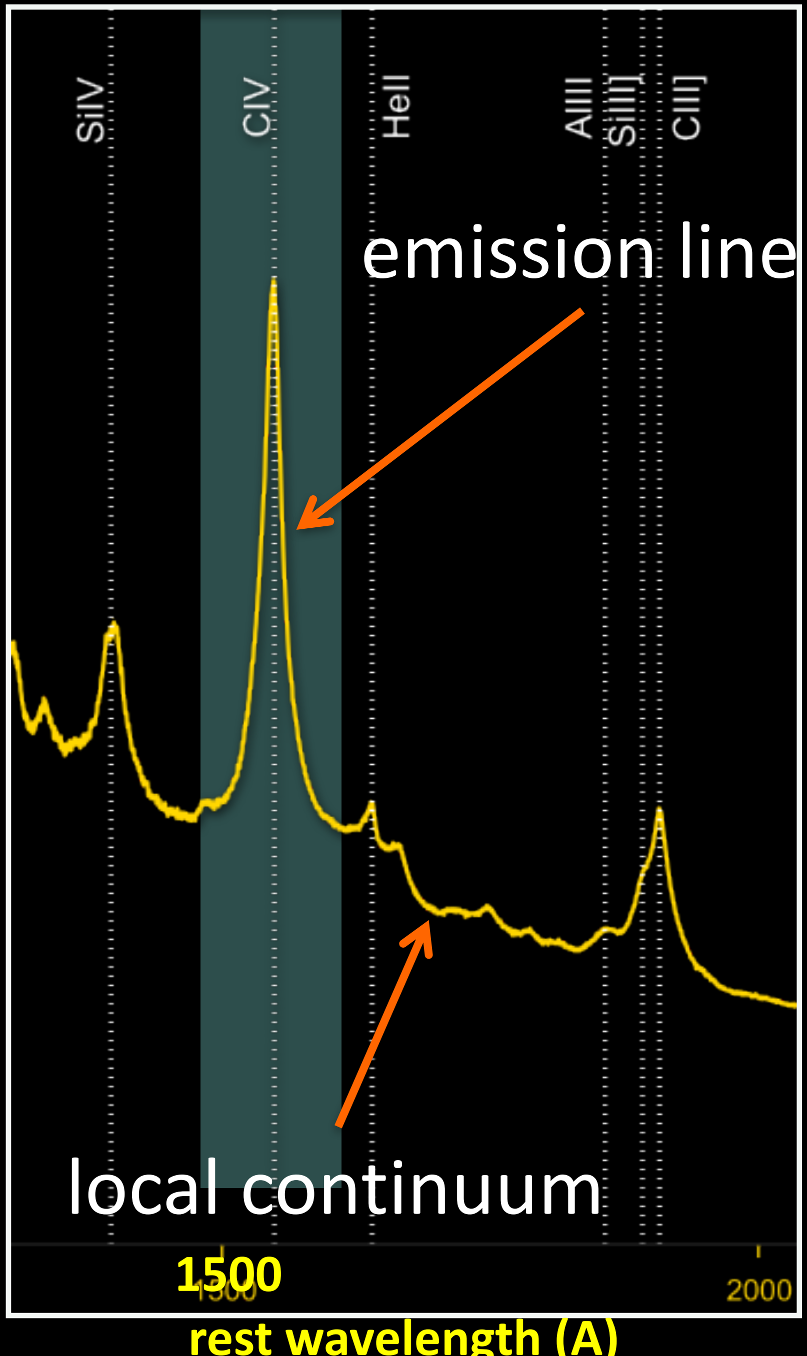
Requirements: Spectrophotometry

Legacy from RM campaigns

Goal: detect low-amplitude continuum and emission-line variations

→ S/N~30 @ line centre
→ relative line/continuum flux calib ~3-4%

Ideally: supporting multi-band photometry
- → extends time baseline
- → increases time cadence
- → aids flux calibration



Spectrophotometric Uncertainty Considerations

systematics

- → *telescope pointing*
- → *fibre-to-fibre differences*
- → *fibre placement errors*
- → *seeing-dependent flux losses*
- → *modeling standard-star spectra*

mitigating observing strategies

- → *always use same fibre for a target*
- → *more standard star and sky fibres (200-500 per field)*
- → *supporting concurrent photometry (LSST for some fields)*

Maunakea Spectroscopic Explorer

MSE Science Capabilities
Key for Quasar RM

Accessible sky	30000 square degrees (airmass<1.55)						
Aperture (M1 in m)	11.25m						
Field of view (square degrees)	1.5						
Etendue $= FoV \times \pi (M1/2)^2$	149						
Modes	Low		Moderate	High			IFU
Wavelength range	0.36 - 1.8 µm		0.36 - 0.95 µm	0.36 - 0.95 µm ♯			IFU capable; anticipated second generation capability
	0.36 - 0.95 µm	J, H bands		0.36 - 0.45 µm	0.45 - 0.60 µm	0.60 - 0.95 µm	
Spectral resolutions	2500 *(3000)*	3000 *(5000)*	6000	40000	40000	20000	
Multiplexing	3200		3200	1000			
Spectral windows	Full		Half	λ/30	λ/30	λ/15	
Sensitivity	m=24 *		m=23.5 *	m=20.0 ♮			
Velocity precision	30 km/s *		10 km/s *	< 100 m/s ♮			
Spectrophotometric accuracy	< 3 % relative		< 3 % relative	N/A			

♯ Dichoric positions are approximate

* SNR/resolution element = 2

♮ SNR/resolution element = 10

- **Aperture / field-of-view / etendue / sensitivity**

MSE Science Capabilities Pushed by Quasar RM

Maunakea Spectroscopic Explorer

Accessible sky	30000 square degrees (airmass<1.55)						
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- **Aperture / etendue / sensitivity**
- **Wavelength range: pushing to longer wavelengths**

MSE Science Capabilities Pushed by Quasar RM

Maunakea Spectroscopic Explorer

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♯ Dichoric positions are approximate

* SNR/resolution element = 2

♮ SNR/resolution element = 10

- Aperture / etendue / sensitivity
- Wavelength range: pushing to longer wavelengths
- Photometric accuracy

The MSE Engineering Team

Maunakea Spectroscopic Explorer

- Purpose:
  - Produce a **Construction Proposal**, 2014 - 2018, to inform decision to proceed
  - Lead/coordinate technical, scientific and partnership development, including recruiting partners into the project

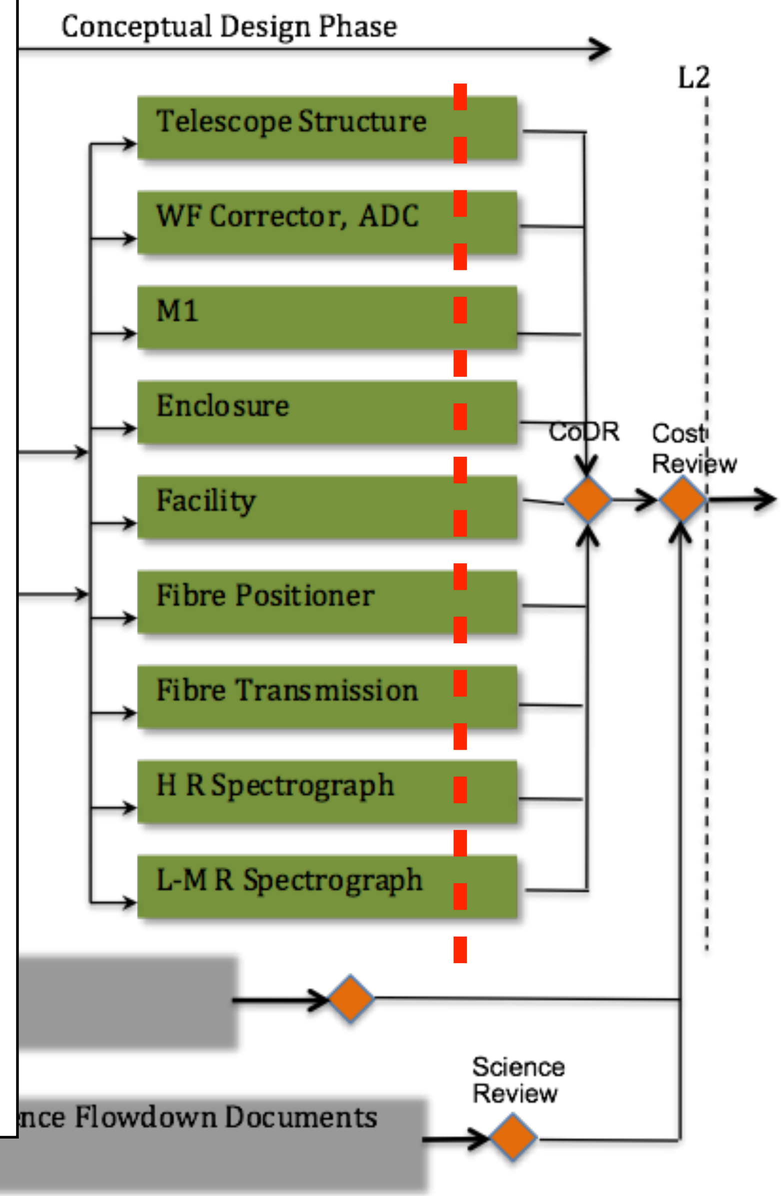
- **Project Manager**: Rick Murowinski
- **Project Engineer**: Kei Szeto
- **Project Scientist**: Alan McConnachie
- **Systems Scientist**: Nicolas Flagey
- **Project Office Engineer**: TBD

- Distributed Engineering Team

MSE All-Team Meeting, Madrid, April 2016

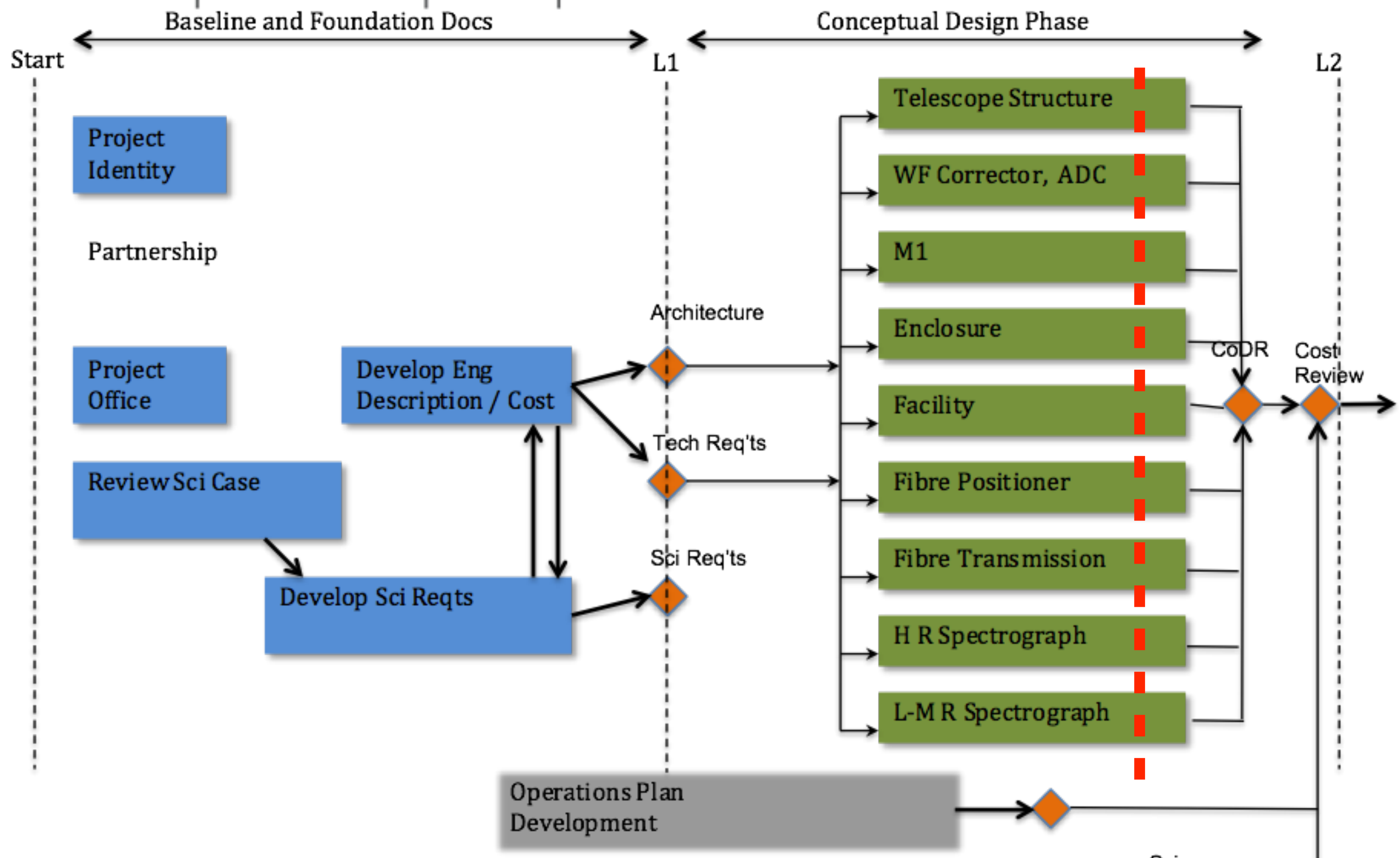
Project Status

- ✓ Science communities have enunciated a consistent vision for MSE science (Waikoloa Science Workshop)
- ✓ International distributed engineering team has been established and is effective,
- ✓ Science Requirements approved, observatory architecture developed, system engineering tools established.
- ✓ Key architectural decisions taken after extensive evaluation and consensus building:
  - ✓ Enclosure type and building structural revision
  - ✓ Telescope optical design
  - ✓ Multiplexing strategy
- ✓ MSE partners stepping up (in-kind) to design challenges
  - ✓ France (spectrograph, WFC/ADC, hexapod, rotator, system engineering)
  - ✓ China (spectrograph, fiber positioner, M1 segments)
  - ✓ Canada (fiber transmission system (TBC), project scientist)
  - ✓ Spain (fiber positioner, spectrograph)
  - ✓ Australia (optical design, MOS expertise)
  - ✓ India (M1)



Maunakea Spectroscopic Explorer

Project Status



Milestone	Date
Conceptual Design Review / Cost Review	26 Jan 2017
Preliminary Design Review	23 Nov 2017
Construction Proposal Review	20 Aug 2018

Maunakea Spectroscopic Explorer

Meanwhile in Canada

MSE High Resolution Multi-Object Spectrograph

PI Kim Venn (U Vic); $12.1M CAD proposal (Oct 2016) to Canadian Foundation for Innovation

Goals:

(1) Construct a prototype HRMOS (from NIAOT design) for testing on CFHT with a Galactic halo survey. ***This can serve as a first-light instrument for MSE.***

(2) Design and implement a software system for survey optimization, including the data pipeline.

LSST Membership

10 Canadian PIs have joined with support from Dunlap Institute (U Toronto), including Gallagher & Hall

→ accurate, well-sampled photometry key for quasar RM

Science capabilities & science case are well defined
→ *survey planning*

- First light (2026): start with a large *legacy survey* designed by the science team (comprised of a dark [extragalactic] & bright [Galactic] component) for all available observing time.

- Later: call for additional ***strategic surveys*** of flexible scope.

The impact, productivity, and allocations of legacy and strategic surveys will be reviewed continually to respond to community needs and science developments.

Survey Data + Future Upgrades

DATA

- available immediately to survey teams + Observatory to quickly provide data products for the MSE community
  - A significant proprietary period on science data enables the MSE community to use the data for frontline science before their worldwide release.
  - > 5 million spectra will be ingested into the archive on a yearly basis (~ a SDSS Legacy Survey every 3 – 4 months).

FUTURE UPGRADES

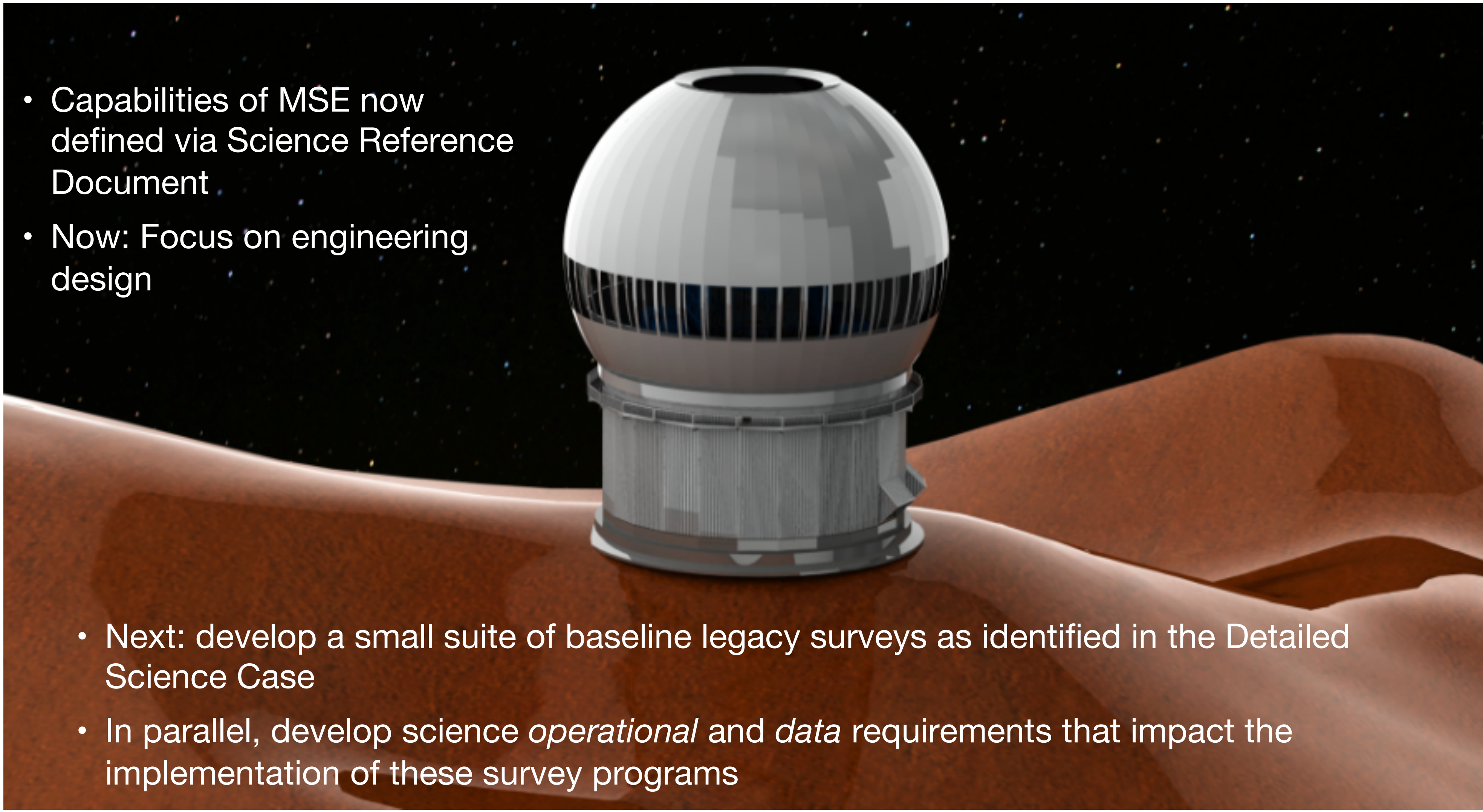
- design of MSE includes path to upgrade components or instruments over the long lifetime of the Observatory
  - A multi-object integral field unit is already anticipated, and the top-end is designed to be upgradable to deliver this capability.

The Elephant in the Room

www.cfht.hawaii.edu/hawaiianstarlight/pics/MaunaKea-Cuillandre-2000.jpg

Maunakea Spectroscopic Explorer

From Requirements to Surveys



- Capabilities of MSE now defined via Science Reference Document
- Now: Focus on engineering design

- Next: develop a small suite of baseline legacy surveys as identified in the Detailed Science Case
- In parallel, develop science *operational* and *data* requirements that impact the implementation of these survey programs