A strawman instrument suite for a European Extremely Large (50- to 100-m) Telescope

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Key Instrumentation Issues

- Identify drivers for telescope design
  - A telescope is useless if you can't built instruments for it
- Ensure realism of science case
  - Instruments are the link between science and telescope
- Provide operational model
  - "Classical" versus large-scale (like particle-physics)
- Assess resources needed
  - Building instruments for ELTs will stress capabilities of instrument-building community

$\Longrightarrow$ "point design" of a few instruments that explore the parameter space

There will be

3 POINT DESIGN STUDIES (PDSs)

- **WFSPEC – Wide Field seeing-limited (or boundary-layer corrected) SPECtrometer**
- **MOMSI – Optical /NIR Multi-Object & Multi-field Spectrometer & Imager**
- **MIDIR – MID-IR diffraction-limited high-resolution spectrometer/imager**

and….

…and 6 Small Studies (SSs):

- **Planet Finder – High dynamic-range (coronographic) imager/spectrometer**
- **HISPEC – O/NIR high spectral resolution instrument**
- **HiTRI – High Time Resolution Instrument**
- **GRB-Catcher – Fast-response broad-band imaging spectrometer for transients**
- **SCUBA-3 (aka SCOWL) – Submm imager**
- **ADC: Atmospheric Dispersion Correction – Basic Study of “AO” aspects of ADC**
- **Innovative instrument designs search**

Point Design Deliverables

- **Link to the Science Case**
- **Design drivers on Telescope and AO systems**
- **Outline Design of instrument**
  - **indicating focal station, mass, volume, moments, handling, data rates etc**
- **Technical Risk Analysis**
- **Functions and Performance Requirements Document (FPRD)**
- **Outline Project Plan, including possible Work Breakdown Plan (over likely participant organizations)**

Point Design Deliverables (2)

- Indicative costing, with effort (FTE) and hardware requirements
- Operational Concepts Definition Document (OCDD) setting out optimum operational mode
  - Classical?
  - “Particle Physics”?
- Calibration requirements statement
- Performance Simulator (nucleus of time estimator?)
- Assessment of resource requirements from telescope infrastructure
  - power, cryogen consumption, labor, likely room-temperature heat dissipation

NB (1):

These instruments (esp. those getting PDSs) are chosen to *discover the challenges* – especially for the telescope design – involved in their provision, NOT *to be a scientifically exhaustive suite*

NB (2):

Interfaces with other work packages (and the science case) are numerous and important, but not yet completely established

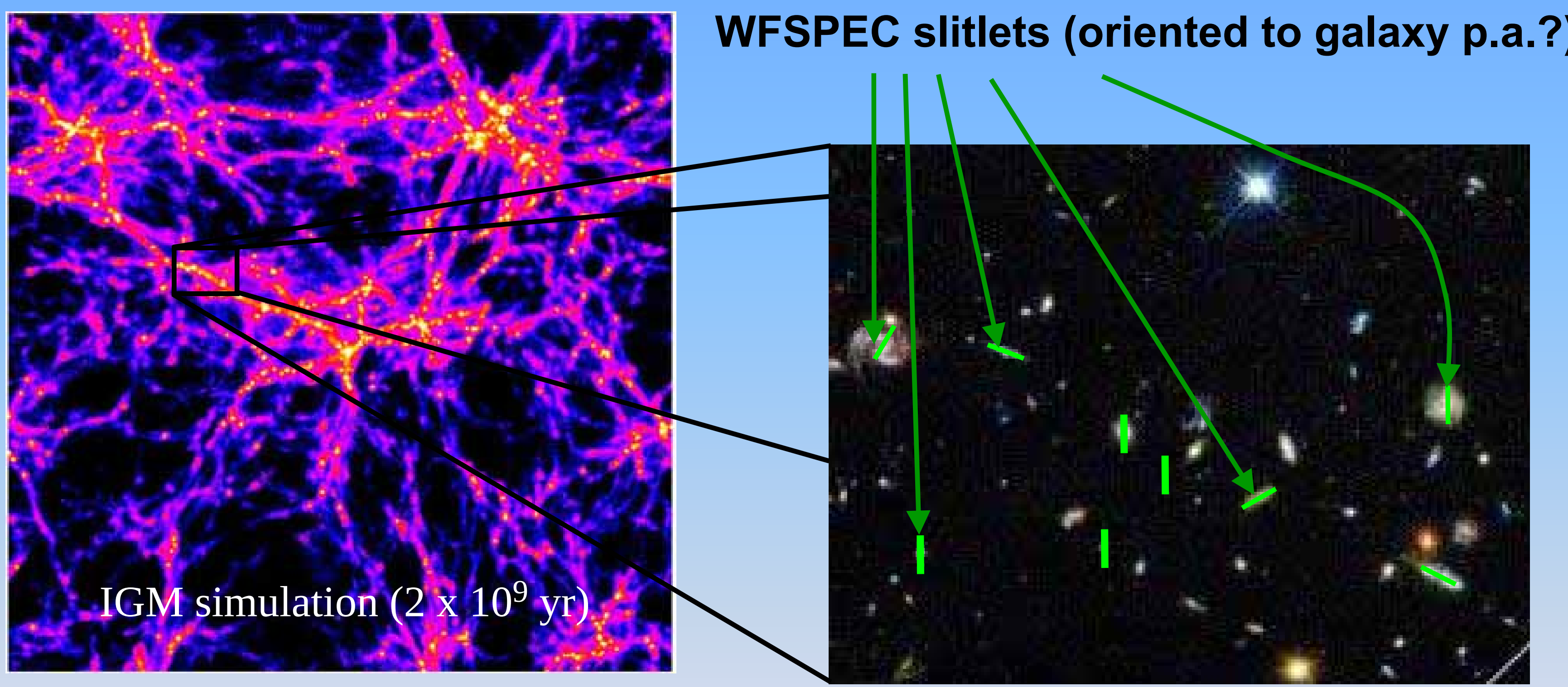
WFSPEC – ***W**ide **F**ield seeing-limited (or boundary-layer corrected) **SPEC**trometer*

Science requirement:

- Spectra of many objects over a field of several (5-10?) arcminutes to investigate
  - Large Scale Structure in the Universe, and its evolution
  - Evolution of the chemical structure of the IGM
  - Redshift surveys of very faint and distant galaxies
  - Properties of SNe at high z

WFSPEC Science: Large-Scale Structure

Primaeval walls now traced by galaxy clusters



Walls (and voids) and their precursors: nowadays, galaxy clusters

WFSPEC – (continued)

- ***Issues (1)***
  - **Matching a seeing-limited image (or even a boundary-layer corrected image) to a reasonably small number of detector pixels is hard! Need either:**
    - **Impossibly fast final F/ratios (for D=100m, need ~ f/0.2 to put 0."3 on a 30 μm array pixel), or**
    - **much larger physical pixels than currently in use (150μm for a final f/1.0: so probably decreased performance), or**
    - **use of smaller (sub)pupils**

WFSPEC – (continued)

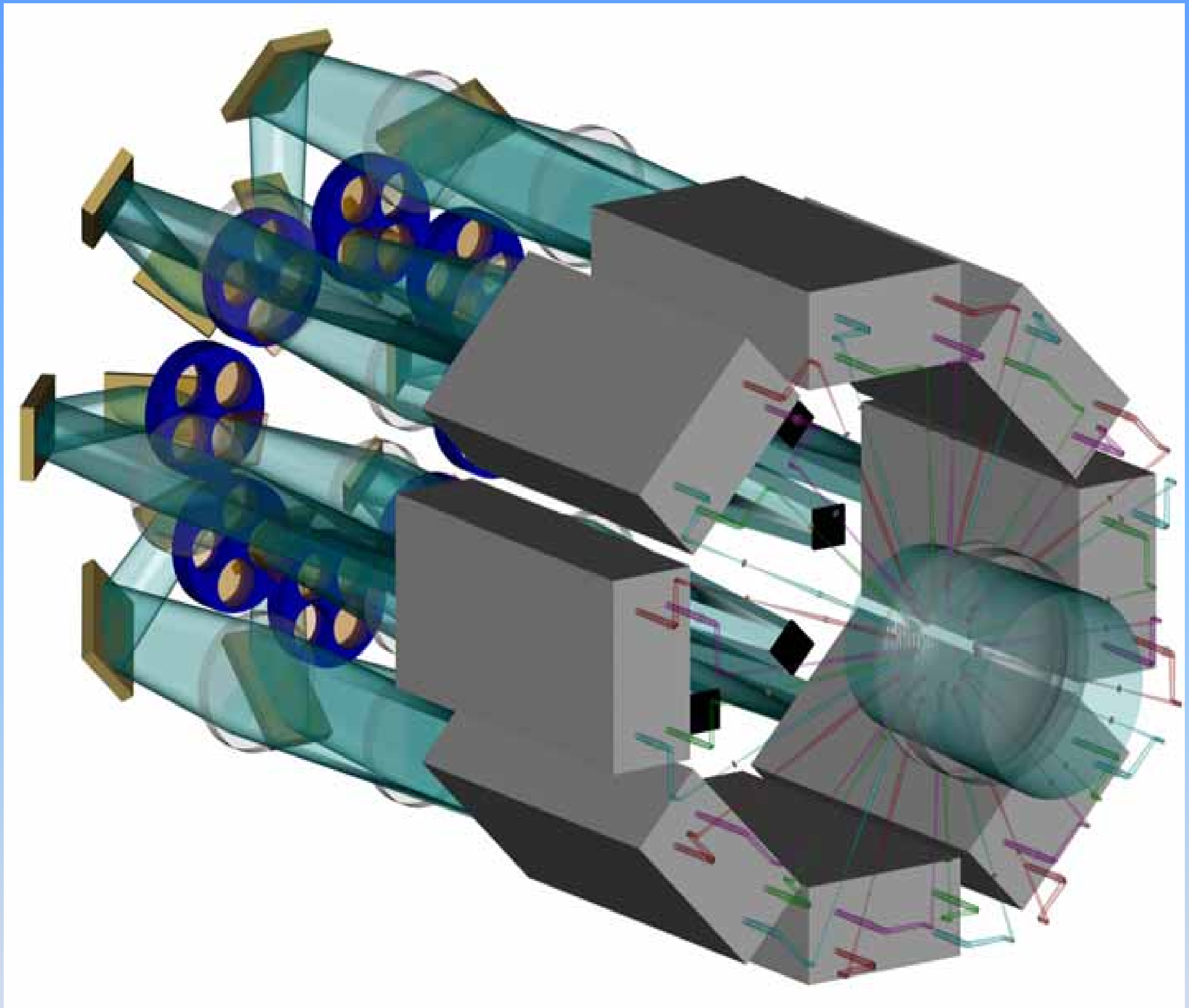
- ***Issues (2)***
  - Do we need an *imager* ?
    - Not currently included in this instrument concept
    - C.f. other large-spatial-volume options such as a smaller, much wider-field telescope.
    - For 0. "12 pixels, need ~5000x5000 array
    - But oversampling / pixel-matching problem remains
- ***Issues (3)***
  - Likely performance of BLC-AO systems is not well known and finding out should be part of the WP

MOMSI –Optical /NIR Multi-Object and Multi-field Spectrometer & Imager

- **This is a core instrument, applicable to many science programmes**
- **It will obtain images and/or spectra of many (exceedingly faint) objects over a field of order an arcmin using MCAO or functional equivalent**
  - **How, when and from what present-day galaxies formed (deduced from their present sub-populations of stars)**
  - **Evolution of galaxies and pre-galactic objects: their structure, dynamics, and composition, from very high redshifts**
  - **Detection of the earliest luminous objects in the universe**

MOMSI –Optical /NIR Multi-Object and Multi-field Spectrometer & Imager

- **For spectroscopy, picking off sub-fields will be essential**
  - **Link to Smart Focal Planes JRP**
- **For imaging, covering the FOV with detectors may be impractical**
  - **~10^{10} resolution elements: *~4000 of the largest current NIR arrays* for critically-sampled imaging at 1μm at the diffraction**
  - **limit over ~2' field**
  - **Alternative – pick off subfields for *imaging* as well**
  - **Allows modularity (but modules will still be physically large)**
- ***Current AO assumptions: Strehl ranging from 0.2 at 0.5μm to 0.5 at 2.2μm, ~ consistent PSF over a 1or 2' FOV***
- ***Issues***
  - **Modular vs monolithic design approaches**
  - ***Likely that the K band will be essential* – implies that pickoff mechanisms, etc will need to operate cryogenically**



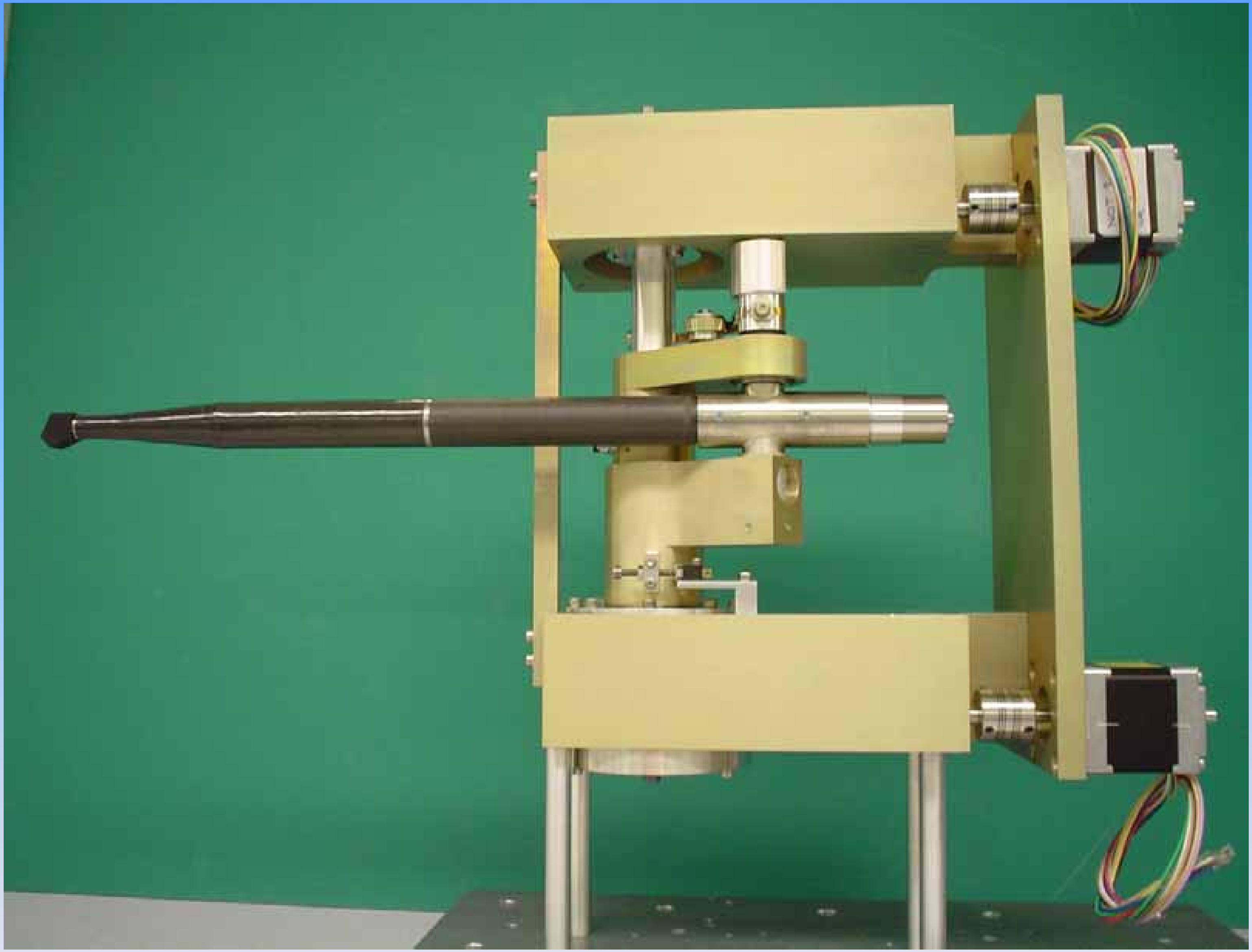
MOMSI-like multi-object spectrometer:

– all cold optics –

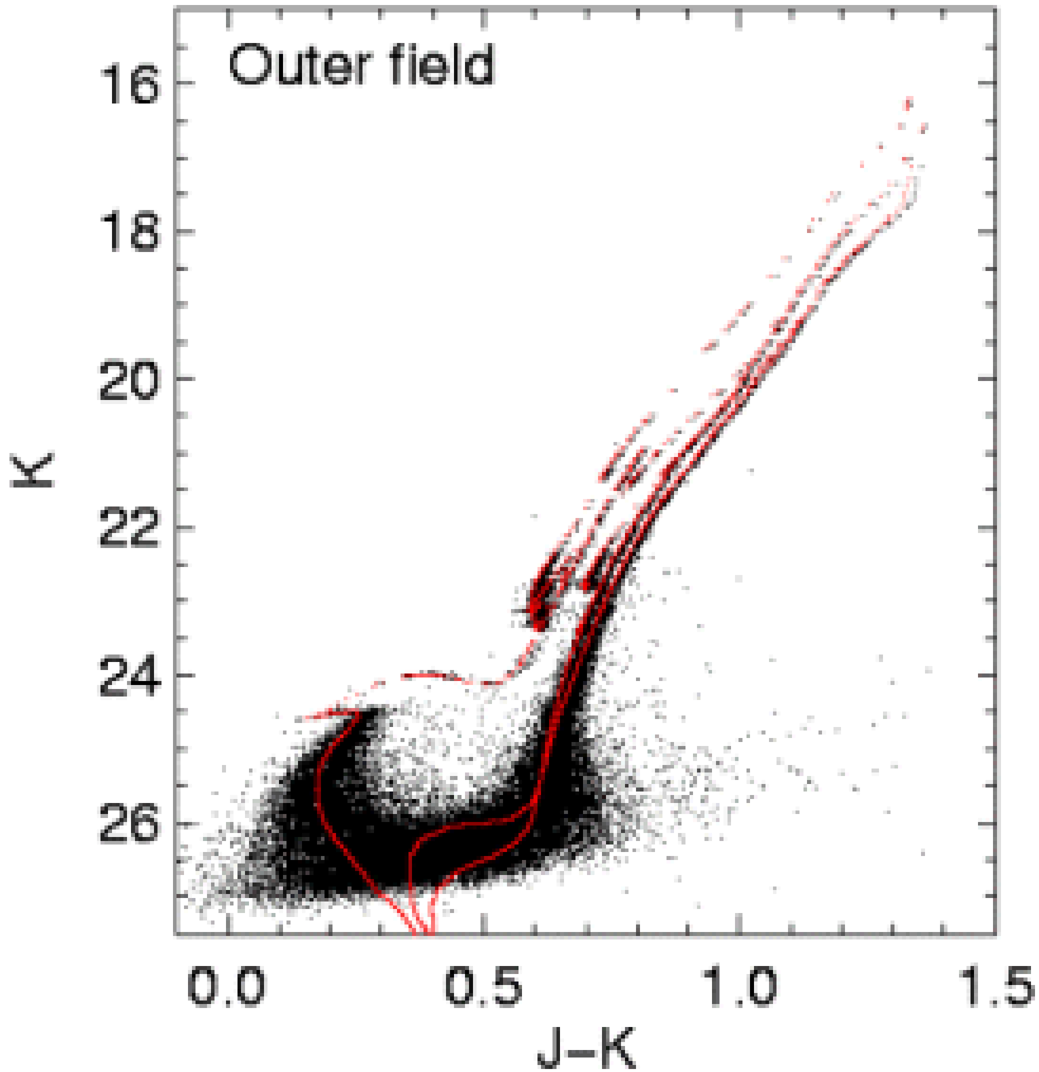
UKATC Design Concept for a Multiple Deployable Integral-field Spectrograph (GIRMOS).

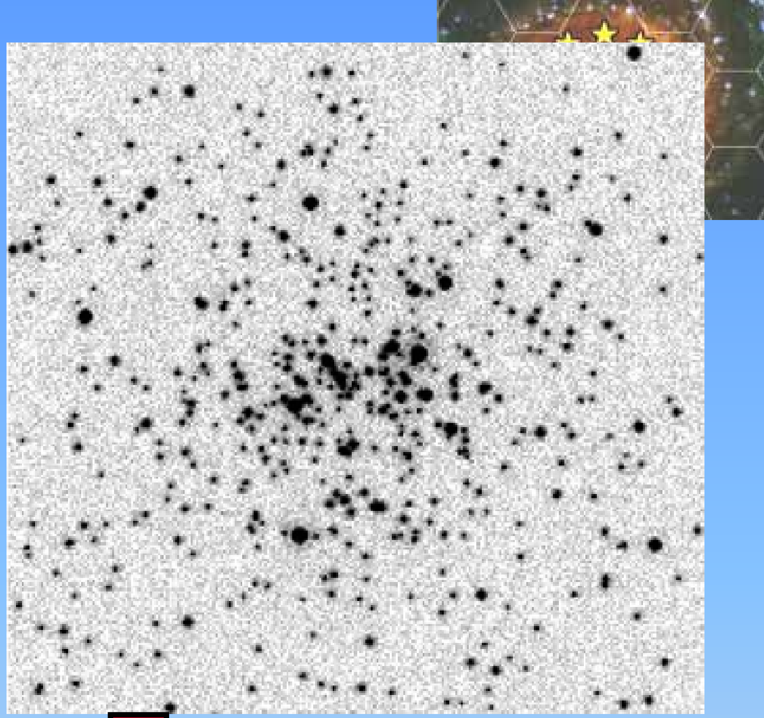
(Scalable to ELTs, but gets pretty big: 2.5m diameter, 6m long, for 100-m tel.)

32 separate, mobile IFUs each with a 3x3 arcsec field of view, 0."15 pixels, ranging over a 5'x5' telescope FOV (on a typical 8-m class telescope).



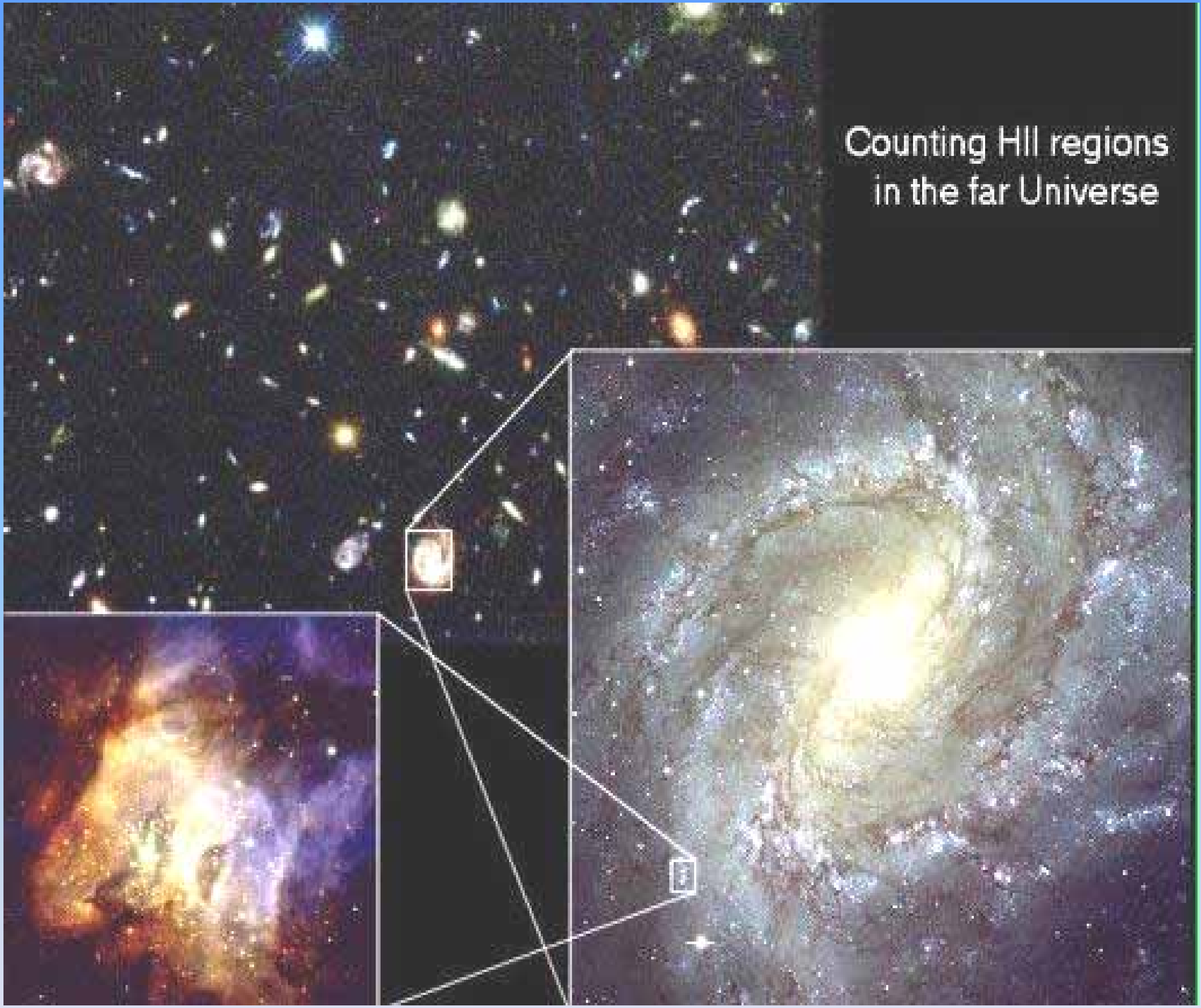
Prototype spectrometer/ imager pickoff arm





IMAGING:
1 $M_\odot$ stars in Virgo

Model CMD (from GSMT book) of an outer field (90" from nuc.) in M32
Populations of various ages & [Fe/H] can be distinguished and characterized.
A 100-m should do this out to Virgo, sampling all types of galaxies.



At Z>1, a 50-100-m telescope will resolve *components* of *substructures* of galaxies (not just the galaxies themselves)
***And MOMSI will get their spectra* at R ~ 10,000**

Illustrative performance of OWL at the diffraction limit in the NIR: Hi-Z Galaxies

PIXEL EXCESS PROBLEM:

- A critically-sampled *IMAGE* at 1µm on a 100-m telescope needs 1 mas pixels
- One covering 2'x2' would need ~1.6 x 10^{10} pixels (~4000 2k x 2k arrays)
- For a 1000-pixel *SPECTRUM* on each point, require 10^3 times more, ~1.4 x 10^{13} px, or 4,000,000 arrays..!
- I.E. we would need *4000 GIRMOS spectrometers* to pay the same average attention per resolution element of a 2' field on OWL as GIRMOS pays in the 5' field on an 8-m..
- STRAWMAN INSTRUMENT:

10 spectrometers and 10 imagers…. about ½% of the GIRMOS attention level …

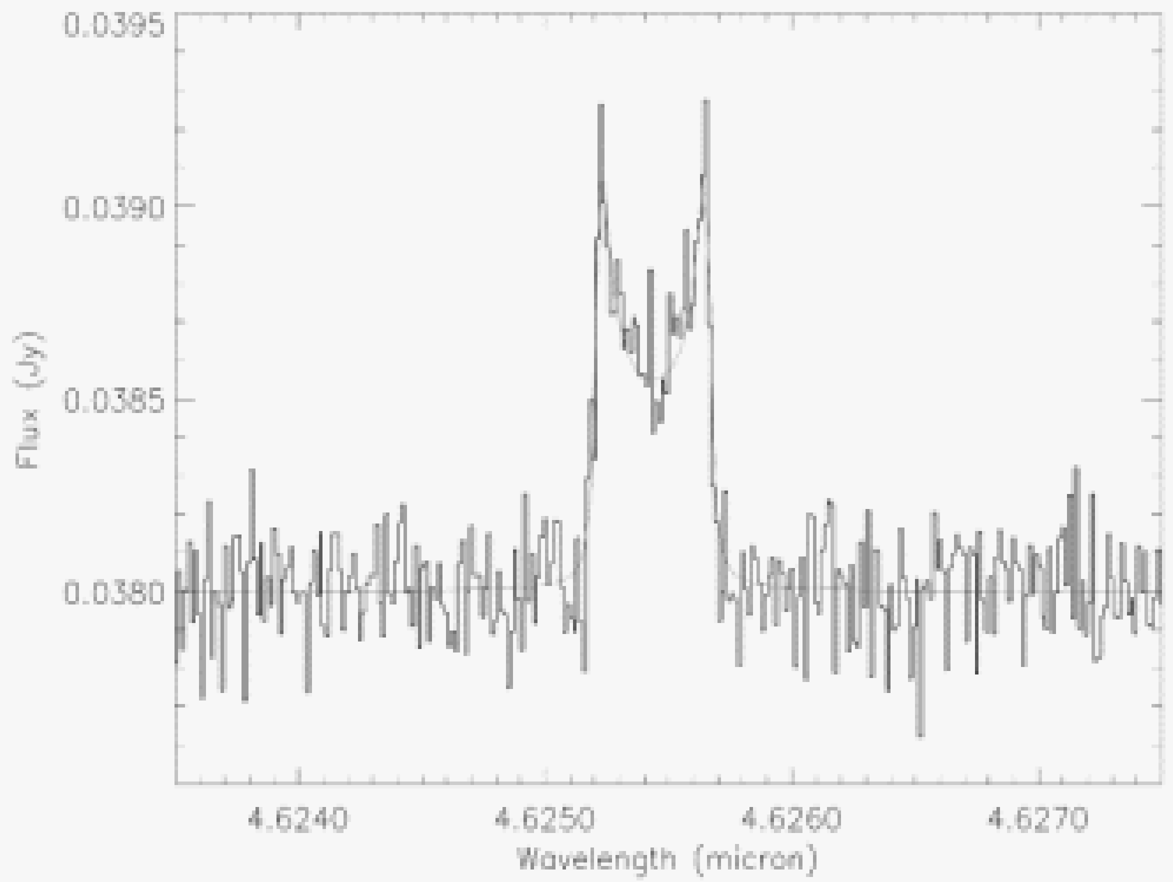
MOMSI – earliest luminous objects:

WMAP: *re-ionization started at Z = 10 – 20, so:*

- Seek Lyα dropouts in J & H bands at Z ~ 8 - 14 (OK if first ionization sources are point-like (true if they are globular-cluster sized: 1mas ~10 pc at z ≥ 1)
- Confirm using spectroscopy
  - Verify Lyα identification (actually can see to Z~19!)
  - Seek asymmetry of Lyα line (but hard even for OWL??)
- Seek first ([Fe/H=0]) stellar populations:
  - Lyα in H band (to Z ~ 14) and HeII 164nm in K band...

MIDIR - Mid-IR diffraction-limited high-resolution spectrometer/imager

- **In the mid-IR the *unique* angular resolving power of an AO-corrected ELT (and its considerable sensitivity) makes it a powerful complement to space telescopes such as the JWST and to ALMA**
- **The design of such an instrument is likely to be related to that of the Multi-Object MCAO Spectrometer/ Imager MOMSI**
- ***Current AO assumptions: 2' FOV as for MOMSI but Strehl ~0.5 to ~0.8***



Simulated high-resolution spectrum of CO from a gap in a circum-stellar disc made by a 1 M_J planet

(from the GSMT "book")

MIDIR - continued

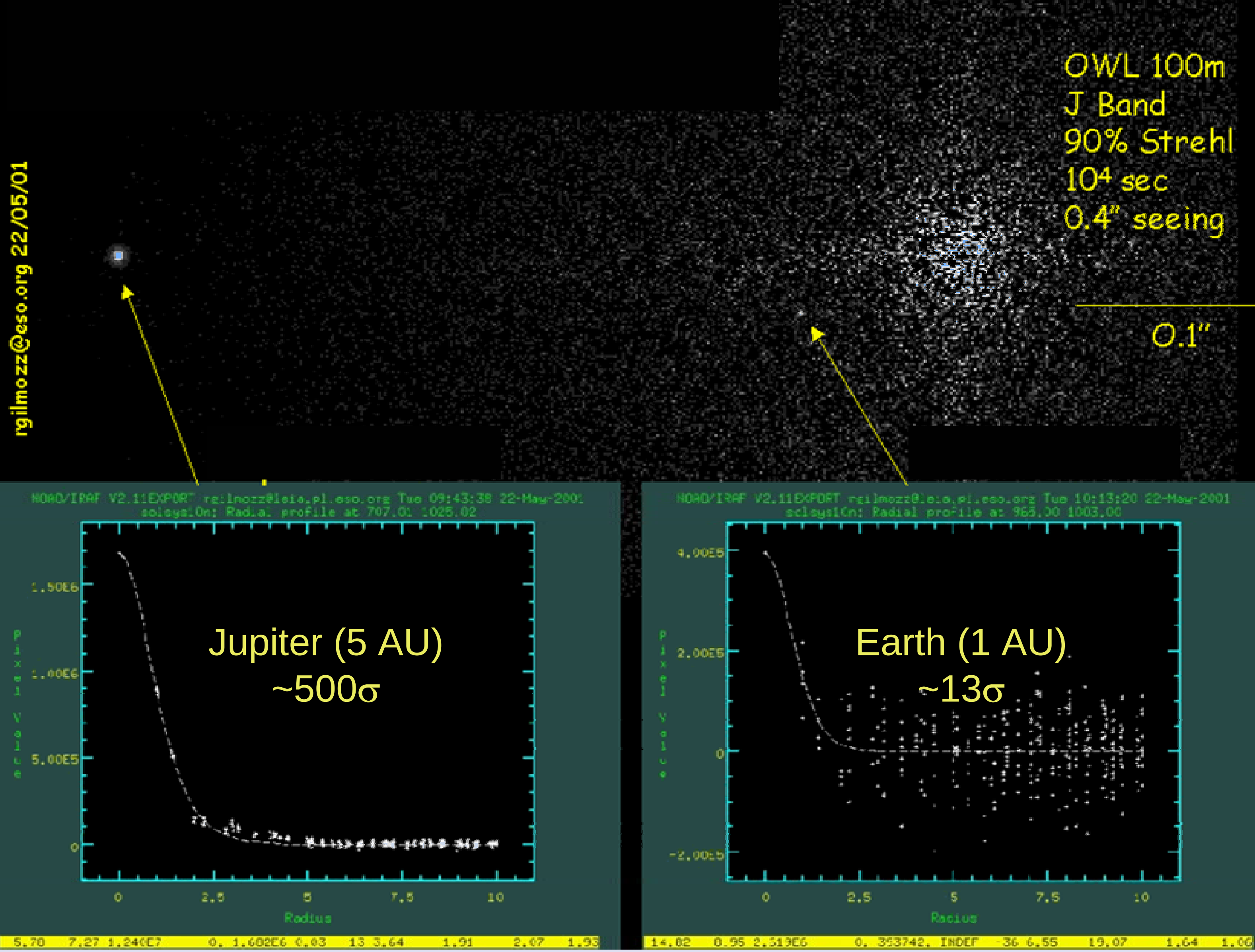
- CELT study for a *mid-IR prime focus instrument with its own AO system* should be examined
- Though the OWL design is AO-friendly it has 6 surfaces ahead of any instrument, so for realistic coatings the overall emissivity is unlikely to be below 10%
  - *A cold AO system may be necessary*
  - *This is a potential cost driver*
- ***Strong*** pressure for a high dry site
- Large-format high-background detectors needed
  - Could be a substantial cost driver (development programme)
- Pressure to include twilight and daytime operations

SMALL STUDIES

- **General picture of practicability of instrument type on 50-100m ELT**
- **Identify early problems**
- **Ensure initial approaches validated**
- **Begin to solve generic problems (e.g. AO-ADC or AODC)**

PLANET FINDER – Extreme-AO high dynamic-range (coronographic) imager/ spectrometer

- “The Killer App” Direct detection of planets, ***including earth-like ones***, around a large number of nearby stars
  - **Time-dependent photometry and spectroscopy of planets**
  - **Searching for biomarkers in the Earth-like examples (light curves, spectral features)**
- **Challenges**
  - **Stray light suppression, coronographic removal of the bright source, maximum possible starlight in the image core by very high-order AO (Strehl ratios >0.7 are sought)**
  - **Spectroscopy will be hard and NIR photon-counting detectors are likely to be important**



Solar System from 10 pc seen with OWL (star image removed: noise only)

PLANET FINDER (continued)

An Issue (and potential show-stopper):

- ***Segmentation effects:***
  - **Diffraction structures (static hexagonal array of mini-PSFs (~10^{-5} to 10^{-4} of central peak): lots of gaps, but exposure-smearing may leave little room for finding planets at 10^{-10}!**
  - **Speckle effects: Quasi-static (bad news??) or variable at seeing frequency? What exactly are the AO requirements?**

HiTRI – high time-resolution photo (polari) meter spectrometer

- **Expect only single point sources (optical pulsars, short-periods variables of several classes, AGNs and Blazars) occurring sparsely, but anywhere in sky.**
- **Photometric, polarimetric and time-resolved spectroscopic variations**
- **Novel detector technologies will be explored (part of the "detectors" JRP covers this area)**

HISPEC – O/NIR high spectral resolution (R = few 10^4 to 10^6) instrument

- **Absorption line cosmology of elements other than hydrogen (how the heavy elements in the ISM/ IGM/ ICM evolved)**
- **Stellar dynamics in “nearby” (z<1?) galaxies**
- **Detailed examination of the physics of the galactic ISM**
- **The field size required is *TBD – science input needed***
- **Therefore AO requirements not well determined, but certain to need consideration**
- **For several reasons (e.g. acquisition, efficiency) it should probably employ at least one IFU (perhaps a single MOMSI pickoff) even if it is a single-object instrument**

SCUBA-3 (nee SCOWL) – submm imager (but not just for OWL….)

- **SCUBA-3 will carry out the first all-sky submm surveys at resolutions comparable to the Schmidt surveys in the optical (~10^6 gains over ALMA for this purpose)**
- **It would provide the first deep observations at the peak of the FIR spectral energy distribution (200µm)**
- **SCUBA-3 could be an ideal poor-seeing and cirrus backup instrument**
- **It would employ large arrays of TESs being developed for SCUBA-2**
- **Absolutely no AO requirements, but needs ~0."5 telescope performance, maybe without WFS.**

GRB-catcher – fast-response broad-band imaging spectrometer

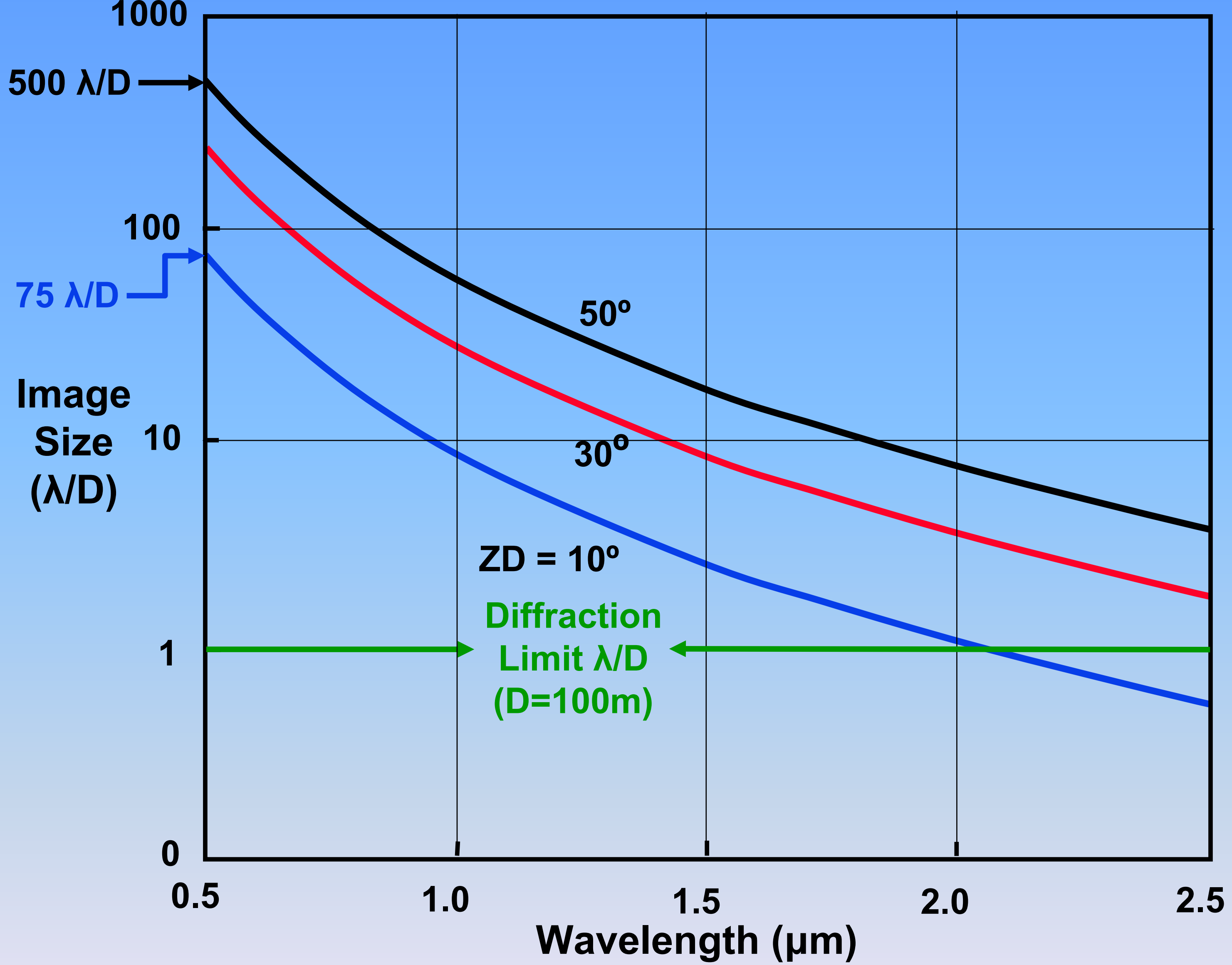
- This instrument is designed for extremely rapid-response observations (ideally, respond in seconds: change insts. during slew) of objects such a Gamma Ray Bursters which evolve on timescales of seconds to minutes
- Probably need one or more IFUs able to secure images and moderate resolution spectra in a range of simultaneous wavebands
- Range from the blue end of the visible though the mid-IR
- Each band probably requires its own ADC and AO facility
- Challenging instrument to design
- Compromises in image quality may be needed in order to secure fast response times

Atmospheric Dispersion Correction

– a specialized branch of Adaptive Optics?

- **In the Optical and NIR a new level of ADC will be needed if λ/D resolution is to be achieved with 50 – 100m telescopes**

- **Life is 100s of times harder now:**



Atmospheric Dispersion modelled for Mauna Kea (4200m)

(Units of diffraction spot size)

Atmospheric Dispersion Correction

— a specialized branch of Adaptive Optics?

- **At only 10º ZD, Atmospheric Dispersion (over an R=5 band pass) exceeds the diffraction limit of a 100-m for λ < 2 μm**

- **At 50º ZD dispersion is *<u>more than an order of magnitude</u>* larger than the diffraction spot at H and shorter wavelengths**

Atmospheric Dispersion Correction

– a branch of Adaptive Optics? (cont[d])

- ***For ~0.2 λ/D performance levels*** **(10% Strehl degradation) local atmospheric T and P gradients may be significant; if so**
- ***Adaptive (AO) control of ADCs*** **may be required if adequate correction is to be achieved.**
- ***Questions*** **that must be answered:**
  - **What are the relevant bandwidths?**
  - **Will “dispersion sensors” be required in the ADC control loop?**
  - **How can “dispersive AO” corrections be applied? (LCD developments?)**

ADC – continued

- **Constraints on the design of ADC systems:**
  - **May require location in collimated beams**
  - **Optical components transmissive and will be large**
  - **Beyond ~1.6 µm will need to be cooled**
  - **Control may add to the requirements on AO systems**
- **Issues**
  - **Short-timescale chromatic atmospheric effects and development of schemes for monitoring them**
  - **No technology for *adaptive* ADC**
  - **May be a serious shortage of specialist glasses**
- **We propose a preliminary study (1st 6-9 months) of**
  - **“normal” (quasi-static) ADC**
  - **the need for “adaptive” ADC**
  - **to establish control and bandwidth criteria and guidelines for ADC for all instruments**

… and finally

INNOVATIVE INSTRUMENT DESIGNS

- a survey

- **An attempt to ensure that no new and original ideas likely to be important for ELT instrumentation have been omitted**

- **Literature search, visits to instrument groups**

SUMMARY

1. **Instruments need to be considered *ab initio;***
2. **Incorrect telescope design decisions may prevent the deployment of the instruments needed to carry out the design (and other front-line!) science;**
3. **Instruments will (and should) be a significant fraction of the capital budget of the telescope project;**
4. **We plan to investigate designs of indicative examples to explore implications for telescopes;**
5. **Atmospheric Dispersion Correction needs to be addressed early on in any telescope/instruments system study.**