Astro 500

Techniques of Modern Observational Astrophysics

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Lecture Outline

5. Cutting-edge and future OIR instruments
   a. Ground-based instruments on 10m telescopes
      i. MUSE, VIRUS, MOS
   b. Space-based instruments: JWST
   c. Ground vs space
      i. Backgrounds
      ✓ Why build bigger telescopes?
   d. Ground-based instruments on 30-100m telescopes:
      i. AO-driven designs
      ii. Specific examples of TMT instrumentation
   e. Unexplored options: a brief list

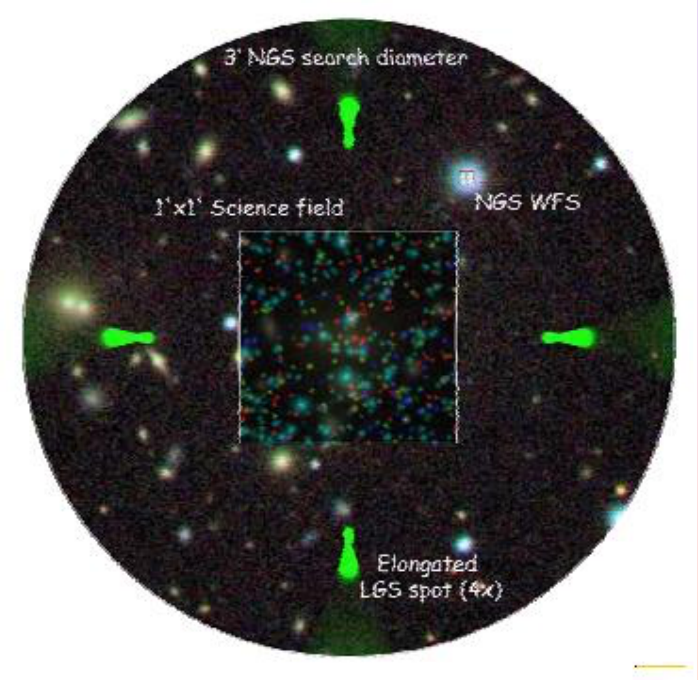
Cutting-edge Instruments

Ground-based instruments on 10m telescopes

- State-of-the-art spectroscopic instruments
  - MUSE
  - VIRUS
  - KMOS
- Common themes:
  - object multiplexing
  - instrument multiplexing

Cutting-edge Instruments
MUSE

- Science goals
  - Detailed study of high-redshift galaxies, structure formation, discovery.
- Technical approach
  - Replicate 24 modest-resolution spectrographs fed with advanced (catadioptric) images slicers.
  - Premium on image quality and information.
  - Ground-layer AO (GLAO) assisted.
- Instrument capabilities
  - VLT 8m
  - Two scales:
    - o 1 $arcmin^2$ FoV, (0.04 $arcsec^2$ elements)
    - o 56 $arcsec^2$ FoV, (6.3×10^{-3} $arcsec^2$)
  - integrally sampled
  - 0.465-0.93 nm range (one shot)
  - ~2000 spectral elements (R~3000)
  - $\varepsilon \sim 0.24$



Bacon et al. '04

Cutting-edge Instruments
MUSE

- The instrument - wow!

Light path
from telescope

24 spectrographs
6 stacks of 4

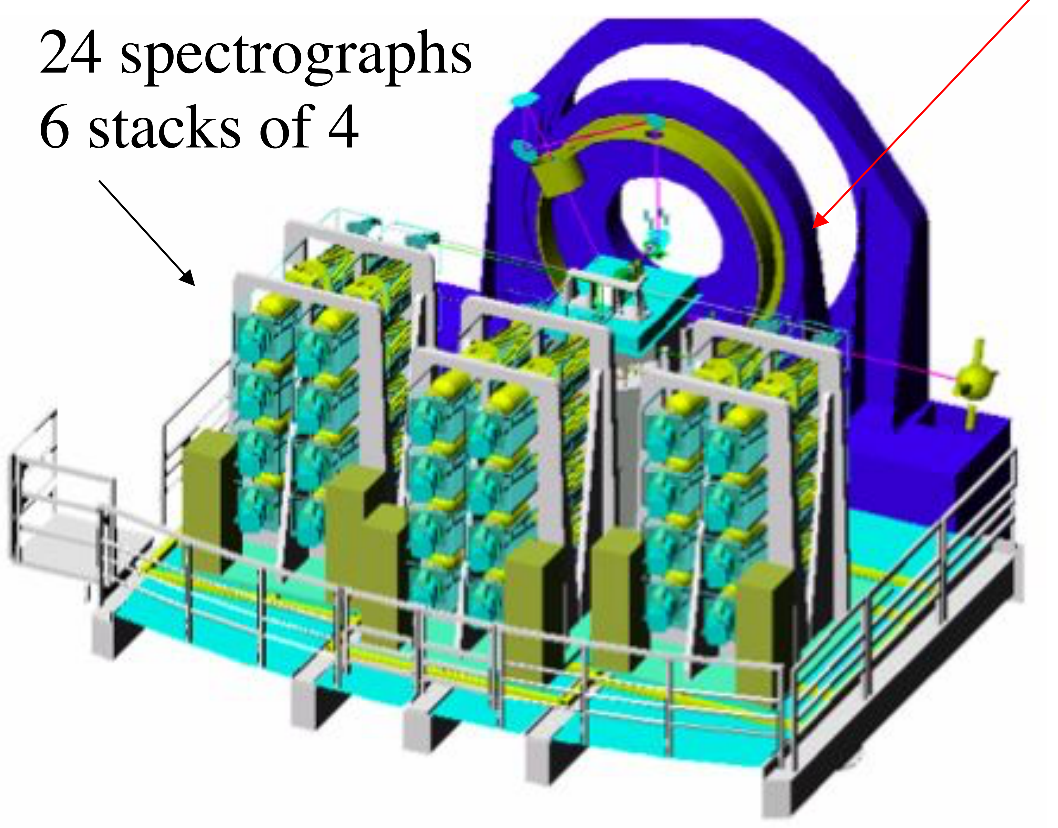
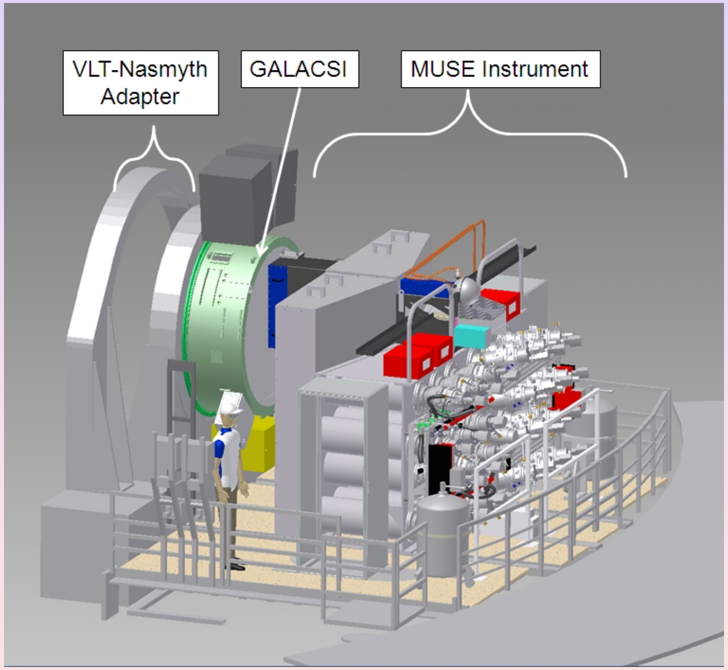


Figure 3-2: MUSE instrument installed at the VLT Nasmyth platform

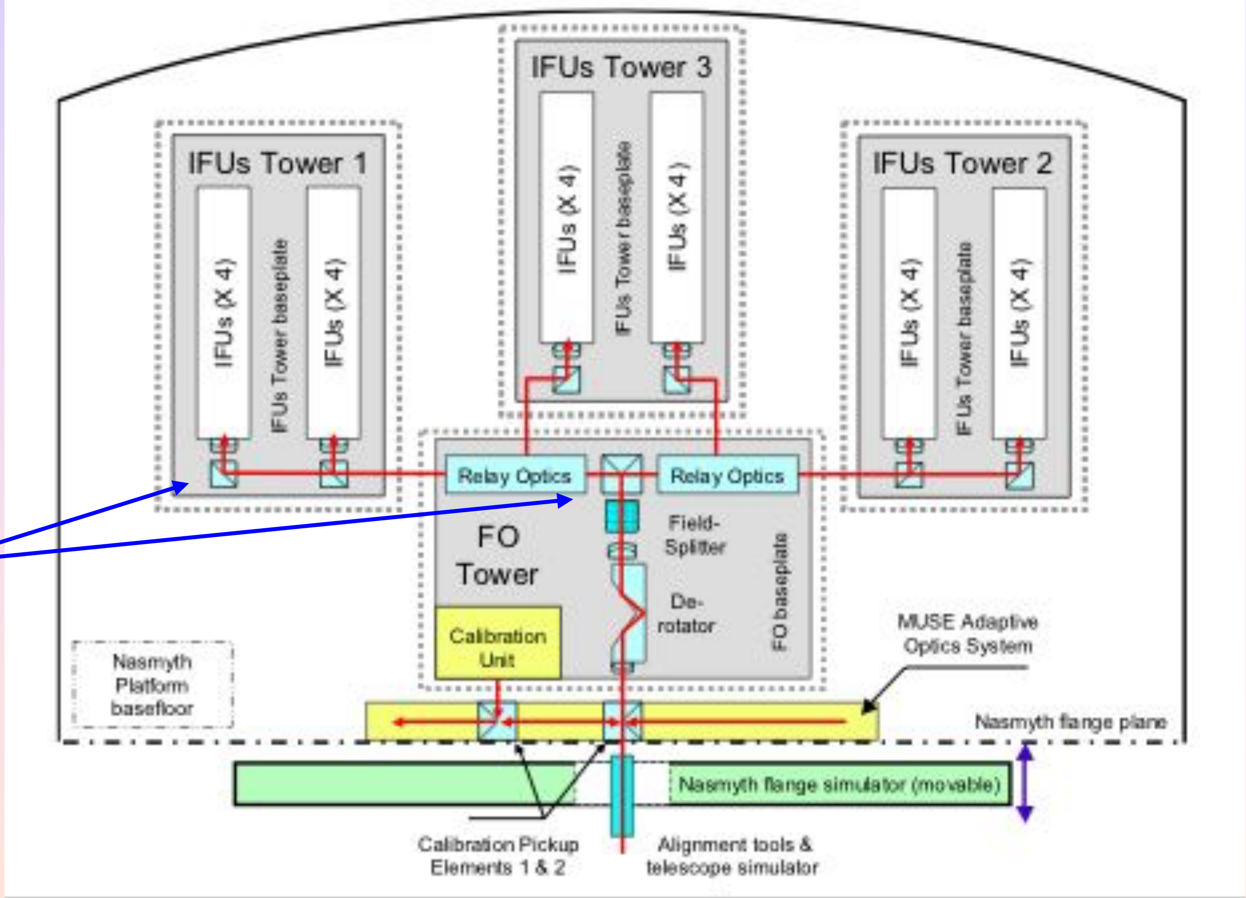


Henault et al. '04

Cutting-edge Instruments
MUSE

- The instrument - wow!

relay optics are the trick -- critical



Henault et al. '04

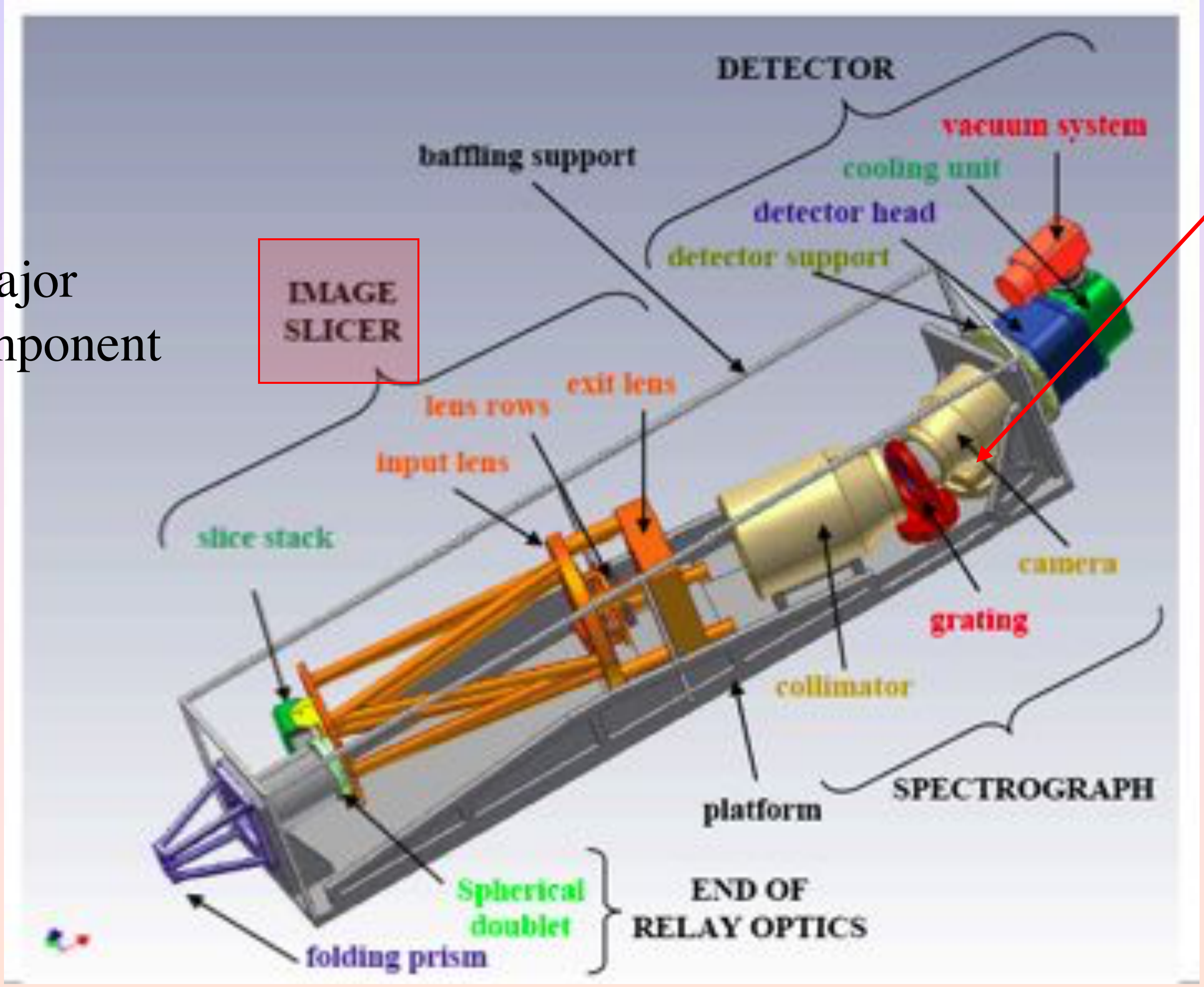
Cutting-edge Instruments

MUSE

- Slicer + spectrograph unit

Articulated camera for VPH gratings

Slicer is major optical component



Henault et al. '04

Cutting-edge Instruments

MUSE

- Catadioptric Image Slicer (CIS) for MUSE

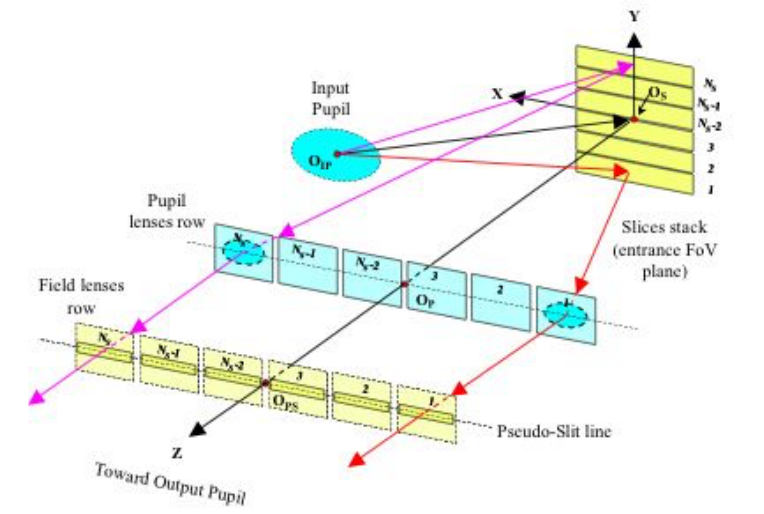


Figure 4-1: Principle of a Catadioptric Image Slicer

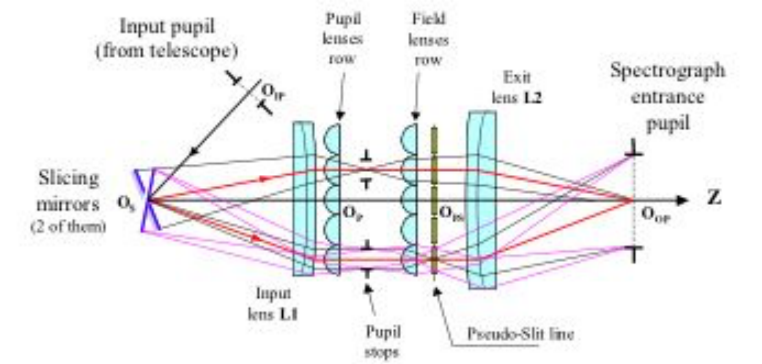
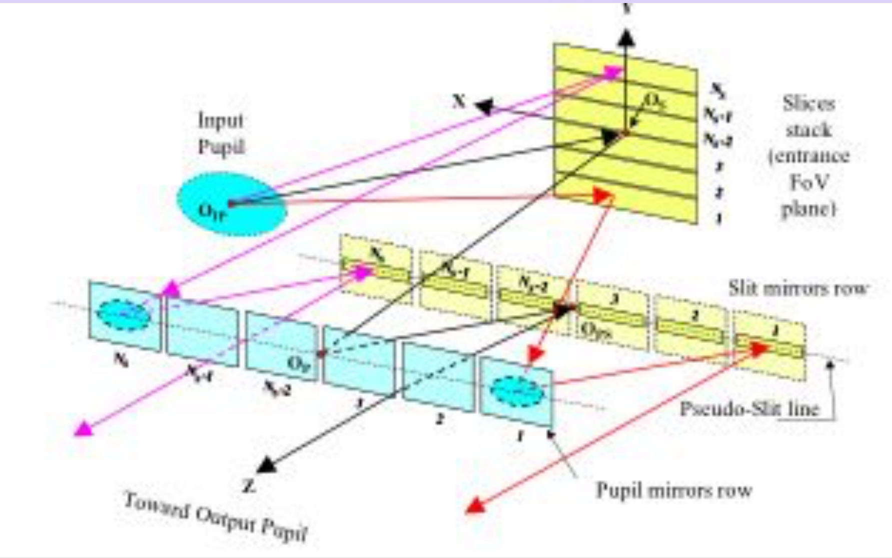


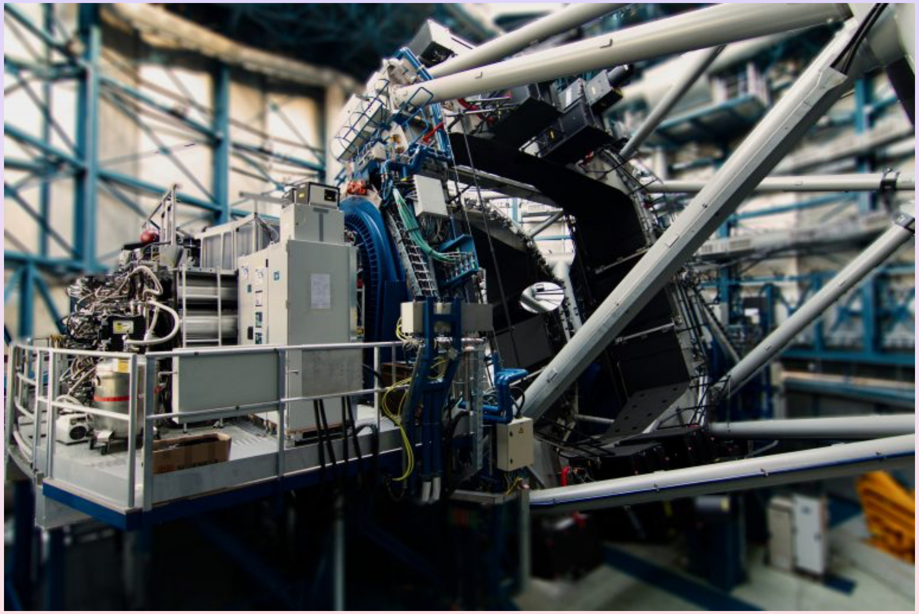
Figure 4-3: Final optical principle of the CIS

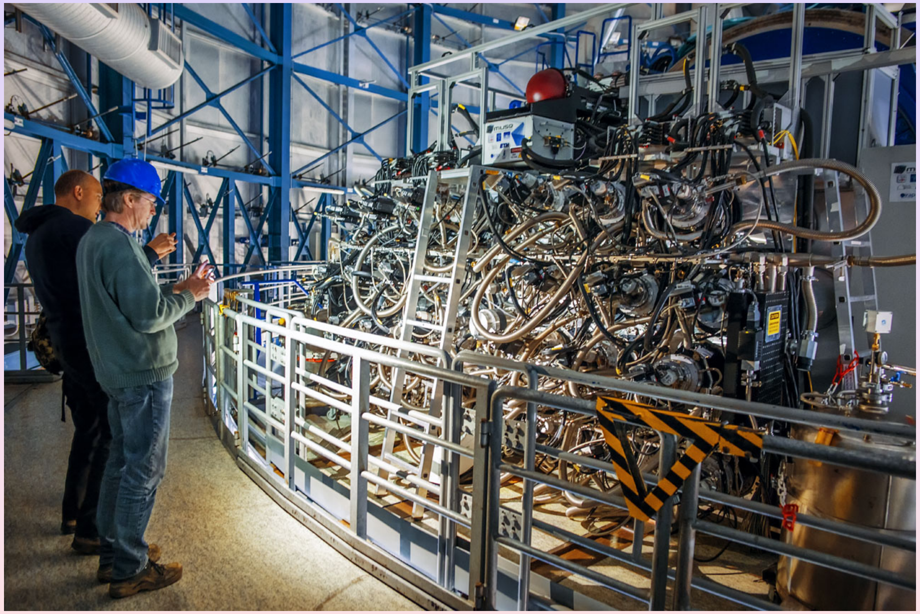


Henault et al. '03

Cutting-edge Instruments

MUSE – the Medusa

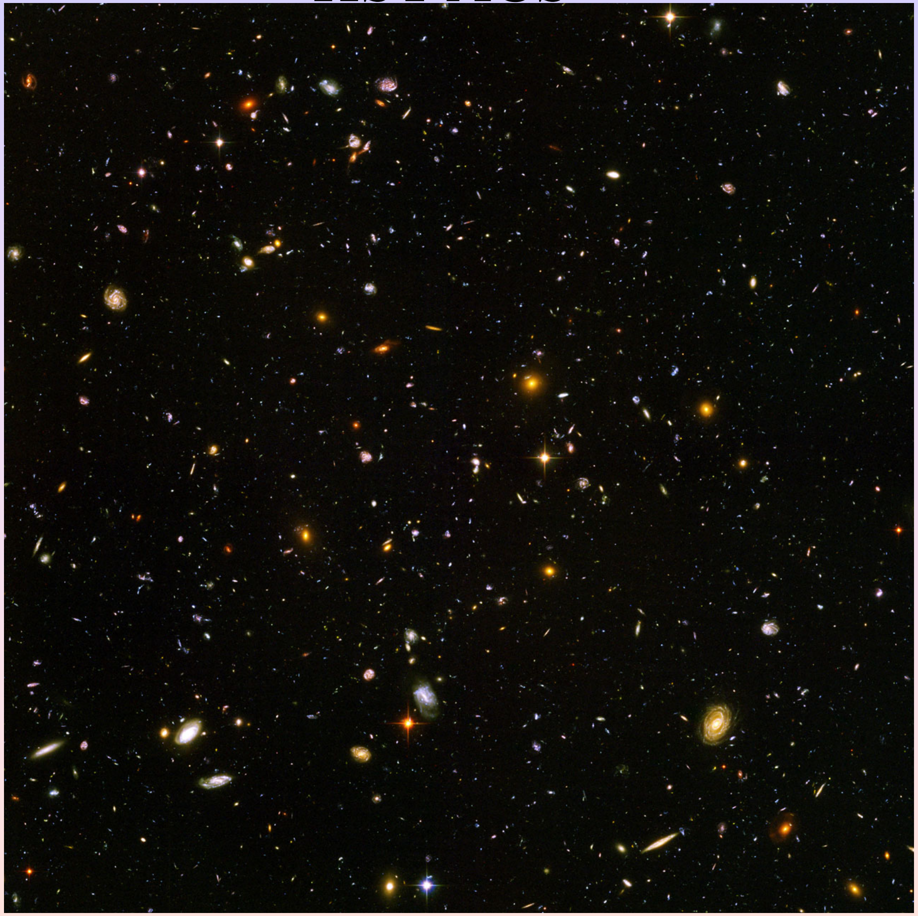




Cutting-edge Instruments

MUSE – Hubble Ultra Deep Field

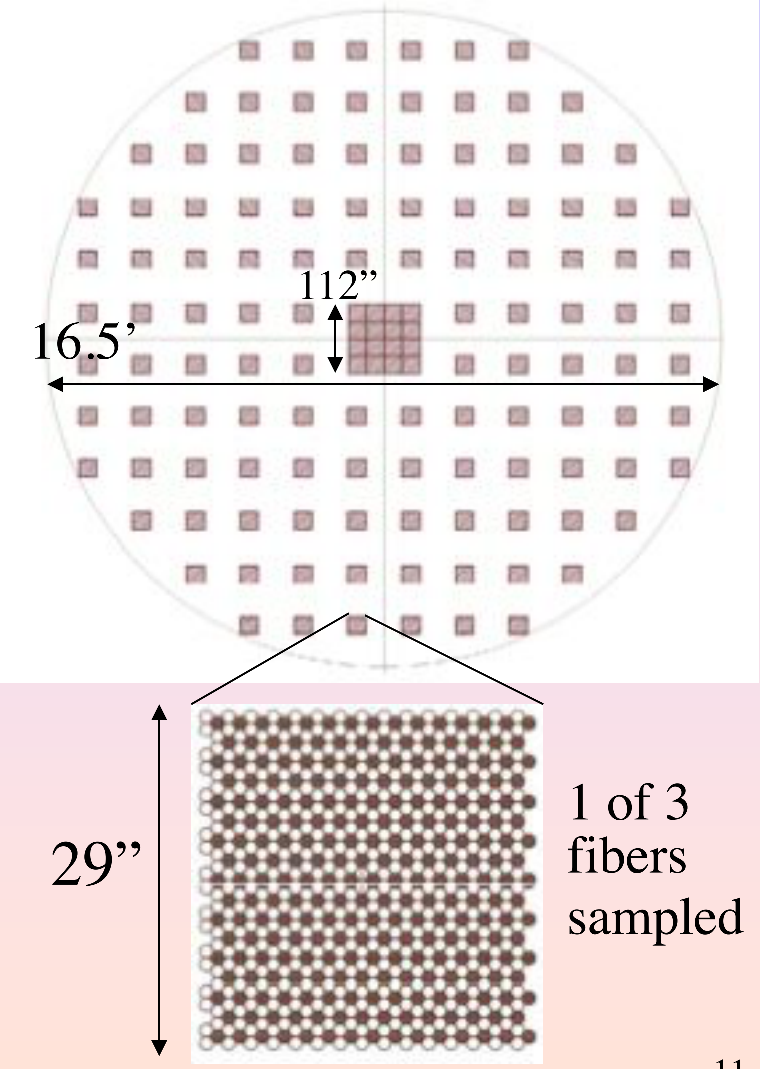
HST ACS



VLT MUSE

Cutting-edge Instruments
HETDEX: VIRUS-156

- Science goals
  - ➢ Measure baryon (acoustic) oscillations in power spectrum of large-scale structure of Lyα-emitting galaxies $1.8<z<3.7$.
- Technical approach
  - ➢ Replicate, small, cheap, low-resolution bare-fiber fed spectrographs
- Instrument capabilities
  - ➢ HET 9.2m + new corrector (16' field)
  - ➢ 215 arcmin^2 FoV, sparsely sampled
  - ➢ 32604 spatial elements (1 arcsec^2 each)
  - ➢ 340-570 nm range (one shot)
  - ➢ 410 spectral elements (R~800)
  - ➢ $\varepsilon \sim 0.15$



Hill et al. ‘04

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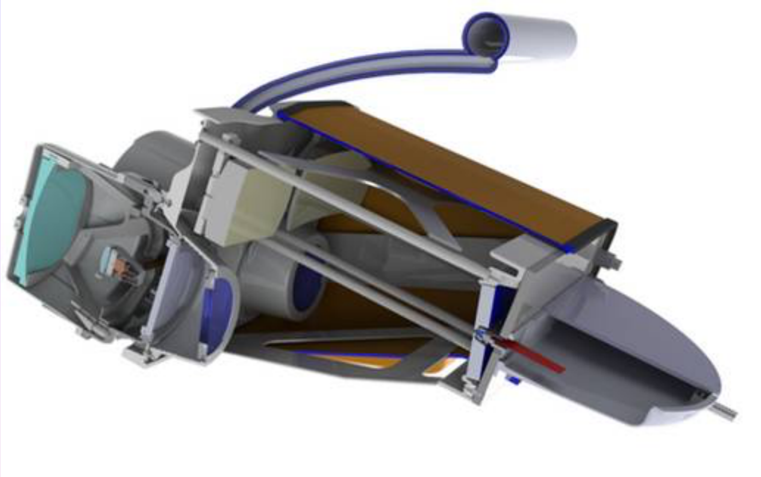

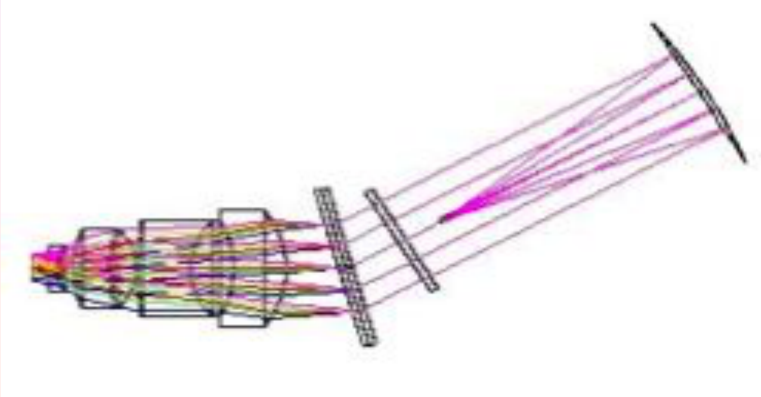

Hill et al. '04

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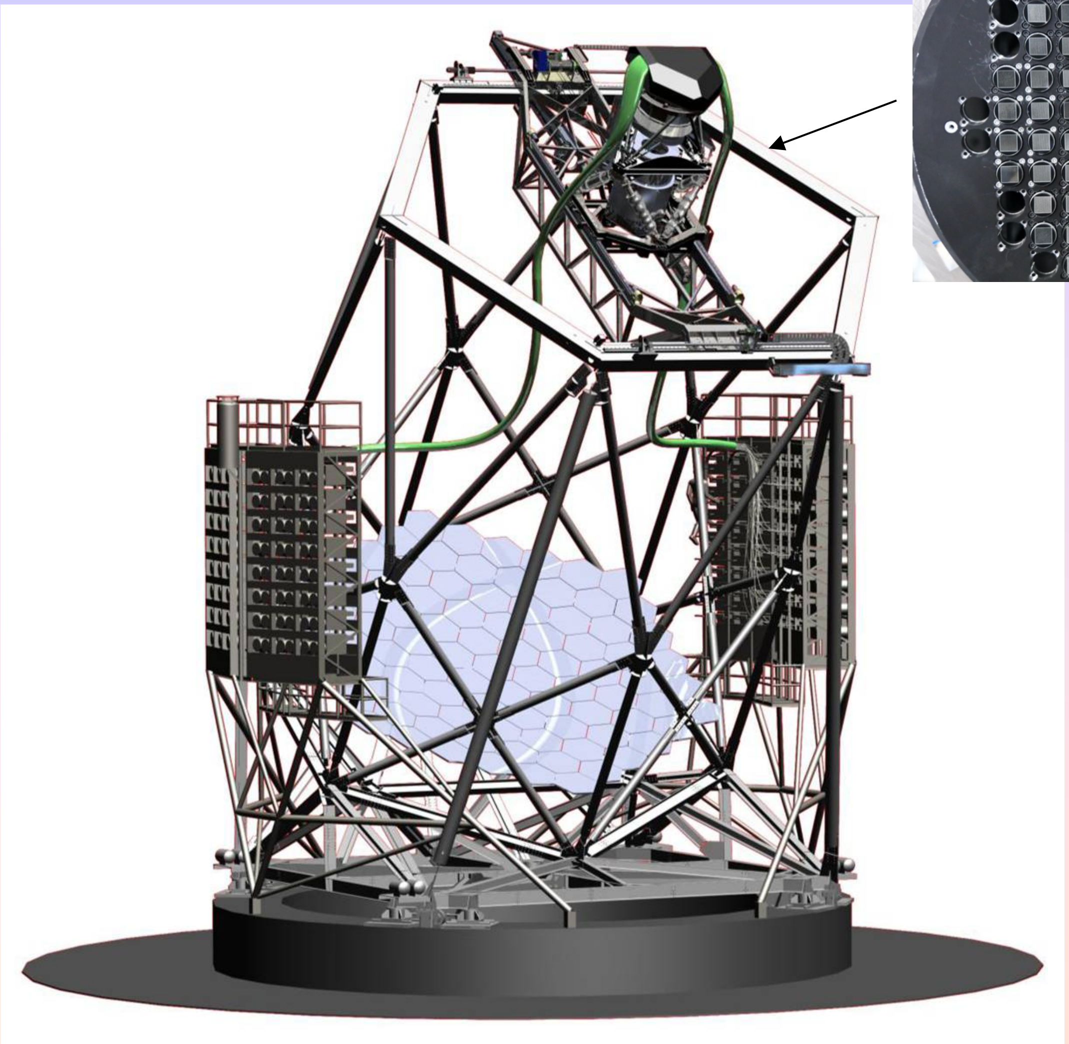
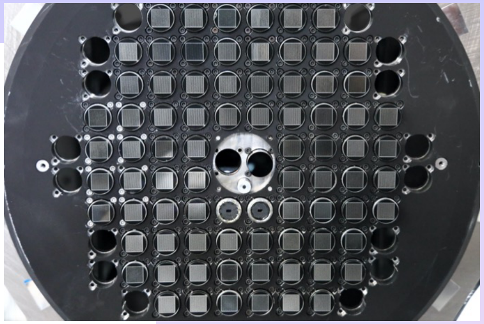
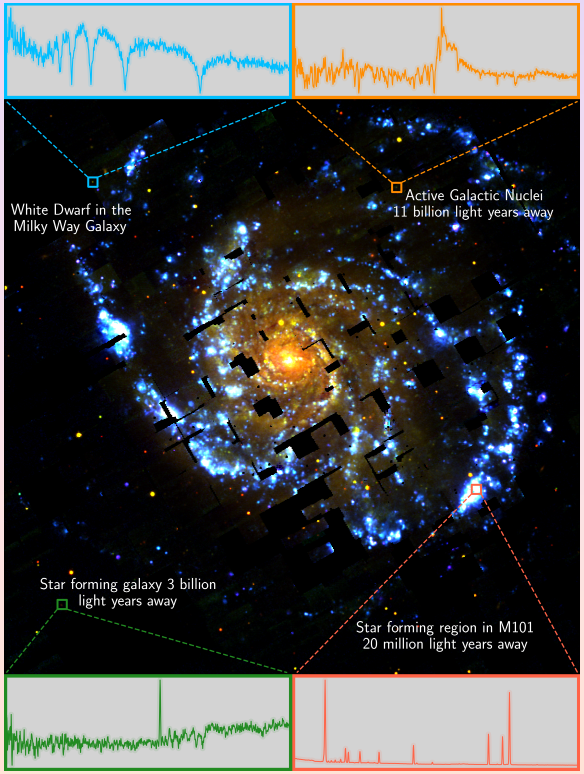




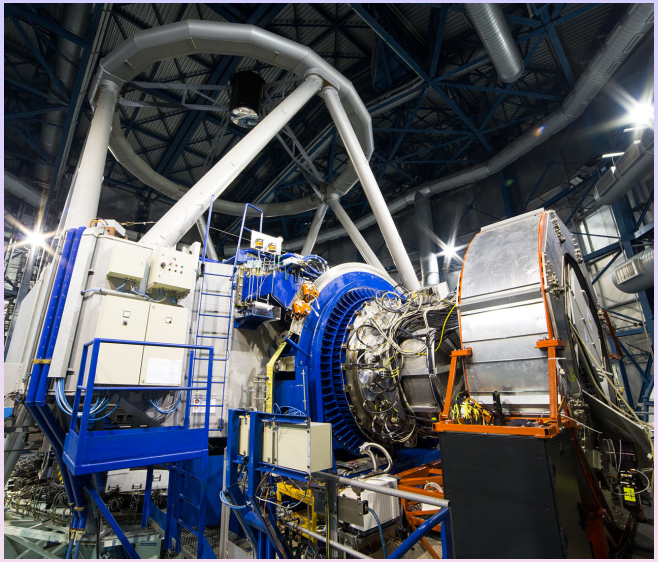


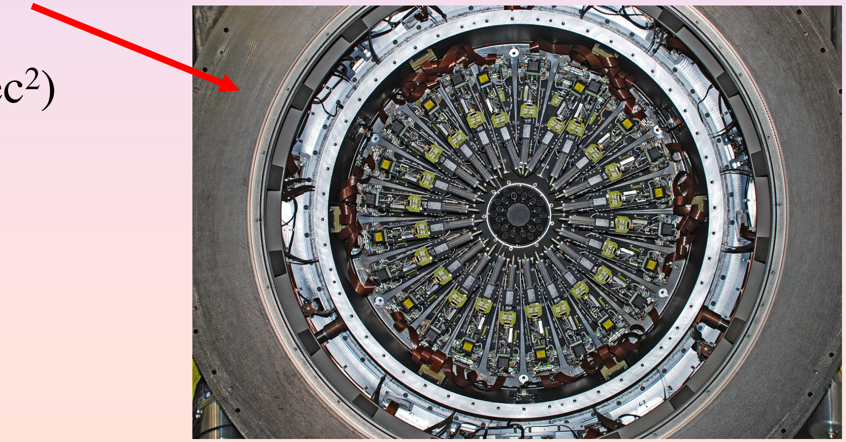
Cutting-edge Instruments
KMOS

- Science goals
  - Investigate physical properties driving galaxy formation/evolution; measure comoving star-formation rate.
- Technical approach
  - Multi-object image slicer feeding cryogenic spectrographs (3).
- Instrument capabilities
  - VLT 8m
  - 24 MOS probes, 2.8x2.8 arcsec each, sampled at 0.2 arcsec (14 slices)
  - 4704 spatial elements total (188 $arcsec^2$)
  - 7.5 arcmin diameter patrol field
  - 1-2.5 μm range
  - 1000 spectral elements (R~3600)
  - ε = ?

Sharples et al. '04

[See also: Thatte et al. '00]





Cutting-edge Instruments

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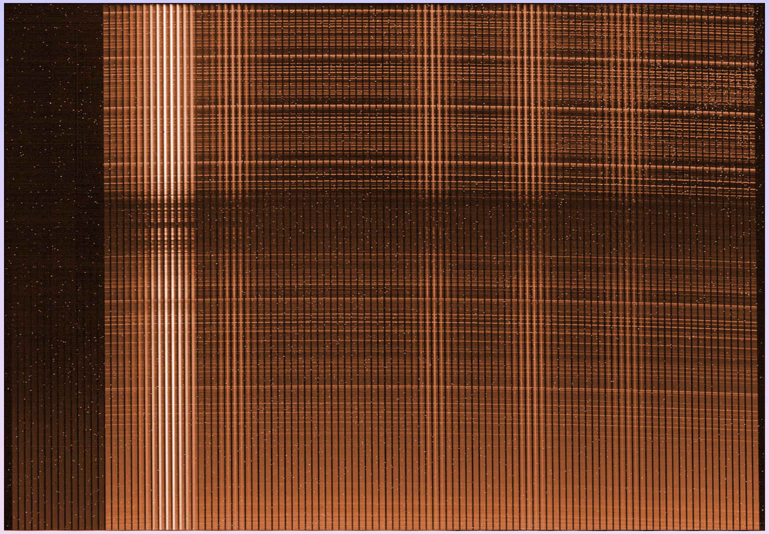
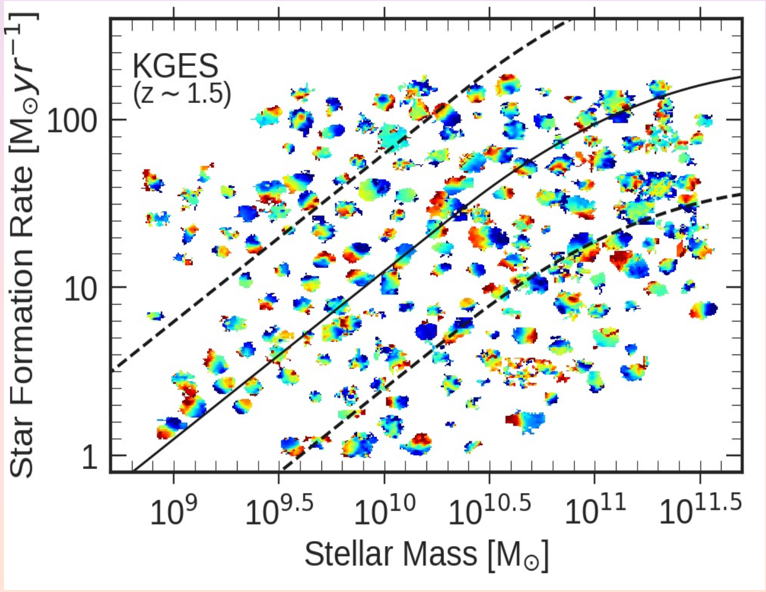




Cutting-edge Instruments

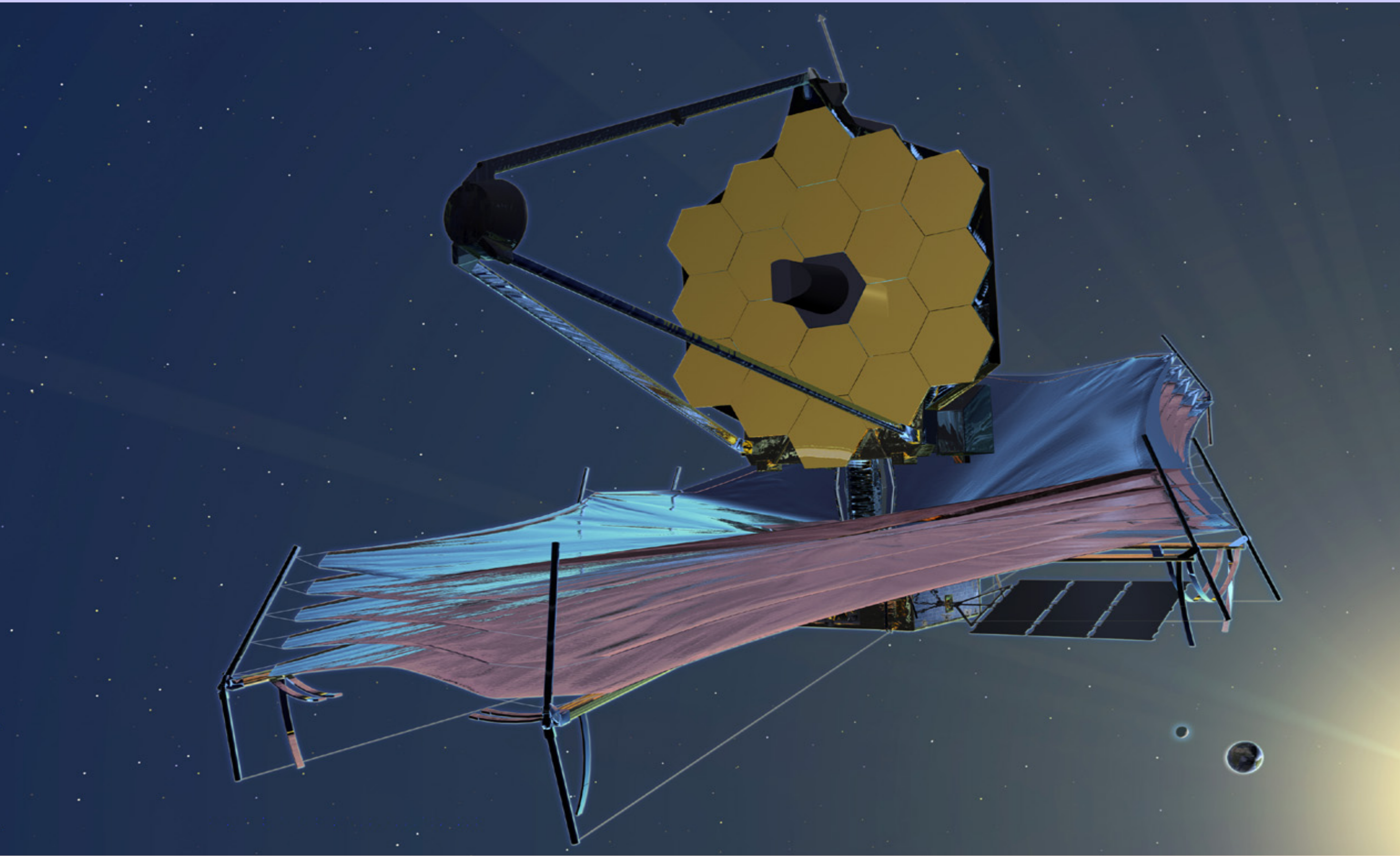
Ground-based instruments on 10m telescopes

Recap:

- State-of-the-art instruments *(only some of them!)*
  - MUSE
  - VIRUS
  - KMOS
- Common themes:
  - All have large AΩ by virtue of instrument multiplex
  - None have large specific grasp AdΩ
  - object multiplexing: *science-driven*
    - *Science cases are varied; KMOS and MUSE are similar, but VIRUS is a departure both in science case (dedicated cosmology survey) and technical aproach (bare fibers).*
  - instrument multiplexing: *cost-driven*
    - *Looking for economies of scale*
    - *Instrument cost go as D^x_{optic}, where $x>2$ (~2.2)*

Cutting-edge Instruments

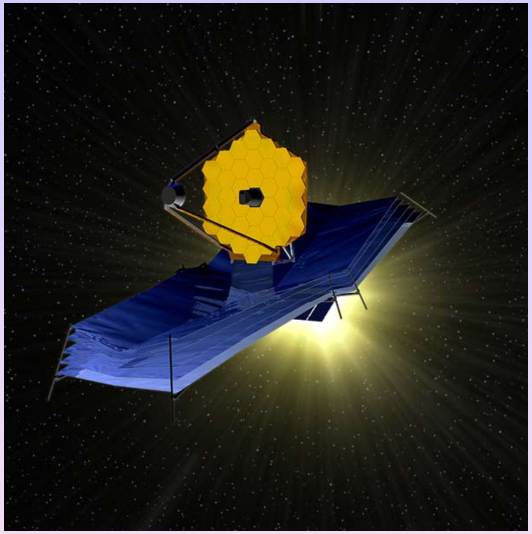
Space-based instruments: JWST



Cutting-edge Instruments

Space-based instruments: JWST

- JWST
  - 6.5m telescope (25 m^2)
  - 0.6-29 μm coverage
  - 0.1 arcsec resolution or better
  - opertating temperature < 50^o K
  - 5-10 year lifetime
  - Launch 2013 or later into 1.5 Mkm orbit at L2

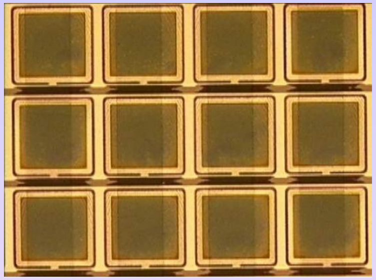


- Science mission
  - first light
  - galaxy assembly
  - birth of stars and proto-planets
  - planetary systems / origins of life

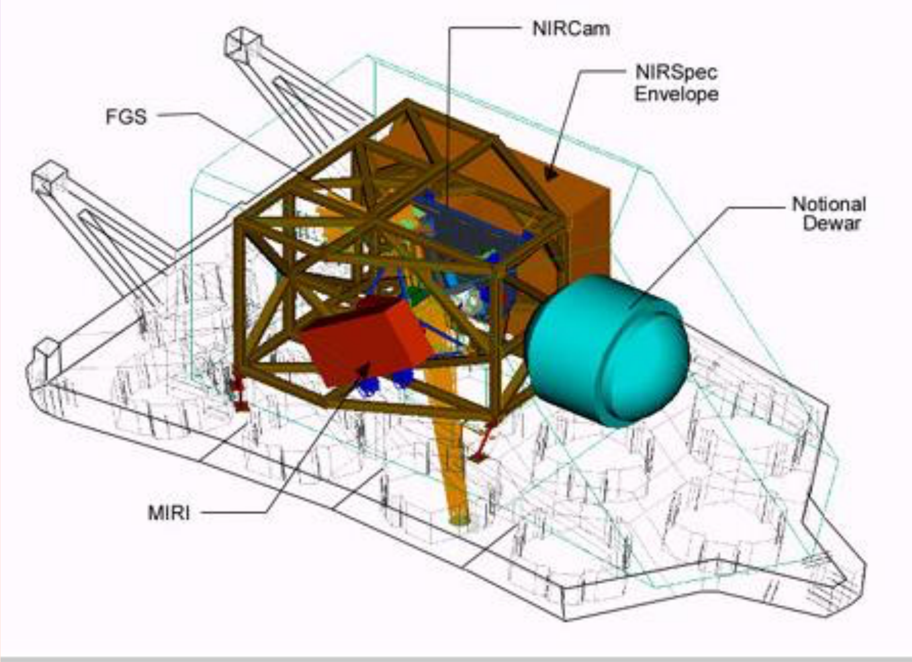
- Instruments
  - NIRCam
  - NIRSpec
  - ~~FGS-TF~~
  - MIRI

IFU capability

Cutting-edge Instruments
Space-based instruments: JWST



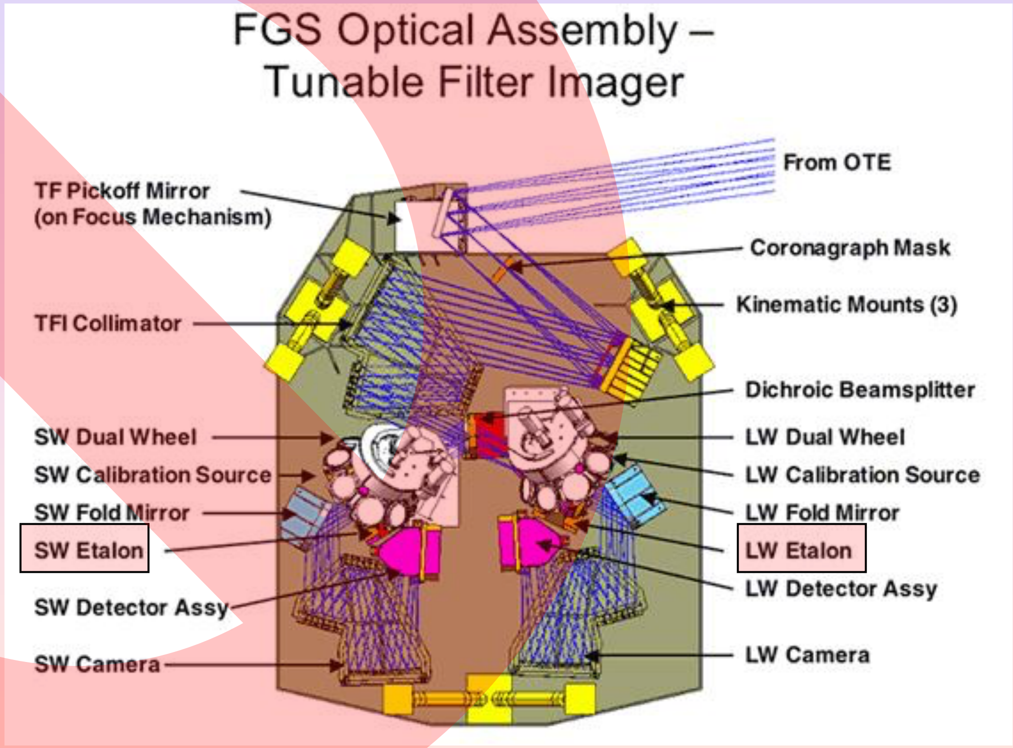
- NIRSpec
  - 3.5x3.5 arcmin field for MOS using MEMS devices
  - IFU mode: 3x3 arcsec at R = 3000
  - advanced slicer: 40 3x0.075 arcsec slices feeding 2×2048^2 arrays
  - 0.8-5 μm



Cutting-edge Instruments

Space-based instruments: JWST

- FGS-TF: Fine-Guidance Sensors -Tunable Filter
  - Dual Fabry-Perot imaging cameras covering 1-5 mm
  - 2.3 x 2.3 arcmin field
  - R ~ 100
  - Two cameras: short (1.2-2.1 μm), long (2-4.8 μm)

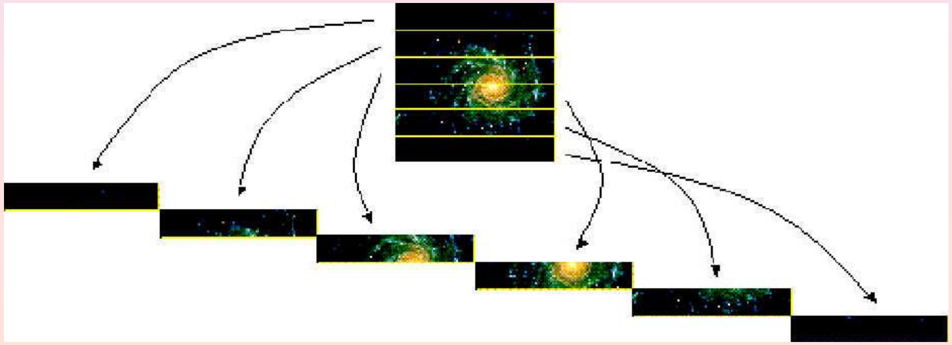


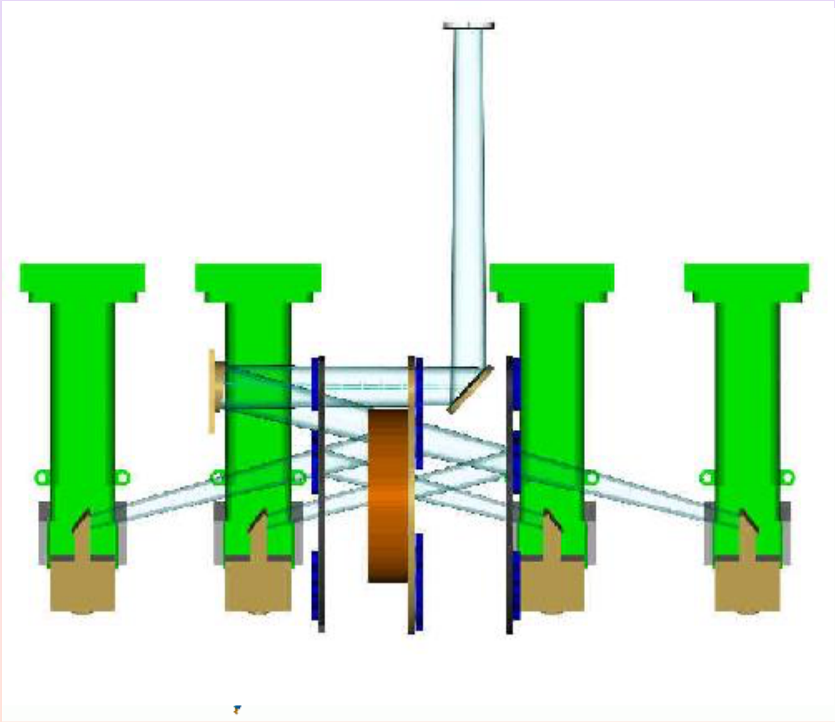
Future instruments

Space-based instruments: JWST

- MIRI: Mid-InfraRed camera and spectrometer
  - 5-28 μm
  - 4 simultaneous image slicers

channel	1	2	3	4
Wavelength (μu)	5-7.7	7.7-11.9	11.9-18.3	18.3-28.3
Slice width (“)	0.17	0.28	0.39	0.64
Pixel (“)	0.2	0.2	0.24	0.27
FoV (“)	3x3.9	3.5x4.4	5.2x6.2	6.7x7.7
R	~3000	~3000	~3000	~2200





Cutting-edge Instruments
Space-based instruments: SUMMARY

- **JWST** has IFUs with (typically)
  - 3x3 arcsec fields mapped with image slicers
  - 0.15 arcsec sampling -- lower than TMT
  - 100 < R < 3000 -- lower-to-comparable to TMT
  - Optical to mid-infrared coverage *with low backgrounds*
- One near-infrared FP offers narrow-band imaging over a 2.3 arcmin field.
- There are no large-grasp systems that take advantage of the low backgrounds of space.
- There are no high- (or even medium) resolution spectrographs.

Table 6. Future Space-Based Integral Field Instruments

Instrument	Coupling Method	Telescope	D_T (m)	Ω (arcsec^2)	$d\Omega$ (arcsec^2)	N_θ	$\Delta\lambda/\lambda$	R	N_R	ϵ
MIRI	advanced-slicer	JWST	6.5	51.8	0.30	173	1.48	2800.	4096	-1.
NIRSpec	advanced-slicer	JWST	6.5	9.	0.0056	1600	0.34	3000.	1024	-1.

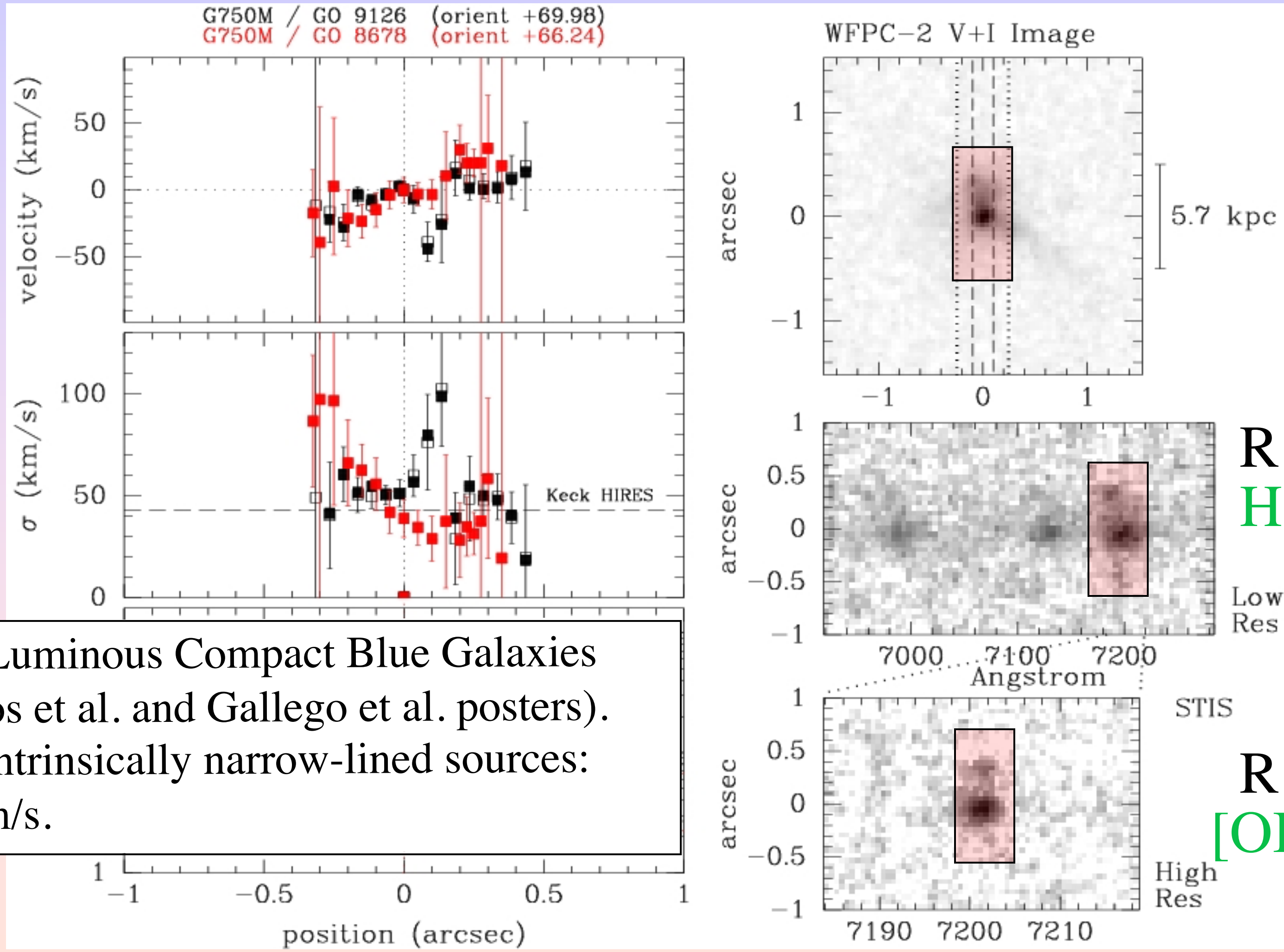
A **warning** about space-based measurements of galaxy kinematics

- Remember: Your spectrum is a continuum of monochromatic images of your slit.
- An unresolved emission-line will appear as a slit image,
  - i.e., the detailed structure of the line profile is just the (demagnified) image formed on your slit.
- This occurs at "low" spectral resolution.
  - "low" depends on the intrinsic internal velocities of your source.
- This applies to any data where the PSF is significantly smaller than the slit width *and* instrinsic image structure is of order the scale of the slit width or smaller.
- Such data will have artificial "kinematic" features which have to be interpreted with prior information about the spatial distrution of flux within the slit.
- The solution is "trivial:"
  - Observe at higher spectral resolution: $R >> \lambda / \theta_w * \gamma$

Slit width (angle)

Angular dispersion

An example: STIS Spectra of LCBGs



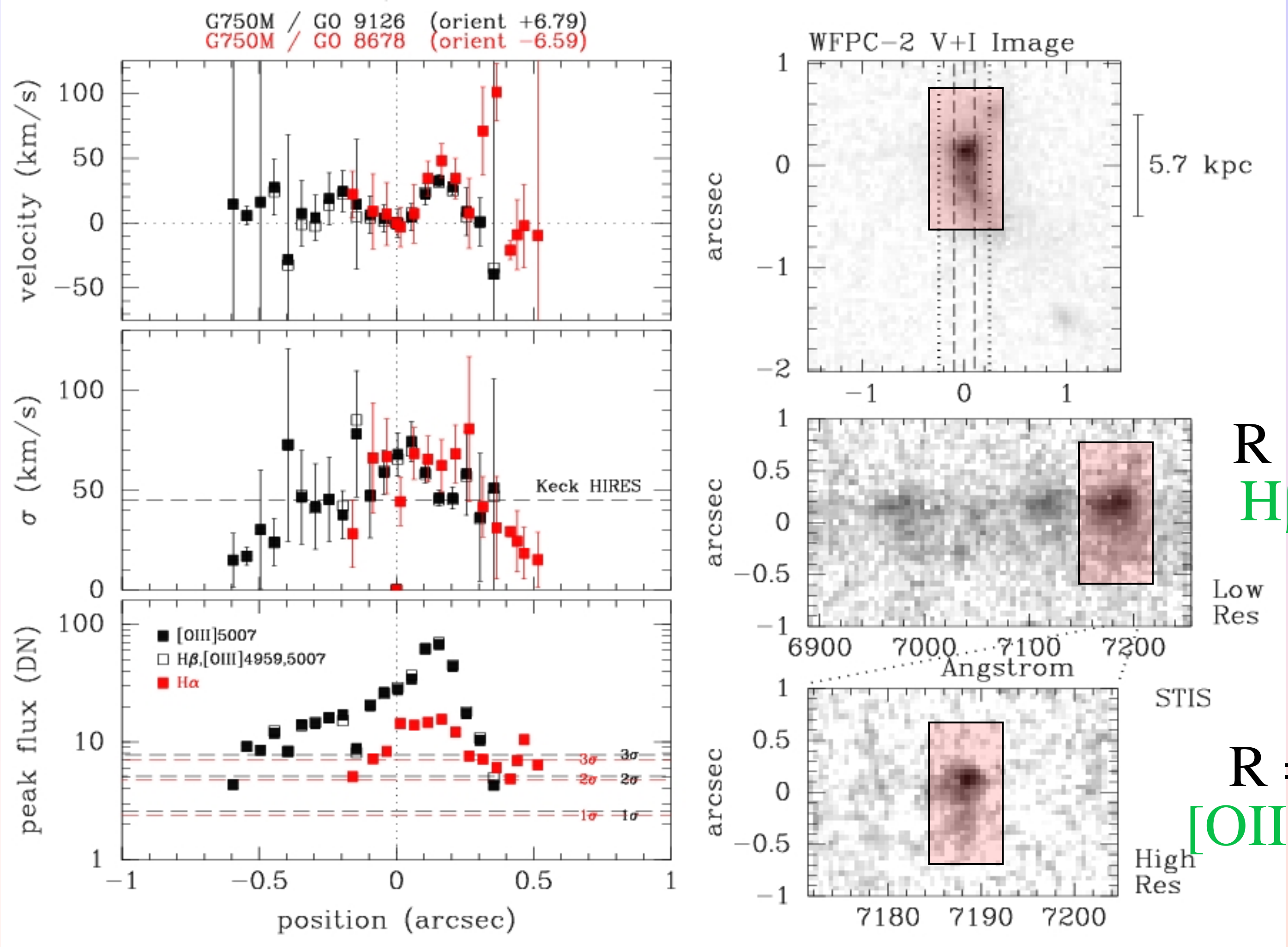
R = 800
Hβ+[OIII]

R = 7000
[OIII]λ5007

LCBGs: Luminous Compact Blue Galaxies (see Hoyos et al. and Gallego et al. posters). This are intrinsically narrow-lined sources: σ < 70 km/s.

S110601, z=0.44, V/σ ~ 1   Bershady, Vils, Hoyos, Guzman, Koo ‘04

…We didn't just get "lucky"…

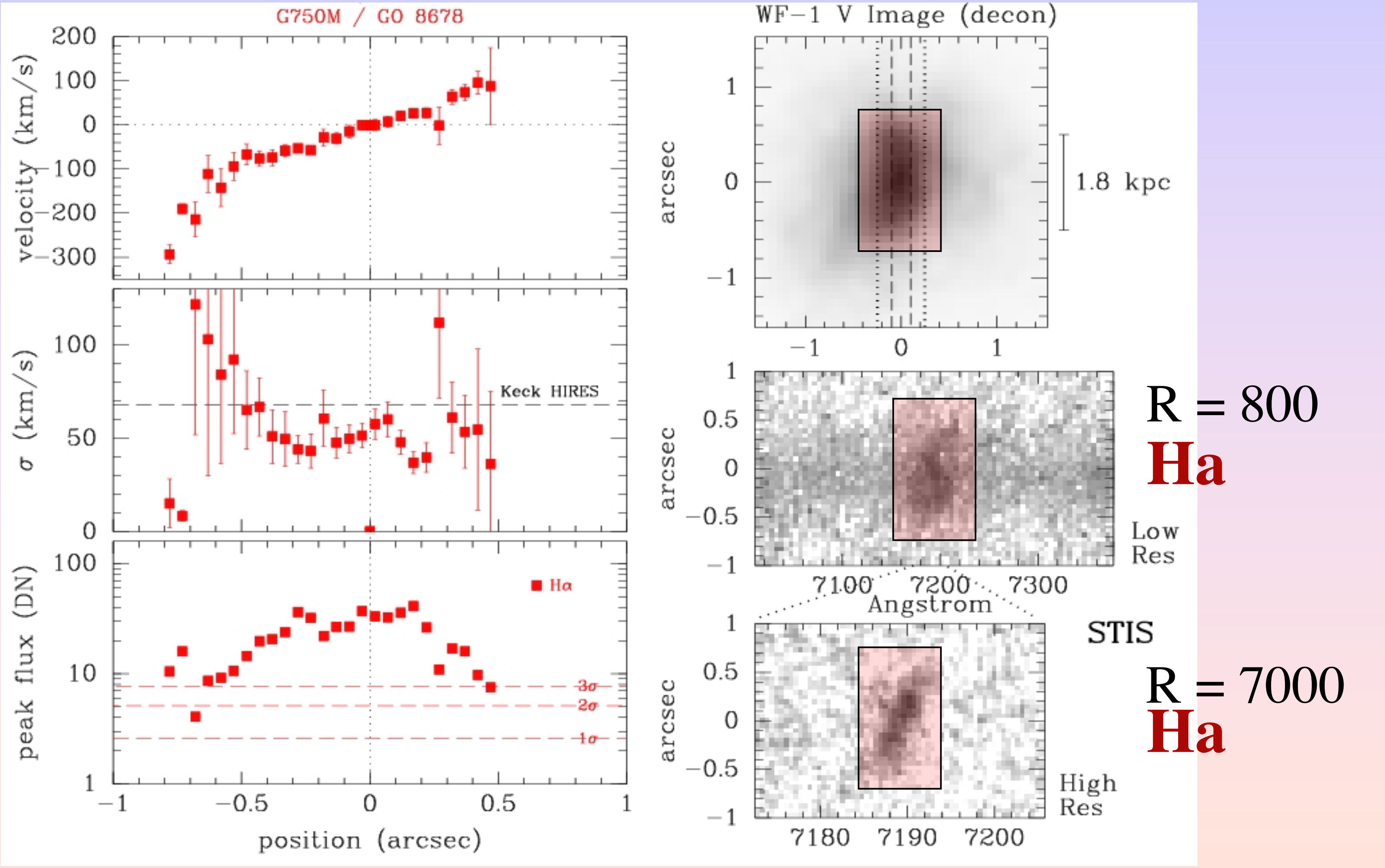


R = 800
Hβ+[OIII]

R = 7000
[OIII]λ5007

H313088, z=0.44, V/σ ~ 0.45 Bershady, Vils, Hoyos, Guzman, Koo '04

Here's another:



H313385, z=0.10, V/σ ~ 3.4 Bershady, Vils, Hoyos, Guzman, Koo '04

Take-home message

Be very careful with high-angular resolution data which is observed at low dispersion.

Future instruments
Ground vs space

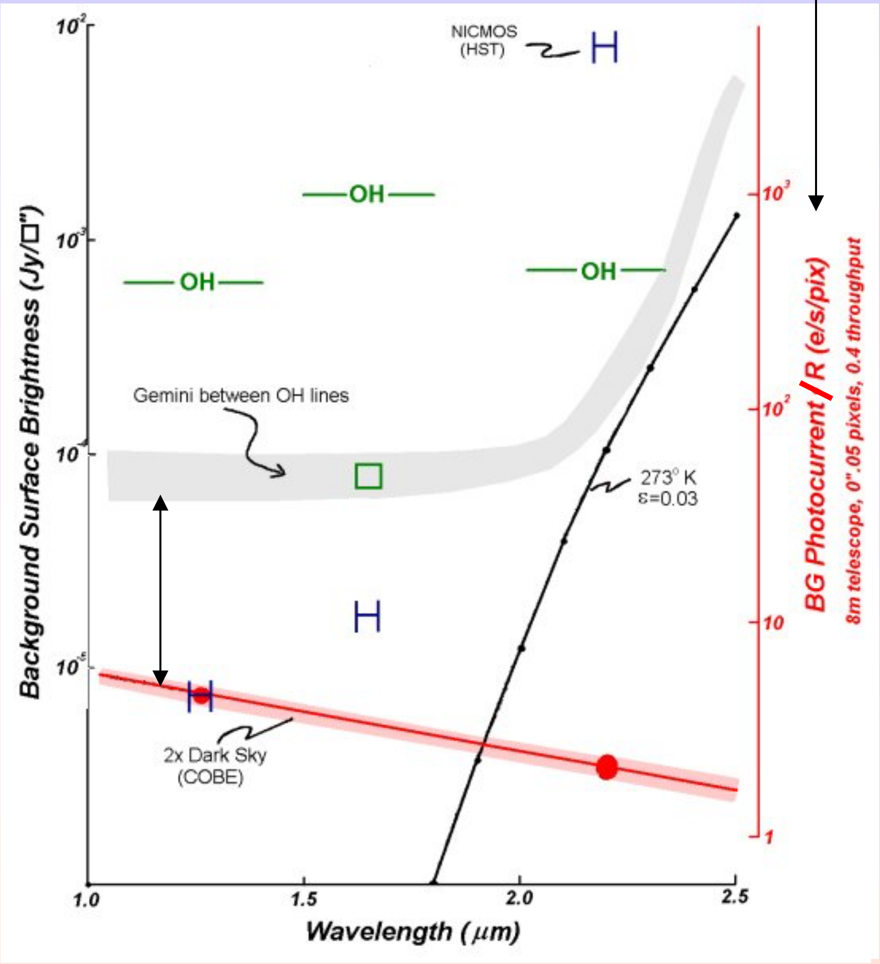
- Backgrounds
  - ➢ background or detector limited
    - o Wavelength and resolution dependent
- Cost and flexibility
  - ✓ ground-based telescopes always win

✓ Why build bigger telescopes?

Future instruments
Ground vs space

note

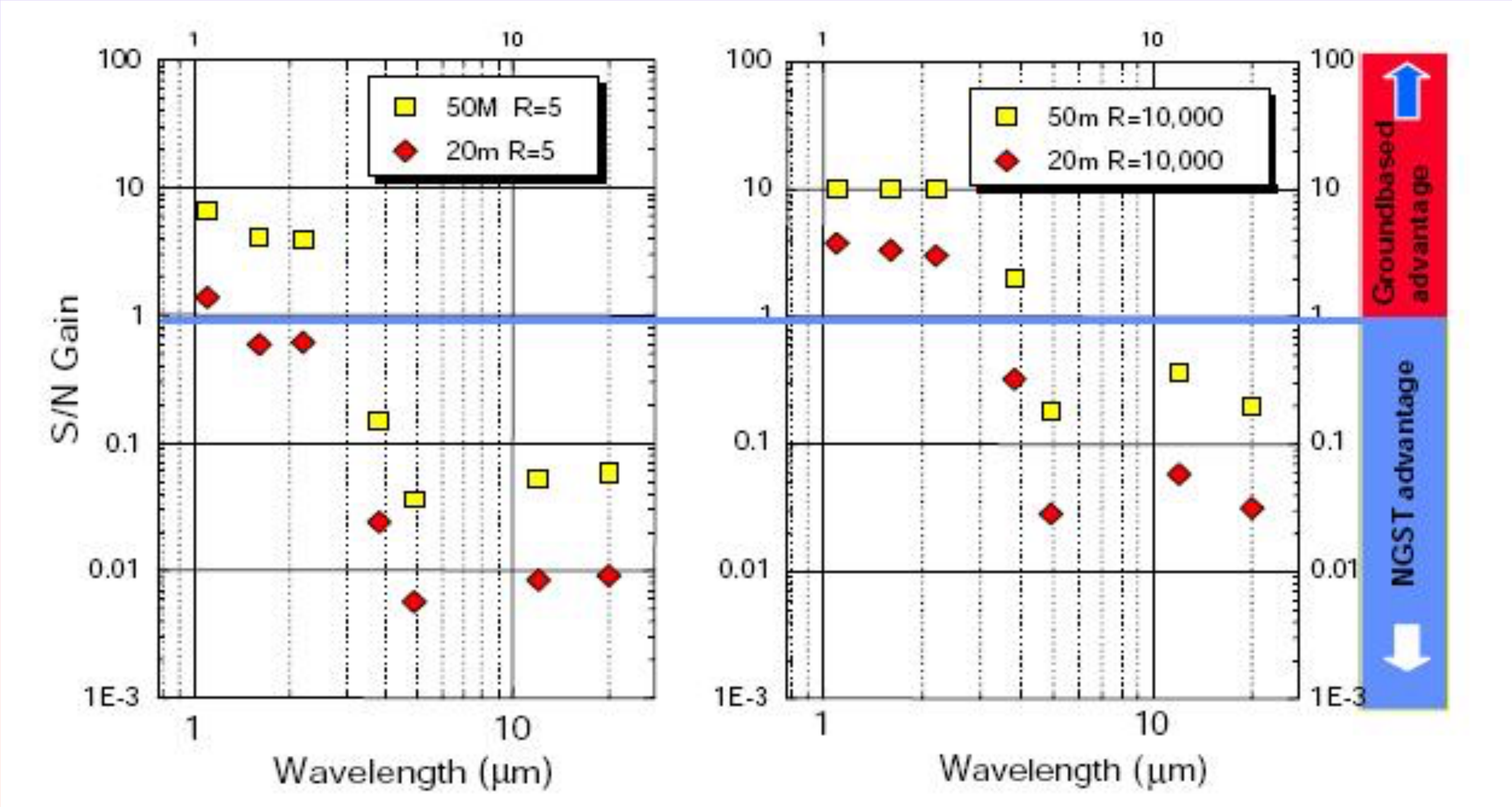
- Backgrounds:
  - ➢ a cooled space-craft has significantly lower background compared to the ground even at high spectral resolution.
    - o dramatic for λ>2.5µm
  - ➢ Above R~1000, 8m-class space telescopes are detector-limited (0.05” apertures).



Gillet & Mountain ‘97
MAXAT

Future instruments
Ground vs space

- Competiveness:
  - assumes diffraction-limited performance for stellar spectroscopy.



AURA MAXAT report, 1999

Future instruments
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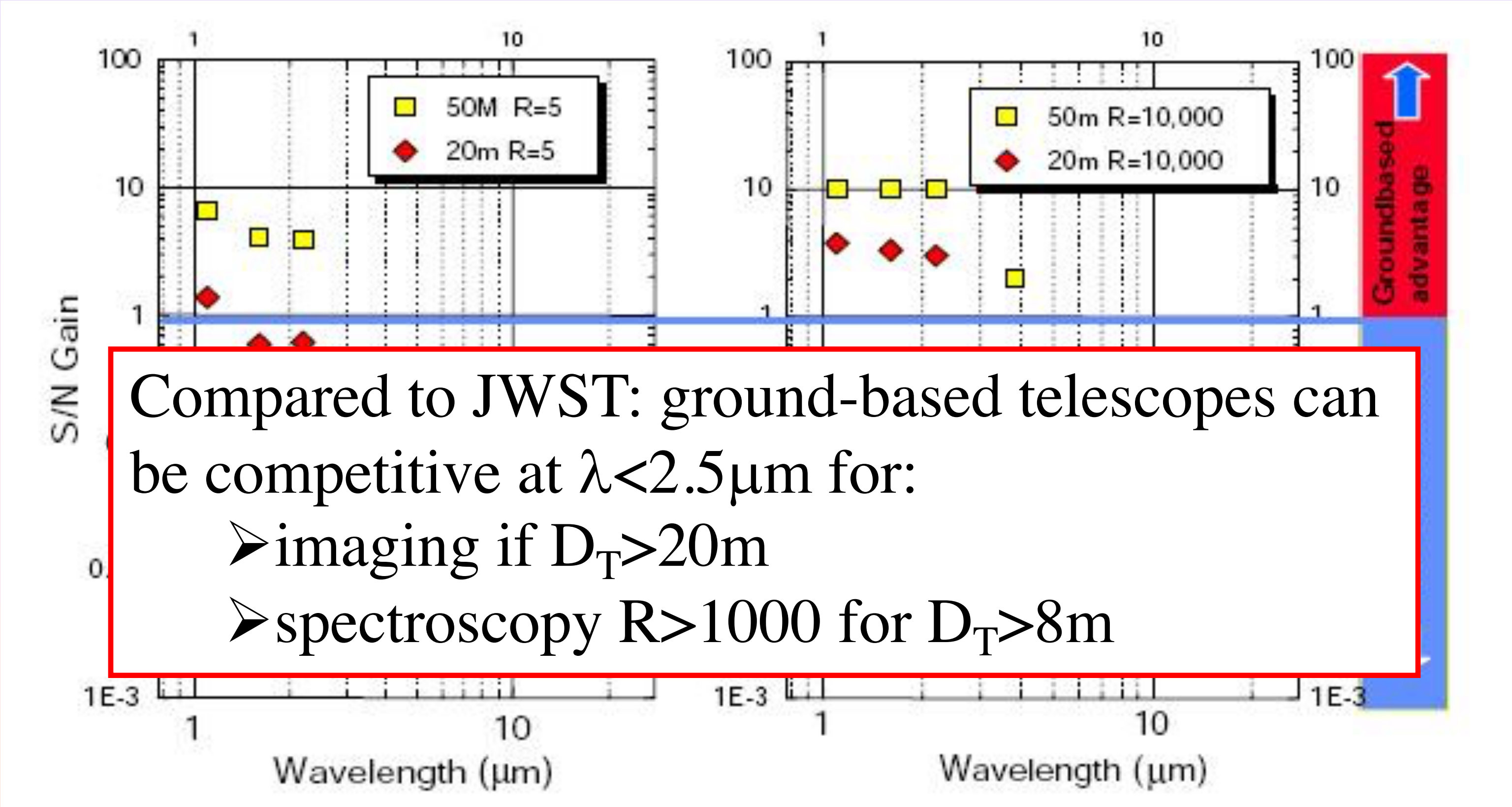


Compared to JWST: ground-based telescopes can be competitive at $\lambda<2.5\mu m$ for:

- imaging if $D_T>20m$
- spectroscopy R>1000 for $D_T>8m$

AURA MAXAT report, 1999

Future instruments

Ground-based instruments on 30-100m telescopes

- The ~~horror~~ challenge of large telescopes
  - ➢ instrument size at the diffraction limit
  - ➢ AO-driven designs
  - ➢ unique parameter space: the photon limit at high resolution
- Specific examples of TMT instrumentation

  (D. Crampton)
  - ➢ different kinds of AO
  - ➢ WFOS - seeing-limited
  - ➢ IRIS - NIRFAOS, diffraction limited
  - ➢ IRMOS - MOAO, multi-object

ELT: See also Eisenhauer et al. ‘00, Russell et al. ‘04

Future instruments

Ground-based instruments on 30-100m telescopes

- Why the challenge?
  - AΩ is conserved
  - If you want field (Ω), you are going to have to pay for it by building a massive instrument.
  - Only one way out: work at the diffraction limit since

    $\theta \sim \lambda / D_T$

    The instrument entrance aperture (and hence the instruments size itself) for diffraction-limited sources is independent of telescope diameter.
  - This is ok for individual stars or planetary systems, but galaxies are extended, and everybody wants "field" for survey work.
  - Science case driven to high-angular resolution because technical case is achievable and attractive.
    - Dangerous?

Future instruments

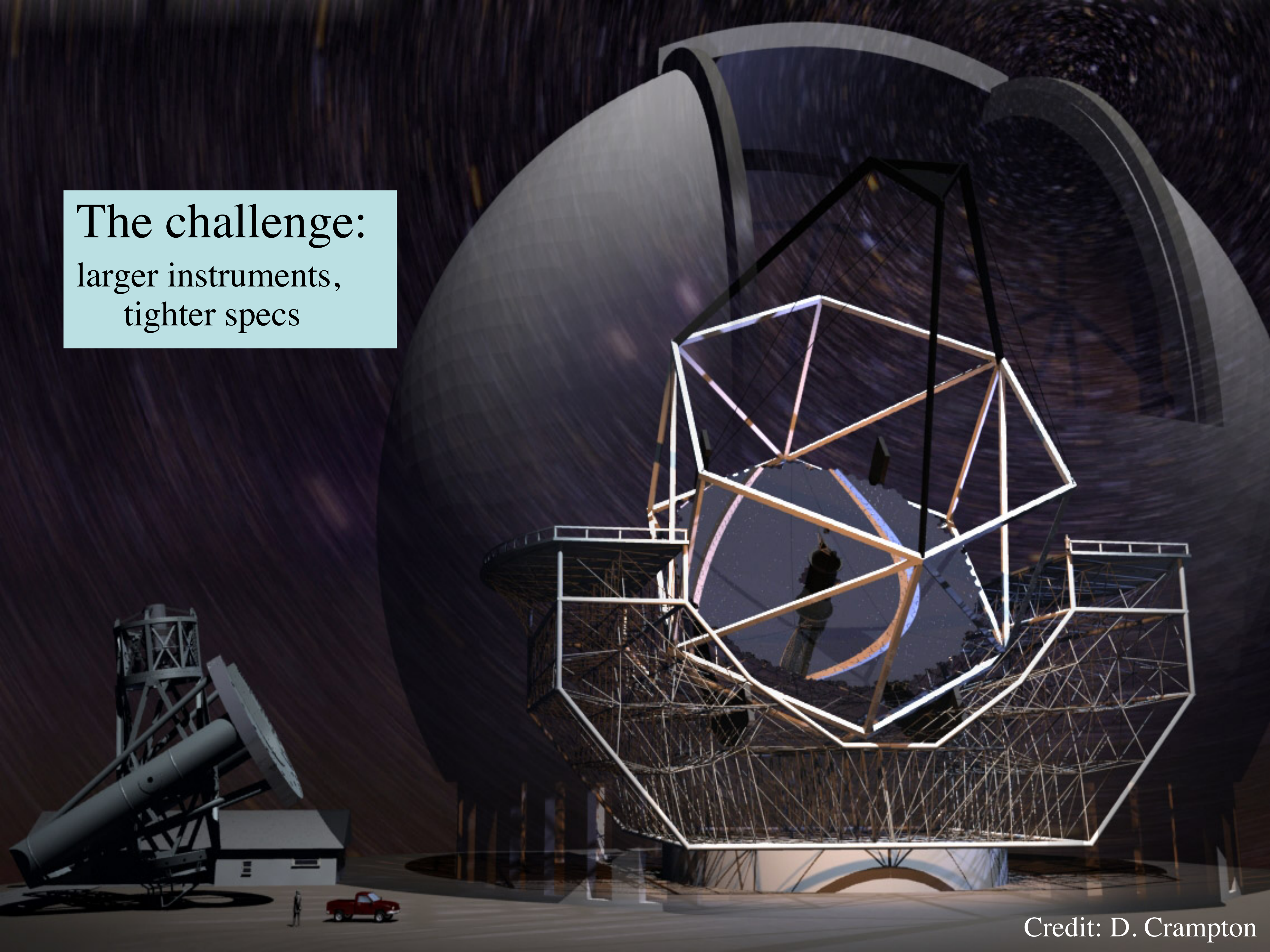
Ground-based instruments on 30-100m telescopes

- AO-driven designs
  - Different kinds of AO
    - Level of correction (from tip-tilt to extreme AO)
    - Area which is corrected
    - Single or multiple areas
  - What instrument you build depends on what AO you think you can deliver.
    - Is this backwards? What's the *a priori* science goal?

- Unique parameter space:
  - The photon limit at high resolution
    - *High spectral or spatial resolution?*
  - The diffraction limit…
    - …especially at long wavelength requires large aperture.
    - But this is where you win in space, so focus on near-infrared.

The challenge:

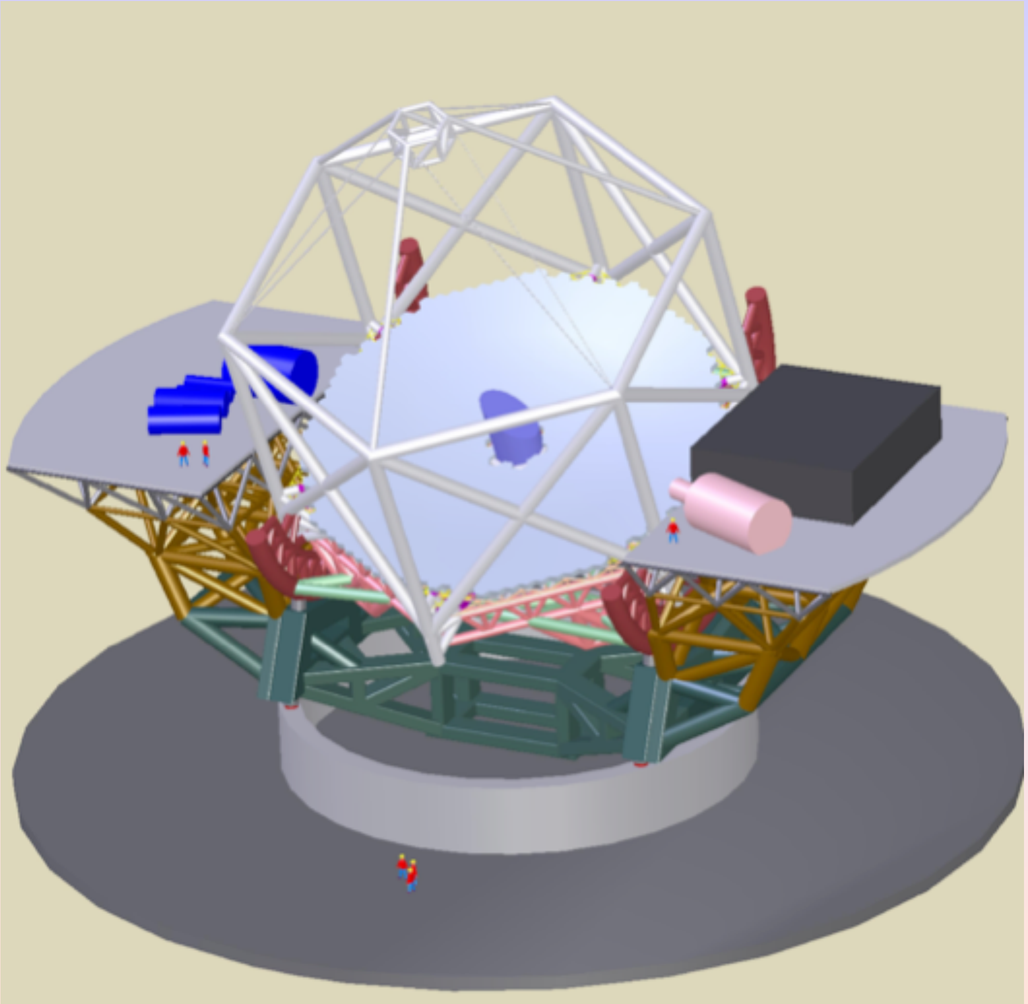
larger instruments,
tighter specs



Credit: D. Crampton

Single TMT Reference Design

- 30m filled aperture, highly segmented (738)
- Aplanatic Gregorian (AG) telescope
- f/1 primary
- f/15 final focus
- Field of view 20 arcmin
- Wavelength coverage 0.31 – 28 μm
- Operational zenith angle range 1° thru 65°
- Instruments (and their AO systems) are located on large Nasmyth platforms, addressed by an articulated tertiary mirror.
- Both seeing-limited and adaptive optics observing modes



Credit: D. Crampton

SRD Science Instruments

- Adaptive Optic systems defined
  - **NFIRAOS** (Narrow Field facility AO system) for first light
  - **MOAO** (“Multi-Object Adaptive Optics” ~20 positionable, 5” compensated patches in 5’)
  - **MIRAO** (MidIR AO)
  - **MCAO** (wide field AO, optimized for photometric and astrometric goals)
- Eight Instruments identified
  - **IRIS**, a NIR imager and integral field spectrograph working at the diffraction limit, fed by NFIRAOS
  - **WFOS**, a wide field, seeing-limited optical spectrograph
  - **IRMOS**, a NIR multi-object integral field spectrograph fed by MOAO
  - **MIRES**, a mid-IR echelle spectrograph fed by MIRAO
  - **PFI**, a “planet formation instrument”, which combines a high contrast AO system and an imaging spectrograph.
  - **NIRES**, a NIR echelle spectrograph, also fed by NFIRAOS
  - **HROS**, a high spectral resolution optical echelle spectrograph
  - **WIRC**, a wide field NIR camera fed by multi-conjugate AO

Credit: D. Crampton

IRIS: Infrared Imaging Spectrograph

Integral Field Spectrograph and Imager working at the diffraction limit

- **Wavelength range:** 0.8-2.5μm; goal 0.6-5μm
- **Field of view:** < 2 arcsec for IFU, up to 10" for imaging mode
- **Spatial sampling:** 0.004 arcsec per pixel (Nyquist sampled) over 4096 pixels for IFU; over 10x10 arcsec for imaging
  - Plate scale adjustable 0.004, 0.009, 0.022, 0.050 arcsec/pixel
  - 128x128 spatial pixels with small ($\Delta\lambda/\lambda \leq 0.05$) wavelength coverage
- **Spectral resolution**
  - R=4000 over entire J, H, K, L bands, one band at a time
  - R=2-50 for imaging mode
- Low background (increase inter-OH sky + tel by no more than 15%)
- Detector: Dark current and read noise ≤ 5% of background for t=2000s
- Throughput: as high as practical

Credit: D. Crampton

IRMOS:
Infrared Multi-Object Spectrograph

MOAO/Deployable IFU spectrometer

- **Wavelength range:** 0.8-2.5μm
- **Field of View:** IFU heads deployable over 5 arcmin field
- Wavefront quality: preserve that delivered by AO system
- **Image quality:** diffraction-limited images, tip-tilt ≤0.015 arcsec rms
- **Spatial sampling**
  - 0.05x0.05 arcsec pixels, IFU head 2.0 arcsec, ≥ 10 IF units
- **Spectral resolution**
  - R=2000-10000 over entire J, H, K bands, one band at a time
  - R=2-50 for imaging mode
- Low background (increase inter-OH sky + tel by no more than 15%)
- Detector: Dark current and read noise ≤ 5% of background for t=2000s
- Throughput: as high as practical

Credit: D. Crampton

WFOS:
Wide Field Optical Spectrograph

Multi-object spectroscopy over as much of 20' field as possible

- **Wavelength range:** 0.31-1.1μm (0.31-1.6μm goal). ADC required
- **Field of view**: 75 arcmin^2 ; goal: 300 arcmin^2
- Total slit length ≥ 500 arcsec
- Image quality: ≤ 0.2 arcsec FWHM over any 0.1μm
- **Spatial sampling:** ≤0.15 arcsec per pixel, goal ≤ 0.10 arcsec
- **Spectral resolution:** R=5-5000 for 0.75" slit; goal: 150-6000
- Throughput: ≥ 30%
- Sensitivity: photon noise limited for all exposures > 60s
- Background subtraction systematics must be negligible compared to photon noise for total exposure times as long as 100 Ks
- Stability: Flexure < 0.1 pixel at the detector is required
- Desired: cross dispersed mode, IFU option, narrow band imaging, enhanced image quality using adaptive optics

Credit: D. Crampton

Future instruments

Ground-based instruments on 30-100m telescopes

TMT SUMMARY

- High-priority IFS is in the near-infrared
  - High angular resolution (< 0.1 arcsec)
  - Small fields of view (< 7 arcsec)
  - Modest spectral resolution for an ELT (<10000, more like 2-4000)
- WFOS has potential for modest-grasp IFU with good spectral power, but modest spectral resolution (<6000)

Table 5. Future TMT Integral Field Instruments

Instrument	Coupling Method	Telescope	D_T (m)	Ω (arcsec^2)	$d\Omega$ (arcsec^2)	N_θ	$\Delta\lambda/\lambda$	R	N_R	ϵ
IRIS	slicer	TMT	30.	0.26	1.6e-5	16384	0.05	4000.	200	-1.
IRIS	slicer	TMT	30.	1.33	8.1e-5	16384	0.05	4000.	200	-1.
IRIS	slicer	TMT	30.	7.93	4.8e-4	16384	0.05	4000.	200	-1.
IRIS	slicer	TMT	30.	41.0	2.4e-4	16384	0.05	4000.	200	-1.
IRMOS	slicer	TMT	30.	40.	0.01	4000	0.25	2000.	500	-1.
IRMOS	slicer	TMT	30.	40.	0.01	4000	0.25	10000.	2500	-1.
WFOS	fiber+lens	TMT	30.	810.	0.56	1440	1.37	5000.	6850.	0.3

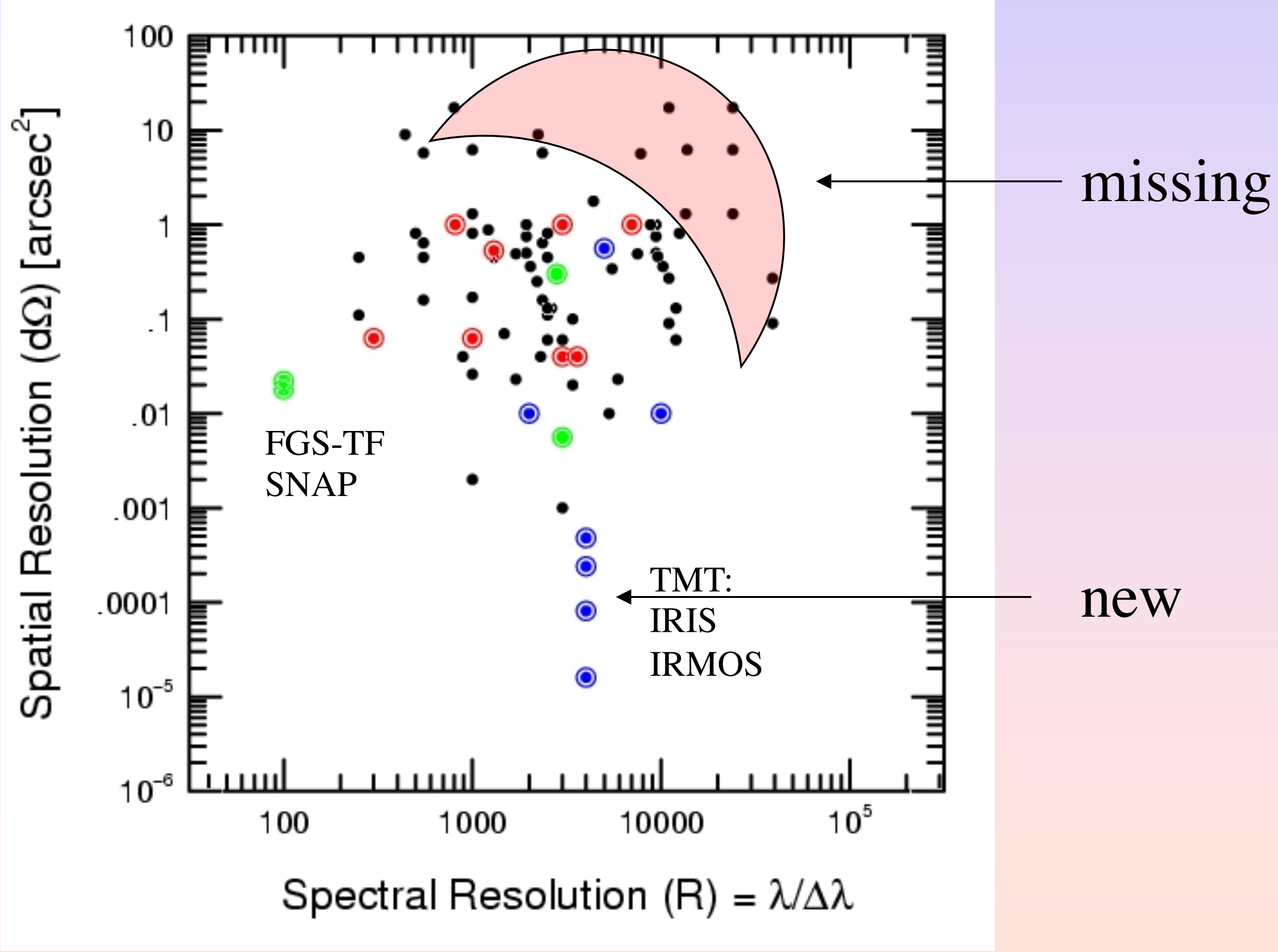
Future instruments
SUMMARY

Existing

New Ground 2-10m

Future Ground 30m

JWST Space



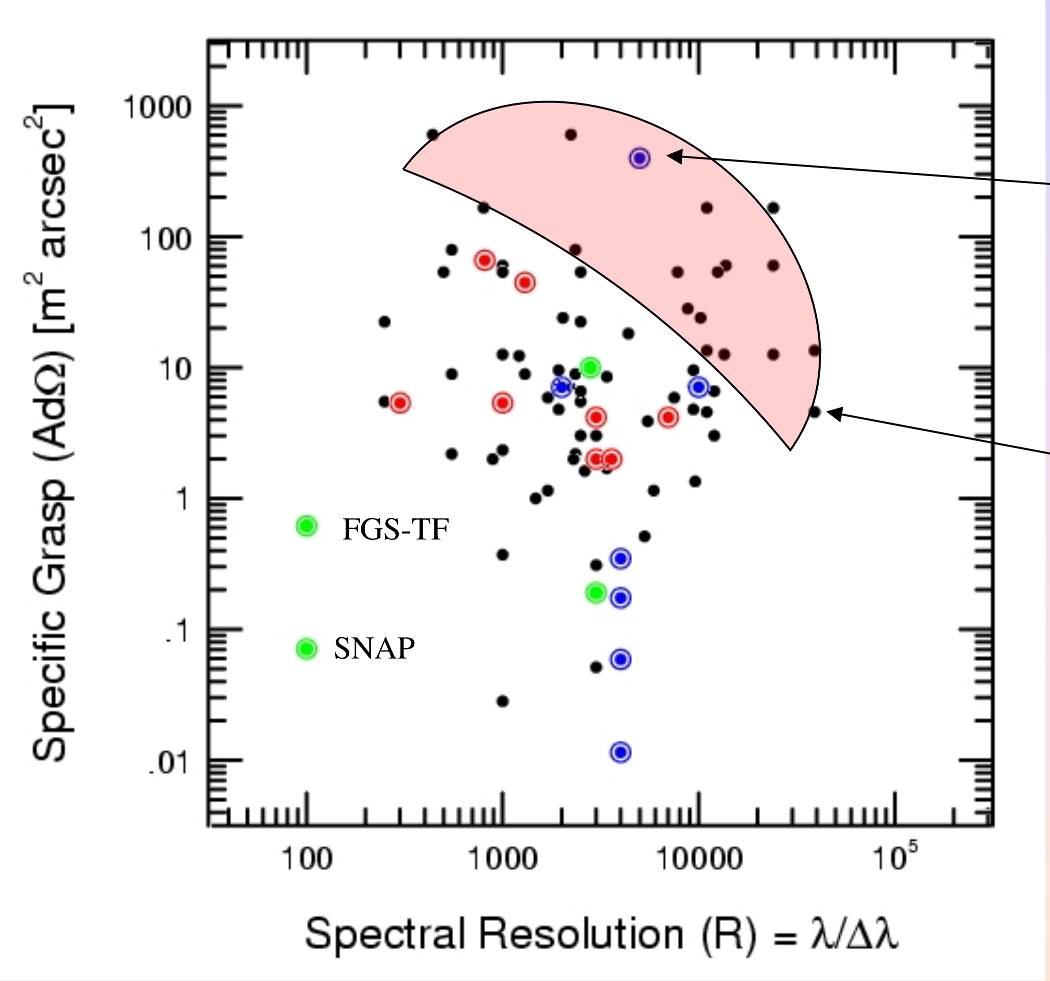
Future instruments
SUMMARY

Existing

New Ground 2-10m

Future Ground 30m

JWST Space



Aha!
WFOS

Still missing: high spectral resolution

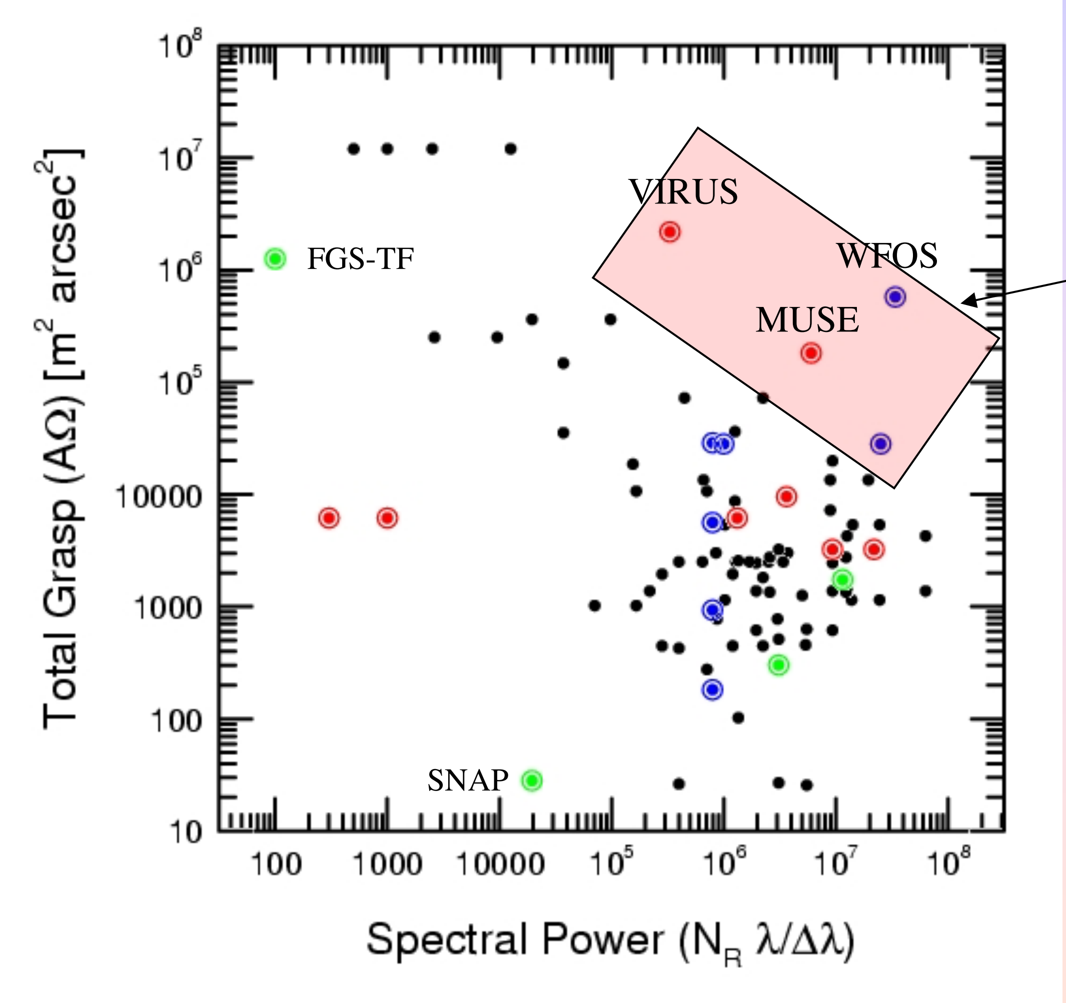
Future instruments
SUMMARY

Existing

New Ground 2-10m

Future Ground 30m

JWST Space



Added AΩ at high spectral power.

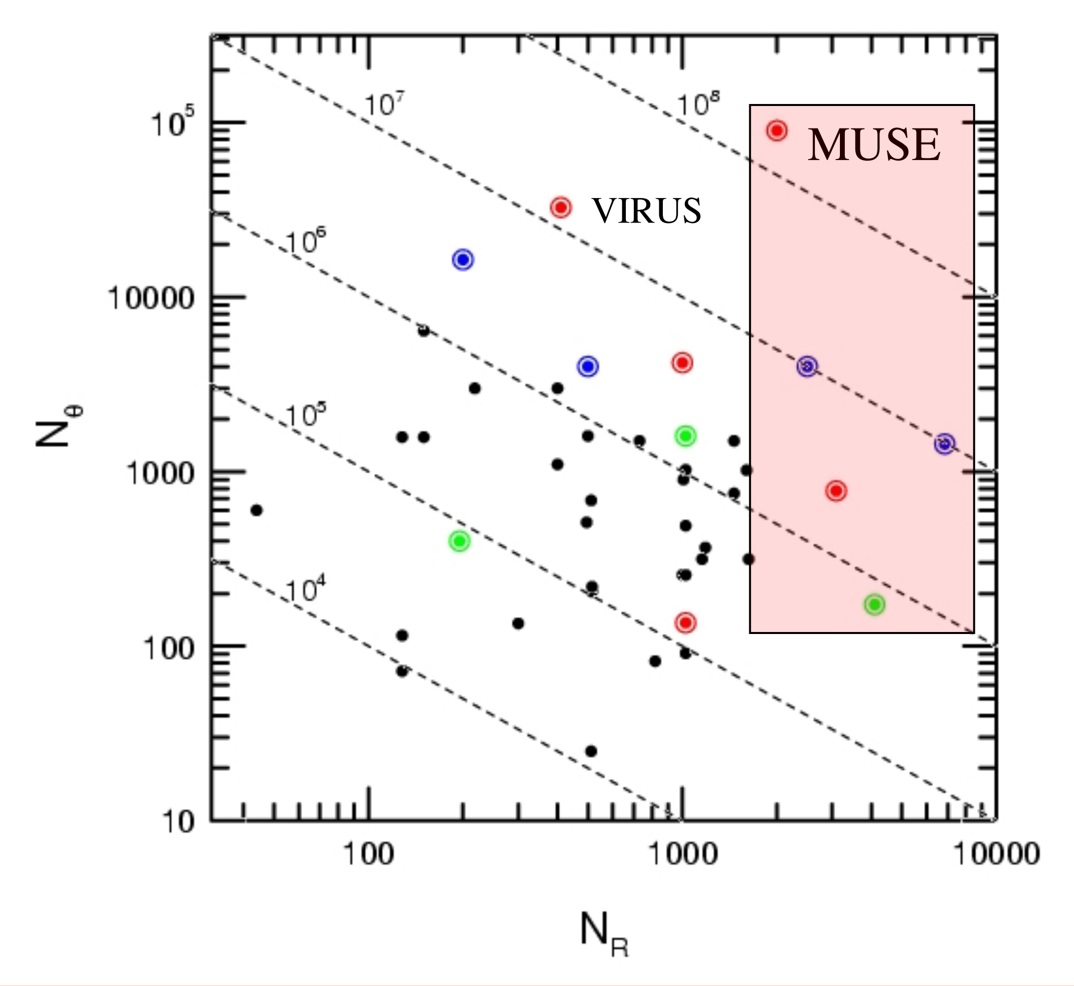
Future instruments
SUMMARY

Existing

New Ground 2-10m

Future Ground 30m

JWST Space



New instruments are adding total resolution elements *and* spectral resolution elements.

10m-class instruments appear more ambitious than 30m-class instruments…
… *stay tuned!*

Future instruments
Unexplored options: some examples

- Notch and double gratings on existing or new grating-dispersed 3D spectrographs
- large-grasp IFUs at high spectral resolution
  - multiplexed “conventional” grating-dispersed spectrographs
  - SHS fed with fiber or lenselet array
  - FP options?