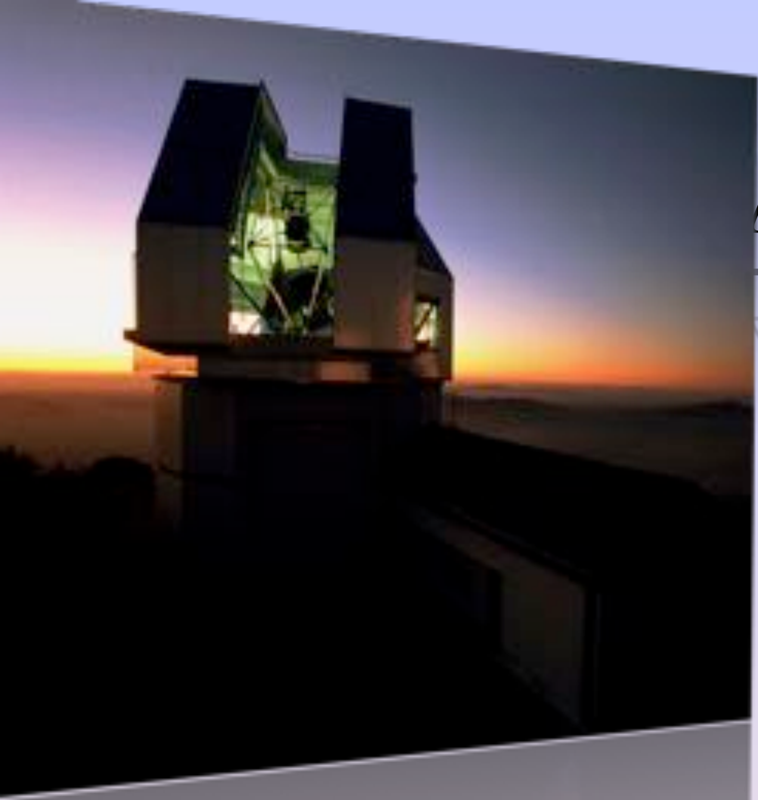


# Astro 500

## Techniques of Modern Observational Astrophysics

Matthew Bershady
University of Wisconsin

# Lecture Outline

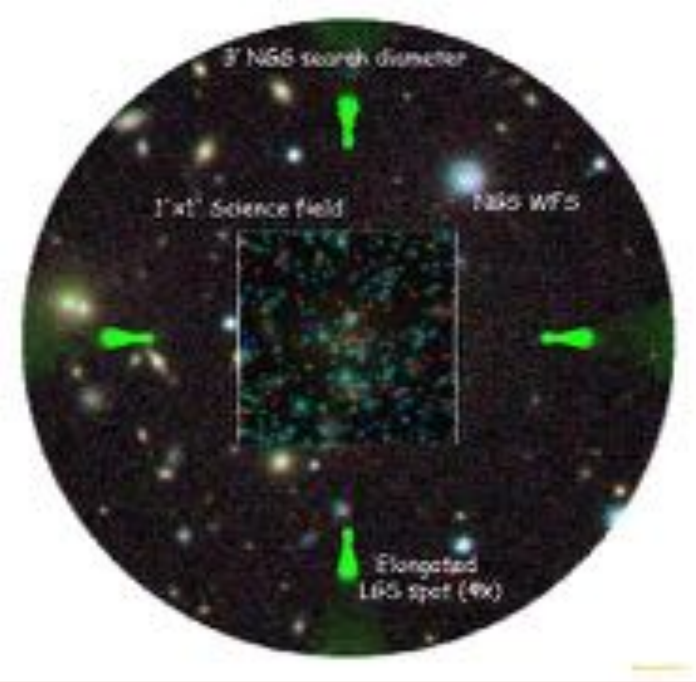
5. Future instruments
   a. Ground-based instruments on 10m telescopes:
      i. Next-generation instruments
   b. Ground vs space
      i. Backgrounds
      ✓ Why build bigger telescopes?
   c. Ground-based instruments on 30-100m telescopes:
      i. AO-driven designs
      ii. Specific examples of TMT instrumentation
   d. Space-based instruments: JWST and SNAP
      i. planned instruments
   e. Unexplored options: a brief list

# Future instruments
## Ground-based instruments on 10m telescopes

- Next-generation instruments
  - MUSE
  - VIRUS
  - KMOS
- Common themes:
  - object multiplexing
  - instrument multiplexing

# Future 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, (6.3x10$^{-3}$ arcsec$^2$)
  - integrally sampled
  - 0.465-0.93 nm range (one shot)
  - ~2000 spectral elements (R~3000)
  - $\varepsilon \sim 0.24$



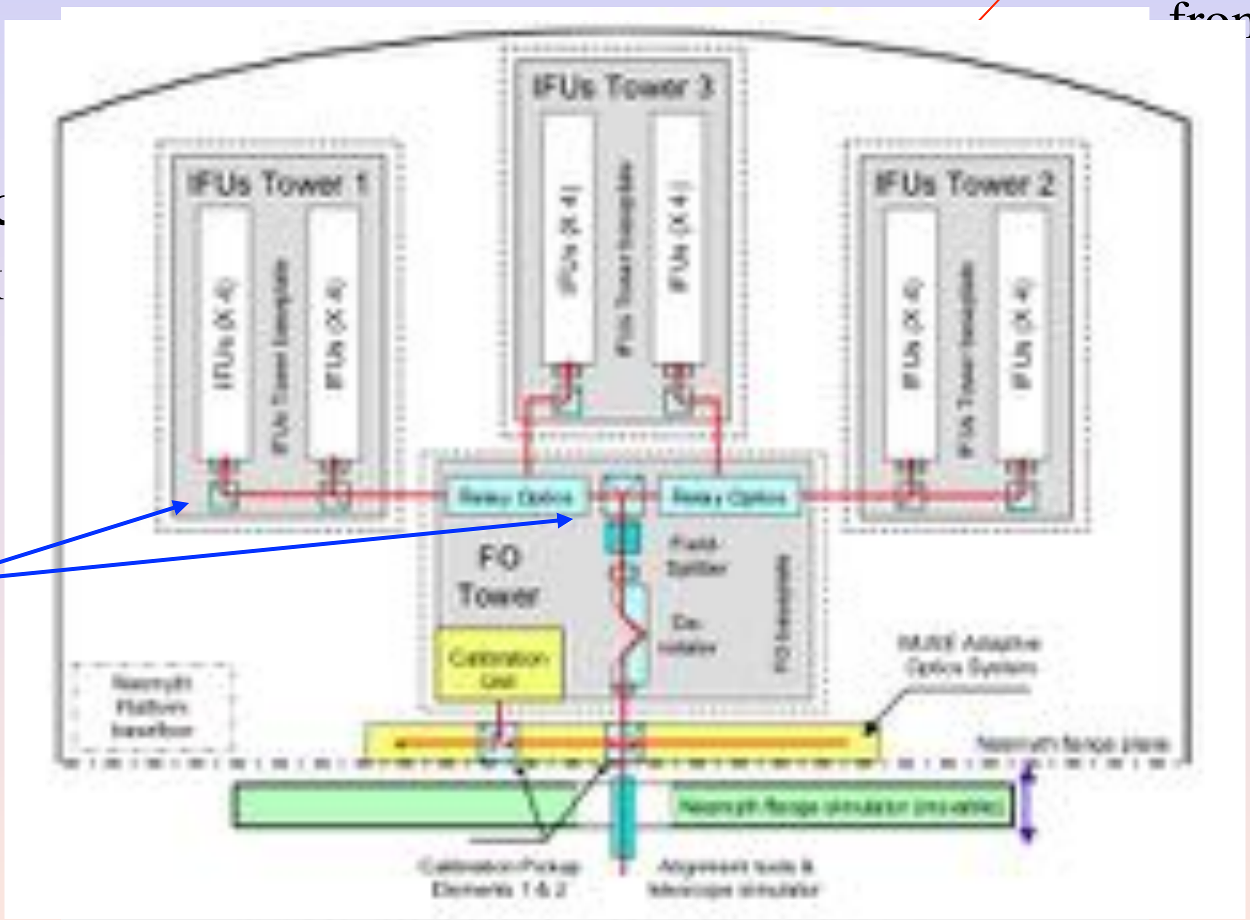

Bacon et al. '04

# Future instruments
## MUSE

- The instrument - wow!

Light path
from telescope

24 spec
6 stack




relay
optics are
the trick --
critical

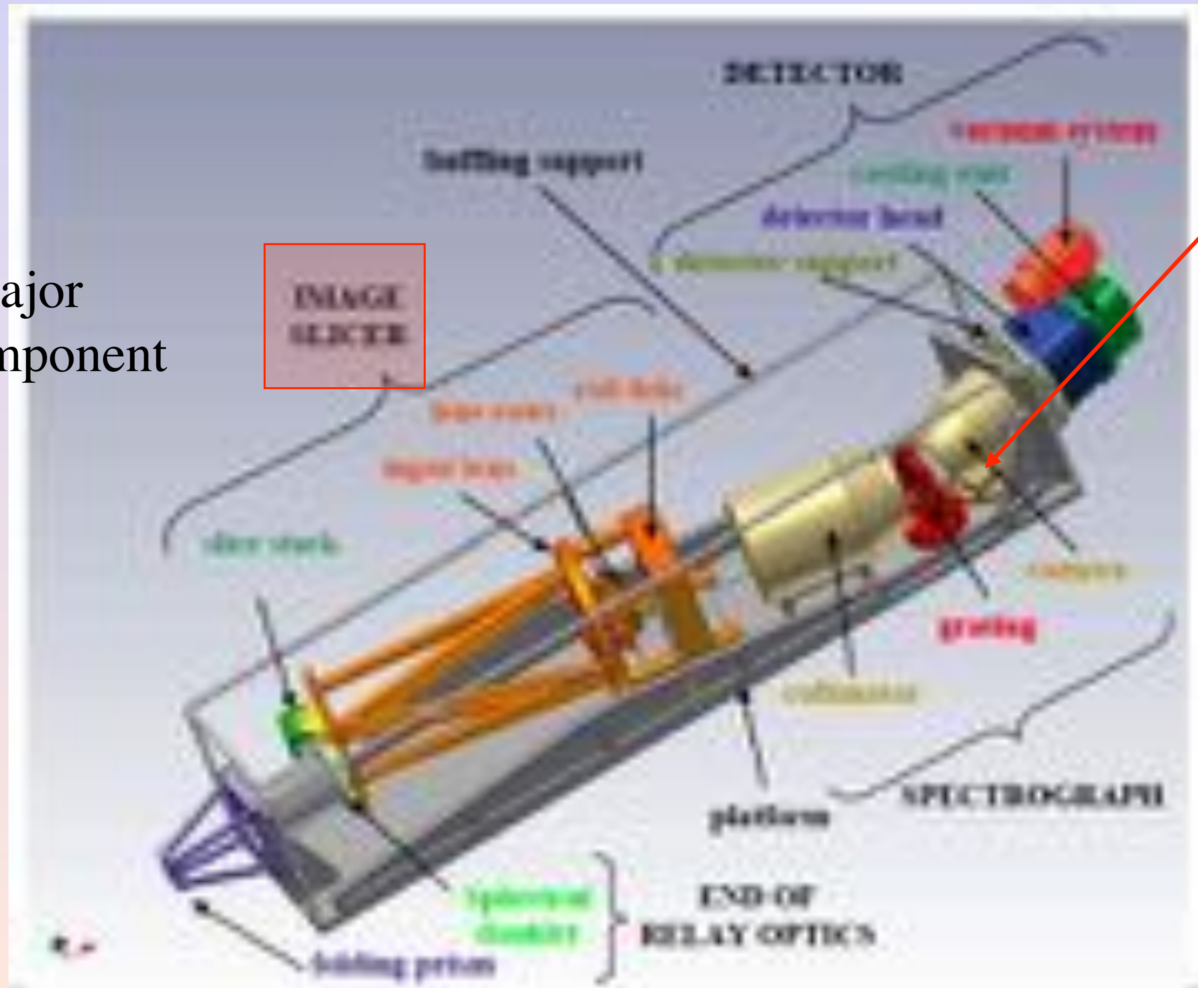
Henault et al. ‘04

# Future instruments
## MUSE

- Slicer + spectrograph unit

Articulated camera for VPH gratings

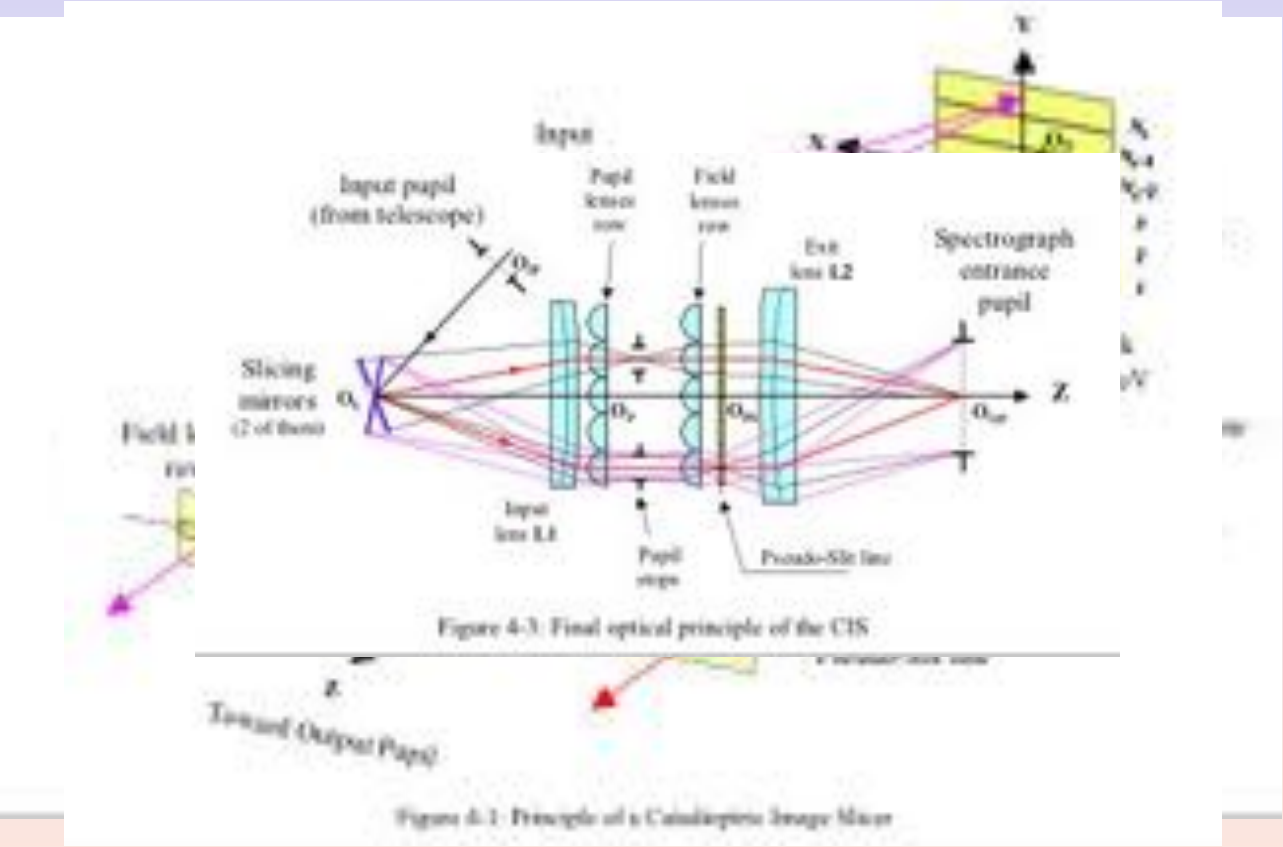
Slicer is major optical component




Henault et al. ‘04

# Future instruments
## MUSE

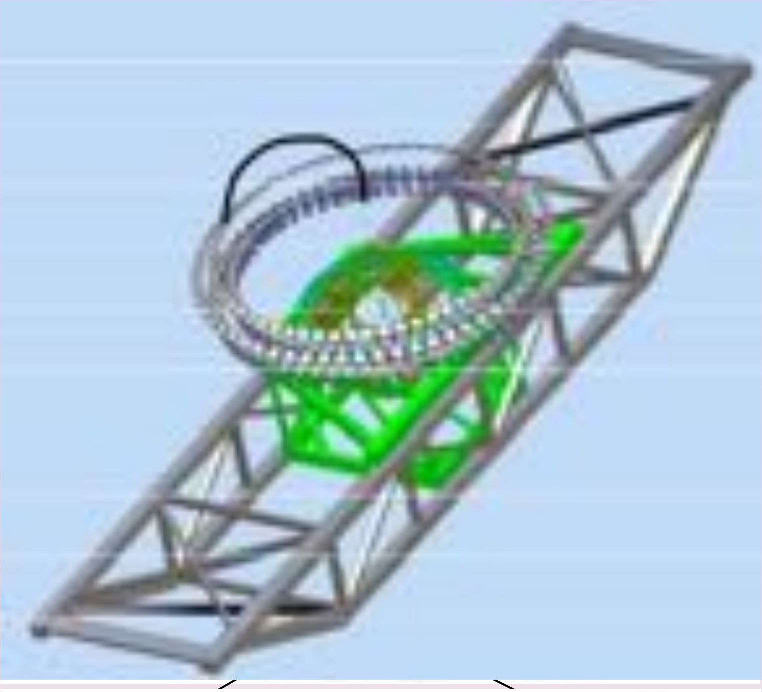
- Catadioptric Image Slicer (CIS) for MUSE

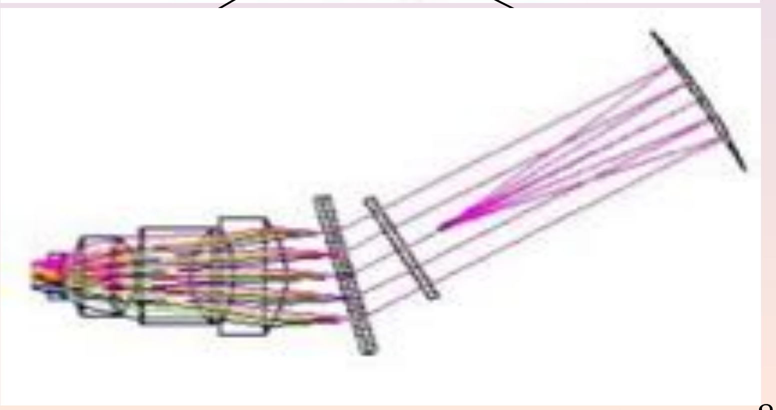



Henault et al. ‘03

# Future instruments
## VIRUS-132

- 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)
  - $\varepsilon \sim 0.15$





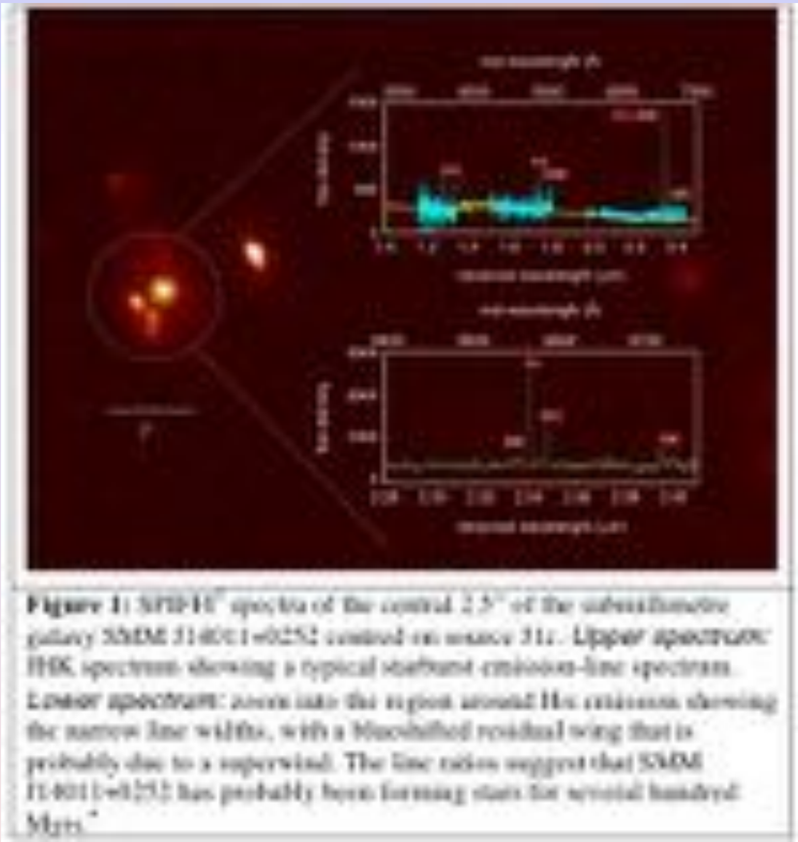
Hill et al. ‘04

# Future 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)
  - $\varepsilon$ = ?

Sharples et al. ‘04

[See also: Thatte et al. ‘00]



*SPIFFI data!*

# Future instruments
## Ground-based instruments on 10m telescopes

*Recap:*

- Next-generation 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)*

# Future instruments
## Ground vs space

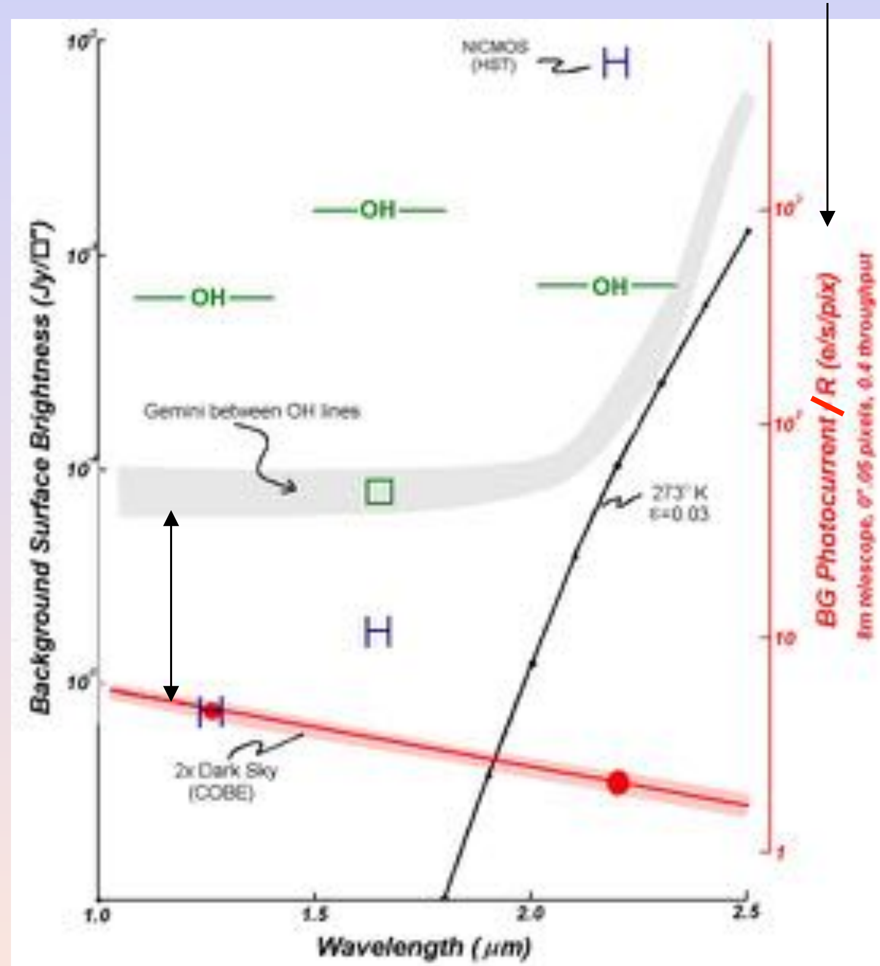
- Backgrounds
  - ➢ background or detector limited
    - o Wavelength and resolution dependent
- Cost and flexibility
  - ✓ ground-based telescopes always win

✓ Why build bigger telescopes?

# Future instruments
## Ground vs space

- 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).

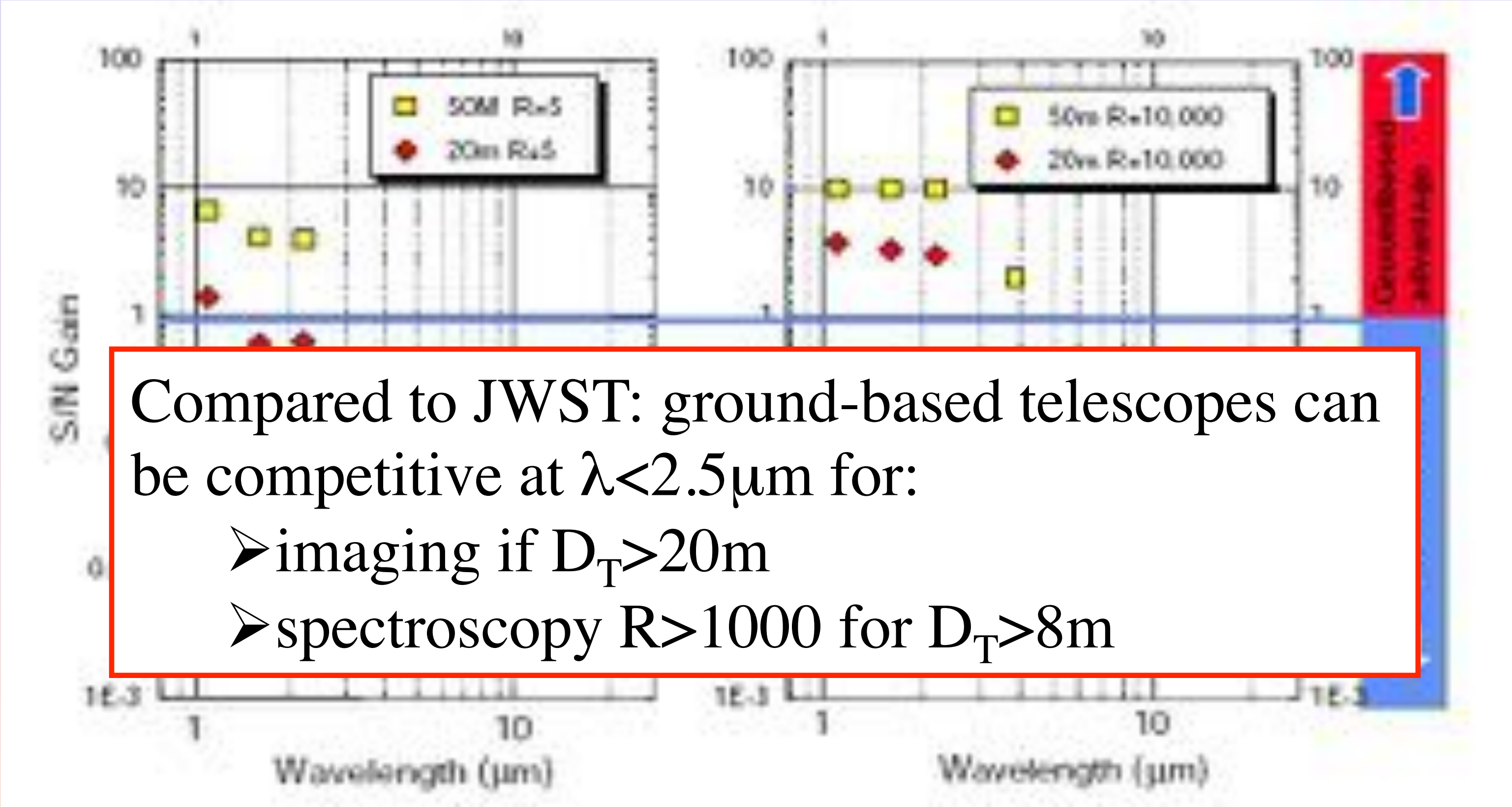
note




Gillet & Mountain ‘97 MAXAT

# Future instruments
## Ground vs space

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




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

# Why build bigger telescopes?

## An example: resolved galaxy kinematics at high-*z*

**How far can we go in redshift?**

- Track a spectral feature with redshift

◦ evolving source surface brightness per spatial resel (s):

$$I = I_z\ (1+z)^{-3}\ s^2$$

◦ background (spectral continuum) $\propto \lambda^{2.5}$ per resolution element:

$$B = B_0\ (1+z)^{2.5}\ s^2$$

Recall: some uncertainties here

- Achieve S/N per resolution element (background-limited):

$$S/N \ \propto \ D_T \sqrt{\frac{t\epsilon}{R}}\ I_z\ s\ (1+z)^{-4.25}$$

R is resolution

$\Longrightarrow$ Limiting redshift

This is an optimistic scenario because it assumes the desired angular resolution element is constant when in fact it will decrease for $z<0.7$.

# Why build bigger telescopes?

## An example: resolved galaxy kinematics at high-$z$

**Use WIYN IFU performance to scale to Gemini**

WIYN: Hα, nearby Sbc-Scd galaxies, 1-3 kpc resolution

| | WIYN/SPak | Gemini | |
|---|---|---|---|
| $\epsilon$ | 4% | 30% | mean throughput |
| $D_T$ | 3.5m | 8m | telescope diameter |
| $s$ | $4.''2$ | $0.''5$ | aperture width (square) |
| $R$ | 10,000 | 5000 | $\lambda/\Delta\lambda$ |
| $t$ | 0.5h | 10h | integration time |
| $S/N$ | 15 | 10 | S/N per spatial channel, $s$ |
| $I$ | $I_0$ | $2I_0$ | line flux |
| $z$ | 0 | $\sim$1 | source redshift |

**Limiting redshift:**

$$1+z = 1.9 \left(\frac{I_z}{2I_0}\,\frac{s}{0.''5}\,\frac{10}{S/N}\right)^{4/17} \left(\frac{t}{10h}\,\frac{\epsilon}{0.30}\,\frac{5000}{R}\right)^{2/17}$$

agressive

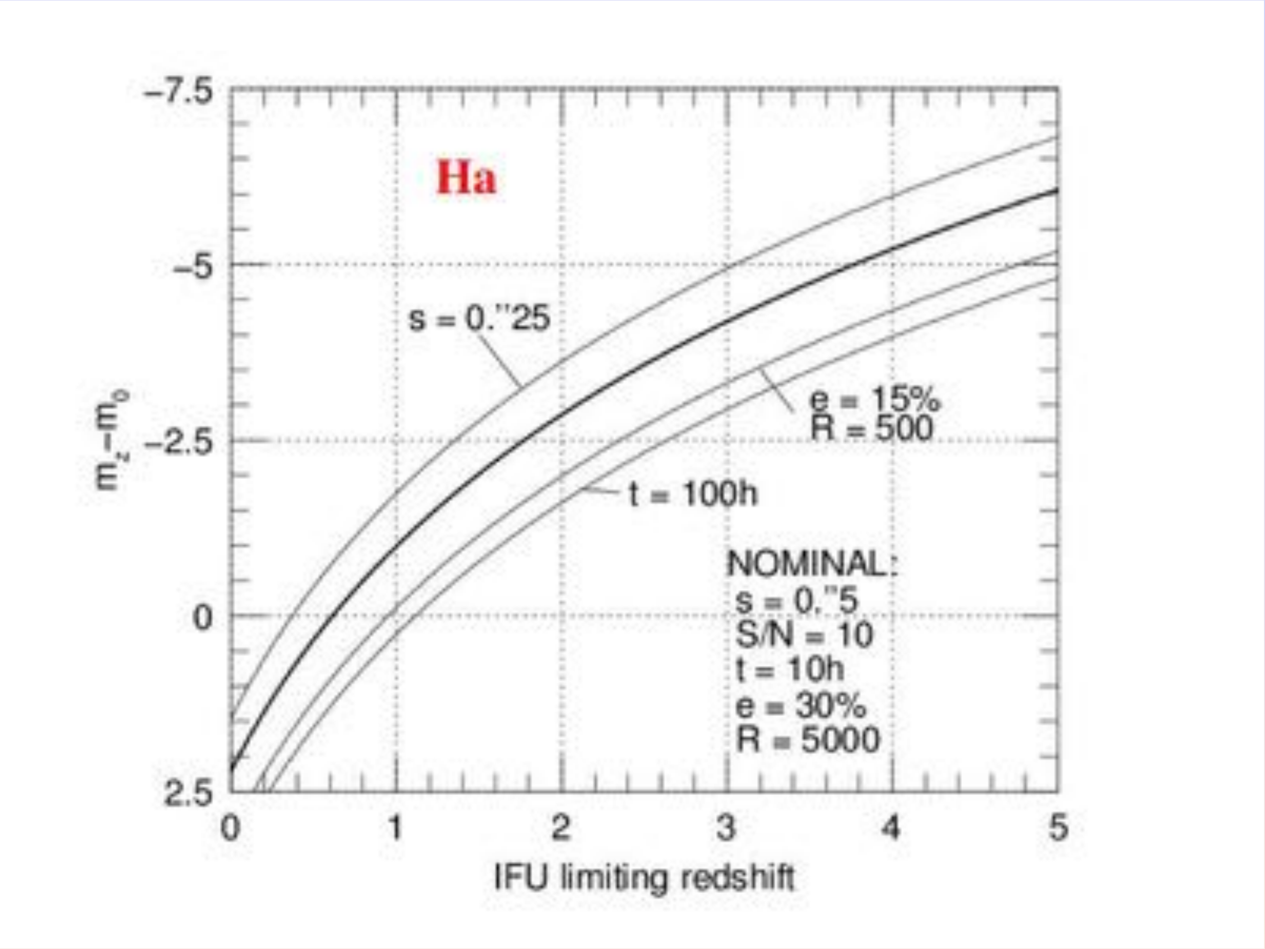
low

large

To reach z = 2-3, need factors of $\begin{cases} \text{10-20 in } I_z,\ s, \text{ or } S/N \\ \text{50-500 in } t \text{ or } R \end{cases}$

# Why build bigger telescopes?

## An example: resolved galaxy kinematics at high-*z*



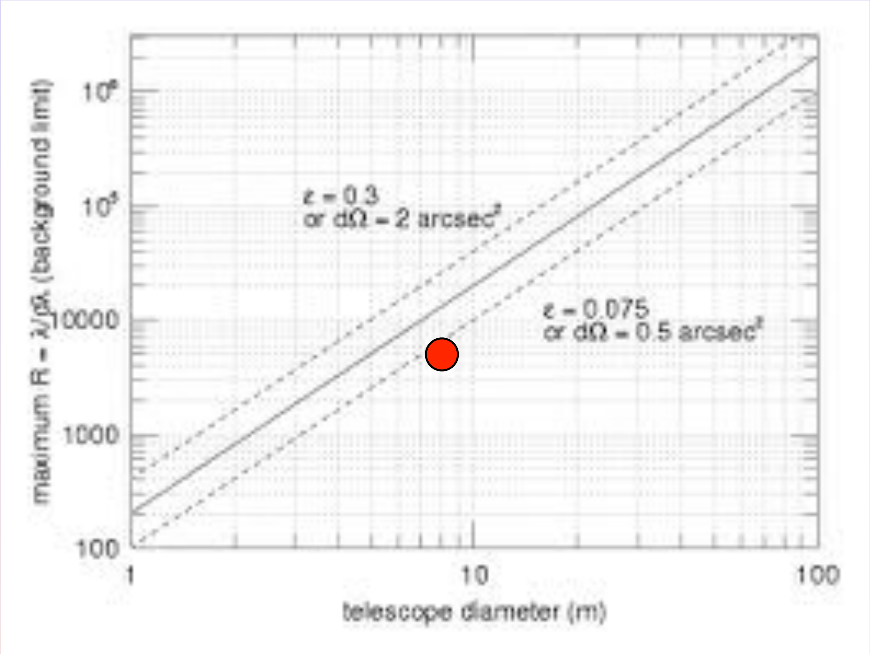
# Why build bigger telescopes?

## An example: Resolved galaxy kinematics at high-*z*

One way to do better:

- Switch from Ha to [OII]: gain 20% in z or a factor of 2 in *L* or *s*

- With *s* = 0.25 (dΩ = 0.06) and R = 5000, very close to RN-limit:
  Need best detectors or bigger telescope!



# Why build bigger telescopes?

## An example: resolved galaxy kinematics at high-*z*

| | 10m telescope | 30m telescope + AO |
|---|---|---|
| absorption | $z = 0.1 - 0.2$ | $z \sim 0.3 - 0.5$ |
| emission | $z = 1^+$ | run out of disks ?! |

- Long integrations needed for stellar kinematics -- even on ELTs.
- Need ELTs to stay background-limited with apertures < 0.25 arcsec and R>5000.

# 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

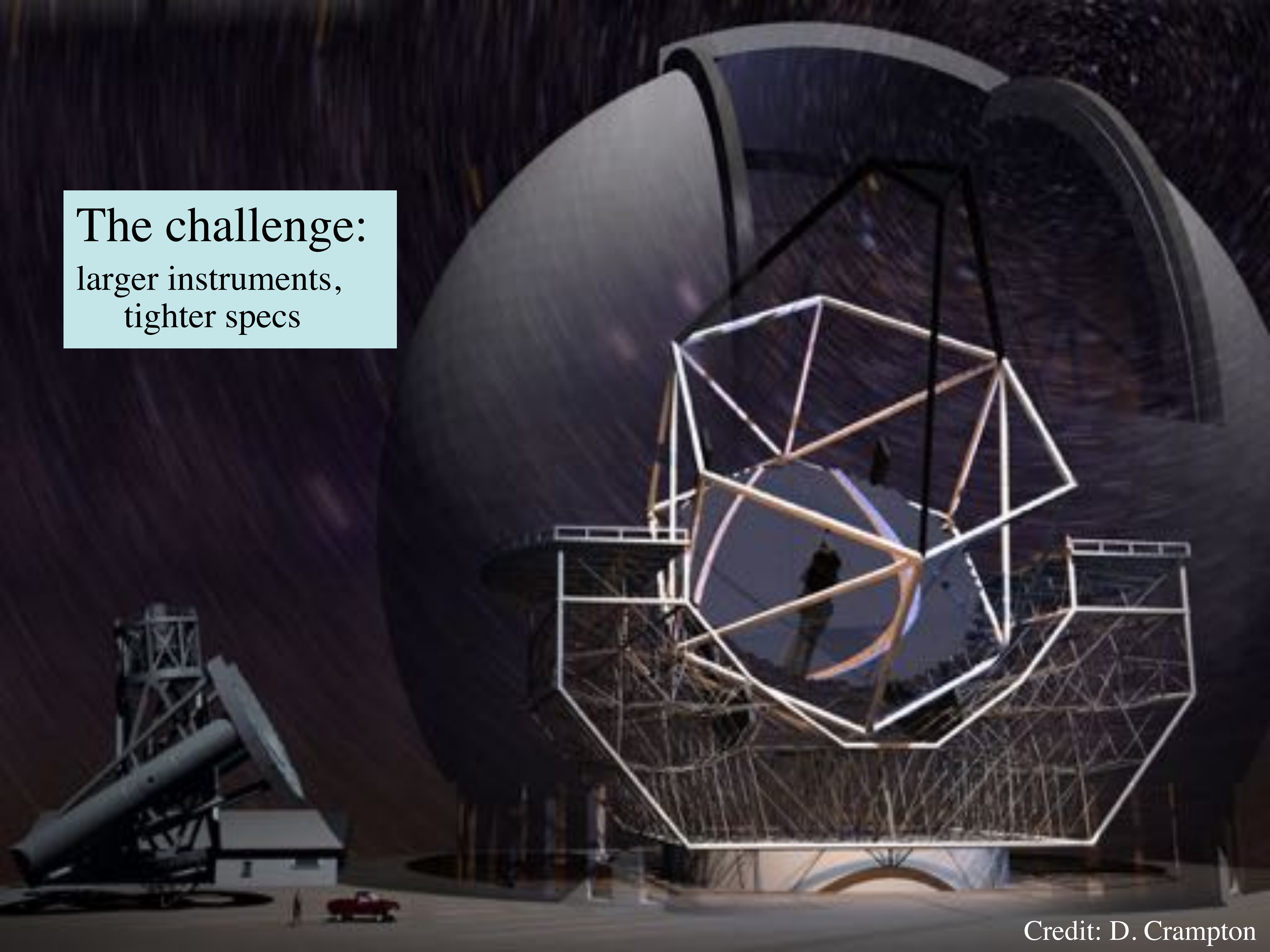
    $\theta \sim \lambda / D_T$

    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?

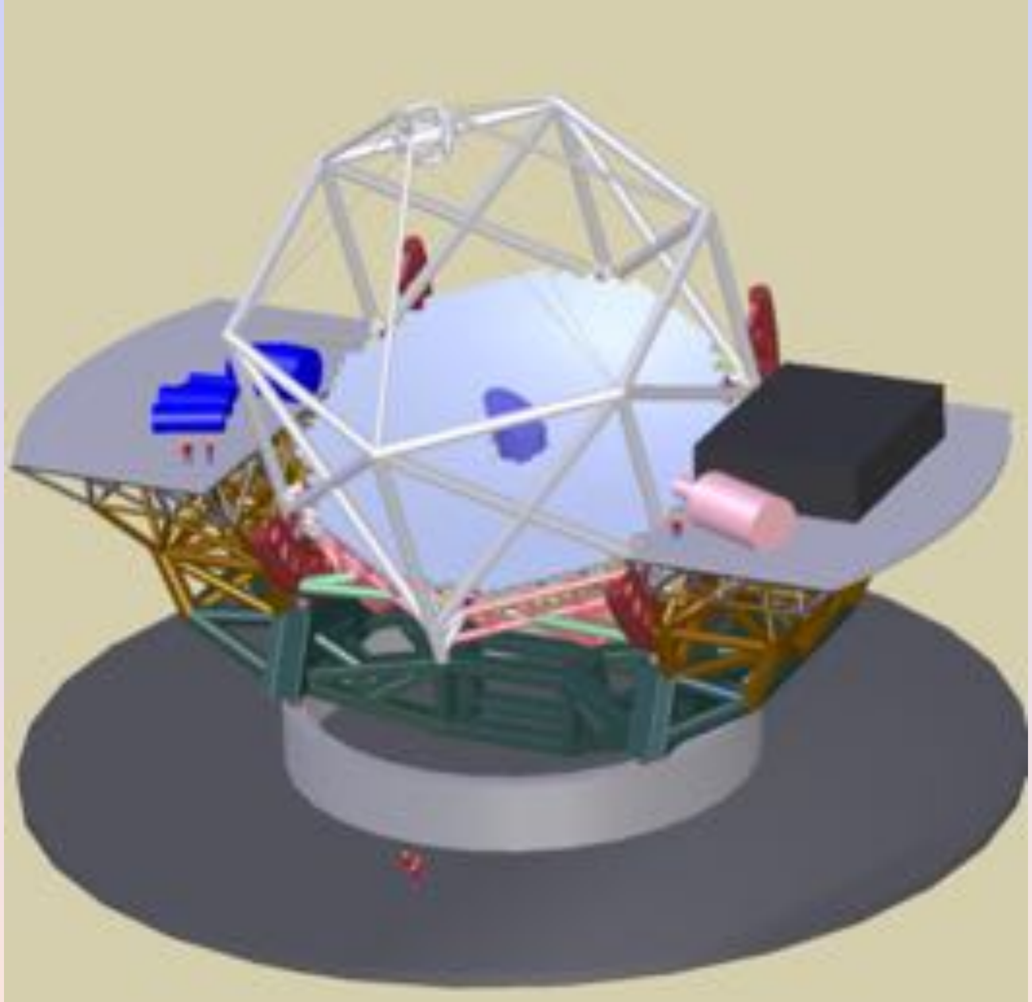
- Unique parameter space:
  - The photon limit at high resolution
    - *High spectral or spatial resolution?*
  - The diffraction limit…
    - …especially at long wavelength requires large aperture.
    - But this is where you win in space, so focus on near-infrared.




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 $\mu$m
- 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:** 0.8-2.5$\mu$m; goal 0.6-5$\mu$m
- **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:** 0.8-2.5$\mu$m
- **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:** 0.31-1.1$\mu$m (0.31-1.6$\mu$m 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 0.1$\mu$m
- **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

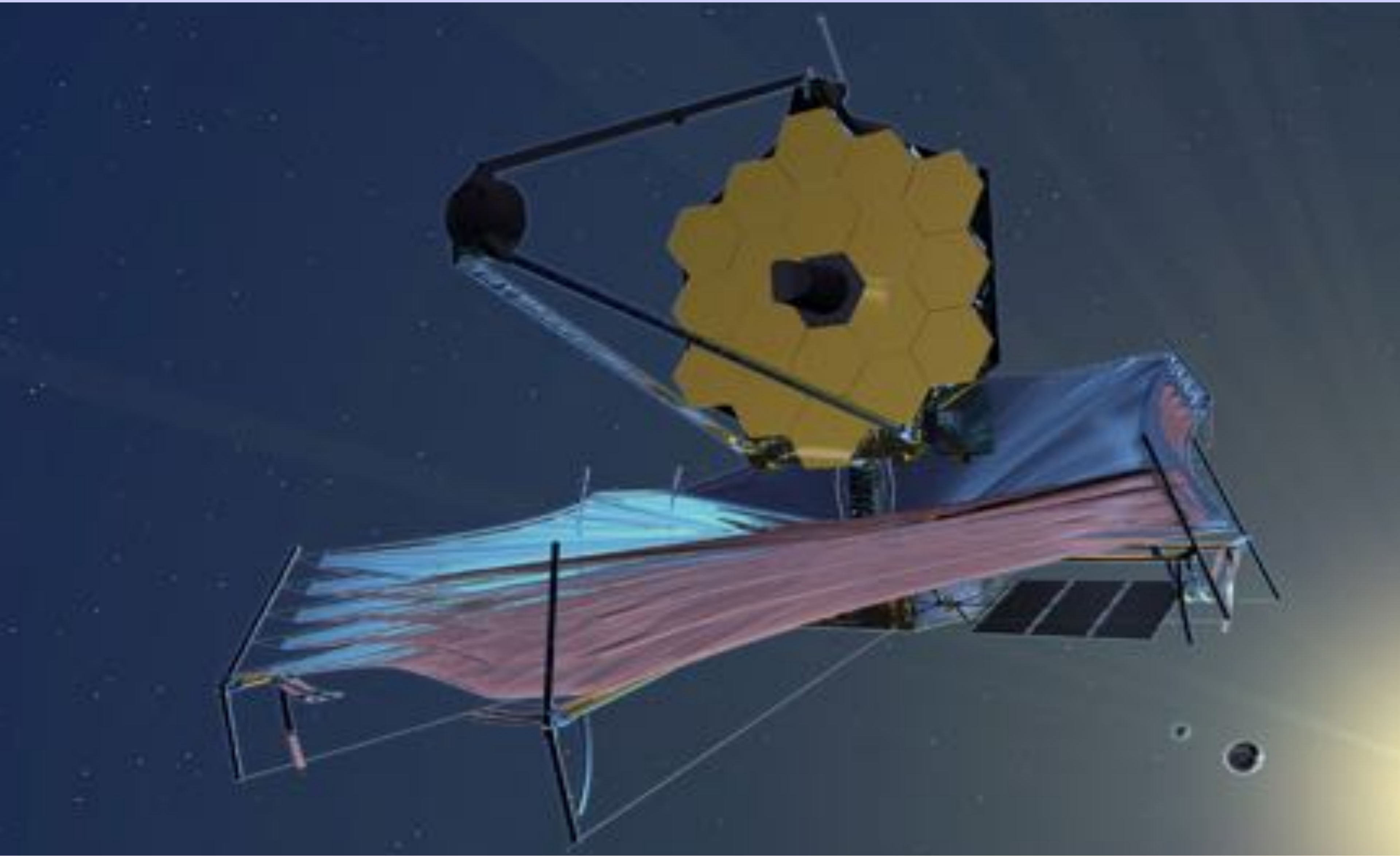
TMT SUMMARY

- 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)

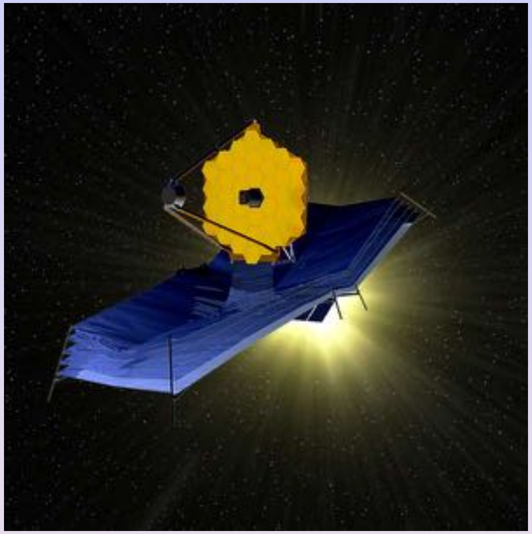
Table 5. Future TMT Integral Field Instruments

| Instrument | Coupling Method | Telescope | $D_T$ (m) | $\Omega$ (arcsec$^2$) | $d\Omega$ (arcsec$^2$) | $N_s$ | $\Delta\lambda/\lambda$ | R | $N_R$ | $\epsilon$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 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
## Space-based instruments: JWST and SNAP



# Future instruments
## Space-based instruments: JWST



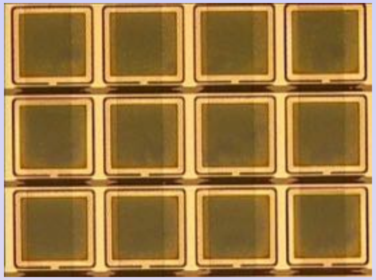
- JWST
  - 6.5m telescope (25 $m^2$)
  - 0.6-29 μm coverage
  - 0.1 arcsec resolution or better
  - opertating temperature < $50^o$ K
  - 5-10 year lifetime
  - Launch 2013 or later into 1.5 Mkm orbit at L2

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

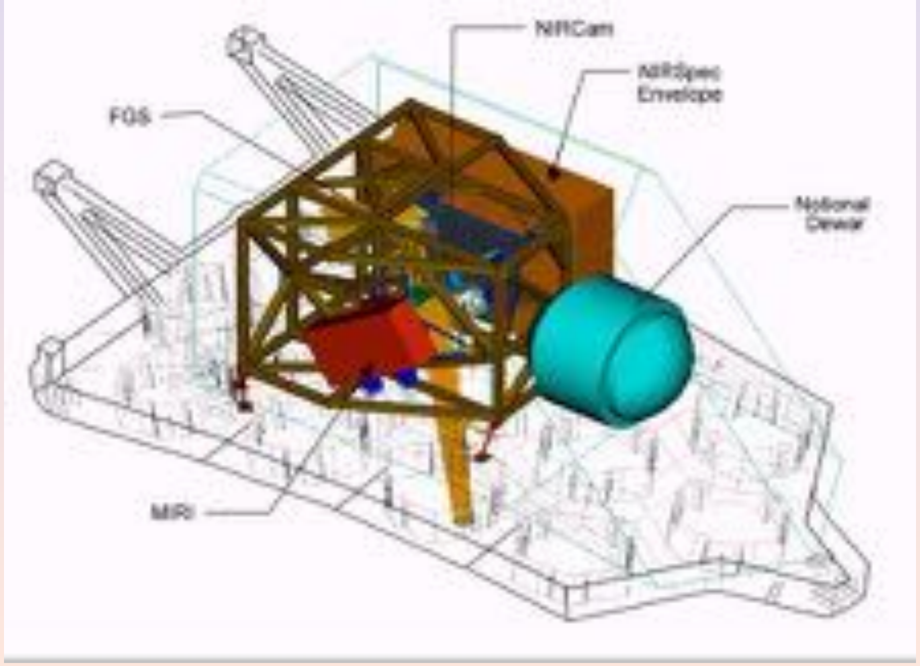
- Instruments
  - o NIRCam
  - o NIRSpec
  - o FGS-TF
  - o MIRI

IFU capability

# Future instruments
## Space-based instruments: JWST

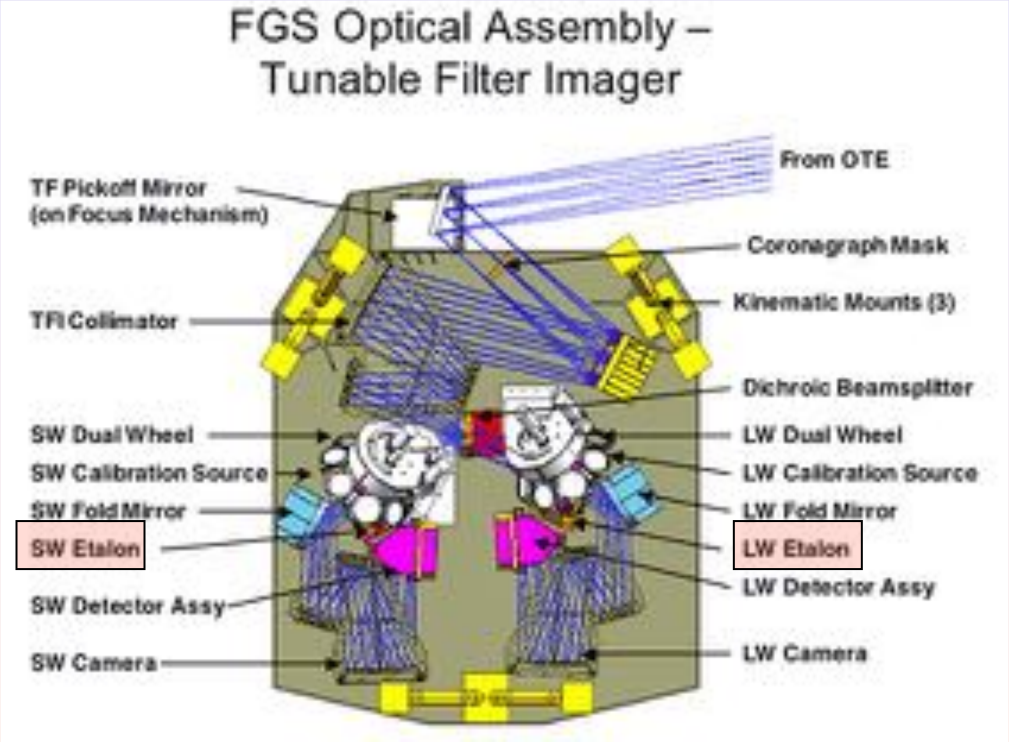


- NIRSpec
  - ➢ 3.5x3.5 arcmin field for MOS using MEMS devices
  - ➢ IFU mode: 3x3 arcsec at R = 3000
  - ➢ advanced slicer: 40 3x0.075 arcsec slices feeding 2x$2048^2$ arrays
  - ➢ 0.8-5 μm



# Future instruments
## Space-based instruments: JWST

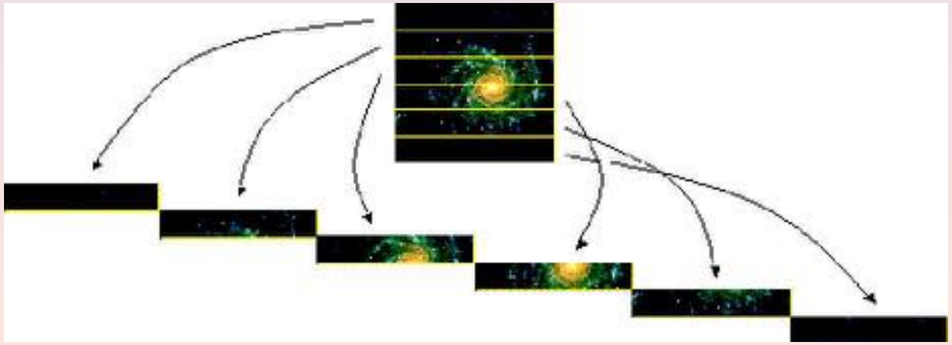
- FGS-TF: Fine-Guidance Sensors -Tunable Filter
  - Dual Fabry-Perot imaging cameras covering 1-5 mm
  - 2.3 x 2.3 arcmin field
  - R ~ 100
  - Two cameras: short (1.2-2.1 μm), long (2-4.8 μm)

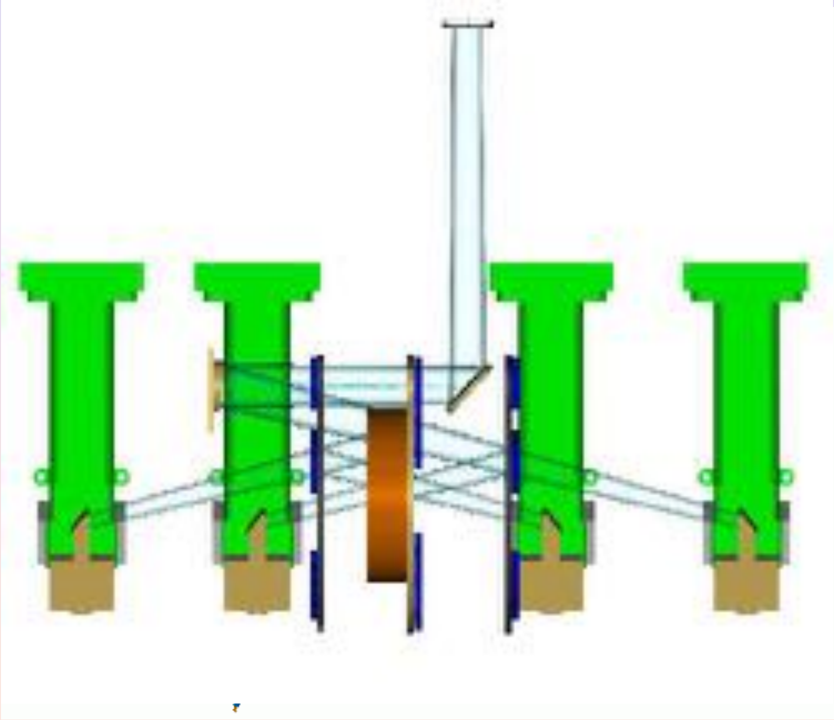


# Future instruments
## Space-based instruments: JWST

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

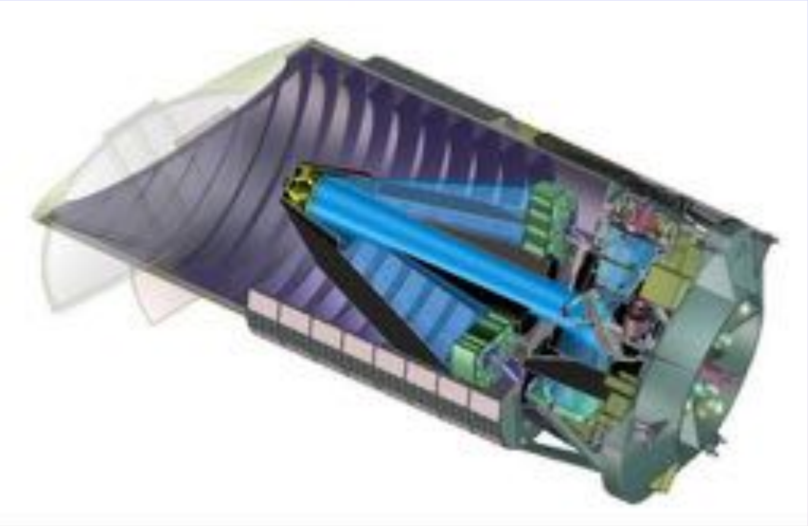
| channel | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Wavelength (μu) | 5-7.7 | 7.7-11.9 | 11.9-18.3 | 18.3-28.3 |
| Slice width (“) | 0.17 | 0.28 | 0.39 | 0.64 |
| Pixel (“) | 0.2 | 0.2 | 0.24 | 0.27 |
| FoV (“) | 3x3.9 | 3.5x4.4 | 5.2x6.2 | 6.7x7.7 |
| R | ~3000 | ~3000 | ~3000 | ~2200 |

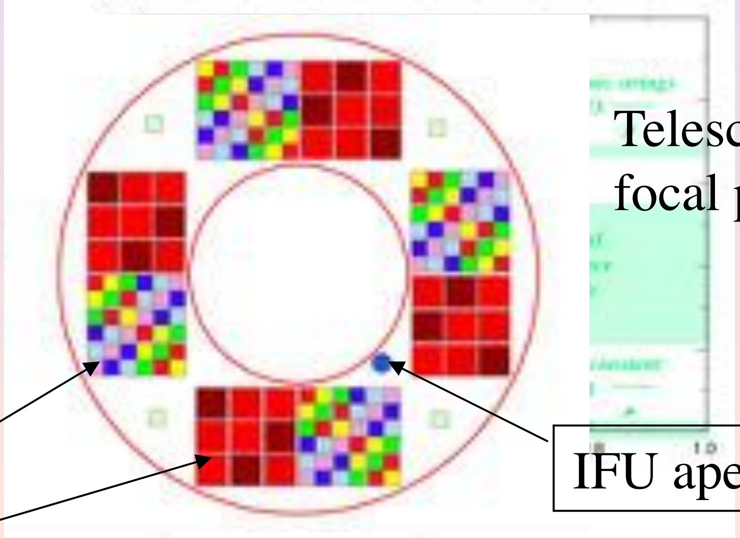




# Future instruments
## Space-based instruments: SNAP

- SNAP: Super Novae / Acceleration Probe
  - ➢ 2m space telescope
  - ➢ Science mission: Determine cosmic equation of state and nature of dark energy via measurement of ~2000 SNe-Ia out to $z$~1.7
  - ➢ Imaging survey with small, but capable IFU to ID SNe






Aldering et al. '04

# Future instruments
## Space-based instruments: SNAP

- SNAP IFU

dual beam

advanced slicer

| Property | Visible | IR |
|---|---|---|
| Wavelength coverage (μm) | 0.35-0.98 | 0.98-1.70 |
| Field of view | 3.0" × 3.0" | 3.0" × 3.0" |
| Spatial resolution element (arcsec) | 0.15 | 0.15 |
| Number of slices | 20 | 20 |
| Spectral resolution, $\lambda/\delta\lambda$ | 100 | 100 |

Table 1: Spectrograph main specifications.

| | telescope | Relay optics | Slicer Optic | Slicer straylight | Slicer diffra. | Spectro Mirrors | Spectro prism | Spectro dichroic | Detector Visible | Detector NIR |
|---|---|---|---|---|---|---|---|---|---|---|
| #elements | 4 | 3 | 3 | 1 | 1 | 3 | 1 | 1 | 1 | 1 |
| Efficiency/ elt | 0.98 | 0.98 | 0.98 | 0.99 | 0.98 | 0.98 | 0.81 | 0.95 | 0.9 | 0.6 (0.8) |
| cumulative | 0.94 | 0.89 | 0.83 | 0.82 | 0.81 | 0.76 | 0.62 | 0.59 | 0.53 | 0.35 (0.47) |

Table 3: cumulative efficiency

Ealet et al. '02

# Future instruments
## Space-based instruments: JWST and SNAP

- SNAP IFU product
  - Thousands of spectra of SNe and their host galaxies at R~100.
  - Small telescope and modest-depth integrations, however, coadded data-sets should yield superb spectrophotometry.

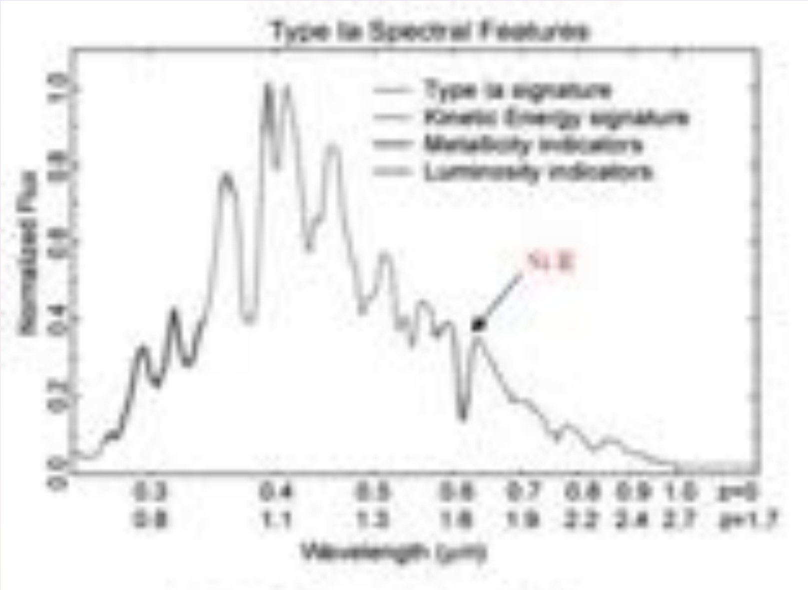


Figure 1: Typical spectrum of SN Ia

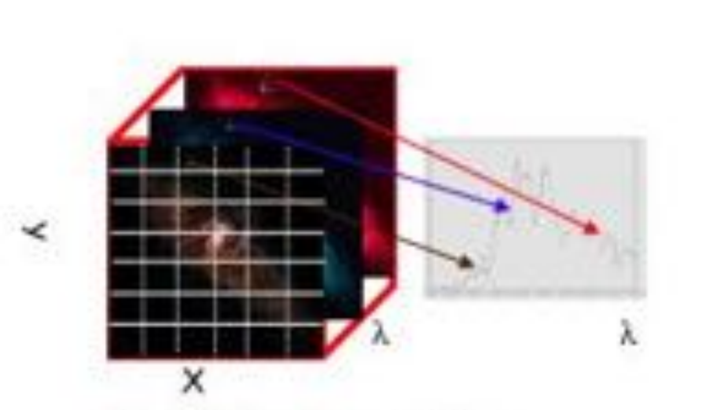


Figure 2: 3D spectroscopy illustration.

Ealet et al. '02

# Future instruments
## Space-based instruments: SUMMARY

- JWST and SNAP have 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) | $\Omega$ (arcsec$^2$) | $d\Omega$ (arcsec$^2$) | $N_\theta$ | $\Delta\lambda/\lambda$ | R | $N_R$ | $\epsilon$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 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. |
| FGS-TF | fabry-perot | JWST | 6.5 | 38088. | 0.018 | 2.10e7 | 0.01 | 100. | 1 | -1. |
| SNAP-IFU | advanced-slicer | SNAP | 2. | 9.0 | 0.022 | 400 | 1.95 | 100. | 195 | 0.44 |

# Future instruments
## Space-based instruments: SUMMARY

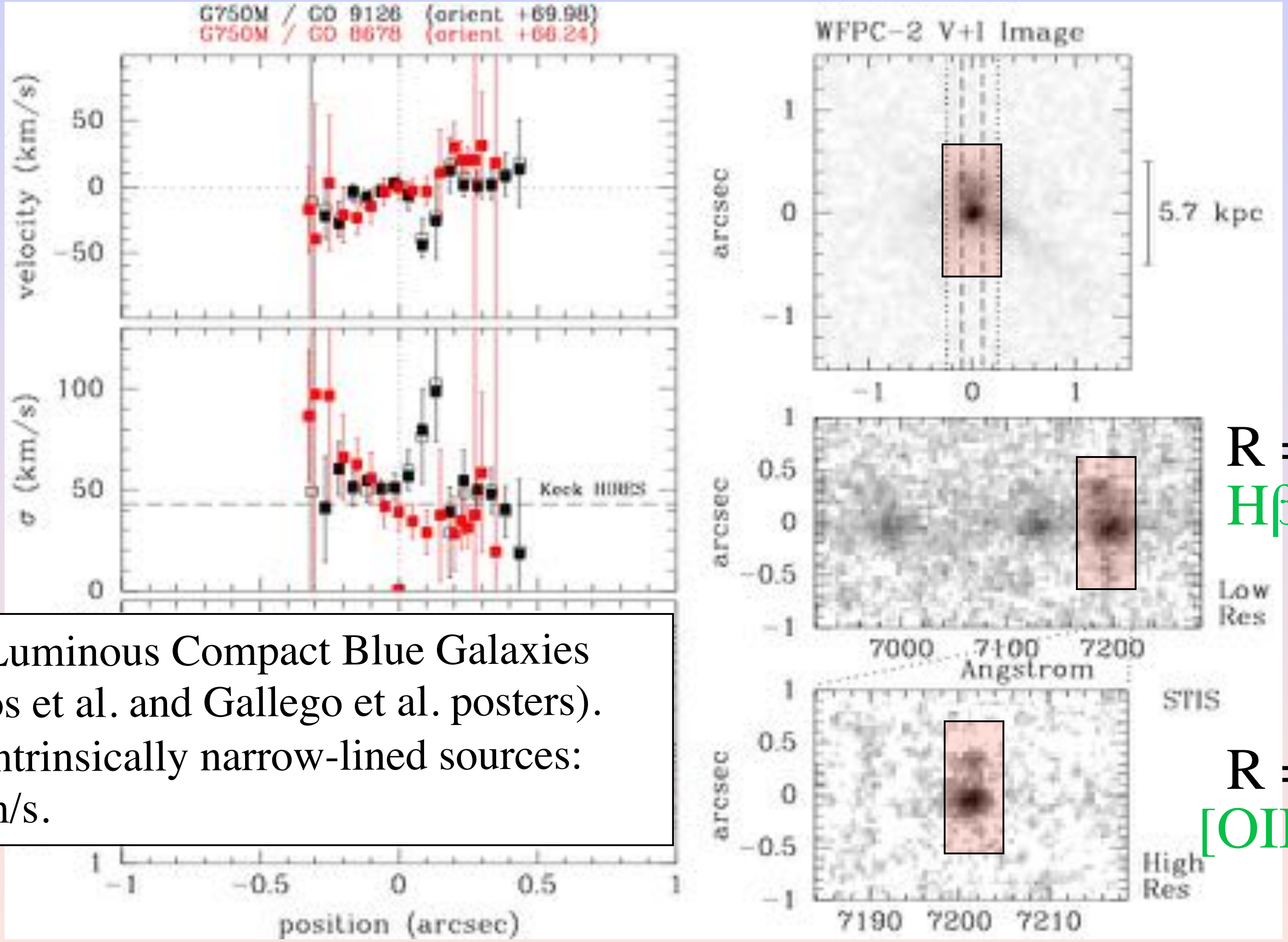
- And now for some bad news (for space-based IFU fans):
  - SNAP project was killed a few years ago…
  - Subsumed into a joint NASA-DOE project called JDEM (joint dark-energy mission)
  - JDEM project was killed relatively recently…
  - There may have been a few more false-starts along the way…
  - Now we have WFIRST (endorsed by Decadal review) which includes some of the SNAP science and capabilities, but who knows…
  - WFIRST probably will be delayed due to JWST…
  - Likely the Europeans will build something like SNAP or JDEM, e.g., Euclid.

# 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



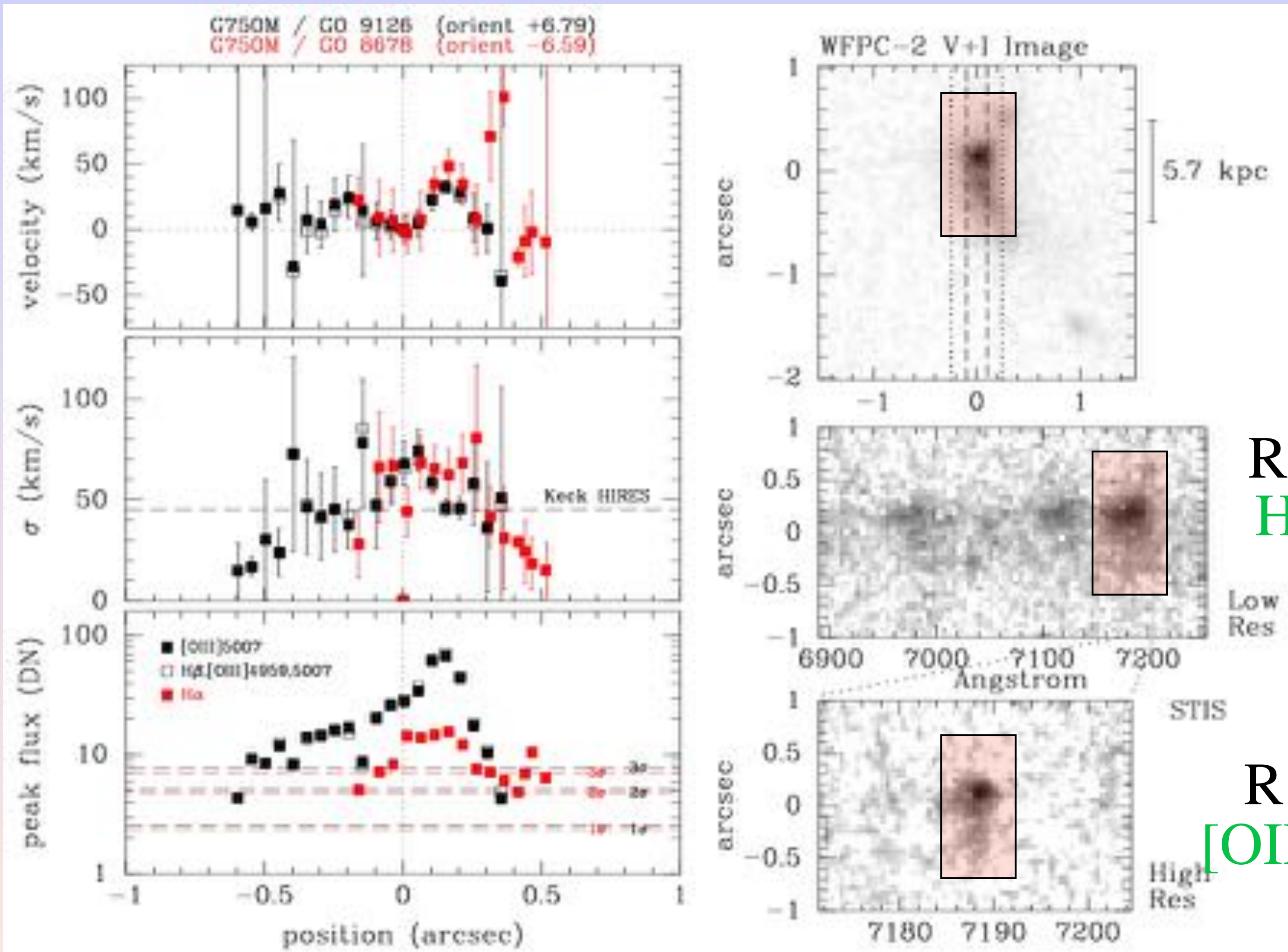

R = 800
Hβ+[OIII]

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"…

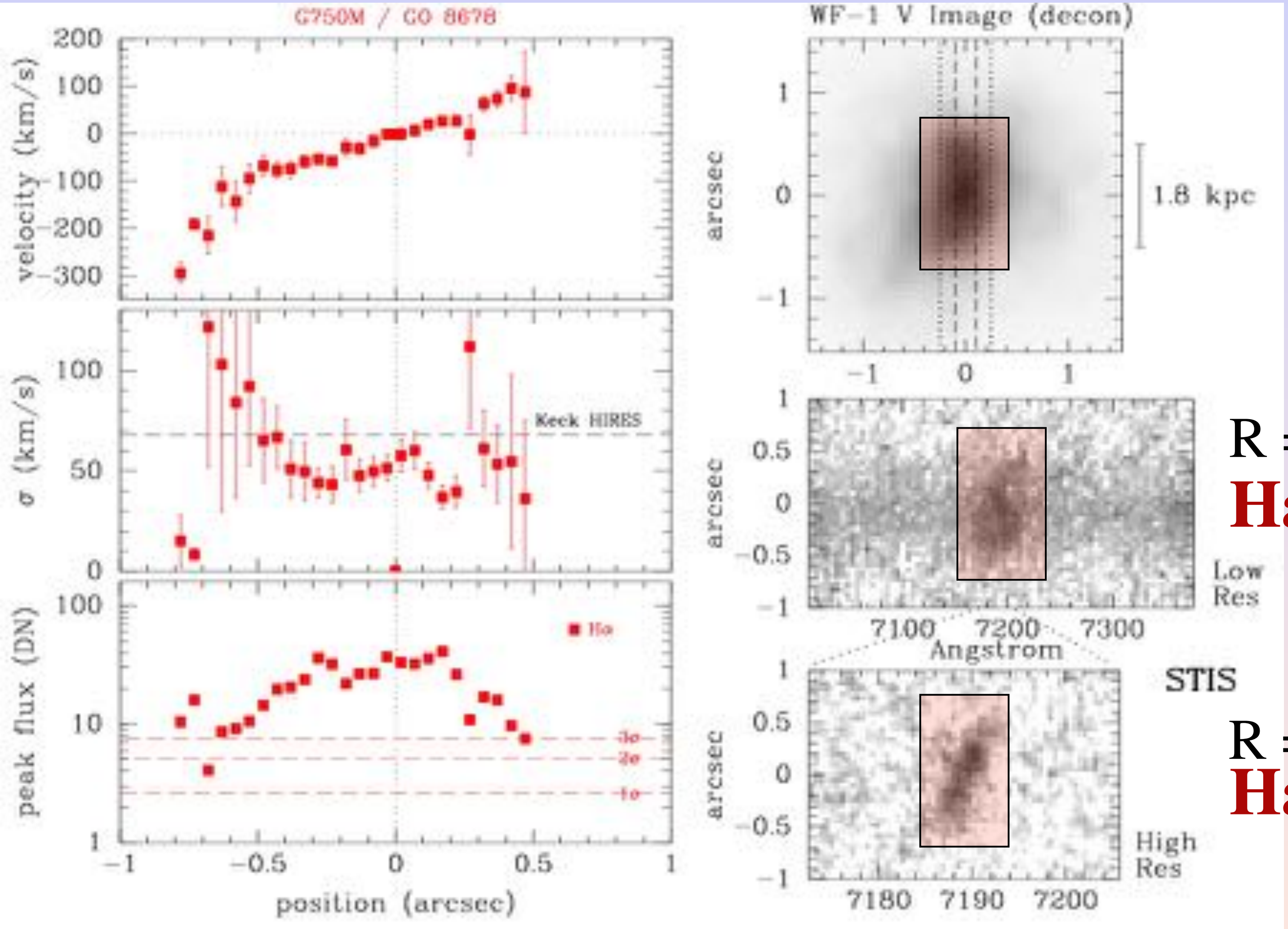



R = 800
Hβ+[OIII]

R = 7000
[OIII]λ5007

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

# Here's another:




R = 800
**Ha**

R = 7000
**Ha**

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.

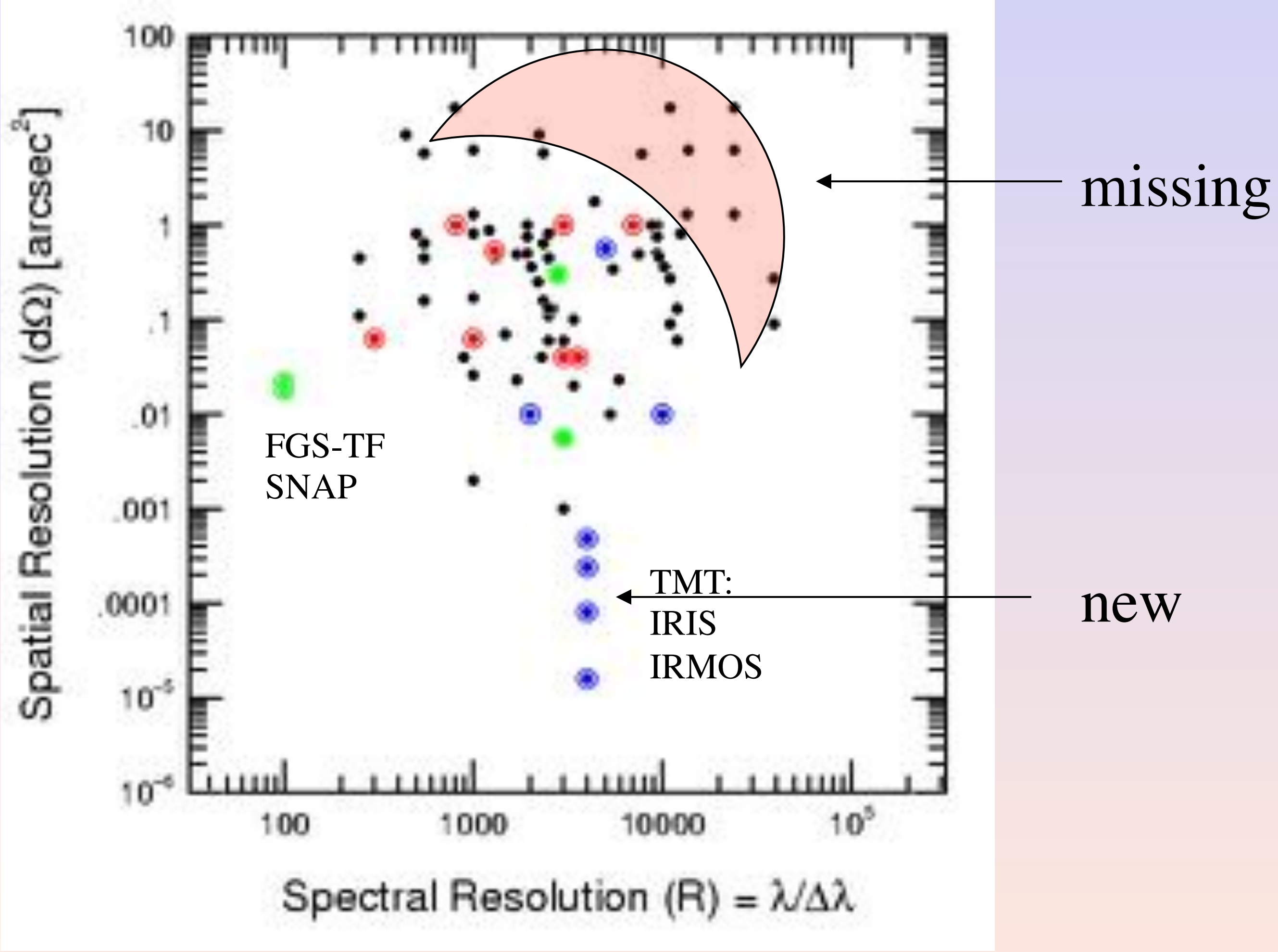
# Future instruments
## SUMMARY

Existing

Future Ground 2-10m

Future Ground 30m

Future Space



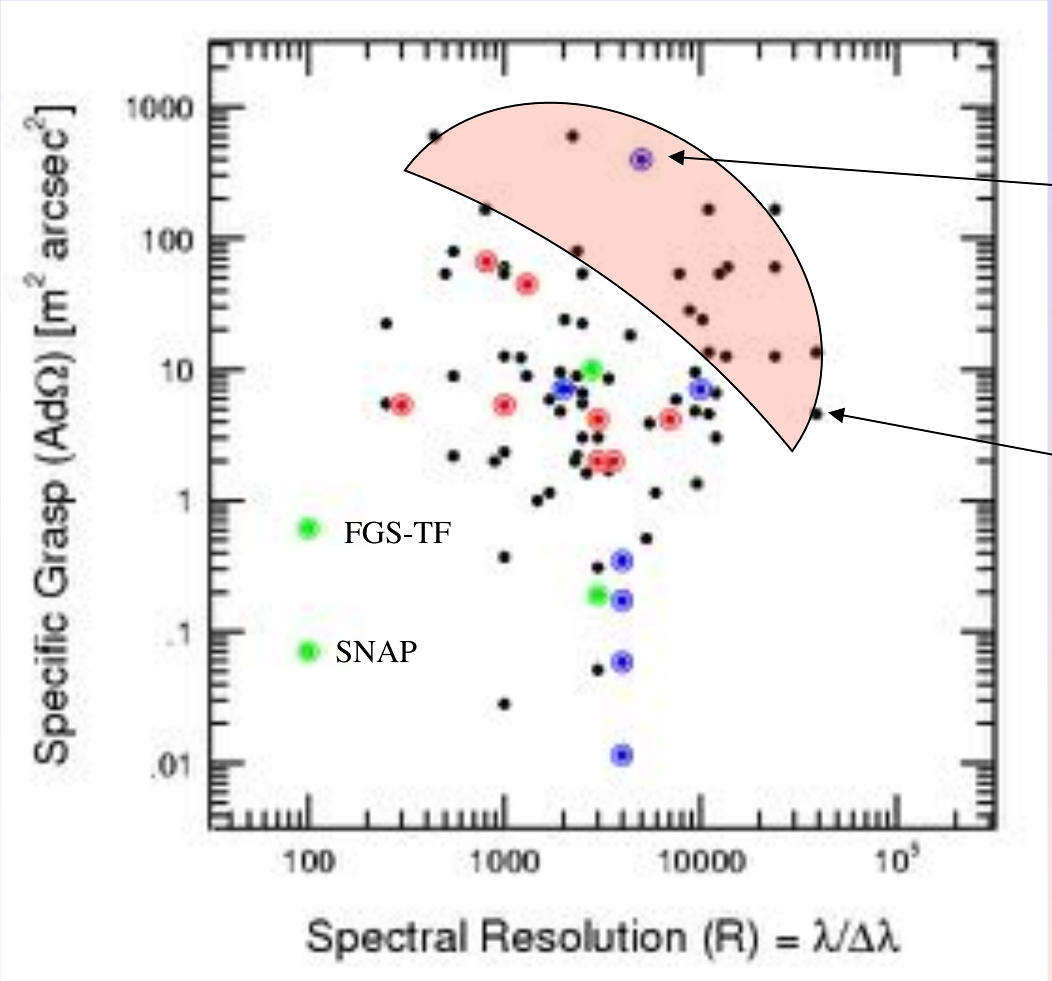
# Future instruments
## SUMMARY

Existing

Future Ground 2-10m

Future Ground 30m

Future Space




Aha! WFOS

Still missing: high spectral resolution

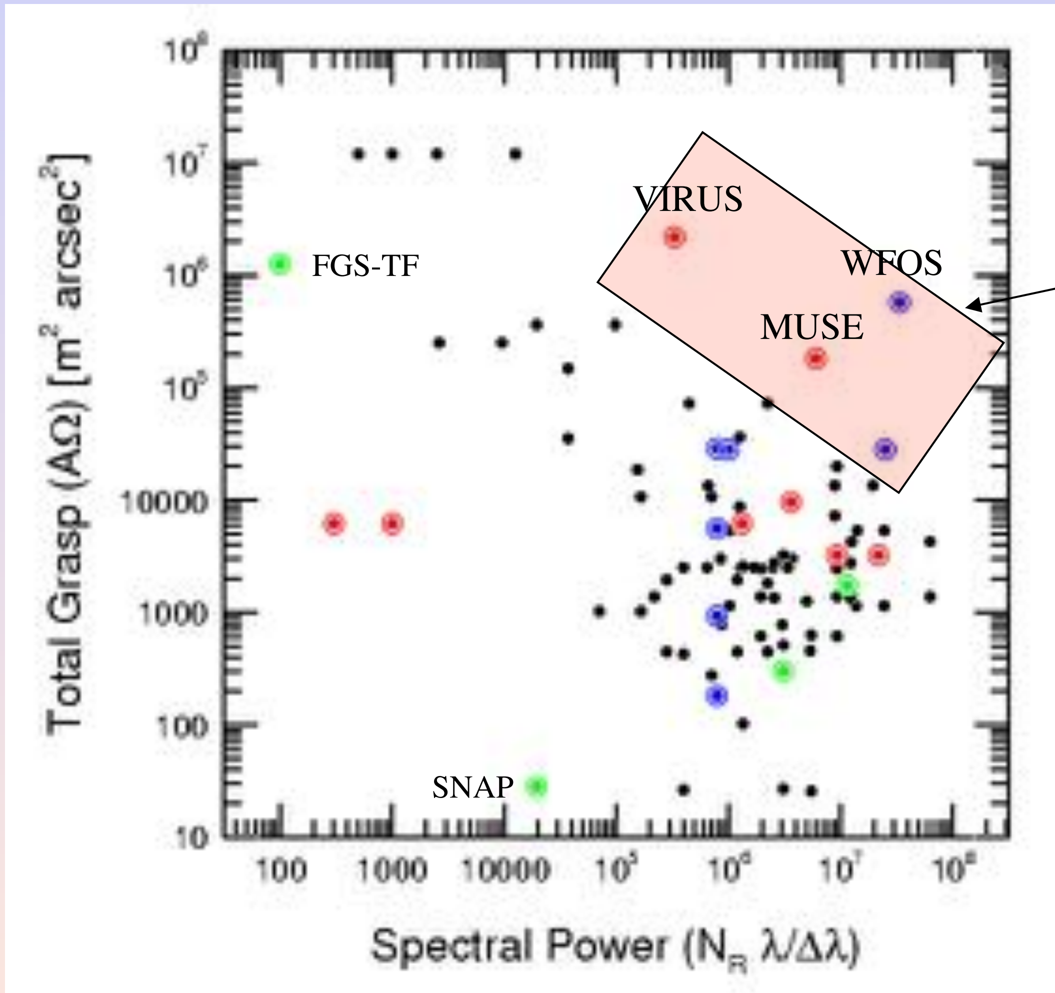
# Future instruments
## SUMMARY

Existing

Future Ground 2-10m

Future Ground 30m

Future Space




Added AΩ at high spectral power.

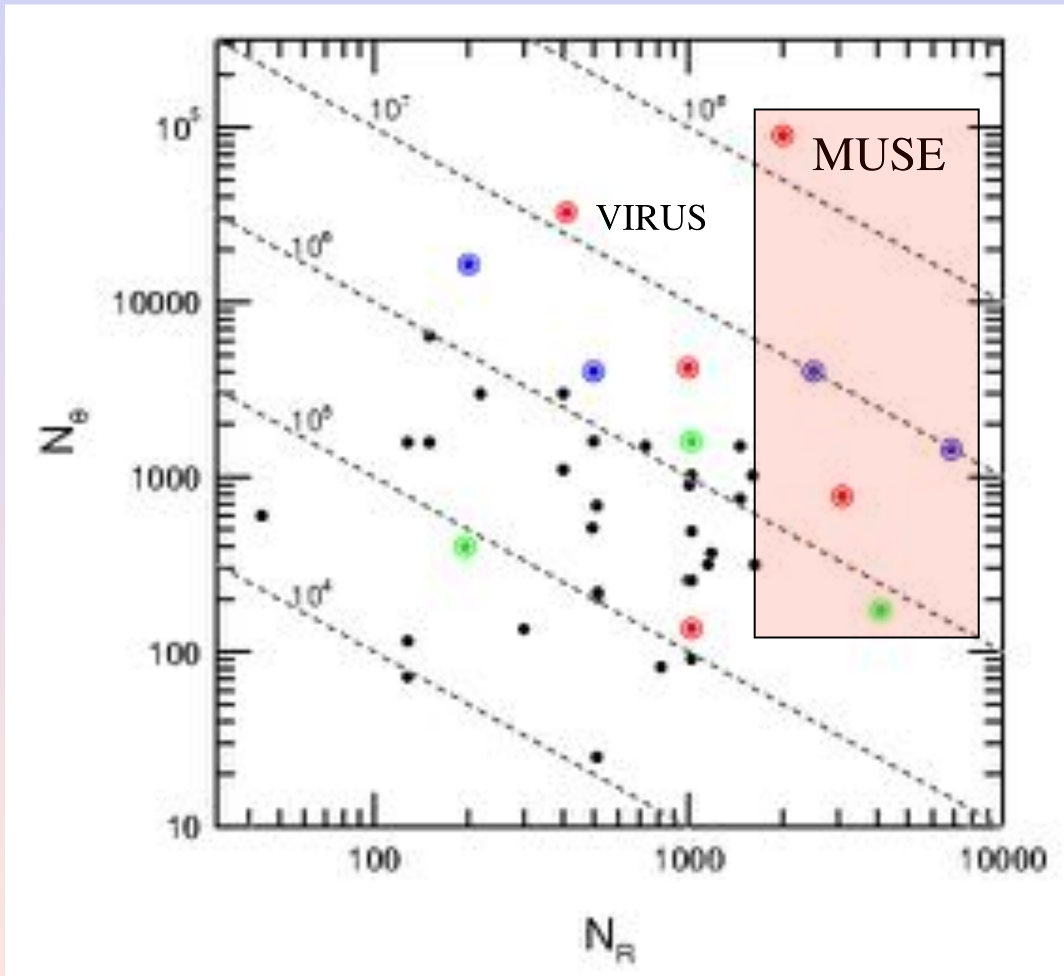
# Future instruments
## SUMMARY

Existing

Future Ground 2-10m

Future Ground 30m

Future 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?