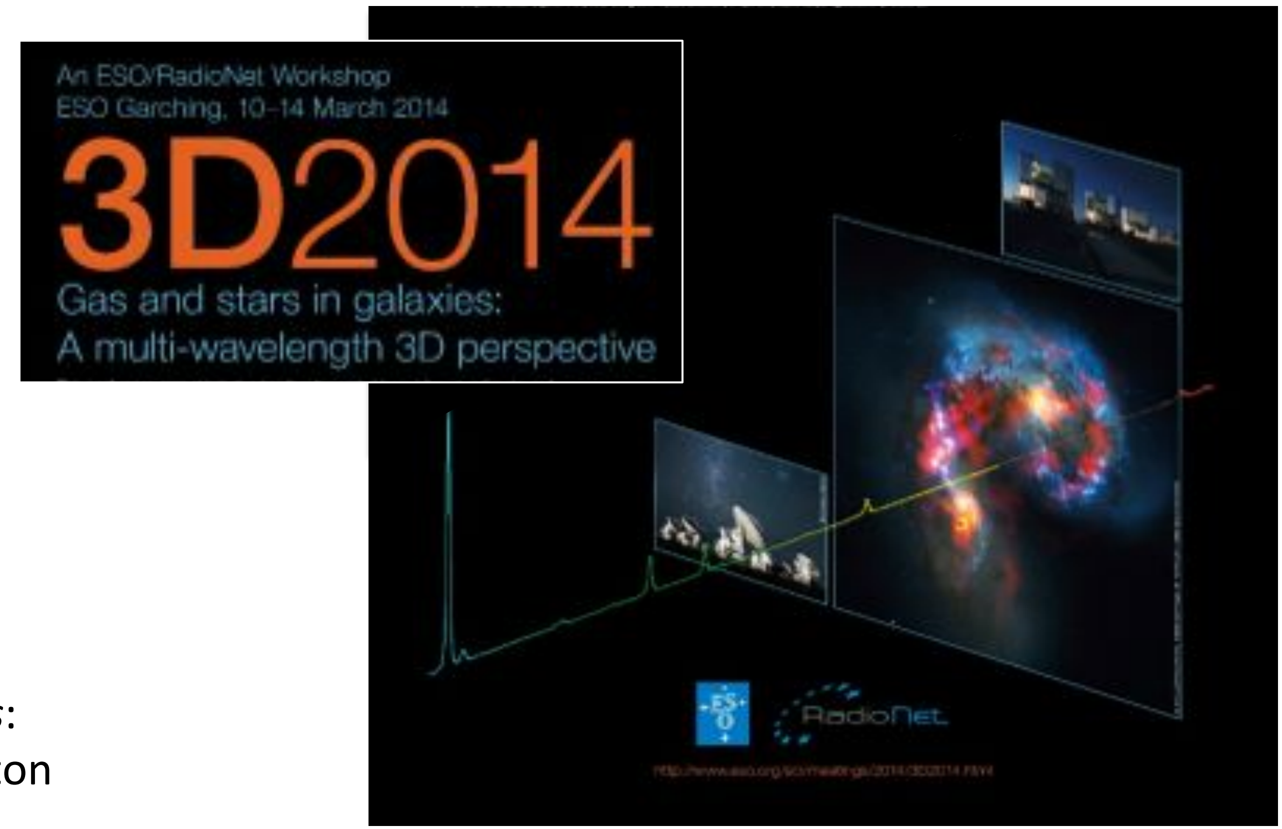
IFS Futures from Ground & Space



Credits:
G. Dalton
G. Hill
M. Mateo
D. O'Donoghue
S. Trager
SDSS-IV/MaNGA team

Matthew Bershady
University of Wisconsin-Madison

Outline

- State of the Art
  - Monoliths, Megaliths & MOS
  - Variable pitch
- Futures
  - Ground: from 2m to 40m
  - Space: JWST and beyond—*UV anyone?*
  - New techniques: …*better and transformative*
  - Trends: what and *who* is missing?

Examples for future

What do we need for ALMA and SKA?

Two challenges: (1) *find* the baryons; (2) *extend* Galactic archaeology to 20Mpc

I. State of the Art

- *The future just arrived*
  - MUSE – VLT 8m
  - VIRUS – HET 9m
  - MOS
    - KMOS – VLT 8m
    - SAMI – AAT 3.9m
    - MaNGA – Sloan 2.5m

Wide-field

  - Variable pitch
    - HexPak, ▽Pak – WIYN 3.5m
    - SED machine – P60

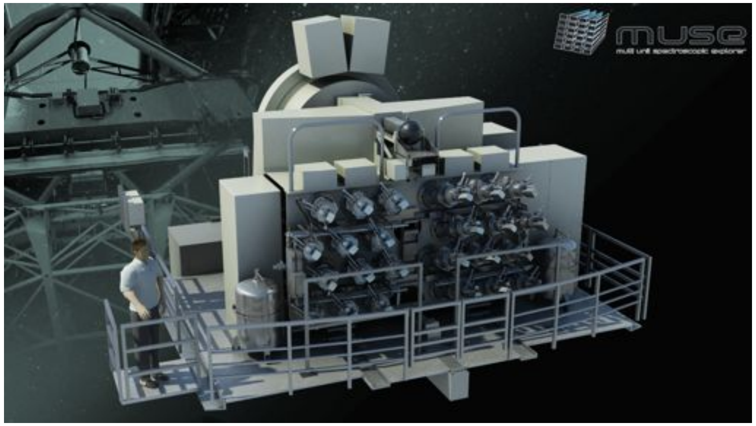
- Common themes:
  - Large AΩ 🡐instrument multiplex
  - Few have large specific grasp AdΩ
  - **object multiplex**:
    different solutions
    - *KMOS and MUSE: slicers*
    - *VIRUS, SAMI, MaNGA: fibers*
  - **instrument multiplex**:
    cost-driven
    - *Economies of scale*
    - *Limited camera field*

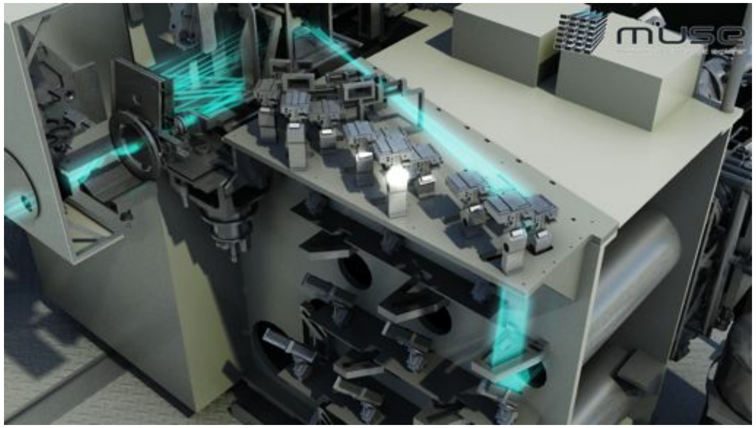
MUSE

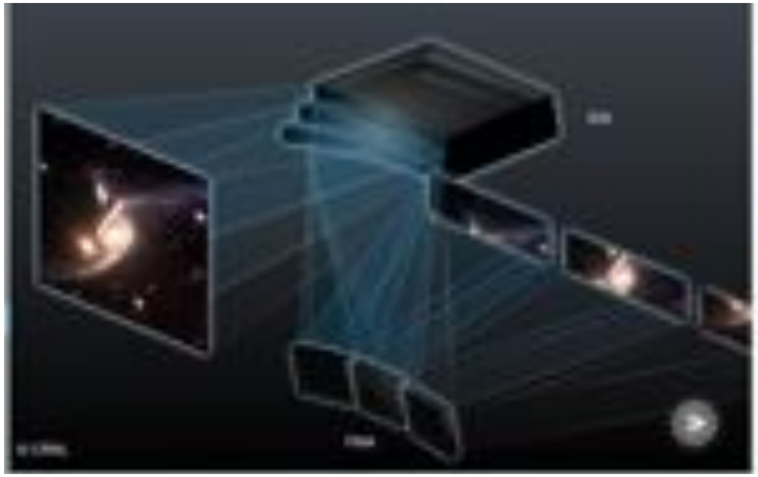
WOW!

- 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 / information.
  - Ground-layer AO (GLAO) assisted.
- Instrument capabilities
  - VLT 8m
  - Two scales:
    - 1 arcmin^2 FoV, (0.04 arcsec^2 elements)
    - 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~~ 0.35

Bacon et al. '04



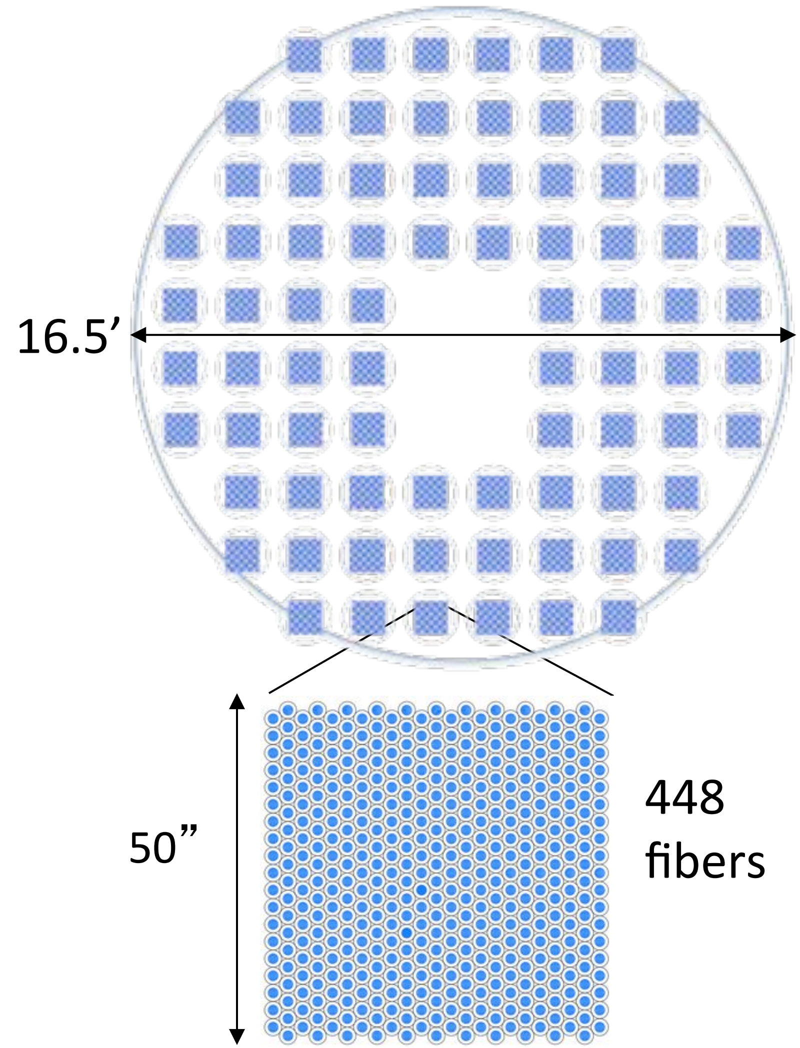


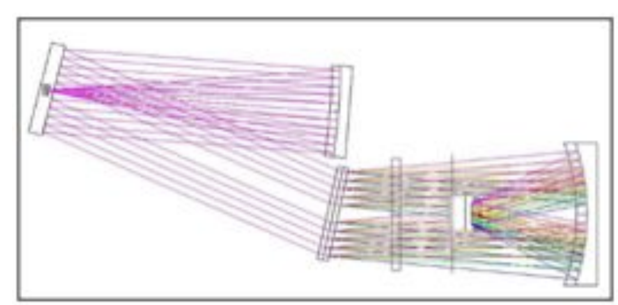


VIRUS

- Science goals
  - Measure BAO from Lyα-e's at 1.8<z<3.7: **HETDEX**
- Technical approach
  - Replicate 150, small, cheap, low resolution bare-fiber fed spectrographs
- Instrument capabilities
  - HET 9.2m + new corrector
  - 16.5' field, sparsely sampled
  - 75 IFUs, 16.5 arcmin^2 coverage
  - 33600 fibers (1.5" diam.)
  - 350-550 nm range (one shot)
  - 410 spectral elements (R~700)
  - ε ~ 0.15

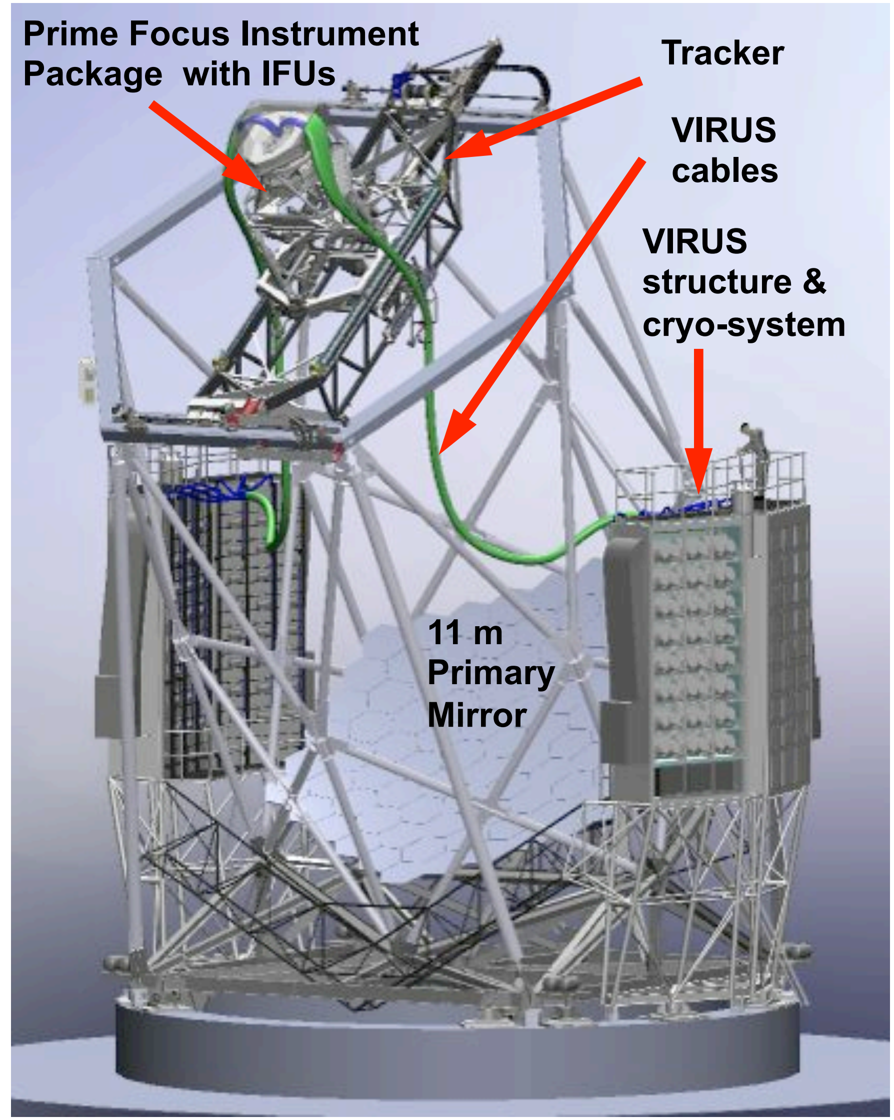
Hill+'12a,b





VIRUS

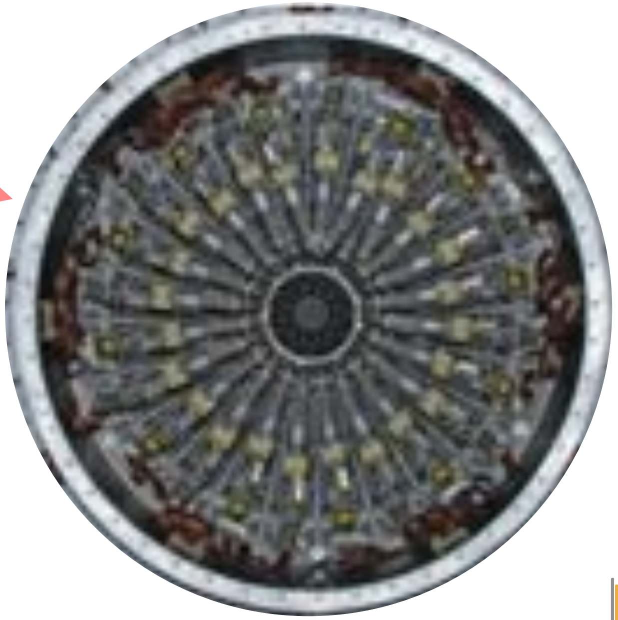
- Science goals
  - Measure BAO from Lyα-e's at 1.8<z<3.7: **HETDEX**
- Technical approach
  - Replicate 150, small, cheap, low resolution bare-fiber fed spectrographs
- Instrument capabilities
  - HET 9.2m + new corrector
  - 16.5' field, sparsely sampled
  - 75 IFUs, 16.5 arcmin^2 coverage
  - 33600 fibers (1.5" diam.)
  - 350-550 nm range (one shot)
  - 410 spectral elements (R~700)
  - ε ~ 0.15



Hill+'12a,b

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 $arcsec^2$)
  - 7.2 arcmin diameter patrol field
  - 0.8-2.5 μm range
  - 1000 spectral elements (R~3600)
  - ε = 0.3 * telescope * atmosphere



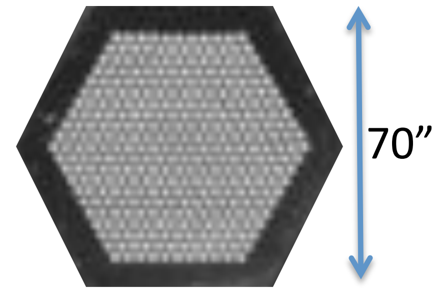
Sharples+12

SAMI and MaNGA

- Science goals
  - Dissect nearby galaxy population to determine dynamics *and* composition physical properties driving galaxy formation/evolution;
- Technical approach
  - Multi-object fiber IFUs feeding dual-beam spectrographs.
- Instrument capabilities

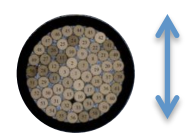
	CALIFA	SAMI	MaNGA
D_{TEL}	CA 3.5m	AAO 3.9m	SDSS 2.5m
Patrol FoV		1 deg	3 deg
# IFU	1	13	17
# fibers	382	819	1423
D_{fiber}	2.7”	1.6”	2.0”
IFU FoV	70”	15	12-32”
spectrograph	PMAS	AAOmega	BOSS
λ coverage (nm)	380-730	370-570, 625-735	350-1050
R=λ/dλ	1500,1100	1730,4500	1400-2700
Efficiency, ε	0.13	0.09,0.14	0.30

CALIFA:
Sanchez+’12
PPK: Verheijen+’04, Kelz+’06
PMAS: Roth+’05

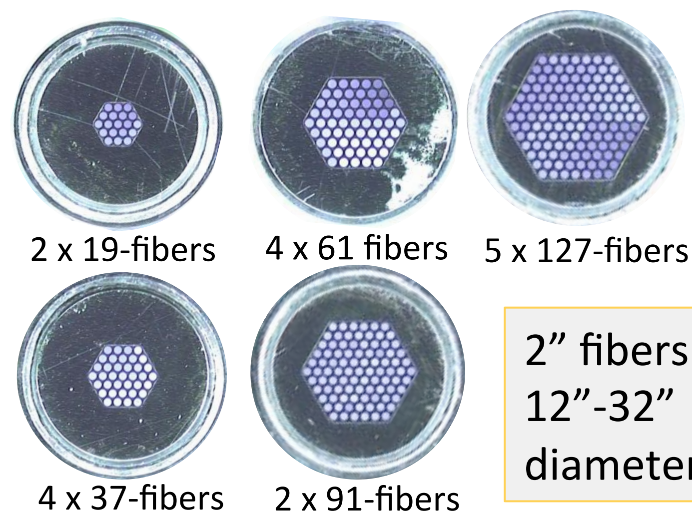


SAMI: Croom+’12

13 x 61 fibers



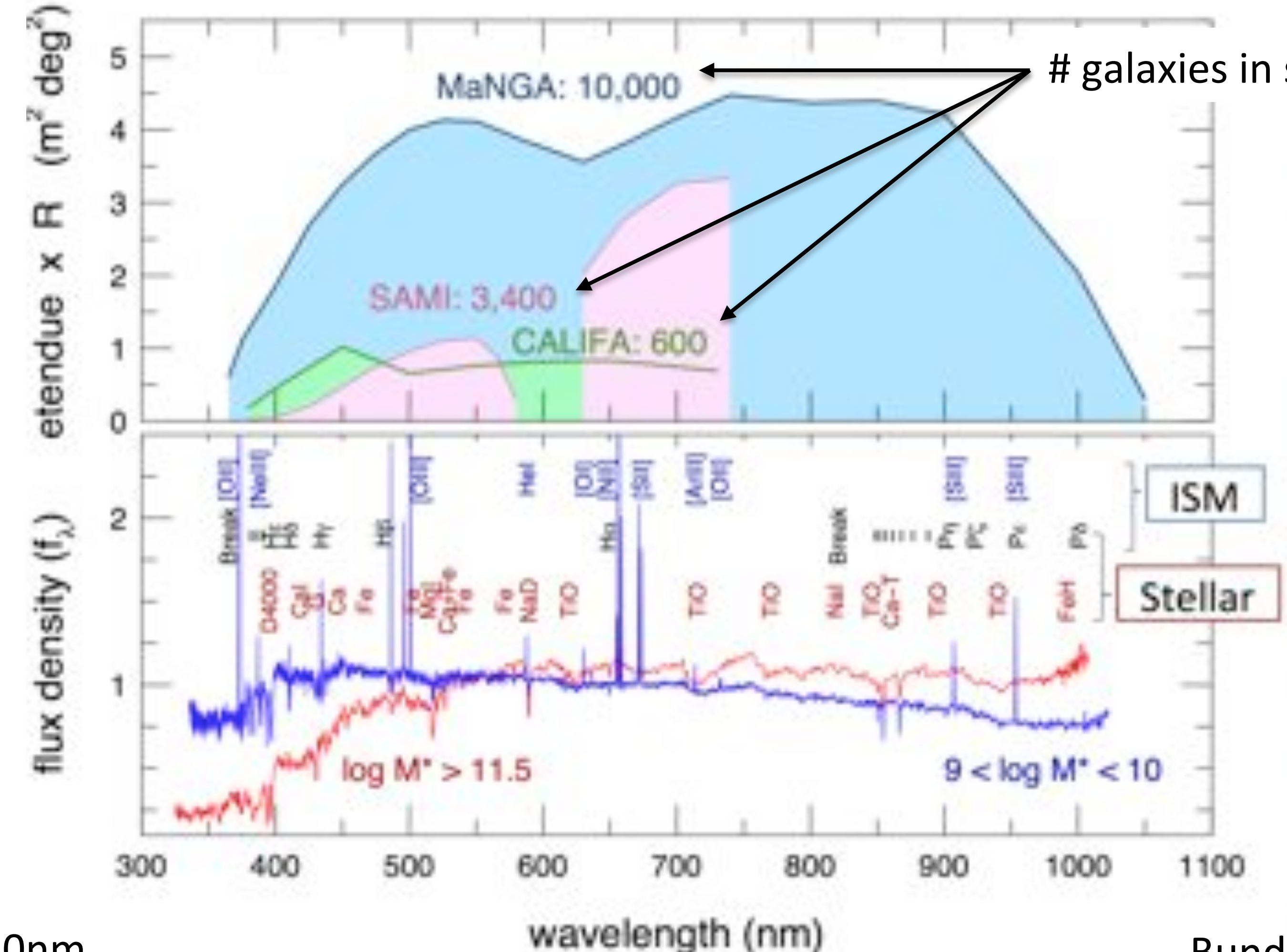
MaNGA: Bundy+’14



2” fibers
12”-32”
diameters

MaNGA / SDSS-IV

Sloan 2.5m telescope, 3 deg FoV, two dual-channel spectrographs



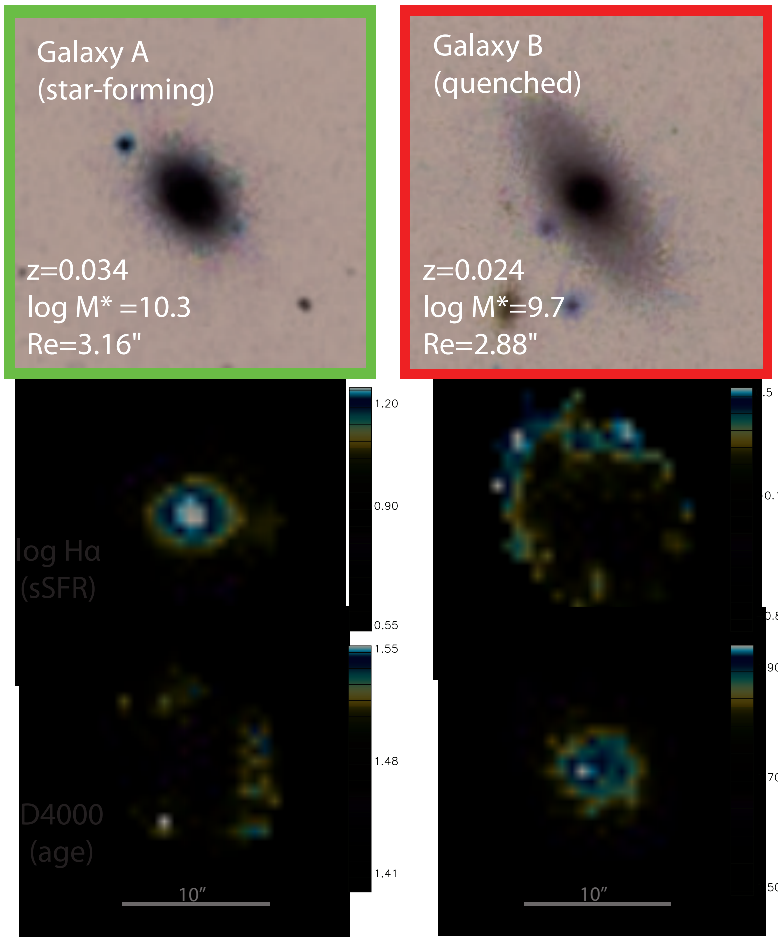
See also:
Yan, this
conference

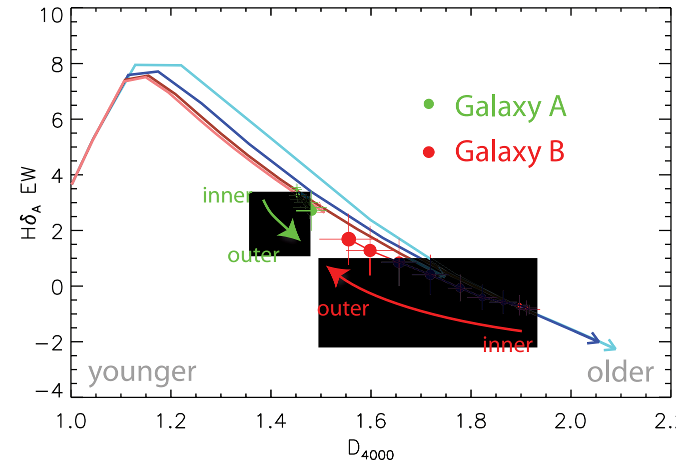
17 IFUs
1423 fibers
2” diameters
12”-32” IFU FoV
R=2000, 360-1050nm

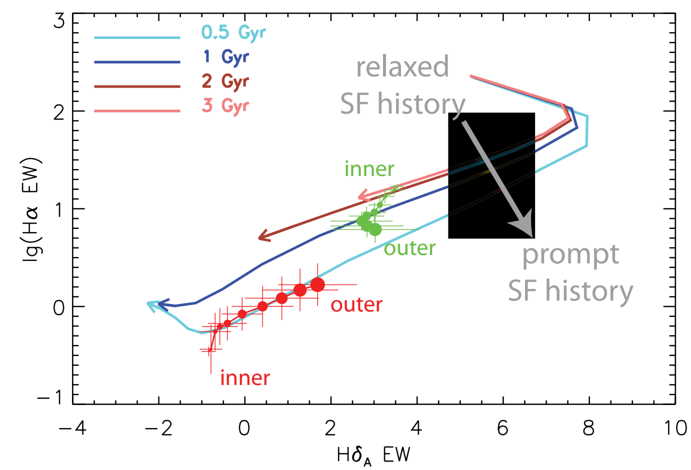
Bundy: PI

MaNGA: exploiting blue sensitivity

Spatially resolved SFH and quenching: D4000, Hδ absorption, Hα emission maps





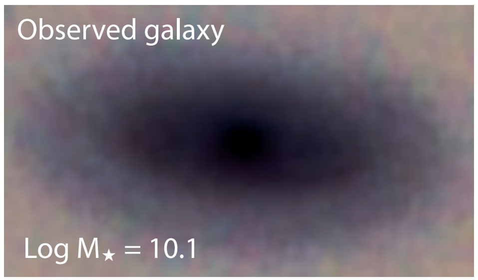


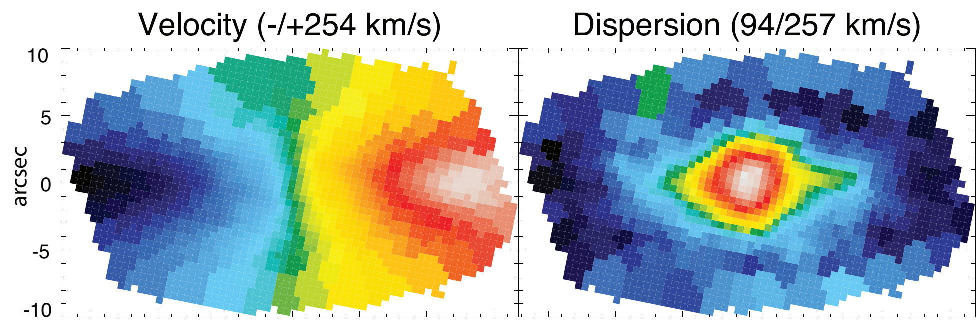
Gradients!
NB: single fibers vs IFU

C. Li, E. Wang, L. Lin, C. Tremonti, K. Bundy+'14

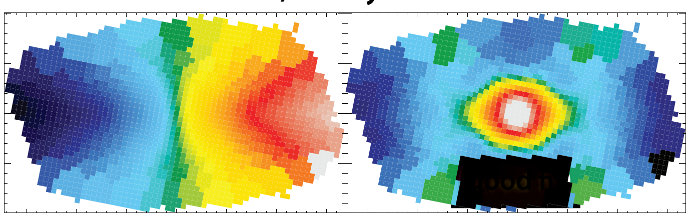
MaNGA: kinematics *and* red sensitivity

Mass modeling capable of uniquely identifying dark and baryonic components

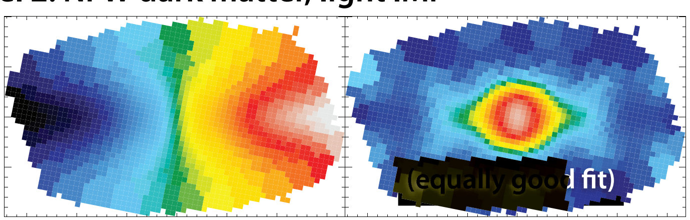




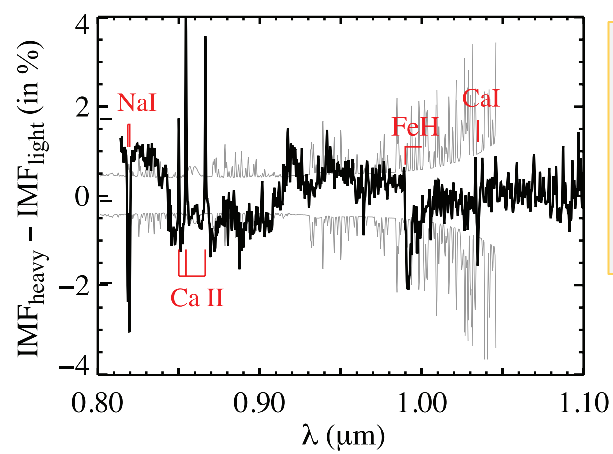
Model 1: No dark matter, heavy IMF



Model 2: NFW dark matter, light IMF



Near-IR features break the degeneracy



Degeneracies:
Υ_* and gradients;
f_{DM} and halo shape

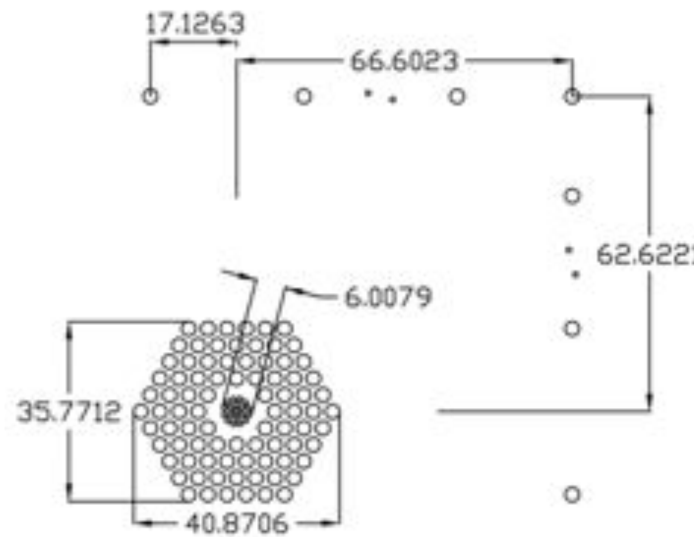
R. van den Bosch, C. Conroy, K. Bundy+'14

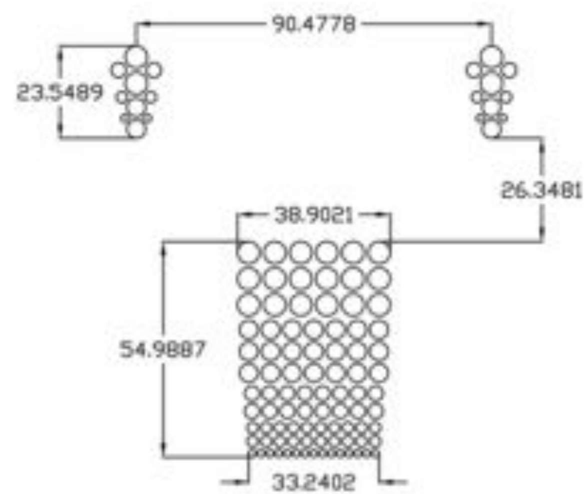
Variable pitch

The universe is logarithmic; why aren't our instruments?

HexPak & ▽Pak

- Science goals
  - Probe disk gradients in composition and kinematics, resolved in the center and mid-plane and detected at low-surface-brightness outskirts.
- Technical approach
  - Variable-pitch IFUs feeding Bench Spectrograph with dual slit
- Instrument capabilities
  - WIYN 3.5m
  - HexPak:
    - 37” hex + 6” circular core
    - 114 fibers: 2.9” hex, 0.94” core
  - ▽Pak:
    - 55” x 39”
    - 110 fibers: 1.9”, 2.9”, 3,7”, 4.7”, 5.6” fiber
  - Bench Spectrograph:
    - 1000 resolution elements
    - 1000 < R < 20,000
    - $\varepsilon = 0.15$





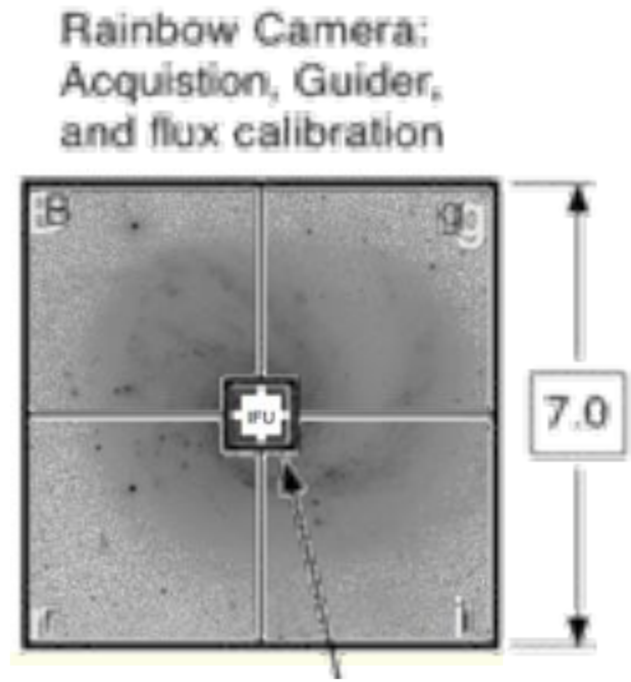
First-light: Nov’13

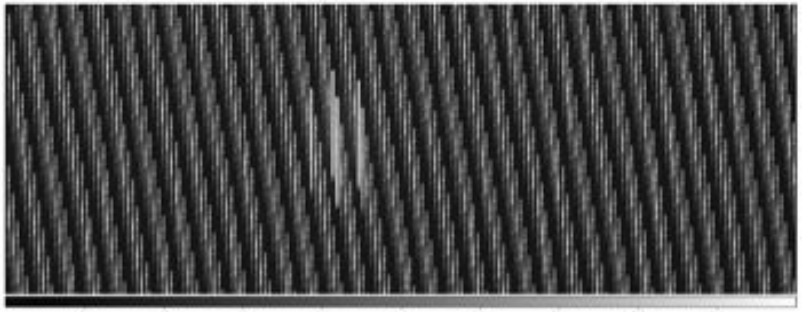
Wood+’12

SED Machine

- Science goals
  - Robotic classification of transients
- Technical approach
  - Lenslet array IFU using triple-prism +4-channel imager
- Instrument capabiities
  - Palomar 60”
  - 7’ imaging field
  - 45” IFU field
  - 60x60 spaxels
  - 0.75” each (0.5mm)
  - R-100, 370-920mm (one shot)

First-light: Nov’13





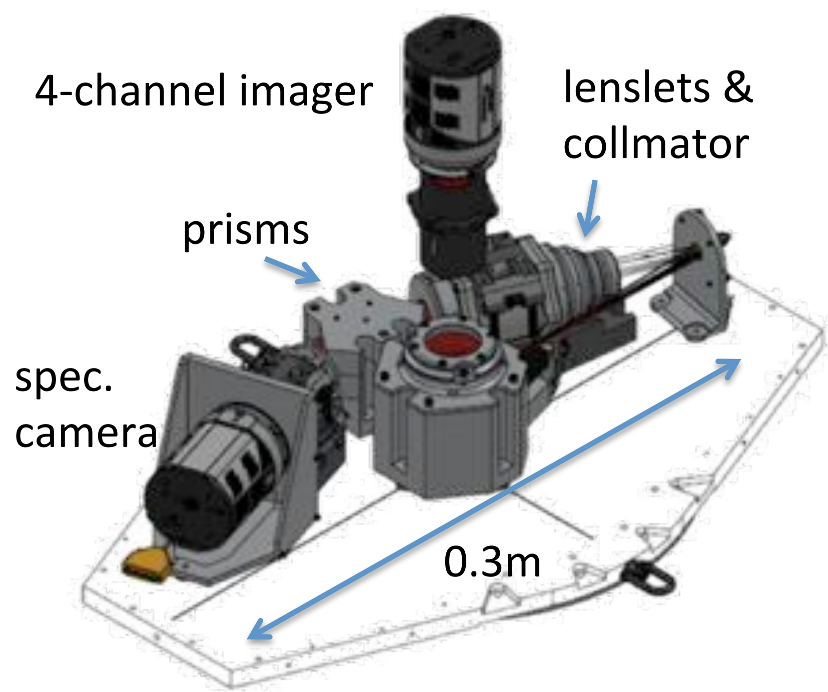
Like Tiger or SAURON (Bacon+’95)

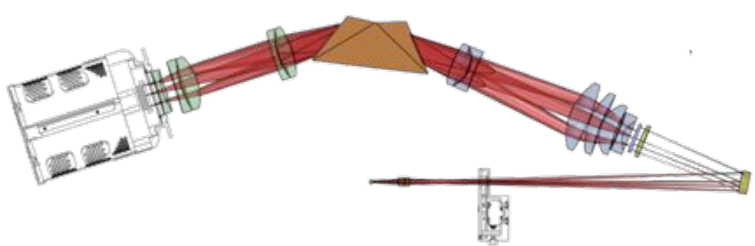
Ben-Ami+’12 (Kondaris-PI)

SED Machine

- Science goals
  - Robotic classification of transients
- Technical approach
  - Lenslet array IFU using triple-prism +4-channel imager
- Instrument capabiities
  - Palomar 60”
  - 7’ imaging field
  - 45” IFU field
  - 60x60 spaxels
  - 0.75” each (0.5mm)
  - R-100, 370-920mm (one shot)

Small optics (30mm beam)
“off the shelf” detectors
Compact: 0.3m
Cheap: $500k





Ben-Ami+’12 (Kondaris-PI)

Futures

Every MOS instrument can be converted into 3D –
....let no spectrograph go to waste

- Ground
  - 2-5m
  - 6-12m
  - 20-40m

E-ELT: EU, Chile

TMT: California; Canada, China, India, Japan

GMT: Arizona, California, D.C., Illinois, Massachusetts, Texas; Australia, Chile, Korea

Institutions in 5/50 US states with 29% total US population; only two public institutions.

Futures: Ground 2-5m

- WEAVE[1,2] – WHT 4.2m
- HECTOR[2] – AAT 3.9m
- **Future conversions**
  - BigBOSS[3] (KPNO 4m)
  - 4MOST[1,3] (VISTA 4m)
  - VXMS[3] (VISTA 4m)

Science drivers: 3 general cases

1-Galactic evolution (+Gaia)
    -stellar RVs, abundances
2-Nearby galaxies
    -kinematics and composition maps
    -stellar & ISM
3-Cosmology / redshifts
    -galaxy clusters masses (+eROSITA)
    -BAO

Wide-field: 1-3 deg patrol
Full optical band-pass
Modest spatial resolution: 1-2.5”
Medium spectral resolution: 2000-20k
IFU Multiplex: 10’s to 100
Fiber multiplex: 1000-10k
Spectrograph multiplex: 2-10

~All fibers

GONE:
    single spectrographs
    single channels

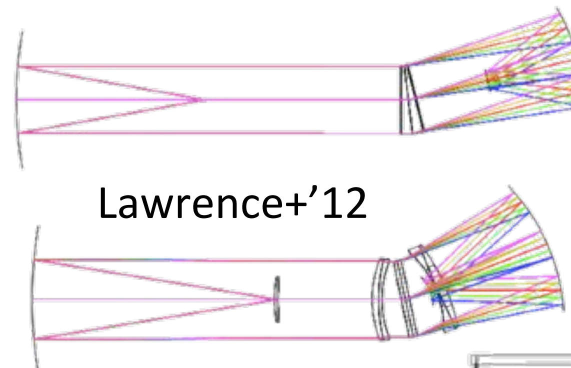
Futures: Ground 2-5m

- WEAVE[1,2] – WHT 4.2m
- HECTOR[2] – AAT 3.9m
- **Future conversions**
  - BigBOSS[3] (KPNO 4m)
  - 4MOST[1,3] (VISTA 4m)
  - VXMS[3] (VISTA 4m)

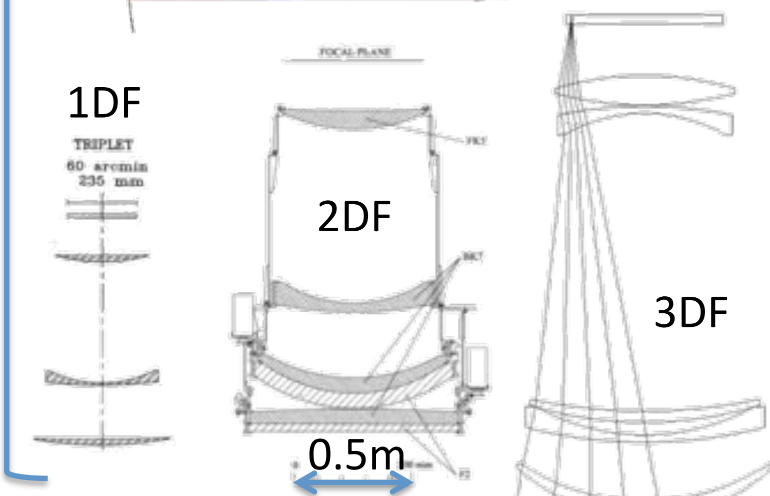
Wide-field: 1-3 deg patrol
Full optical band-pass
Modest spatial resolution: 1-2.5”
Medium spectral resolution: 2000-20k
IFU Multiplex: 10’s to 100
Fiber multiplex: 1000-10k
Spectrograph multiplex: 2-10

15”
1.6” fibers

50-100 x 61 core hexabundles
2-3 deg patrol field
3-6 spec, R~4000



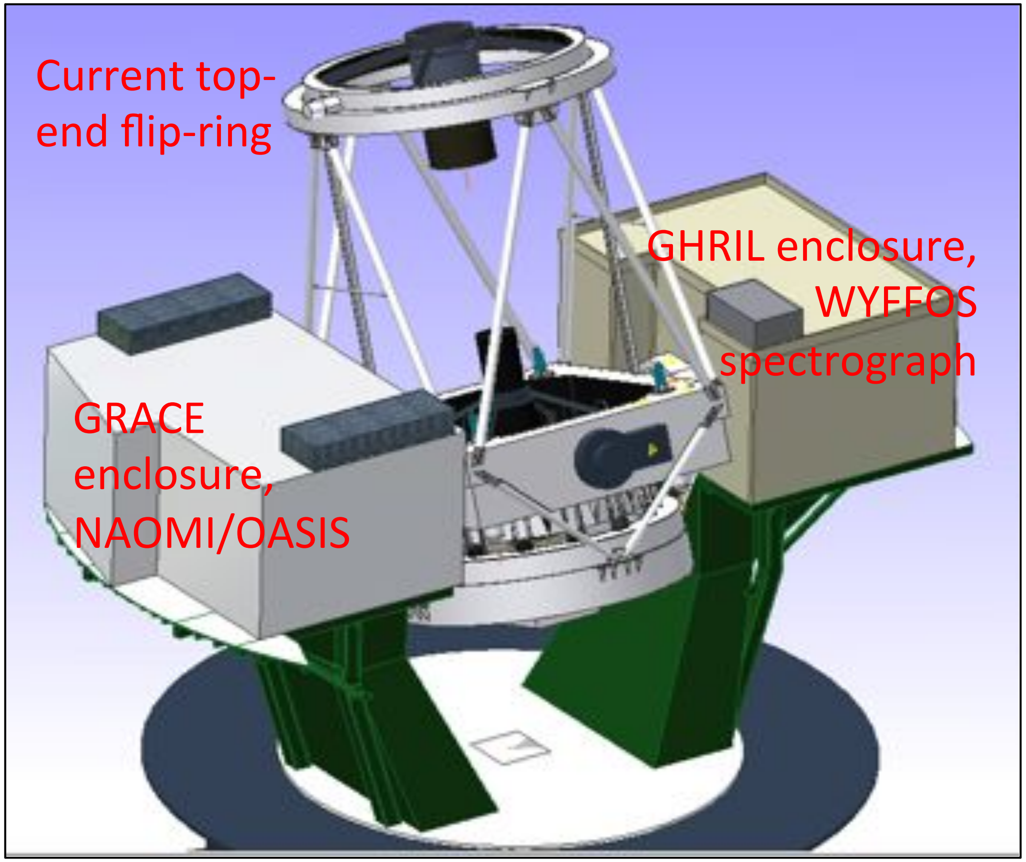
Lawrence+’12



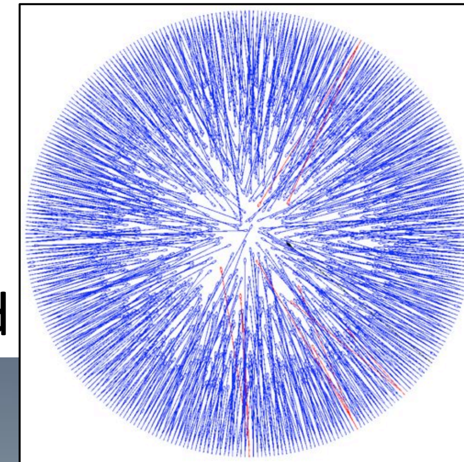
Gillingham+’12

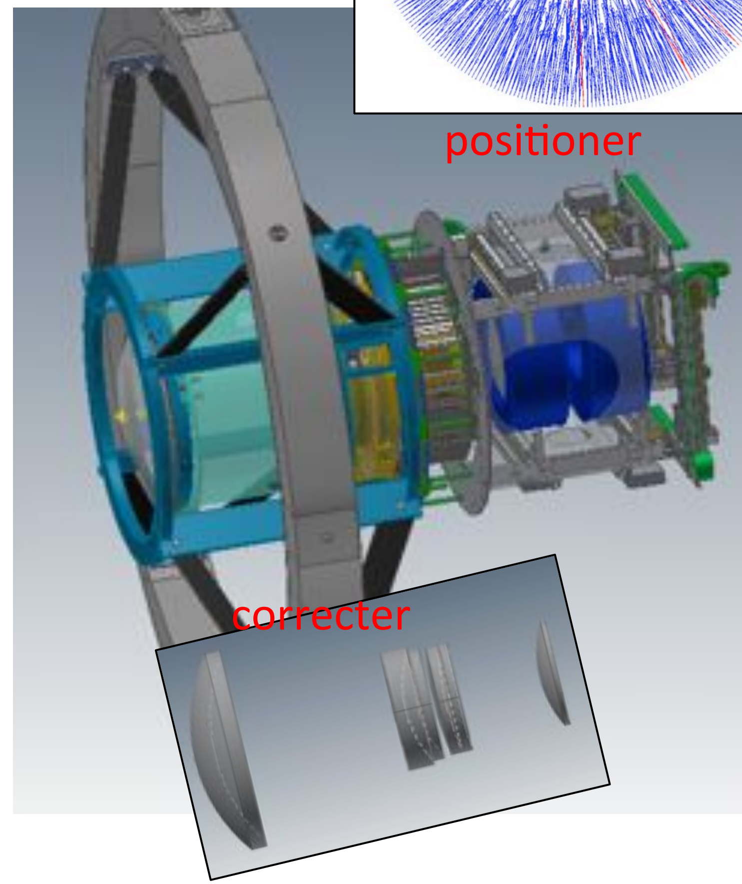
WEAVE / WHT 4.2m

Current WHT configuration



New top end



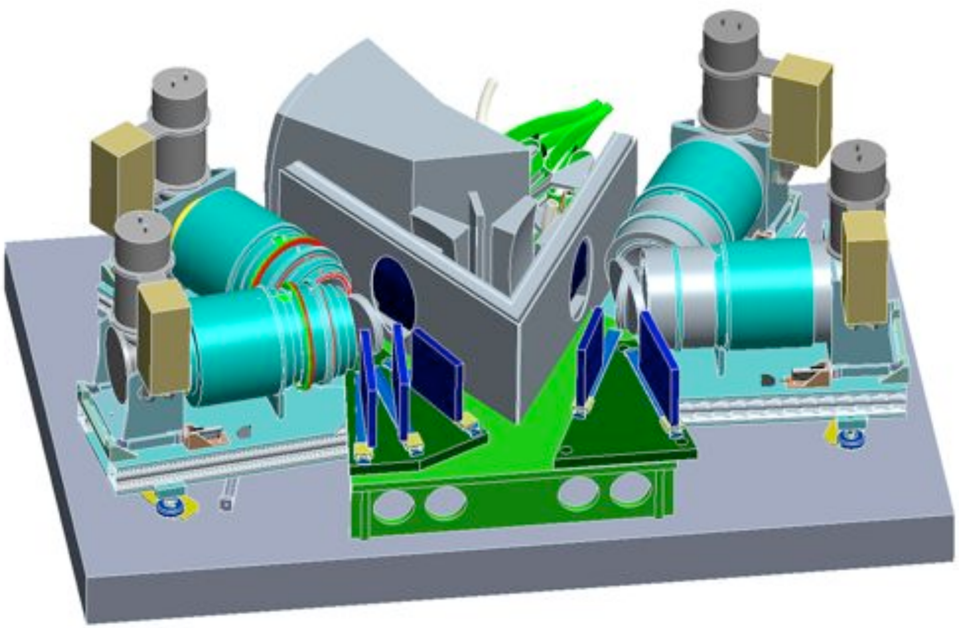


6-lens corrector and ADC: 2 deg field

Dalton+’12 (credit also: S. Trager)

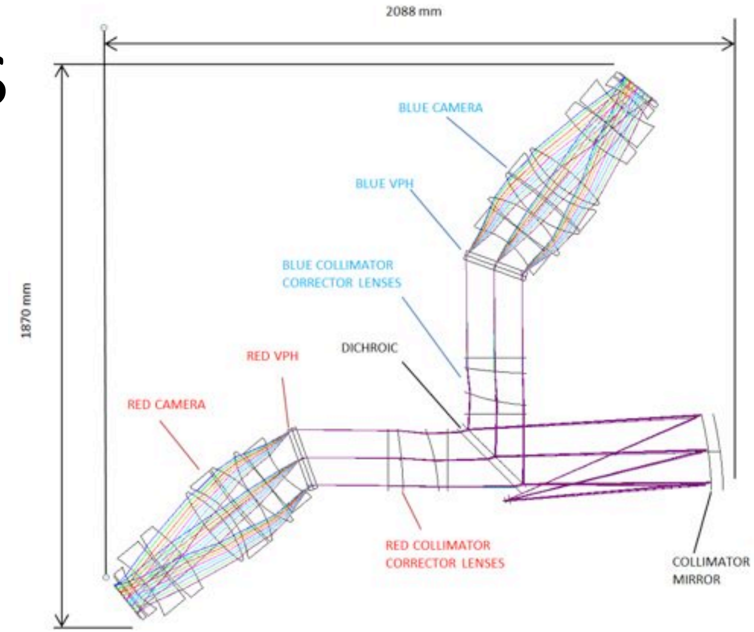
WEAVE / Spectrographs

RAL Optical Design
NOVA opto-mechanics

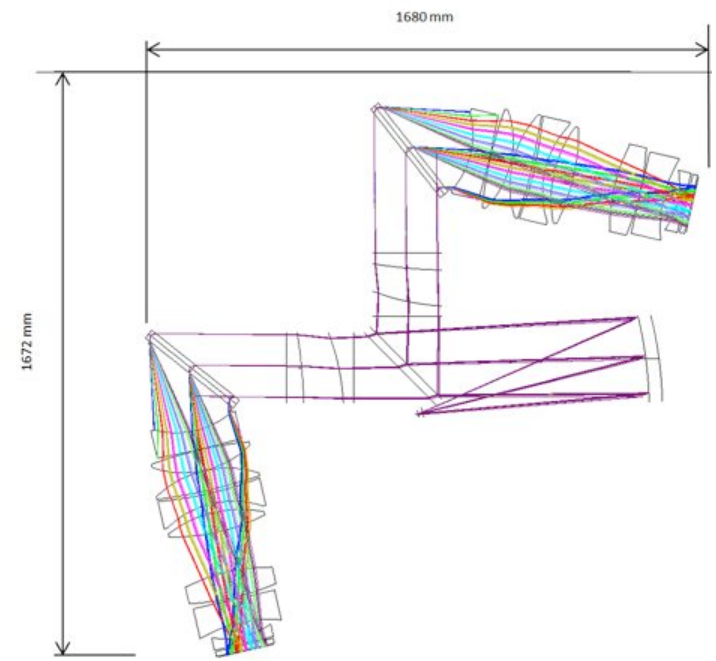


32m fiber run

Low res



High res

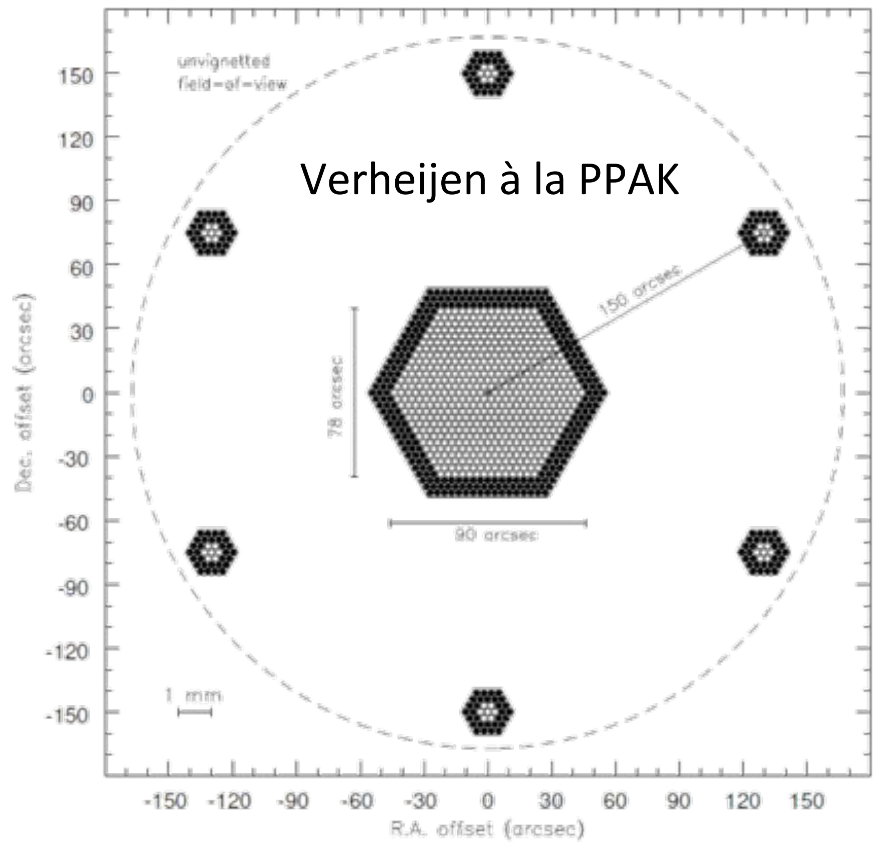


Dalton+’12 (credit also: S. Trager)

WEAVE / IFUs and key parameters

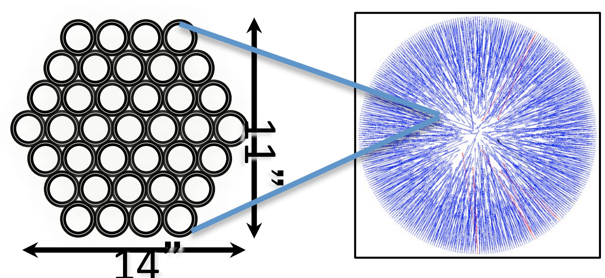
Telescope, diameter	WHT, 4.2m
Field of view	2°
MOS fibers	~1000 x 1.3" diameter
Number of small IFUs, size	20, 10"x14" (1.3" spaxels)
LIFU size	1.5'x1.2' (2.6" spaxels)
Low-resolution mode	R = 4300–7200 366–984 nm
High-resolution mode	R=18560–21375 404–465, (473–545) 595–685 nm

NB: 32m fiber run – UV attenuation



20 mini-IFUs coexist with MOS

20 x



Dalton+'12 (credit also: S. Trager)

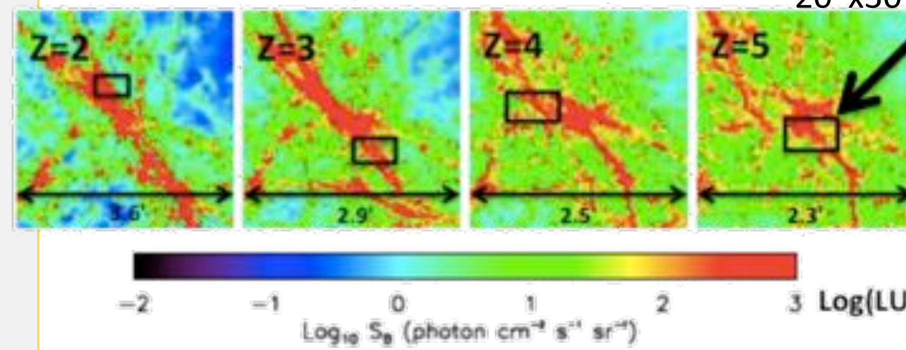
Futures: Ground 6-12m

- KCWI [1] – Keck 10m
- MEGARA [2] – GTC 10.4m
- FRIDA [3] – GTC 10.4m
- **Future conversions**
  - MOONS [4] – VLT 8m
  - PFS [5] – Subaru 8m

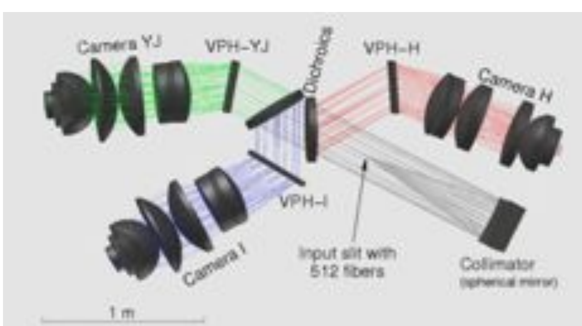
IGM science: The cosmic web at 2<z<5

Where the are all the baryons?

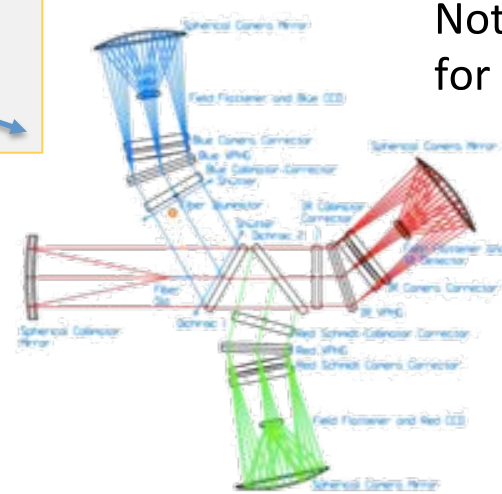
20"x30"



2x



4x



Note: nothing planned for Gemini, LBT, SALT

[1]Morrissey+'12
[2]Gil de Paz+'12
[3]Sanchez+'12
[4]Cirasuolo '12
[5]Sugai+'12

Futures: Ground 6-12m

- Where are all the spectrographs?

[1] single spectrograph and single channel

	type	FoV	spaxel	N_{spax}	R	N_R	λ range
KCWI [1+]	slicer	20”0x8” to 20”33”	0.5”x0.35” to 0.5”x1.4”	920	1k-6k	565 (x2)	350-530nm (530-1050nm)
MEGARA[1]	Fiber+ lenslet	8.5”x6.7” 12.5”x11.3”	0.42” 0.62”	368	7-20k	1235	360-900nm
FRIDA[1]	slicer	0.65”x0.65” to 2.6”x2.6”	10 to 40 mas	4225	1.5k, 4.5k, 30k	645	900-2500nm
Moons	fiber	25’ patrol	1.2” diam.	1000	5k,8k,20k	4444	800-1800nm
PFS	Fiber+ lenslet	1.3° patrol	1.1” diam.	2400	2k-4k	3276	380-1300nm

Here they are!

	N_{spax}	R	N_R	λ range
VIRUS:	3.2e4	0.8k	410	465-930nm
MUSE:	9e4	3k	2000	350-550nm

- Fewer spaxels

+ Better spectral resolution

+ and/or more wavelength coverage

Futures: Ground 20-40m

The ~~horror~~ challenge:

larger instruments, tighter specs

Credit: D. Crampton

Futures: Ground 20-40m

- ➢ AO driven designs: diffraction-limited image-size constant (spectrographs don't need to be bigger)

		E-ELT – 39m	TMT – 30m	GMT – 21.6m
First-light	OIR IFU	HARMONI	IRIS	GMTIFS
	MIR Hi-$\lambda/\delta\lambda$	METIS	MICHI	
ELT-MOS	Optical MOS	OPTIMOS (DIORAMAS)§	(MOBIE) §	GMACS*
ELT-MOS	NIR MOS	EAGLE	(IRMS) §	NIRMOS*

§Multi-slit; not clear upgrade path to IFS

…in 2022

*MANIFEST saves the day$_{\wedge}$: (Goodwin+'12)
20 arcmin field fiber positioner (starbugs)

First-light optical-infrared IFS

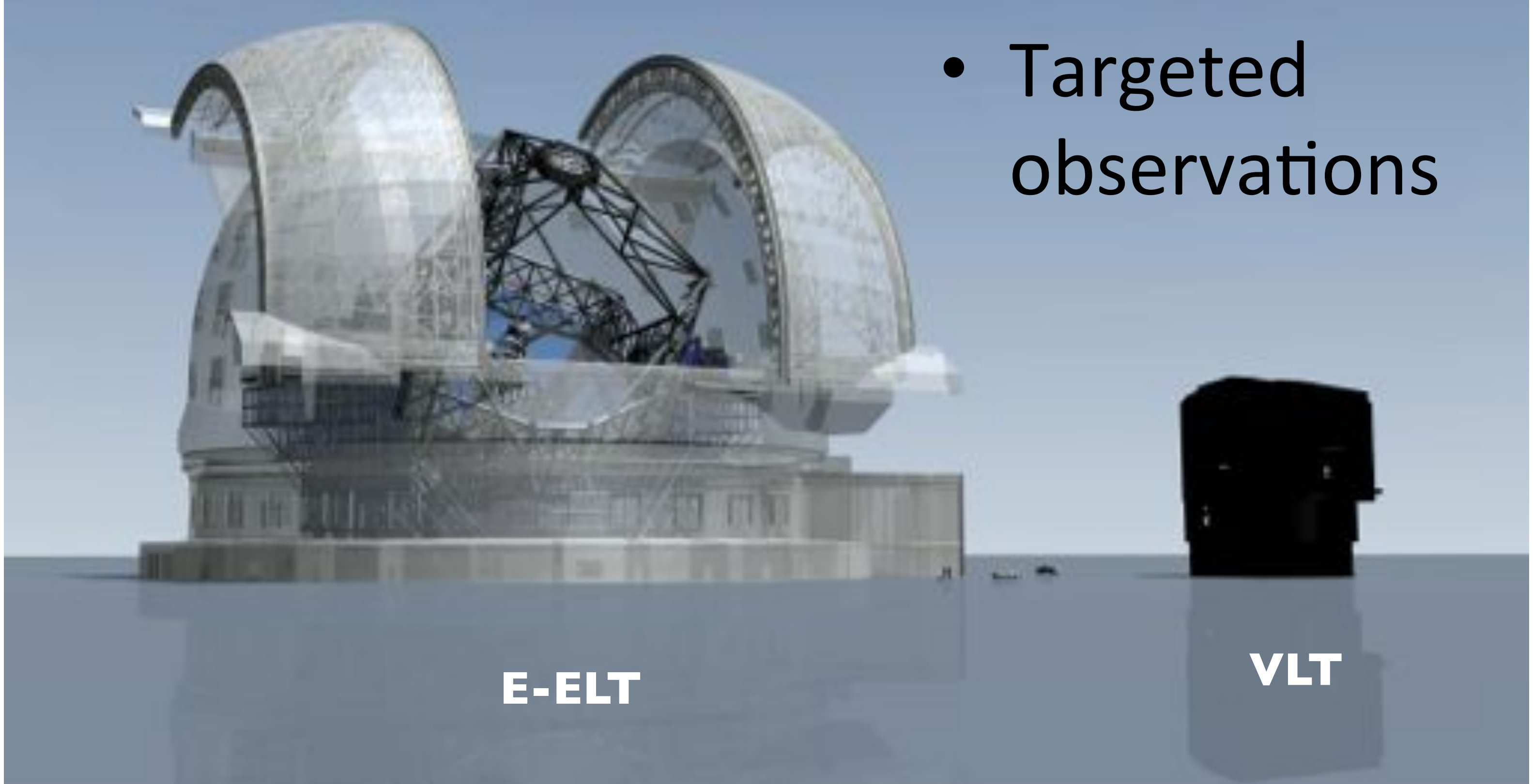
	type	FoV	spaxel	N_{spax}	R	N_R	λ range
HARMONI (E-ELT)	slicer	0.6”x0.9” 1.5”x2.1” 3.0”x4.3” 6.4”x9.1”	4x4 mas 10x10 mas 20x20 mas 60x30 mas	32500	500,3500, 8000,2e4	3000	0.47-2.5μm
IRIS (TMT)	Lenslet or slicer	0.18”x0.35” to 2.2”x4.4”	4,10 mas 24,50 mas	3872	4000	200	0.84-2.4μm
GMTIFS (GMT)	slicer	0.3”x0.5” to 2.25”x4.4”	6,12,25,50 mas	3960	5000 1e4	1000	0.84-2.4μm

- **Comparable spatial resolution but HARMONI has 10x field coverage**
- **HARMONI has larger dynamic range in spectral resolution and more resolution elements.**

HARMONI: Thatte+’12
IRIS: Larkin+
GMTIFS: McGregor+’12

HARMONI / E-ELT

- AO driven design
- 4 dual-channel spectrographs, 0.45-2.5µm
- Targeted observations



Credit: Niranjan Thatte / HARMONI consortium

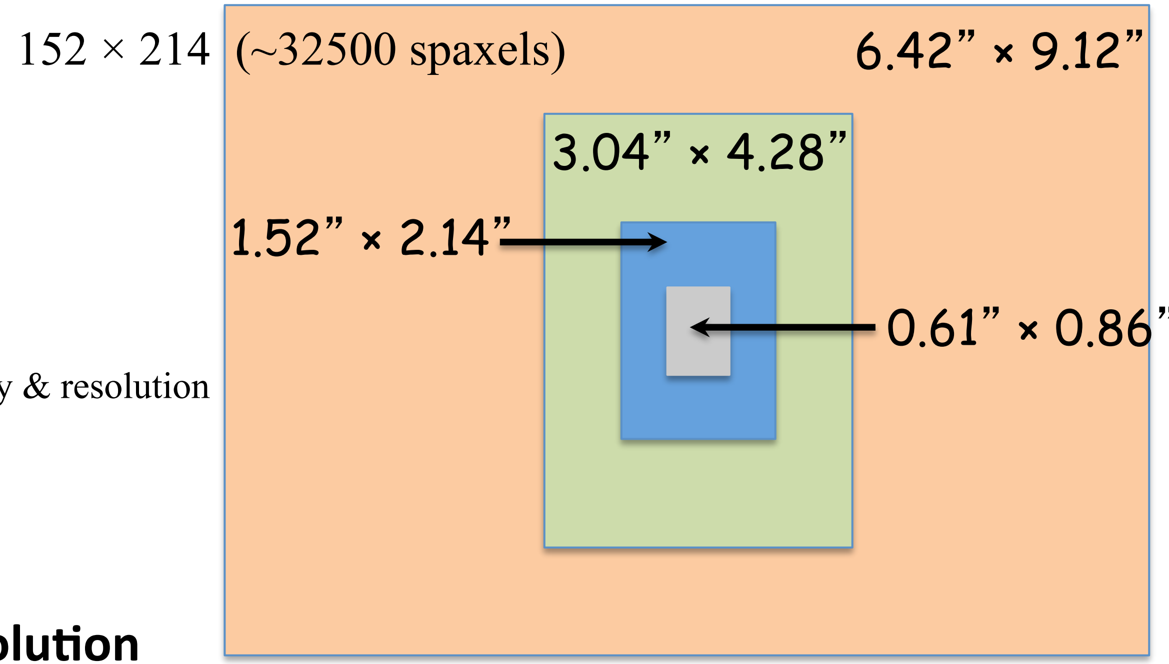
Thatte+'12

HARMONI / E-ELT

Spaxels

- 60 mas × 30 mas — Non-AO & visible observations
- 20 mas — Optimal sensitivity
- 10 mas — Optimize sensitivity & resolution
- 4 mas — Diffraction limited

Field of view



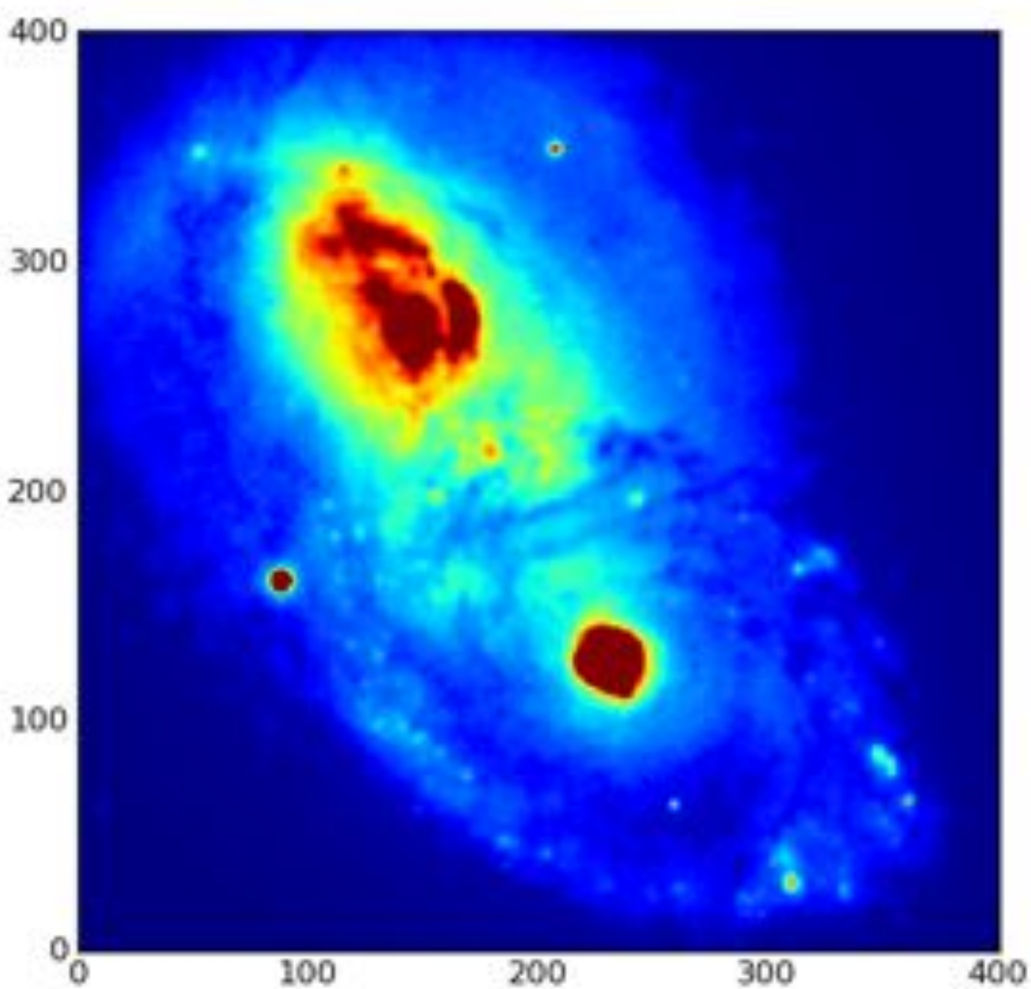
Spectral coverage and resolution

Wavelenth coverage	R
Simultaneous V+R and I to K	~3500, ~500
“V+R” or “I+z+J” or “H+K”	~3500
“I+z” or “J” or “H” or “K”	~8000
“Z” or “J_high” or “H_high” or “K_high”	~20000

N_R~3000

Thatte+’12

HARMONI / E-ELT



Simulation:
LIRG z~2
Hα in K band

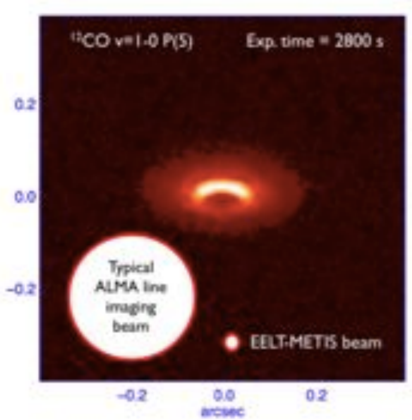
Note: Point-source vs diffuse sensitivity

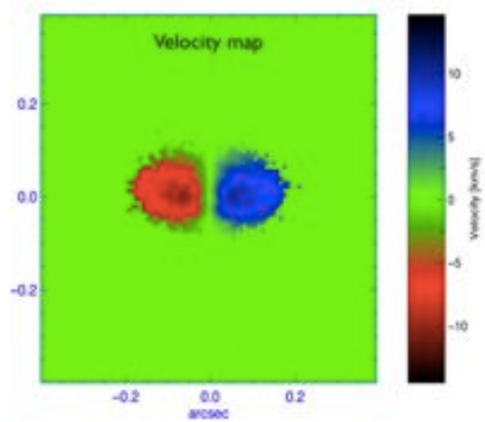
Credit: Niranjan Thatte / HARMONI consortium

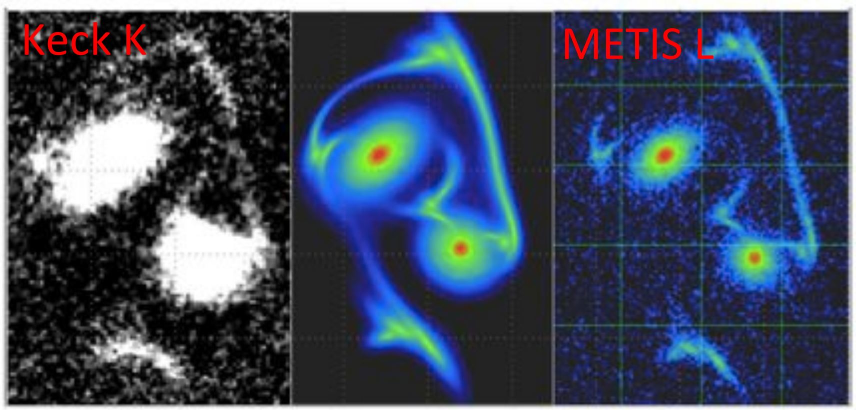
METIS: Game-changer in the MIR

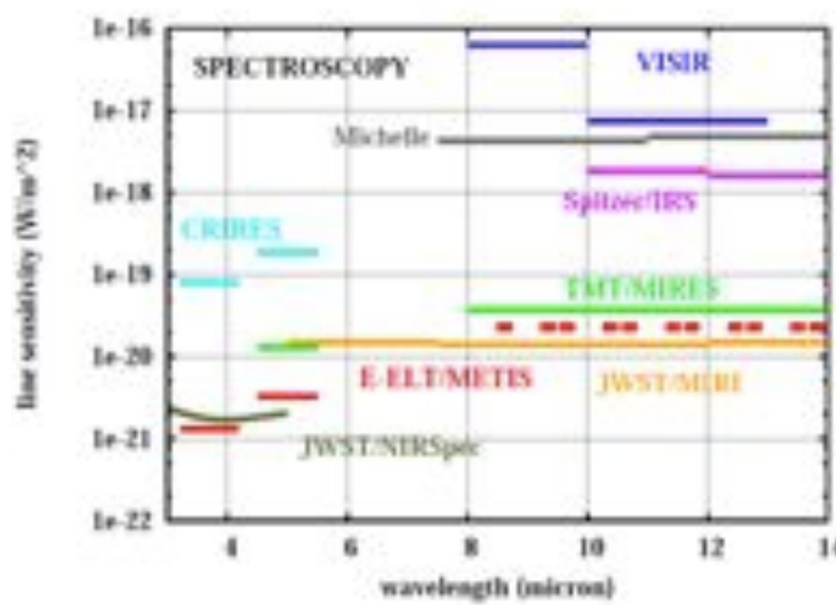
- Science goals
  - Exo-planets, proto-planetary disks, high-redshift galaxies

	type	FoV	spaxel	N_{spax}	R	N_R	λ range
METIS		0.4" x 1.5"	17mas	2160	1e5	2000	2.9-5.3µm









Brandl+12

Futures: E-ELT and GMT OIR MOS

	type	FoV	spaxel	N_{spax}	R	N_R	λ range
OPTIMOS -EVE (E-ELT)	Fiber + lenslet	240x 0.9” 70x 0.9” 40x 0.81” 30x 1.8”x3” 7.8”x13.5”	0.3” 0.18” 0.09” 0.3” 0.3”	240x 7 70x 19 40x 61 30x 52 1170	6000 18e3 3e4 6000 6000	4000	0.37-1.7μm
GMACS* (GMT)	fiber	605 $arcsec^2$	0.5” diam	3085	2500	2350	0.36-1μm
EAGLE (E-ELT)		20 x 1.65”x1.65”	37.5 mas	20 x 1936	8000	2000	0.8-2.45μm
NIRMOS* (GMT)	fiber	54 $arcsec^2$	0.25” diam	1114	5000	2000	1-2.5μm

For reference:

VIRUS:	3.2e4	800	410	0.46-0.93μm
MUSE:	9e4	3000	2000	0.35-0.55μm

These are all interesting.

EAGLE: Cuby+’10, Morris+’12
OPTIMOS-EVE: Navarro+’12
NIRMOS: Fabricant+’12
GMACS: DePoy+12

Query:

- Why aren't we putting MUSE and VIRUS on E-ELT and GMT, respectively?
  - If not literally, then their conceptual clones?

✖

MUSE:
8m, f/15 ➔ 39m, f/17.48
assume foreoptics (➔ 39m, f/15)
0.2" ➔ 41mas

Very comparable to Harmoni but with lower spectral resolution and smaller wavelength coverage

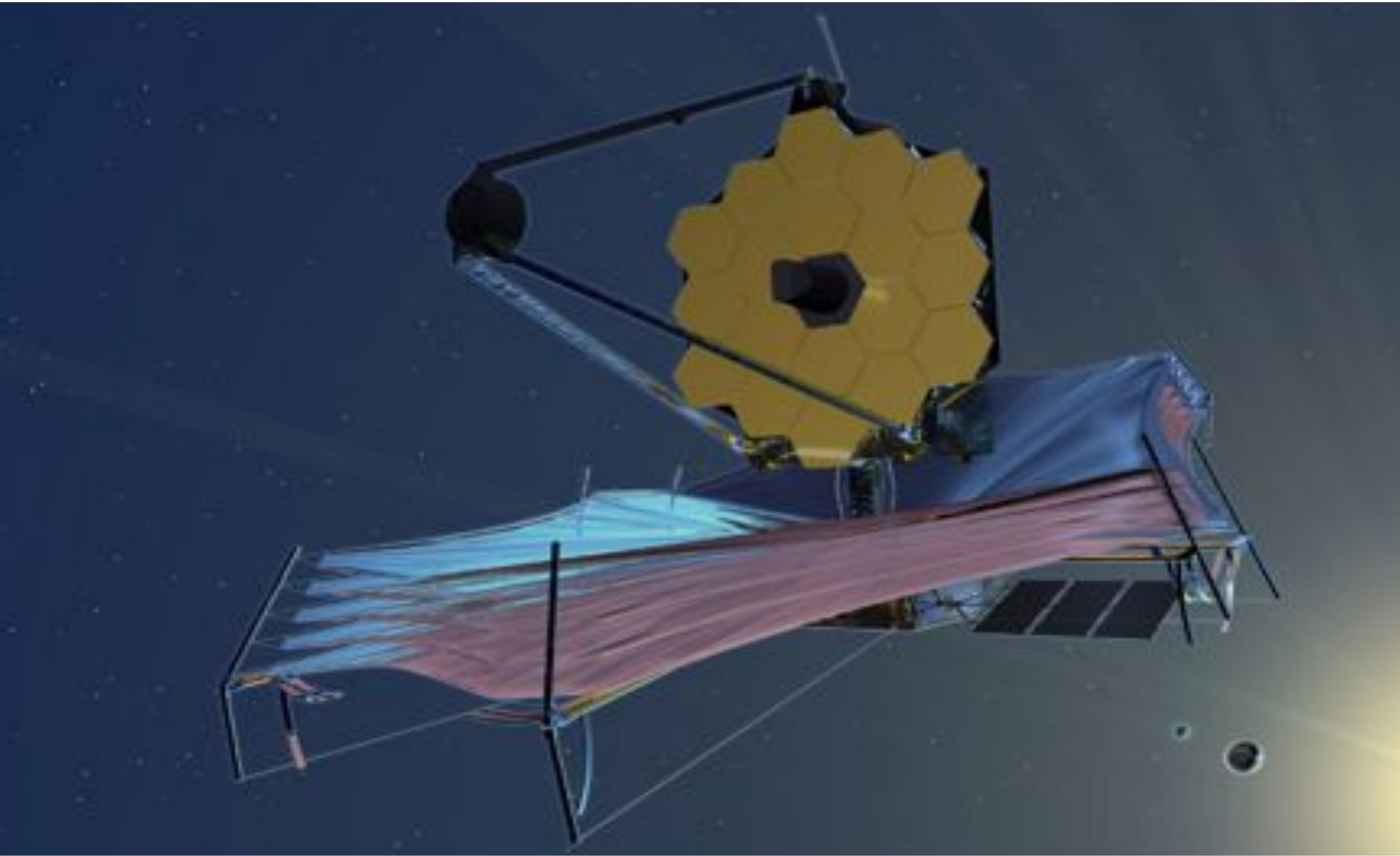
✔

VIRUS:
10m, f/3.65 ➔ 25.4m, f/8.3
assume foreoptics (➔ 25.4m, f/3.65)
1.5" ➔ 0.59"

Good match to natural seeing; 10x more spaxels than anything else on GMT

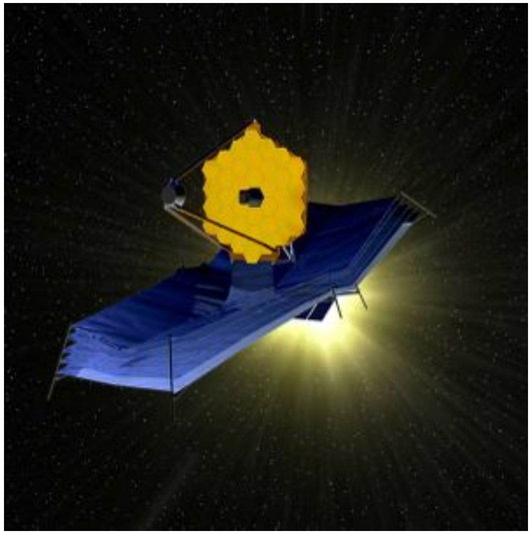
Futures: Space-based instruments

JWST, WFIRST, EUCLID



JWST

- JWST
  - 6.5m telescope (25 m^2)
  - 0.6-29 μm coverage
  - 0.1 arcsec resolution or better
  - opertating temperature < 50° 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
  - NIRISS
  - NIRSpec
  - MIRI

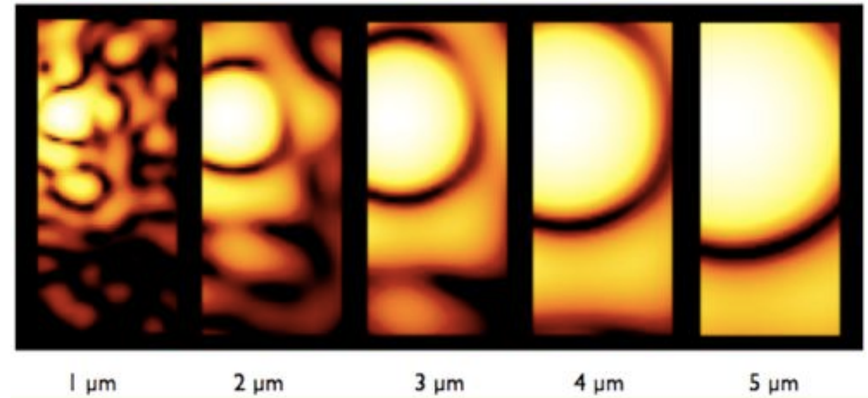
2.2'x2.2' field slitless spectroscopy
R=150, 0.8-2.2μm; R=2000, 2.4-5μm

IFU capability

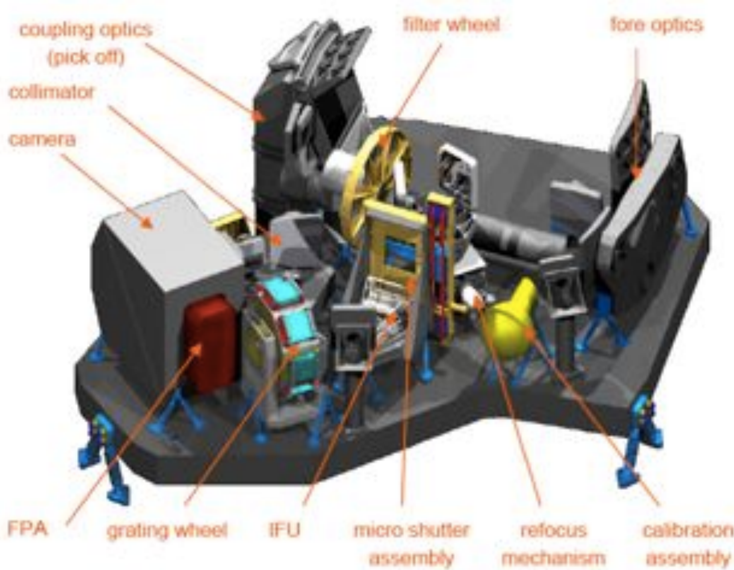
JWST

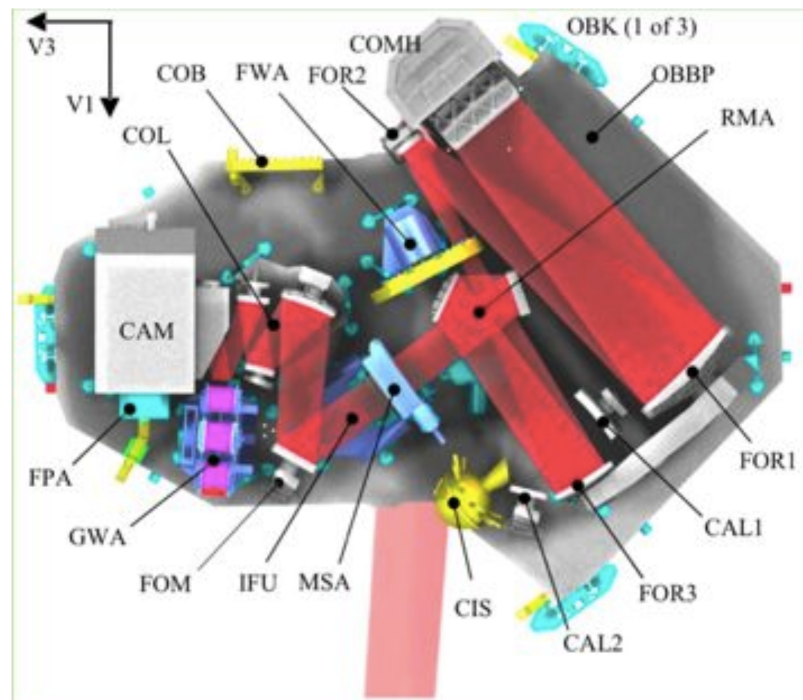
PSF

0.2”x0.46”



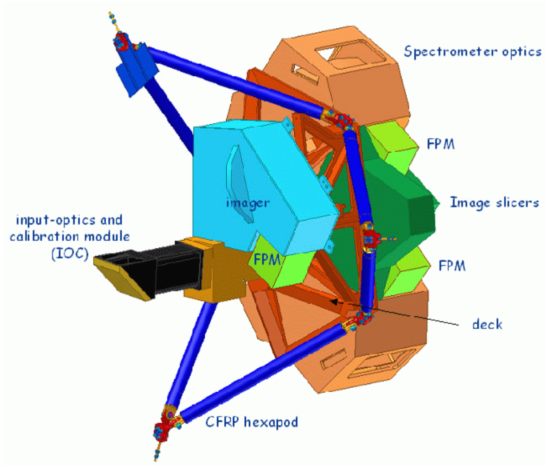
- NIRSpec
  - 3.5x3.5 arcmin field for MOS using micro-shutter arrays
  - IFU mode: 3x3 arcsec at R = 100-2700
  - advanced slicer: 40 3x0.075 arcsec slices feeding 2x2048^2 arrays
  - 0.6-5 μm



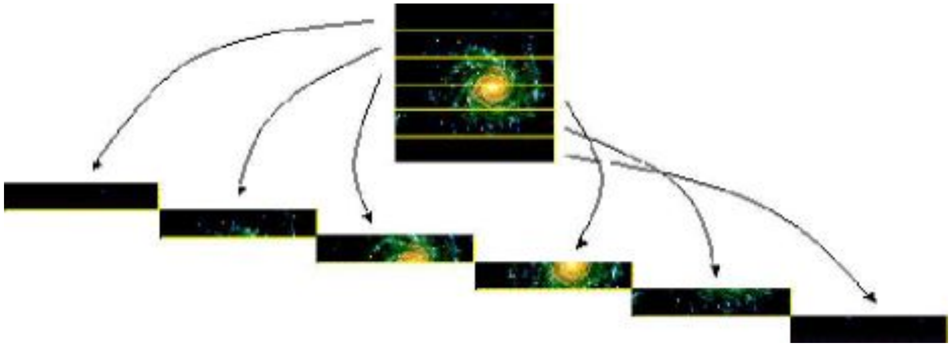


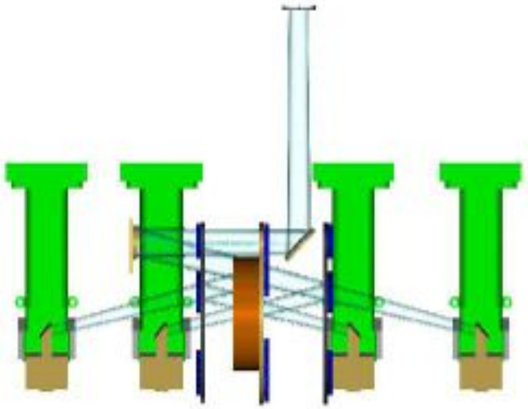
JWST

- 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

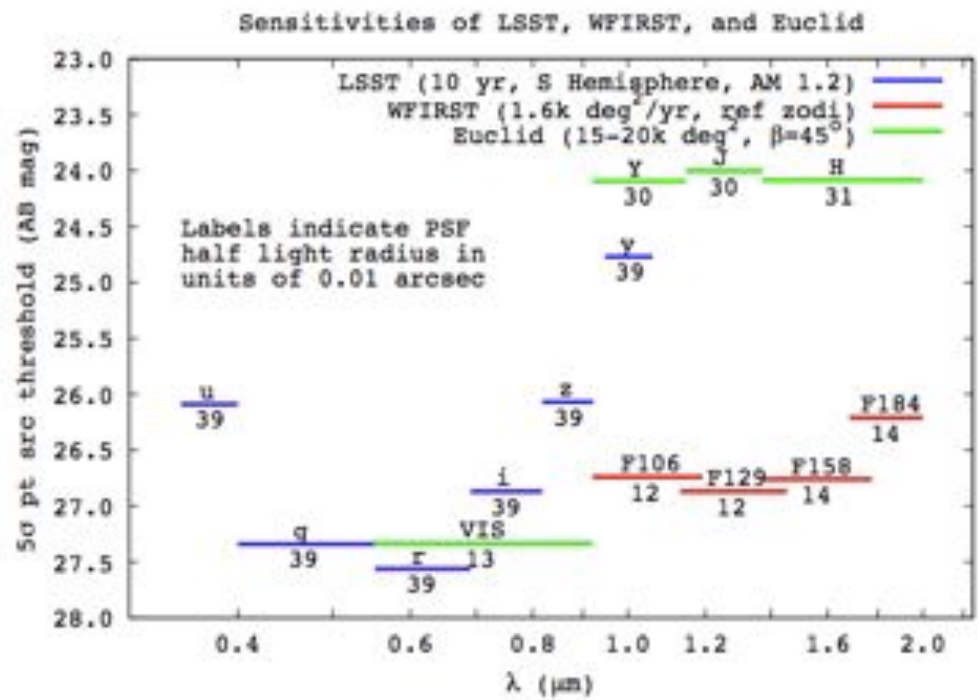




WFIRST and EUCLID

"….recent improvements in infrared detector technology enable a mission that would achieve dramatic advances across a wide range of astrophysics, including dark energy, the demographics of planetary systems, and studies of galaxy evolution, quasar evolution, and stellar populations of the Milky Way and its neighbors." Spergel+'13 (WFIRST)

	Slitless spectroscopy		IFU
	EUCLID	WFIRST	WFIRST
D_T	1.2m	2.4m	2.4m
FoV	0.55 deg^2	0.28 deg^2	3"x3.15"
spaxel	0.3"/pix	0.11"/pix	
$\Delta\lambda$	1.1-2µm	1.35-1.95µm	0.6-2µm
$R=\lambda/\delta\lambda$	250	700	100
N_{pix}	67Mpix	302Mpix	

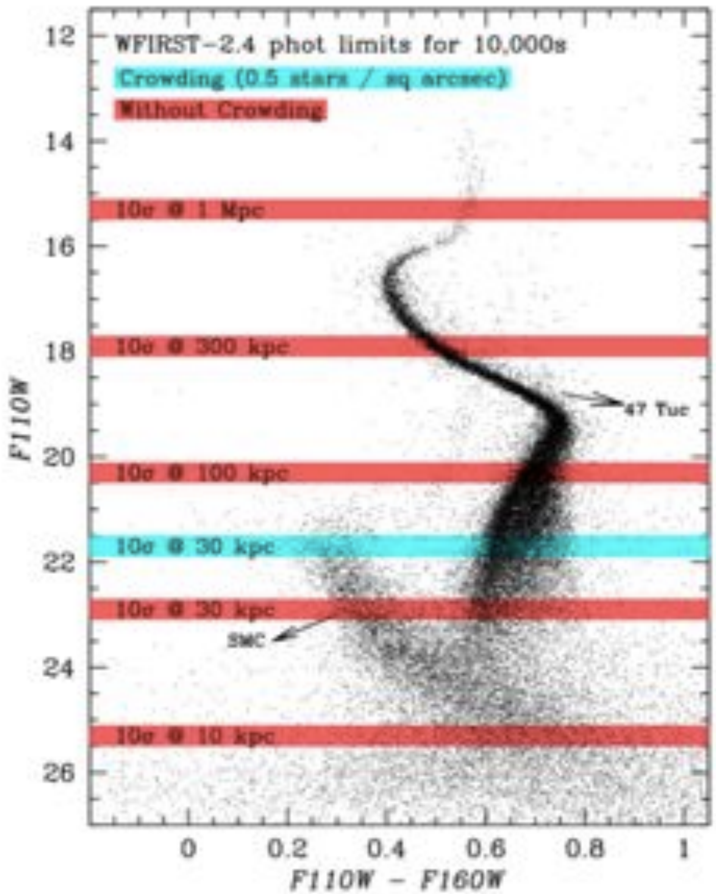


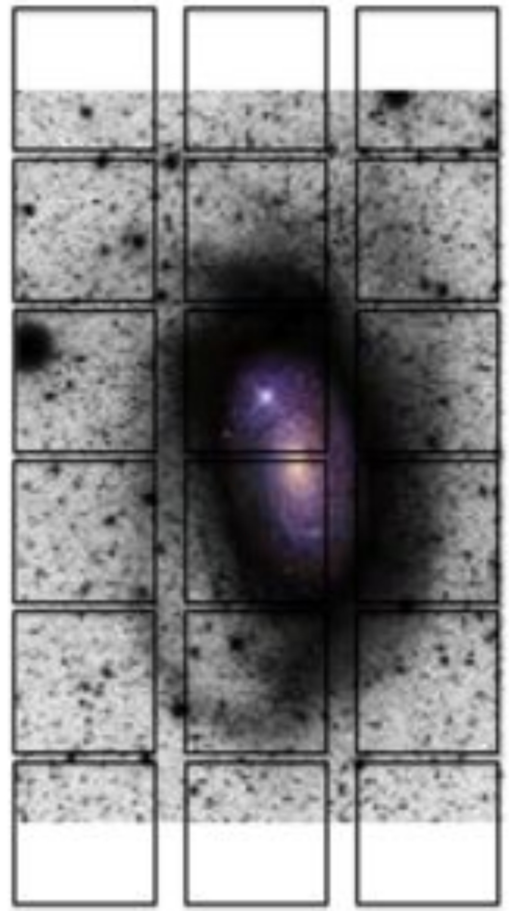
EUCLID: http://sci.esa.int/euclid, Prieto+'12

Which will launch? (recall SNAP and JDEM)

WFIRST and EUCLID

The power of WFIRST-2.4 for GO programs in the Milky Way and local volume.





Spergel+'13

The future's challenge

Great, but here's what's needed:

- *RVs and abundances for each of these stars*

Future instruments
Space-based instruments: SUMMARY

- JWST and WFIRST 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*
- There are no large-grasp systems that take advantage of the low backgrounds of space.
- There are no high- (or even medium) resolution spectrographs.

QUERY:

Why would we build and launch both Euclid and WFIRST?

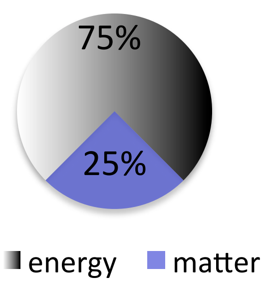
WFIRST is the demonstrably superior facility; it will get the cosmology experiment done in <half the time with room to spare for Guest Observer Programs to study stars & galaxies. *Collaboration would ensure the best science.*

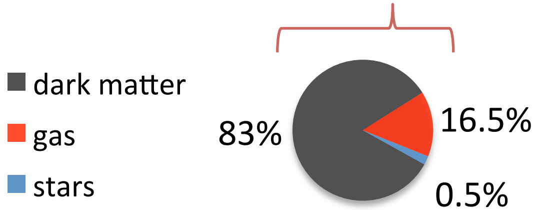
UV IFS

- **Starving in the UV**
  - WSO-UV (170mm space telescope – Hermanutz+’12
    - ISSIS (slitless spectroscopy, 35”x65”, 115-175nm, 185-320nm) - Gomez de Castro+’12
  - FIREBALL – long-duration balloon, 1m telecope
    - Gen1: Fiber IFU (200nm) – Tuttle+’12
    - Gen2: multi-slit
  - + rocket experiments
- **Science question:** WHERE ARE ALL THE BARYONS?

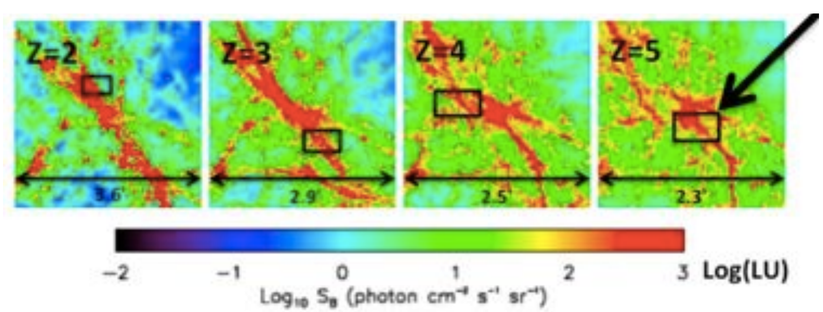
We desperately need FUV and NUV IFU over *wide field* to detect hot gas down to *low z*

e.g., WMAP





Presumably very hot gas in IGM (cosmic web and halos)



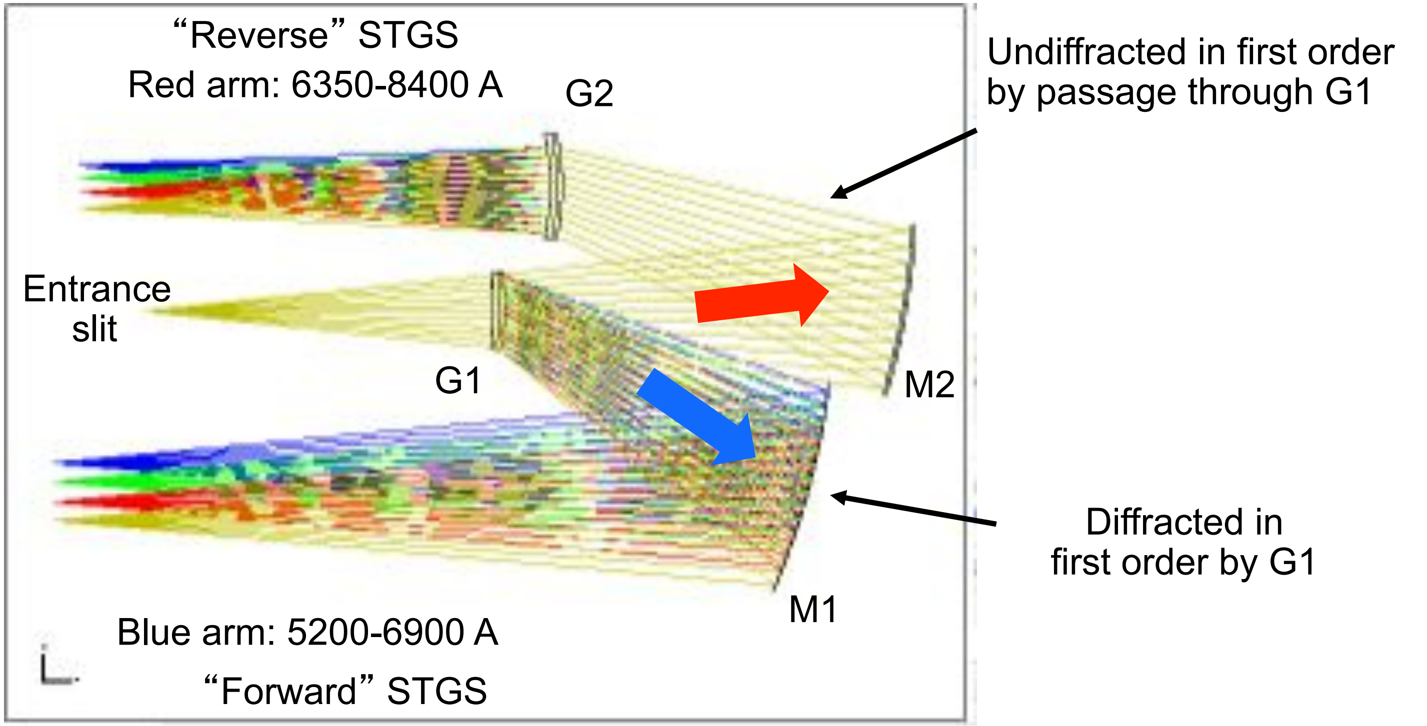
Lyα and OVI doublet (103.2, 103.8nm; primary coolant for T=3e5K near solar gas, Otte+’03)

Futures: New techniques

- Can we break the cost curve?
  - Novel spectrograph design
  - Superconducting detector technology
  - Interferometery (not so new, just forgotten)
    - Fourier transform spectrometers (FTS)
    - Spatial heterodyne spectrometers (SHS)
    - Grating-dispersed Fabry-Perot (FP)
  - Photonics

Spherical Transmission Grating Spectrometer

STGS-type double beam spectrometer



Enabling technology: spherical VPH transmission grating.

- ✓ Compact, few optics and surfaces (efficient, low cost)
- ✓ Excellent image quality (Offner-like aberration cancellation)
- ✓ Light not diffracted in first order by G1 (via M1) passes to G2 (via M2)
- ✓ No dichroic break, maximum efficiency at overlapping wavelengths

Credit: D. O'Donoghue (SALT), C. Clemens (UNC)

Super-conducting detector technology

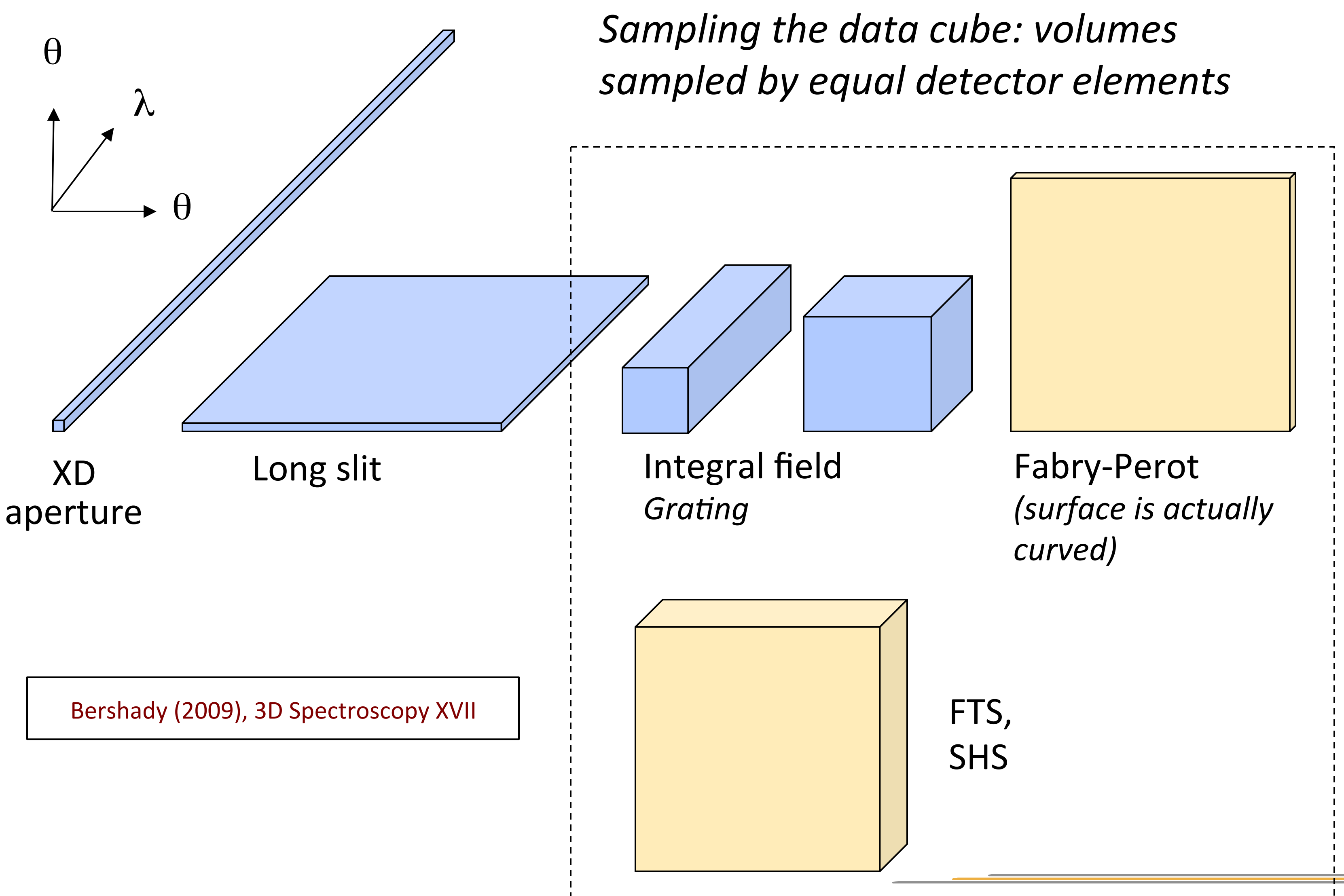
- Microwave Kinetic Inductance Detector (MKID)
  - Up to 10^5 pix, currently 100μm/pix
  - R ~ 50 energy resolution
    - (theoretical limit of R=150)
  - 2μs photon rate/time res.
  - 0.35-1.35μm wavelength sensitivity
- R2 echelle order separator requires R ~ 20

➔ Multi-order echelle with not cross-dispersion

Mazin+'12, O'Brien+'12

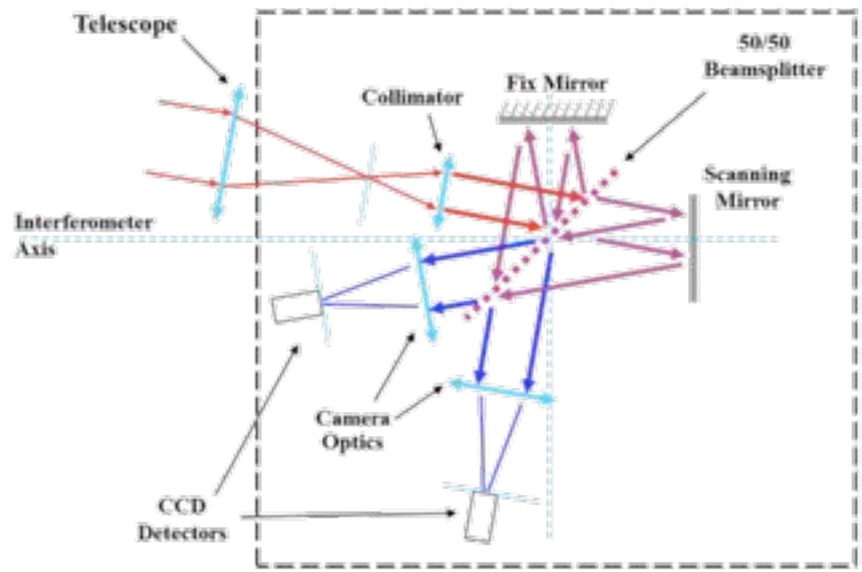
The detector limit: Interferometry

Three into two dimensions revisited



Interferometry: Fourier Transform Spectroscopy

- Spectral resolution does not have 1st order dependence on beam size or entrance aperture
  - + Small instruments
  - - Wavelength multiplex disadvantage



Proof of concept:
SpIOMM, OMM 1.6m: Hα, continuum, kinematics

FUTURE:
SITELLE, CFHT 3.6m
11x11 arcmin,
350-900nm,
1 < R < 10,000

Drissen+'12
Grandmount+'12

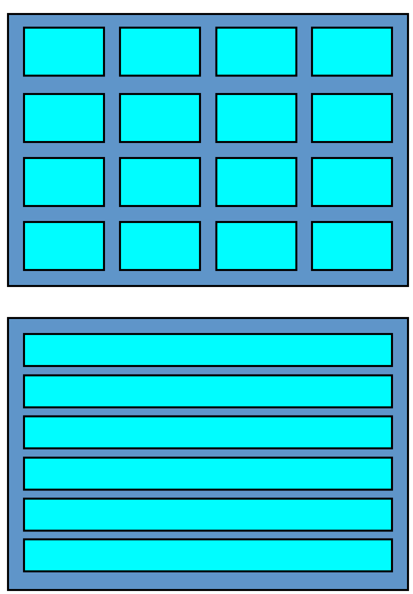
Interferometry: Spatial-heterodyne spectroscopy

Instrument concept: grating-dispersed Michelson, one shot, no scanning.

Pupil, slit or lenslet array can be placed here

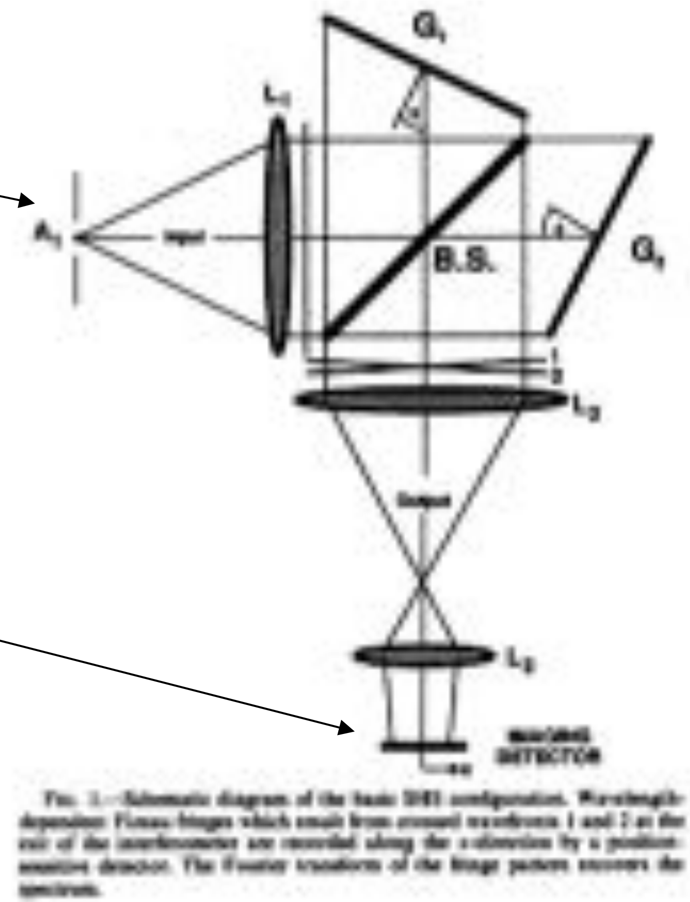
lenslets

slit



spatial or XD

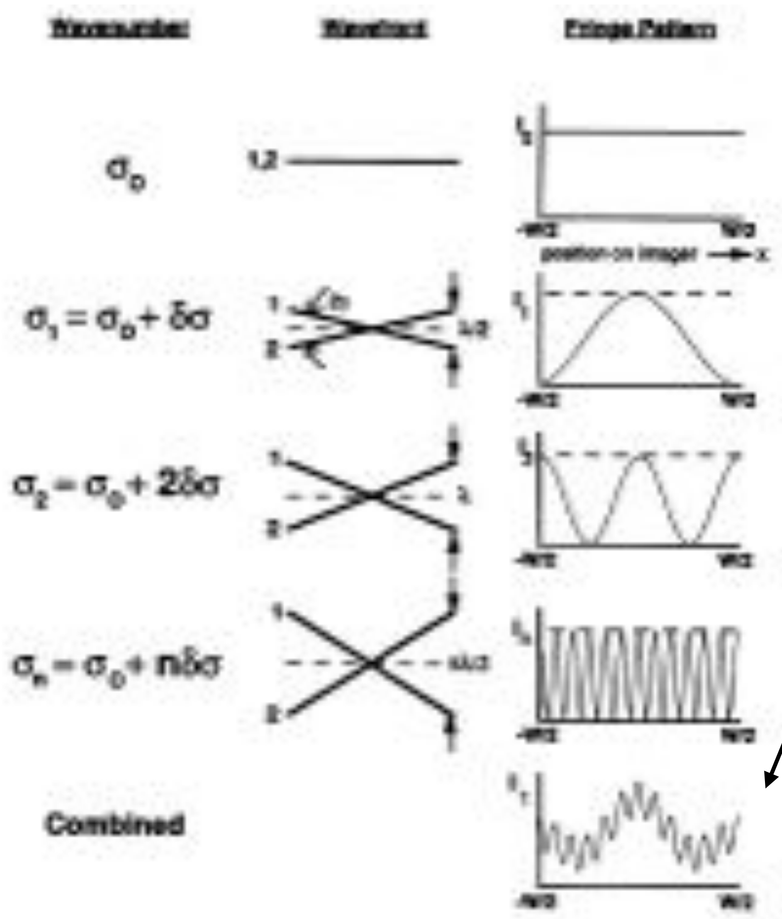
spectral



Harlander et al. ‘92

Interferometry: Spatial-heterodyne spectroscopy

Principles of operation



- Gratings diffract light at wavelength-dependent angles.
- Wavefronts produce interference patterns with frequencies set by wavelength.

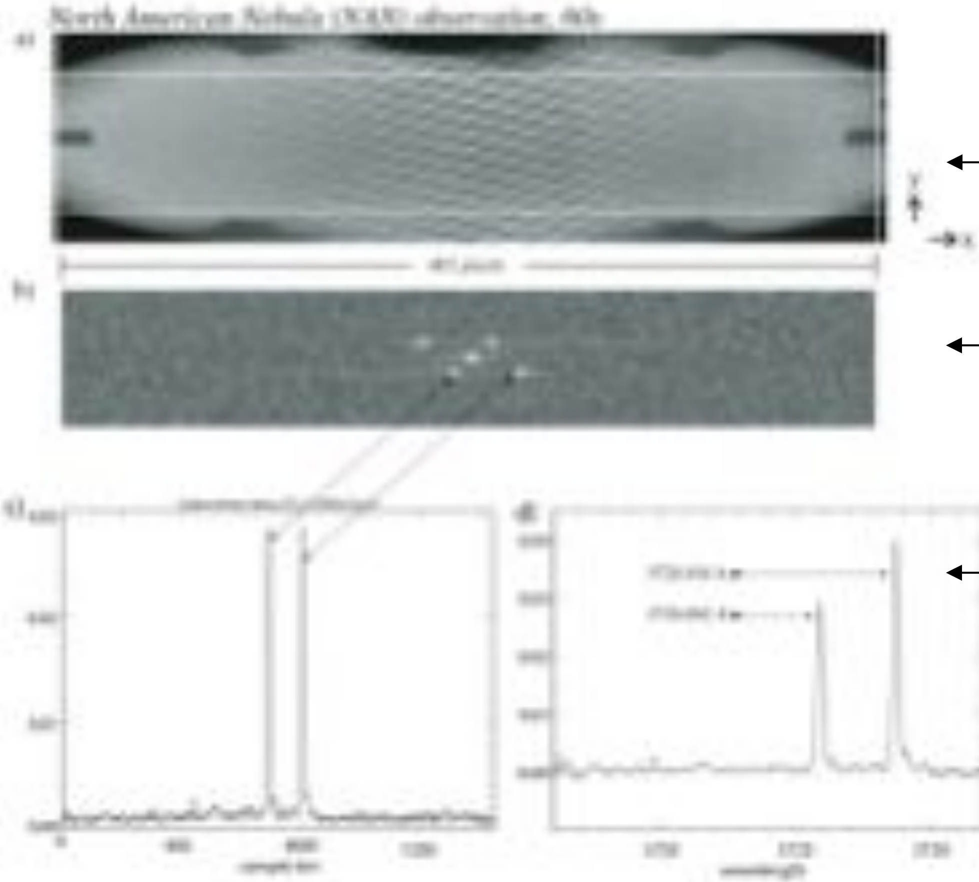
- *Resolution* is set by the grating aperture diameter.
- *Bandwidth* is set by the length of the detector (how many frequencies can be sampled depends on the number of pixels)

The signal is heterodyned about the frequency of the central wavelength.

Harlander et al. ‘92

Interferometry: Spatial-heterodyne spectroscopy

[OII] SHS interferogram from south-west Wisconsin…



[OII]3727 interferogram
with cross-dispersion
via grating tilt

FT power spectrum

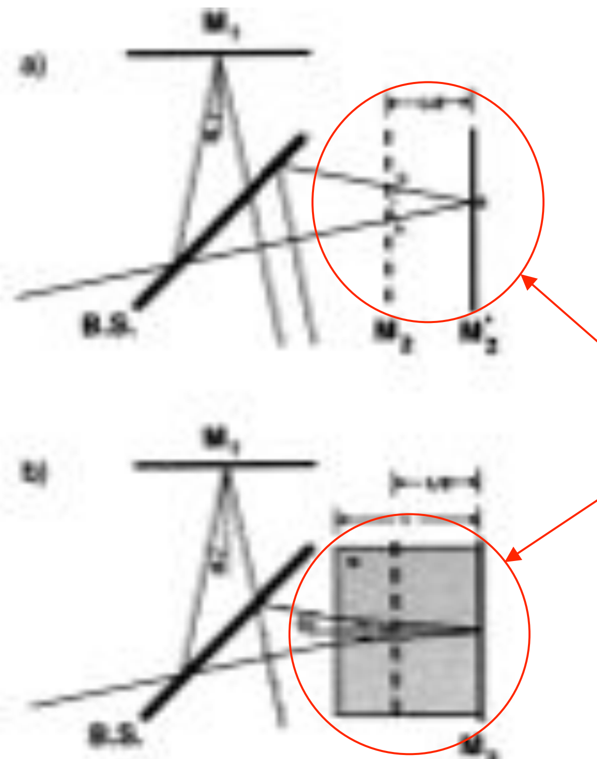
Wavelength calibrated,
filter-corrected [OII] spectrum

…resulting [OII] spectrum

PBO SHS data courtesy
Harlander, Roesler, and Reynolds

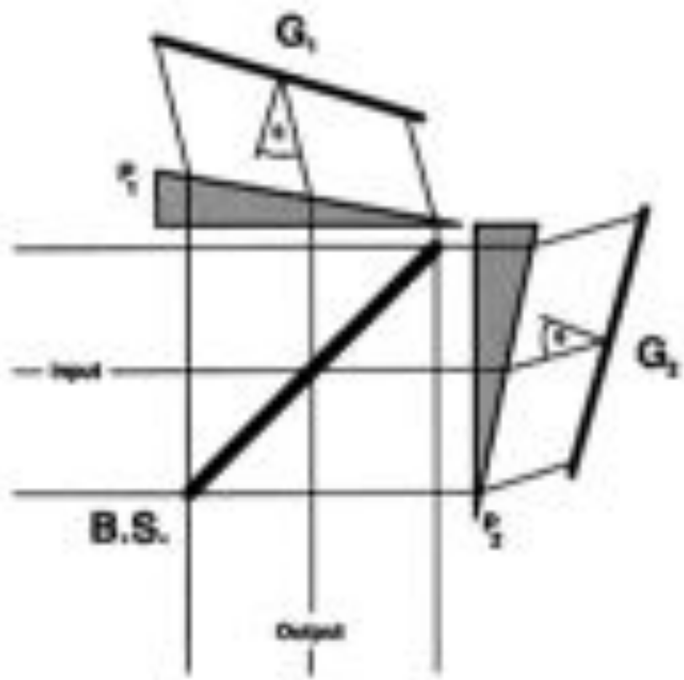
Interferometry: Spatial-heterodyne spectroscopy

Field-widened Michelson



compare

Field-widened SHS

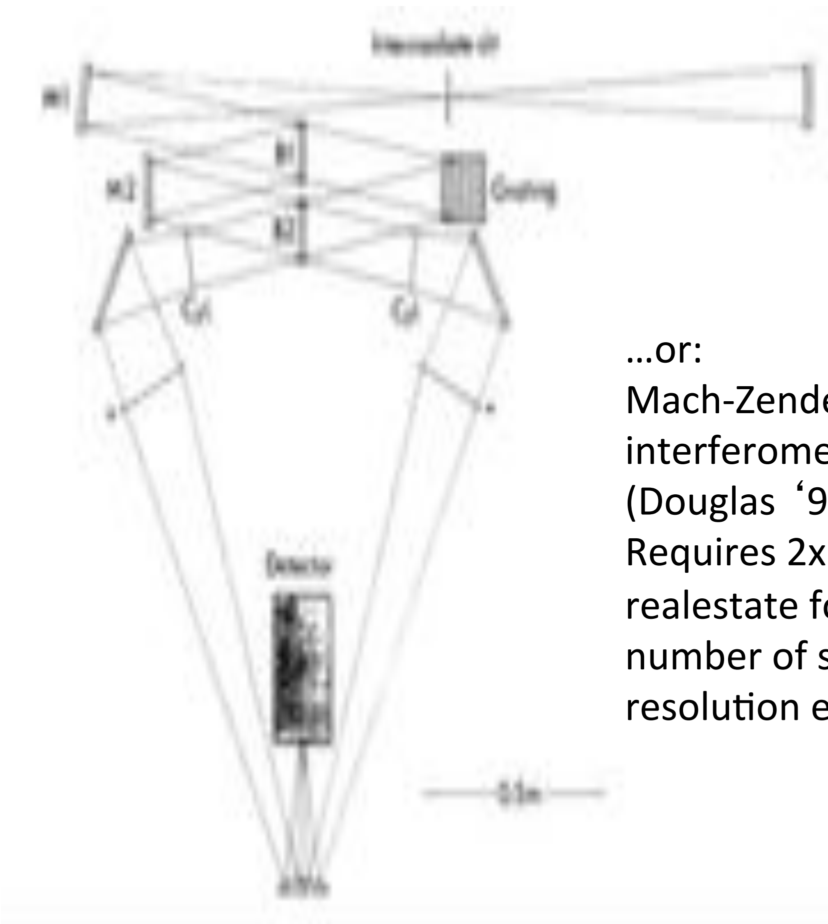


Prisms give gratings geometric appearance of being perpendicular to the optical axis.

Harlander et al. '92

Interferometry: Spatial-heterodyne spectroscopy

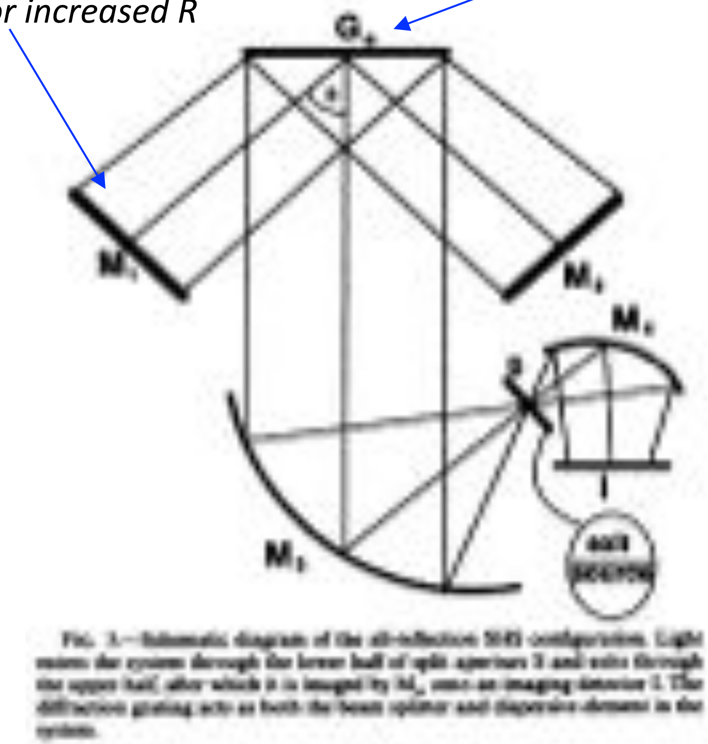
Standard Michelson and SHS lose half the light right from the start, but efficient configurations do exist:



…or:
Mach-Zender style interferometer (Douglas '90).
Requires 2x detector realestate for same number of spectral resolution elements.

Add prisms for field-widening or gratings for increased R

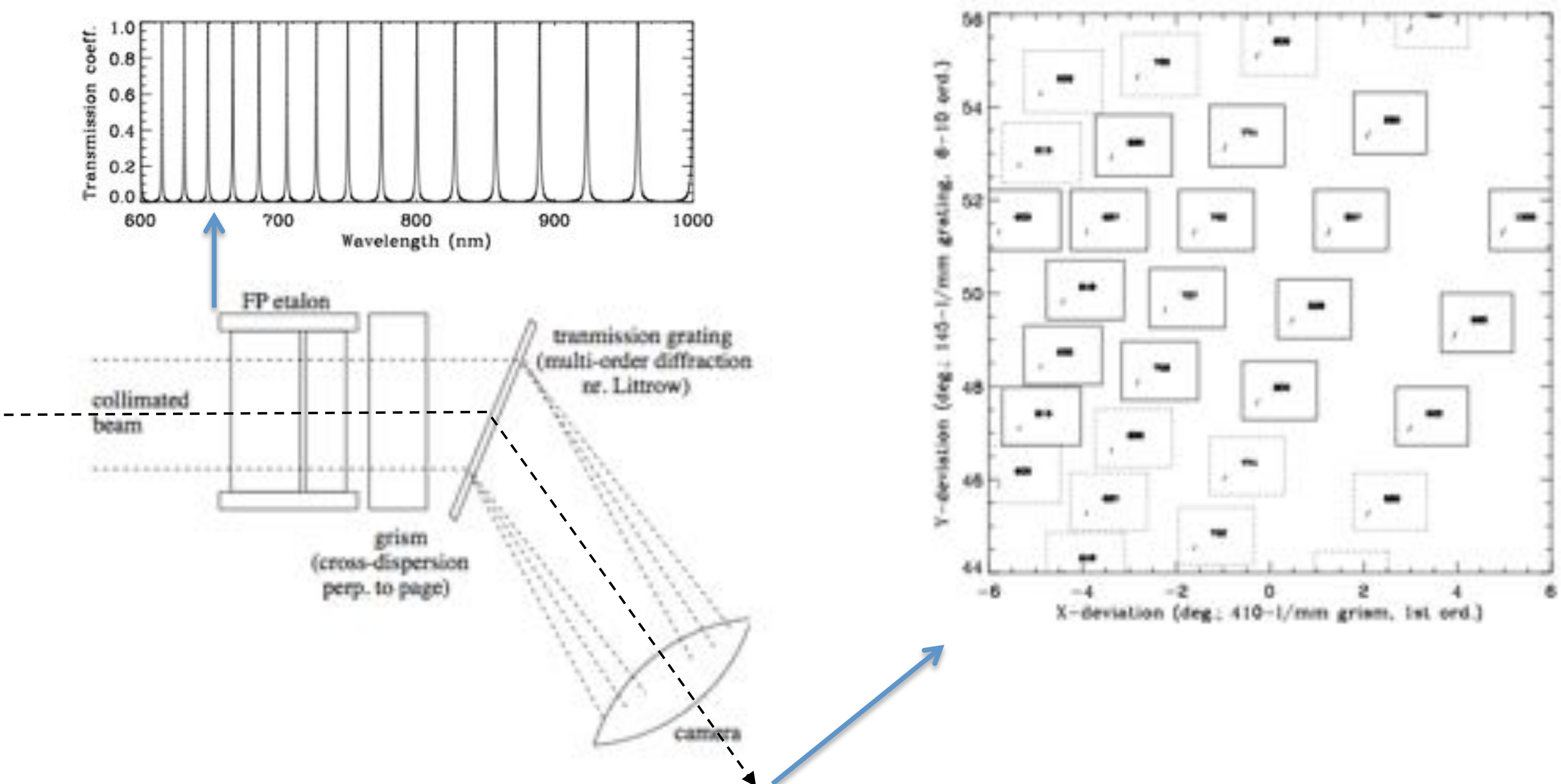
Perfect application for holographic grating



Harlander et al. '92

Interferometry: grating-dispersed Fabry-Perot

Fabry-Perot orders are dispersed and cross-dispersed to form multiple monochromatic images of field within Jaquinot spot ("bull's eye") on CCD detector:

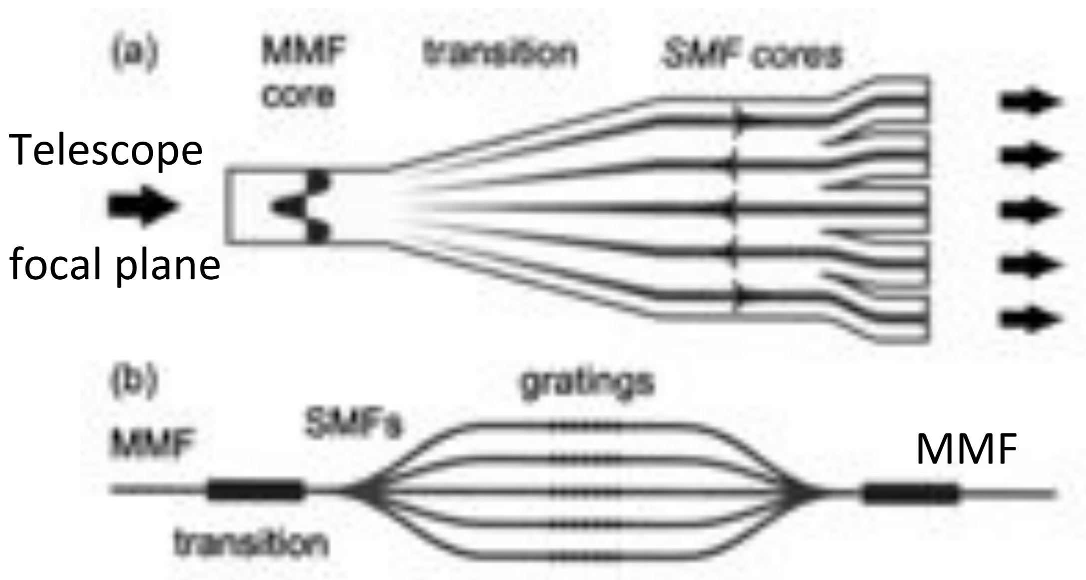


Baldry & Bland-Hawthorn'00

Photonics

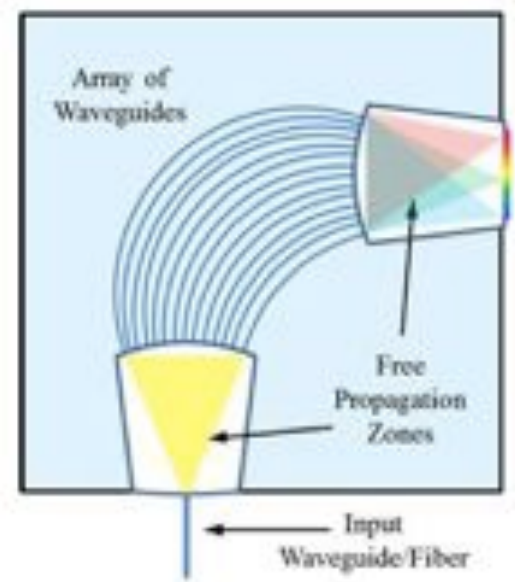
Photonic lanterns: convert conventional multi-mode fiber (MMF) to *many* singe-mode fibers (SMF). SMF's behave like diffraction-limited spectrograph apertures ➔ small spectrographs.

Leon-Saval+'05



Index-modulation in SMF leads to aperiodic Bragg gratings that can be used for **OH suppression**.

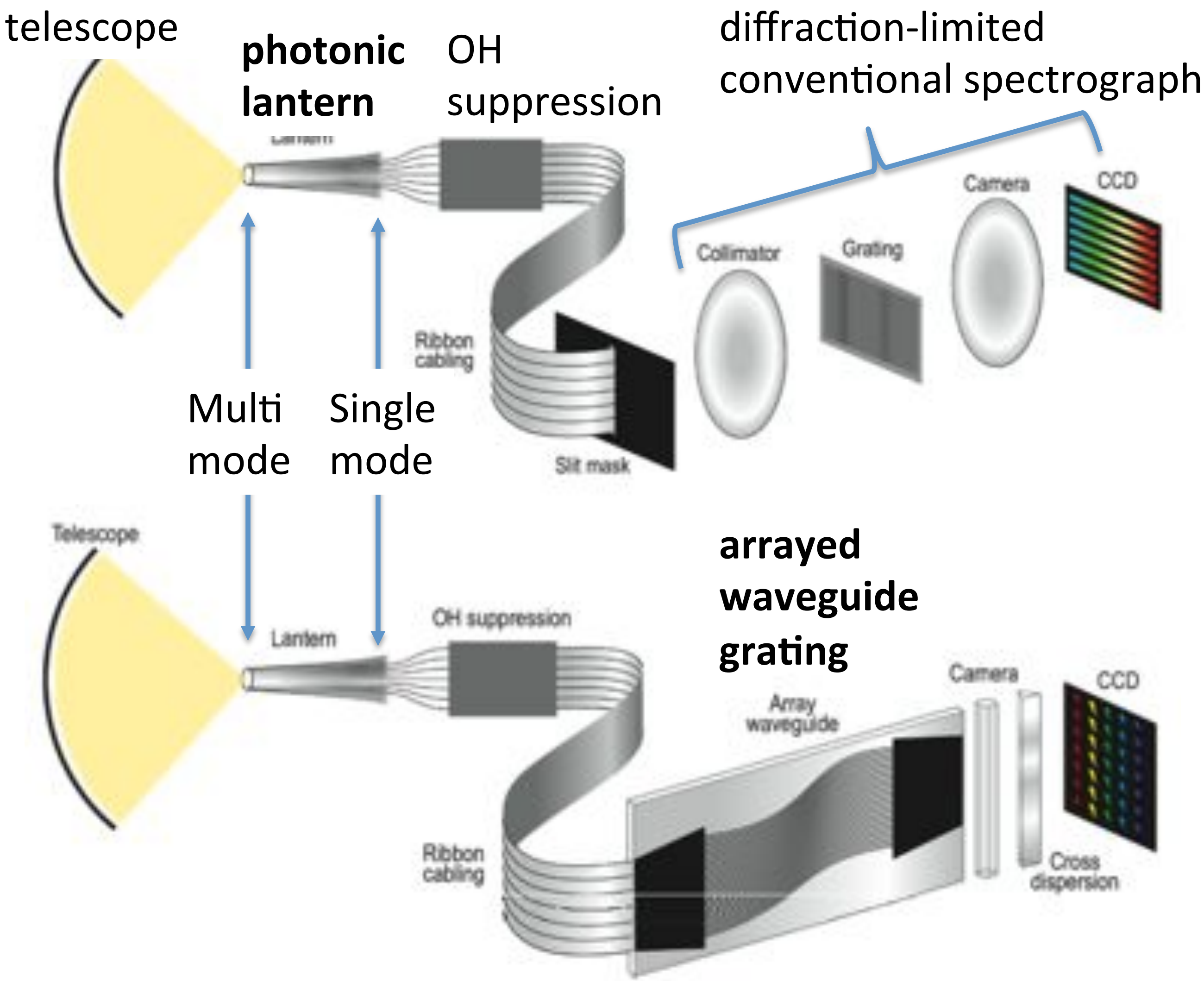
See Trinh+'13 (GNOSIS)



Arrayed wave guide acts as a grating working in high order (small free spectral range)

Cvetojevic+'12

Photonics



1 multi-mode fiber yields 8 $[(D/\lambda)\ NA]^2 + 1$ single-mode fibers, where D is the MMF fiber core diameter and NA is its numerical aperture.

PIMMS: Bland-Hawthorn+'10

Beyond the nation state

- Estimated participants

EU	122	Excluding UK; 33 ESO – 438M
UK	19	Including Scotland – 64M
US	19	Including California – 318M
AU	14	23M
JP	7	127M

  - *NB: proximity effects*
  - Most-represented countries contain 13% of 7.2G world population
  - Few each from Brazil, Canada, Chile, China, India, Iran, Mexico, Russia
- Huge potential, changing landscape
  - Open access journals, including instrumentation

Summary

- **Observations**:
  - New instruments add spectral resolution & elements.
  - Best 10m-class instruments appear more ambitious than some 30m-class instruments; E-ELT's instruments are suitably ambitious.
  - ALMA well-matched to 30m-class instruments; SKA requires wide-field multi-object IFS on smaller (4-10m) telescopes.
- **Challenges**:
  - UV IFS: needed to detect the missing baryons.
  - Wide-field space/AO IFS: needed to measure RVs & abundances for giants *en masse* in galaxies outside the Local Group.
- **Recommendations**:
  - Don't build a spectrograph unless it has more than one channel. Build at least a few of them.
  - Implement emerging technology; exploit interferometric spectroscopy to break the cost-curve.
  - Provide open access to all journals including instrumentation.