The **Local Volume Mapper** in SDSS-V:

Connecting Stellar Feedback with the ISM in the Milky Way and Local Group

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SDSS-V Panoptic Spectroscopy Surveys

panoptic: adj. presenting a comprehensive or panoramic view of the whole

(Near-)identical set-ups in ***two*** hemispheres -> all-sky

- *Black Hole Mapper* (>400,000 targets & monitoring) **(BHM)**
  - QSO reverberation & changing-look QSOs
  - eRosita (X-ray survey) 1st-pass follow-up
- Milky Way Mapper (>6,000,000 targets & multi-epoch) **(MWM)**
  - Galactic genesis
  - Stellar Astrophysics
  - Spectral complement to Kepler, Gaia, TESS
- Local Volume Mapper (>25,000,000 spectra & >3000 sqdeg) **(LVM)**
  - Ultra-wide field IFU spectroscopy with 6”-37” spaxels and 1800-fiber bundles
  - focus on the ISM

Kollmeier+2017

Director: Juna Kollmeier

Project Scientist: Hans-Walter Rix

What is LVM?

- LVM is an optical **integral-field spectroscopic** survey of the **Milky Way** and the **Local Group (LMC/SMC/M31/M33)**

- The LVM is the first IFU survey of complete galactic systems to **isolate and resolve** distinct environments within galaxies (operations planned for 2020-2025)

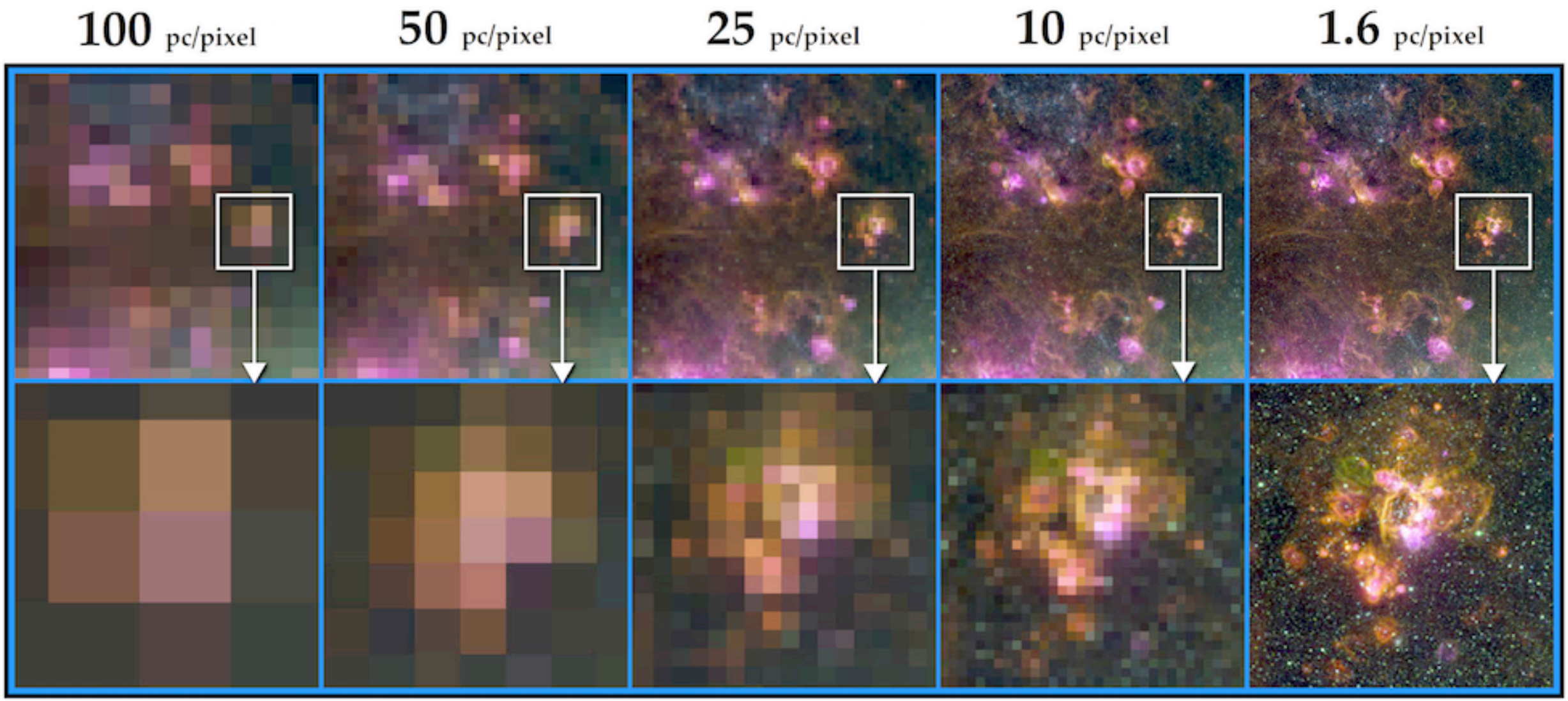
- LVM is the first IFU survey to cover significant fractions of the night sky, **~1 sterad**

Why LVM?

- The ISM regulates the baryon cycle, from star formation to feedback
- This requires data spanning a large dynamic range in size:
    - < 1 pc scale of individual sources
    - to clusters and clouds (10-50 pc)
    - to kpc scales of in/outflows, galactic fountains, winds, and disk dynamics
- We need to map these multi-scale processes across galactic scales
- We aim to resolve individual sources of feedback in the Local Group

Spatially sampling the ISM

At resolutions of better than 25 pc, the filamentary structure of the ISM is starting to be resolved



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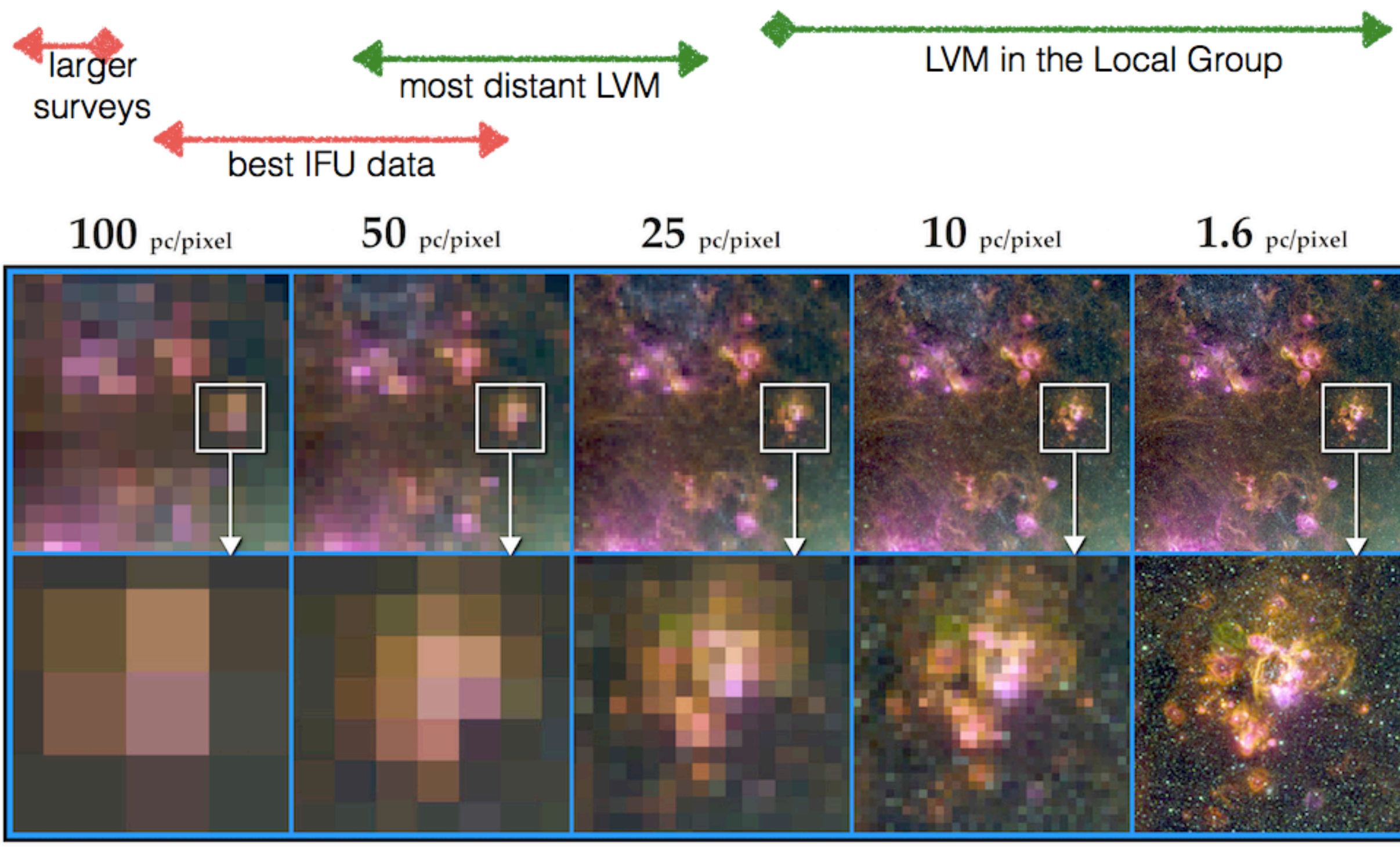

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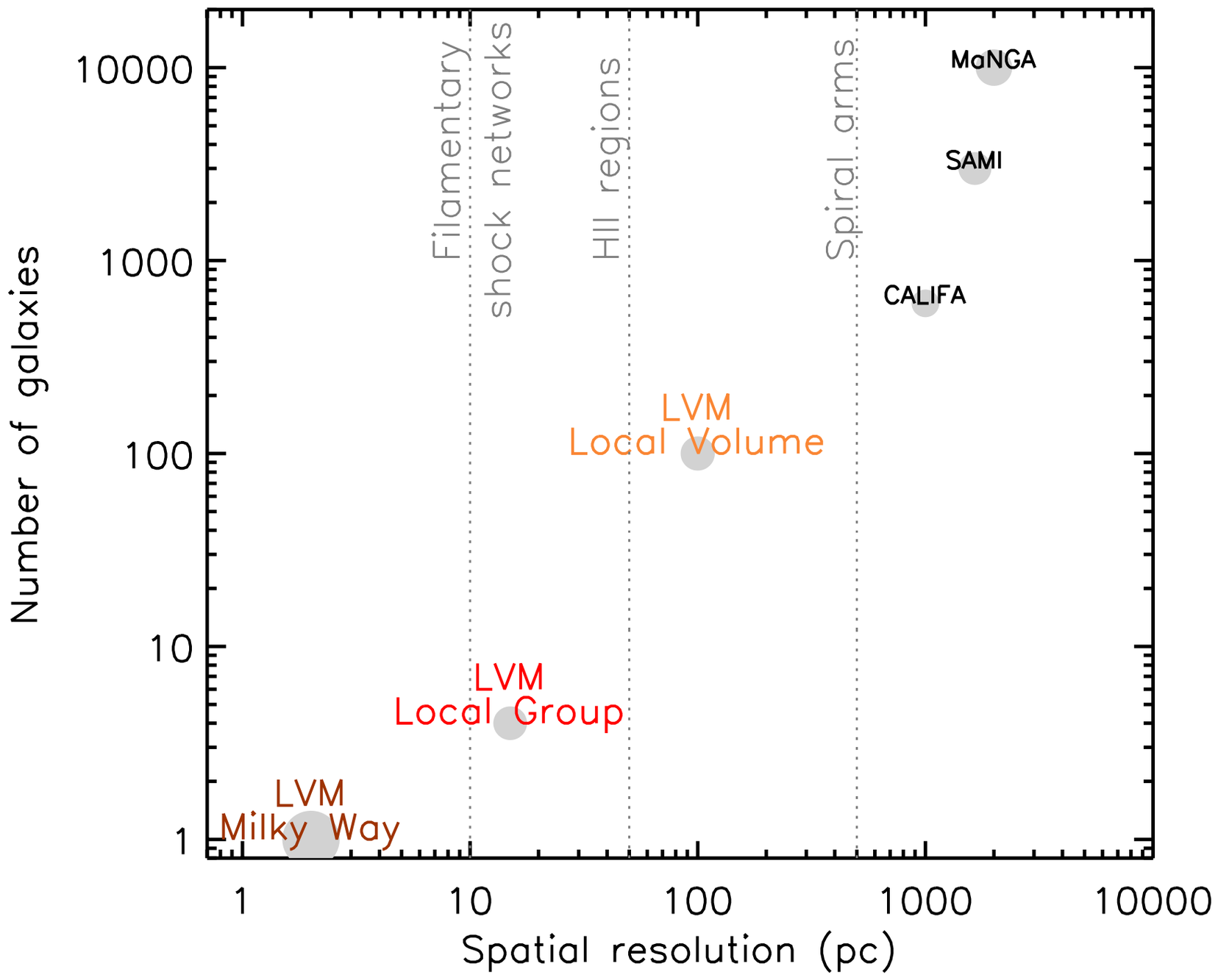


How LVM?

- At fixed f-ratio (fibers!), conservation of AΩ implies that the telescope aperture sets nothing but the plate scale

- Choose **telescope aperture** to give **desired spatial sampling** at a given target **distance**

  - 1 pc in Milky Way requires ~30” spaxels
  - 10 pc in LMC, SMC require ~30” spaxels

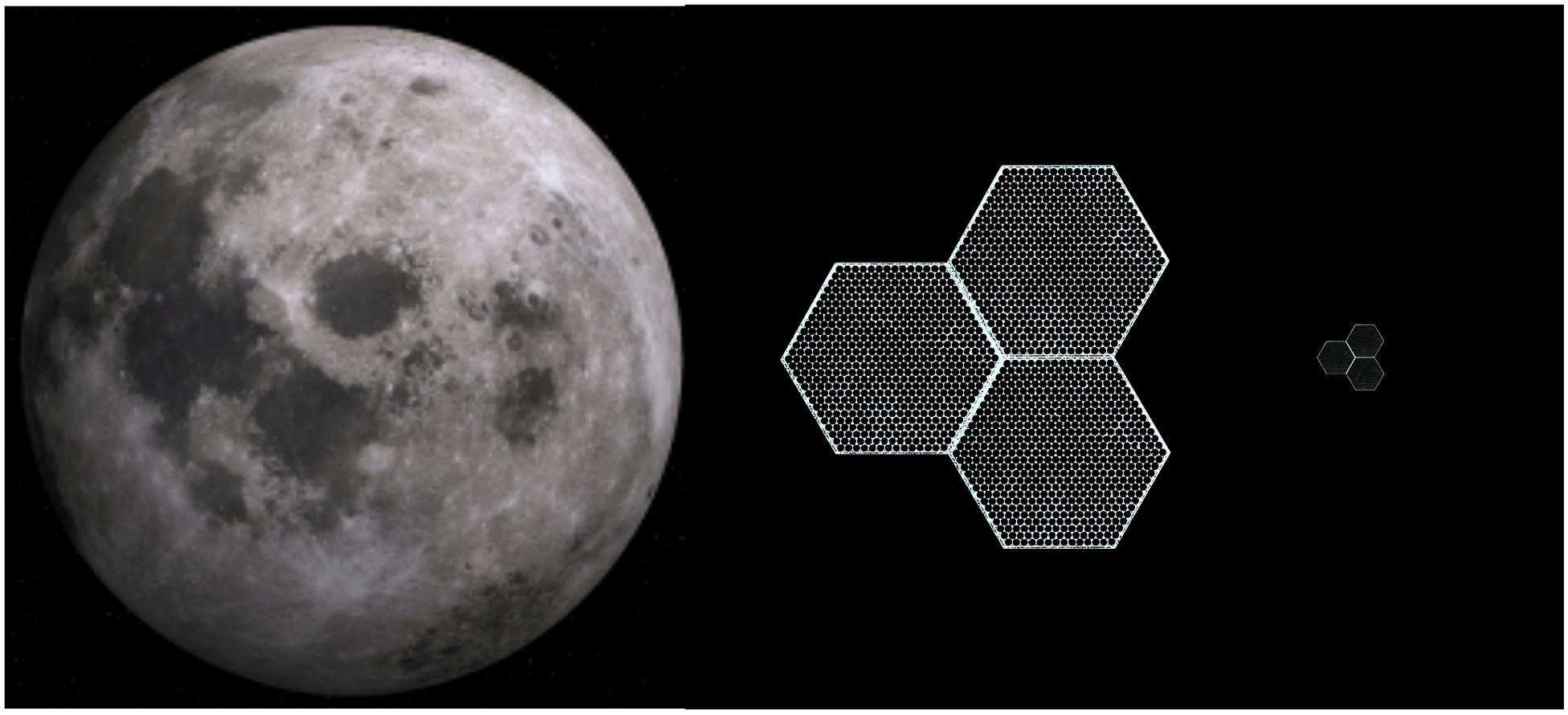
  → 16cm

  - ~20 pc in M31/M33 require ~6” spaxels

  → 1m

Big IFUs

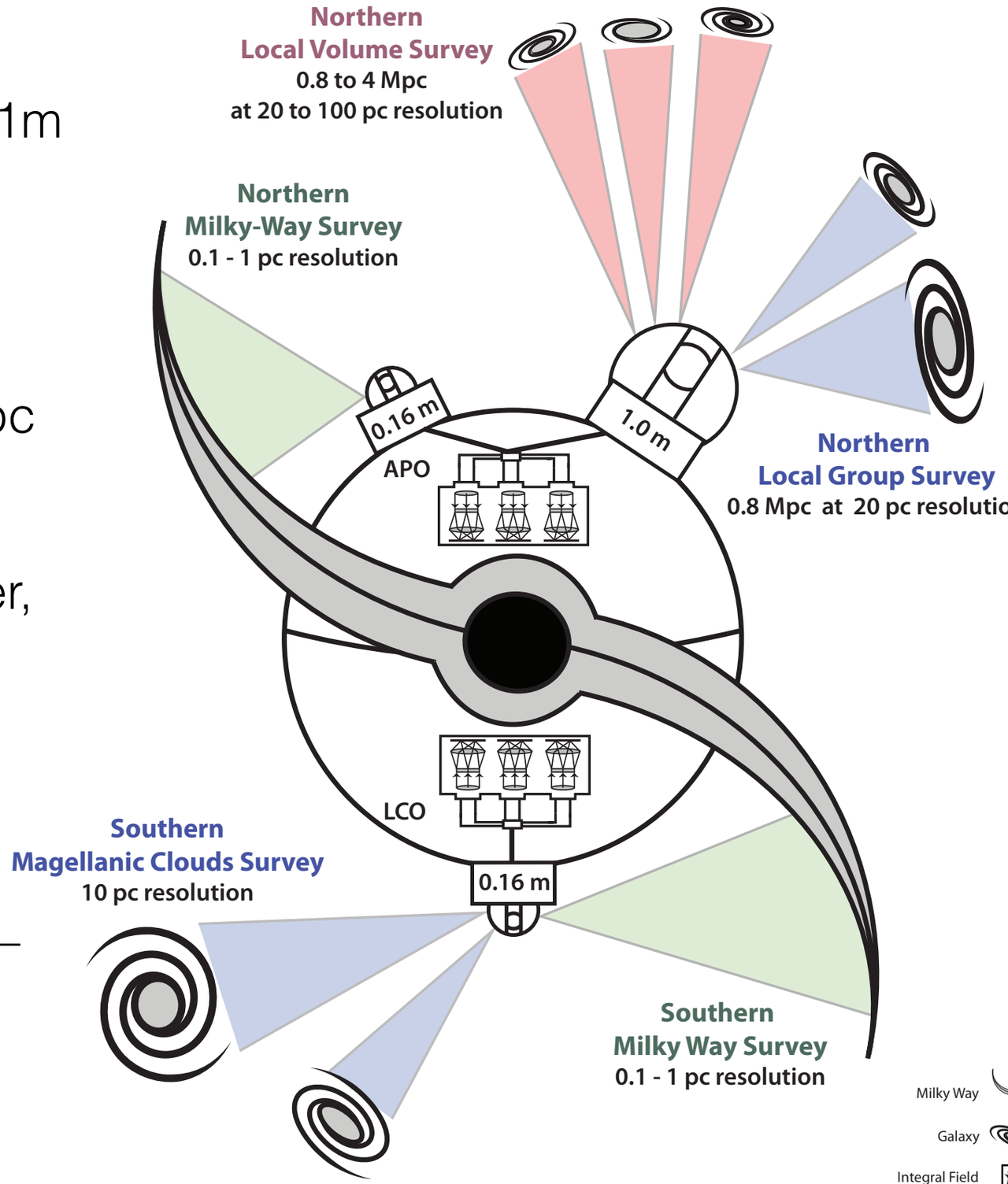
- 490 arcmin^2 @ 0.16 m
- 12 arcmin^2 @ 1 m



LVM Overview

Using 2 telescope sizes of 16cm and 1m and an array of IFU-coupled spectrographs at *R*~4000 and 3600-10000Å, we survey

- ~3000 sq. deg. in the **MW** @ 0.1-1 pc resolution,
- ~300 sq. deg. in the **MW** 10x deeper,
- **LMC & SMC** @ 10 pc resolution,
- **M31 & M33** @ 20 pc resolution,
- **nearby galaxies** (D≲4-8 Mpc) @ 50–100 pc resolution



Now is the time
to join the team
and influence
what LVM will be!

LVM Spectroscopy

- LVM spectroscopy spans **3600–9800Å at R~4000** (~2500 blue – 5000 red, ~30 km/s)
- Cover both strong lines and weak auroral lines
  - [O II]3727,3729, Hß, [O II]4959,5007, [NII]6549,6583, Hα, [S II]6717,6731, [S III]9069,9532, Paschen-8
  - [S II]4068,4076, [O III]4363, [N II]5755, [S III]6312, [OII]7320,7330
- Detect the stellar continuum
- Stable, bench-mounted and environmentally controlled instrument
- High-quality ~5% flux calibration (see MaNGA; Yan+2016)
- Uniform data with maximum coverage
- Wide applicability to gas and stars

Emission Line Science

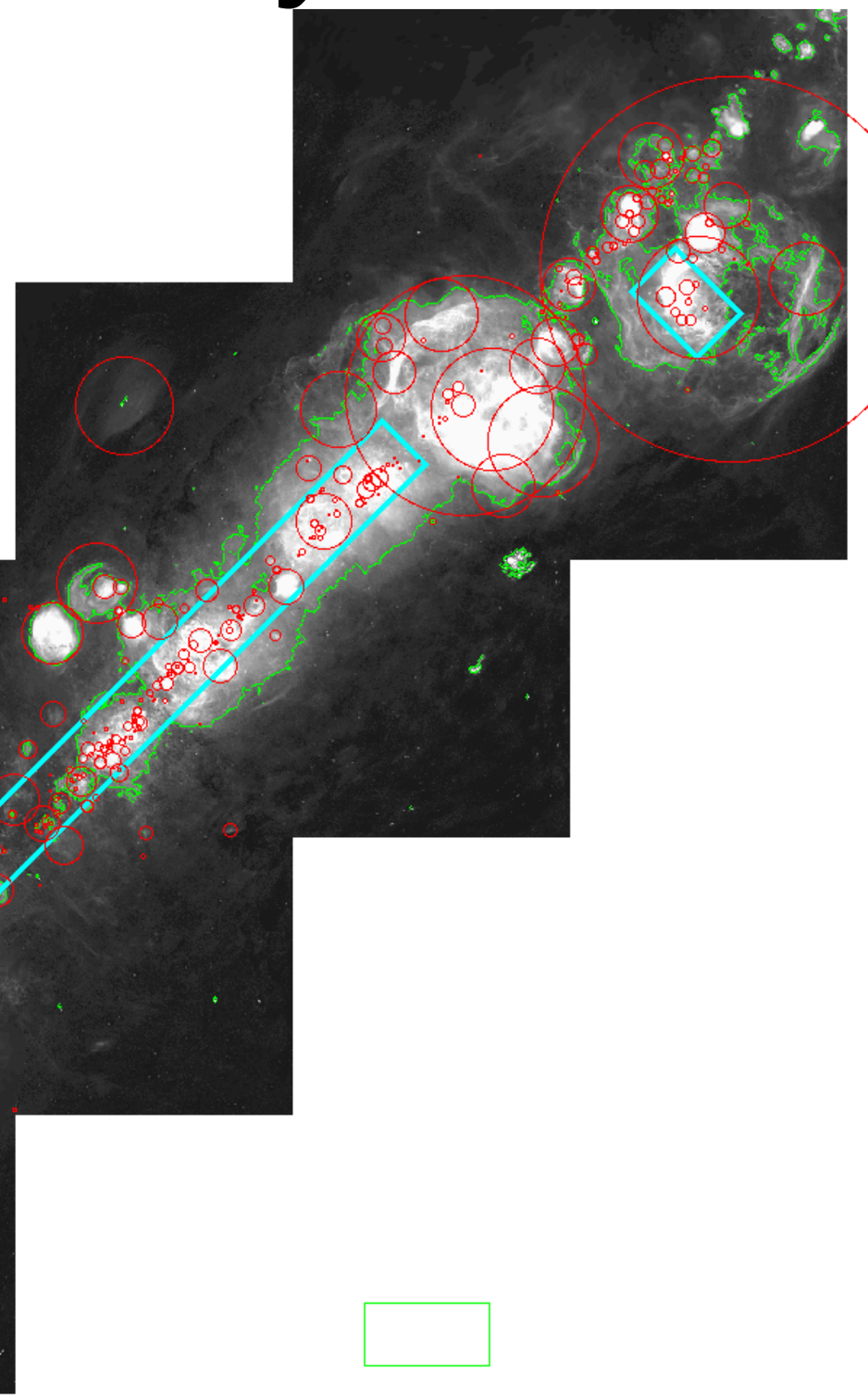
- HII regions
- Diffuse ionized gas
- Supernova Remnants
- Planetary Nebulae
- WR stars

LVM & ancillary data

- LVM will tie into and make use of wide range of ancillary data from the X-ray to the radio. A few examples:
  - The Galactic Plane: **atomic** (e.g. THOR, Beuther+2016), **molecular** (e.g. Dame+2001) dust (GLIMPSE, Churchwell+2009; Hi-GAL, Molinari+2016; ATLASGAL, Schuller+2009) angular resolutions similar to LVM or better
  - M31 & M33 have been covered in the **NIR–IR** by Spitzer, Hershel SAGE (Meixner+2006; Gordon+2011), HERITAGE (Meixner+2010) and HELGA (Fritz+2012)
  - M31 CARMA (**CO**) at 20 pc (Shruba+), 10 pc by Leroy+; VLA (**HI**) Koch+, Rosolowsky+
  - eROSITA will reveal ALL **X-ray** binaries in the LMC, SMC
  - PHAT, APOGEE, GAIA, … **stellar spectroscopy and imaging**
- The combination of stellar, cold & warm gas and dust data offers a unique window into star-ISM interactions (SF + feedback)

LVM MW Survey

- MW: ~3000 square degrees
- All strong lines >6x10^{-17}
- Auroral lines in brighter regions
- HII regions D<10 kpc



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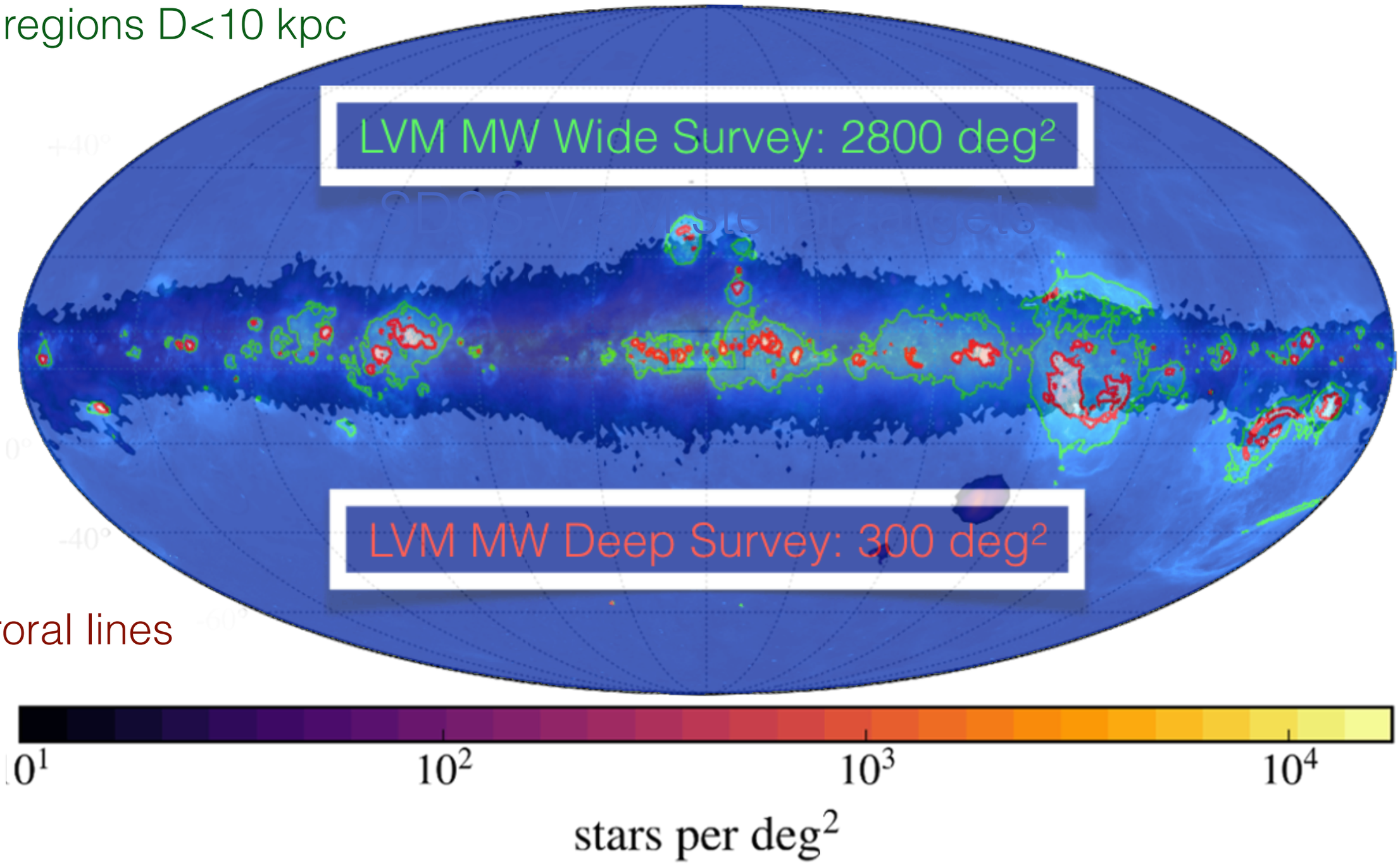
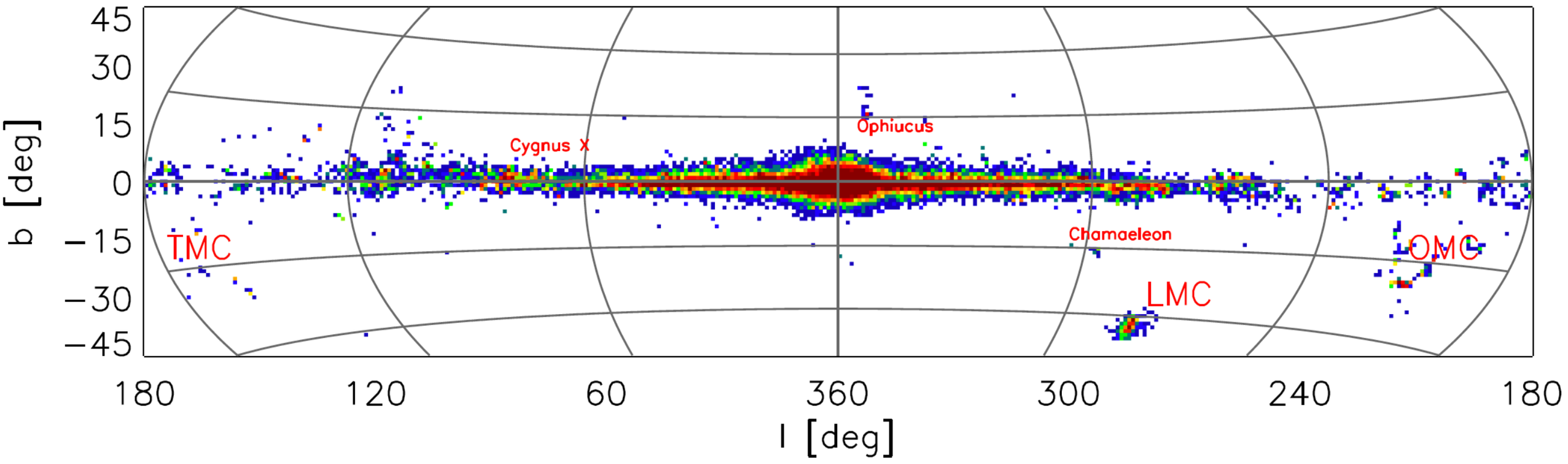


- Auroral lines

Synergy with SDSSV-Milky Way Mapper (MWM)



Mapping ~100,000 young stars across our Galaxy
“all” YSOs and M>8M* with H<11
>2 epochs

Orion

- M42 0.07 pc / spaxel
- APOGEE stars (yellow)
- Combine information from gas and stars to map the interaction between stars and ISM
- Have Teff, L, Z, [X/H], f_{uv}, (age) for each star
- Gas: temperature, density, kinematics, abundances

Images: ESO 2.2m

NGC 3576

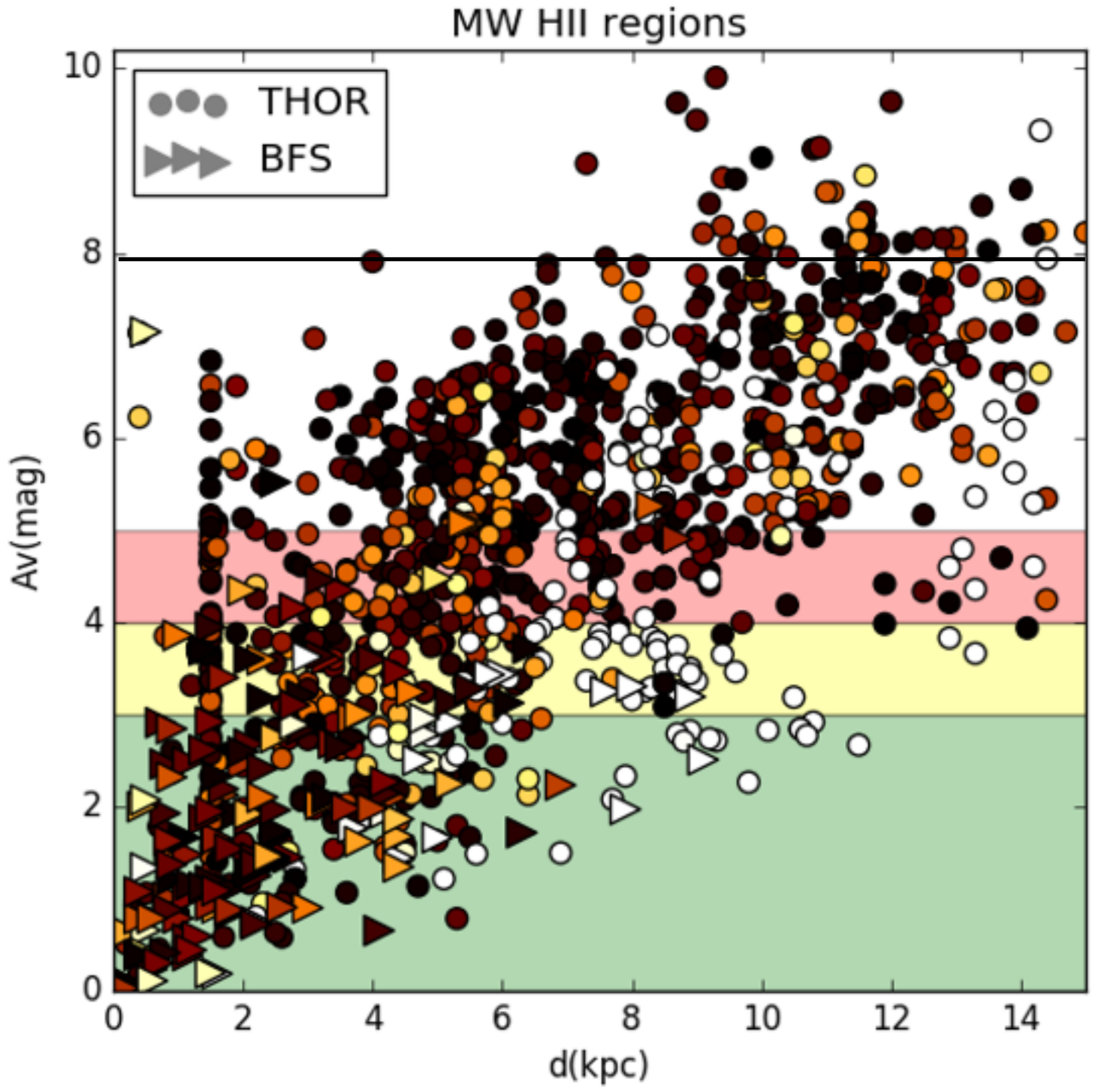
- NGC 3576 in Carina
- 0.5 pc / spaxel

Images: ESO 2.2m

LVM MW Survey

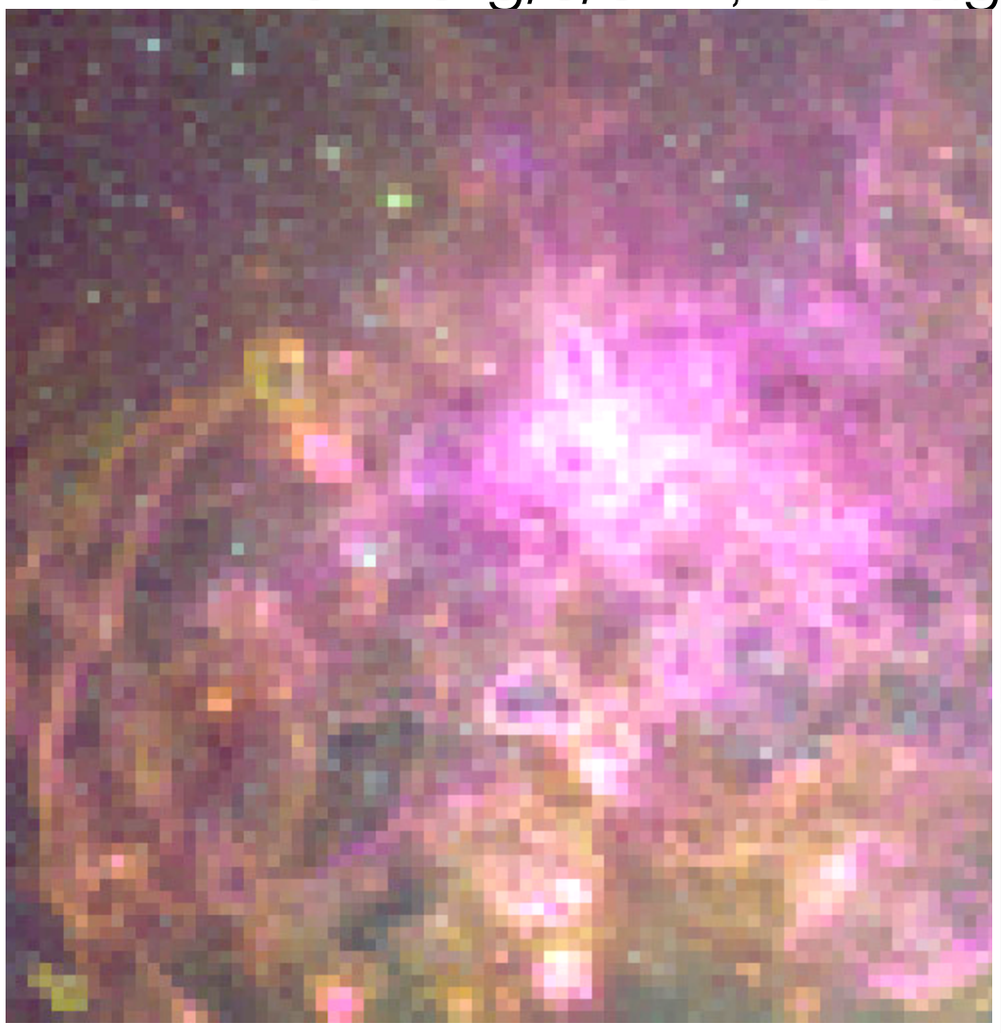
- Effectively dust-limited in distance to ≤ 3kpc by Hb (A_V~3-5)

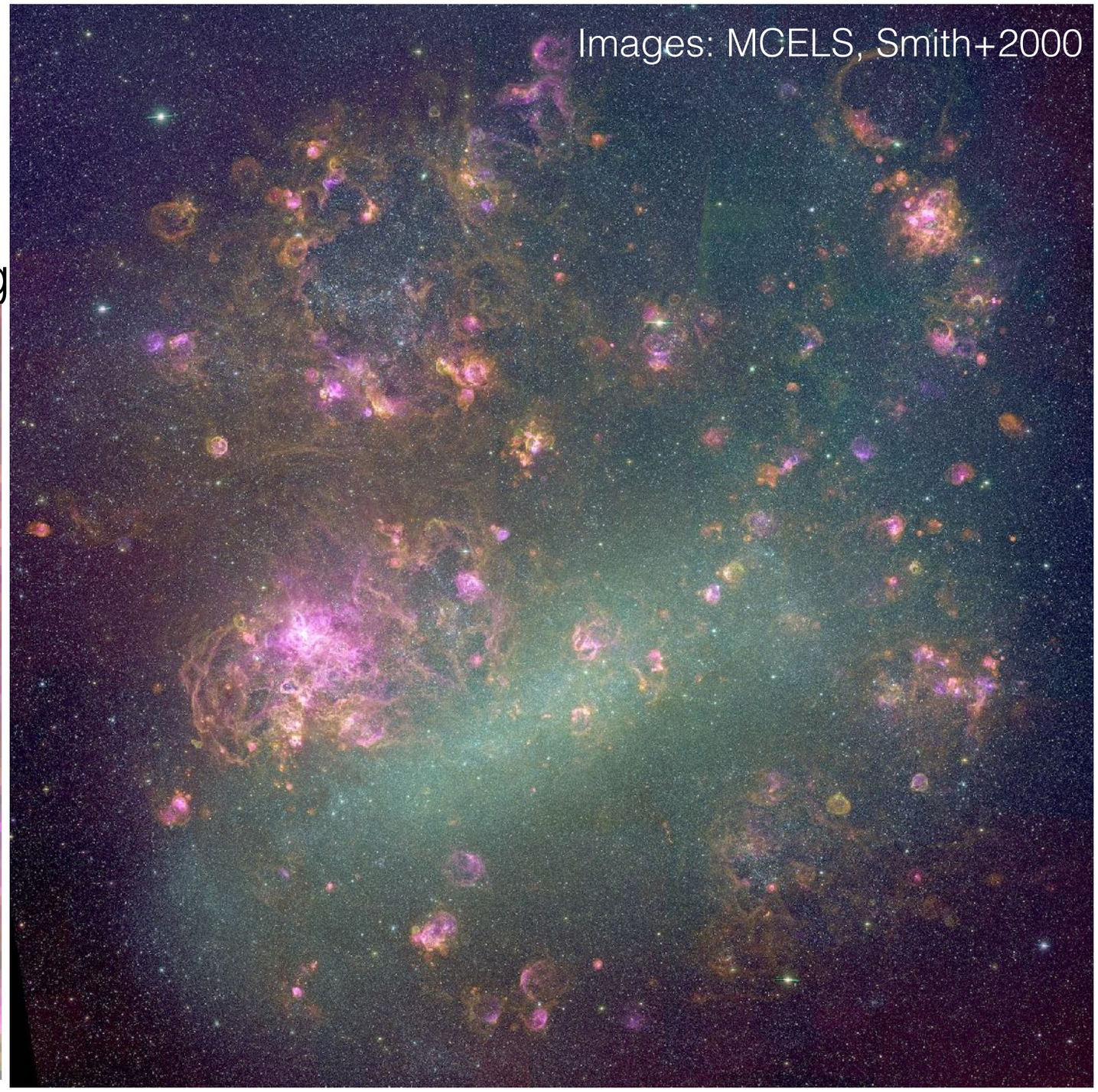
- IR Paschen lines (e.g. P8 9546A) open up distances up to 10 kpc (A_V~6-8)



LVM LMC/SMC Survey

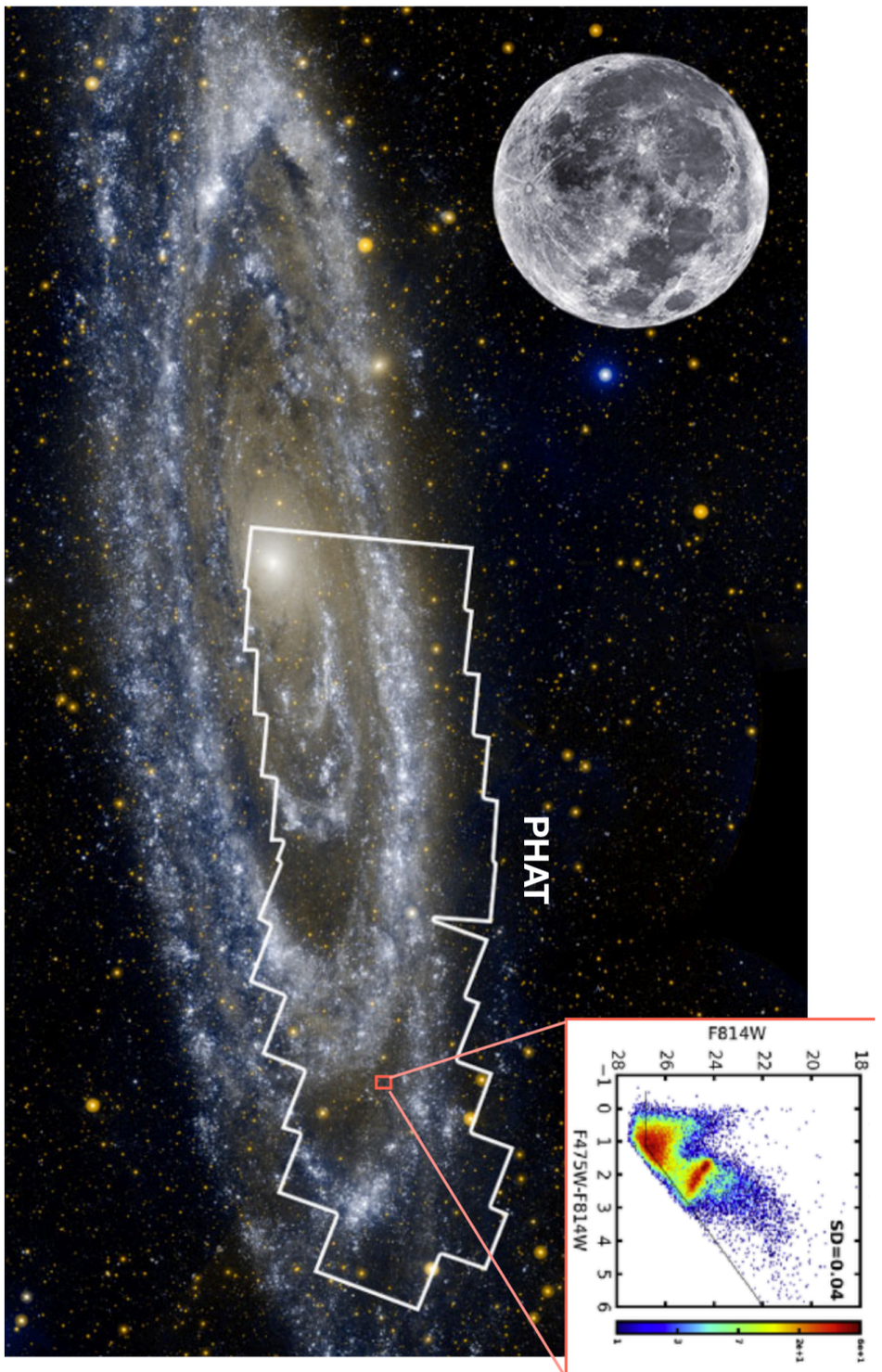
- LMC @ 10 pc / spaxel
- 10^6 resolution elements
- Every pixel in image will have a spectrum!
- < 2×10^{-18} erg/s/cm^2, 23 mag



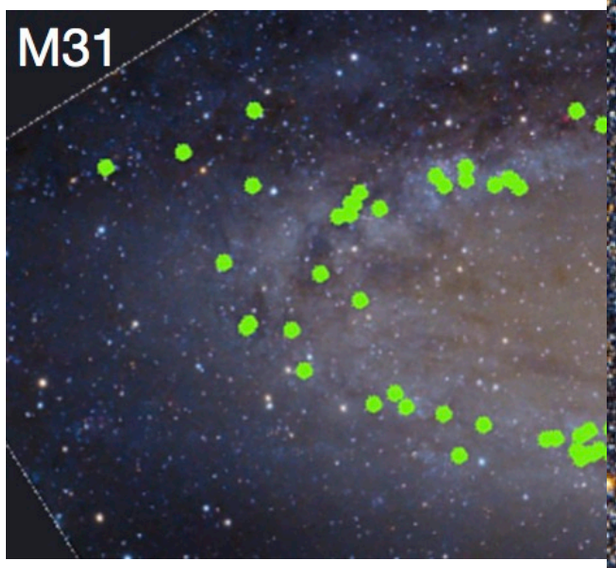


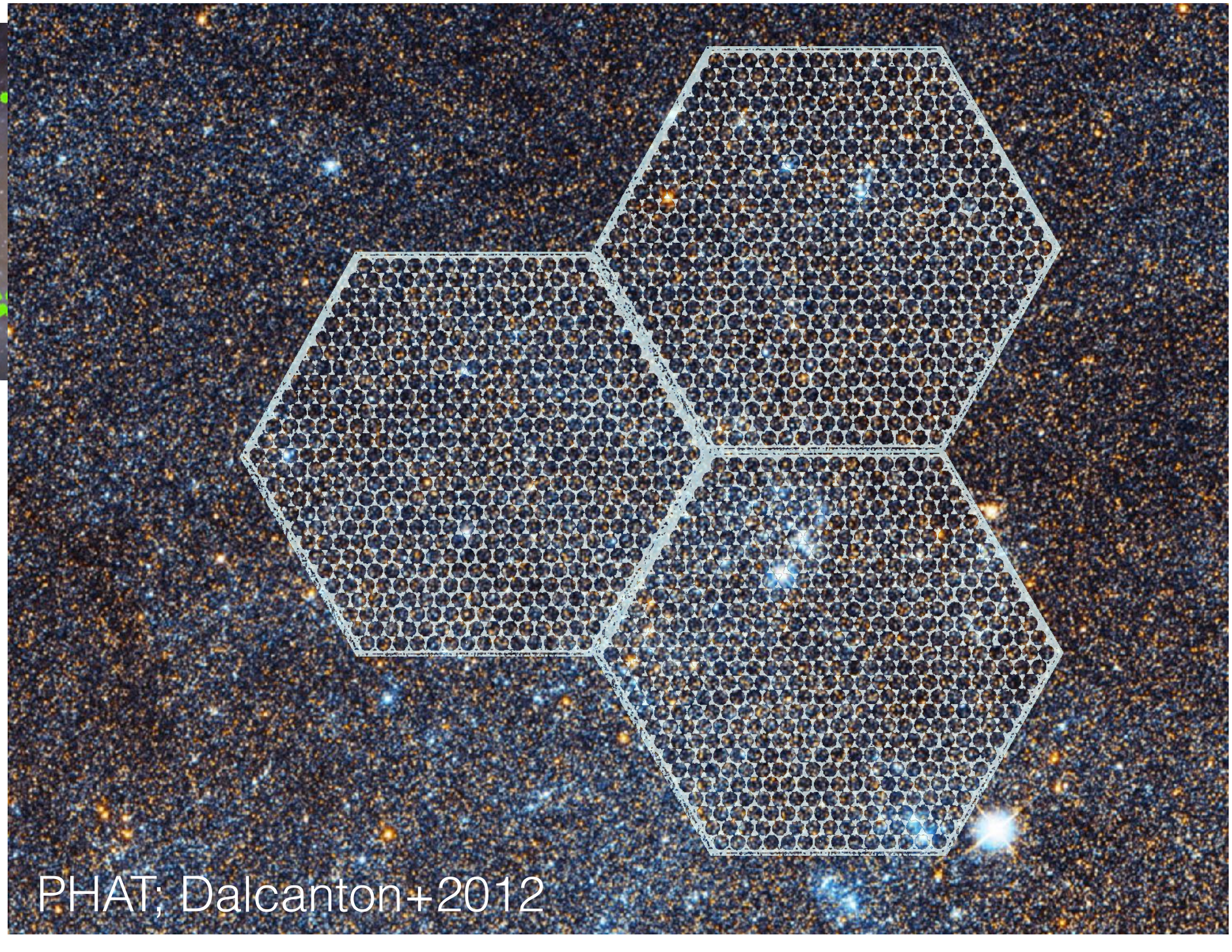
LVM M31/M33 Survey

- M31/M33: At least the regions coverd by HST/PHAT, likely more
- All strong lines
- Auroral lines in brighter regions
- < $2x10^{-18}$ erg/s/cm^2
- Continuum to 23 mag/arcsec^2
- HST CMDs

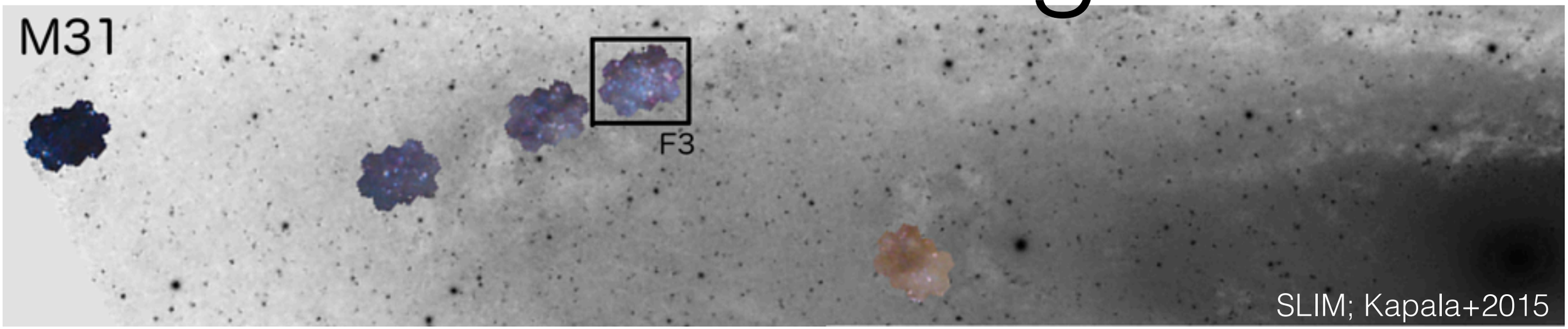


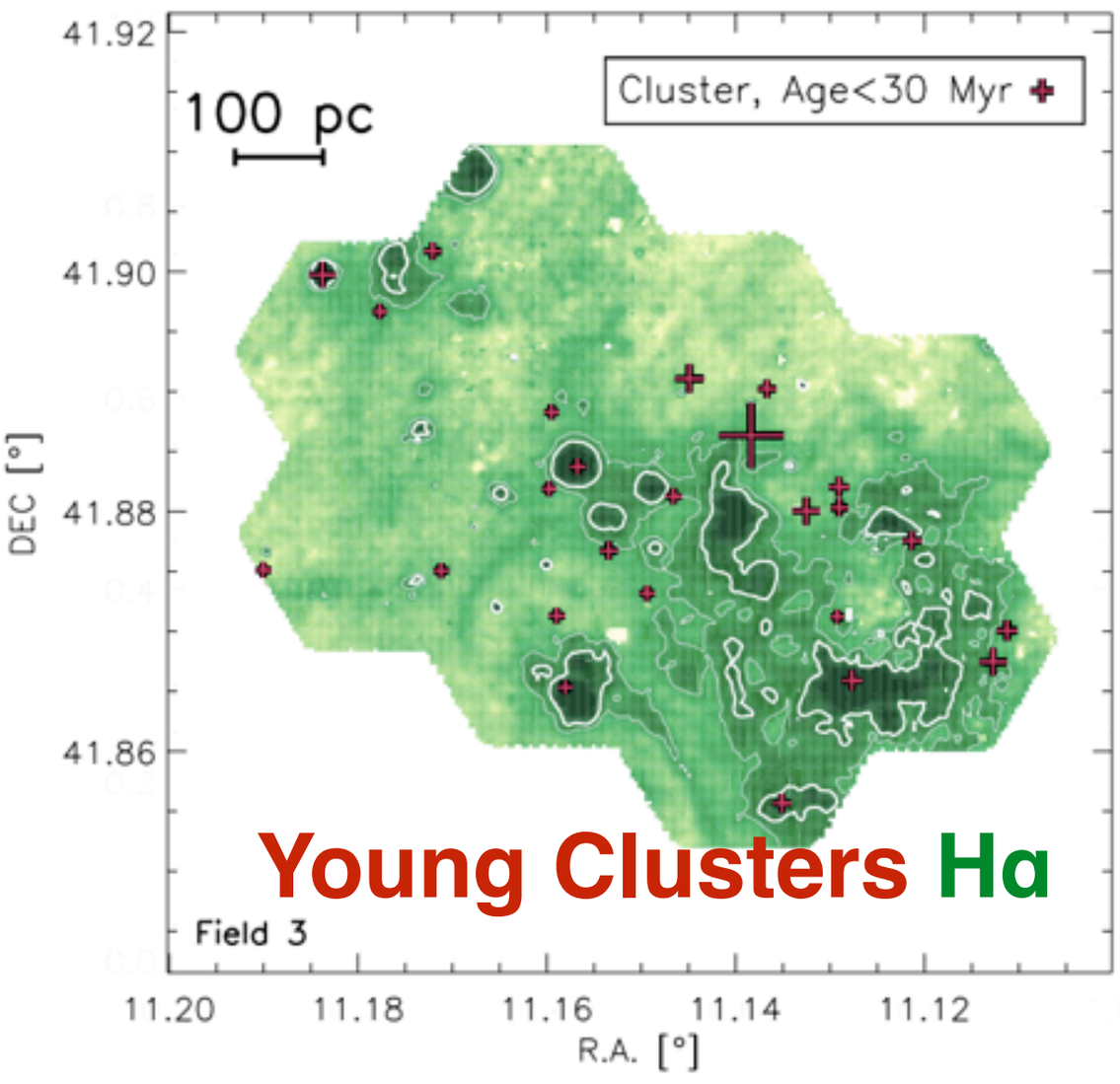
LVM M31 Survey

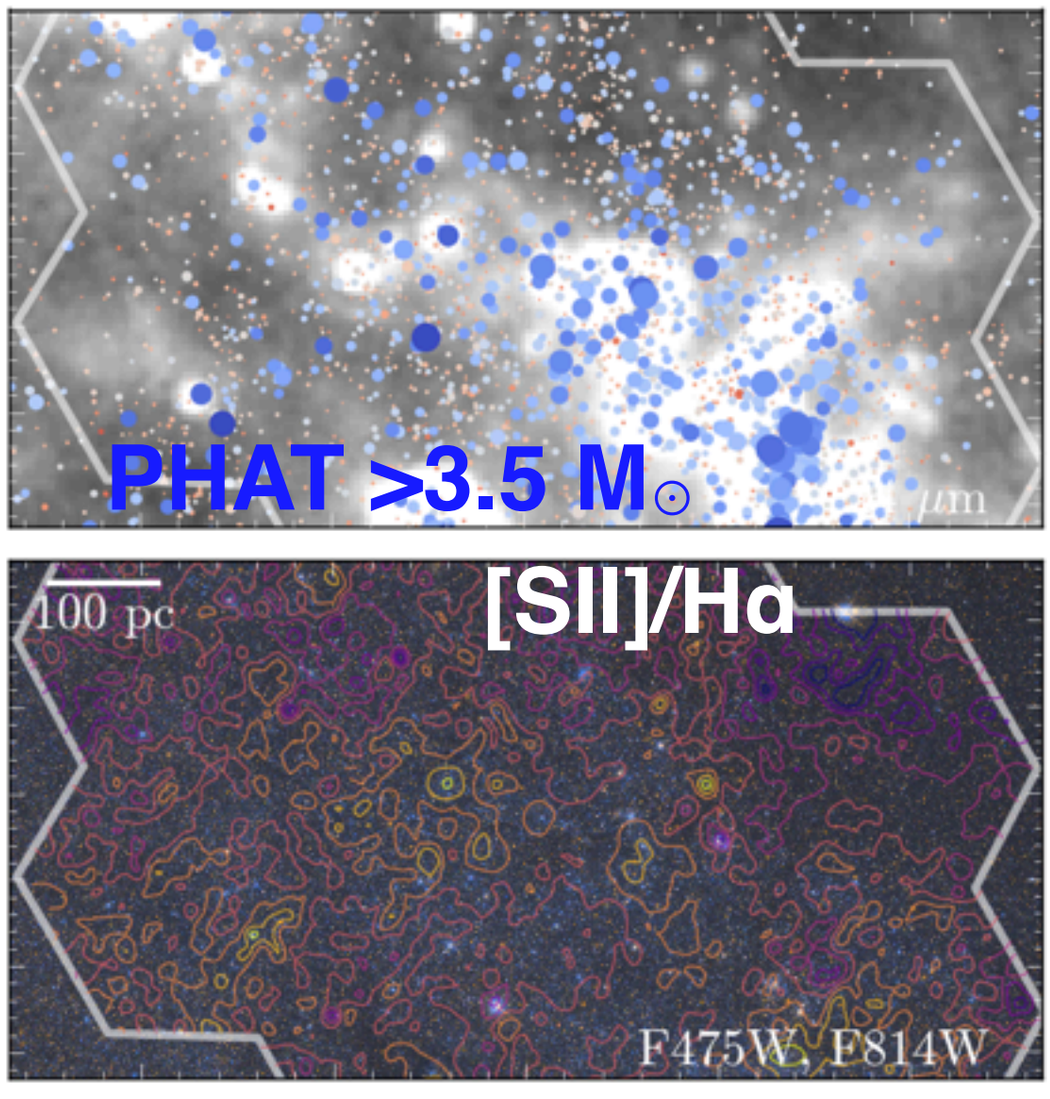




M31 stars & gas

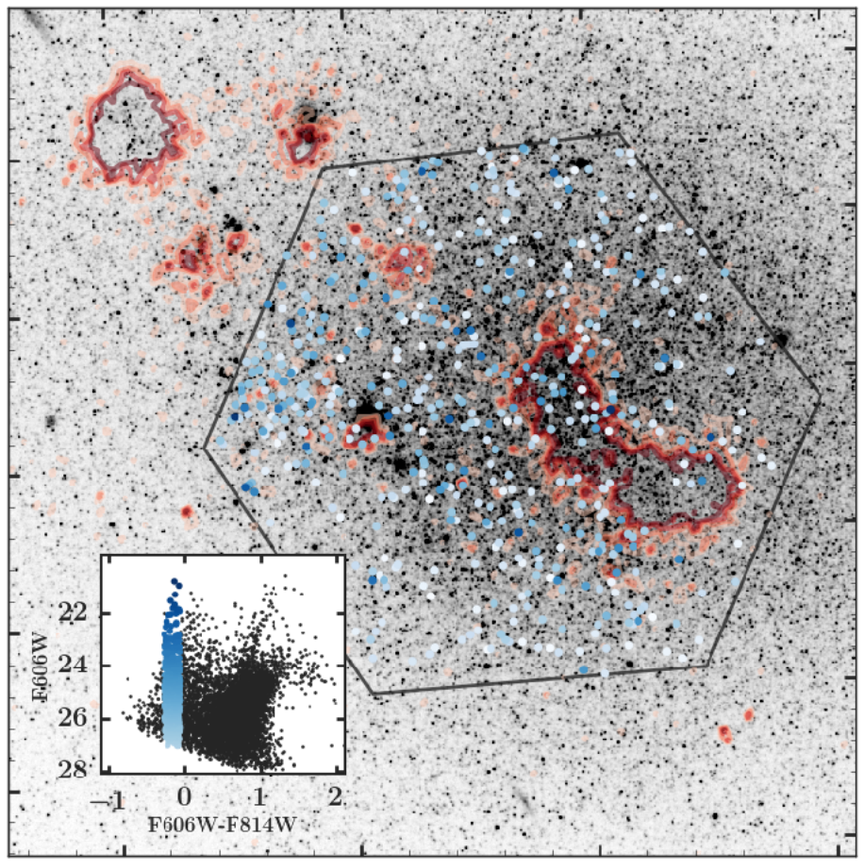


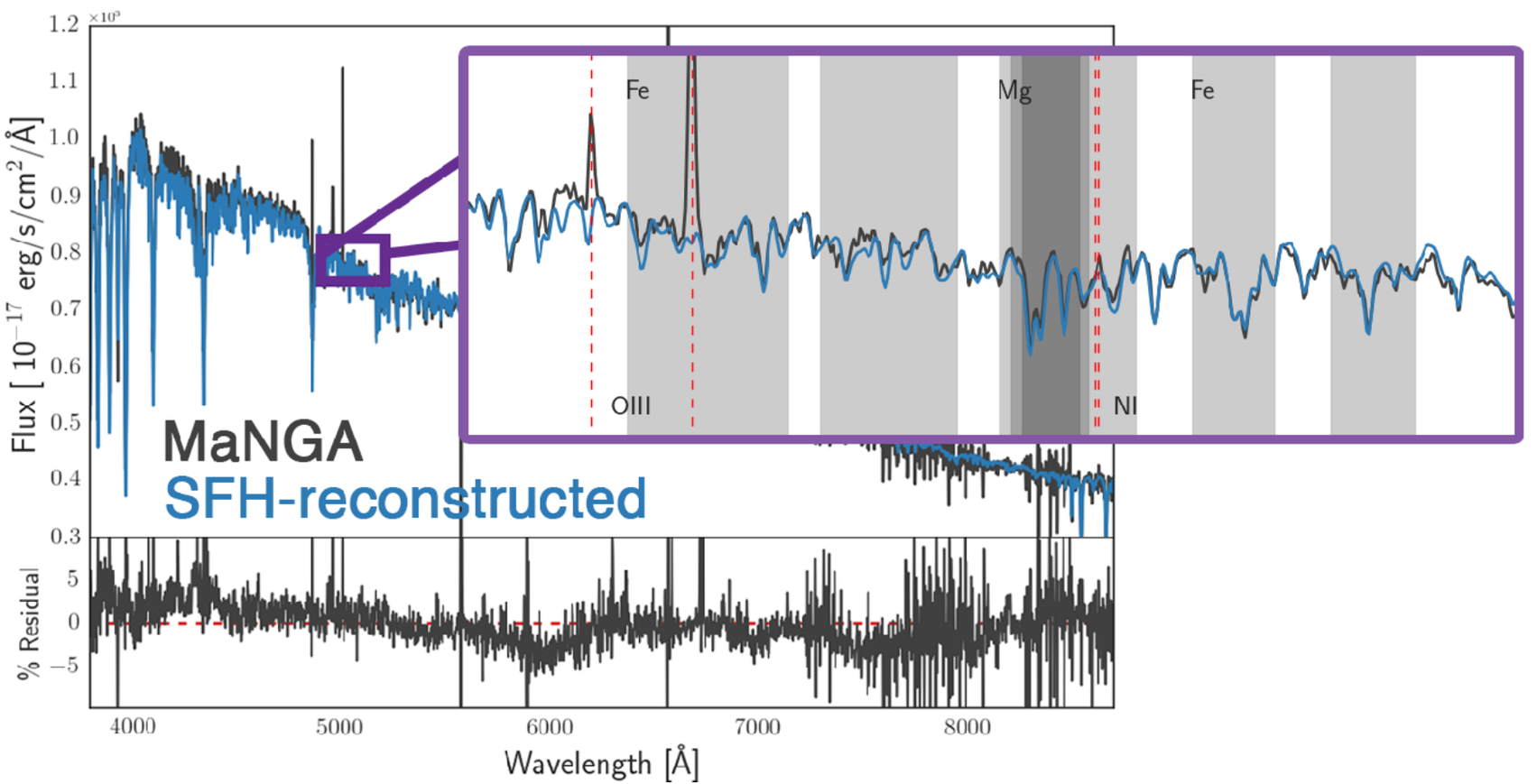




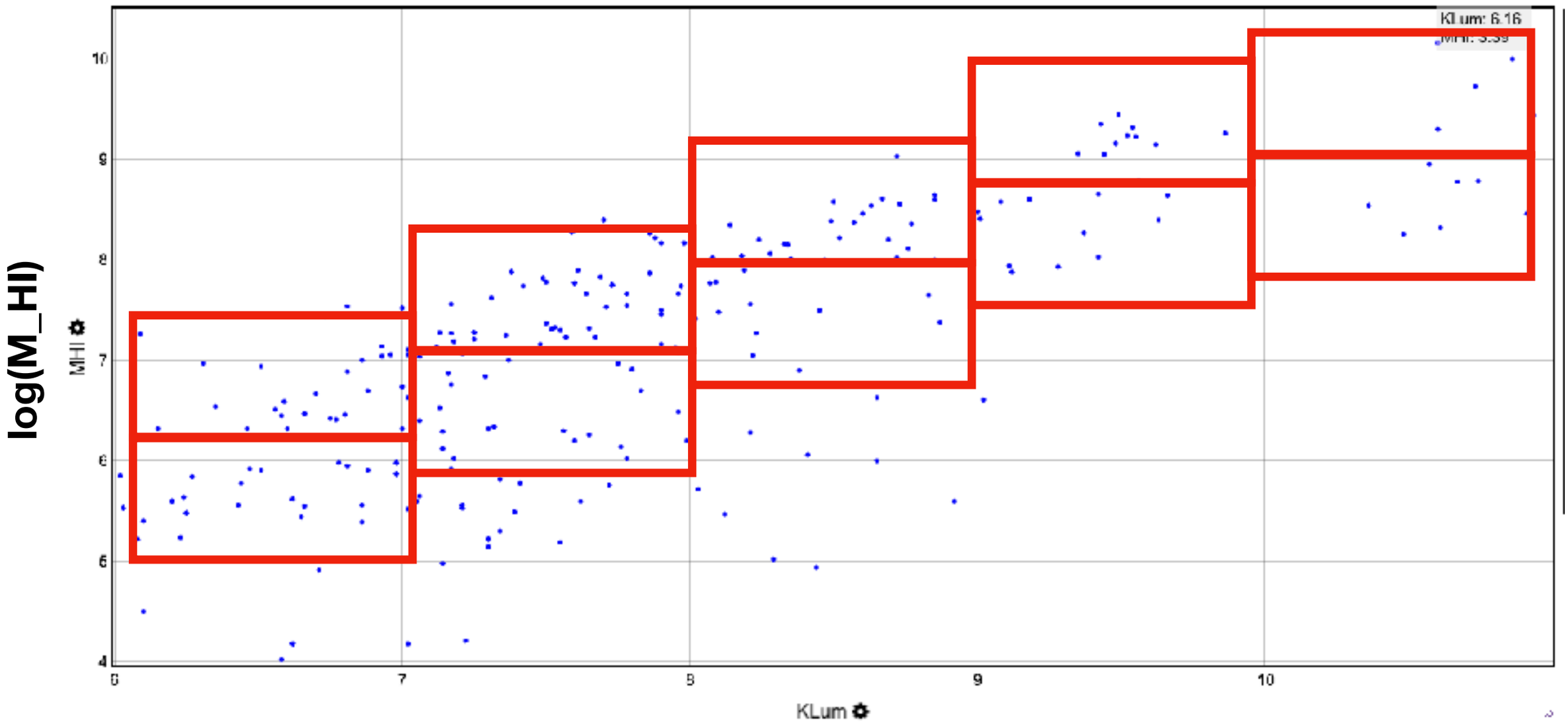
Stellar Populations

- SFH reconstructed from CMD (the best we can ever hope to do!)
- Stellar population synthesis (SPS) of spectrum
- Comparison with the IFU observations – fundamental calibration of SPS
- MaNGA has demonstrated this in NGC 4163 and M31 (in prep; Byler+2017)





LVM beyond the LG



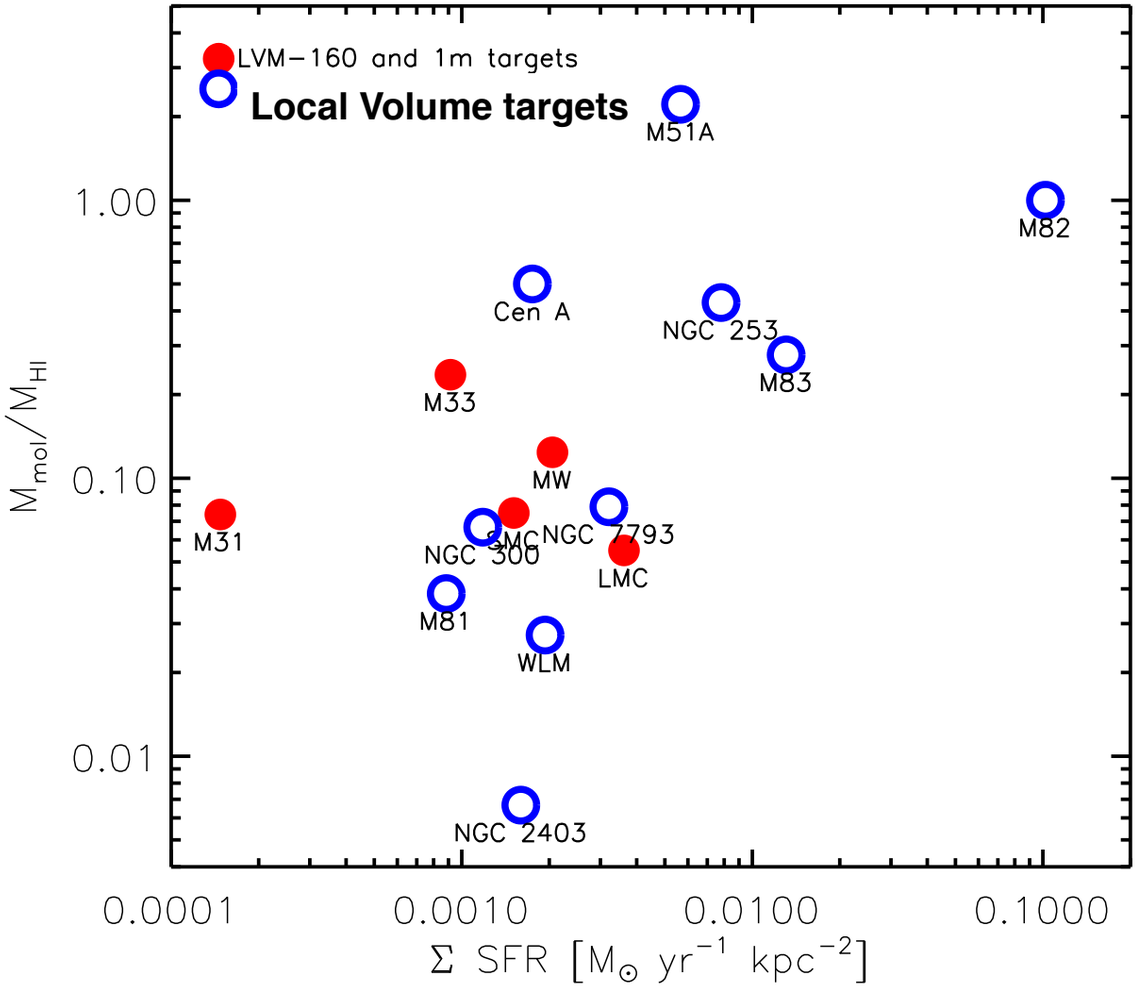
Karachentsev et al. 2013

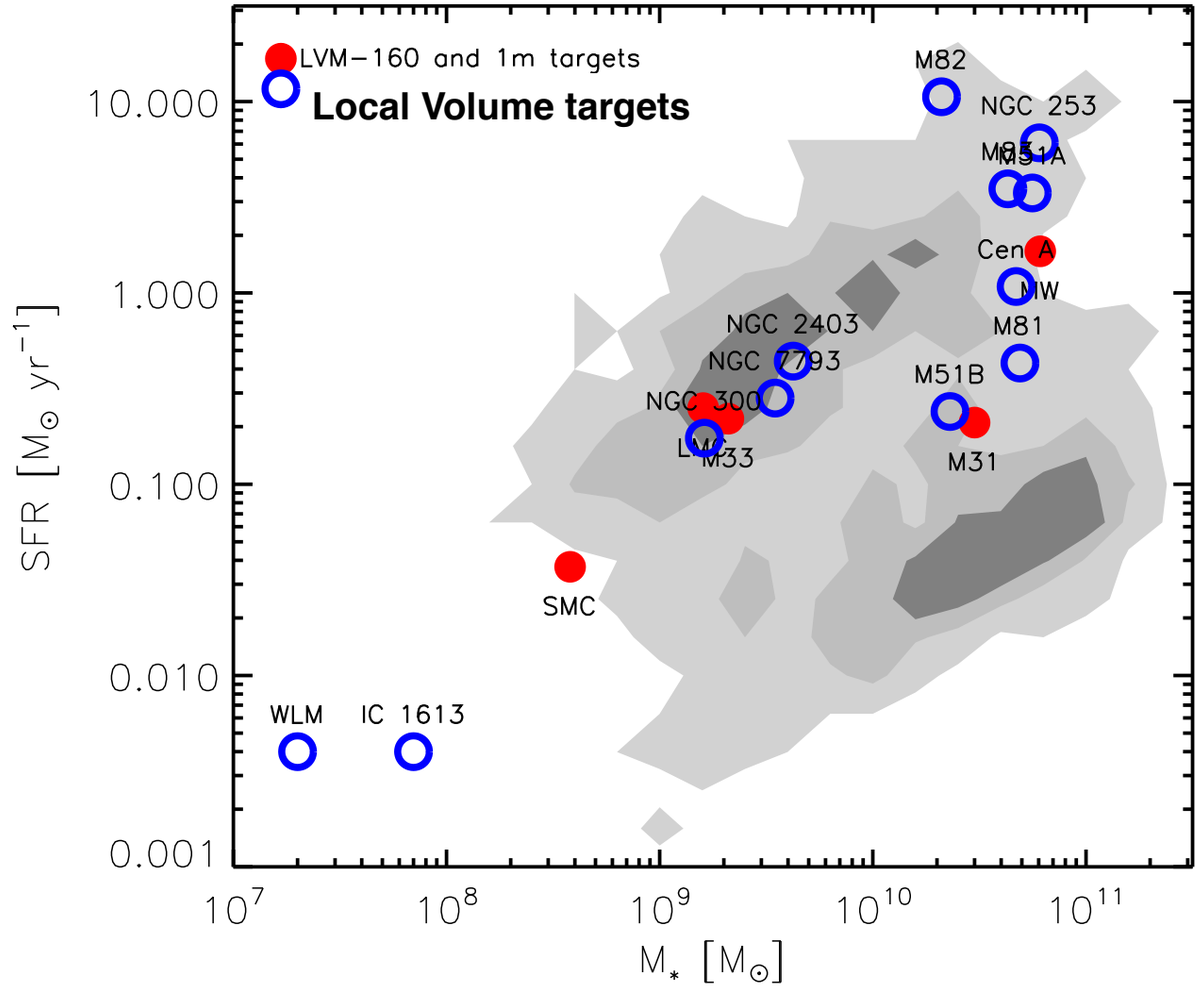
In 600 hr with LVM 1m we can map 40 D<2 Mpc galaxies at <50 pc resolution.

LVM beyond the LG

- Place the MW, M31 and the dwarfs LMC & SMC in the cosmological context

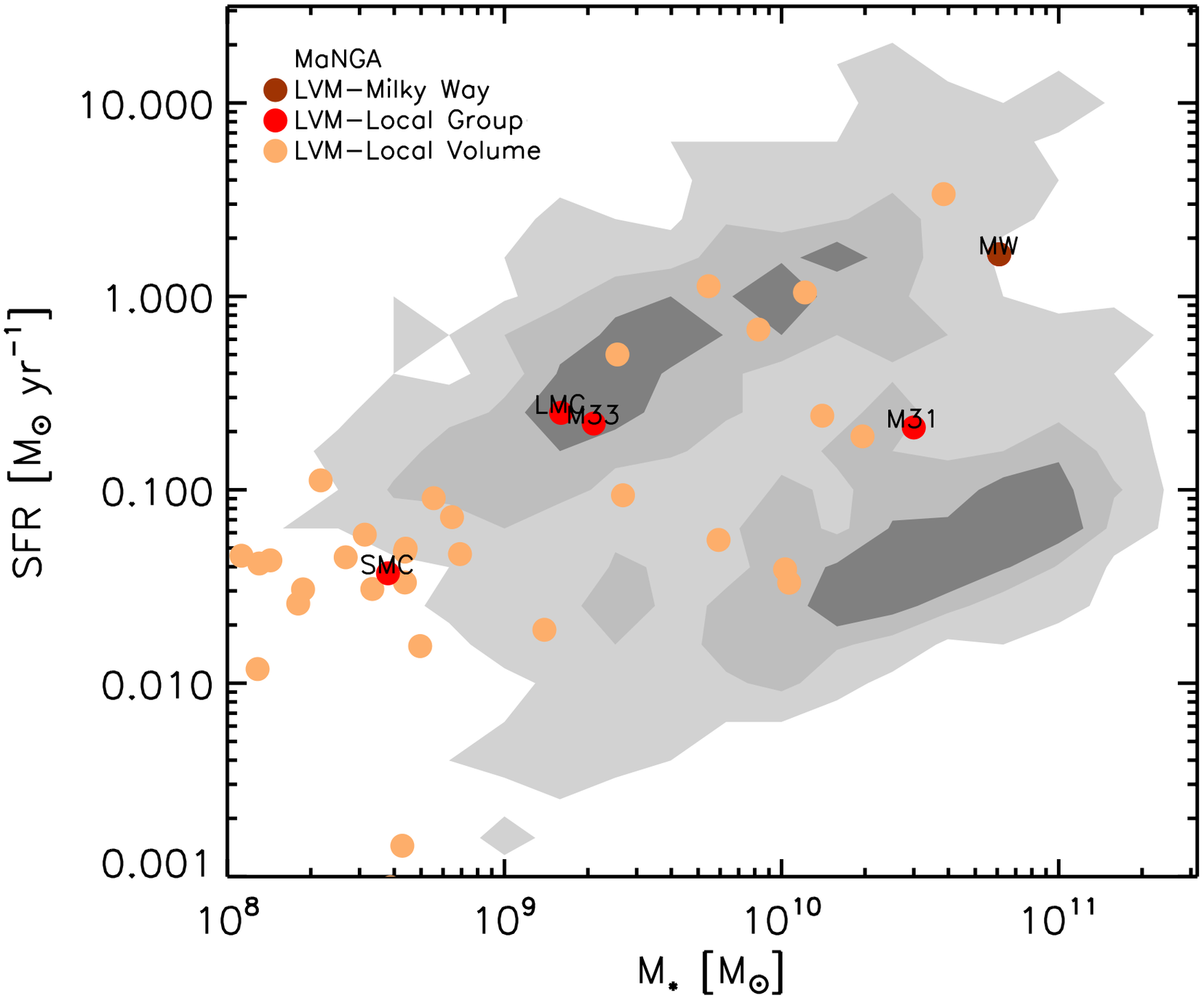
- Sample the Local Volume to ~5 Mpc and a wider range of galaxies



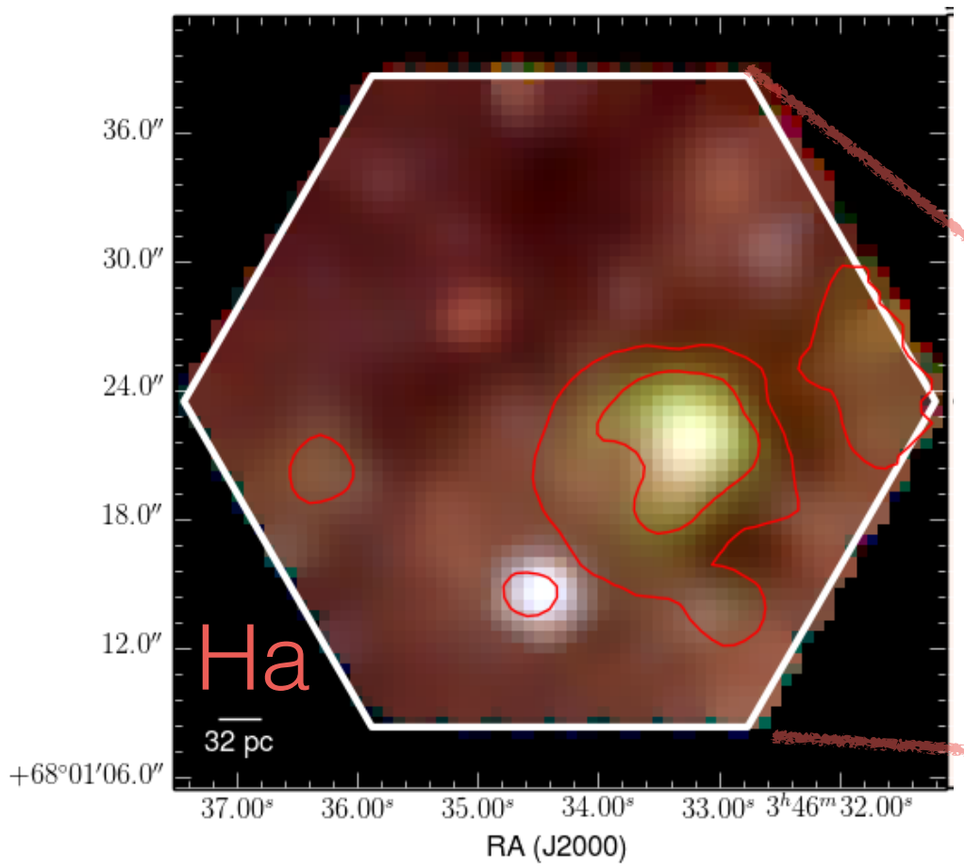


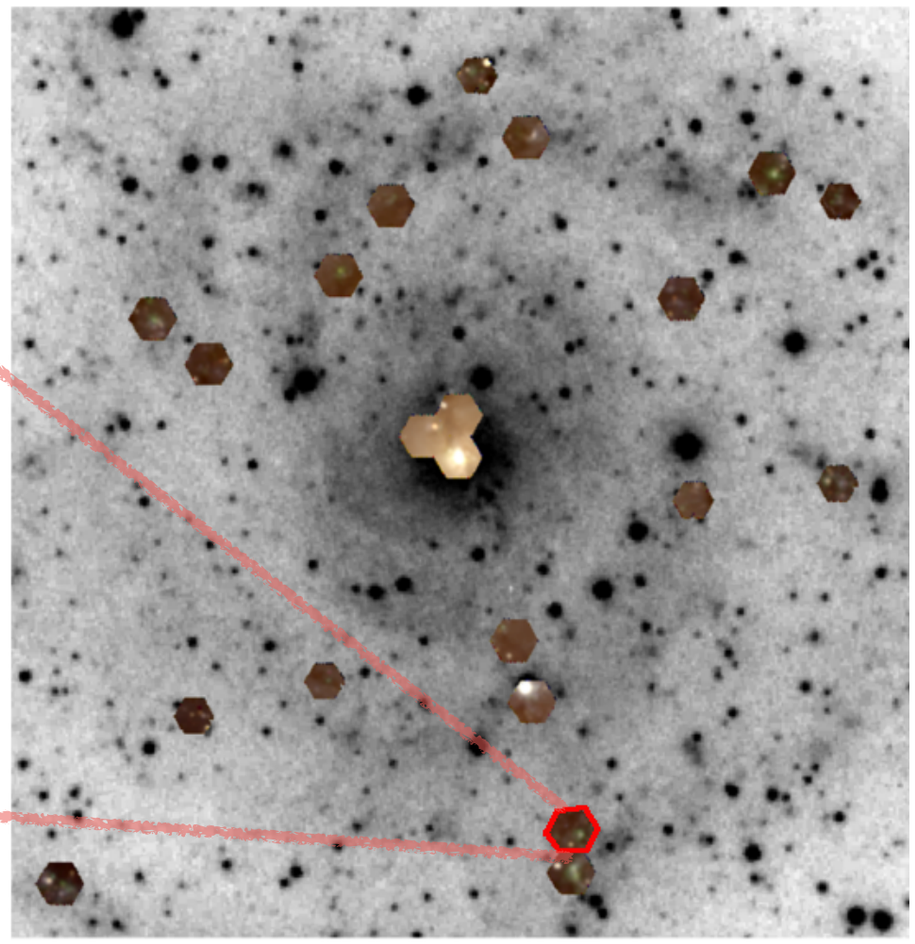
LVM beyond the LG

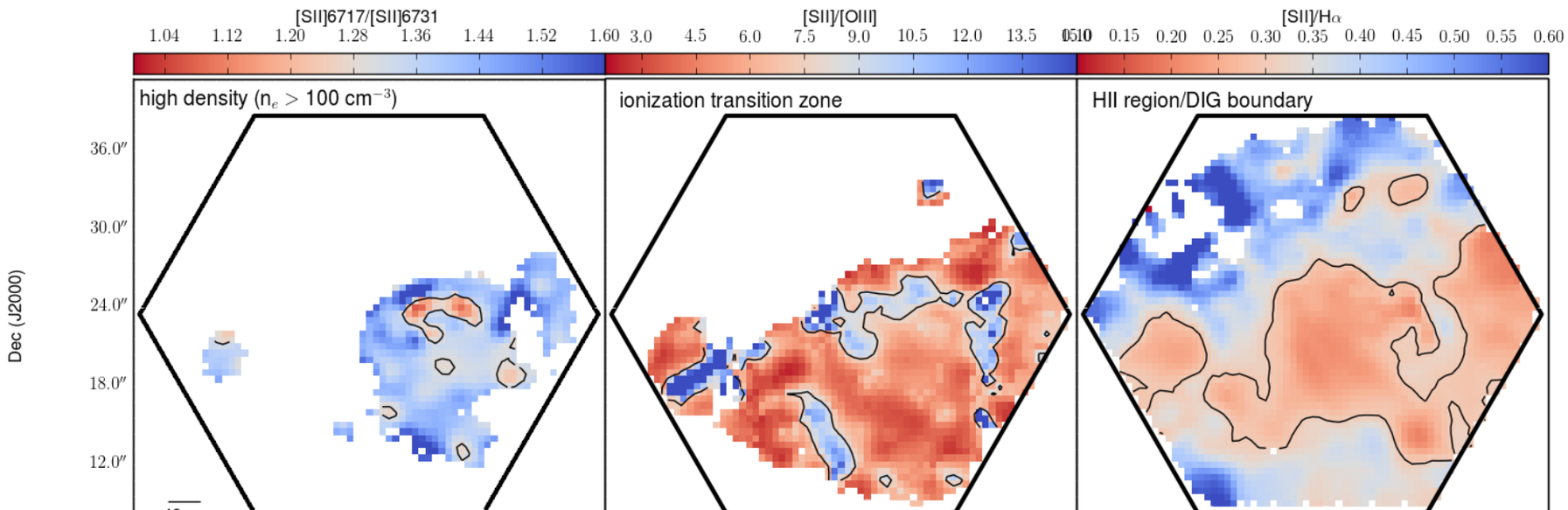
- In 600h we can map ~40 galaxies (<4 Mpc) at ~50 pc resolution
- Place the Local Group in the cosmological context
- Sample the SF main sequence and connect to MaNGA



MaNGA @ IC 342







PI:Kreckel

Contained in SDSS-IV DR15 (Dec 2018)

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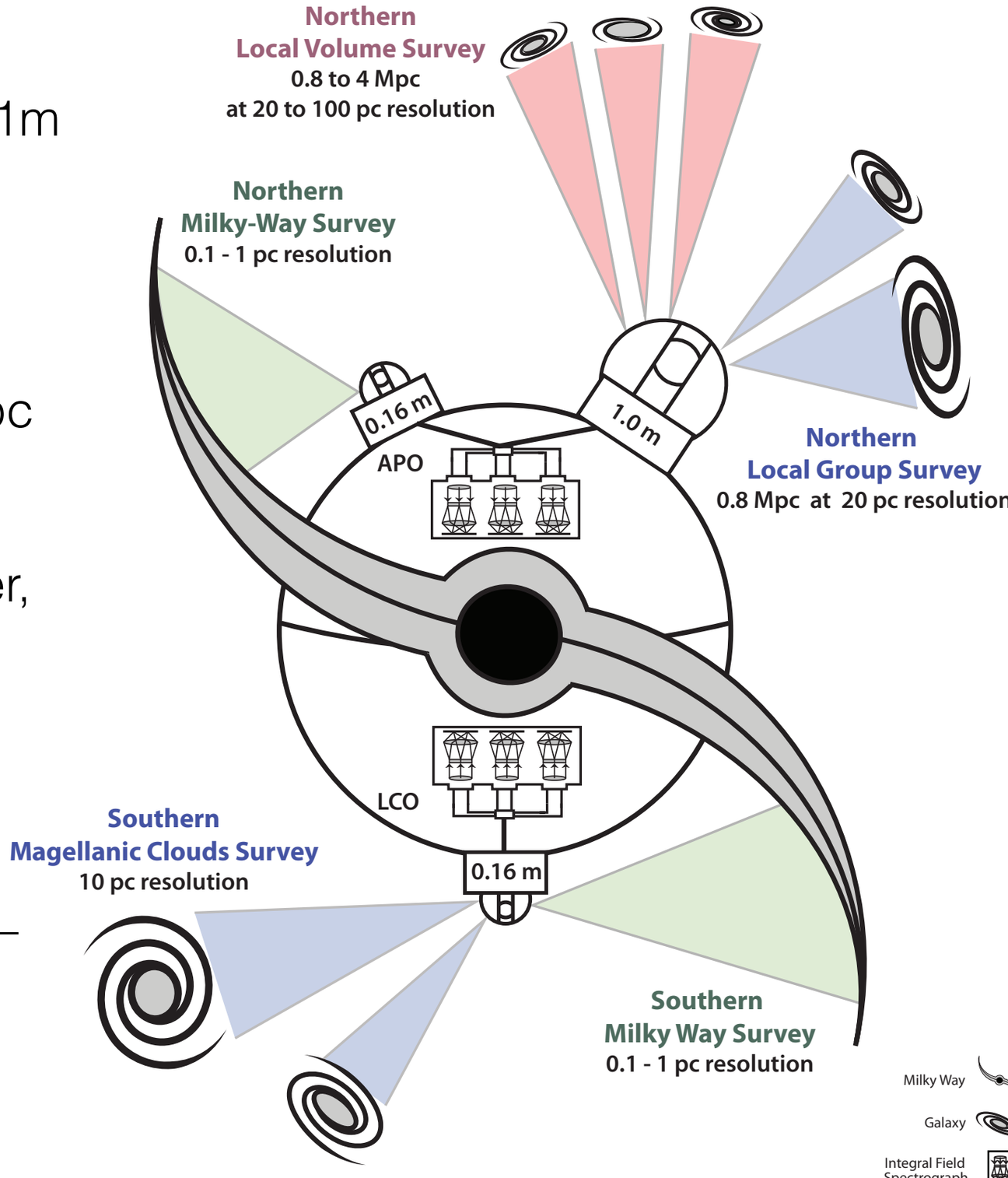


Join SDSS-V and be part of it!

SDSS

Science Highlights

- **The energetics of feedback; energy sources and sinks**
  - LVM nebular emission morphology, line ratios and kinematics will probe the dynamics, density, temperature, ionization, and shock structure of the gas
  - Directly observe how energy and momentum from known sources is deposited into the ISM, and how the balance between thermalization, the driving of turbulence, and the buildup of coherent bulk motions of gas (fountains and outflows) proceeds from small cloud scales up to kpc and galactic scales
  - Trace energy deposited into the gas from scales of single sources (hot stars, young clusters) to galactic scales

Science Highlights

- **The life cycle of GMCs**
  - Observations of SF as a function of galactic environment
  - Resolve the Jeans scale (<100pc) of GMCs
  - Combination of CO (cold) and ionized warm gas with resolved stellar populations to map the interactions between SF regions and the GMCs
  - How are clouds affected by proximate SF? How long until they are disrupted? How does it depend on galactic environment?
  - How does it correlate with stellar content, ages, local and global SFH?

Science Highlights

- **Precision abundances**
  - Resolving the structure of HII regions enables more realistic photoionization models
  - Strong and weak lines enable measurement of hardness, temperatures, and densities within HII regions (at least 4363 accessible in the LMC,SMC)
  - Stellar data allow constraining the ionizing radiation field
  - Separation of local and diffuse ISM emission
  - Precision calibration of abundance indicators
  - Abundance gradients around HII regions allow observations of enrichment and mixing in action

Science Highlights

- **Calibrating Sub-grid Physics**
  - Resolving the structure of HII regions and SF regions in a statistical sample across a wide range of galactic environments
  - High-quality data on feedback sources and sinks
  - Correlation with other phases of ISM
  - Allow calibration of sub-grid physics in simulations of galaxy formation which are now reaching similar scales of few pc in a cosmological context

Science Highlights

- **The co-evolution of stars and the ISM**
- **Next-generation SPS modeling**
- **Radiative transfer modeling the ionized ISM**
- **Small and large-scale distribution of metals in gas and stars**
- **…**

SDSS-V

- SDSS-V is (astro-ph/1711.03234; Pioneering Panoptic Spectroscopy)
    - Milky Way Mapper,
    - Black Hole Mapper, and
    - Local Volume Mapper
- Single fiber programs are full sky and synoptic using new robot fiber positioner
- Time domain spectroscopy of 100,000 quasars
- 5M stars with H<11 and G-H>3.5 at S/N>40
- Synergy with astroseismology & transits with TESS & PLATO
- RVs across the HR diagram for binary studies at all masses
- YSO targets in SF regions, IR spectroscopy
- **MWM + LVM: unique stellar and ISM census of the MW**

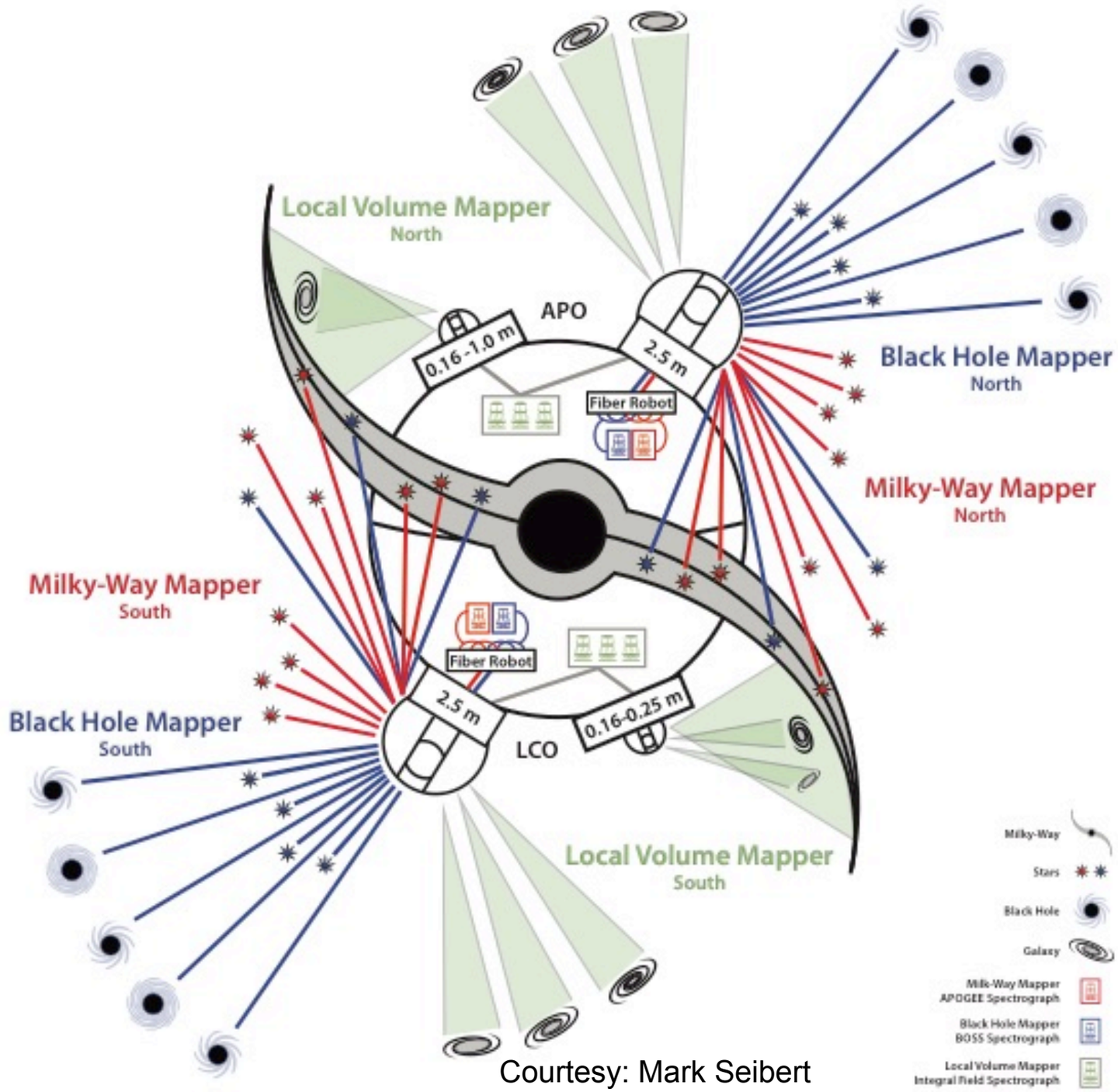
SDSS-V

- an observing facility:
  telescopes, hardware, software

- a science survey program:
  panoptic spectroscopy

- a consortium and collaboration

- in definition, implementation and fund-raising phase
  to start 2020 (…5 years



Courtesy: Mark Seibert

What are SDSS-V's Unique Capabilities

- (Near-)identical set-ups in ***two*** hemispheres → all-sky
  - MW is all around us
  - Gaia, (Kepler), Tess, eROSITA are all-sky missions
  - Data homogeneity!
- Rapid robotic fiber configuration (300 nearIR/ 500 opt) over ≈5sqdeg
  - enables short exposure time (13min) H<11
  - can cover the whole sky once a year (and in parts much more often)
- Wide-field, multi-object, high-res. Spectroscopy (APOGEE)
  - No other near-IR spectroscopy comes close to all-sky & 5M targets
- Push (optical) IFU spectroscopy to unprecedented regime
  - from 0.05deg^2 → 3000deg^2 (huge pixels, small telescope)

SDSS-V Panoptic Spectroscopy Surveys

- Milky Way Mapper (>6,000,000 targets & multi-epoch)
  - Galactic genesis
  - Stellar Astrophysics
  - Spectral complement to Kepler, Gaia, TESS
- *Black Hole Mapper* (>400,000 targets & monitoring)
  - QSO reverberation & changing-look QSOs
  - eRosita (X-ray survey) follow-up
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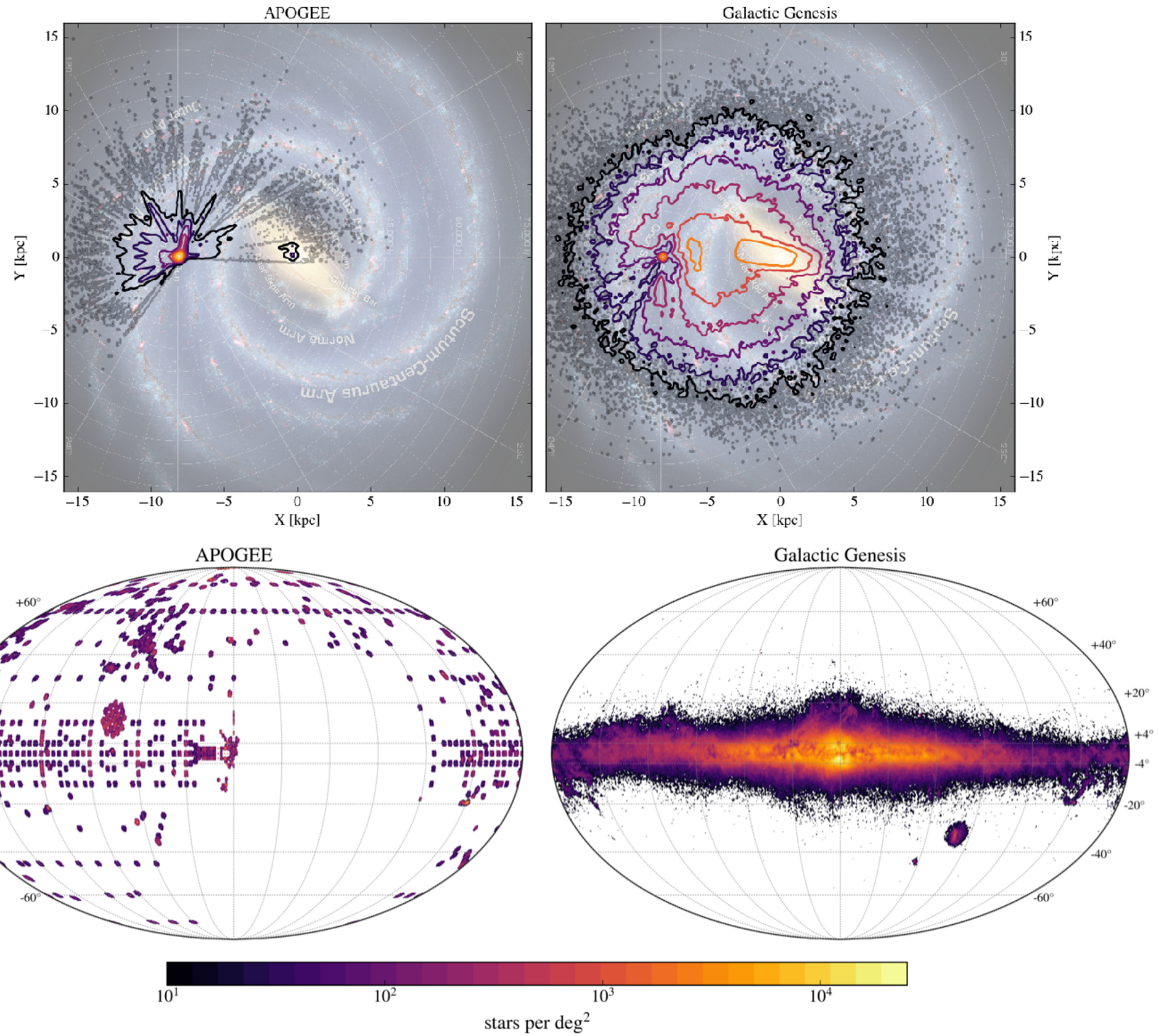
  - Ultra-wide field IFU spectroscopy, focus on the ISM

Milky Way Mapper



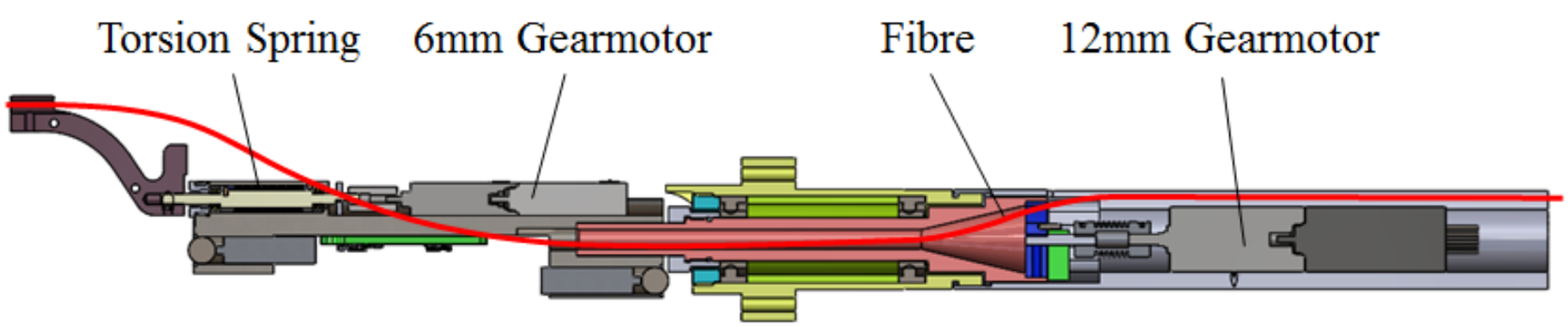
MWM Details ...

Galactic Genesis & Stellar Astrophysics Targeting Classes					
Name	**Instrument**	**Selection**	**$N_{Targets}$**	**N_{Epoch}**	Comment
Galactic Genesis	APOGEE	H<11, $G-H>$ 3.5	4,800,000	1	dust-extincted disk
	APOGEE	$\|z\|<200$ pc, H< 11, distance <5 kpc	125,000	1	to complete hi-res dust map
Binaries with Compact Objects	BOSS	PTF, ZTF, Gaia photo variability	30,000	3	binaries w/WD, NS & BH
	BOSS	Gaia parallaxes	30,000	1	wide WD+MS/RGB binaries
Solar Neighborhood Census	APOGEE *and* BOSS	d <100 pc, $G<20$, $H<12$	400,000	2	1000x increase in volume & stars
White Dwarf Chronicle	BOSS	$G<20$	300,000	3	15x increase in sample size
TESS Exoplanet Host Candidates	APOGEE	H<= 13.3	300,000	1-8	All short-cadence targets & planet hosts
Binaries Across the Galaxy	APOGEE	H< 13.4 & $N_{visit}>=6$ by start of SDSS-V	60,000	6-18	Gives orbits with 24-40 epochs for all targets with long baseline
Gaia Astrometric Binaries	APOGEE, BOSS	d <3 kpc	200,000	1	rare types of systems
TESS Red Giant Variability	APOGEE	H <12.5	250,000	1	only stars with at least 80 days of observation
Convective Core Sample	APOGEE	H <12	200,000	2	Detection of single vs. binary systems
	APOGEE	H<12	500	25	current samples <10
Young Stellar Objects	APOGEE	H< 12, d<1 kpc	20,000	12	nearby SF regions
	APOGEE	H< 12	3,500	8	high-mass star-formation regions
	APOGEE	H<12, $\|b\|<2$	10,000	2	Galactic Plane massive young stars
	APOGEE	H< 13	10,000	2	Central Molecular Zone

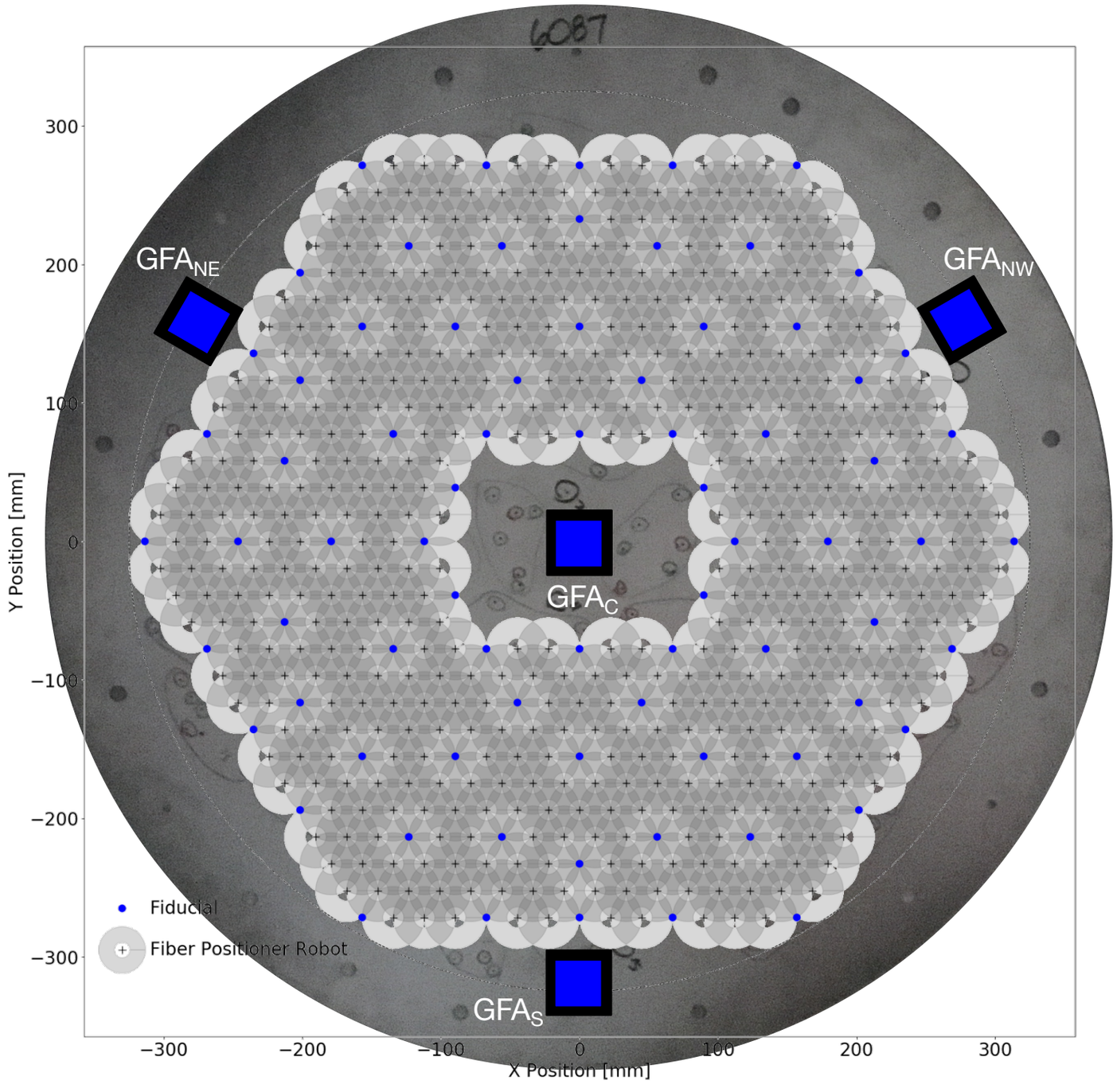
Fiber Robot

SDSS-V Prototype Design

Rick Pogge,OSU

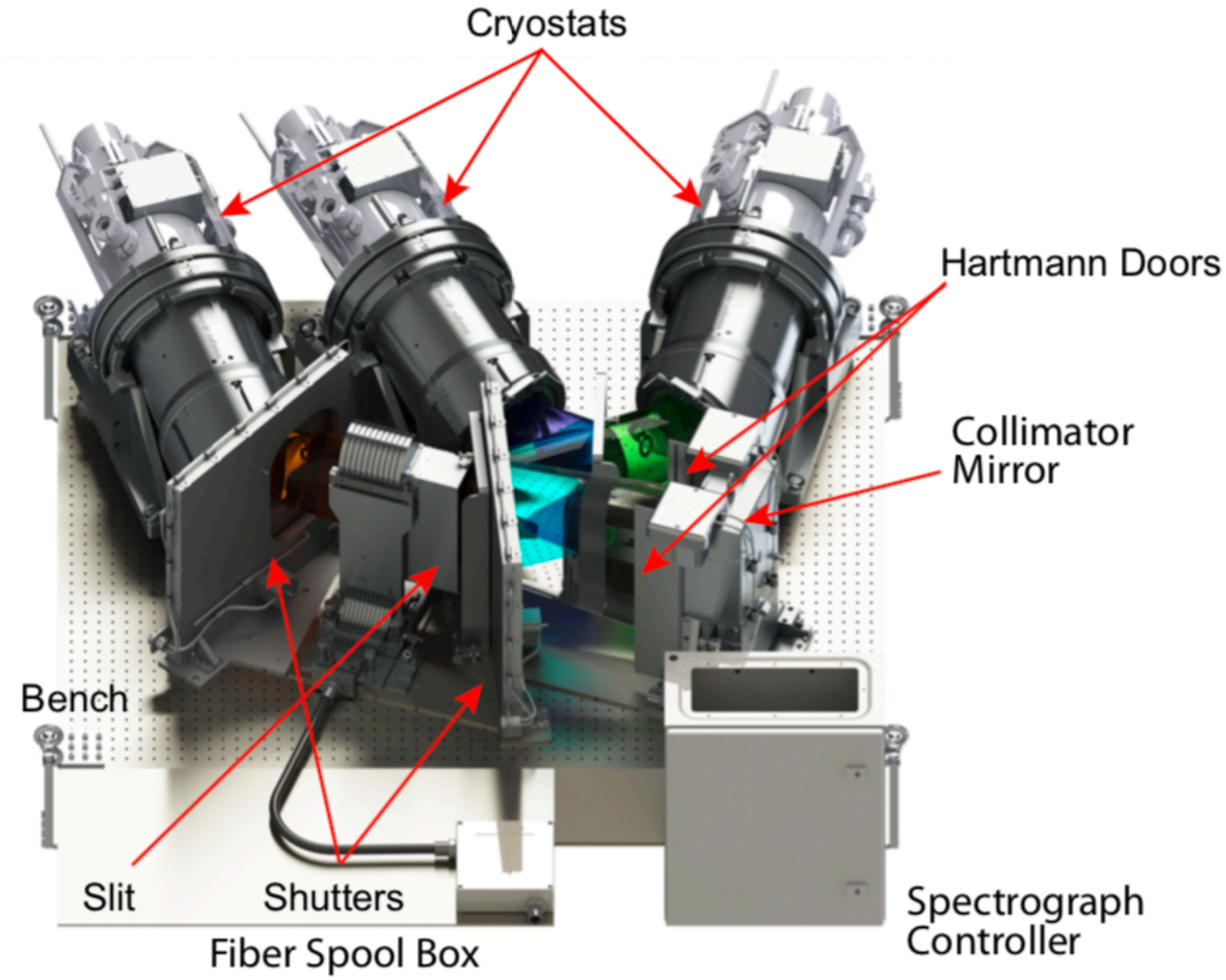


Focal Plane


6087
GFA$_{NE}$
GFA$_{NW}$
GFA$_{C}$
GFA$_{S}$
Fiducial
Fiber Positioner Robot
Y Position [mm]
X Position [mm]
300
200
100
0
−100
−200
−300
−300
−200
−100
0
100
200
300

LVM Spectrograph

- DESI 3-channel design 3600-9800 Å, 2000 < R <5100
- 3 4k CCDs

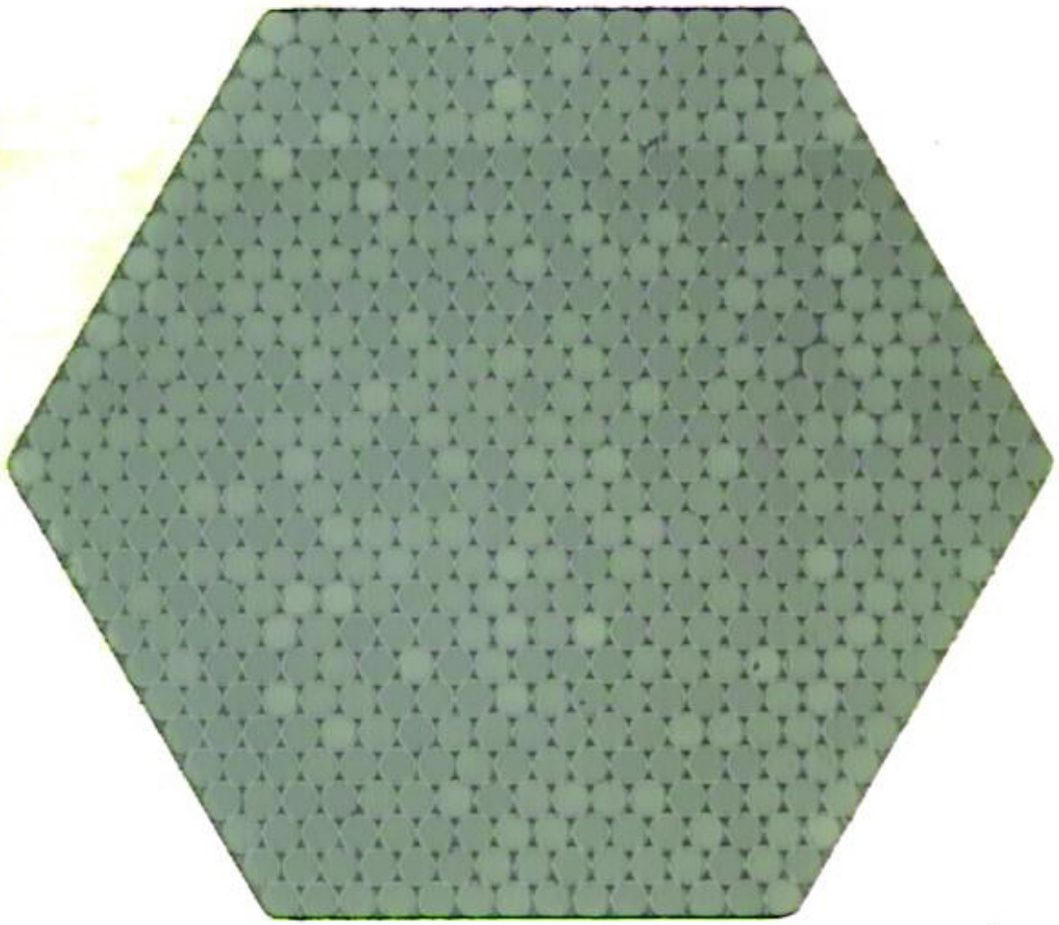


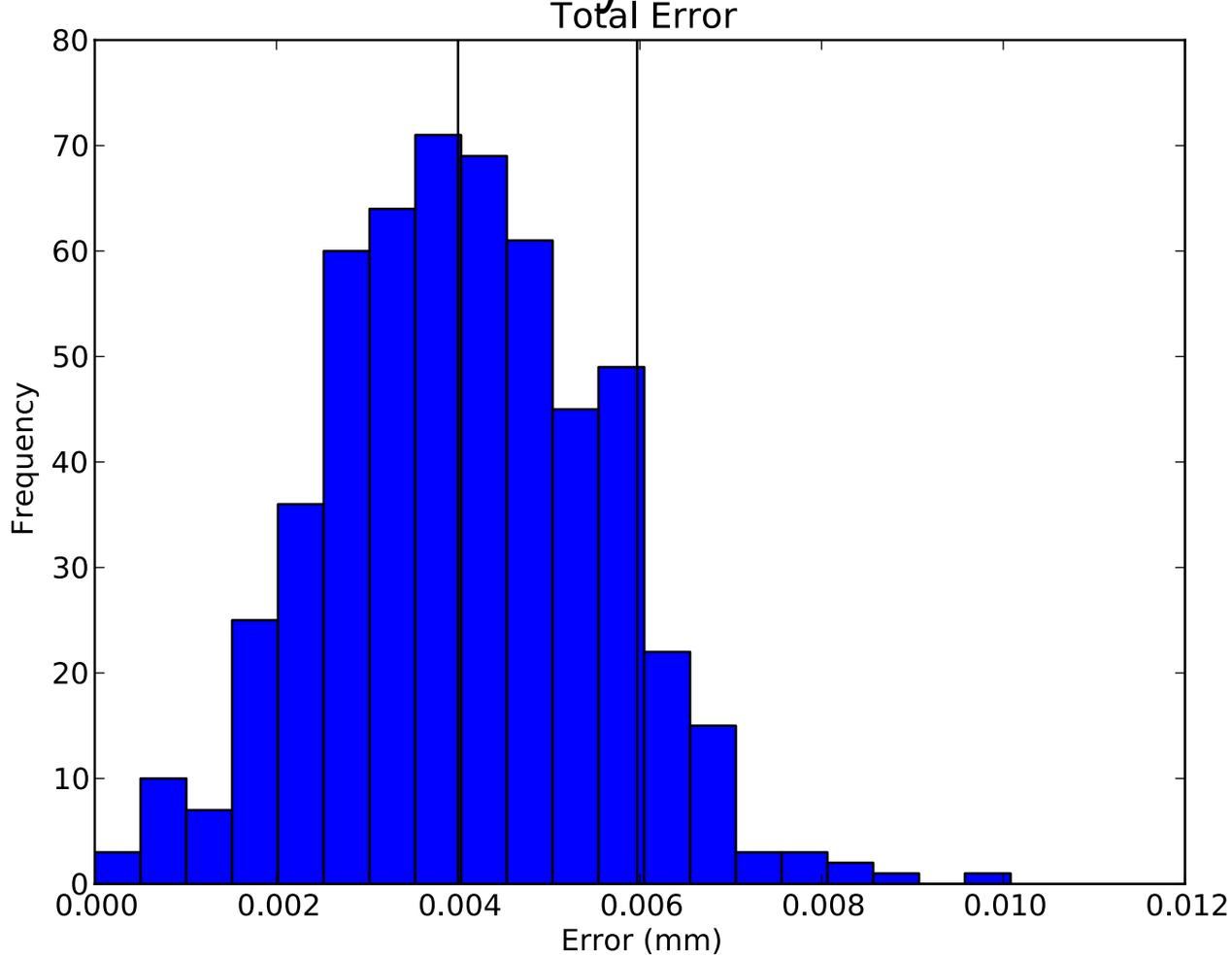
360 – 980 nm, 3 channels
Resolution average = ~3,500
- Blue 360–555 nm, R~2,000–3,200
- Green 555–656 nm, R~3,200–4,100
- Red 656–980 nm, R~4,100–5,100

Throughput max = 56% at 650 nm
Throughput min = 21% at 360 nm
Collimator f-ratio = 3.57
Pixel samplings = 3.4
Detectors = 4k x 4k w/ 15 um pixels
Slit length = 120.9 mm
Mass = ~500 kg
Size = 1.8 x 1.4 x 0.6 m

LVM IFU Tech

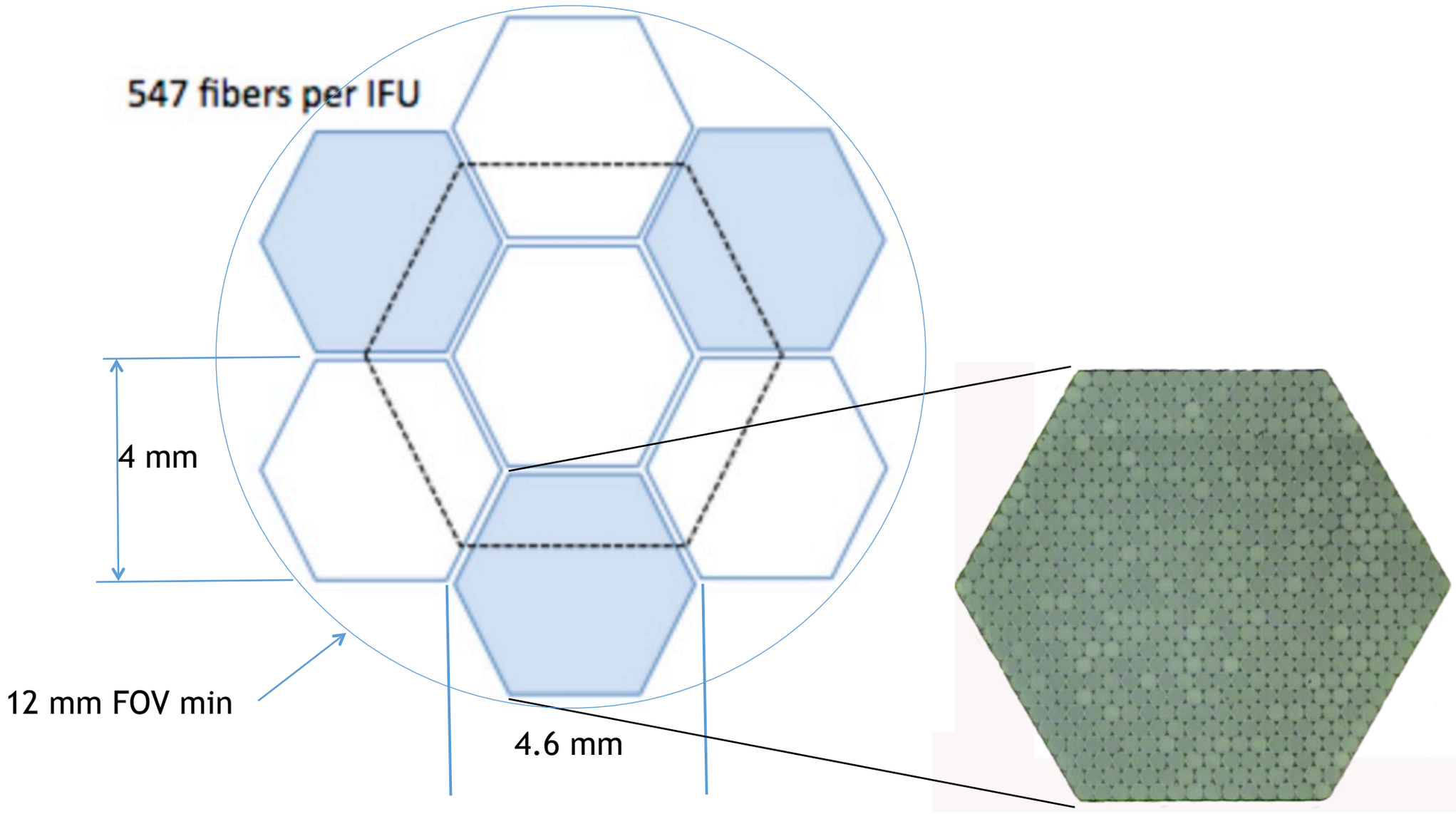
- IFUs based on MaNGA hexagonal insertion ferrule technology
- Lenslet coupling
- 547-fiber unit feeding one spectrograph
- 547 fiber ferrule made at UW shows scalability of the tech





LVM Focal Plane

- IFUs are spaced by one 547 fiber group.
- Tiling is then interlaced to provide full coverage.
- Registration between IFUs must be good to the ~1/10 of a fiber size or 10 microns.

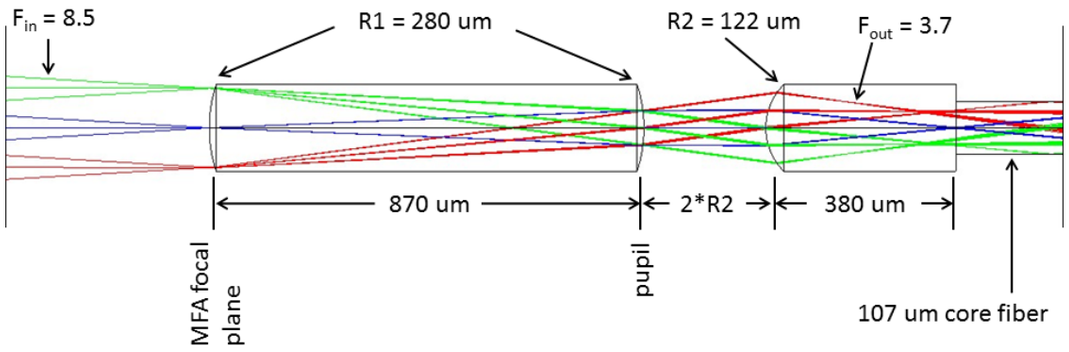


LVM Lenslets

- Lenslet designs under investigation
- Pupil/near-field imaging onto fiber
- Further scrambling options being considered

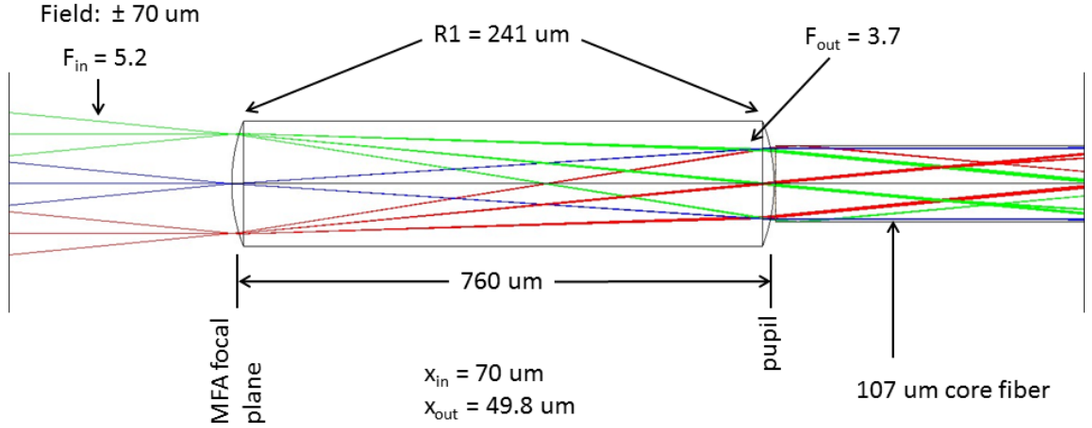
Near-field imaging onto fiber:

F_{in}/F_{out} = R1/R2 = 2.3
Field: ± 80 um



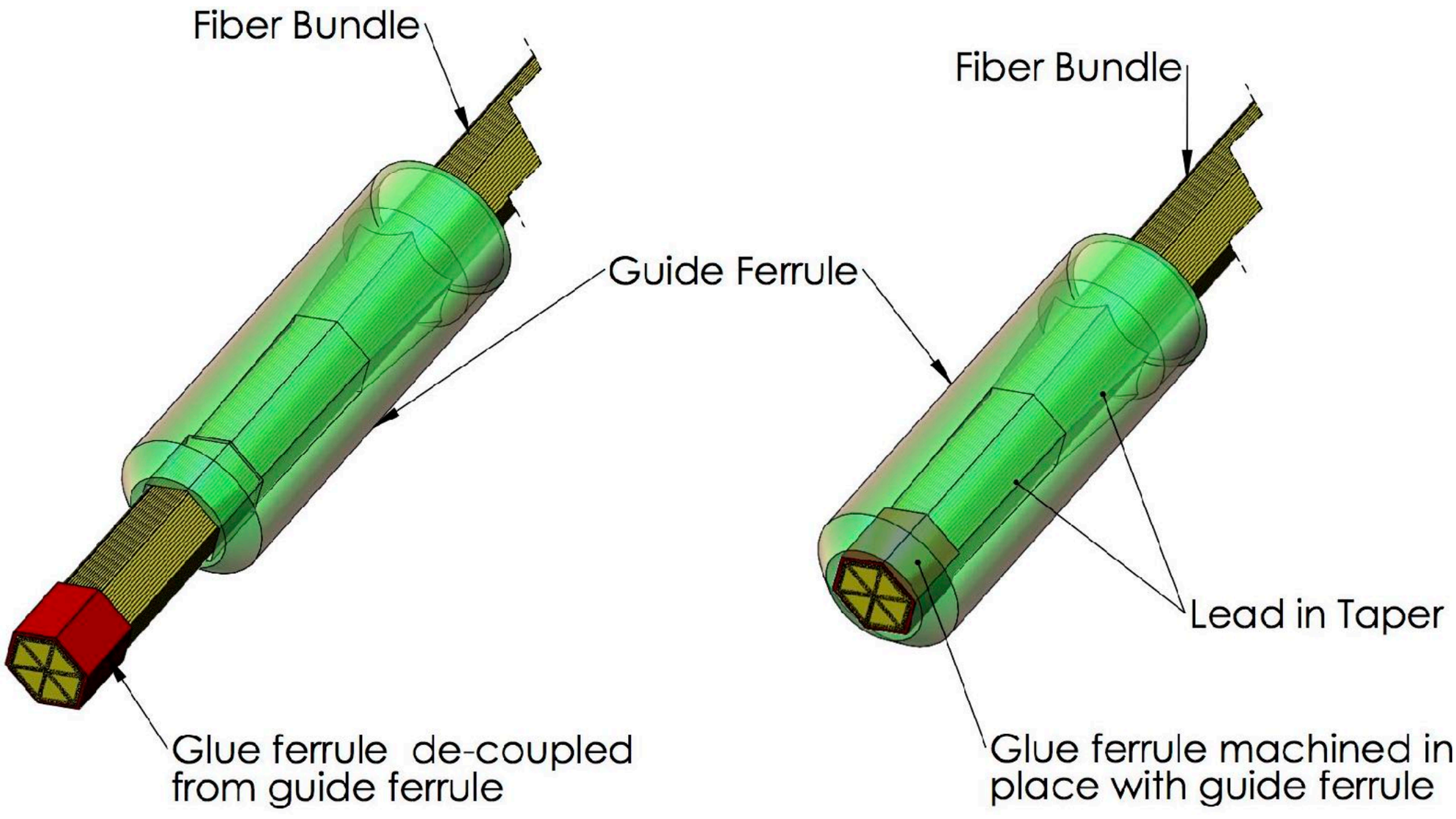
Pupil imaging onto fiber:

x_{in}/x_{out} = 1.4
Field: ± 70 um



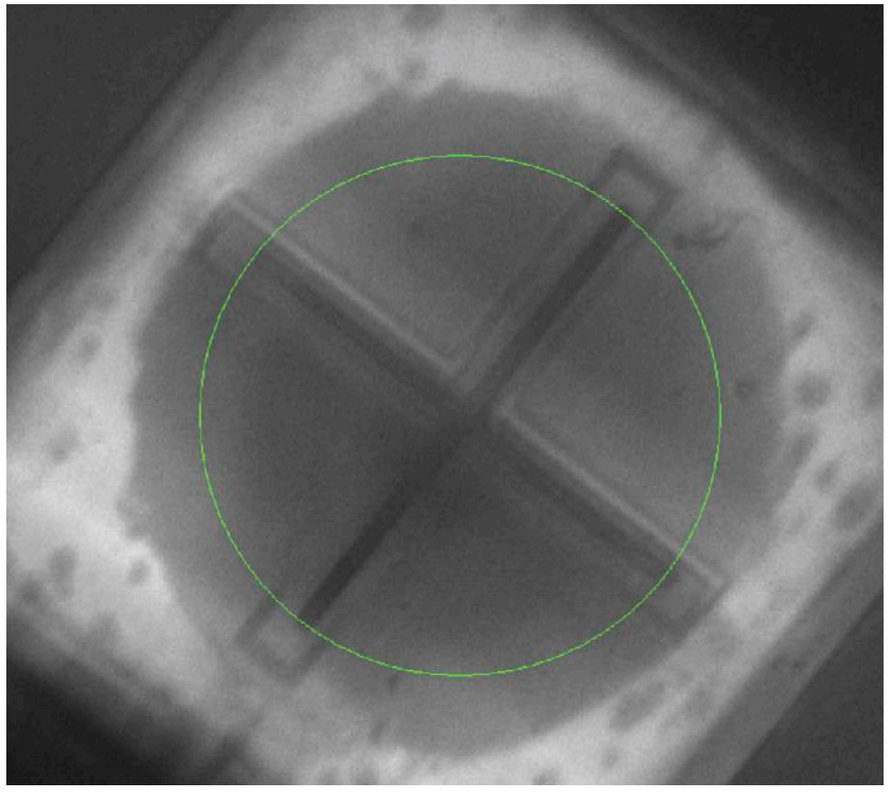
LVM IFU Tech

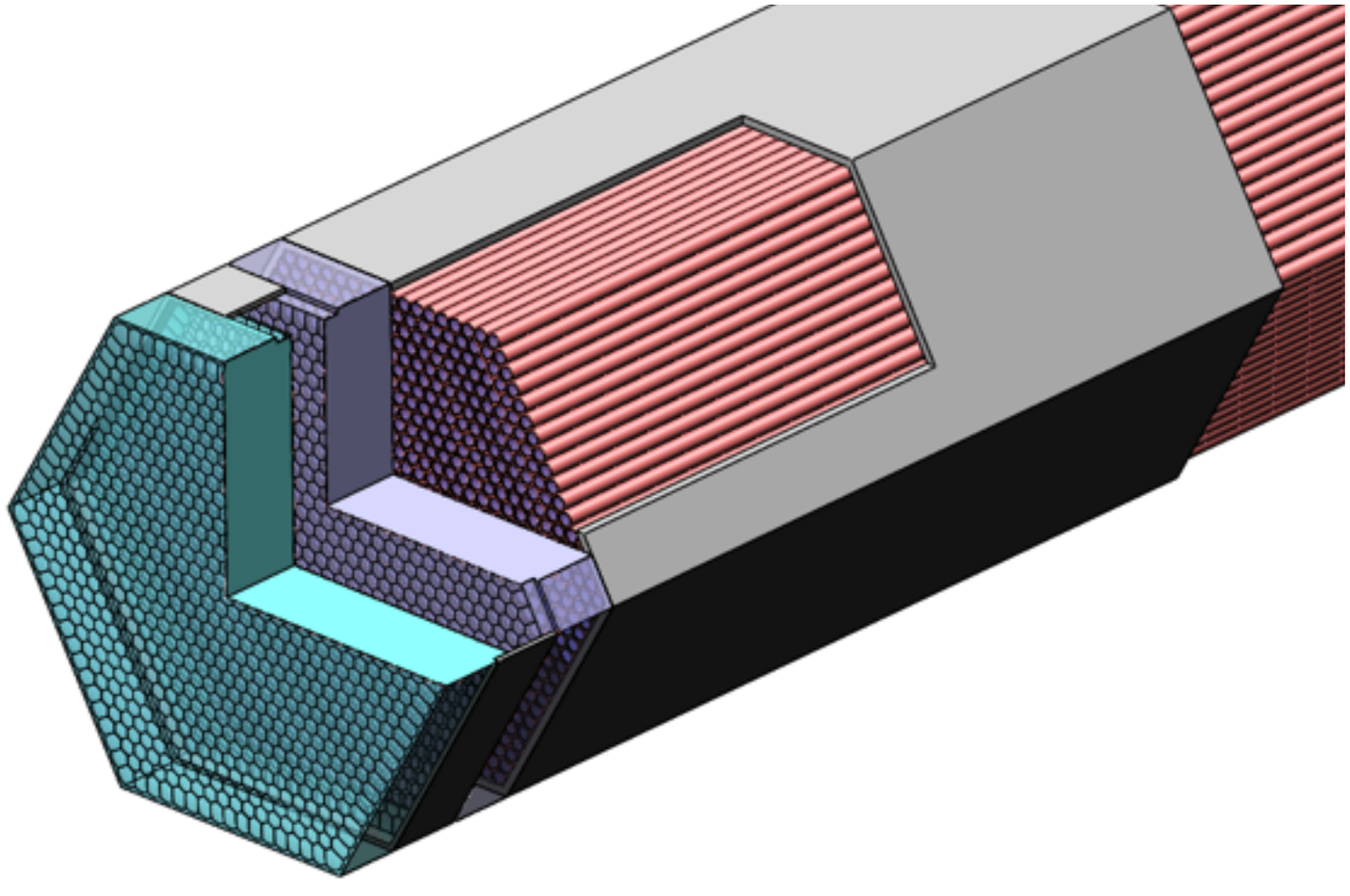
- Abuttable IFUs based on the insertion ferrules but with removable tip that holds the finished IFU



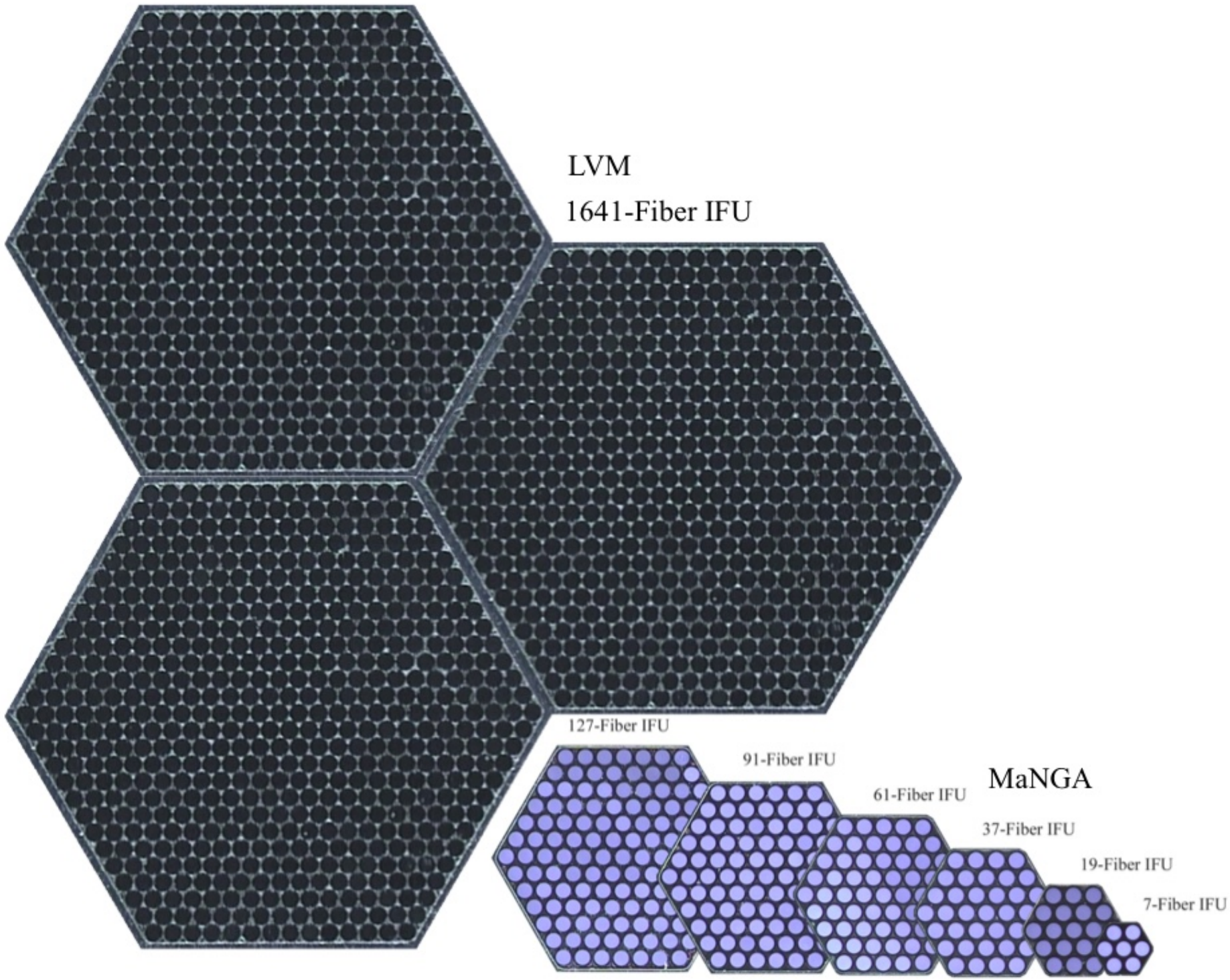
LVM Microlenses

- Microlens arrays with integrated alignment targets (see LRS2, Hill et al.) allow high-precision μm alignment
- MLAs made to match IFU





LVM IFU


LVM
1641-Fiber IFU
127-Fiber IFU
91-Fiber IFU
61-Fiber IFU
37-Fiber IFU
19-Fiber IFU
7-Fiber IFU
MaNGA

Project Status

- SDSS-V received a $16M grant from the Sloan Foundation in October 2017. First payment expected end of 2017
- ~50% of budget in hand
- SDSS-V to take over operations from SDSS-IV mid 2020
- We have 2.5 yr to build the LVM hardware!
- Minimize R&D (fiber system only), use pre-developed or commercial solutions wherever possible
- We have signed an MOU with US DoE for licensing the DESI designs and IP, and access to the DESI vendors (in particular Winlight)
- **We need more people to take on work! Please join us.**
- SRD close to completion; CoDR Jan 13-14, 2018

Summary

- LVM is the first step towards a full sky IFU survey
- 1 sterad in the MW, Local Group, and Local Volume covering the Galactic Plane, M31, M33, LMC, SMC as well as 12 nearby galaxies
- Resolve Jeans scale in all objects and HII regions in the LG
  - 50 pc in distant objects
  - 10–20 pc in the Local Group
  - 0.1–1 pc in the Milky Way
- Full optical bandpass ar R~4000
- Unique dataset in combination with resolved stellar spectroscopy (MW) and imaging (M31/33 and LMC/SMC)
- Wide range of ancillary data from X-ray to radio at matching resolution

Join SDSS-V and be part of it!