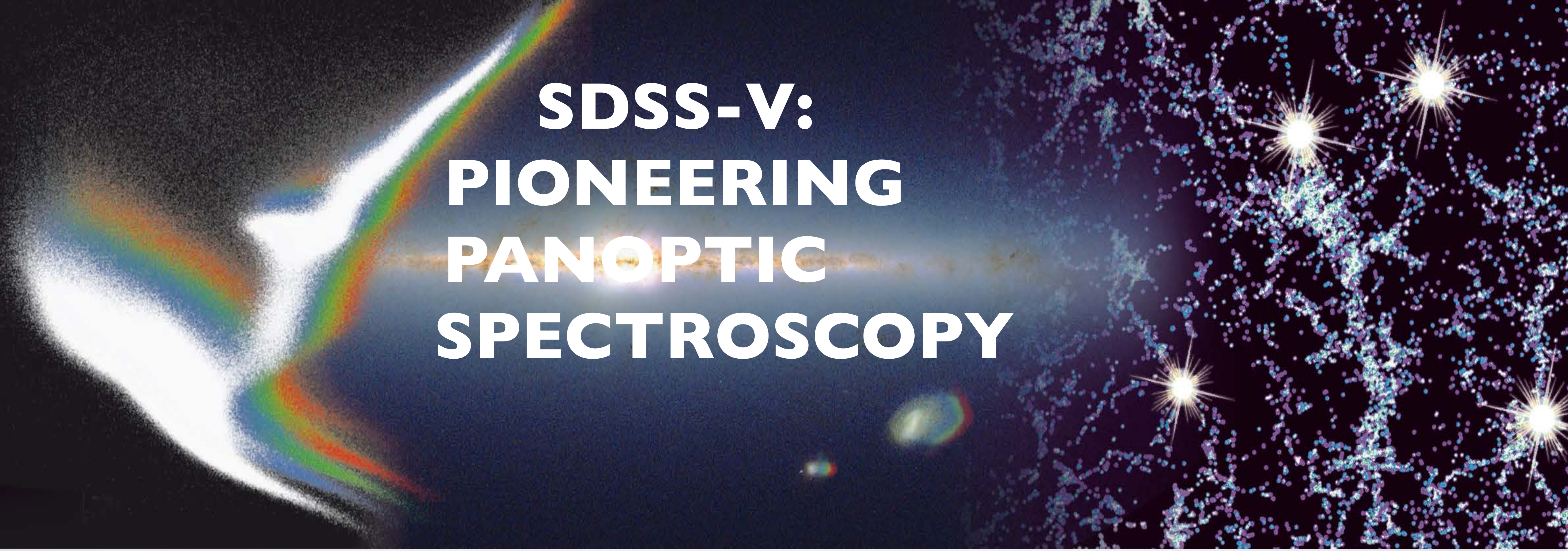
SDSS-V: PIONEERING PANOPTIC SPECTROSCOPY

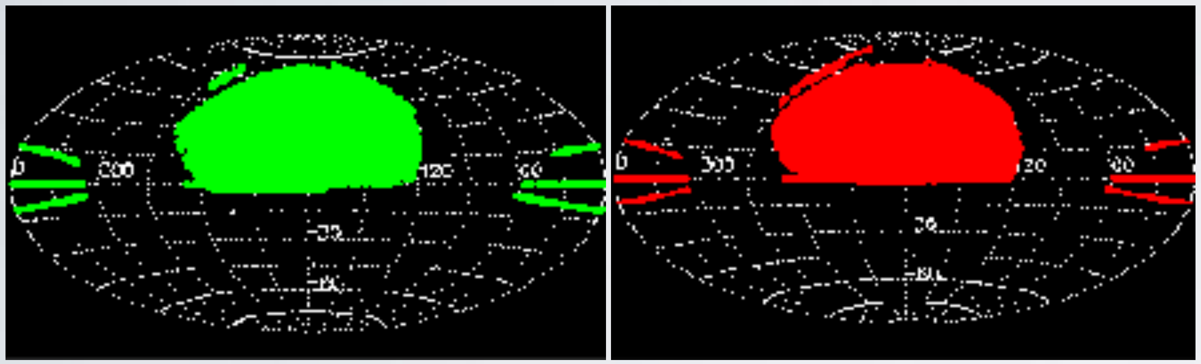


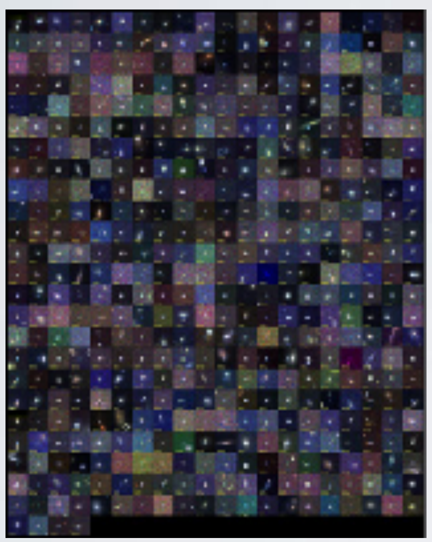
Juna A. Kollmeier

CARNEGIE OBSERVATORIES
CARNEGIE INSTITUTION OF WASHINGTON

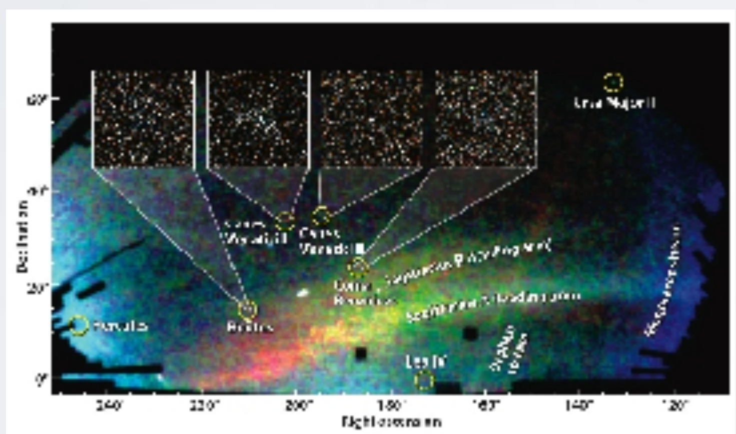
SDSS

SDSS: A HISTORY OF INNOVATION AND REVOLUTION

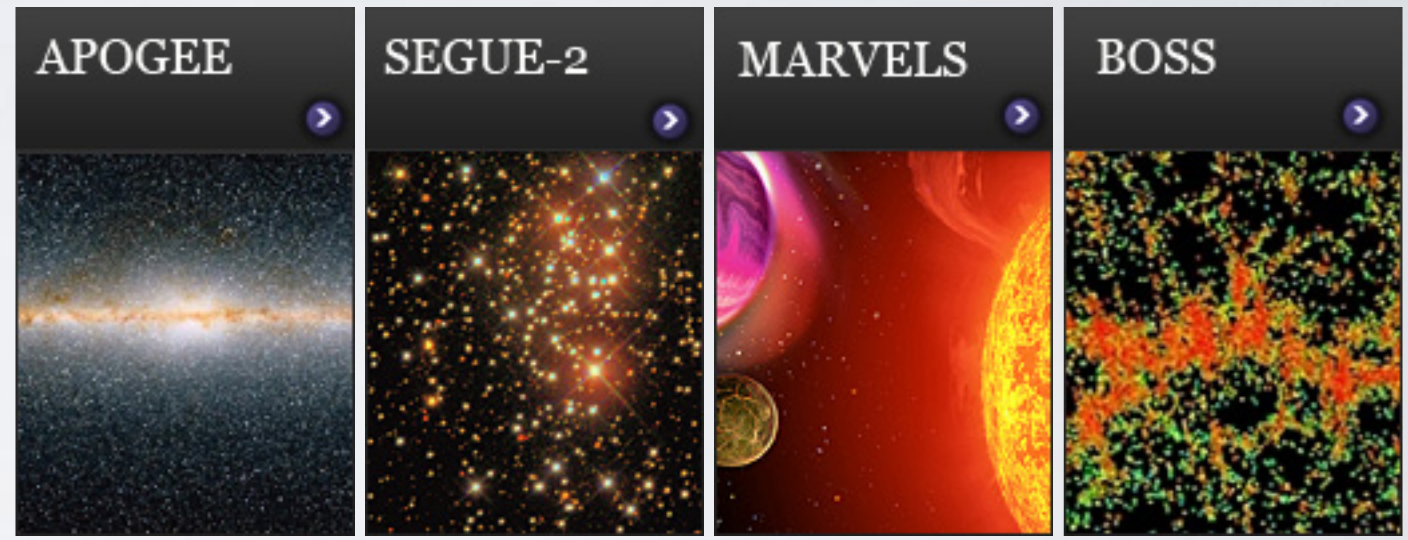




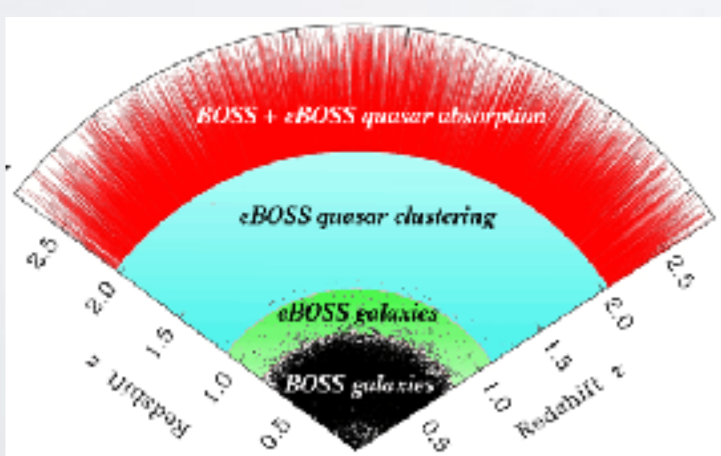
SDSS-I/II



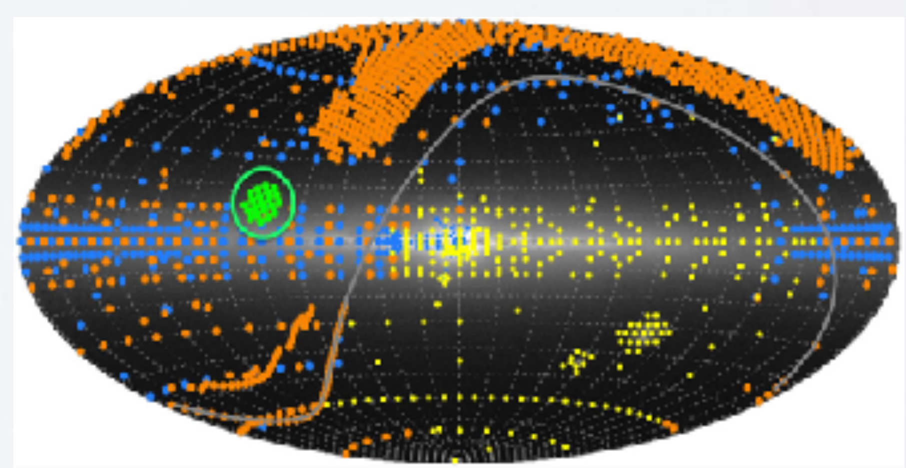
SDSS-III



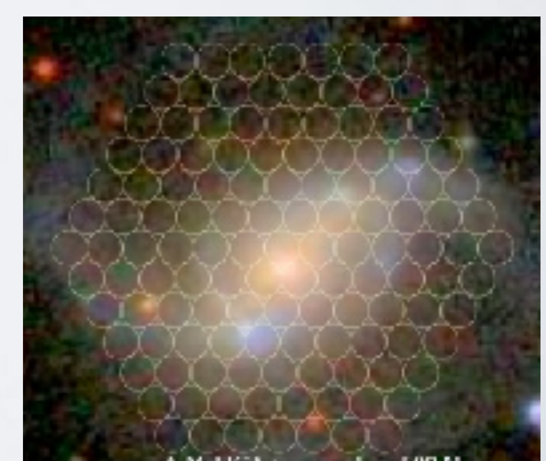
SDSS-IV



e-BOSS

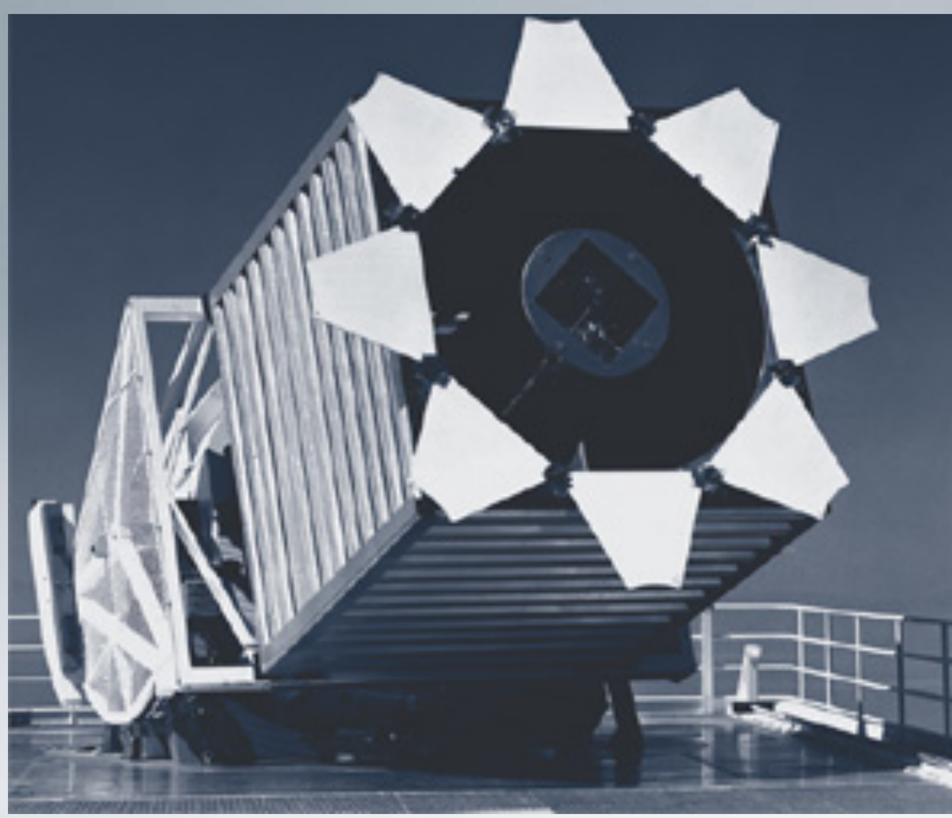


APOGEE-2



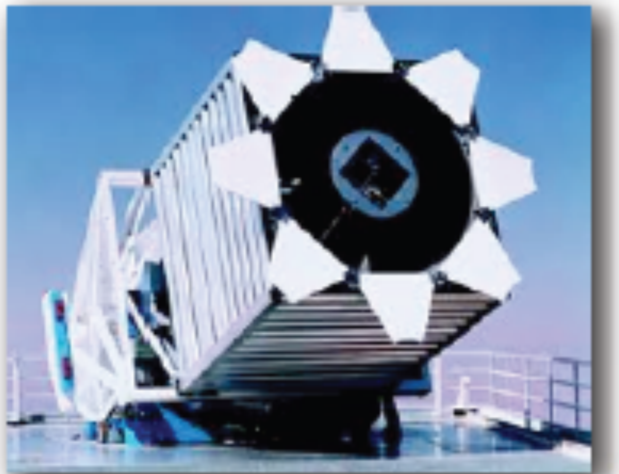
MaNGA

SDSS-IV

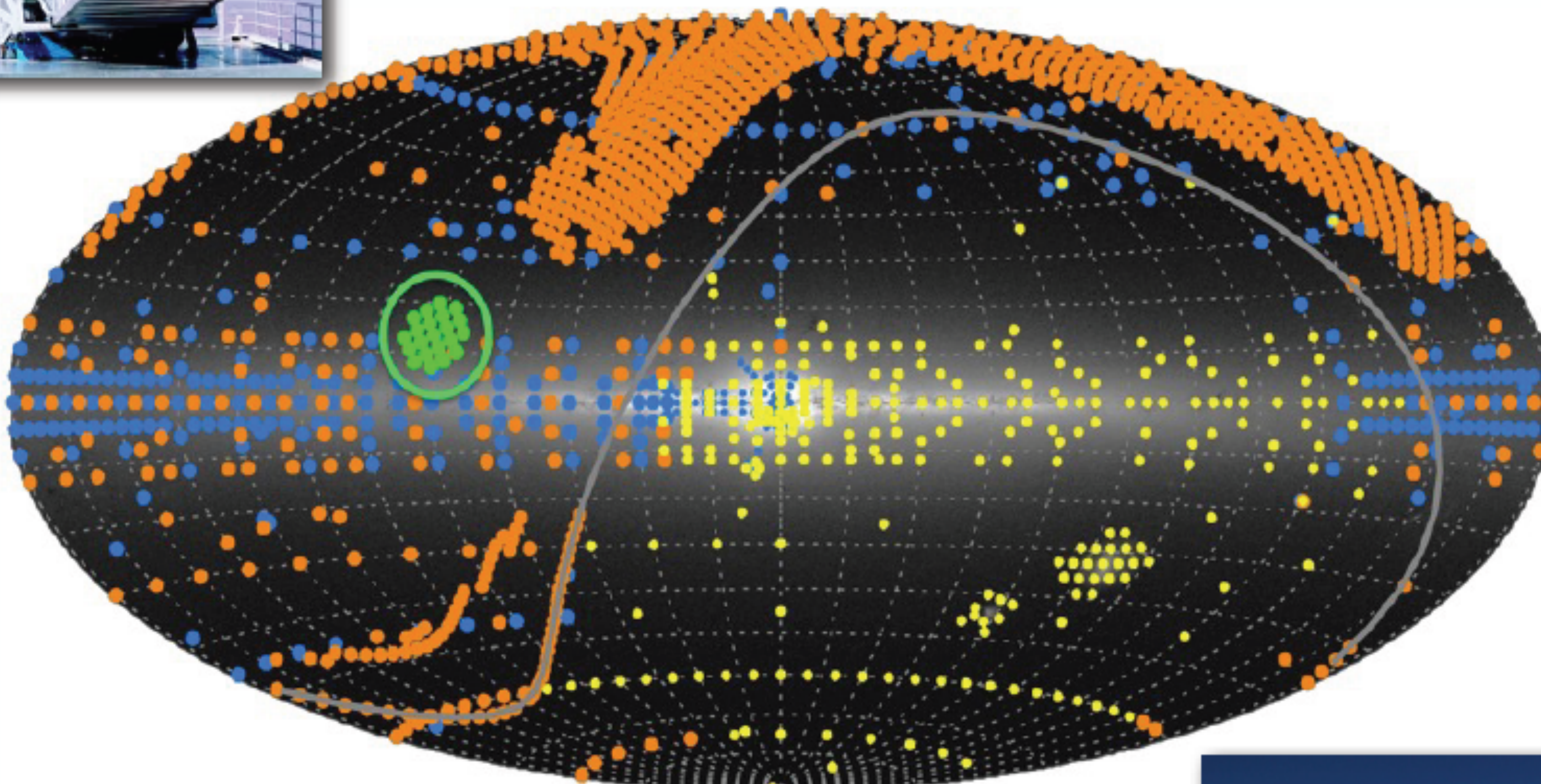


SDSS Telescope

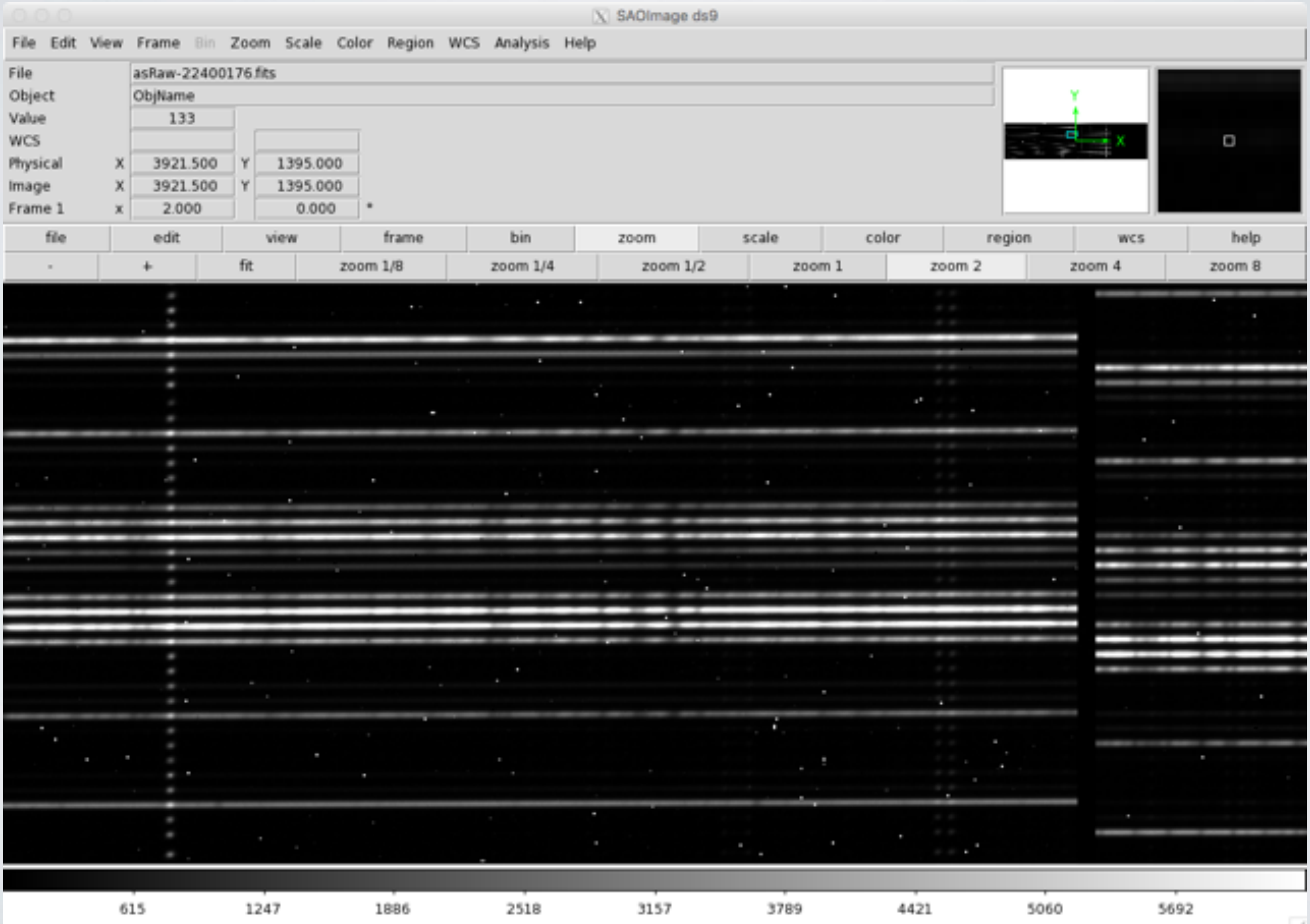
Carnegie's duPont Telescope



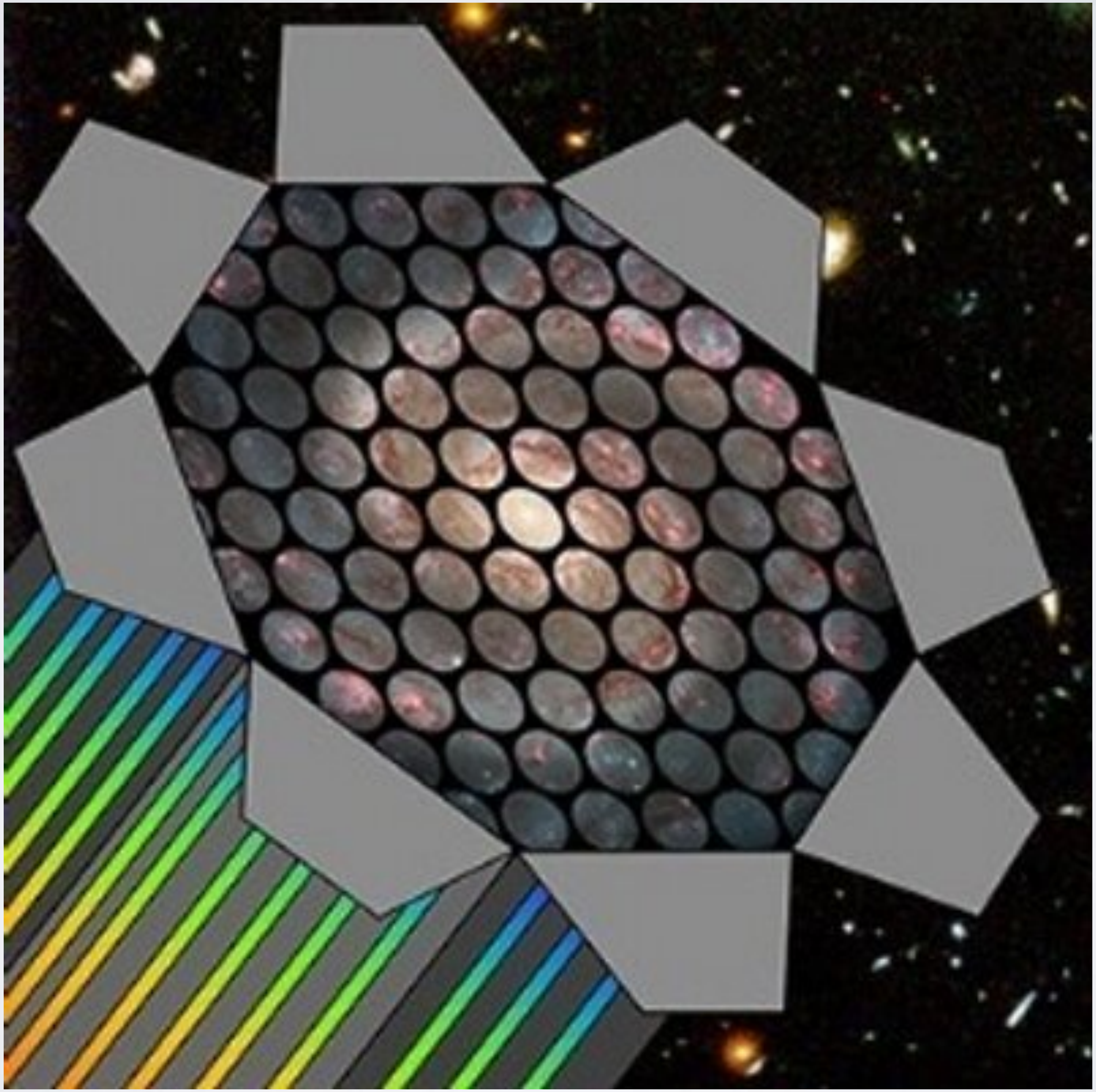
SDSS-IV Revolution #1: SDSS Goes "All Sky"!



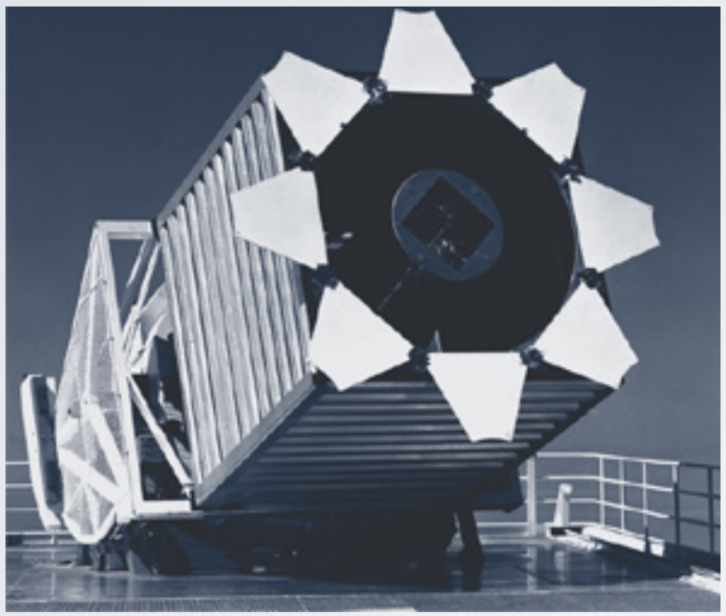
FEBRUARY MILESTONE! APOGEE-S WORKS!!!



SDSS-IV Revolution #2: SDSS Goes "Contiguous"!



CURRENT HARDWARE



2 **BOSS** spectrographs:
- 1000 fibers each
- R~2000
- 3600-10,400 Angstroms

APOGEE spectrograph:
- 300 fibers
- R~22,500
- 1.5-1.7 micron

MaNGA IFUs:
- 17 IFUs across 7deg^2 field
- 127 fibers/IFU

APOGEE-2 spectrograph:
- 300 fibers
- R~22,500
- 1.5-1.7 micron

Other non-survey instruments

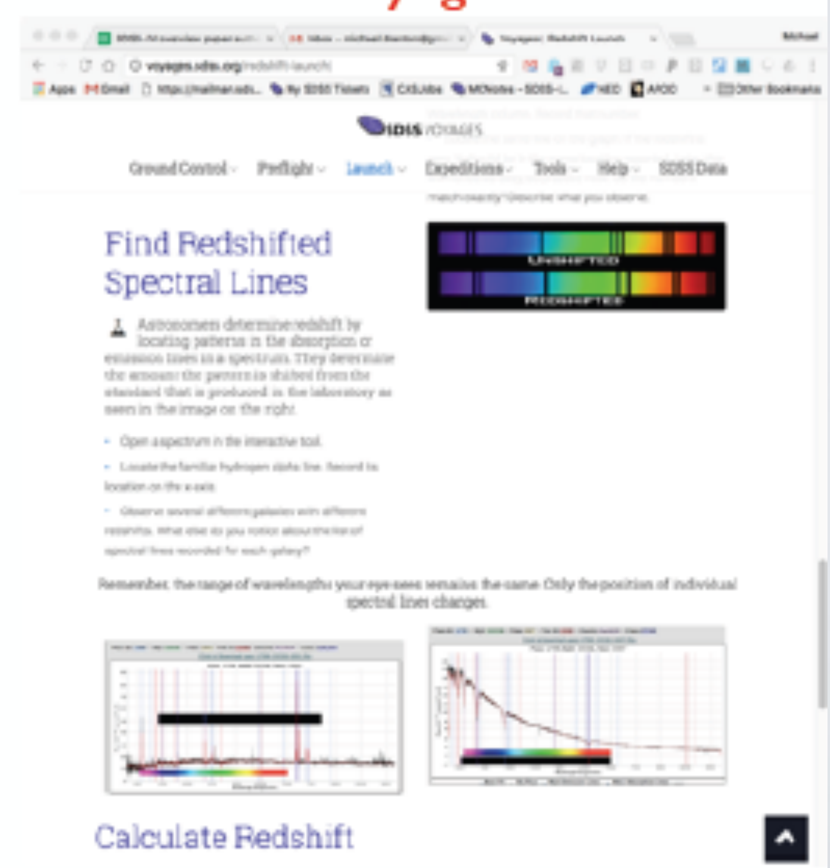
TAKING DATA NOW!!!

Public Data Releases

- First in 2001, latest in July **2017** (**DR14**), next planned in July **2018**
- Large science impact:
  - *> 7,000 papers involving SDSS data*
  - *~ 80% are outside collaboration*
- Comprehensive system serving many audiences:
  - *millions of queries per year*
  - *500 helpdesk requests per year*
  - *1000s of students*

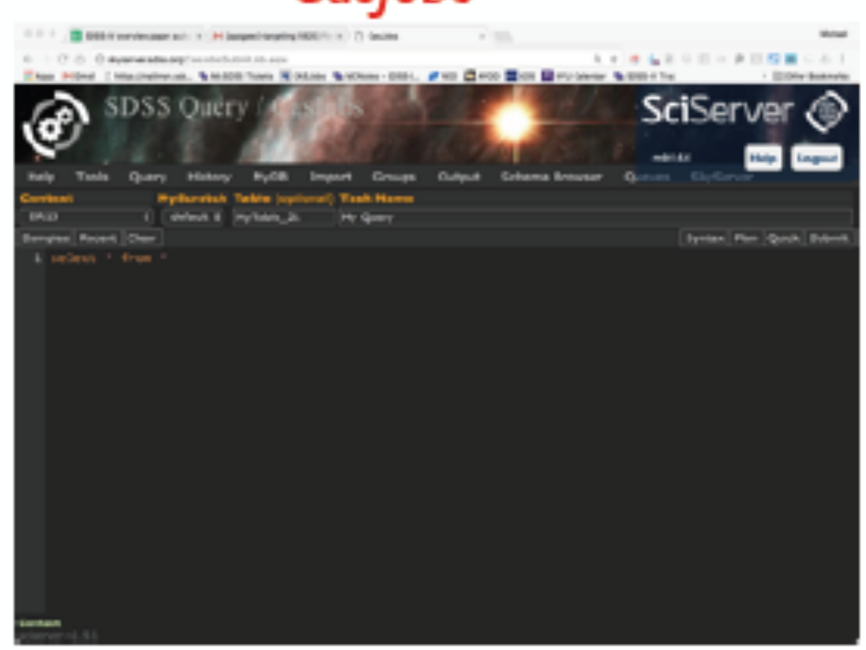
Science Archive Server

Voyages



SkyServer

CasJobs



WHAT NEXT? "AS4" = AFTER SDSS-IV

- SDSS-IV goes through mid-2020
- Planning process initiated by ARC through its Futures Committee
- SDSS is a SCIENTIFIC COLLABORATION not an Institution
- Each incarnation needs to be created "anew" based on the scientific needs and interests in the field
- Is there a "peerless Next"?

3/2016

SC Formed

Juna Kollmeier (Chair)
Conny Aerts
Scott Anderson
Matt Bershady
Mike Blanton
Dan Eisenstein
Dani Maoz
Hans-Walter Rix
Connie Rockosi
David Weinberg
Bruce Gillespie (ex officio)
Rene Walterbos (ex officio)

5/2016

Calls for Letters of Intent

Proposal Writing Workshops

9/2016

Calls for Full proposals

10/2016

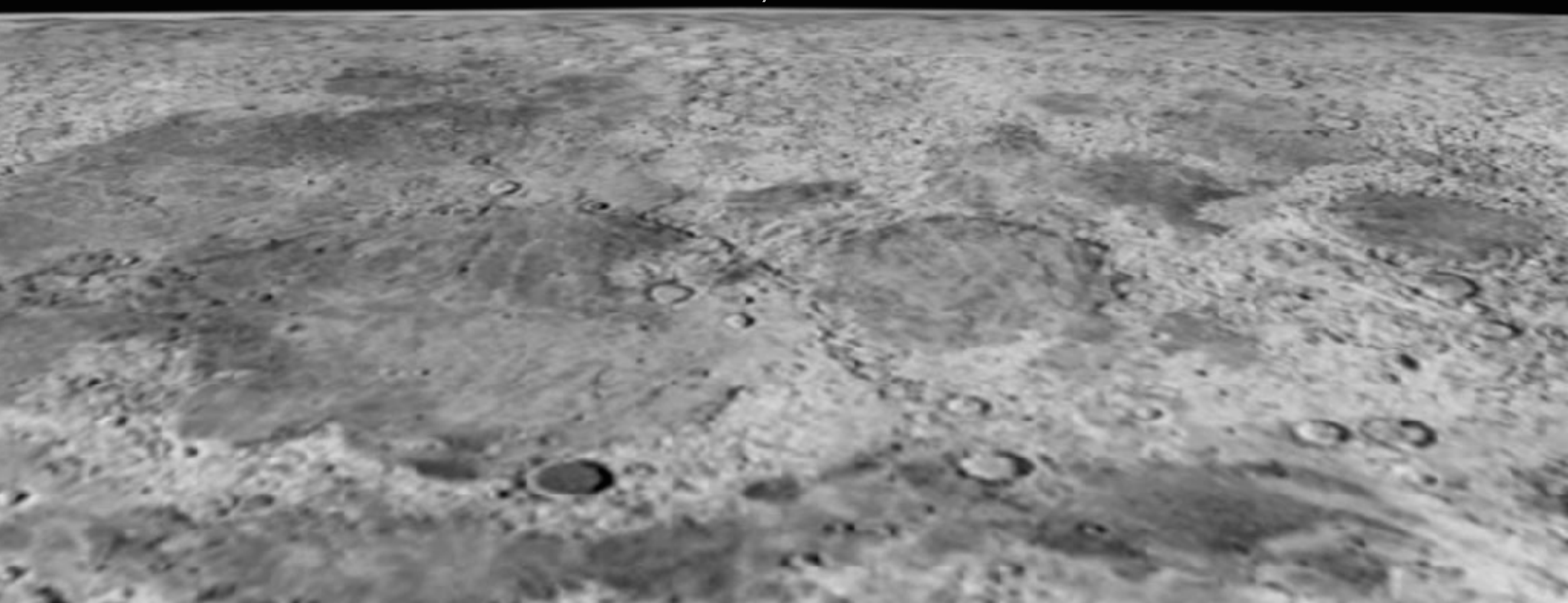
External Reviews complete October 19

11/2016

Recommendations to ARC/OCIS

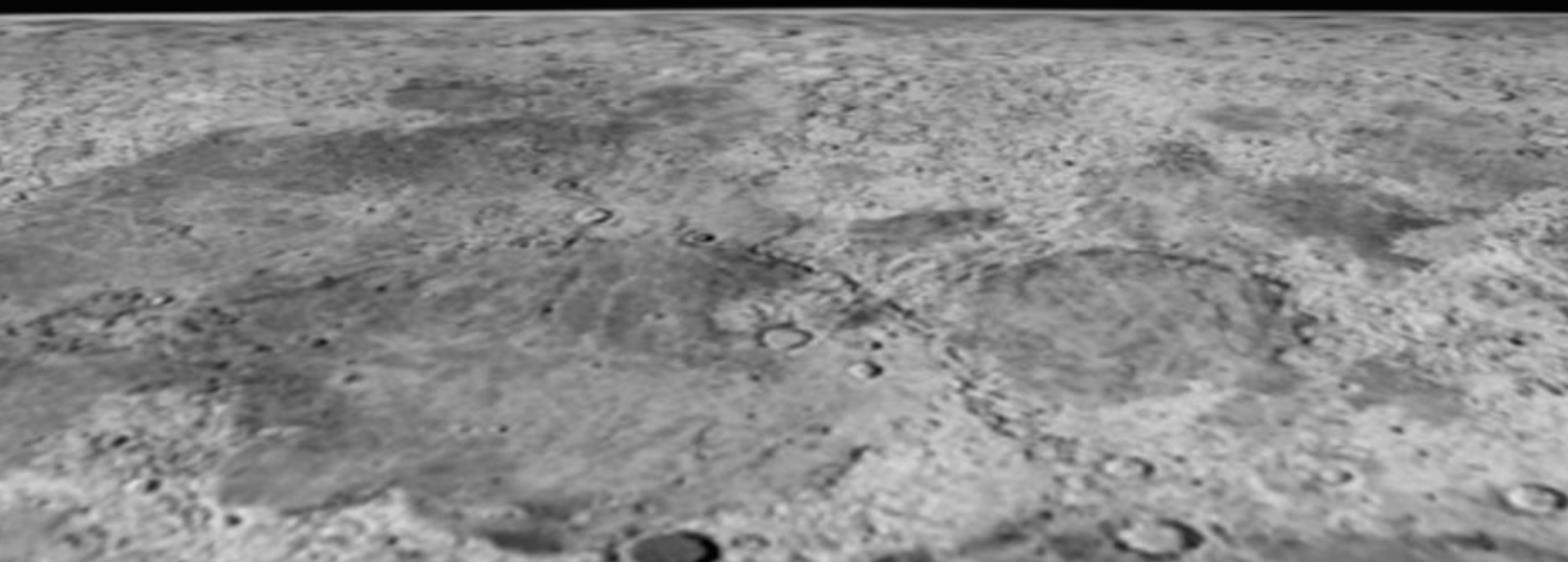
ASTRO LANDSCAPE 2020-2025

—Time Domain Astronomy
—Big Data Science in Astrophysics
—Stellar Astrophysics Revolution
—Gravitational Wave Astronomy



WHAT ROLE WILL SDSS PLAY IN THIS EPOCH?

1. Wide-field infrared capability (totally unique)
2. Dual Hemisphere coverage
3. Gold-standard for collaboration infrastructure, data archive & distribution



3/2017 — 6/2017 — 9/2016 — 11/2017 — Now

MC Formed

Juna Kollmeier (Director)
Hans-Walter Rix
Gail Zasowski
Scott Anderson
Niv Drory
Jennifer Johnson
Jon Bird
Guillermo Blanc
Nathan DeLee
Kathryn Kreckel
Andrea Merloni
Melissa Ness
Yue Shen
Andrew Tkachenko

Proposal to Sloan Foundation

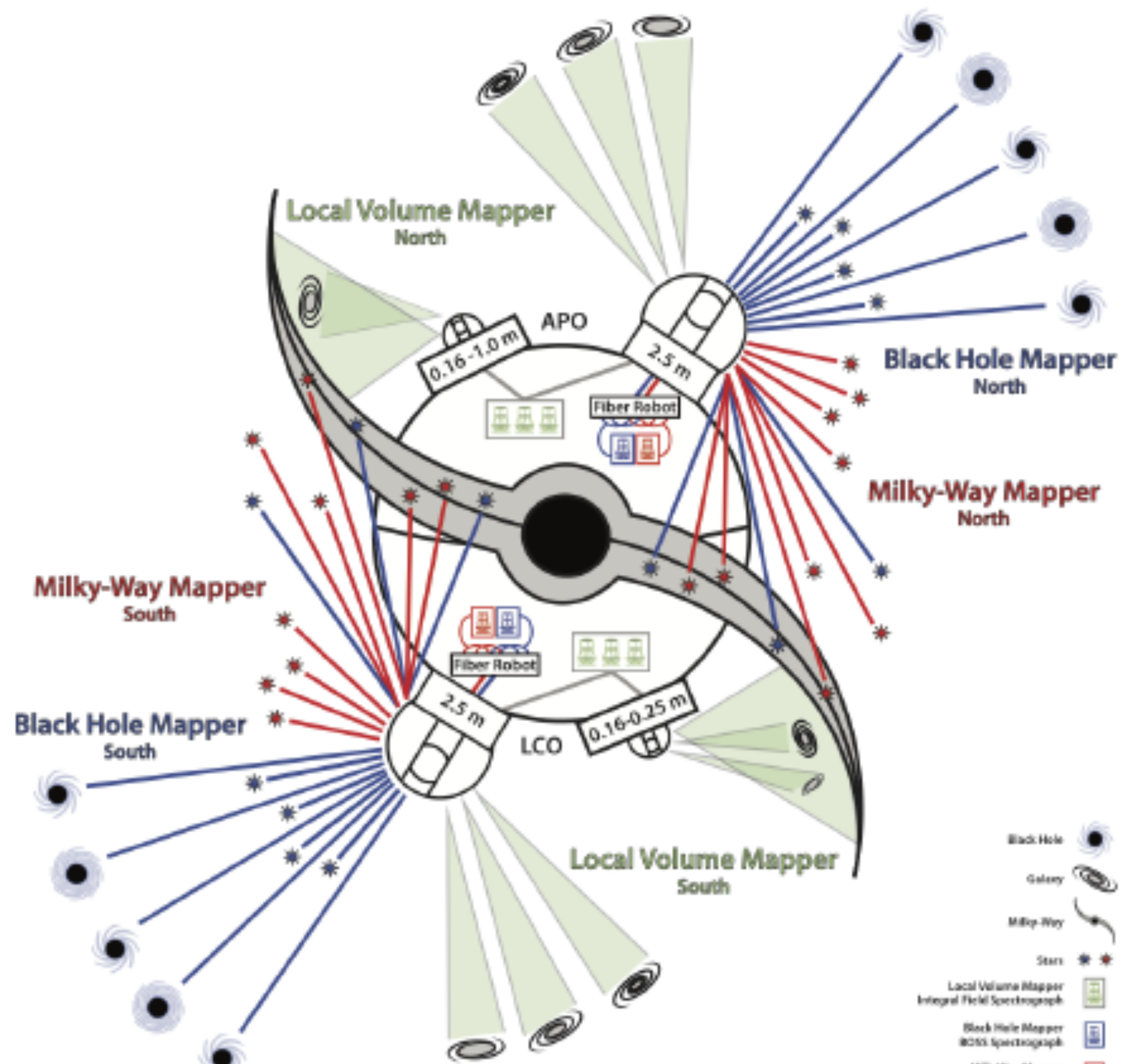
External Reviews complete

SDSS-V!

GO!

The Project

- 5-year program beginning mid-2020 in both hemispheres
- 3 Science Programs:
    - Milky Way Mapper, Black Hole Mapper, Local Volume Mapper
- 2 infrastructure builds (FPS + LVM) in 2 Hemispheres



Credit M. Seibert

Details

Program	Science Targets	$N_{Objects}$ and/or Sky Area	Primary Spectral Range and Hardware	Primary Science Goals
Milky Way Mapper (MWM)	Stars across the Milky Way	>6M stars; all-sky	IR; APOGEE ($R \sim 22,000$) with fiber-positioning system	Understanding the formation of the Milky Way and the physics of its stars
Black Hole Mapper (BHM)	Primarily supermassive black holes	>400,000 sources; all-sky	Optical; e.g., BOSS ($R \sim 2000$) with fiber-positioning system	Probing black hole growth and mapping the X-ray sky
Local Volume Mapper (LVM)	ISM & stellar populations in the MW, Local Group, and nearby galaxies	>25M contiguous spectra over 3,000 deg^2	Optical; new integral field spectrographs covering 3600-10000Å at $R \sim 4000$	Exploring galaxy formation and regulation by star formation; feedback, enrichment, & ISM physics

Space Missions

Wide-field Space Missions			
Mission	Science Goals / Data Products	Timeframe	primary magnitude range
Kepler/K2	(transiting) exoplanets & stellar astrophysics (seismology) from precision lightcurves	2009-2018	$m_V \sim$ 7-17; selected fields
Gaia	positions, distances, motions from astrometry; basic stellar parameters	2013-2020	$m_G \sim$7-17; all-sky
TESS	(transiting) exoplanets & stellar astrophysics (seismology) from precision lightcurves	2018-2022	$m_i \sim$ 8-14; $\sim$ all-sky
eROSITA	X-ray fluxes & spectra	2018-2022	$f^{lim}_{0.5-2keV} \sim 10^{-14} erg/s/cm^2$; $\sim$ all-sky

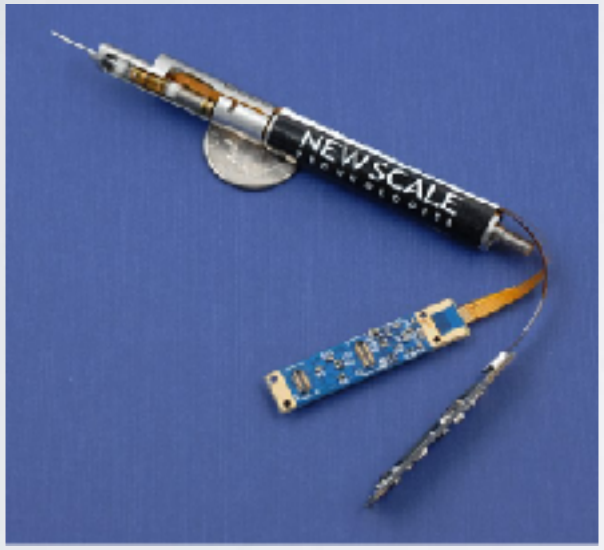
Spectroscopic Surveys

Spectroscopic Survey Facilities around the Year 2020								
Survey (facility)	N_{target}	R_{spec}	N_{res}	$\overline{\lambda}[\mu m]$	Ω_{sky}	N_{epoch}	Timeframe	$m_{primary}$
SDSS-V	7×10^6	22,000 2,000	500	1.51-1.7 0.37-1	4π	$4-60$	2020-2024	$m_H \leq 12$ $m_G \leq 18$
Gaia (RVS)	2×10^6	8000	270	0.85-0.87	4π	~ 60	2013-2020	$m_G \leq 12$
Gaia-ESO	0.1×10^6	$17,000$	140	0.55& 0.85	0.02π	~ 1	2013-2018	$m_G < 17$
GALAH	0.8×10^6	$28,000$	400	0.40- 0.85	π $\|b\| > 10$	~ 1	2015-2020	$m_G \leq 13$
WEAVE	0.8×10^6	$5,000$& 20,000	1000	0.37-0.9	$\sim \pi$	$\sim 1-2$	2018-2023	$m_G < 19$
DESI	8×10^6	$3,000$	5000	0.36-0.98	$\sim \pi$ $\|b\| \geq 25$	$\sim 1 \quad 2$	2019-2024	$m_G \leq 19$
LAMOST	8×10^6	$1,800$	4000	0.4-0.9	0.5π	~ 1	2010-2020	$m_G \leq 16$
4MOST	10×10^6	$5,000$& 20,000	1600& 800	0.4-0.9	1.5π	$1-2$	2023-2028	$m_g \leq 21$ $m_V < 16$
APOGEE-1& -2	5×10^5	22,000	300	1.51-1.7	0.5π	~ 4	2011-2019	$m_H \leq 12$
PFS	1×10^6	$3,000$	2400	0.4-1.6	0.05π	1	2018-2021	$m_g \leq 22$
MOONS	2×10^6	$5,000$& 20,000	1000	0.6-1.8	0.05π	1	2020-2025	$m_g \leq 22$ $m_H < 17$

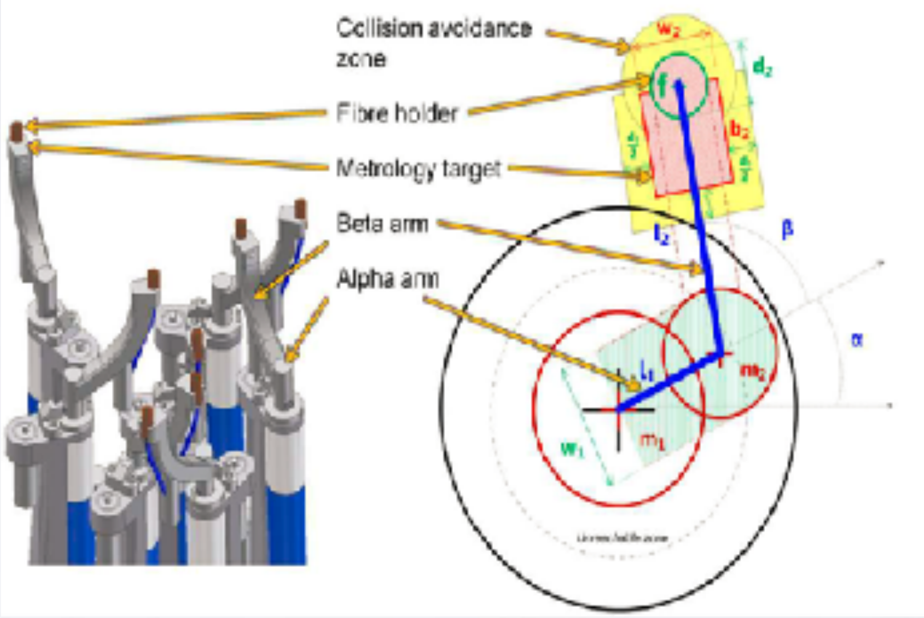
O + IR ; ALL SKY ; TIME DOMAIN!

FIBER ROBOT: WHY NOW?

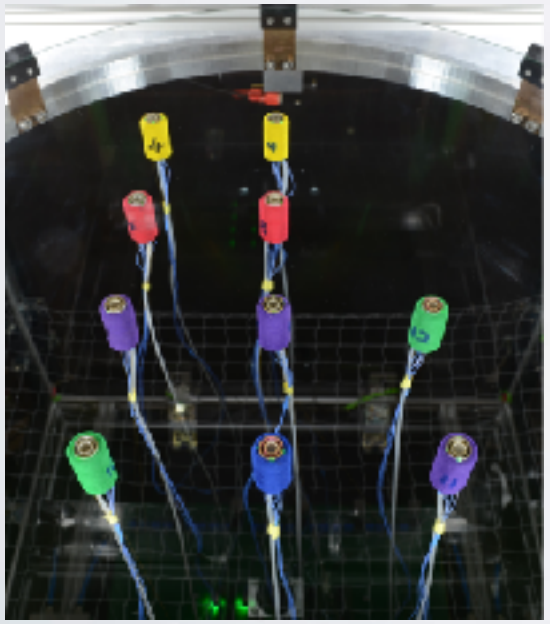
External Technology development (due to investments from large cosmology experiments) has made the technology more mature & robust



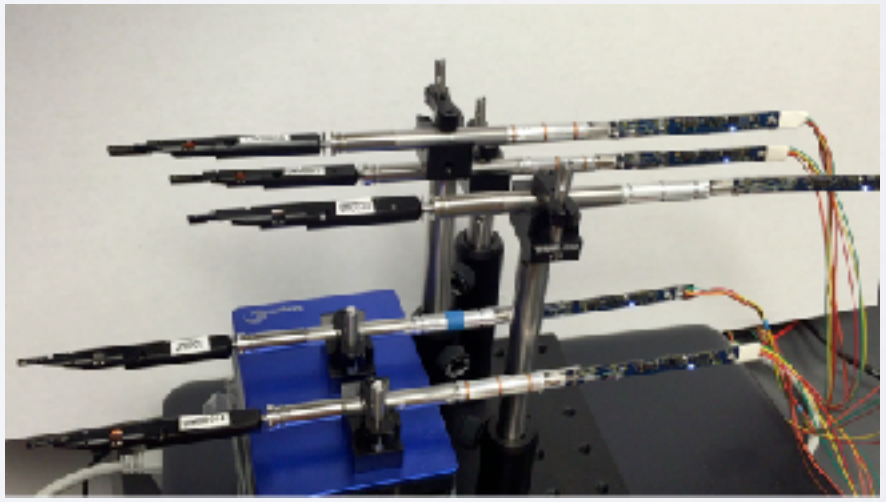
PFS Positioners



MOONS

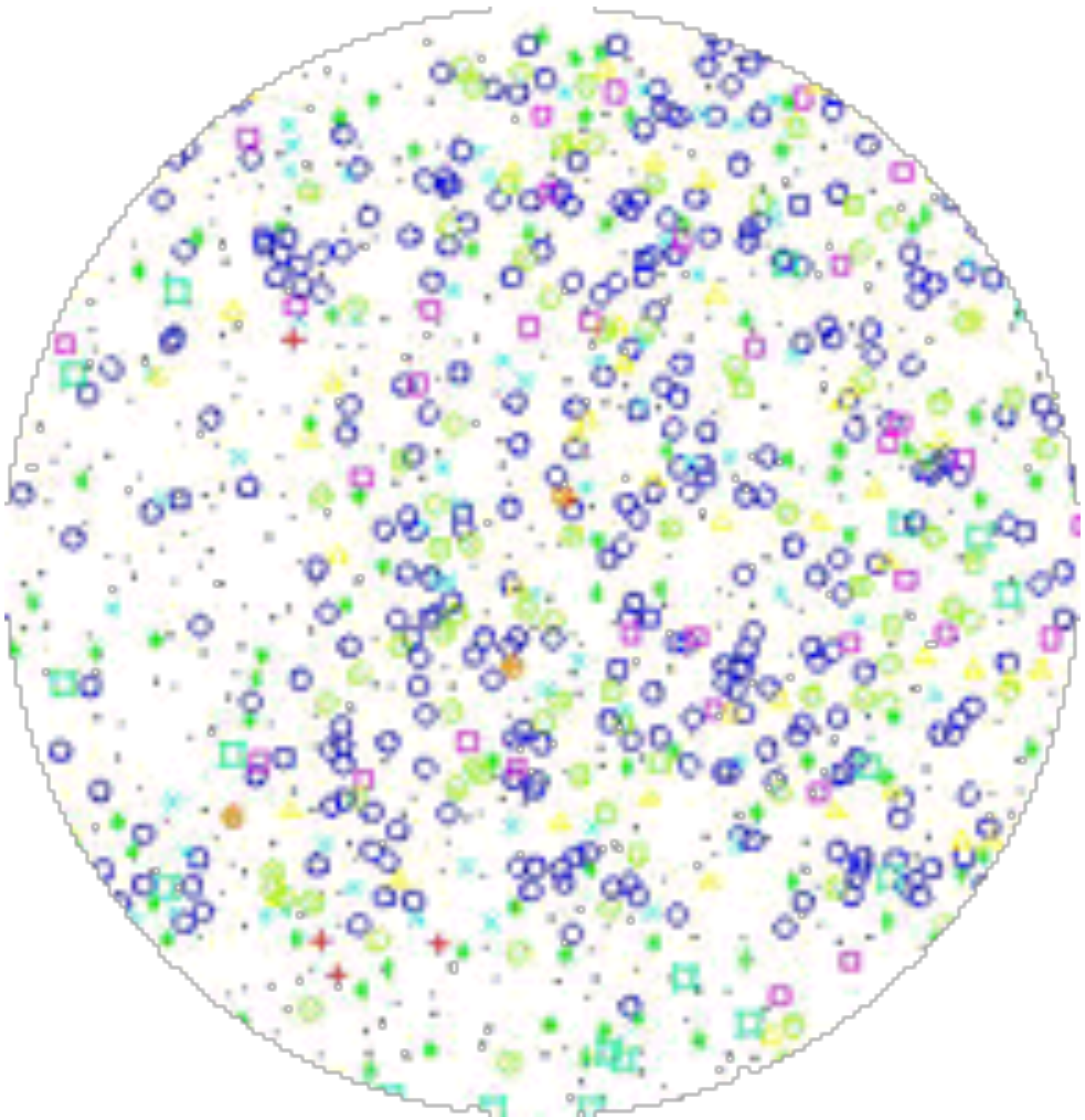


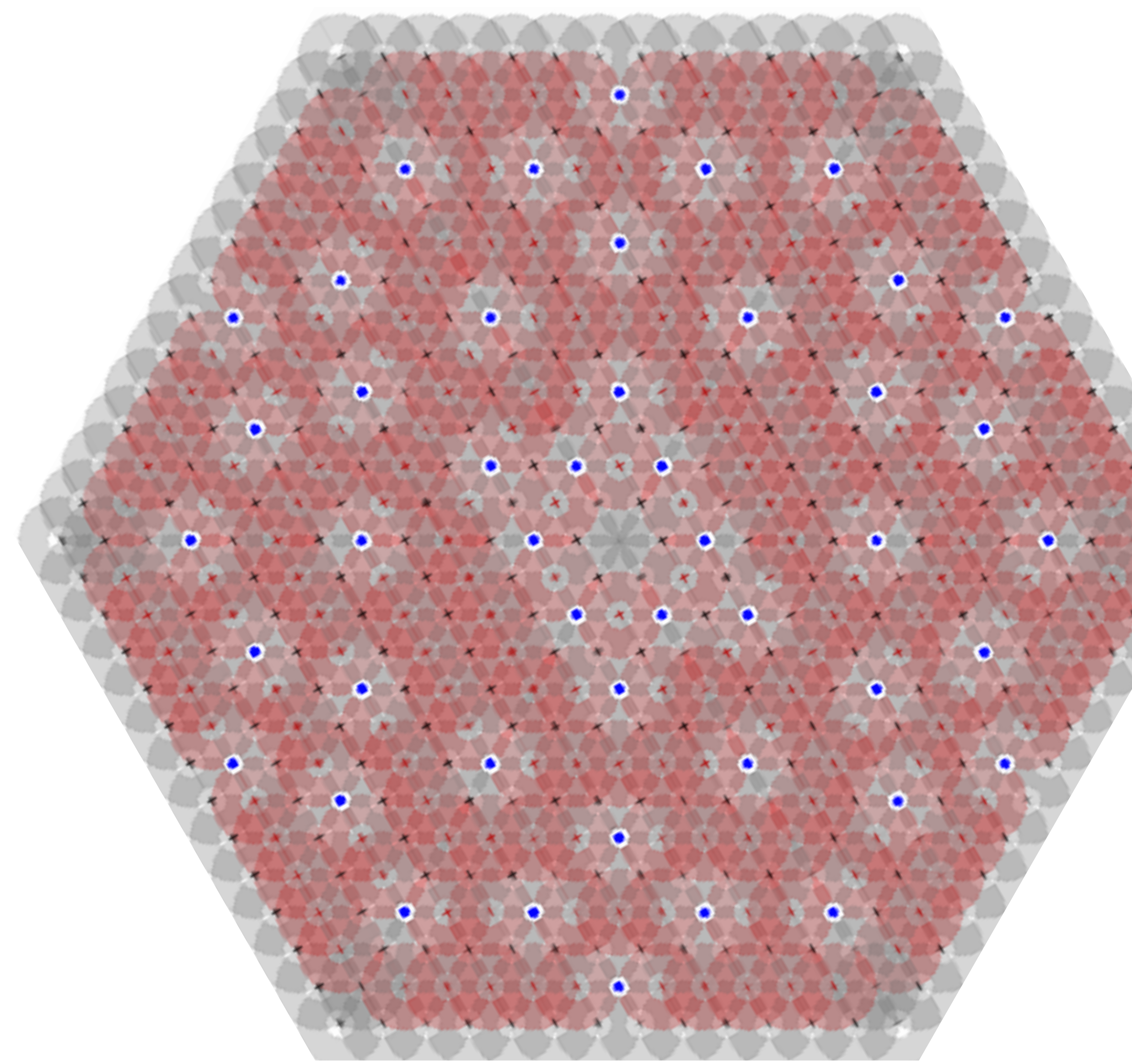
Starbugs



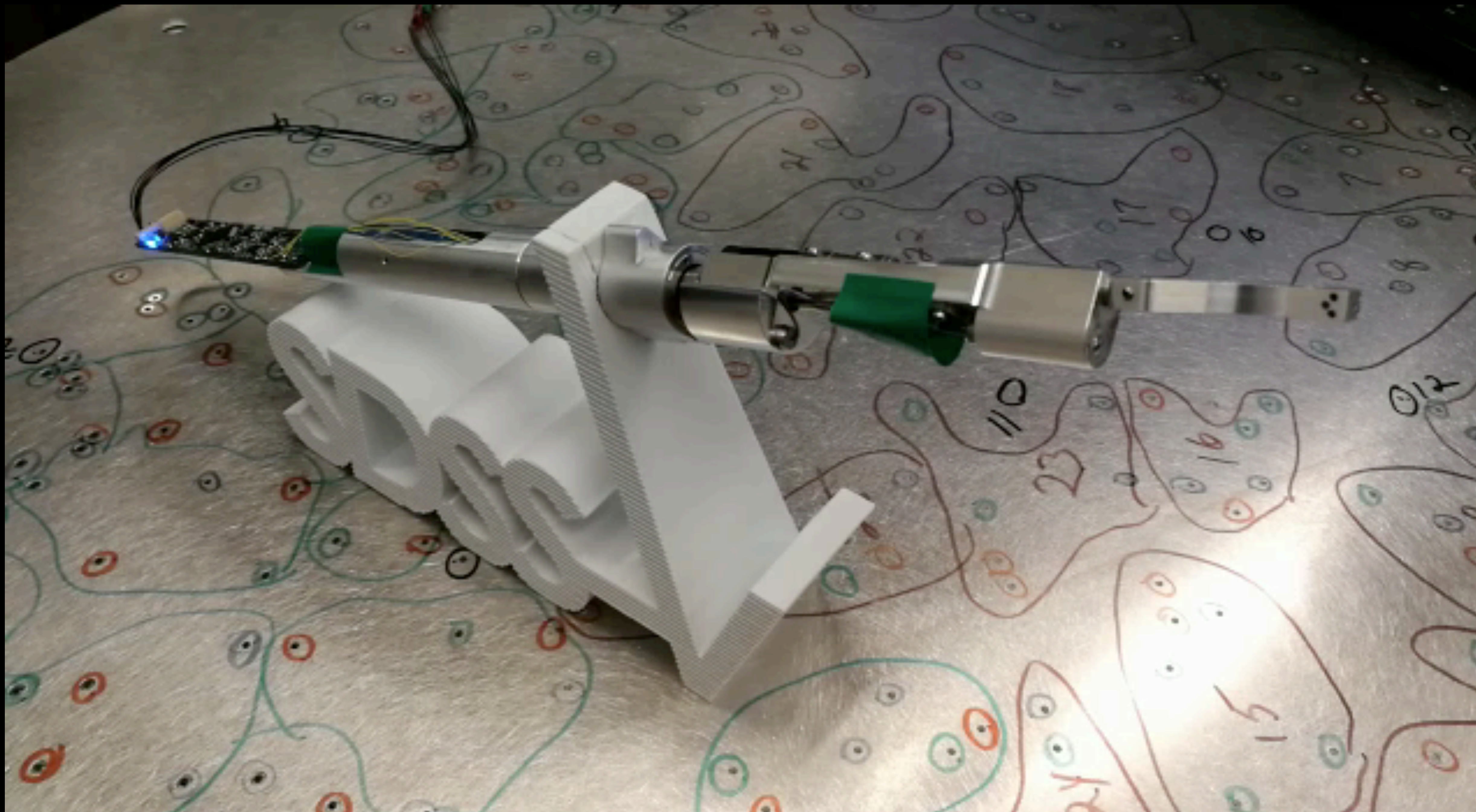
DESI

ROBOTIC FIBER POSITIONERS TO FEED SPECTROGRAPHS





SDSS-V PROTOTYPE!

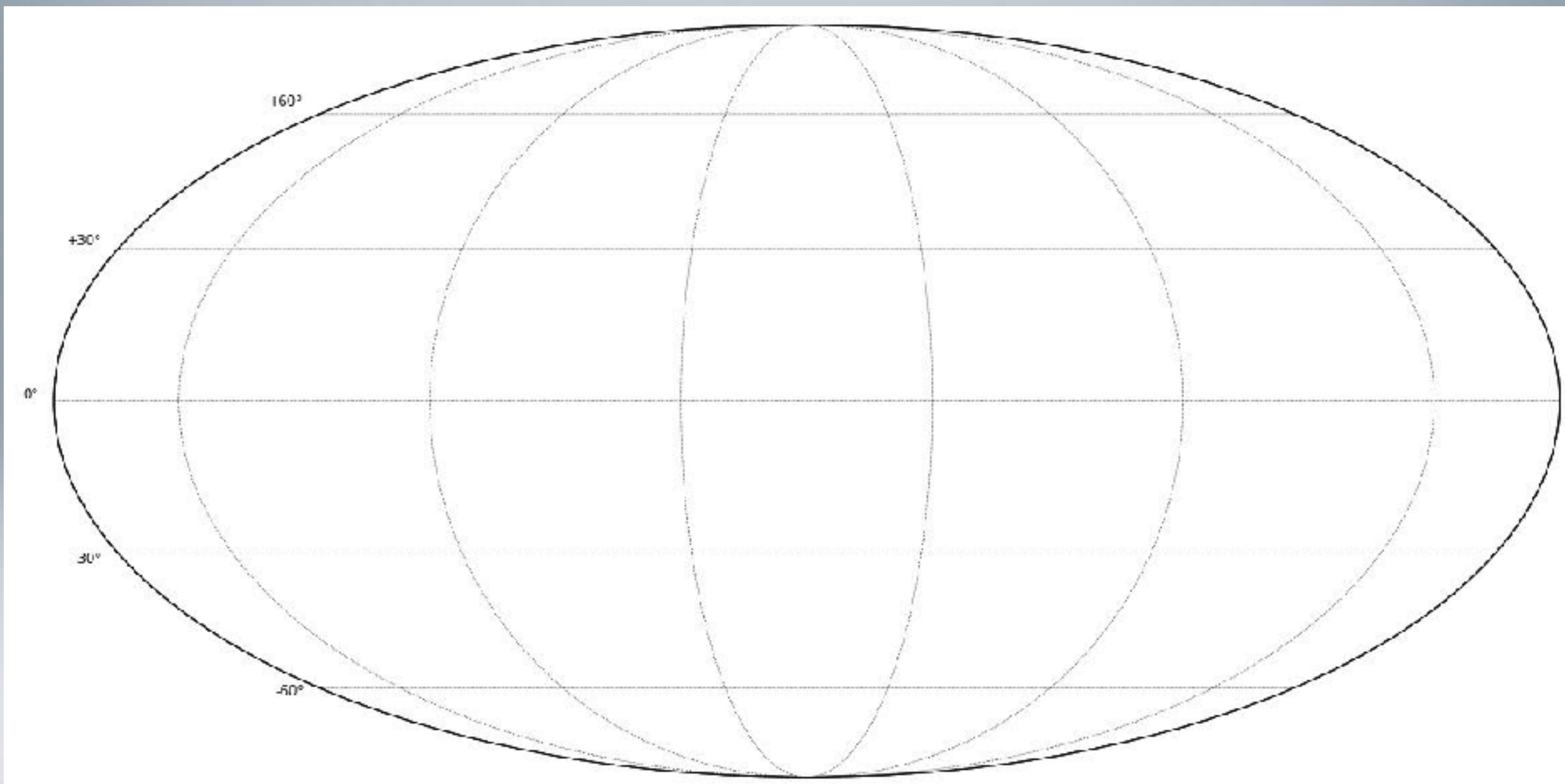


Courtesy J-P Kneib & EPFL Team

AS4 OPERATIONS

Spectroscopic Time Domain Astronomy

2 minute reconfiguration time + 13 minute exposure time



Movie from Mike Blanton

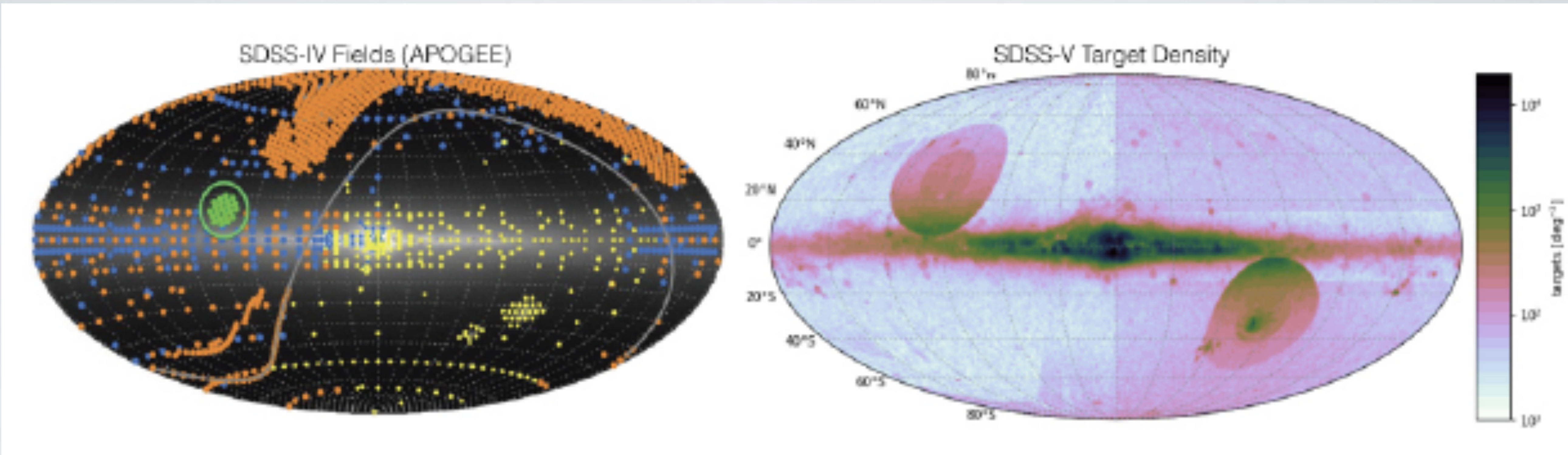
Not the targeting plan!

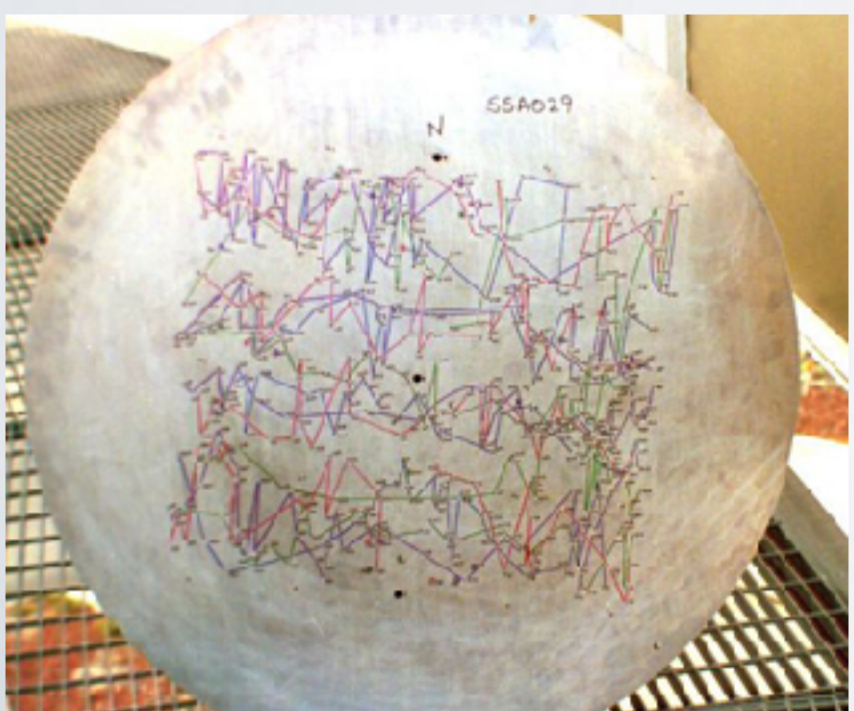
Bright Time

Dark Time

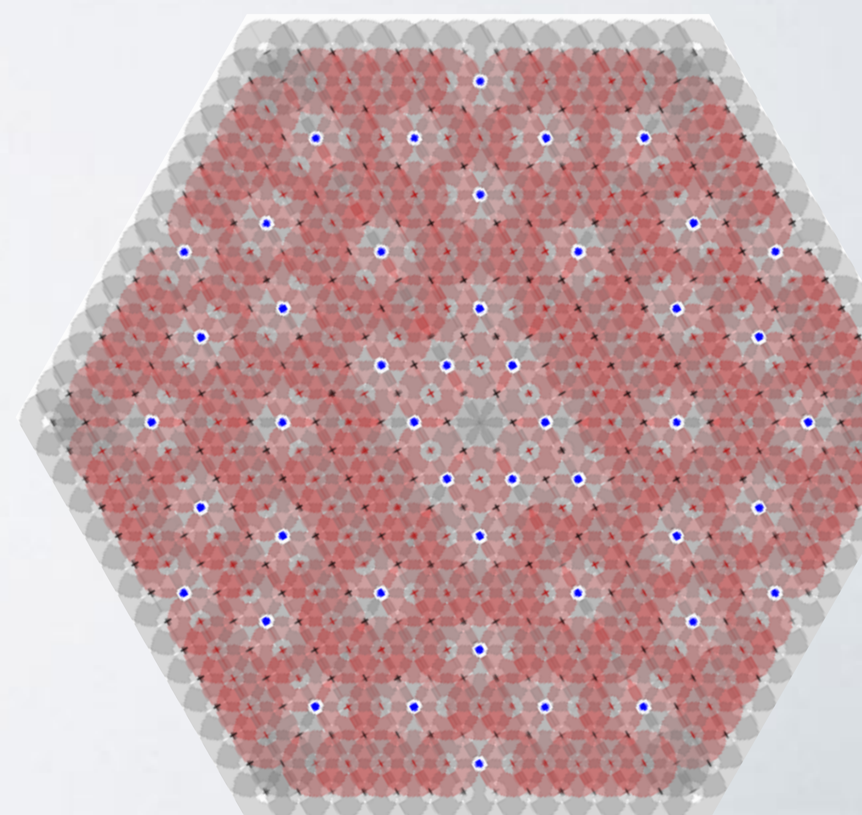
PLATES —> ROBOTS

EVOLUTION OF THE REVOLUTION

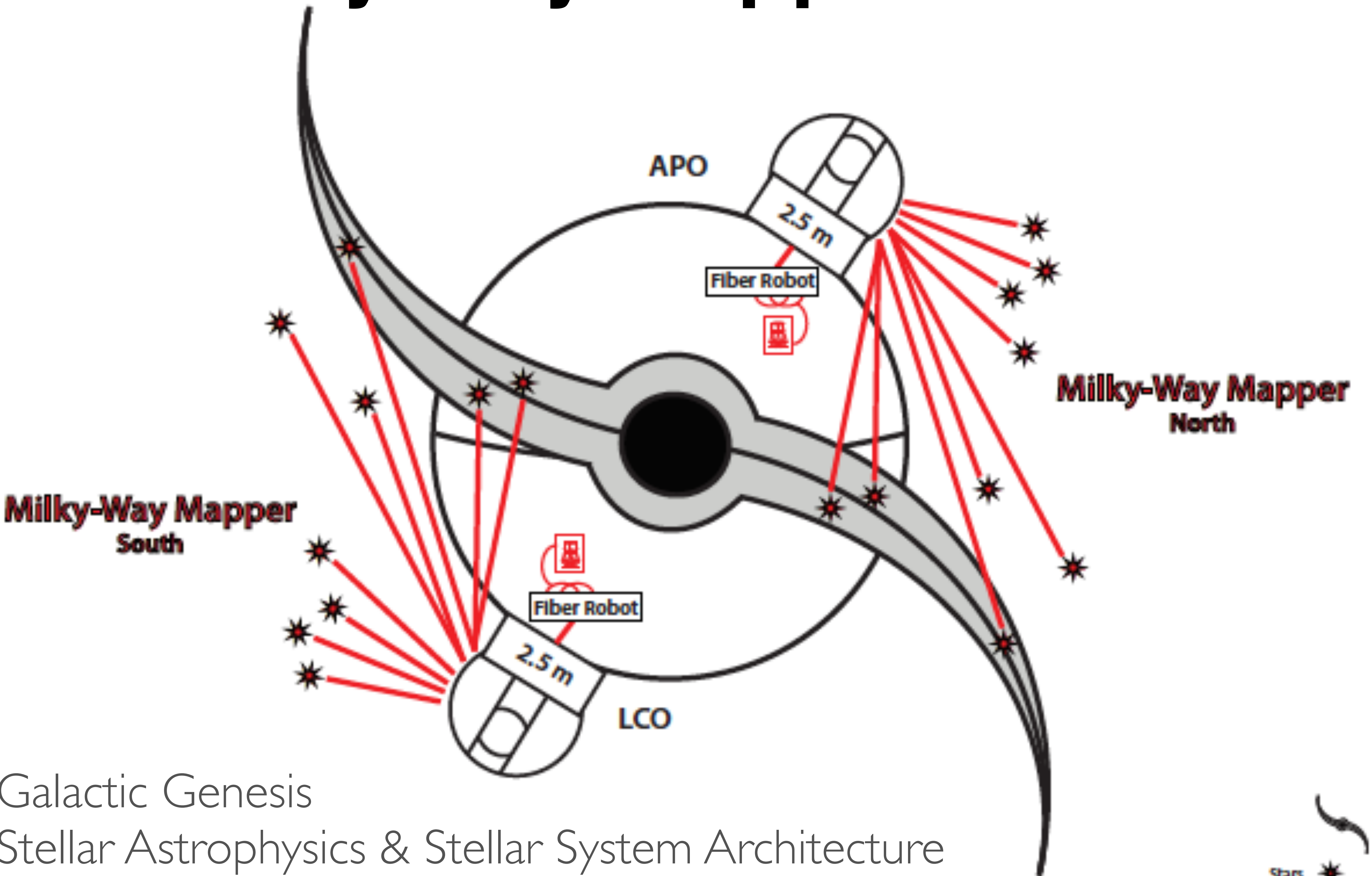




ALL Sky
Dust-Penetrating
Multi-epoch (1-60)
High-quality
spectroscopy



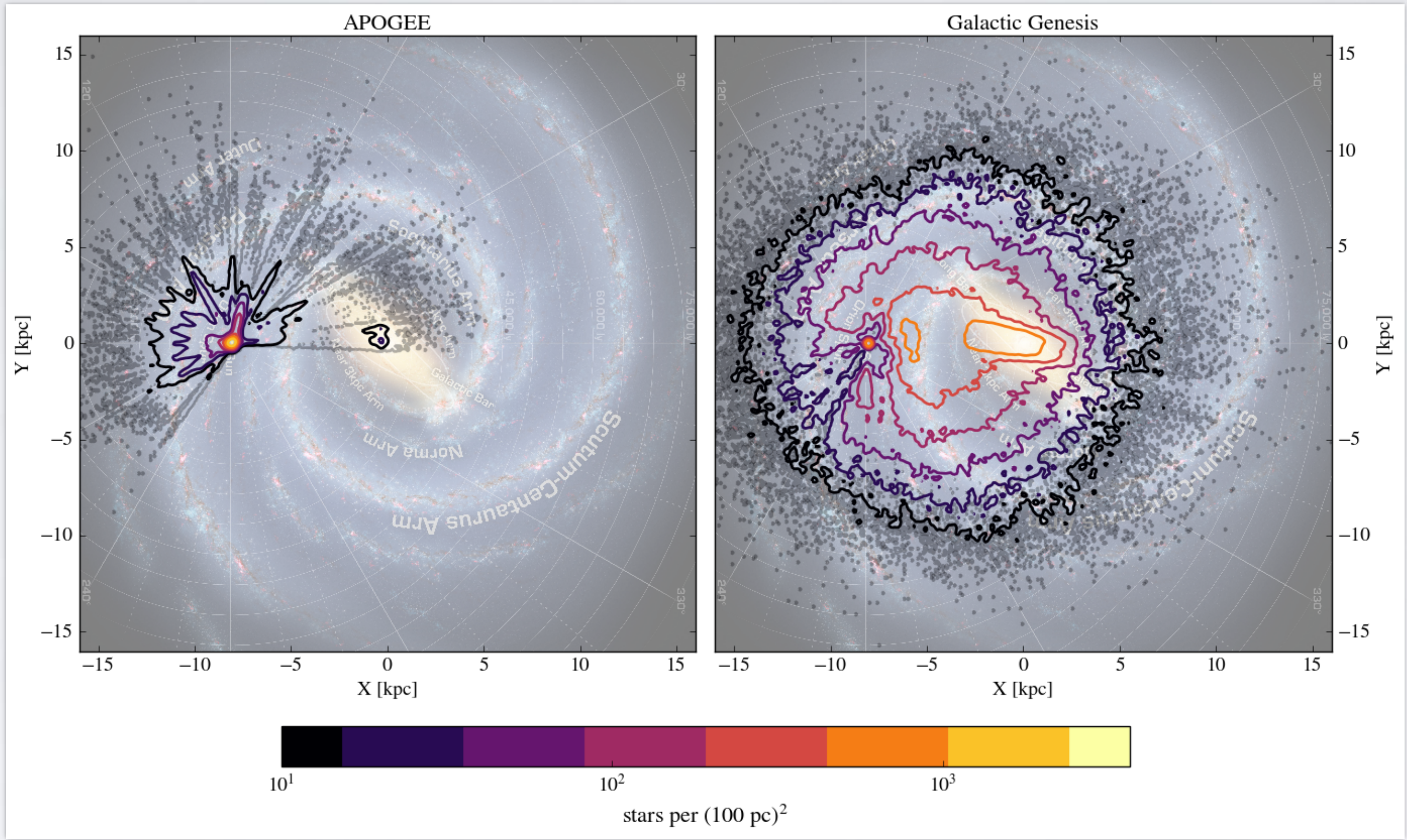
Milky Way Mapper: MWM



Galactic Genesis
Stellar Astrophysics & Stellar System Architecture
Young Stellar Objects

THE MAKING OF THE MILKY WAY: GALACTIC GENESIS

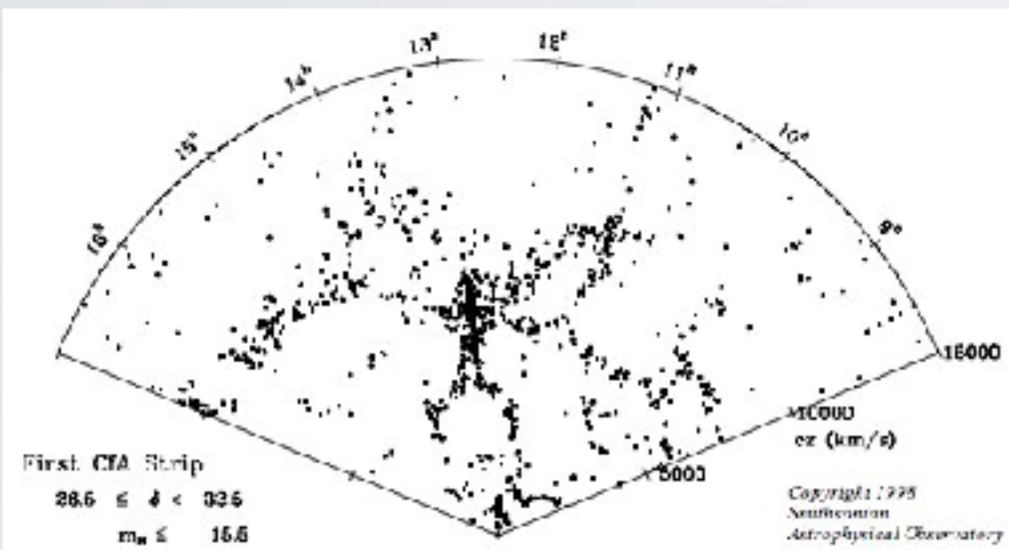
Exploiting **advances in Data Science** from SDSS-IV and **stellar physics** from time-domain surveys (e.g. asteroseismology, TDA)

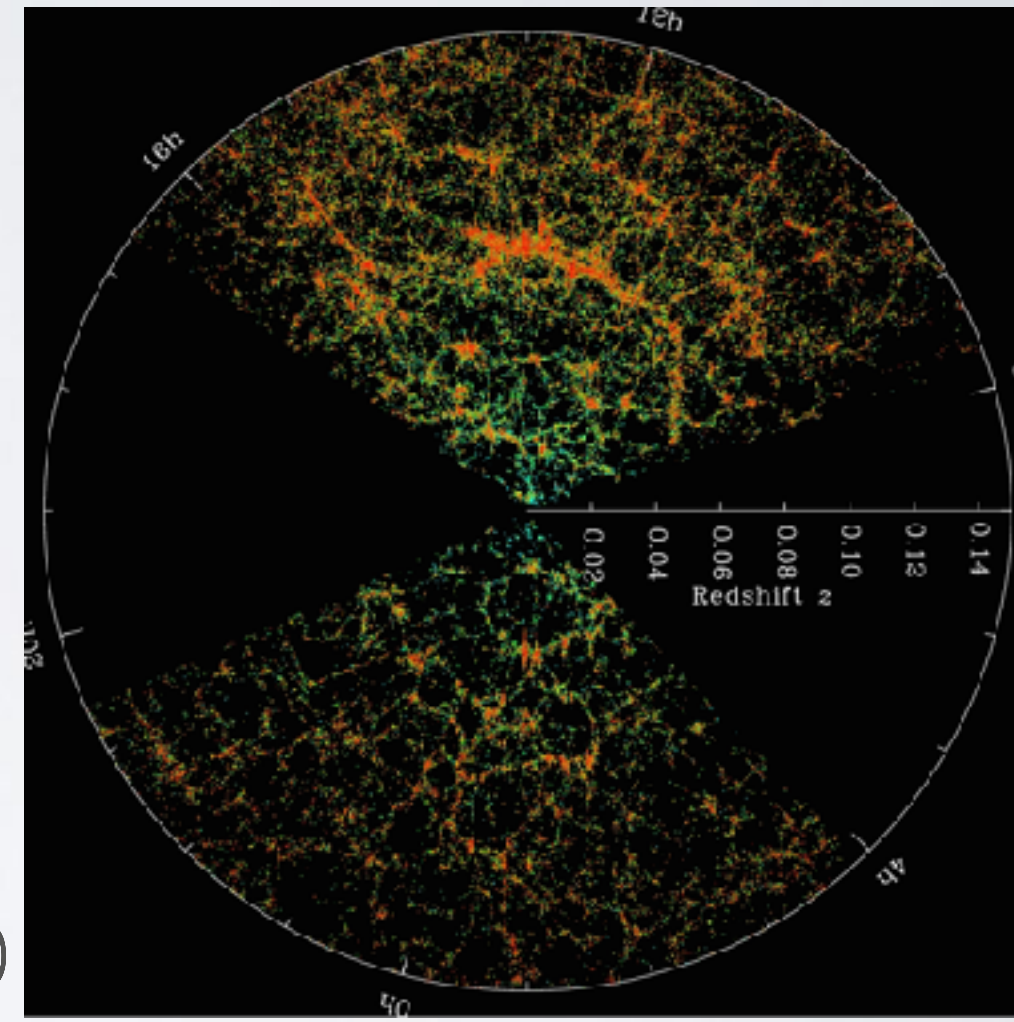


Chemodynamical mapping of the Milky Way and its Dust. Roughly 6 million stars. Shorter exposures of brighter (H<11) stars to enable **contiguous** full sky coverage

100-x improvement over State-of-the Art!

STELLAR ASTROPHYSICS UNDERGOING REVOLUTION





N~10000 → N~1,000,000

SDSS HAS OPPORTUNITY TO PLAY TRANSFORMATIVE ROLE

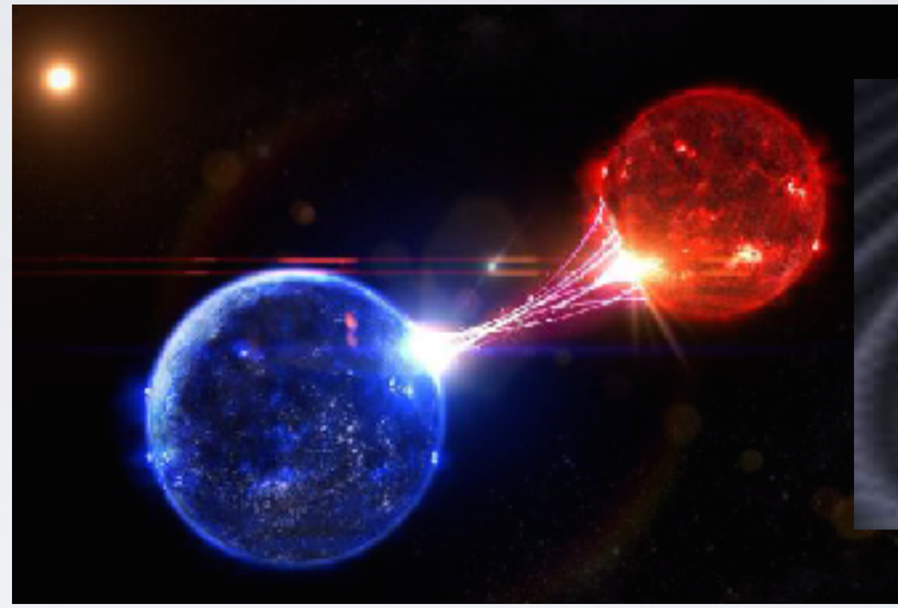
SCIENCE GOALS

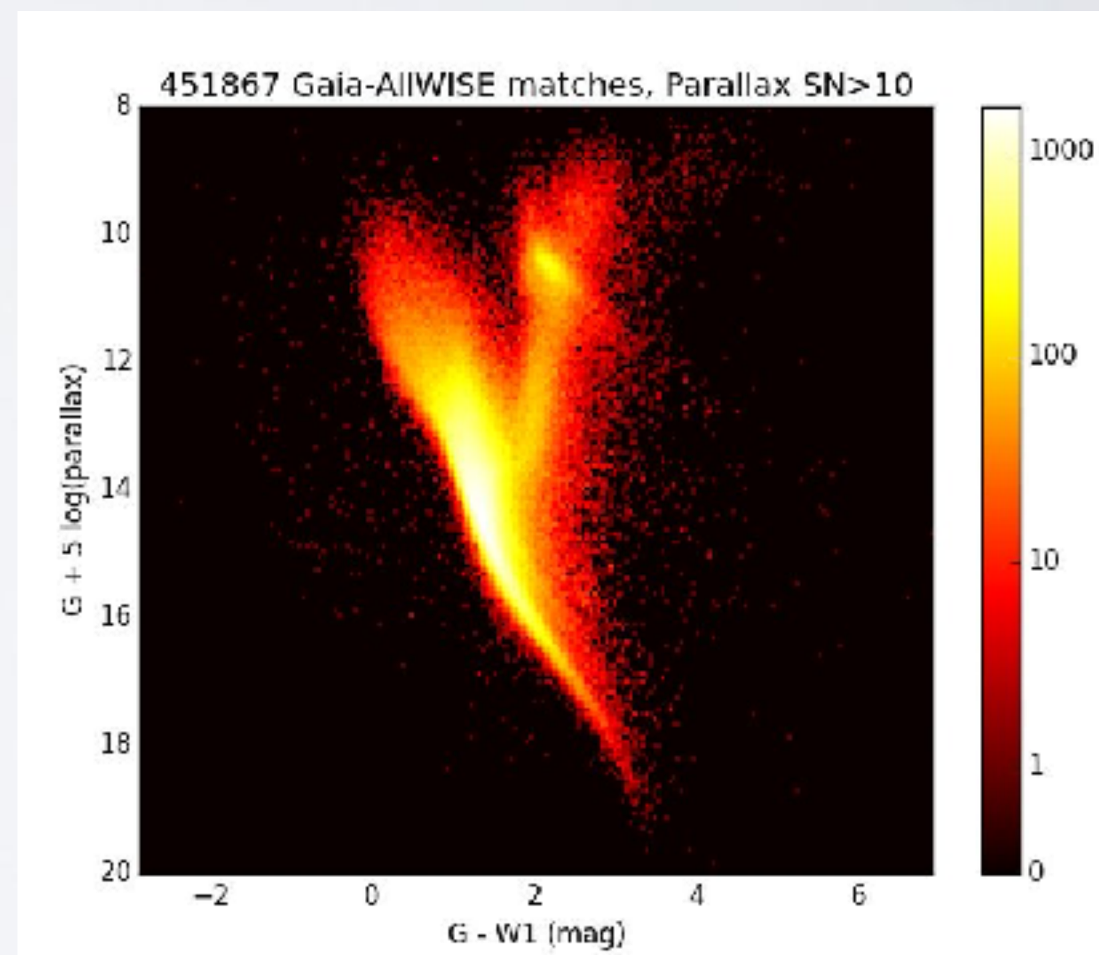
- **1) How do stars live, evolve, and die (and affect transient/GW universe)?**

- **2) What stars host planets?**

- **3) What IS the stellar multiplicity across the HR diagram? Role of binaries in Stellar Evolution**

- **4) Origin of Supernovae and the heavy elements**

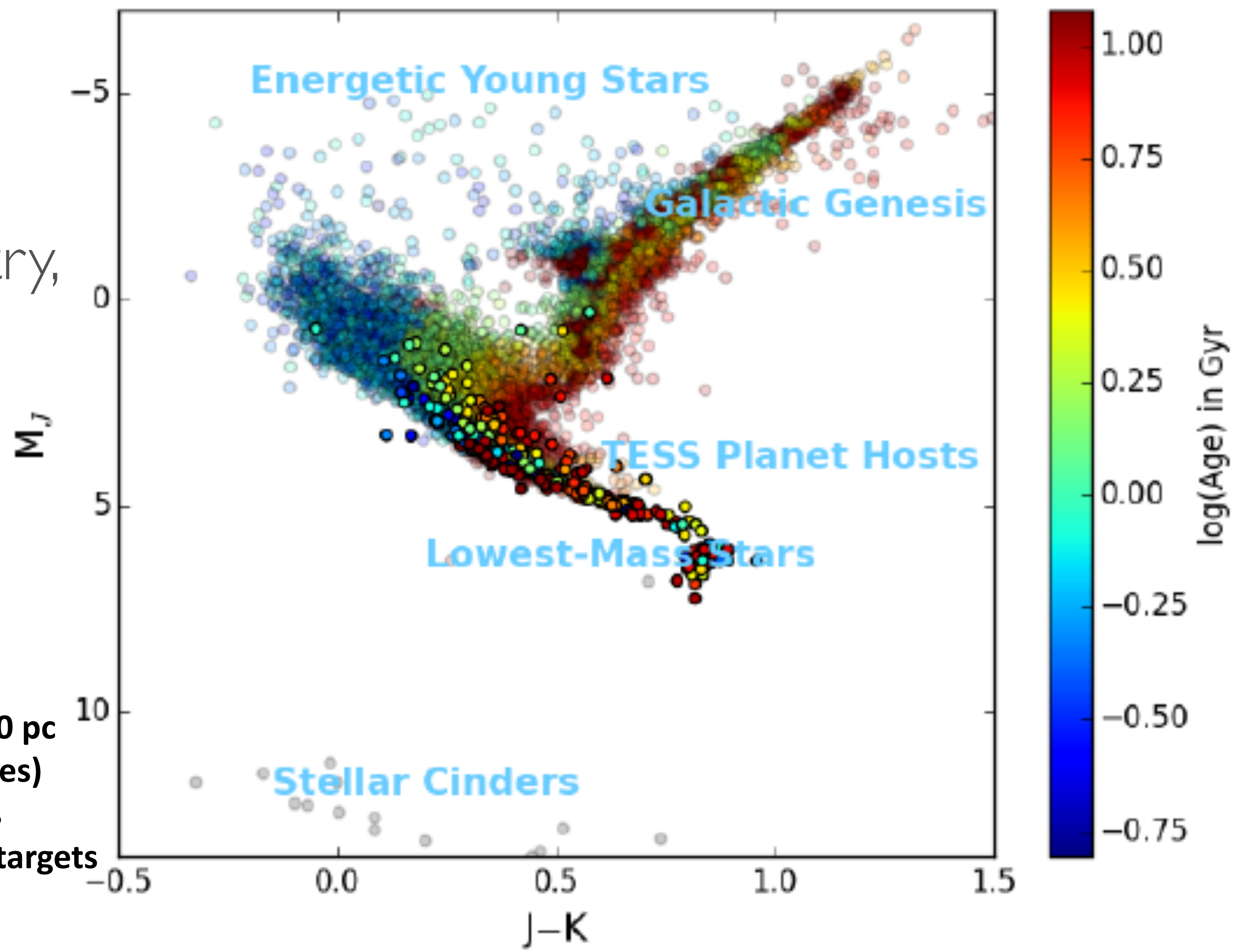




From D. Lang

STELLAR AGES!

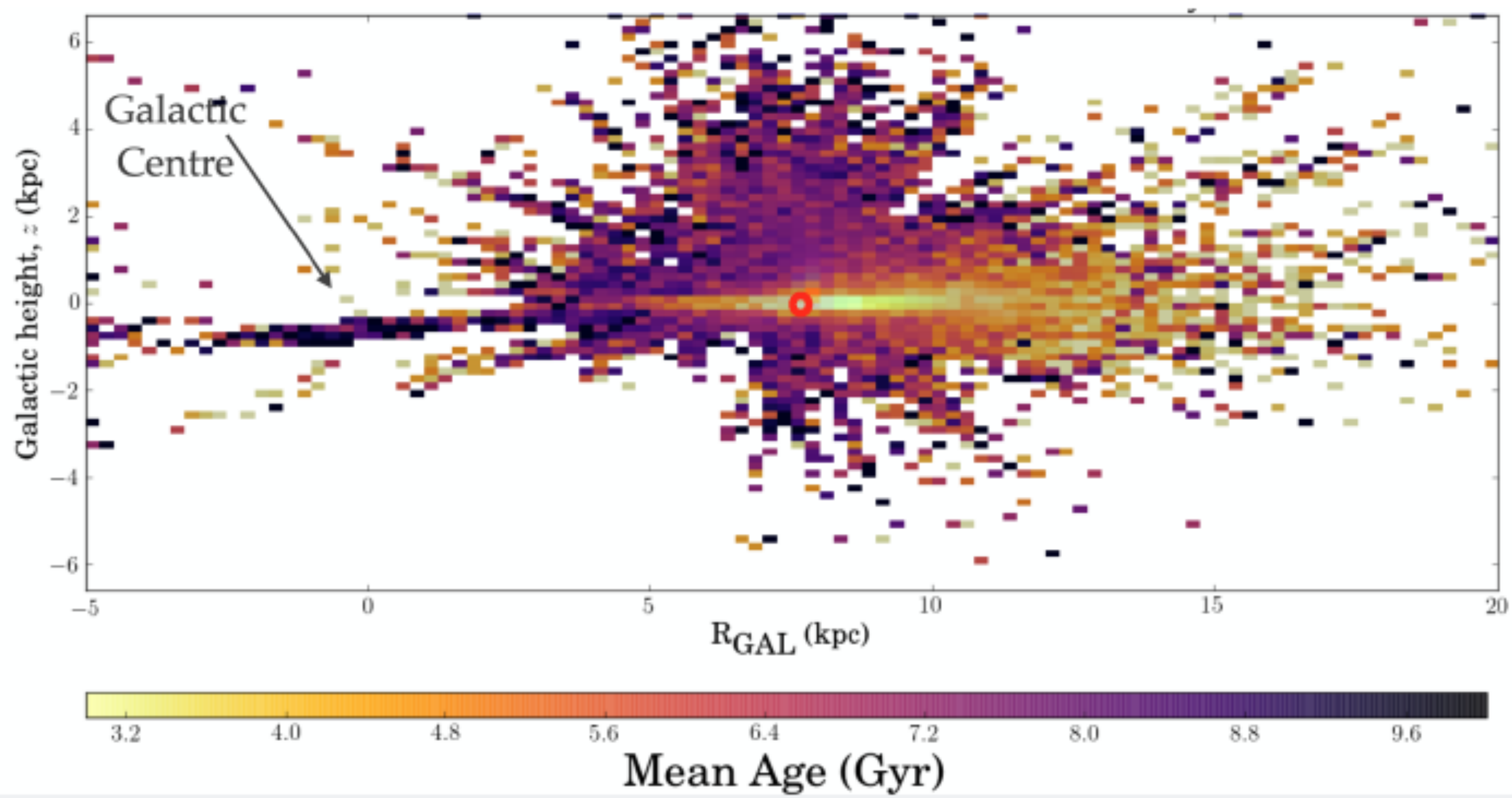
Ages from asteroseismology, precision photometry, gyrochronology
+
Spectroscopy!



good spectra of ALL stars within 100 pc
300,000 WD's (incl. 1000's of binaries)
binaries with BH or NS companions
high.rez spectra for >300.000 TESS targets

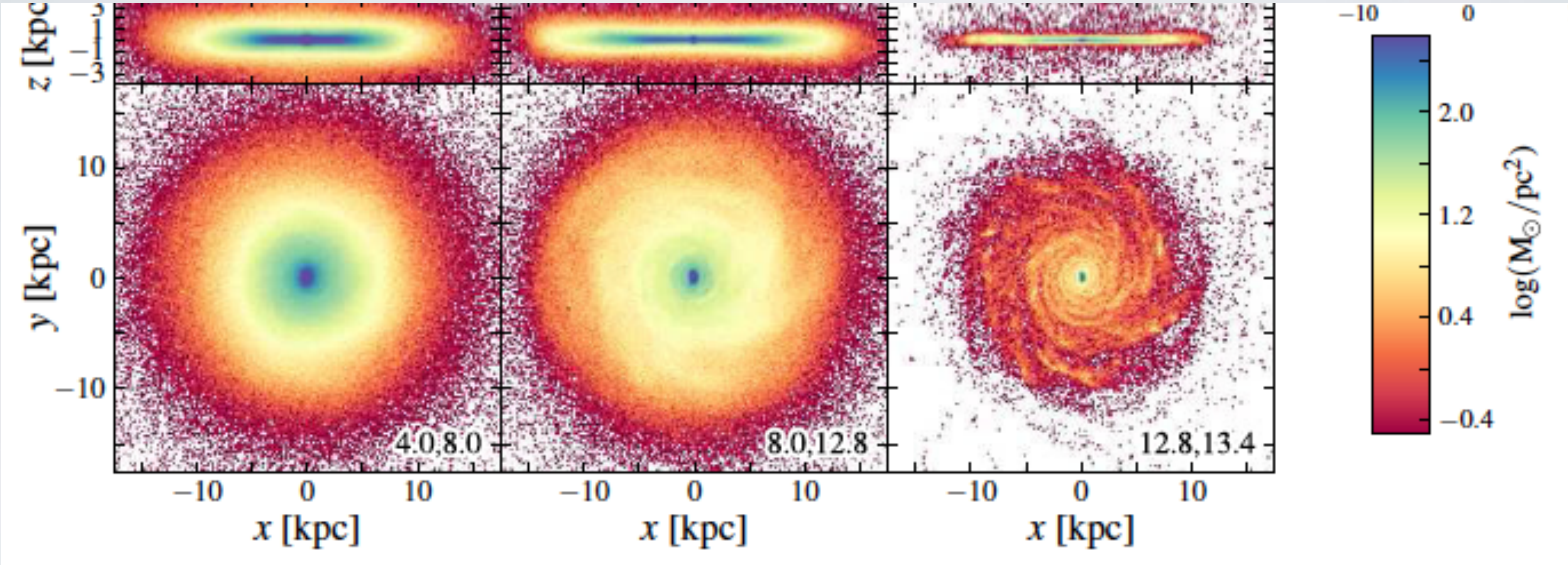
Spectroscopic age map of the Milky Way using APOGEE

75,000 red giants from beyond Galactic centre to outer disk



From M. Ness et al. 2016

AGES ALLOW US TO *DISSECT* THE MILKY WAY



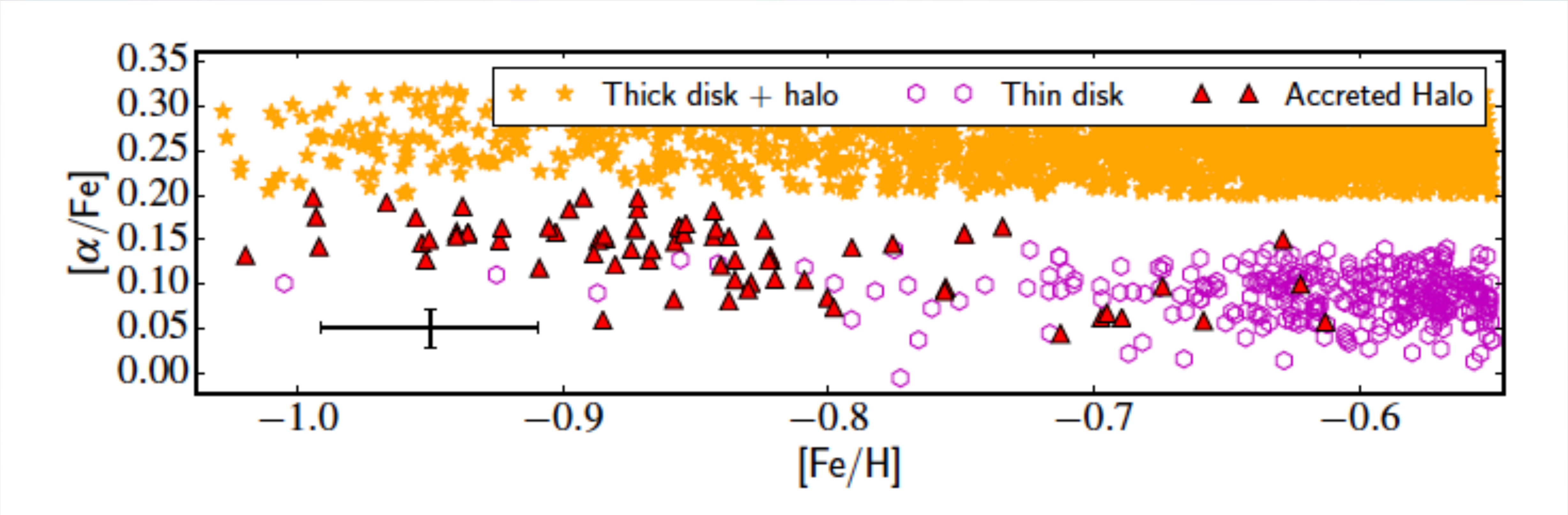
OLDEST STARS

YOUNGEST STARS

Milky Way in a cosmological context
Do our theories match our Galaxy?
(This is why you should care high-z folks!)

Bird et al. 2013
from *Eris* sims

CHEMICAL TAGGING: THE POWER OF CHEMISTRY

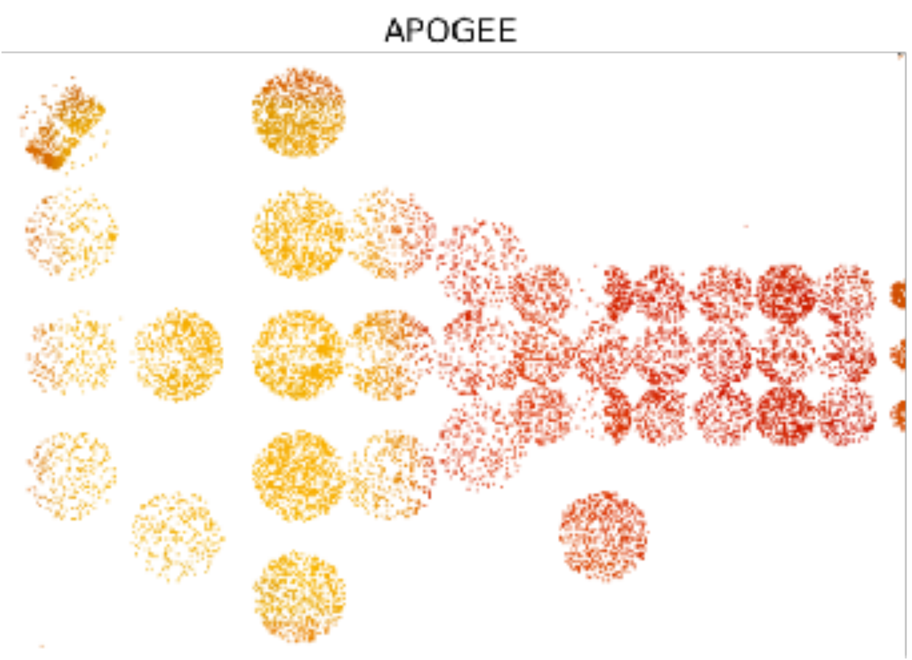


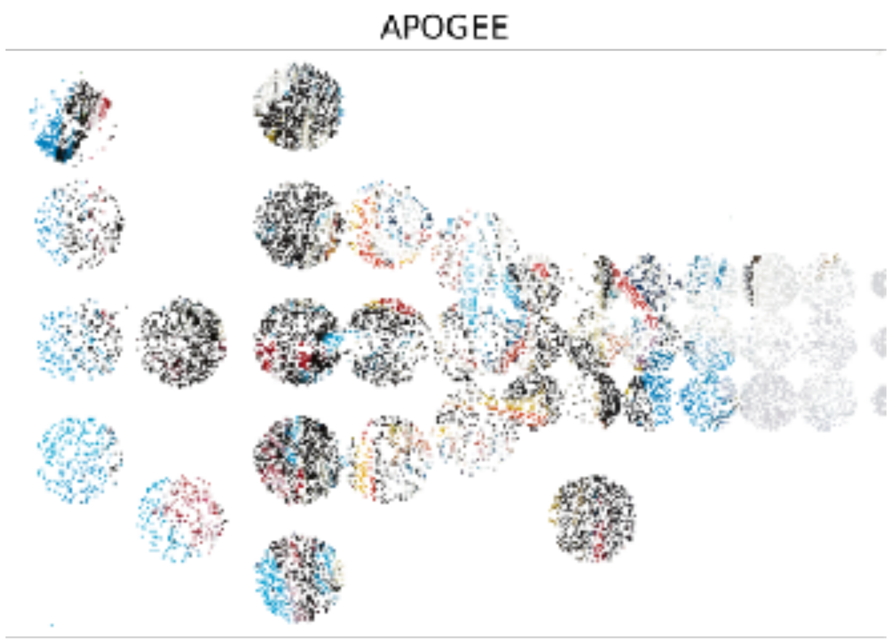
Hawkins et al. 2015

Finding chemical "twins" is an N^2 process

The gains are huge as N gets large!

Current State of the Art with APOGEE





Milky Way Model A

Milky Way Model B

As Sampled in SDSS-V

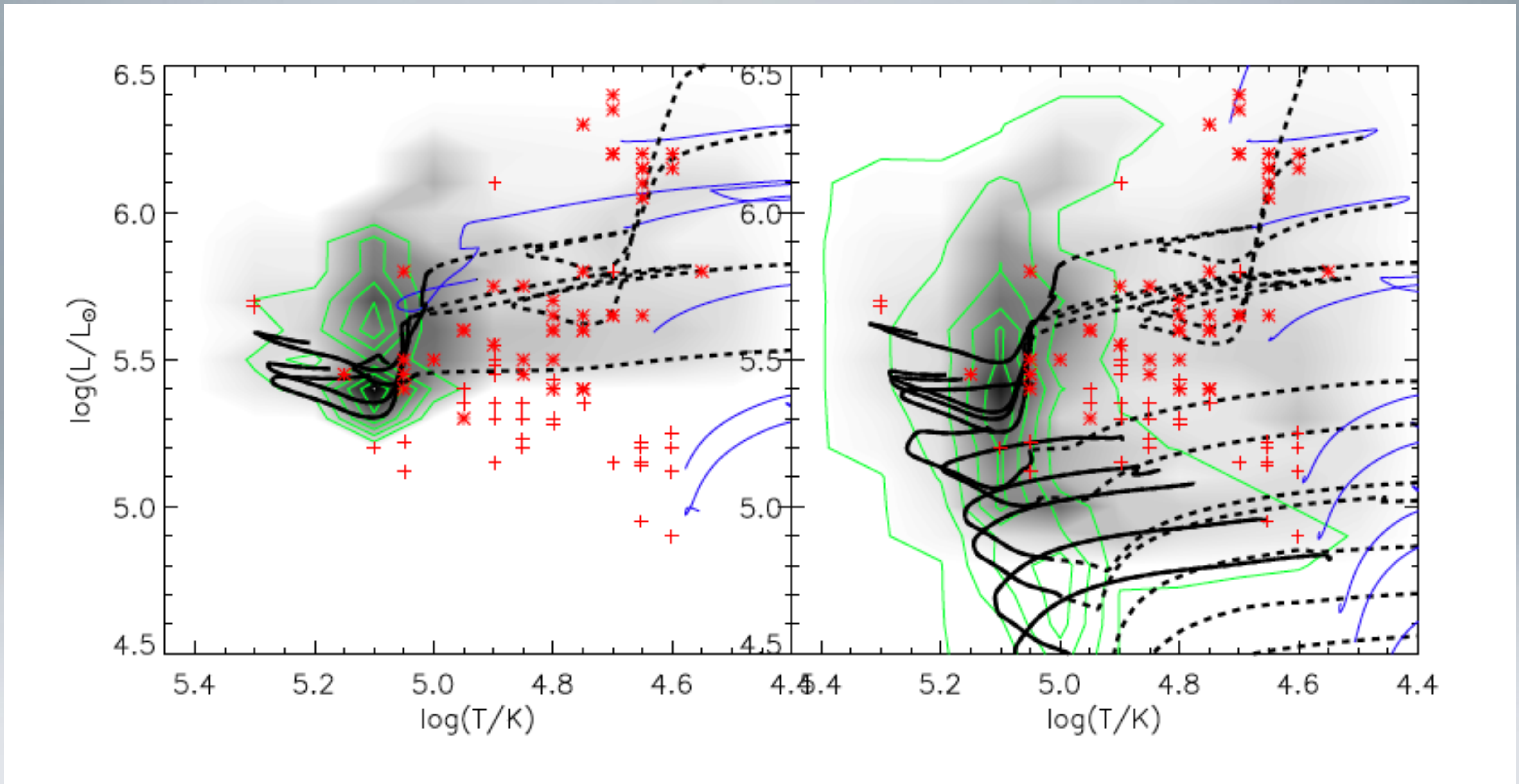
Milky Way "Model A"
Mark Rothko *Orange and Yellow*

Milky Way Model B
Jean-Michel Basquiat *Untitled*

SDSS-V will tell us which Milky Way we live in!

Galactic Genesis & Stellar Astrophysics Targeting Classes				
Instrument	**Selection**	**$N_{Targets}$**	**N_{Epochs}**	**Comments**
Galactic Genesis Survey: mapping the dusty disk				
APOGEE	$H<11$, $G-H>3.5$	4,800,000	1	dust-extinguished disk
APOGEE	$\|z\| < 200$ pc, $H<11$, d<5 kpc	125,000	1	to complete high-res ISM map
Binaries with Compact Objects: enumerating the populations of binaries with white dwarfs, neutron stars, or black holes, selected by variability				
BOSS	PTF, ZTF, *Gaia* variability	30,000	3	binaries with WDs, NSs, and BHs
BOSS	*Gaia* parallaxes	30,000	1	wide WD+MS/RGB binaries
Solar Neighborhood Census: observing all stars within 100 pc, giving the best probe of low-mass stars, whether in single or binary systems				
APOGEE, BOSS	d<100 pc, $G < 20$, $H < 12$	400,000	2	1000× increase in volume & stars
White Dwarf Chronicle: using white dwarfs and their evolved companions to measure the SFH and age-metallicity relation				
BOSS	$G < 20$	300,000	3	15× increase in sample size
TESS Exoplanet Host Candidates: observing all TESS short-cadence targets in the CVZs				
APOGEE	$H \leq 13.3$	300,000	1–8	all short-cadence targets & planet hosts
Binaries Across the Galaxy: measuring environmental dependence of binary fraction in the disk, bulge, halo, and stellar clusters; probing the brown-dwarf desert beyond solar-type stars				
APOGEE	$H<13.4$, $N_{Epoch} \geq 6$ by the start of SDSS-V	60,000	6–18	gives orbits with 24–40 epochs for all targets with long APOGEE baselines
Gaia Astrometric Binaries: characterizing rare systems that have good astrometric orbits but limited other information, from *Gaia*'s sample of > 10 million stars				
APOGEE, BOSS	$d < 3$ kpc	200,000	1	rare types of systems
TESS Red Giant Variability: measuring spectroscopic properties for red giants in TESS that have seismic and/or granulation lightcurve signatures				
APOGEE	$H < 12.5$	250,000	1	stars with at least 80 days of TESS observation
Massive, Convective Core Stars: combining dynamic and asteroseismic measurements of binary OBAF stars in the TESS CVZs and characterizing their multiplicity				
APOGEE	$H < 12$	200,000	2	detection of single vs. binary systems
APOGEE	$H < 12$	500	25	>10× increase in current sample size
Young Stellar Objects: quantifying the stellar populations in star-forming regions, including identifying sources of ionizing radiation and characterizing the binary frequency				
APOGEE	$H < 12$, $d < 1$ kpc	20,000	12	nearby star-formation regions
APOGEE	$H < 12$	3,500	8	high-mass star-formation regions
APOGEE	$H < 12$, $\|b\| < 2°$	10,000	2	massive young stars in the Galactic Plane
APOGEE	$H < 13$	10,000	2	Central Molecular Zone

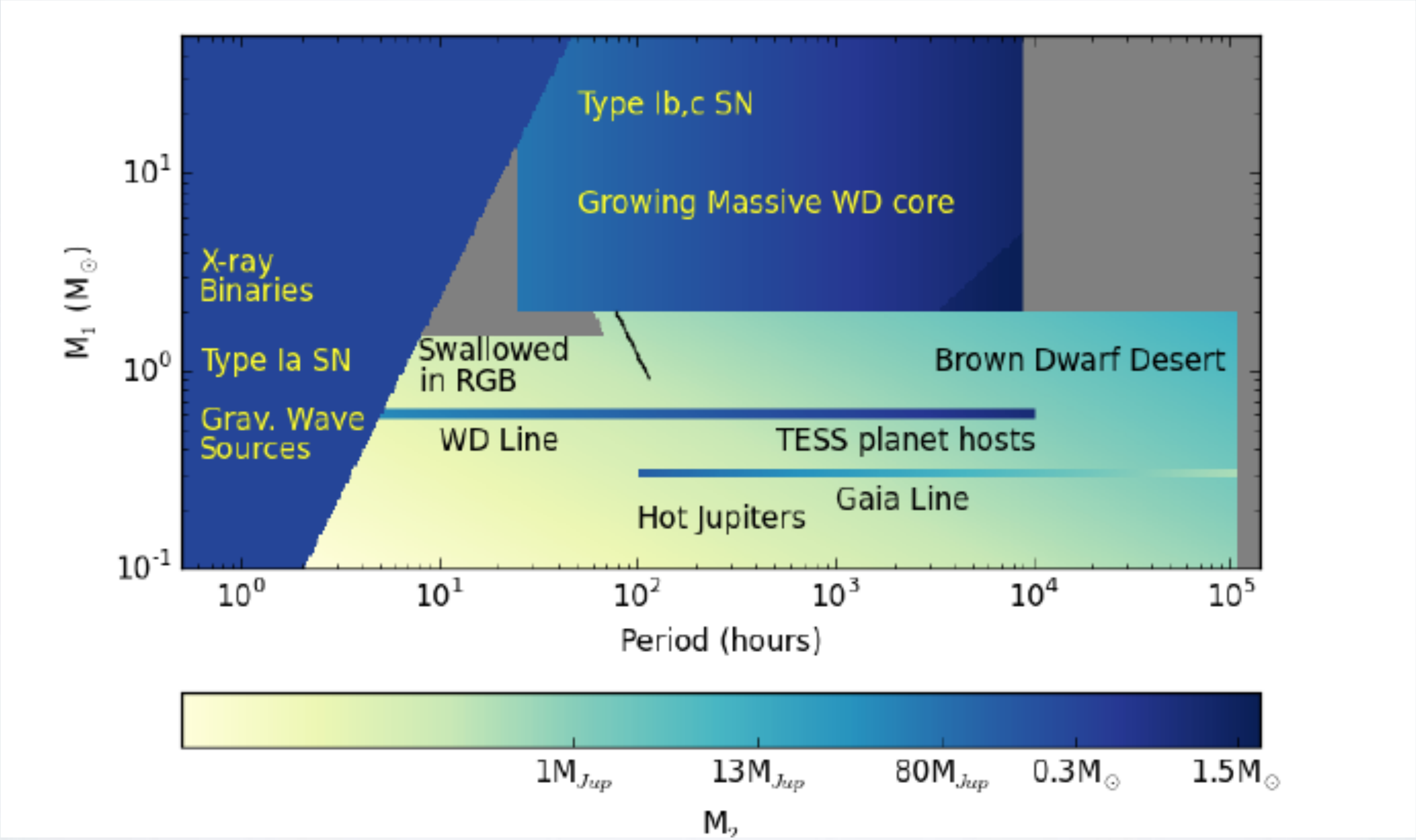
BINARIES! THEY EXIST!



Huge range in possible outcomes from model uncertainties!

From Eldrige et al. 2013

STELLAR MULTIPLICITY

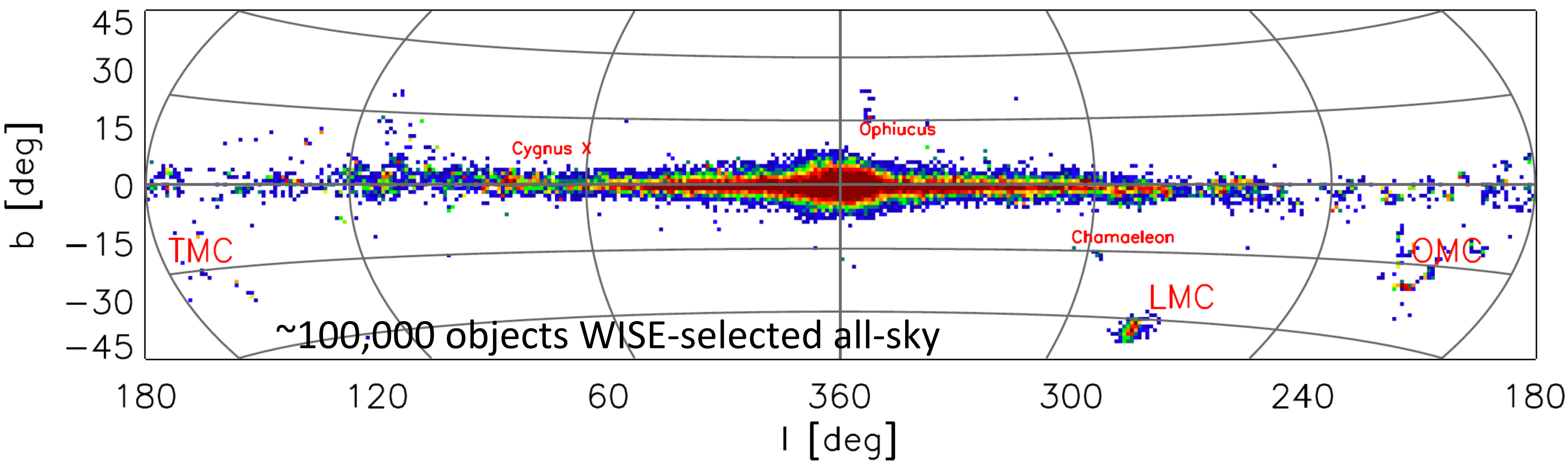


For a given primary & period, *minimum* SDSSV—detectable secondary is shown

Mapping the Young Stars Across our Galaxy

“all” YSO and $M>8M_o$ with H<11

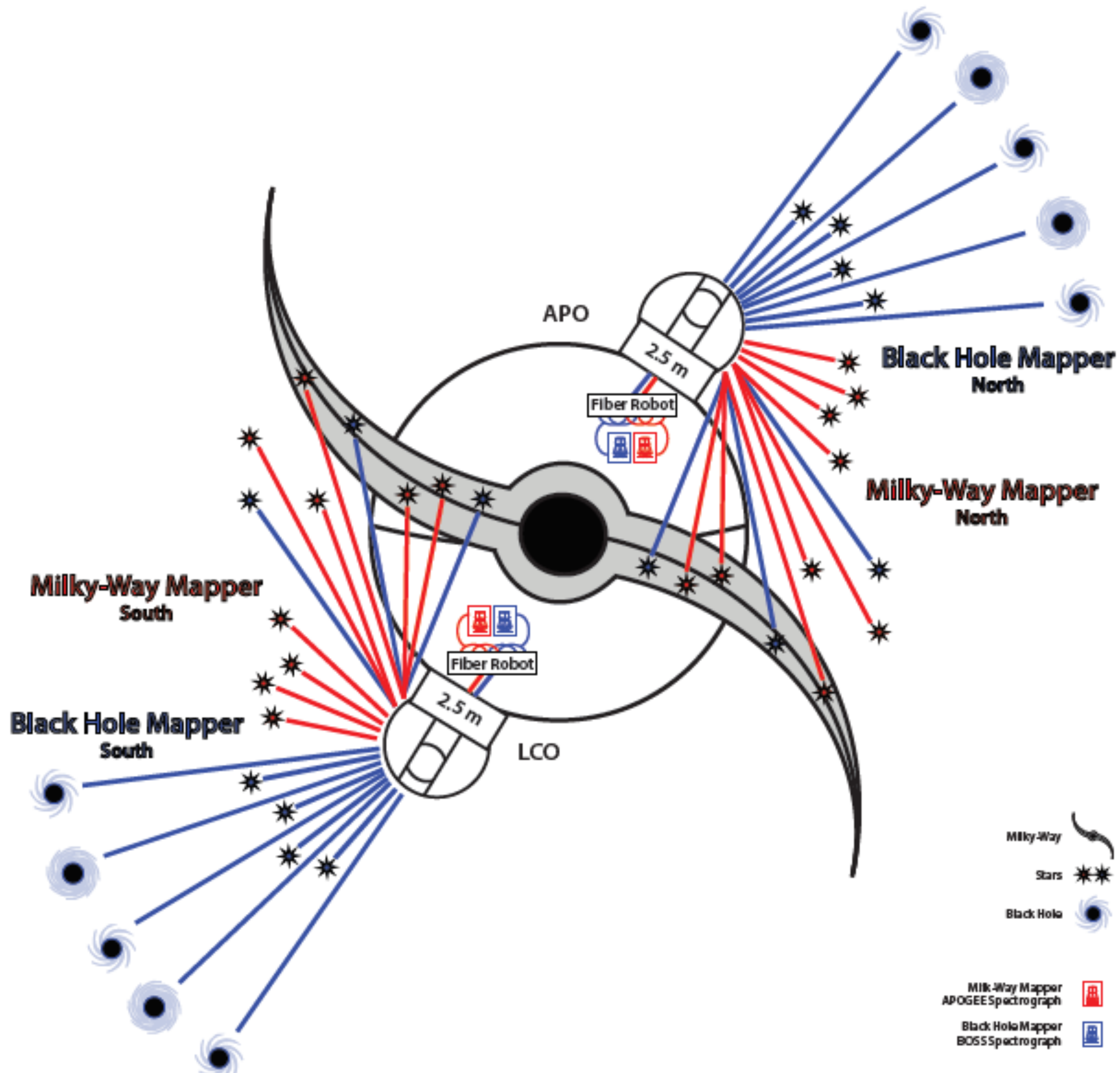
>2 epoch



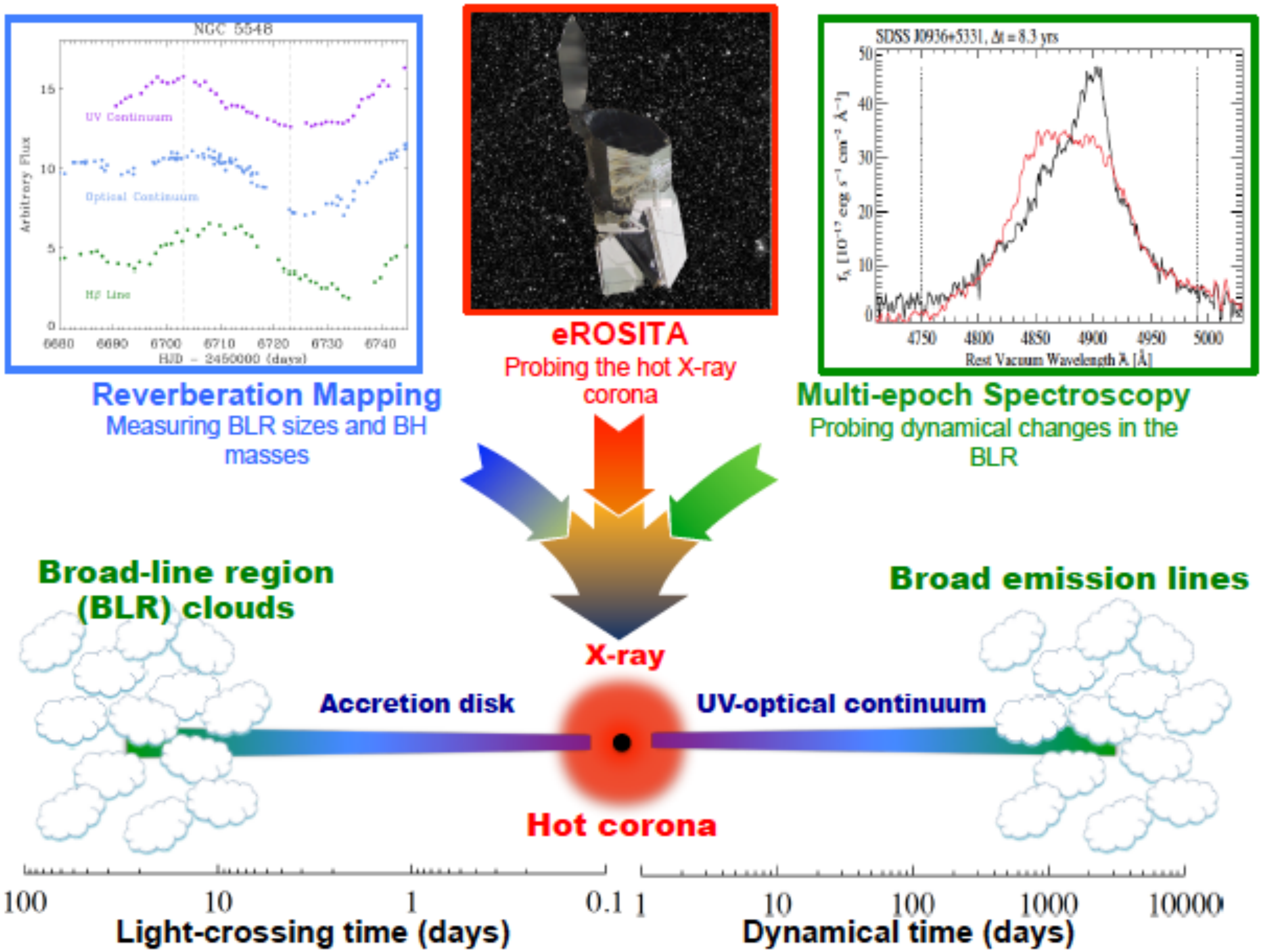
Binarity among massive stars is prevalent

… and matters for GW and even for cosmic re-ionization

BLACK HOLE MAPPER: BHM

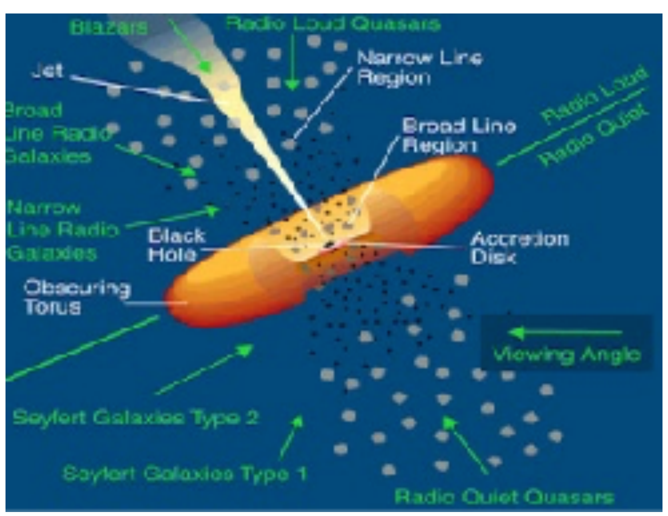


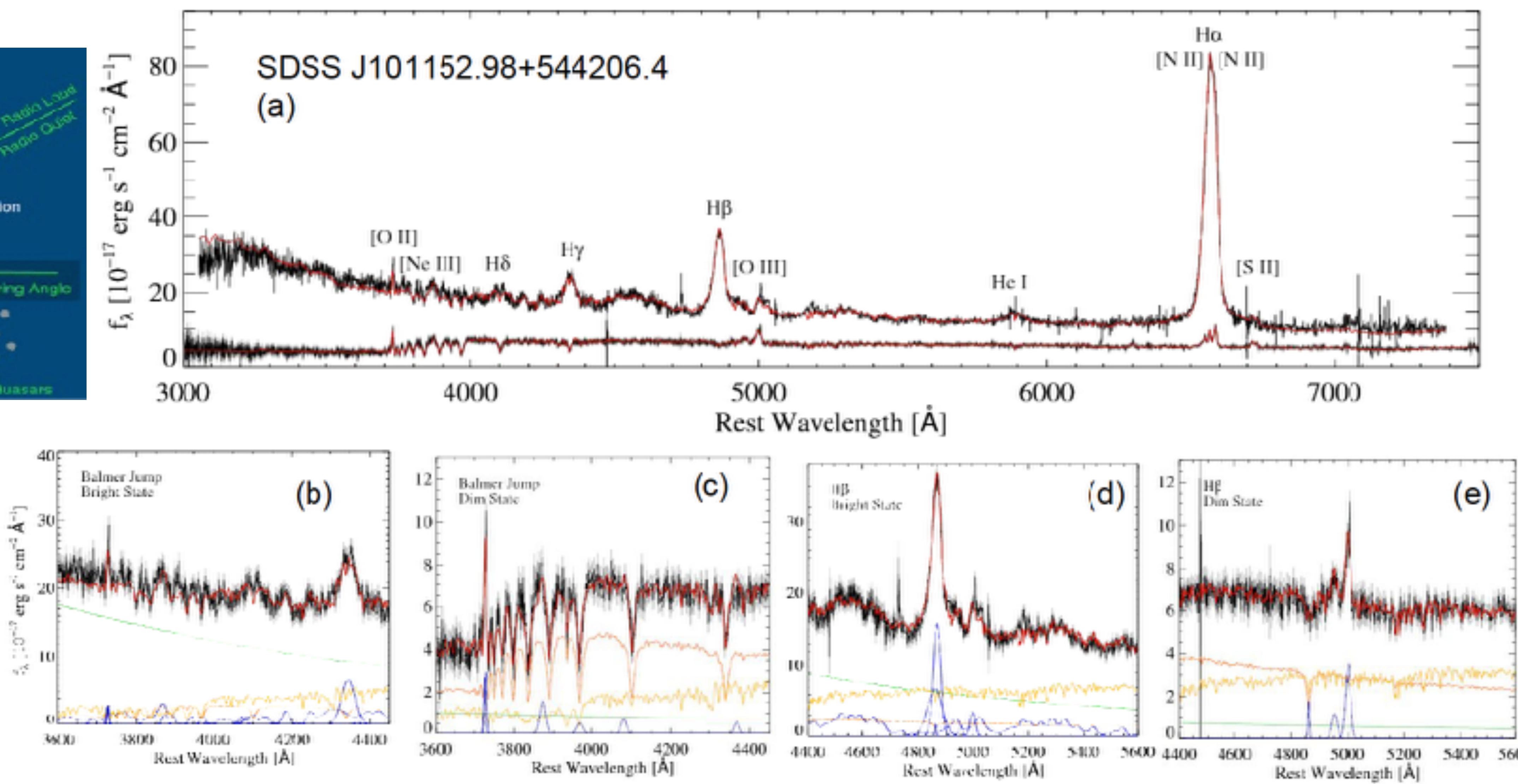
BLACK HOLE MAPPER:
UNDERSTANDING BLACK HOLE GROWTH



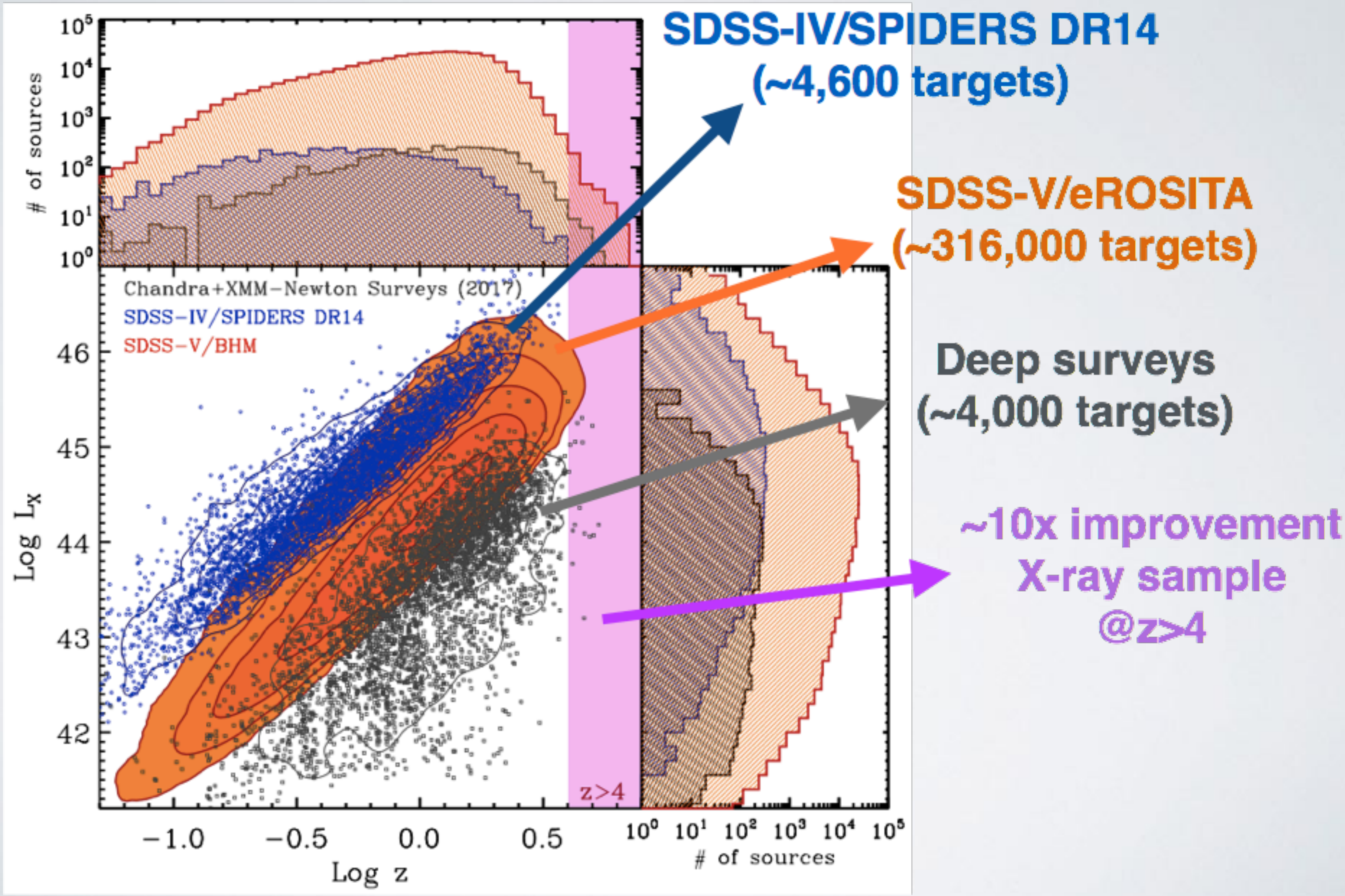
BHM Targets Categories

SDSS-V Black Hole Mapper Targeting				
Science Goals	**Primary Selection**	**Density [deg^{-2}]**	**$N_{targets}$**	**N_{epochs}**
Reverberation mapping, BH masses	Optical QSOs, $i < 20$	30–50	1,500	174
BH accretion and outflow astrophysics, changing look quasars	Optical QSOs, $i < 19$	10	25,000	3–13
eROSITA follow-up, AGN, X-ray binaries, galaxy clusters	$f_{X-ray} \geq 2.5 \times 10^{-14}$ erg s^{-1} cm^{-2}, $i < 21.5$	20–50	400,000	1–3

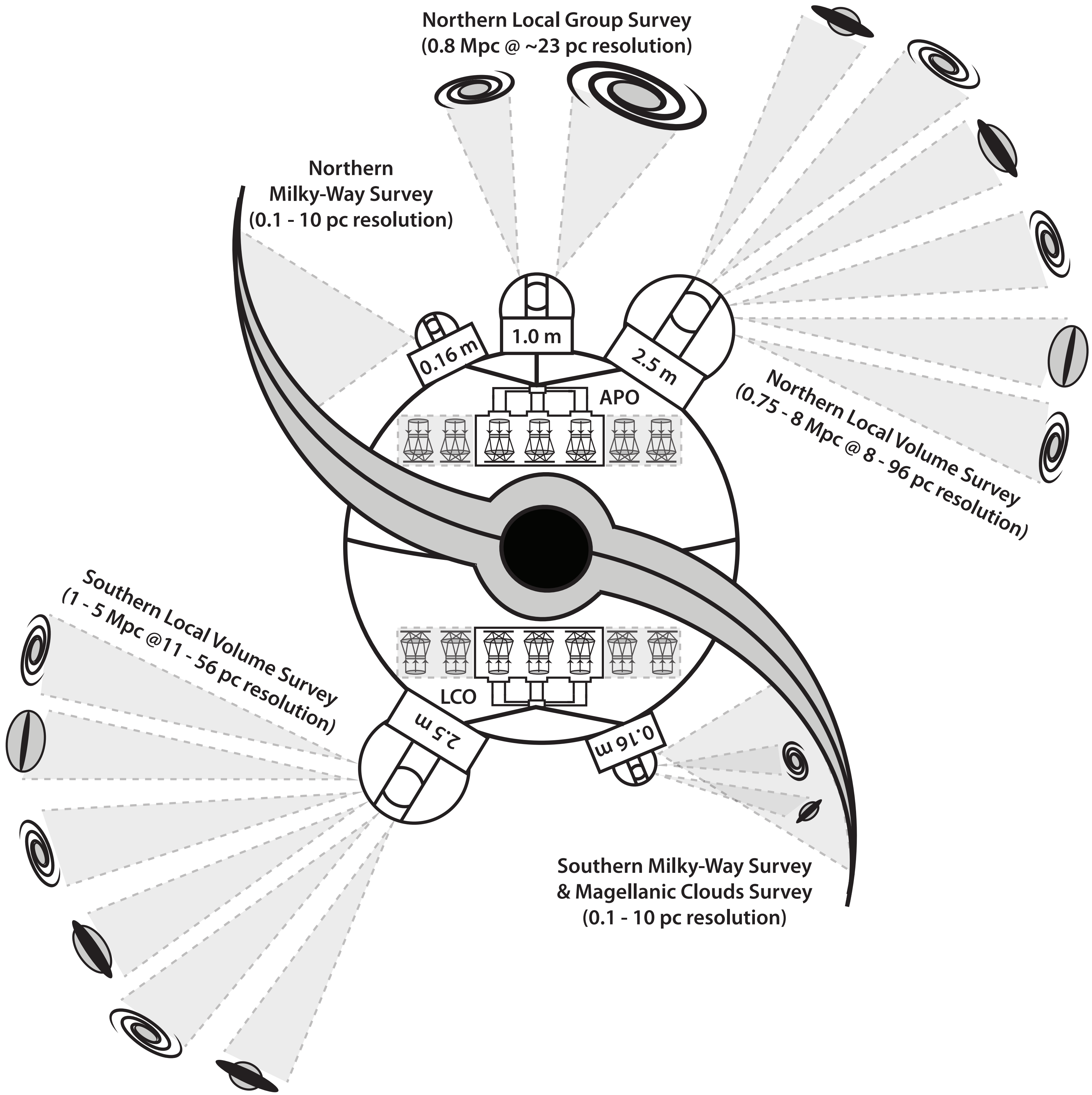




EROSITA SOURCE FOLLOW-UP



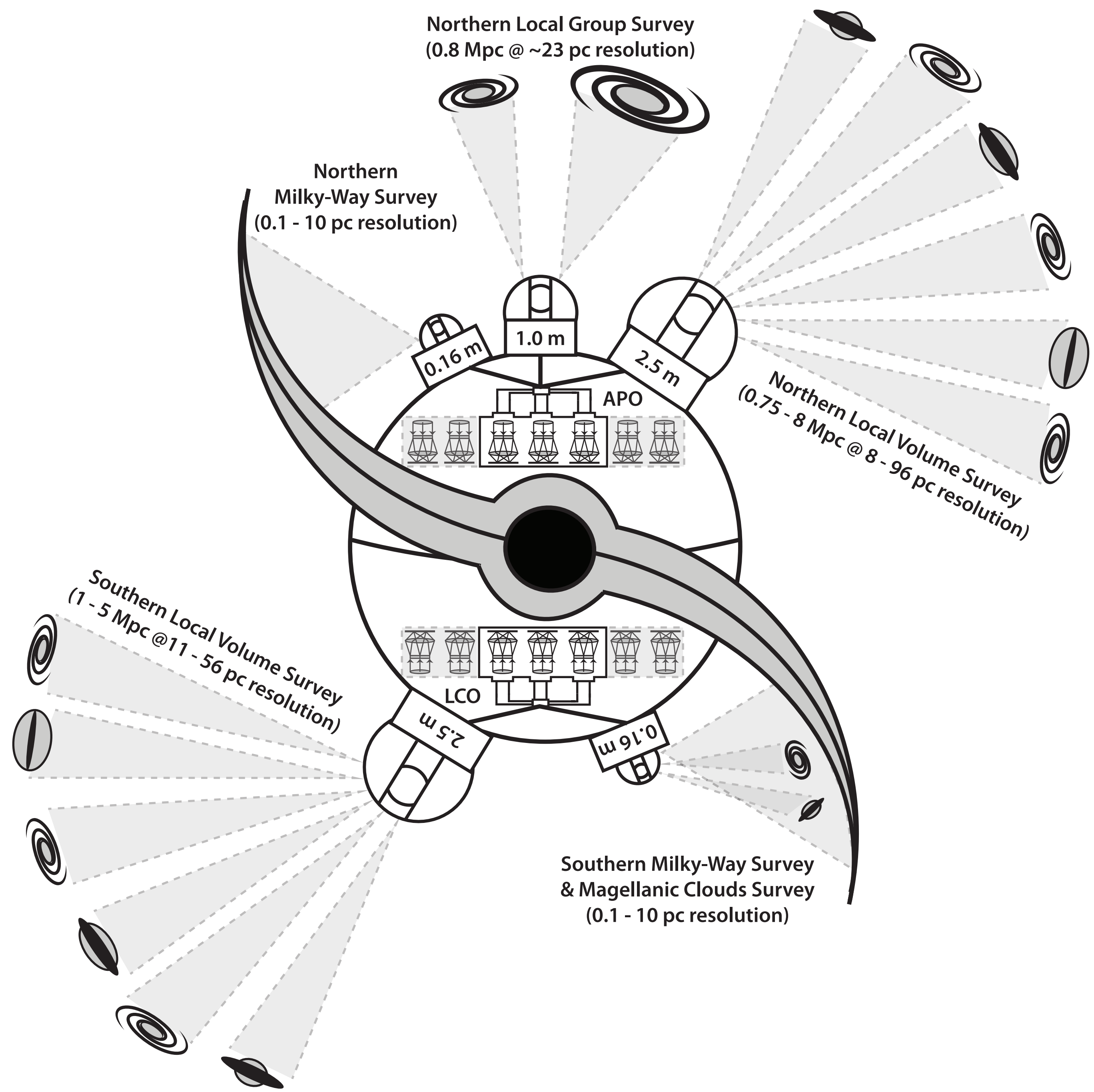
Local Volume Mapper: LVM



LVM Overview

Using different telescope sizes of and an array of IFU-coupled spectrographs at *R*~4000 and 3600-10000Å, we survey

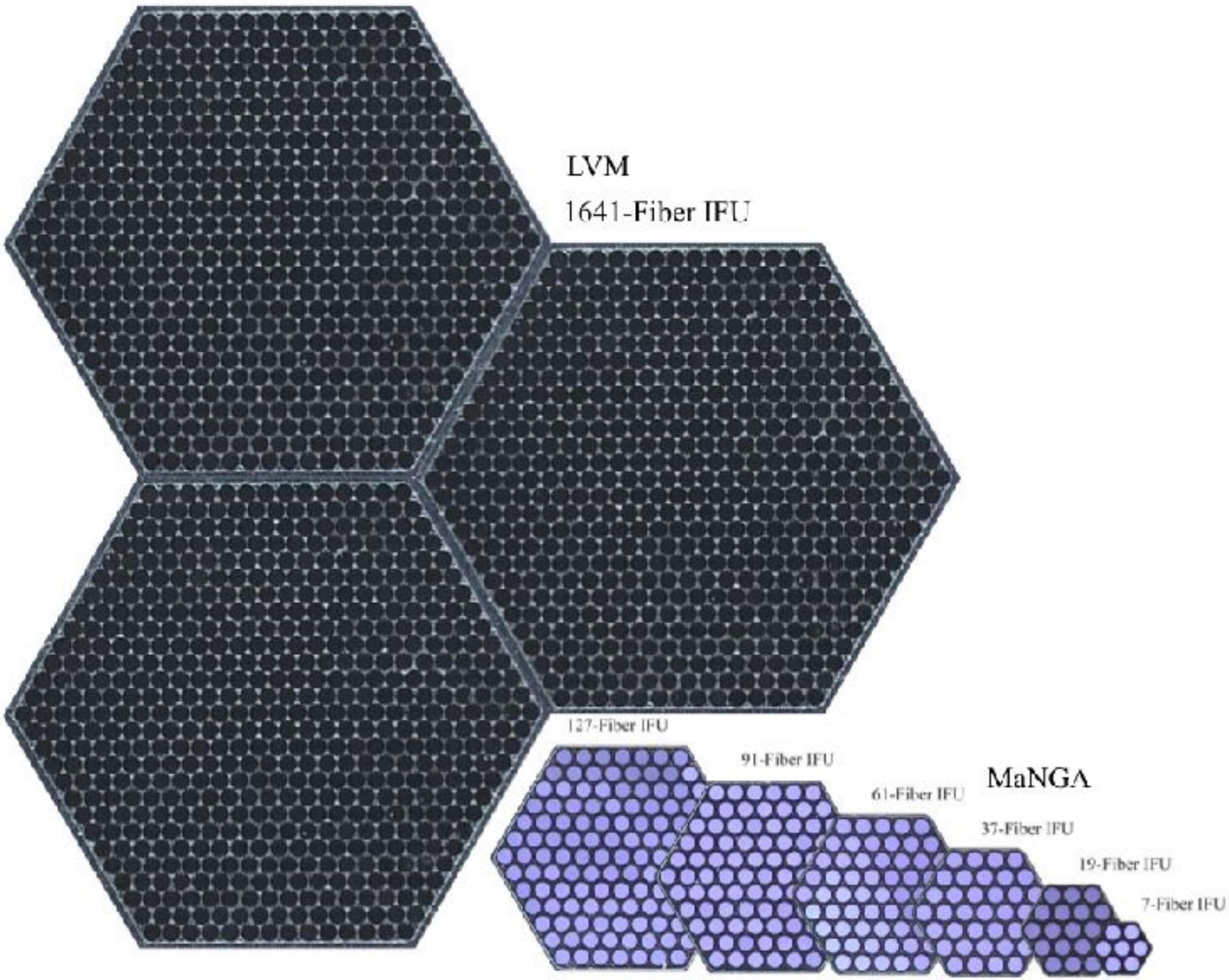
- 2800 sq. deg. in the MW @ 0.1-1 pc resolution,
- 300 sq. deg. in the MW 10x deeper,
- LMC & SMC @ 10 pc resolution,
- M31 & M33 @ 20 pc resolution, and
- 12 nearby galaxies (D≲5 Mpc) @ 50 pc resolution



How LVM?

- At fixed f-ratio (fibers!), conservation of AΩ means that the ONLY thing controlled by telescope aperture is 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 ~6” spaxels
  - 10 pc in M31 requires 2.5” spaxels

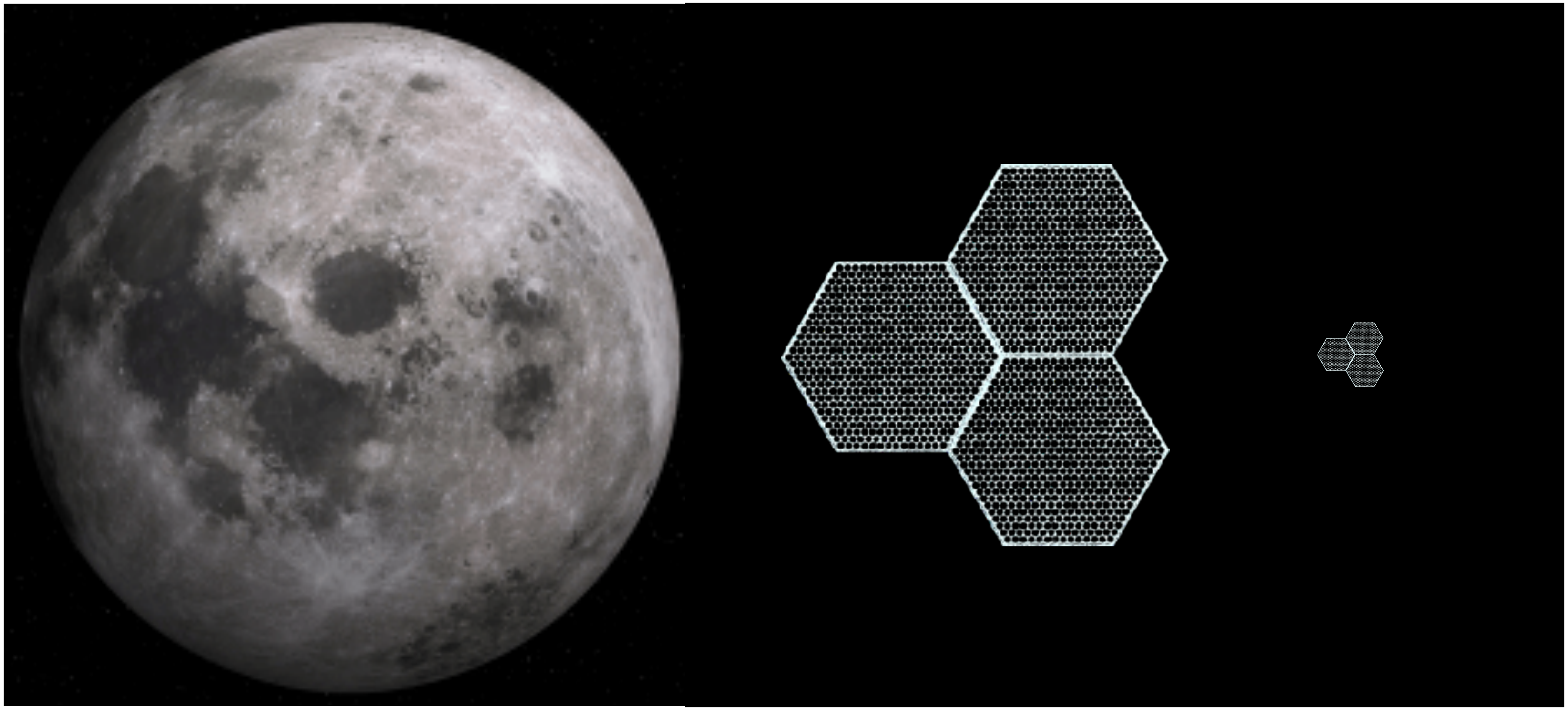
LVM IFU


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

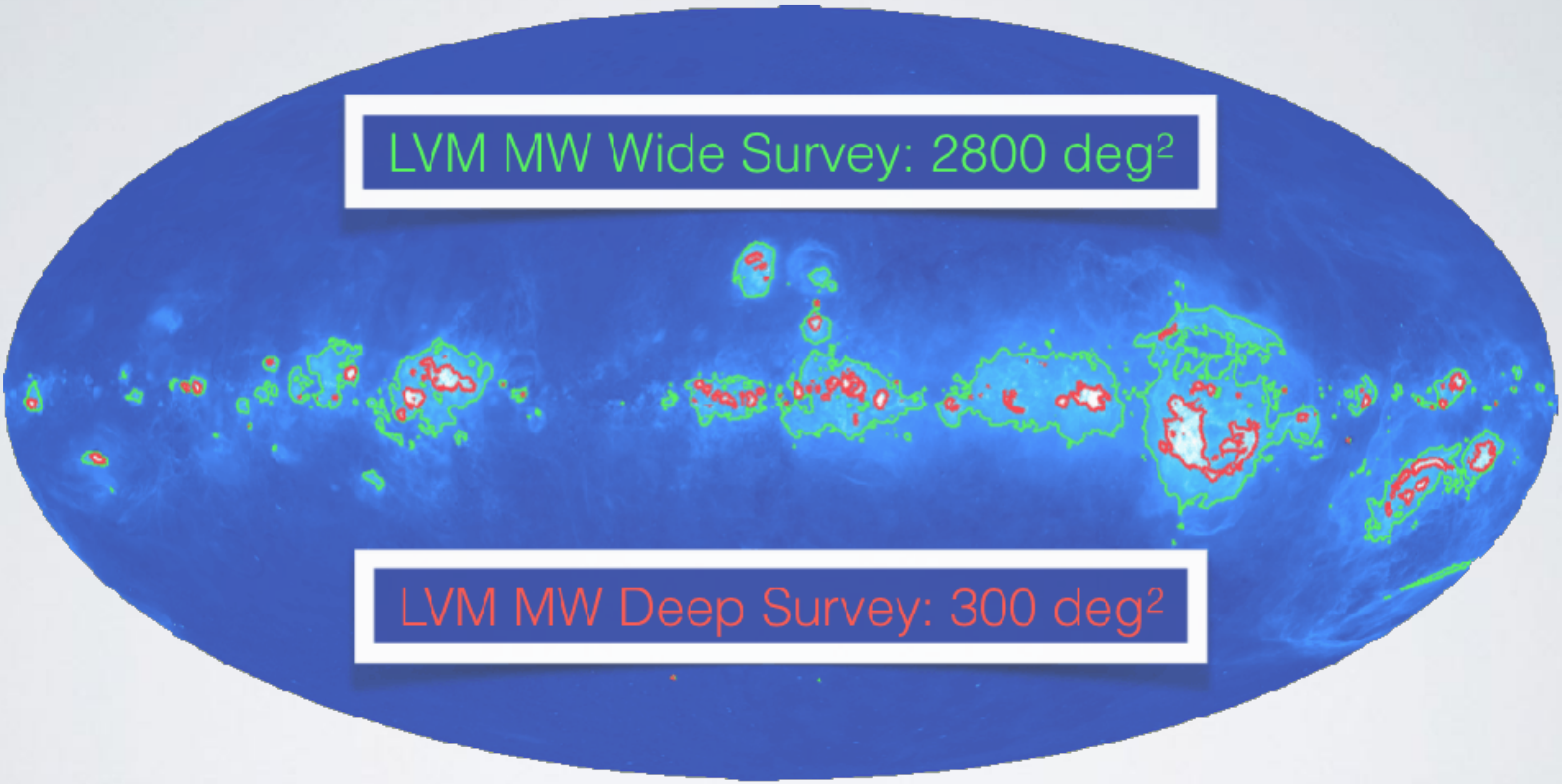
LVM hardware

IFU design

- 490 arcmin2 @ 0.16 m
- 12 arcmin2 @ 1 m



OBSERVING GALAXIES AT THE "ENERGY INJECTION SCALE": LOCAL VOLUME MAPPER



Cosmological Zoom-In Observations!

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

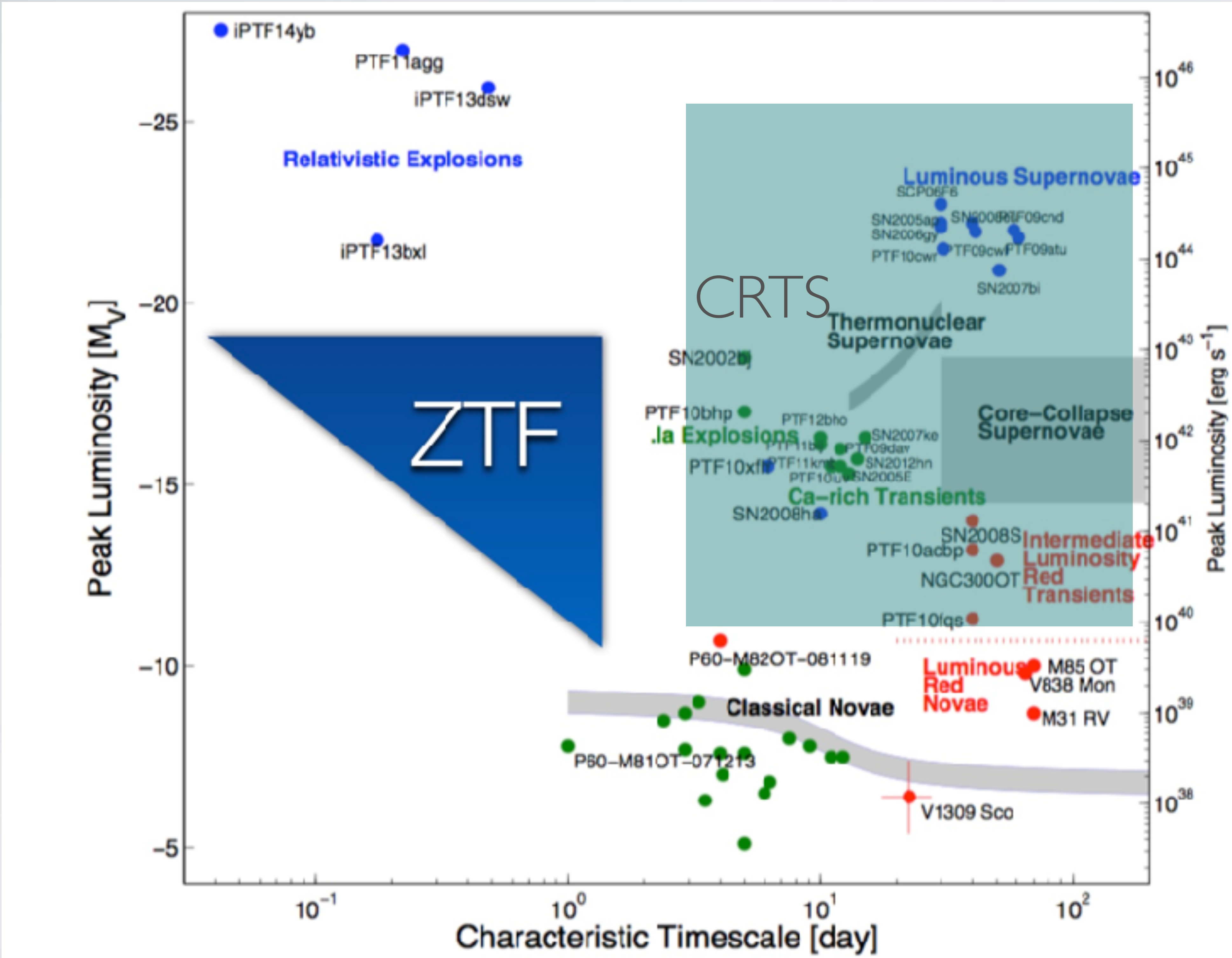
Images: ESO 2.2m

BASELINE LVM TARGETS

Object	RA+DEC	D (Mpc)	A_{25} ($'^2$)	A_B (mag)	M_* ($10^9 M_\odot$)	telescope diameter (m)	spaxel size (pc)	fractional coverage
M31	00:43+41	0.77	9356	0.27	30	1	22	0.7
M33	01:34+31	0.85	2402	0.18	2.1	1	24	0.7
M81	09:56+69	3.18	211	0.18	49	2.5	42	1
IC 1613	01:05+02	0.73	186	0.11	0.07	2.5	8.4	1
M51a	13:30+47	8.4	61	0.15	56	2.5	96	1
NGC 2403	07:37+66	2.94	44	0.09	4.2	2.5	36	1
M82	09:56+70	3.53	37	0.69	21	2.5	40	1
M51b	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.5	[illegible]	1
LMC	05:23-70	0.05	2.8×10^5	0.32	1.6	0.16	9.0	1
SMC	00:53-73	0.06	51472	0.17	0.38	0.16	10.8	1
Cen A	13:25-43	3.75	405	0.50	47	2.5	43	1
NGC 300	00:55-38	2.15	267	0.06	1.8	2.5	25	1
NGC 253	00:48-25	3.94	131	0.08	60	2.5	45	1
M83	13:37-29	4.92	116	0.28	43	2.5	56	1
NGC 7793	23:58-33	3.91	46	0.08	3.5	2.5	45	1
WLM	00:02-15	0.97	36	0.16	0.02	2.5	11	1

IS YOUR FAVORITE ON THIS LIST?

TRANSIENTS!



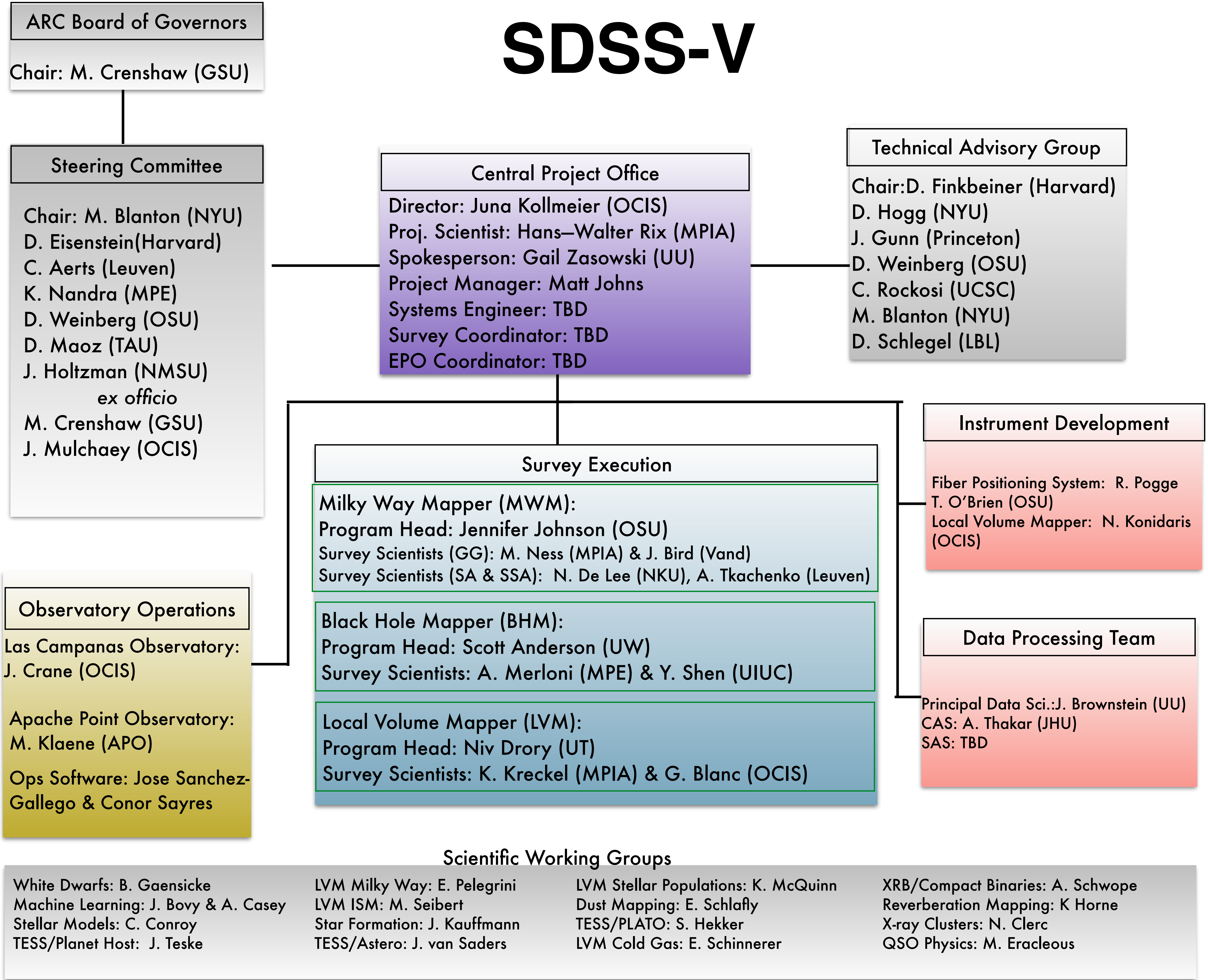
Rapid reconfiguration (SLOAN-BOTS!)

Full Sky coverage

O/IR

Perfect complement to an extended ZTF, LSST, and future IR sky surveys

B. Penpraese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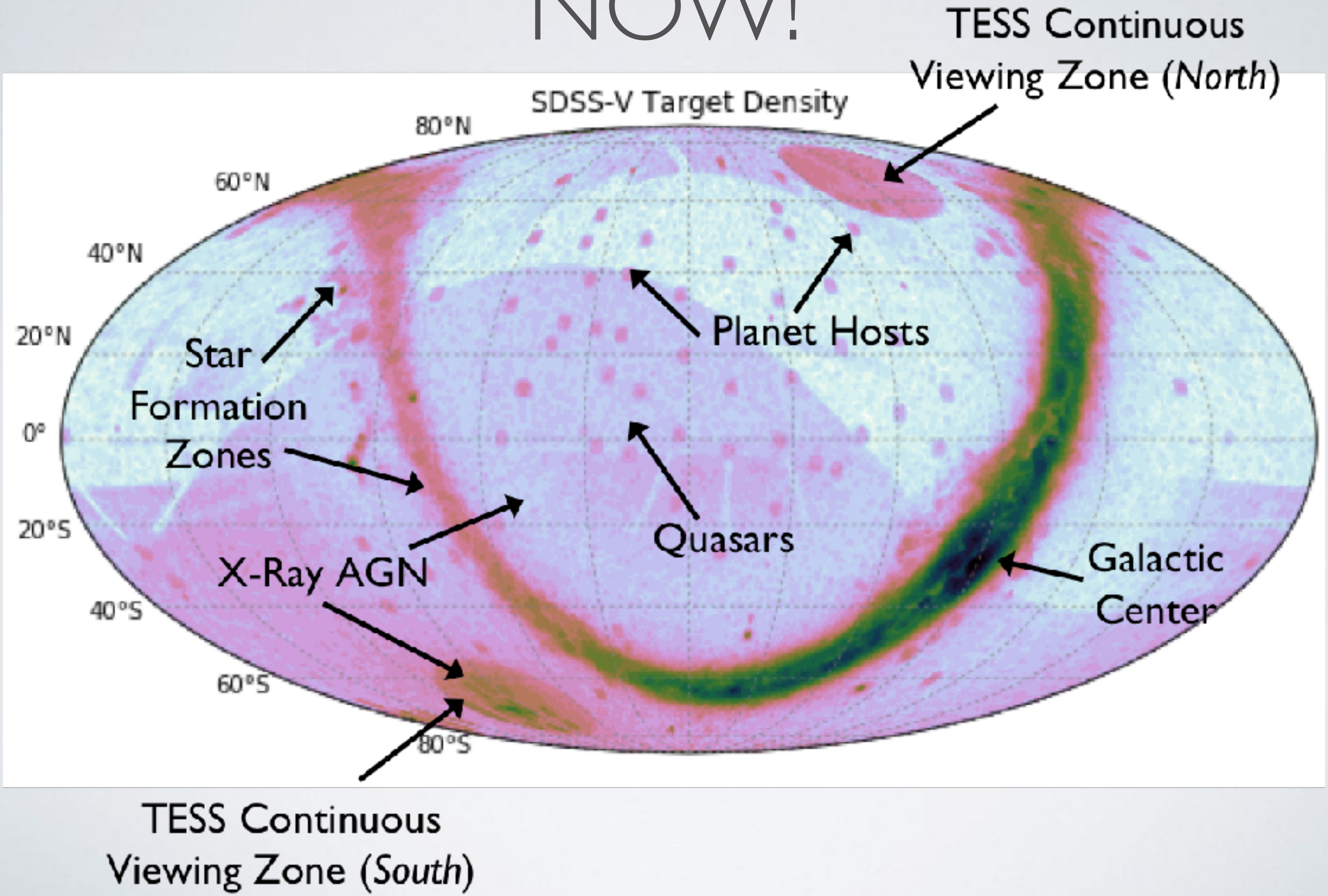
LVM Cold Gas: E. Schinnerer
XRB/Compact Binaries: A. Schwope
Reverberation Mapping: K Horne
X-ray Clusters: N. Clerc
QSO Physics: M. Eracleous

Where Are We?

- Successful proposal to the Sloan Foundation!
- SDSS-V Pathfinder observing programs in SDSS-IV **approved** in N & S! (TESS CVZ, RM focus)
- Currently in phase transition —-we are doing this & building collaboration!
- See http://www.sdss.org/future for more!

SURVEY PLAN BEING MADE NOW!



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- MoUs in draft: Carnegie Institution for Science, Chilean Participation Group, UIUC, Harvard, OSU, NMSU, ICORE, U. Wisconsin, AIP, U. Warwick, Vanderbilt, U. Washington, KIAA, Penn State, TAU
- Seed fund contributors: Georgia State, Caltech, STScI
- Active Discussions: University of California, MPA, MIT, U. Kentucky, Johns Hopkins University, Australia National University, NOAO, NAOC, University of Heidelberg, Oxford, York University, University of St Andrews, UVA, UNAM, SHAO, SJTU, NJU

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