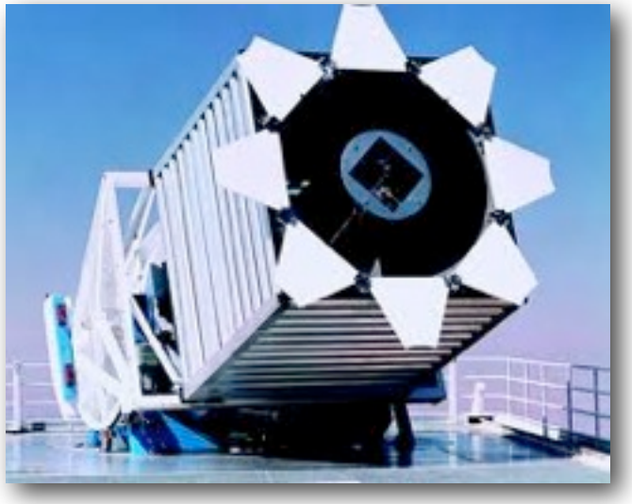


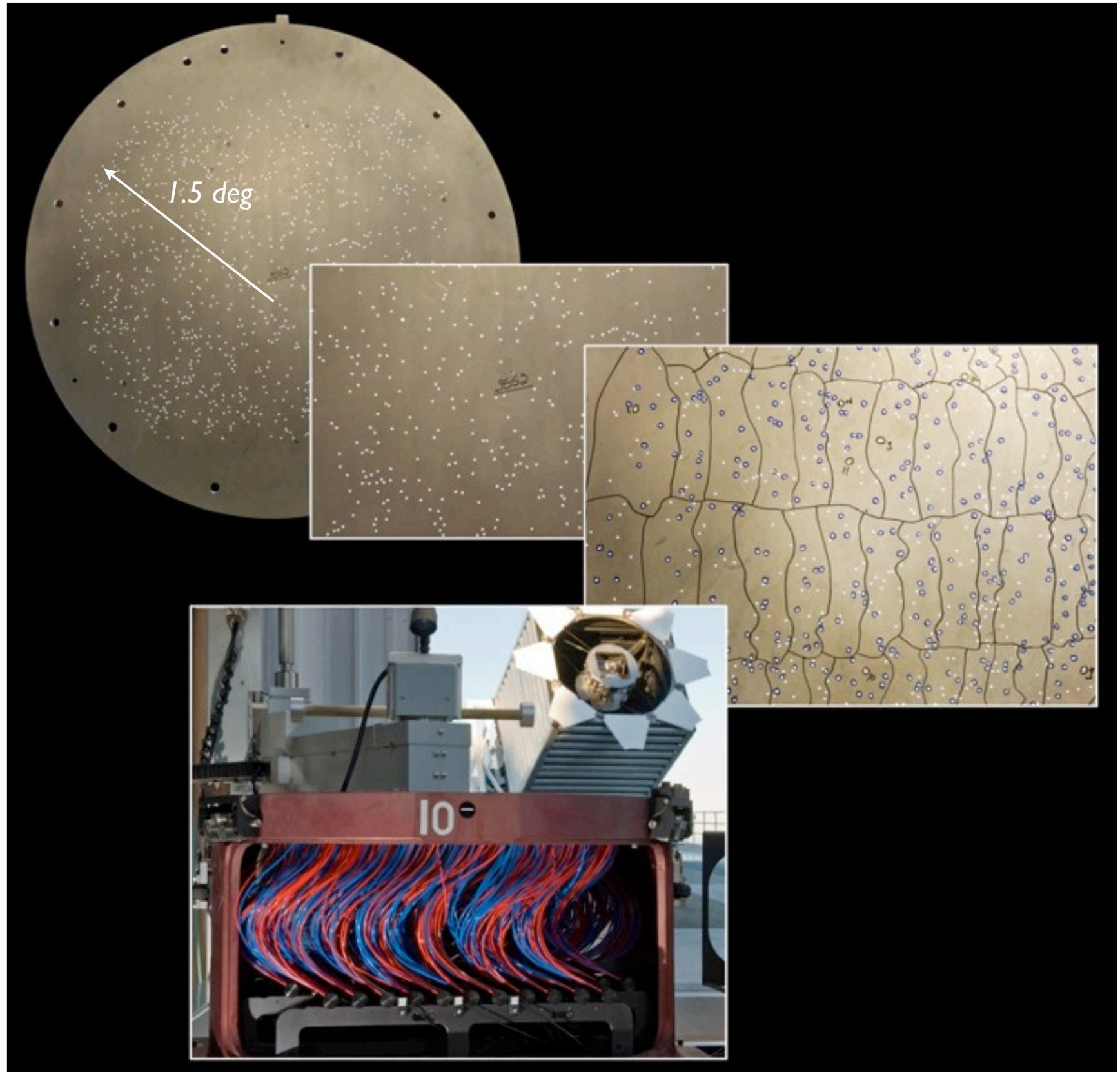
The Future of the Sloan Digital Sky Survey (2014 - 2020)

1. **Introduction**
2. **APOGEE**: Galactic archaeology over the full Milky Way
3. **MaNGA**: dissecting the nearby galaxy population
4. **eBOSS**: measuring dark energy over 10 billion years

Michael Blanton, Center for Cosmology and Particle Physics, New York University

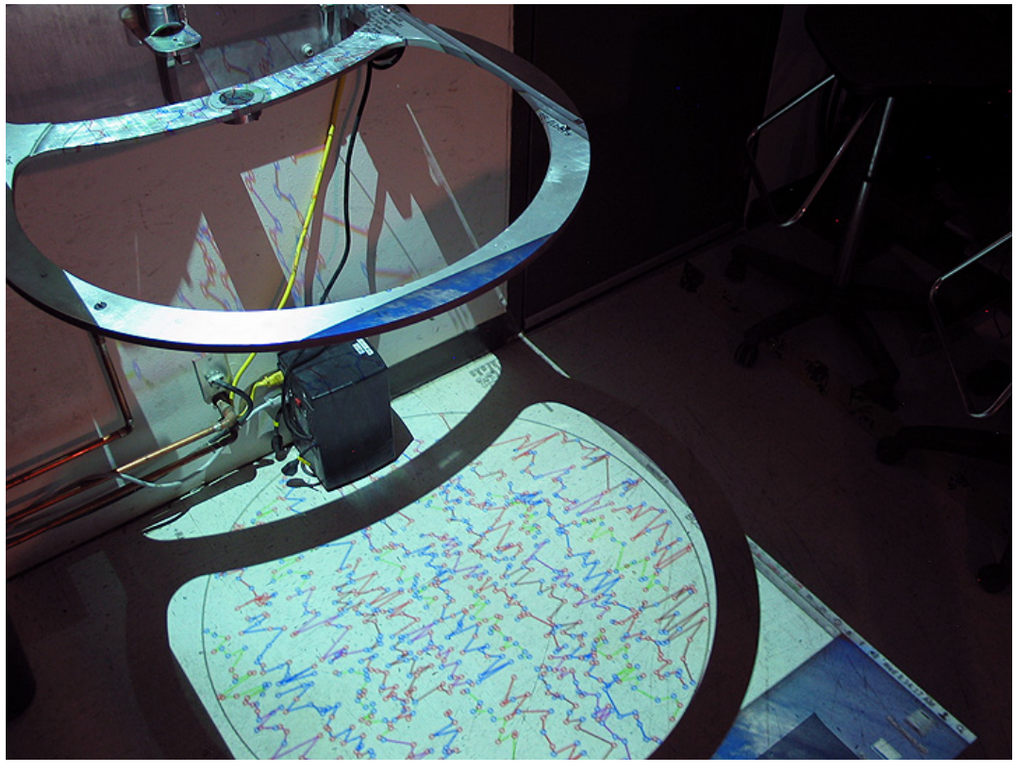
Introduction: plates plugged with optical fibers

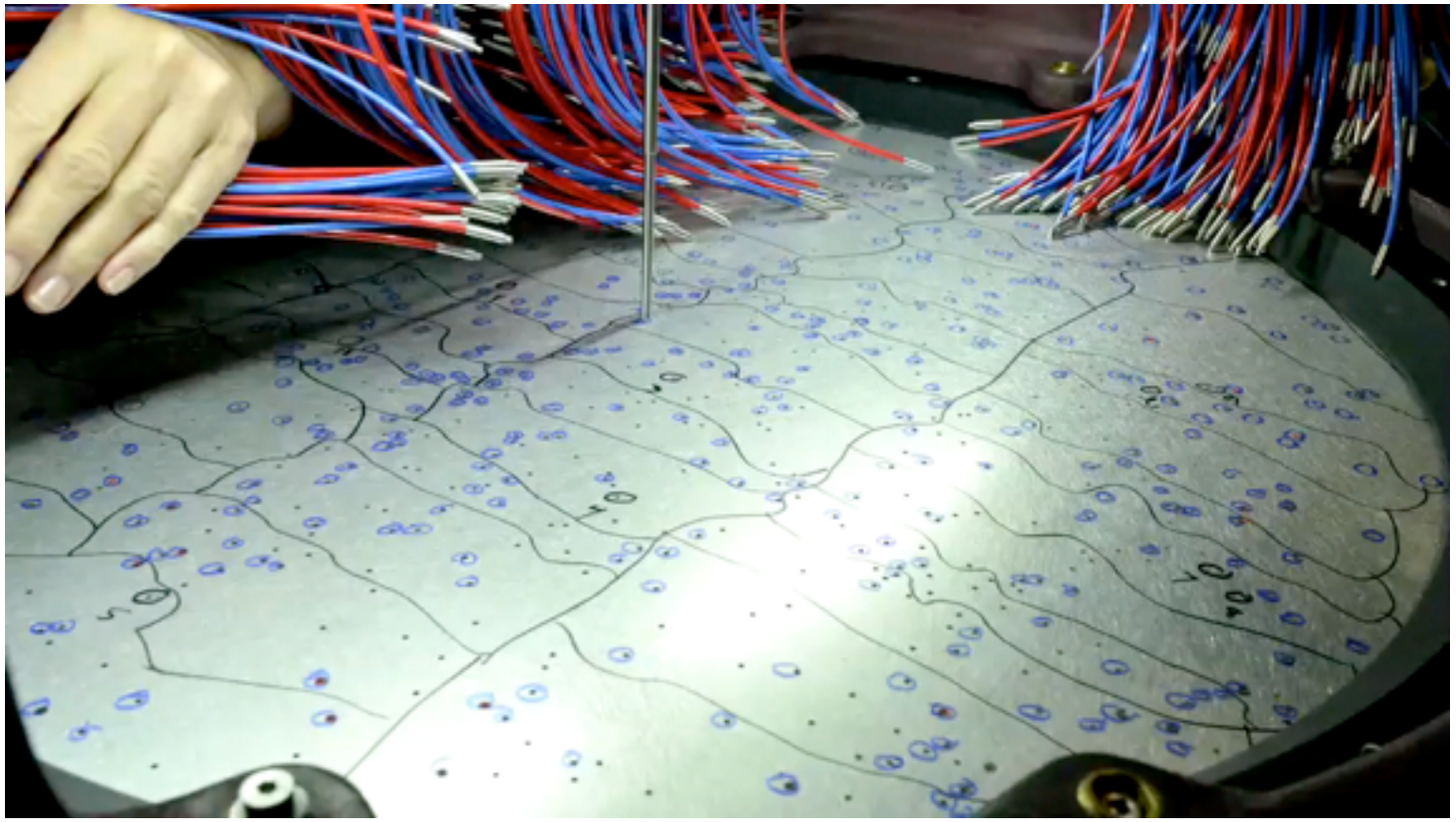
- *1000 fibers for BOSS*
- *300 fibers for APOGEE*
- *We observe 8 or 9 plates per night, on the Sloan Foundation 2.5-m Telescope.*
- *Allows rapid accumulation of spectra over a wide sky area.*
- *Real-time data reduction controls how long we spend on each plate.*
- *Full reduced catalogs available to science collaboration next day.*
- *Regular, well-documented data releases to the public (latest was DR9 on July 31, 2012).*

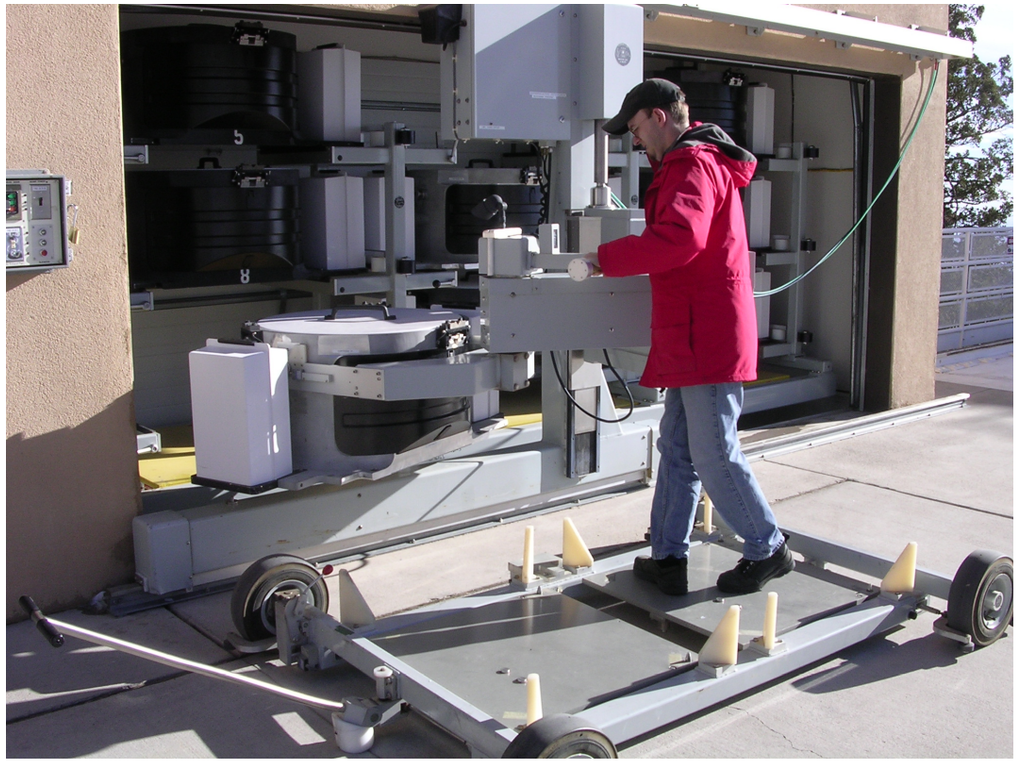


Credit: Mary Kawamura, Gaelen Sayres

Introduction: plates plugged with optical fibers







Introduction: the history

SDSS-I (2000 to 2005):

*the **Legacy survey** of galaxies and quasars*

SDSS-II (2005 to 2008):

finishing Legacy

SDSS Supernova Survey (cosmology)

SEGUE survey of Milky Way stars

SDSS-III (2008 to 2014):

SEGUE-2 optical survey of stars

***BOSS** survey of galaxies and quasars*

MARVELS planet search

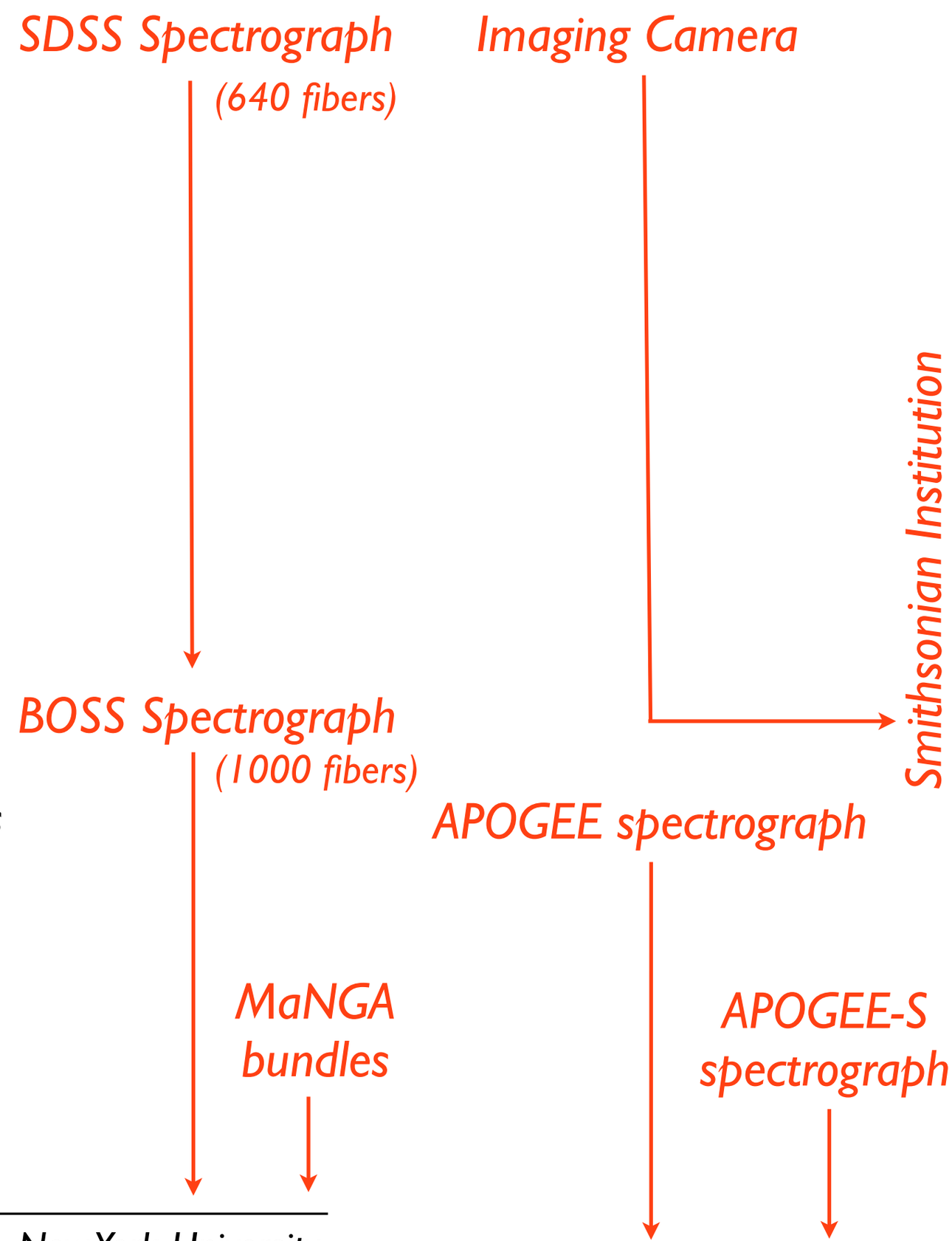
***APOGEE** high-resolution NIR survey of stars*

SDSS-IV (2014 to 2020):

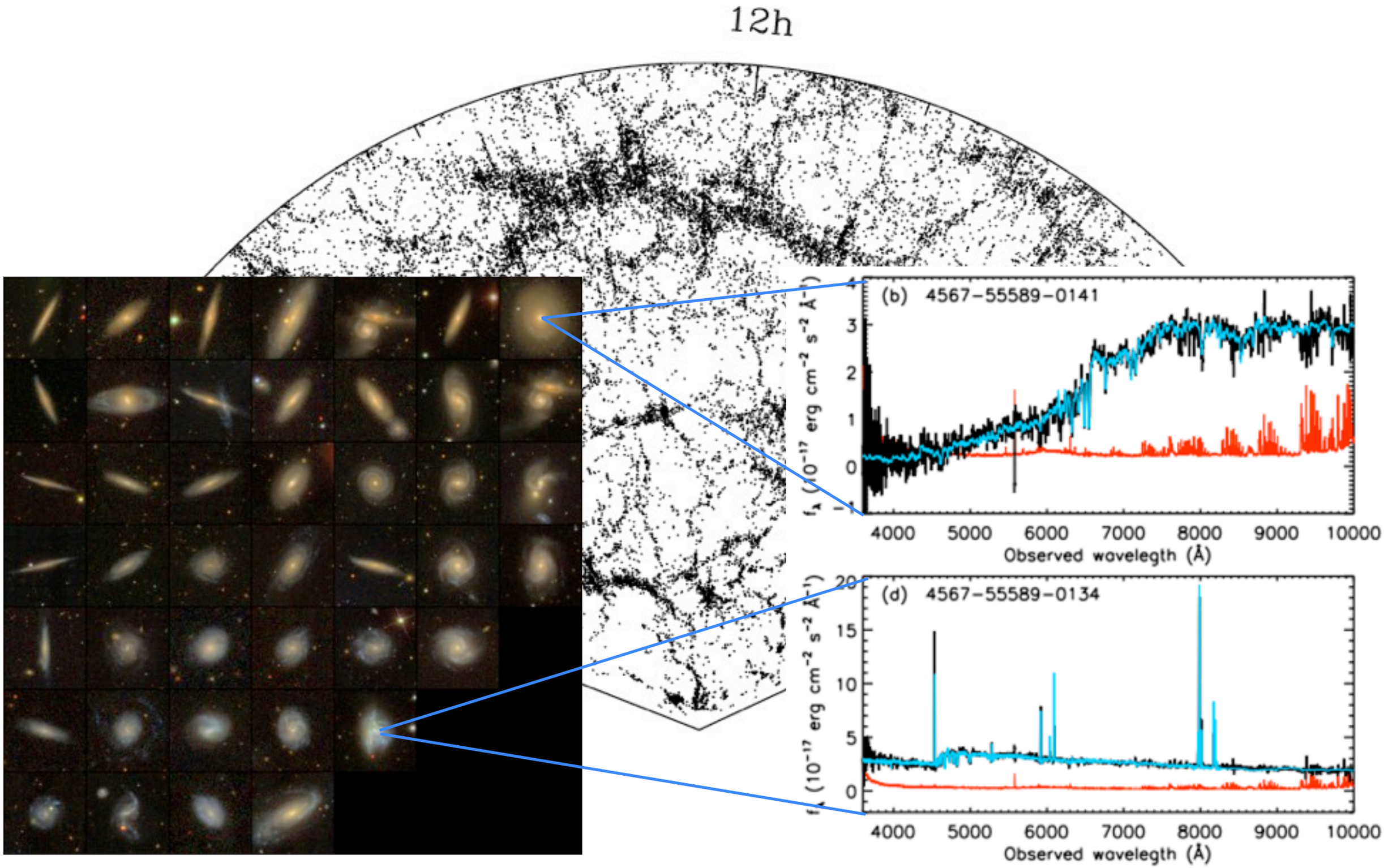
APOGEE-2 high-resolution NIR survey of stars

MaNGA survey of nearby galaxies

eBOSS survey of galaxies and quasars

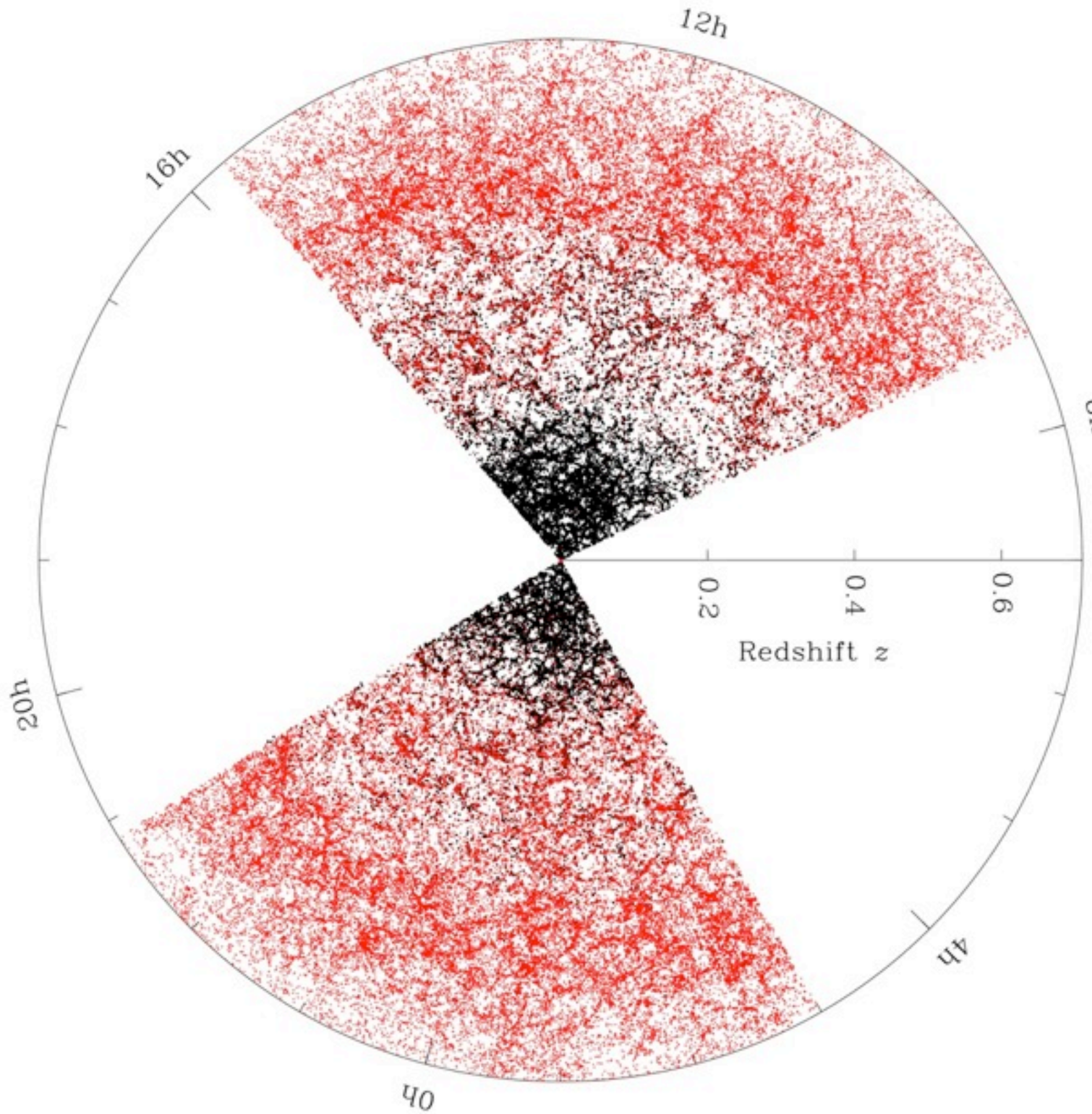


SDSS Legacy Survey (2000-2008)

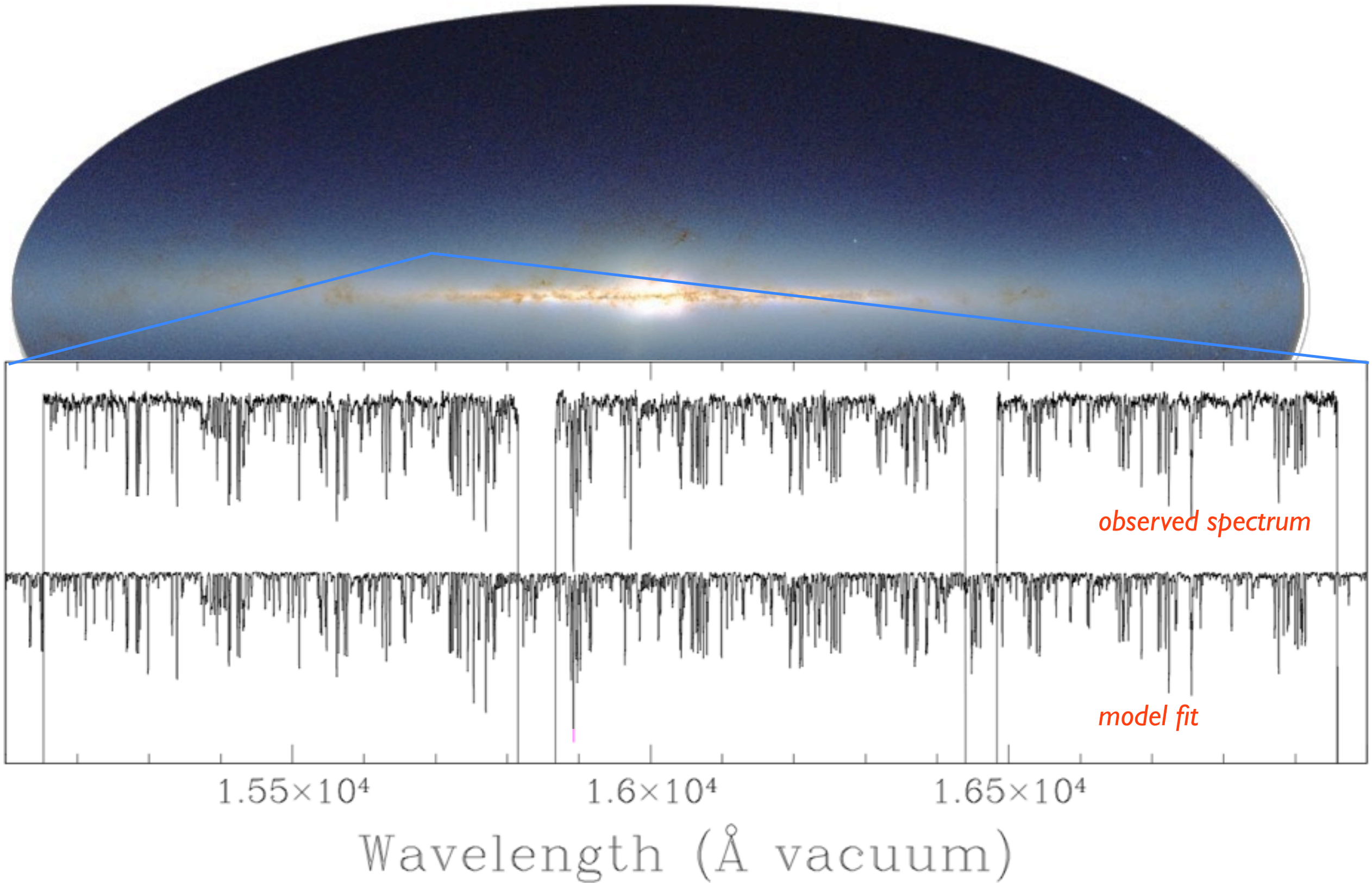


BOSS (2009-2014)

- 10,000 sq deg.
  - *1.6 million LRGs (z < 0.7)*
  - *200,000 QSOs (2.15 < z < 3)*
- Baryon Oscillations
- Large-scale structure
- Massive galaxy evolution
- Quasar evolution

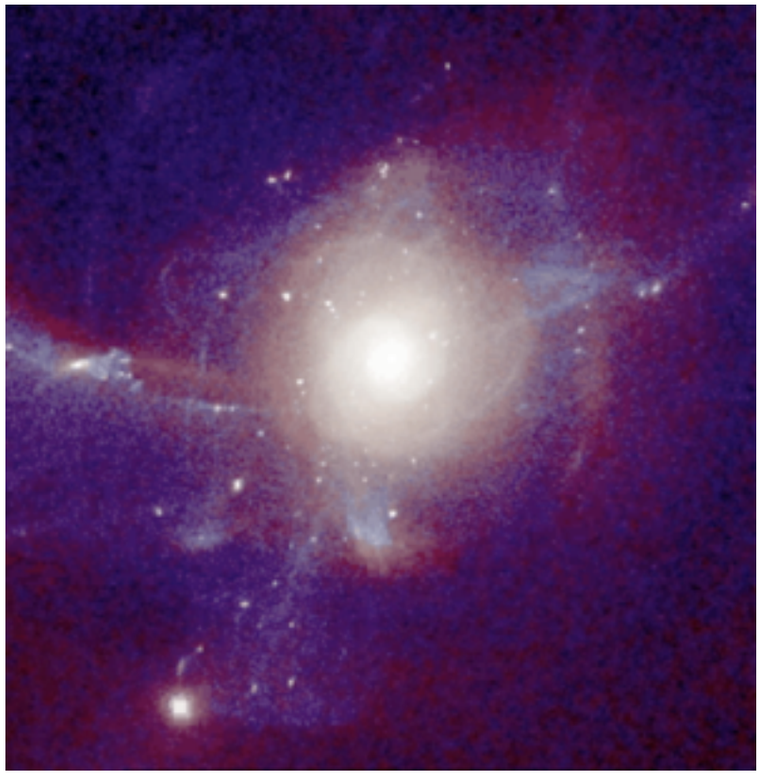


APOGEE (2011-2014)



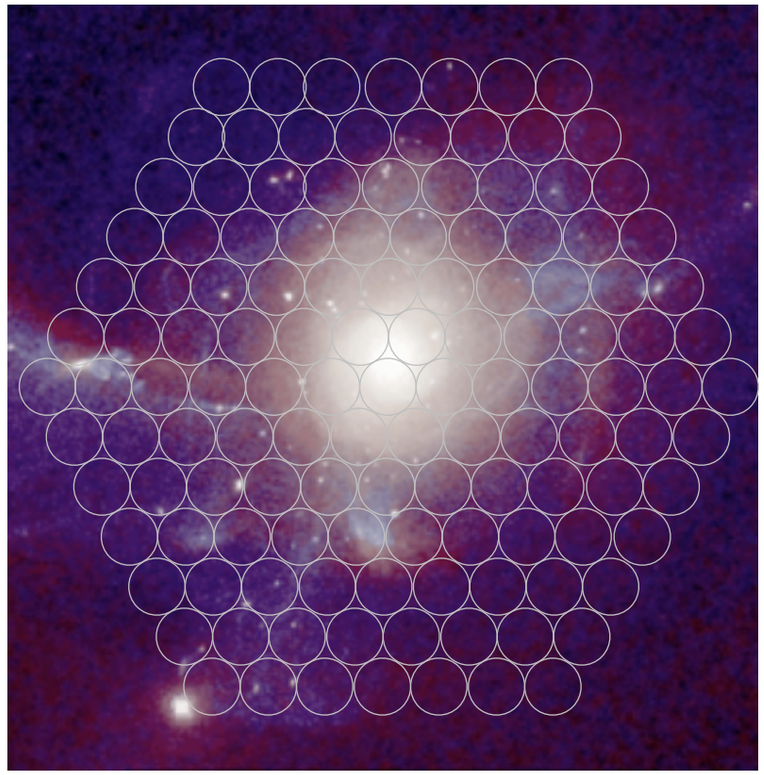
Post-2014 SDSS surveys

APOGEE-2



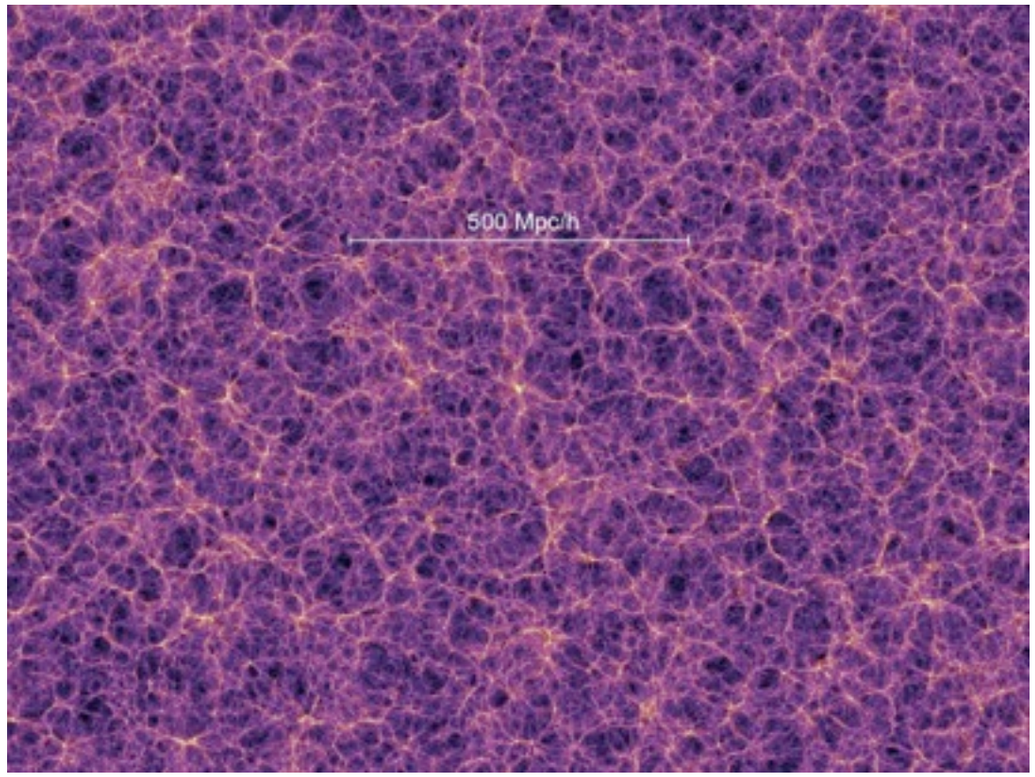
100s of thousands of individual stars in the Milky Way

MaNGA



Maps thousands of nearby galaxies

eBOSS



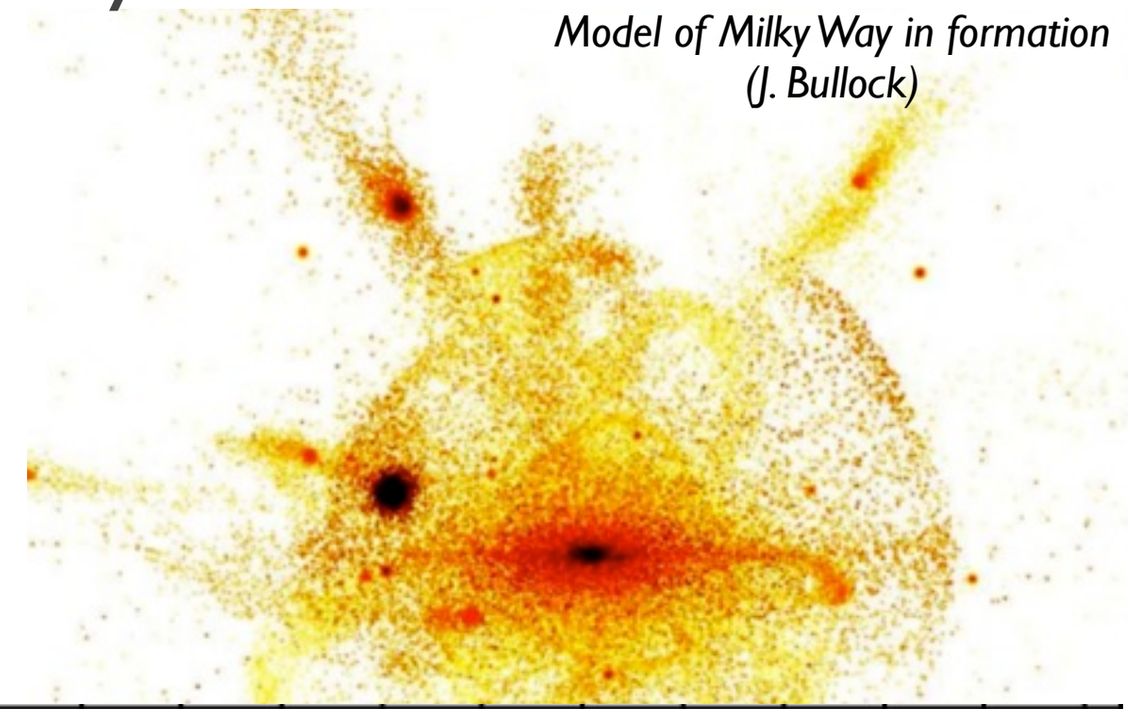
Map of the Universe

galaxy evolution & dark matter

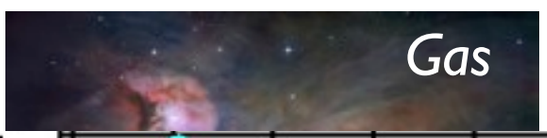
dark energy & cosmology

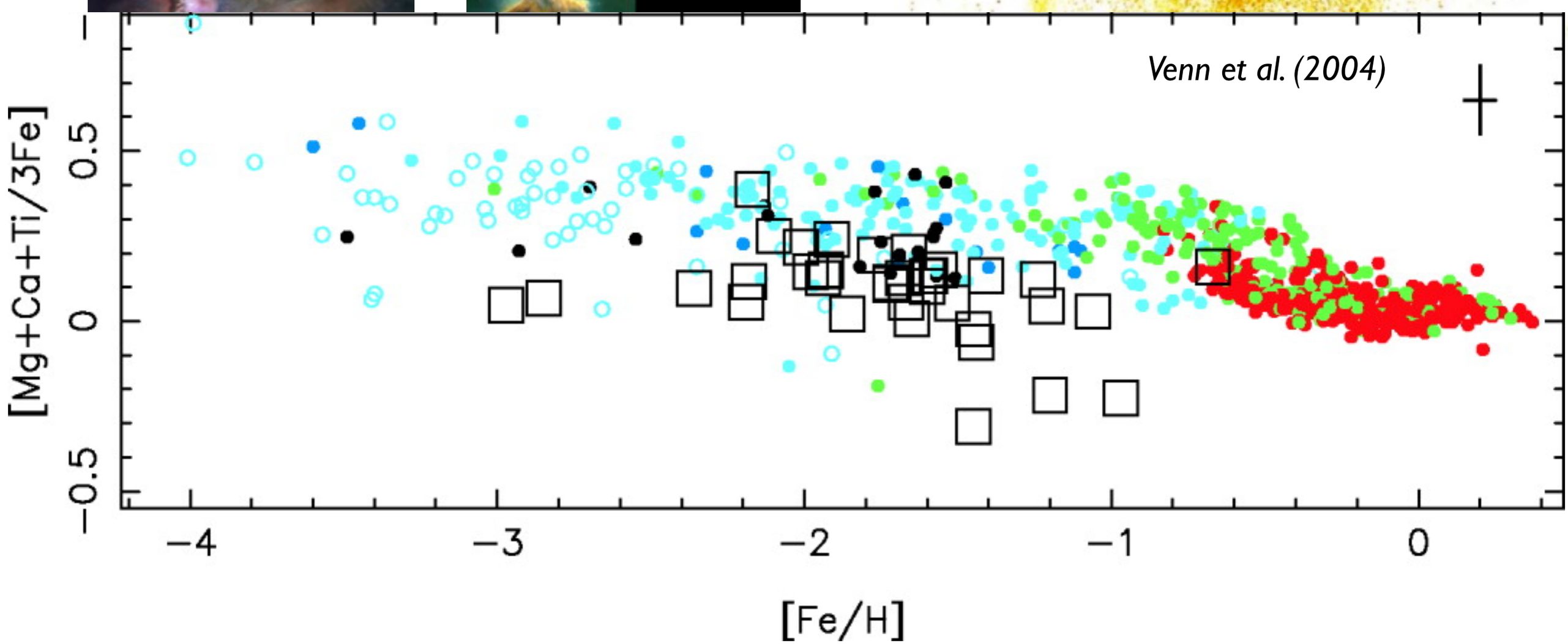
APOGEE-2: *assembly of the Milky Way and creation of the heavy elements*

(S. Majewski, PI)

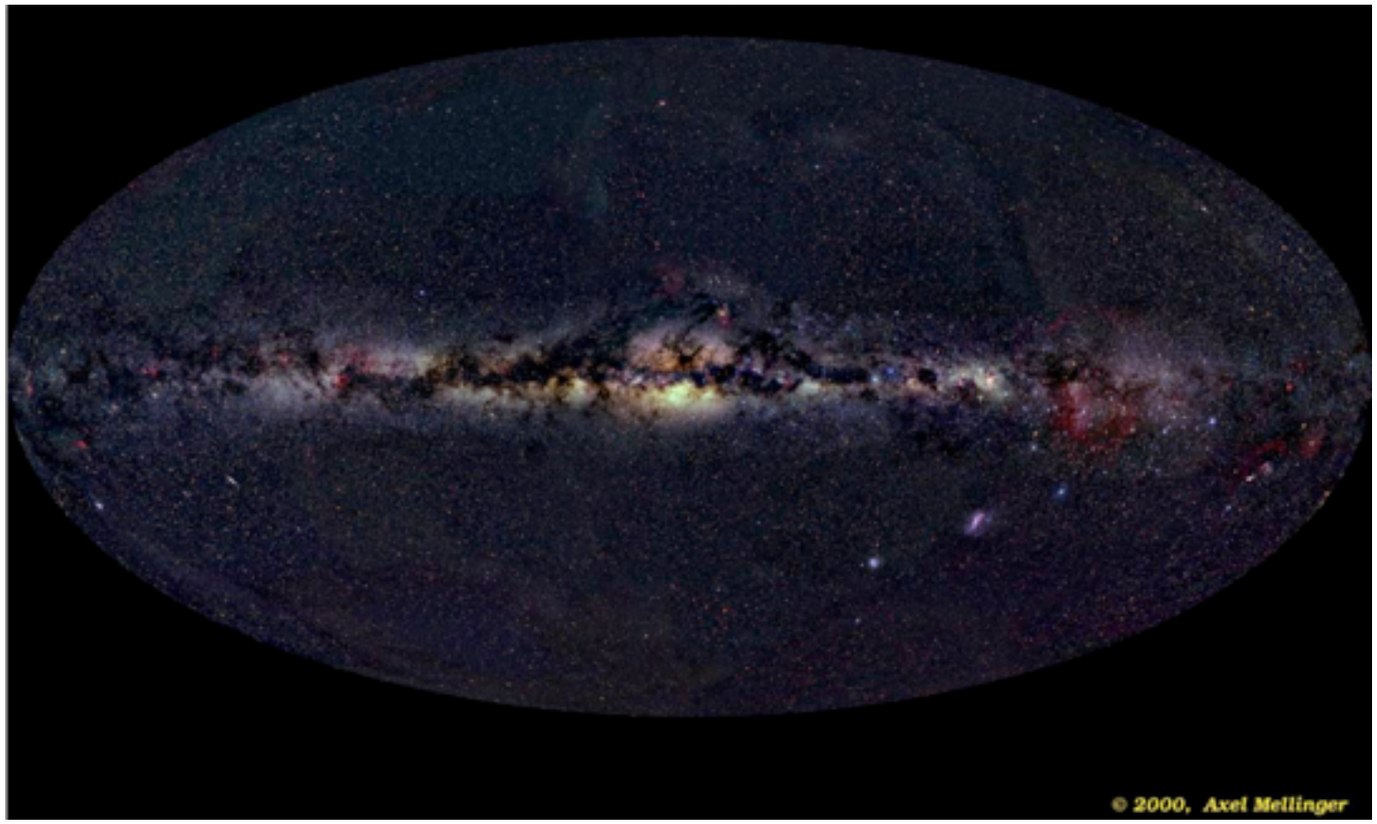


Patterns of elemental abundances tell us about the history of how stars formed in Milky Way and its progenitors. E.g. alpha abundances yield info on star-formation history

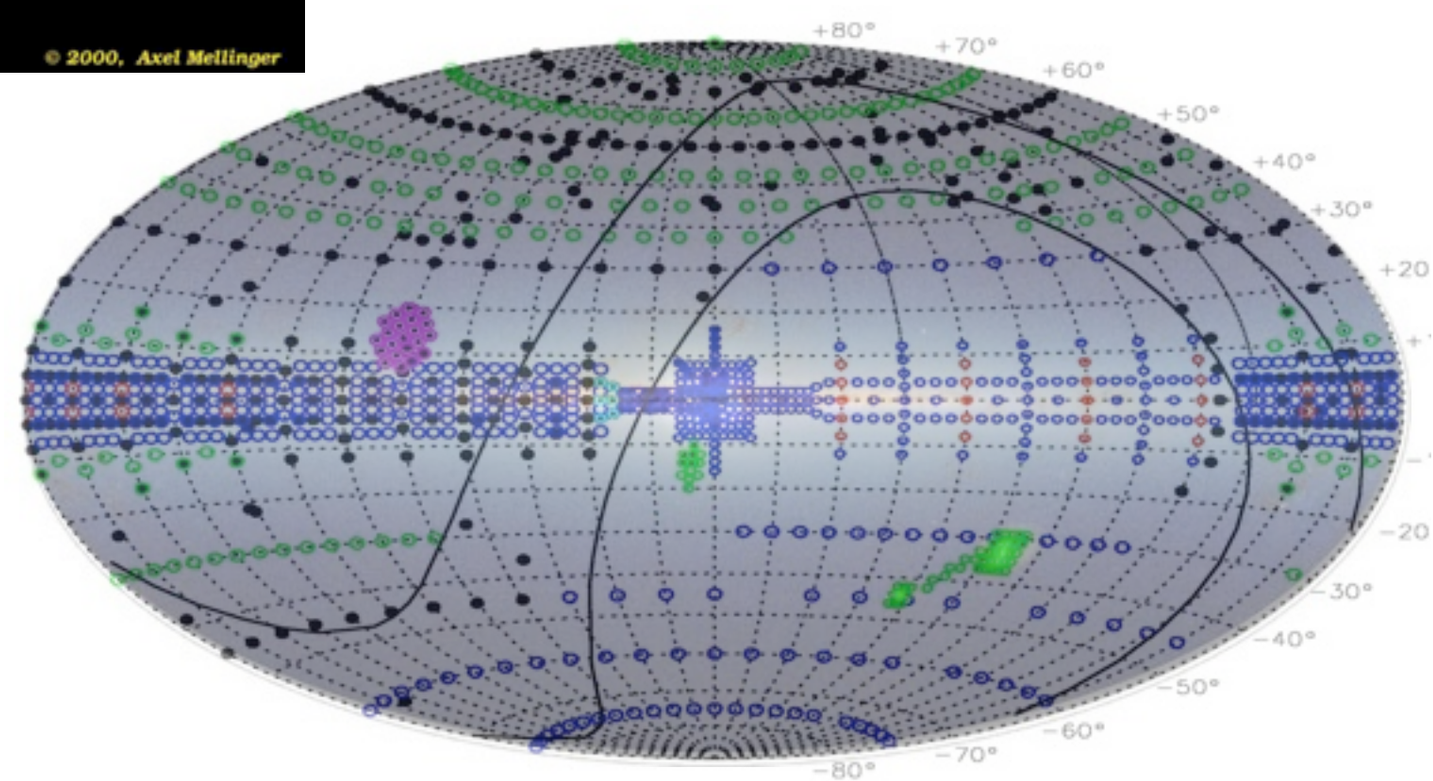




APOGEE-2: *peering through dust in H-band (1.6 microns)*



SDSS-III + SDSS-IV observations



Milky Way in infrared light (2MASS)

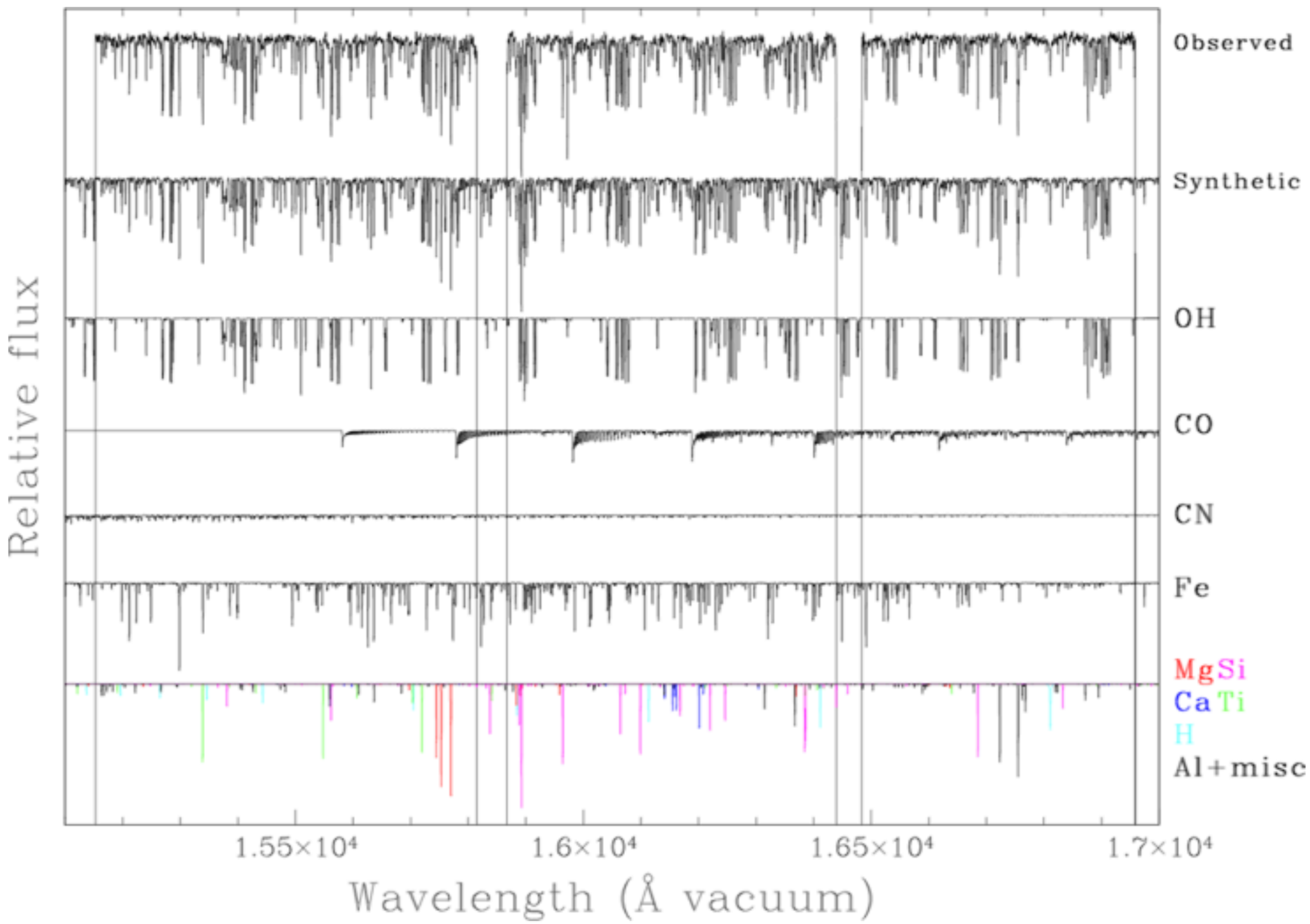
APOGEE-2: *information in high-resolution spectra*

R ~ 22,500

S/N > 100 per pixel

RV error < 100 m/s

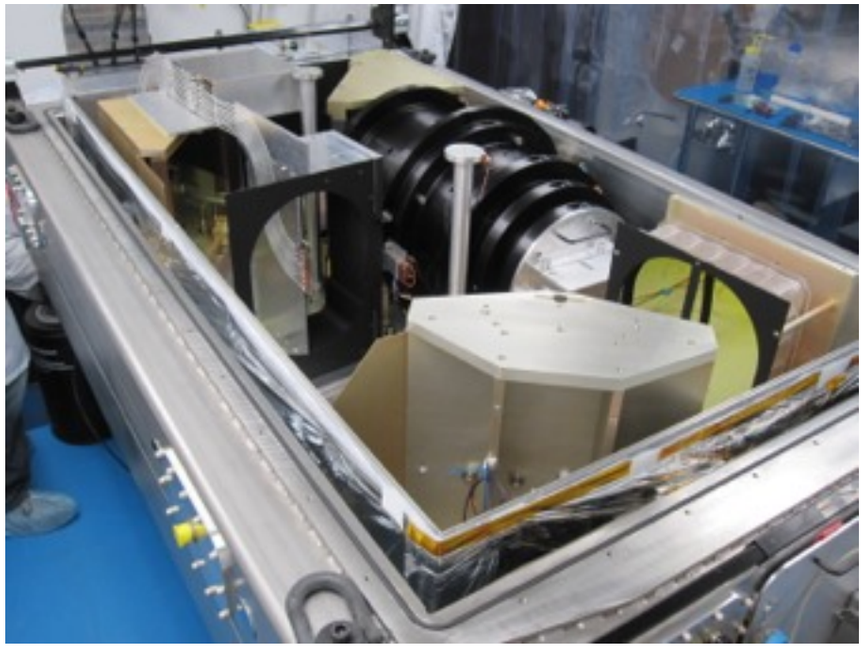
Goal is 0.1 dex precision for 15 elements (Fe, C, N, O, alphas + others). Challenge is automating this analysis!



APOGEE-2: *capitalizing on SDSS-III's success*

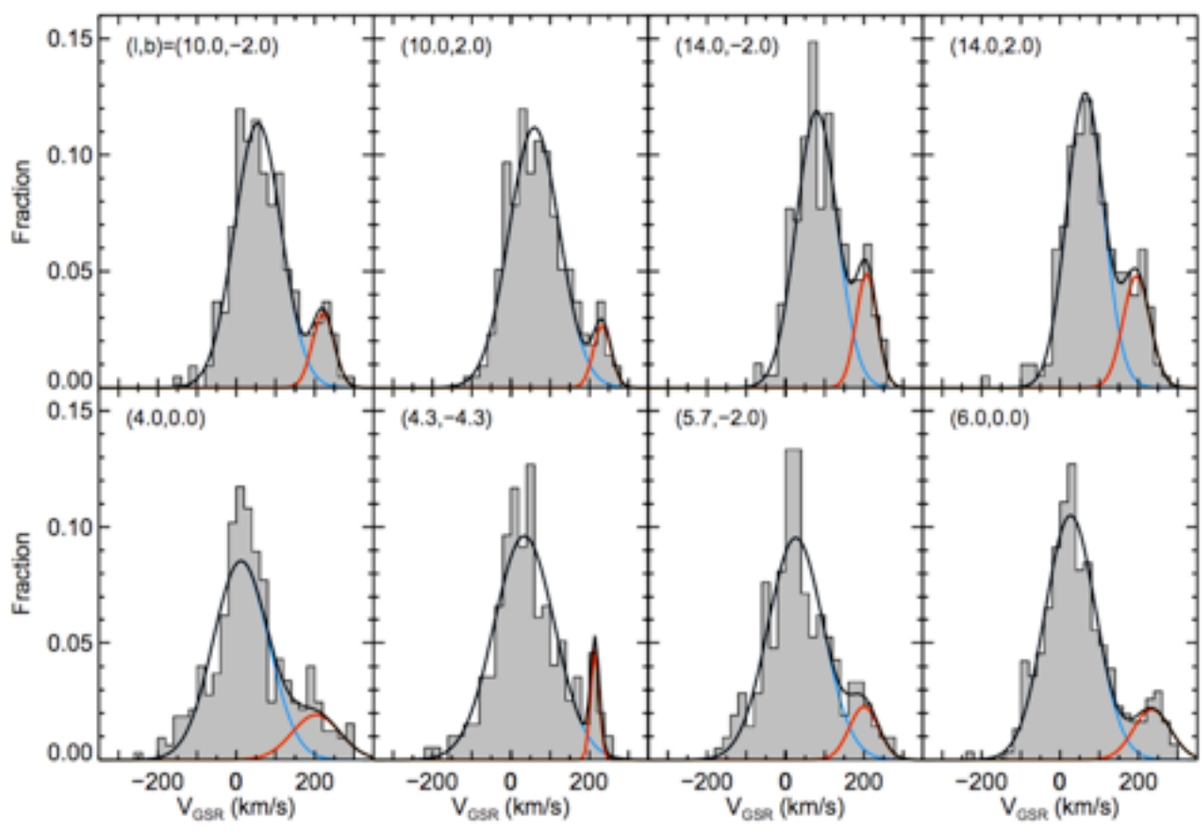
Instrument commissioned successfully in Spring 2011:

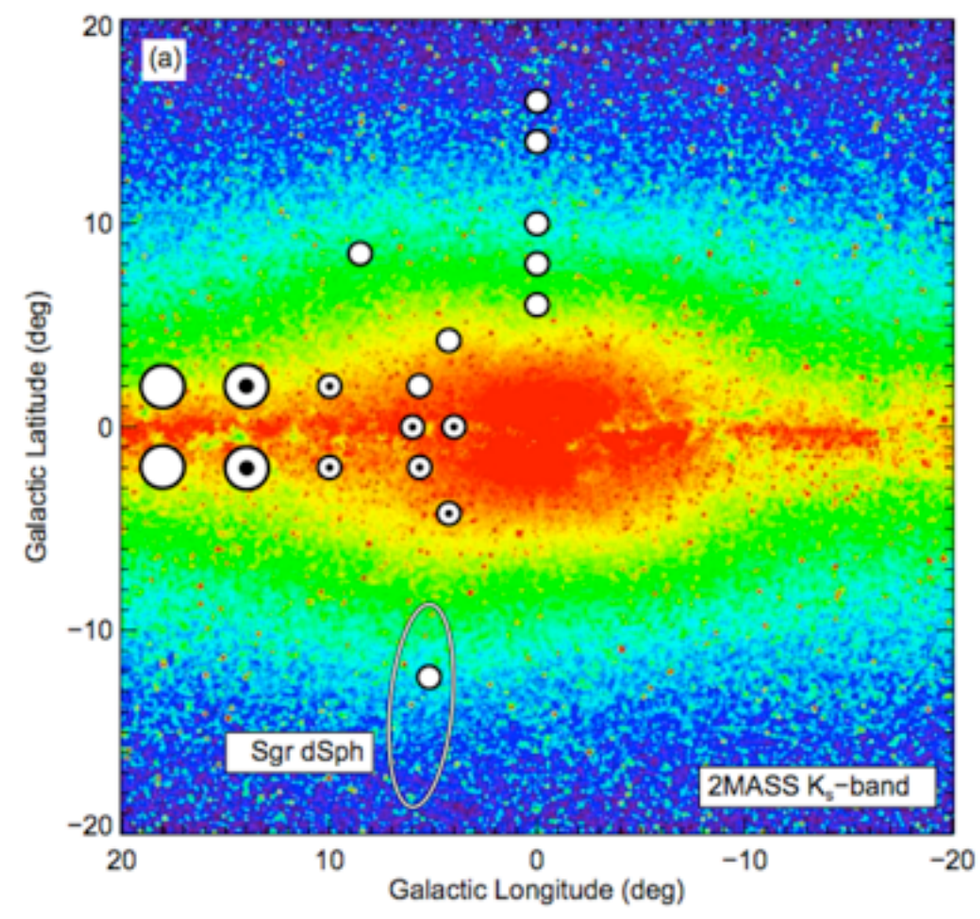
- Survey commenced on time and on budget
- Currently, more than 40,000 stars
- Baseline schedule being met.
- 10 times the # of similar previous spectra



Preparing for data release in 2013.

Commissioning data uncovered new structures near the Milky Way's center.



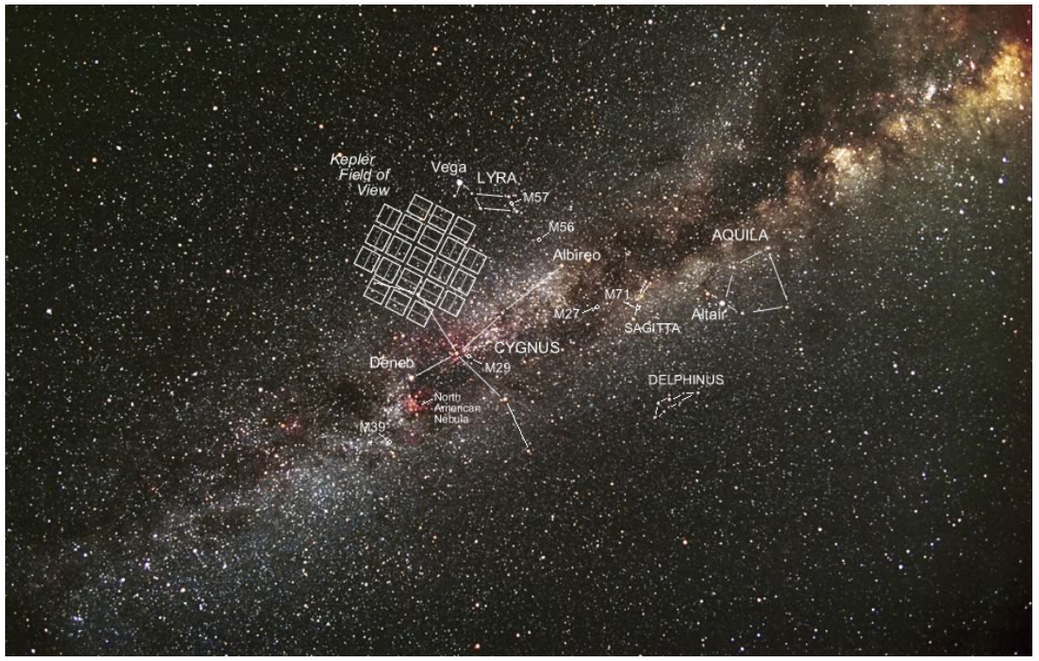


APOGEE-2: *asteroseismology!*

Kepler fields: 21 x 2 visits, ~10,000 stars

Kepler measures asteroseismic frequencies for ~10k giants:

gravity
radius
mass



APOGEE provides abundances:

Combined w/asteroseismic info, yields ages to 20% precision for field stars
Strict constraints on chemical evolution models, beyond solar neighborhood.
Helps calibrate APOGEE reduction pipelines.

program to be greatly enhanced with the northern component of APOGEE-2

APOGEE-2: *exoplanets!*

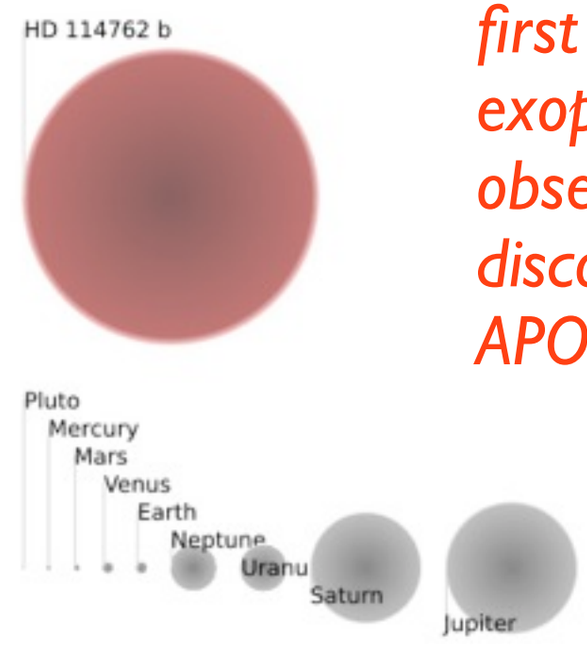
APOGEE strategy uses multiple observations over different nights.

Allows us to observe changes in Doppler velocities of stars, which can reveal that they have companions.

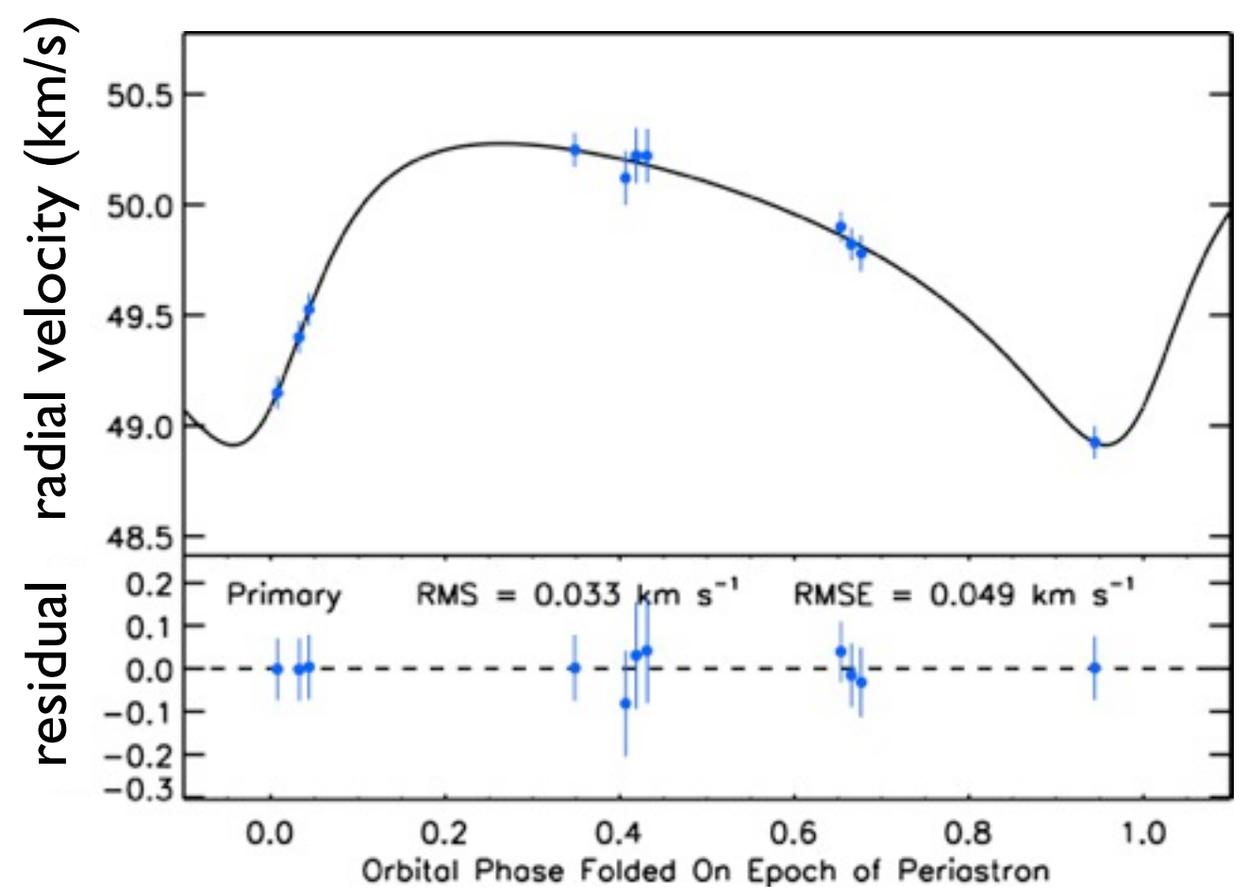
Precision of APOGEE turns out to be sufficient to find planetary companions of other stars ("exoplanets"). 100 candidates being pursued.

APOGEE is partnering with Kepler, a NASA satellite detecting exoplanets and studying "asteroseismology":

- *how chemistry drives planet formation*
- *false positive elimination (Fleming et al.)*

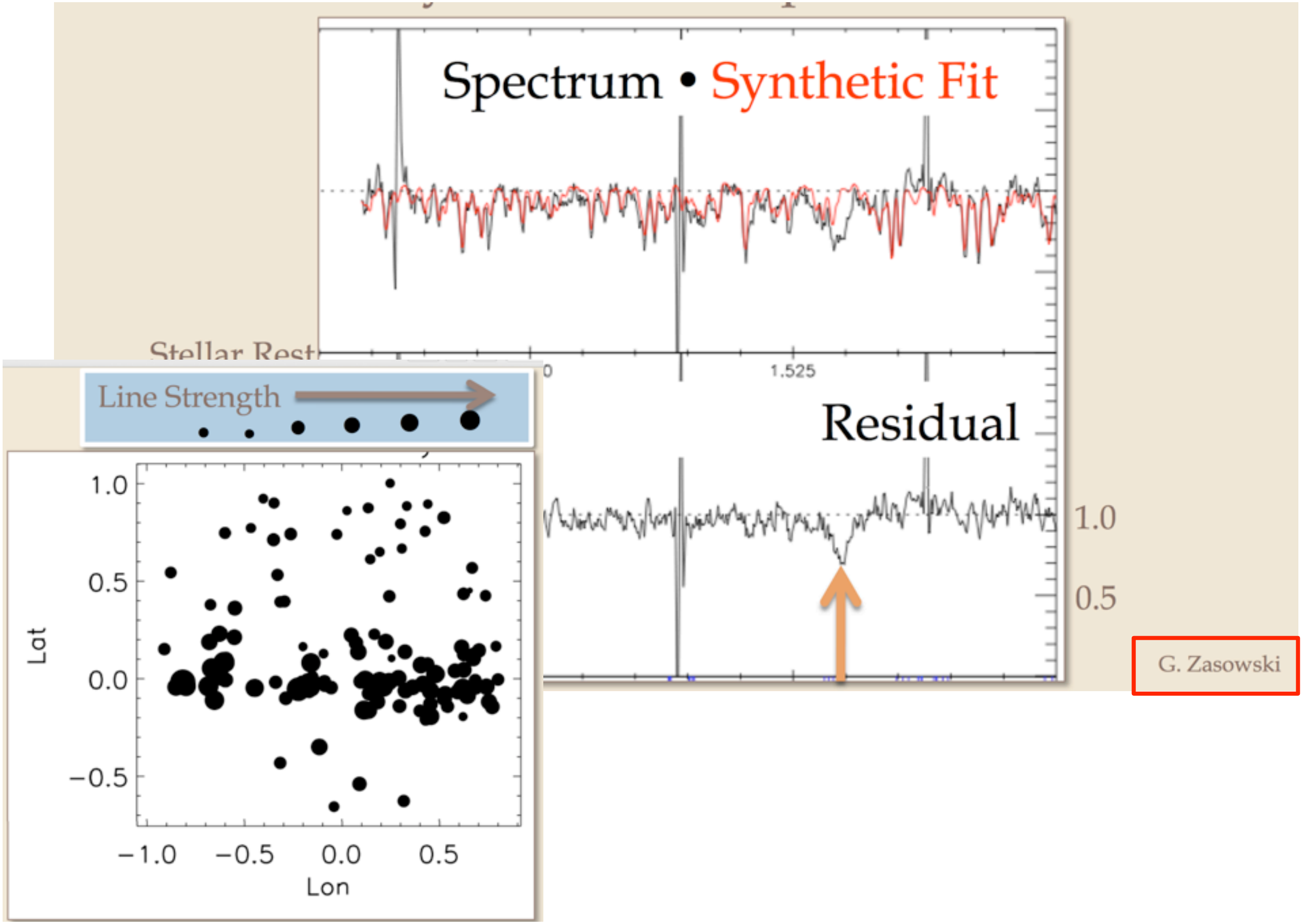


first detected exoplanet, accidentally observed and re-discovered within APOGEE (D. Nidever)



time

APOGEE-2: *interstellar medium!*



APOGEE-2: *science plan*

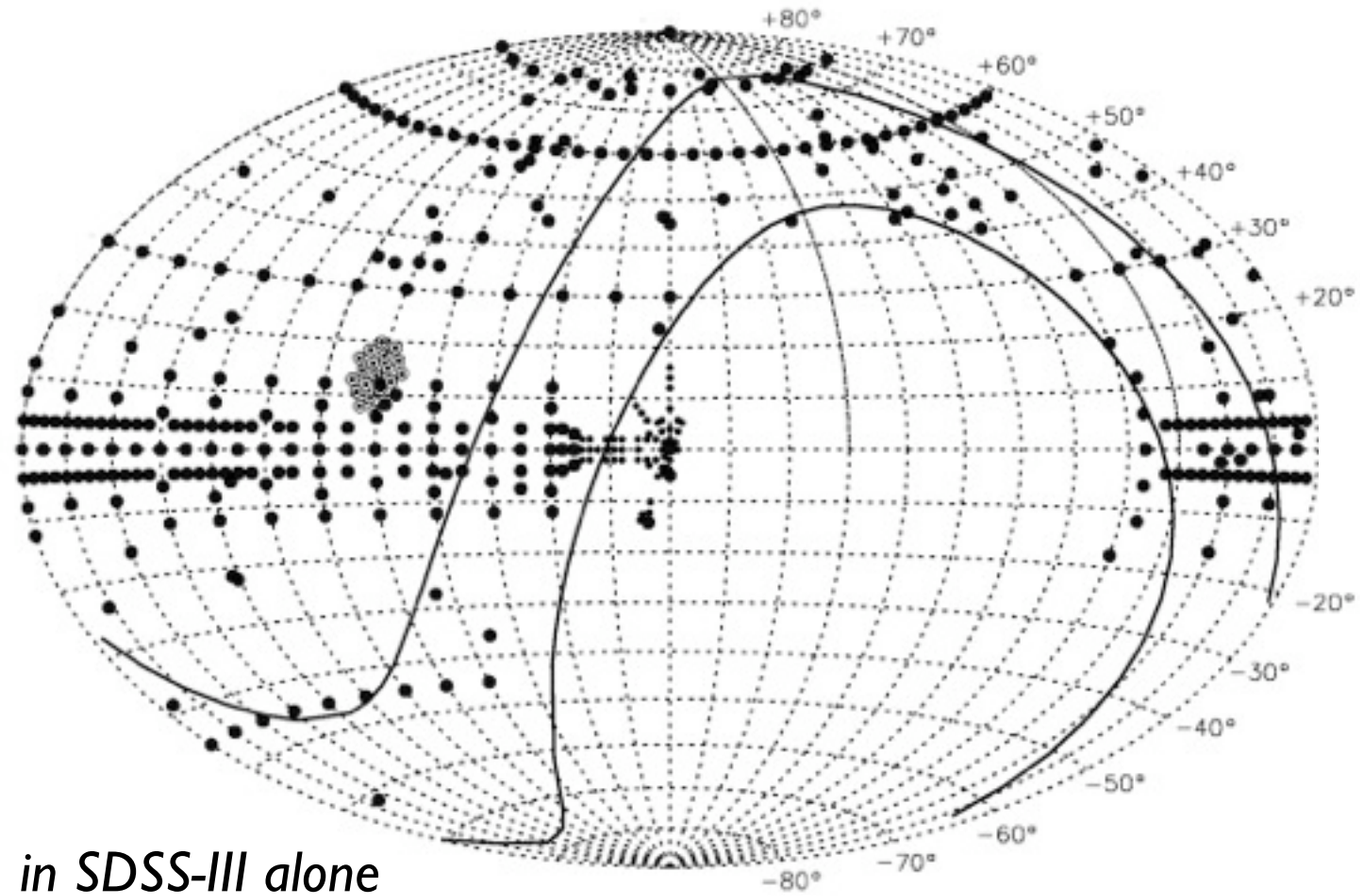
Northern program:

- *Kepler follow-up*
- *fuller sampling of disk + halo*
- *increase time-series data*

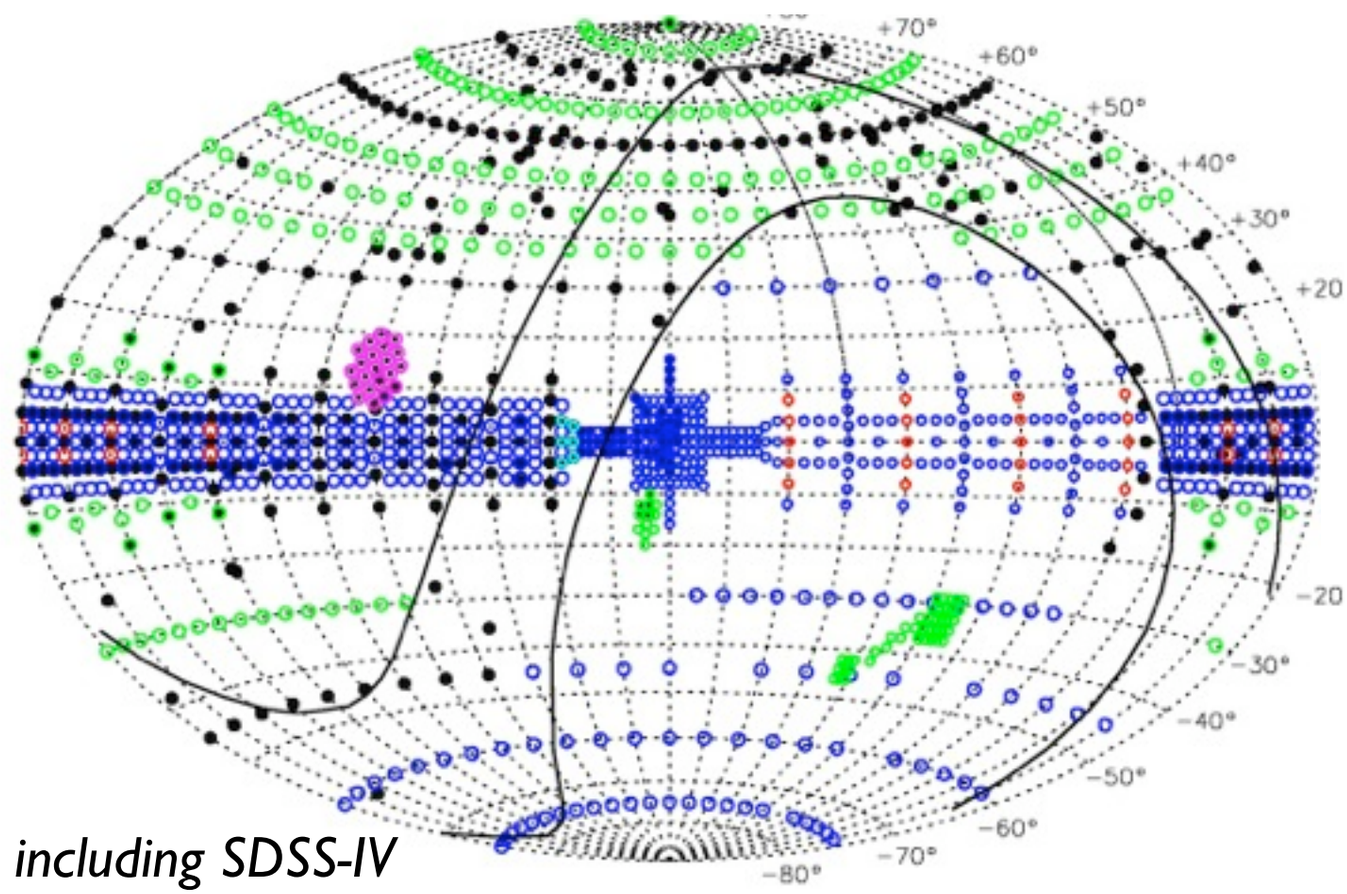
Southern program:

- *full bulge sample*
- *Magellanic clouds, Sagittarius*
- *Globulars!!*
- *Jasmine, OGLE, VVV overlap*

Dual hemisphere facility well-positioned for Gaia follow-up in the long term



in SDSS-III alone



including SDSS-IV

eBOSS: *measuring dark energy*

(J-P Kneib, PI)

Key goal for modern astronomy has been establishing the distance scale.

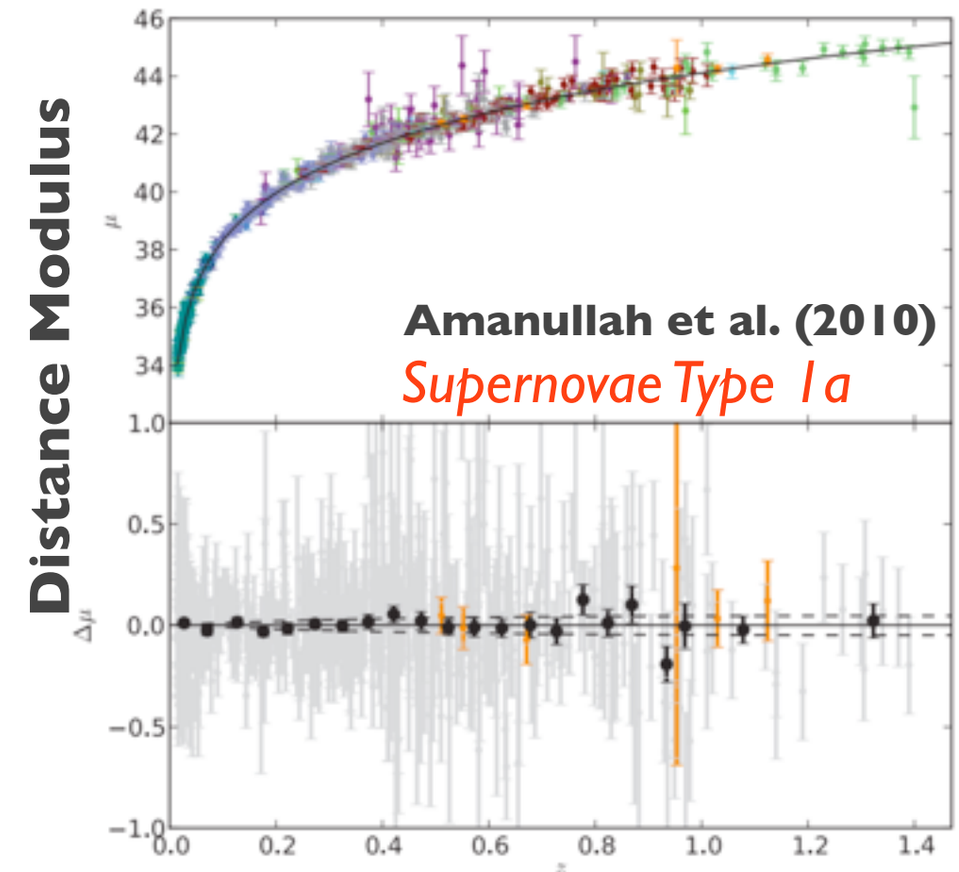
Revealed acceleration of Universe, caused by something == "dark energy"

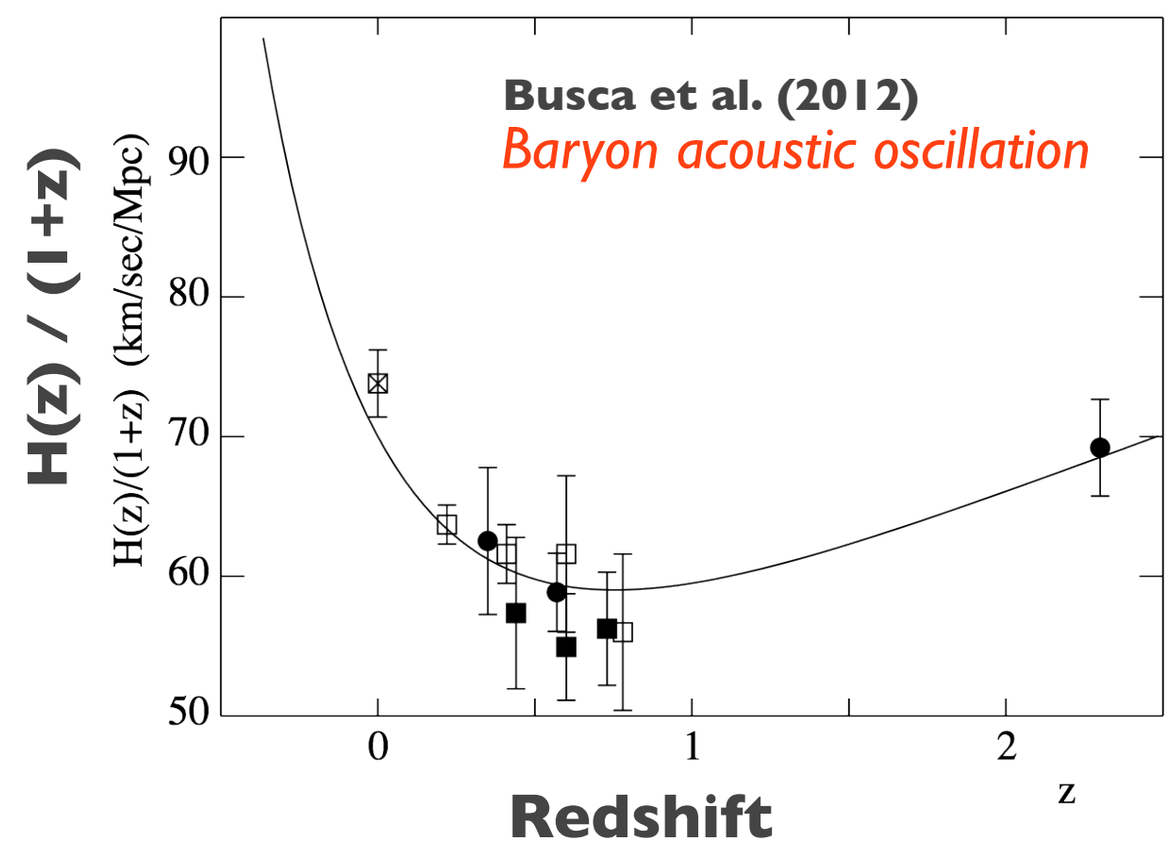
Supernovae Type 1a

- *harder to control systematics*
- *in principle, infinite statistics*
- *model-dependent through luminosity distance*

Baryon Acoustic Oscillation

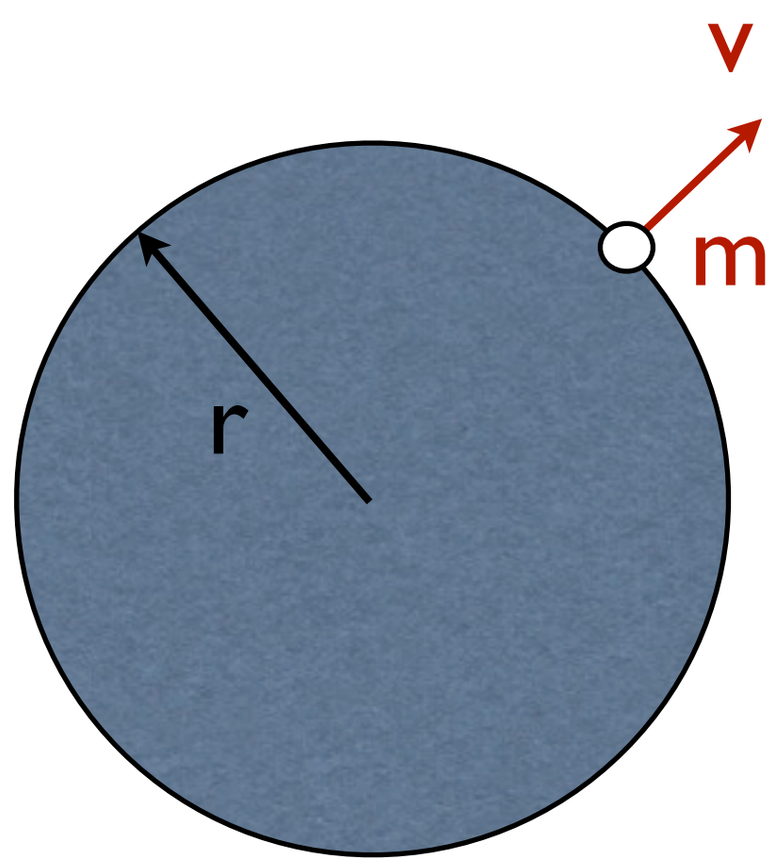
- *tiny systematic errors*
- *statistical errors set by cosmic variance*
- *direct measurement of H(z)*





What does the expansion tell you?

$$E = \frac{1}{2}mv^2 - \frac{GM(<r)m}{r} + m\phi(r) - \frac{m\Lambda}{6}r^2$$



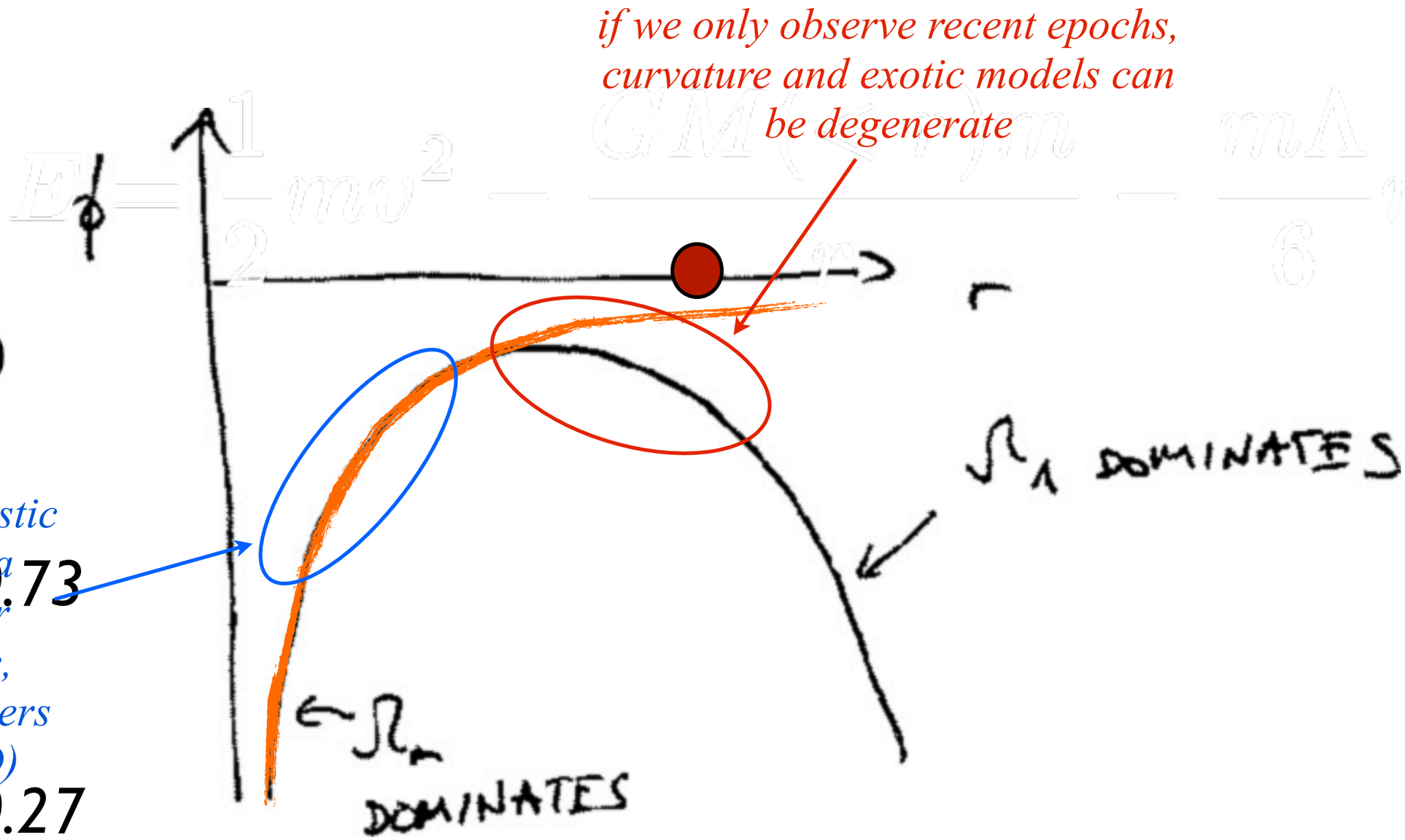
$$\Omega_m + \Omega_\Lambda + \Omega_k = 1$$

$$\Omega_k = \frac{2Er^2}{mH_0^2} \approx 0$$

$$\Omega_\Lambda = \frac{\Lambda}{3H^2} \sim 0.73$$

$$\Omega_m = \frac{8\pi G\rho}{3H^2} \sim 0.27$$

observations in the ballistic phase constrain only a combination of matter content and curvature, before dark energy matters (or before it SHOULD)



Modifications other than Lambda?

$$E = \frac{1}{2}mv^2 - \frac{GM(<r)m}{r} - \frac{m\Lambda}{6}r^2$$

$$\Lambda \rightarrow \Lambda_0 r^{-3(1+w)}$$

"dark energy" -- for cosmological constant, w=-1

$$w = \frac{P}{\rho}$$

in relativistic terms, this comes about because of the "equation of state"

$$w(a) = w_0 + w_a(1-a)$$

dependent on redshift?

this is just one possible way of parametrizing what is really an infinite set of possibilities, if you are willing to consider alternative gravity models or exotic physics (cf. Dvali, Gabadadze, Porrati, etc.); most of these also can impact other observables, like the clustering of galaxies

Modifications other than Lambda?

$$E = \frac{1}{2}mv^2 - \frac{GM(<r)m}{r} - \frac{m\Lambda}{6}r^2$$

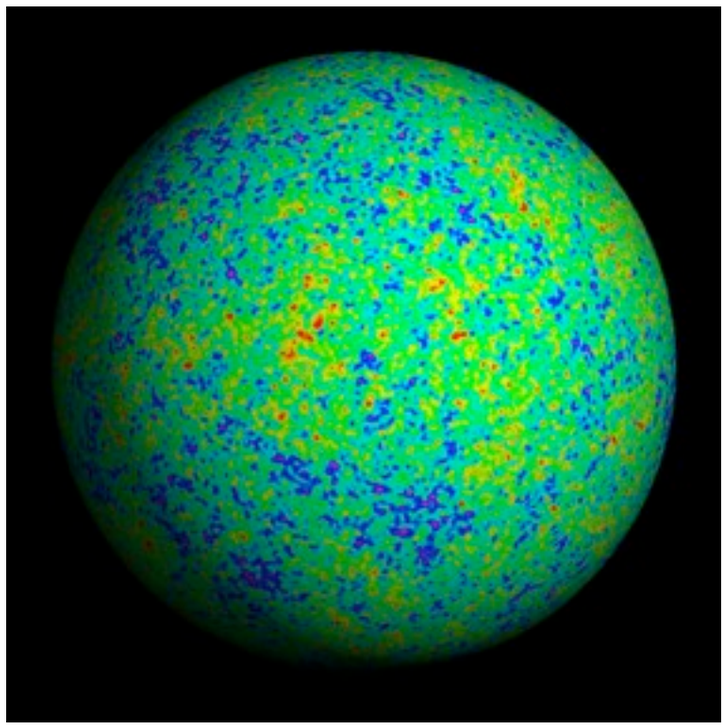
$$\Lambda \longrightarrow \Lambda_0 r^{-2(1+w)}$$

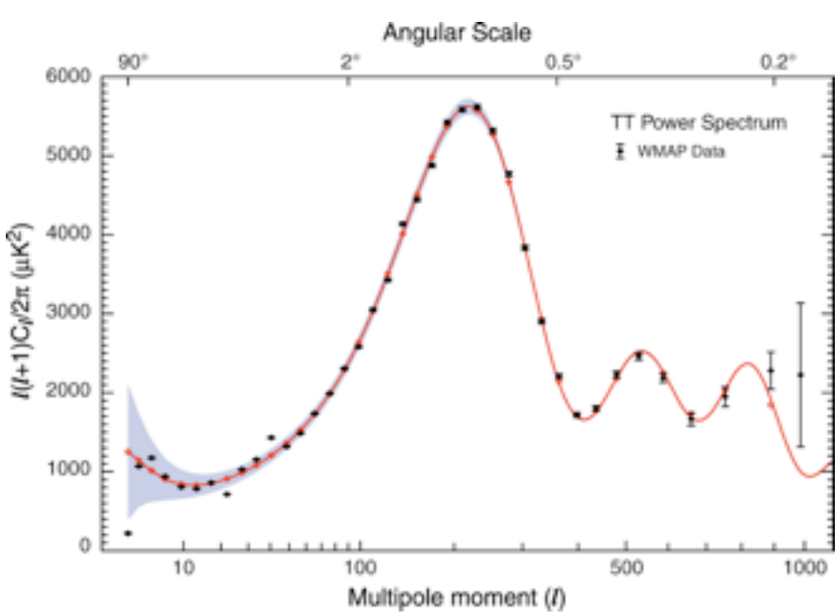
All models, including the vanilla LCDM model, are contrived and have very little theoretical motivation.

We should probably just measure the expansion very carefully across a full range of redshifts.

eBOSS: *baryon acoustic oscillation*

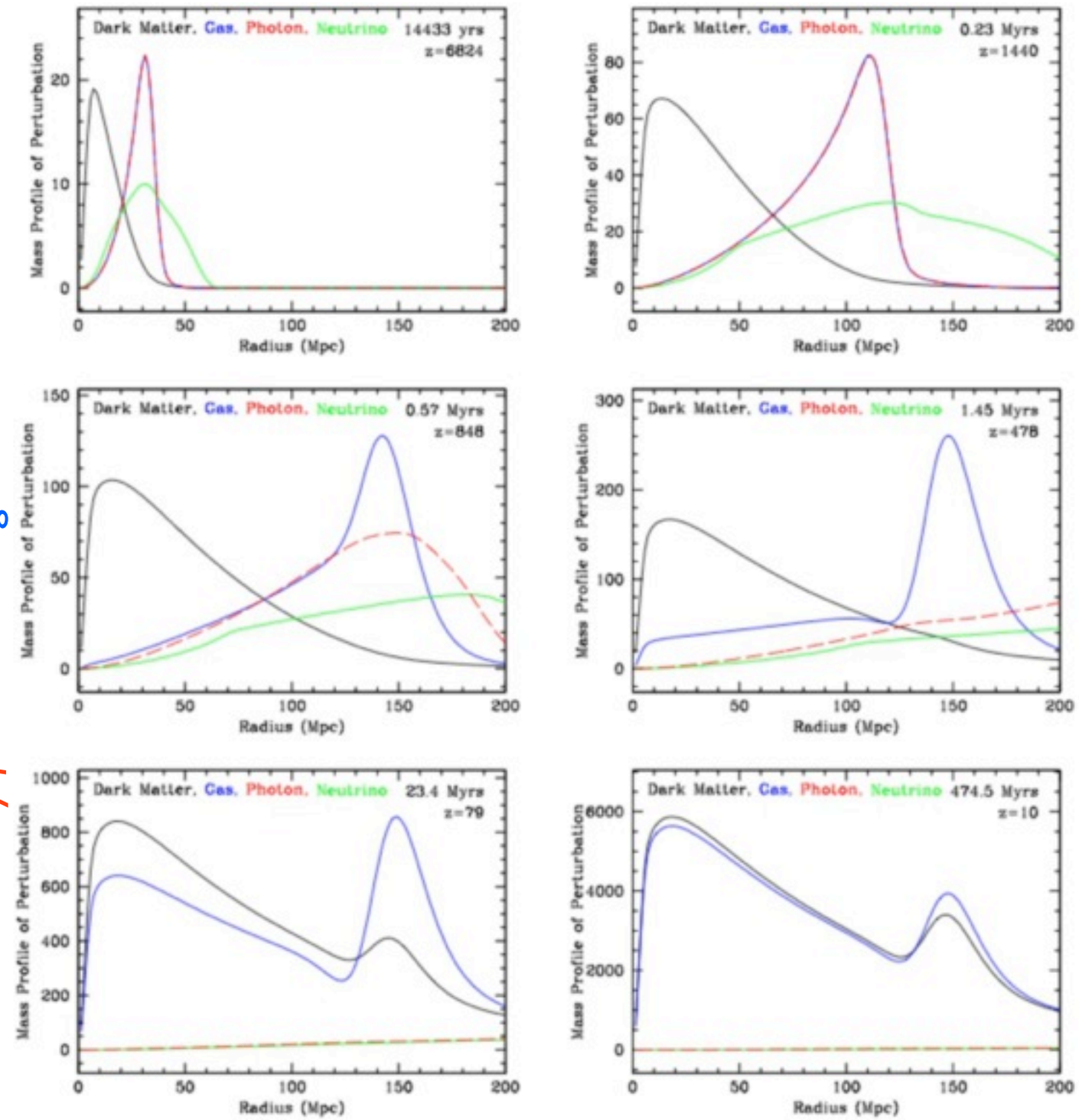
Until recombination (400,000 yrs), sound waves travel outwards from dense regions. Physical scale in Mpc determined by CMB experiments.





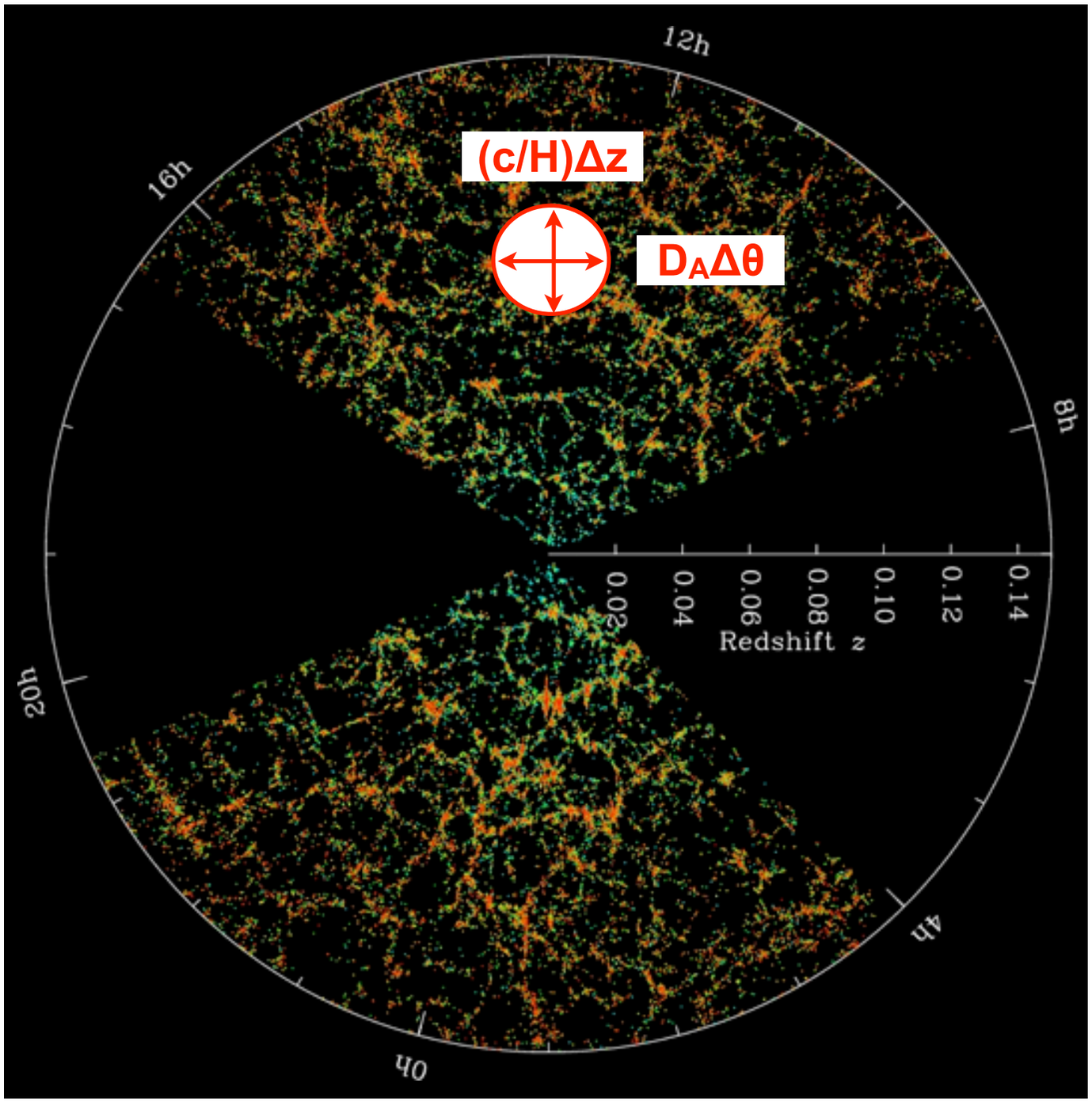
radius (Mpc)

density fluctuation in gas and dark matter



Remnant signal detectable in matter fluctuations observed today by redshift surveys, but in units of km/s.

eBOSS: baryon acoustic oscillation in redshift space



Spectroscopic BAO measures two standard rulers:

- *Angular diameter distance, D_A*
- *Line-of-sight Hubble parameter, H*

D_A is the integral of H

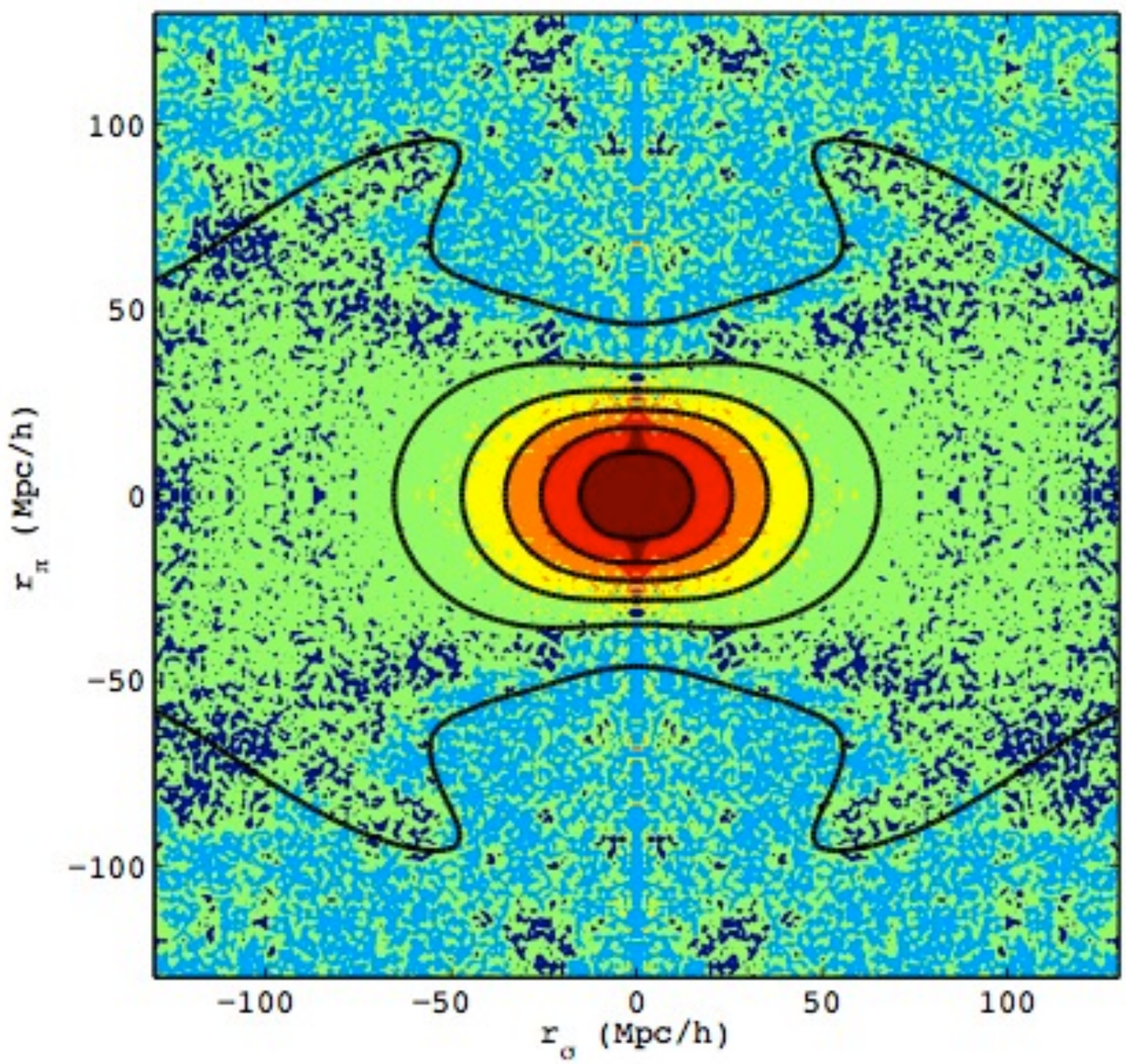
$$H(z) = \sqrt{\Omega_M(1+z)^3 + (1-\Omega_M-\Omega_\Lambda)(1+z)^2 + \Omega_\Lambda}\,, \tag{2.4}$$

$$d_A(z) = \begin{cases} (-K)^{-1/2}\sinh\left[(-K)^{1/2}\chi(z)\right] & K<0\,, \\ \chi(z) & K=0\,, \\ K^{-1/2}\sin\left[K^{1/2}\chi(z)\right] & K>0\,, \end{cases} \tag{2.5}$$

where

$$K = 1-\Omega_M-\Omega_\Lambda, \qquad \chi(z) = \int_0^z \frac{dz'}{H(z')} \tag{2.6}$$

eBOSS: *redshift space distortion constraints on gravity*

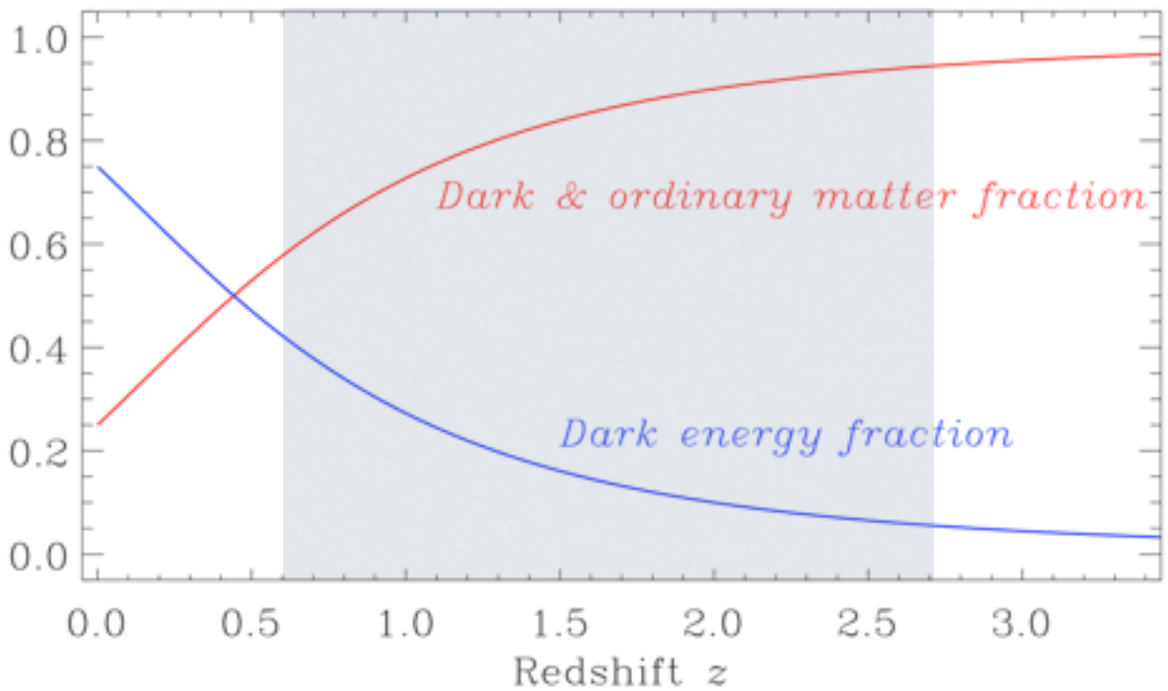


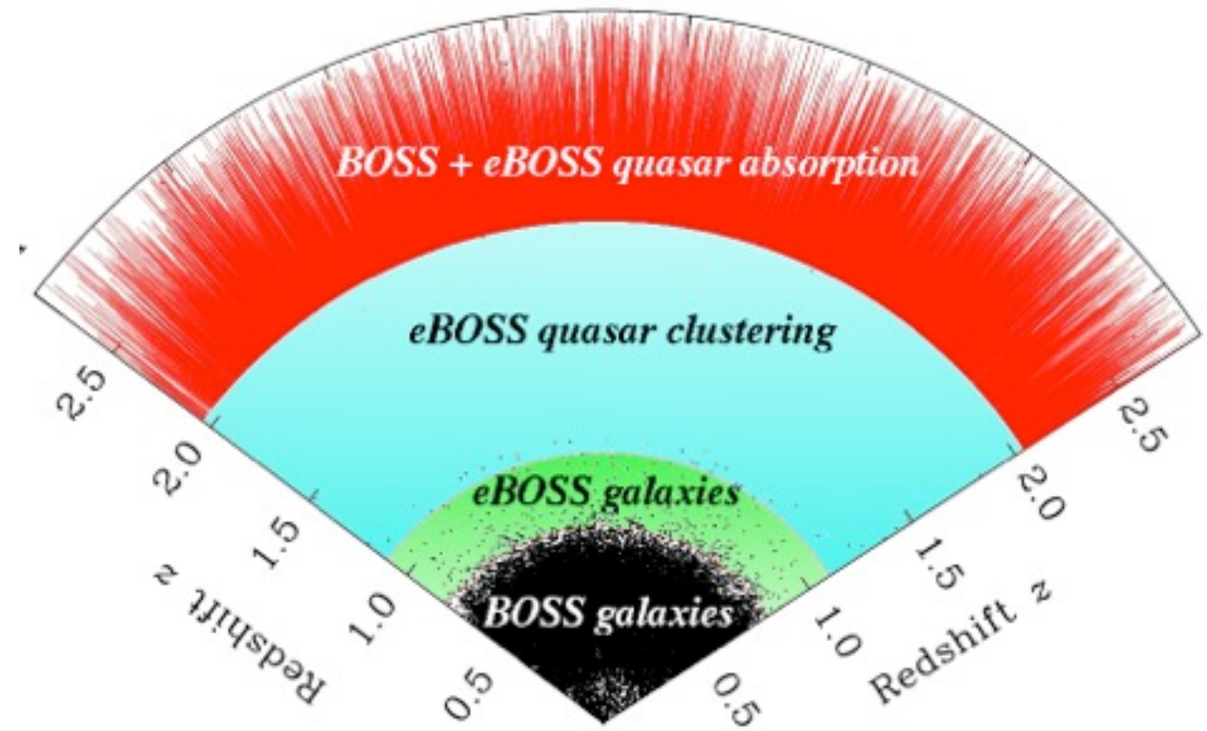
Very well-measured linear redshift-space distortions constrain growth of structure and general relativity

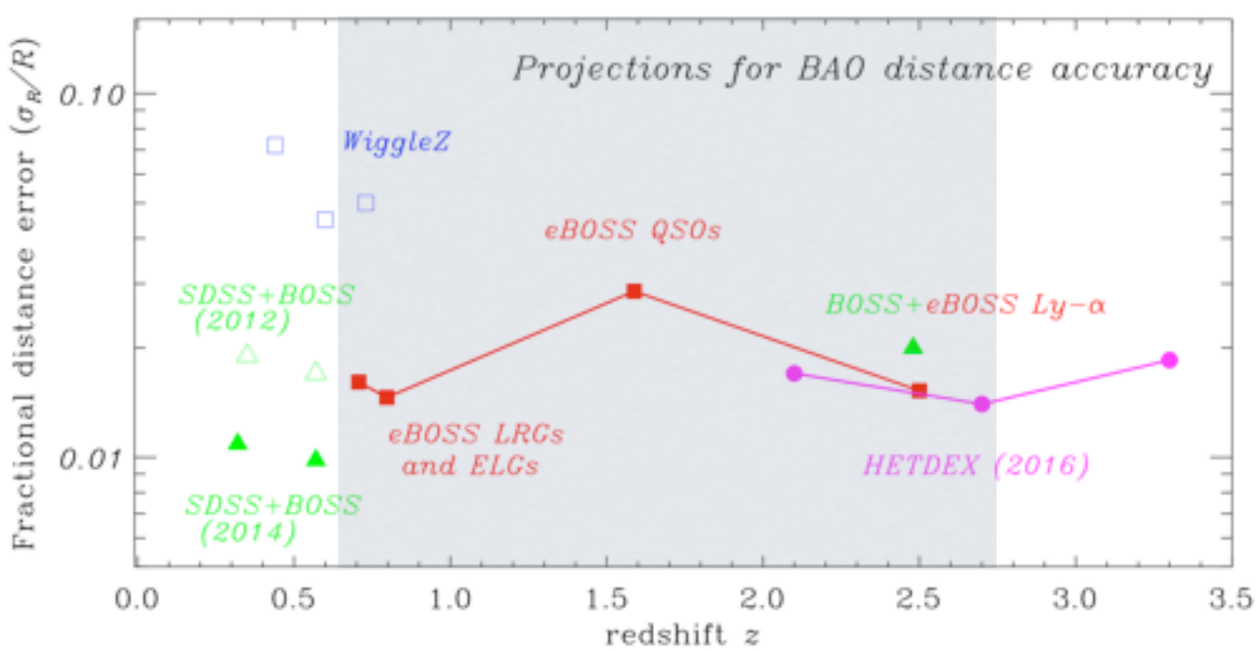
First BOSS results from Reid et al (2012) at z = 0.57

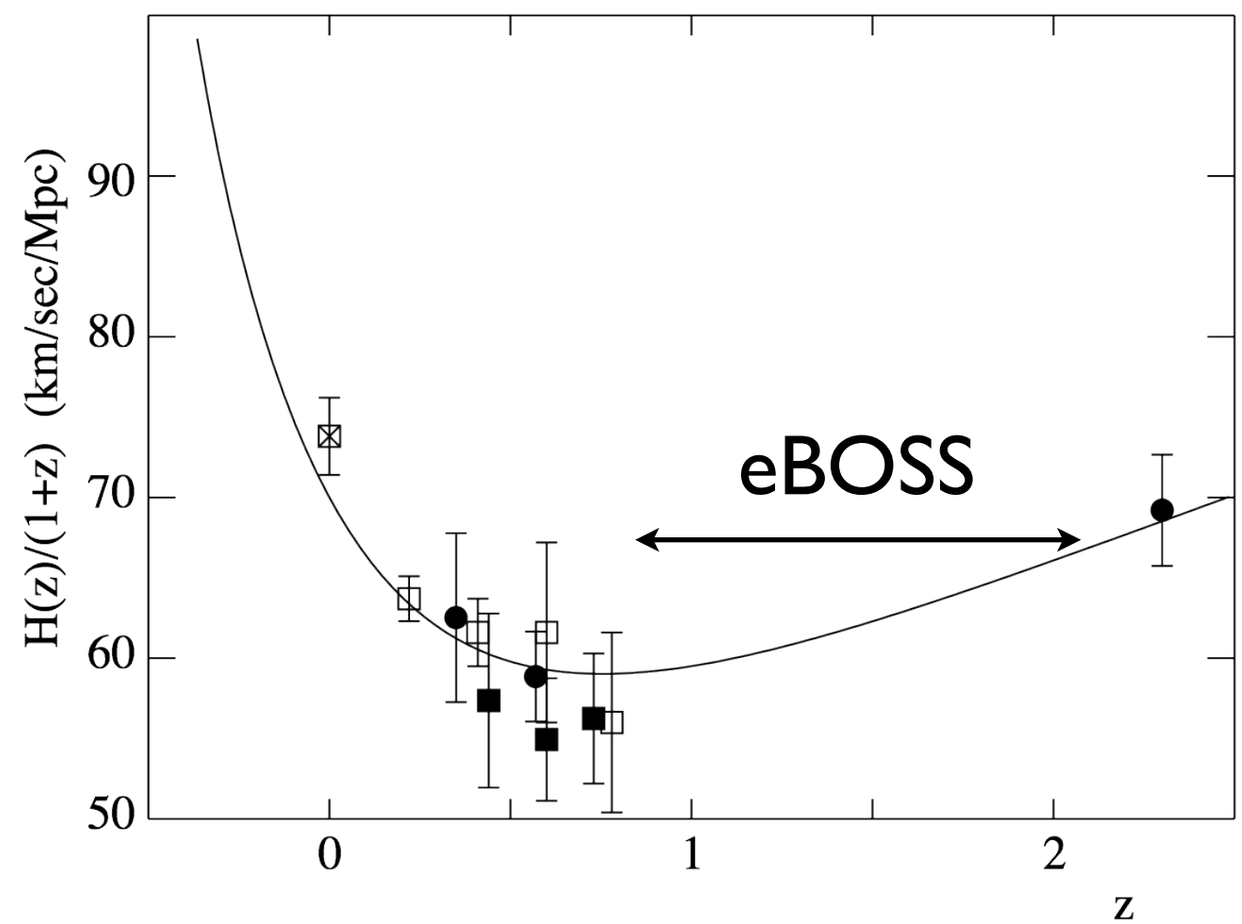
D_A = 2190 +/- 61 Mpc
H(z)= 92.4 $^{+4.5}_{-4.0}$ km/s/Mpc
Growth rate $d\sigma_8$ / dlna = 0.43 $^{+0.069}_{-0.063}$

eBOSS: *filling the gap between z ~ 1 and 2 with quasars*









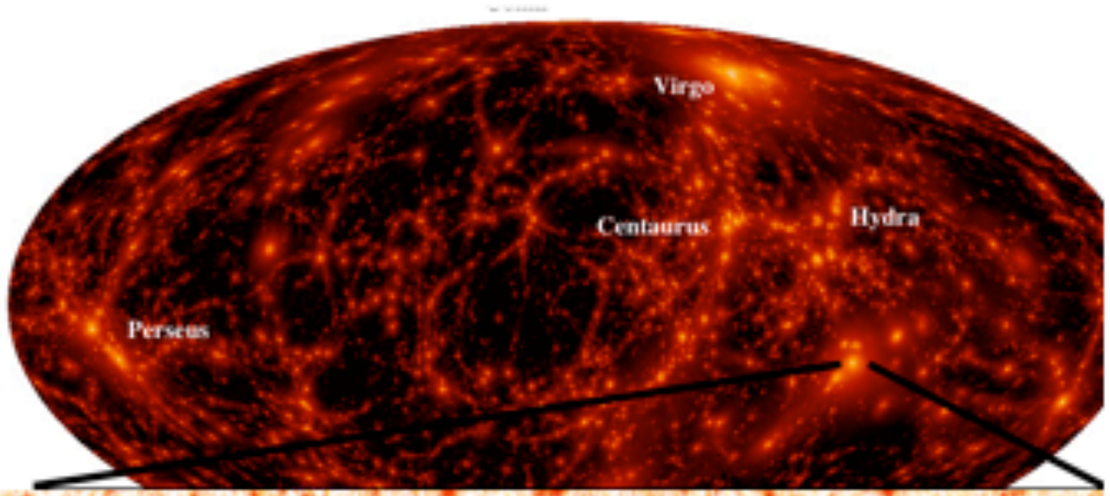
eBOSS: *in a nutshell*

- 7500 sq. deg with:
  - *600,000 QSOs ($1 < z < 3$)*
  - *350,000 LRGs ($0.6 < z < 0.8$)*
- 1500 sq deg. of which also has:
  - *250,000 ELGs ($0.6 < z < 1$)*
- QSO+LRG survey provides:
  - *first baryon acoustic distances between $z \sim 0.7$ and $z \sim 2$*
  - *redshift space distortion measurements of gravity*
  - *bias measurements of non-Gaussianity*

- ELG survey provides pathfinder to MS-DESI/BigBOSS program
- At least 500 sq. deg overlaps Dark Energy Survey:
  - *weak lensing / RSD constraints*
  - *photo-z calibration (Newman)*

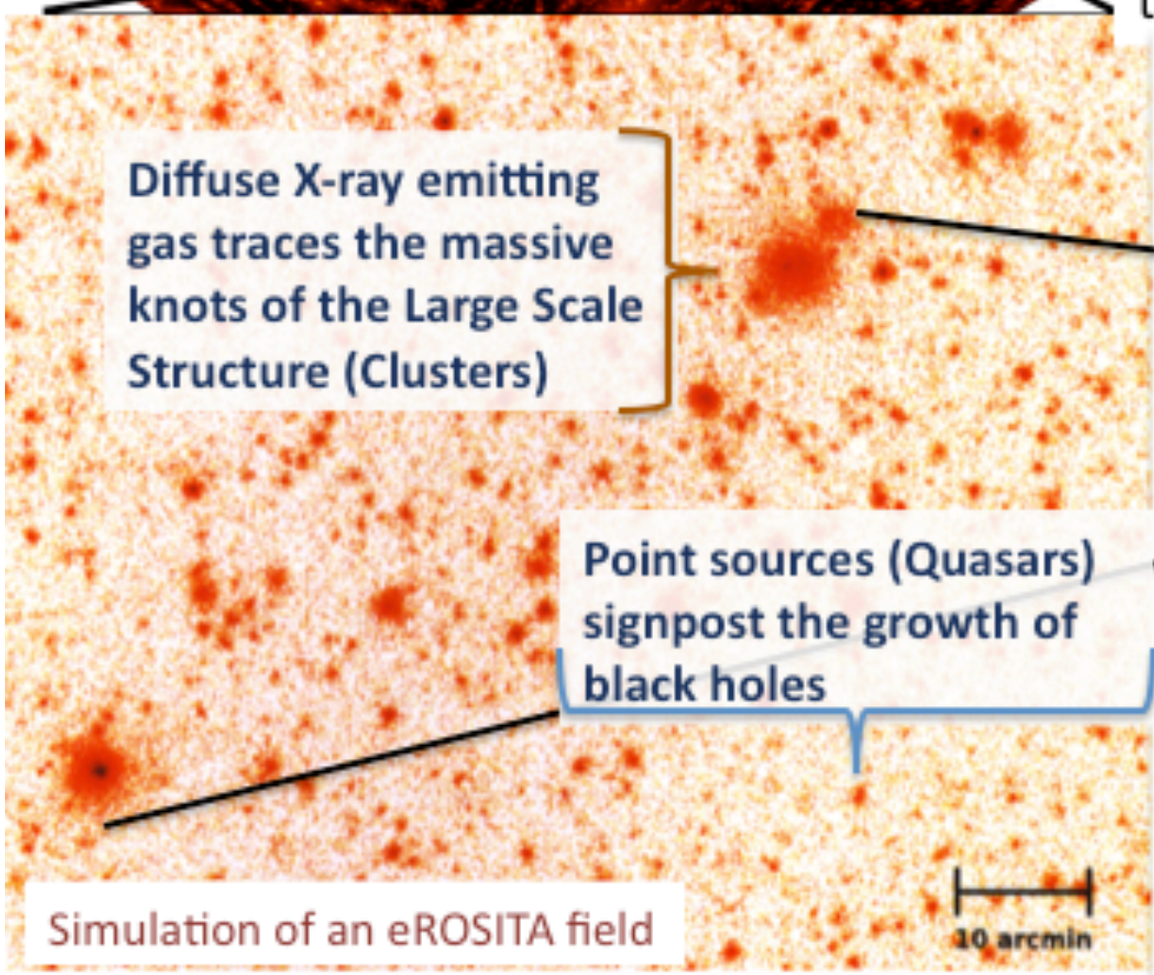
SPIDERS: Spectroscopic IDentification of EROSITA Sources

X-ray surveys (eROSITA)

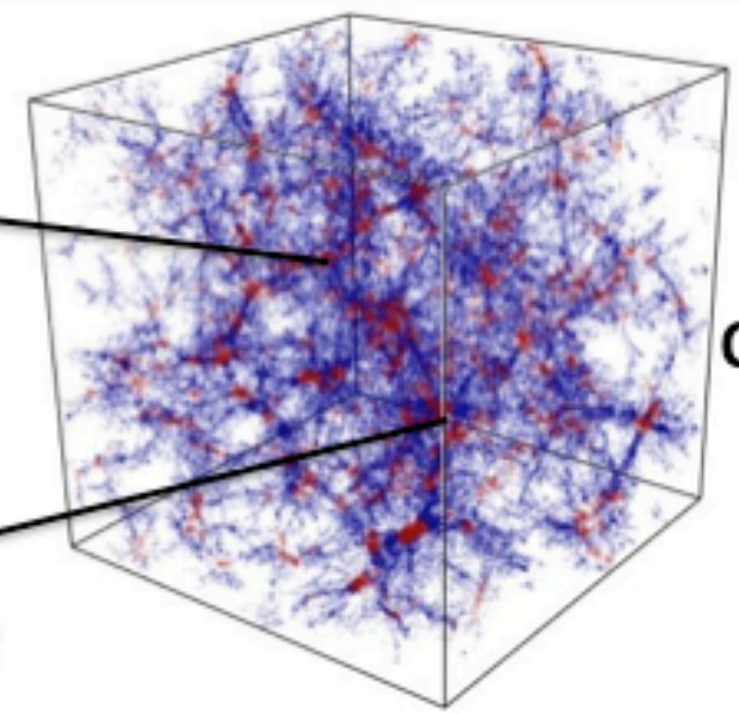


eROSITA (*) will study Dark Energy by detecting the diffuse emission from the hot gas in the most massive structures in the Universe (Clusters). Further, eROSITA will provide a full census of millions of growing black holes (Quasars).

SPIDERS will measure the distance of the X-ray sources detected by eROSITA and locate them within the 3-dimensional Large Scale Structure



Simulation of an eROSITA field



Optical surveys (SPIDERS)

(*) **eROSITA** is a German X-ray telescope onboard the Russian SRG satellite that will perform a revolutionary all-sky survey starting in 2014.

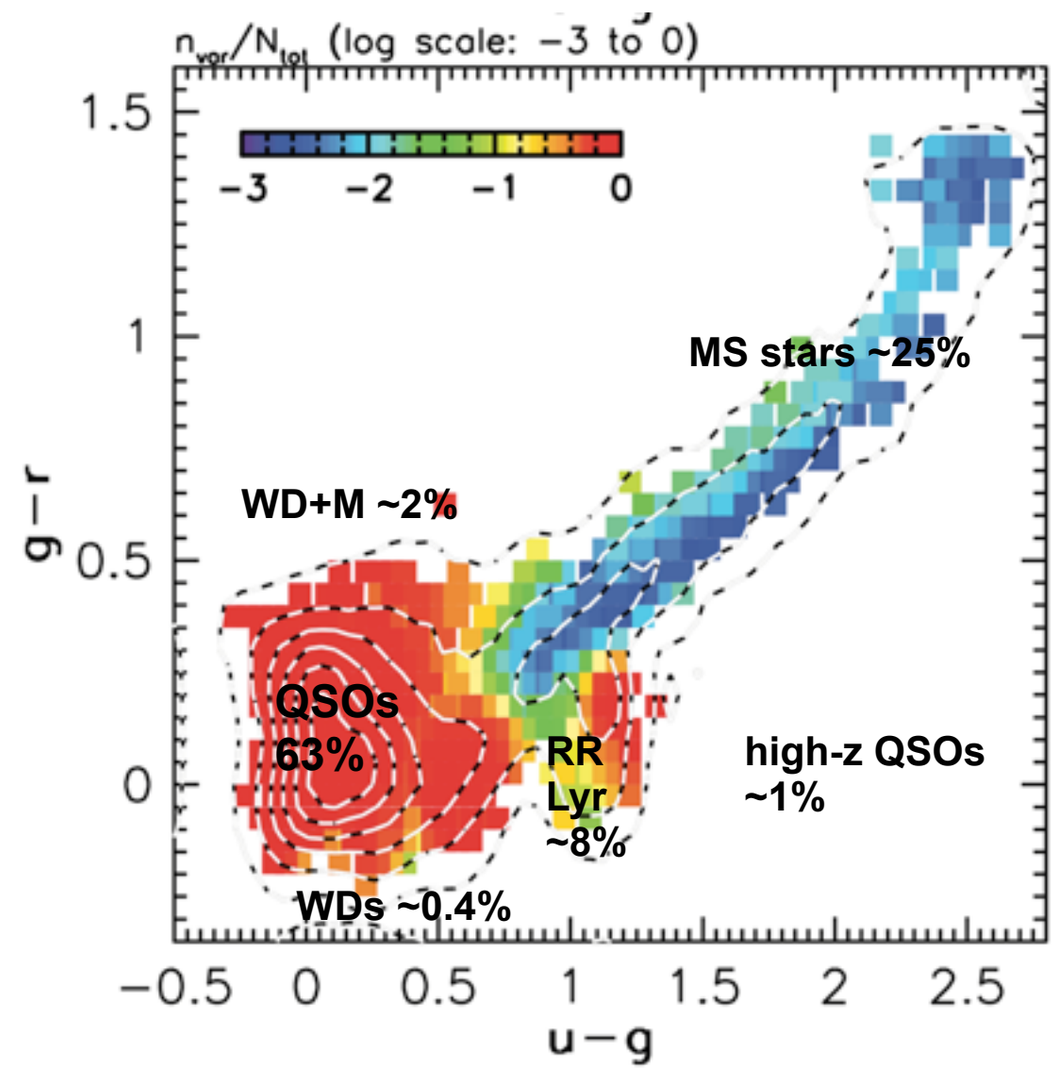
Time Domain Spectroscopic Survey (TDSS)

AS3 BOSS Spectroscopy of Celestial Variables

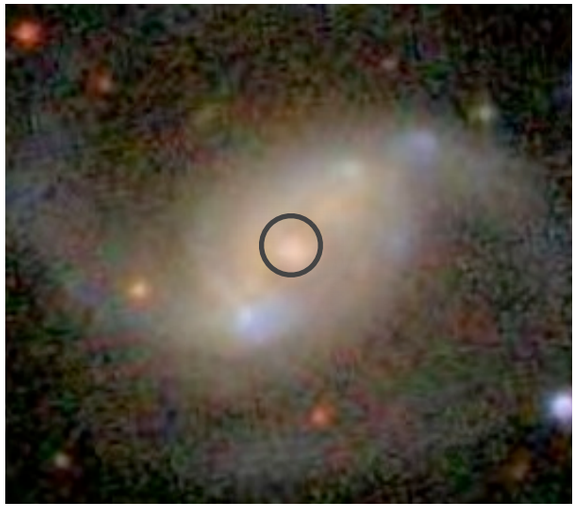
- The first large sky area spectroscopic survey of variables.
- Pathfinder for LSST, GAIA.
- Up to 30 deg^{-2} or ~ 100,000 spectra of variables
- Selected from PanSTARRS-1 3π survey:

~ 12 imaging epochs in *grizy* bands over 30,000 deg^2

- Boost QSO completeness amid the stellar locus (z~0.9 and z~.27)
- Constrain accretion disk models
- New M/L dwarfs and eclipsing binaries
- RR Lyr to map halo kinematics
- New pulsating WDs
- CVs
- Transient hosts (SNe, TDEs, GRBS)
- Systematic serendipity!

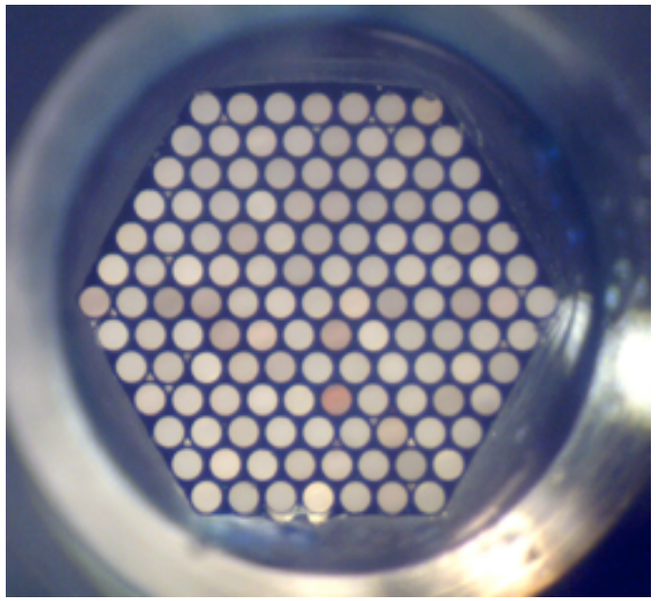


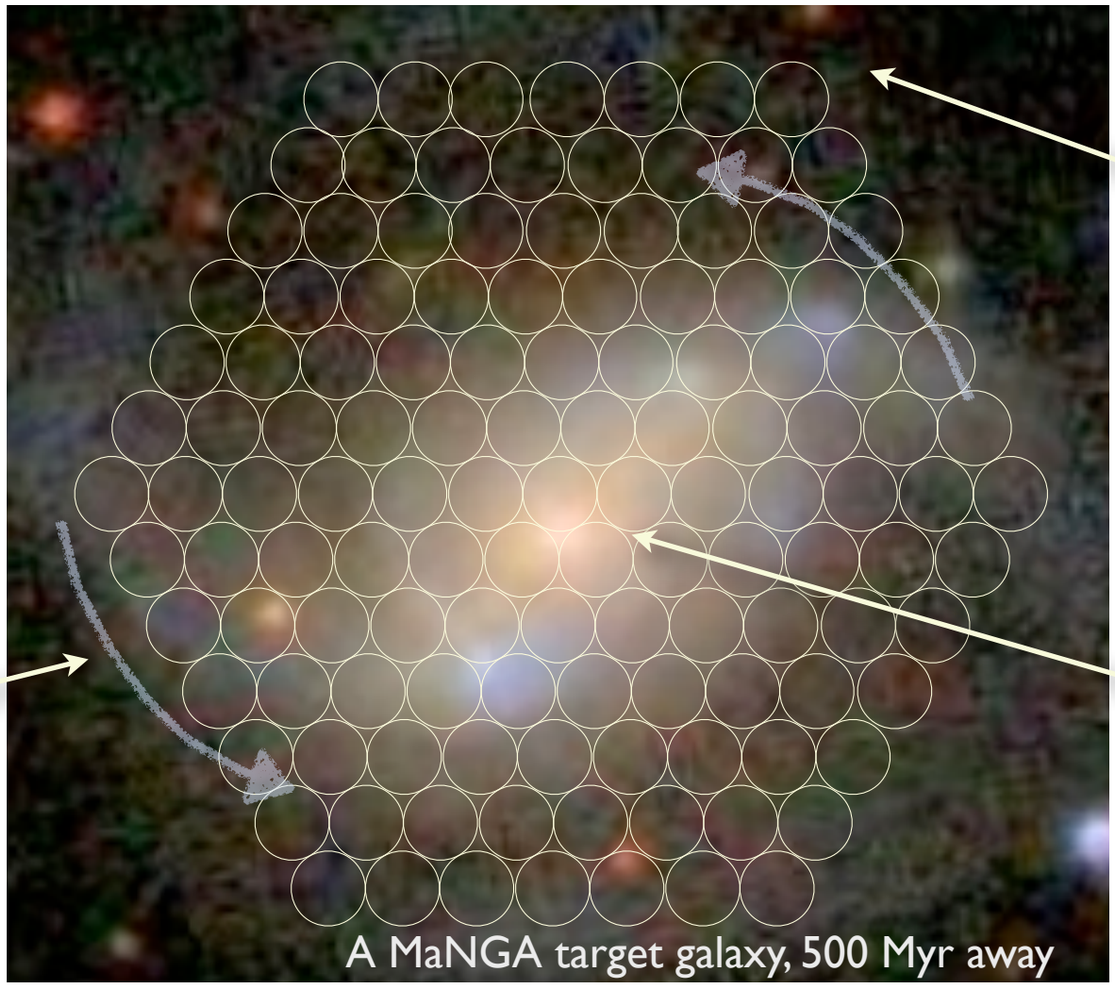
MaNGA: Mapping Nearby Galaxies at APO *(K. Bundy, PI)*



SDSS-I only used a central light-collecting fiber

Aim is 10,000 galaxies



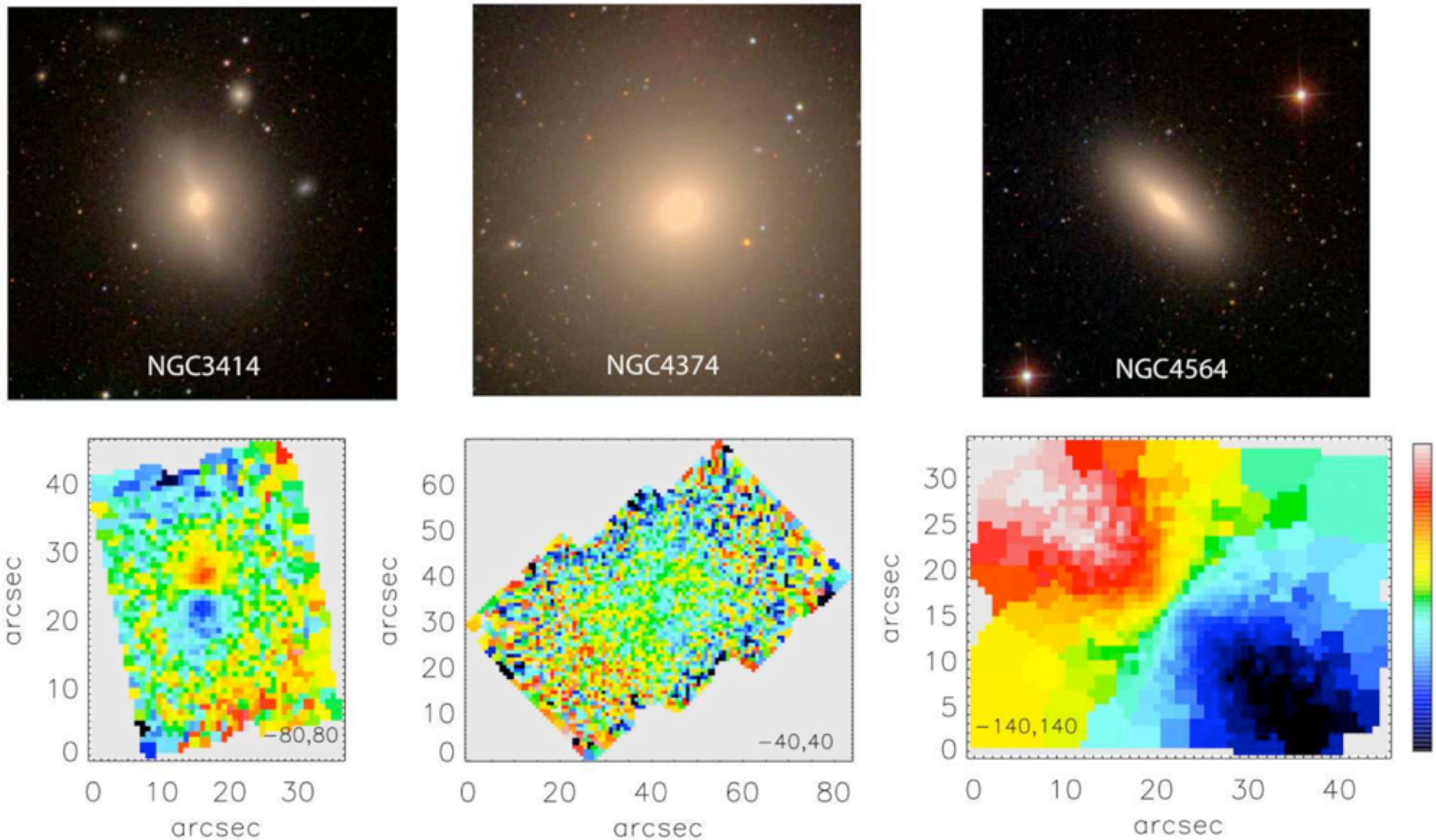


Birth:
Rotational motion records early formation within a dark matter halo

Life:
New stars forming from fresh gas?

Death:
Is the "quenching" of star-formation in galaxies due to central black hole feedback?

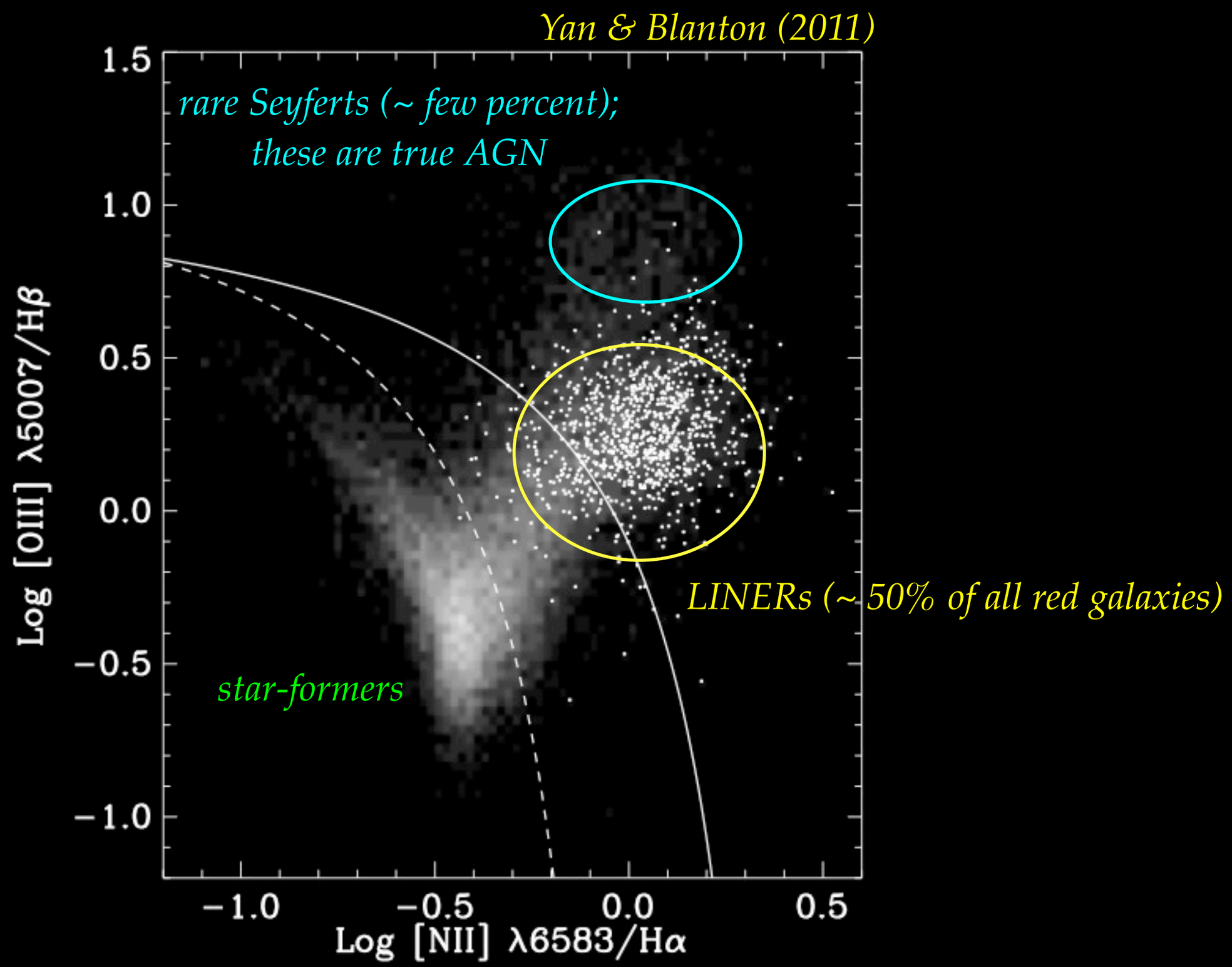
MaNGA: revealing the internal structure of galaxies



MaNGA: *the power of spatially resolved spectroscopy*

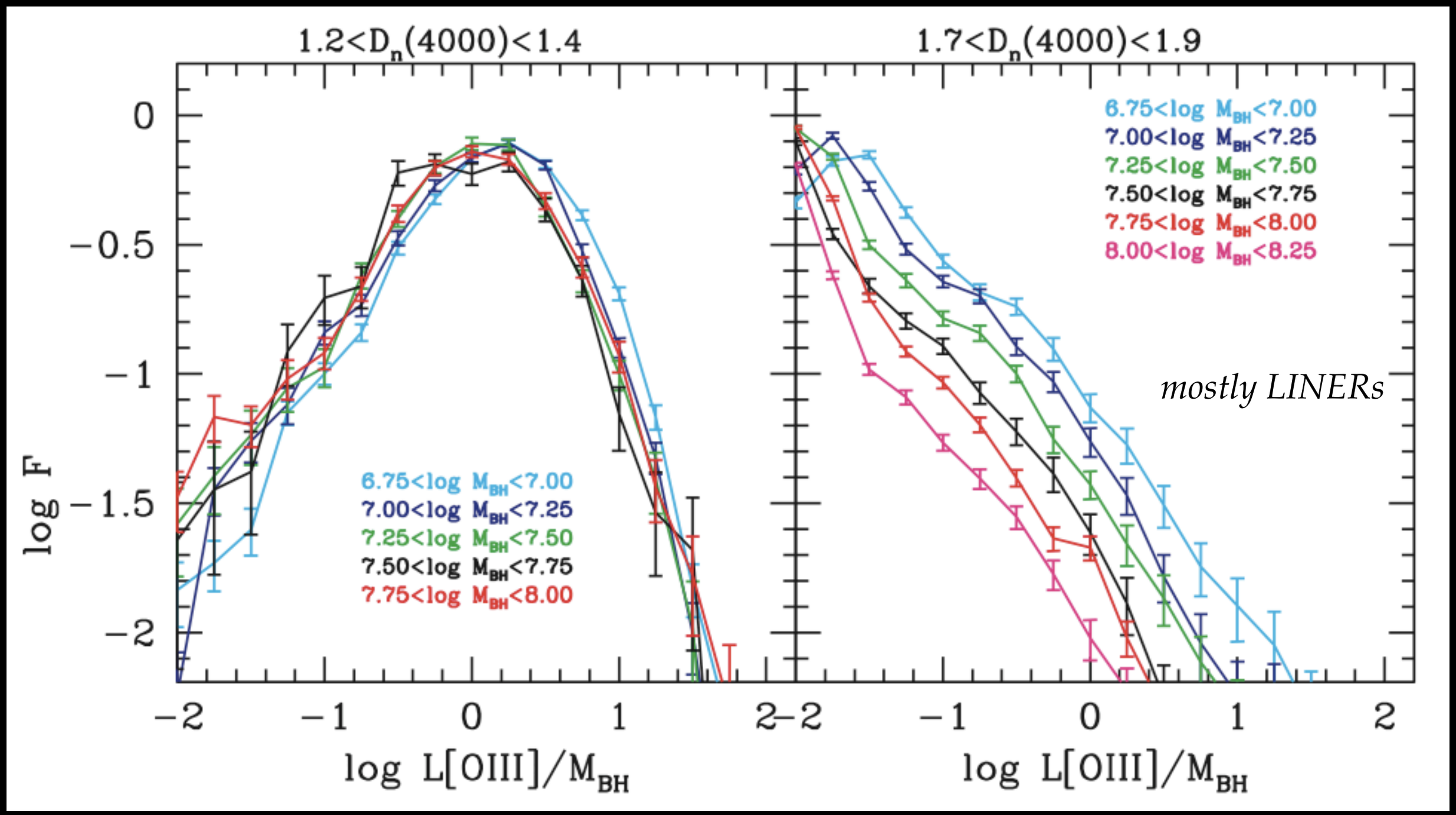
- SAURON survey demonstrated how valuable this ones, by observing 50 early type galaxies:
  - *calibrating viral mass estimators*
  - *distinguishing fast-/slow-rotators*
  - *extended LINER emission*
  - *stellar initial mass function constraints from dynamics*
  - *stellar population gradients*
- ATLAS-3D and CALIFA are following up on a few hundred more galaxies
- MaNGA will expand these studies, with a much larger and more representative sample
- Takes advantage of the uniquely high quality (and large wavelength range) of the BOSS spectrograph

How active are black holes in ellipticals?



Are the LINERs growing black holes?

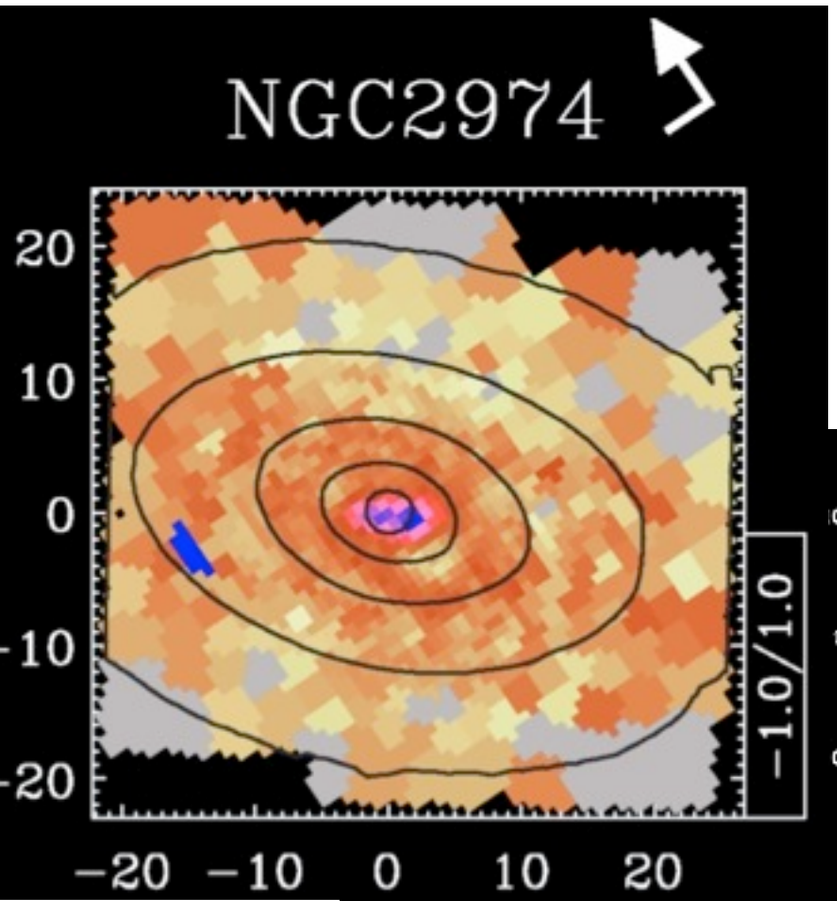
young galaxies (mostly Seyferts) *old galaxies (mostly LINERs)*

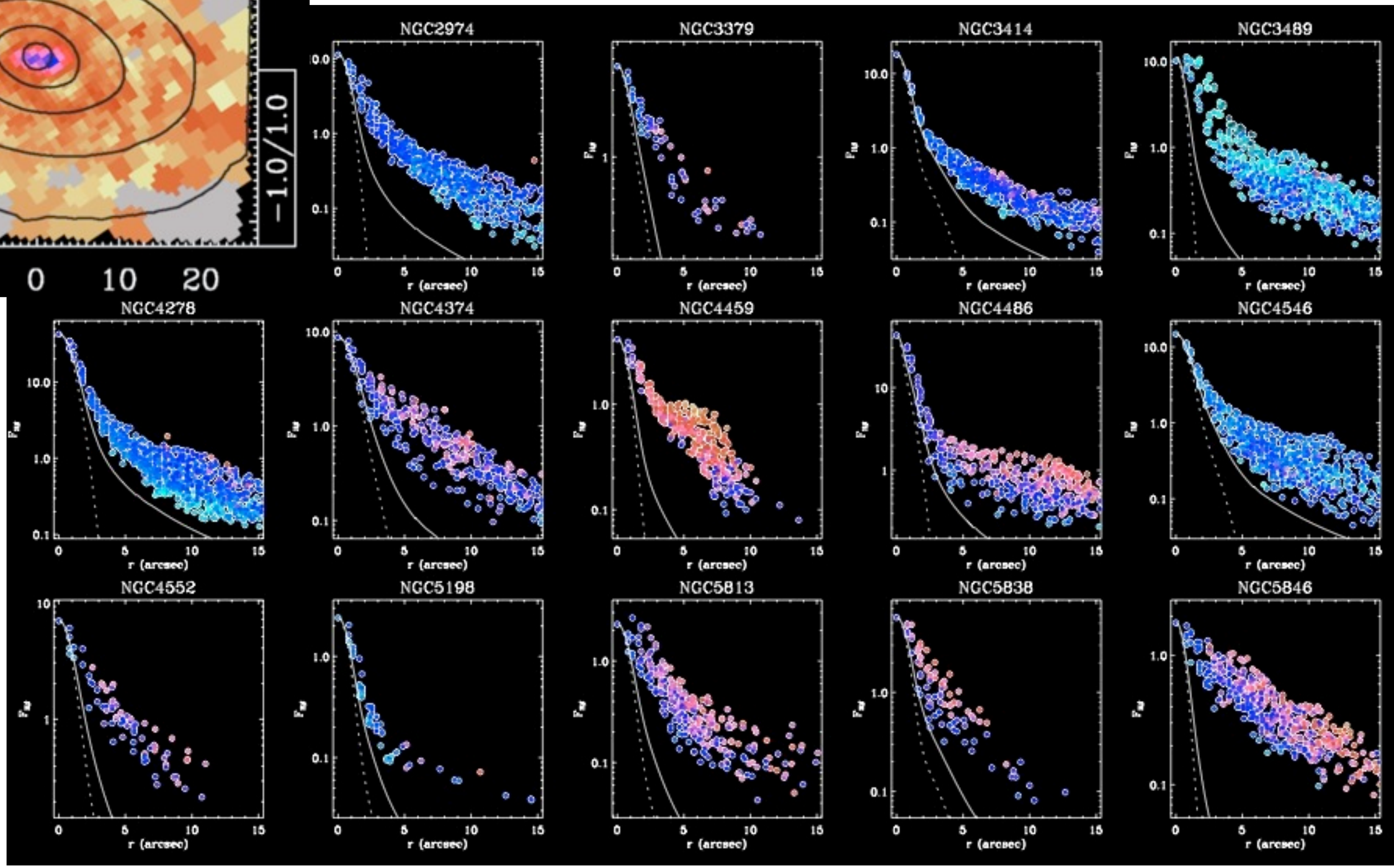


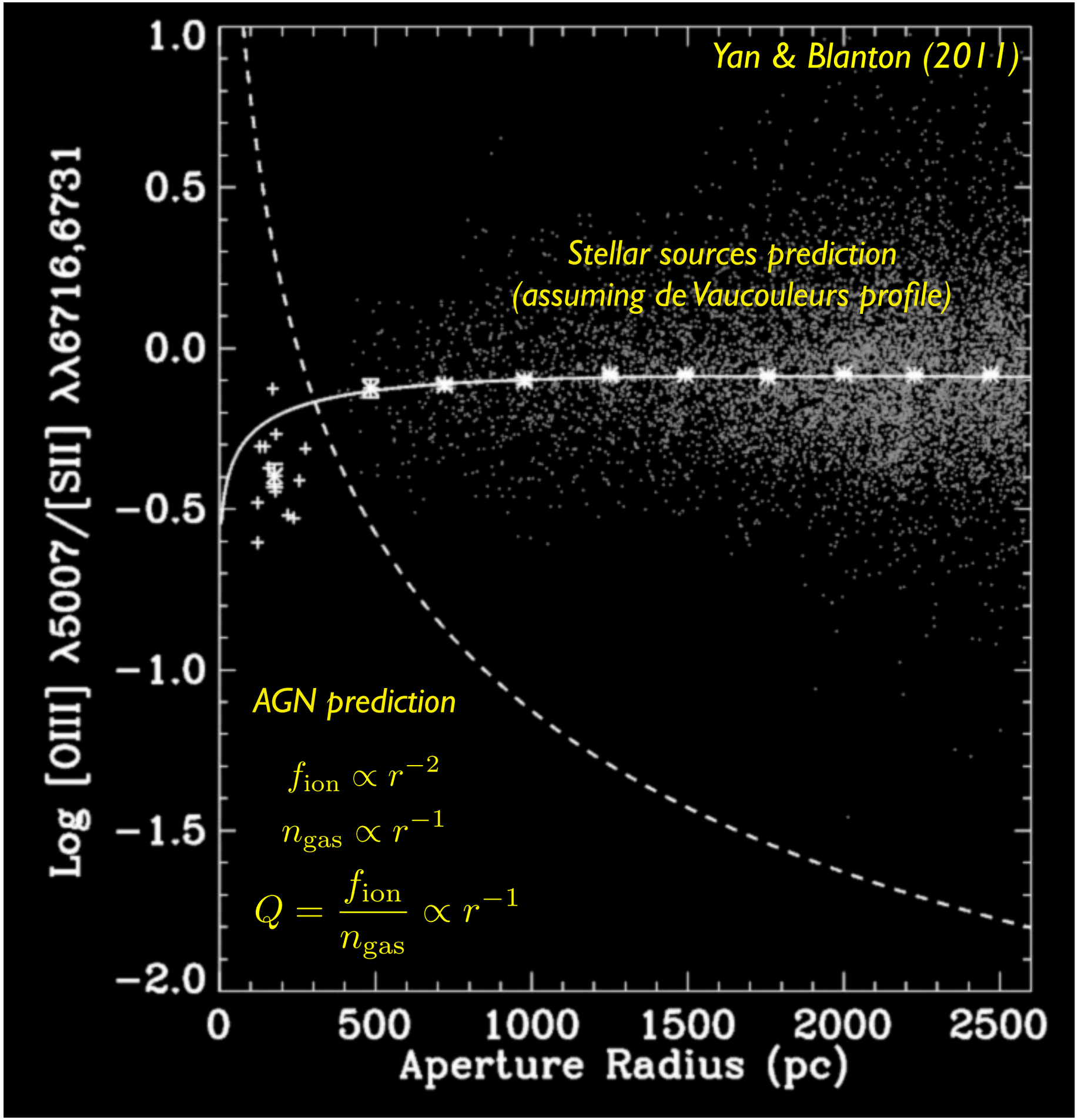
Kauffmann & Heckman (2009)

Growing evidence LINERs are not BH accretion-powered

Sarzi et al. (2010), SAURON data






Yan & Blanton (2011)
Stellar sources prediction
(assuming de Vaucouleurs profile)
AGN prediction
$f_{\rm ion} \propto r^{-2}$
$n_{\rm gas} \propto r^{-1}$
$Q = \frac{f_{\rm ion}}{n_{\rm gas}} \propto r^{-1}$
Log [OIII] λ5007/[SII] λλ6716,6731
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
0
500
1000
1500
2000
2500
Aperture Radius (pc)

MaNGA: *hardware design*

BOSS spectrograph: New slit heads to accommodate more fibers (can tolerate greater cross talk)

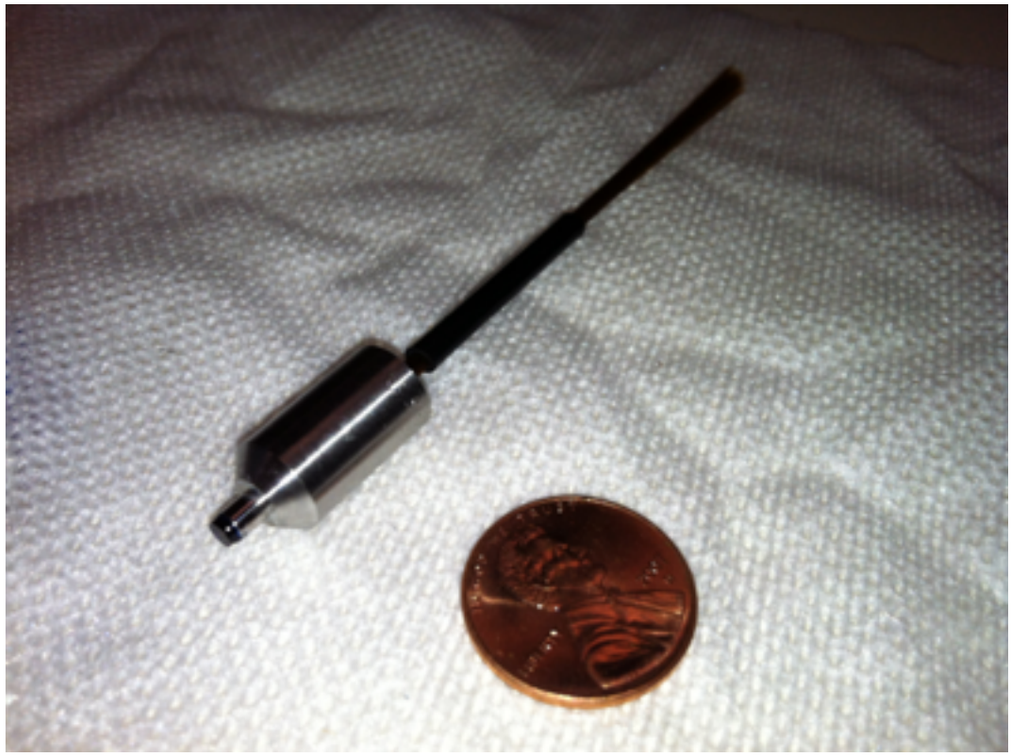
Multiplexed observations: 15 or 20 bundles per plate (depending on fiber distribution and total number of fibers), spread over 1.5 deg radius field

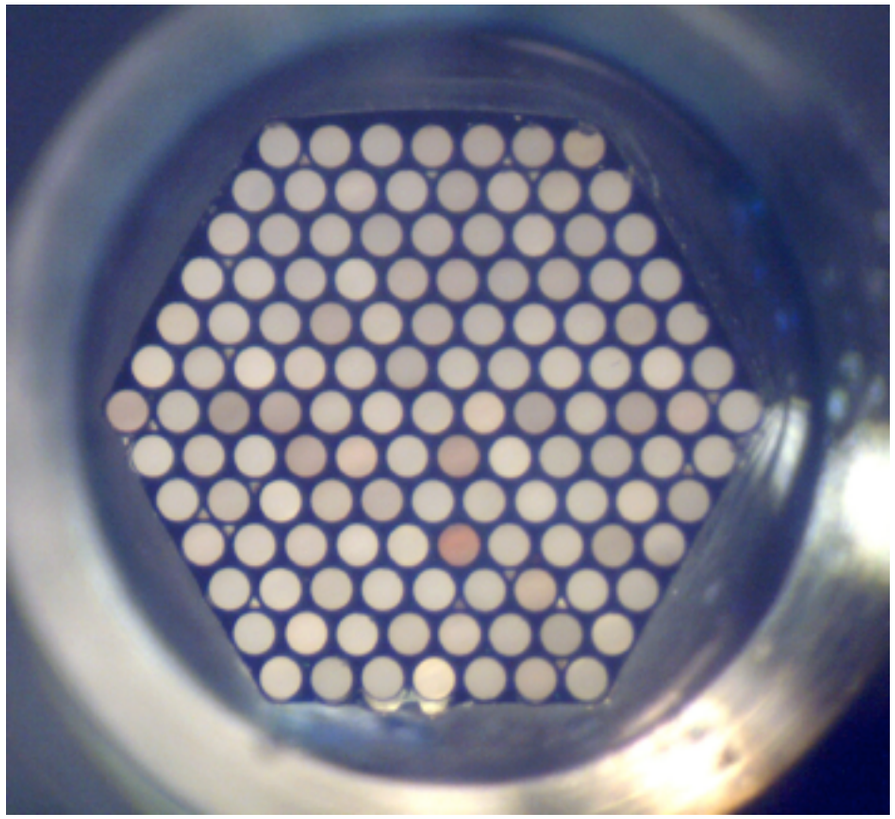
Range of bundle sizes: 19, 37, 61, 91,127-fiber bundles, tuned to target angular size

Spectrophotometry: Bundles on standards? Fat fibers? Range of fiber sizes?

(Unlike standard fiber spectrophotometry, we do not want ADR contribution to throughput)

Guiding + focus: Tougher constraints



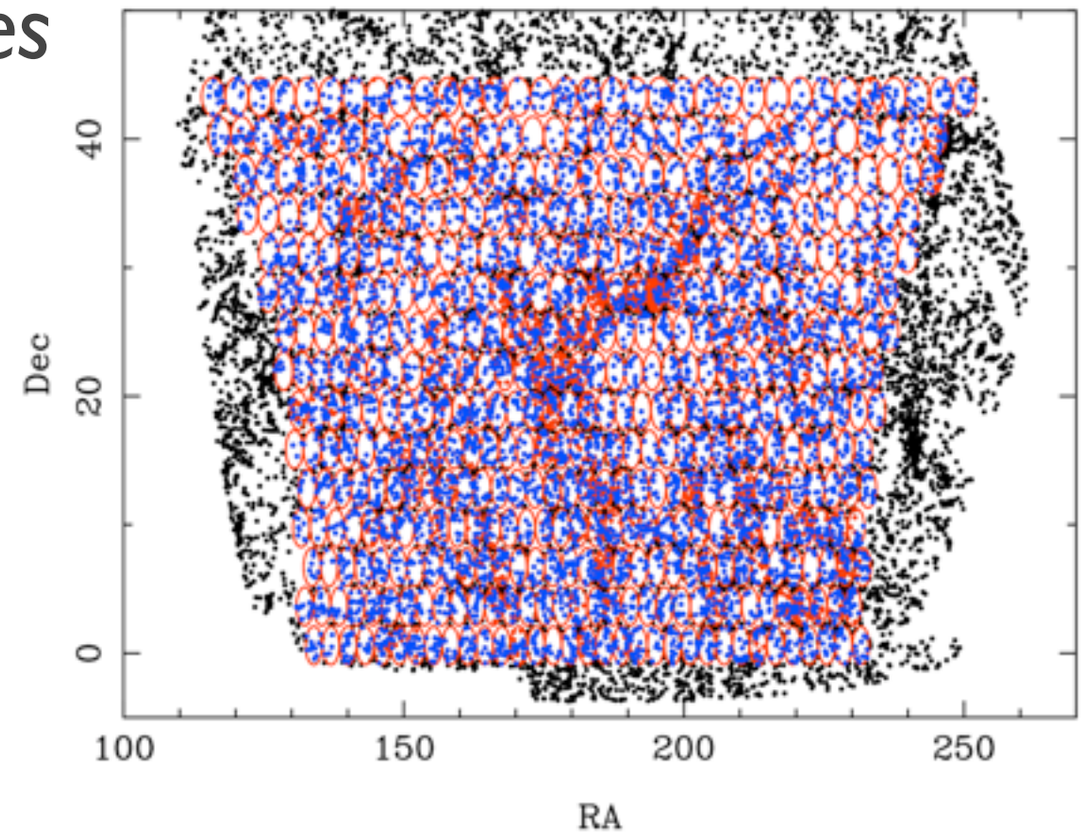


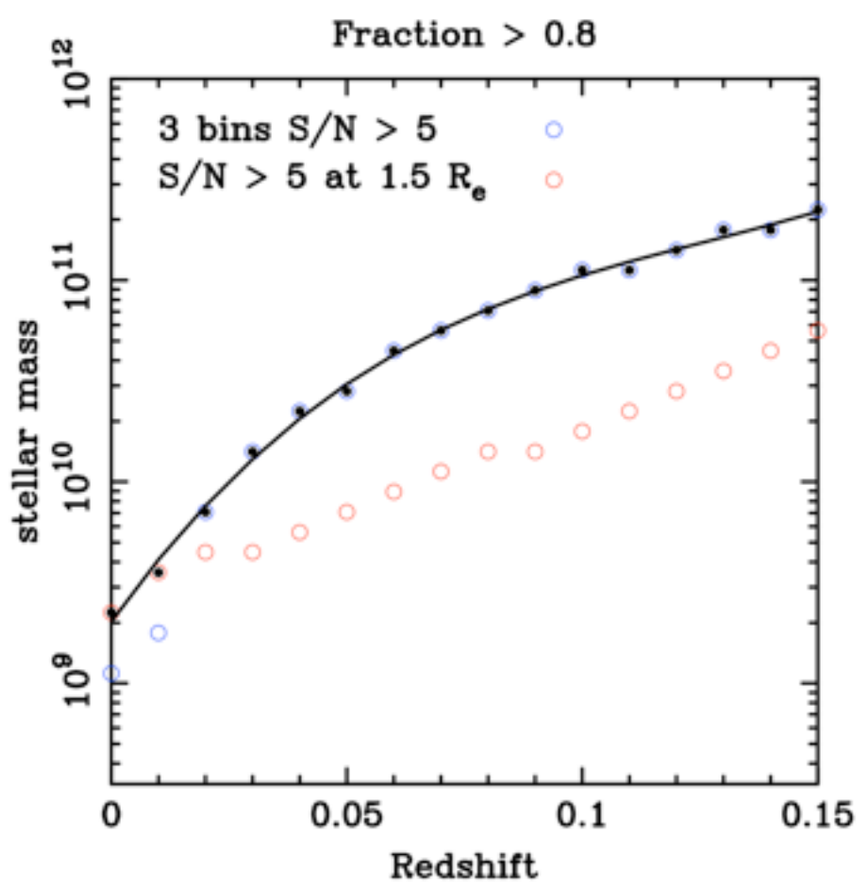
MaNGA: *designed for 10,000 galaxies*

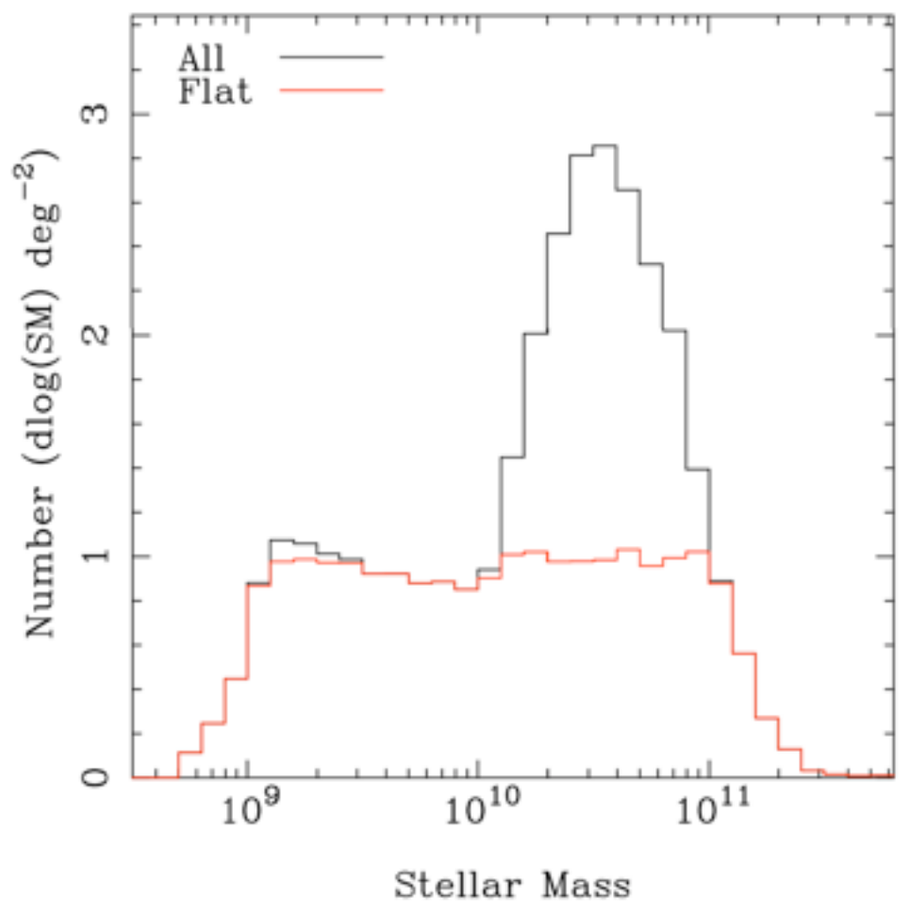
Simple selection: based on mass and redshift only, for clean statistics (no environmental selection, etc.)

Deep exposures: 3 hours per plate

Wide sky coverage: ~ 5000 sq. deg. necessary to get enough galaxies!







MaNGA: *comparison to other surveys*

Size & homogeneity:

-10,000 galaxies allows binning in environment, mass, type, etc.

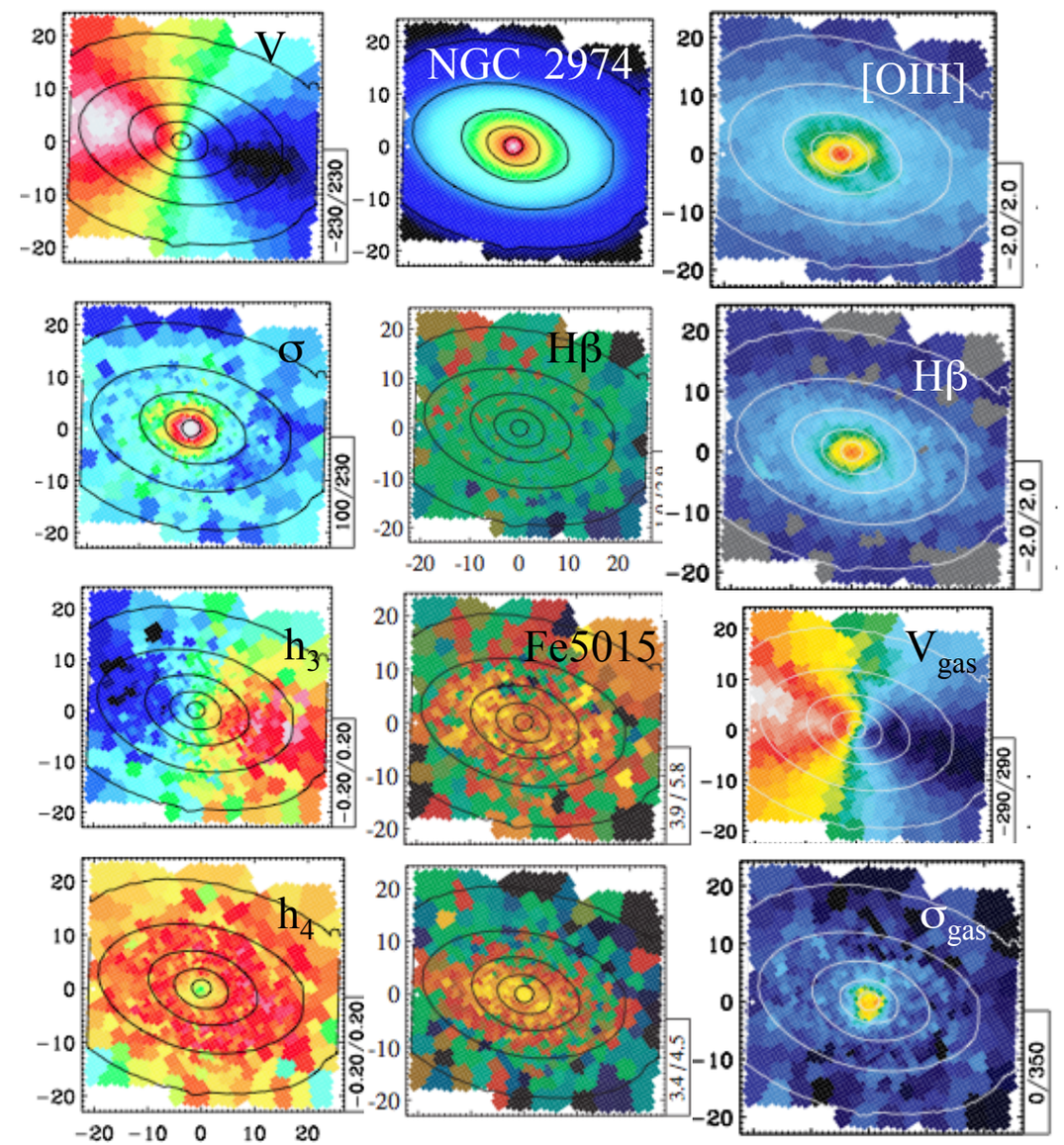
- Largest other planned survey with observing time is CALIFA (600 galaxies)

- SAMI at AAO might get a few 1000

Wavelength coverage:

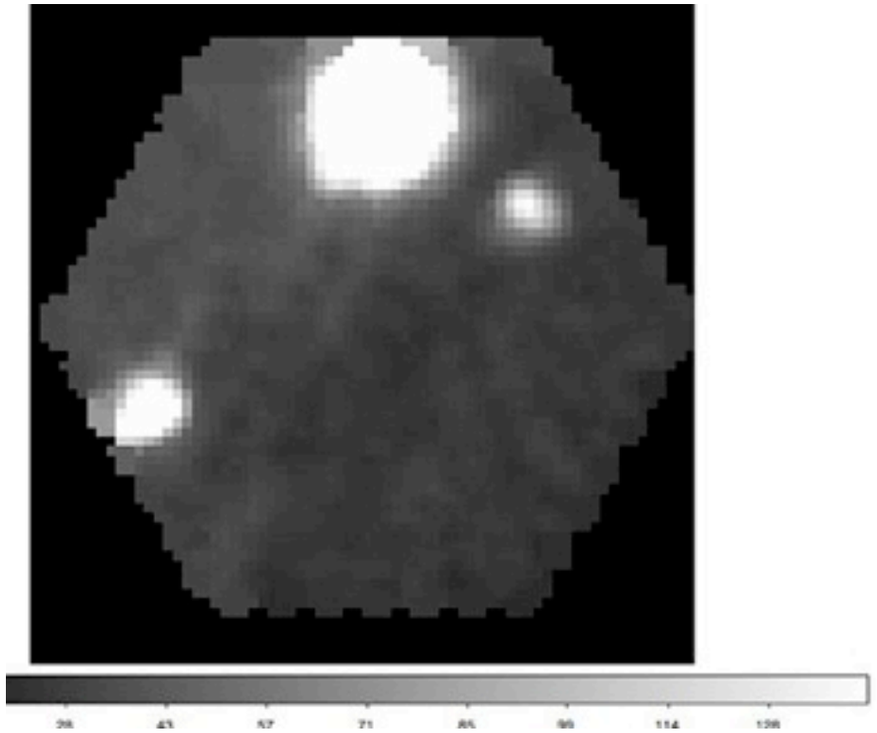
- uniquely broad for IFU observations
- 3600 to 10,500 Angstroms
- Covers [OII] *through* FeH!

Star-formation, active nuclei, stellar IMF constraints, chemical evolution gradients, etc.

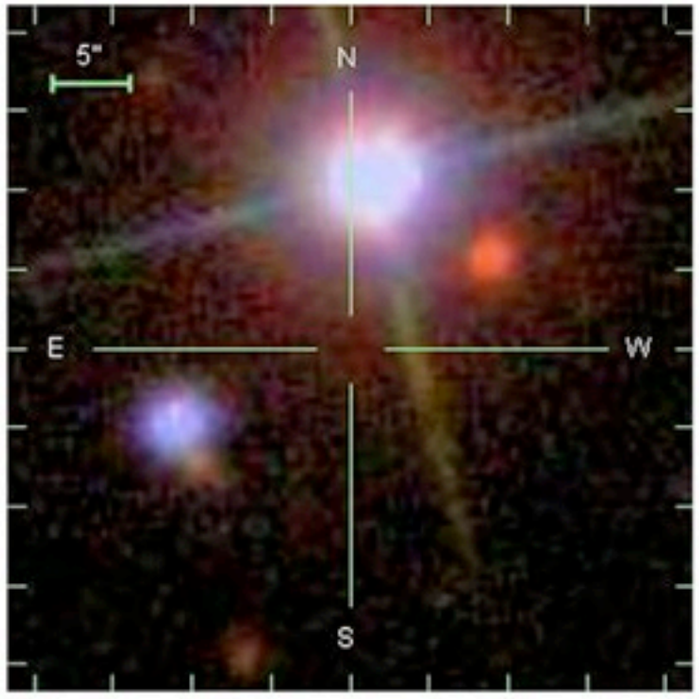


Example of quantities calculated from SAURON survey: comparable for thousands from MaNGA

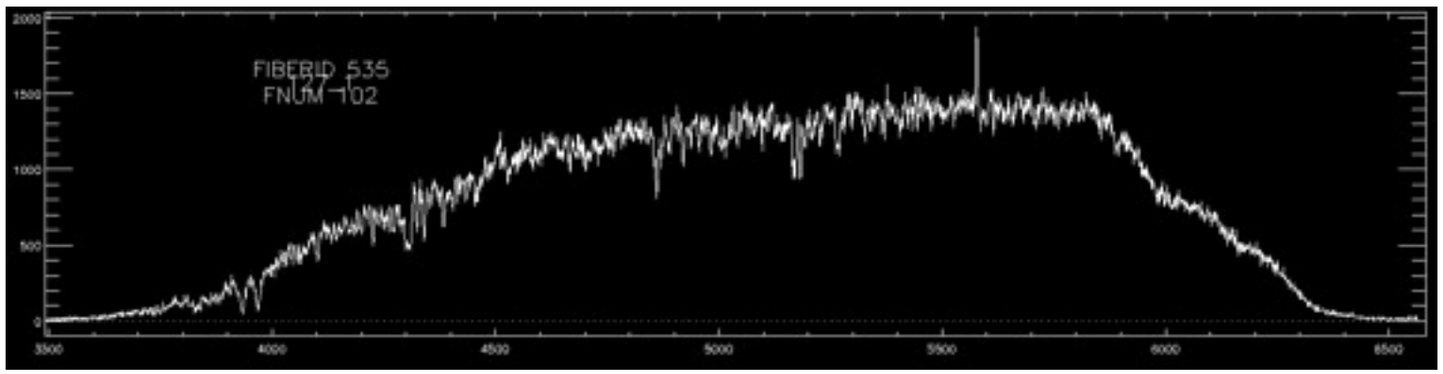
MaNGA: *first light December 2012*



integrated image through BOSS spectrograph with MaNGA bundles

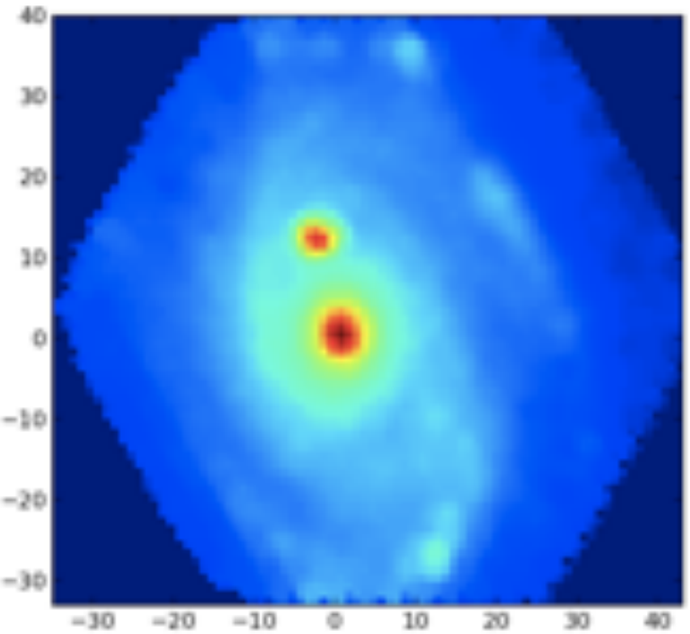


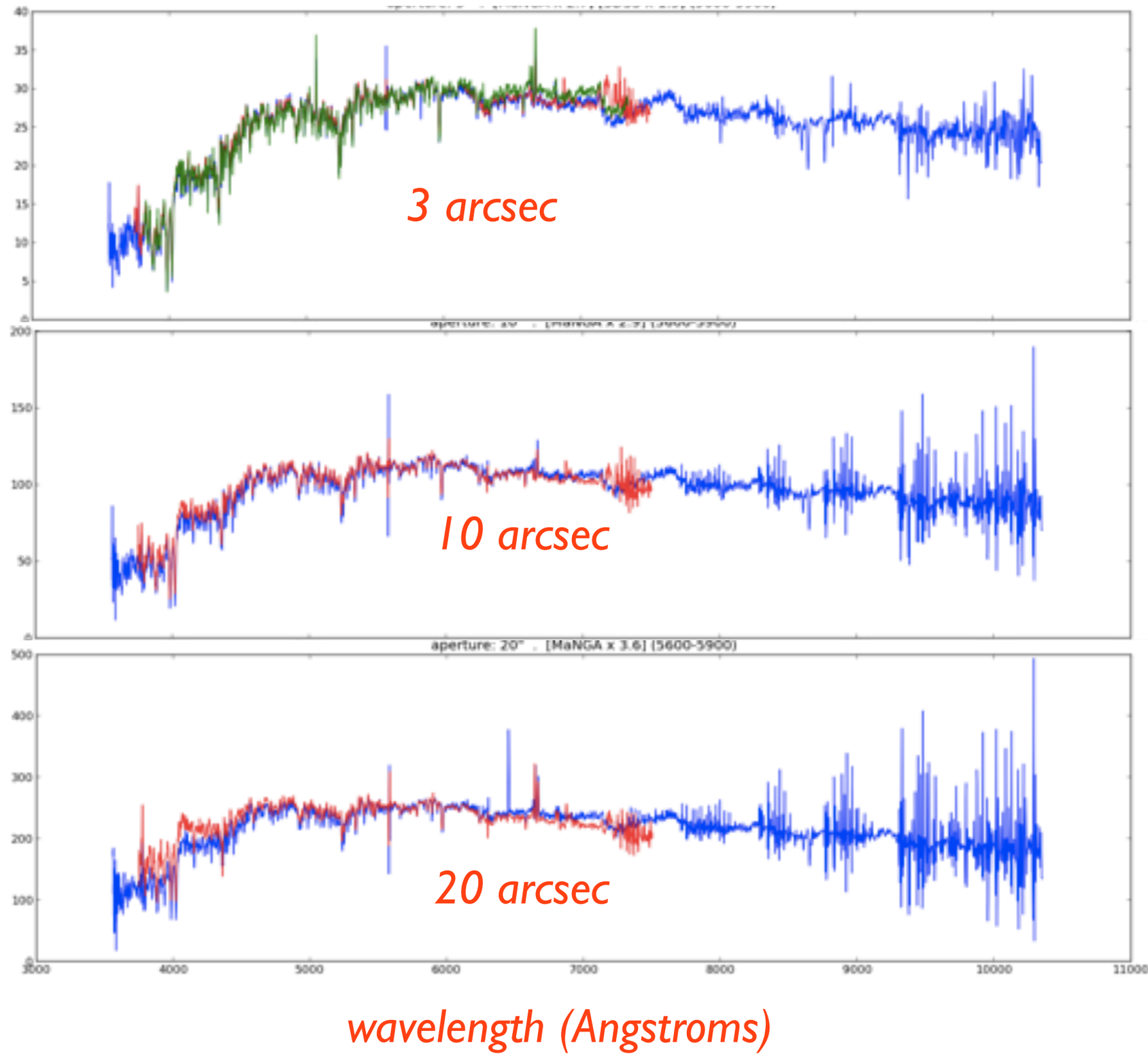
gri image of same location from SDSS imaging camera



Spectrum from single fiber in bundle (blue spectrograph, uncalibrated)

MaNGA: *first galaxy observations January 2013*





Timeline

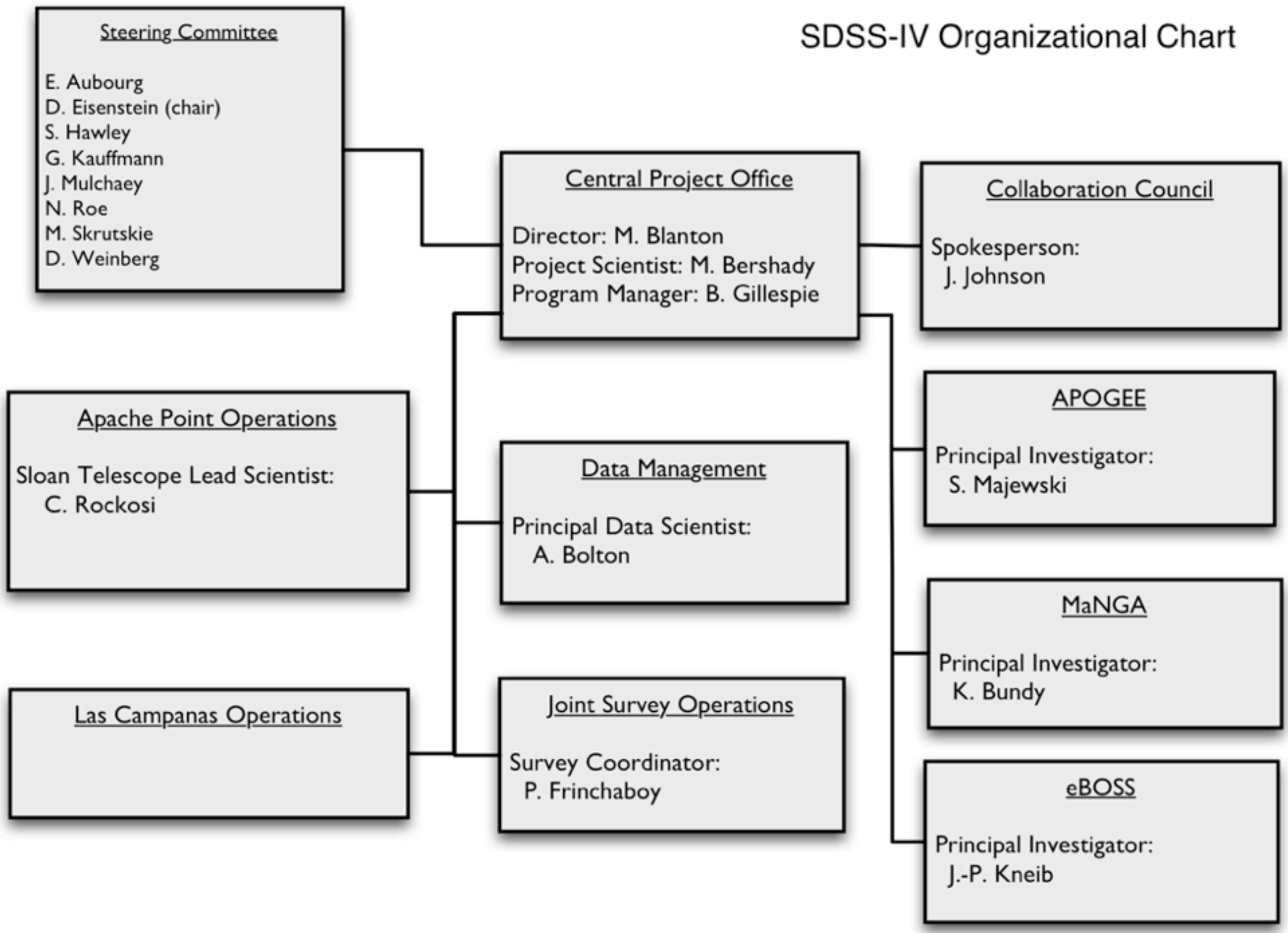
1. January 2012 through June 2014
   a. *MaNGA hardware development and on-sky tests*
   b. *APOGEE-2S instrument + du Pont infrastructure*
   c. *eBOSS targeting algorithm development*
2. July 2014 through June 2020

APO dark moon time: MaNGA & eBOSS

APO bright moon time: APOGEE-2N

du Pont: APOGEE-2S

SDSS-IV Team


SDSS-IV Organizational Chart
Steering Committee
E. Aubourg
D. Eisenstein (chair)
S. Hawley
G. Kauffmann
J. Mulchaey
N. Roe
M. Skrutskie
D. Weinberg
Central Project Office
Director: M. Blanton
Project Scientist: M. Bershady
Program Manager: B. Gillespie
Collaboration Council
Spokesperson:
J. Johnson
Apache Point Operations
Sloan Telescope Lead Scientist:
C. Rockosi
Data Management
Principal Data Scientist:
A. Bolton
APOGEE
Principal Investigator:
S. Majewski
MaNGA
Principal Investigator:
K. Bundy
Las Campanas Operations
Joint Survey Operations
Survey Coordinator:
P. Frinchaboy
eBOSS
Principal Investigator:
J.-P. Kneib

Collaboration: *funding progress*

- Full project budget is $59M
- We have had a Sloan Foundation grant of $10M approved.
- We gathered $1.6M of seed money in 2012 to fund development in 2013.
- Looking now to sign up institutional partners: similar scale as SDSS-III (~ 40 institutions at various levels)
- Partners buy in to the project as a whole (not just one component)
- IMPORTANT: This is a "new ball game." Institutional and individual participation do not carry over automatically from SDSS-III!

http://sdss3.org/future

Collaboration: *contributing institutions*

- Carnegie Mellon University
- CEA Saclay
- Royal Observatory at Edinborough
- French Participation Group
- Harvard University
- Instituto de Astrofisica de Canaria
- IPMU (University of Tokyo)
- Max Planck Institut, Extraterrestrische Physik (MPE)
- Max Planck Institut für Astronomie (MPIA)
- Max Planck Institut für Astrophysik (MPA)
- National Astronomical Observatory of China
- New Mexico State University
- New York University
- Penn State University
- The Ohio State University
- Shanghai Astronomical Observatory
- Texas Christian University
- Tsinghua University
- Universidad Nacional Autónoma de México
- University of Cambridge
- University of Colorado, Boulder
- University of Kentucky
- University of Oxford
- University of Pennsylvania
- University of Pittsburgh
- University of Portsmouth
- University of Utah
- University of Toronto
- University of Washington
- University of Wisconsin, Madison
- Vanderbilt University
- Yale University

Collaboration: *activities and communication*

- Wiki sign-up here (> 200 registered users so far):
  - *http://howdy.physics.nyu.edu/projects/as3*
- Mailing lists, teleconferences, etc. described there. Teams have formed and are meeting regularly.
- All teams could do with help in planning and preparing for upcoming proposals.
- A good time to join, to drive observational and science planning where you want it to go.

- Upcoming full SDSS-IV meeting in JHU in mid-June

http://sdss3.org/future

Summary

- SDSS-IV has had a successful first year of development.
- Major scope and risk questions have been addressed:
  - *MaNGA fiber bundles*
  - *eBOSS survey planning*
  - *APOGEE-2S planning*
- Challenges for the next year:
  - *MaNGA hardware procurement*
  - *eBOSS survey & targeting design*
  - *APOGEE-2S infrastructure design*
  - *APOGEE MRI proposal*
- This is a great time to join the project and begin contributing scientifically (and otherwise).