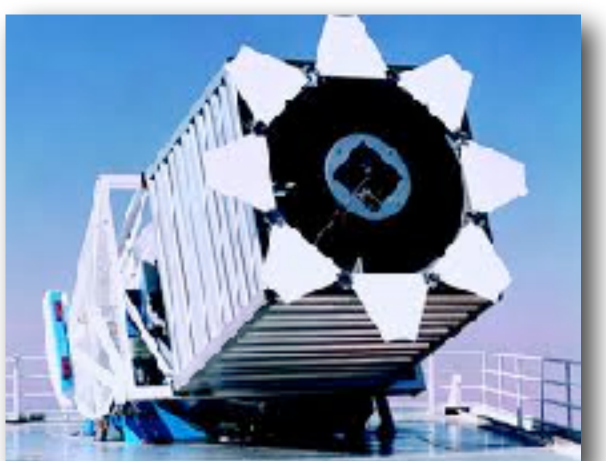
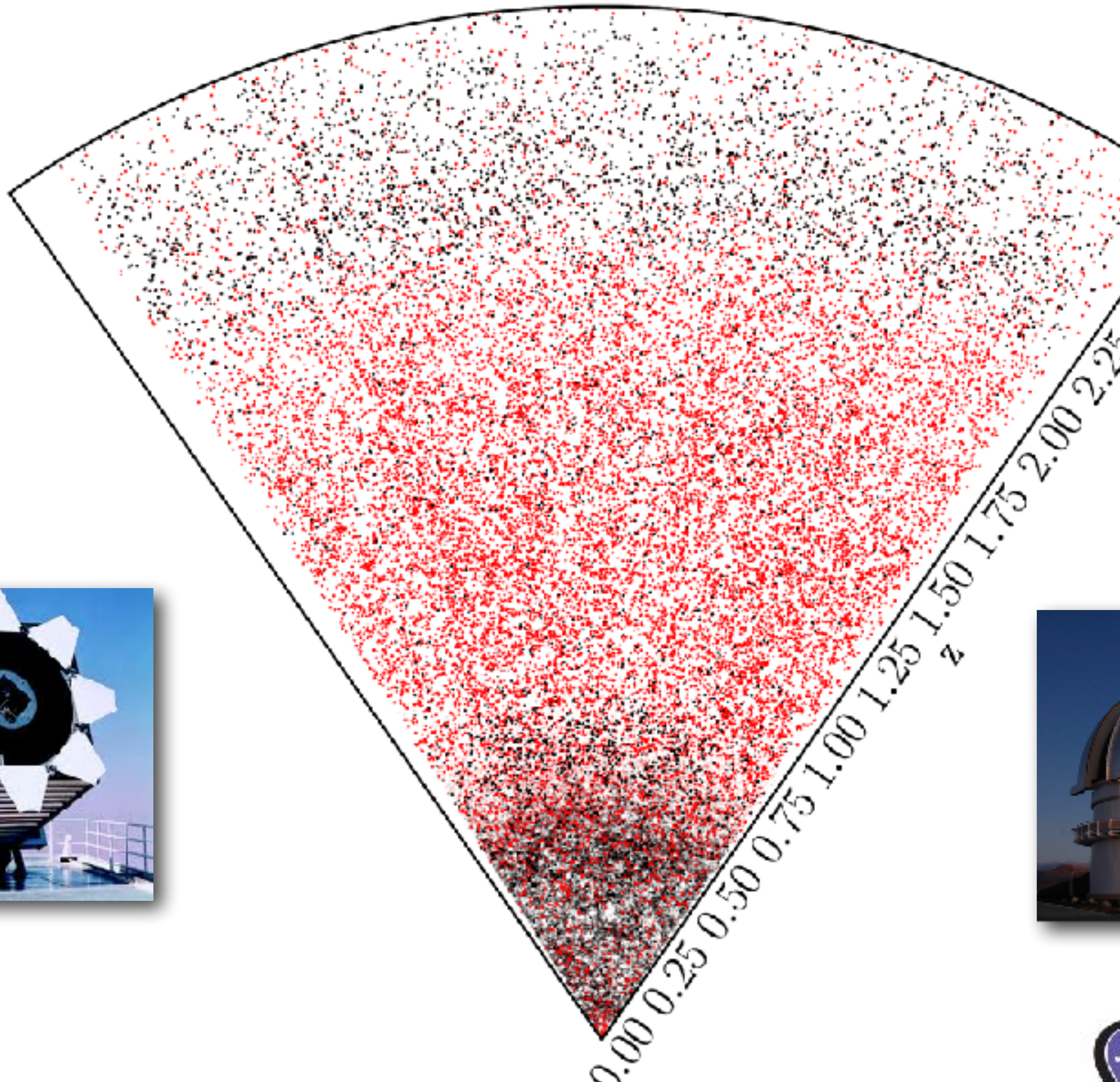
The present and future of the Sloan Digital Sky Survey





SDSS

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

Outline

- How the SDSS works
- Redshift surveys and cosmology: Legacy, BOSS, and eBOSS
- Near-field cosmology: APOGEE & MaNGA
- What's next for SDSS

A history of SDSS

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 survey of stars

BOSS survey of galaxies and quasars

MARVELS planet search

APOGEE high-resolution survey of stars

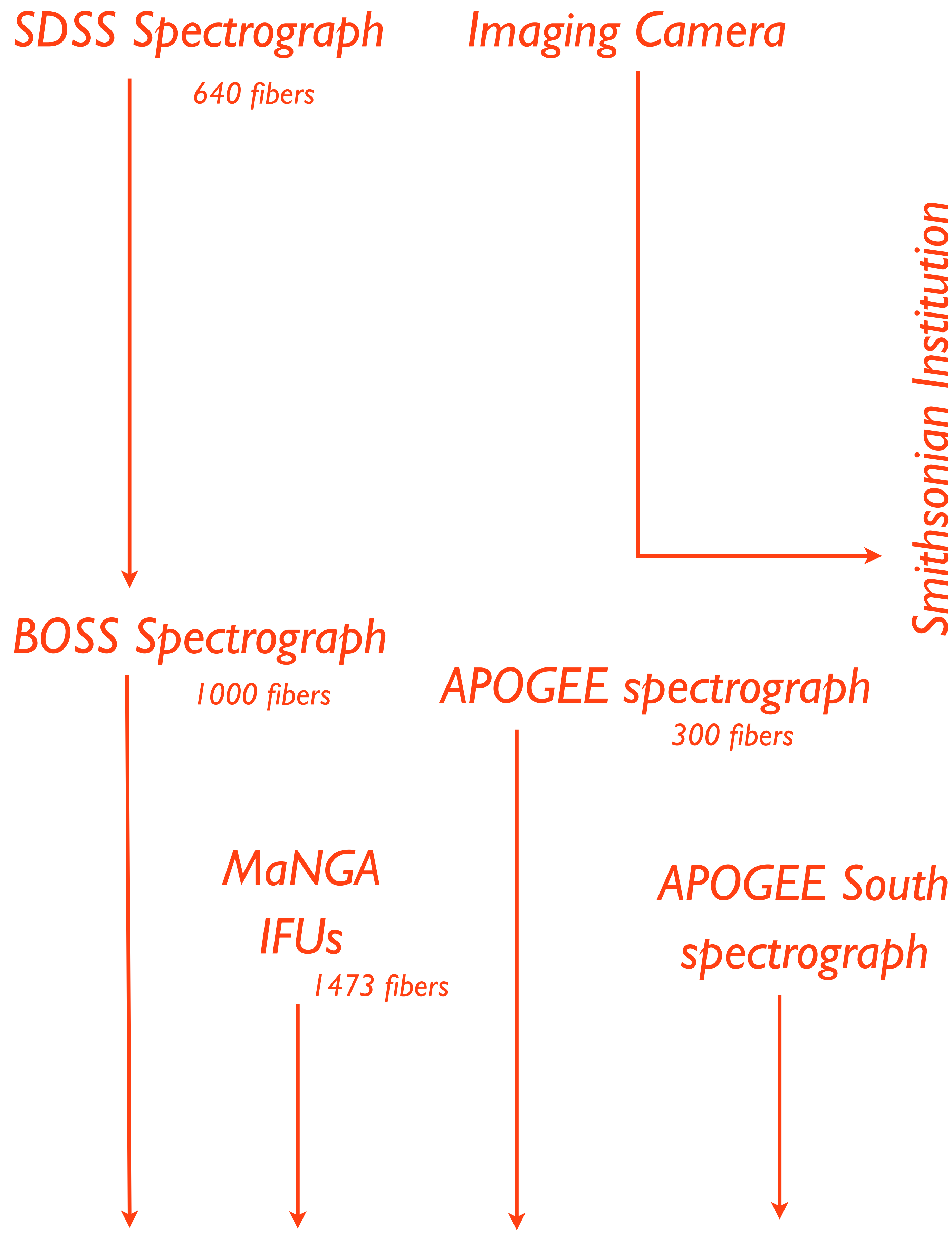
SDSS-IV (2014 to 2020):

APOGEE-2 high-resolution survey of stars

MaNGA survey of nearby galaxies

eBOSS survey of galaxies and quasars

SDSS-V (2020 to 2025)



A history of SDSS

SDSS-I (2000 to 2005):

the Legacy survey of galaxies and quasars

SDSS-II (2005 to 2008): *Fermilab era*

finishing Legacy

SDSS Supernova Survey (cosmology)

SEGUE survey of Milky Way stars

SDSS-III (2008 to 2014):

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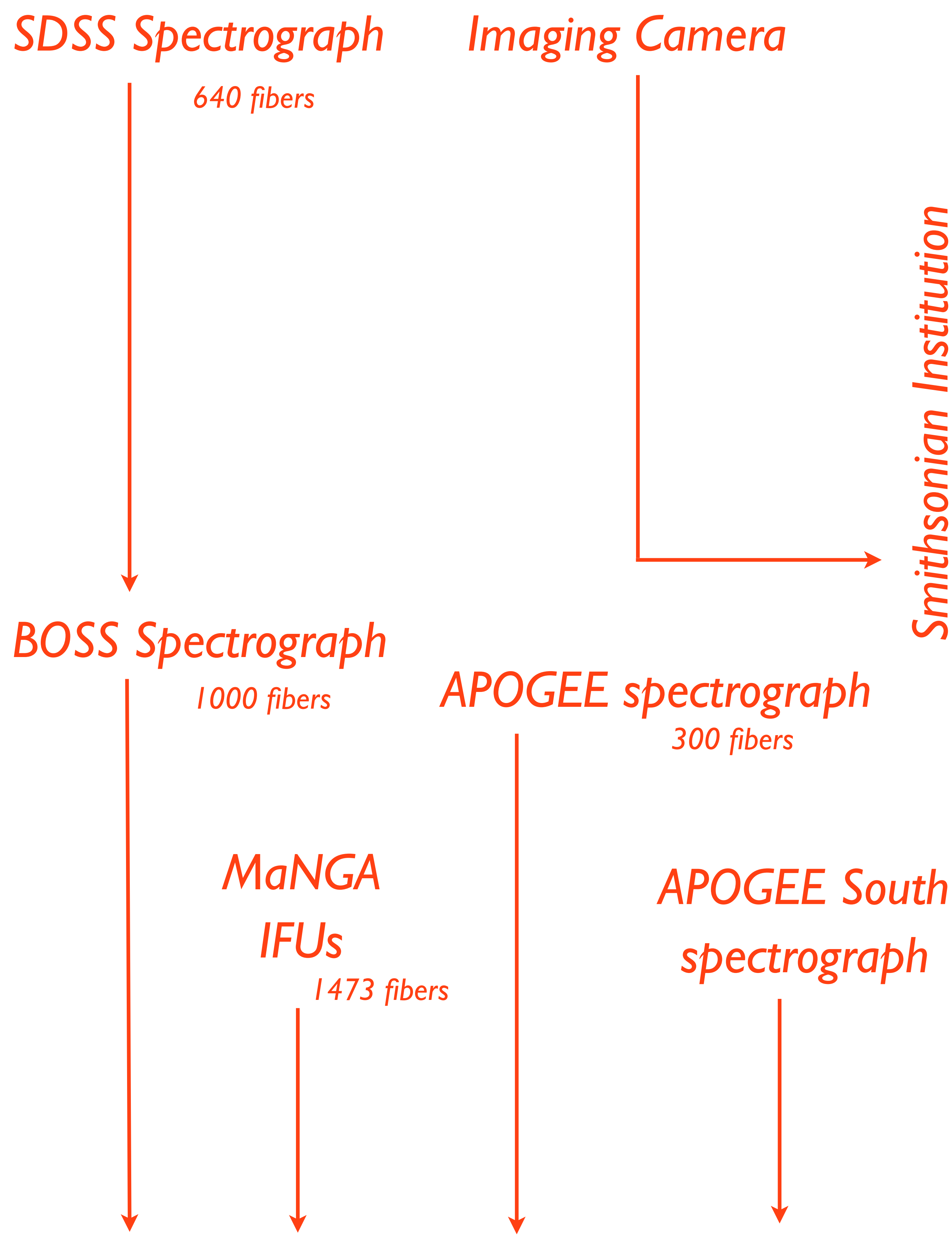


The SDSS-IV Collaboration (2014-2020)

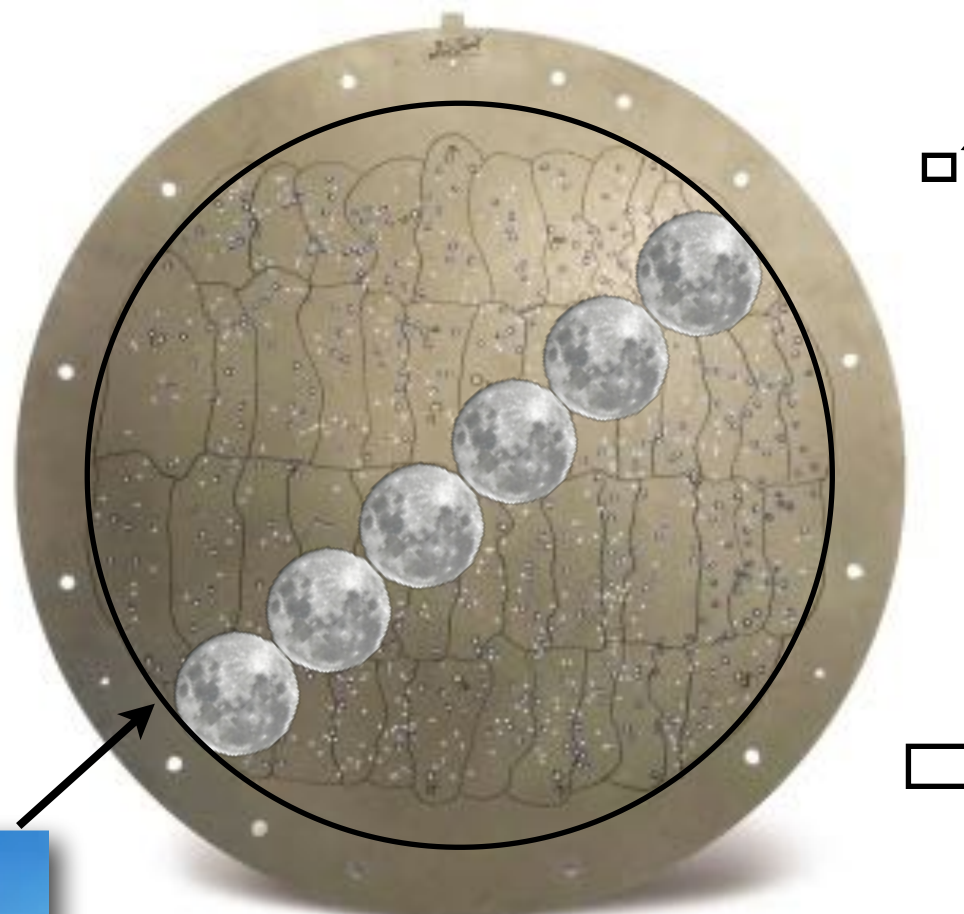
- SDSS-I had ~ 15 member institutions and groups; collaboration has grown! SDSS-IV has over 50 member institutions and groups.

- More than 1000 active scientists.
- Funded by the Sloan Foundation, the U.S. Dept. of Energy, but PRIMARILY by institutions.

Power of Sloan Telescope is its "field of view"

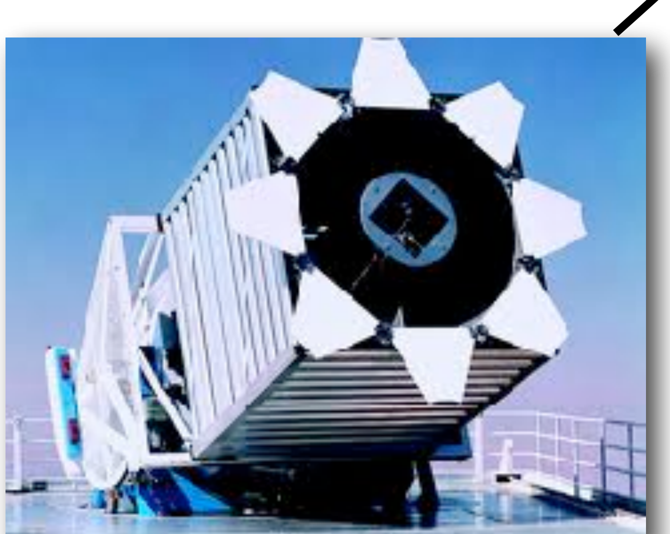
2.5-meter Sloan Foundation Telescope
Apache Point Observatory, New Mexico

- Multiplexed spectroscopy:
  - *1000 fibers for eBOSS*
  - *17 IFUs for MaNGA*
  - *300 fibers for APOGEE*
- 8 or 9 plates per night



2.5-meter Hubble Space Telescope

The 10-meter Keck Telescopes
Mauna Kea Observatory, Hawaii

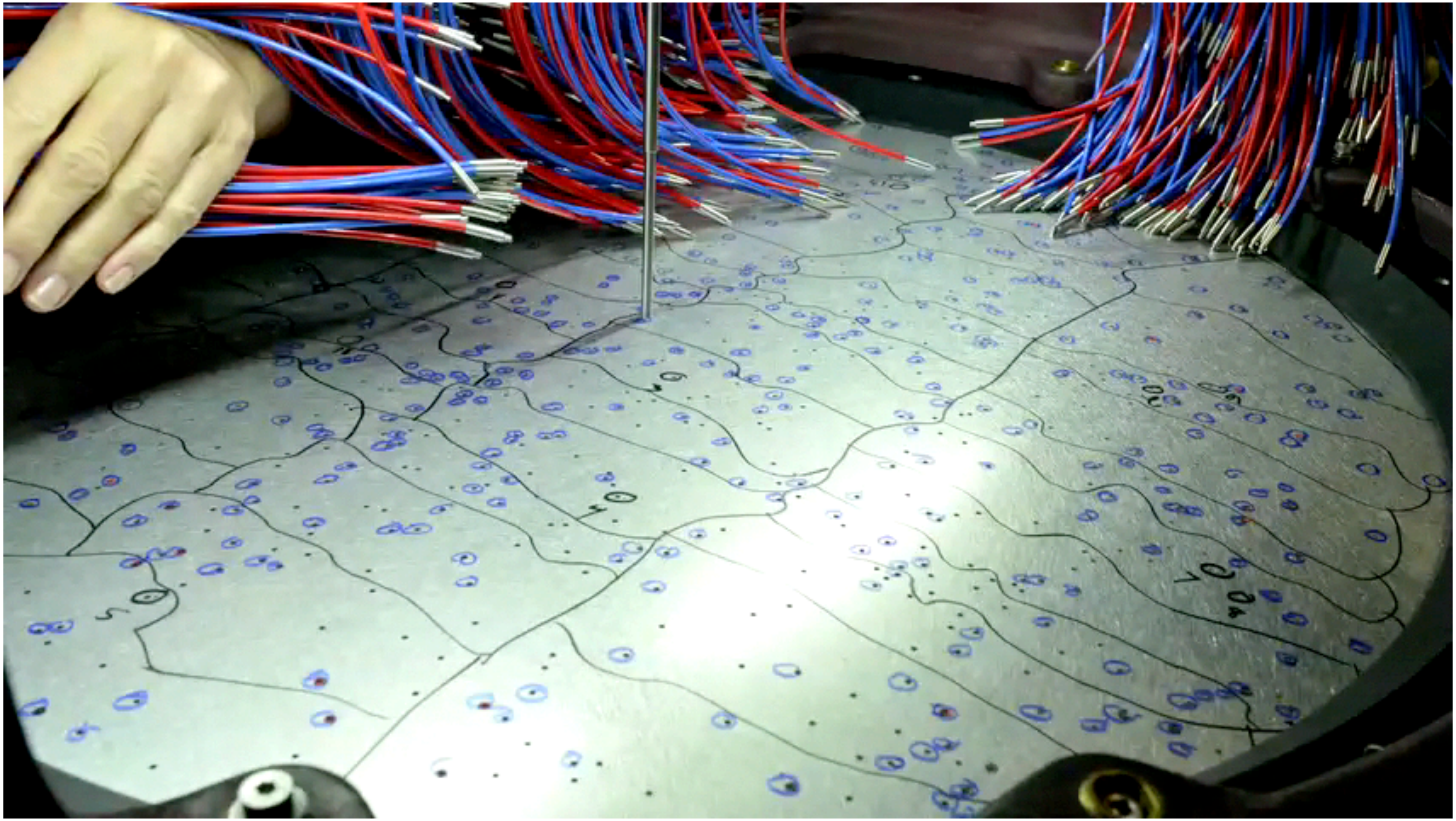


Credit: Mary Kawamura, Gaelen Sayres

Credit: Mary Kawamura, Gaelen Sayres

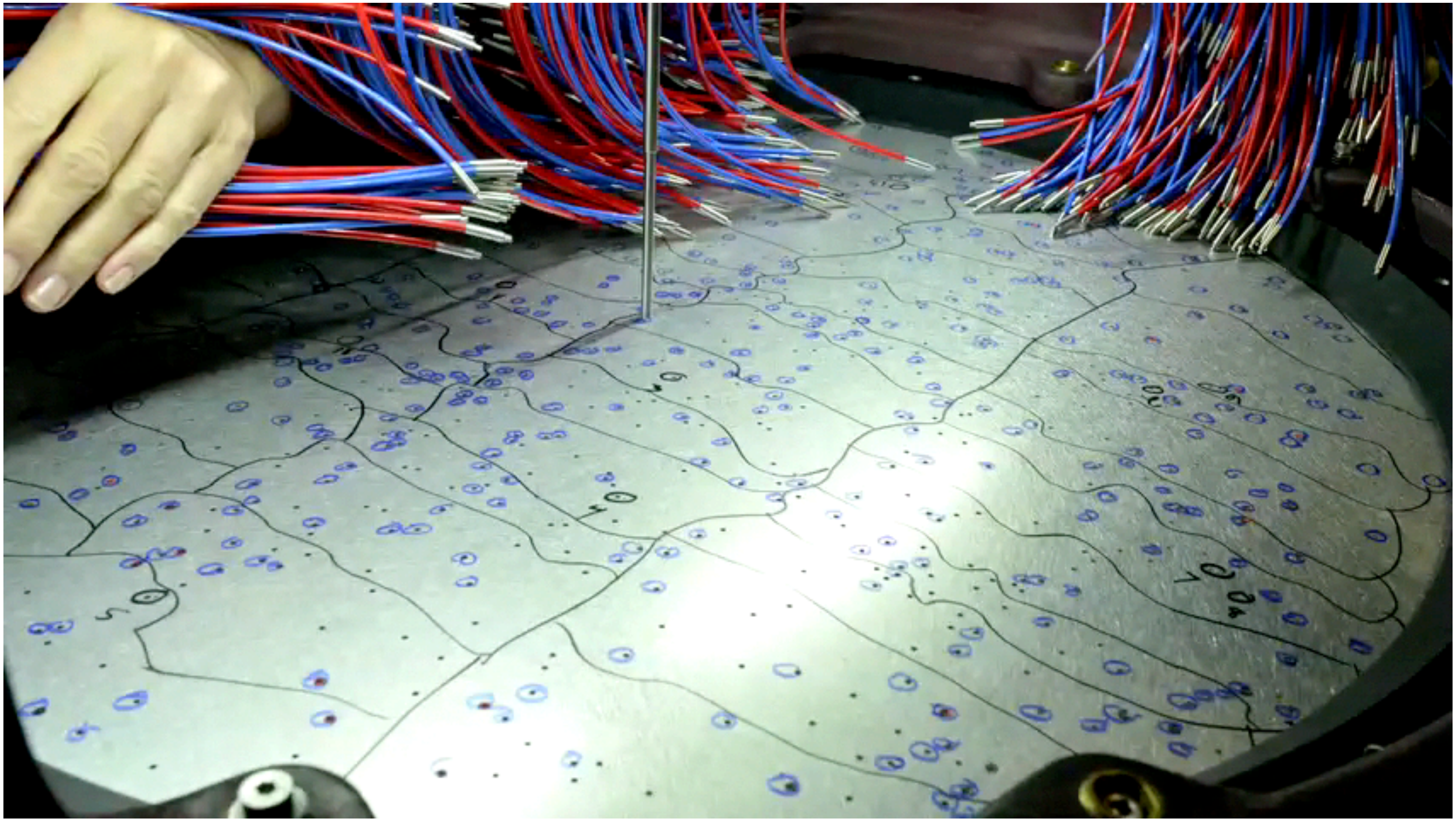
SDSS operations: *plates plugged with optical fibers*

"A thousand VISIBLE threads"



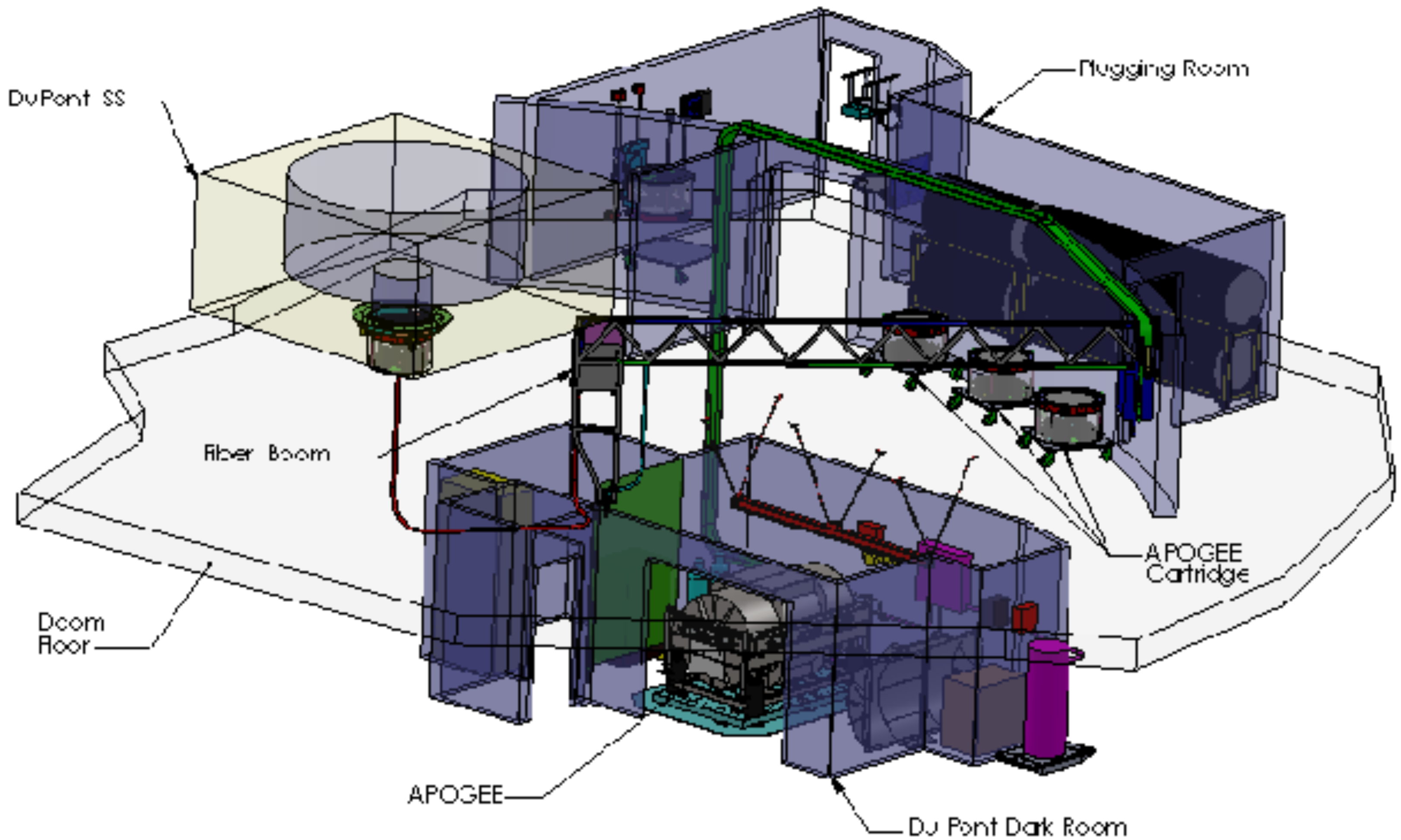
SDSS operations: *plates plugged with optical fibers*

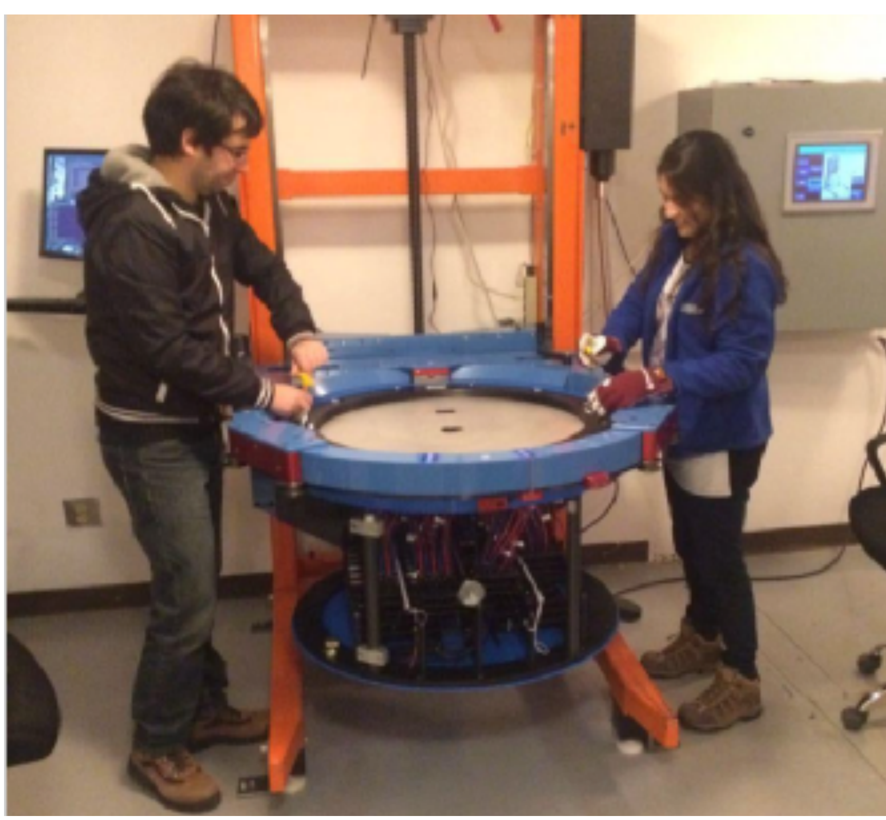
"A thousand VISIBLE threads"

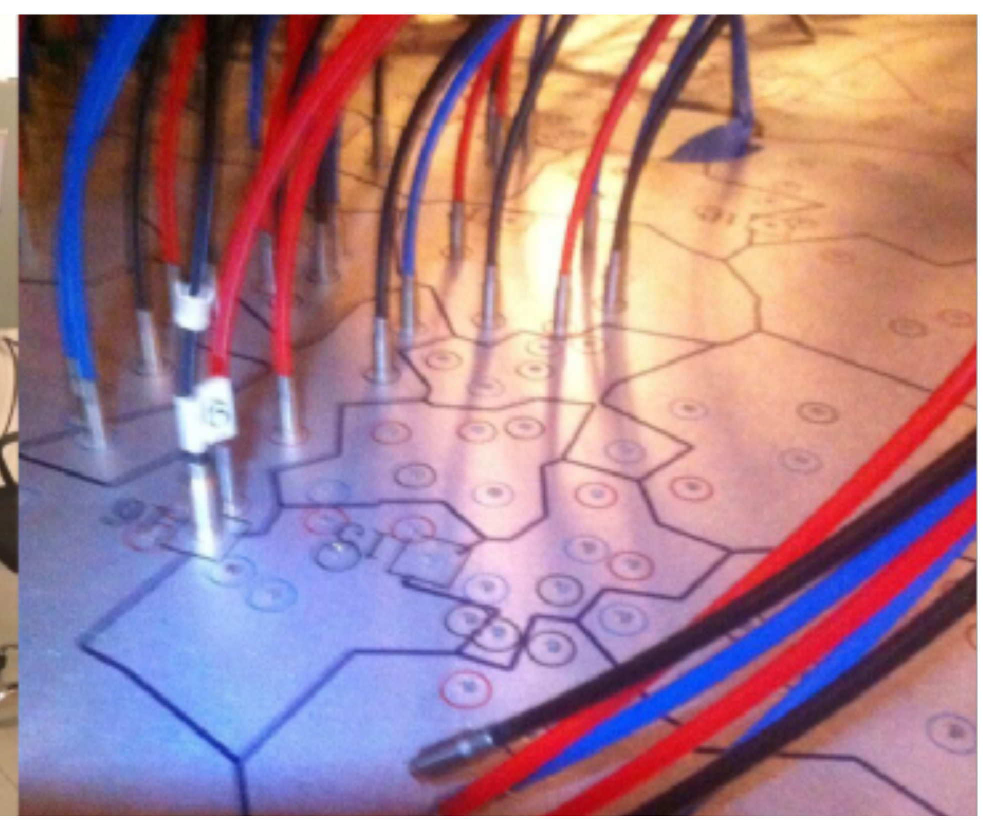


SDSS operations: *now at Las Campanas*

- New APOGEE South spectrograph (+ associated fiber infrastructure) returns du Pont Telescope to wide-field fiber spectroscopy after 20+ years.





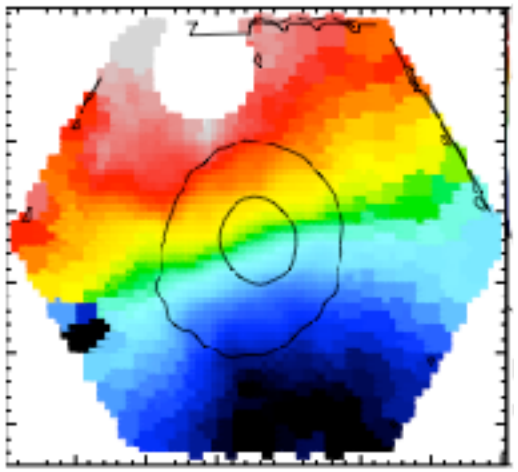


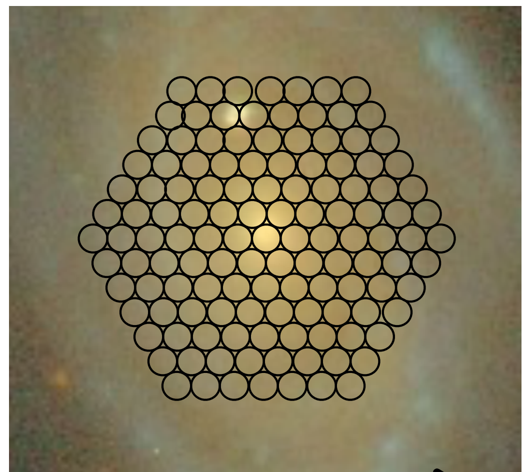
One more thing: *public data releases*

- Public data releases were a hallmark of SDSS from the beginning and are a critical reason for its influence.
- Now approaching DR15.
- > 80% of all SDSS papers (more than 8,000 to date) are written with the public data.
- Don’t forget that it costs money and time though!

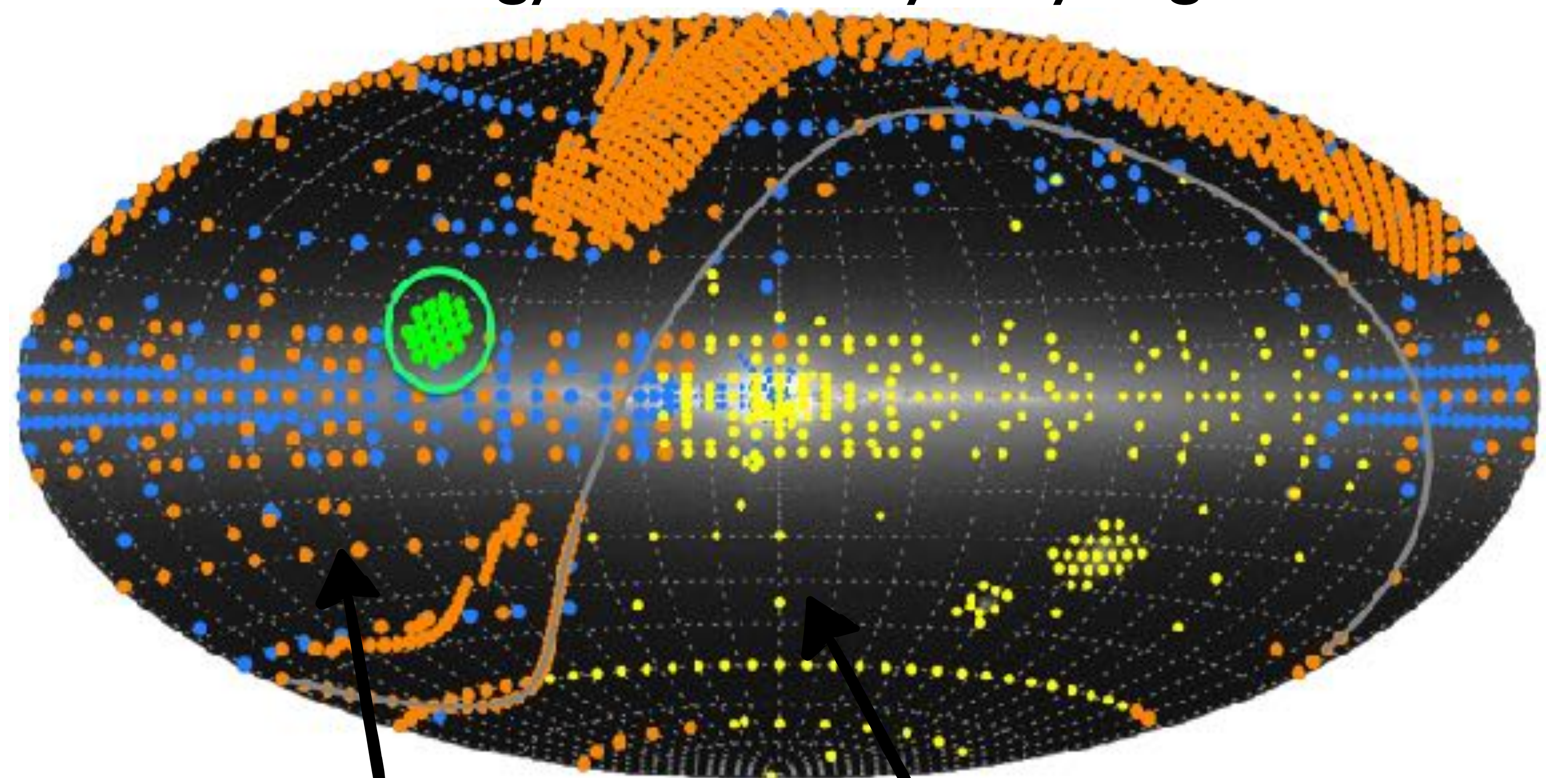
“DocuVana”
Latest in series of documentation festivals

MaNGA: 10,000 galaxies with spatially resolved spectroscopy

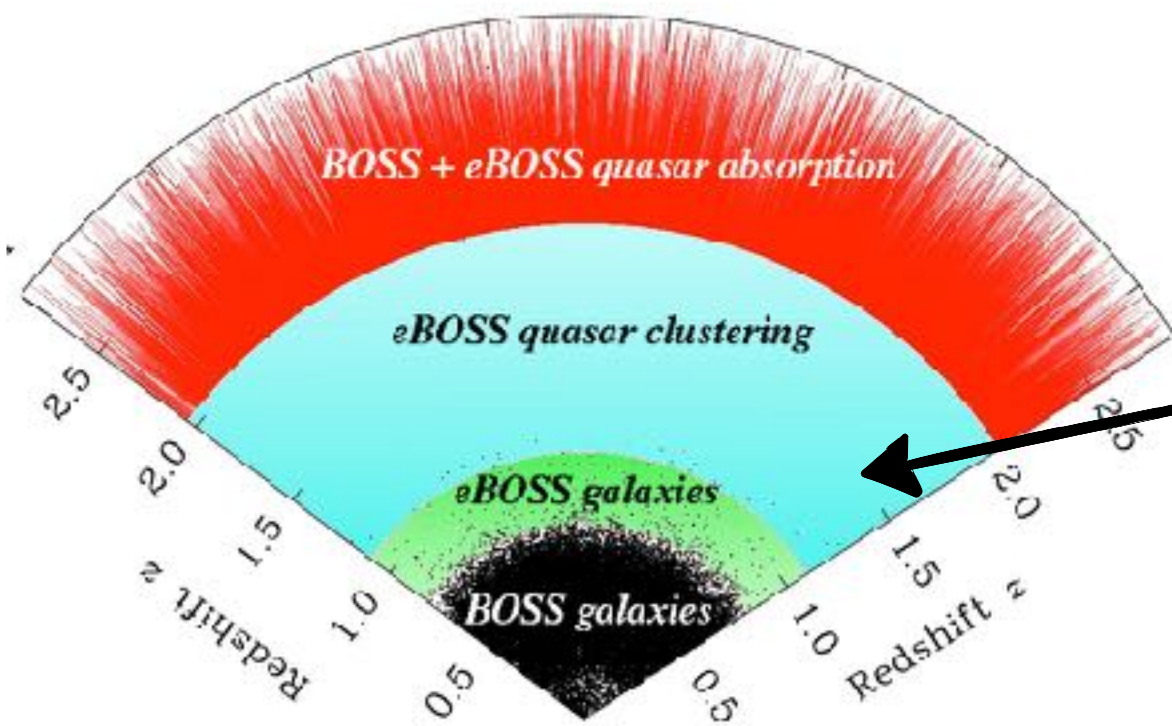




APOGEE-2: Massively expanded Galactic archeology for all Milky Way regions



eBOSS: Studying cosmic acceleration in a new redshift regime with the largest ever quasar sample



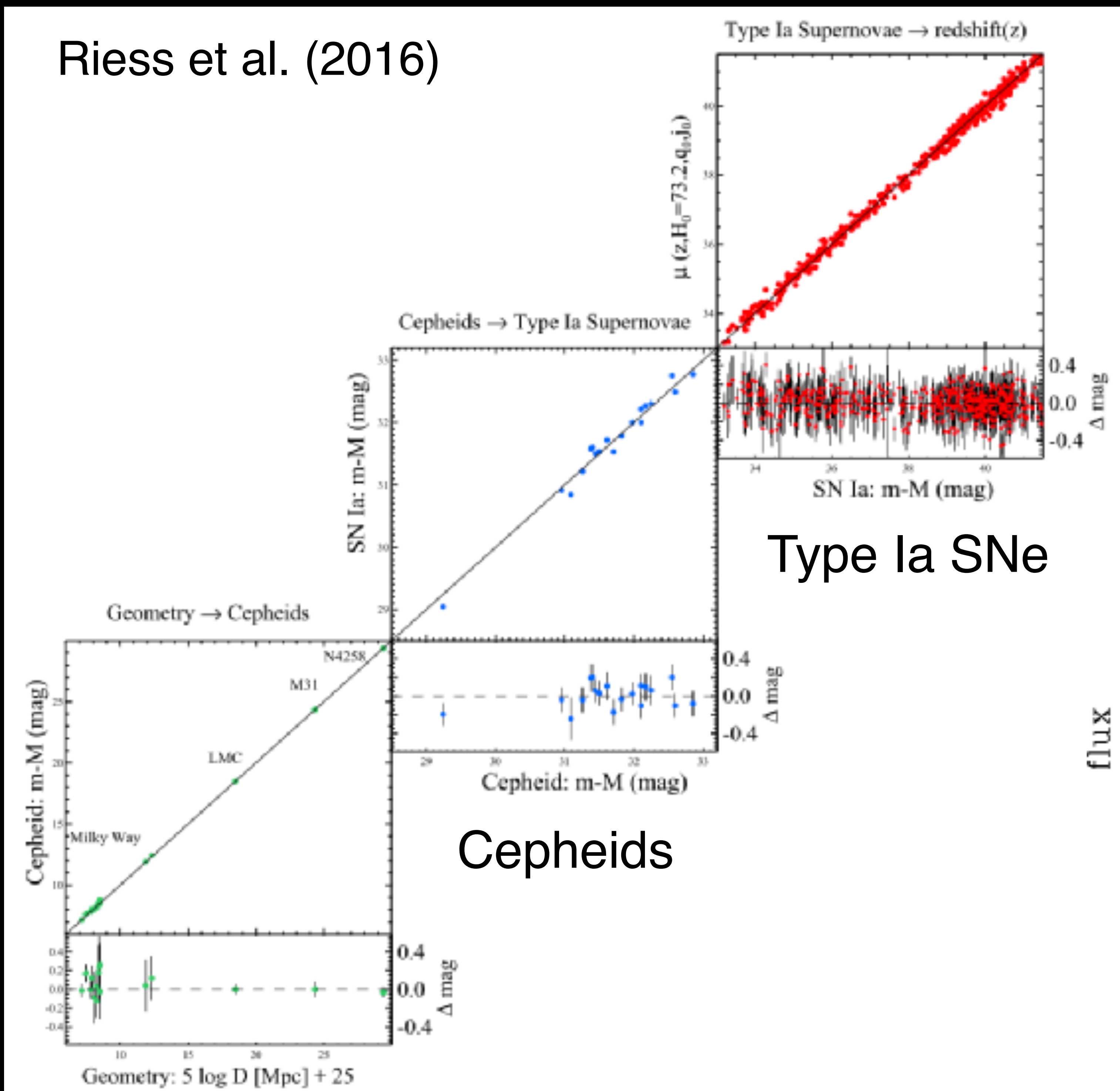
Sloan Foundation Telescope

du Pont Telescope

Large-scale structure redshift surveys in SDSS

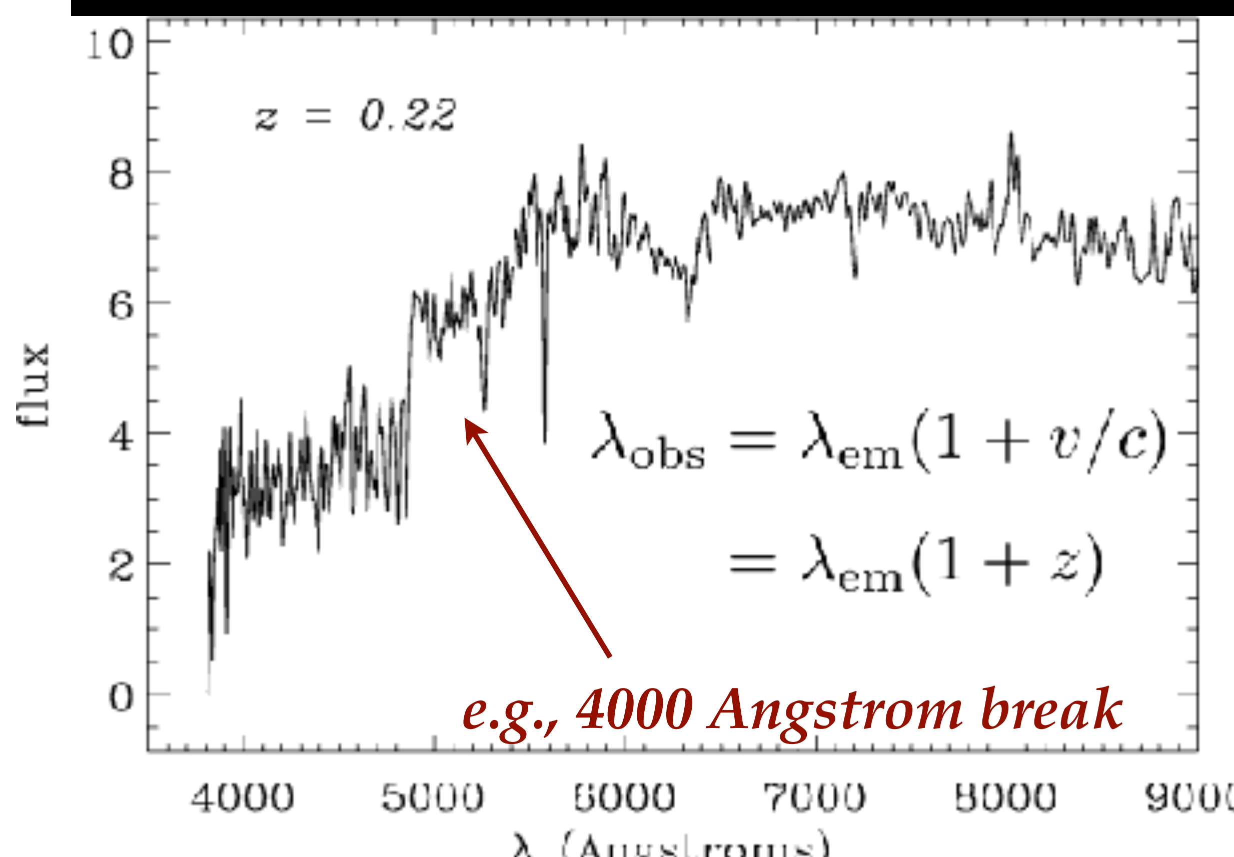
- Legacy (2000 - 2008)
  - *Main sample ($z < 0.25$)*
  - *Luminous red galaxies ($0.20 < z < 0.45$)*
- BOSS (2009 - 2014)
  - *Luminous red galaxies ($0.35 < z < 0.7$)*
  - *Lyman-alpha forest ($2.1 < z < 3.5$)*
- eBOSS (2014 - 2019)
  - Luminous red galaxies ($0.65 < z < 0.8$)
  - Emission line galaxies ($0.7 < z < 1.1$)
  - Quasars ($0.7 < z < 2.2$)
  - Lyman-alpha forest ($2.1 < z < 3.5$)

Climbing the distance ladder: Hubble's Law

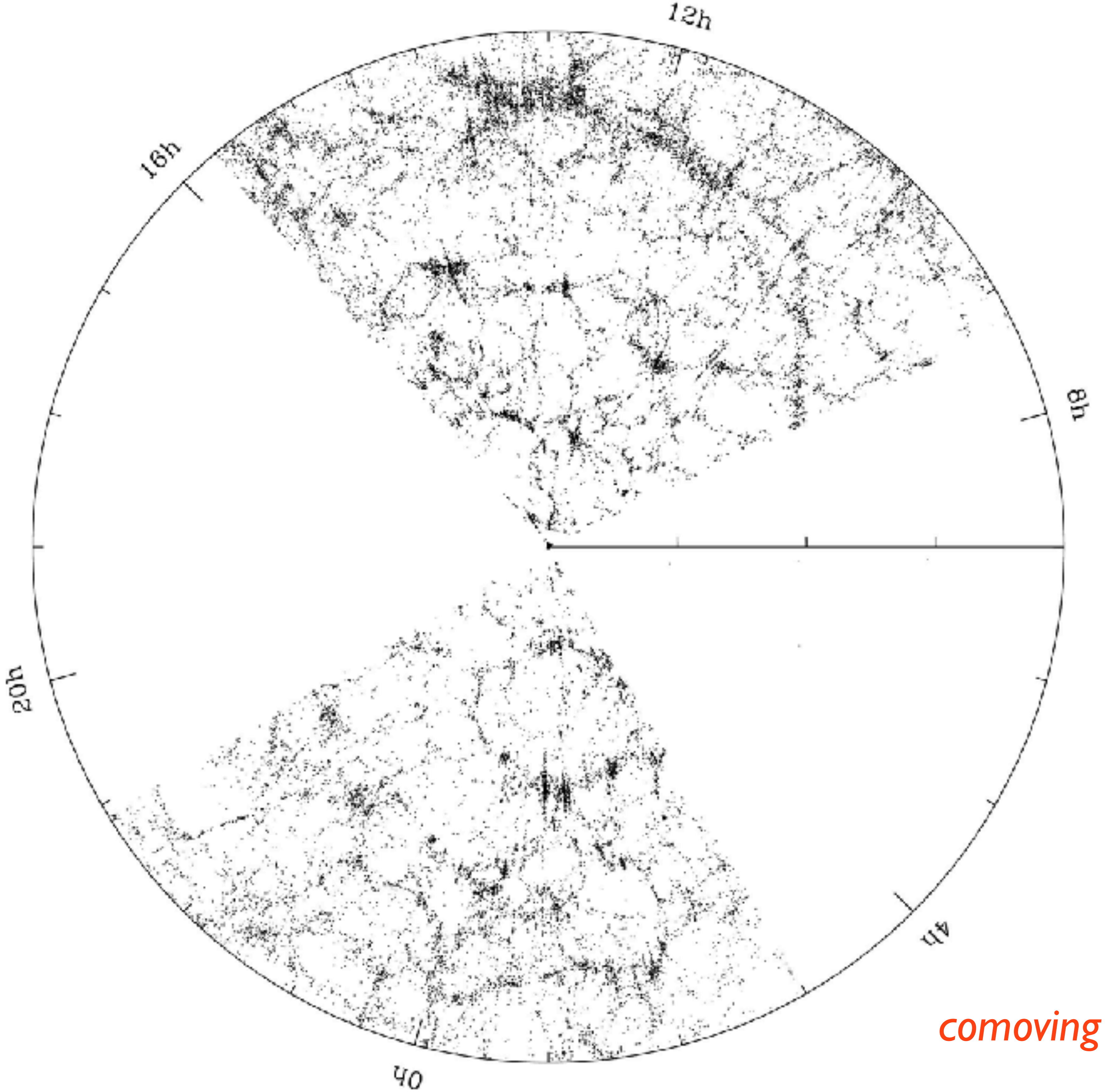


$$v = H_0 d$$

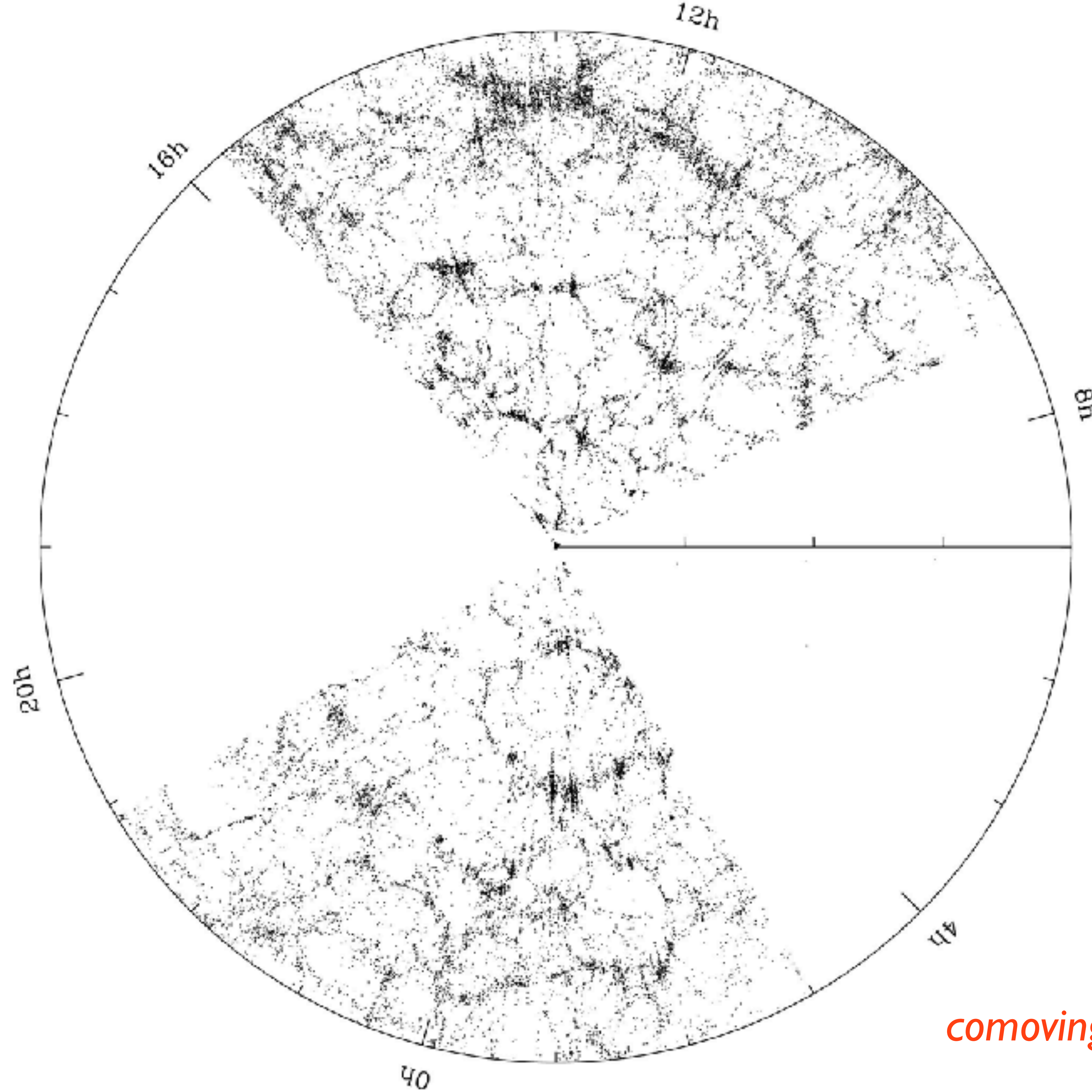
$$H_0 \approx 70 \text{ km/s/Mpc}$$



Large-scale structure redshift surveys in SDSS-I to -III



Large-scale structure redshift surveys in SDSS-I to -III

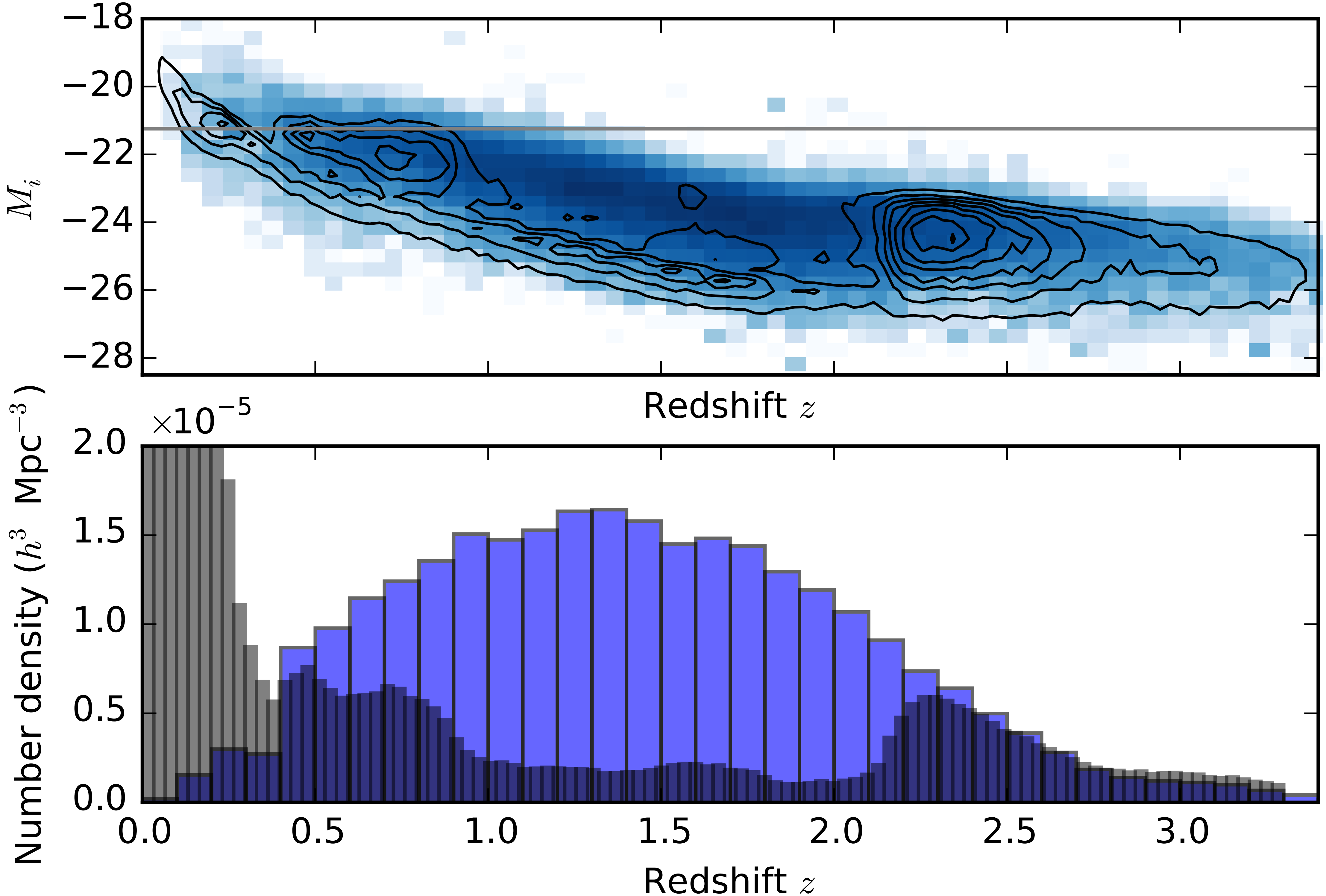


comoving distance

eBOSS: *huge quasar + galaxy survey to measure dark energy*

(K. Dawson, PI; J-P Kneib, Deputy PI; W. Percival, Survey Scientist)

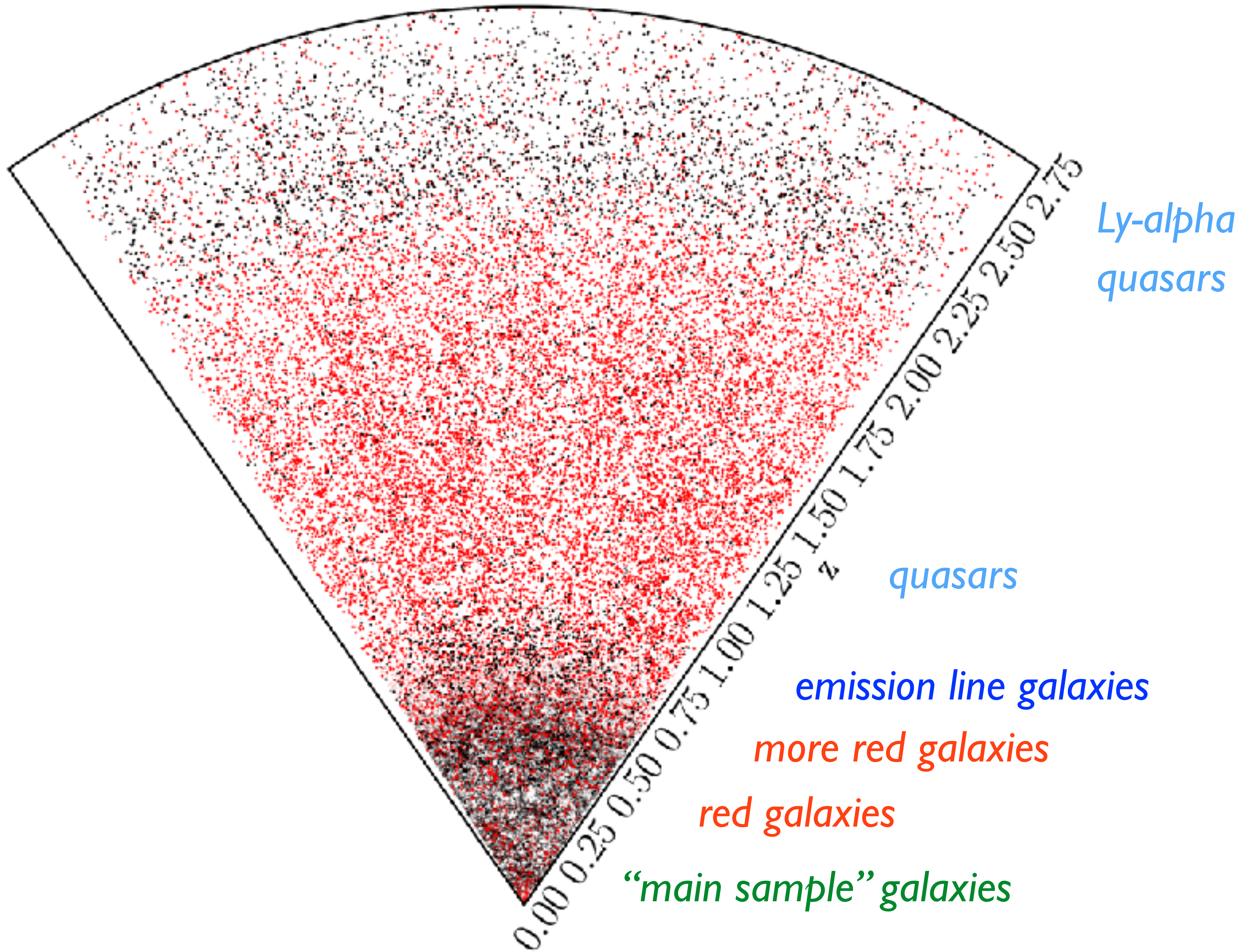
previous quasars (contours) vs. eBOSS quasars (blue-scale)



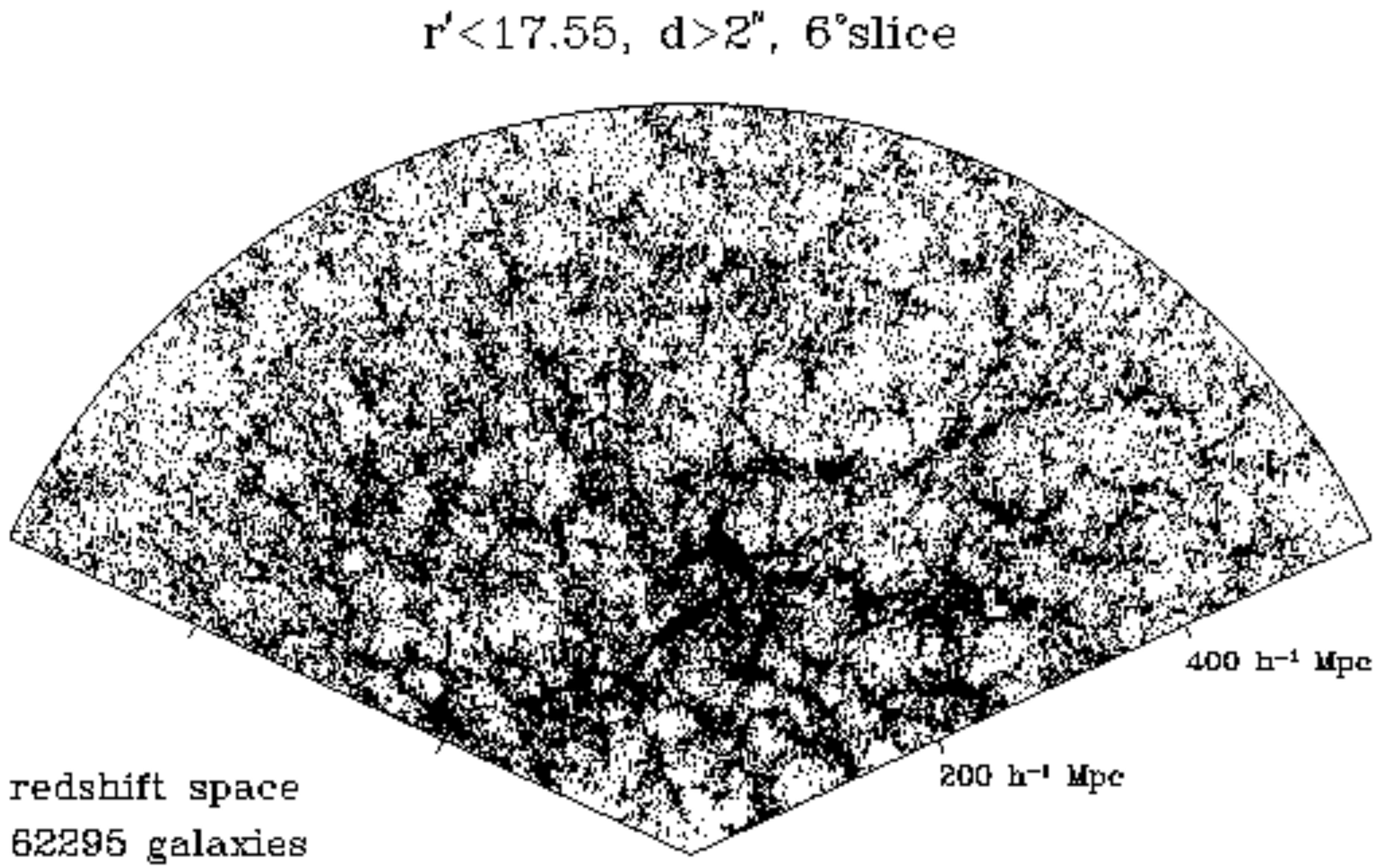
quite a lot of quasars, to quite faint limits

eBOSS: *huge quasar + galaxy survey to measure dark energy*

(K. Dawson, PI; J-P Kneib, Deputy PI; W. Percival, Survey Scientist)

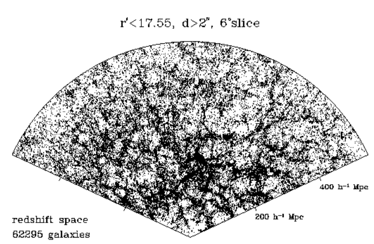


Original SDSS survey conception

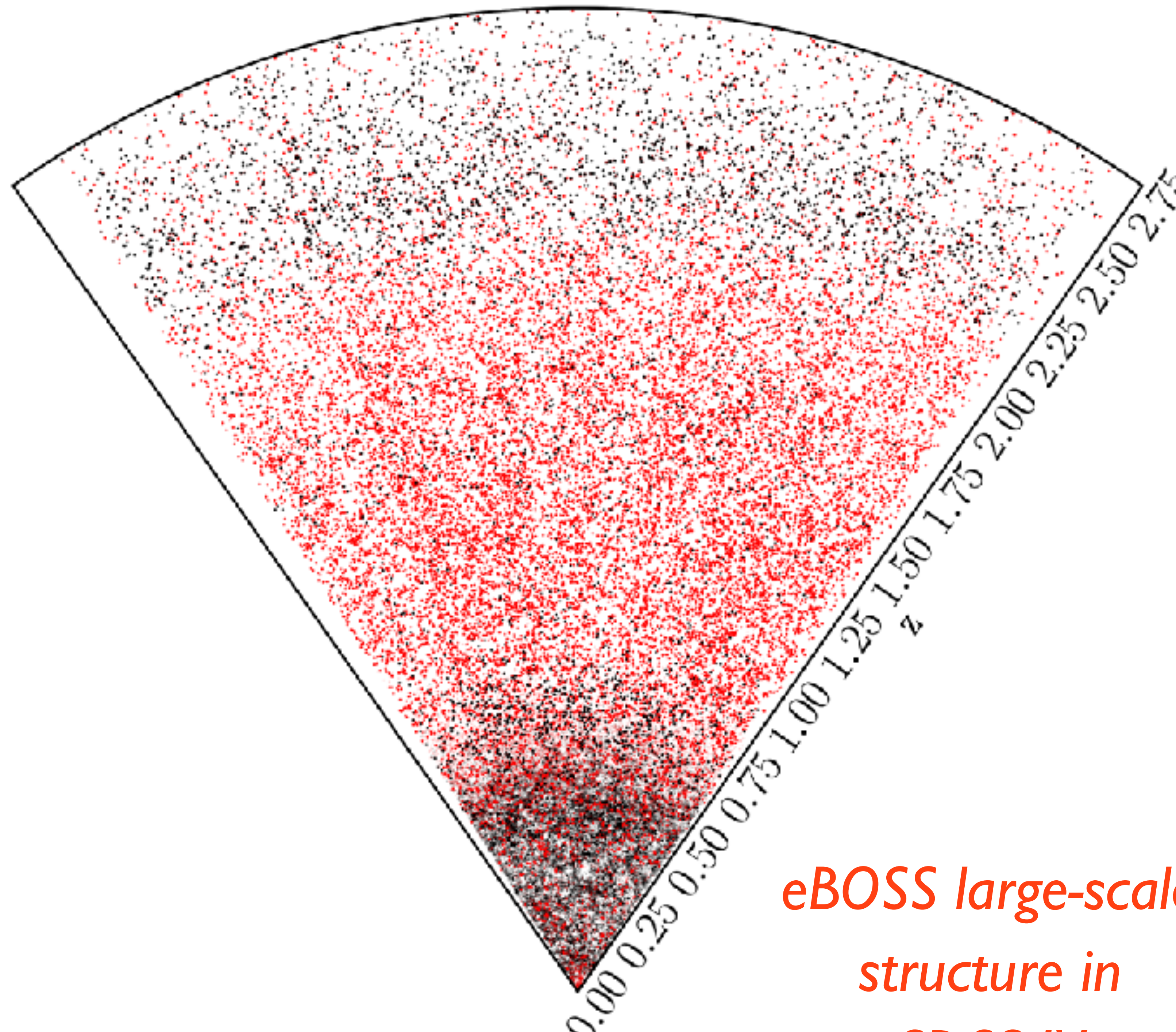


Changbom Park & Rich Gott's simulation of SDSS circa 1997 (from SDSS Project Book)

eBOSS: ending early in February 2019



conception of volume for large-scale structure Legacy survey in SDSS-I (including LRGs)



eBOSS large-scale structure in SDSS-IV

Why we are measuring large scale structure

- Basic questions about the Universe
  - *How old is the Universe?*
  - *What is its expansion history?*
  - *How much dark matter and what else is in the Universe?*
  - *How do structures growth over cosmic time?*
- More pointed question:
  - *What is the cause of cosmic acceleration?*

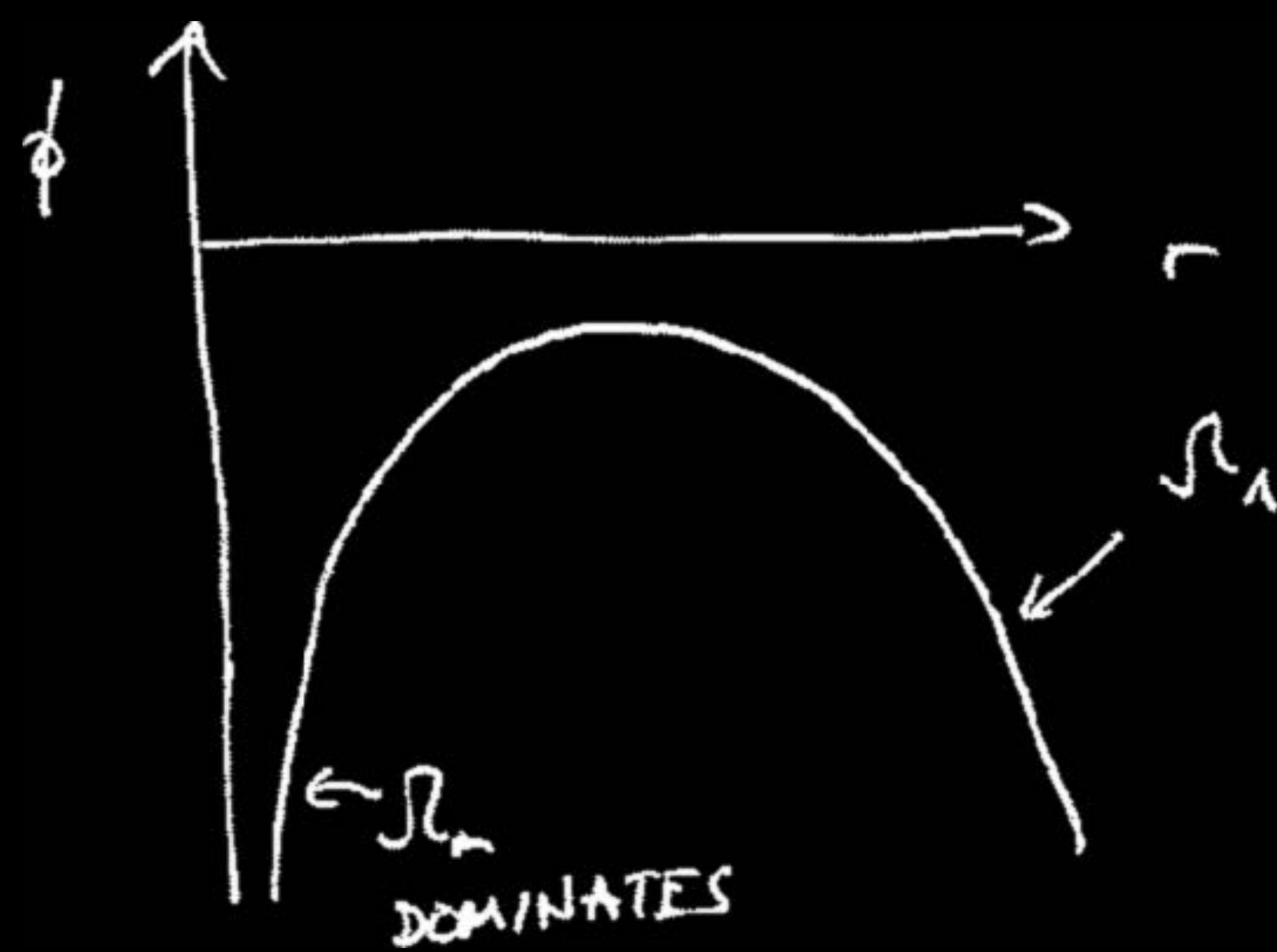
Defining cosmological parameters

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

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

$$\Omega_m = \frac{8\pi G\rho}{3H^2}$$ *~ 0.24 today*

$$\Omega_\Lambda = \frac{\Lambda}{3H^2}$$ *~ 0.76 today*



Defining cosmological parameters

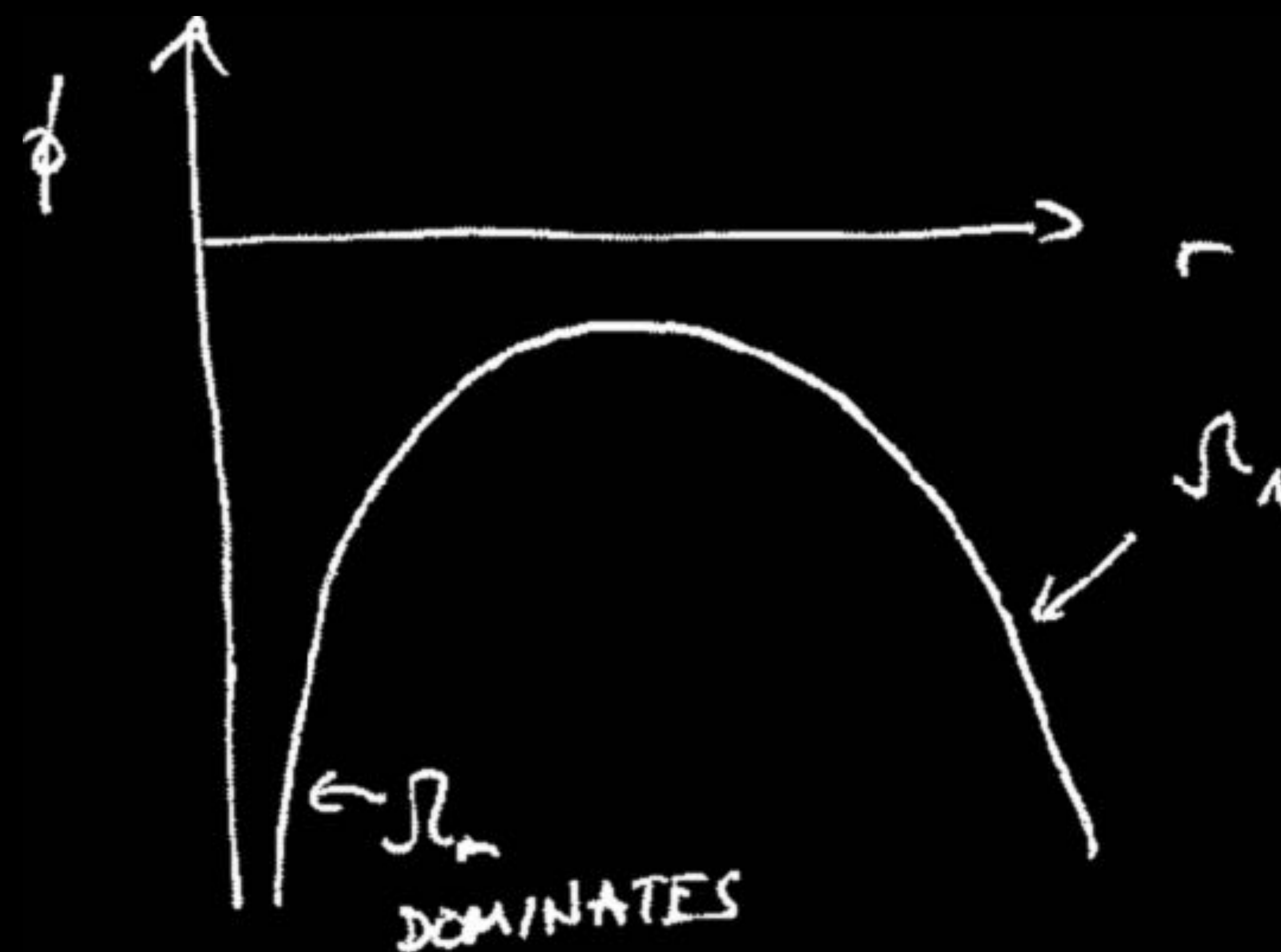
matter — *"dark energy" or "cosmological constant"* — *curvature*

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

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

$$\Omega_m = \frac{8\pi G\rho}{3H^2}$$ *~ 0.24 today*

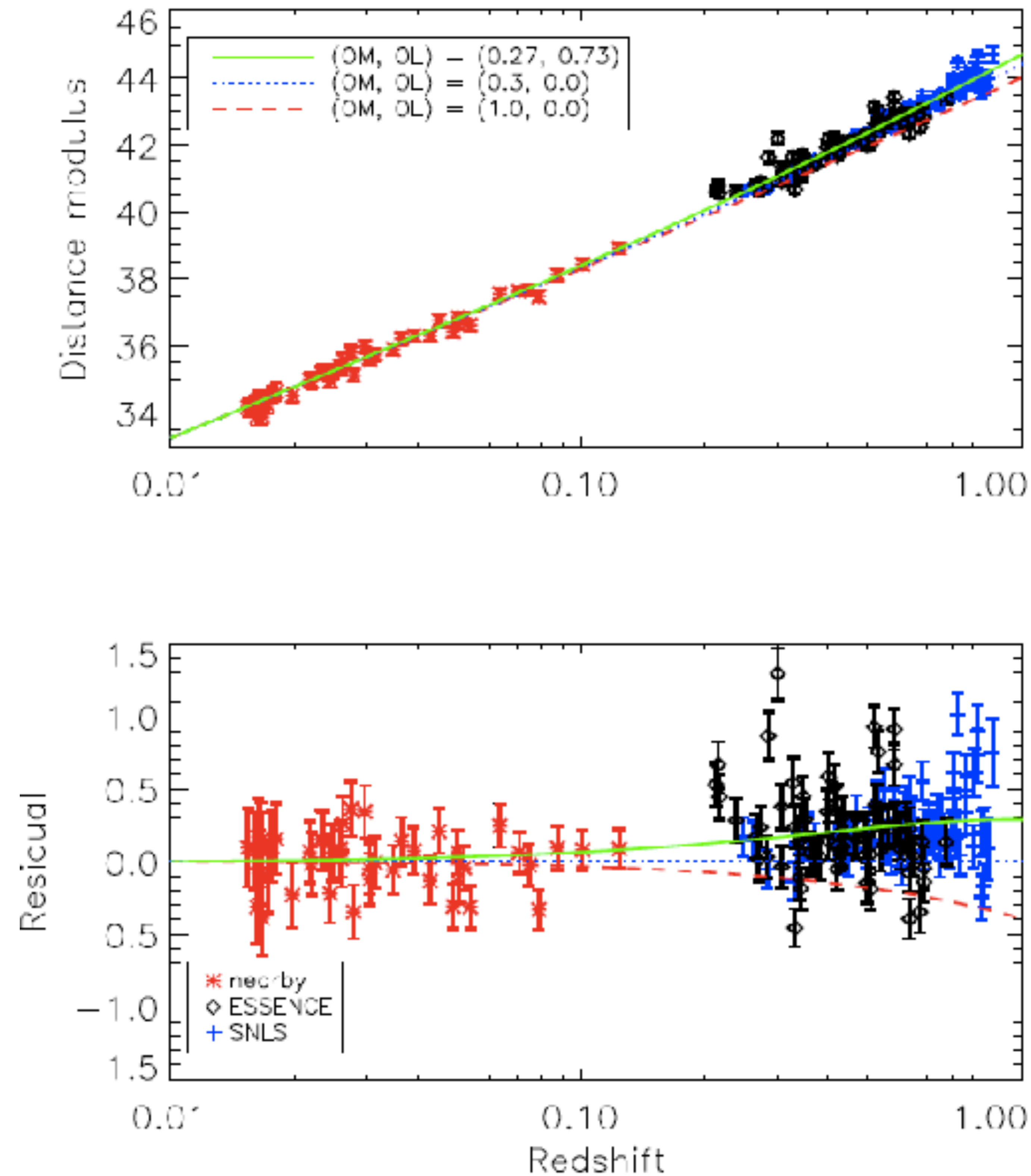
$$\Omega_\Lambda = \frac{\Lambda}{3H^2}$$ *~ 0.76 today*



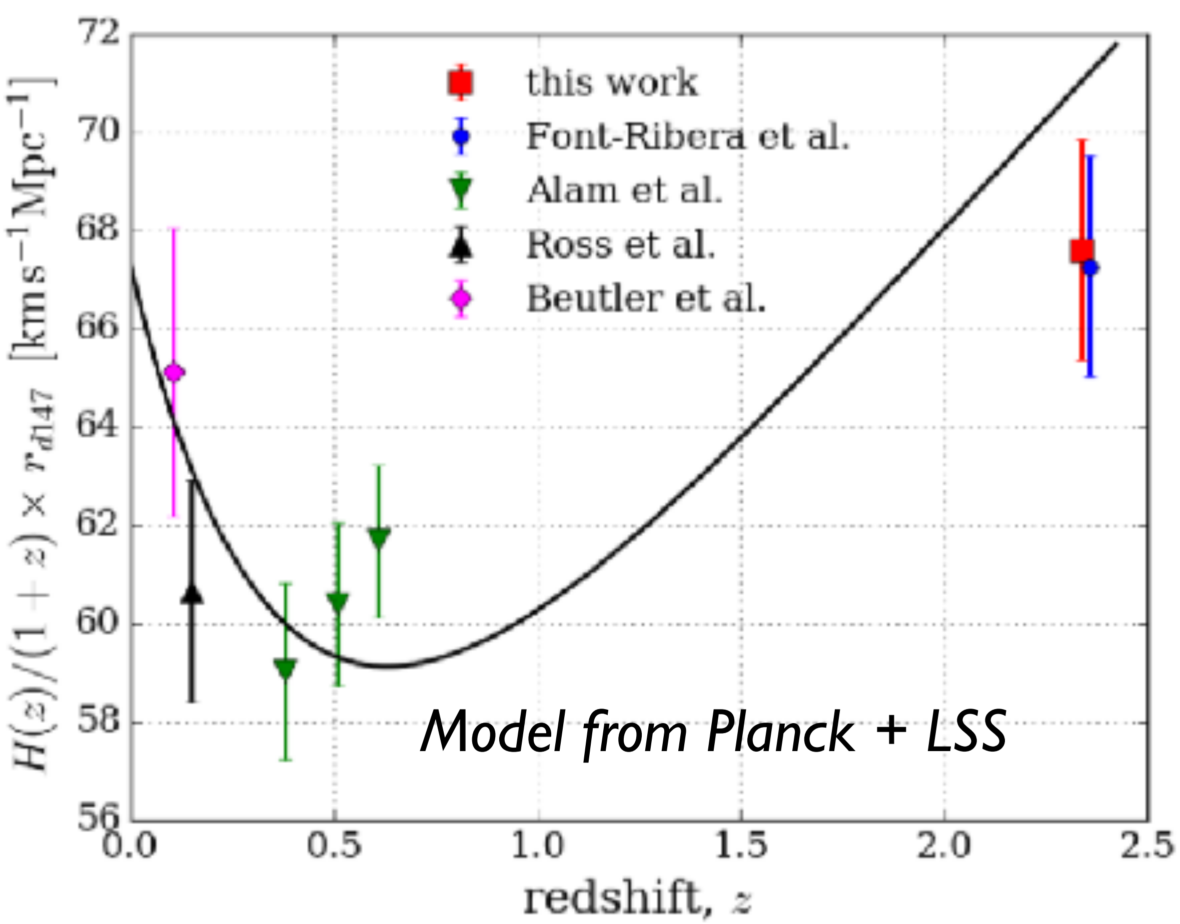
Detection of acceleration with supernovae + LSS

$$\Omega_\Lambda > 0$$

SNe Type Ia; Wood-Vasey et al. (2007)



LSS; Bautista et al. (2017)



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"

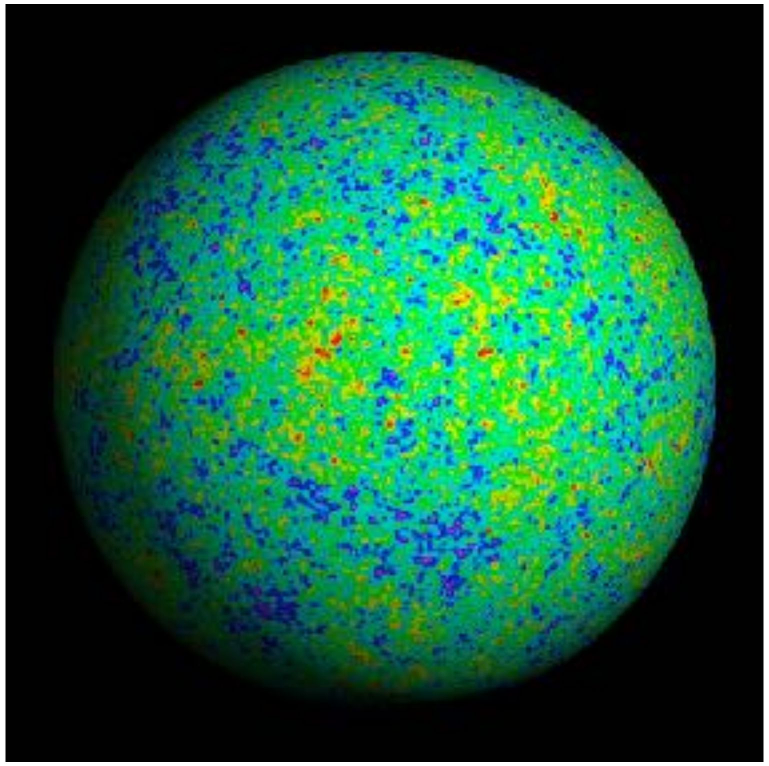
$$w(a) = w_0 + w_a(1-a)$$

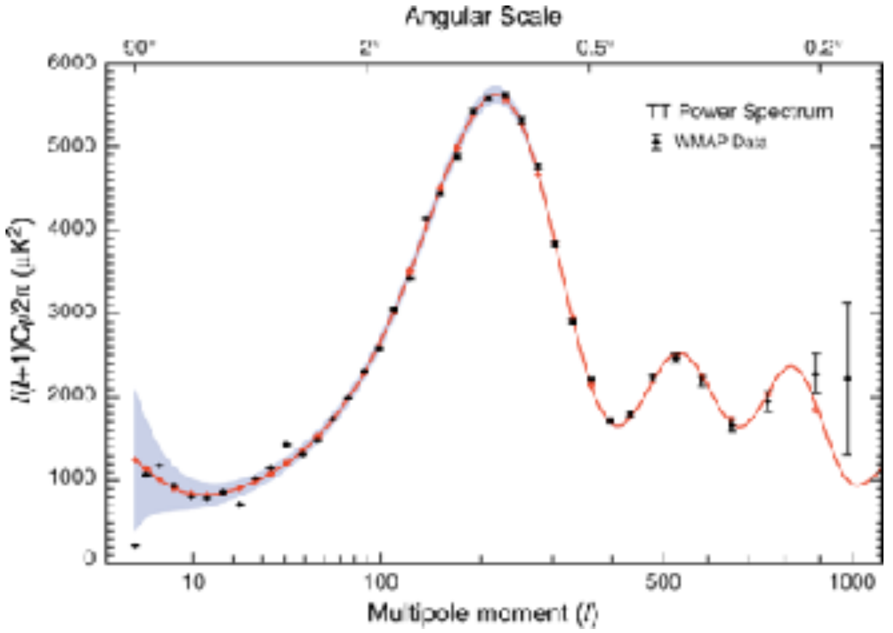
dependent on redshift?

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

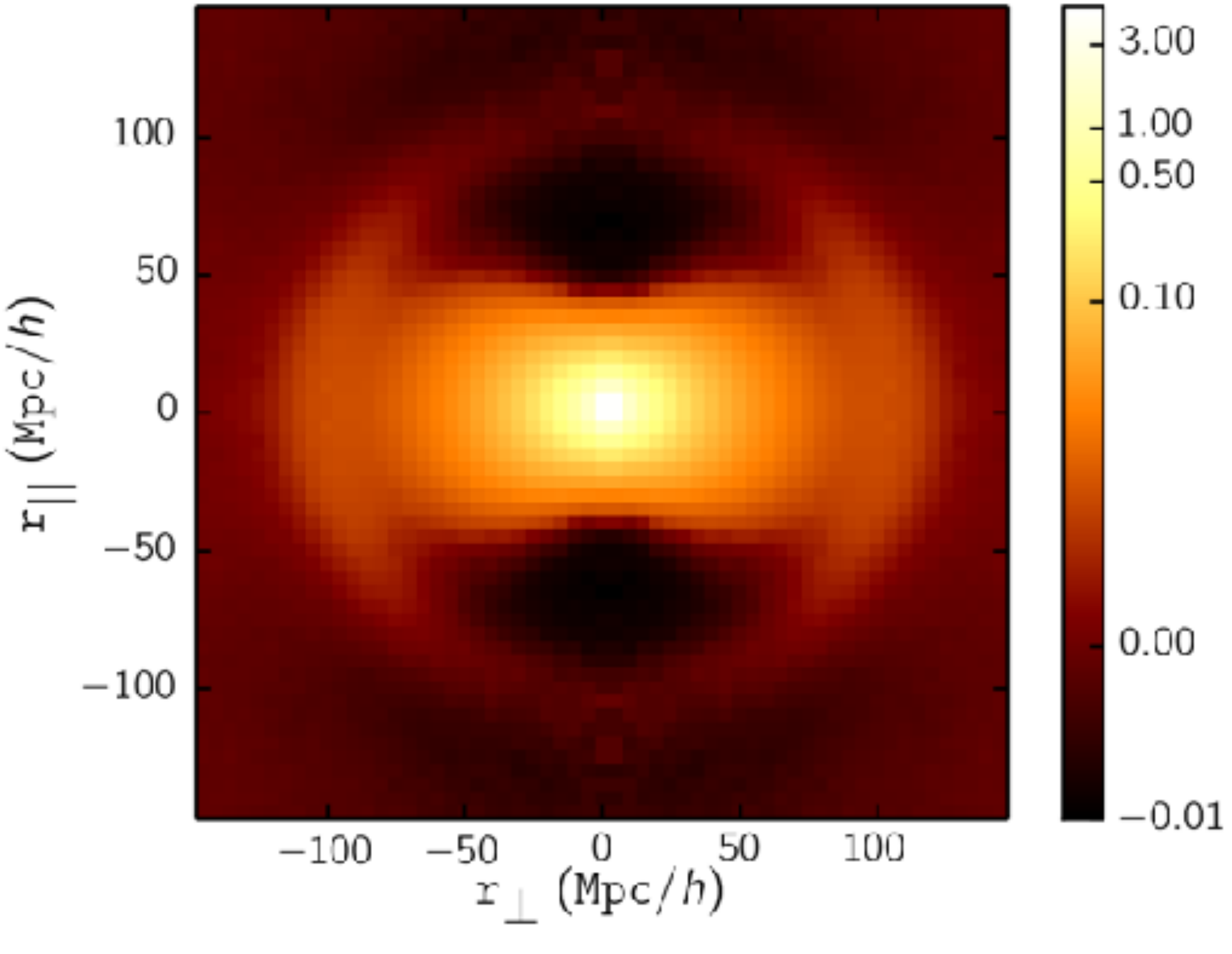
Baryon Acoustic Oscillation: *correlation function*

Physical scale of feature measured in CMB at z ~ 1100





Redshift scale of feature measured at z ~ 0 in large-scale structure



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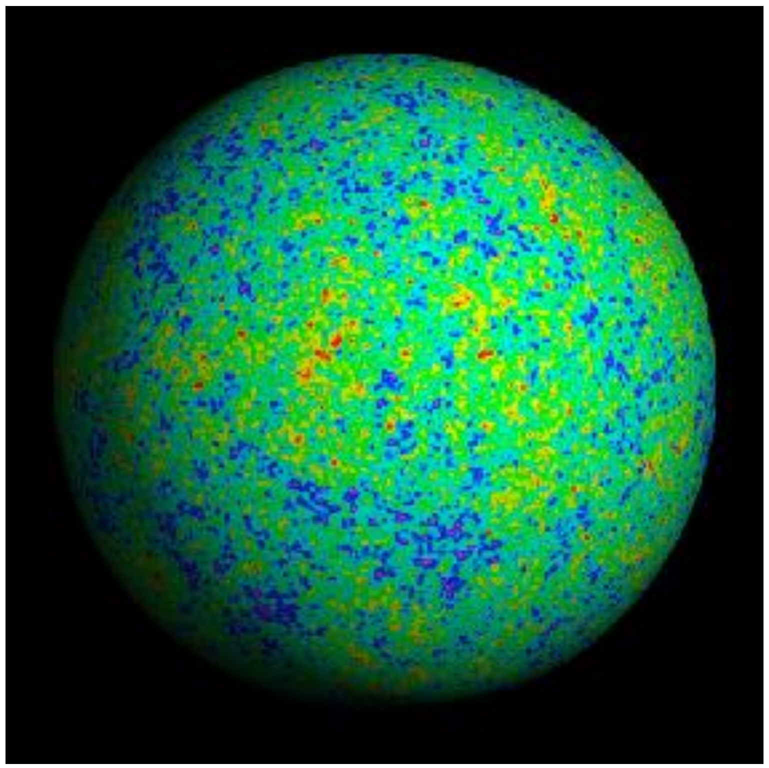
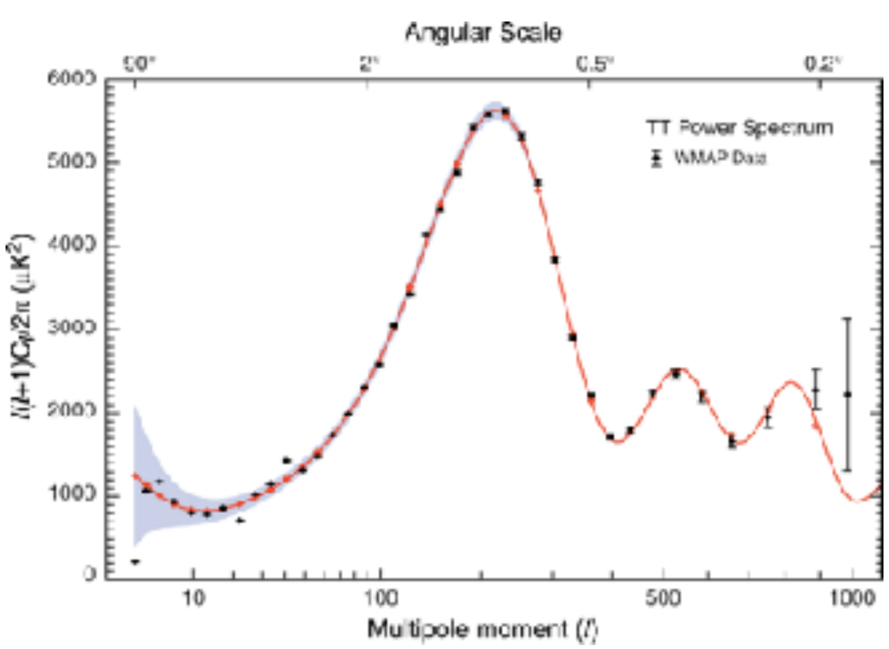
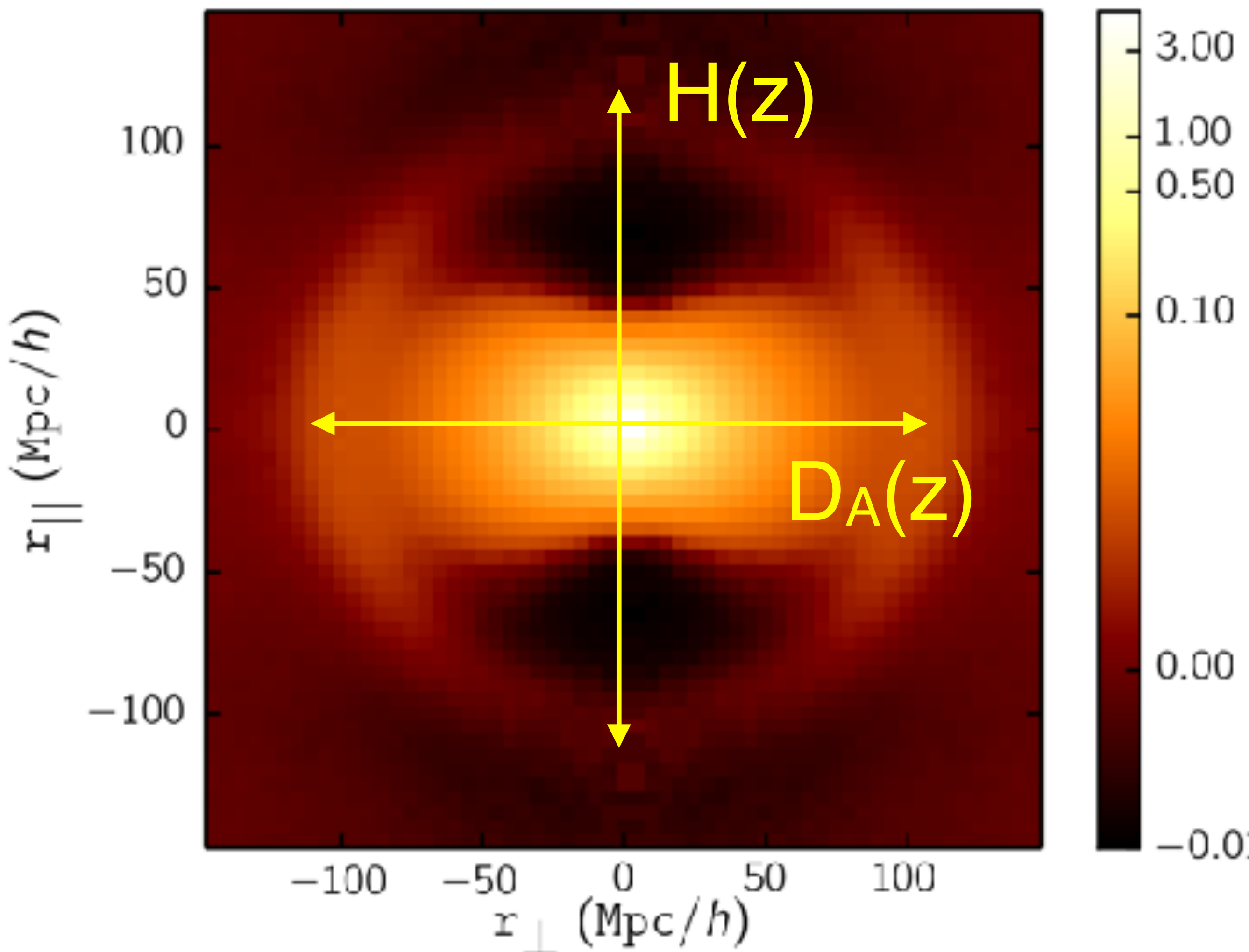




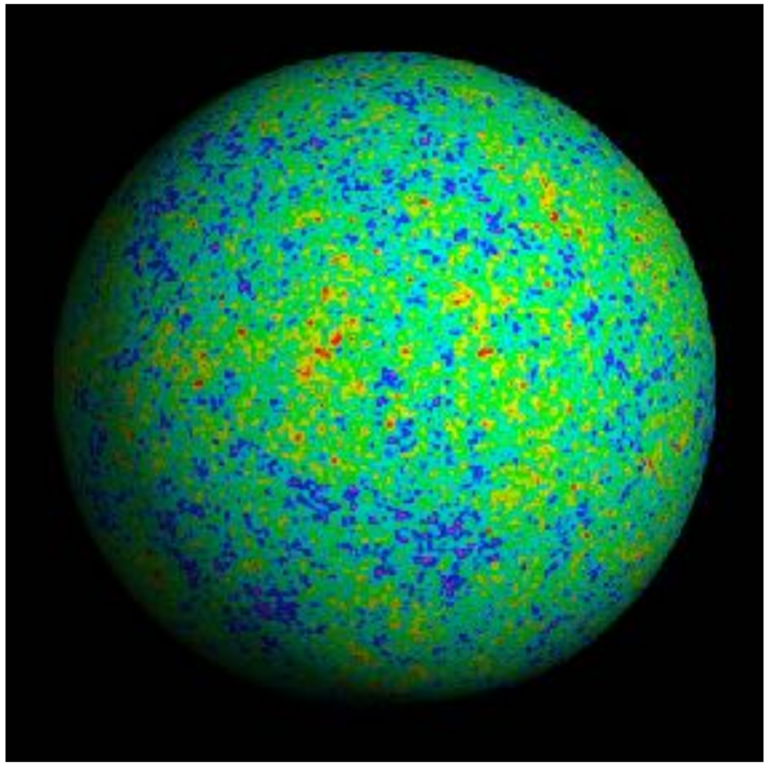
Redshift scale of feature measured at z ~ 0 in large-scale structure

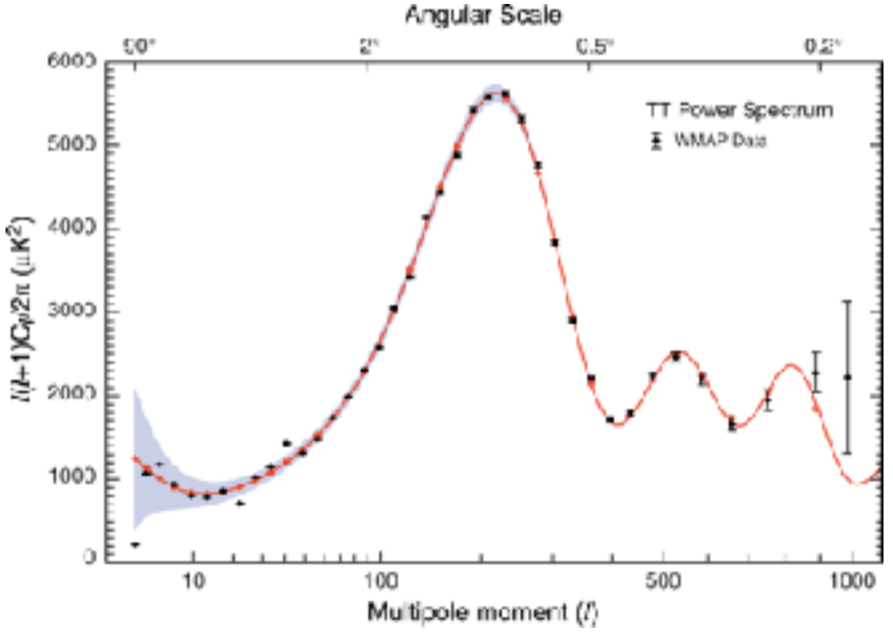


A standard ruler of ~ 1% precision.

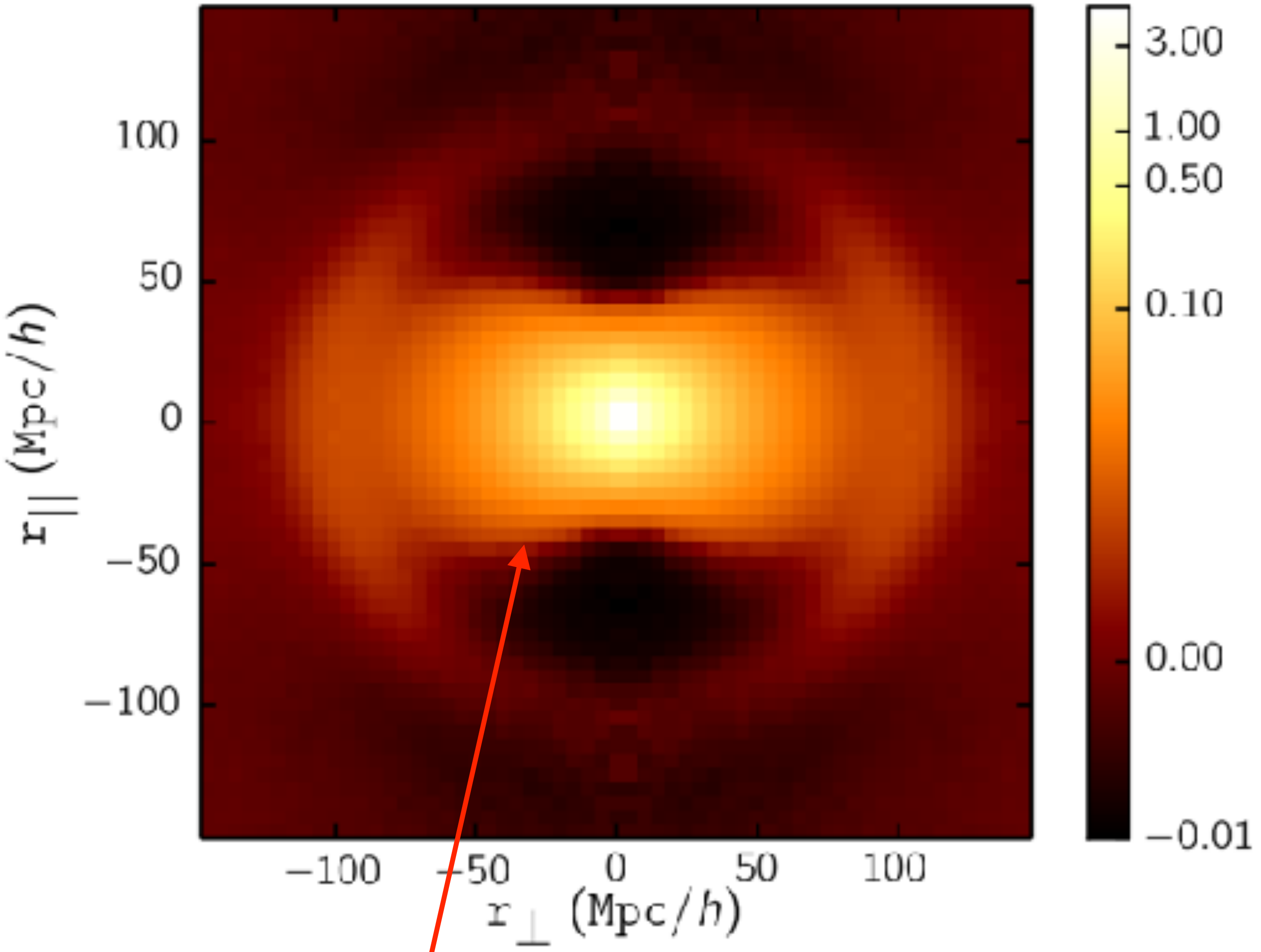
Baryon Acoustic Oscillation: *correlation function*

Physical scale of feature measured in CMB at z ~ 1100





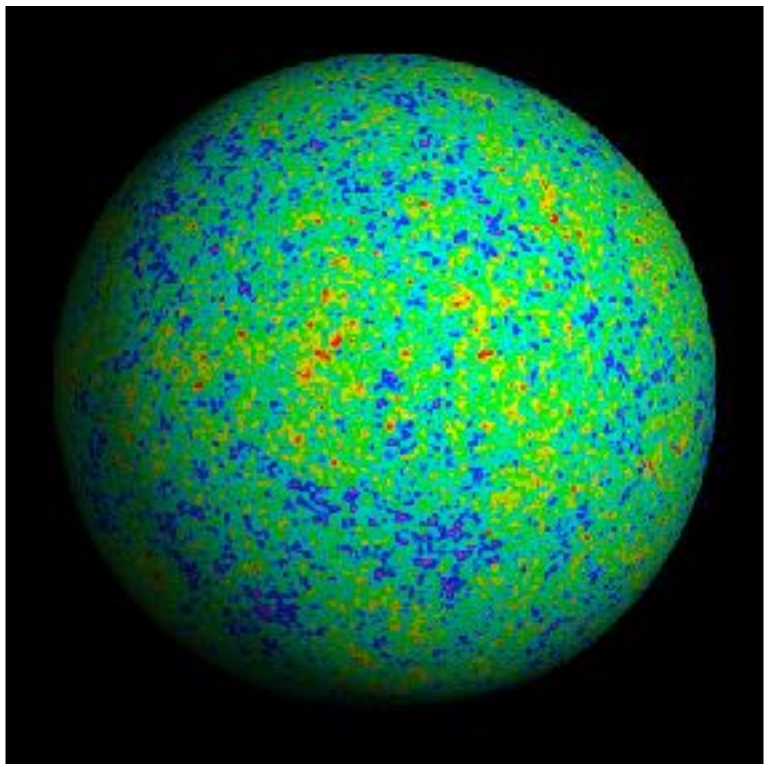
Redshift scale of feature measured at z ~ 0 in large-scale structure

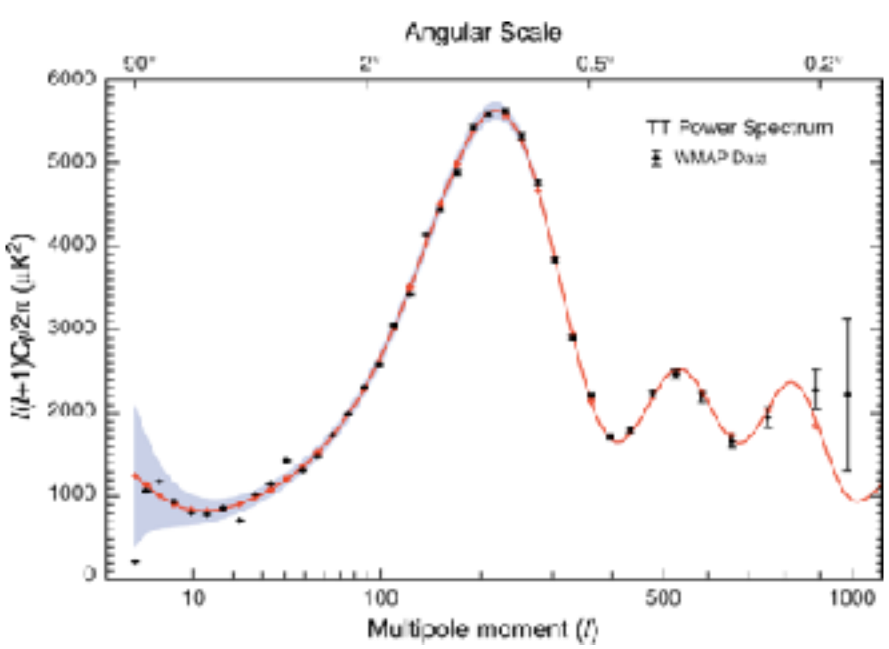


"Redshift space distortions" yield growth rate of structure

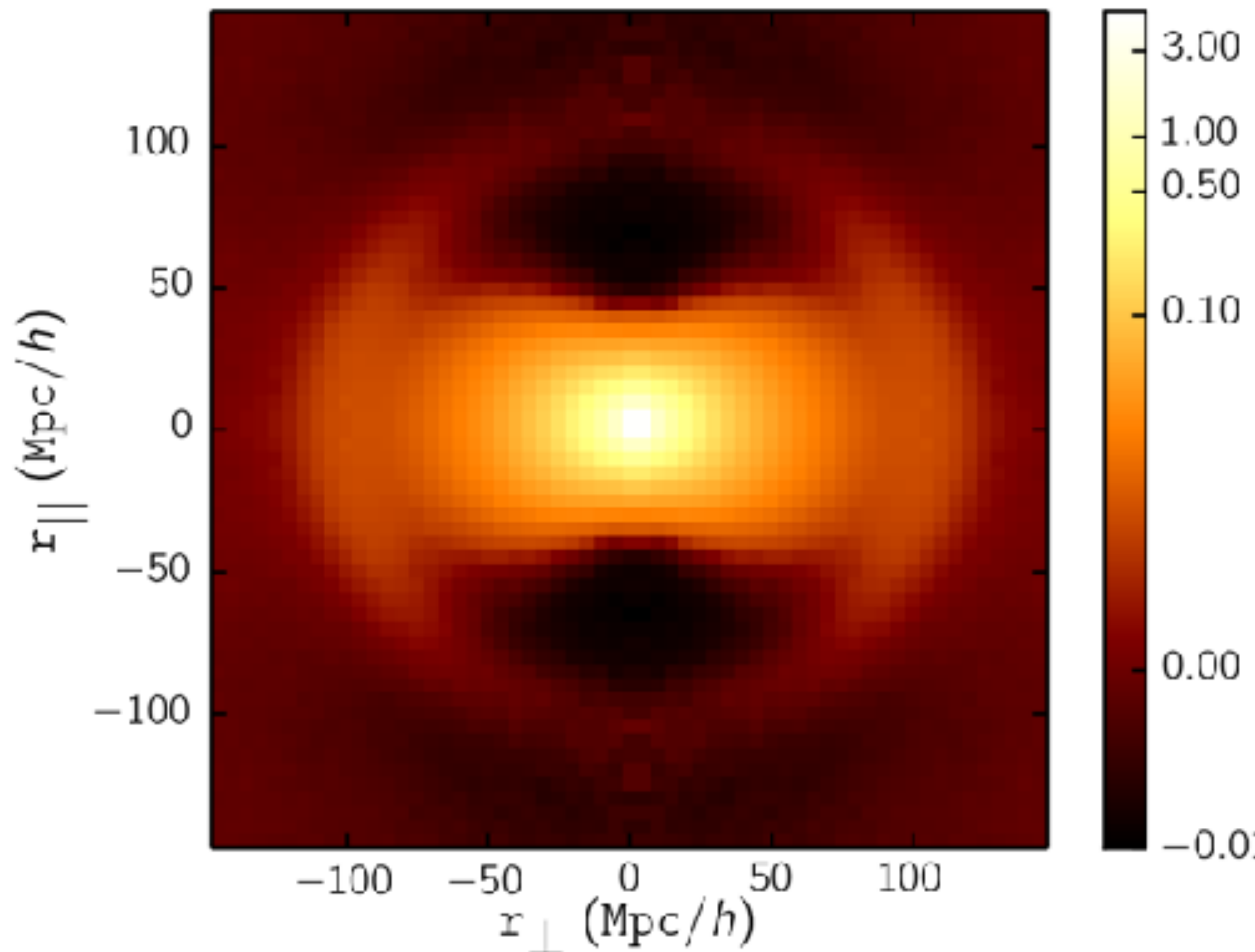
Baryon Acoustic Oscillation: *correlation function*

Physical scale of feature measured in CMB at z ~ 1100





Redshift scale of feature measured at z ~ 0 in large-scale structure



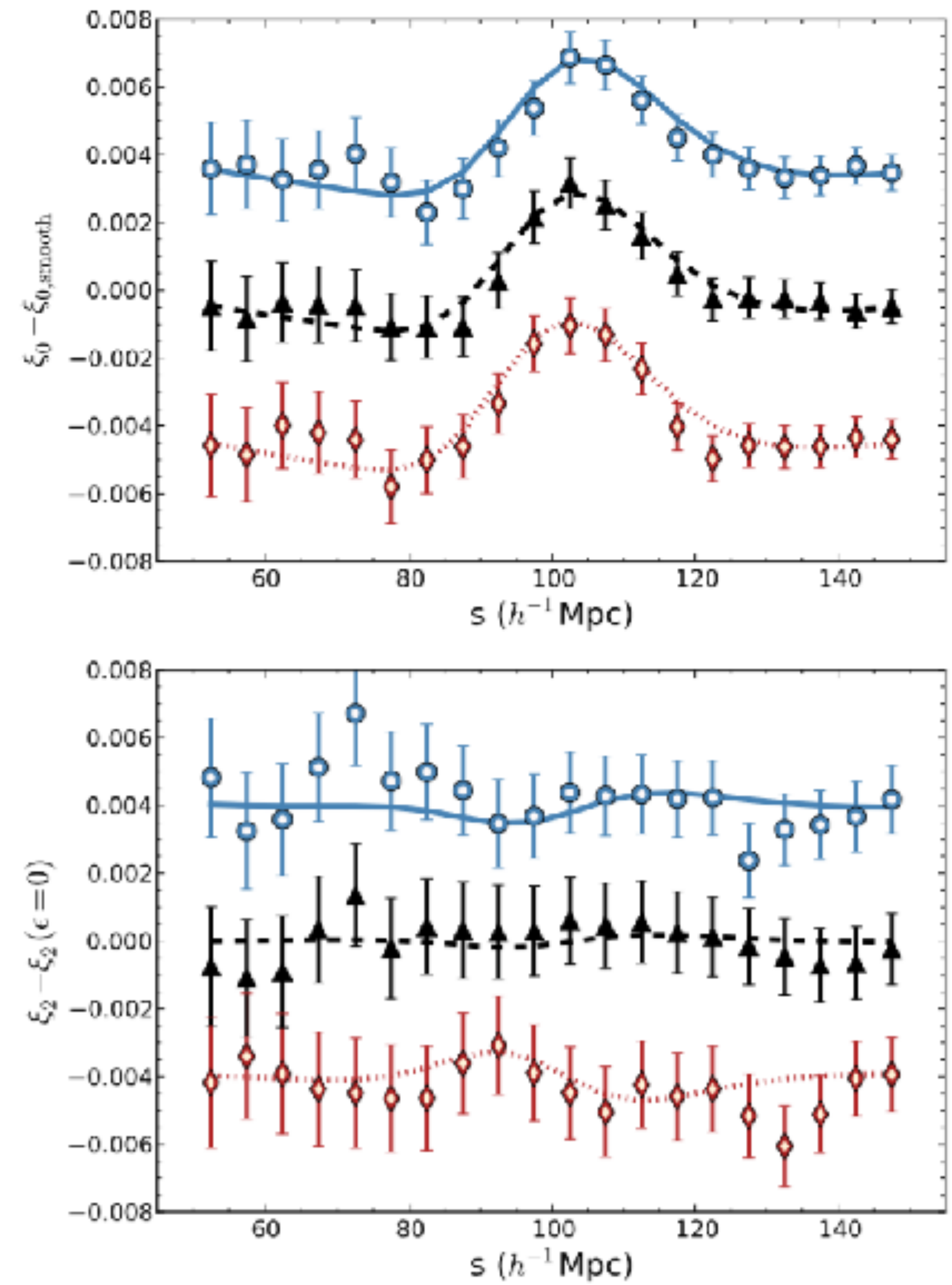
quantify line-of-sight vs. transverse using monopole and quadrupole

Final BOSS BAO measurements

correlation function

monopole

quadrupole



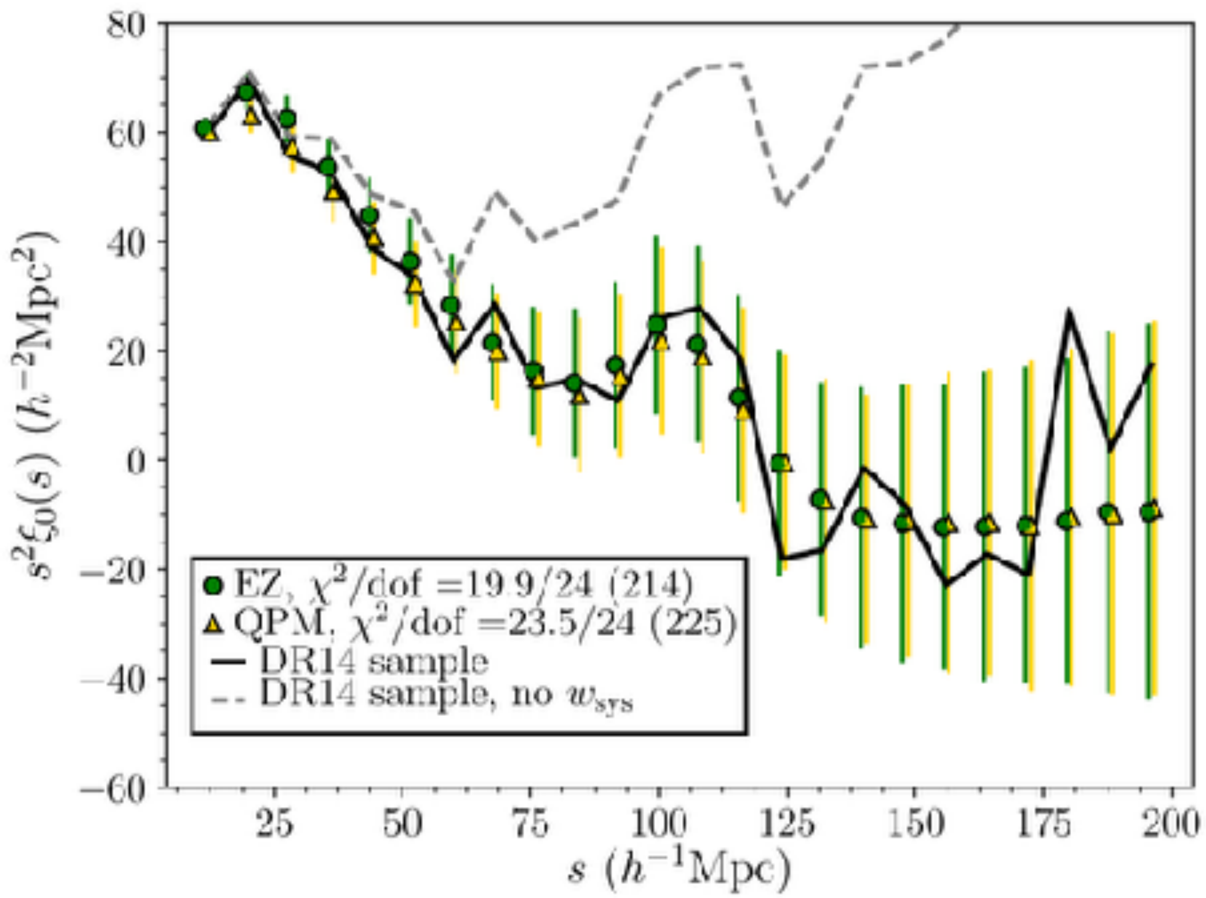
redshift separation (Mpc / h)

Alam et al. (2017); SDSS-III

eBOSS 2-year BAO measurements

quasar correlation function

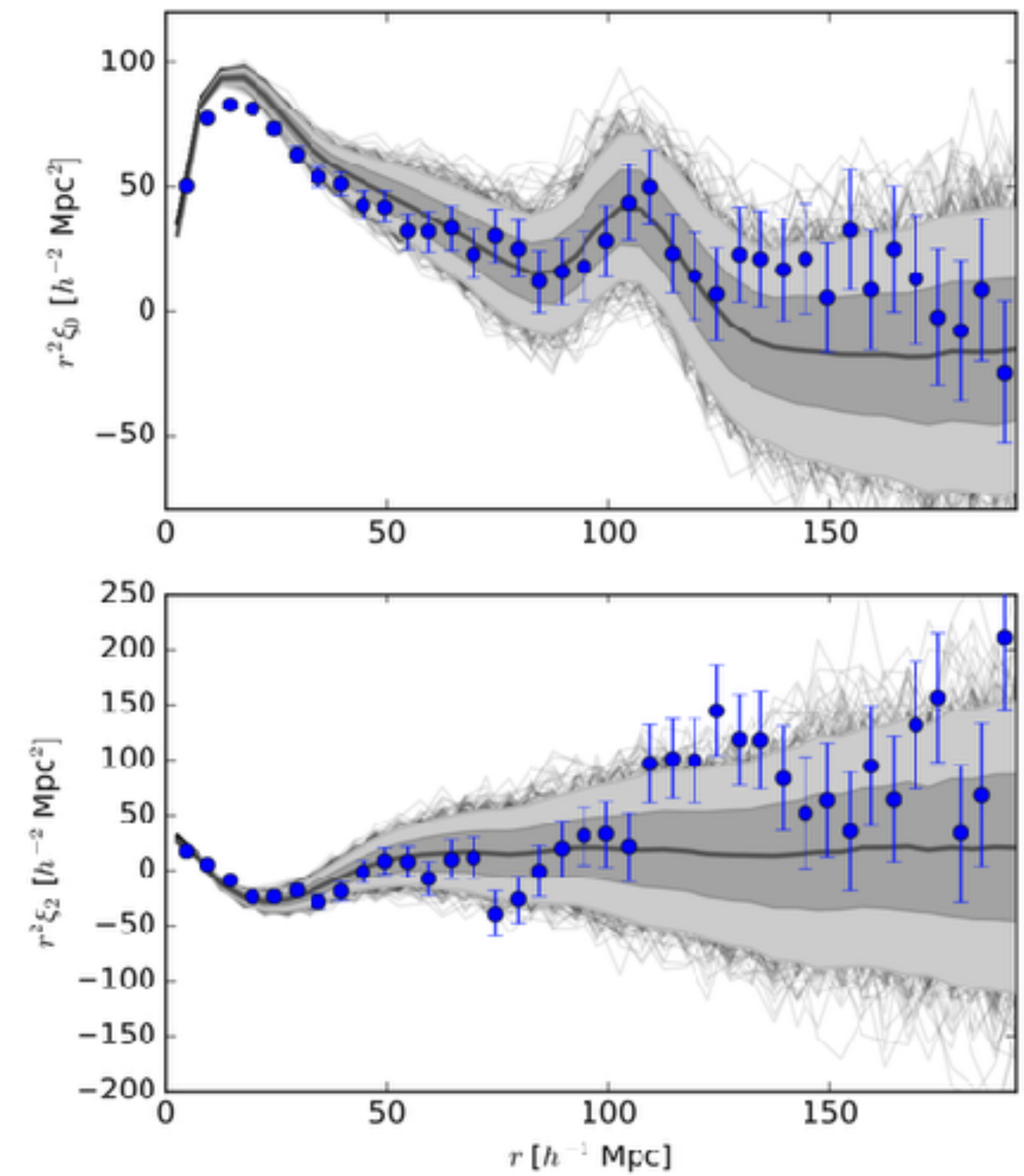
Ata et al. (2017); SDSS-IV



separation (Mpc / h)

luminous red galaxy correlation function

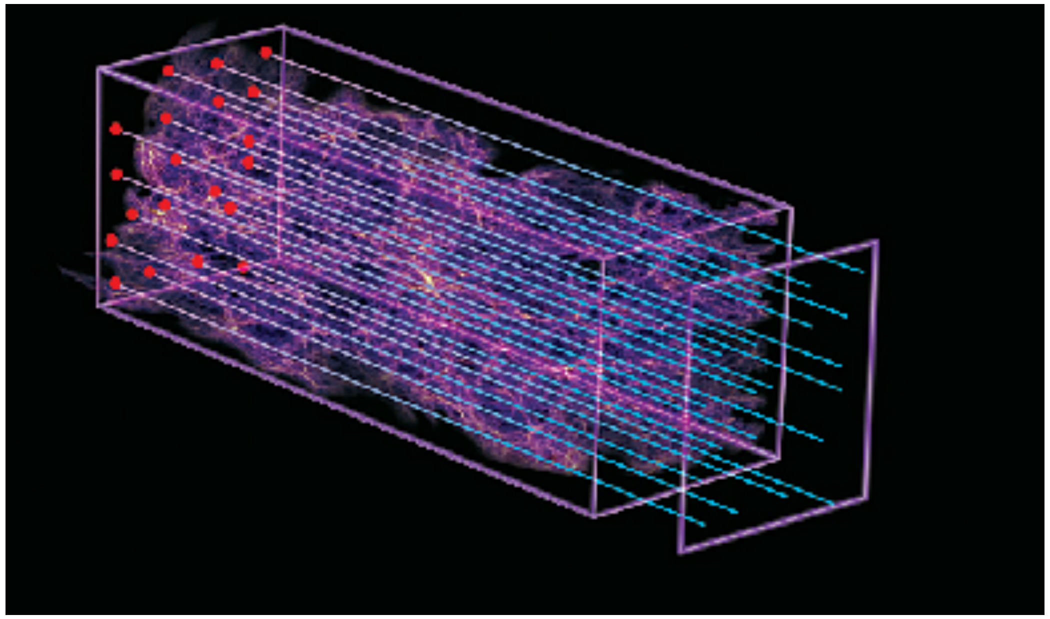
Bautista et al. (2018); SDSS-IV



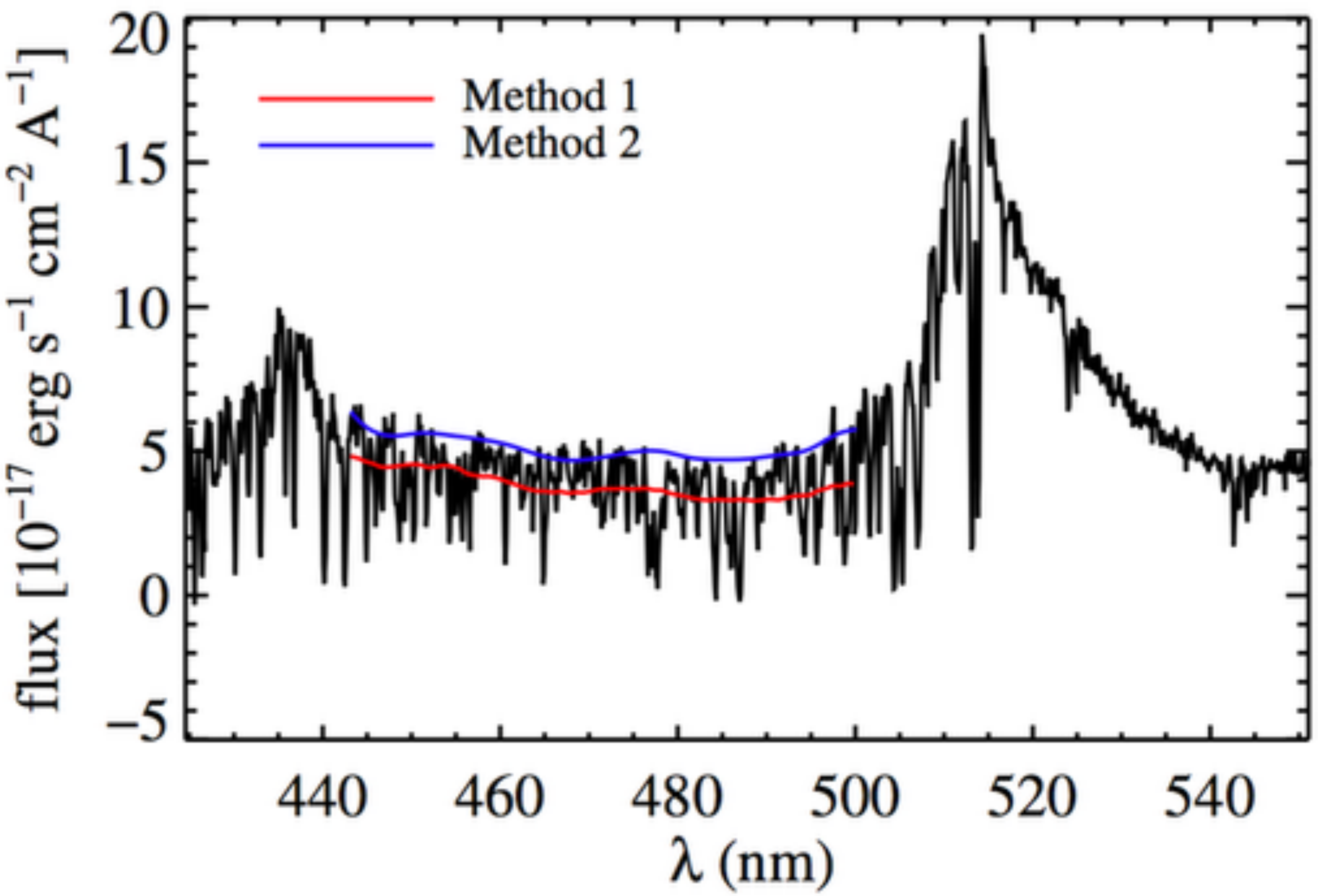
separation (Mpc / h)

after reconstruction

BOSS and eBOSS: *Lyman-alpha forest at z ~ 2.5*



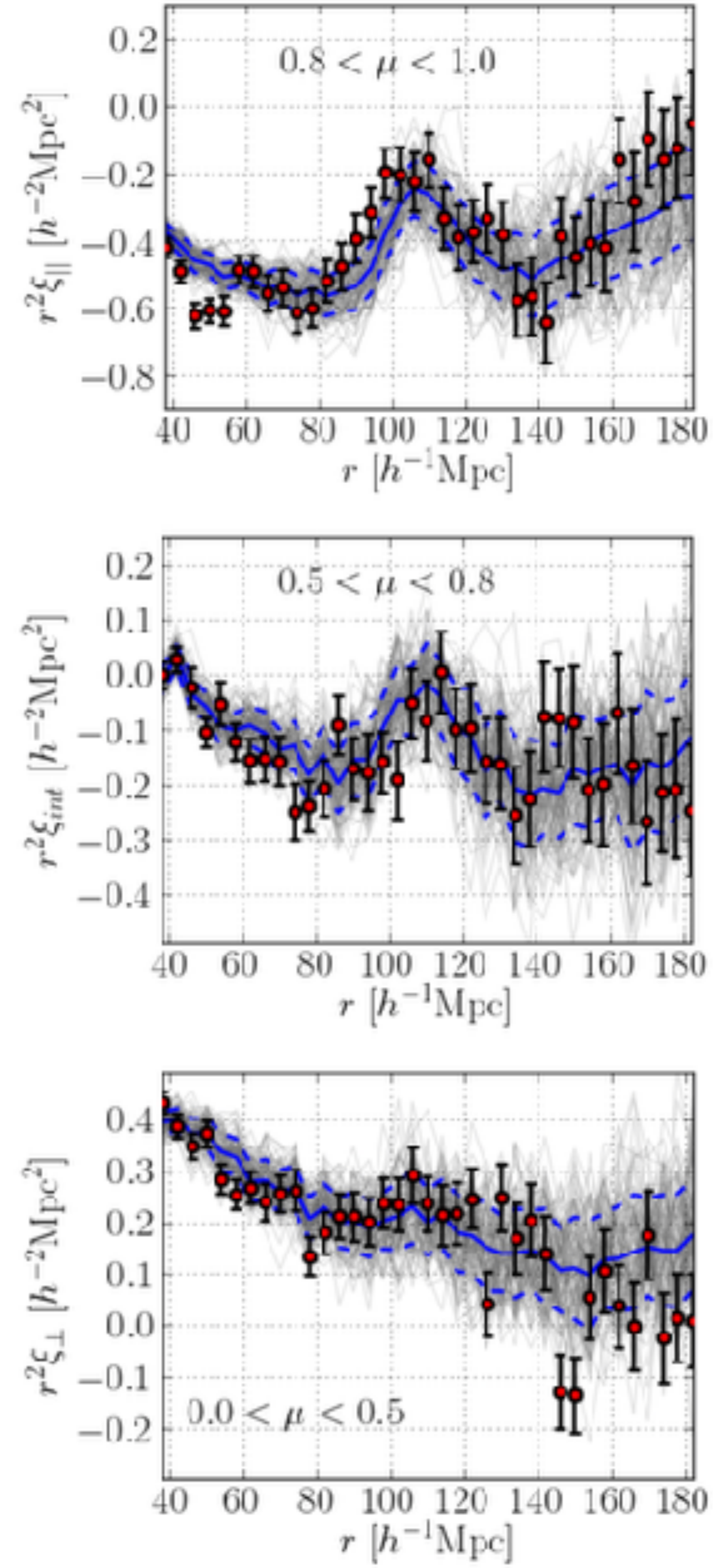
Busca et al. (2013); SDSS-III



line of sight

in between

transverse

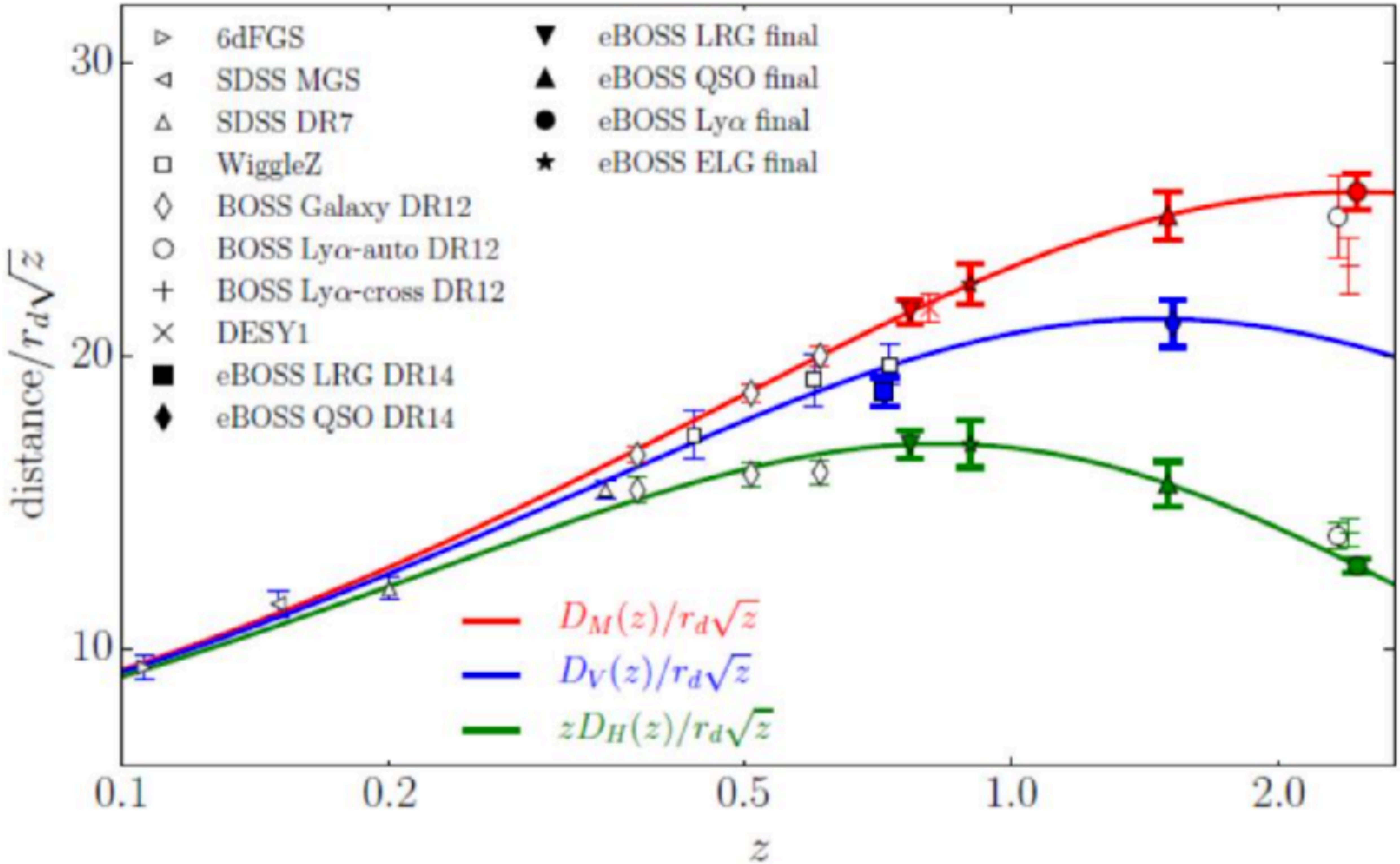


separation (Mpc / h)

Delubac et al. (2015)

BAO Hubble Diagram

slide from K. Dawson



BAO Hubble Diagram

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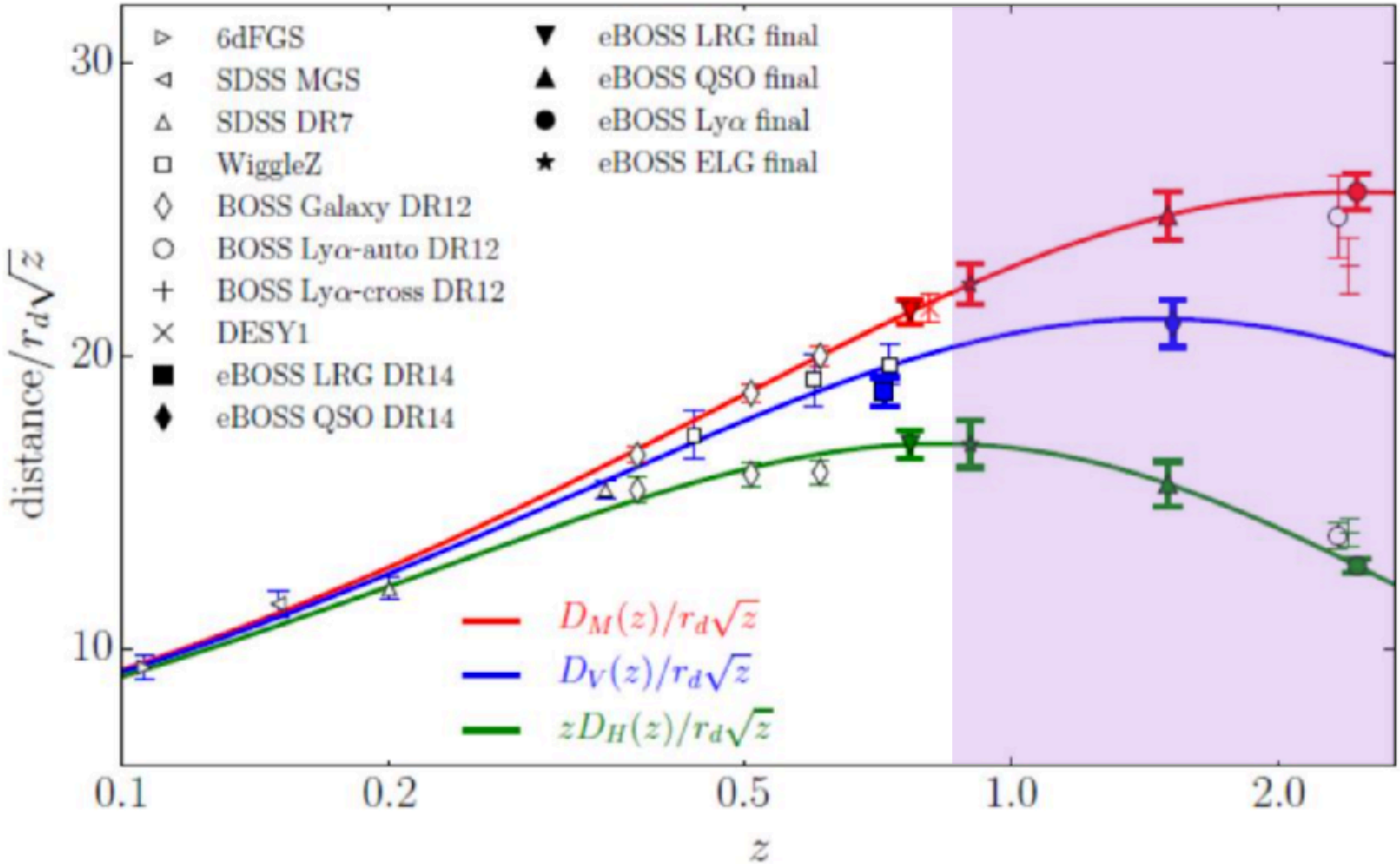
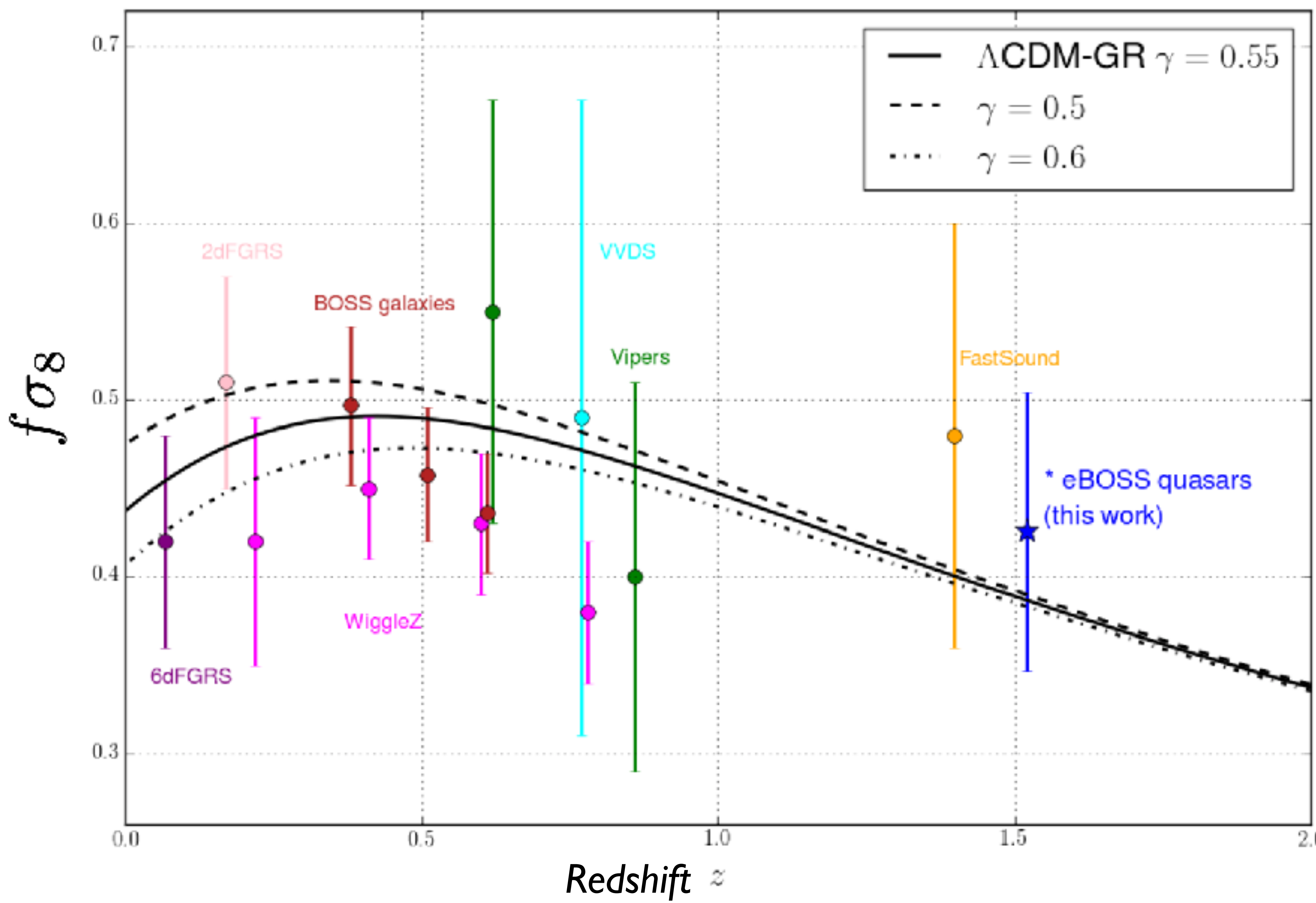


Growth of Structure

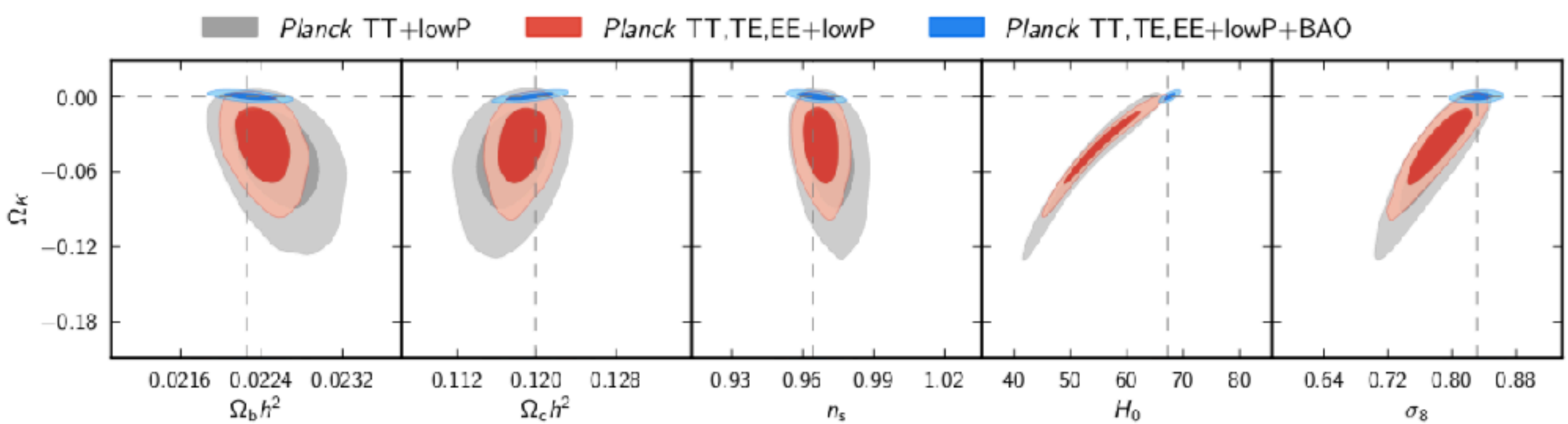
Zarrouk et al. (2018)



How LSS relates to: cosmic microwave background

- Cosmic Microwave Background constrains spectrum of fluctuations, the state of the universe at z ~ 1100, and integrals over redshift between z ~ 0 and z ~ 1100. *Very* tightly constrains "flat" universe models with a cosmological constant (with degeneracies with Hubble constant).

- LSS nails down Hubble Constant and curvature (and other extensions) of the "base" model.



How LSS relates to: Supernova Type Ia

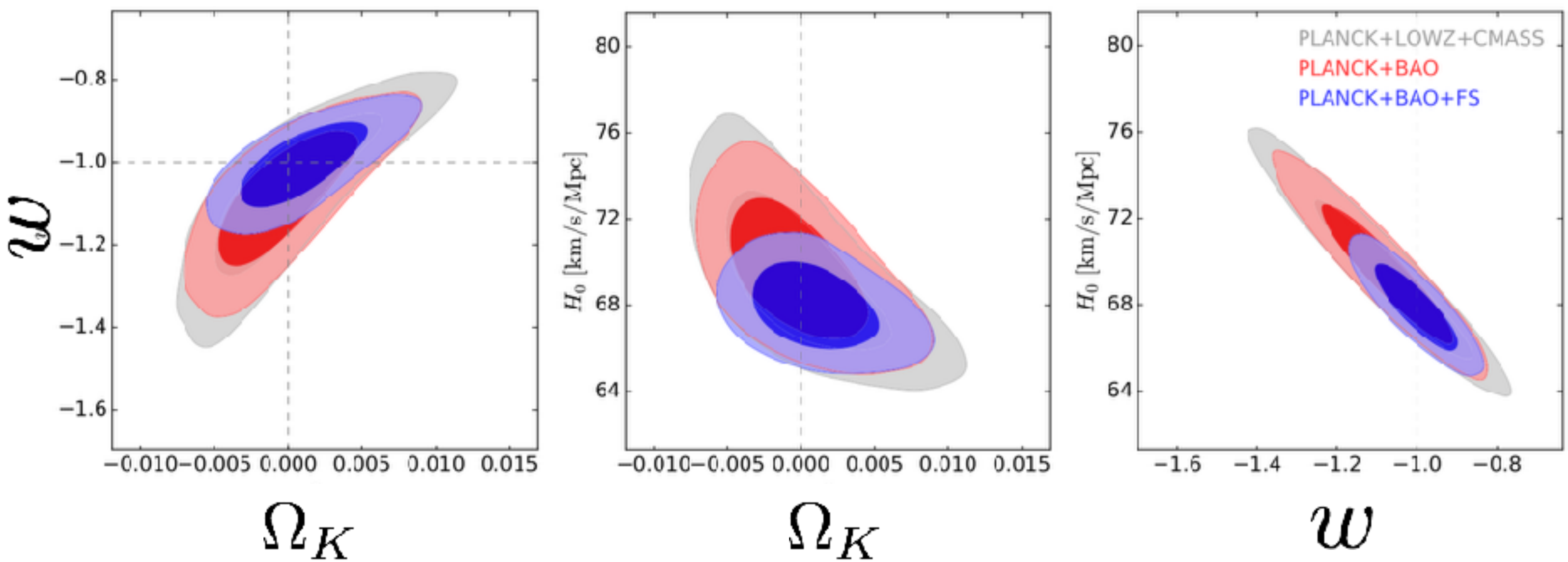
- SN Type Ia were used for discovery of dark energy in 1998.
- BAO and Supernovae Type Ia both measure distance vs. redshift
  - *BAO precision is limited by volume of Universe, SN Type Ia limited only by telescope resources.*
  - *BAO accuracy theoretically very high (~ 0.5%), SN Type Ia needs extensive astrophysical calibration, leading to systematic uncertainties.*

How LSS relates to: Weak Lensing

- Weak gravitational lensing is used by Dark Energy Survey to map dark matter *directly* by measuring its lensing effect on background sources.
- Redshift space distortions and weak lensing both measure the growth of structure.
  - *With current experiments they are of comparable precision.*
  - *Redshift space distortions require somewhat more astrophysical calibration to use all of the information available.*
  - *Comparison of weak lensing and redshift space distortions yields test of general relativity.*

Constraints from large-scale structure: *parameters*

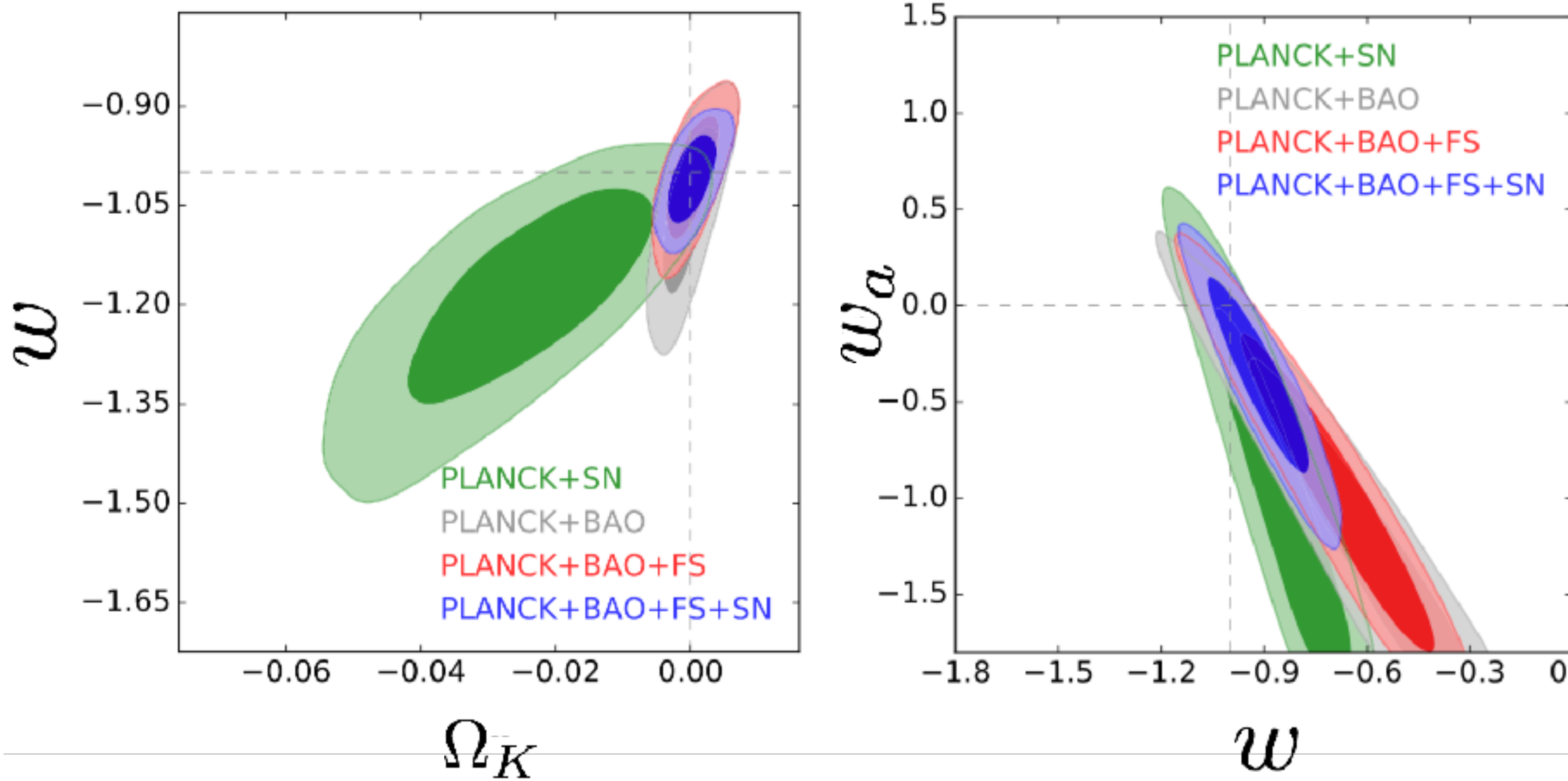
Alam et al. (2017)



(non-flat, w not -1) model returns standard cosmology

Constraints from large-scale structure: *parameters*

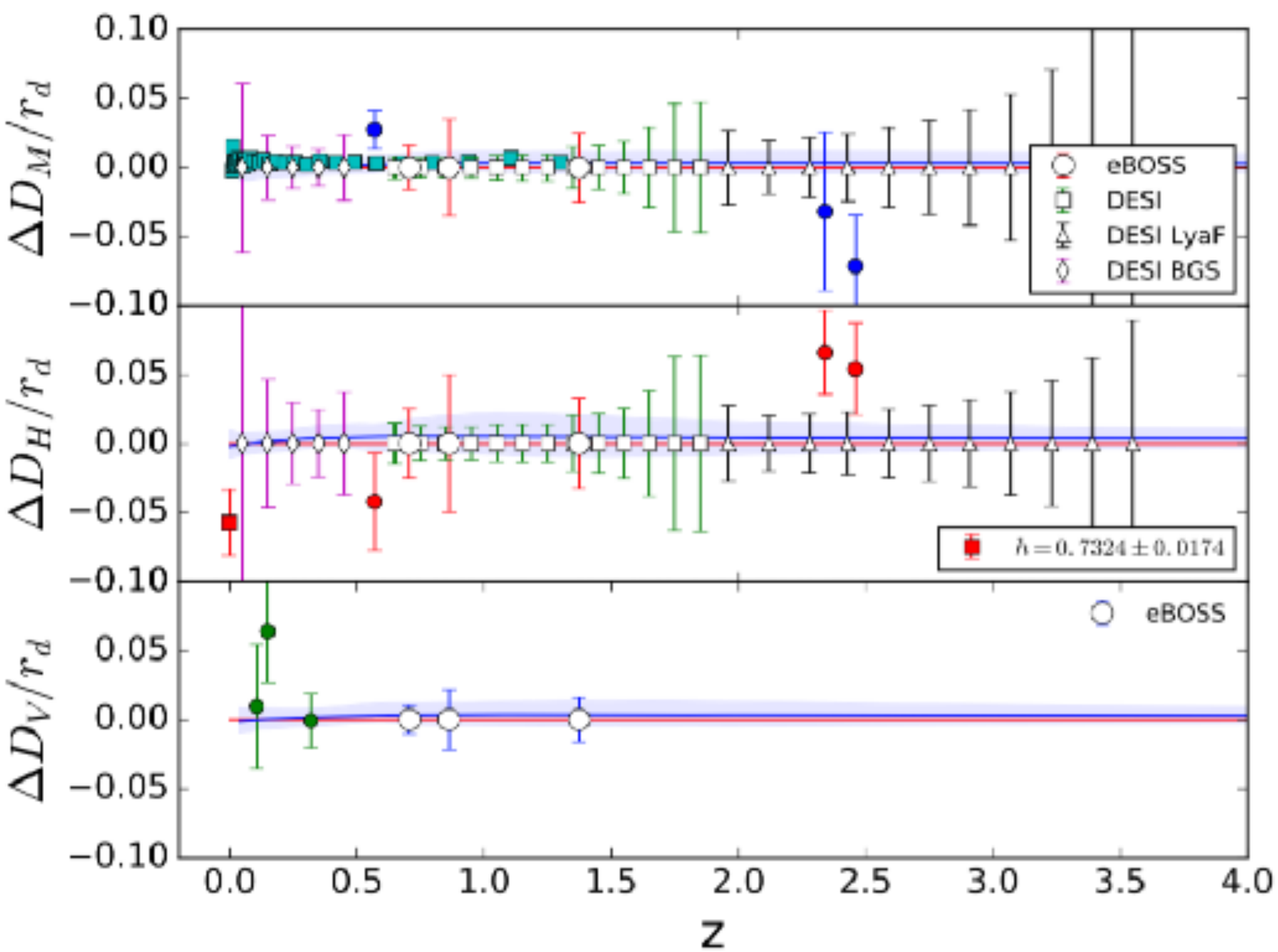
Alam et al. (2017)



non-flat, varying equation of state model also favors simplicity

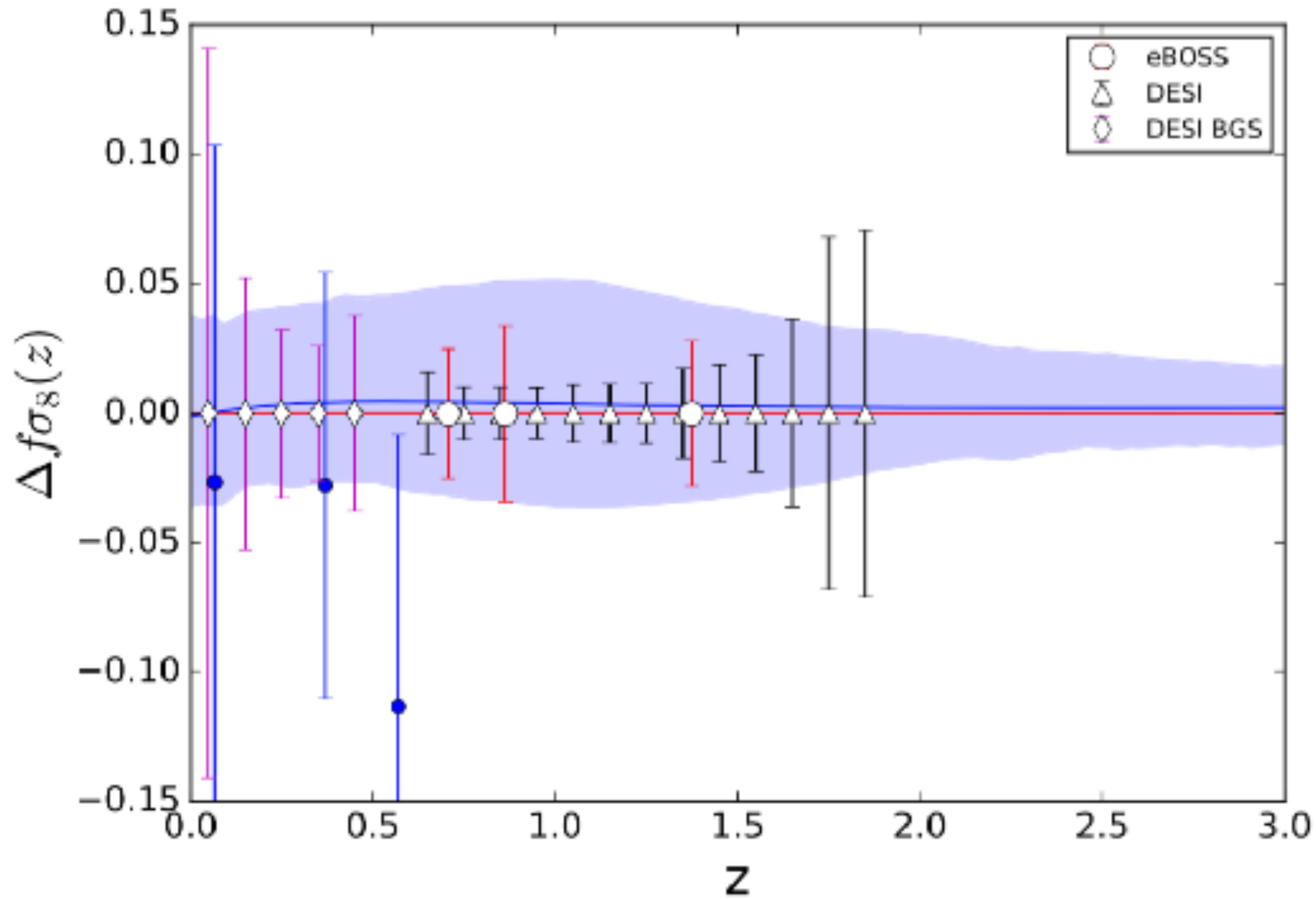
Constraints from large-scale structure: *is the model right?*

expansion



Redshift

growth of structure



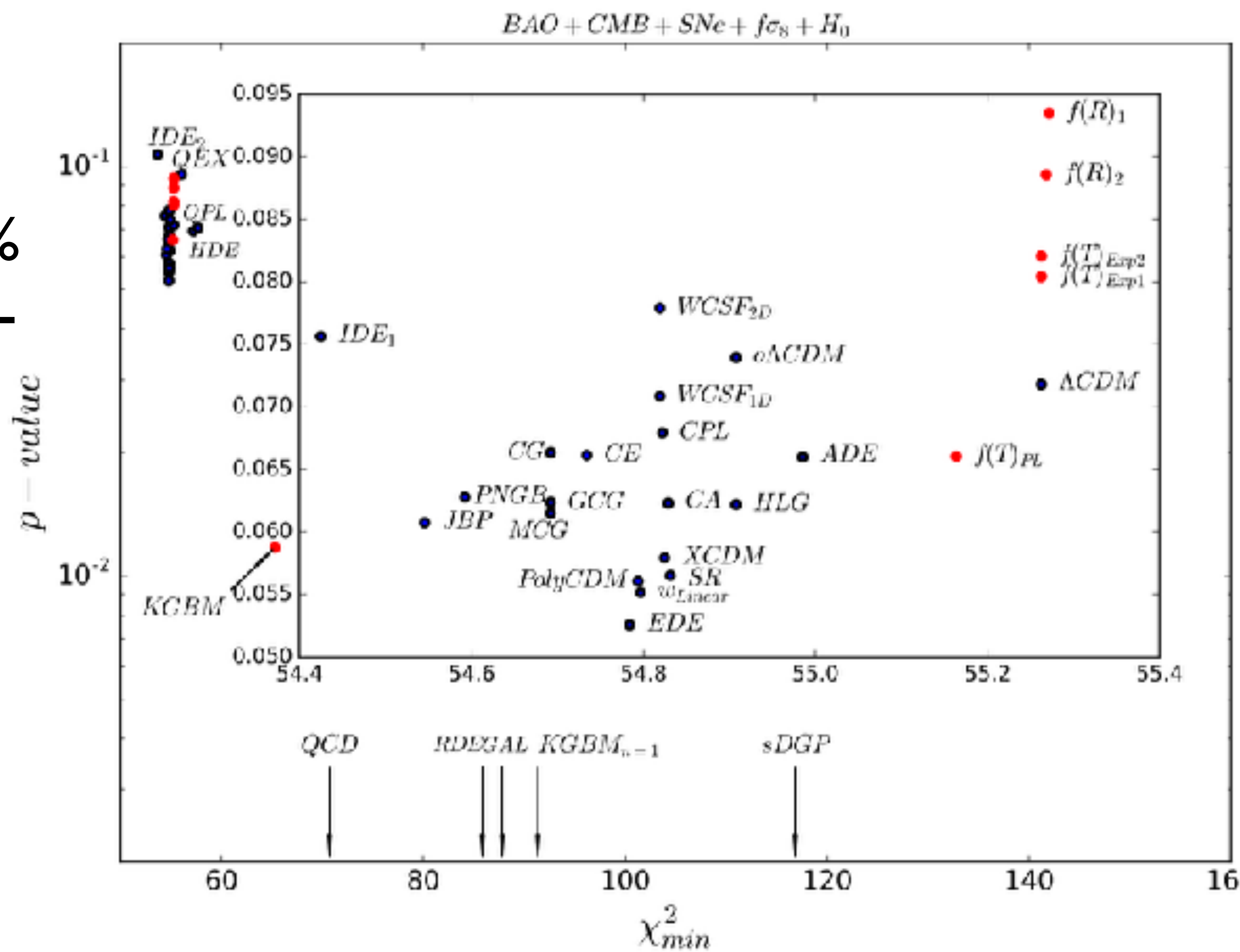
Redshift

w_0-w_a parametrization of dark energy equation of state

Zhai, Blanton, Tinker, Slosar (2017)

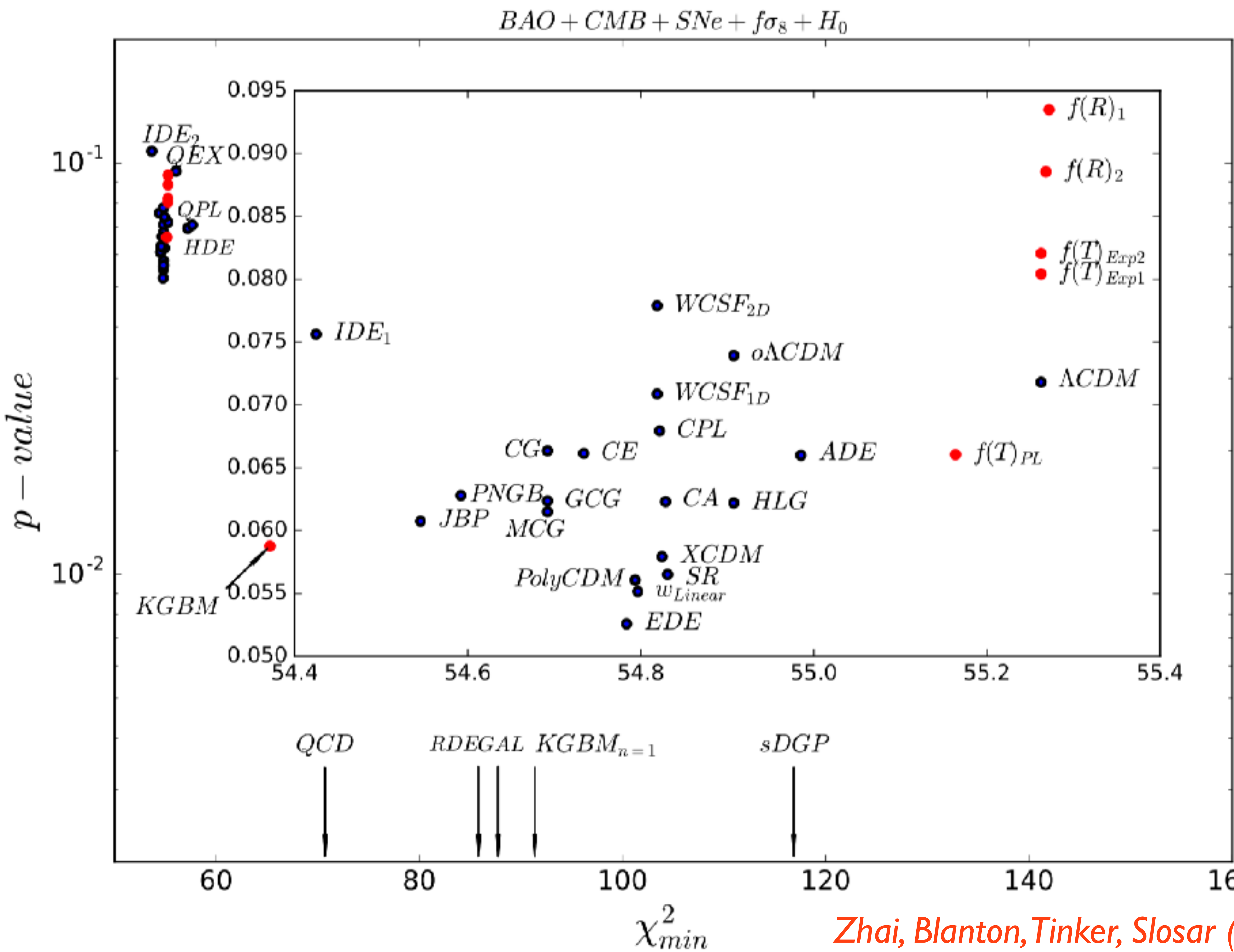
Constraints from large-scale structure: *is the model right?*

- For a standard LCDM cosmology, BAO+CMB+SNe+H0 is a 5-10% outlier from expectations in chi-squared, *globally.*
- No physical model does much better, and phenomenological models have to be very tuned.
- But H_0 is pretty far off *locally,* with local measurements 3-sigma high relative to BAO+CMB inference.



Zhai, Blanton, Tinker, Slosar (2017)

t?



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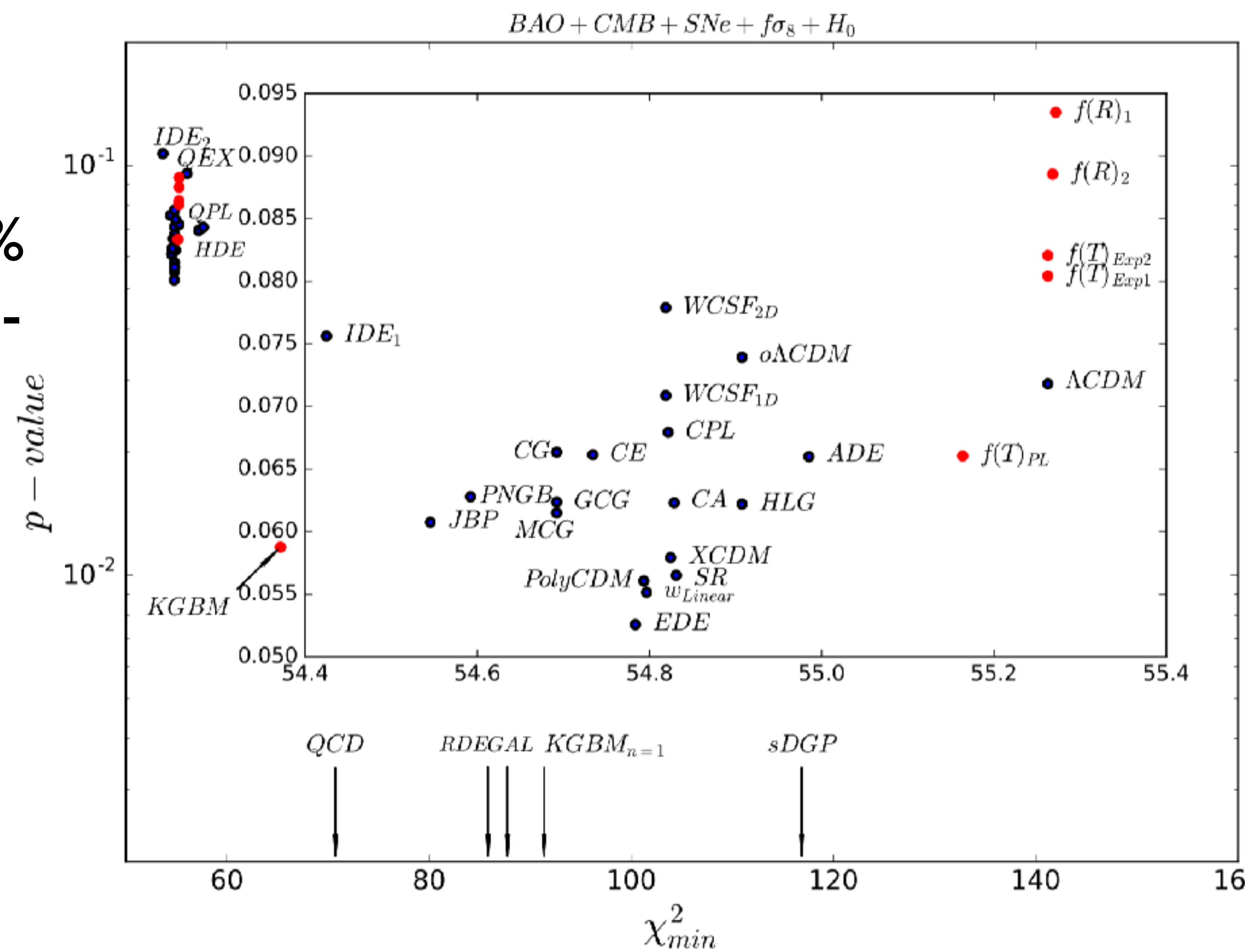

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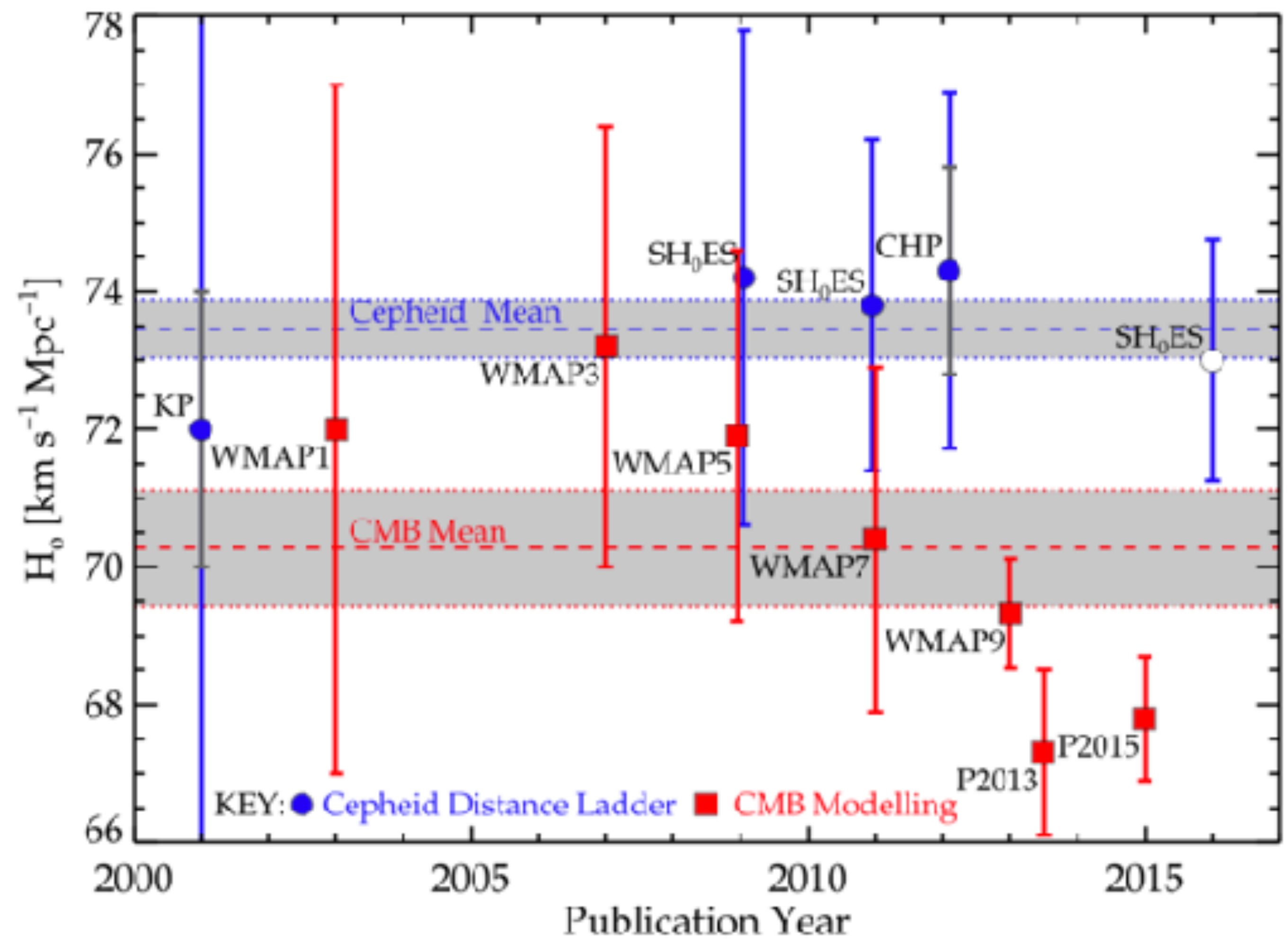
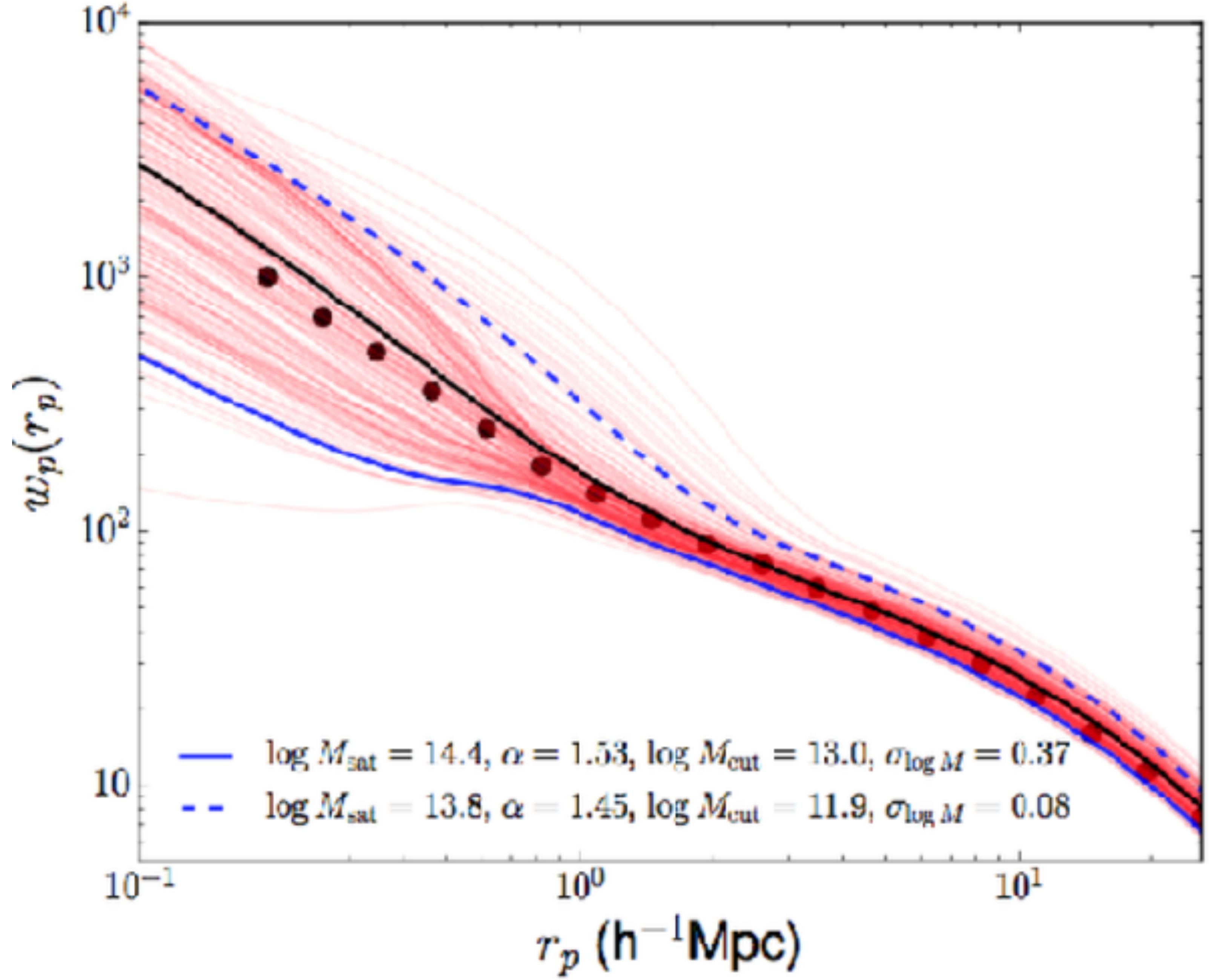


Beaton et al. (2016)

Beyond the basics: *pushing to small scales*

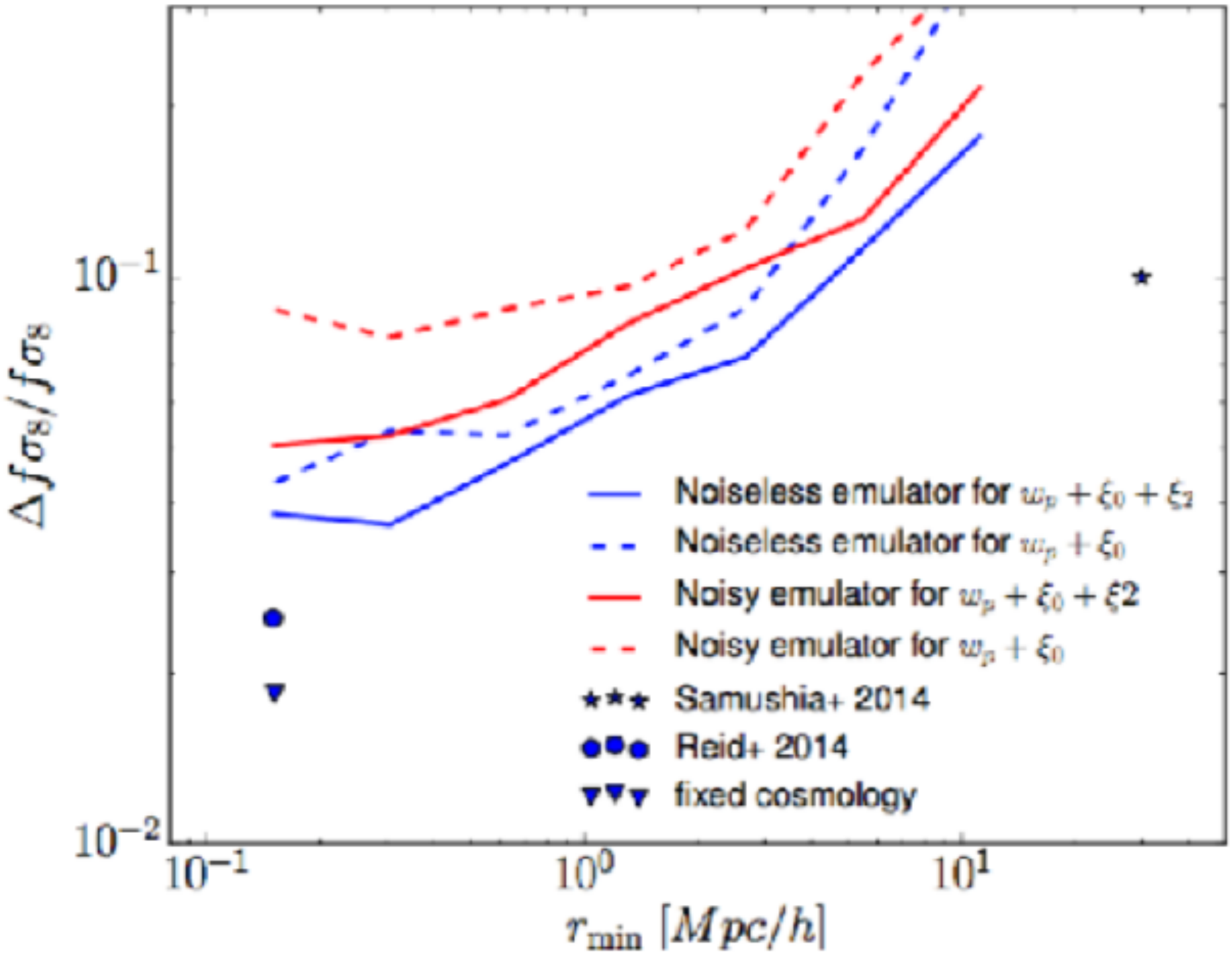
- Statistical power in many LSS samples is mostly on scales of around a Mpc: nonlinear scales in gravity and galaxy bias.
- Need efficient methods to predict based on cosmology and galaxy formation.
- One approach is emulation: train a Gaussian process on a range of cosmology and halo model parameters, and optimize on the Gaussian process predictions.



Zhongxu Zhai, Jeremy Tinker, Risa Wechsler, Eduardo Rozo, Joe DeRose, Sean McLaughlin, Tom McClintock; the Aemulus Project

Beyond the basics: *pushing to small scales*

- For example, using monopole and quadrupole predictions, make growth of structure measurements using scales less than a Mpc.
- Factor of several increase in precision.

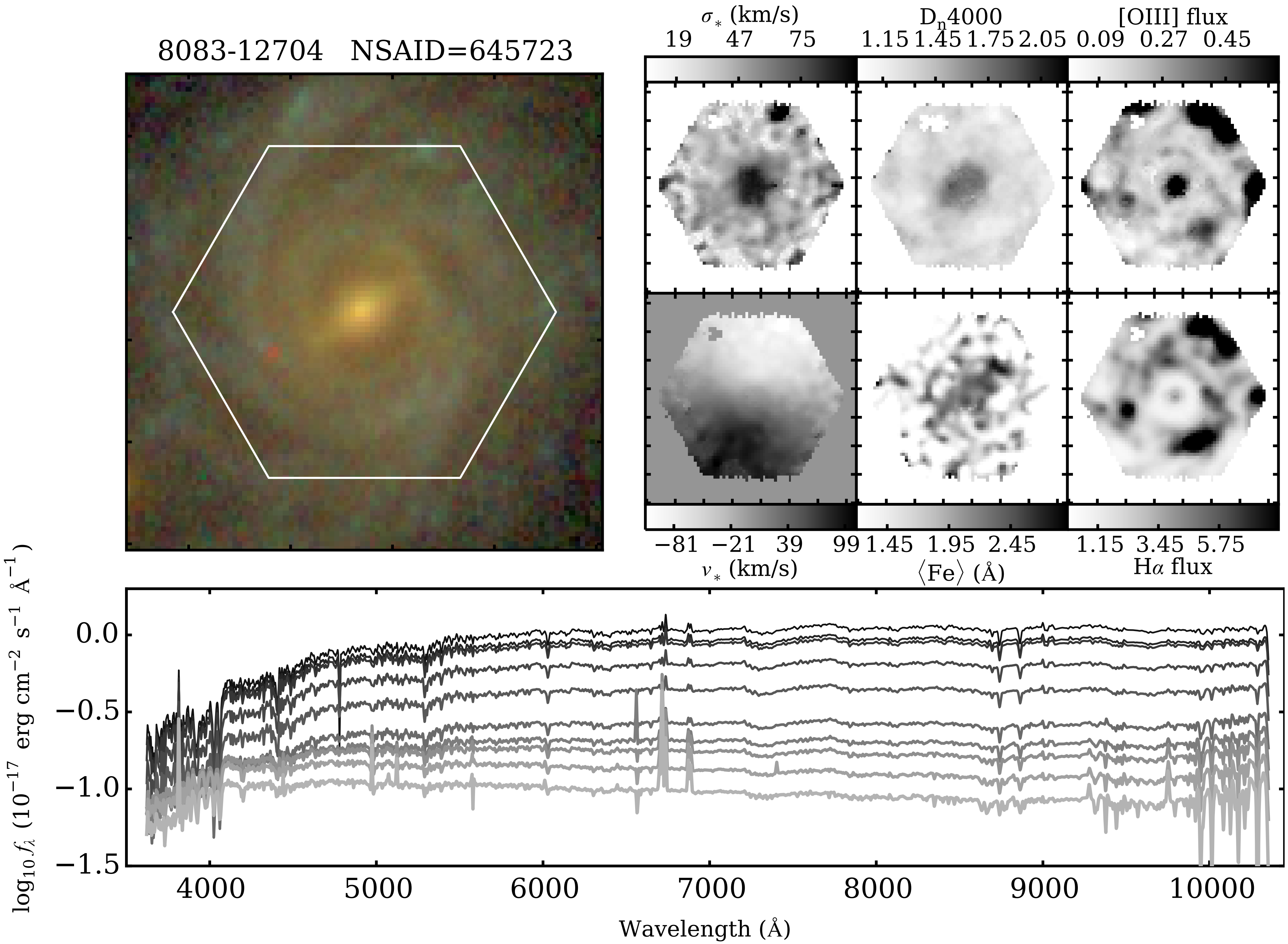


Zhongxu Zhai, Jeremy Tinker, Risa Wechsler, Eduardo Rozo, Joe DeRose, Sean McLaughlin, Tom McClintock; the Aemulus Project

Summary of large scale structure

- Large-scale structure supplies an *absolute scale* for the low redshift Hubble parameter, based on the CMB.
- Constrains variations from flat cosmology arising from late time phenomena — dark energy, etc.
- Measures growth of structure, providing another constraint on extensions.
- **Flat cosmology holds.**
- **Hubble constant is problem, maybe within almost any model).**
- … next phase of LSS experiments requires bigger telescopes. eBOSS ends in February 2019. Dark Energy Science Instrument (DESI) planned to come on-line late 2019.

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



data like this for 10,000 galaxies in a statistically well-understood sample

note that age gradient in stellar population also noticeable for this galaxy …

see Drory et al., Bundy et al., Law et al., Yan et al., Belfiore et al., Wilkinson et al., Li et al., etc.

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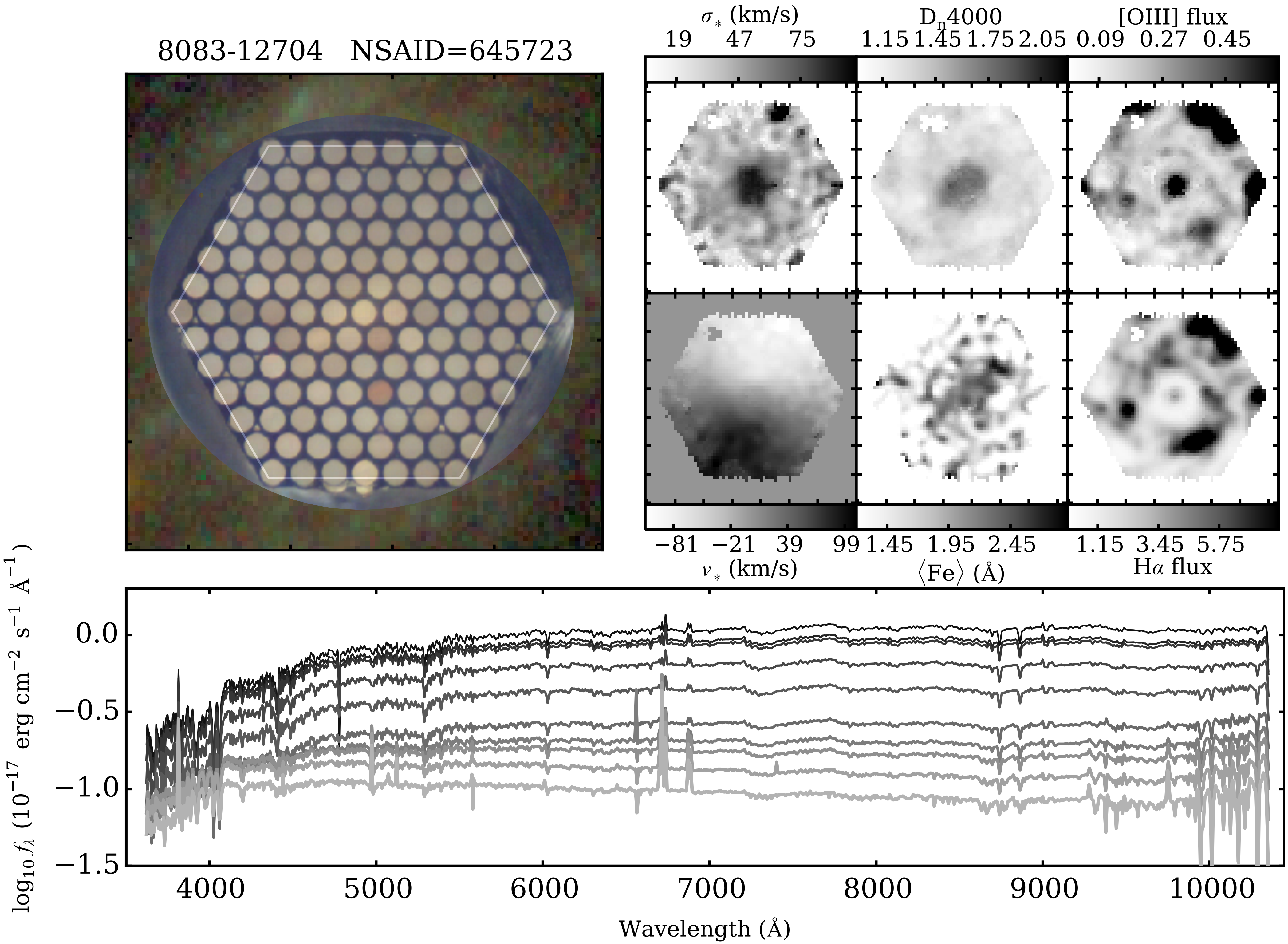

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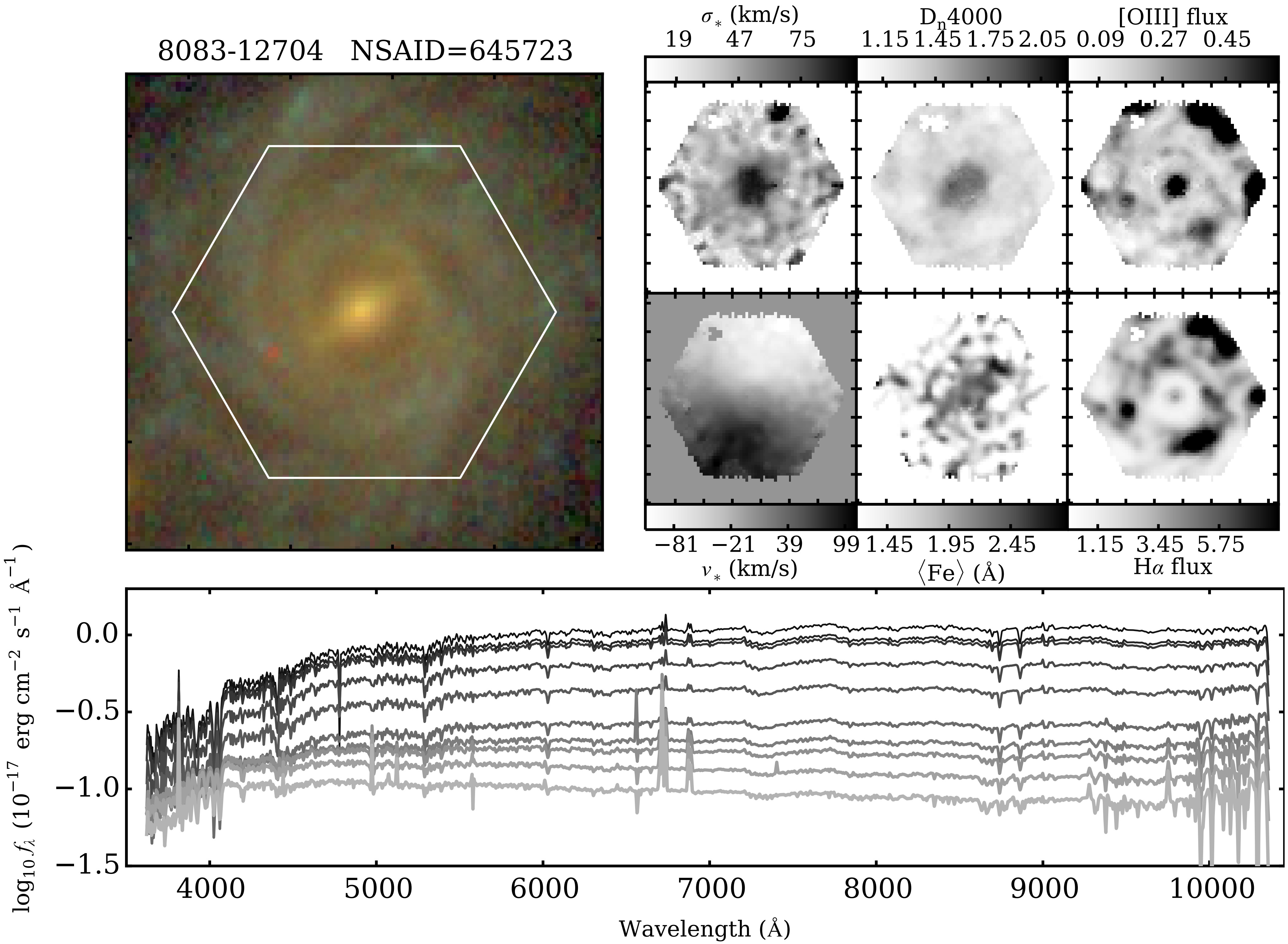

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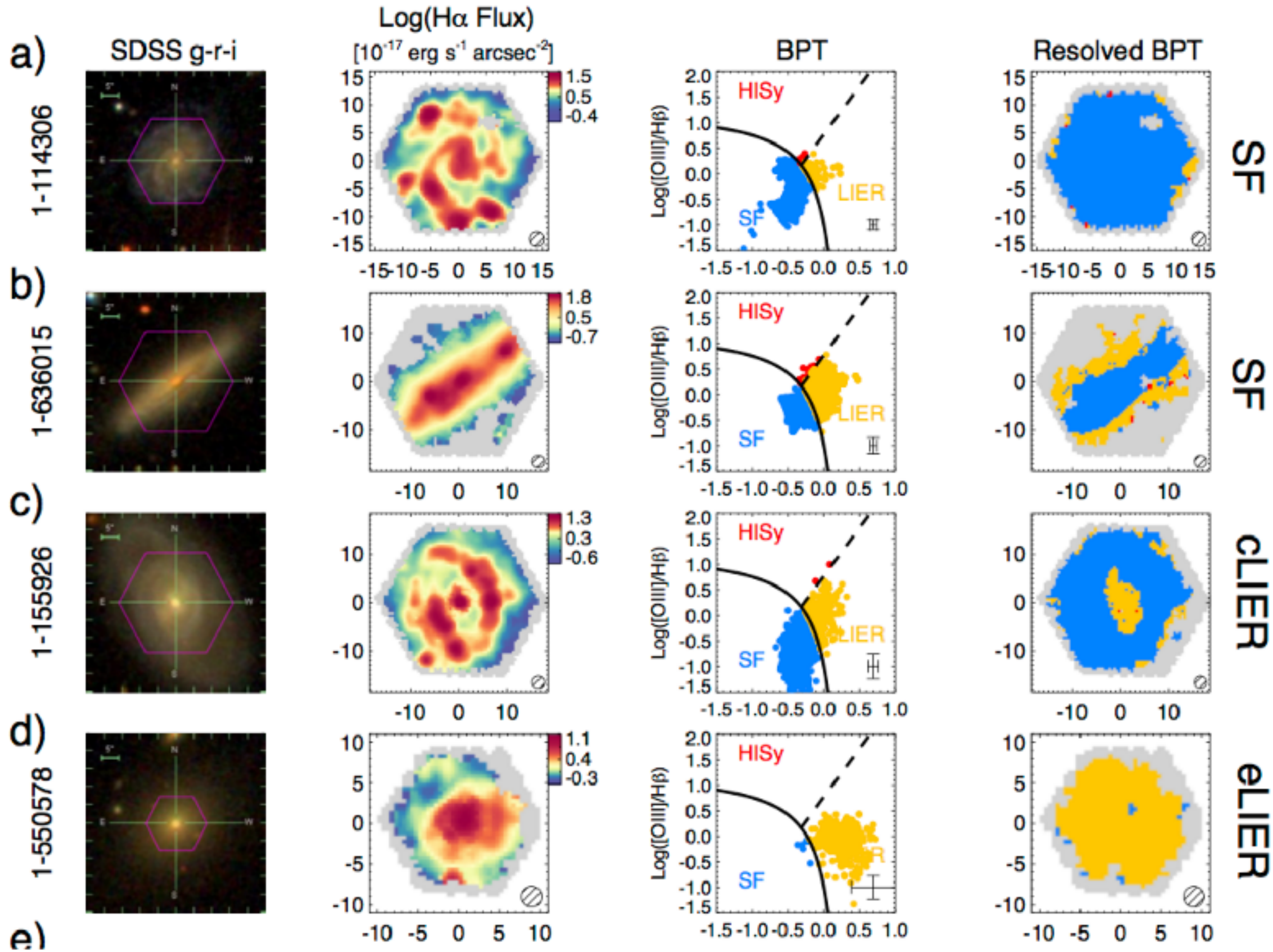
Line emission in galaxies

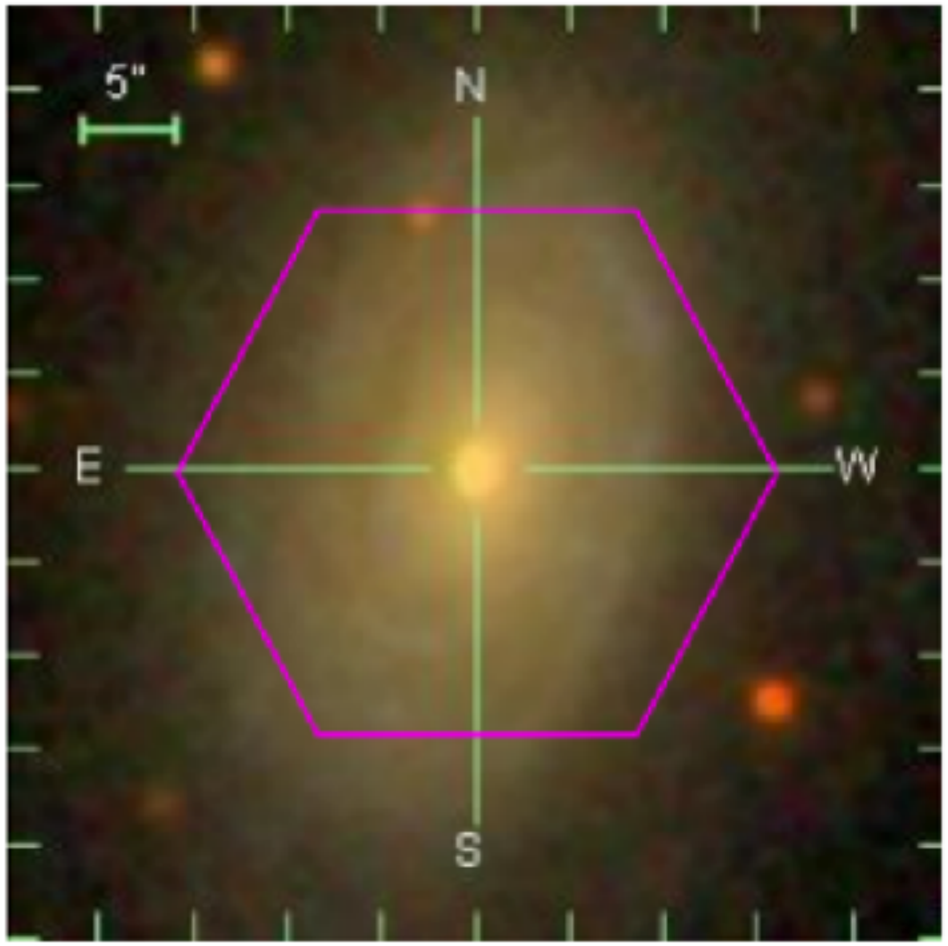


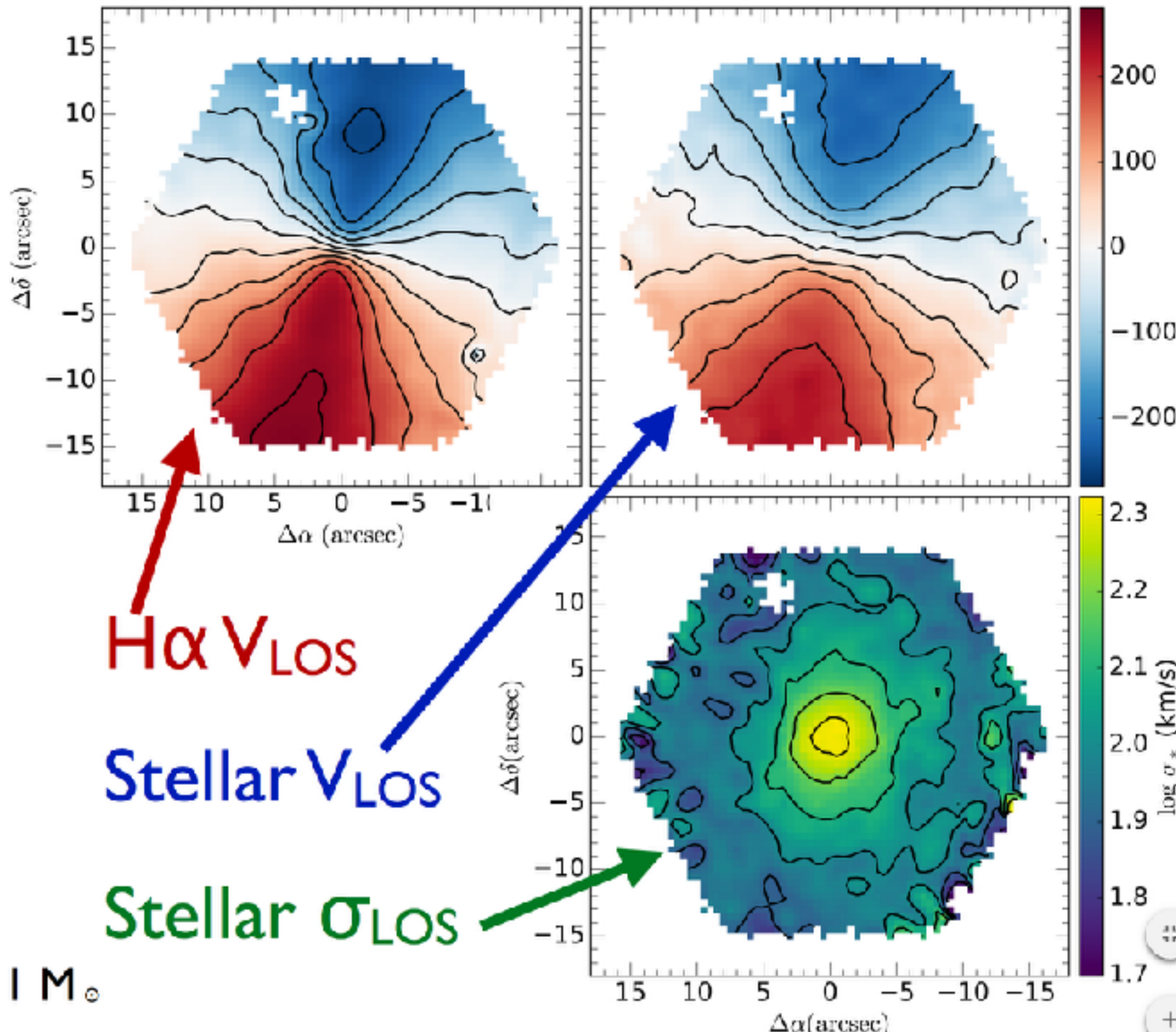
star-forming

non-star-forming

Belfiore et al. (2016) provides a comprehensive view of this, again supporting the evolved star hypothesis.

Example: gas and stellar dynamics



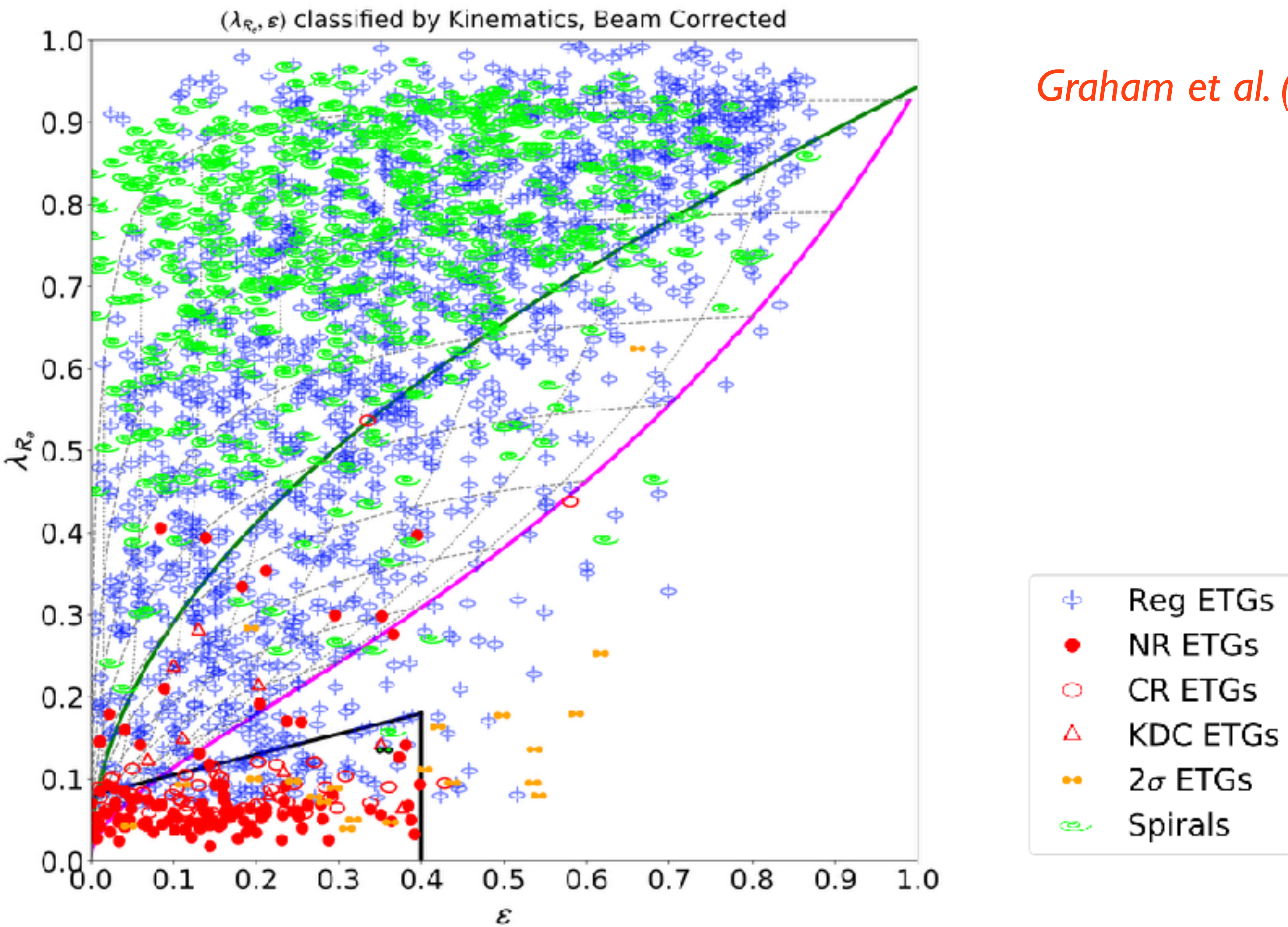


MaNGA ID: 1−339041

M_i = -22.6
NUV-r = 4.0
g-i =1.2
z = 0.031
$M_{*,NSA}$ = 1.0e11 $M_\odot$

Westfall et al. in prep

Example: angular momentum



specific angular momentum

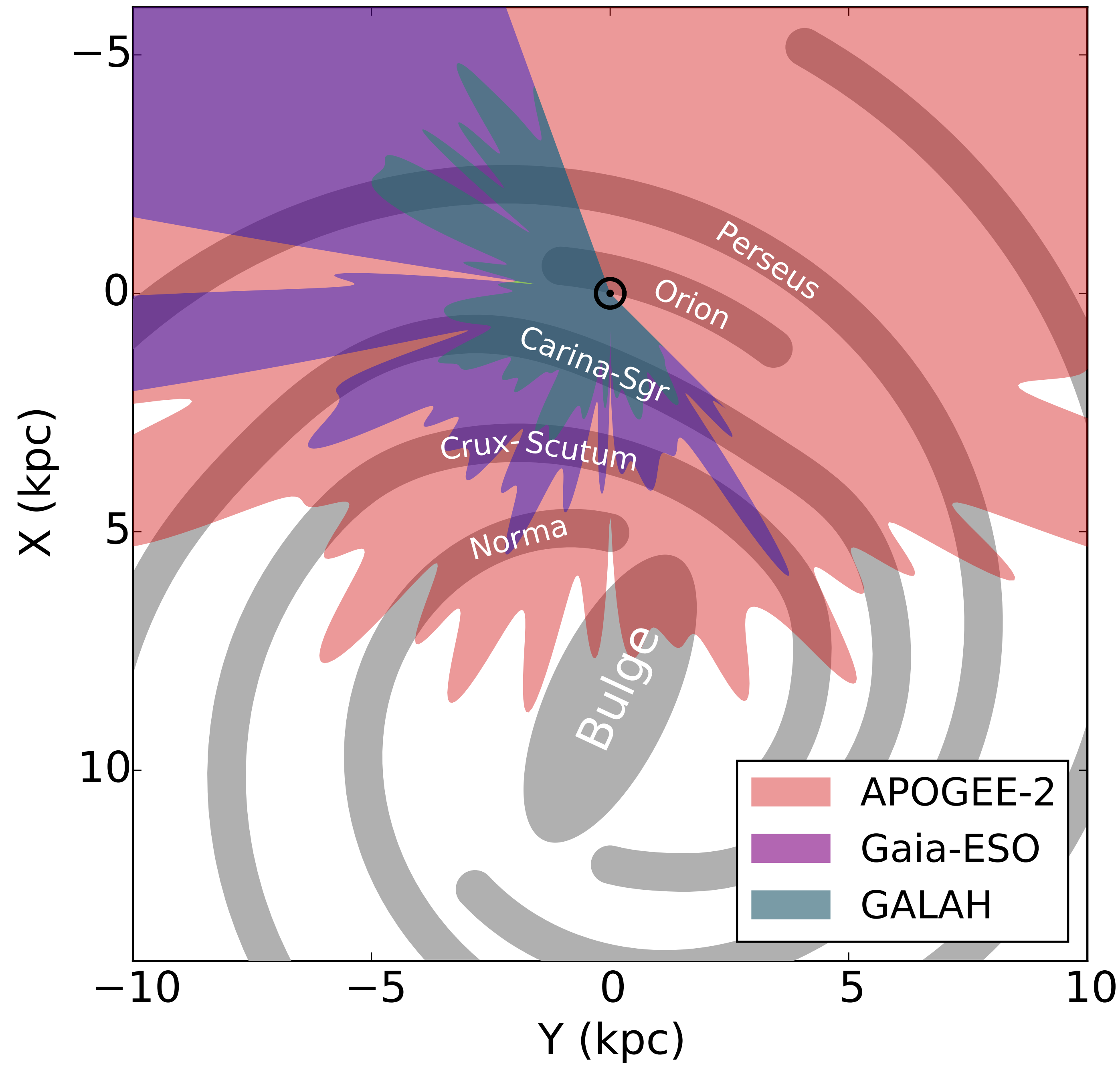
ellipticity of galaxy

Graham et al. (2018)

APOGEE-2: *mapping the Milky Way*

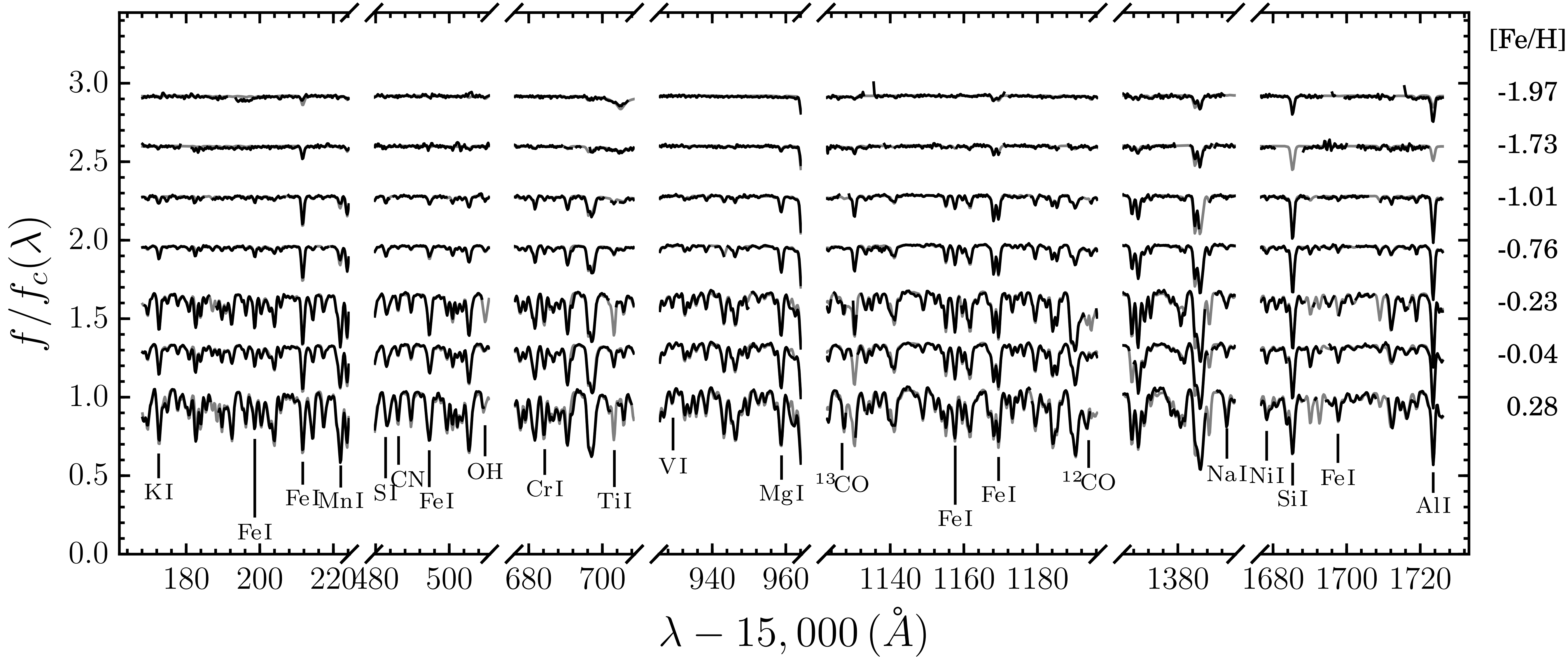
(S. Majewski, PI)

- Spectroscopy of Milky Way stars at high resolution and signal-to-noise.
- Explores *all* regions of the Milky Way in detail.
- Velocities, 15-20 element abundances, stellar parameters.
- Synergy with *Gaia, Kepler, TESS*, …



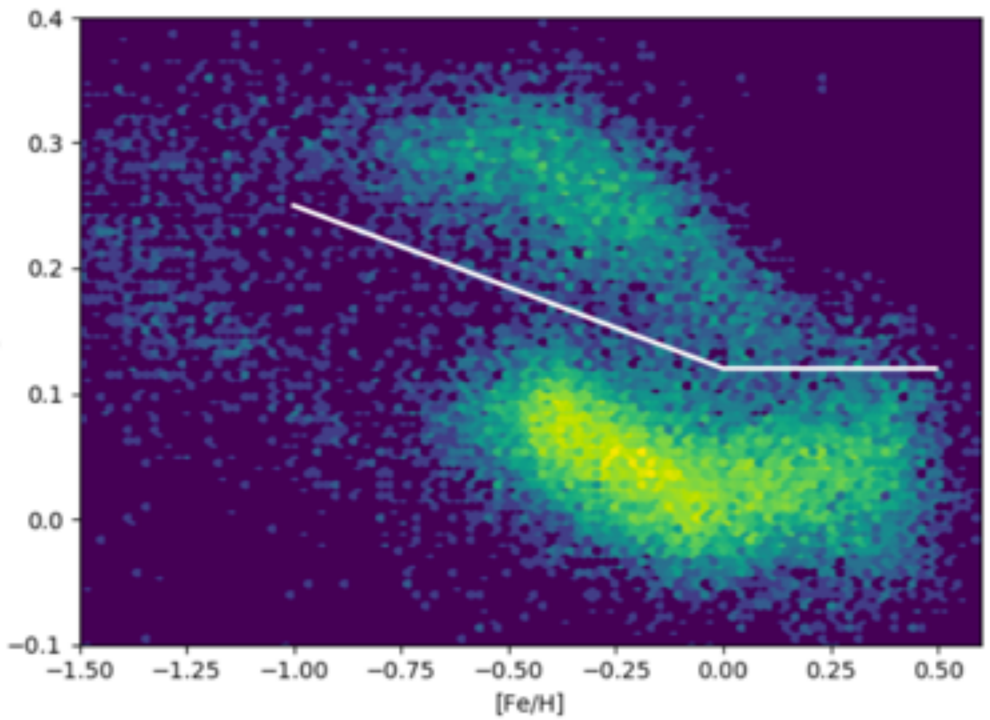
estimates from Jon Bird for ~ 2 solar mass TRGB star

Mapping the Milky Way: *APOGEE measures stars precisely*



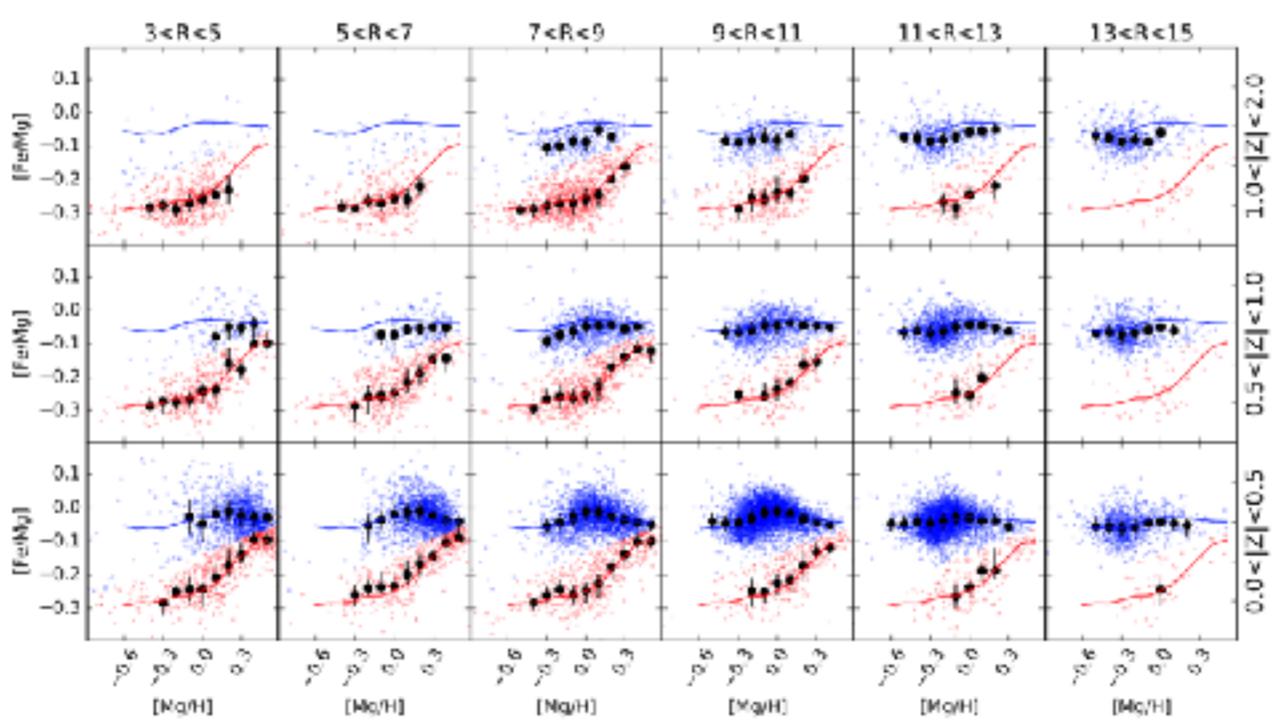
15 - 20 precisely measured abundances
(including C, N, O, and many others)

Mapping the Milky Way: *APOGEE measures stars precisely*

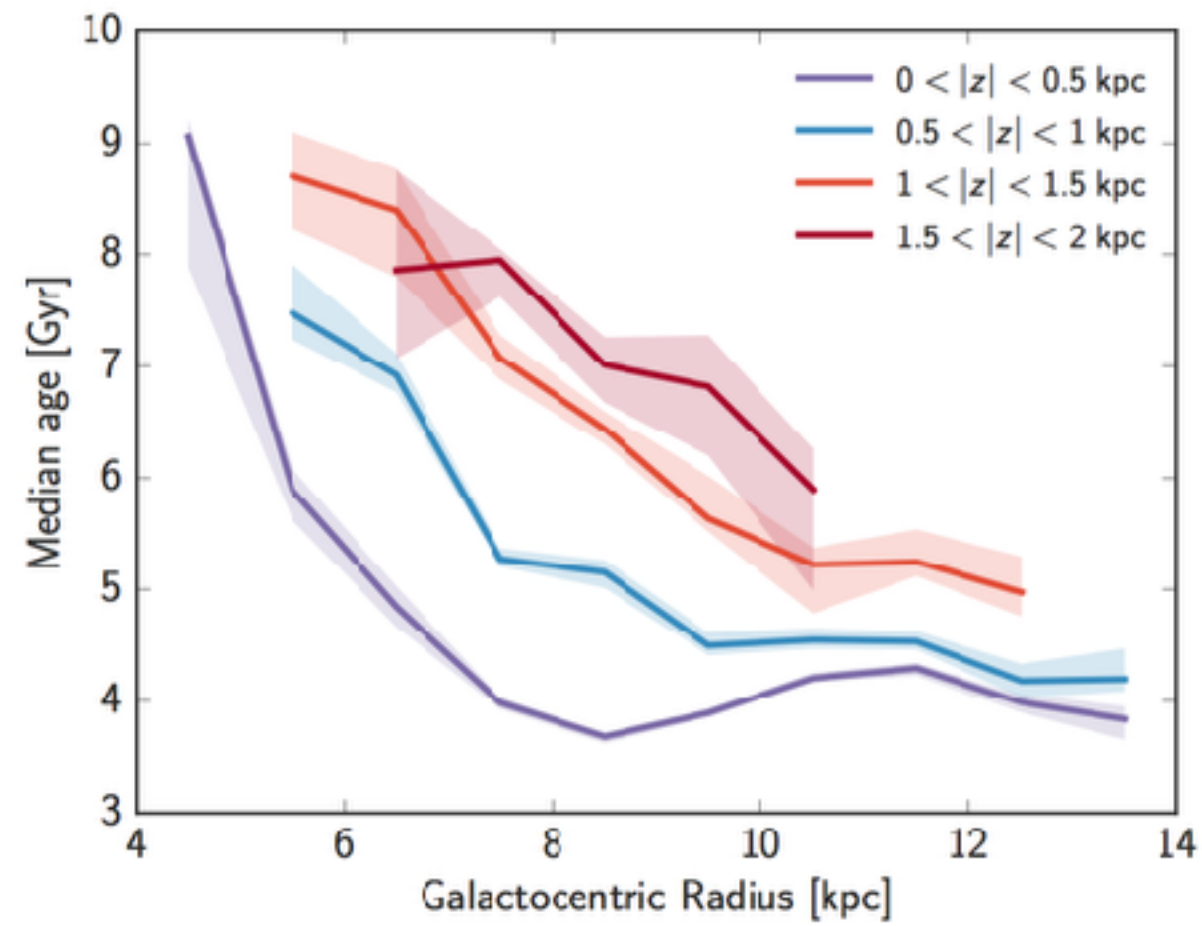


Mg/Fe abundance

metallicity

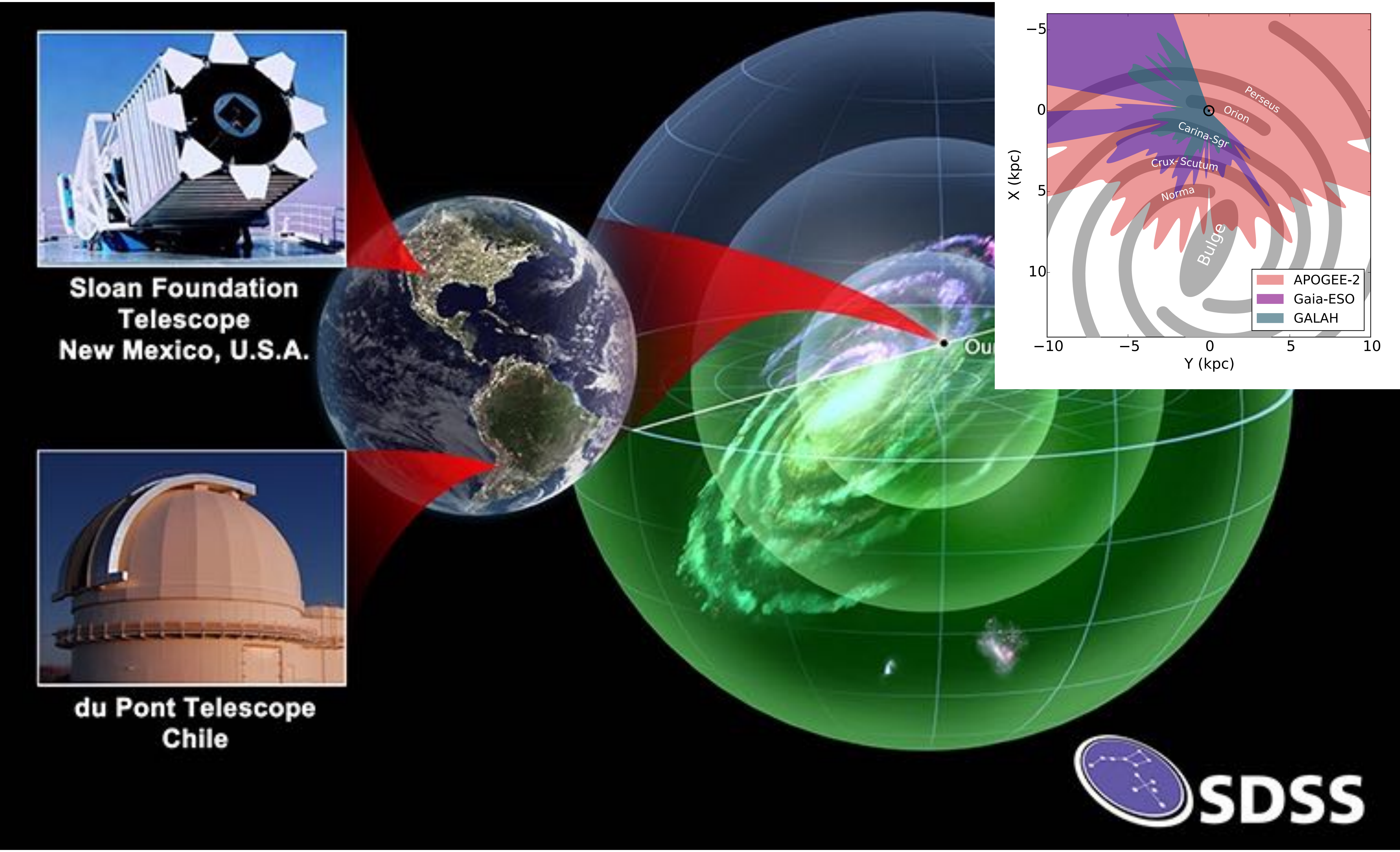


patterns vs. Galactic zone;
Weinberg et al. in prep



Ness et al. (2016);
Martig et al. (2016)

Mapping all parts of the Milky Way: *APOGEE South!*



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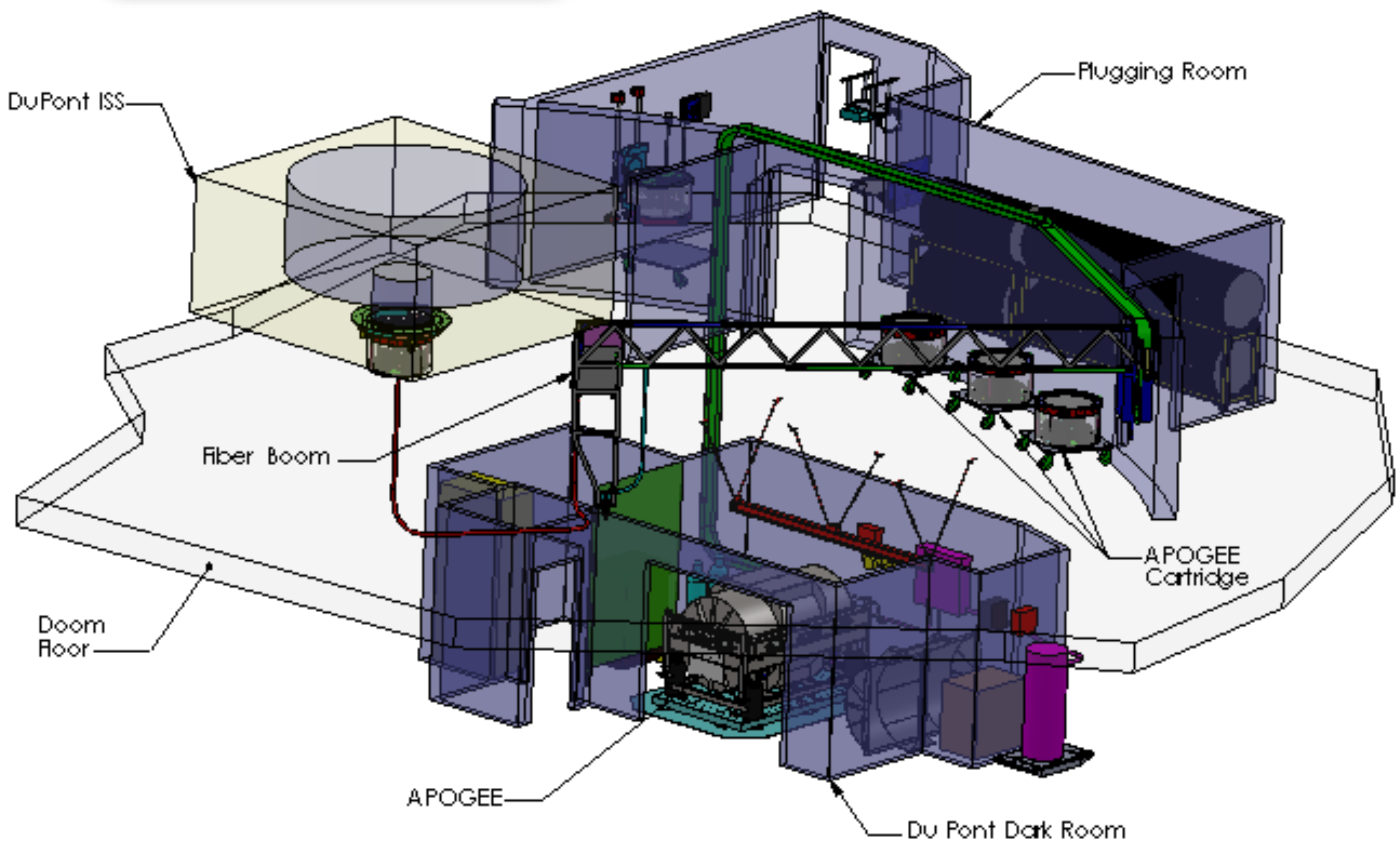
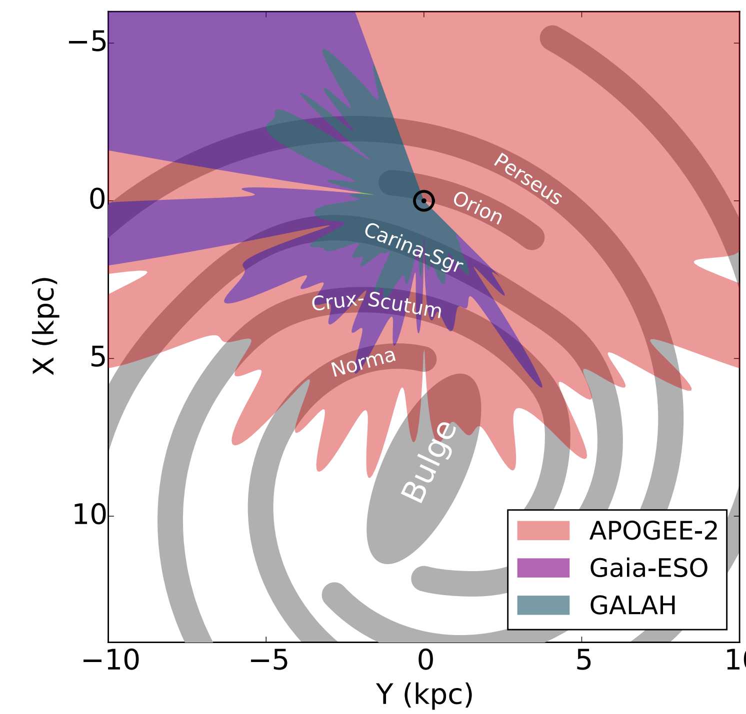




photos from Lead Observer Andres Almeida

MaNGA & APOGEE-2: *near-field cosmology*

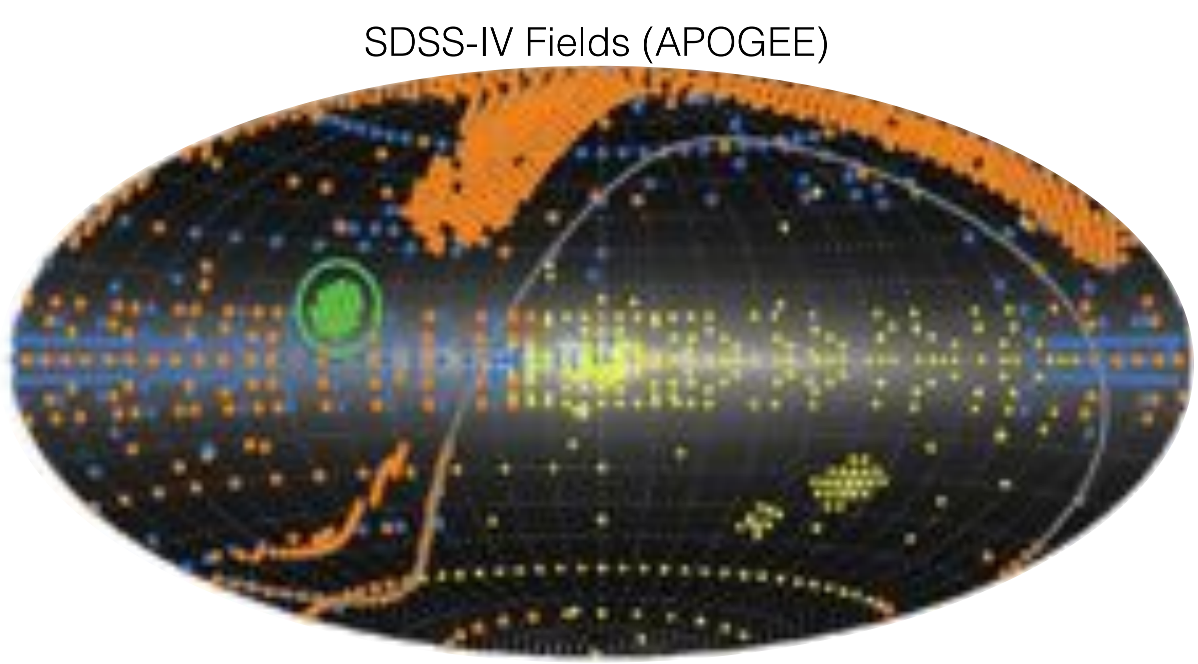
- Small-scale structure, dark matter content, formation history of galaxies through dynamical, gaseous, stellar population, and lensing signatures.
- Complex physics and phenomena, but ultimately will be untangled and may reveal new dark matter physics.

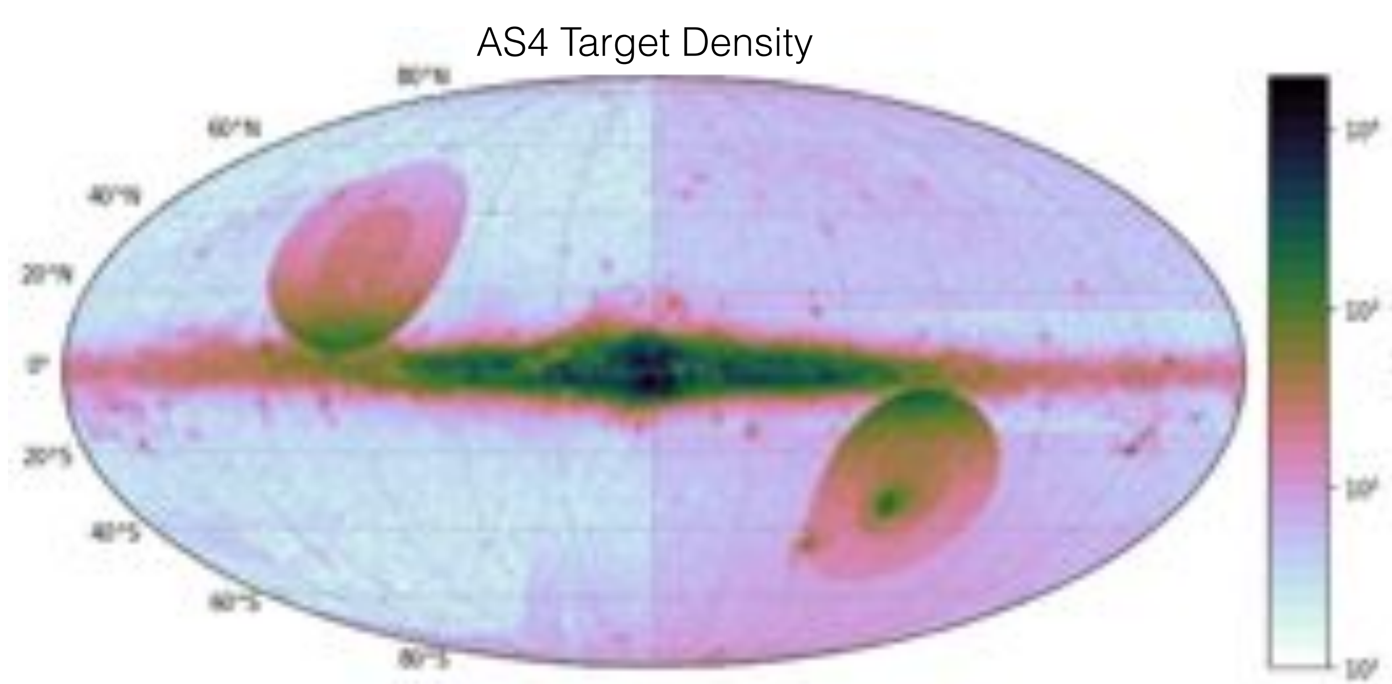
What comes after SDSS-IV? SDSS-V.

http://www.sdss.org/future/

Kollmeier et al. (2017)

- Director: Juna Kollmeier
- Project Scientist: Hans-Walter Rix
- Milky Way Mapper (Jennifer Johnson, Program Head)
- Black Hole Mapper (Scott Anderson, Program Head)
- Local Volume Mapper (Niv Drory, Program Head)

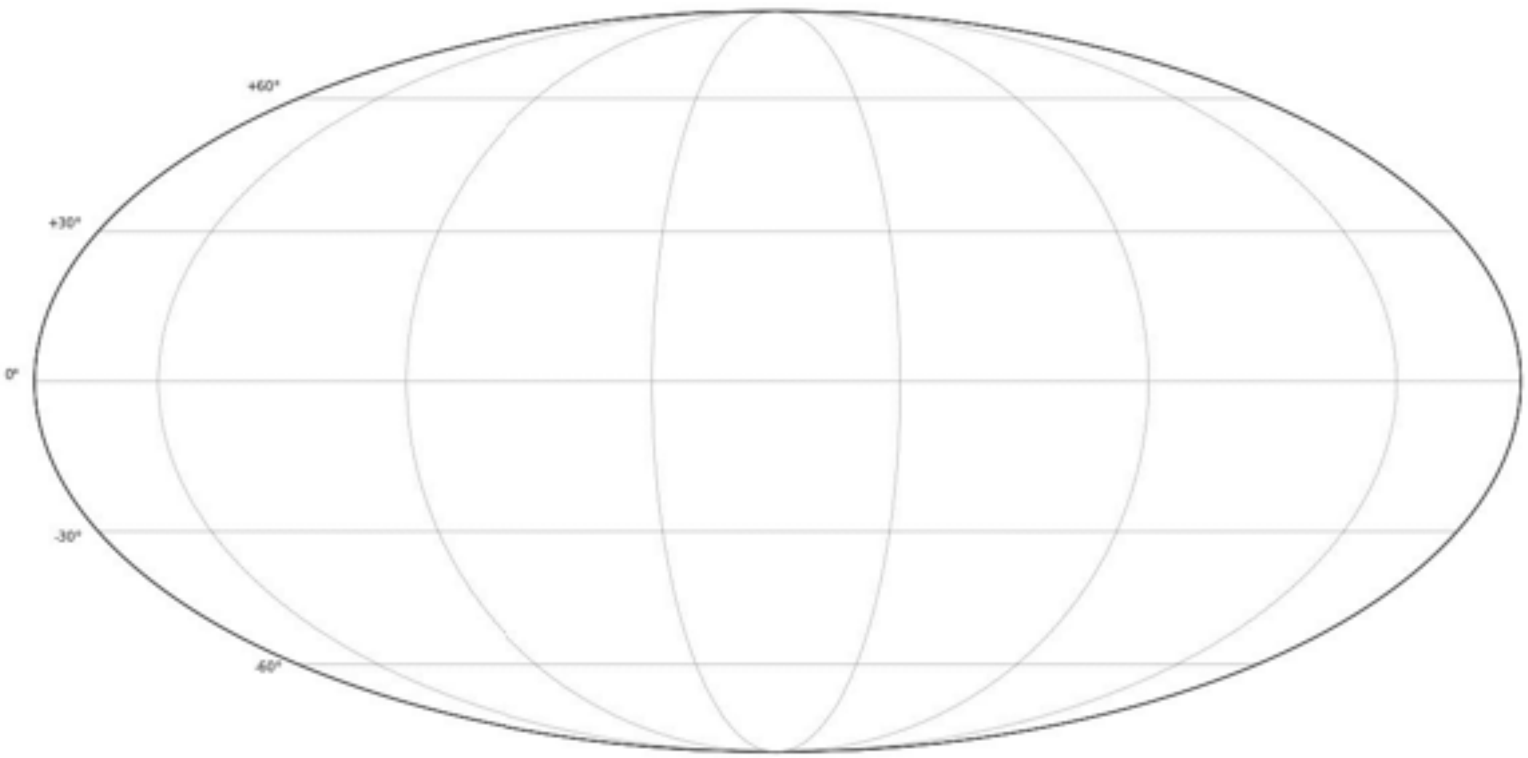


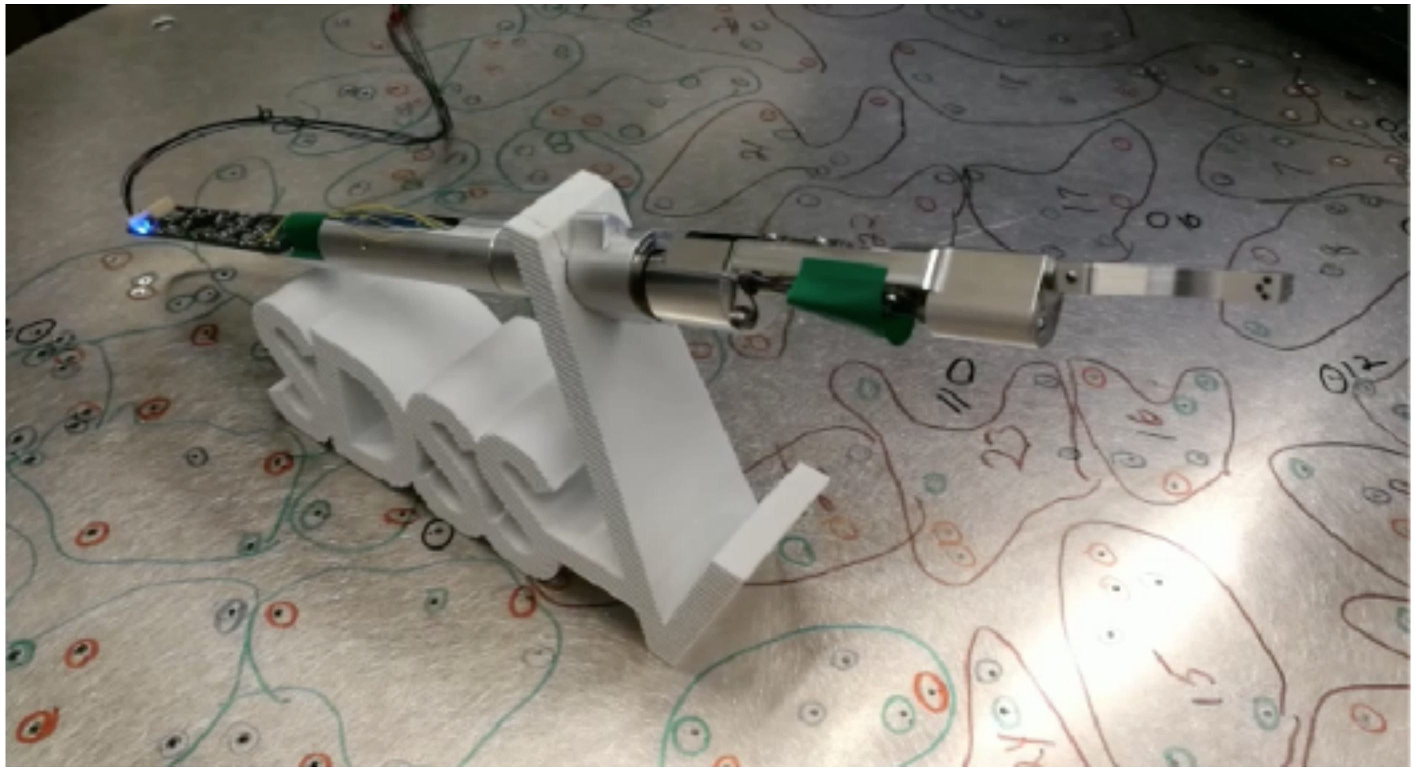


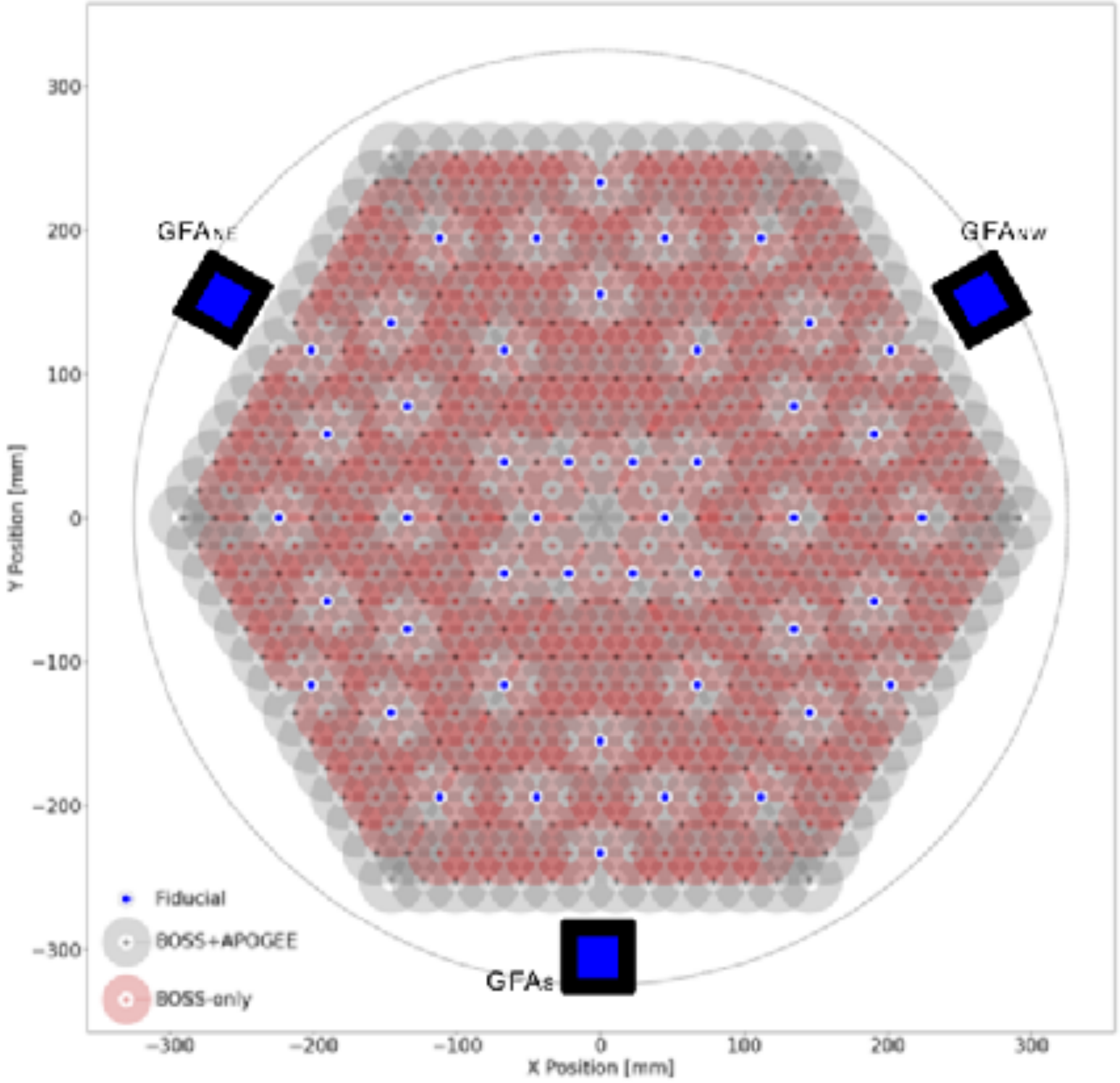
Robot for Milky Way Mapper and Black Hole Mapper

video is 2016-era concept, don't take literally

http://www.sdss.org/future/







At both Apache Point and at Las Campanas

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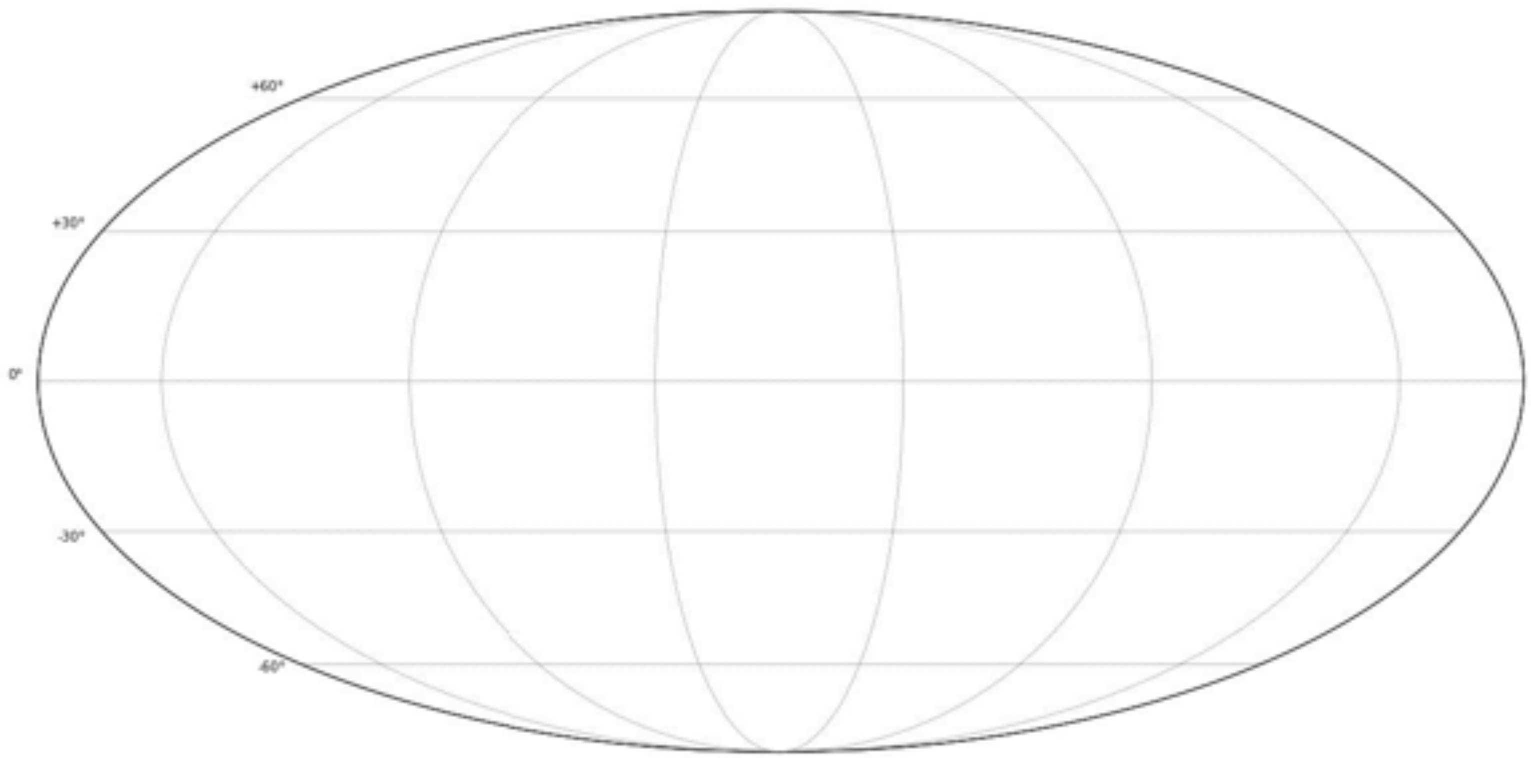

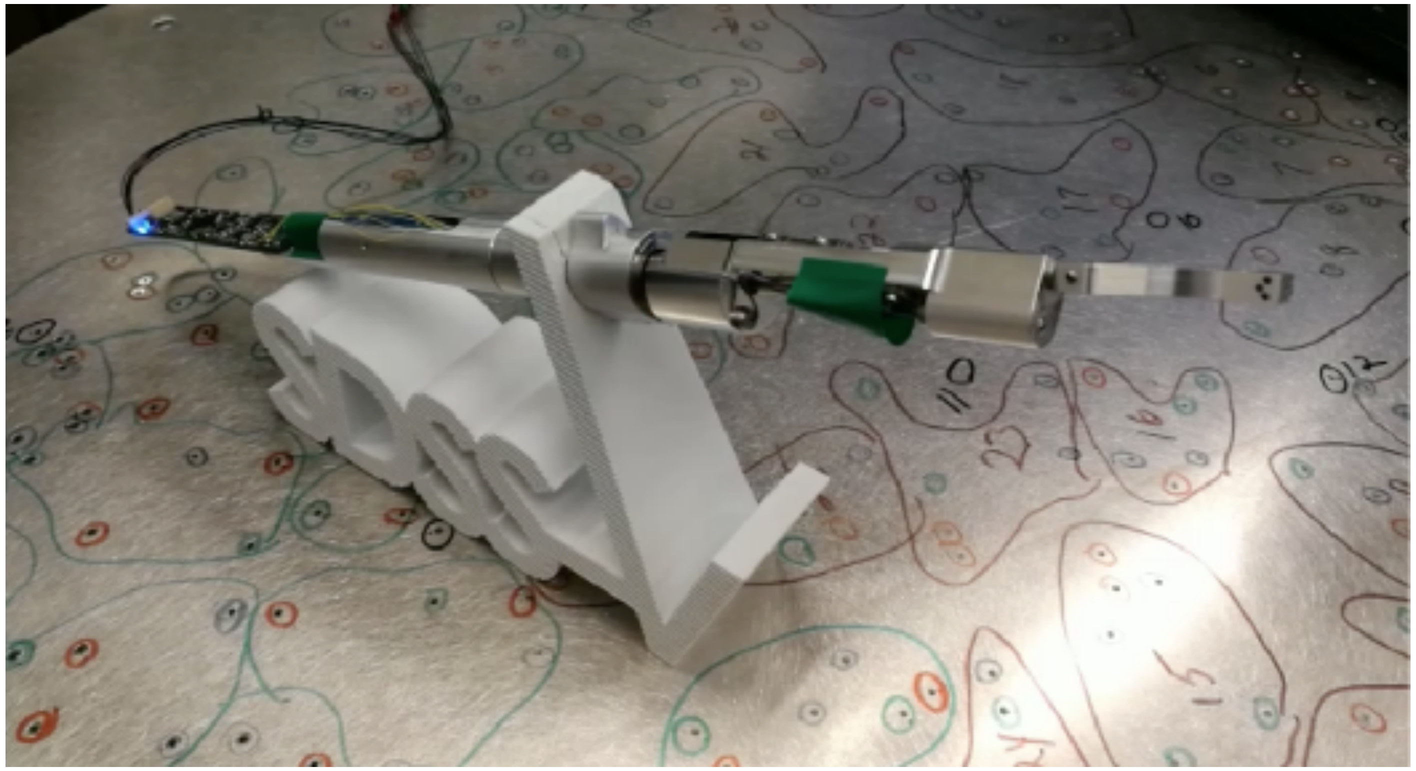

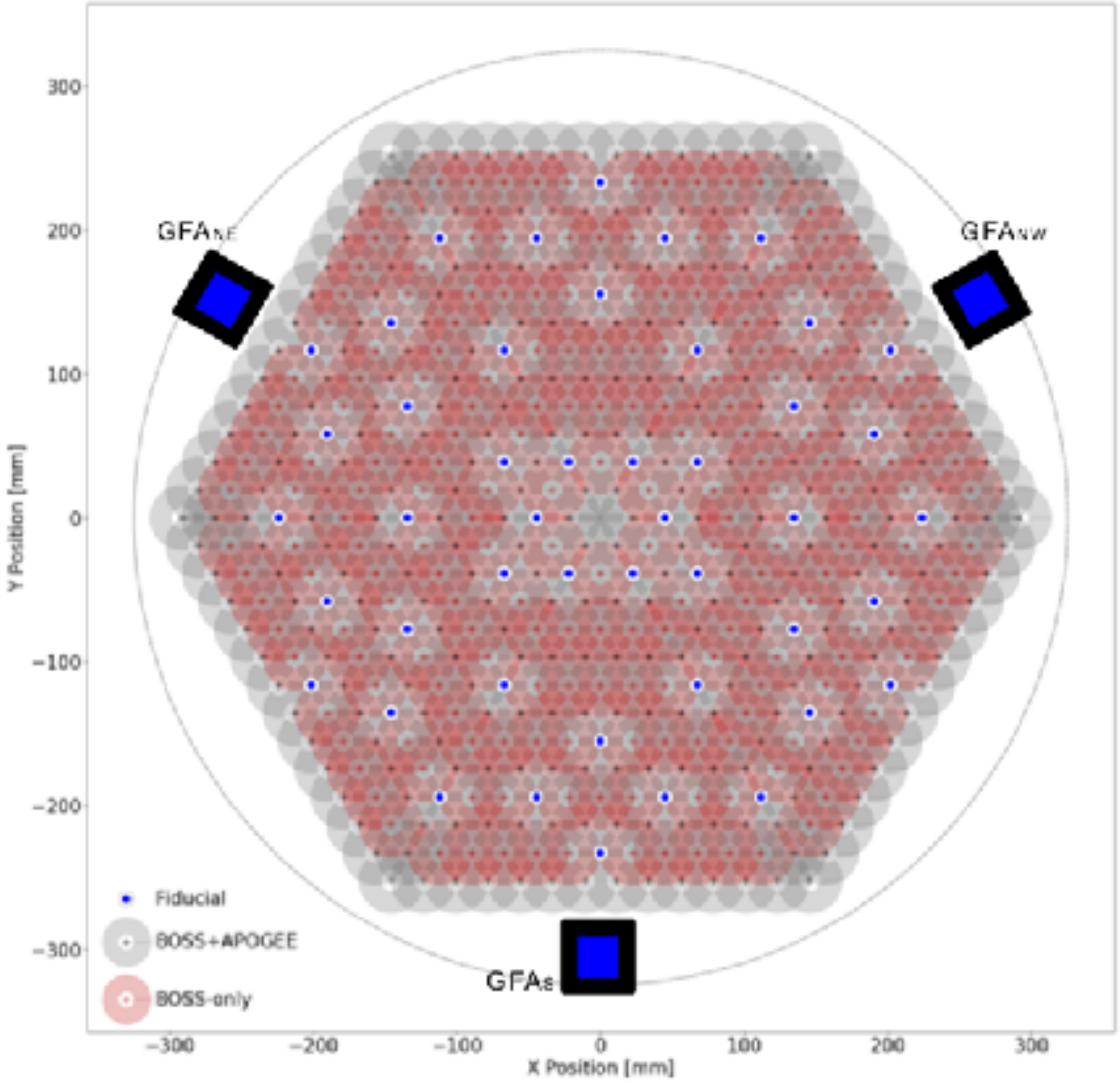

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Local Volume Mapper

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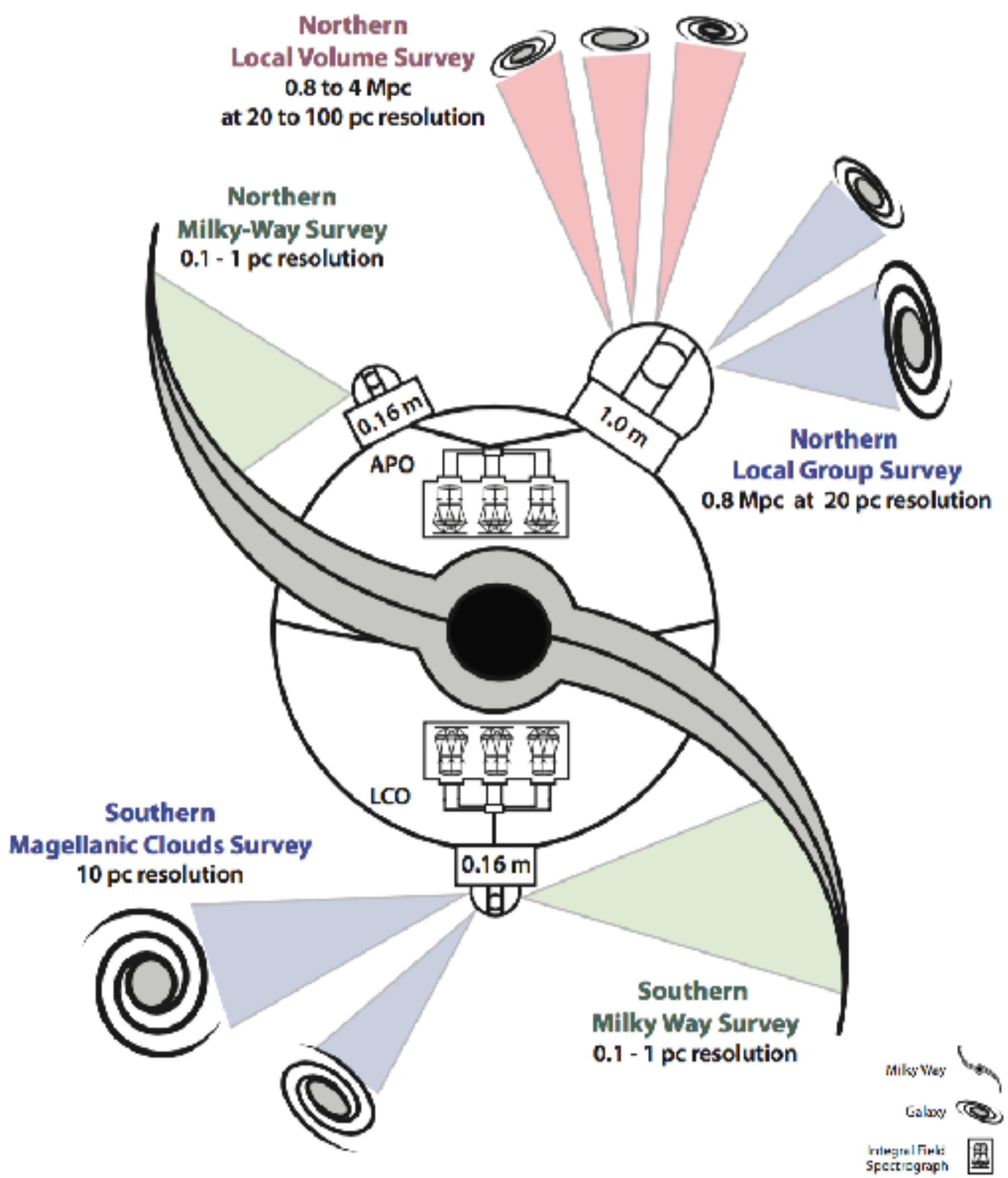

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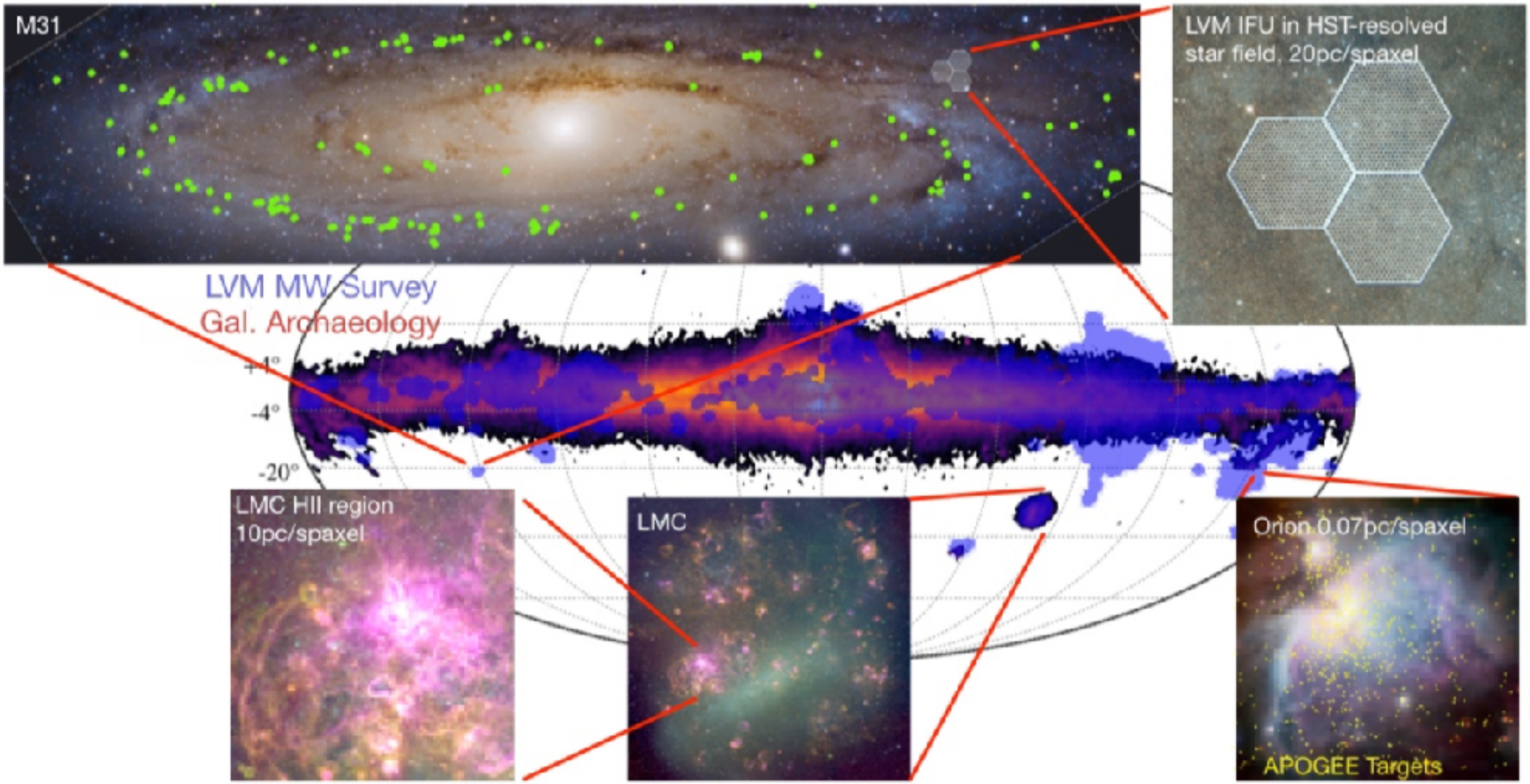

Summary

- SDSS is still going!
- Soon finishing its redshift surveying mission, leaving a rich legacy in cosmology.
- Focusing now on near-field cosmology, stellar astrophysics, and quasar astrophysics.
- The physicists should not ignore this — new cosmological tools have often arisen out of better understanding of astrophysics.