The Sloan Digital Sky Survey

L. Bartoszek

For the

Naperville Astronomical Association

1/5/21

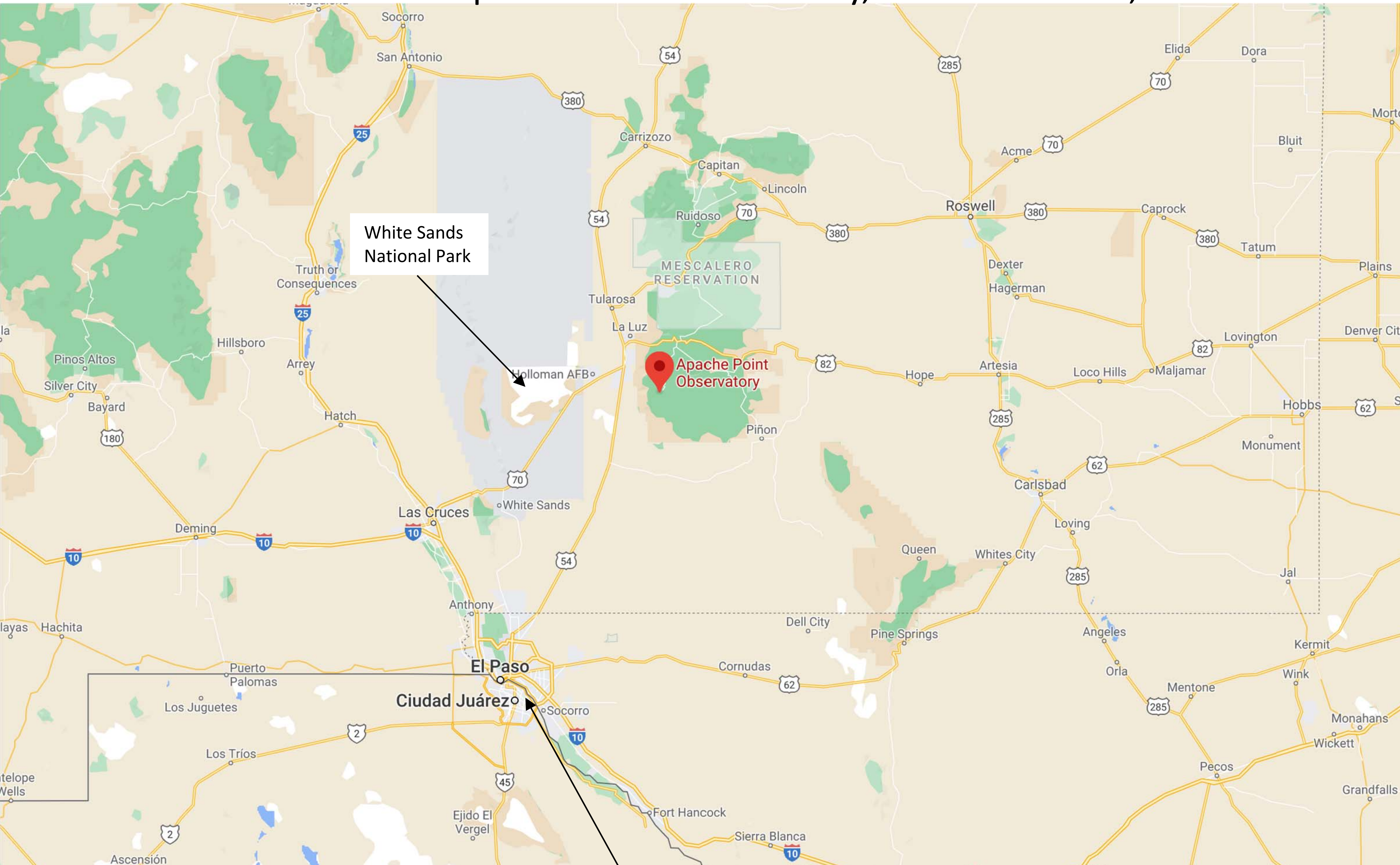
Outline

- This talk will outline the whole Sloan Digital Sky Survey (SDSS) program, history, future goals and impact
  - Much of the text and pictures were drawn from the many excellent SDSS web pages
- The last part of the talk will focus on the original 2.5 m telescope at Apache Point Observatory that I helped build

What is the Sloan Digital Sky Survey?

- The Sloan Digital Sky Survey (SDSS) is a multi-spectral imaging and spectroscopic redshift survey that started with a dedicated 2.5-m wide-angle optical telescope at Apache Point Observatory in New Mexico, United States
- The project was named after the Alfred P. Sloan Foundation, which contributed significant funding
- Data collection began in 2000
- Fermilab (where I used to work,) designed the data acquisition system
- It has added telescopes in other parts of the world to image more of the sky

The location of Apache Point Observatory, near Cloudcroft, NM

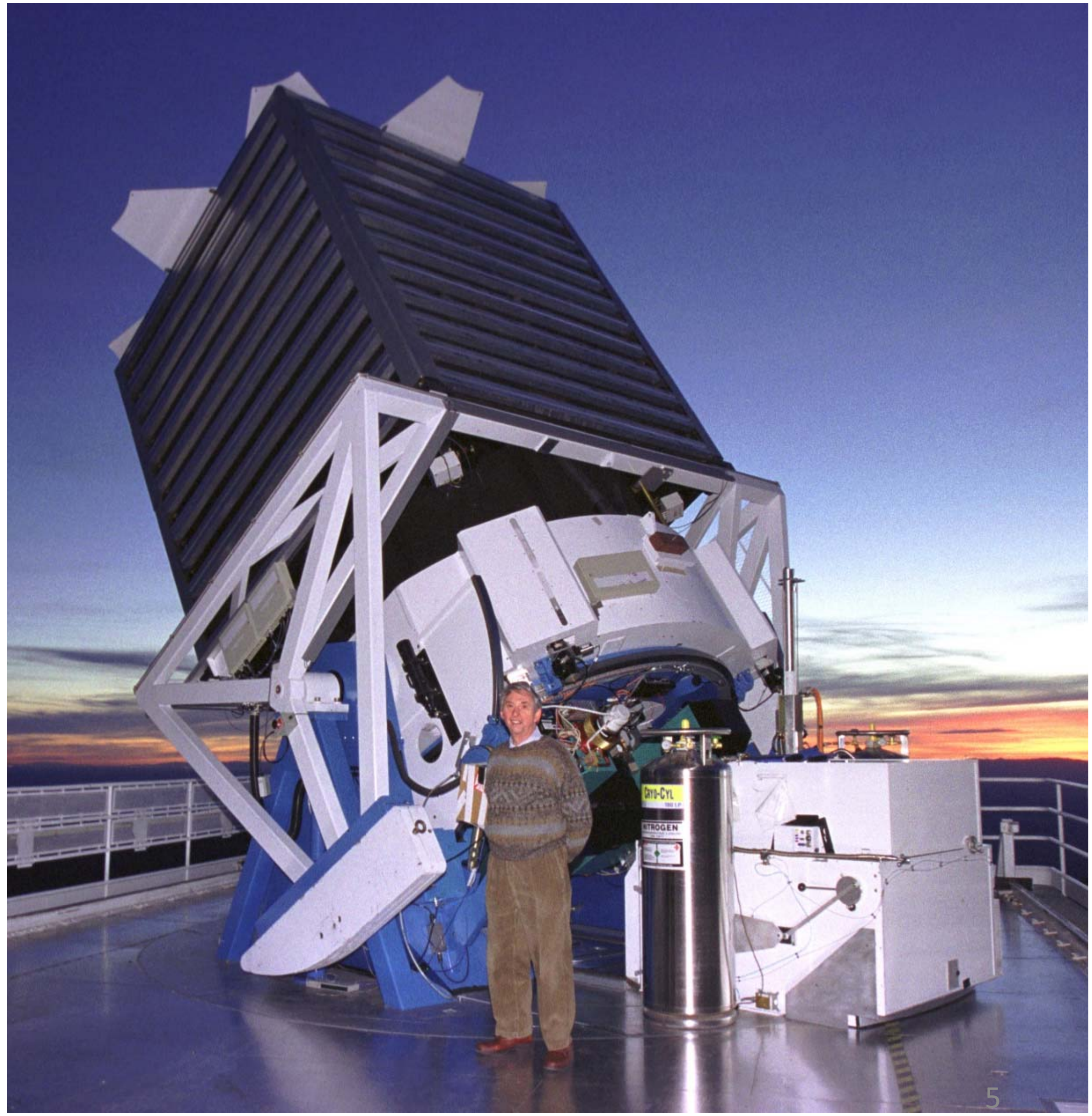


You fly into El Paso to get to Apache Point

The telescope I helped build:

The 2.5m Sloan Digital Sky Survey Telescope

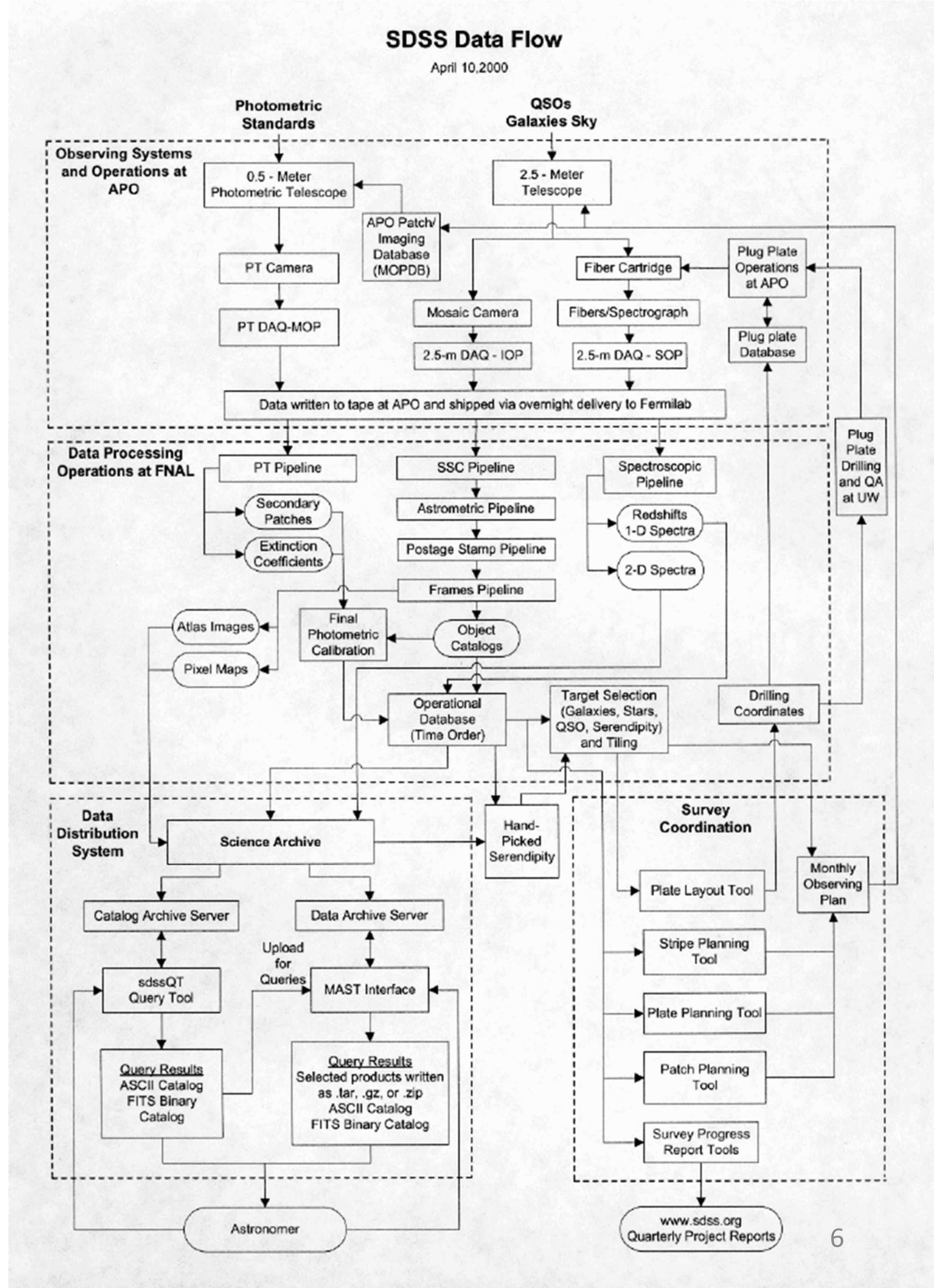
Apache Point Observatory, NM



Why did Fermilab get involved?

- Astronomers had never collected data like this before
  - It looks like a HEP experiment
- How much data does the APO telescope collect?
  - Every night it produces ~200 GB of data
  - ~70 TB/year
- How much does a typical HEP experiment collect?
  - ATLAS gets 3200 TB/year (today)

http://skyserver.sdss.org/dr1/en/sdss/data/data.asp



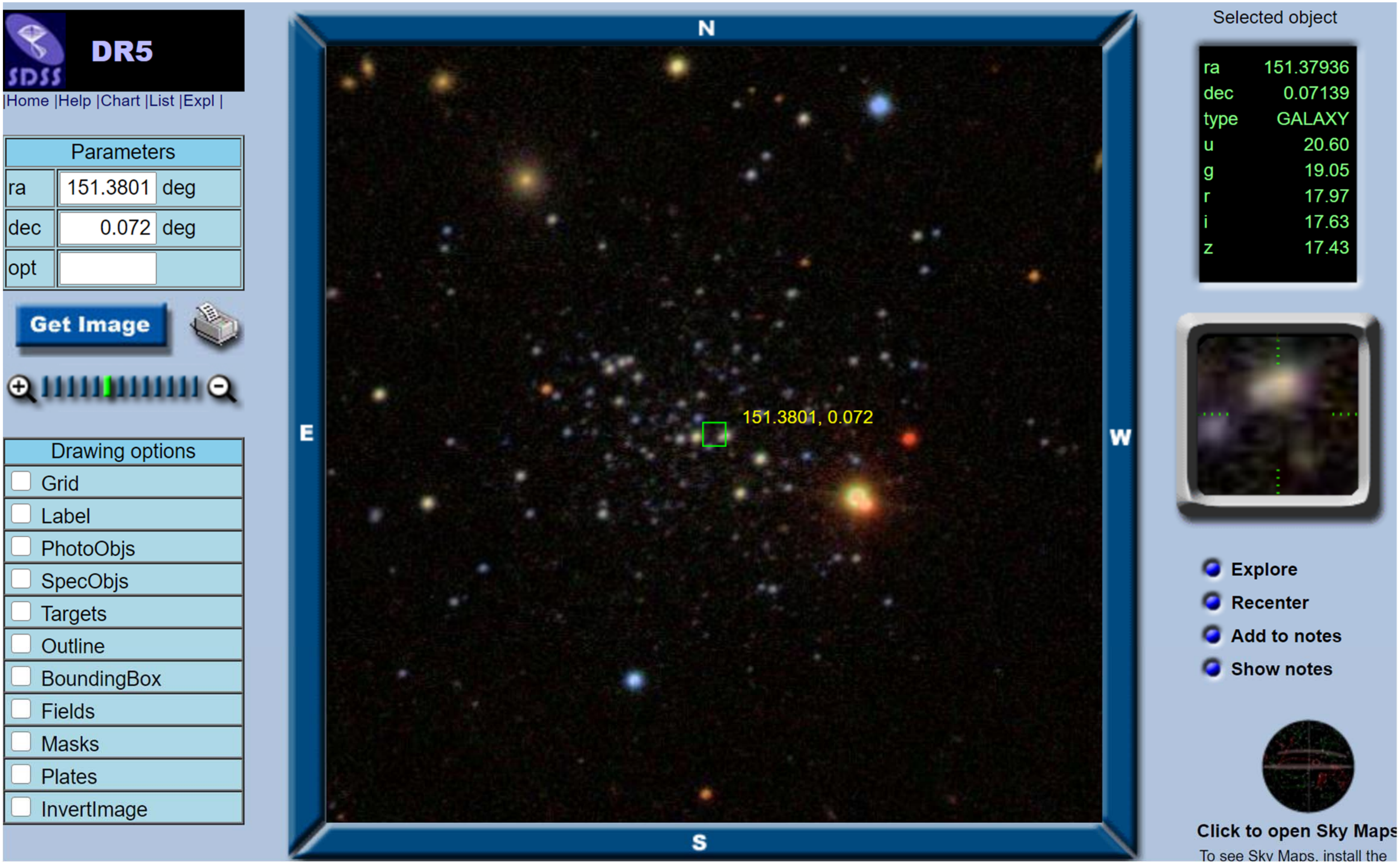
Phases of SDSS (so many names!)

- SDSS-I (2000-2005)—SDSS Legacy Survey
- SDSS-II (2005-2008)—SDSS Legacy Survey, Supernova Survey, SEGUE-1
  - https://classic.sdss.org/ (no longer updated, but still available)
- SDSS-III (2008-2014)—BOSS, SEGUE-2, APOGEE, MARVELS
  - http://sdss3.org/ (no longer updated, but still available)
- SDSS-IV (2014-2020)—eBOSS (SPIDERS, TDSS), APOGEE-2, MaNGA
  - https://www.sdss.org/surveys/#sdssiv
- SDSS-V (2020-)—Milky Way Mapper, Black Hole Mapper, Local Volume Mapper
  - https://www.sdss.org/future/

SDSS-I & II—The Legacy Survey (2000-2008)

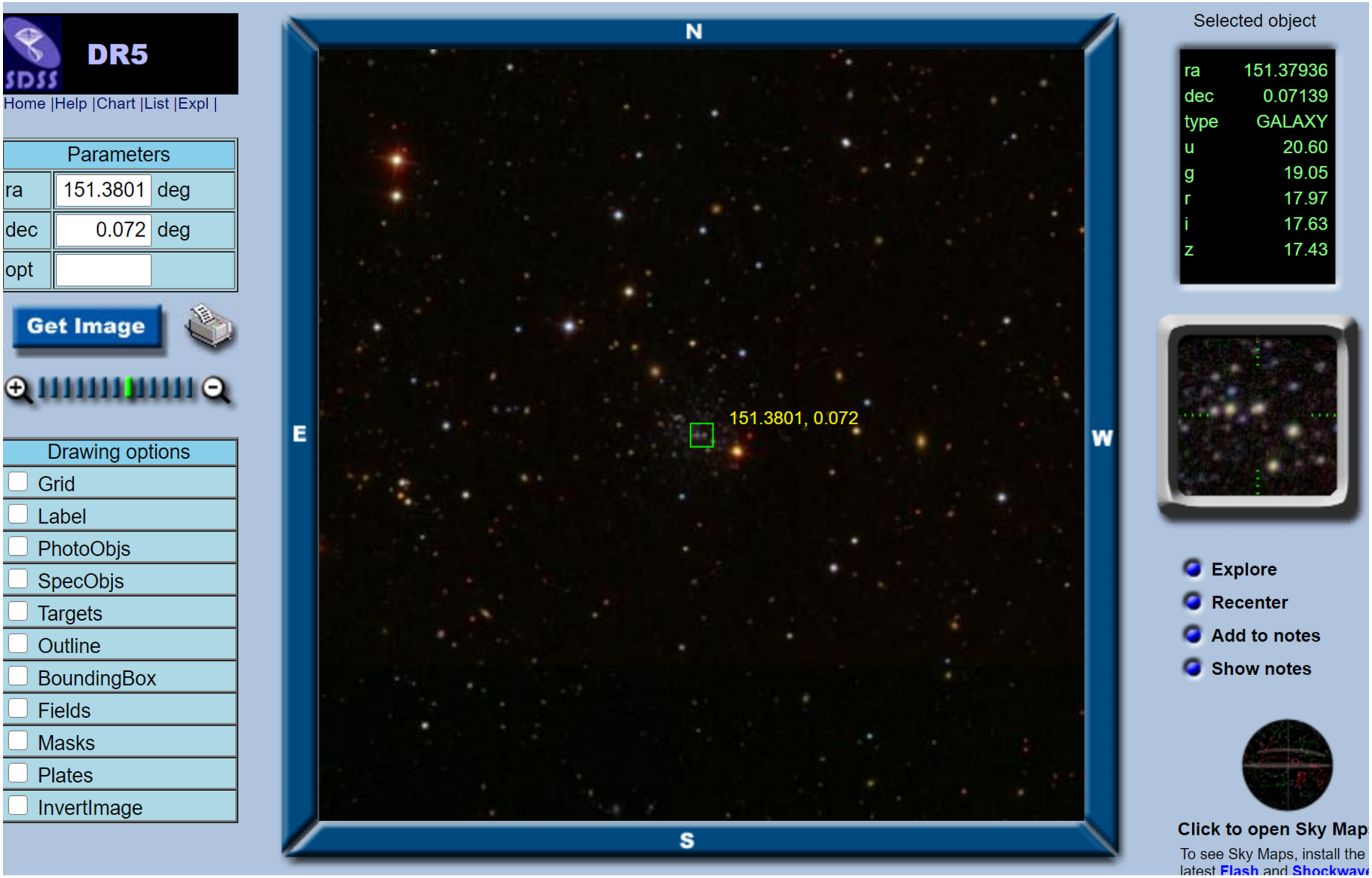
- The original SDSS observing plan resulted in a uniform, well-calibrated map of the Universe that will be used for decades to scientific studies ranging from asteroids to the large-scale structure of the Universe.
- All SDSS date is available on the web.
  - https://www.sdss.org/
- The next few slides compare data between SDSS and POSS-1, the Palomar Observatory Sky Survey done in the ’50s
  - It was recorded on glass plates and digitized to be made available on the web

Screenshot of Pal 3, a globular cluster, from SDSS



http://skyserver.sdss.org/dr5/en/proj/advanced/skysurveys/poss.asp
is an article comparing the data from POSS-1 and SDSS

I had to zoom out two steps to get an image that matched the POSS image on the next slide

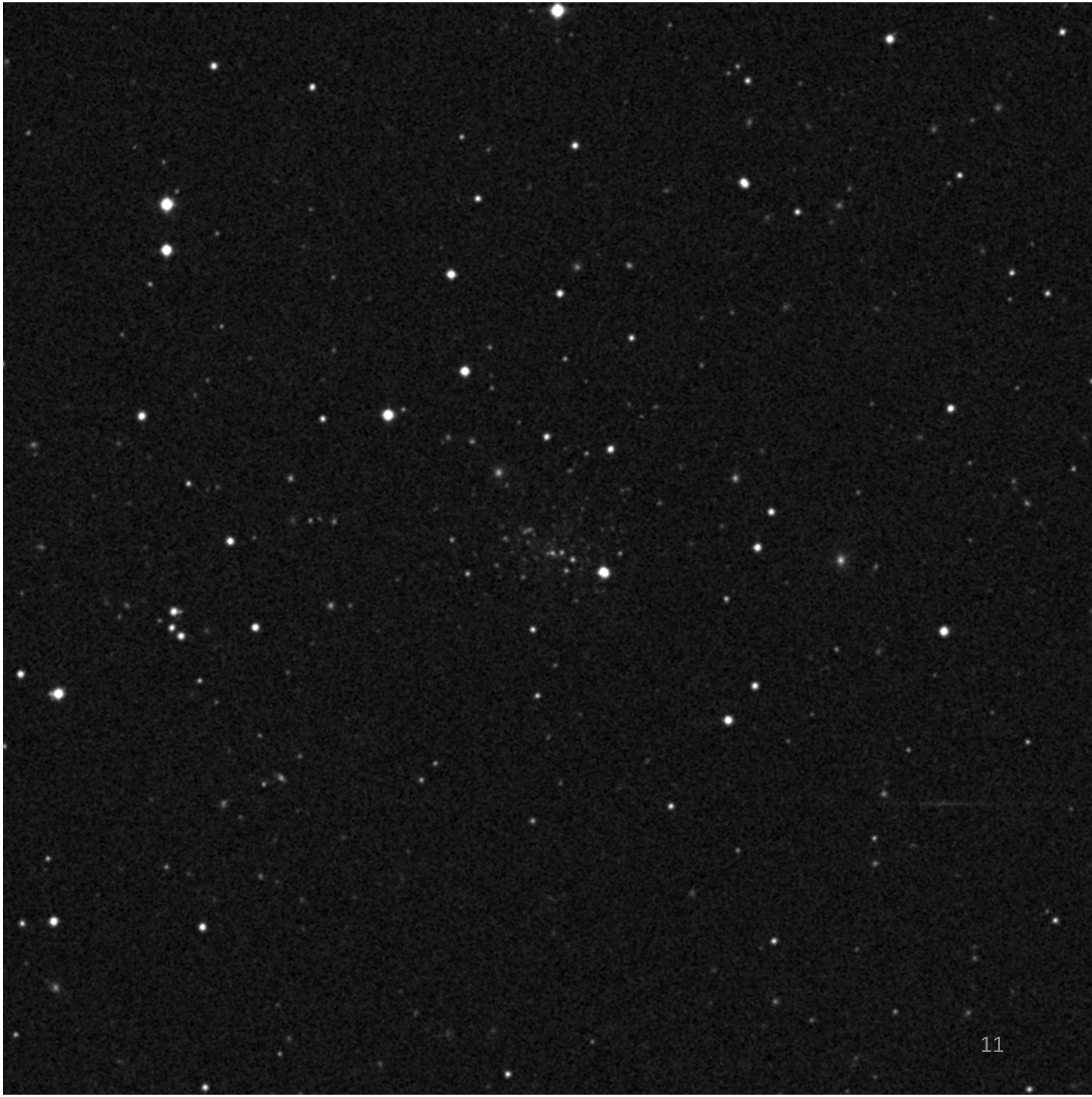


The same Pal 3 image from the POSS-1 website.

I had a hard time figuring out whether the image was the same as the SDSS image until I zoomed out a couple of steps. Then it became obvious they were the same.

The lack of color doesn't help figure it out either.

There is more detail in the zoomed in SDSS image.



This is what the POSS-1 web page looks like. By changing the File Format to GIF, and clicking on RETRIEVE IMAGE, you can display the image on the previous slide.

I'm not sure why the coordinates displayed here are different from the SDSS format, but when I entered the same numbers as on the SDSS page, I got the same image.

The STScI Digitized Sky Survey

NOTE: To obtain target coordinates for **HST Phase 2 proposals**, select the HST Phase 2 (GSC2) survey option.

[*New!* | Help | FAQ | © | Acknowledging DSS | Other DSS Sites | Archive | STScI]

Get an Object's Coordinates

Object name [ ] GET COORDINATES | Clear

Get coordinates from (•) SIMBAD ( ) NED

Retrieve an Image

Target: Sextans C (*Cl)   Resolved by: SIMBAD

Retrieve from

- POSS2/UKSTU Red
- POSS2/UKSTU Blue
- POSS2/UKSTU IR
- POSS1 Red
- POSS1 Blue
- Quick-V
- HST Phase 2 (GSC2)

(**detailed information about the Surveys**)

RA 10 05 31.86 **Dec** +00 04 20.9 J2000

Height 15.0 **(max: 60.0) Width** 15.0 **(max: 60.0) arcminutes**

File format FITS **Compression (FITS only)** None

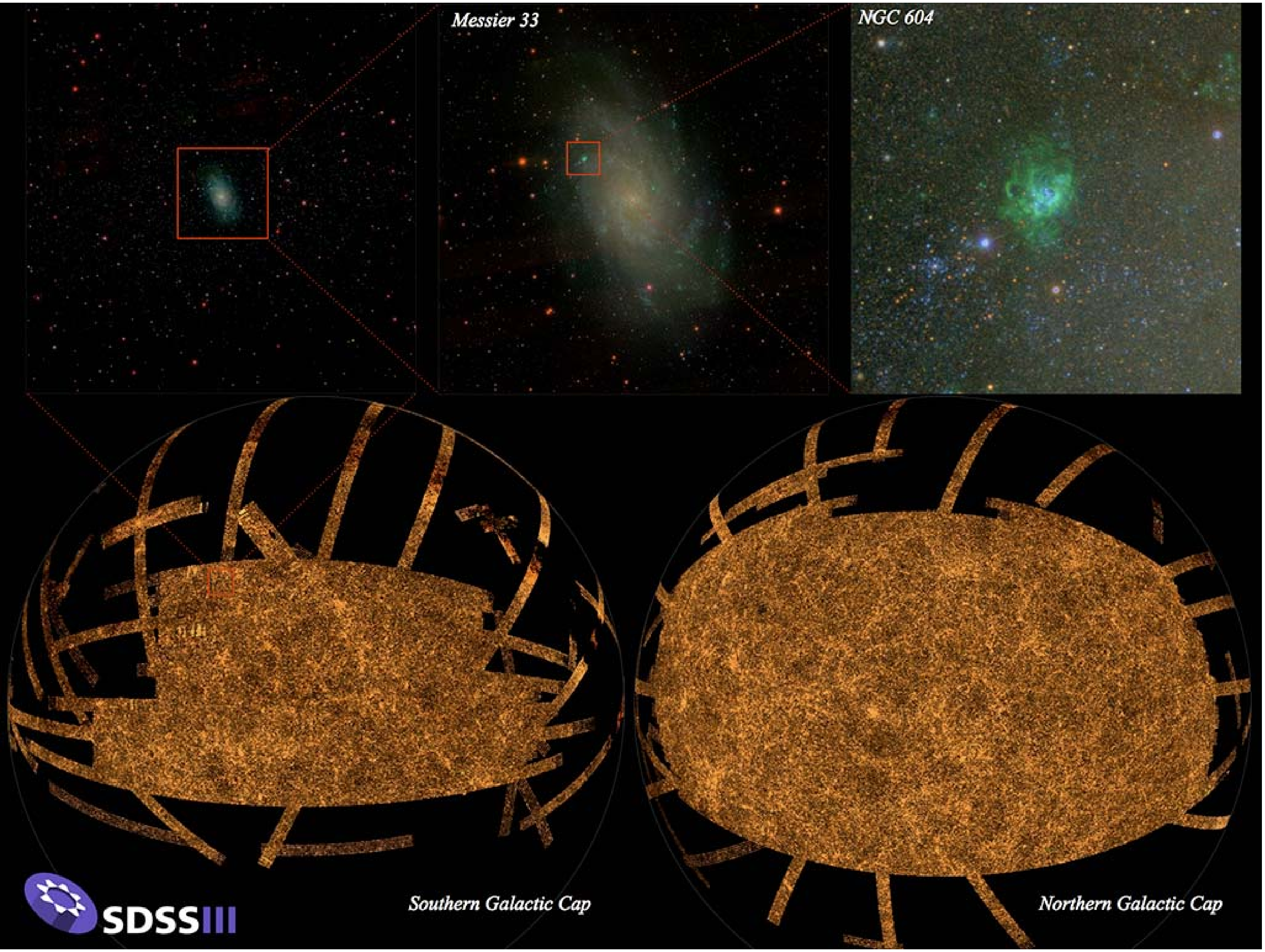
[ ] **Save file to disk (instead of displaying)**

HST Field of View Overlay (1st generation GIF only): NONE

Roll angle (V3): [ ]

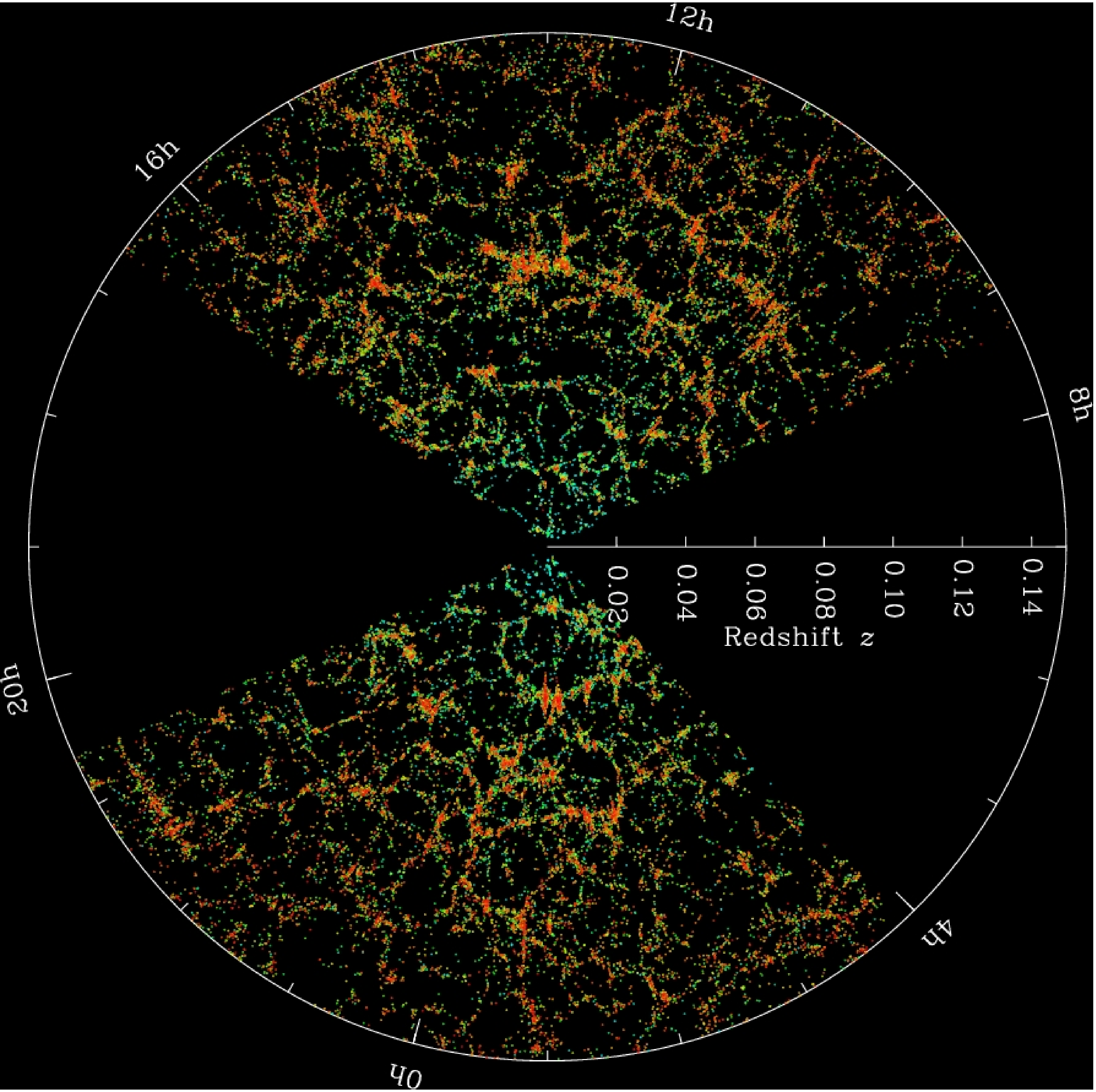
RETRIEVE IMAGE | Reset values to defaults

[*New!* | Help | FAQ | © | Acknowledging DSS | Other DSS Sites | Archive | STScI]



The SDSS "Orange Spider". This illustrates the wealth of information on scales both small and large available in the SDSS I/II and III imaging. The picture in the top left shows the SDSS view of a small part of the sky, centered on the galaxy Messier 33 (M33).

The middle and right top pictures are further zoom-ins on M33. The figure at the bottom is a map of the whole sky derived from the SDSS image. Visible in the map are the clusters and walls of galaxies that are the largest structures in the entire universe.
Figure credit: M. Blanton and SDSS

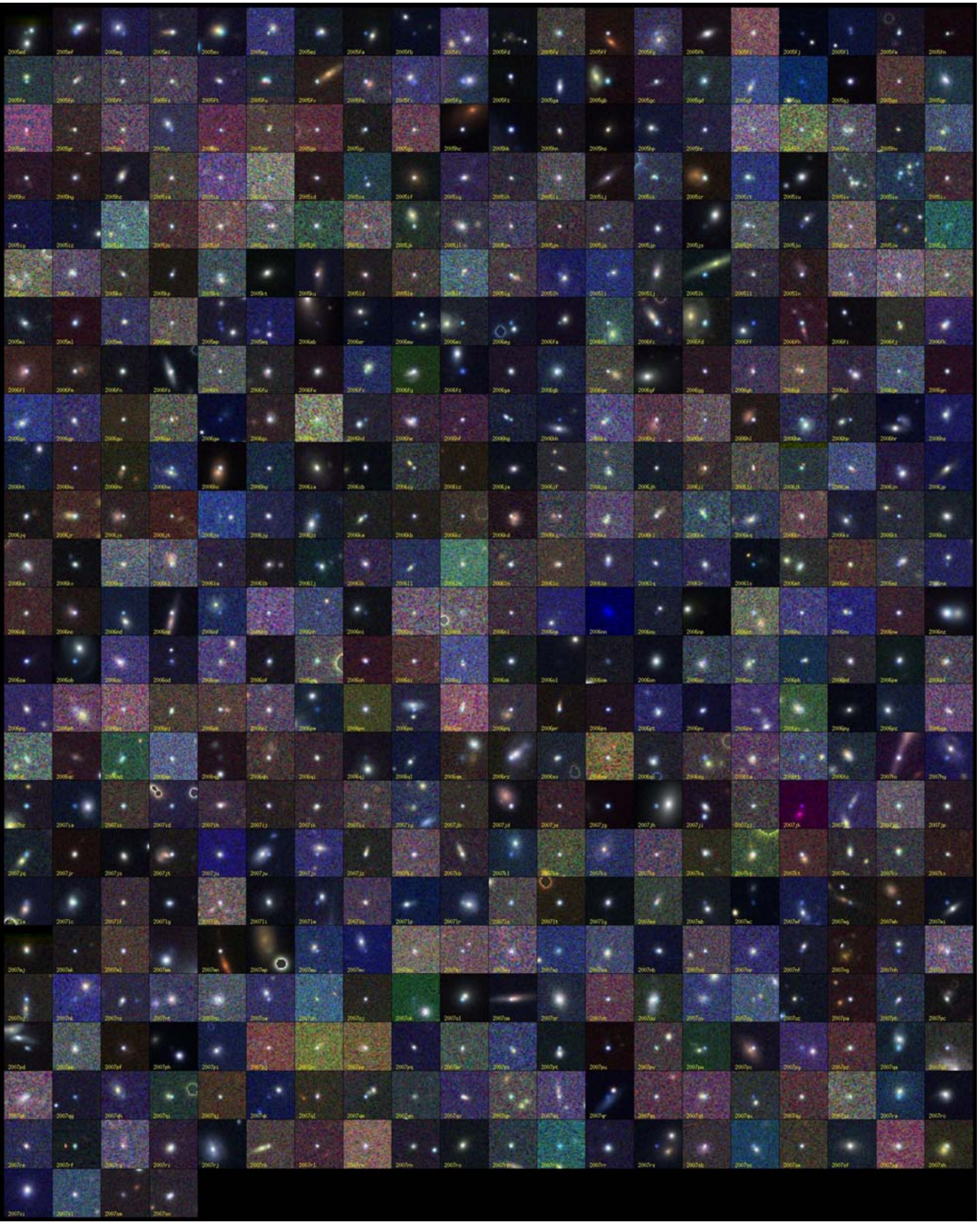


Large scale structure in the northern equatorial slice of the SDSS main galaxy redshift sample. The slice is 2.5 degrees thick, and galaxies are color-coded by g-r color.

Green indicates lower density, red indicates higher density of galaxies. The Milky Way is in the exact center of the picture.

SDSS-II—Supernova Survey

- The SDSS Supernova Survey, which ran from 2005 to 2008, performed repeat imaging of one stripe of sky along the celestial equator. The project discovered more than 500 type Ia supernovae, which have led to a deeper understanding of the history of the Universe.
- Type 1a supernovae are critical to understanding the acceleration rate of the universe leading to the theory of Dark Energy



Images of all the Supernovae from the 2005-2007 observing campaigns.

Each image is centered on the supernova, which usually stands out as a bright point near or within the galaxy that hosts it.

The light of the supernova, powered by the thermonuclear explosion of a single white dwarf star, can outshine that of the tens of billions of stars in its host galaxy.

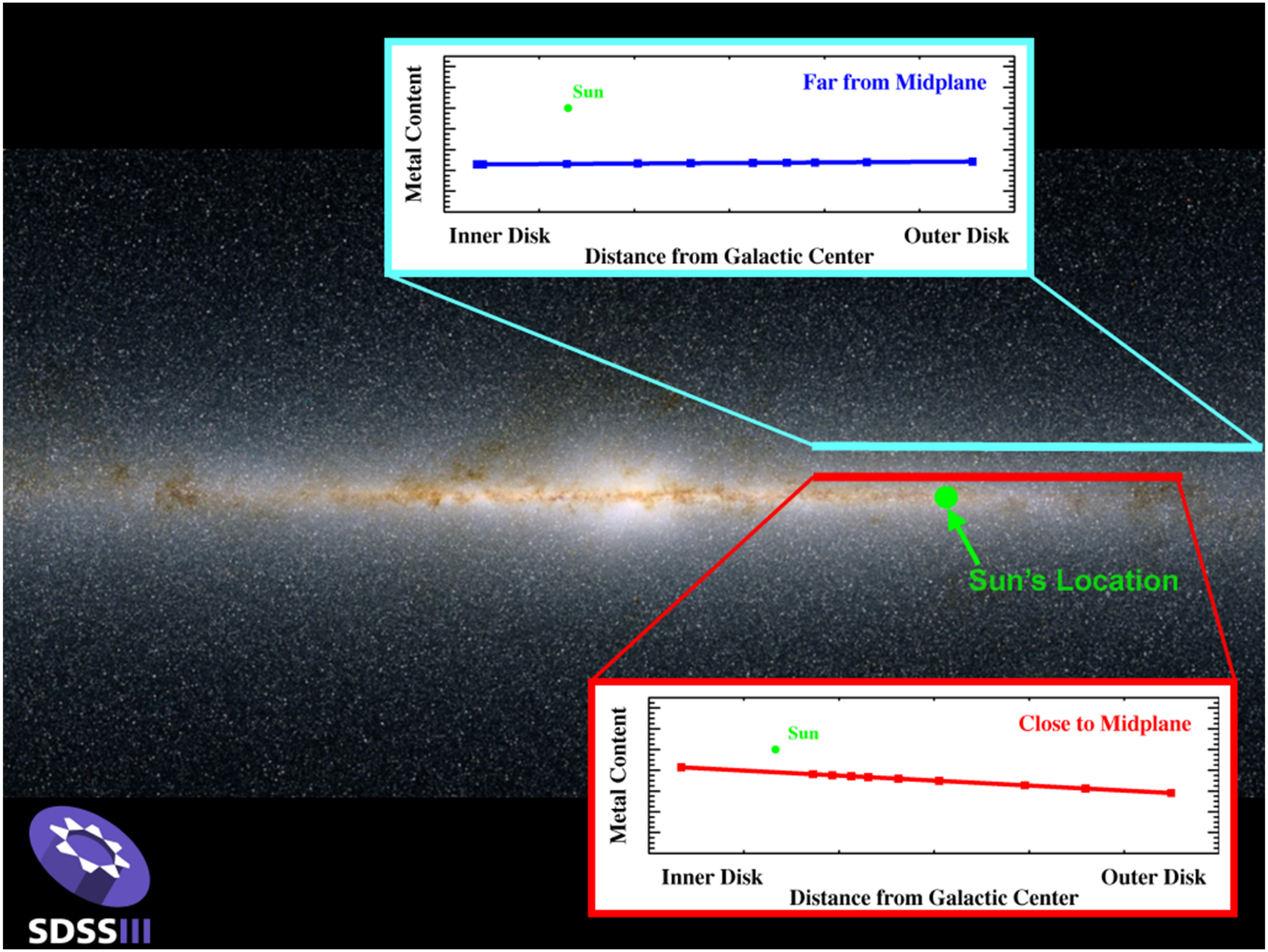
Caveats on Type 1A Supernovae

- Recent work from the Sloan Digital Sky Survey and others shows that there are several different mechanisms to produce Type 1A supernovae
- The downside of this is that the Type 1A supernova might lose its standing as a Standard Candle for measuring galactic distances
- This could change our view of Dark Energy
- There are new models that predict the expansion without invoking Dark Energy

SDSS-II—SEGUE-1

- **S**loan **E**xtension for **G**alactic **U**nderstanding and **E**xploration (SEGUE)
- The primary goal of SEGUE-1 was the kinematic and stellar population study of the high-latitude thick disk and halo of the Milky Way
- (SEGUE-1) obtained spectra of nearly 230,000 unique stars over a range of spectral types to investigate Milky Way structure.

SEGUE: Mapping the Outer Milky Way



2008-2014, 4 simultaneous surveys

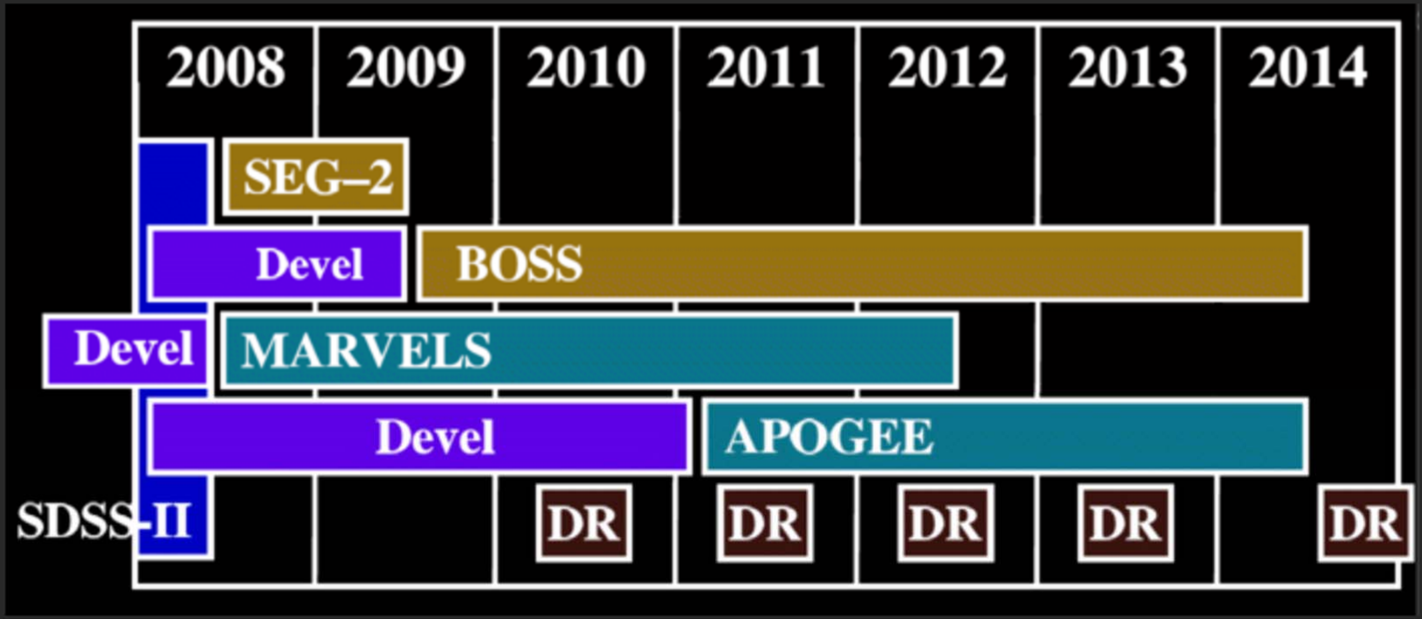
SDSS-III

SDSS-III: Four Surveys Executed Simultaneously

SDSS-III consists of four surveys executed on the same 2.5m telescope: the Apache Point Observatory Galactic Evolution Experiment (APOGEE) the Baryon Oscillation Spectroscopic Survey (BOSS), the Multi-Object APO Radial Velocity Exoplanet Large-area Survey (MARVELS), and the Sloan Extension for Galactic Understanding and Exploration 2 (SEGUE-2).

BOSS focuses on mapping the Universe on the largest scales, creating the largest volume three-dimensional map of galaxies ever created. SEGUE-2 and APOGEE focus on the structure and evolution of our own Milky Way galaxy. MARVELS searches very nearby stars for evidence of "exoplanets" surrounding them.

The BOSS and SEGUE-2 programs require "dark" time when the Moon is less than 60% illuminated, or below the horizon. The APOGEE and MARVELS programs are executed during the remaining "bright" time.



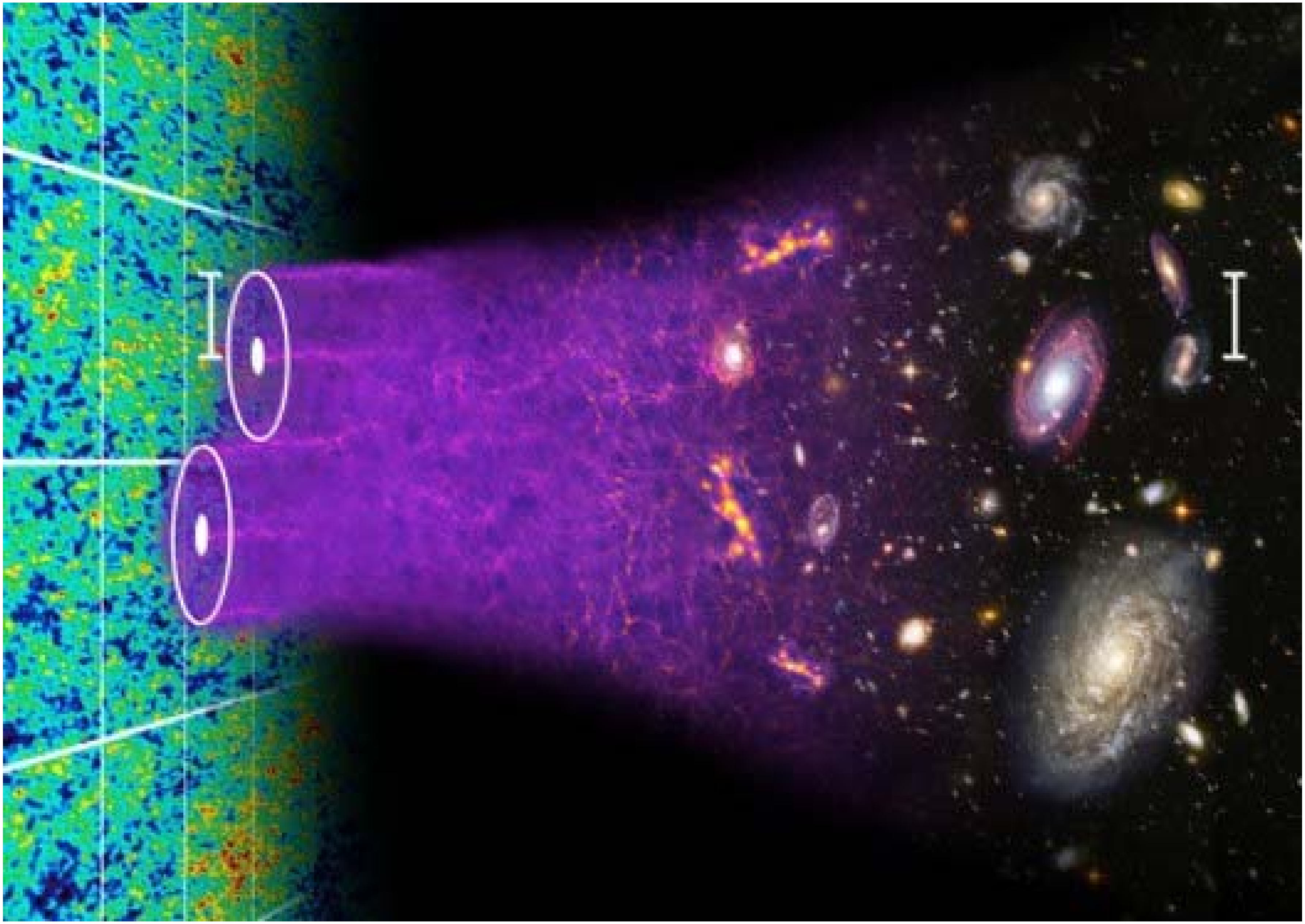
High-level SDSS-III schedule. Dark-time observing programs are marked in orange, bright-time observing programs marked in green.

SDSS-III—APOGEE-1

- The **A**pache **P**oint **O**bservatory **G**alactic **E**volution **E**xperiment (APOGEE)
- APOGEE-1 employed high-resolution, high signal-to-noise infrared spectroscopy to penetrate the dust that obscures significant fractions of the disk and bulge of our Galaxy.
- APOGEE surveyed over 100,000 red giant stars across the full range of the Galactic bulge, bar, disk, and halo.

SDSS-III—BOSS

- The **B**aryon **O**scillation **S**pectroscopic **S**urvey (BOSS)
- The SDSS's Baryon Oscillation Spectroscopic Survey (BOSS) mapped the spatial distribution of luminous red galaxies (LRGs) and quasars to detect the characteristic scale imprinted by *baryon acoustic oscillations* in the early Universe.
- Sound waves that propagate in the early Universe, like spreading ripples in a pond, imprint a characteristic scale on cosmic microwave background fluctuations.
- These fluctuations have evolved into today's walls and voids of galaxies, meaning this baryon acoustic oscillation (BAO) scale (about 150 Mpc) is visible among galaxies today.



An illustration of the concept of baryon acoustic oscillations, which are imprinted in the early Universe and can still be seen today in galaxy surveys like BOSS. (Illustration courtesy of Chris Blake and Sam Moorfield.)

SDSS-III—MARVELS

- The **M**ulti-object **A**PO **R**adial **V**elocity **E**xoplanet **L**arge-area **S**urvey
- MARVELS monitored the radial velocities of 11,000 bright stars, with the precision and cadence needed to detect gas giant planets that have orbital periods ranging from several hours to two years.
- With well-characterized sensitivity and a broad range of target star properties, MARVELS provided a critical dataset for testing theoretical models of the formation, migration, and dynamical evolution of giant planet systems. It will have unique sensitivity to rare systems such as extreme eccentricity planets or objects in the "brown dwarf desert."

SDSS-III—SEGUE-2

- Combining SEGUE-1 and 2 reveals the complex kinematic and chemical substructure of the Galactic halo and disks, providing essential clues to the assembly and enrichment history of the Galaxy.
- In particular, the outer halo is expected to be dominated by late-time accretion events.
- SEGUE can help constrain existing models for the formation of the stellar halo and inform the next generation of high resolution simulations of Galaxy formation.
- In addition, SEGUE-1 and SEGUE-2 help uncover rare, chemically primitive stars that are fossils of the earliest generations of cosmic star formation.

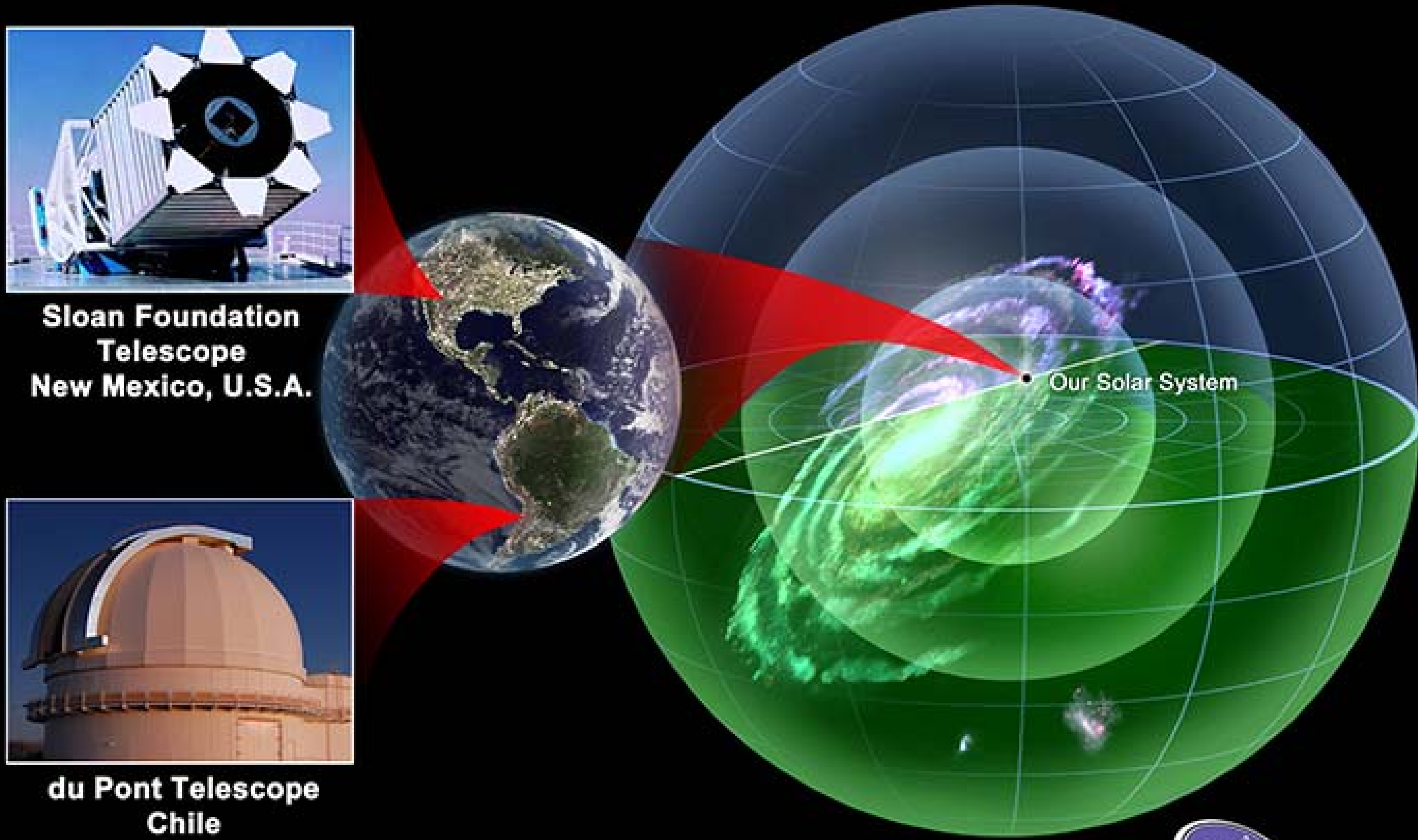
2014-2020, data from the southern hemisphere also

SDSS-IV

SDSS-IV—APOGEE-2

- A stellar spectroscopic survey of the Milky Way, with two major components: a northern survey using the bright time at APO (APOGEE-2N), and a southern survey using the 2.5m du Pont Telescope at Las Campanas, Chile (APOGEE-2S).

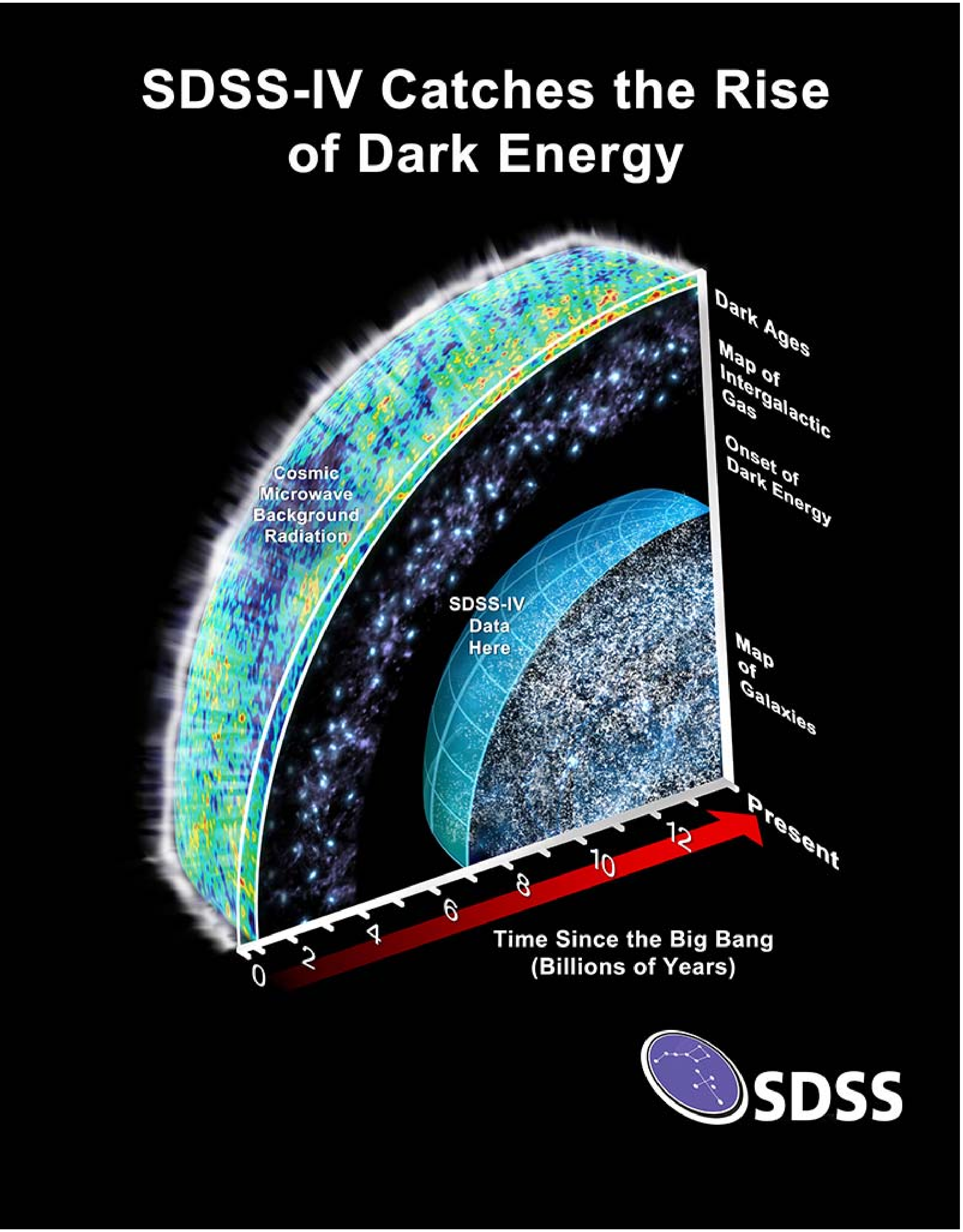
SDSS-IV Can View the Whole Milky Way



SDSS

SDSS-IV—eBOSS

- The **e**xtended **B**aryon **O**scillation **S**pectroscopic **S**urvey
- A cosmological survey of quasars and galaxies, also encompassing subprograms to survey variable objects (TDSS) and X-Ray sources (SPIDERS).
- eBOSS concentrates on the observation of galaxies and quasars, in a range of distances (redshifts) currently left completely unexplored by other three-dimensional maps of large-scale structure in the Universe. In filling this gap, eBOSS creates the largest volume survey of the Universe to date.



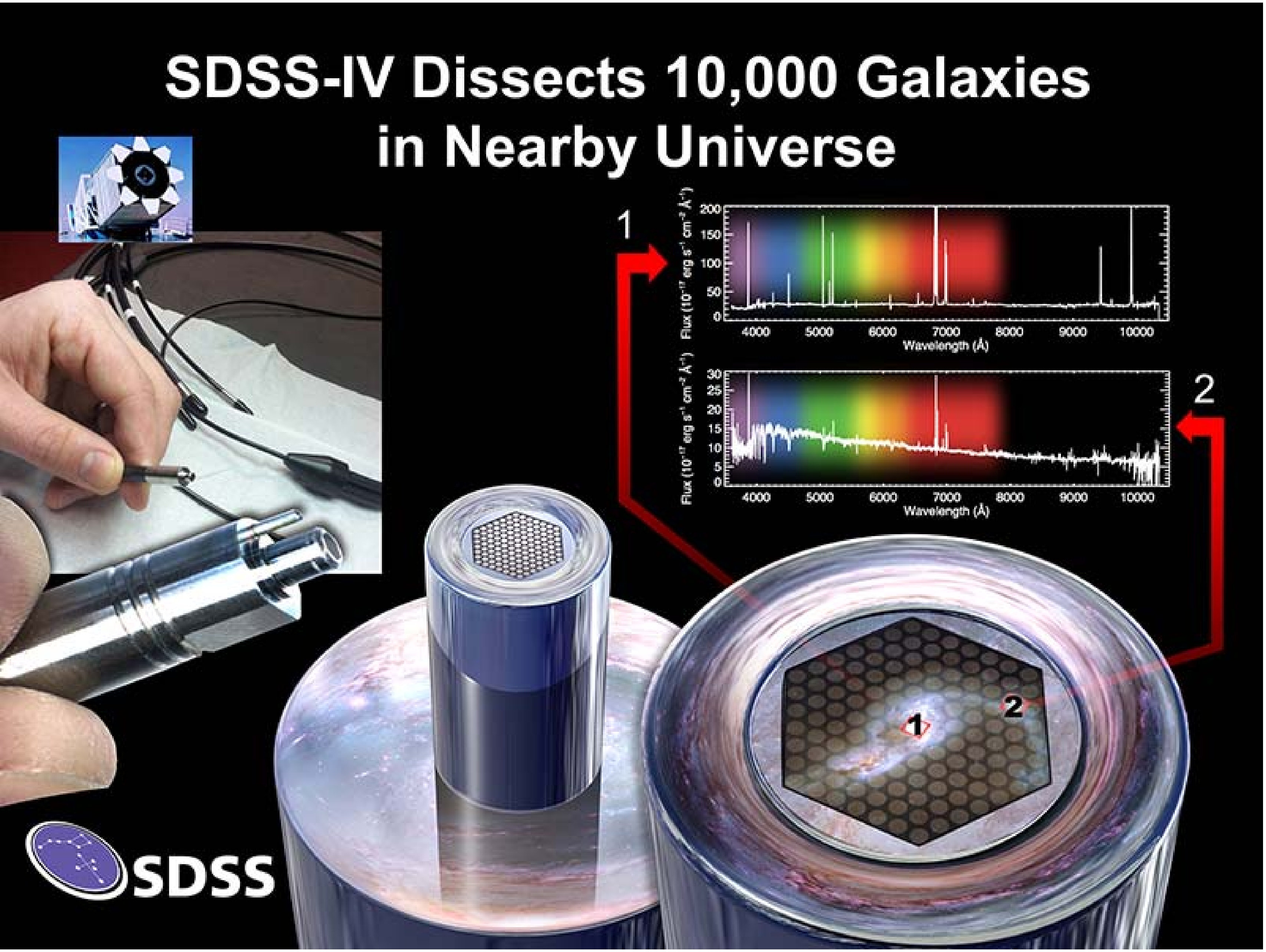
eBOSS maps the distribution of galaxies and quasars from when the Universe was 3 to 8 billion years old, a critical time when dark energy started to affect the expansion of the Universe. At higher redshifts, during a time when the Universe was matter-dominated, eBOSS uses the Lyman-alpha forest* to map out the matter distribution.

*Large distribution of absorption lines all coming from the Lyman-alpha transitions of hydrogen. As light travels through multiple gas clouds with different red shifts, multiple lines form.

Image Credit: Dana Berry / SkyWorks Digital Inc. and the SDSS collaboration.

SDSS-IV—MaNGA

- **Ma**pping **N**earby **G**alaxies at **A**PO (MaNGA)
- Unlike previous SDSS surveys which obtained spectra only at the centers of target galaxies, MaNGA enables spectral measurements across the face of each of ~10,000 nearby galaxies thanks to 17 simultaneous "integral field units" (IFUs), each composed of tightly-packed arrays of optical fibers.
- MaNGA's goal is to understand the "life history" of present day galaxies from imprinted clues of their birth and assembly, through their ongoing growth via star formation and merging, to their death from quenching at late times.



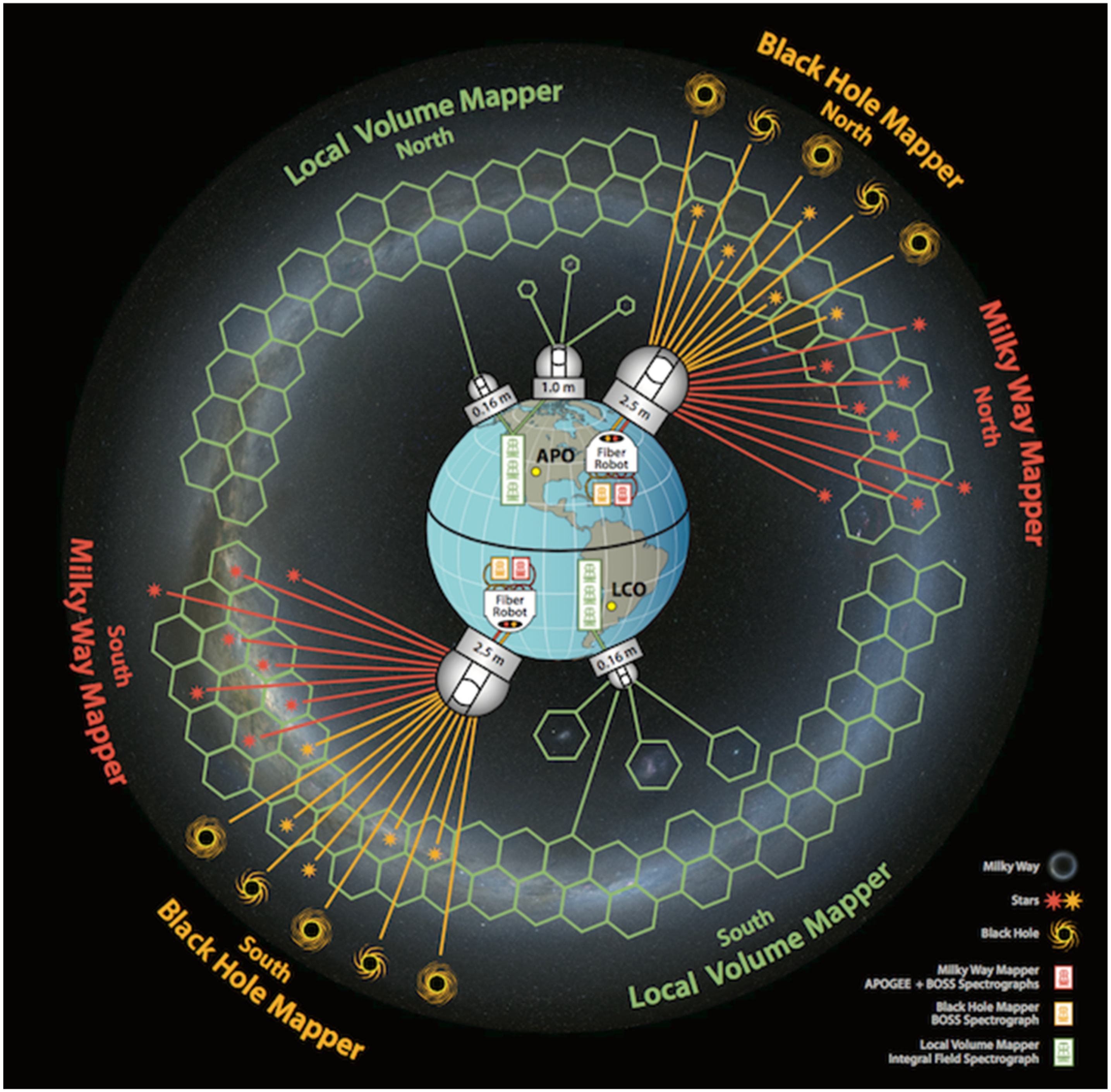
MaNGA obtains spectra across the entire face of target galaxies using custom designed fiber bundles.
The bottom right illustrates how the array of fibers spatially samples a particular galaxy.

The top right compares spectra observed by two fibers at different locations in the galaxy, showing how the spectrum of the central regions differs dramatically from outer regions.
Image Credit: Dana Berry / SkyWorks Digital Inc., David Law, and the SDSS collaboration.

2020- , The future of SDSS

SDSS-V

SDSS-V



SDSS-V will be carried out in both hemispheres, at Apache Point Observatory (APO) in the USA and Las Campanas Observatory (LCO) in Chile. Multi-object fiber spectroscopy will be obtained with two 2.5m telescopes, each feeding a near-infrared APOGEE spectrograph and an optical BOSS spectrograph, for the Milky Way Mapper and Black Hole Mapper programs. The Local Volume Mapper will make use of smaller telescopes to perform its optical integral-field spectroscopy. *Image credit: M. Seibert (OCIS) & SDSS-V team.*

SDSS-V—Milky Way Mapper

- The Milky Way Mapper (MWM) will target 4-5 million stars across the Milky Way, collecting infrared spectra with an APOGEE spectrograph and/or optical spectra with a BOSS spectrograph.
- The MWM seeks to understand the evolution of the Milky Way, the physics of its stars and interstellar medium, and the architecture of multiple-star and planetary systems.

SDSS-V—Black Hole Mapper

- The Black Hole Mapper (BHM) in SDSS-V is a multi-object spectroscopic survey that will emphasize optical spectra (often also with multiple epochs of spectrosopy) for well more than 300,000 quasars to jointly understand the masses, accretion physics, and growth and evolution over cosmic time of supermassive black holes.
- BHM will make use of the existing BOSS spectrographs, which provide wide optical spectral coverage with a spectral resolution of R~2000. BHM will operate on the 2.5m telescopes at both Apache Point and Las Campanas Observatories.

SDSS-V—Local Volume Mapper

- The Local Volume Mapper (LVM) is an optical, integral-field spectroscopic survey that will target the Milky Way, Small and Large Magellanic Clouds, and other Local Volume galaxies.
- LVM will make use of new small telescopes and newly built spectrographs that cover a wavelength range of 3600-10000 Å, with spectral resolution R~4000 (based on the DESI spectrograph design).
- It will collect roughly 20 million contiguous spectra over 2,500 square degrees of sky.

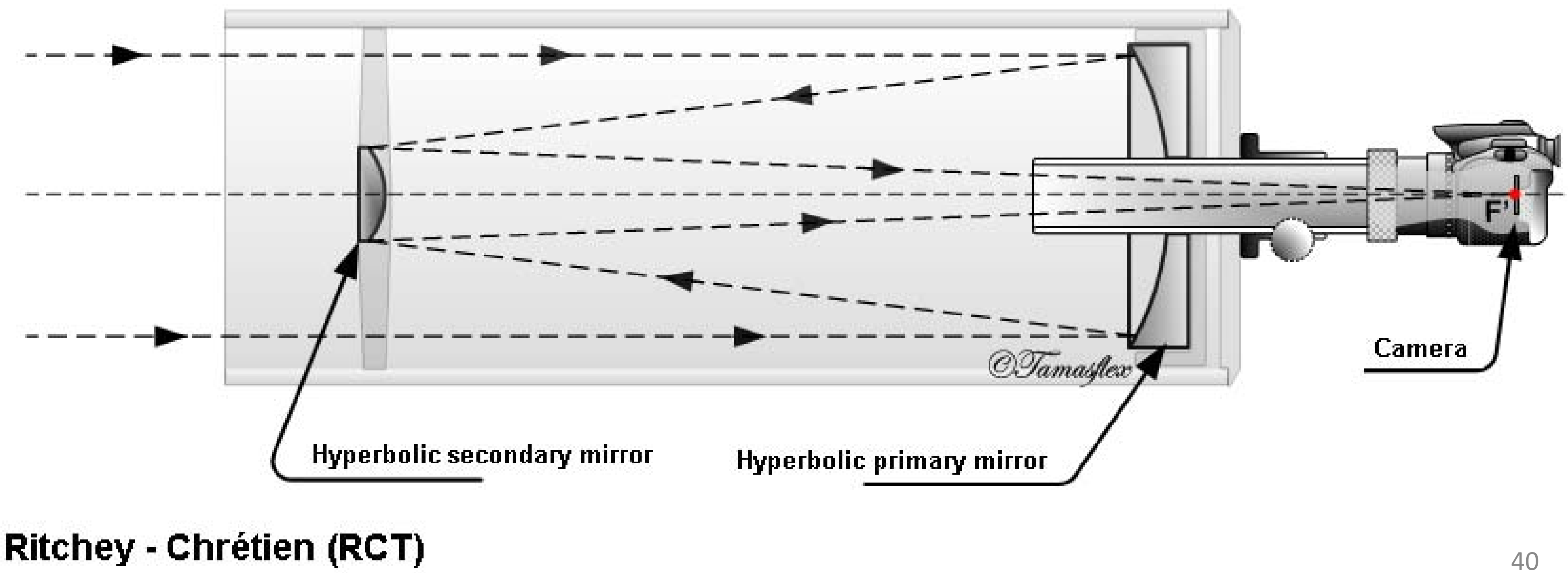
My first time building a telescope on top of a mountain

DETAILS OF THE CONSTRUCTION OF THE 2.5 M APO TELESCOPE

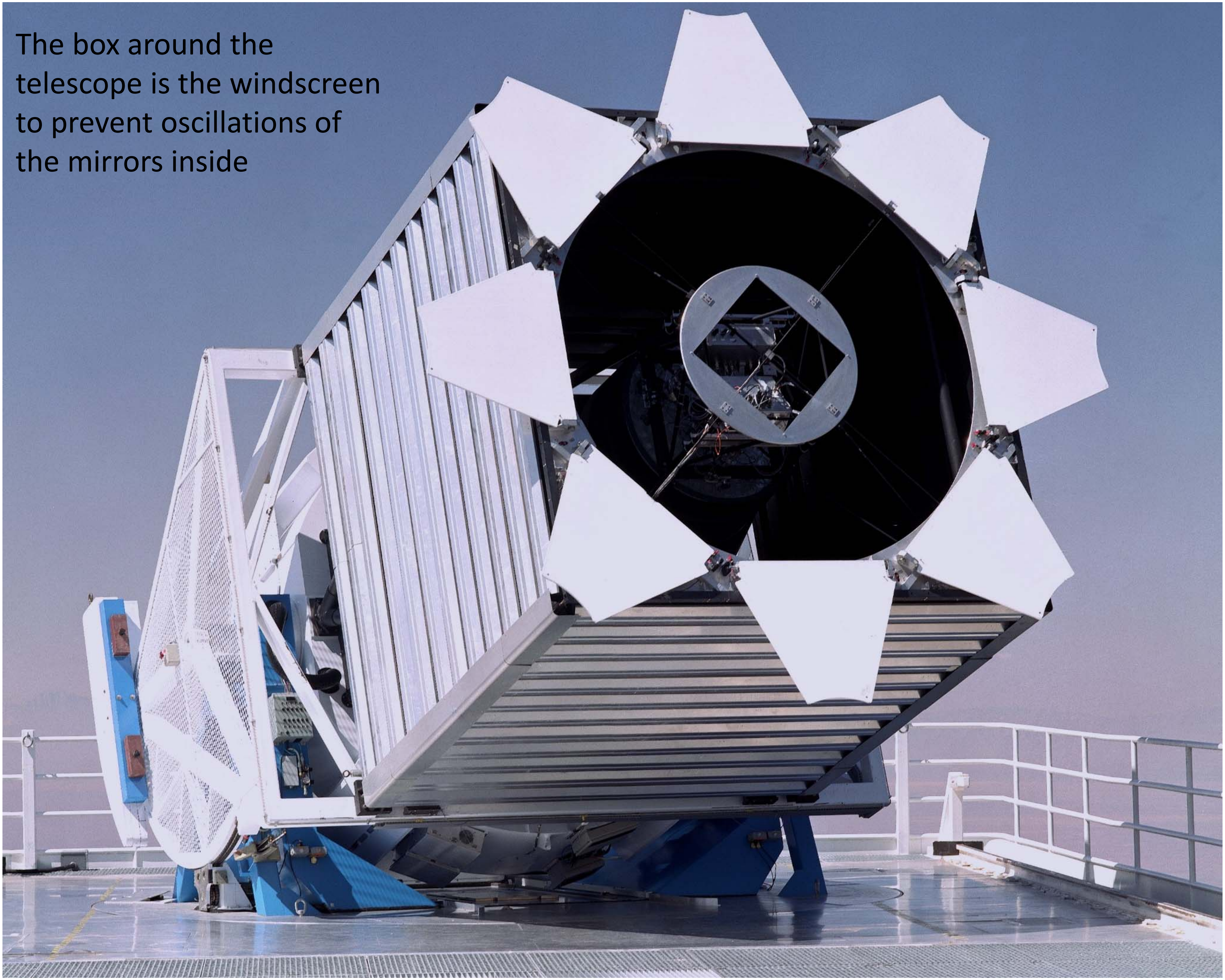
Schematic diagram of a Ritchey-Chretien Telescope

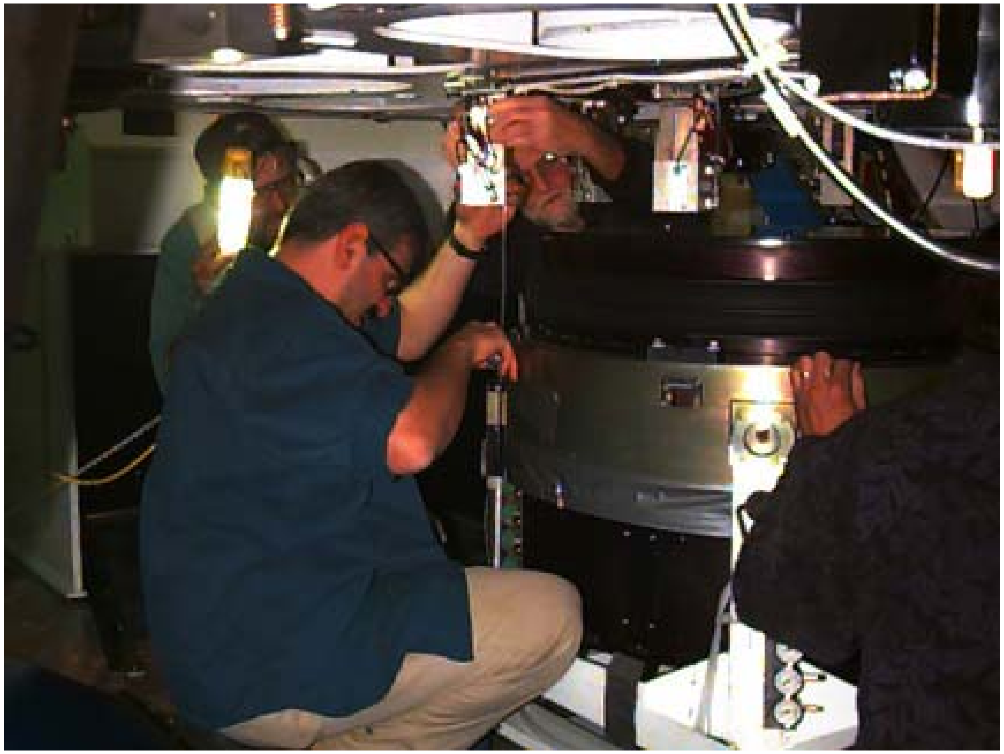
"The telescope is a modified two-corrector Ritchey-Chrétien design with a 2.5 m, f/2.25 primary, a 1.08 m secondary, a Gascoigne astigmatism corrector, and one of a pair of interchangeable highly aspheric correctors near the focal plane, one for imaging and the other for spectroscopy. The final focal ratio is f/5."

From:
https://iopscience.iop.org/article/10.1086/500975#:~:text=The%20telescope%20is%20a%20modified,focal%20ratio%20is%20f%2F5.

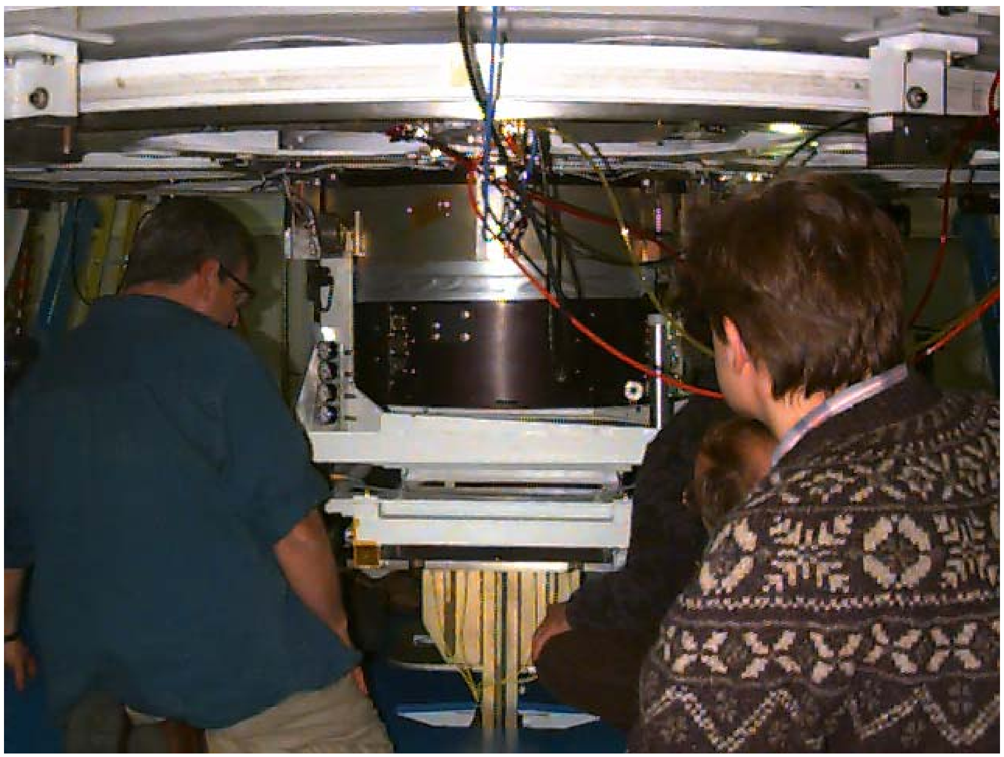


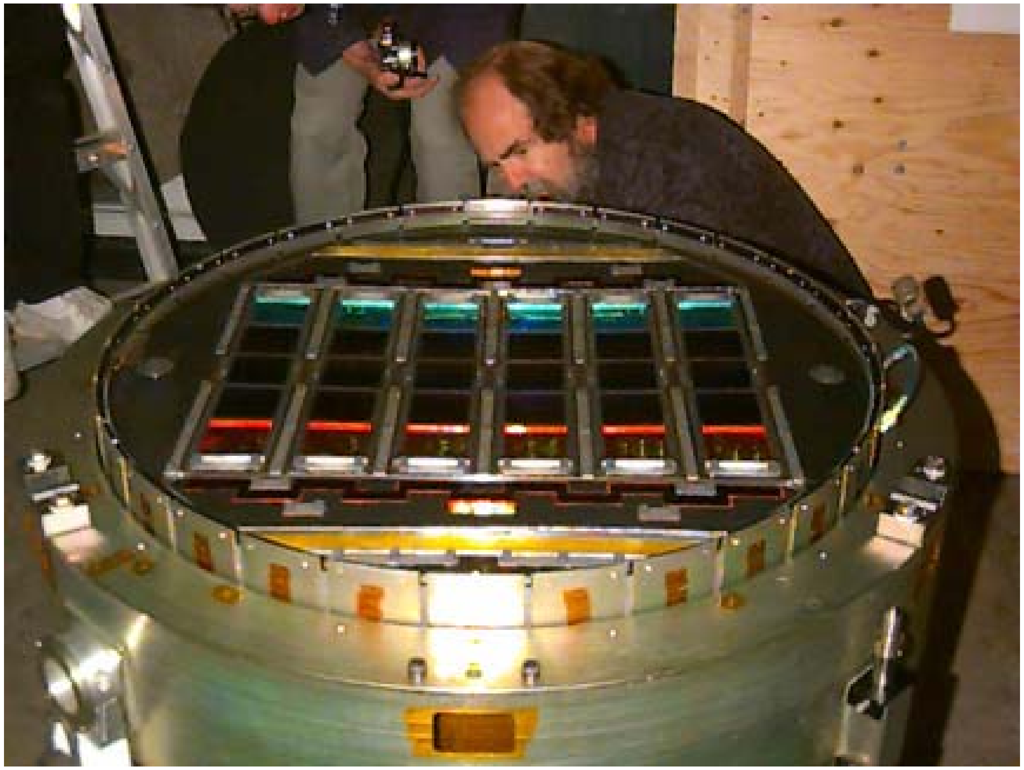
The box around the telescope is the windscreen to prevent oscillations of the mirrors inside





Pictures from the very first time the camera was mated to the bottom of the telescope.





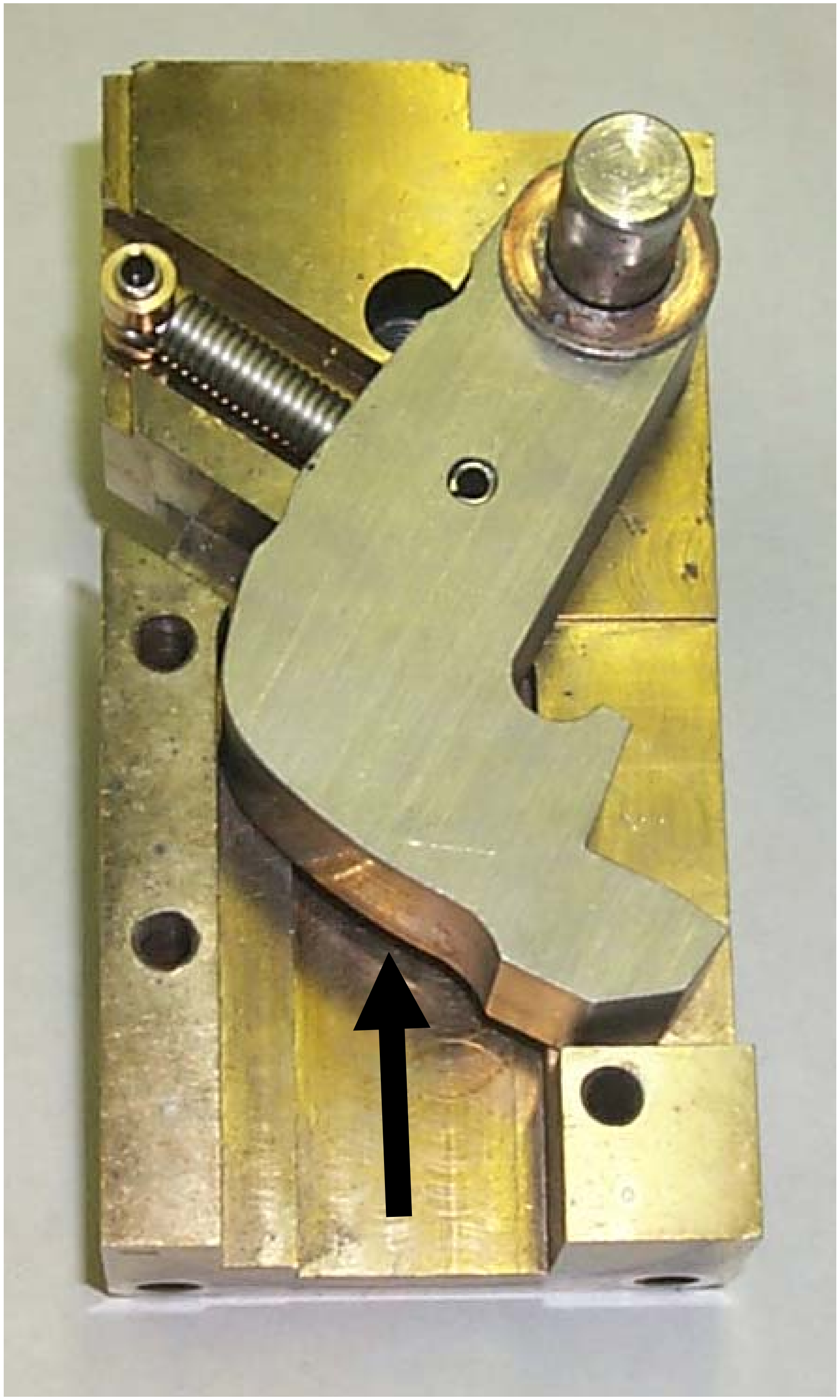
←The man behind the camera is astronomer Jim Gunn.

These pictures are of the 120 megapixel CCD drift camera.

(The new camera built for the Dark Energy Survey is 570 megapixels!)

My role in SDSS

- I was hired by Fermilab in December, 1996, to debug and finish the design of "latches", (pneumatic clamps,) that hold the $4M camera, and the spectroscopes, to the bottom of the telescope
- The original design of the latches didn't work
- I discovered that they had too many "belts and suspenders" and that by simplifying the design they would work fine
- The latches needed to be 100% reliable or something disastrous would happen to the camera or spectroscope

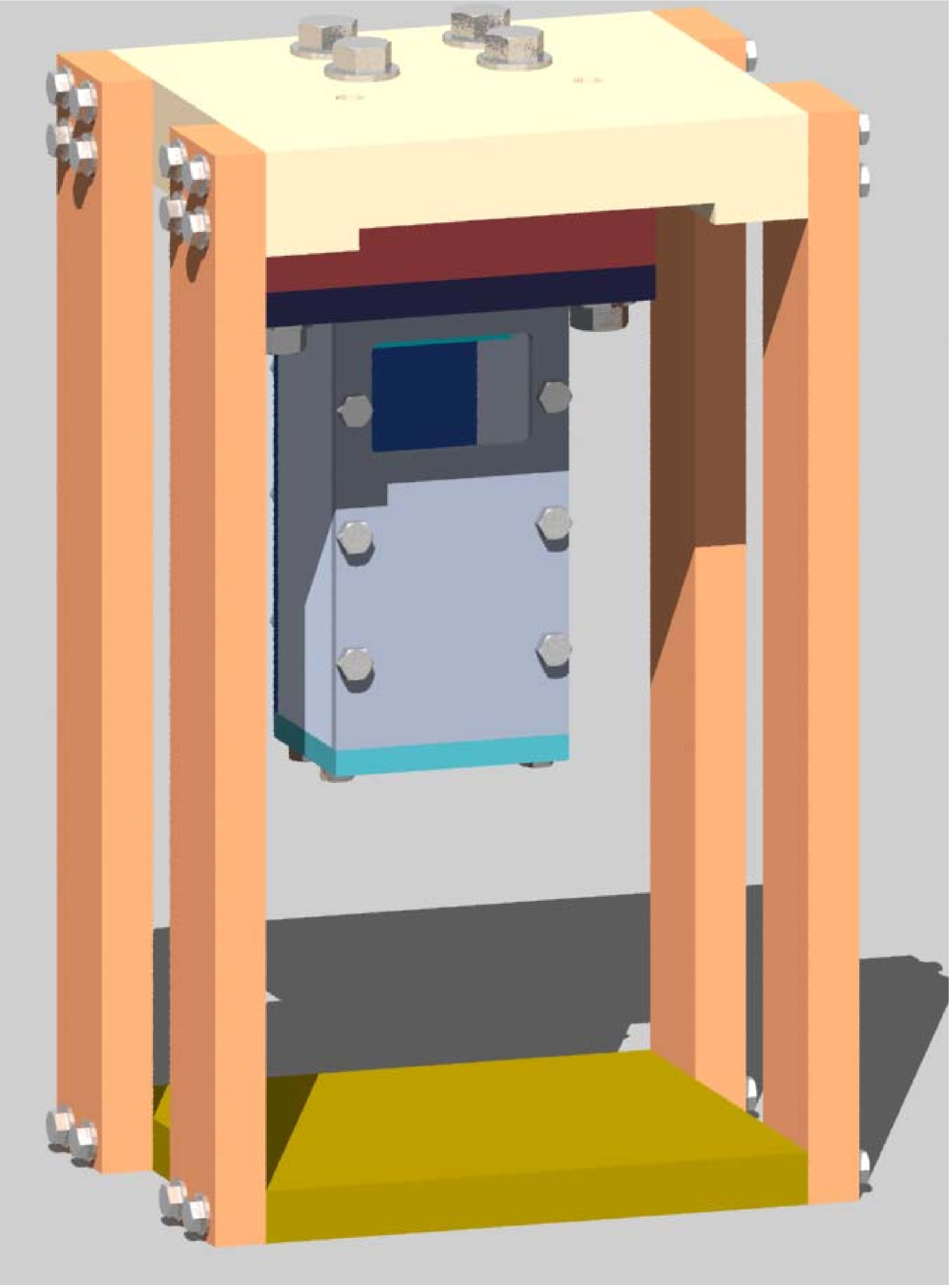


A latch partially disassembled showing the latch bar that rotates on a pin (upper right corner of picture.)

The pneumatic cylinder was attached to the bottom surface of the latch and the piston pushed upwards with a roller that forced the bar to rotate outwards. (The arrows shows the position and action of the pneumatic piston.)

Once the bar was extended out it was locked by the pneumatic piston. When the piston retracted, the spring would retract the latch bar.

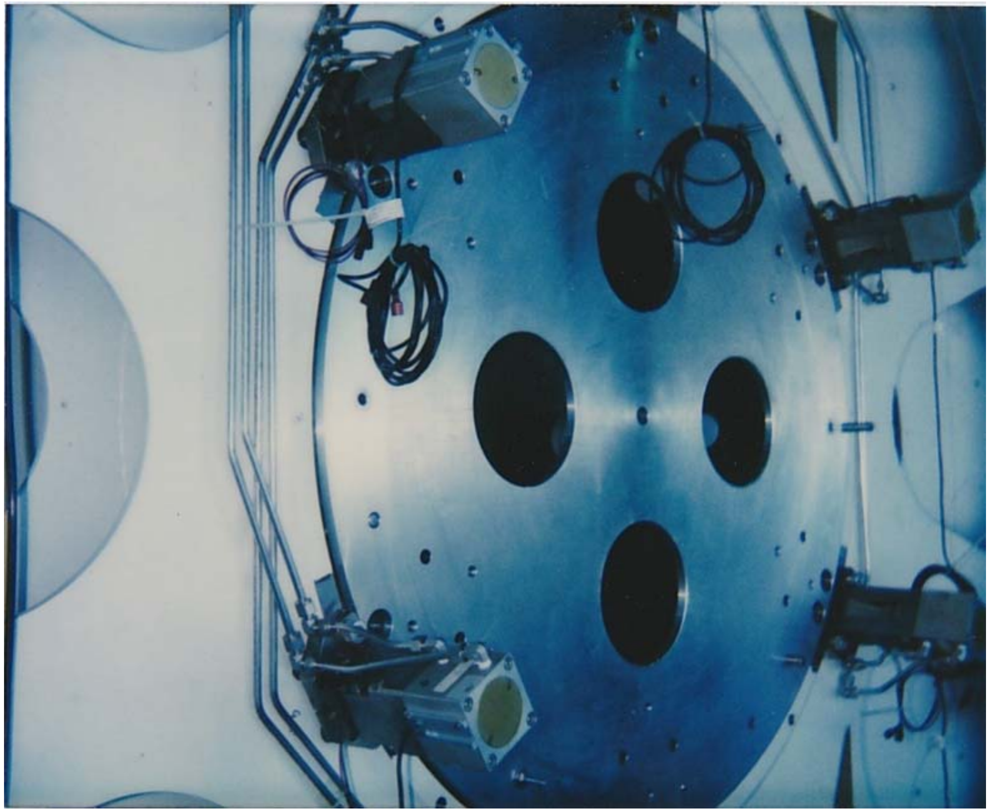
The telescope could lose air pressure once the camera was latched in place and the latches would not retract.



Unfortunately, I don’t have any photos of testing the latches. Here is a rendering of the 3D model of the life testing fixture we used in the freezer at Fermilab.

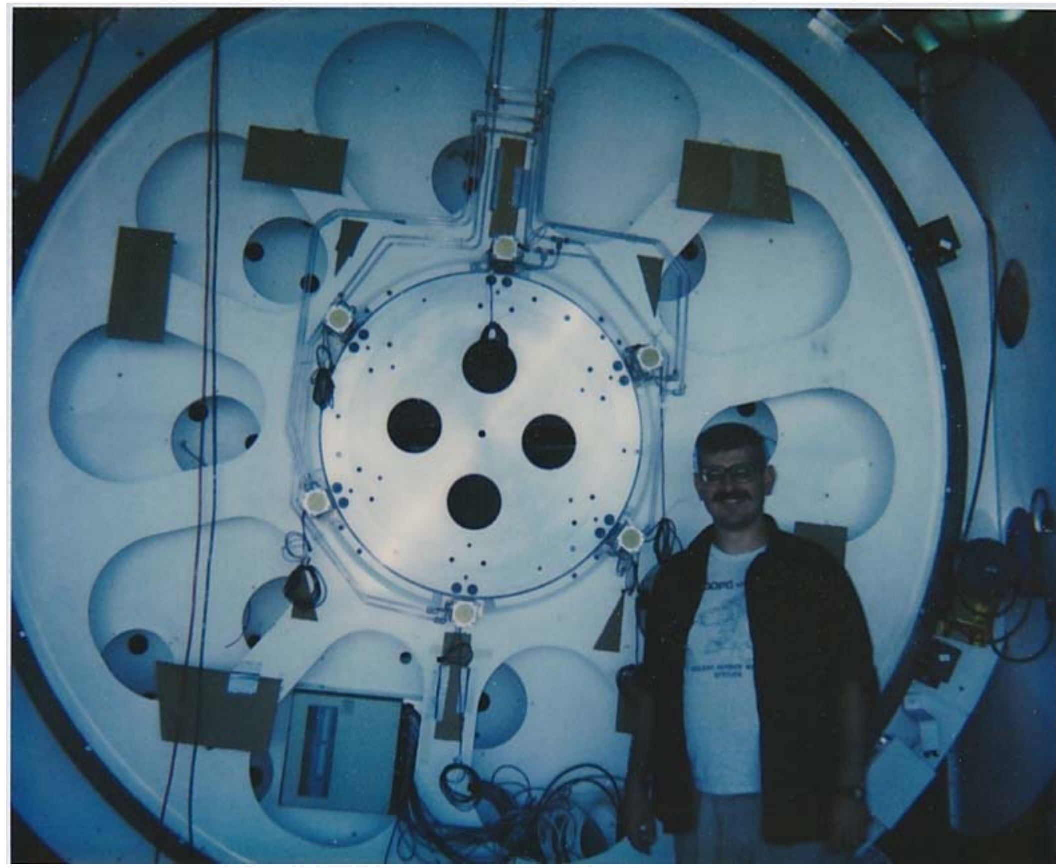
The latch operated against a stack of springs to simulate the camera mounting.

We had to iterate on the alloy of the latch bar and its coatings to finally get a design that didn’t flake off coatings after extended operations.



←Closer view of the pneumatic latches I installed to hold the camera and spectroscope on the telescope. They could not ever fail or we would drop a $4 million camera.
The latches were life tested in a freezer at Fermilab to ensure their operation in cold weather.

I had just spent several days at Apache Point Observatory attaching and installing the pneumatic piping for the latches →



The Sloan Telescope Process

1. One night the telescope would scan across the sky recording the images with a large optical CCD camera
2. Astronomers would look at the images and select objects for spectroscopic analysis
3. A “plug plate” was made with individual holes for each object selected
4. The camera was taken off and a spectroscope was mounted with optical fibers to each hole in the plug plate (so each individual object’s light could be separately analyzed)
5. On a following night, the telescope looked at the same patch of sky with the spectroscope and the light of each object was separated into its spectrum to observe the redshift of the object
   – Farther objects are whole galaxies, not single stars

Attaching the optical fibers between the plug plate and the spectroscope

More on SDSS

- In July 2020, after a 20-year-long survey, astrophysicists of the Sloan Digital Sky Survey:
  - published the largest, most detailed 3D map of the universe so far
  - fill a gap of 11 billion years in its expansion history
  - provide data which supports the theory of a flat geometry of the universe
  - confirms that different regions seem to be expanding at different speeds.
    - From the Wikipedia

SDSS accomplishments

- The Sloan Digital Sky Survey has created the most detailed three-dimensional maps of the Universe ever made and spectra for more than three million astronomical objects.
- SDSS helped create the first map of the Dark Matter in the Universe
- The data are all available to the public