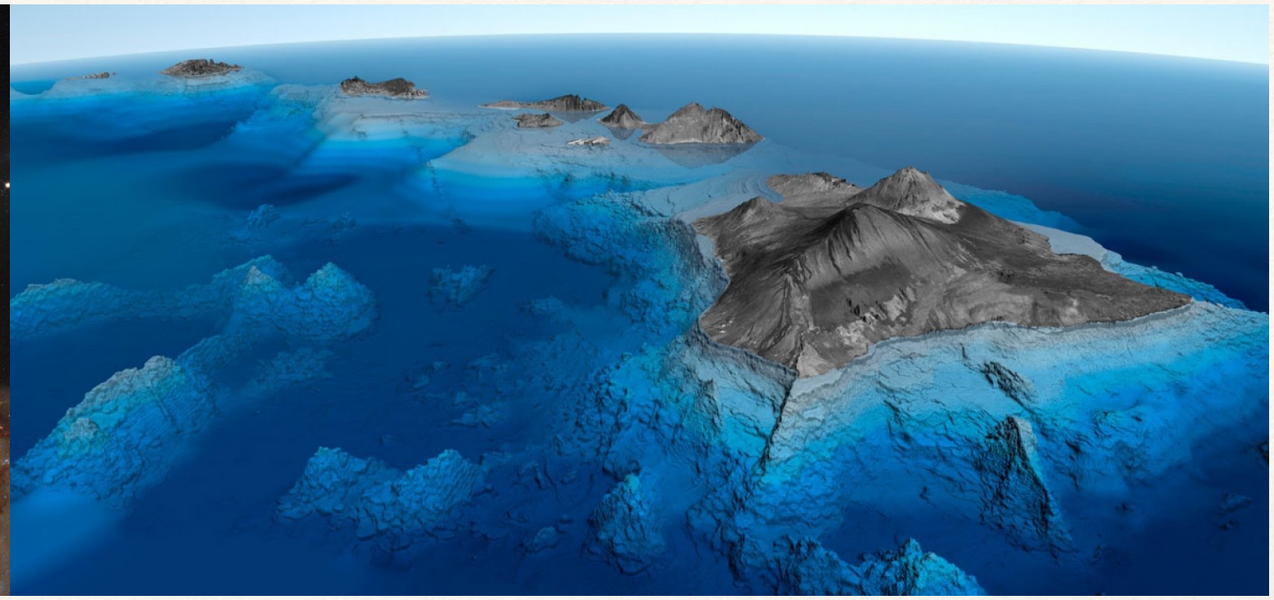

Getting to know the "island universes" out there.

Galaxies I

ASTR 555
Dr. on olt an

Warm-up

- **Write for 2 minutes** about the following questions:
  - How would you classify these two galaxies visually (using the Hubble/de Vaucouleurs system)?
  - For each of the non-parametric measures (C, A, S, G, M20), which galaxy has a larger value?

Warm-up

- **Write for 2 minutes** about the following questions:
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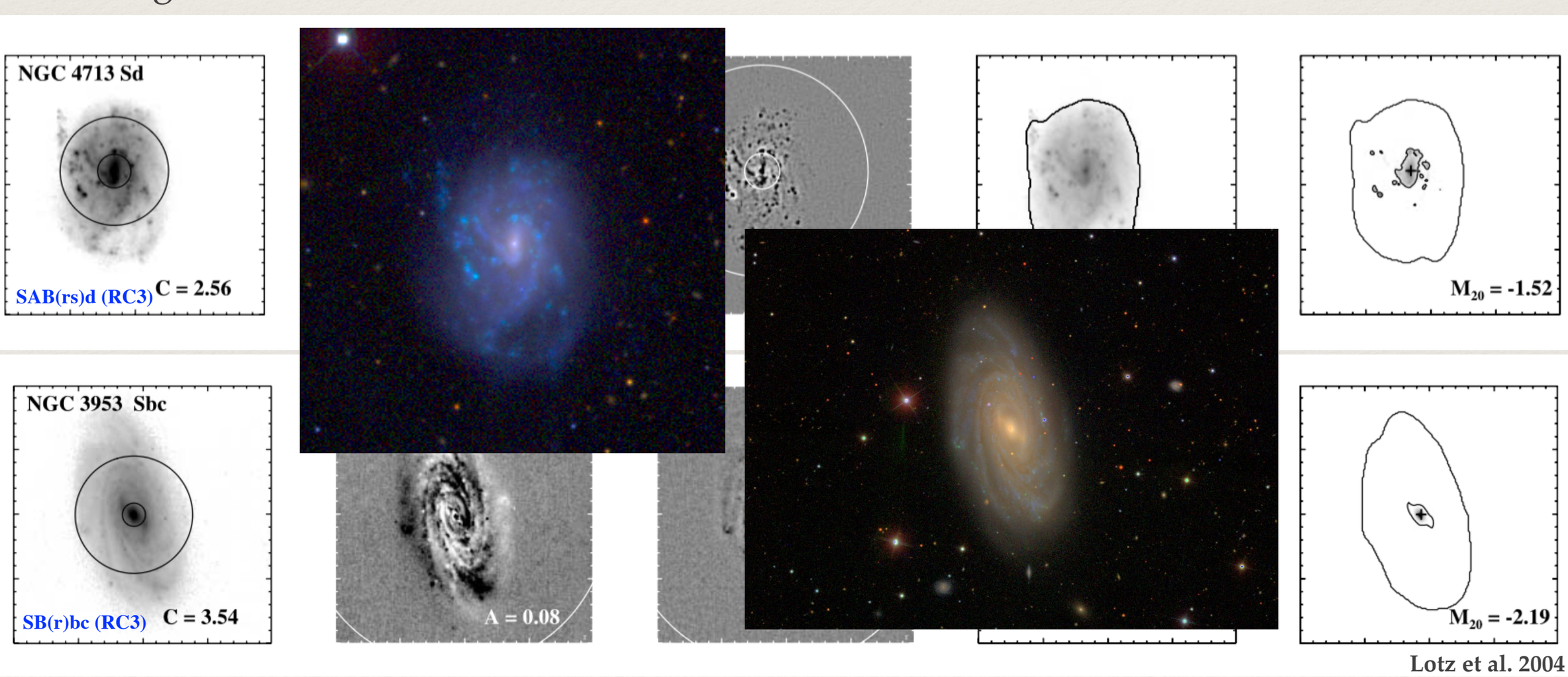


Lotz et al. 2004

Outline for Today

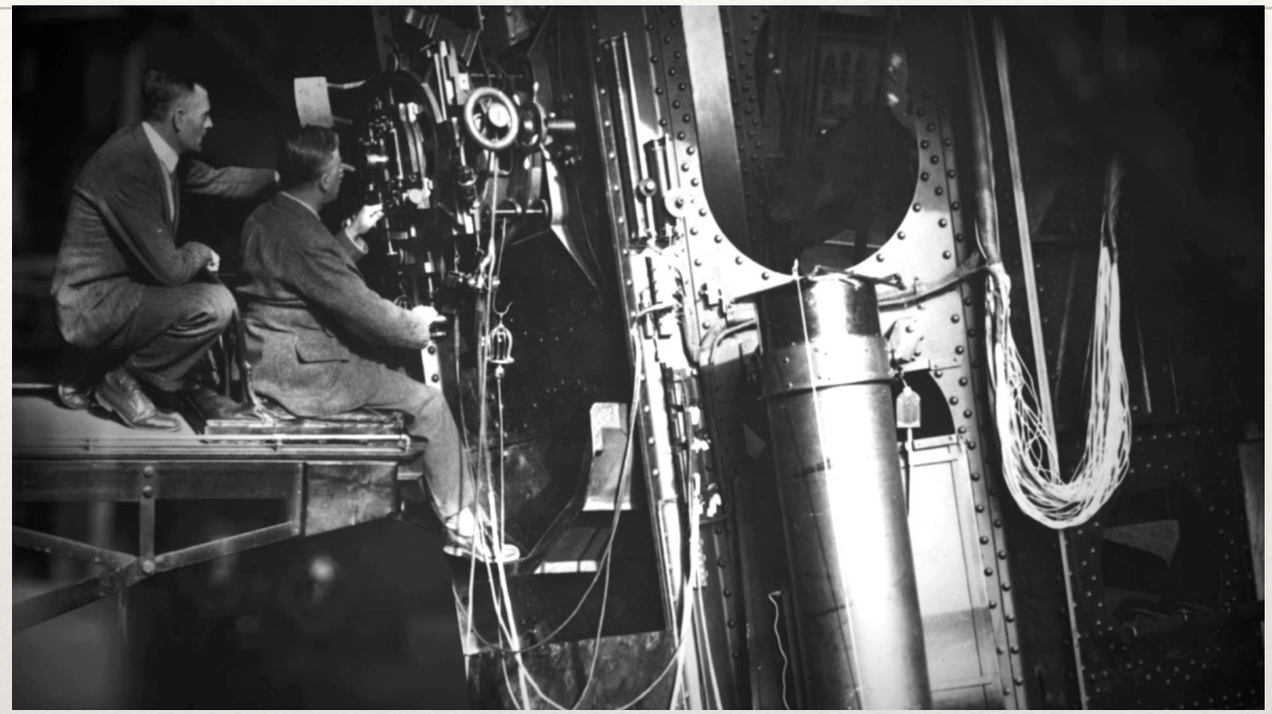
- Observing Galaxies - Surveys & Catalogs:
  - Classic catalogs
  - Surveys:
    - Wide / All-sky Imaging
    - Deep Imaging
    - Spectroscopy
- Selecting Galaxies

NGC1232 (ESO)

Setting the stage

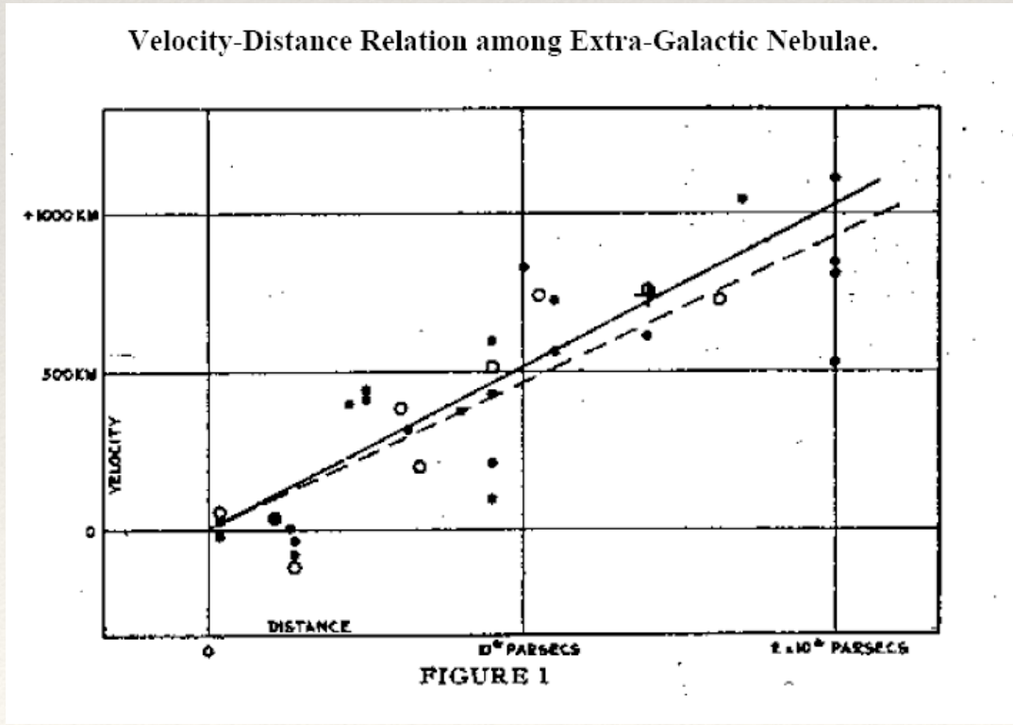
ALL PHOTOGRAPHS COURTESY LOWELL OBSERVATORY UNLESS OTHERWISE NOTED

Vesto Slipher



Edwin Hubble & Milton Humason

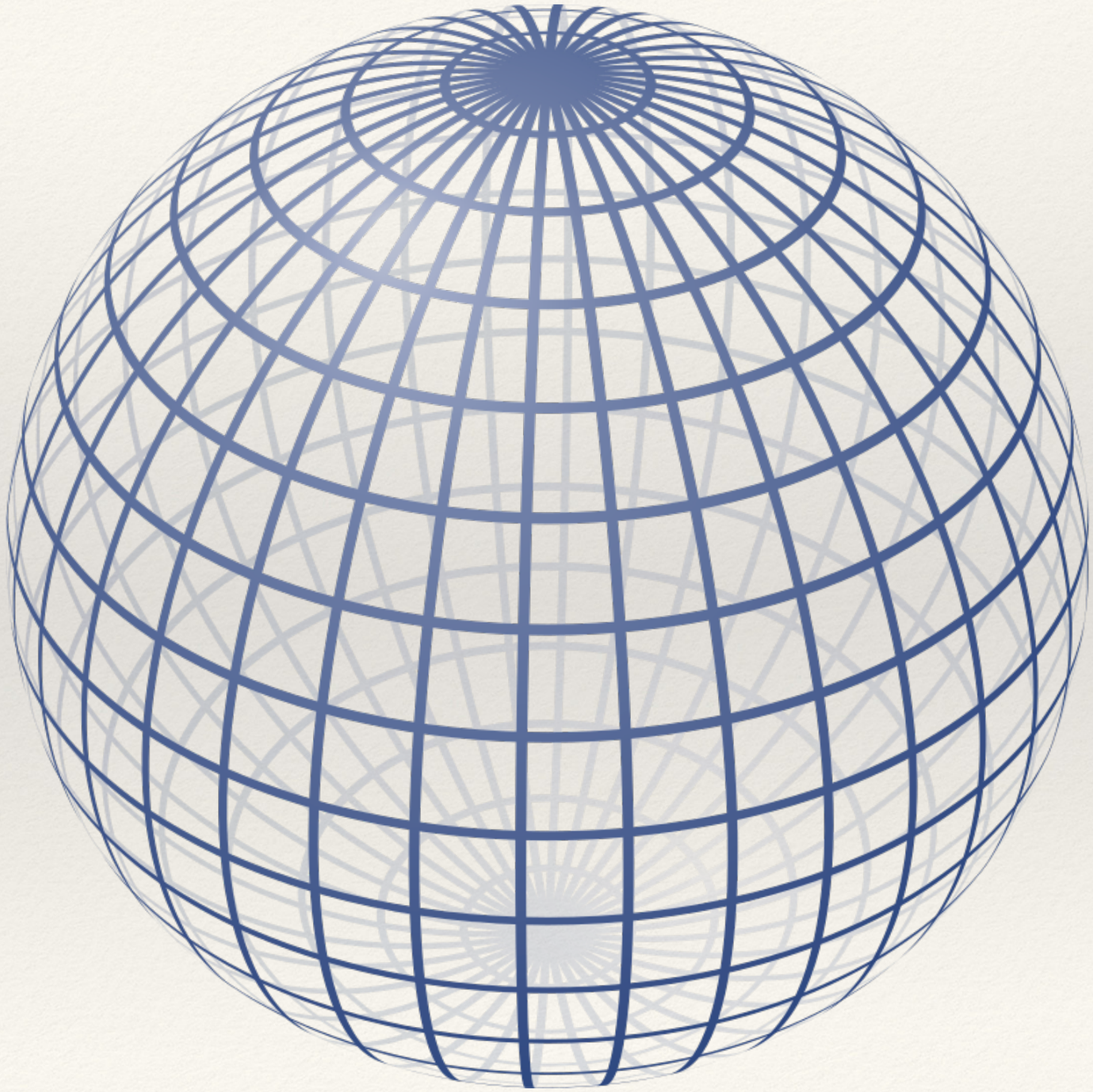
- Slipher measures redshifts of galaxies (1910s)
- Hubble & Humason measure distances (1920s-1930s)
- Galaxies are “island universes” and the universe is expanding!



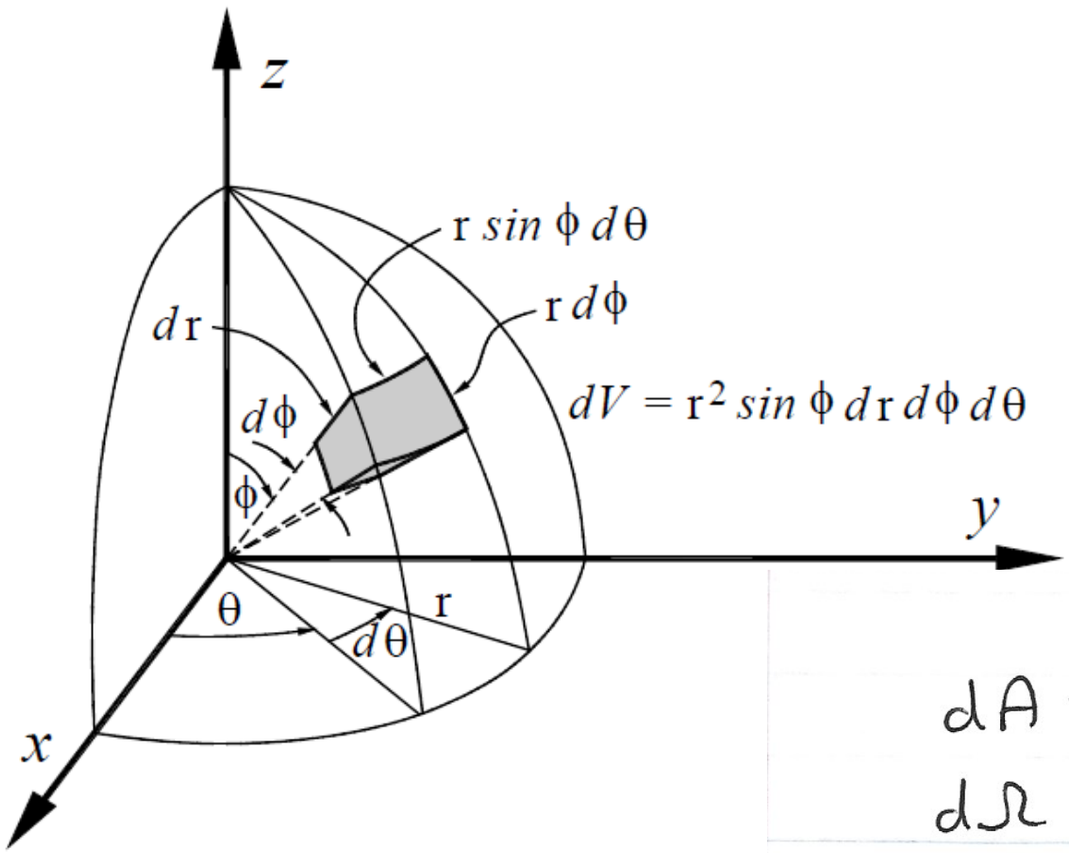
Hubble 1929

Quick Question

- How many square degrees in the sky?
- Consider a Kodak 103a-E photographic plate (1950s era) with a field of view of 6.5x6.5 degrees.
- How many images would it take to map the entire sky?



x Question



$$dA = r^2 \sin\phi \, d\theta \, d\phi$$

$$d\Omega = dA / r^2$$

$$d\Omega = \sin\phi \, d\theta \, d\phi$$

$$\Omega = \int_0^{\pi} \int_0^{2\pi} \sin\phi \, d\theta \, d\phi = (-\cos\phi)\Big|_0^{\pi} \theta\Big|_0^{2\pi}$$

$$\Omega = (-(-1) - (-1))(2\pi - 0)$$

$$\Omega = 4\pi \text{ steradians (square radians)}$$

$$= 4\pi \left(\frac{180^\circ}{\pi \text{ radians}}\right)^2$$

$$\approx 41253 \text{ square degrees}$$

So $41253\ \square^\circ / (6.5^\circ \times 6.5^\circ) = \sim 976$ images

Observing Galaxies - Surveys & Catalogs: Wide/All-sky

- To develop uniform catalogs of astronomical objects, need large area/all sky surveys:
  - Palomar Sky Survey, POSS I (1950s)
  - Southern version, ESO-SERC (1970s)

POSS I/II: The 48-inch Oschin Schmidt telescope, Mount Palomar Observatory

M81 (POSS I - B band) **M81 (POSS I - R band)**

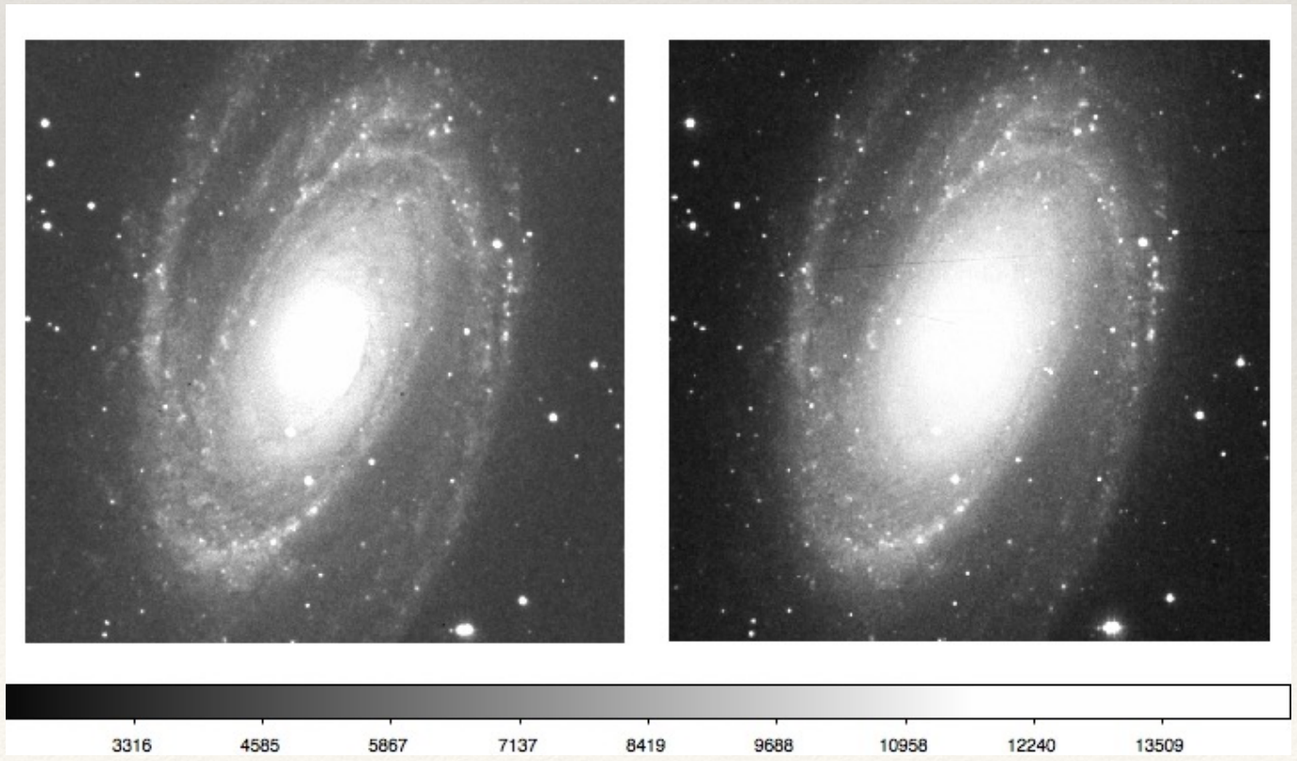


Plate camera, Kodak 103a-E film: https://uiobservatory.omeka.net/items/show/6

Observing Galaxies - Surveys & Catalogs: Wide/All-sky

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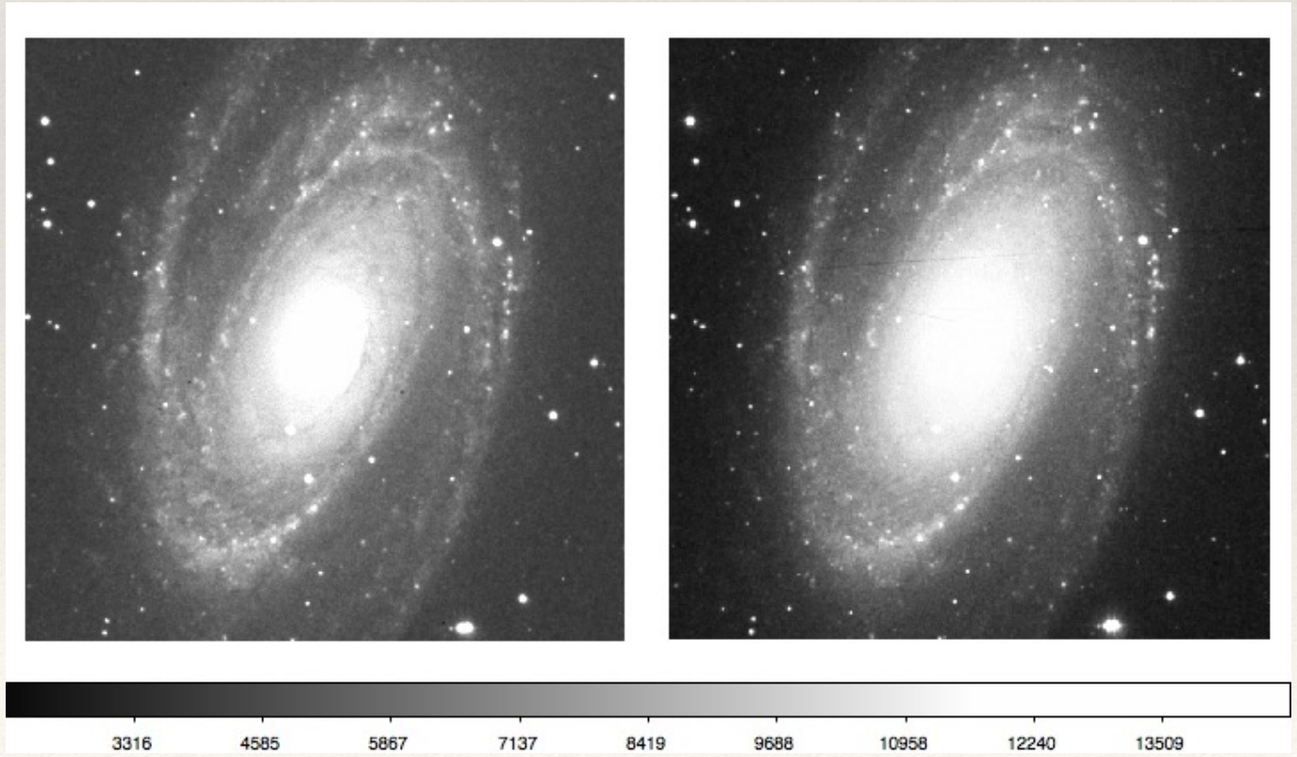


Plate filing cabinets: https://sotonastroart.wordpress.com/sky-surveys/

Observing Galaxies - Surveys & Catalogs: Classic Catalogs

- Once have a survey, the next step is to make a catalog!
  - Object name, position, size, brightness, color, etc.
- A handful of "classic catalogs":
  - **NGC/IC**: New General Catalog and Index Catalogs (Dreyer 1888, 1895, 1908) — ~13,226 galaxies
  - **CGCG**: Catalog of Galaxies and Clusters of Galaxies (Zwicky 1961-68) — ~31,000 galaxies, ~10,000 galaxy clusters
  - **MCG**: Morphological Catalog of Galaxies (Vorontsov-Velyaminov & Arhipova, 1964) — ~29,000 galaxies
  - **Arp**: Atlas of Peculiar Galaxies (Arp 1966) — 340 peculiar galaxies
  - **UGC**: Uppsala General Catalog (Nilsen 1973) — 12,939 galaxies
  - **RC3**: Third Reference Catalogs (de Vaucouleurs 1991) — 23,024 galaxies

Observing Galaxies - Surveys & Catalogs: Classic Catalogs

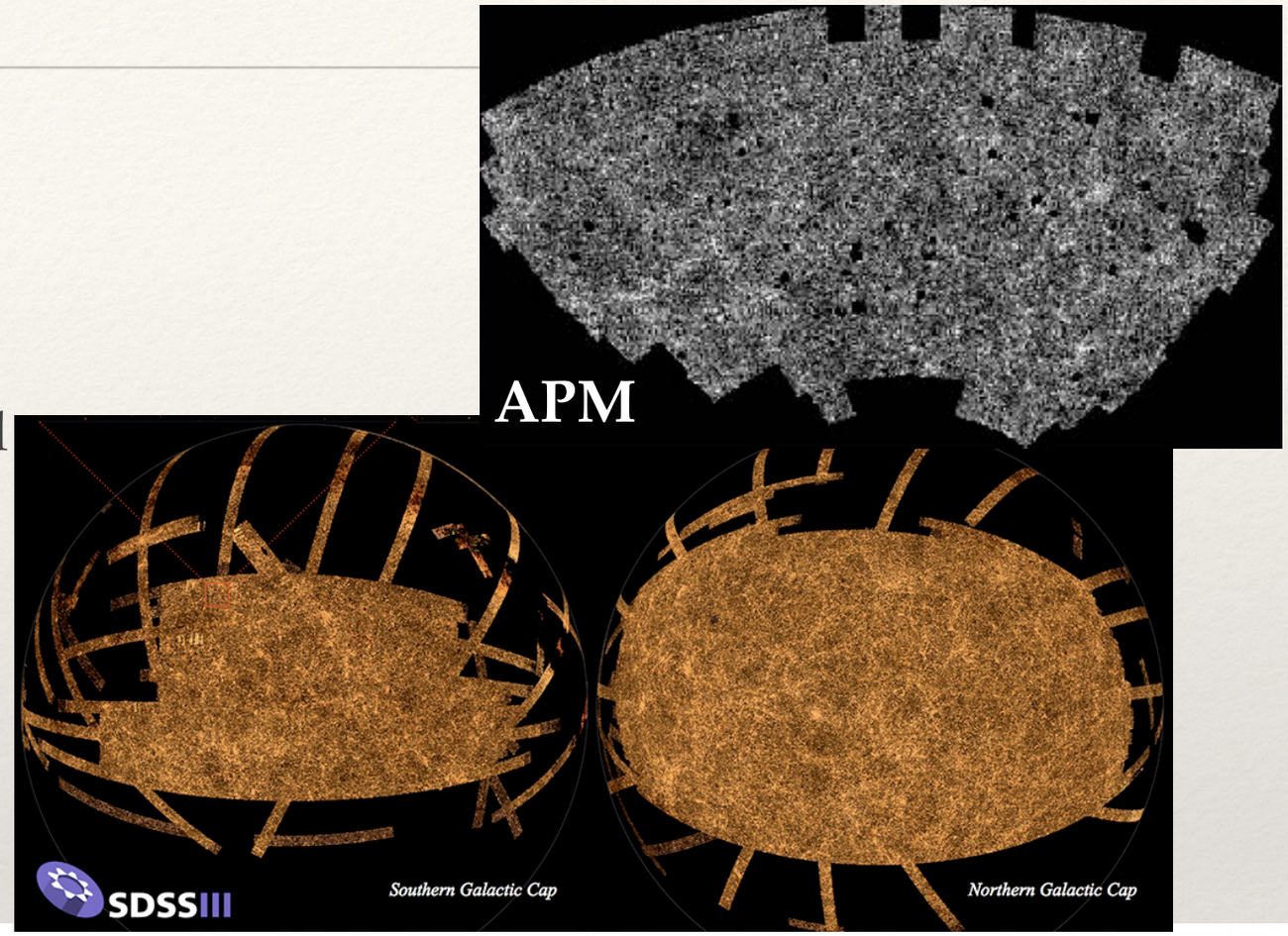
- One galaxy can have lots of names!
- For example, the Whirlpool Galaxy is called M51, NGC 5194, UGC 8493, Arp 85

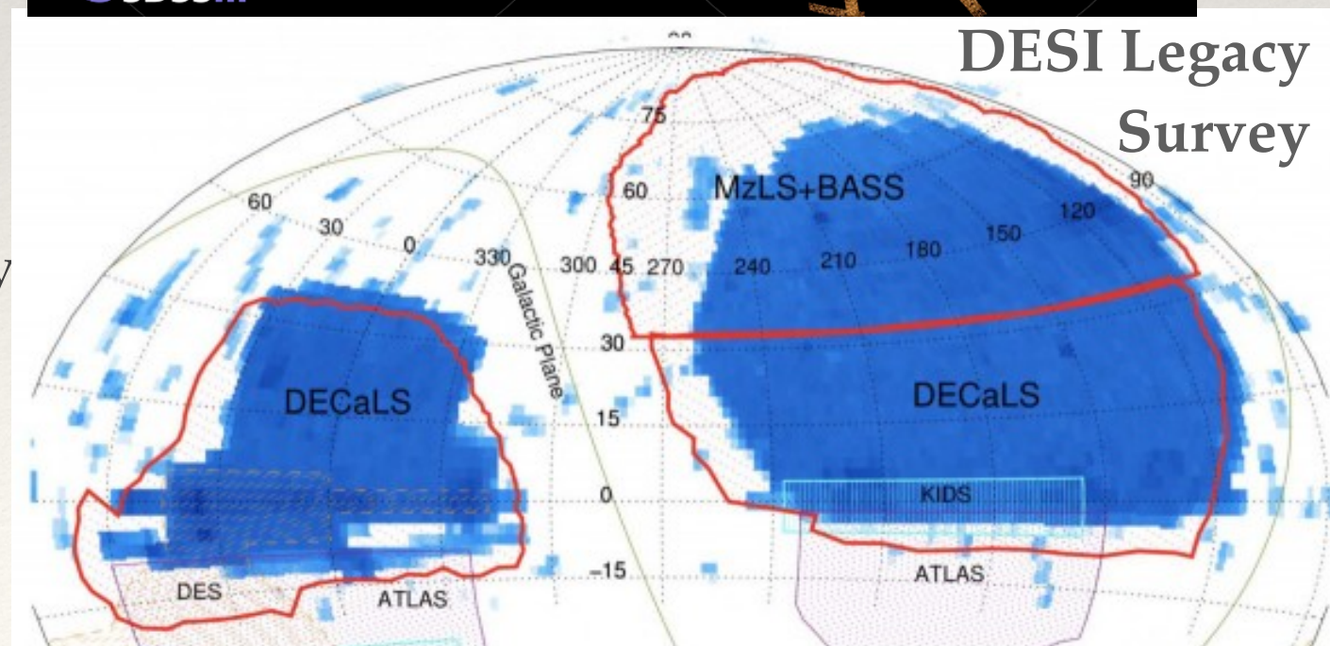
Image: William Parsons, Third Earl of Rosse, using 72-inch meridian-based telescope on the grounds of Birr Castle in Ireland (1845)

NASA/ESA

Observing Galaxies - Surveys & Catalogs: Wide/All-sky

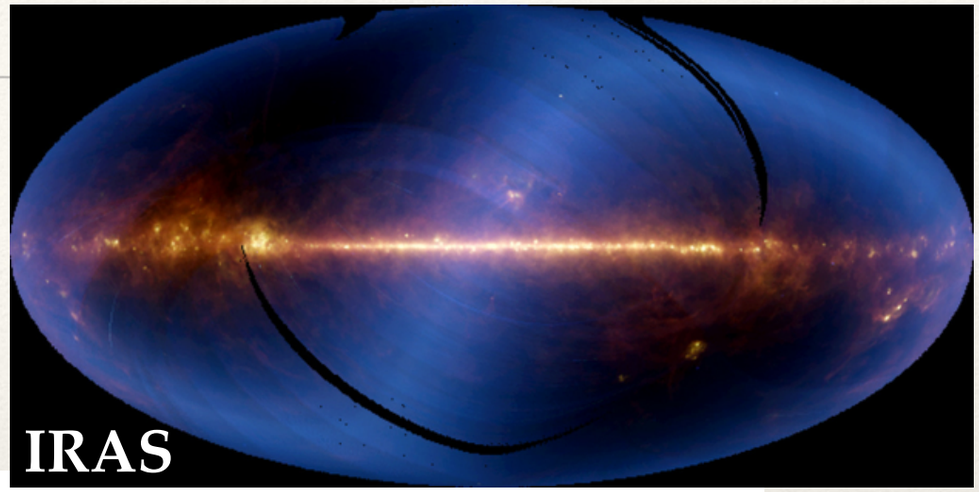
- **Optical wide/all-sky surveys:**
  - DSS: "Digitized Sky Survey" of POSS + ESO/SERC, 1990s; ~entire sky
  - UKST/APM: UK Schmidt survey, digitized version, 1990s; ~4300 sq. degrees
  - SDSS I-III: Sloan Digital Sky Survey, imaging 2000s; ~14,000 sq. degrees
  - PanStarrs: sky north of dec=-30, 5 bandpasses
  - DESI Legacy Survey: ~14,000 sq. degrees; three optical and four IR bands, 2014-2019
  - Vera Rubin Observatory/LSST: will survey entire visible sky every 3 nights over 10 years, ~2022-2032

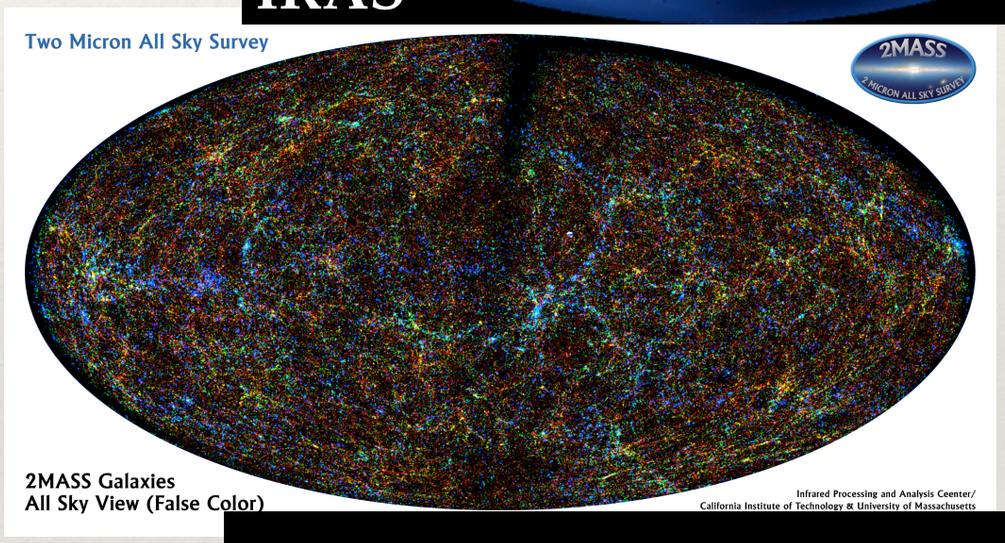


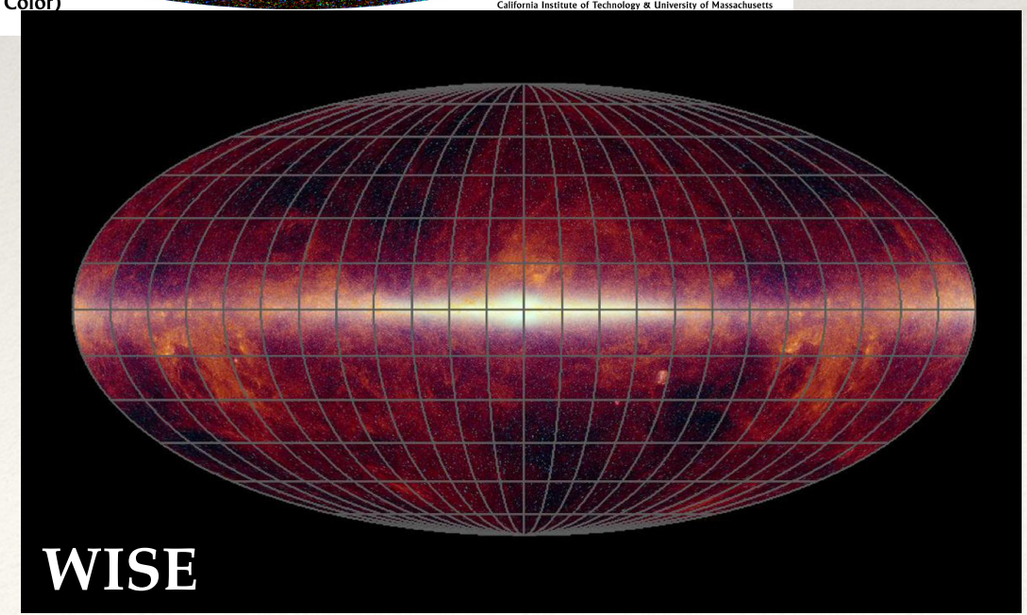


Observing Galaxies - Surveys & Catalogs: Wide/All-sky

- **Infrared all-sky surveys:**
  - IRAS: satellite, full IR, ~4 arcmin resolution, 1983
  - 2MASS: ground, near-IR, few arcsec resolution, 2000s
  - WISE: satellite, full IR, few arcsec resolution, 2011

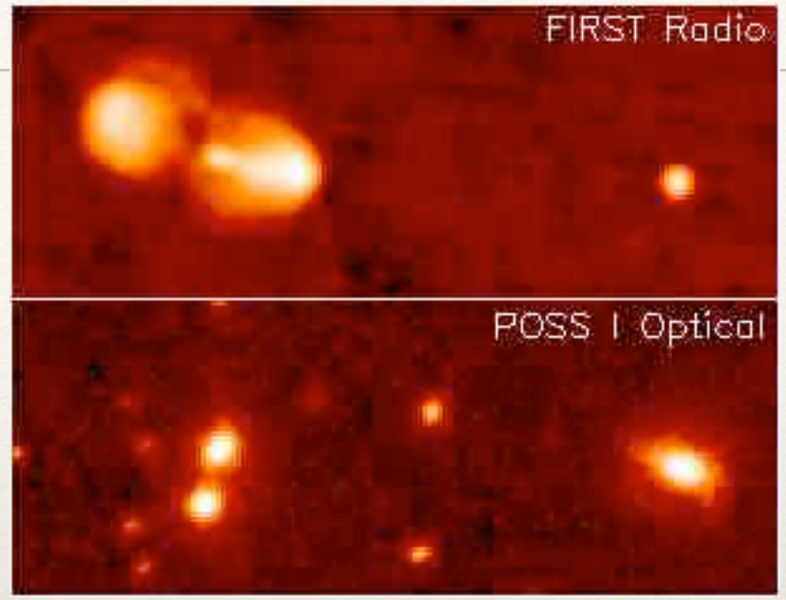




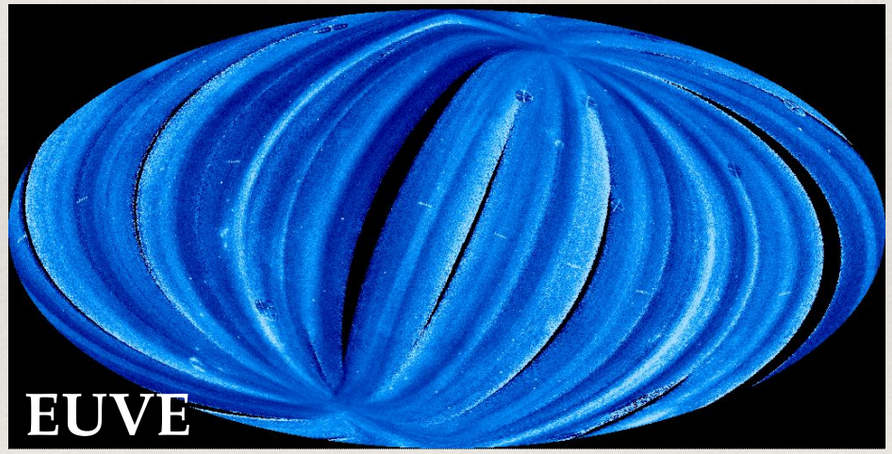


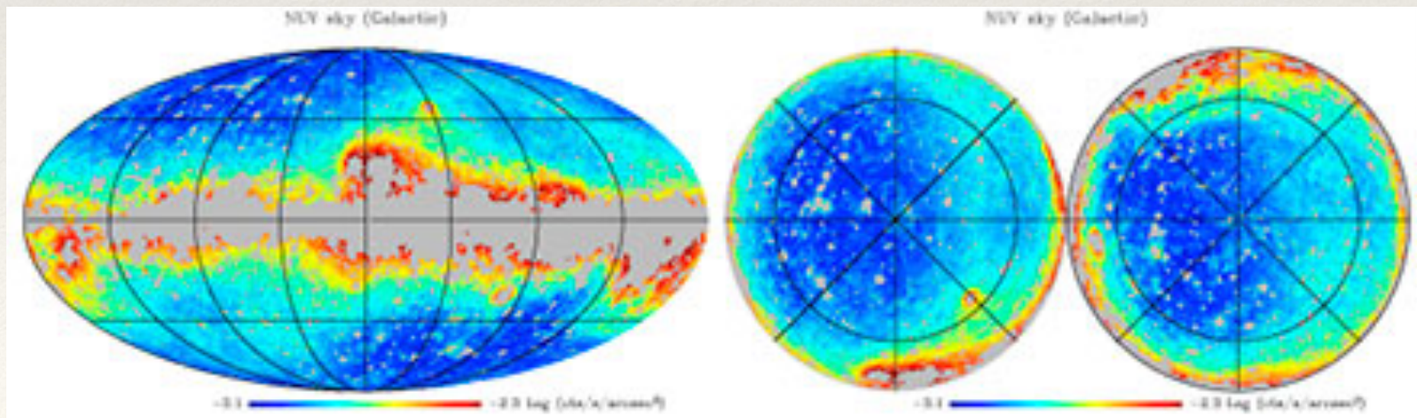
Observing Galaxies - Surveys & Catalogs: Wide/All-sky

- **Radio wide-area surveys:**
  - FIRST: VLA north Galactic cap, ~10,000 sq degrees, 5 arcsec resolution, 1994-2004
  - NVSS: all sky north of -40 degrees declination, 34,000 sq degrees, 45 arcsec resolution, 1998
- **UV (satellite) all-sky surveys:**
  - EUVE: 70-760 Å, first dedicated extreme UV mission, 6 arcmin resolution, 1990s; ~entire sky
  - GALEX: far-UV (1350-1750 Å) & near-UV (1750-2800 Å), few arcsec resolution, 2003-2013; ~entire sky



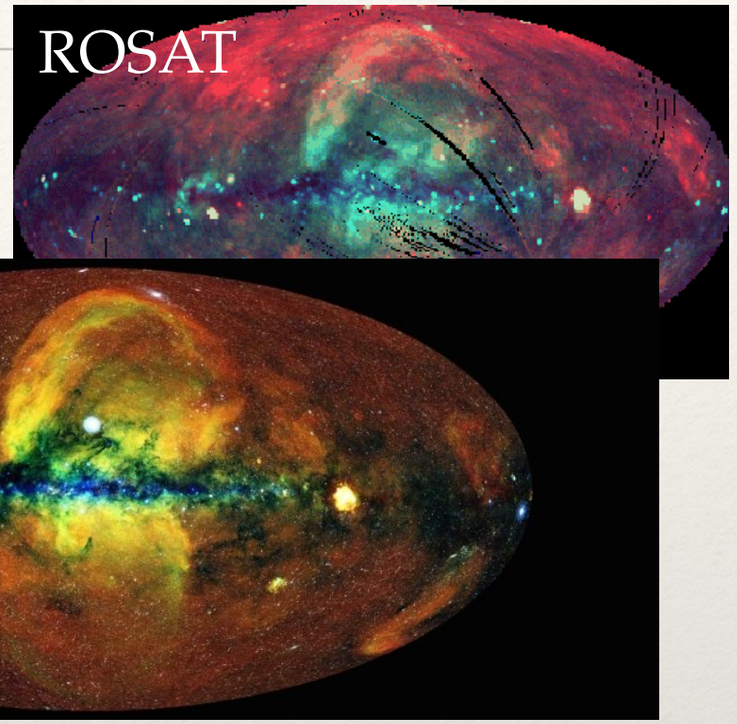
Faint Images of the Radio Sky at Twenty-Centimeters (FIRST)

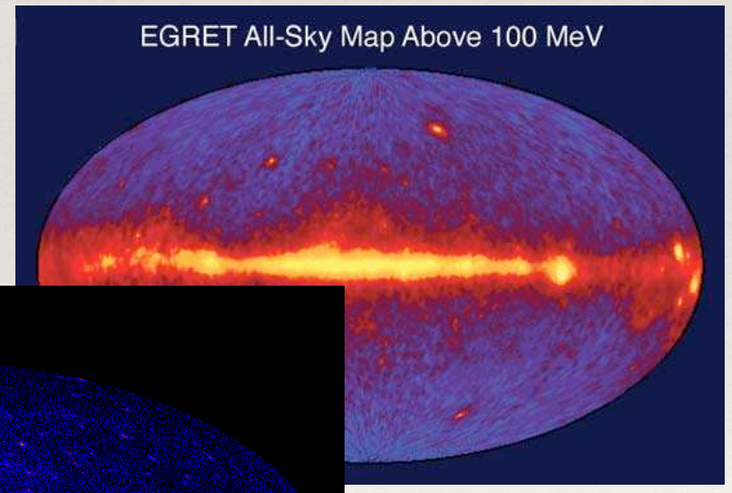


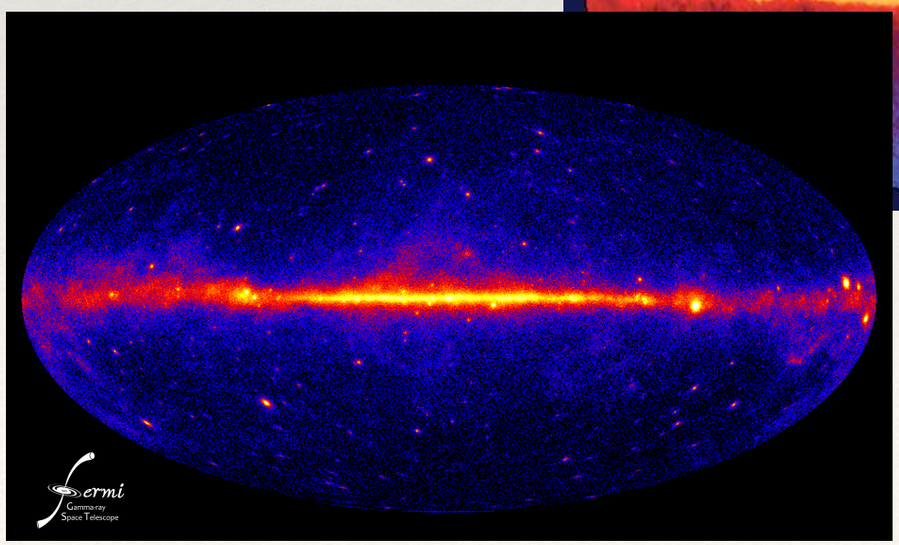

GALEX UV Sky Background Map

Observing Galaxies - Surveys & Catalogs: Wide/All-sky

- **X-ray (satellite) all-sky surveys:**
  - ROSAT All-Sky Survey: 0.1-2 keV, 2 degree resolution, 1990s
  - RXTE All-Sky Survey Slew Catalog: 1 degree resolution; 1996-2002
  - eROSITA All-Sky Survey: 0.3-2.3 keV; 10 arctic resolution 2019-2020
- **Gamma-Ray (satellite) all-sky surveys:**
  - CGRO: e.g., EGRET, 5-10 arcmin resolution, 1990s
  - Fermi Gamma-Ray Space Telescope: few degree resolution, launched 2008







Thought Question

- What do we learn from an all-sky imaging survey?
- What are we missing in an all-sky imaging survey?

Observing Galaxies - Surveys & Catalogs: Deep

- **Deep field surveys with the Hubble Space Telescope:**
  - HDF-N/HDF-S: 6 sq arcmin
  - HUDF: 11 sq arcmin, within CDF-S (Chandra X-ray)
  - GOODS-N and S: 320 sq arcmin, HDF-N and CDF-S
  - AEGIS: 0.5-1 sq degree
  - COSMOS: 2 sq degree
  - CANDELS: 5 deep fields

Hubble Deep Field - North (NASA/ESA)

Observing Galaxies - Surveys & Catalogs: Deep

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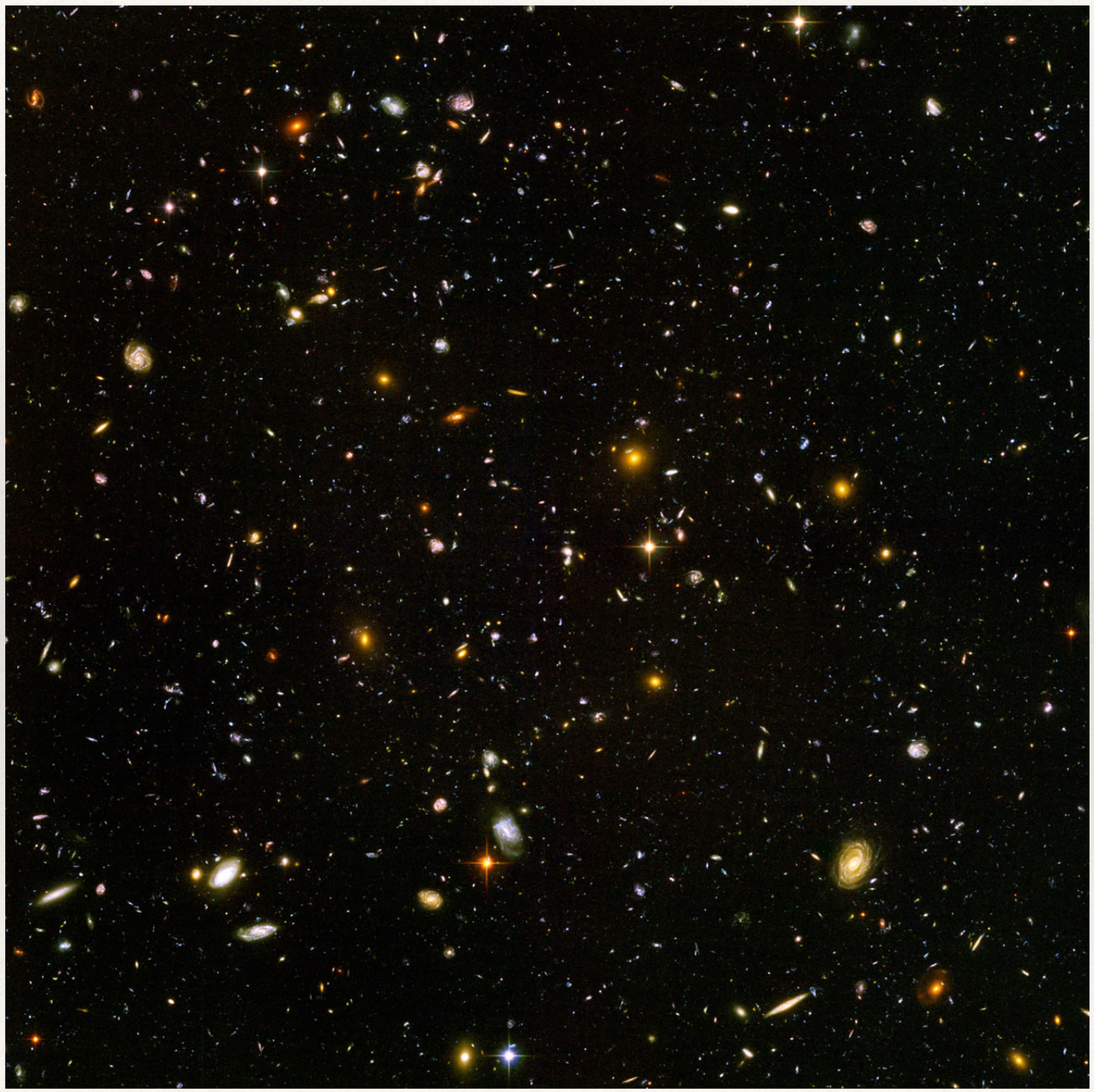

Hubble Ultra Deep Field (NASA/ESA)

Observing Galaxies - Surveys & Catalogs: Deep

- **Deep field surveys with the Hubble Space Telescope:**
  - HDF-N/HDF-S: 6 sq arcmin
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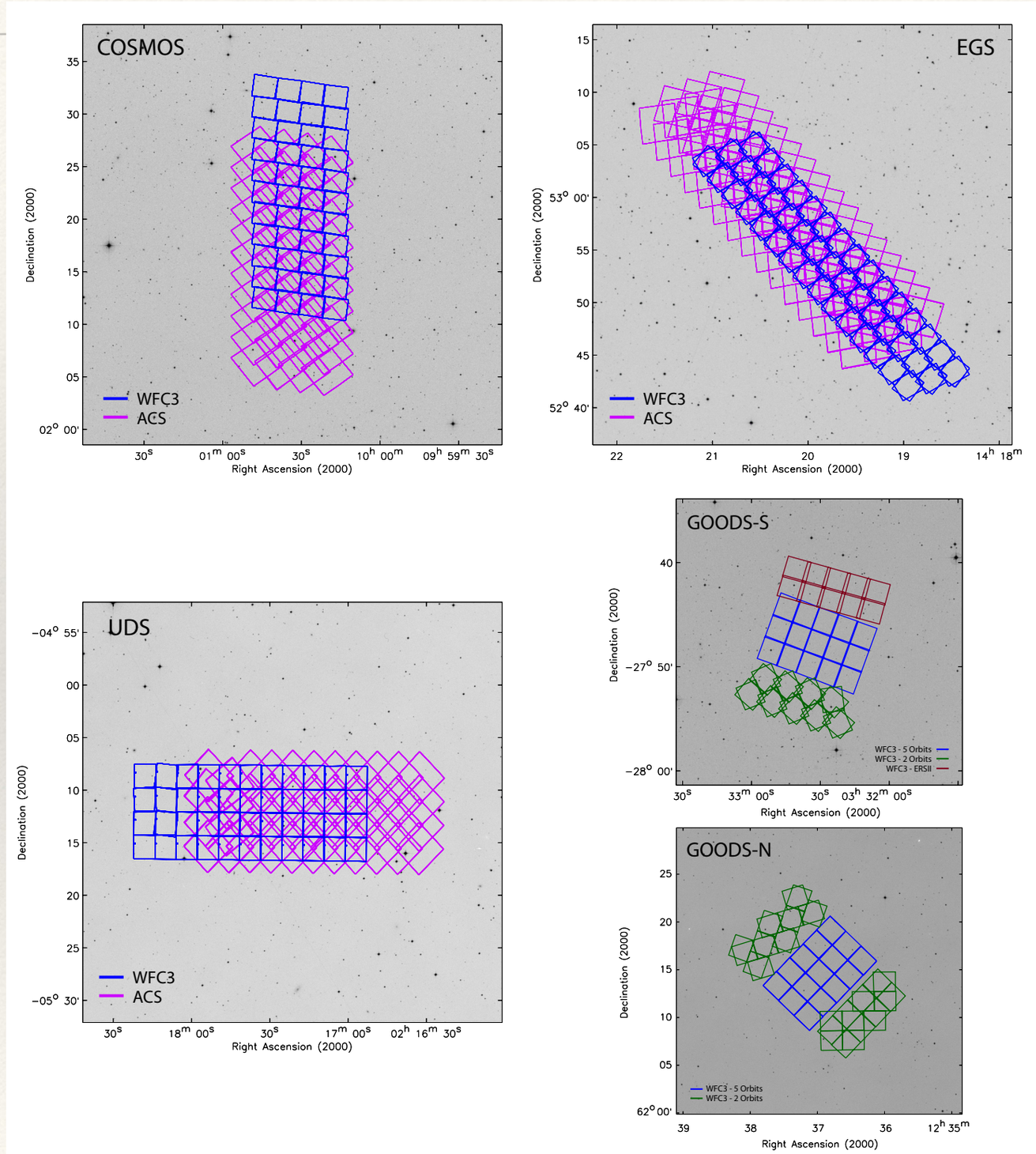
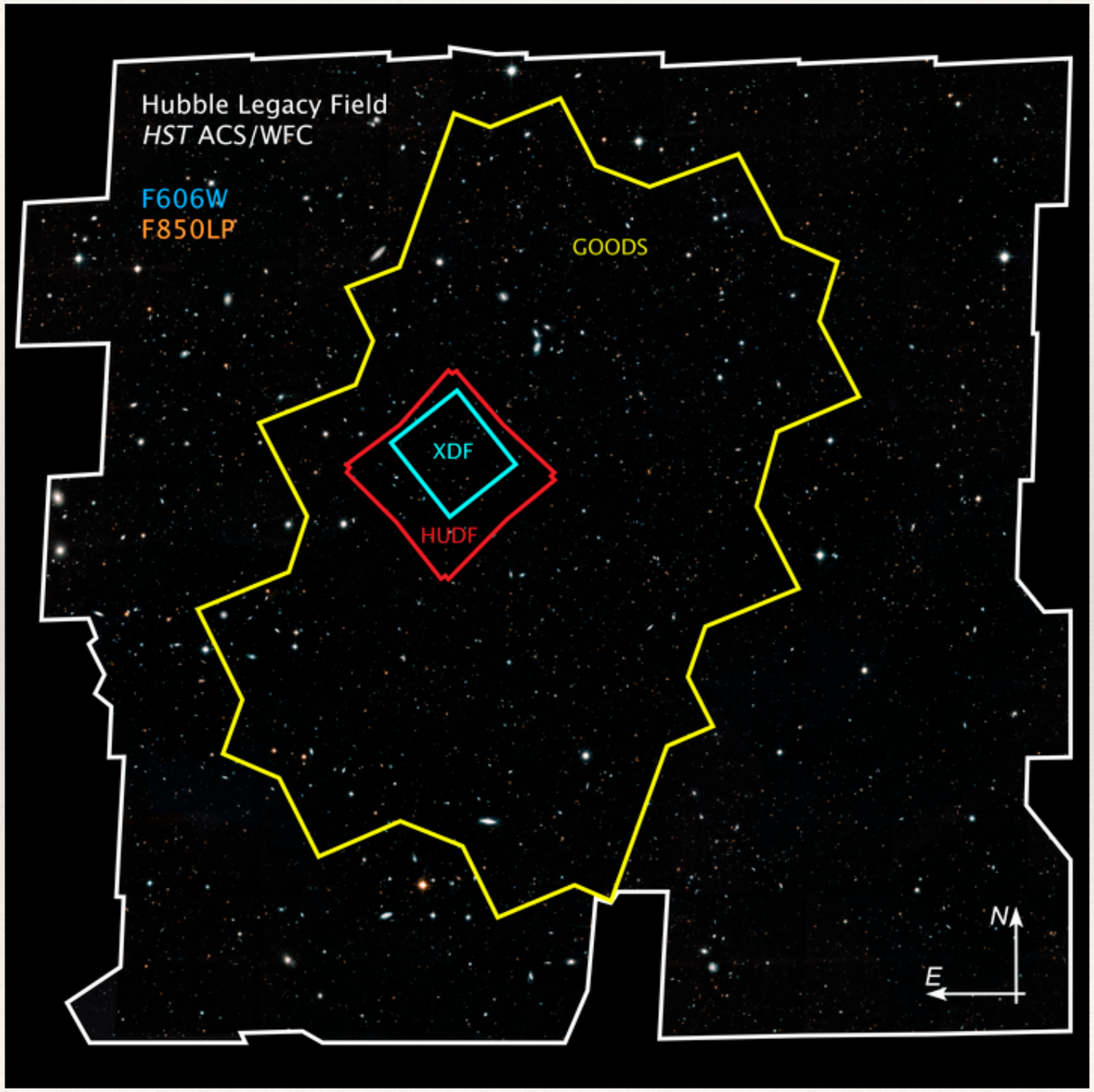
  - GOODS-N and S: 320 sq arcmin, HDF-N and CDF-S
  - AEGIS: 0.5-1 sq degree
  - COSMOS: 2 sq degree
  - CANDELS: 5 deep fields



http://candels.ucolick.org/survey/Field_Maps.html#sizes

Observing Galaxies - Surveys & Catalogs: Deep

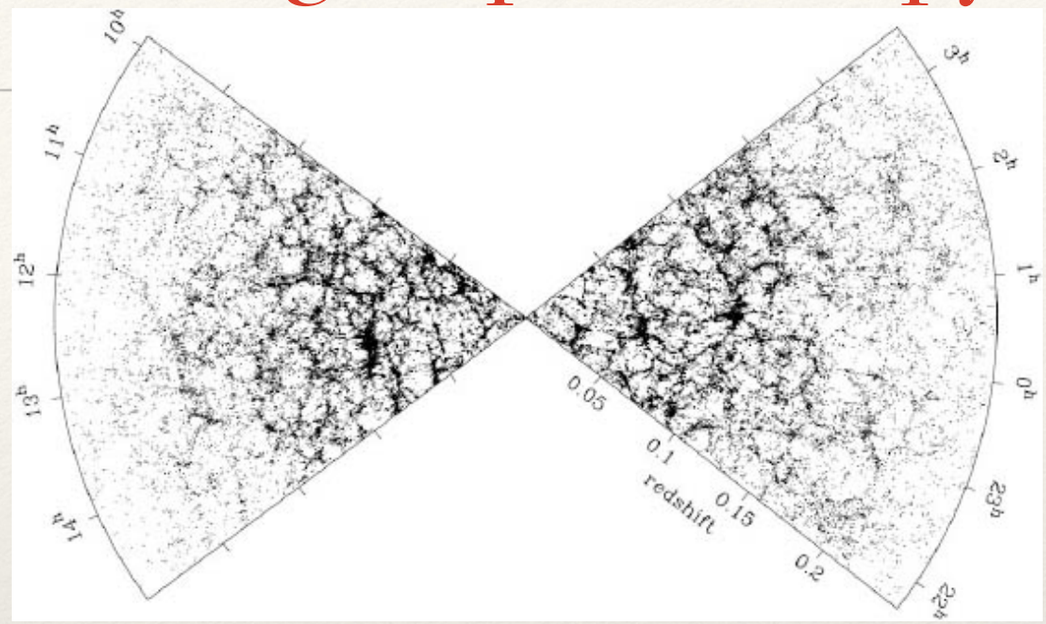
- **Deep field surveys with the Hubble Space Telescope:**
  - HDF-N/HDF-S: 6 sq arcmin
  - HUDF: 11 sq arcmin, within CDF-S (Chandra X-ray)
  - GOODS-N and S: 320 sq arcmin, HDF-N and CDF-S
  - AEGIS: 0.5-1 sq degree
  - COSMOS: 2 sq degree
  - CANDELS: 5 deep fields
  - Hubble Legacy Field: ~625 sq arcmin



Credit: NASA, ESA, Hubble Legacy Field team

Observing Galaxies - Surveys & Catalogs: Spectroscopy

- **Spectroscopic surveys:**
  - CfA redshift survey (1980s)
  - Las Campanas Redshift Survey, LCRS (1990s) ~20,000 galaxies
  - Canadian Network for Observation Cosmology, CNOC (1990s) ~ clusters
  - 2dF (2000-2005) ~ 2000 sq. degrees
  - …



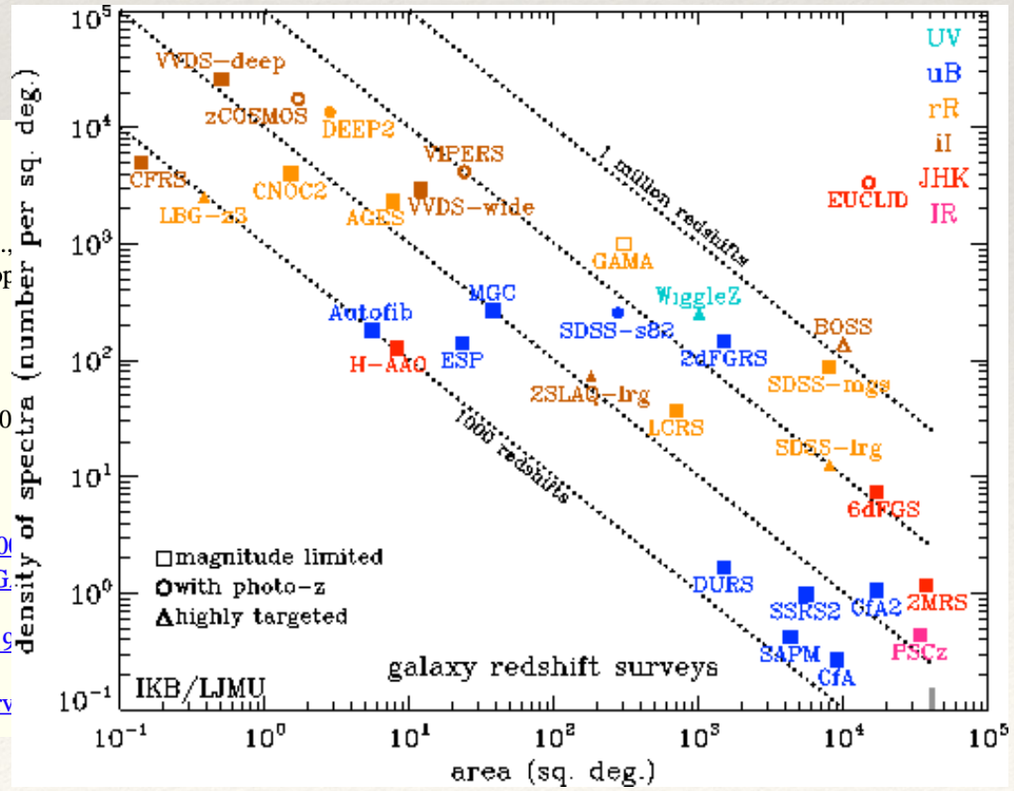
2dF: https://ned.ipac.caltech.edu/level5/March07/Reshetnikov/Reshetnikov3.html

List of galaxy redshift surveys

Galaxy redshift surveys aim to provide fundamental data on galaxies and the distribution of galaxies. The criteria for this list is: (1) a field survey, i.e., structure is targeted; (2) spectroscopic redshifts obtained with resolving power > 100; (3) well defined selection criteria with magnitude limits from op IR, i.e., predominantly stellar light, quasar surveys are not included; (4) more than 5000 galaxy redshifts obtained.

Optical to near-infrared surveys listed in alphabetical order:

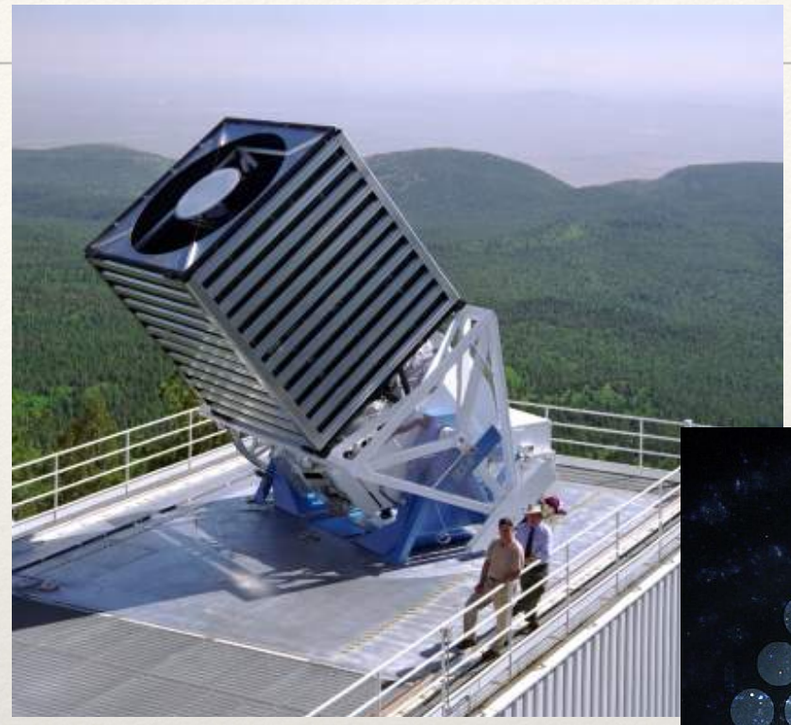
- AGN and Galaxy Evolution Survey (**AGES**): completed 18000 redshifts (galaxy targets) over 7.7 sq.deg., various selections including R < 20.0 21.3; links AGES web site, survey paper (2012).
- **CfA2** Redshift Survey: completed 18000 redshifts over 17000 sq.deg., B < 15.5; links CfA web site, related paper (1999).
- **CNOC2** Field Galaxy Redshift Survey: completed 6000 redshifts over 1.5 sq.deg., R < 21.5; links CNOC2 web site, survey paper (2000).
- **DEEP2** Redshift Survey: completed 38000 redshifts over 2.8 sq.deg., R_{AB} < 24.1 with color selection; links DEEP2 web site, survey paper (20
- Galaxy And Mass Assembly (**GAMA**) redshift survey: aims for 300000 redshifts over 300 sq.deg., r < 19.8 and other limits in z and K; links G survey paper (2010).
- Las Campanas Redshift Survey (**LCRS**): completed 26000 redshifts over 700 sq.deg., R < 17.5 nominal; links LCRS web site, survey paper (19
- Millennium Galaxy Catalogue (**MGC**): completed 10000 redshifts over 37.5 sq.deg., B < 20.0; links MGC web site, survey paper (2003).
- 6dF Galaxy Survey (**6dFGS**): completed 125000 redshifts over 17000 sq.deg., K < 12.75 and other limits in BRIJH; links 6dFGS web site, surv (2009)

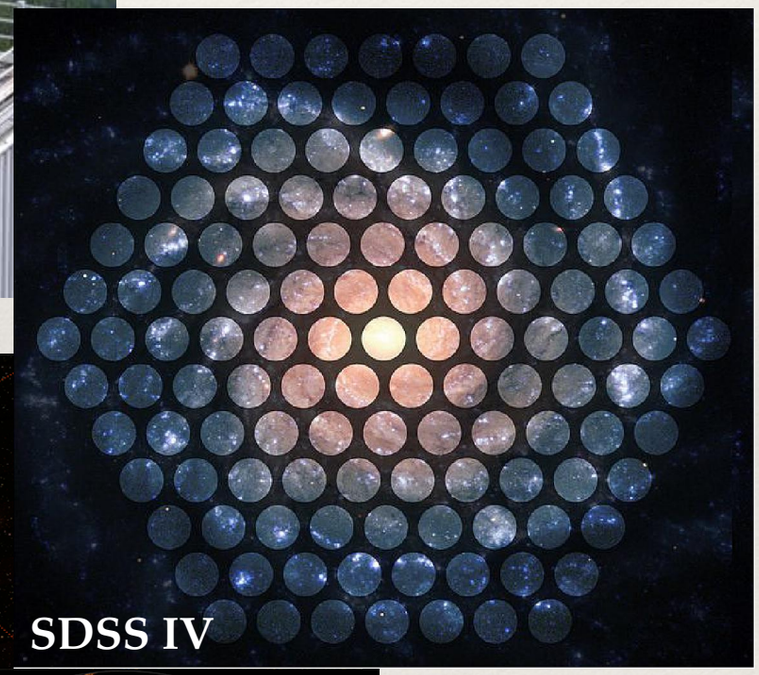


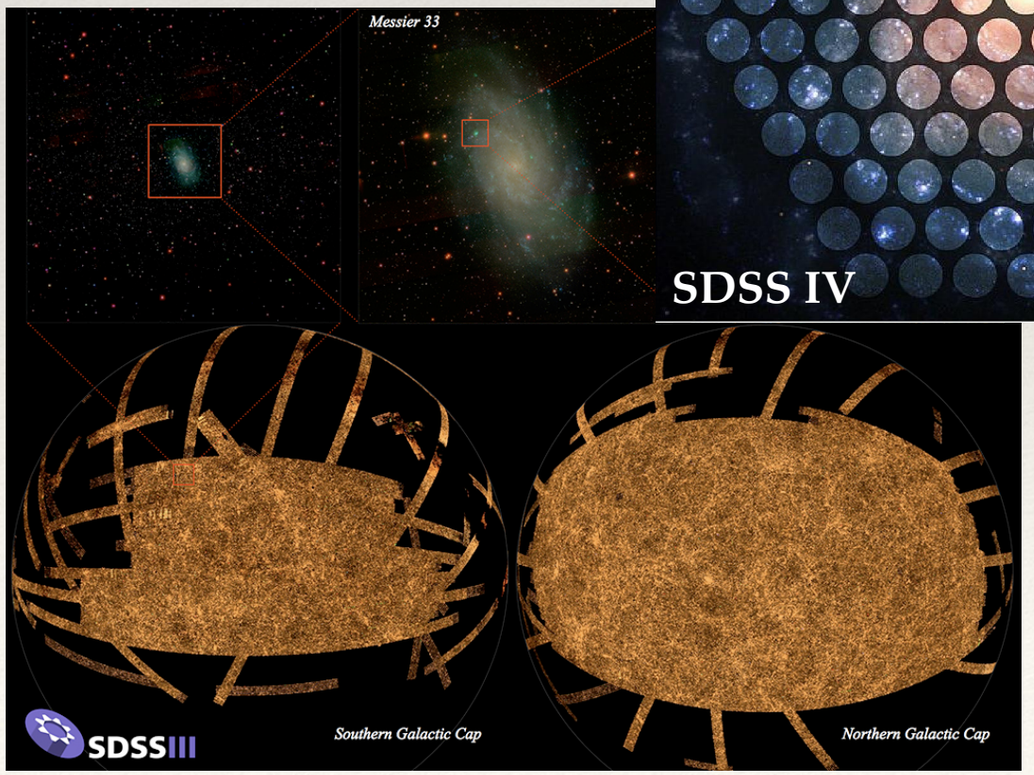
http://www.astro.ljmu.ac.uk/~ikb/research/galaxy-redshift-surveys.html

Observing Galaxies - Surveys & Catalogs: SDSS

- **Sloan Digital Sky Survey**
  - Telescopes:
    - Sloan Foundation 2.5m at Apache Point Observatory
    - Irénée du Pont 2.5m at Las Campanas Observatory (as of SDSS IV)
  - Phases:
    - SDSS I/II (2000-2008)
    - SDSS III (2008-2014)
    - SDSS IV (2014-2020)
    - SDSS V (2020-2025)

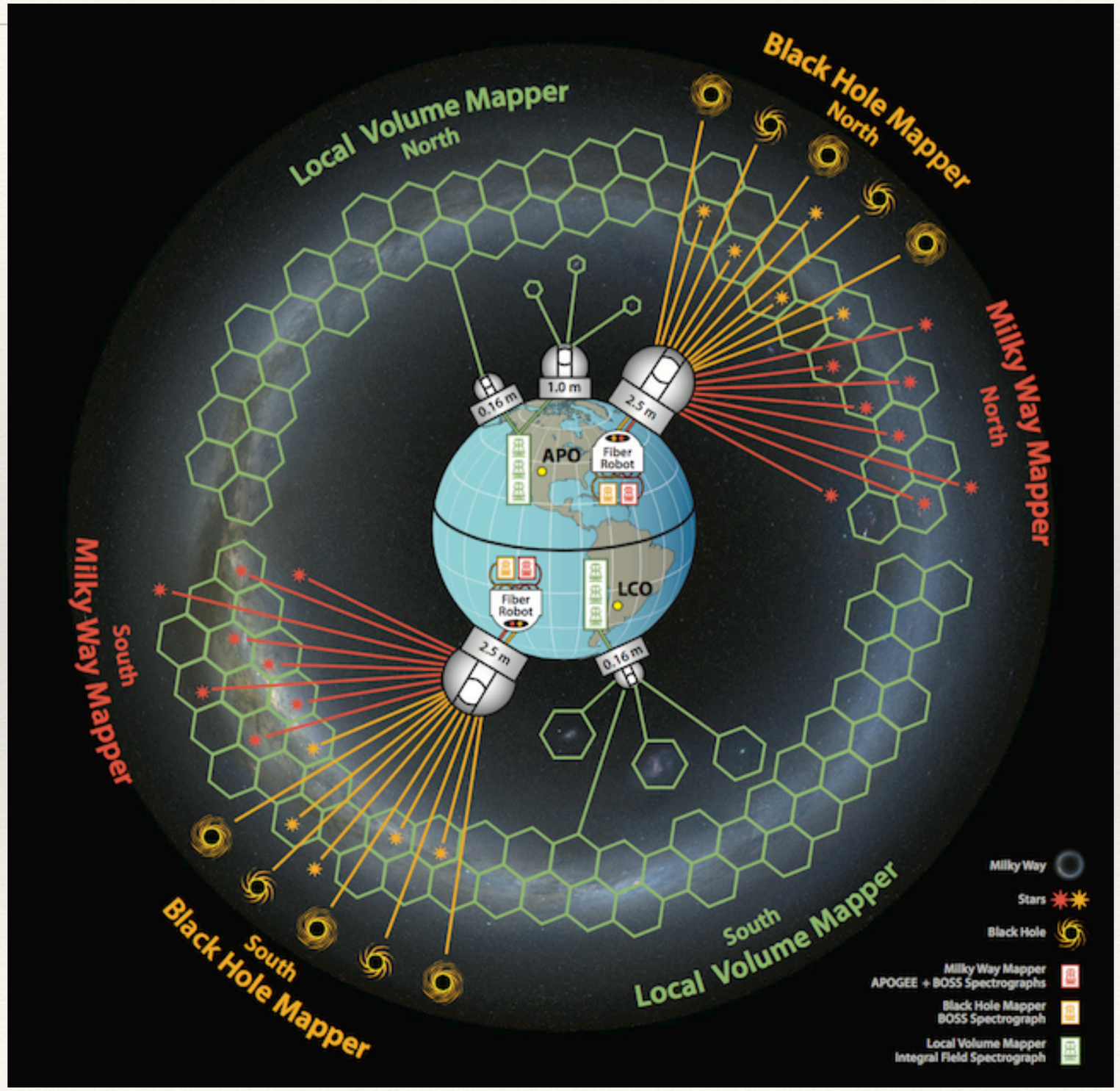






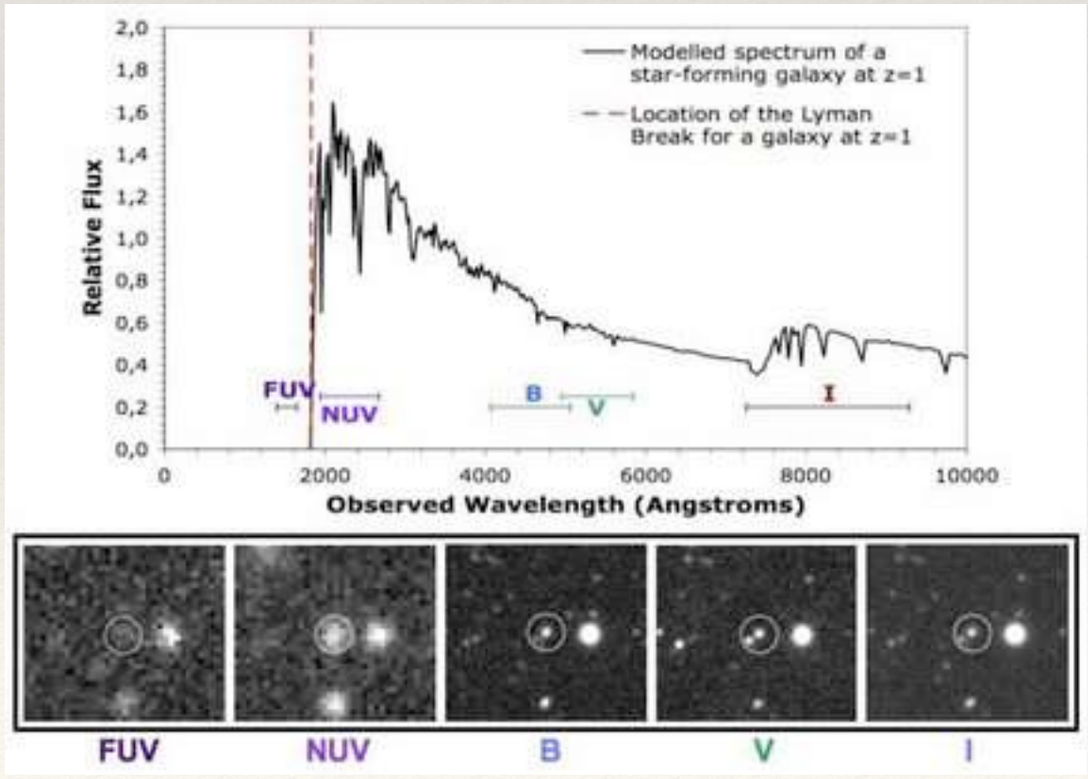
Observing Galaxies - Surveys & Catalogs: SDSS

- Multi-epoch spectroscopic survey
- Optical/IR spectra of >6 million objects over 5 years (2020-2025)
- Survey the entire sky in 3 campaigns:
- **Milky Way Mapper** — mapping the Milky Way using rapid, repeated observations.
- **Local Volume Mapper** — mapping Local Volume galaxies using wide-angle integral field spectroscopy.
- **Black Hole Mapper** — mapping black holes using time domain spectroscopy of quasars and bright X-ray sources.



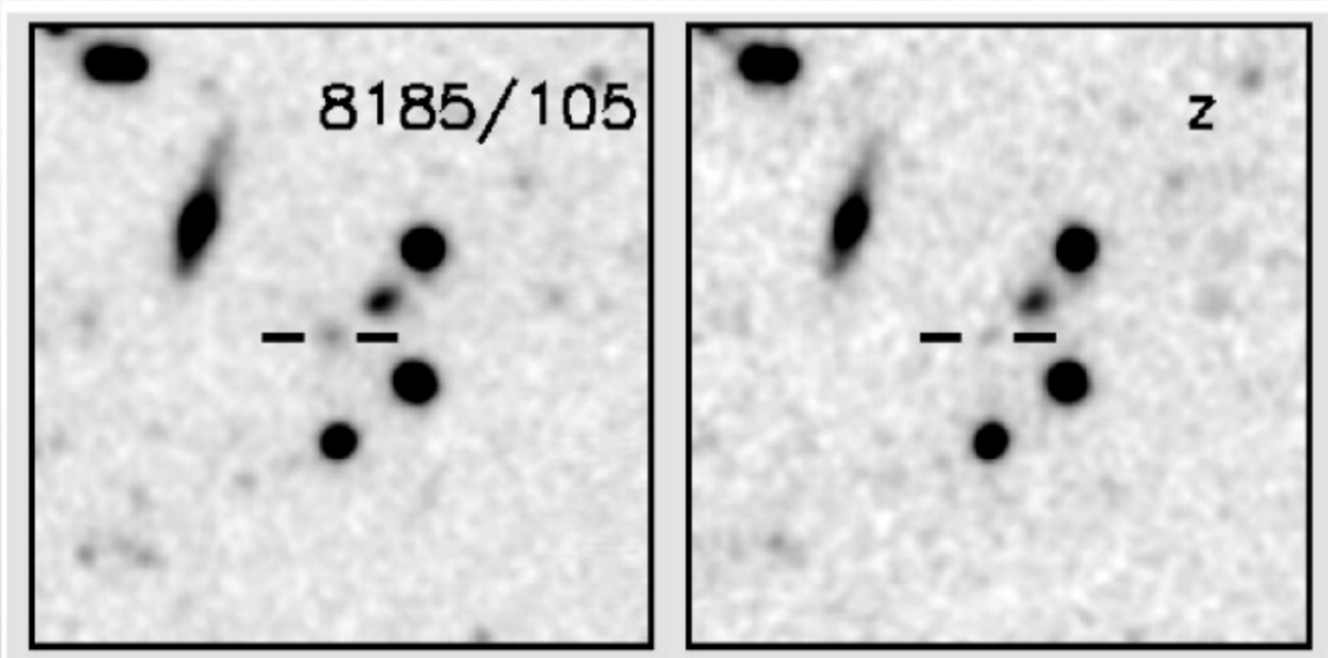
Observing Galaxies - Surveys: Selecting Galaxies

- 1) All galaxies above a certain brightnesss threshold (magnitude-limited)
  - size threshold (size-limited)
- 2) Broadband color selection (e.g., Steidel et al. 1996)
  - Lyman Break Galaxies (LBGs) or “drop-outs”

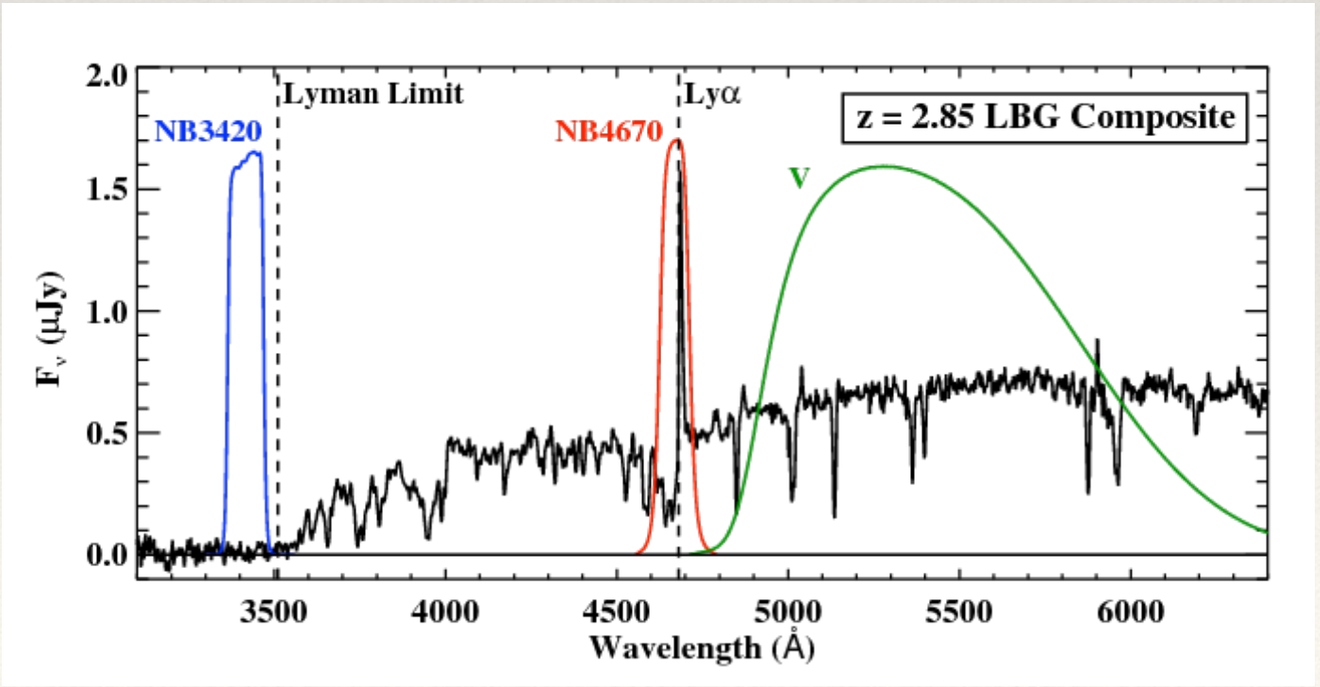


Observing Galaxies - Surveys: Selecting Galaxies

- 3) Narrowband excess (e.g., Hu et al. 1999)
- Lyman-alpha emitting galaxies (LAEs)



Hu et al. 1999



Mostardi et al. 2013

Observing Galaxies - Surveys: Selecting Galaxies

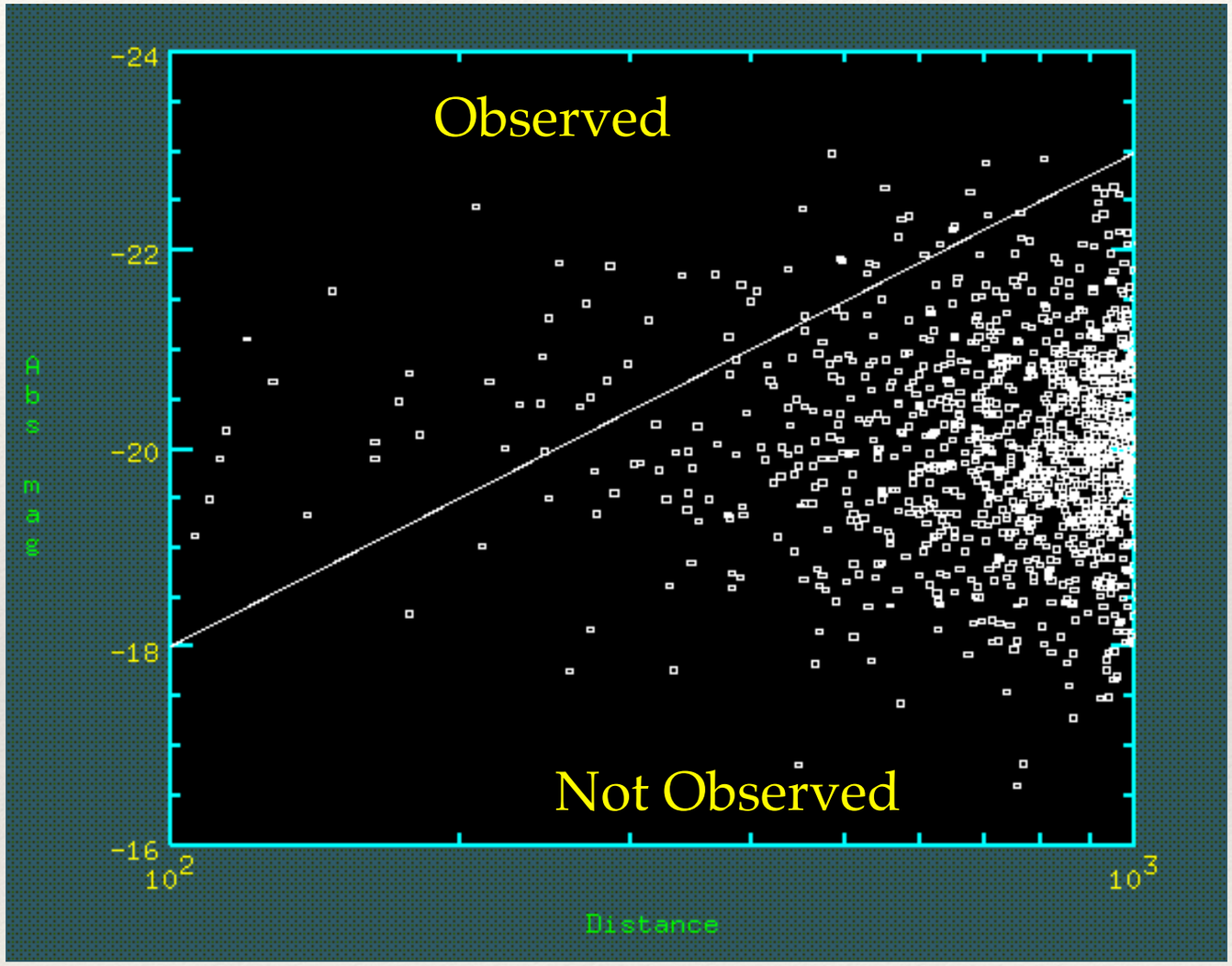
- A "**complete**" catalog has all objects that satisfy well-defined selection criteria.
  - But can still be biased! Consider **selection function**.
- The principal criteria that can exclude galaxies:
  - Apparent magnitude / flux
  - Angular size
  - Surface Brightness

Thought Question

- Consider a simple galaxy population with (a) a uniform spatial distribution and (b) the same Gaussian distribution of absolute magnitude at every redshift.
- What would a plot of absolute magnitude versus Log(distance) look like?
- Draw a magnitude limit for a hypothetical survey, i.e., a line dividing the galaxies we would detect from those we wouldn't be able to see.

Observing Galaxies - Surveys: Selection Effects

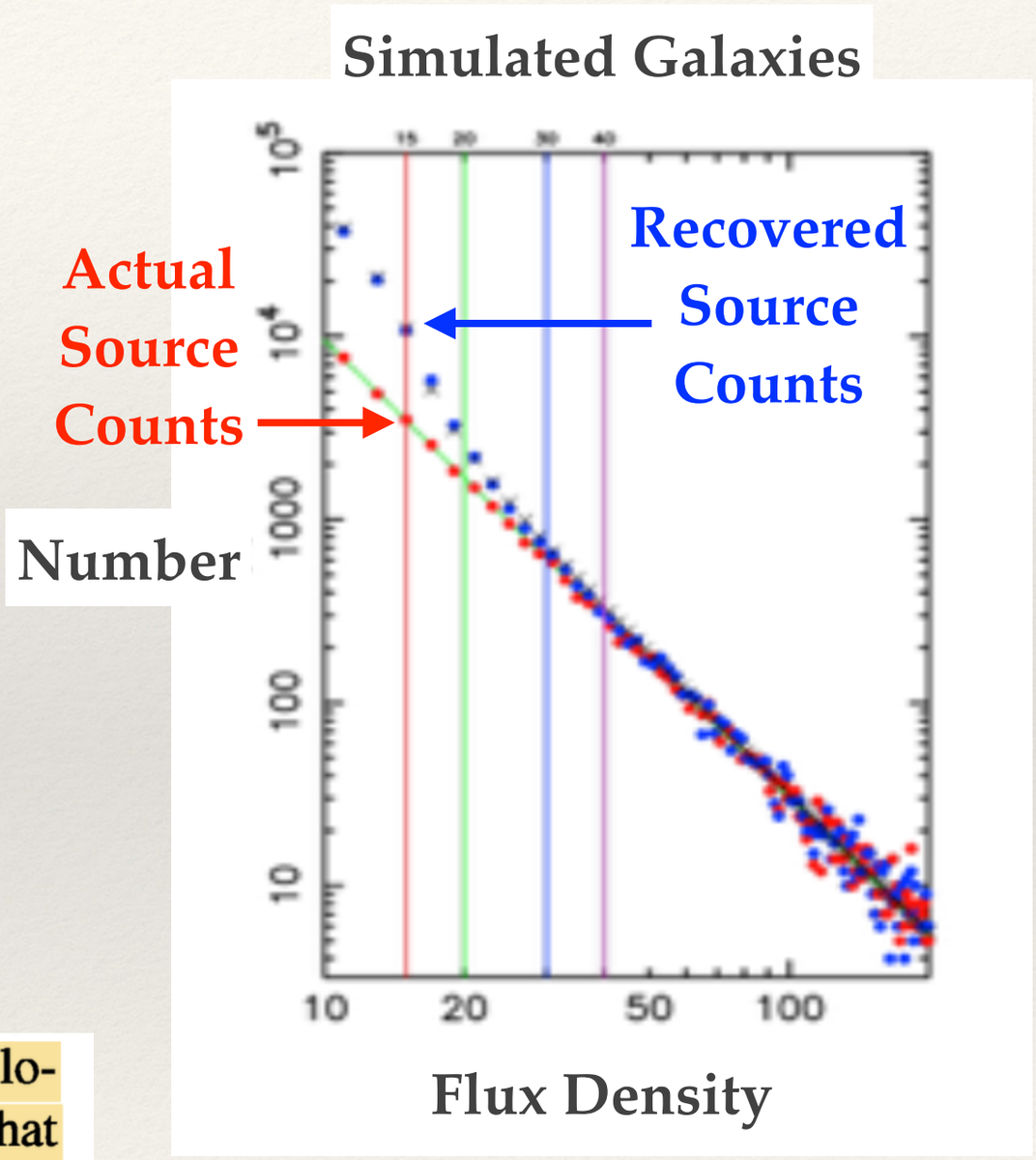
- **Malmquist Bias (Malmquist 1922, 1925):**
  - Luminous objects detected to larger distances and therefore from a larger volume.
- For flux/magnitude limited samples, observed distribution artificially skewed to high luminosities.



http://people.virginia.edu/~dmw8f/astr5630/Topic03/Lecture_3.html# top

Observing Galaxies - Surveys: Selection Effects

- **Eddington Bias (Eddington 1913):**
  - Measurements have some statistical error.
  - Usually, there are more intrinsically faint objects than bright ones.
  - A few bright sources scatter into fainter bins, but many faint sources scatter into brighter bins.
  - related: Lutz-Kelker bias



www.astro.ubc.ca/people/jvw/ASTROSTATS/lectures/PL_15_2013_www.pdf

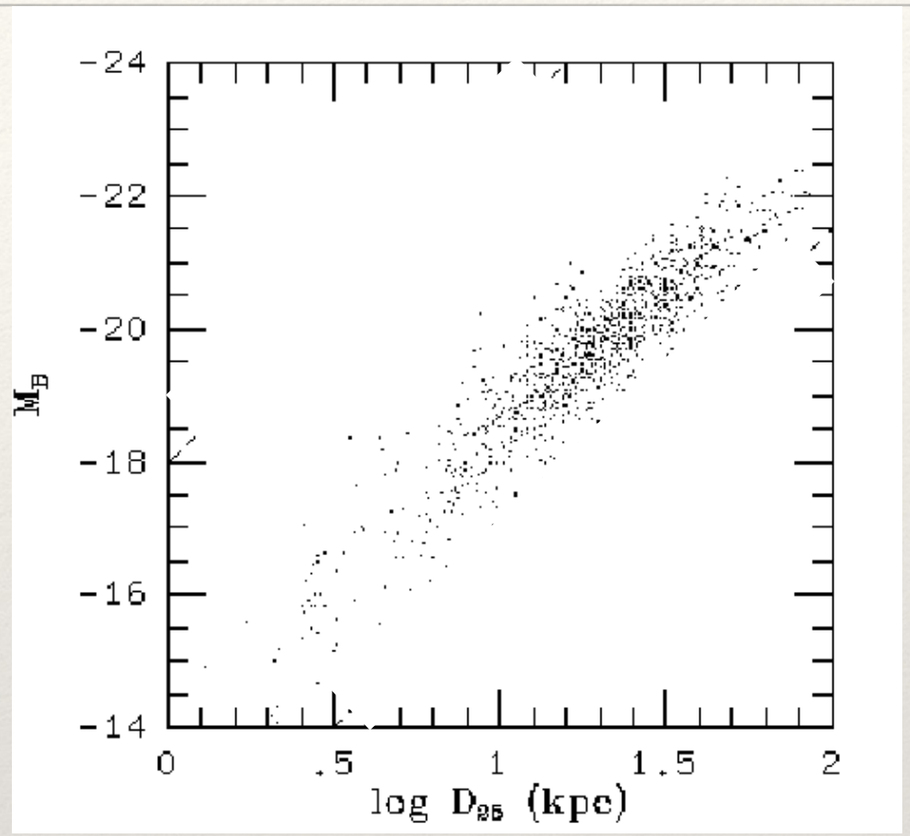
be justified. Any large gathering of observational cosmologists today will include at least one person who thinks that someone else in the room does not understand the Malmquist effect.

Trimble 1996, PASP, 108, 1073

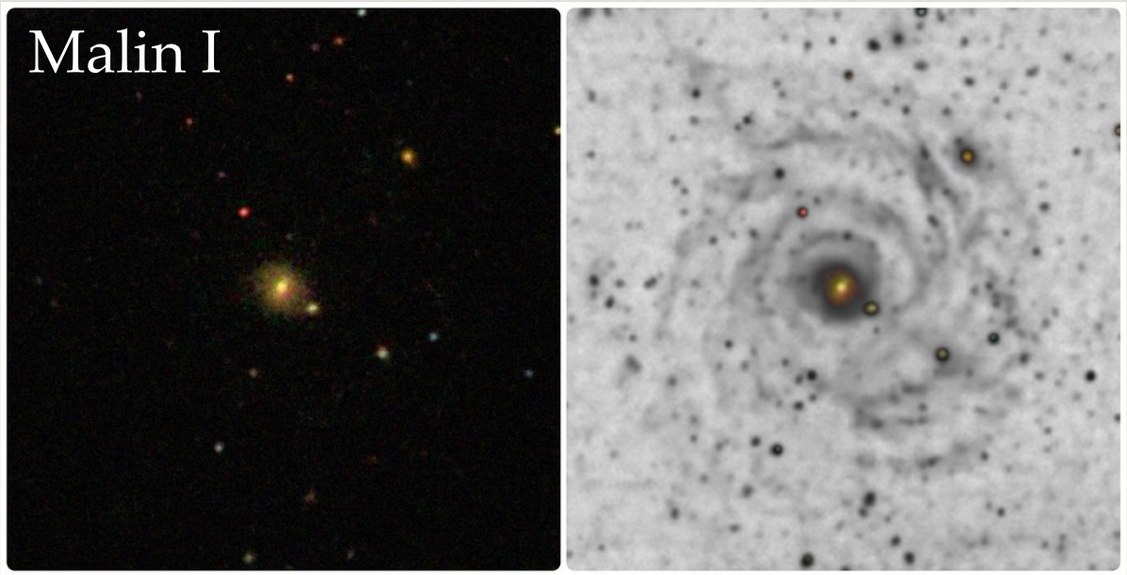
Observing Galaxies - Surveys: Selection Effects

- **Other Selection Biases:**
  - surface brightness
  - diameter
  - color
- Whenever you see a correlation, consider selection effects!

Biases are widespread in astronomy. (Beware!)



http://people.virginia.edu/~dmw8f/astr5630/Topic03/Lecture_3.html#top



Credit: SDSS/Giuseppe Donatiello (https://www.flickr.com/photos/133259498@N05/28295856819)

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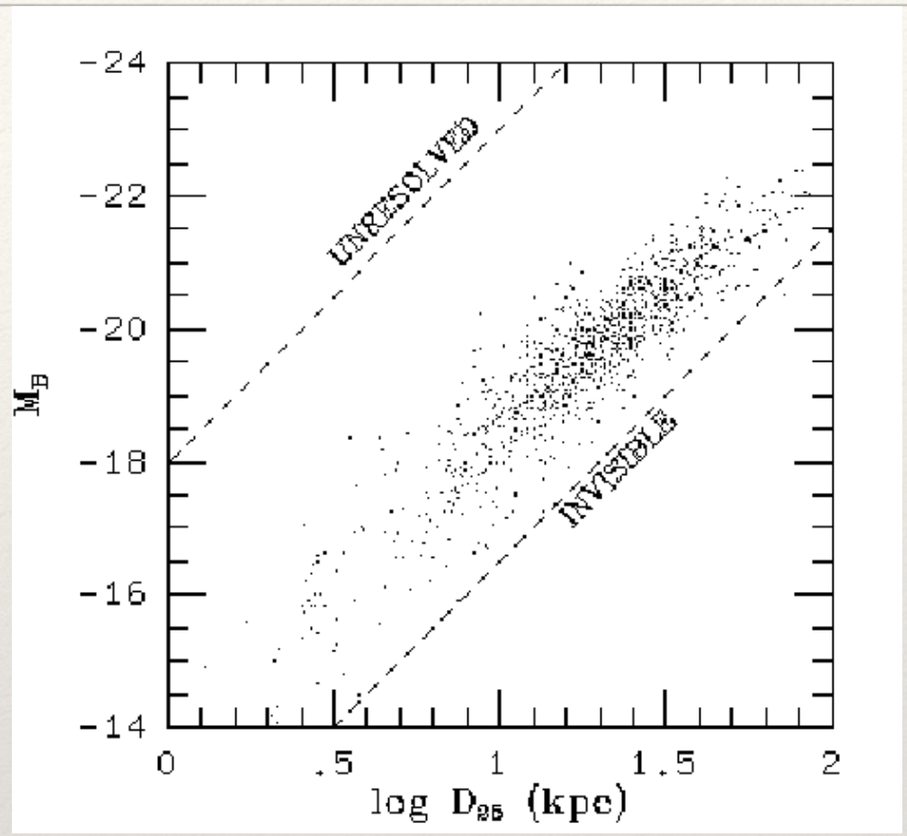
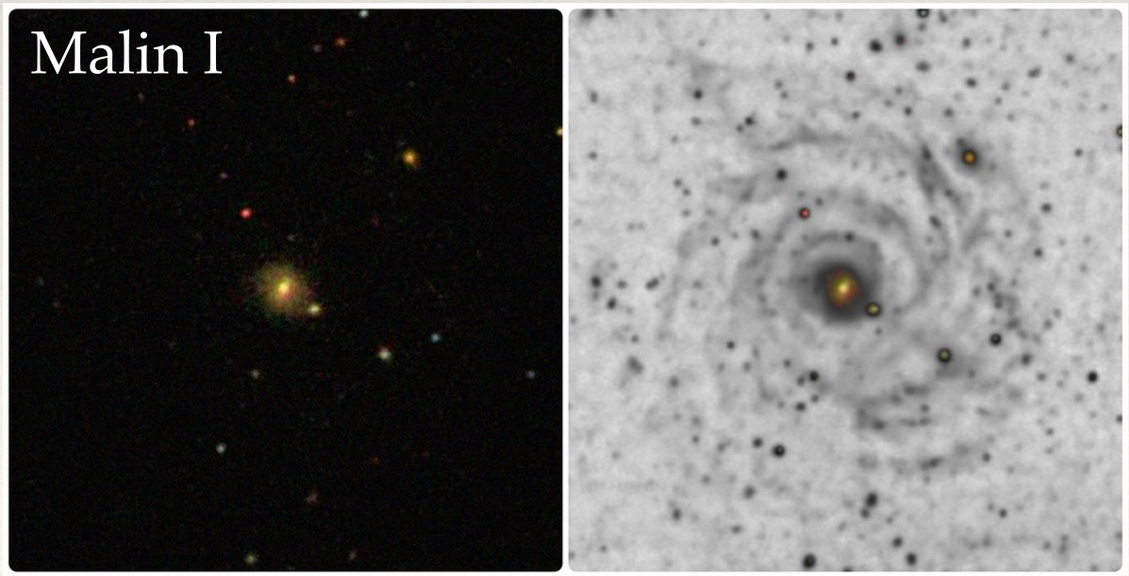


http://people.virginia.edu/~dmw8f/astr5630/Topic03/Lecture_3.html#top



Credit: SDSS/Giuseppe Donatiello (https://www.flickr.com/photos/133259498@N05/28295856819)

Observing Galaxies - Surveys: Selection Effects

- Must know, and then correct for, the "**selection function**" — can be difficult and uncertain.
- Best approach: “forward model”, i.e. model underlying distribution of objects, put through sample selection function, and compare vs. observed properties.
- Can't correct, or model, what you can't see!