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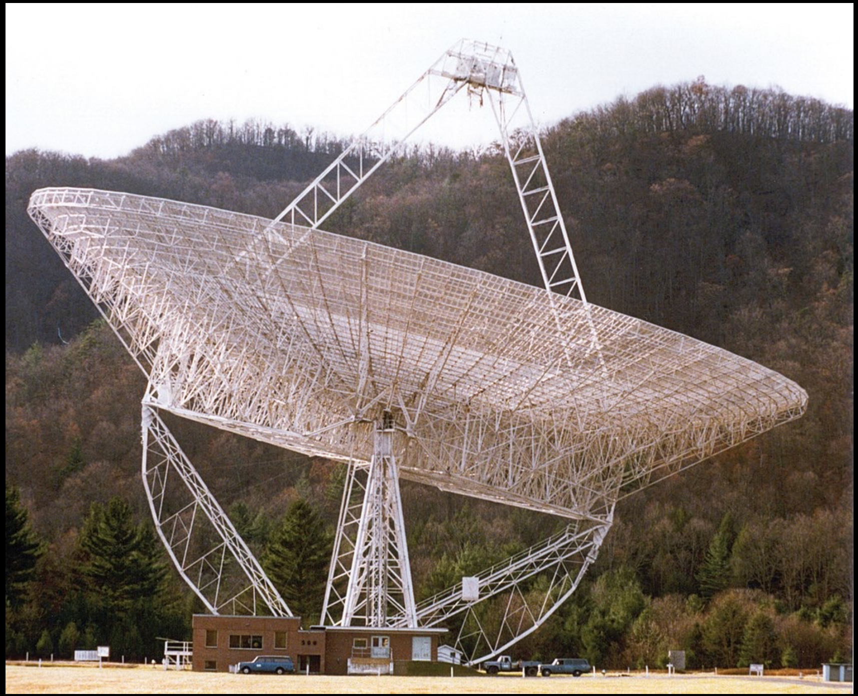
Galaxies at 21cm from the Green Bank Observatory



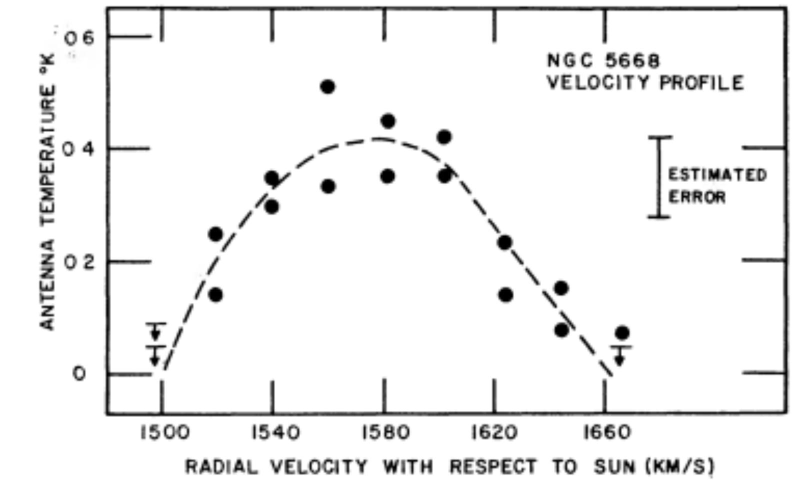


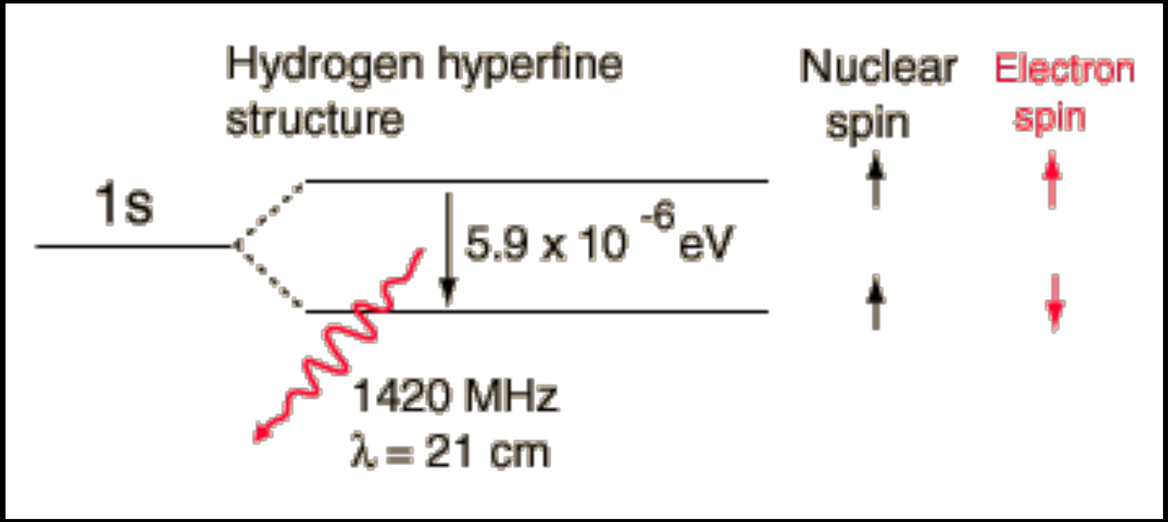
FIG. 2.—Velocity profile for NGC 5668

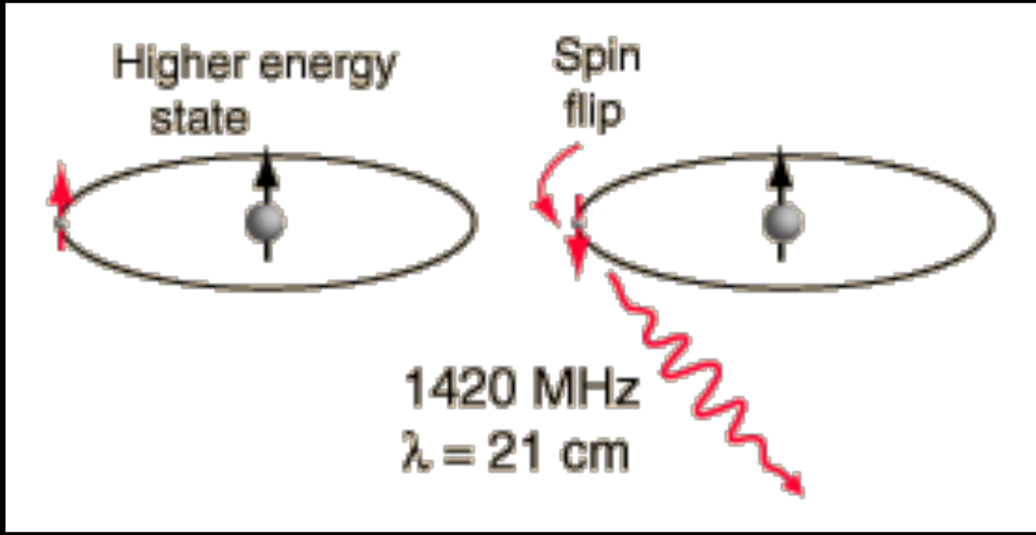
Roberts (1965)

Karen Masters

Haverford College, USA

Primer: Astrophysics of HI in Galaxies

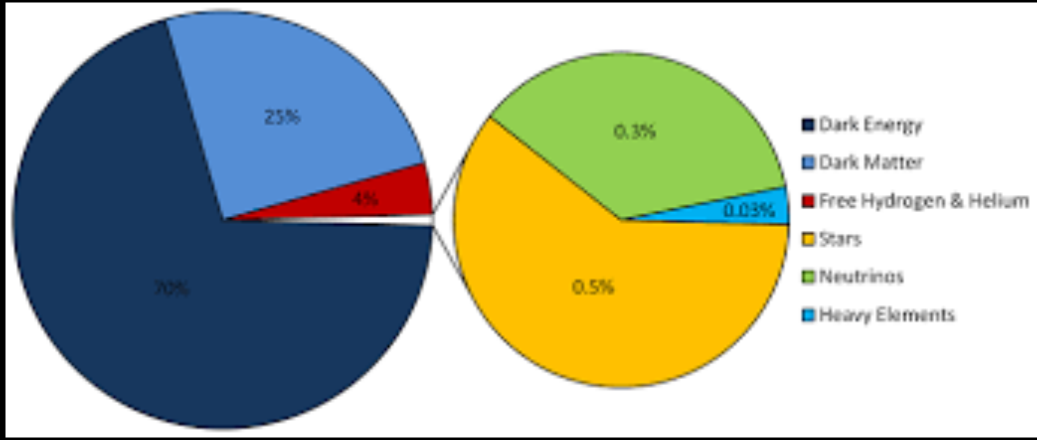




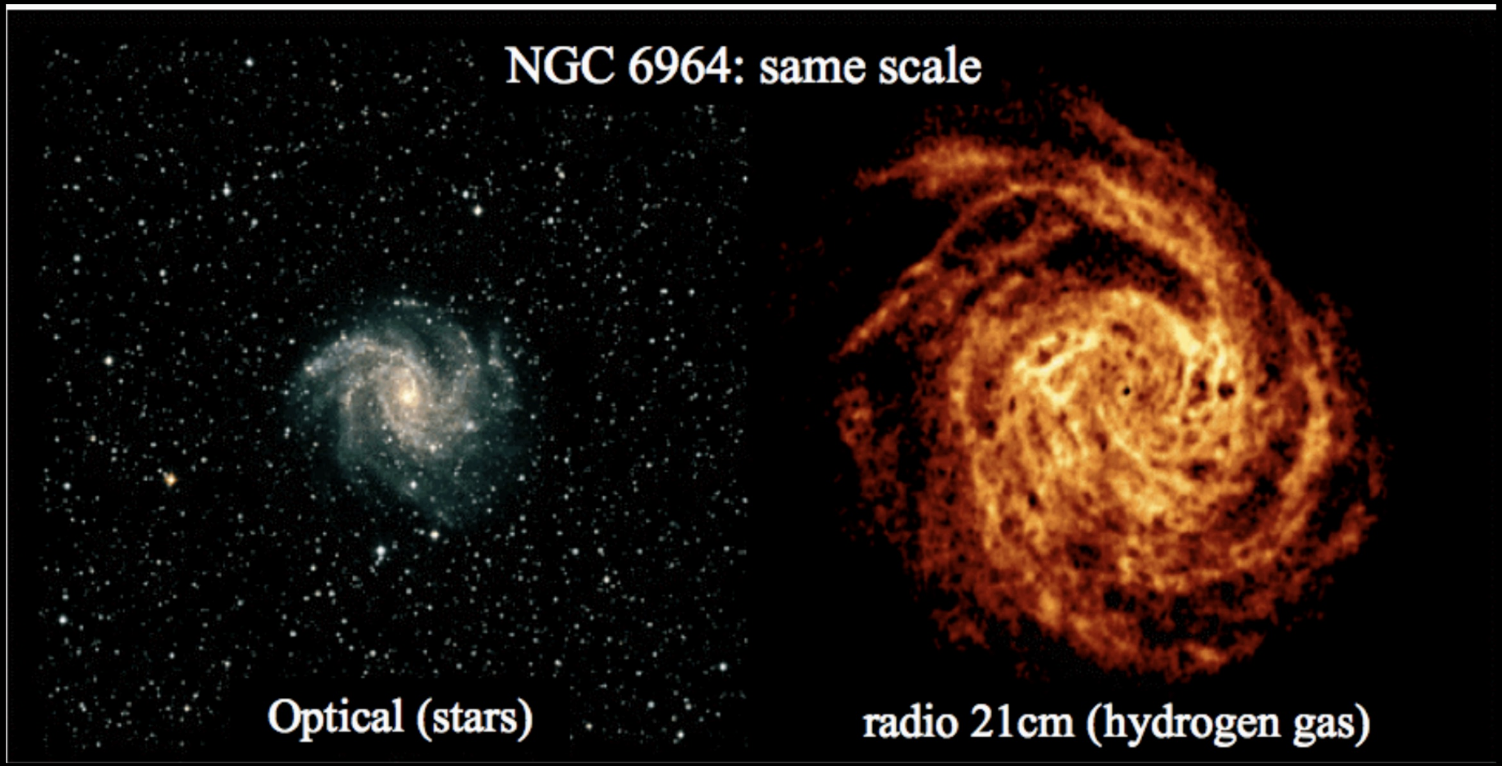
Existence of 21cm/1420 Mhz line predicted in 1944. Highly forbidden – lifetime 10 million years! But, ~73% of baryons in the Universe are hydrogen

HI line first observed in 1951 (in our Galaxy, Ewen & Purcell) and 1954 (in external galaxies LMC/SMC Kerr et al.).

GBO established a few years later (~1957). I found HI observations with 300ft published in 1962.



Galaxy assembly is highly dependent on gas!



Stars (optical) **Gas (radio)**

You cannot make new stars without:

(1) The raw material (cold gas)

(1) The conditions necessary for that gas to collapse into dense clouds/stars

Galaxy assembly is highly dependent on gas!

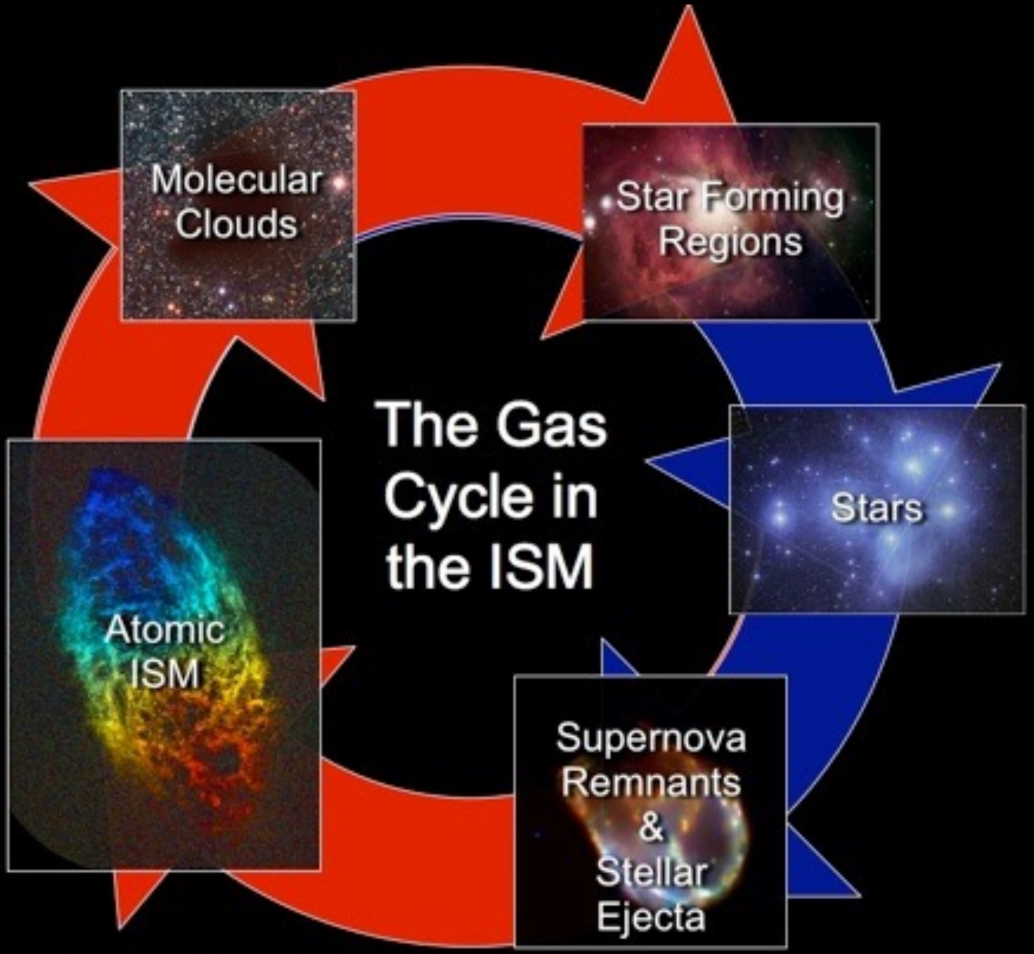


Photo Credits: R. Gendler ,the FORS Team, D. Malin, SAO/Chandra, D. Thilker

You cannot make new stars without:

(1) The raw material (cold gas)

(1) The conditions necessary for that gas to collapse into dense clouds/stars

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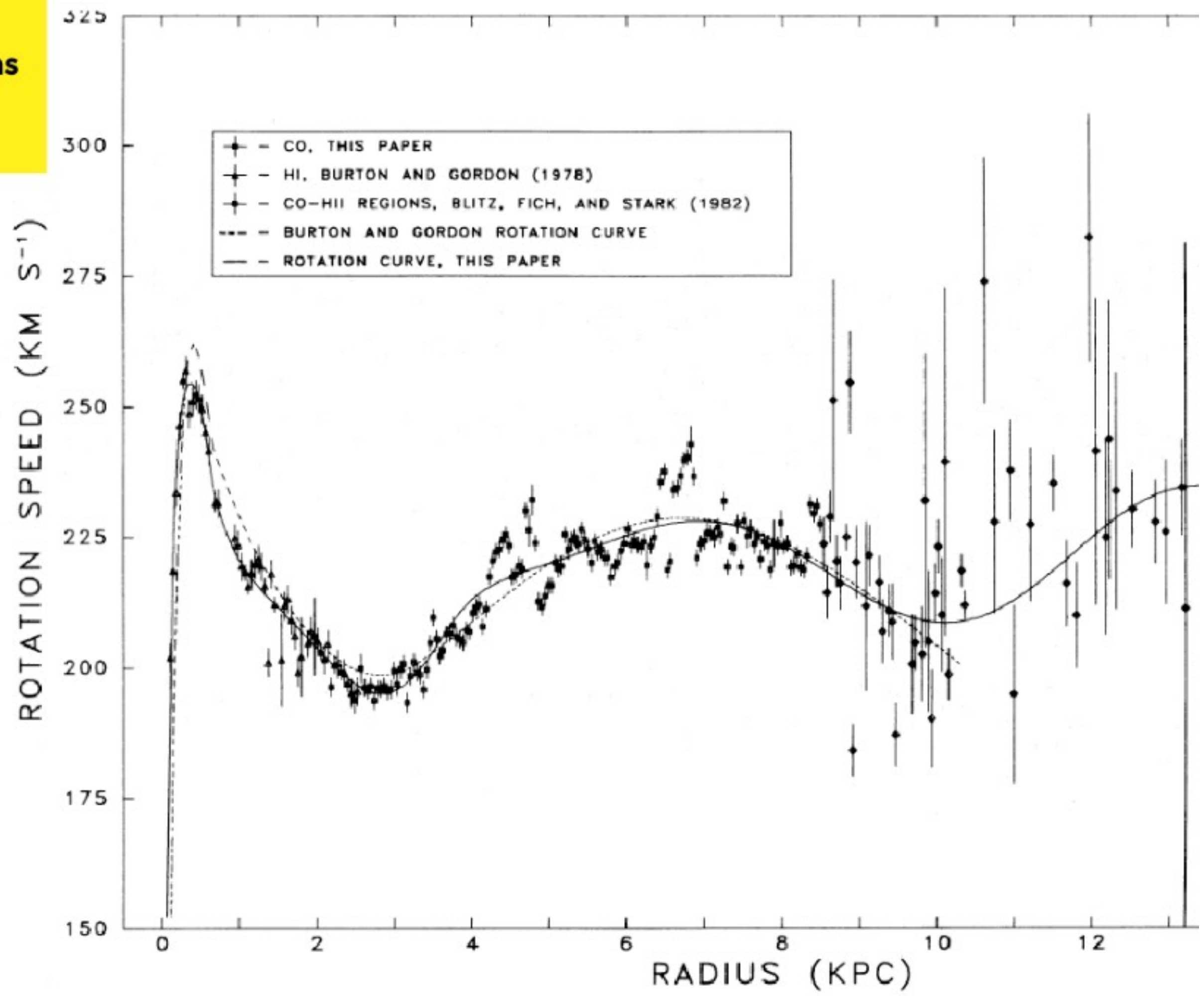
Cold Gas in a galaxy

* Neutral Hydrogen (HI Regions):
    * Average density: 1 atom/cm^3
    * Average Temp: 10-100k (fairly cold)
    * Emits only 21-cm radiation
    * Flat and thinish disk..
    * R=3-25 Kpc, *h*=160pc, flares at large R.
* Molecular Hydrogen (H_2 Clouds):
    * Average density: 100-10^6 atom/cm^3
    * Average Temp: 10-20k (really cold)
    * Inner galaxy, and very thin
    * R=3-8 kpc, *h*=<90pc (25% of thin disk)
    * No emission lines (symmetric molecule)
    * Traced by CO emission - for every CO molecule there are about 10,000 hydrogen molecules

MW Rotation Curve and Map from HI

Clemens 1985



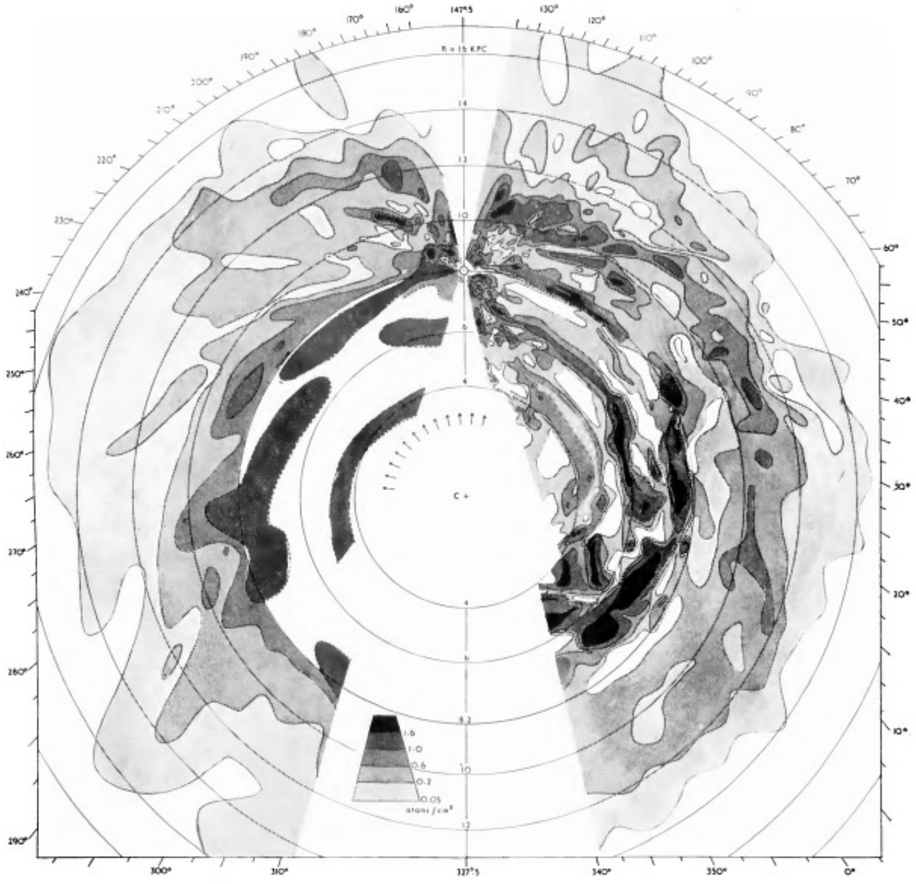


FIG. 4.—*Distribution of neutral hydrogen in the Galactic System. The maximum densities in the z-direction are projected on the galactic plane, and contours are drawn through the points.*

Oort et al. 1958 (not GBO)

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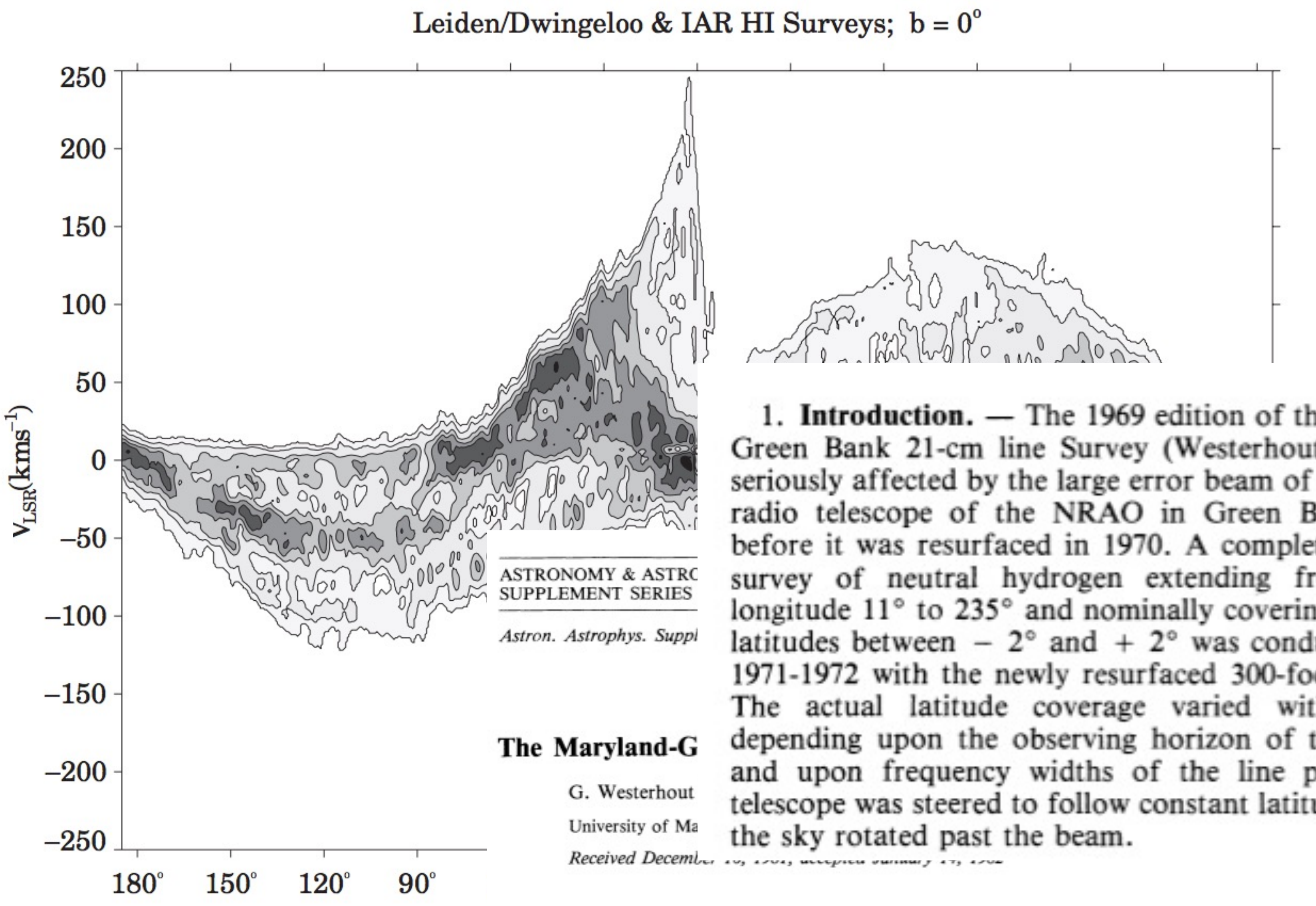
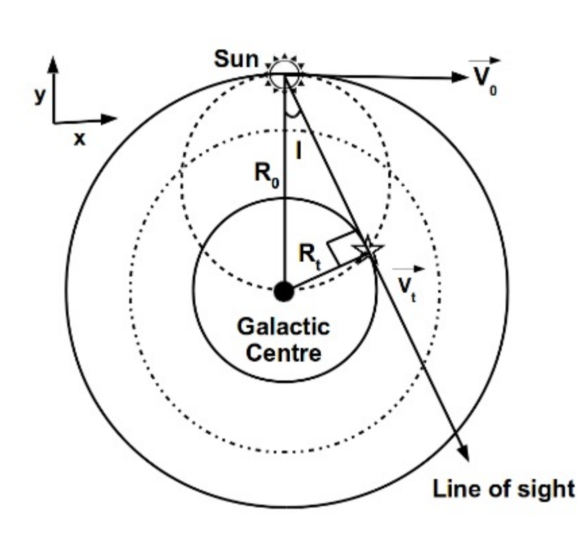
Velocity of HI on different sight lines





ASTRONOMY & ASTRO
SUPPLEMENT SERIES

Astron. Astrophys. Suppl

The Maryland-G

G. Westerhout

University of Ma

Received Decemb...

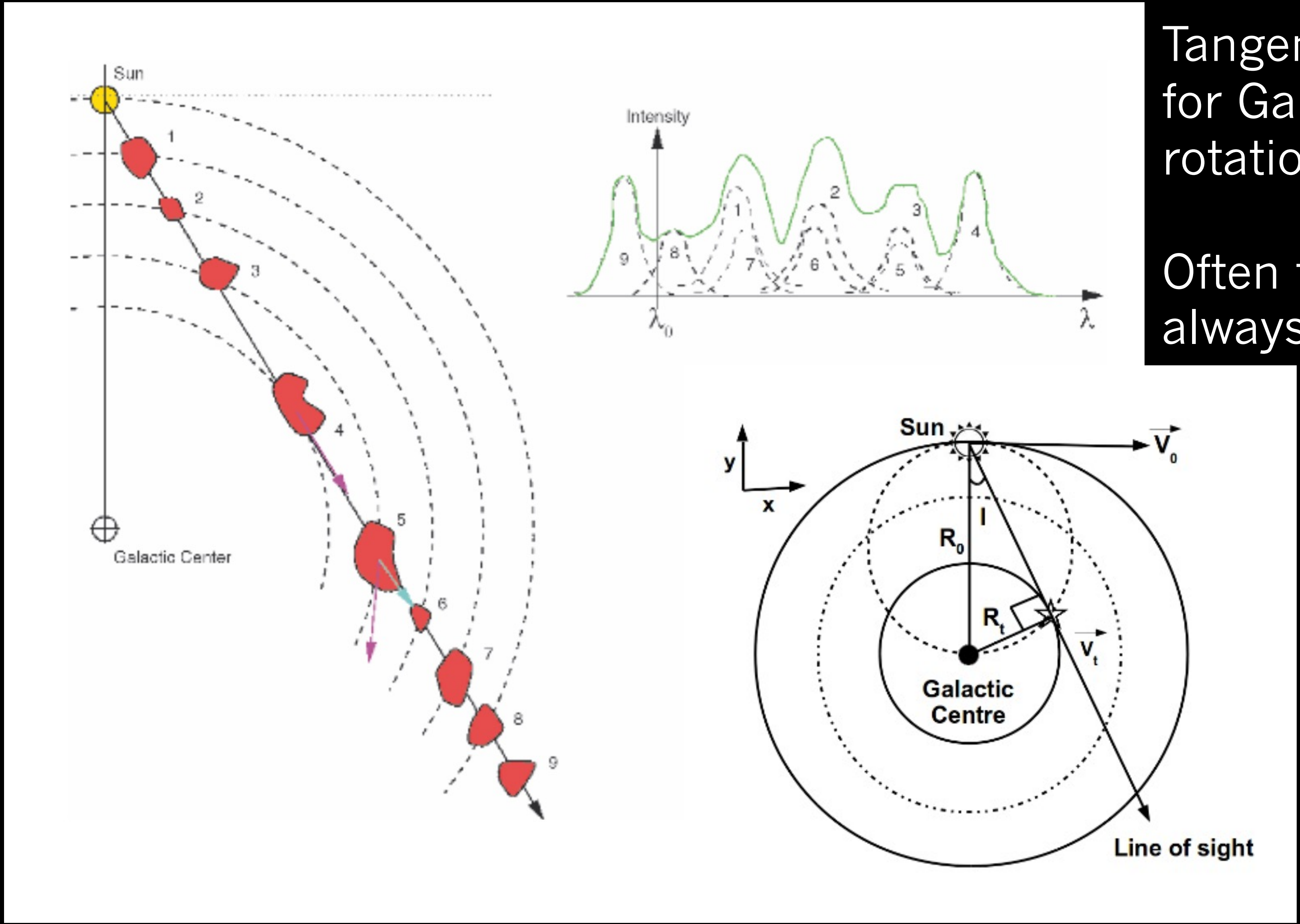
Summary. — An atlas is presented of the distribution of the 21-cm line emission from neutral hydrogen in the Galaxy, covering the region from galactic longitude 11° to 235°, with galactic latitude coverage of approximately + 2° to − 2°. The data were obtained with the 300-foot radio telescope of the NRAO ([1]) at Green Bank, W.Va. They are presented in the form of contour maps, giving cross sections perpendicular to the galactic equator at intervals of 0°.2 in galactic longitude. The spatial resolution is 0°.22, the velocity resolution 2 km/s.

Key words : Radioastronomy — Galactic Structure — 21-cm line — Surveys.

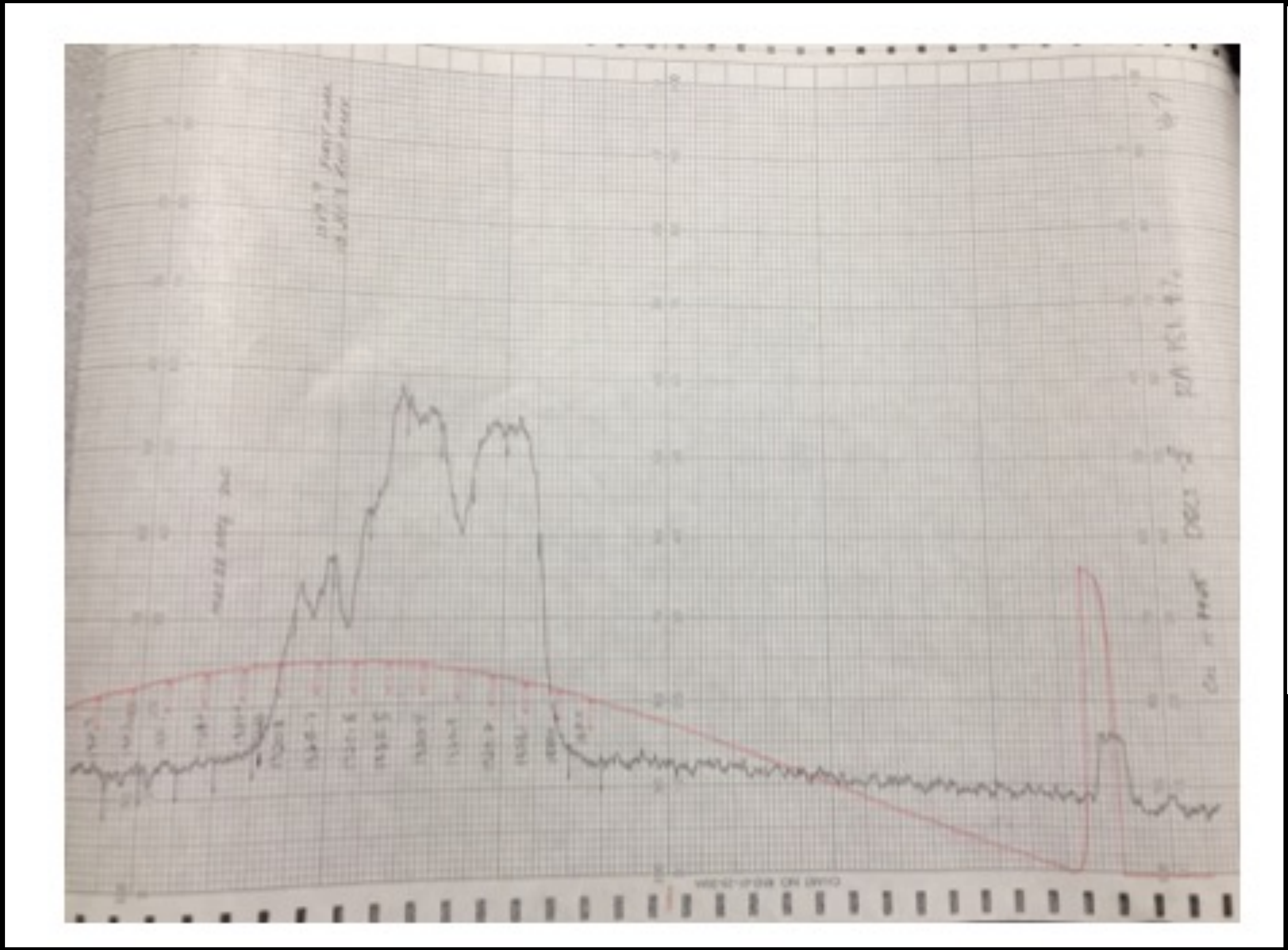
1. **Introduction.** — The 1969 edition of the Maryland-Green Bank 21-cm line Survey (Westerhout, 1969) was seriously affected by the large error beam of the 300-foot radio telescope of the NRAO in Green Bank, W.Va. before it was resurfaced in 1970. A completely sampled survey of neutral hydrogen extending from galactic longitude 11° to 235° and nominally covering a range of latitudes between − 2° and + 2° was conducted during 1971-1972 with the newly resurfaced 300-foot telescope. The actual latitude coverage varied with longitude depending upon the observing horizon of the telescope and upon frequency widths of the line profiles. The telescope was steered to follow constant latitude tracks as the sky rotated past the beam.

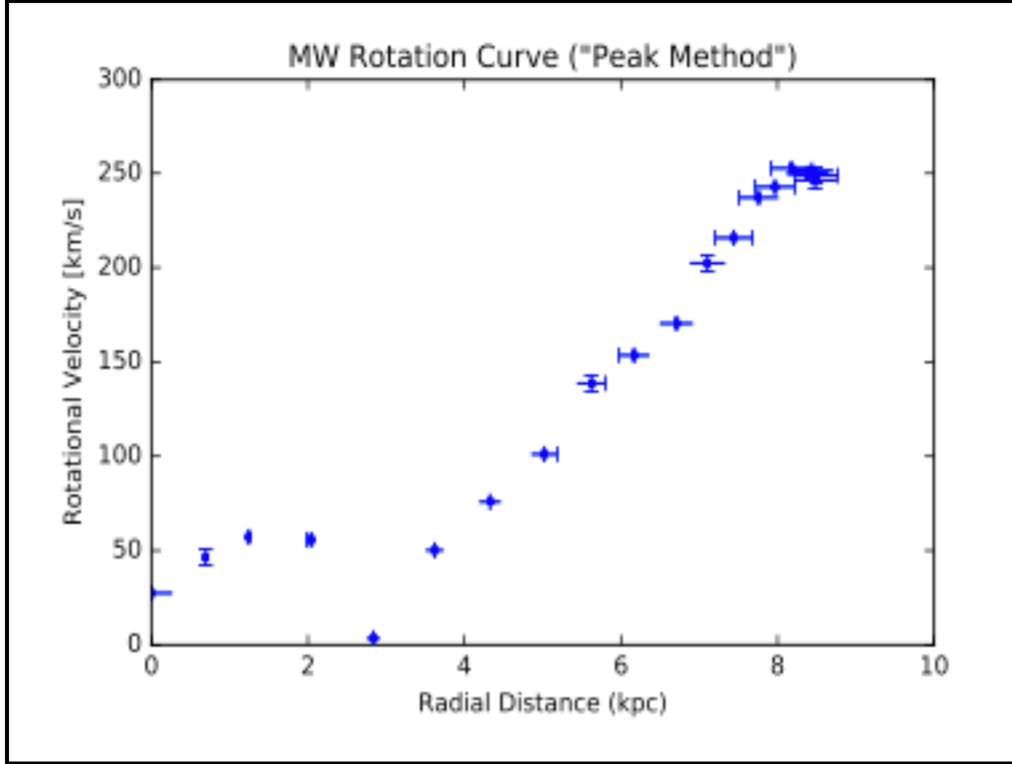
Tangent method for Galactic rotation curves

Often from HI (not always)



GBO 40ft Data for this Experiment





Analysis by Nick Sweeney ’20
(data collection during 2019 visit by Nick Sweeney, Justin Otter, Sydney Dorman and Emily Harrington)

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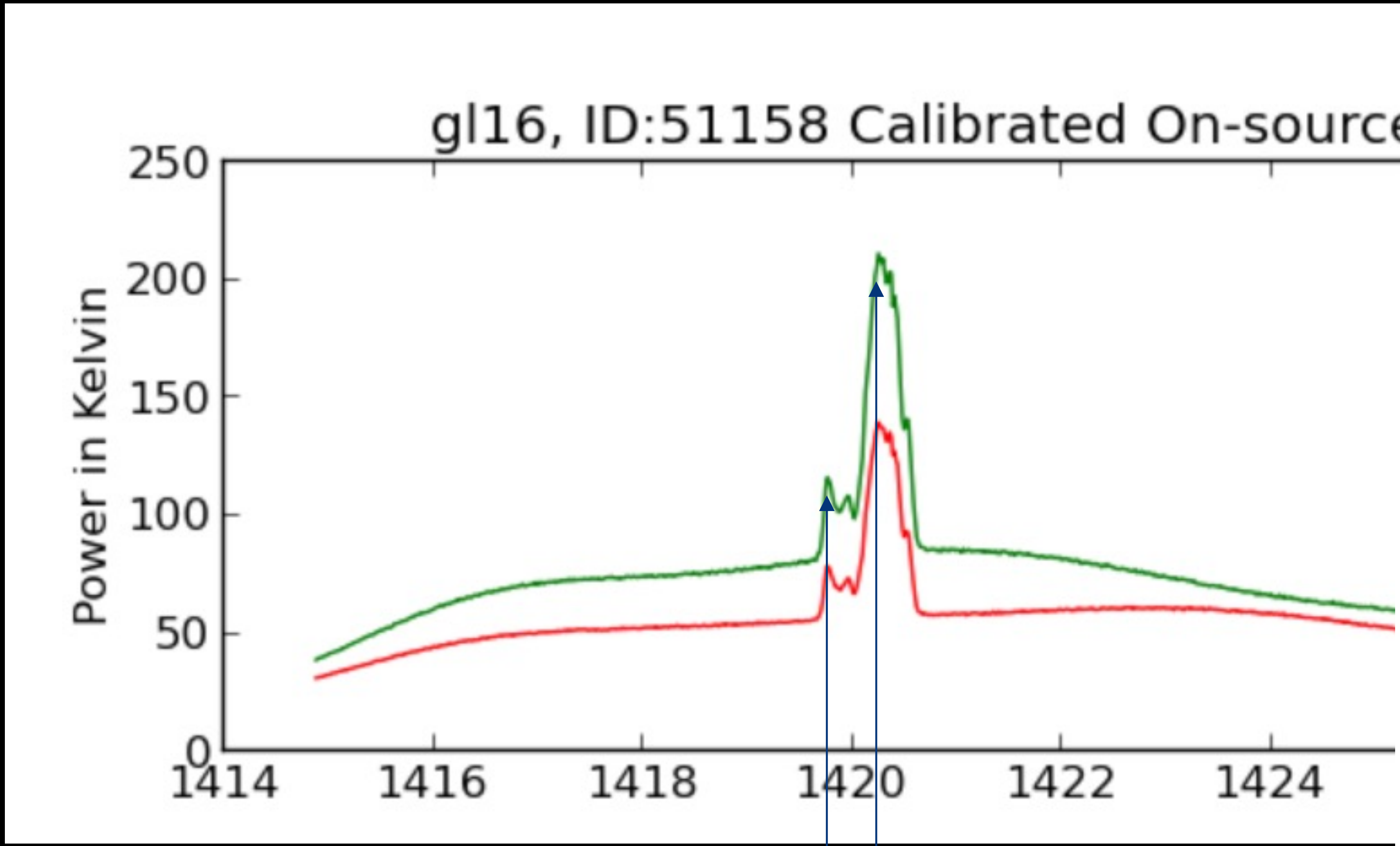
GBO 20m Data For this Experiment

Fall 2020 data, Kevin Sang '22



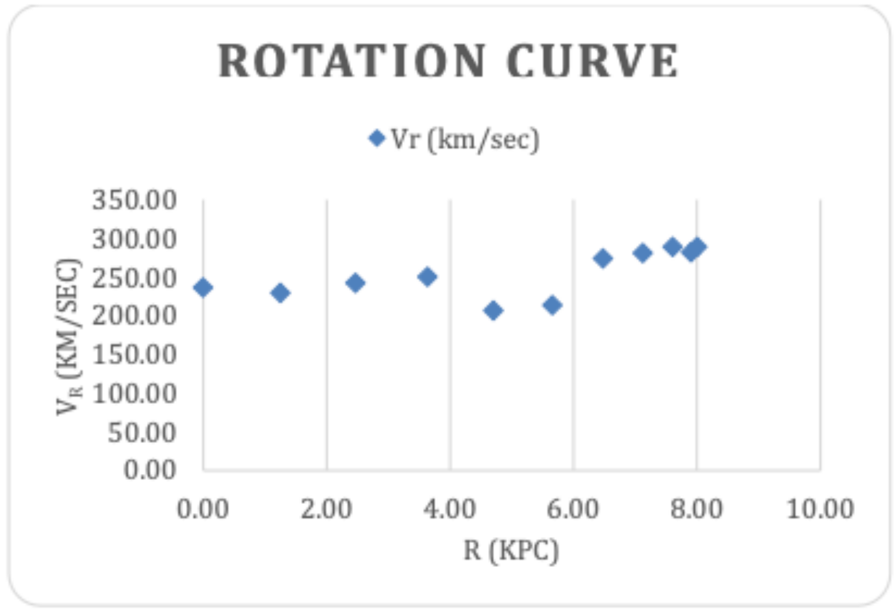


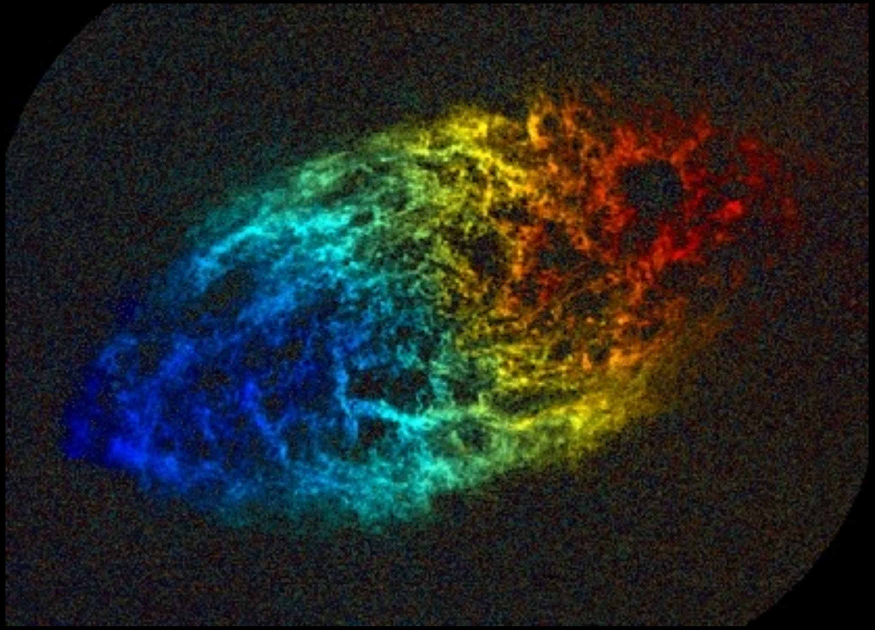
Fig 3. Rotation curve of Milkyway galaxy

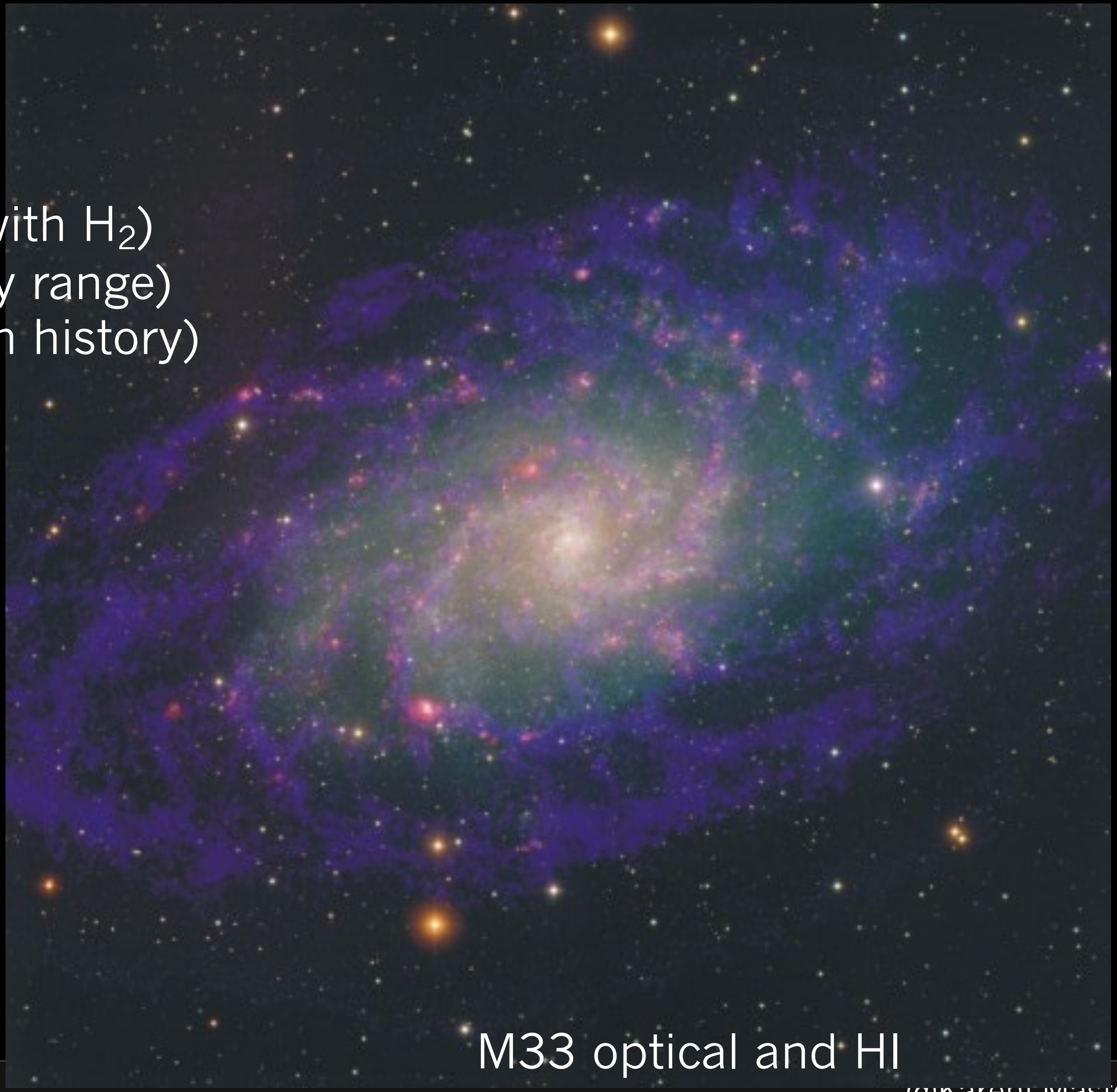
RA,DEC=18:19:55.50, -15:01:21.95
L,b=16deg,0deg

Two "lumps" at two freqs (lowest freq is highest radial velocity – biggest redshift)
Use "Live spectrum" feature to measure 1420.25 MHz and 1419.75 MHz

Neutral Hydrogen in External Galaxies

- Typically ~twice as extended as stars (optical light)
    - Trace potential well to larger radii
    - First component affected by environment
- HI -> H_2 -> stars
- Common to find HI holes in the centre (often filled in with H_2)
- Radius correlates with content (because narrow density range)
- Content correlates with galaxy colour (ie. star formation history)
- Emission line = dynamics "for free"



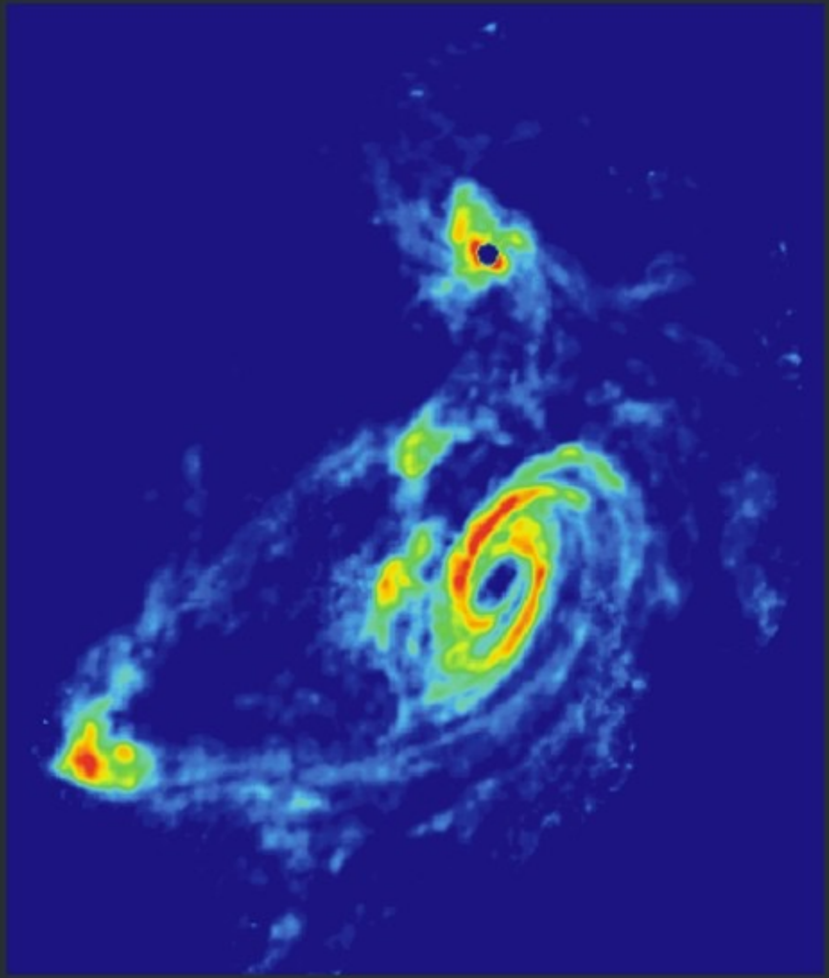


M33 optical and HI

TIDAL INTERACTIONS IN M81 GROUP

Stellar Light Distribution

21 cm HI Distribution



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THINGS
The HI Nearby Galaxy Survey
10 kpc
THINGS
Data: Walter et al 2008
Milky Way HI map: Oort et al (1958)
Milky Way art: NASA/JPL, R. Hurt (SSC)

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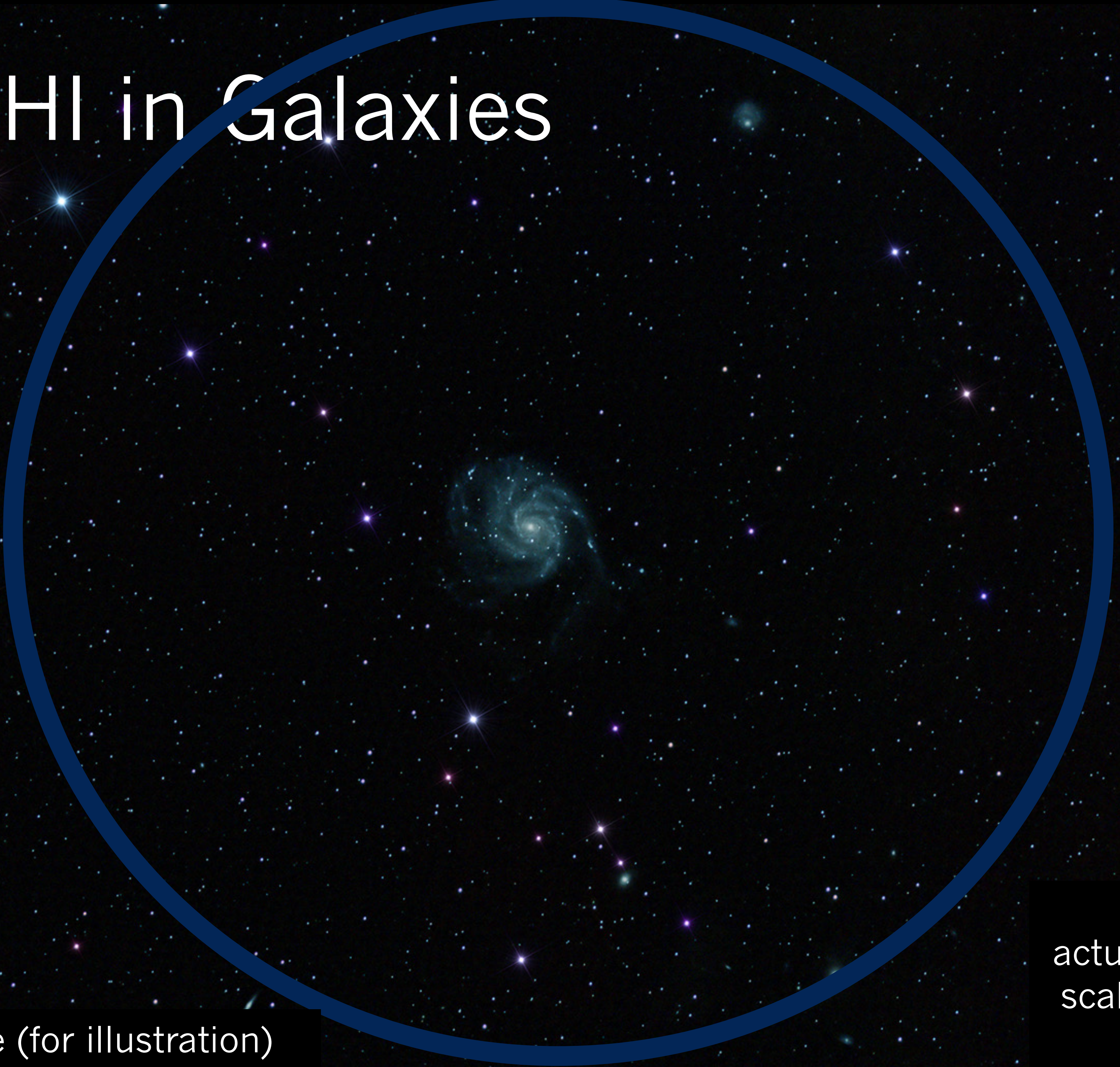
Single Dish HI in Galaxies

Green Bank Radio Telecope:
100m

HI emits at 21cm

$\theta = 1.22\ \lambda/d \sim 9$ arcmin



Not actually to scale with M101

Optical image of M101 by Mike Hyde (for illustration)

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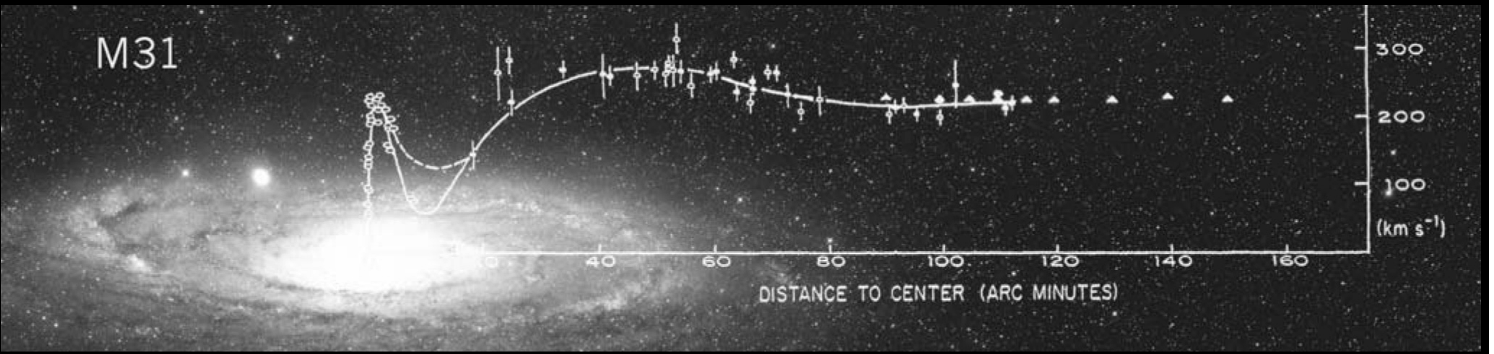
Early HI in External Galaxies from GBO

24. A HIGH-RESOLUTION STUDY OF M31

B. F. Burke, K. C. Turner, and M. A. Tuve
Carnegie Institution of Washington, Department of Terrestrial Magnetism

The great nebula in Andromeda, M31, is a particularly interesting external galaxy, since it is a giant spiral system, presumably much like our own Galaxy, and is close enough to be resolved with existing radio telescopes. During parts of November 1962, and from December 5, 1962, to January 20, 1963, the 300-foot transit telescope of the N.R.A.O. at Green Bank, W.Va., was used in conjunction with the Carnegie multichannel H-line spectrograph to study M31. The following is a preliminary account of these first observations.

1963 IAU Meeting Proc.



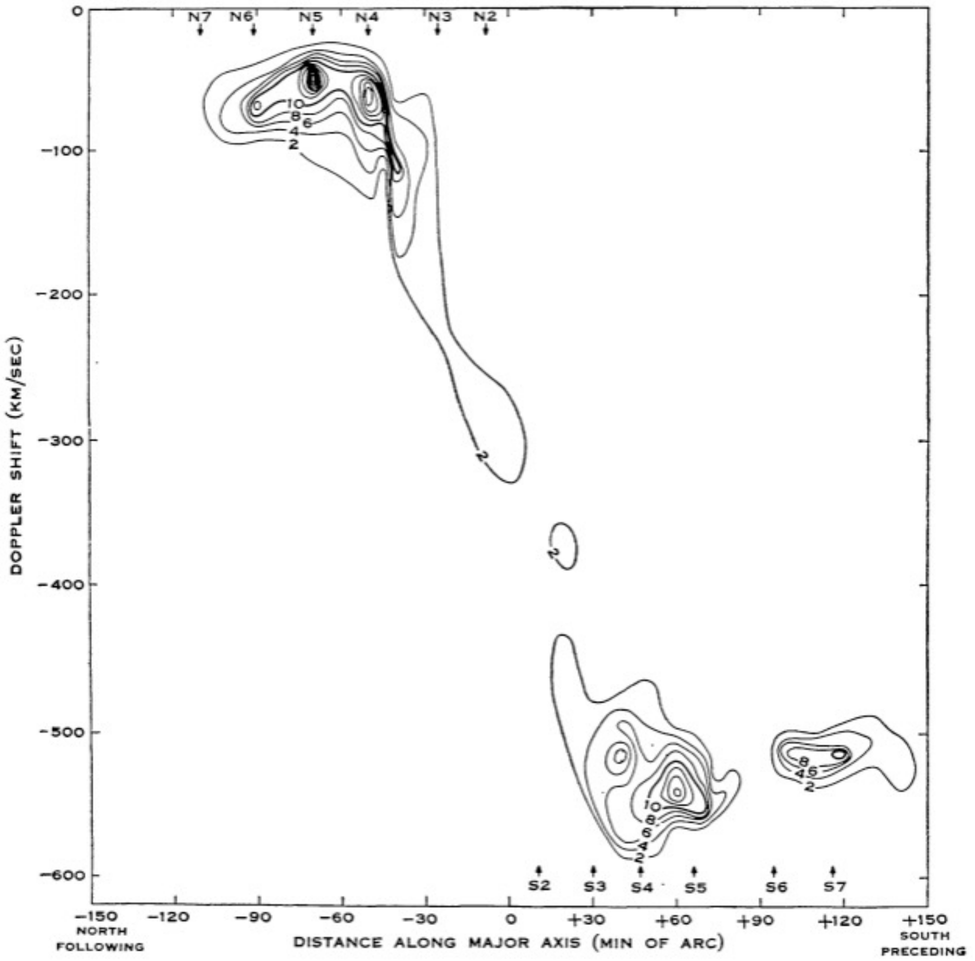


Fig. 1.—Observed antenna temperatures along major axis of M31. Velocity is with respect to local standard of rest. Baade's spiral arm crossings are shown.

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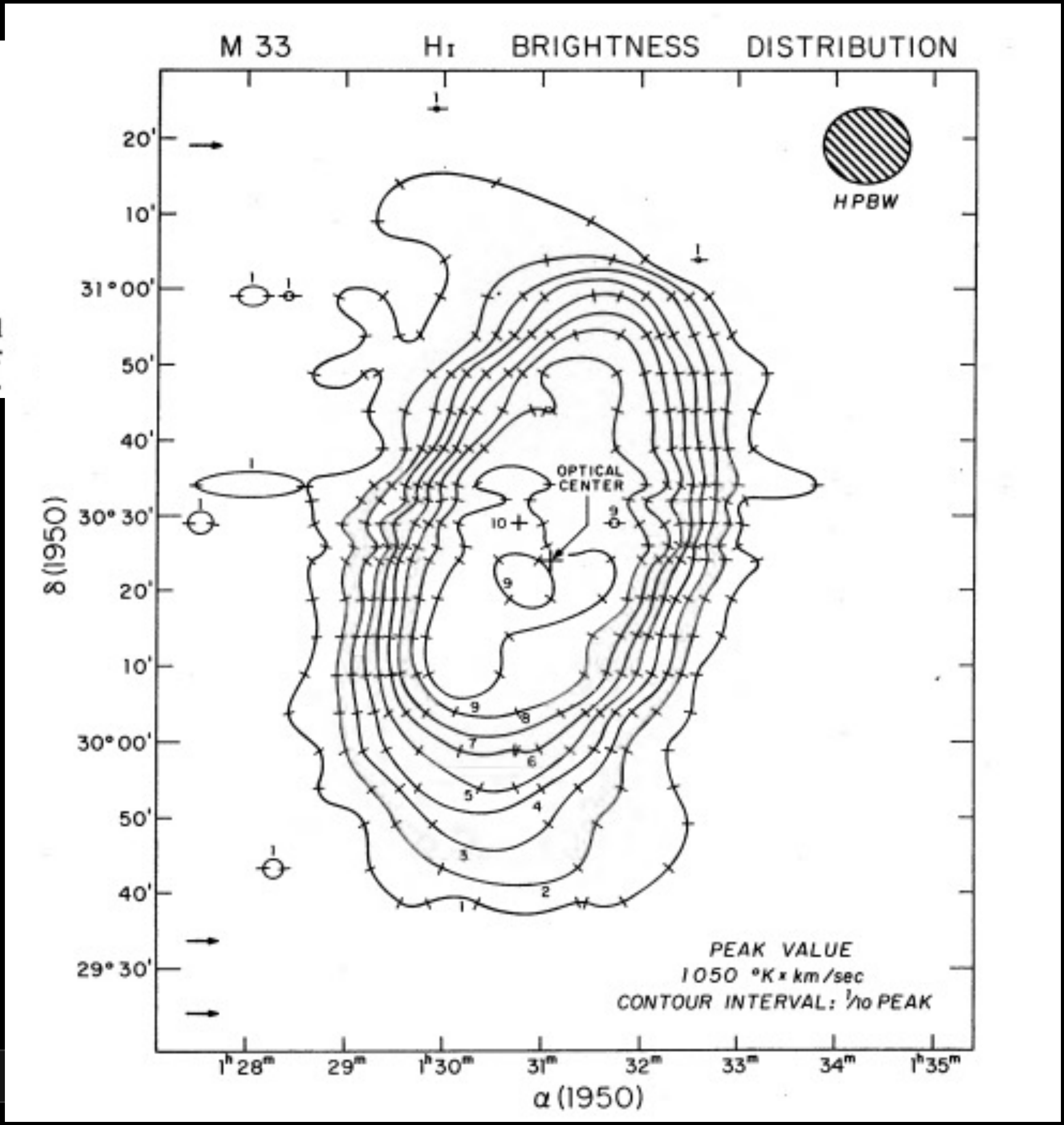
GREEN BANK OBSERVATORY

A 21-CENTIMETER STUDY OF THE SPIRAL GALAXY MESSIER 33*

KURTISS J. GORDON
National Radio Astronomy Observatory,† Green Bank, West Virginia 24944, and
Hampshire College, Amherst, Massachusetts 01002
Received 1970 May 25; revised 1971 June 9

ABSTRACT

The distribution of neutral atomic hydrogen and the kinematic properties of the late-type spiral galaxy M33 are derived from observations obtained at 21-cm wavelength with a multichannel radiometer attached to the 300-foot paraboloidal transit telescope of the National Radio Astronomy Observatory.



Early HI in External Galaxies from GBO

21-CM HYDROGEN MEASUREMENTS OF NGC 5668
A RELATIVELY DISTANT GALAXY

MORTON S. ROBERTS
National Radio Astronomy Observatory,* Green Bank, West Virginia
Received Janu

ABSTR

1965 – highest redshift 21cm line at the time - previous record was 650 km/s.

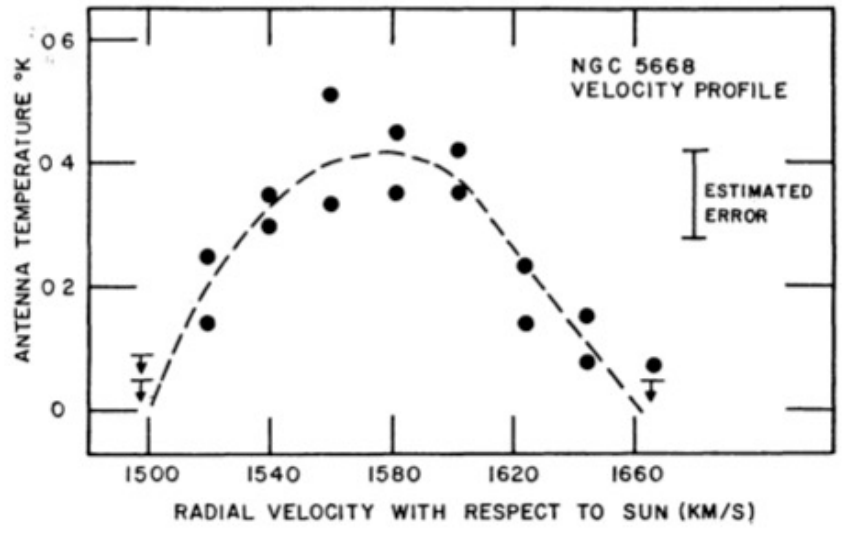


FIG. 2.—Velocity profile for NGC 5668

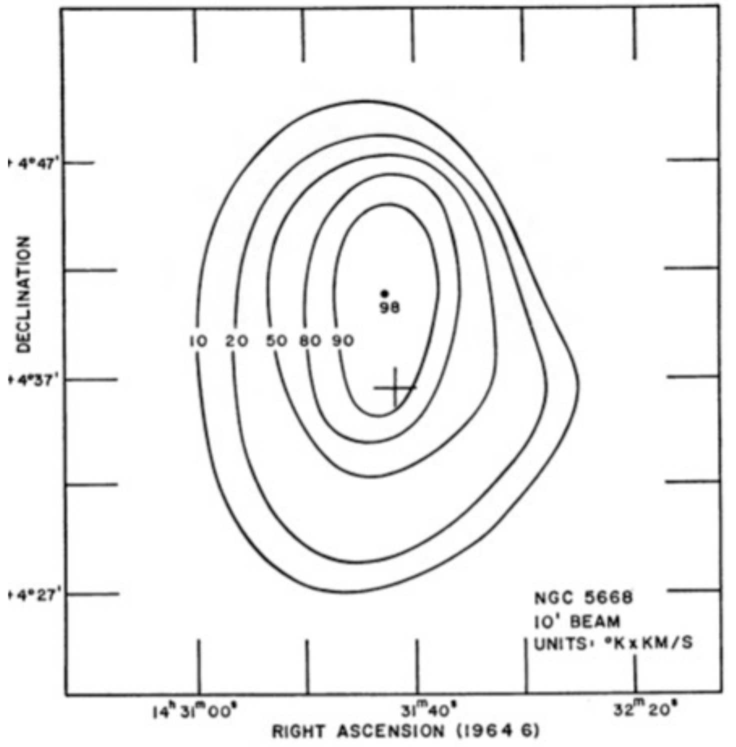
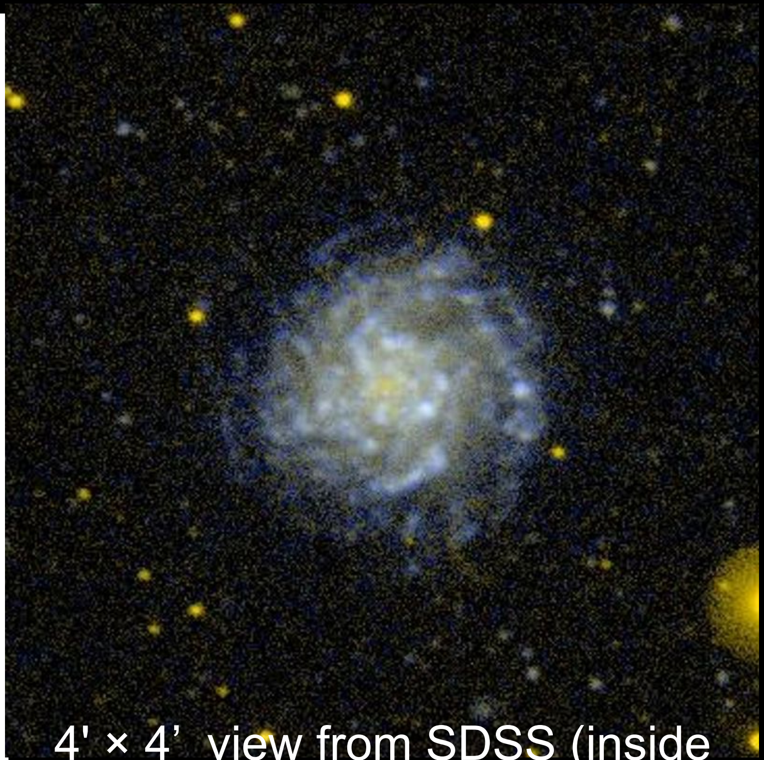
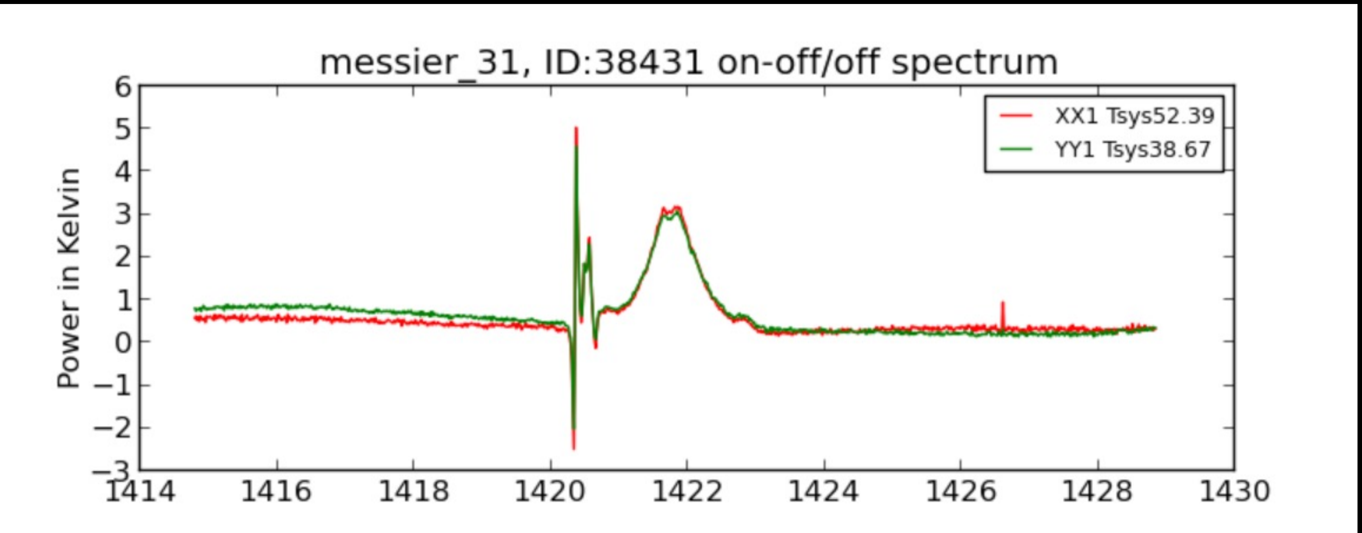


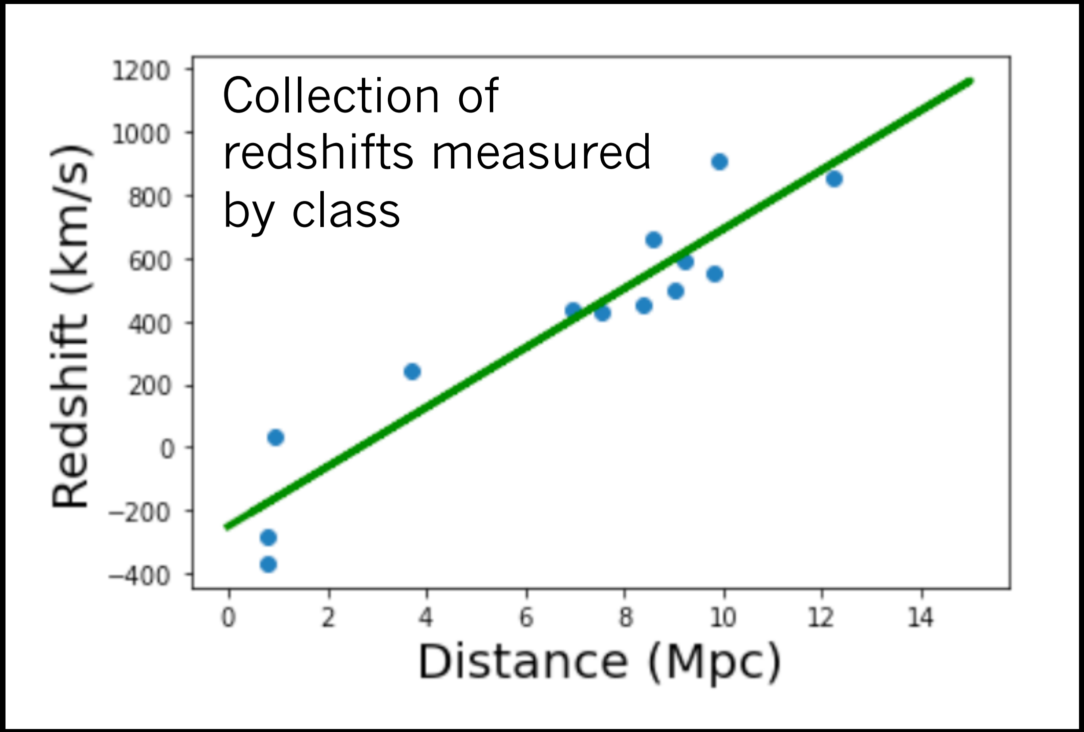
FIG. 3 —Contours of equal integrated brightness temperature for NGC 5668

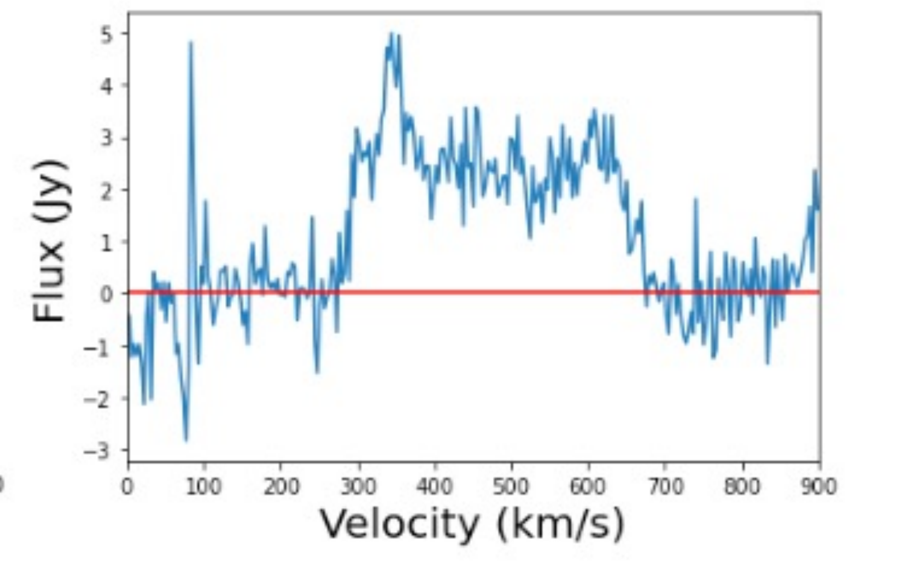


4' × 4' view from SDSS (inside first contour)

Galaxies in 21cm Using the 20m (teaching)







HI Mass (M⊙)	Stellar Mass (M⊙)	HI Fraction	Total Mass (M⊙)	Dynamical Mass (M⊙)	Dark Matter Fraction
3.59E10	5.90E10	-0.496	1.04E10	2.10E11	0.506

NGC5055, by August Muller '23 (Fall 2021 class)

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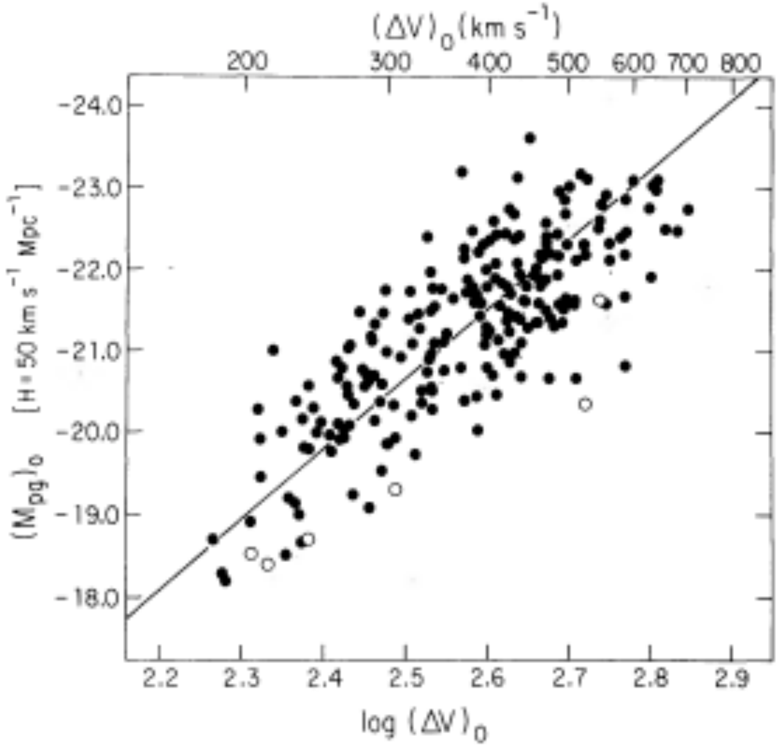


FIG. 8. The corrected absolute magnitude $(M_{pg})_o$ for a Hubble constant of 50 km s^{-1} Mpc^{-1} versus the intrinsic line width. The mean of the two regressions is shown as the solid line. The open circles represent six of the ten calibrating galaxies used by Tully and Fisher (1977). The remaining four lie to the left and beyond the range of values shown here. This sample is for $i \geq 45°$.

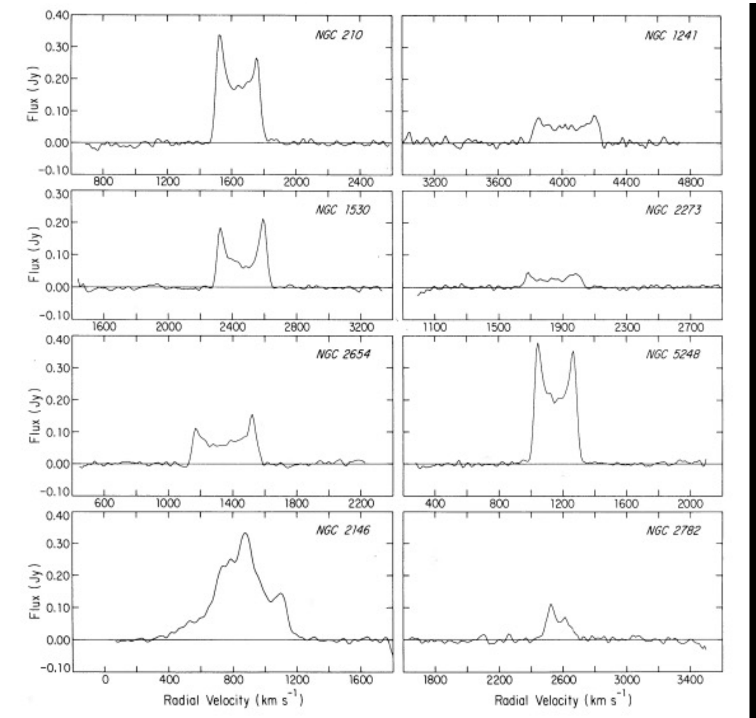
JOURNAL VOLUME 83, NUMBER 9 SEPTEMBER 1978

TWENTY-ONE CENTIMETER LINE WIDTHS OF GALAXIES

MORTON S. ROBERTS
National Radio Astronomy Observatory,[a] Green Bank, West Virginia
Received 17 May 1978

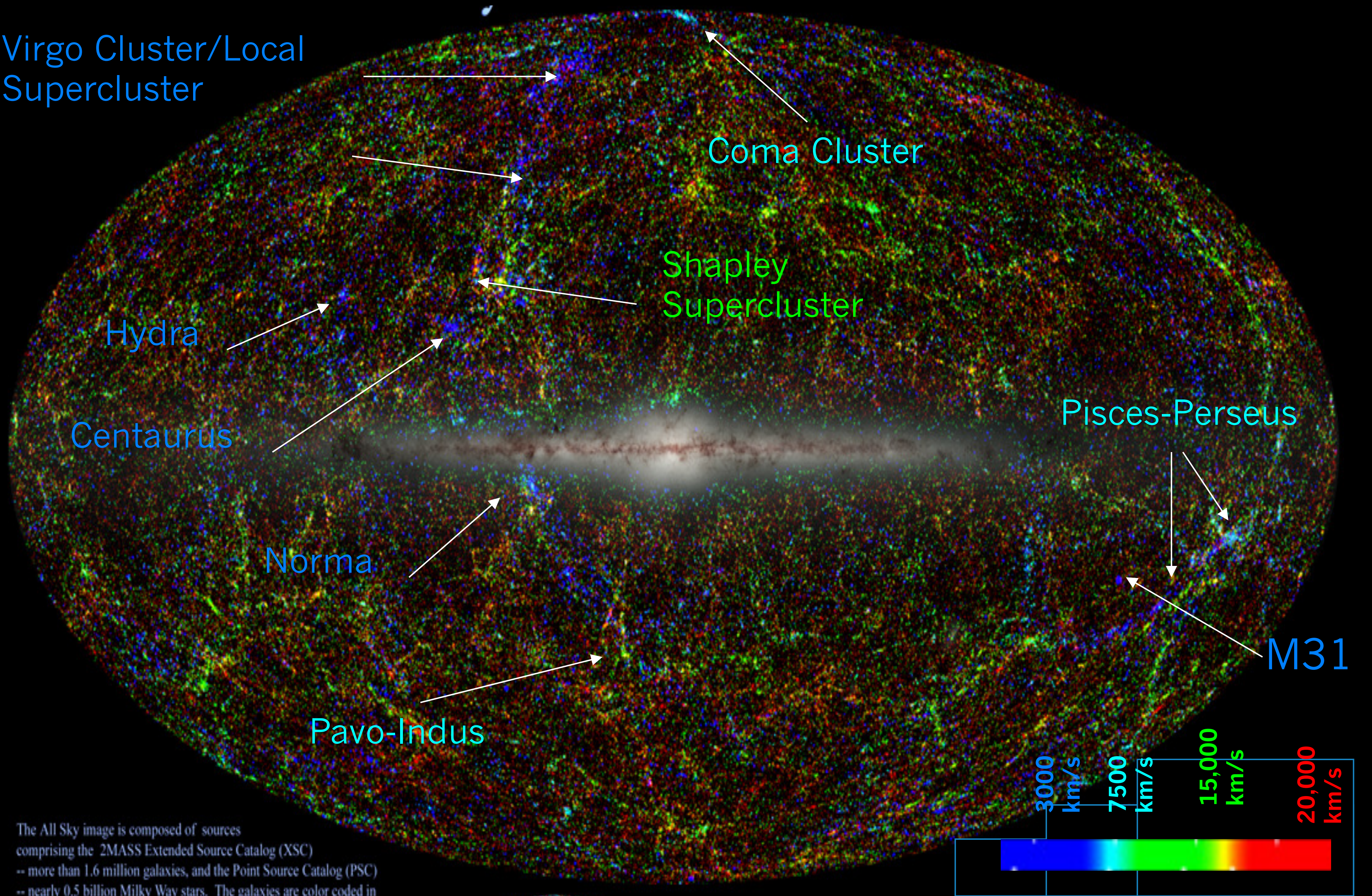
- Roberts (1978)
- Collection of 500 galaxies observed at 21cm with 300ft
- “homogenized” data

Many more examples not covered here!



2MASS Redshift Survey

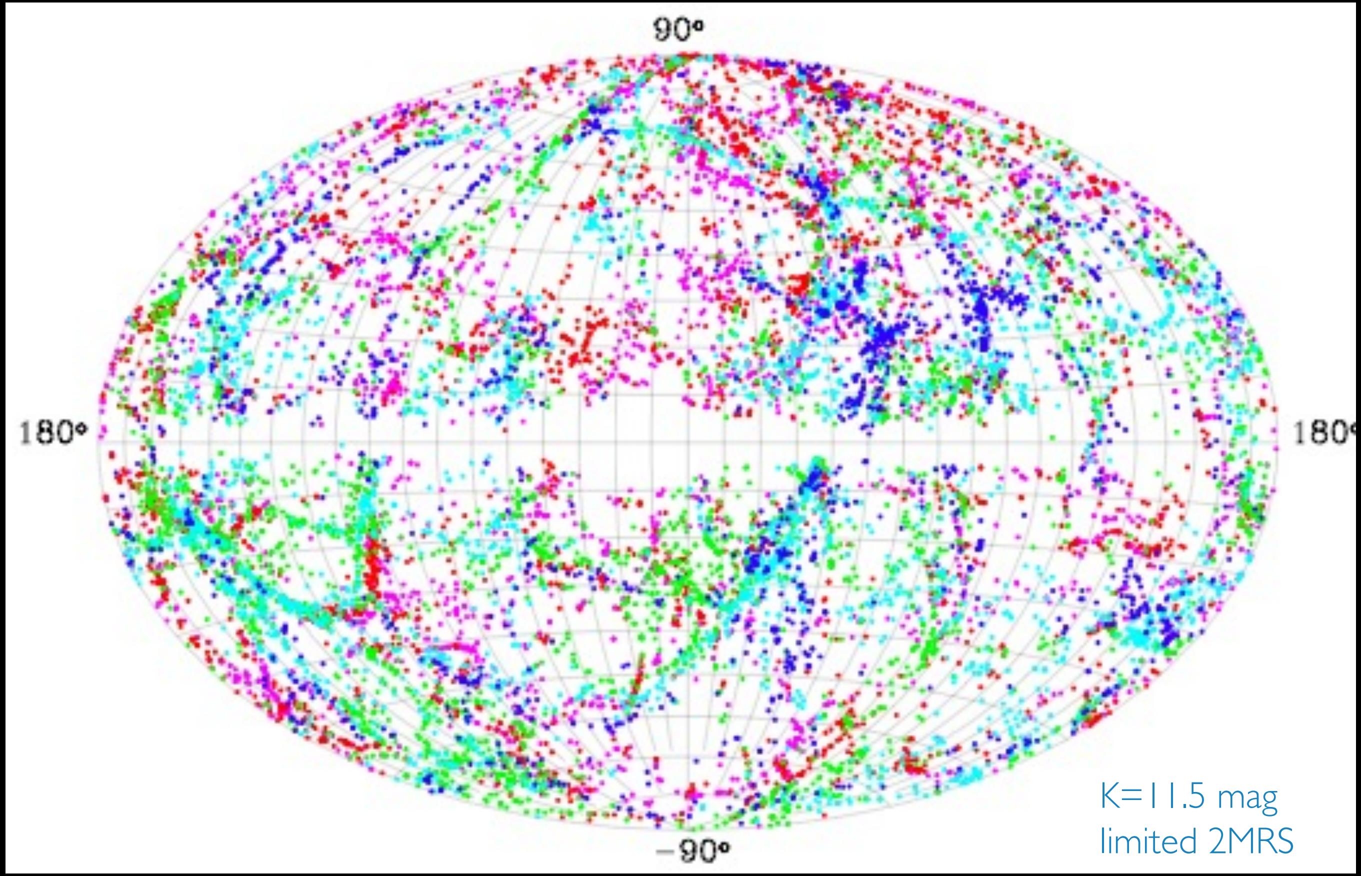
Huchra, Macri, Masters et al, 2012 (published after John's untimely death in 2010 largely based on his work).



2MASS Tully-Fisher Survey (2MTF)

Masters PI as a postdoc work with John Huchra.
GBT observations in 2005-2008

- source list from 2MASS redshift survey
  - NIR => stellar mass
  - redshifts a priori
  - small Galactic plane
  - uniform sky coverage
- Tully-Fisher distances for inclined spirals
  - 2MASS photometry
  - published widths + new observations



2MTF - Bright inclined spirals from 2MRS

N~2100 (inc 1194 from GBO)

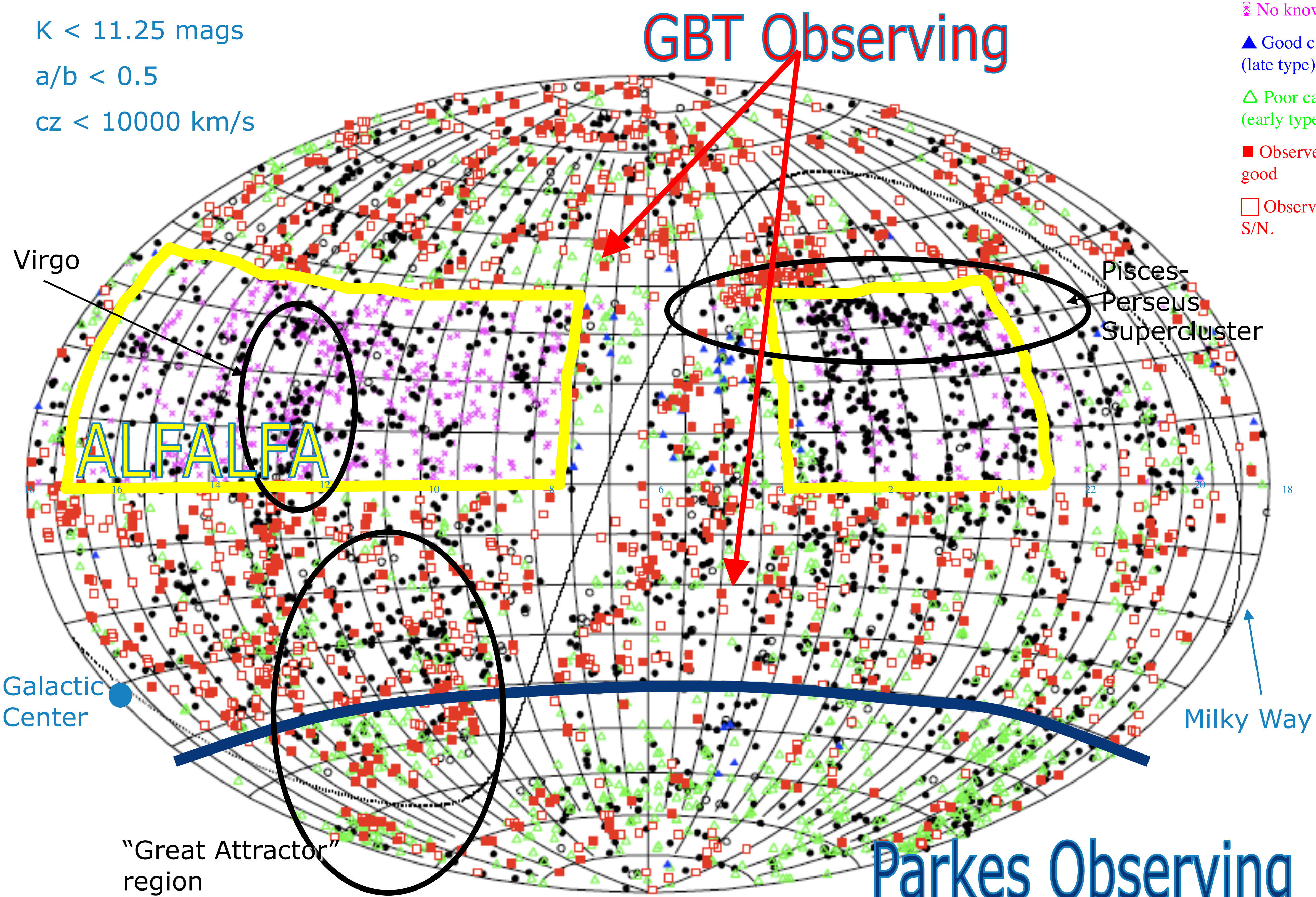
K < 11.25 mags

a/b < 0.5

cz < 10000 km/s

KEY TO SYMBOLS

- • Width in literature
- ⌛ No known width
- ▲ Good candidate for observing (late type)
- △ Poor candidate for observing (early type)
- ■ Observed - detected and width good
- □ Observed. Not detected or low S/N.



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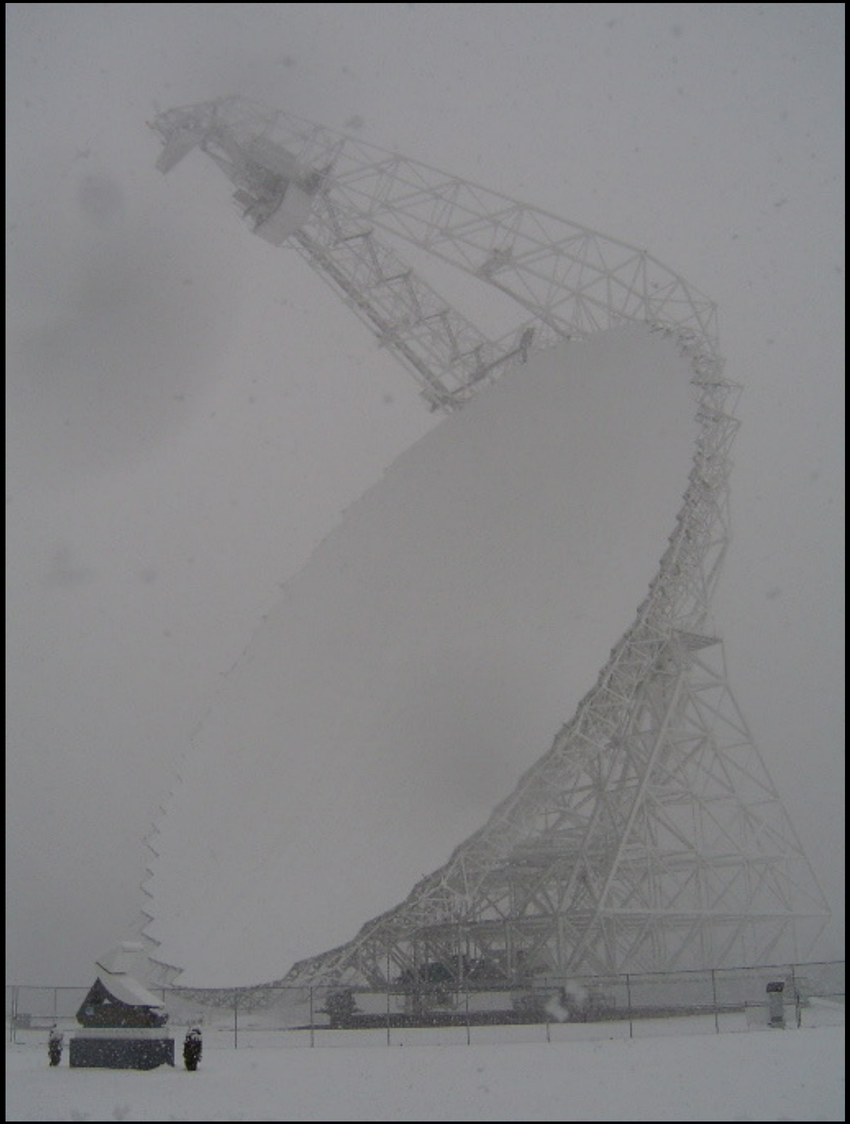
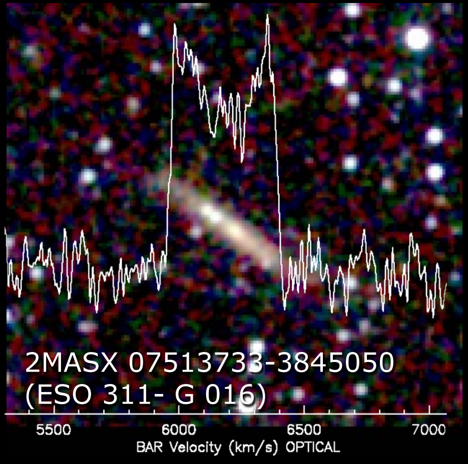
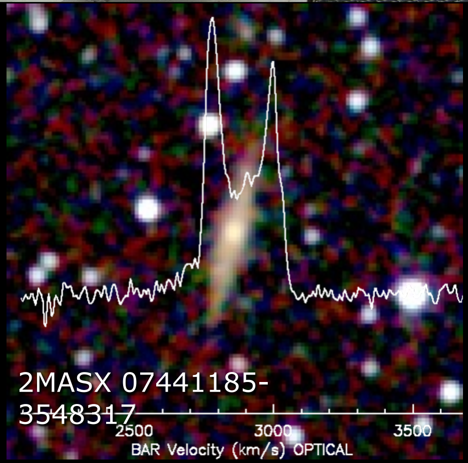
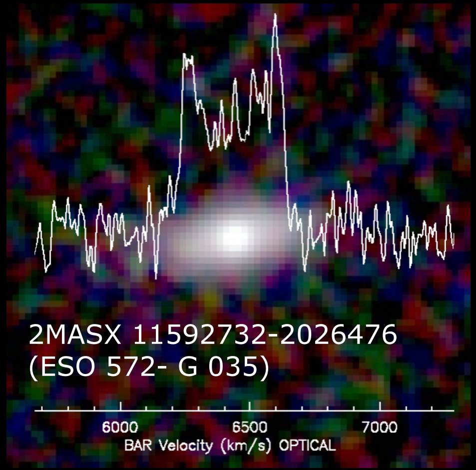
2MTF: GBT Observing

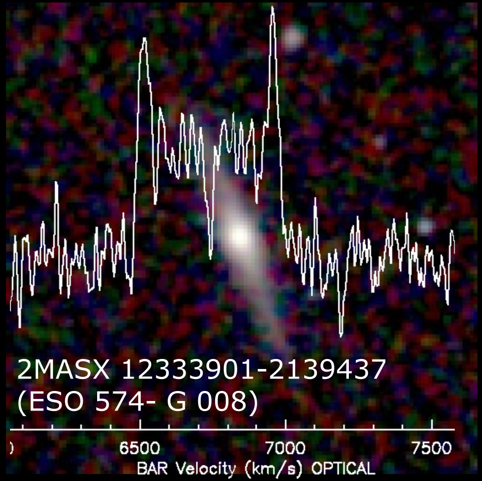


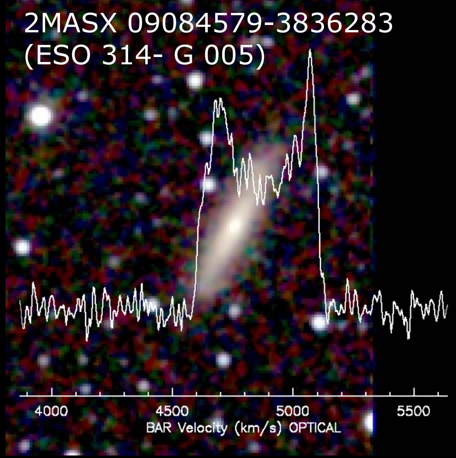
- 464 hours on GBT (Feb 2006-Aug 2008)
- GBT06A-027, GBT06B-021, GBT06C-049, GBT08B-003: “Mapping Mass in the Nearby Universe with 2MASS”, PI Karen L. Masters.
- 1194 galaxies observed in total (5-20 minutes each t_{int})

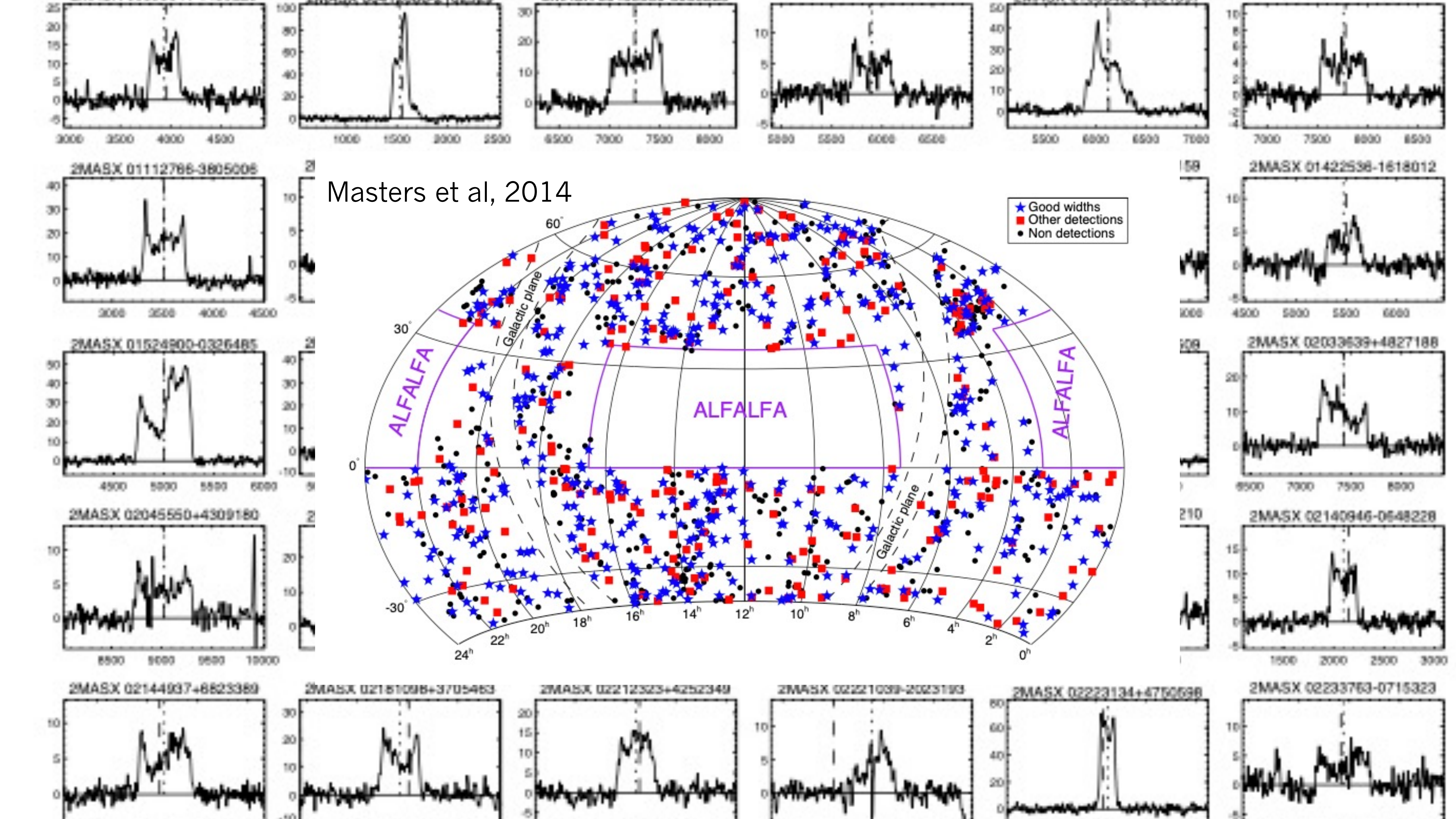












Masters et al, 2014
Good widths
Other detections
Non detections
ALFALFA
ALFALFA
ALFALFA
Galactic plane
Galactic plane
60°
30°
0°
-30°
24h
22h
20h
18h
16h
14h
12h
10h
8h
6h
4h
2h
0h
2MASX 01112766-3805006
2MASX 01422536-1618012
2MASX 01524900-0326485
2MASX 02033639+4827188
2MASX 02045550+4309180
2MASX 02140946-0648228
2MASX 02144937+6823389
2MASX 02181098+3705463
2MASX 02212323+4252349
2MASX 02221039-2023193
2MASX 02223134+4750598
2MASX 02233763-0715323

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2MTF Publications

1. Masters, K.L., Springob, C.M., Huchra, J.P. 2008. 2MTF. I. The Tully-Fisher Relation in the Two Micron All Sky Survey J, H, and K Bands.
2. Hong, T. and 8 colleagues 2013. 2MTF - II. New Parkes 21-cm observations of 303 southern galaxies.
3. **Masters, K.L. and 7 colleagues 2014. 2MTF III. H I 21 cm observations of 1194 spiral galaxies with the Green Bank Telescope.**
4. Hong, T. and 8 colleagues 2014. 2MTF - IV. A bulk flow measurement of the local Universe.
5. Springob, C.M. and 9 colleagues 2016. 2MTF - V. Cosmography, beta, and the residual bulk flow.
6. Howlett, C. and 9 colleagues 2017. 2MTF - VI. Measuring the velocity power spectrum.
7. Qin, F., Howlett, C., Staveley-Smith, L., Hong, T. 2018. Bulk flow in the combined 2MTF and 6dFGSv surveys.
8. Qin, F., Howlett, C., Staveley-Smith, L., Hong, T. 2019. Bulk flow and shear in the local Universe: 2MTF and COSMICFLOWS-3.
9. Hong, T. and 10 colleagues 2019. 2MTF - VII. 2MASS Tully-Fisher survey final data release: distances for 2062 nearby spiral galaxies.
10. Qin, F., Howlett, C., Staveley-Smith, L. 2019. The redshift-space momentum power spectrum - II. Measuring the growth rate from the combined 2MTF and 6dFGSv surveys.

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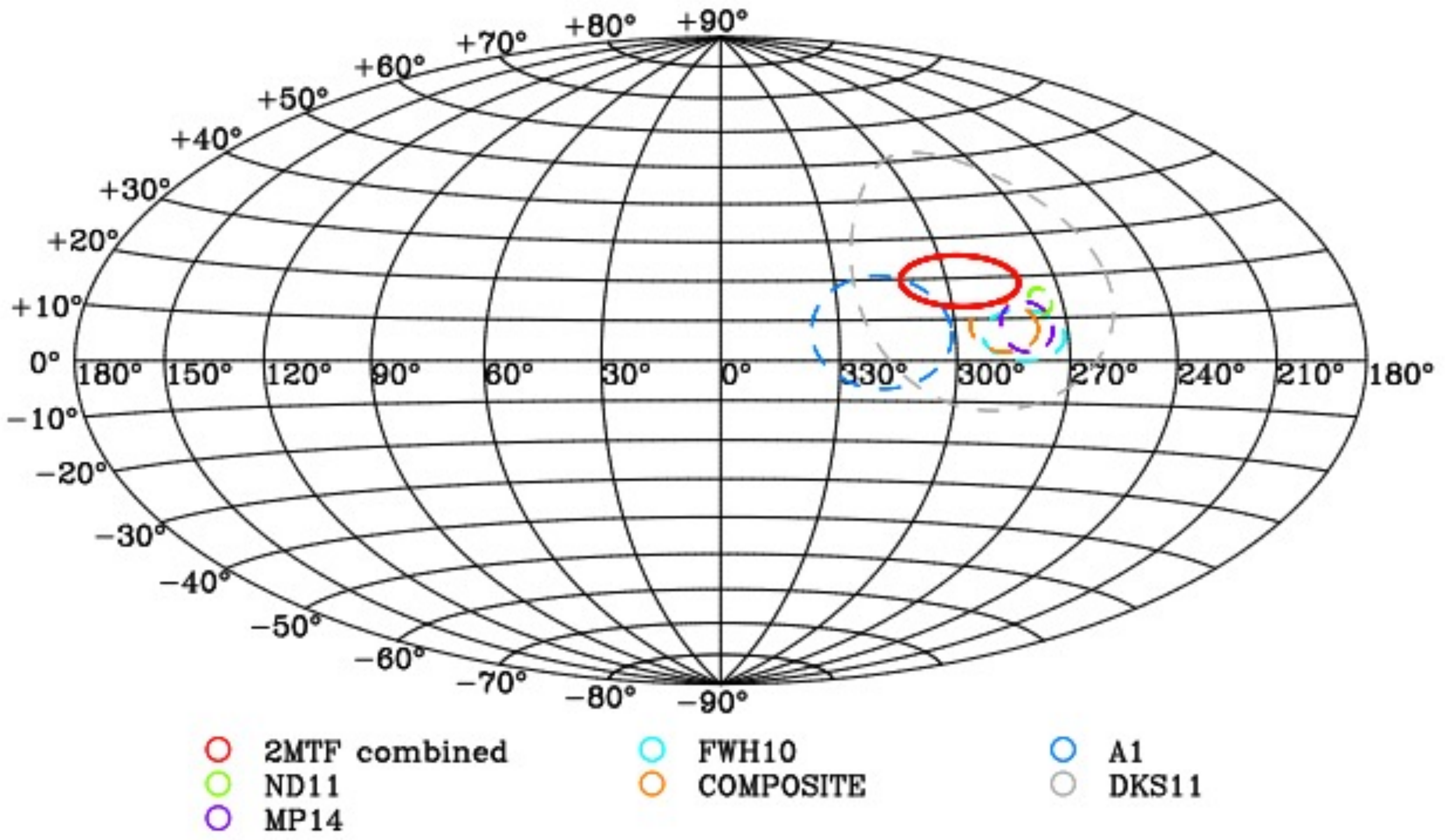


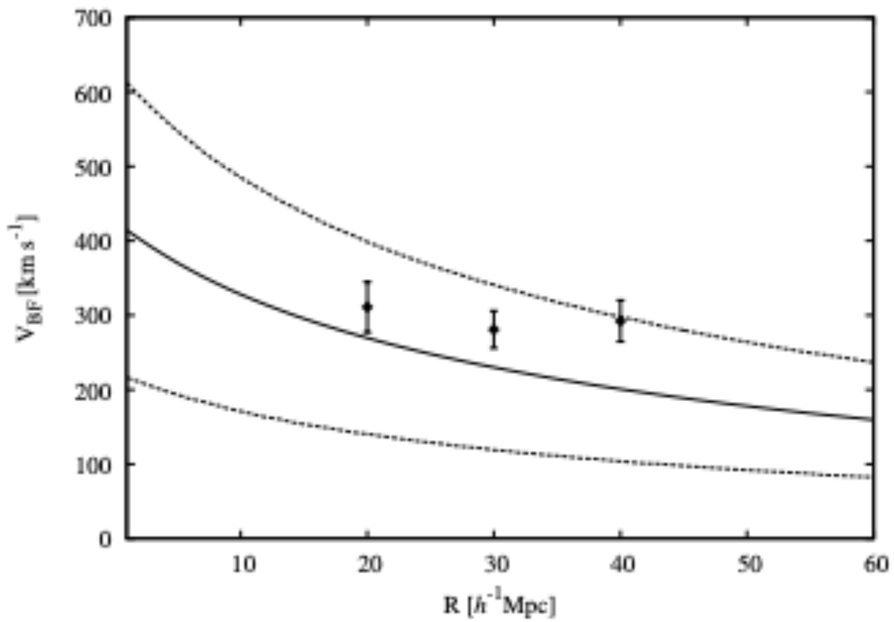


Figure 10. The comparison between the bulk flow velocity amplitude from the 2MTF sample and the ΛCDM prediction using the WMAP-7yr parameters (Larson et al. 2011). The diamonds with error bars indicate the bulk flow velocity amplitude measured from the 2MTF '3 bands combined' sample using the χ^2 minimization method, with the depth R_I = 20, 30 and 40 h^{-1}Mpc respectively. The solid line shows the theoretical curve and the dashed lines indicate the sample variance at the 1σ level.

Hong, T. and 8 colleagues 2014. 2MTF - IV. A bulk flow measurement of the local Universe

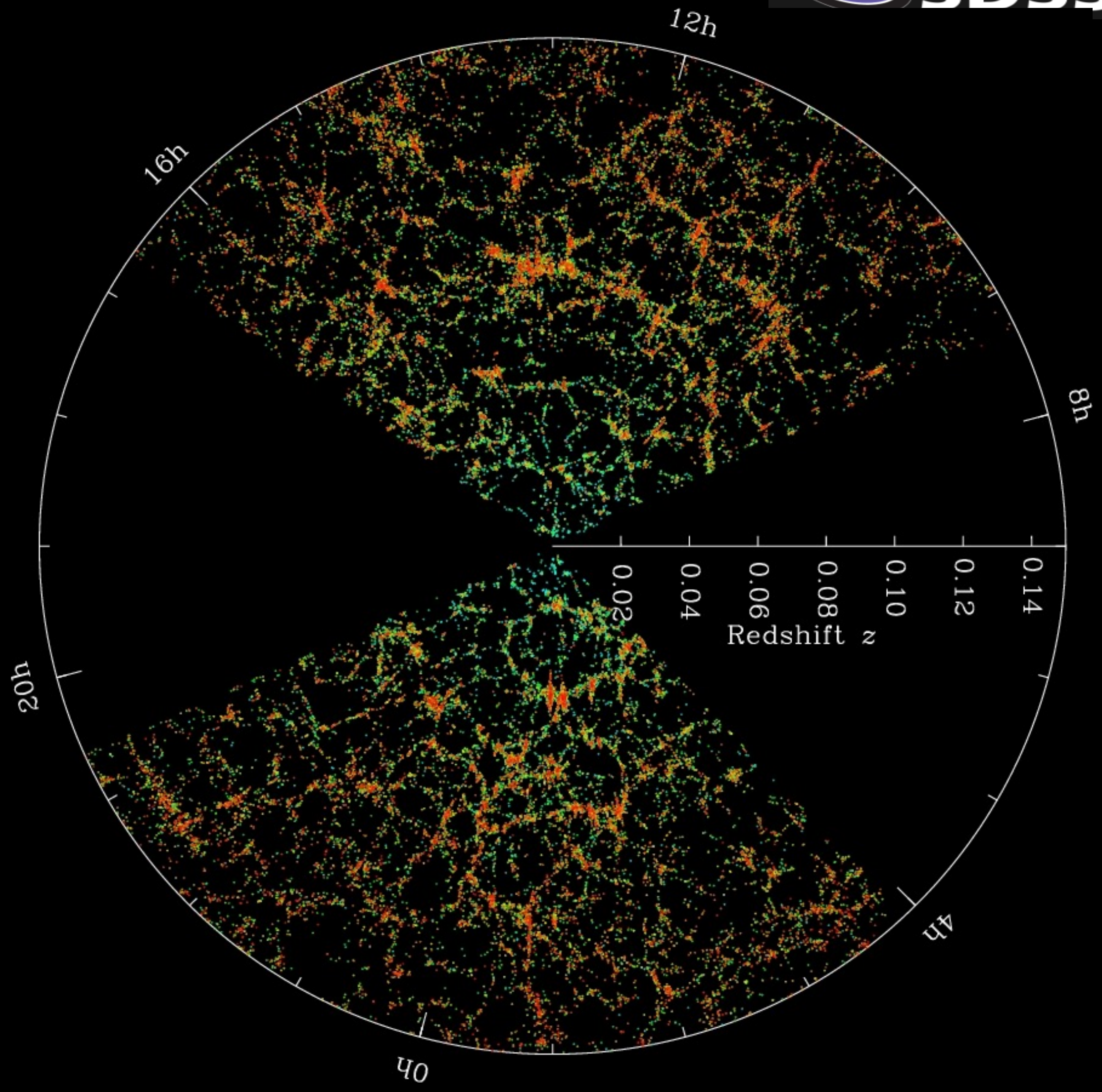
Twenty Years of the Sloan Digital Sky Survey

18 public data releases

DR18 – Dec 2018

Images cover 35% of the sky

More than 4 million spectra



5000+ scientific papers

Cited more than 200,000 times

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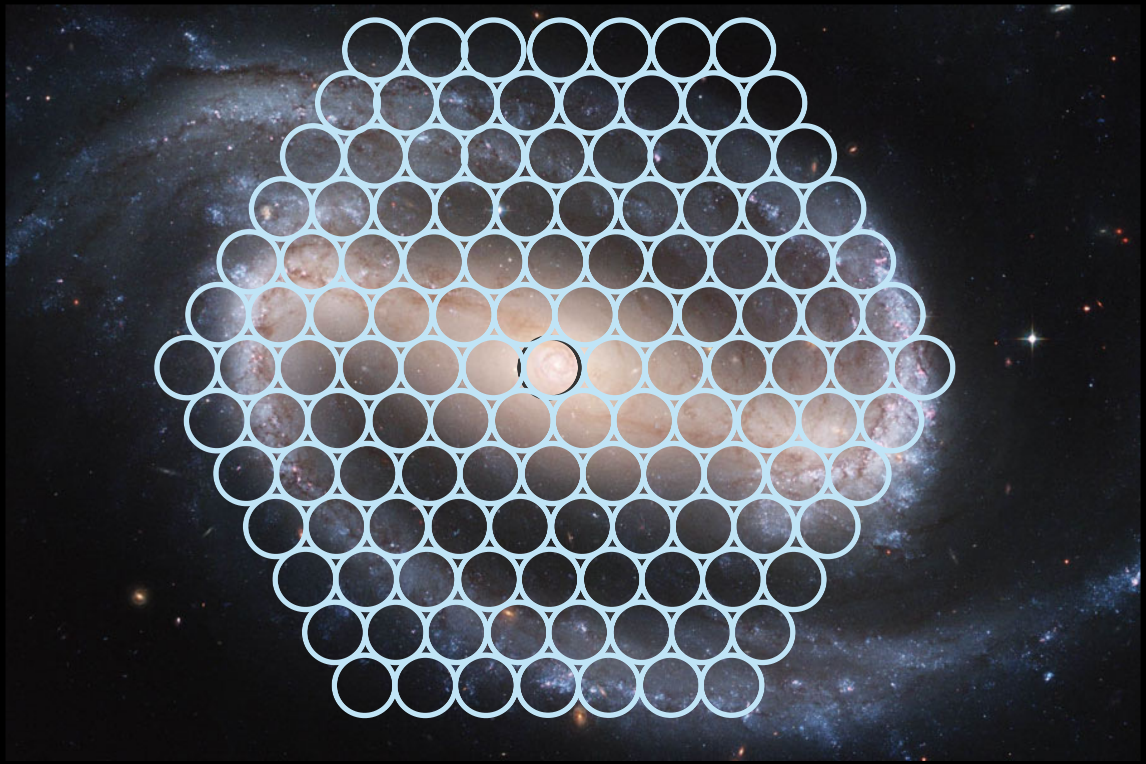
HI-MaNGA: HI Follow-up for MaNGA



Previous optical galaxy spectra from SDSS – single fibres

MaNGA – 19 to 127 resolution elements in a hexagon

- Optical spectroscopy of nearby galaxies (0.025<z<0.15)
- Part of SDSS-IV
- IFU survey (spectral maps)
- Observations 2014-2021
- 10k galaxies

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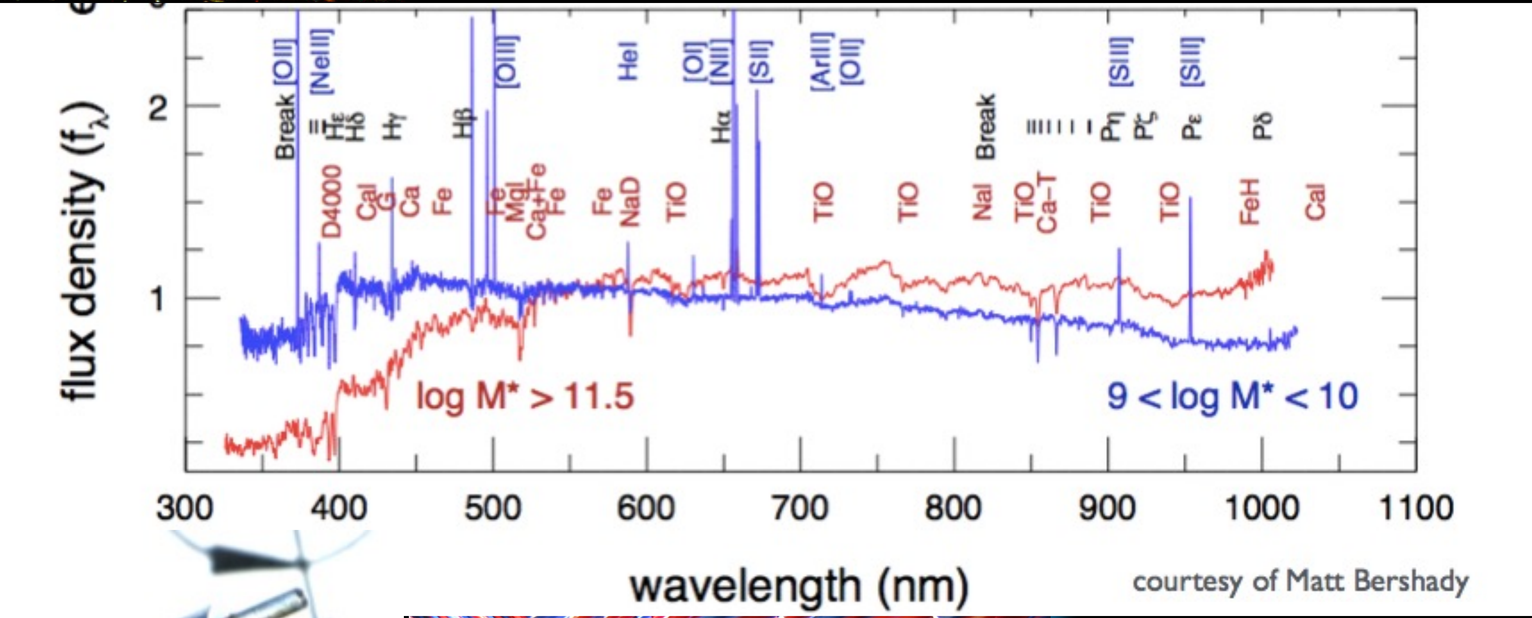
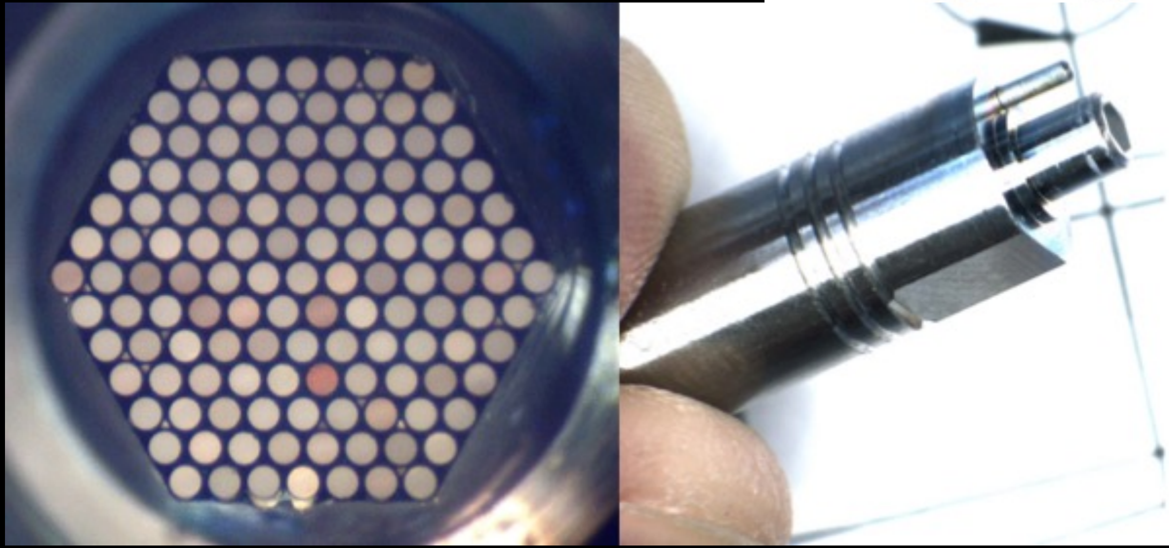
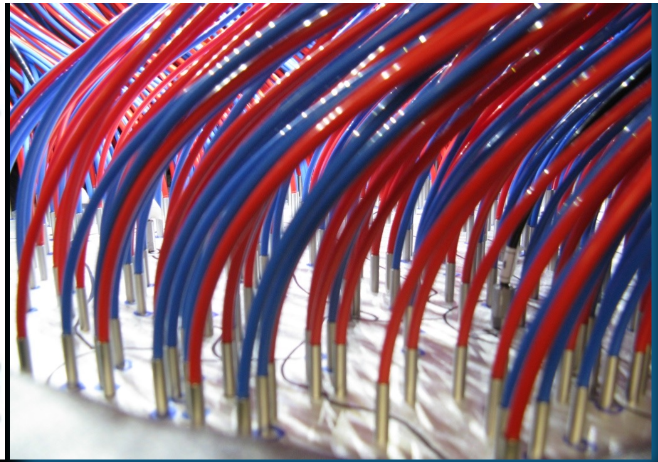
MaNGA Concept

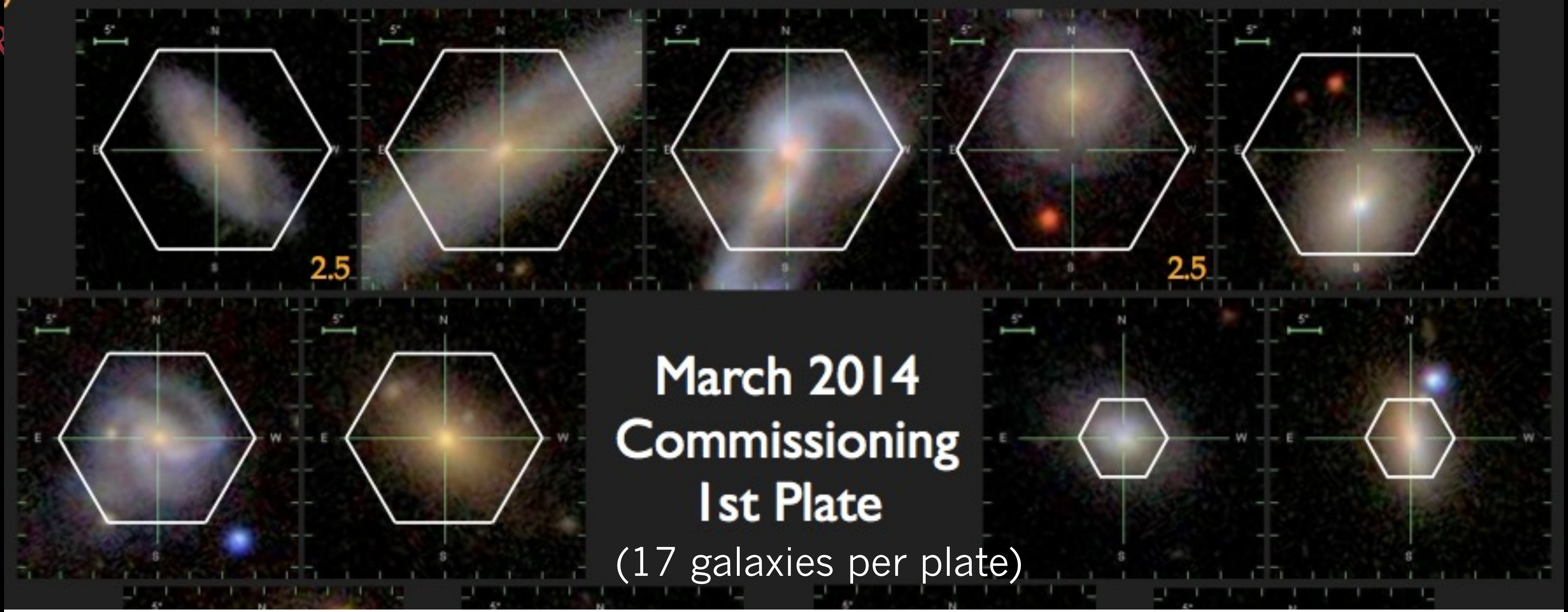
- Bundle fibres together in IFUs
  - use SDSS-III BOSS spectrographs (3600-10,000 A)

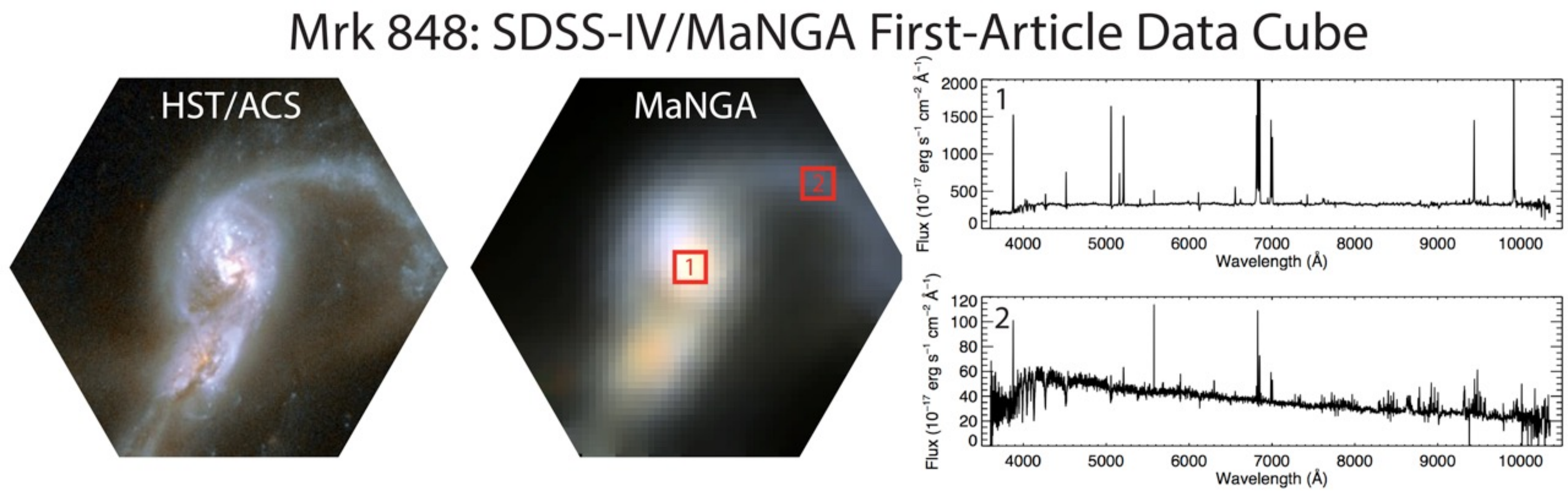


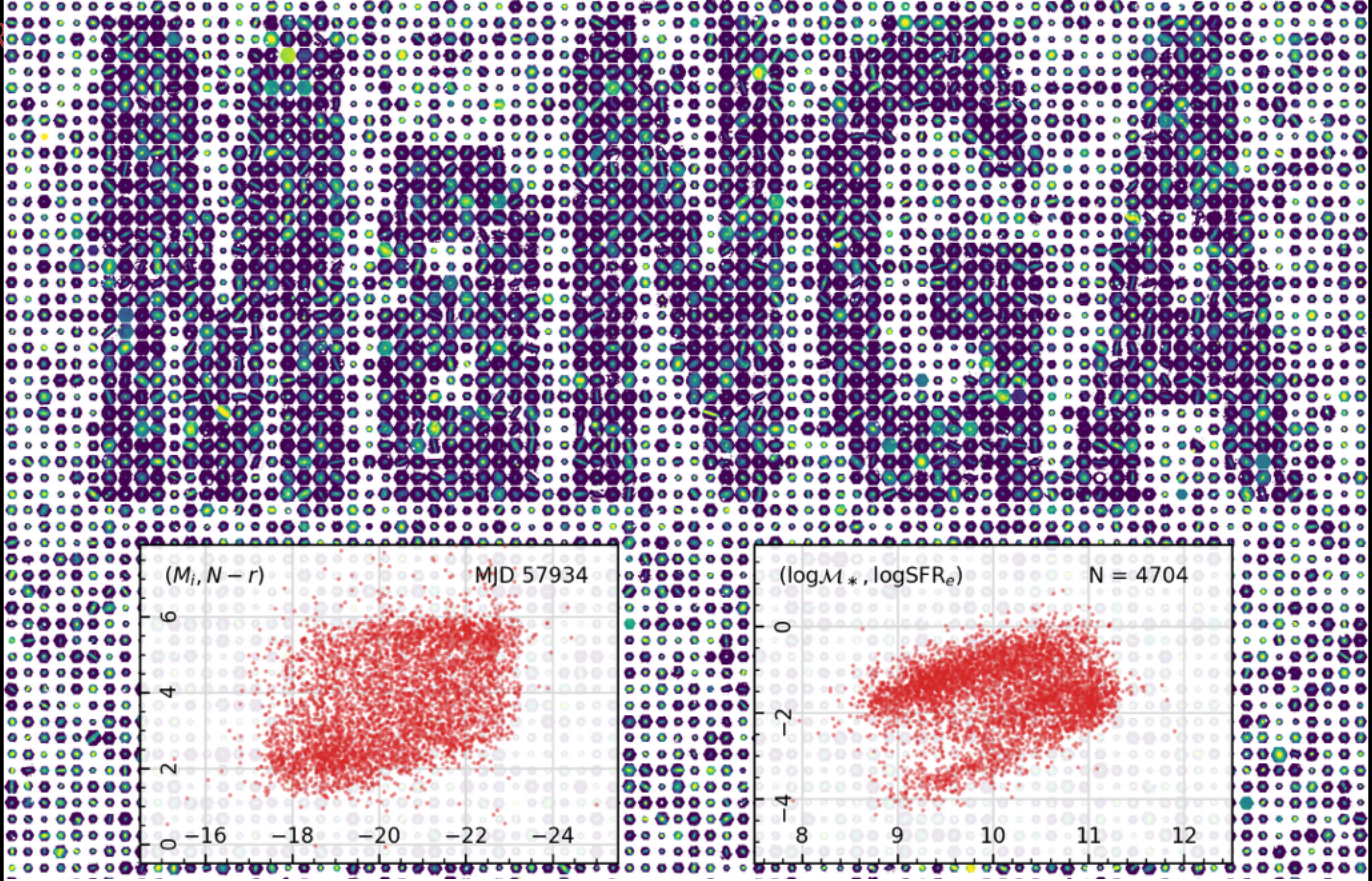




- Plug bundles in plate
- 17 bundles per plate, (19 to 127 fibers per bundle)


March 2014
Commissioning
1st Plate
(17 galaxies per plate)
2.5
2.5

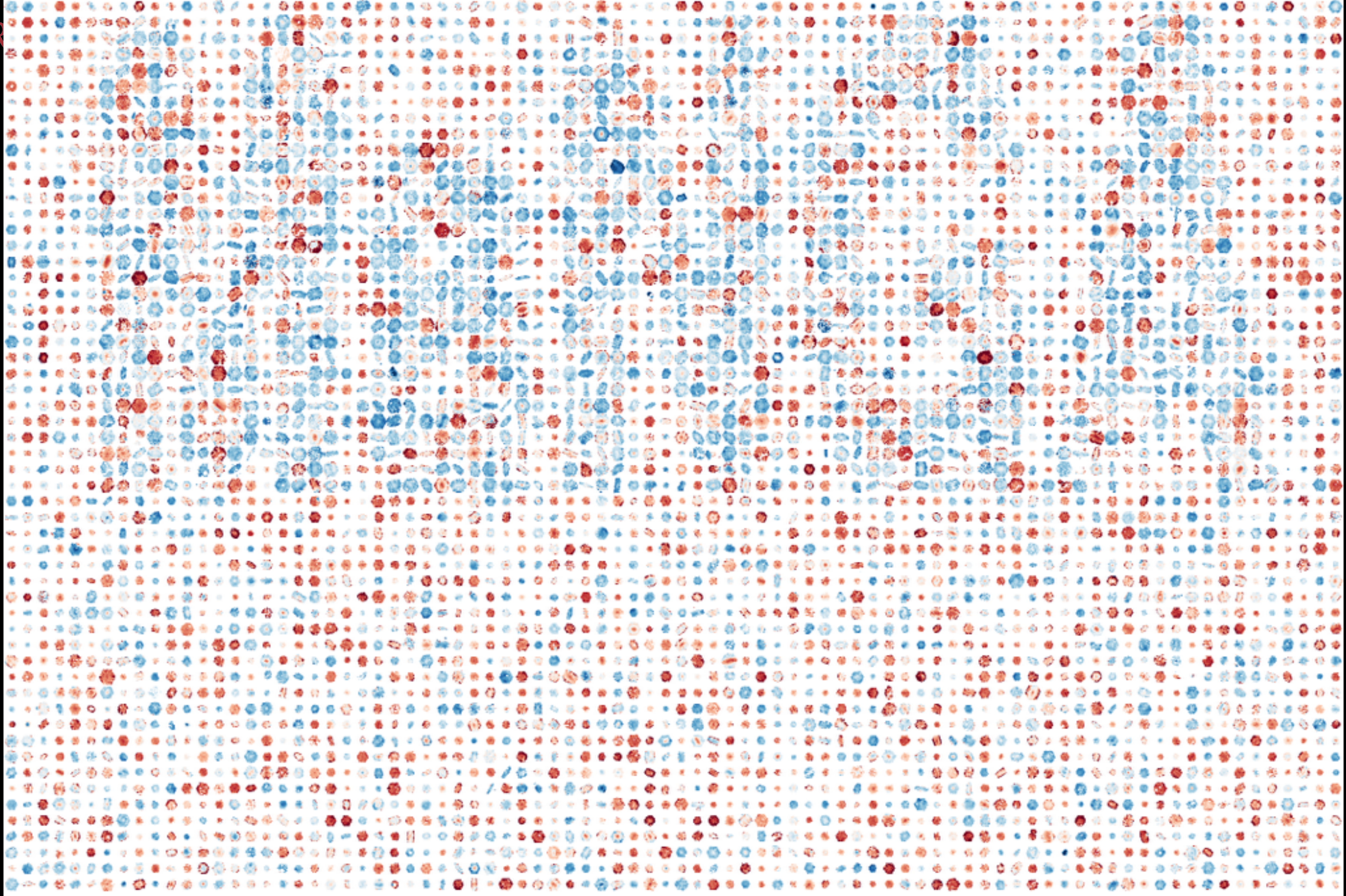

Mrk 848: SDSS-IV/MaNGA First-Article Data Cube
HST/ACS
MaNGA
1
2
Flux (10^{-17} erg s^{-1} cm^{-2} Å^{-1})
Wavelength (Å)



MaNGA observes ~1400 galaxies a year, for 6 years for ~10k in total.
Wake et al. 2017 for details of selection 10^9<Mstar<10^{11} Msun; 0.025<z<0.15

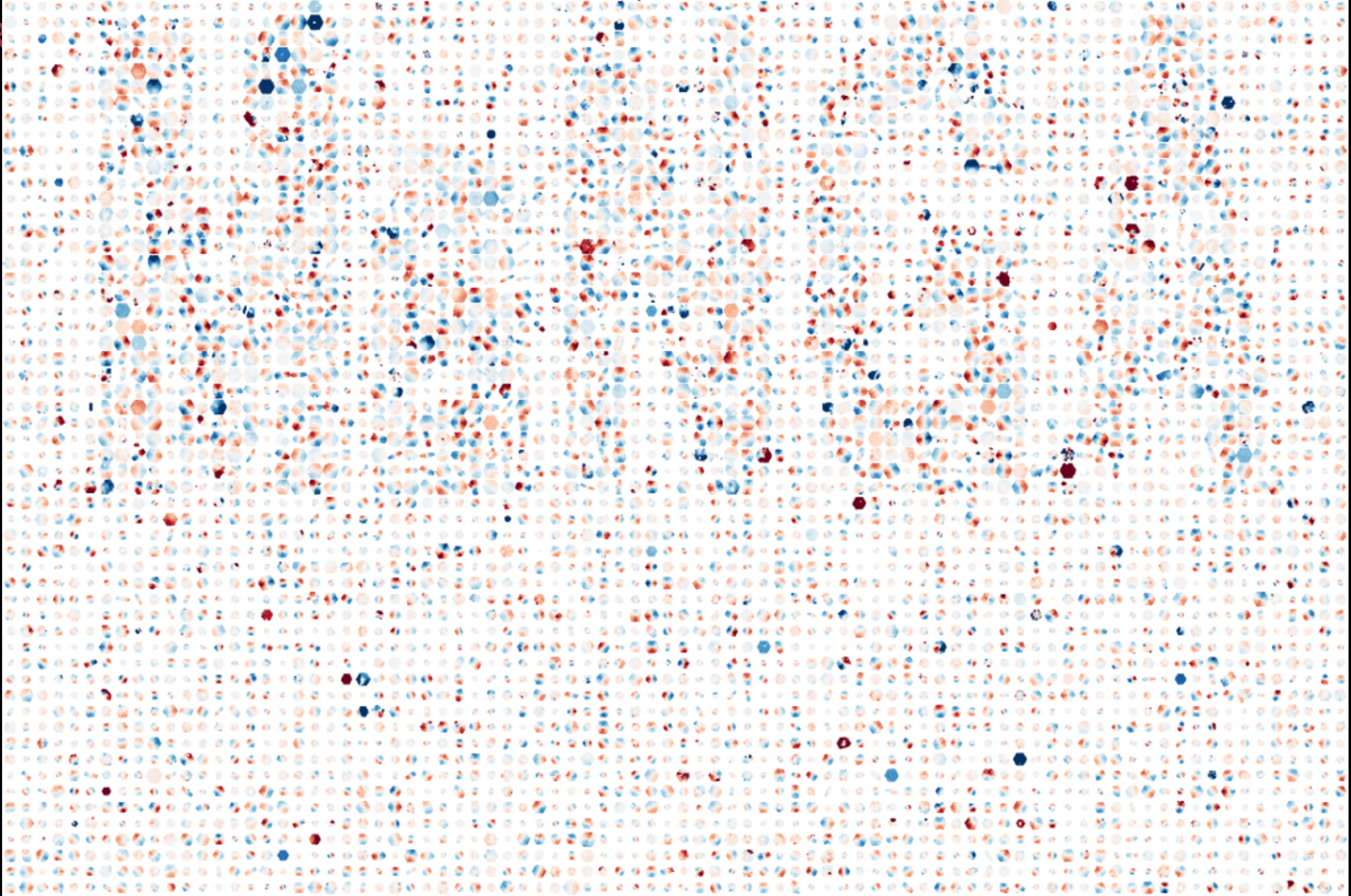
(Star formation or other ionization processes)

Ha flux



(Correlates with age of stellar population)

D4000



Stellar Velocity

MaNGA’s goal: the life history of galaxies

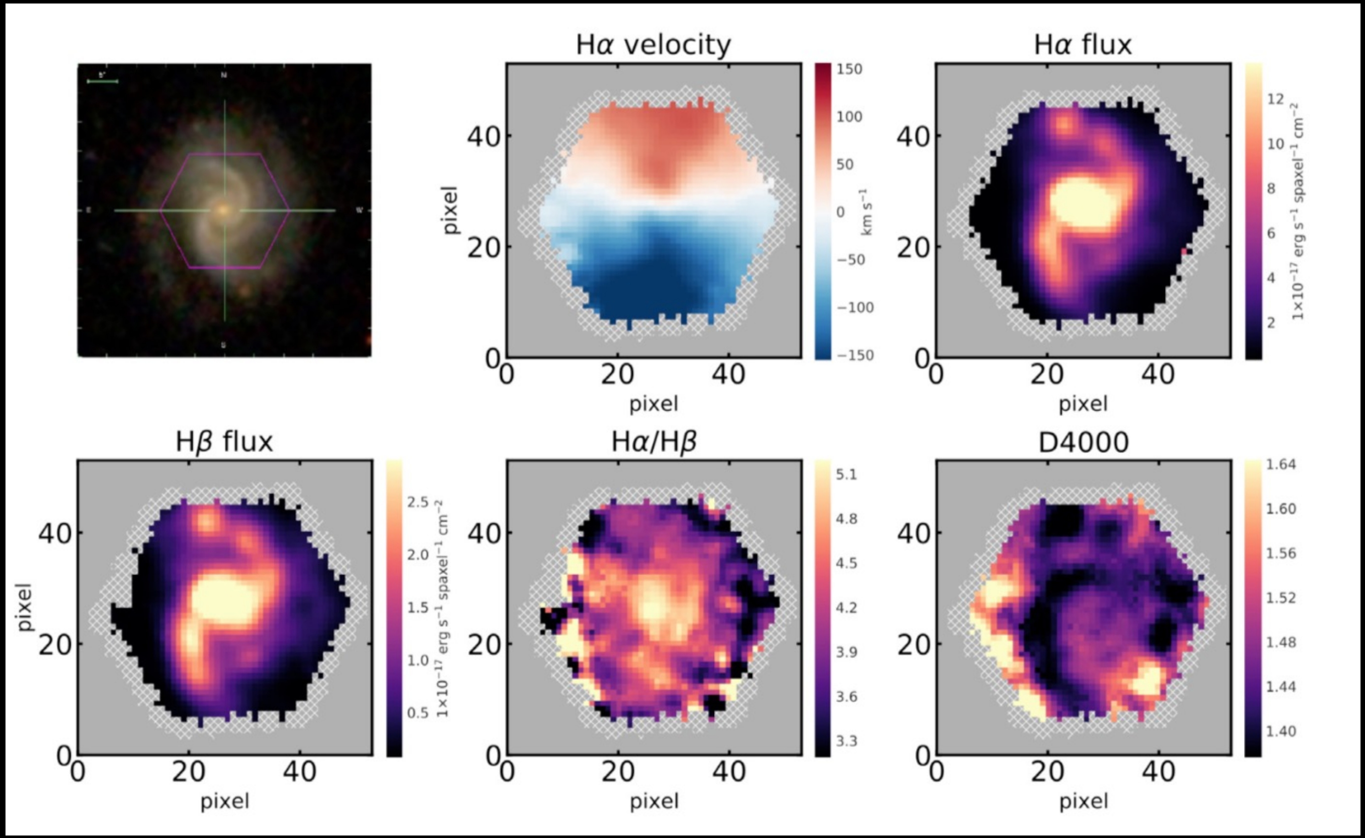
BIRTH
GROWTH } OF GALAXIES
DEATH

All heavily linked to gas physics

- **How does gas accretion drive growth?**
- **What quenches star formation?**
- **How is angular momentum distributed among different galaxy components?**
- **How do various galaxy components assemble and influence one another?**

HI-MaNGA: Science Case

Builds on MaNGA's Key Questions:

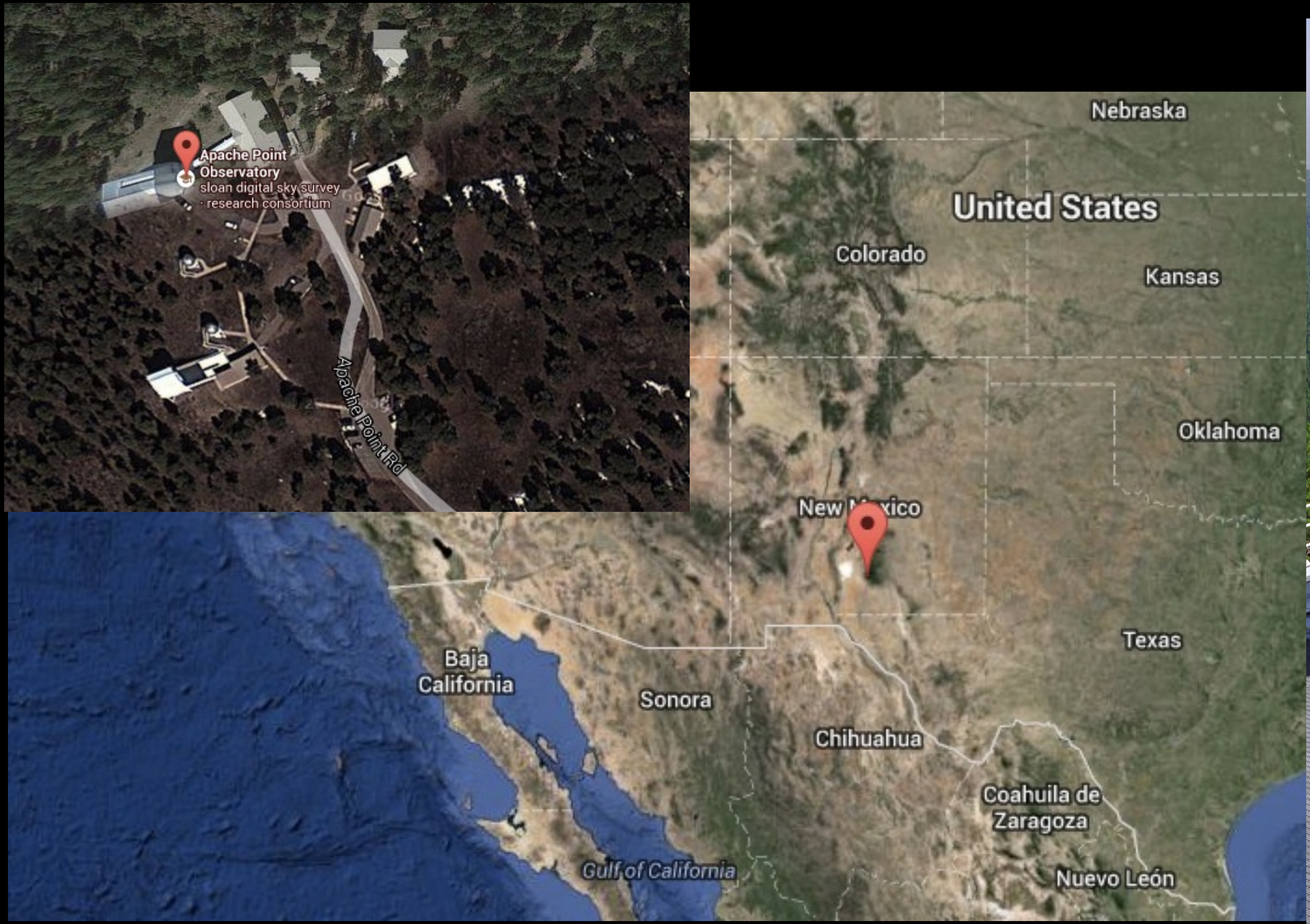


HI-MaNGA: PIs: Karen Masters (Haverford College) and David Stark (Haverford, University of Washington, STScI)

Add cold gas (HI) content information - crucial to help trace full baryonic content as well as providing information on angular momentum

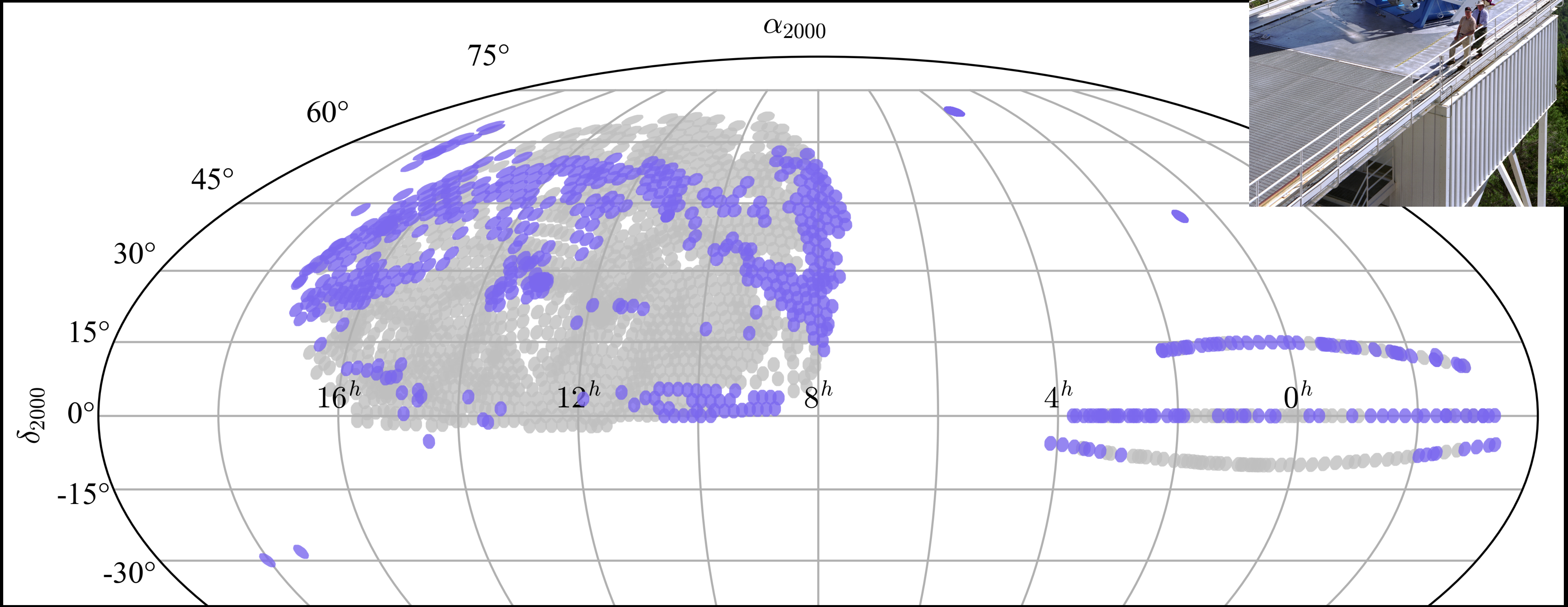
MaNGA strength is numbers – need to match with HI data

Apache Point Observatory

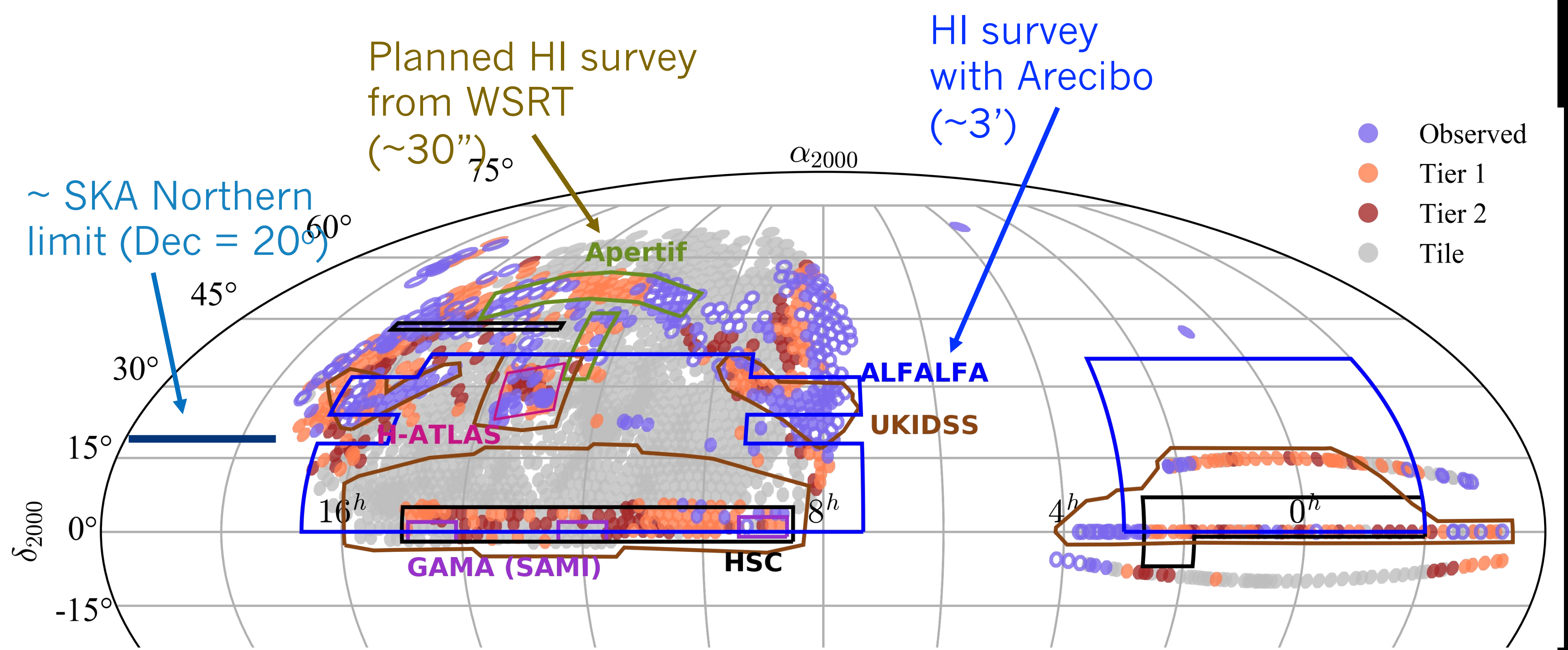


MaNGA Final Sky Coverage

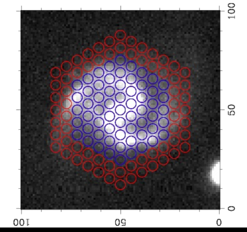
Purple: MaNGA observed. Grey: MaNGA targets in SDSS-I/II footprint



Other existing/future HI



Plot credit: Jose Sanchez-Gallego



MaNGA bundle sizes 12-33" across

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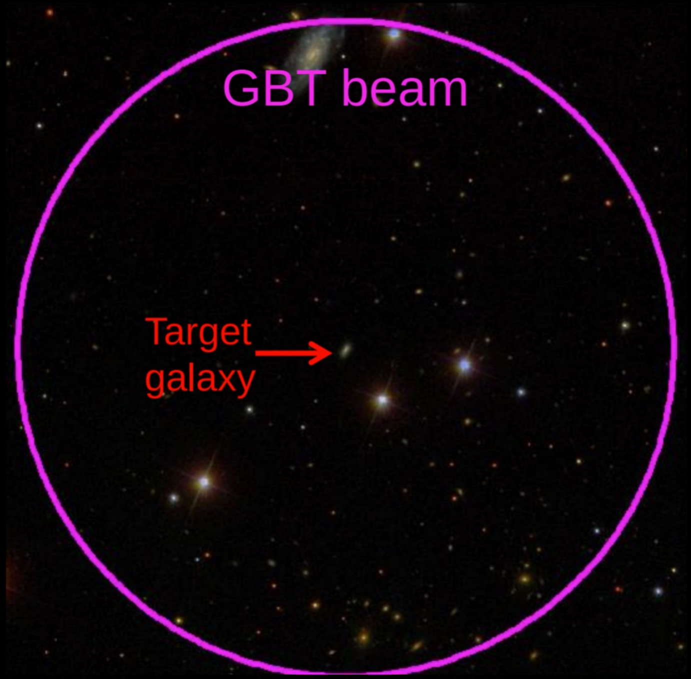
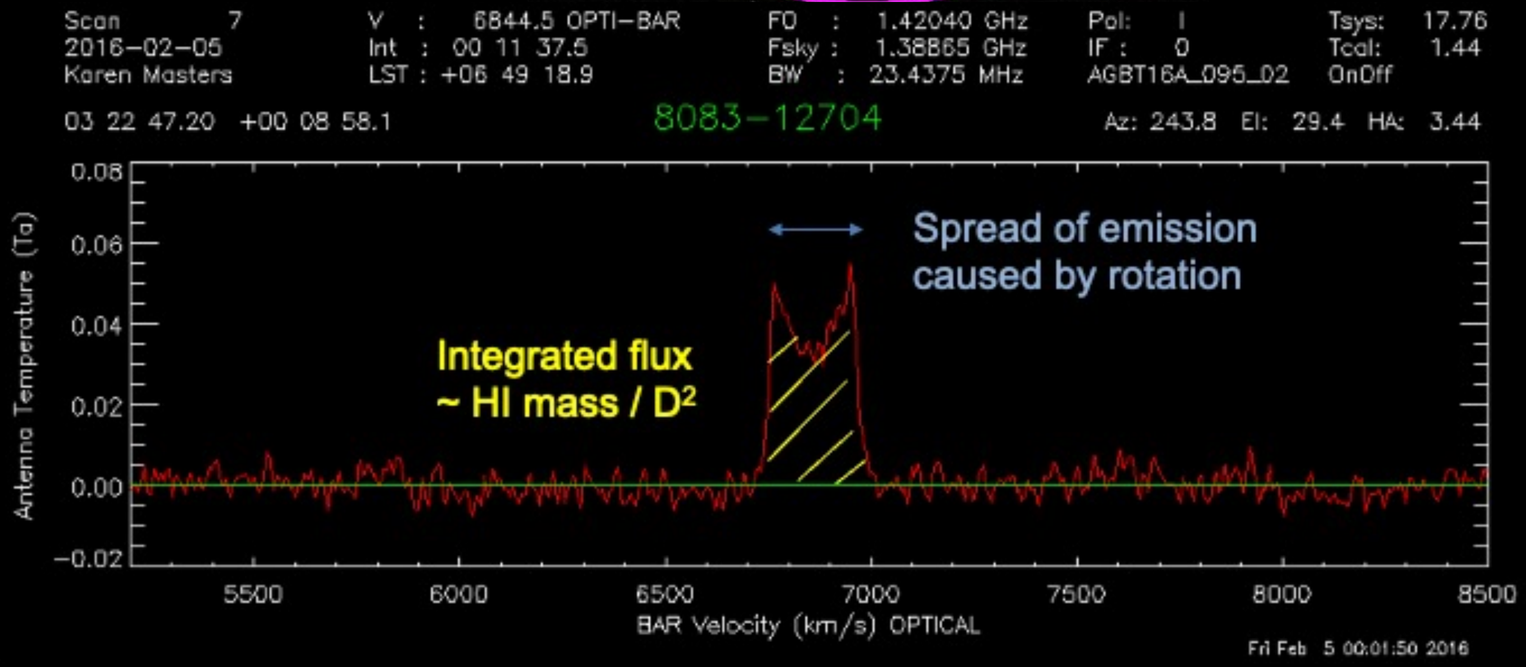
HI images, would be awesome, but not (yet) feasible at this sample size

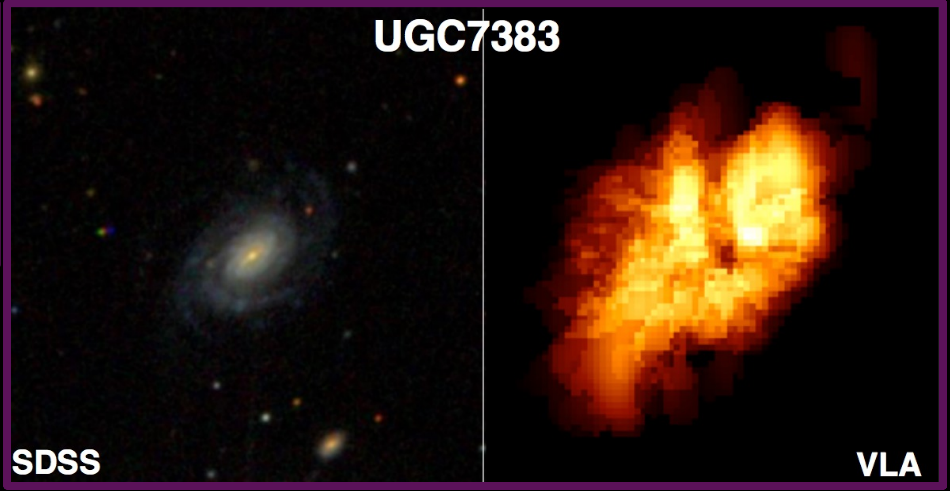
Dish diameter D = 100m
λ = 21cm
Ang. res. $\Theta \approx \lambda/D$ = 9 arcmin





Observing HI (aka why GBT)

Facility	Time per galaxy	Resolution
VLA	Many hours	4-10”
APERTIF	~hours	~30”
Arecibo (ALFALFA)	~40s drift scan	3’
GBT	15mins ONOFF (35 mins tot)	9’



Newnham et al. 2020

GBT Observing program

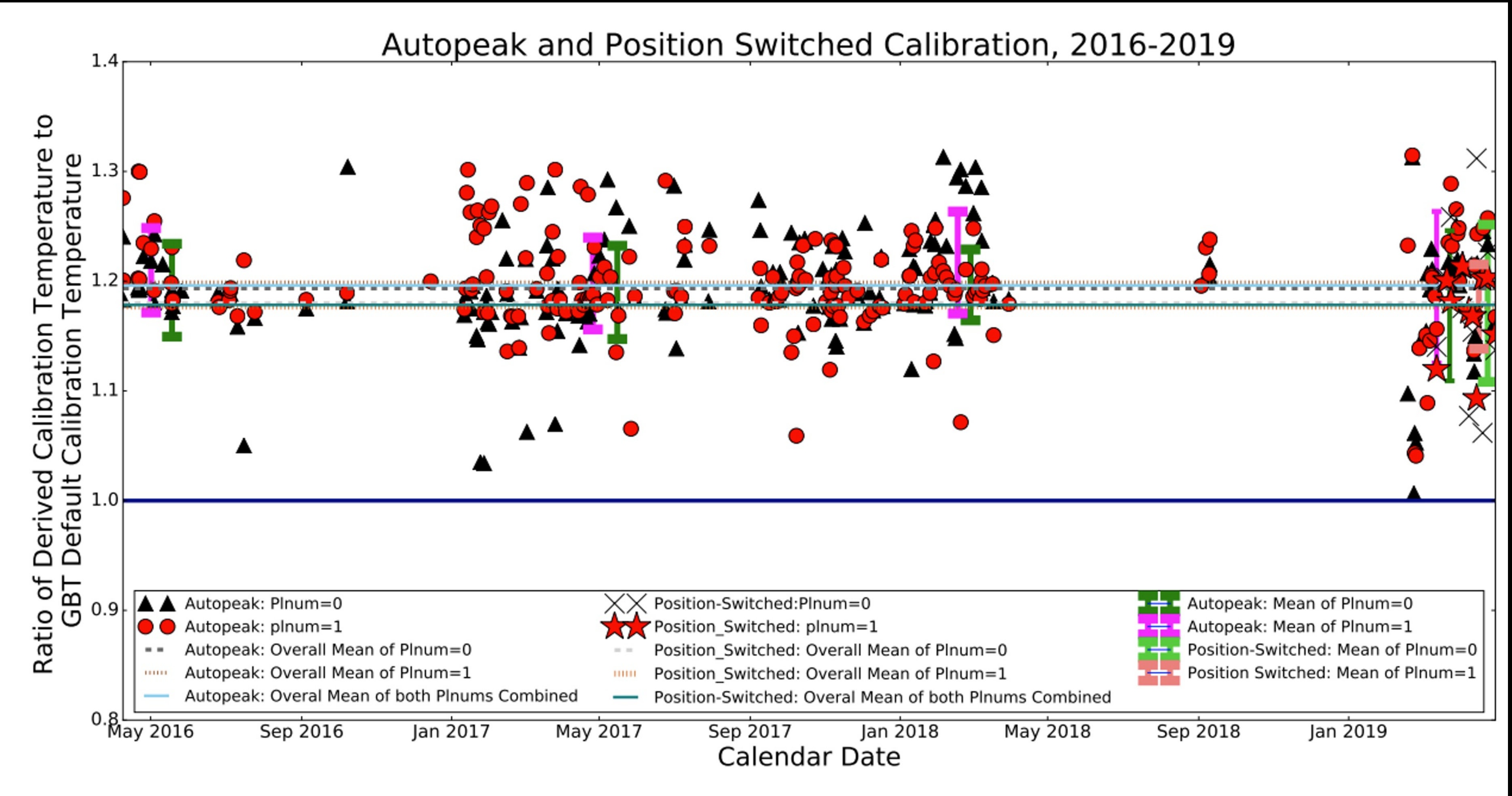
2500 hours of GBT time between 2016A and 2022A

- 4104 galaxies observed (36 min per galaxy)
  - Plus 2800 from ALFALFA
- 2500 hours of GBT time manageable thanks to
  - A fully automated GBT observing program (https://github.com/dvstark/himanga/tree/master/observing)
  - A well-behaved/stable telescope

Automated Observing script

- Chooses targets to minimize overhead
- Runs calibrations
- Updates observing catalogs
- Allows target prioritization

A stable telescope/receiver



Flux calibration 20% higher than default, but *very* stable over ~4 years

Goddy, Stark, Masters (2020)

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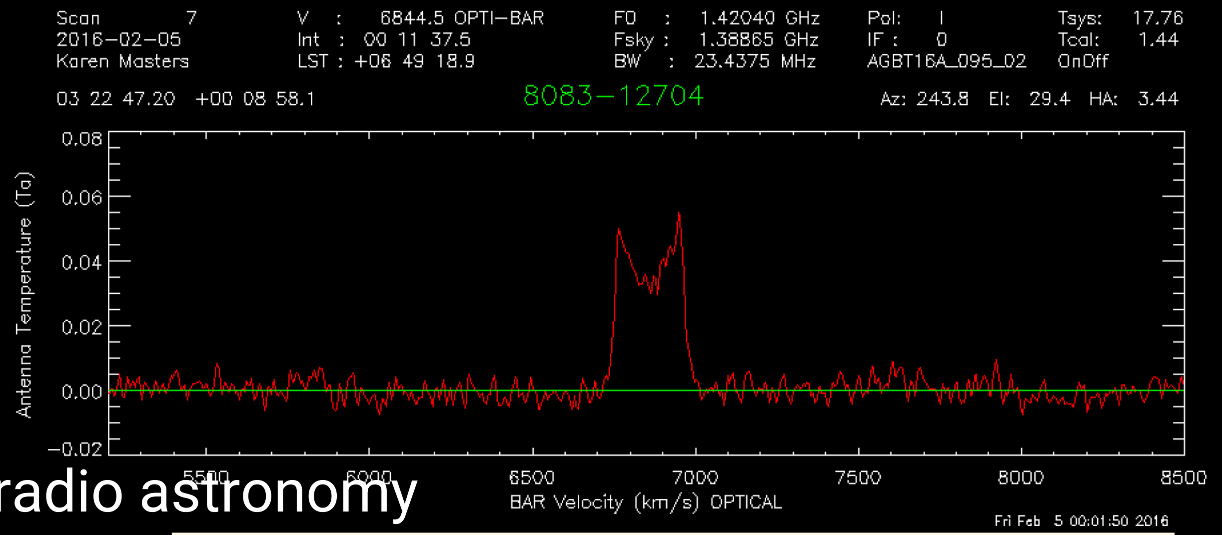
An accessible program for students

- Pipeline designed with novices in mind
  - Scan combination, data inspection, RFI flagging, baseline fitting *automated and simplified as much as possible*
- Good entry point for undergrad researchers
  - Little prior knowledge of programming, radio astronomy
  - ~20 undergrads contributed to data reduction



Bonus: education and faster data processing!

```
;;;;;;;;;;;;;;;;;;;;;;;;;
Choose a task:
0: Load Scans
1: Inspect Scans (optional)
2: Trim Edges
3: Remove RFI (optional)
4: Smooth Data
5: Set Baseline Regions
6: Fit Baseline
7: Measure RMS
8: Measure Profile Parameters (optional)
9: Measure HI mass/upper limit
10: Write Out Spectra
q: Quit
x [x0 x1]: set x (leave x0,x1 empty to unzoom)
y [y0 y1]: set y (leave y0,y1 emplty to unzoom)
;;;;;;;;;;;;;;;;;;;;;;;;

:
```

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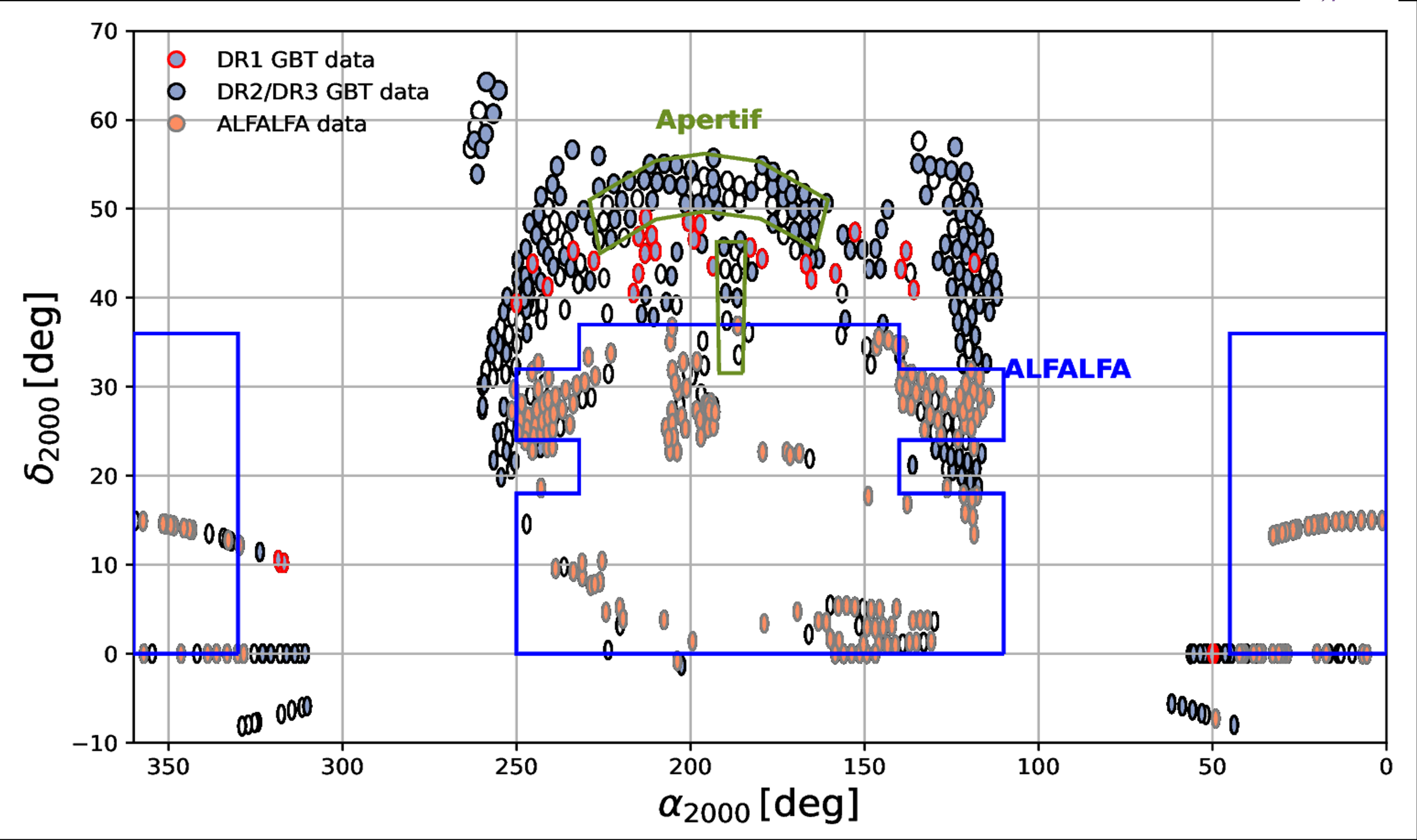
~7000 galaxies in HI-MaNGA



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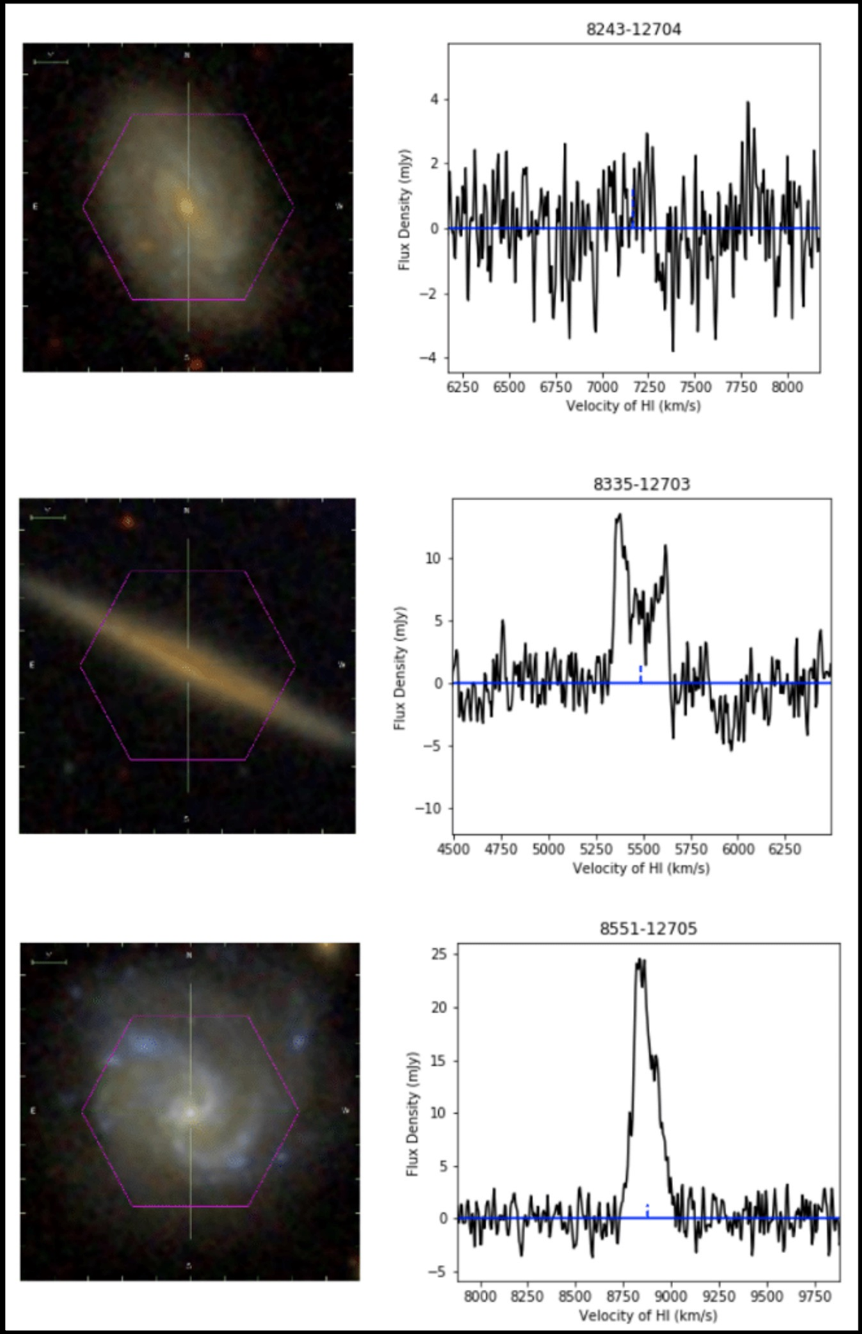
Public data available

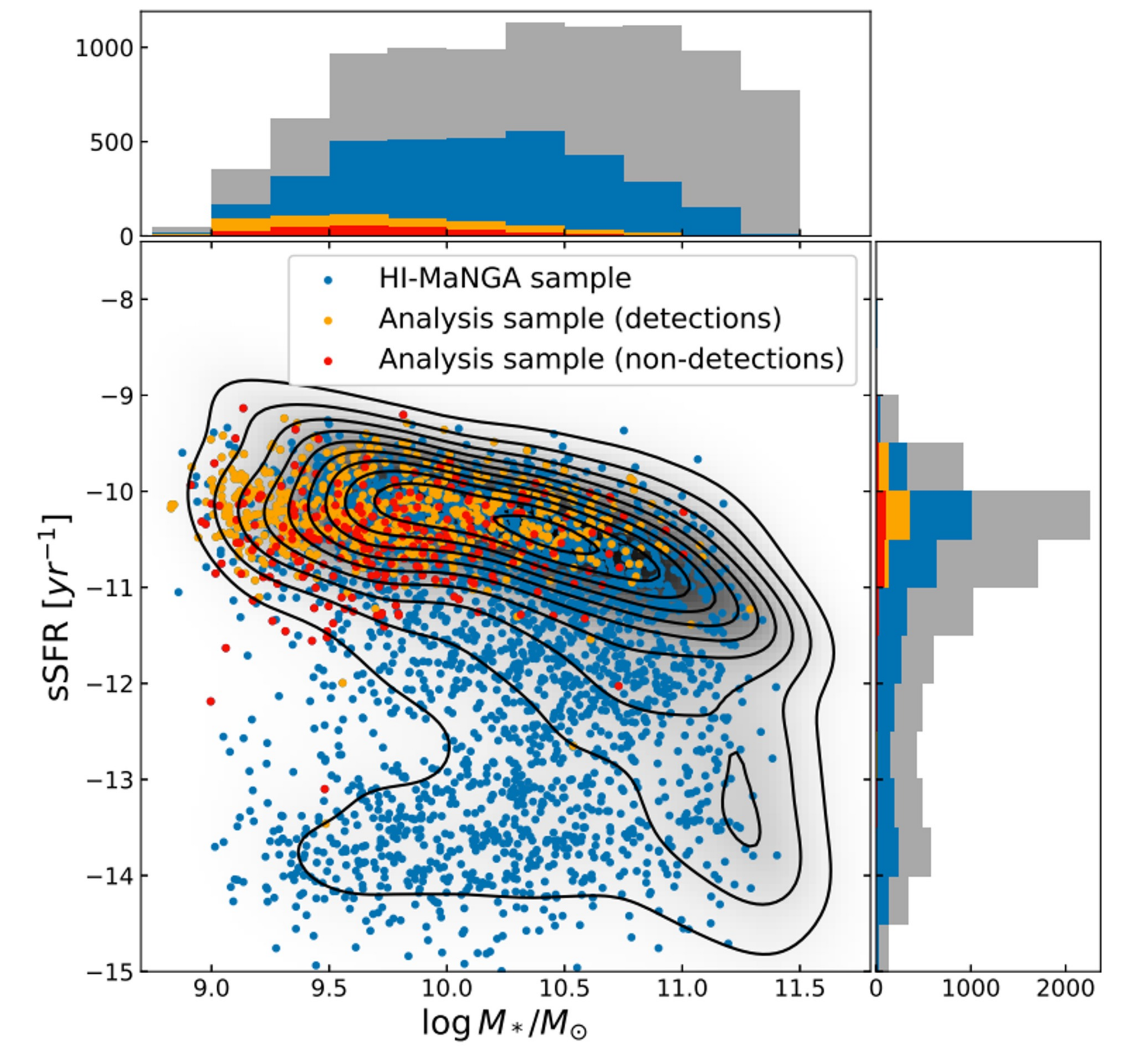
- Data for 6632 galaxies now publicly available
  - Part of SDSS DR17
  - Homogenized catalog of derived parameters (ALFALFA + GBT data)
  - Optical counterparts and ***source confusion probability*** (Stark et al. 2021)
  - Reduced and baseline subtracted spectra for all galaxies

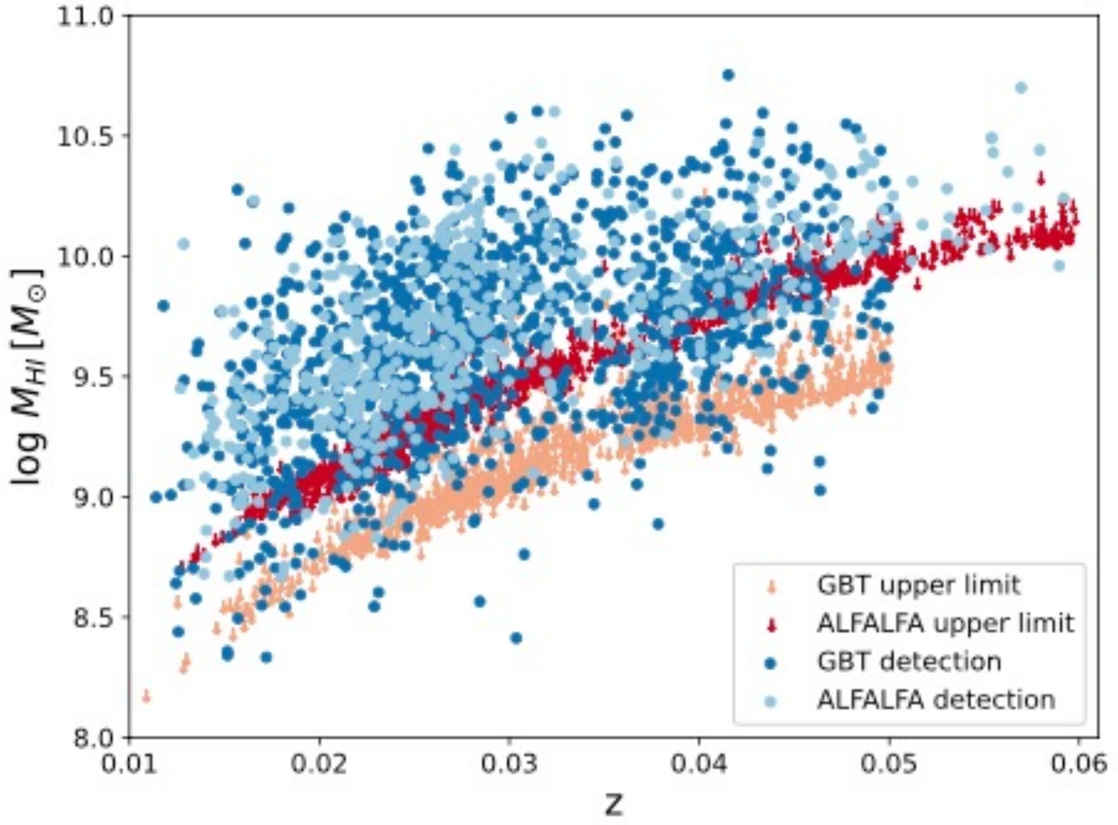
- Access via:
  - GBO site (https://greenbankobservatory.org/science/gbt-surveys/hi-manga/)
  - SDSS site (https://www.sdss.org/dr17/manga/hi-manga/)
  - Marvin (Python package for interfacing with MaNGA data; Cherinka et al. 2019)

Google "HI-MaNGA survey"



Masters et al. 2020





Stark et al. 2021
(DR2 sample)

HI correlates best with star formation averaged over long timescales

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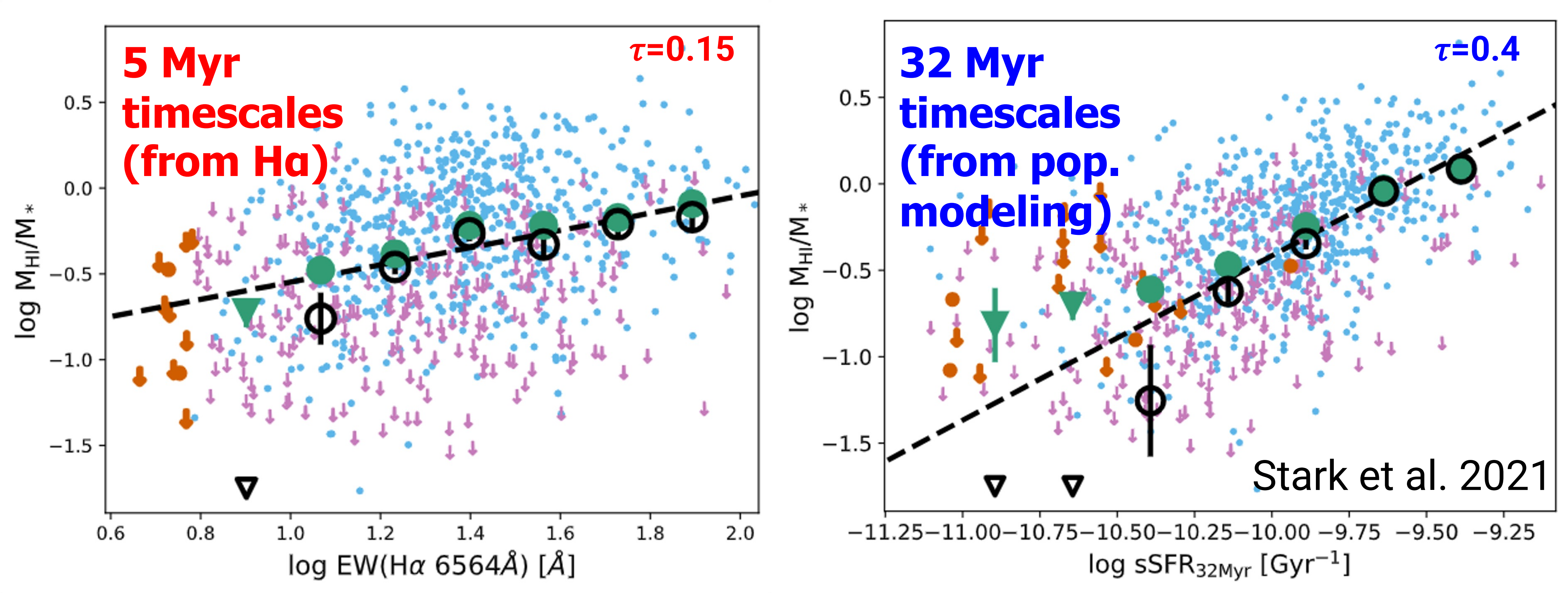


Implication: HI ***sustains*** SF (see also Kannappan et al. 2013)

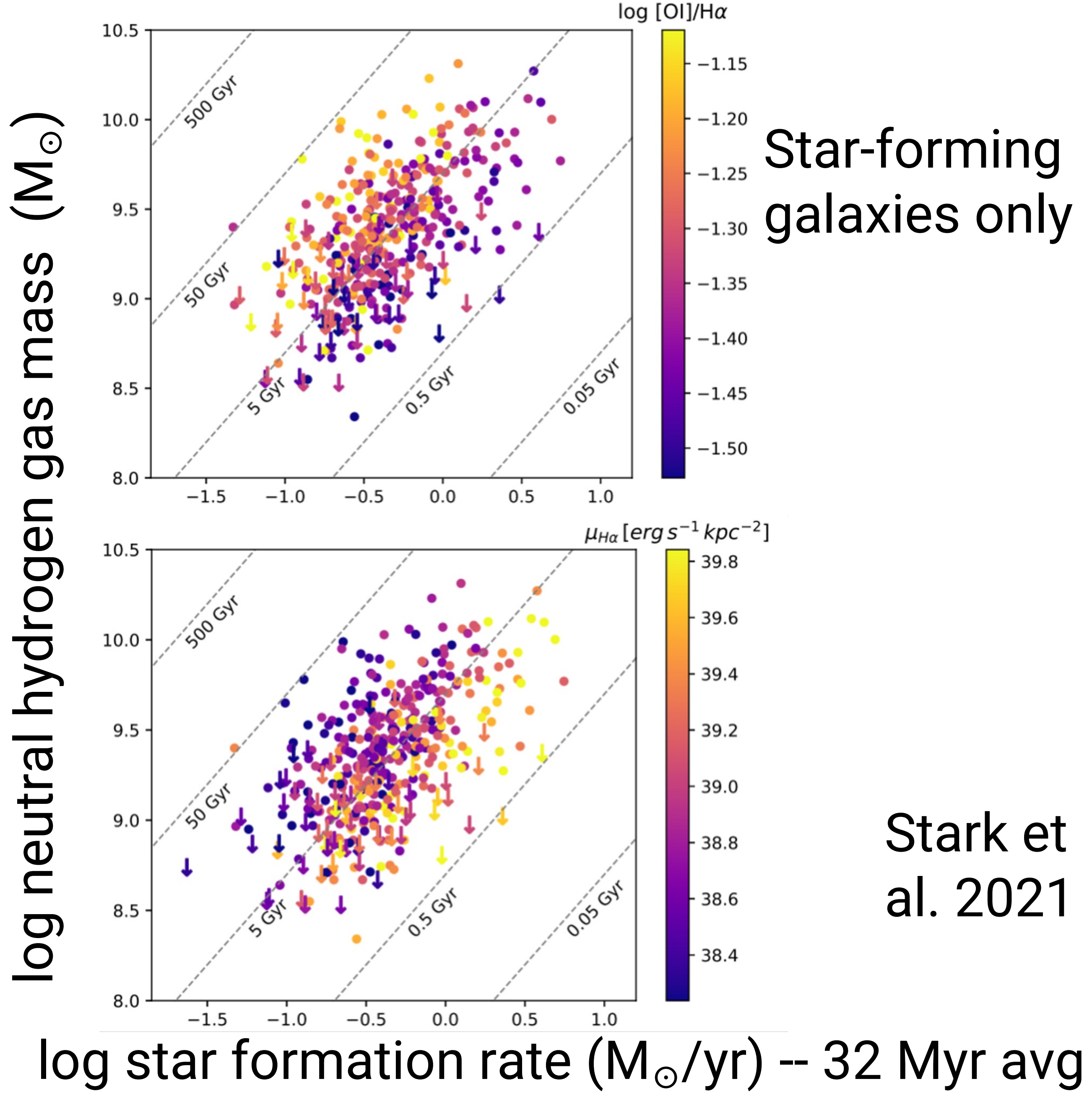
How efficiently do galaxies process their HI?

Typical HI depletion time (M_{HI}/SFR)~5 Gyr, but ***lots of scatter***

Long depletion times correspond to **high [OI]/Hα ratios** and **low Hα surface brightness**

Indicates (1) a larger than average fraction of *diffuse* gas and/or (2) a large amount of *shock heating*

→ Natural explanation for long-depletion times (ISM conditions less conducive to dense cloud formation)



Star-forming galaxies only

Stark et al. 2021

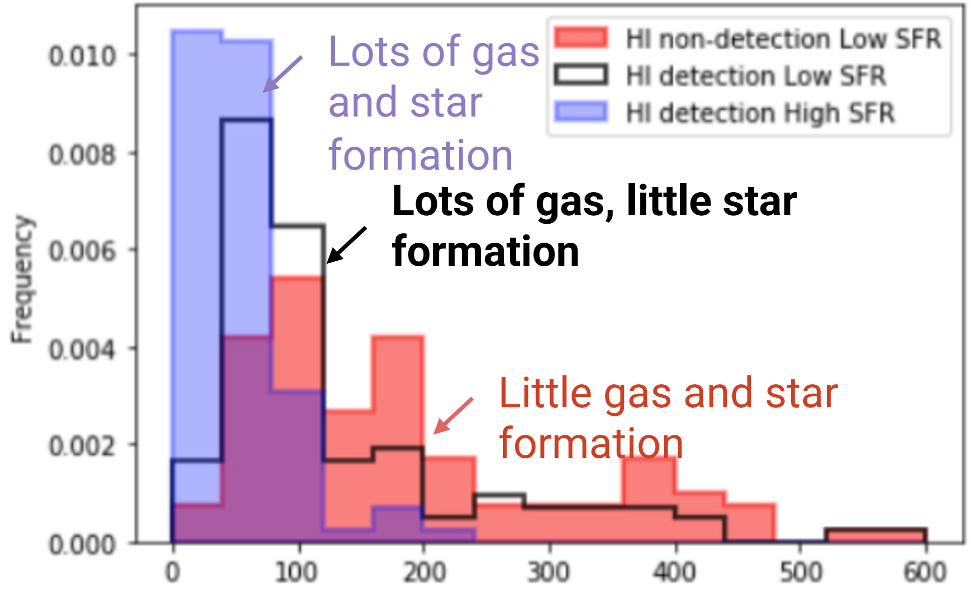
Extreme cases: lots of gas but no star formation

With Anubhav Sharma (Haverford College undergraduate) and Dave Stark

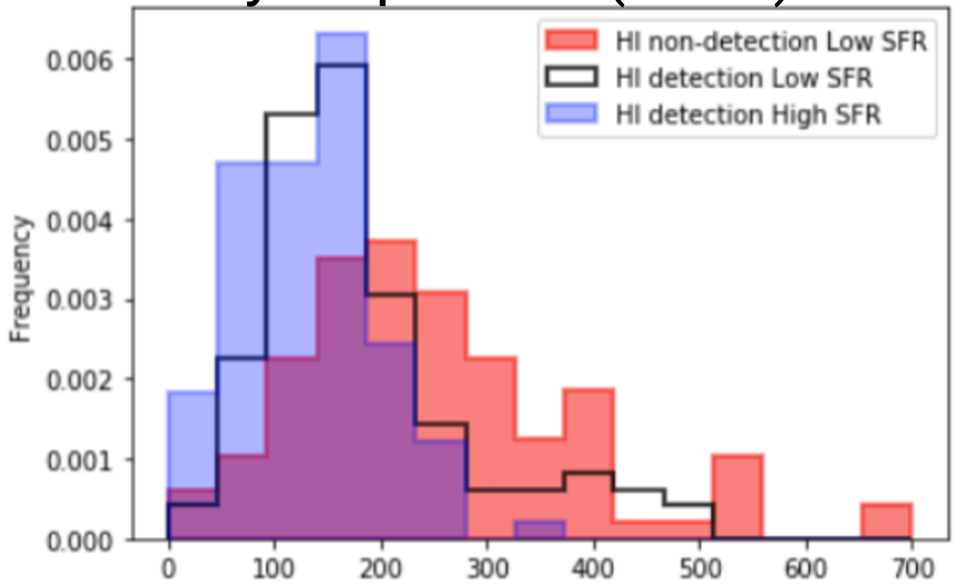
Gas (Halpha) has high velocity dispersion and rotation speed -- resisting gravitational collapse

Gas (Halpha) frequently counter-rotating with respect to stars

What is driving this behavior? Best idea is minor mergers/gas accretion

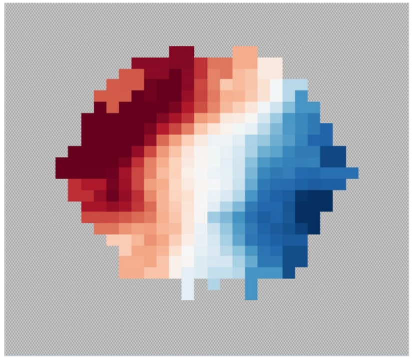


Velocity dispersion (km/s)

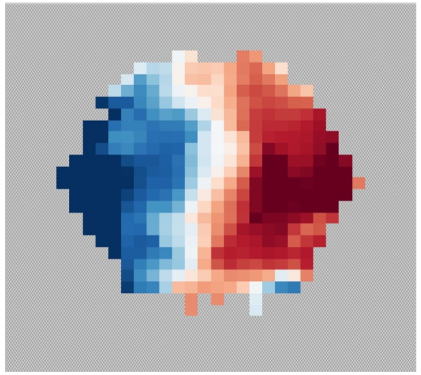


Rotation velocity (km/s)

Gas (Halpha)



stars



Sharma et al. submitted (Haverford ugrad)

Many HI-MaNGA student projects

- L-band Calibration of the Green Bank Telescope fro 2016-2019 (Goddy et al. 2020)
- Testing Algorithms for Identifying Source Confusion in the HI-MaNGA survey (Shapiro et al. 2022)
- HI content of MaNGA Red Geysers (Frank et al. in prep.)
- Assessing the rate of GPS interference at GBT from 2016-2022 (Turner et al. in prep)

- A comparison of the Baryonic Tully-Fisher relation in HI-MaNGA and IllustrisTNG (Goddy et al. submitted)
- The origin of HI-rich but low star formation rate galaxies (Sharma et al. submitted)
- Reconstructing HI Radial Profiles from Single Dish and Optical IFU data (Washington/Goodman ongoing).

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SDSS DR15 VAC
Masters et al 2019

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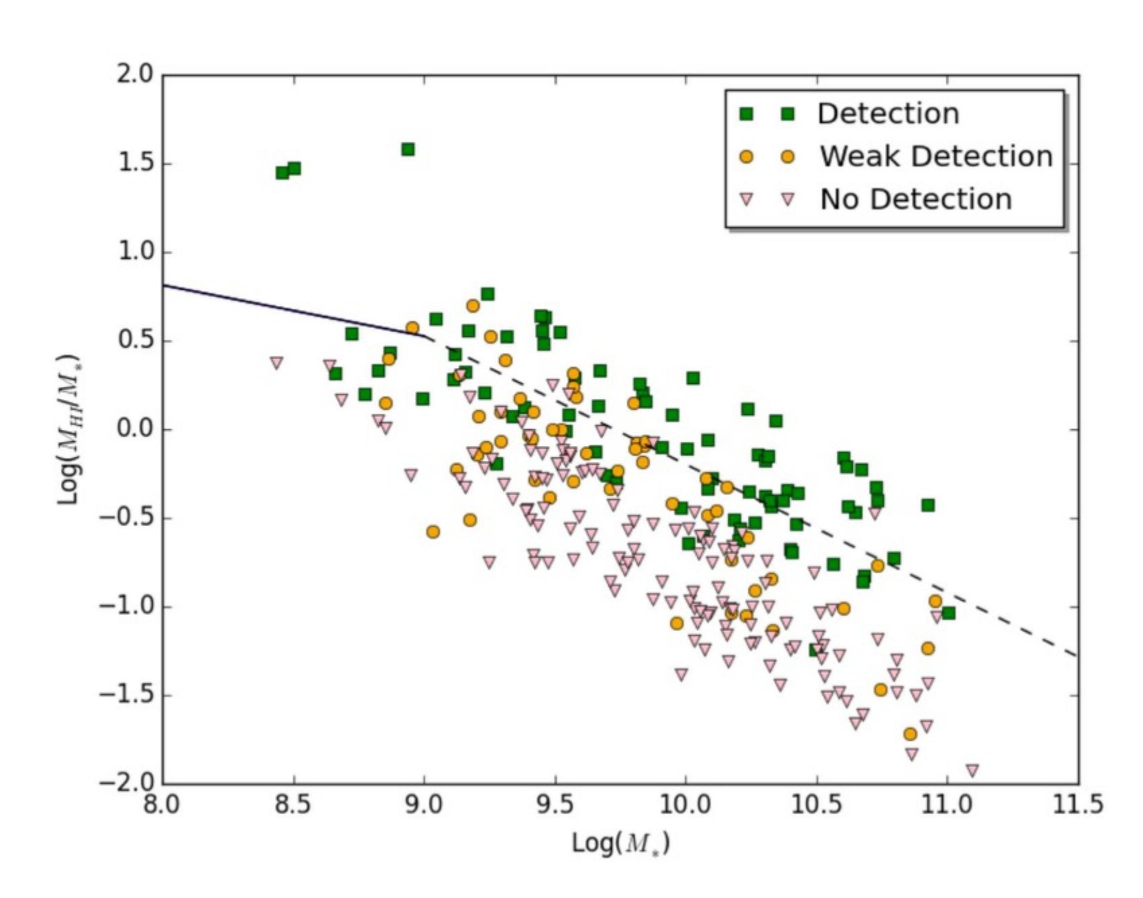
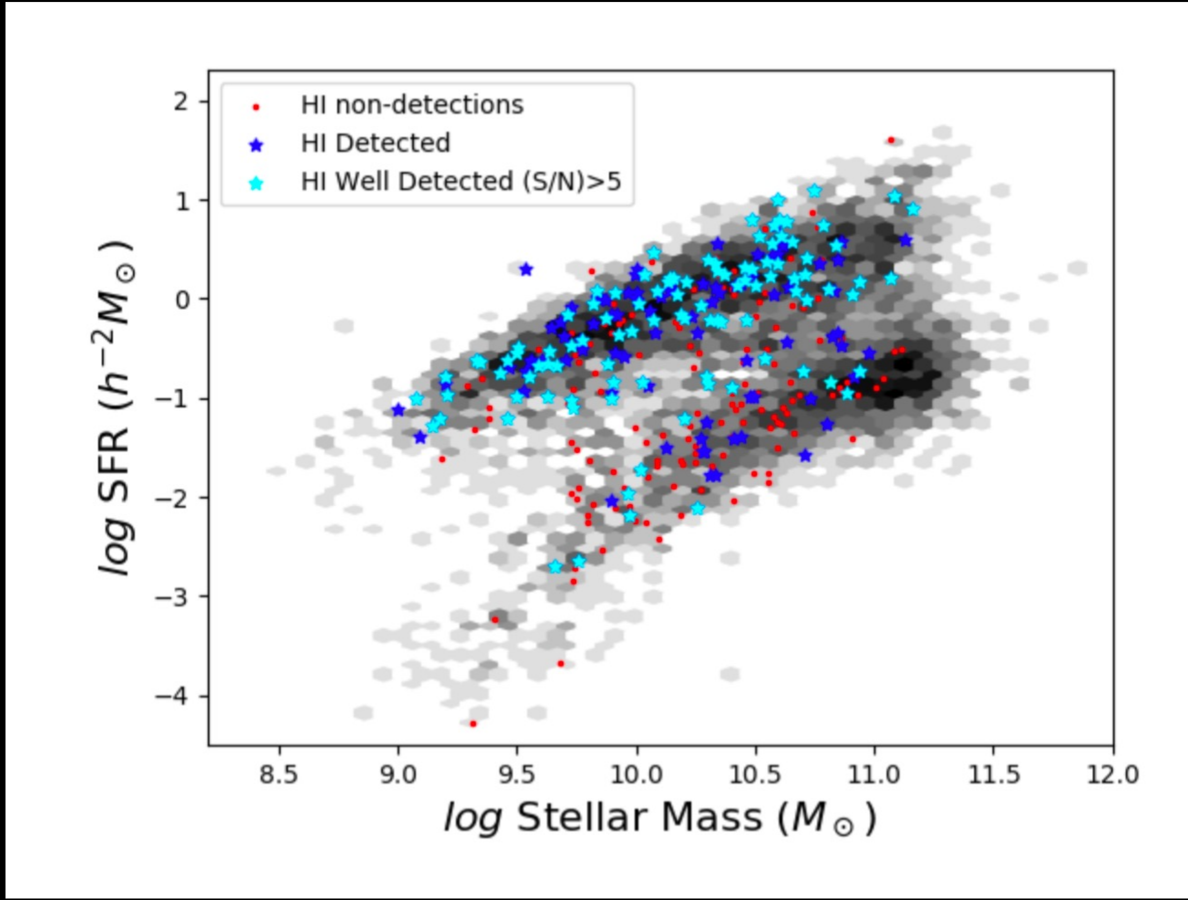
Student Work

Lines: fits to relation from ALFALFA data (Huang et al. 2012)



Plot credit: Frederika Phipps (Southampton undergrad)

SFR from Pipe3D analysis of MaNGA- Sanchez et al. (2018)



Plot credit: Emily Harrington (Bryn Mawr undergrad)

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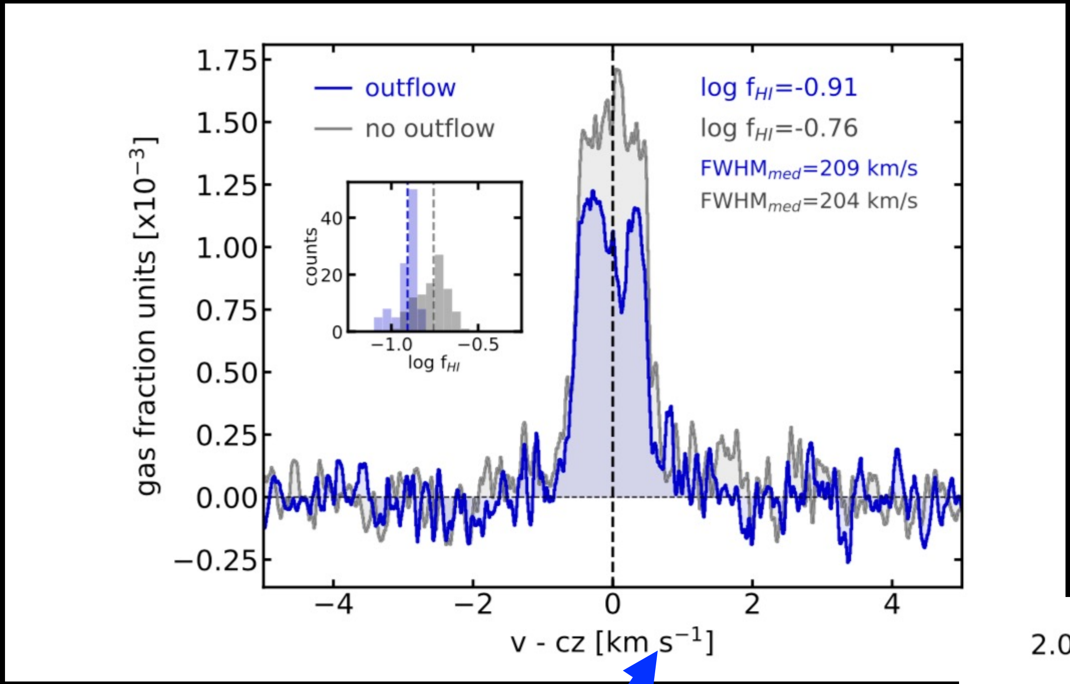
Science Result - Outflows



Roberts-Borsani et al. 2020

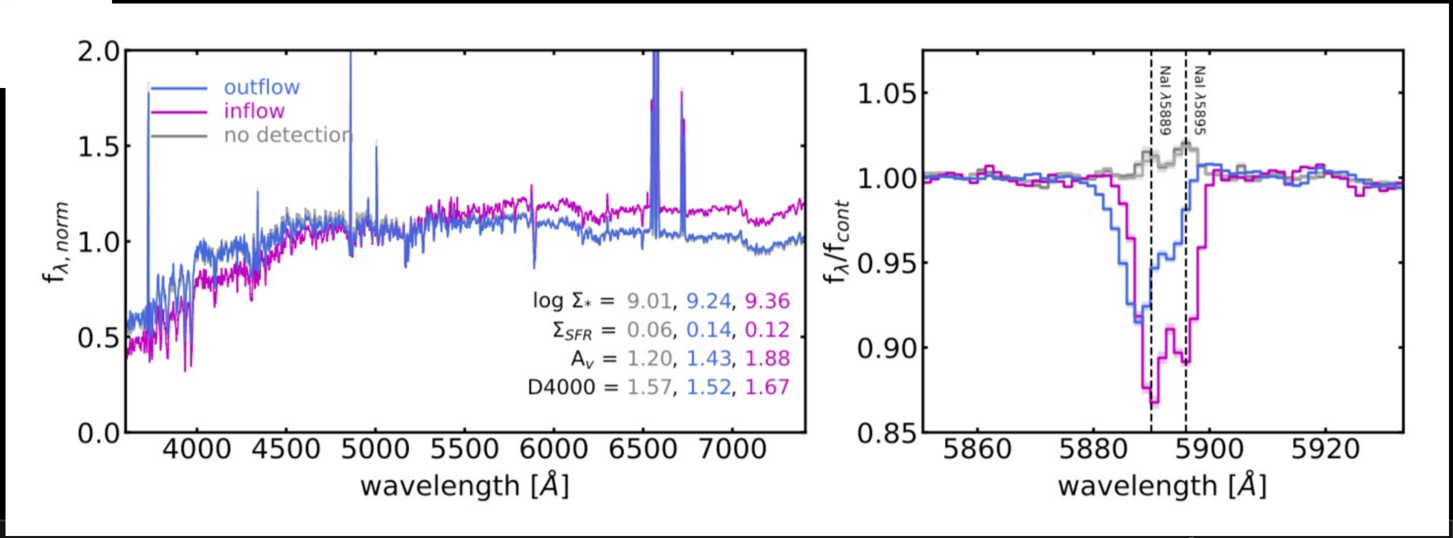
Stacking analysis (on matched galaxies)

Galaxies with NaD selected outflows have lower HI gas fractions

Hint of central depletion?

GBT data

MaNGA data



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HI Content of MaNGA Mergers

Q. Yu et al. 2022 (no HI-MaNGA team members involved).

Some evidence of gas depletion due to merging.

4 YU ET AL.

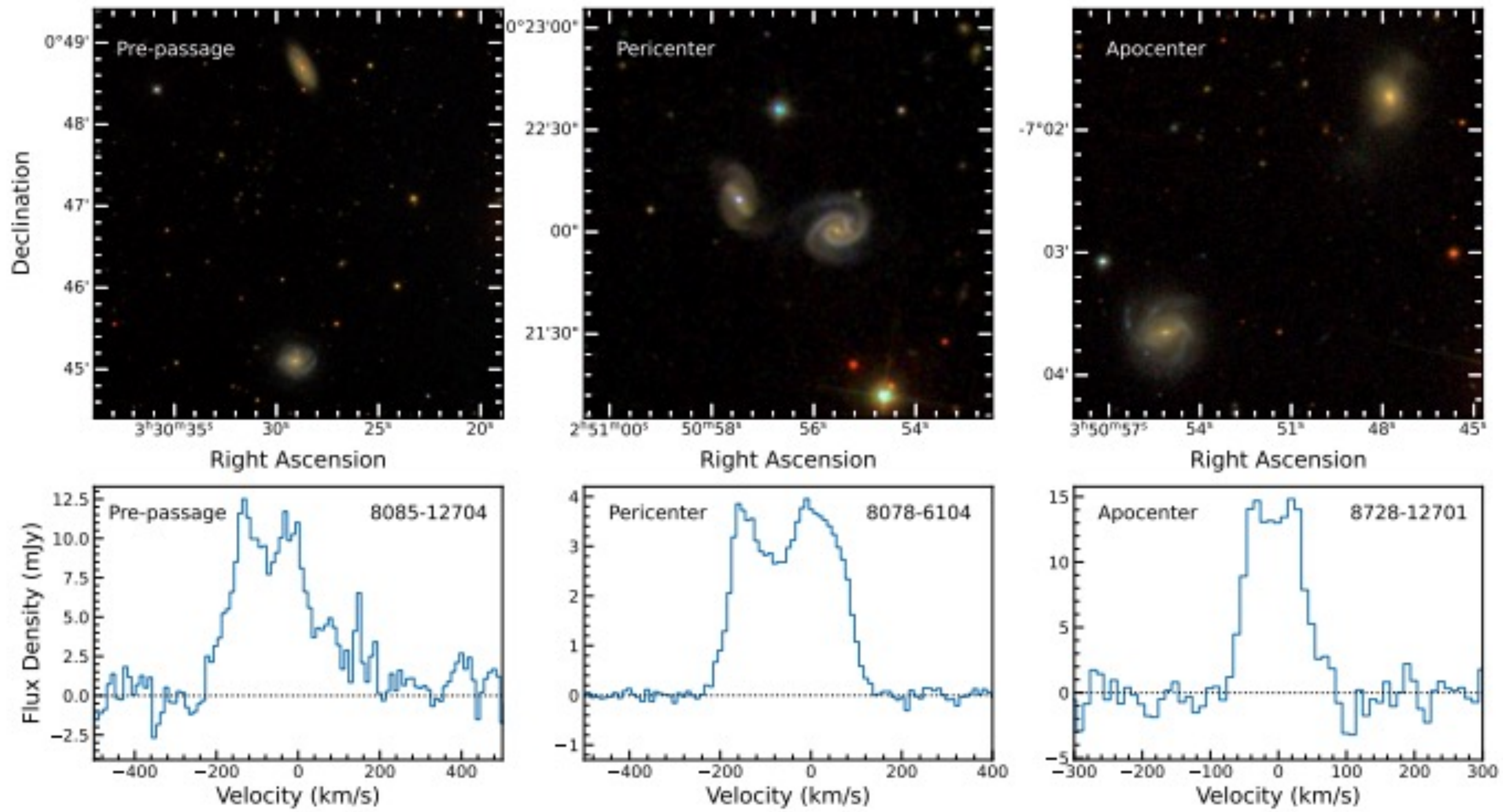

Figure 1. The upper panels present examples of SDSS optical images of galaxy pairs at pre-passage, pericenter, and apocenter stages, respectively. The lower panels show the corresponding H I line profiles of each galaxy pair. The MaNGA plate-ifu IDs are labeled on the top right of each spectrum.

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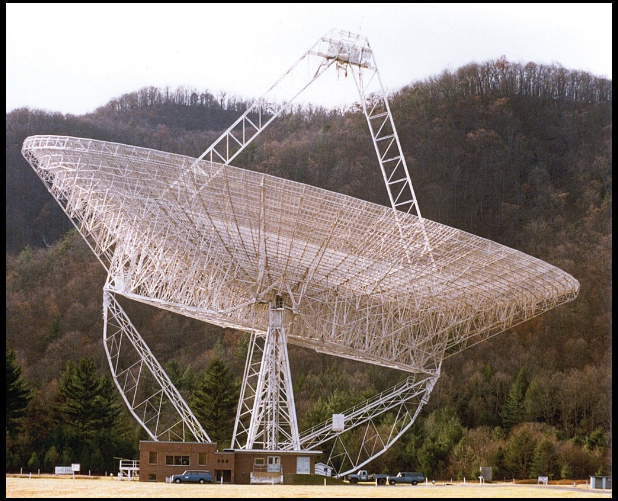
(Thanks GBT in galaxies from writing.galaxyzoo.org)



I recognise that the Green Bank Observatory is located on Calicuas and Moneton land, and pay respect and honour to the caretakers of that land, from time immemorial until now, and into the future.