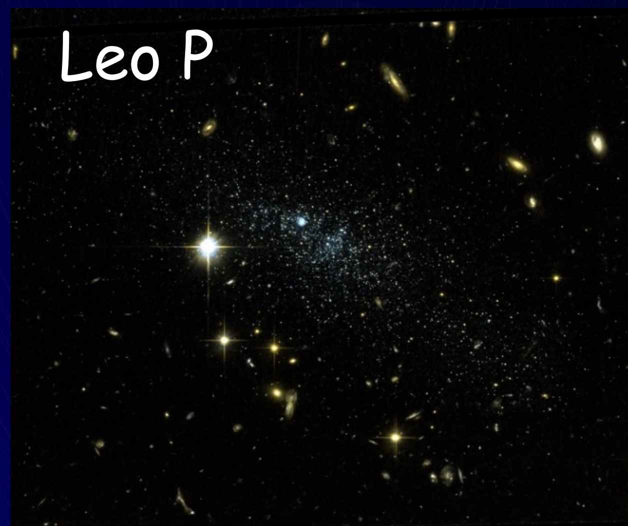
What HI tells us about Galaxies and Cosmology



Martha Haynes June 2019

UAT19.06

ALFALFA

ALFALFA: A Census of Gas-bearing Galaxies

- A galaxy is a gravitationally bound object that consists of billions (and billions) of stars, gas clouds (of varying temperature and density = interstellar medium), dust clouds (mixed with the gas), and (so it seems), 90% dark matter.
- Optical surveys, like the Sloan Digital Sky Survey, detect the **stellar component** of galaxies.
- ALFALFA is designed to detect the **cool** (not hot; not cold) atomic gas in and near galaxies.
- ALFALFA is a **blind** survey; we observe the whole area of sky, whether or not we think/know there is an optical galaxy there.
- ALFALFA is a **spectroscopic** survey; not only do we detect the HI line flux, we also measure its frequency (velocity) and the width of the HI line (a measure of rotational velocity).

The HI 21 cm line @ 1.42 GHz

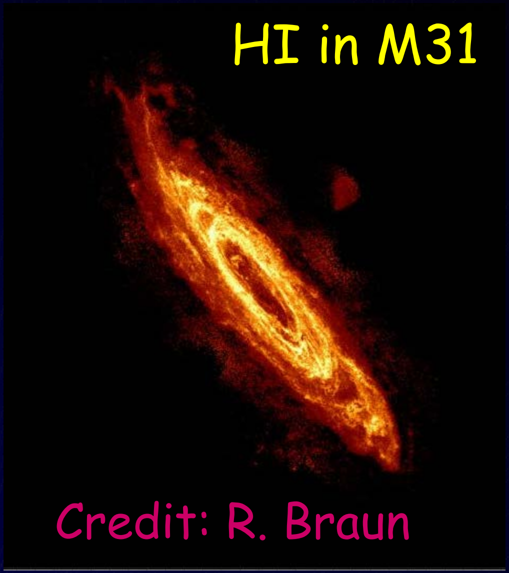
HI : Why do we care ?

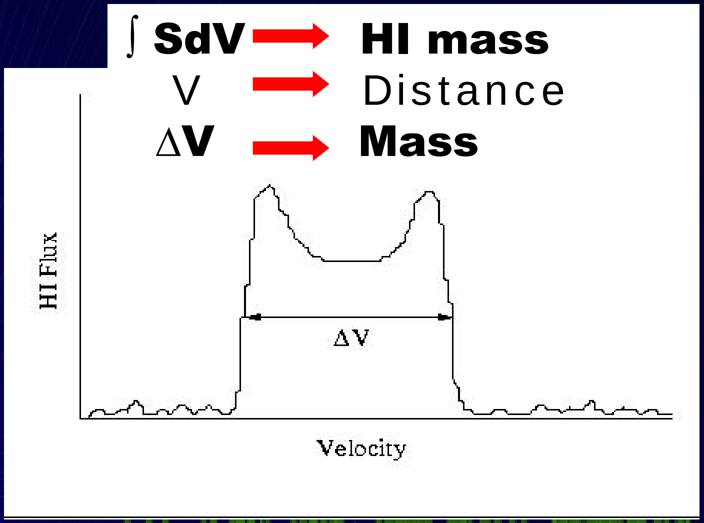
- Easy to detect, simply physics ➔ cold gas mass
- Good index of SF fertility ➔ future SF
- Comparative HI content => HI deficiency
- Excellent tracer of host dynamics ➔ dark matter
- Useful Cosmology tool ➔ HI mass function, HI velocity width function, Tully-Fisher relation, “dark” galaxies(?)
- Interaction/tidal/merger tracer
- Can be dominant baryon form in low mass galaxies

- ALFALFA vs APPSS:
  - A blind survey detects everything that is bright “enough”, so ALFALFA conducted a statistically-robust census including “surprises” (objects we might not expect to have HI)
  - The targeted observations of APPSS let us detect fainter objects, but we have to make decisions about where to point and now long to integrate (“stare“).

Clues from the HI line

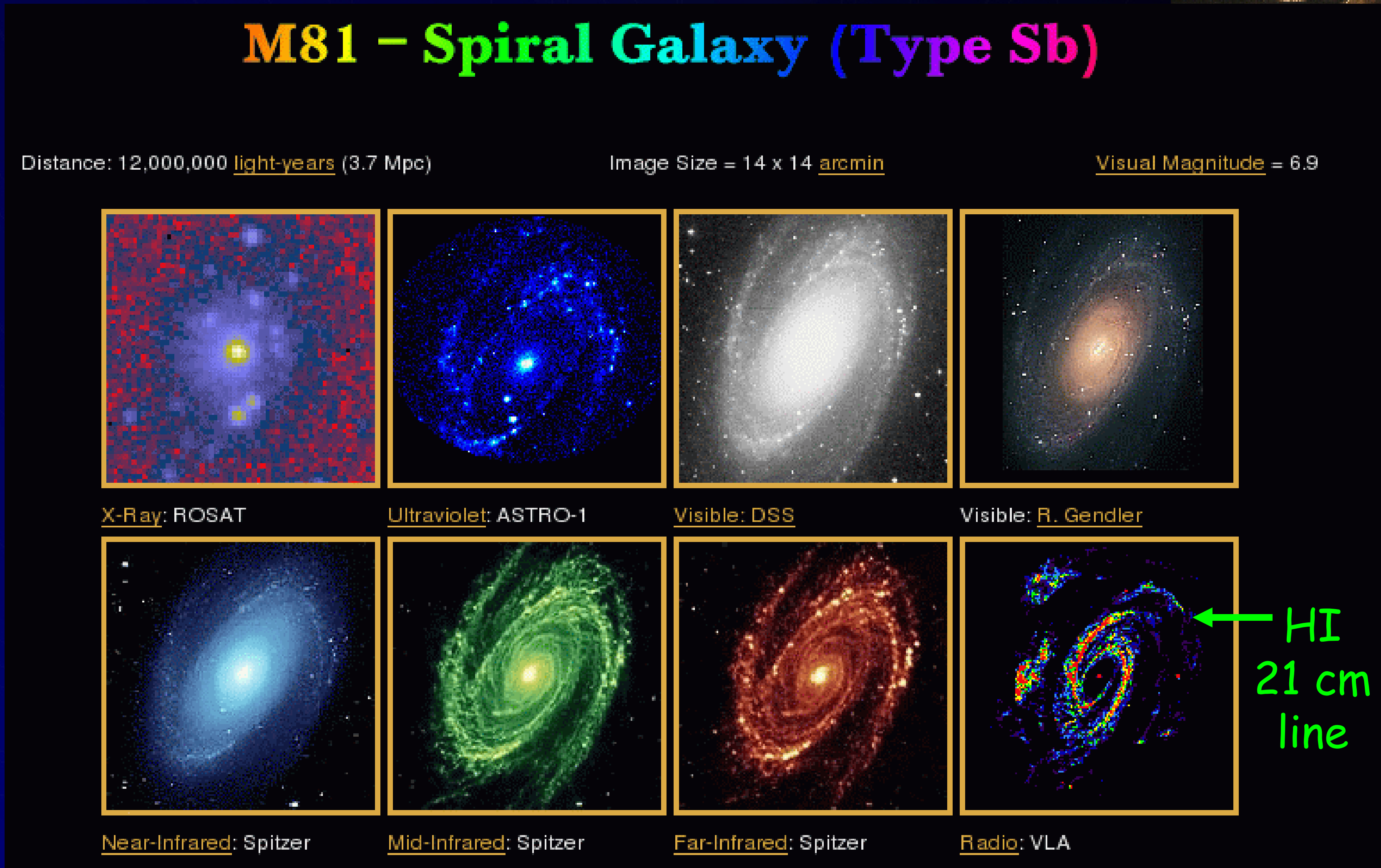
- Redshifts (=> distances via Hubble's Law)
- HI mass and distribution (for extended objects)
  - Potential for future star formation (HI content)
  - HI deficiency in clusters
  - History of tidal events
- Rotational velocities
  - Dark matter distribution
  - Redshift-independent distances via the Baryonic Tully-Fisher relation





Thanks to Catie for laying the groundwork for me!

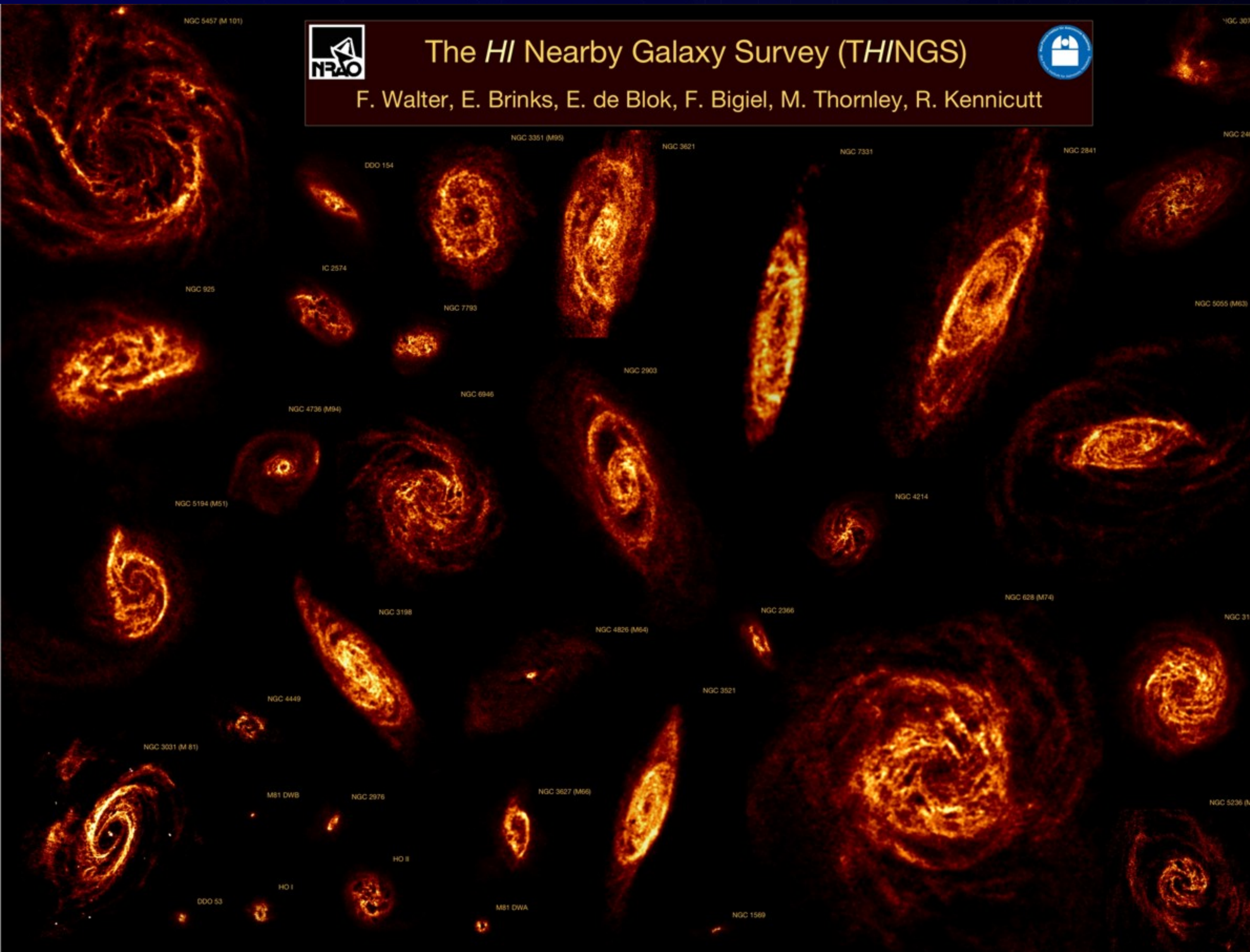
HI: The fuel for star formation



HI
21 cm
line

http://coolcosmos.ipac.caltech.edu/cosmic_classroom/multiwavelength_astronomy/multiwavelength_museum/m81.html

HI distributions



- HI found in the disk
- Often extends beyond the optical disk
- In spirals, "hole" in center (bulge); irregulars, Gaussian-like

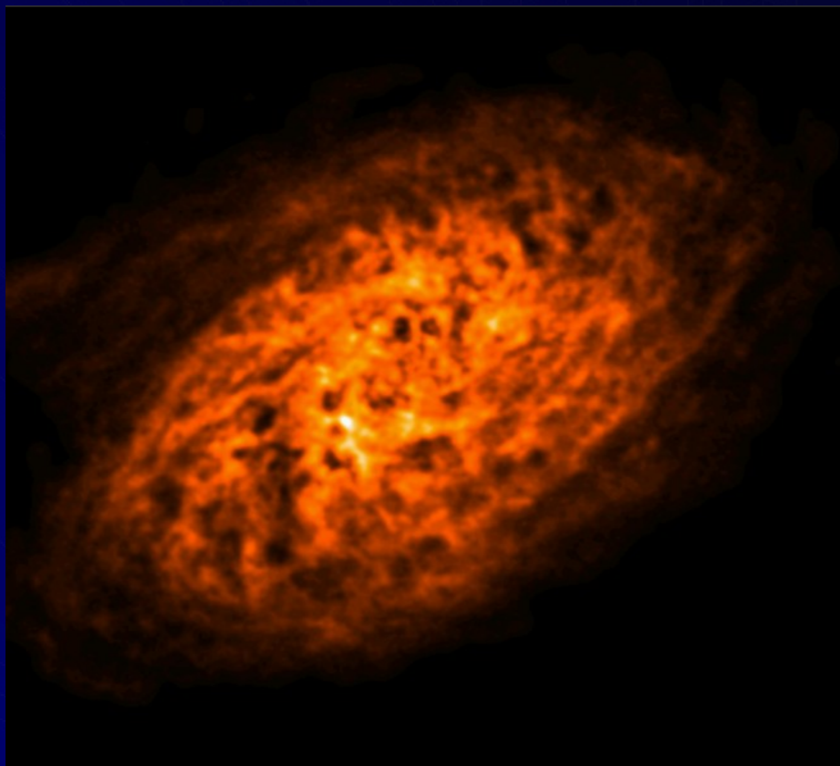
Stars in NGC 2403

Discovered in 1788 by William Herschel

Distance: 2.5 Mpc.

starlight

HI in NGC 2403



HI distribution

starlight

HI traces beyond the stellar disk =>dark matter halo

HI traces interactions!

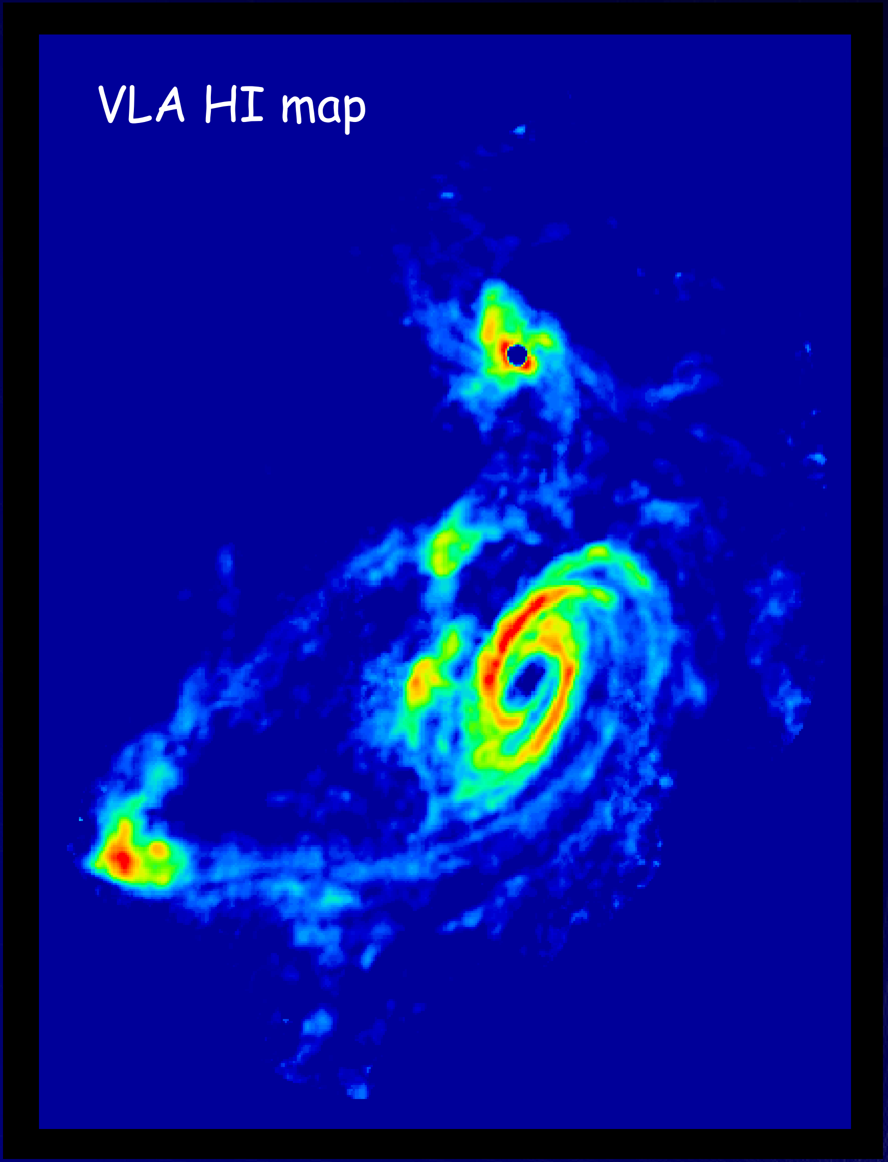
Gravitational interacts perturb preferentially the outer regions of the galaxies.

HI shows both the HI distribution and the velocity field.

HI is an excellent tracer of tidal interactions.

The M81/M82/NGC 3077 system as seen in optical light => the stars!

HI traces interactions!



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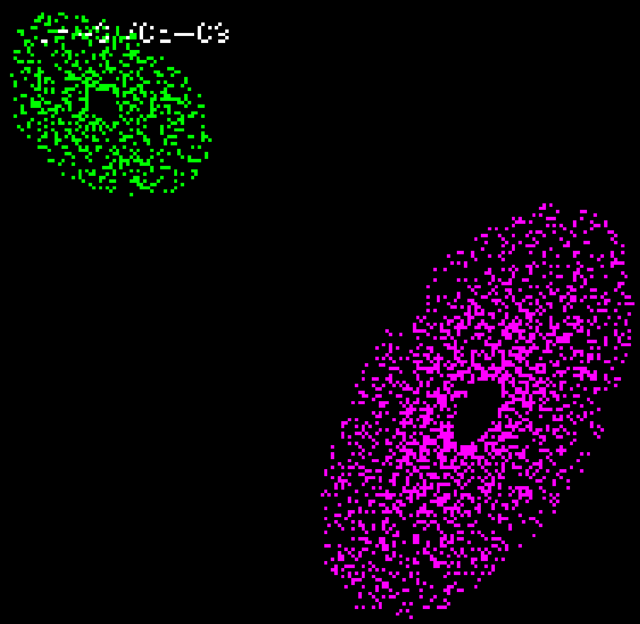

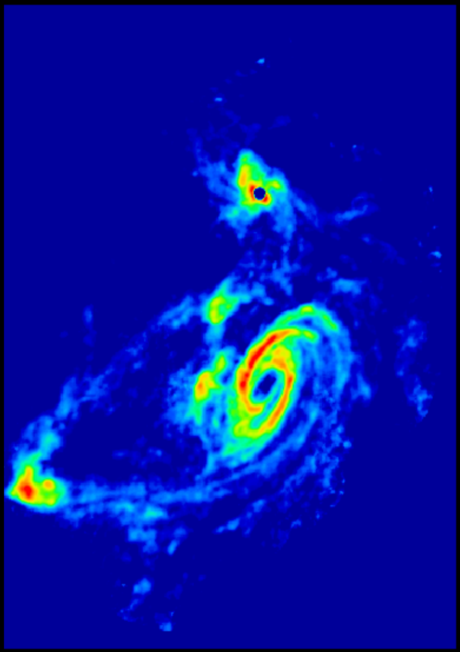

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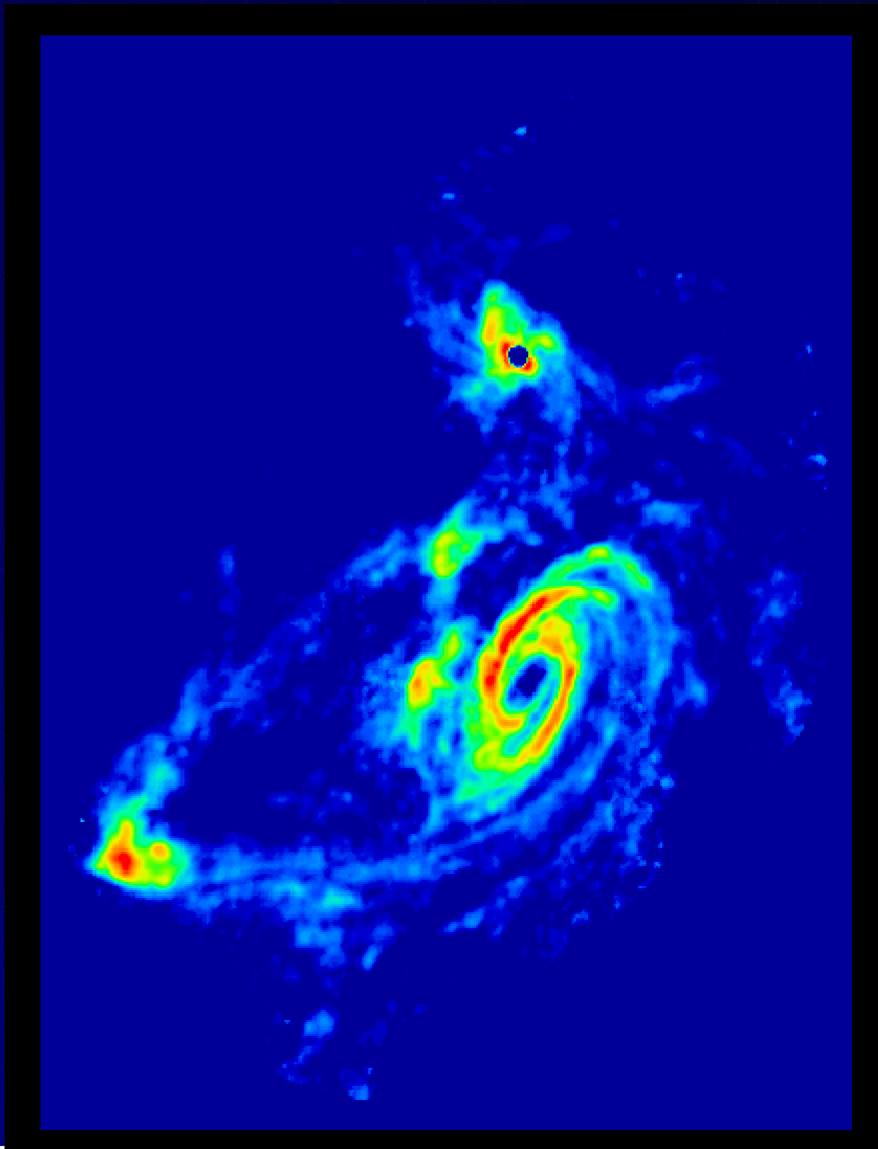
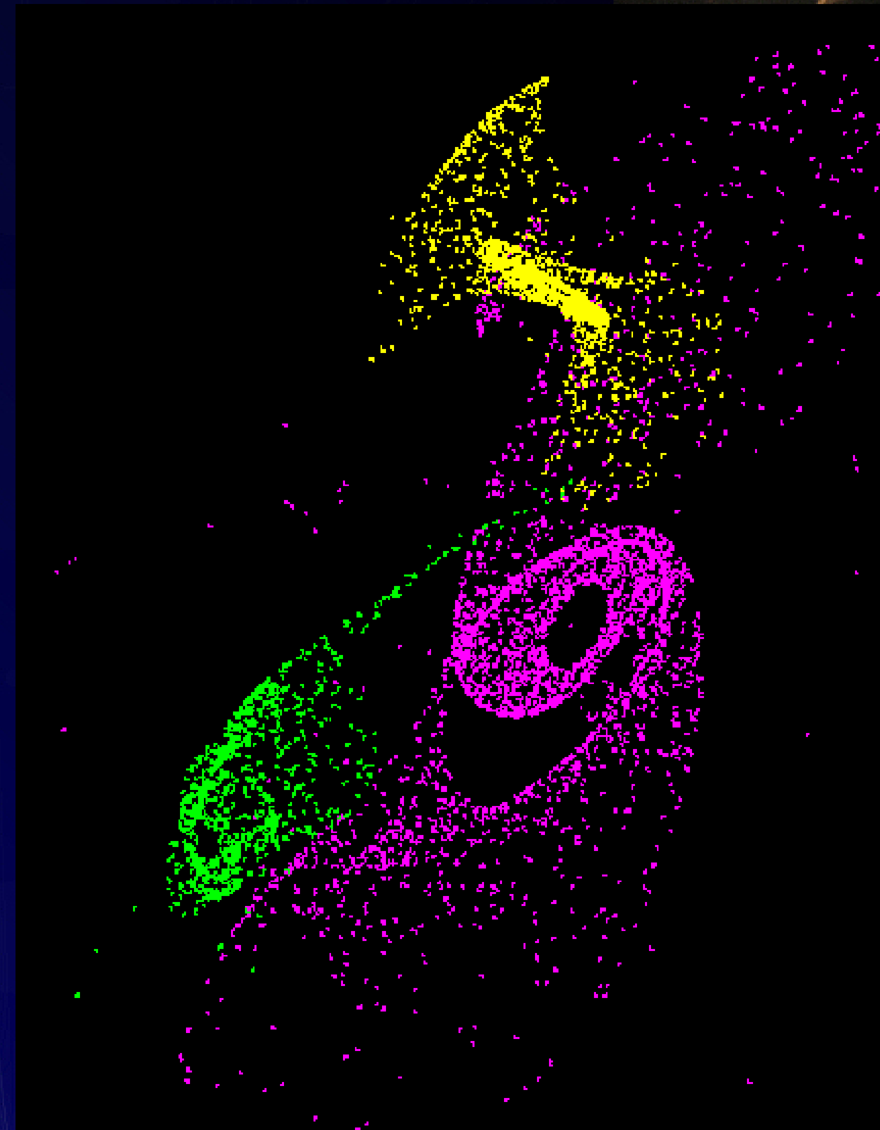
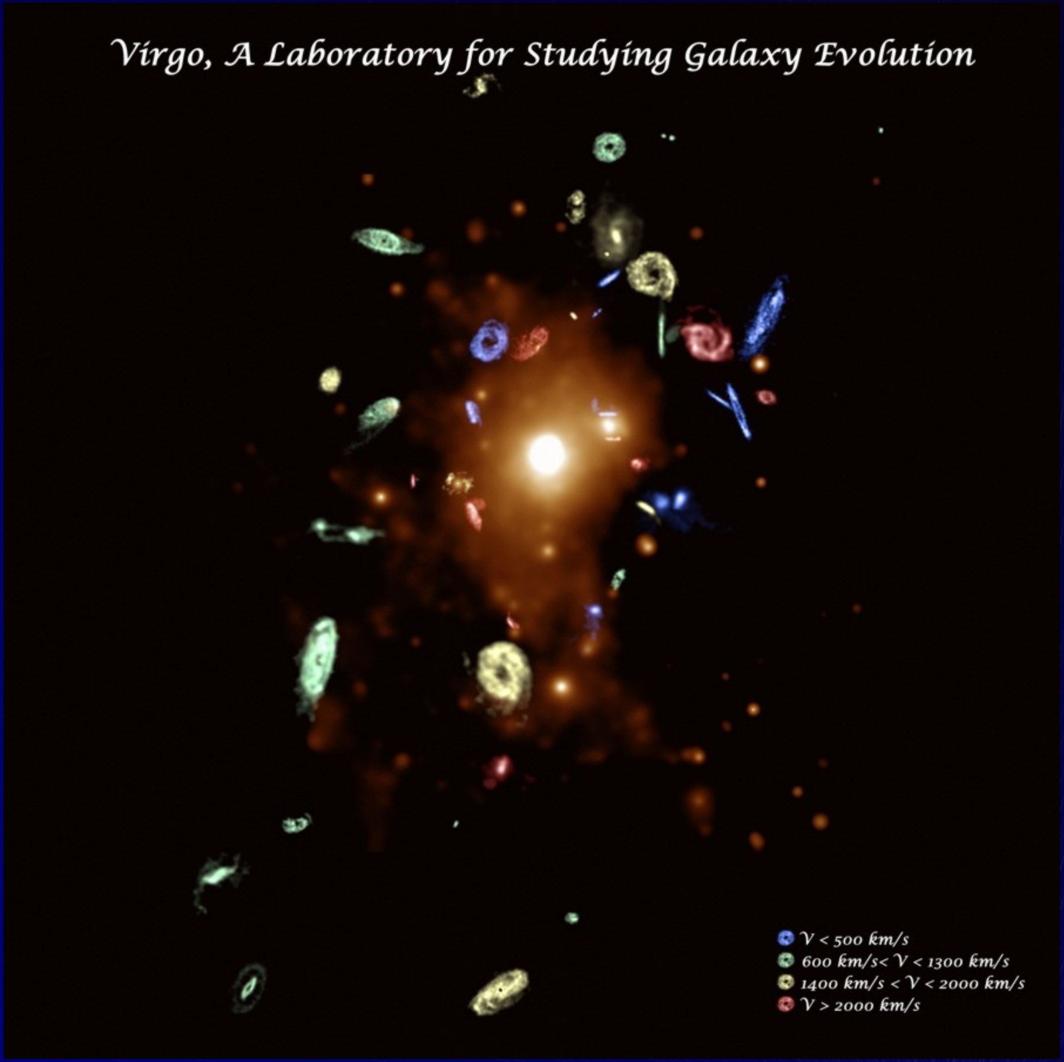




And sometimes HI is lost!

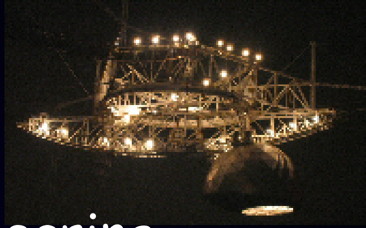


The HI gas in galaxies moving through the hot intracluster medium of clusters of galaxies is stripped by the pressure of the hot gas

⇒ Ram pressure stripping

- Galaxies are HI deficient (lower than expected HI masses)
- HI disks of deficient galaxies are smaller in size (shrunken)

The HI-selected population

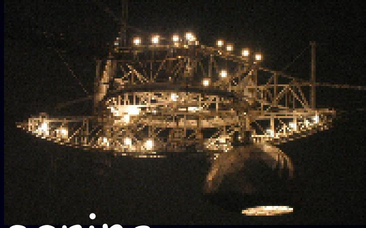


ALFALFA is a “blind” survey: it conducts a census of HI-bearing galaxies.

- Not all galaxies contain HI: We detect spirals but not ellipticals
- Galaxies in clusters are HI deficient: We detect galaxies outside clusters but not so many in clusters

Virtually all SF galaxies contain HI but the “red sequence” galaxies contain (none).

The HI-selected population



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the "red sequence" galaxies contain (none).

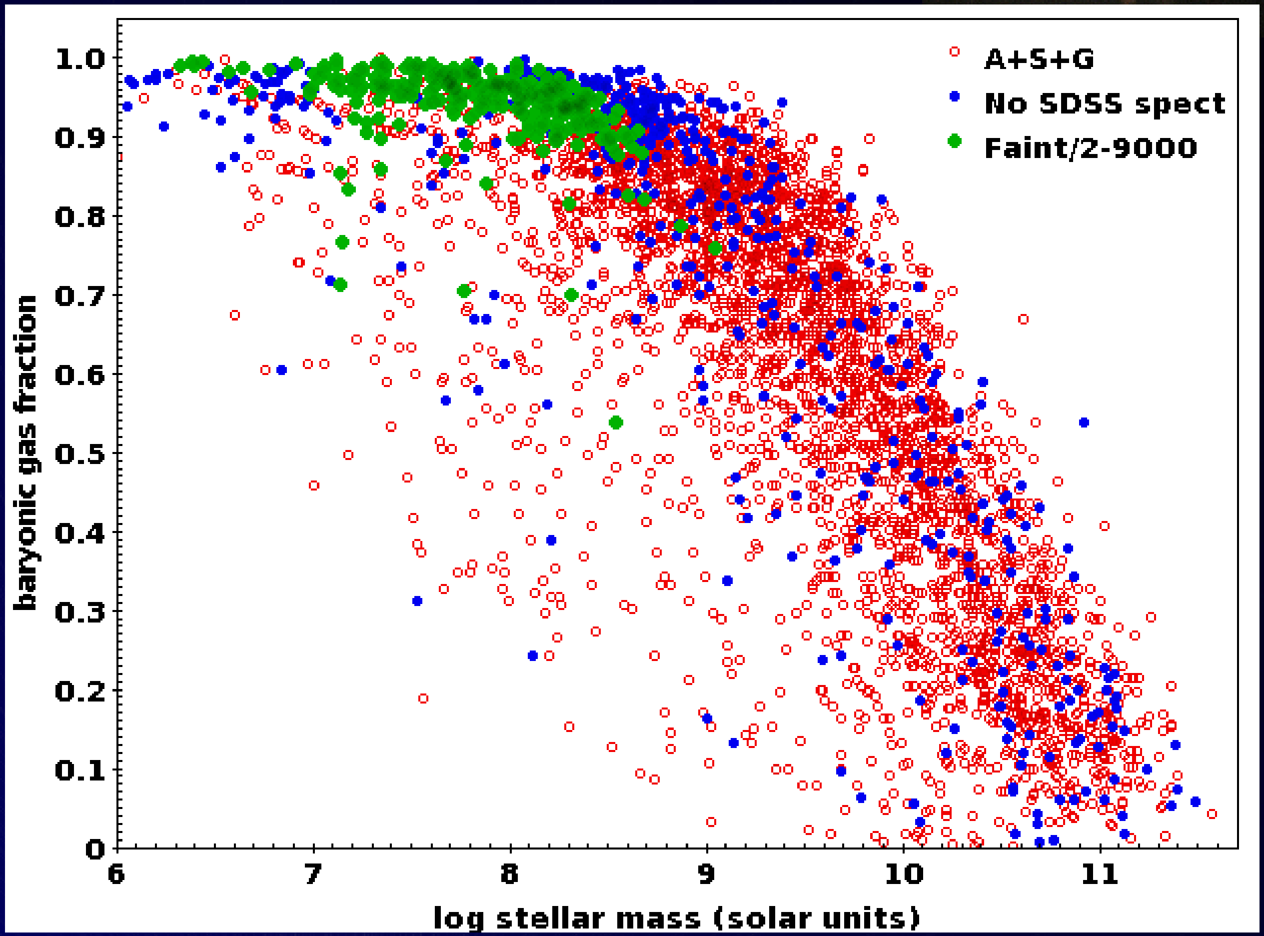
The fraction of the baryonic mass in gas (vs. stars) varies with stellar mass (or stellar luminosity)

- HI fraction falls as the stellar luminosity/mass increases
- Low luminosity SF galaxies are **HI-dominated** (more mass in HI than in stars)
- HI represents the fuel for future star formation.

Huang+(2012b) ApJ 756, 113

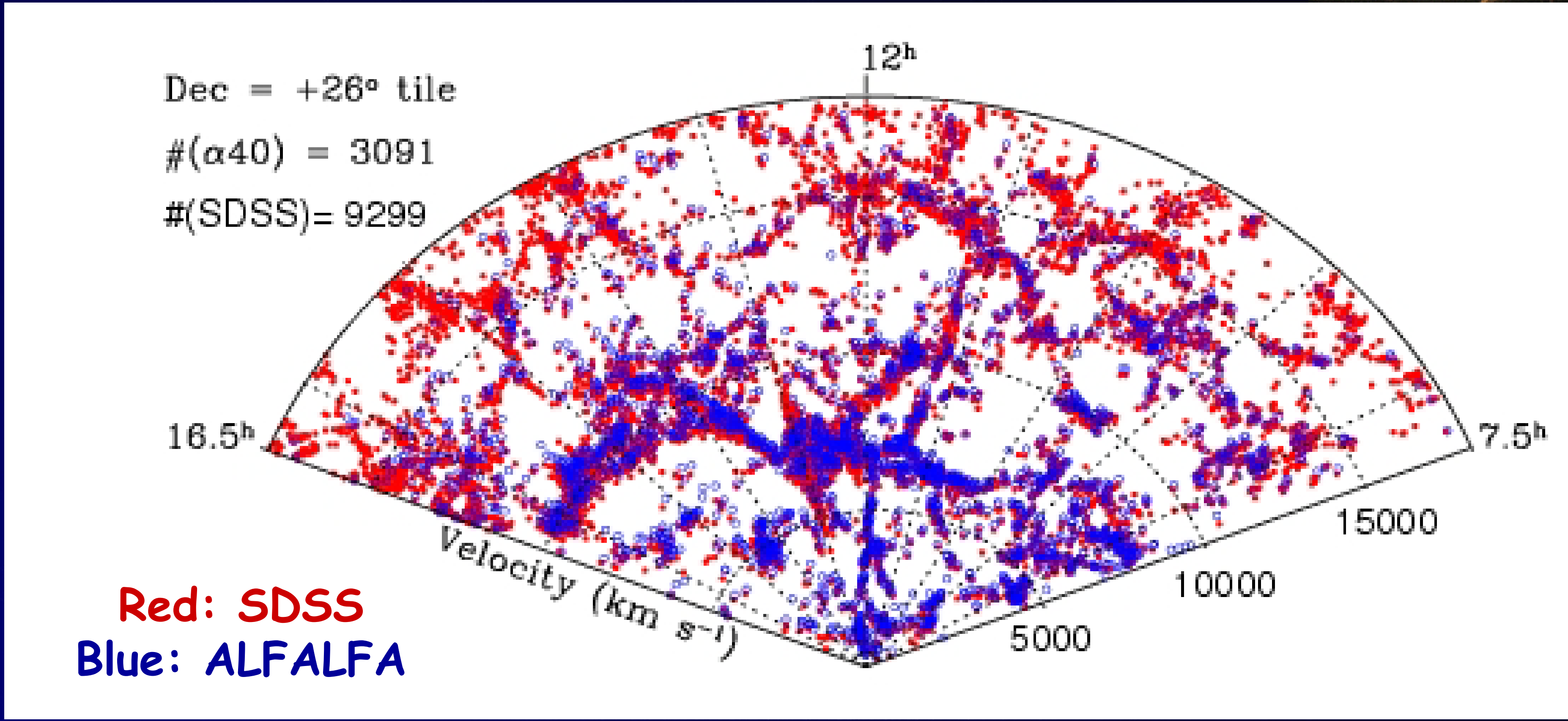
Low mass galaxies: HI dominated

- At low M_{star}, the baryonic gas fraction $M_{HI} / (M_{HI} + M_{star})$ approaches 1.
- Many low HI mass dwarfs are LSB and patchy, so their stellar masses are uncertain.
- For low mass star forming galaxies, most of the baryonic mass is in HI!!!!



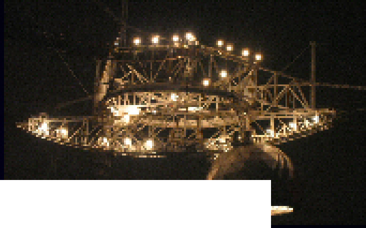
ALFALFA

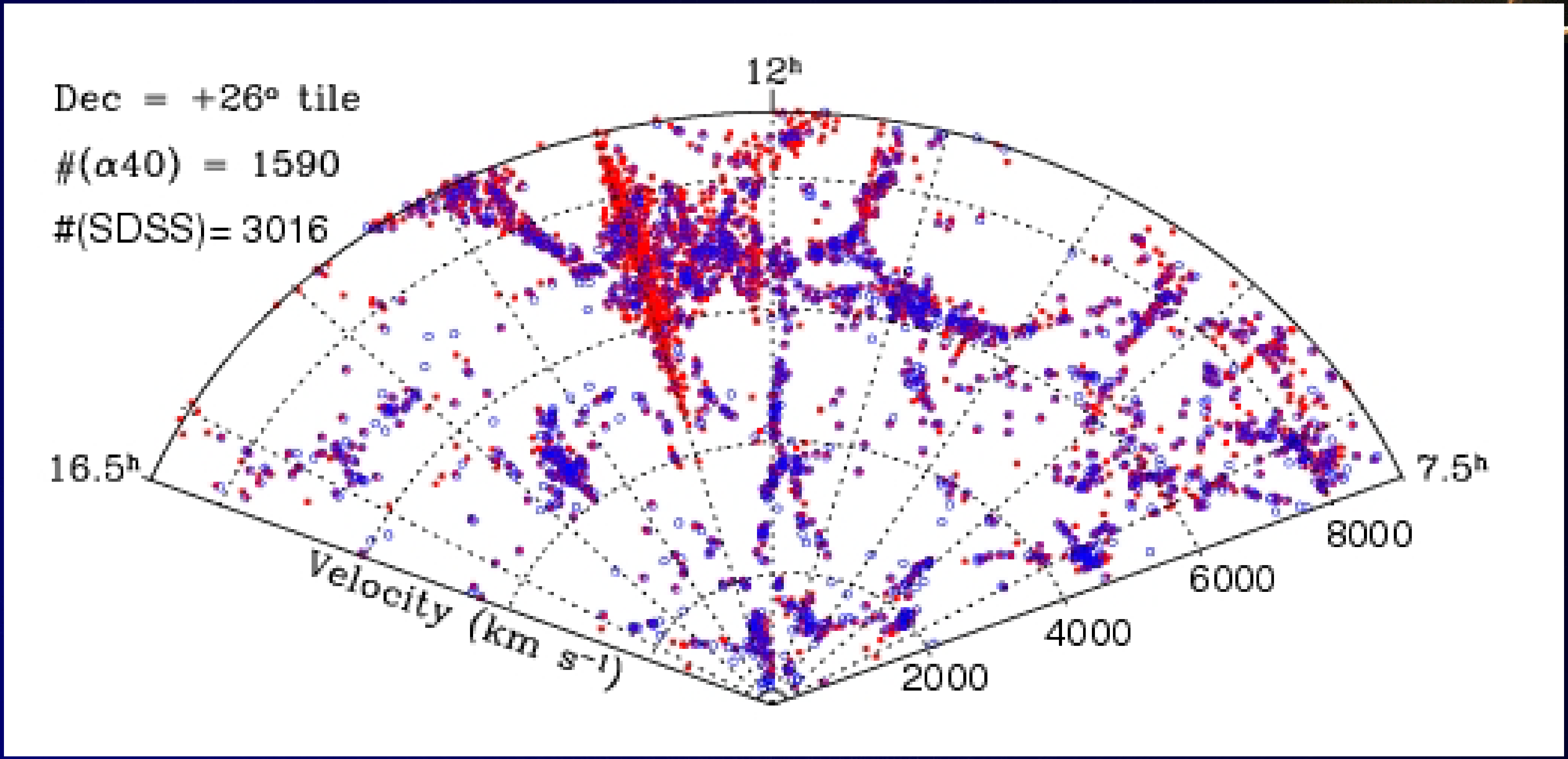
The ALFALFA population



"Cone diagram" illustrates 3-D distribution along a slice of sky
The SDSS is "deeper" than ALFALFA in that it samples galaxies at much larger distances.

The ALFALFA population





- Nearby, the two surveys **do not** detect all the **same** galaxies.

Nearly all star formating galaxies contain HI.

- Low mass SF galaxies are HI-dominated.
- Cluster galaxies are HI deficient or "red and dead".

ALFALFA

HI cosmology

- The HI Mass Function: # galaxies per interval of HI mass per unit volume (analogous to a luminosity function) (Martin+2010 ApJ 723, 1359)
  - Cosmic density of HI at redshift 0: how much HI is there?
    - Buildup of stellar pop and metals ⇔ decrease in gas

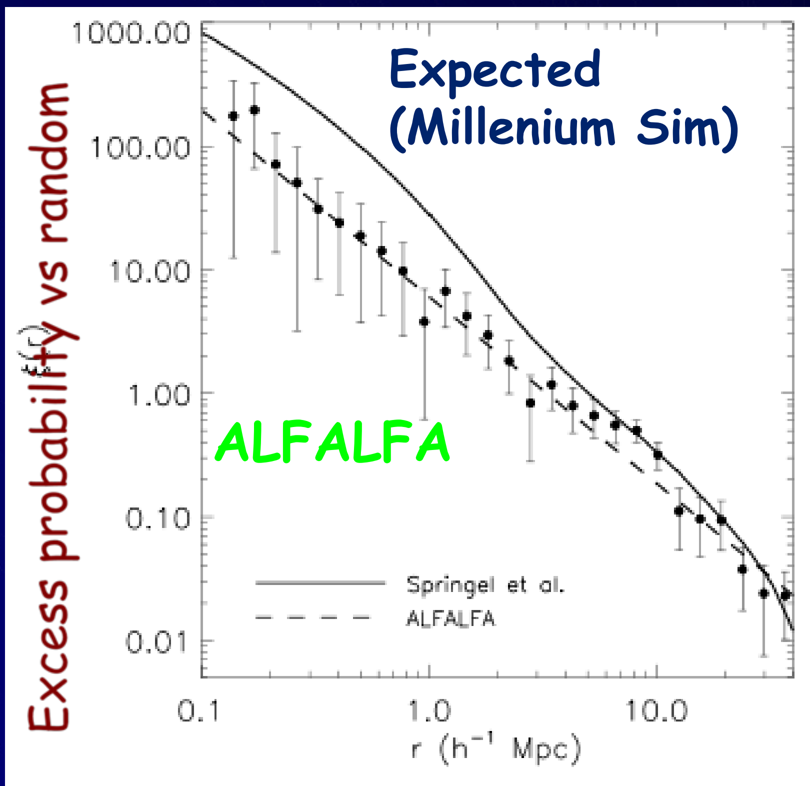
- The HI correlation function: how do HI galaxies cluster? (Martin+ 2012 ApJ 750, 38)
  - HI galaxies are the least-clustered galaxy population

- The HI velocity width function gives a perspective on the dark matter halo mass function. (Papastergis+ 2011 ApJ 739, 38)
  - We don't understand how gas/stars fit into halos
  - But gas richness is related to halo angular momentum

All of these yield insight into the distribution of dark matter halos, in this case ones **which** are gas-bearing, regardless of their stellar content.

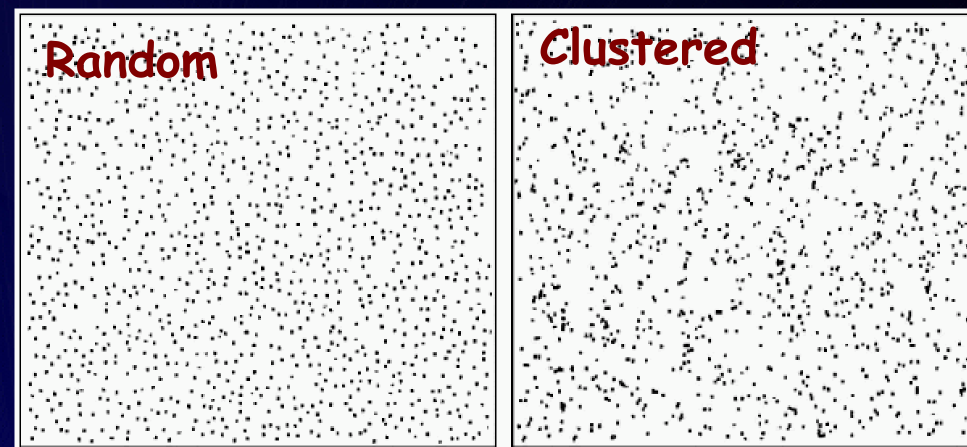
HI-selected ALFALFA population

The HI population is **much less clustered** on small scales, but follows the DM on large scales.



Martin + (2012) Ap J 750, 38

"correlation function": excess over random of finding a nearby galaxy



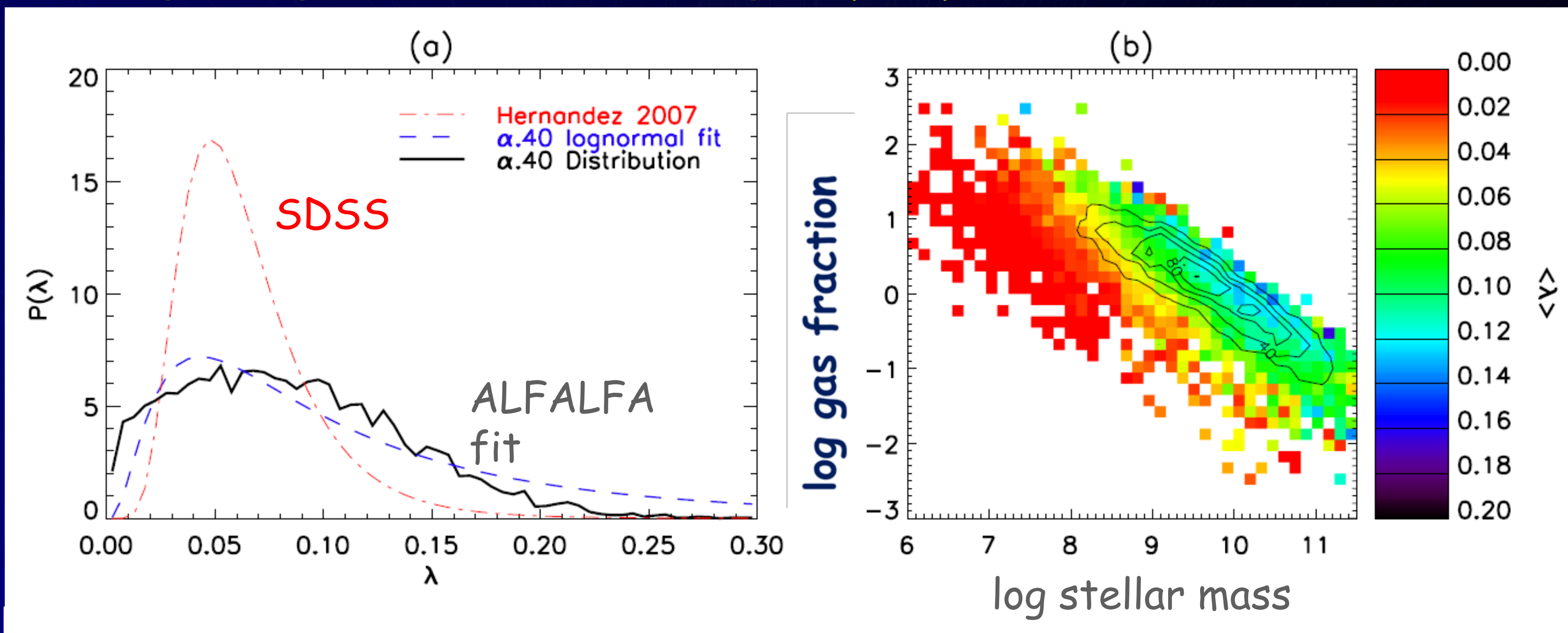
The HI population is the **least clustered known =>** environmentally-driven processes are minimized.

DM halo spin ⇔ gas richness

Halo spin parameter: $\lambda = J|E|^{1/2} G^{-1} M^{-5/2}$

Observationally (not so easy) $\lambda = 21.8 \dfrac{R_d\ (\mathrm{kpc})}{(V_{rot}\ [\mathrm{km/s}])^{3/2}}$

Higher gas fraction ⇔ high spin parameter of DM halo!



Shan Huang+ (2012b) ApJ 756, 113

The Discovery of Leo P

A needle in the ALFALFA haystack
- Strong HI signal in ALFALFA
- V_{helio} = 263 km/s
  - Distance very uncertain

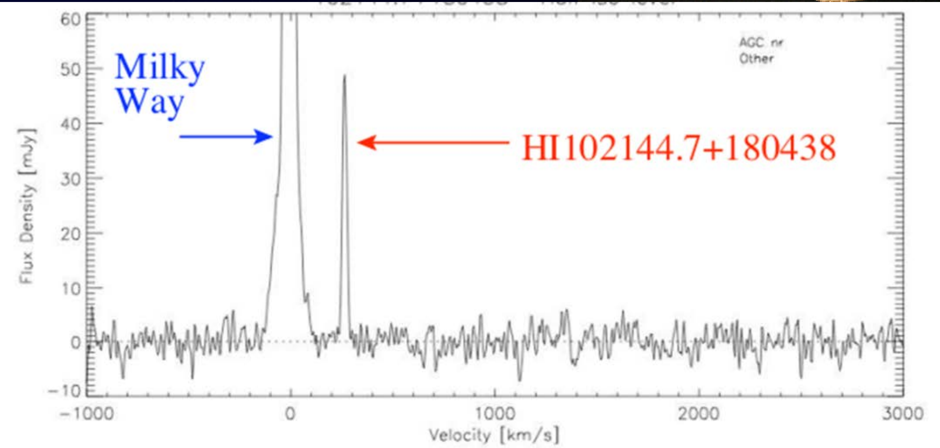
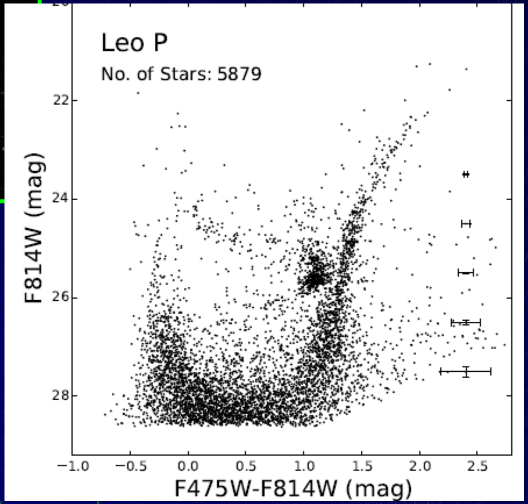


Figure 1: Discovery HI spectrum of HI1022 from the ALFALFA survey. Milky Way foreground gas is denoted in blue, and the HI associated with the newly discovered Local Group candidate dwarf galaxy is denoted in red. Note the low recessional velocity and narrow HI line width.

HST distance (TRGB) = 2.6 Mpc



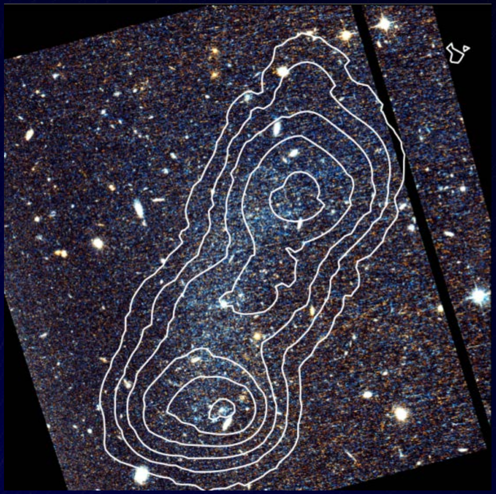
- M_V = -9.27; single HII region
- $M_{star} = 5.6 \times 10^5\ M_\odot$
- $M_{HI} = 8.1 \times 10^5\ M_\odot$
- SFR(Hα) = $4.3 \times 10^{-5}\ M_\odot$/yr
- 12+log(O/H) = 7.17 (3% solar)

ALFALFA: Are there "dark galaxies"?

- In agreement with previous results, ALFALFA finds that fewer that 2% of (clearly extragalactic; not ALFALFA UCHVCs) HI sources cannot be identified with an optical counterpart.
- The majority of objects without OC's are found near to galaxies with similar redshifts.

"Dark galaxies":
The burden is always on us to prove that
(1) the HI signal is real
(2) there is no OC even at LSB
(3) the HI is not tidal in origin
(4) not an OHM at z~0.2

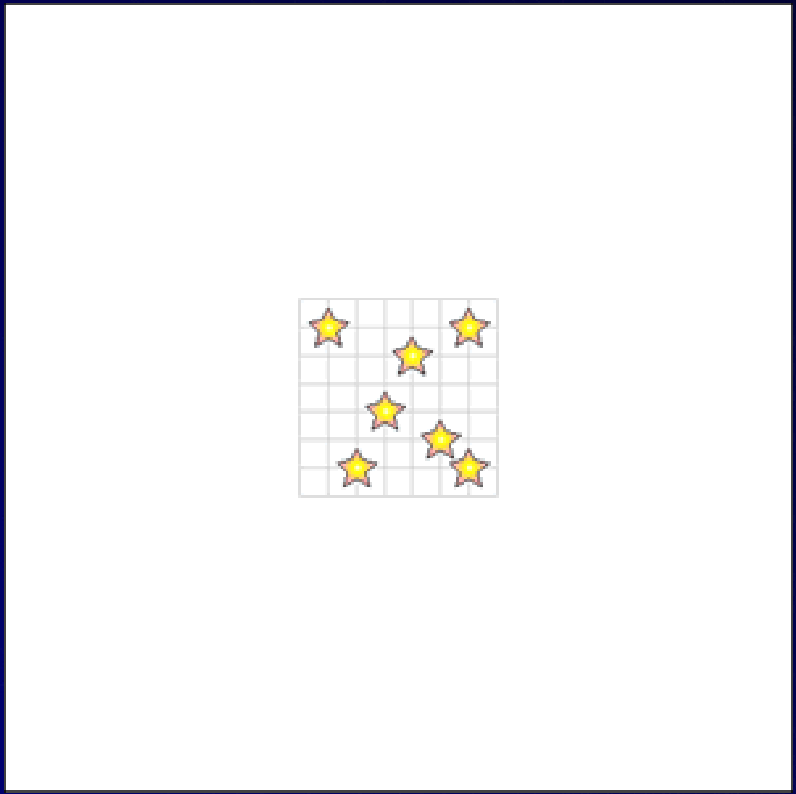
Ask Luke and Catie!!!



Coma P
Ball+
2018
WSRT
/VLA
on HST

- Why has their gas not formed stars?
- What are the HI-bearing Ultra Diffuse Galaxies

Smooth Hubble Flow



- The dominant motion in the universe is the smooth expansion, known as the Hubble Flow.

↕

- **<u>Cosmological principle</u>**: On large scales, the universe is homogeneous and isotropic.

But: *galaxies cluster !*

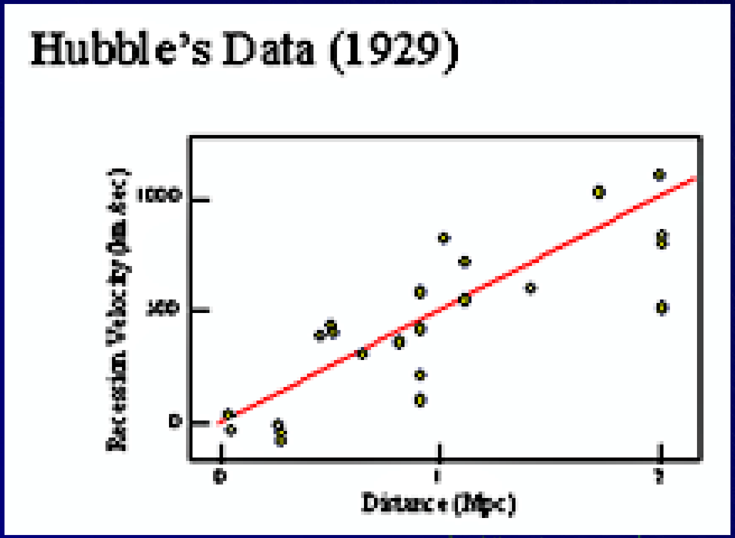
Hubble's Law

- **Slipher** (~1912) noticed that spiral nebulae showed almost predominantly redshifts.
  - By 1925 he had radial velocities for 40 galaxies

Vesto Melvin Slipher
1875-1969

- **Hubble** used the 100-inch telescope on Mt. Wilson to measure distance to 18 galaxies
  - Found linear relation between increasing redshift and increasing distance, now known as Hubble's law

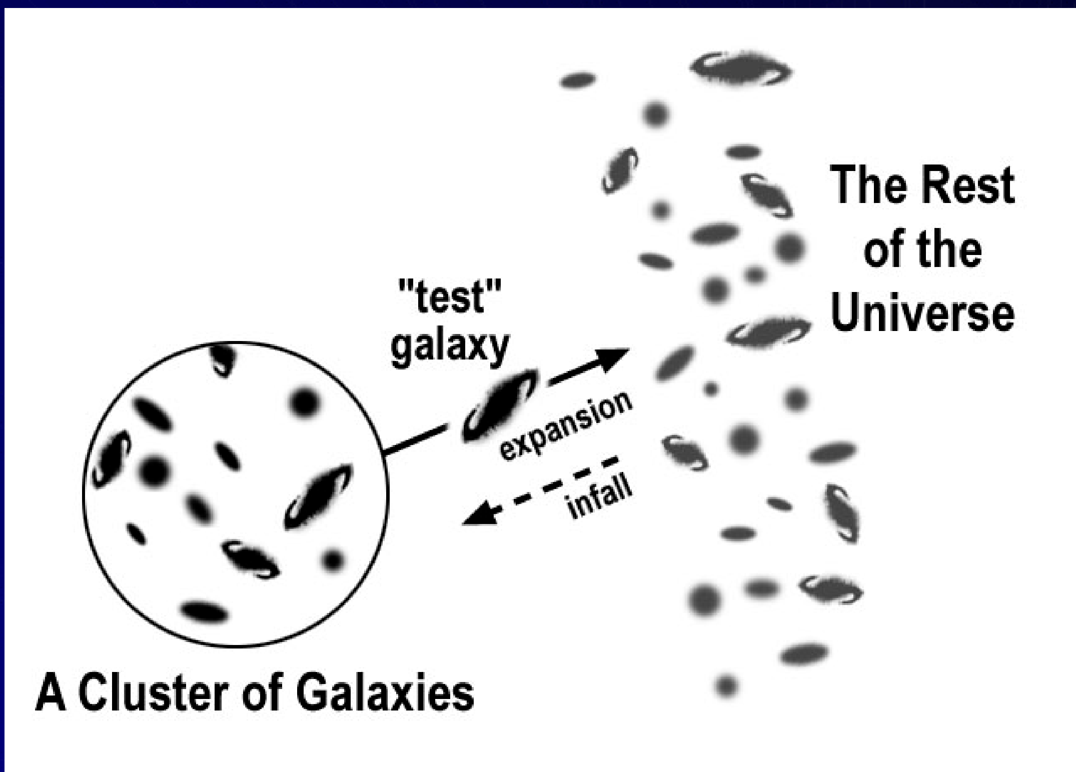
$$H_o\, d = v \sim cz$$



- Offers simple way to determine the distances to galaxies.
- Provided evidence that the Universe is expanding which in turn suggests that it is finite in time.

Deviations from Hubble Flow

But on smaller scales, inhomogeneities in the density => perturbations in the gravity field => the velocity field.



<u>"Peculiar velocities"</u>

$$V_{obs} = V_{Hubble} + Vpec$$

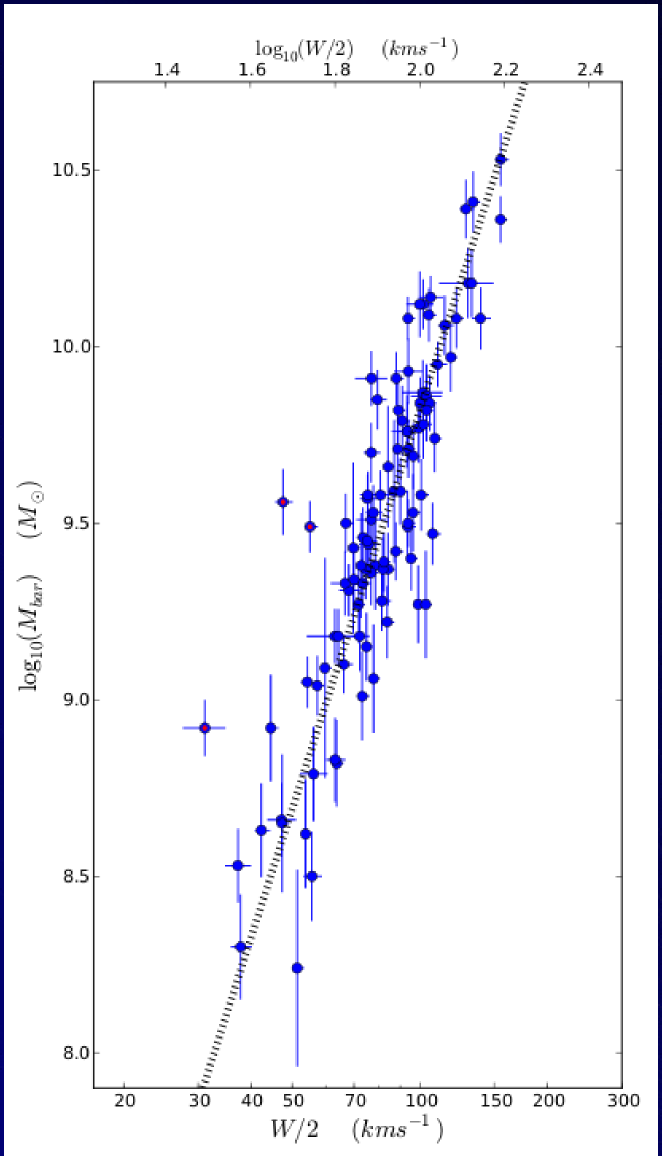
V_{pec} includes components of:

- Orbital motion in cluster/group
- Infall/outflow from regions of over/under-density
- "noise" on the pure Hubble flow

Trace V_{pec} ⇔ Trace mass

Tully *et al* 2014 Nature

ALFALFA



Baryonic Tully-Fisher Relation (BTFR)

- The **rotational velocity** of a disk galaxy is related to its **baryonic mass**.
- The BTFR can be used to predict the galaxy's baryonic mass if its rotational velocity is measured.
- This is turn allows the possibility to predict the distance to the galaxy independent of the redshift.
    - Predict velocity from distance
    - Compare to observed velocity
    - Recover "peculiar velocity"

Papastergis+ 2016 A&A 593, A39

What HI teaches us

A lot about:

- How the interstellar medium in galaxies is distributed
- How gas is converted into stars
- How galaxy evolution is impacted by local environment
- How galaxies acquire and lose baryons
- How gas-bearing galaxies are distributed
- How dark matter is distributed both within galaxies and on larger scales