Cool Gas in (late type) Galaxies

How to think about the cool ISM

The distribution of HI within galaxies

HI velocity dispersion & turbulence

HI demographics

HI in unusual places

Why care about cool gas?

Amount & distribution of gas tracks:

Past baryon accretion history

Efficiency of past star formation

Potential for future star formation

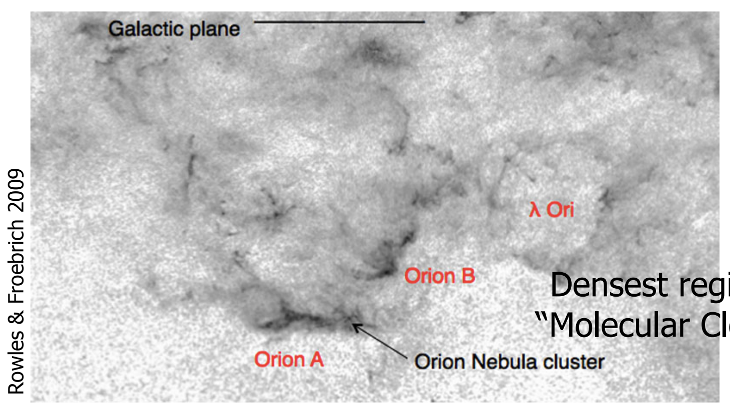
Effectiveness of baryonic "feedback"

Environmental disturbance (stripping)

Fundamentals of cool gas

The cool ISM is highly turbulent

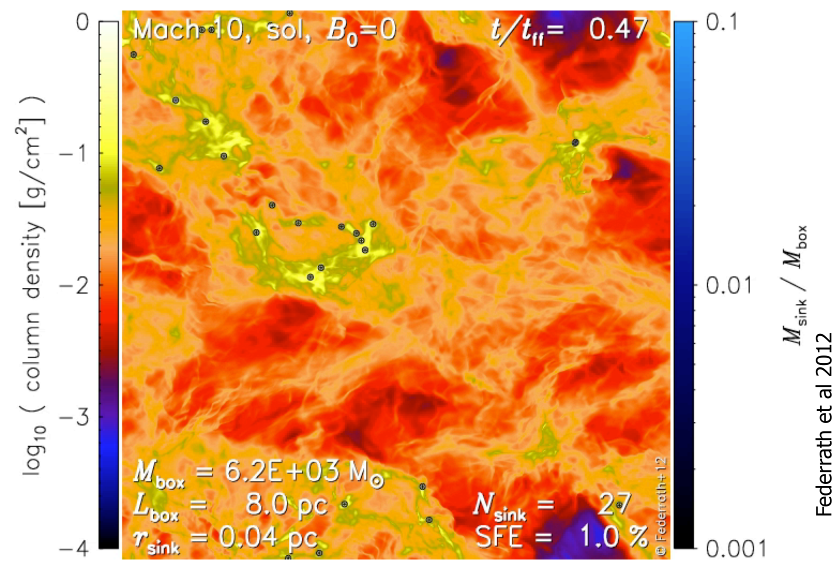
Not a smooth slab of gas



Densest regions: "Molecular Clouds"

Extinction map showing structure of cold gas (few 100 pc)

Simulation of turbulence+SF

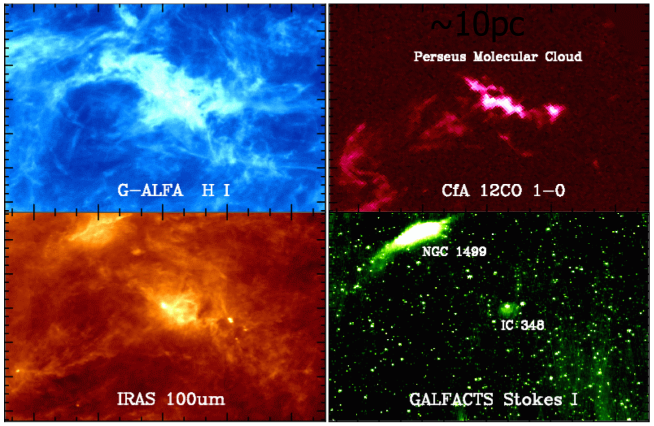


Major issue: What drives turbulence?

Fundamentals of cool gas

The ISM is “multiphase” even on small scales

HI



CO

thermal black-body emission from warm dust

continuum emission from ionized gas

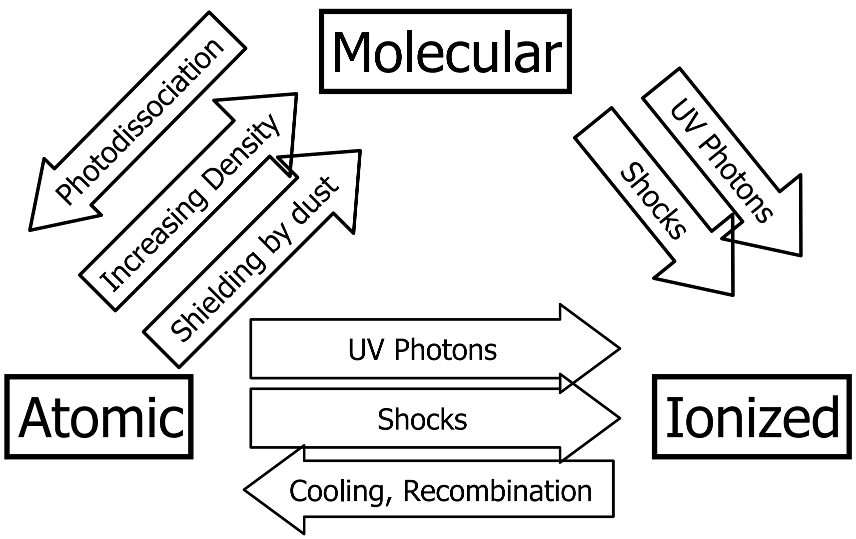
http://www.naic.edu/alfa/galfa/highlights/per/

Fundamentals of cool gas

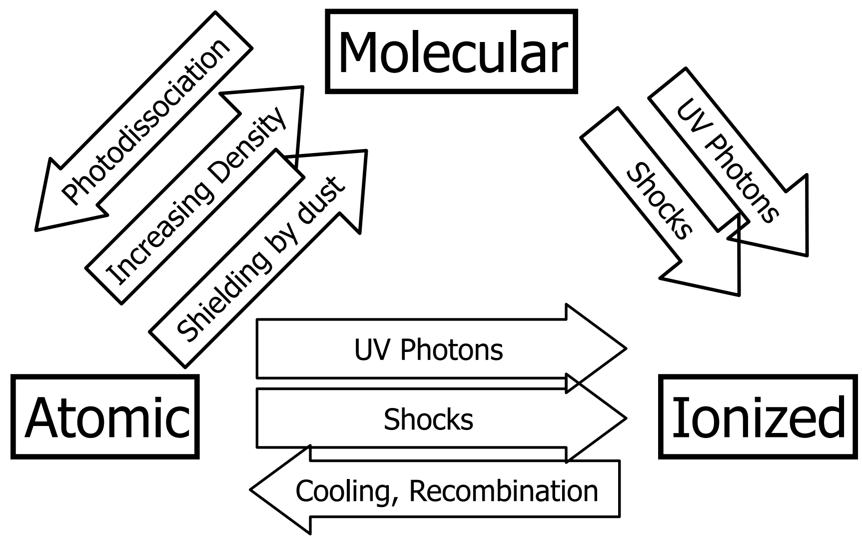
The state of the gas is highly transient

Dissipative, so structure can reach high densities quickly

Rapidly changes phase in response to changes in density, pressure, UV photon density



Characteristic timescales can be <10 Myr



Global fractions of the different phases depends on balance between many processes

Fundamentals of cool gas

The state of the gas is highly transient

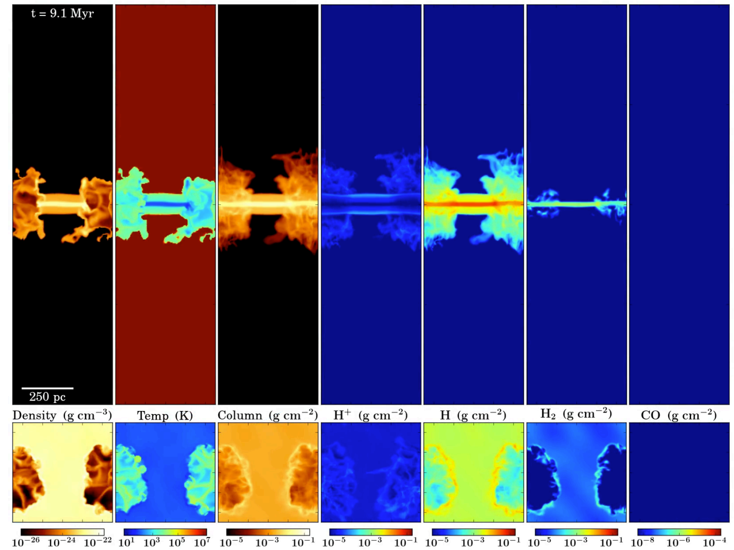
- Dissipative, so structure can reach high densities quickly
- Rapidly changes phase in response to changes in density, pressure, UV photon density

Simulations show strong sensitivity to exact implementation of these processes & what drives them (SNe, cooling, dust)

Simulation of SF disk w/ SNe

Walch et al 2015

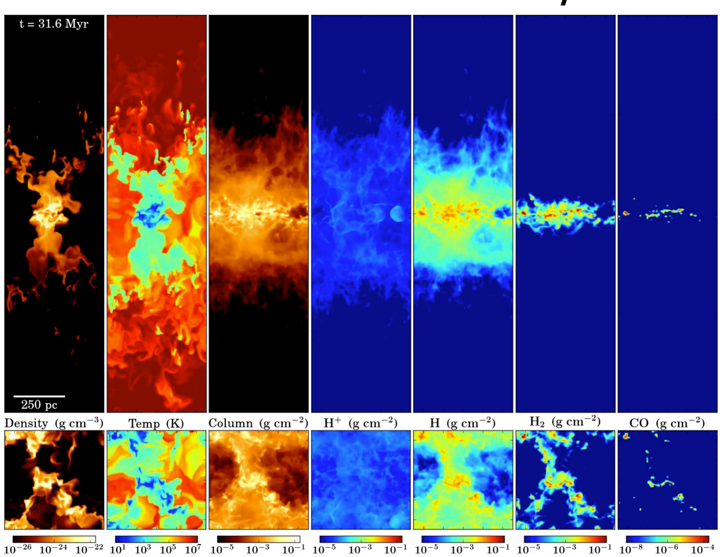
https://hera.ph1.uni-koeln.de/~silcc/



SNe set off at peaks in gas density

Simulation of SF disk w/ SNe

Walch et al 2015

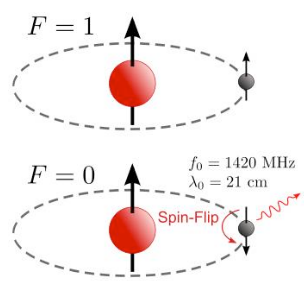


Some SNe drift from peaks, + TypeIa

Tracing Cool Gas

Neutral Hydrogen

Spin-flip "hyperfine" transition at 21 cm

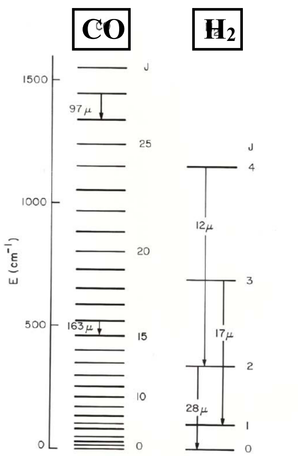


Low ΔE = Nearly any collision can excite e- into higher energy state. Subsequent decay produces emission line.

Tracing Cool Gas

Molecular Hydrogen? Strike one...

CO: Energy Levels Closely Spaced



H_2: Large Energy Separations (hard to excite)

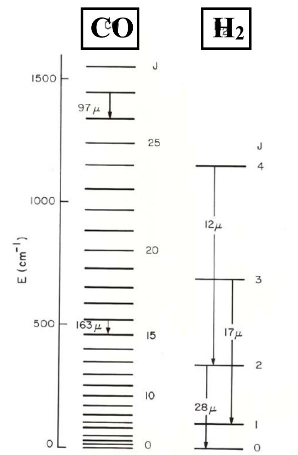
13 Energy level diagrams showing lowest energy rotational states

Tracing Cool Gas

Molecular Hydrogen? Strike two...

Permitted transitions for asymmetric molecules:

$\Delta J=1$



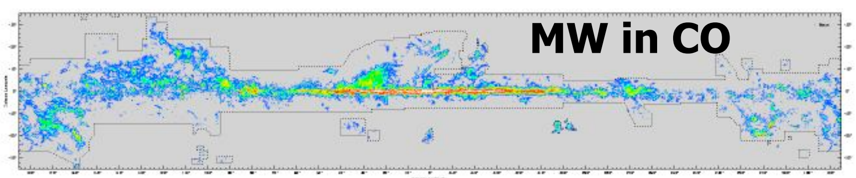
Permitted transitions for symmetric molecules:

$\Delta J=2$

(Only quadrapole transitions, since no dipole moment)

14 Lowest energy transition for H_2 requires fast collisions (hot gas!)

Almost all molecular mapping relies on CO



Dame et al 2002

Yay CO!
- Most abundant molecule after H_2.
- Rotational transitions are low energy & easy to excite ($T_{exc} \approx T_{kin}$)

Boo CO!
- It's not H_2. Need conversion factor.
- It may not live in the same place as H_2.
- Optically thick at low densities.

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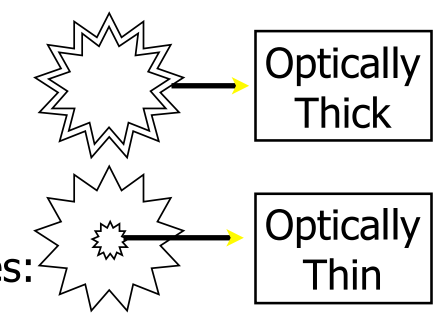
Tracing Cool Gas

Molecular gas

Other molecules used to trace densest gas

CO:

Rare Molecules:



Use:
- Complex molecules (NH_3)
- Less abundant elements
- Isotopes of common molecules (HD, ^{13}CO)

Tracing Cool Gas

Molecular gas

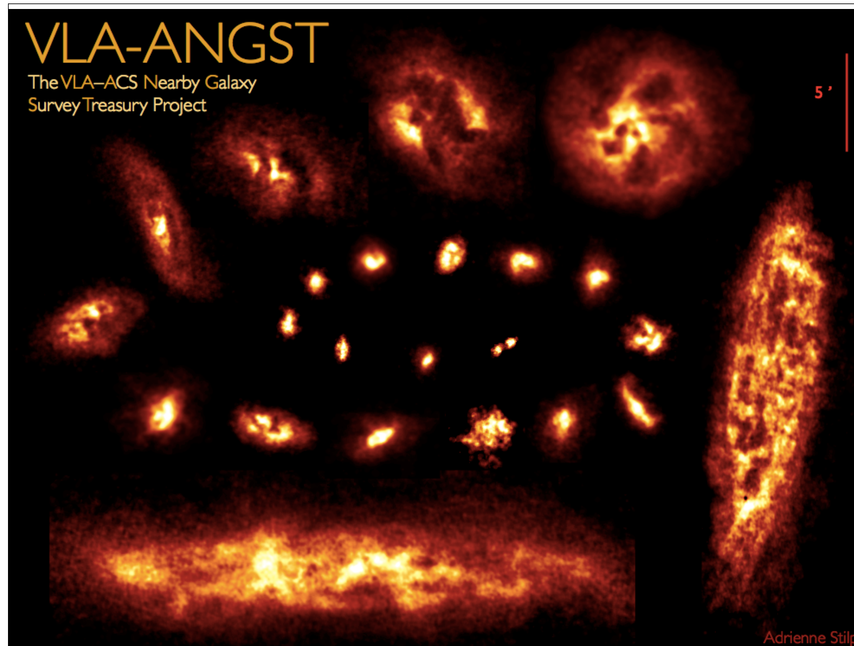
In the Milky Way, dust extinction also used

Dame et al 2002

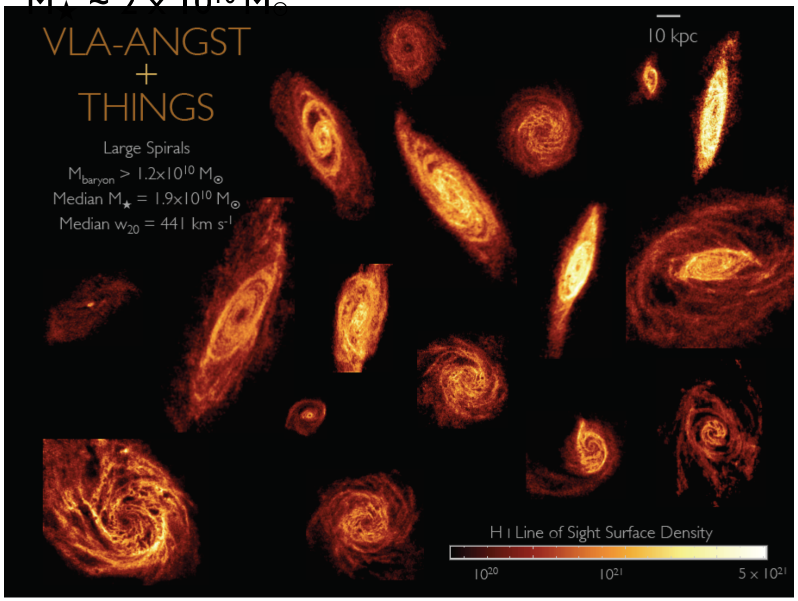
Broad Distribution of Cold Gas

Atomic Hydrogen

Atomic + molecular

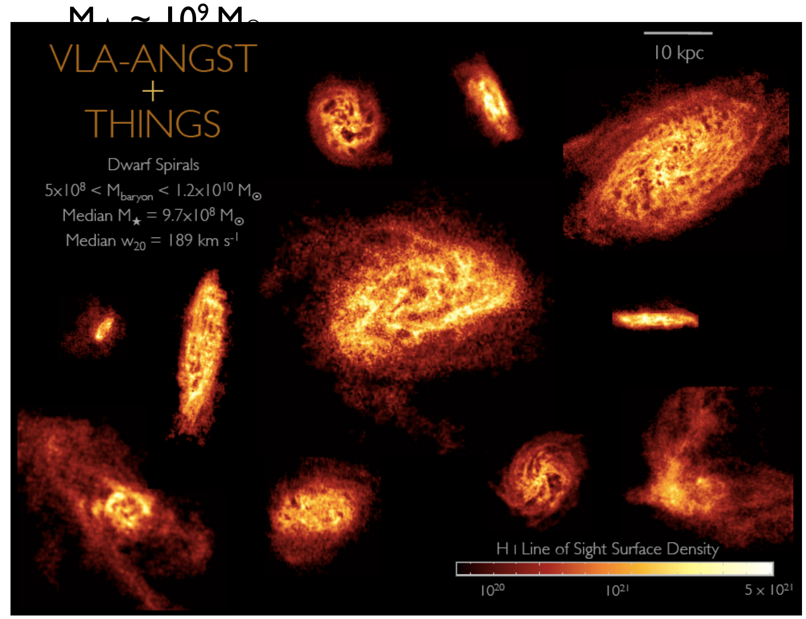


$M_\star \sim 2 \times 10^{10}\, M_\odot$



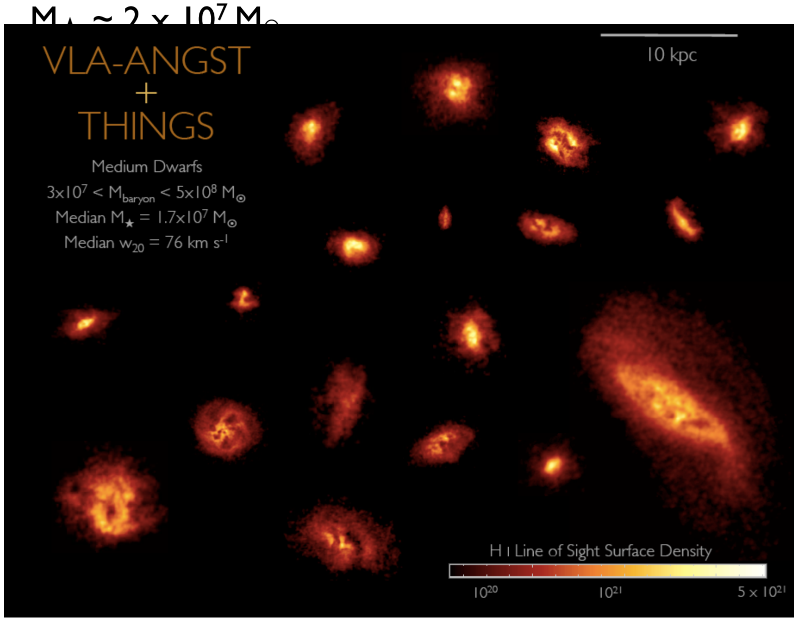
Courtesy: Adrienne Stilp — Ott et al 2012, Walter et al 2008

$M_\star \sim 10^{9}\, M_\odot$



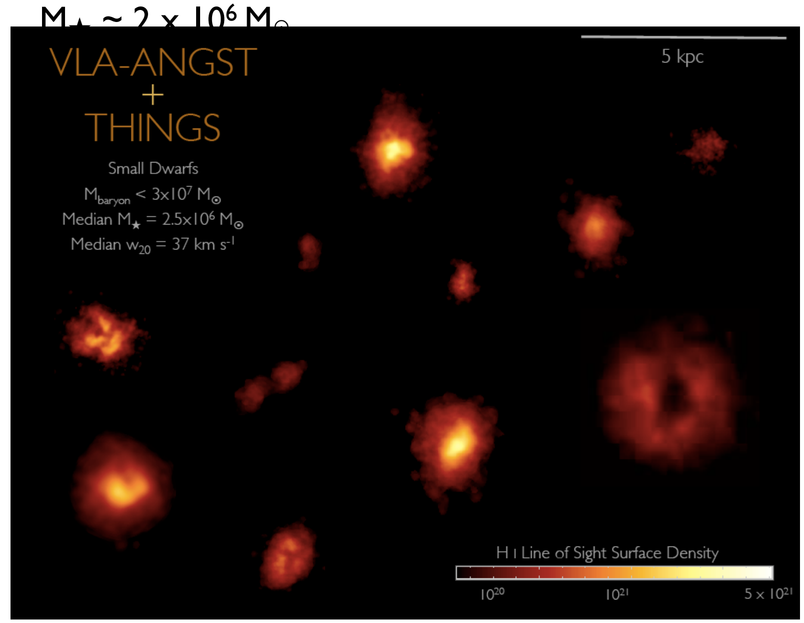
Courtesy: Adrienne Stilp — Ott et al 2012, Walter et al 2008

$M_\star \sim 2 \times 10^{7}\, M_\odot$

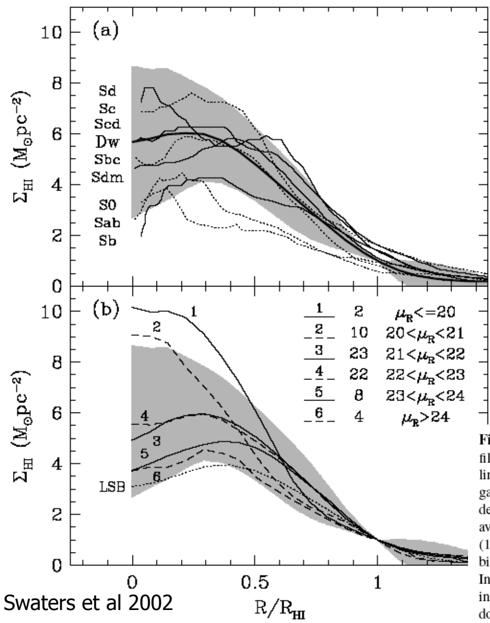


Courtesy: Adrienne Stilp — Ott et al 2012, Walter et al 2008

$M_\star \sim 2 \times 10^{6}\, M_\odot$



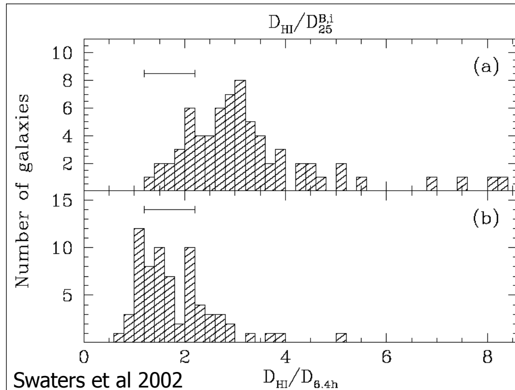
Courtesy: Adrienne Stilp — Ott et al 2012, Walter et al 2008



Swaters et al 2002

HI surface density generally declines with radius, but flattens toward center

Fig. 10. a) Comparison of the range in radial H I surface density profiles among dwarf galaxies and bright spiral galaxies. The thick black line indicated by "Dw" represents the average profile of all dwarf galaxies in our sample, and the shaded area indicates one standard deviation at each radius around the mean. The other lines represent average profiles for different morphological types from Cayatte et al. (1994). **b)** Radial H I surface density profiles of the dwarf galaxies, binned by central disk surface brightness as indicated in the top right. In front of the range in surface brightnesses the number of galaxies in each bin is given. The shaded area is the same as in panel **a)**. The dotted line is the average profile for LSB galaxies from de Blok et al. (1996).



Swaters et al 2002

HI Sizes: More extended than the optical -- gas reservoir at large radii

Fig. 6. Histogram of $D_{\rm H\,I}/D_{25}^{B,i}$ (top panel) and of $D_{\rm H\,I}/6.4h$ (bottom panel). The horizontal bar in both panels indicates the range of $D_{\rm H\,I}/D_{25}^{B,i}$ for spiral galaxies, as found by Broeils & Rhee (1997).

D_{25} = optical diameter at μ=25 mag/arcsec^2 isophote
(not robust measure of size -- varies with surface brightness)

Sometimes the HI extent is absurd

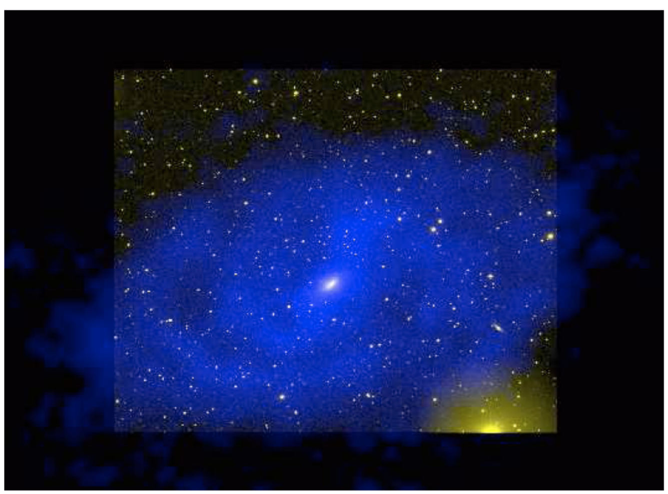
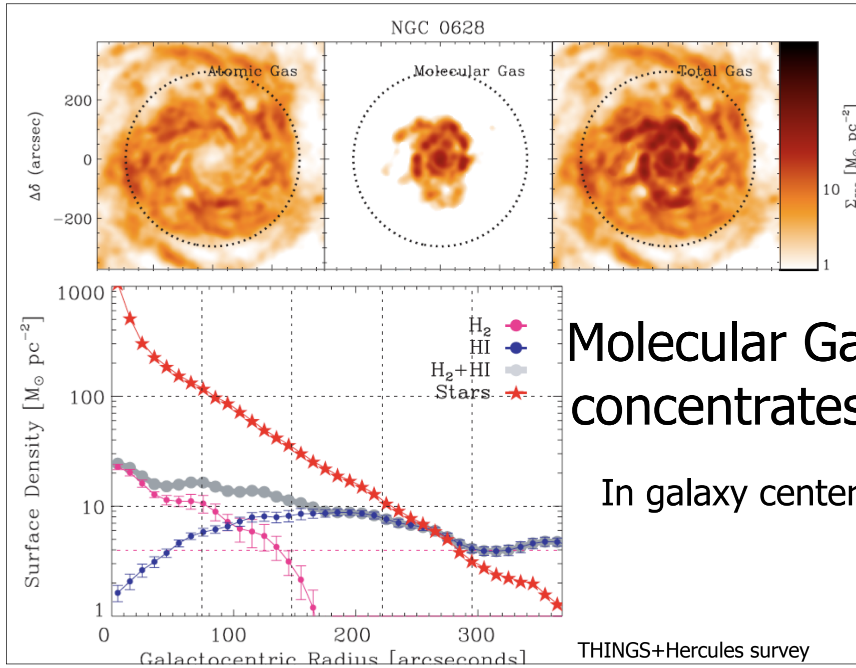


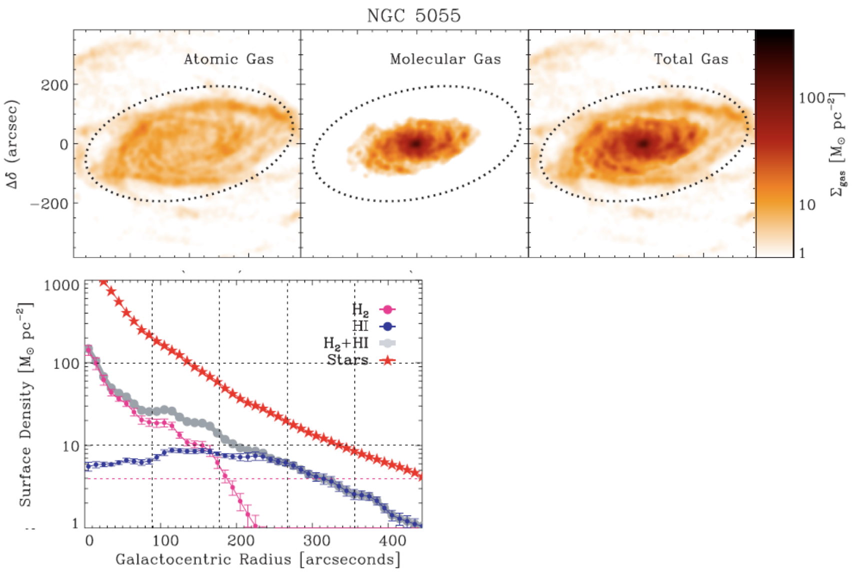
Fig. 9 Composite optical (yellow) and HI (blue) image of the dwarf galaxy NGC 2915 from Meurer et al. (1996) [81].



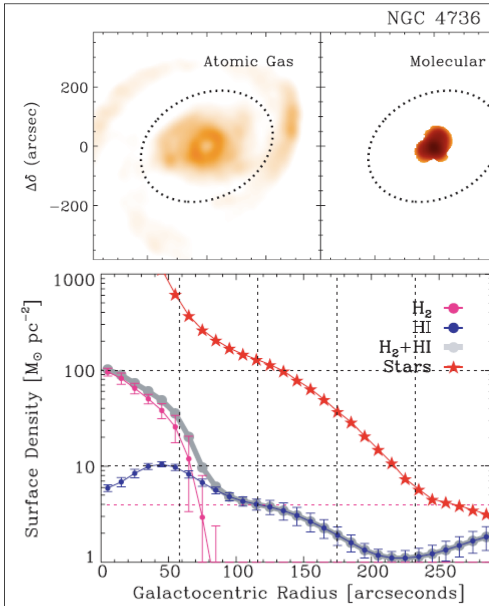
Molecular Gas concentrates:

In galaxy centers

THINGS+Hercules survey



THINGS+Hercules survey



Often reaches very high densities in galaxy centers.

THINGS+Hercules survey

Both phases concentrate in high density spiral arms

I_{CO}/I_{HI}

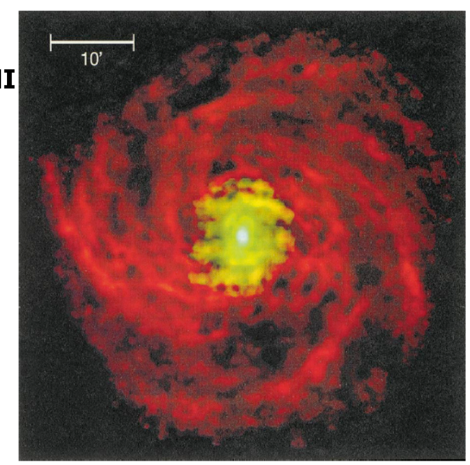
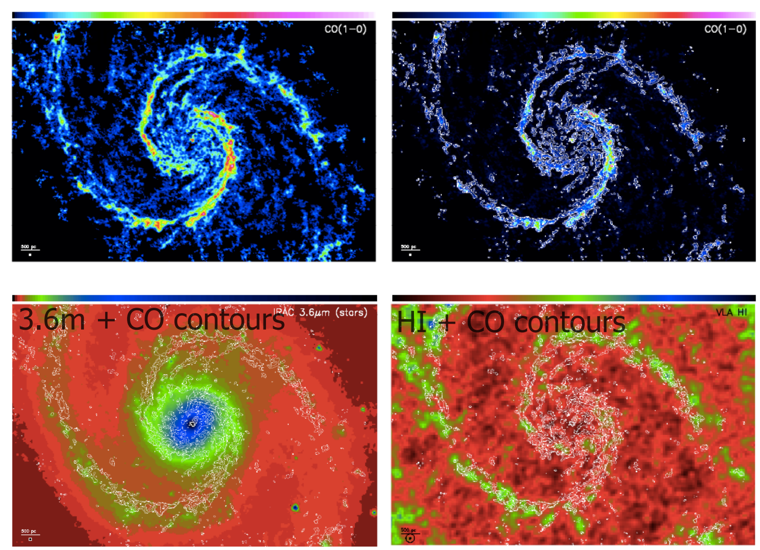


FIG. 4.—I_{CO}/I_{HI} comparison for IC 342. I_{CO} is shown in green. I_{CO} along the bar is also shown in blue in order to emphasize the molecular bar. I_{HI} is shown in red. Regions of I_{CO}/I_{HI} overlap, where the molecular and atomic gas phases are at similar surface densities ($2 \times N_{H_2} \sim N_{HI} \sim 10^{21}$ cm^{-2}), appear in yellow. The CO bar region has been enhanced by including blue color channel for $N_{H_2} > 2 \times 10^{21}$ cm^{-2}.

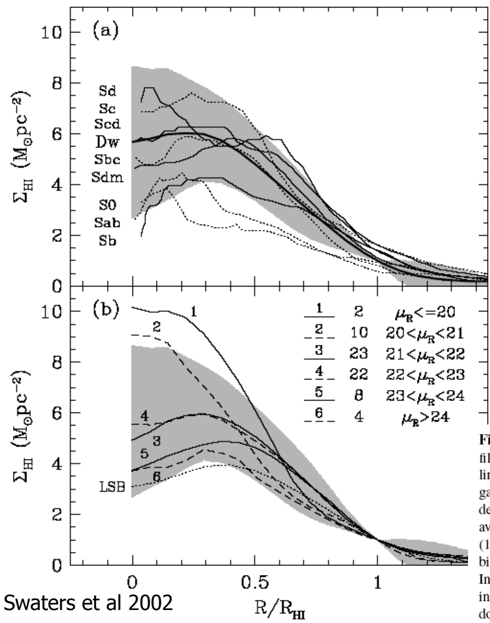
Crosthwaite et al 2001

High resolution/sensitivity M51:



Plateau de Bure: Schinnerer et al 2013

Central HI surface densities span a small range (3-9 $M_\odot/pc^2$, or ~$10^{20.5}$ atoms/cm^2)



Swaters et al 2002

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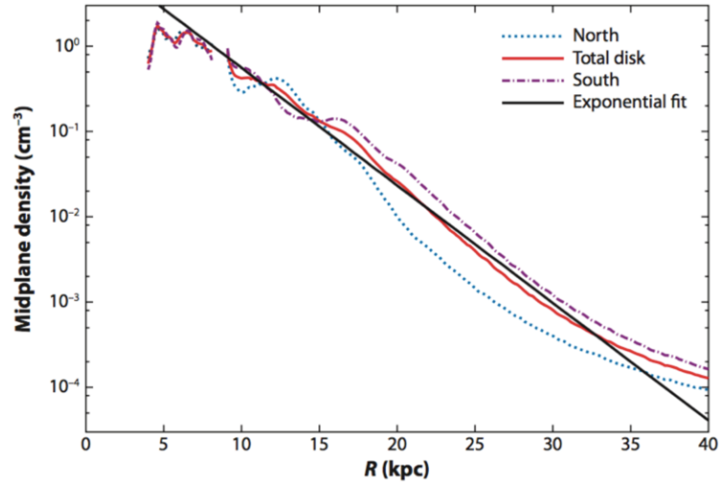
HI space densities < 1 n_H/cm^3



Kalberla & Kerp 2009 ARA&A

Average HI Surface Densities ($M_{HI}/\pi R_{HI}^2$)

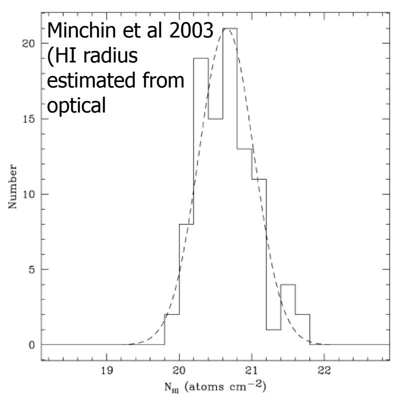
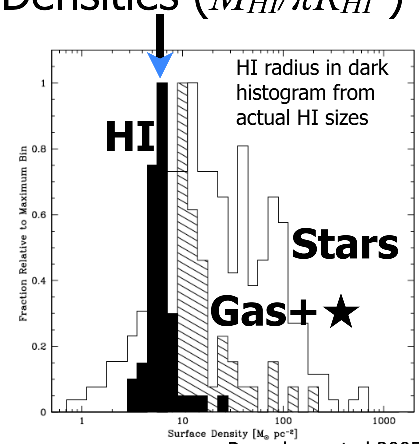


Figure 21. Distribution of inferred column densities of HIDEEP sources. The dashed line indicates a Gaussian with a mean of 20.65 and a scatter of 0.38. It can be seen that this is a fairly good description of the distribution.



Rosenberg et al 2005

FIG. 9.—Distribution of mass surface densities of gas, stars, and baryons. The gas surface densities, indicated by the dark-shaded histogram, come from the RS sample galaxies with measured H I sizes. The open histogram shows the stellar mass surface densities of the RS and SS galaxies using the *J*-band luminosity to estimate stellar mass and the *J*-band sizes. The total baryonic mass surface density (*hatched histogram*) is estimated using the sum of gas and stars and the optical size of each galaxy.

Very Narrow Distribution!

Why is HI Surface Density Range So Narrow?

Ionized by UV background?
"Spin Temperature Freeze Out"?

Disney 2008

Converts to H_2?
Ionized by SF?
Optically Thick?

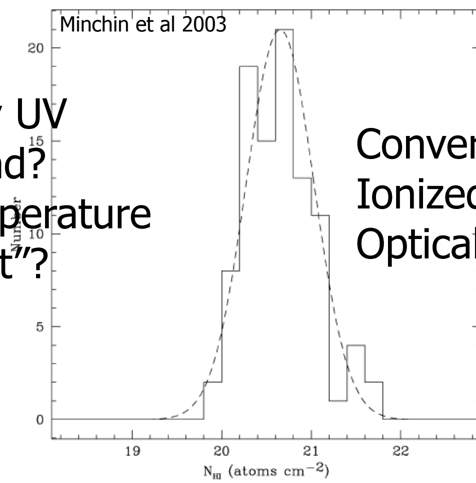


Figure 21. Distribution of inferred column densities of HIDEEP sources. The dashed line indicates a Gaussian with a mean of 20.65 and a scatter of 0.38. It can be seen that this is a fairly good description of the distribution.

N_{HI} varies with galaxy surface brightness

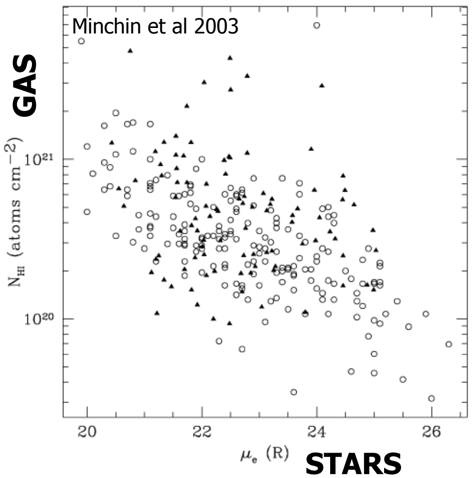
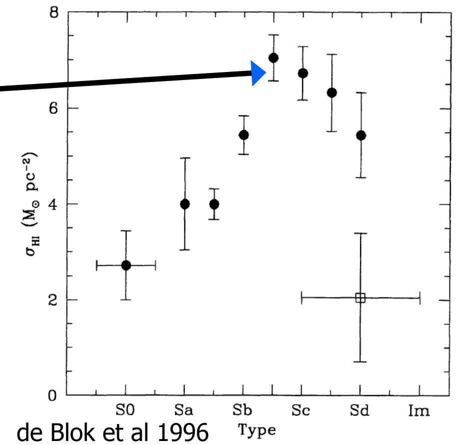


Figure 23. Comparison between the surface brightness–column-density distribution for HIDEEP (triangles) and Impey et al. (1996), converted to R band assuming $B - R = 1.1$ (open circles). Error bars have been omitted for the sake of clarity.

N_{HI} varies w/ Hubble Type

Peak HI surface density occurs in late-type spirals

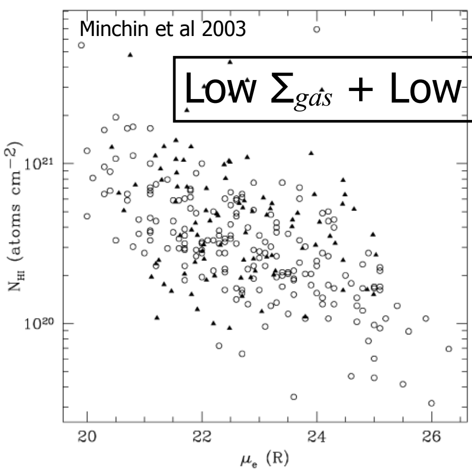


Why is there a peak?

de Blok et al 1996

Figure 4. LSB galaxies and their place in the Hubble-type – average H I surface density diagram. The average surface density is defined as the average surface density of the H I within half of the optical radius R_{25}. Filled circles are HSB galaxies from the sample of Cayatte et al. (1994). Vertical error bars are the 1σ errors in the mean. The open square represents our sample of LSB galaxies. Horizontal error bars denote the range in type in our sample; vertical error bars are 1σ deviations from the mean.

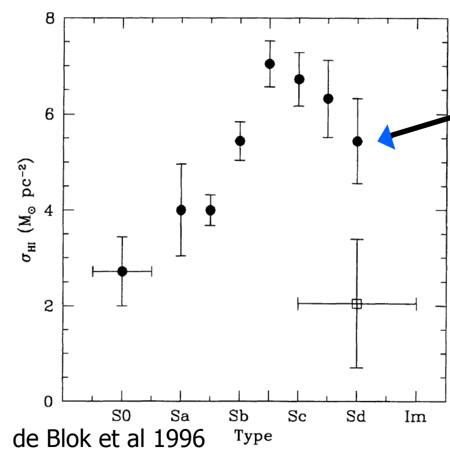
LSBs have low baryonic surface density



Low Σ_{gas} + Low Σ_{stars} → Low $\Sigma_{baryons}$

Figure 23. Comparison between the surface brightness–column-density distribution for HIDEEP (triangles) and Impey et al. (1996), converted to R band assuming $B - R = 1.1$ (open circles). Error bars have been omitted for the sake of clarity.

Low stellar surface densities are primarily due to low baryonic surface densities, not a failure to convert gas into stars.



Falls because baryonic disk has lower surface density

de Blok et al 1996

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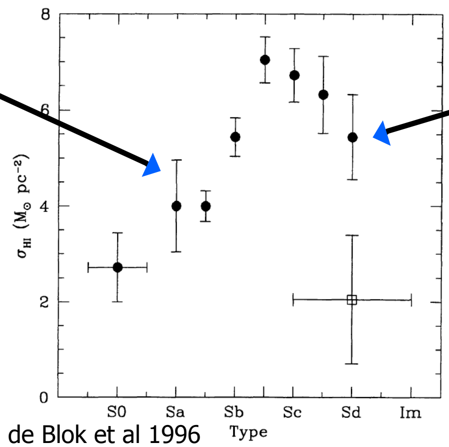
Falls because gas has been used up making stars or ejected. Also, higher fraction of molecular gas.



Falls because disks have lower baryonic surface density

de Blok et al 1996

Figure 4. LSB galaxies and their place in the Hubble-type – average H I surface density diagram. The average surface density is defined as the average surface density of the H I within half of the optical radius R_{25}. Filled circles are HSB galaxies from the sample of Cayatte et al. (1994). Vertical error bars are the 1σ errors in the mean. The open square represents our sample of LSB galaxies. Horizontal error bars denote the range in type in our sample; vertical error bars are 1σ deviations from the mean.

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HI Velocity dispersion

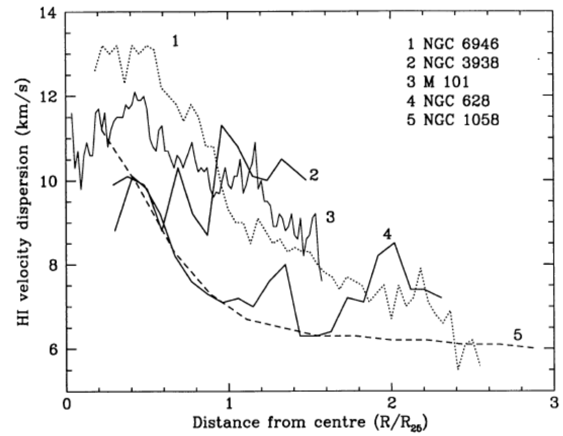


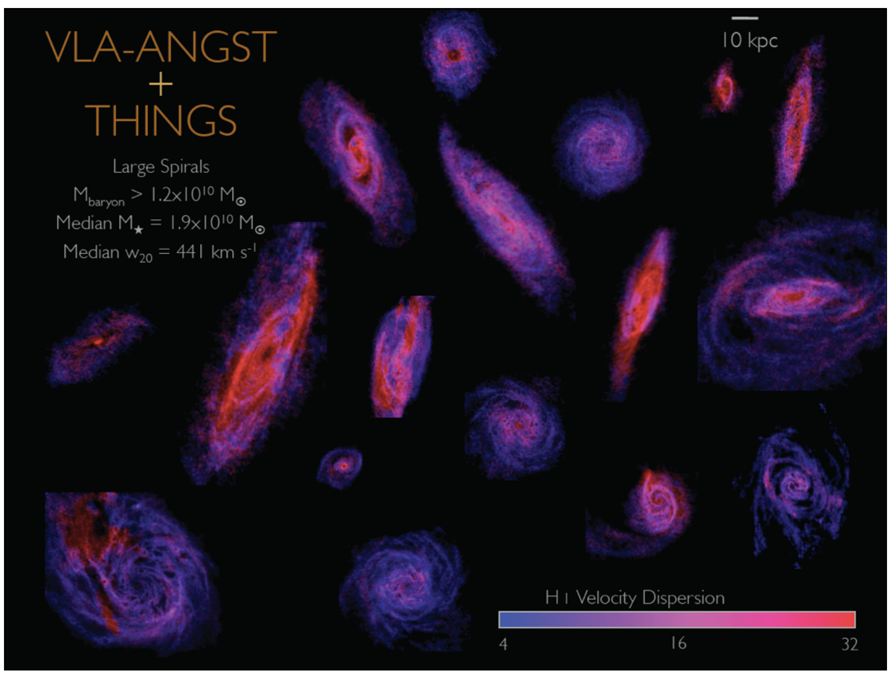
Figure 22. Azimuthally averaged HI velocity dispersion as a function of normalized galactocentric radius in 5 face-on galaxies.

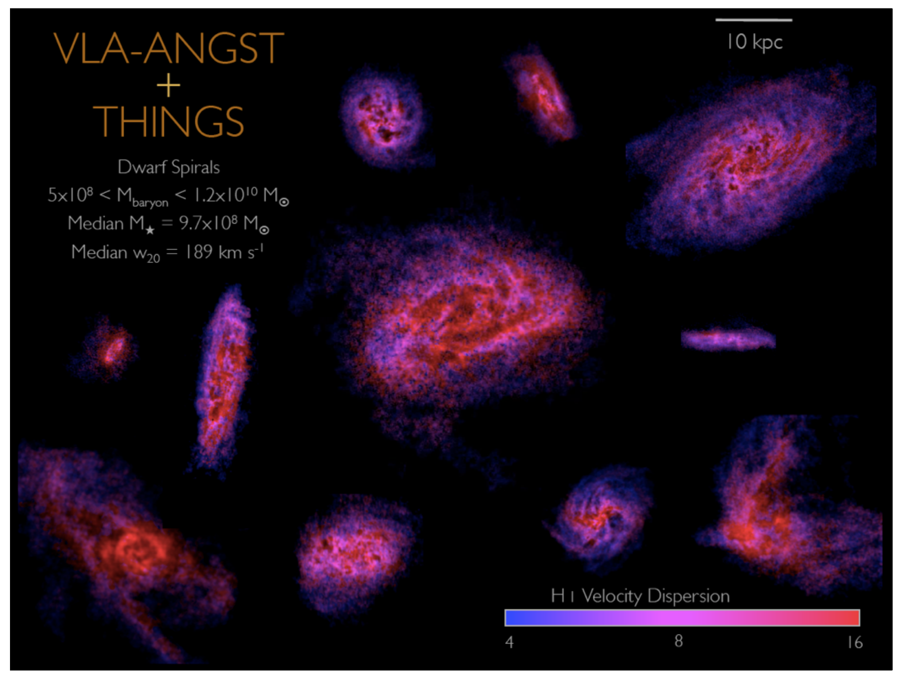
10-20 km/s in center, then declines

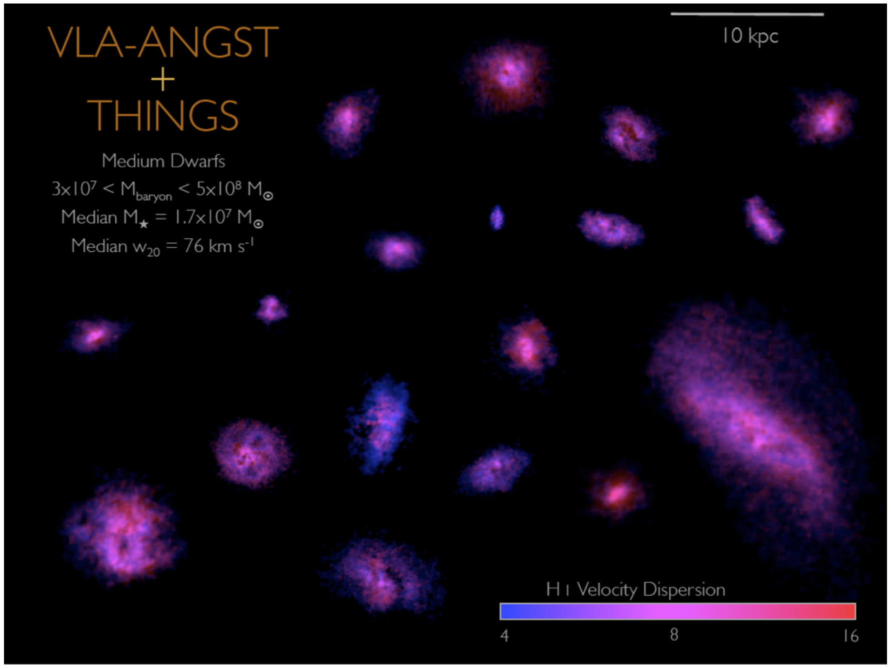
Implies dynamical pressure >> thermal pressure

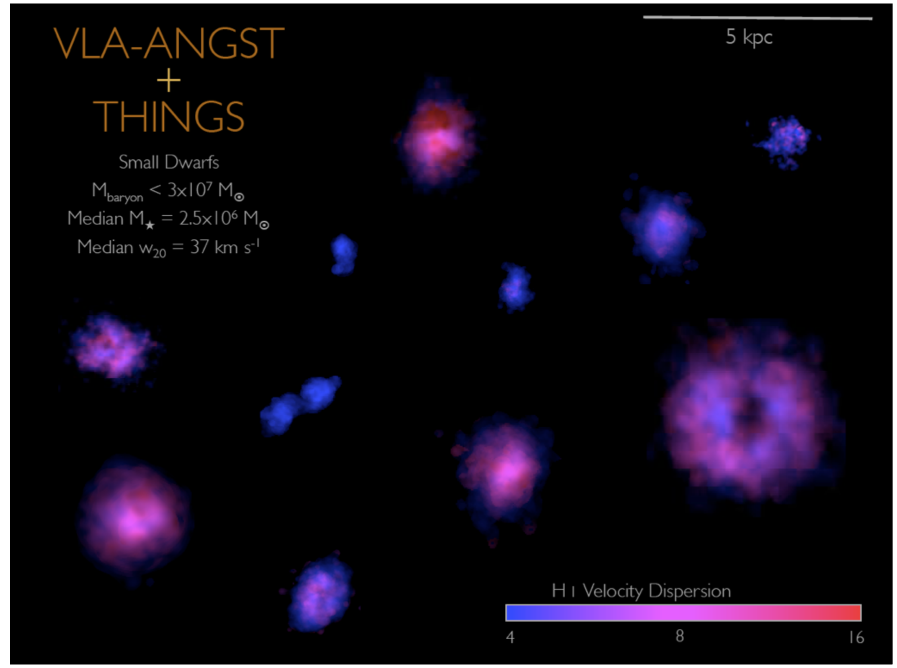
Disk supported vertically by turbulence

42 Van der Hulst 1996









What Sets Velocity Dispersion?

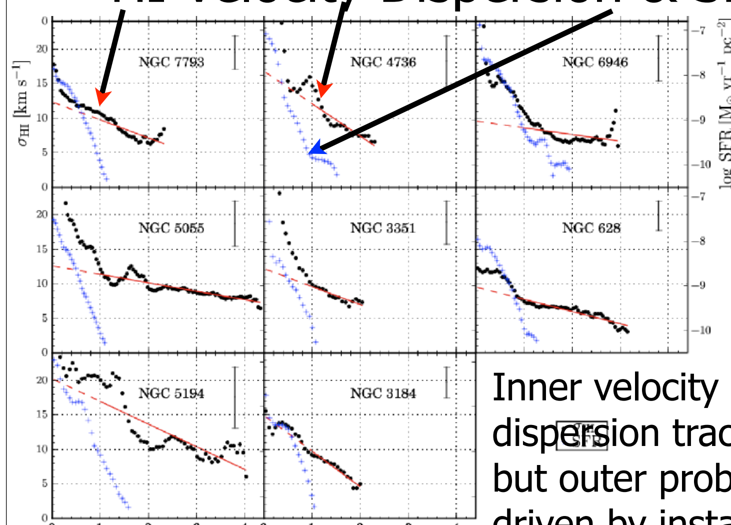
Velocity dispersion is manifestation of turbulence.

Turbulence decays quickly.

Must be source of energy to continually drive turbulence.

- Gravitational instabilities
- Magneto-rotational instabilities ("MRI")
- Star formation feedback

HI Velocity Dispersion & SFR



Inner velocity dispersion tracks SF, but outer probably driven by instabilities.

Tamburro et al 2009

FIG. 1.— Radial profiles of HI velocity dispersion, σ_{HI}, for the galaxies of our sample (§ 4.1). The filled circles represent azimuthal averages of σ_{HI} calculated from the second moment (Eq. 3) as a function of radius r in units of r_{25}. The error bar on the top right of each panel shows the average standard deviation of azimuthal scatter of σ_{HI}. The blue crosses denote the radial profiles of $\log \Sigma_{SFR}$ with the scale indicated on the right side of the plot. Here, only those values above the noise threshold ($\log \Sigma_{SFR}/[M_\odot\ yr^{-1}\ pc^{-2}] \geq -10$) are plotted (§ 3.4). The labeled galaxies are sorted by increasing dynamical mass (v_{max} de Blok et al. 2008; Tamburro et al. 2008).

Demographics of Cold Gas

Most typically traced with HI

Tracks reservoir readily available for forming stars

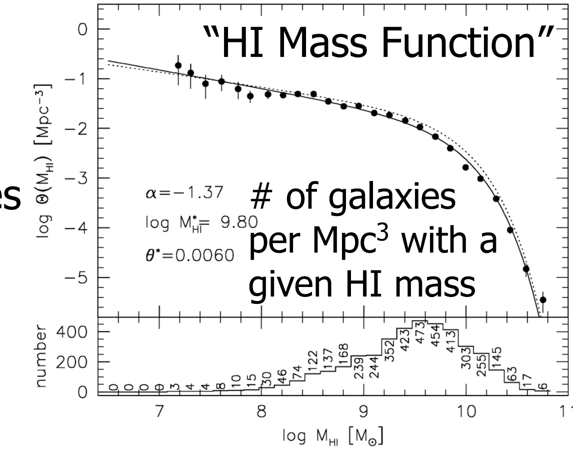
When compared to stellar or baryonic mass ("gas fraction"), informs evolutionary state

How Much HI is there?

Lots of galaxies with small HI masses (dwarfs)

Integrated density in HI is small

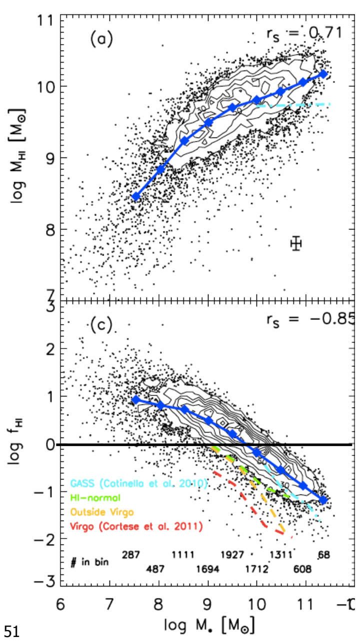
"HI Mass Function"



# of galaxies per Mpc^3 with a given HI mass

Figure 1. Top: H I mass function from HICAT. The solid line is a Schechter fit to the points; the best-fitting parameters are shown in the lower left corner. Bottom: distribution of H I masses used for the HIMF calculation.

$$\Omega_{\rm HI} = (3.5 \pm 0.4 \pm 0.4) \times 10^{-4}$$



How does HI content vary among galaxies?

High mass galaxies have more HI

Low mass galaxies have a higher fraction of HI

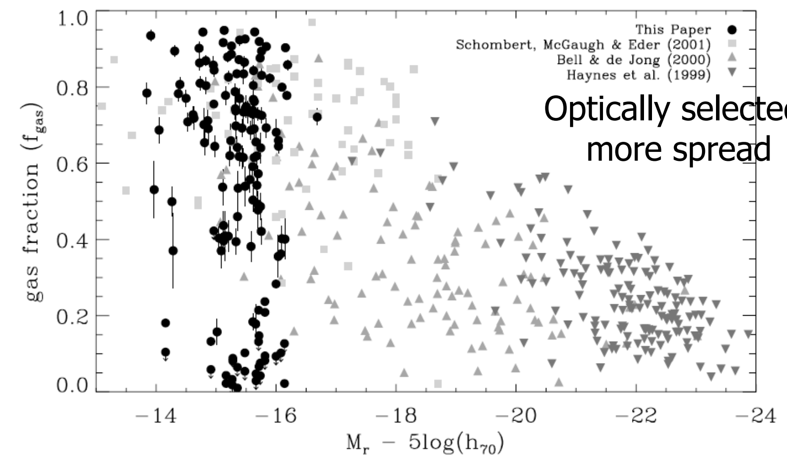
$$f_{\rm HI} = M_{\rm HI}/M_*$$

Editoral Note: I think this is a much sillier way to talk about gas mass fractions than M_HI/(M_HI+M_star)

HI selected, so biased for gas rich

ALFALFA+SDSS+GALEX: Huang et al 2012

Gas mass fraction ($f_g = M_{gas}/M_{baryon}$)



Optically selected: more spread

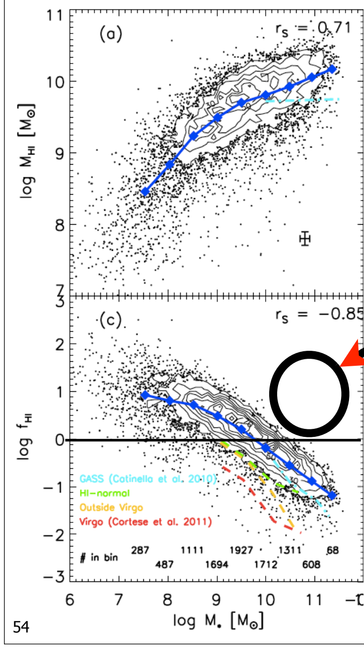
Geha et al 2006

FIG. 3.— Gas fraction, $f_{\rm gas} = M_{\rm gas}/(M_{\rm gas} + M_{\rm star})$, plotted as a function of absolute r-band magnitude. The majority of dwarf galaxies in this paper (*circles*) are dominated by the gas mass, rather than the stellar mass, with gas fractions as high as 95%. Galaxies that were not detected in H I are plotted as upper limits. Objects with the same baryonic mass lie on tracks that run from the lower left to the upper right in this figure. For comparison, we plot data from Schombert et al. (2001; *squares*), Bell & de Jong (2000; *upward-pointing triangles*), and Haynes et al. (1999; *downward-pointing triangles*). We infer from this plot that, compared to more luminous galaxies, dwarf galaxies are far less efficient at turning gas into stars over their lifetimes.

Traditionally used M_{HI}/L_B as measure of M_{gas}/M_{stars}.

Why might gas fraction vary?

- Variation in star formation efficiency
  - low density gas converts to stars more slowly
- Variation in gas expulsion/stripping
  - efficiency of feedback (AGN or SN)
  - environment
- Variation in recent accretion history



How does HI content vary among galaxies?

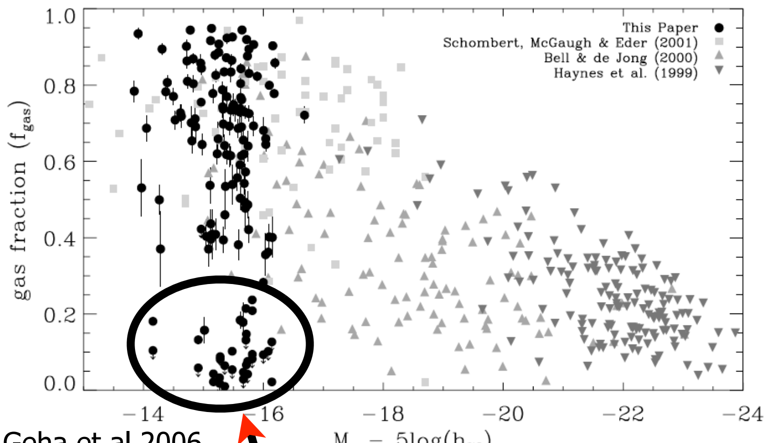
Essentially no gas rich massive galaxies

$$f_{\rm H\,I} = M_{\rm H\,I}/M_*$$

HI selected, so biased for gas rich

ALFALFA+SDSS+GALEX: Huang et al 2012

Big spread in gas richness of dwarfs

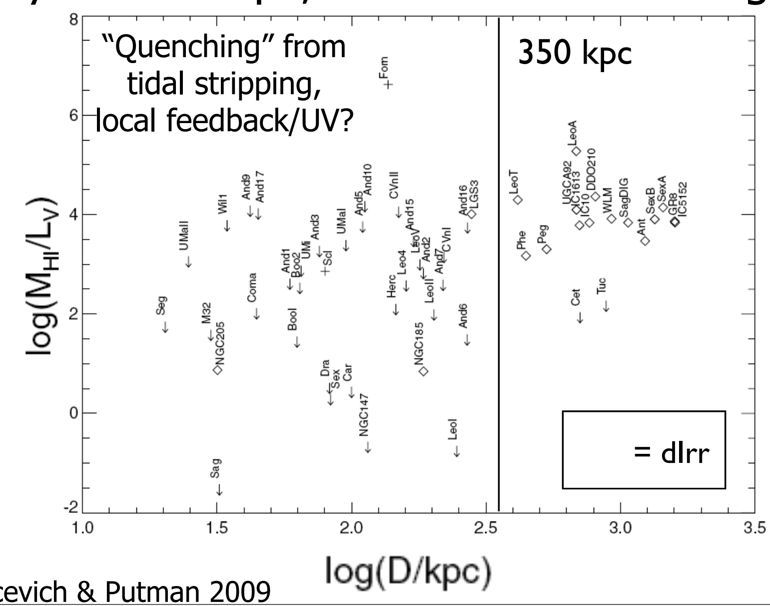


Geha et al 2006

FIG. 3.— Gas fraction, $f_{gas} = M_{gas}/(M_{gas} + M_{star})$, plotted as a function of absolute *r*-band magnitude. The majority of dwarf galaxies in this paper (*circles*) are dominated by the gas mass, rather than the stellar mass, with gas fractions as high as 95%. Galaxies that were not detected in H I are plotted as upper limits. Objects with the same baryonic mass lie on tracks that run from the lower left to the upper right in this figure. For comparison, we plot data from Schombert et al. (2001; *squares*), Bell & de Jong (2000; *upward-pointing triangles*), and Haynes et al. (1999; *downward-pointing triangles*). We infer from this plot that, compared to more luminous galaxies, dwarf galaxies are far less efficient at turning gas into stars over their lifetimes.

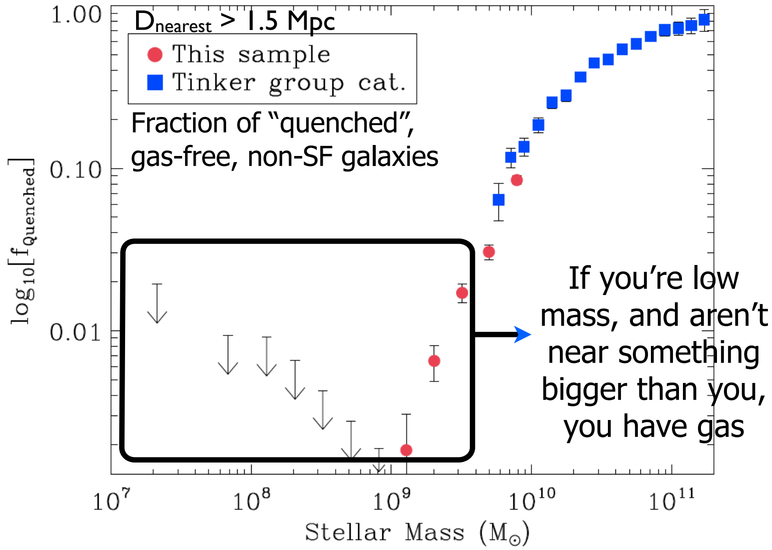
Most of these are in dense environments

Beyond 350 kpc, all MW dwarfs have gas



Grcevich & Putman 2009

All Field/Central Dwarfs have gas



Geha et al 2012

Gas Rich Galaxies: Low M_{star} & Blue

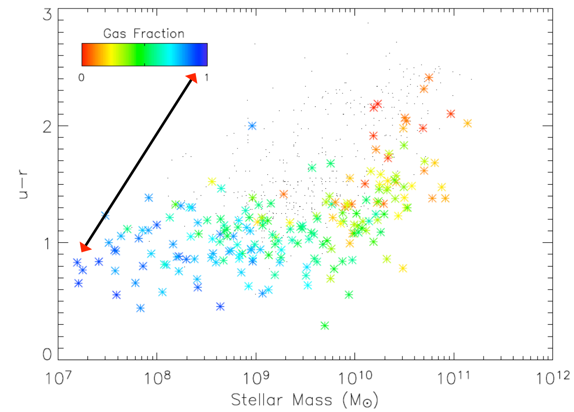
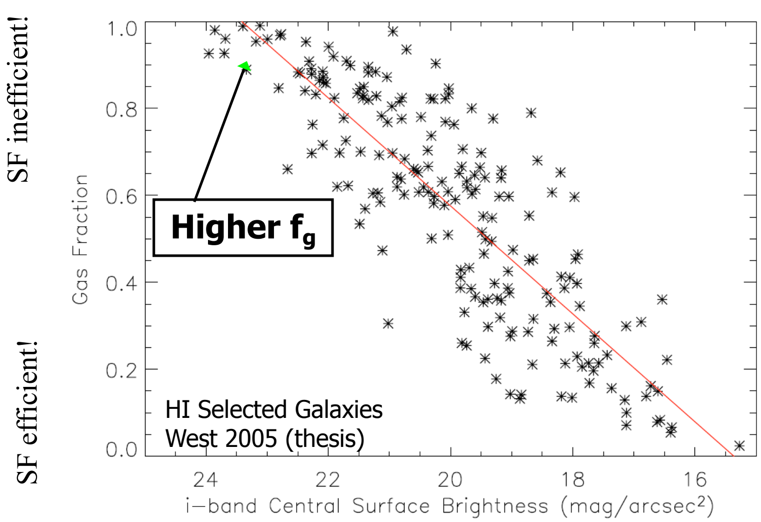


Figure 5.1 $u - r$ color as a function of stellar mass. HI selected galaxies have been color coded according to their gas fraction. The black dots are a volume limited sample from SDSS DR4. All photometric corrections have been applied to the data. The HI selected galaxies are slightly bluer and extend to lower stellar masses than many of their SDSS counterparts.

Inefficient SF means that SF can still be going on today. Lots of gas left with which to make young blue stars

Gas Richness Correlates with Surface Density



HI as a tracer of weird stuff

Can trace mass distributions that haven't formed stars.

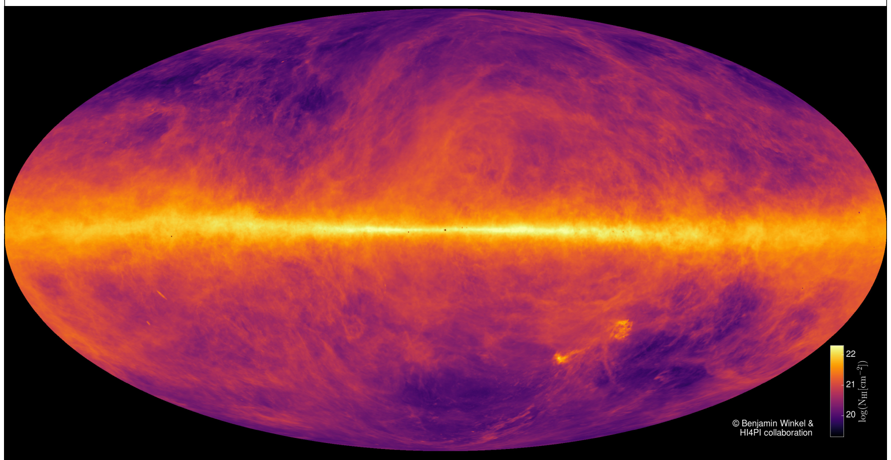
Extended, so easier to tidally disrupt than stars

Good tracer of past interactions

Good tracer of on-going accretion

HI in Unusual Places:

High Latitude HI Emission

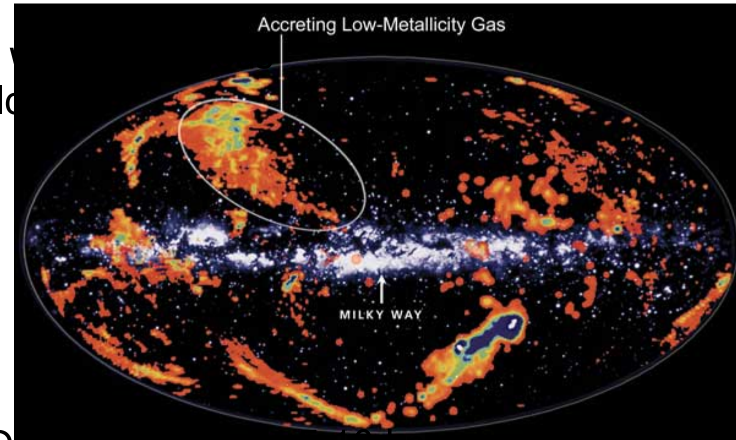


All-sky HI map

High-velocity clouds (HVCs)

HI v
velo

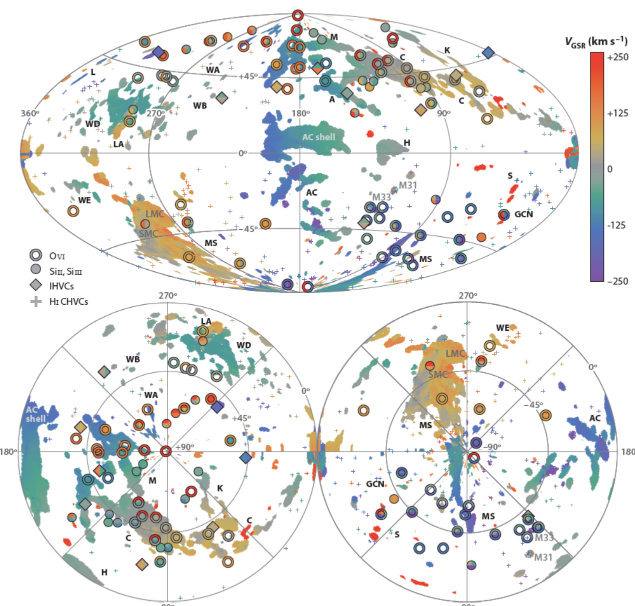
by
l 2012



- Distances likely z~5-10 kpc above the plane (except "magellanic stream")
- Origins varied: Outflow? Infall? Tidal debris?
- Metallicities between 0.1-1 solar

Comparison between HVCs and absorption lines

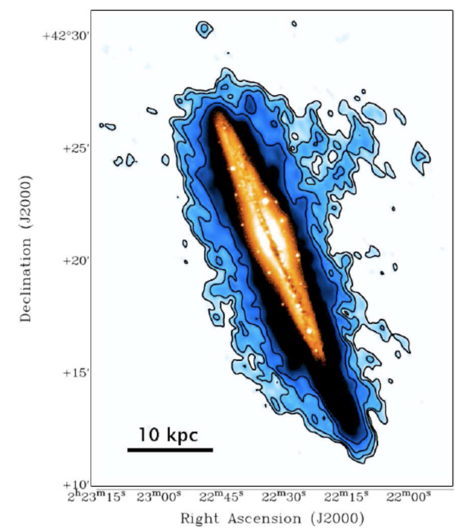
- High Velocity ionized gas at poles (outflow?).
- Rest of ionized gas seems associated w/ HI



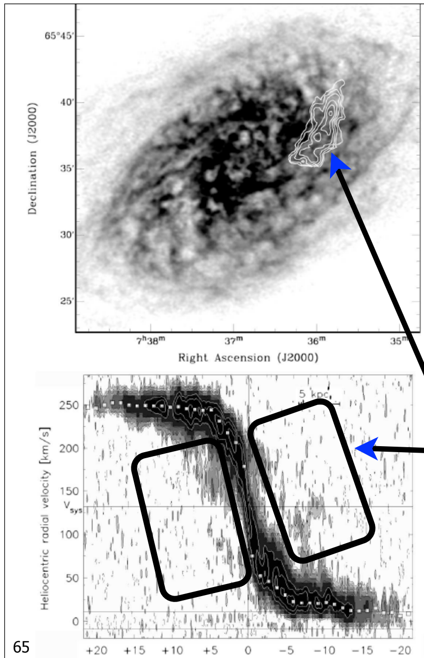
Putnam, M.E. et al. 2012. Annu. Rev. Astron. Astrophys. 50:491–529.

Putnam et al 2012

Some (not all) other galaxies show high-latitude HI



NGC 891



Can be detected kinematically

Extra gas that does not follow expectation for a rotating disk

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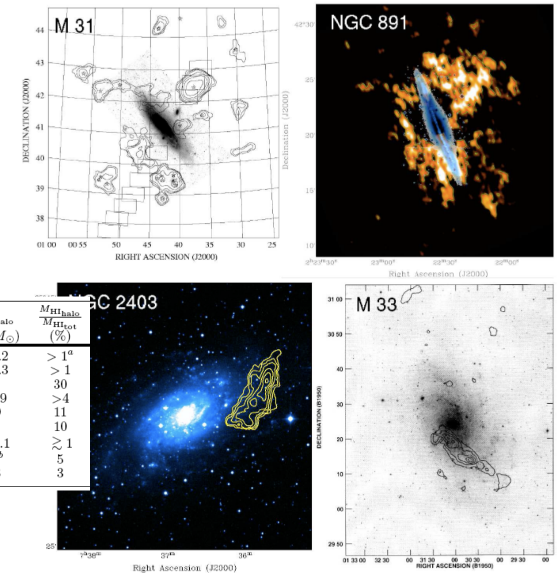
High Velocity Gas in other galaxies

Galaxy	Type	incl (deg)	v_{flat} ($km\,s^{-1}$)	$M_{HI_{halo}}$ ($10^8\,M_\odot$)	$\frac{M_{HI_{halo}}}{M_{HI_{tot}}}$ (%)
Milky Way	Sb	-	220	> 0.2	> 1^a
M 31	Sb	77	226	> 0.3	> 1
NGC 891	Sb	90	230	12	30
NGC 6946	Scd	38	175	>2.9	>4
NGC 4559	Scd	67	120	5.9	11
NGC 2403	Scd	63	130	3	10
UGC 7321	Sd	88	110	$\gtrsim$ 0.1	$\gtrsim$ 1
NGC 2613	Sb	~80	~300	4.4^b	5
NGC 253	Sc	~75	~185	0.8	3



Accreted?
Ejected?

Fig. 7 Examples of extra-planar gas complexes around nearby galaxies. From top: High-Velocity Clouds in the Milky Way, extra-planar gas features in M 31 and NGC 891. The bottom panels show two massive H I filaments in NGC 2403 and M 33.

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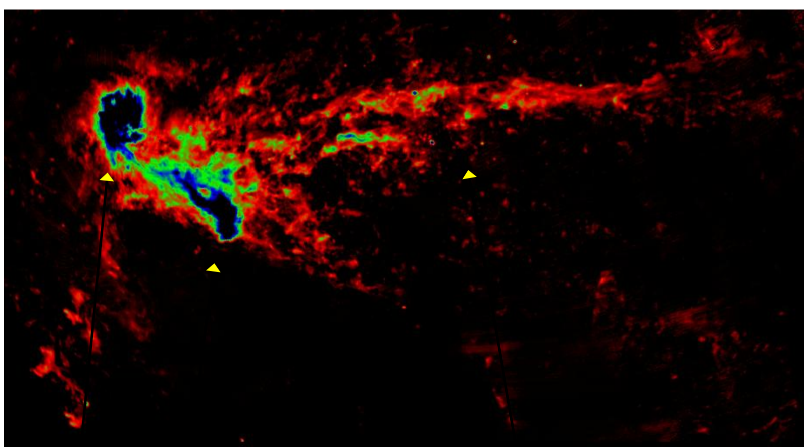
Tidally Stripped Gas



LMC/SMC in HI: "Magellanic Stream"

Putnam et al

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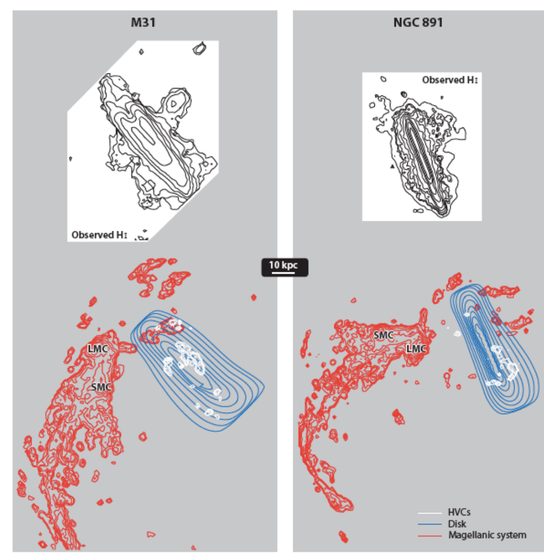
Magellanic Stream very different than HVCs

Comparison w/ MW viewed at same scale & inclination



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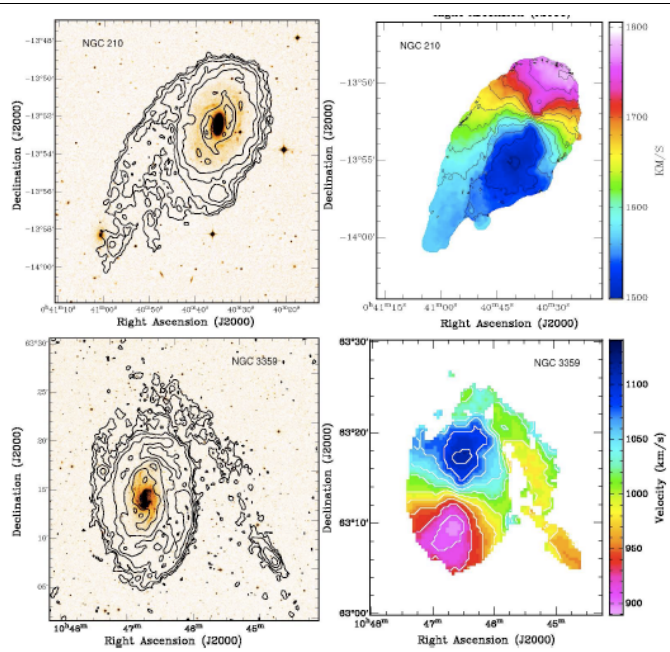
HI as tracer of interactions

HI's larger extent makes it less tightly bound and more susceptible to tidal disruption

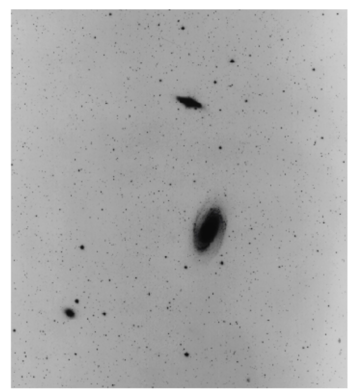
HI (blue) on 2MASS image: Koribalski

http://ned.ipac.caltech.edu/level5/Sept11/Duc/Duc4.html

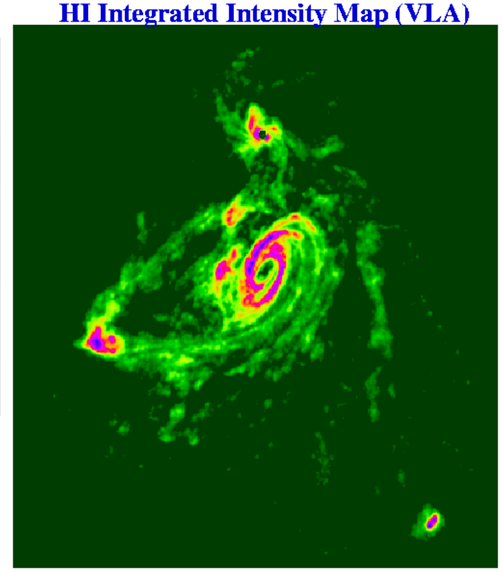


HI Tidal Signature in the M81 Group

Optical Image (DSS)



HI Integrated Intensity Map (VLA)



VLA 12-beam mosaic
from M. S. Yun
(see Yun et al. 1994)

HI observations of unusual E's