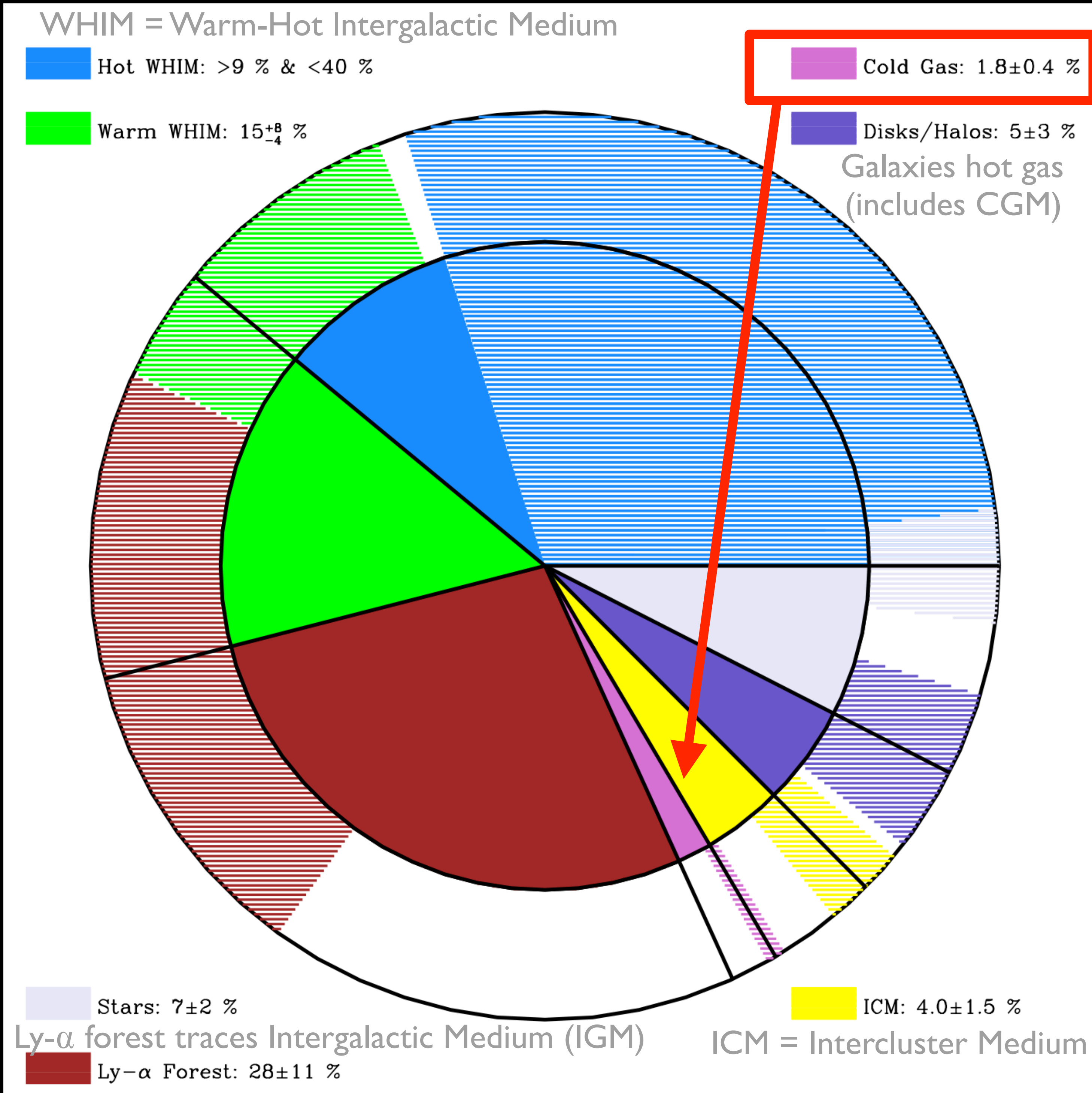
Galaxies in Equilibrium: Gaseous Disks

First, some overall context.

Note: This is the ugliest data viz ever.



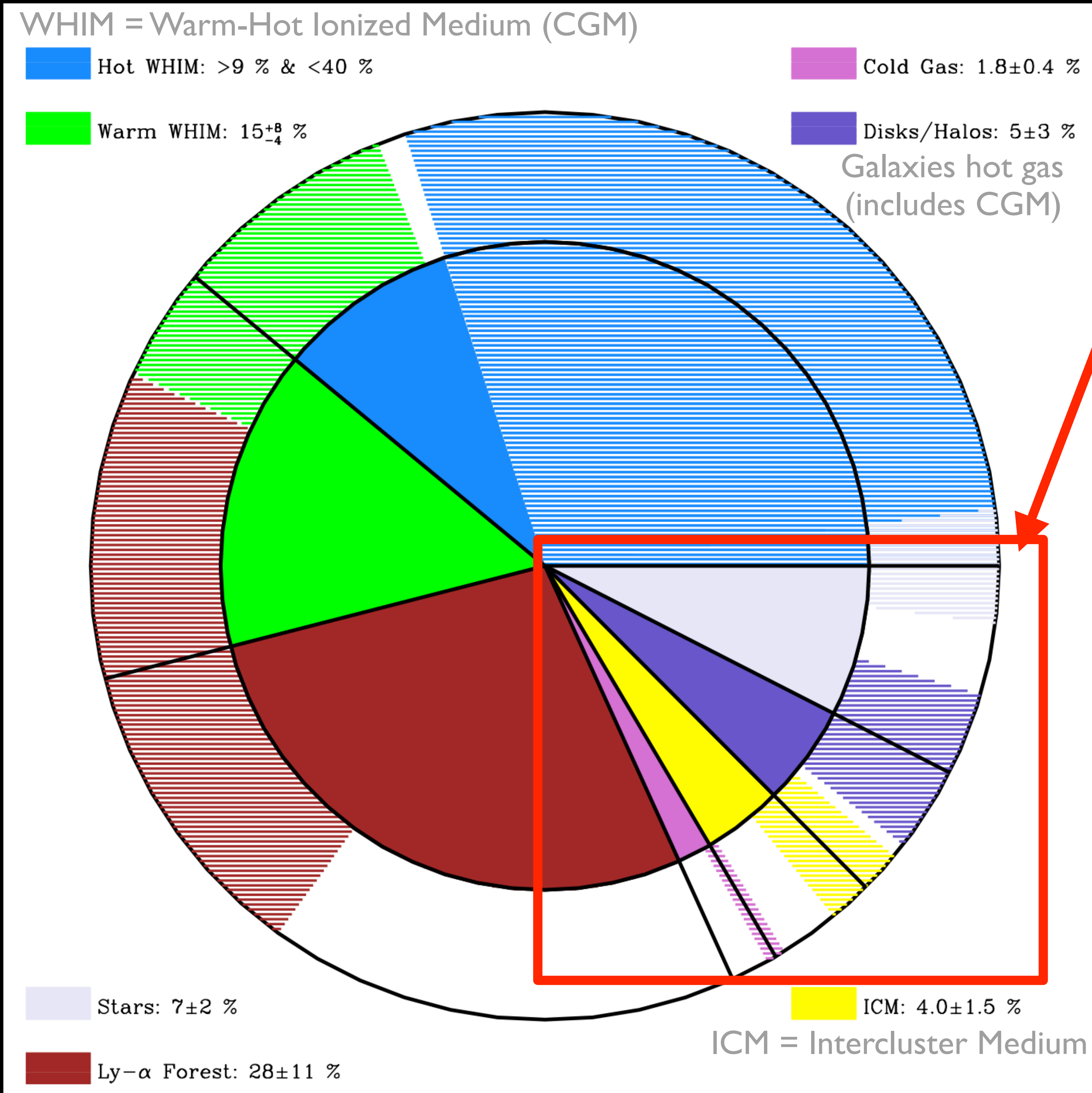
Gaseous disks: tiny fraction of the baryon budget today

Most low-z baryons probably in CGM/IGM

IGM Systematics:

- EUV radiation field
- Oxygen metallicity
- Ioniz corrections
- Cloud geometry

Nicastro et al 2018; see also Shull et al 2012



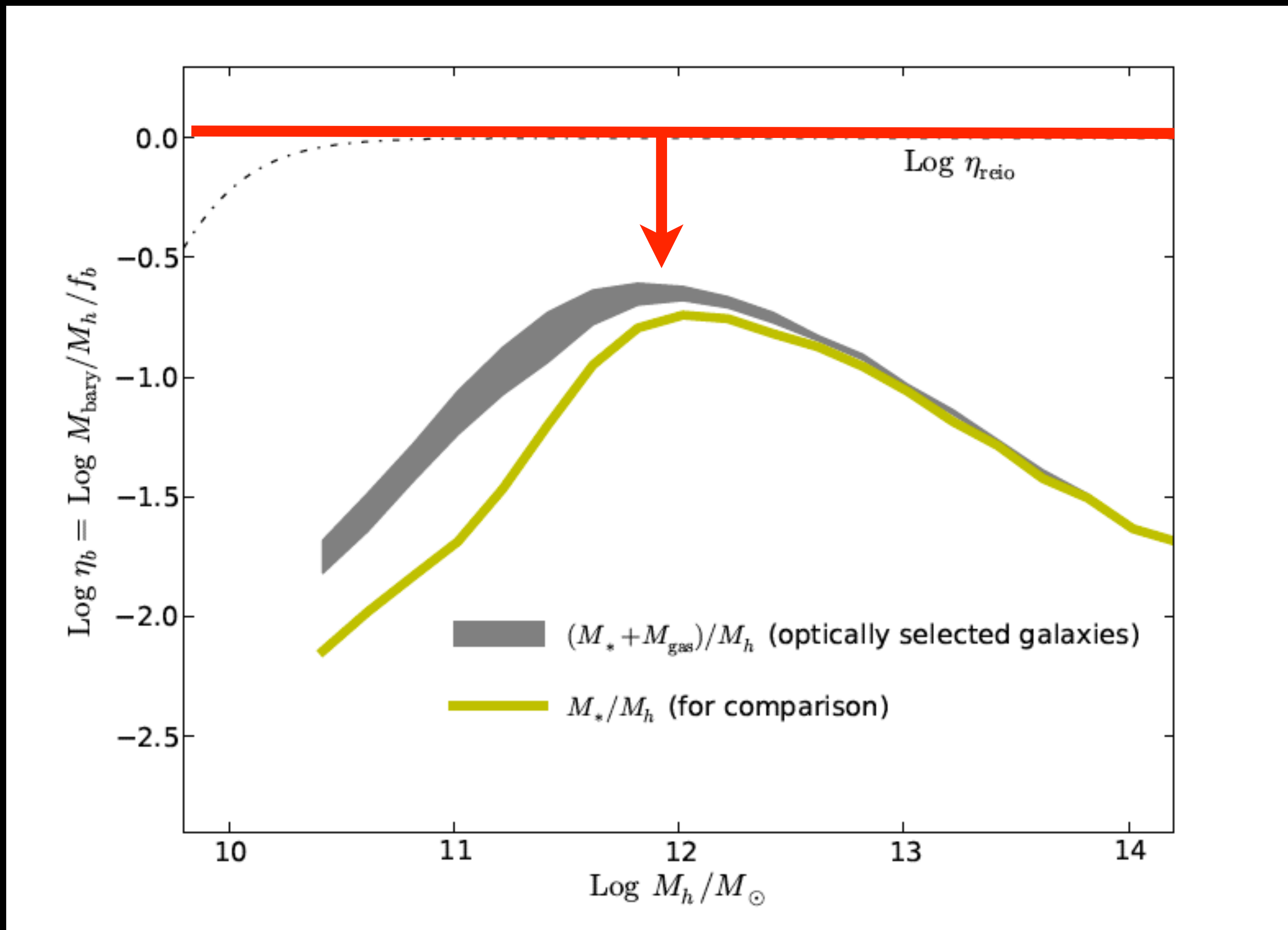
Even including stars and CGM and material stripped from galaxies in massive clusters doesn't help

IGM Systematics:

- EUV radiation field
- Oxygen metallicity
- Ioniz corrections
- Cloud geometry

Nicastro et al 2018; see also Shull et al 2012

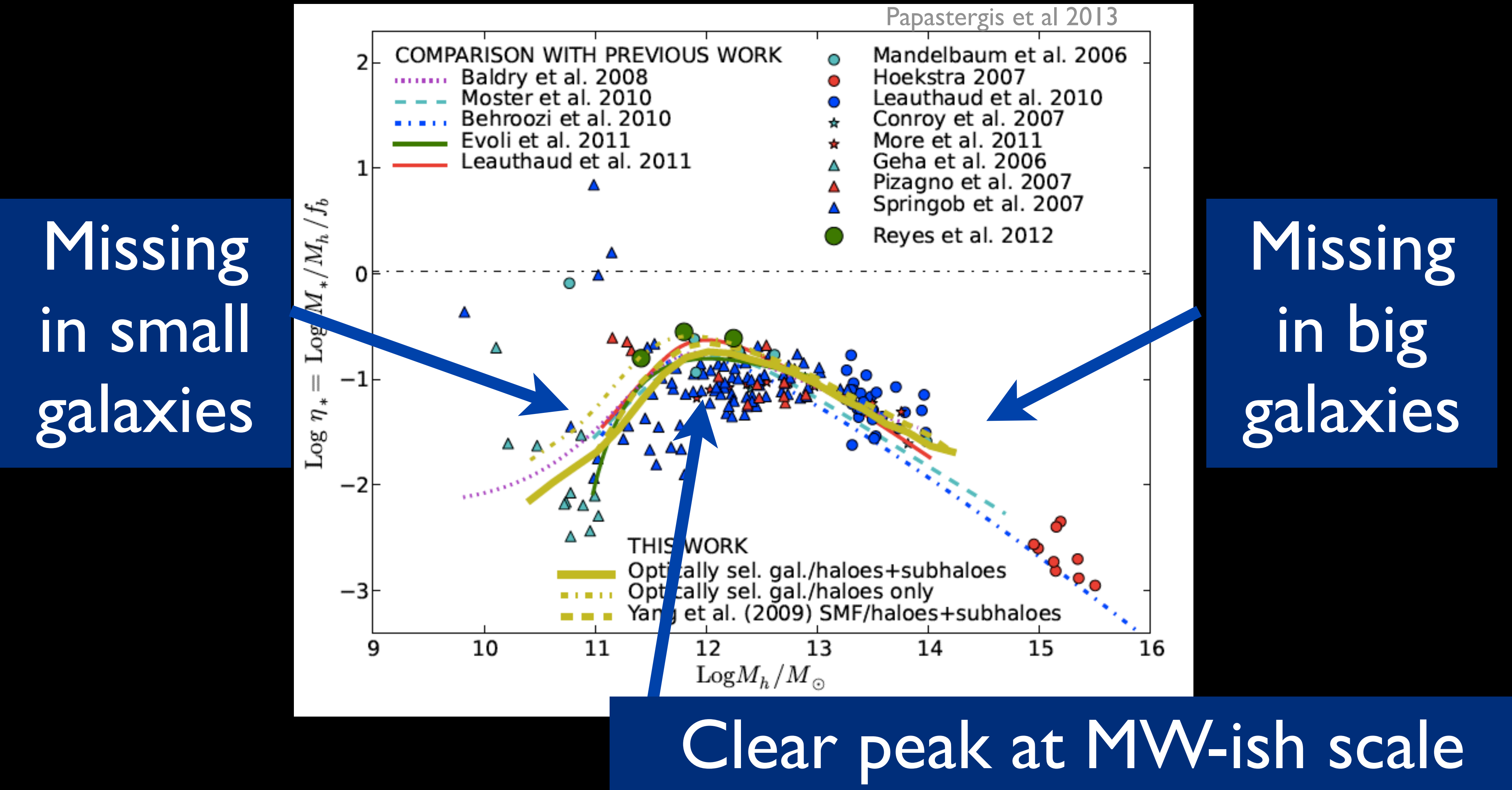
The baryon fraction of galaxies (gas+stars/total) is below the cosmic mean ($f_b = \Omega_b/\Omega_m \approx 0.16$)



Papastergis et al 2012

The amount below the mean depends on galaxy mass

Baryon fractions ≲20% of global f_b



Either the baryons never came in, or they came in and went out....

Why talk about such a puny component?

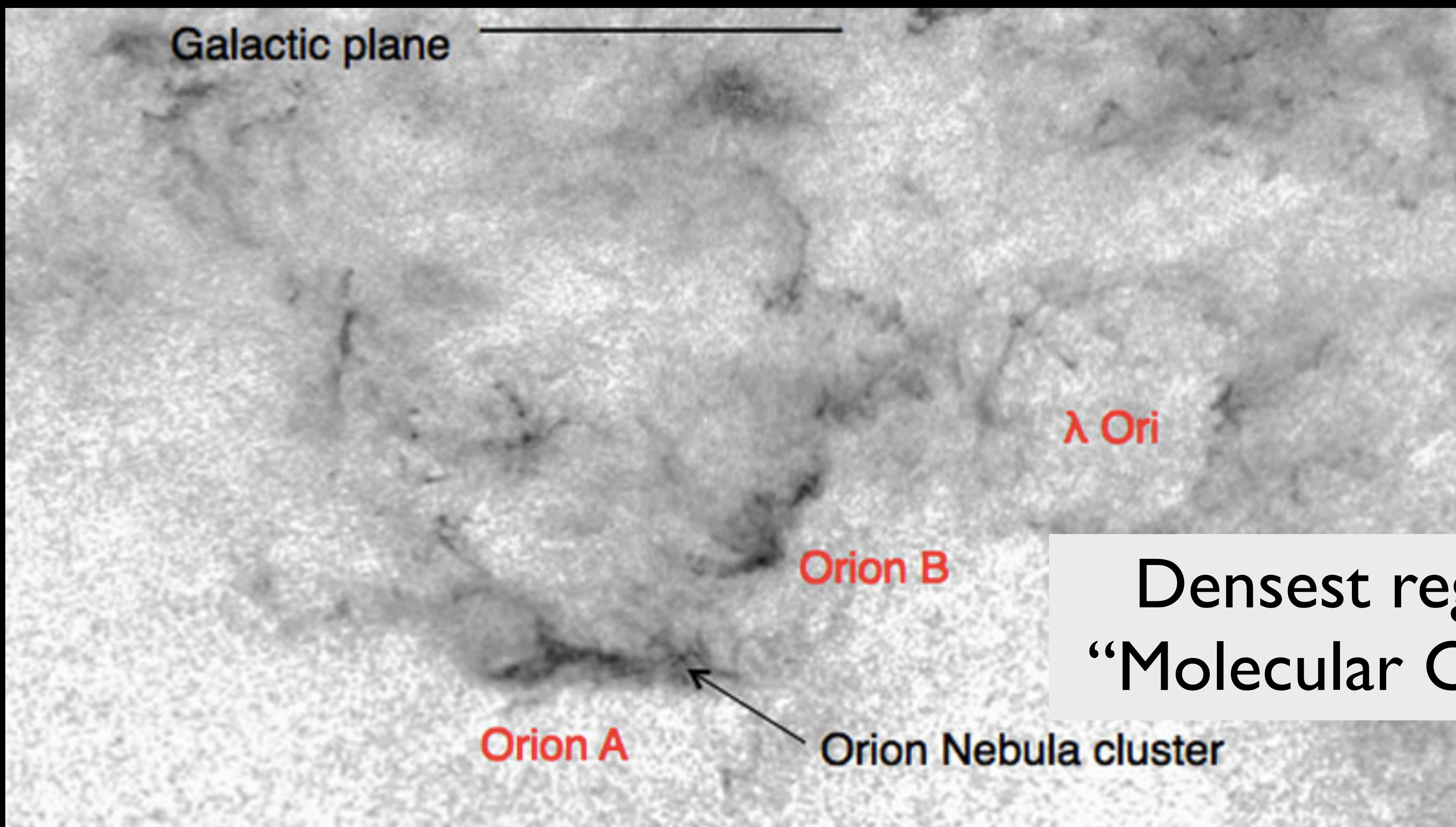
- Immediate fuel for star formation
- Short dynamical time, so responds rapidly to pertubations
- Excellent kinematic tracer
- Cold reservoirs easy to detect
- Reflects past baryon accretion history
- Properties reflect baryonic “feedback”

We will focus on largely-equilibrium structures observed *at the present*

But, given that the universe starts with all baryons in nearly uniformly distributed gas, evolution with redshift will be substantial.

Fundamentals of cool gas

1. The cool ISM is highly turbulent
   - <u>Not</u> a smooth slab of gas

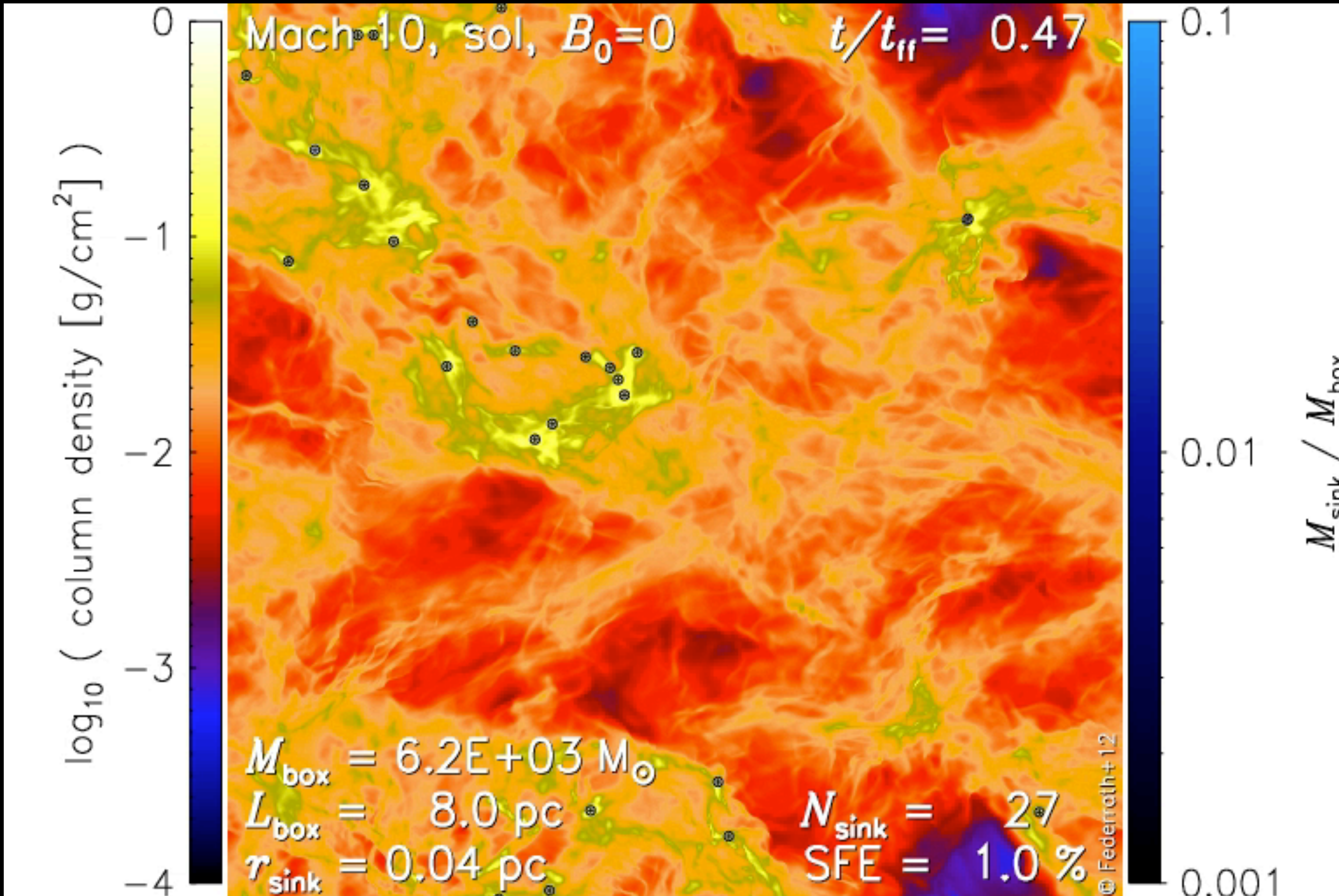


Rowles & Froebrich 2009

Densest regions: "Molecular Clouds"

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

Simulation of turbulence+SF



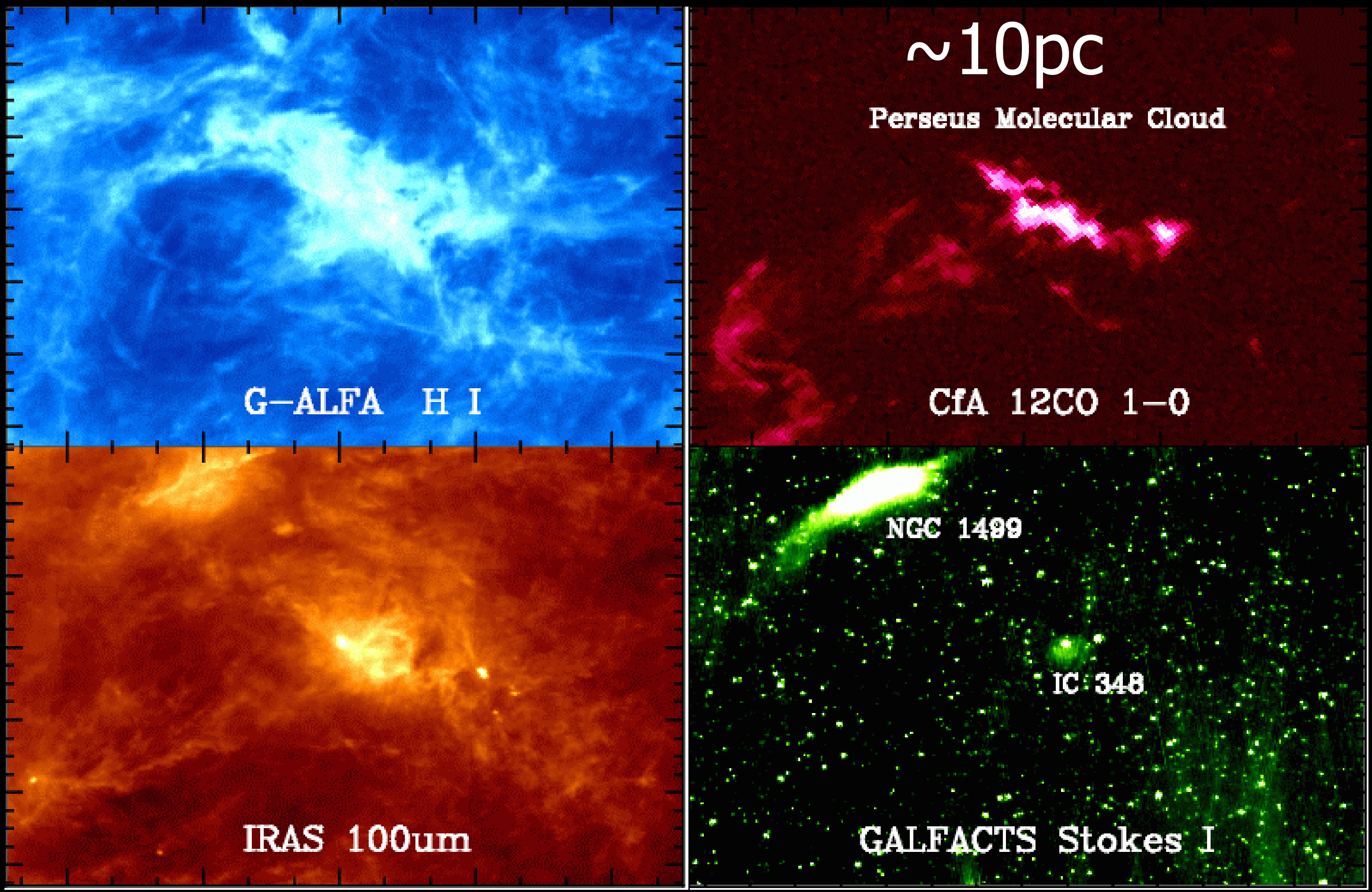
Federrath et al 2012

Major question: What drives turbulence?

Fundamentals of cool gas

2. The ISM is "multiphase" even on small scales

HI



CO

thermal black-body emission from warm dust

continuum emission from ionized gas

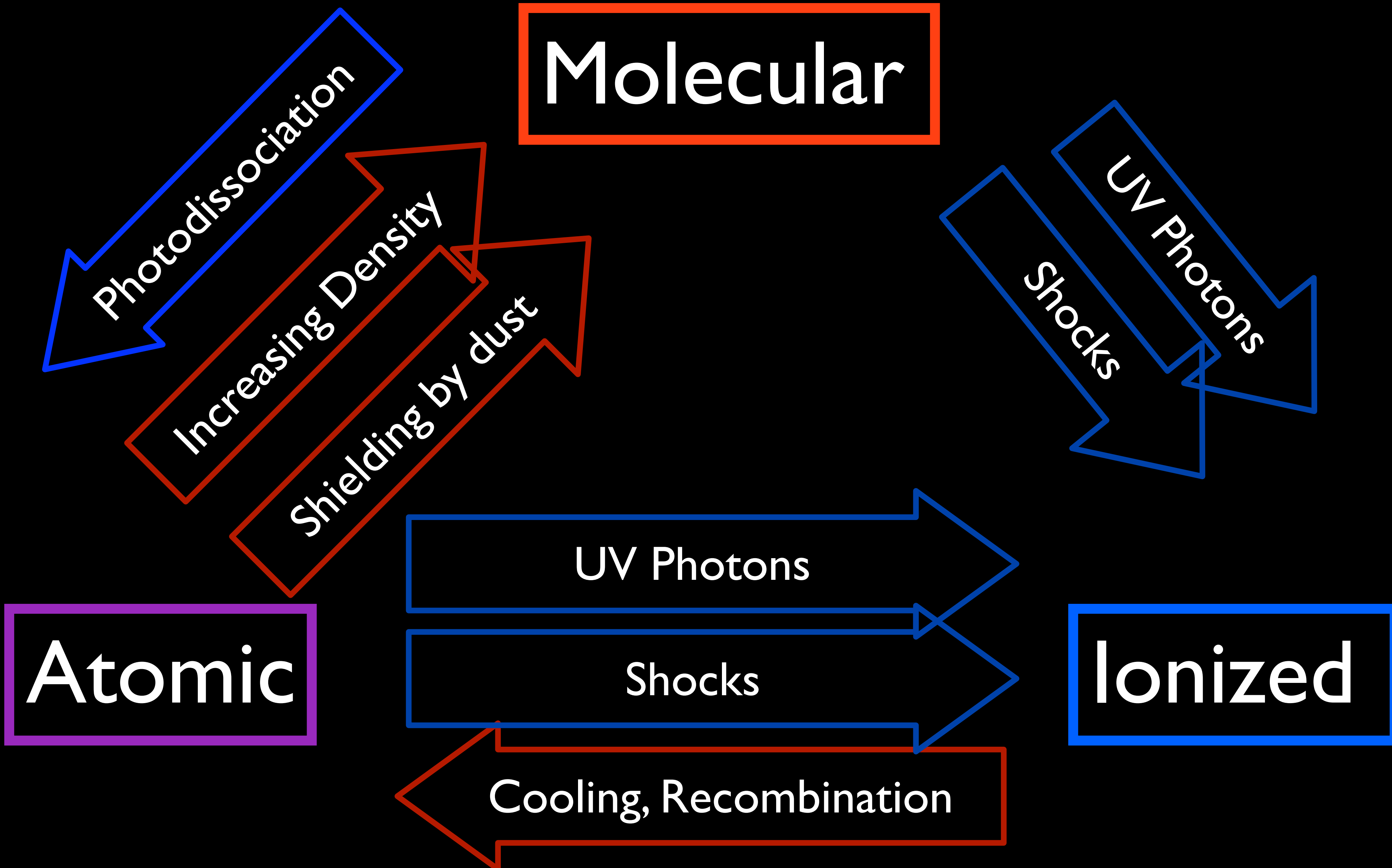
http://www.naic.edu/alfa/galfa/highlights/per/

Fundamentals of cool gas

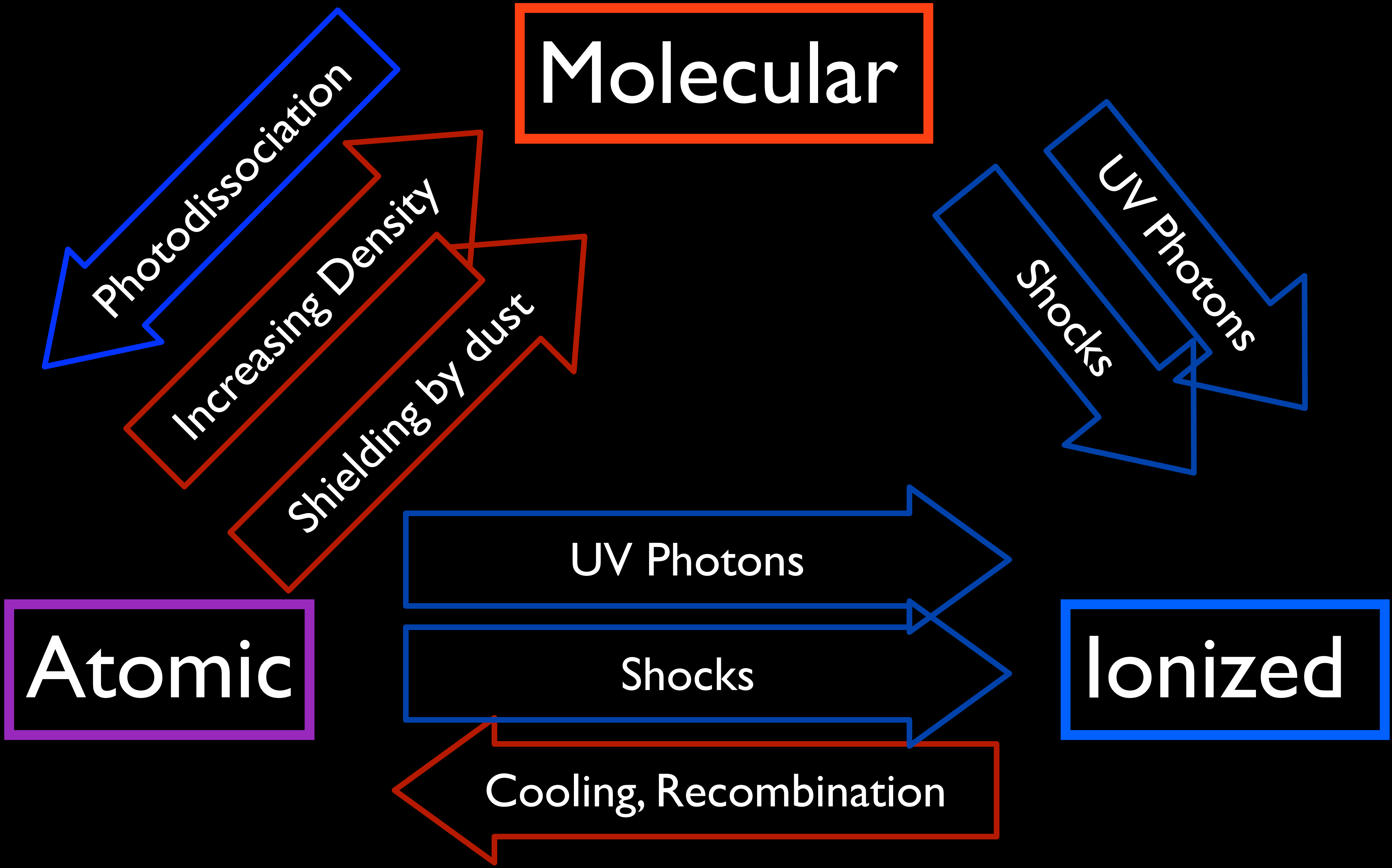
3. The local state of the gas is highly transient

   – Dissipative, so structure can reach high densities

   – 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

3. The local state of gas is highly transient

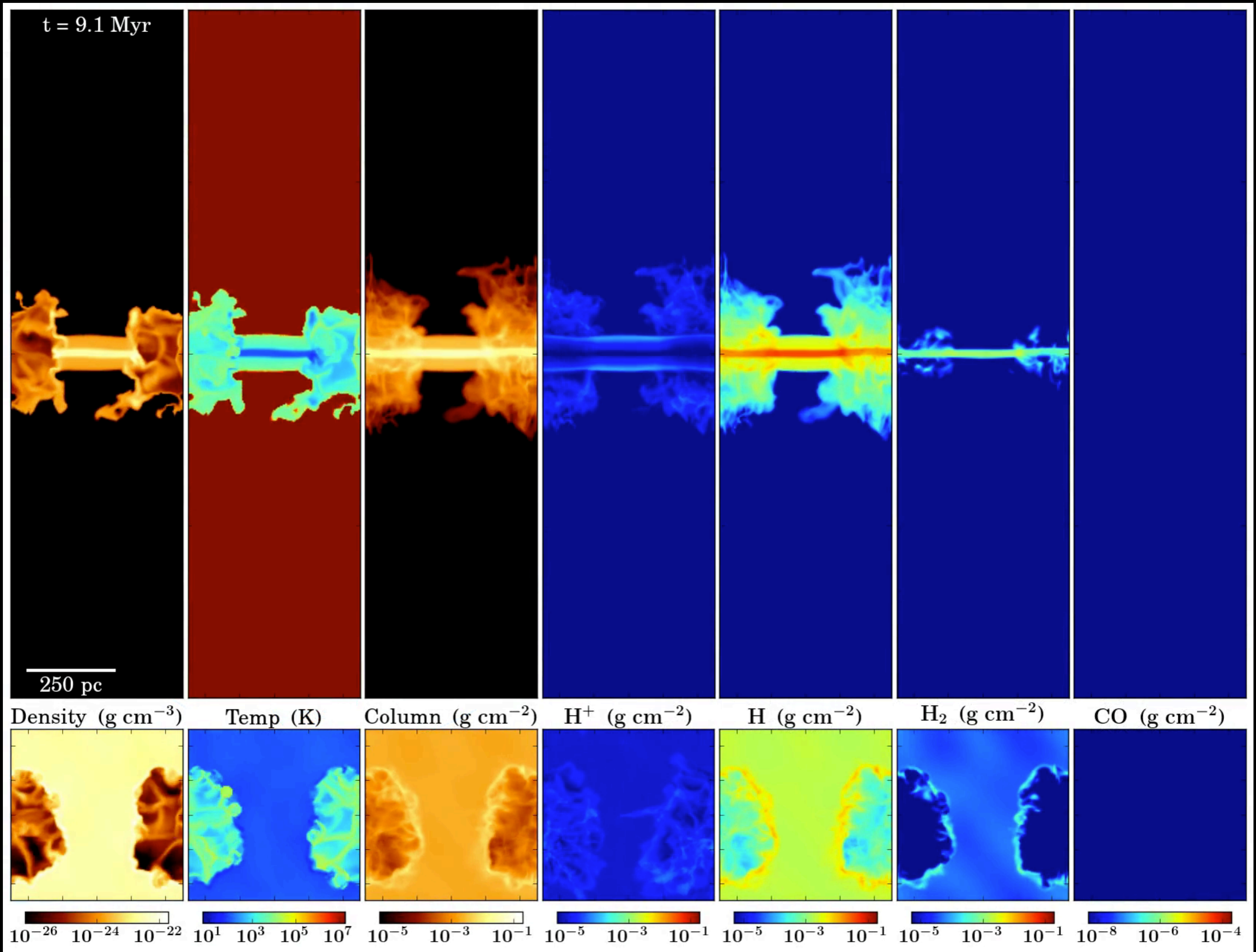
   – Dissipative, so structure can reach high densities

   – 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

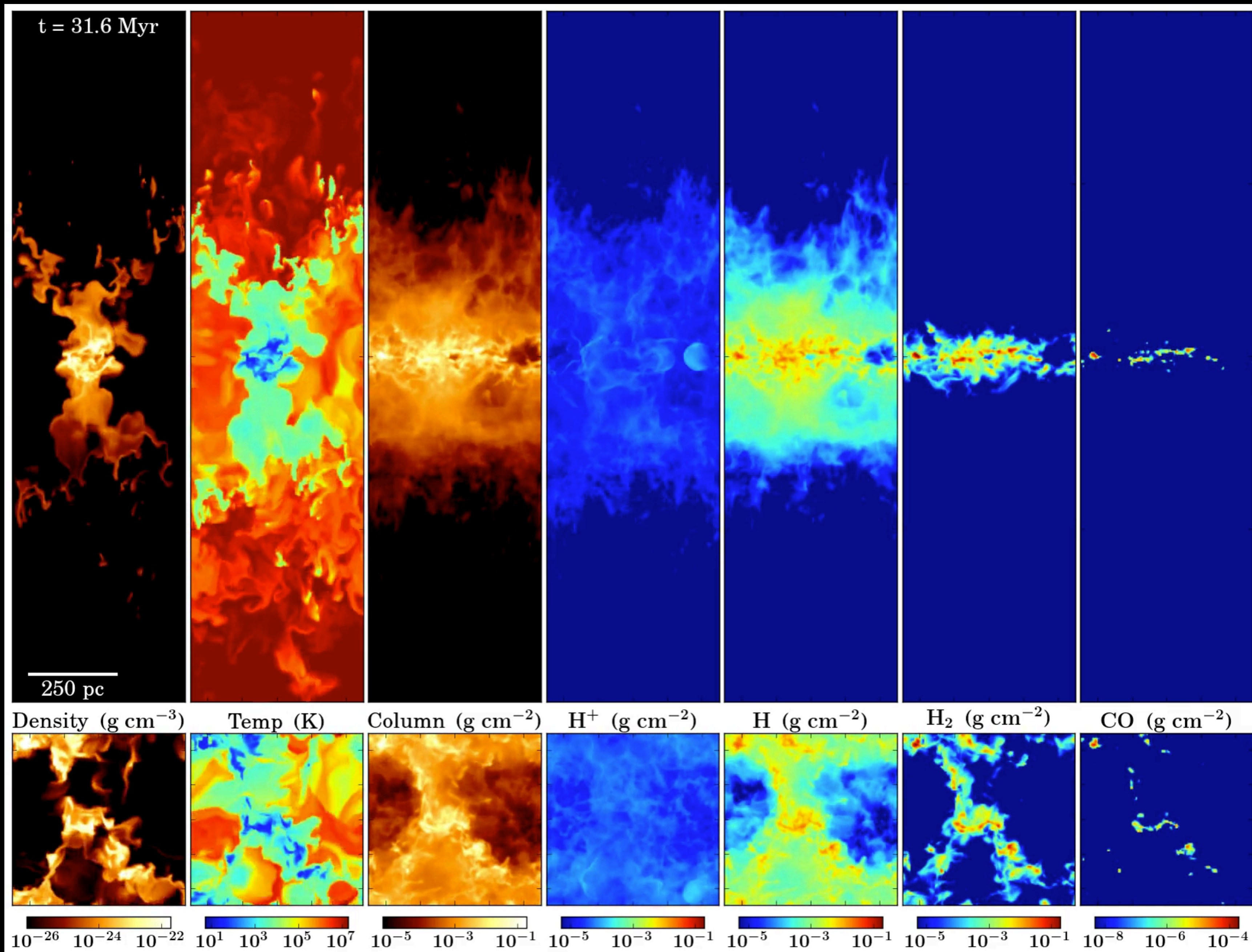


https://hera.ph1.uni-koeln.de/~silcc/

SNe set off at peaks in gas density

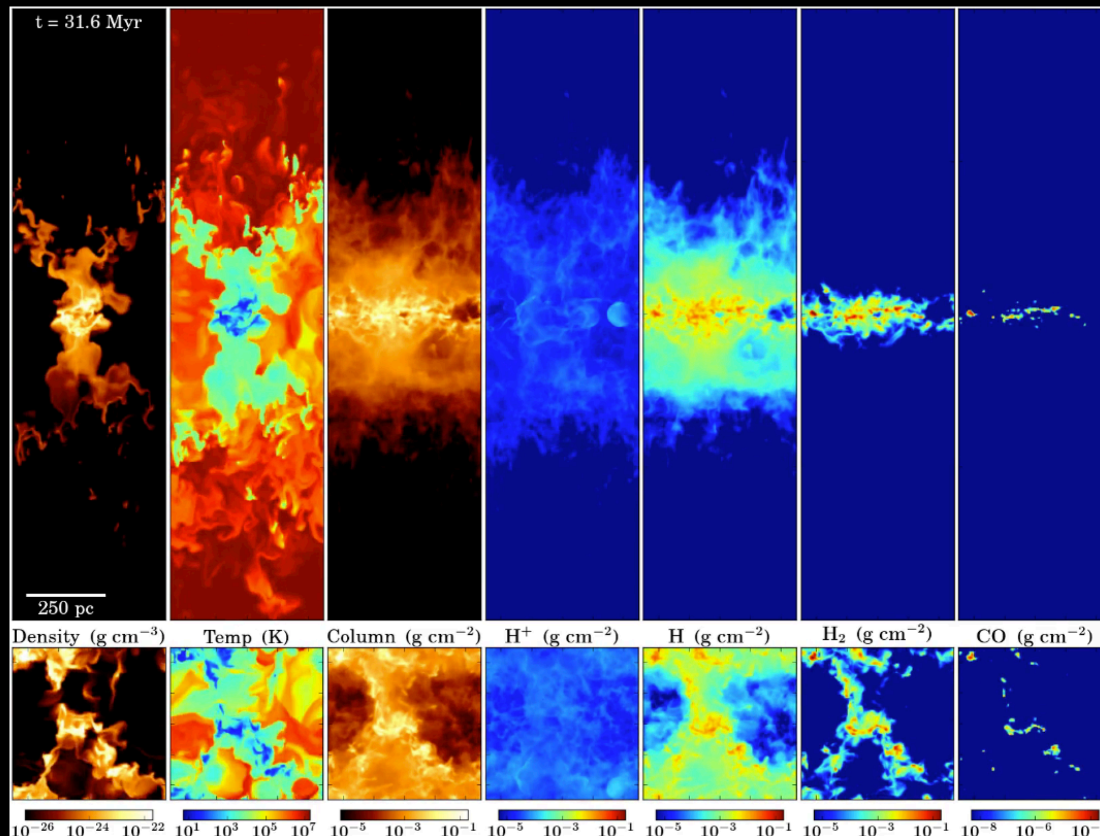
Simulation of SF disk w/ SNe

Walch et al 2015



Some SNe drift from peaks, + TypeIa

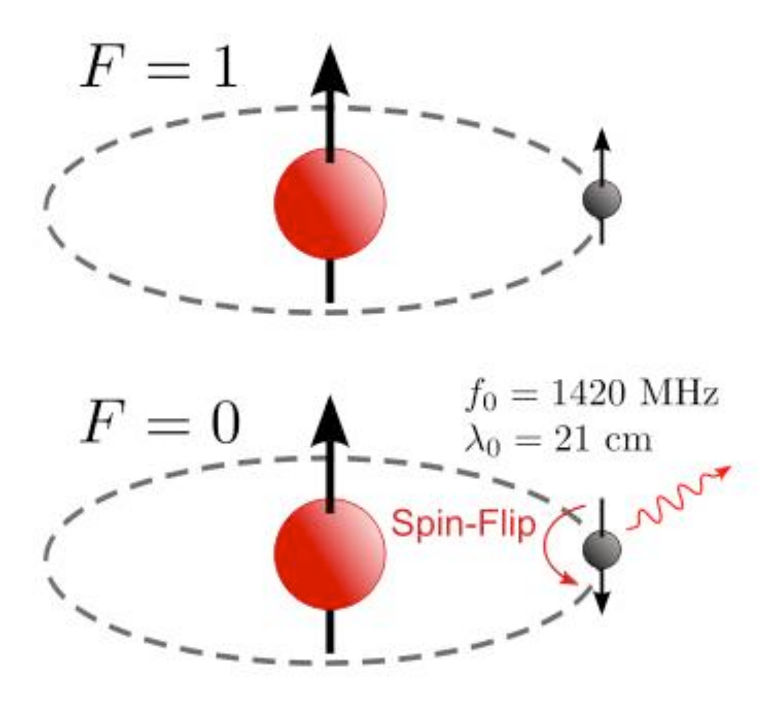
Fundamentals of cool gas



For this lecture, we will focus on the large-scale, quasi-equilibrium, bulk properties, recognizing that there is a *lot* going on under the hood…

Tracing Cool Gas

- Neutral Hydrogen
  - Spin-flip “hyperfine” transition at 21 cm



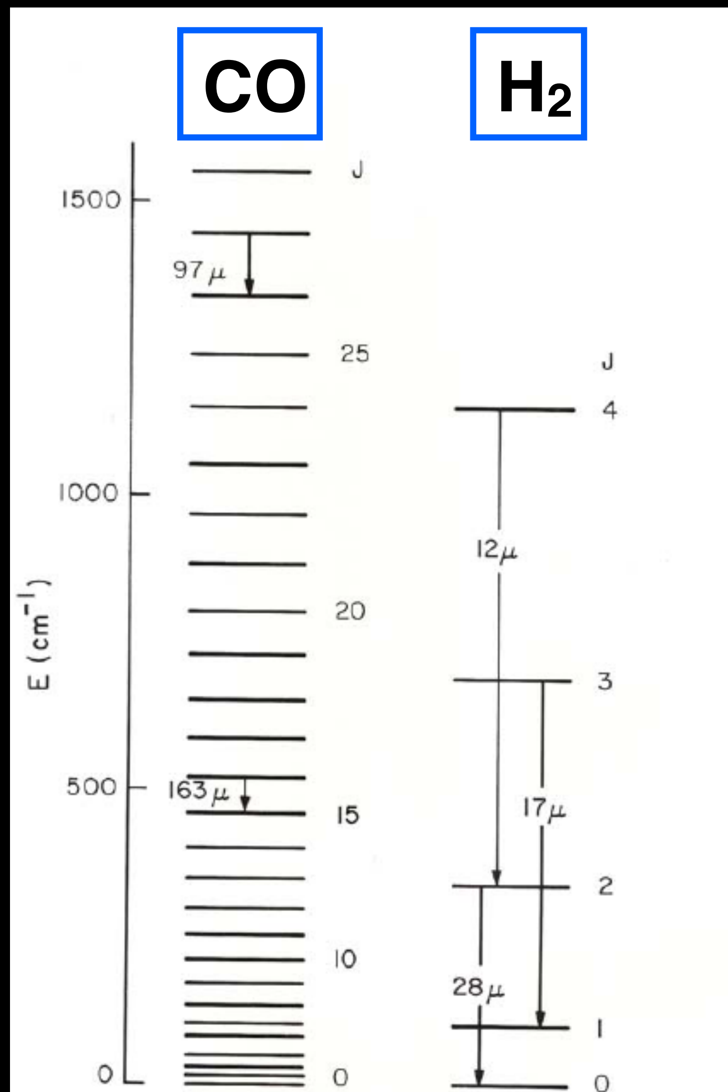
Low ΔE = Nearly any collision* can excite e- into higher energy state. Subsequent decay produces emission line.

*At very low densities, the rate of collisions may be too low to excite the atom…

Tracing Cool Gas

- Molecular Hydrogen? Strike one...

CO: Energy Levels Closely Spaced



H_2: Large Energy Separations (hard to excite)

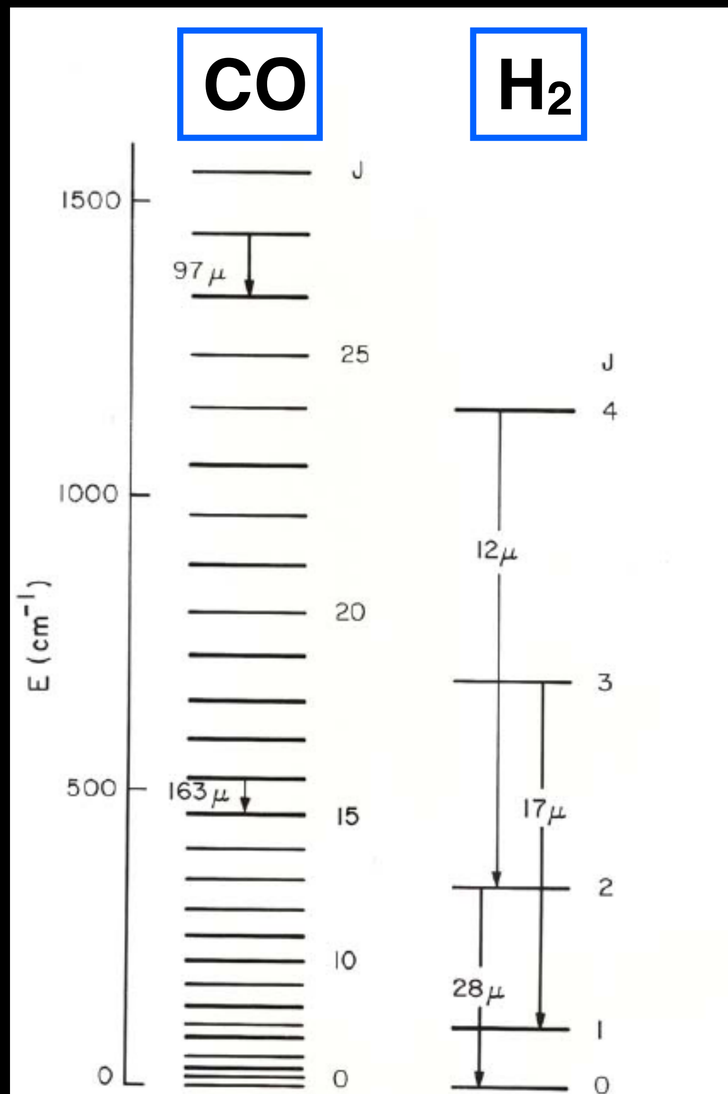
Energy level diagrams showing lowest energy rotational states

Tracing Cool Gas

- Molecular Hydrogen? Strike two...

Permitted transitions for asymmetric molecules:

$\boxed{\Delta J = 1}$



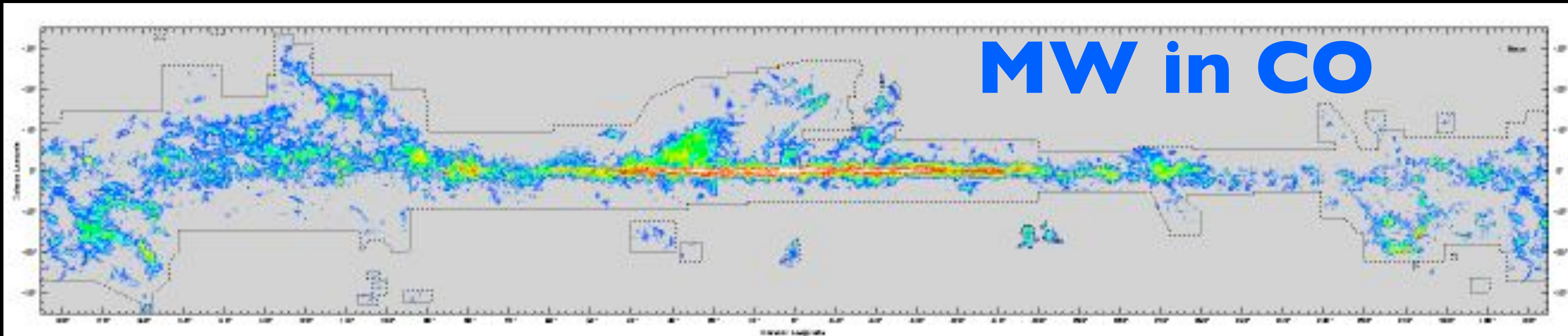
Permitted transitions for symmetric molecules:

$\boxed{\Delta J = 2}$

(Only quadrapole transitions, since no dipole moment)

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

Almost all molecular mapping relies on CO



Dame et al 2002

Yay CO!

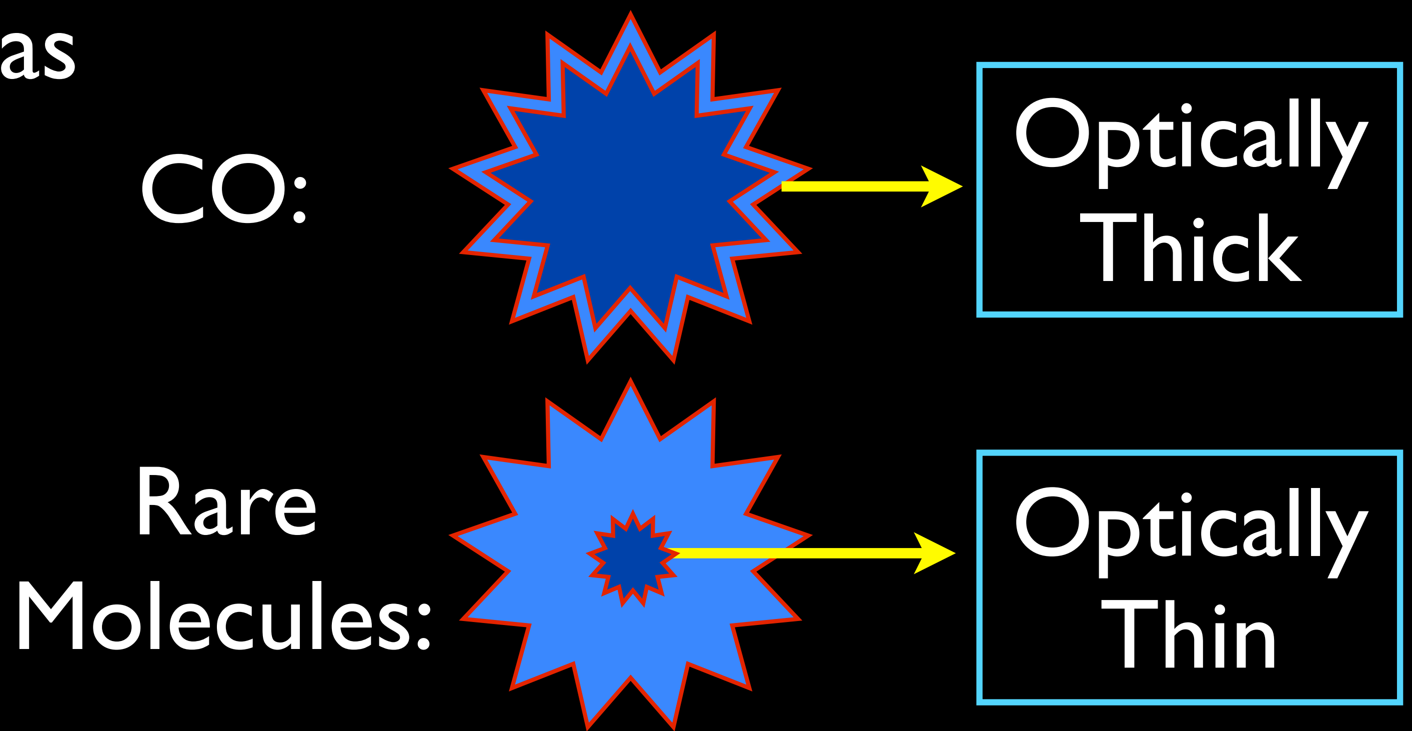
- Most abundant molecule after H_2.
- Rotational transitions are low energy & easy to excite ($T_{exc} \approx T_{kin}$)

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.

Tracing Cool Gas

- Molecular gas
  - Other molecules used to trace densest gas



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

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

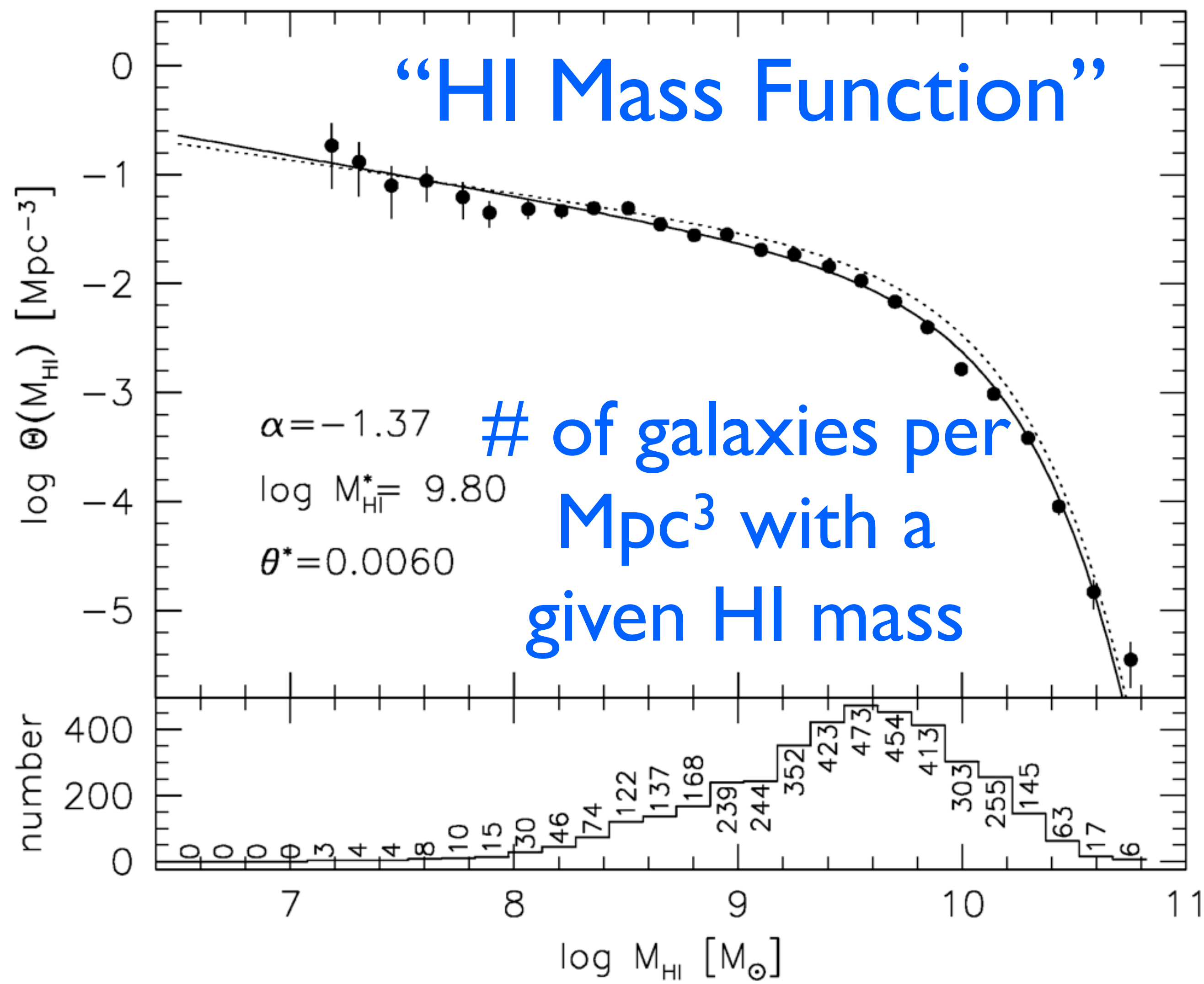
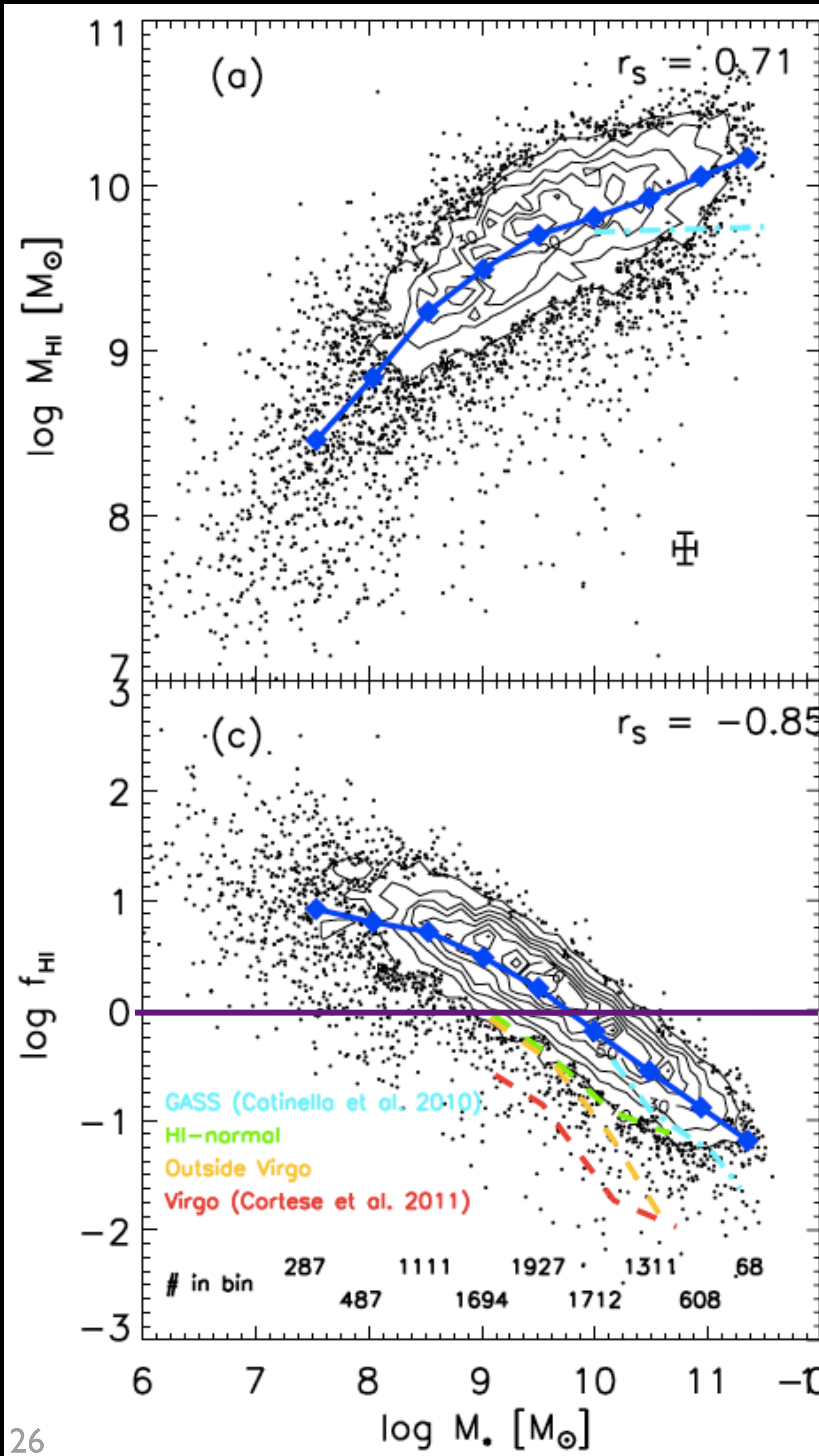


Figure 1. Top: H I mass function from HICAT. The solid line is a Schechter fit to the points; the best-fitting parameters are shown in the lower left corner. Bottom: distribution of H I masses used for the HIMF calculation.

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



How does HI content vary among galaxies?

- High mass galaxies have more HI
- Low mass galaxies have a higher fraction of HI

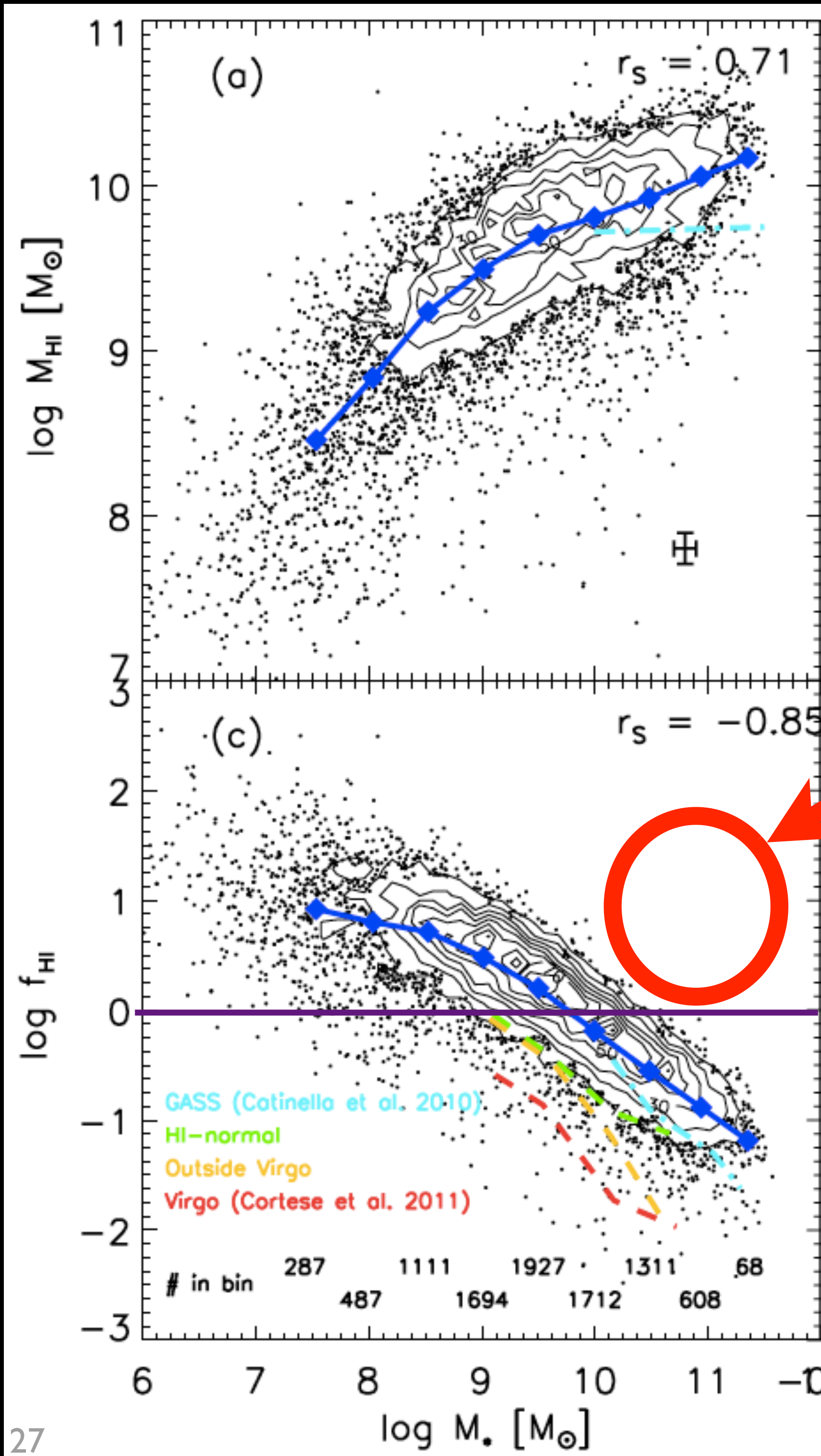
$$f_{\mathrm{H\,I}} = M_{\mathrm{H\,I}}/M_*$$

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; Different color lines show different selection surveys

ALFALFA+SDSS+GALEX: Huang et al 2012

How does HI content vary among galaxies?

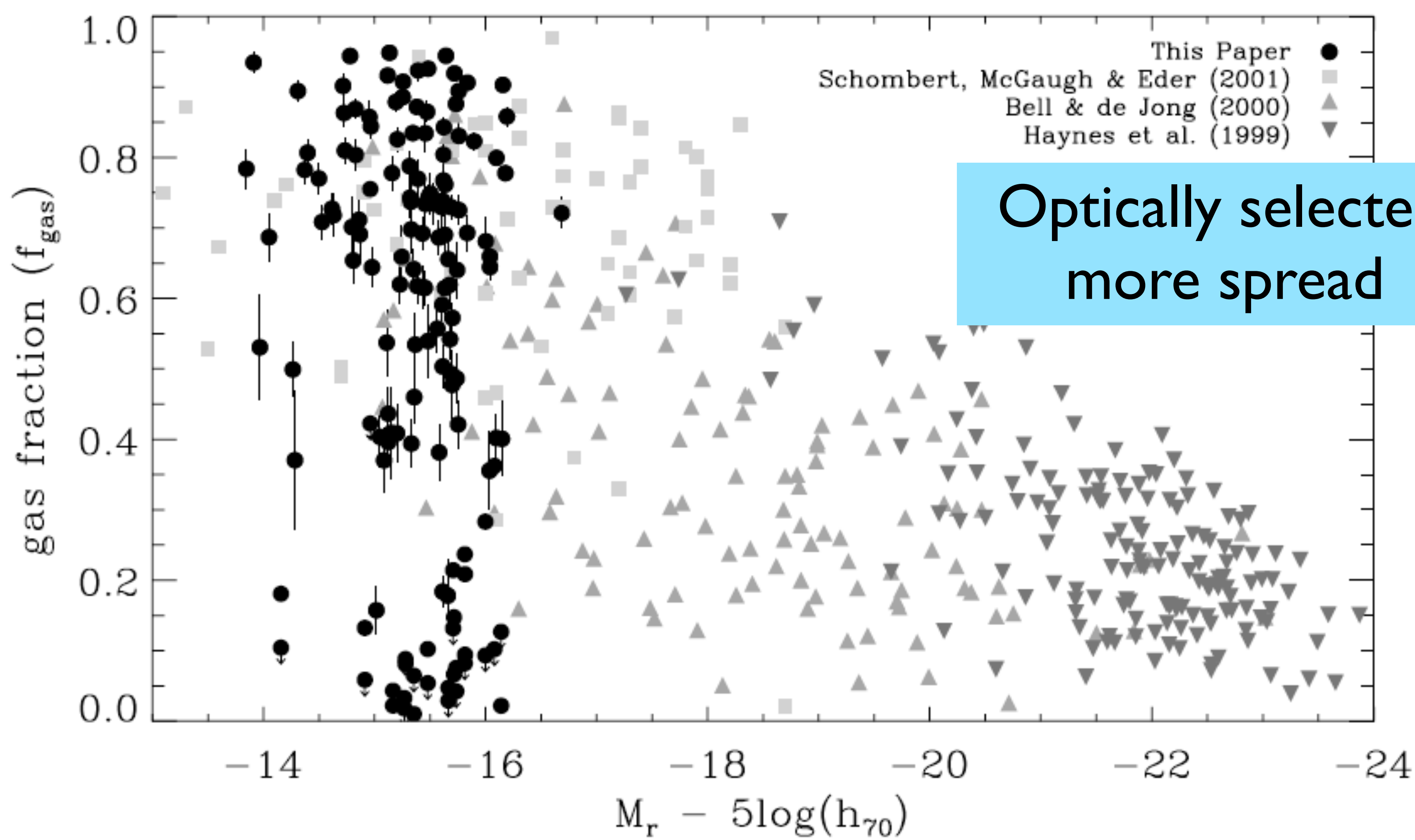


Essentially no gas rich massive galaxies
(even in a HI-selected survey biased to detect them)

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

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

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.

Geha et al 2006

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

Big spread in gas richness of dwarfs

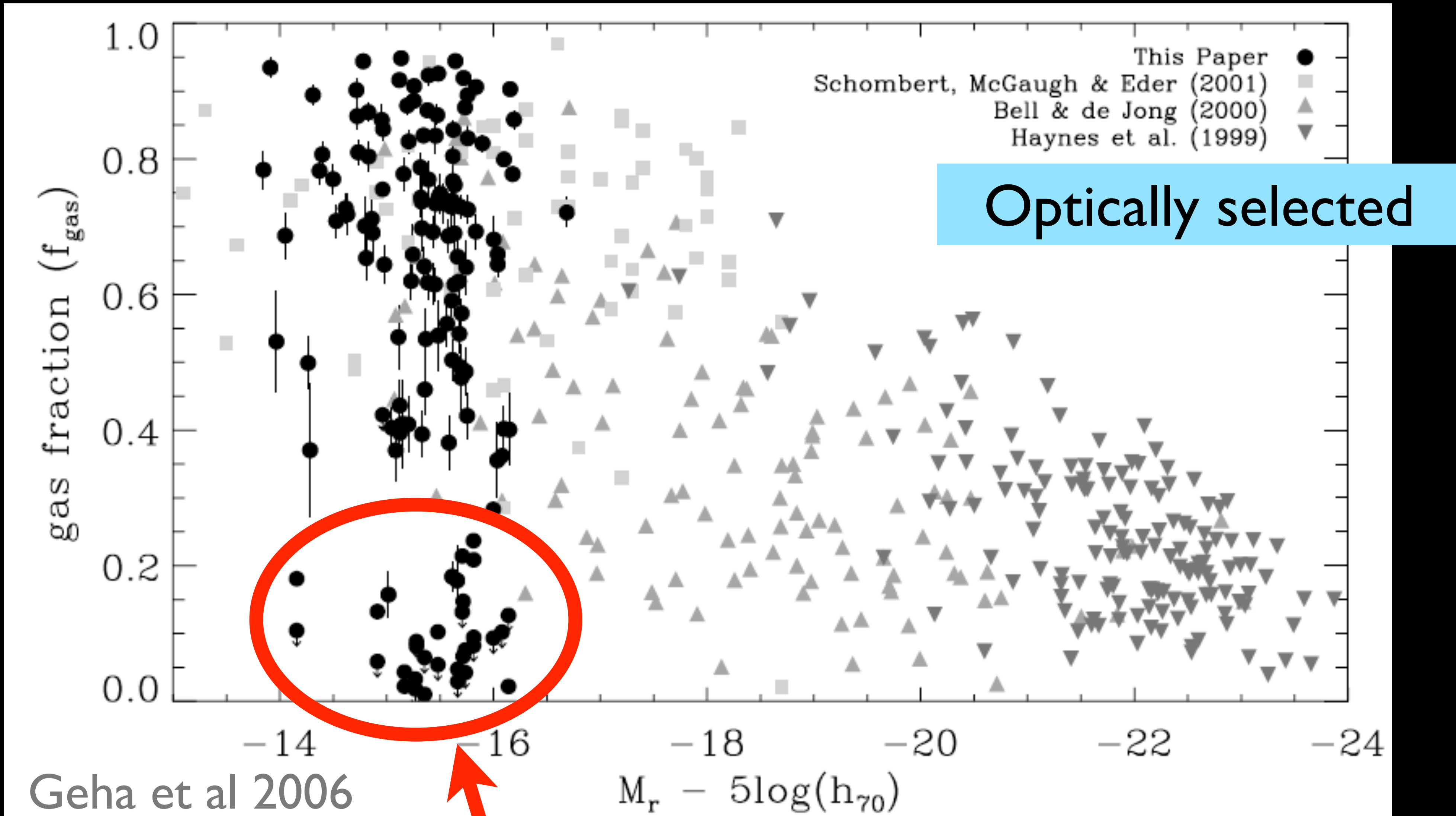


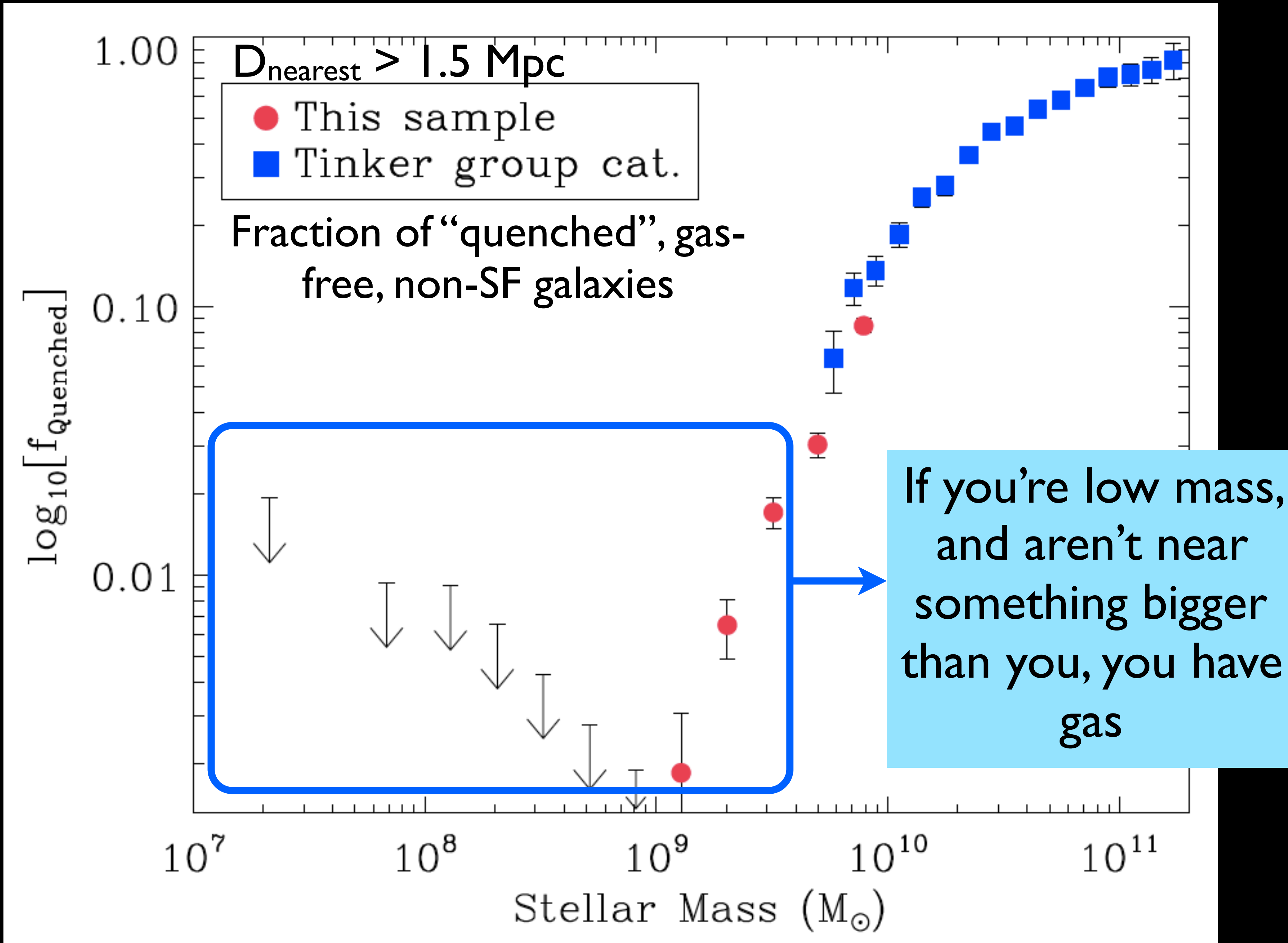
FIG. 3.— Gas fraction, $f_{gas} = M_{gas}/(M_{gas} + M_{star})$, plotted as a function of absolute r-band magnitude. The majority of dwarf galaxies in this paper (*circles*) are dominated by the gas mass, rather than the stellar mass, with gas fractions as high as 95%. Galaxies that were not detected 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.

There are gas-poor dwarfs, but only in dense environments

Why might gas fraction vary?

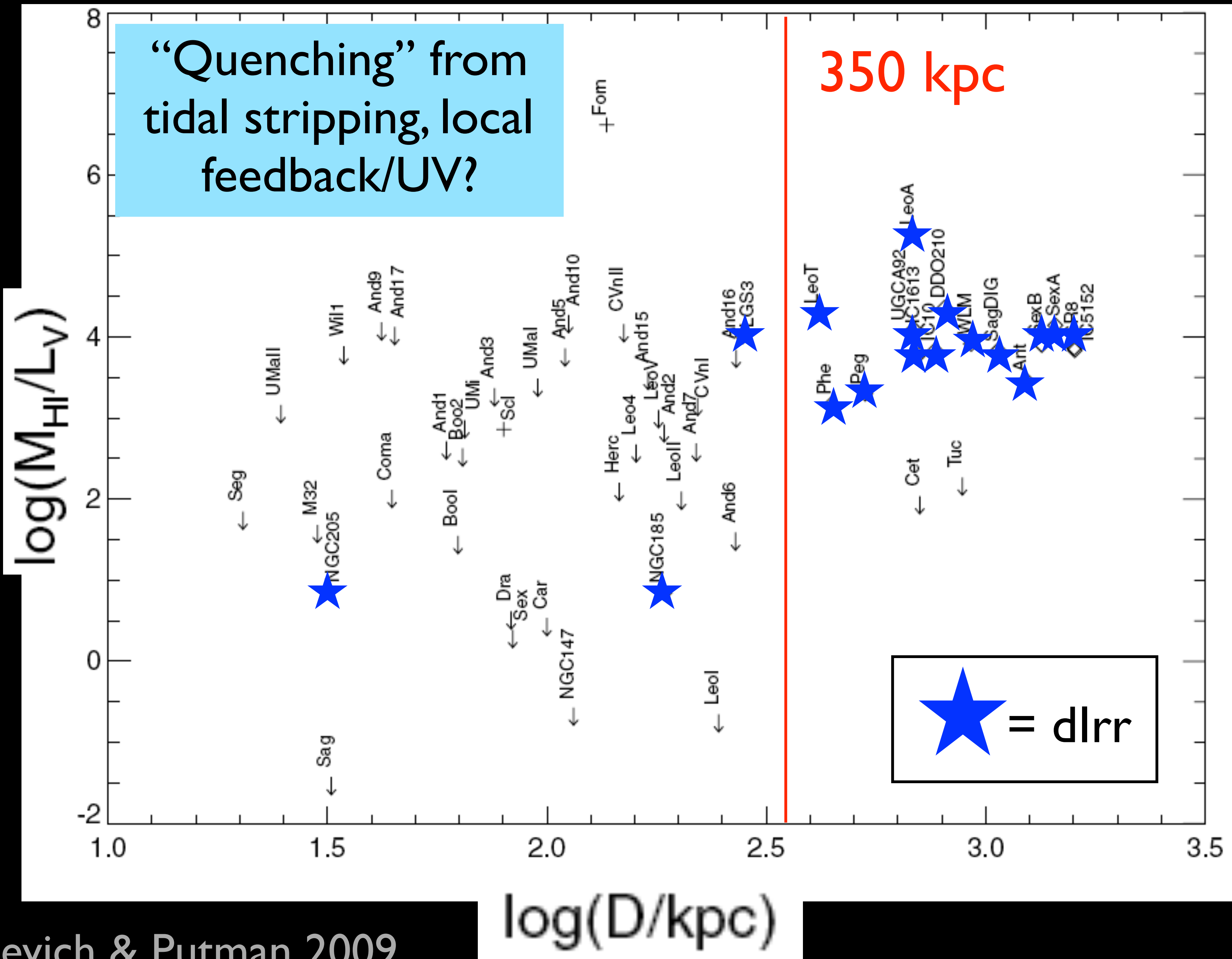
- Variation in star formation efficiency
  - low density gas converts to stars more slowly
- Variation in recent accretion history
- Variation in gas expulsion
  - efficiency of feedback (AGN or SN)
  - environment (tidal or ram pressure forces)

All Field/Central Dwarfs have gas



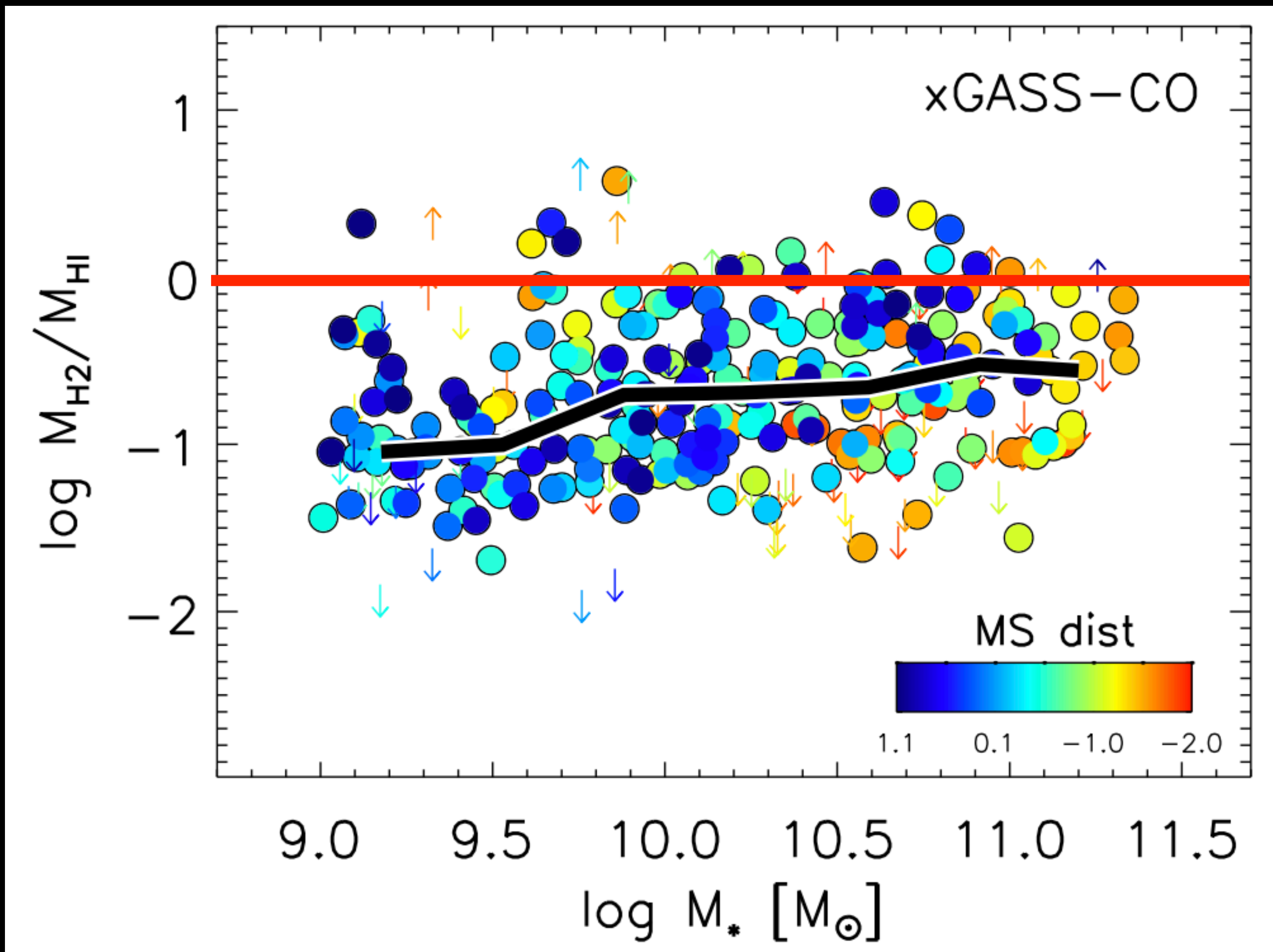
Geha et al 2012

Within 350 kpc, almost no MW dwarfs have gas



Grcevich & Putman 2009

Molecular gas mass is typically much less than atomic gas mass



xCOLDGASS; Cantinella et al 2018

Important for star formation, but not a singificant part of the cold gas mass budget

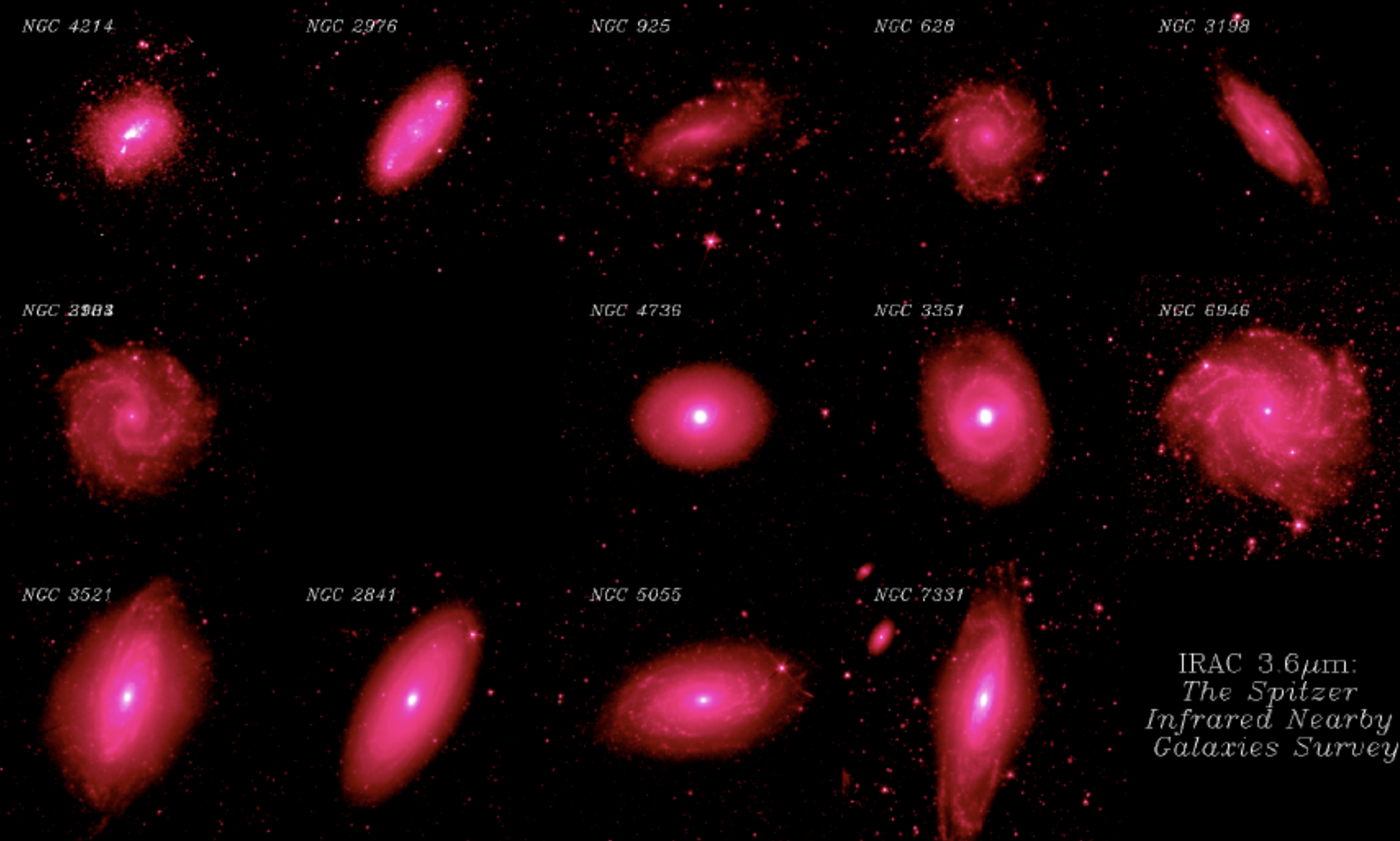
Based on above, galaxy-scale structure of cold gas* is primarily about:

- Disk galaxies (i.e., not the most massive, spheroidal systems)
- Relatively isolated dwarf galaxies outside of the "virial radius" of more massive galaxies (~300 kpc for the Milky Way)

*at the present day…

How is the gas distributed radially?

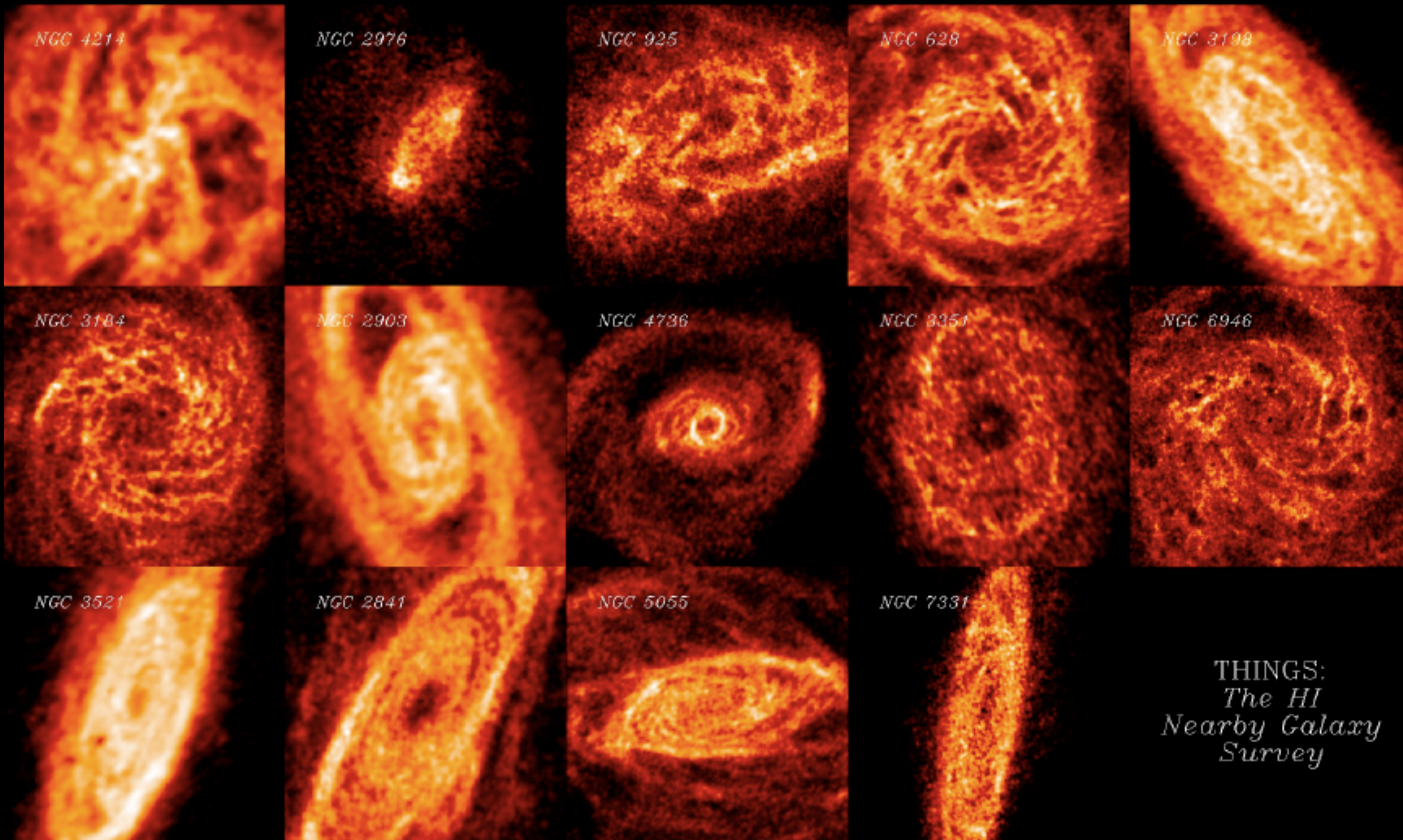
NIR traces (oldish) RGB/AGB stars



Approximate map of stellar mass

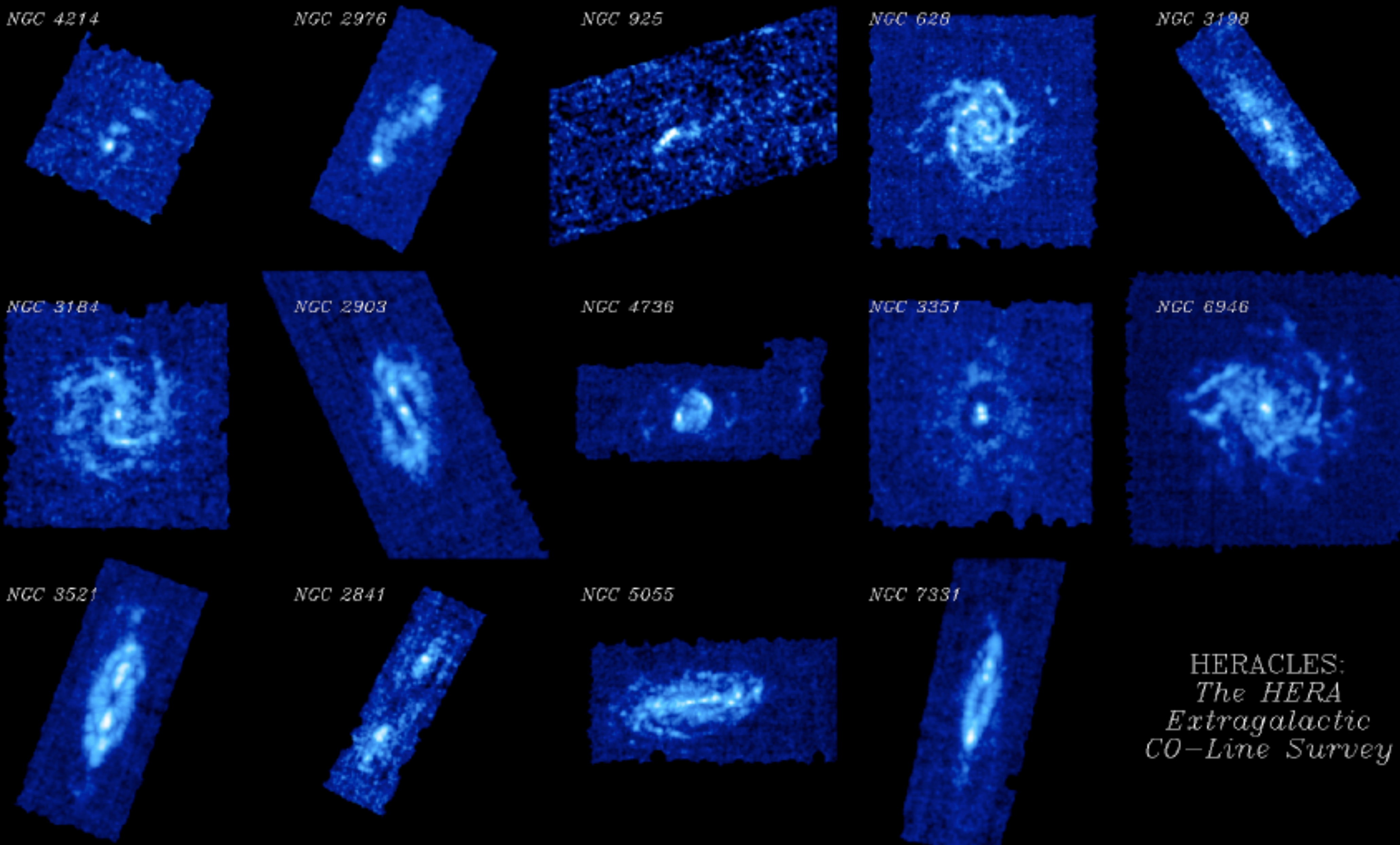
Slides from A. Leroy

HI is Structured & Extended



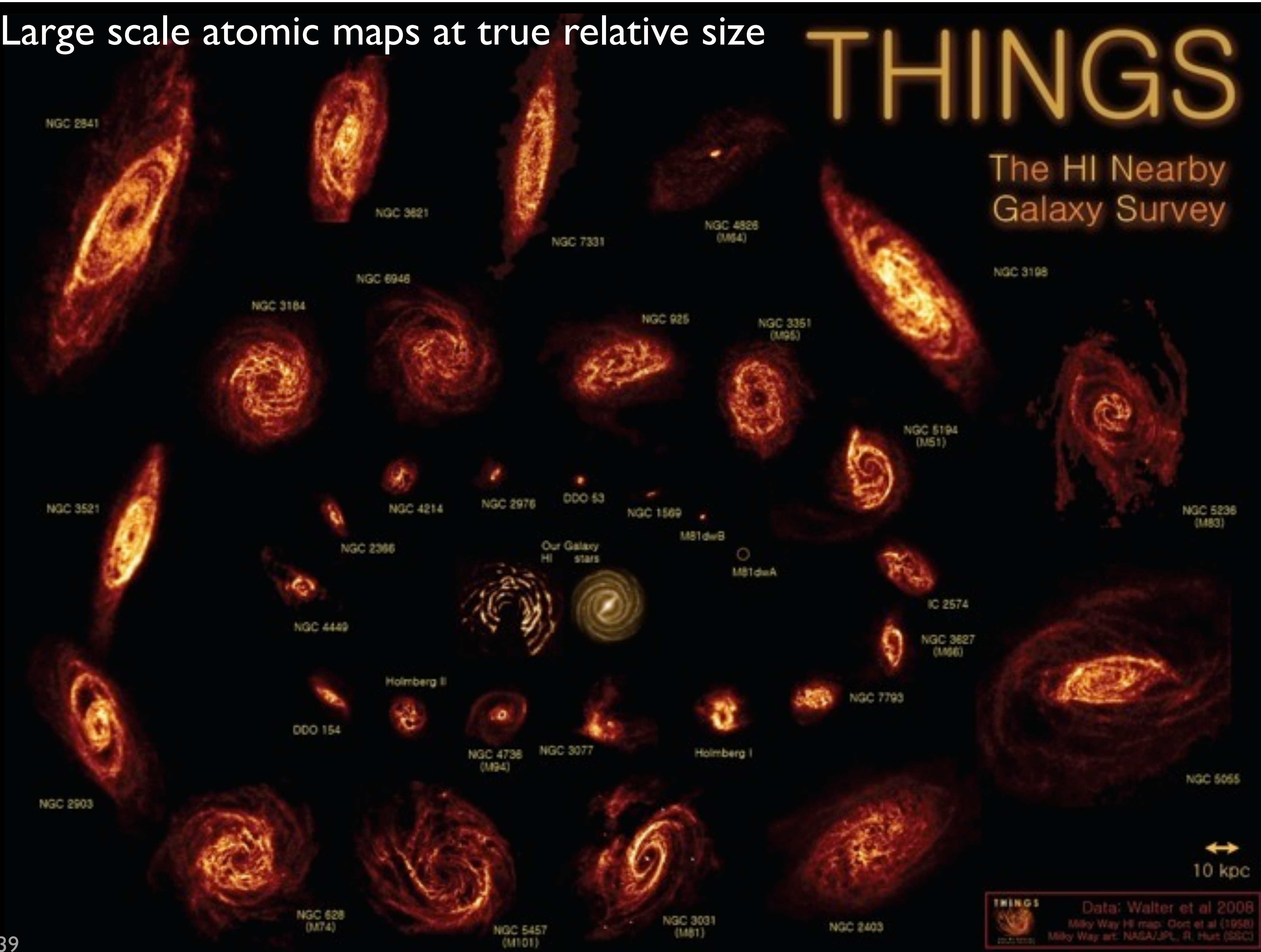
Frothy -- SNe driven bubbles? HI depressed in center, often

Molecular gas is centrally concentrated



Largely confined to spiral arms & centers. Note: CO, not H_2!

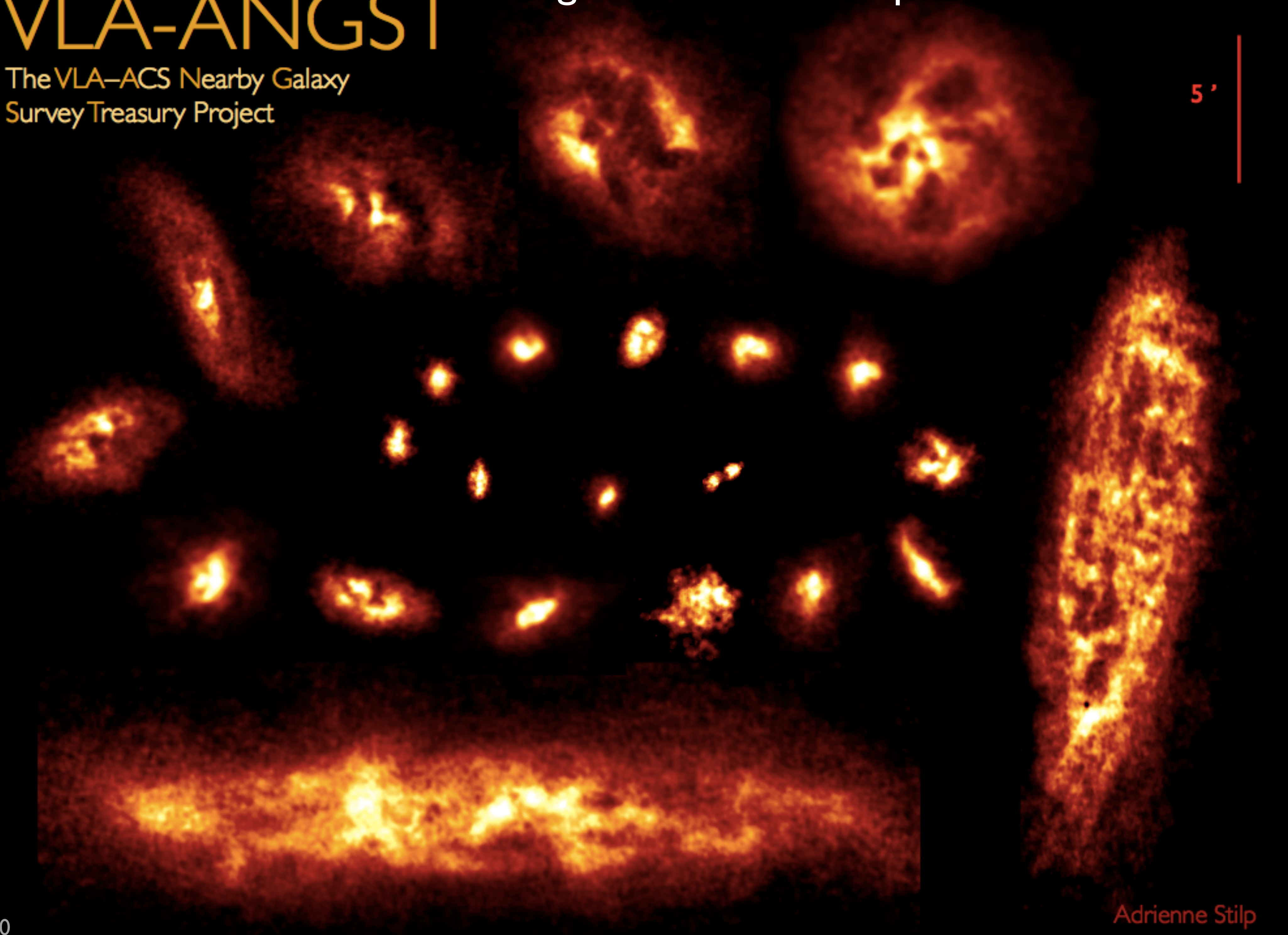
Large scale atomic maps at true relative size



Large scale atomic maps at true relative size

VLA-ANGST

The VLA–ACS Nearby Galaxy Survey Treasury Project



Adrienne Stilp

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

Courtesy: Adrienne Stilp

Ott et al 2012, Walter et al 2008

$M_\star \sim 10^9 M_\odot$

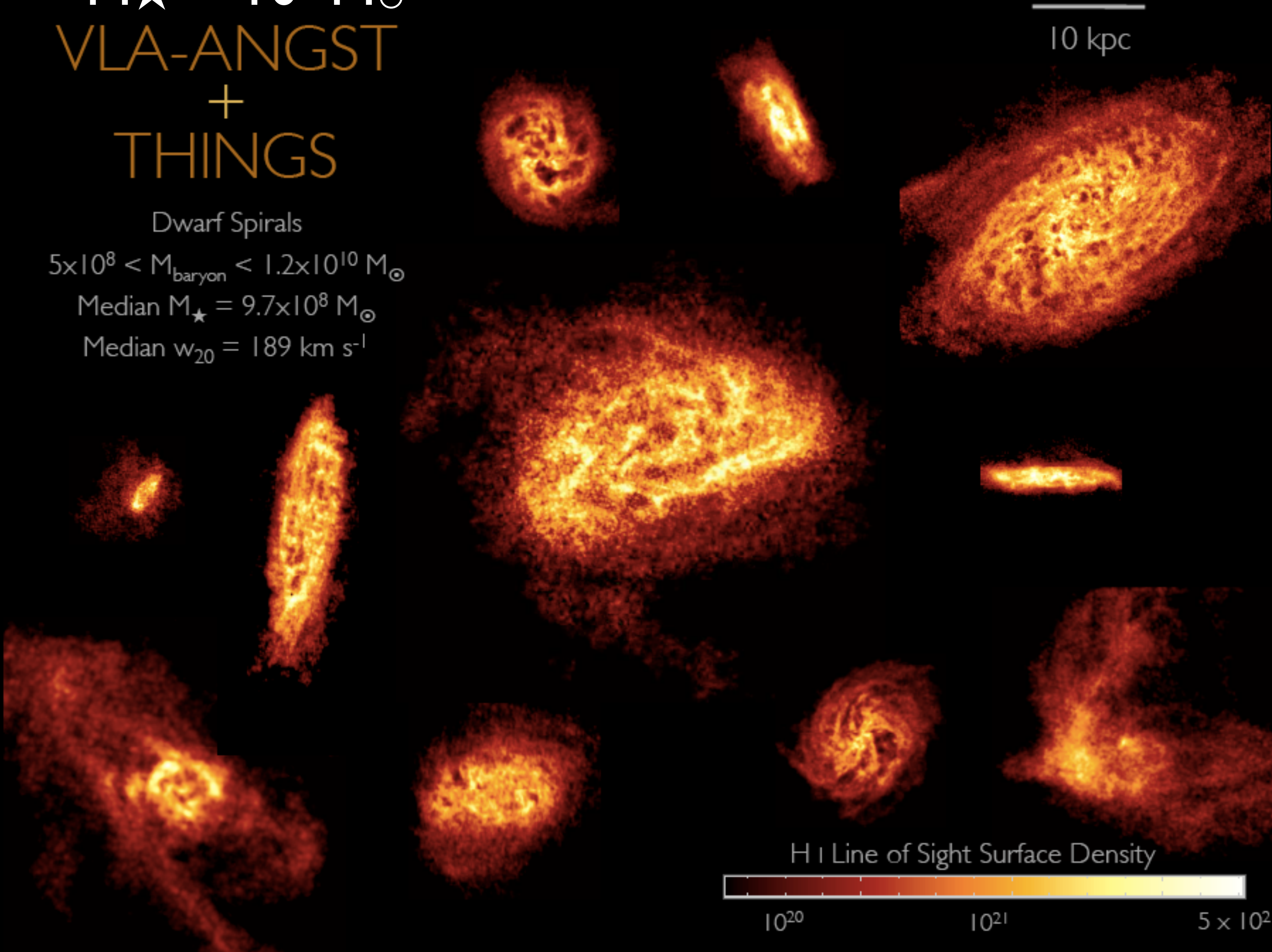
VLA-ANGST + THINGS

Dwarf Spirals

$5\times10^8 < M_{baryon} < 1.2\times10^{10} M_\odot$

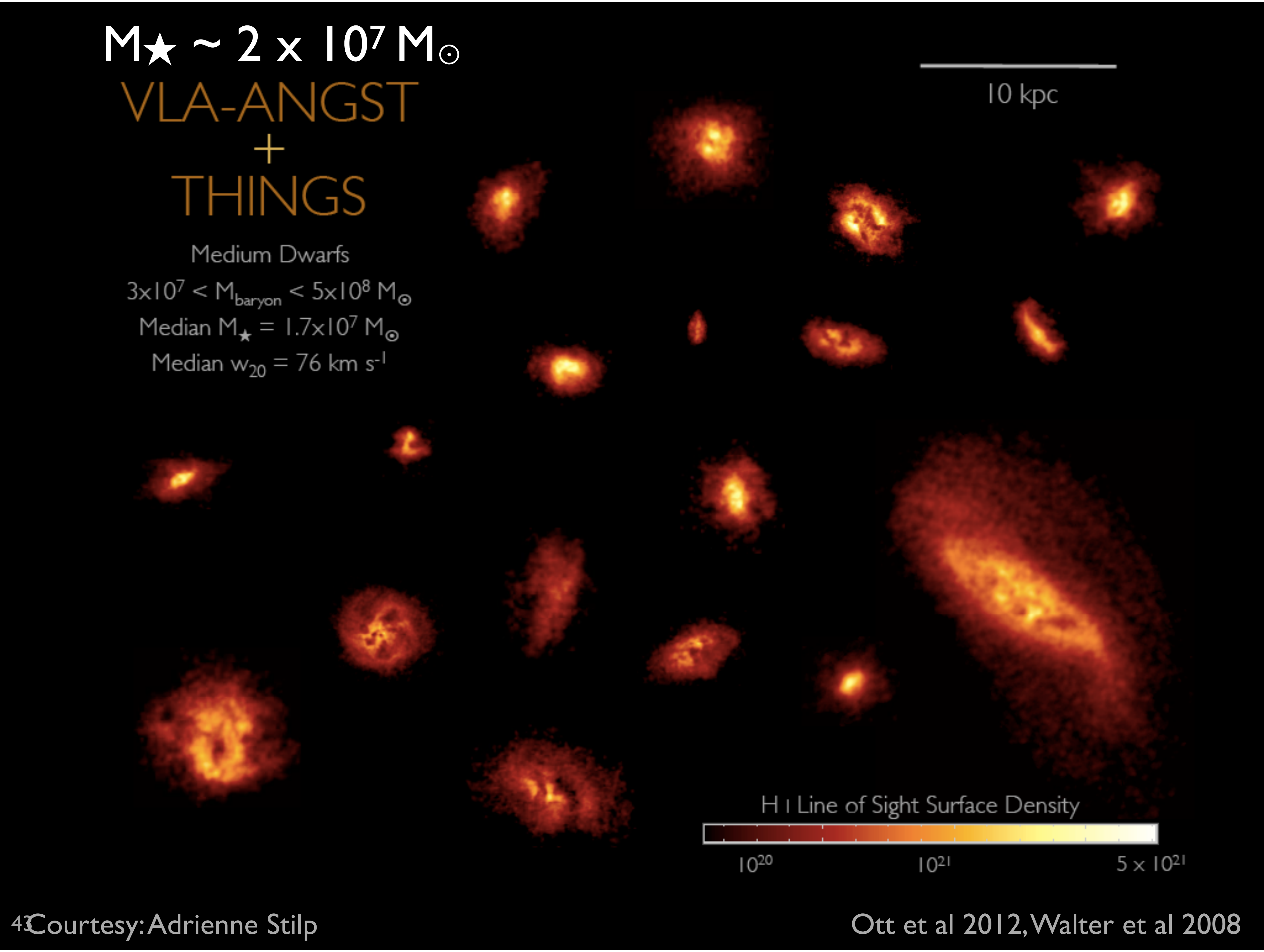
Median $M_\star = 9.7\times10^8 M_\odot$

Median $w_{20} = 189$ km s^{-1}

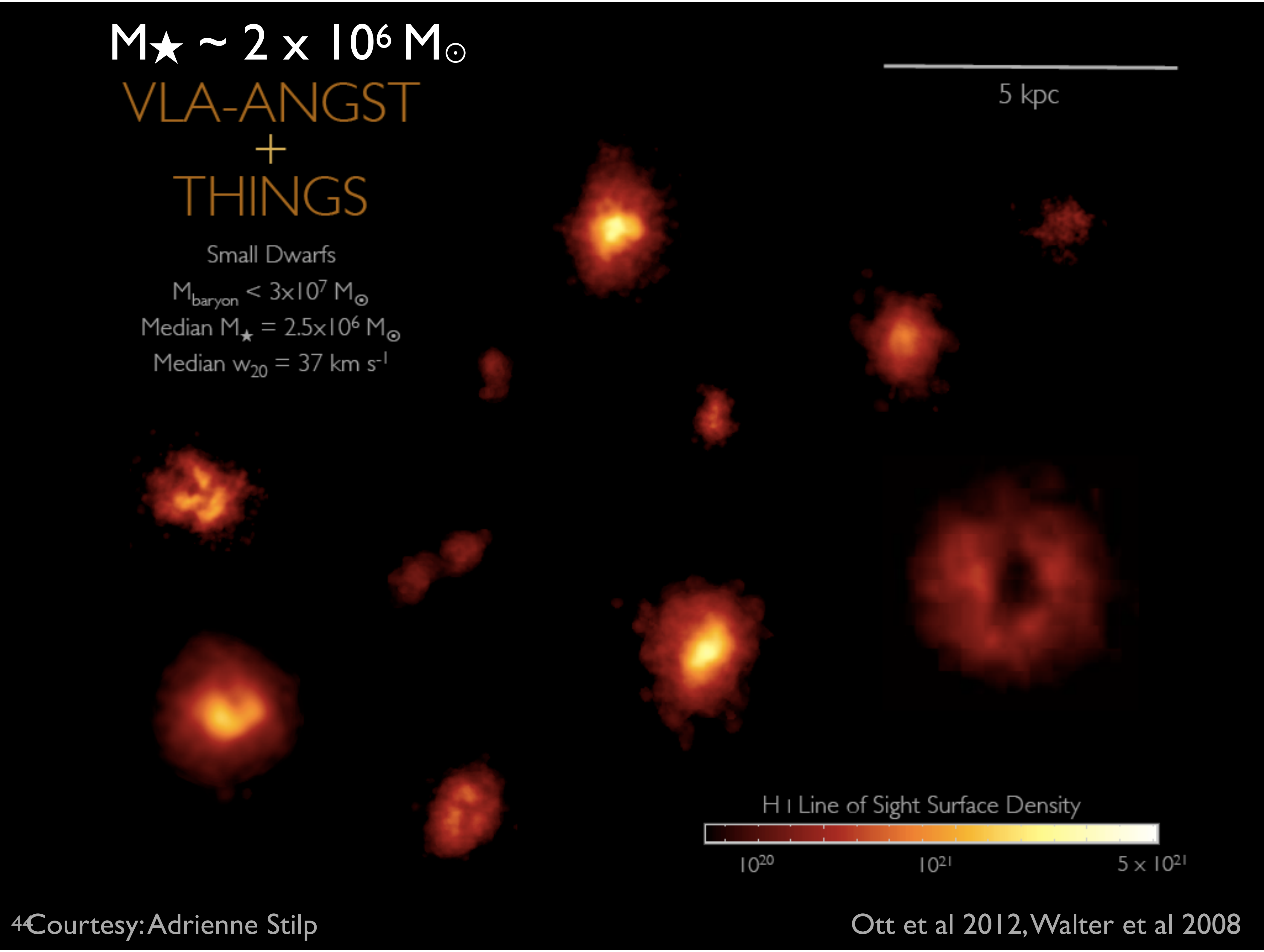


Courtesy: Adrienne Stilp

Ott et al 2012, Walter et al 2008



M★ ~ 2 x 10⁷ M☉
VLA-ANGST
+
THINGS
Medium Dwarfs
3x10⁷ < M_baryon < 5x10⁸ M☉
Median M★ = 1.7x10⁷ M☉
Median w20 = 76 km s-1
10 kpc
H I Line of Sight Surface Density
10²⁰
10²¹
5 x 10²¹
Courtesy: Adrienne Stilp
Ott et al 2012, Walter et al 2008


M★ ~ 2 x 10⁶ M☉
VLA-ANGST
+
THINGS
Small Dwarfs
$M_{baryon} < 3 \times 10^7\ M_\odot$
Median $M_\star = 2.5 \times 10^6\ M_\odot$
Median $w_{20} = 37$ km s^{-1}
5 kpc
H I Line of Sight Surface Density
10^{20}
10^{21}
5×10^{21}
Courtesy: Adrienne Stilp
Ott et al 2012, Walter et al 2008

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

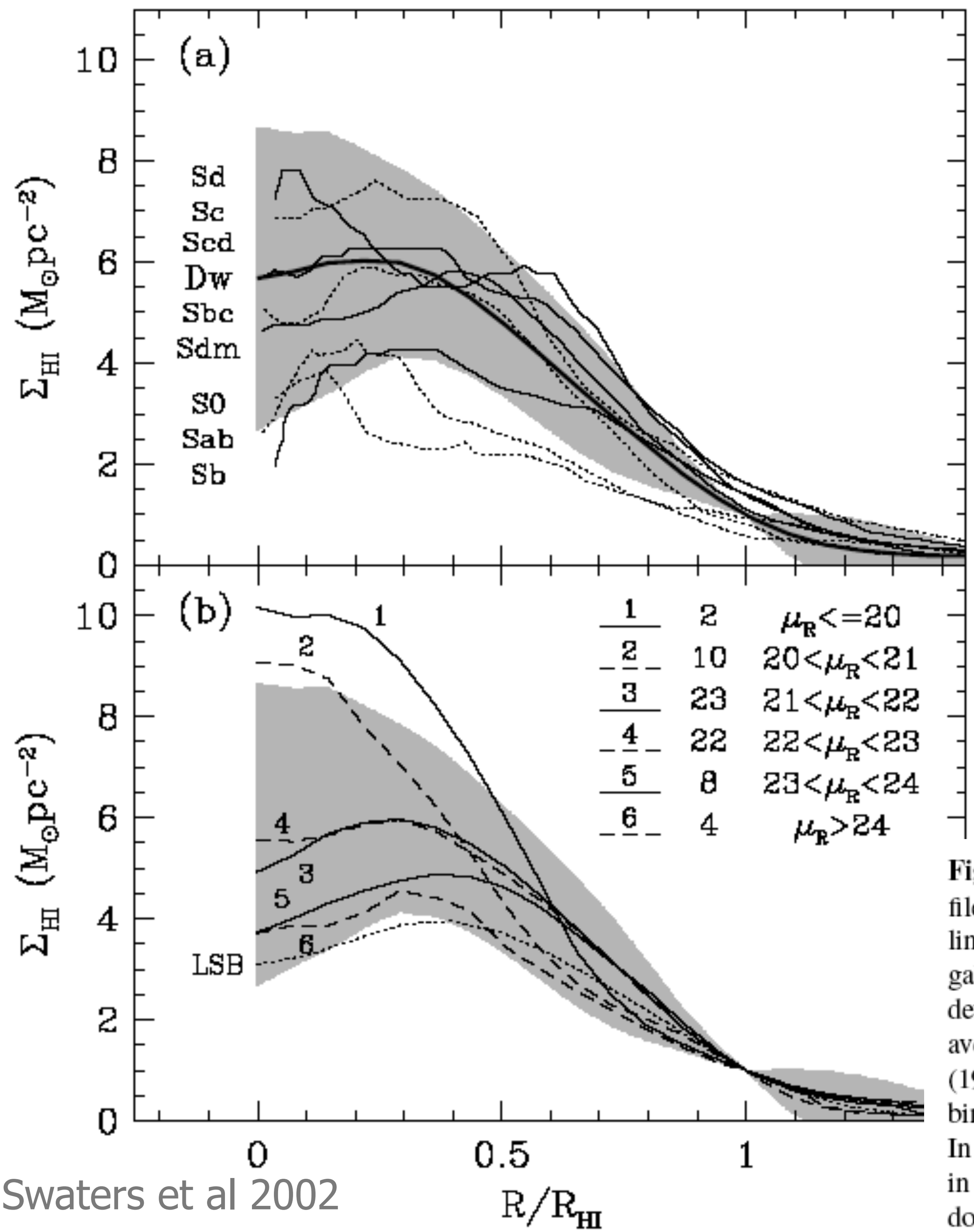
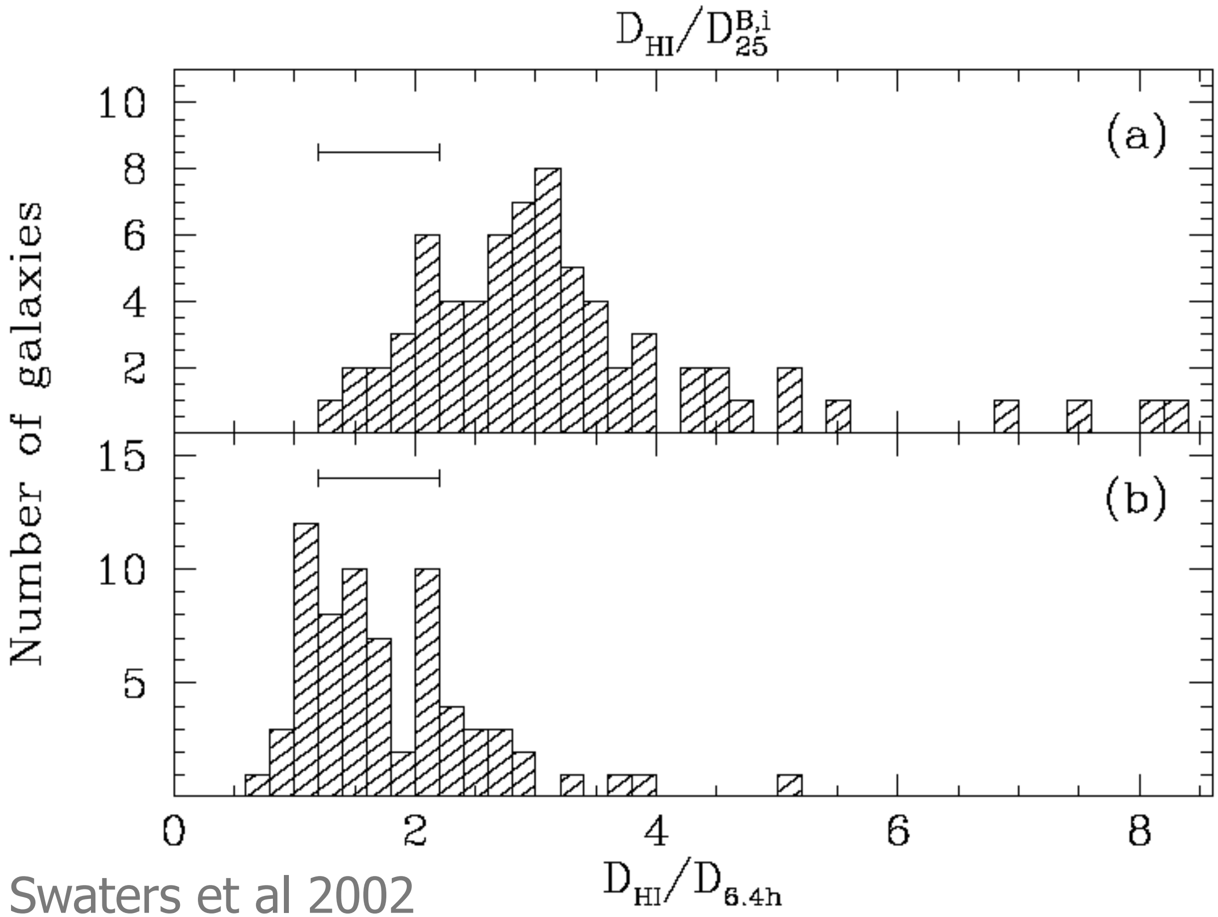


Fig. 10. **a)** Comparison of the range in radial H I surface density profiles among dwarf galaxies and bright spiral galaxies. The thick black line indicated by "Dw" represents the average profile of all dwarf galaxies in our sample, and the shaded area indicates one standard deviation at each radius 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



Swaters et al 2002

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

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

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

Bottom panel $D_{6.4h}$ = diameter at 6.4 disk scale lengths
(Much more robust to varying surface brightness)

Sometimes the HI extent is absurd

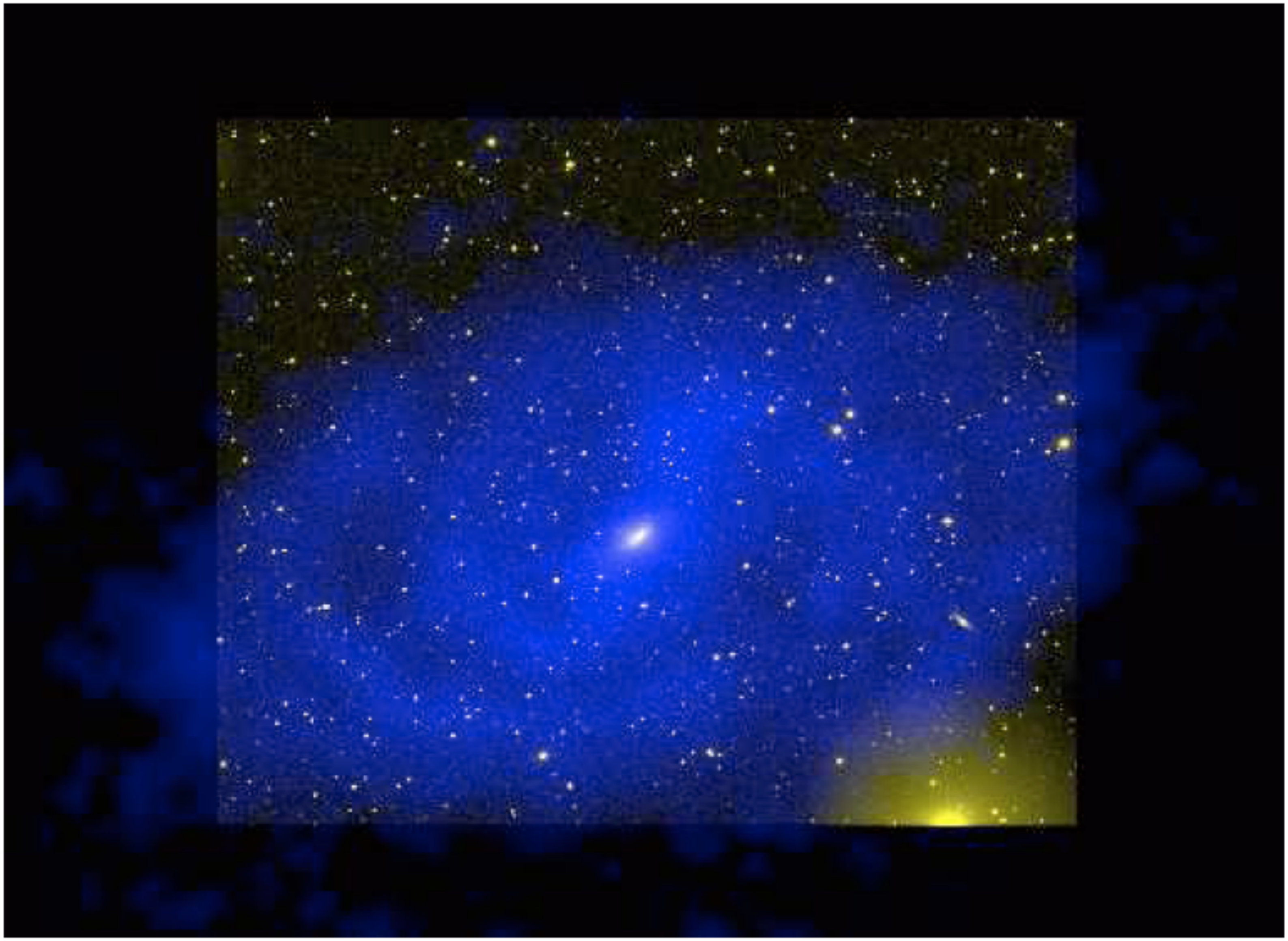
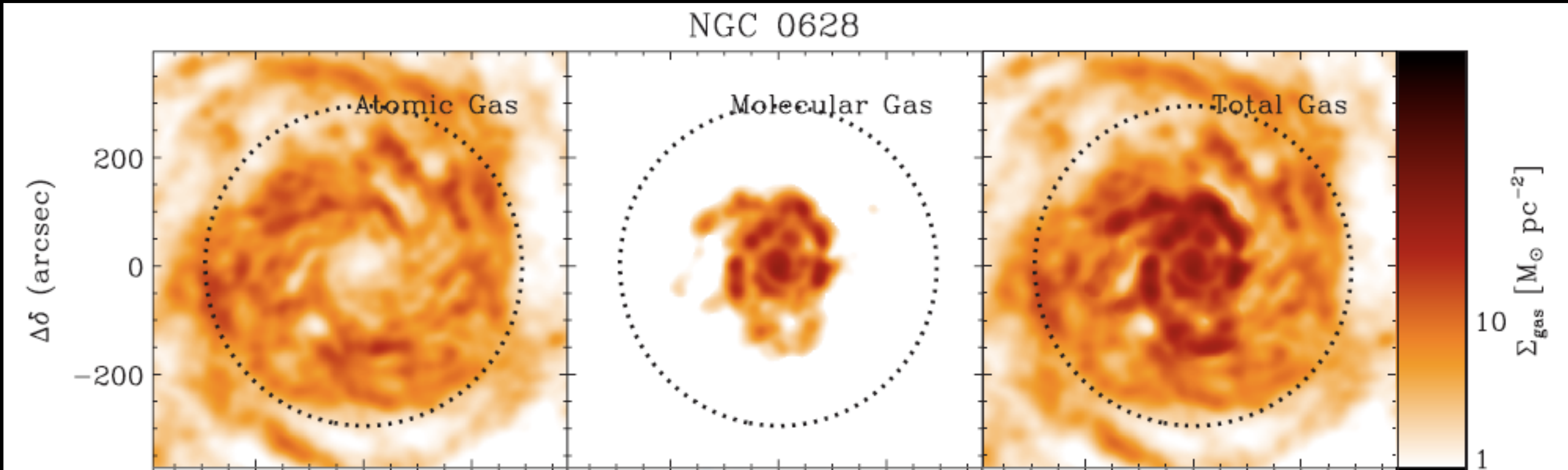
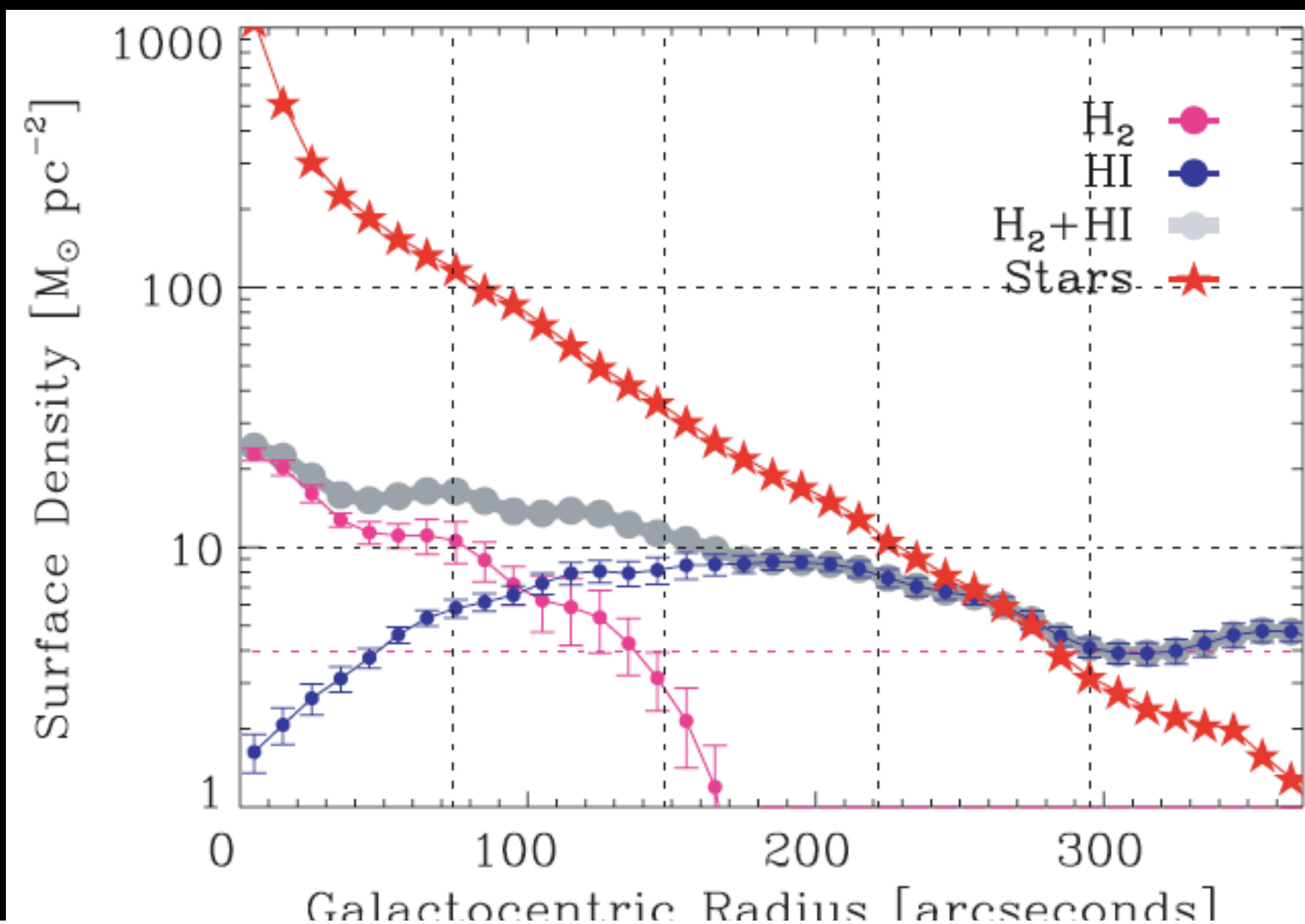


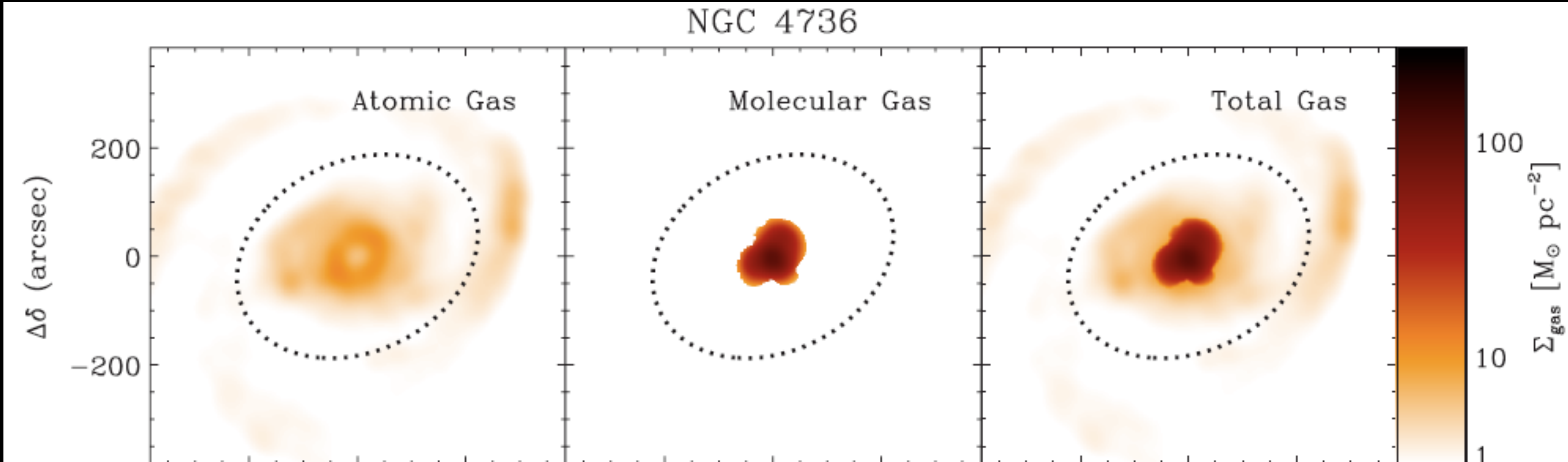
Fig. 9 Composite optical (yellow) and H I (blue) image of the dwarf galaxy NGC 2915 from Meurer et al. (1996) [81].

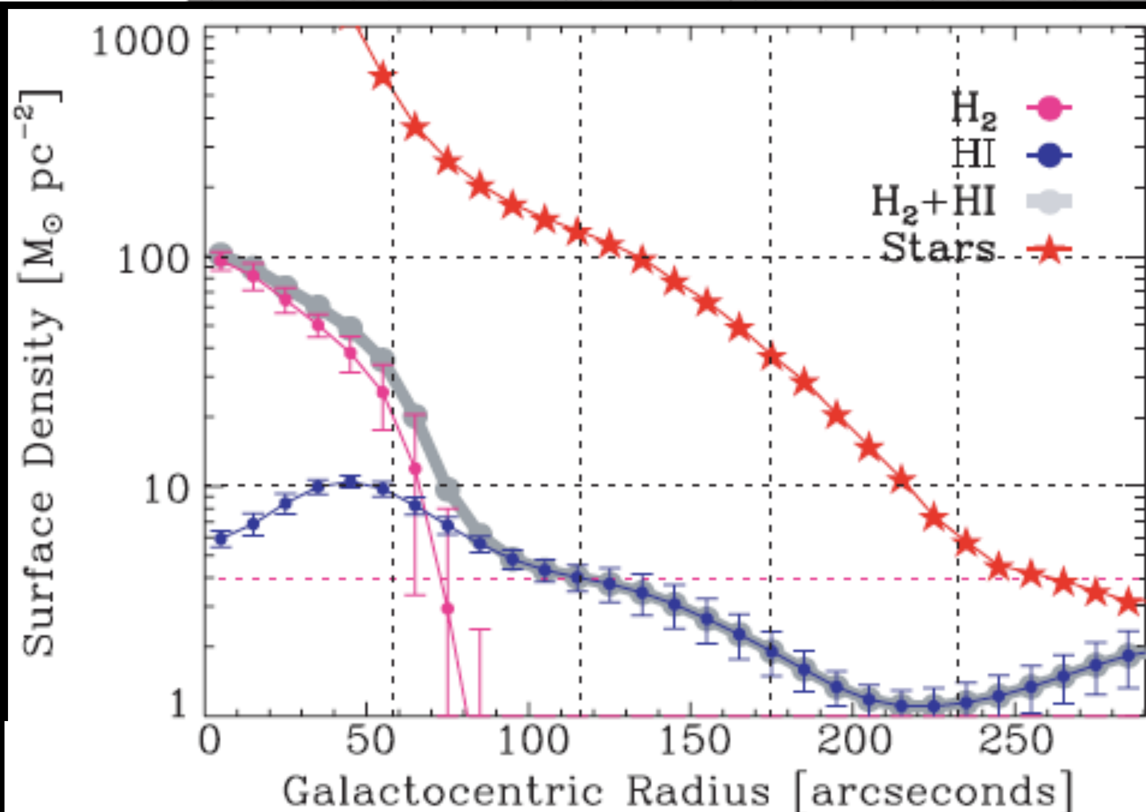




Molecular gas concentrates in galaxy centers

THINGS+Hercules survey

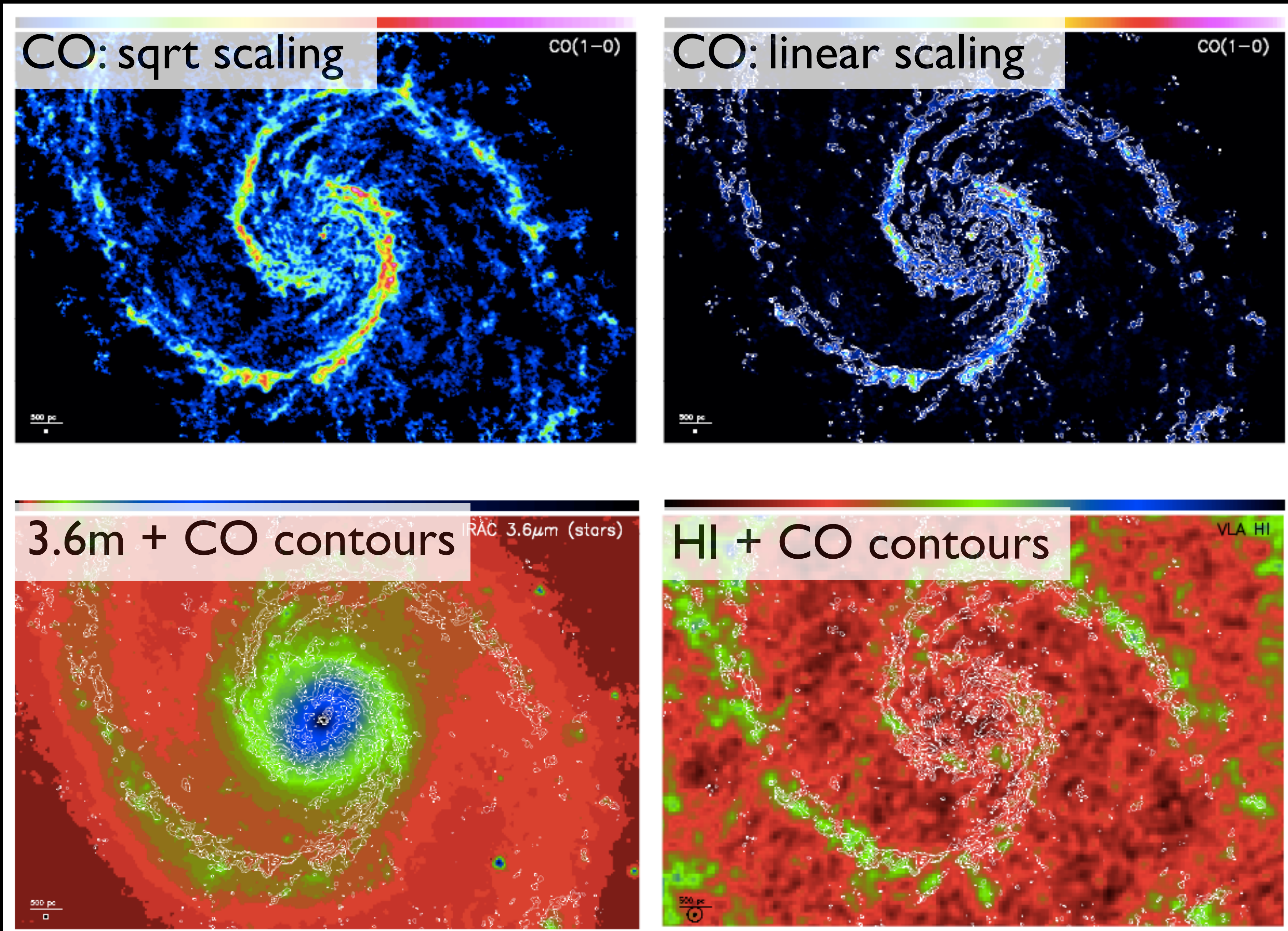




Often reaches very high densities in galaxy centers.

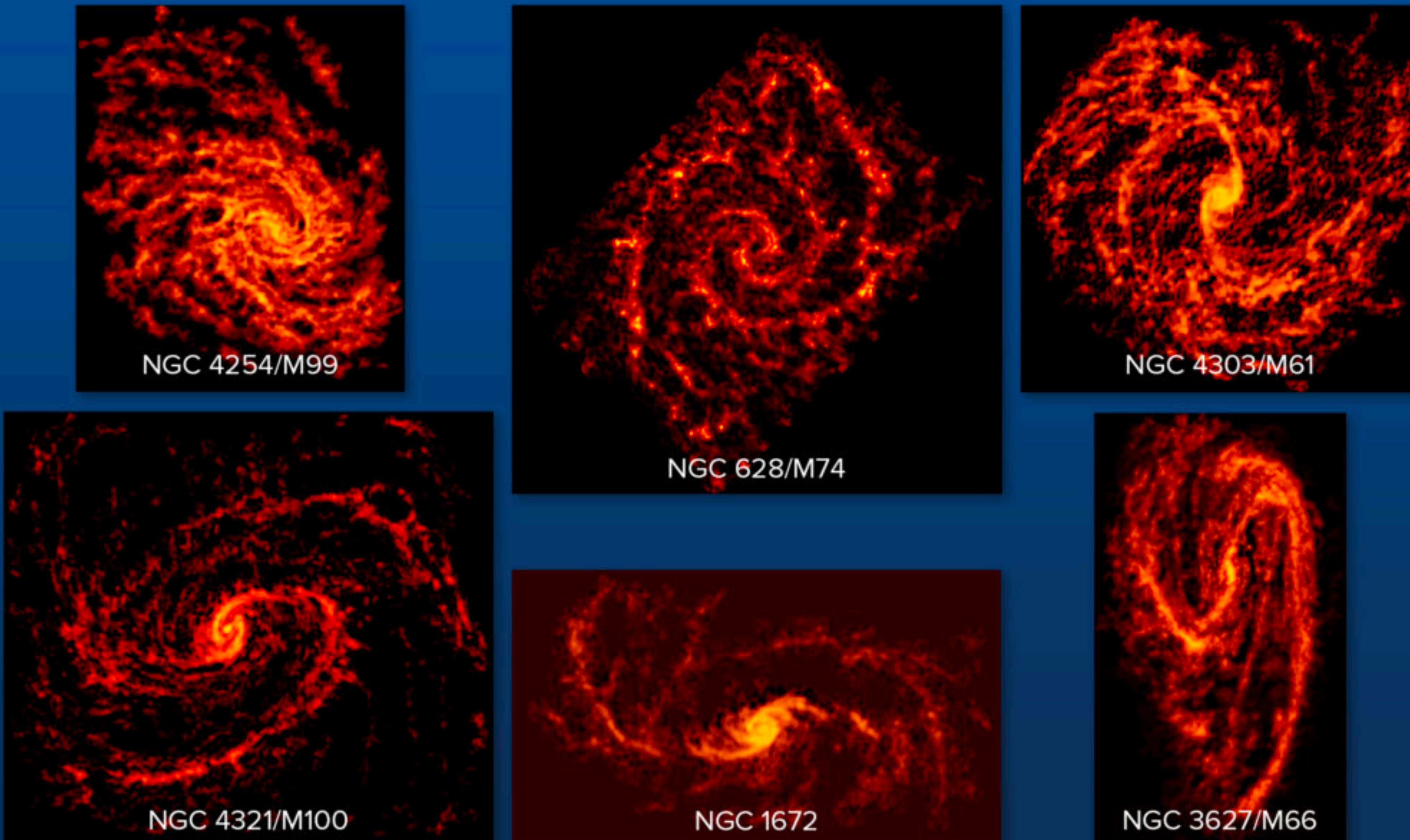
THINGS+Hercules survey

Both phases concentrate in spiral arms



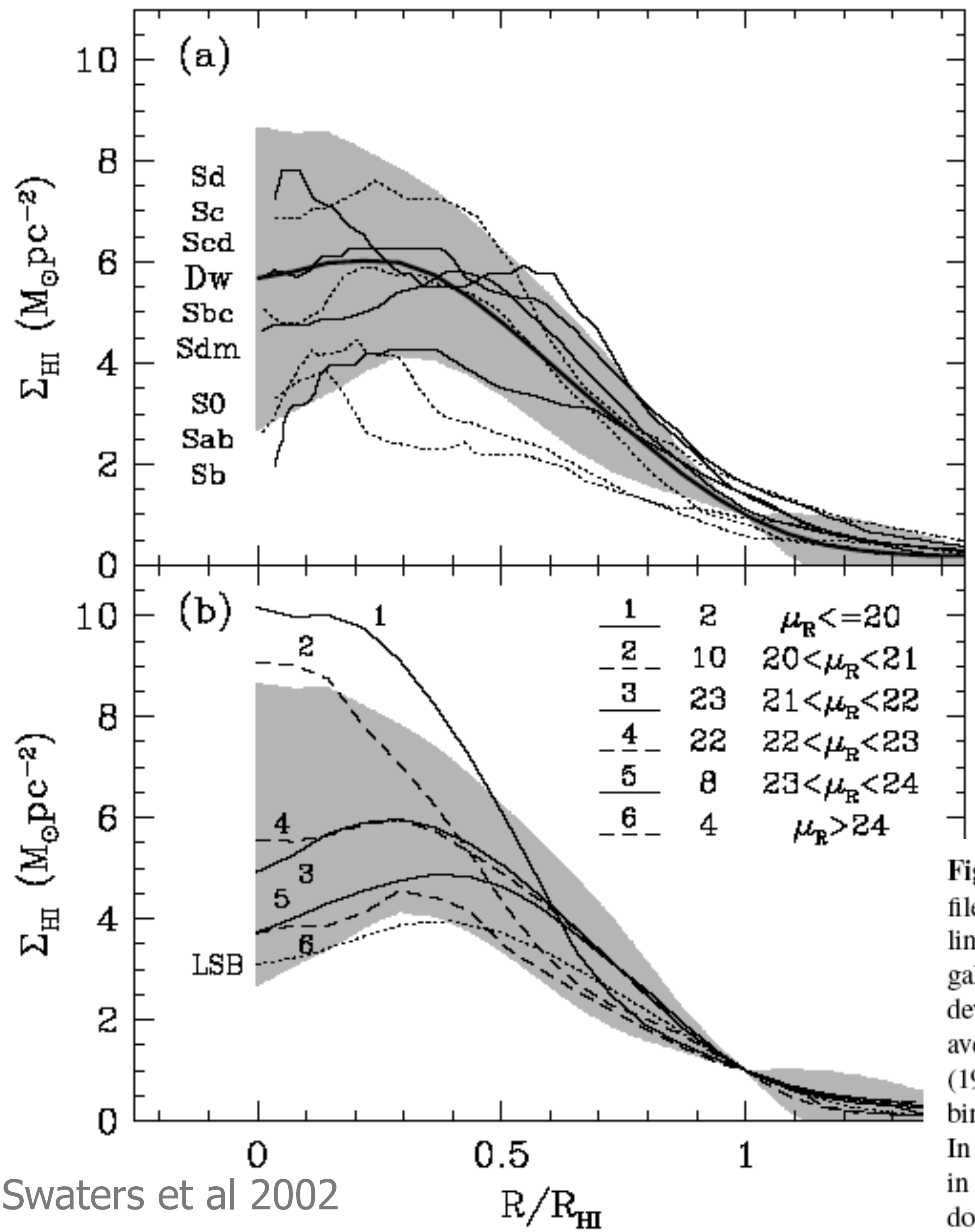
Hi-res/sensitivity M51 Plateau de Bure: Schinnerer et al 2013

“PHANGS”: new ALMA survey resolving giant molecular cloud scales



https://public.nrao.edu/news/2019-alma-phangs/

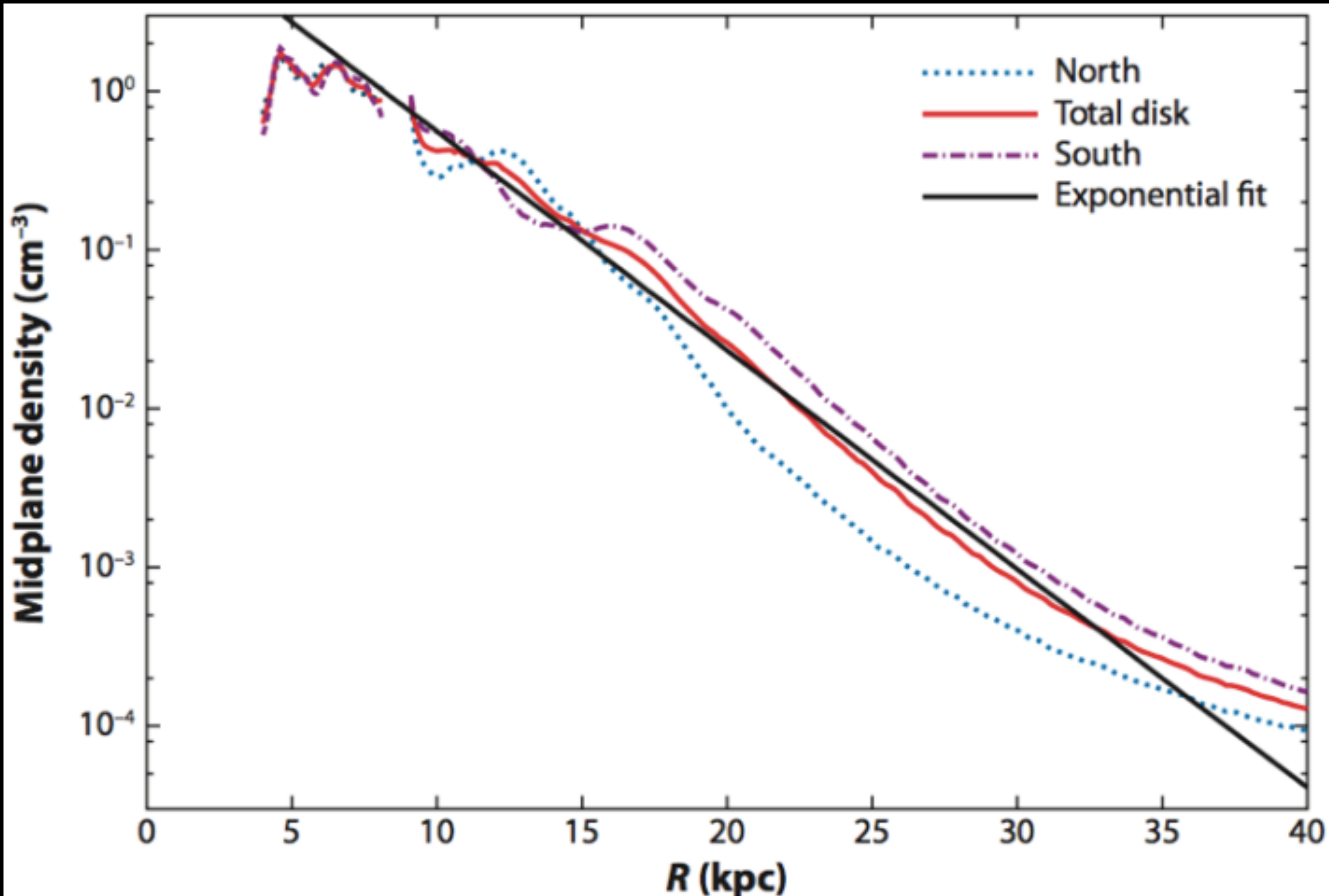
Central HI surface densities span a small range ($3\text{-}9\ M_\odot/pc^2$, or $\sim 10^{20.5}$ atoms/cm^2)



Swaters et al 2002

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).

HI space densities < 1 n_H/cm^3



Kalberla & Kerp 2009 ARA&A

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

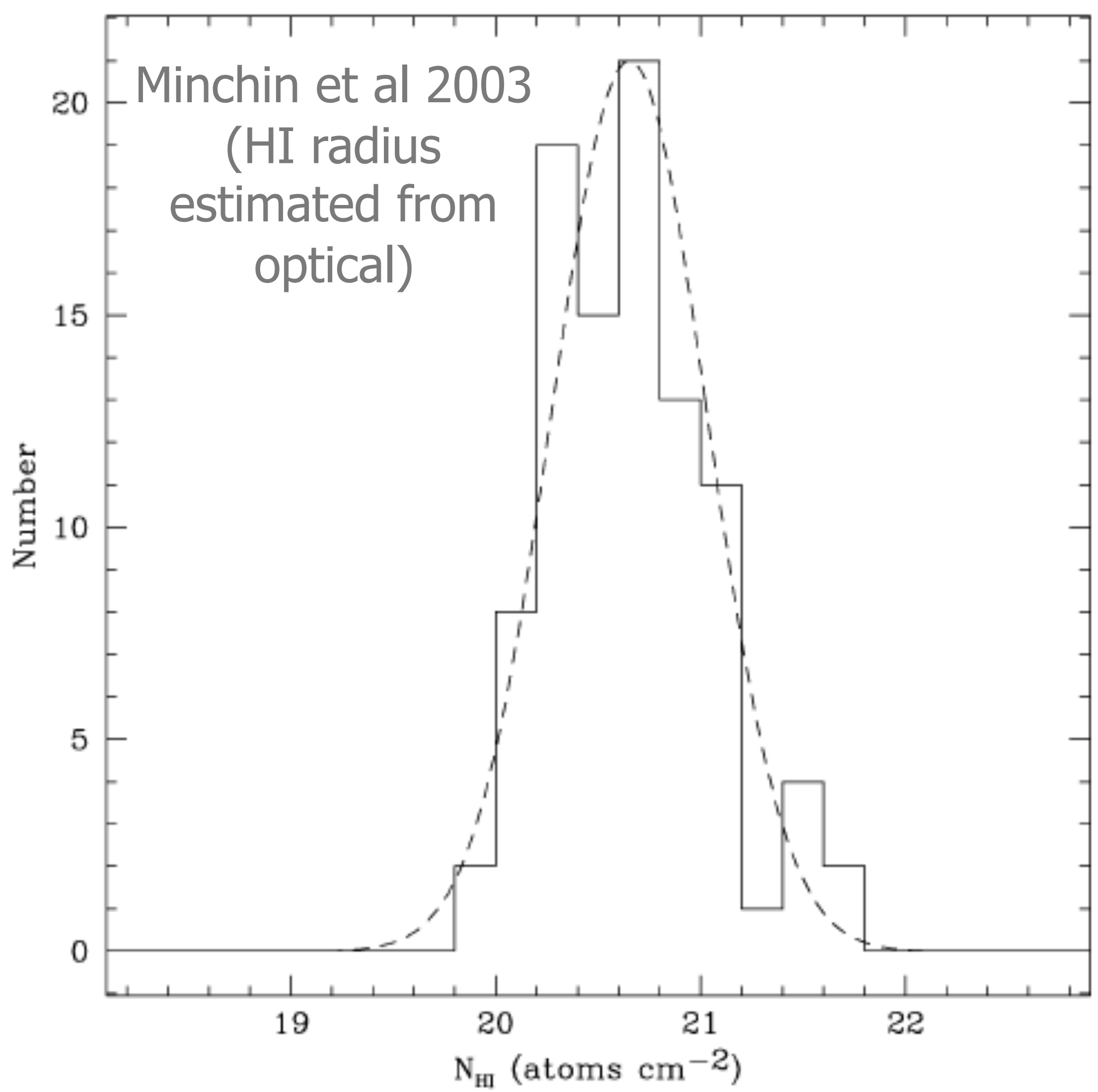


Figure 21. Distribution of inferred column densities of HIDEEP sources. The dashed line indicates a Gaussian with a mean of 20.65 and a scatter of 0.38. It can be seen that this is a fairly good description of the distribution.

Very Narrow Distribution!

Why is HI Surface Density Range So Narrow?

Ionized by UV background?
“Spin Temperature Freeze Out”?

Converts to H_2?
Ionized by SF?
Optically Thick?

Disney 2008

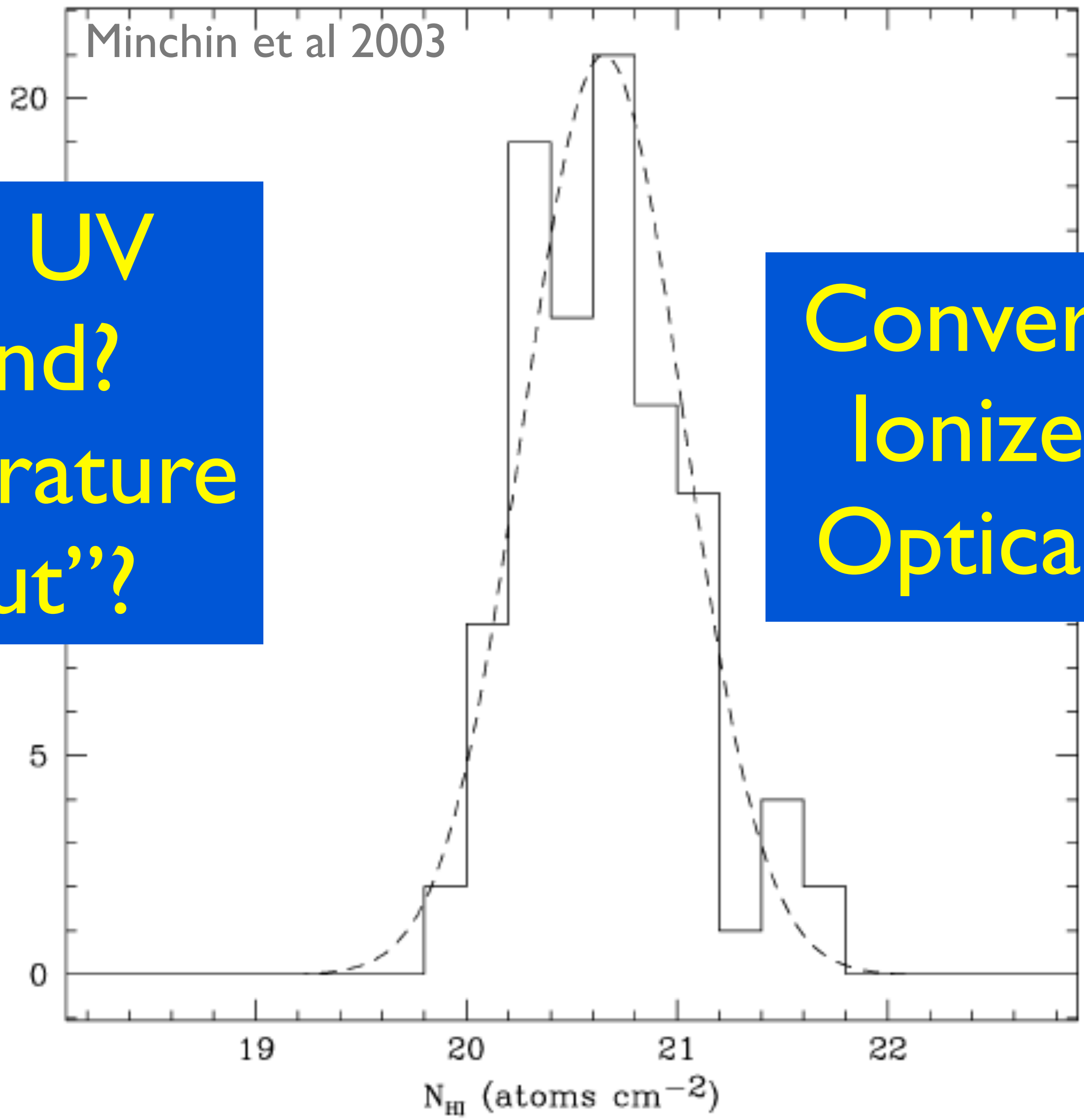


Figure 21. Distribution of inferred column densities of HIDEEP sources. The dashed line indicates a Gaussian with a mean of 20.65 and a scatter of 0.38. It can be seen that this is a fairly good description of the distribution.

N_{HI} varies with galaxy surface brightness

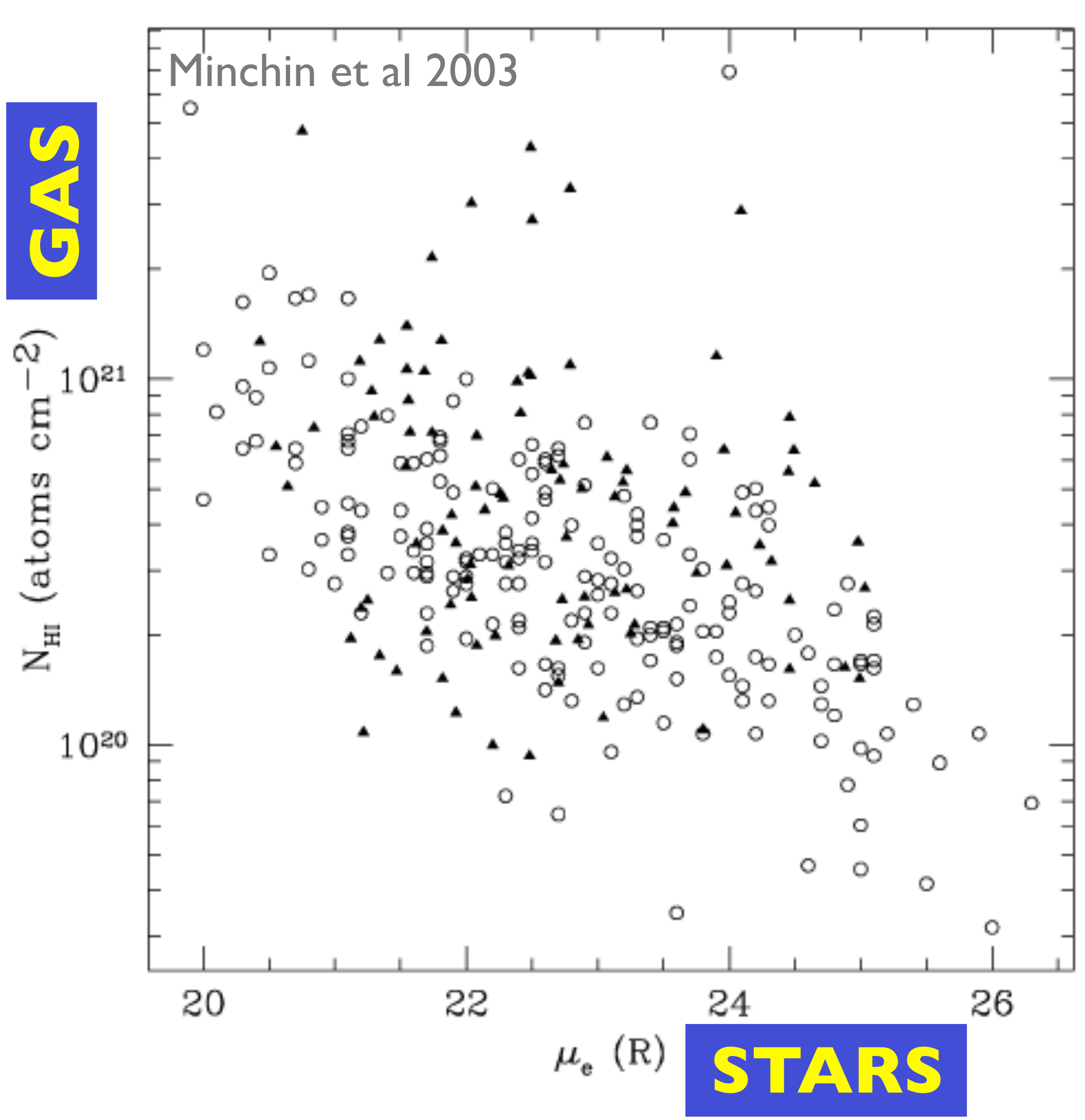
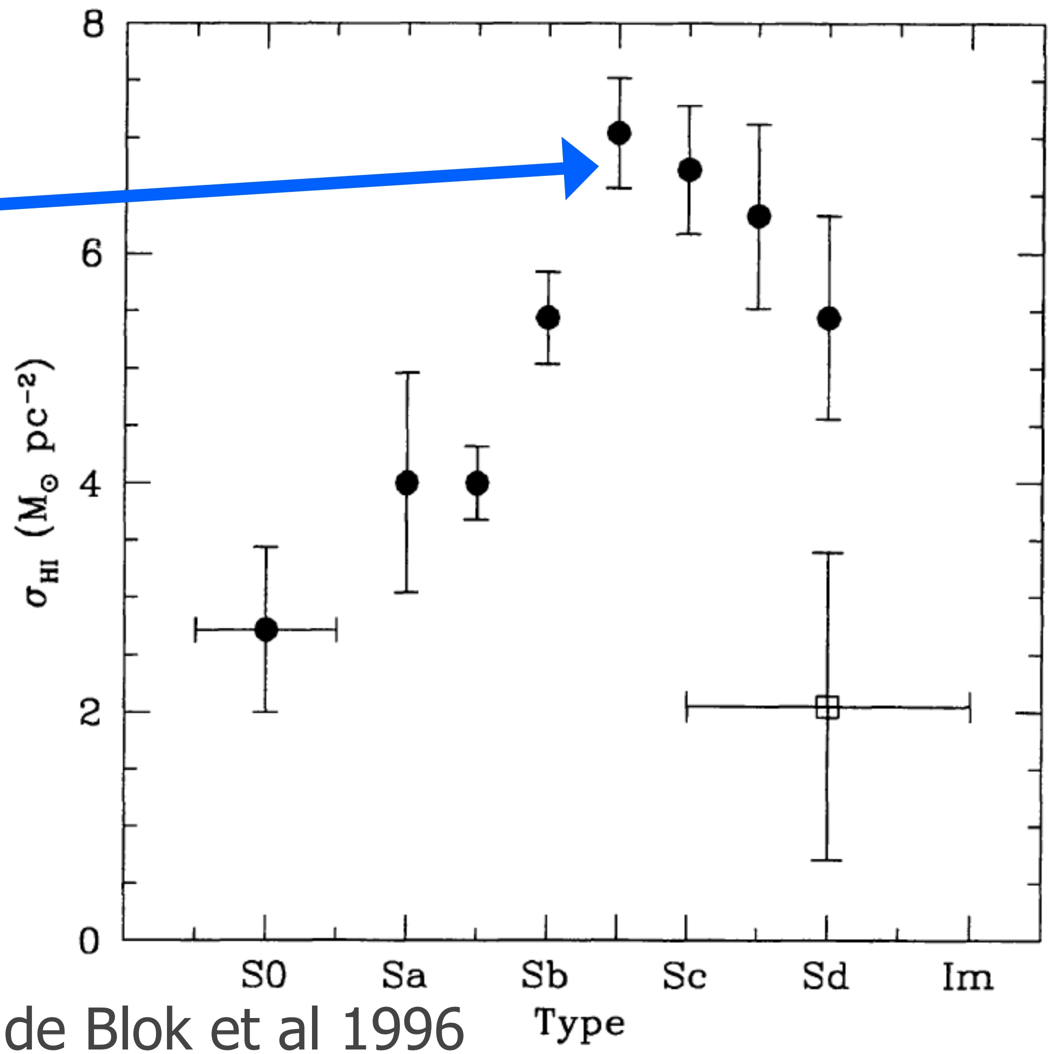


Figure 23. Comparison between the surface brightness–column-density distribution for HIDEEP (triangles) and Impey et al. (1996), converted to R band assuming $B - R = 1.1$ (open circles). Error bars have been omitted for the sake of clarity.

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

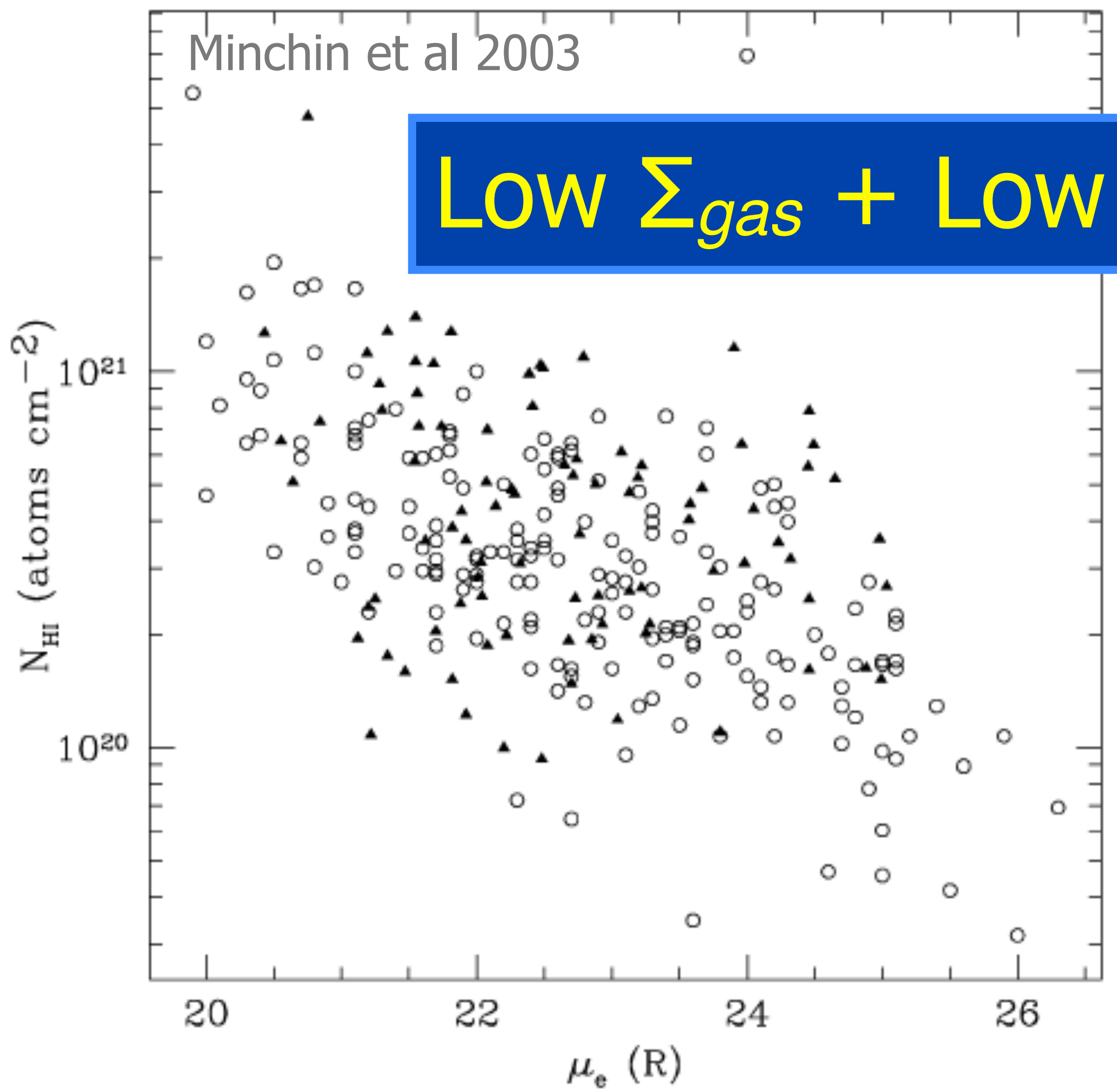
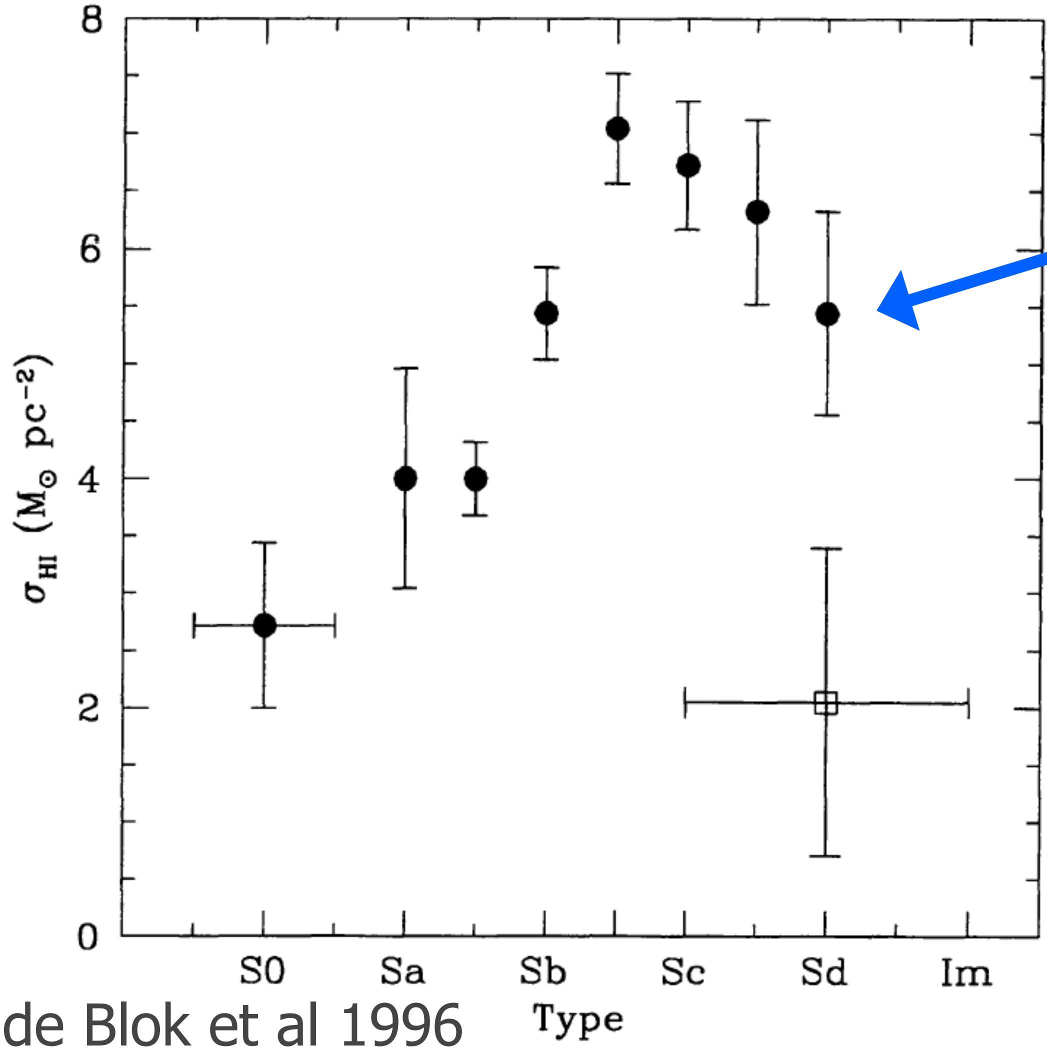


Figure 23. Comparison between the surface brightness–column-density distribution for HIDEEP (triangles) and Impey et al. (1996), converted to R band assuming $B - R = 1.1$ (open circles). Error bars have been omitted for the sake of clarity.

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

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

Avg. HI surface density varies w/ Hubble Type



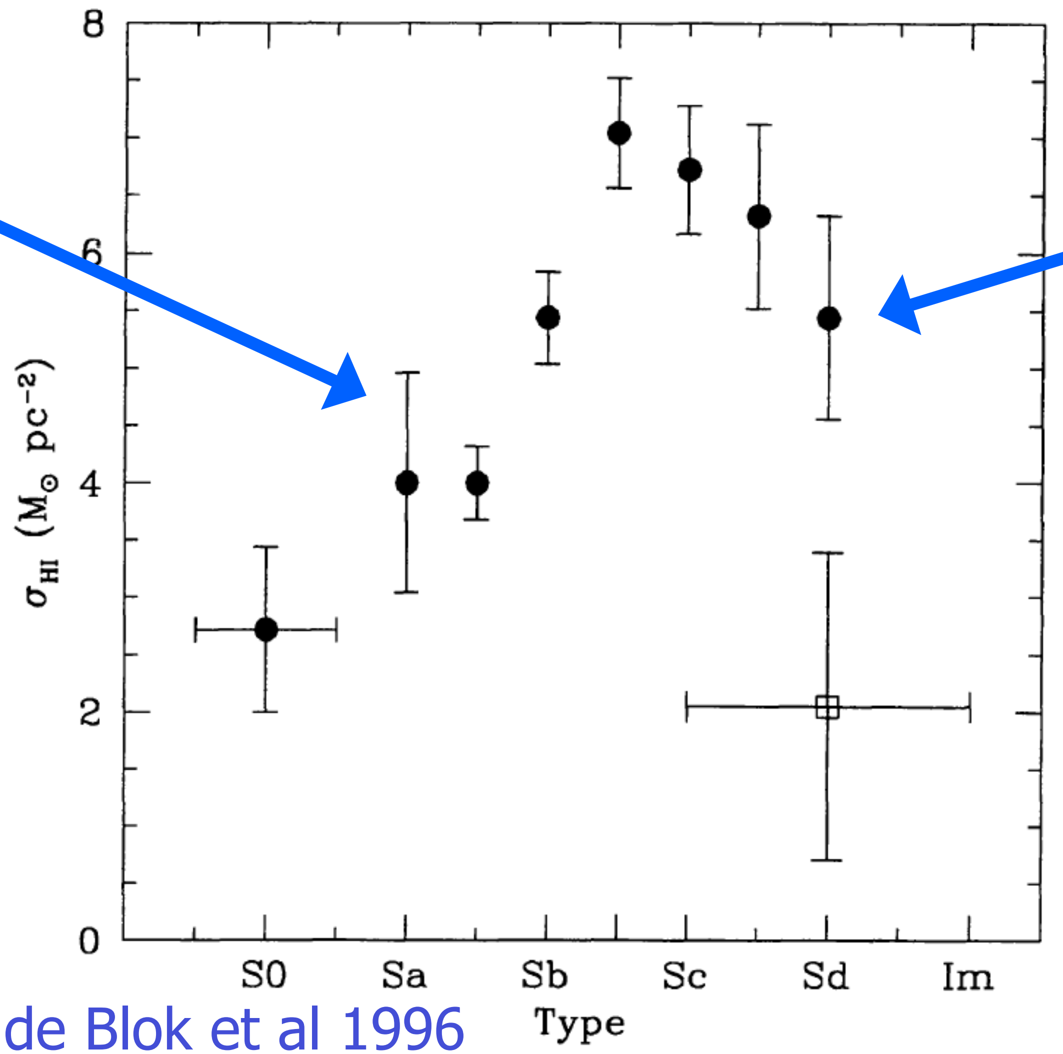
de Blok et al 1996

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.

Falls because baryonic disk has lower surface density

Avg. HI surface density varies w/ Hubble Type

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

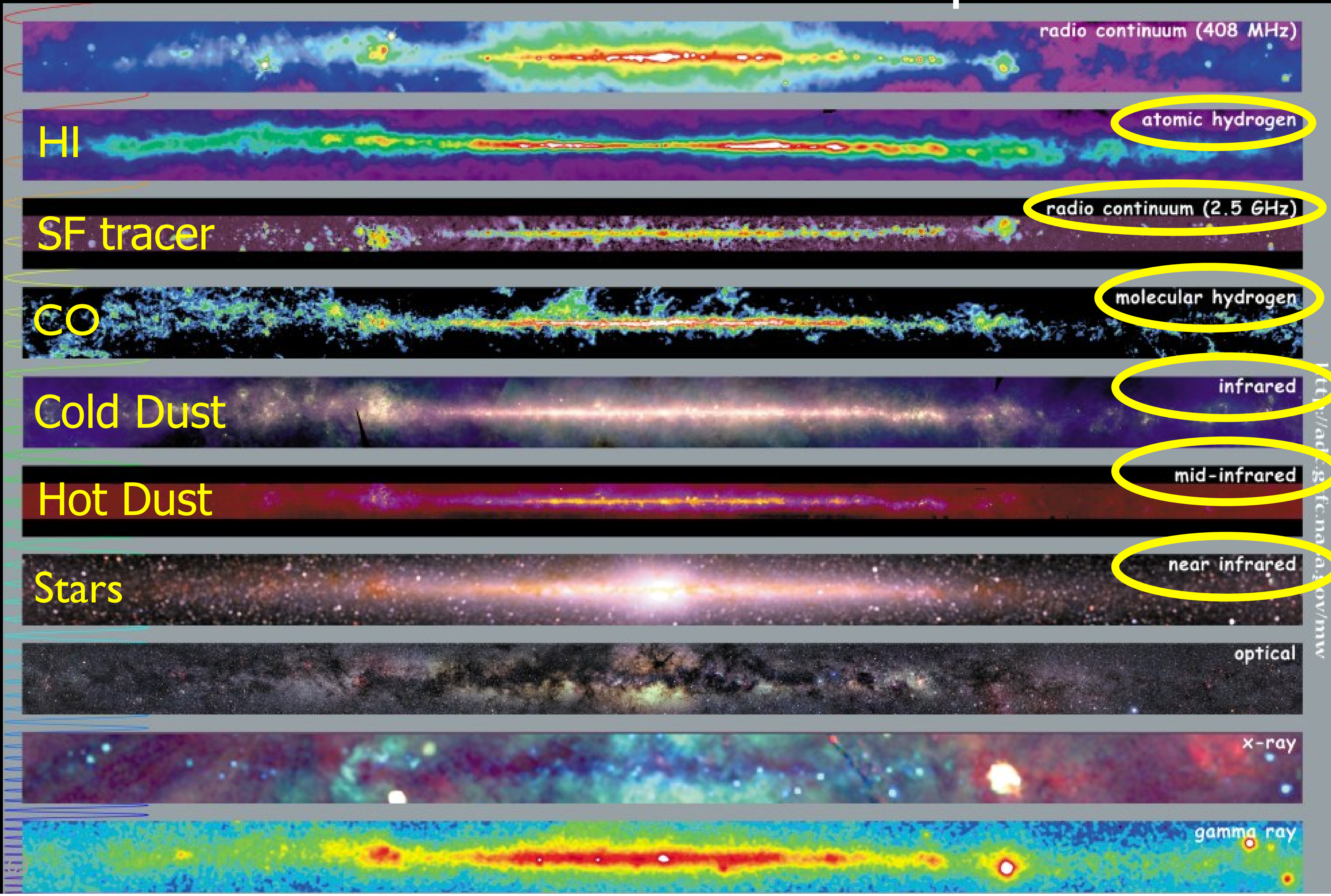
Figure 4. LSB galaxies and their place in the Hubble-type – average H I surface density diagram. The average surface density is defined as the average surface density of the H I within half of the optical radius R_{25}. Filled circles are HSB galaxies from the sample of Cayatte et al. (1994). Vertical 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.

How is the gas distributed vertically?

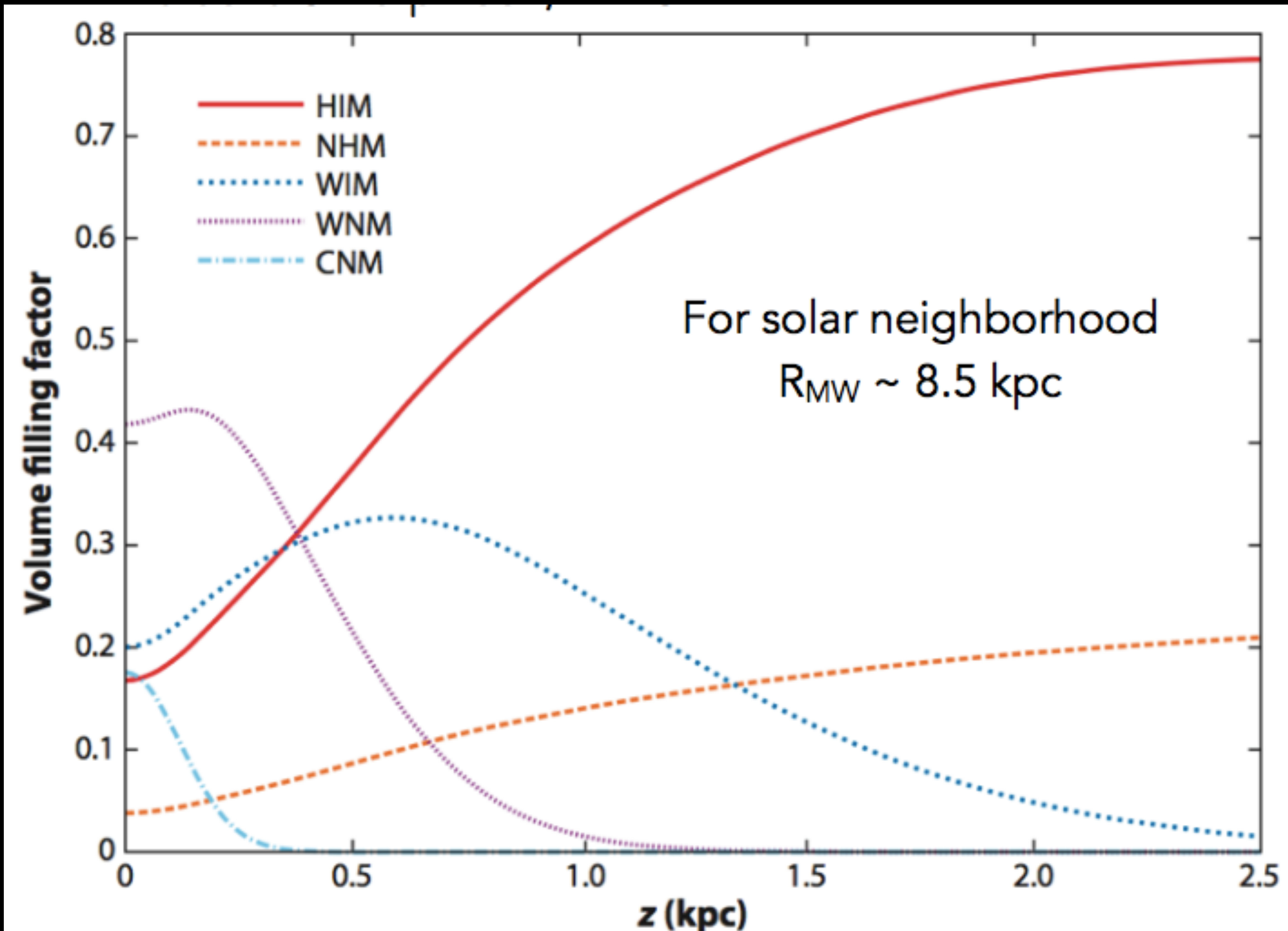
Note:

Vertical support of cold is primarily through turbulence (i.e., dynamical pressure), not thermal pressure

Vertical structure varies, with cold components more confined to the disk plane



ISM scale heights in the Milky Way

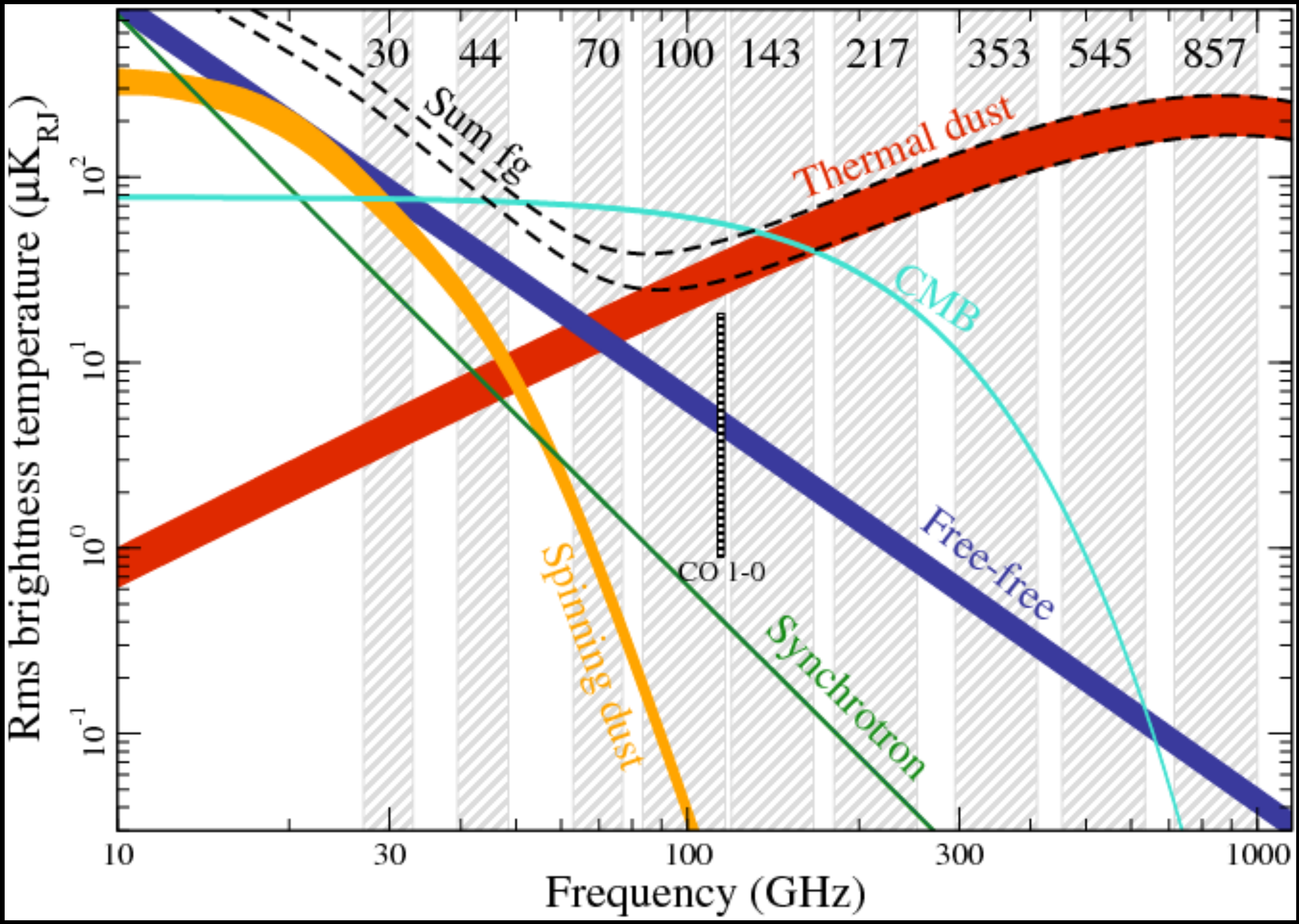


HIM: Hot ionized medium, NHM: Neutral halo medium, WIM=Warm ionized medium

Kalberla & Kerp 2009 ARA&A

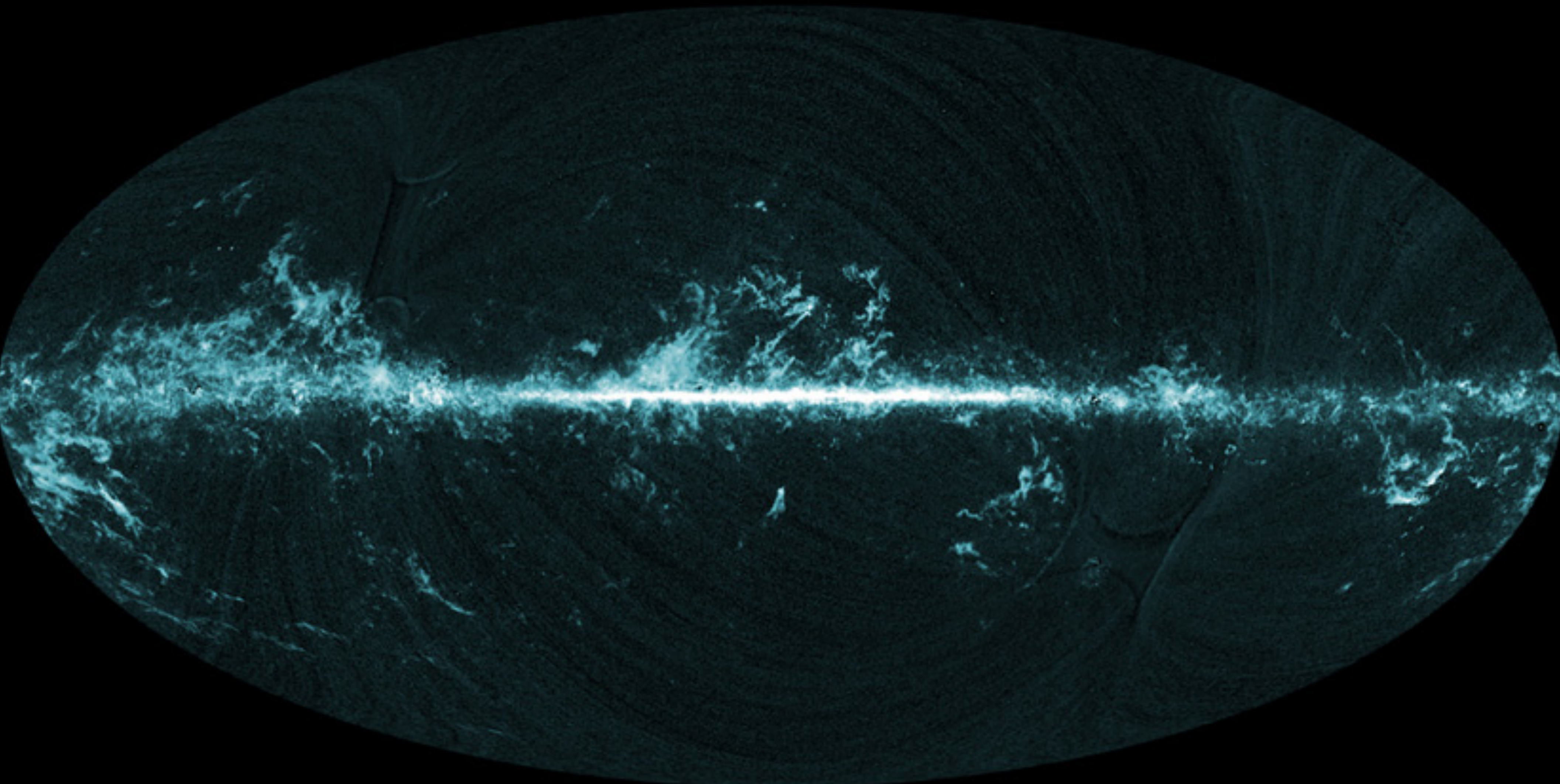
All sky maps of key ISM components

- Direct mapping of emission
- Inference from multi-frequency spectral fitting w/ Planck



http://adsabs.harvard.edu/abs/2016A%26A...594A...1P

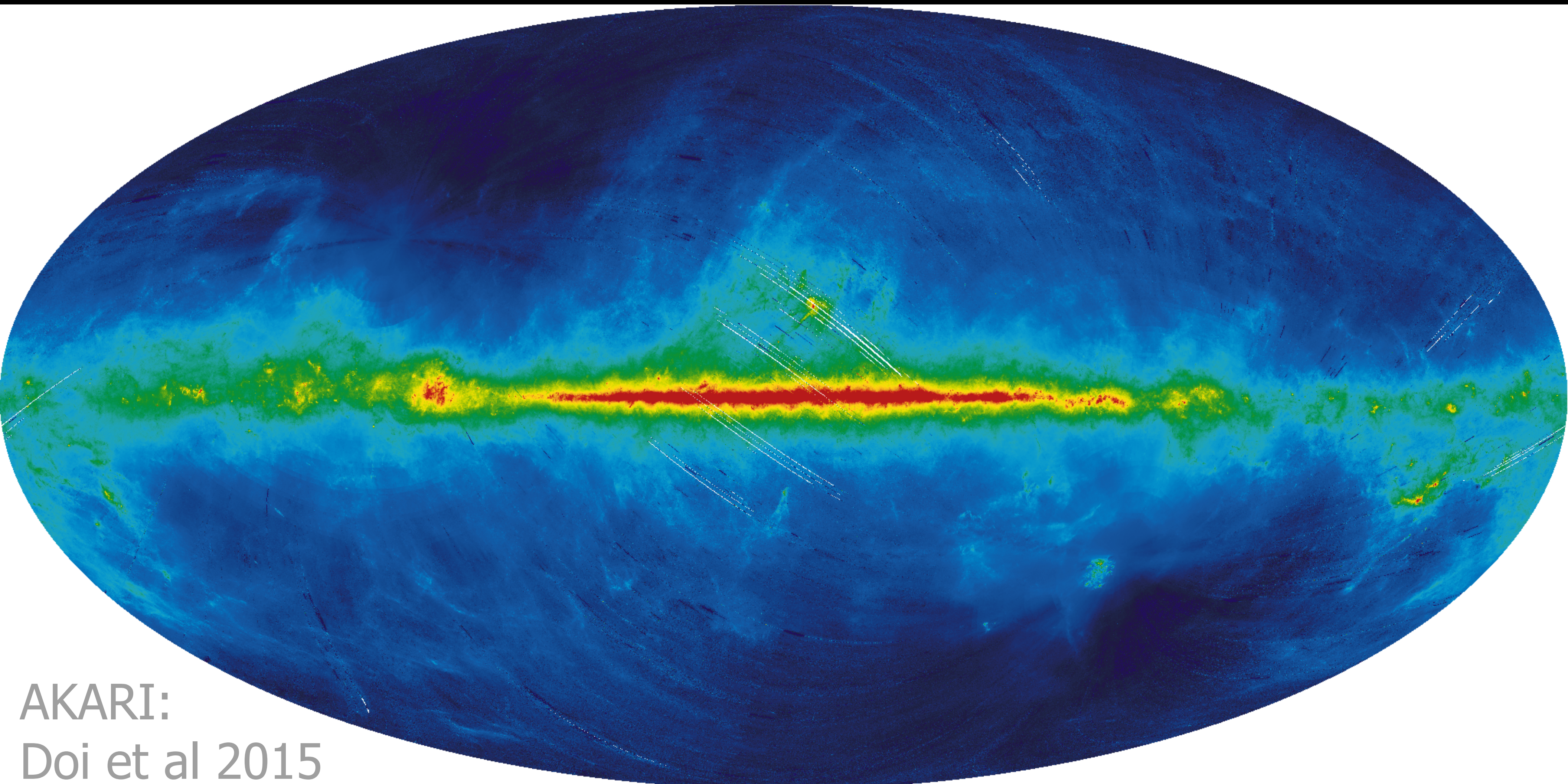
Molecular Gas



CO map from Planck

http://sci.esa.int/planck/50004-new-planck-maps-reveal-unseen-details-across-the-milky

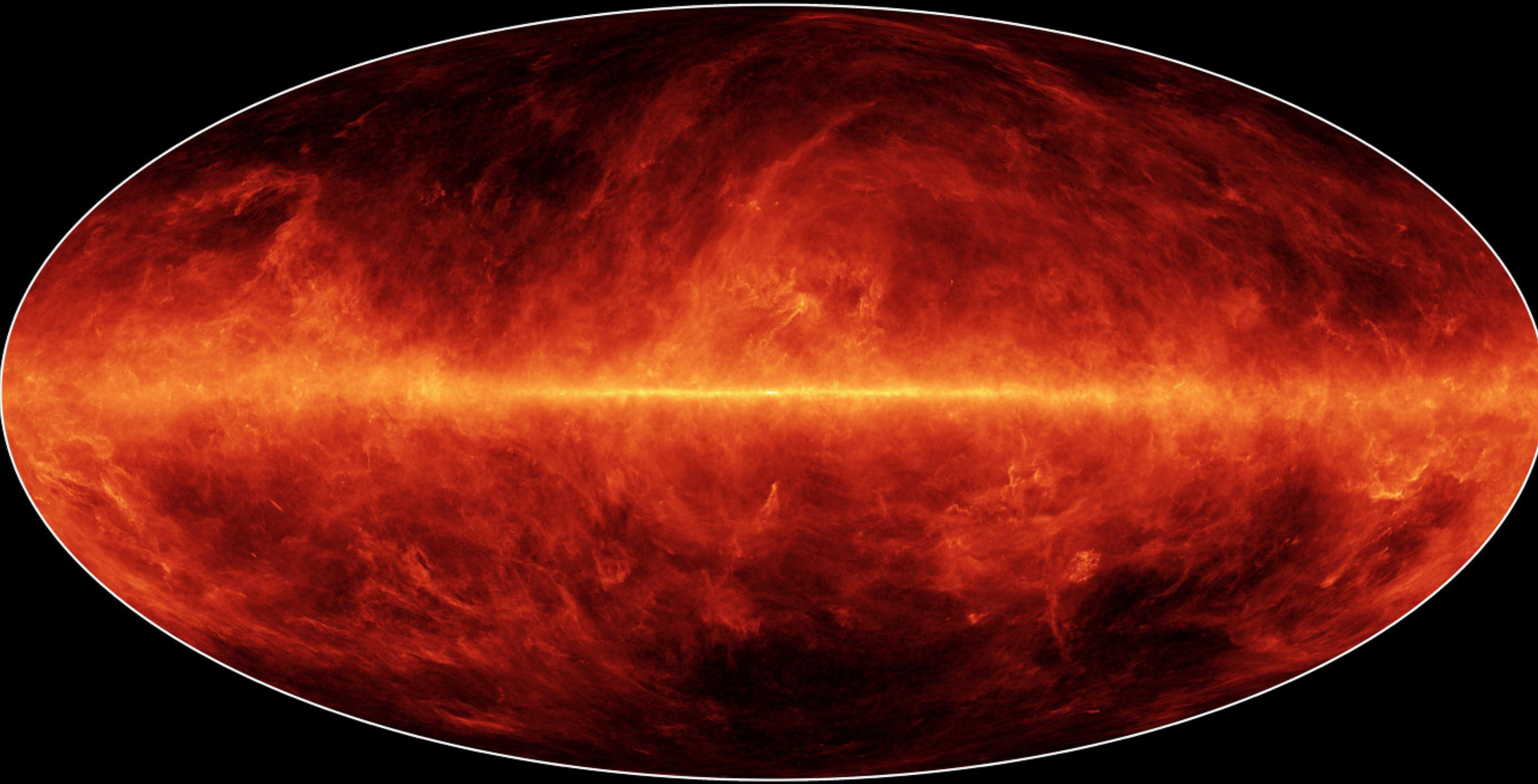
160μm Warm+Cool Dust Emission



Note correspondence w/ CO structure

https://lambda.gsfc.nasa.gov/product/foreground/f_images

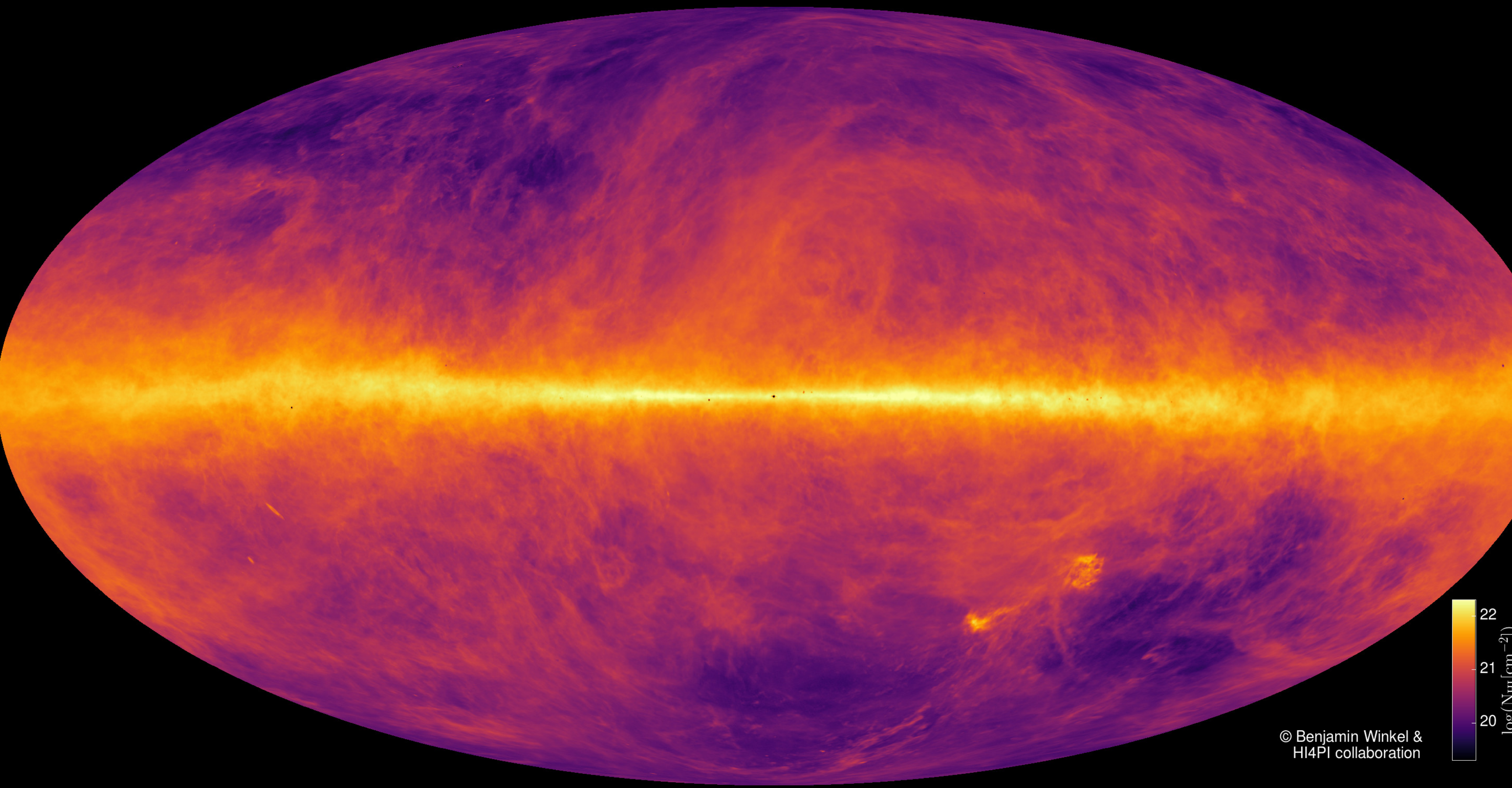
Longer-wavelength Cool Dust Emission



545 GHz, corresponding to ~20K dust: Planck Collaboration 2015

https://astronomynow.com/2015/02/06/planck-reveals-first-

Atomic Hydrogen



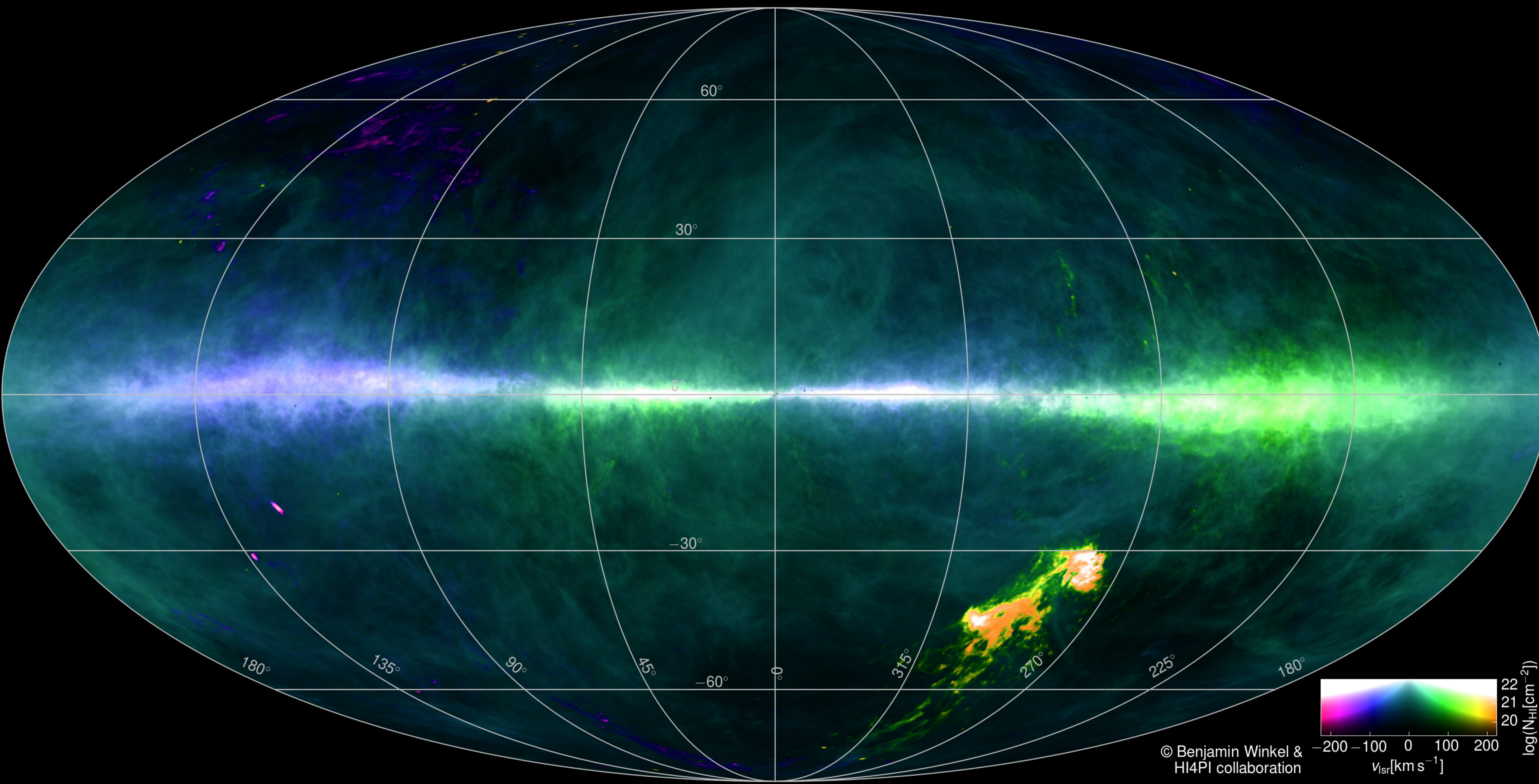
Note correspondence w/ cold dust

Effelsberg-Bonn HI Survey

Winkel et al 2016

https://astro.uni-bonn.de/~bwinkel/research.h

Velocity structure of HI



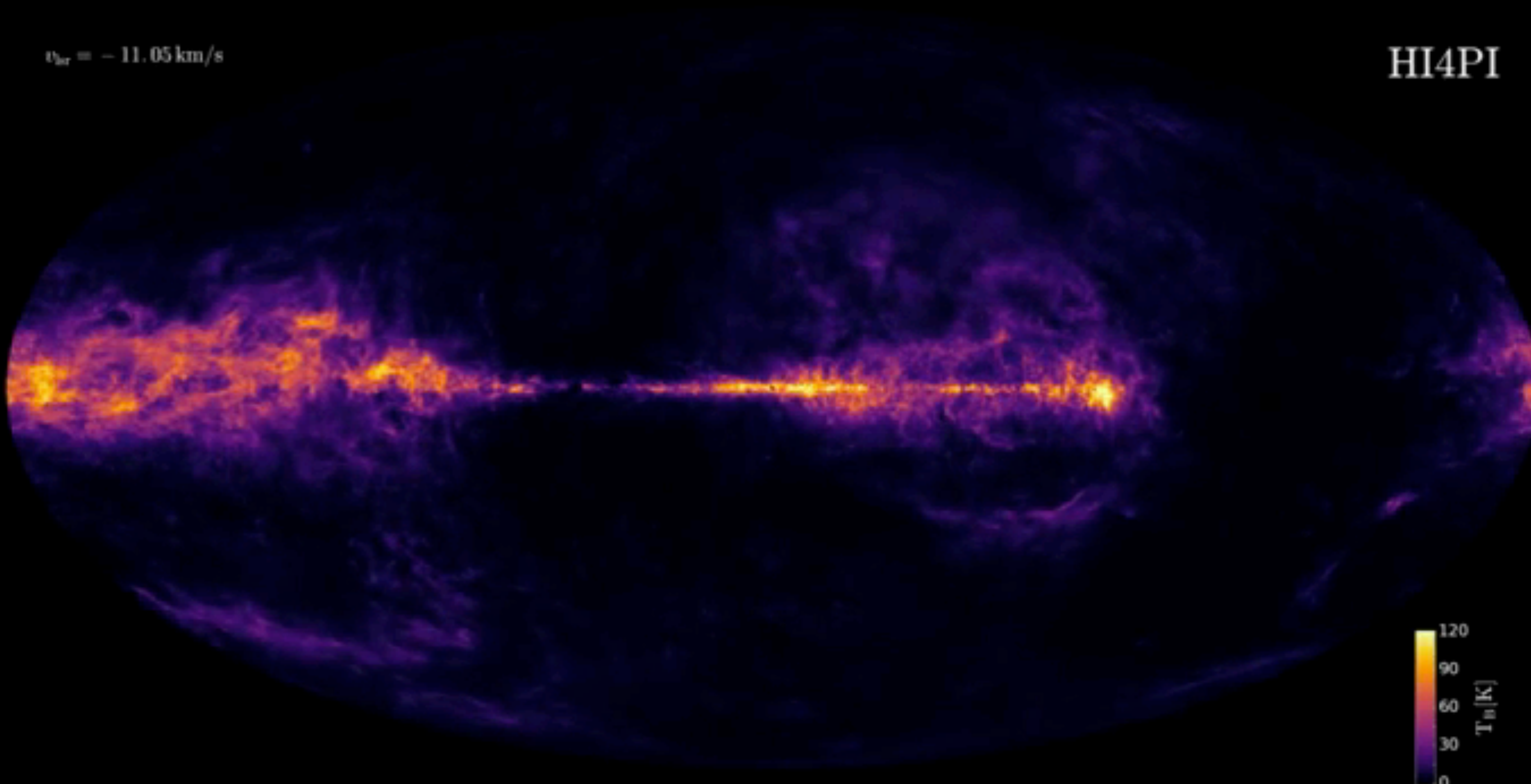
https://www.youtube.com/watch?v=Q2mgpsTFuV8

Effelsberg-Bonn HI Survey
Winkel et al 2016

https://astro.uni-bonn.de/~bwinkel/research.h

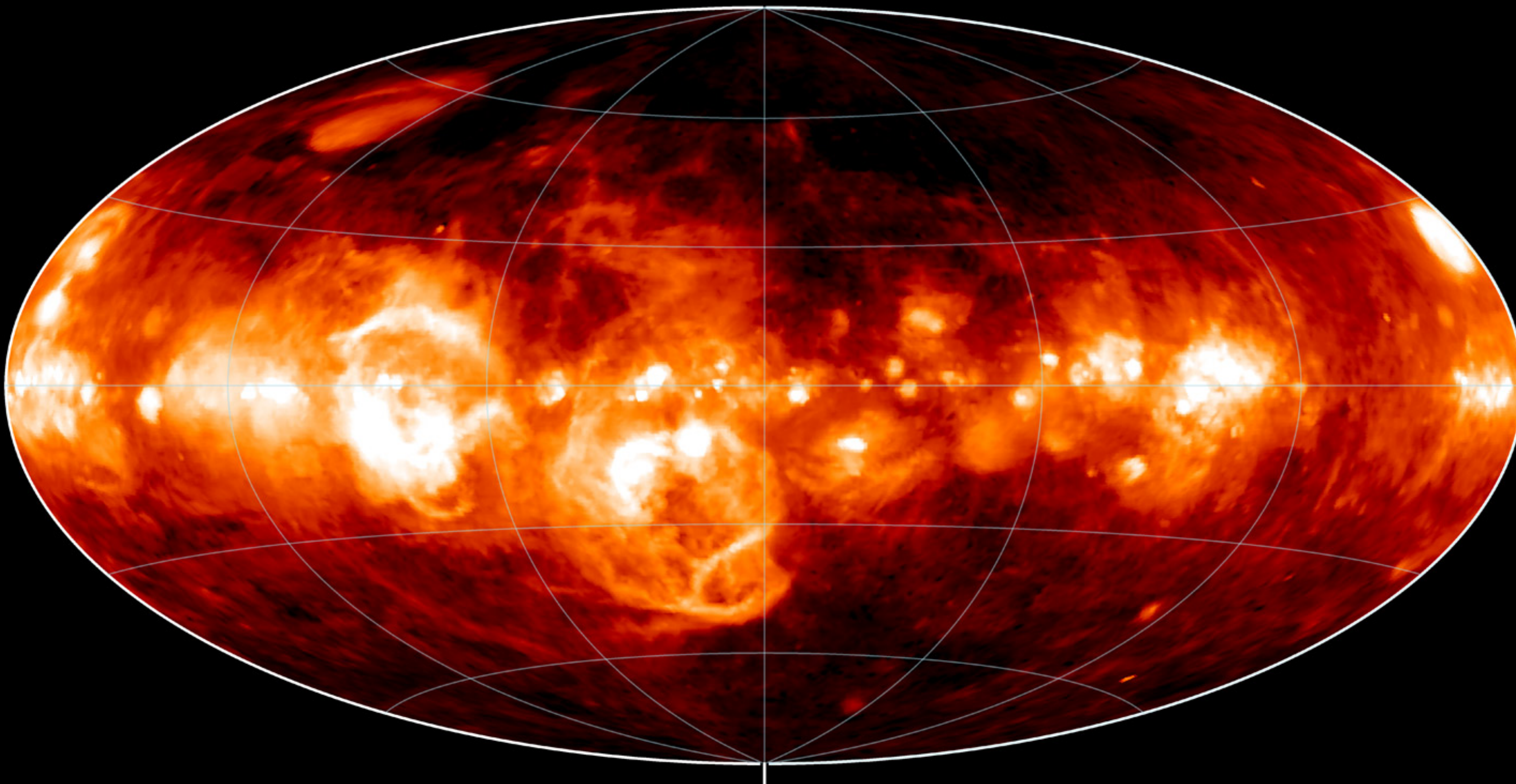
Velocity structure of HI

https://www.youtube.com/watch?v=Q2mgpsTFuV8



https://astro.uni-bonn.de/~bwinkel/research.h

Hα Map of Milky Way

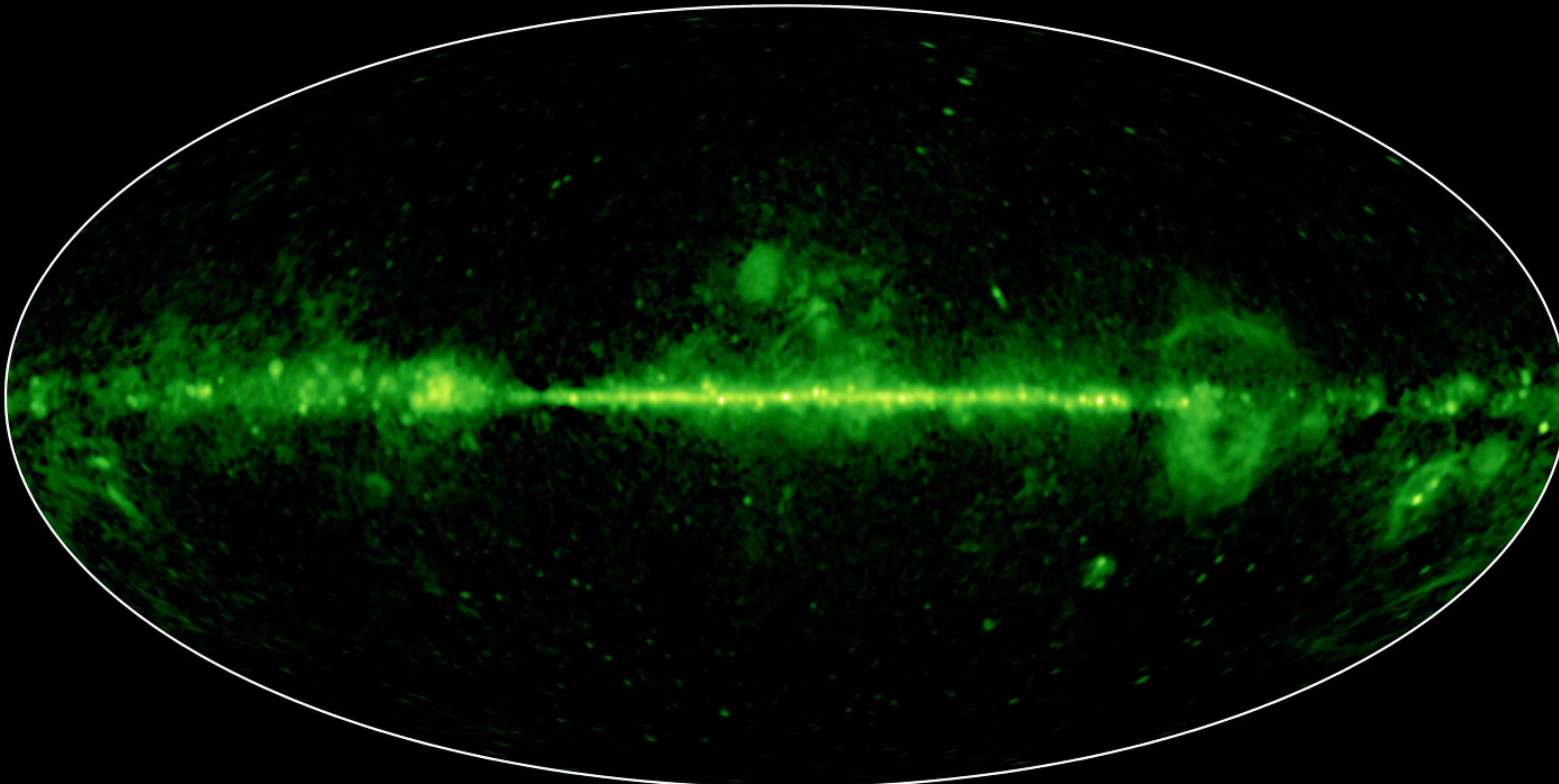


WHAM: Wisconsin H-Alpha Mapper
Haffner et al 2017

http://news.wisc.edu/uw-project-brings-milky-ways-ionized-hydrogen-into-focus/

Free-free emission

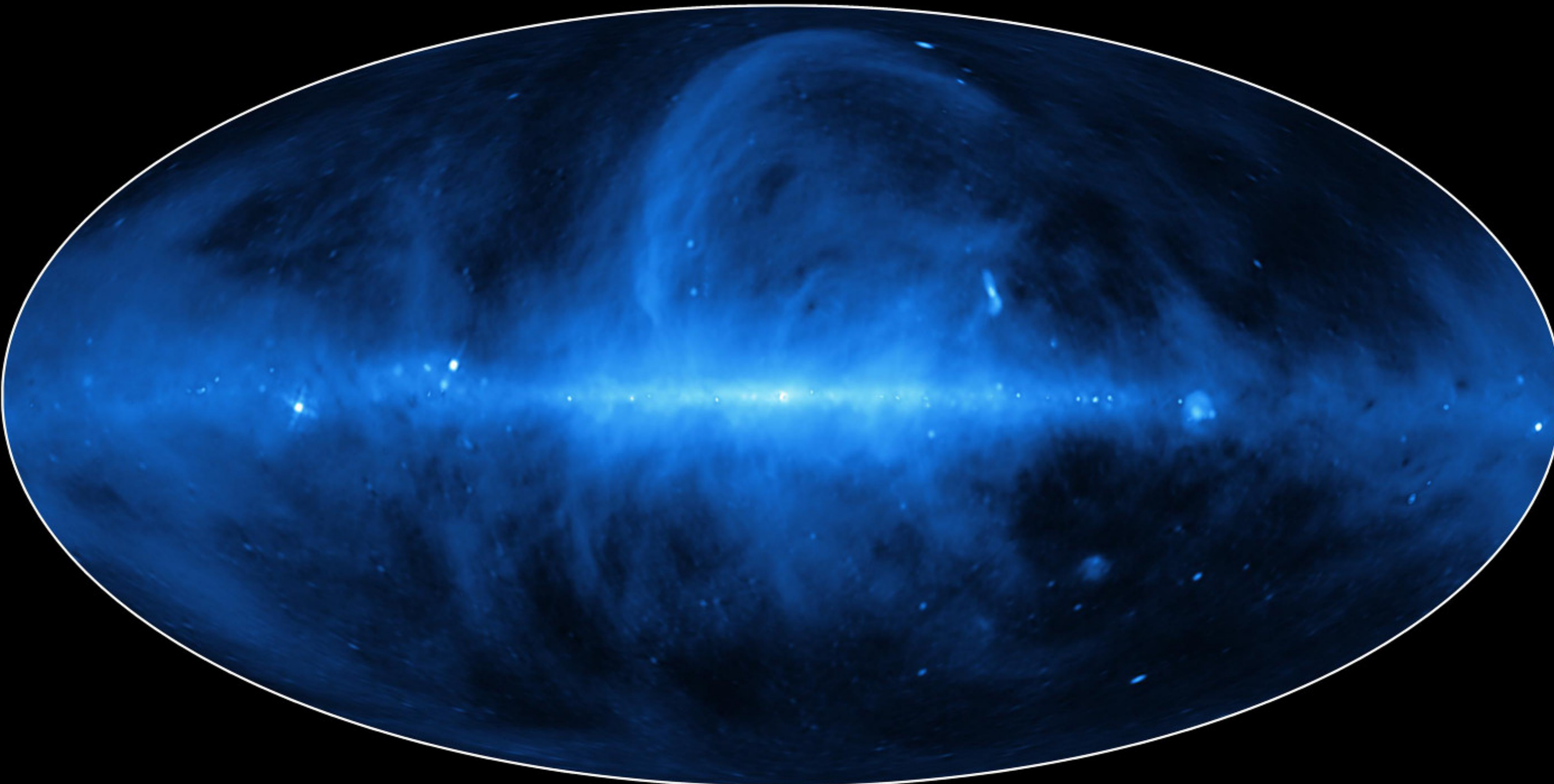
(Ionized gas, unaffected by dust obscuration)



Planck Collaboration 2015

https://astronomynow.com/2015/02/06/planck-reveals-first-stars-were-born-

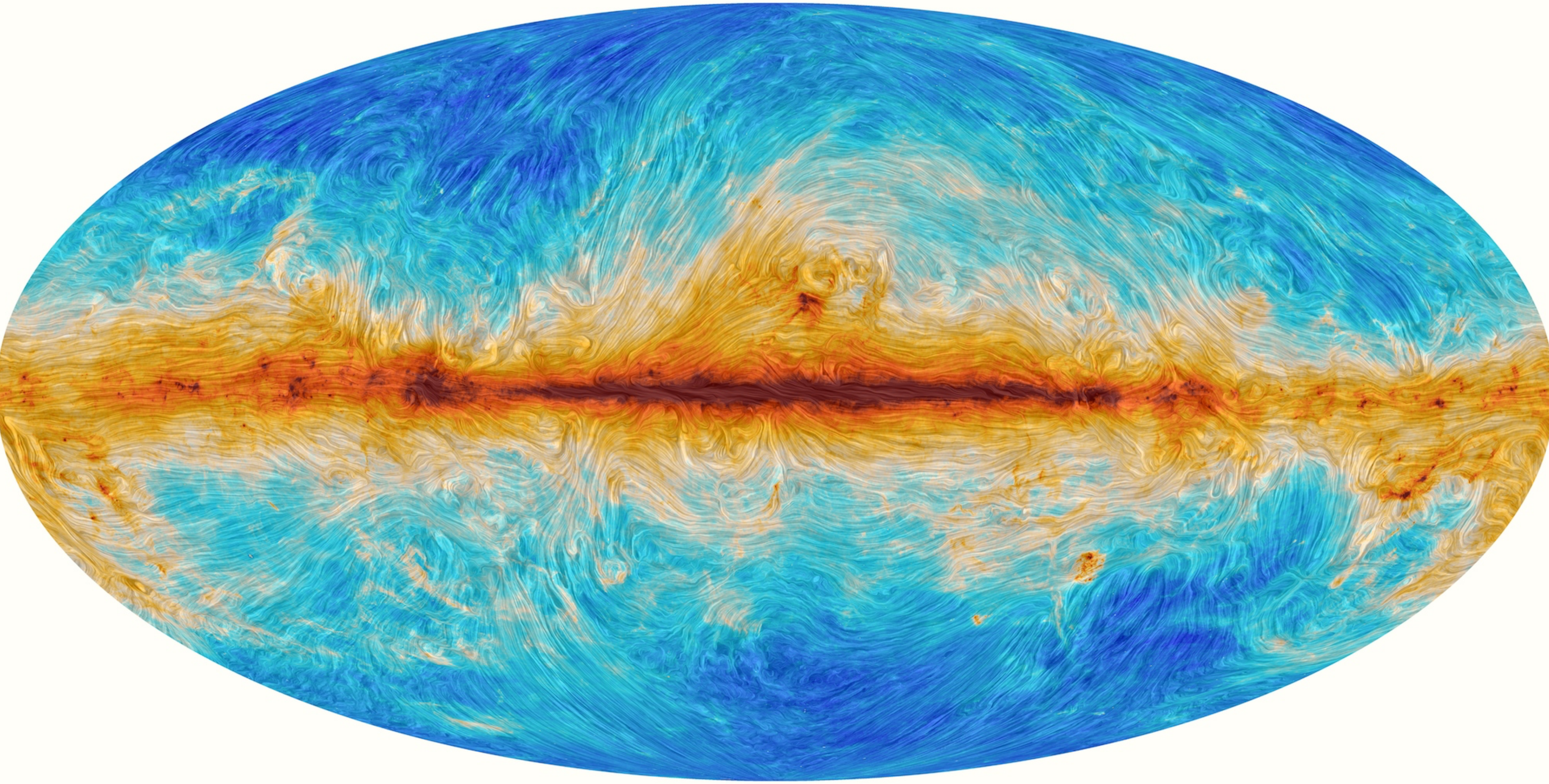
Magnetic fields play a role



Synchrotron emission; Planck collaboration 2015

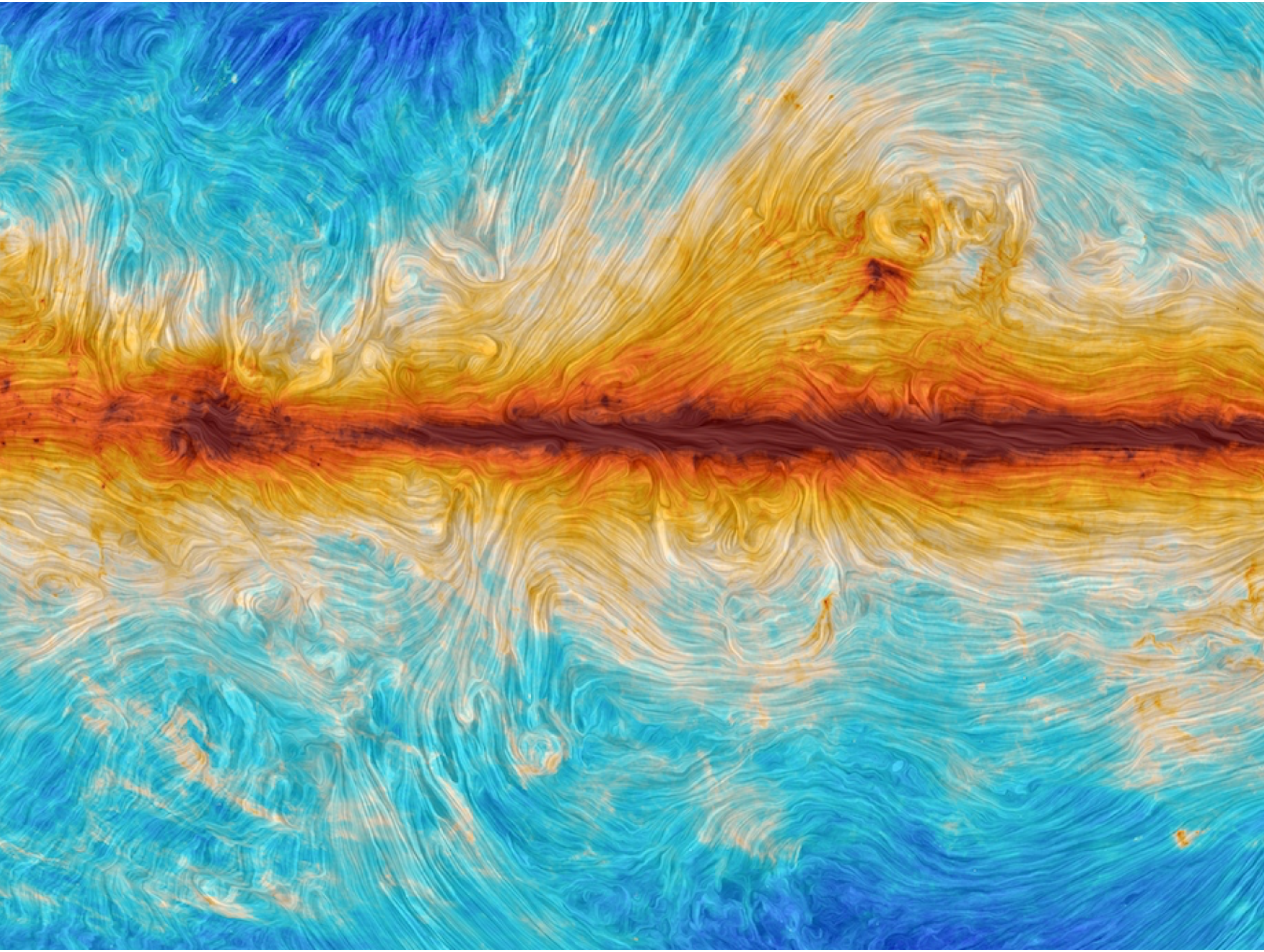
 https://astronomynow.com/2015/02/06/planck-reveals-first-stars-were-born-later/

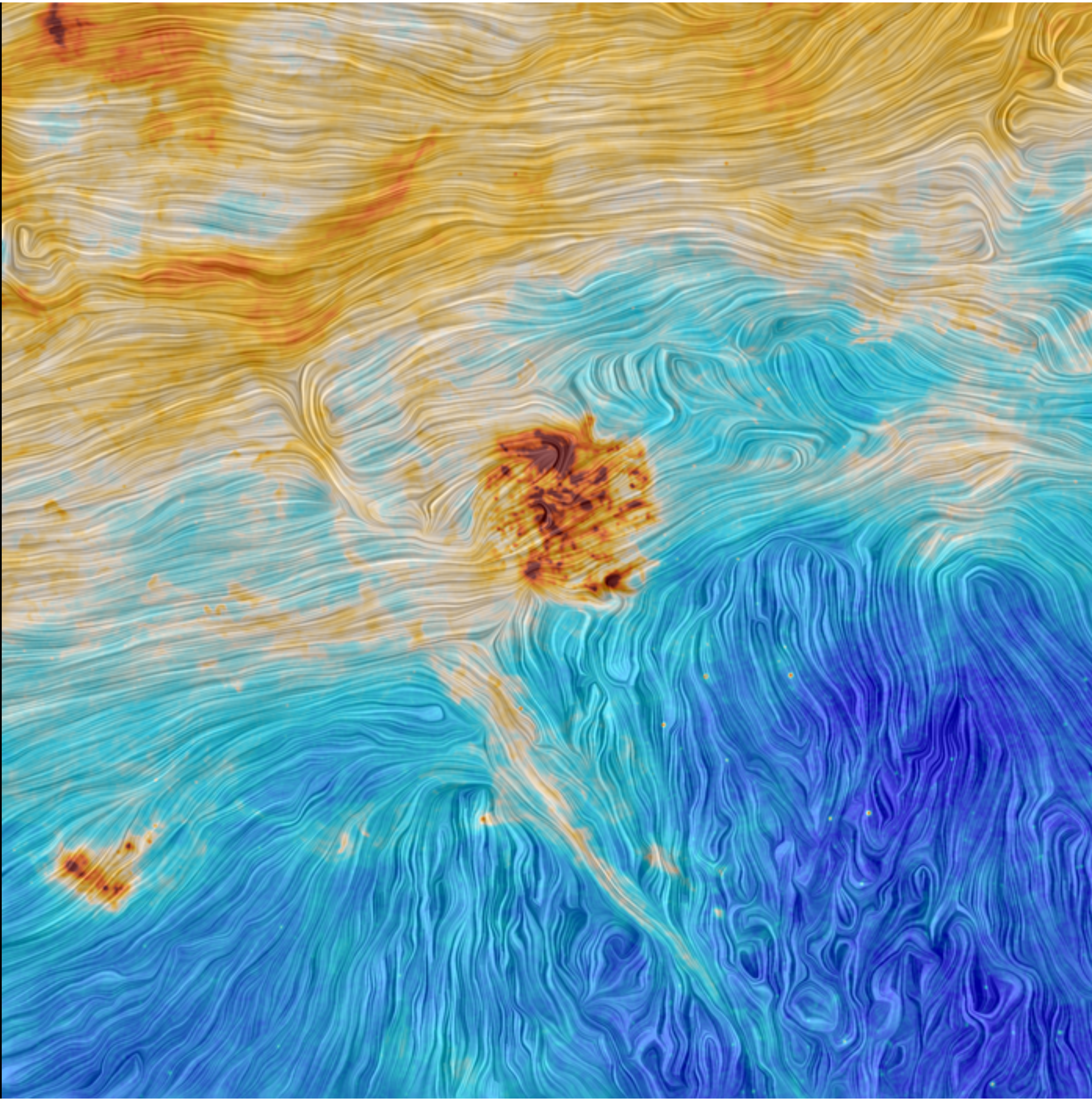
Magnetic fields play a role



Planck collaboration https://arxiv.org/abs/1405.0871
Polarization of thermal dust emission, due to alignment of dust grains w/ magnetic fields

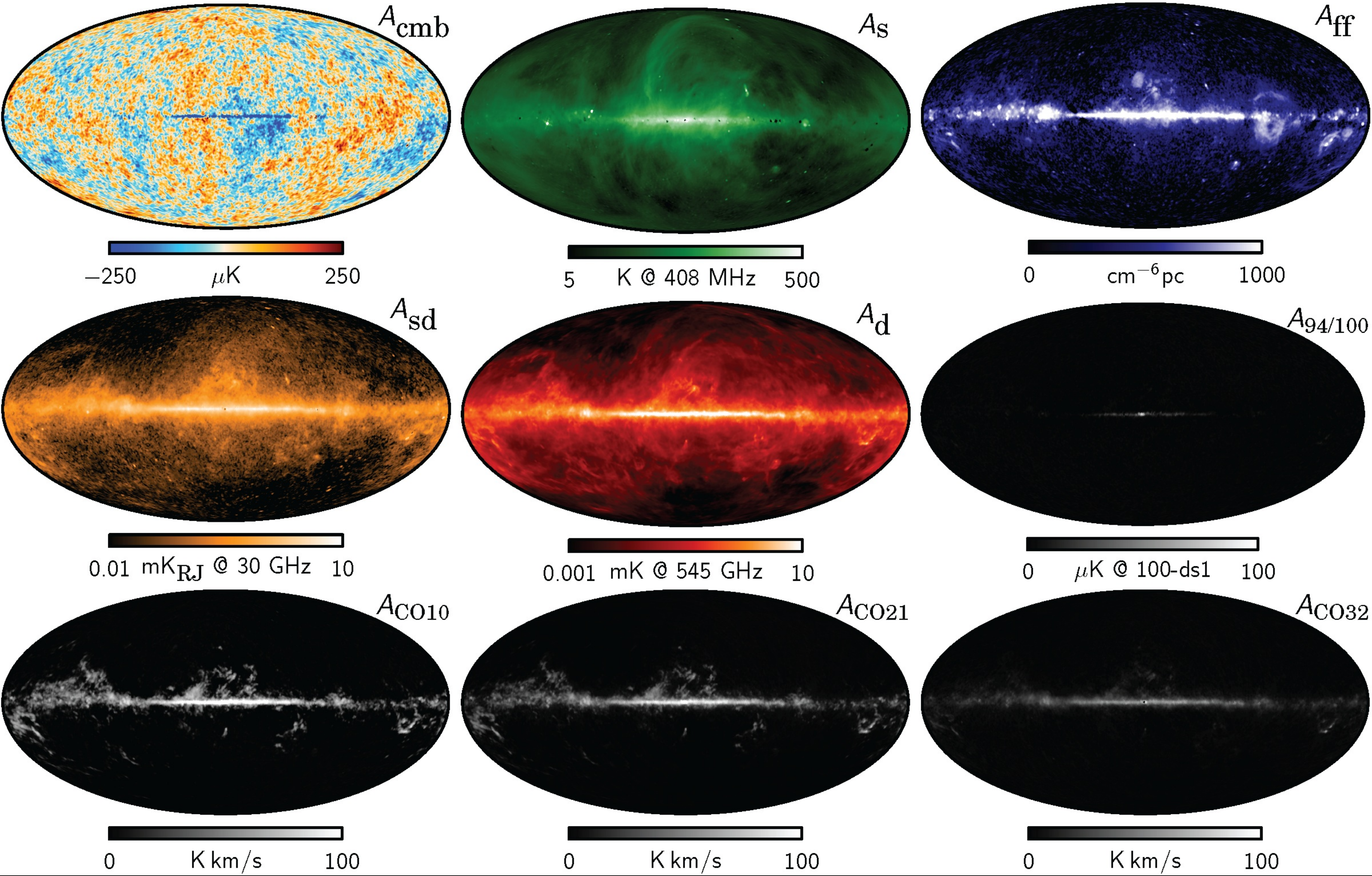
http://www.esa.int/spaceinimages/Images/2015/02/Polarised_emission_from_Milky_Way_dust





Magellanic Clouds

http://
www.esa.int/
spaceinimages/
Images/2015/09/
The_Magellanic_
Clouds_and_an_
interstellar_filam

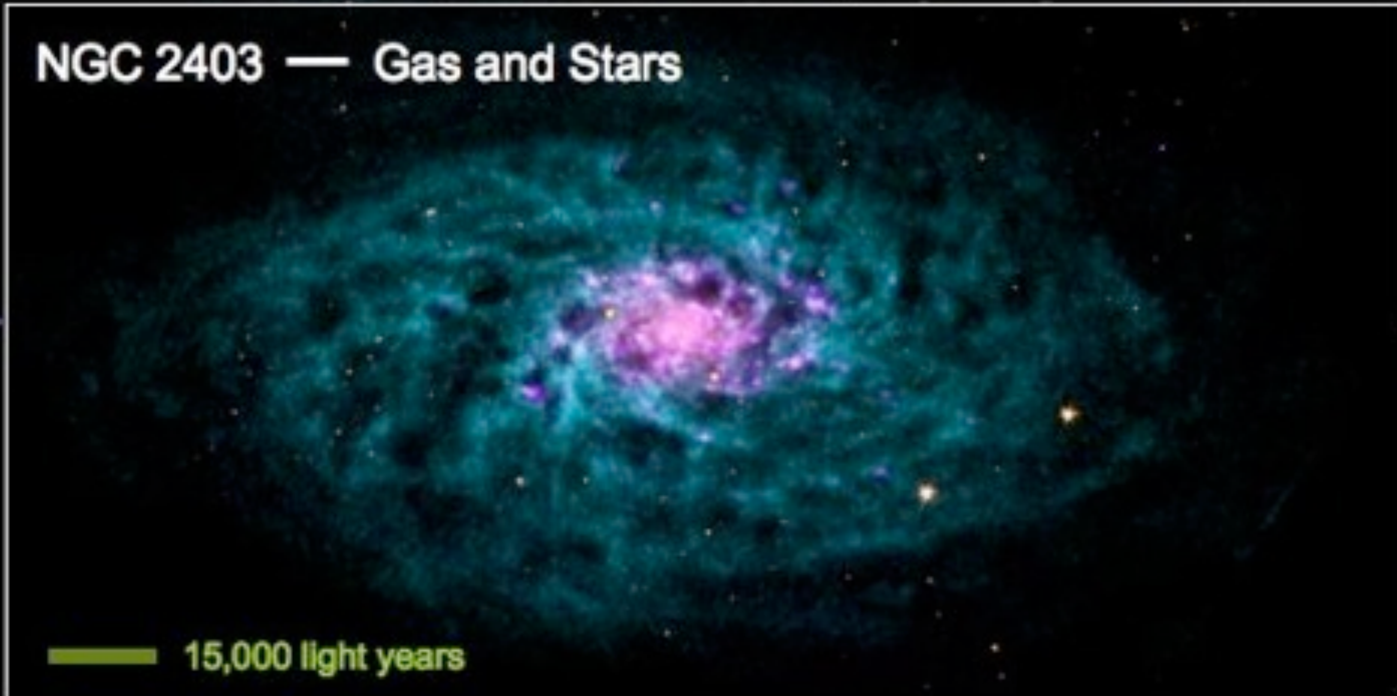


A_{cmb}
−250 μK 250
A_{s}
5 K @ 408 MHz 500
A_{ff}
0 $\mathrm{cm}^{-6}\mathrm{pc}$ 1000
A_{sd}
0.01 $\mathrm{mK}_{\mathrm{RJ}}$ @ 30 GHz 10
A_{d}
0.001 mK @ 545 GHz 10
$A_{94/100}$
0 μK @ 100-ds1 100
A_{CO10}
0 K km/s 100
A_{CO21}
0 K km/s 100
A_{CO32}
0 K km/s 100

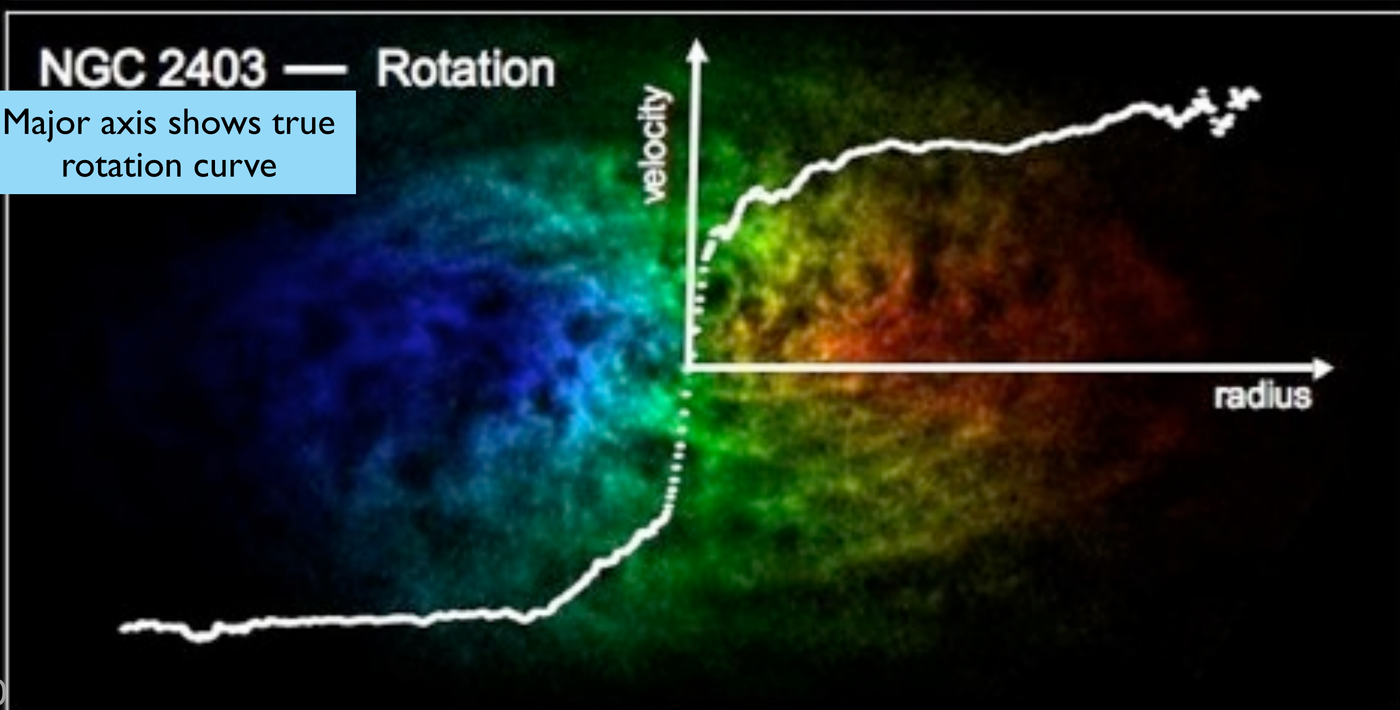
The gas disks are typically rotating*

*HI is critical for measuring rotation curves, since goes much further out into the dark matter halo than optical disk. But, lower angular resolution so worse probe of kinematics at the center.

Galaxy Dynamics in THINGS — The HI Nearby Galaxy Survey



Color Coding:
THINGS Atomic Hydrogen
(Very Large Array)
Old stars
(Spitzer Space Telescope)
Star Formation
(GALEX & Spitzer)



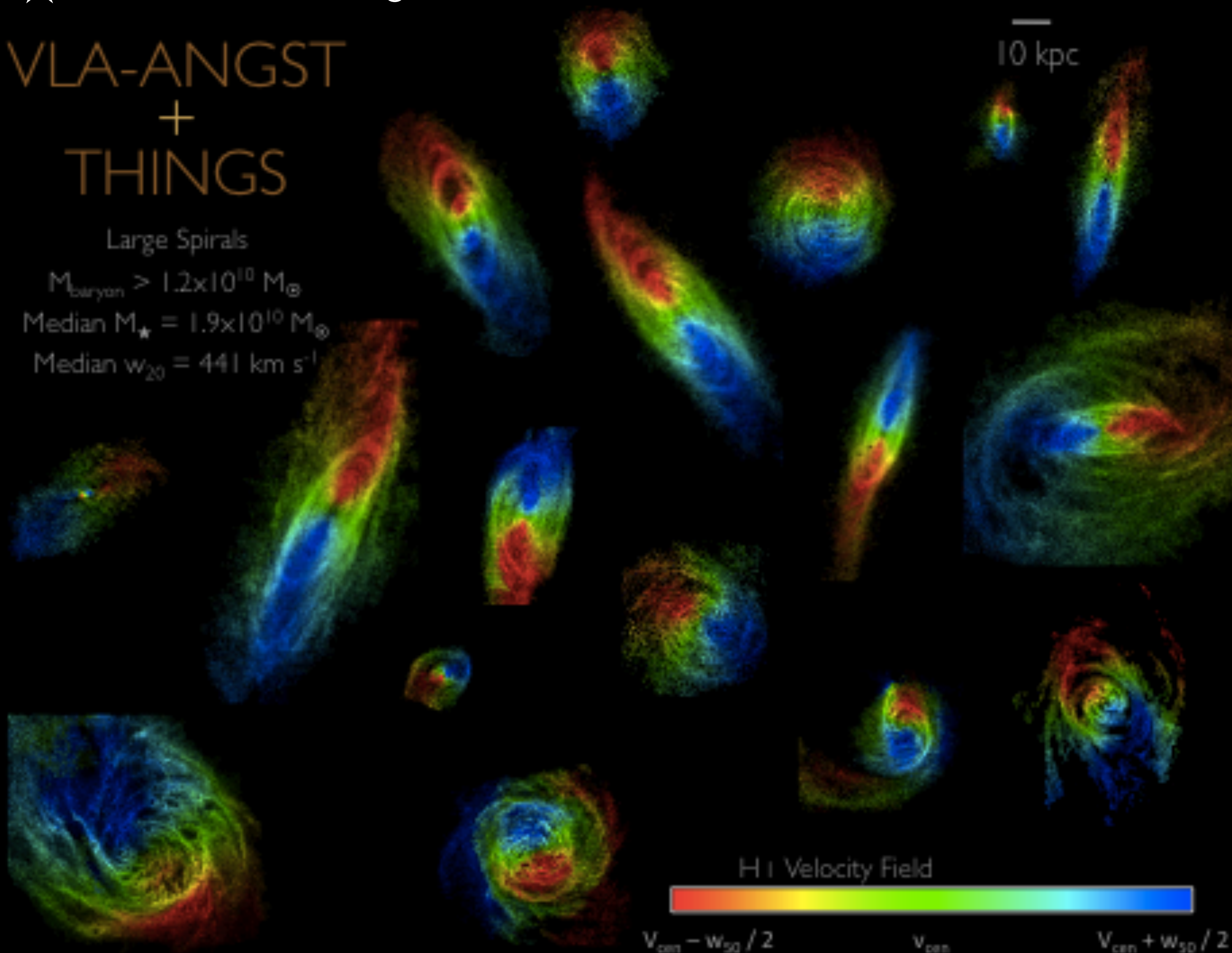
Major axis shows true rotation curve

Color coding:
THINGS HI distribution:
Red-shifted (receding)
Blue-shifted (approaching)
Rotation Curve

"Spider diagram" of "isovelocity contours", expected for a rotating disk

Spitzer SINGS: Kennicutt et al. 03
GALEX NGS: Gil de Paz et al. 07
Rotation Curve: de Blok et al. 08

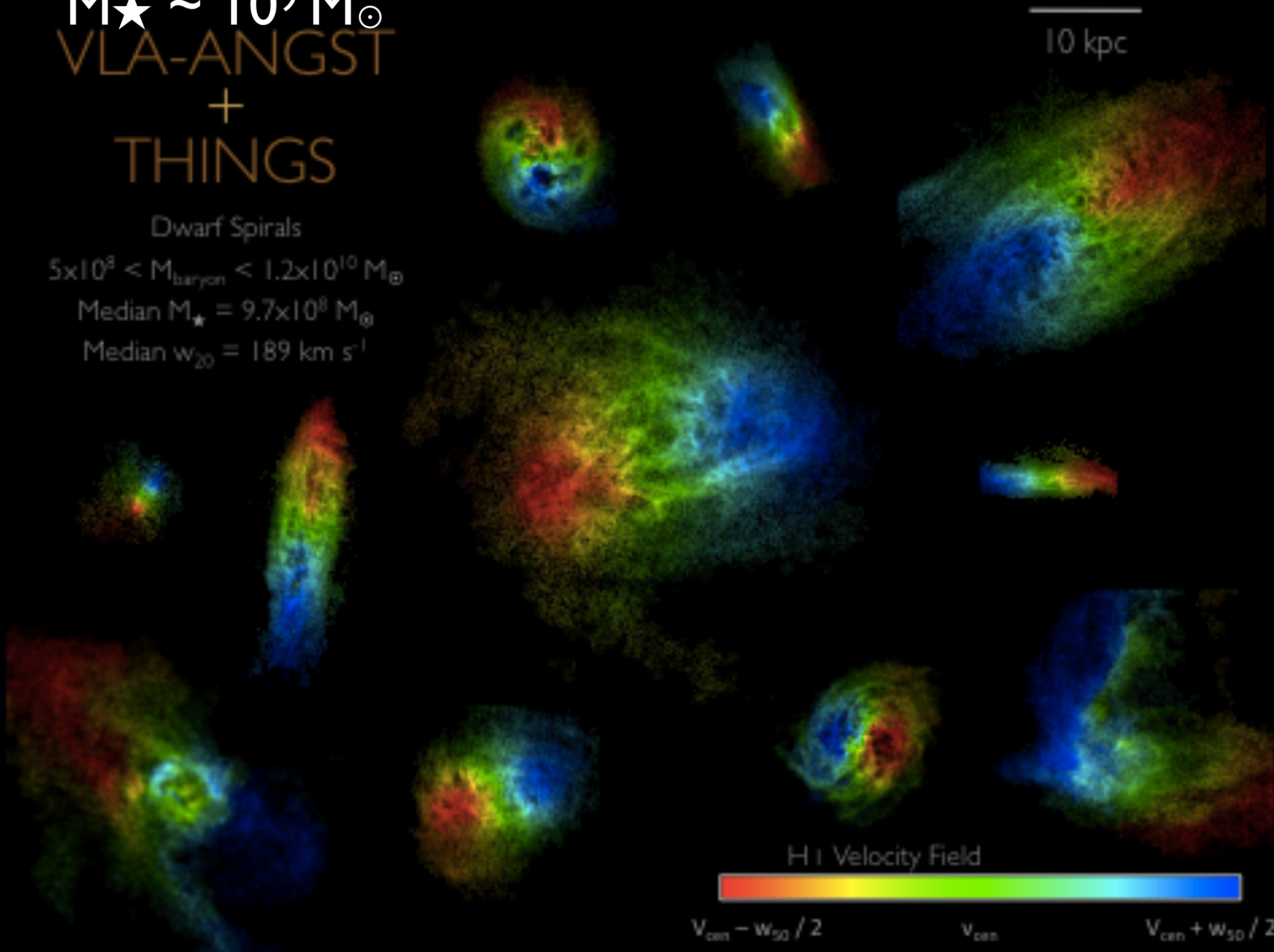
$M_\star \sim 2 \times 10^{10} M_\odot$



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

$M_\star \sim 2 \times 10^7\ M_\odot$

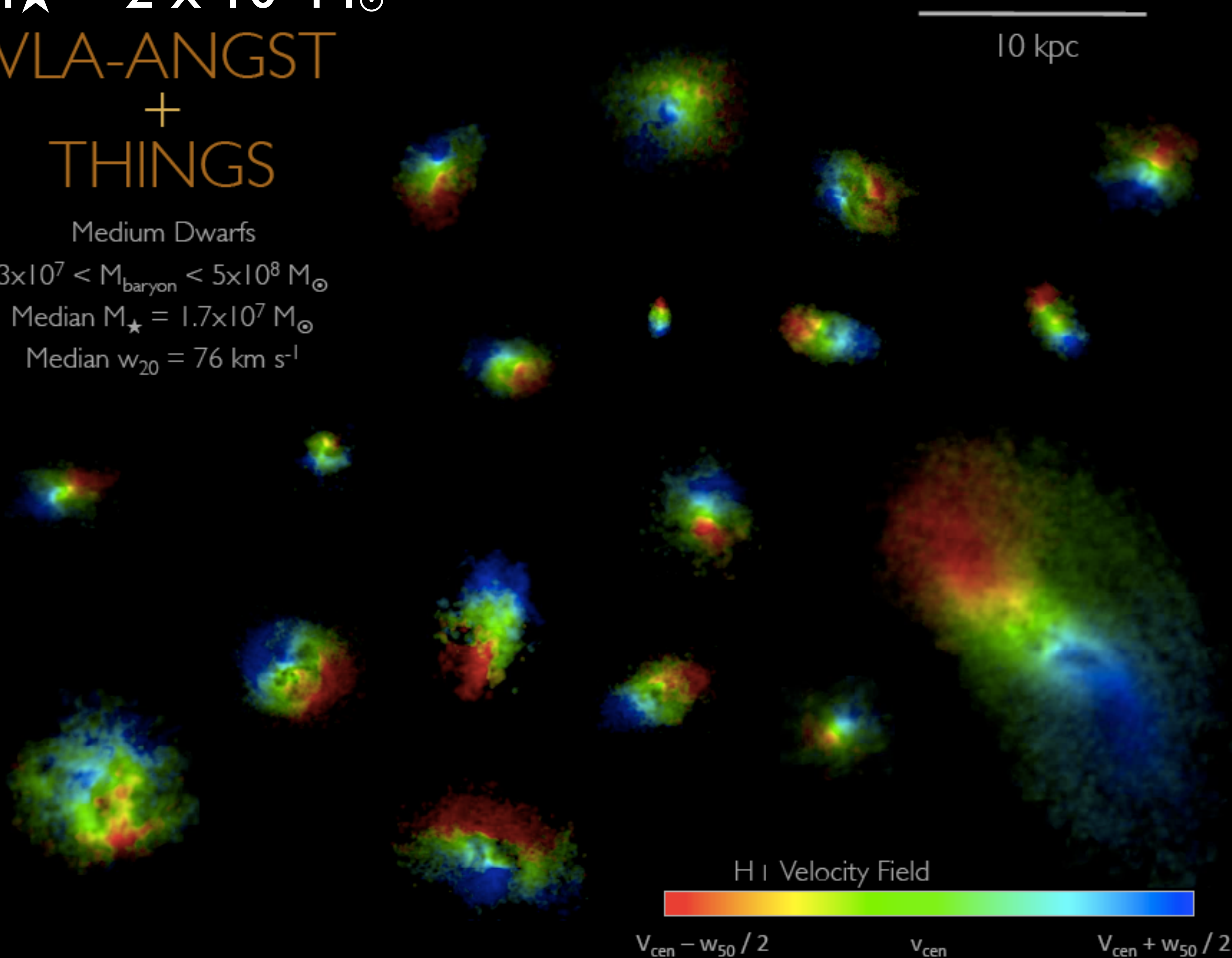
VLA-ANGST + THINGS

Medium Dwarfs

$3\times10^7 < M_{baryon} < 5\times10^8\ M_\odot$

Median $M_\star = 1.7\times10^7\ M_\odot$

Median $w_{20} = 76$ km s^{-1}



 Courtesy: Adrienne Stilp

Ott et al 2012, Walter et al 2008

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

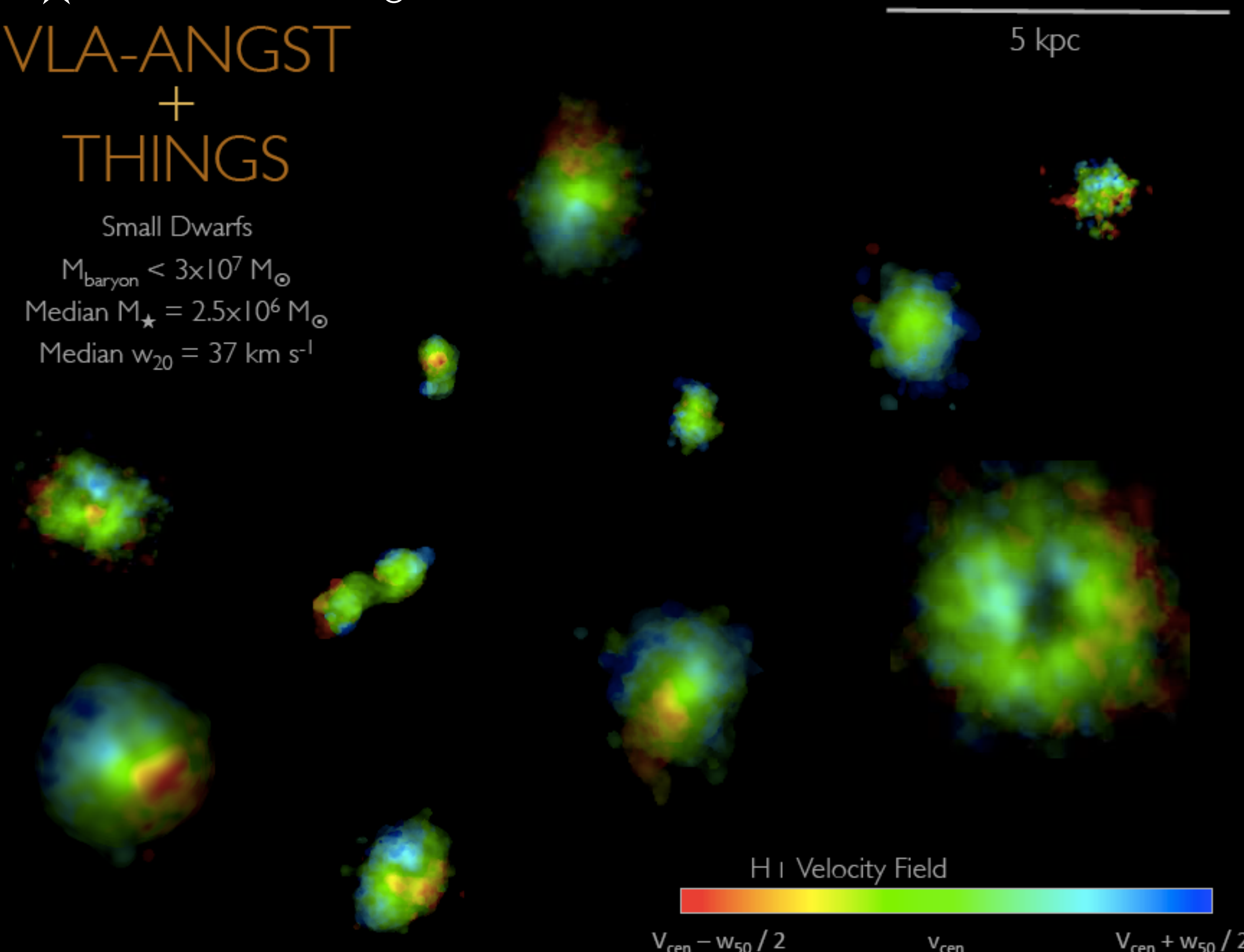
VLA-ANGST
+
THINGS

Small Dwarfs

$M_{baryon} < 3\times10^7\, M_\odot$

Median $M_\star = 2.5\times10^6\, M_\odot$

Median $w_{20} = 37$ km s^{-1}



Courtesy: Adrienne Stilp

Ott et al 2012, Walter et al 2008

The gas disks have a velocity dispersion that supports the disk vertically against gravity.

These are random, turbulent motions.

HI Velocity dispersion

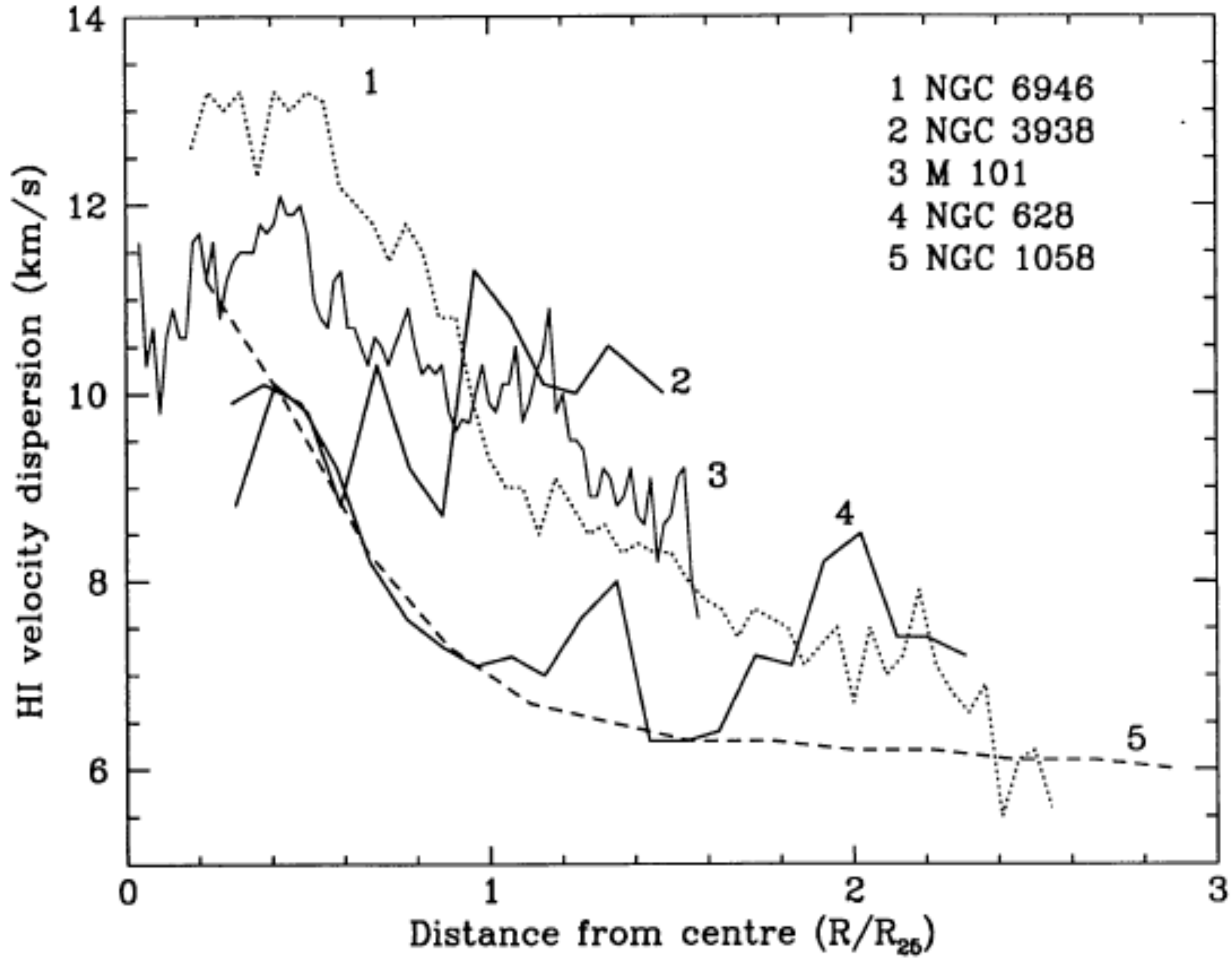
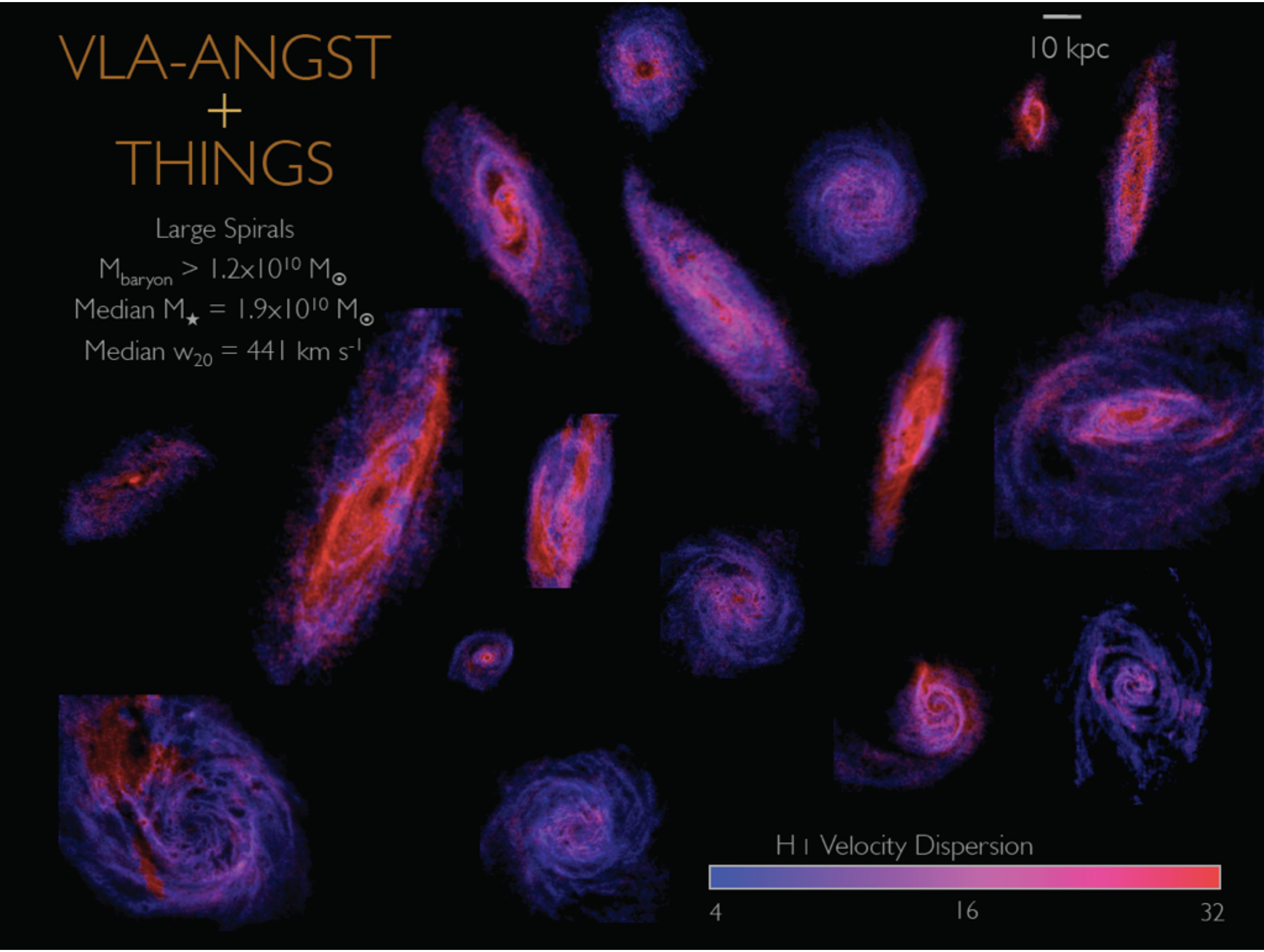
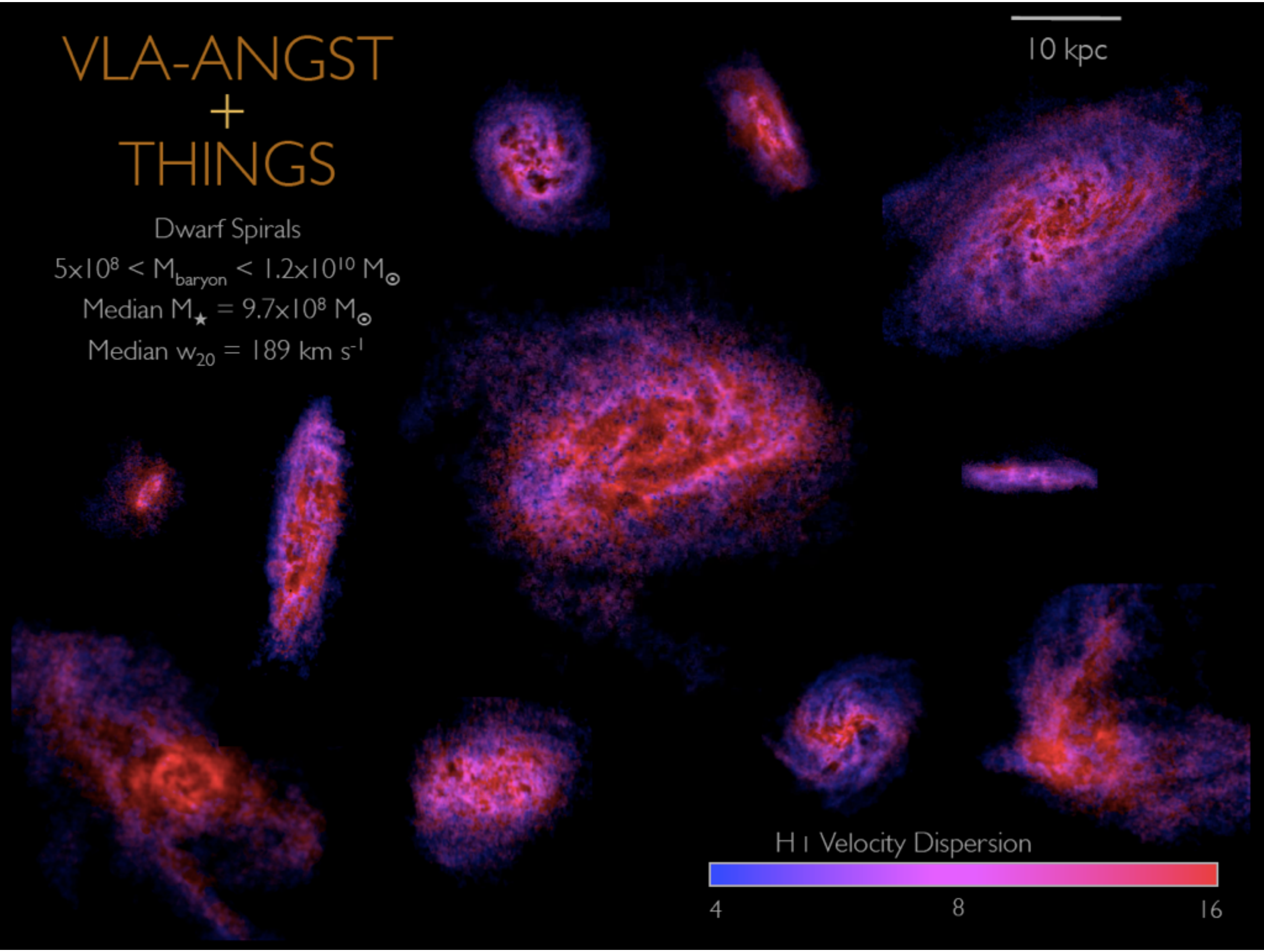


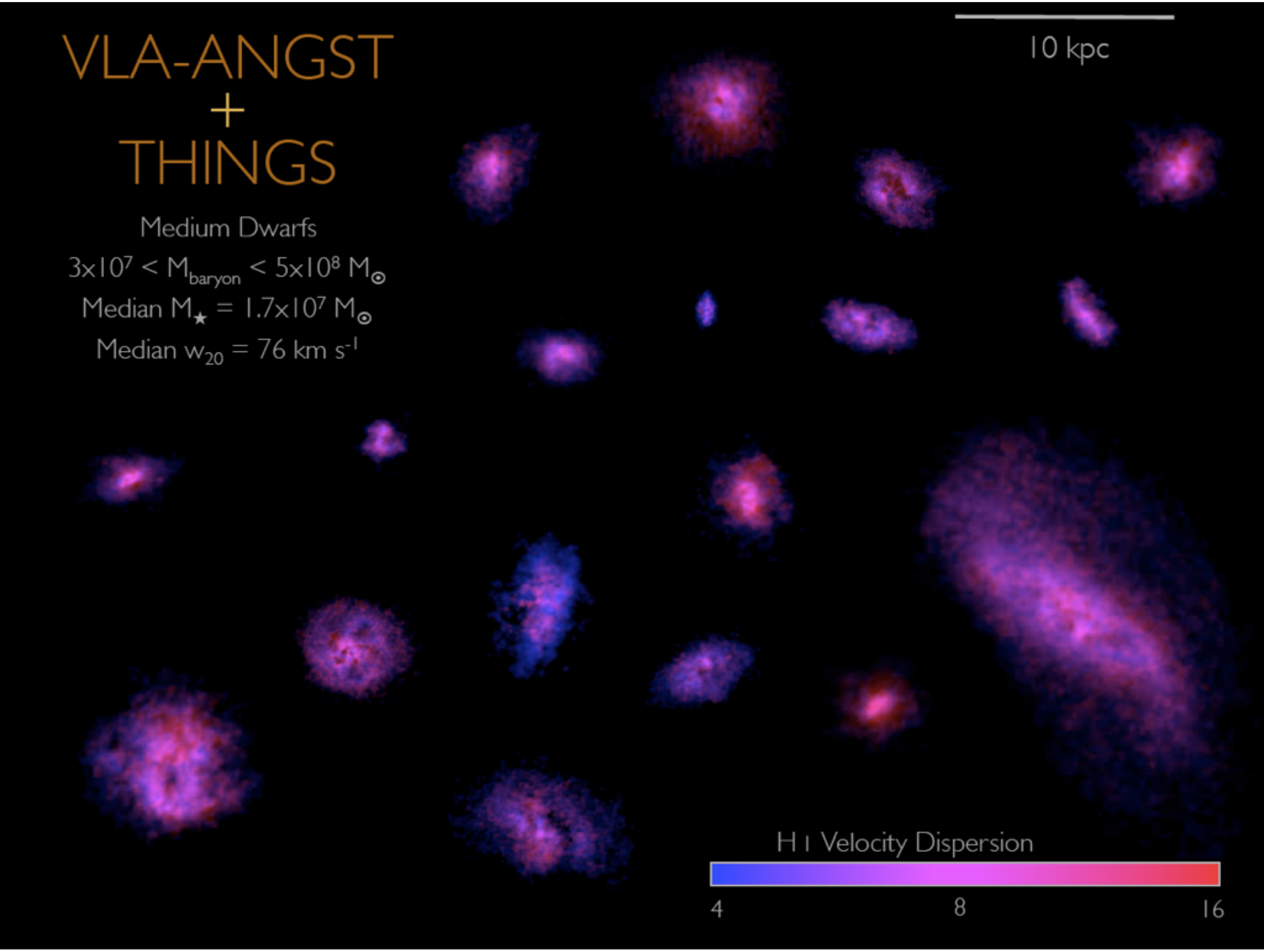
Figure 22. Azimuthally averaged HI velocity dispersion as a function of normalized galactocentric radius in 5 face-on galaxies.

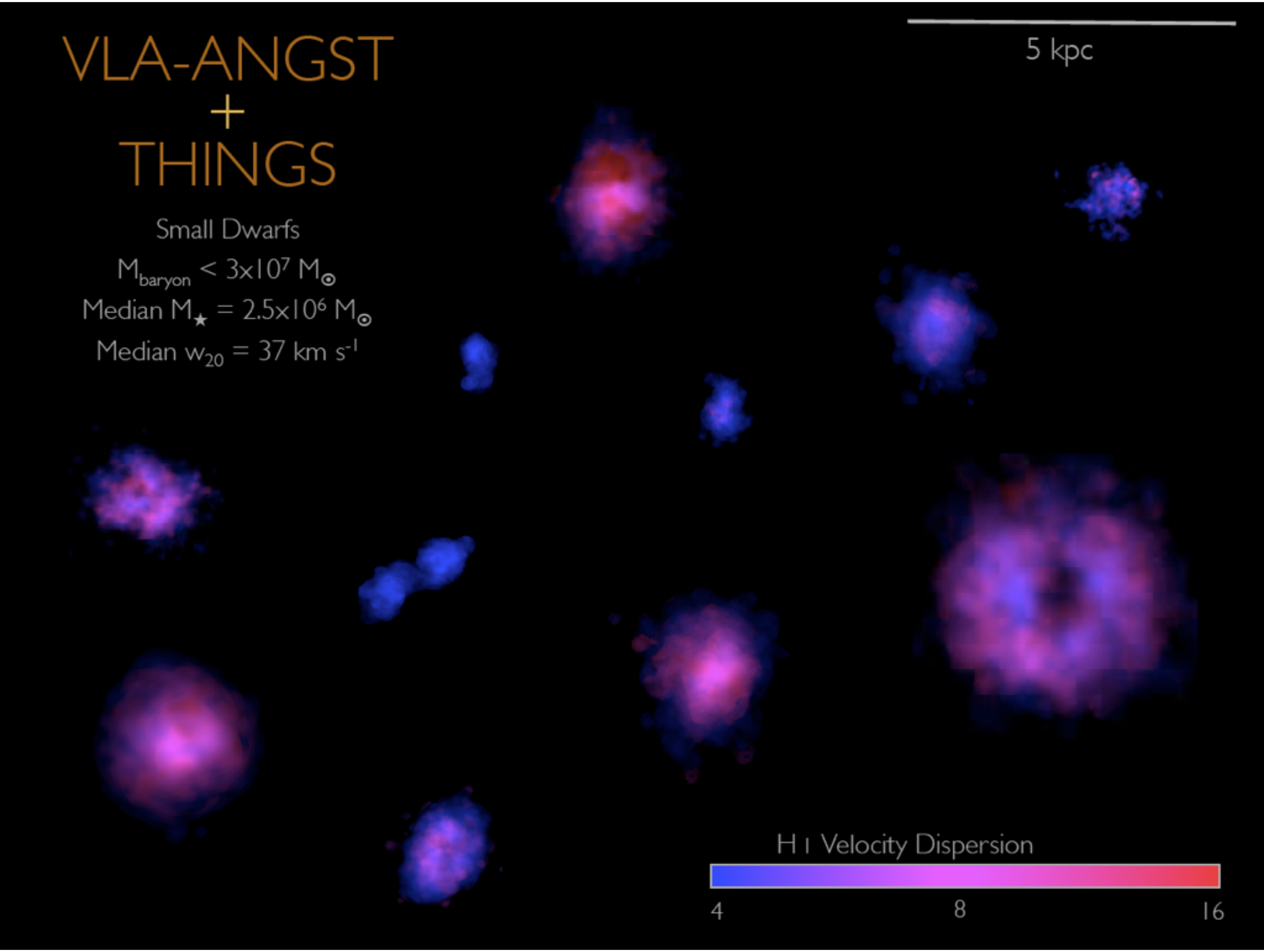
- 10-20 km/s in center, then declines
- Implies dynamical pressure >> thermal pressure
- Disk supported vertically by turbulence

 Van der Hulst 1996


VLA-ANGST
+
THINGS
Large Spirals
$M_{baryon} > 1.2 \times 10^{10}\ M_\odot$
Median $M_\star = 1.9 \times 10^{10}\ M_\odot$
Median $w_{20} = 441\ \mathrm{km\ s^{-1}}$
10 kpc
H I Velocity Dispersion
4
16
32


VLA-ANGST
+
THINGS
Dwarf Spirals
$5\times10^8 < M_{baryon} < 1.2\times10^{10}\ M_\odot$
Median $M_\star = 9.7\times10^8\ M_\odot$
Median $w_{20} = 189$ km s^{-1}
10 kpc
H I Velocity Dispersion
4
8
16


VLA-ANGST
+
THINGS
Medium Dwarfs
$3\times10^7 < M_{baryon} < 5\times10^8\ M_\odot$
Median $M_\star = 1.7\times10^7\ M_\odot$
Median $w_{20} = 76$ km s^{-1}
10 kpc
H I Velocity Dispersion
4
8
16


5 kpc
VLA-ANGST
+
THINGS
Small Dwarfs
M_baryon < 3x10^7 M_⊙
Median M_★ = 2.5x10^6 M_⊙
Median w_20 = 37 km s^-1
H I Velocity Dispersion
4
8
16

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

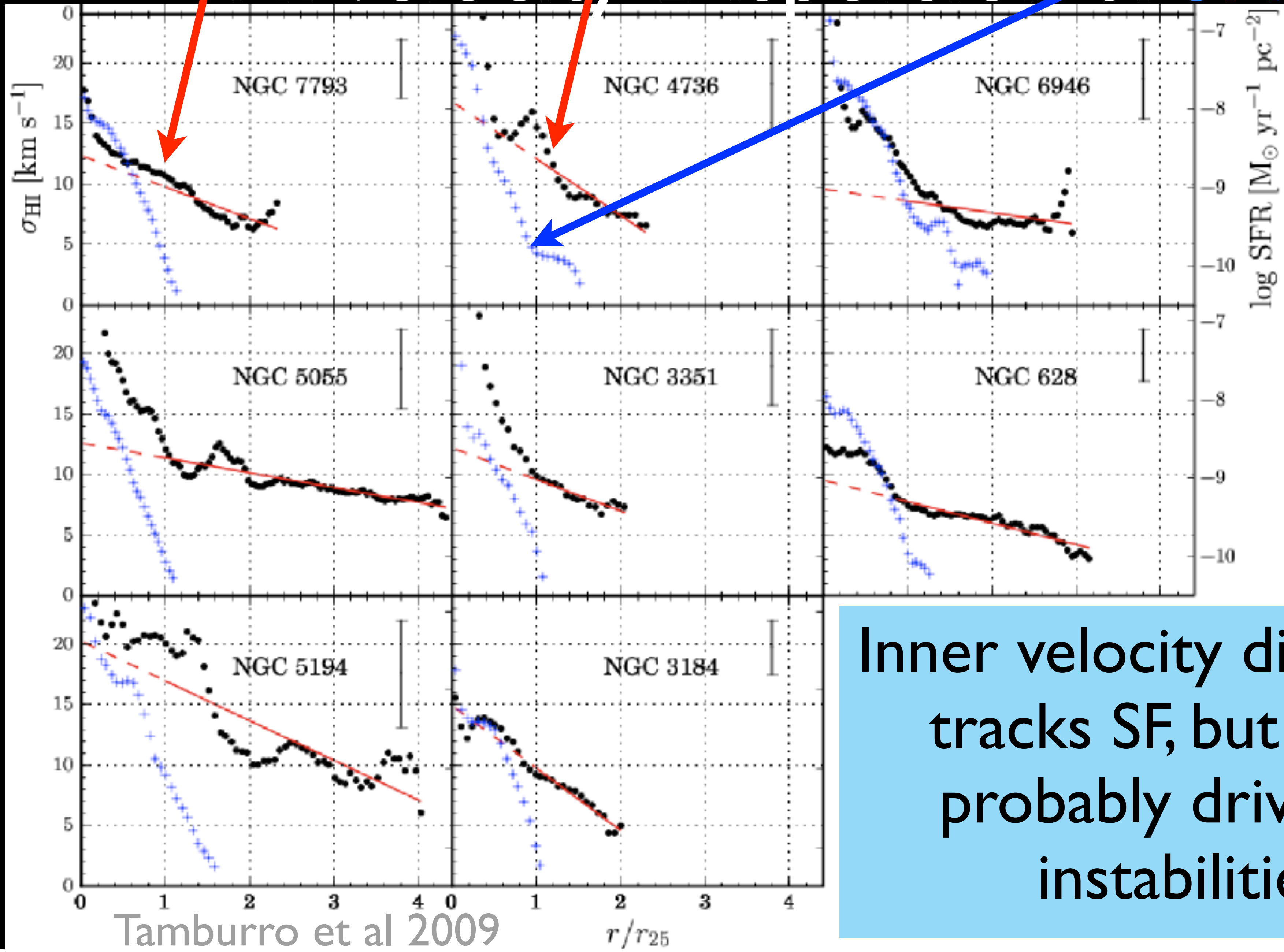


FIG. 1.— Radial profiles of HI velocity dispersion, $\sigma_{\rm HI}$, for the galaxies of our sample (§ 4.1). The filled circles represent azimuthal averages of $\sigma_{\rm HI}$ calculated from the second moment (Eq. 3) as a function of radius r in units of r_{25}. The error bar on the top right of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

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