The H_2 / HI Transition in Nearby Galaxies

Adam Leroy (NRAO)

Fabian Walter(MPIA), Karin Sandstrom (MPIA), Andreas Schruba (CalTech),
Gonzalo Aniano, Bruce Draine (Princeton – the dust!)
the HERACLES, THINGS (Elias), & KINGFISH (many here!) teams

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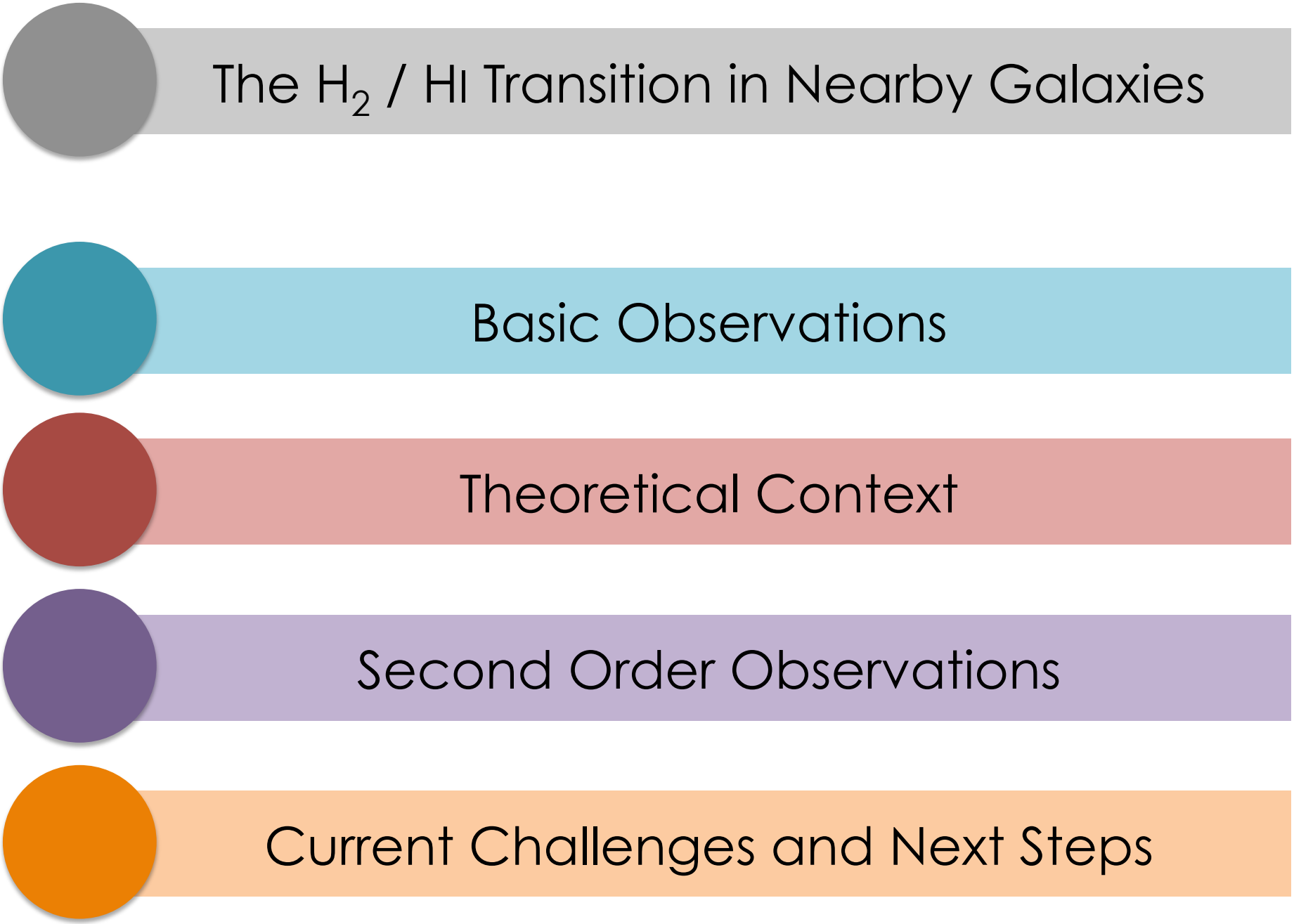
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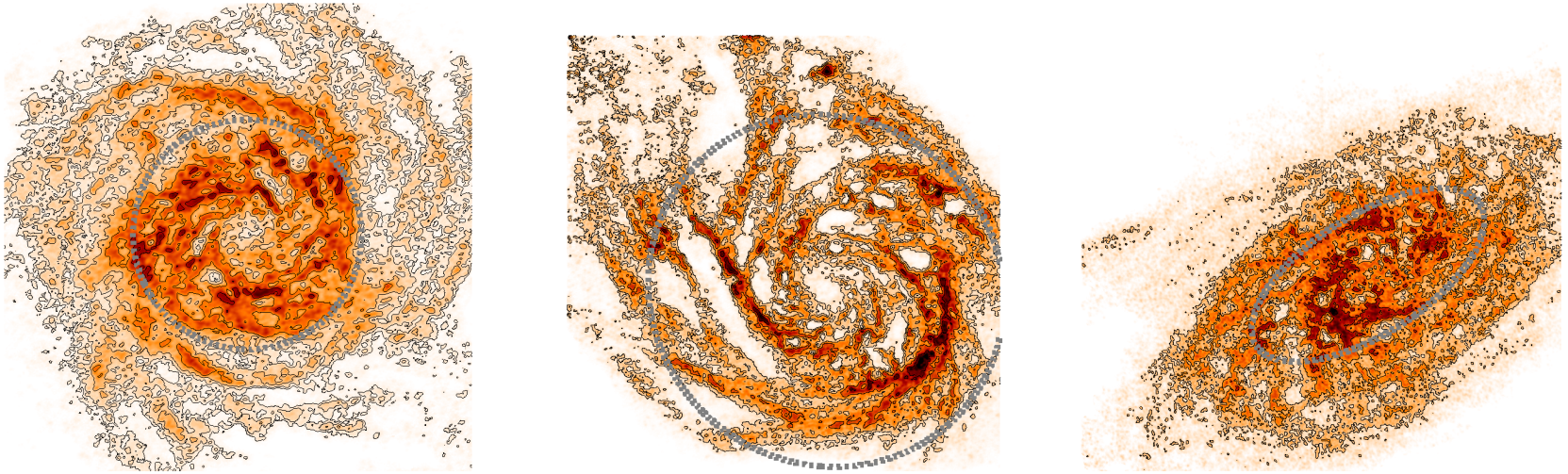
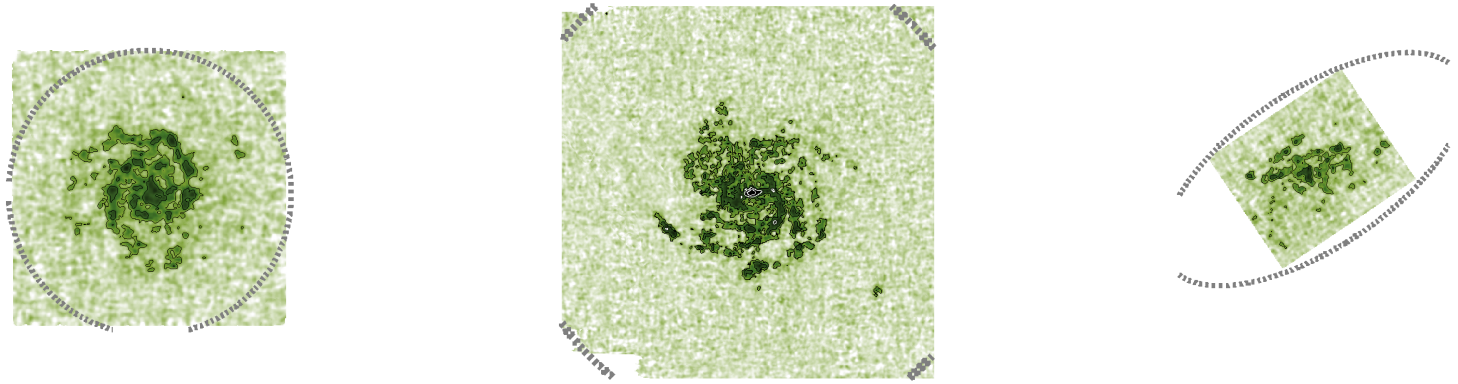
Basic Observations
Theoretical Context
Second Order Observations
Current Challenges and Next Steps

H_2/HI Varies Strongly and Systematically

THINGS HI

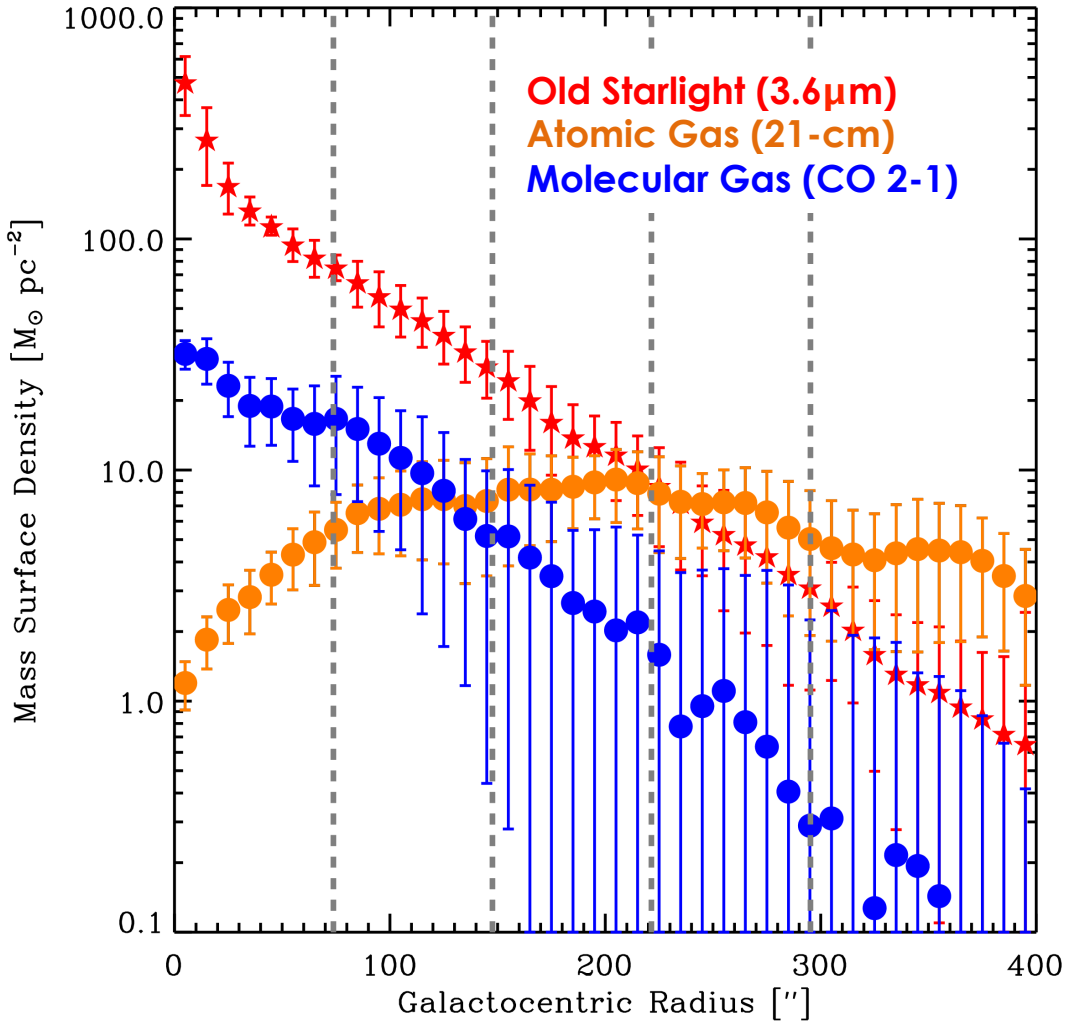


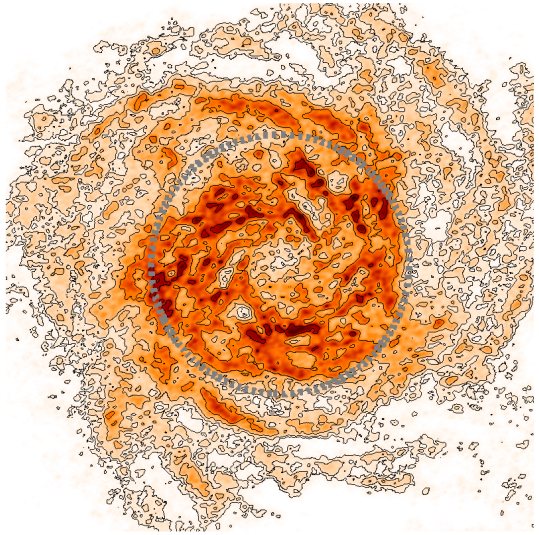
HERACLES CO



Maps of HI and CO 2-1 (Walter+ 2008, Leroy+ 2009)

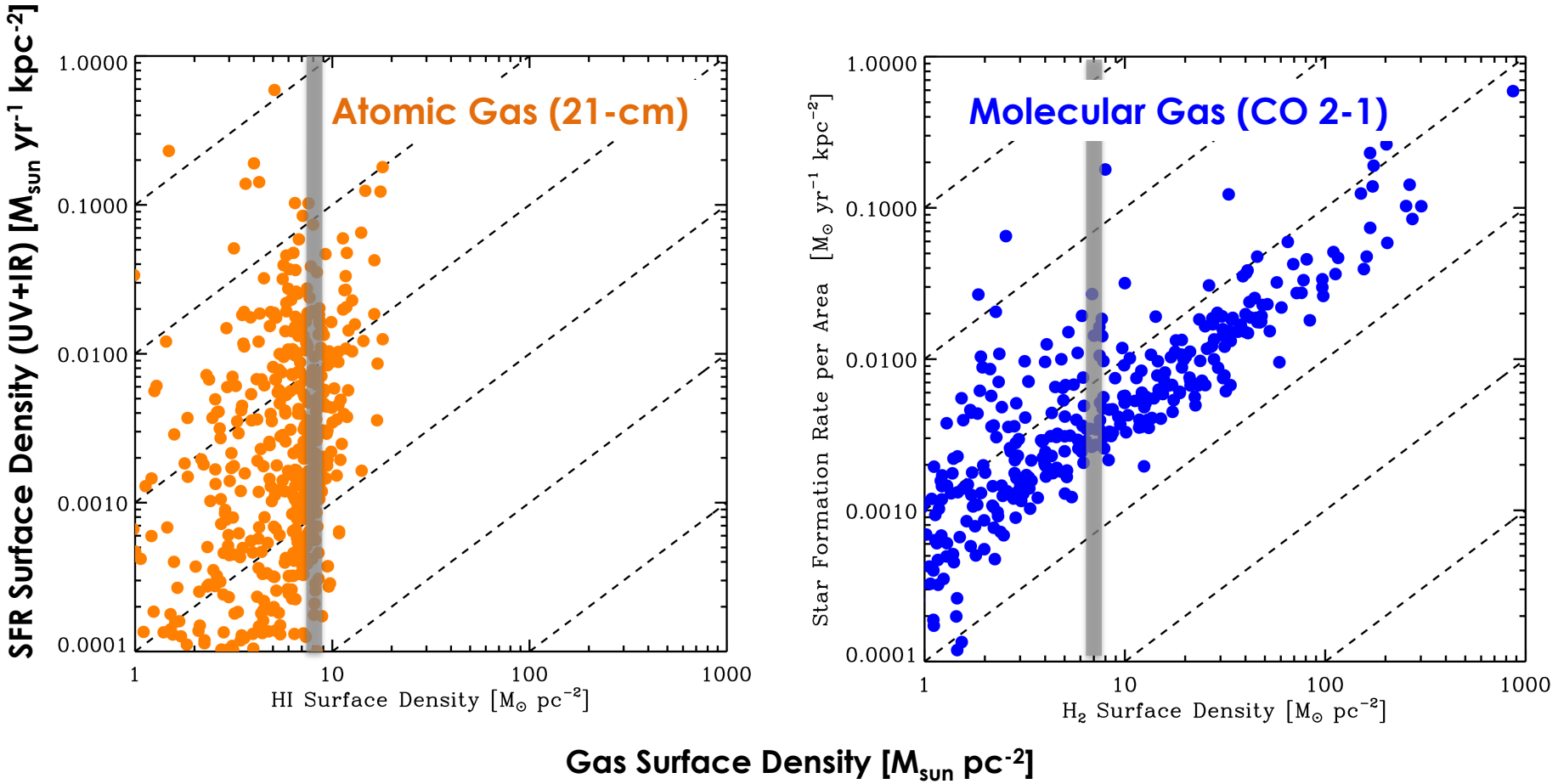
H_2/HI Varies Strongly and Systematically





Azimuthally averaged profiles of M74 (Leroy+ 2008)

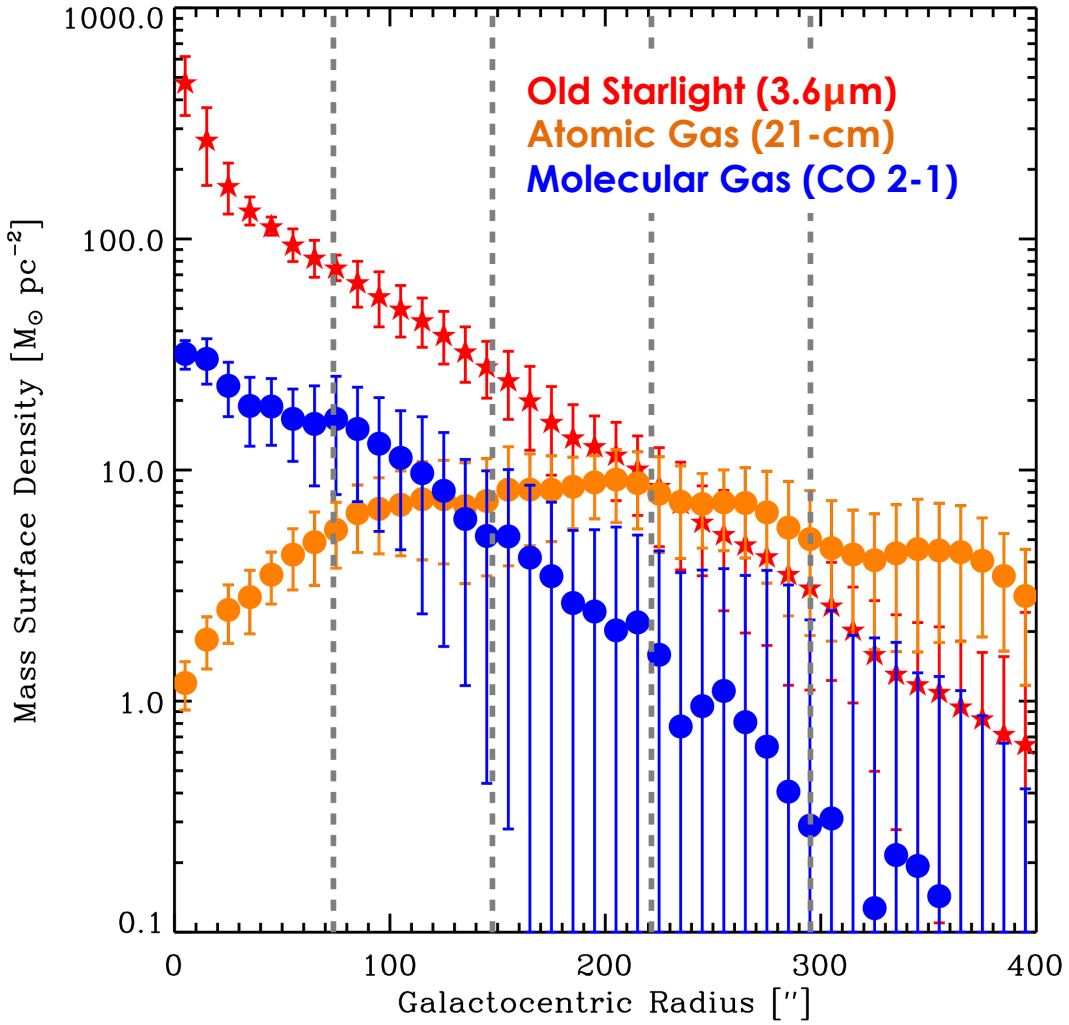
HI is Most of the Mass, but H_2 Forms Stars

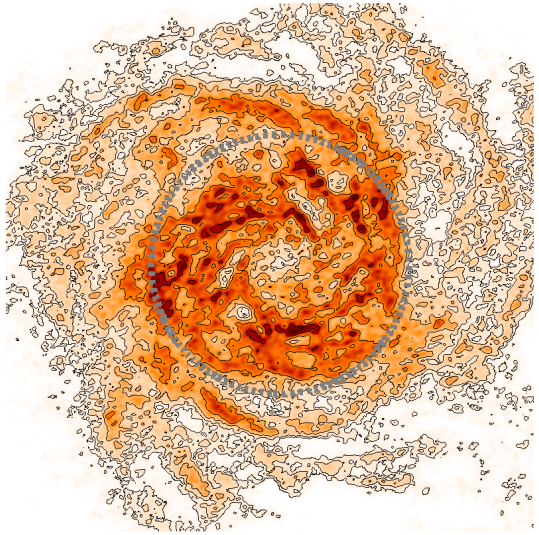


Azimuthally averaged profiles of 30 disk galaxies (Schruba+ 2011)

H_2/HI subtleties see Glover & Clark 2011, Krumholz 2012 but not key in this regime.

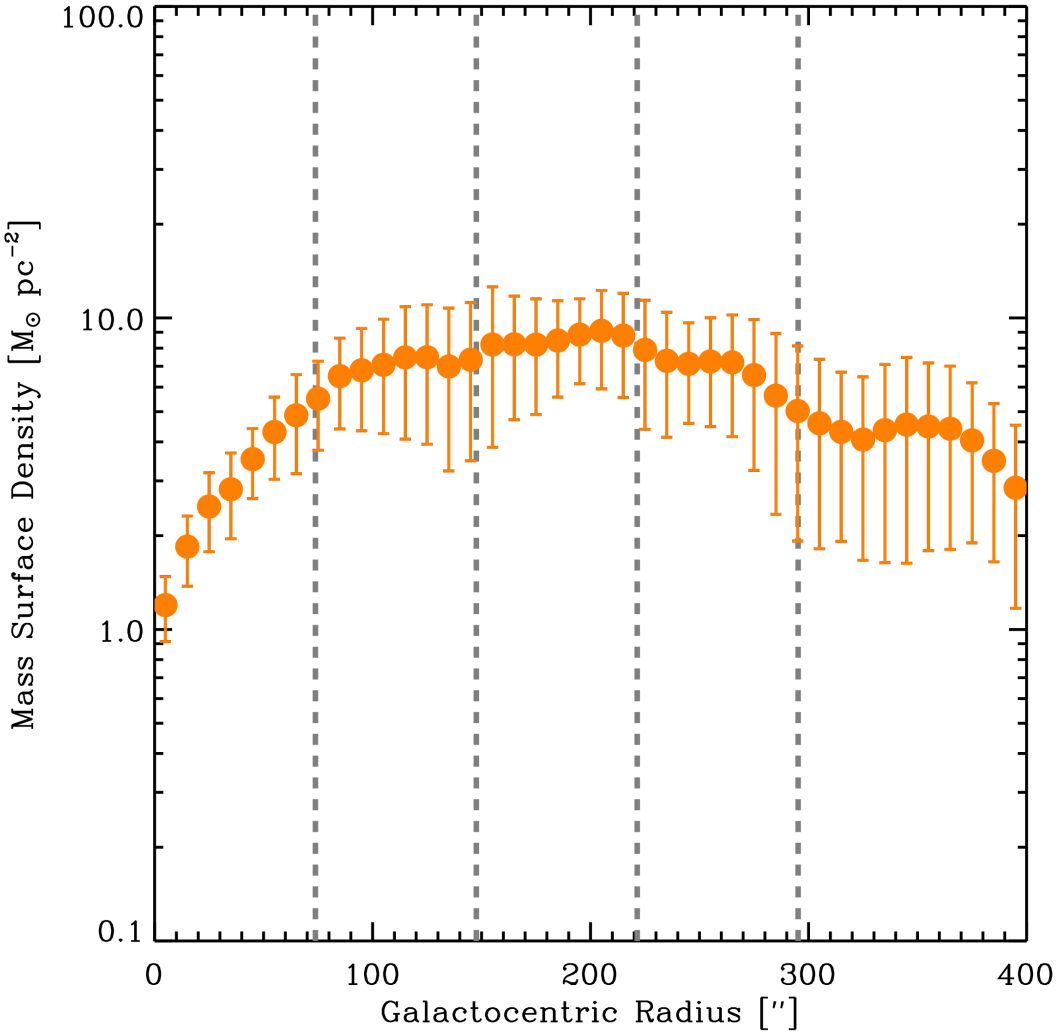
H_2/HI Varies Strongly and Systematically

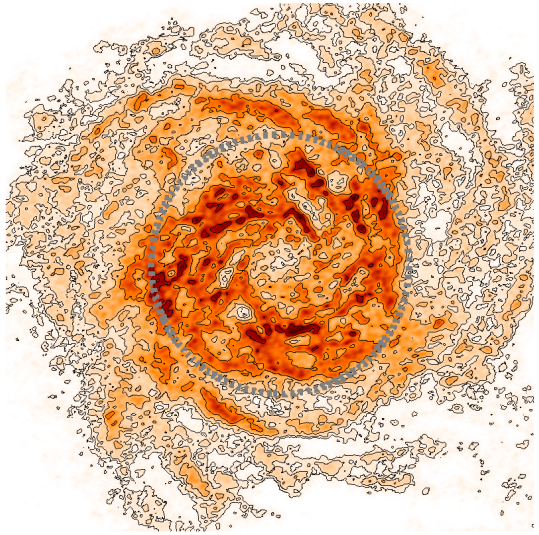




Azimuthally averaged profiles of M74 (Leroy+ 2008)

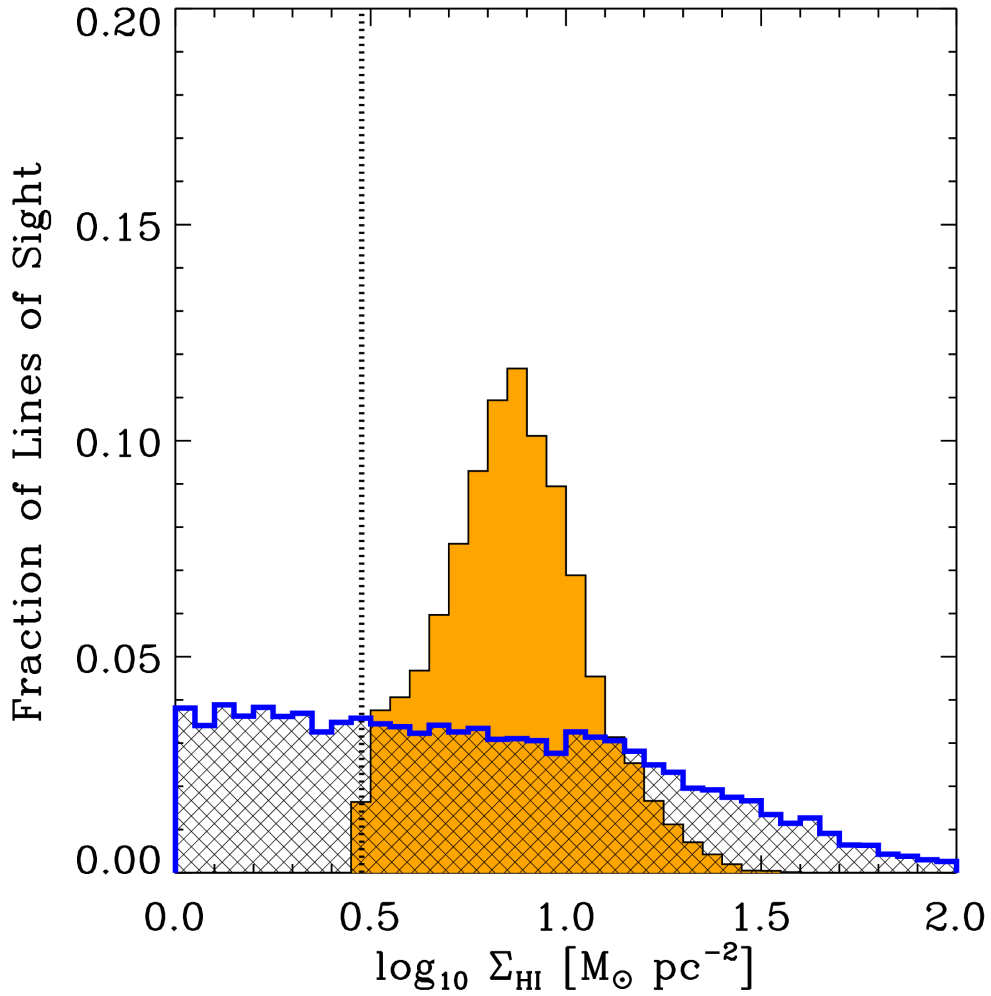
HI Appears to "Saturate"





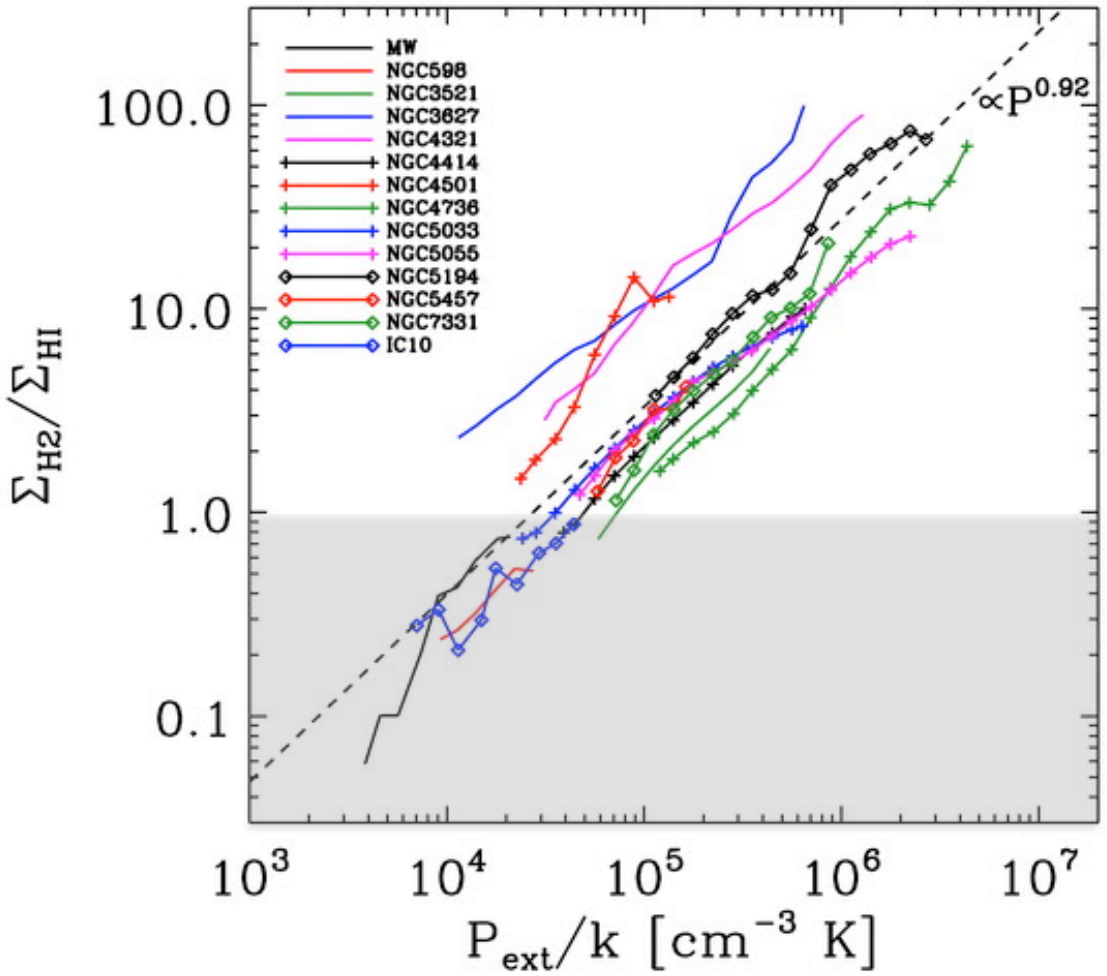
Azimuthally averaged profiles of M74 (Leroy+ 2008)

HI Shows a Narrow Range of Σ



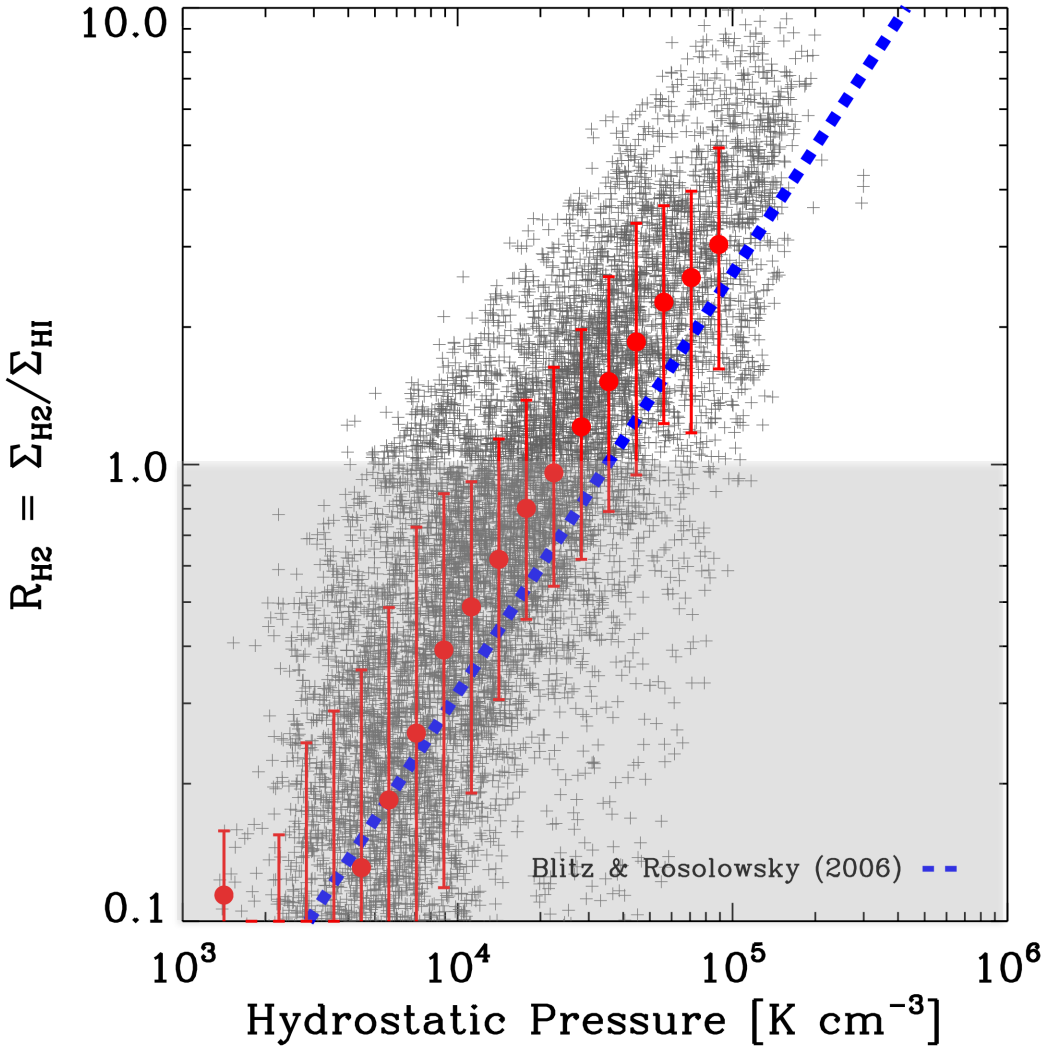
Histogram of kpc resolution surface densities in 23 disk galaxies (Leroy+ in prep)

H_2/HI Varies With Hydrostatic Pressure



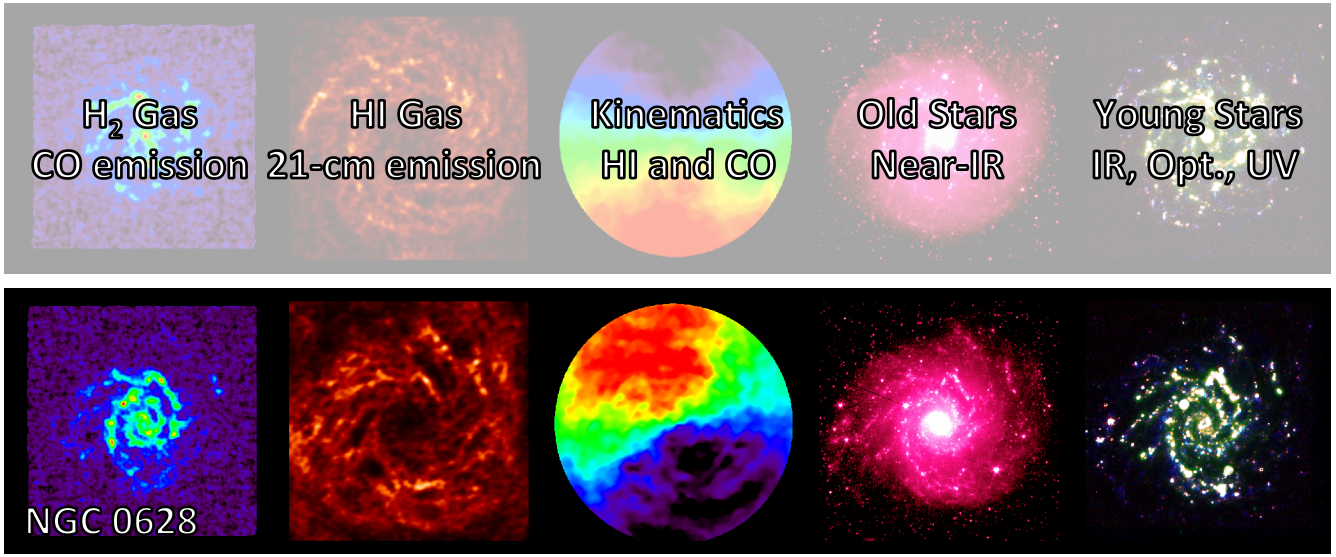
Binned profiles of 14 galaxy disks (Blitz & Rosolowsky 2006)

H_2/HI Varies With Hydrostatic Pressure

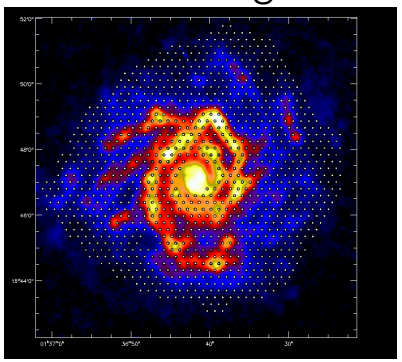


Kpc lines of sight in 23 galaxy disks (Leroy+ in prep, Leroy+ 2008)

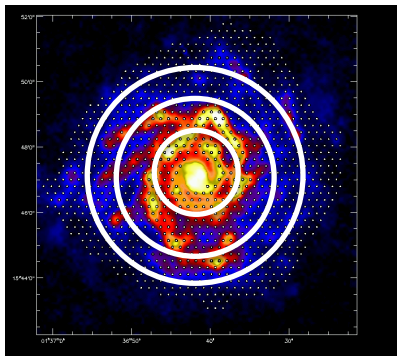
What's in a Point? ~30 galaxies at kpc Resolution



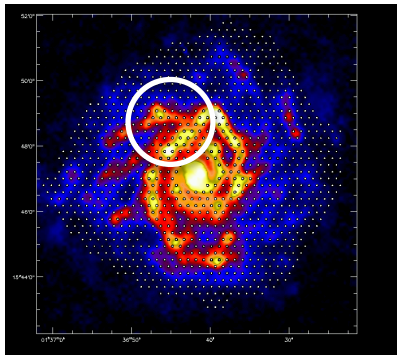
Lines of Sight



Azimuthal Averages



Selected Pointings



H_2 from CO (2-1)

HI from 21-cm

SFR from IR, Hα, UV

Dust from IR

UV field from IR

Stars from near-IR

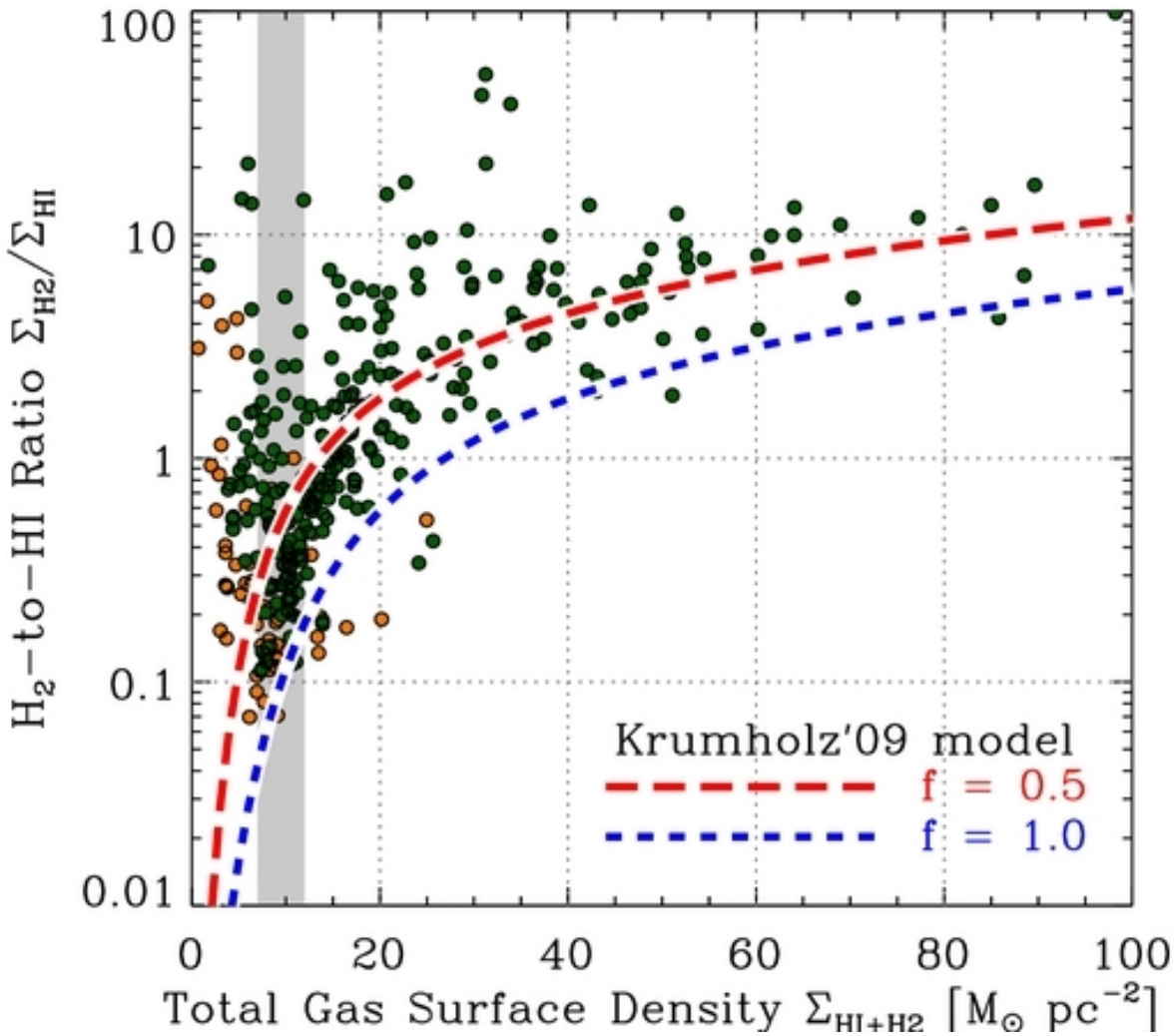
Rotation from HI

Metallicity

HCN (selected pts)

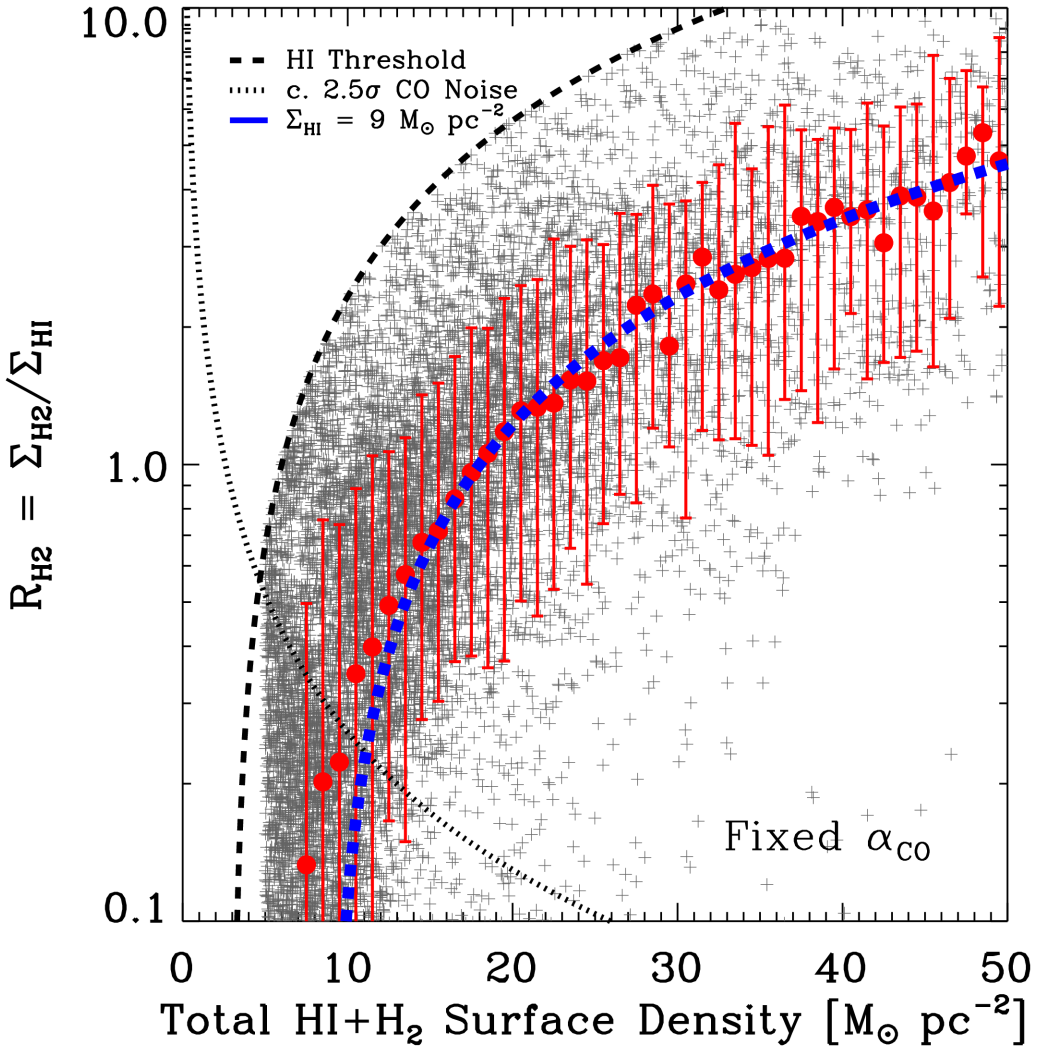
Leroy et al. '08, '12, '13, Walter+ '08, Schruba+ '11, 12, Sandstrom+ '13

H_2/HI Varies With Total Column



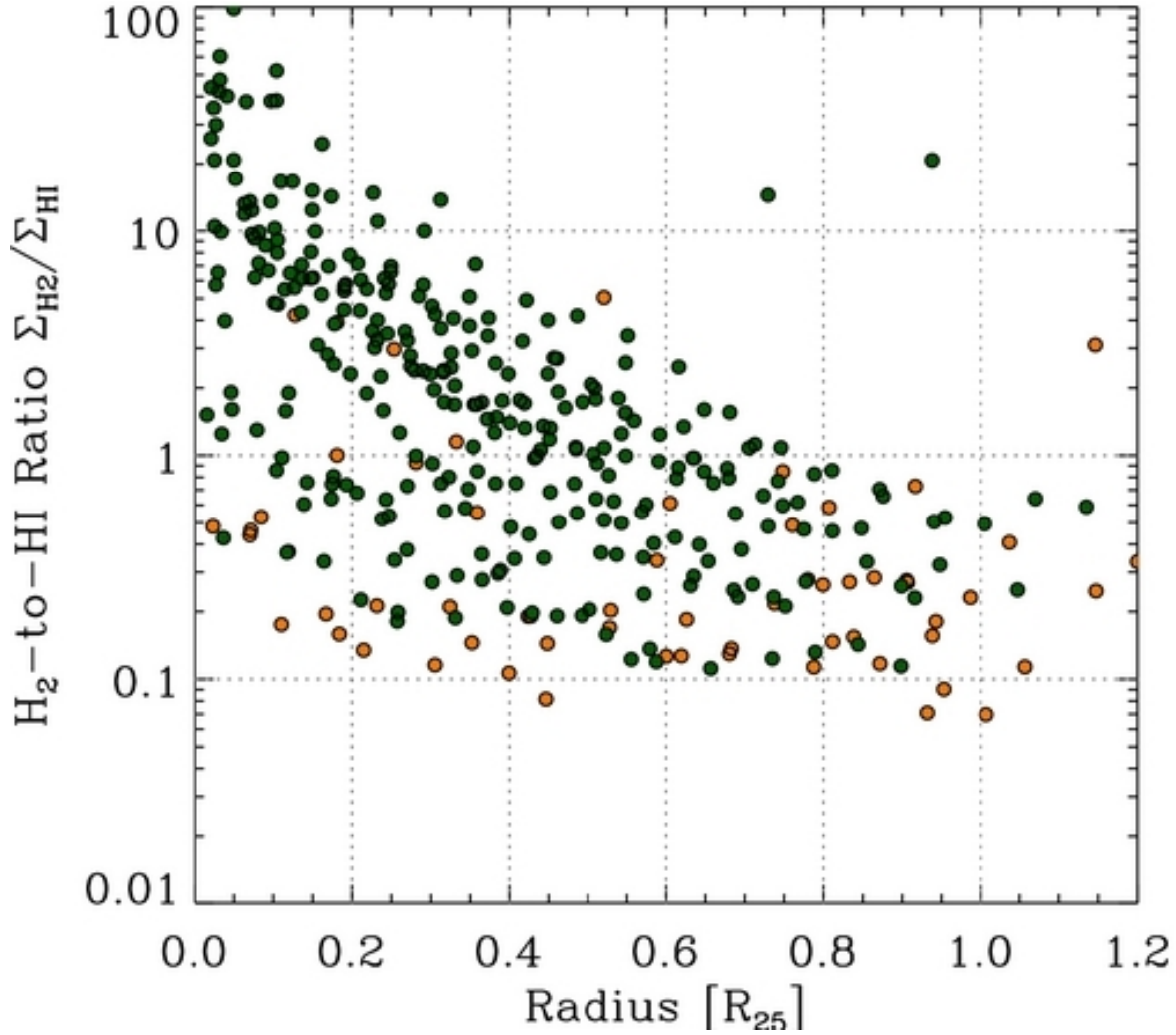
Azimuthal averages of 30 disk galaxies (Schruba+ 2011)

H_2/HI Varies With Total Column



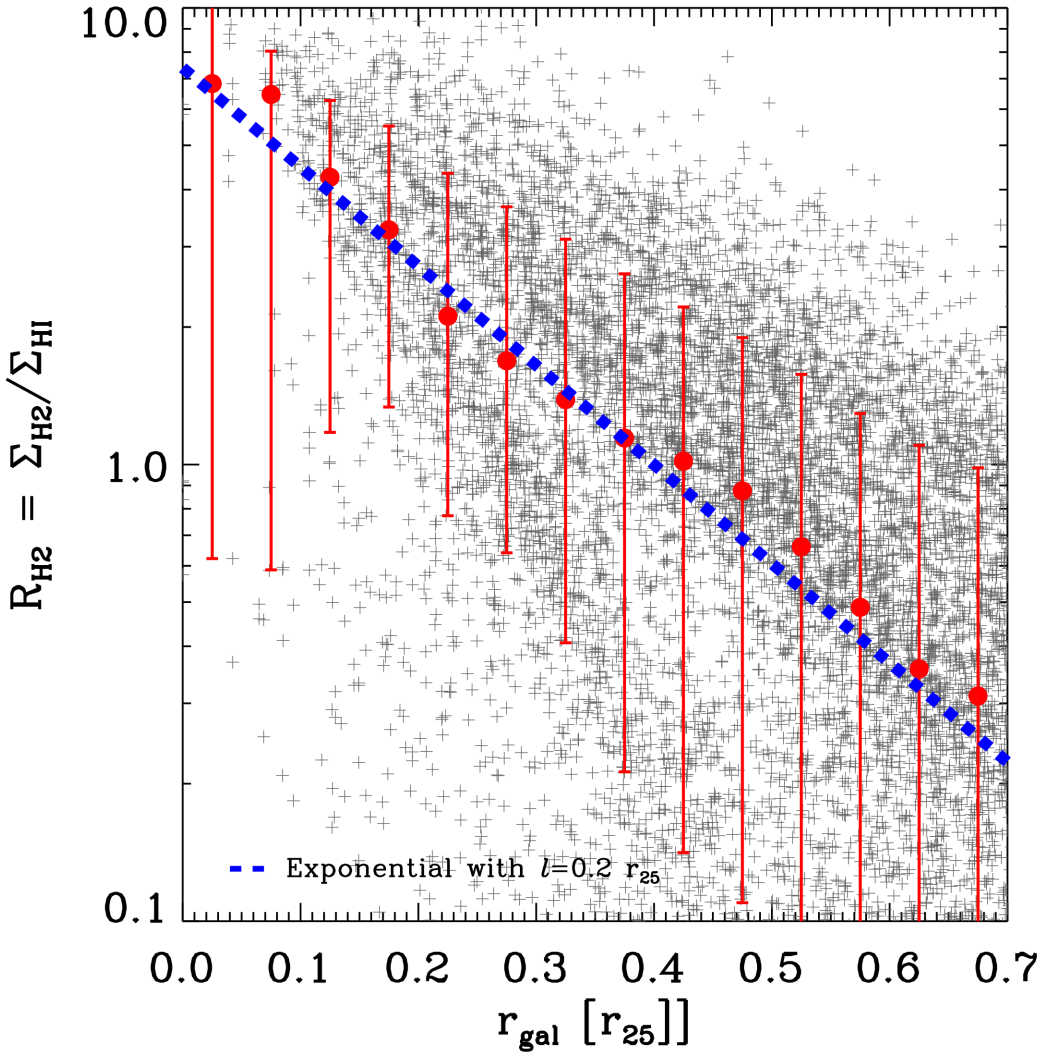
Kpc lines of sight in 23 galaxy disks (Leroy+ in prep, Leroy+ 2008)

H_2/HI Varies With Galactocentric Radius



Azimuthal averages of 30 disk galaxies (Schruba+ 2011)

H_2/HI Varies With Galactocentric Radius

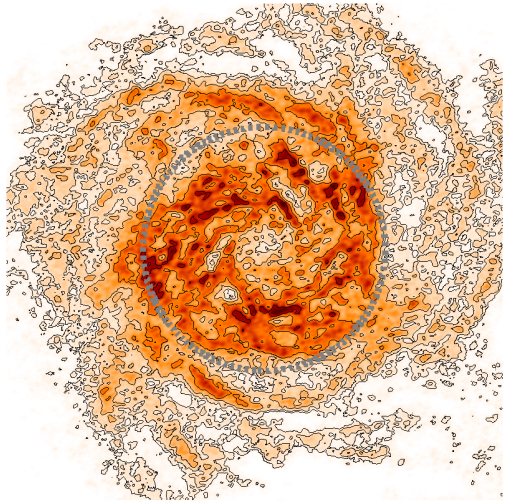


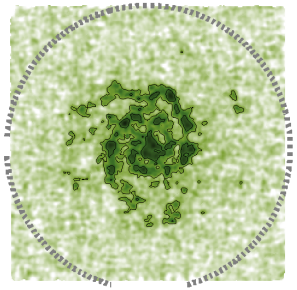
Kpc lines of sight in 23 galaxy disks (Leroy+ in prep, Leroy+ 2008, Schruba+ 2011, Wong & Blitz '02, Regan+ '01)

Basics for H_2/HI in Nearby Galaxies

- H_2 traced by CO and HI show dramatically different distributions.
- HI usually dominates the mass.
- H_2 is coincident with star formation.
- HI shows a saturation / narrow range of Σ at kpc scales.
- H_2 / HI varies with column, hydrostatic pressure, radius.
- Hydrostatic pressure linked to column and surface density

Basics for H_2/HI in Nearby Galaxies





The distributions of HI and H_2 starkly differ in nearby disk galaxies, with HI in a relatively smooth component representing most of the mass and H_2 more concentrated, clumpy, and coincident with star formation. H_2 becomes an increasingly large fraction of the ISM towards the centers of galaxies, in regions of high column density, high stellar surface density, and large implied hydrostatic pressure.

The H_2 / HI Transition in Nearby Galaxies

Basic Observations

Theoretical Context

Second Order Observations

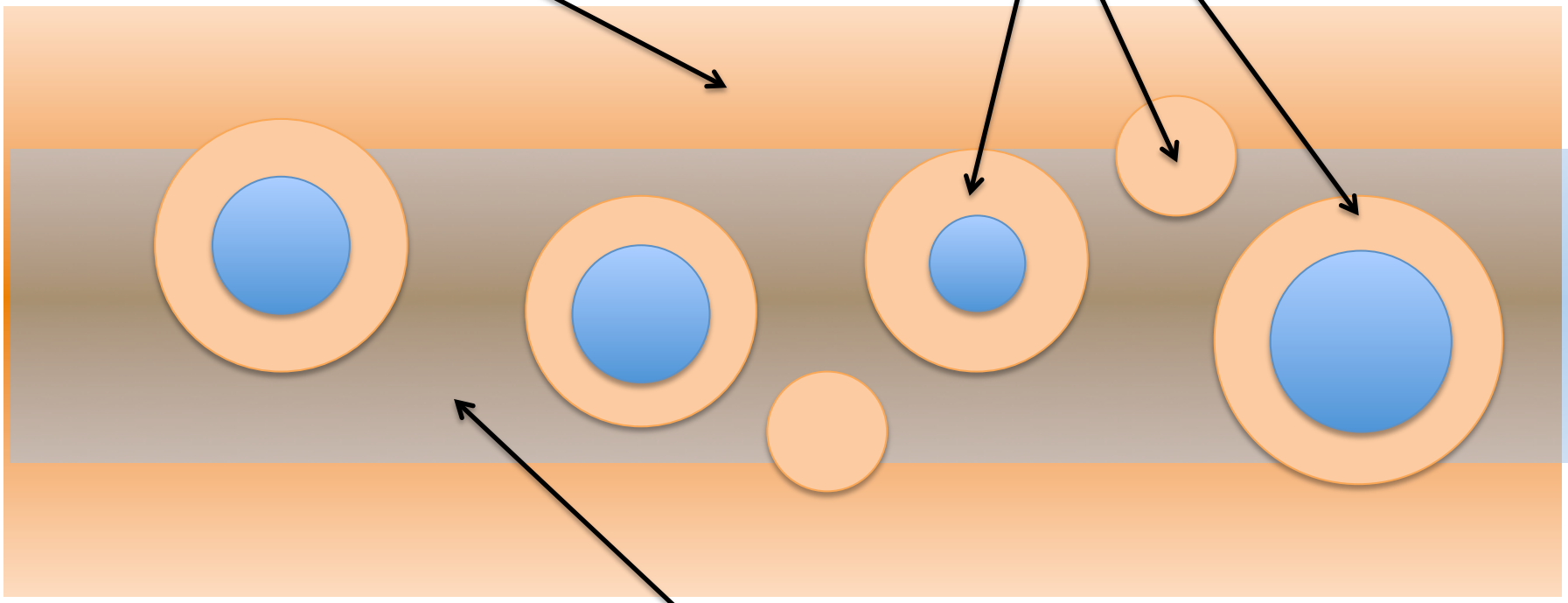
Current Challenges and Next Steps

Theoretical Context

Molecular
Atomic

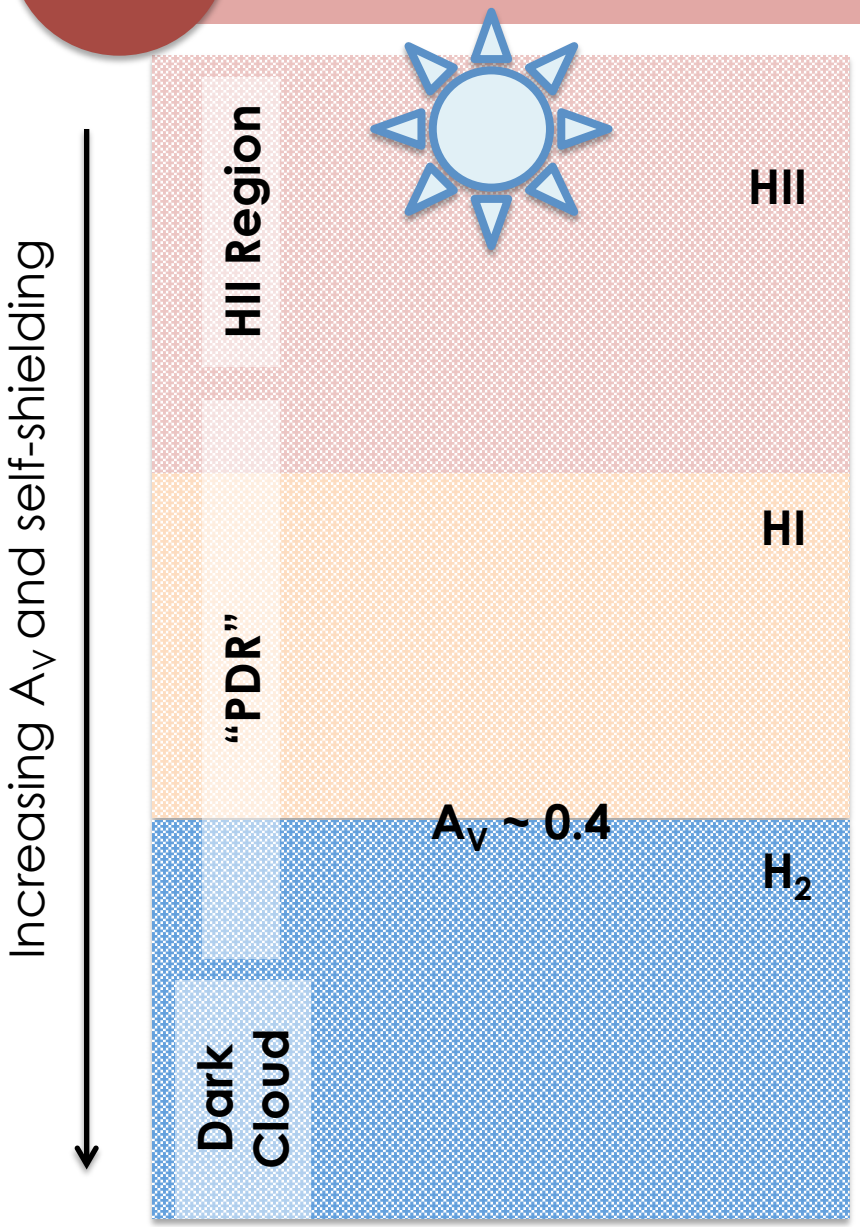
Diffuse Atomic Gas
(both CNM/WNM)

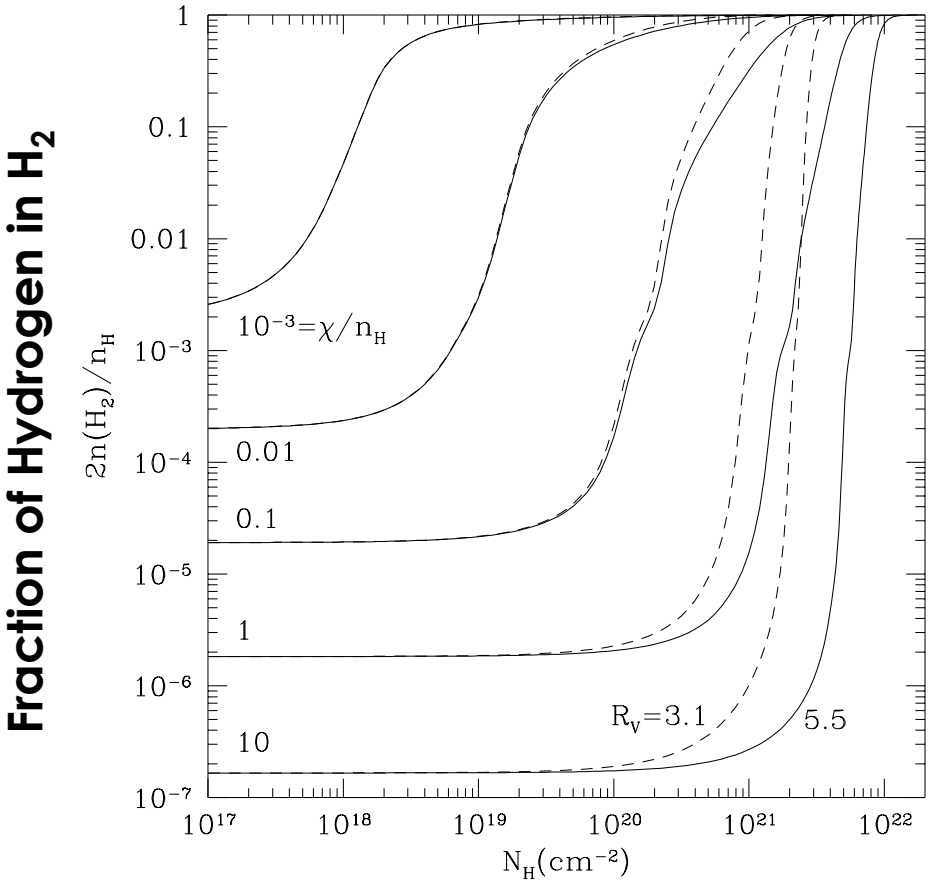
Bound (or dense) Clouds



Diffuse Molecular Gas? Not currently modeled…

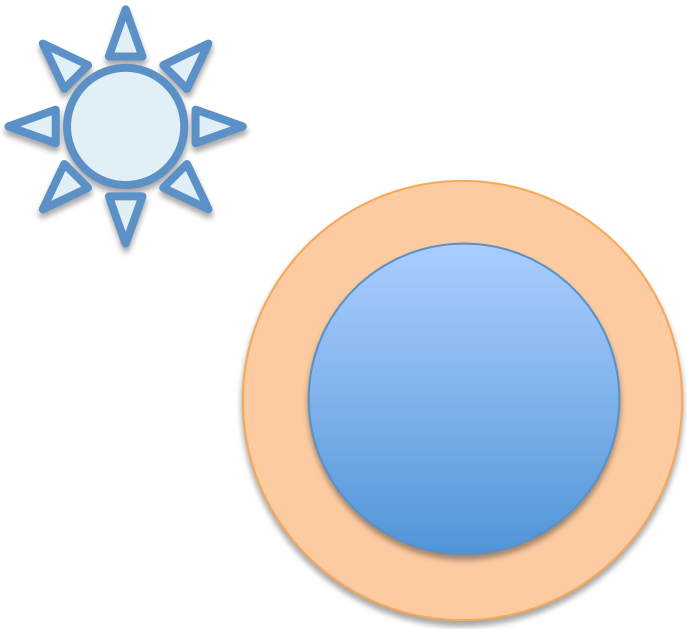
PDR Structure: Shielding from HII to H_2



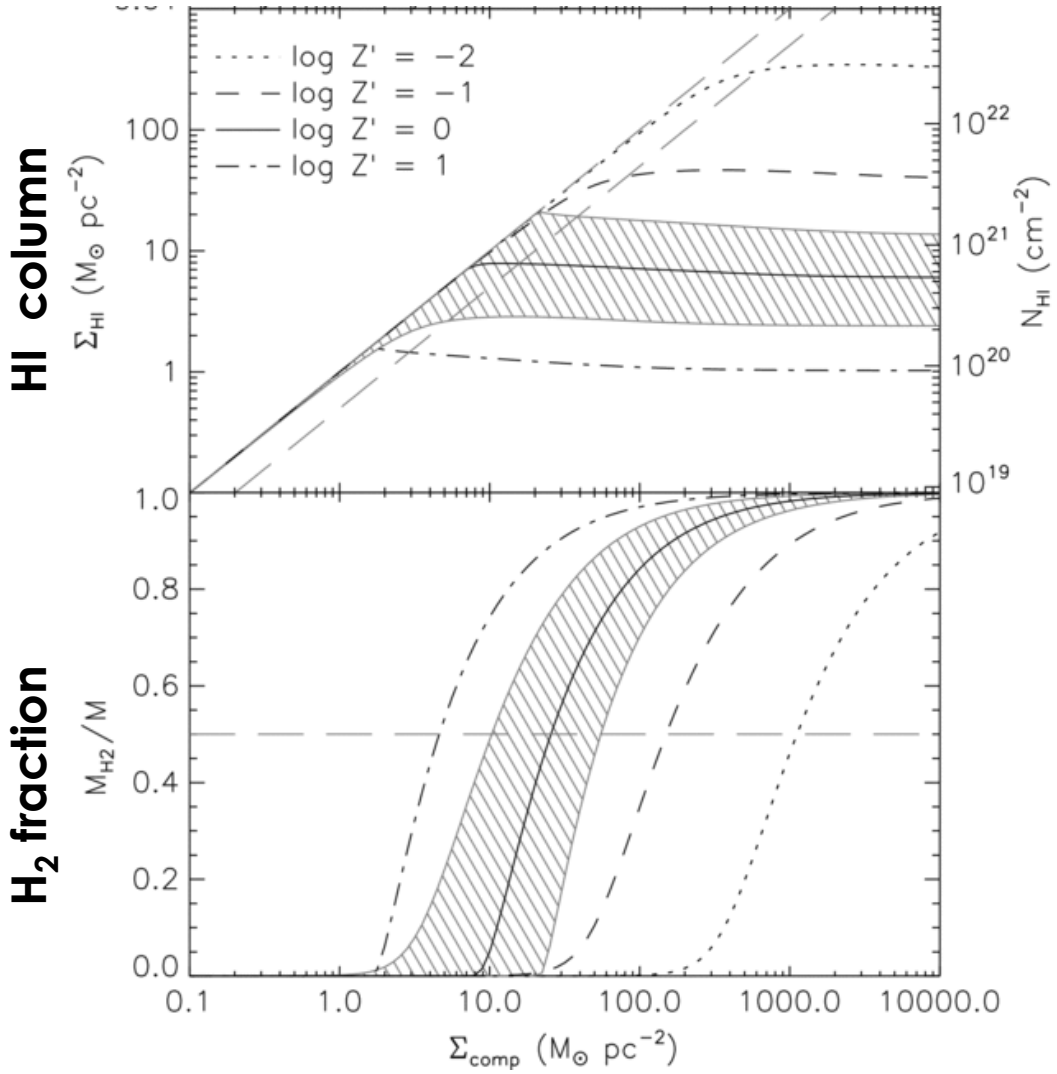


Draine & Bertoldi 1996, Wolfire+ 2010

Clouds: HI Saturation as a Shielding Layer

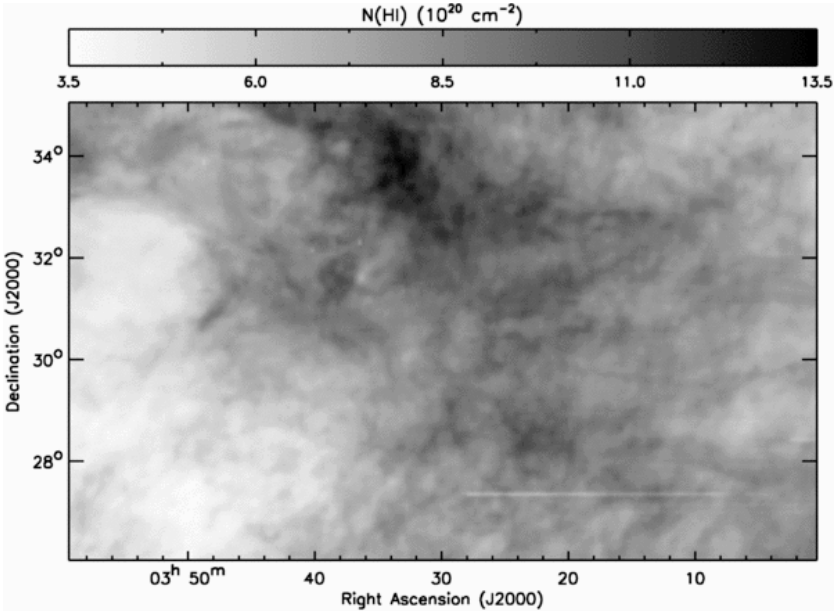


- Spherical PDR model
- Natural HI saturation
- D/G prediction

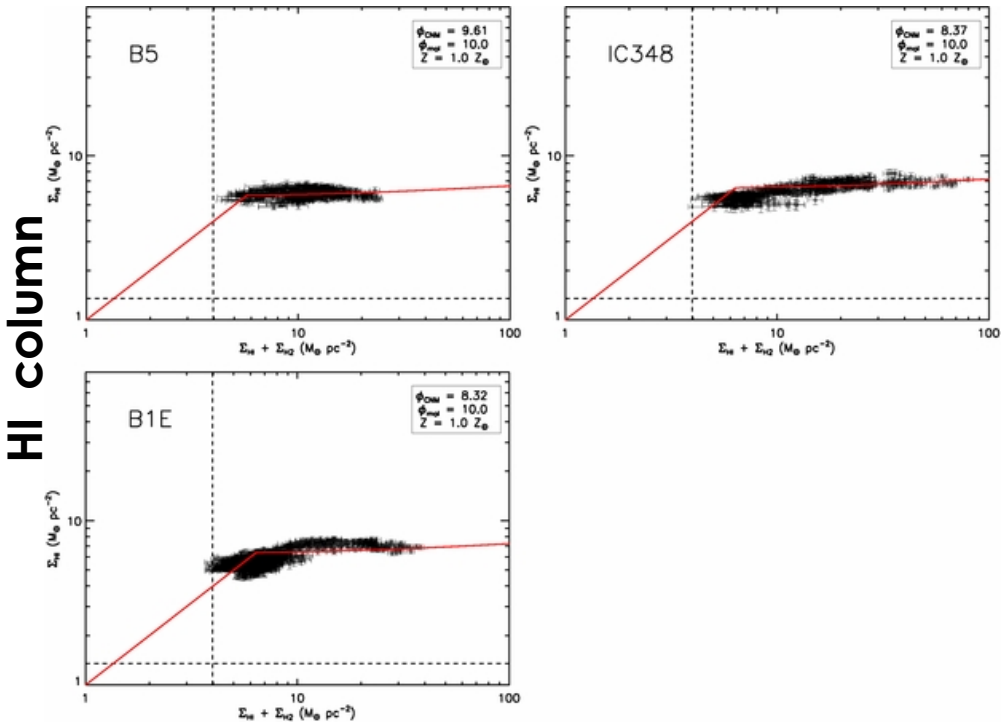


Krumholz+ 2009ab

Galactic Clouds: Shielding Layer Observed



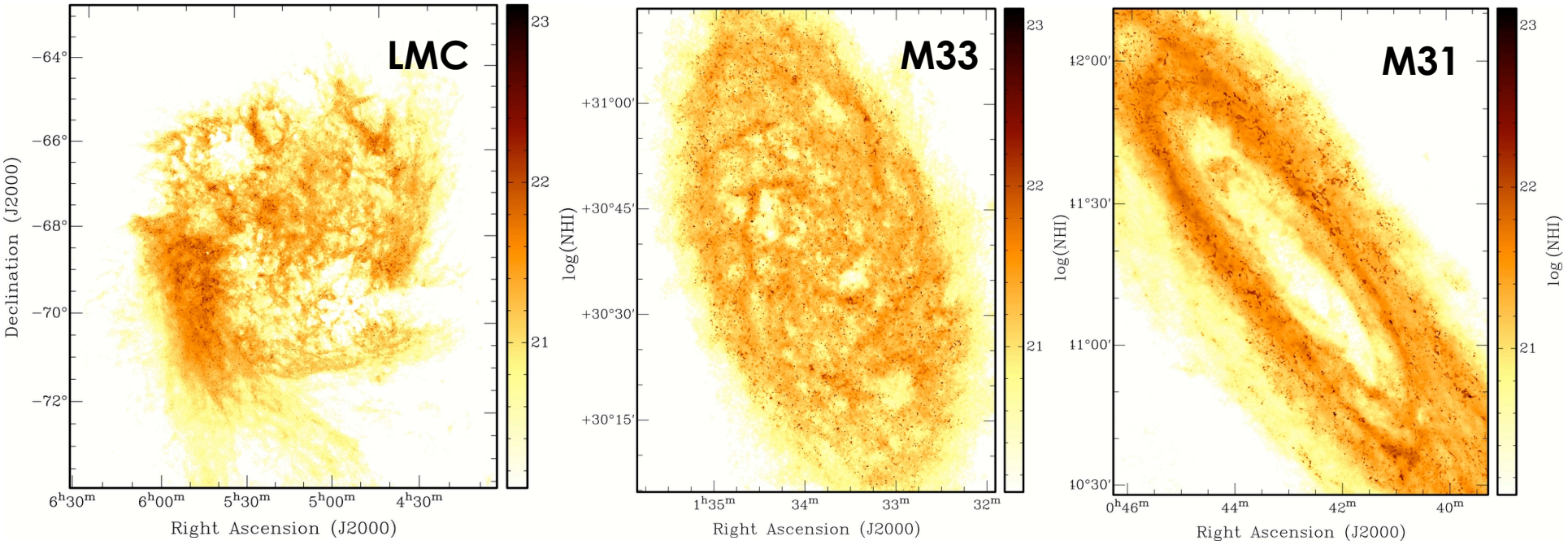
Perseus Molecular Cloud



Lee, Stanimirovic+ 2012

The Problem With Clouds: Diffuse HI

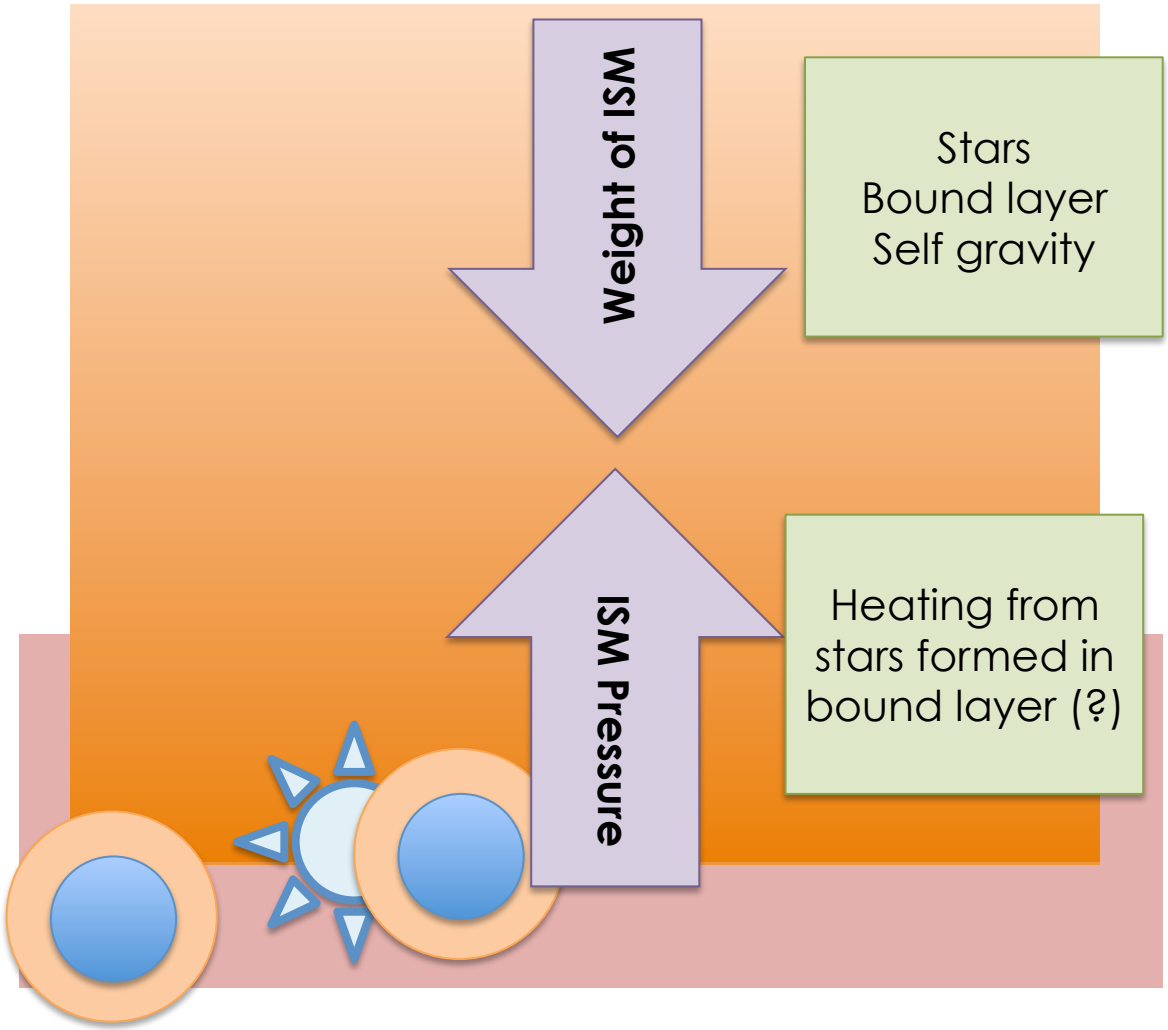
HI distributed broadly, smoothly, not just cloud complexes.

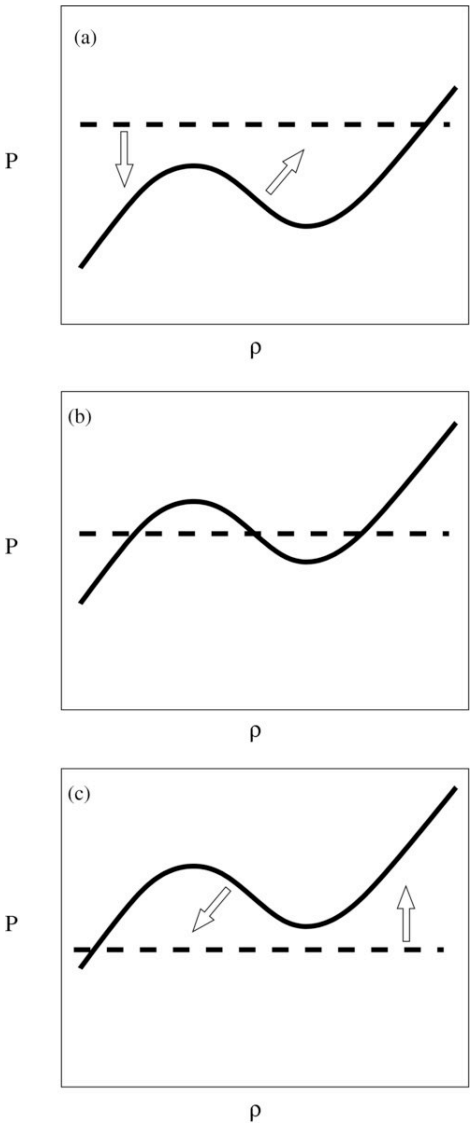


Cloud models provide **no prediction** for diffuse-cloud balance.
(Resolution-dependent tests illustrate the problem.)

Maps compiled by Braun 2012

Diffuse vs. Clouds: Equilibrium Arguments



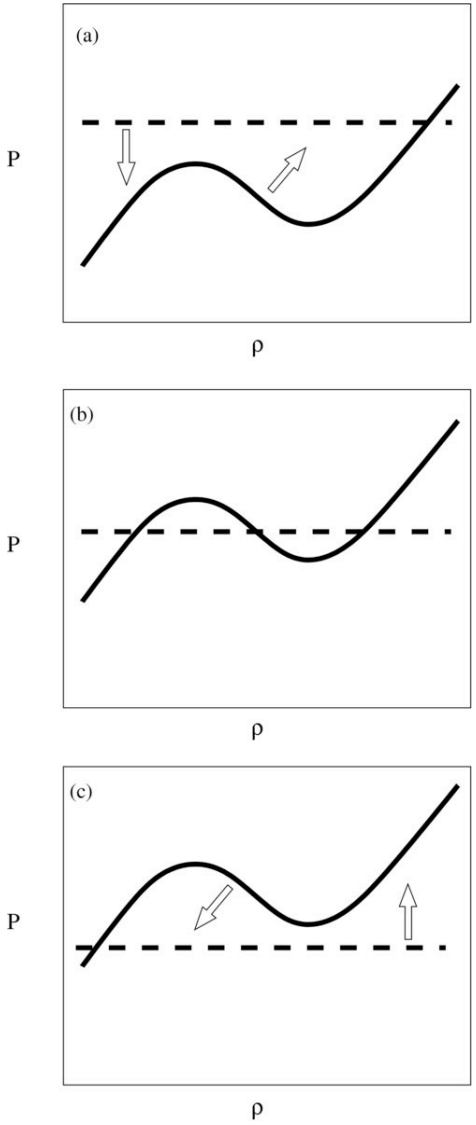


Ostriker+ 2010

Diffuse vs. Clouds: Equilibrium Arguments

Low star formation → Low pressure and **less** vertical support → More bound clouds and **more** star formation

High star formation → High Pressure and **more** vertical support → Less bound clouds and **less** star formation

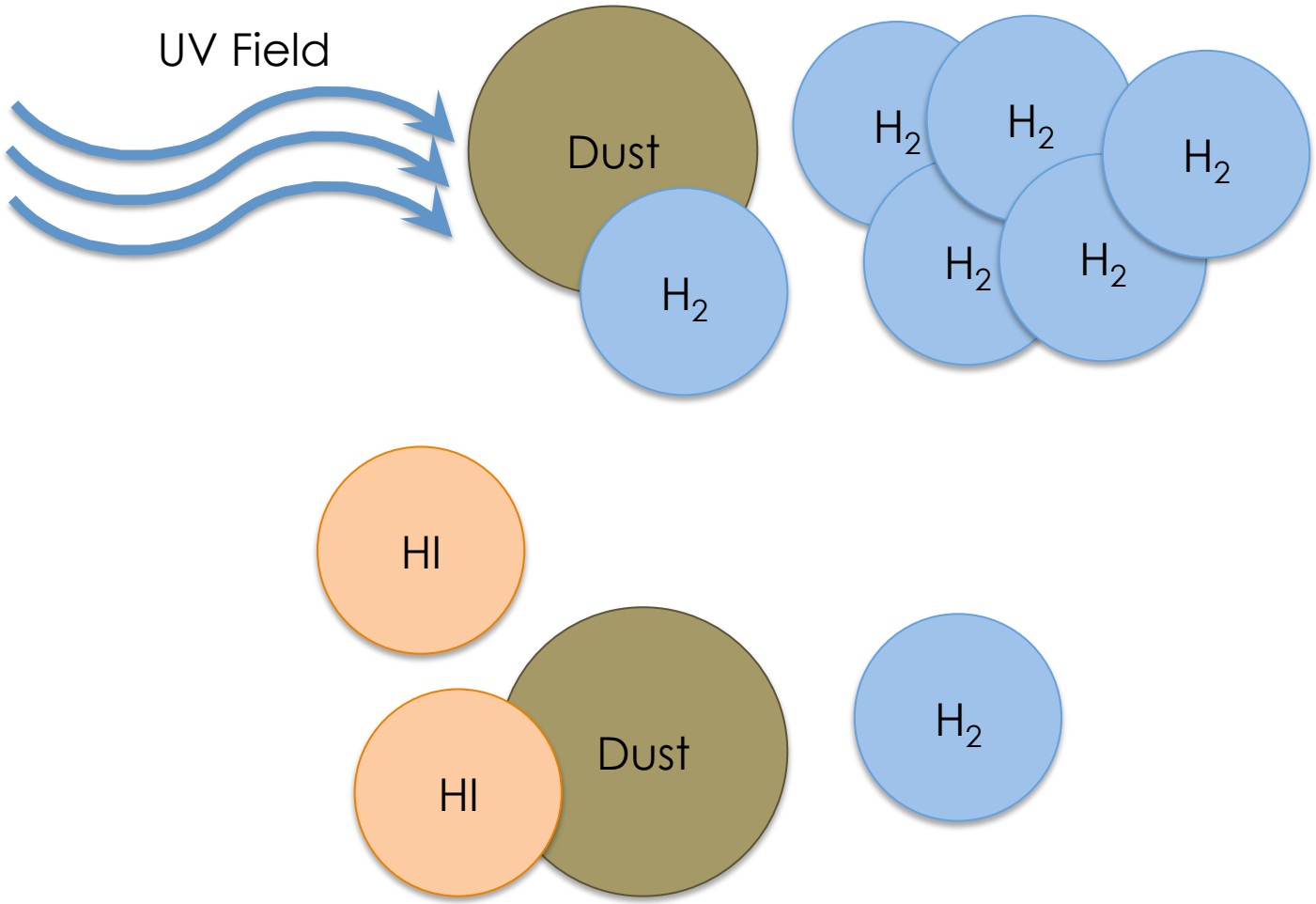


- Equilibrium prediction for diffuse column
- Must be merged with cloud structure models
- Requires linkage between P_{hyd} and $P_{thermal}$

Ostriker+ 2010, Bolatto+ 2011

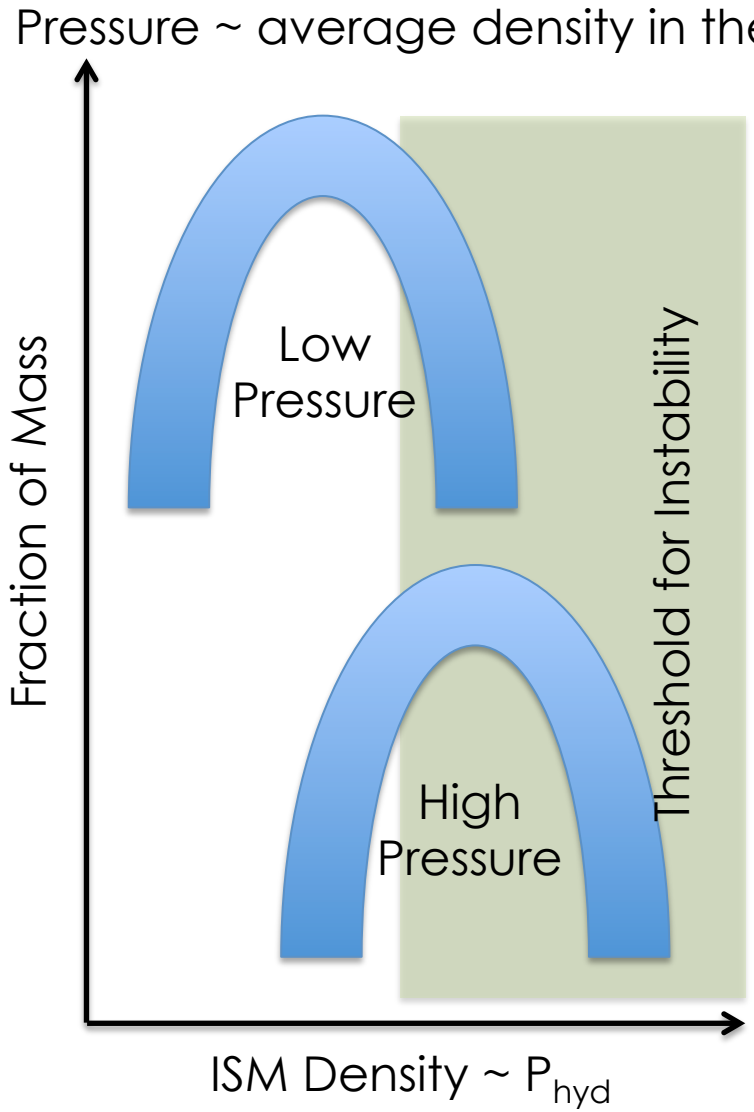
Pressure and Density

Pressure ~ small-scale volume density



Hollenbach & Tielens 1976, Elmegreen & Parravano 1994

Pressure and Density

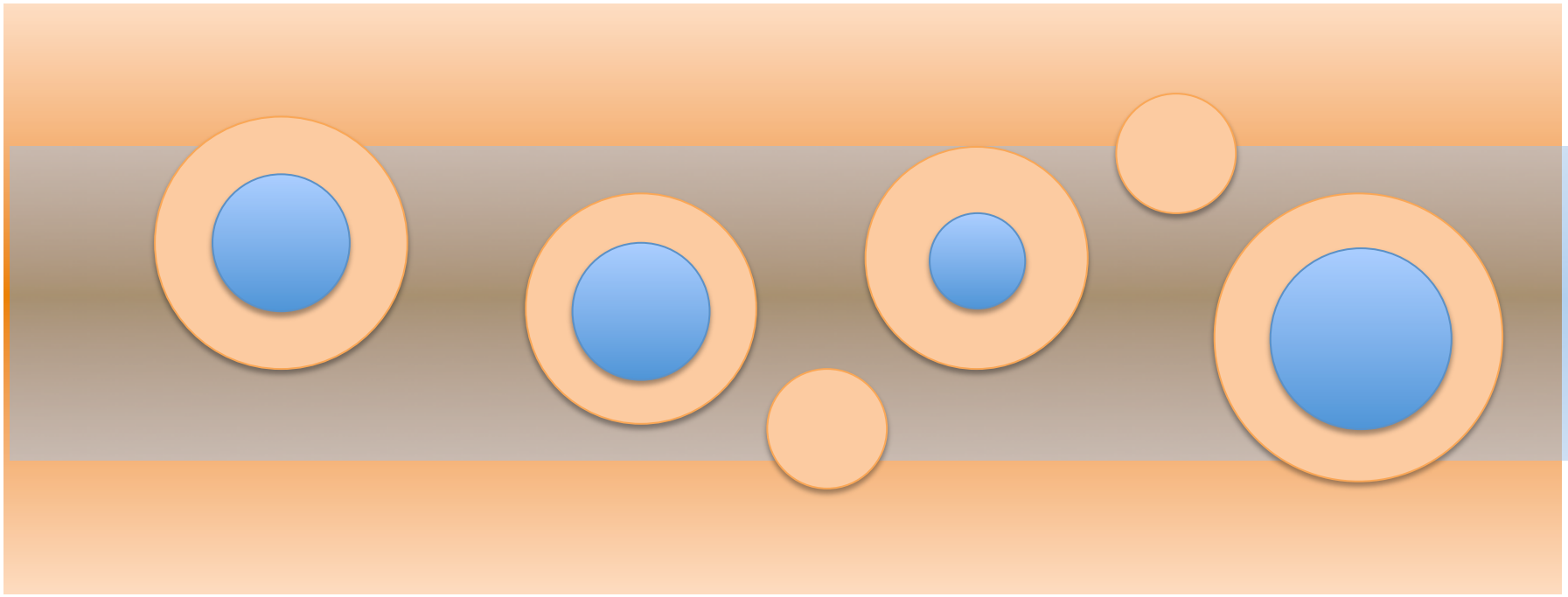


Elmegreen & Parravano 1994, Schaye 2004

Theoretical Context

- Cloud/PDR structure explains HI as shielding layer.
- Works in Milky Way clouds (so far).
- Structure of HI (bound/diffuse) poses problems for these models.
- Bound/diffuse balance can be modeled in equilibrium.
- "Pressure" correlations linked to both micro- and macrophysics.
- Resolution, metallicity, disk structure, UV field add key constraints.
- Photodissociation? Especially in inner galaxies at high H_2/HI?
- Large scale stability? Measurements challenging and uncertain.
- Diffuse CO? Currently not treated?
- Complete models are still emerging…

Theoretical Context



A complete model of the H_2-HI balance in galaxies must account for the structure of individual clouds (or PDRs) and the mixture of diffuse gas and bound/dense clouds. Scalings with resolution, metallicity/dust-to-gas ratio, pressure, and column density represent key tests. The mlecule-rich and molecule-poor regimes may have different dominant processes.

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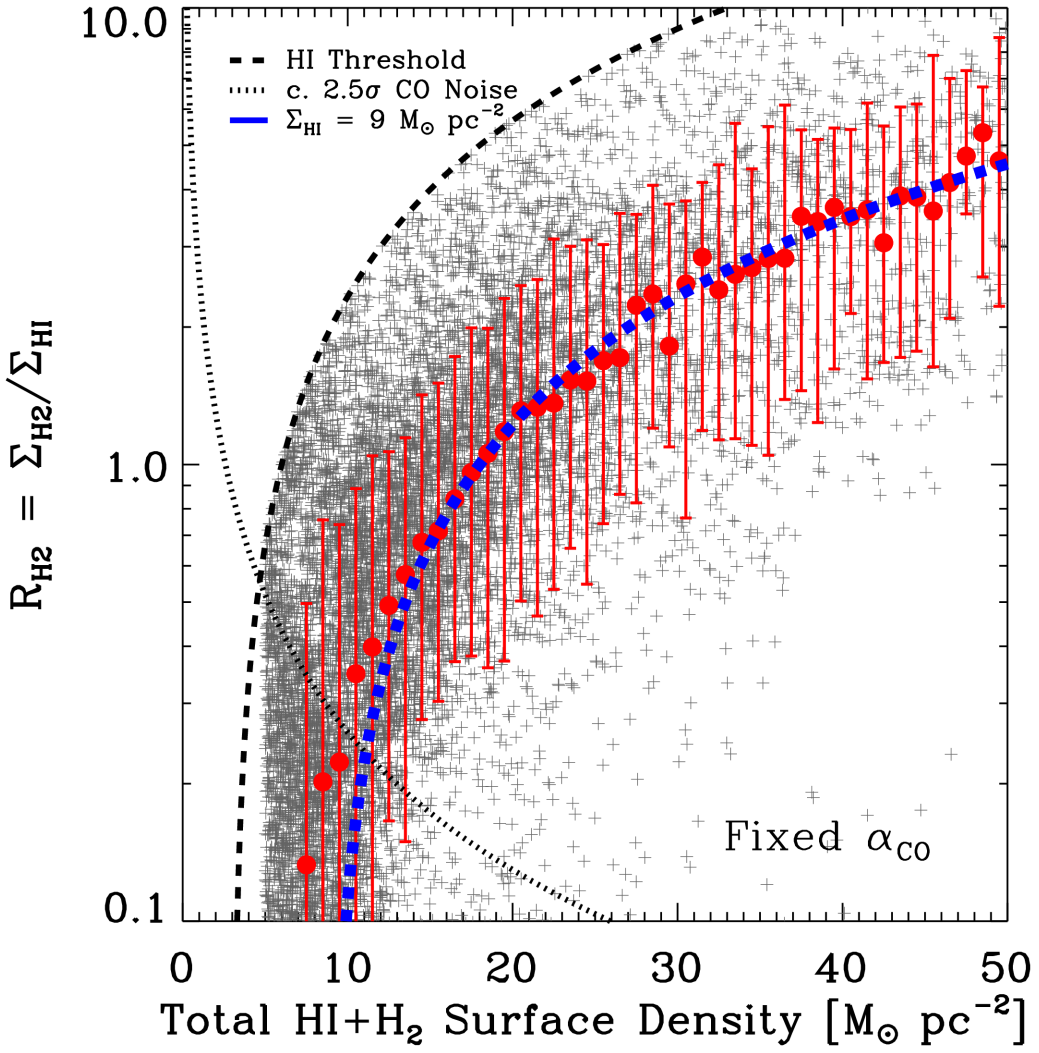
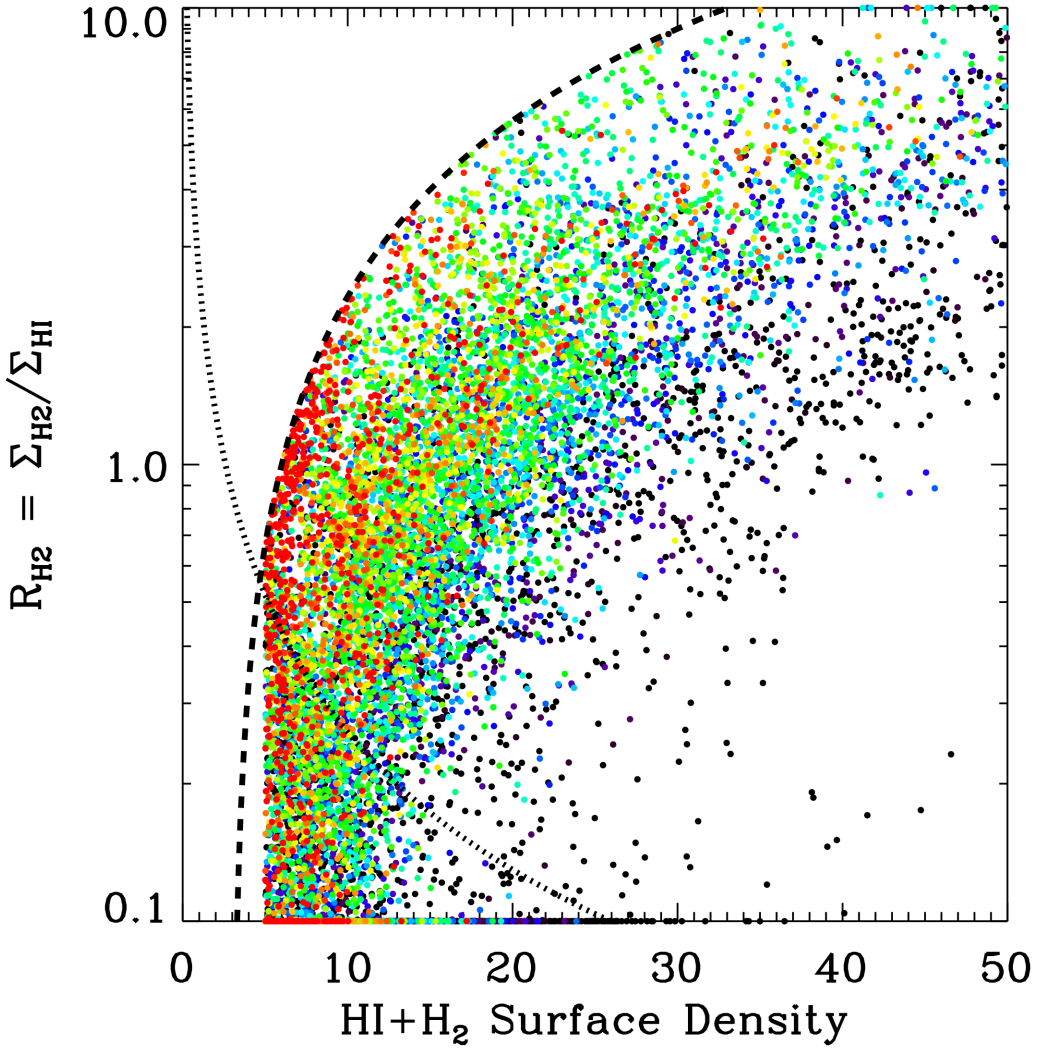
H_2/HI vs. Σ_{gas} at kpc Resolution



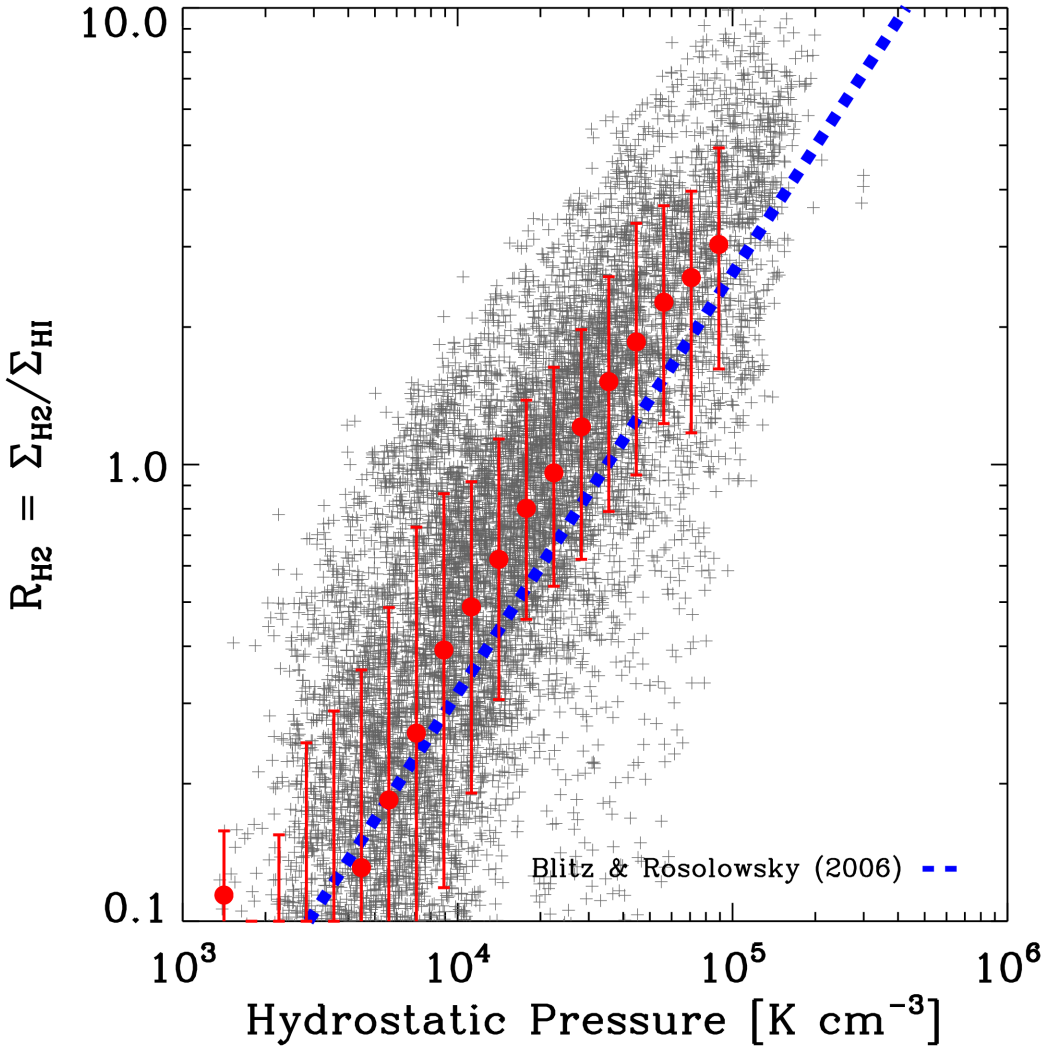
Leroy et KINGFISH (Aniano, Draine) + HERACLES + THINGS in prep.

Dust-to-Gas As a Second Parameter



Leroy et KINGFISH (Aniano, Draine) + HERACLES + THINGS in prep.

H_2/HI vs. P_{hyd} at kpc Resolution



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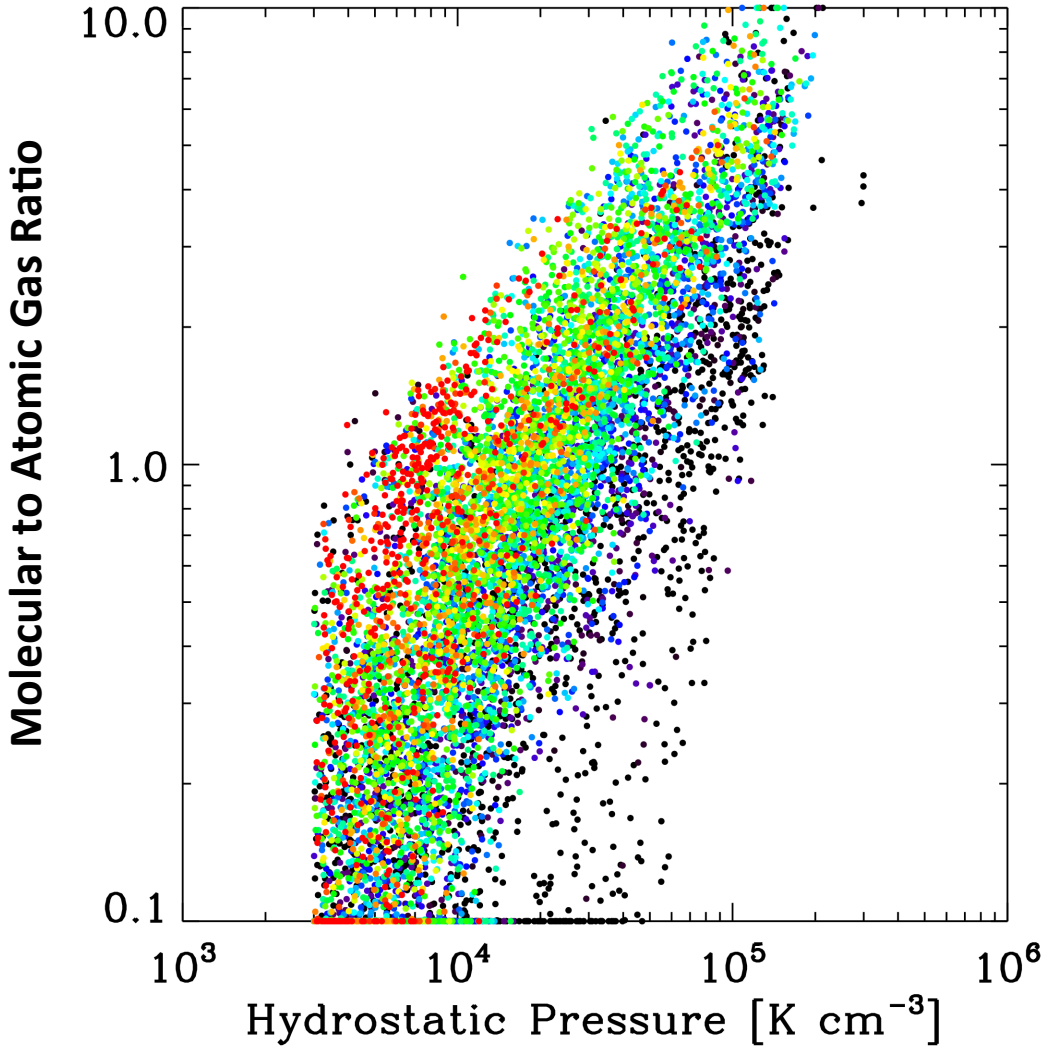

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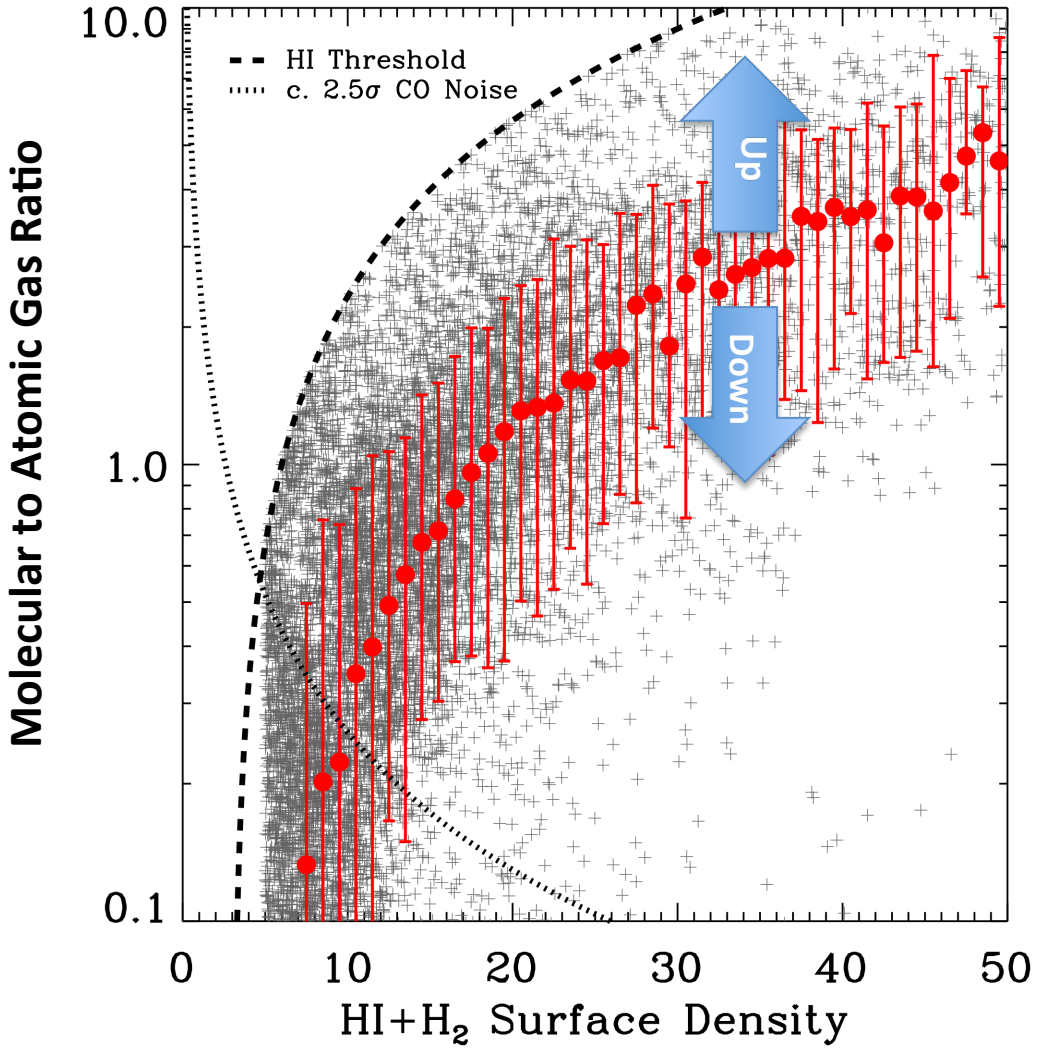

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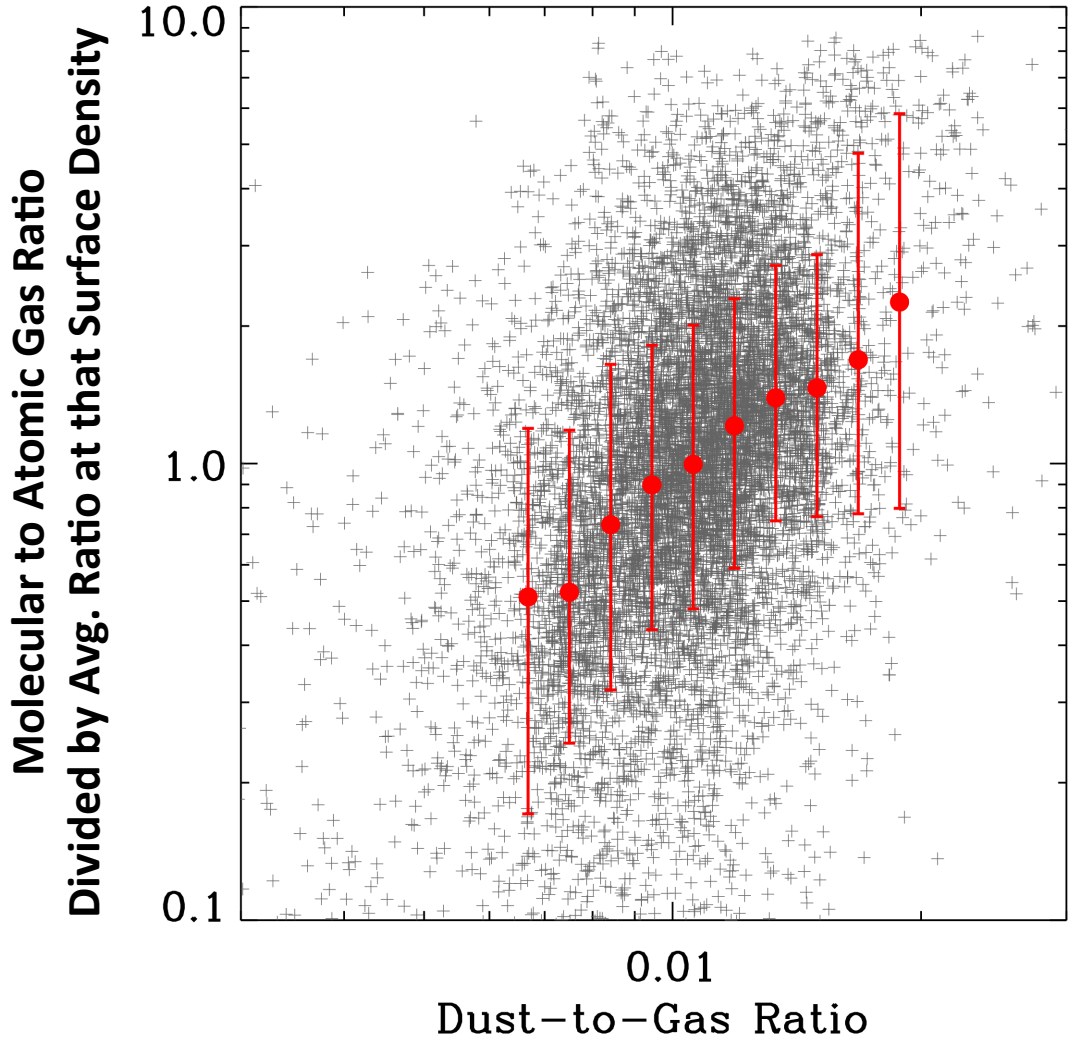
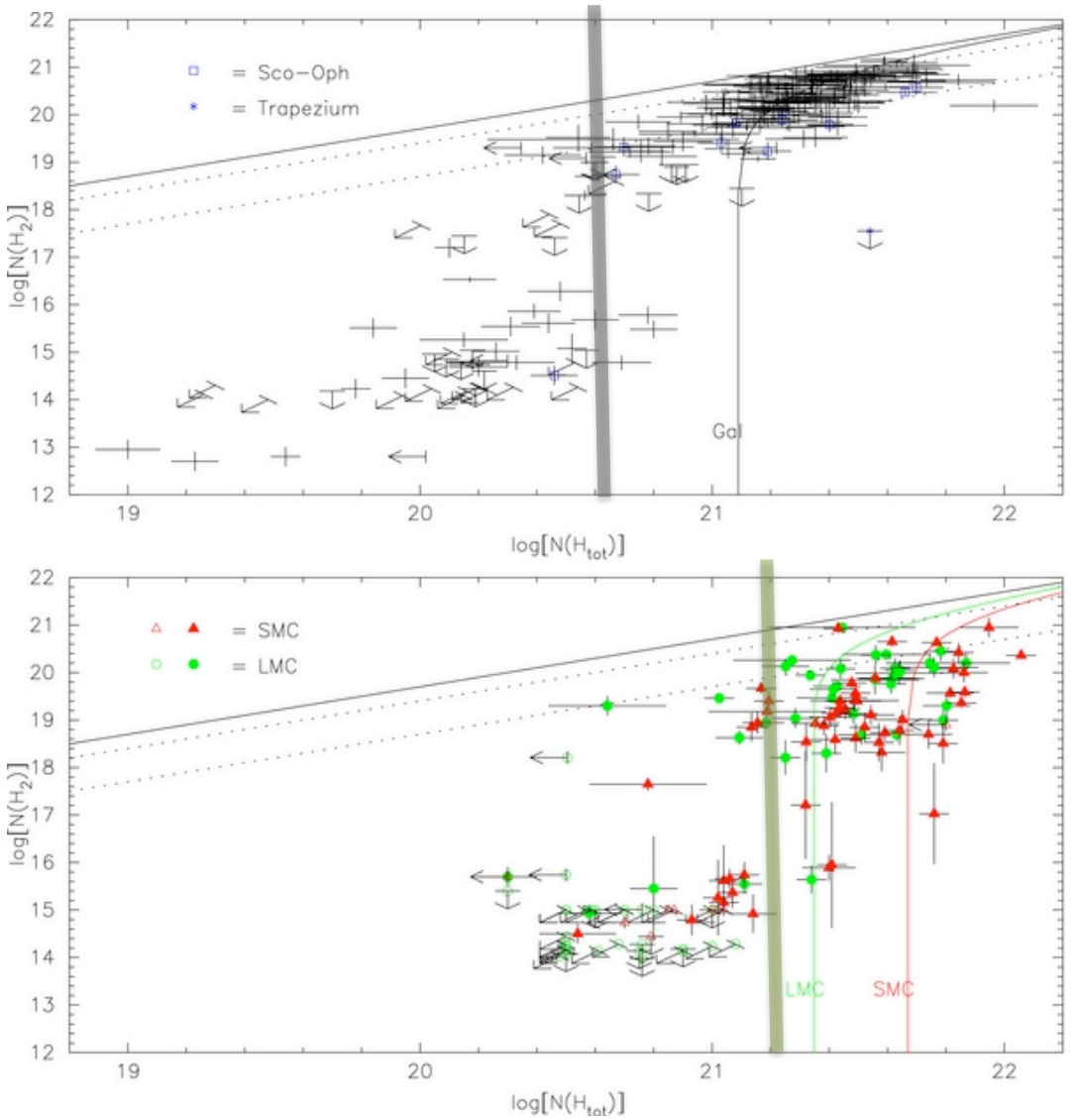


Leroy et KINGFISH (Aniano, Draine) + HERACLES + THINGS in prep.

The Best "Galactic" Extragalactic Study

FUSE in SMC/LMC

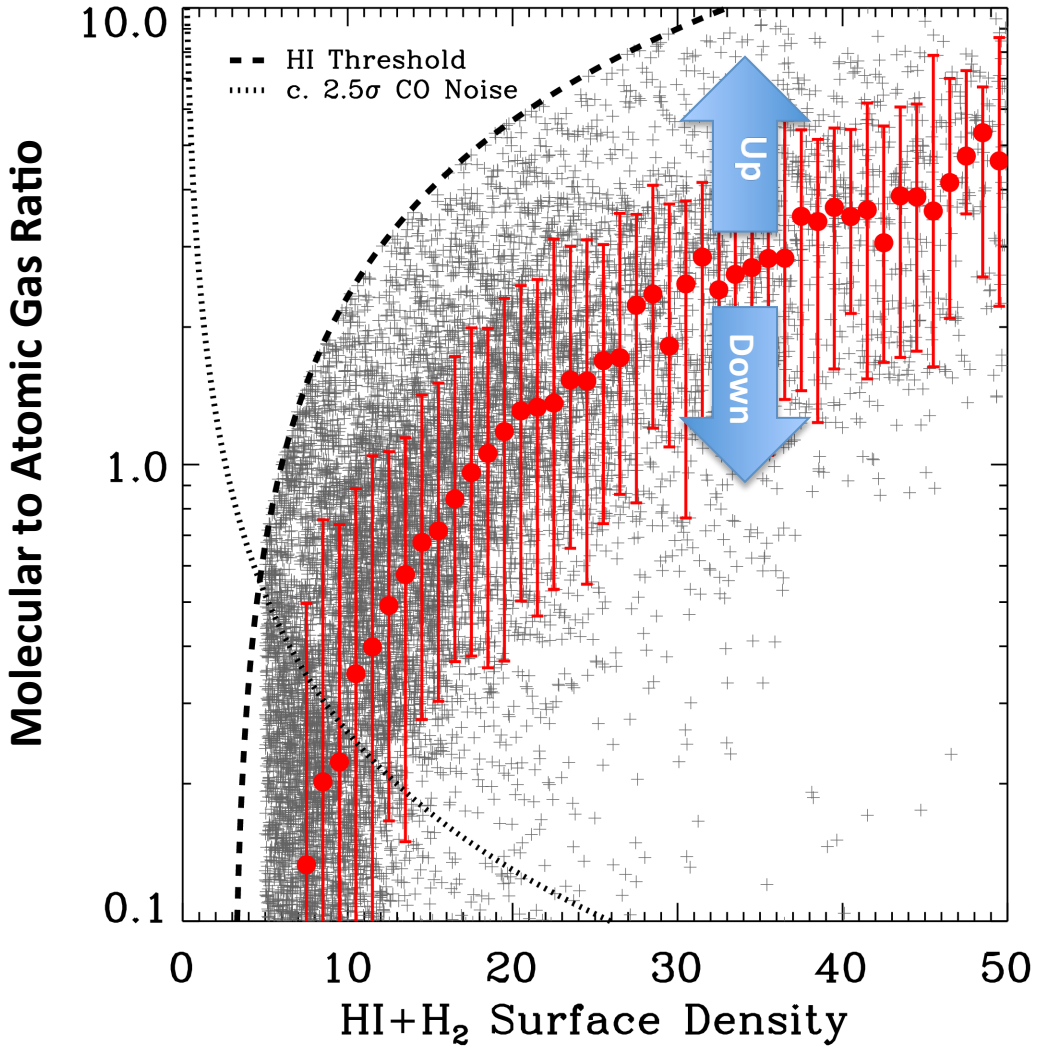


H_2 Column Density

Total Column Density

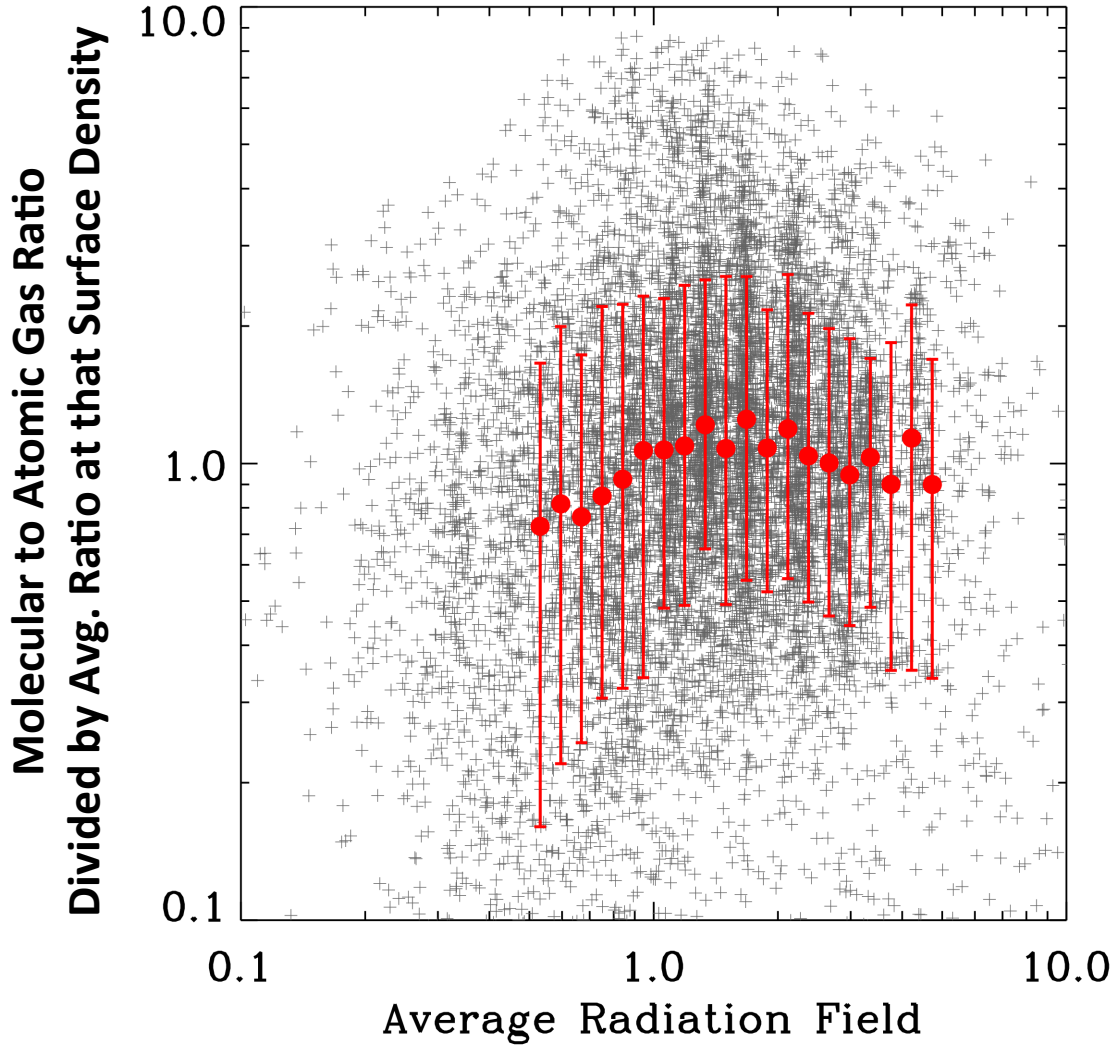
Welty+ 2012

Dust-to-Gas As a Second Parameter



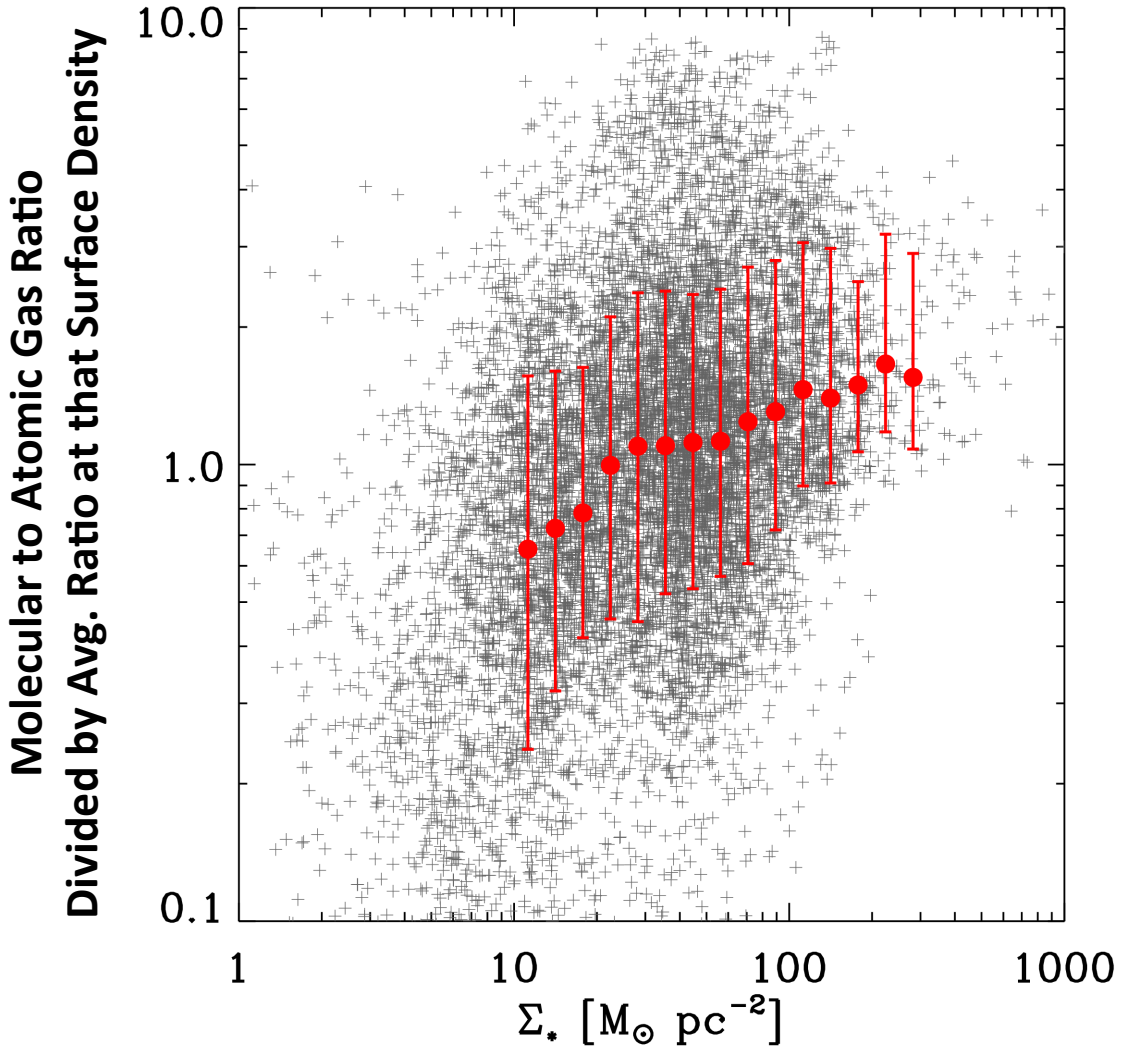
Leroy et KINGFISH (Aniano, Draine) + HERACLES + THINGS in prep.

No Clear Correlation With Radiation Field



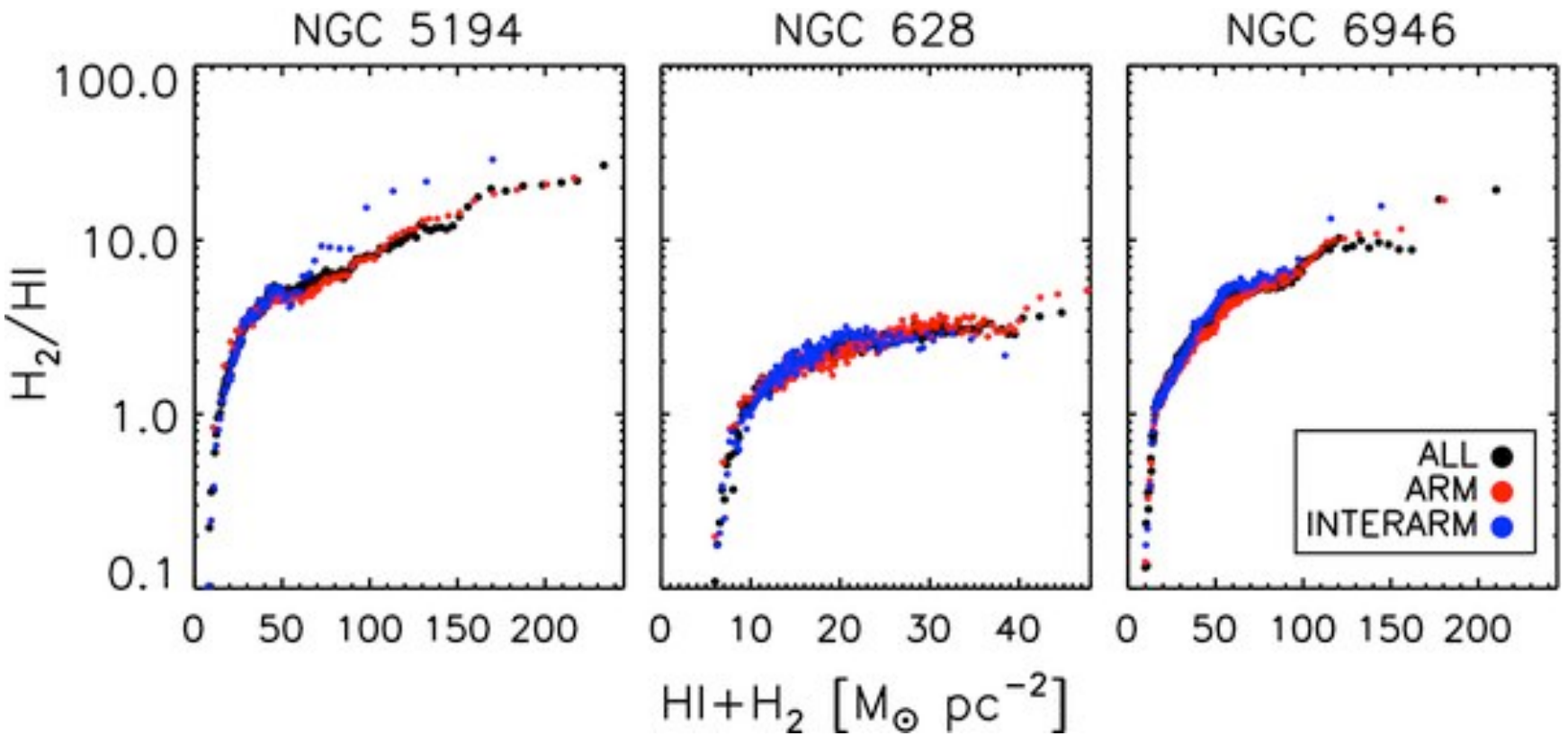
Leroy et KINGFISH (Aniano, Draine) + HERACLES + THINGS in prep.

Stellar Surface Density



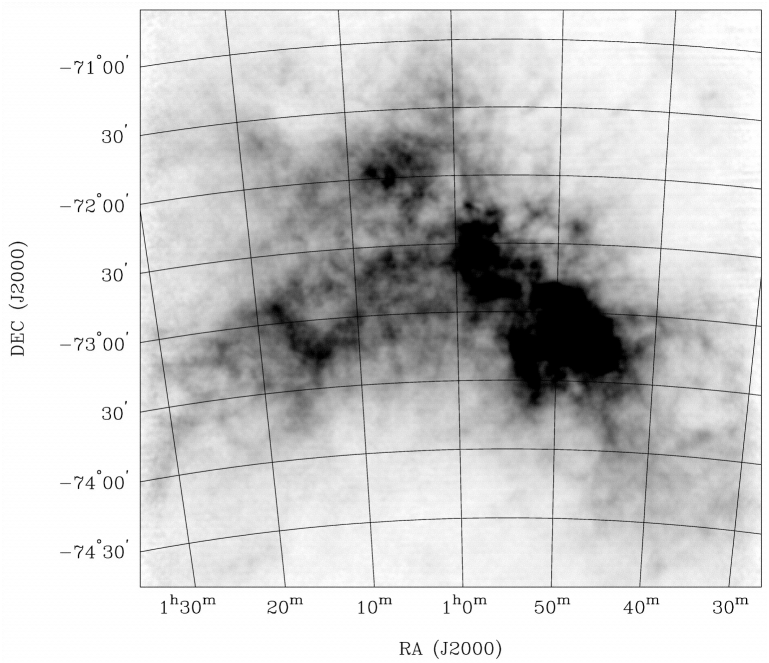
Leroy et al in prep.; Meidt+ '13 stellar surface density maps

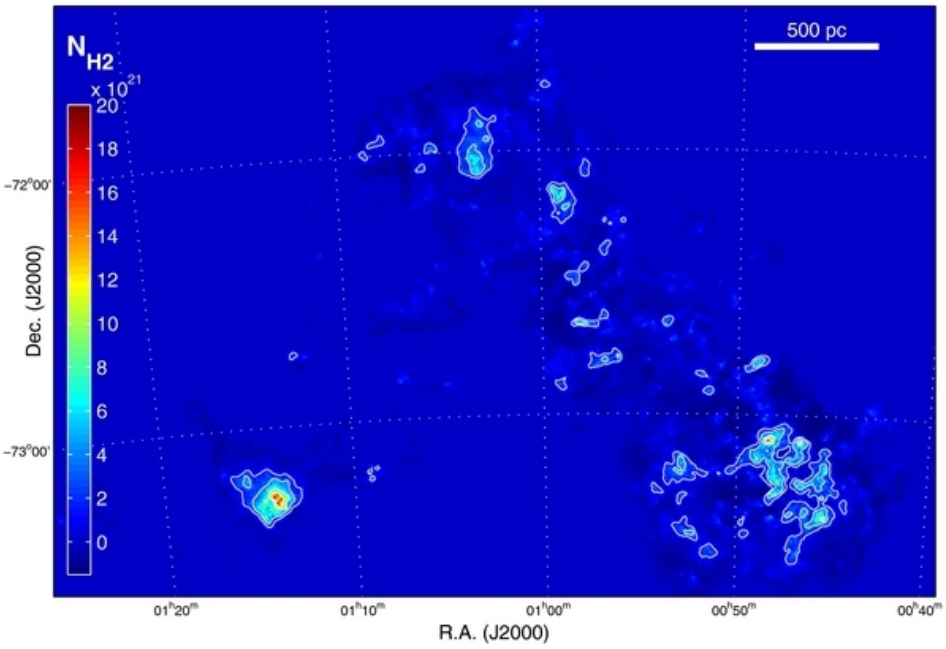
The Role of Arms



Foyle+ 2010

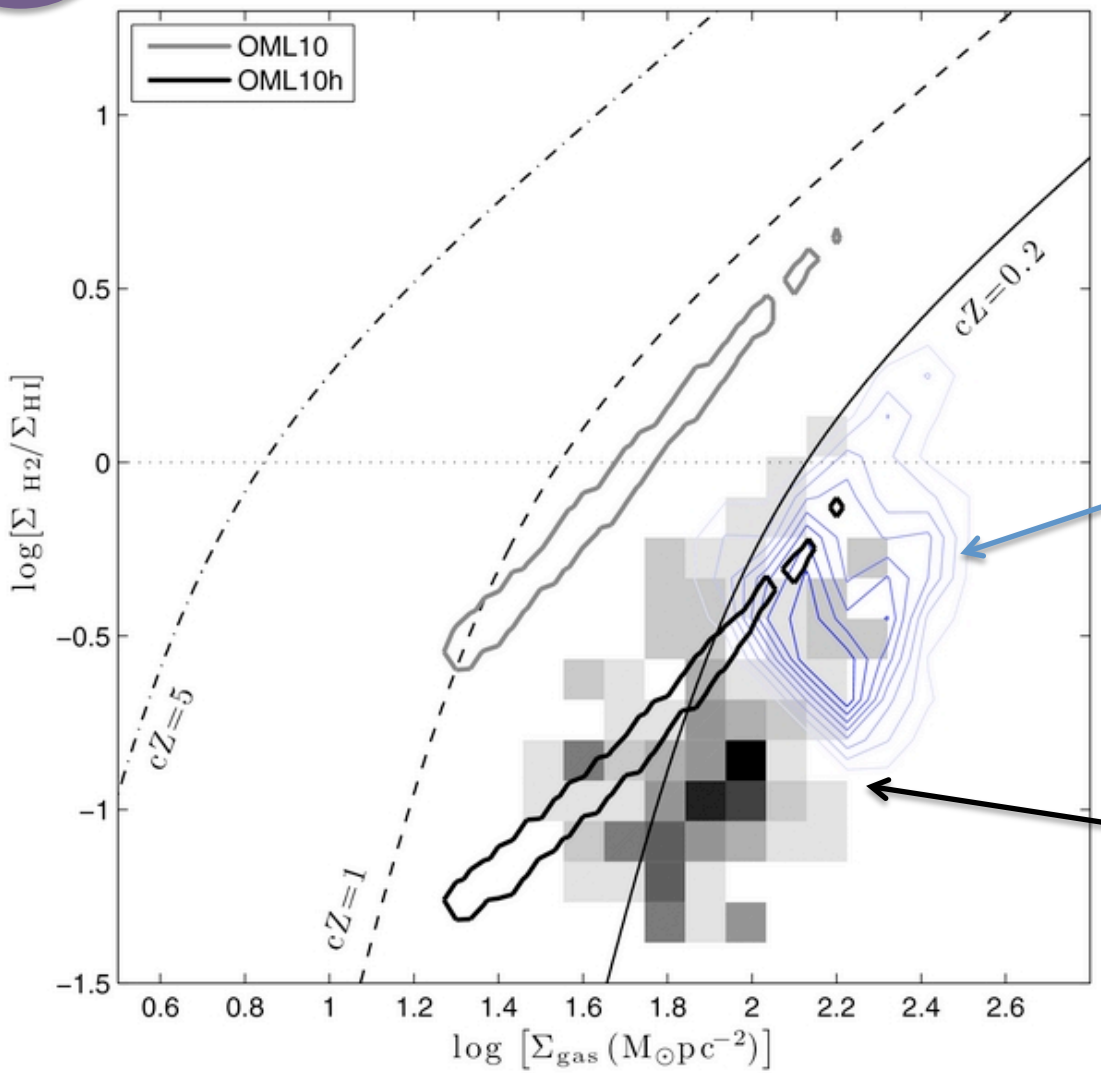
The Small Magellanic Cloud as Testbed





H_2 and HI at 30 pc and low z - Stanimirovic+ 2004; Bolatto+ 2011

The SMC Breaks Models



Molecular to Atomic Gas Ratio

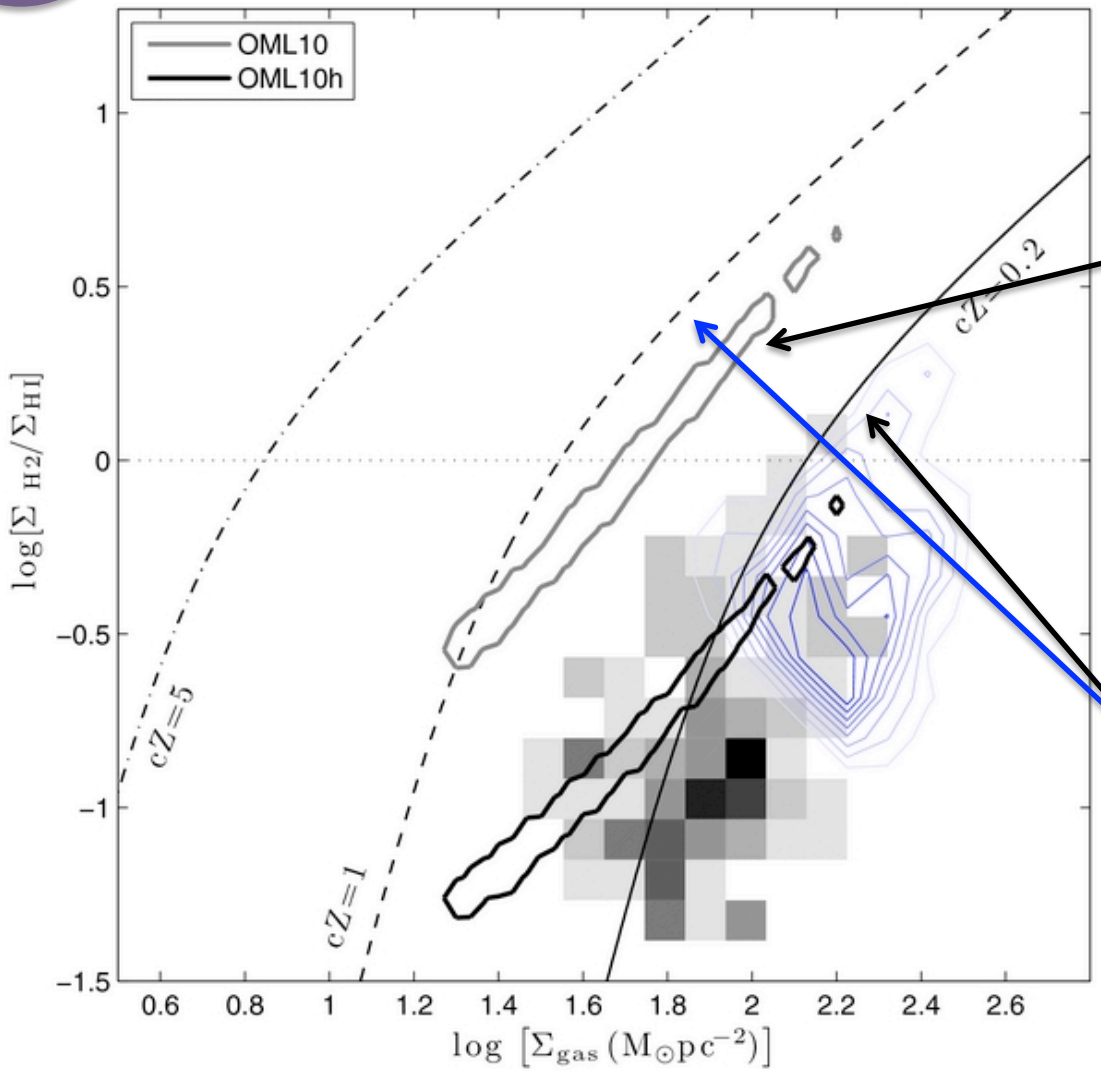
Total Gas Surface Density

SMC data at
200 pc resolution

SMC data at
~10pc resolution

Bolatto+ 2011

The SMC Breaks Models



Molecular to Atomic Gas Ratio

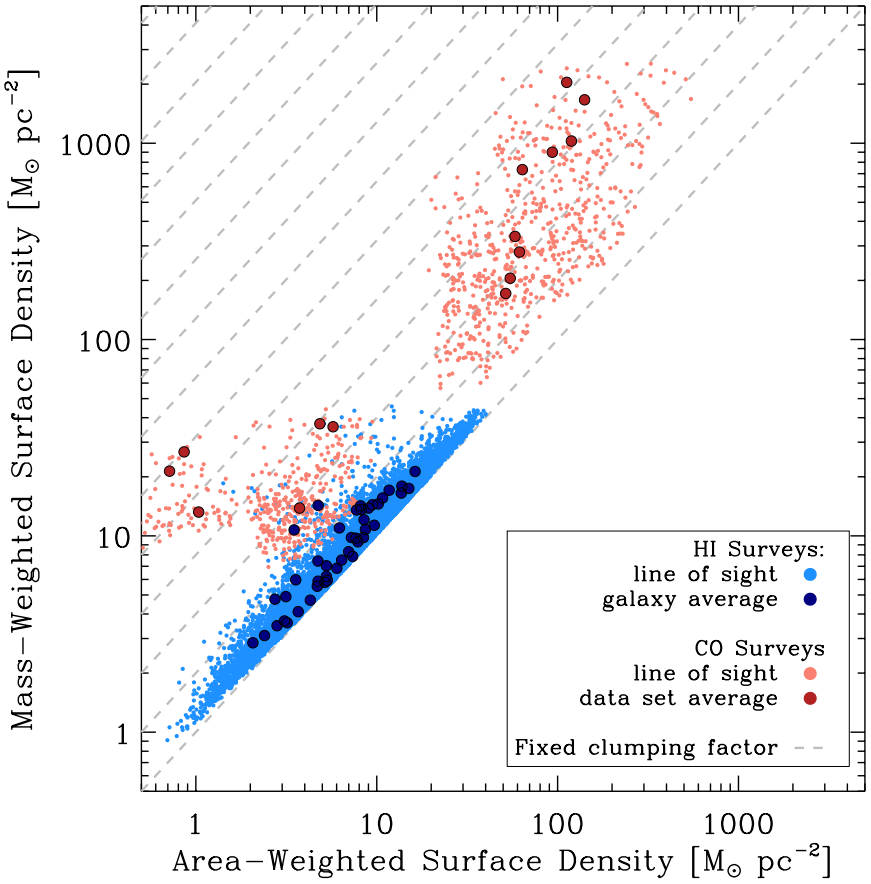
Total Gas Surface Density

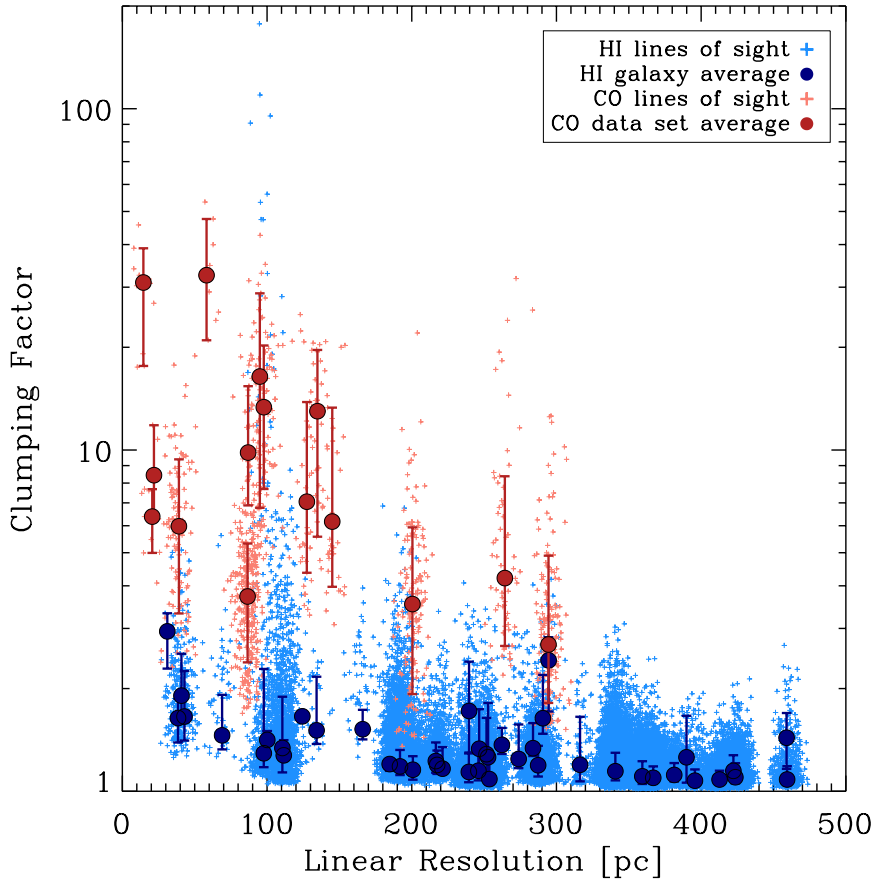
Ostriker+ '10
diffuse/bound
equilibrium
fails on metallicity
dependence…

Krumholz+ '09
Cloud shielding
fails on scale
dependence /
diffuse fraction.
Blue should be at
cz=1…

Bolatto+ 2011

Resolution and Surface Densities



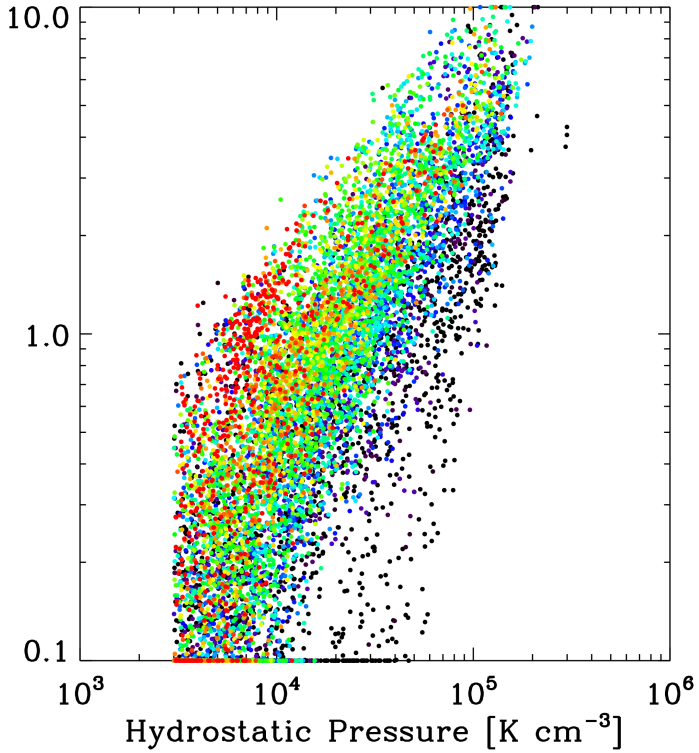


Leroy+ 2013

Second Order Observations

- Dust-to-gas ratio a clear second parameter about scalings
- Stellar surface density also shows trend, radiation field not clear
- Metallicity effects also evident from spectroscopy in LMC/SMC
- At low resolution in small sample, arms shift H2/HI along scalings
- High resolution SMC observations reveal problems with all models.

Second Order Observations



Observations clearly reveal that the H2/HI ratio is not predicted by a single parameter. Both dust-to-gas ratio (metallicity) and pressure, column, or stellar surface density play key, measurable roles. Disk structure and cloud structure both play a role and resolution-dependent tests are critical to distinguish the two.

The H_2 / HI Transition in Nearby Galaxies

Basic Observations

Theoretical Context

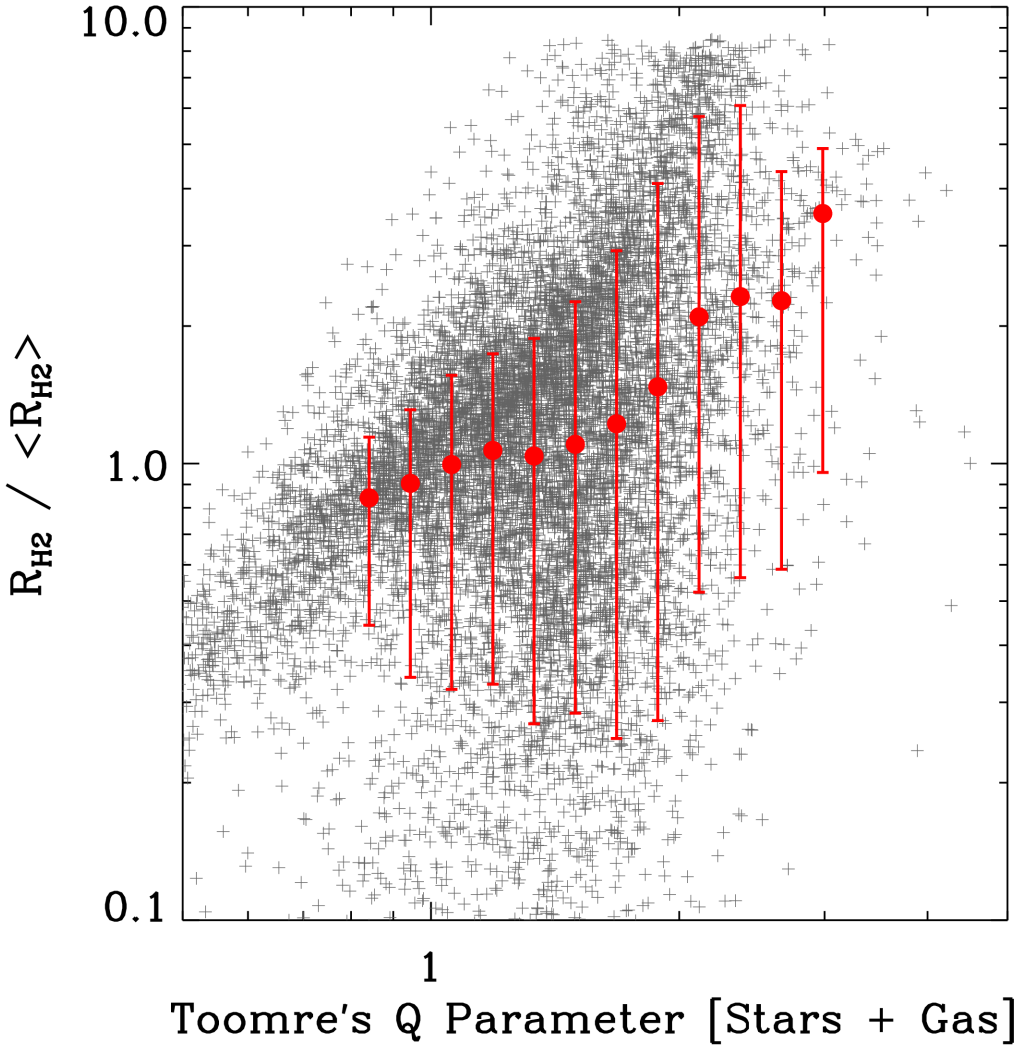
Second Order Observations

Current Challenges and Next Steps

Current Challenges and Next Steps

- Models that include cloud and galaxy structure.
- Better mapping of kpc surface densities to physical conditions.
- Better – high resolution, multi-scale tests of models.
- Tracers in extreme regimes – need X_{CO} to test very low D/G.
- Separate treatment of the molecule-rich regime?
- Key tests at low H_2/HI – where cloud formation regulates SF.

Toomre's Q Parameter



Each Point:
1 kpc resolution line of sight in a galaxy, 22 galaxies combined