An Observational View of the Interstellar Medium in Nearby Galaxies

1. Foreword

2. Phases of the ISM in z=0 Galaxies and Common Observational Techniques

3. Components of the ISM in z=0 Galaxies

4. Structure of the ISM in z=0 Galaxies

5. Star Formation in z=0 Galaxies

6. Conclusions

Goal of this Lecture

My goal is to give an overview of:

- ***How we observe the different phases*** *of the interstellar medium in low redshift galaxies.*
- *The* ***interstellar medium content*** *of low redshift galaxies.*
- *The* ***structure*** *of the interstellar medium in low redshift galaxies, including a few words on star formation.*

I am going to aim to be:

- ***High level*** *– accessible to all participants.*
- ***Brief*** *– we only have 1.5 hours.*

This also means I will simplify and go fast in a few places. There are a host of good reviews and books that offer the chance to follow up.

Relation to Other Lectures

The material here connects with the other lectures in many places:

- *Many of the observing techniques used to observe different ISM phases are common between low z, high z, and the Milky Way (Elbaz, Ferrara, Boulanger, Motte).*

- *We often learn about the mechanisms for the build-up of galaxies by contrasting the properties of low z and high z galaxies (Elbaz, Ferrara).*

- *We often combine detail from Milky Way studies with the big picture and wider range of conditions from surveying galaxies (Boulanger, Motte).*

- *Interpretation of observations relies on detailed physical models that leverage rich spectral and multi-wavelength information (Ferland, Bron, Cabrit, Demyk, Buat).*

My goal – since this is the first lecture – will be to introduce phases, basic observational approaches, and terminology that will be picked up and expanded on in these other lectures.

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Atomic Gas – HI

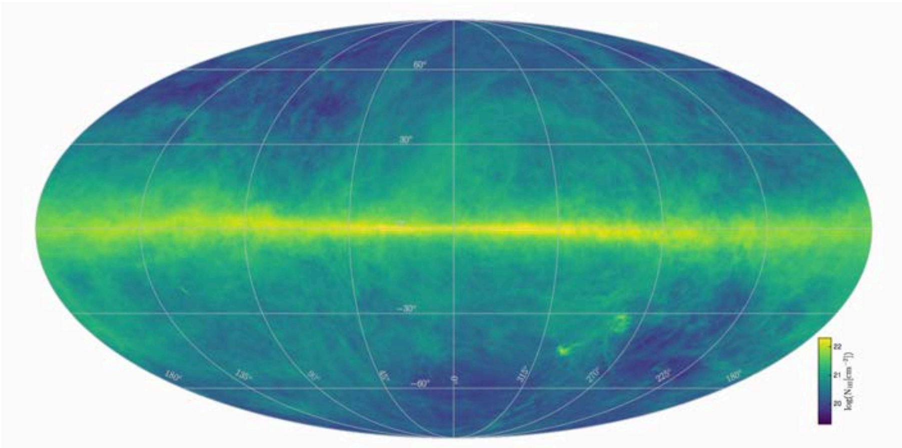
In a galaxy like the Milky Way, the majority of the mass in the interstellar medium of the disk of the galaxy is atomic gas, or HI. This gas has was range of temperatures and densities. In the classical view, this is organized into two phases in pressure equilibrium, though intermediate phase gas is now thought to be common.

HI thermal pressure:
$P/k_B \sim 3000\ \mathrm{cm}^{-3}\ \mathrm{K}$

Cold neutral medium:
$T \sim 100$ K, $n \sim 30\ \mathrm{cm}^{-3}$
modest (few percent) volume filling

Warm neutral medium:
$T \sim 5000$ K, $n \sim 0.6\ \mathrm{cm}^{-3}$
volume filling of ~ 40-50%

Unstable gas also present

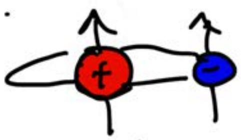


HI column density traced by 21-cm emission in the Milky Way from HI4PI collaboration et al. 2016. The atomic fills this disk and the high latitude sky – it's everywhere!

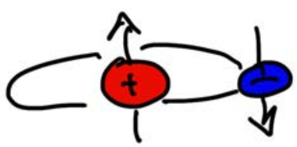
The 21-cm Line

The overwhelming bulk of observations of atomic gas in other galaxies have been obtained using the ***21-cm line of HI.*** *For most reasonable ISM densities and assuming optically thin emission, this hyperfine transition at λ=21cm, ν=1420 MHz* ***directly traces the mass and kinematics of atomic gas****. Telescopes operating at this frequency include the Jansky VLA, MeerKAT, FAST, ASKAP, WSRT, and soon the SKA.*

Given about 10 Myr, a hydrogen atom in this state:



decays to this



and emits a photon with

$\lambda = 21\text{cm}$

$\nu = 1420$ MHz

which is far in the radio.

The GBT (from gbtobservatory)

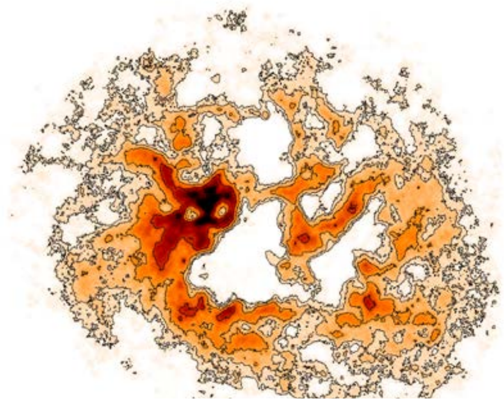
FAST (from Wikipedia)

MeerKAT (from SARAO)

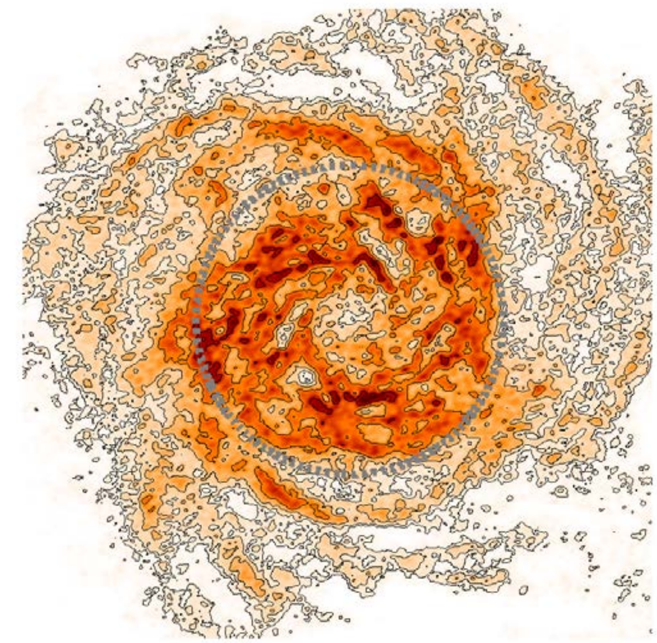
Jansky VLA (from Wikipedia)

The 21-cm Line

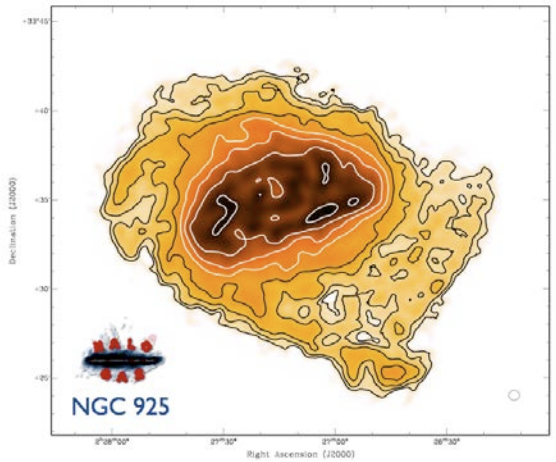
Images of galaxies obtained observing the 21-cm line. This is a map of the atomic gas mass as long as the transition is optically thin (this is mostly okay, but not 100% right) and the density of the gas is above about 0.001 cm^{-3} (this is basically always fine).



Local Group Dwarf IC 1613
Hunter et. LITTLE THINGS



Nearby Spiral NGC 0628 (M74)
Walter et THINGS

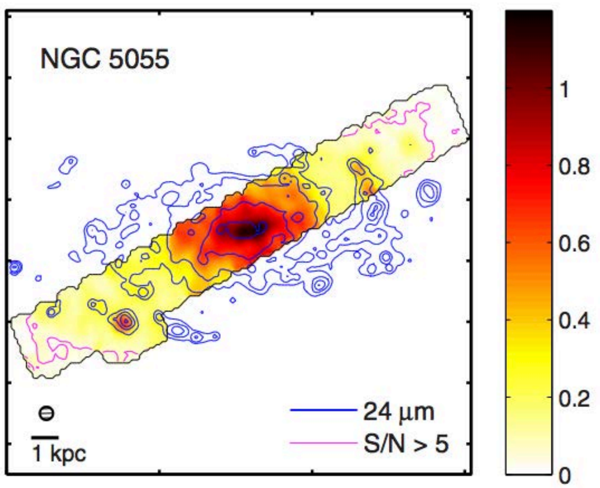


Nearby Spiral NGC 0925
Heald et. HALOGAS

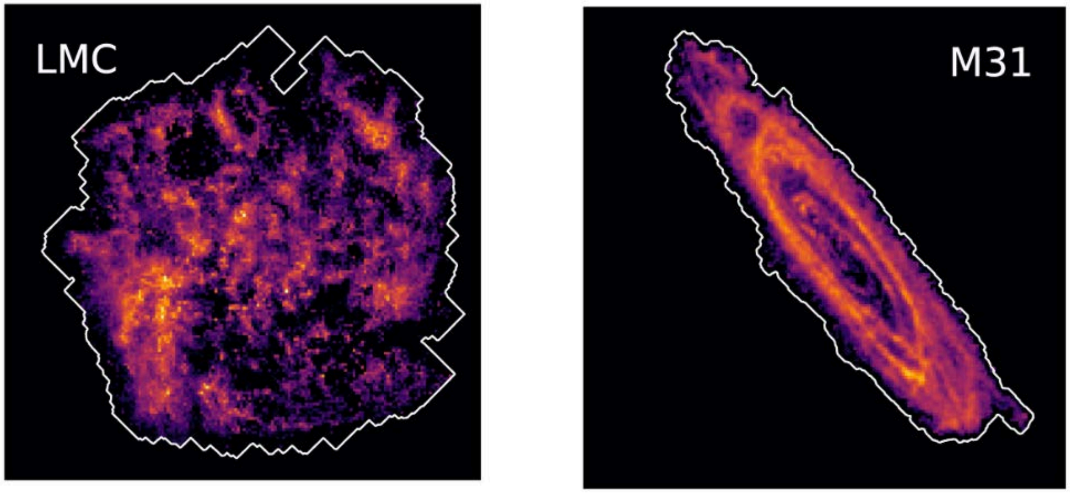
If all you want is a mass and line width – this is overkill and single dish spectra are great!

Other Ways to Study Atomic Gas

Atomic gas can also be studied via hydrogen absorption lines in the radio or ultraviolet or a wide suite of metal absorption lines in the ultraviolet and optical. The main cooling comes from fine structure lines visible in the far infrared. The 158 μm [CII] line is the brightest of these and is studied across redshift but its interpretation is complex because it arises from both the atomic CNM, molecular and atomic gas. Atomic gas is also mixed with dust, which can be observed via extinction in the optical or ultraviolet and emission in the infrared and submillimeter.



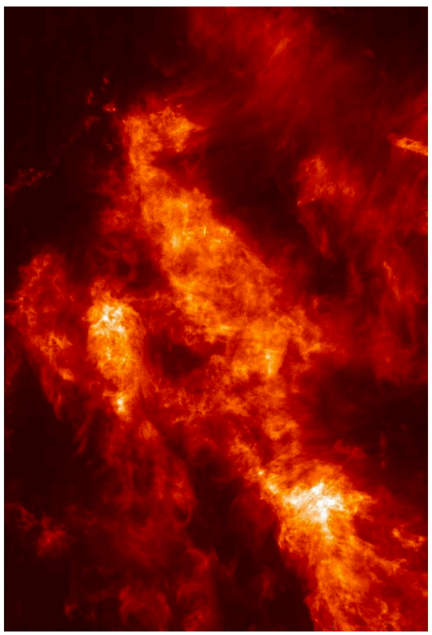
CII (color) observed by *Herschel* along a strip through a nearby galaxy (blue shows dust emission). The CII traces cooling by atomic gas but also molecular gas and ionized gas. From Herrera-Camus ea 2018.



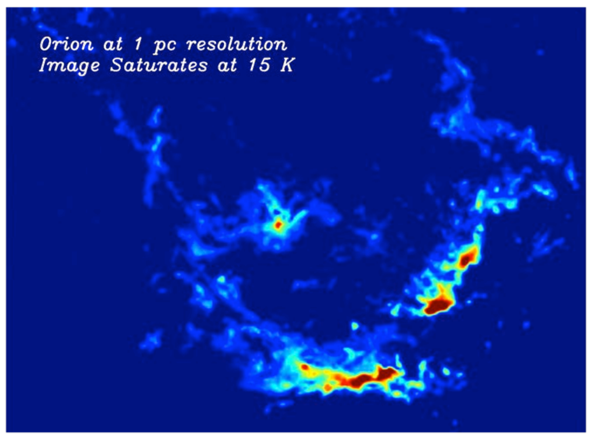
Dust mass maps from SED modeling by Utomo et al. (2019) – the dust is optically thin and mixed with the gas, so that it can serve as a tracer of the ISM. But it is also mixed with molecular gas and the abundance may vary.

Molecular Gas – H_2

The molecular gas phase is the one most directly associated with star formation in both the Milky Way and other galaxies, in terms of spatial location and correlation of rates and masses. In the Milky Way roughly 20% of the overall ISM in the disk lies in molecular gas. This gas is very "clumped" up into (marginally) bound turbulent clouds with a high degree of structure and a wide range of densities and low temperatures, T ~ 10-50 K.



FCRAO CO image of Taurus molecular cloud. G. Narayanan , M. Heyer



Orion Molecular Cloud at 1 pc
Wilson et al. (2005)

Molecular clouds

Mass: ~ $10^4 – 10^7\ M_\odot$
Temp: 10 - 50 K
Densities: n ~ $10^2 – 10^5+$ cm^{-3}
Size: 10 – 100 pc
Motions: dominated by turbulence
Structure: clumpy and filamentary
Dynamical state: roughly bound

Observing H_2 (is the Worst)

At the densities and temperatures found in most molecular clouds the H_2 itself is practically invisible. As a result observations of molecular gas in galaxies use a variety of proxies. The most common extragalactic tracers of molecular gas are emission from other molecules, with CO the workhorse tracer, and dust emission. In the Milky Way and a few other special cases, gamma rays, UV absorption by H2, and a few other tracers are also possible. CII and CI emission can also be useful. All of these indirect tracers come with important caveats.

When we try to trace H_2 with a tracer line or species, we are worried about:

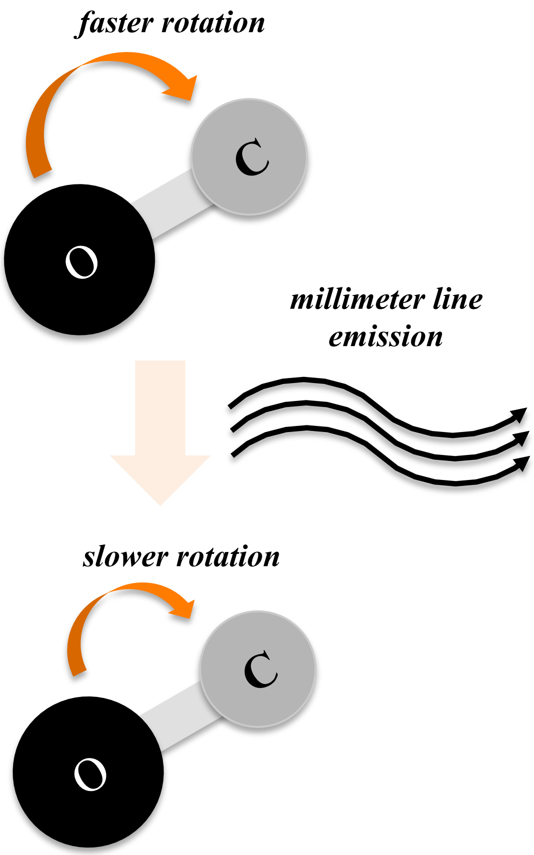
1) ambiguity (is it also mixed with HI and HII?),

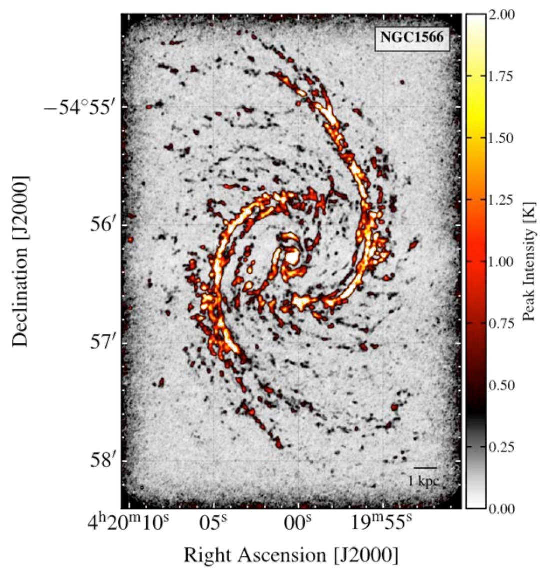
2) ability to convert luminosity to mass (is it a stable tracer?)

3) detectability (is it super faint or blocked by dust)

CO Emission

CO is the second most abundant molecule in most molecular gas and the primary reservoir of gas-phase carbon in molecular gas. Because it is easily excited and has a relatively low effective critical density, low J (e.g., J=1-0, J=2-1, or J=3-2) CO emission has been widely used as a tracer of the distribution, mass, and kinematics of molecular gas in other galaxies for almost 50 years. The mass-to-light ratio relating CO emission to molecular gas mass is referred to as X_{CO} or α_{CO} depending on the units and is a crucial but still actively researched topic.





A picture of a galaxy in CO emission from Leroy et al. 2021

The CO-to-H_2 conversion factor
"Just" a mass to light ratio
Empirically determined

$X_{CO}^{MW} \sim$ 2E20 cm^{-2} (K km/s)$^{-1}$
$\alpha_{CO}^{MW} \sim 4.35\ M_{\odot}$ (K km/s pc^2)$^{-1}$

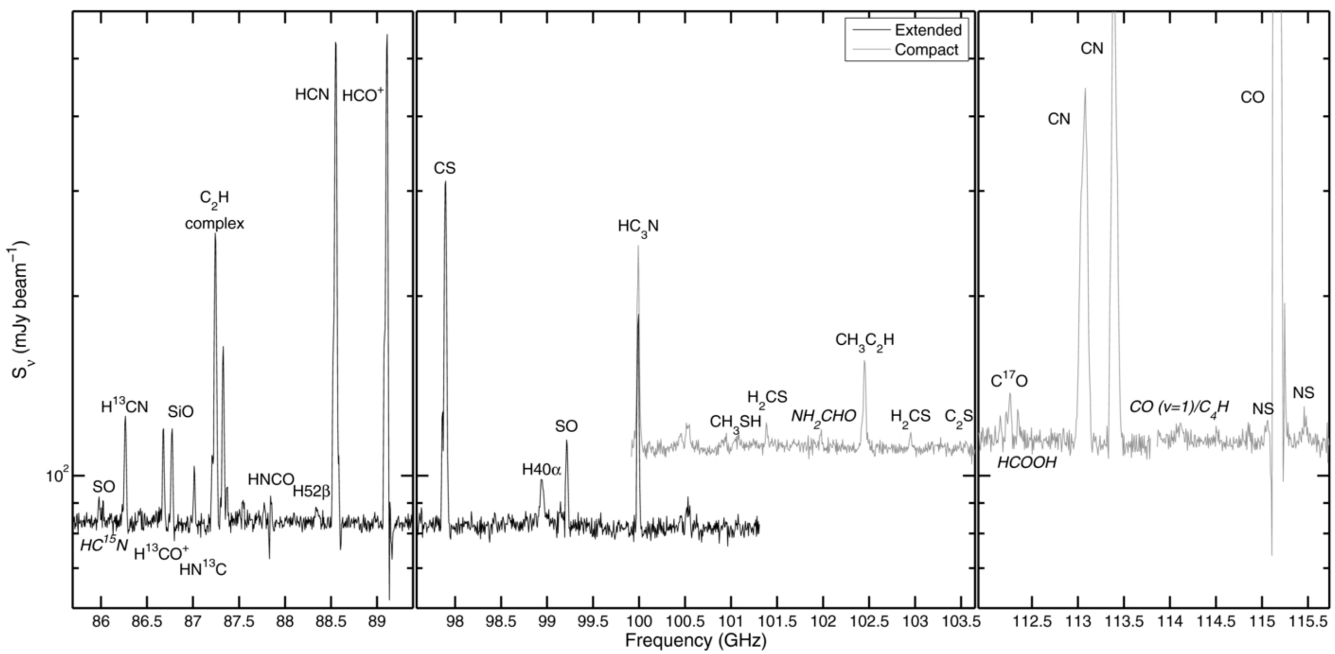
Depends on metallicity (higher in low mass, low metallicity galaxies)

Depends on excitation and optical depth (lower in diffuse, optically thin, and hot, excited gas)

Bolatto et al 2013 for more

Other Molecular Lines

In addition to CO, a host of other molecules are mixed with H_2. Emission from these molecules is visible throughout the radio, millimeter, sub-millimeter, and even infrared. The emission of individual lines has different sensitivities to temperature, density, chemistry (i.e., molecular abundances), and other physical conditions related to excitation and abundances. These lines are almost always fainter than CO but together provide a toolbox that can be used to probe the physical conditions and chemistry of the molecular medium.



Part of the 3mm spectrum of a nearby starburst from Meier et a. (2015)
ALMA ALCHEMI should soon provide a way better version!

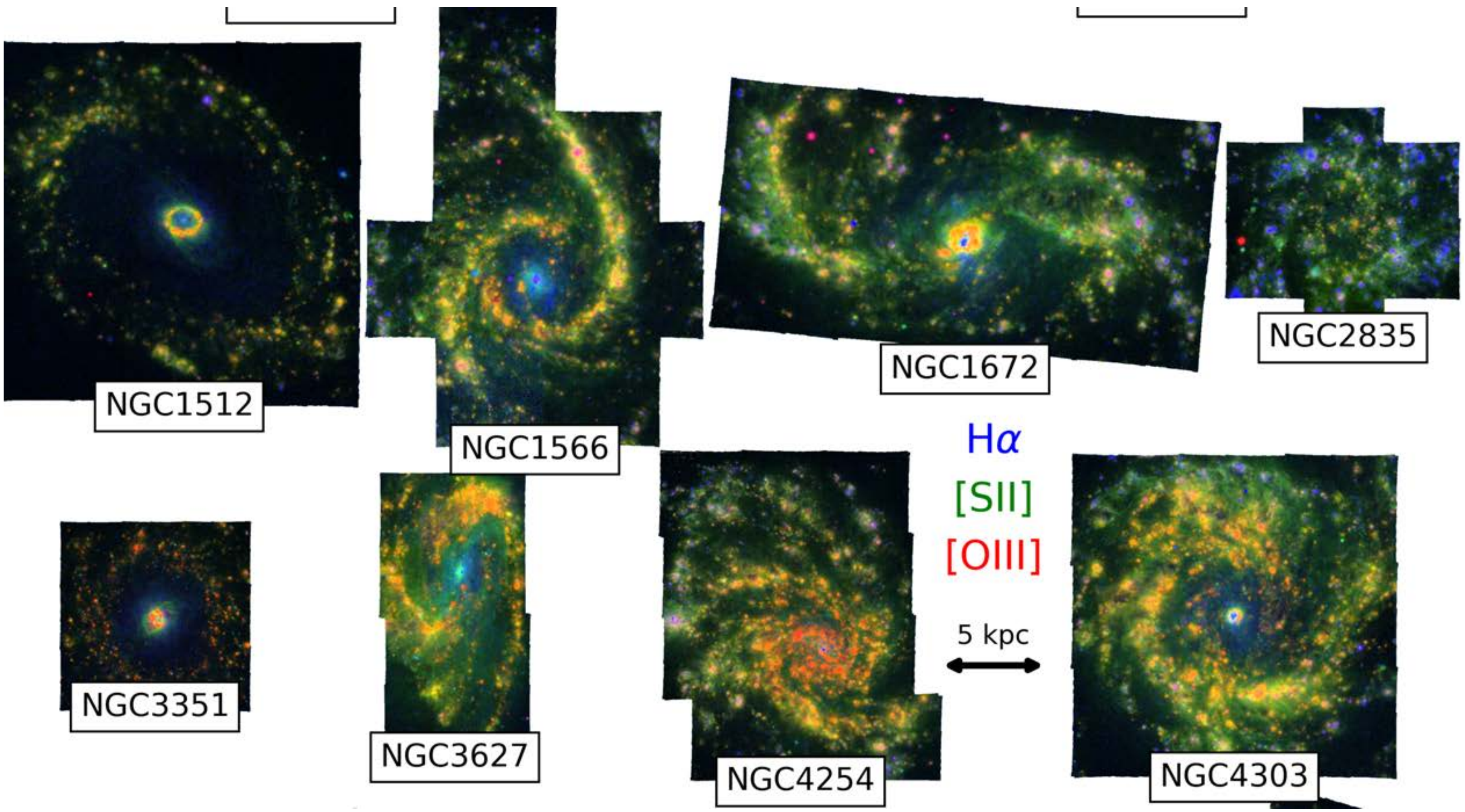
Observing Molecular Gas

ALMA, NOEMA, and the SMA image molecular line emission from galaxies at high angular resolution and trace the molecular gas, its structure, and its physical conditions by combining many lines. Single dish telescopes like the IRAM 30-m, the Nobeyama 45-m, the Green Bank Telescope, the JCMT, APEX, and more are excellent tools to capture the integrated molecular line emission from galaxies. Submillimeter observations to trace the dust missed with gas can be carried out with ALMA, the SMA, or bolometer arrays on single dish telescopes. Currently only SOFIA can access the peak of the infrared distribution in low redshift galaxies and IR work is largely archival, relying on Herschel, WISE, Sptizer, IRAS, and other past missions.

ALMA (from ESO)

Warm Ionized Gas – HII regions, WIM, DIG

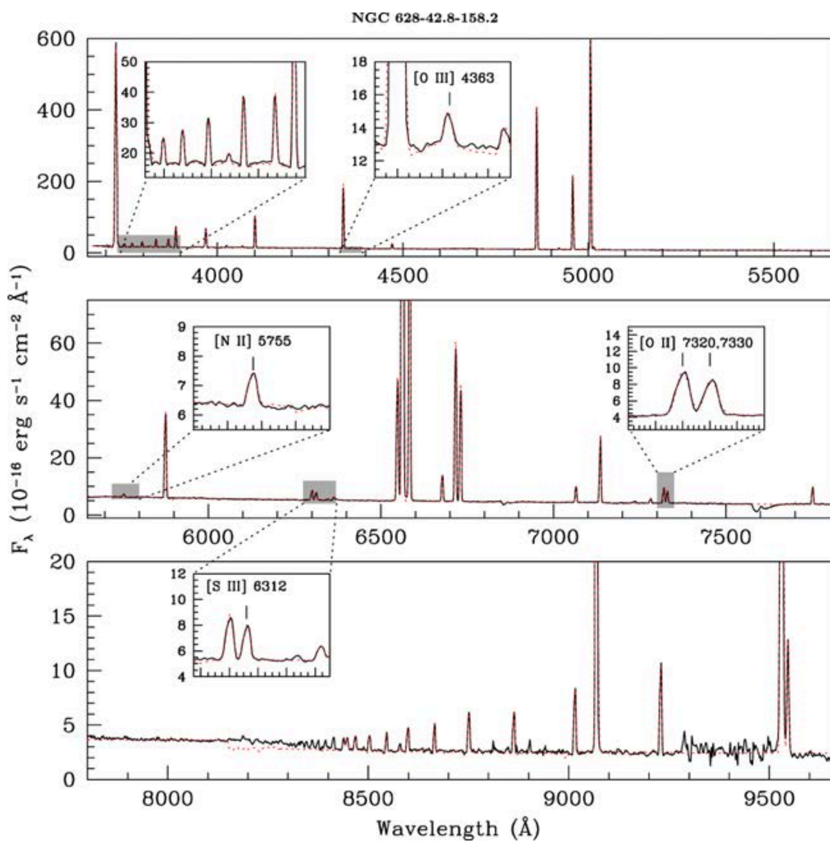
"Warm" (5,000 – 20,000 K) ionized gas surrounds young massive stars as HII regions and also pervades galaxies in the form of "diffuse ionized gas" or a "warm ionized medium." HII regions serve as signposts of massive star formation and the warm ionized medium may account for as much as ~30% of the mass in the disk of a galaxy like the Milky Way.



MUSE emission line maps showing ionized gas in nearby galaxies from E. Emsellem et al. (submitted)

Warm Ionized Gas – Diagnostics of Everything

While not dominant by mass, warm ionized gas produces line emission that gives us observational access to a host of crucial conditions in the ISM. Recombination line emission from HII regions (e.g., Hα) directly traces the ionizing photon production of the stellar population (and with, e.g., He can get the shape of the radiation field). The temperature of HII regions depends on metal content via its influence on cooling, so that gauging the temperature is a main probe of metallicity. Ratios among electronic transitions of different atoms and ions can reveal the relative influence of shocks, star formation, and AGN activity.

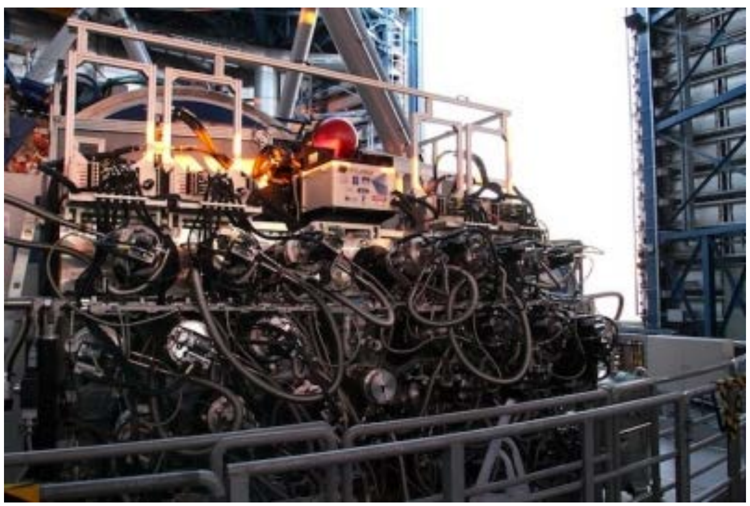


The rich optical spectra of HII regions containing diagnostics of metallicity/temperature, recent star formation, and more

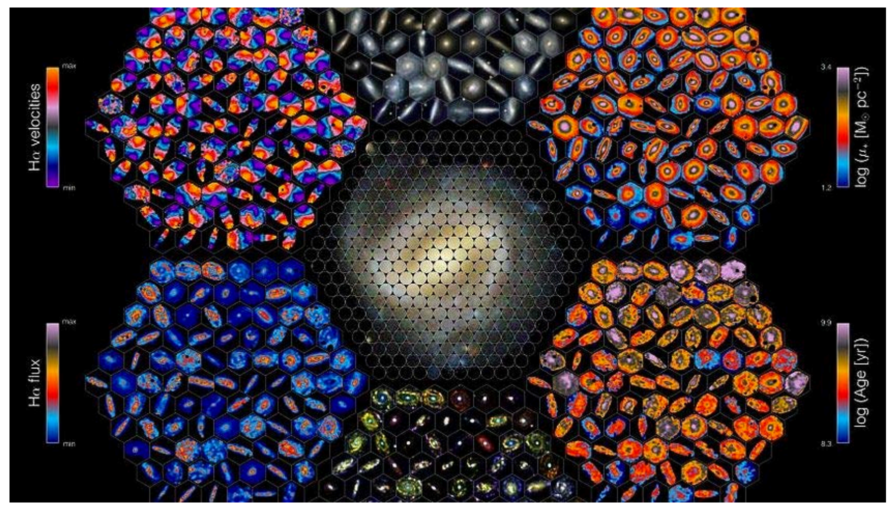
From Berg et al. (2015)

Observing Ionized Gas

To trace physical conditions in the warm ionized gas, we observe electronic transition of different atoms in the optical, near-infrared, and ultraviolet. Some work can also be done using narrow-band imaging to pick out individual lines. A major direction over the last ~10 years has been the widespread deployment of "integral field units" – optical instruments that map full or partial optical spectra point-by-point across large parts of galaxies. CALIFA, MaNGA, SAMI, SAURON/ ATLAS3D, VLT/MUSE, Keck/KCWI have (or are currently) exploded our knowledge of ionized gas in galaxies. JWST promises to bring much of the same power to the near- and mid-infrared albeit with a very small field of view.



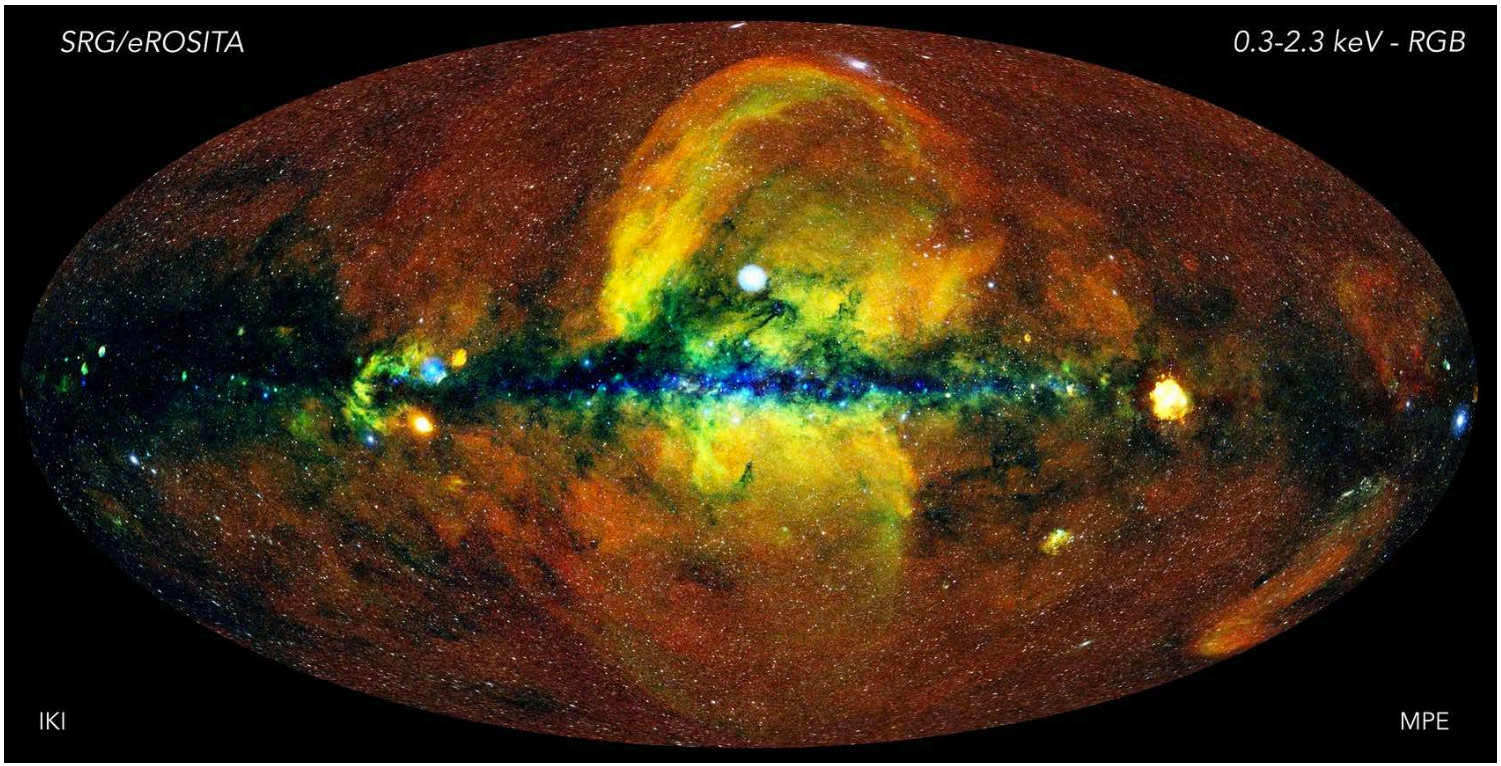
This monster is MUSE (Bacon et al. 2010), with a good claim to being the most powerful optical instrument in the world.



CALIFA (Sanchez et al. 2012) along with SAURON and ATLAS3d pioneered big optical IFU surveys of low redshift galaxies

Hot Ionized Gas – HIM, Coronal Gas

Hot, ~ million Kelvin ionized gas fills about half of the volume of the ISM. The gas is heated by supernova shocks. While it fills a huge volume, it constitutes only a minor fraction of the mass of the total ISM because of its very low density. This gas produces continuum and line emission visible in X-rays and can be detected via absorption studies in the X-ray and ultraviolet. Because of its low density, the hot ionized gas is can be difficult to survey in emission, but it is seen in other galaxies and has been extensively studied in the Milky Way. eROSITA will be very exciting!



eROSITA's view of the X-ray sky – look at all that hot gas

Dust and Metals

By mass, the interstellar medium in a galaxy like the Milky Way is about 2% elements heavier than hydrogen and helium, with 1% in the gas phase and 1% in the solid phase ("dust"). Despite this small mass, both gas-phase metals and dust play a large role in the physical state of the ISM. Metals play a crucial role in cooling the gas (and some in heating) and dust contributes crucial shielding and acts as a catalyst for interstellar chemistry (e.g., H_2 is made on the surfaces of dust grains in present day galaxies).

Table 2 Abundances and depletions in the Milky Way and the Magellanic clouds.

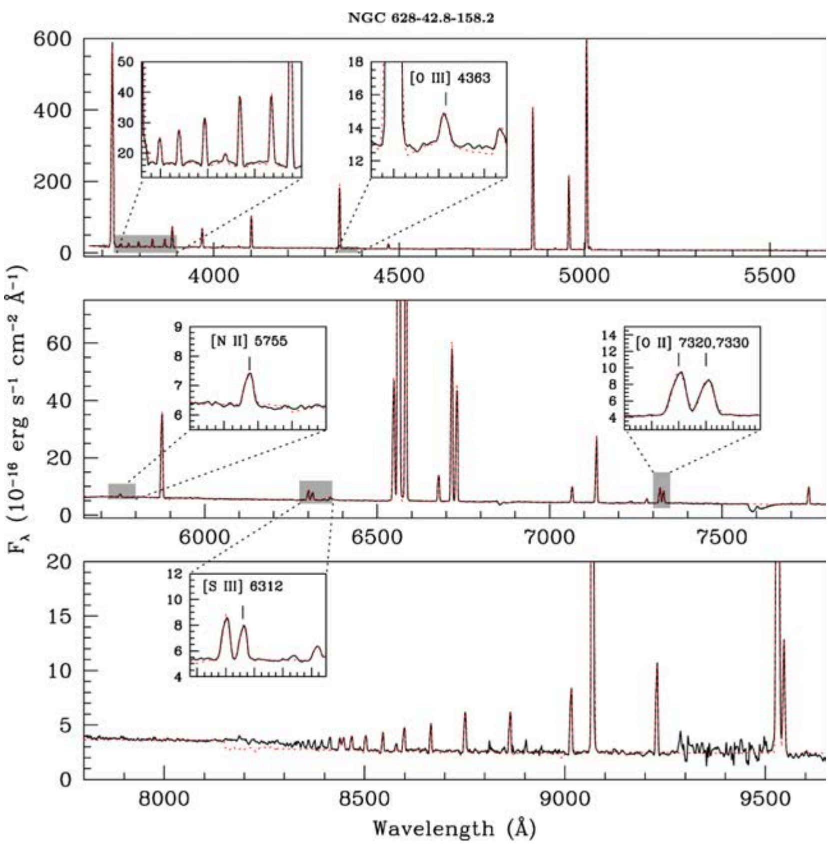
X	C	O	Mg	Si	Fe	Mass ratio
			Milky Way			
$10^6(\mathrm{X/H})_{\mathrm{ref}}$	290^{+30}_{-20}	580^{+70}_{-60}	42^{+2}_{-2}	41^{+2}_{-2}	35^{+2}_{-2}	$Z_\odot = 1/75$
$[\mathrm{X_{gas}/H}]_0$ (%)	23^{+27}_{-23}	$2.3^{+12.3}_{-2.3}$	46^{+3}_{-4}	40^{+5}_{-5}	89^{+1}_{-1}	$Z_{\mathrm{dust}}^{(F_\star=0)} = 1/330$
$[\mathrm{X_{gas}/H}]_0 + A_\mathrm{X}$ (%)	39^{+9}_{-11}	42^{+7}_{-8}	95^{+1}_{-1}	96^{+1}_{-1}	99^{+1}_{-1}	$Z_{\mathrm{dust}}^{(F_\star=1)} = 1/140$
			LMC			
$10^6(\mathrm{X/H})_{\mathrm{ref}}$	87^{+25}_{-19}	320^{+90}_{-70}	18^{+4}_{-3}	22^{+6}_{-5}	21^{+4}_{-4}	$Z = 1/2\ Z_\odot$
$[\mathrm{X_{gas}/H}]_0$ (%)	$\simeq 31$	$\lesssim 20$	...	52^{+3}_{-3}	89^{+1}_{-1}	$Z_{\mathrm{dust}}^{(F_\star=0)} = 1/750$
$[\mathrm{X_{gas}/H}]_0 + A_\mathrm{X}$ (%)	...	...	...	94^{+1}_{-1}	99^{+1}_{-1}	$Z_{\mathrm{dust}}^{(F_\star=1)} = 1/250$
			SMC			
$10^6(\mathrm{X/H})_{\mathrm{ref}}$	33^{+9}_{-7}	140^{+30}_{-20}	$7.6^{+1.2}_{-1.1}$	$9.1^{+2.7}_{-2.0}$	$7.8^{+1.6}_{-1.4}$	$Z = 1/5\ Z_\odot$
$[\mathrm{X_{gas}/H}]_0$ (%)	$\simeq 28$	$\simeq 32$	49^{+6}_{-6}	40^{+3}_{-3}	89^{+1}_{-1}	$Z_{\mathrm{dust}}^{(F_\star=0)} = 1/2760$
$[\mathrm{X_{gas}/H}]_0 + A_\mathrm{X}$ (%)	...	...	71^{+11}_{-18}	95^{+1}_{-1}	99^{+1}_{-1}	$Z_{\mathrm{dust}}^{(F_\star=1)} = 1/630$

(MW) solar abundance compilation and depletions from Jenkins (2009). **(LMC)** stellar abundance compilation and depletions from Tchernyshyov et al. (2015); [C/H] and [O/H] from Korn et al. (2002). **(SMC)** stellar abundance compilation from Tchernyshyov et al. (2015); depletions from Jenkins & Wallerstein (2017); [C/H] from Peña-Guerrero et al. (2012)'s H II modelling of NGC 456; [O/H] derived from Mallouris (2003)'s [O/Zn] (Sk 108, $\log N(\mathrm{H\,I}) = 20.5 \Rightarrow F_\star \simeq 0$) and Jenkins & Wallerstein (2017)'s [Zn/H]. Values in grey indicate an estimate from nebular emission lines.

Compilation of abundances and depletion into the solid phase for key elements from review by Galliano et al. (2018)

Tracing Metals

The abundance of heavy elements in other galaxies is most traced via spectroscopy of atomic emission lines from ionized gas. Because the cooling is sensitive to the heavy element abundance, diagnosing the temperature of the region gives a strong constraint on its metallicity. Absorption of metal lines (especially in the UV) against background continuum sources also offers a powerful diagnostic but is hard to deploy in other galaxies, which tend to be small on the sky. In the Milky Way and Magellanic Clouds (which are big) absorption measurements are crucial to establish which elements are "missing" from the gas phase (and so in dust).



(Repeated figure)
The rich optical spectra of HII regions containing diagnostics of metallicity/temperature, recent star formation, and more

From Berg et al. (2015)

Tracing Dust

Dust absorbs starlight. We can measure the structure and amount of dust in galaxies via its impact on optical, ultraviolet, and near-infrared light (i.e., extinction and reddening) or by the re-emission of the absorbed energy in the infrared and submillimeter. For surveying dust content from galaxies, emission tends to be more widely used. The infrared spectral energy distribution reflects a combination of the heating radiation field, the optical properties of dust, the amount of dust, and the dust size distribution. Modeling this is the subject of another lecture.

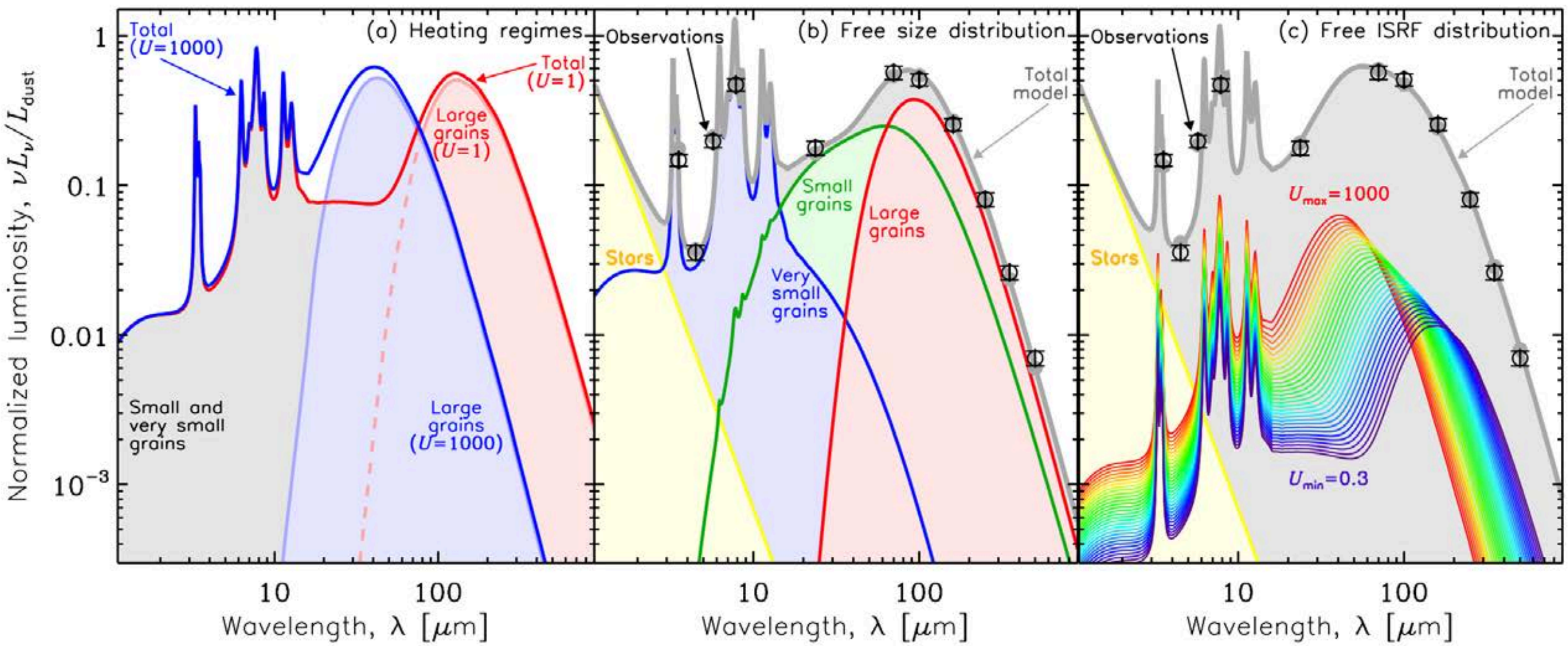
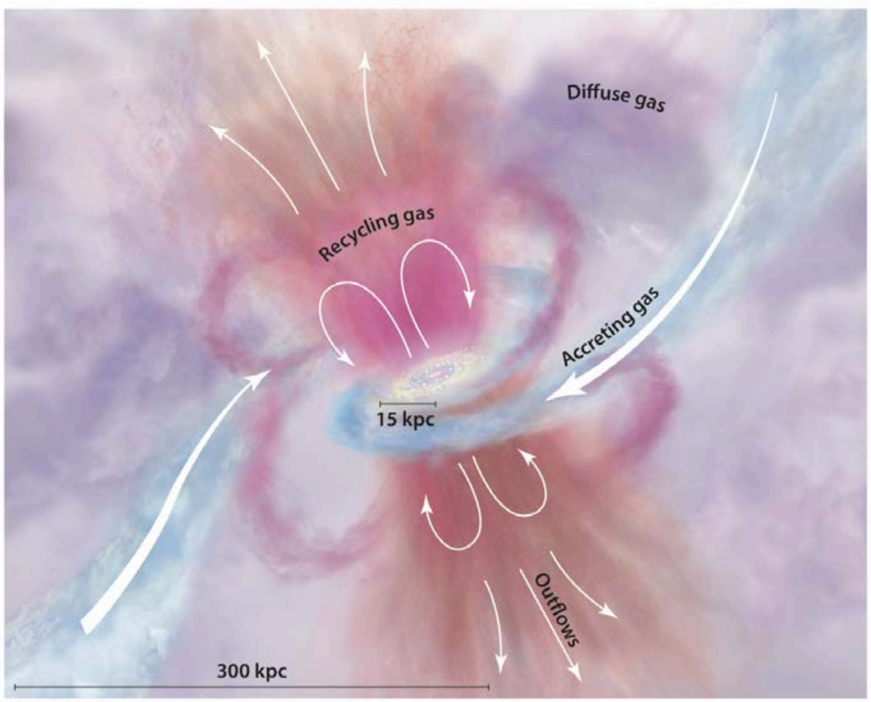


Illustration of models and observations of the infrared SED (here of the Milky Way) from review by Galliano et al. (2018)

Gas Around Galaxies

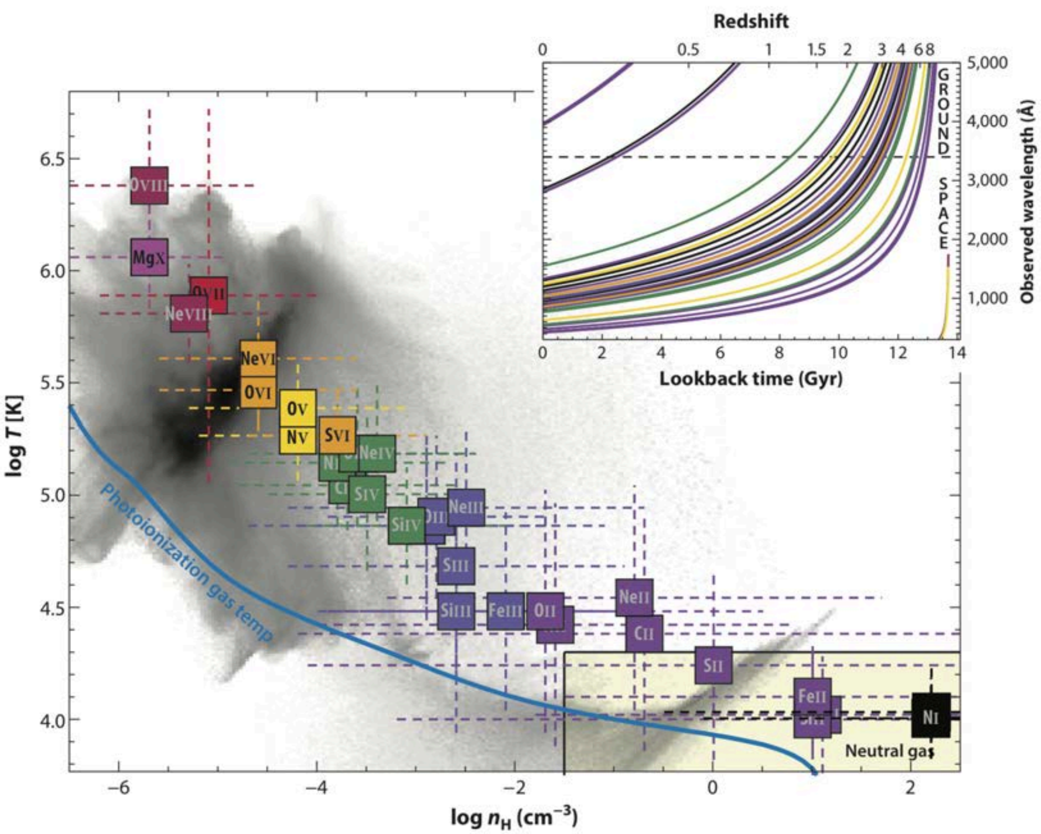
A large amount of research in the last 10 years has focused on understanding the gas around galaxies. The circumgalactic medium is massive, low density, hot, and because of these properties it is very hard to see! The CGM in a galaxy like the Milky Way has gas ranging from a few 100,000 K up to more than a million K and may include as much mass as the whole disk, sprawling out for several hundred kpc. Because galaxies receive fuel from the CGM and return energy and material (including metals) to the CGM, the view of the disk and CGM as coupled has become very important to how we understand the ISM and galaxies.



Watercolor view of the circumgalactic medium around galaxies from Tumlinson et al. (2017) review

Observing Gas Around Galaxies

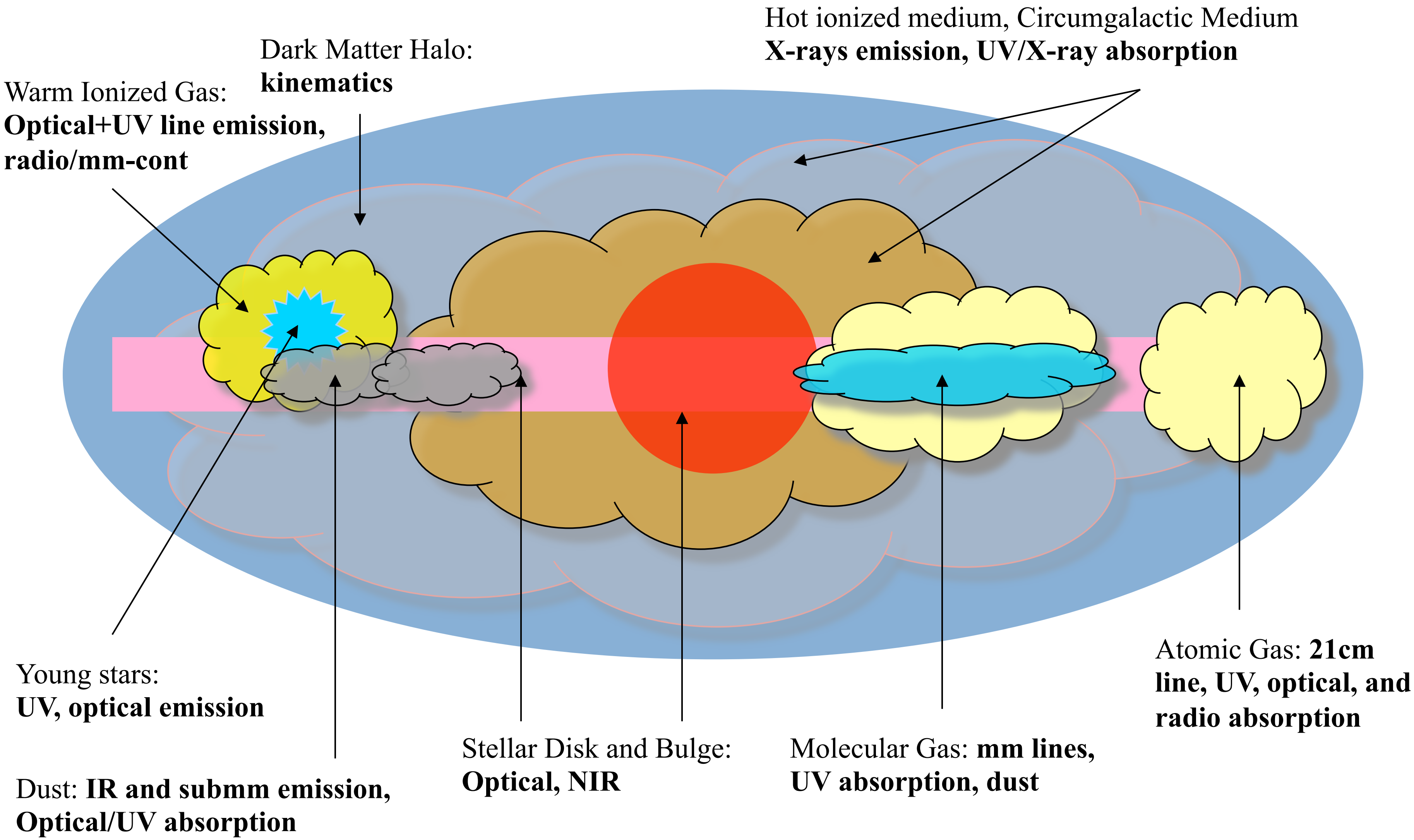
Seeing the CGM is difficult because the gas is ionized, hot, and low density. Absorption experiments using ultraviolet or X-ray (mostly in the Milky Way) spectroscopy have been a main way that we learn about the CGM (though it can also be searched for via 21-cm emission or other techniques like the SZ effect). Such experiments require fortuitous background sources (or picking targets near background sources) but especially thanks to the Hubble Space Telescope we have built a picture of the CGM around massive galaxies over the last decades.



Also from Tumlinson et al. (2017) – how absorption lines in the UV and optical probe physical conditions in the gas (over a simulated phase diagram). At low redshift space-based absorption studies are crucial to study the CGM.

A Very Rough Summary Figure

The ISM represents a mix of phases. HI and hot gas fill much of the volume, stars form in H_2 and heavy elements and dust play crucial roles in heating, shielding, and chemistry.



Rhyming Summary of Part 1

The spin-flip line reveals atomic gas,
Which fills the space and holds a lot of mass.

New stars are born in clouds we can't directly see,
We get around this by observing states of C.

Warm bubbles of dense gas encase each massive star,
But their ionizing light still makes it pretty far.

The light from these young stars runs headlong into dust,
To trace these grains, IR emission is a must.

When massive stars explode, they blast the gas away,
And shock what's left to upwards of a million K.

Last, while this disk of gas can let the system grow,
It's still not much compared to the halo …

A Couple Notes (Just for the Slides – Not the Lecture)

There are a few general principles of ISM observations worth keeping in mind:

1. *Emission from lines below the critical density (where radiative and collisional de-excitations match) depends sensitively on the density of the emitting material. As a result, emission lines often (but not always) have an "n^2" dependence. The "emission measure" integrating $n^2\,dl$ is not the same as the "column density" integrating $n\,dl$.*

2. *Absorption lines tend to offer more direct probes of the column density (or at least the optical depth) but require correction by a partition function or for ionization. The major obstacle to deploying absorption studies is the need for a bright background continuum source.*

3. *Ratios among lines with different sensitivities to local physical conditions (e.g., temperature, density) coming from the same region are a powerful probe of the physical state of the ISM – you will get lots more on this.*

4. *Practically the strength of various features matters a lot – you can do big surveys of bright lines or features, while detailed spectroscopy of faint lines implies a more "case study" approach. CII, CO, HI, the IR continuum, Hα and other strong optical lines are all "workhorse" bright features that are highly tractable to surveys.*

Slide Blank for Notes and Questions

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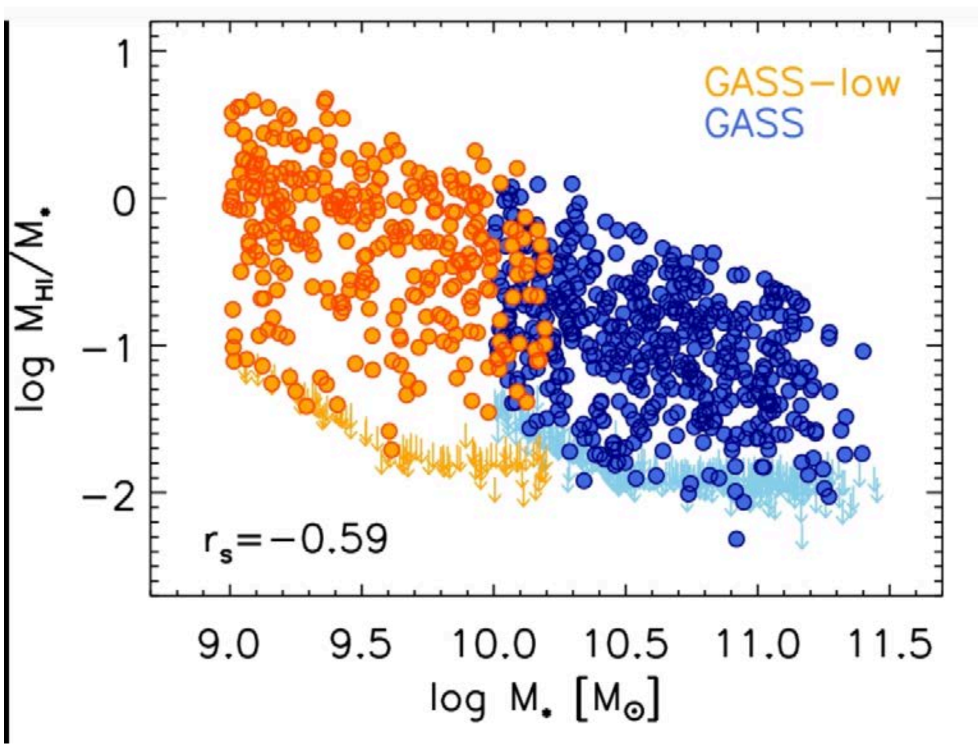
5. *Star Formation in z=0 Galaxies*

6. *Conclusions*

Atomic Gas in Galaxies

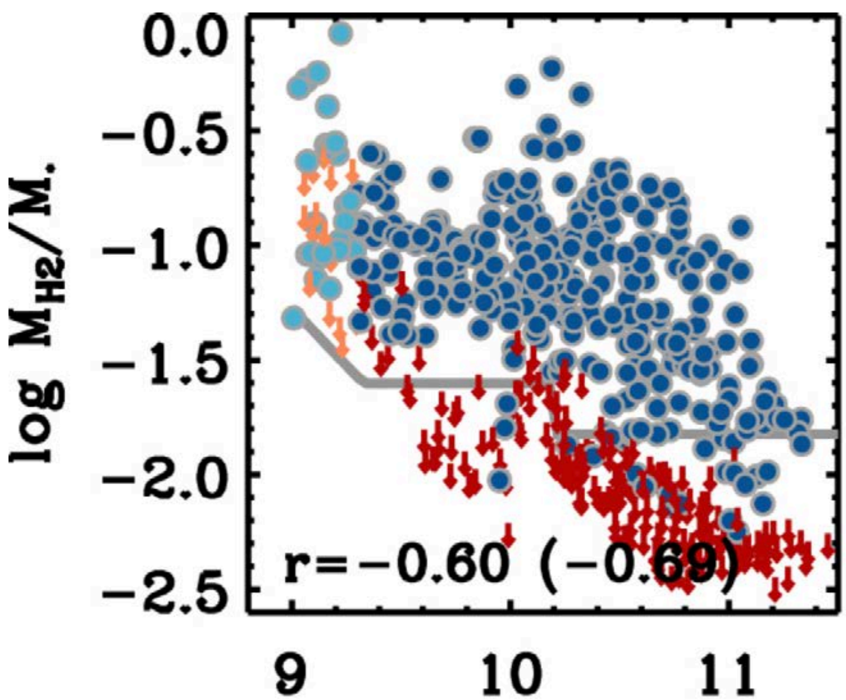
Atomic gas (HI) makes up most of the mass in star-forming galaxies at low redshift. For a big star-forming galaxy like the Milky Way, about 10% of the mass of the baryonic disk may be tied up in the ISM with about half of that in HI. For galaxies with lower stellar mass the fraction of the galaxy's baryonic mass in HI increases, so that for a galaxy like the Small Magellanic Cloud the baryonic mass of the galaxy is half HI, half stars. To first order, dwarf galaxies are overall more gas-rich than more massive galaxies.



From Catinella et al. (2018) – dependence of HI mass to stellar mass ratio on stellar mass – see the steady decline in gas fraction with mass.

Molecular Gas in Galaxies

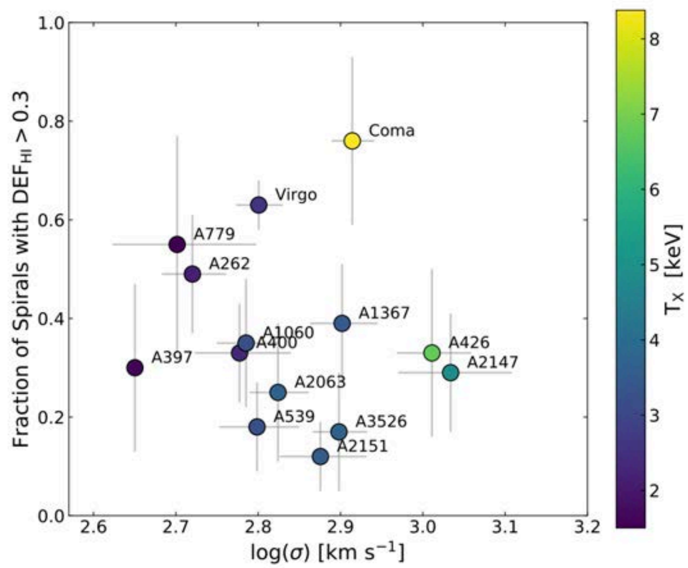
For the Milky Way or similar, the ratio of molecular to atomic gas is something like 1-to-3. Lower mass galaxies have much less molecular gas relative to atomic gas, although their ratio of molecular gas to stellar mass may be much more stable. The mass-metallicity relation implies strong metallicity variations, which in turn imply CO-to-H_2 conversion factor variations that affect inferred trends. But to first order, dwarf galaxies hold only a small part of their gas in the molecular phase while bigger galaxies are more molecule rich. However, this conclusion depends very sensitively on the adopted CO-to-H_2 conversion factor.



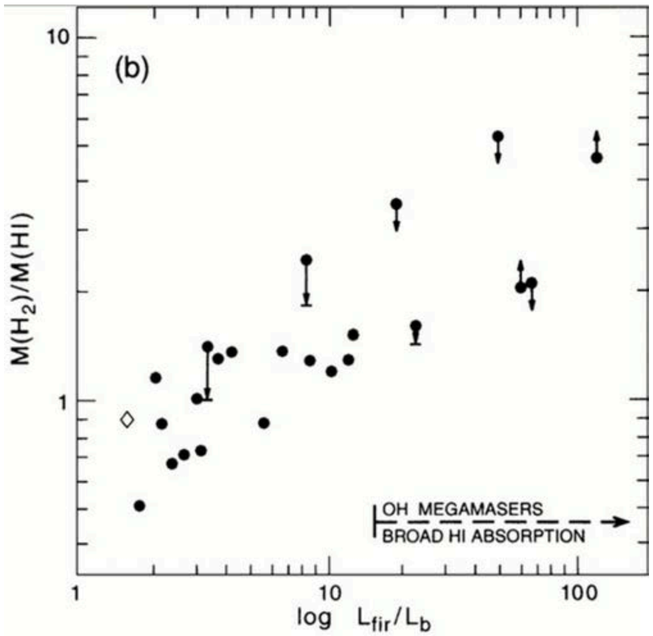
From Saintonge et el. (2017) – dependence of H2 mass to stellar mass ratio on stellar mass – see the more nearly constant behavior here but note that this depends on how the CO-to-H2 conversion factor works.

Interactions and Environment

The gas mass and phase balance of a galaxy also depends on its environment. Galaxies in dense cluster environments tend to have their extended HI envelopes stripped away by the ram pressure of moving through the intracluster medium. Galaxies undergoing major mergers have enhanced star formation and molecular gas activity. In fact at low redshift (and only low redshift) ultra-luminous infrared galaxies (ULIRGs) are essentially all major mergers and are among the most actively star forming, molecular gas rich, dense systems in the present-day universe.



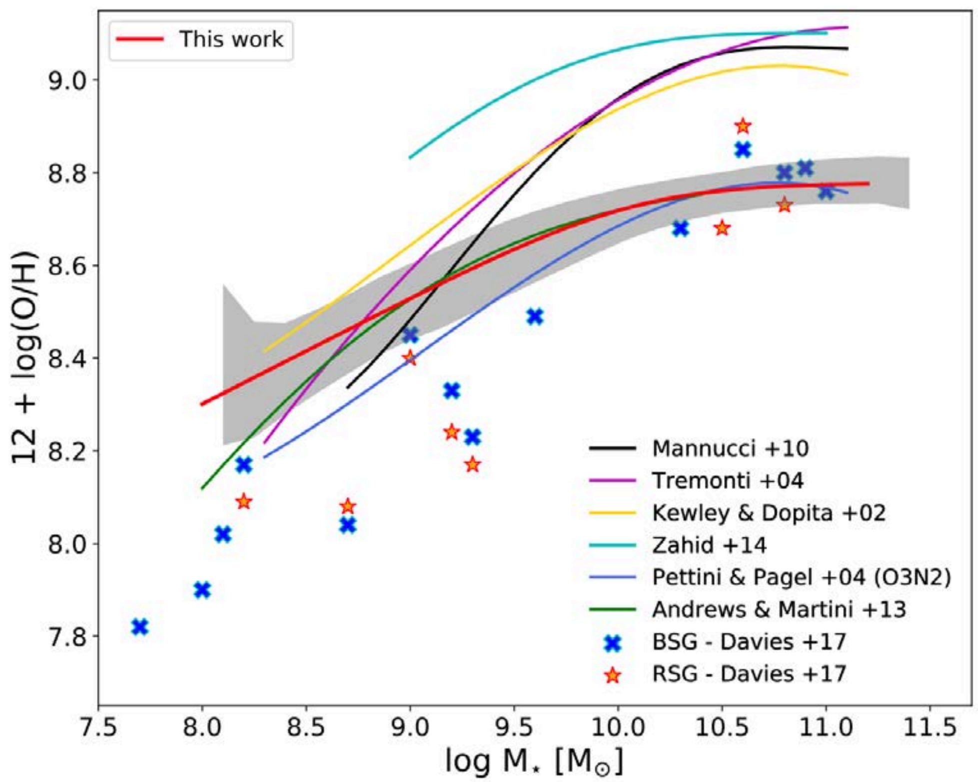
From review by Cortese et al. (2021) – the fraction of HI-deficient galaxies in various clusters as a function of their velocity dispersion and intra-cluster medium temperature (color)



From Sanders and Mirabel 1996 – the ratio of H2-to-HI as a function of IR-to-optical color. The sense is that merging galaxies have more and more CO emission and more and more dense, molecular gas.

Metals in Galaxies

More massive galaxies have higher metallicity (meaning more metals per unit gas mass). There is a well-defined stellar mass-metallicity relation observed to hold in star forming galaxies. Lower mass galaxies like the Magellanic Clouds have lower metallicity than more massive galaxies like the Milky Way.

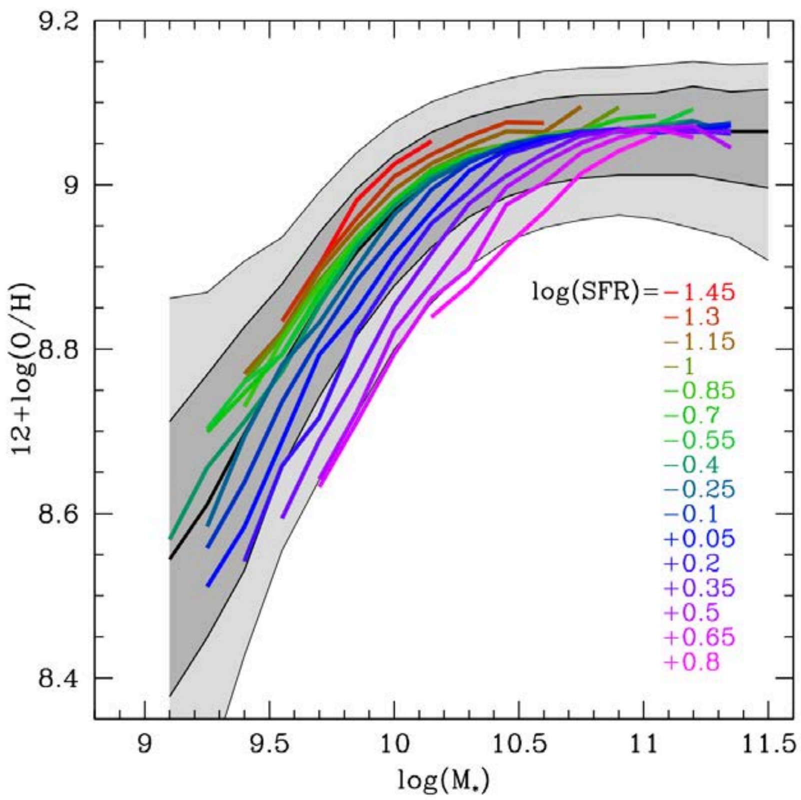


Gas phase mass metallicity relation compilation from Maiolino and Mannucci 2019.

Calibrating metallicities remains tough but the sense is always the same: little galaxies have fewer metals.

Metals in Galaxies

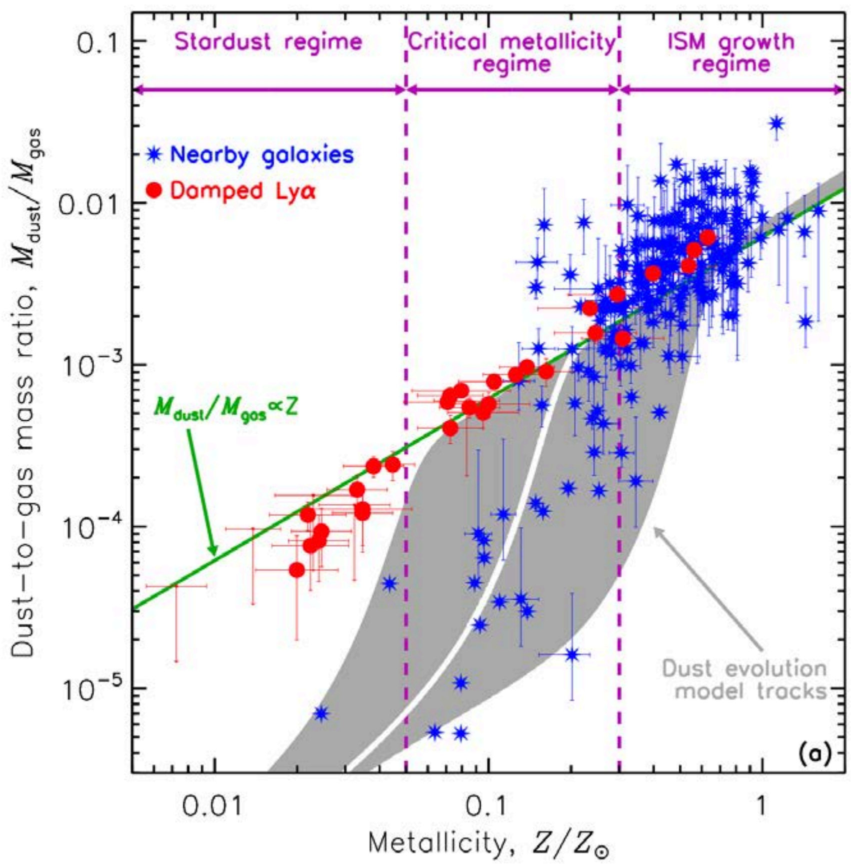
Reasonable evidence suggests a third parameter in this relation, with more actively star forming galaxies at fixed stellar mass having fewer metals, but this remains less widely accepted. Lower metallicity in lower mass galaxies has many implications for the ISM.



Mass metallicity relation with star formation rate as a third parameter from review by Maiolino and Mannucci 2019.

Dust in Galaxies

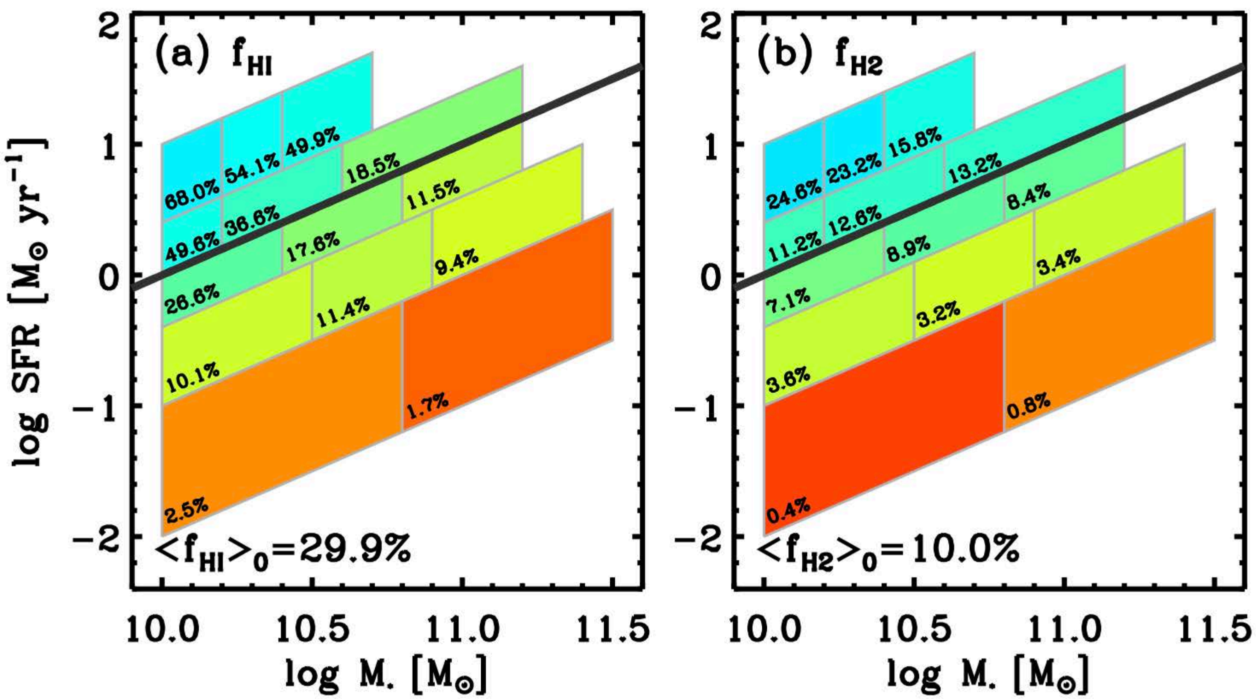
In the Milky Way, about half of the heavy elements are in dust and the dust-to-gas ratio is about 1 to 150 at the Solar Neighborhood. At the most basic level, the dust-to-gas ratio scales with metallicity. Low metal-content galaxies also have low dust content. In more detail, low mass galaxies often have less of the metals tied up in dust. In other words, the dust-to-metals ratio drops in low mass galaxies, though with quite some scatter.



Dust to gas ratio vs. gas phase metallicity from Galliano et al. (2018) – the green line shows fixed a dust-to-metal ratio. See how the lower mass galaxies have less metals in solids than expected from this.

Early Type Galaxies

The trends we have described here are for star forming "main sequence" galaxies, which is roughly (though not exactly) "late type" galaxies. Early type galaxies with low star formation rates per unit stellar mass do also have interstellar material, e.g., roughly 30% of early type galaxies have detectable molecular gas. But the normalized gas content of early type galaxies tends to be much lower than that of later type, more actively star-forming galaxies.



Stacked results in SFR-M_* space from Saintonge et al. (2016) – note here how the average ISM content changes as one moves to low SFR/M_* galaxies. Despite this, quite a few early type and green valley galaxies do have measured atomic and molecular gas.

Putting a Sketch Together

A good first-order observationally motivated sketch of low redshift galaxies would be:

- *The gas fraction of galaxies depends on stellar mass, with high mass galaxies having more stellar mass relative to gas mass. Dwarf galaxies like the Small Magellanic Clouds have comparable gas and stellar mass.*

- *The molecular gas fraction of galaxies depends on stellar mass, with high mass galaxies having more molecular gas relative to atomic gas. Even a massive galaxy like the Milky Way has more atomic gas than molecular gas.*

- *Metallicity scales with stellar mass and star formation rate. The dust to gas ratio tracks metallicity to first order but in more detail the dust-to-metals ratio drops in lower mass galaxies – much more on this later in the week.*

- *Cluster environments suppress atomic gas content. Mergers and interactions enhance molecular gas and star formation. Late type galaxies often have gas but usually a lower normalized gas content than late type star forming galaxies.*

Rhyming Summary of Part 2

At z of naught, HI's the bulk of gas by far,
A little dwarf can even have more gas than stars,

Fractionally, the H2 remains quite low,
Though in detail this depends on XCO,

Clusters strip gas and major mergers make it dense,
And early types have gas but just a few percents,

The metal content follows from the system's weight,
With little dwarfs at metallicities of eight,

Solids? The dustiness tracks metallicity,
But with a steep dependence, leaving dwarfs dust-free.

Slide Blank for Notes and Questions

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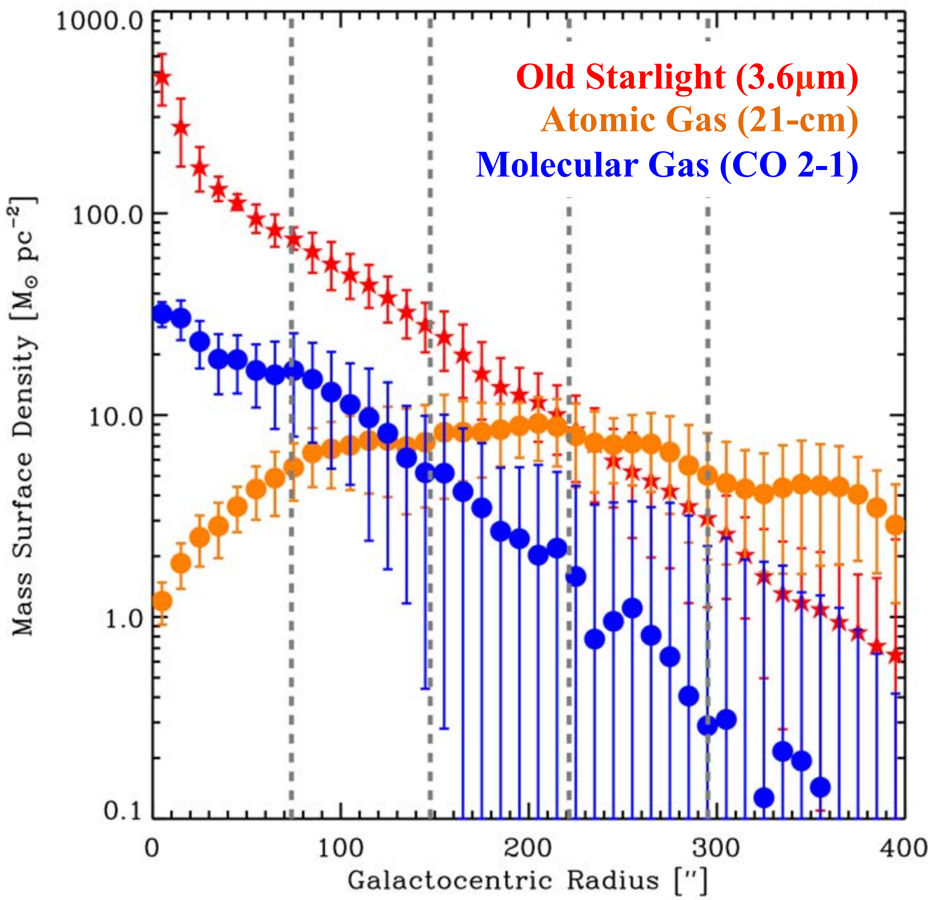
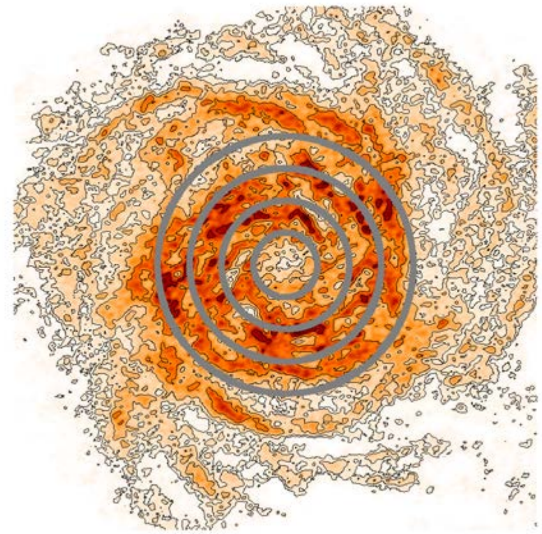
6. *Conclusions*

Radial Distributions of Gas in Galaxies

The different phases of the ISM are distributed in different ways. To first order, in late type galaxies molecular gas follows the stellar disk, showing an exponential distribution of surface density vs. radius. The stars and star formation rate do roughly the same thing. By contrast, the (massive) atomic gas disk tends to show a much more extended distribution with a much narrow range of surface density than the other phases.





Radial profiles of stellar, atomic gas, and molecular gas surface density in M74 – the gray lines show 0.25, 0.5, 0.75, and 1 times the classical "optical radius" r25.

Radial Distributions of Gas in Galaxies

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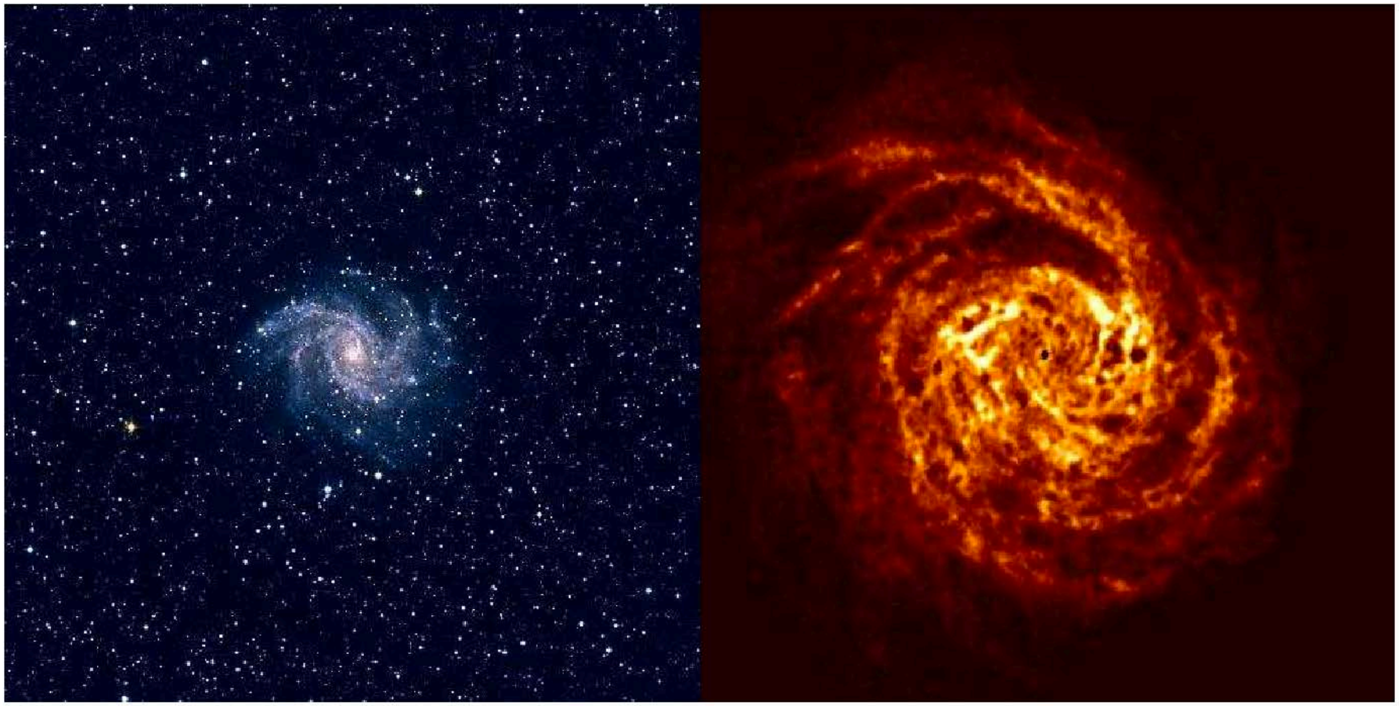
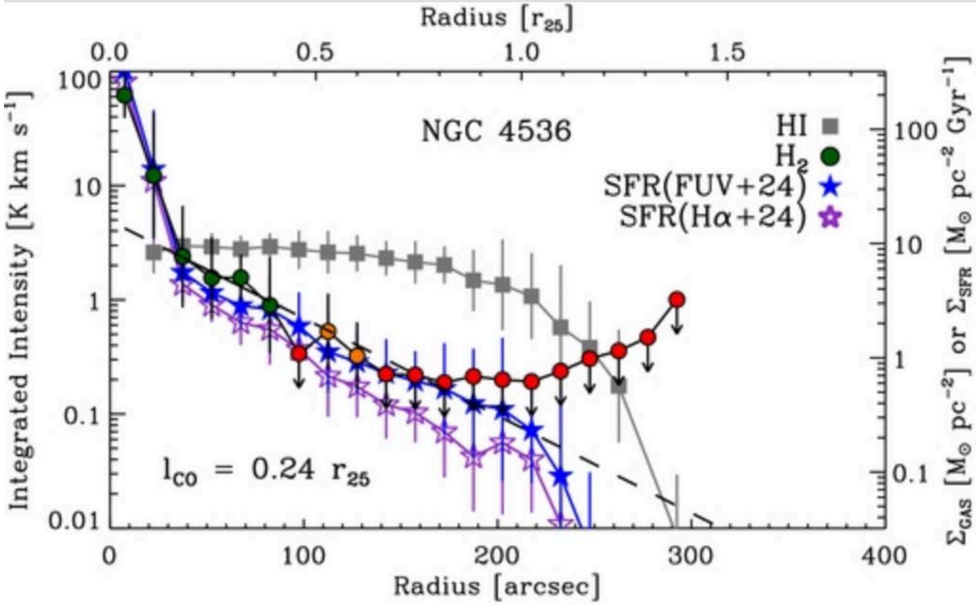


Visual demonstration of the extent of the HI disk in nearby galaxies – here from NGC 6946 from Boosma et al. (2008)

Stellar Bars and Galaxy Centers

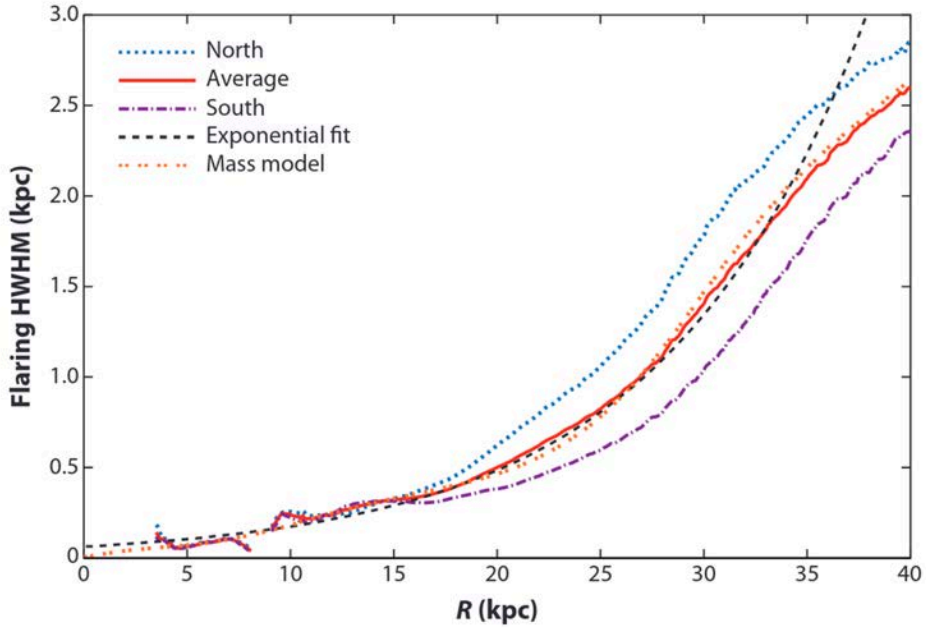
These basic radial trends are strongly affected by the presence of bulges (which can often be gas free) and stellar bars. Stellar bars are present in about 2/3 of present day galaxies at some strength, and they act to funnel gas through galaxies. Their most dramatic effect is to channel gas from the disk to the galaxy center creating dense concentrations of gas: "nuclear starbursts" or "central molecular zones" (named after the CMZ in the Milky Way created by our own bar).

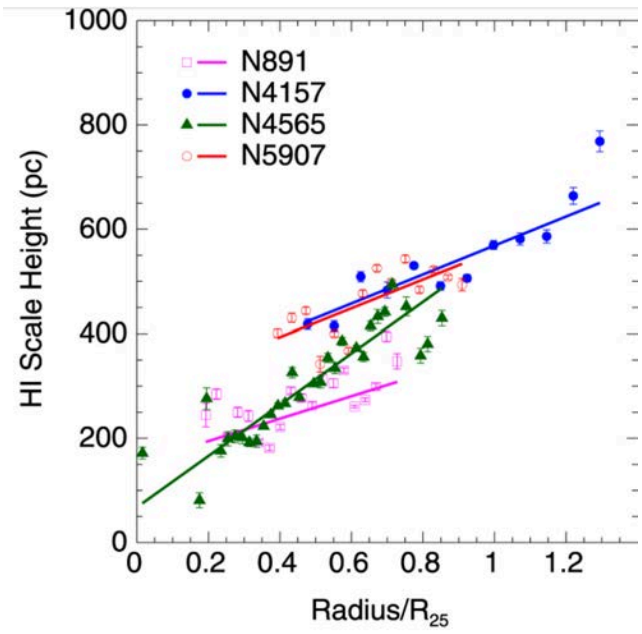


Left – illustration of the cold gas lanes along a bar feeding a nuclear condensation (from PHANGS-ALMA). Above, illustration of a radial profile showing a central concentration (from Schruba et al. 2011).

Vertical Distributions of Gas in Galaxies

In the Milky Way and similar galaxies, the scale height of atomic gas in the inner disk is a couple hundred parsecs. The height of the disk is understood to reflect the gas sitting in a dynamical equilibrium with the galaxy potential with energy input by stellar feedback. In the outer parts of galaxies, the height of the HI layer increases ("flaring") reflecting a shallower and shallower gravitational potential well.

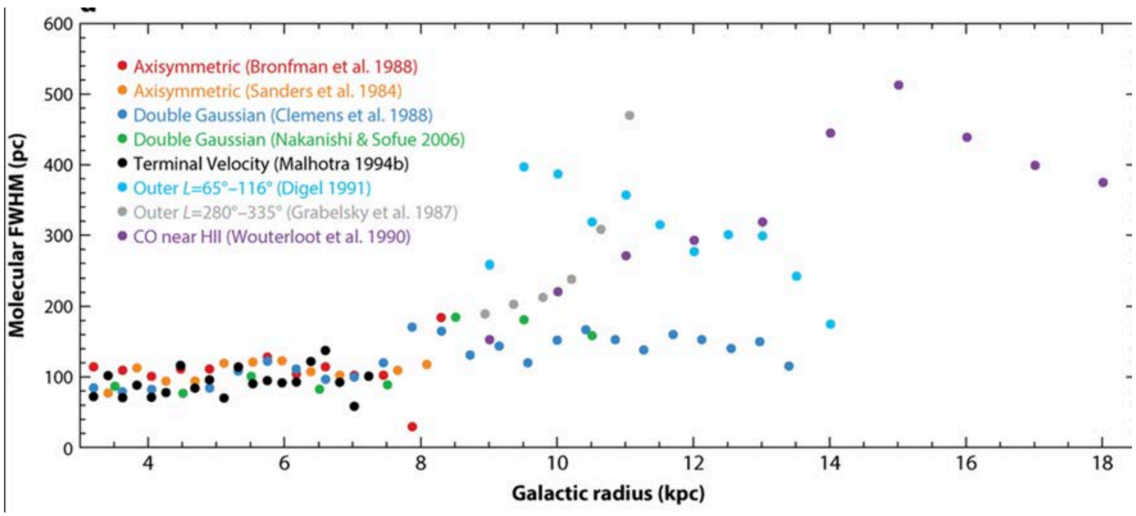


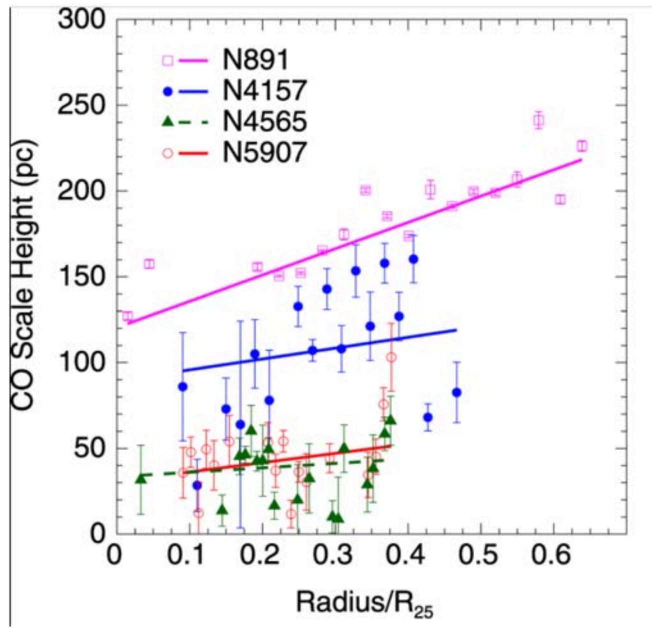


Left – from Kalberla & Kerp (2009) the vertical height of the HI layer in the Milky Way, right from Yim et al. (2018), the vertical height of the HI layer in four edge-on external galaxies. See the steady "flaring" with radius in both cases.

Vertical Distributions of Gas in Galaxies

The molecular layer in the Milky Way shows a thin scale height – order 100 pc FWHM. This layer also has a structure that reflects gravity and may show some evidence of flaring.

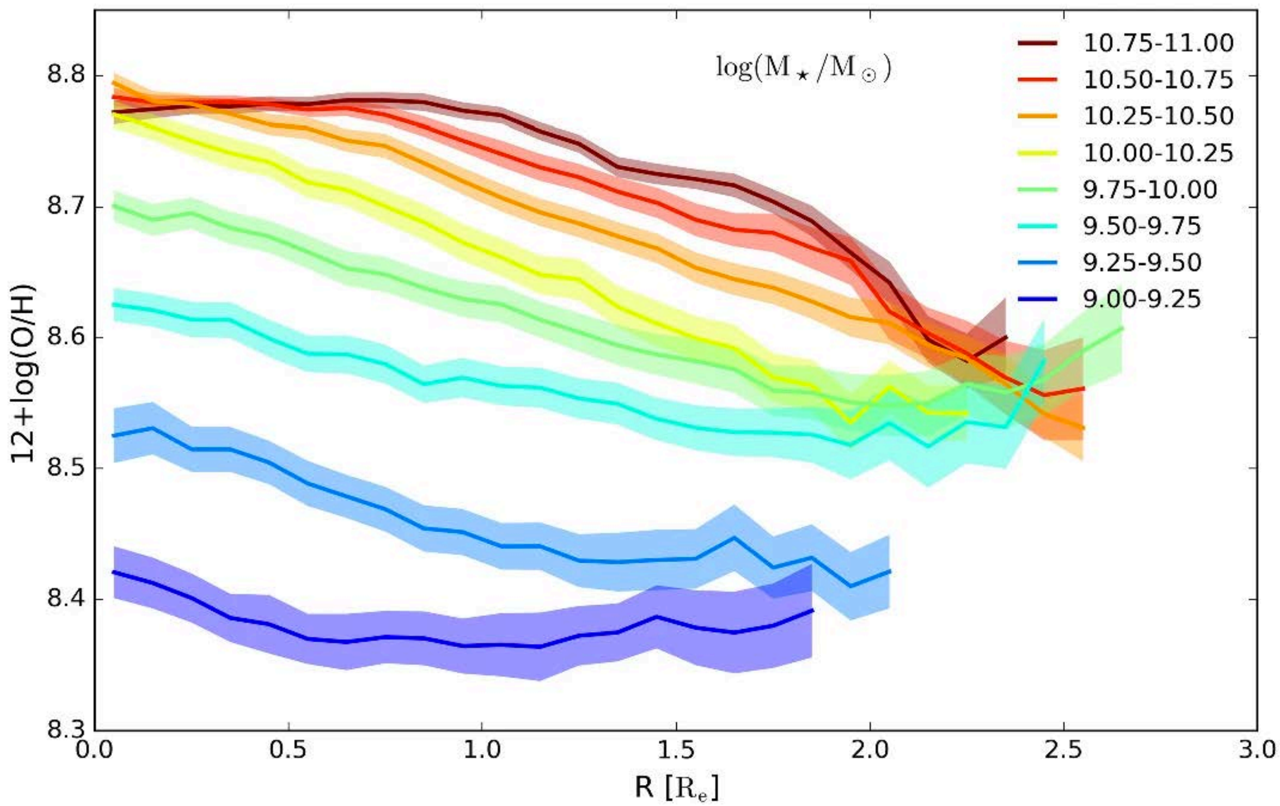




Left – from Heyer and Dame (2015) the vertical height of the CO layer in the Milky Way, right from Yim et al. (2018), the vertical height of the CO layer in four edge-on external galaxies. See the thinness of the disk in all cases and some evidence of flaring at large radii in both the Milky Way and the other galaxies.

Metal Distributions in Galaxies

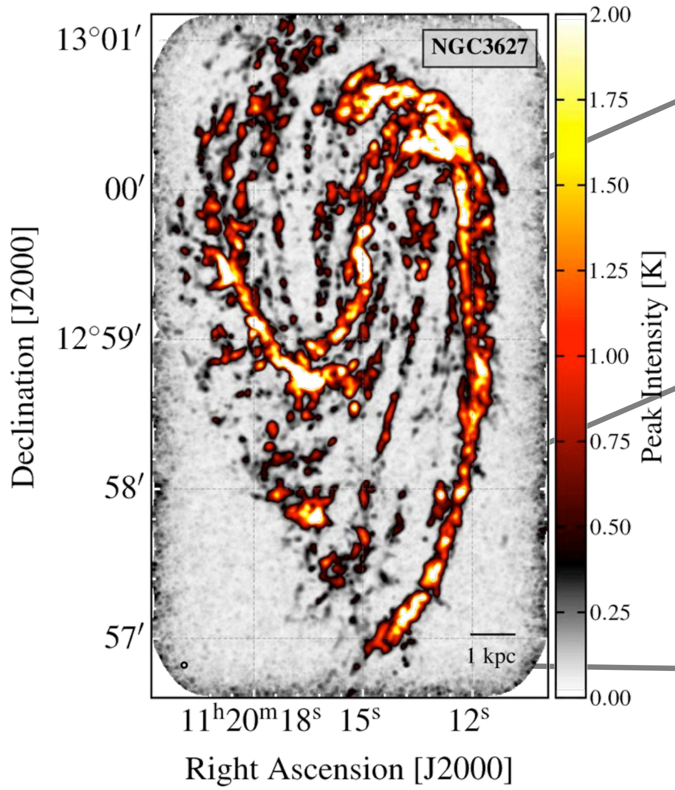
Metallicity (metals per unit gas mass) also drops with galactocentric radius. Typically the metallicity declines by 0.2 or 0.3 dex over the full optical radius of the galaxy, though both shallower and steeper gradients are observed. The dust abundance also drops, and dust can become very scarce in the outer disks of galaxies.

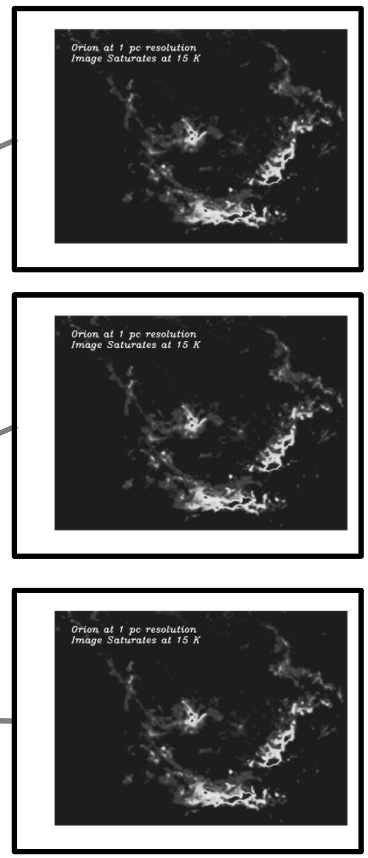


Belfiore et al. (2017) – see also Maiolino & Mannucci (2019) average metallicity gradients for MaNGA galaxies by mass.

Resolved Molecular Gas – Molecular Clouds

That molecular gas traced by CO isn't in a smooth gas layer – it's heavily clumped up into molecular clouds. These are dense, roughly gravitationally bound collections of material that serve as stellar nurseries. When you observe a galaxy in molecular gas at high enough resolution, it resolved into these individual features.



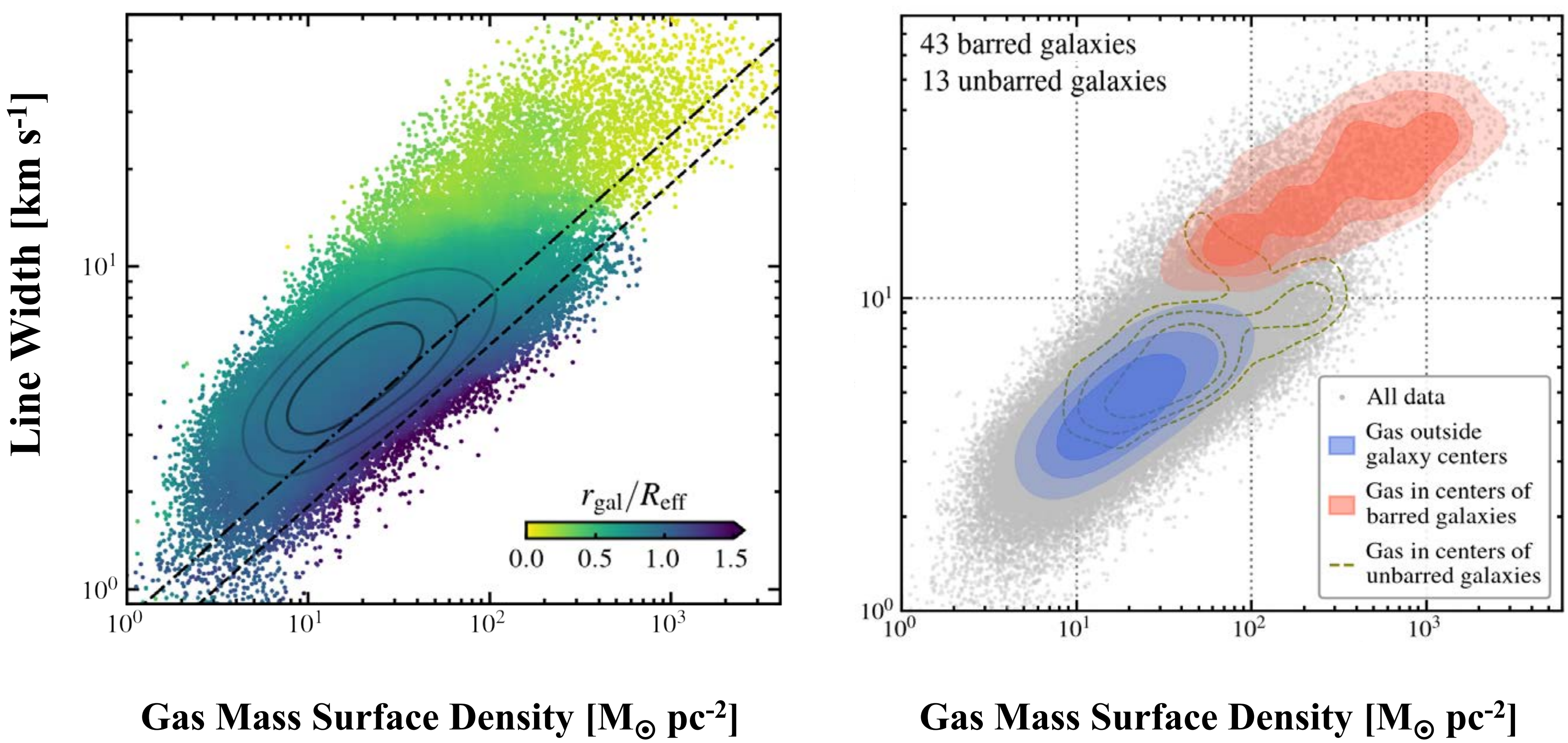


Molecular clouds

Mass: ~ $10^4 – 10^7$ $M_\odot$
Temp: 10 - 50 K
Densities: n ~ $10^2 – 10^5$+ cm^{-3}
Size: 10 – 100 pc
Motions: dominated by turbulence
Structure: clumpy and filamentary
Dynamical state: roughly bound

Resolved Molecular Gas – Molecular Clouds

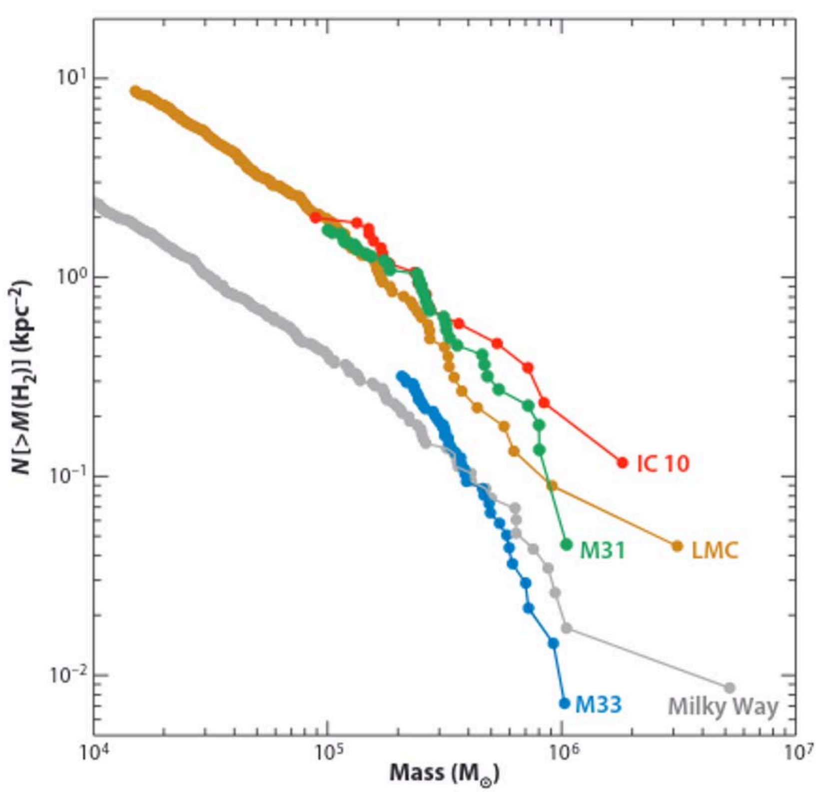
The properties of GMCs have been studies for a long time. At present, a reasonable view is that the surface density of GMCs (or at least H_2) varies some with galactic environment, and that the gas tends to look nearly gravitationally self-bound (but just nearly). The motions in the gas are overwhelmingly turbulent, not thermal, and the gas in galaxy centers and major mergers appears to be even more turbulent (and more loosely bound to itself) than that in disks.



Sun et al. (2020, 2018) – see also Rosolowsky et al. (2021) – line width and surface density of gas in galaxies at ~100 pc.

Resolved Molecular Gas – Molecular Clouds

When we pick out individual clouds and attempt to build a mass spectrum, the slope of the GMC mass spectrum often comes out near -1.5 with some evidence for an upper truncation a la a Schechter function. This implies that the more massive clouds hold most of the mass and activity, though steeper slopes are measured in a few places and details matter.



Fukui & Kawamura (2010) review – see also Rosolowsky (2005) – showing mass functions of GMCs picked out in Local Group galaxies. Massive clouds host a lot of the mass and a lot of the star formation action.

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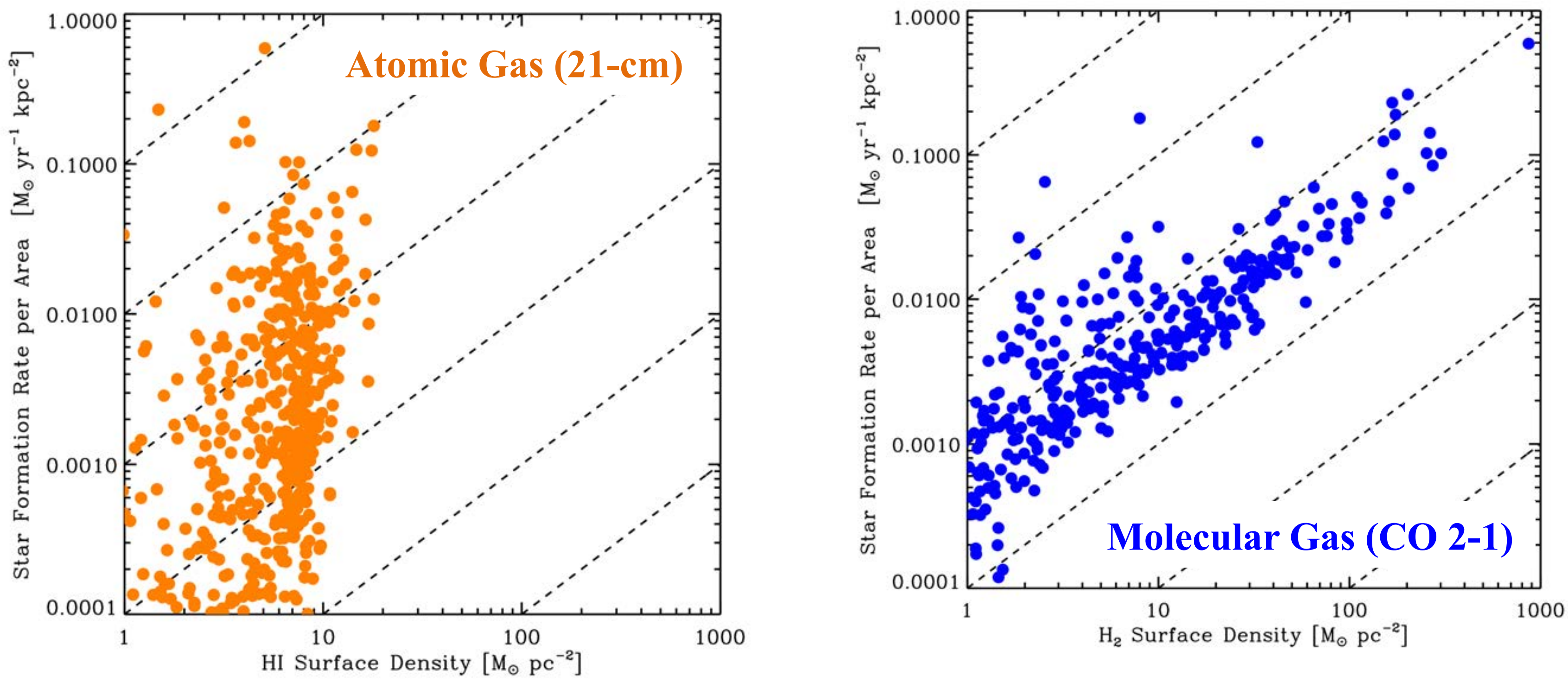
Star Form in Molecular Gas

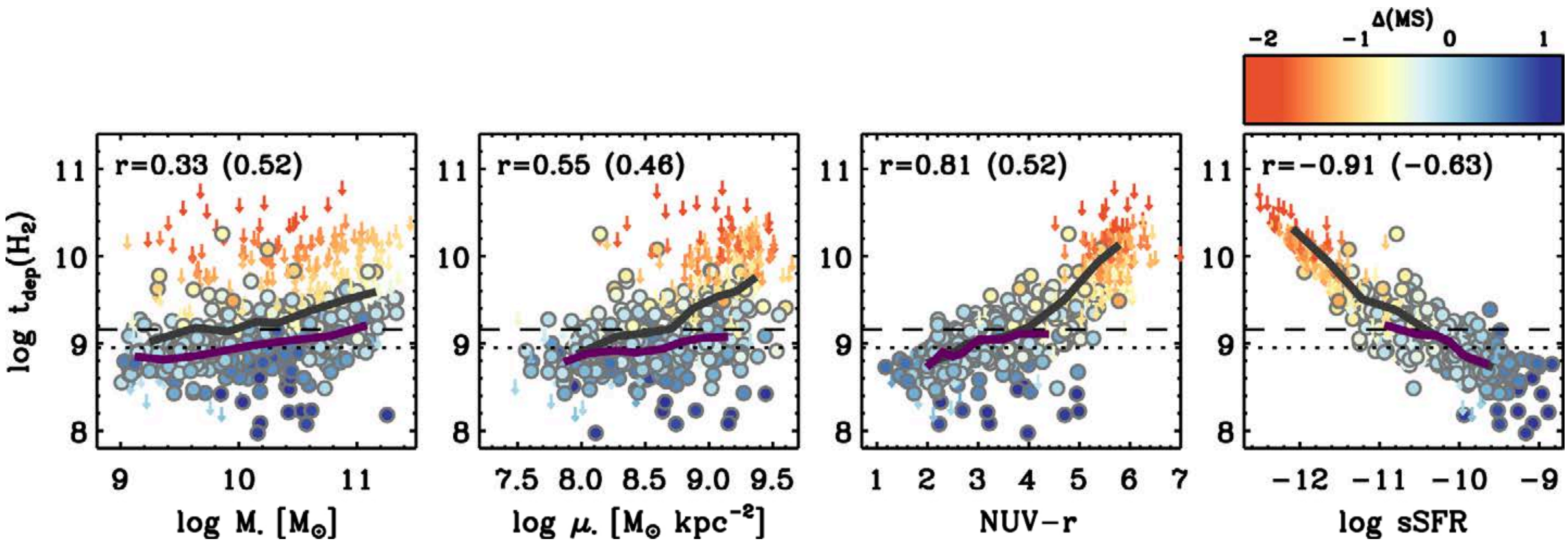
Within galaxies, the locations of star formation show an excellent correspondence to the location and amount of molecular gas. Variations in the "depletion time" (M_{H2}/SFR) or "star formation efficiency" (SFR/M_{H2}) are seen in galaxy centers, bulges, and other locations, but the first order picture that stars form from the molecular phase seems clear and the local relationship between atomic gas and star formation is complex.



Star formation in regions of galaxies is almost 1-to-1 with H_2 and shows a steep relationship to HI from Schruba et al. (2011)

Molecular Gas Depletion Times

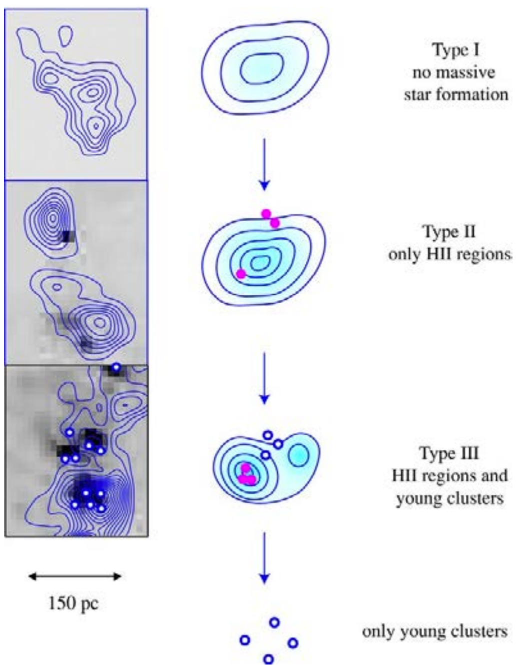
A key metric for how the star formation process changes is the "molecular gas depletion time." Formally it's how long it would take star formation to consume the gas supply if everything just proceeds "as is." Physically, it's a measure of the SFR-per-unit-gas mass (but inverted). The molecular gas depletion time is observed to correlate with the specific star formation rate and it may depend on stellar mass. But this is incredibly dependent on how you treat the CO-to-H2 conversion factor because it depends on estimating H2 mass as metallicity changes.



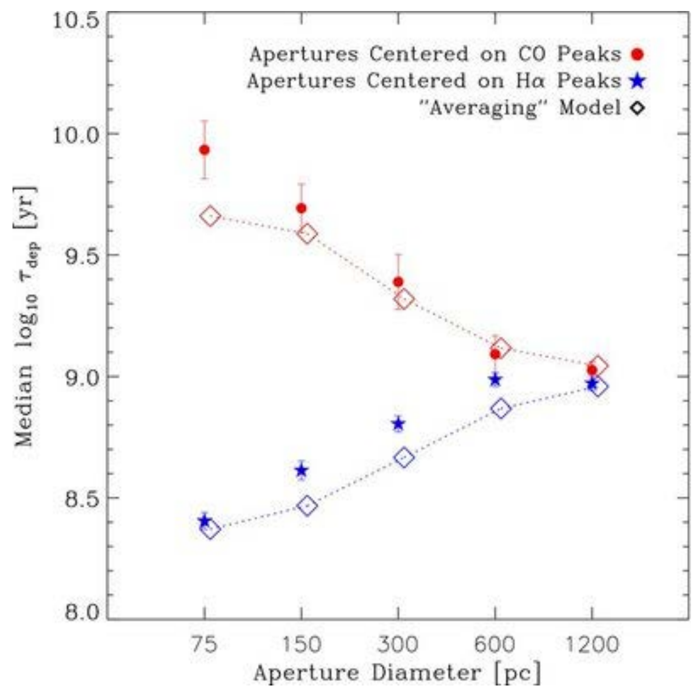
Dependence of molecular gas depletion time on stellar mass, surface density, color, and specific star formation rate from Saintonge et al. (2017)

Resolving the Star Formation Process

Individual regions proceed through a cycle of cloud formation, star formation, feedback, and cloud destruction on a 10-30 Myr timescale, of order a dynamical time or a crossing time. As a result when galaxies are observed at high resolution, the distinct phases of the star formation process: cloud, HII region, cluster, etc. begin to scatter relative to one another in a way that reflects the evolution of individual regions.



Classification of clouds in the LMC by star formation activity – Kawamura et al. (2009)



Molecular gas depletion time at high resolution depends on what type of region you focus on – Schruba et al. (2010)

Putting a Sketch Together

A good first-order observationally motivated sketch of resolved behavior would be:

- *Molecular gas, stars, and star formation activity fall off roughly as an exponential in disk galaxies. This situtation is perturbed by the presence of bulges and stellar bars. Bars funnel gas to galaxy centers, creating concentrations of gas and star formation.*

- *In the inner disk both molecular and atomic gas show evidence of being in a thin layer (the WIM is a bit thicker). As you move out with radius, HI in both the Milky Way and other galaxies "flares" increasing its scale height.*

- *The metallicity of galaxies also drops with radius within a galaxy, with typical gradients of order 0.2 to 0.3 dex across a full optical radius. Dust shows similar or steeper trends.*

- *Molecular gas is not smooth but clumped up into giant molecular clouds that are dense and turbulent and hover near being bound by self-gravity. Their properties vary across the galaxy population, with more turublent less bound gas in starbursts and galaxy centers.*

- *Star formation tracks molecular gas, with depletion time variations as a function of stellar mass and specific star formation rate. At high enough resolution, the active cycle of cloud formation, star formation, feedback, and cloud destruction becomes visible.*

Rhyming Summary of Part 3

As an exponential disk, CO and starlight fall,
While HI at a nearly fixed N(H) just sprawls,

A stellar bar can cause a deviation from this scheme,
Since gas inflow can make the center quite extreme.

Now the cold gas in the inner disk – it lies in a thin layer,
But at large "r" with fewer stars, the HI disk does flare.

Increasing radius, it also drops the metal count,
Which may go down by point three dex before the stars run out.

That H2 gas, of course, its clumped up in GMCs,
Cold, dense clouds that play the role of stellar nurseries,

The speed with which that cold, dense gas supply gets ate,
It varies as function of the mass and star formation rate,

So – that's my low-z ISM collection,
Now to you – I ask for questions and corrections?

Resolved Molecular Gas – Molecular Clouds

In the Milky Way and similar galaxies, the scale height

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Rhyming Summary of Part 1

The spin-flip line reveals atomic gas,
Which fills the space and holds a lot of mass.

New stars are born in clouds we can't directly see,
We get around this by observing states of C.

Warm bubbles of dense gas encase each massive star,
But their ionizing light still makes it pretty far.

The light from these young stars runs headlong into dust,
To trace these grains, IR emission is a must.

When massive stars explode, they blast the gas away,
And shock what's left to upwards of a million K.

Last, while this disk of gas can let the system grow,
It's still not much compared to the halo …

Rhyming Summary of Part 2

At z of naught, HI's the bulk of gas by far,
A little dwarf can even have more gas than stars,

Fractionally, the H2 remains quite low,
Though in detail this depends on XCO,

Clusters strip gas and major mergers make it dense,
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Bibliography

This is ***super incomplete*** *but it's an okay starting reading list that I drew plots and details from:*

CGM: *Tumlinson et al. 2017, Putman et al. 2012*
Dust: *Galliano et al. 2018*
HI in the MW: *Kalberla & Kerp 2009*
H2 in the MW: *Heyer & Dame 2015*
Metals (so much metals): *Maiolino & Mannucci 2019*
Molecular clouds: *Fukui & Kawamura 2010, Sun et al. 2018, 2020, Rosolowsky et al. 2021*
Scaling relations across redshift: *Tacconi et al. 2020*
Integrated gas scaling relations: *Catinella et al. 2018, Saintonge et al. 2016, 2017*
The ISM in general: *Cox et al. 2005*
Mergers: *Sanders and Mirabel 1996*
Gas in clusters: *Cortese et al. 2021*
Resolved galaxies: *Schruba et al. 2011, 2010*

As always hit the "references to" bit in ADS ☺

PHANGS: *If you want to read more about where some of the field is going, I refer you to www.phangs.org and the three overview papers: PHANGS-ALMA (Leroy et al. 2021), PHANGS-MUSE (Emsellem et al. submitted), and PHANGS-HST (Lee et al. 2021)*