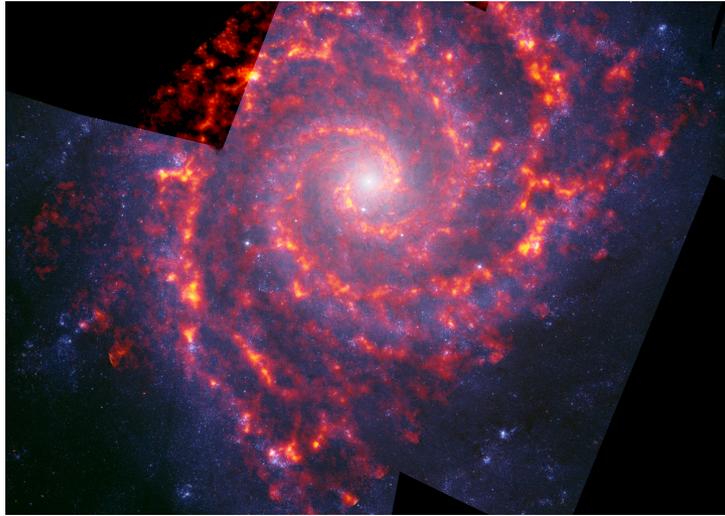
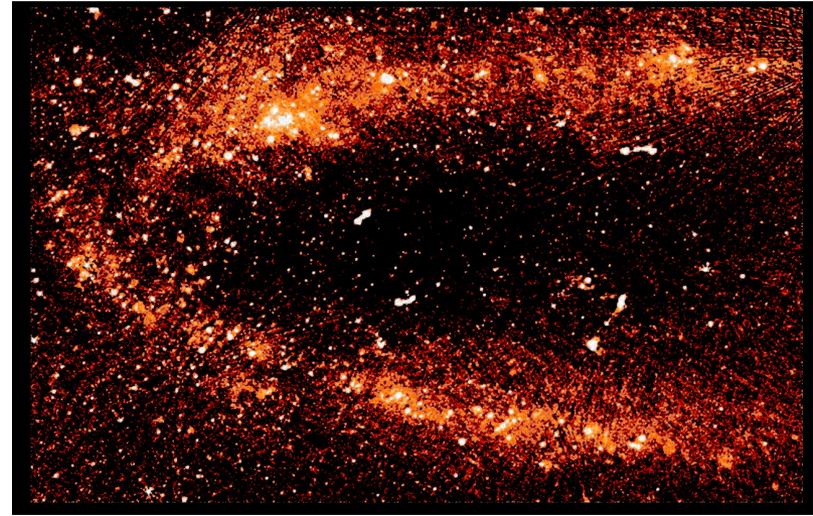


Infrared opportunities in the era of cloud-scale CO, IFU-based metallicity maps, and hyper-detailed HI surveys



**ALMA CO (red) over *Hubble* image of starlight
in NGC 628 (M74) from PHANGS ALMA, HST**

*NRAO/AUI/NSF, B. Saxton: ALMA
(ESO/NAOJ/NRAO); NASA/Hubble*



**1-2 GHz continuum from a large part of M31's star
forming ring from the Local Group L Band Survey**

Sumit Sarbadhicary

**Adam K. Leroy (Ohio State), Jiayi Sun (McMaster), I-Da Chiang (ASIAA), Eric Koch (CfA)
on behalf of the PHANGS-ALMA and LGLBS teams**

www.phangs.org and www.lglbs.org

Motivation – the Nearby Ecosystems

*It's 5pm on the last big science day, so I'm going to take our desire to understand the **physical conditions, timescales, efficiencies, and composition of the ISM and star formation** as given.*

The “nearby ecosystems” specifically contribute a few key angles to this view:

- **Statistics and diversity of environments – key to general results**
- **External perspective – key to place ISM and feedback in context**
- **Ability to achieve a complete accounting via multiwavelength data**

And we are making amazing progress on this topic – as we have heard this week already. But increasingly resolved IR spectroscopy and imaging are the limiting reagent to make progress.

Conclusions (People Version)

A lot of what I will tell you reflects great thesis and post-doc work by three amazing first term postdocs. Please check out their papers, invite them for talks, and reach out to them!



Jiayi Sun

*CITA National Fellow at
McMaster*

**Cloud-scale molecular
gas and star formation
in context across the
local galaxy population.**



I-Da Chiang

*ASIAA Postdoctoral
Fellow*

**The resolved dust-to-
metals ratio and CO-
to-H₂ conversion factor
in low redshift galaxies.**



Eric Koch

*SMA/NSERC Postdoctoral
Fellow at CfA*

**New views of atomic gas
in the Local Group and
highly resolved studies of
the ISM.**

A Picture of My Dog

It has been amazing to be back in person and it's been a great conference. But the one thing I predict we will all miss from the bad old zoom days is the prevalence of cute pets in talks.



Outline

We are in an exciting time to study star formation in local galaxies, with major new surveys from ALMA, Hubble, the VLT, AstroSat, and soon JWST. The infrared accessed by SOFIA or similar future observatories contains key diagnostics to make the most of these data!

- **Cloud-scale CO and star formation**
- **Dust and metals in galaxies**
- **The elusive, but important, cold neutral medium**

Outline

We are in an exciting time to study star formation in local galaxies, with major new surveys from ALMA, Hubble, the VLT, AstroSat, and soon JWST. The infrared accessed by SOFIA or similar past and future observatories contains key diagnostics to make the most of these data!

- **Cloud-scale CO and star formation**

- *Molecular gas is closely coupled to host galaxy*

- *Gas and star formation at high resolution*

- *Precision α_{CO} remains a major obstacle*

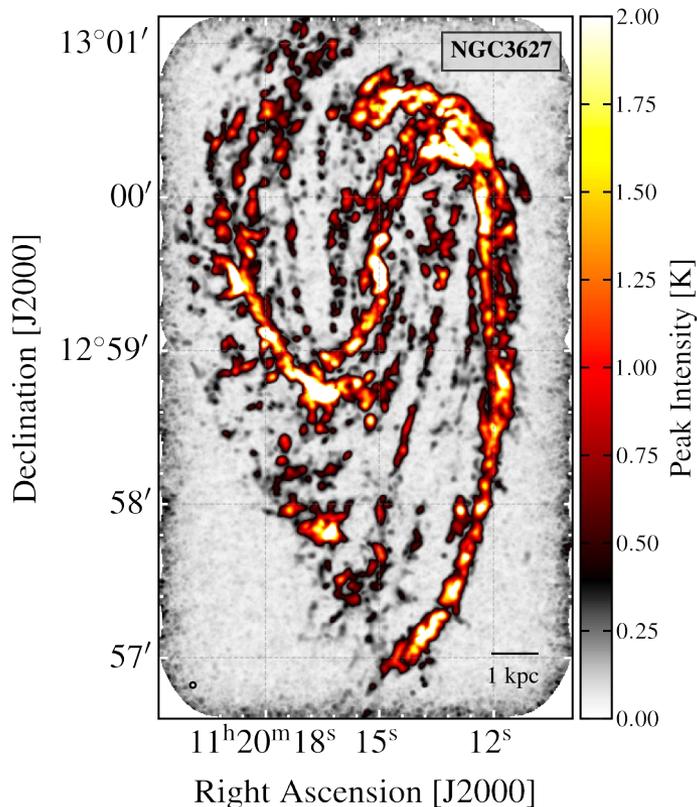
- **The CII-to-CO ratio is a key but often missing quantity**

- **Dust and metals in galaxies**

- **The elusive, but important, cold neutral medium**

Nearby galaxies in unprecedented detail

ALMA, Hubble, AstroSat, optical IFUs, and soon JWST have covered the nearby galaxy population as part of a series of programs (PHANGS, LEGUS, CALIFA, SDSS IV, etc.). The PHANGS surveys: PHANGS-ALMA, PHANGS-MUSE, PHANGS-HST have mapped a large sample of very nearby galaxies in tracers of cold gas, stars, star formation, and feedback.



PHANGS-ALMA CO 2-1
Leroy, Schinnerer et al. (2021)



PHANGS-MUSE
Emsellem et al. (2021)



PHANGS-HST
Lee et al. (2021)

Three views of M66
star-forming gas with ALMA,
ionized gas with VLT-MUSE,
and stars and dust with *Hubble*

A new sharp view of molecular gas in galaxies

PHANGS-ALMA mapped the CO 2-1 emission from 90 nearby, massive star-forming galaxies (i.e., most of them) at $\sim 1''$ or $\sim 100\text{pc}$ resolution. This sharpens our view by ~ 10 times compared to previous single dish mapping of large samples and gives us a “cloud scale” view.

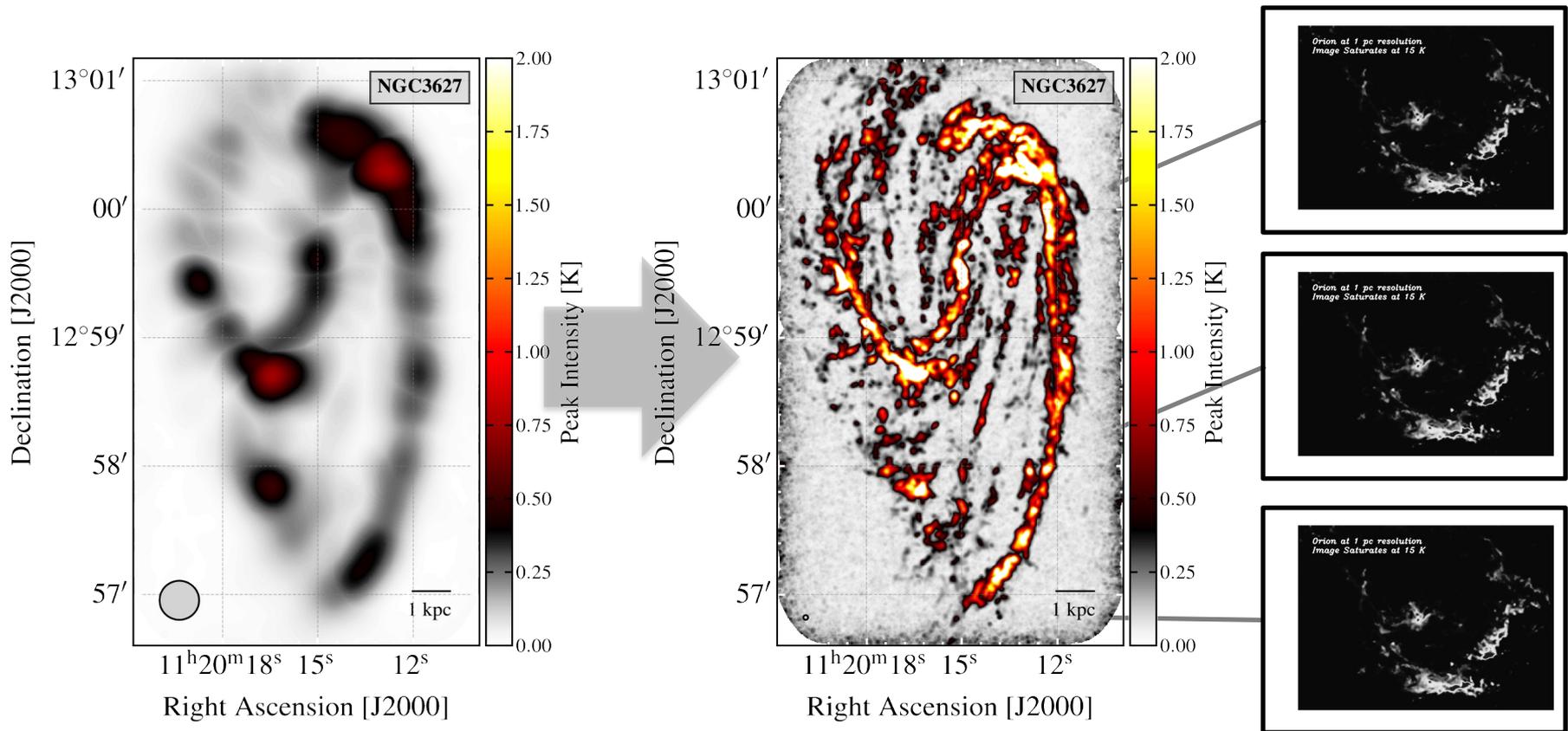
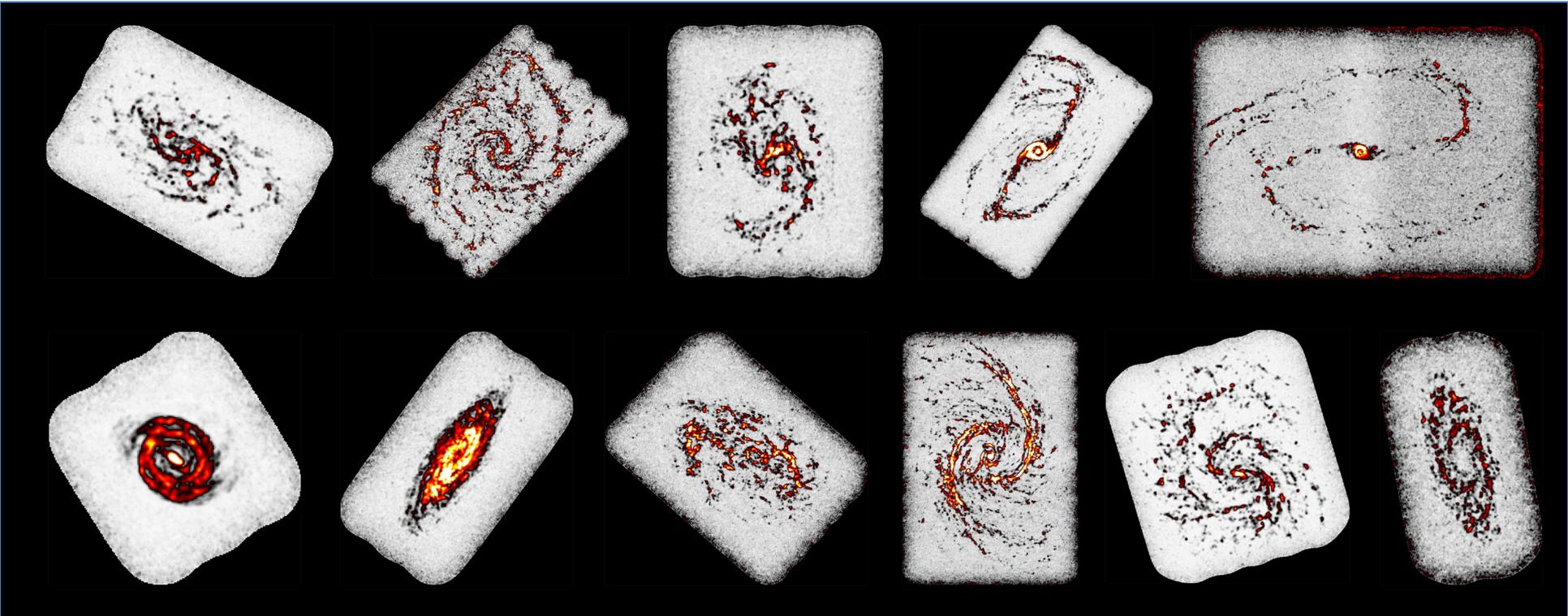


Illustration of how PHANGS-ALMA improves the resolution of CO mapping surveys from \sim kiloparsec (left) to ~ 100 pc, the scale at which each resolution element corresponds to an individual cloud or cloud complex.

Leroy, Schinnerer et al. (2021)

We have cloud-scale CO 2-1 observations of almost 100 galaxies!

PHANGS-ALMA aimed to map all of the massive star-forming galaxies visible to ALMA within about 17 Mpc – these 100 galaxies reasonably sample the main sequence of star-forming galaxies and give us a sharp, sensitive new view of the molecular ISM. They are all public!



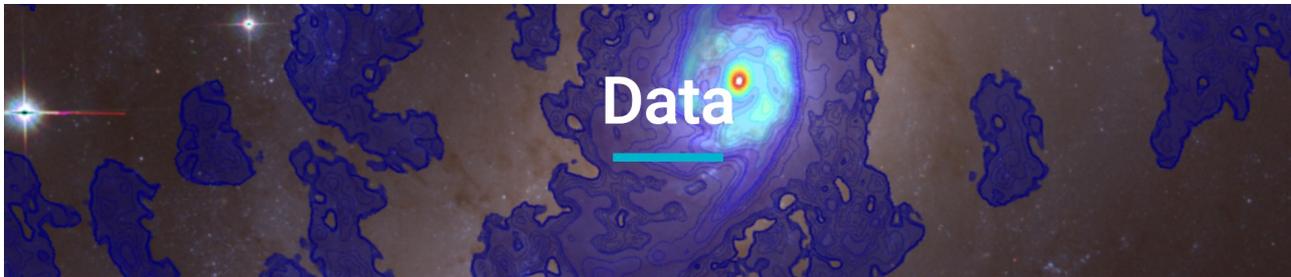
<https://sites.google.com/view/phangs/home/data>

Leroy, Schinnerer et al. (2021)

YOU have cloud-scale CO 2-1 observations of almost 100 galaxies!

The CO data, the MUSE VLT IFU data, HST images, and a host of higher level data products and software are all public. We want you to use them (Please! We worked really hard on them!)

<https://sites.google.com/view/phangs/home/data>



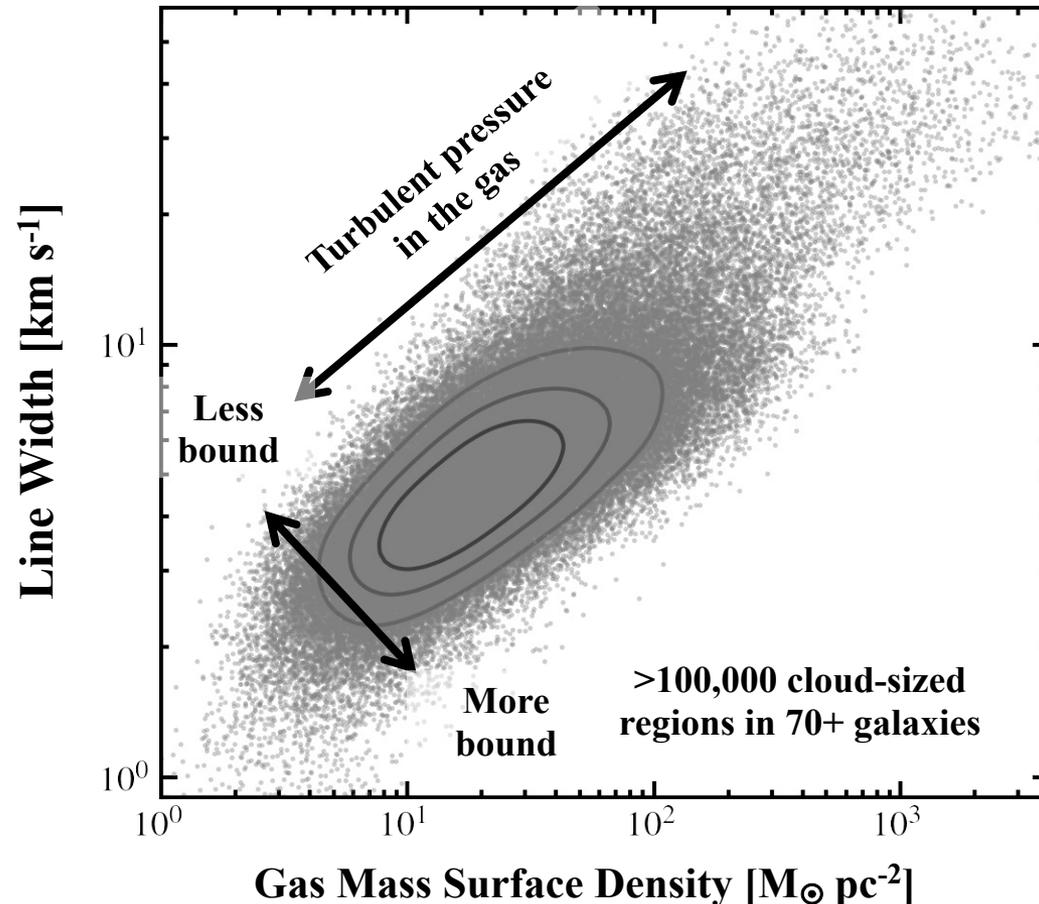
REVERSE CHRONOLOGICAL ORDER:

- *Stellar Structures, Molecular Gas, and Star Formation across the PHANGS sample of nearby galaxies* by Querejeta et al. (2021) environmental masks for 74 PHANGS galaxies ([link](#))
- **PHANGS-MUSE Public Release**
 - PHANGS-MUSE Public Release (via ESO [Link](#) • via CADC: [Link](#))
 - Emsellem et al. (2021) Survey Paper ([PDF](#))
 - Description ([PDF](#))
- **PHANGS-ALMA Public Release** (90 galaxies via [Link](#))
 - PHANGS-ALMA Public Release (74 galaxies via JAO [Link](#))
 - [README](#)
 - Leroy et al. (2021) Survey Paper ([arXiv](#))
 - Leroy et al. (2021) PHANGS Pipeline paper ([ADS](#))
 - CADC archive coming soon
 - *PHANGS-ALMA image atlas* ([pdf](#) ; [individual images](#))
- **PHANGS-HST data release DR 1** ([link](#))

Molecular gas at ~ 100 pc resolution knows about its host galaxy



A major result from these surveys is that the properties of molecular gas on ~ 100 pc scales varies within and among galaxies and shows a close coupling to the host galaxy. The internal (probably turbulent?) pressure of clouds represents a primary axis of variation.

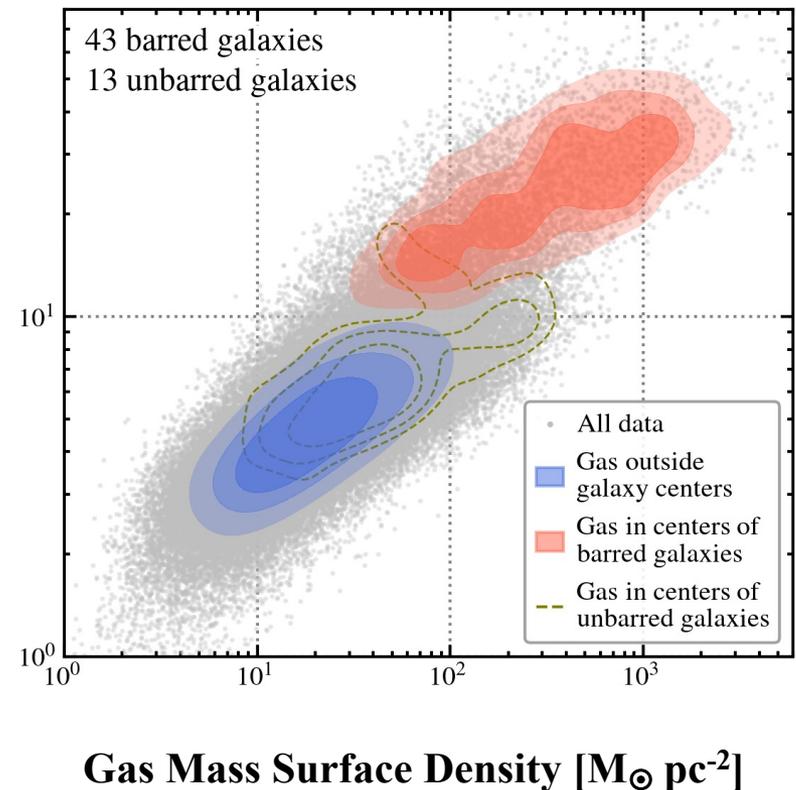
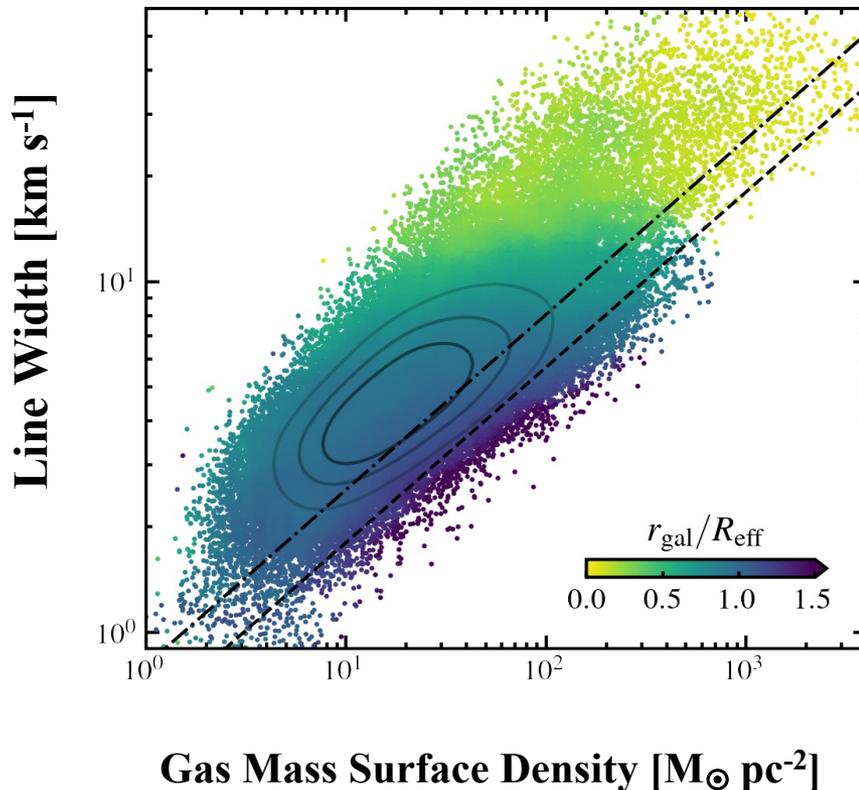


Sun et al. (2018, 2020b) and see Rosolowsky et al. (2021) for similar results using cloud segmentation

Molecular gas at ~ 100 pc resolution knows about its host galaxy



One can predict the mean properties of the local ~ 100 pc scale molecular gas from the local environment and global galaxy properties. Molecular clouds (or at least gas at 100 pc scales) are an integrated part of the galaxy disk, not universal, decoupled objects.



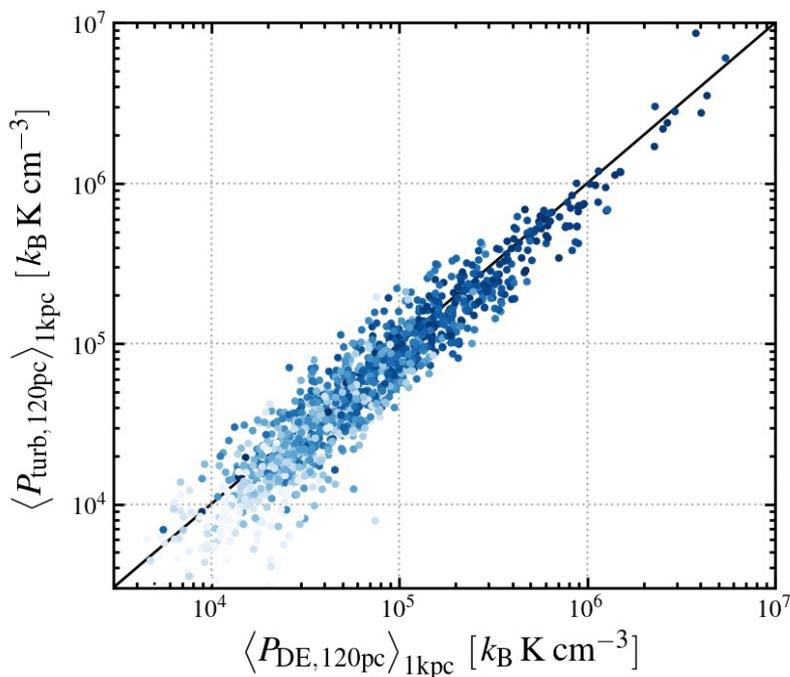
Sun et al. (2018, 2020b) and see Rosolowsky et al. (2021) for similar results using cloud segmentation

Molecular gas at ~100 pc resolution is closely coupled to its host galaxy



One can predict the mean properties of the local ~100 pc scale molecular gas from the local environment and global galaxy properties. Molecular clouds (or at least gas at 100 pc scales) are an integrated part of the galaxy disk, not universal, decoupled objects.

Turbulent pressure in the molecular gas



Pressure to support the local disk calculated from hydrostatic equilibrium

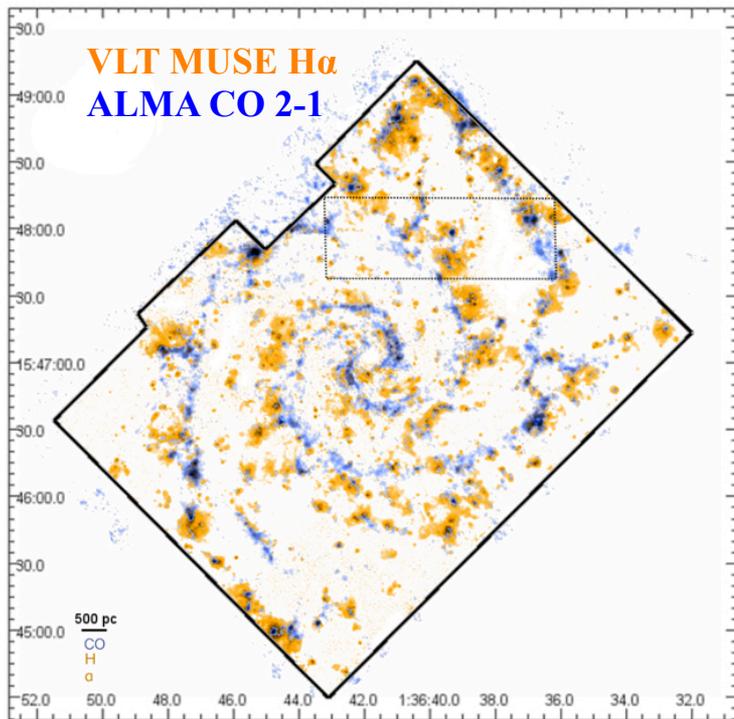
Cloud scale gas properties

	local environmental metrics							global galaxy properties				
	r_{gal}	Σ_{mol}	Σ_{atom}	Σ_{\star}	Σ_{SFR}	Ω_{disc}	A_{Oort}	r_{disk}	M_{mol}	M_{atom}	M_{\star}	SFR
$\langle M_{\text{obj}, 150\text{pc}} \rangle$	-0.10	0.78	0.30	0.42	0.62	0.18	0.13	-0.01	0.33	0.03	0.19	0.24
$\langle R_{\text{obj}, 150\text{pc}} \rangle$	0.02	-0.25	-0.15	-0.06	-0.29	-0.07	-0.14	0.04	-0.19	-0.07	0.04	-0.06
$\langle \Sigma_{\text{obj}, 150\text{pc}} \rangle$	-0.11	0.87	0.35	0.42	0.76	0.22	0.24	-0.05	0.42	0.07	0.13	0.26
$\langle \Sigma_{\text{pix}, 150\text{pc}} \rangle$	-0.16	0.92	0.32	0.46	0.81	0.26	0.27	-0.02	0.46	0.09	0.16	0.32
$\langle \sigma_{\text{obj}, 150\text{pc}} \rangle$	-0.23	0.57	0.16	0.36	0.57	0.39	0.40	0.06	0.29	0.14	0.15	0.29
$\langle \sigma_{\text{pix}, 150\text{pc}} \rangle$	-0.25	0.79	0.20	0.52	0.74	0.38	0.37	0.09	0.40	0.12	0.21	0.34
$\langle P_{\text{turb, obj}, 150\text{pc}} \rangle$	-0.19	0.84	0.31	0.48	0.77	0.33	0.33	0.02	0.40	0.12	0.17	0.31
$\langle P_{\text{turb, pix}, 150\text{pc}} \rangle$	-0.20	0.85	0.29	0.53	0.78	0.31	0.28	0.05	0.41	0.09	0.21	0.32
$\langle \alpha_{\text{vir, obj}, 150\text{pc}} \rangle$	-0.17	-0.35	-0.25	-0.05	-0.21	0.24	0.26	0.12	-0.17	0.08	-0.01	-0.00
$\langle \alpha_{\text{vir, pix}, 150\text{pc}} \rangle$	-0.29	-0.09	-0.29	0.10	0.01	0.38	0.39	0.15	-0.06	0.16	0.01	0.07
VIF	26	5.5	3.0	6.2	5.4	20	17	35	33	5.7	23	19

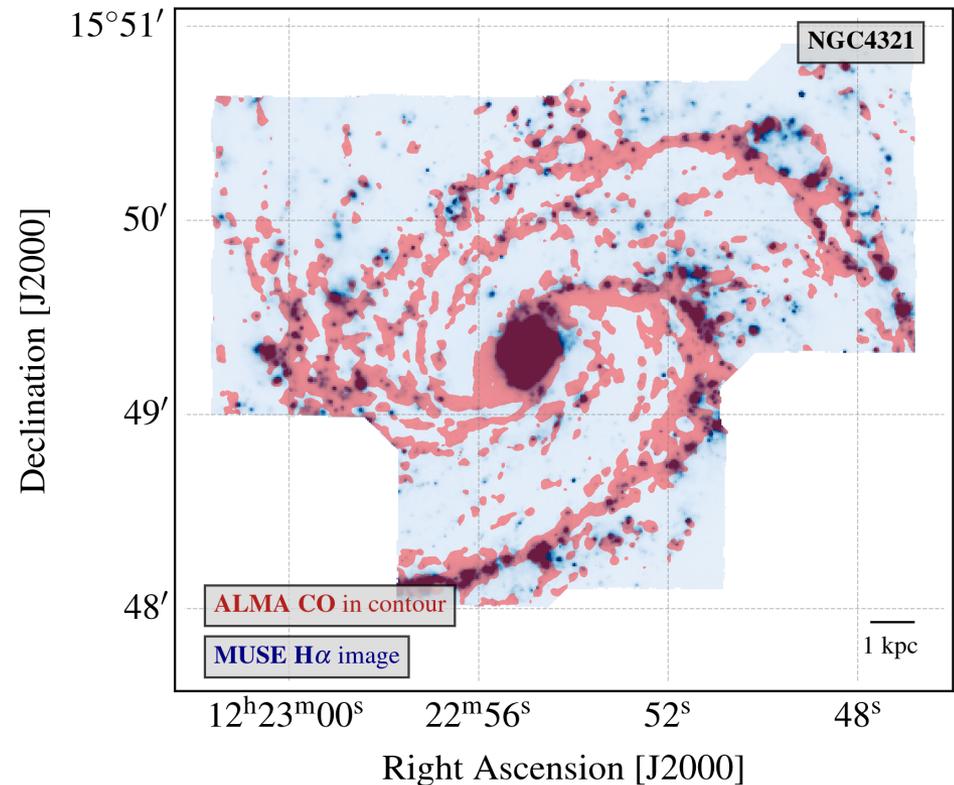
Spearman r relating local to large scale properties

Resolving the Gas-Star Formation-Feedback Cycle

By cutting across wavelength these same observations sample the star formation process at different stages. The visible association and separation of tracers of massive stars ($H\alpha$, IR) and the fuel for star formation (CO) provides a clear, quantitative observable signature related to the evolution of individual star forming regions via feedback and star formation.



NGC 0628 (M74) from Kreckel et al. (2018)

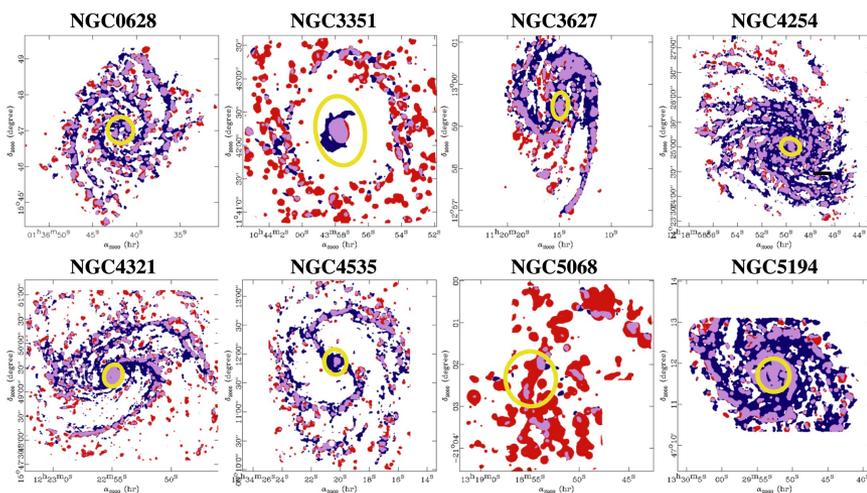


Illustrations of how $H\alpha$ (tracing massive young stars) and CO (tracing cold star-forming gas) appear in different locations when observed at high resolution. See the visible separation of the two.

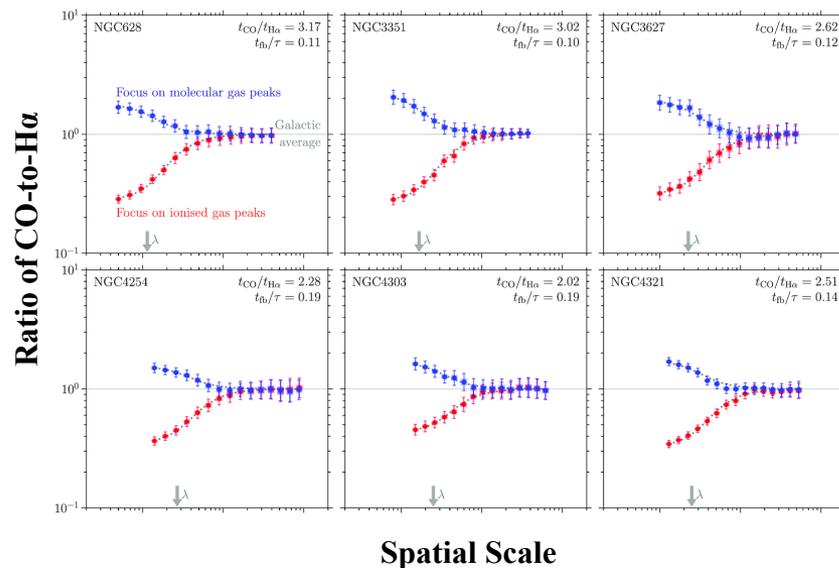
Resolving the Gas-Star Formation-Feedback Cycle



From statistical analysis of the fractional coverage, separations, or scale-dependent flux ratios, one has access to the life cycle of star forming regions. Covered in detail in great talk earlier in the week by Jayeon Kim!



One approach we are pursuing is to look at the distributions of pixels where H α (red), CO (blue), or both (purple) are bright at different scales.



Another approach is to look at how the ratio of CO-to-H α focused on CO or H α peaks depends on spatial scale.

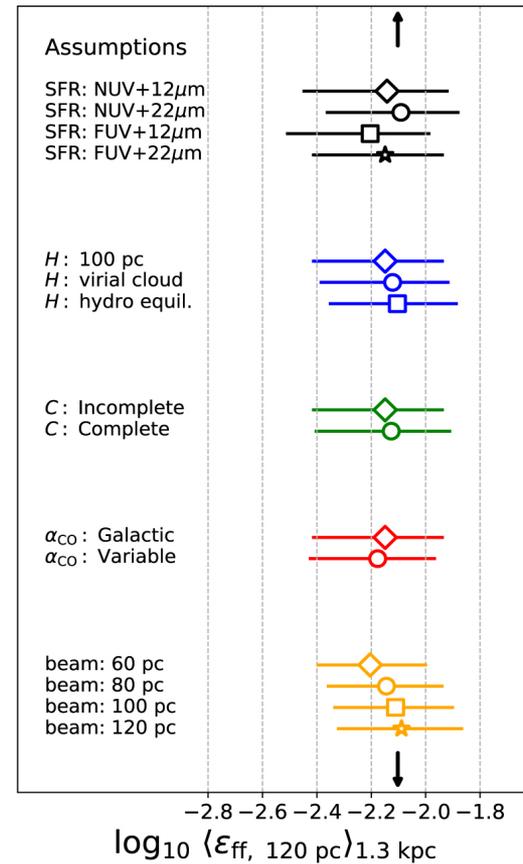
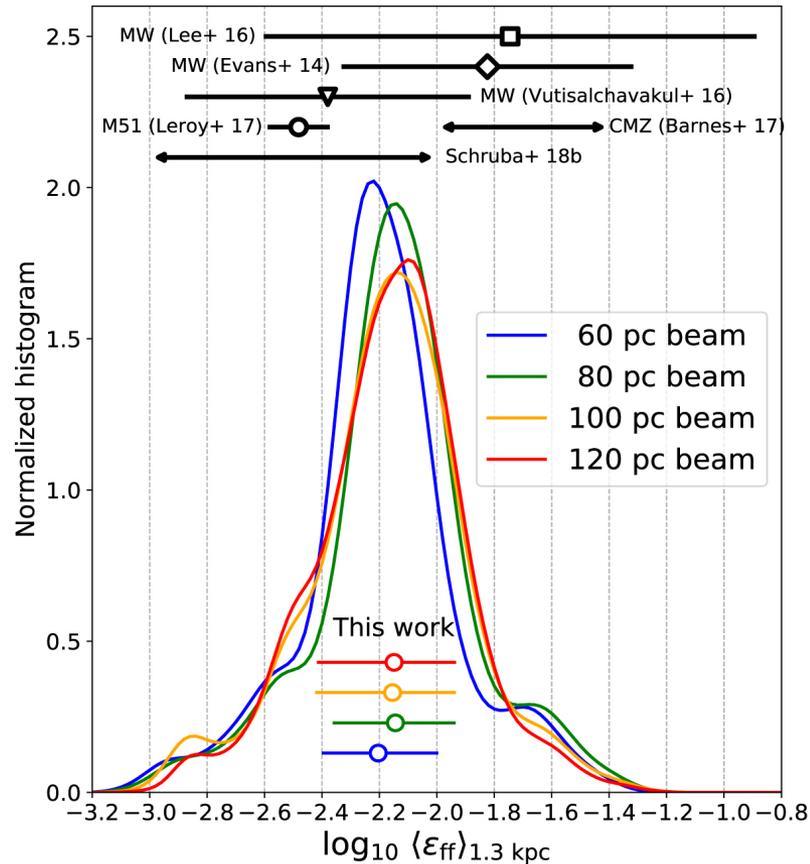
From Schinnerer et al. (2019), Chevance et al. (2020), see Kim et al. (2021+in prep.), Pan et al. 2022 And: Kawamura et al. (2009), Corbelli et al. (2017), Grasha et LEGUS 2019, Turner, Dale et al. (sbum.)

Star Formation Efficiency



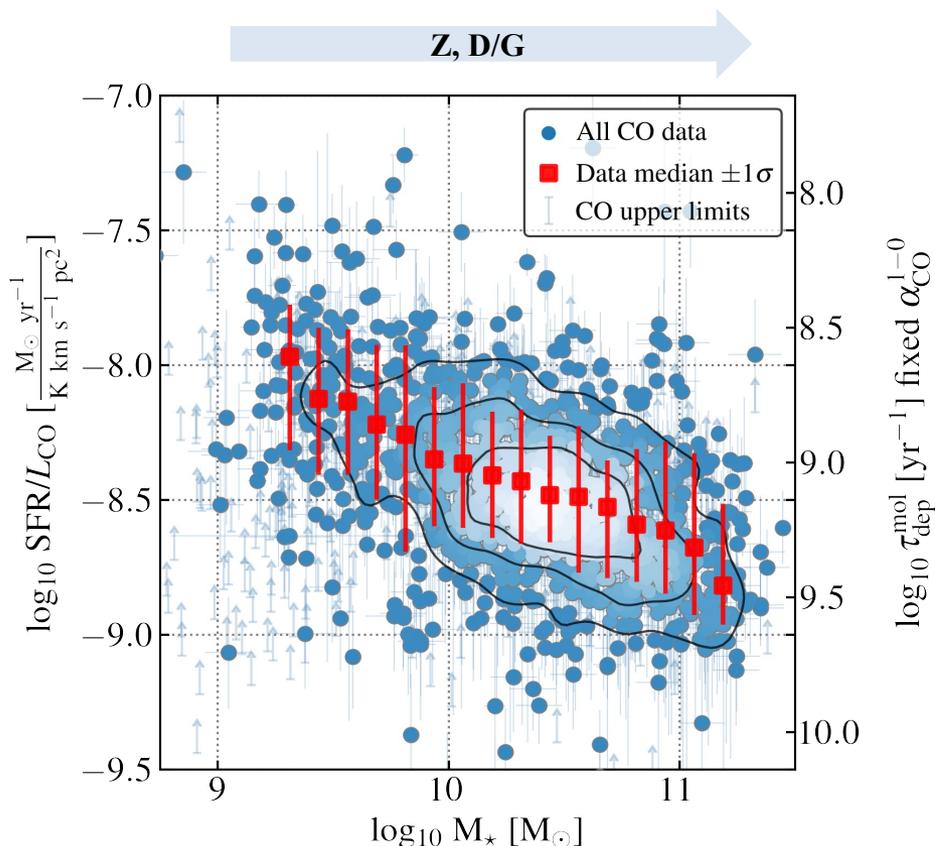
The same data allow us to estimate 100 pc-scale densities and make quantitative estimates of the mean efficiency per free fall time. The result is the largest, most systematic direct estimate of the efficiency per free fall time. In Utomo et al. (2018) we found ϵ_{ff} of 0.7% - lower than some Milky Way estimates, but in reasonable agreement with previous less direct estimates and current theoretical expectations.

Distribution of efficiency per gravitational free-fall time for 2000+ regions in 18 galaxies. 70+ galaxies coming soon.



This all goes through CO and we know α_{CO} varies

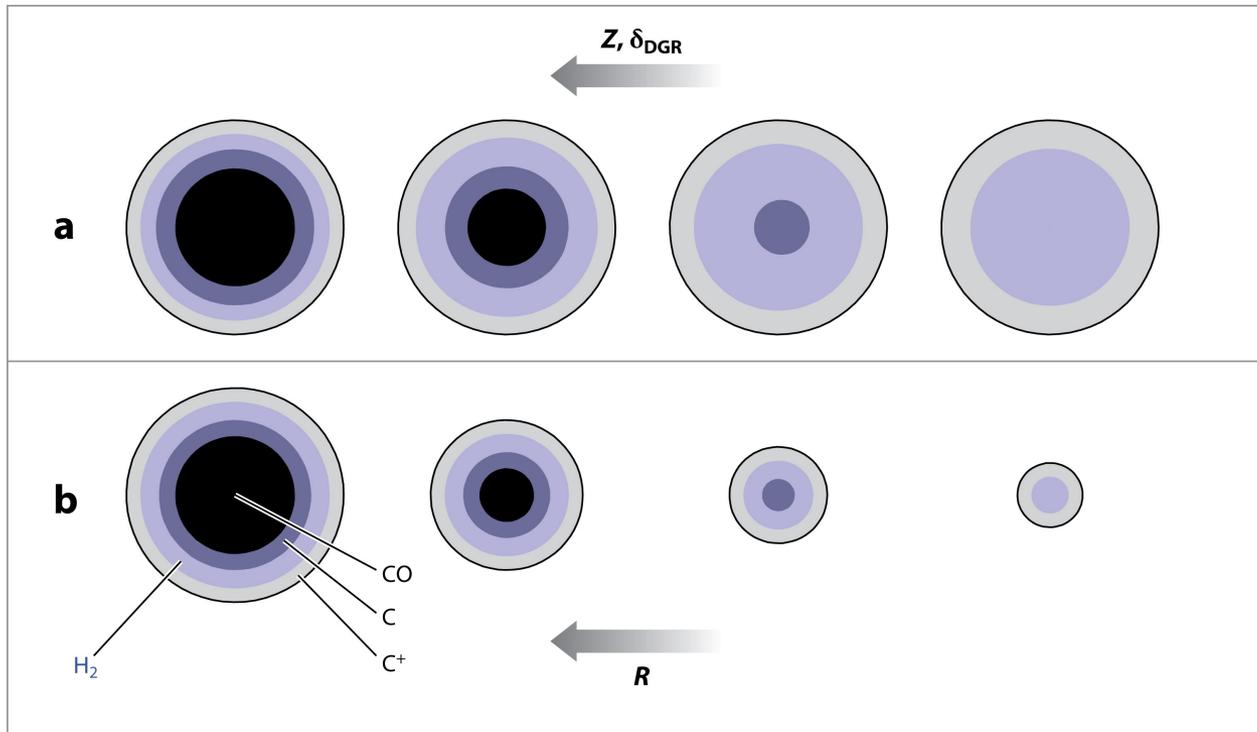
Essentially every single one of these measurements relies on the use of CO to trace molecular gas. This does work at a basic level, but we know α_{CO} varies with metallicity, excitation, and opacity of the gas – which makes the interpretation of results ambiguous. We want to move as close to “precision α_{CO} ” as we can to make the most of these amazing new-generation data.



SFR/CO in star-forming galaxies (each point is a galaxy). The CO relative to star formation drops at low metallicity – a trend that appears in most analyses of SFR in galaxies. How much is CO-to-H₂ and how much is physics?

CII-to-CO as a key to this problem

The CII line intensity is a fundamental observable that has direct, crucial bearing on half of this problem and is only accessible in the IR, and only from SOFIA right now. CII is the dominant, observable phase of C mixed with the “CO dark” phase of the molecular gas. It is a crucial complement to (and not replaced by) multi-line, multispecies molecular modeling.

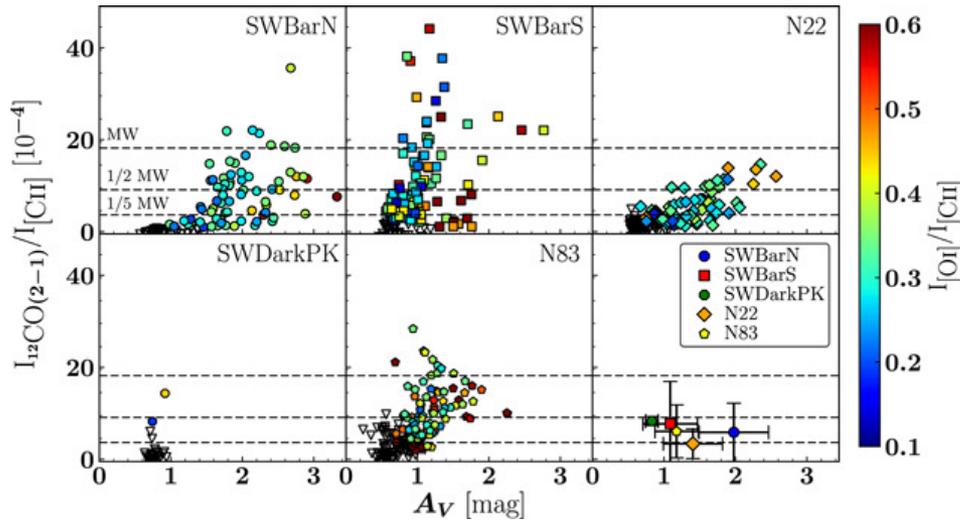


Toy molecular cloud at changing D/G or z . See how H_2 mixed with CII becomes dominant over H_2 mixed with CO as the metallicity and dust content decrease.

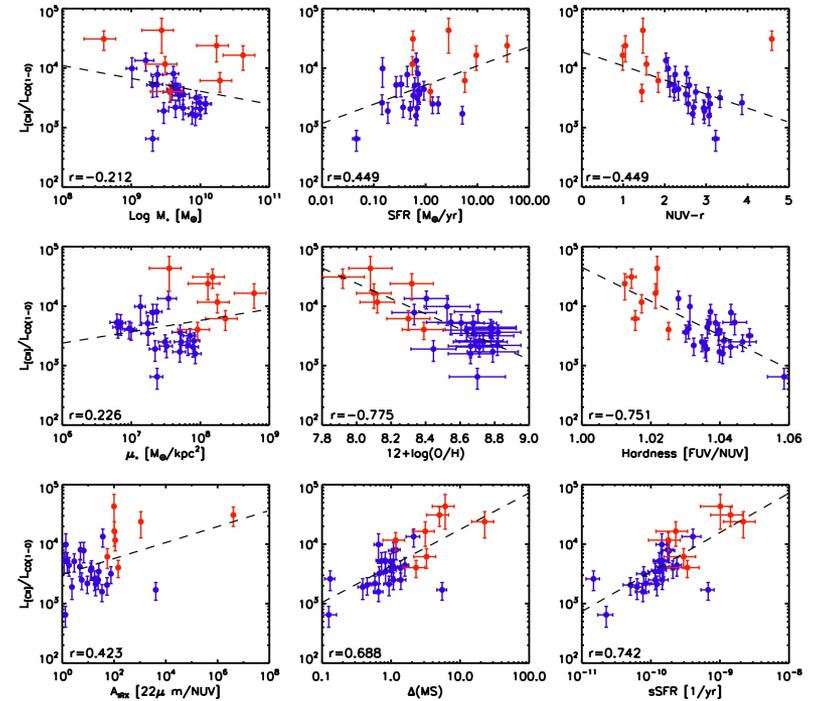
CII-to-CO as a key to this problem



*Observations that combine CII, CO, and (ideally) the information needed to estimate the CII emissivity of the gas and contribution of potential contaminants offer a power way to probe the CO-dark gas reservoir. This is one of our best ways (along with dust) to calibrate CO or trace molecular gas as a function of metallicity – which is critically important! **SOFIA is our only access to this critically important observable now or for the foreseeable future.***



Jameson, Bolatto, Wolfire et al. 2018 – CII + CO maps of SMC clouds used to solve for XCO within clouds in the SMC. Yields value, extinction dependence, one of the best low-metallicity determinations of the conversion factor.



Accurso et al. (2017) - galaxy-integrated CII-to-CO scaling relations (combined with DGS) to estimate galaxy-integrated XCO.

Outline

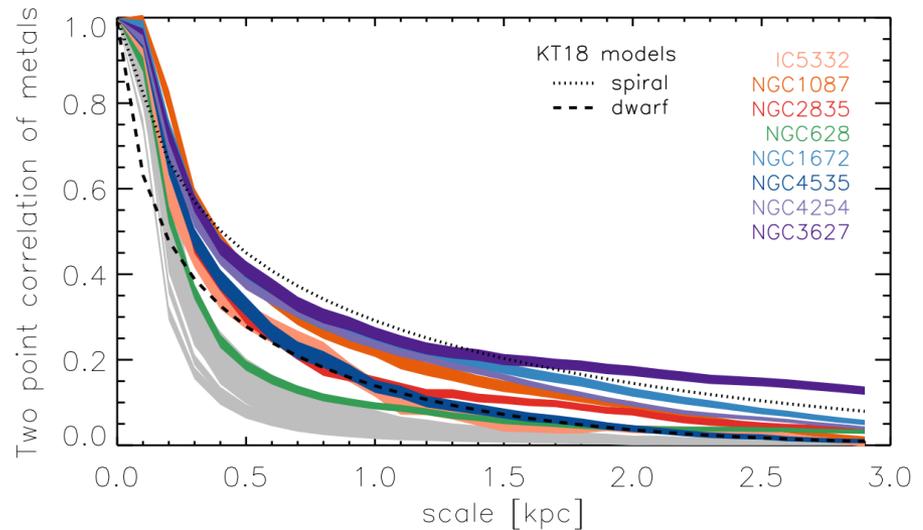
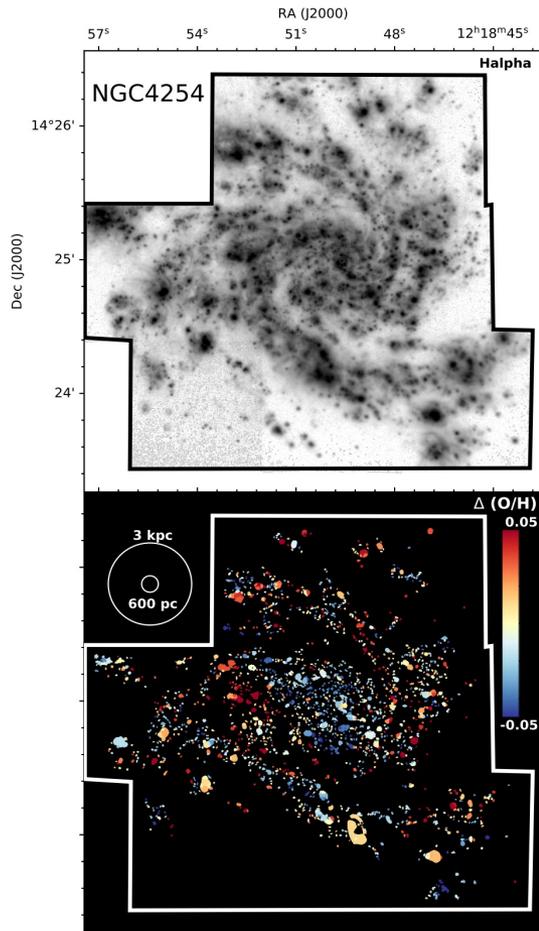
We are in an exciting time to study star formation in local galaxies, with major new surveys from ALMA, Hubble, the VLT, AstroSat, and soon JWST. The infrared accessed by SOFIA or similar past and future observatories contains key diagnostics to make the most of these data!

- **Cloud-scale CO and star formation**
- **Dust and metals in galaxies**
 - *Many (most?) “metallicity” effects in galaxies are “dust” effects*
 - *The dust to metals ratio is strongly environment dependent*
 - **We need access to the IR peak to push this field forward**
- **The elusive, but important, cold neutral medium**

Mapping of metallicity in galaxies is a booming industry



The last decade has seen many new optical IFU maps (from CALIFA, MaNGA, SAMI, and PHANG—MUSE) that yield resolved tracers of metallicity across galaxies. Metallicity impacts the ISM, can act as a tracer of the history of the gas, and is a view of the buildup of galaxies. We are resolving metallicity across galaxies as never before.

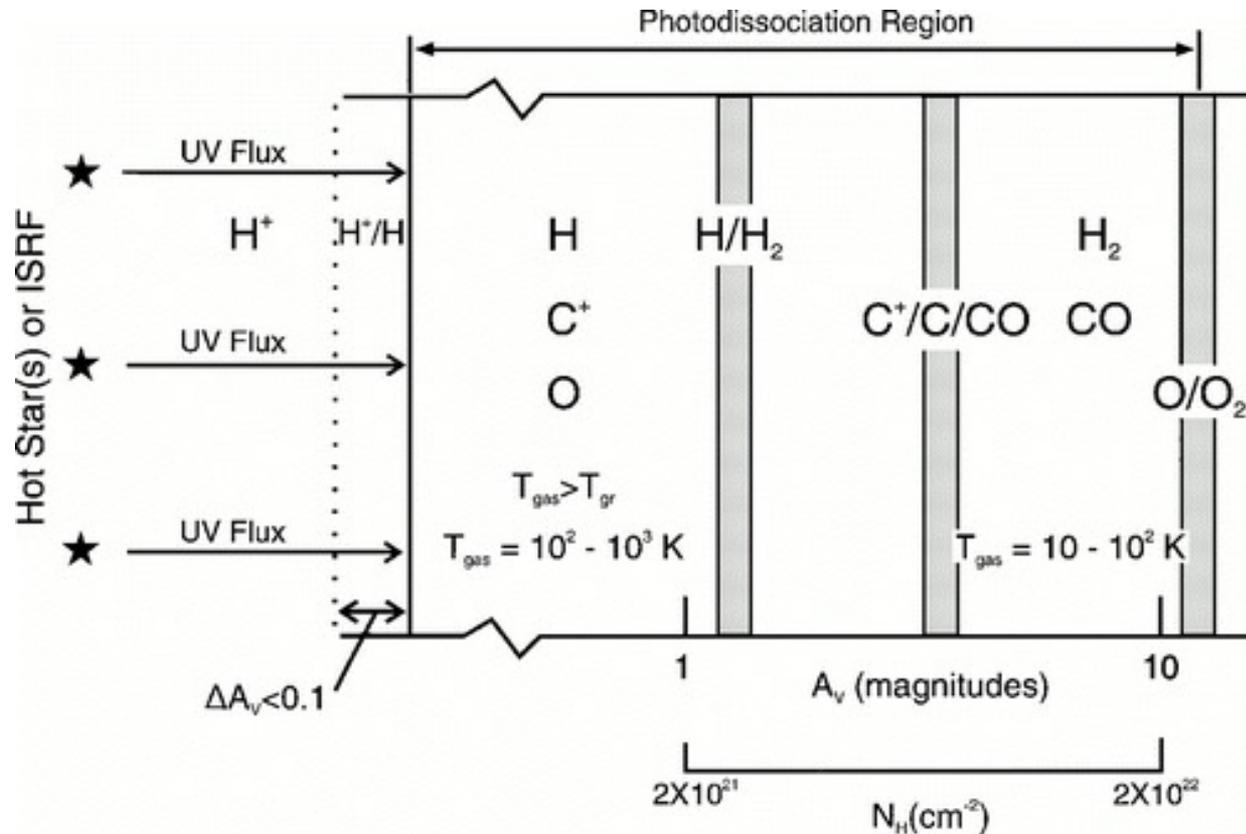


Kreckel et al. (2019, 2020) – MUSE IFU maps of galaxies yield resolved patterns of chemical abundance in galaxies. Here the highly resolved view allows detailed measurements of local coherence in the metallicity field. Large samples from CALIFA, SAMI, and MaNGA yield “big data” on enrichment patterns in galaxies.

Kreckel et al. (2019, 2020) and see Sanchez & Maiolini+Mannucci reviews

“Metallicity” effects are dust effects for a large swath of nearby galaxy science

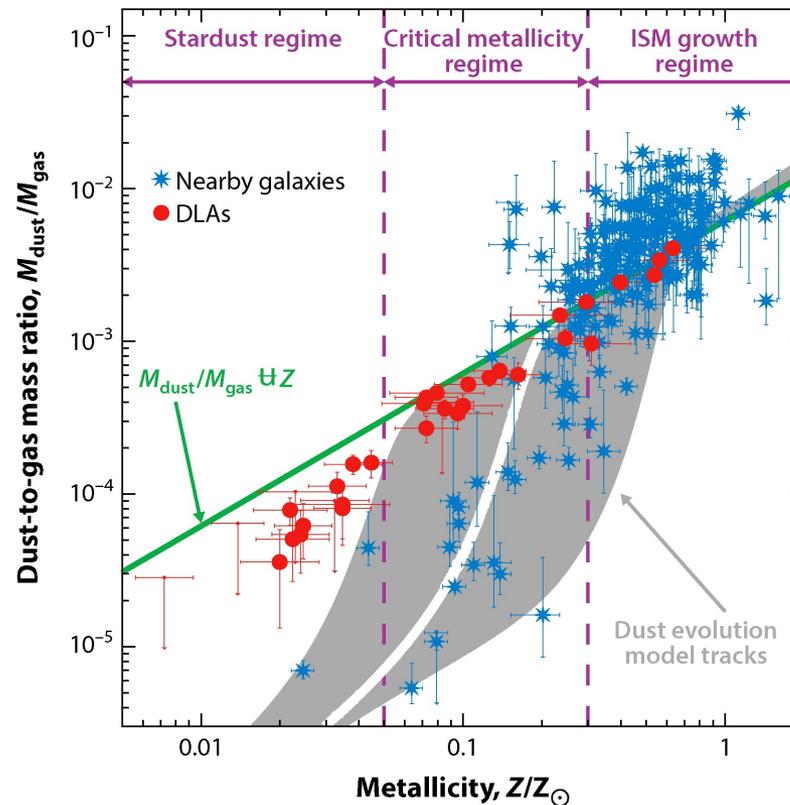
For star formation, “metallicity” affects the CO-to-H₂ conversion factor, H₂ abundance, radiation pressure into and a host of other topics related the structure of ISM in galaxies. But for many (not all) of these applications, “metallicity” means “the dust-to-gas ratio.”



Hollenbach and Tielens (1997) - PDR structure laid out as a function of dust shielding. Dust-to-gas ratio, not just metallicity, is a controlling parameter for the structure of PDRs (the structure is often even framed in terms of A_v from the surface of the cloud).

The dust-to-metals ratio varies (a lot! [and systematically!])

A major result from multiple Herschel programs (and HST absorption work) has been that the dust-to-metals ratio is not fixed (so that D/G is not simply a factor times metallicity), but varies with metallicity (or mass fraction) and phase of the ISM. This complicates how we think about “metallicity” effects on star formation and the ISM.

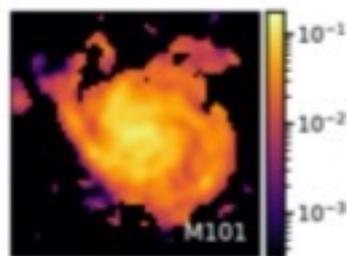


Galliano et al. (2018) summarizing especially Remy Ruyer et al. (2014, 2015) and Del Cia (2016) showing the dust-to-metals ratio to drop with metallicity for whole galaxies (Fixed is the green line). But data are sparse.

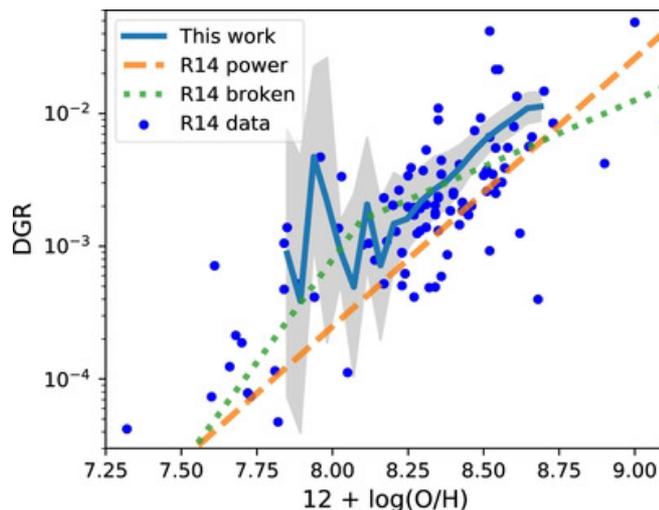
Dust-to-gas ratio and metallicity



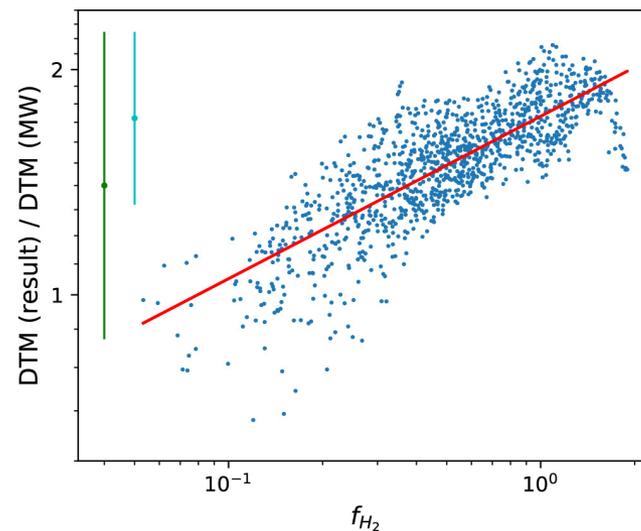
A next major frontier here is to resolve the dust-to-metals ratio across galaxies. This requires maps of metallicity, HI (atomic gas), CO, and dust (plus ideally a lot of other things). This offers the prospect to constrain the conversion factor, resolve the impact of density or ISM phase on the dust-to-metals ratio, and generally figure out how dust works in galaxies.



Dust map of M101 from far-IR SED modeling. M101 outstanding gas and metallicity data.



Dust to gas ratio vs. metallicity from resolved measurements in M101 (gray+blue lines) and integrated data.



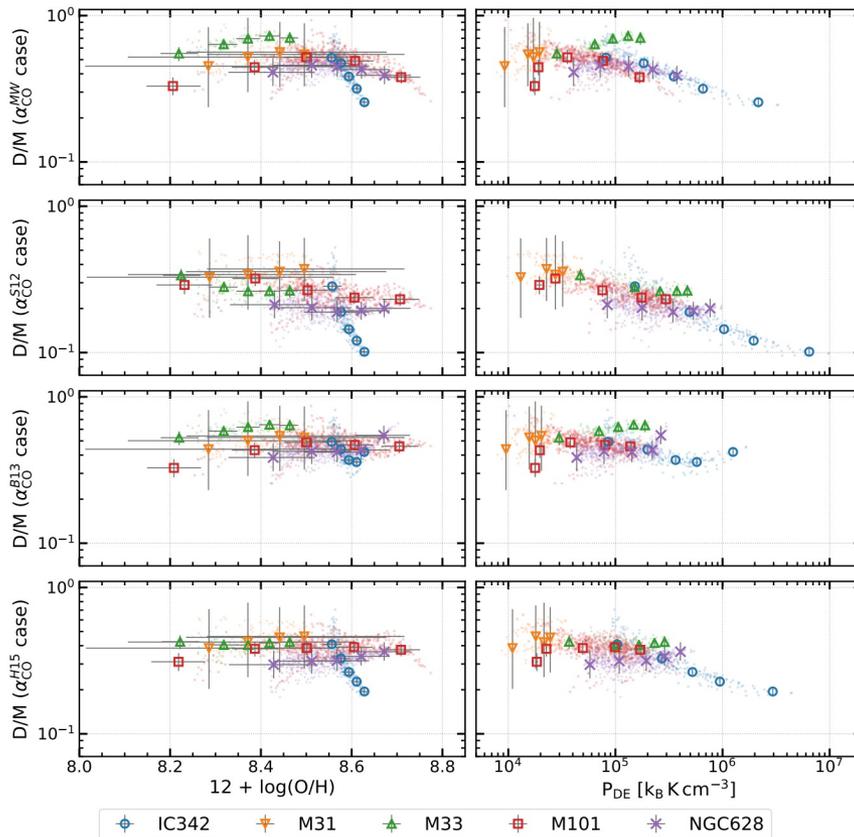
Dust-to-metals as a function of H₂/HI, accessible from resolved measurements spanning M101. Consistent with Milky Way measurements showing density-dependent depletions,

Dust-to-gas ratio and metallicity



A next major frontier here is to resolve the dust-to-metals ratio across galaxies. This requires maps of HI (atomic gas), CO, and dust (plus ideally a lot of other things). This offers the prospect to constrain the conversion factor, resolve the impact of density or ISM phase on the dust-to-metals ratio, and generally figure out how dust works in galaxies.

Dust-to-metals here for different conversion factor cases



Example looking for a workable joint dust-to-metals and CO-to-H2 conversion factor solution.



Preferred case based on this analysis

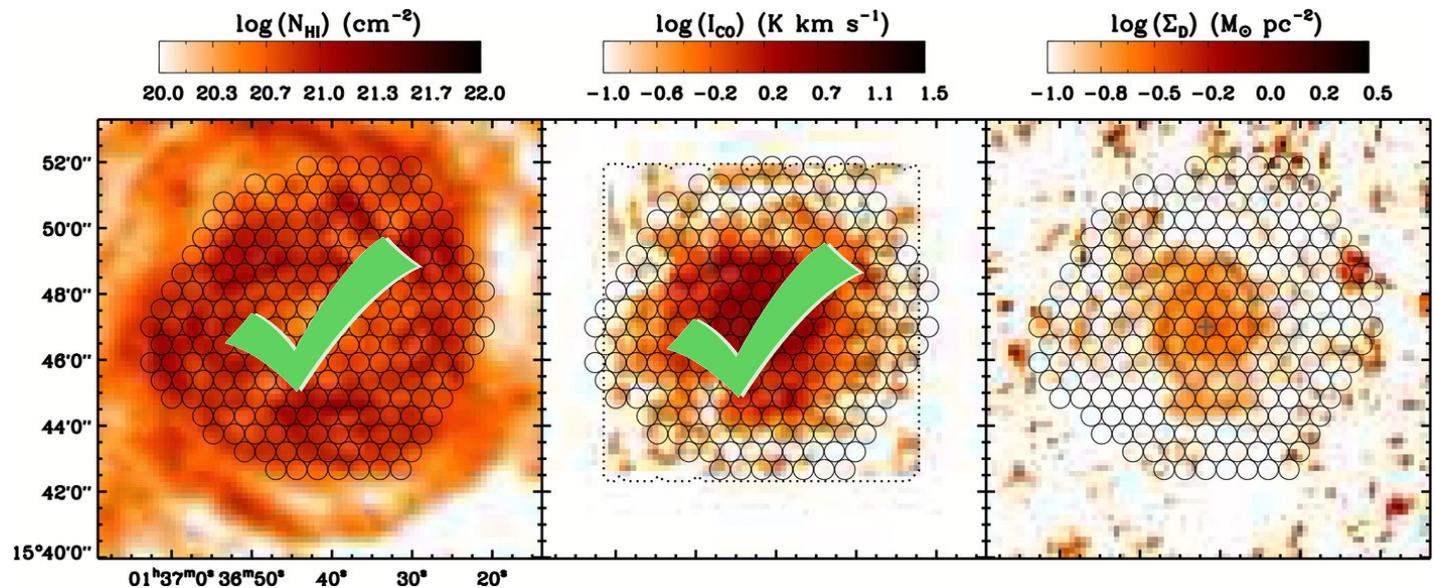
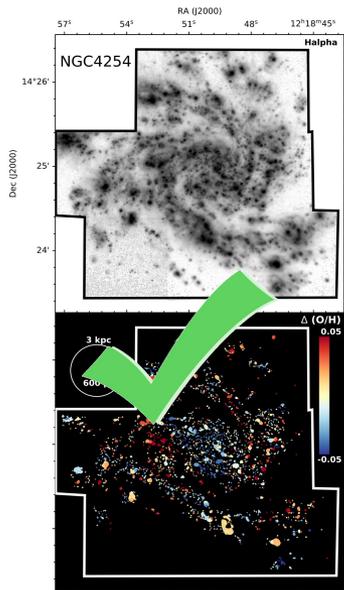
Metallicity and Pressure – we have basic expectations for how D/M would behave vs. these quantities.

I-Da Chiang, Karin Sandstrom, Jeremy Chasten et al. (2018, 2021, and in prep.)

To move forward we need to be able to map dust mass



In almost a complete reversal from a decade ago, we are not really limited by metallicity maps of galaxies, CO, or HI data, but are instead limited by the inability to make new dust maps. IR emission remains the most powerful way to map all of the dust, but to do this we need a temperature, which means observing around the peak of the dust SED (then this can complement bolometer surveys at mm- or submm- wavelengths). This capability appears restricted to SOFIA for the foreseeable future.



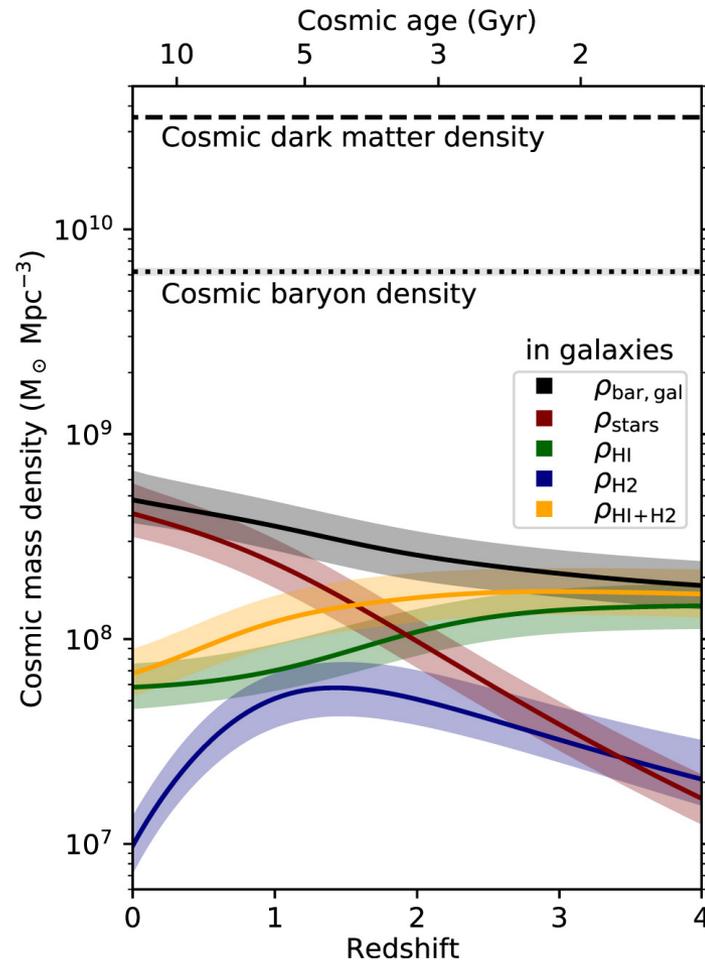
Outline

We are in an exciting time to study star formation in local galaxies, with major new surveys from ALMA, Hubble, the VLT, AstroSat, and soon JWST. The infrared accessed by SOFIA or similar past and future observatories contains key diagnostics to make the most of these data!

- **Cloud-scale CO and star formation**
- **Dust and metals in galaxies**
- **The elusive, but important, cold neutral medium**
 - *HI remains the most massive phase of the ISM in disk galaxies*
 - *The CNM is cold and dense and may outmass molecular gas*
 - **The CII-to-HI ratio can help constrain this quantity**

Most gas in galaxies is HI, making HI a key to star formation

While we have made amazing progress in studying the molecular ISM over the last decade, progress on the atomic ISM has been slower (totally understandably). But atomic gas makes up most of the gas in galaxies at essentially all redshifts. We need to understand the physics of the atomic medium, how it forms cold, molecular gas, and how it experiences feedback! (Orr talk!)



Global densities of various mass components vs. redshift. See that **green** line higher than the **blue** everywhere?

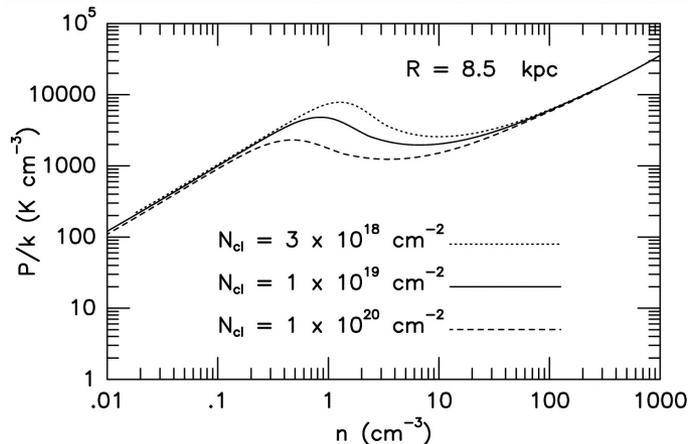
The cold neutral medium remains elusive but really important

The HI shows a wide range of densities and temperature and the H2/HI ratio shows a huge range in galaxies. We know that about a 25-35% of the HI is cold and dense near us in the Milky Way, but the detailed distribution and variations in the location and properties of the cold neutral medium in other galaxies remain substantially unknown.

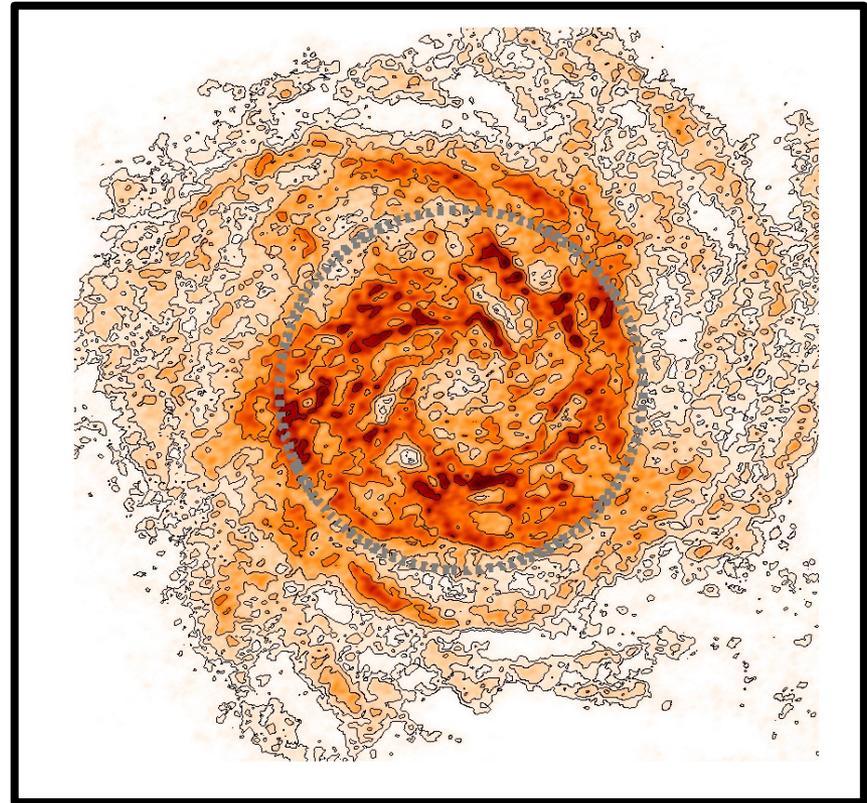
TABLE 3
HI MASS FRACTIONS

Phase	Absorption	Total
CNM	0.56 ± 0.10	0.28
UNM	0.41 ± 0.10	0.20
WNM	0.03 ± 0.05	0.52

Murray et 21-SPONGE (2018) – breakdown of local Milky Way atomic gas by phase.



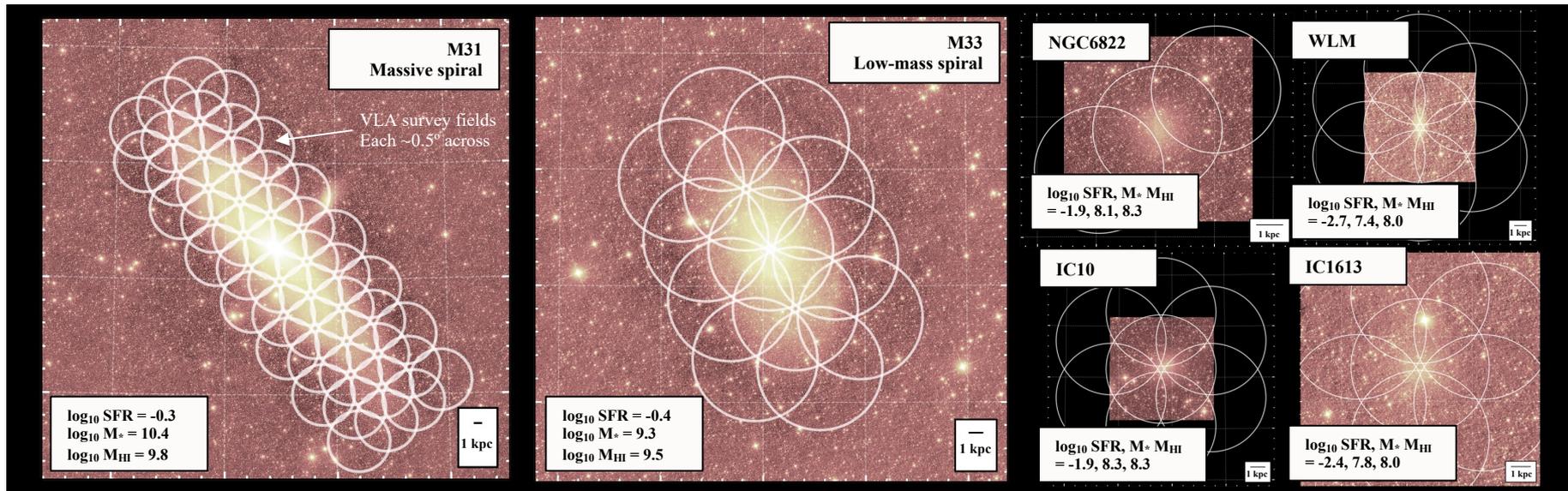
Wolfire et al. (2003) – illustrating expected multiphase structure of the HI at fixed pressure



Water et THINGS (2008) - 21-cm view of M74

The Local Group L Band Survey aims to resolve the physics of atomic gas

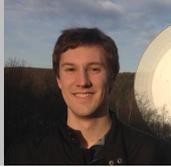
We (including Jeremy, Liz, Remy) are trying to address this with new, sensitive 21-cm, OH, and 1-2 GHz continuum imaging targeting the closest galaxies using an “extra large” VLA program. Aims include extending “Milky Way-style” absorption, structure, and kinematic analysis to the northern Local Group targets – M31, M33, NGC6822, IC 10, IC 1613, WLM.



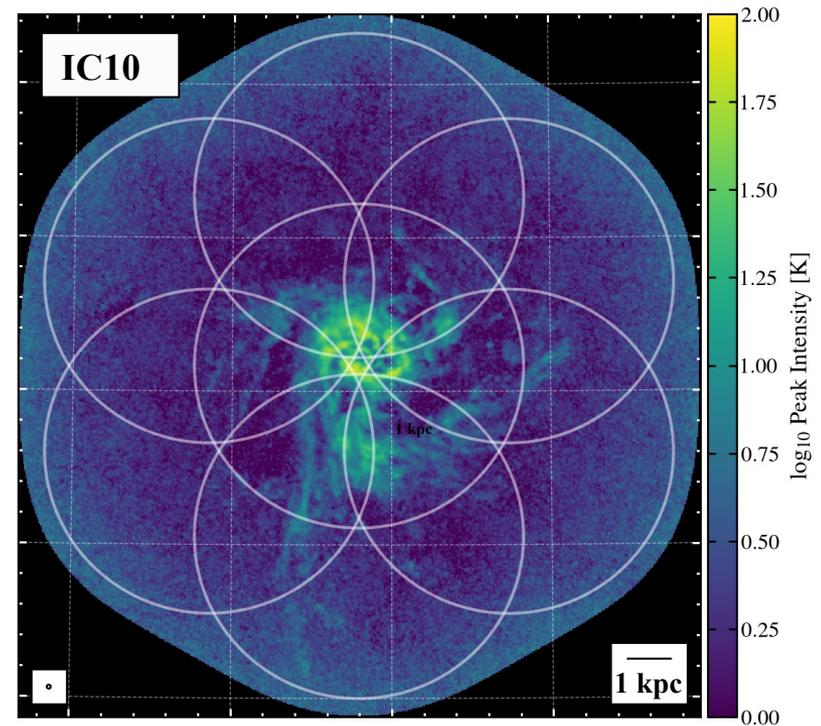
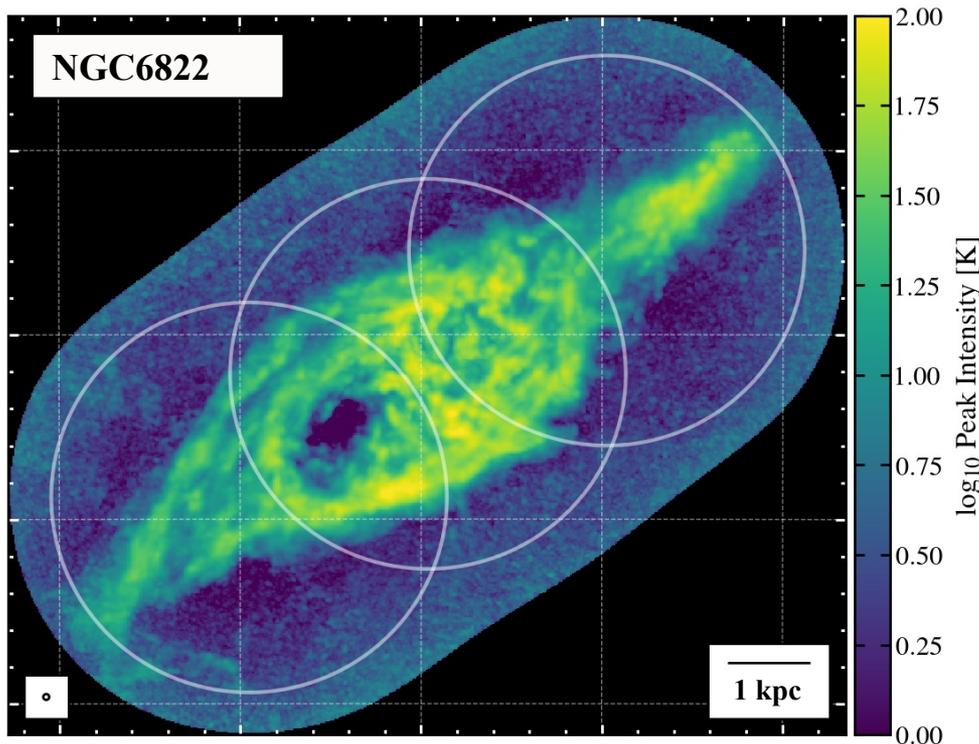
www.lglbs.org

Leads: Chomiuk, Dalcanton, Leroy, Rosolowsky, Stanimirovic, Walter
*Doing the lion's share of awesome work: **Eric Koch, Sumit Sarbadhicary***

The Local Group L Band Survey aims to resolve the physics of atomic gas



The 1-2 GHz continuum reveals star forming regions and supernova remnants at < 10 pc resolution. The HI reaches resolution 20-40 pc and < 1 kms spectral resolution. The survey will give an unparalleled look at the physical state and structure of HI and a deep inventory of the past and present star formation in each target.



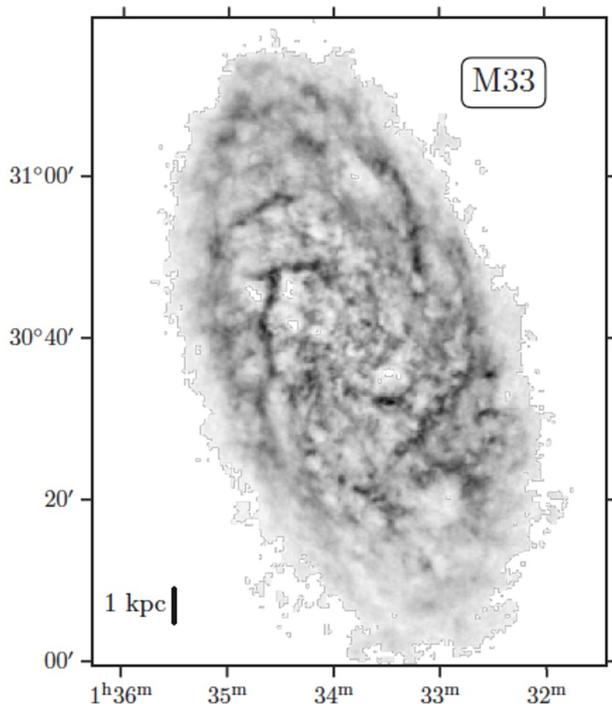
21-cm in two of our targets after the first compact configs, linear resolution will get about 3-4x better

Eric Koch et al (in preparation – expect 2022)

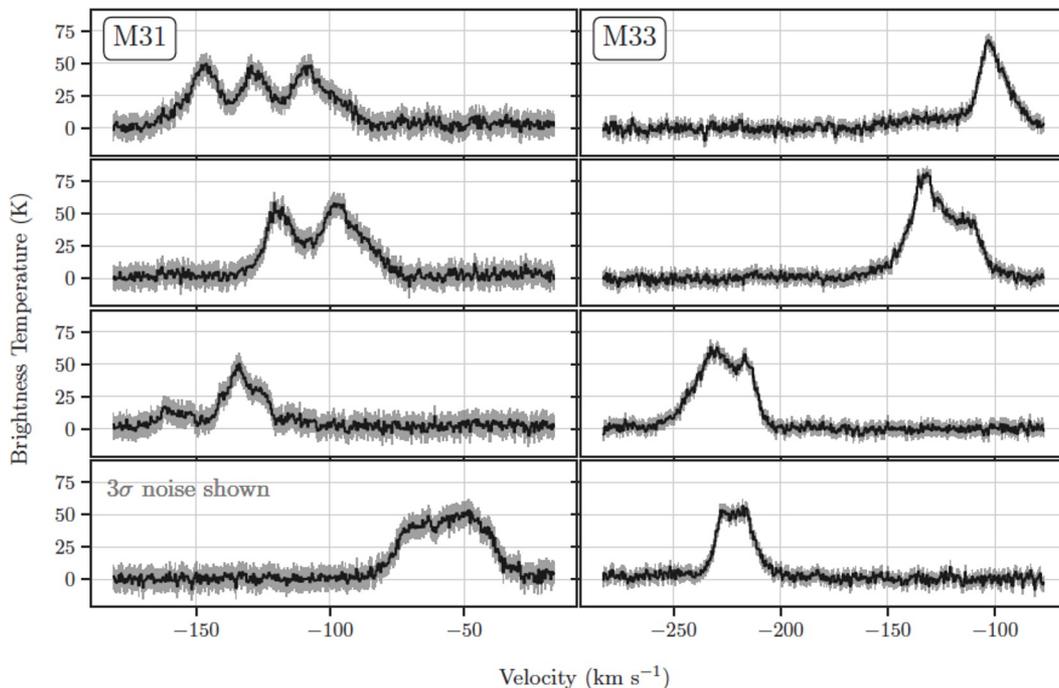
The Local Group L Band Survey aims to resolve the physics of atomic gas



The 1-2 GHz continuum reveals star forming regions and supernova remnants at < 10 pc resolution. The HI reaches resolution < 40 pc and < 1 kms spectral resolution. The survey will give an unparalleled look at the physical state and structure of HI and a deep inventory of the past and present star formation in each target.



Spatial resolution

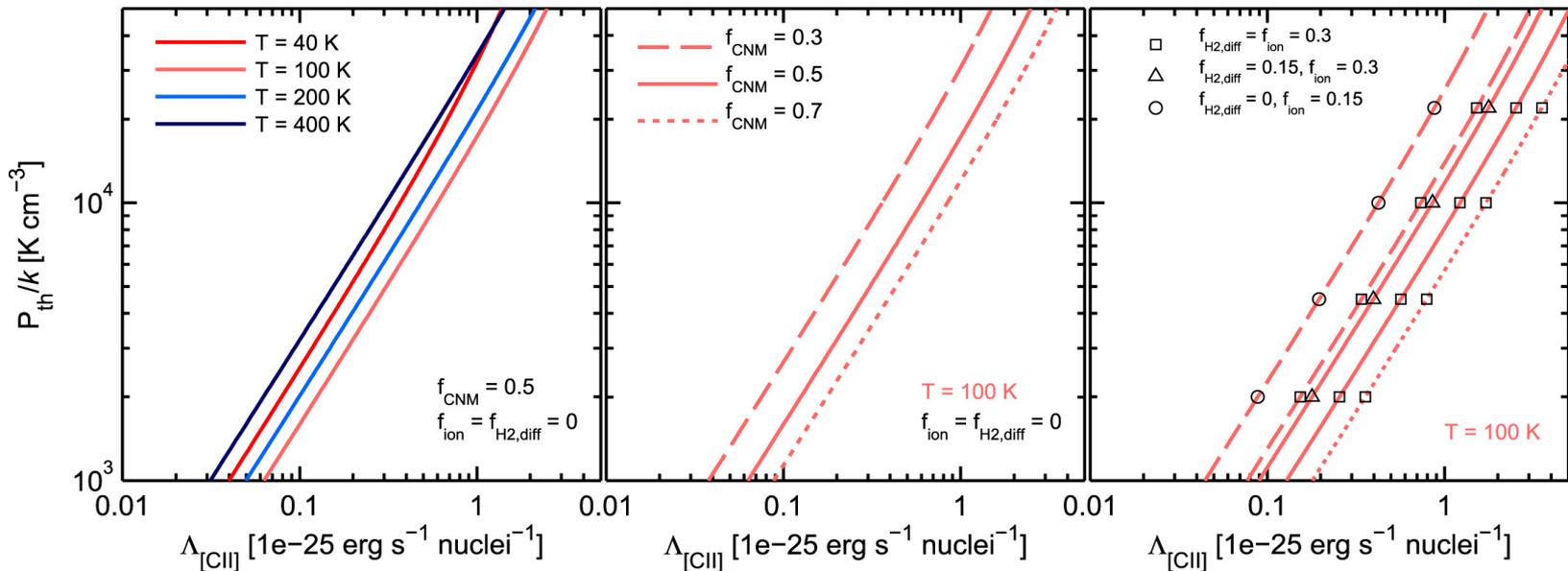


Spectral resolution < 1 km/s is a major gain

The CII-to-HI ratio



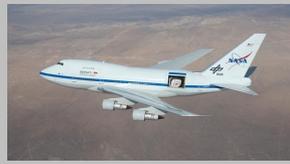
Absorption and very high resolution are hard and substantially confined to close, big-on-the-sky galaxies. We need some ability to trace the phase breakdown of HI across the whole galaxy population. One of the best tools we have here is the CII-to-HI ratio where gas is mostly HI. The emissivity of CII mixed with CNM is much higher than the emissivity of CII mixed with WNM – see Tielens talk.



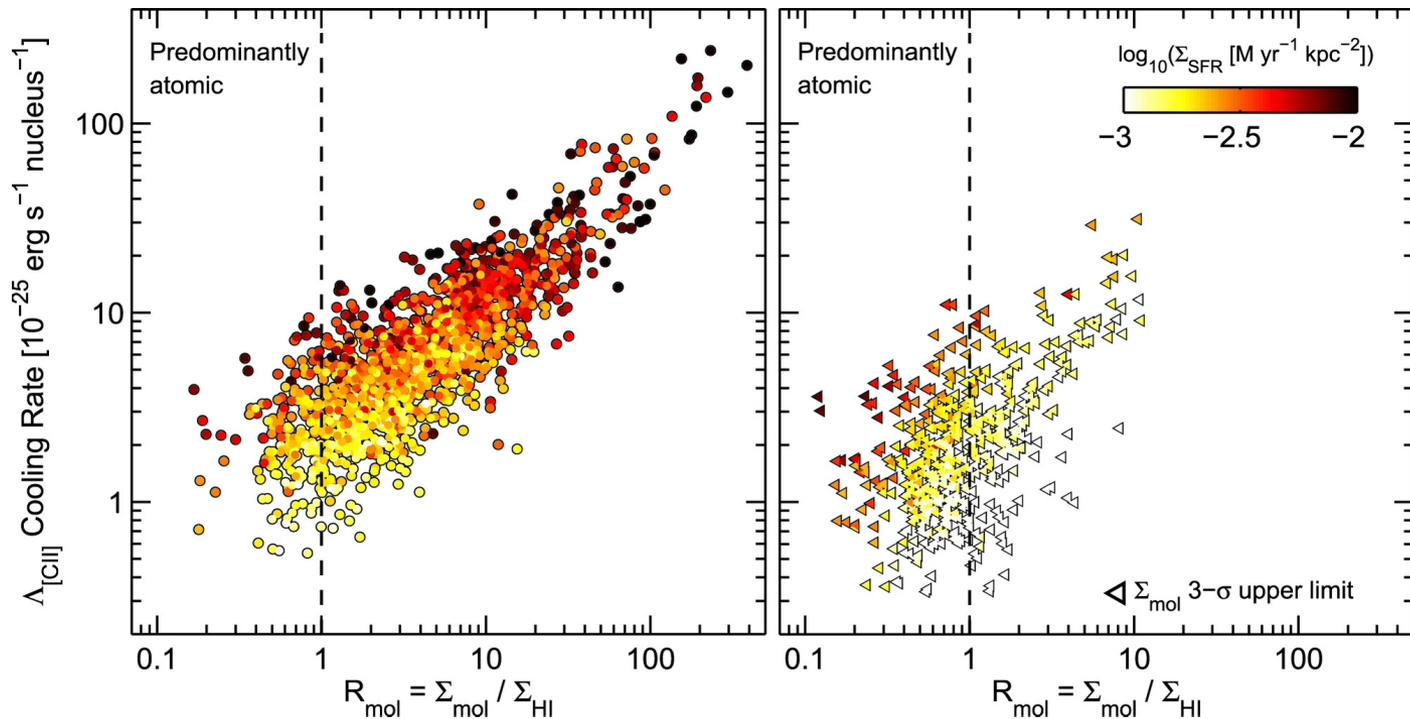
CII emissivity (x-axis) vs. pressure changing CNM temperature (left), CNM mass fraction (middle), and H₂ contribution (right). CII-to-HI contributes a key piece of information and is very widely observable.

From Herrera Camus et al. (2017) and see Tarantino et al. (2021) and (I think?) Tarantino talk!

The CII-to-HI ratio



This makes the CII-to-HI ratio in regions where HI dominates the mass a key observable. Interpretation is not always trivial but this is one of our only ways to get at a combination of CNM abundance and thermal pressure in the atomic gas of distant galaxies. Currently there have been some inspiring FIFI-LS maps, but a lot of the work still rests on Herschel coverage. This is an area where we still have a HUGE amount to learn.



From Herrera Camus et al. (2017) and see Tarantino et al. (2021) and (I think?) Tarantino talk!

Conclusions

We are in an exciting time to study star formation in local galaxies, with major new surveys from ALMA, Hubble, the VLT, AstroSat, and soon JWST. The infrared accessed by SOFIA or similar past and future observatories contains key diagnostics to make the most of these data!

▪ **Cloud-scale CO and star formation**

- *Molecular gas is closely coupled to host galaxy*
- *Gas and star formation at high resolution*
- *Precision α_{CO} remains a major obstacle*
- **The CII-to-CO ratio is a key but often missing quantity**

▪ **Dust and metals in galaxies**

- *Many (most?) “metallicity” effects in galaxies are “dust” effects*
- *The dust to metals ratio is strongly environment dependent*
- **We need access to the IR peak to push this field forward**

▪ **The elusive, but important, cold neutral medium**

- *HI remains the most massive phase of the ISM in disk galaxies*
- *The CNM is cold and dense and may outmass molecular gas*
- **The CII-to-HI ratio can help constrain this quantity**

PRIMA

THE PROBE FAR-INFRARED MISSION FOR ASTROPHYSICS

A community-driven general-observer-accessible far-IR-optimized observatory for 2030.

- JPL implementation lead, GSFC key contributions.
- International partnerships in development.
- A cryogenic telescope with a target aperture of 2-3 meters.

Science and hardware formulation underway – inputs welcome.

Potential instrumentation capabilities:

Imaging / Polarimetry: ~10 to 300 μm

- Mapping speed: $\sim 10 \left(\frac{\text{deg}^2}{\text{hour}}\right) \left(\frac{F}{1 \text{ mJy}}\right)^2 \left(\frac{1}{\text{SNR}}\right)^2$ (Extragalactic confusion limited for $\lambda > 70 \mu\text{m}$).

Base low-resolution spectroscopy w/ wideband gratings: ~25 to 330 μm .

- Resolving power 60 to 250.
- Unprecedented line surface brightness sensitivity (bottom center figure).
- Spectral-line sensitivity when pointed: 5σ , 1 hour of 5×10^{-20} to $2 \times 10^{-19} \text{ W/m}^2$ (top right).
- Full instantaneous coverage of at least one \sim octave bandwidth spectrometer band at a time, multiple bands simultaneously on source is a goal.
- Mapping speed: 10^{-1} to 10^{-4} sq degrees per hour to $3 \times 10^{-19} \text{ W/m}^2$ (bottom right figure).

Medium-resolution capability using addition to low-resolution gratings:

same 25-330 μm band.

- Available resolving power: up to 5000-8000.
- Sensitivity range: 5σ , 1 hour of 10^{-19} to $2 \times 10^{-18} \text{ W/m}^2$ per spectral resolution element (or unresolved line).
- Mapping speed in medium-res mode: modest, to be determined, depends on R desired.

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