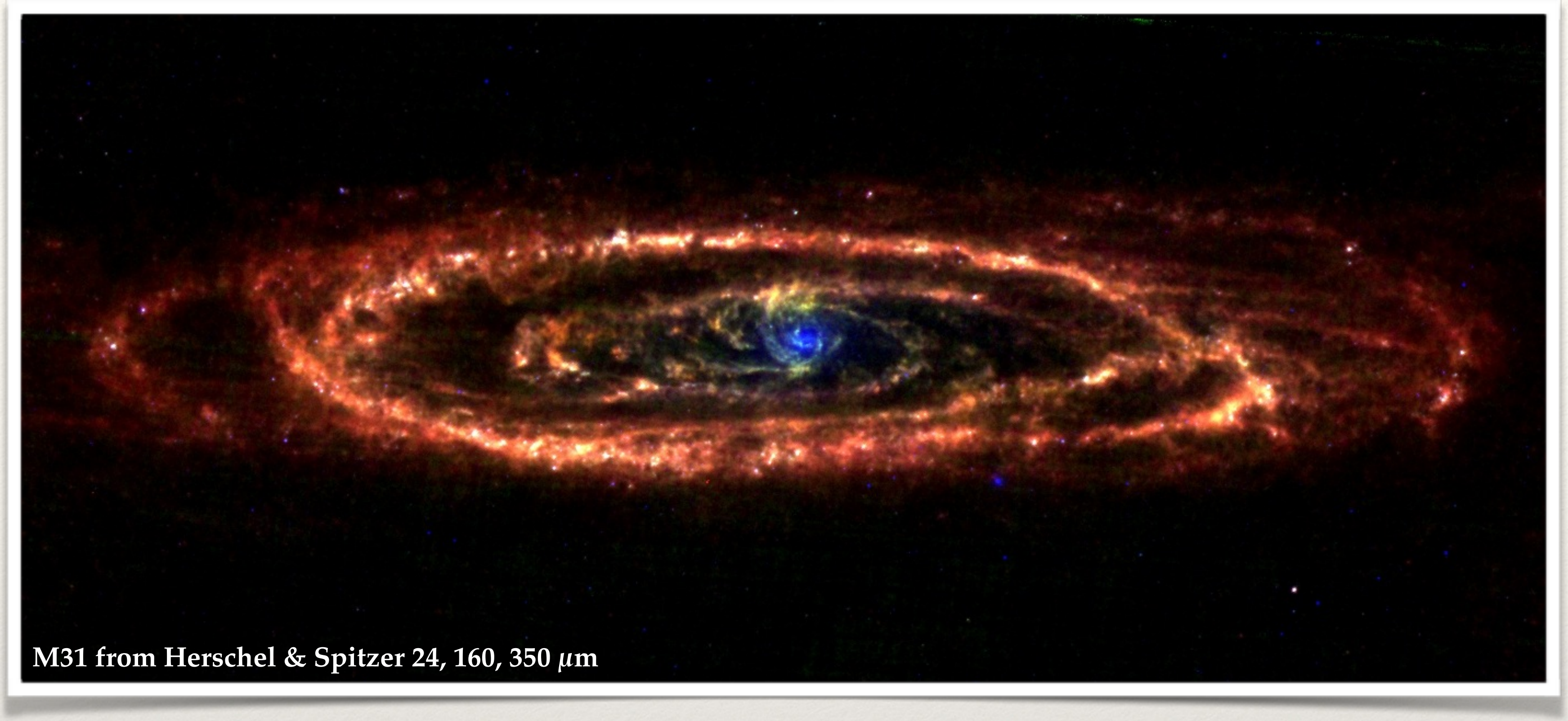


Far-IR Community Workshop - May 12-13, 2014

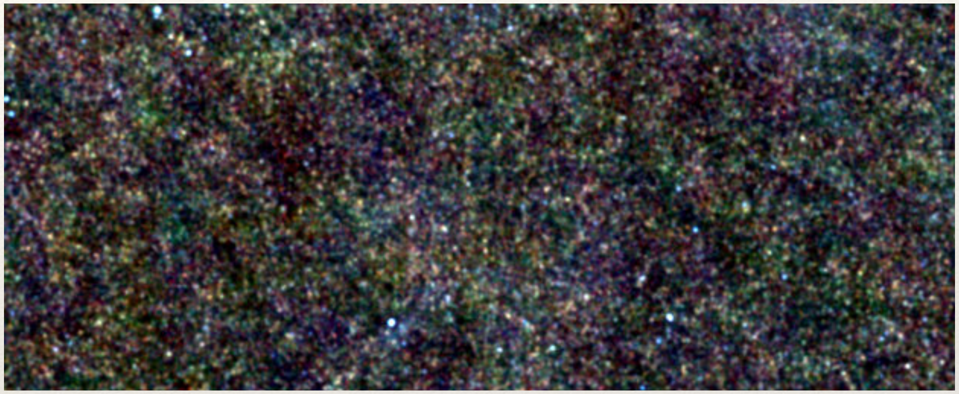
Studying Nearby Galaxies with Future IR Space Telescopes

Karin Sandstrom
University of Arizona

What can we learn from nearby galaxies?

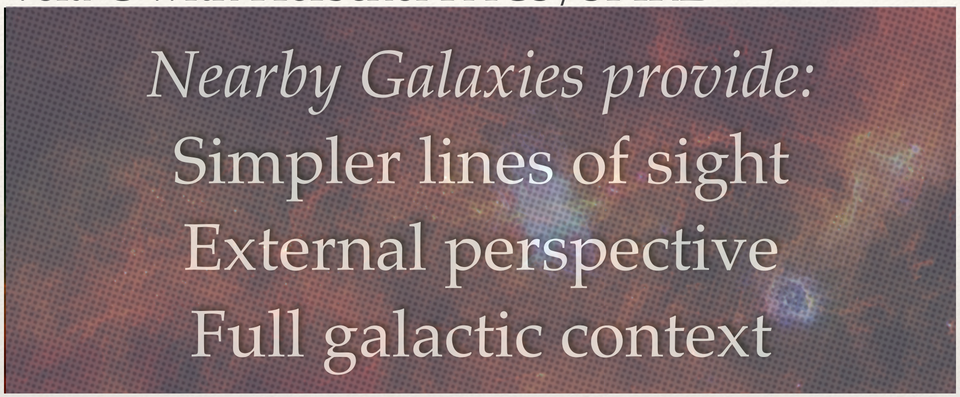
Vela C with Herschel PACS/SPIRE

Lockman Hole with Herschel SPIRE

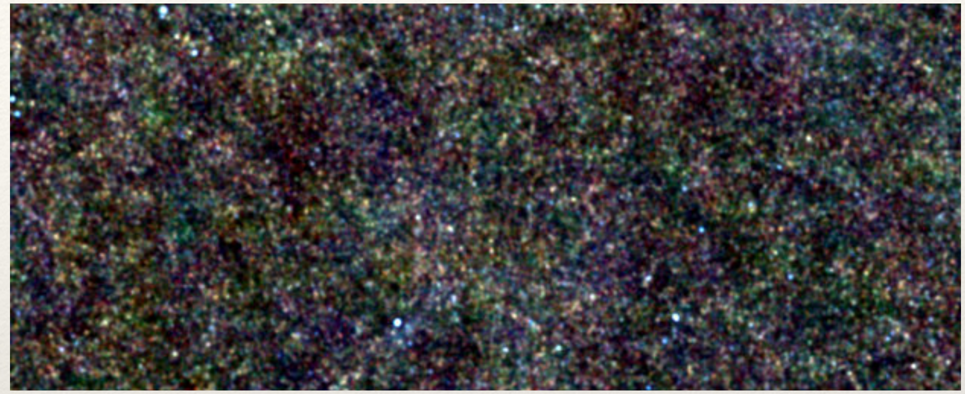


Nearby galaxies bridge what we can learn in the Milky Way with what we learn from galaxy evolution

What can we learn from nearby galaxies?



Vela C with Herschel PACS/SPIRE

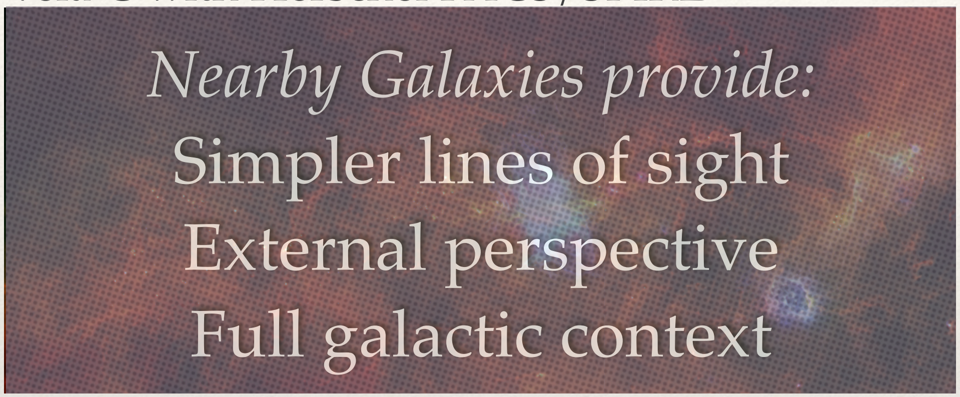

Lockman Hole with Herschel SPIRE

Nearby galaxies bridge what we can learn in the Milky Way
with what we learn from galaxy evolution

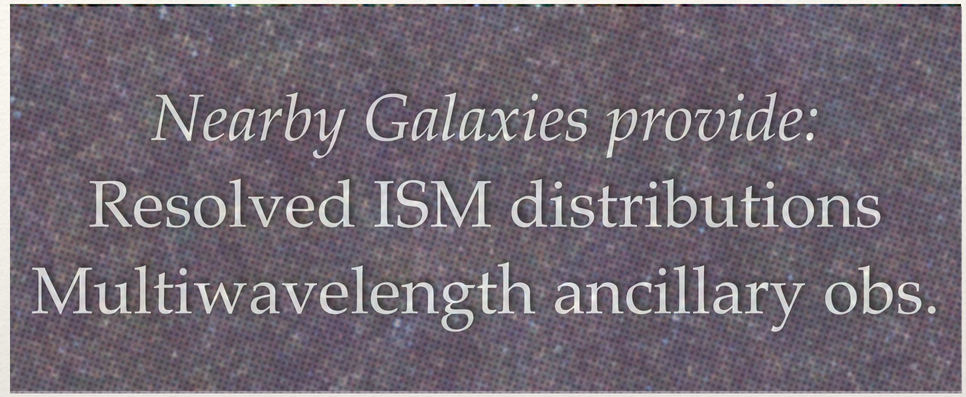

M31 from Herschel & Spitzer 24, 160, 350 μm

What can we learn from nearby galaxies?

Vela C with Herschel PACS/SPIRE



Lockman Hole with Herschel SPIRE



Nearby galaxies bridge what we can learn in the Milky Way with what we learn from galaxy evolution

What can we learn from nearby galaxies?

- The Life Cycle of Dust
- Calibration of Metallicity Scales
- Resolving SF Feedback Processes
- ISM Phase Balance

A biased & incomplete list…

The Life Cycle of Dust

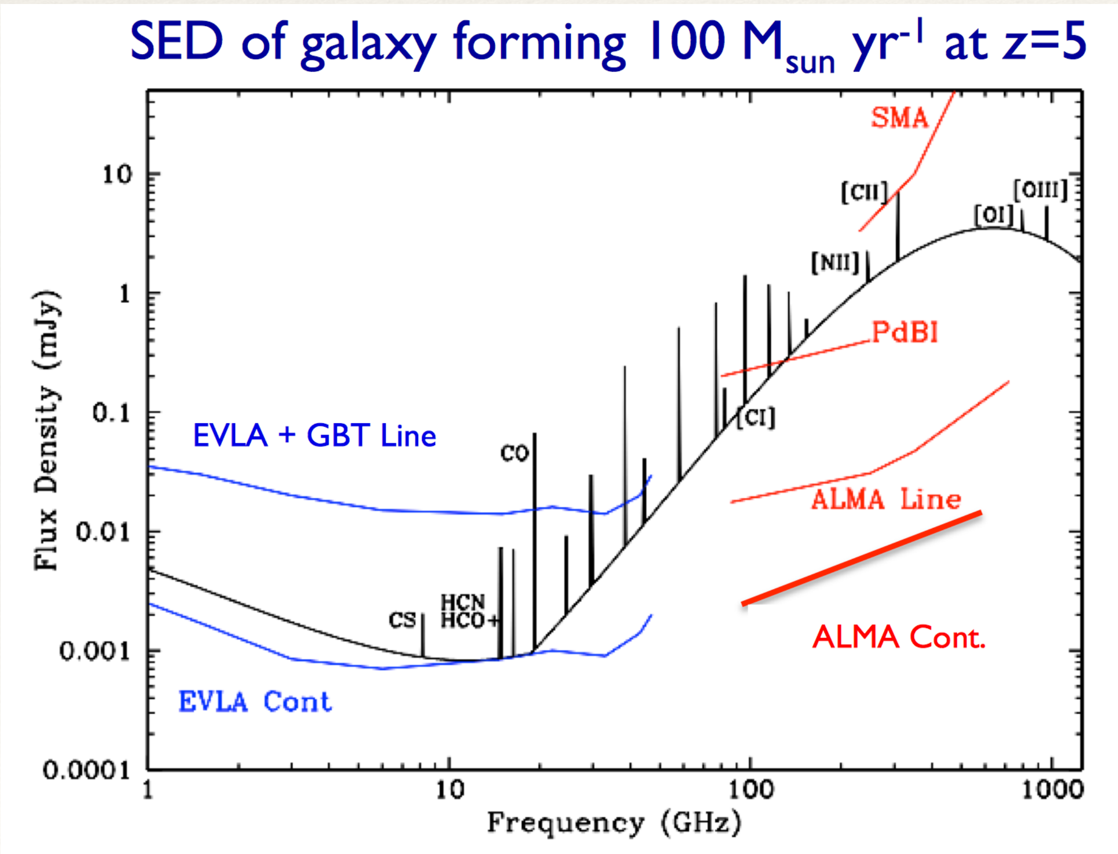
Dust is a crucial part of the ISM but we are just beginning to understand its life-cycle.

- Dust-to-gas Ratio
- Grain Size Distribution
- Grain Composition
- Grain Charge

How are these key parameters affected by galactic environment?

The Life Cycle of Dust

Dust emission in redshifted sub-mm range is a sensitive tracer of high-z galaxies with ALMA.



plot from A. Leroy

Sub-mm dust continuum as an ISM tracer requires knowledge of:

dust-to-gas ratio

sub-mm dust emissivity

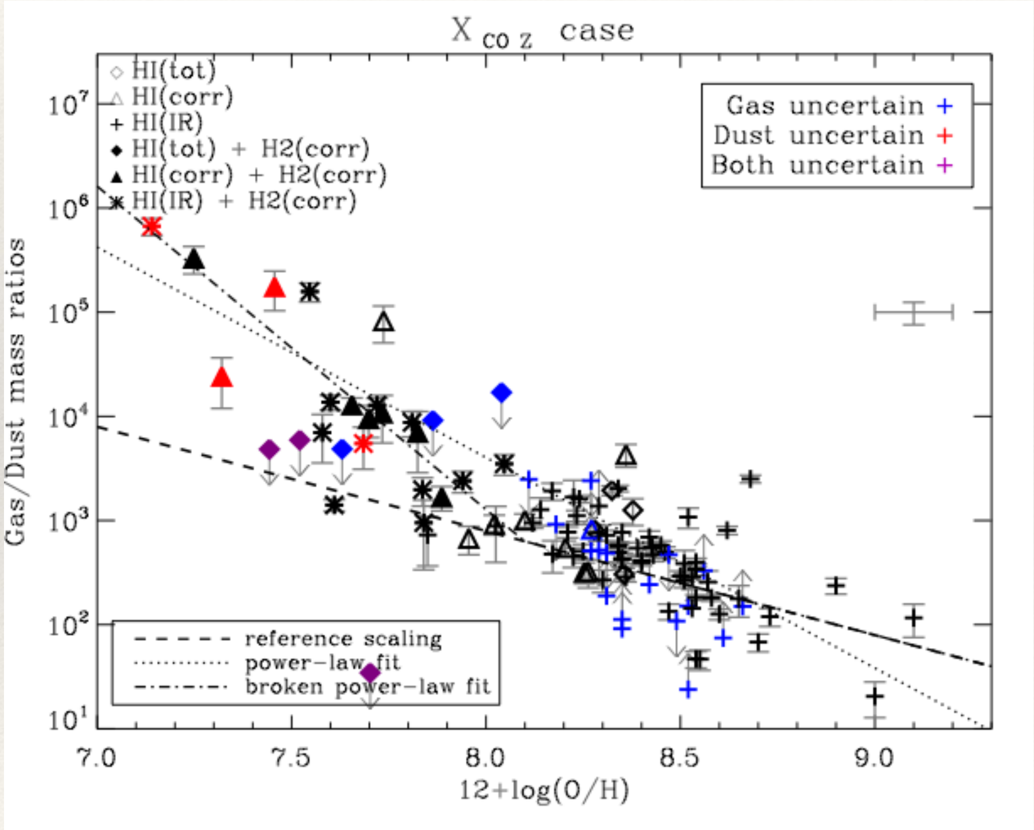
dust temperature

Studies of nearby galaxies needed to understand these key properties.

The Life Cycle of Dust

Galaxy-average dust-to-gas ratio is not a simple function of metallicity.

Remy-Ruyer et al. 2014 -
Dwarf Galaxies Survey with Herschel



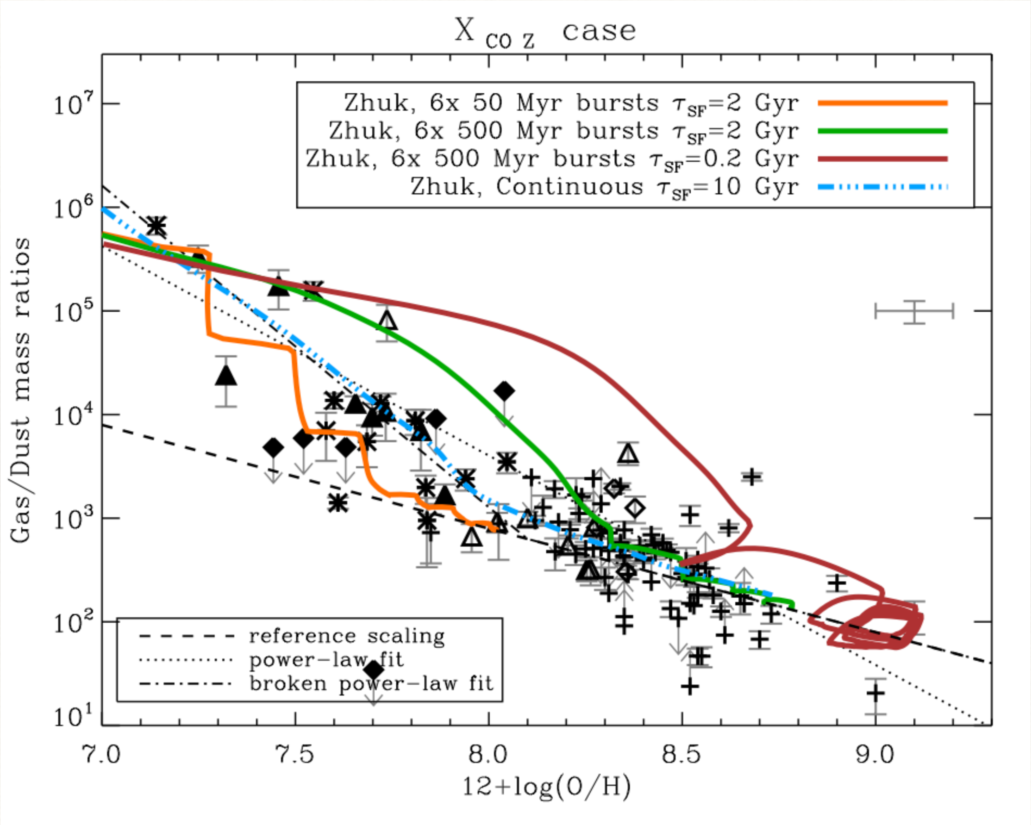
The Life Cycle of Dust

Galaxy-average dust-to-gas ratio is not a simple function of metallicity.

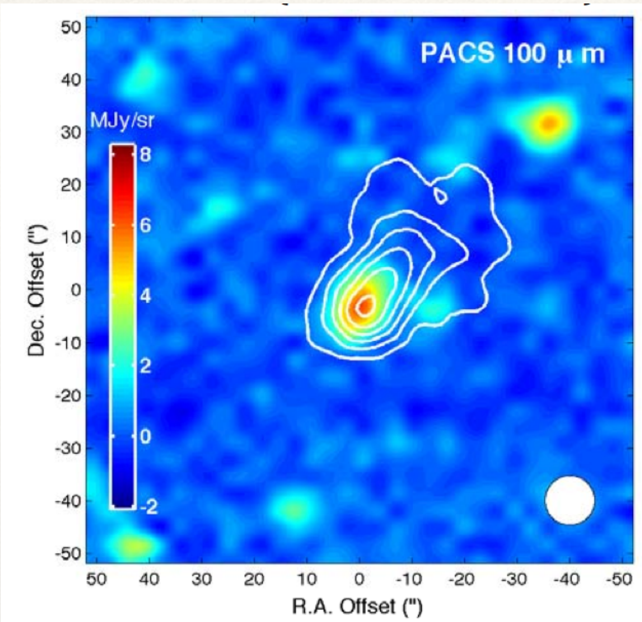
SF history & influence on dust life cycle seems to be key for setting DGR.

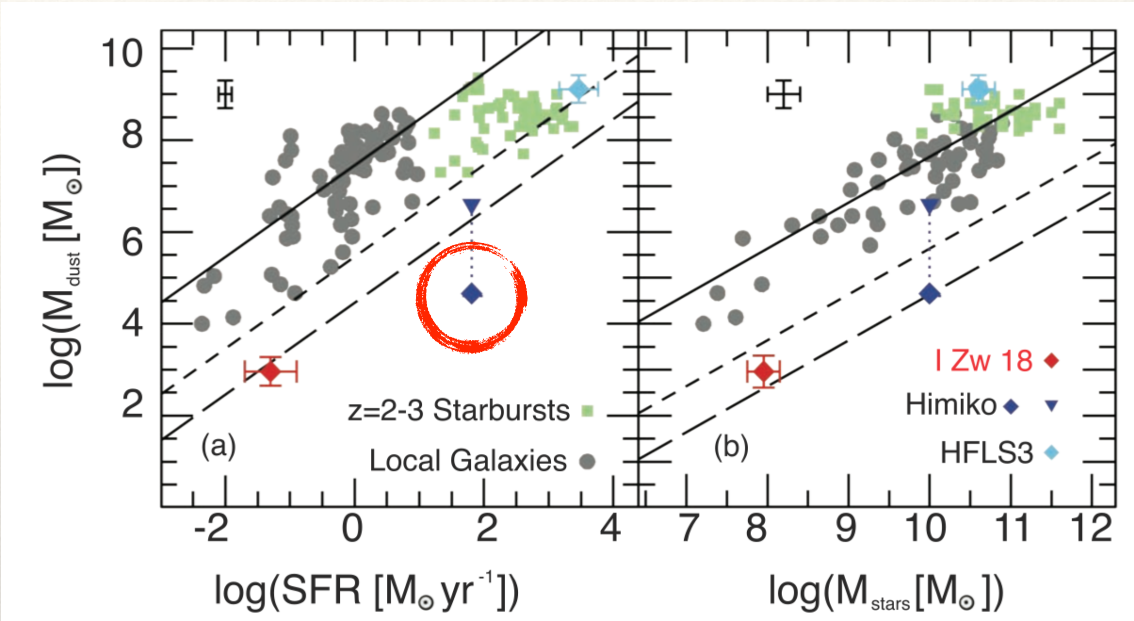
e.g. Lisenfeld & Ferrara 1998, Dwek 1998, Galliano et al. 2008, **Zhukovska et al. 2014**

Remy-Ruyer et al. 2014 -
Dwarf Galaxies Survey with Herschel



The Life Cycle of Dust





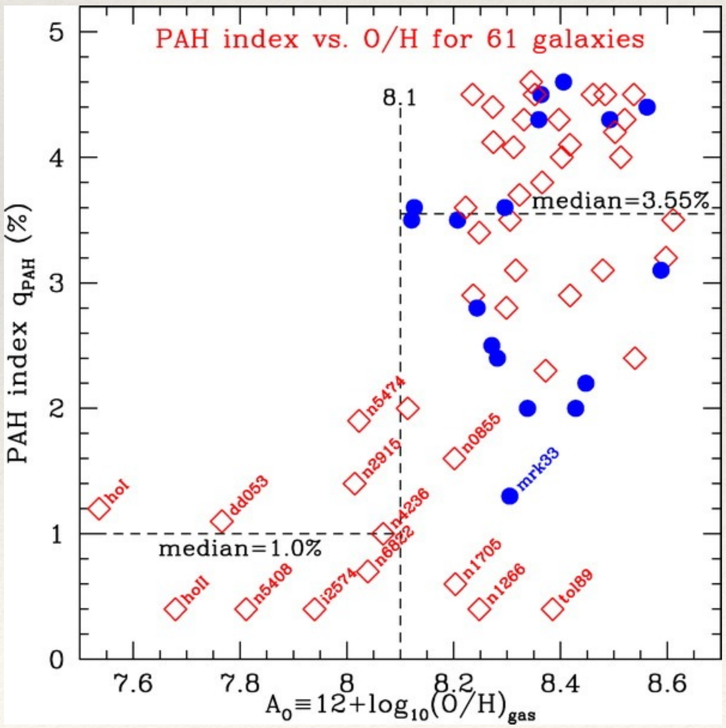
Fisher et al. 2014 - Herschel Obs of I Zw 18 (HI contours)

DGR behavior may prove crucial for studying high-z galaxies.

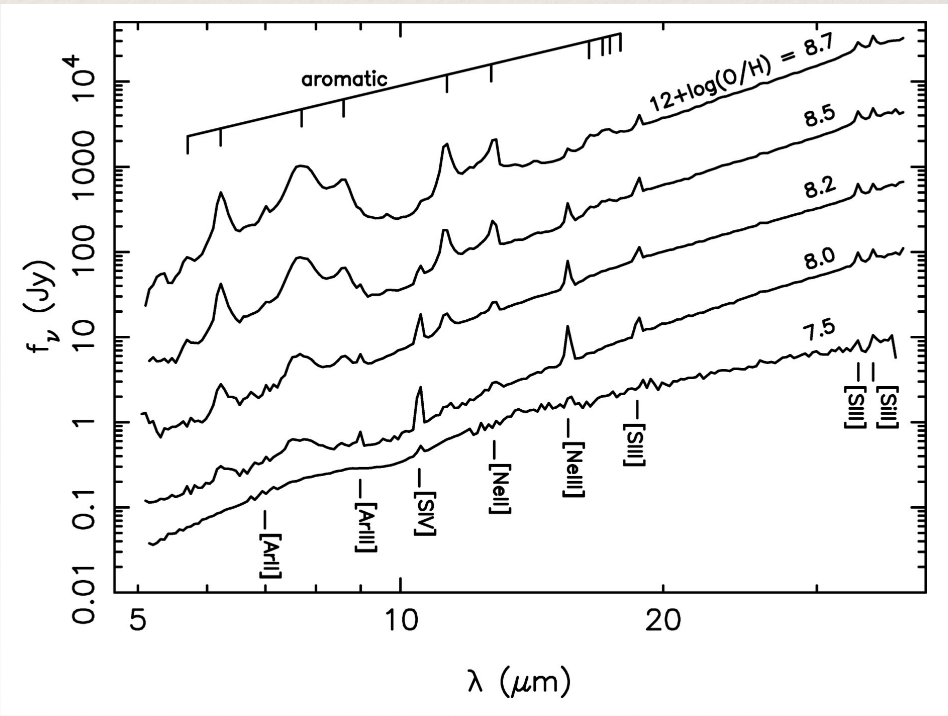
The Life Cycle of Dust

DGR is not the only thing changing -
composition & grain size distribution also vary.

Draine et al. 2007
SINGS study of PAH abundance



Engelbracht et al. 2008
Spitzer IRS study of dwarf galaxies



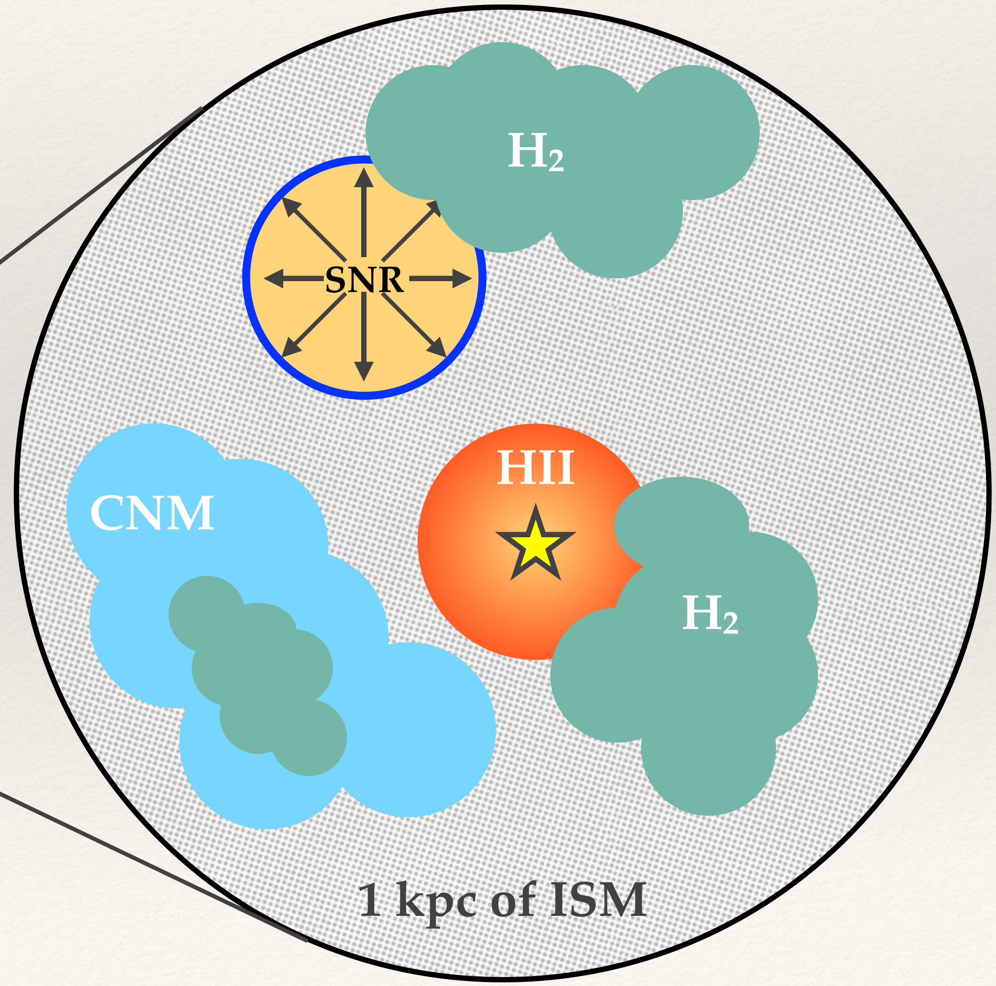
The Life Cycle of Dust

The drivers of dust life-cycle act on small scales.

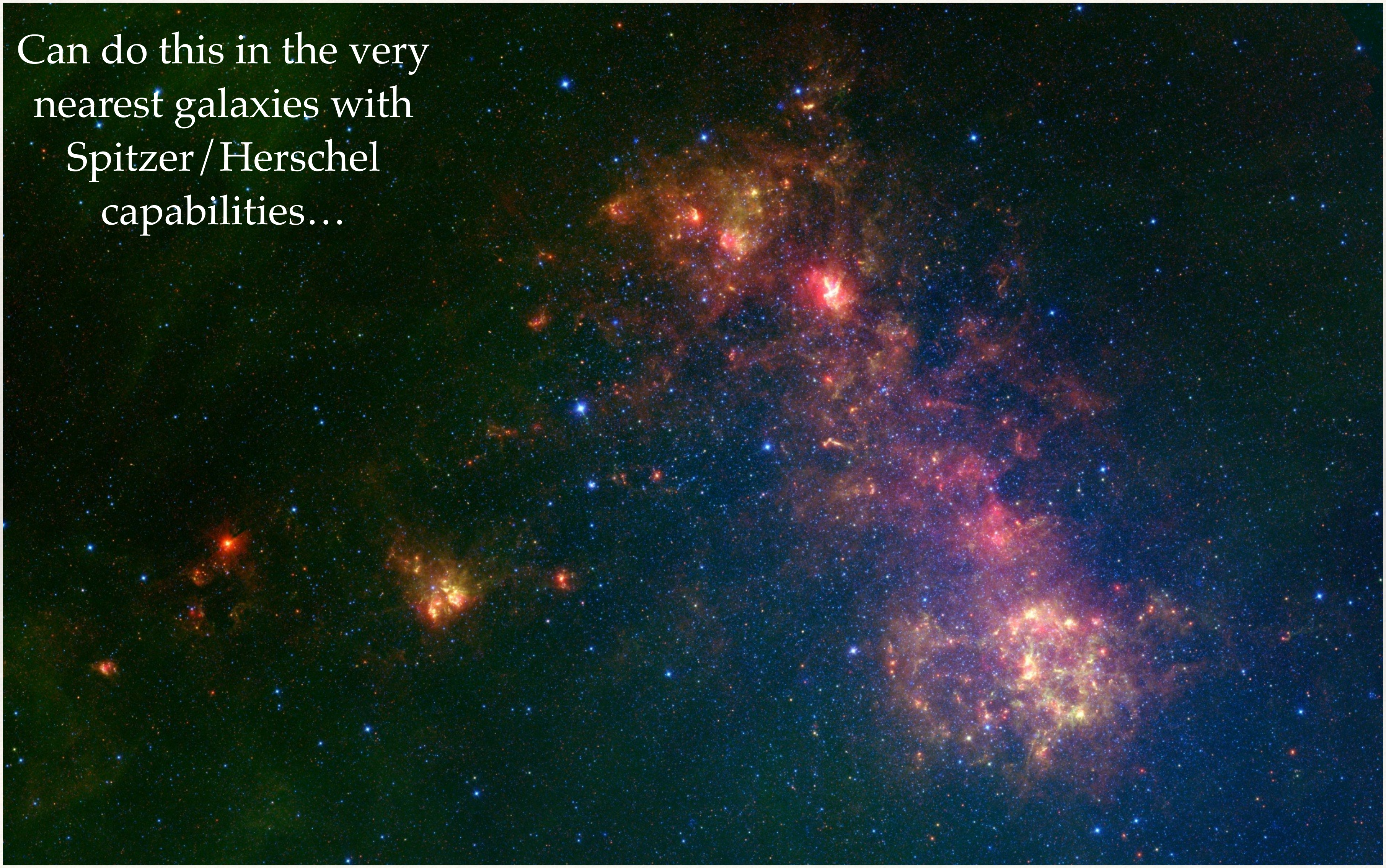
Need to resolve these scales…

HI/H2 transition, SNe, irradiation, stellar winds

NGC 6946 from KINGFISH
Herschel PACS & SPIRE

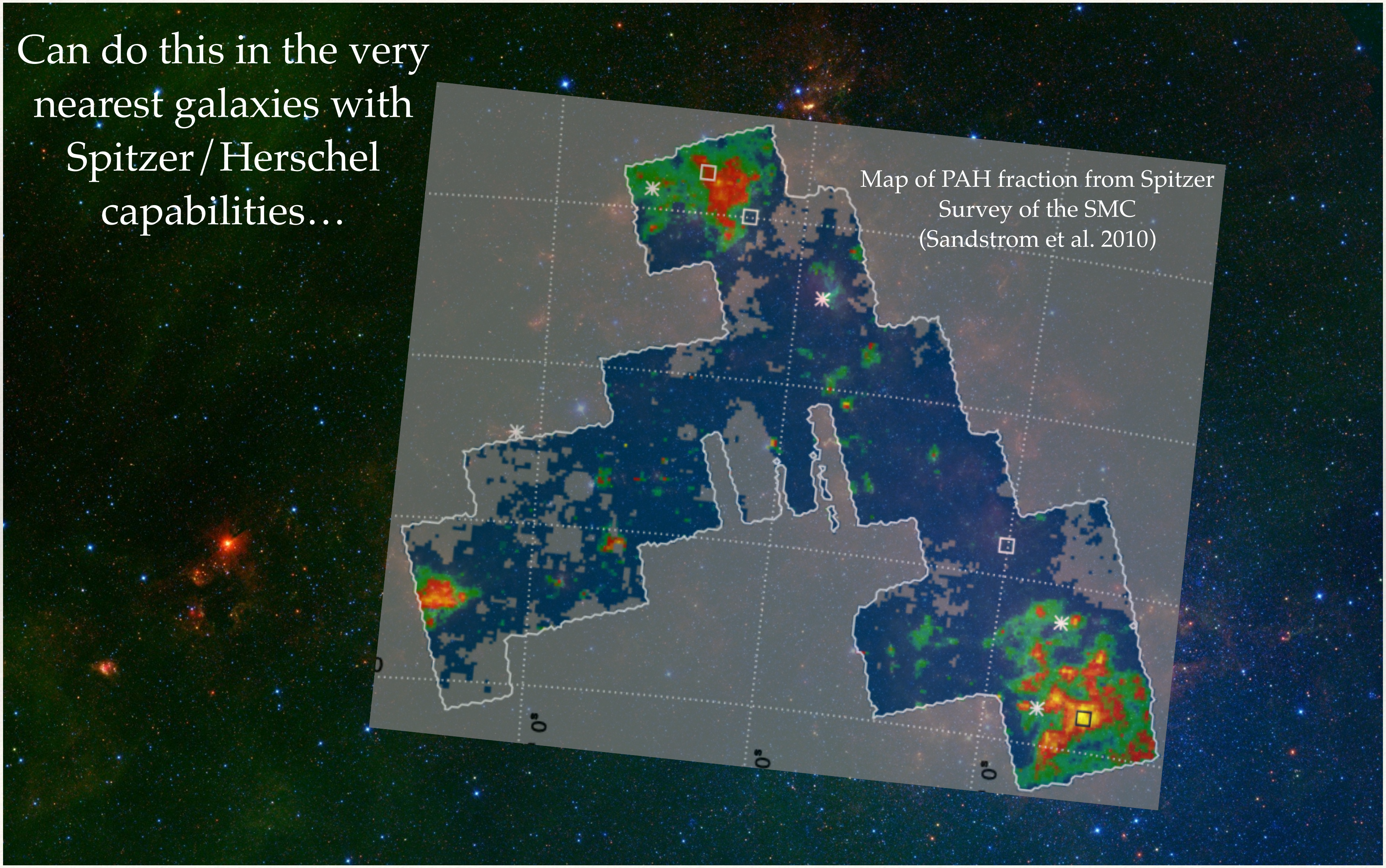


The Life Cycle of Dust



The Life Cycle of Dust

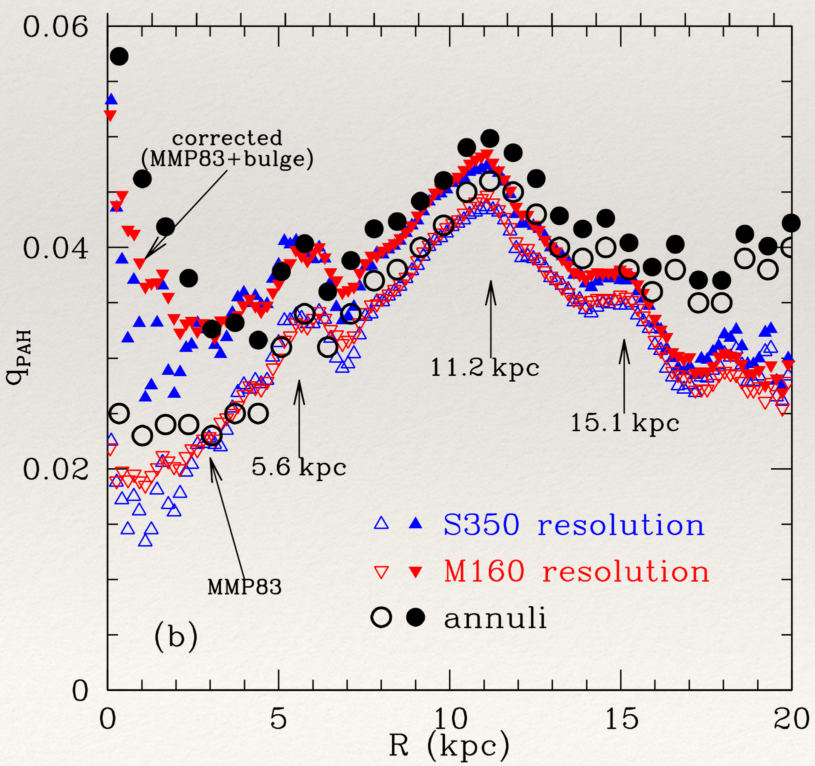
Can do this in the very nearest galaxies with Spitzer / Herschel capabilities…



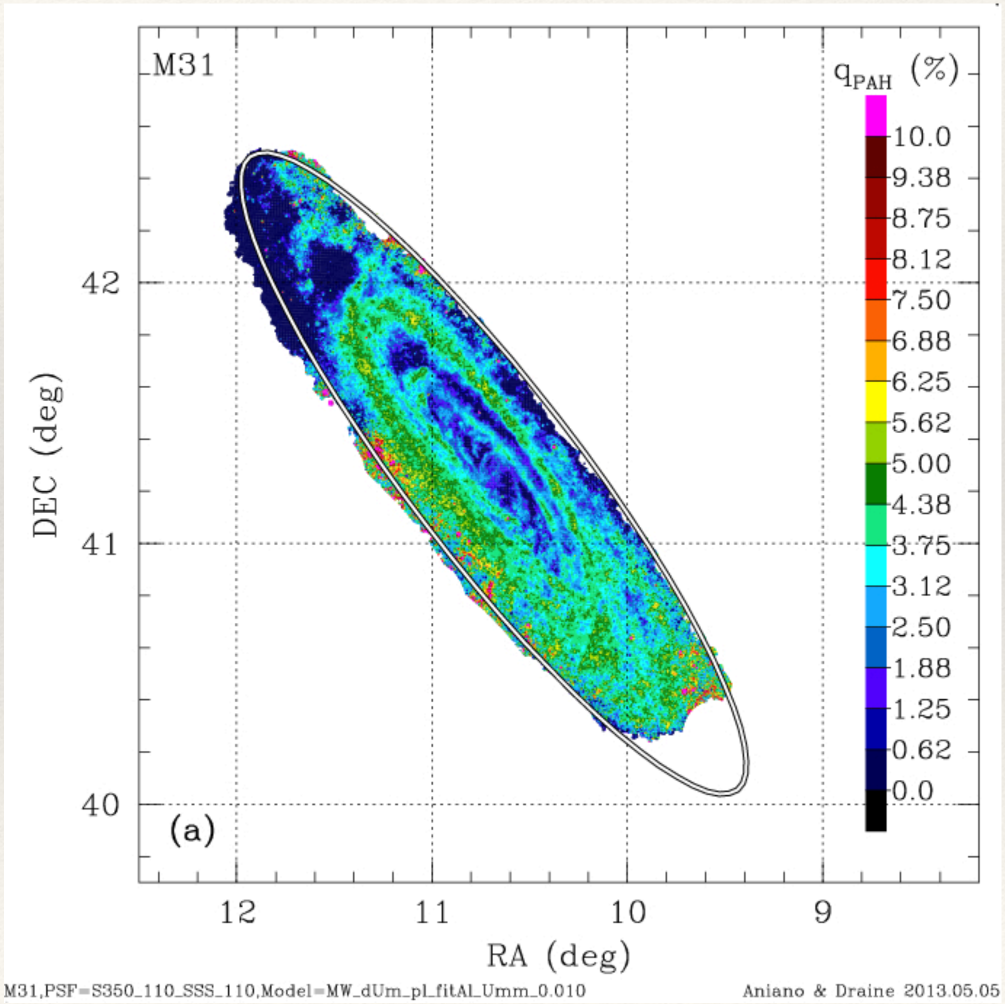
Map of PAH fraction from Spitzer Survey of the SMC (Sandstrom et al. 2010)

The Life Cycle of Dust

Can do this in the very nearest galaxies with Spitzer/Herschel capabilities…

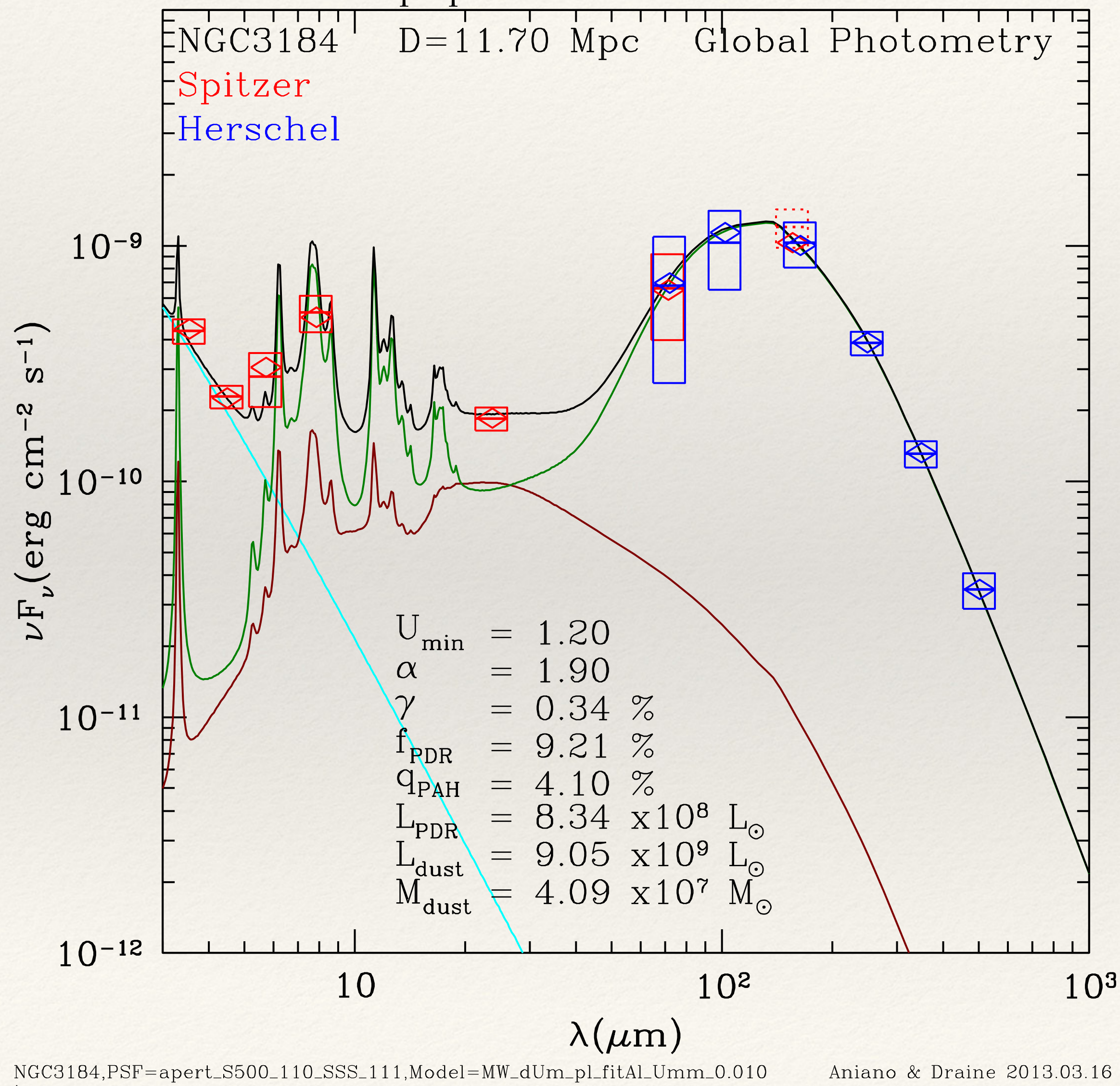


Map of PAH fraction in M31 from Spitzer & Herschel observations (Draine et al. 2014)



The Life Cycle of Dust

Aniano et al. in prep



But understanding dust life cycle from the galaxy evolution perspective means *we need to move beyond the Local Group.*

Killer App:

Molecular cloud scale maps of dust properties in nearby (D ≲ 20 Mpc) galaxies.

The Life Cycle of Dust

What will this require?

Molecular cloud scale resolution: ~50 pc which is ~0.5″ for D = 20 Mpc

Coverage of peak of dust SED: 70-300 μm

- ALMA alone isn't sufficient (doesn't get peak of IR SED, filters out larger scale structures)
- JWST alone isn't sufficient (only gets mid-IR)

Sensitivity target: measure dust mass of something comparable to Taurus (R~25 pc, 10^3 $M_\odot$ of dust, T_d~15K) in a D=20 Mpc galaxy

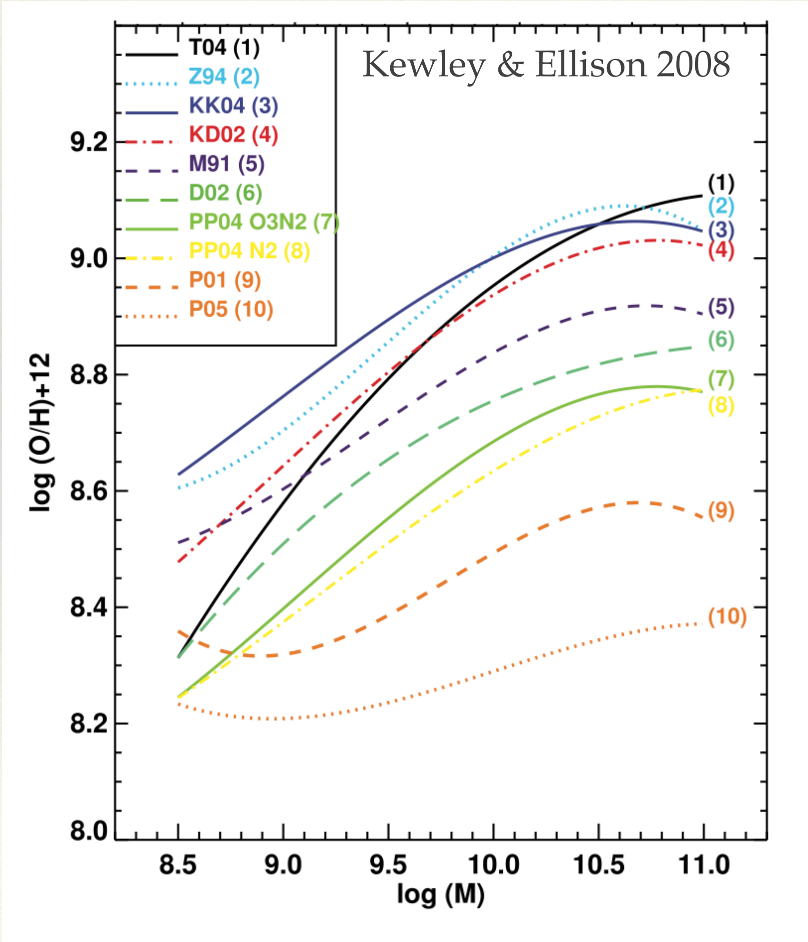
The Life Cycle of Dust

What will this require?

Parameter	Units	Value or Range
Wavelength range	μ*m*	*70-300 μm*
Angular resolution	*arcsec*	*~0.5″ for 50 pc in a D=20 Mpc galaxy (well matched to ALMA and JWST)*
Spectral resolution, (λ/Δλ)	*dimensionless*	*n.a.*
Continuum sensitivity	μ*Jy*	*10-100*
Spectral line sensitivity	*10e-19 W m*	*n.a.*
Instantaneous FoV	*arcmin*	*~1*

Calibration of Metallicity Scales

We know *surprisingly little* about metallicity, even in nearby galaxies.



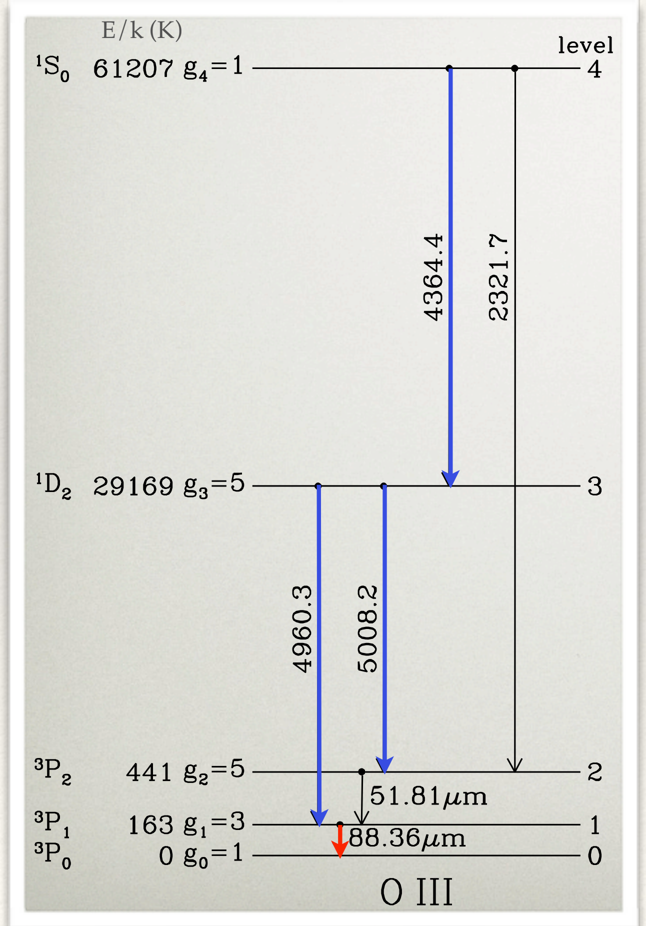
Mass-Metallicity relationship for SDSS $z < 0.1$ galaxies

range of metallicity calibrations gives order-of-magnitude uncertainty

Why?

Calibration of Metallicity Scales

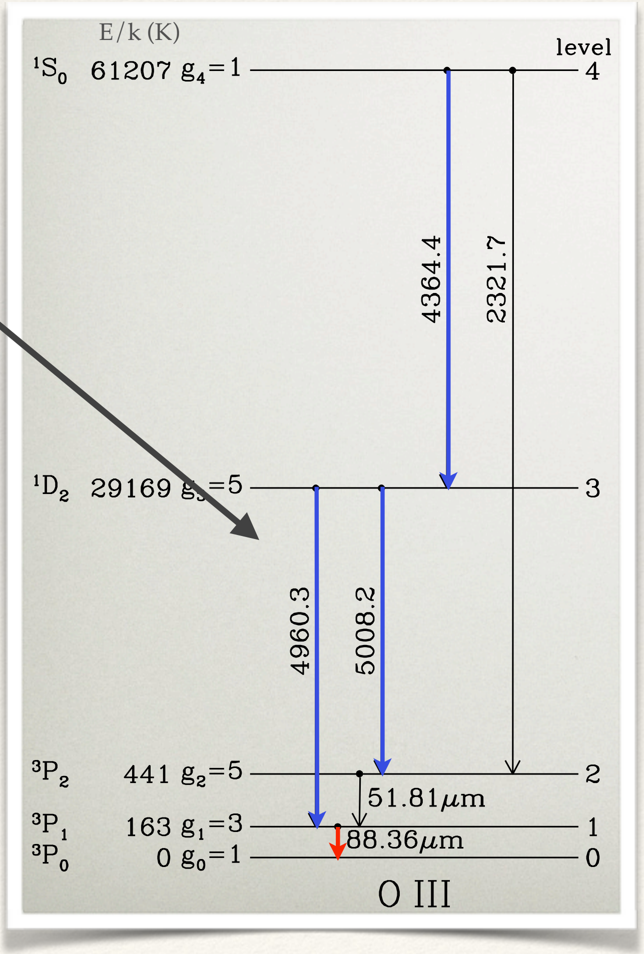
We know surprisingly little about metallicity, even in nearby galaxies.



Calibration of Metallicity Scales

We know surprisingly little about metallicity, even in nearby galaxies.

Strong line calibrations require knowledge of n_e and T_e as well as A_V to compare with Hα.



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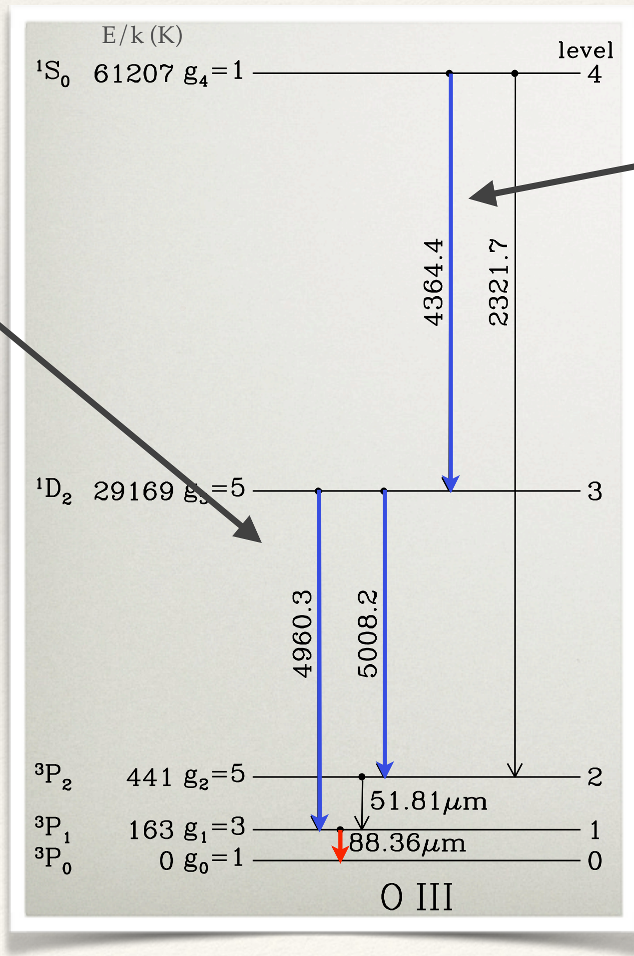

Temperature fluctuations in HII regions and faintness of line at higher Z complicate "direct" abundances.

Calibration of Metallicity Scales

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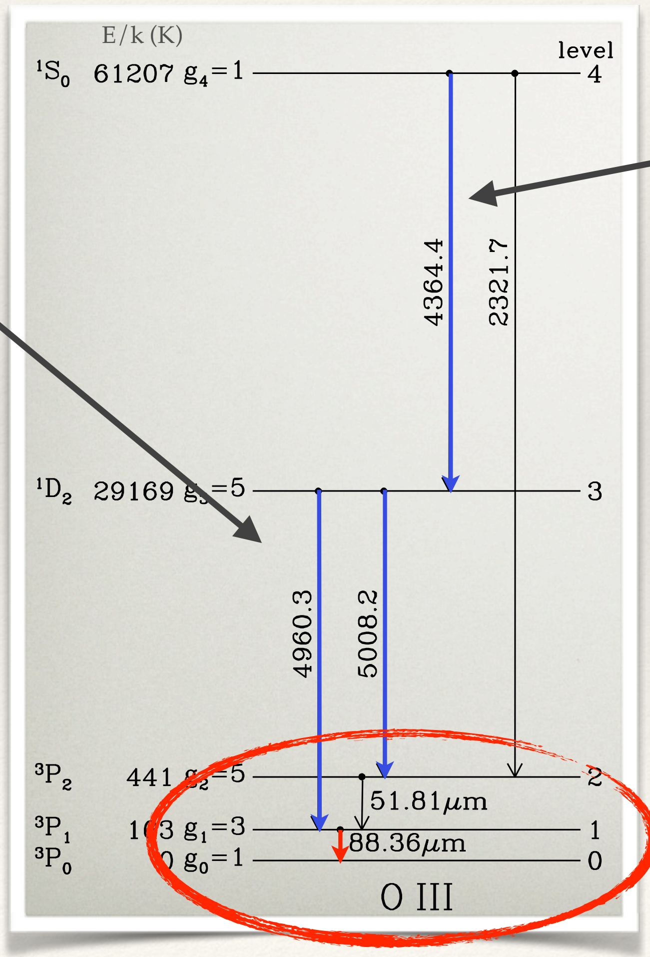
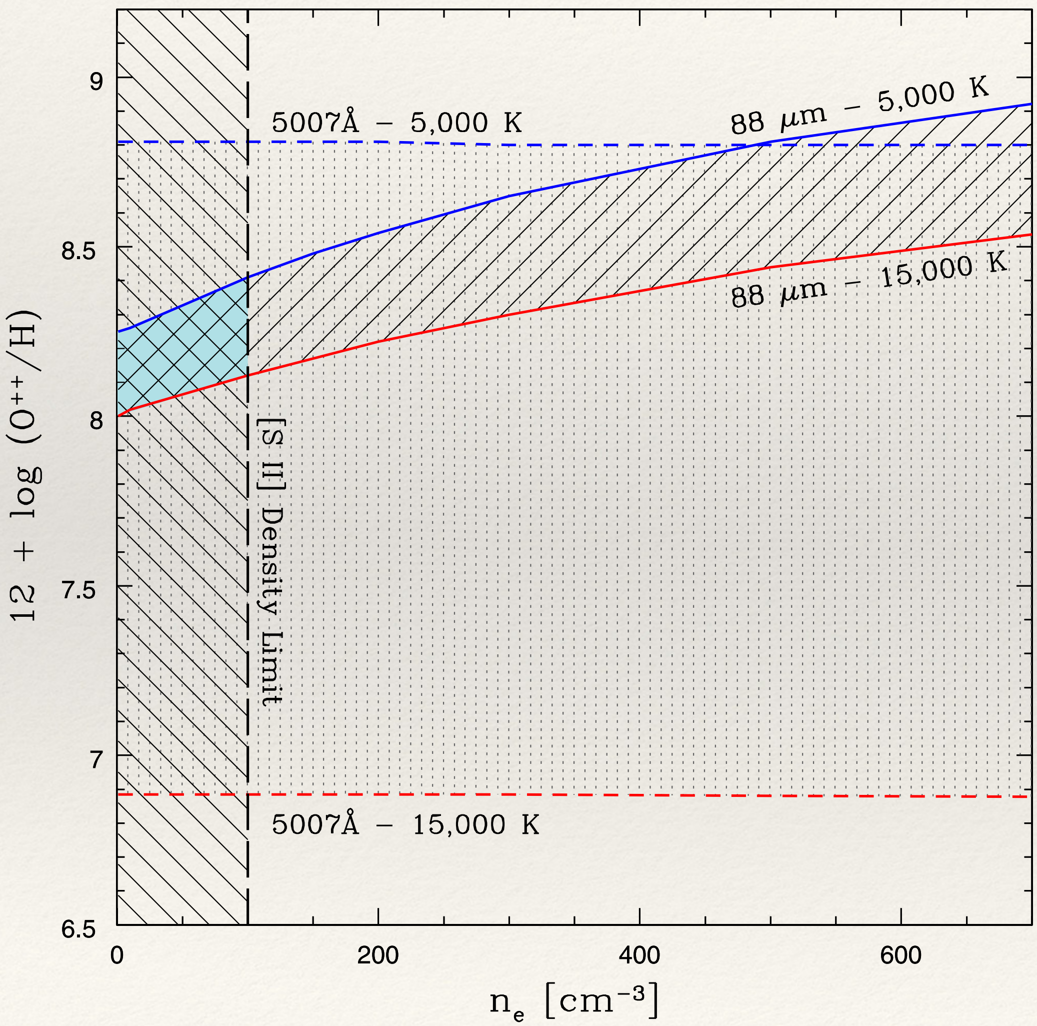


Temperature fluctuations in HII regions and faintness of line at higher Z complicate "direct" abundances.

Solution may be found by using far-IR [OIII] lines.

Calibration of Metallicity Scales

Croxall et al. 2012 - KINGFISH [OIII] 88 μm



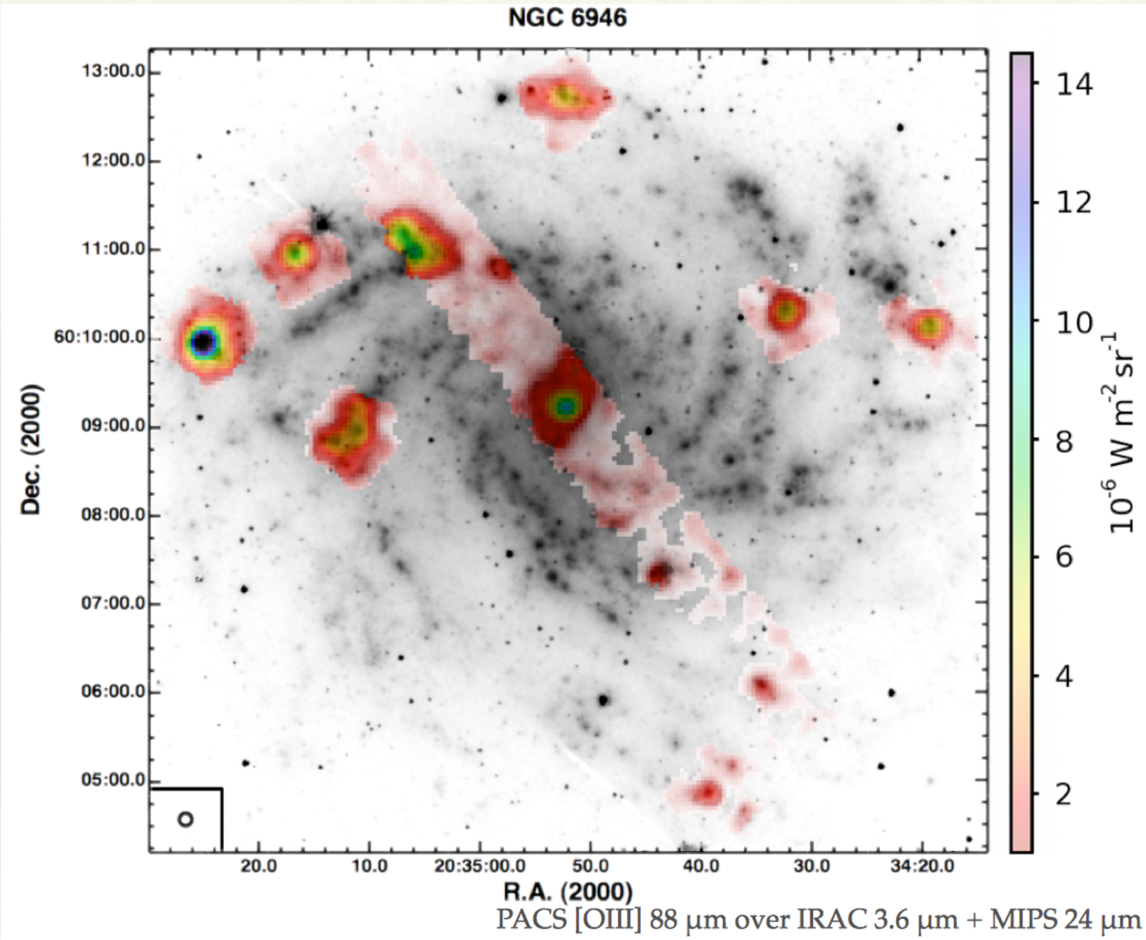
With measurements of both [OIII] 52 and 88 μm get very good handle on O^{++} abundance.

To get O/H, still need:

- ionization correction for total O
- measurement of H^+

Mid-IR lines with JWST:
Brackett, Pfund, Humphreys lines of H;
ionization from [Ne III]/[Ne II],
[S IV]/[S III], [Ar III]/[Ar II]

Calibration of Metallicity Scales



Croxall et al. 2014, in prep.

Killer App:

Measurements of [OIII] 52, 88 μm matched to mid-IR diagnostics from JWST, covering many HII regions in a galaxy.

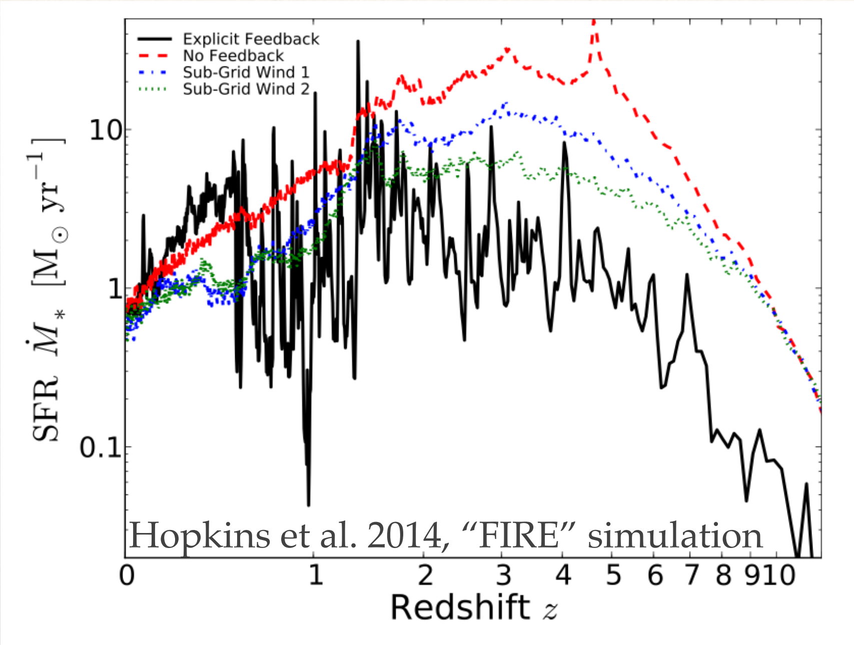
Calibration of Metallicity Scales

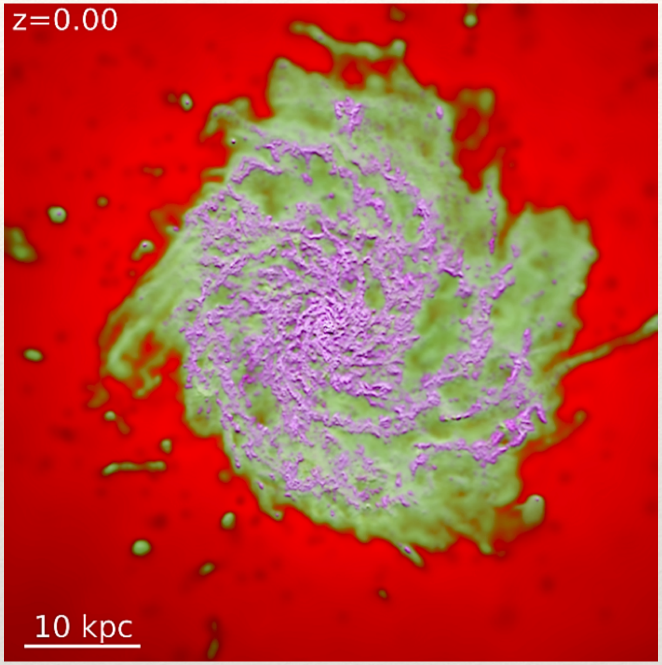
What will this require?

Parameter	Units	Value or Range
Wavelength range	µ*m*	*50-100 µm*
Angular resolution	*arcsec*	*~few"*
Spectral resolution, (λ/Δλ)	*dimensionless*	*1000-5000 comparable to PACS*
Continuum sensitivity	µ*Jy*	*n.a.*
Spectral line sensitivity	*10e-19 W m*	*comparable to MIRI, 0.1-1*
Instantaneous FoV	*arcmin*	*~1*
Number of target fields	*dimensionless*	*more is better to get several HII regions per pointing*

One other thing this will require: Coordination with JWST observations!

Resolving SF Feedback

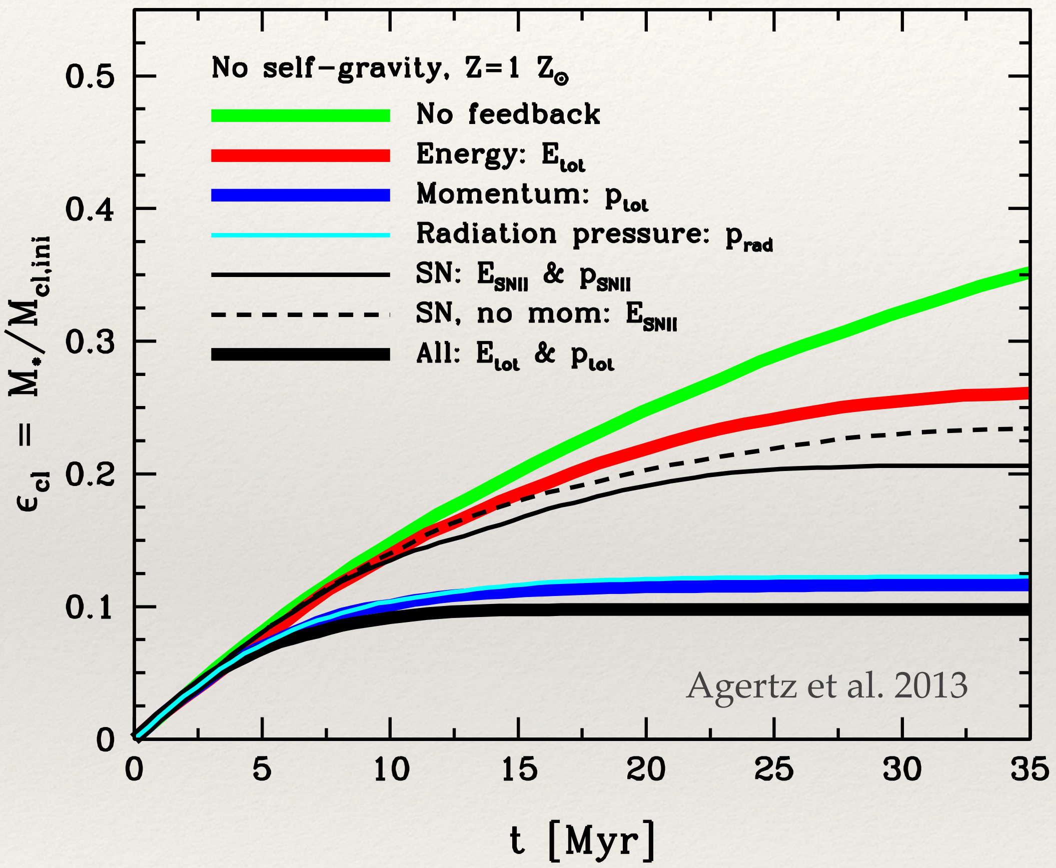




The importance of feedback in the regulation of star formation is widely recognized.

In simulations - feedback is needed to match star formation histories, stellar masses, disk properties of galaxies.

Resolving SF Feedback

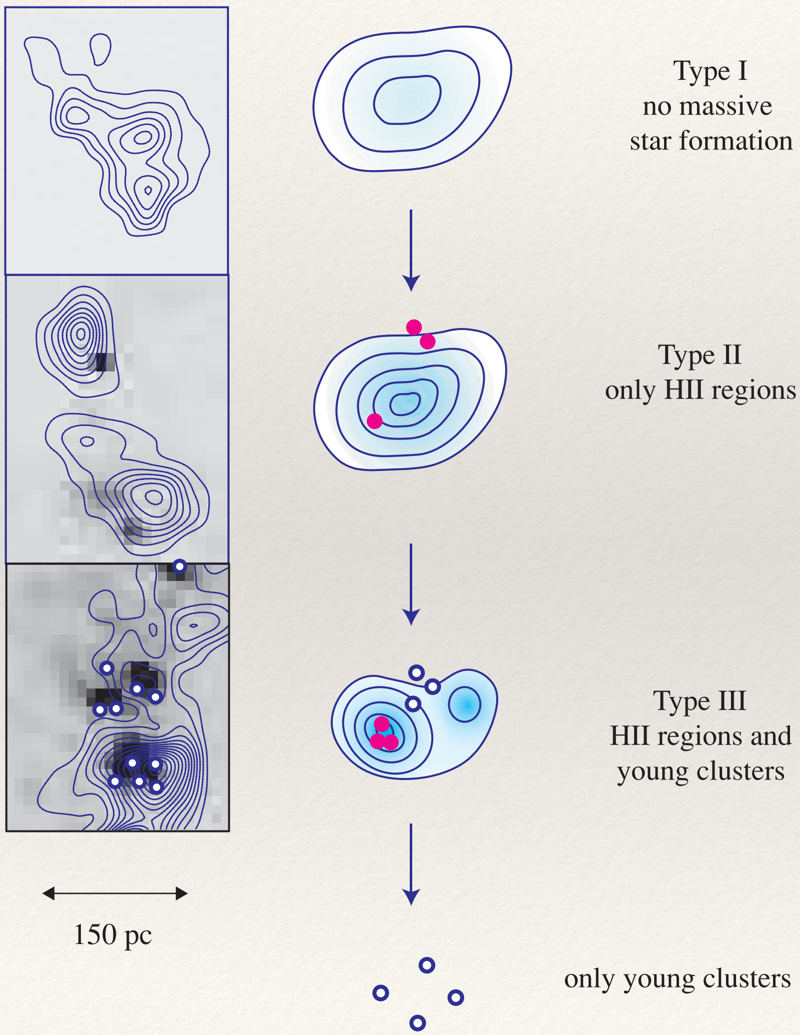


Feedback in GMCs needed to keep star-formation "inefficient", i.e. only ~few% of the mass gets turned into stars.

What is the dominant feedback source?
How does that vary with environment?

Resolving SF Feedback

Kawamura et al. 2009



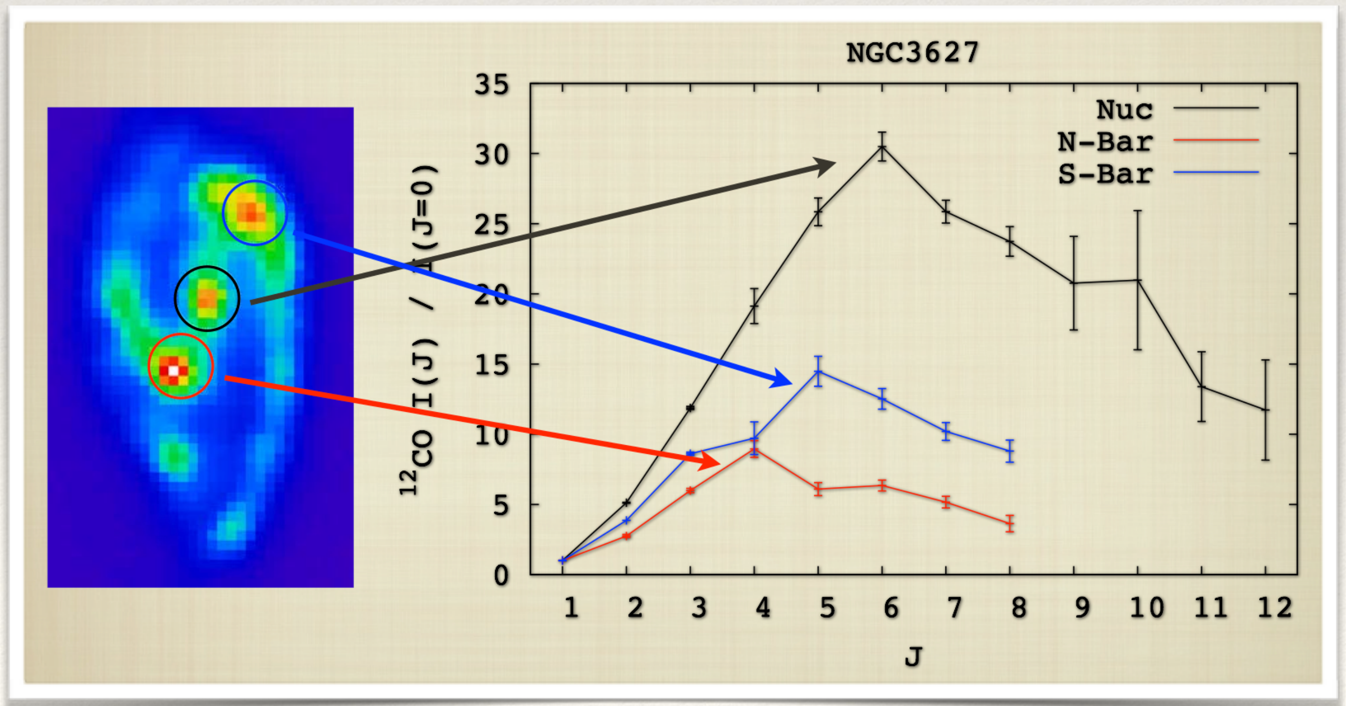
Possible to observe GMCs at various evolutionary states now with ALMA in nearby galaxies (~0.1-1″ scales).

Cloud properties vs evolutionary state tells us about feedback. (gas temp, dust temp, velocity dispersion, etc).

Resolving SF Feedback

These questions can be addressed by studying molecular gas excitation with high-J CO for individual clouds.

ALMA will be great for lower CO rotational levels at GMC scales.

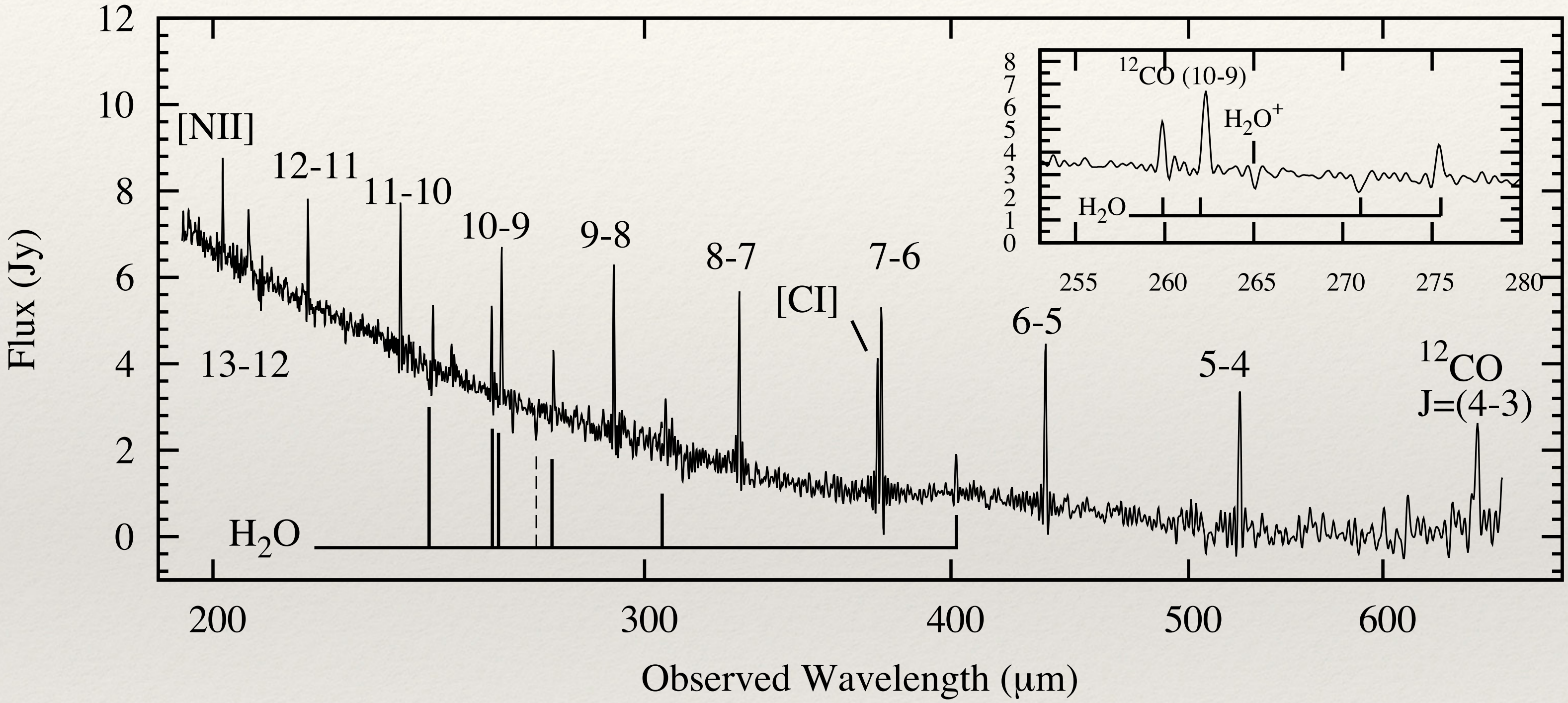


Herschel SPIRE-FTS made exciting progress on ~kpc scale.

^{12}CO ladders in NGC 3627 from the Herschel Program "Beyond the Peak" (PI JD Smith)

Resolving SF Feedback

NGC 1266 with SPIRE-FTS; Pellegrini et al. 2013



Other lines in the far-IR will be interesting for feedback studies as well. (e.g. H_2O, rotational lines of other molecules, OH+).

^{13}CO ladder gives excellent handle on gas properties.

Resolving SF Feedback

Killer App:

^{12}CO and ^{13}CO high-J ladders for many individual GMCs at various evolutionary states in nearby galaxies.

Matched ALMA resolution in nearby galaxies ~1″ for low-J CO lines.

SPIRE-FTS has done these type of observations on kpc scales for ^{12}CO, necessary sensitivity on ~50 pc scales will depend on clumpiness, factor of >10 improvement for ^{13}CO ladder.

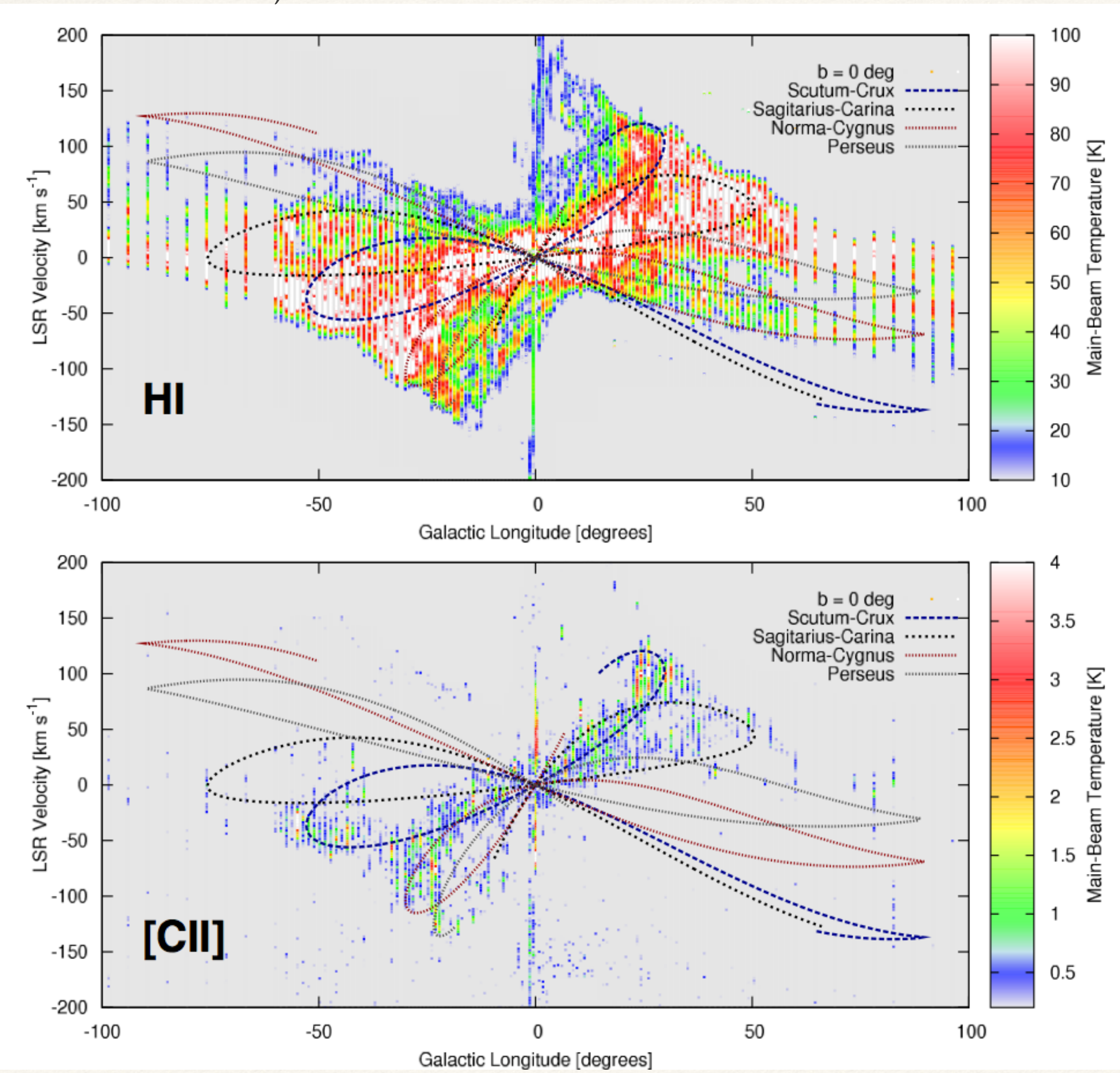
Resolving SF Feedback

What will this require?

Parameter	Units	Value or Range
Wavelength range	μ*m*	*200-600 μm*
Angular resolution	*arcsec*	*~1″*
Spectral resolution, (λ/Δλ)	*dimensionless*	*comparable to SPIRE FTS, 300-1500*
Continuum sensitivity	μ*Jy*	*n.a.*
Spectral line sensitivity	*10e-19 W m*	*~1-10 (for 13CO ~1)*
Instantaneous FoV	*arcmin*	*~1*

ISM Phase Balance

Pineda et al. 2013; GOT C+



New high velocity resolved [CII] 158 μm observations have given new insight into ISM phases in the MW.

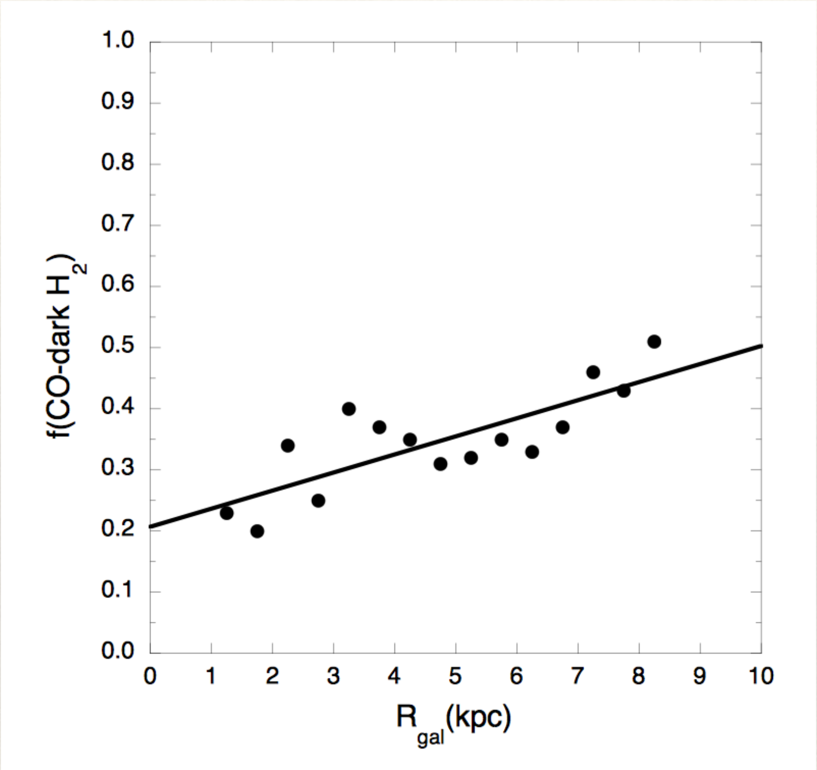
Comparison with HI, CO at comparable resolution - separate different phases contributing to [CII].

Herschel Key Program GOT C+

Langer et al. 2014, Pineda et al. 2013, Velusamy et al. 2012, and others

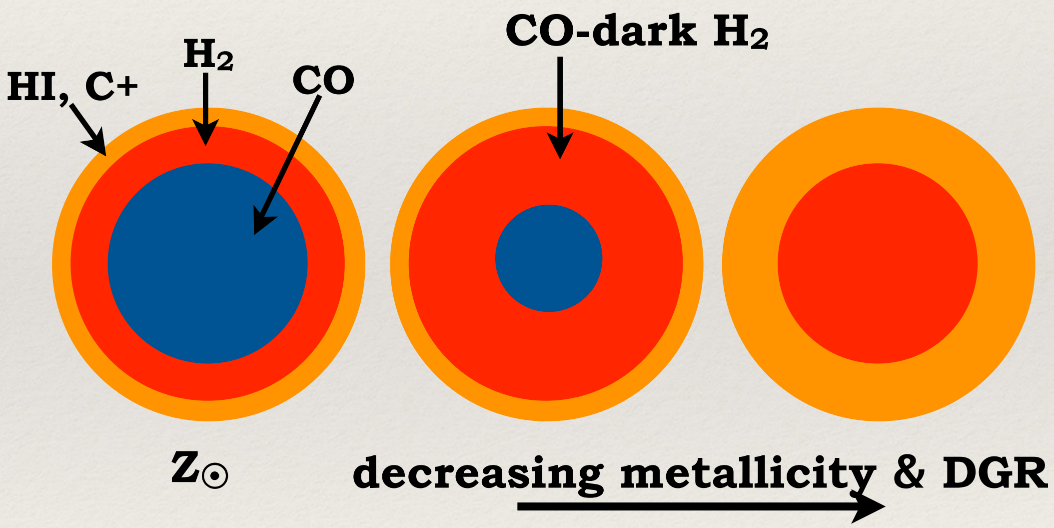
ISM Phase Balance

Langer et al. 2014; GOT C+



GOT C+ measurement of CO-dark H_2 fraction in the MW ISM.

High-velocity resolution [CII] compared to CO/HI is one of the only ways to directly detect "CO-dark" H_2.



Maloney & Black 1988, Bolatto et al. 1999, Wolfire et al. 2010, Glover & Mac Low 2011

ISM Phase Balance

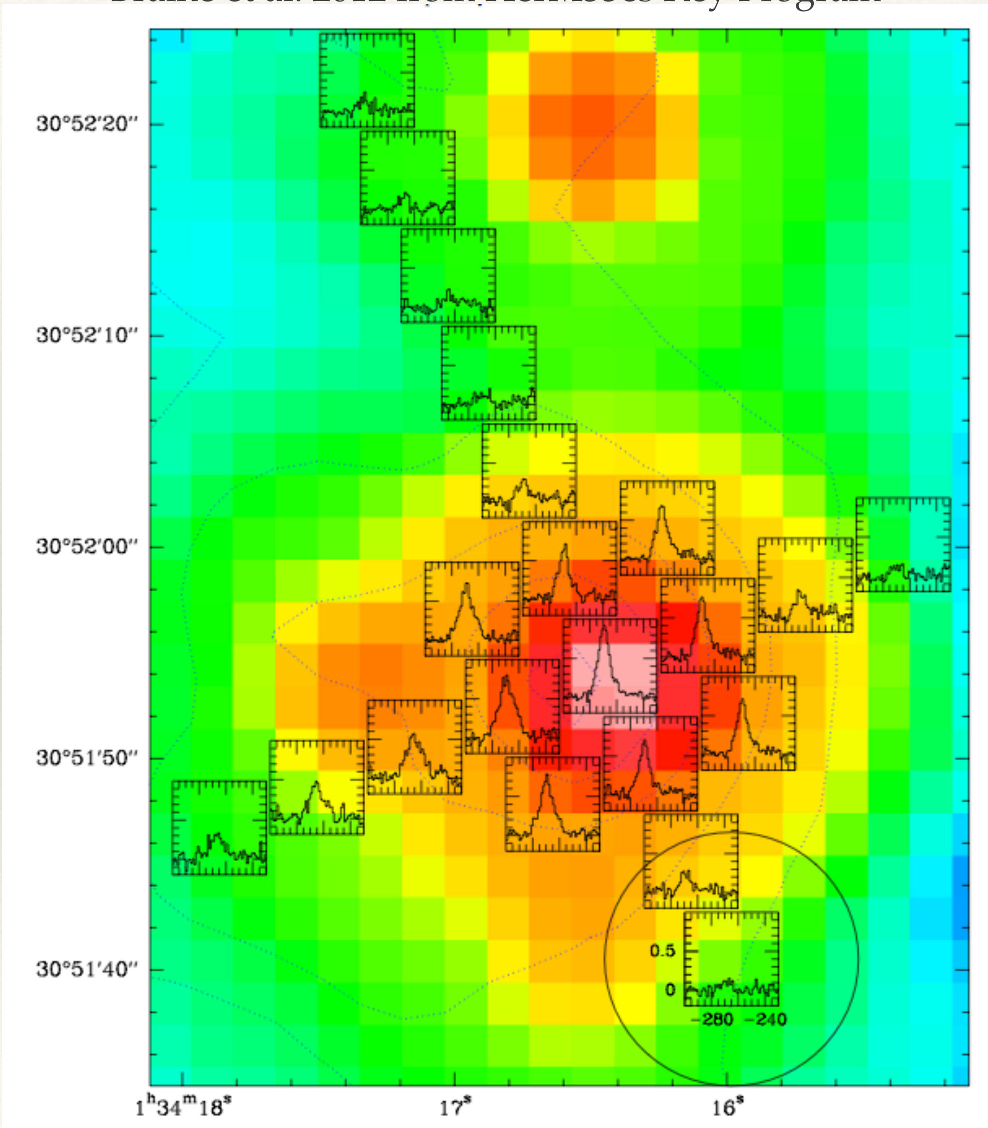
Some studies in nearby galaxies
with Herschel-HIFI
(esp. HerM33es)

Several recent or planned SOFIA-GREAT observations

Killer App:

High velocity resolution *mapping* in nearby galaxies, e.g. GOT C+ in other galaxies.

Braine et al. 2012 from HerM33es Key Program



ISM Phase Balance

What will this require?

Parameter	Units	Value or Range
Wavelength range	μ*m*	*50-250 μm ([CII] 158 μm, [OI] 63 μm, [NII] 122, 205, others)*
Angular resolution	*arcsec*	*~few"*
Spectral resolution, (λ/Δλ)	*dimensionless*	*~10e6*
Continuum sensitivity	μ*Jy*	*n.a.*
Spectral line sensitivity	*10e-19 W m*	*~1 (based on kpc-scale [CII] in nearby galaxies + need to measure detailed line profile)*
Instantaneous FoV	*arcmin*	*multi-pixel array is best - map ~arcmin size fields*

Observational Goals for Nearby Galaxies

Summary:

- ~1″ resolution in far-IR continuum and line observations.
- Coordination between ALMA and JWST observations and future far-IR telescope - needs planning since at least JWST probably won't overlap.
- High velocity resolution far-IR line observations.