The ISM & Star Formation in Nearby Galaxies with the FIR Surveyor

NGC 0628
Credit: NASA/ESA, Hubble Heritage

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Far-IR Surveyor Workshop
June 3, 2015

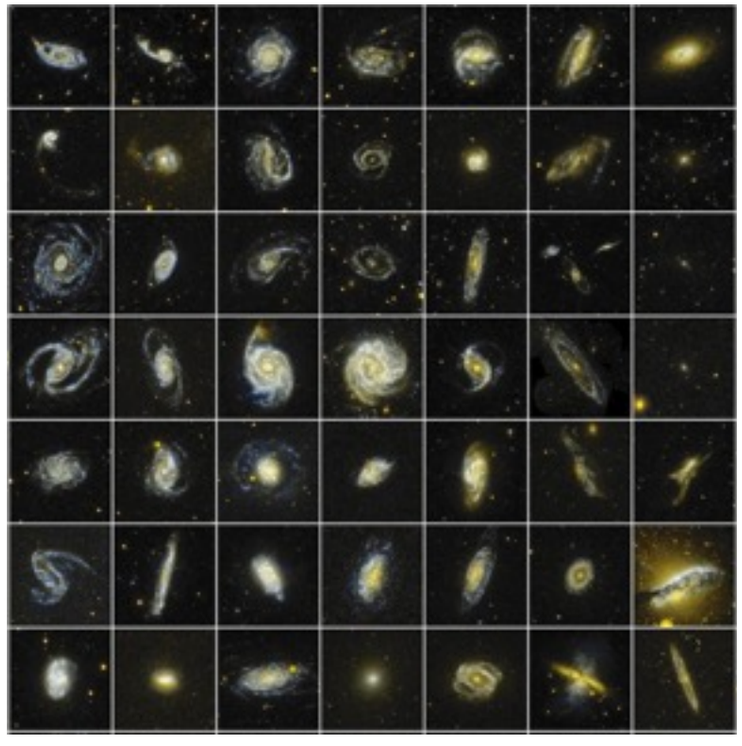
Nearby Galaxies let us connect ISM Physics with Galaxy Evolution

M101 with Spitzer 24, 8, 3.6 μm

Galaxies can be resolved & studied in detail.

I Zw 18 with HST

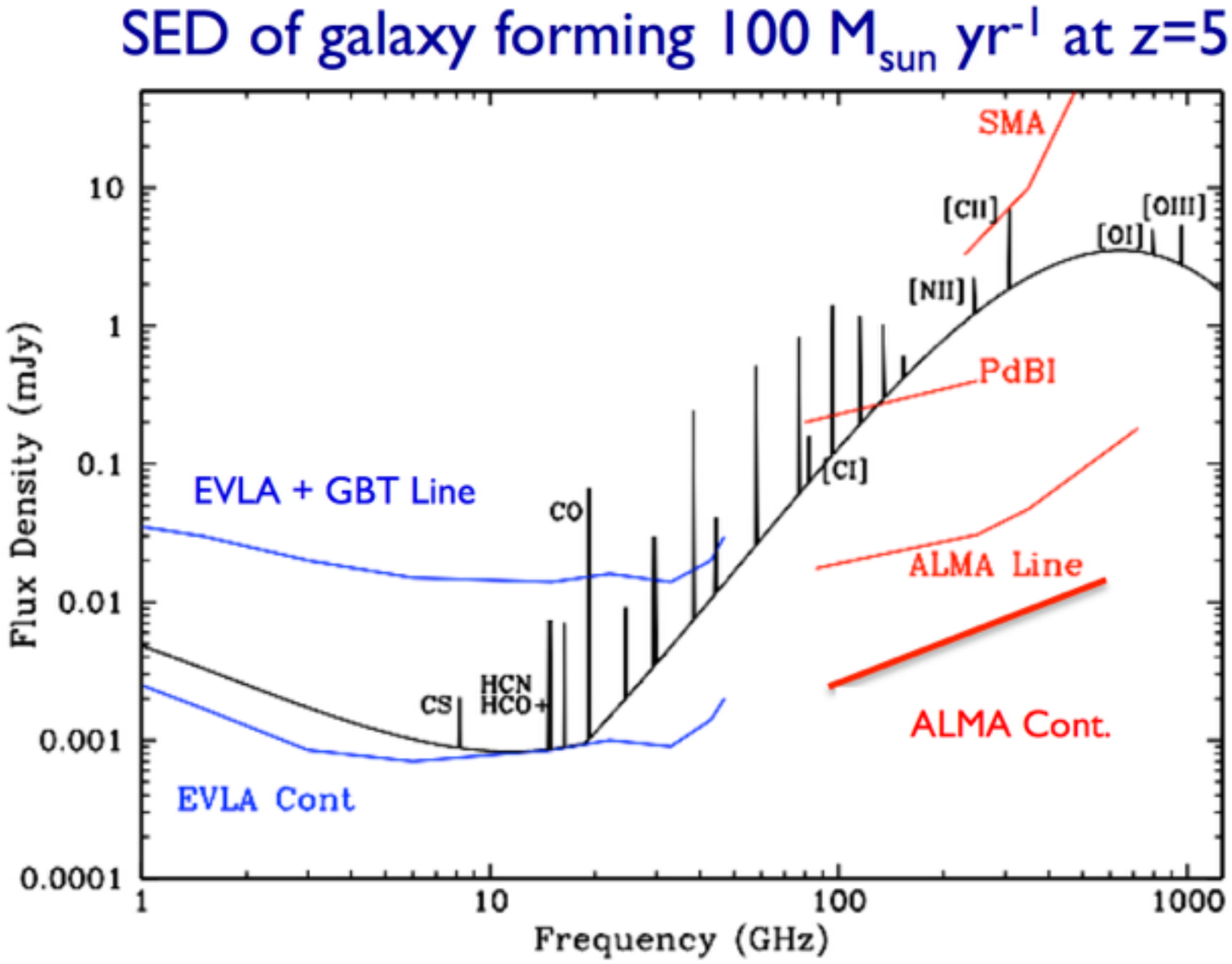
Can explore different conditions from MW.



GALEX Nearby Galaxies Survey

Large, representative galaxy samples available.

Nearby Galaxies let us understand tracers used to study high-z



plot from A. Leroy

Use of tracers like dust continuum or [CII] 158 μm to measure SFR, ISM mass, etc *must be calibrated locally*.

Key Nearby Galaxy Science Areas

- Life Cycle of Interstellar Dust
- Role of Feedback in SF & Galaxy Evolution
- ISM Phase Balance

Key Nearby Galaxy Science Areas

Ways to push forward on these topics:

- more sensitive measurements
- higher spectral/angular resolution
- larger samples
- multiwavelength coverage

Other Telescopes in the 2020's for nearby galaxy studies

JWST - targeted mapping of regions or small samples of nearby galaxies with MIRI, larger scale mapping with NIRCAM

ALMA - wide range of molecular gas diagnostics at ~arcsec resolution plus sub-mm dust continuum

SKA - full sky high sensitivity & resolution HI mapping

E-ELT/TMT/GMT - resolved stellar populations in nearby galaxies, star formation history maps, stellar energy input

MANGA & future - full optical IFU mapping of galaxies at arcsec resolution

The Life Cycle of Interstellar Dust

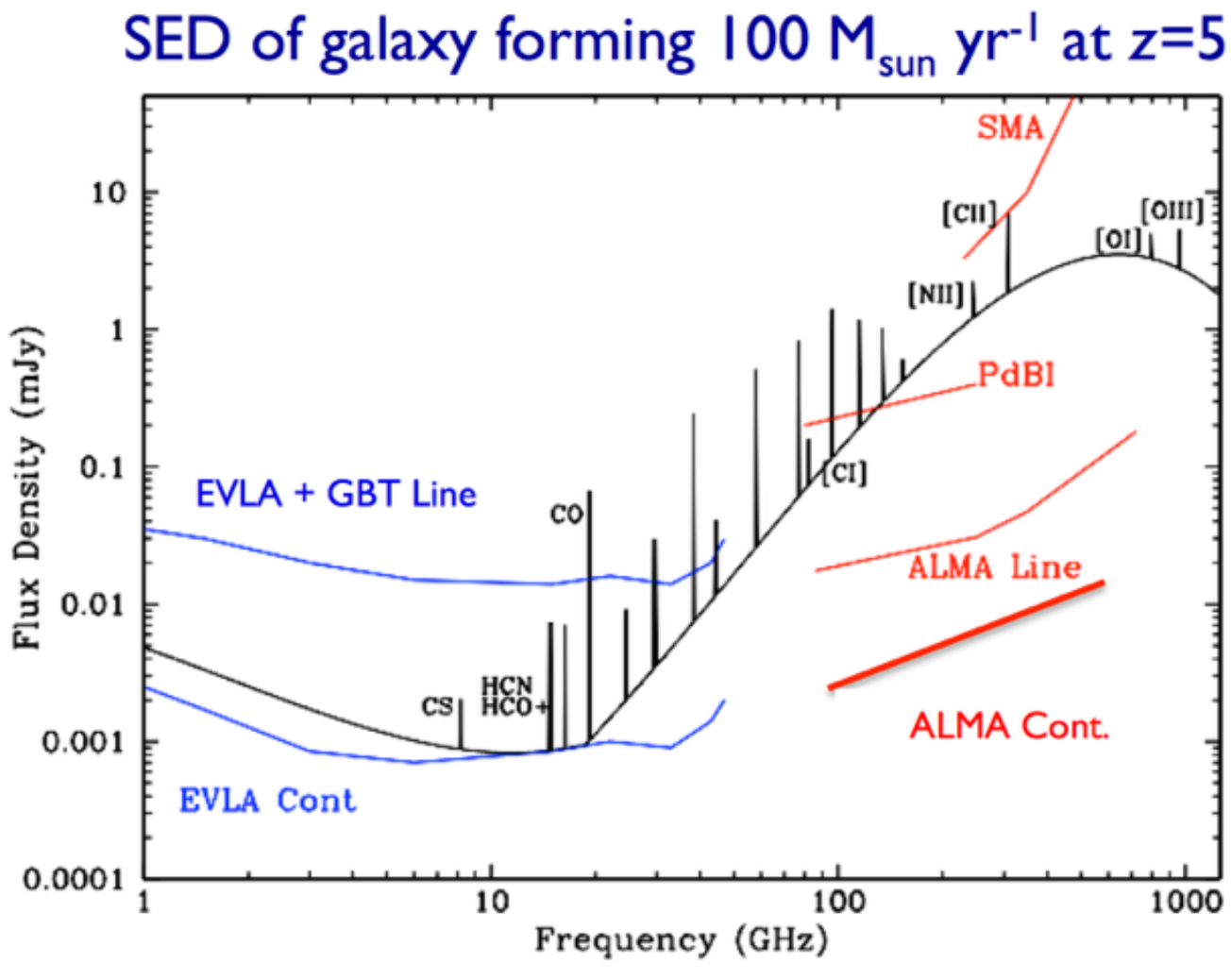
Dust is a crucial part of the ISM but we are just beginning to understand its life-cycle.

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

How are these key parameters affected by galactic environment?

The Life Cycle of Interstellar 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 Interstellar Dust

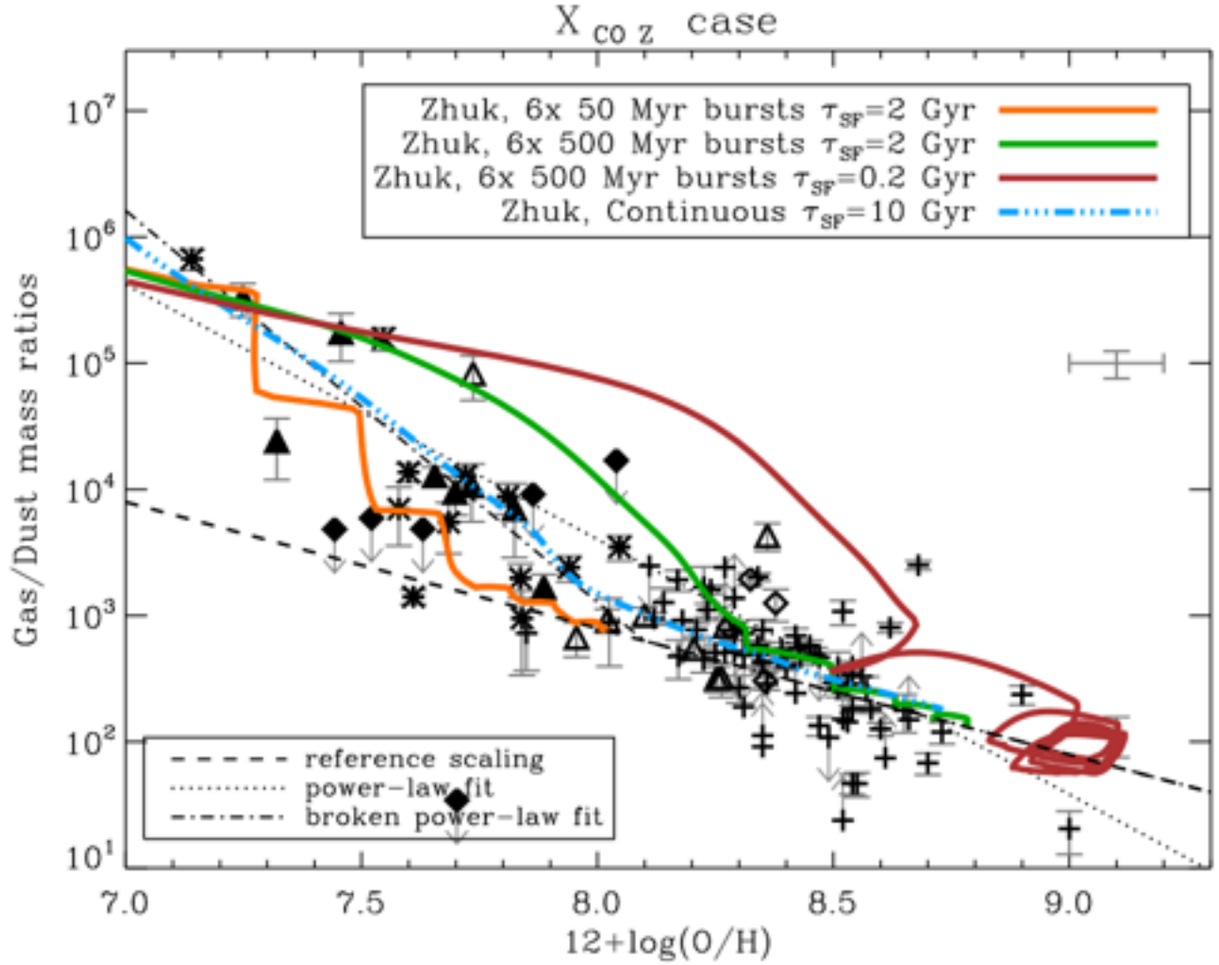
*Dust-to-gas ratio **not** a simple function of metallicity in all conditions.*

Galaxy-average DGR is not a can deviate from linear scaling by orders of magnitude at low Z.

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**

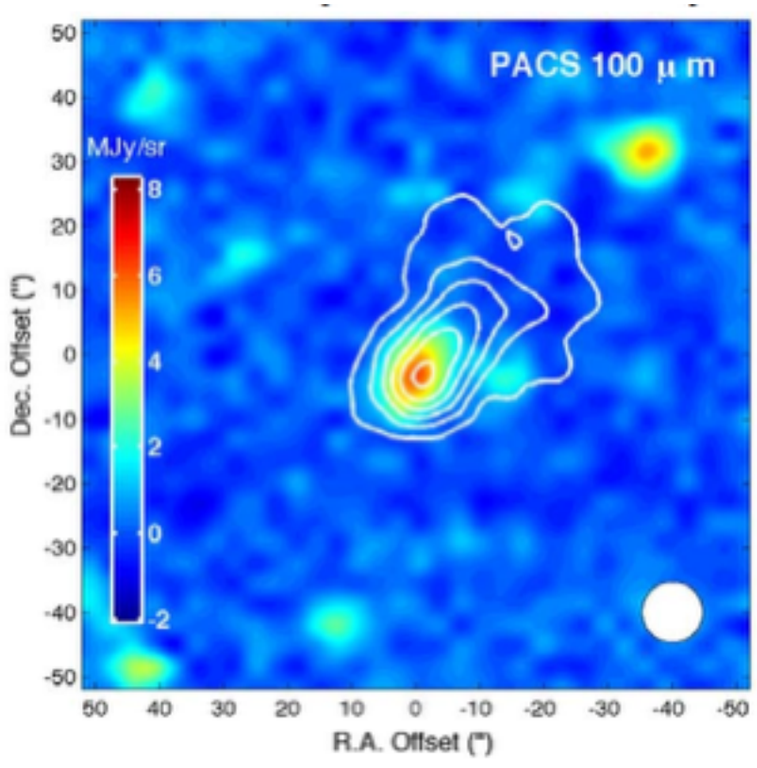
Remy-Ruyer et al. 2014 -
Dwarf Galaxies Survey with Herschel

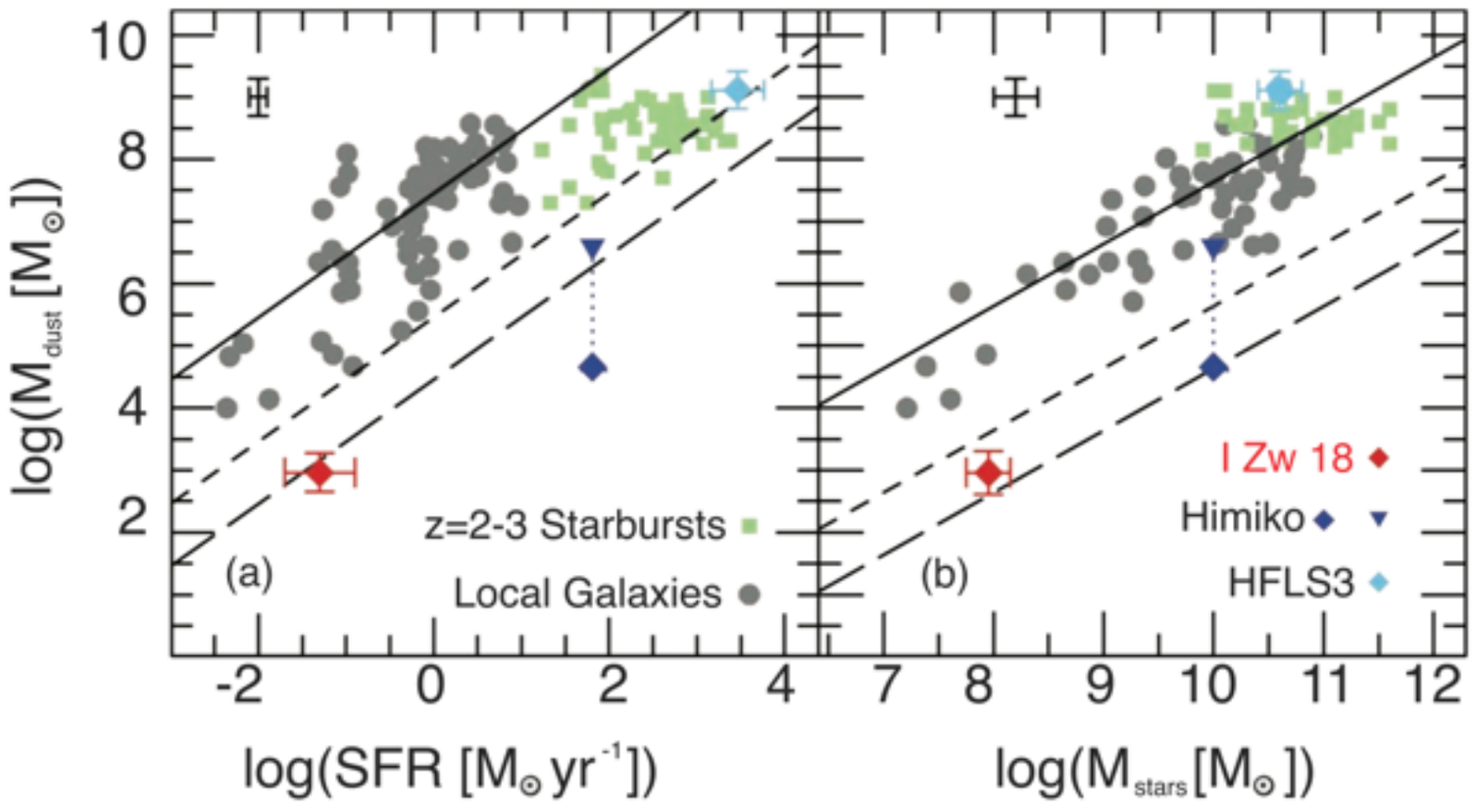


The Life Cycle of Interstellar Dust

*Dust-to-gas ratio **not** a simple function of metallicity in all conditions.*

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





This is extremely important for high-z galaxies.

The Life Cycle of Interstellar Dust

Dust-to-gas ratio may change between ISM phases as dust grains accrete material & coagulate.

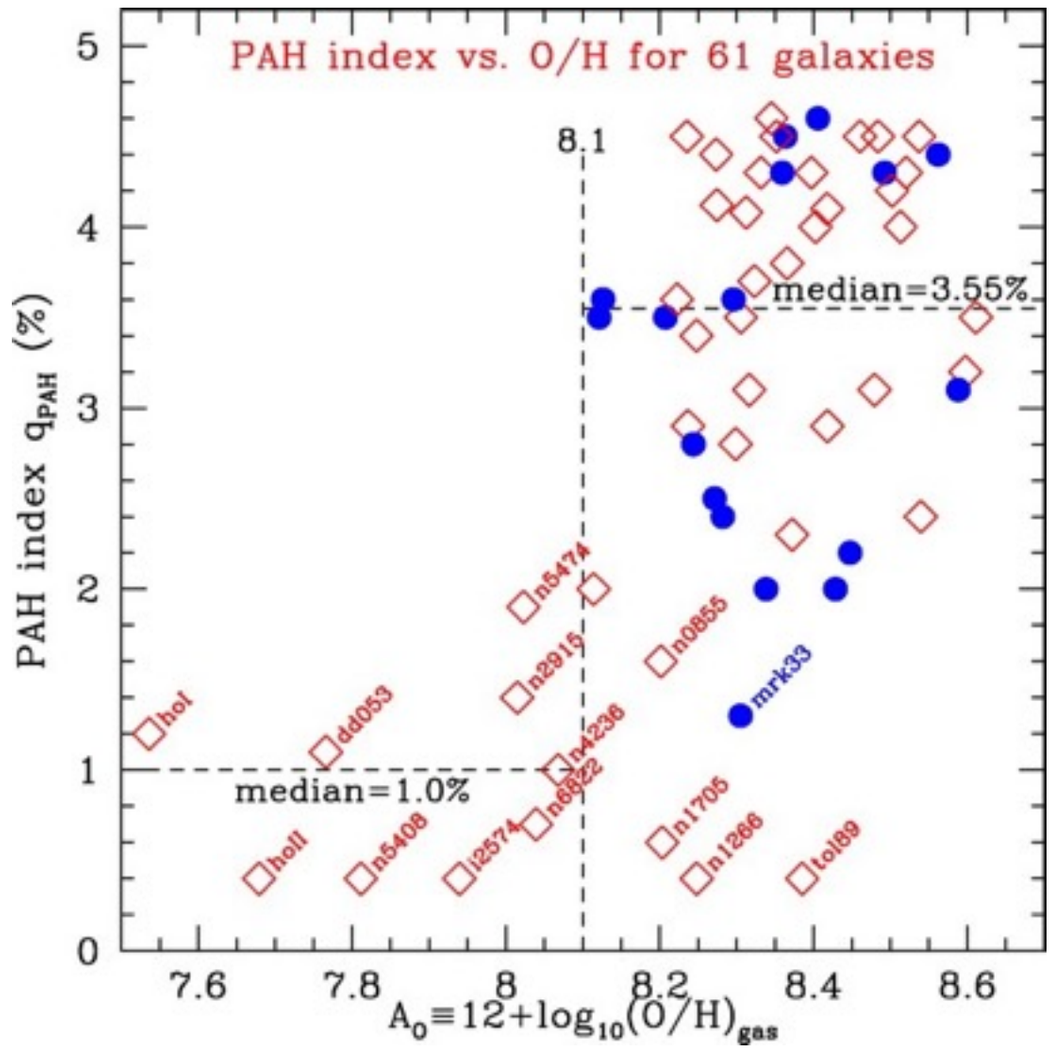
McKinnon, Torrey & Vogelsberger 2015 -
dust/metals in cosmological zoom-in simulations

DGR can vary with ISM phase: a key issue in using dust continuum as a tracer of total ISM mass.

The Life Cycle of Interstellar Dust

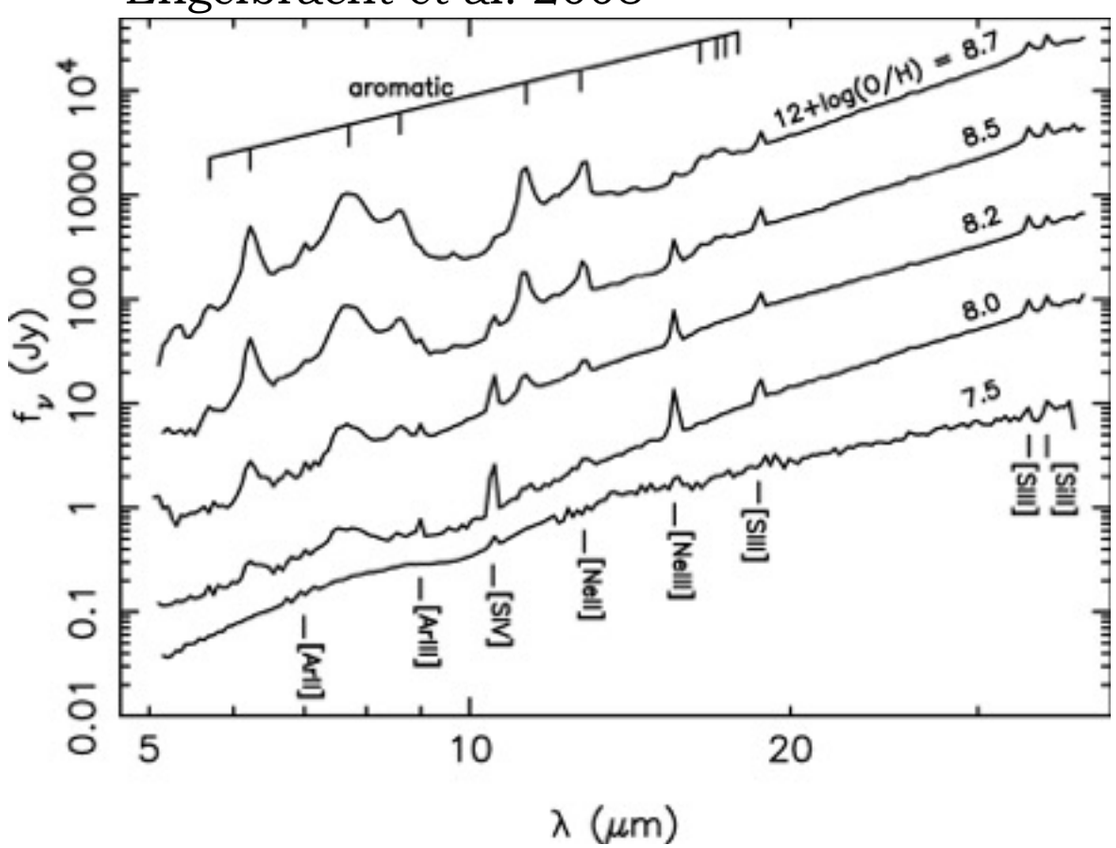
DGR is not the only thing changing -
composition & grain size distribution also vary.

Draine et al. 2007



e.g. PAH abundance

Engelbracht et al. 2008

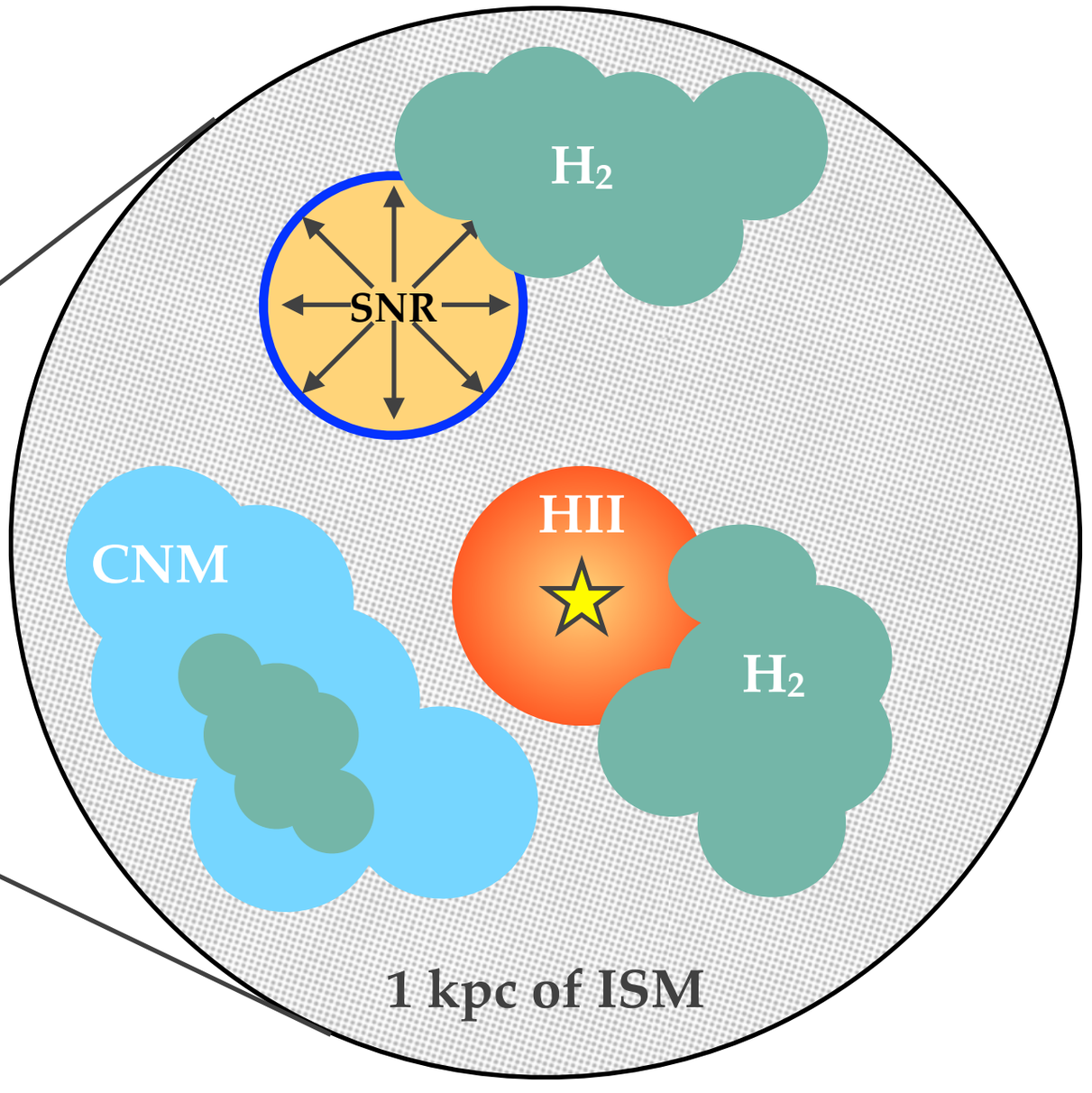


The Life Cycle of Interstellar Dust

Dust-to-gas ratio may change between ISM phases as dust grains accrete material & coagulate.

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

NGC 6946 from KINGFISH
Herschel PACS & SPIRE

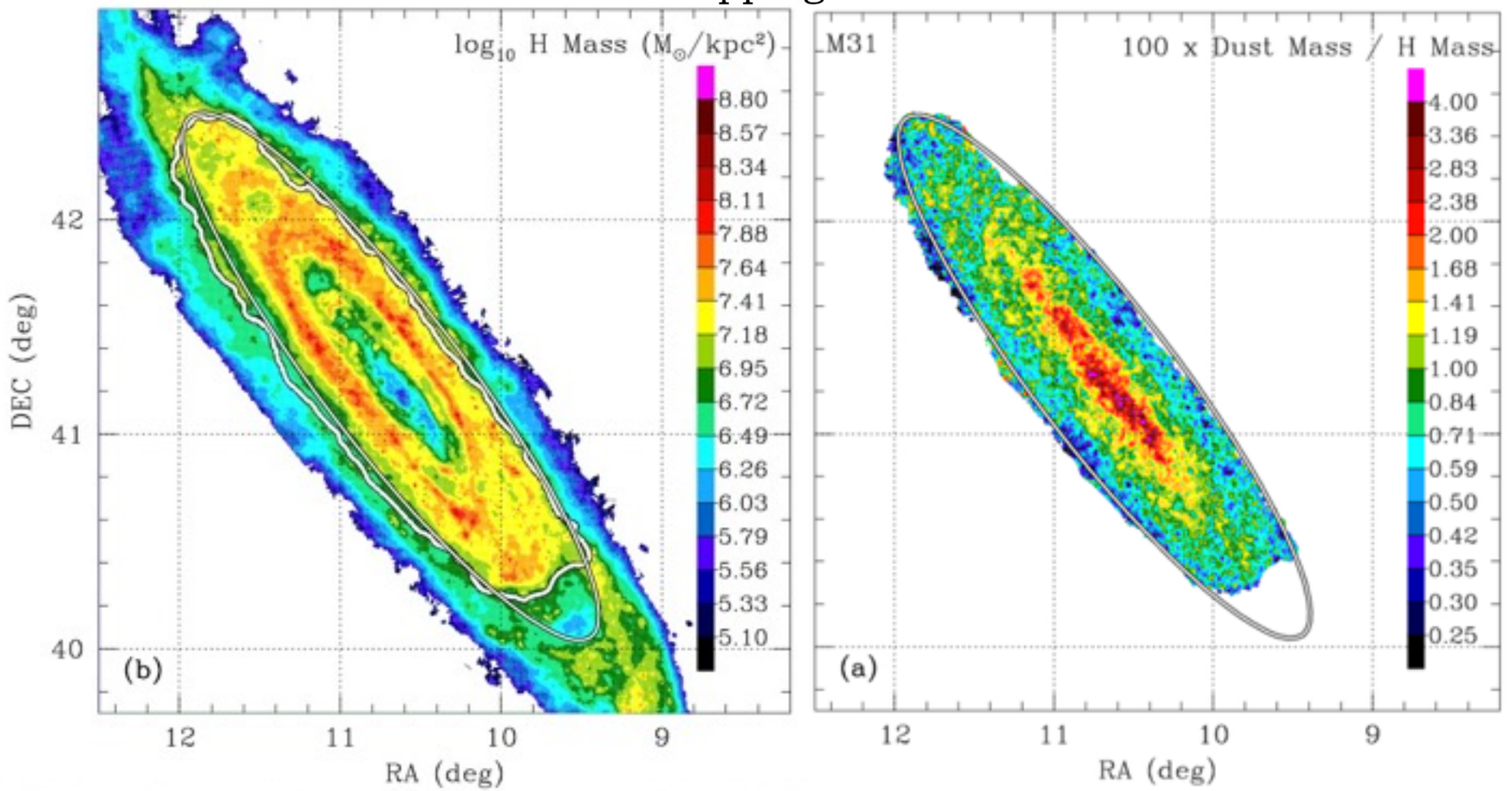


The Life Cycle of Interstellar Dust

Dust-to-gas ratio may change between ISM phases as dust grains accrete material & coagulate.

Current/past instruments can resolve this scale only in the Local Group.

Draine et al. 2014 - M31 Dust Mapping



The Life Cycle of Interstellar Dust

Studying dust life cycle with the Far-IR Surveyor

Singe Aperture

Similar to Herschel's resolution, but much higher sensitivity.

- Deep mapping of large numbers of galaxies, behavior of dust in representative sample
- Measurement of DGR & dust properties in low metallicity regions (i.e. outskirts of galaxies, dwarfs)

The Life Cycle of Interstellar Dust

Studying dust life cycle with the Far-IR Surveyor

Interferometer

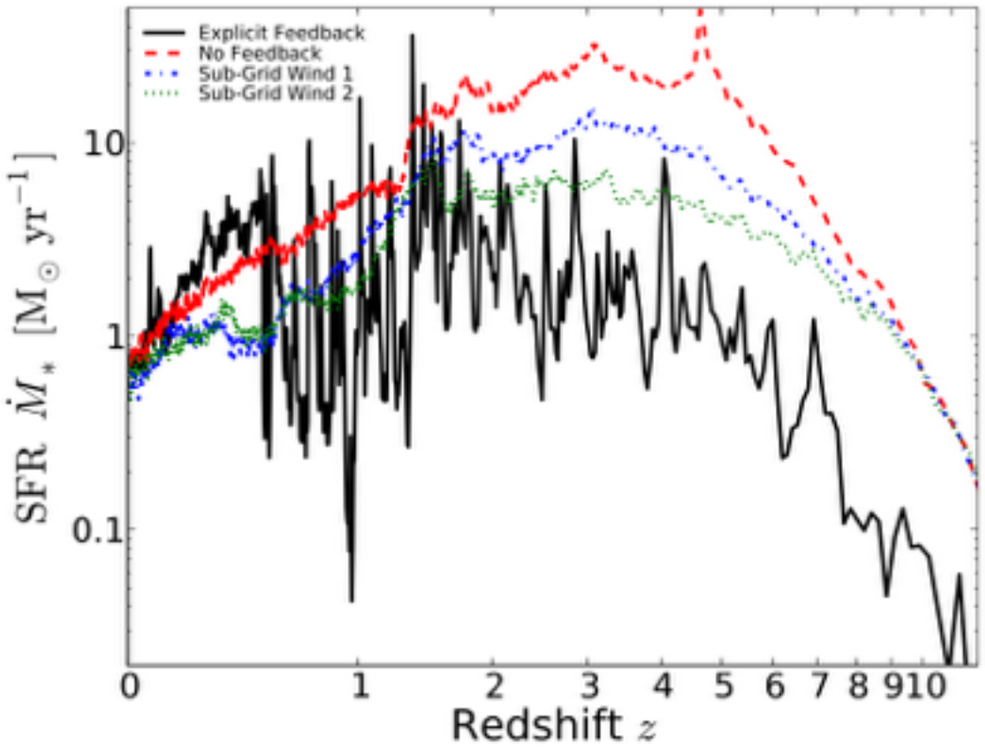
Very high resolution, but lower sensitivity and hard to do large samples of galaxies.

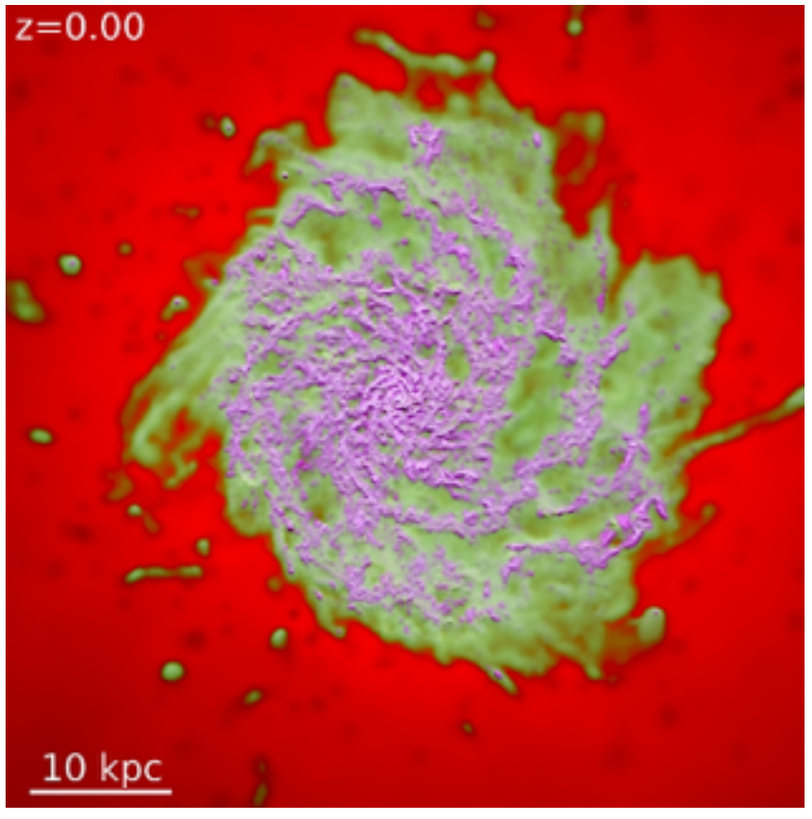
- Cloud scale mapping of dust emission combined with JWST & ALMA to trace evolution of dust vs ISM phase.

The Role of Feedback in SF & Galaxy Evolution

Feedback driven by star formation plays a key role in galaxy evolution.

Hopkins et al. 2014, “FIRE” simulation

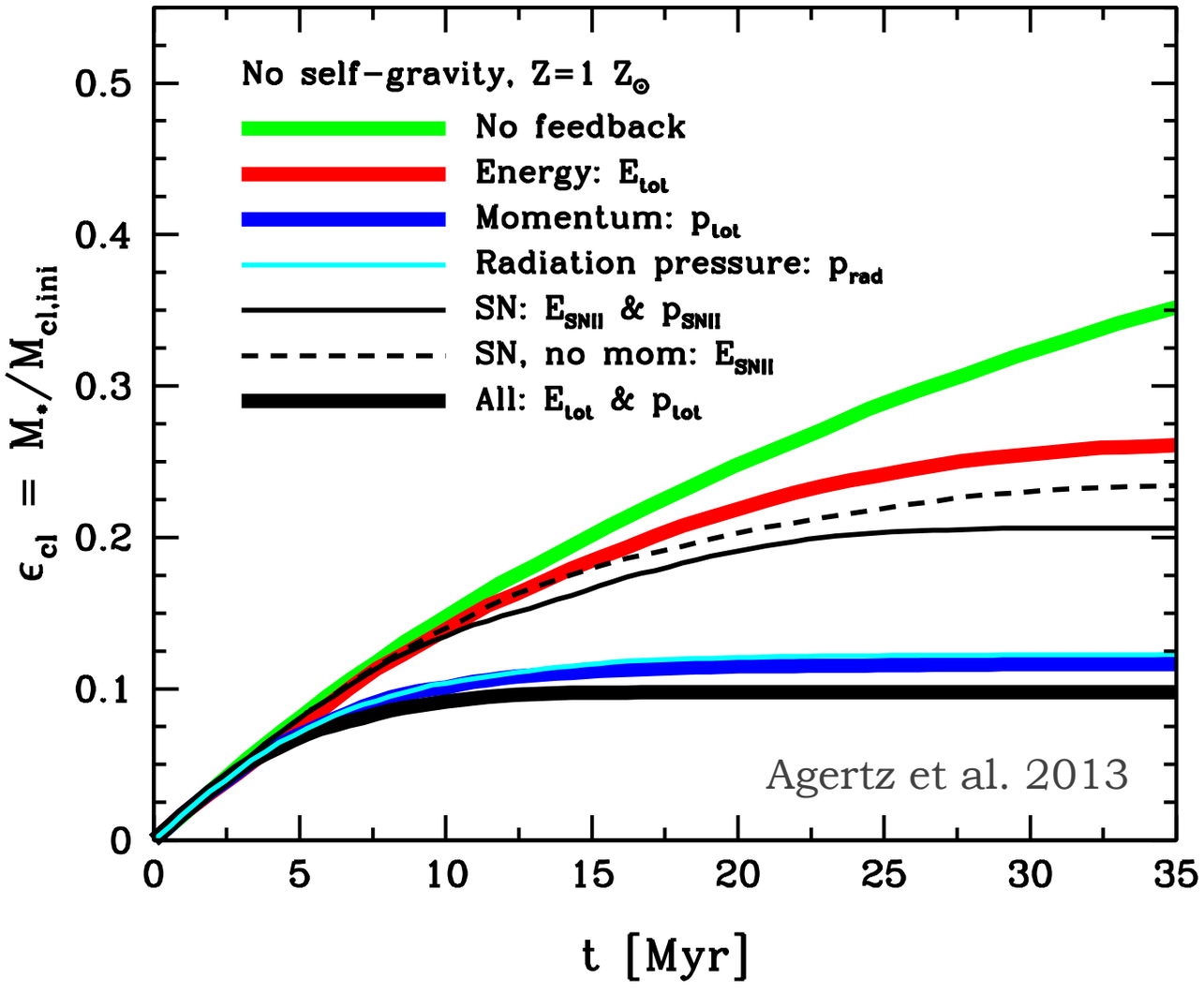




In simulations - feedback is needed to match star formation histories, stellar masses, disk properties of galaxies.

The Role of Feedback in SF & Galaxy Evolution

Feedback regulates star formation in molecular clouds.



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

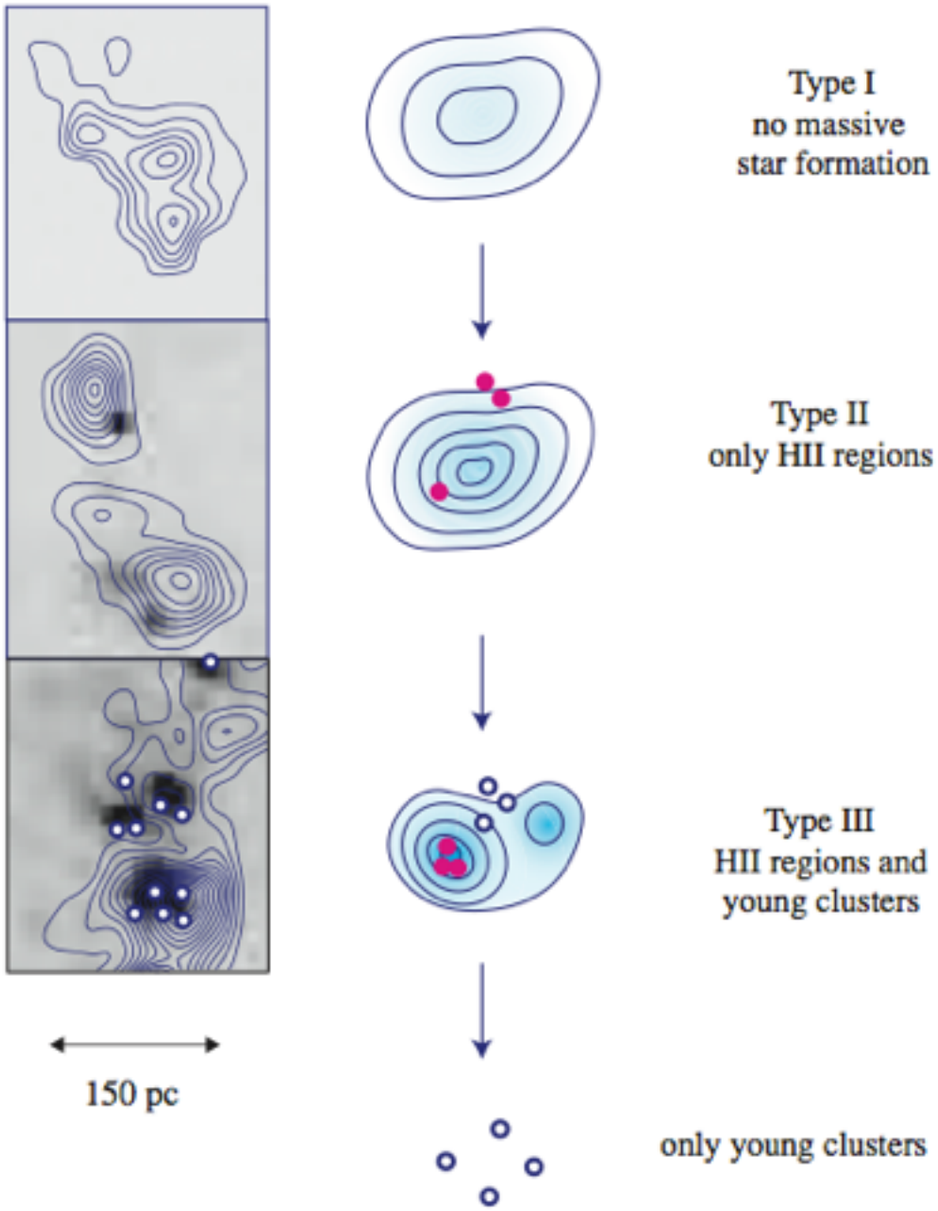
What is the dominant feedback source?

How does that vary with environment?

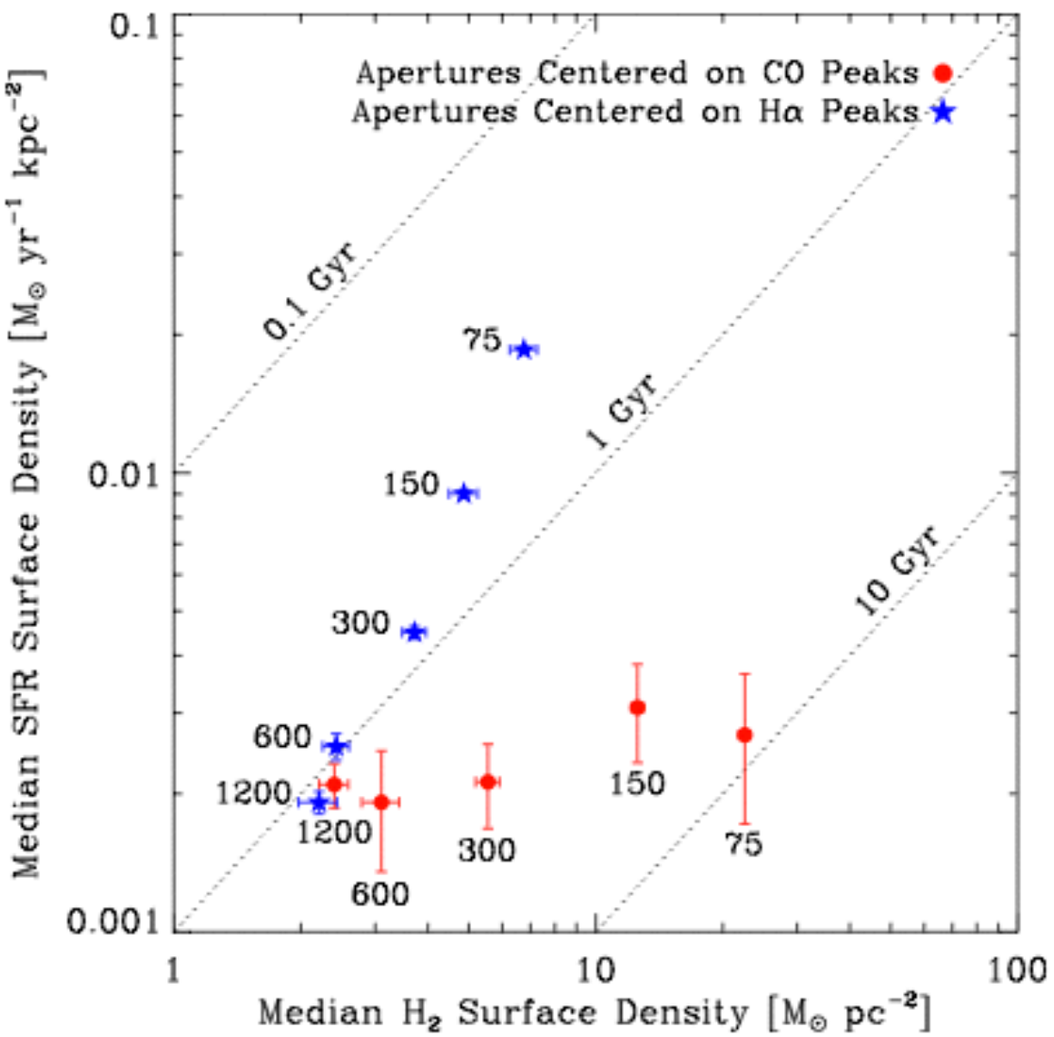
The Role of Feedback in SF & Galaxy Evolution

Some combination of radiation pressure, ionizing radiation, SNe, etc disrupt clouds.

Kawamura et al. 2009



Schruba et al. 2011

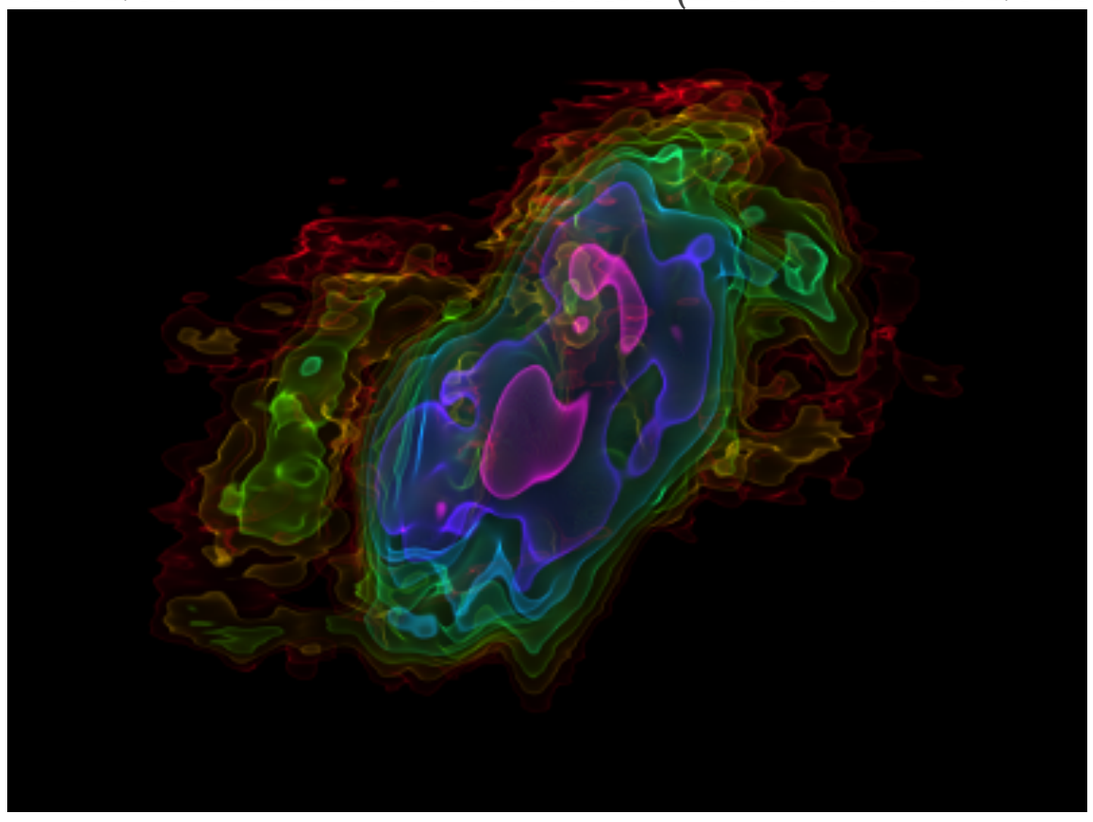


The Role of Feedback in SF & Galaxy Evolution

On galactic scales, winds eject material into the CGM and thereby regulate galaxy's gas reservoir.

M82 wind (optical/Hα)

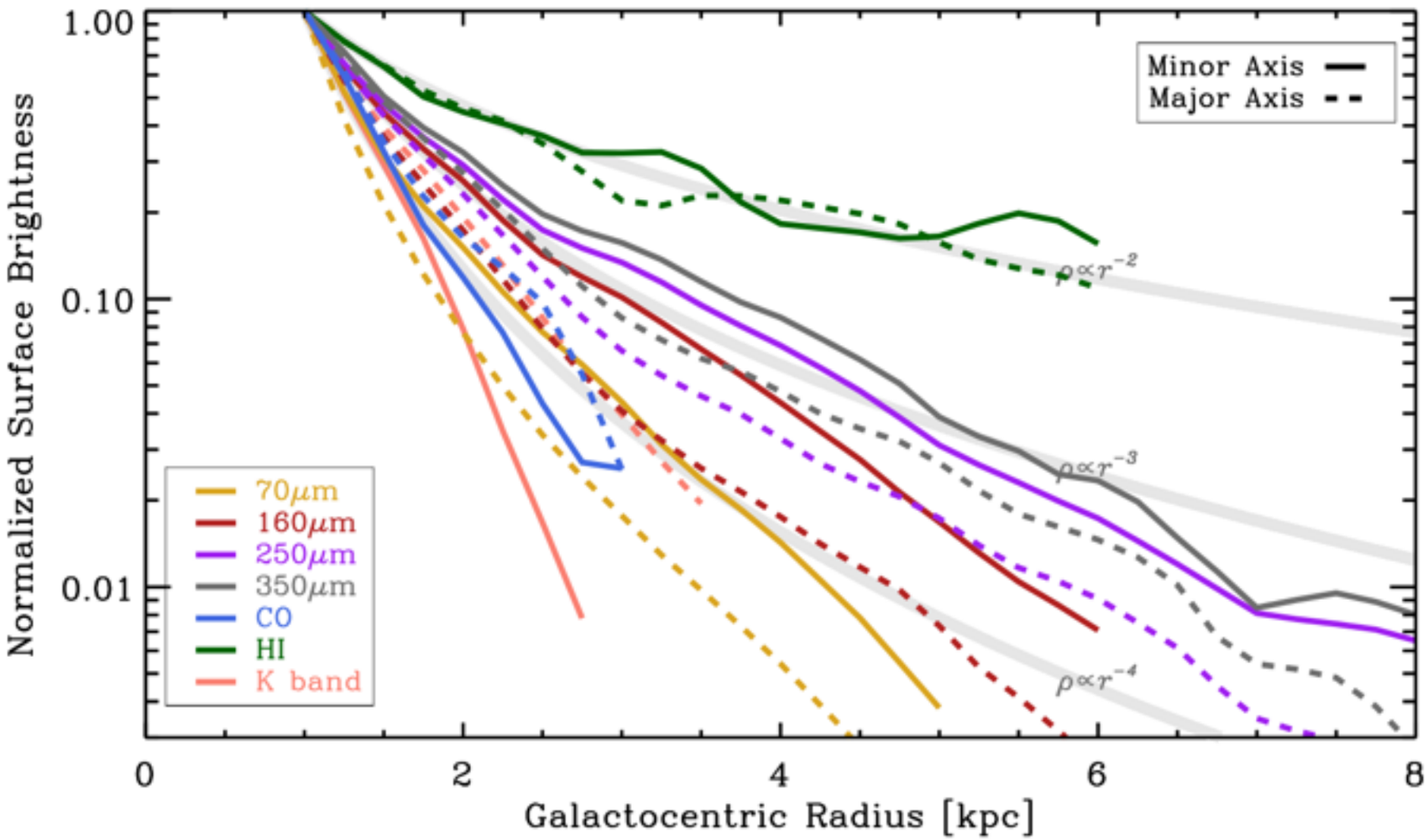
NGC 253 - ALMA CO contours (Bolatto et al. 2013)



The Role of Feedback in SF & Galaxy Evolution

Winds are comprised of multi-phase gas & dust.

Profiles of M82 wind at IR, CO, HI and K band (Leroy et al. 2015)



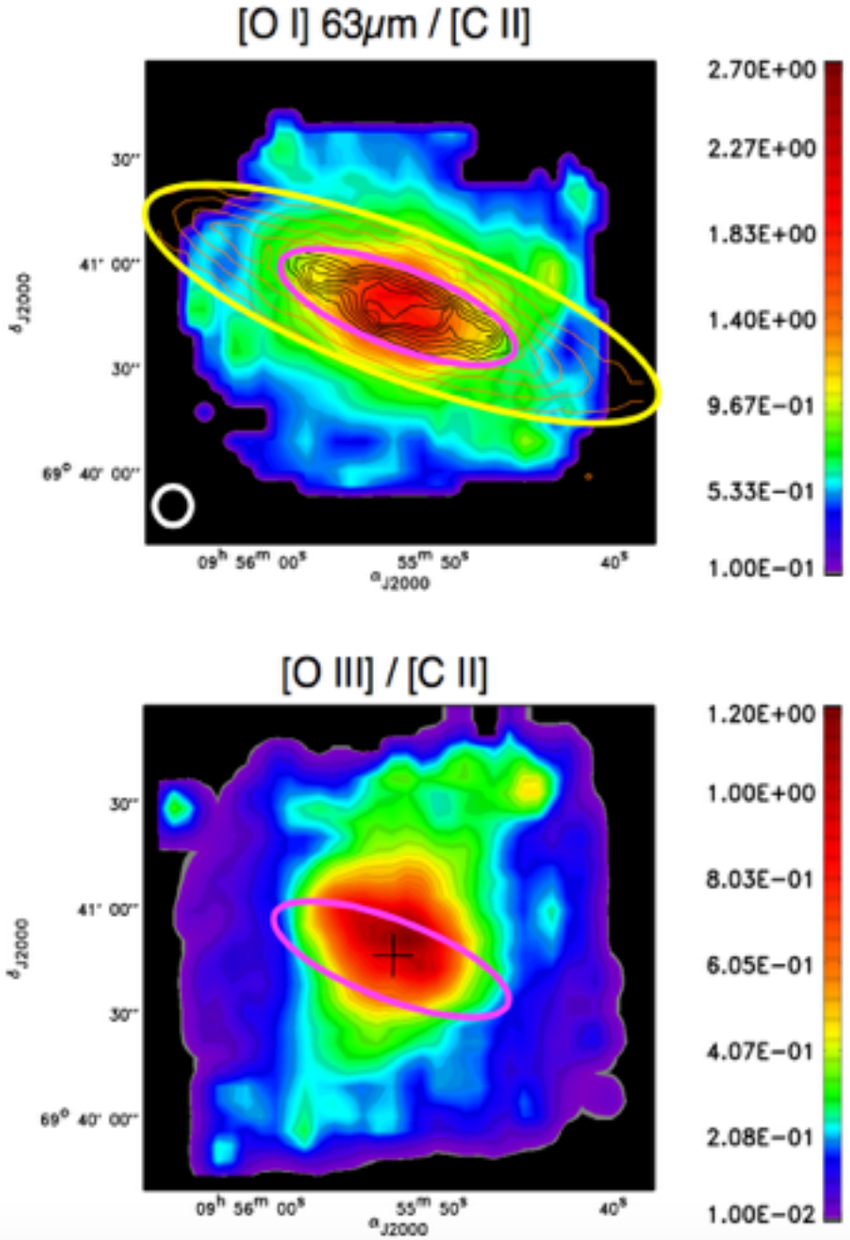
Assessing mass outflow is crucial to understanding galactic winds.

But wind material has ionized, atomic and molecular phases.

The Role of Feedback in SF & Galaxy Evolution

Far-IR line diagnostics give insight into phase structure of winds.

M82 Wind - Contursi et al. 2013



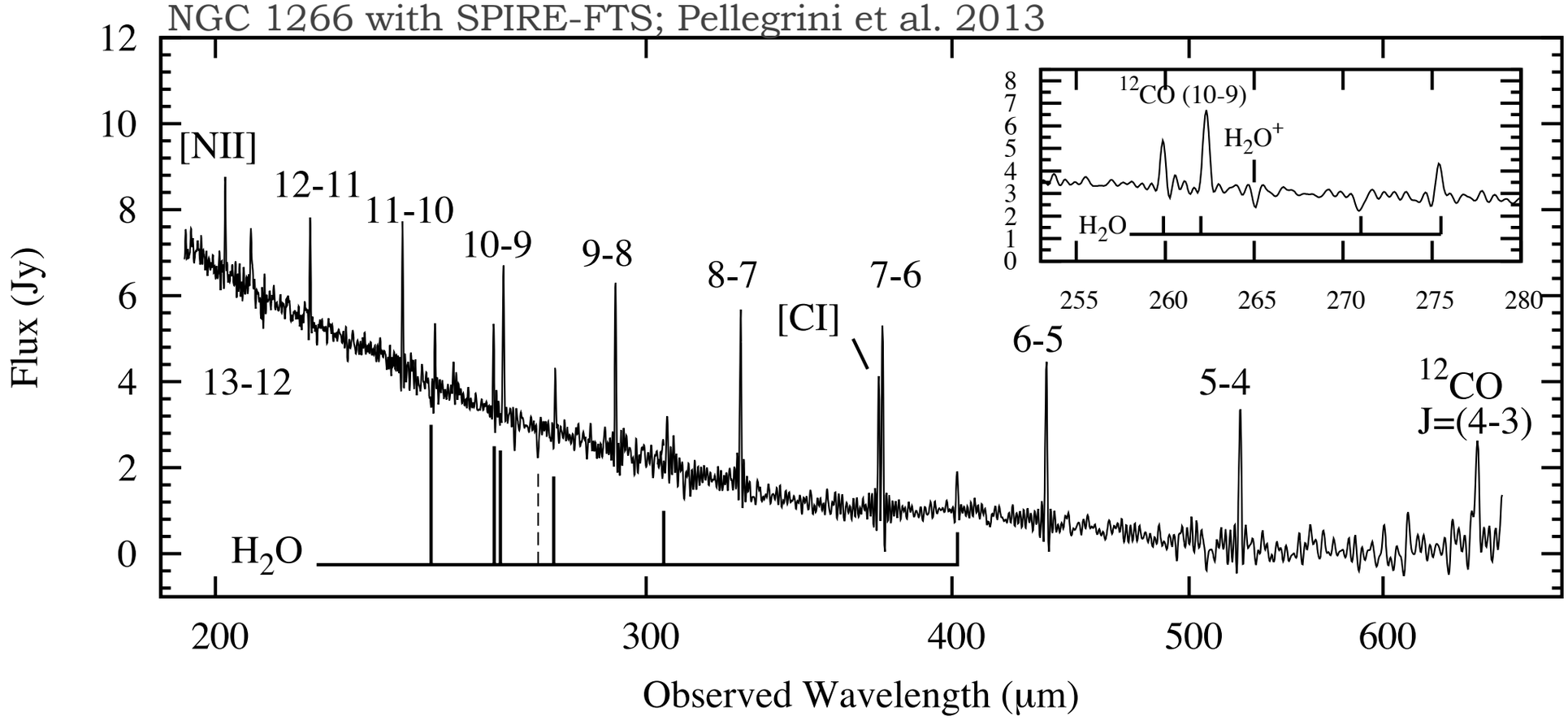
Far-IR lines provide diagnostics of phase structure & energetics of outflowing material.

Dust continuum (converted to gas with DGR & temp) gives total mass.

The Role of Feedback in SF & Galaxy Evolution

Excitation of molecular gas provides key insights into physics of feedback.

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



Other lines in the far-IR trace feedback as well.
(e.g. H_2O, rotational lines of other molecules, OH+).

^{12}CO and ^{13}CO ladder gives excellent handle on gas properties.

The Role of Feedback in SF

Studying feedback with the Far-IR Surveyor

Singe Aperture

High sensitivity to far-IR lines & dust at ~10-20″ resolution.

- [CII], [OI] & other far-IR line maps of galactic winds to dissect phases.
- Molecular gas excitation from ^{12}CO and ^{13}CO ladder at cloud scales in Local Group & kpc scales in many nearby galaxies constrains cloud disruption processes.
- Deep dust maps to trace outflow masses.

The Role of Feedback in SF

Studying feedback with the Far-IR Surveyor

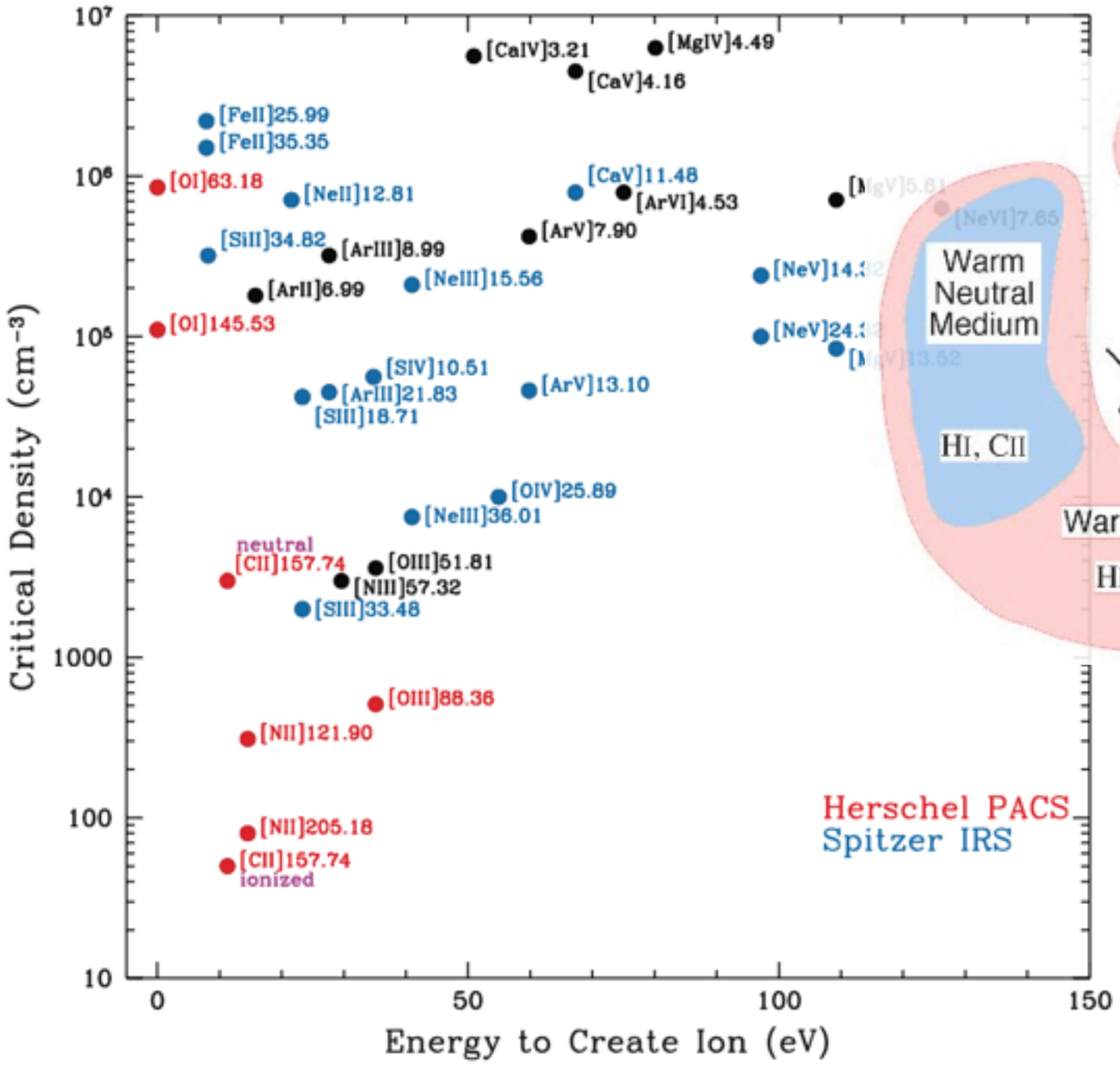
Interferometer

Cloud scale resolution far-IR line, dust and CO ladder measurements.

- High spatial resolution study of wind launching.
- Cloud-by-cloud molecular gas properties to constrain what causes disruption.

ISM Phase Balance

The far-IR lines give diagnostics of ISM phases and measurements of gas heating rates.



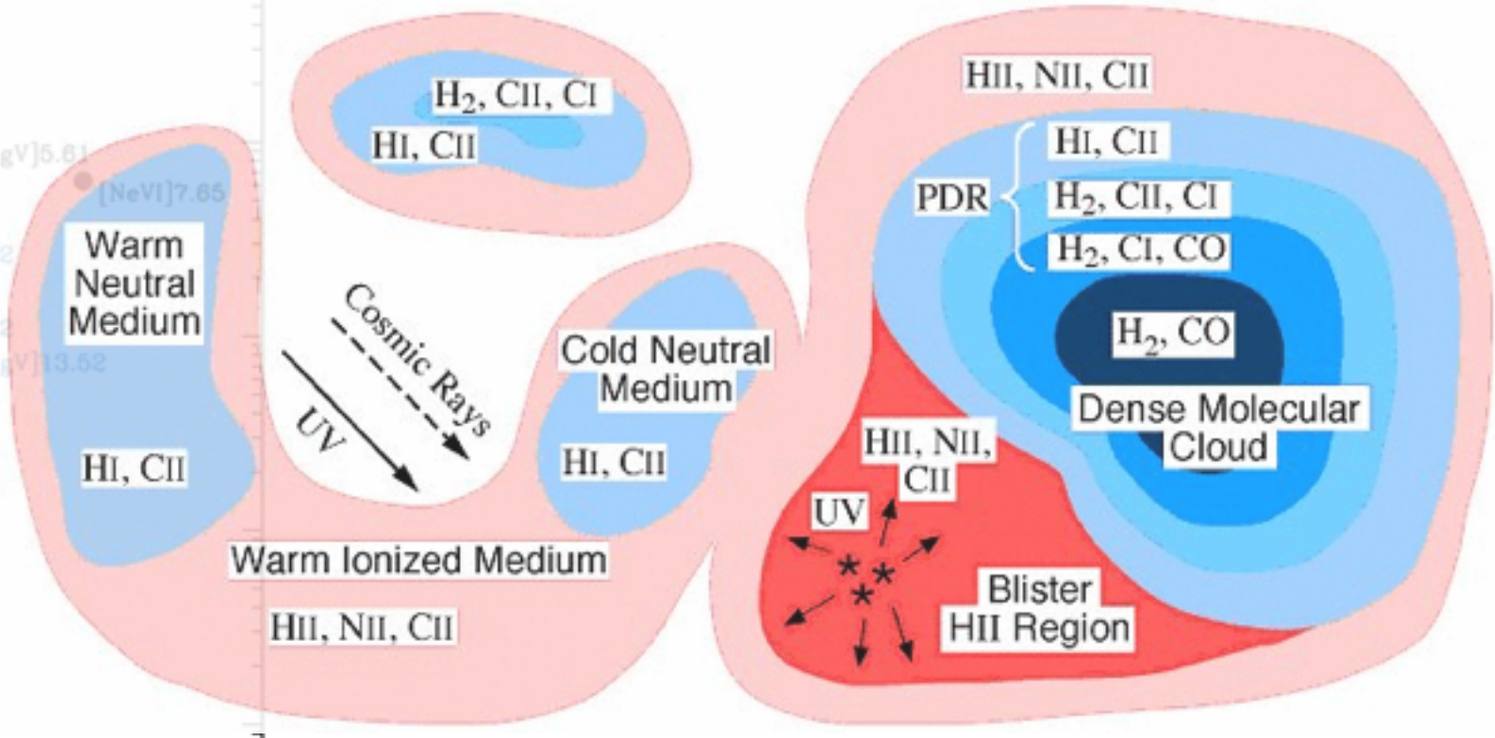
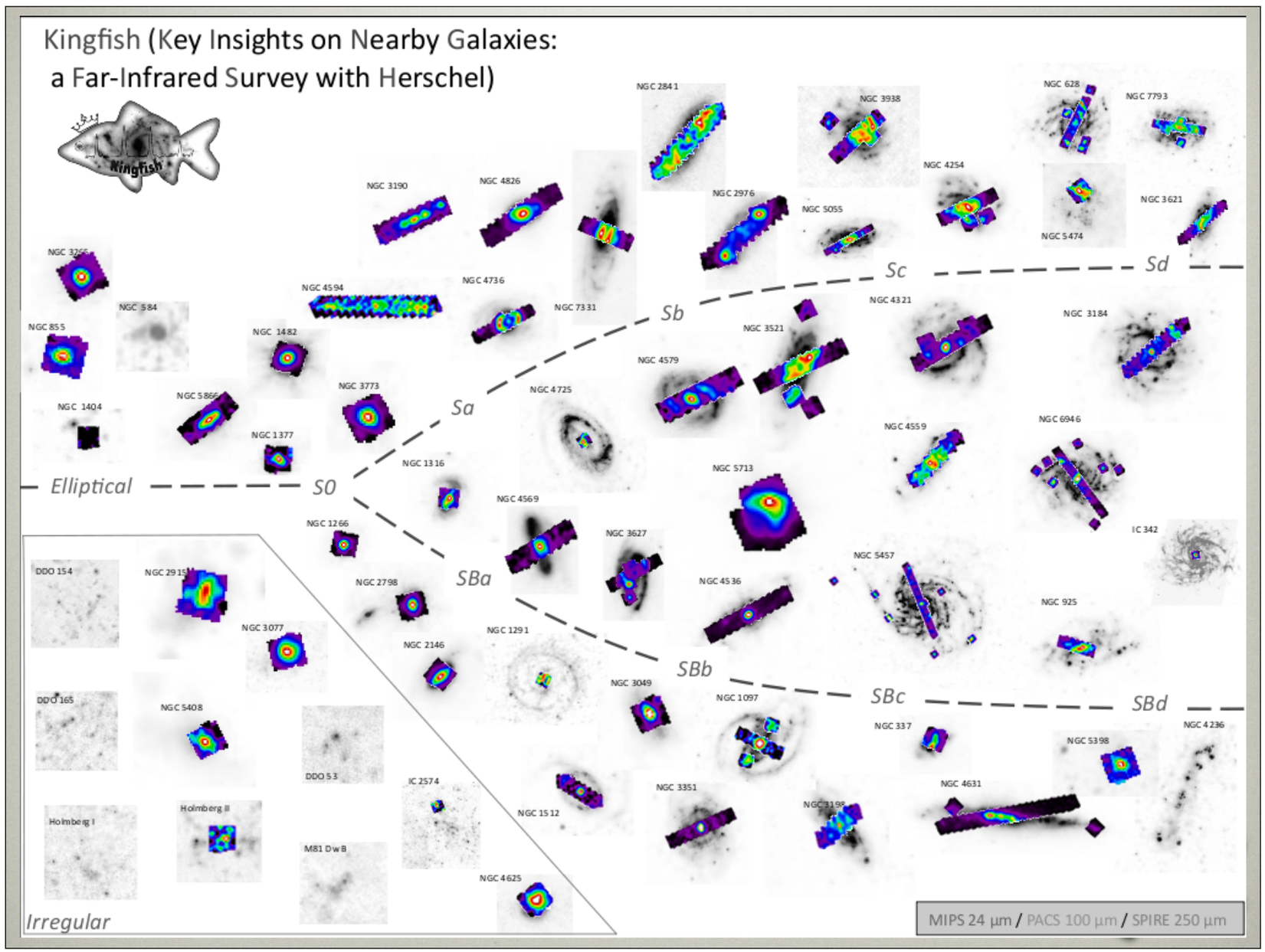


Figure from C. Kulesa & M. Wolfire

ISM Phase Balance

The far-IR lines give diagnostics of ISM phases and measurements of gas heating rates.



Measurements from Spitzer, Herschel & others have covered bright regions of nearby galaxies, with low (~200 km/s) velocity resolution and ~kpc spatial resolution.

ISM Phase Balance

The far-IR lines give diagnostics of ISM phases and measurements of gas heating rates.

Higher Velocity Resolution

ISM phase separation, e.g. GOT C+ but in nearby galaxies.

Higher Sensitivity

Studying the outer gas reservoir of galaxies, dwarf galaxies.

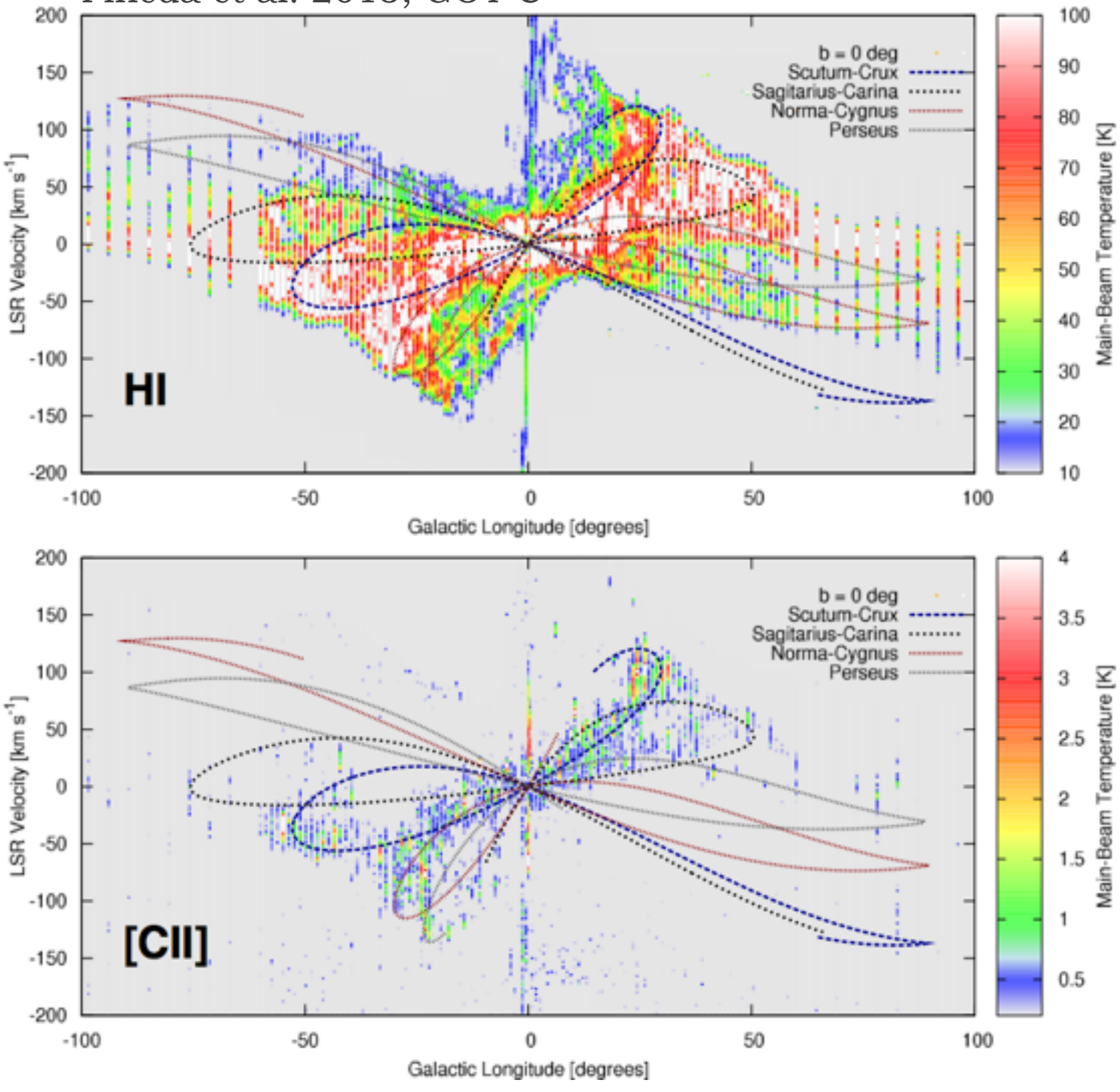
Higher Angular Resolution

Resolved studies of ISM phase transisitons.

ISM Phase Balance

ISM phase separation, e.g. GOT C+ but in nearby galaxies.

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

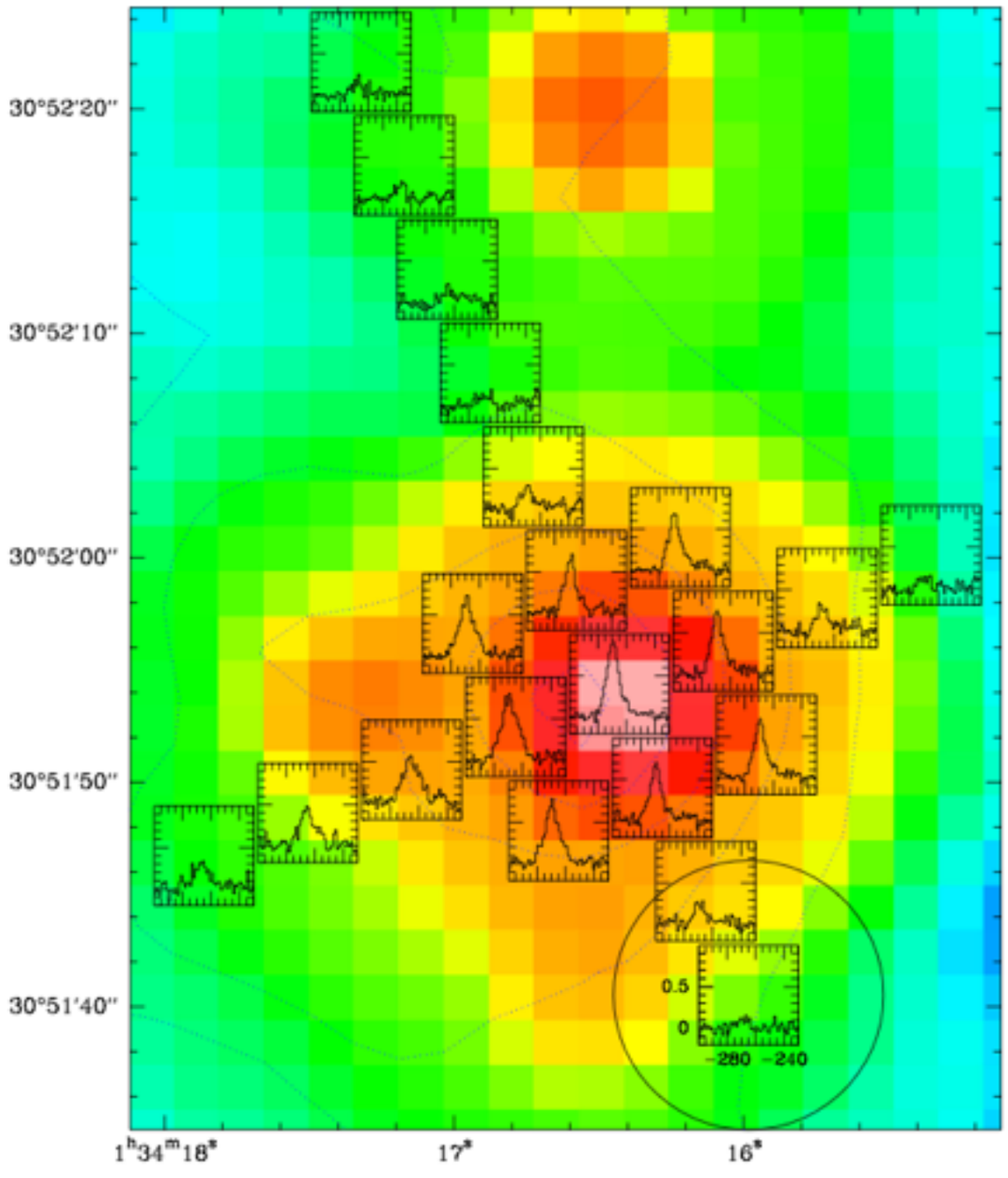
ISM phase separation, e.g. GOT C+ but in nearby galaxies.

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

Several recent or planned SOFIA-GREAT observations

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

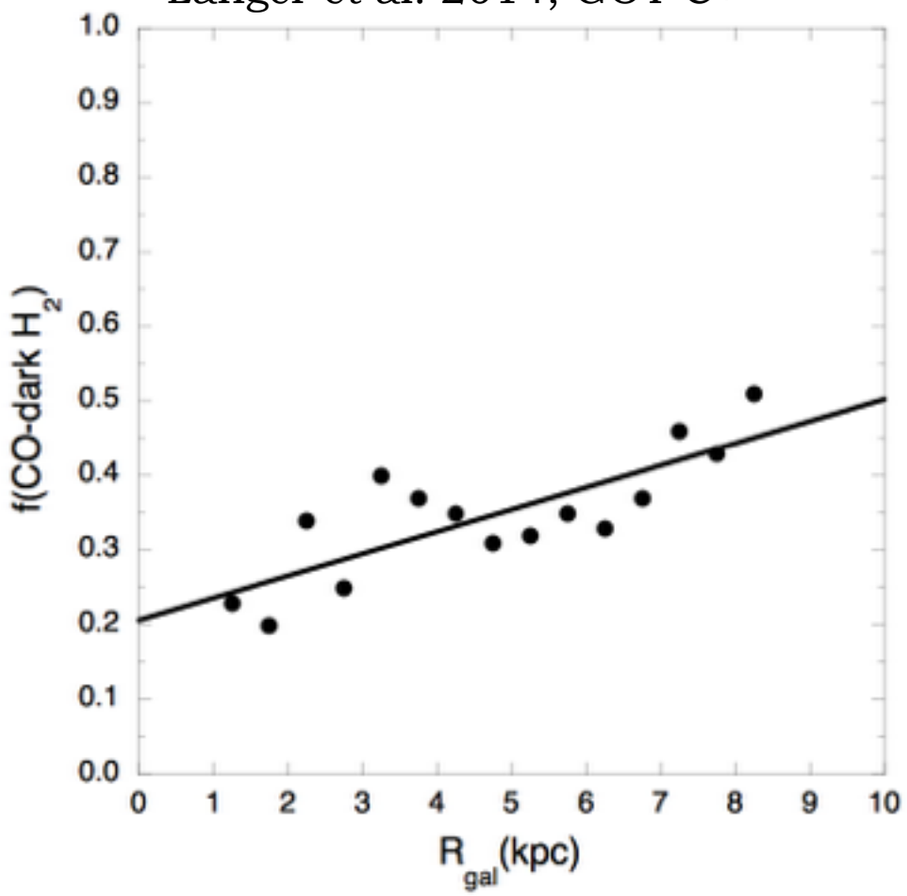
Braine et al. 2012 from HerM33es Key Program



ISM Phase Balance

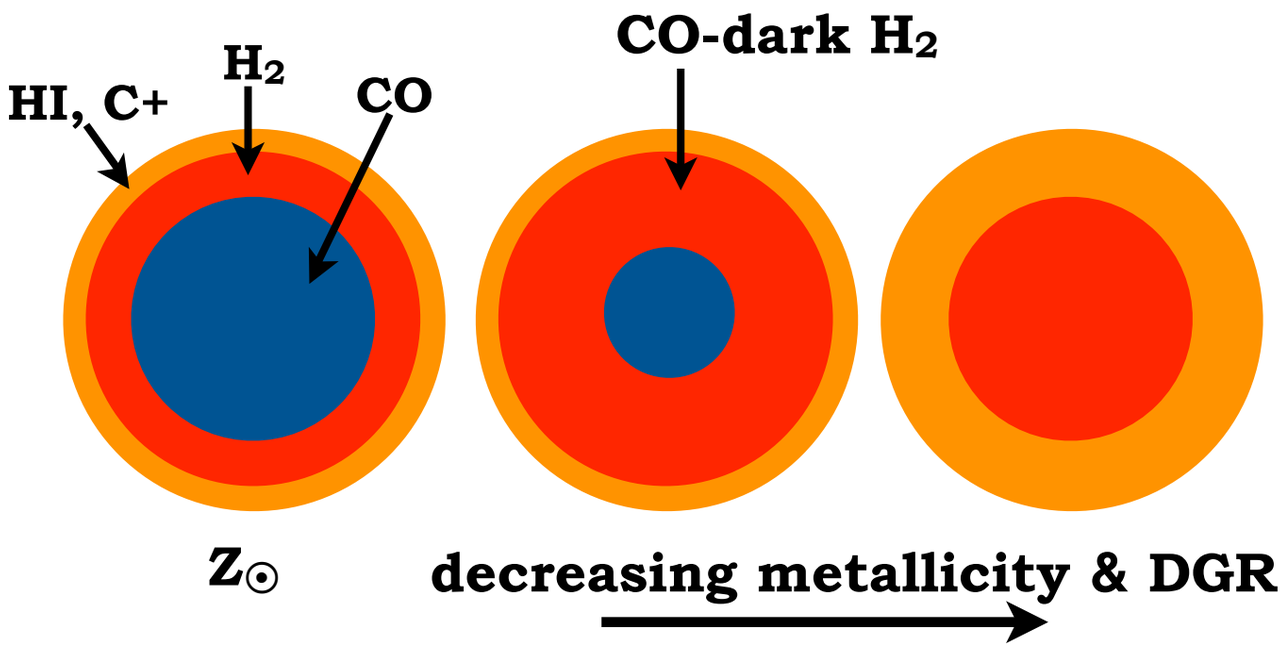
ISM phase separation, e.g. GOT C+ but in nearby galaxies.

Langer et al. 2014; GOT C+



GOT C+ measurement of CO-dark H2 fraction in the MW ISM.

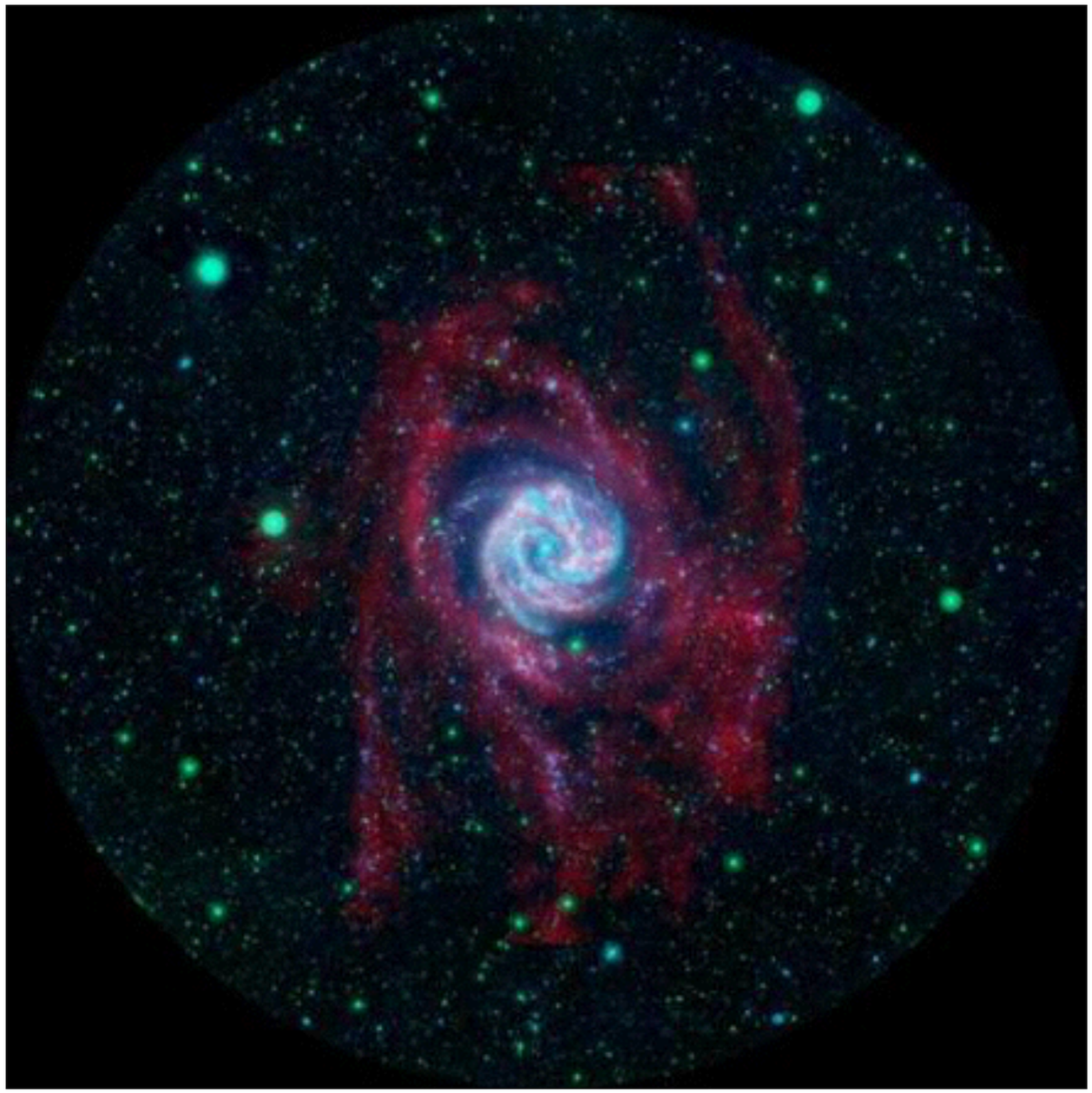
High-velocity resolution [CII] compared to CO/HI is one of the only ways to directly detect “CO-dark” H2.



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

ISM Phase Balance

Studying the outer gas reservoir of galaxies, dwarf galaxies.

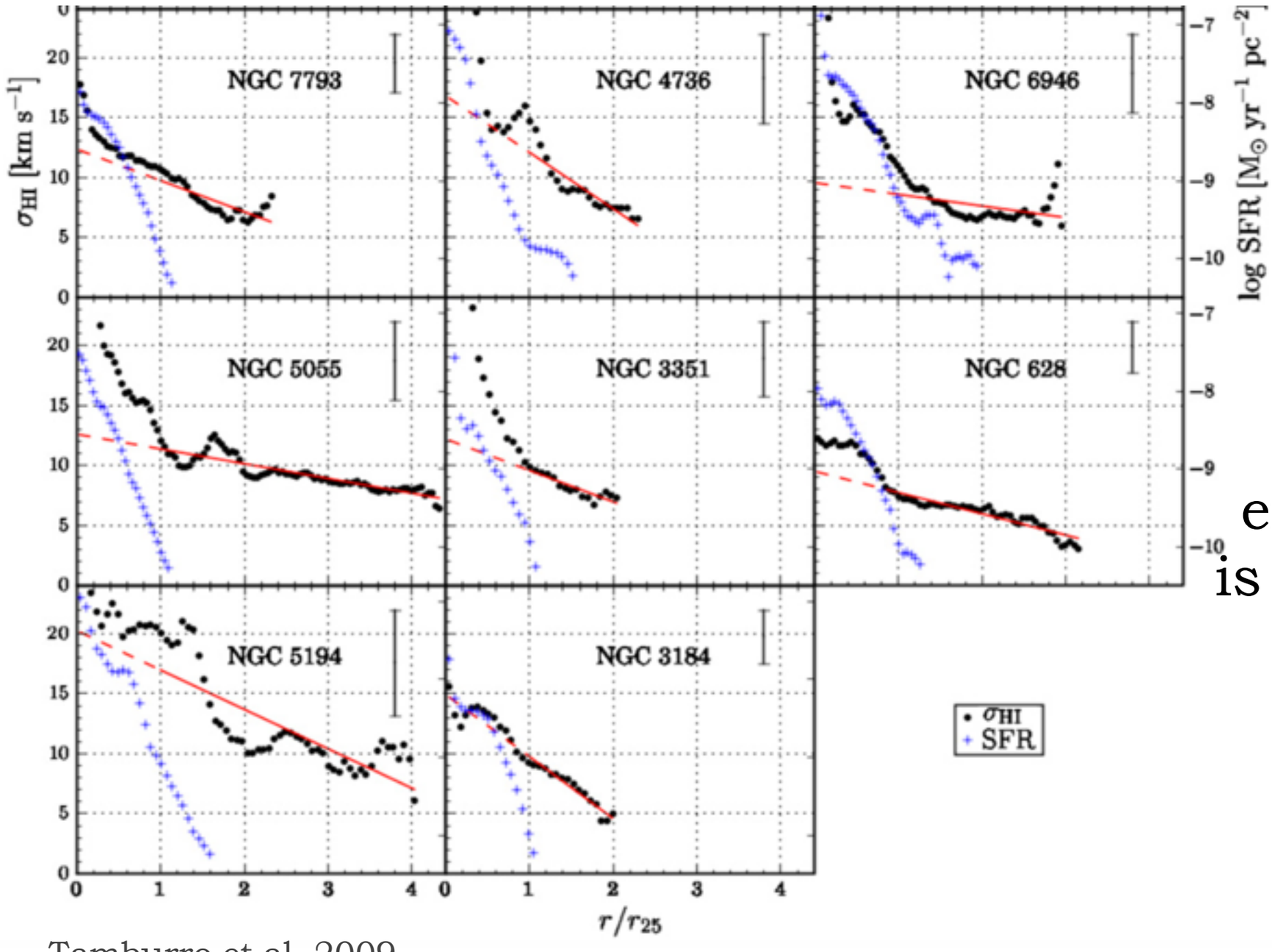


M83 - GALEX (blue,green) and HI (red)

Many star forming galaxies have large HI reservoirs in outer disks.

ISM Phase Balance

Studying the outer gas reservoir of galaxies, dwarf galaxies.



Tamburro et al. 2009

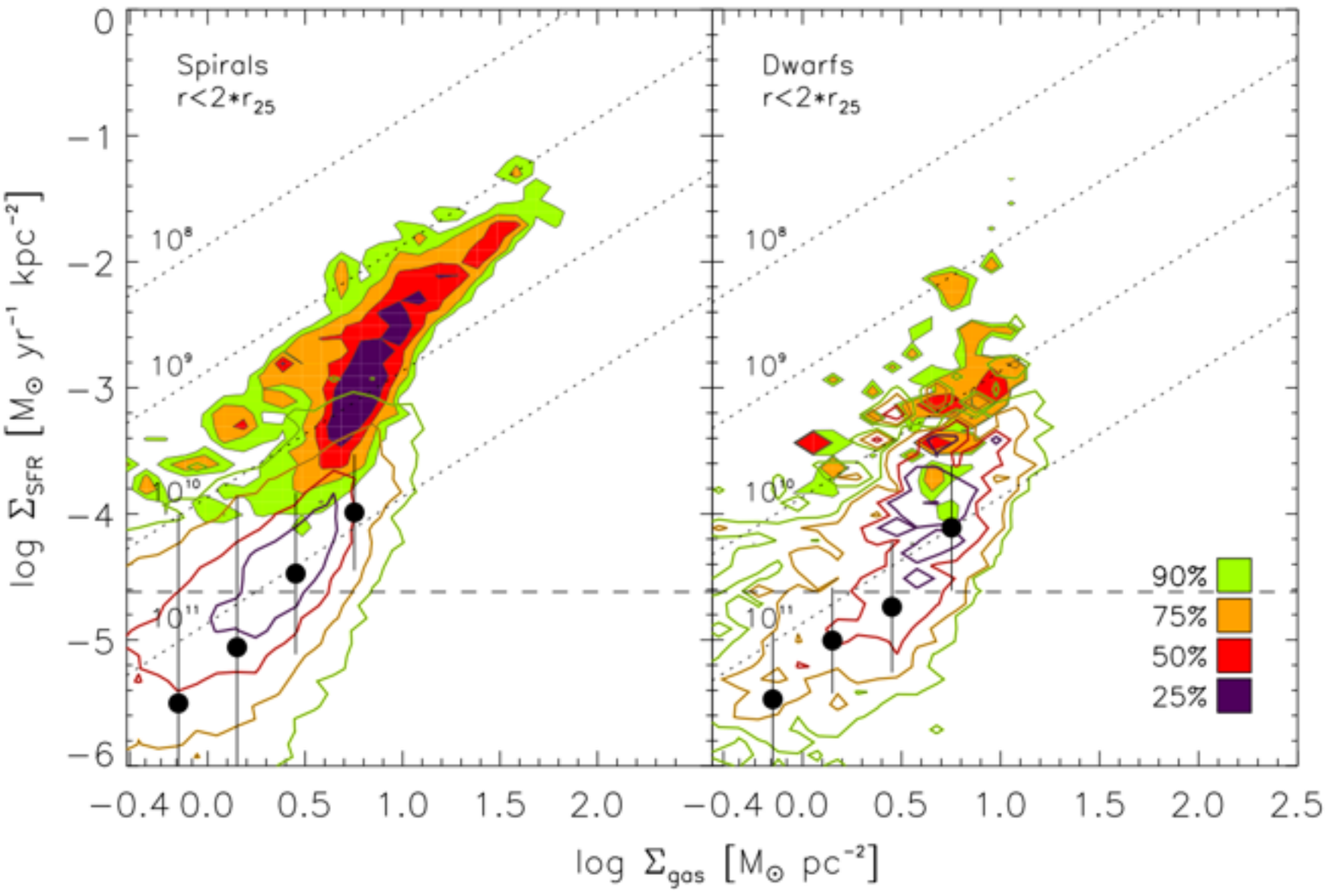
Many star forming galaxies have large HI reservoirs in outer disks.

Phase balance and energetics of this gas is not well understood.

ISM Phase Balance

Studying the outer gas reservoir of galaxies, dwarf galaxies.

Bigiel et al. 2010



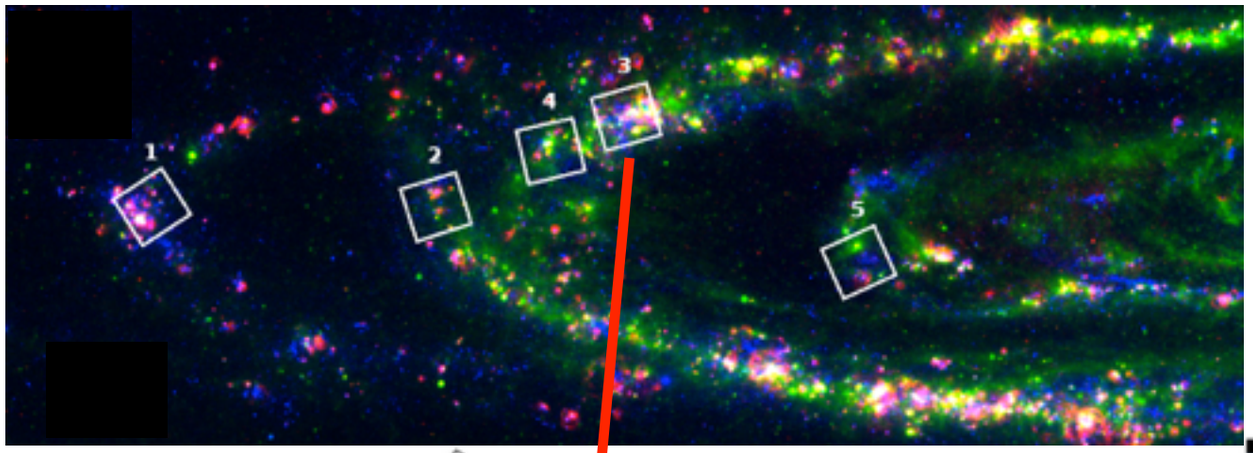
Many star forming galaxies have large HI reservoirs in outer disks.

Phase balance and energetics of this gas is not well understood.

Key to understand why SF is very inefficient in these conditions.

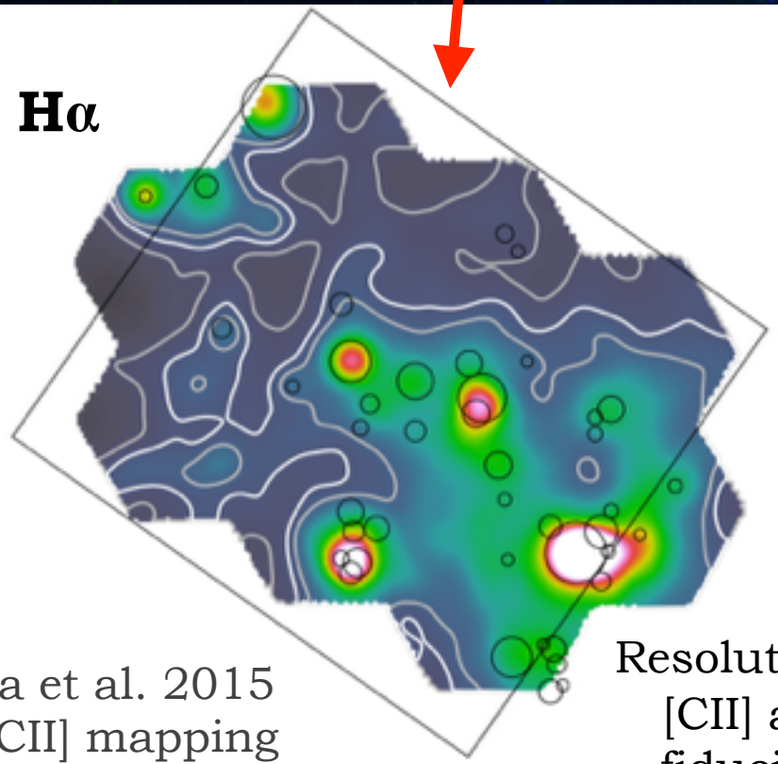
ISM Phase Balance

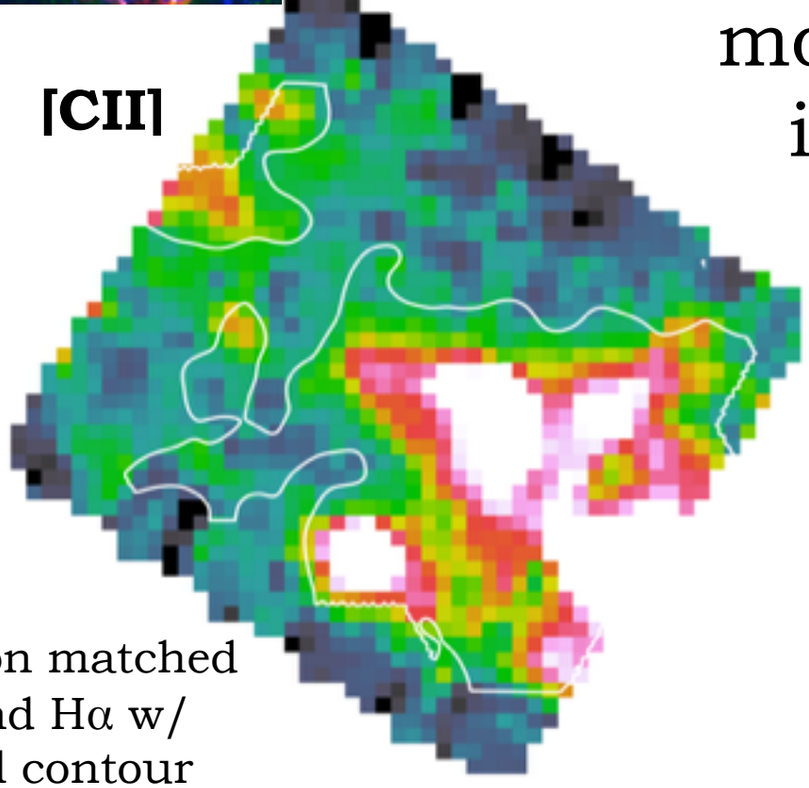
Resolved studies of ISM phase transitions.



Hα

[CII]





Kapala et al. 2015
M31 [CII] mapping

Resolution matched
[CII] and Hα w/
fiducial contour

1.0e36 5.0e38 1.0e39 1.5e39 2.0e39 2.5e39 3.0e39 3.5e39

erg s^{-1} kpc^{-2}

Cloud-scale (~50 pc) resolution would allow spatially separating far-IR line emission from molecular/atomic/ionized phases.

ISM Phase Balance

Studying ISM phases with the Far-IR Surveyor

Singe Aperture

High sensitivity to far-IR lines & dust at ~10-20″ resolution.

- Far-IR line maps of outer disks, dwarfs to address ISM phase balance & SF regulation.
- Identification of “CO-dark” gas with high velocity resolution measurements.

ISM Phase Balance

Studying ISM phases with the Far-IR Surveyor

Interferometer

Cloud scale resolution far-IR line measurements.

- Cloud-by-cloud study of ISM conditions revealed by far-IR lines in galaxies out to 30 Mpc.

Nearby Galaxy Science Summary

Interferometer

Dust continuum & far-IR lines at **GMC scale resolution** (~50 pc) in D<30 Mpc galaxies. **Targeted studies**, matched with ALMA/JWST resolution.

- Evolution of dust properties between diffuse/dense ISM.
- Spatial dissection of far-IR line emission from various ISM phases.
- Cloud-by-cloud diagnostics of feedback from SF.

Single Aperture

Dust continuum & far-IR lines at ~kpc resolution in D<30 Mpc galaxies. **High sensitivity** maps. **Large samples of galaxies**.

- Deep maps of far-IR lines and dust to trace outflows, ISM phase balance in outer gas disks & dwarfs.
- Dust properties low metallicity conditions.
- Cloud scale measurements in the Local Group, especially CO ladders, to study feedback processes.