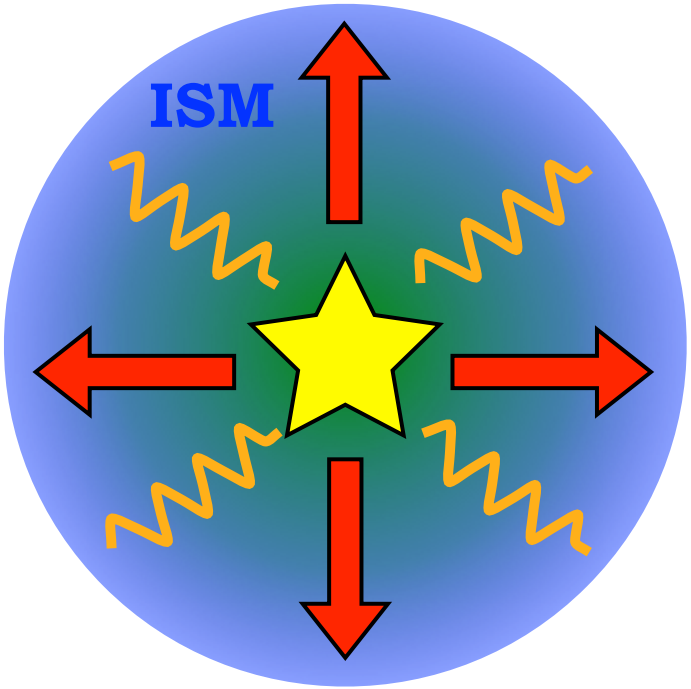
# Observing Stellar Energy Input into the ISM in Nearby Galaxies


Karin Sandstrom
Bok Fellow - University of Arizona

"Fire Down Below" - KITP April 15, 2014

# What We'd Like to Learn about Feedback



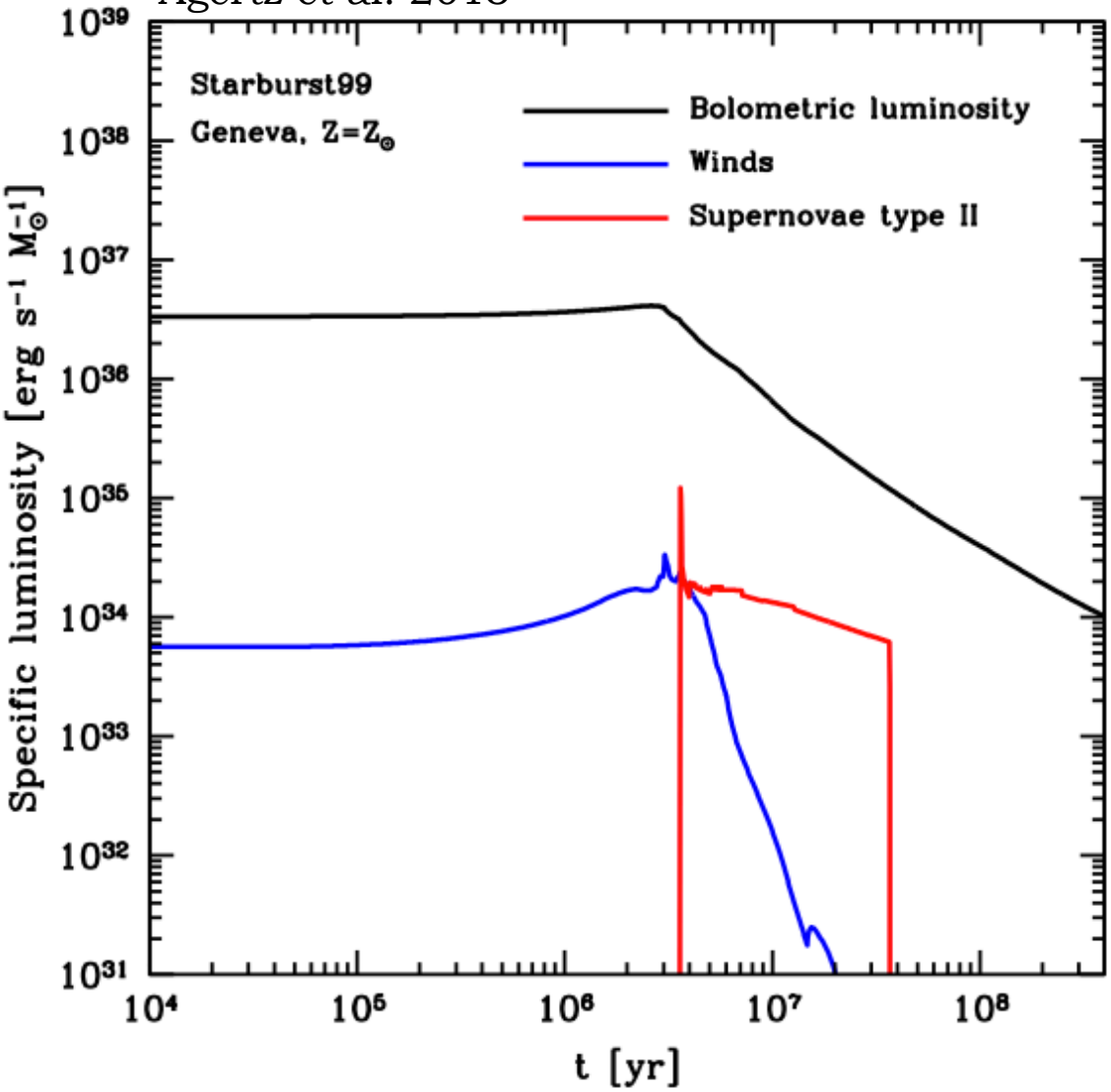

Energy = radiative & mechnical

- Energy(time)
- Energy(position)
- Energy(ISM phase)

# What We'd Like to Learn about Feedback

*Stellar Evolution gives us this…*

Agertz et al. 2013



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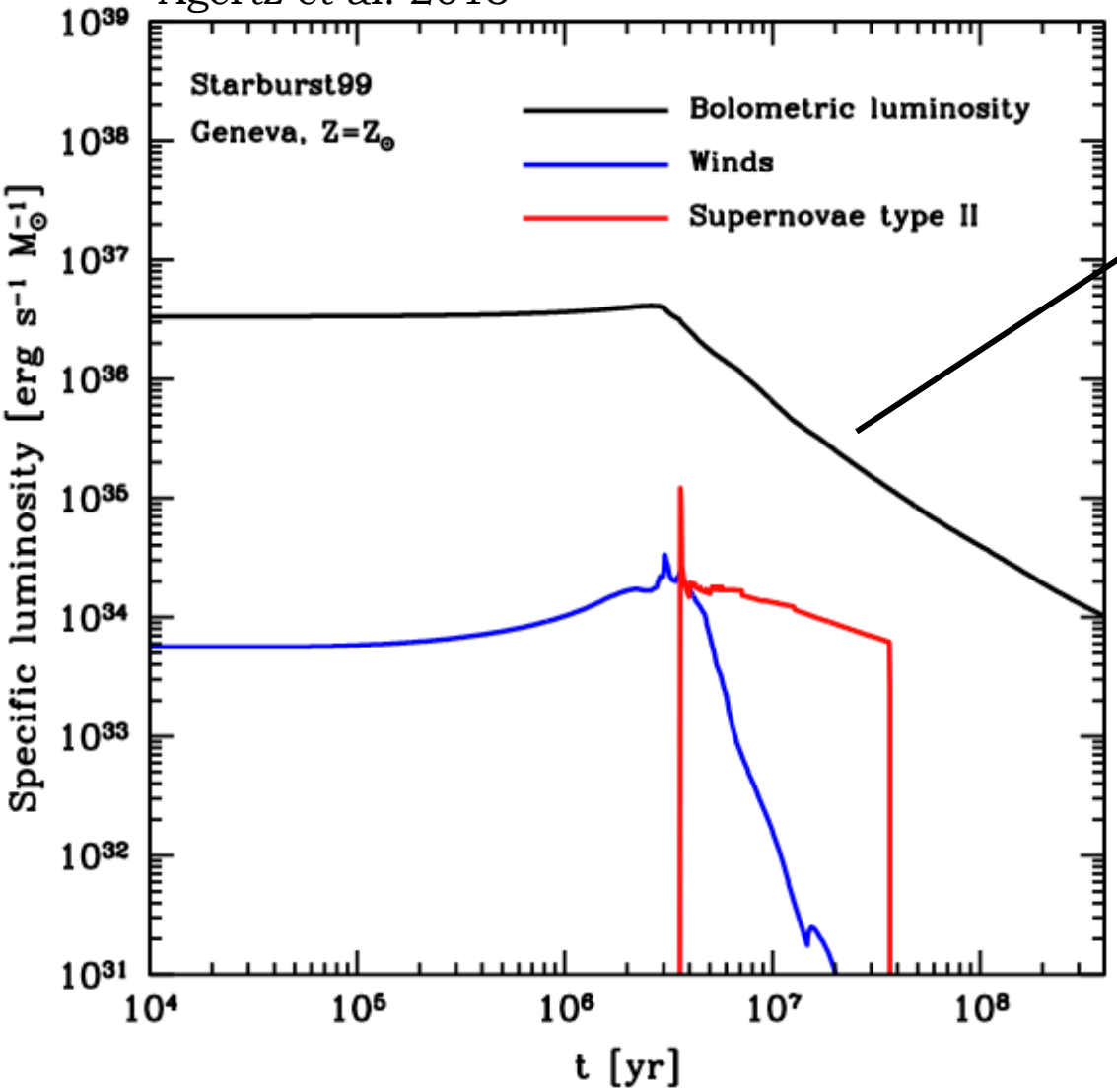


fraction into ionization, photoelectric heating, dust heating?

deposited where?

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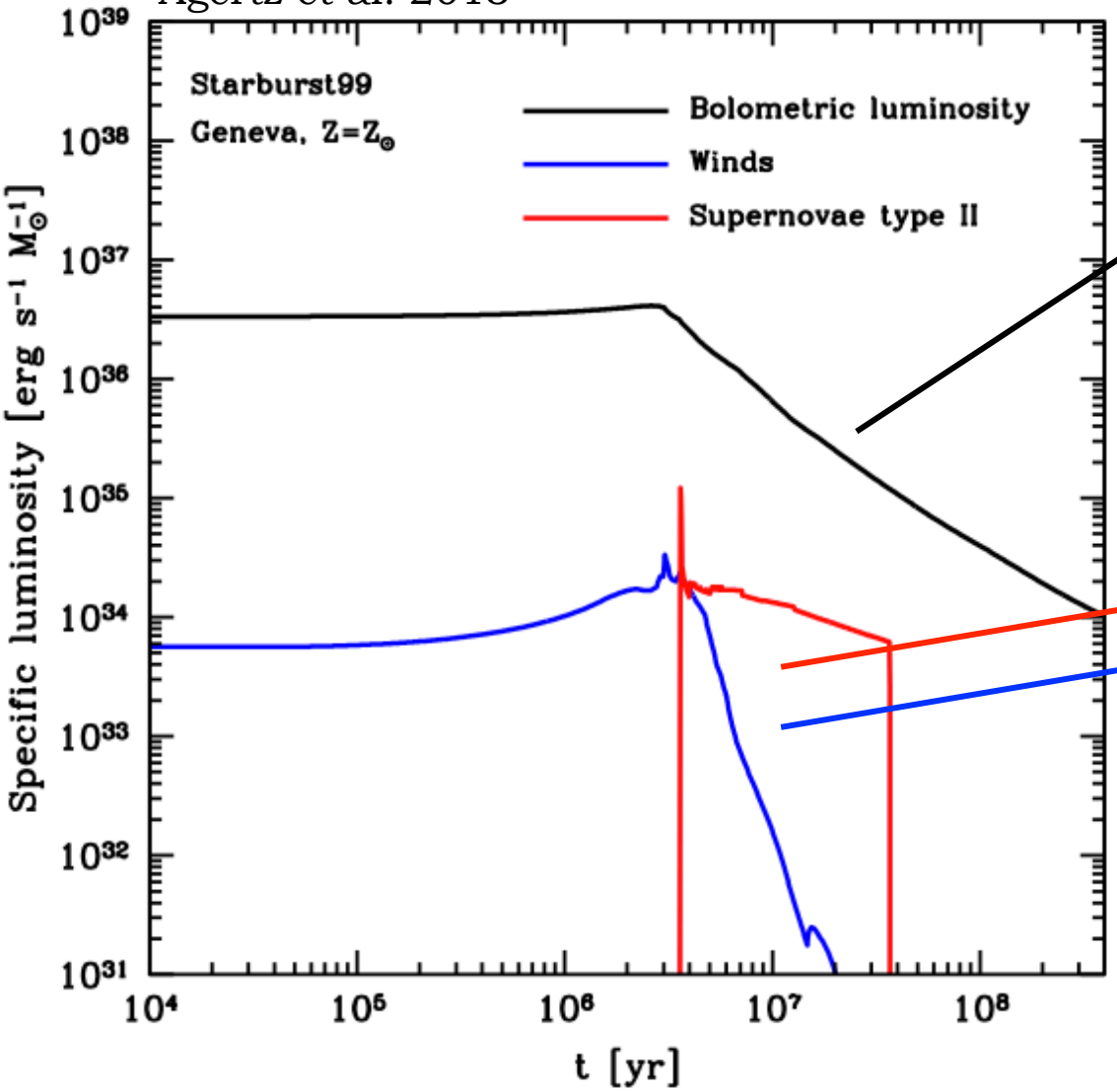


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which phases is this deposited into, at what distances from stars?

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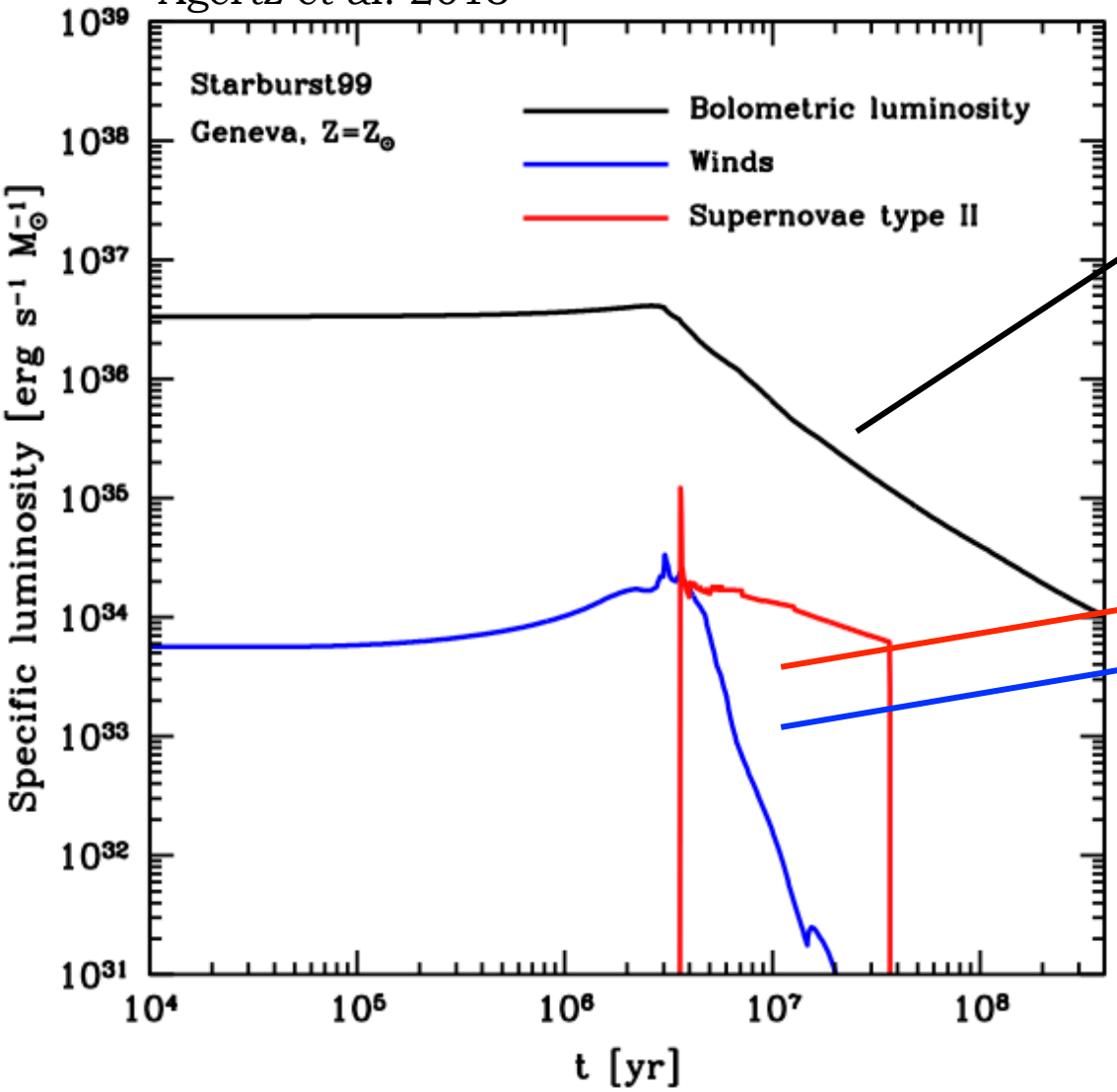


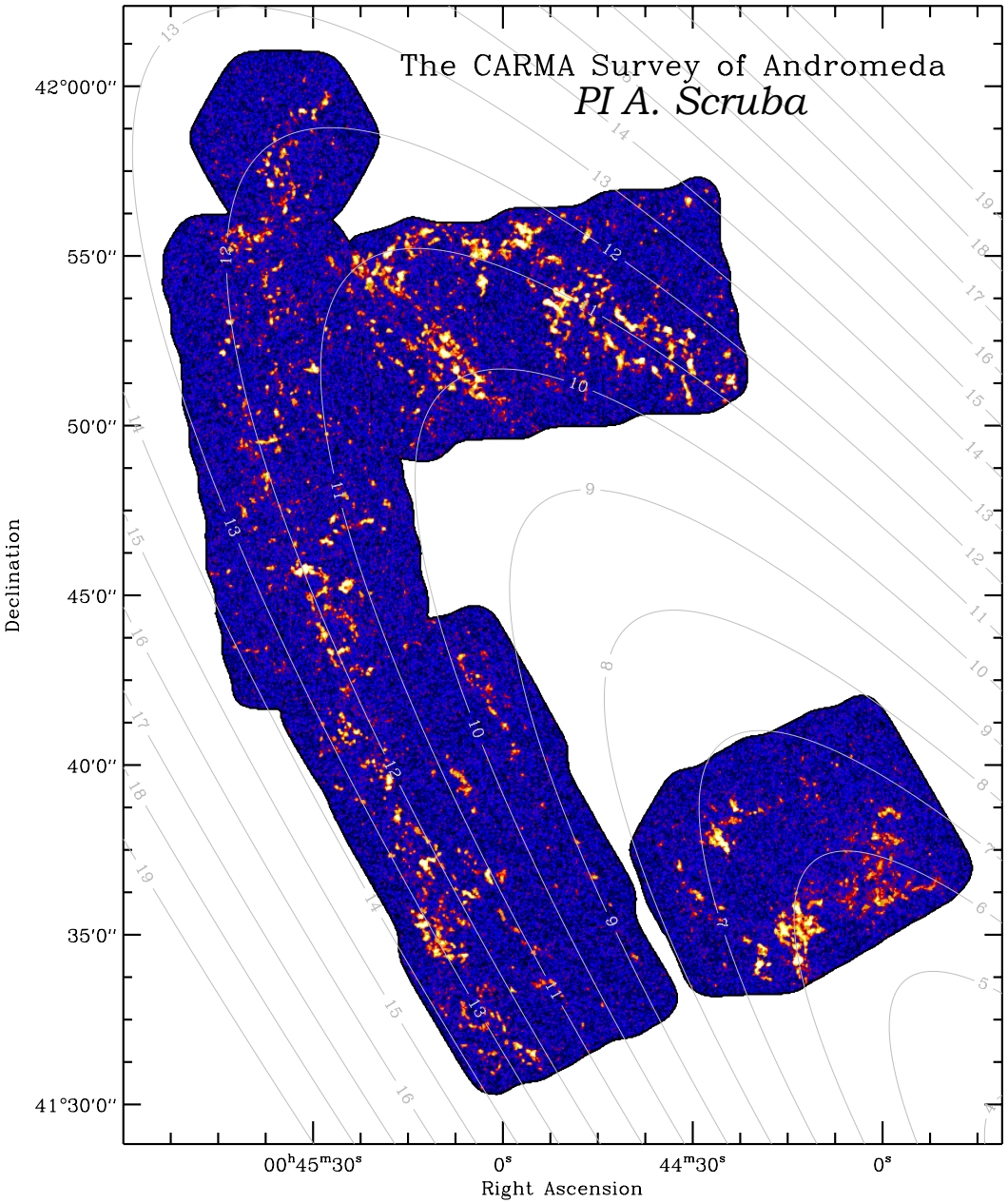

fraction into ionization, photoelectric heating, dust heating?

deposited where?

which phases is this deposited into, at what distances from stars?

Time variability of all of the above!

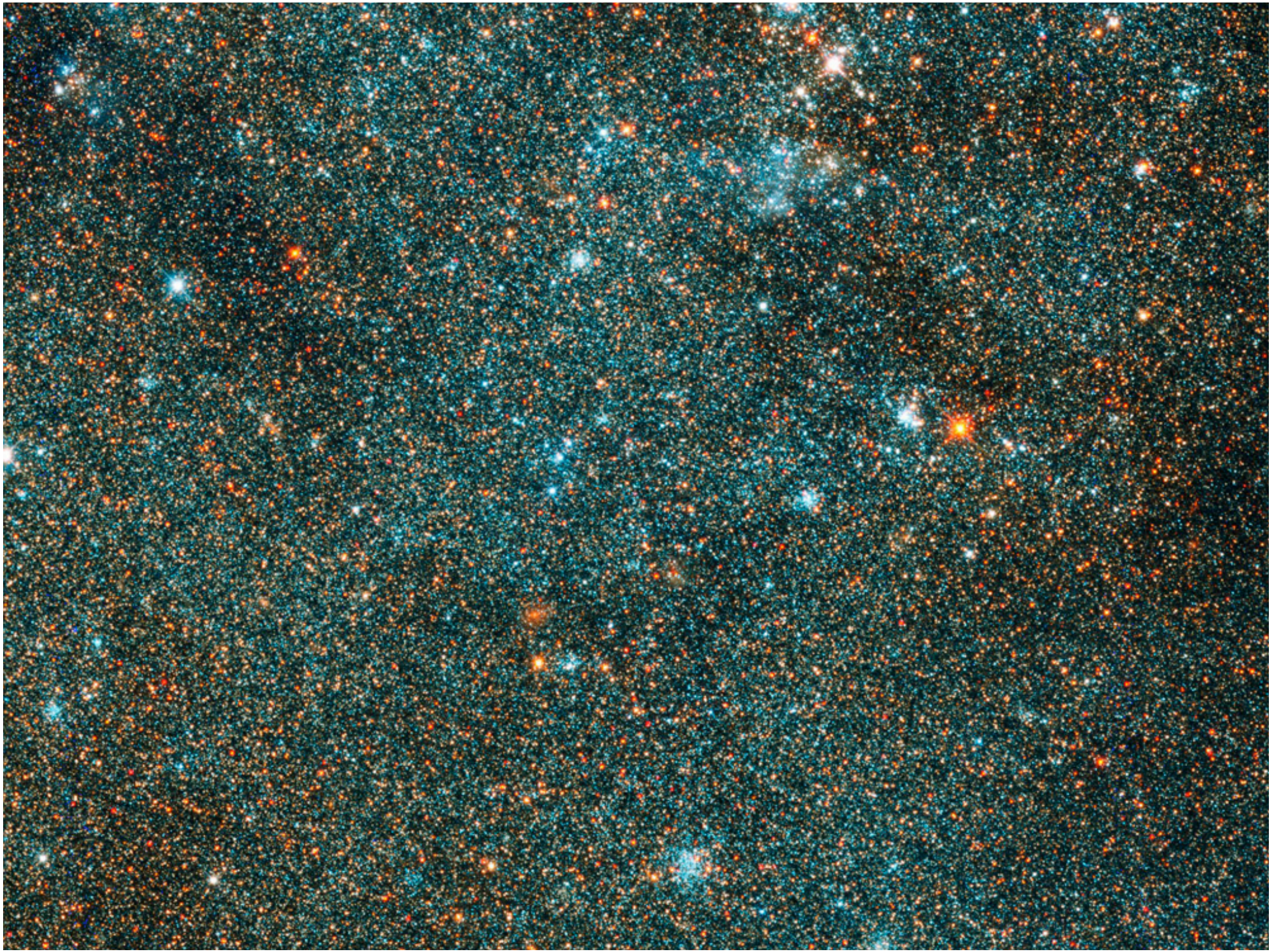
# The Importance of Local Group galaxies




*Only in the Local Group can we...*

Resolve structures on the scale of GMCs and cover large galactic scales simultaneously.

CARMA Andromeda Survey
0.1 deg$^2$, 20 pc resolution
$^{12}$CO and $^{13}$CO (1-0)



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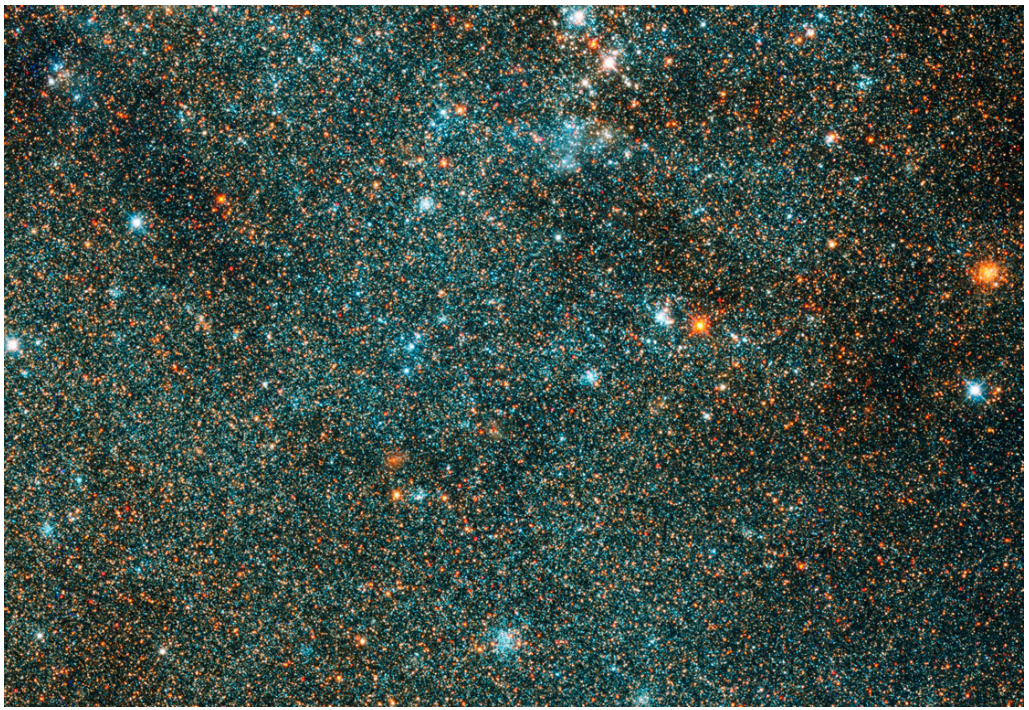


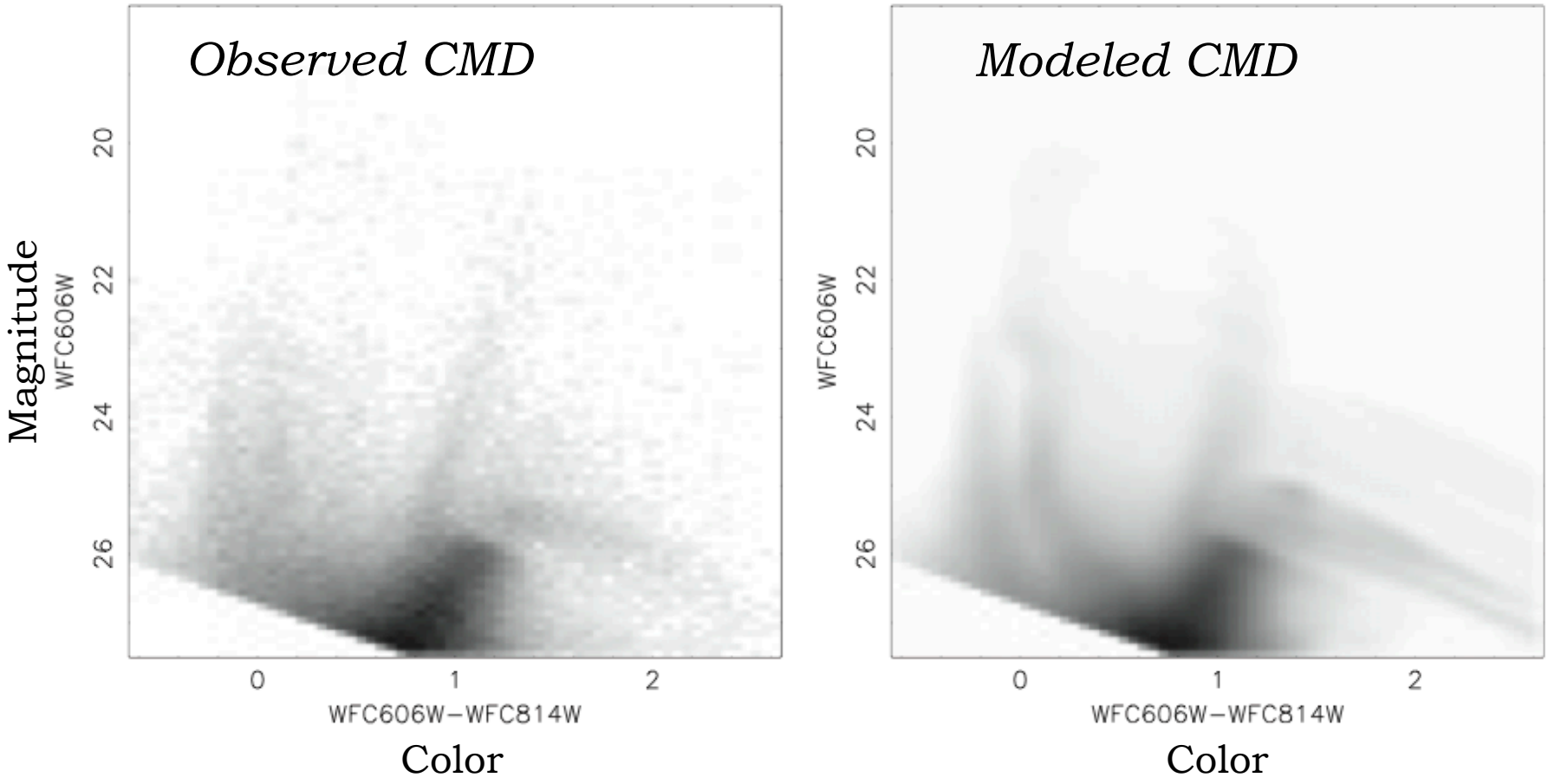
*Only in the Local Group can we...*

Resolve individual stars and use their colors & magnitudes to measure stellar properties and SFH.

Panchromatic Hubble Andromeda Treasury near-UV to near-IR HST photometry (PI J Dalcanton)

# The Importance of Local Group galaxies

McQuinn et al. 2010, ApJ, 721, 297

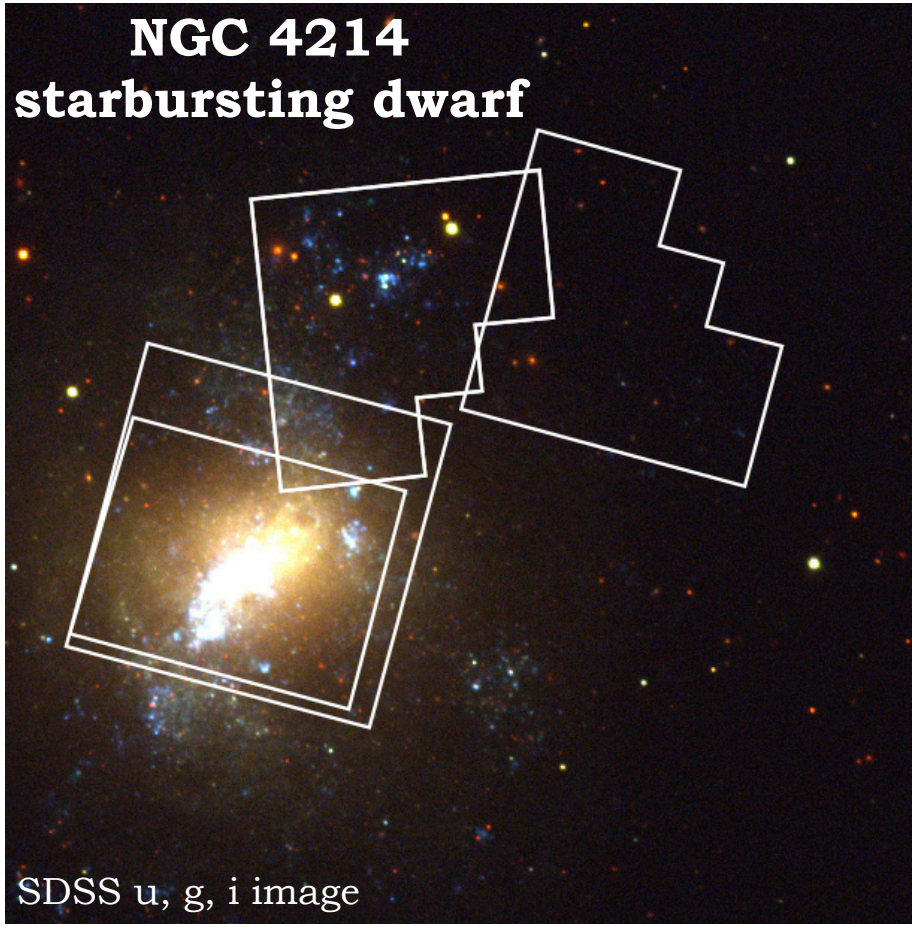


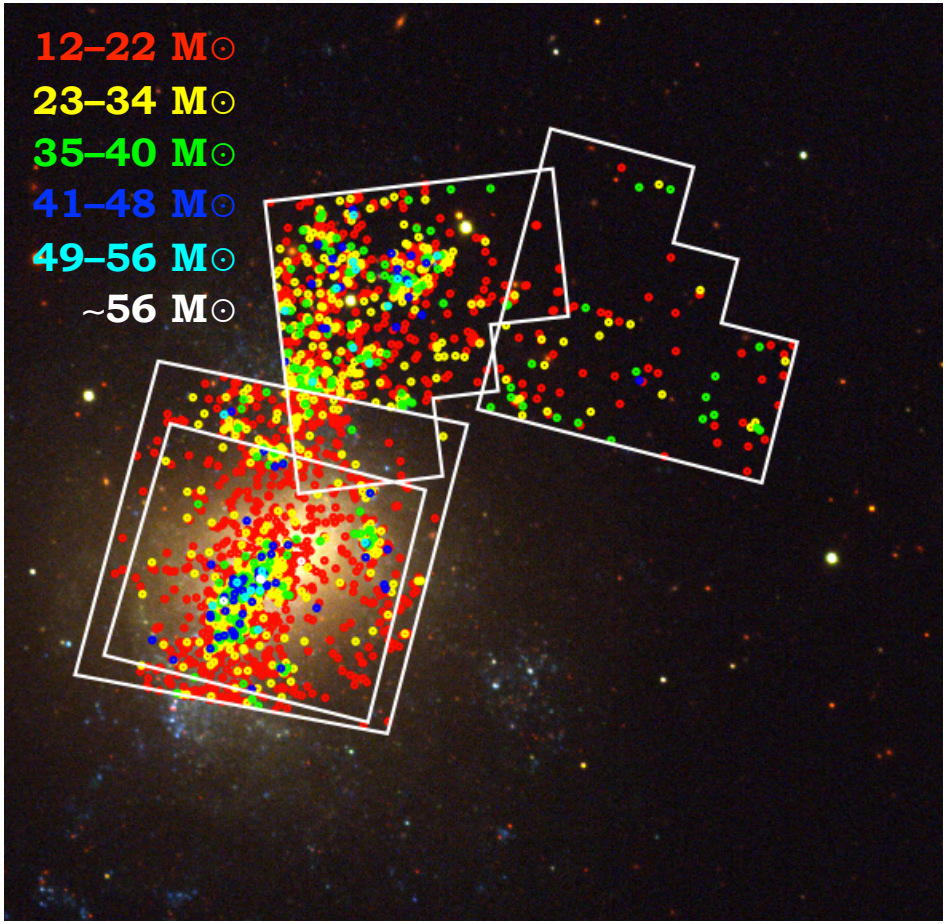

CMD of resolved stars yields star-formation history.

Dolphin 2002, Weisz et al. 2008, Harris & Zaritsky 2009 & many more.

# The Importance of Local Group galaxies

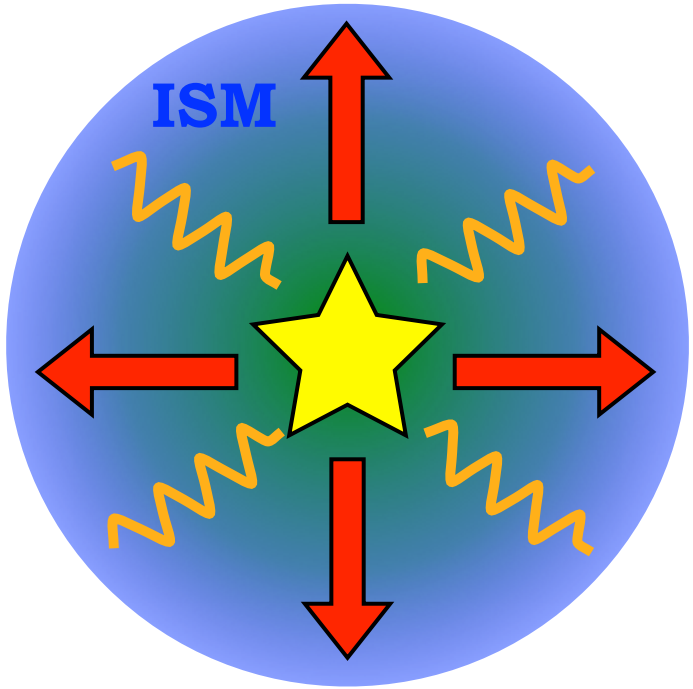
Williams et al. 2011, ApJ, 735, 22




Stellar properties & extinction can be disentangled using multi-band photometry & SED fitting.

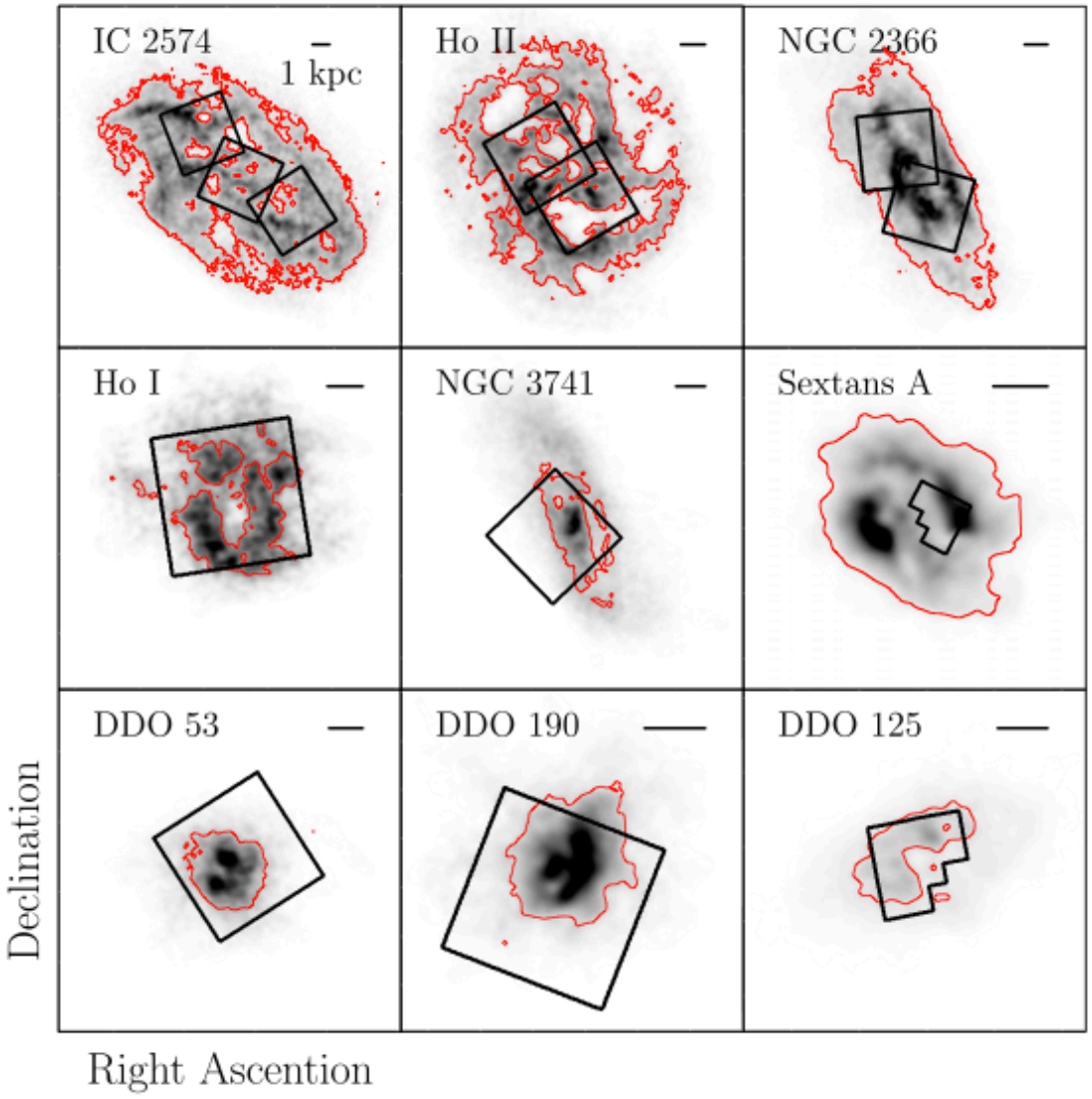
# Feedback Energy vs Time in the Local Group




- **Energy(time)**
- Energy(position)
- **Energy(ISM phase)**

# Connecting HI Energetics & Star Formation

Stilp et al. 2013, ApJ, 772, 124




Comparison between SFH and HI energetics resolved in nearby galaxies.

SFH from:
ACS Nearby Galaxies Treasury
(Dalcanton et al. 2009)

HI energetics from:
VLA-ANGST (Ott et al. 2012) &
THINGS (Walter et al. 2008)

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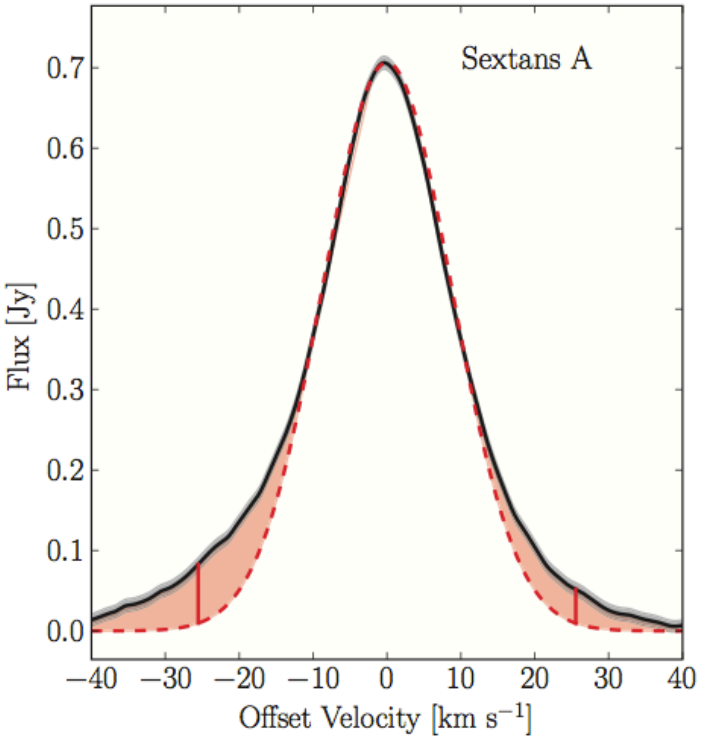
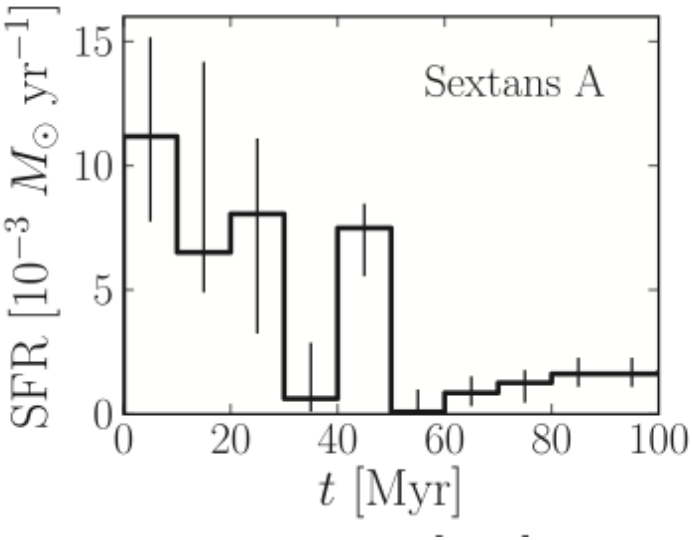
Stilp et al. 2013, ApJ, 772, 124




Assessment of energetics from HI line profiles, separated into energy in line core, wings, total.




SFH measured in matched aperture from color-magnitude diagram.

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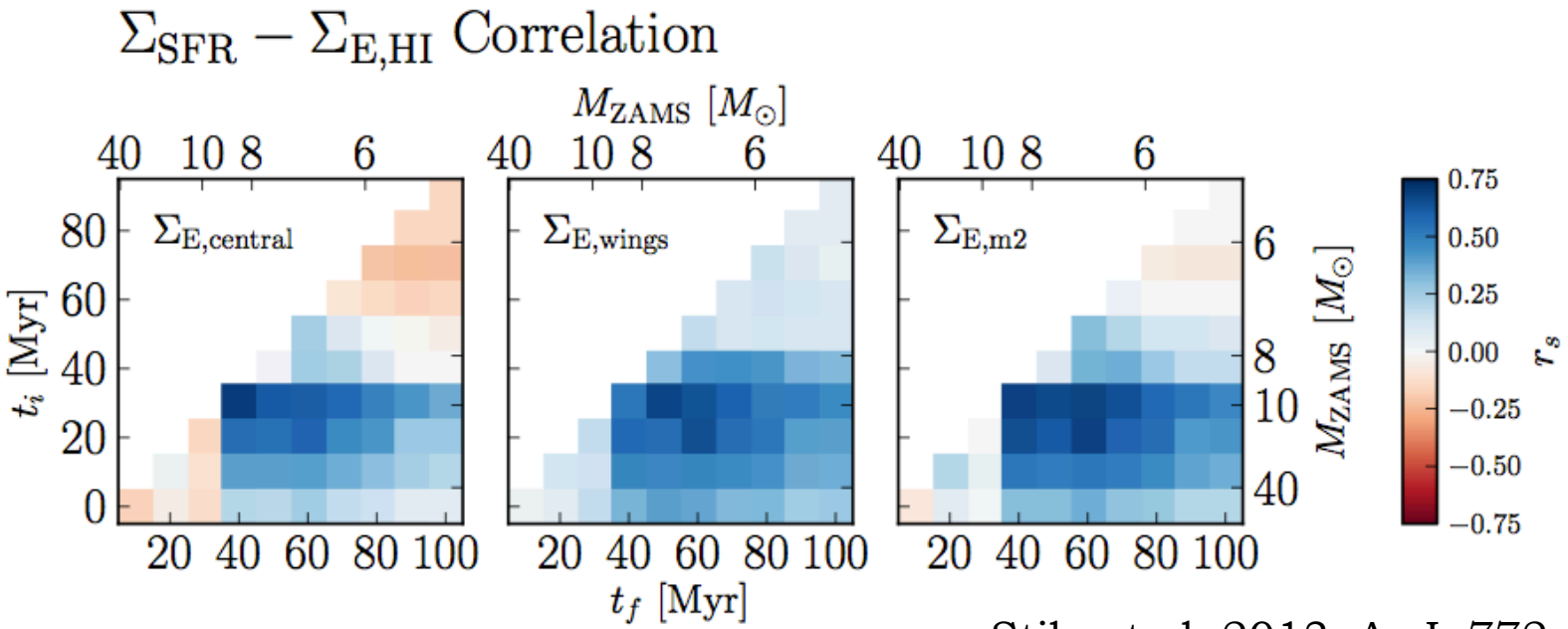


Stilp et al. 2013, ApJ, 772, 124

Strongest correlation between HI energetics & SFH at 30-40 Myr. Approximately the timescale for SNe for 8-10 $M_\odot$ stars.

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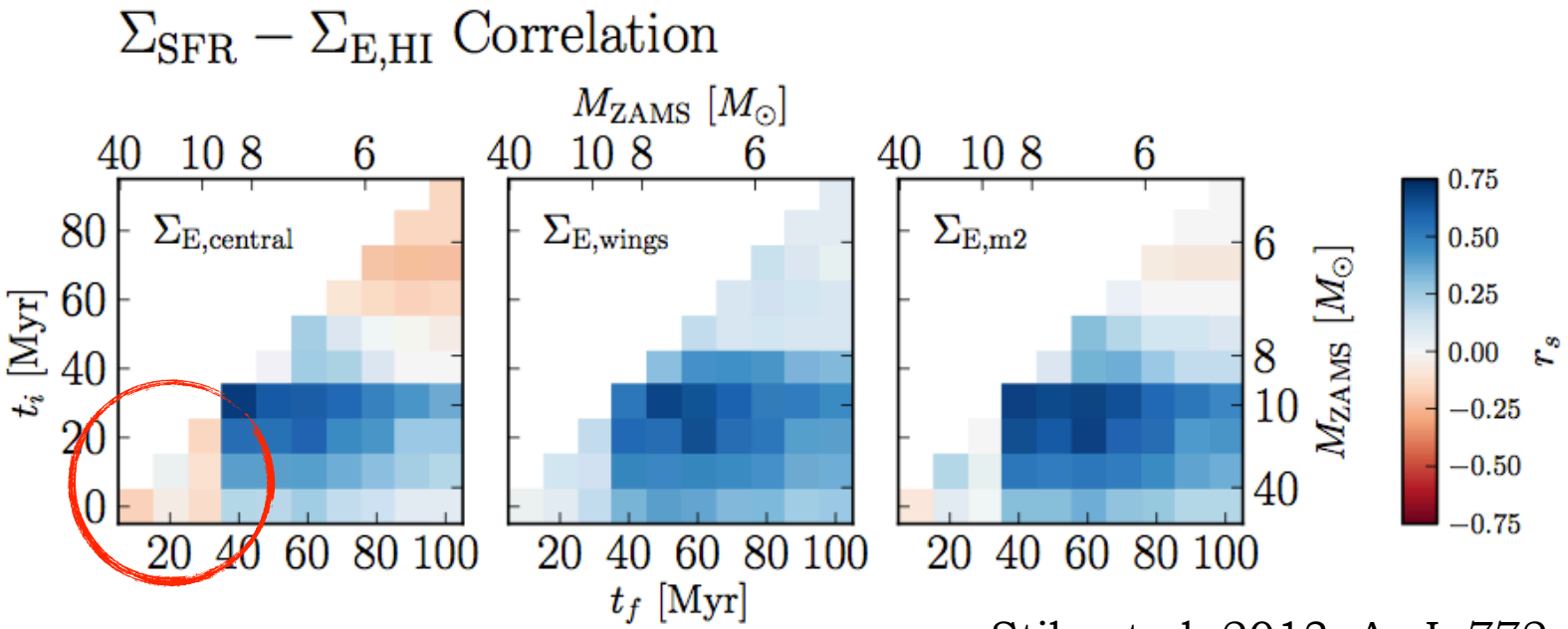
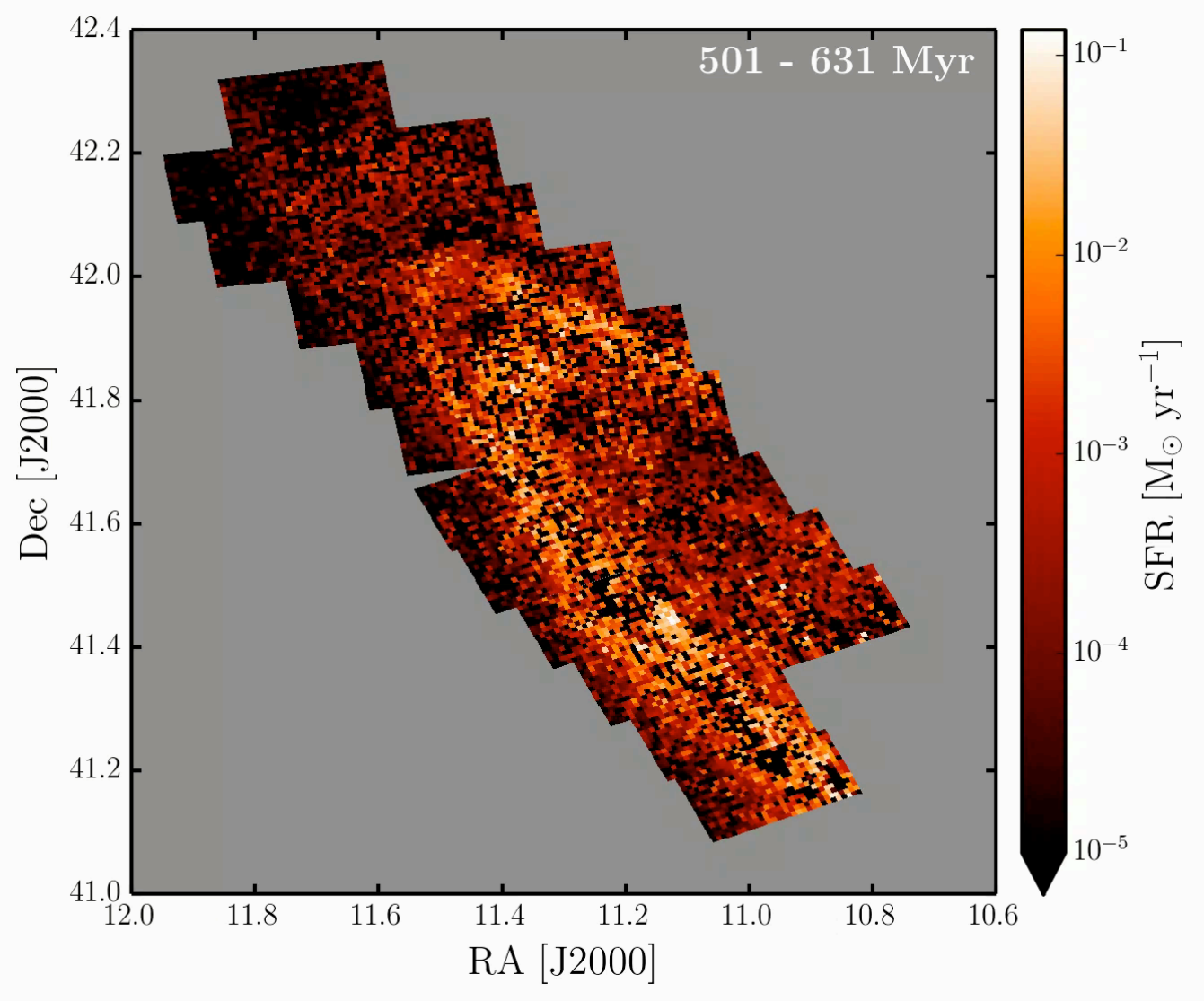



Stilp et al. 2013, ApJ, 772, 124

What about radiation pressure feedback?
Molecular gas coupling?

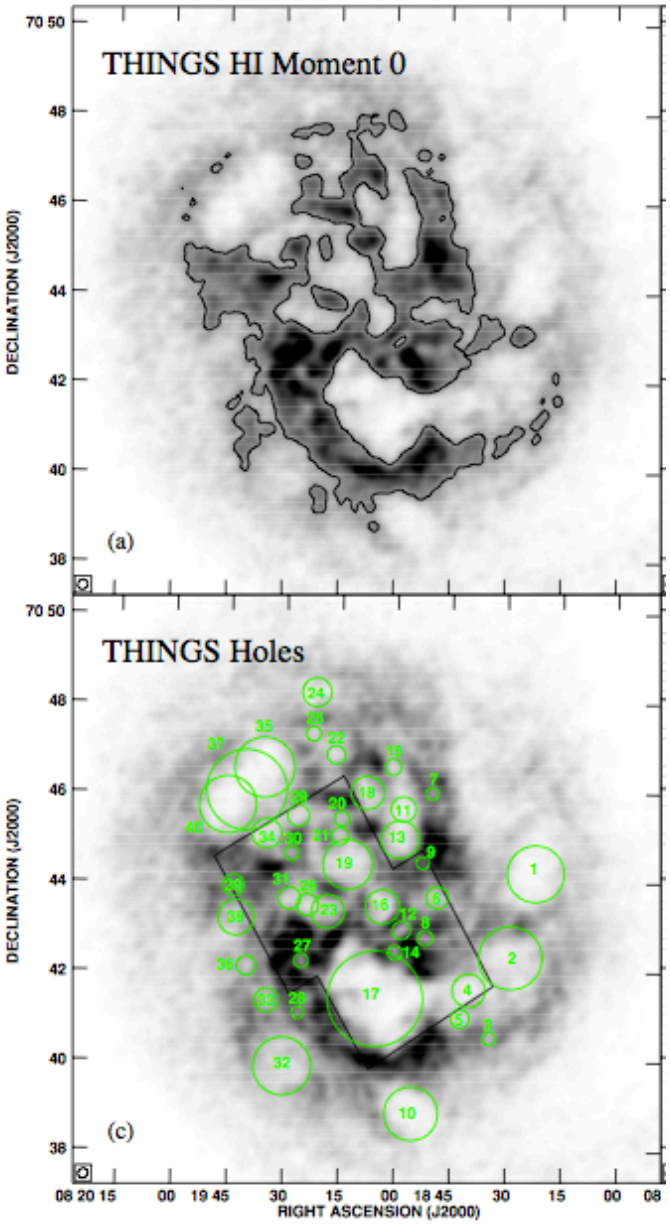
# Connecting HI Energetics & Star Formation




Lewis et al. in prep
SFH of M31 from PHAT

Resolved maps of energy input for 1/3 of the galaxy.

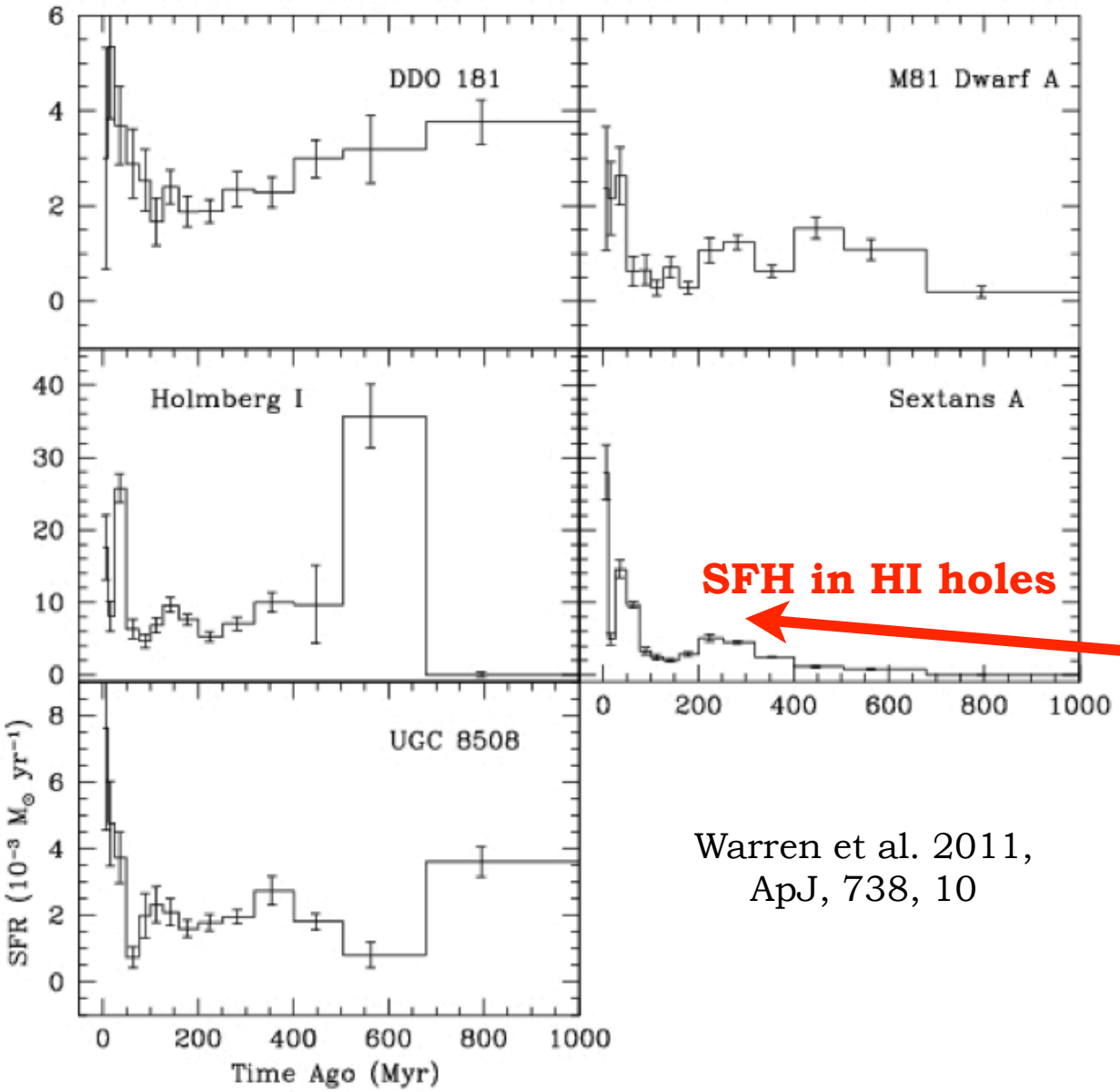
# Connecting HI Energetics & Star Formation




Recent studies of SFH and ISM in galaxies also address question of HI holes.

Long-standing issue of how these are created, whether they are due to feedback or other effects (grav instability, accretion, etc)

# Connecting HI Energetics & Star Formation

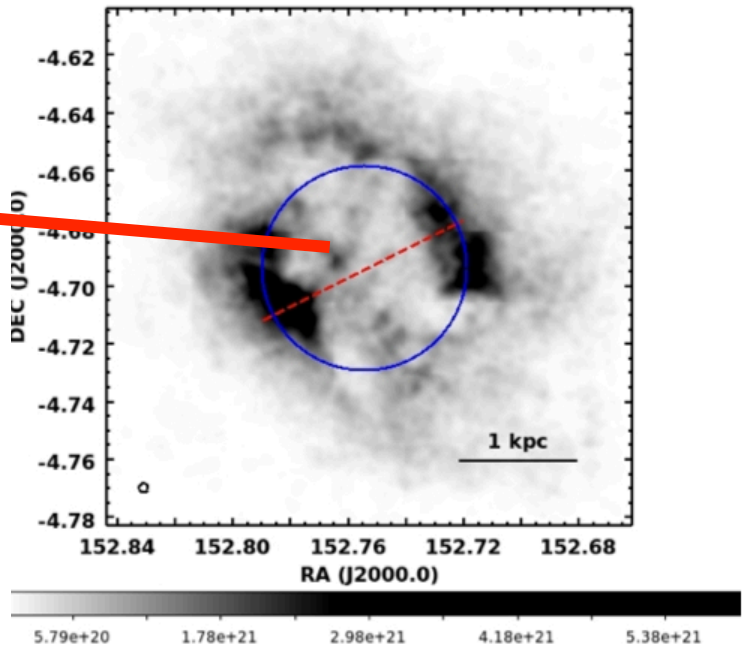



SFH of stellar populations inside HI holes in dwarfs.
(ANGST, VLA-ANGST)

**SFH in HI holes**

Warren et al. 2011, ApJ, 738, 10

Sextans A



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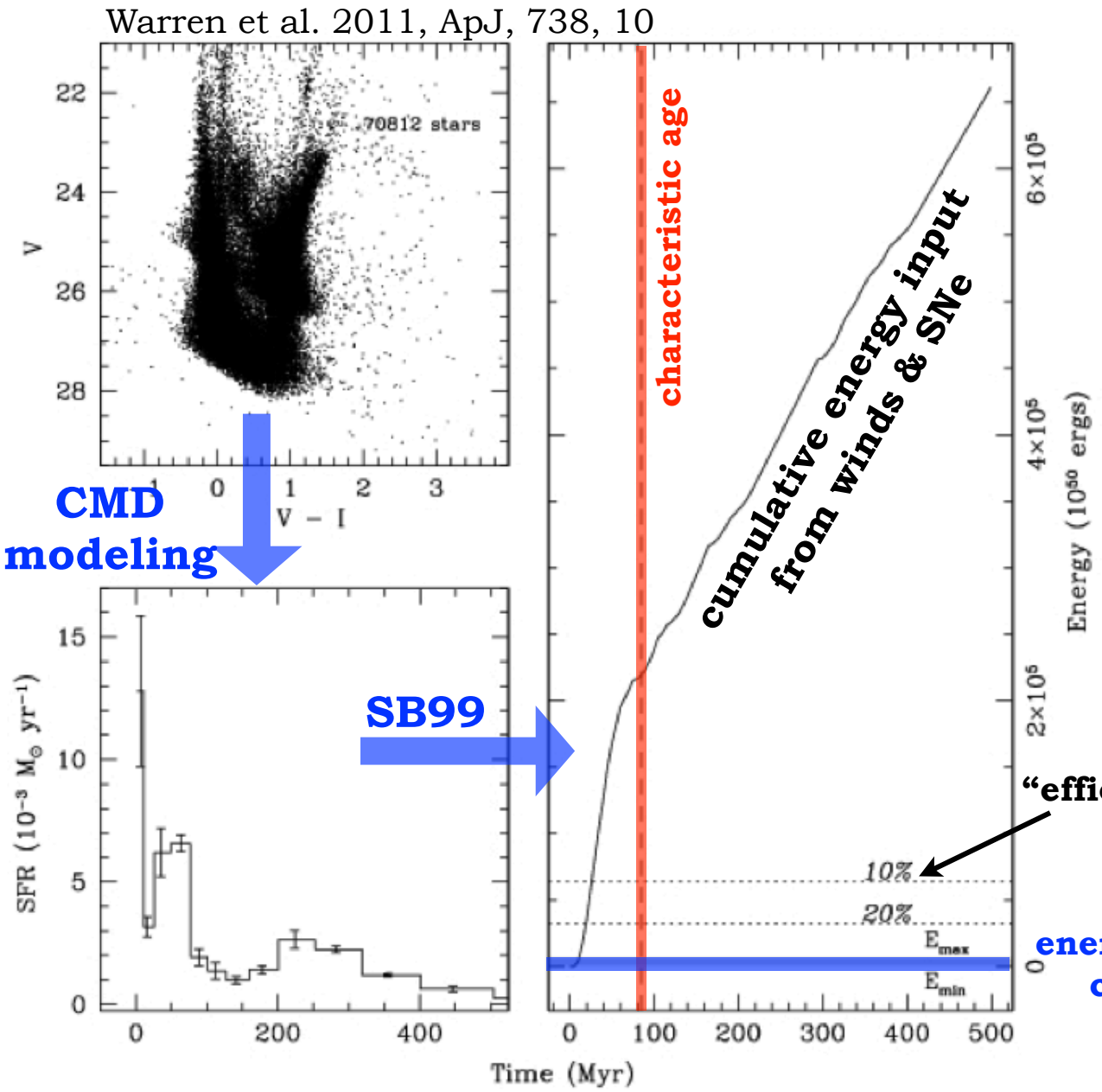
Warren et al. 2011, ApJ, 738, 10

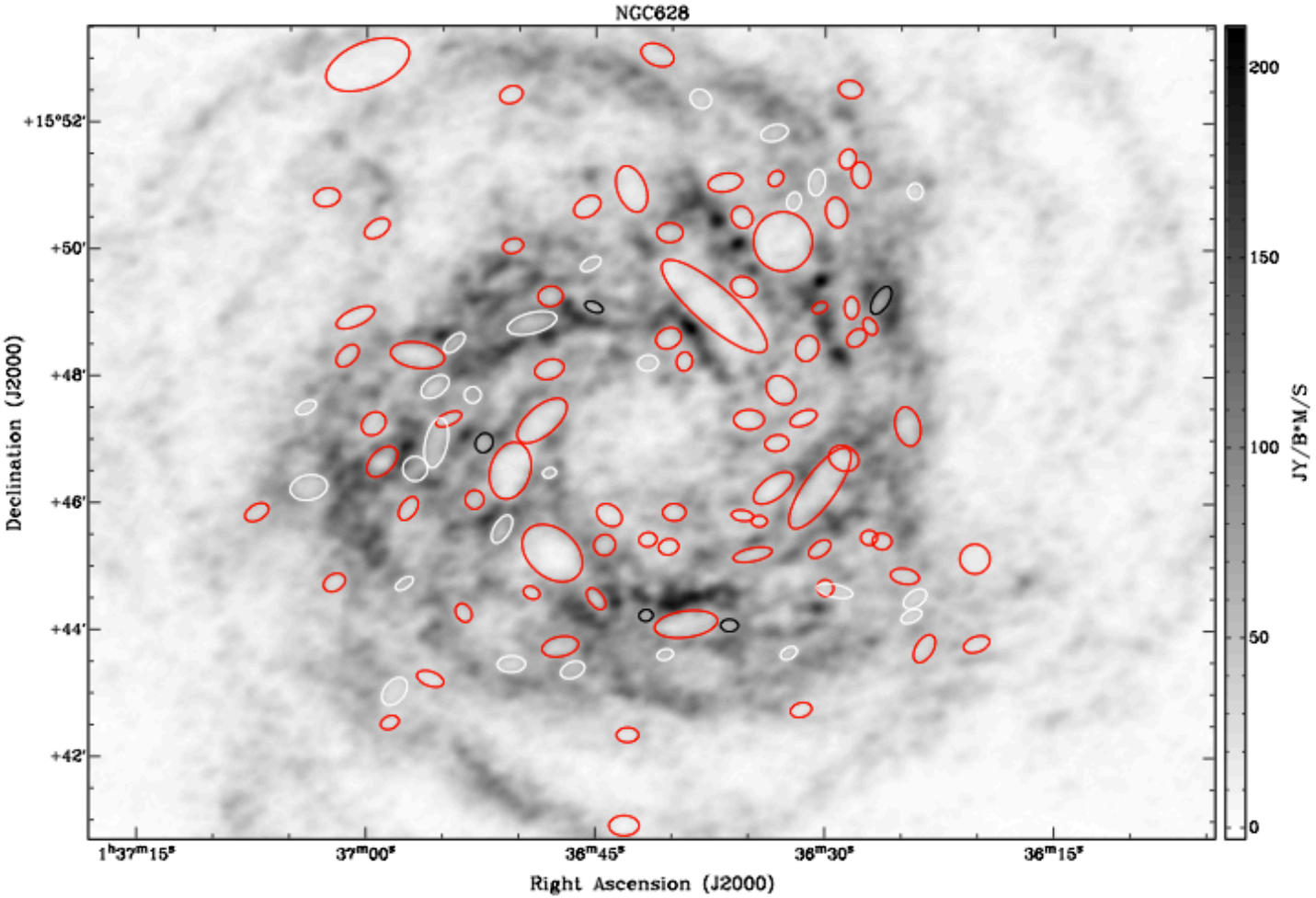



Stellar populations produce enough energy to create hole.

But, not a single age population from one burst.

see also Weisz et al. 2009, Cannon et al. 2011

# Connecting HI Energetics & Star Formation

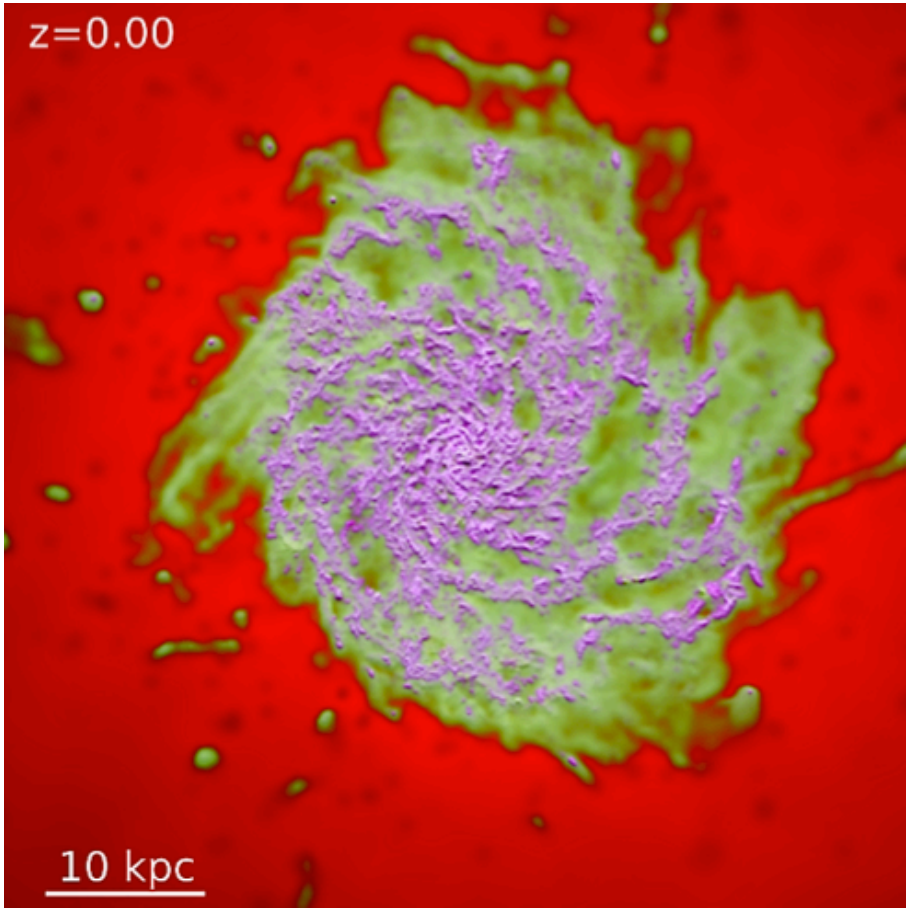



**Type 1** - blown out top & bottom
**Type 2** - blown out on one side
**Type 3** - neither side blown out

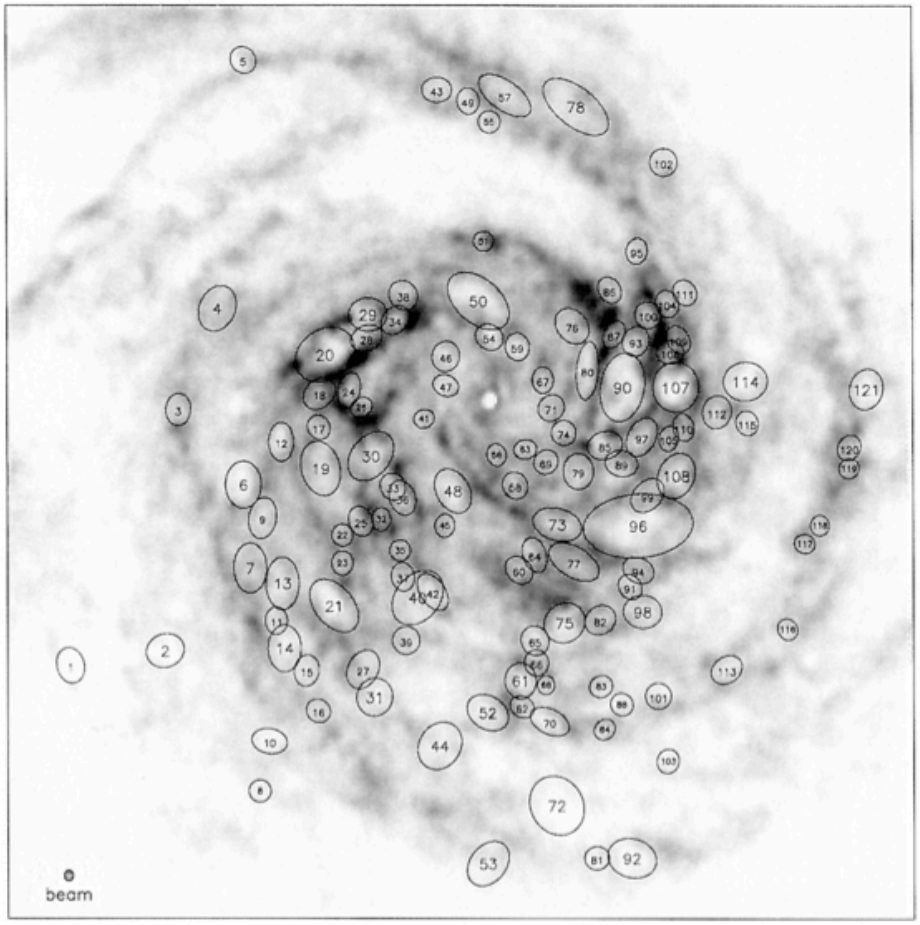
Bagetakos et al. 2011
THINGS holes

# Connecting HI Energetics & Star Formation

Hole properties - diagnostic of feedback mechanism?



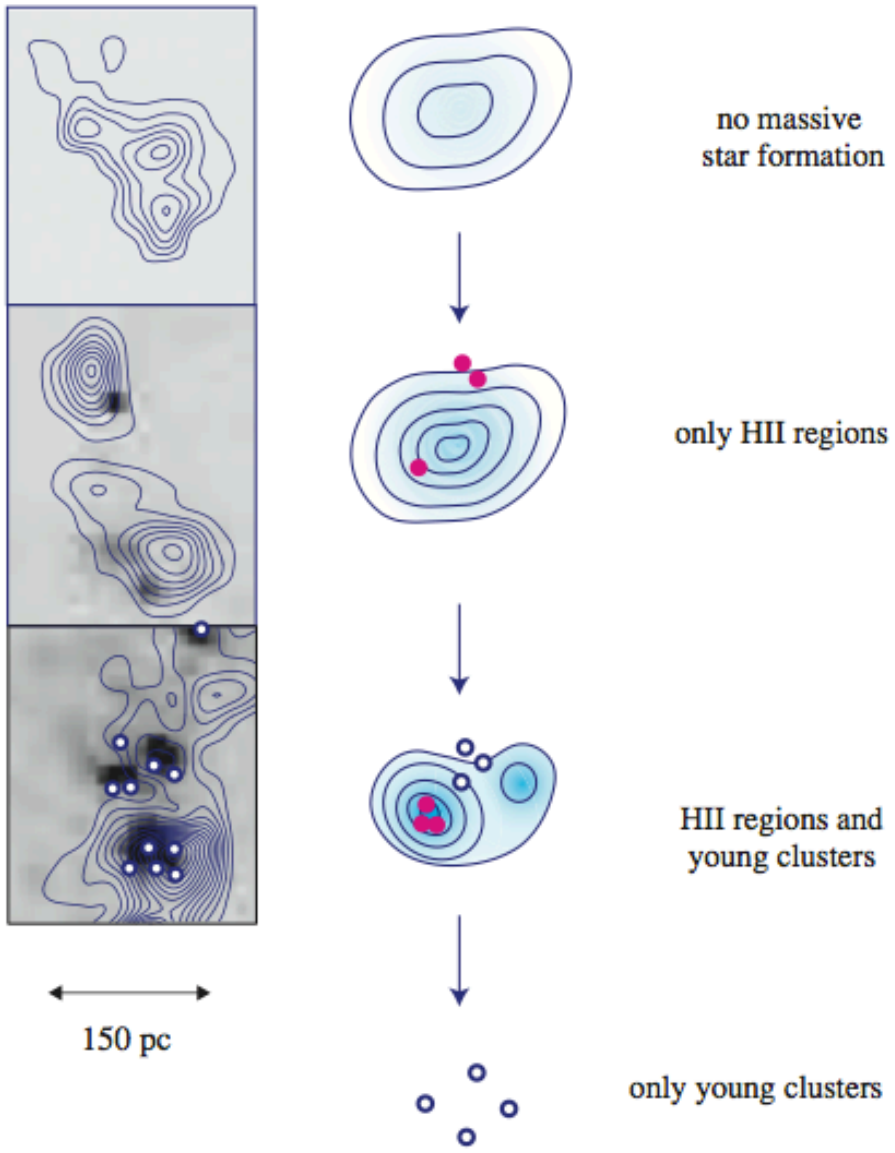

FIRE galaxy - Hopkins et al. 2014




NGC 6946 - Boorsma et al. 2008

# Connecting GMC Disruption & Star Formation

Kawamura et al. 2009

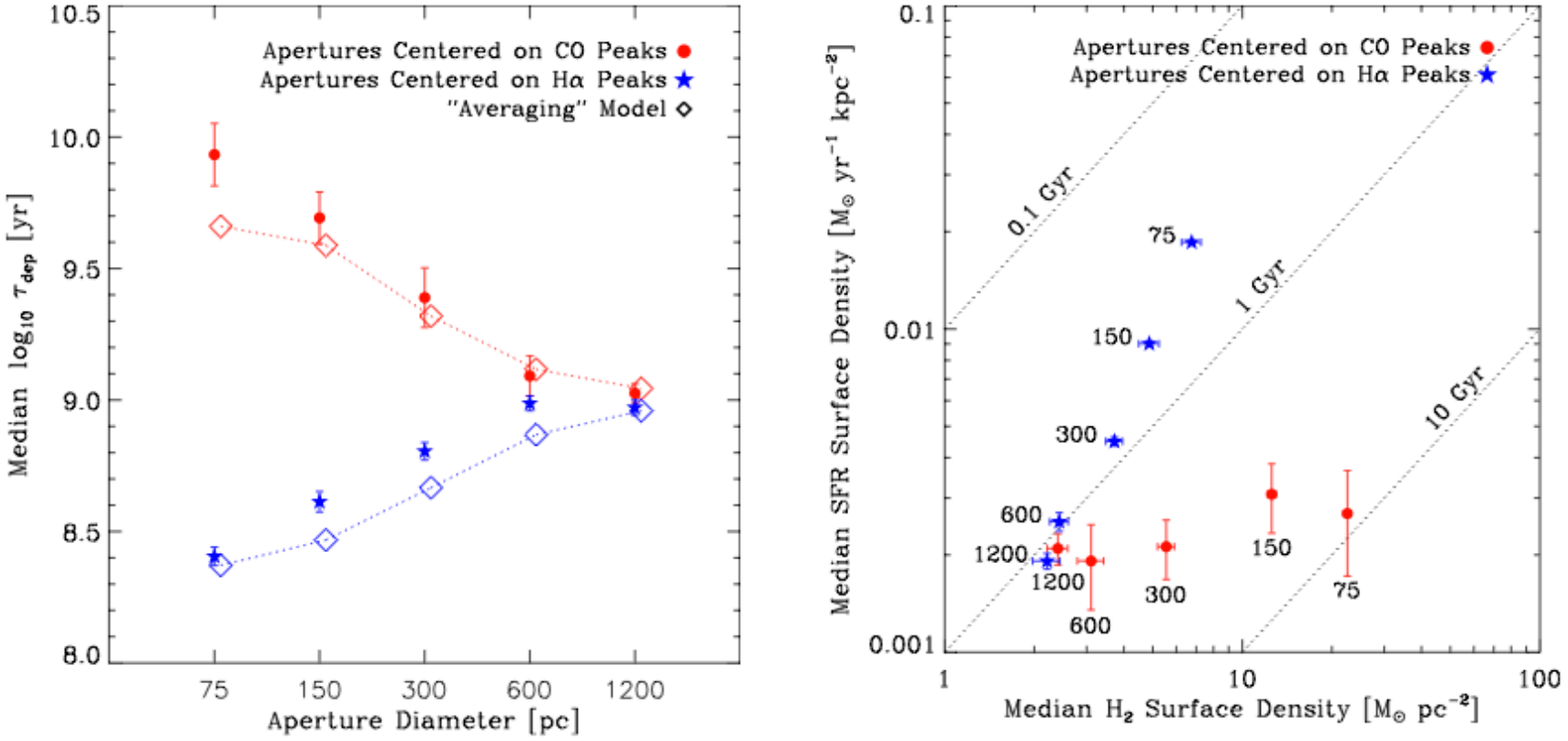



Molecular cloud lifetimes are set by feedback processes.

Associating age dated clusters w/GMCs in the LMC gives 20-30 Myr lifetimes.

# Connecting GMC Disruption & Star Formation

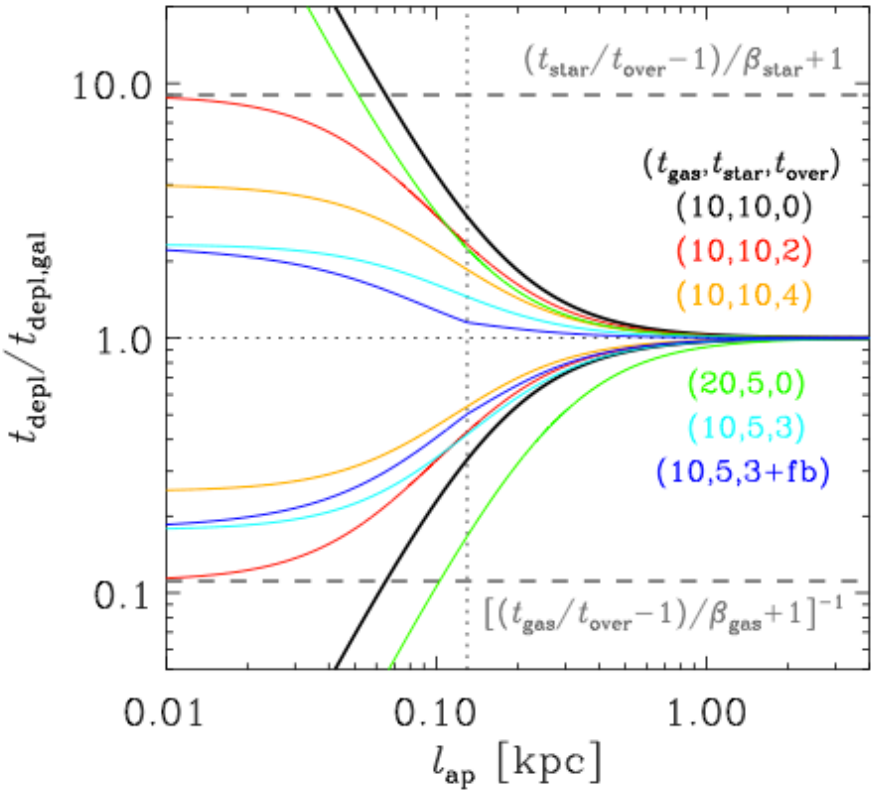
Schruba et al. 2010 - K-S Relationship in M33

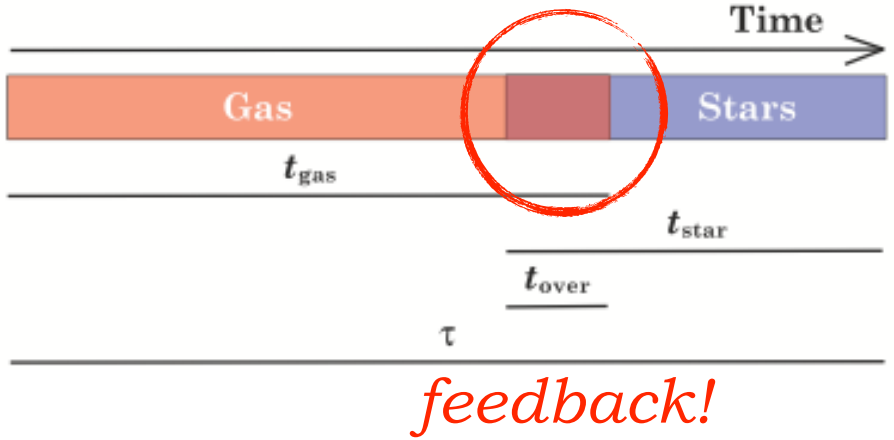



Scatter & offsets from K-S as a function of scale is an observational consequence of feedback processes.

# Connecting GMC Disruption & Star Formation

Kruijssen & Longmore 2014



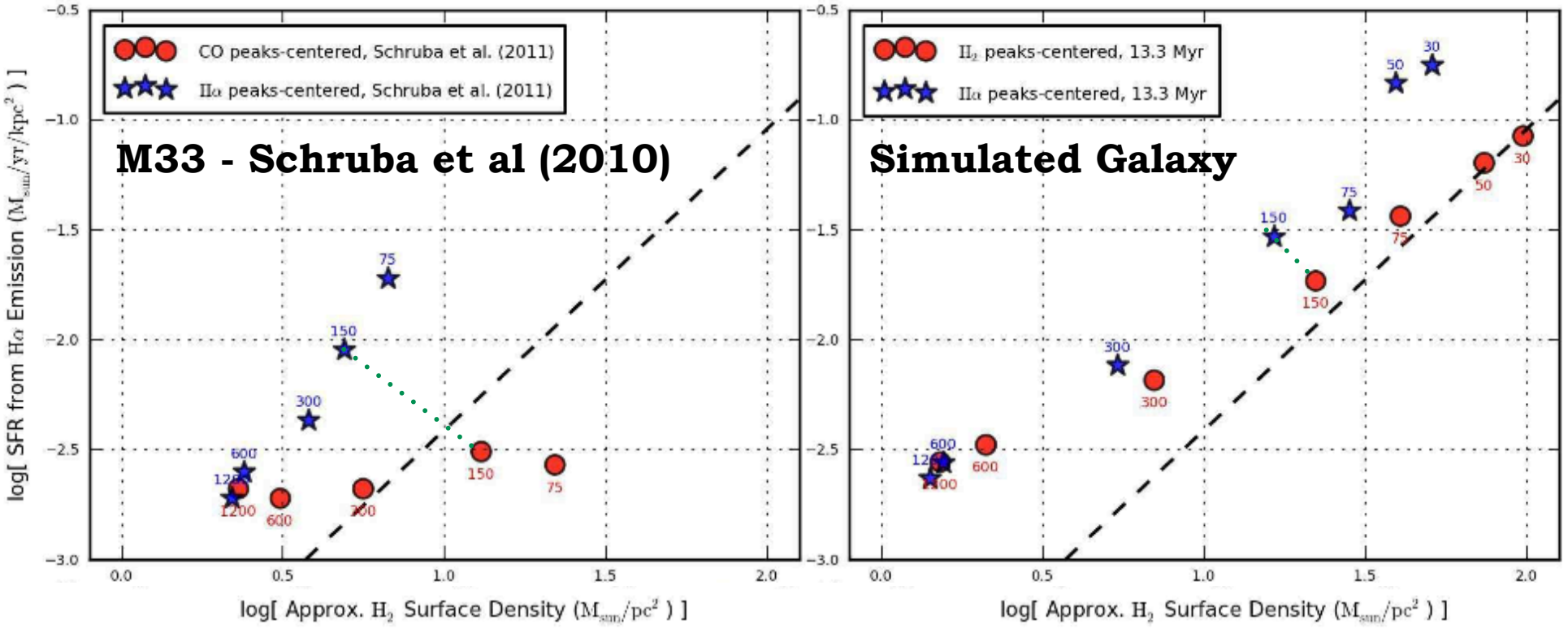




*feedback!*

Properties of K-S scatter at small scales is diagnostic of feedback.

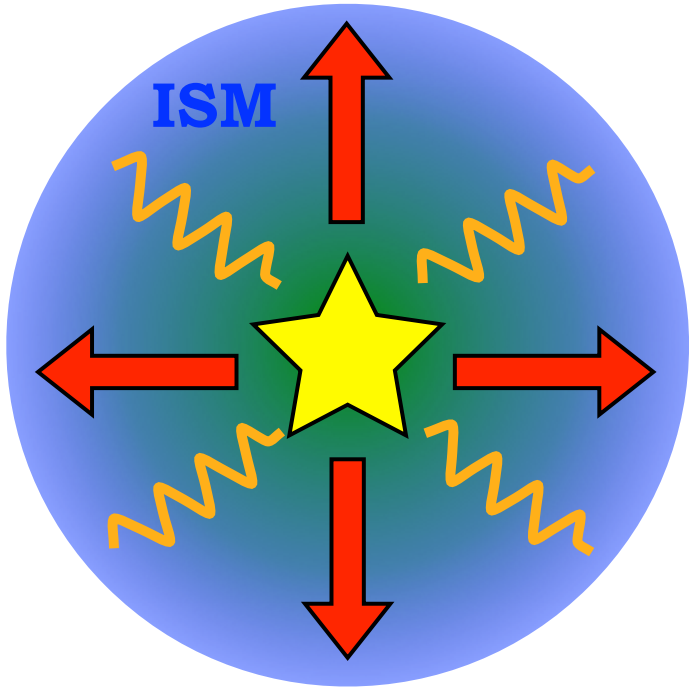
# Connecting GMC Disruption & Star Formation

Kim, Krumholz et al. 2013




Smaller offset in KS between $H_2$/Hα peaks suggests feedback not strong enough in simulated galaxy?

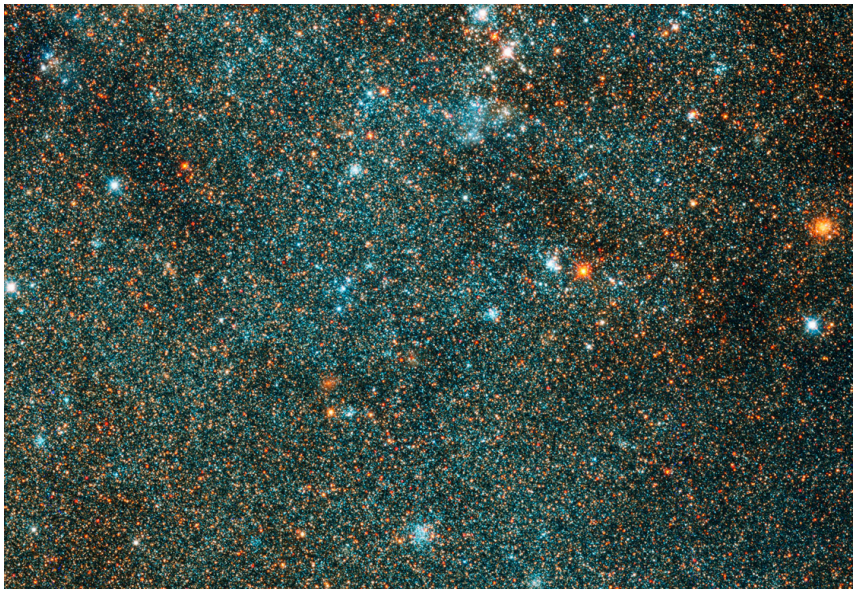
# Feedback Energy vs Position in the Local Group

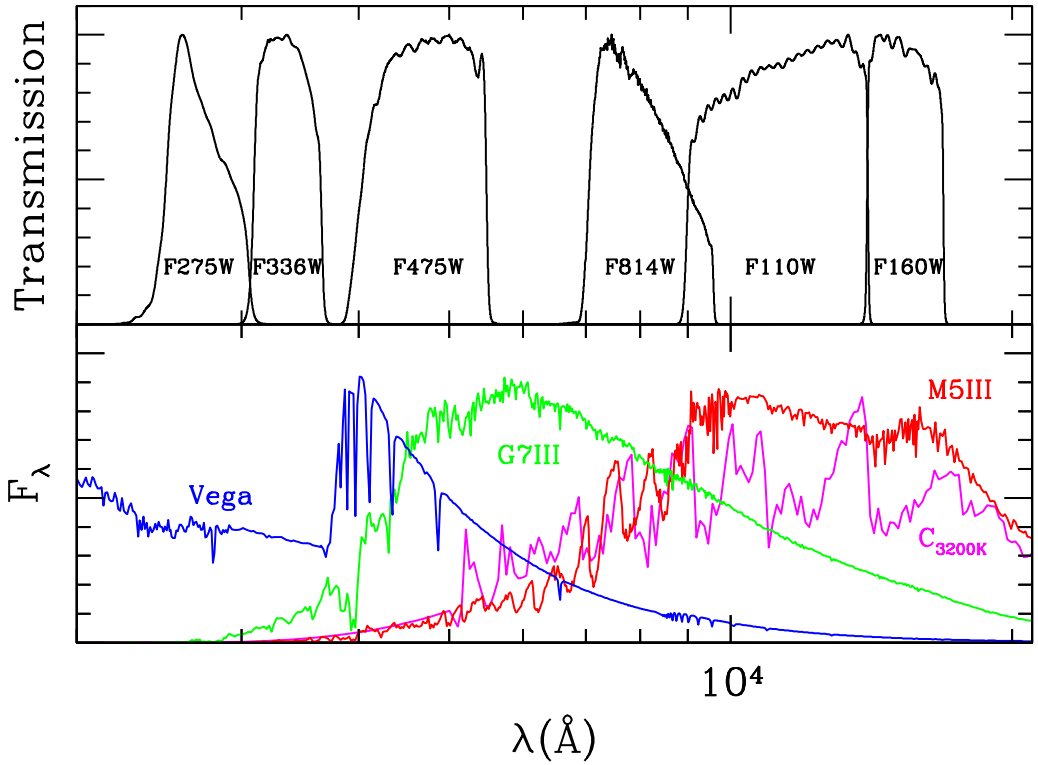



- Energy(time)
- **Energy(position)**
- Energy(ISM phase)

# Assessing UV Radiation Input in Local Group

work in progress by Maria Kapala (MPIA), Yumi Choi (UW) & PHAT team






SED fits to multi-band photometry yield stellar & extinction curve properties - Gordon et al. (in prep)

→ Map of unextincted UV flux input from stars.

# Assessing UV Radiation Input in Local Group

Position & ISM phases where UV is deposited...

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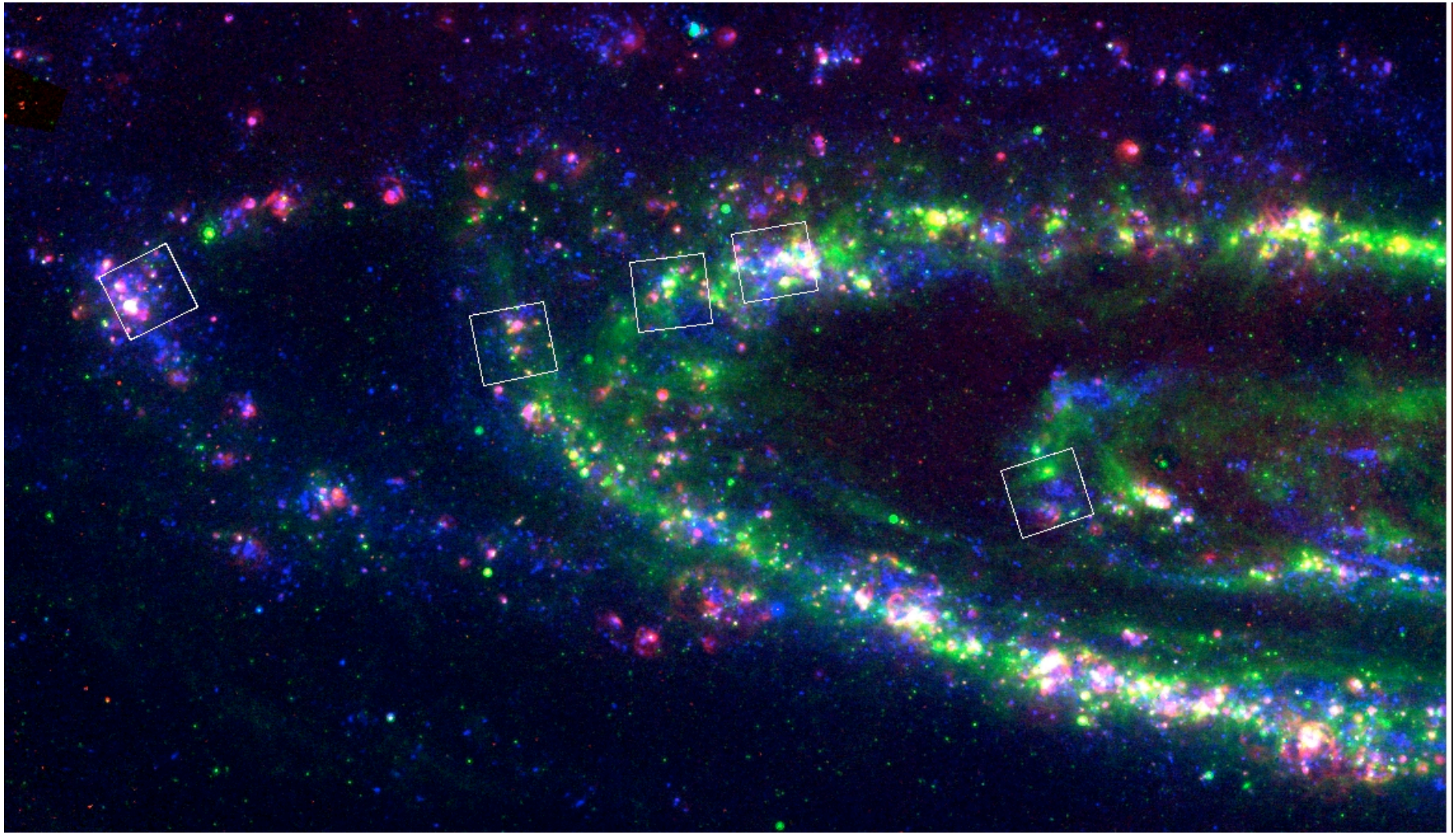

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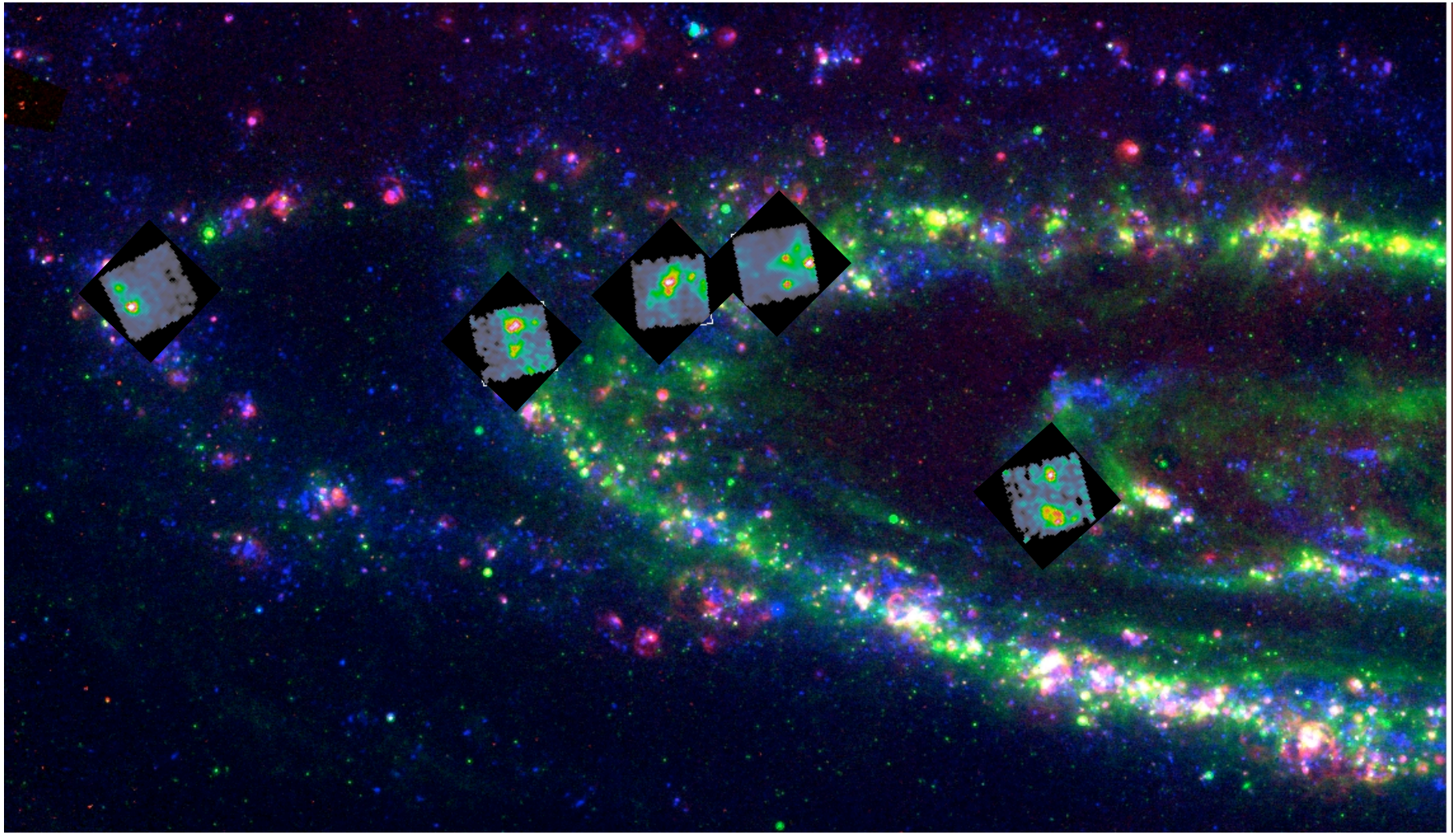

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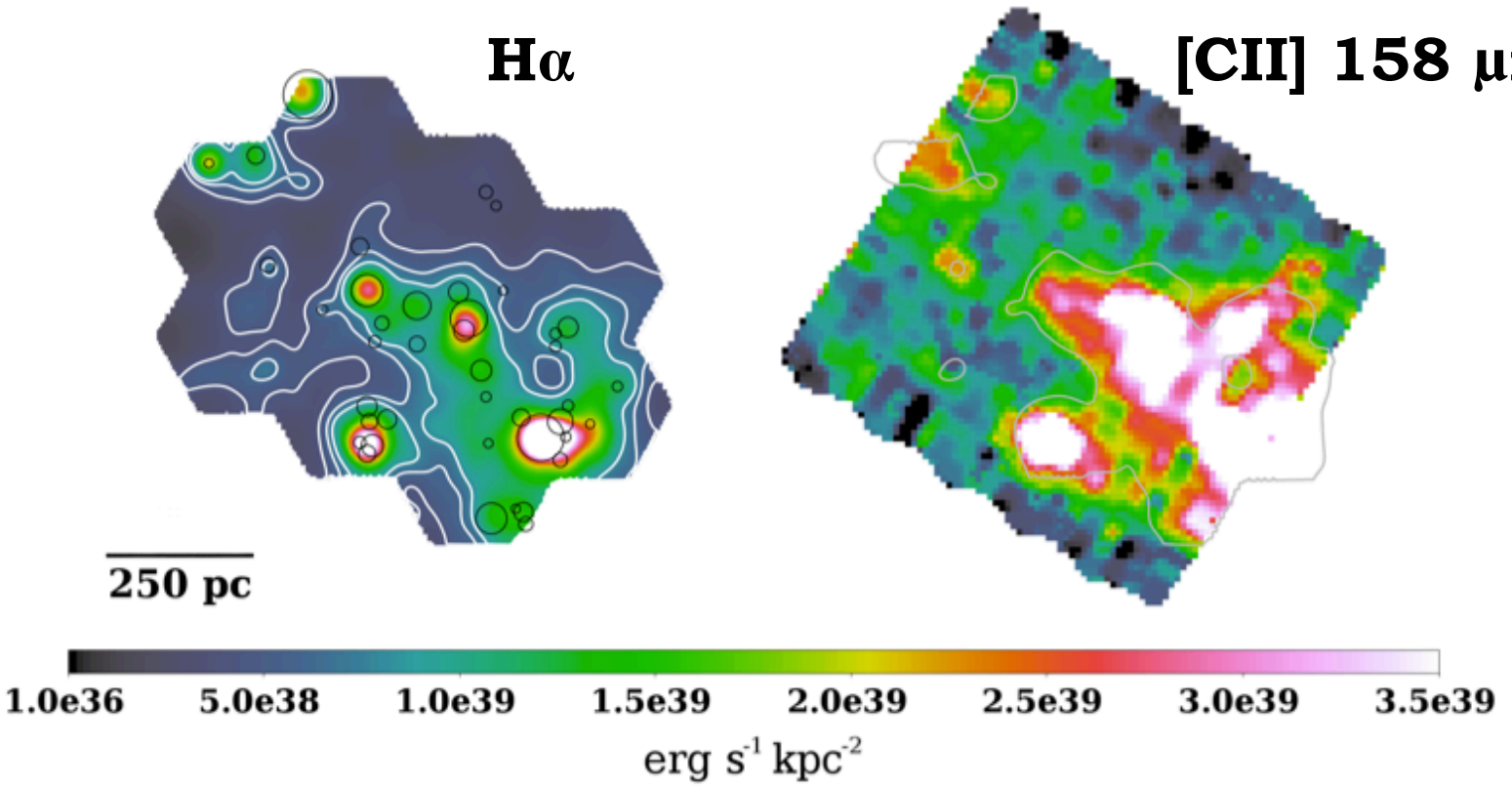
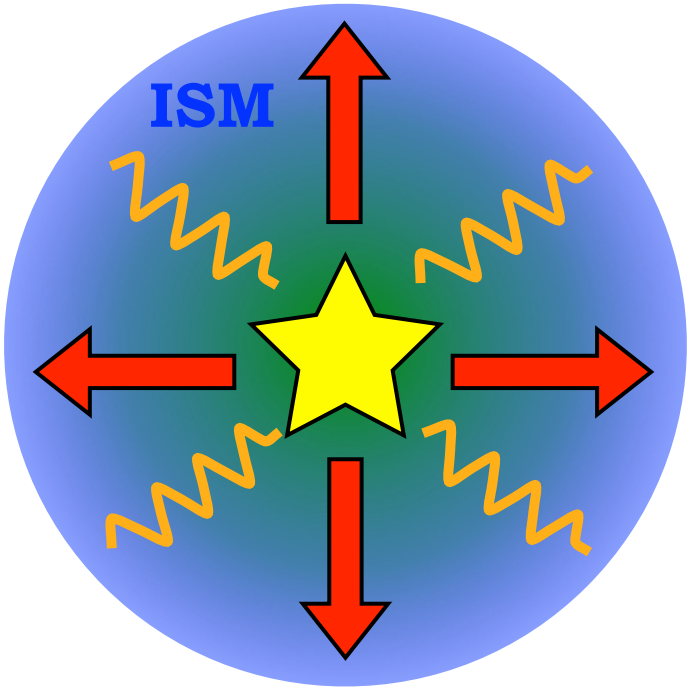



Work by Maria Kapala (MPIA) comparing the energy input from stars to the observed distribution of gas cooling (e.g. heating), dust and ionized gas.

# Dust is Key

*Dust important for radiation pressure, ionization, gas heating via photoelectric effect.*




- **Energy(time)**
- **Energy(position)**
- **Energy(ISM phase)**

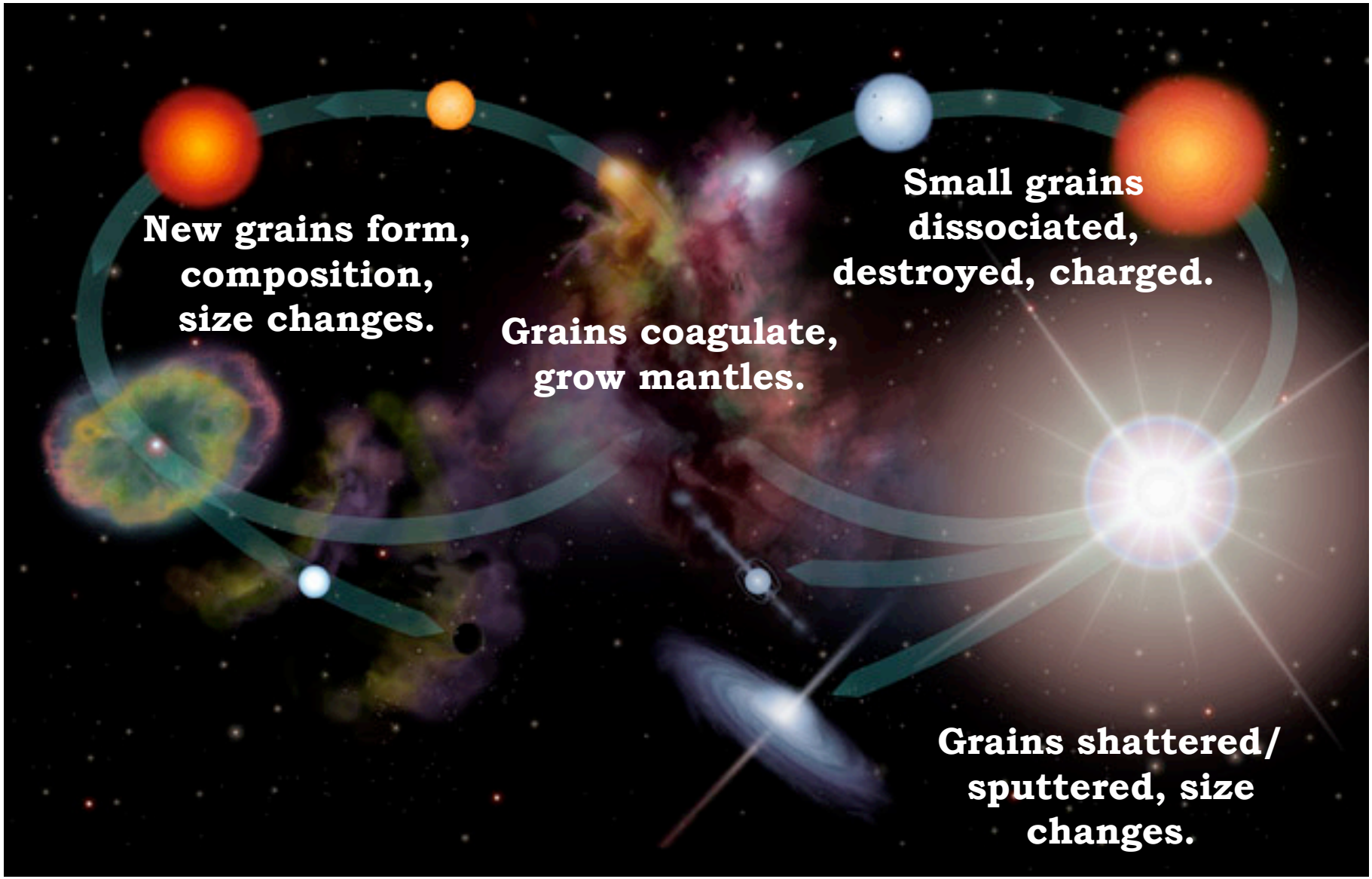
Evolution of Dust Properties tied to Feedback

&

Effectiveness of Feedback tied to Dust Properties

- Gas-to-Dust Ratio
- Grain Size Distribution
- Grain Composition
- Ionization State

# Evolution of Dust Properties tied to Feedback



# Evolution of Dust Properties

*Changes in the effectiveness of UV extinction*

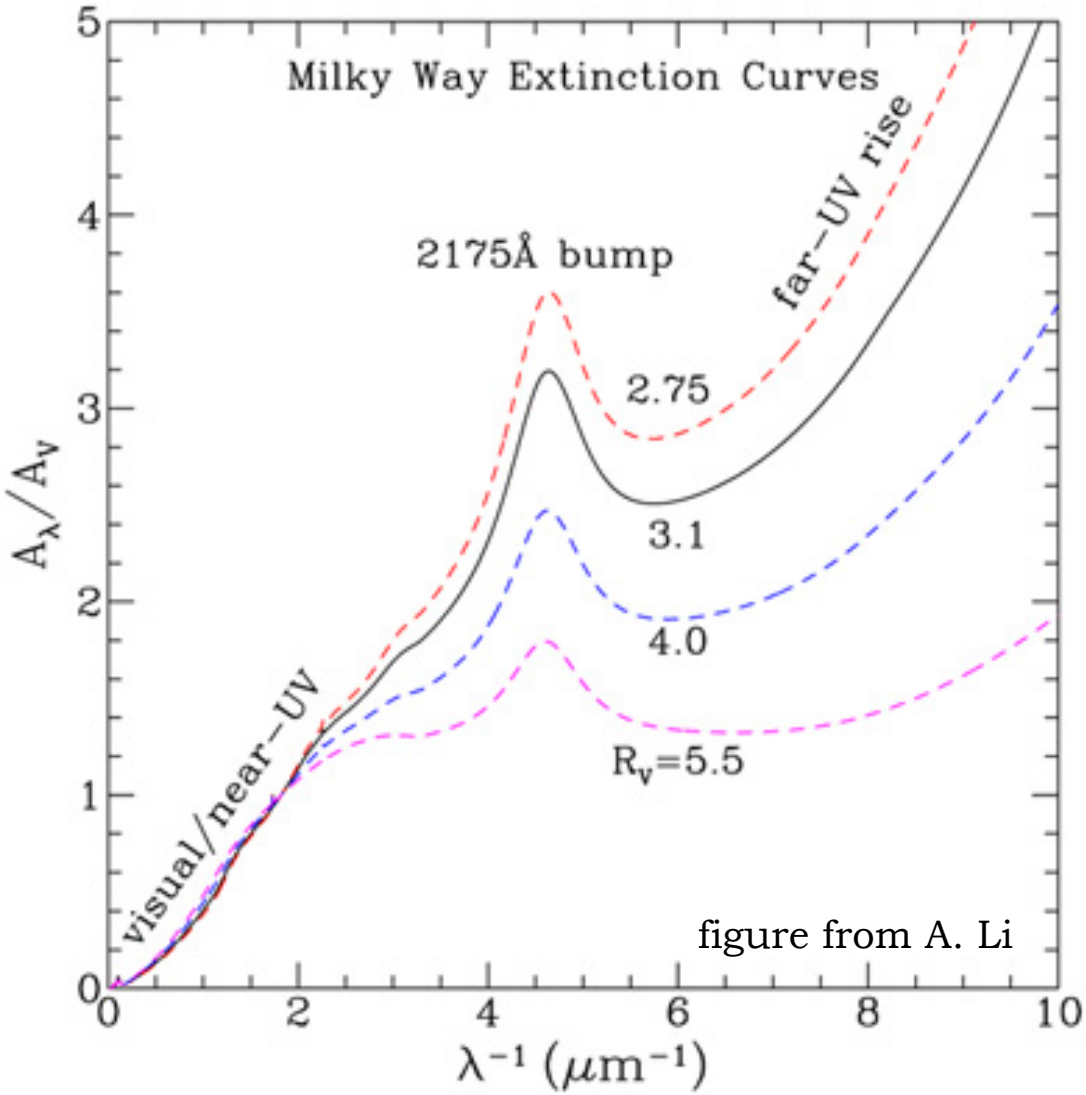
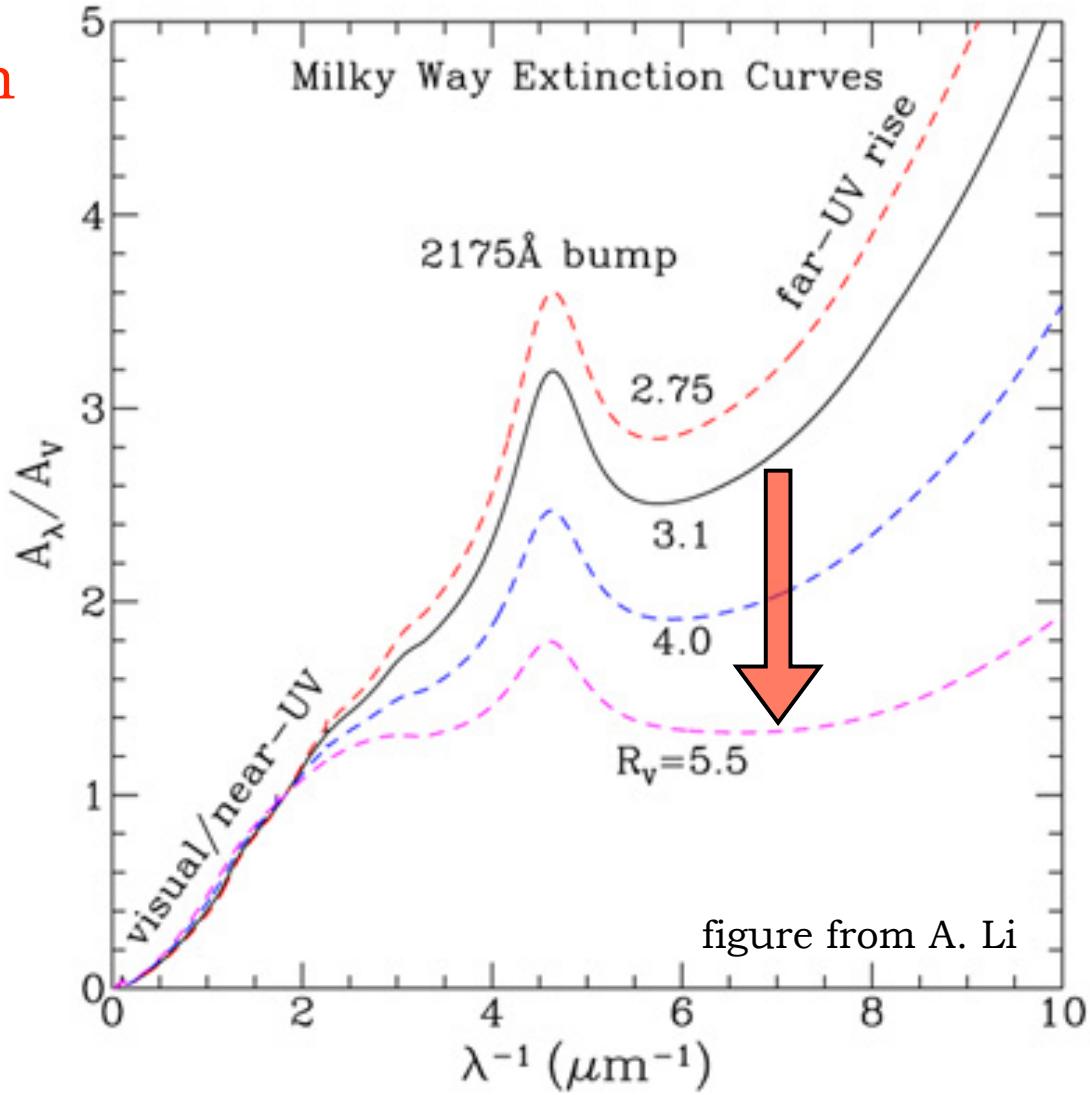



figure from A. Li

# Evolution of Dust Properties

*Changes in the effectiveness of UV extinction*

Molecular Cloud formation
grain growth/coagulation

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*Changes in the effectiveness of UV extinction*

Molecular Cloud formation
grain growth/coagulation

Shocks shatter grains,
increase the small grain
abundance.

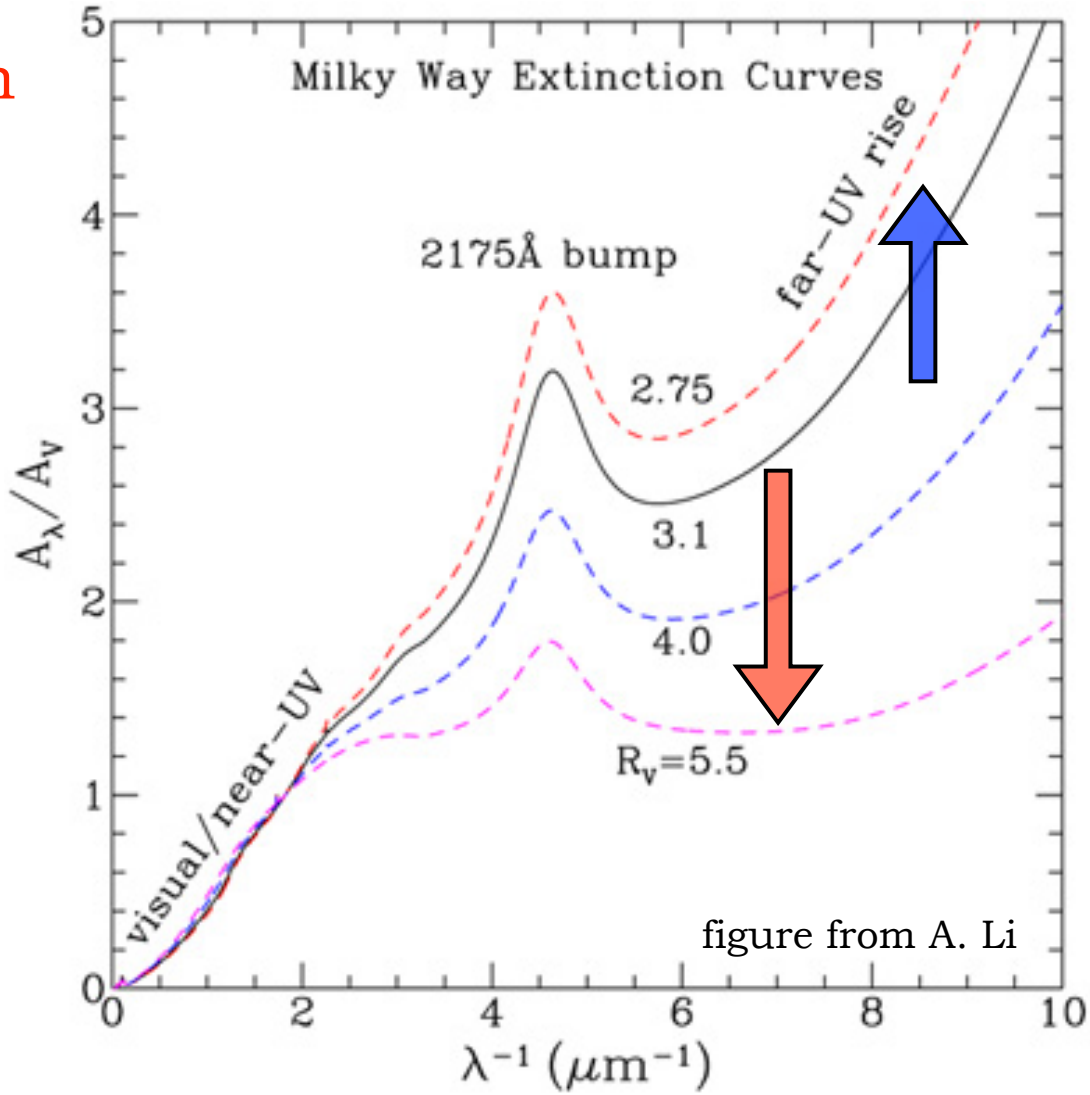



figure from A. Li

# Evolution of Dust Properties

*Changes in the effectiveness of UV extinction*

Molecular Cloud formation
grain growth/coagulation

Shocks shatter grains,
increase the small grain
abundance.

Bump carrier (PAHs?)
photodissociated? created by
shattering? Uncertain!

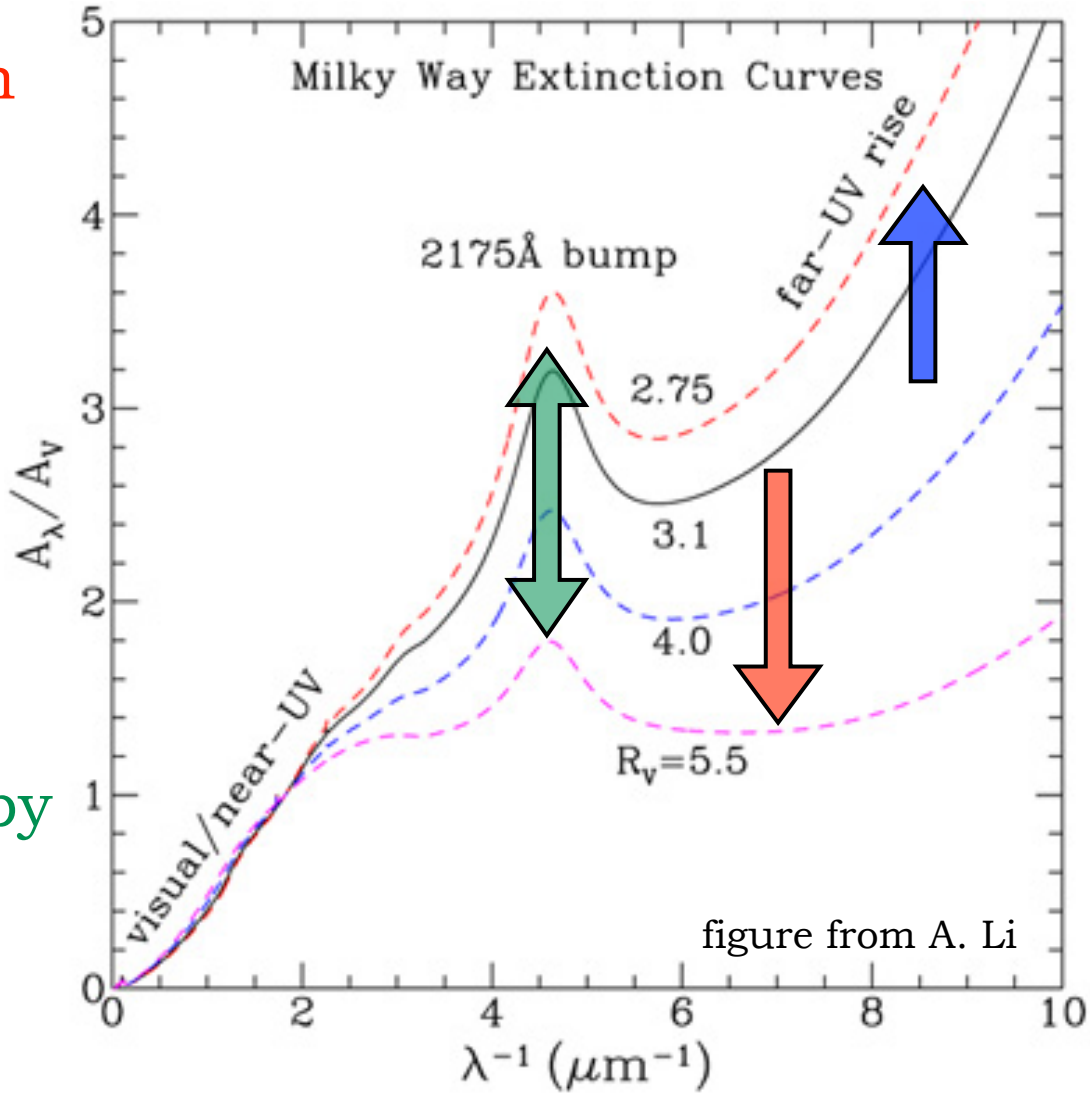
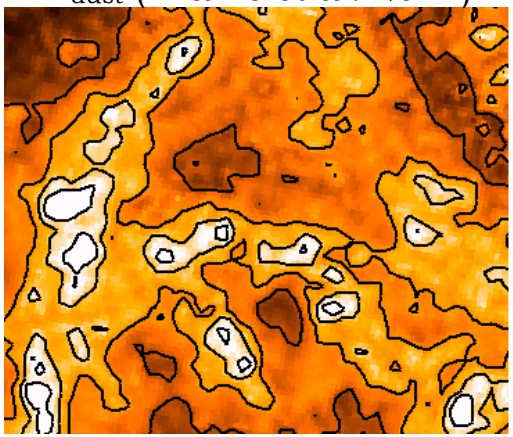


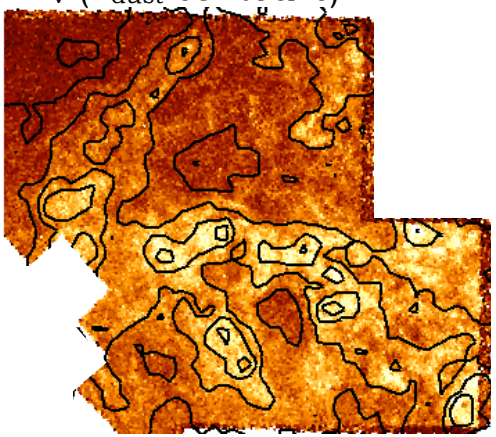

figure from A. Li

# Grain Size Distribution Evolves in Dense Gas

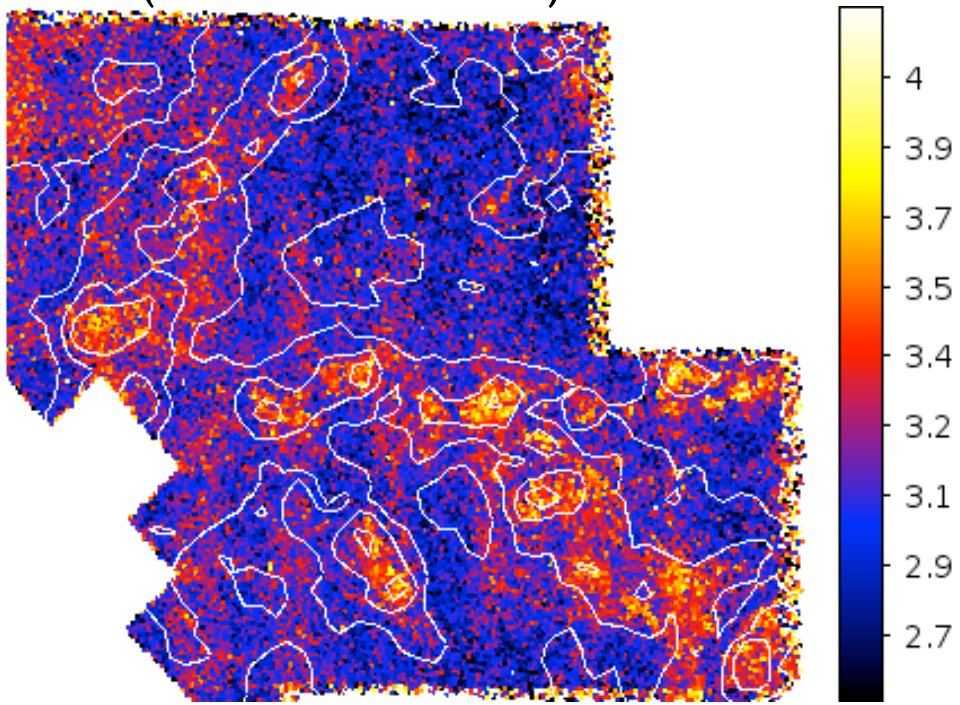
$\Sigma_{dust}$ (Draine et al. 2014)

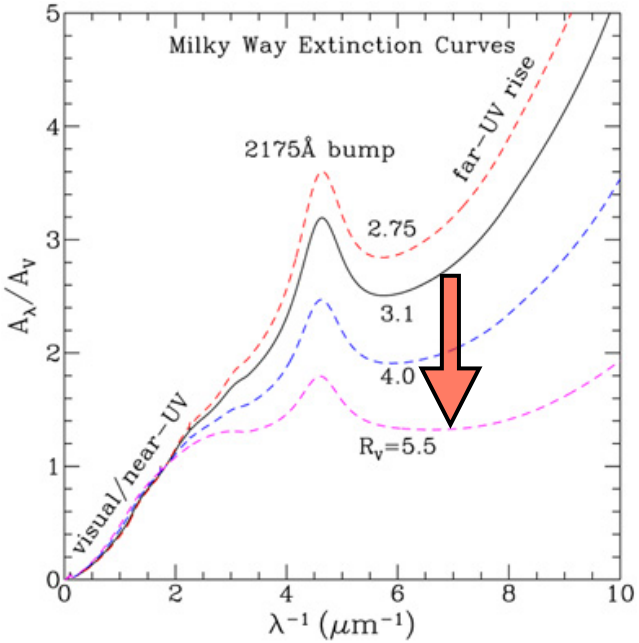


$A_V$ ($\Sigma_{dust}$ contours)



$R_V$ ($\Sigma_{dust}$ contours)




*Maps* of $R_V$ in M31 from stellar SED fitting

(Gordon & PHAT team, in prep)

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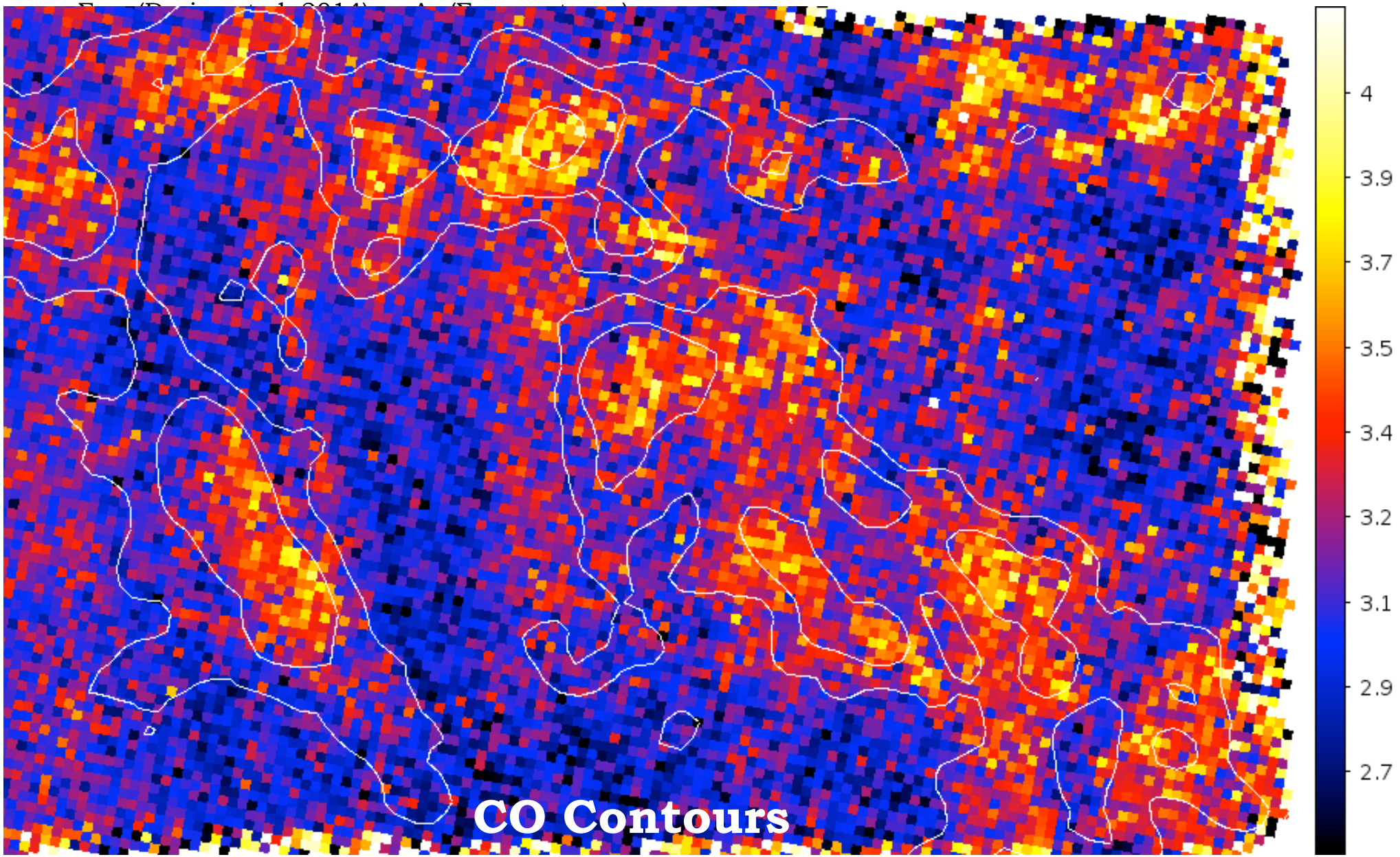
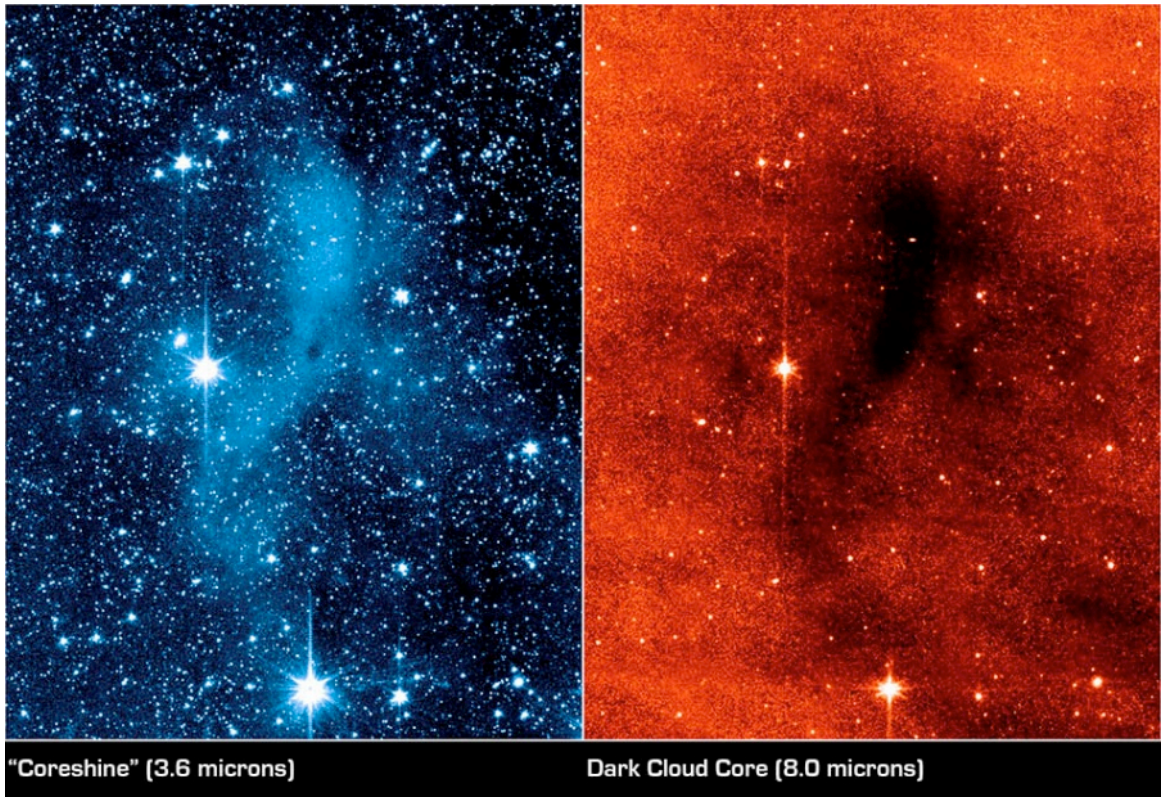
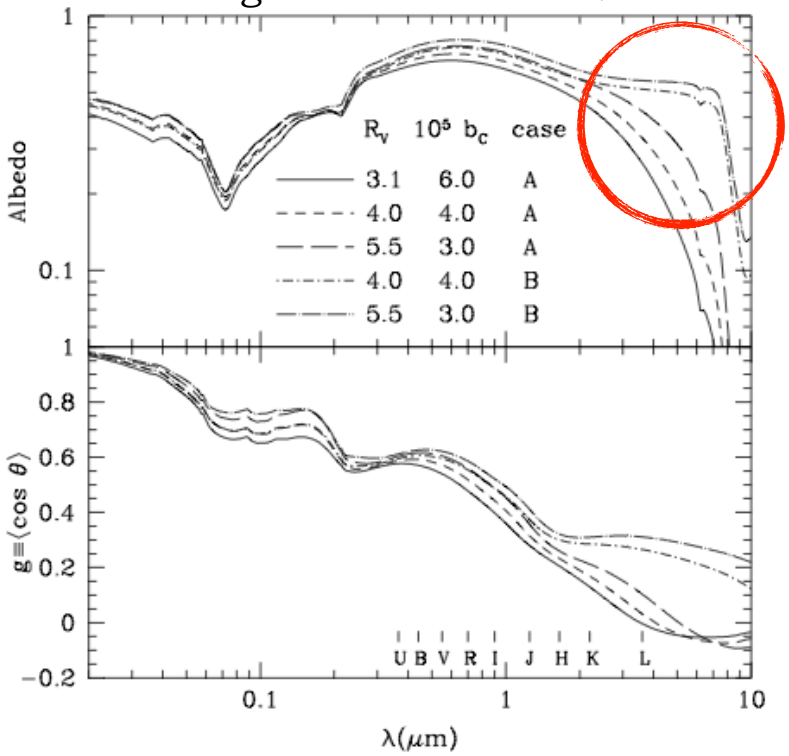


# Grain Size Distribution Evolves in Dense Gas




Steinacker et al 2010

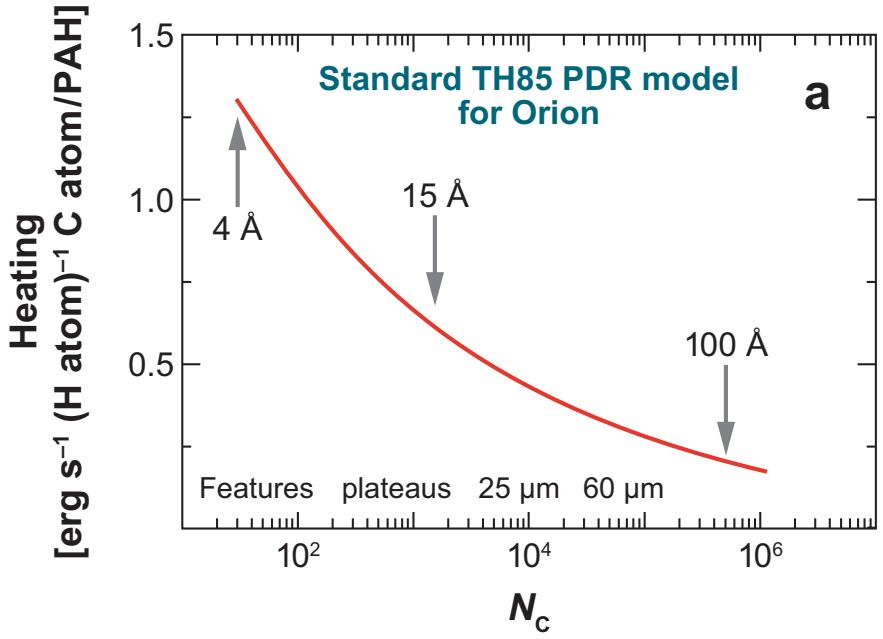
Weingartner & Draine 2001



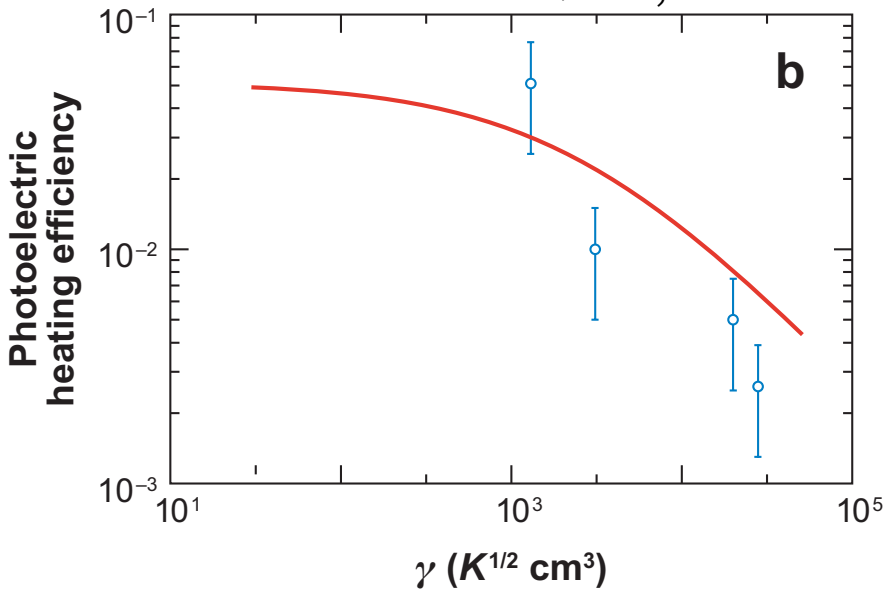

Near- and mid-IR scattering also reveals changes in grain size distribution - grains grow.

# Evolution of Dust Properties

*Changes in the effectiveness of photelectric heating*




Tielens 2008, ARA&A




proxy for grain charge

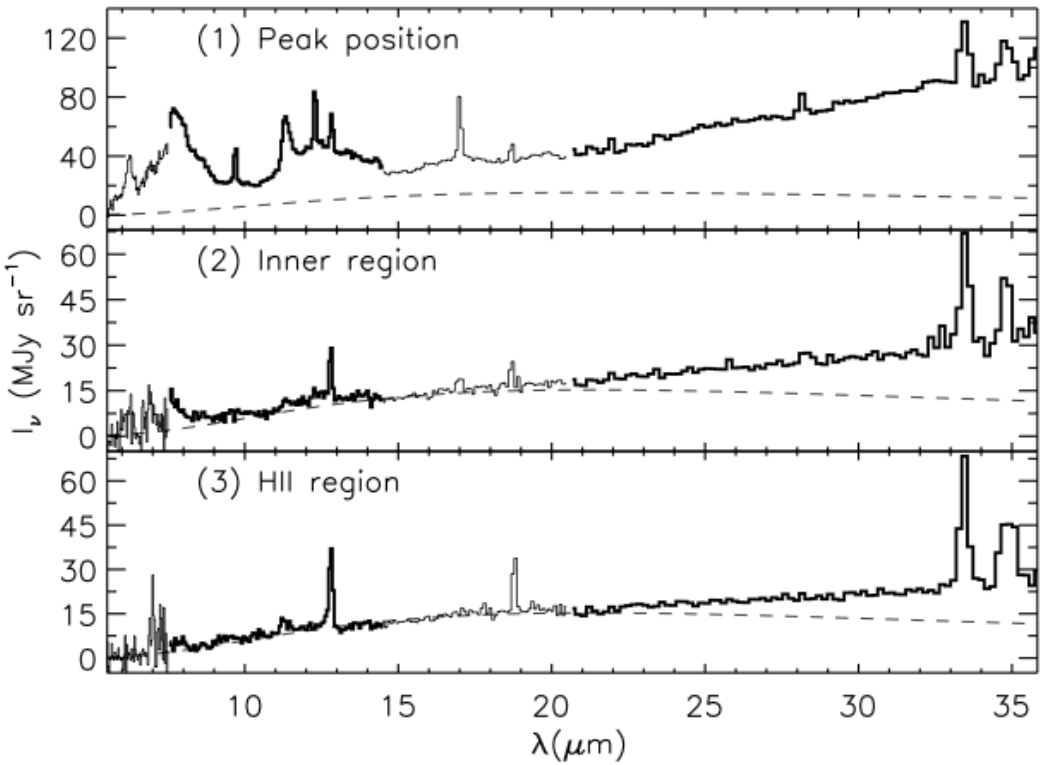
In the MW ~50% of photoelectric heating is due to PAHs ($N_C < 10^3$).

Efficiency will depend on PAH abundance, size distribution & charge.

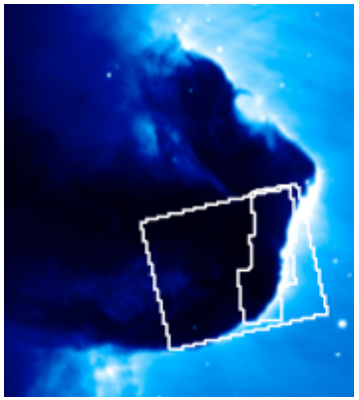
# PAH Abundance Changes with ISM Phase

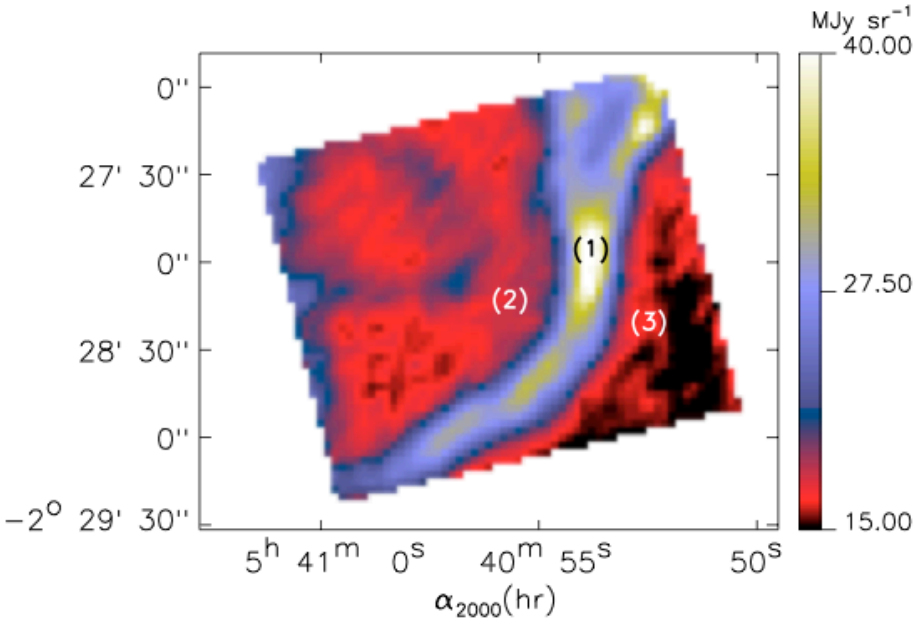
PAHs are destroyed in regions of ionized gas.

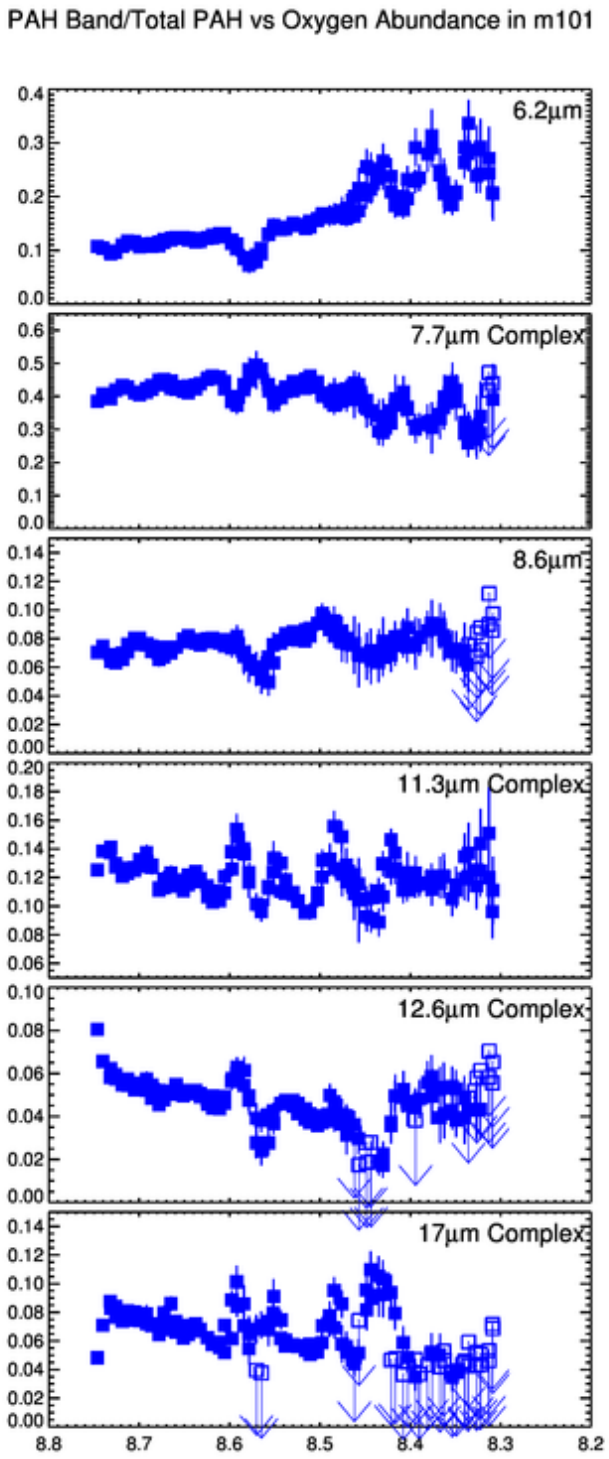
Compiegne et al. 2007




Horsehead Nebula PDR - mid-IR mapping from *Spitzer*





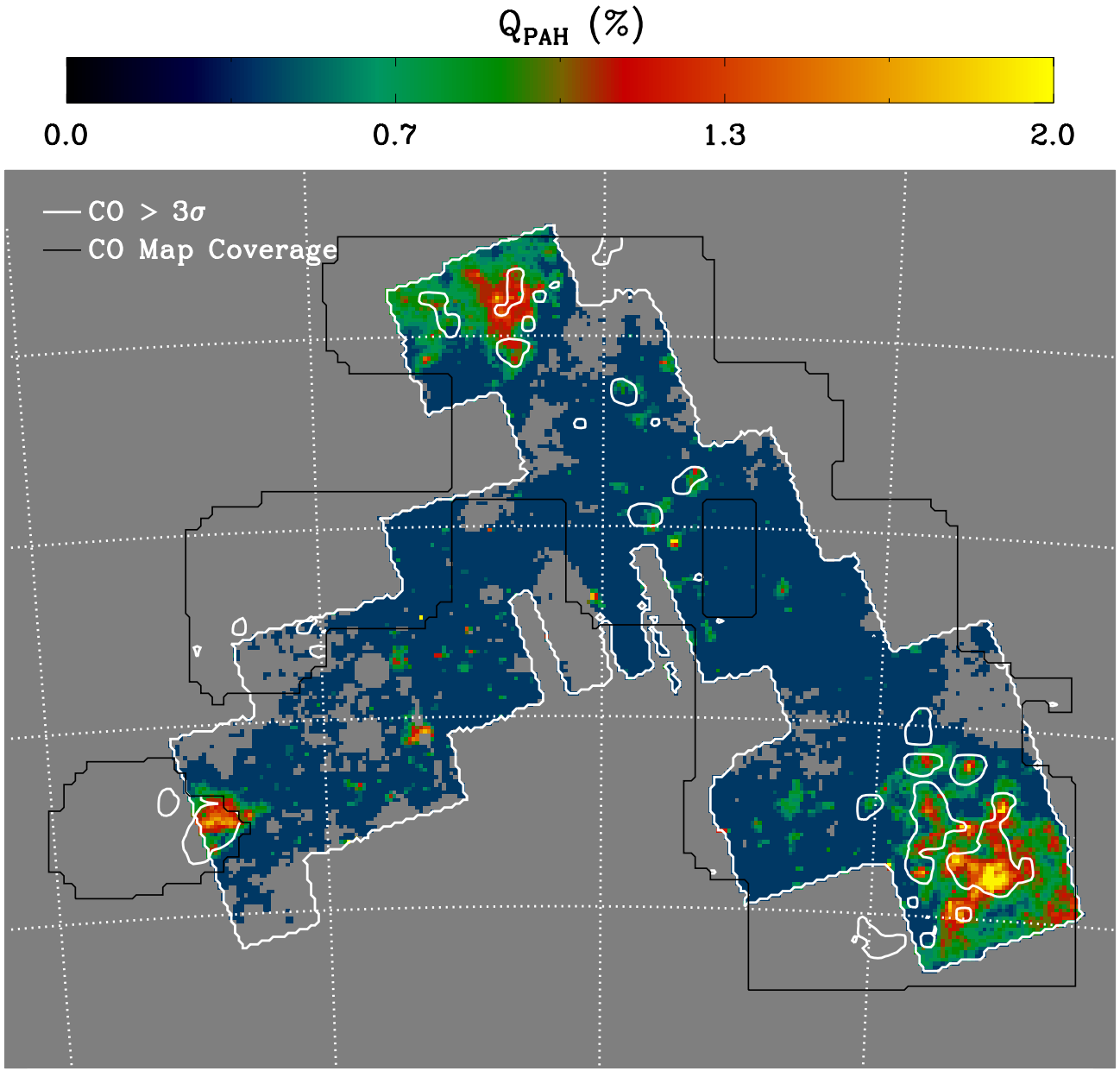



# PAH Properties Vary within Galaxies

Ratios of different PAH bands trace ionization, size, structure.

PAH band ratios in
M101, NGC 628, NGC 2403
Starkey et al. in prep

# PAH Abundance Changes with ISM Phase




In the SMC, PAH abundance is very low in the diffuse ISM, higher in molecular clouds.

Sandstrom et al. 2010

# Measuring Impact of PAHs on PE Efficiency

$$\text{PE Heating Efficiency} \sim \frac{\text{Energy into photoelectrons}}{\text{Energy into grain heating}}$$

# Measuring Impact of PAHs on PE Efficiency

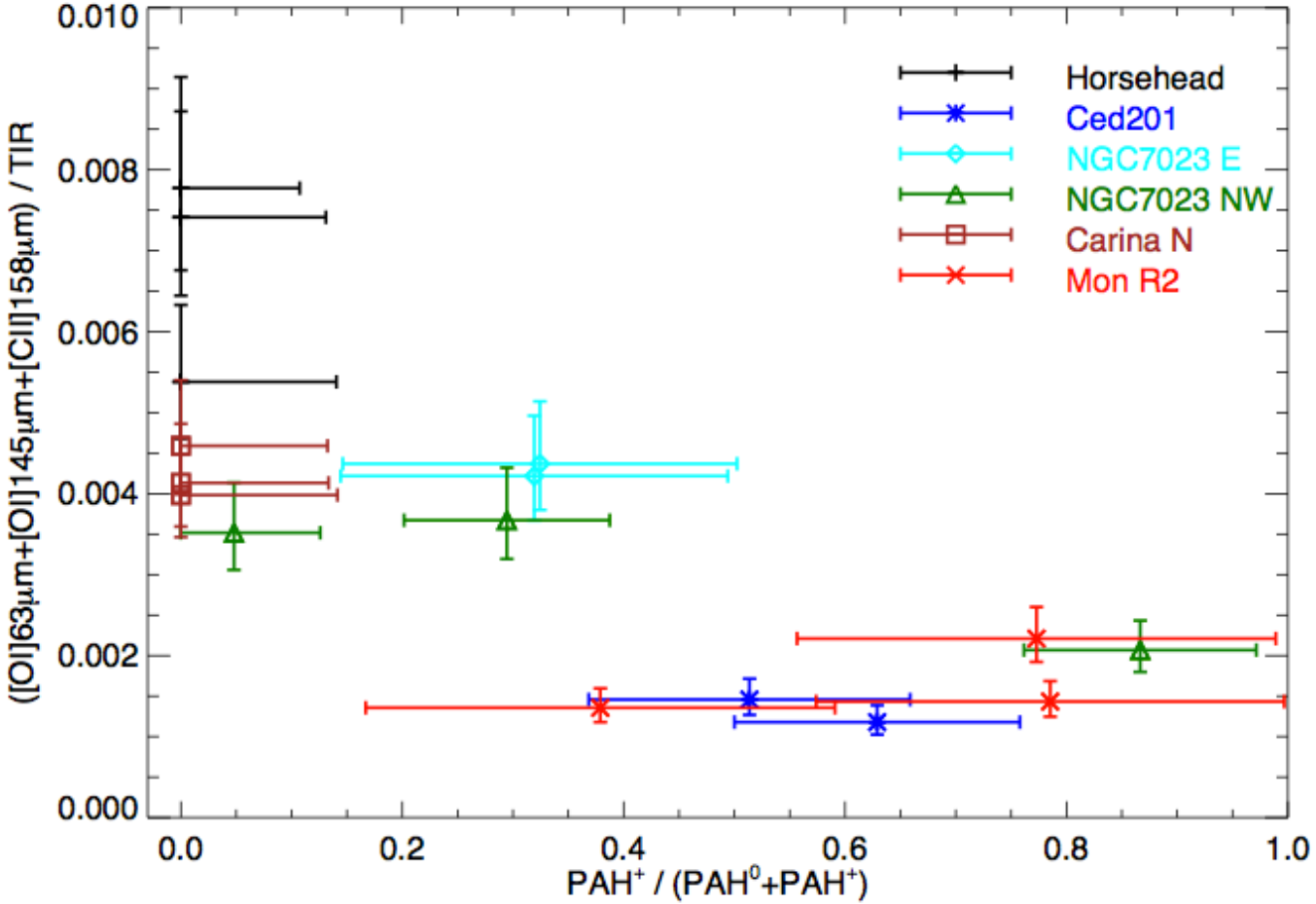
$$\text{PE Heating Efficiency} \sim \frac{\text{Energy into photoelectrons}}{\text{Energy into grain heating}}$$

$$\sim \frac{\text{Total(Gas Cooling)}}{\text{Total(Dust Cooling)}}$$

$$\sim \frac{\text{[CII] + [OI] (+ others)}}{\text{TIR}}$$

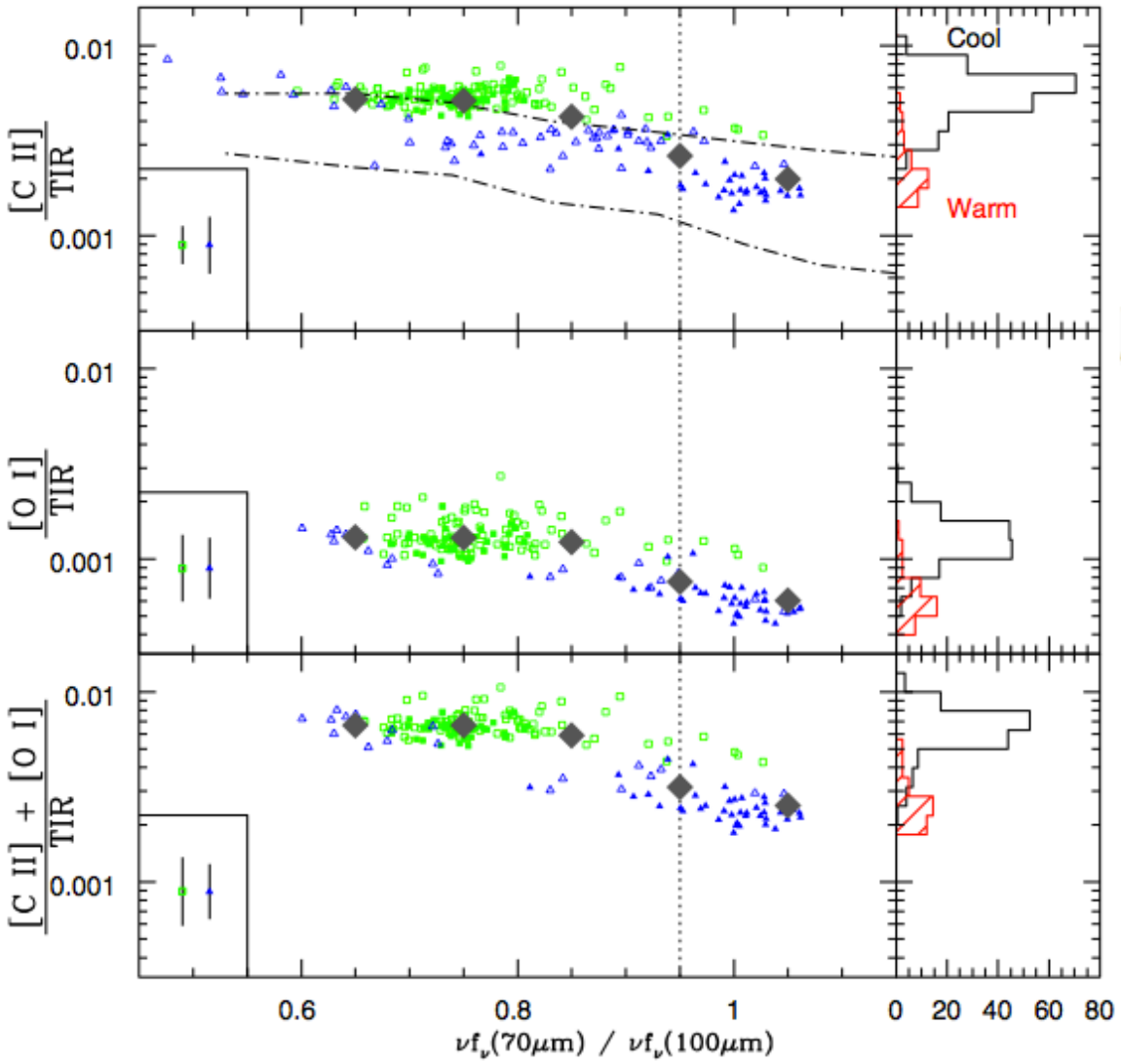
# Measuring Impact of PAHs on PE Efficiency

Okada et al. 2013, A&A, 553, 2



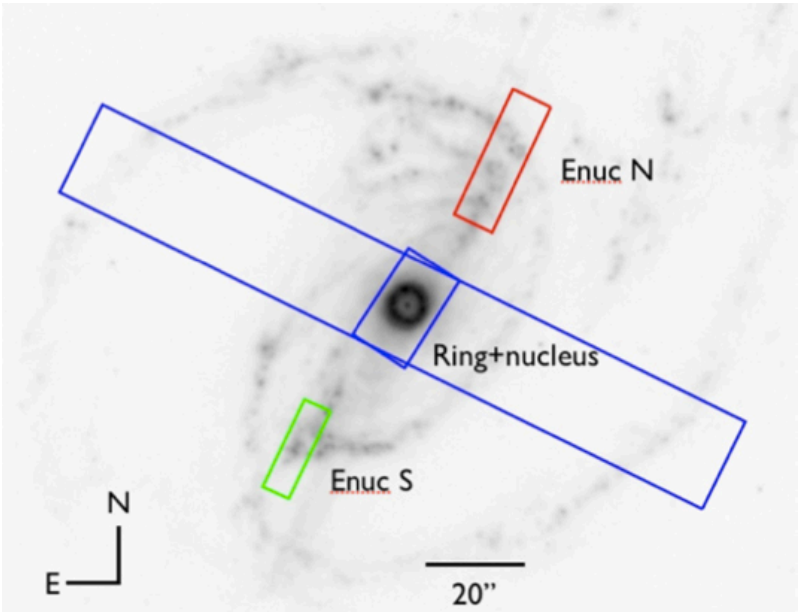

*Herschel* & *Spitzer* studies of MW PDRs find decreased efficiency when PAHs are ionized.

# Measuring Impact of PAHs on PE Efficiency

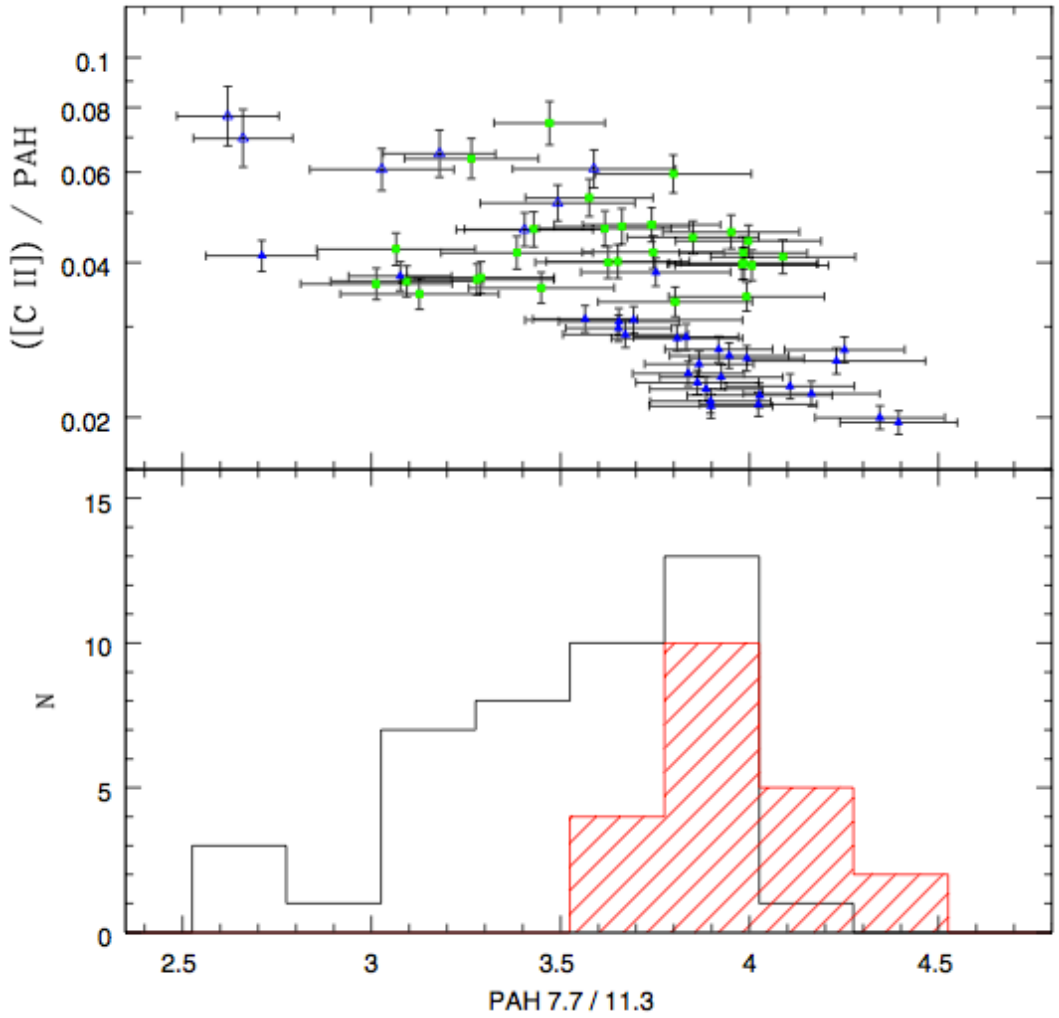



On galactic scales, "[CII] Deficit" may be related to PAH properties.

Beirao et al. 2012, Croxall et al. 2012
KINGFISH & SINGS observations of
NGC 4559 & NGC 1097



# Measuring Impact of PAHs on PE Efficiency




Tracer of PAH charge ⟶

On galactic scales, "[CII] Deficit" may be related to PAH properties.

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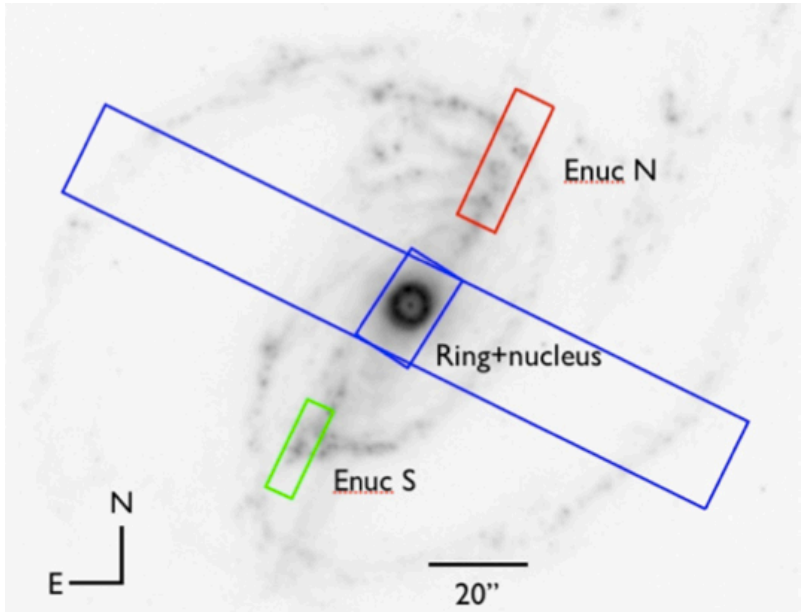
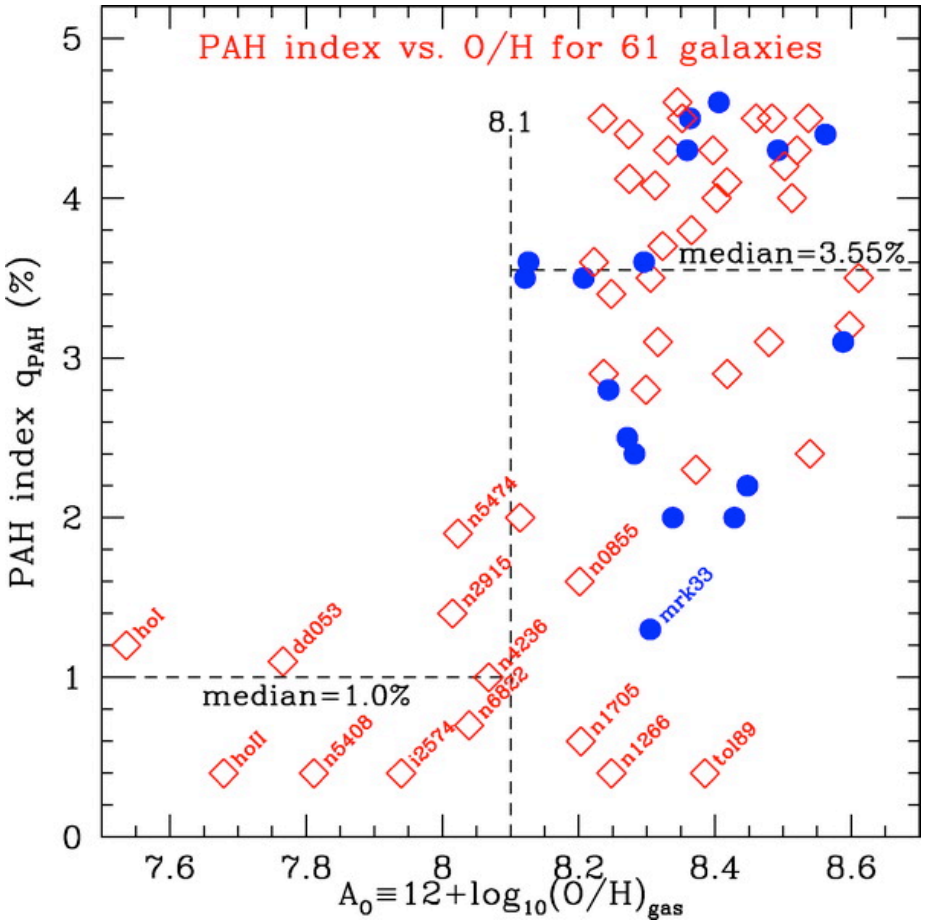
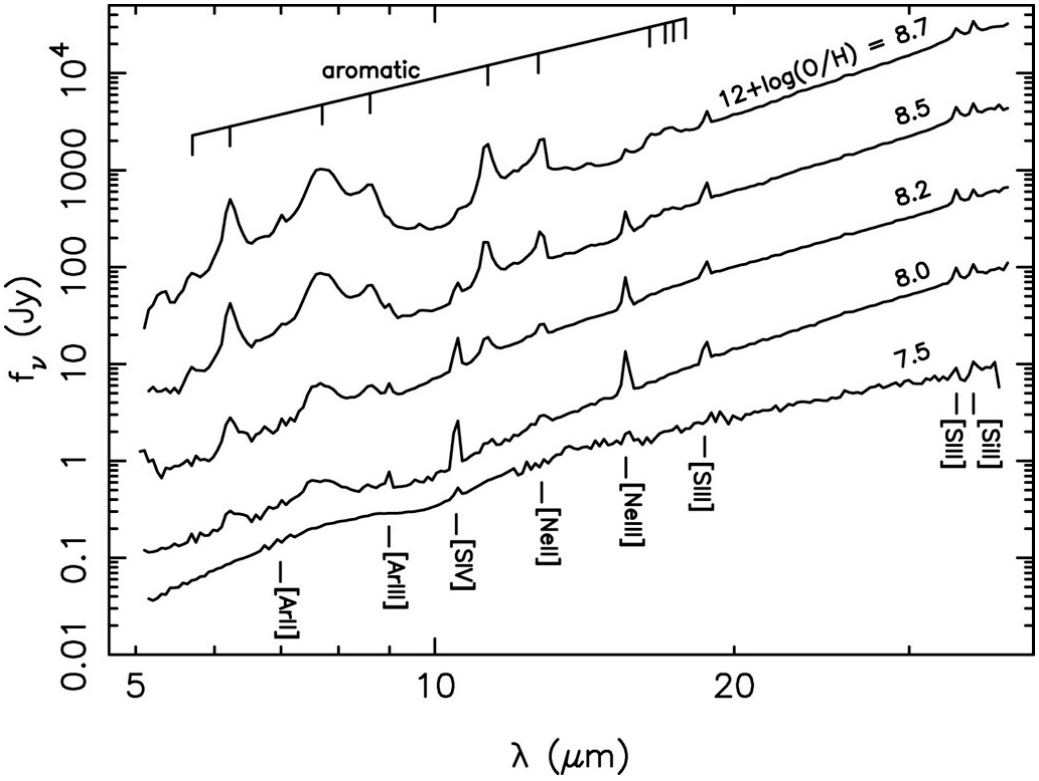


# PAH Abundance Varies Strongly with Z

Draine et al. 2007



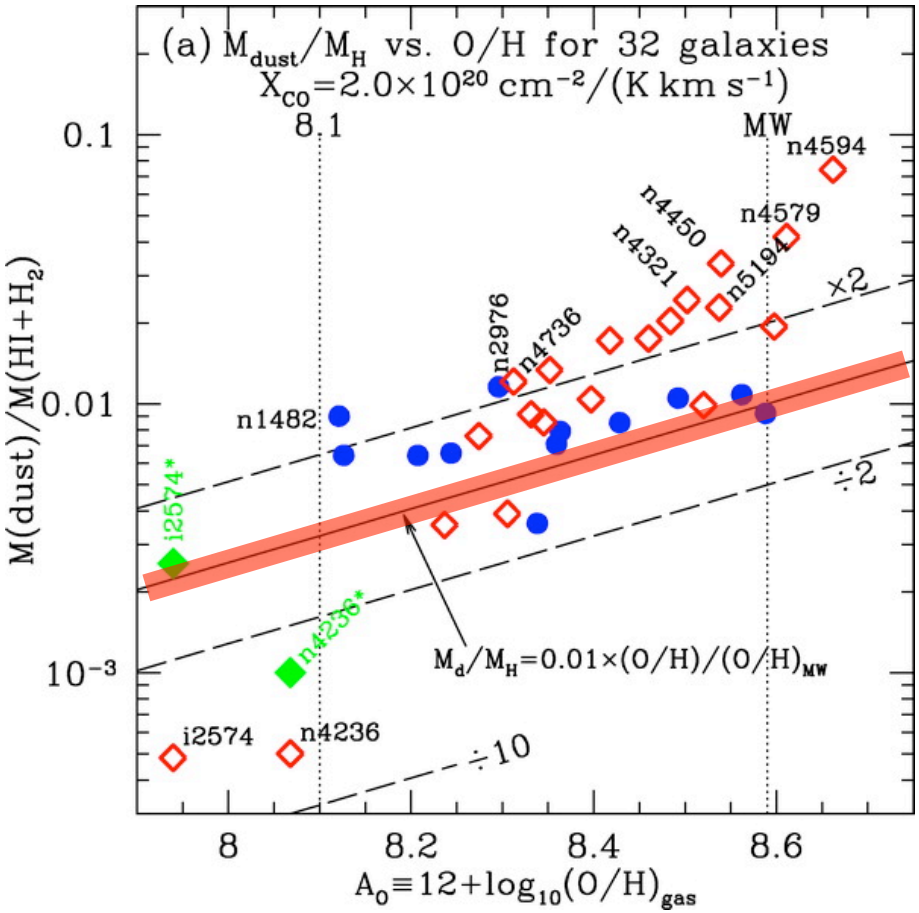

Engelbracht et al 2008



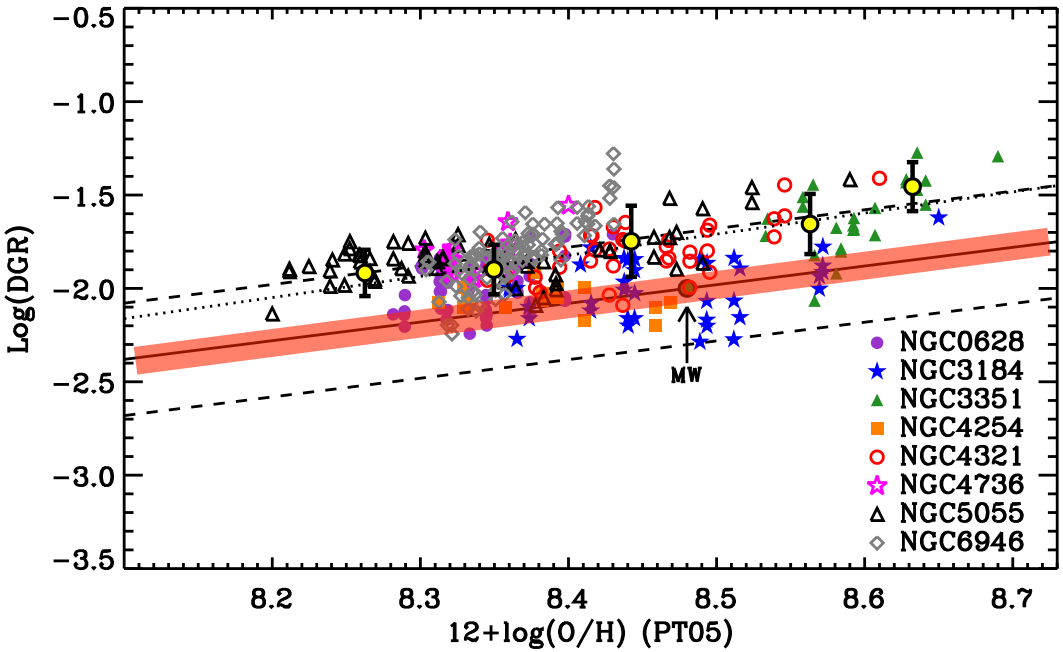
# Is Dust-to-Gas Ratio a Simple Function of Z?

Above 12+log(O/H) ~ 8, DGR(Z) appears to be reasonably well behaved.

Draine et al. 2007

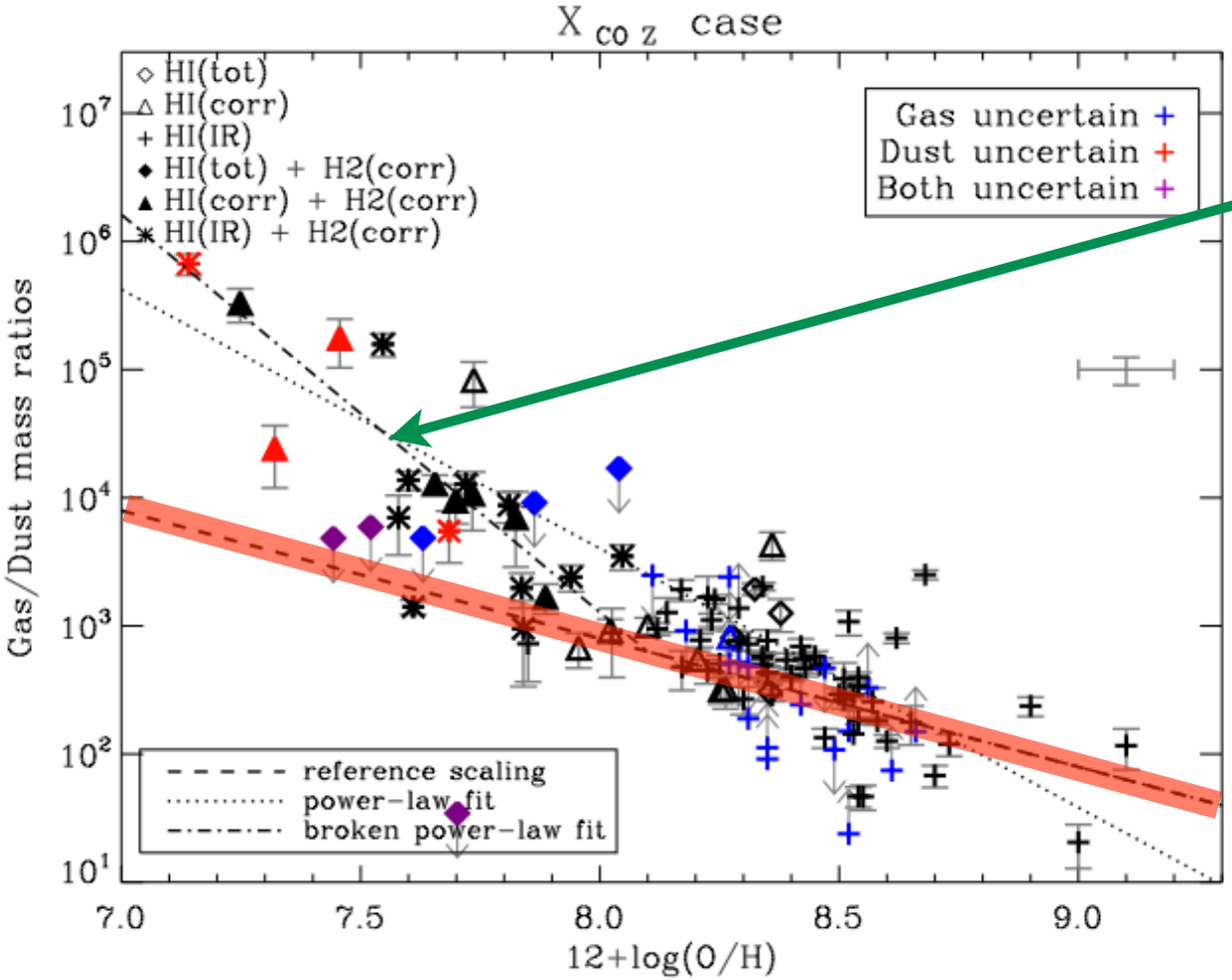



Sandstrom et al. 2013




Constant Dust/Metals = Linear DGR(Z)

# Is Dust-to-Gas Ratio a Simple Function of Z?

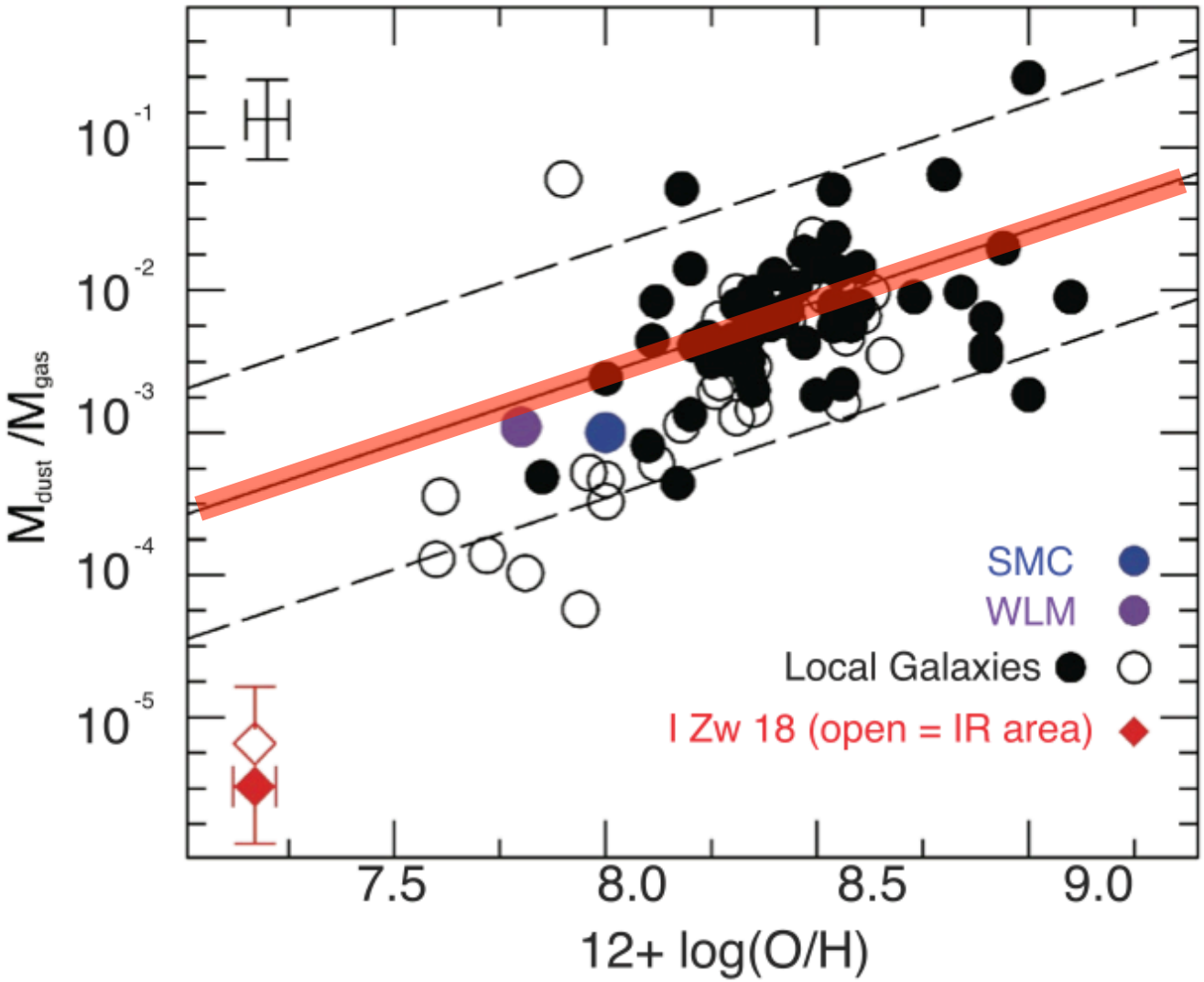



DGR(Z) steeper than linear below 12+log(O/H)~8.

Dwarf Galaxies Survey
Rémy-Ruyer et al. 2014

Linear scaling can overpredict amount of dust by >1 order of magnitude.

# Is Dust-to-Gas Ratio a Simple Function of Z?



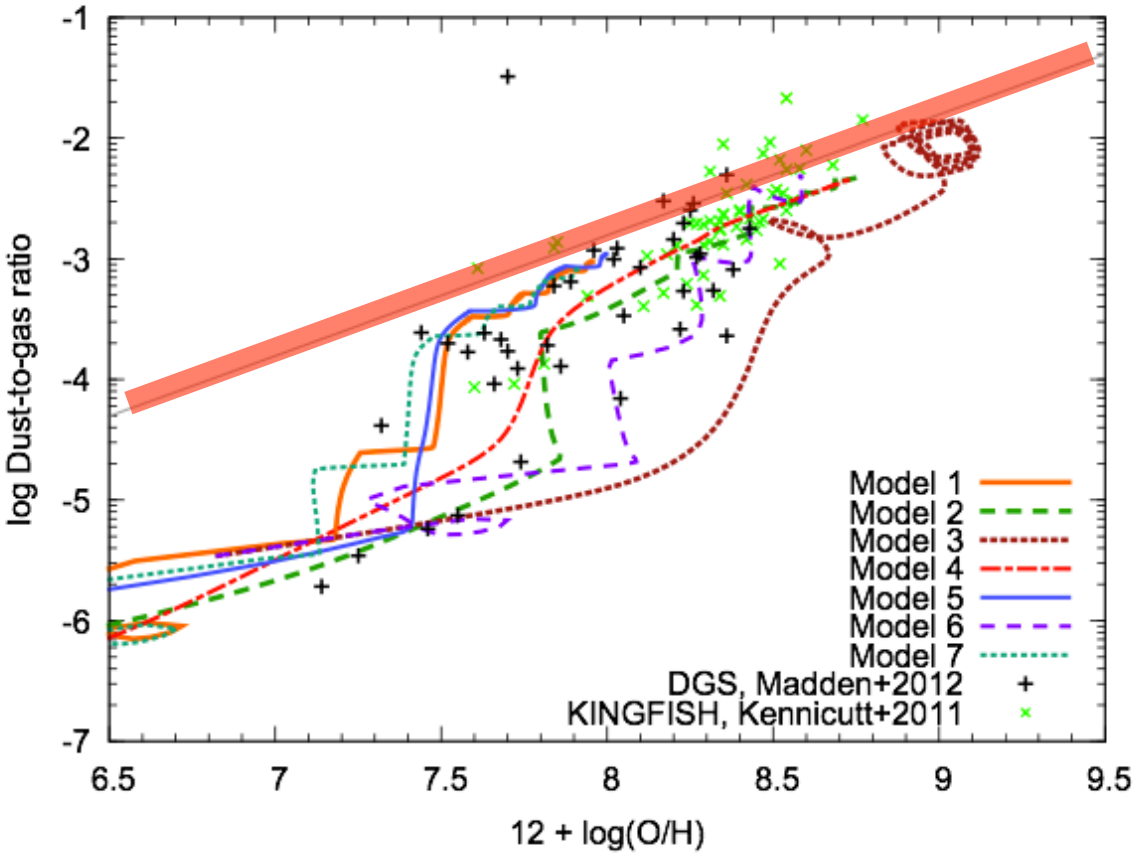

*Herschel* observations of I Zw 18 show much less dust than metallicity would predict.

Fisher et al. 2013

# Is Dust-to-Gas Ratio a Simple Function of Z?

*Not always...*

Zhukovska 2014




| Model | $n_{burst}$ | $t_{burst}$ Gyr | $dt_{burst}$ Myr | $\tau_{SF}$ Gyr | $\tau_{inf}$ Gyr |
|---|---|---|---|---|---|
| Model 1 | 6 | 0, 1, 2, 5, 7, 11 | 50 | 2 | 0.3 |
| Model 2 | 6 | 0, 1, 2, 5, 7, 11 | 500 | 2 | 0.3 |
| Model 3 | 6 | 0, 1, 2, 5, 7, 11 | 500 | 0.2 | 0.3 |
| Model 4 | - | - | - | 10 | 0.3 |
| Model 5 | 3 | 1, 5, 11 | 100 | 2 | 0.3 |
| Model 6 | 5 | 0, 0.3, 0.6, 1, 7 | 50 | 0.2 | 0.3 |
| Model 7 | 6 | 0, 1, 2, 5, 7, 11 | 50 | 2 | 1 |

Star formation history can alter dust-to-metals ratio substantially.

Model includes:
- formation by AGB, SNe
- growth in ISM
- destruction by SNe

# Summary

- Studies of Local Group galaxies provide unique constraints on feedback.
- HI energetics correlated to SFH at t=30-40 Myr.
- HI holes due to multiple generations of stars.
- K-S scatter is observable consequence of feedback & diagnostic for simulations.
- Variations in dust properties are both consequence of & influence on feedback processes.
- DGR depends on Z and on SFH.