Resolved Observations of the Dust-to-Gas Ratio in Nearby Spiral Galaxies

Karin Sandstrom
Max Planck Institute for Astronomy

June 28, 2011 - From Dust to Galaxies

Collaborators

the KINGFISH Team -

P.I. Robert Kennicutt, Daniela Calzetti,
Gonazlo Aniano, Phillip Appleton, Lee Armus, Pedro Beirao, Alberto Bolatto, Bernhard Brandl, Alison Crocker, Kevin Croxall, Daniel Dale, **Bruce Draine**, Chad Engelbracht, Maud Galametz, Armando Gil de Paz, Karl Gordon, Brent Groves, Caina Hao, George Helou, Joannah Hinz, Leslie Hunt, Ben Johnson, Jin Koda, Oliver Krause, **Adam Leroy**, Eric Murphy, Nurur Rahman, Hans-Walter Rix, Helene Roussel, Marc Sauvage, Eva Schinnerer, Ramin Skibba, J. D. Smith, Sundar Srinivasan, Laurent Vigroux, **Fabian Walter**, Bradley Warren, Christine Wilson, Mark Wolfire & Stefano Zibetti

the HERACLES Team -

P.I. Fabian Walter, Adam Leroy,
Frank Bigiel, Elias Brinks, Erwin de Blok, Daniela Calzetti, Kelly Foyle, Gaelle Dumas, Robert Kennicutt, Carsten Kramer, Sharon Meidt, Hans-Walter Rix, Erik Rosolowsky, Eva Schinnerer, Andreas Schruba, Karl Schuster, Antonio Usero, Axel Weiss

- Dust-to-Gas Ratio (DGR) Introduction
- The Importance of Xco
- DGR & Xco from Resolved Observations of Nearby Galaxies
- Results from KINGFISH & HERACLES
- DGR & Xco versus metallicity

The Dust-to-Gas Ratio

- DGR(Z) - relative fraction of heavy elements locked up in dust.
- Deviations from DGR $\propto$ Z tell us about dust life-cycle (formation, destruction & processing in ISM).
- Abundance of dust important for ISM physics (photoelectric heating, H_2 formation, etc).

Limitations on DGR measurements in nearby galaxies:

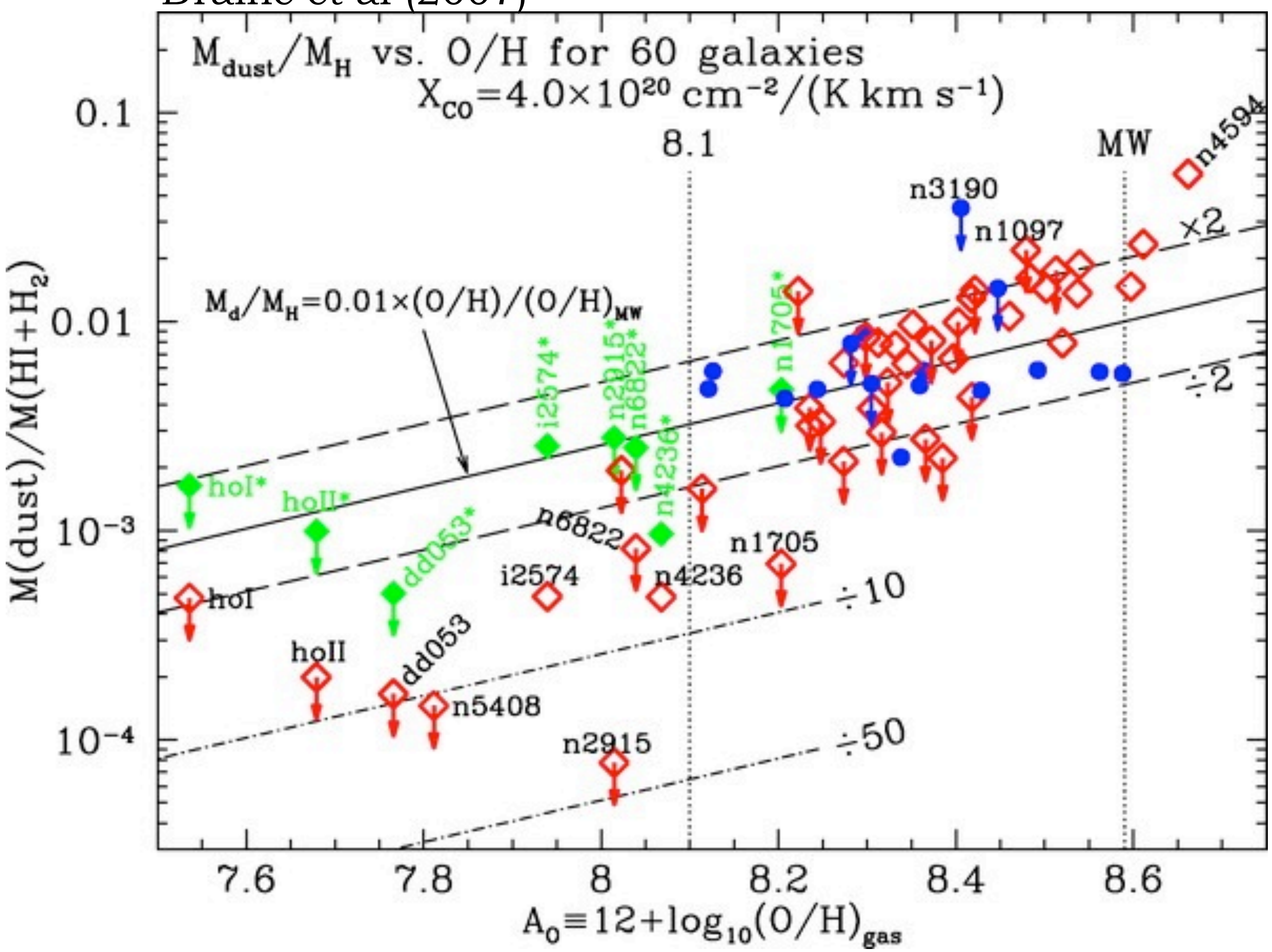
1. large beam size (few resolution elements per galaxy)
2. poor long-λ constraints on dust SED
3. lack of high-sensitivity CO measurements
4. poor constraints on CO-to-H_2 conversion factor X_{CO}

Can be overcome with new Herschel & CO observations.

The Dust-to-Gas Ratio

What we know from unresolved studies of nearby galaxies:

Draine et al (2007)



1. Integrated galaxy DGR from SINGS suggest ~constant fraction of metals in dust when 12+log(O/H) > 8.1
(if X_{CO} ~ 4×10^{20})

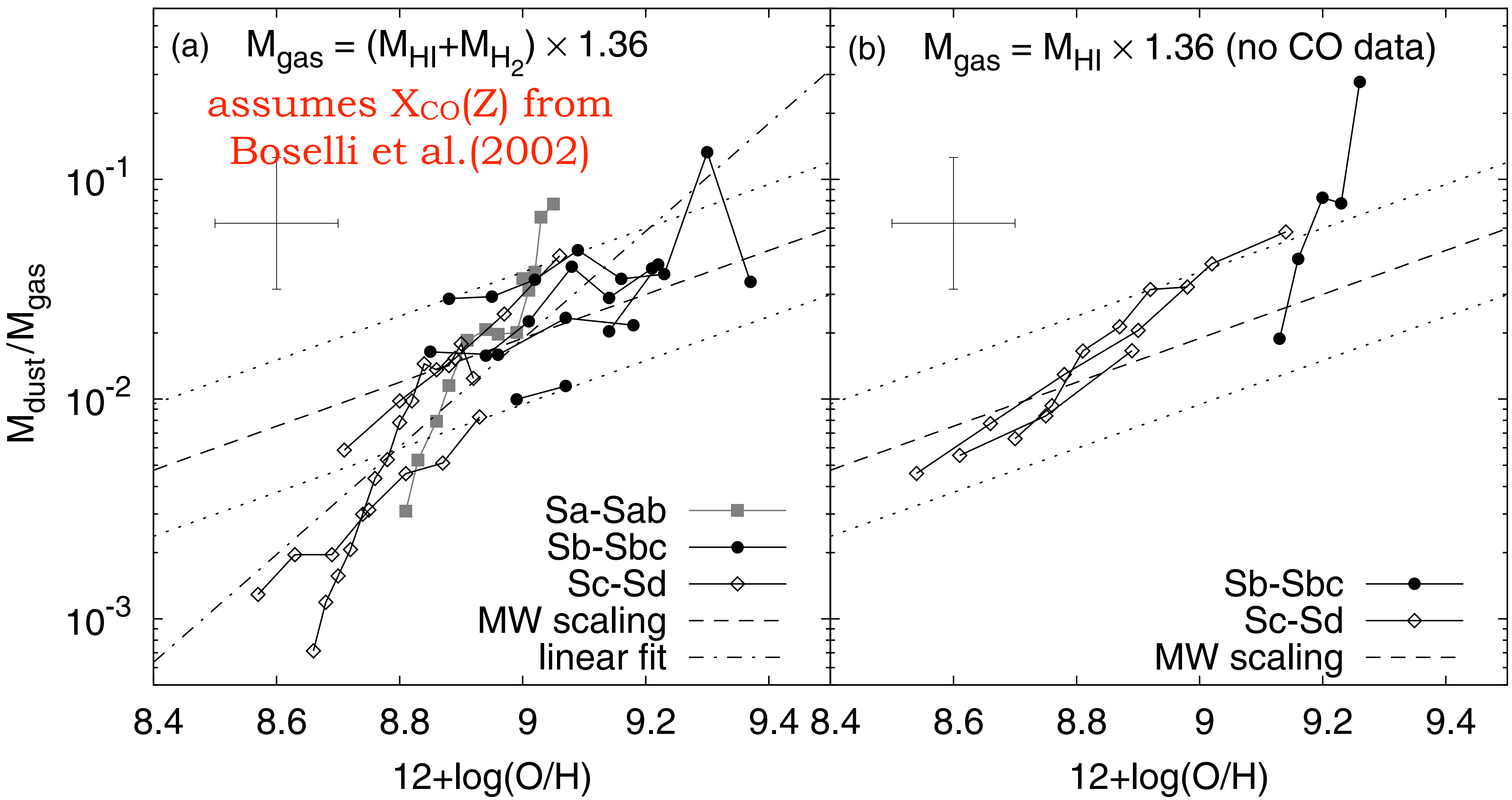
2. Low metallicity, Irr galaxies - DGR lower than trend, but less so if only regions with IR detections considered.
(also found by many studies of low-metallicity dwarf galaxies)

Blue - with SCUBA fluxes
Red - without SCUBA

Green - just where IR is detected
Upper Limits - no CO measurement

The Dust-to-Gas Ratio

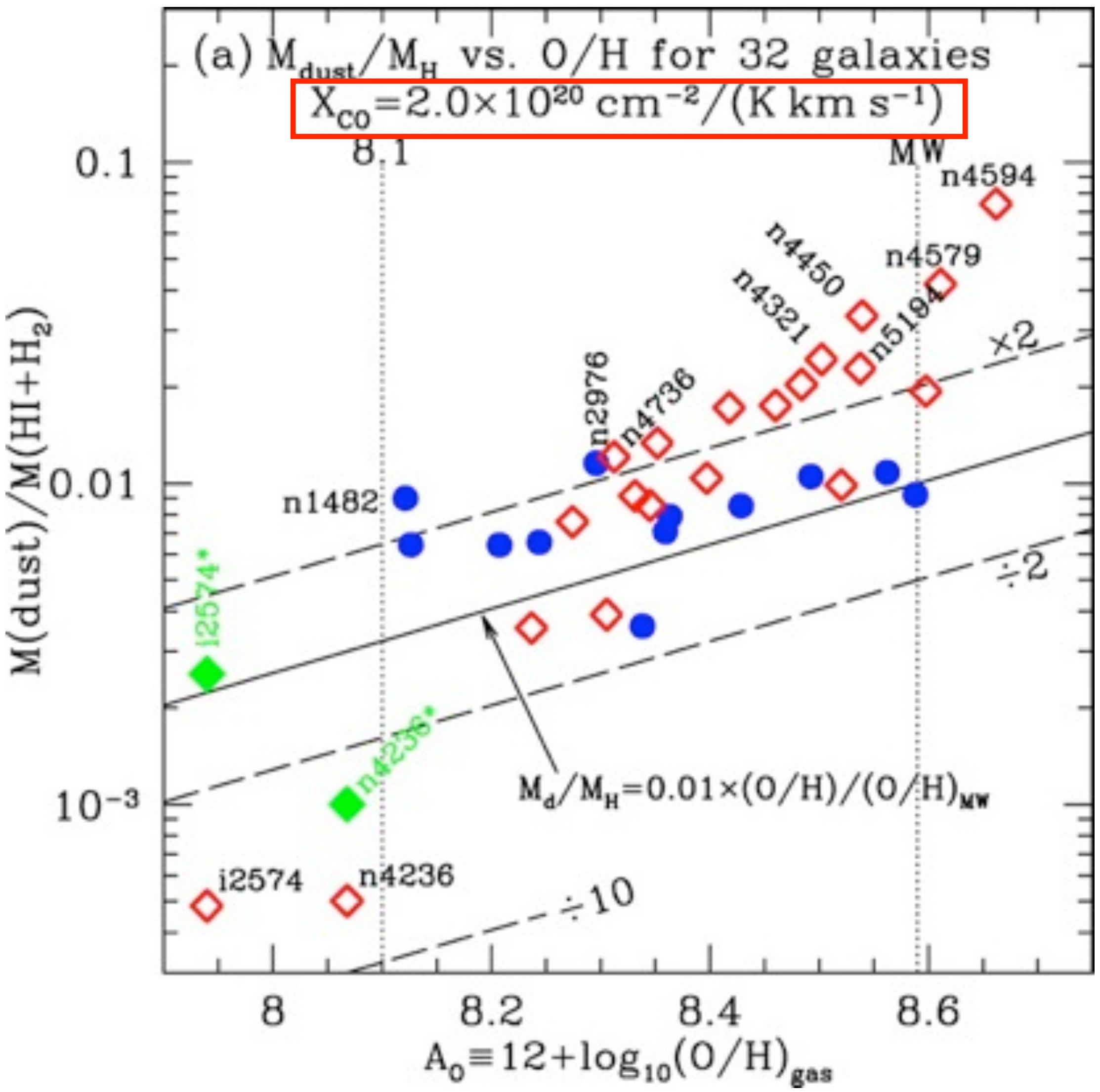
Resolved studies of nearby galaxies:



Munoz-Mateos et al. (2009): SINGS sample + Σ_D from DL07 models

Radial profiles suggest steeper DGR(Z) compared to integrated measurements.

Measuring Dust-to-Gas Ratios



H I mass surface density

Σ_{H2}

$$DGR = \Sigma_D/(\Sigma_{HI} + \alpha_{CO} I_{CO})$$

dust mass surface density

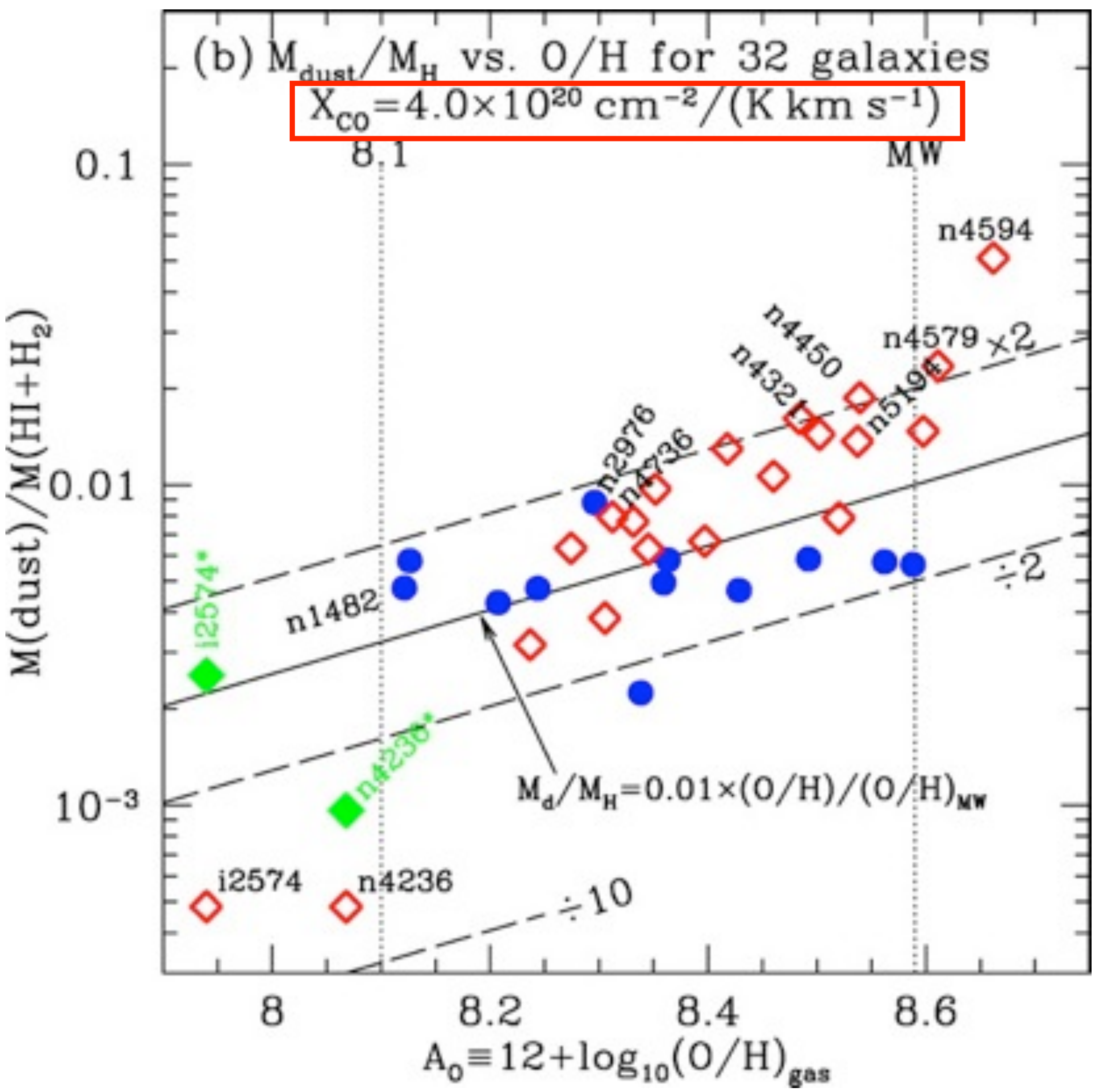
α_{CO} = X_{CO} in surface mass density units [$M_\odot$ pc^{-2} (K km s^{-1})$^{-1}$]

note: Xco defined here for unresolved clouds

α_{CO} = 4.35 when $X_{CO} = 2\times10^{20}$

DGR and X_{CO} are closely linked - *must account for molecular gas*!

Measuring Dust-to-Gas Ratios



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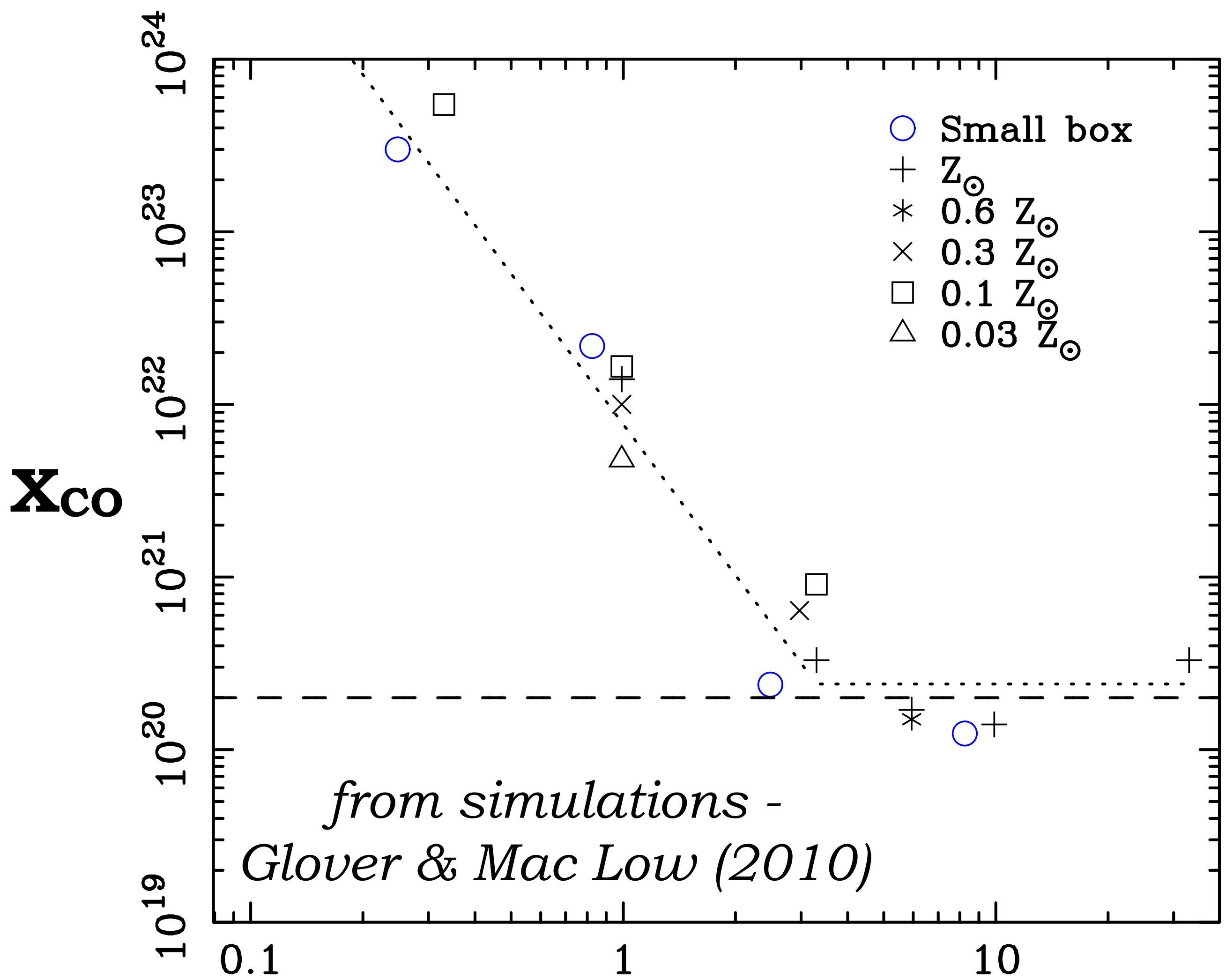
X_{CO} & Environment

Assuming X_{CO} may not be straightforward...

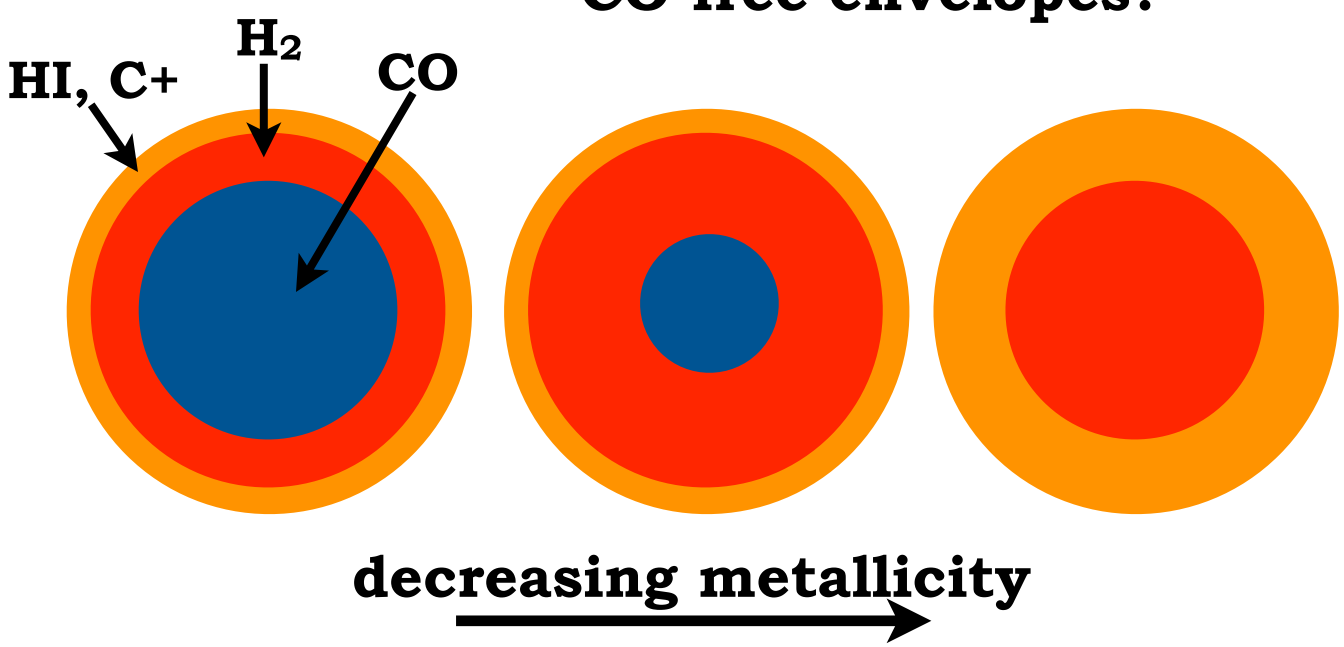
X_{CO} could depend on:
metallicity, radiation field,
DGR, etc.



Why could X_{CO} change?

- changes in CO excitation
- lower C & O abundances
- envelopes of CO-free H_2 around molecular clouds (CO dissociated while H_2 self-shields)

CO-free envelopes?



(Maloney & Black 1988, Bolatto et al. 1999, Wolfire et al. 2010, etc.)

Measuring X_{CO}

- γ-rays (interaction of CR & gas produces γ-rays, used to trace total gas column - e.g. Strong & Mattox 1996, Abdo et al. 2010)
  - difficult (need CR density), only possible in very local galaxies
- Virial Masses (measure CO luminosity mass and virial mass - e.g. Solomon et al. 1987, Bolatto et al. 2008)
  - not robust to envelopes of CO-free of H_2
  - need high spatial resolution CO observations to measure GMC size
- LVG or other multi-line analysis
  - only brightest targets
- Dust (use dust as a tracer of total gas column - e.g. Israel 1997, Leroy et al. 2007, 2009)

X_{CO} from Dust

Possible Techniques:

unknowns $$DGR = \Sigma_D / (\Sigma_{HI} + \alpha_{CO} I_{CO})$$ observables

- Fix DGR based on expected DGR(Z).
  - circular (how do you know DGR(Z) to start?)
- Fix DGR based on nearby atomic gas dominated line-of-sight.
  - only possible in very nearby galaxies (i.e. Local Group)
  - Julia Roman-Duval's presentation yesterday
- ***Keep both DGR & X_{CO} as free parameters and use spatially resolved measurements to solve for both.***

Constraining both DGR & X_{CO} with spatially resolved measurements.

$$DGR = \Sigma_D / (\Sigma_{HI} + \alpha_{CO} I_{CO})$$

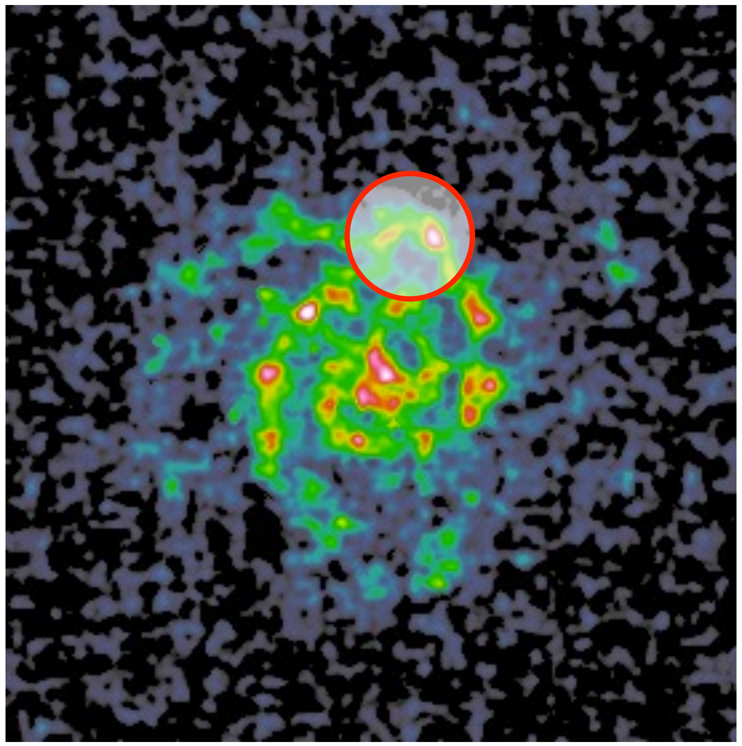
solve for

1. Assume we can represent some region of a galaxy with ***one DGR and one X_{CO}.***

2. Make resolved measurements of Σ_D, Σ_{HI}, and I_{CO} in that region.

3. Step through a grid of X_{CO} and find the value of that gives you the least scatter in measured DGR.

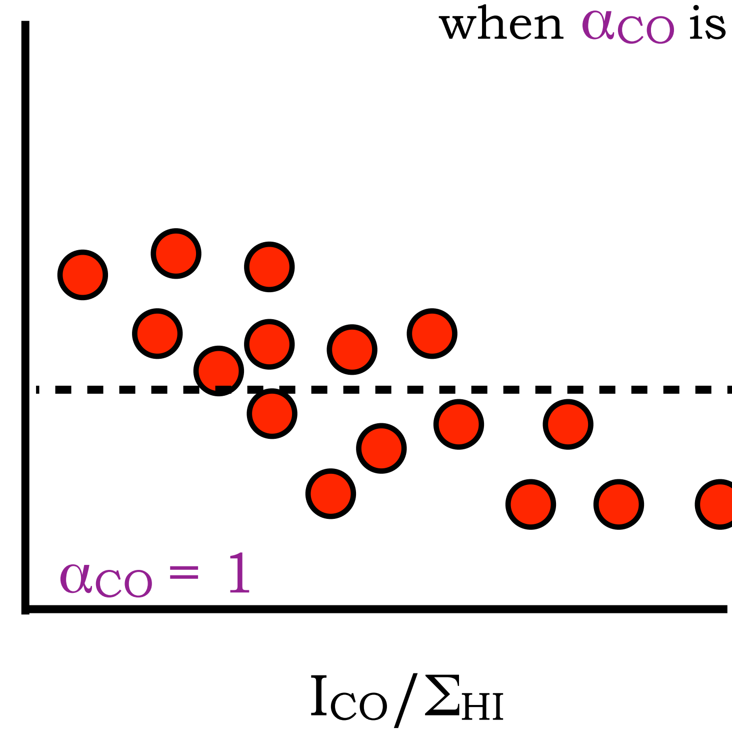
When/where will this work?



assume DGR & Xco
constant in this region

cartoon of what happens to DGR
when α_{CO} is adjusted

$$\mathrm{DGR} = \frac{\Sigma_{dust}}{\Sigma_{HI} + \alpha_{CO} I_{CO}}$$



- both CO and H I are detected
  ⟶ Need good S/N maps of CO & HI.
- a range of I_{CO}/Σ_{HI} values are present
  ⟶ Need many resolution elements.
- region is small, ok to assume DGR & Xco ~ constant
  ⟶ Must select small chunk of galaxy, so need high resolution.

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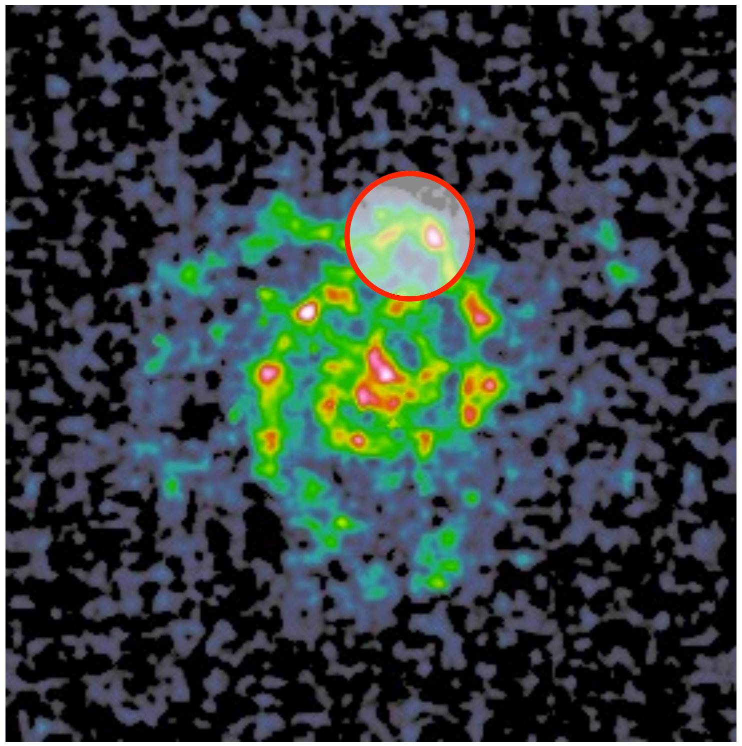

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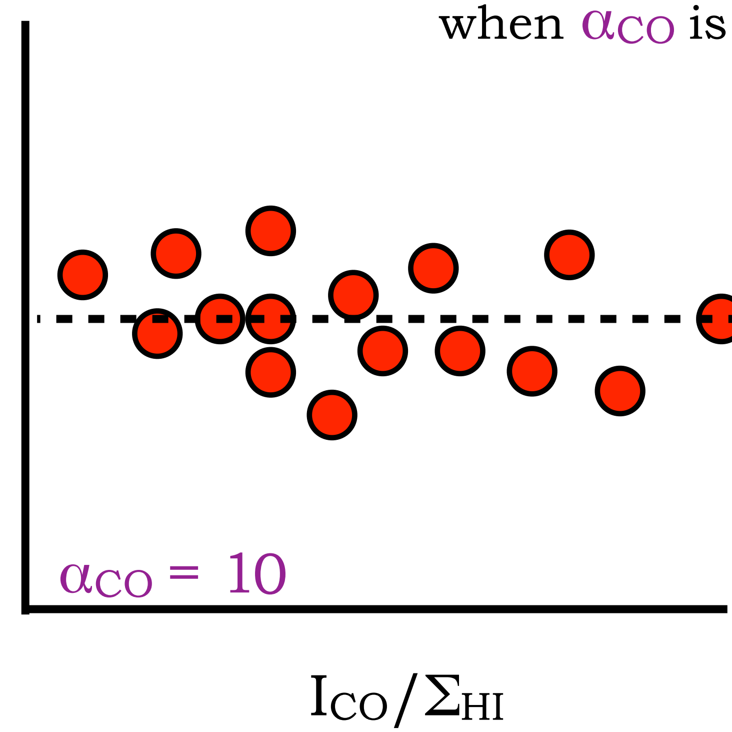

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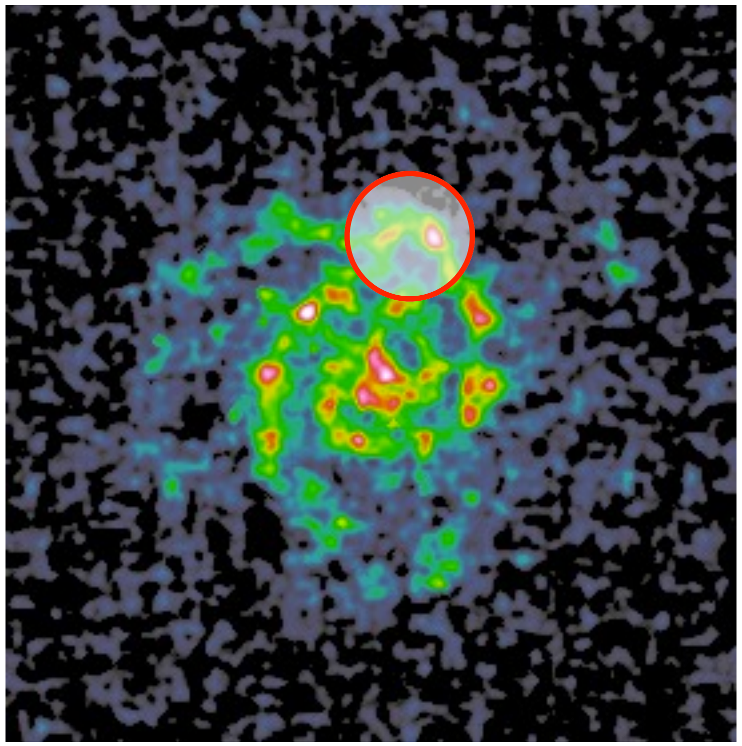

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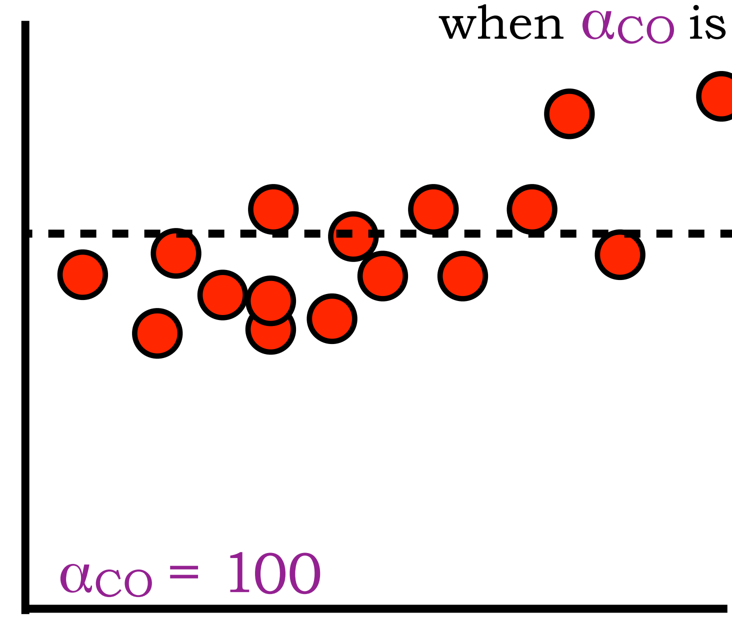

I_{CO}/Σ_{HI}

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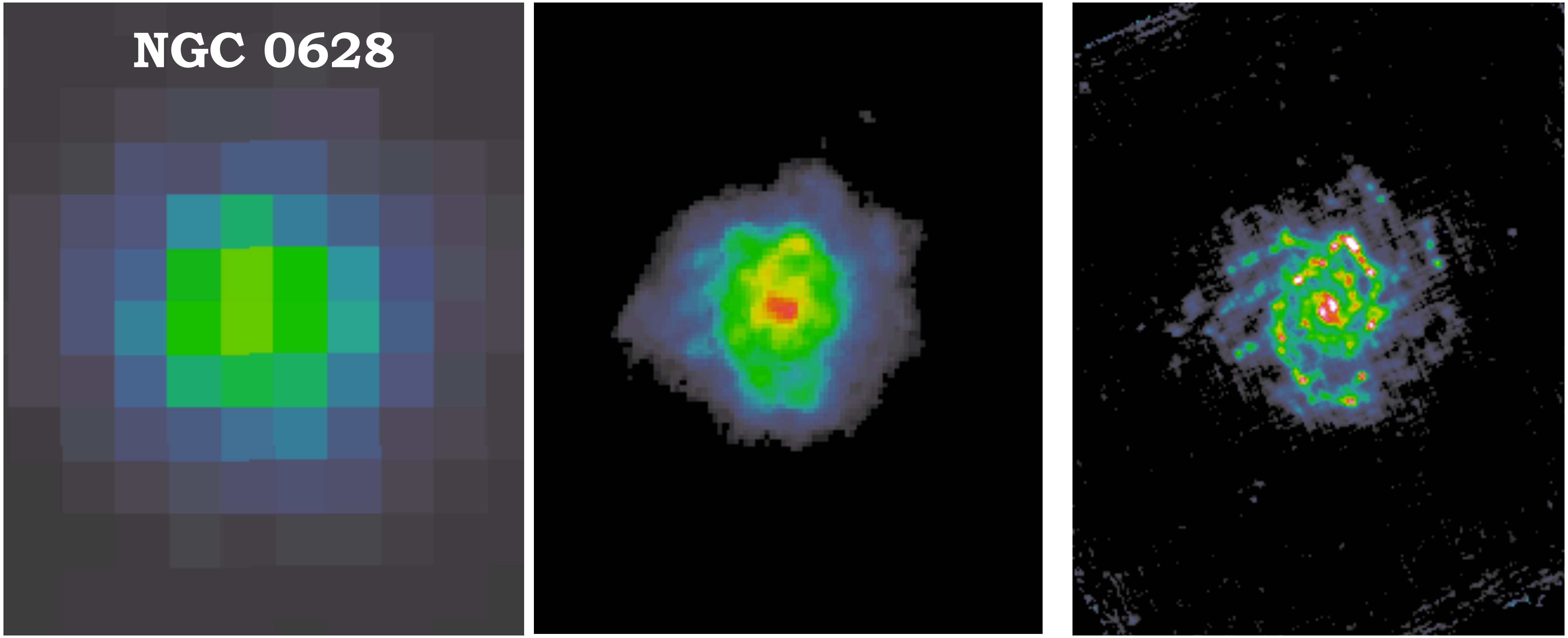
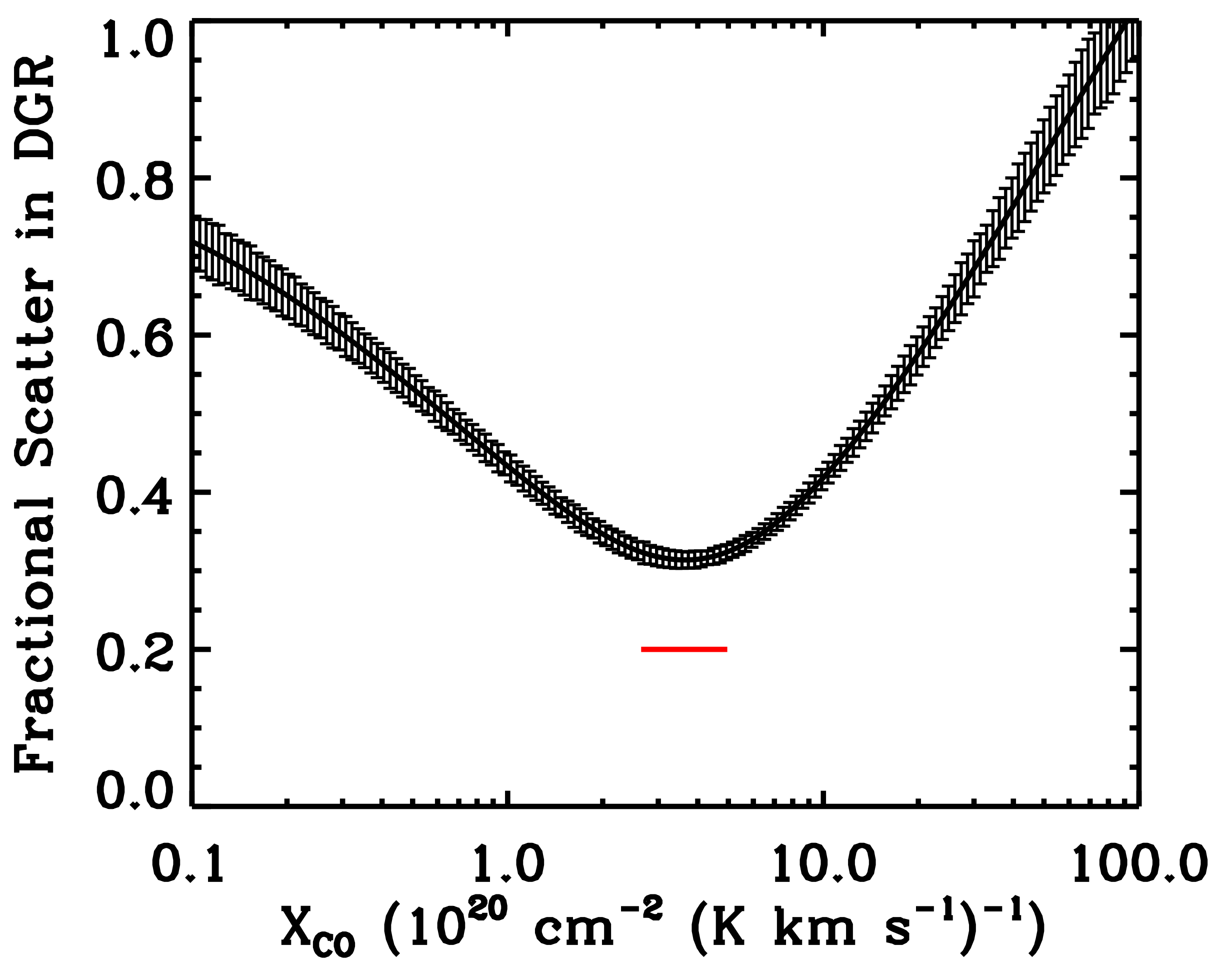


IRAS 100 μm Spitzer MIPS 160 μm Herschel PACS 160 μm

Herschel observations of nearby galaxies can resolve scales of ~few ×100 pc at the peak of the dust SED.

With new Herschel & CO maps, requirements on resolution and S/N in nearby galaxies can now be met.

Example of the Technique



Importance of CO & HI in accounting for $\Sigma_D/DGR = \Sigma_{gas}$

Error bars from bootstrapping.

Red line = 1-σ contraint on X_{CO}.

Requires both HI & CO detections - not effective where HI or H_2 dominates.

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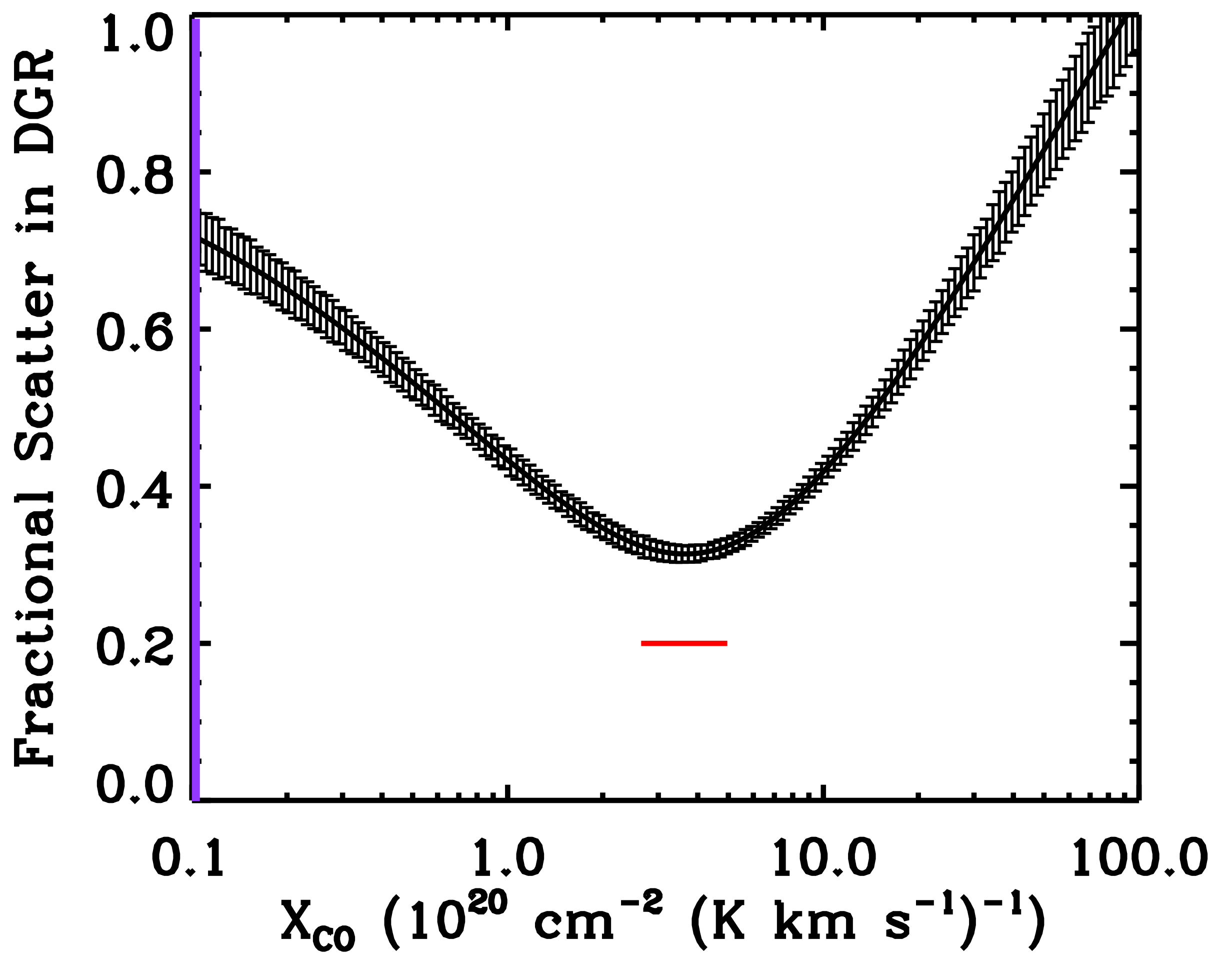

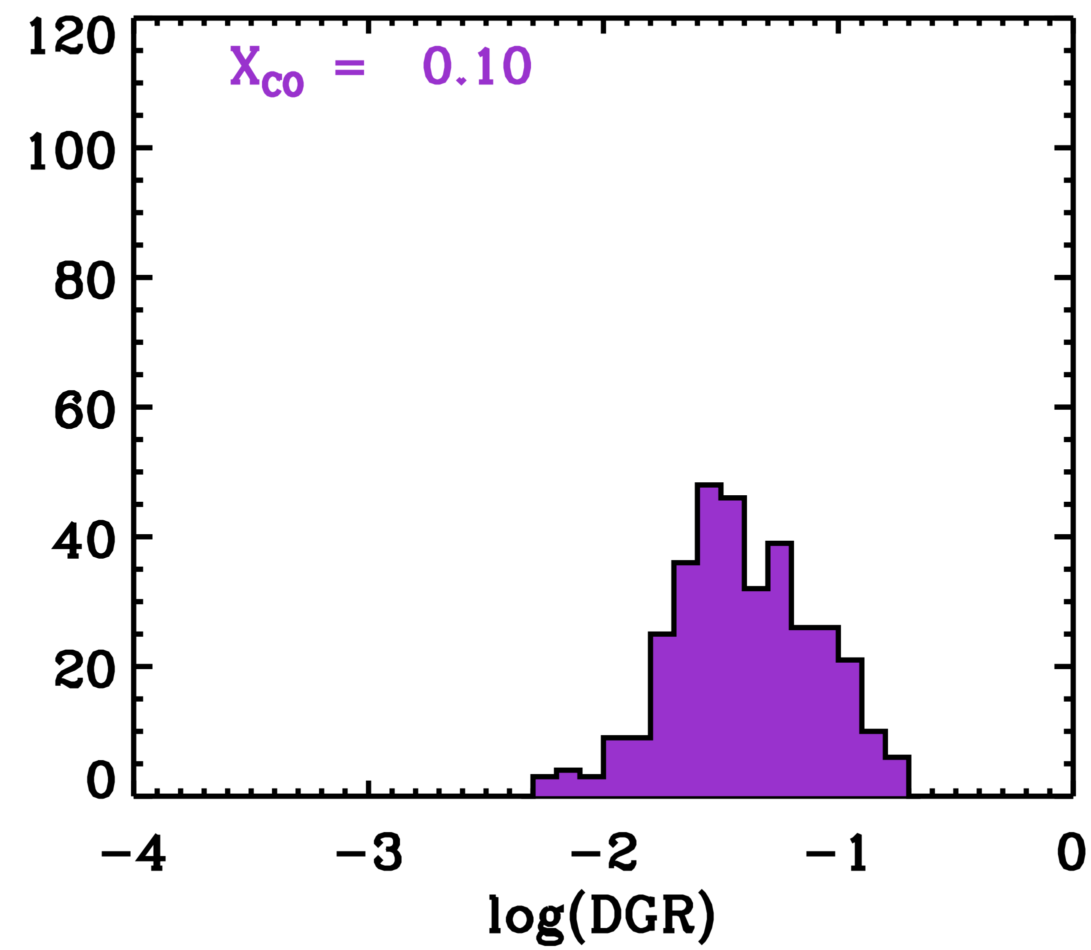

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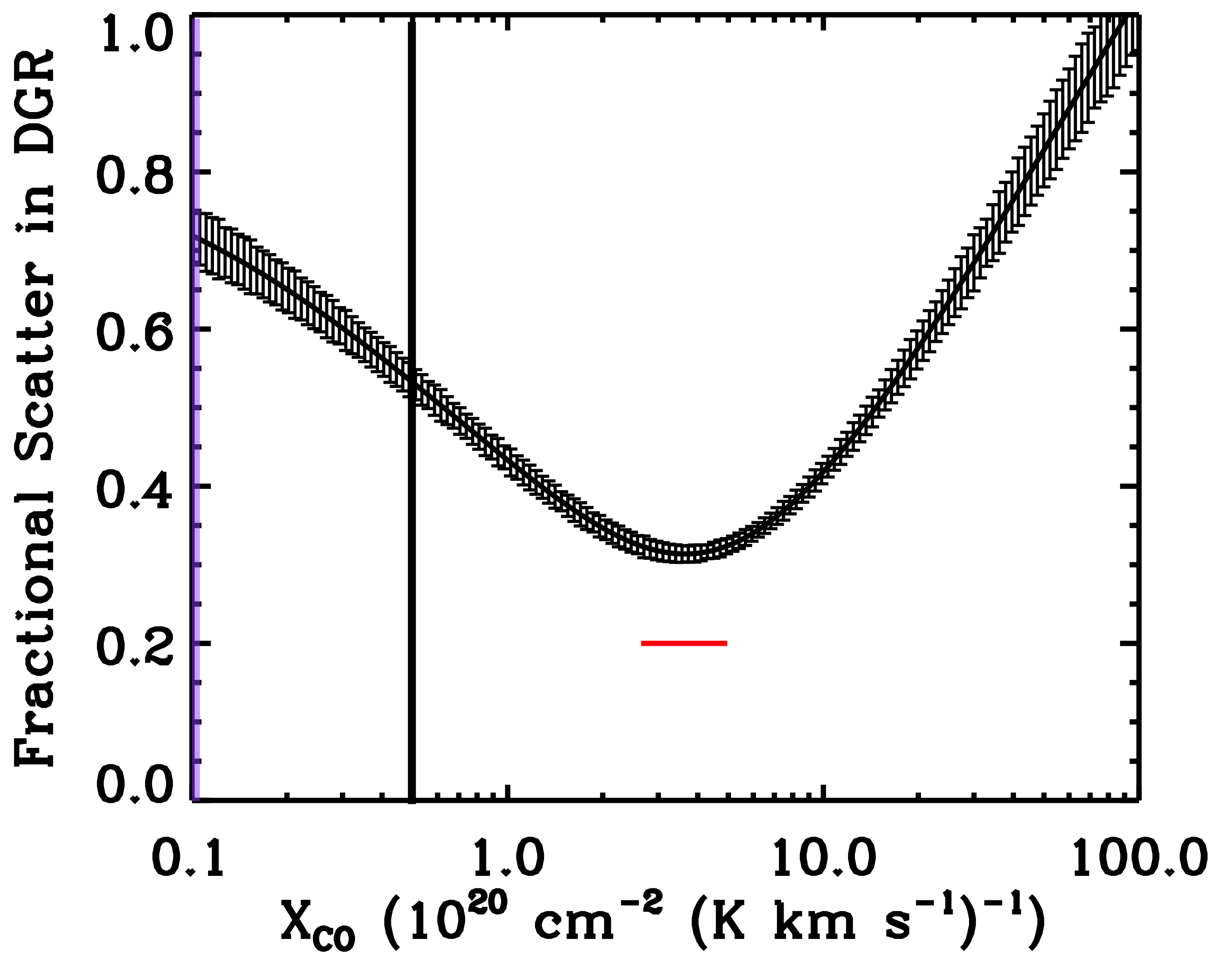

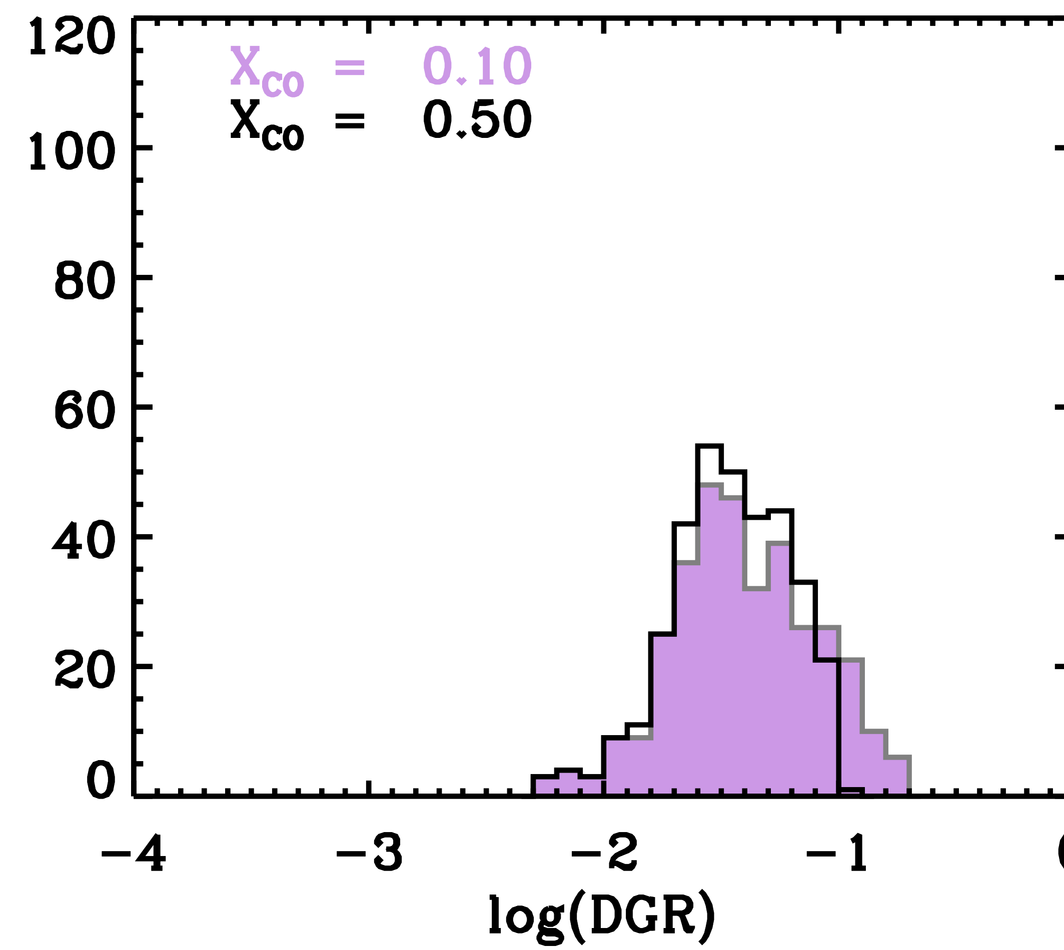

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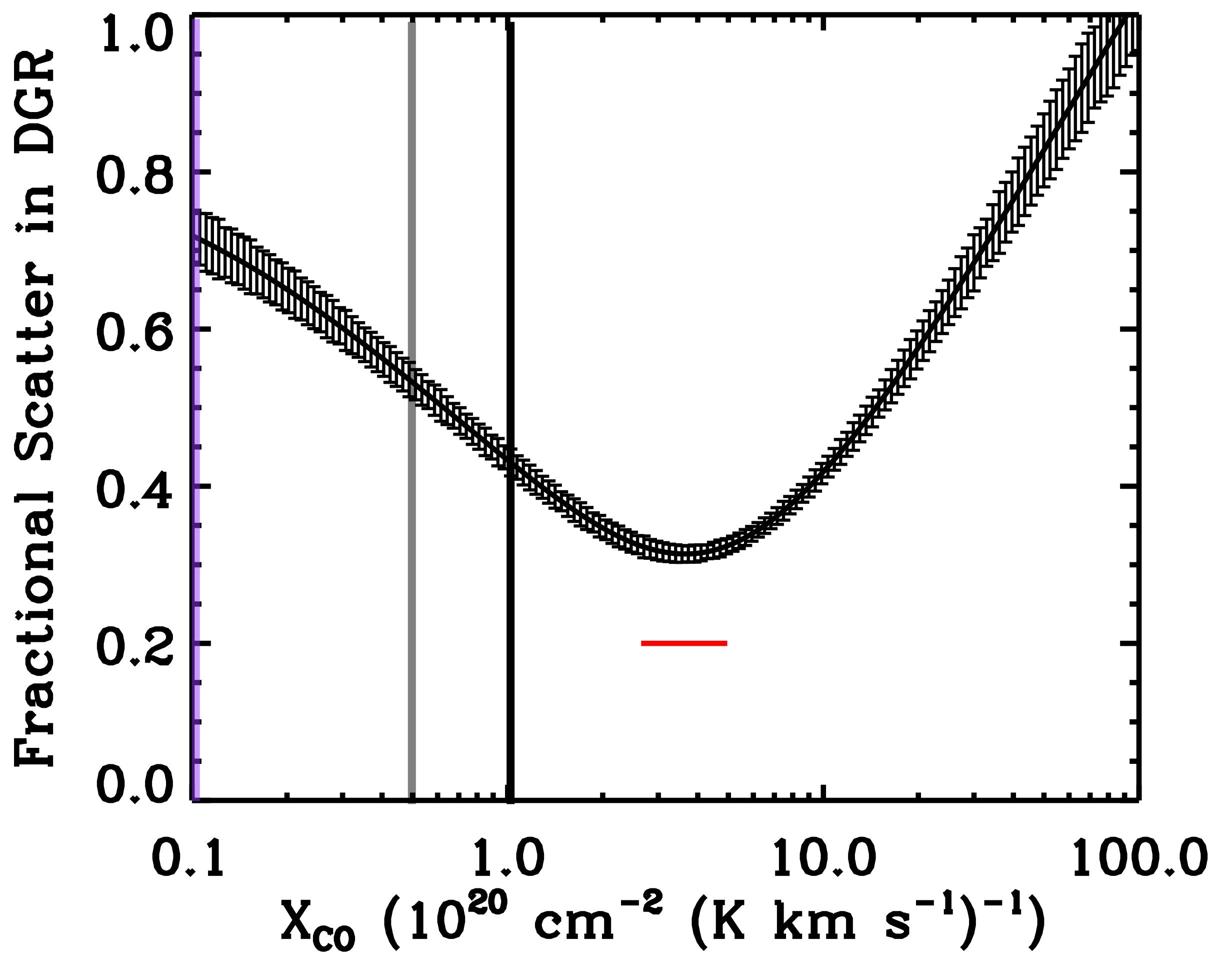

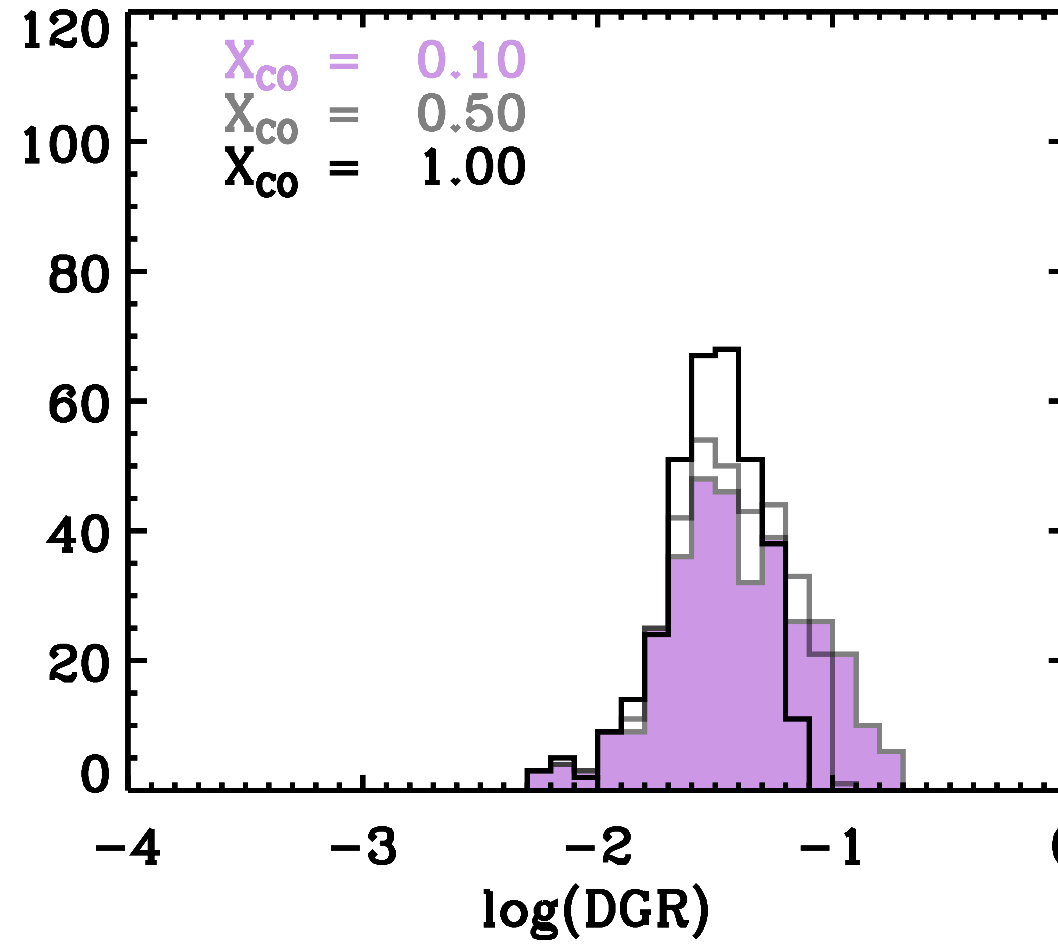

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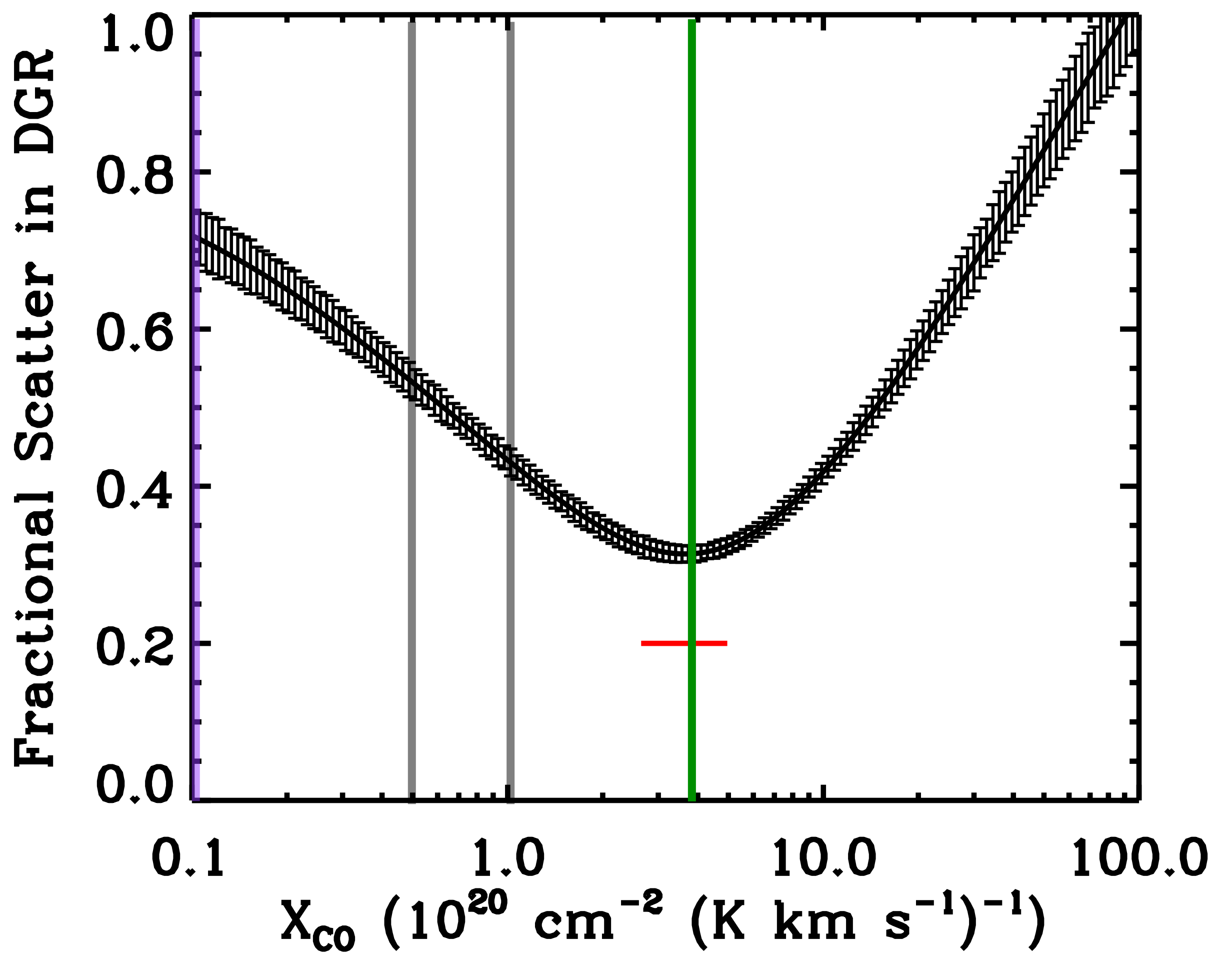

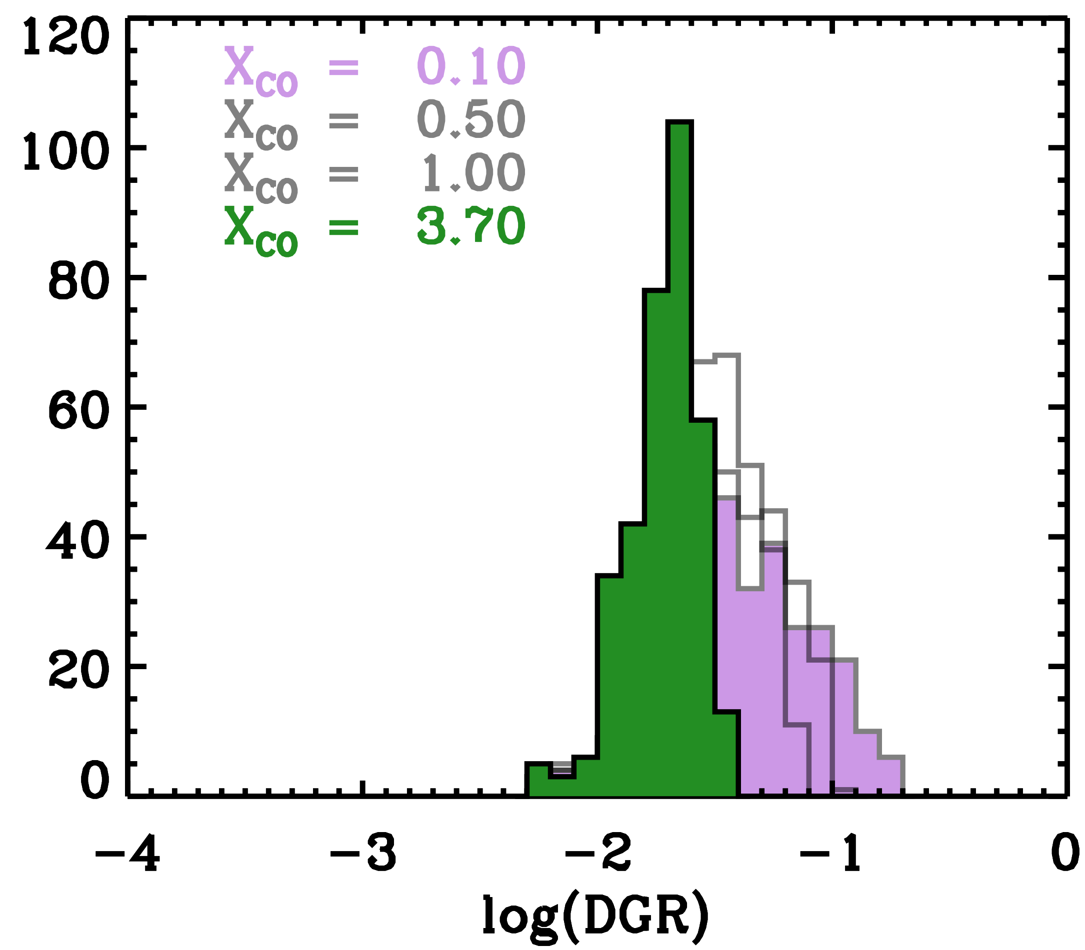

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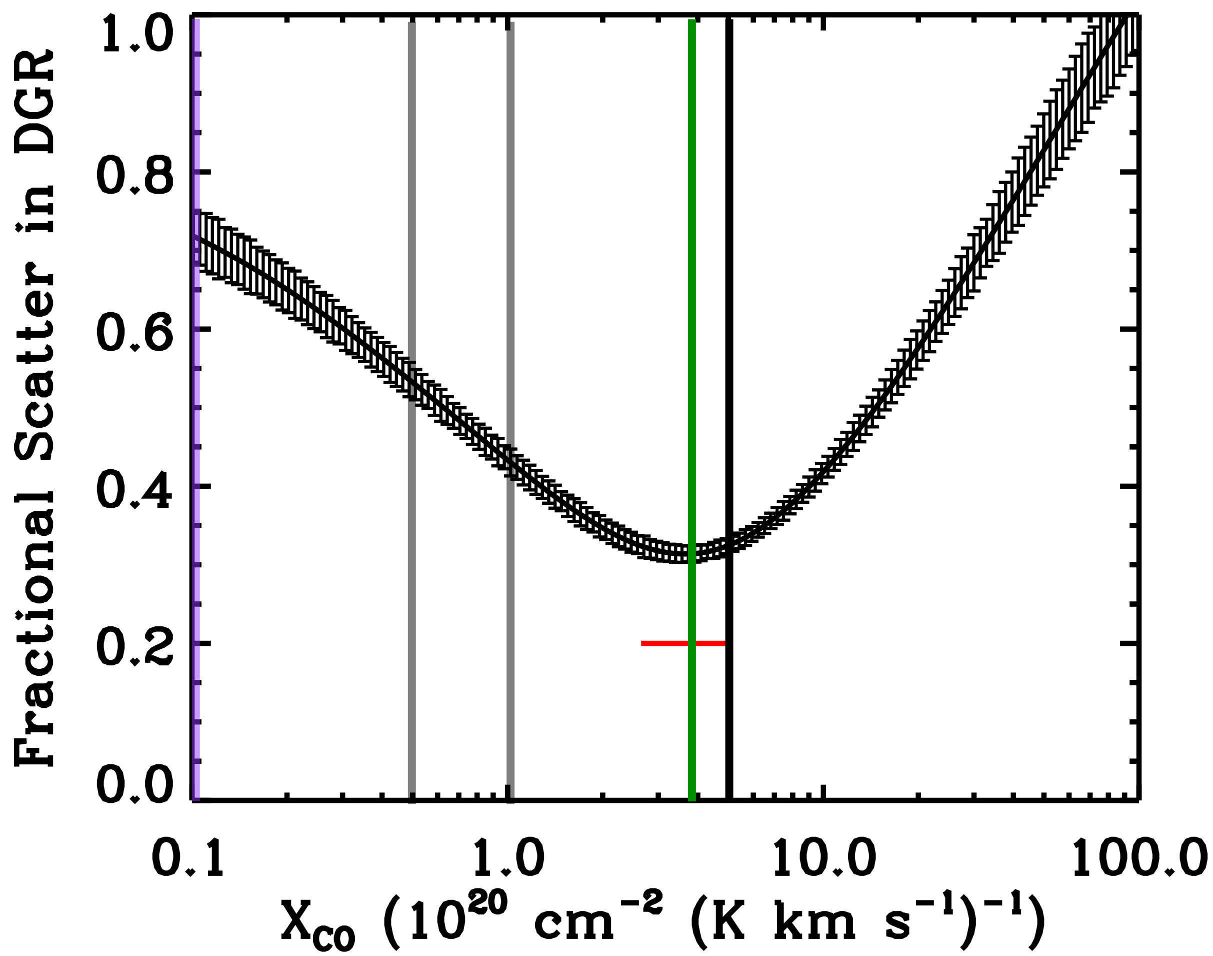

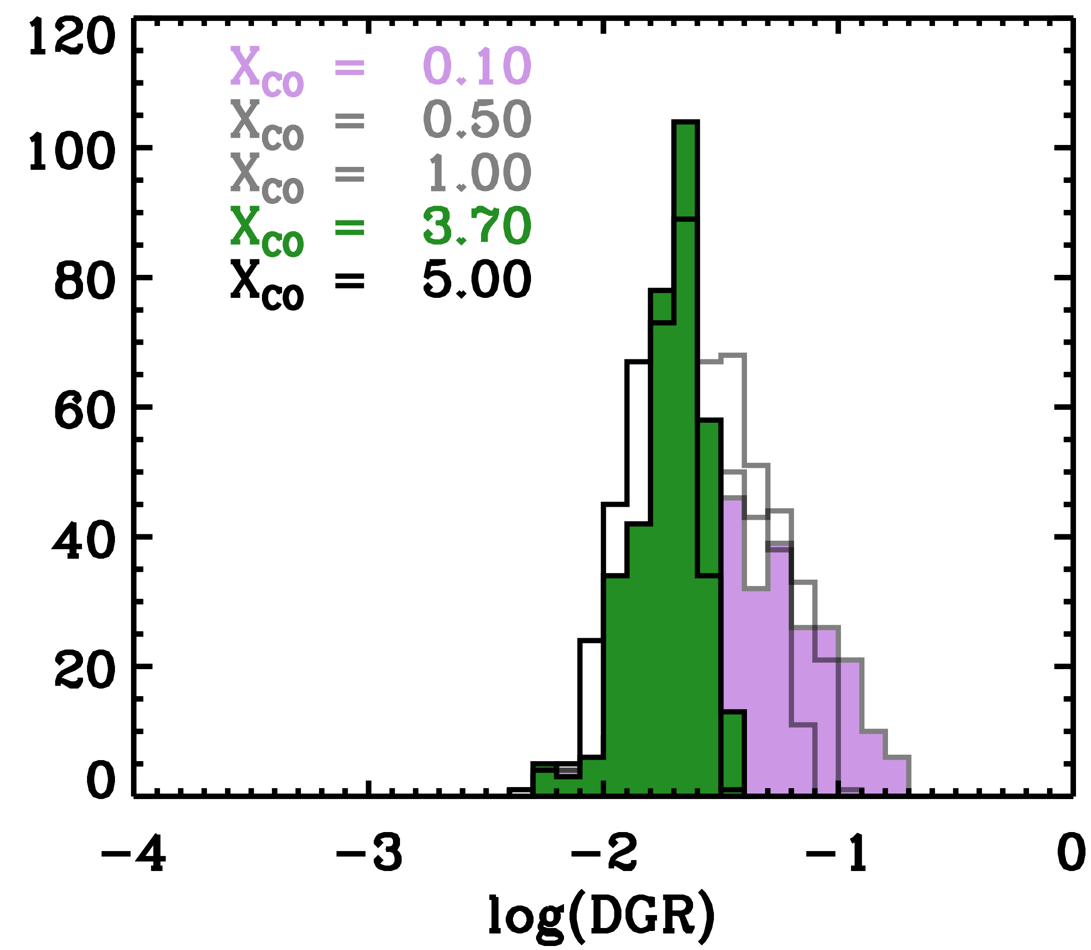

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Wednesday, July 6, 2011

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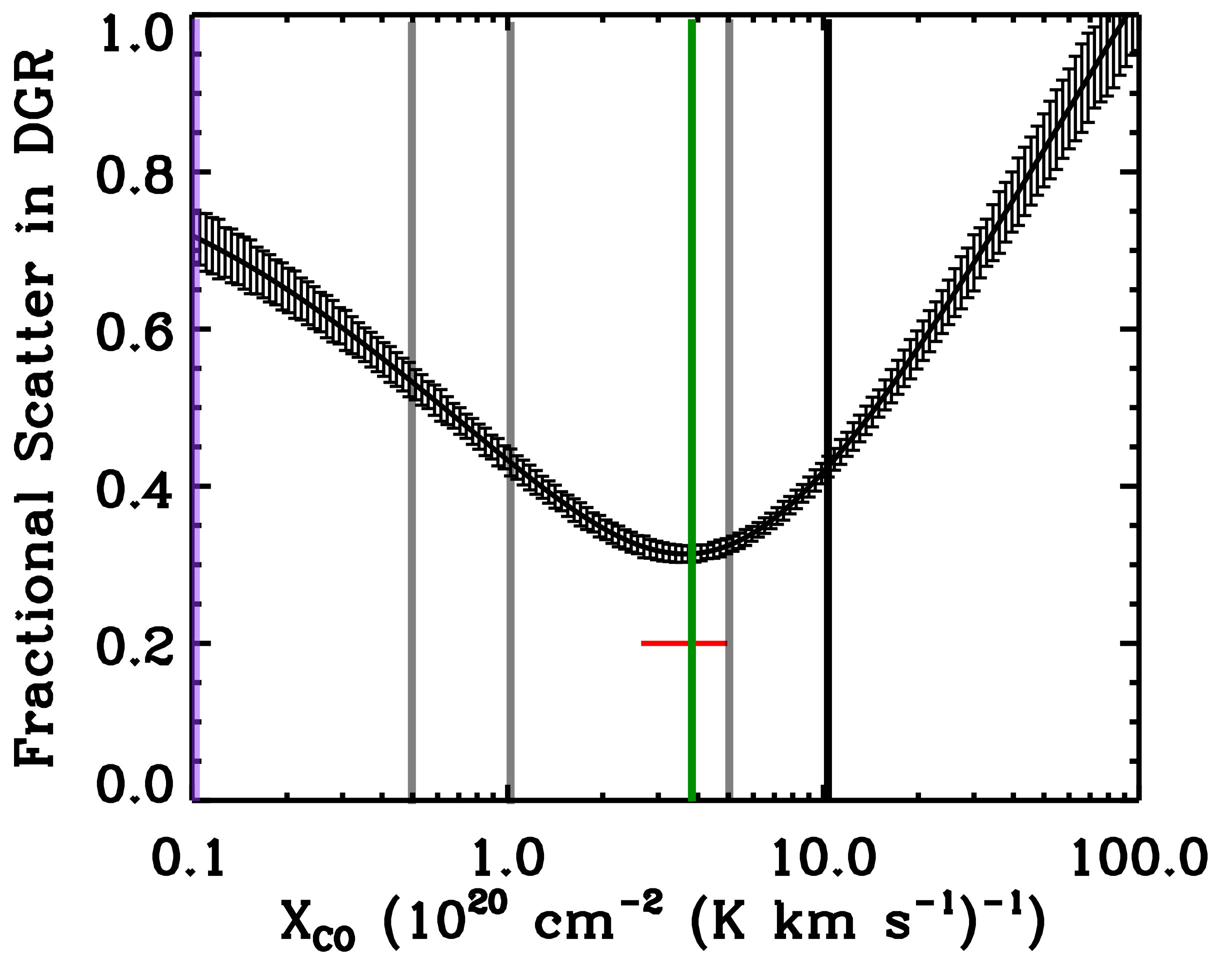

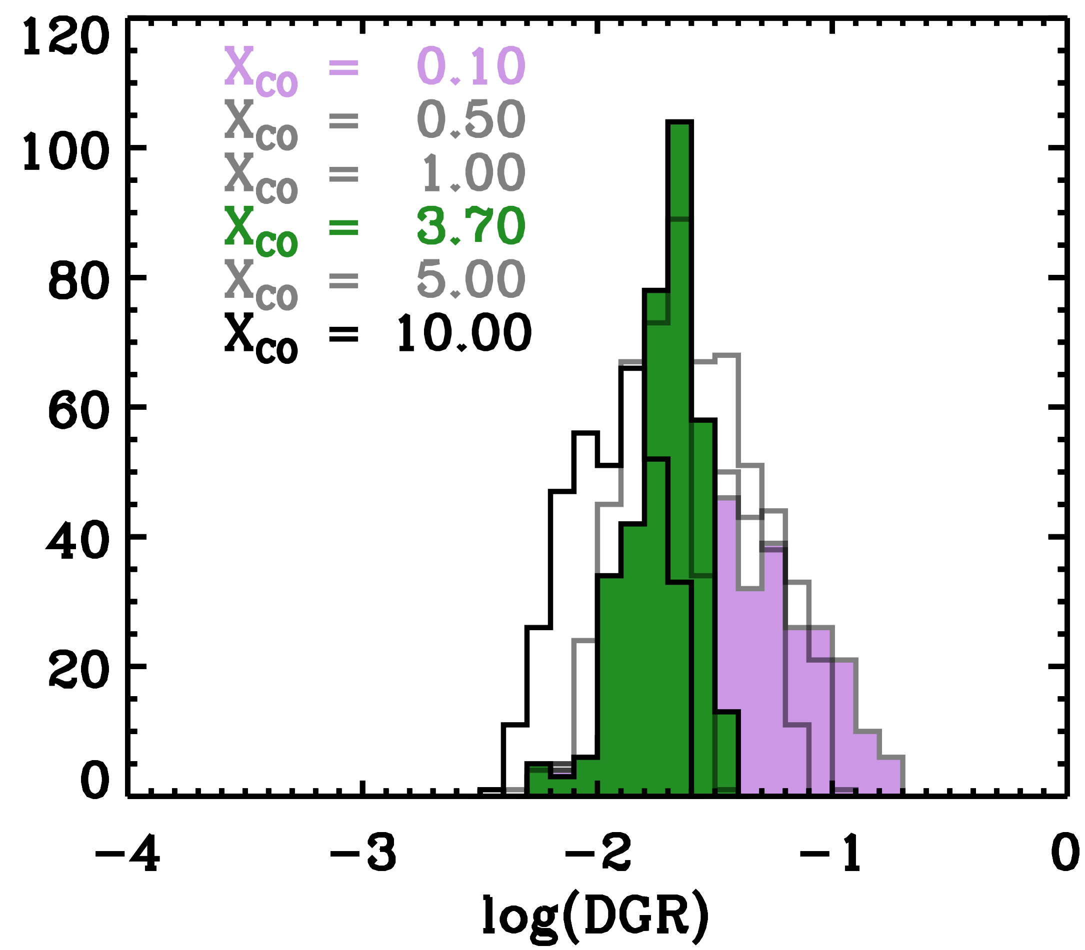

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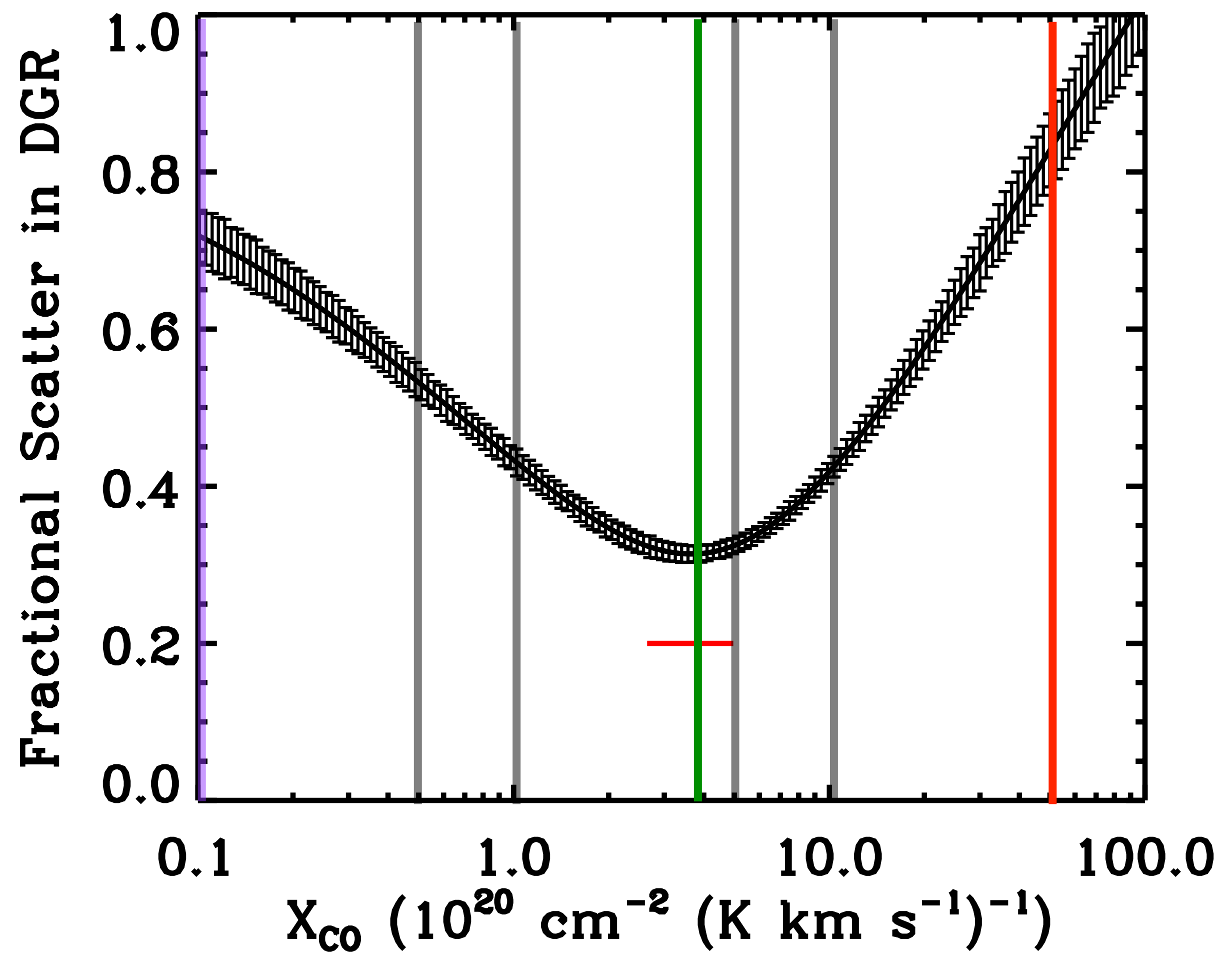

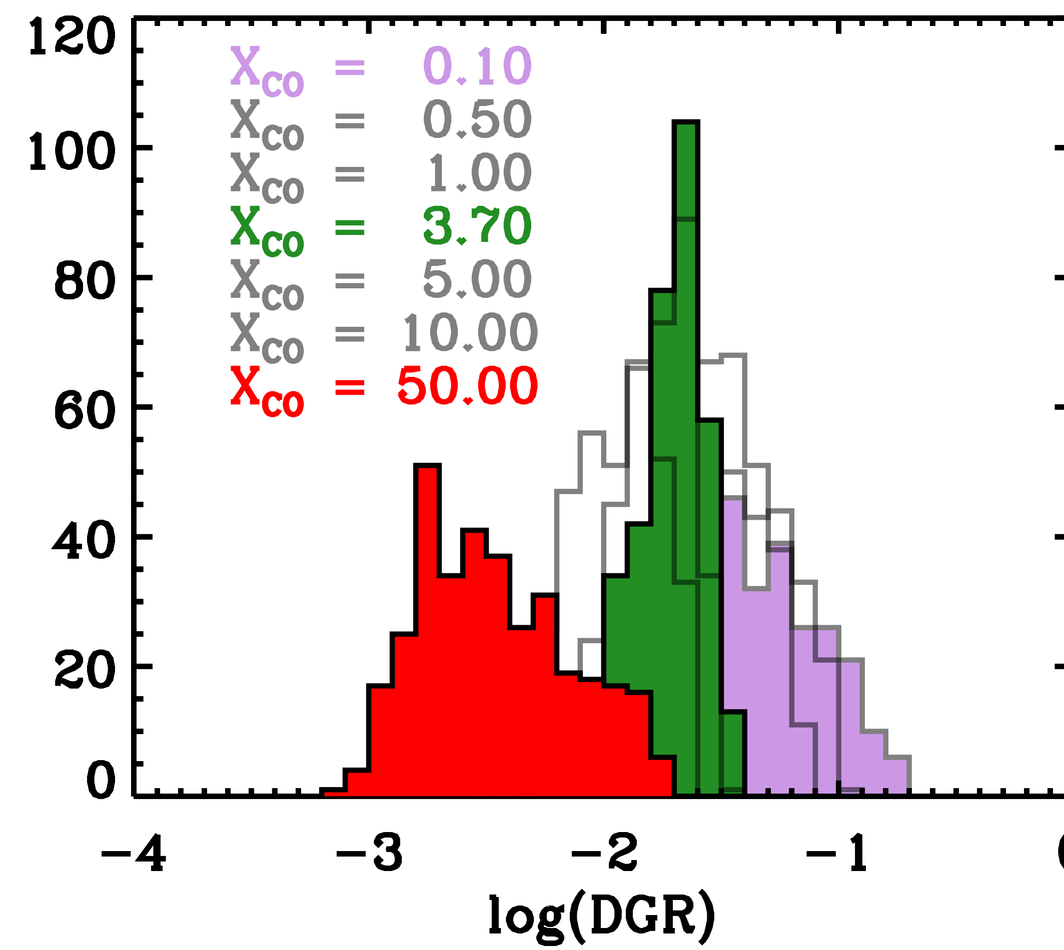

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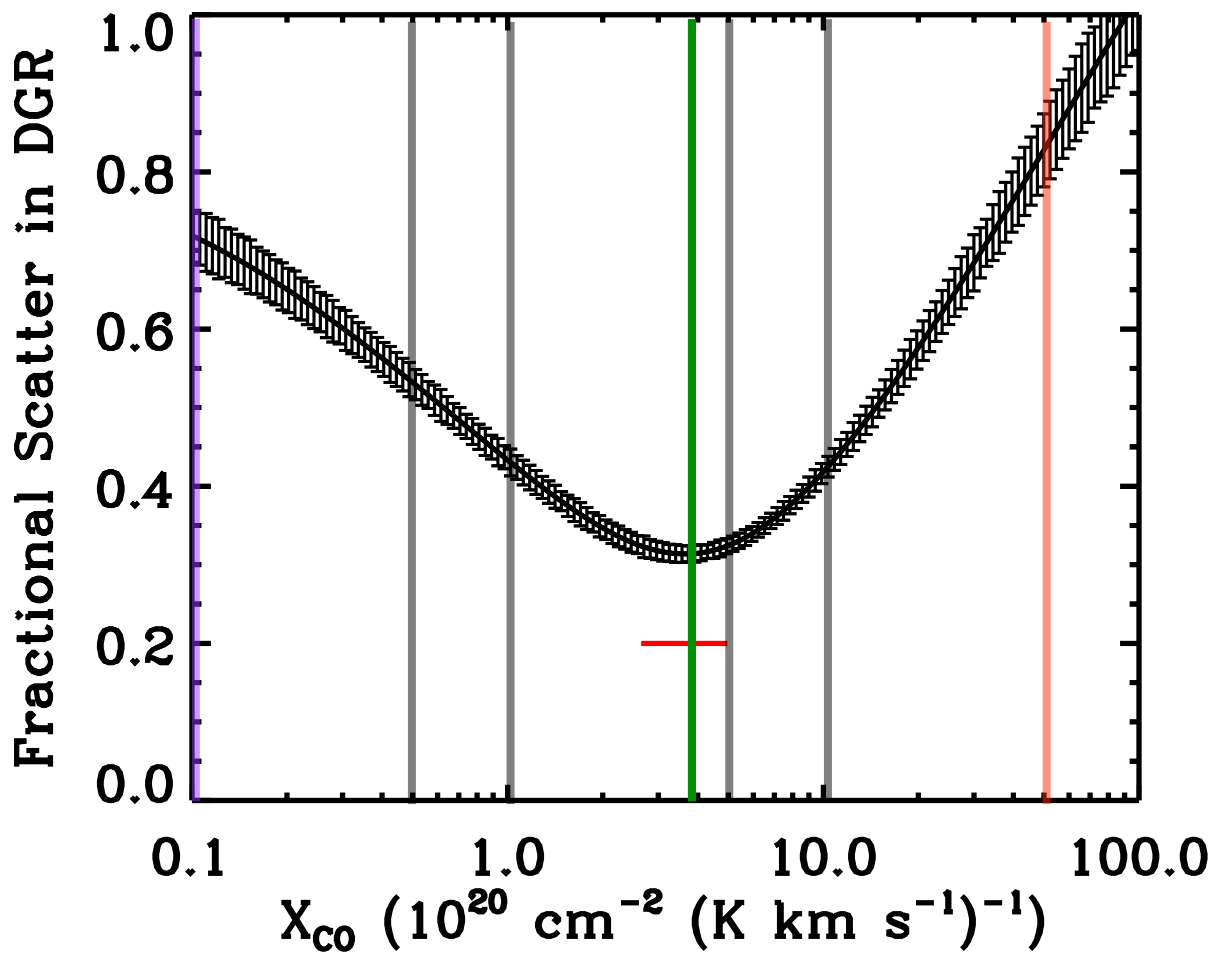

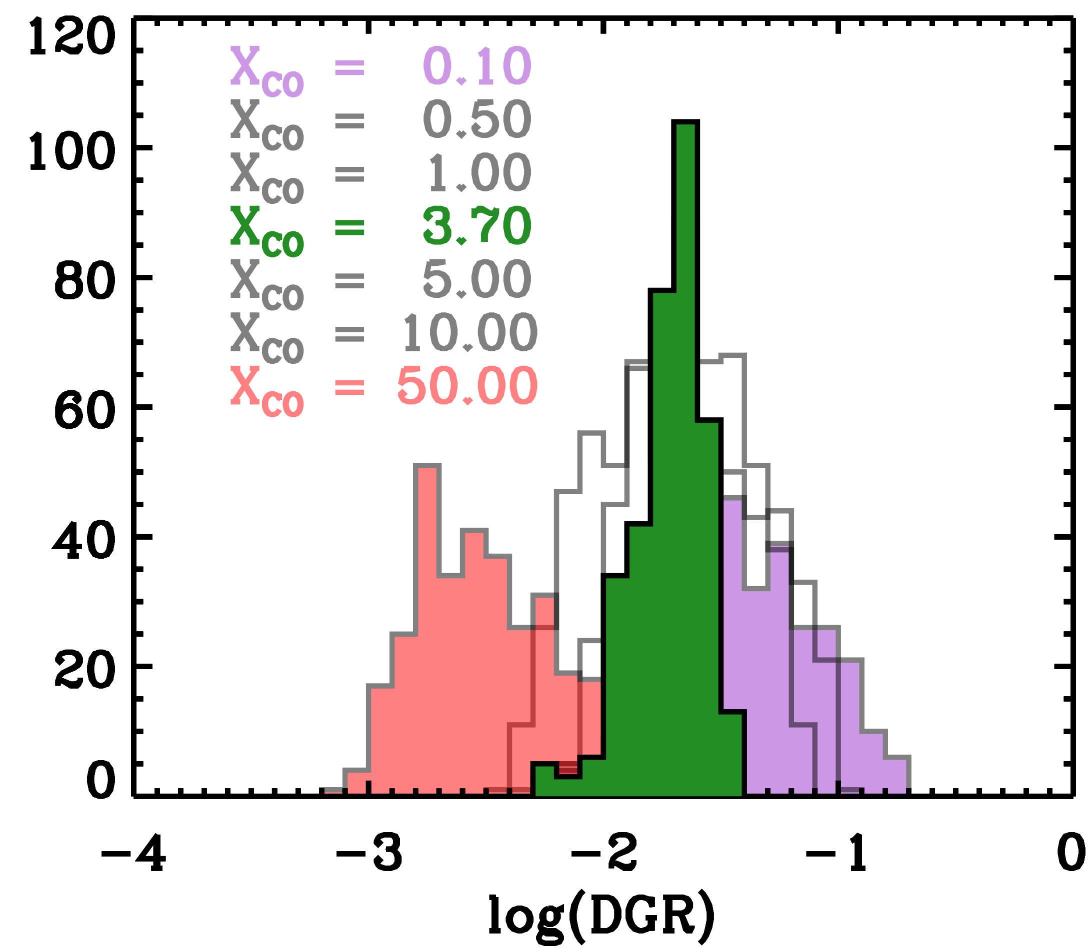

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The Observations

$$DGR = \Sigma_D / (\Sigma_{HI} + \alpha_{CO} I_{CO})$$

KINGFISH

Key Insights into Nearby Galaxies:
A Far-IR Survey with Herschel

70-500 μm imaging & spectroscopy of 62 nearby galaxies with Herschel
Kennicutt et al. 2011 (in prep)

To get Σ_D: SED modeling from 3.6 - 250 μm
(preserves SPIRE 250 μm's 18" resolution while still covering the peak of the dust SED)

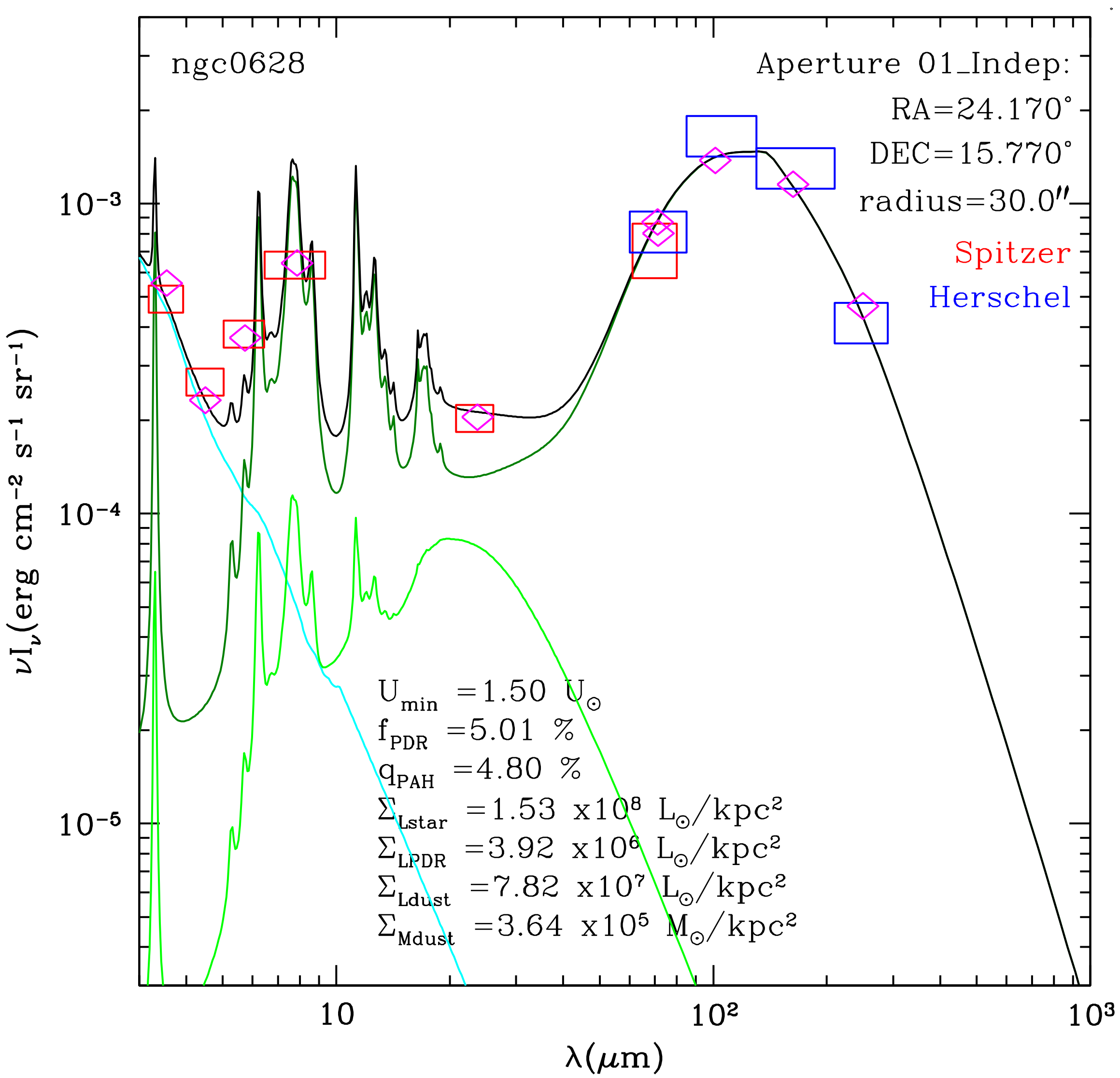
3.6 - 24 μm from SINGS and LVL.
(Kennicutt et al. 2003, Dale et al. 2009)

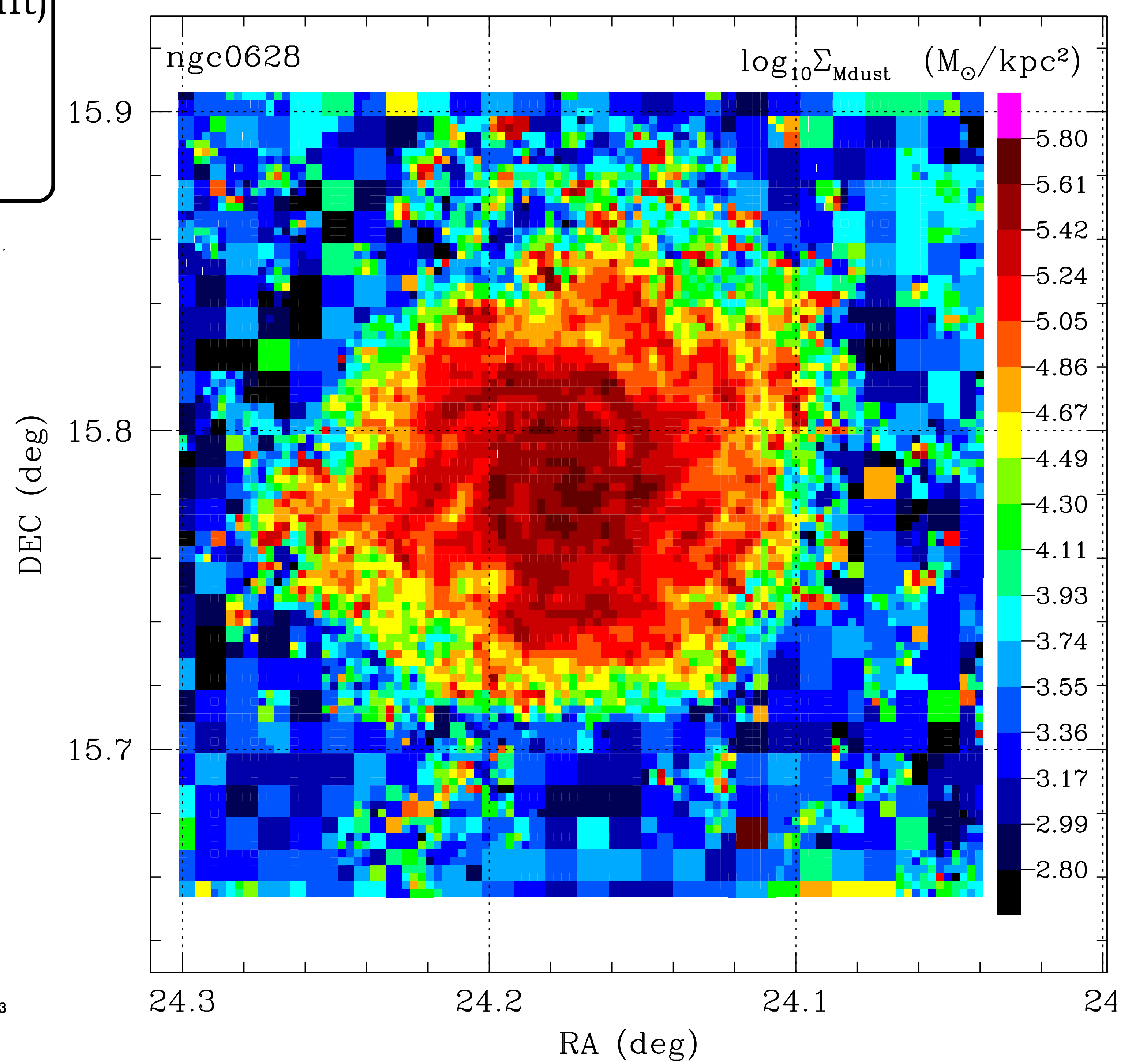
Aniano, Draine et al (in prep)

Pixel-by-pixel SED fitting from 3.6-500 μm using the Draine & Li (2007) models for all KINGFISH galaxies.

see posters by Gonzalo Aniano

- dust model (*fixed* - size distribution, composition, PAH properties)
- description of radiation field (*variable* - power law + delta function at U_{min})
- starlight (*fixed* SED, *variable* amount)
- PAH fraction q_{PAH} (*variable* - 0.4 - 4.6%)





The Observations

$$DGR = \Sigma_D / (\Sigma_{HI} + \alpha_{CO} I_{CO})$$

THINGS

The HI Nearby Galaxies Survey

HI survey of 34 nearby galaxies with the VLA
Walter et al. (2008)

Resolution of ~12”

HI column density determined directly from 21cm line.

The Observations

$$DGR = \Sigma_D / (\Sigma_{HI} + \alpha_{CO} I_{CO})$$

HERACLES

Institut de Radioastronomie Millimétrique

HERACLES

HERA CO-Line Emission Survey

CO J=(2-1) survey of 48 nearby galaxies with
HERA on the IRAM 30m.
Leroy et al. (2009)

Resolution of ~13"

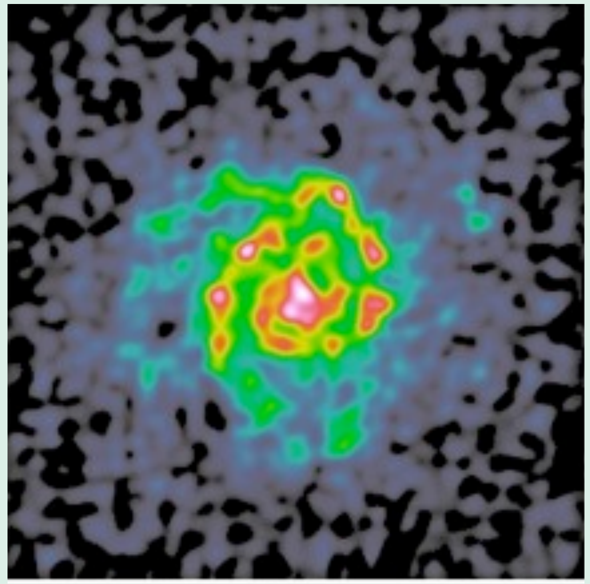
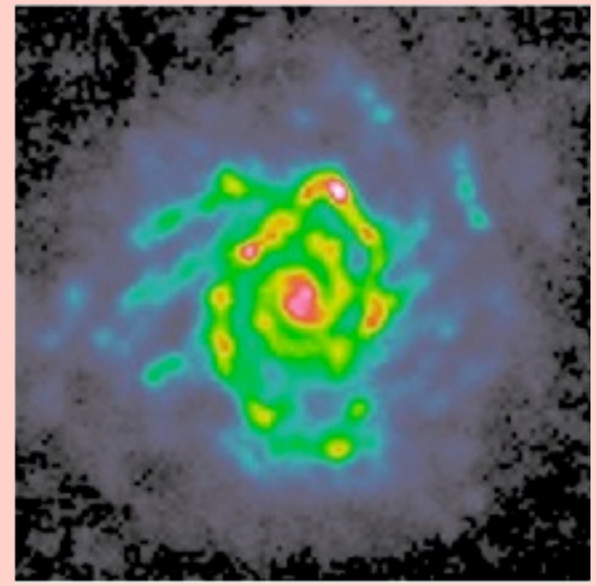
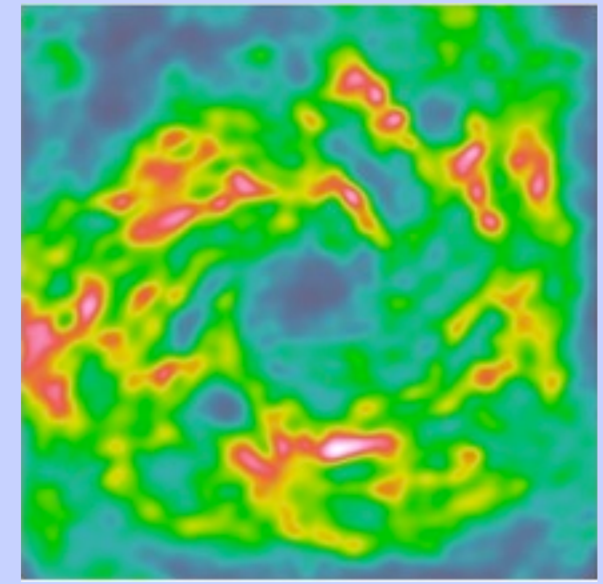
Assume (2-1)/(1-0) = 0.8 - (Leroy et al. 2008)

The Targets

	CO J=(2-1)	Spire 250	H I

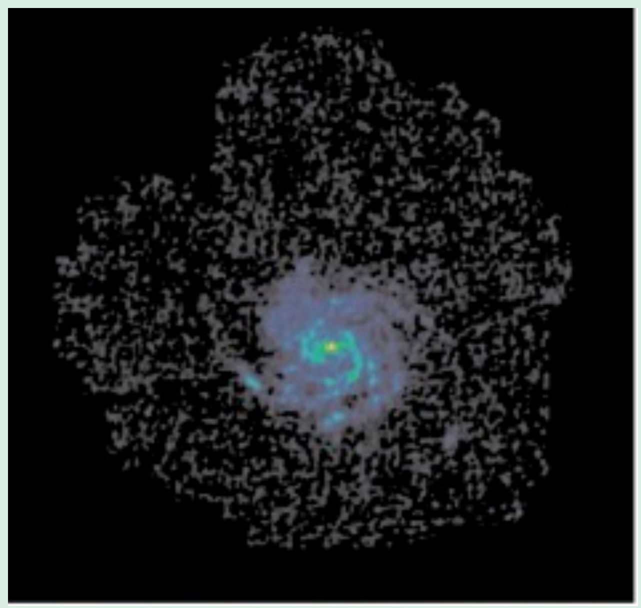
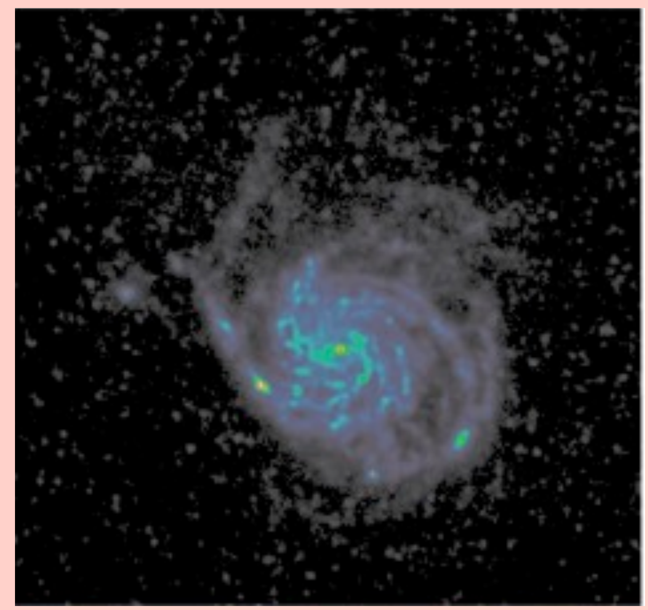
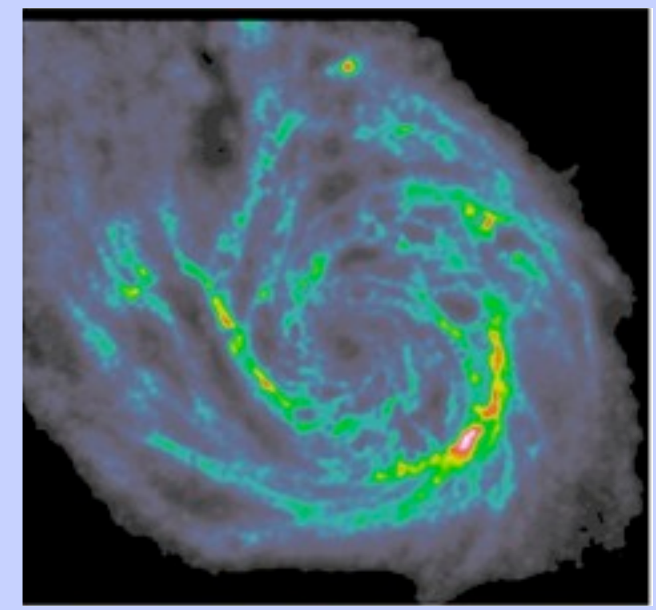
NGC 0628

D = 7.3 Mpc
large metallicity gradient
10' x 10' map

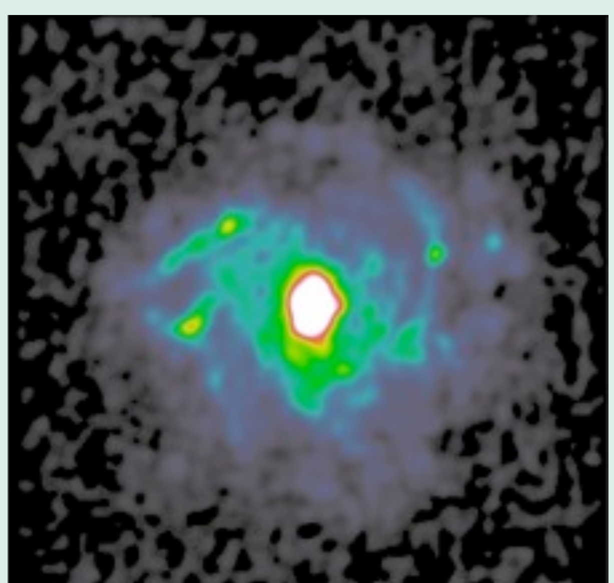
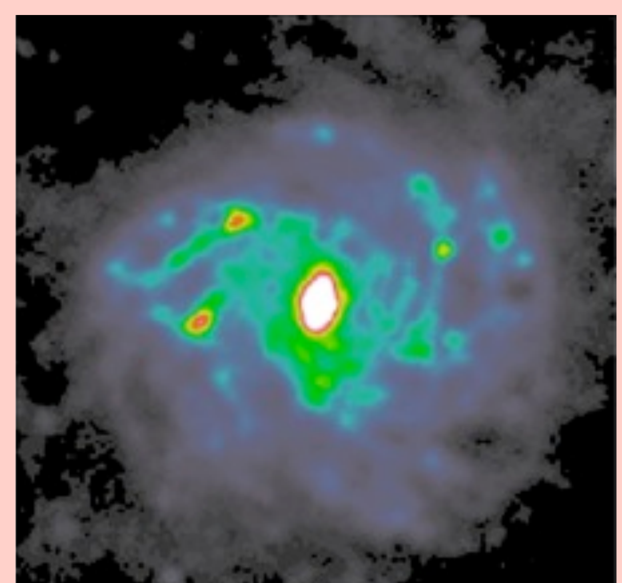
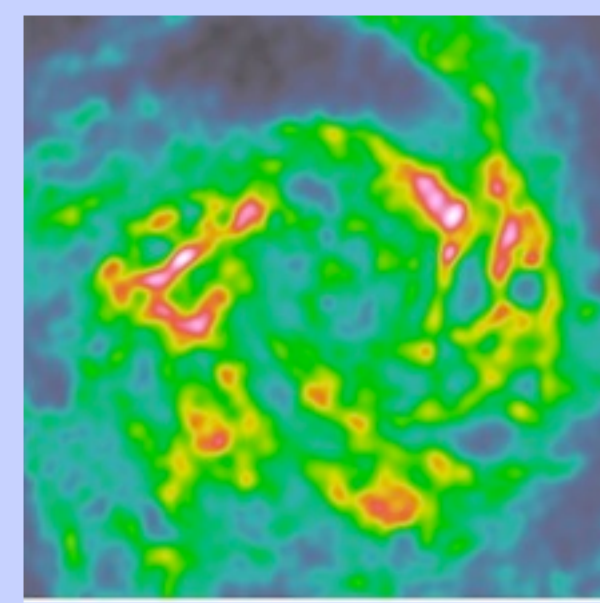
NGC 5457

D = 7.1 Mpc
large metallicity gradient
33' x 33' map

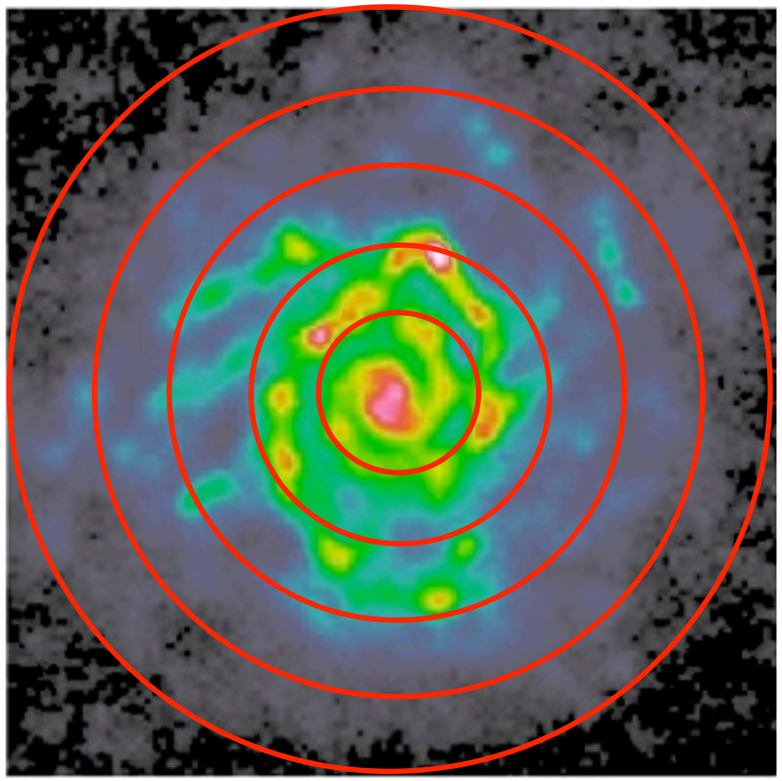




NGC 6946

D = 6.8 Mpc
small metallicity gradient
12' x 12' map

NGC 0628

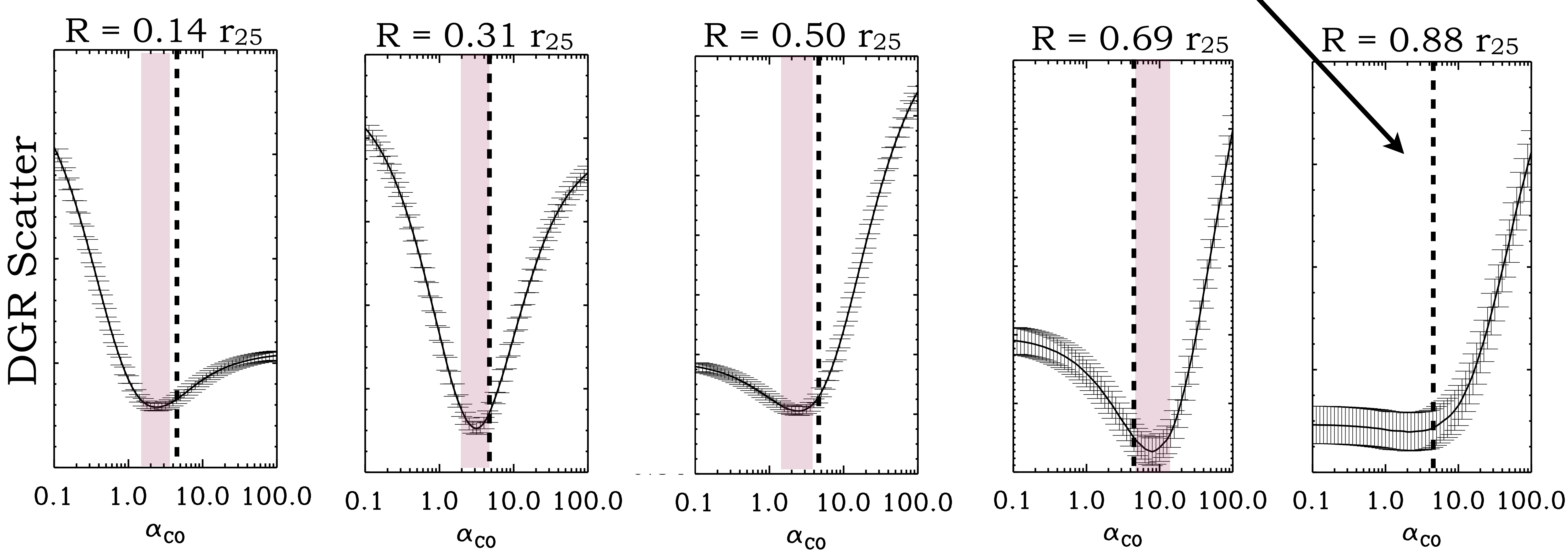


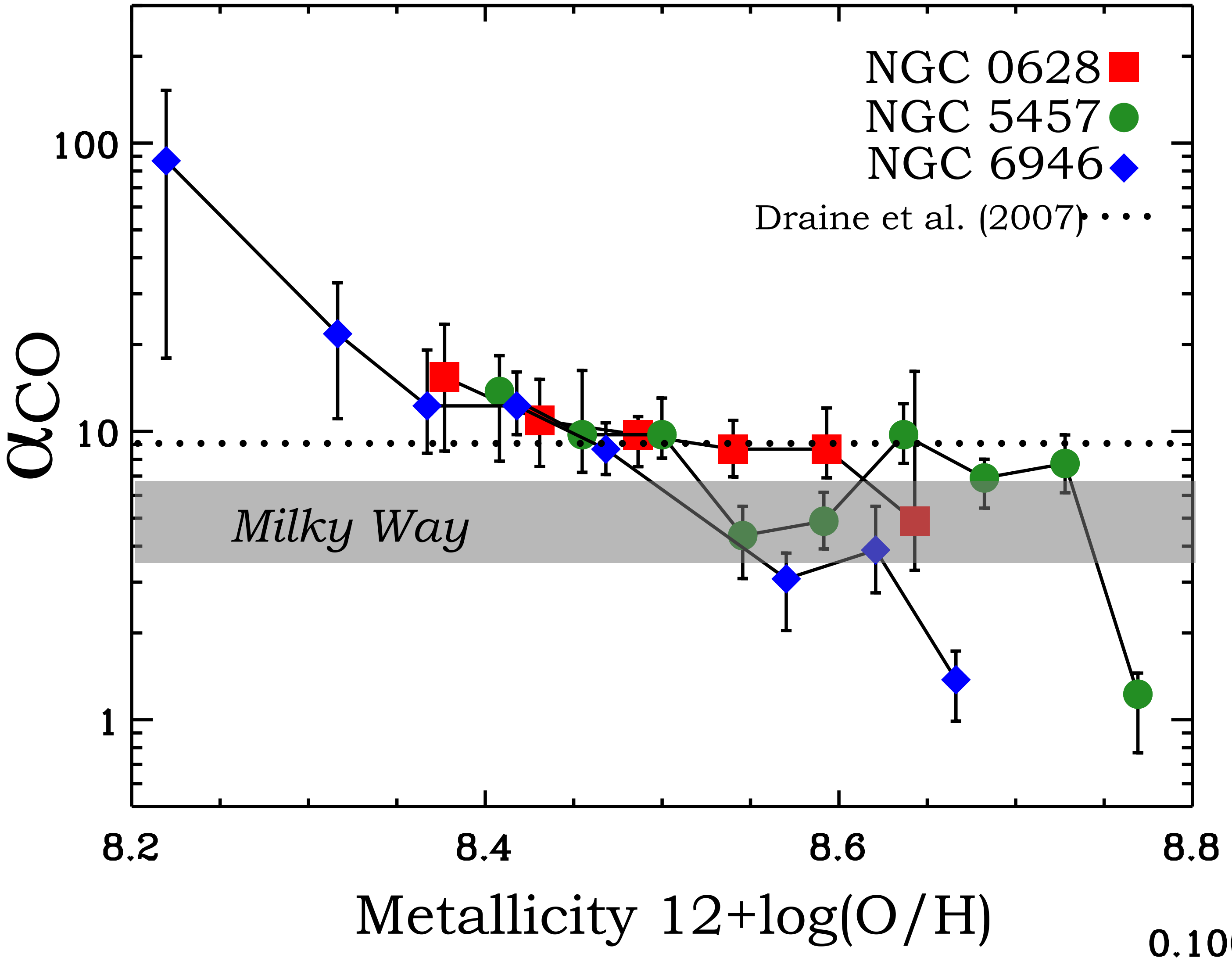
bins of galactocentric radius (r_{25})

Radial Solution Example

Divide galaxy up into radial bins, solve for α_{CO} and DGR in each bin.

Technique can fail in outskirts where CO is weakly detected.





Results

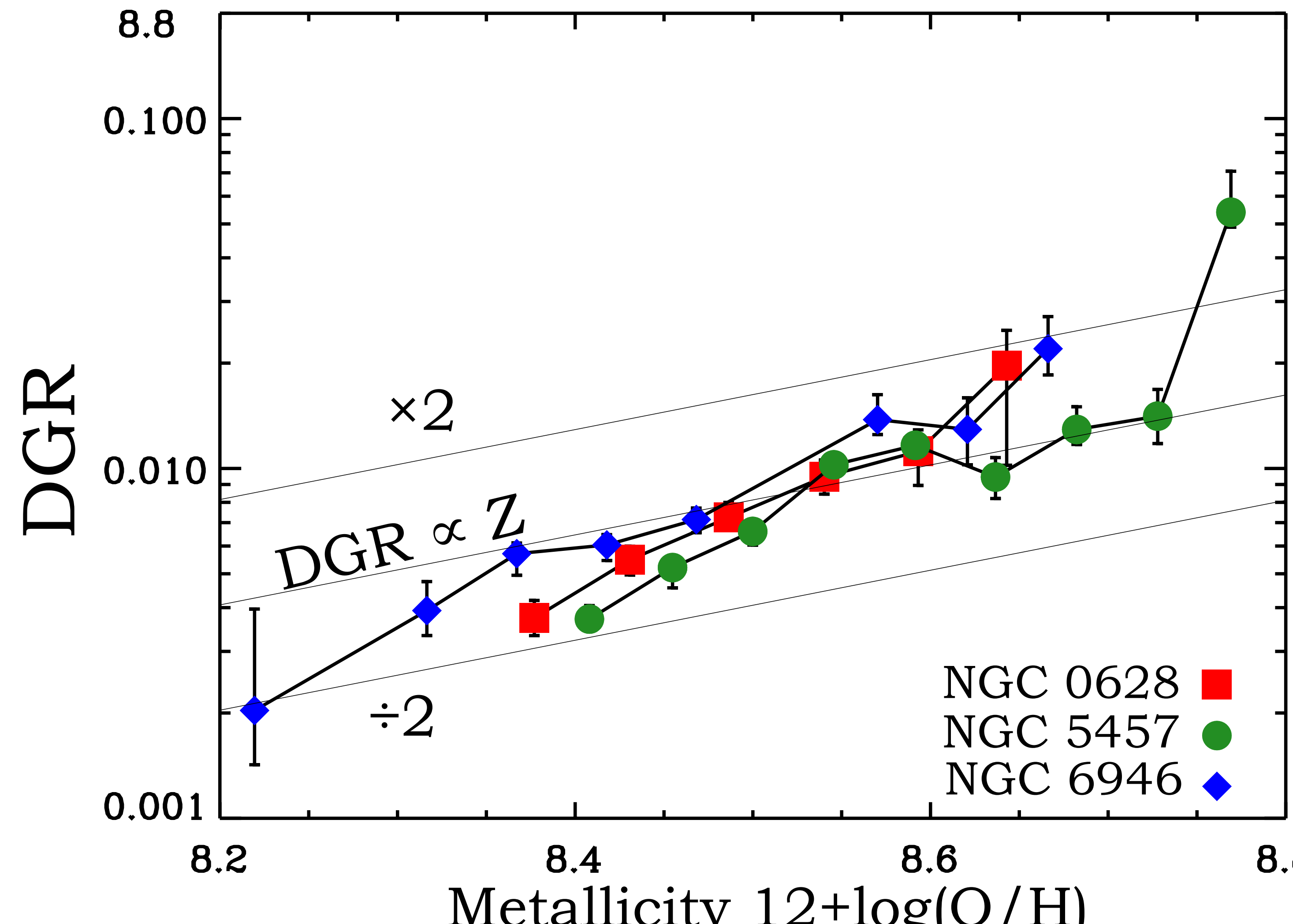
note - no assumption made about either DGR or α_{CO} vs Z!

α_{CO} jump around 12 + log(O/H) ~ 8.3-8.4.
(consistent with Local Group results)

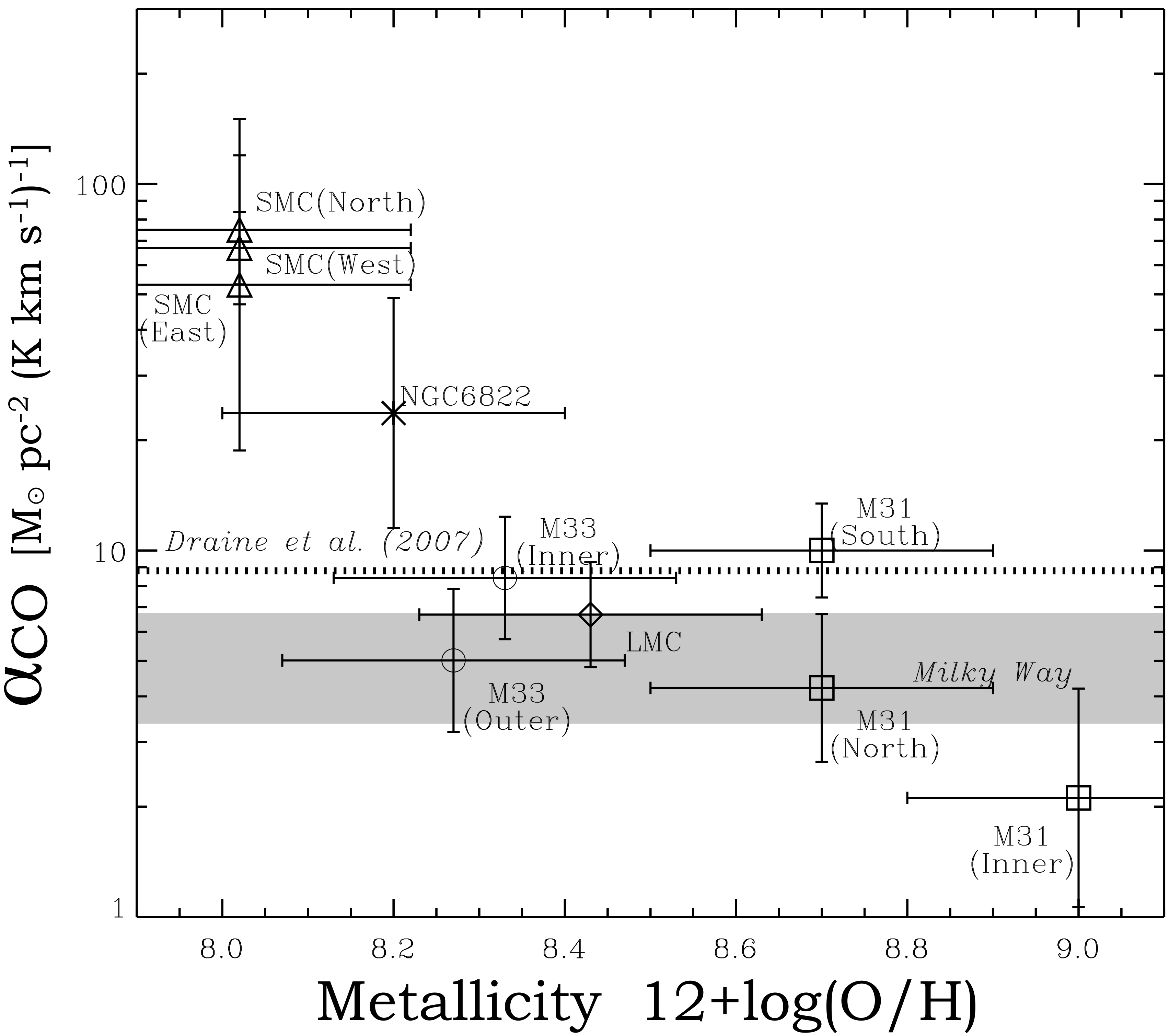
Galaxy centers have low X_{CO}
(cf Dahmen et al. 1998, Regan 2000
Israel 2009a,b)

DGR shows smooth, linear (or slightly super-linear) dependence on metallicity.

Constant fraction of metals in dust within factor of 2.



Recent Local Group Results



Leroy et al. 2011

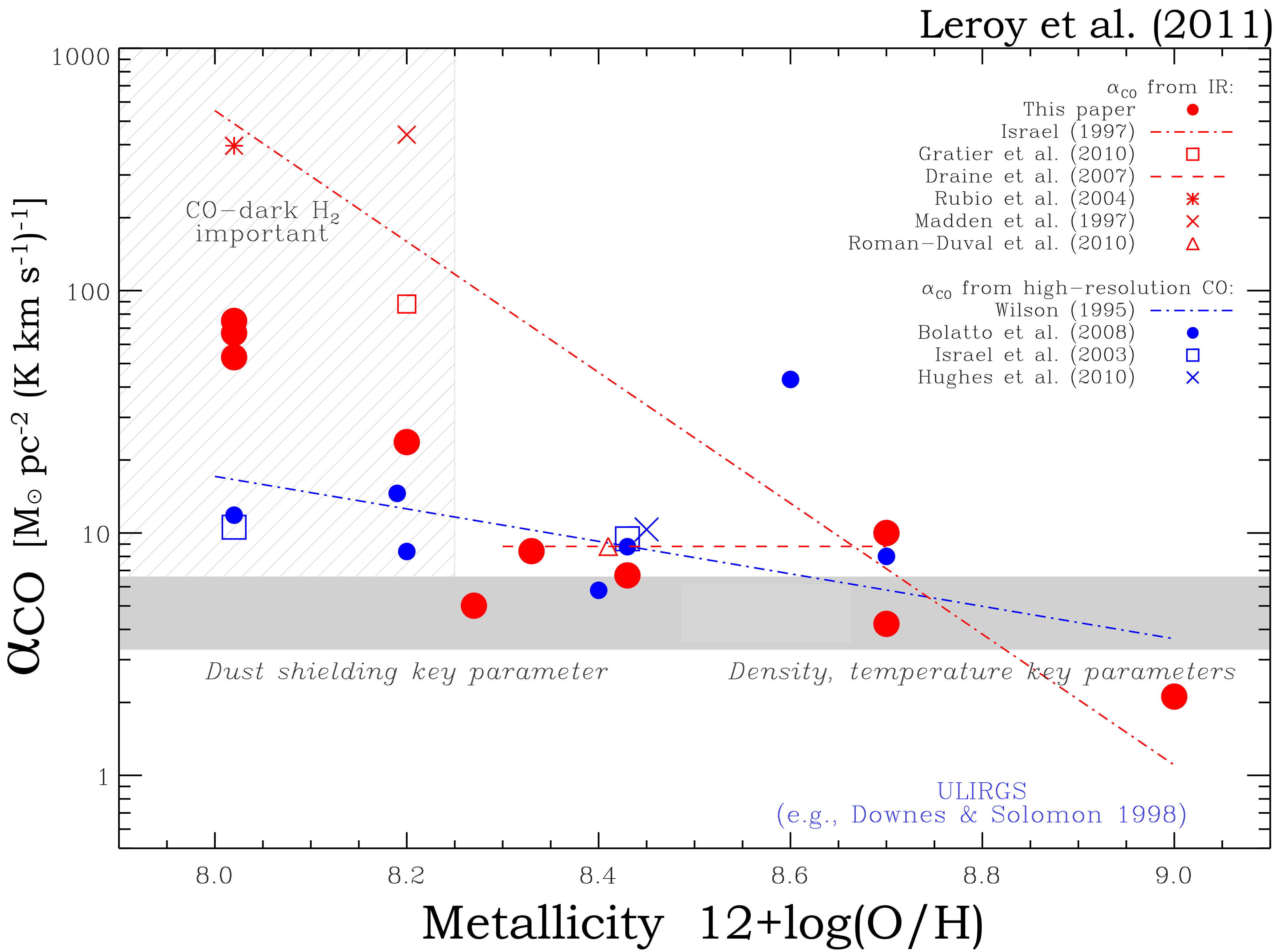
Use same technique to constrain X_{CO} and DGR as here.

Find high X_{CO} below 12+log(O/H)~8.2.

Aside from inner region of M31 and low-Z galaxies, X_{CO} scatters around MW value.

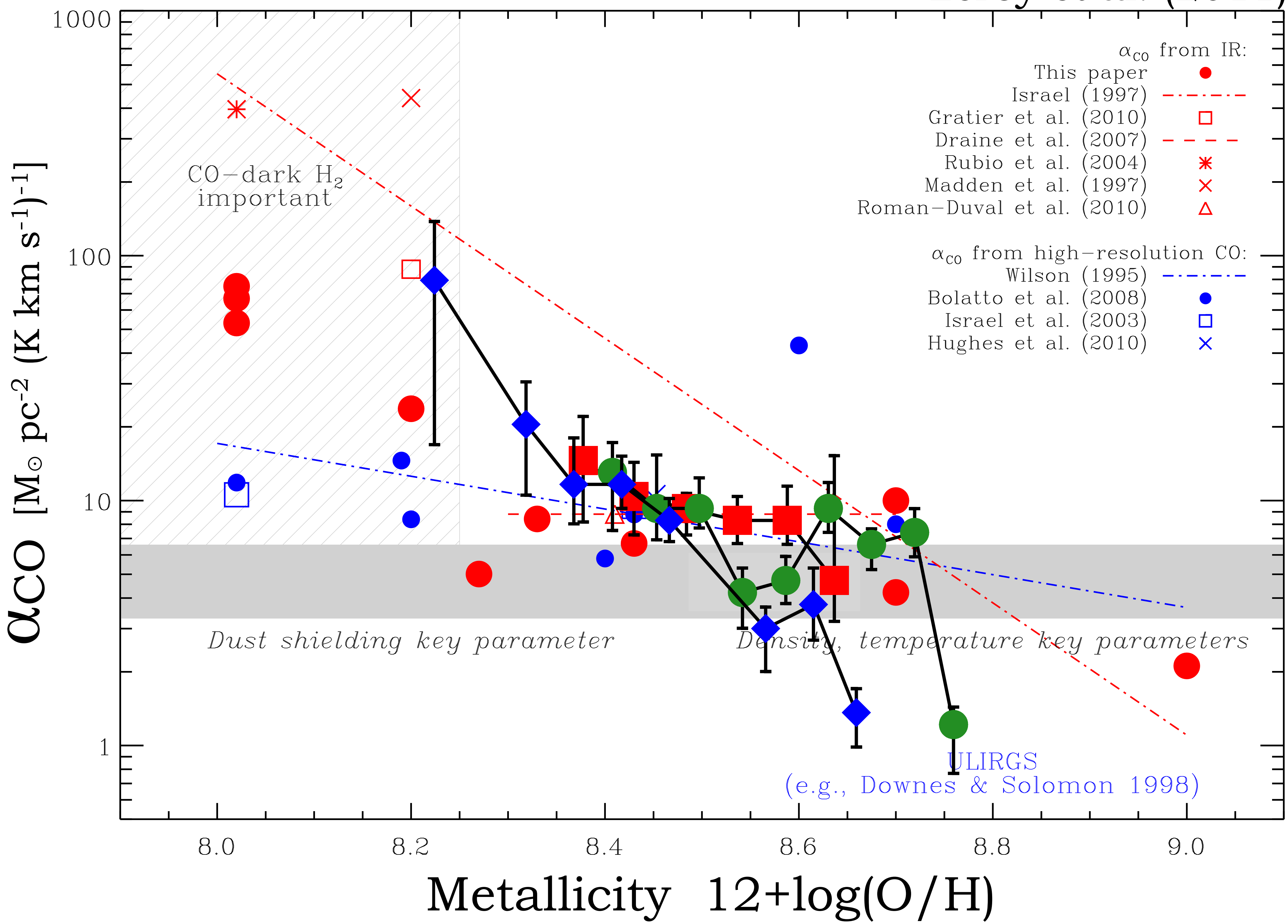
Agrees very well with NGC 0628, 5457 and 6946 radial trends.

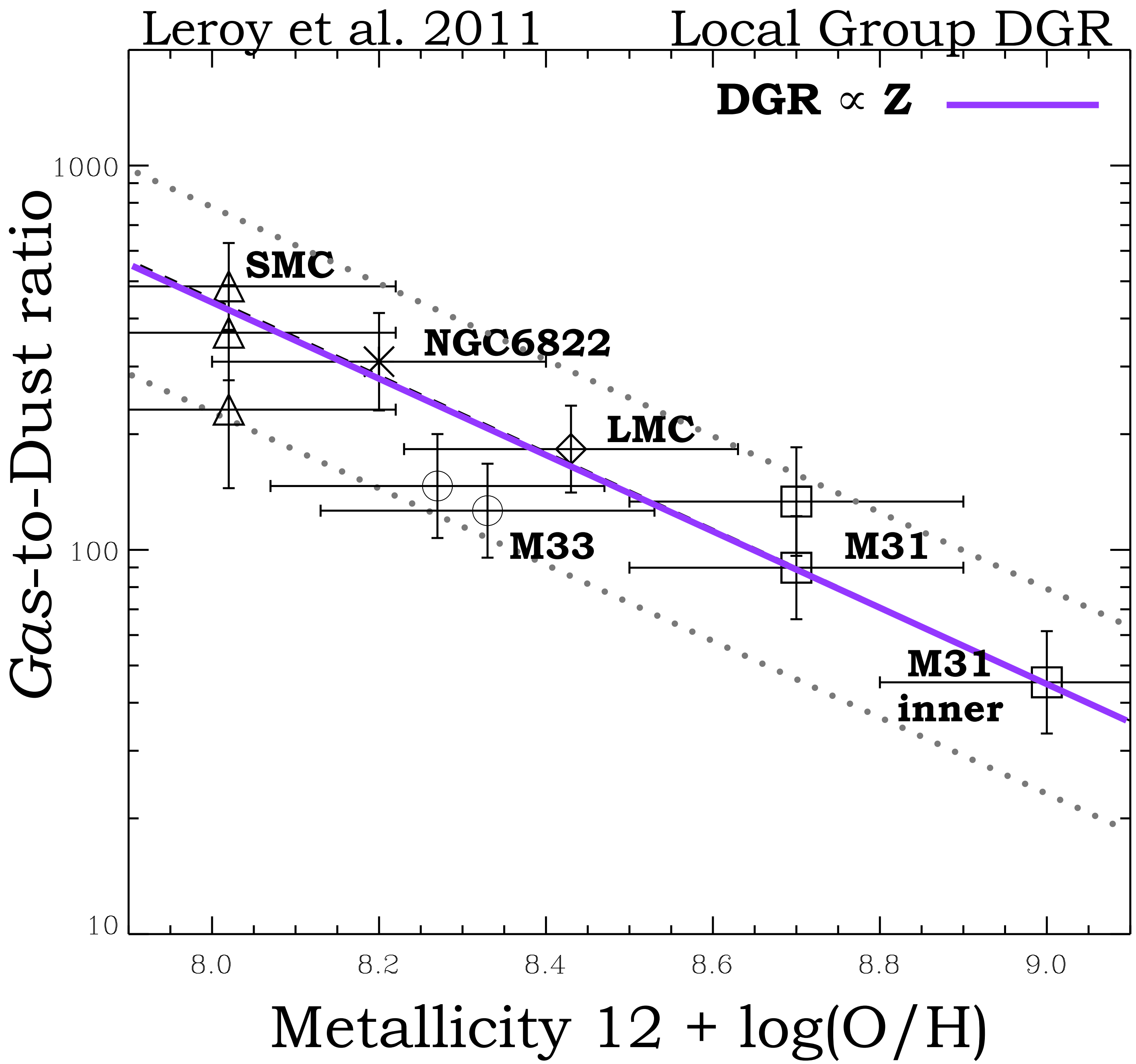
What we've learned about X_{CO}.



What we've learned about X_{CO}.

Leroy et al. (2011)



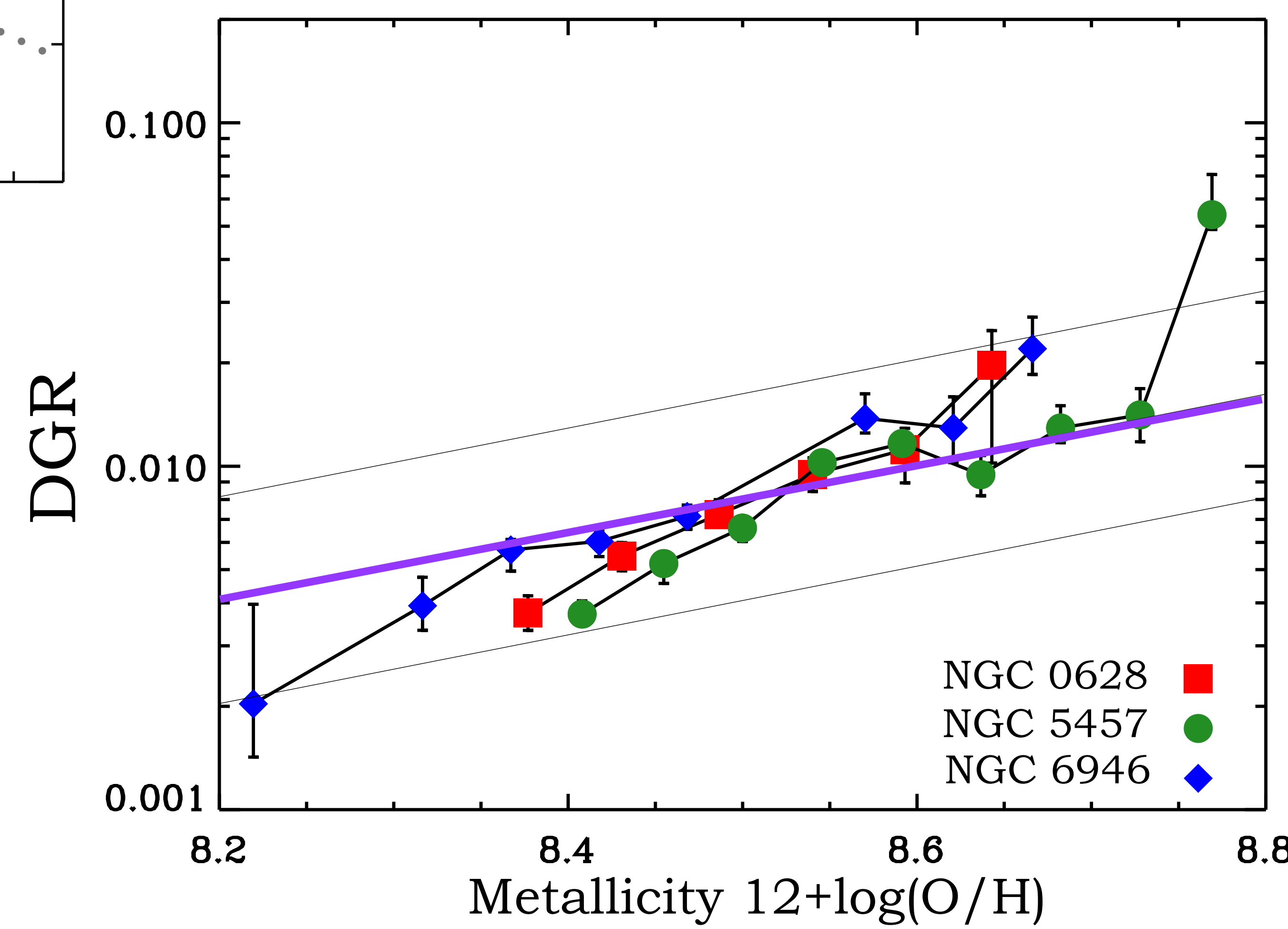


What have we learned about the DGR?

By solving for both X_{CO} and DGR:

resolved DGR approx. linear with Z (or slightly steeper).

Recent work with same technique shows DGR ~ Z across the Local Group.

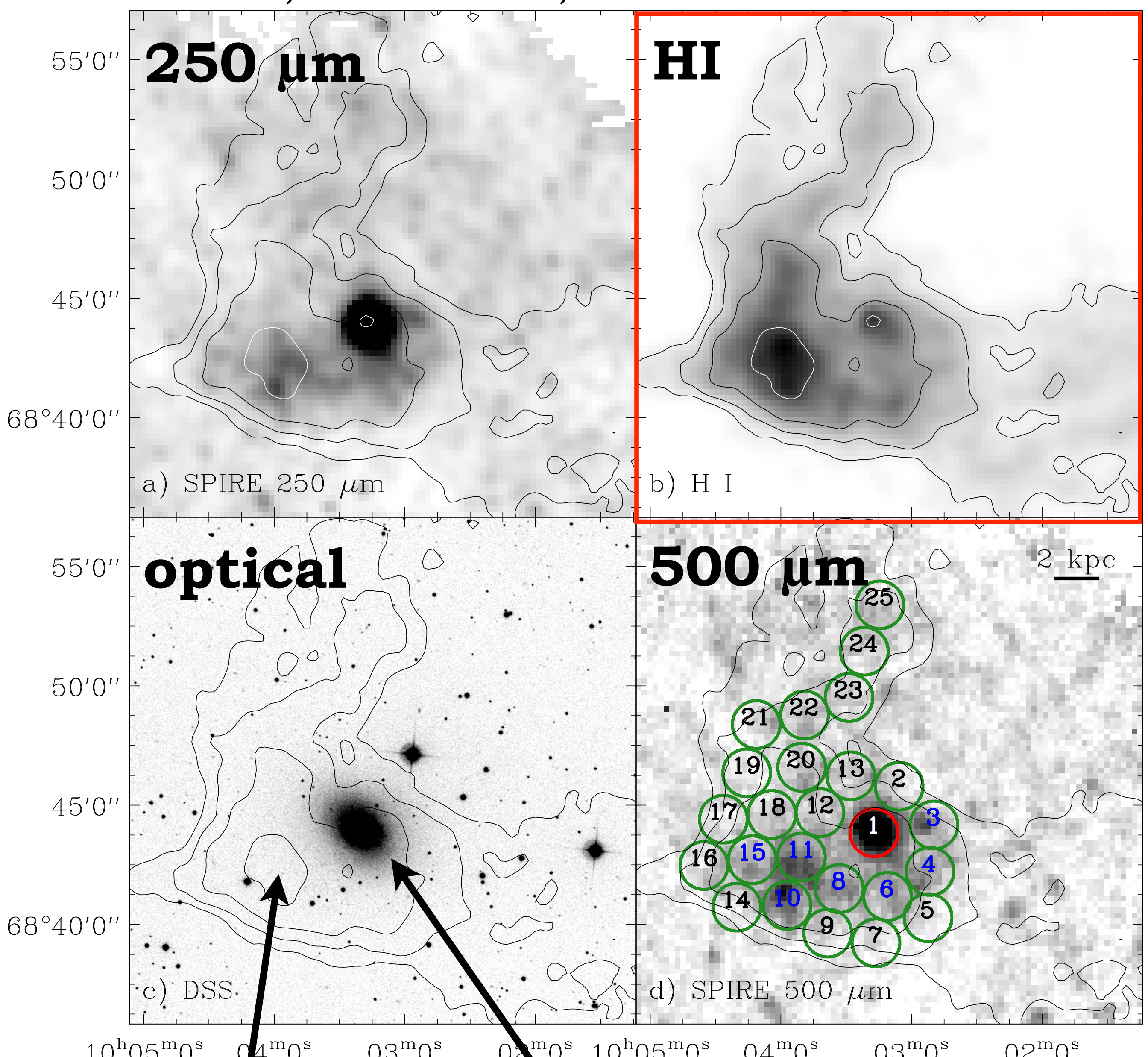


Wednesday, July 6, 2011

DGR in the NGC 3077 Tidal Feature

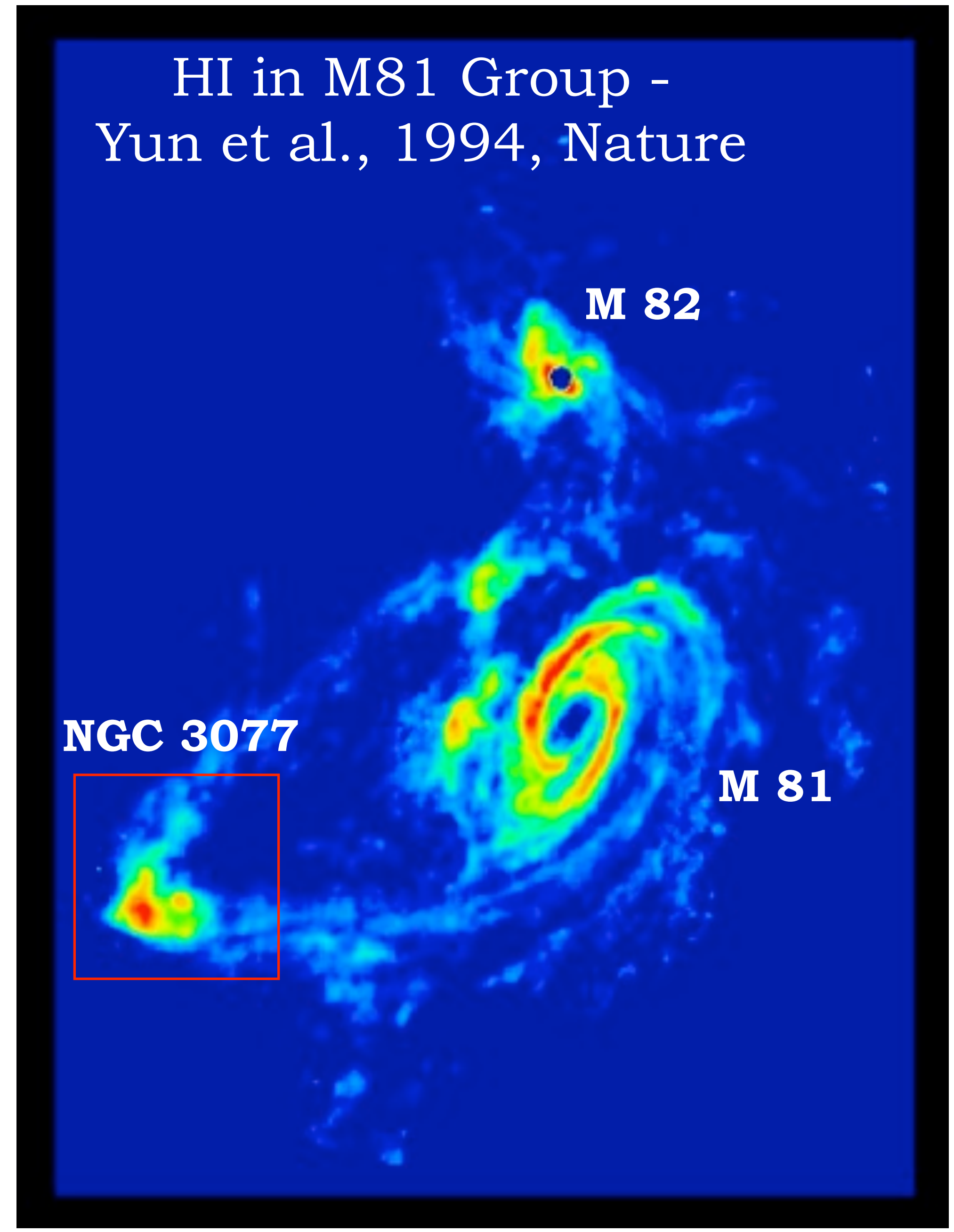
A short digression...

Walter, Sandstrom, & KINGFISH team 2011

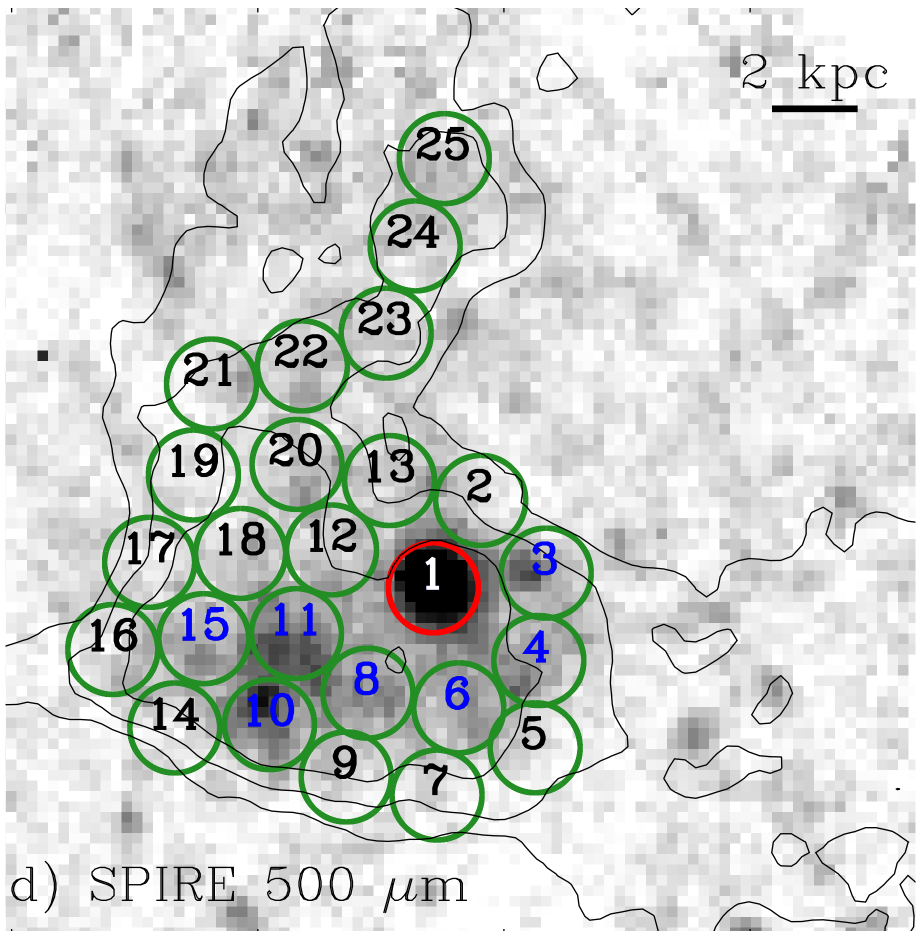


tidal feature
aka "The Garland"

NGC 3077
(starbursting
irregular galaxy)

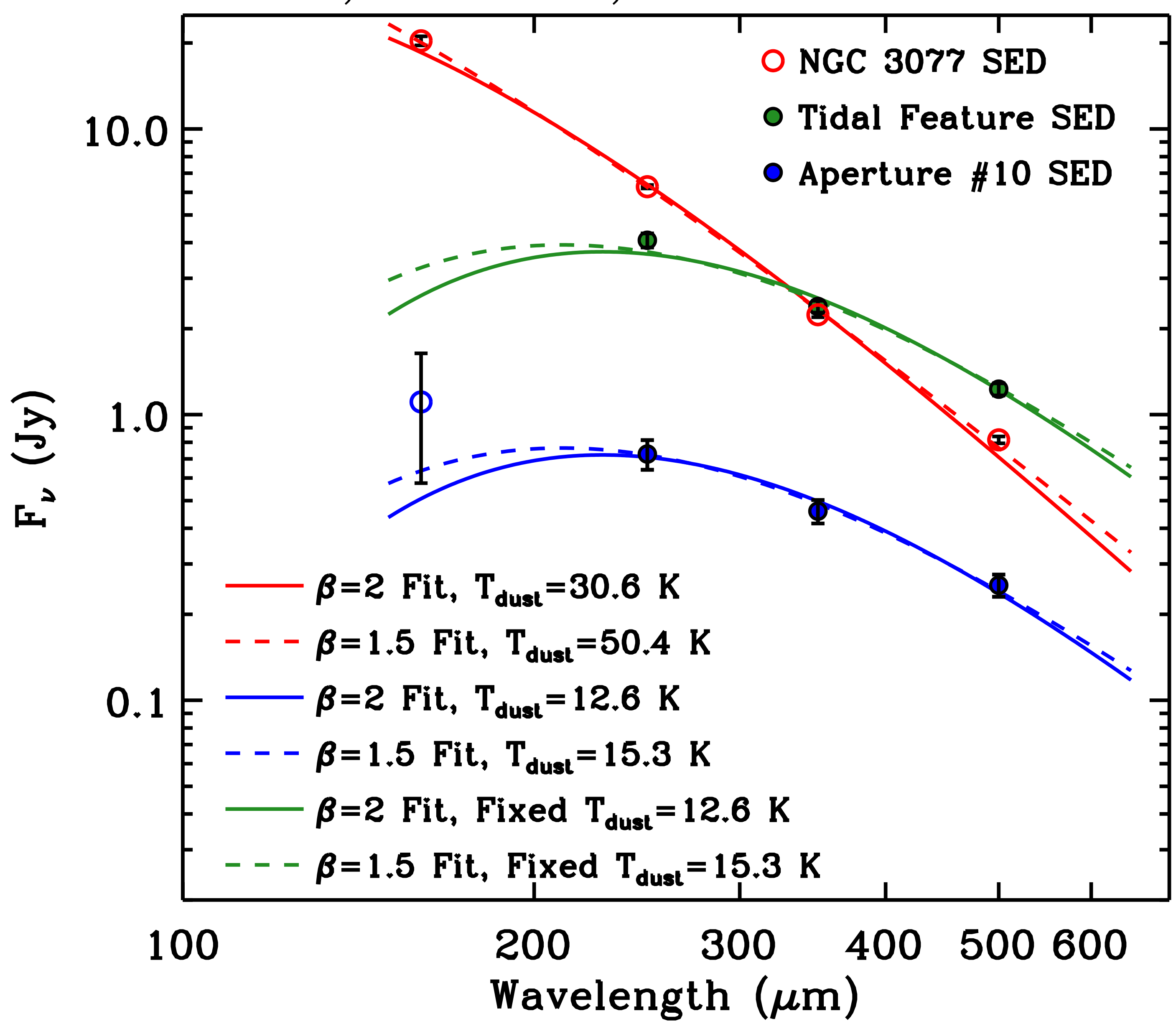


NGC 3077 Tidal Feature
(aka "the Garland")



Dust in tidal feature is cold (~13 K).
~10x more dust in tidal feature than in NGC 3077 itself.

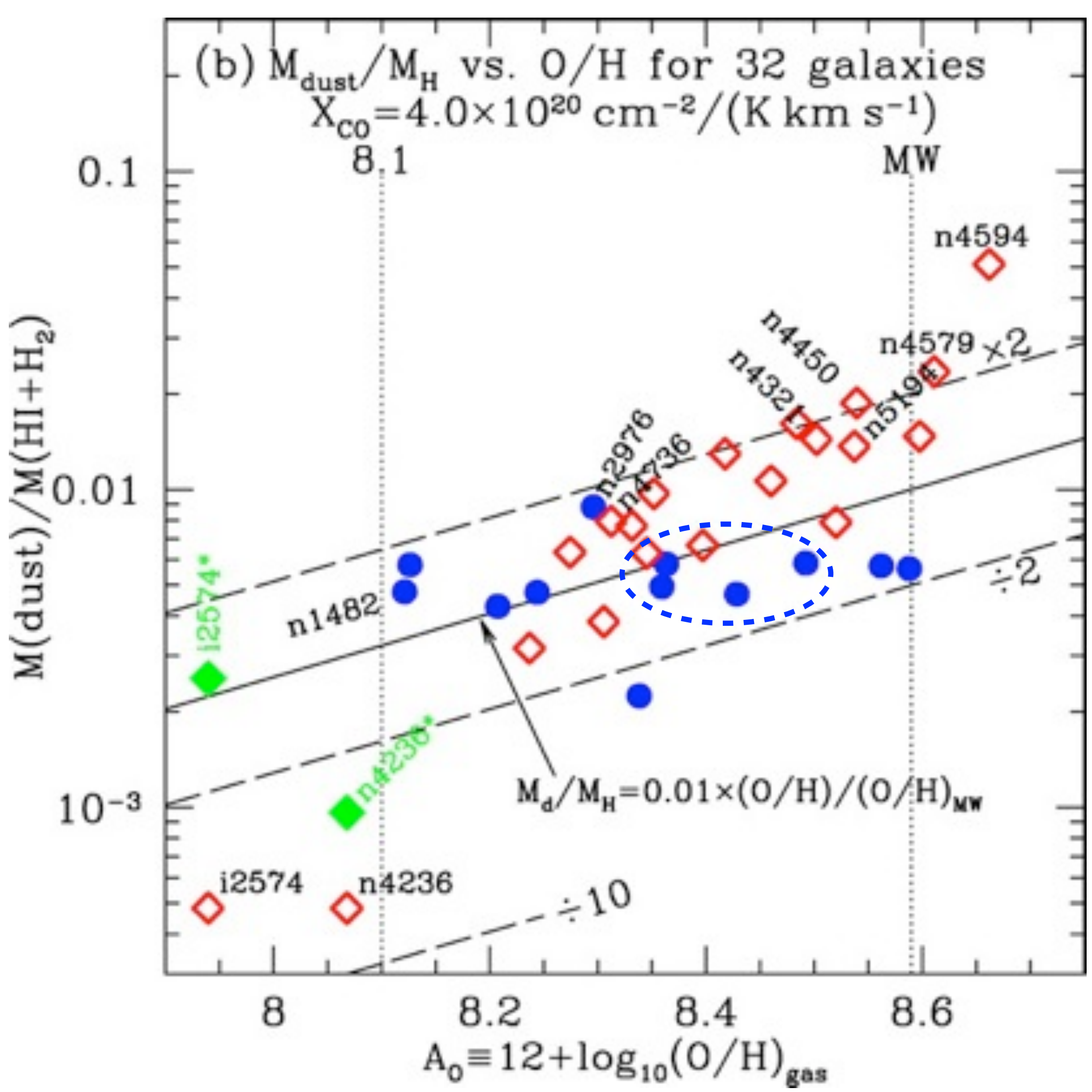
Walter, Sandstrom, & KINGFISH team 2011



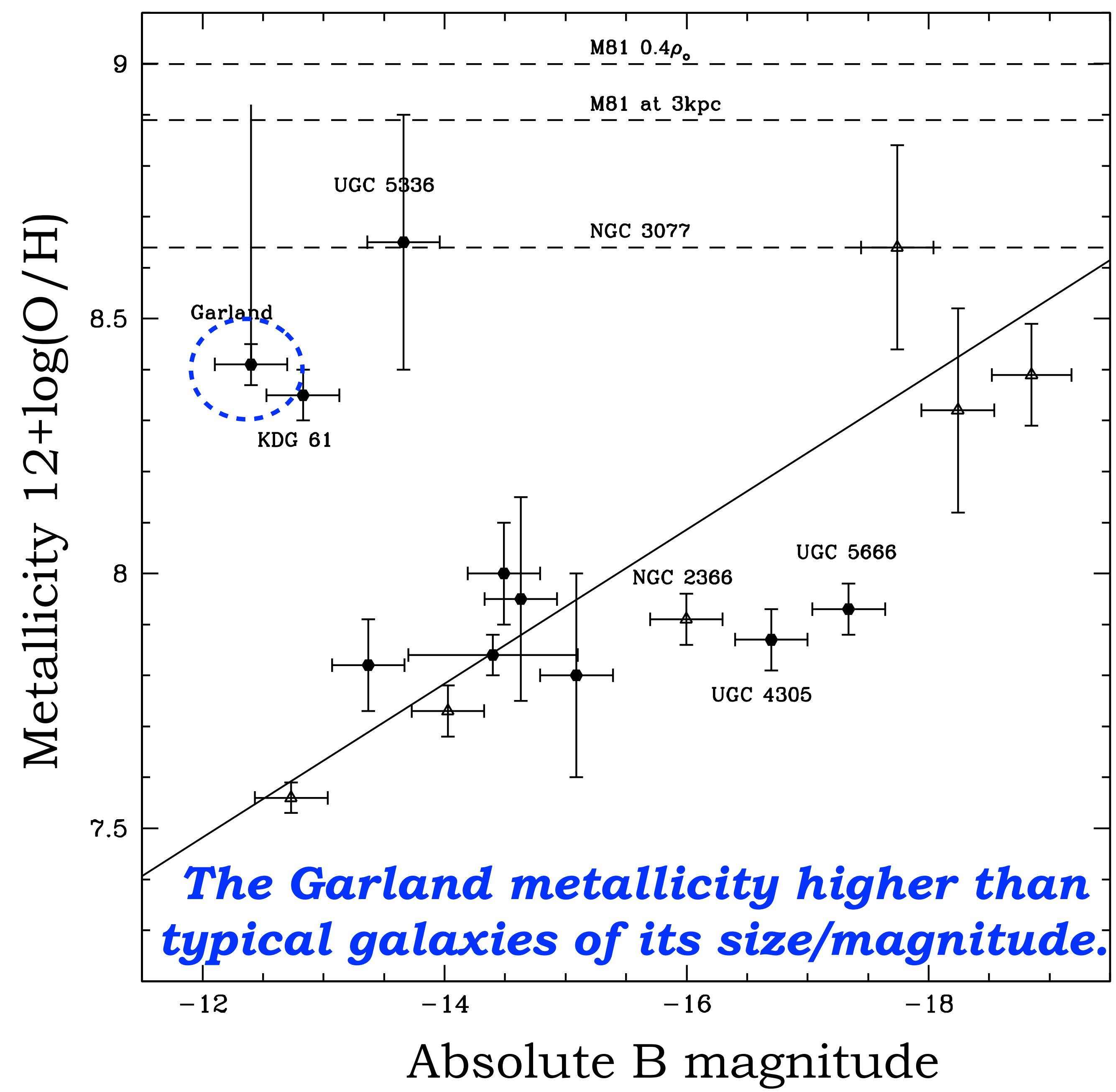
Dust-to-gas ratio ≈ 0.006 in tidal feature.

NGC 3077 Tidal Feature (aka "the Garland")

Although it appears to be a dIrr, the DGR in the tidal feature is consistent with its approx. MW metallicity.



Croxall et al 2009



Conclusions

- Using dust to trace total gas (HI + H_2) can let us constrain DGR and X_{CO} simultaneously.
    - Important systematics: emissivity and/or DGR variations between diffuse and dense gas.
- Below 12+log(O/H)~8.2, X_{CO} becomes large.
- DGR shows approximately linear dependence on metallicity between 12+log(O/H) = 8.0-9.0.
- NGC 3077 tidal feature shows DGR appropriate for its metallicity, but not its morphology.
- Future work will expand this technique to the whole KINGFISH/HERACLES sample overlap.