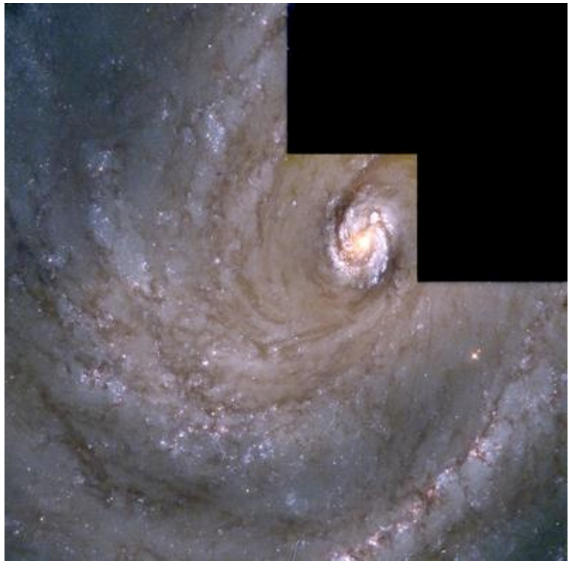
Molecular Gas in the Centers of Nearby Galaxies



Dr. Karin Sandstrom
Marie Curie Postdoctoral Fellow

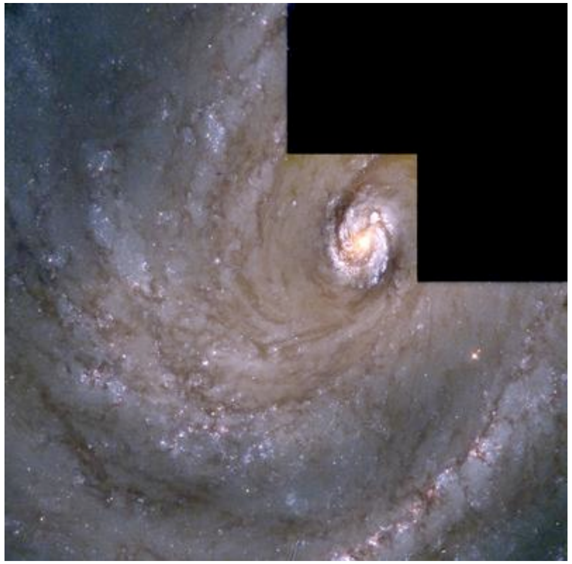
RSF13 - Ringberg

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

and **Beyond the Peak** - especially **Eric Pellegrini**

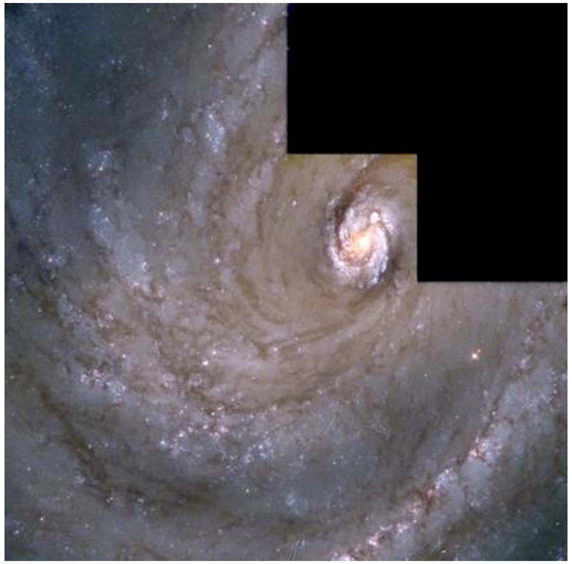
the THINGS & HERACLES Teams -
P.I. Fabian Walter, Adam Leroy,
Frank Bigiel, Elias Brinks, Erwin de Blok, Daniela Calzetti, Kelly Foyle, Gaelle Dumas, Robert Kennicutt, Carsten Kramer, Sharon Meidt, Hans-Walter Rix, Erik Rosolowsky, Eva Schinnerer, Andreas Schruba, Karl Schuster, Antonio Usero, Axel Weiss



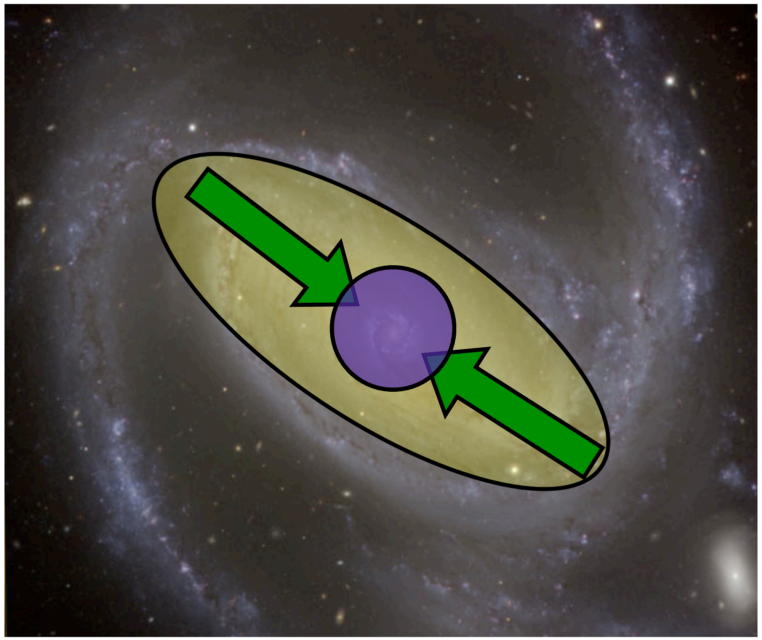
Galaxy centers are a more extreme SF environment:

- short orbital periods
- strong dynamical effects
- higher stellar density
- higher ISM pressure
- more intense radiation fields
- higher metallicity
- influence of AGN
- etc!

How is star formation different under these conditions?


Star formation occuring in galaxy centers
can drive secular evolution.



Stellar Bar

Drives gas inflow

Gas concentration builds in center

Star formation & pseudobulge growth

In studying galaxy centers, the CO-to-H_2 conversion factor makes our lives hard.

All of the things that make centers interesting...

- strong dynamical effects
- higher stellar density
- higher ISM pressure
- more intense radiation fields
- higher metallicity
- influence of AGN
- etc!

could change α_{CO}.

$$\Sigma_{H2} = \alpha_{CO}\, I_{CO}$$

α_{CO} = 4.35 $M_\odot$ pc^{-2} $(K\ km\ s^{-1})^{-1}$

↕

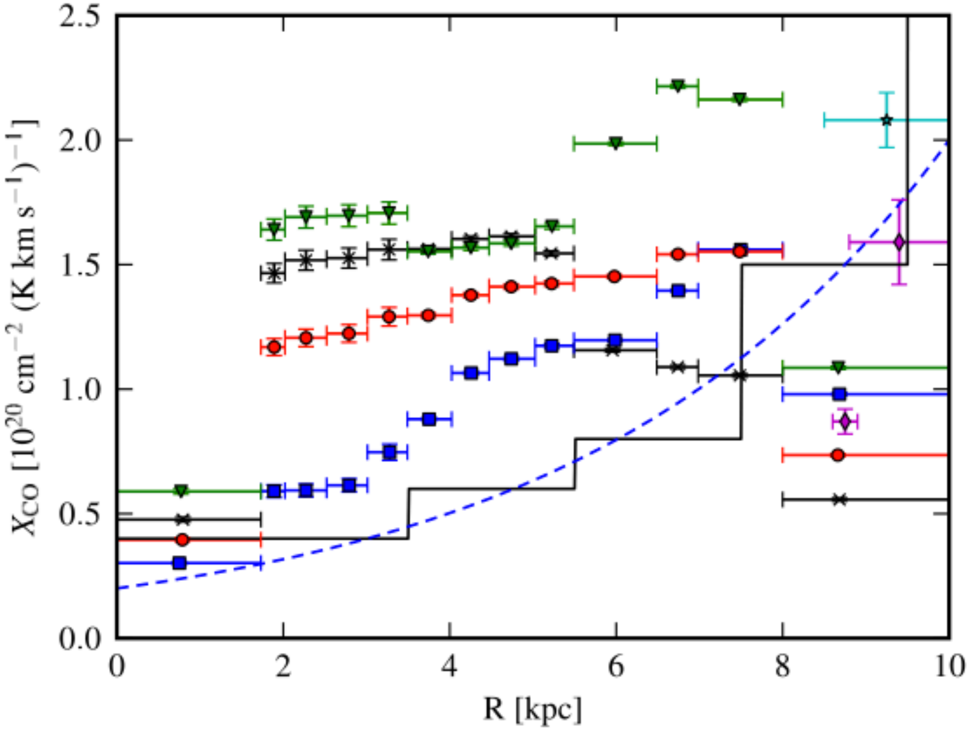
$X_{CO} = 2\times10^{20}$ cm^{-2} $(K\ km\ s^{-1})^{-1}$

note: α_{CO} defined here for unresolved clouds, includes He

For example... The Galactic Center

Ackermann et al. 2012
Fermi-LAT γ-ray contstraints

α_{CO} consistently found to be low in central ~kpc.



Dahmen et al. 1998
$C^{18}O$ observations

MW disk α_{CO} overestimates mol. mass by factor ~10

Sodroski et al. 1995
Σ_{dust} + DGR(Z)

MW disk α_{CO} overestimates mol. mass by factor ~3-10

α_{CO} in Nearby Galaxies

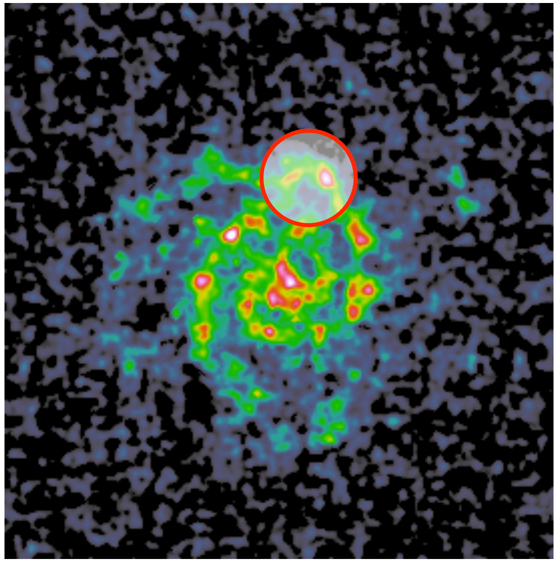
using dust as a tracer of total gas mass

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

unknown *observable*

Solve for both DGR & α_{CO} using spatially resolved measurements.

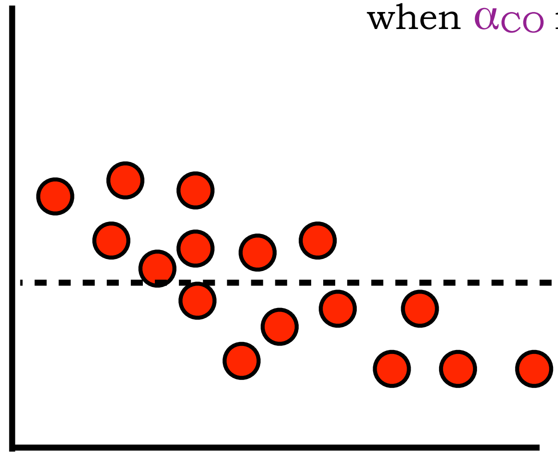
Sandstrom et al. 2013, arXiv 1212.1208



assume DGR & Xco constant in this region

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

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



I_{CO}/Σ_{HI}

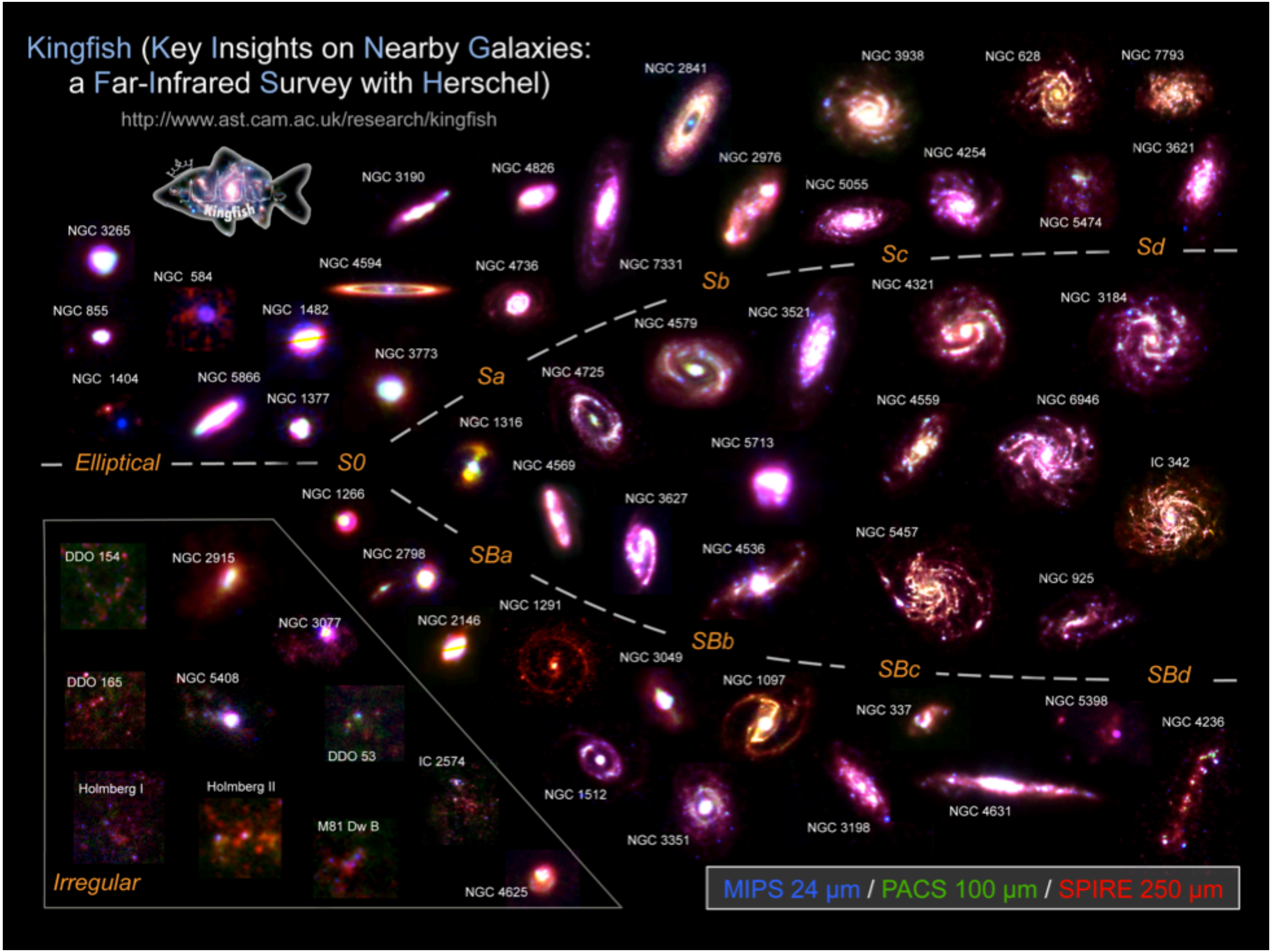
The Observations

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

KINGFISH

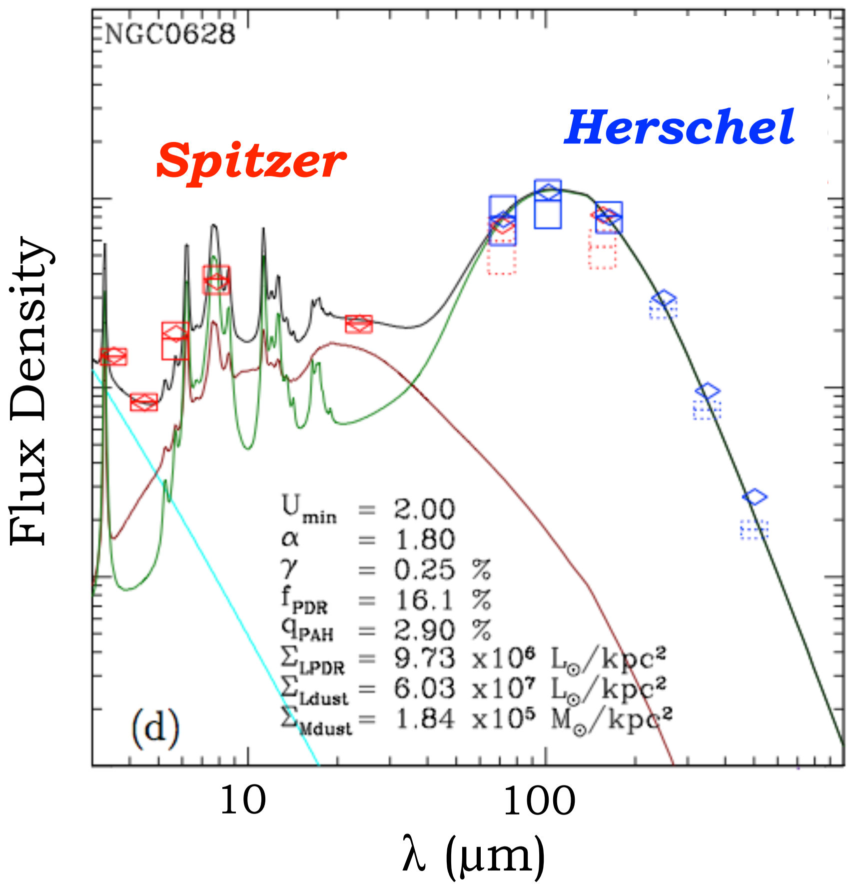
Key Insights into Nearby Galaxies: A Far-IR Survey with Herschel

Herschel key program observing 62 nearby galaxies.
Kennicutt et al. (2011)


Kingfish (Key Insights on Nearby Galaxies:
a Far-Infrared Survey with Herschel)
http://www.ast.cam.ac.uk/research/kingfish
Kingfish
Elliptical
S0
Sa
Sb
Sc
Sd
SBa
SBb
SBc
SBd
Irregular
NGC 3265
NGC 855
NGC 584
NGC 1404
NGC 5866
NGC 1482
NGC 1377
NGC 3190
NGC 4594
NGC 3773
NGC 4826
NGC 4736
NGC 7331
NGC 2841
NGC 2976
NGC 3938
NGC 628
NGC 7793
NGC 5055
NGC 4254
NGC 5474
NGC 3621
NGC 4321
NGC 3184
NGC 4579
NGC 3521
NGC 4725
NGC 1316
NGC 4569
NGC 4559
NGC 6946
NGC 5713
IC 342
NGC 3627
NGC 1266
NGC 2798
NGC 4536
NGC 5457
NGC 925
NGC 2146
NGC 1291
NGC 3049
NGC 1097
NGC 337
NGC 5398
NGC 4236
NGC 1512
NGC 3351
NGC 3198
NGC 4631
DDO 154
NGC 2915
NGC 3077
DDO 165
NGC 5408
DDO 53
IC 2574
Holmberg I
Holmberg II
M81 Dw B
NGC 4625
MIPS 24 μm / PACS 100 μm / SPIRE 250 μm

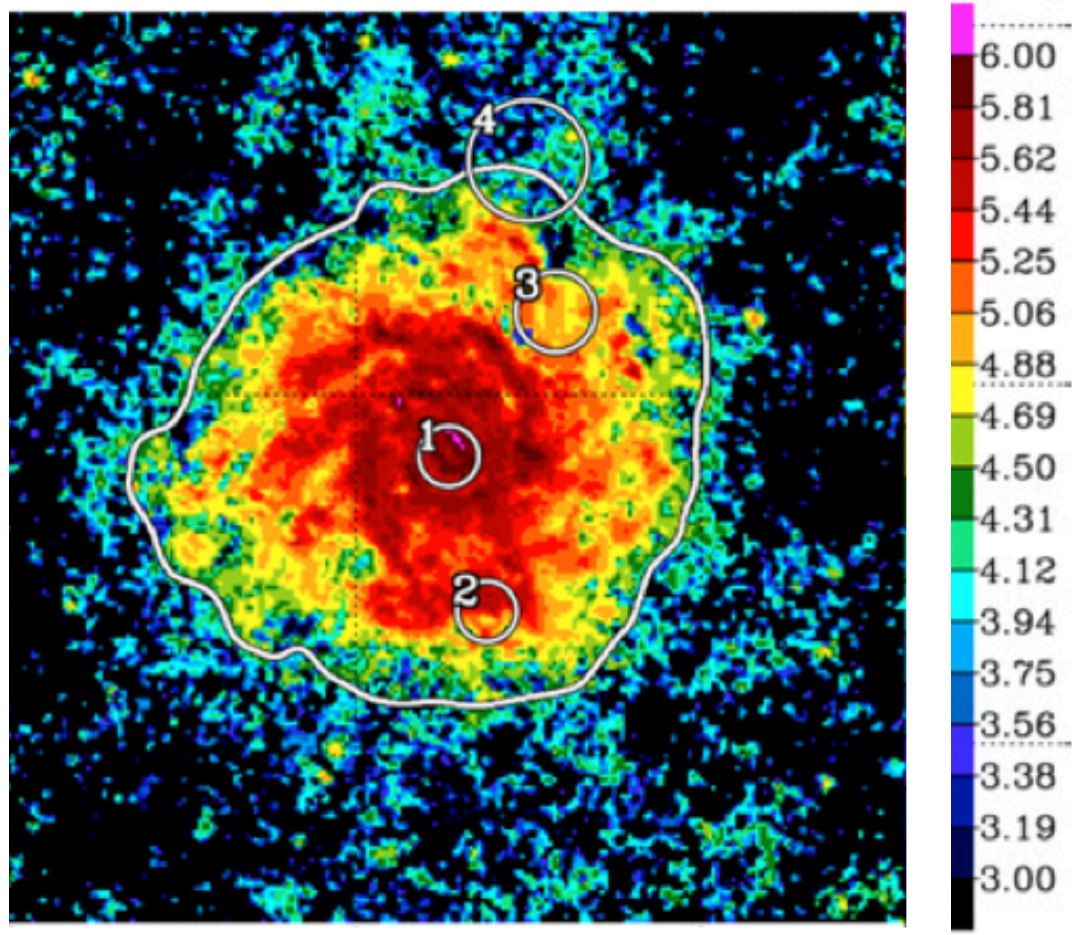
Measuring the CO-to-H_2 Conversion Factor.

Pixel-by-pixel modeling of the dust SED in the KINGFISH galaxies.
(Aniano et al. 2012)



NGC 0628
Dust Mass Surface Density

Log Σ_{dust} ($M_\odot$ kpc^{-2})



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)

HI column density determined directly from 21cm line.

The Observations

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

HERACLES
Institut de Radioastronomie Millimétrique

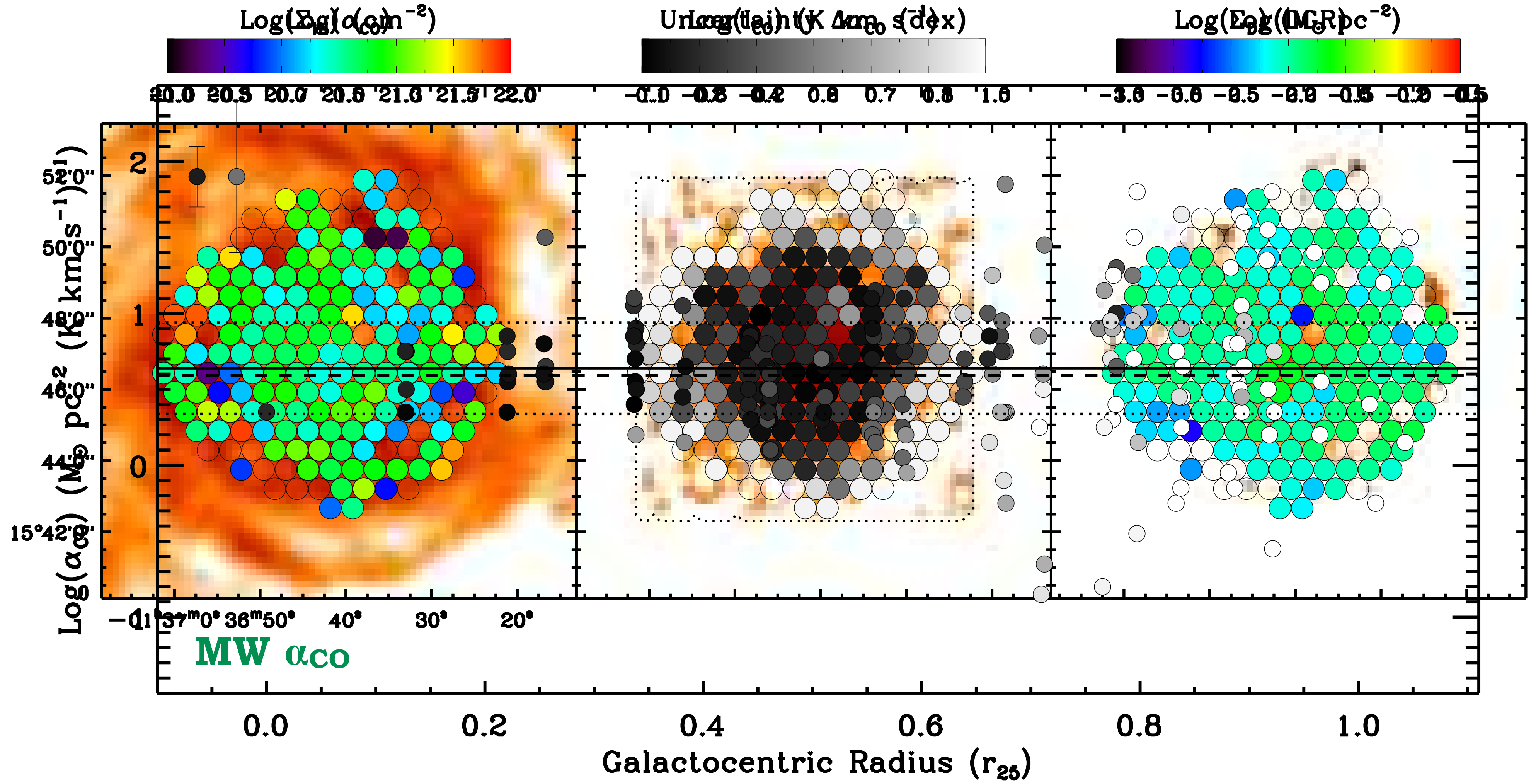
HERACLES

HERA CO-Line Emission Survey

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

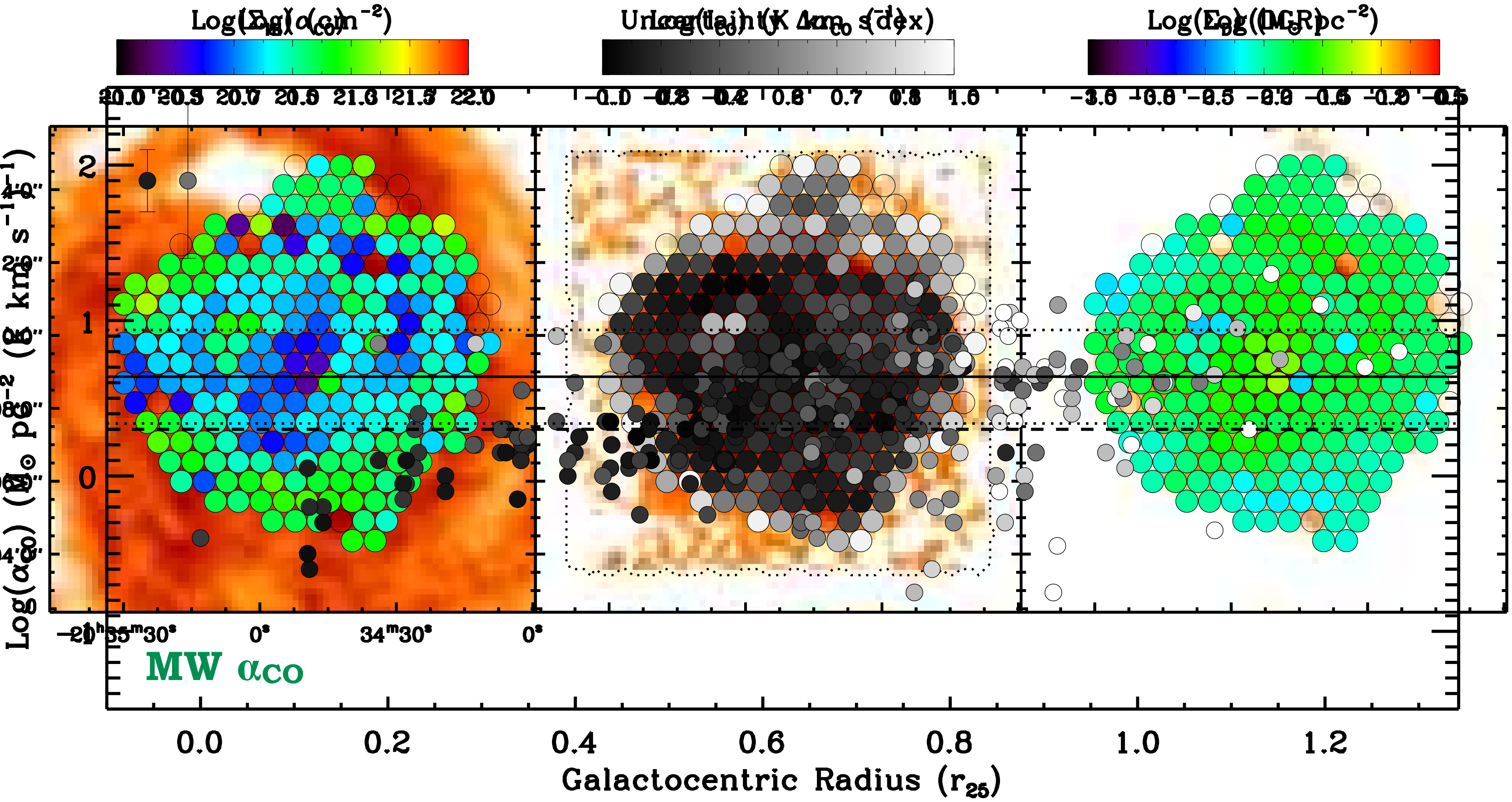
note: measured α_{CO} for CO J=(2-1), but we convert to (1-0) units for convenience

NGC 0628 Results



Sandstrom et al. 2013, arXiv 1212.1208

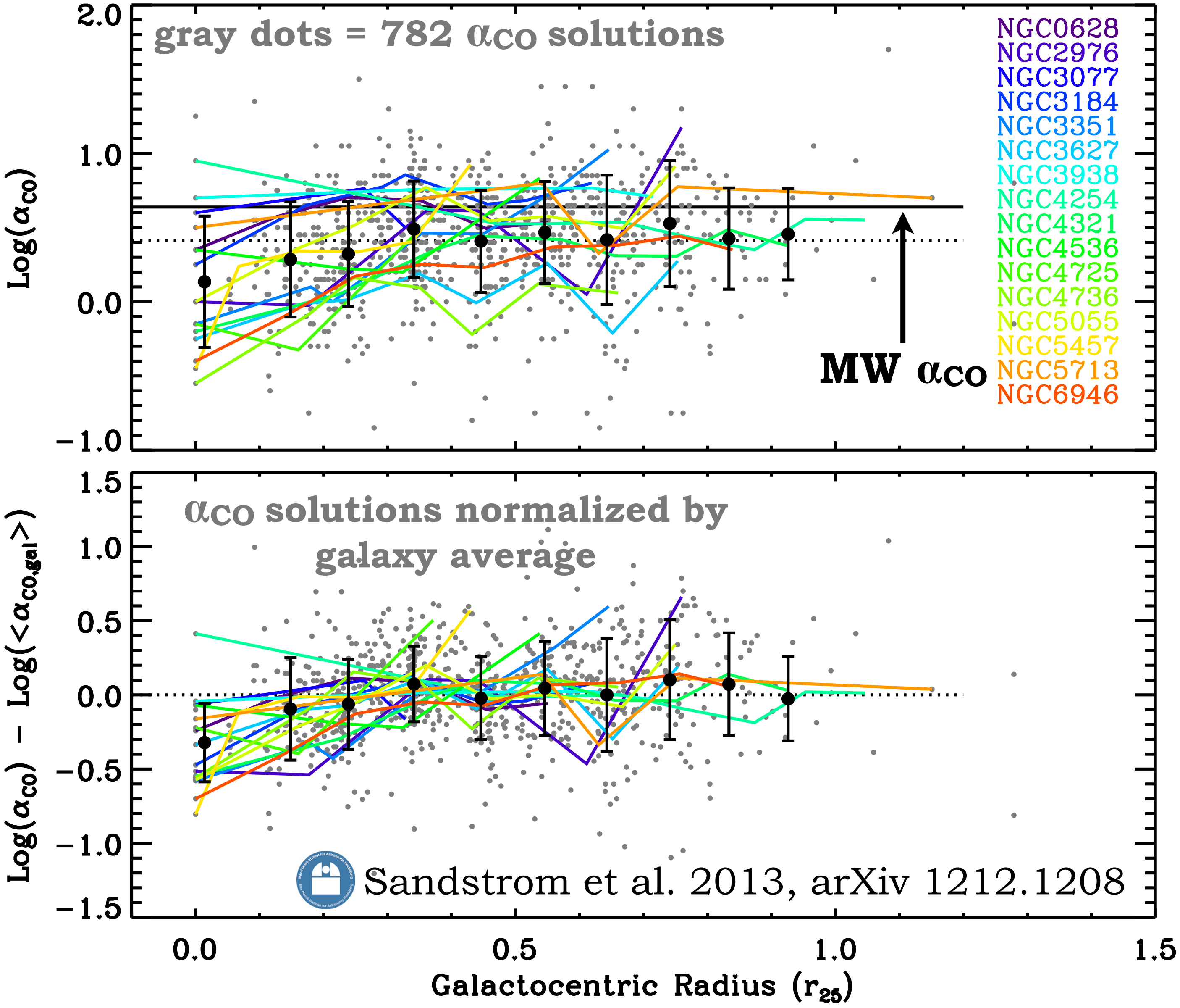
NGC 6946 Results



Sandstrom et al. 2013, arXiv 1212.1208

What do we know about α_{CO}?

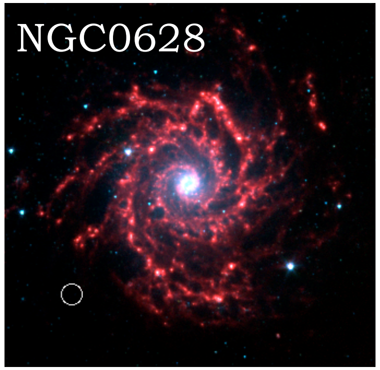
...from nearby galaxies

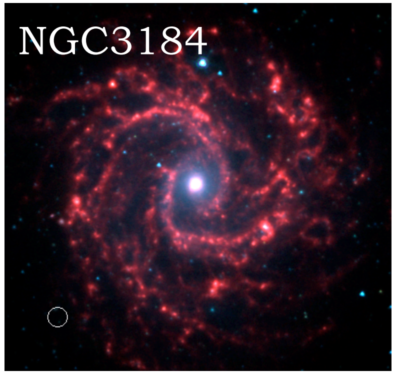


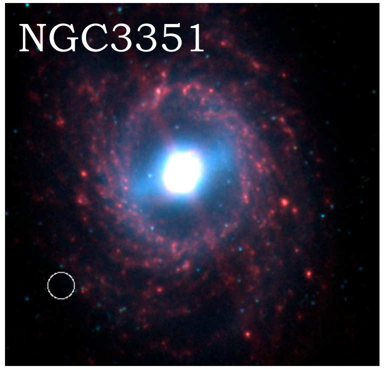
In regions with high CO surface brightness:

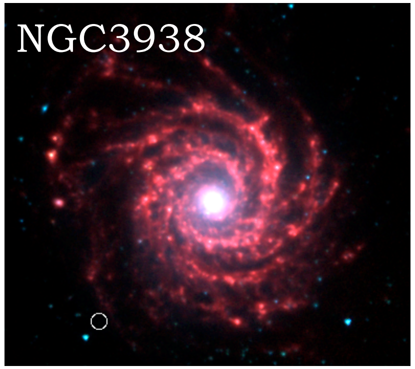
- radial profile ~flat
- average α_{CO} = 3.1 $M_\odot$ pc^{-2} (K km $s^{-1})^{-1}$
- central α_{CO} often low
- some galaxies show central α_{CO}, up to 10× lower than MW

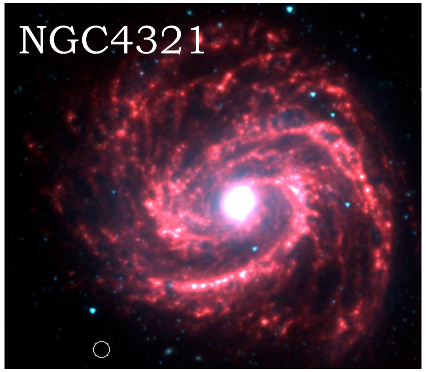
RGB - Spitzer IRAC 8.0, 4.5 and 3.6 µm

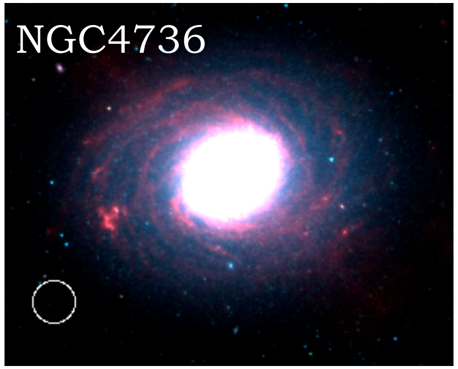


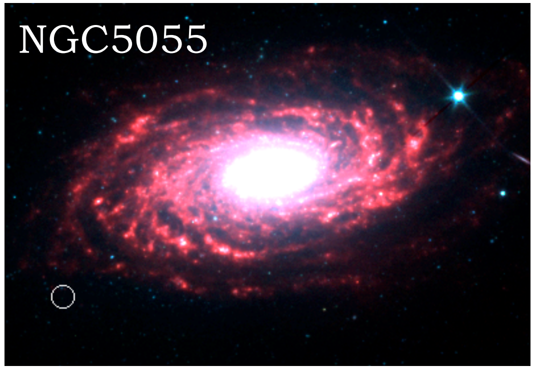


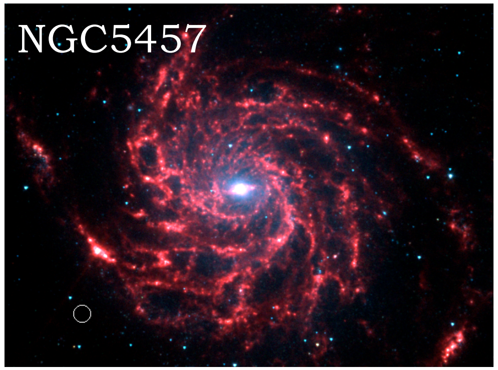


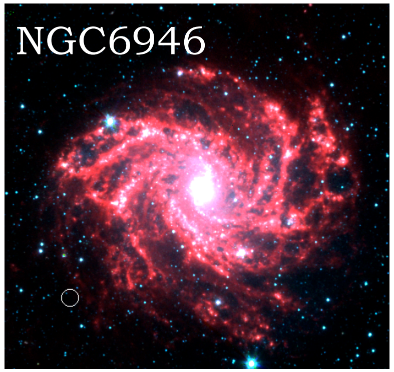






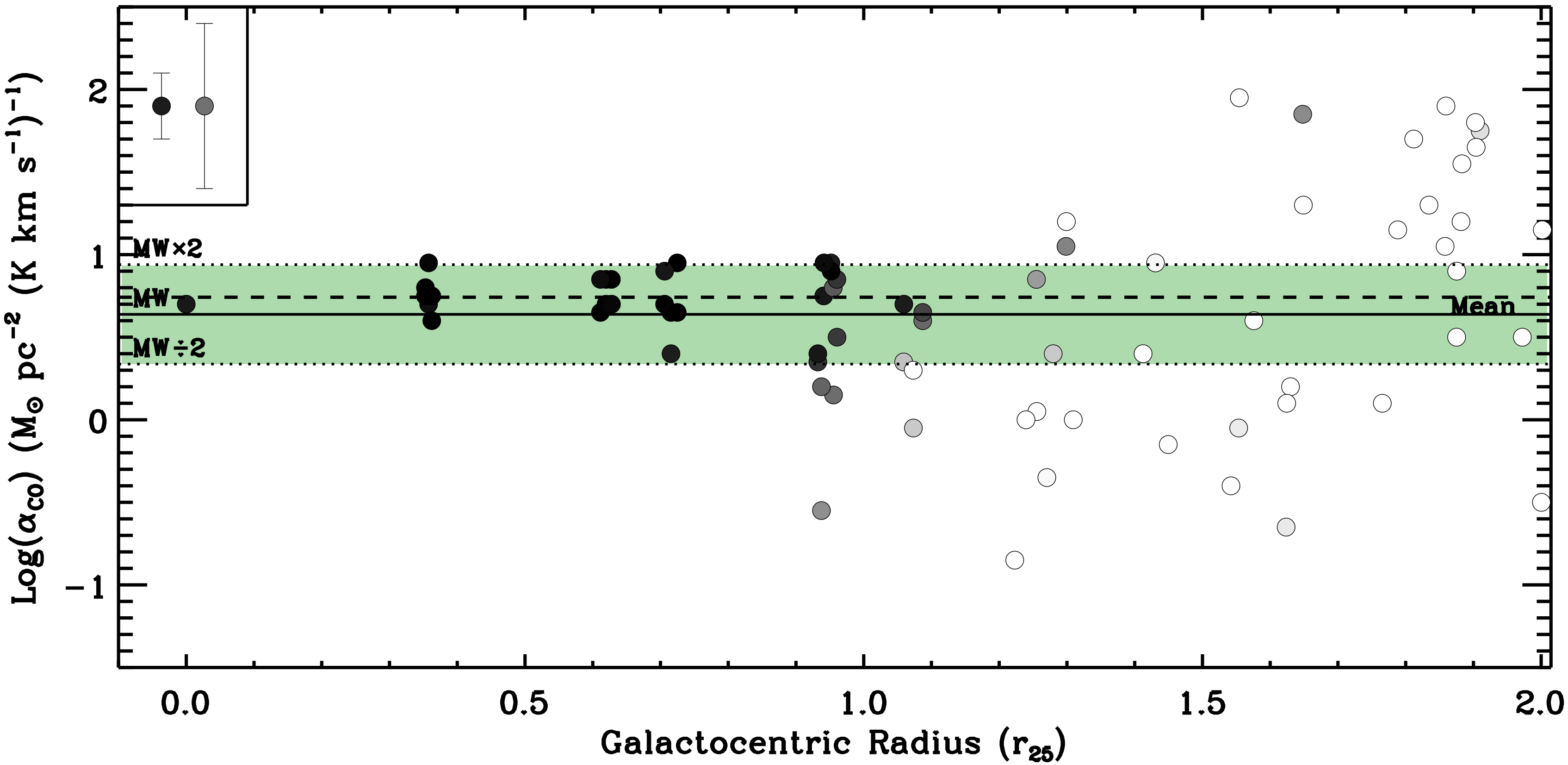






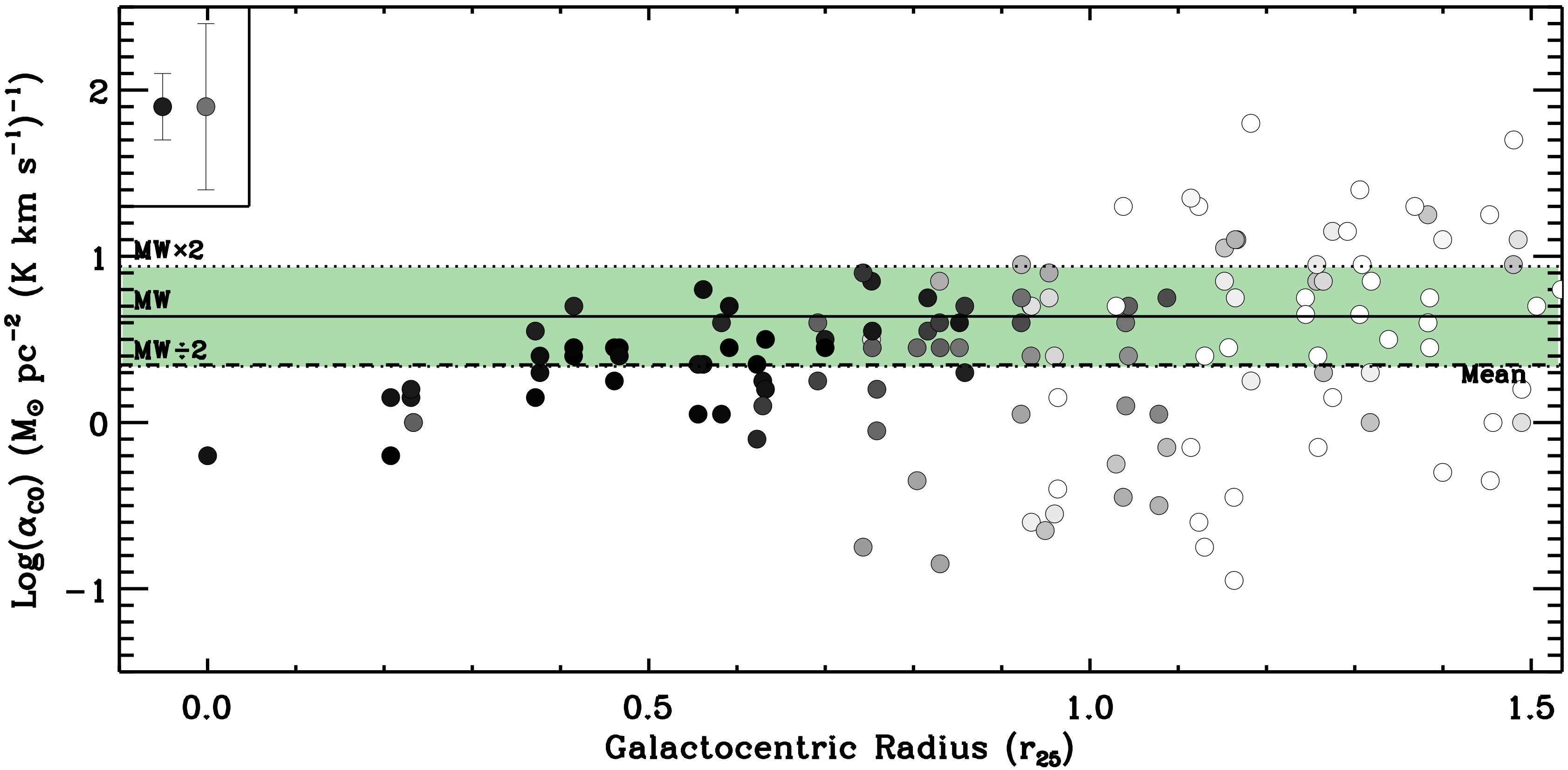
A subset of low-inclincation, well measured α_{CO} galaxies.

NGC 3938

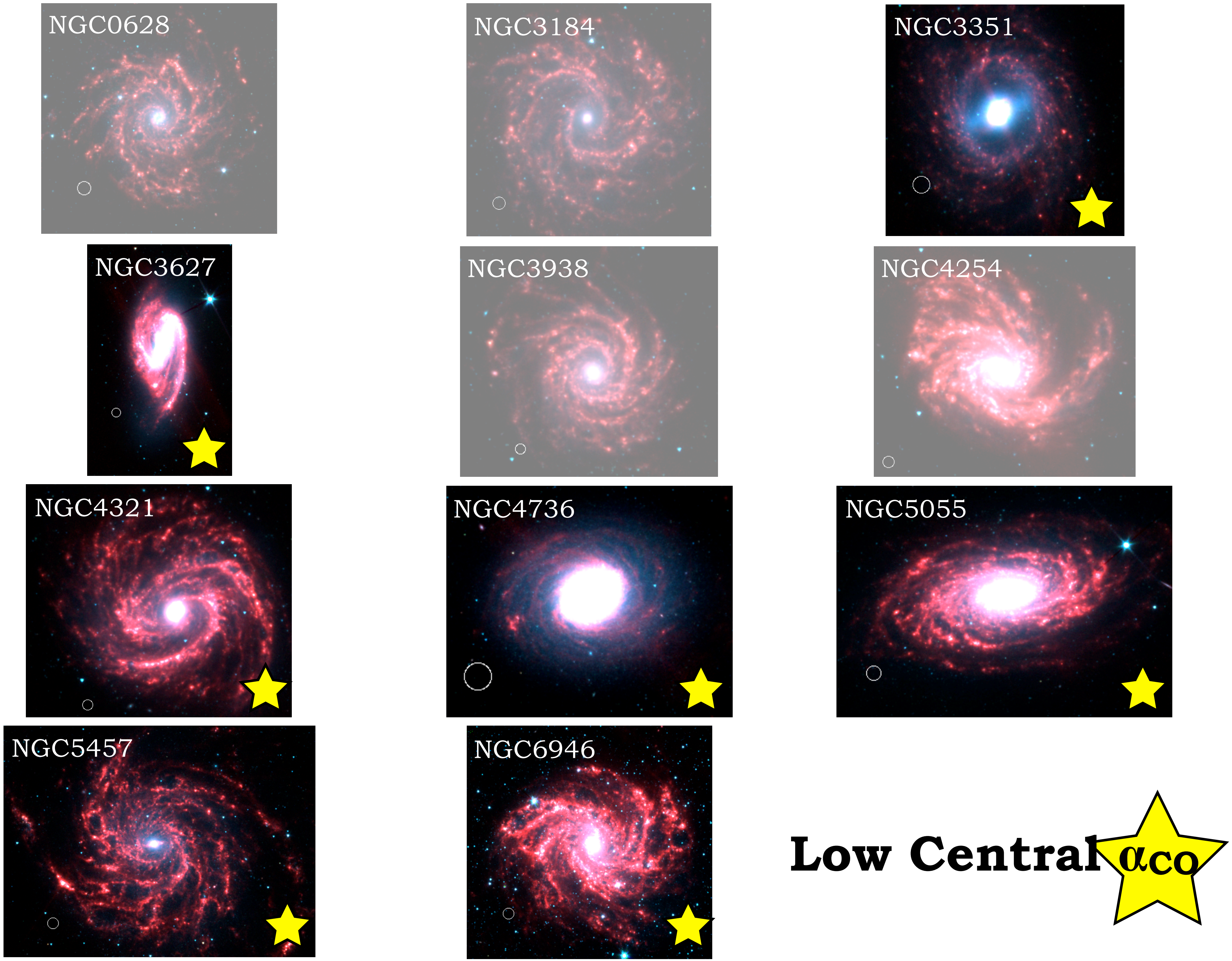


Log(α_{CO}) ($M_\odot$ pc^{-2} (K km s^{-1})$^{-1}$)
2
1
0
−1
MW×2
MW
MW÷2
Mean
0.0
0.5
1.0
1.5
2.0
Galactocentric Radius (r_{25})

NGC 4321



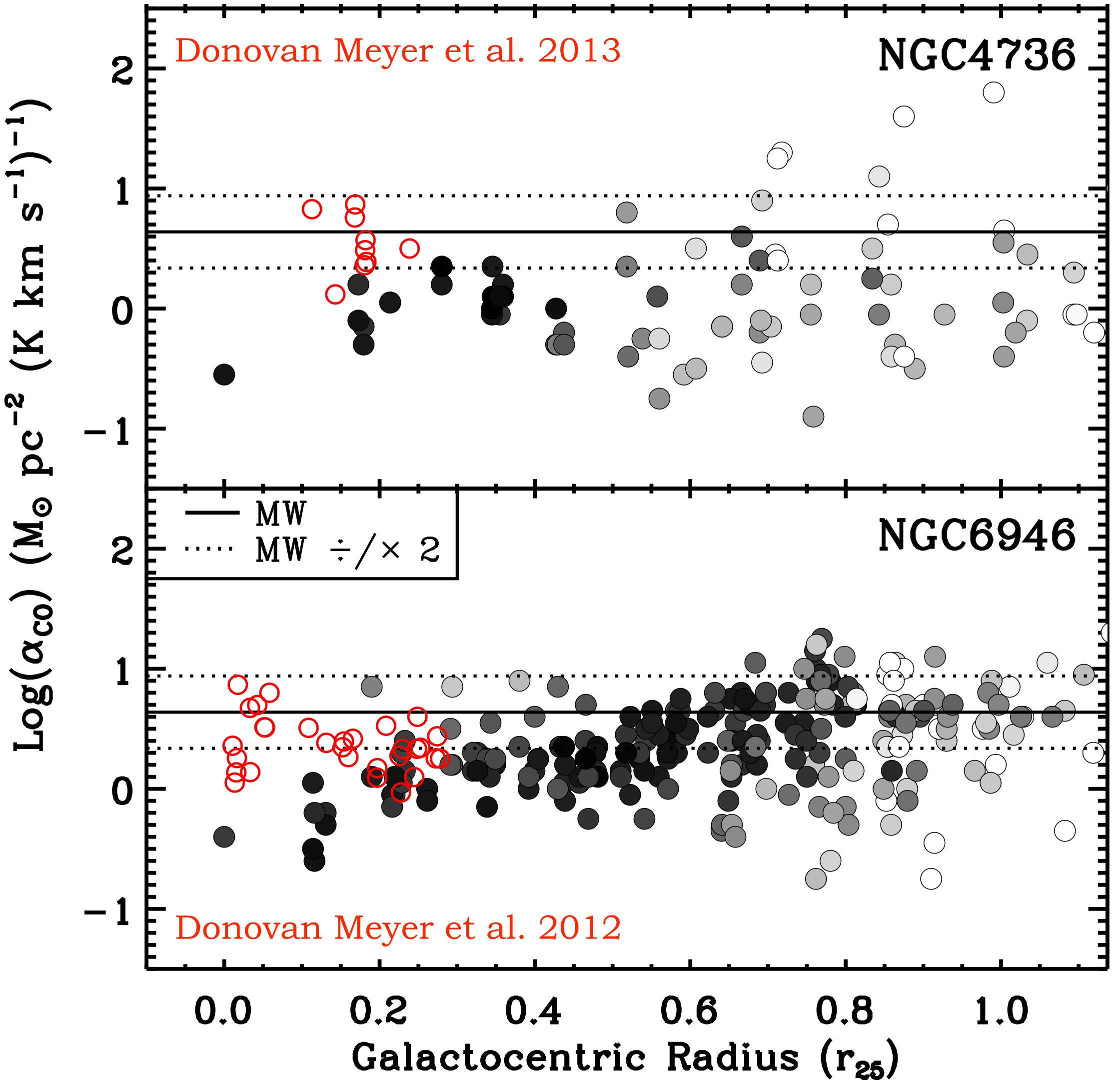
Log(α_{CO}) ($M_\odot$ pc^{-2} (K km s^{-1})$^{-1}$)
Galactocentric Radius (r_{25})
MW×2
MW
MW÷2
Mean
2
1
0
−1
0.0
0.5
1.0
1.5

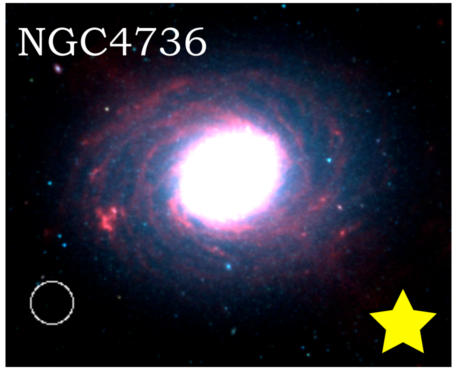

NGC0628
NGC3184
NGC3351
NGC3627
NGC3938
NGC4254
NGC4321
NGC4736
NGC5055
NGC5457
NGC6946
Low Central αco

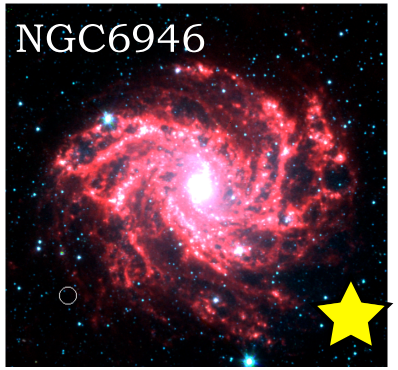
Why do some galaxies have low central α_{CO}?

- Scenario 1: molecular gas in bound clouds
  - ✳ gas temperature is enhanced
  - ✳ velocity dispersion enhanced (additional turbulence, external pressure)
- Scenario 2: some molecular gas in a diffuse phase
  - ✳ chemistry/radiative transfer/excitation can lead to lower α_{CO} (e.g. Liszt & Pety 2010)
  - ✳ CO still optically thick, but velocity dispersion is enhanced due to gravitational potential of stars and dynamics of center (e.g. ULIRGs)
- Scenarios 3-N: suggestions?

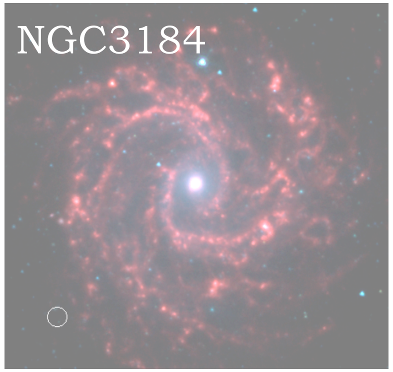
Insights from comparing with virial mass α_{CO} measurements

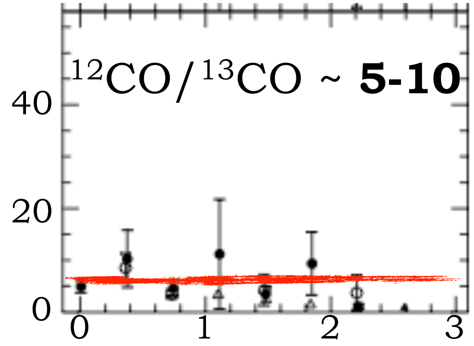






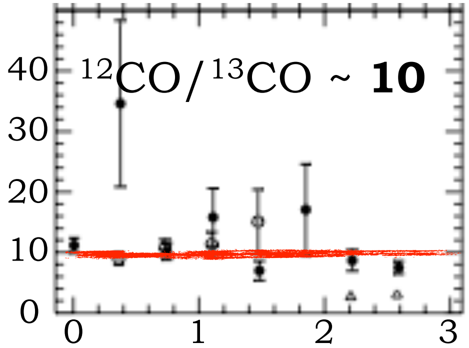
Clouds don't have unusually large σ_V for size, as seen for possibly pressure bound clouds in GC (e.g. Oka et al. 1998)

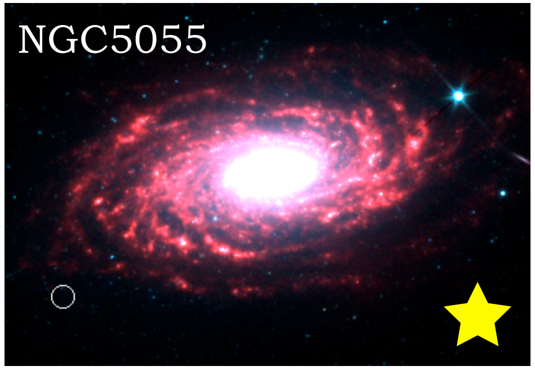


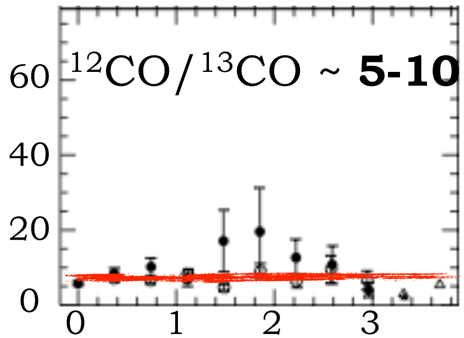


Some evidence for changes in optical depth...

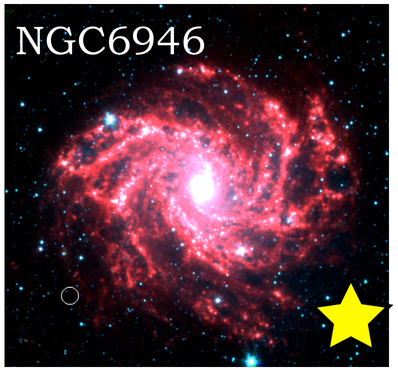
Radial Profiles of $^{12}CO/^{13}CO$ from Paglione et al. 2001

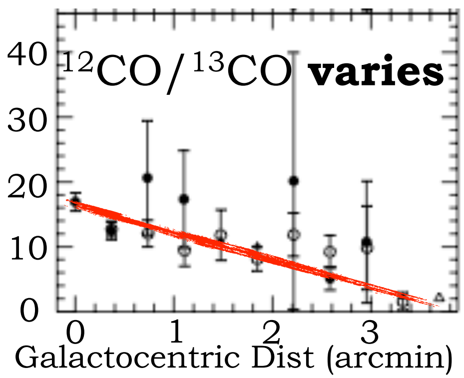






Correspondence between galaxies with low α_{CO} and $^{12}CO/^{13}CO$.

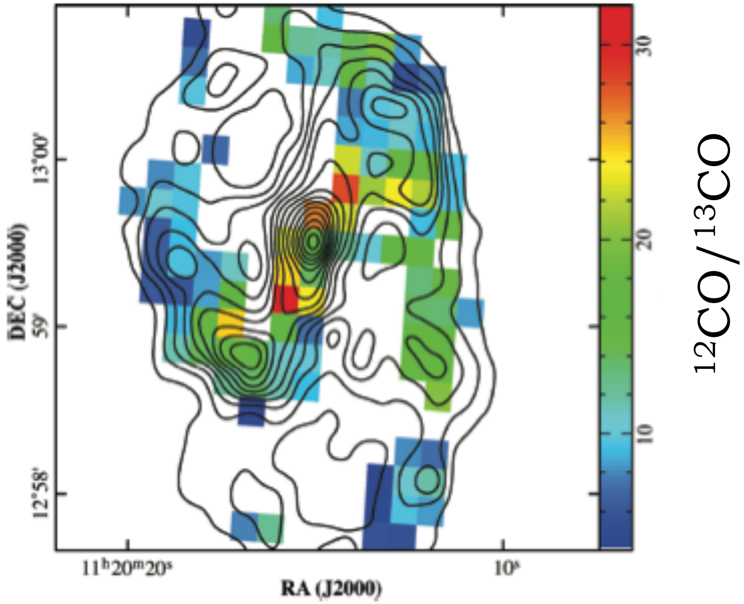




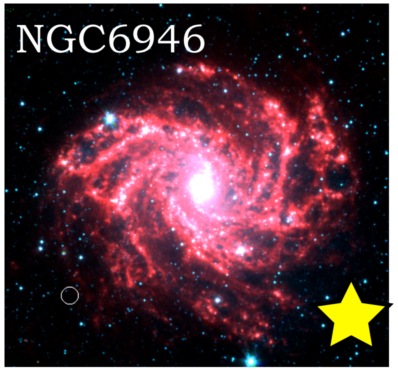
Especially clear in NGC 6946, that ratio is a function of radius.

Watanabe et al. 2011
Map of $^{12}CO/^{13}CO$
for NGC 3627

measure high ratio in bar and center

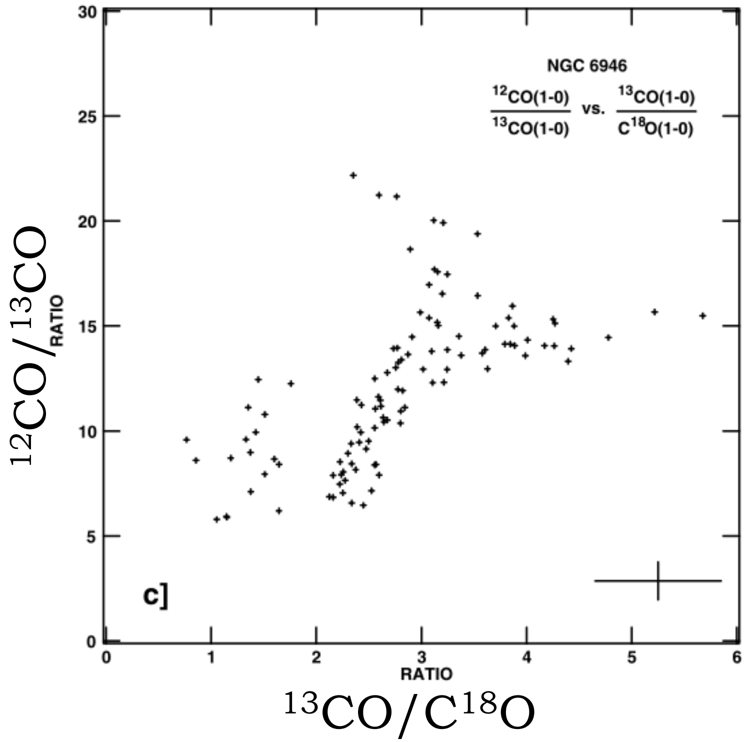


More evidence for changes in optical depth...



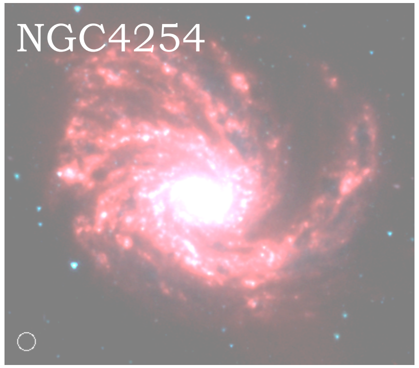
Meier & Turner 2004
^{12}CO, ^{13}CO and $C^{18}O$
observations of
NGC 6946 center

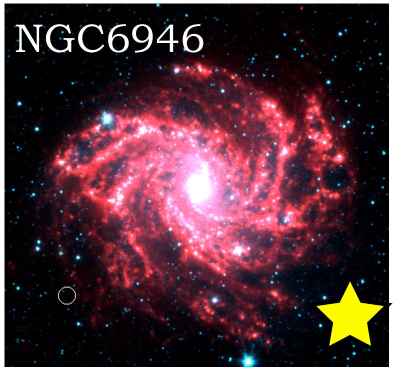
clear evidence for changes in ^{12}CO optical depth

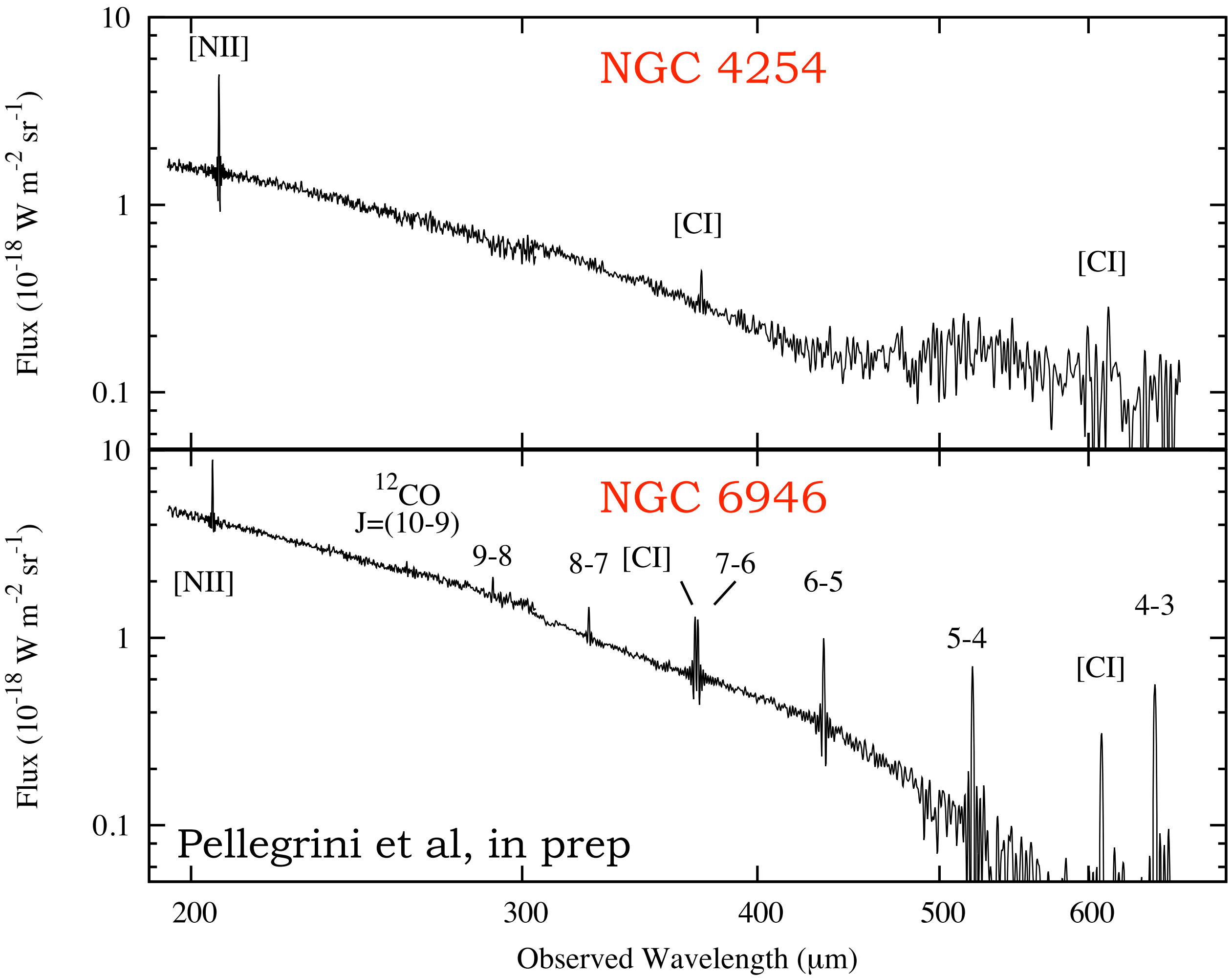


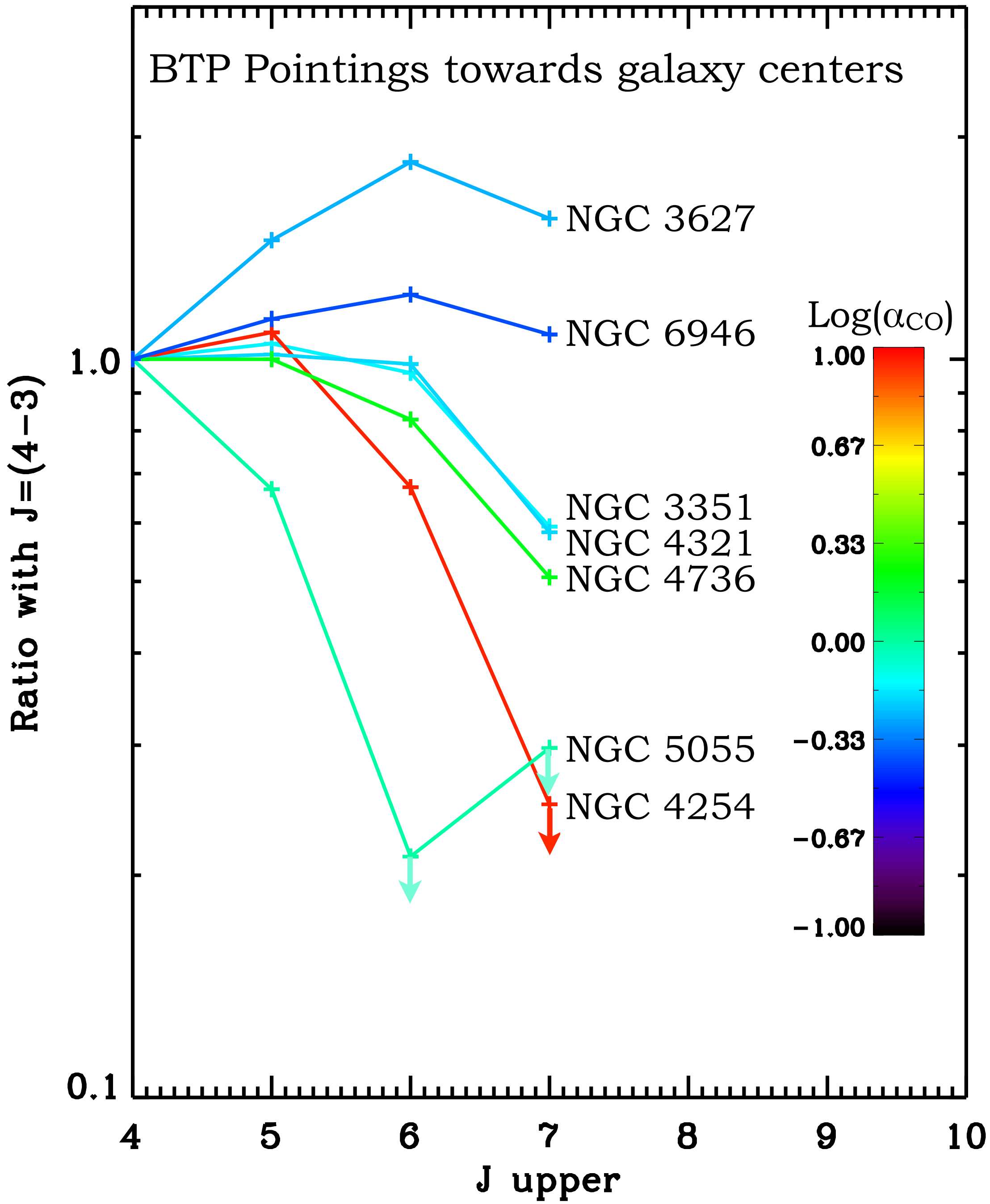
Some evidence for changes in gas temperature...

Survey of 22 galaxies with
Herschel SPIRE-FTS
(200-600 μm spectroscopy)
PI J.D. Smith



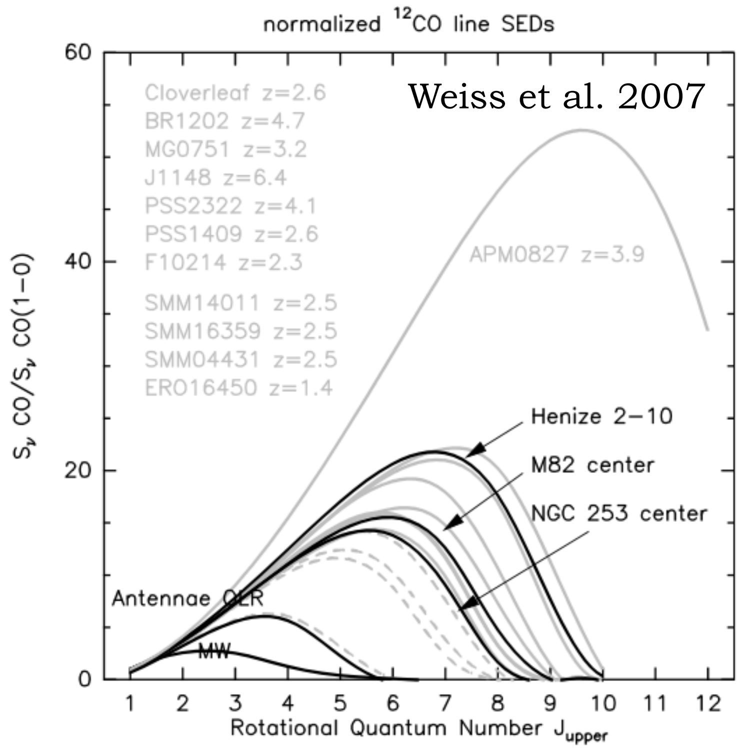






Evidence for enhanced CO excitation in centers with low α_{CO} from BTP.

Many galaxy centers peak at J~6, similar to M82.

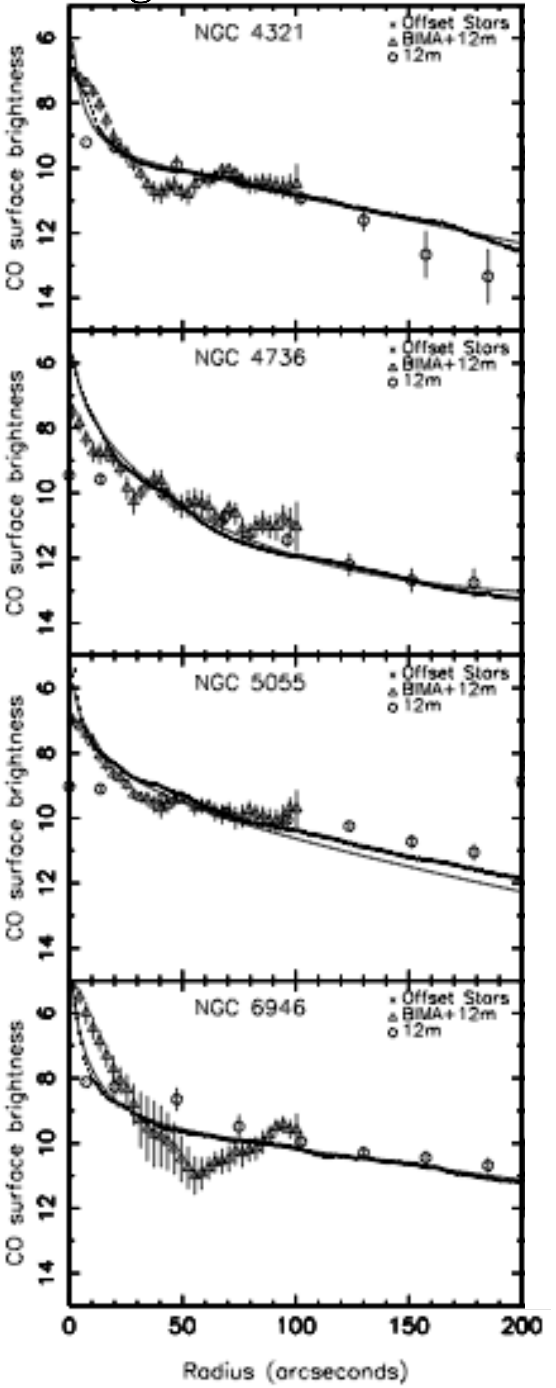


Why do some galaxies have low central α_{CO}?

Evidence for changes in both excitation and optical depth.

Observations of multiple molecular gas lines at high angular resolution needed to understand cause.

Regan et al. 2001



Implications of α_{CO} variations for the radial profile of molecular gas?

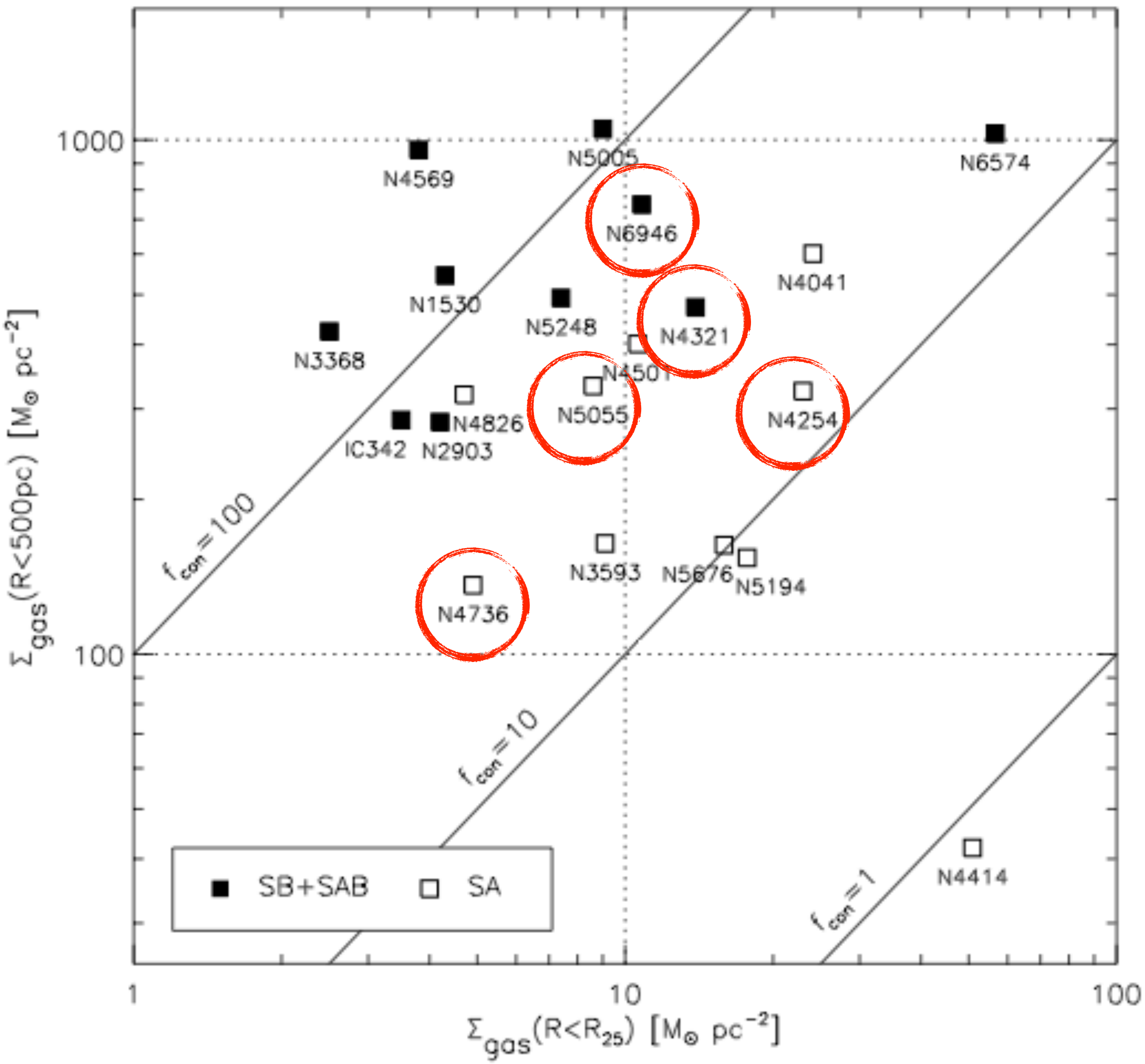
Some galaxies have central excesses of CO emission over the exponential disk.

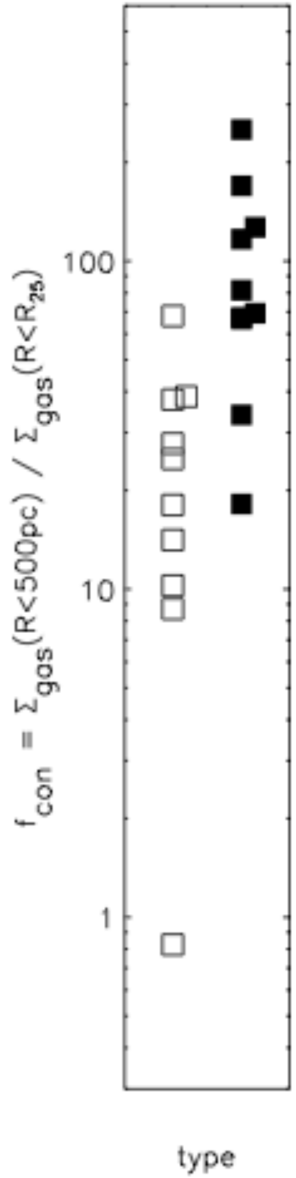
Often attributed to pile-up of gas funnelled into the center by a bar.
(e.g. Sakamoto et al. 1999, Regan et al. 2001, Sheth et al. 2005)

TABLE 4
STELLAR AND CO PROFILE PARAMETERS

Galaxy	Stellar Scale Length (kpc)	CO Scale Length (kpc)	Central Excess?
NGC 0628...	3.4 ± 0.01	5.8 ± 0.2	No
NGC 3351...	2.4 ± 0.02	2.6 ± 0.3	Yes
NGC 3627...	3.5 ± 0.02	1.8 ± 0.6	Yes
NGC 4321...	5.6 ± 0.04	2.8 ± 0.3	Yes
NGC 4736...	0.7 ± 0.01	1.0 ± 0.1	Yes
NGC 5055...	2.2 ± 0.01	2.6 ± 0.1	Yes
NGC 6946...	2.9 ± 0.02	2.1 ± 0.3	Yes

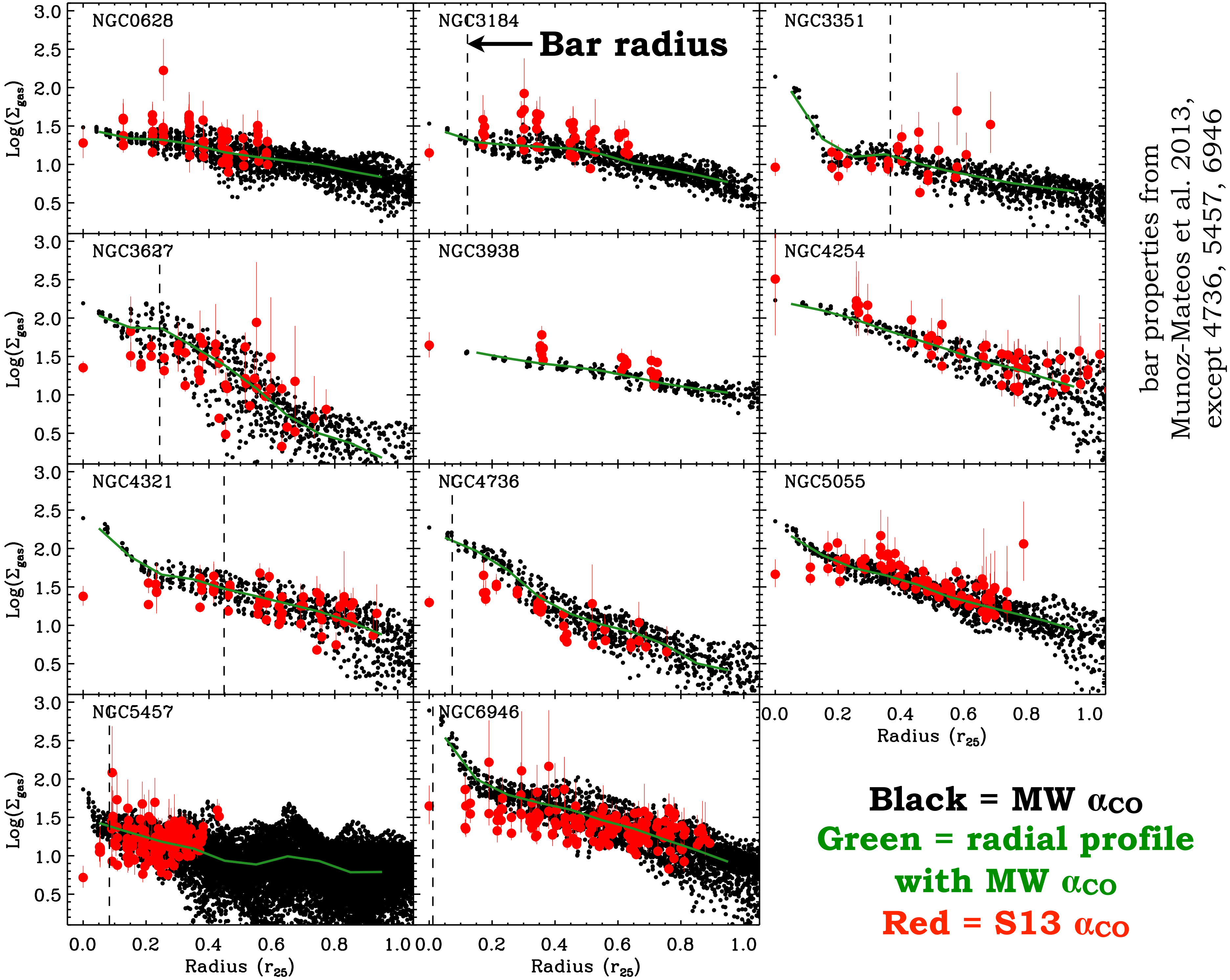
One-to-one correspondence between "excess" and low α_{CO}.



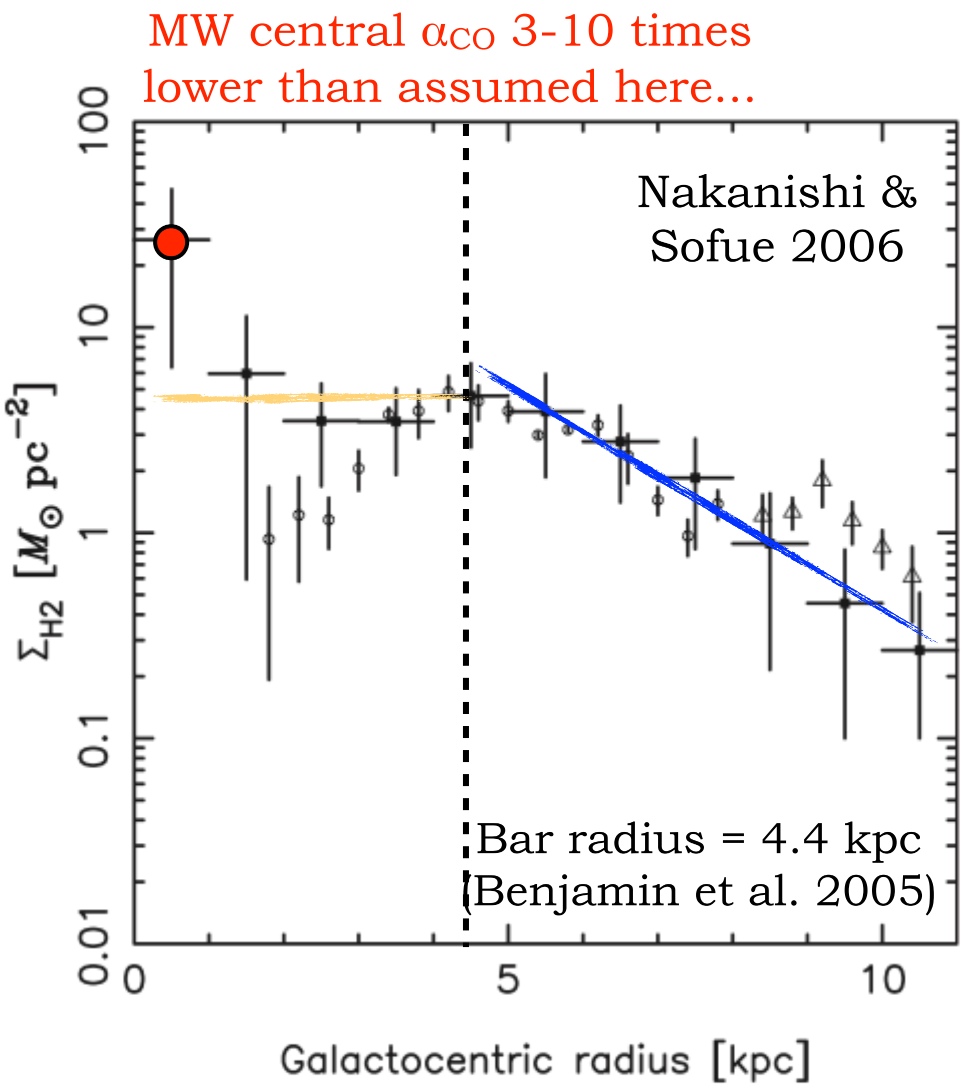


Sakamoto et al. 1999

Barred galaxies have higher central concentrations of gas.

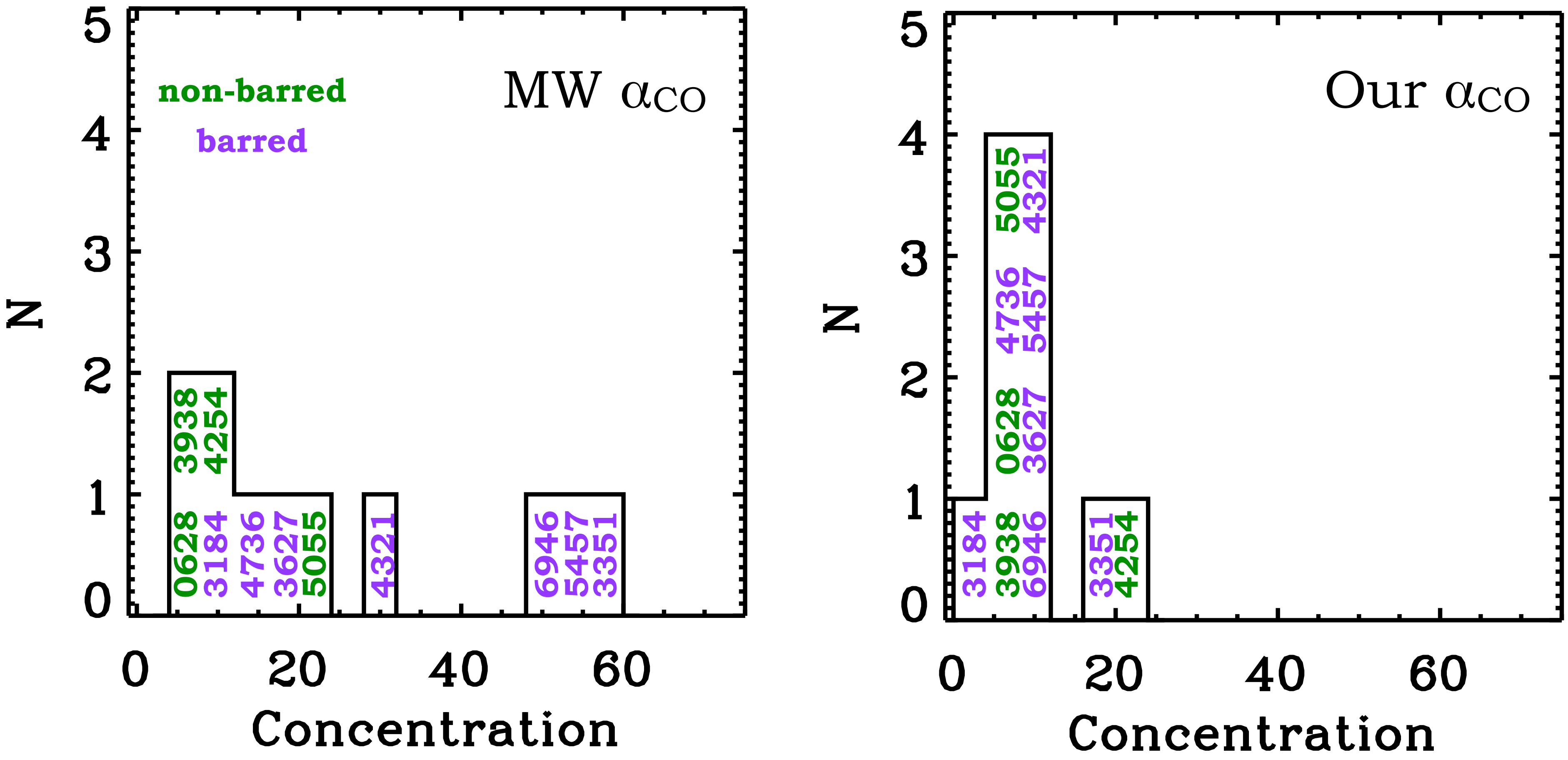

NGC0628
NGC3184
Bar radius
NGC3351
NGC3627
NGC3938
NGC4254
NGC4321
NGC4736
NGC5055
NGC5457
NGC6946
Log(Σgas)
Radius (r25)
bar properties from
Munoz-Mateos et al. 2013,
except 4736, 5457, 6946
Black = MW αCO
Green = radial profile
with MW αCO
Red = S13 αCO

Comparison to the Milky Way



In many of our target galaxies, gas radial profile flattens interior to the bar radius.

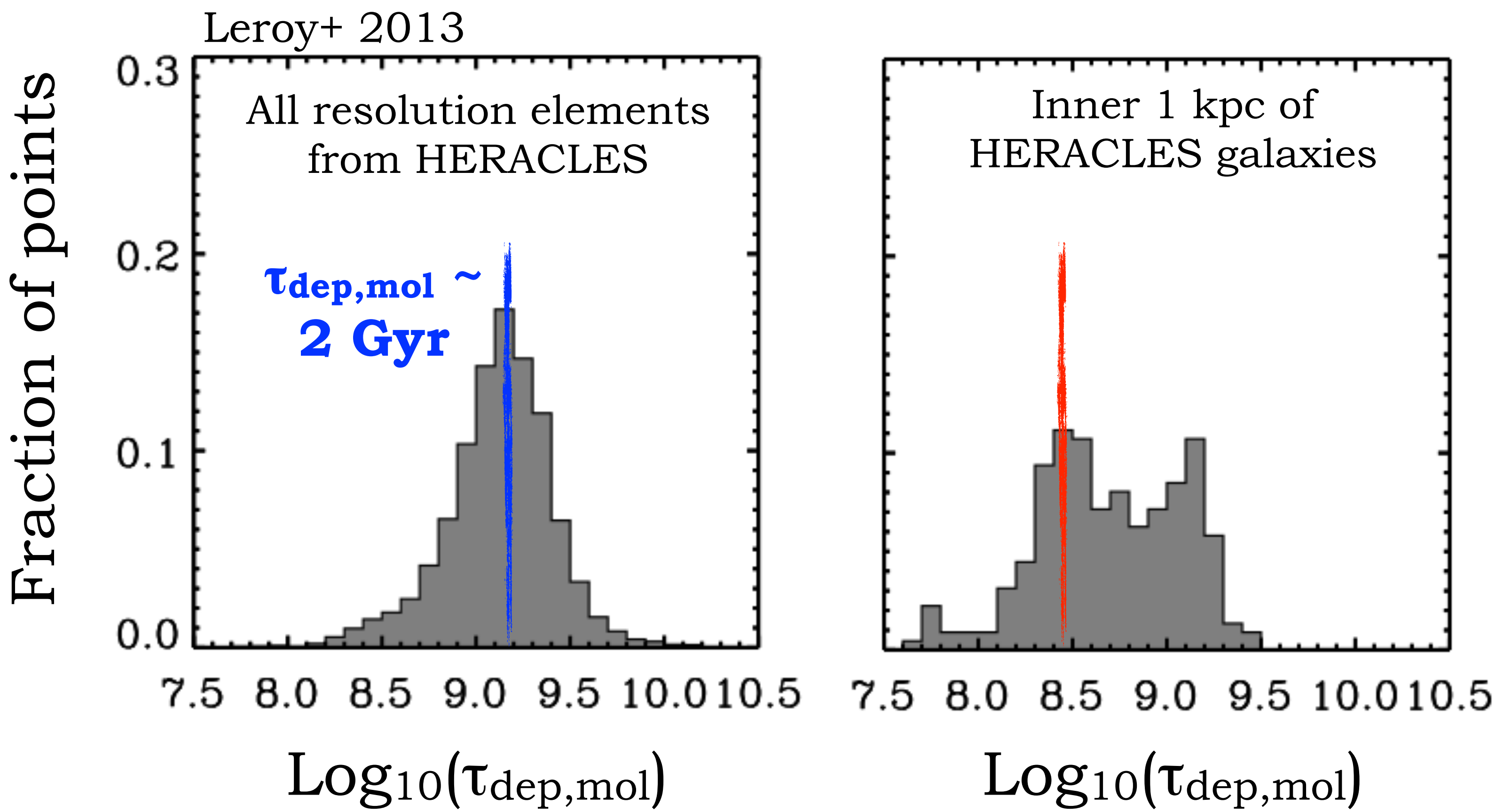
This also happens in the Milky Way, when proper central α_{CO} is used.



$$\text{Concentration} = \Sigma_{gas(<500pc)} / \Sigma_{gas(<r25)}$$

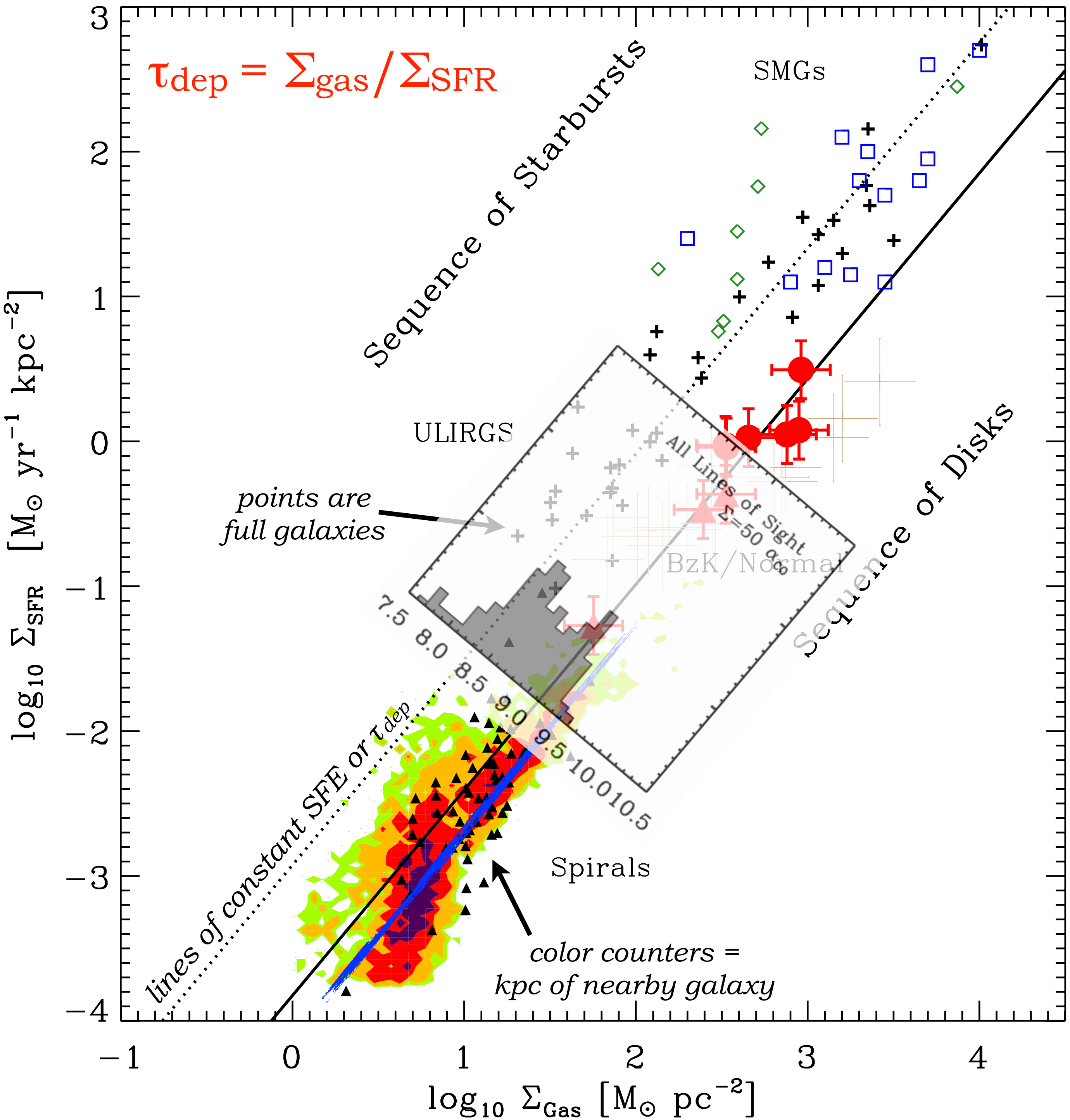
After applying our α_{CO}, barred & non-barred galaxies have similar concentrations.

Implications of α_{CO} variations for the SF relationship?



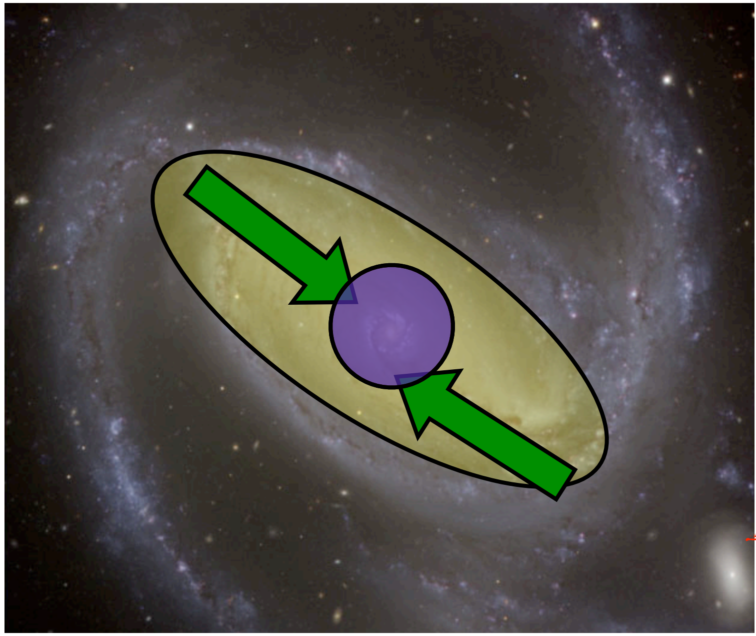
Inner kpc of some nearby galaxies has higher SF efficiency than the rest of the disk.

Daddi et al. 2010



When we use the correct α_{CO}, the centers of some nearby galaxies have τ_{dep} similar to starbursts.

A slight revision to the secular evolution scenario...



Stellar Bar

Drives gas inflow

~~*Gas concentration builds in center*~~

Star formation & pseudobulge growth

Efficient

Basic picture is the same, but instead of gas building up in the center, have more efficient SF.

Conclusions & Summary

- Low α_{CO} in some, but not all, galaxy centers.
- Why? Possibilities include:
  - warmer molecular gas
  - diffuse molecular gas contribution
  - enhanced velocity dispersion in clouds
- Implications for our galaxies: flat Σ_{gas} profile interior to bar, no "excess" of gas in center, higher SFE.
- As for ULIRGs, low α_{CO} and high SFE go hand-in-hand, need to understand why & how to disentangle them.