Measurements of the CO-to-H_2 Conversion Factor and Dust-to-Gas Ratio in Nearby Galaxies

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Collaborators: Adam Leroy, Fabian Walter,
KINGFISH team, HERACLES team

Galactic Scale Star Formation
Heidelberg - August 1, 2012

Measuring the CO-to-H_2 Conversion Factor.

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

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

↕

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

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

To measure α_{CO}:

1. observe CO
2. use another tracer to get total amount of molecular gas
3. compare with observed CO

Other ways to trace the total amount of molecular gas:

Dynamics (i.e. virial masses)

γ-rays

Modeling Line Emission

Dust

Other ways to trace the total amount of molecular gas:

Dynamics
(i.e. virial masses)

ɣ-rays

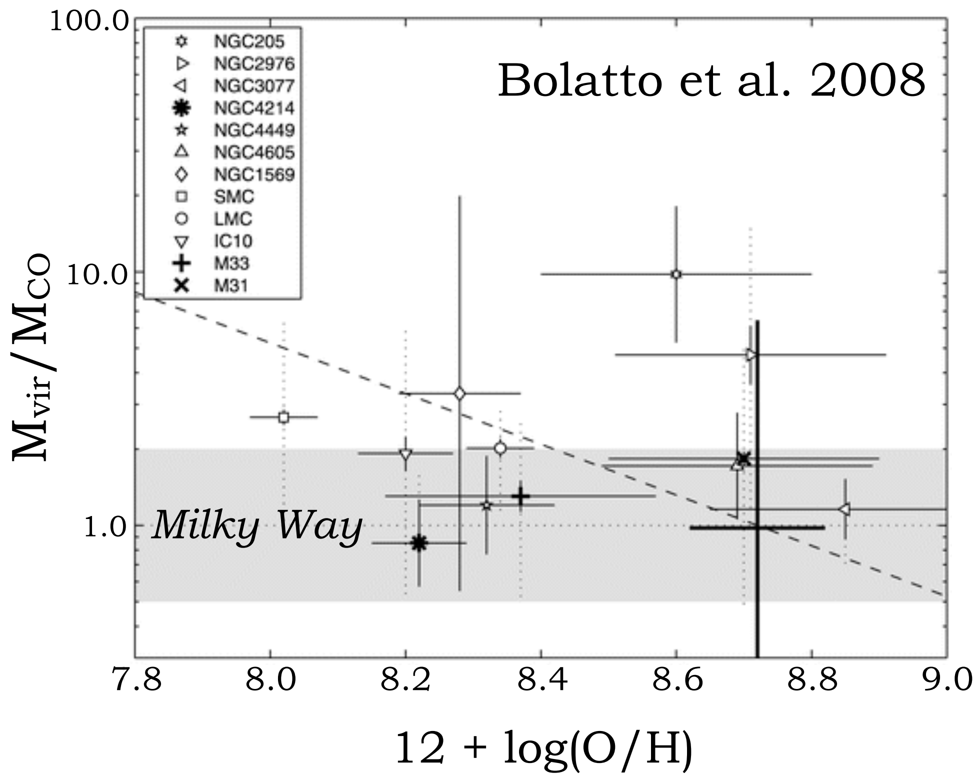
Modeling Line Emission

Dust

Necessary assumptions:
molecular cloud is virialized,
no CO-free layer of H_2

Need to resolve GMCs.
Hard to do outside the Local Group.

Previous results find little variation away from MW α_{CO}~4.35



GMCs in center of NGC 6946 have α_{CO} ~ $\alpha_{CO,MW}/2$
(Donovan Meyer et al. 2012)

Other ways to trace the total amount of molecular gas:

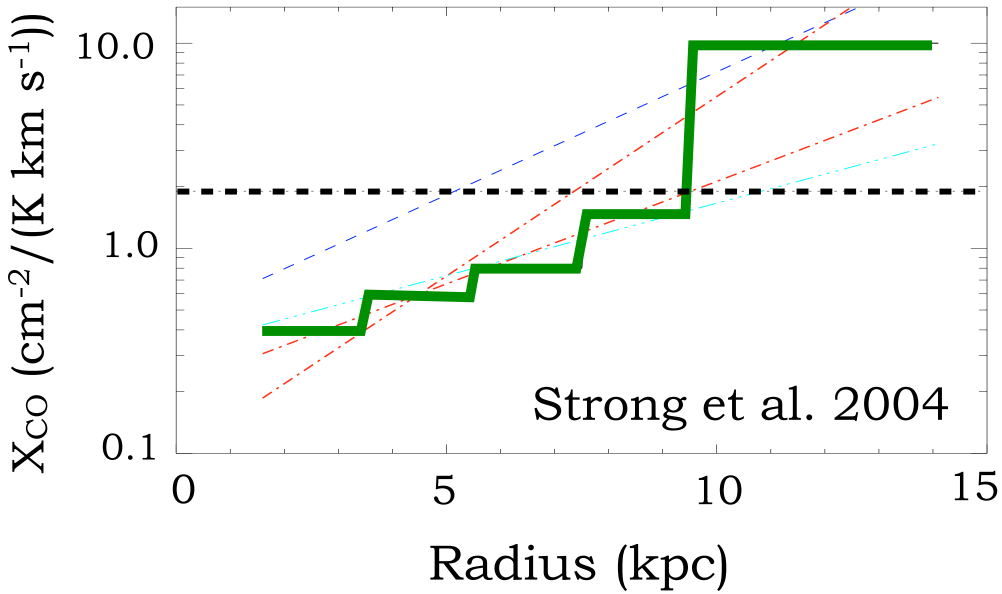
Dynamics **(i.e. virial masses)** | **γ-rays** | **Modeling Line Emission** | **Dust**

Necessary assumptions:
distribution of cosmic rays

Need to observe γ-rays.
Hard to do outside the Local Group.

Measure MW disk α_{CO}~4.35,
MW center α_{CO} 5× lower.

MW X_{CO} radial gradient from γ-rays



Other ways to trace the total amount of molecular gas:

Dynamics
(i.e. virial masses)

γ-rays

Modeling Line Emission

Dust

Necessary assumptions:
number of different gas components, velocity/density structure of cloud, etc.

Need to observe multiple molecular gas lines.

Measure galaxy center α_{CO} 5-10× lower than MW.

(e.g. Israel 2009a,b)

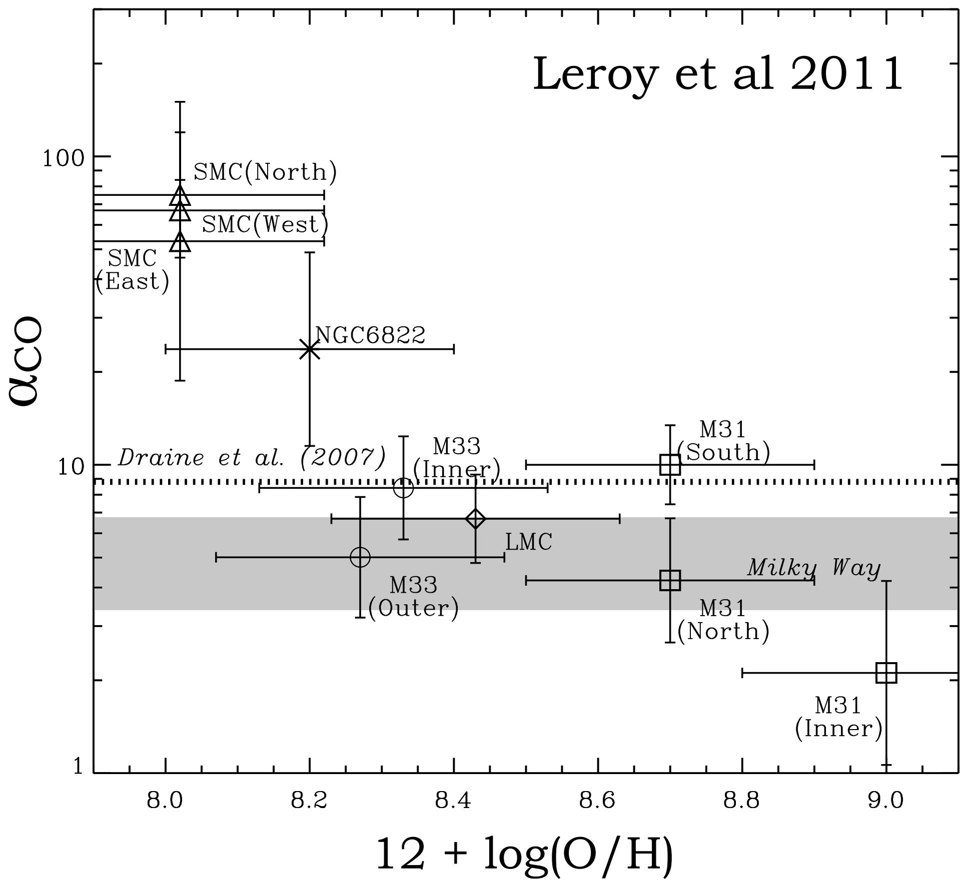
Other ways to trace the total amount of molecular gas:

Dynamics
(i.e. virial masses)

γ-rays

Modeling Line Emission

Dust



Necessary assumptions:
dust & gas are well mixed,
DGR & emissivity don't change with atomic/molecular phase

Need to observe dust mass tracer (typically far-IR + SED modeling).

Widely applied with various techniques...

Measuring the Conversion Factor with Dust.

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

unknown *observable*

- Fix DGR based on some model or expected DGR.
- Fix DGR based on nearby HI-only line-of-sight.
- ***Solve for both DGR & α_{CO} using spatially resolved measurements.***

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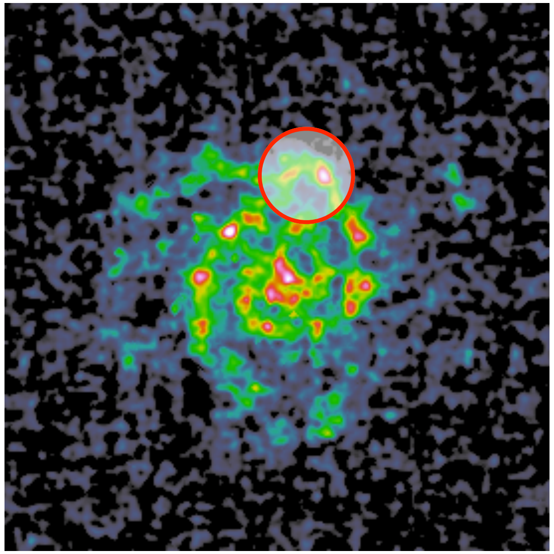
Assumption: DGR constant on kpc scales.

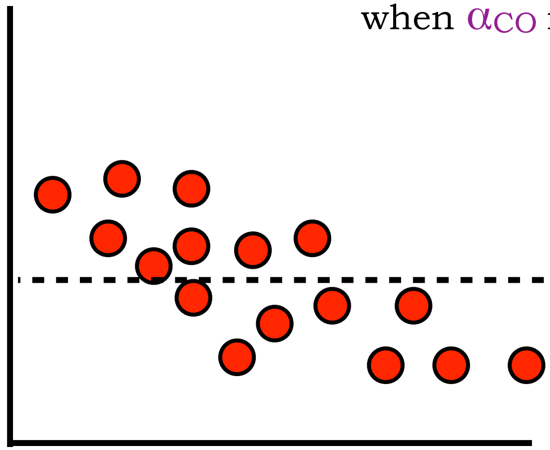
Our Technique:
Minimizing Scatter in DGR on kpc scales



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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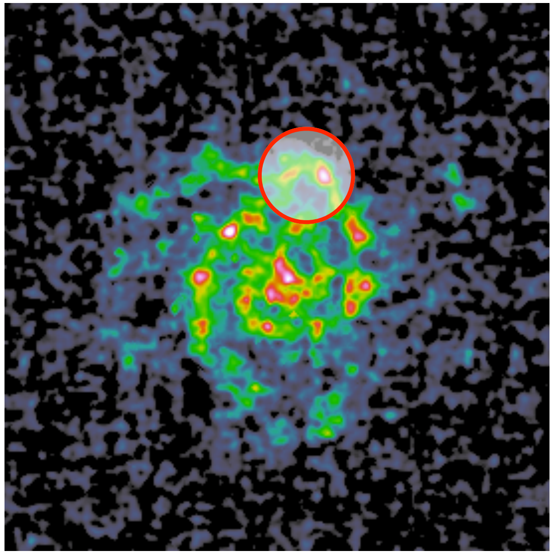

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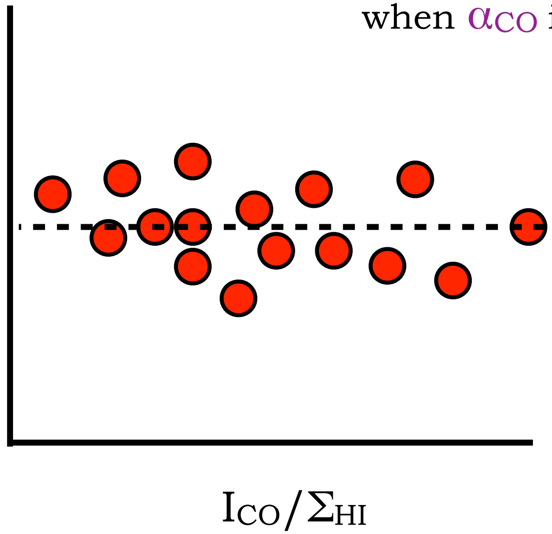

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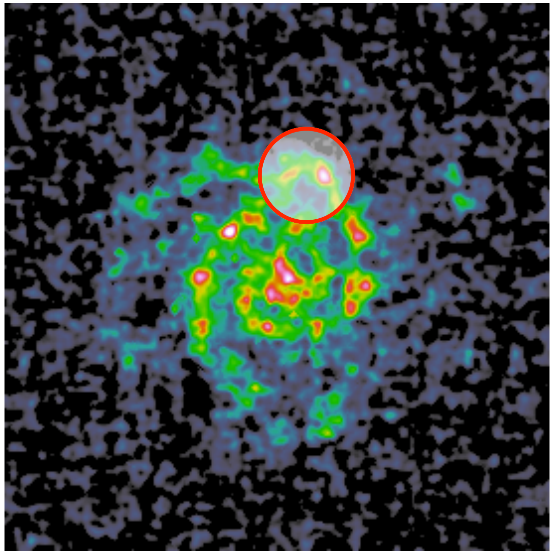

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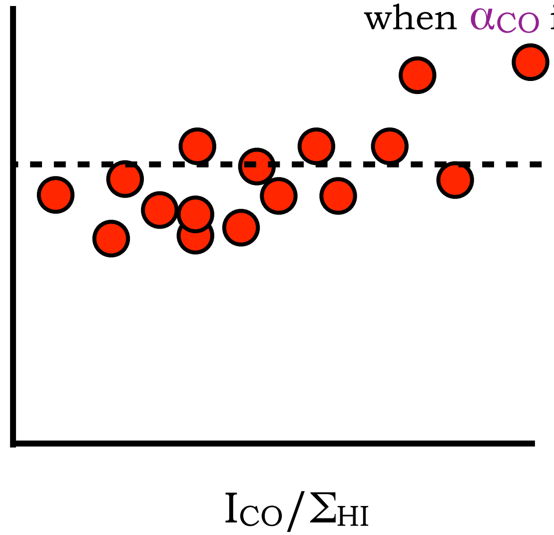

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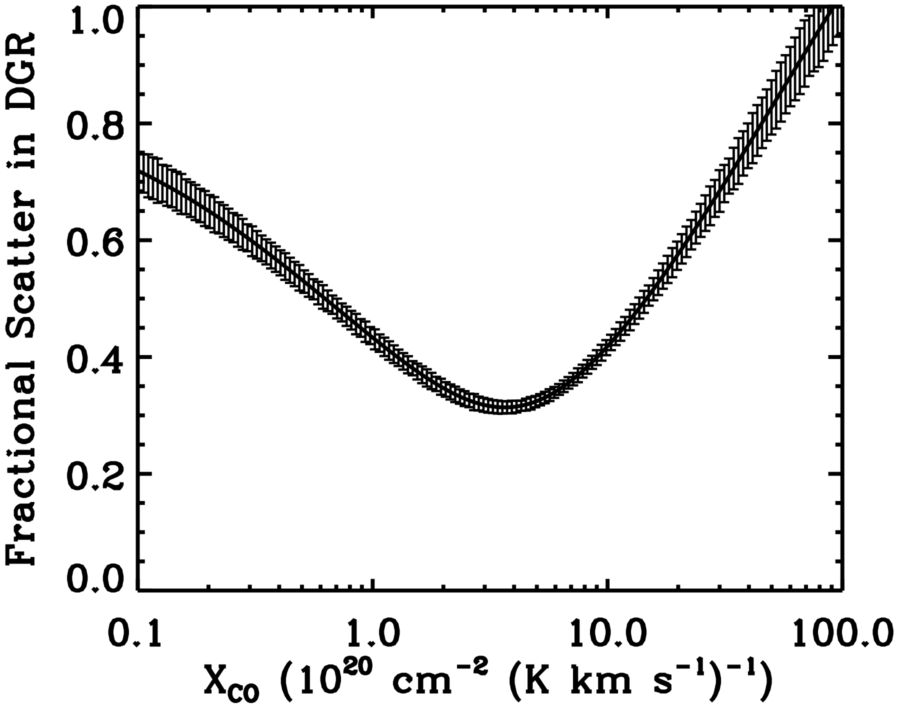
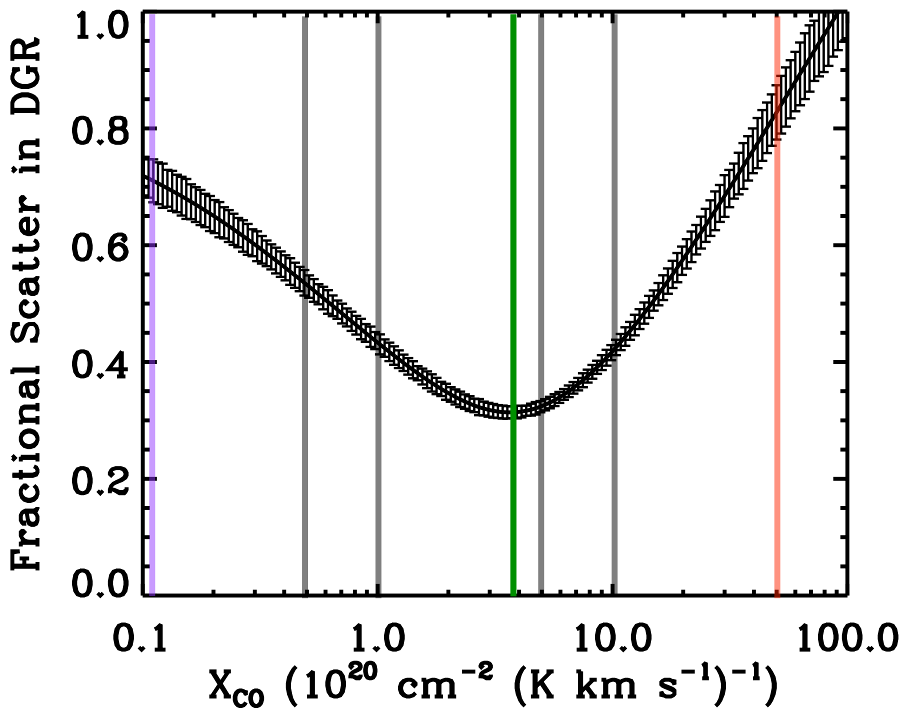
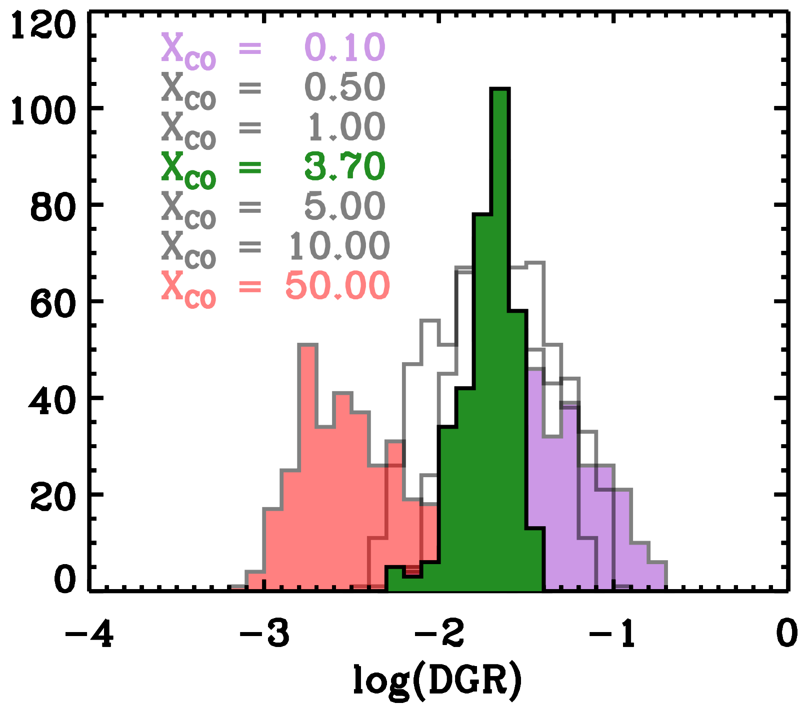
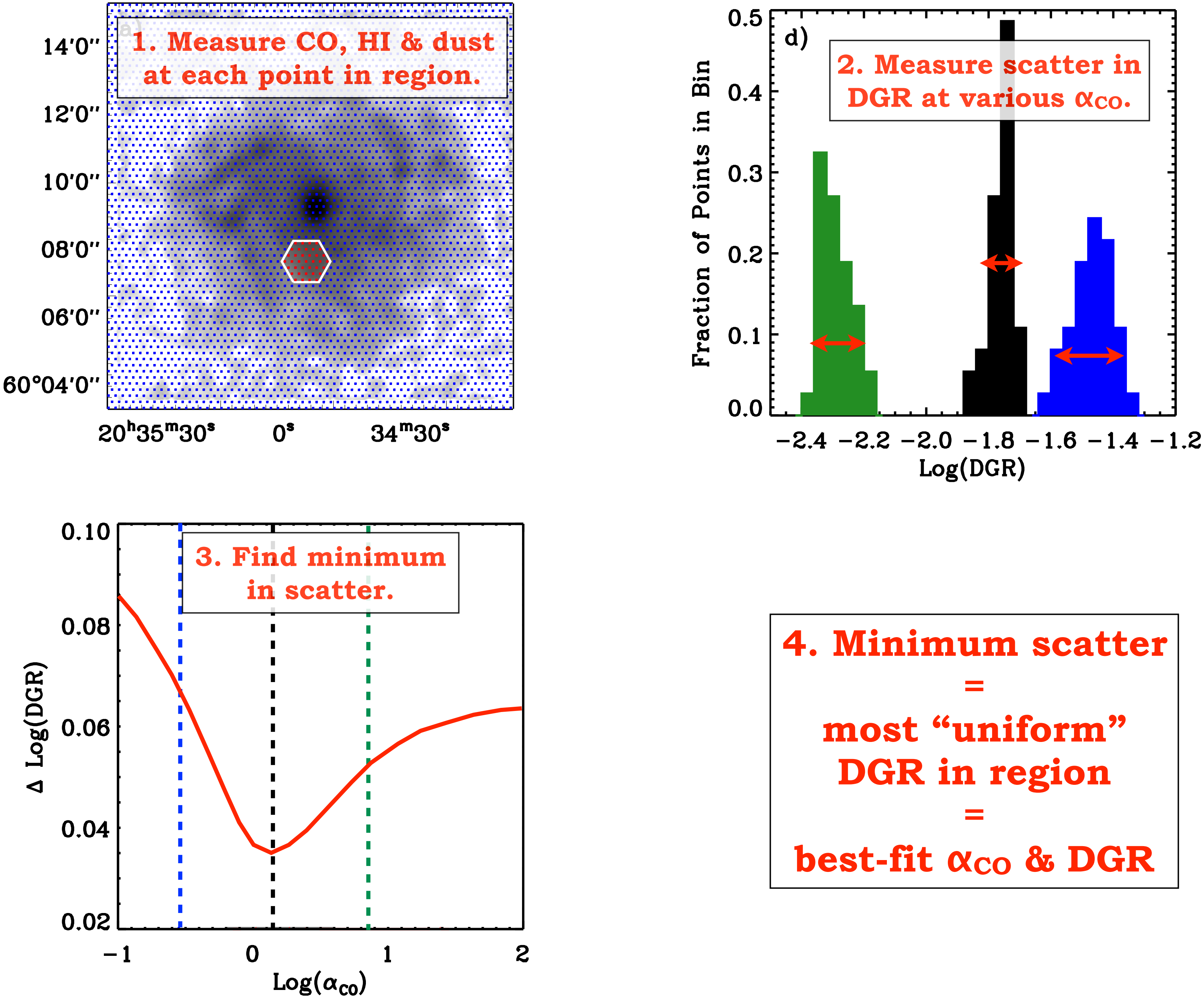
Example of the Technique



Example of the Technique







1. Measure CO, HI & dust at each point in region.
14′0″
12′0″
10′0″
08′0″
06′0″
60°04′0″
20h35m30s
0s
34m30s
d)
2. Measure scatter in DGR at various αCO.
Fraction of Points in Bin
0.0
0.1
0.2
0.3
0.4
0.5
−2.4 −2.2 −2.0 −1.8 −1.6 −1.4 −1.2
Log(DGR)
3. Find minimum in scatter.
Δ Log(DGR)
0.02
0.04
0.06
0.08
0.10
−1
0
1
2
Log(αCO)
4. Minimum scatter
=
most "uniform" DGR in region
=
best-fit αCO & DGR

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

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

To get Σ_D: SED modeling from 3.6 - 350 μm (Aniano+ 2012)
(preserves SPIRE 350 μm's 25" resolution while still covering the peak of the dust SED)

The Observations

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

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

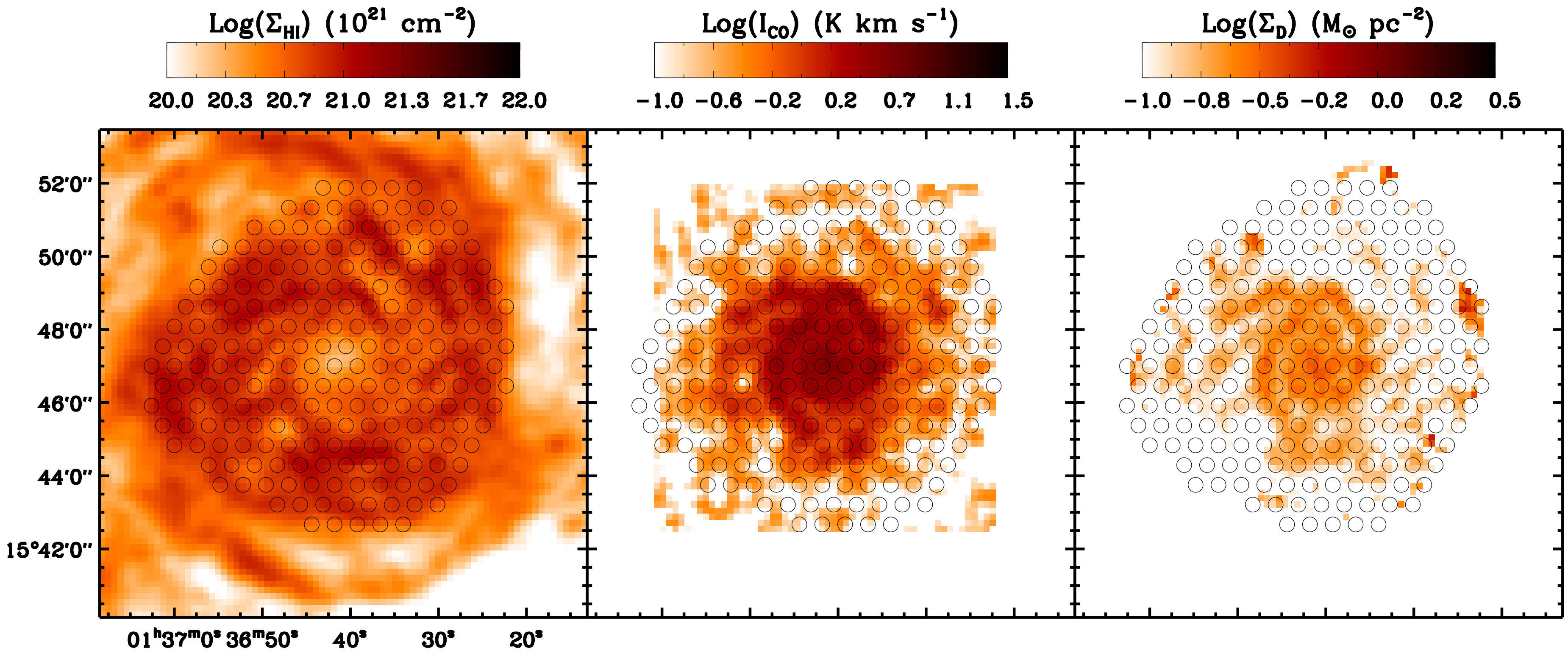
HERA CO-Line Emission Survey

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

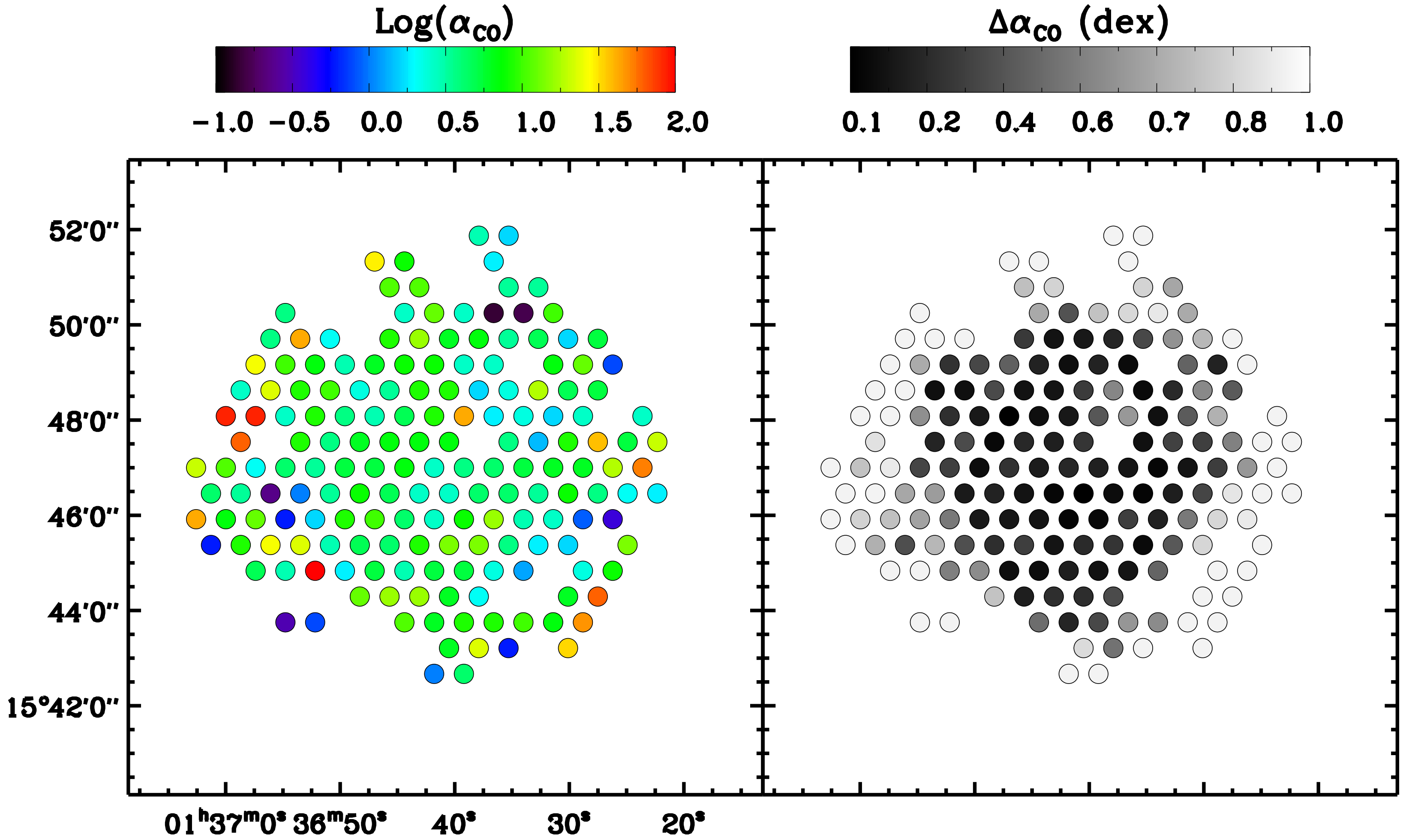
Resolution of ~13”

Assume (2-1)/(1-0) = 0.7 average for HERACLES sample
(Rosolowsky et al., in prep)

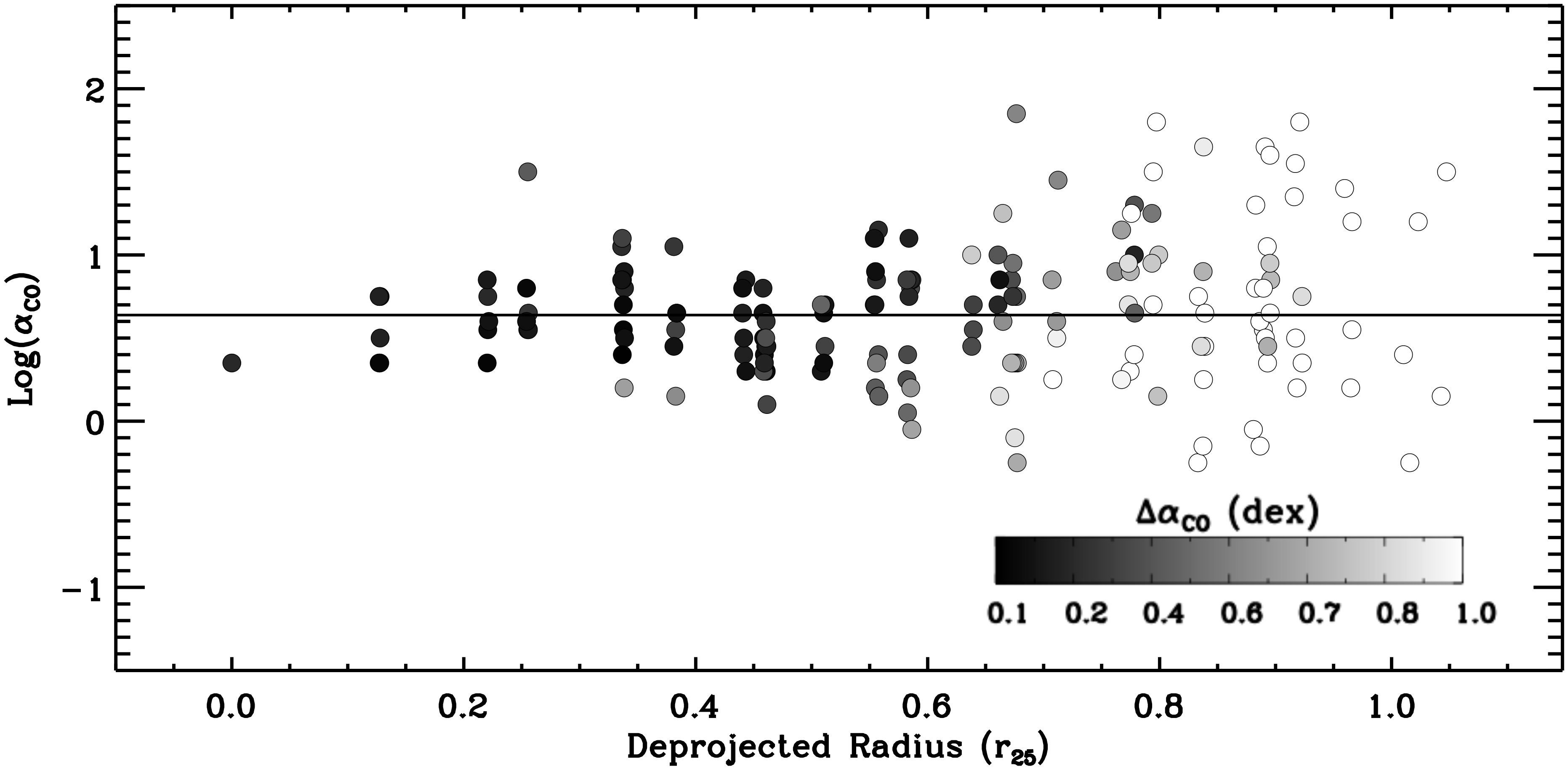
NGC0628 Results



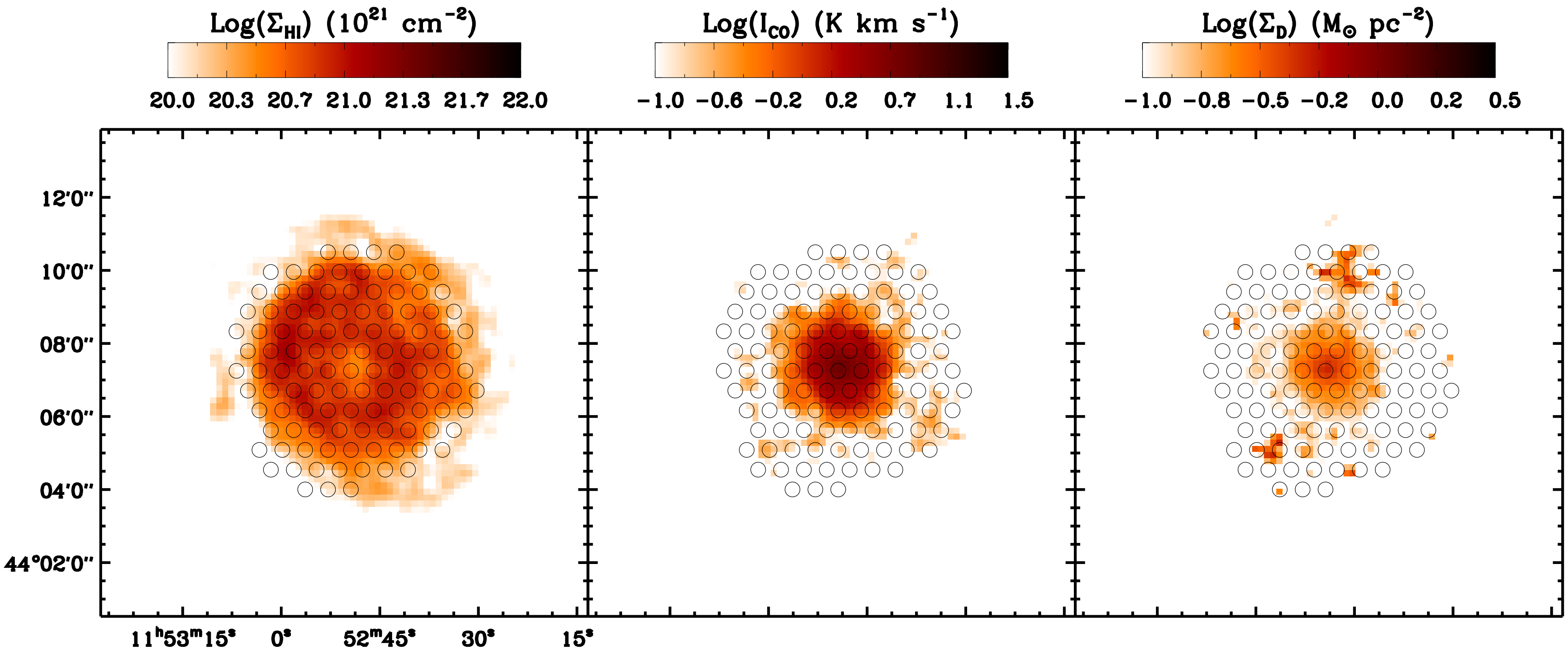
NGC0628 Results



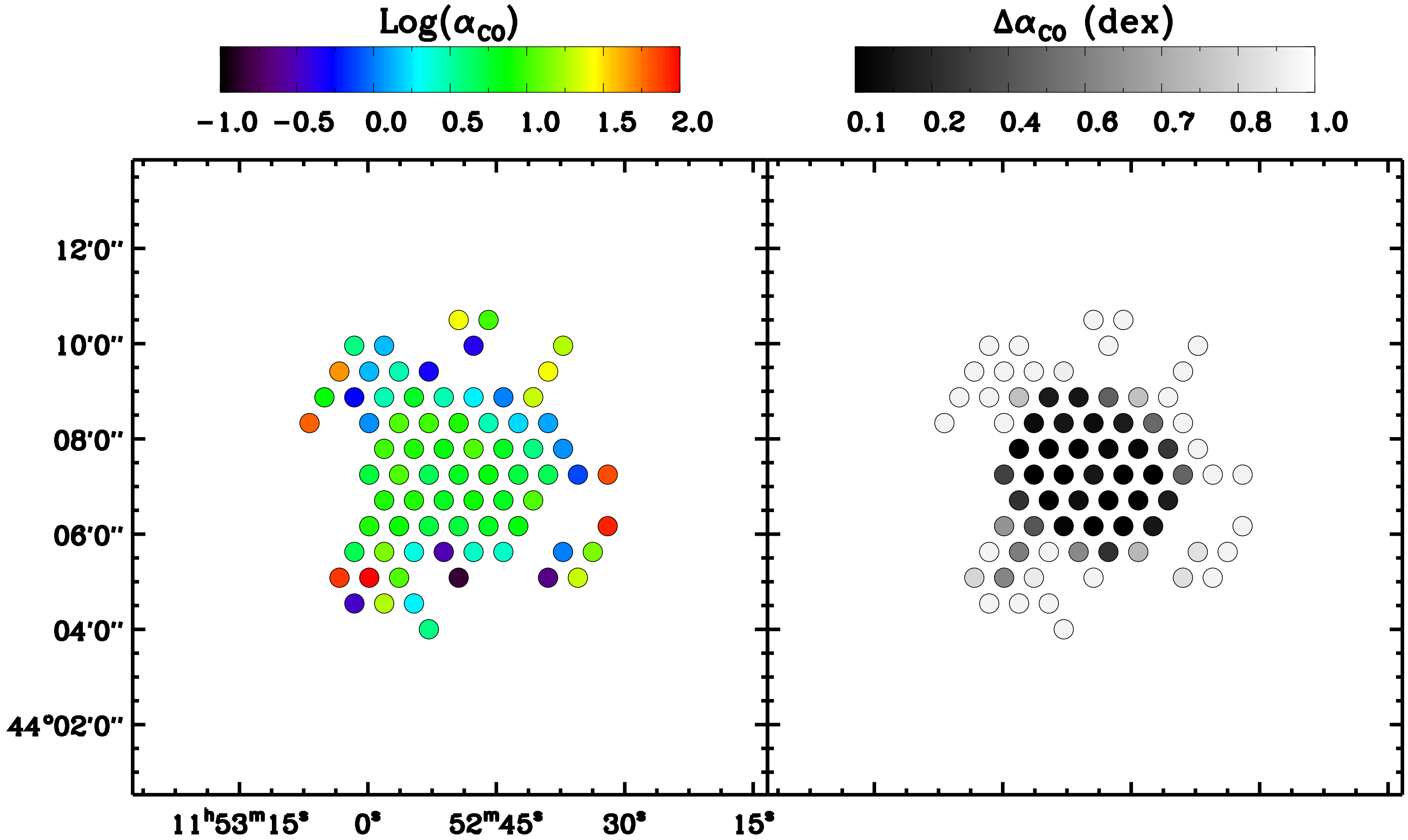
NGC0628 Results



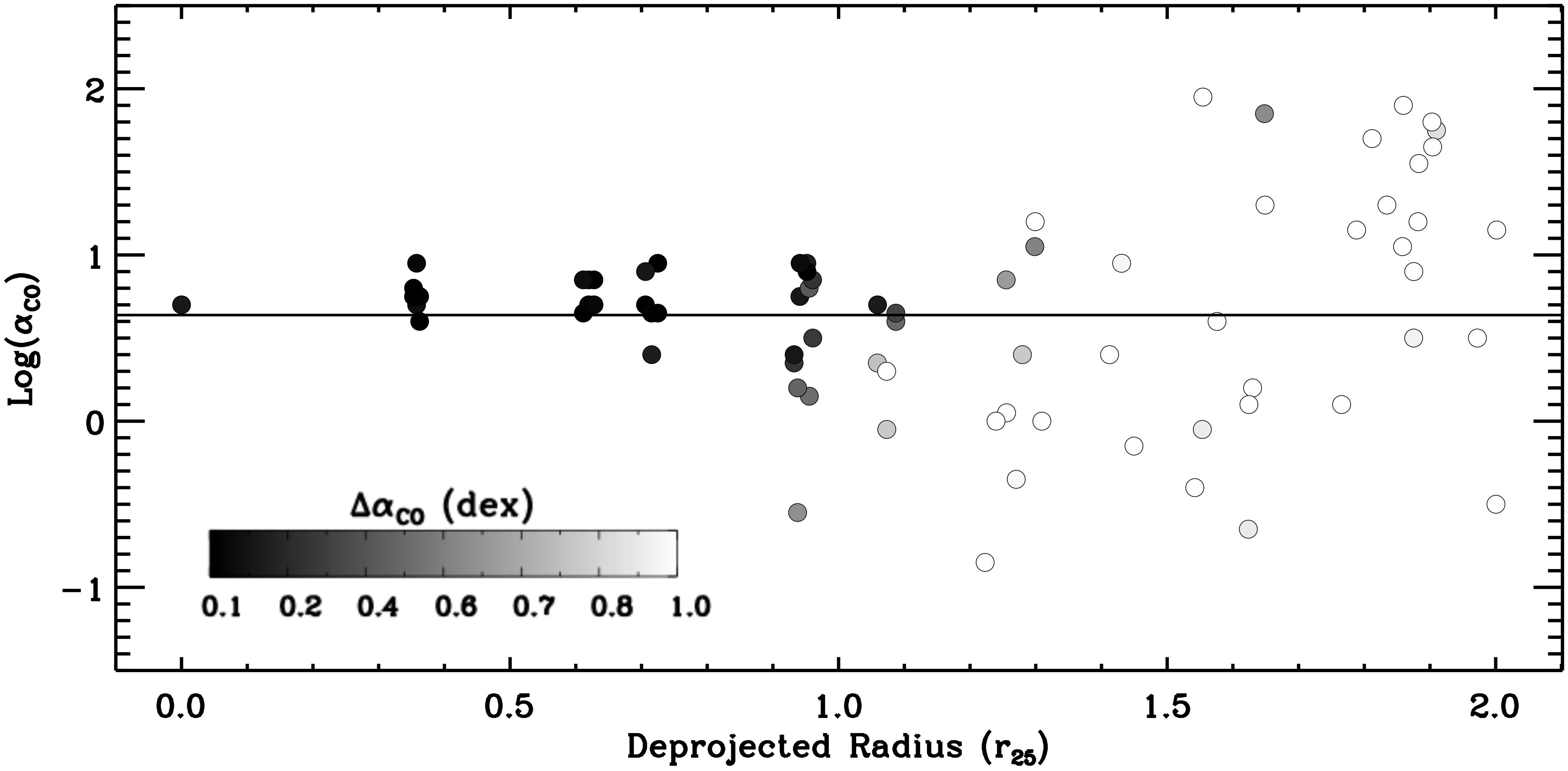
NGC3938 Results



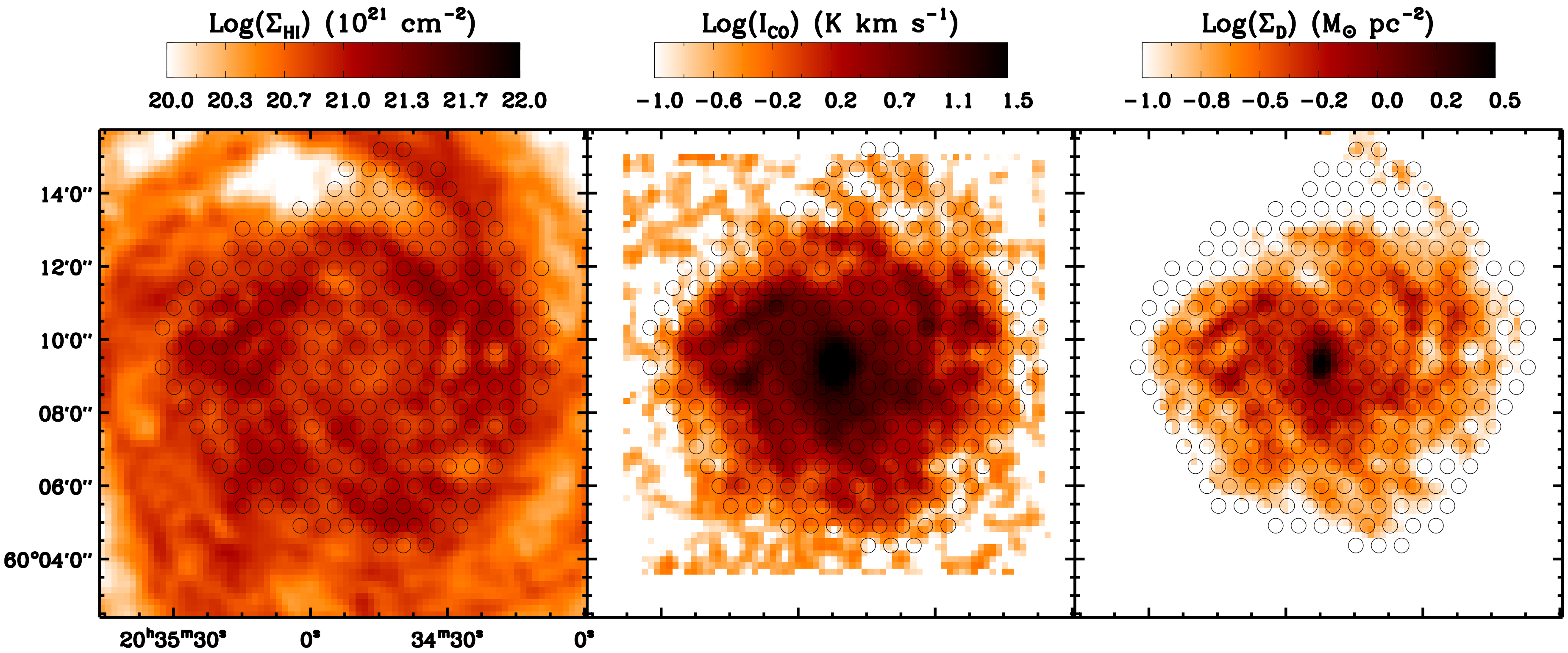
NGC3938 Results



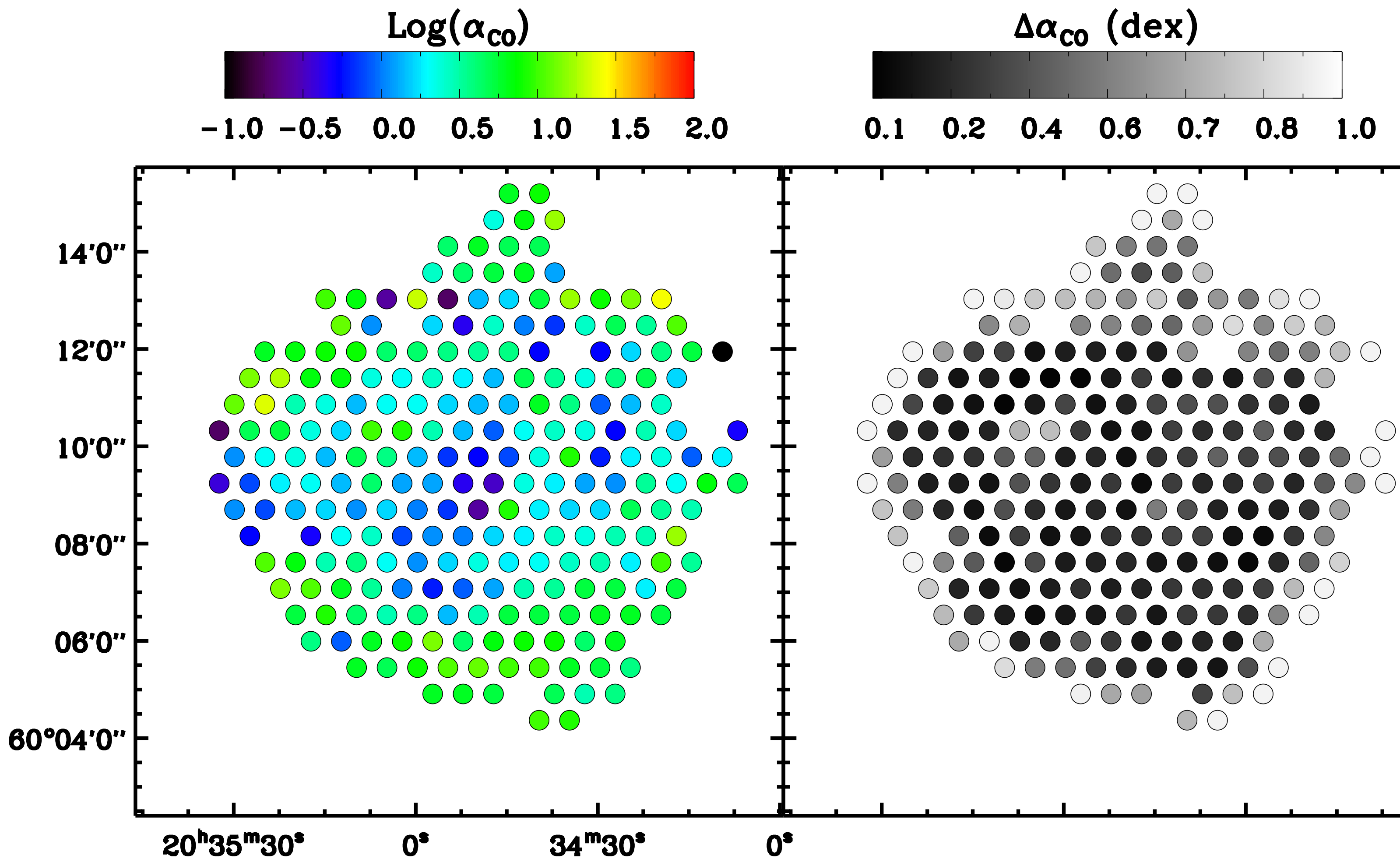
NGC3938 Results



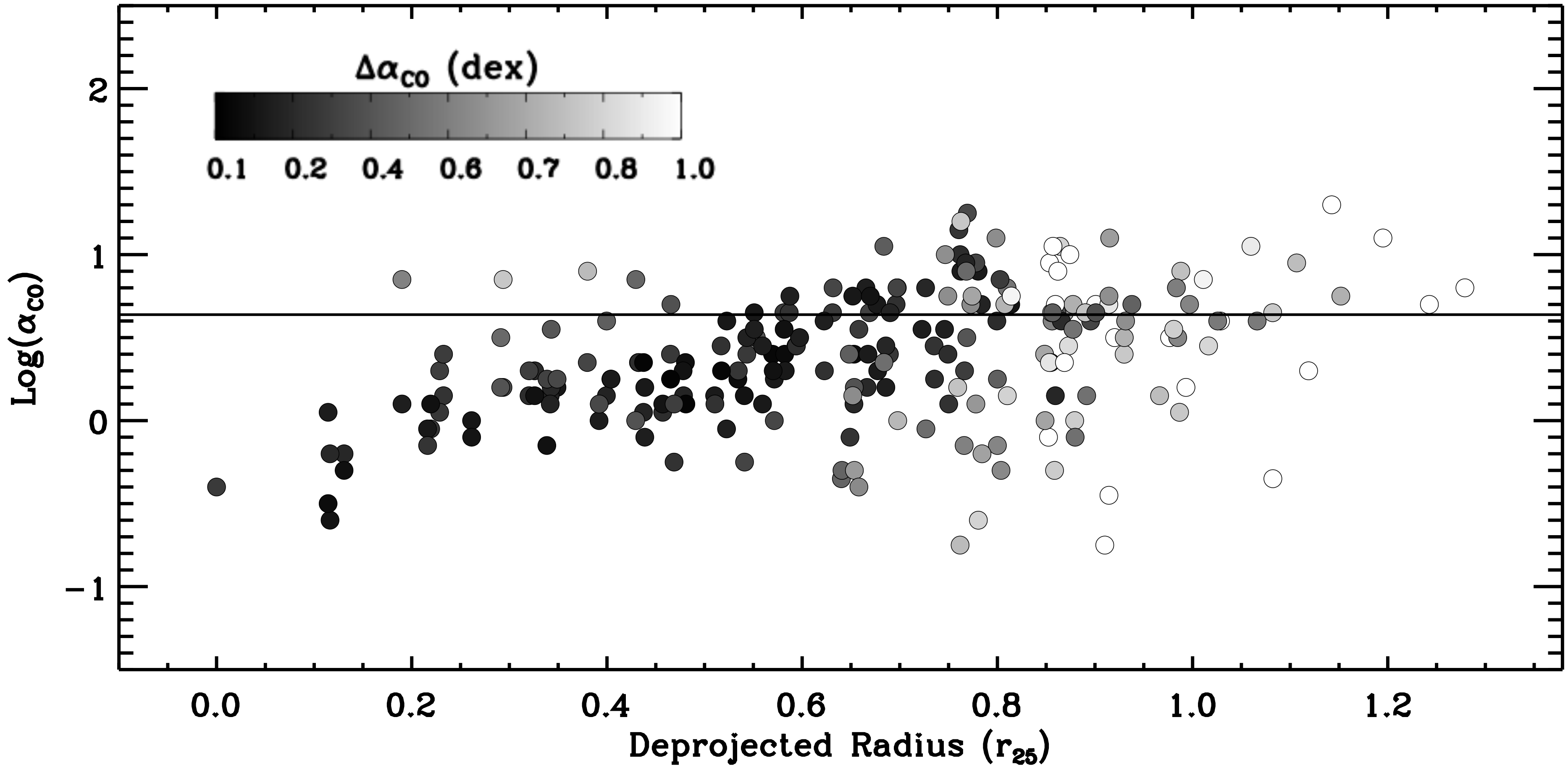
NGC6946 Results



NGC6946 Results



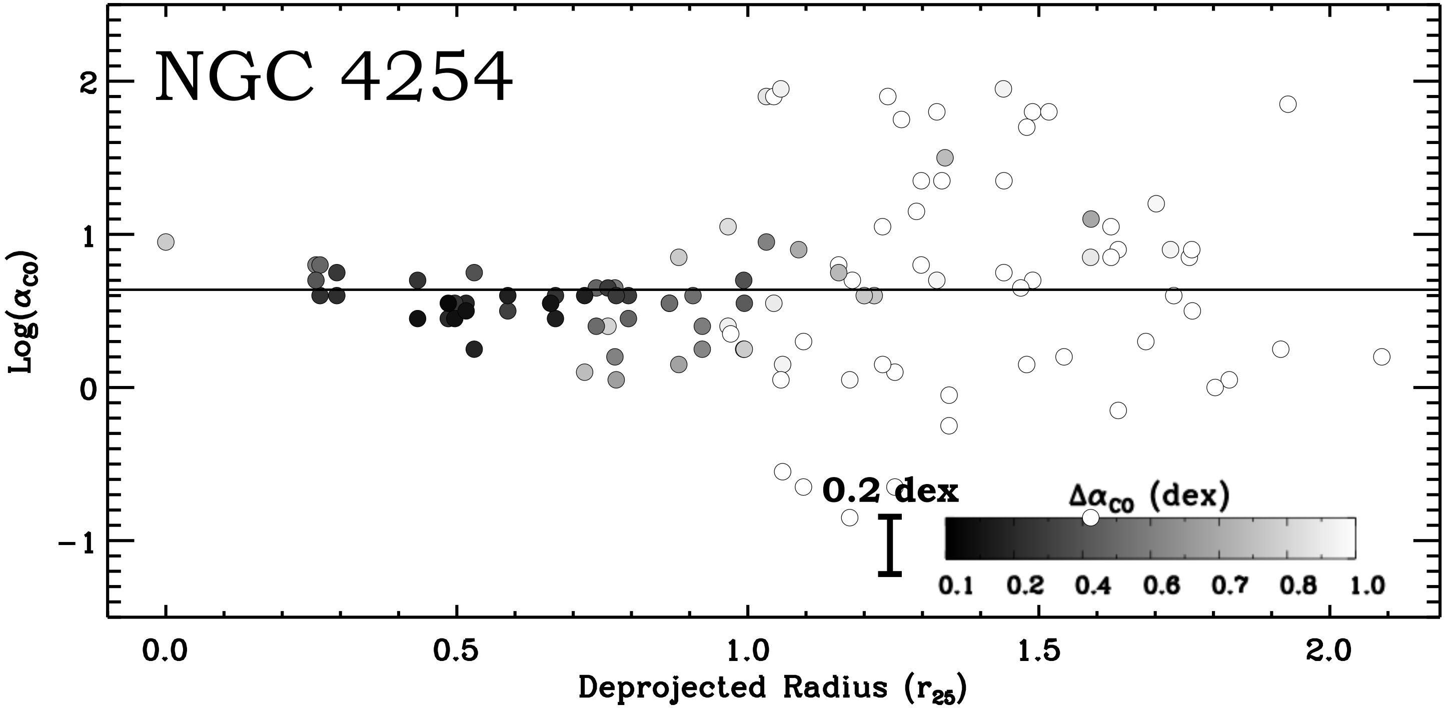
NGC6946 Results

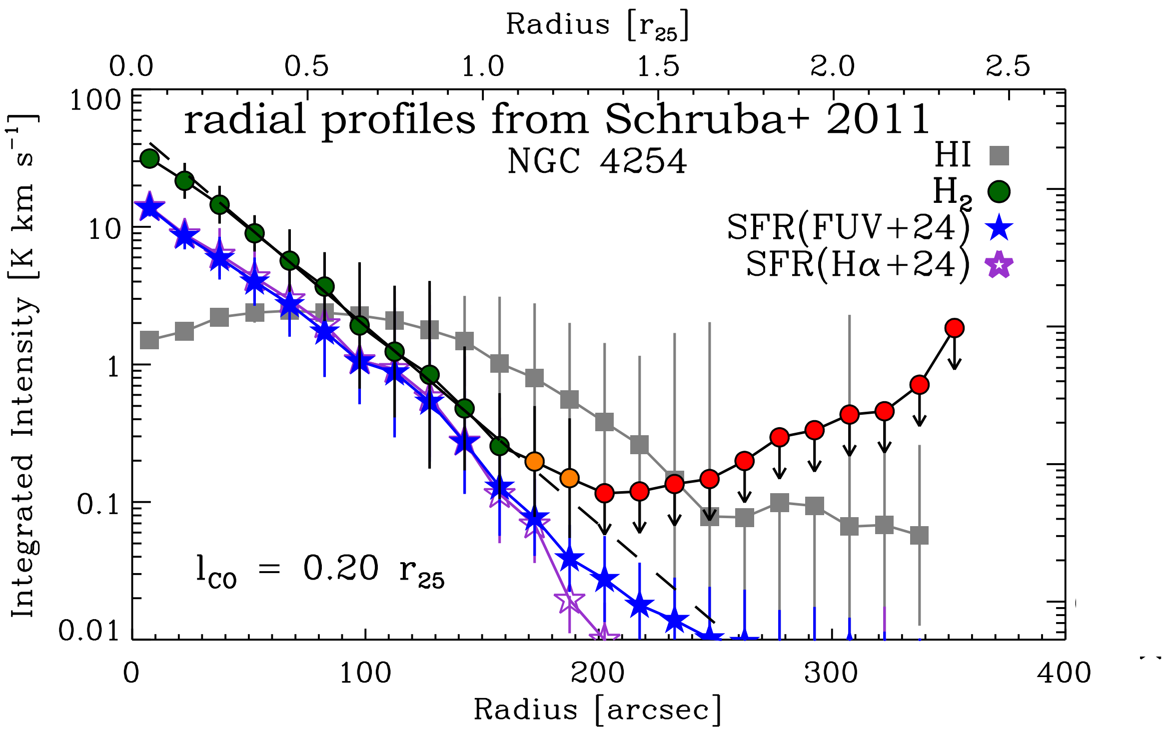


Variations we see in α_{CO}

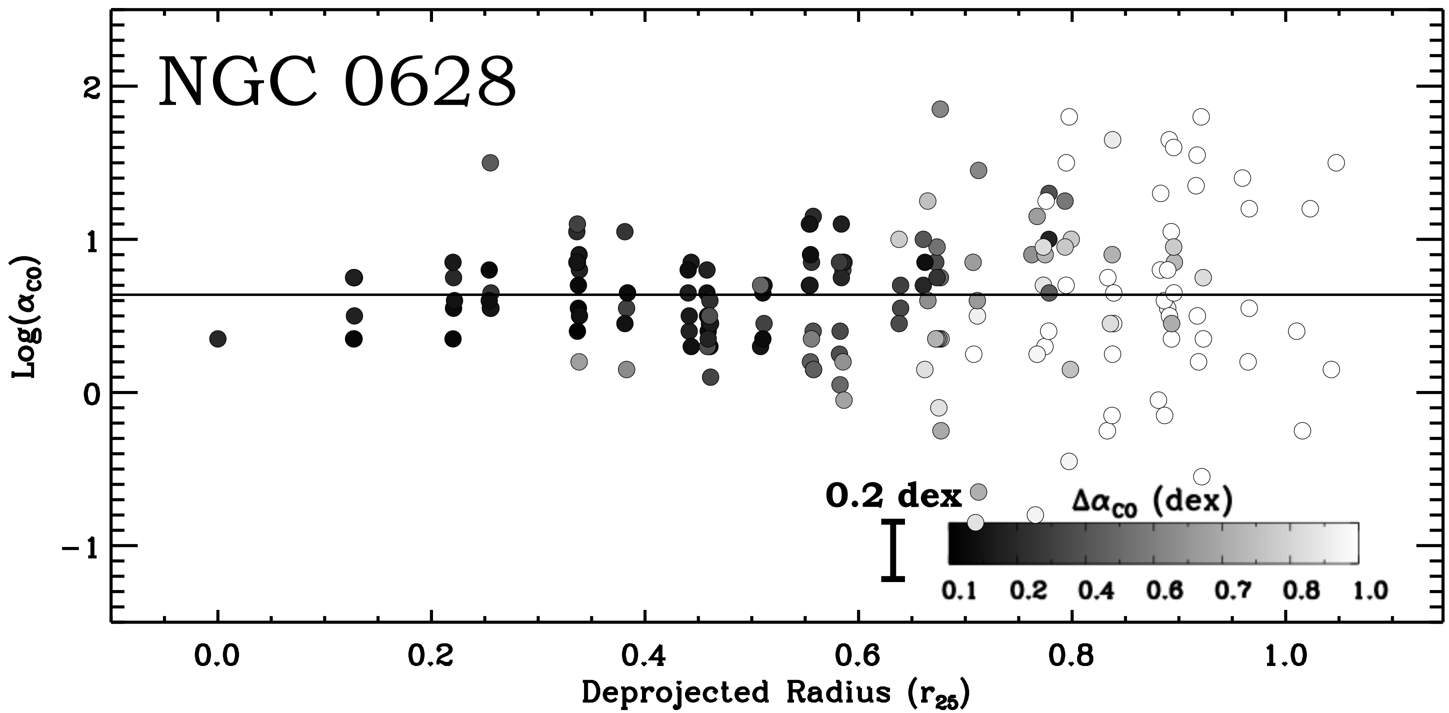
- MW α_{CO}, no trend with radius.
- Flat MW α_{CO} profile + central unresolved dip.
- Overall gradient in α_{CO} with radius.
- Low α_{CO} everywhere, no clear radial trend.

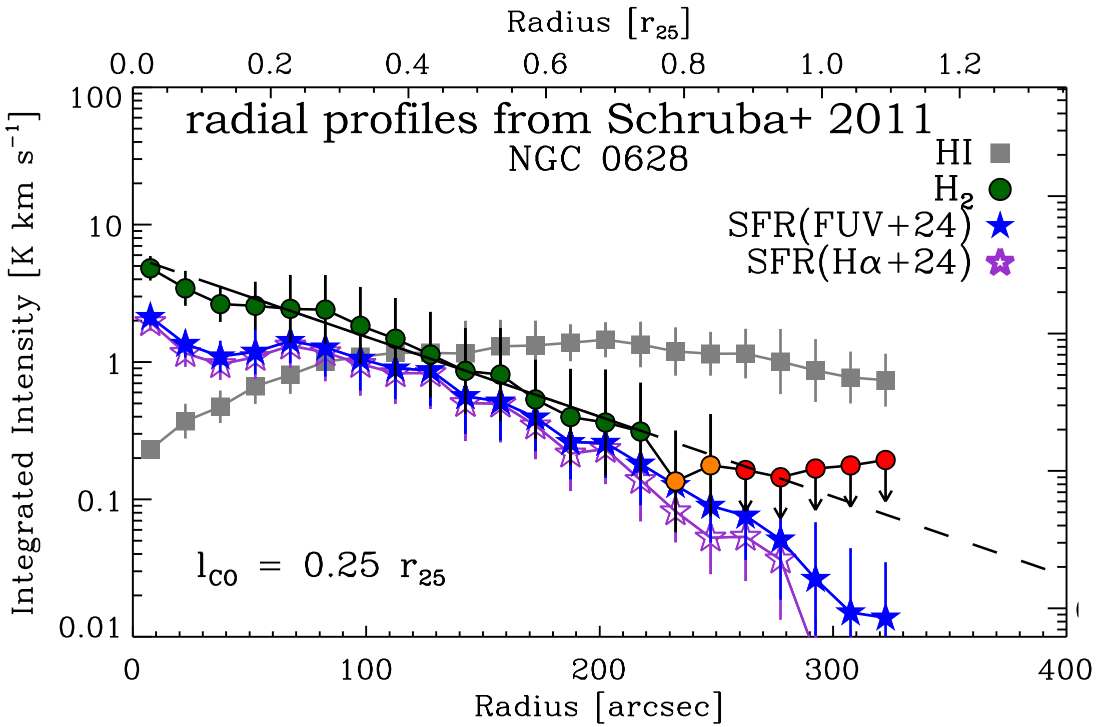
illustrated with a few examples of
~face-on, highly resolved galaxies

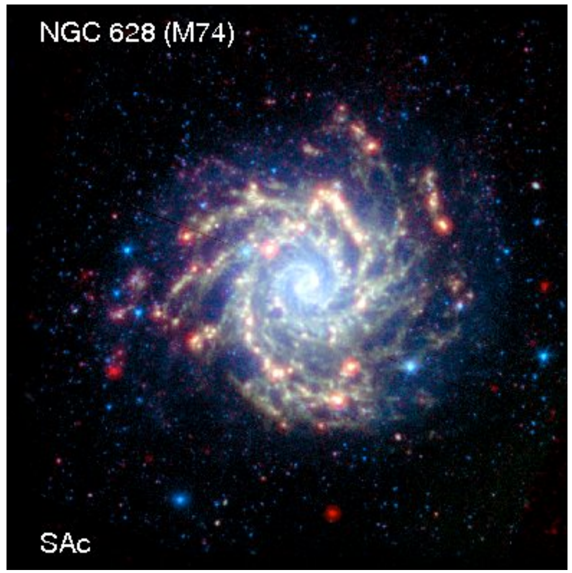

NGC 4254
Log(α_{CO})
2
1
0
−1
0.2 dex
$\Delta\alpha_{CO}$ (dex)
0.1 0.2 0.4 0.6 0.7 0.8 1.0
0.0 0.5 1.0 1.5 2.0
Deprojected Radius (r_{25})

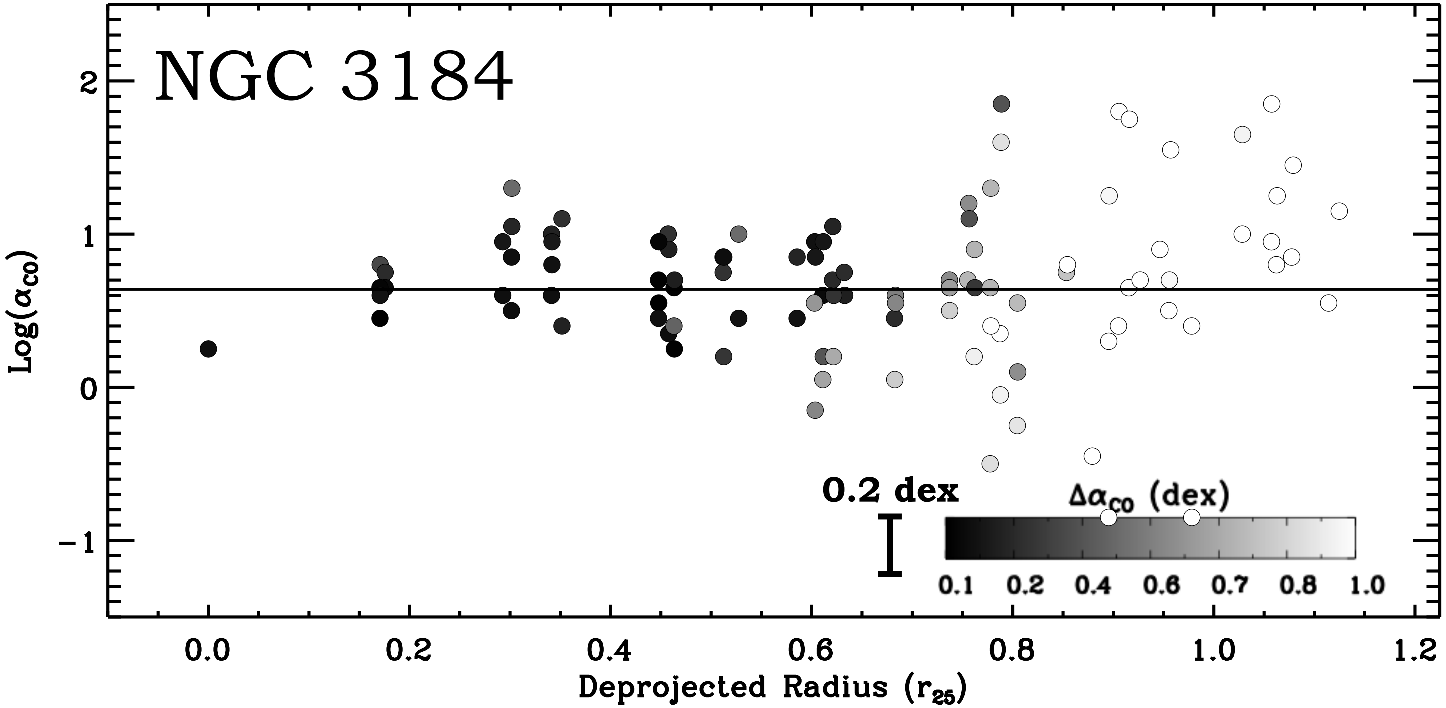

Radius [r_{25}]
0.0 0.5 1.0 1.5 2.0 2.5
radial profiles from Schruba+ 2011
NGC 4254
HI
H_2
SFR(FUV+24)
SFR(Hα+24)
Integrated Intensity [K km s^{-1}]
100
10
1
0.1
0.01
l_{CO} = 0.20 r_{25}
0 100 200 300 400
Radius [arcsec]

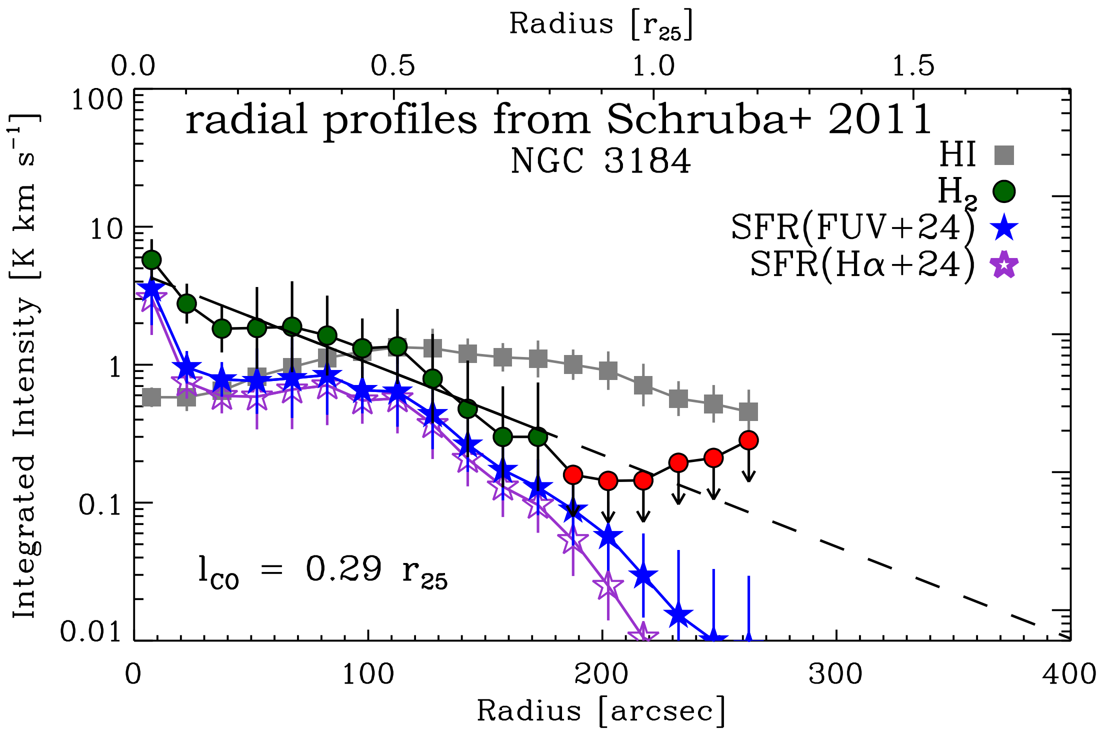

NGC 4254 (M99)
SAc


NGC 0628
Log(αCO)
0.2 dex
ΔαCO (dex)
0.1 0.2 0.4 0.6 0.7 0.8 1.0
Deprojected Radius (r25)


Radius [r25]
radial profiles from Schruba+ 2011
NGC 0628
HI
H2
SFR(FUV+24)
SFR(Hα+24)
lCO = 0.25 r25
Integrated Intensity [K km s-1]
Radius [arcsec]


NGC 628 (M74)
SAc


NGC 3184
Log(α_{CO})
2
1
0
−1
0.2 dex
$\Delta\alpha_{CO}$ (dex)
0.1 0.2 0.4 0.6 0.7 0.8 1.0
0.0 0.2 0.4 0.6 0.8 1.0 1.2
Deprojected Radius (r_{25})

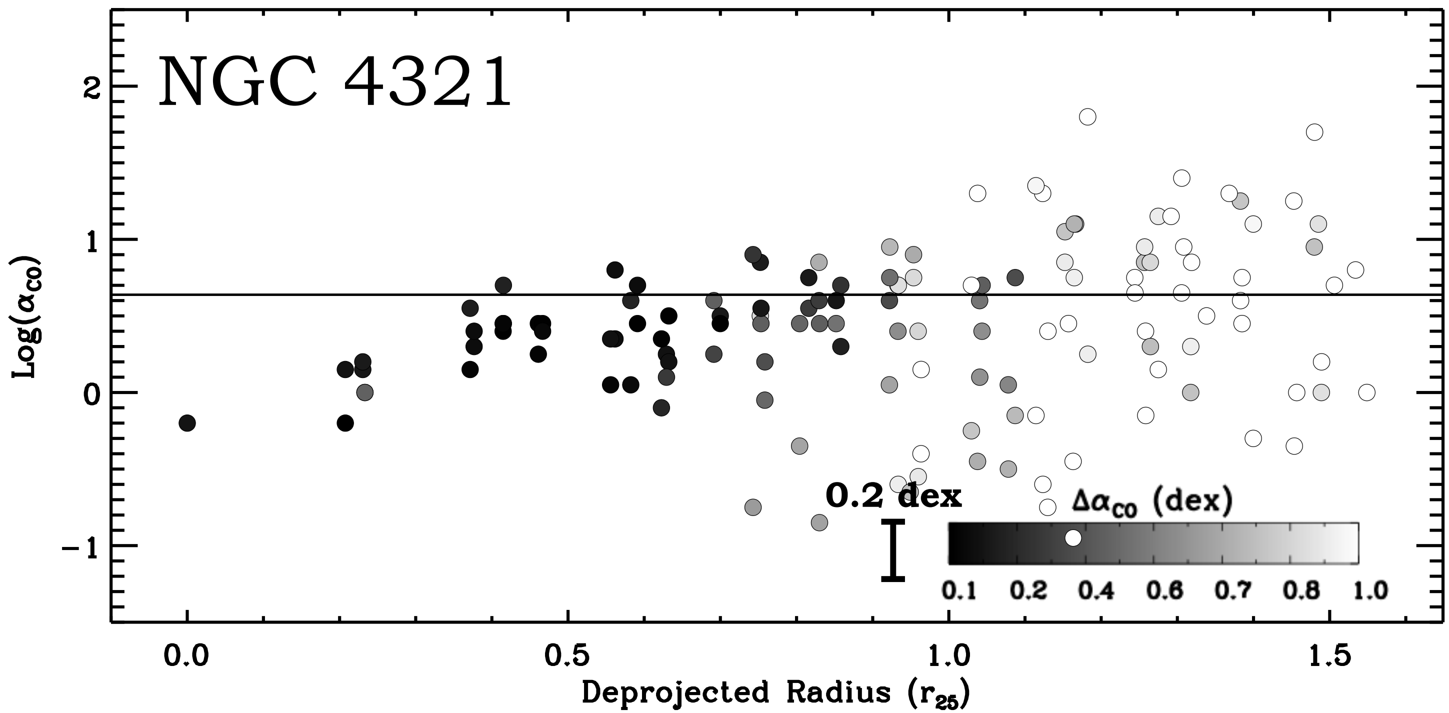

Radius [r_{25}]
0.0 0.5 1.0 1.5
radial profiles from Schruba+ 2011
NGC 3184
HI
H_2
SFR(FUV+24)
SFR(Hα+24)
Integrated Intensity [K km s^{-1}]
100
10
1
0.1
0.01
l_{CO} = 0.29 r_{25}
0 100 200 300 400
Radius [arcsec]

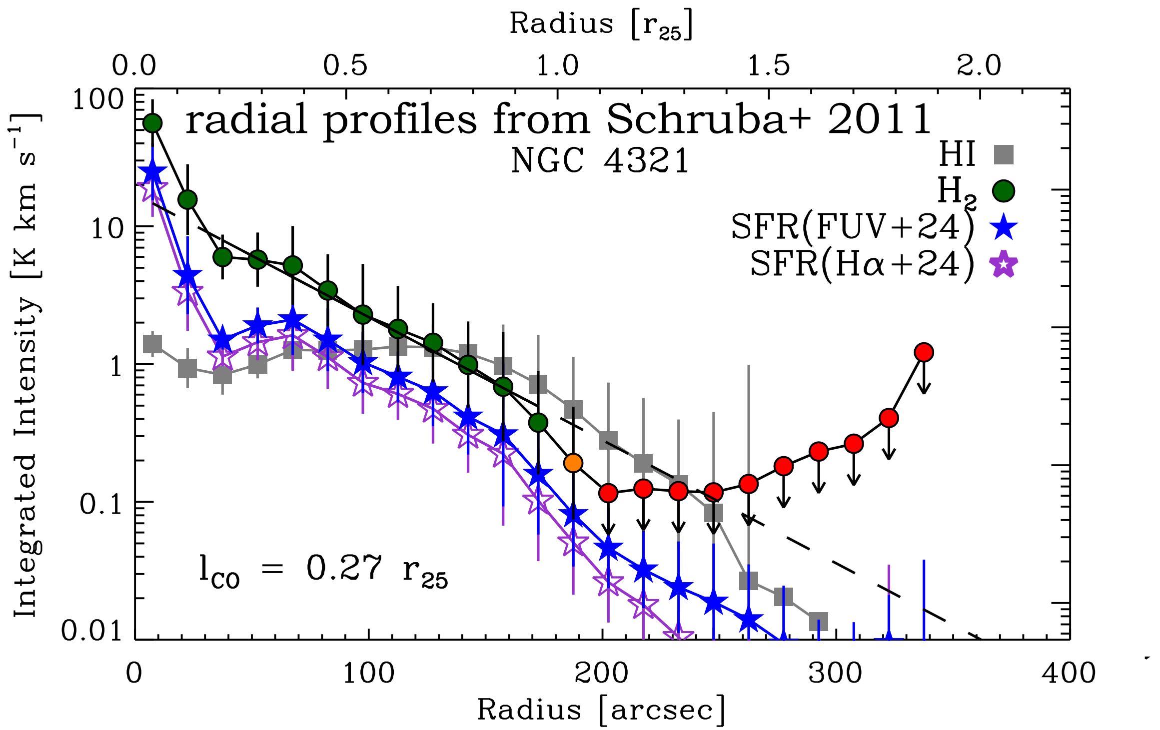

NGC 3184
SABcd

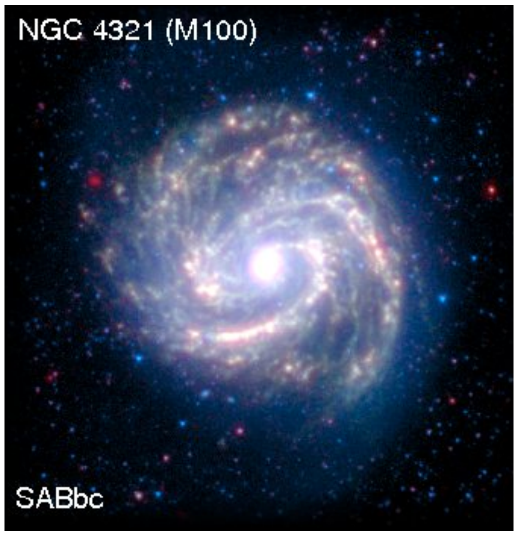
Variations we see in α_{CO}

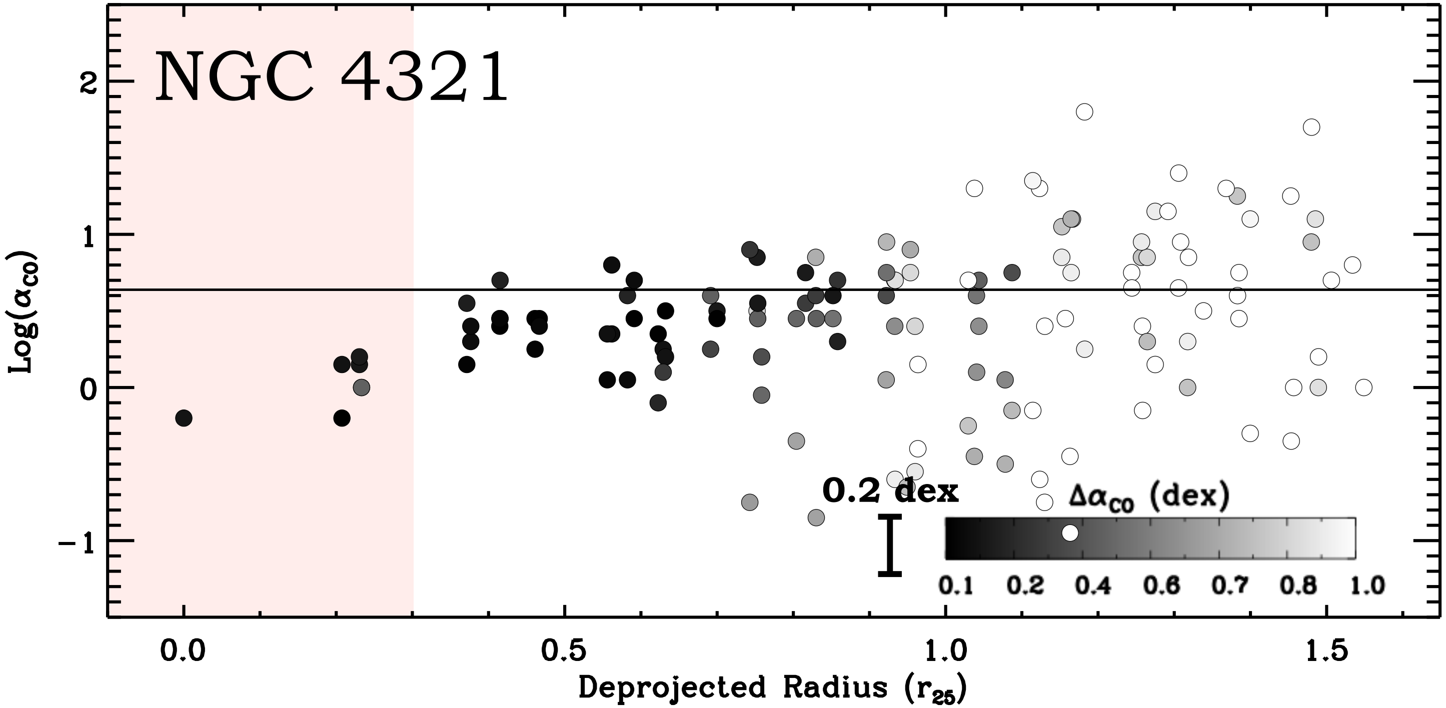
- MW α_{CO}, no trend with radius.
- Flat MW α_{CO} profile + central unresolved dip.
- Overall gradient in α_{CO} with radius.
- Low α_{CO} everywhere, no clear radial trend.

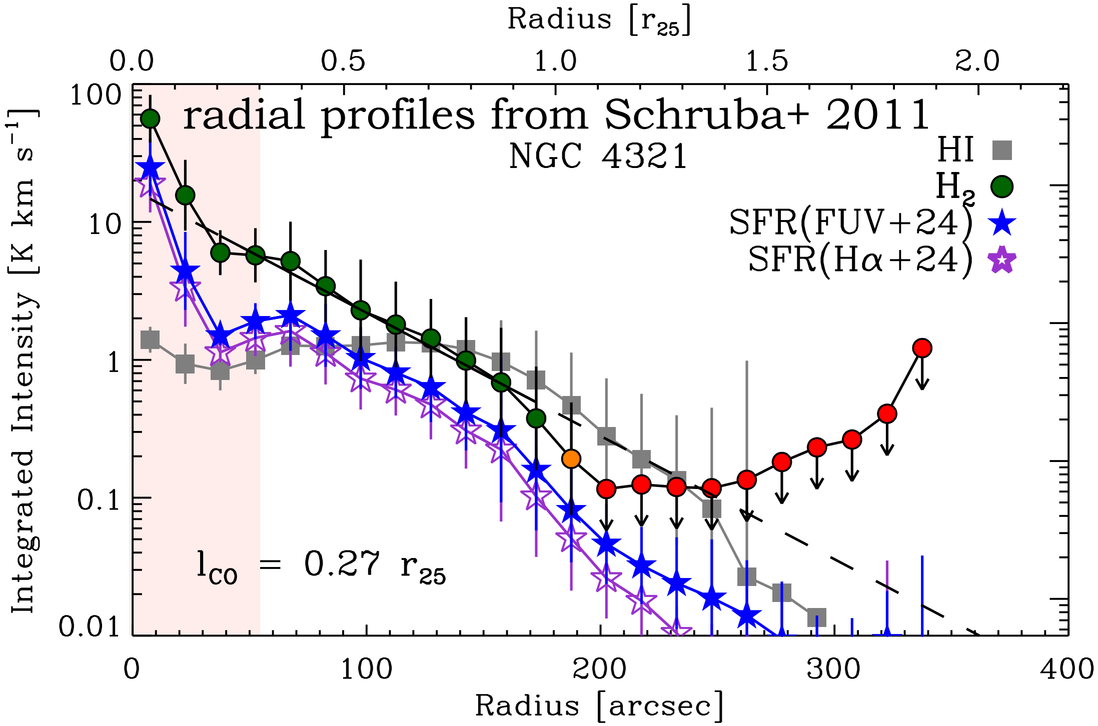
illustrated with a few examples of
~face-on, highly resolved galaxies

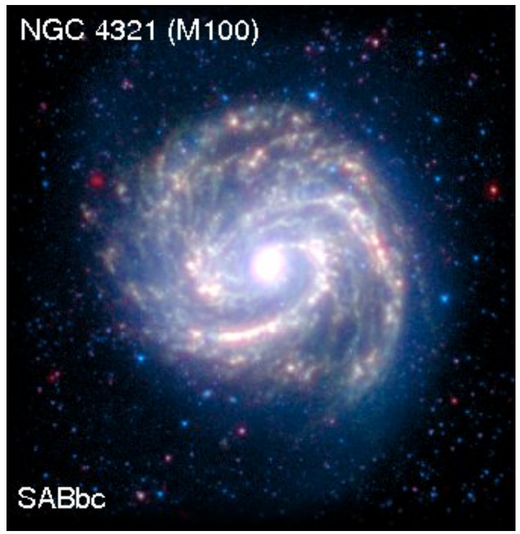

NGC 4321
0.2 dex
Δα_CO (dex)
0.1 0.2 0.4 0.6 0.7 0.8 1.0
Log(α_CO)
Deprojected Radius (r_25)

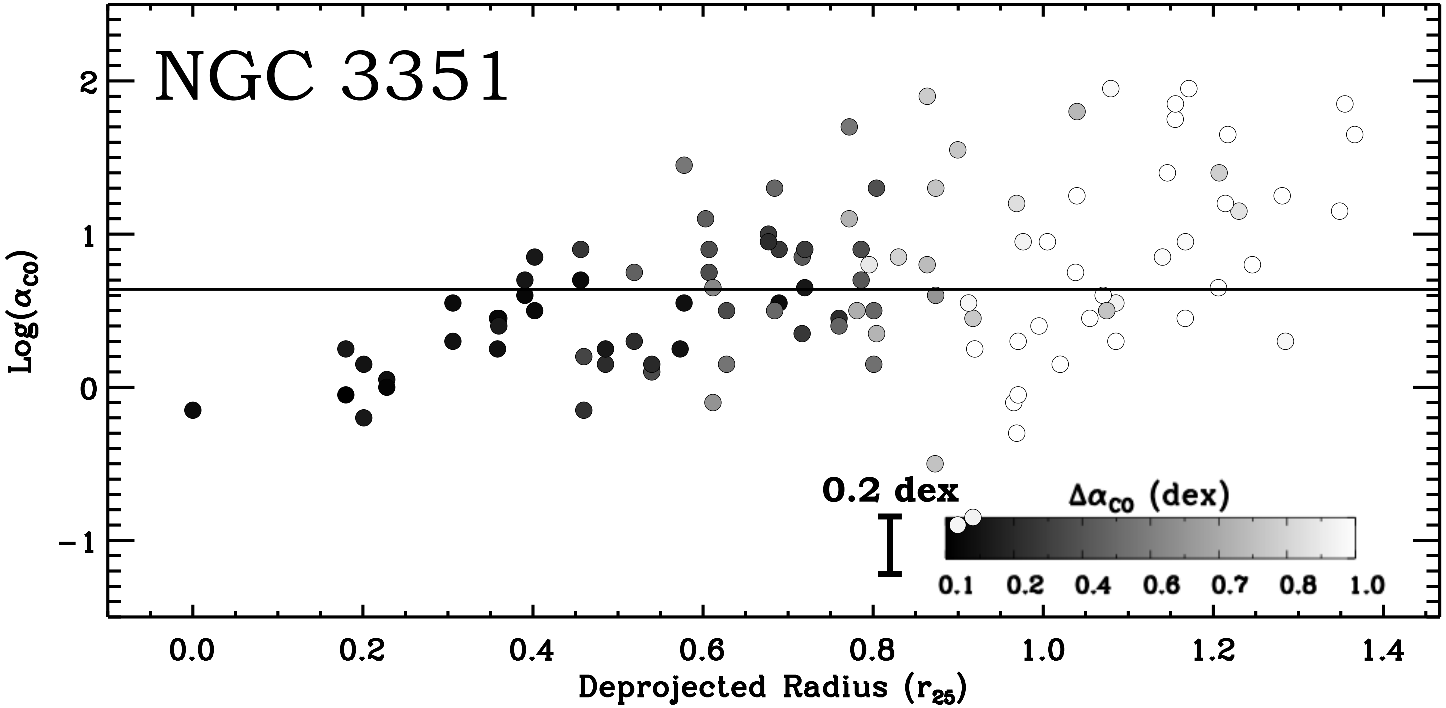

radial profiles from Schruba+ 2011
NGC 4321
HI
H2
SFR(FUV+24)
SFR(Hα+24)
l_CO = 0.27 r_25
Radius [r_25]
Integrated Intensity [K km s^-1]
Radius [arcsec]

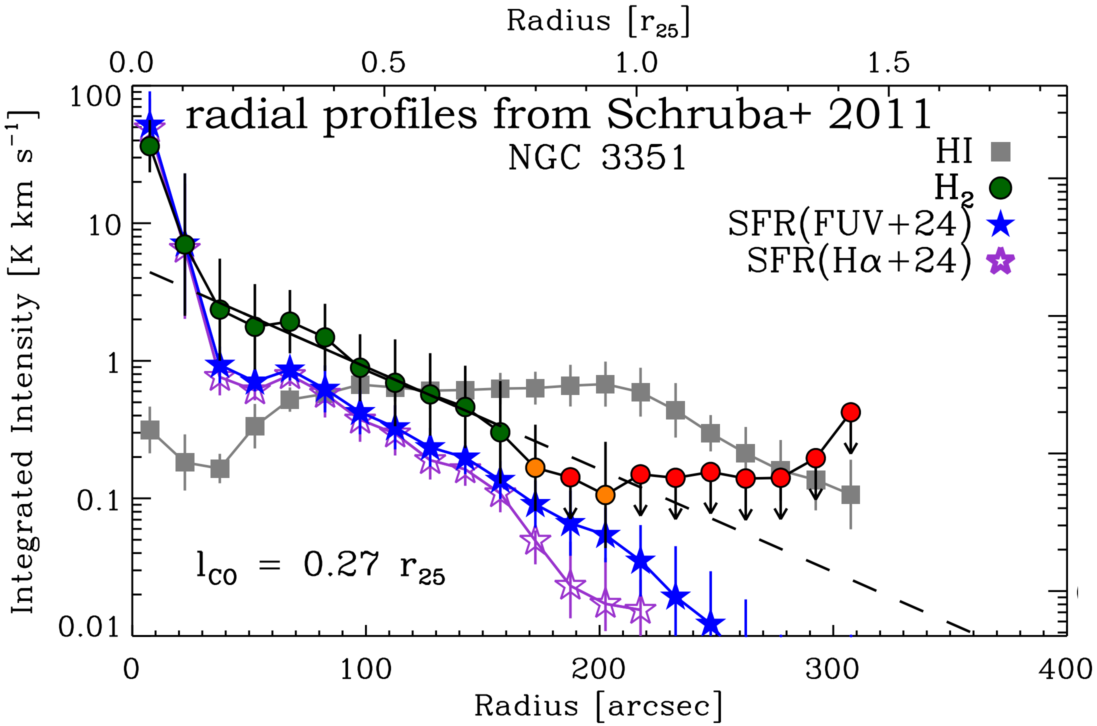

NGC 4321 (M100)
SABbc


NGC 4321
Log(αCO)
2
1
0
−1
0.2 dex
ΔαCO (dex)
0.1
0.2
0.4
0.6
0.7
0.8
1.0
0.0
0.5
1.0
1.5
Deprojected Radius (r25)

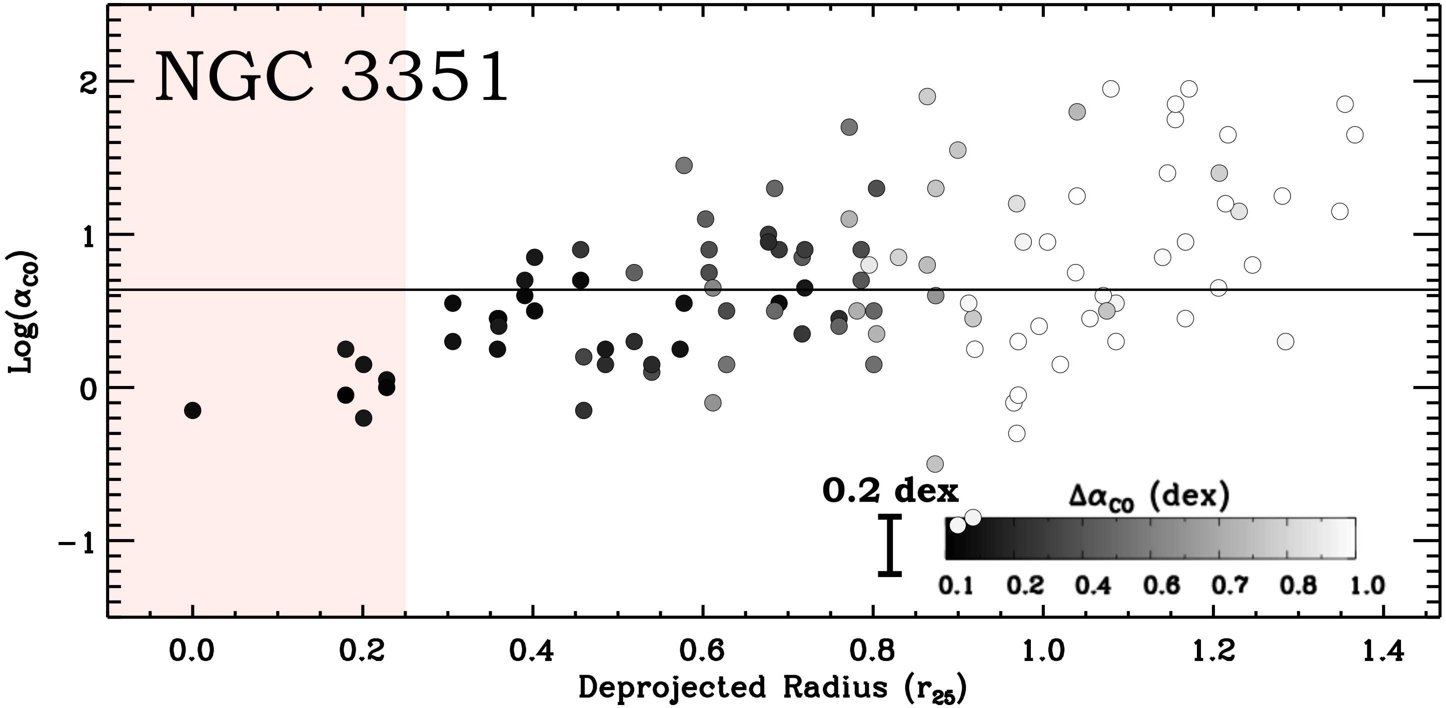

Radius [r25]
0.0
0.5
1.0
1.5
2.0
radial profiles from Schruba+ 2011
NGC 4321
HI
H2
SFR(FUV+24)
SFR(Hα+24)
Integrated Intensity [K km s^-1]
100
10
1
0.1
0.01
lCO = 0.27 r25
0
100
200
300
400
Radius [arcsec]

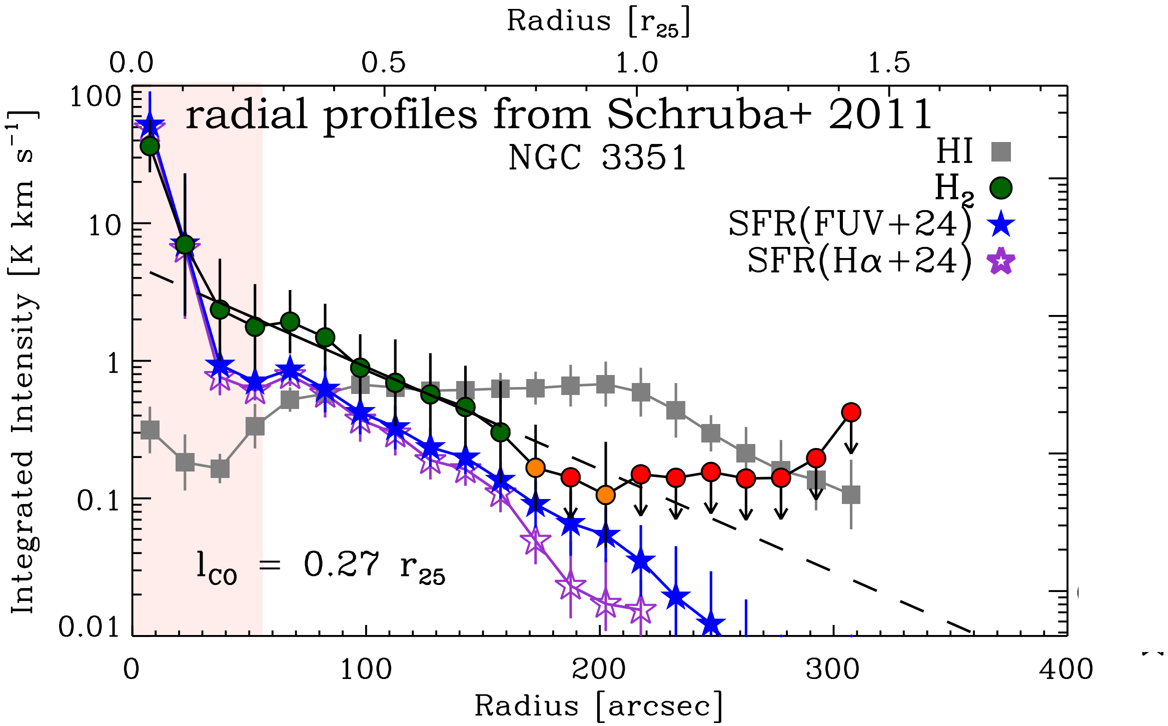

NGC 4321 (M100)
SABbc


NGC 3351
Log(αCO)
Deprojected Radius (r25)
0.2 dex
ΔαCO (dex)
0.1 0.2 0.4 0.6 0.7 0.8 1.0
2
1
0
−1
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4


radial profiles from Schruba+ 2011
NGC 3351
Radius [r25]
0.0 0.5 1.0 1.5
HI
H2
SFR(FUV+24)
SFR(Hα+24)
Integrated Intensity [K km s-1]
100
10
1
0.1
0.01
lCO = 0.27 r25
0 100 200 300 400
Radius [arcsec]


NGC 3351 (M95)
SBb


NGC 3351
Log(αCO)
2
1
0
−1
0.2 dex
ΔαCO (dex)
0.1 0.2 0.4 0.6 0.7 0.8 1.0
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4
Deprojected Radius (r25)


Radius [r25]
0.0 0.5 1.0 1.5
radial profiles from Schruba+ 2011
NGC 3351
HI
H2
SFR(FUV+24)
SFR(Hα+24)
Integrated Intensity [K km s-1]
100
10
1
0.1
0.01
lCO = 0.27 r25
0 100 200 300 400
Radius [arcsec]


NGC 3351 (M95)
SBb

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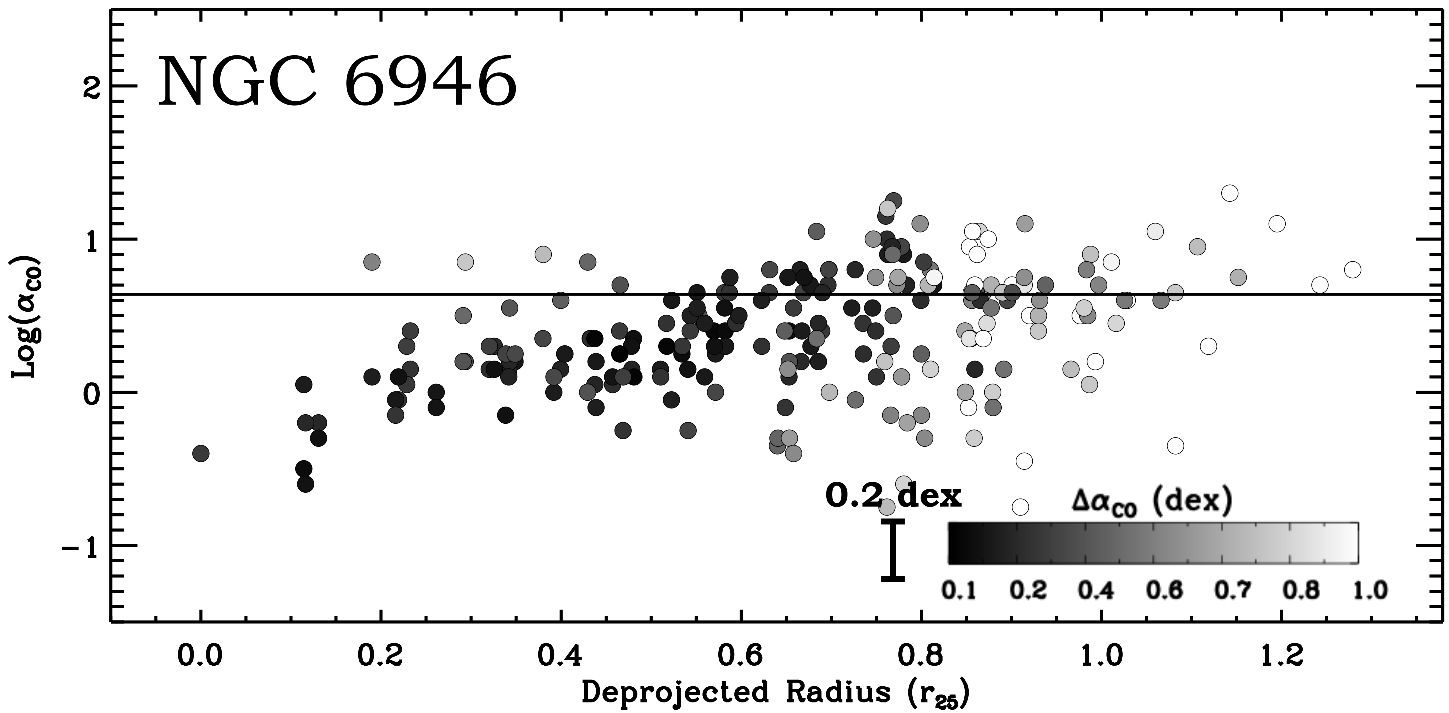
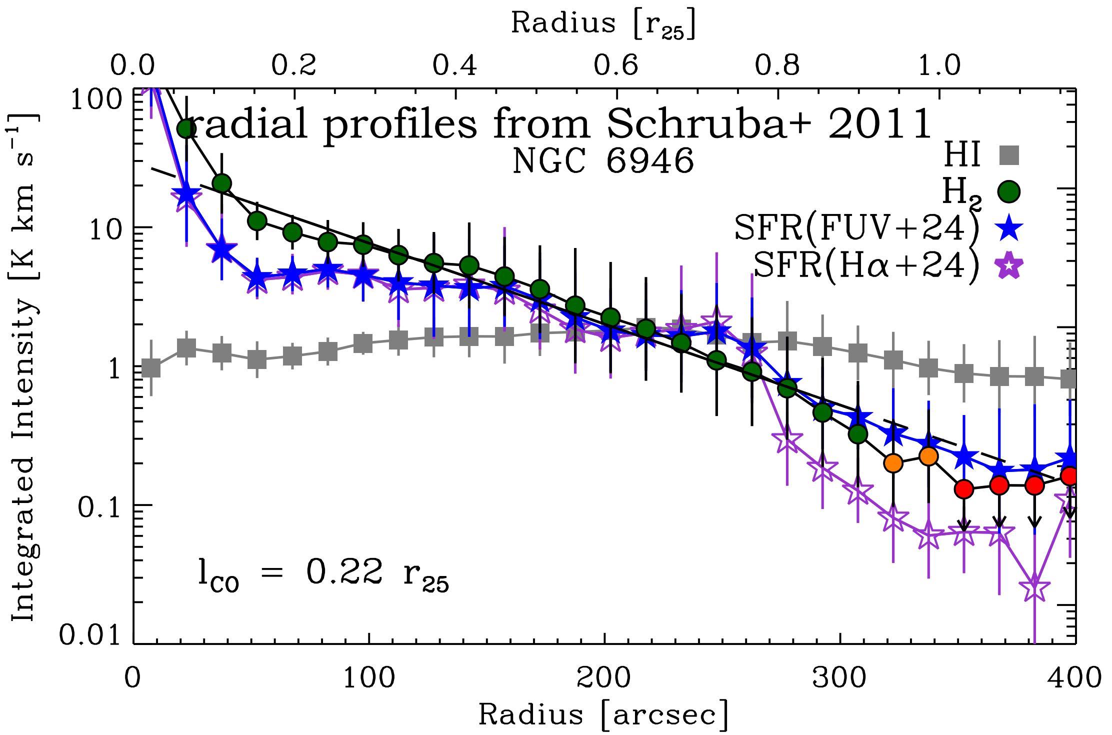
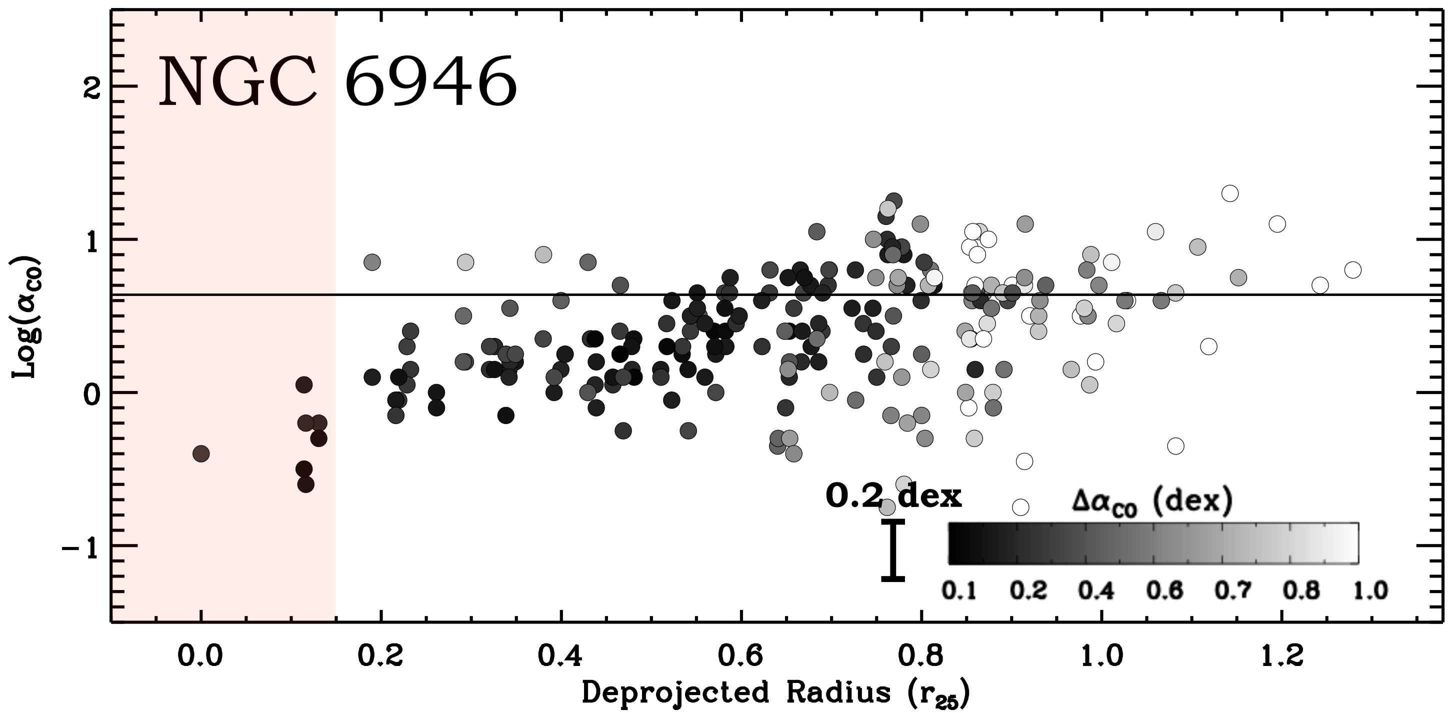
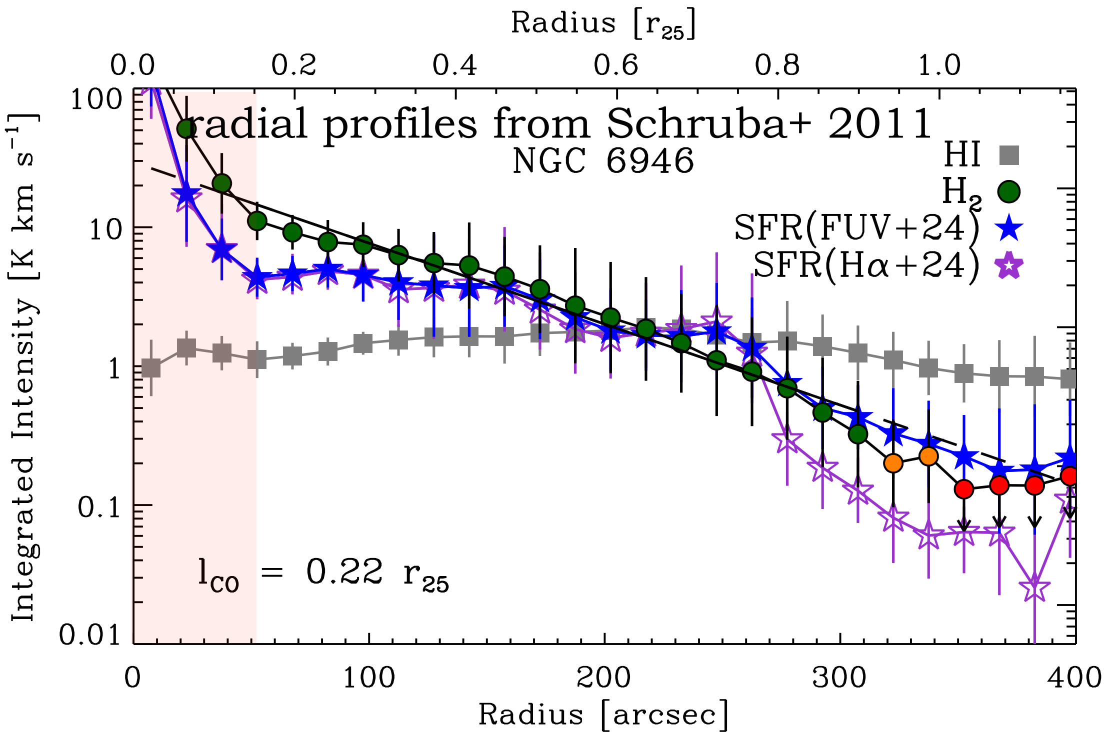

NGC 6946
Log(α_CO)
2
1
0
−1
0.2 dex
Δα_CO (dex)
0.1 0.2 0.4 0.6 0.7 0.8 1.0
0.0 0.2 0.4 0.6 0.8 1.0 1.2
Deprojected Radius (r_25)


Radius [r_25]
0.0 0.2 0.4 0.6 0.8 1.0
radial profiles from Schruba+ 2011
NGC 6946
HI
H_2
SFR(FUV+24)
SFR(Hα+24)
Integrated Intensity [K km s^-1]
100
10
1
0.1
0.01
l_CO = 0.22 r_25
0 100 200 300 400
Radius [arcsec]


NGC 6946
SABcd


NGC 6946
Log(α_{CO})
Deprojected Radius (r_{25})
0.2 dex
$\Delta\alpha_{CO}$ (dex)
0.1 0.2 0.4 0.6 0.7 0.8 1.0

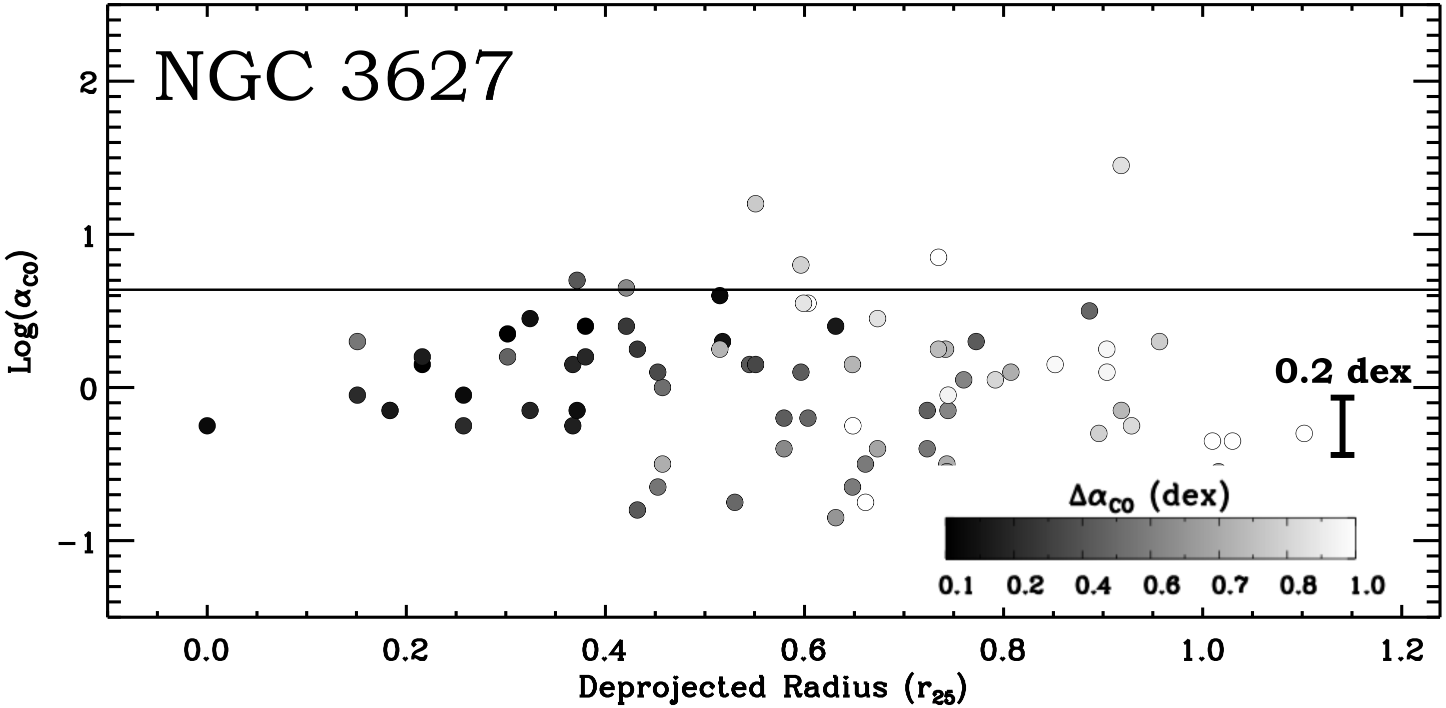

Radius [r_{25}]
radial profiles from Schruba+ 2011
NGC 6946
HI
H_2
SFR(FUV+24)
SFR(Hα+24)
Integrated Intensity [K km s^{-1}]
l_{CO} = 0.22 r_{25}
Radius [arcsec]


NGC 6946
SABcd

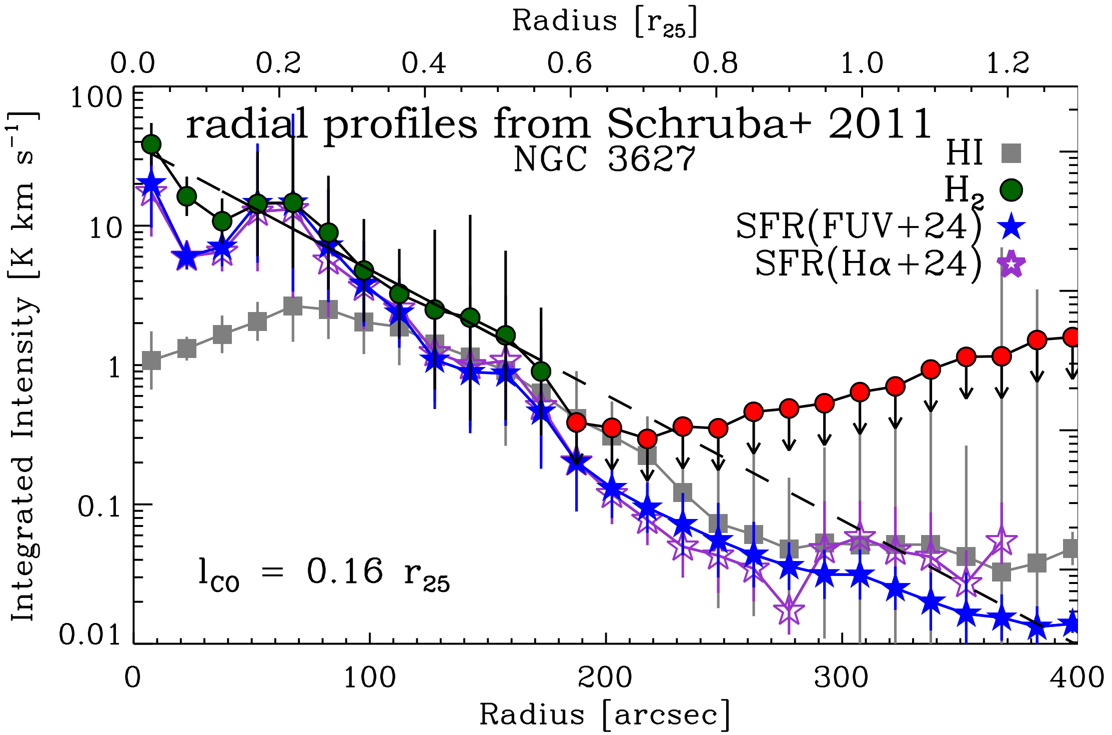
Variations we see in α_{CO}

- MW α_{CO}, no trend with radius.
- Flat MW α_{CO} profile + central unresolved dip.
- Overall gradient in α_{CO} with radius.
- Low α_{CO} everywhere, no clear radial trend.

illustrated with a few examples of
~face-on, highly resolved galaxies



NGC 3627
Log(α_{CO})
0.2 dex
$\Delta\alpha_{CO}$ (dex)
0.1 0.2 0.4 0.6 0.7 0.8 1.0
Deprojected Radius (r_{25})

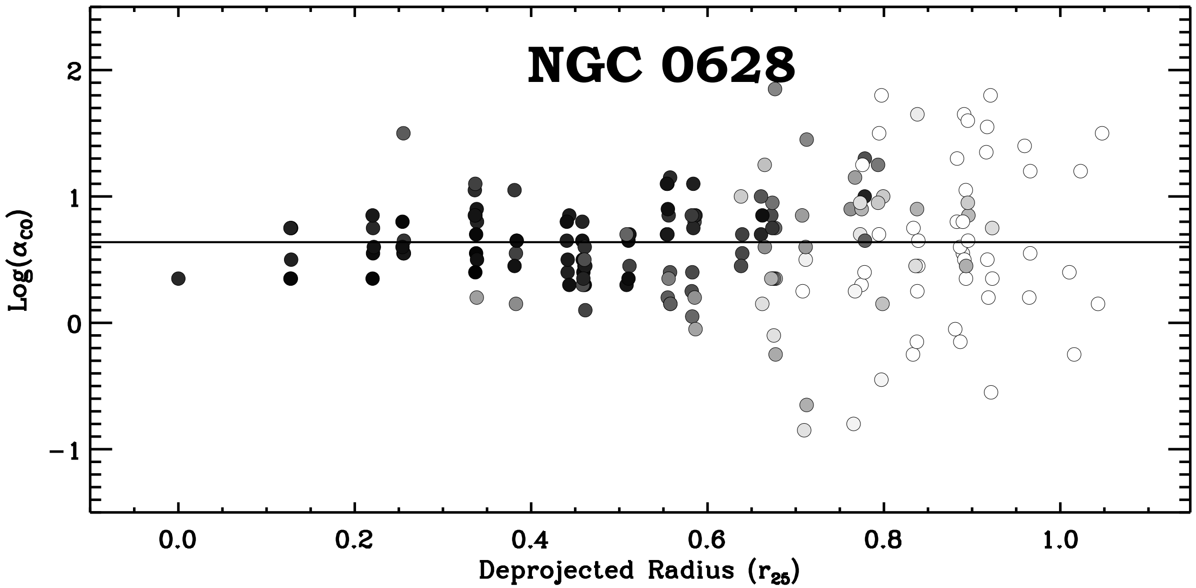


Radius [r_{25}]
radial profiles from Schruba+ 2011
NGC 3627
HI
H_2
SFR(FUV+24)
SFR(Hα+24)
Integrated Intensity [K km s^{-1}]
l_{CO} = 0.16 r_{25}
Radius [arcsec]

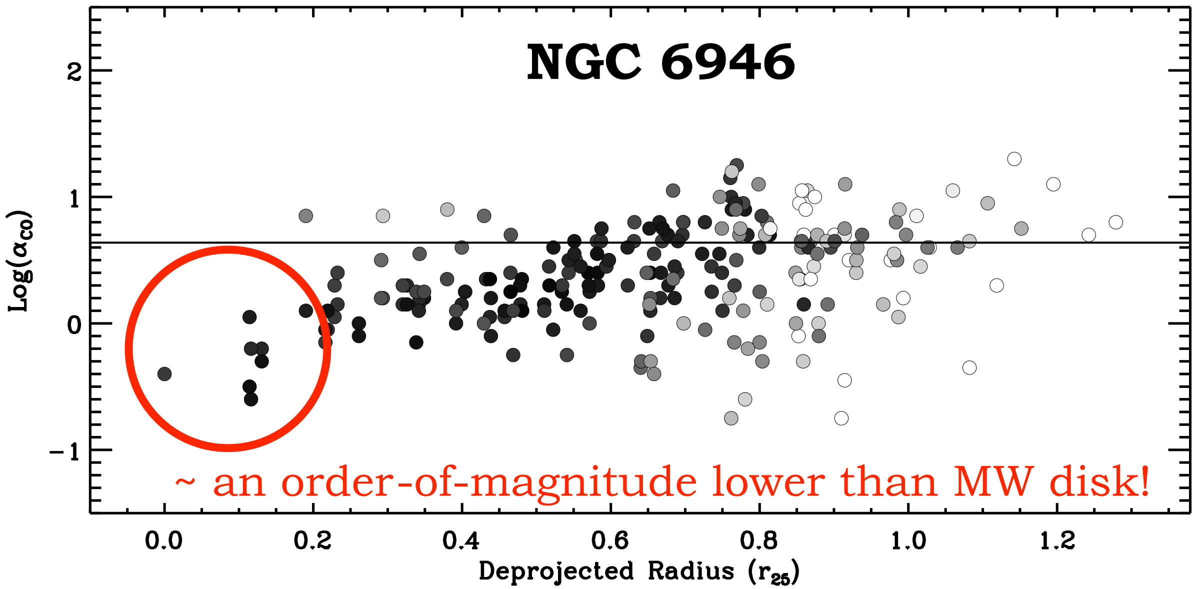
NGC 3627 (M66)
SABb

What drives variations in α_{CO}?

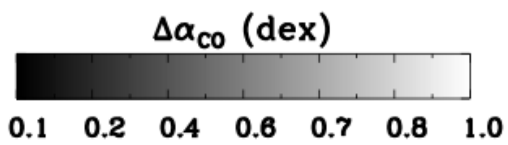
Metallicity?



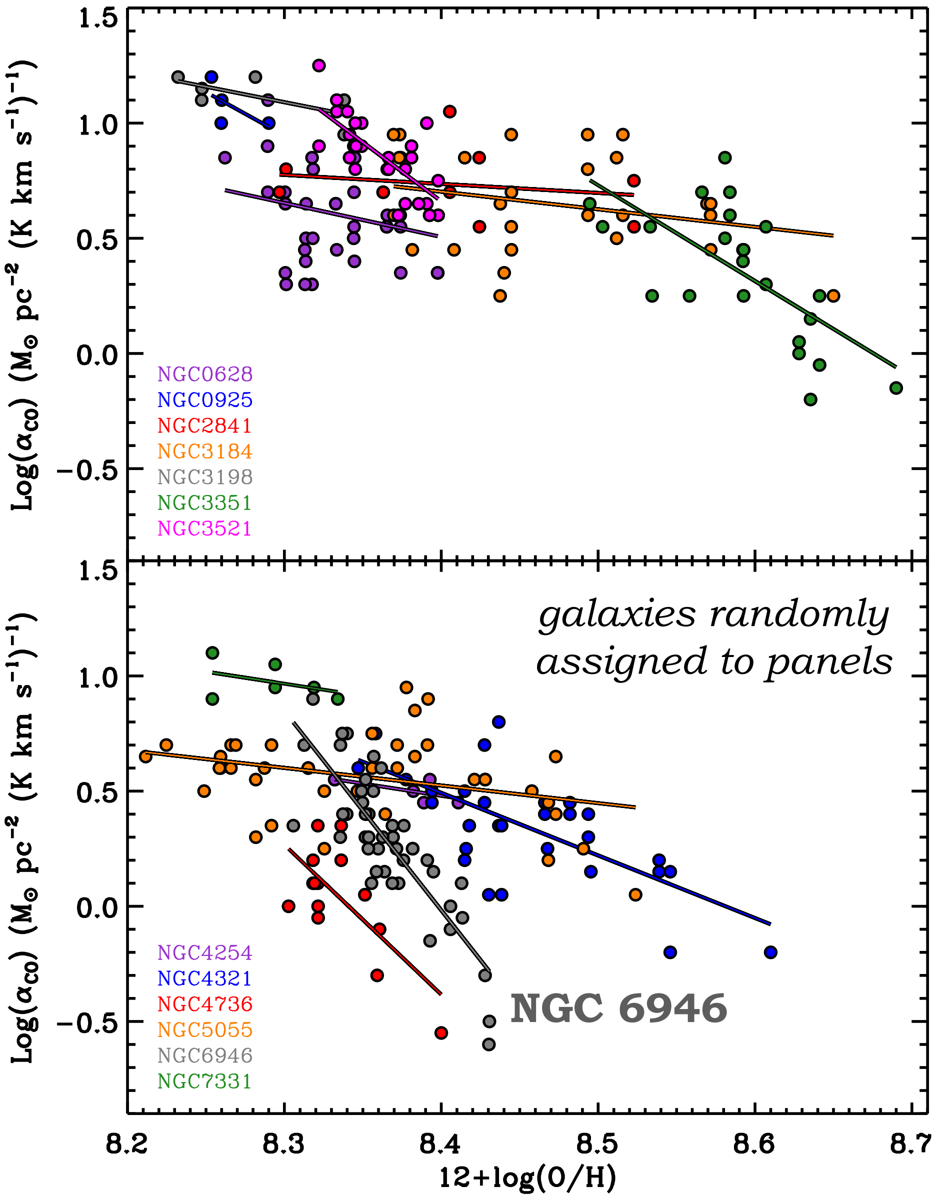
Large metallicity gradient.



Small metallicity gradient.



α_{CO} & Metallicity



uniform metallicity selection from Moustakas et al. 2010

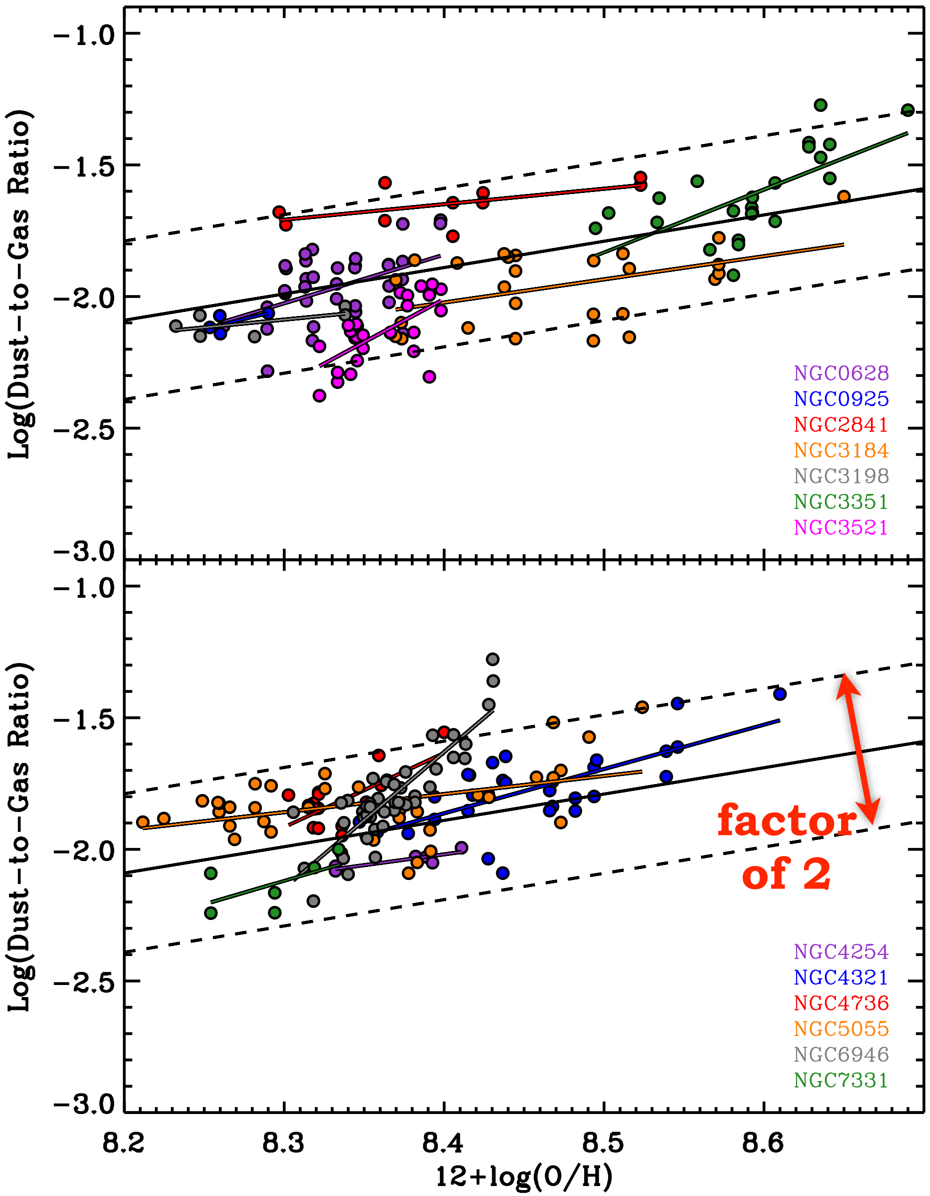
strong-line metallicities with Pilyugin & Thuan 2005 calibration measurements from HII region spectra

General trend for higher α_{CO} at low Z.

but...

significant scatter in α_{CO} at given Z.

Dust-to-Gas Ratio



Linear trend with Z.

Less than a factor of 2 scatter.

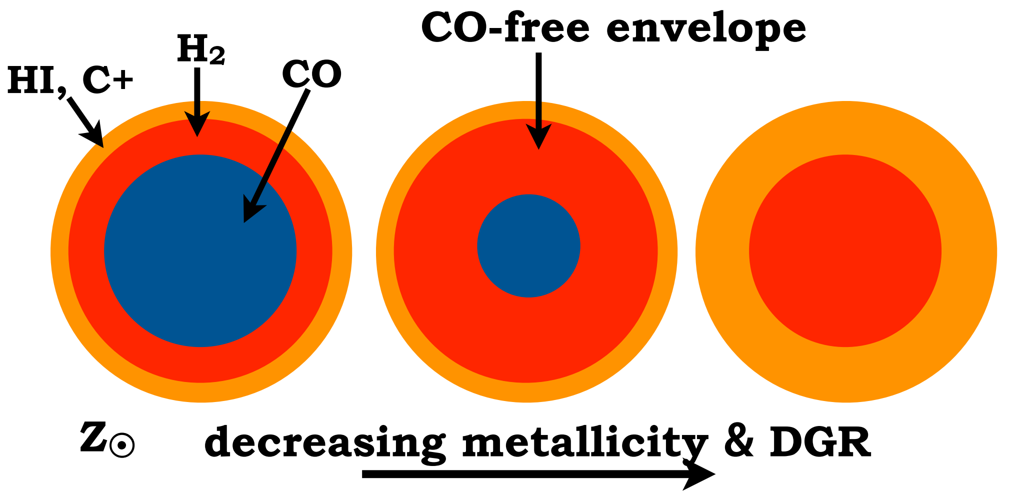
Constant fraction of metals locked up in dust.

Metallicity isn't everything...

Is this what we expect?

- dust shielding controls C+/C/CO transition

- in MW only 30-50% of gas H_2 not in CO layer (Fermi Collab. 2010, Planck Collab. 2011)



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

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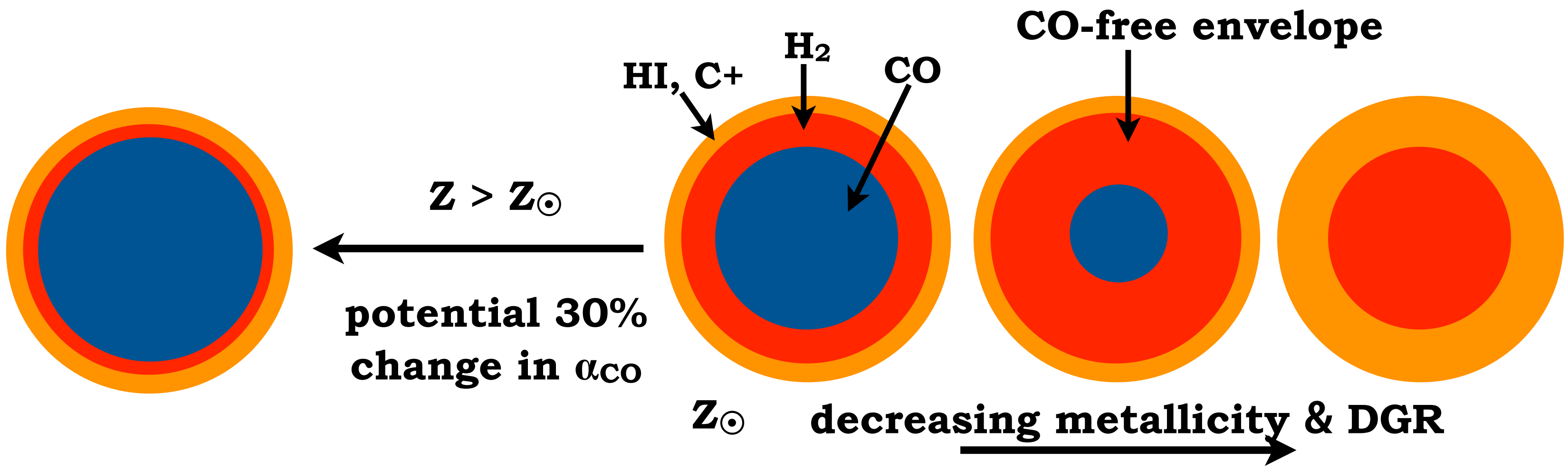

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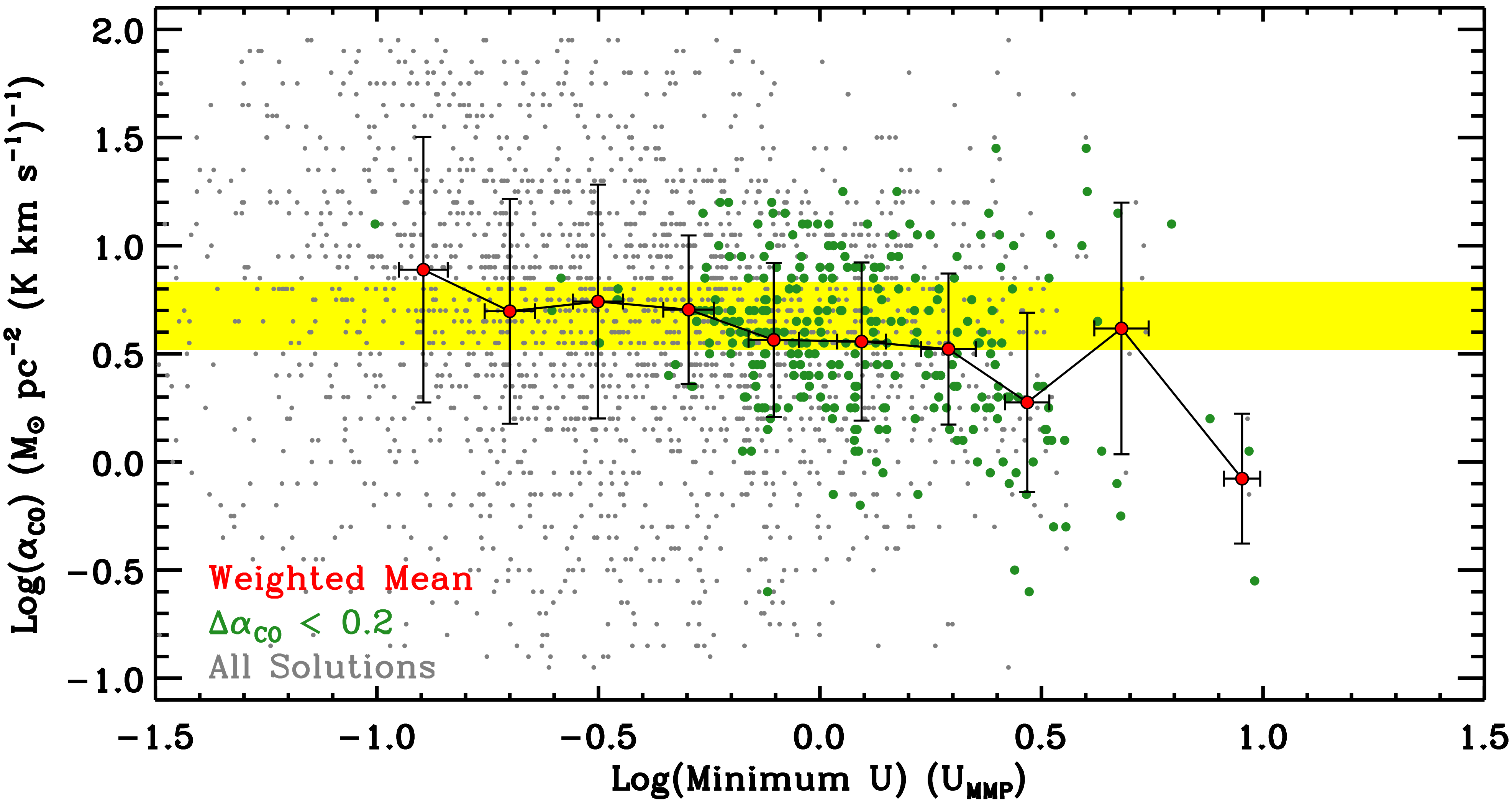
What drives variations in α_{CO}?



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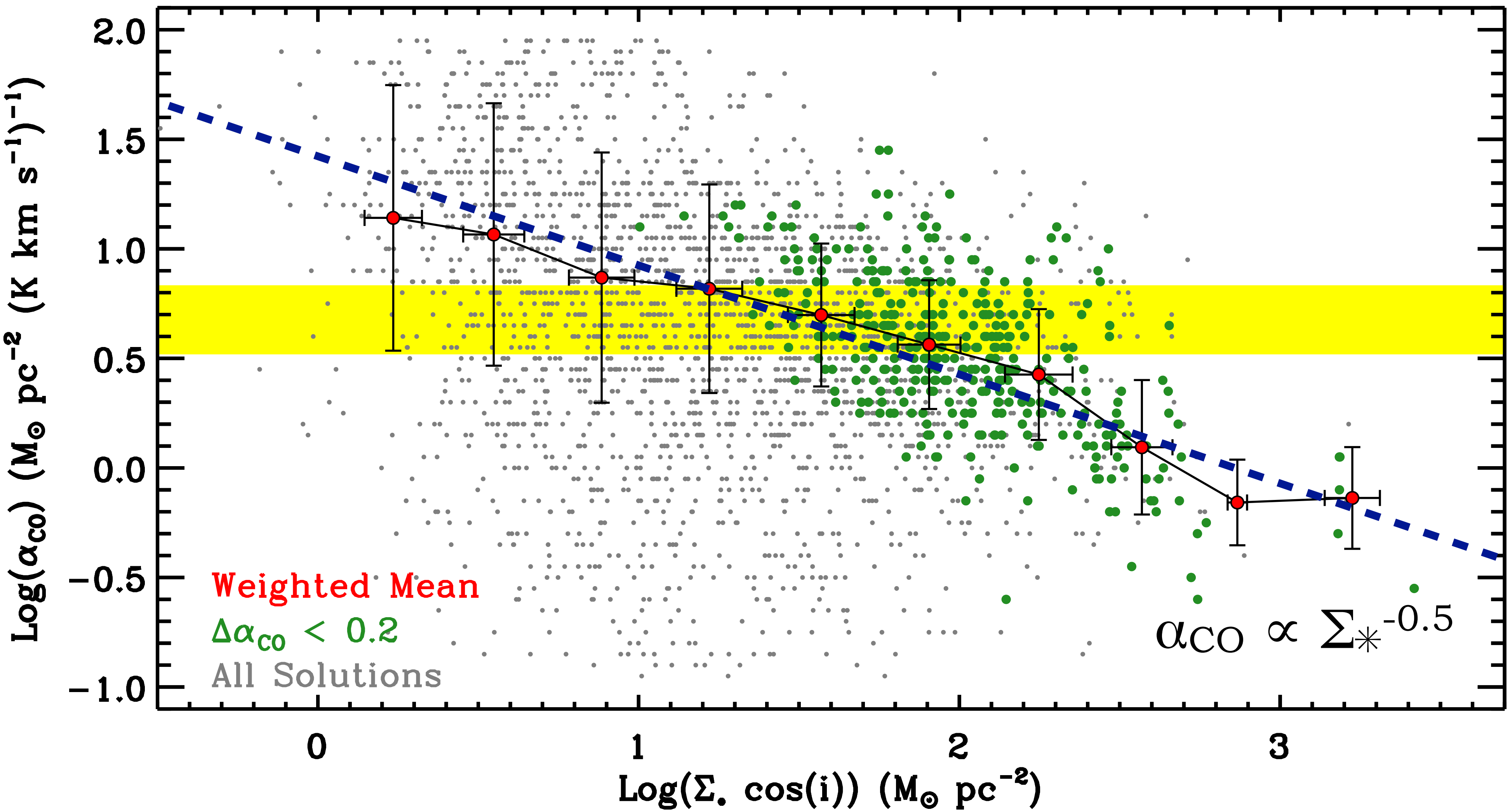
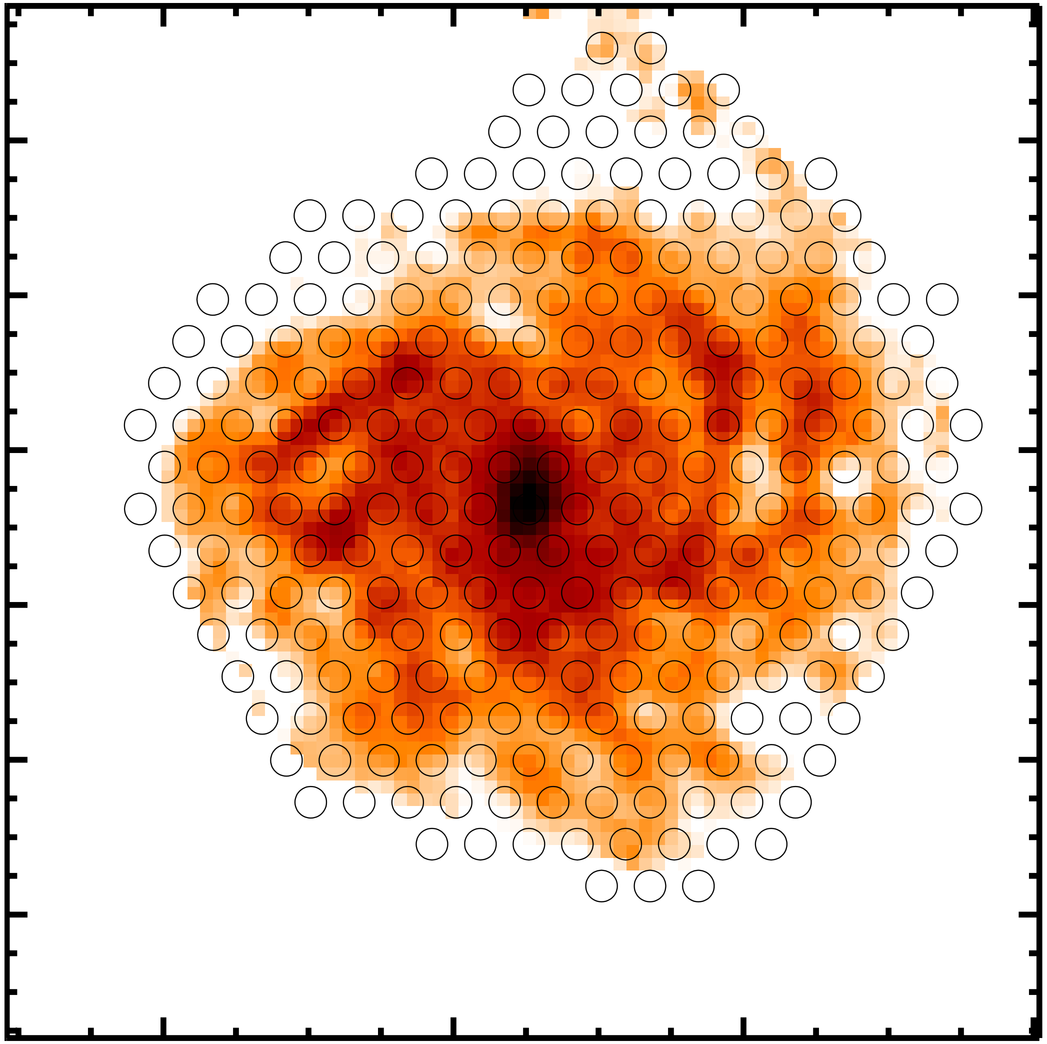


Azimuthal Variations in NGC 6946

Lower α_{CO} along the spiral arms.



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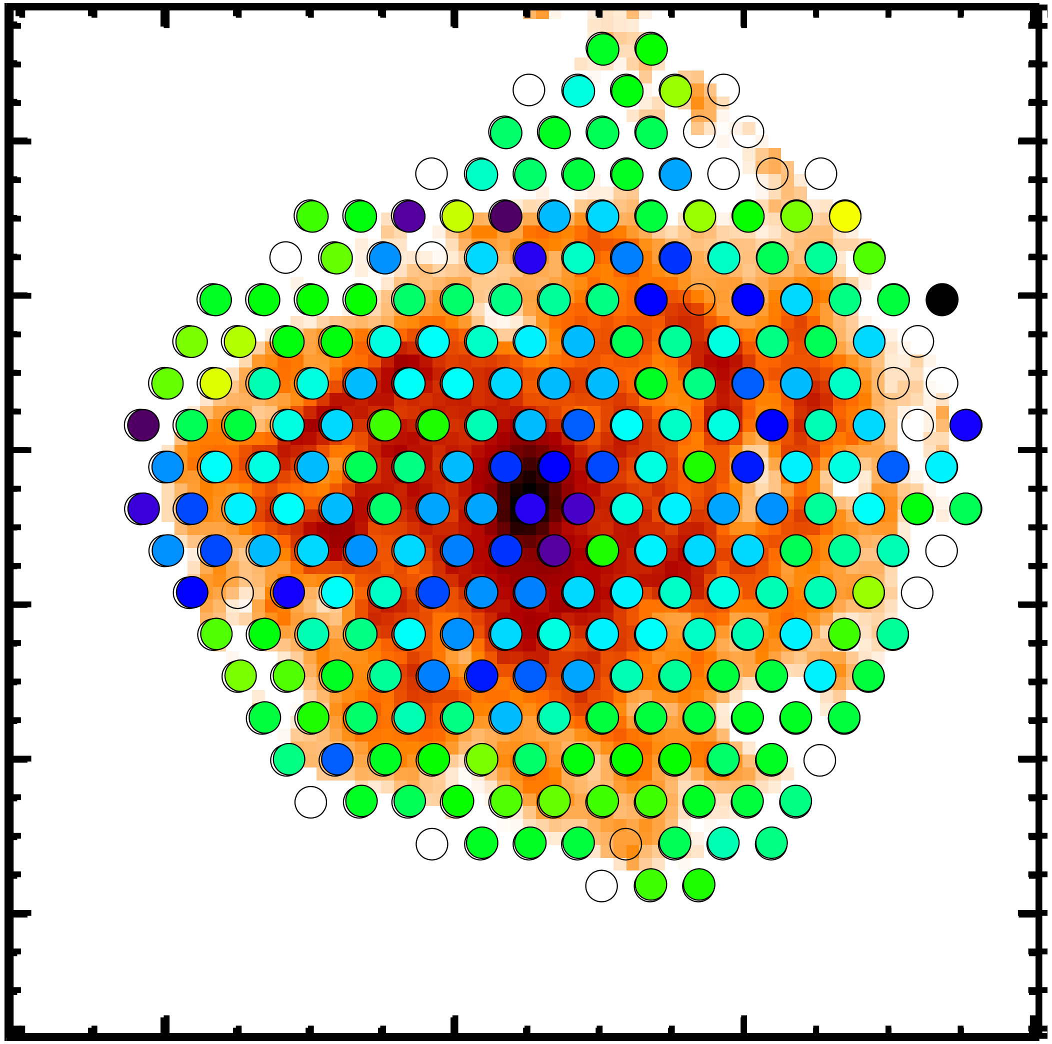
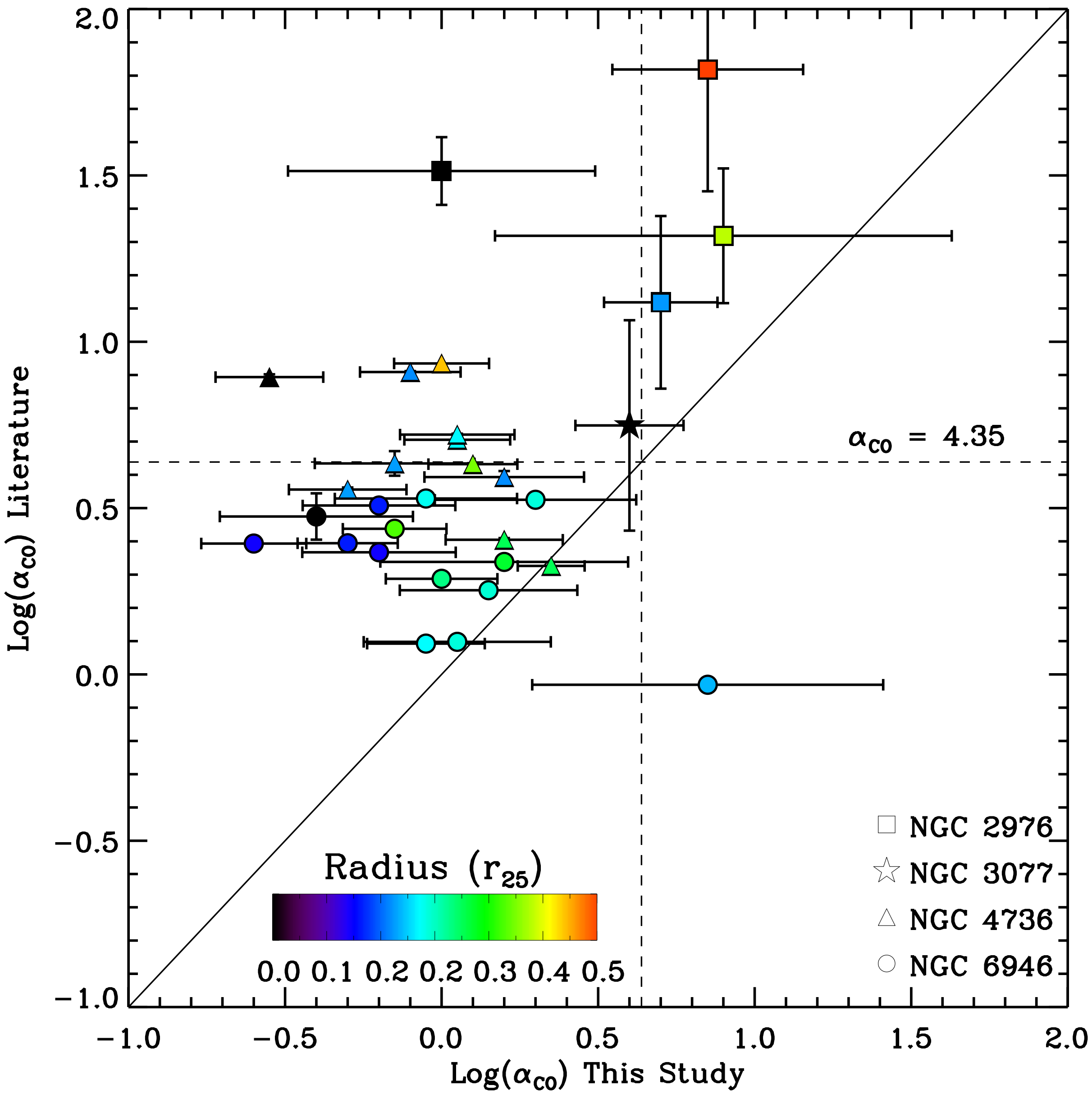


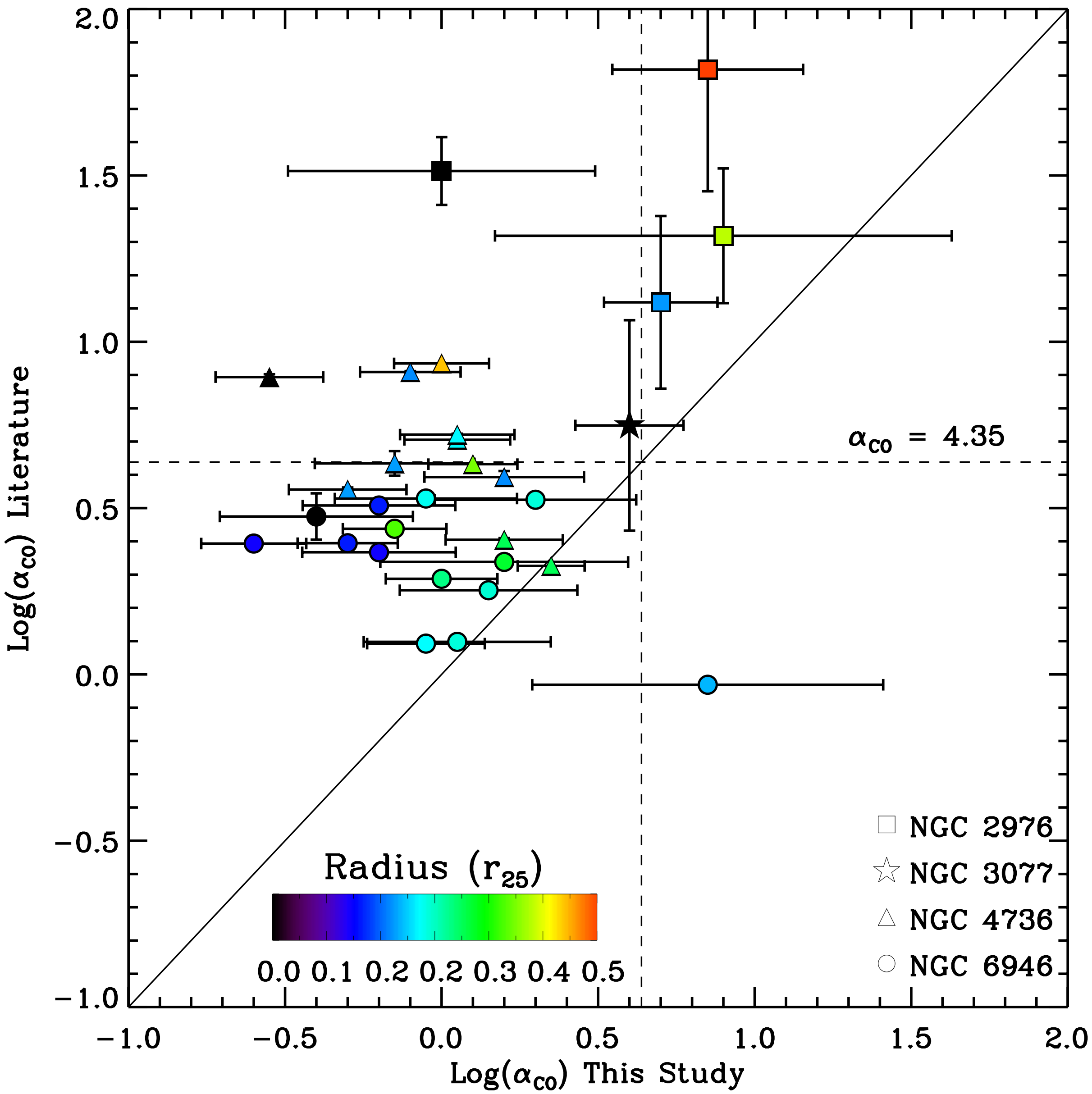
Disagreement with Virial Mass α_{CO} Measurements in the centers



4 Galaxies with virial mass based α_{CO}

Virial masses give ~MW or higher α_{CO} in centers of 2976, 4736 and 6946.

Disagreement with Virial Mass α_{CO} Measurements in the centers



4 Galaxies with virial mass based α_{CO}

Virial masses give ~MW or higher α_{CO} in centers of 2976, 4736 and 6946.

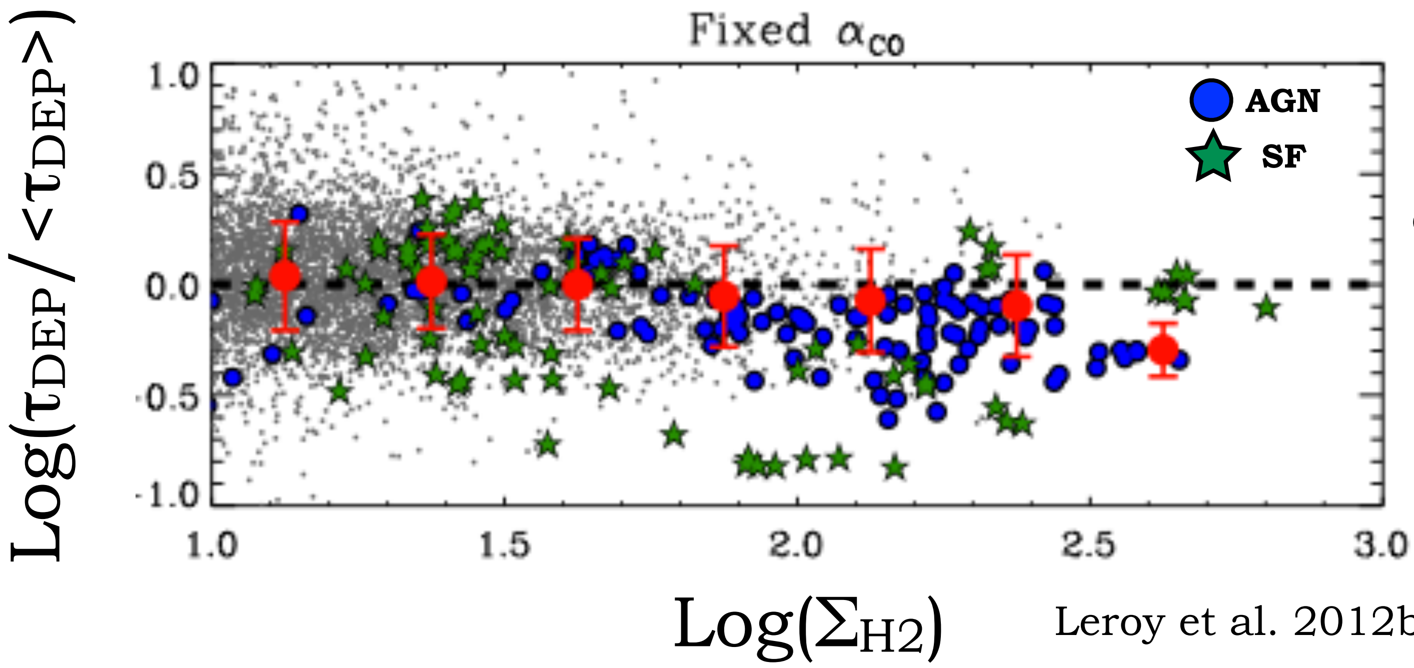
Several galaxies with muti-line modeling α_{CO}

Modeling suggests low α_{CO} in some galaxy centers

NGC 6946 5-10 times lower than MW - Israel & Baas 2001, Walsh et al. 2002, Meier & Turner 2004

Our conversion factors makes some galaxy centers have high star-formation efficiency.

Depletion Time: $\tau_{DEP} = 1/SFE = \Sigma_{H2}/\Sigma_{SFR}$



higher SFE compared to average

Leroy et al. 2012b, submitted

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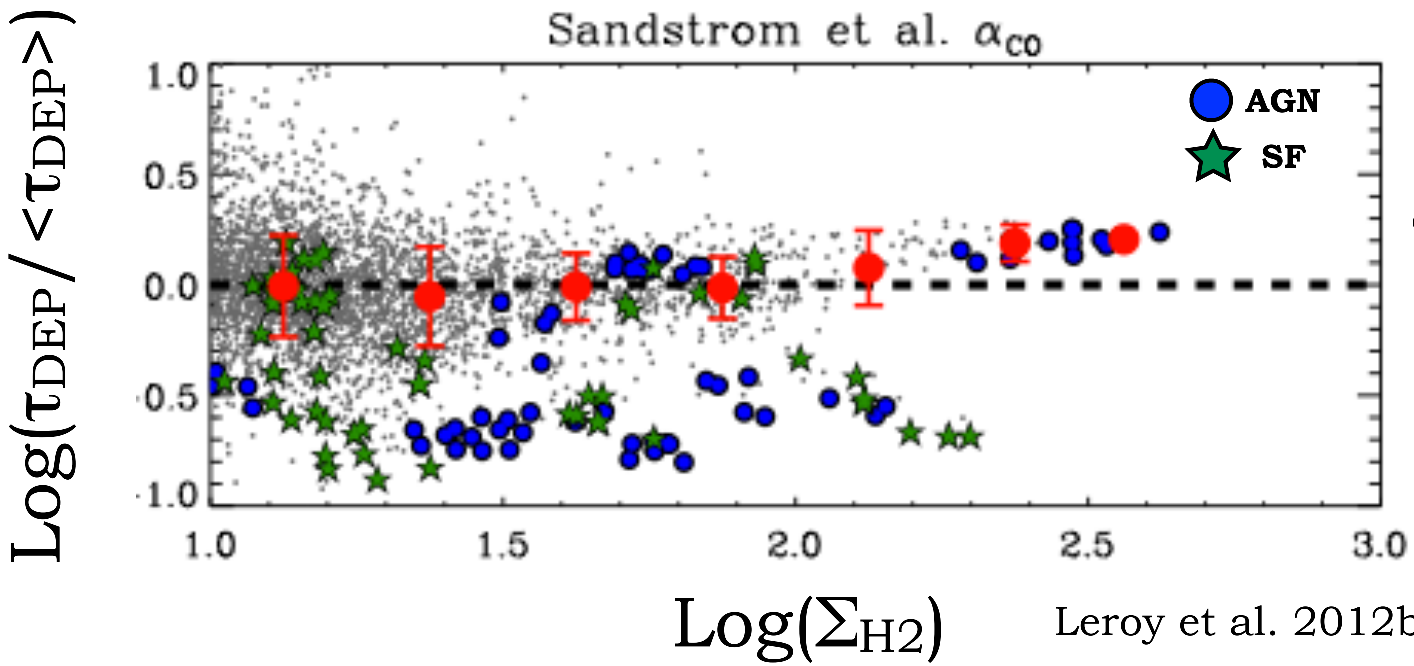

higher SFE compared to average

Leroy et al. 2012b, submitted

Summary

- α_{CO} can vary by factor of 10 in nearby galaxies - especially low in their centers.
- Metallicity not a key driver of α_{CO} at $Z \sim Z_{\odot}$ and above. Expected if main effect is to change dust shielding and alter "CO-dark" gas layer.
- Low measured α_{CO} enhances SFE in some galaxy centers over predictions with fixed converison factor.
- Temperature & velocity dispersion of molecular gas are probably crucial drivers of α_{CO}.