High density tracers of molecular gas in early-type galaxies

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and

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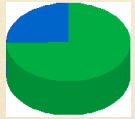
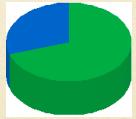
Introduction

- Stereotypical early-type galaxy (E or S0) = "red and dead": no star formation, no cold gas
- But now lots of evidence that this picture does not hold:

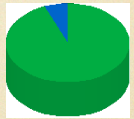
HI: ½ of all *field* ETG (Grossi+ 09, Oosterloo+ 10)



CO: ¼ of ETG (Combes+ 07, Young+ 11)



UV blue: 30% of ETG (Yi+ 05)



Optically blue: 6% of ETG (Schawinski+ 09)

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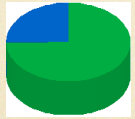

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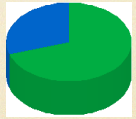

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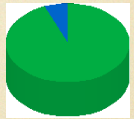

Optically blue: 6% of ETG (Schawinski+ 09)

- Atlas3D project- a multi-wavelength volume-selected survey of 260 early-type galaxies (IFU spectroscopy, optical photometry, CO (single-dish + interferometry), HI, FIR)

Introduction

- As part of Atlas3D, a 12CO(1-0) and (2-1) survey was conducted at the IRAM 30m
  - detected 56/260 (=22%), no trend with mass or environment (see Davis poster, Young+ 11)
  - no slow rotators with CO (the new 'true' ellipticals)

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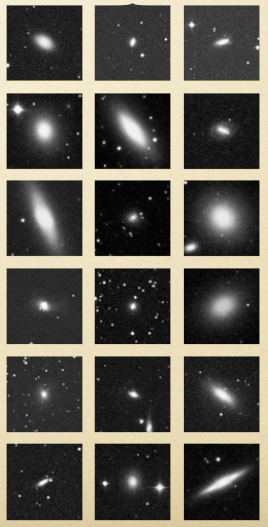
  - no slow rotators with CO (the new 'true' ellipticals)
- **NEXT STEP:** What is the *state of the molecular gas* in early-type galaxies? Unique, relevant properties:
  1. Very central CO distributions → shear important?
  2. Significant hot gas → strong confinement by hydrostatic pressure?
  3. Gas not being replenished (some very low H_2-to-HI ratios)

Observations and Sample

- Observed ~1/3 brightest (=18) ^{12}CO detections in:
  - ^{13}CO(1-0), ^{13}CO(2-1), HCN(1-0), HCO+(1-0)
  - at IRAM 30m

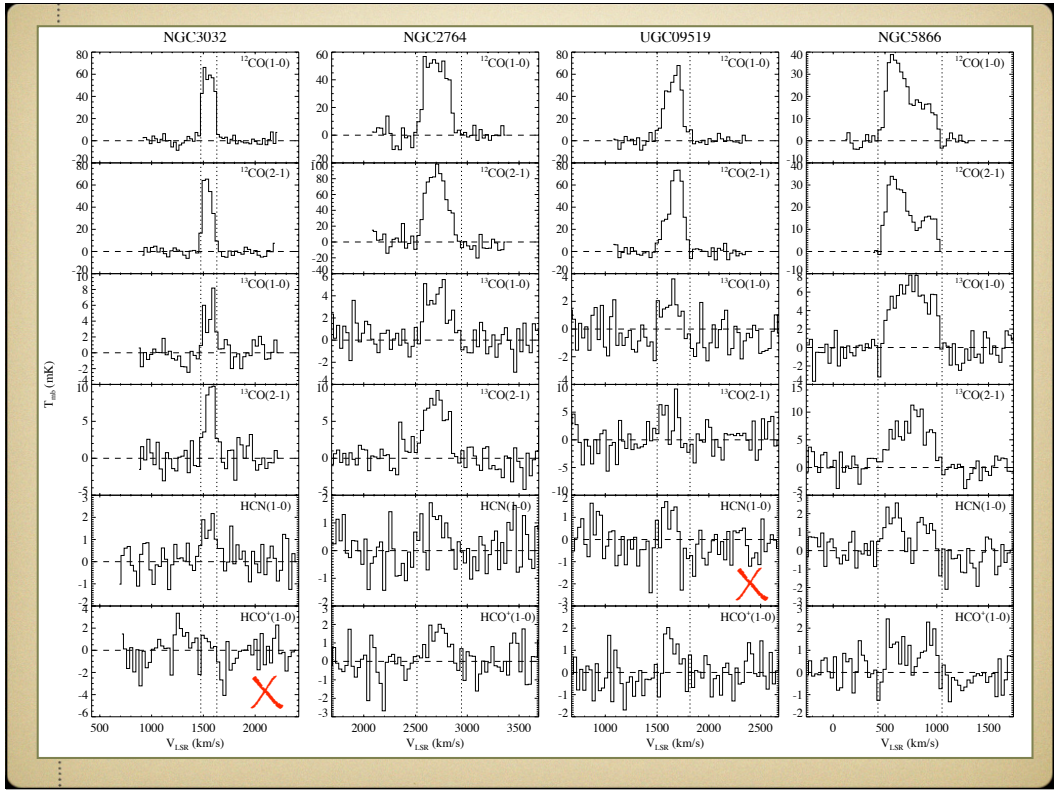


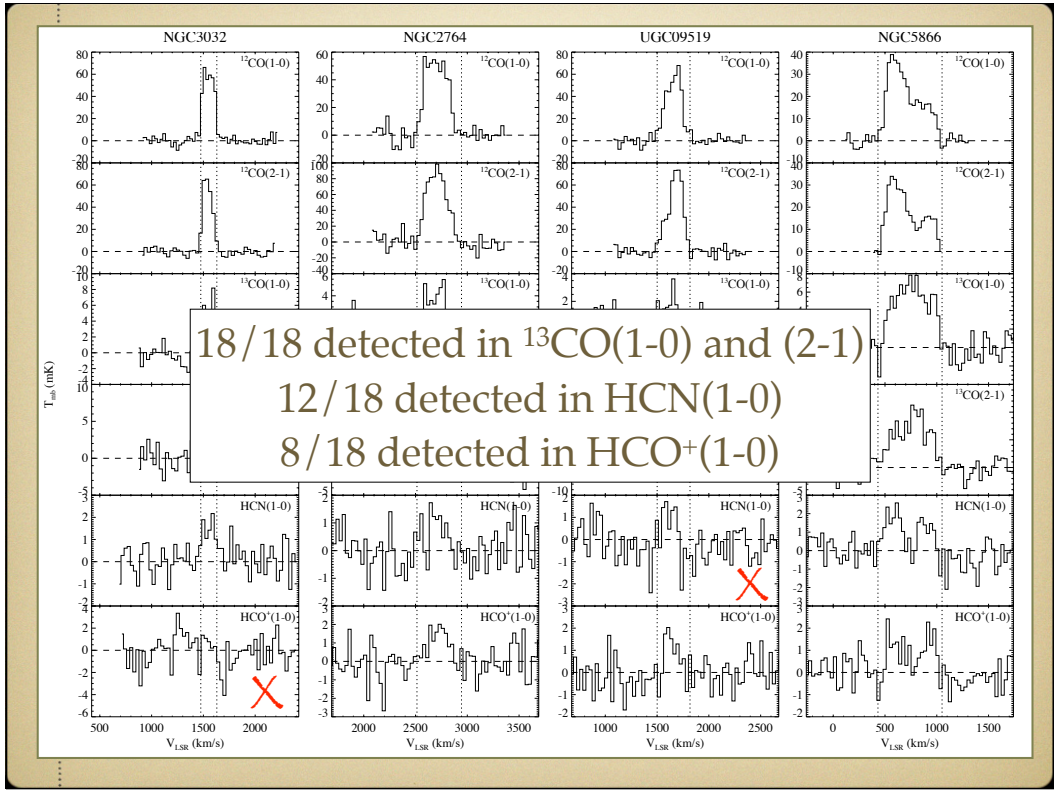
Sample

- H_2 masses: 10^8 - 10^9 $M_\odot$
- Avg. H_2 surface densities: ~10-100 $M_\odot$ pc^{-2}
- Stellar masses: ~10^{10}-10^{11} $M_\odot$
- Mix of cluster, field, group

Plan

- Hope that:
  - $^{12}CO/^{13}CO$ indicates average optical depth of CO
  - $HCN/^{13}CO$ indicates dense gas fraction
- Of course, complications-
  - Abundance issues: $^{12}C/^{13}C$ decreases with chemical enrichment, HCN influenced by AGN(?)
  - Fractionation towards ^{13}CO at cold gas temps (lower $^{12}CO/^{13}CO$)
  - Selective photodissociation of ^{13}CO in PDRs (higher $^{12}CO/^{13}CO$)


NGC3032
NGC2764
UGC09519
NGC5866
^{12}CO(1-0)
^{12}CO(2-1)
^{13}CO(1-0)
^{13}CO(2-1)
HCN(1-0)
HCO$^+$(1-0)
T_{mb} (mK)
V_{LSR} (km/s)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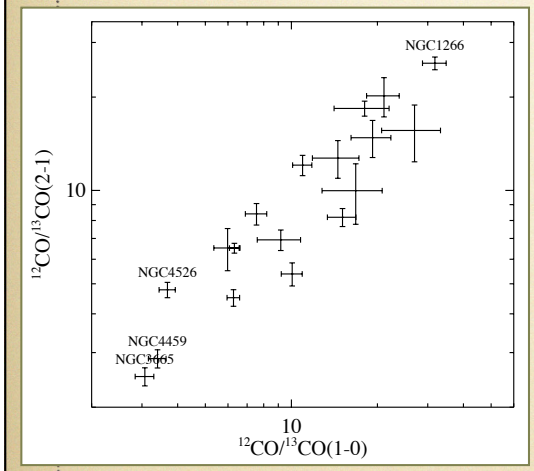
T_{mb} (mK)
V_{LSR} (km/s)
18/18 detected in ^{13}CO(1-0) and (2-1)
12/18 detected in HCN(1-0)
8/18 detected in HCO$^+$(1-0)

$^{12}CO/^{13}CO$

Optically thick ⟶ Optically thin



- Order-of-magnitude range (3-30)
- (1-0) and (2-1) ratios well correlated
  - no huge differences in excitation or beam filling

$^{12}CO/^{13}CO$

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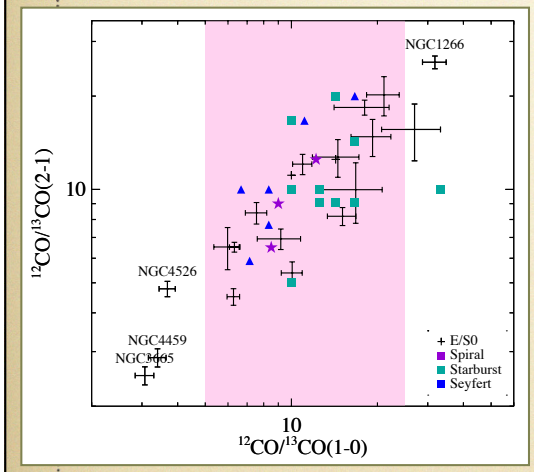
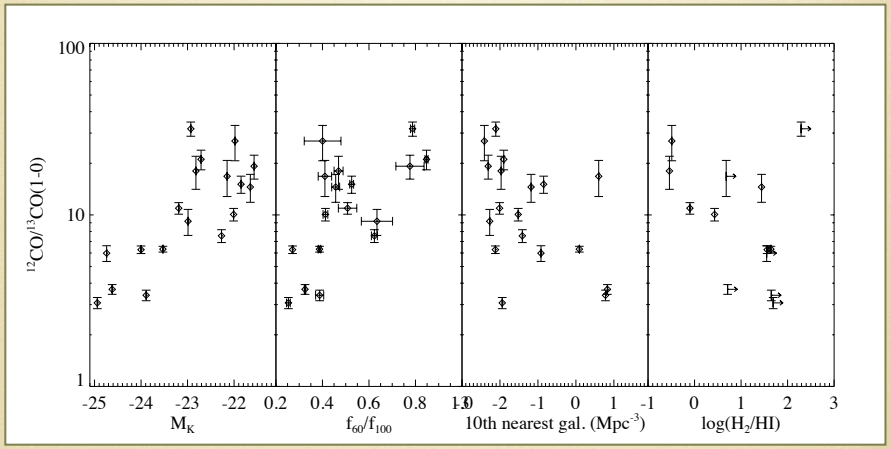


Compilation of Seyferts and starbursts from Krips et al. 2010; spiral range from Paglione et al. 2001

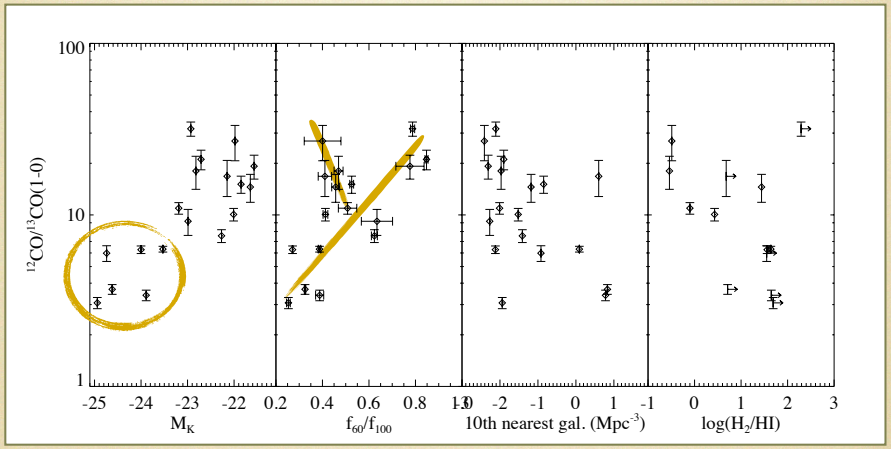
- E and S0s mostly seen in same range as spirals, Seyferts and starbursts
- But 3 galaxies have extremely low ratios, similar to what is observed for MW GMCs! (No diffuse molecular gas?)

$^{12}CO/^{13}CO$



- Galaxies with the lowest $^{12}CO/^{13}CO$ ratios are in the most luminous (massive) galaxies
- Some relation with dust (double branch: starburst and not)
- No clear dependence on environment or H_2/HI ratio

$^{12}CO/^{13}CO$



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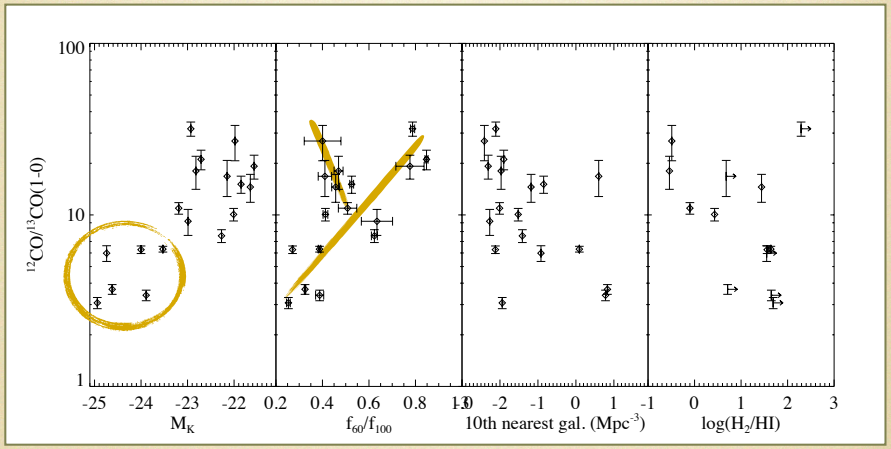
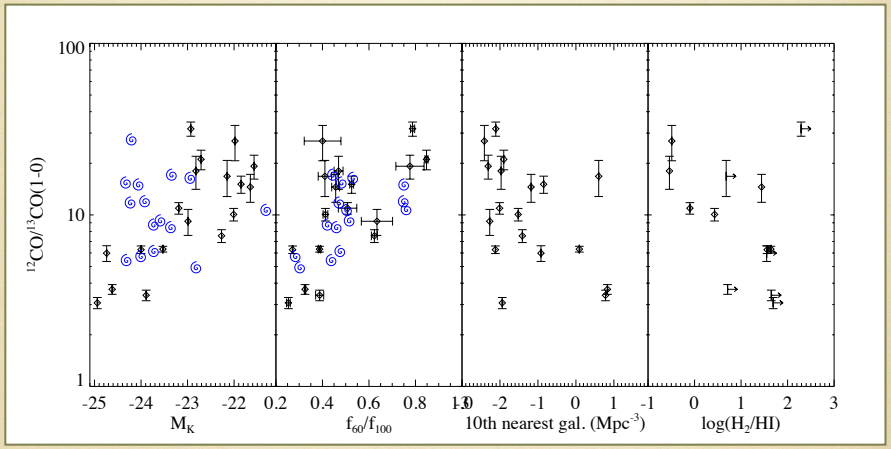


- Why? Some options:
  - low in coldest-dust galaxies -> fractionation
  - low in most massive/highest metallicity -> abundance
  - low in most massive/lowest turbulence gas -> optical depth

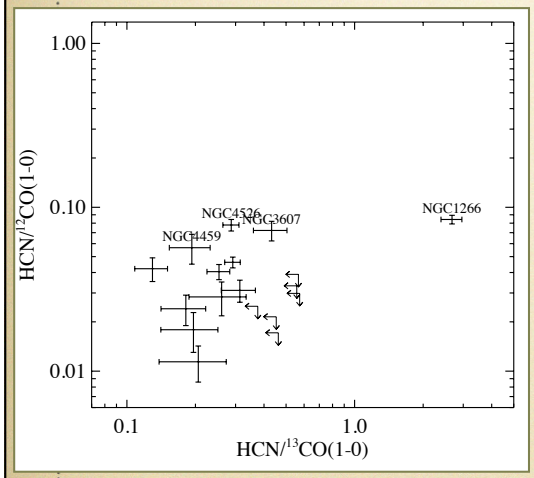
$^{12}CO/^{13}CO$



- Comparison to spirals (Paglione+01)
- Overlap with dust temp, not with mass (if fractionation partly to blame, also working similarly in spirals)

HCN/CO

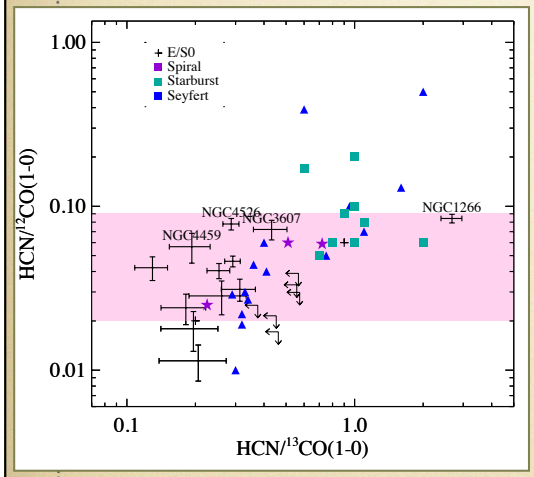
Low dense gas fraction → High dense gas fraction



- Consider HCN/^{13}CO as tracing the fraction of dense molecular gas
- Smallish range 0.1-0.5
- Also the unusual NGC1266 (molecular outflow galaxy, see Alatalo poster!)

HCN/CO

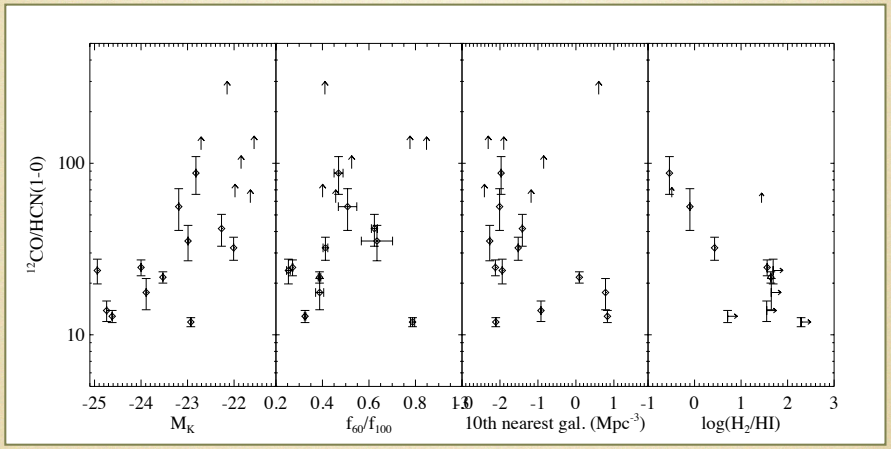
Low dense gas fraction → High dense gas fraction



Compilation of Seyferts and starbursts from Krips et al. 2010

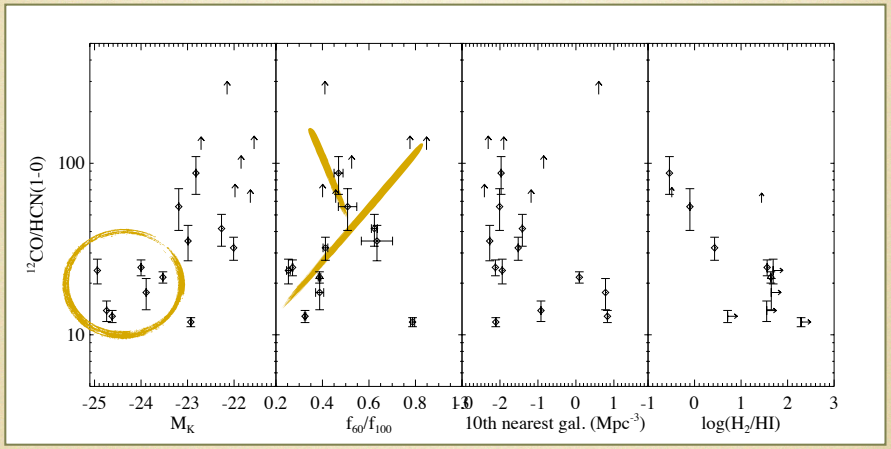
- E and S0s are to the low side- lower than starbursts, Seyferts, possibly spirals
- Thus inefficient at making densest gas.
- 3 optically thick galaxies again 'short' on ^{12}CO

$^{12}CO/HCN$



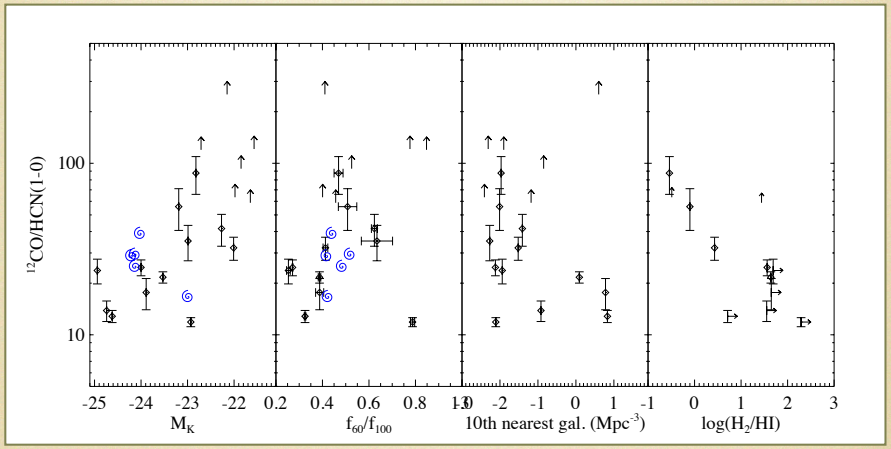
- Again, massive galaxies low in ^{12}CO- not just a ^{12}C vs ^{13}C effect!
- Most likely culprit: high optical depth in ^{12}CO on a global scale for these galaxies.
- Same basic pattern with dust temp (except 1266)

$^{12}CO/HCN$



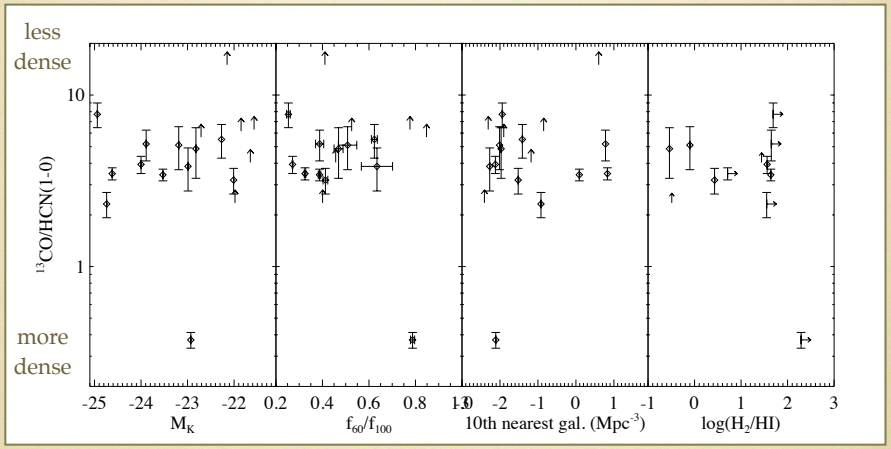
- Again, massive galaxies low in ^{12}CO- not just a ^{12}C vs ^{13}C effect!
- Most likely culprit: high optical depth in ^{12}CO on a global scale
- Is correlation with mass or dust temp more fundamental, or all related to lower turbulence/increased self-absorption?

HCN/^{12}CO



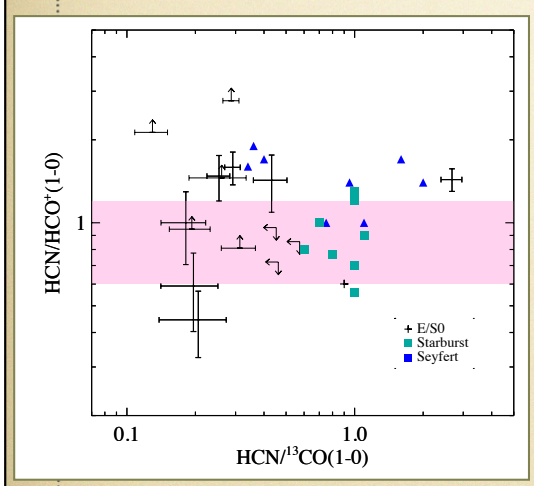
- Add 'normal' spirals from Gao & Solomon 04 (< 10^{10} L_{sun} in FIR)

HCN/^{13}CO



- No clear correlation with luminosity, dust temp, environment or H_2/HI ratio for HCN/^{13}CO
- No uniform spiral comparison sample

HCN/HCO+



- Wider spread in HCN/HCO+ than seen in local GMCs (pink range), but big error bars
- Effect of AGN for some, but not all have an AGN...
- Some other chemical effect?

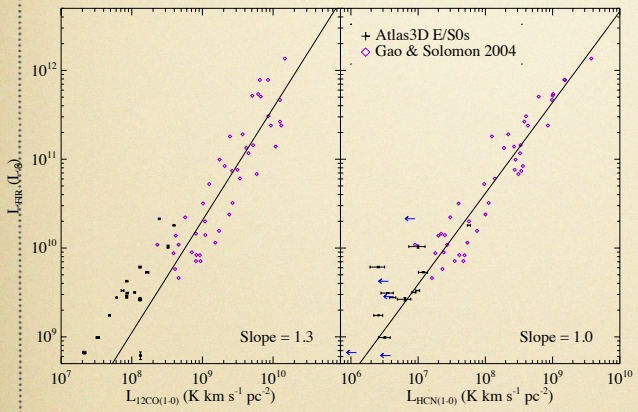
Conclusions

- Most early-type galaxies broadly resemble spirals in terms of $^{12}CO/^{13}CO$, $HCN/^{13}CO$ and $HCN/^{12}CO$ ratios
- More luminous (massive) early-types have more optically thick ^{12}CO (possible effect of lower turbulence)
- Dust temp also correlates with diffuse molecular content (cold dust, less diffuse), but double-branched
- Some interesting HCN/HCO+ ratios, but need to be better understood

Other work and ALMA

- LVG modeling by Bayet (see poster for first results!)
- Herschel line studies of these galaxies (SPIRE FTS + PACS spectroscopy)
- ALMA will enable resolved studies of these high-density tracers in ETG
- ALMA's increased sensitivity will also allow us to probe below these brightest (and most peculiar) ETG to 'normal' star forming ETG
- Of course, need sample readjustment to South...

HCO^+


+ Atlas3D E/S0s
◇ Gao & Solomon 2004
Slope = 1.3
Slope = 1.0
L_{FIR} ($L_\odot$)
$L_{12CO(1-0)}$ (K km s^{-1} pc^{-2})
$L_{HCN(1-0)}$ (K km s^{-1} pc^{-2})