The 25 Meter Telescope and Studies of Nearby Galaxies

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Spectral Lines Available at at High Site

Species	Transition	E.P.[1]	λ (μm)	A (s^{-1})	n_{crit} (cm^{-3})[2]
N^+	$^3P_1 \rightarrow {}^3P_0$	70	205.178	2.1×10^{-4}	4.8×10^{1}
C^0	$^3P_2 \rightarrow {}^3P_1$ $^3P_1 \rightarrow {}^3P_0$	63 24	370.415 609.135	2.7×10^{-7} 7.9×10^{-8}	1.2×10^{3} 4.7×10^{2}
^{12}CO	J = 13→12 J = 11→10 J = 7 → 6	503 430 155	200.273 236.614 371.651	2.4×10^{-4} 1.6×10^{-4} 3.6×10^{-5}	5.6×10^{6} 3.7×10^{6} 3.9×10^{5}
^{13}CO	J = 6 → 5 J = 6 → 5	116 111	433.338 453.497	2.2×10^{-5} 2.0×10^{-5}	2.6×10^{5} 2.3×10^{5}

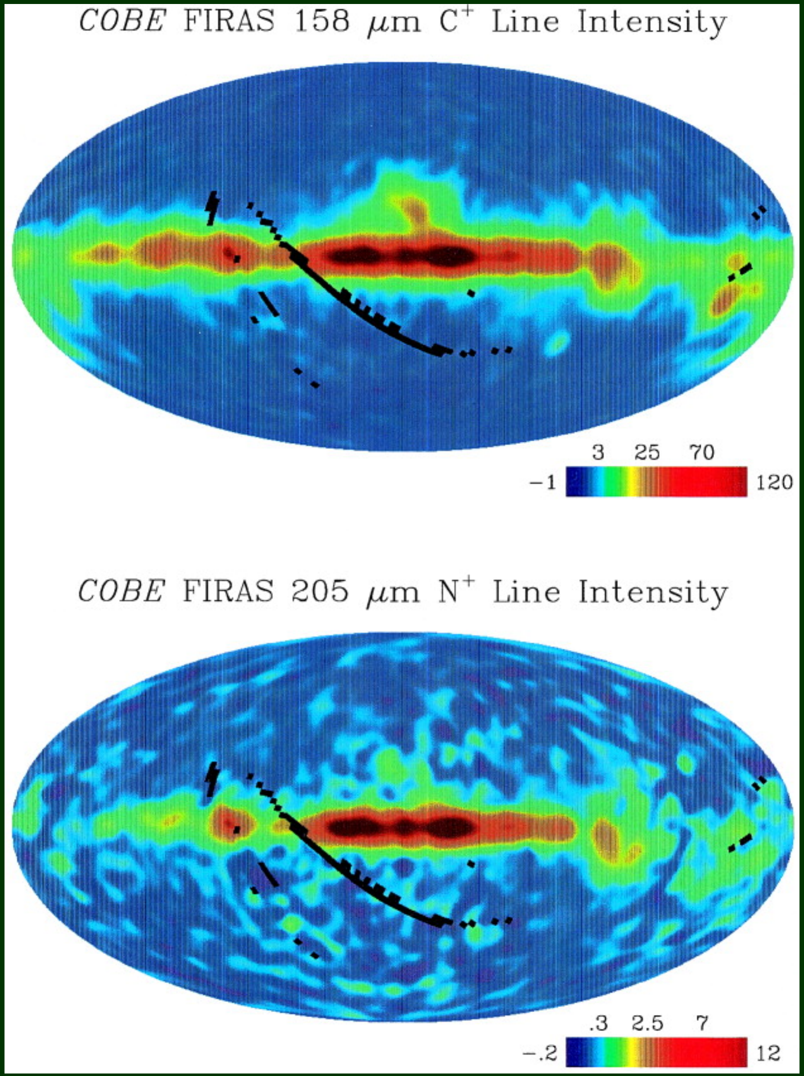
[1]Excitation potential, energy (K) of upper level above ground.
[2]CO: Collision partner H_2 (100 K). [CI]: H & H_2, [NII]: e^-.

Critical Densities, Energy above ground ensure:

- Important astrophysical probes of ionized gas, molecular clouds, photodissociation regions, shocked regions, and astro-chemistry
- Important cooling lines for much of the ISM

COBE FIRAS Spectrum of the Galaxy

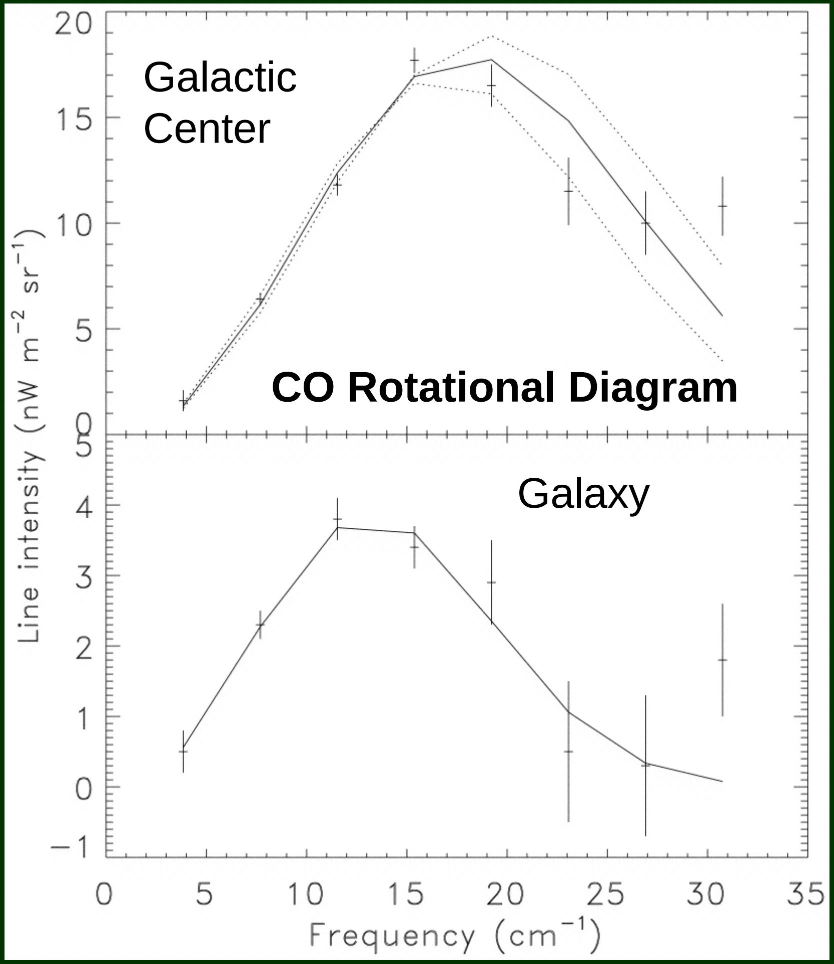
- [CII] line is strongest cooling line from Galaxy ($L \sim 6 \times 7\ L_{\odot}$)
  - Cools molecular cloud surfaces,atomic clouds, and HII regions
- [NII] lines ~ 1/6 and 1/10 as bright as [CII]
  - Important coolants for low density ionized gas
  - Line ratio yields ionized gas density.
  - [NII] $^3P_1$-$^3P_0$ (205 μm) line has same density dependence as [CII] for ionized gas $\Rightarrow$ constrains fraction of [CII] from ionized medium



COBE FIRAS Spectrum of the Galaxy

- CO rotational transitions up to J = 8-7 detected
  - Strength of mid-J lines indicates substantial amounts of warm (T> 40 K), dense gas
  - Gas is particularly high excitation in the inner regions of the Galaxy
- [CI] lines are ubiquitous
  - Cooling in lines together amounts to total cooling in all of the CO lines
  - Line ratio is near unity, temperature sensitive

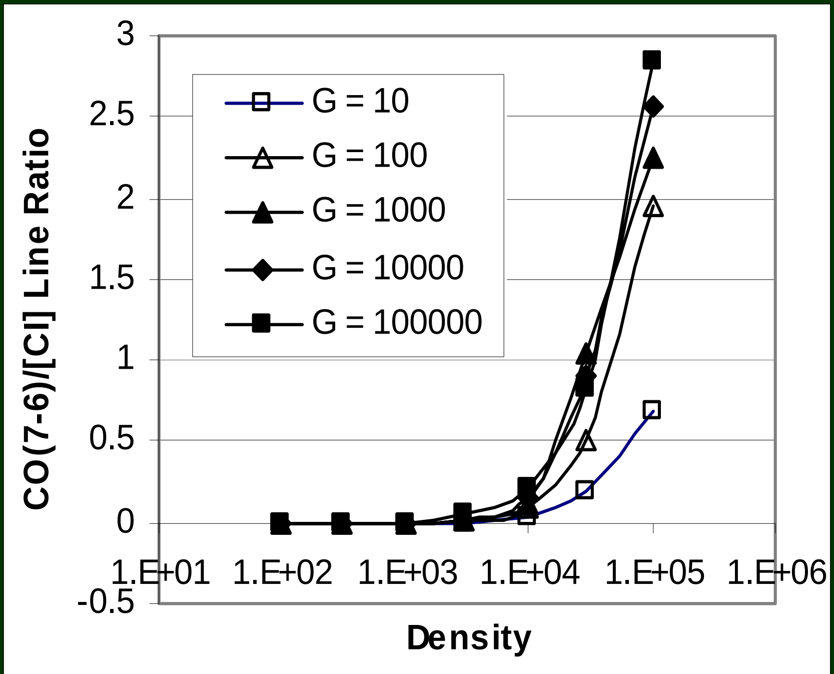
$\Rightarrow T_{gas} \sim 40$ K



The [CI] and CO(7-6) Lines

- [CI] line ratio gives T_{gas}
- Run of CO line intensity with J constrains molecular gas pressure
- The CO(7- 6) and [CI] $^3P_2$-$^3P_1$ (370 μm) lines are only 1000 km s^{-1} (2.7 GHz) apart – easily contained in one extragalactic spectrum ⇒
  - Excellent relative calibration
  - "Perfect" spatial registration

This line ratio of particular interest, as it is very density sensitive



CO(7-6)/[CI] 370 μm line intensity ratio vs. density for various values for the strength of the ISRF (Kaufman et al. 1999)

The Extragalactic Niche

- Low surface brightness in the short submm (200, 230, 350, and 450 um) windows:

  It can be shown that the Atacama 25 m telescope is competitive per beam with any other terrestrial telescope existing or planned at these wavelengths

  -- *This is especially true for continuum work* --

- Extragalactic work requires modest resolving powers: $R = \lambda/\Delta\lambda \sim 1000$ to 10,000, or $\Delta v \sim 300$ to 30 km s^{-1}

  This can be achieved with direct detection spectrometers $\Rightarrow$ significant sensitivity advantages possible

- Nearby galaxies are extended $\Rightarrow$ multiple beam systems are desirable

  At present, large format spectrometers are easier to implement with direct detection systems.

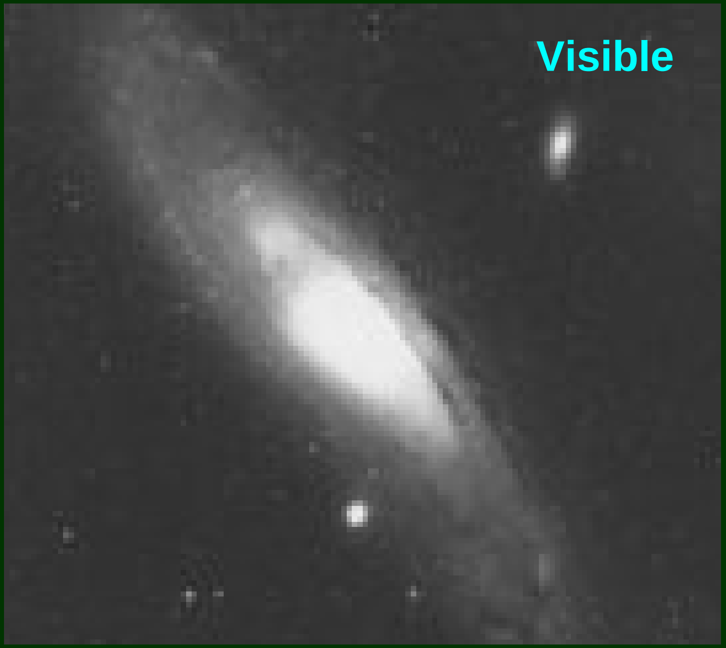
Continuum Observations of Galaxies

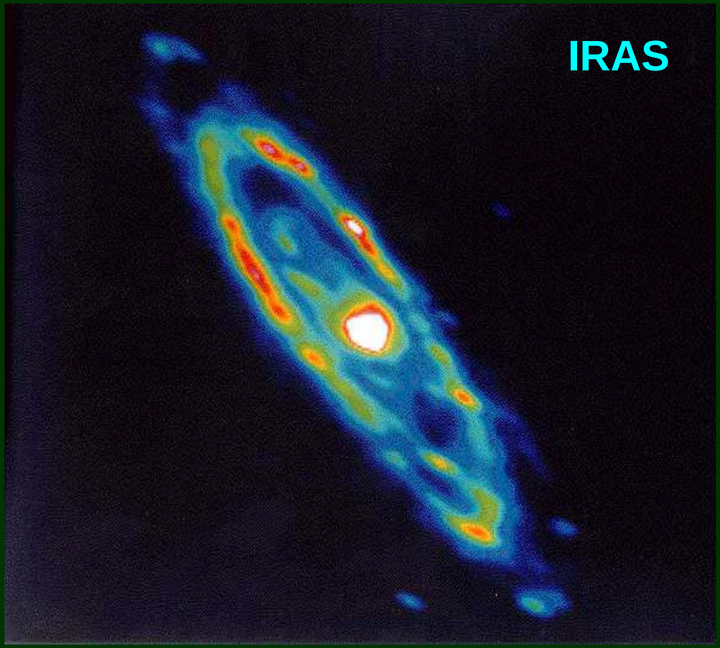
- The far-IR continuum emission from galaxies traces the deposition of optical starlight from nearby OB stars, or the diffuse ISRF

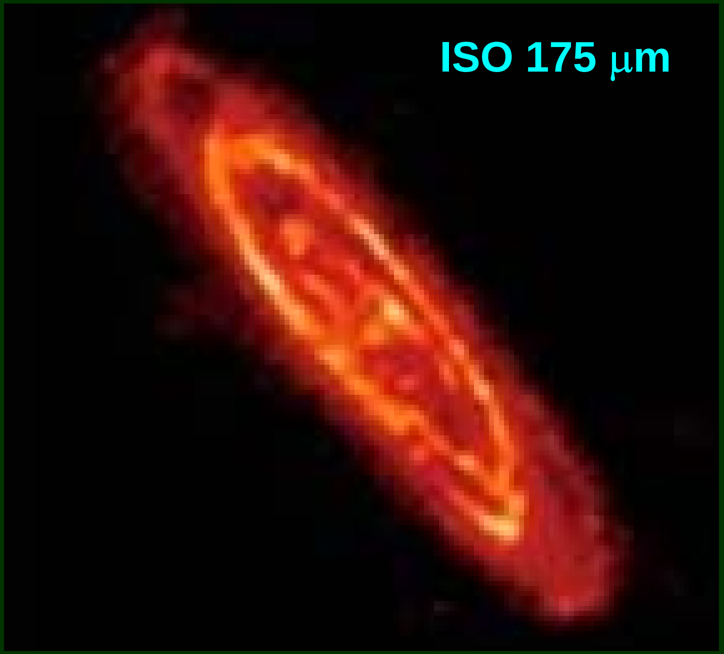
  – *traces regions of star formation in an extinction free manner.*
- Dust that peaks at 200 um is quite cold T ~ 20 K – trace the luminosity and mass of cold dust
- For warmer dust, the submm colors are insensitive to T, since we are typically in the Rayleigh-Jeans tail.
- However the warme dust properties are constrained by examining the apparent emissivity law.
  - Temperature and emissivity law yield dust column (mass)
  - Combined with shorter wavelength observations, we get the far-IR luminosity of the galaxy e.g. 38 or 60 um SOFIA observations, for which θ_{beam} = 3.8” and 6” respectively.

Continuum Observations

- The far-IR and visible morphologies of galaxies may often be quite different
- IRAS and ISO imaging of the (optically) Sb galaxy M31 reveal a ring of cool dust – no spiral pattern is visible
- There is also warm dust (star formation) in the nucleus







M31:
Haas et al. 1998

Continuum Observations of M31

- Most of the dust has a temperature of only 16 K – much cooler than inferred from IRAS data
- The warm dust/cool dust ratio varies little across the galaxy $\Rightarrow$ evidence for distinct dust populations
- Cold dust mass ~ $3 \times 10^7 M_\odot$ ten times greater than that inferred from IRAS data alone!
- New dust mass, even if distributed uniformly would make the disk of M31 moderately opaque in the visible (A_V ~ 0.5)

Far-IR Continuum: Revealing the Starburst

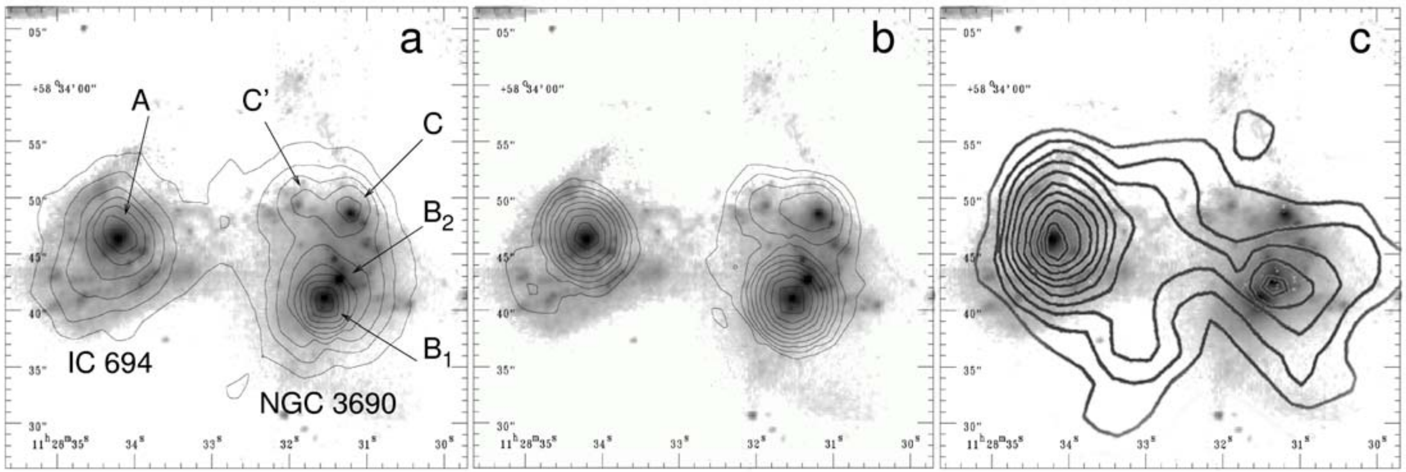


FIG. 1.— a) An ISOCAM 7 μm image of Arp 299 (adapted from Gallais et al. 1998) overlayed on an HST/NICMOS 2.2 μm image from (Alonso-Herrero et al. 2000), were the different components of the galaxy are marked. The 9 contour levels are set with logarithmic spacing between 1 and 33 mJy arcsec^{-1}. b) Same as in a) but using the ISOCAM 15 μm image as an overlay having set the contour limits to 6 and 60 mJy arcsec^{-1}. c) Our 37 μm over the same HST image. The contour levels are 1.5 Jy beam^{-1} beginning at 3 Jy beam^{-1} (6 σ).

Charmandaris, Stacey and Gull 2002)

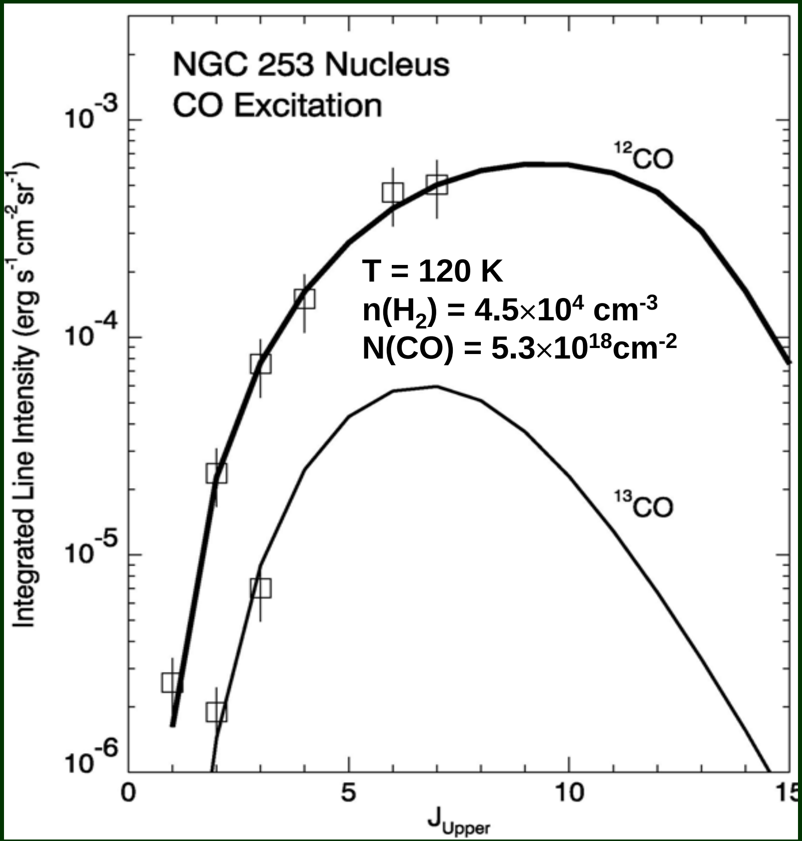
- For IR luminous galaxies, the submm continuum (esp. together with far-IR continuum) traces the far-IR luminosity in an extinction free manner so it reveals the locations and luminosity of the starburst
- For example, in the Arp 299 interacting system, components “B” (NCG 3690 nucleus) and “C” (overlap) appear equally important with “A” (IC 694 nucleus) at even mid-IR wavelengths.
- However, at 38 um the continuum traces reveals that most (~ 75%) of the emission arises in the nucleus of IC 694!

Submm Line Observations: The [CI] and mid-J CO Lines

- The CO(6-5) line first reported from a few starburst nuclei in 1991 (Harris et al. 1991)
  - Run of CO line intensity with J constrains molecular gas conditions
  - Gas is both warm, and dense – modeling was fit into a PDR (stellar UV heating) scenario
- Since then, several galaxies have been detected, and many mapped in the lower J [CI] (610 um) line:
  - The [CI] line intensity traces C^o column (high T, high n limit)
  - The [CI] line is an excellent tracer of molecular clouds in galaxies, *perhaps better than CO* (Gerin and Phillips, 1999)
  - The combined cooling in the [CI] lines is comparable to the CO line cooling – most (85%) of this is in the 370 um line.
  - There is a very high C^o/CO abundance ratio (~ 0.5) in these galaxies – much higher than Milky Way values. This is either due to:
    - Fractionally more photodissociated gas due to cloud fragmentation
    - More C^o produced molecular cloud interiors due to chemical processes associated with high cosmic ray fluxes or non-equilibrium chemistry

Mid-J CO Observations of Galaxies

- Recently, Bradford et al (2002) mapped the starburst nucleus of NGC 253 in the CO(7-6) line.
- They find that find that the run of ^{12}CO and ^{13}CO lines can be modeled as a single component!
  - Warm molecular gas mass ~ 10 - 30 times the PDR gas mass as traced in its [OI] and [CII] line emission
  - PDR scenarios fail to account for heating of this much molecular gas
  - The most likely source of the heating is the strong (800 x MW value) cosmic ray flux from the starburst
  - Also provides a natural mechanism for heating the entire volume of the gas.

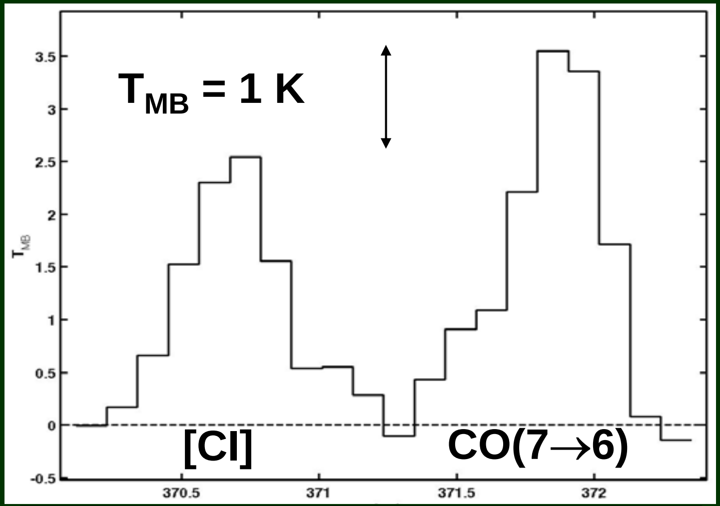


Integrated ^{12}CO and ^{13}CO line intensities from the nucleus of NGC 253 together with our adopted model of the excitation (Bradford et al. 2002)

The [CI] and mid-J CO Observations of Galaxies

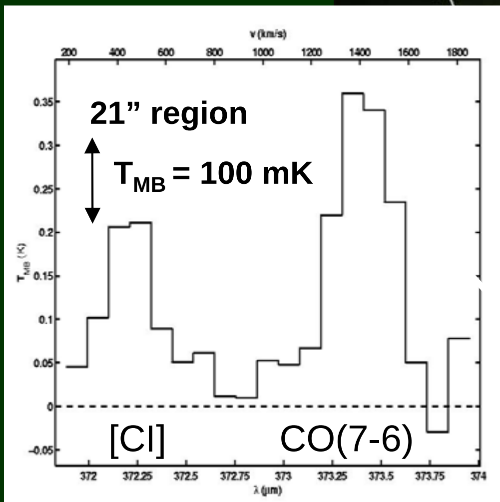
- Recently we have detected and mapped the [CI] and CO(7-6) lines simultaneously from NGC 253:
  - The line ratio is density sensitive: strength of CO(7-6) ⇒ very dense ISM
  - The [CI] (370 um)/(610 um) line ratio (~ 1.9) is sensitive to gas temperature, and yields T_{gas} > 100 K as for the CO gas
  - From distribution and physical conditions, C^o and CO well mixed

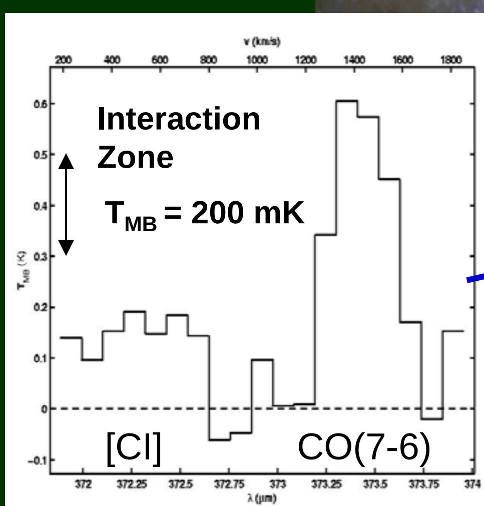
⇒ Cosmic ray enhancement of C^o abundance

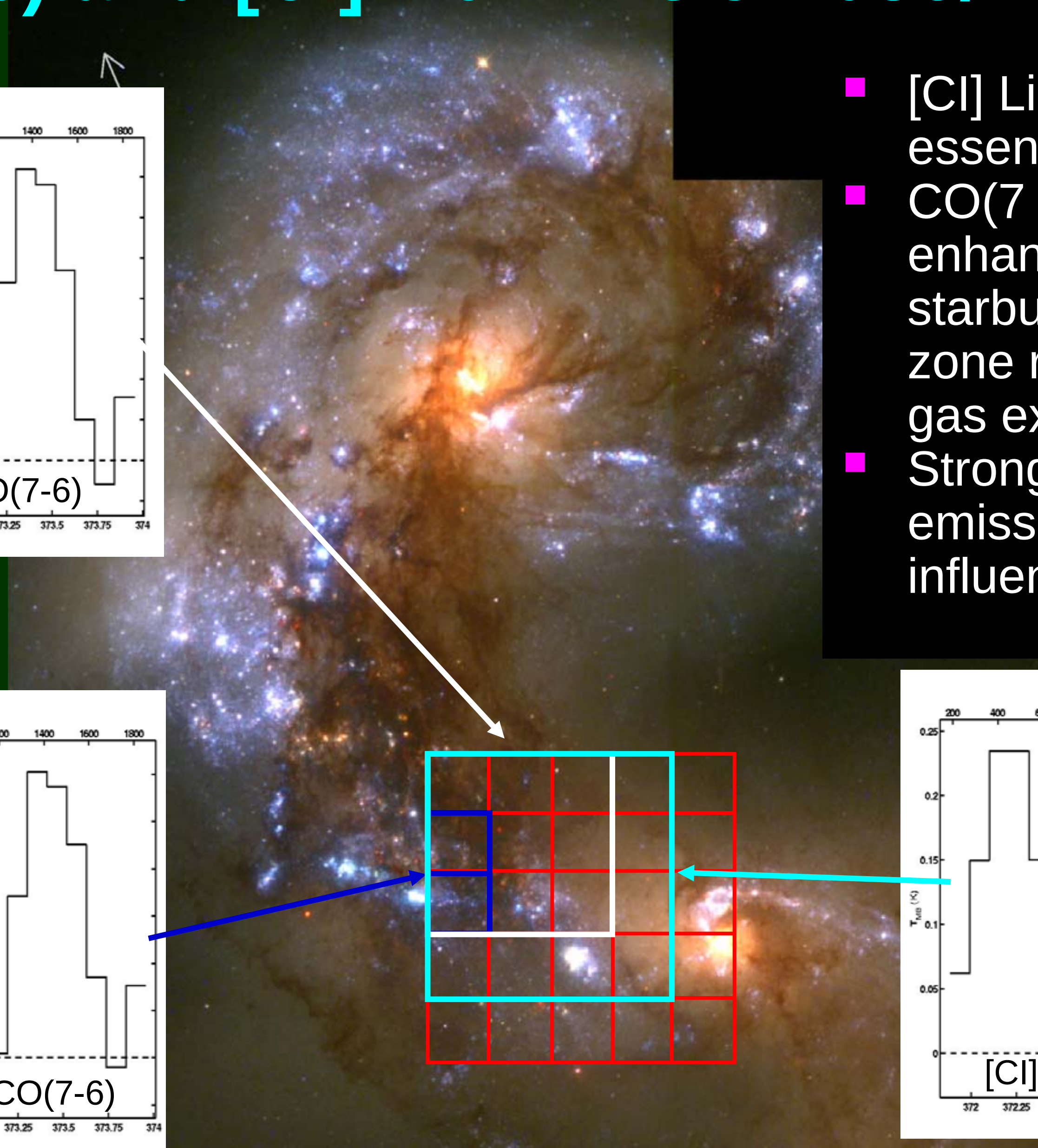


SPIFI-JCMT [CI] 371 um & CO(7→6) (372 um) spectrum of the NGC 253 nucleus.

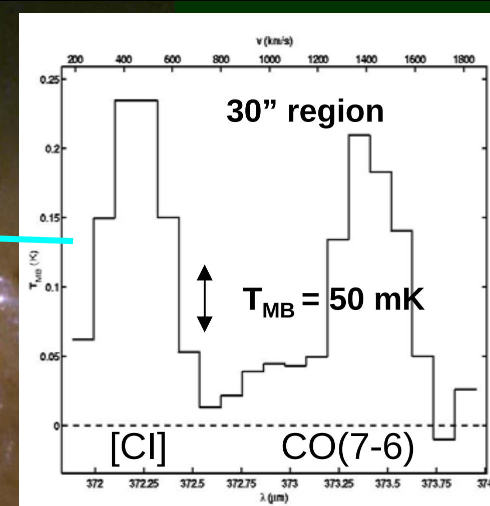
CO(7-6) and [CI] from NGC 4038/4039



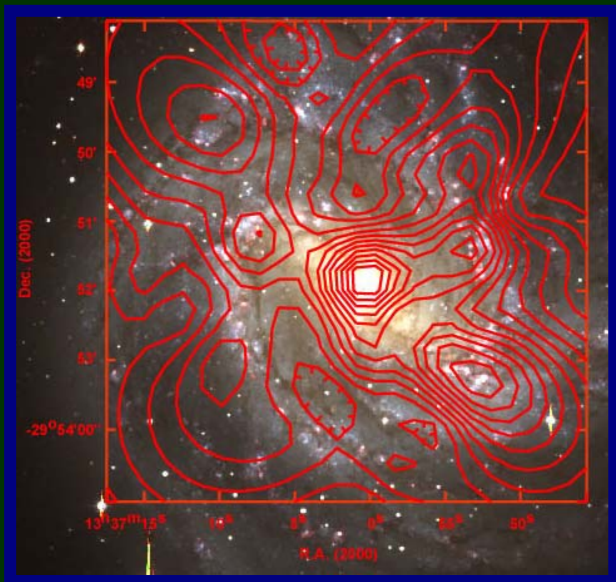




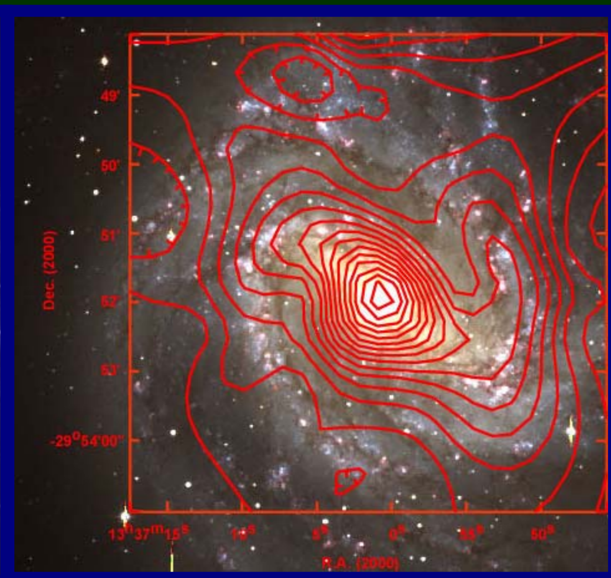
- [CI] Line intensity essentially constant
- CO(7 → 6) greatly enhanced at the starburst interaction zone reflecting the high gas excitation there
- Strong mid-J CO emission reflects influence of OB stars



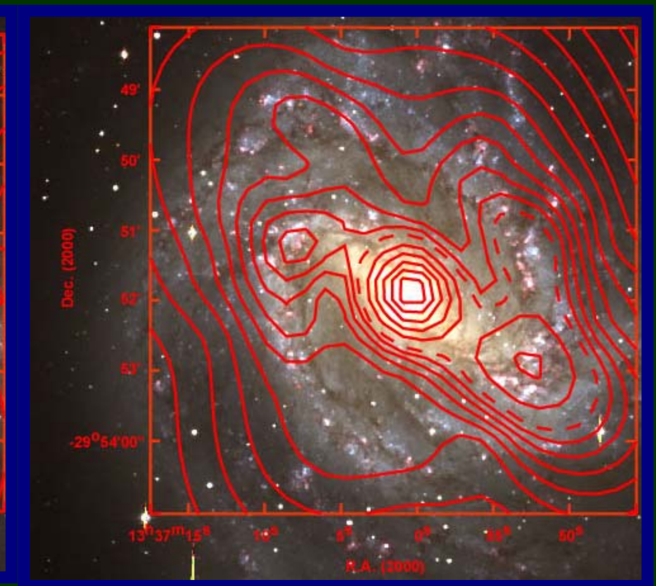
Bars, Spiral Arms, and Starformation: M83



ISO: [OIII] 88 μm



ISO: [NII] 122 μm

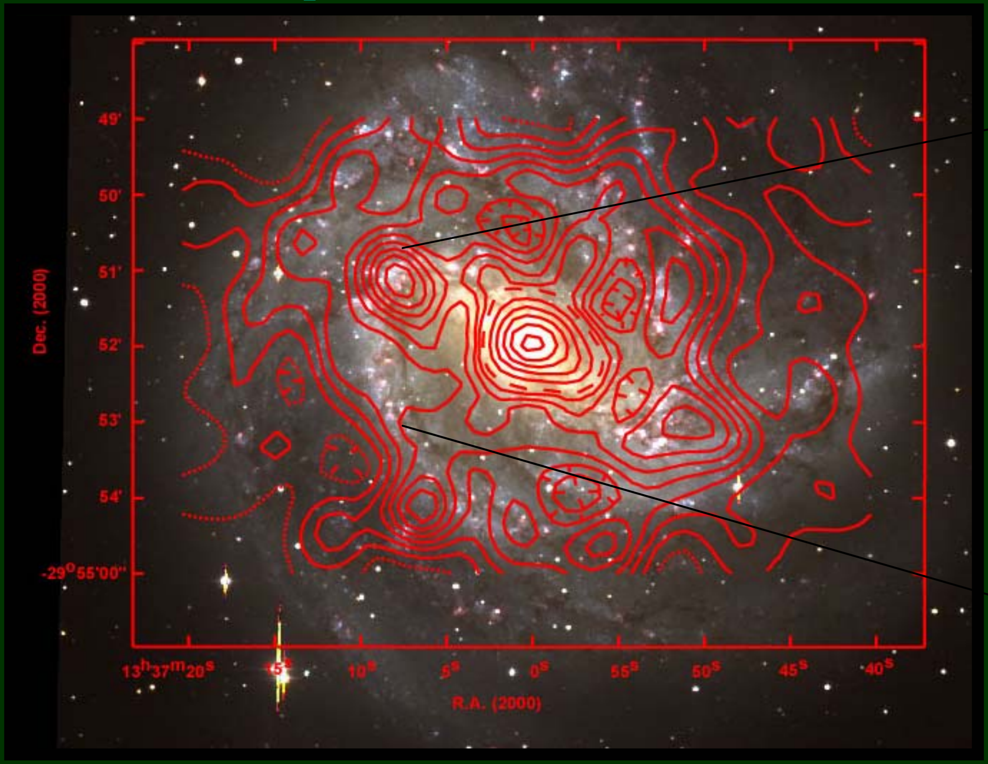


ISO: [CII] 158 μm

Nearby galaxies are easily imaged in the [NII], [CI] and mid-J CO lines

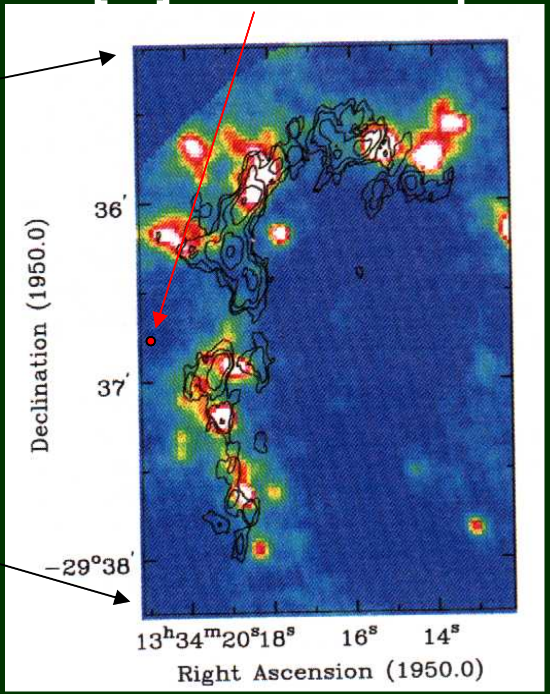
- Spiral arms/inter-arm contrast highest for [OIII] 88 μm line ⇒ earliest type stars (star formation) reside in the spiral arms
- At bar/spiral arm interfaces, [OI], [CII], & [OIII] strongly enhanced ⇒ greatly enhanced starformation activity similar to Orion interface region 0.2 pc from Θ^1C! Expect strong mid-J CO line emission there.
- The SW bar region strong in Hα and CO as well (e.g. Kenney & Lord, 1991) ⇒ *Orbit crowding likely triggers a massive burst of starformation*

Bars, Spiral Arms, and Starformation: M83



KAO Map in [CII] 55” Beam (Geis et al.)

3” [CI] beam ⇔ 70 pc

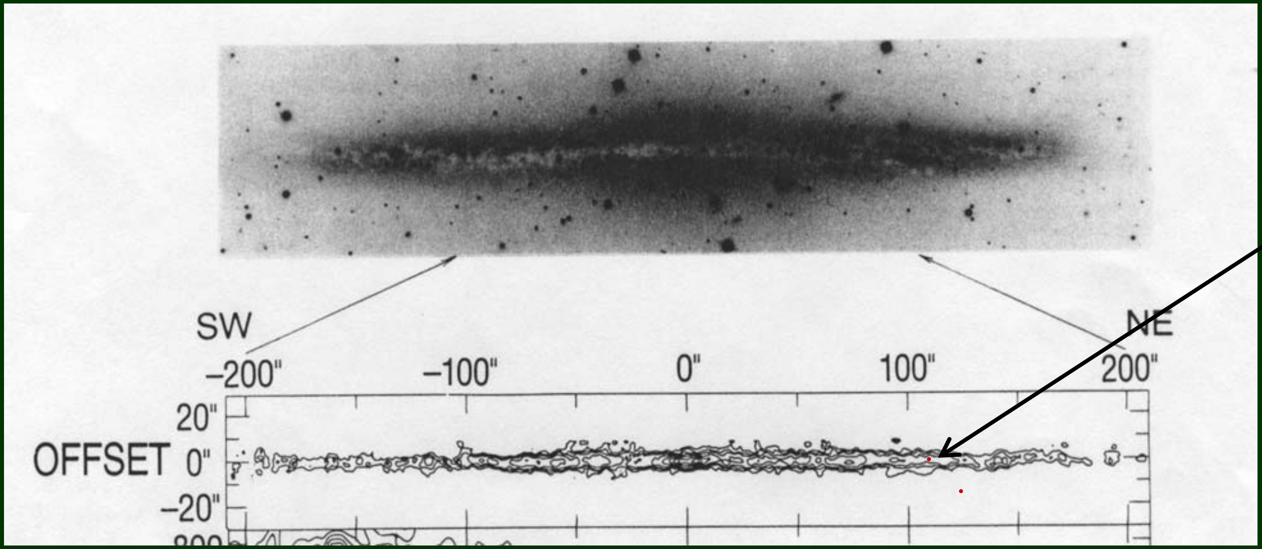


6” Resolution CO (1-0) Map on false-color HI (Rand Lord, & Higdon 1999

Can easily resolve spiral arms:

Tracing far-IR continuum, ionized gas ([NII]), atomic/molecular gas [CI] and dense molecular gas (mid-J CO) as the interstellar medium is compressed and recycled in spiral density waves and bar structures.

Edge on Galaxies: NGC 891



2" beam ⇔100 pc

Easy to image nearby edge-on galaxies in the lines and continuum tracers

- Scale height of ISM – energetics -- super bubbles, chimneys
  - [NII] as extinction free, low excitation probe of ionized gas
  - [CI] traces atomic and/or molecular ISM
  - Regions of high mass star formation should appear in the mid-J CO lines
- Far-IR continuum, star formation and cold dust
- At 10 Mpc, 2" ⇔ 100 pc
- Scoville et al find CO(1-0) scale height ~ 200-300 pc

Seyferts Galaxies: Detecting the Torus?

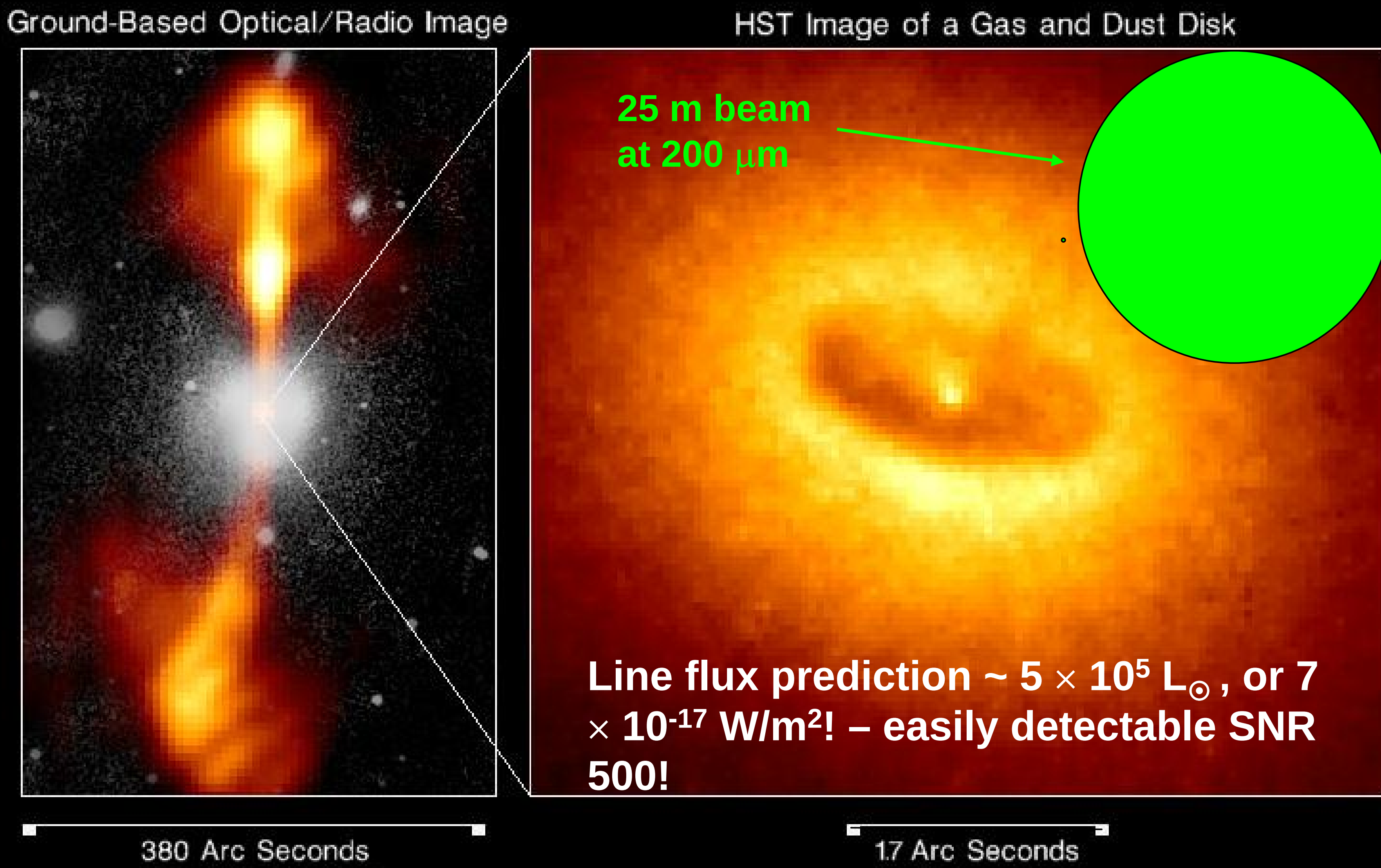
Dominant paradigm is that the jets often seen emanating from the nuclei of active galaxies are confined by a pc scale dense molecular torus

- Krolik and Lepp (1989) predicted that this torus would be very warm (1000 K) and dense (~ 10^7 cm^{-3}):
  - CO molecule pumped up to very high rotational levels
  - Low and mid-J line emission may be difficult to detect due to intervening molecular ISM heated by starburst – in warm, optically thick cloud, the luminosity is proportional to J^3.
  - Key to detection is spatial resolution – to pull the CO emission out of the foreground gas
  - Also need very high sensitivity in the far-IR rotational lines
  - 25 m Atacama telescope might just be the tool – J = 13 – 12 and J = 11-10 lines come through in 200 and 230 um windows.
  - Beam size at 20 Mpc ~ 200 pc – still quite some beam dilution!

Core of Galaxy NGC 4261

Hubble Space Telescope

Wide Field / Planetary Camera



Conclusions

- A powerful Atacama 25 m niche is low resolution spectroscopy of extended extragalactic sources
- The submm continuum is used to trace dust properties and mass, and (together with far-IR continuum) deposition of energy
- Submm lines trace physical properties of ionized, atomic and molecular gas in an extinction free manner
  - Easily excited for typical ISM parameters

    $\Rightarrow$ Are important, if not dominant coolants
- Will study star formation in ULIGs, interacting galaxies, normal spirals, etc, and possibly detect confining torus for Seyfert galaxies.