Journal Club Presentation on "The BIMA Survey of Nearby Galaxies. I. The Radial Distribution of CO Emission in Spiral Galaxies" by Regan et al.

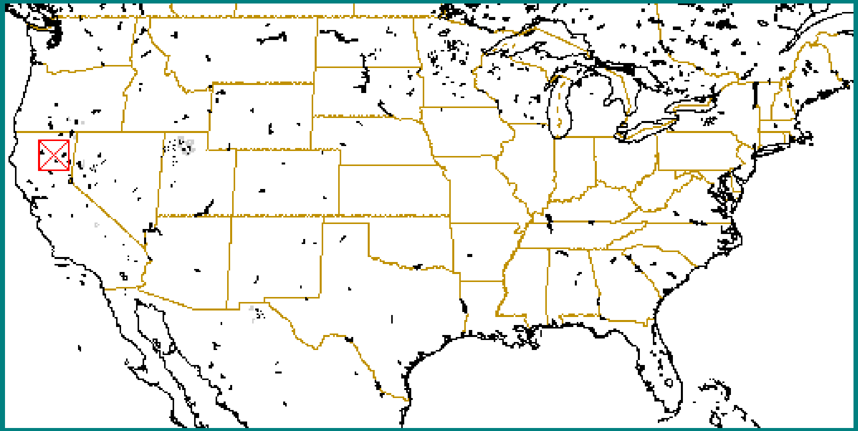
ApJ, 561:218-237, 2001 Nov 1

Fun With Acronyms

- BIMA
  - Berkely
  - Illinois
  - Maryland
  - Association
- SONG
  - Survey
  - Of
  - Nearby
  - Galaxies

BIMA millimeter interferometer

- 10 antennas
- Was located near Hat Creek, California
- Now relocated to Cedar Flat in California, along with the Owens Valley Radio Observatory (OVRO) to form the new Combined Array for Research in Millimeter-wave Astronomy



The New CARMA Array

Why study molecular gas?

- Molecular gas fuels star formation in the Milky Way and in other galaxies. Important to studies of:
  - Triggered star formation in spiral arms
  - Nuclear starbursts
  - Increased star formation seen at ends of bars
- Also, inflow of molecular gas to nuclear region can affect galaxy evolution; may:
  - Change in the central mass concentration
  - Cause a bar to be destroyed

CO as a tracer of H_2

- Most of our knowledge about molecular gas in galaxies comes from studies of carbon monoxide (CO) emission
  - Unlike H_2, CO has a permanent dipole moment
    - Cannot detect H_2 directly in molecular clouds; instead use CO as a tracer
  - CO emits photons with wavelength 2.6 mm when it undergoes the rotational transition J = 1-0
    - Frequency ~ 115 GHz
    - One photon says to another, “Hey man, what’s ‘new’?”

Previous studies of CO in galaxies

- FCRAO Extragalactic CO Survey
  - Young et al. 1995
  - Spectra from 1412 positions in 300 galaxies
  - Showed how molecular content of galaxies depends on Hubble type, luminosity
- Small scale distribution and physical conditions of molecular gas in galaxies still poorly understood
  - Most previous extragalactic observations have been carried out using single-dish telescopes with poor angular resolution
    - Linear resolution ~ many kpc
      - This is 100X larger than a typical giant molecular cloud

Previous studies of CO in galaxies

- Need to use an interferometer in order to get the sub-kpc resolution necessary to study the detailed distribution of molecular gas in galaxies outside of the local group.
  - Sakamoto et al. 1999
    - Mapped the central (within 30” from center) CO distribution in 20 nearby spiral galaxies
    - Focus on how distribution of molecular gas differs for galaxies with and without strong nuclear activity

Motivation for this paper

- Previous interferometer-only studies have suffered from limited field of view and possible “missing flux”.
  - Interferometers are very good at picking up the small scale variations in flux, but can have problems measuring the overall flux level.
    - Smallest baseline (shortest antenna separation) determines largest angular scale you are sensitive to.
    - Imagine trying to build a function f(x) as a sum of sines and cosines of various wavelengths, but not knowing the constant term very well.
  - This makes it difficult to quantitatively compare the molecular (from radio observations of CO) and stellar distributions (from optical or near infrared observations).
- Single-dish only studies are useful for measuring the absolute CO flux, but suffer from poor resolution.
- To get a more complete understanding of the distribution of molecular gas on sub-kpc scales in galaxies, it is necessary to combine both single-dish and interferometer data, and this is the goal of the Regan et al. paper.

BIMA SONG

- This survey produced spatial-velocity data cubes of the centers and inner disks of 44 nearby spiral galaxies.
  - Angular resolution ~ 6”
  - Spatial resolution ~ few hundred parsecs
  - Velocity (spectral) resolution ~ 10 km/s
  - Field of view ~ 10 kpc (~190”)
- Over half of the 44 galaxies were also observed with a single-dish radio telescope (NRAO 12 m).
  - This sub-sample does not suffer from the “missing flux” problem.

NRAO 12 m (now ARO 12 m) Kitt Peak, Arizona

BIMA SONG

- How does this survey differ from previous high-res CO surveys?
  - Sample selection
    - Not based on CO brightness; instead, includes all nearby bright spirals with acceptable declinations and inclinations.
  - Field of view
    - Observed a much larger area, covering a significant portion of the optical disk.
  - Uniform observation and data reduction procedures
  - Incorporates single-dish data
    - Over half the galaxy maps include single-dish data so that all the CO flux can be observed for these galaxies.

Main research question

- "What is the radial surface brightness distribution of molecular gas and how does it compare to that of the stars?"
  - Expect the radial distributions of stellar light and molecular gas to be similar because *stars form from molecular clouds*.
    - This has been studied before, but with conflicting results:
      - Young & Scoville (1982) found similar scale lengths for both single-dish CO and optical *B*-band.
      - Sakamoto et al. (1999) found that scale length of CO (using interferometer-only data) was only ~500 pc, a small fraction of the scale length for stellar light.
      - What's going on here?

Comparison to Optical, NIR

- This paper focuses on a sub-sample of 15 galaxies for which Regan et al. had:
  - Near-infrared or optical images
  - Incorporated single-dish data in radio maps

Sample selection criteria

- Not explicitly based on the CO luminosity of the galaxies.
- Criteria
  - Hubble types between Sa and Sd
  - Heliocentric recessional velocity < 2000 km/s
    - Hubble distances < ~27 Mpc (based on 75 km/s/Mpc)
  - Inclination < 70 degrees
  - Declination > -20 degrees
    - Observable from Hat Creek Radio Observatory
  - Apparent blue magnitude brighter than 11.0
- Sample
  - 45 galaxies found to meet these criteria
    - Used NASA/IPAC Extragalactic Database (NED)
  - 44 of the 45 galaxies observed (excluded M33)
  - Average distance ~11 Mpc
    - 6” beam corresponds to ~330 pc at this distance

Sub-sample of 15 galaxies

- Paper focuses on 15 galaxies for which the authors have obtained both single-dish CO observations and optical or near-infrared images.
  - This sub-sample tends to be biased towards the brighter CO galaxies, but it’s distribution in Hubble type and bar type is fairly representative of the sample as a whole.

TABLE 2

Paper I Subsample

Galaxy	R.A. (J2000)	Decl. (J2000)	V_{LSR} (km s^{-1})	i (deg)	P.A. (deg)	Type	d (Mpc)	Distance Reference	CO Beam Size (arcsec)
NGC 0628......	01 36 41.70	+15 46 59.4	657	24	25	SA(s)c	7.3	1	7.1 × 5.2
NGC 1068......	02 42 40.74	−00 00 47.7	1136	33	13	(R)SA(rs)b, Sy2	14.4	1	8.9 × 5.6
NGC 2903......	09 32 10.05	+21 30 02.0	556	61	17	SAB(rs)bc, H II	6.3	1	6.8 × 5.5
NGC 3351......	10 43 57.98	+11 42 14.4	778	40	13	SB(r)b, H II	10.1	2	7.3 × 5.1
NGC 3521......	11 05 49.26	−00 02 02.3	805	58	164	SAB(rs)bc, LINER	7.2	1	8.7 × 5.6
NGC 3627......	11 20 15.07	+12 59 21.7	727	63	176	SAB(s)b, Sy	11.1	3	6.6 × 5.5
NGC 4258......	12 18 57.52	+47 18 14.2	448	65	176	SAB(s)bc, Sy1	8.1	4	6.0 × 5.3
NGC 4321......	12 22 54.84	+15 49 20.0	1571	30	154	SAB(s)bc, H II	16.1	5	7.2 × 4.9
NGC 4414......	12 26 27.19	+31 13 24.0	716	55	159	SA(rs)c?	19.1	6	6.3 × 5.0
NGC 4736......	12 50 53.06	+41 07 13.6	308	35	100	(R)SA(r)ab, LINER	4.3	1	6.9 × 5.0
NGC 4826......	12 56 44.24	+21 41 05.1	408	54	111	(R)SA(rs)ab, Sy	4.1	1	7.4 × 5.1
NGC 5055......	13 15 49.25	+42 01 49.3	504	56	81	SA(rs)bc, H II/LINER	7.2	1	5.8 × 5.4
NGC 5194......	13 29 52.35	+47 11 53.8	463	15	0	SA(s)bc-pec, Sy2.5	8.4	1	5.8 × 5.1
NGC 6946......	20 34 52.33	+60 09 14.2	48	54	65	SAB(rs)cd, H II	5.5	1	5.9 × 4.9
NGC 7331......	22 37 04.09	+34 24 56.3	821	62	172	SA(s)b, LINER	15.1	7	6.1 × 5.0

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

References.—(1) Tully 1988. (2) Graham et al. 1997. (3) Saha et al. 1999. (4) Maoz et al. 1999. (5) Ferrarese et al. 1996. (6) Turner et al. 1998. (7) Hughes et al. 1998.

BIMA SONG Observations

- BIMA millimeter interferometer in the C and D configurations
  - 1997 November through 1999 June
  - Baselines as short as 7.6 m (6.1 m antennas spaced as closely as possible)
  - Baselines as long as 90 m
  - 2/3 of galaxies observed using a 7-field hexagonal mosaic
    - Half-power mosaic FoV ~ 190” (~10 kpc)
    - 1 minute for each pointing; return to each pointing after ~8 minutes
      - Short enough to ensure excellent sampling of even the longest baselines in the *u-v* plane.
  - Remaining 1/3 of galaxies observed in single pointings
    - FoV ~ 100” FWHM
- NRAO 12 m
  - 1998 April through 2000 June
  - Orthogonal polarizations using redundant back ends:
    - two 256 channel filter banks at spectral resolution 2 MHz (5 km/s)
    - Digital millimeter autocorrelator at 600 MHz with 0.8 MHz resolution (2 km/s)

Optical/Infrared Observations

- Observations taken from the literature when available
- New observations taken at the
  - du Pont 2.5 m at Las Campanas
  - 0.9 m at Kitt Peak
  - 1.5 m at Palomar Observatory

TABLE 3

OPTICAL/INFRARED DATA

Galaxy	Band	Image Reference	$X-K$ Color	Photometry Reference
NGC 0628...	R	1	2.4	9
NGC 1068...	J	2	1.16	9
NGC 2903...	K'	3	...	
NGC 3351...	I	4	1.65	9, 10, 11
NGC 3521...	K'	5	...	
NGC 3627...	K'	3	...	
NGC 4258...	R	4	2.35	9
NGC 4321...	I	4	1.97	9, 12
NGC 4414...	K'	5	...	
NGC 4736...	R	4	2.17	13
NGC 4826...	R	4	...	9
NGC 5055...	K'	5	...	
NGC 5194...	K	6	...	9, 14
NGC 6946...	K	7	...	
NGC 7331...	R	8	...	9

REFERENCES.—Image references: (1)Ferguson et al. 1998. (2) Regan 2000. (3) Regan & Elmegreen 1997. (4) SONG complementary. (5) Thornley 1996. (6) Gruendl 1996. (7) Regan & Vogel 1994. (8) A. Ferguson 2001, private communication. Photometry references: (9) Aaronson 1977. (10) Tifft 1961. (11) Glass 1976. (12) Boroson, Strom, & Strom 1983. (13) Johnson 1966. (14) Ellis, Gondhalekar, & Efstathiou 1982.

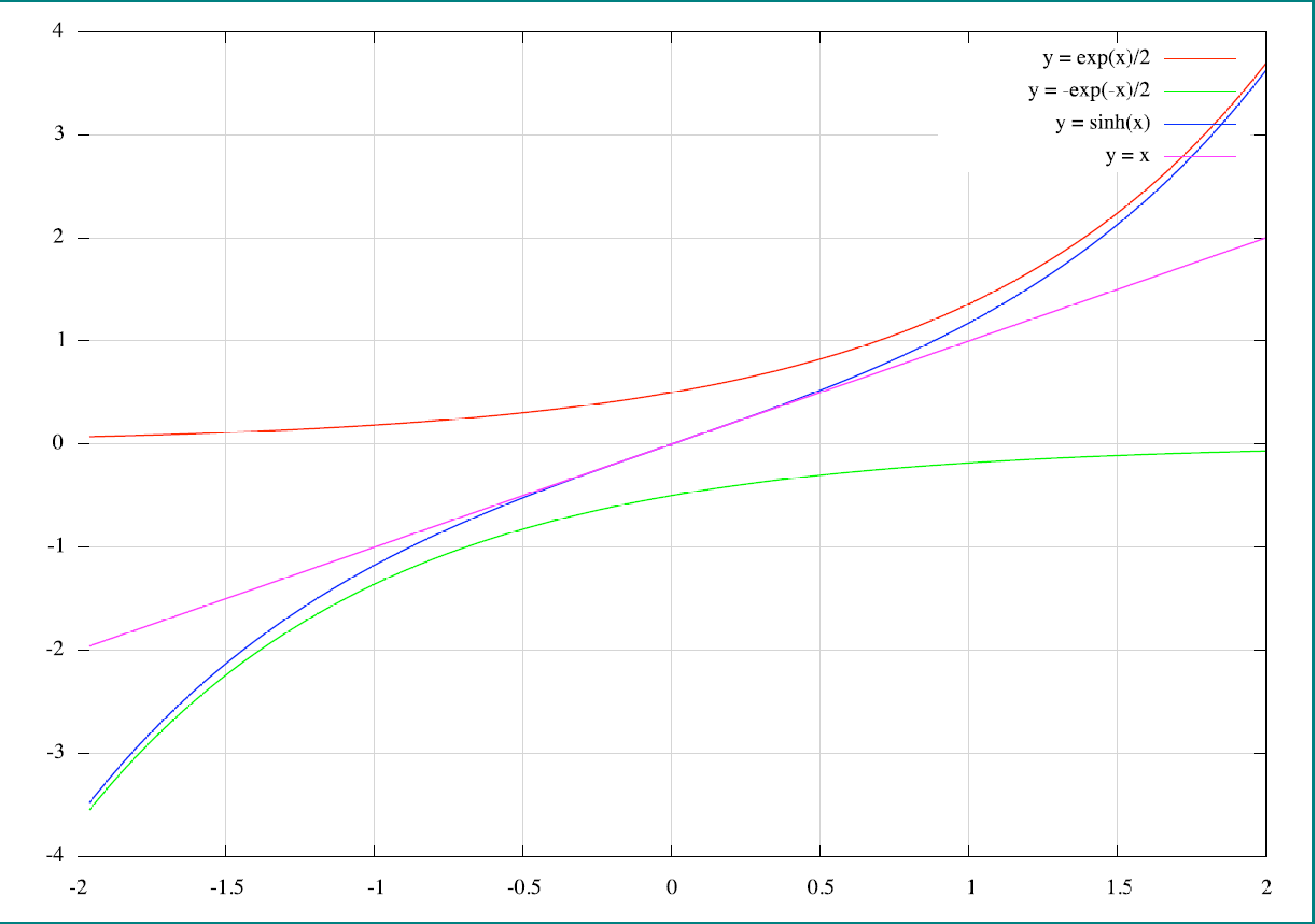
CO Data Reduction and Calibration

- Corrected for phase drift of antennas relative to each other due to differences in column density of water vapor across the array.
- Nearby quasar used for phase calibration as well as amplitude calibration.
  - Quasar flux determined using Mars or Uranus as a primary flux calibrator.
    - 3C 273 used as a secondary calibrator
- Estimate 1 sigma uncertainty in amplitude calibration to be ~15%.

"Inverse Hyperbolic" Magnitudes?!

$$\mu(x) = -2.5\log_{10}(e)\left[\sinh^{-1}\left(\frac{x}{2b}\right) + \ln b\right], \qquad (1)$$

- Either a typo or just notation I'm not used to seeing.
  - (*e*)[] apparently means *e*^[] or exp[]
- Goal is to have a way to calculate magnitudes that is "well behaved" when the brightness approaches the noise level or even goes negative.
  - Flux *x*
  - "Softening parameter" *b*
  - Optimum value for *b* is the noise level of the flux measurement
- Set zero of magnitude scale to 1000 Jy km/s / $arcsec^2$
- Reduces to the regular magnitude scale in the high S/N limit (x/b >> 1).
  - Demonstrate this…



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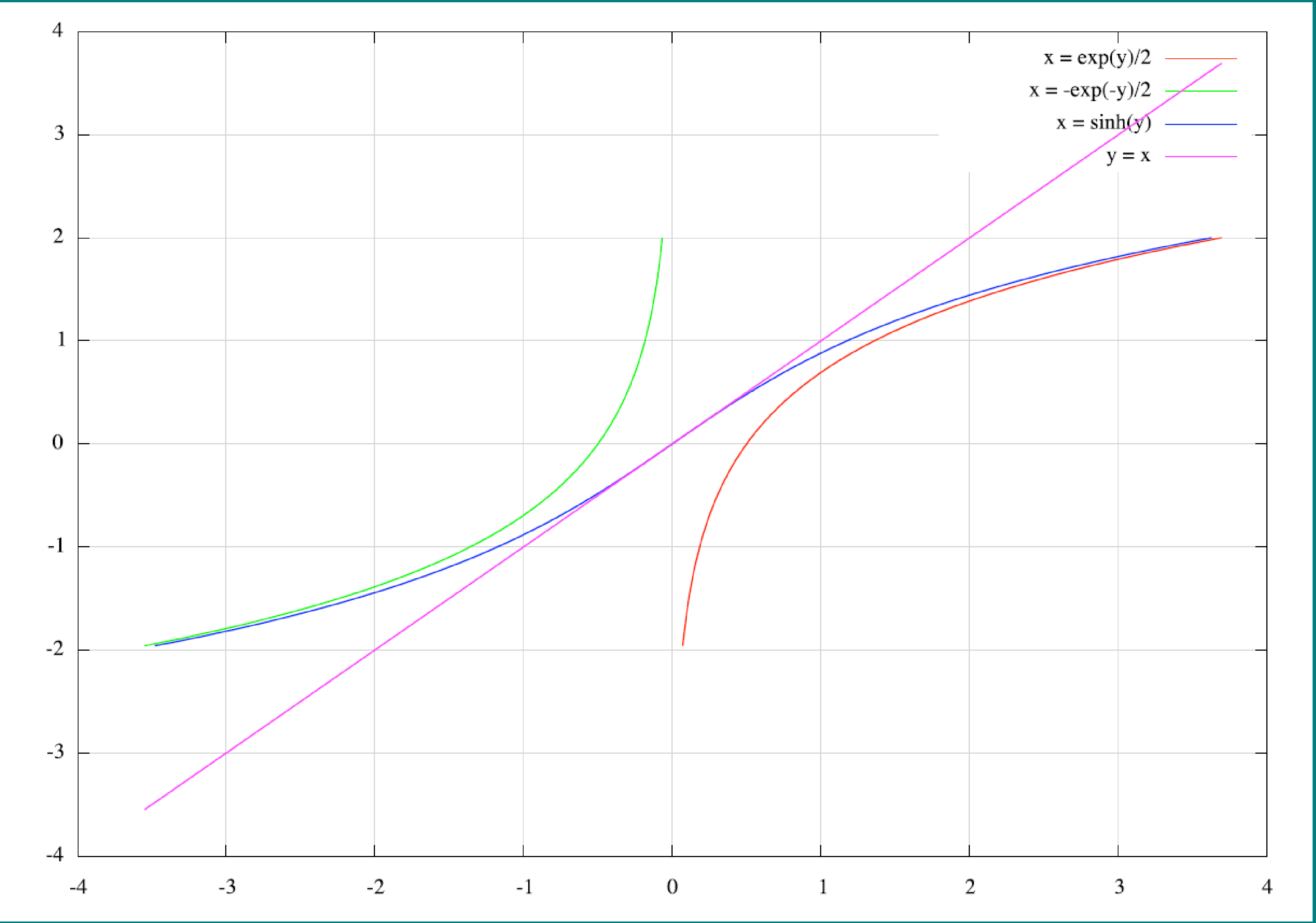
y = -exp(-x)/2
y = sinh(x)
y = x
4
3
2
1
0
-1
-2
-3
-4
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2


x = exp(y)/2
x = -exp(-y)/2
x = sinh(y)
y = x
4
3
2
1
0
-1
-2
-3
-4
-4
-3
-2
-1
0
1
2
3
4

Results

- First, I'll explain what is shown in Figures 1, 2, and 3 (using one example from each).
- Then I'll go through all 15 of the galaxies one by one, showing the parts of figures 1, 2, and 3 for each galaxy.

Figure 1

- Left frame
  - CO contours overlaid on stellar image
    - Each contour is 1 mag (a factor of 2.5119 in flux)
- Right frame
  - Total CO intensity maps
    - Each contour is 0.5 mag (a factor of 1.585 in flux)
  - Vertical bar = 1 kpc
  - Oval = synthesized primary beam
- 2-D CO map obtained from integrating the data cube along the velocity axis, but I'm a bit foggy on the details of how this was done.

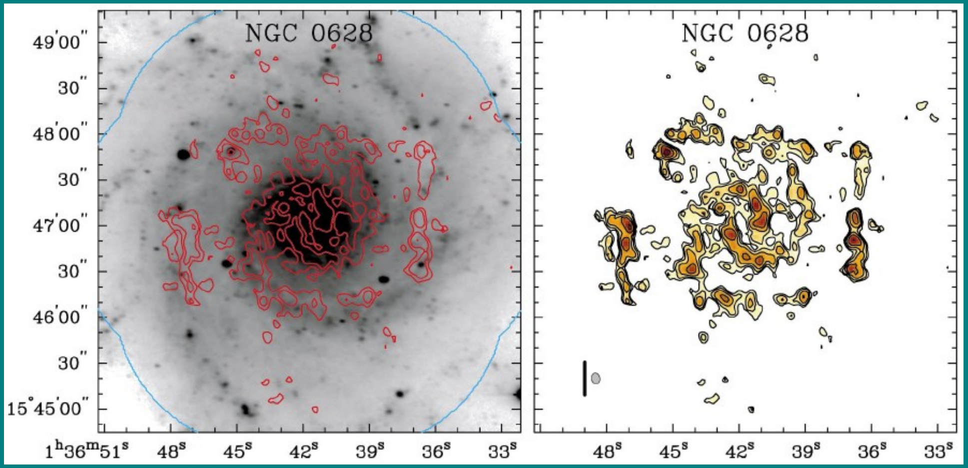
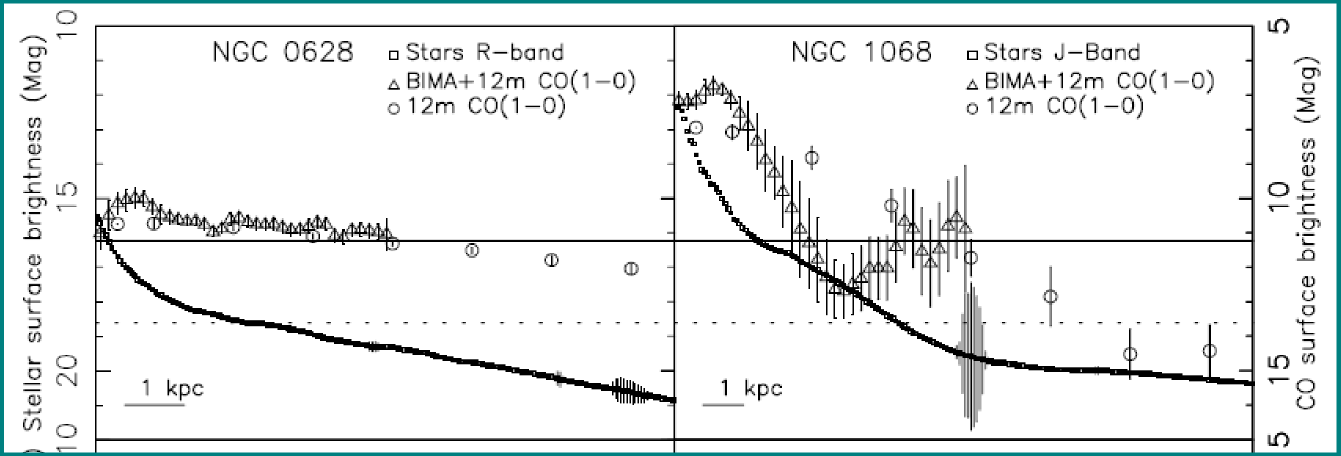


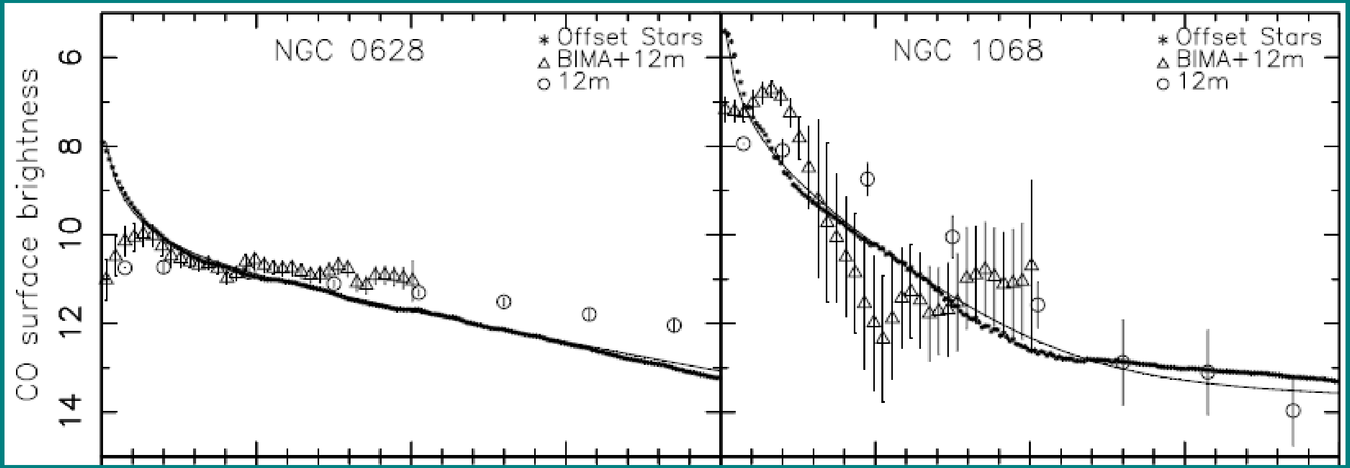
Figure 2

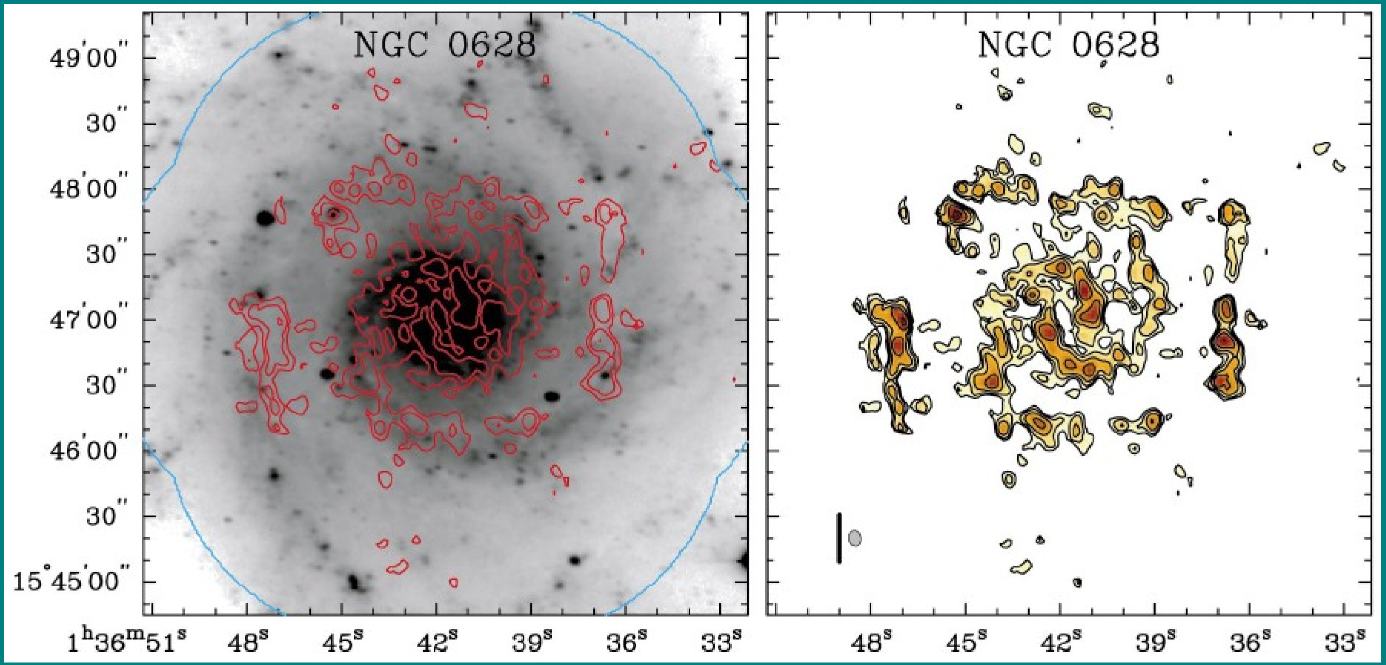


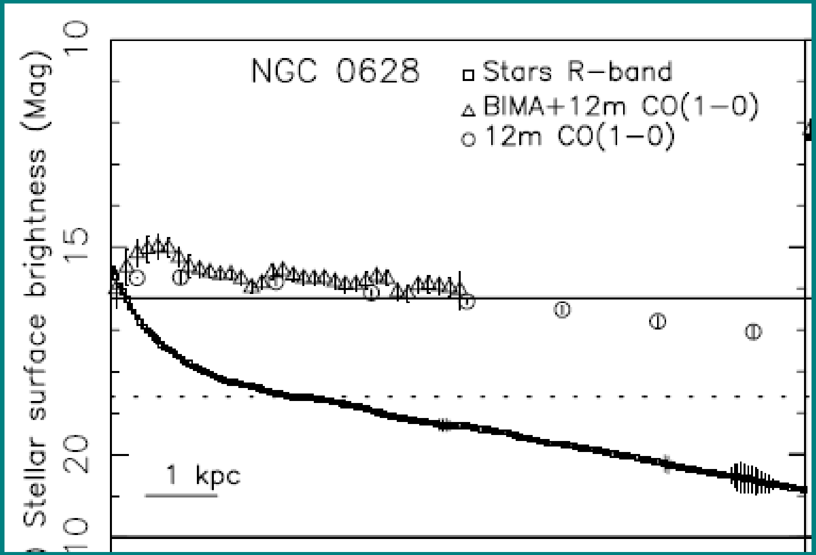
- Squares (looks like solid black line)
  - Stellar surface brightness profile (*K* mag per $arcsec^2$)
  - Median intensity in concentric elliptical annuli spaced 1” apart
- Triangles
  - BIMA+12m map: average brightness in concentric elliptical annuli spaced 3” apart
- Circles
  - 12m-only map: average brightness in concentric elliptical annuli spaced 27” apart

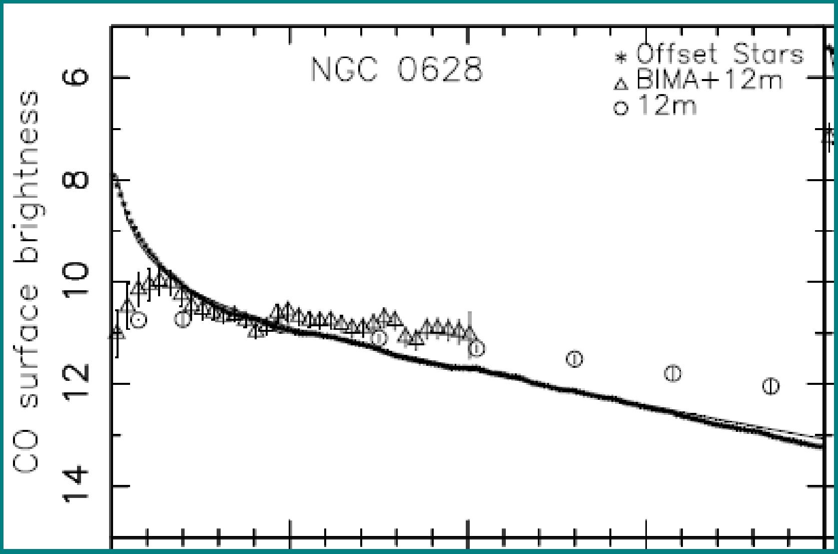
Figure 3

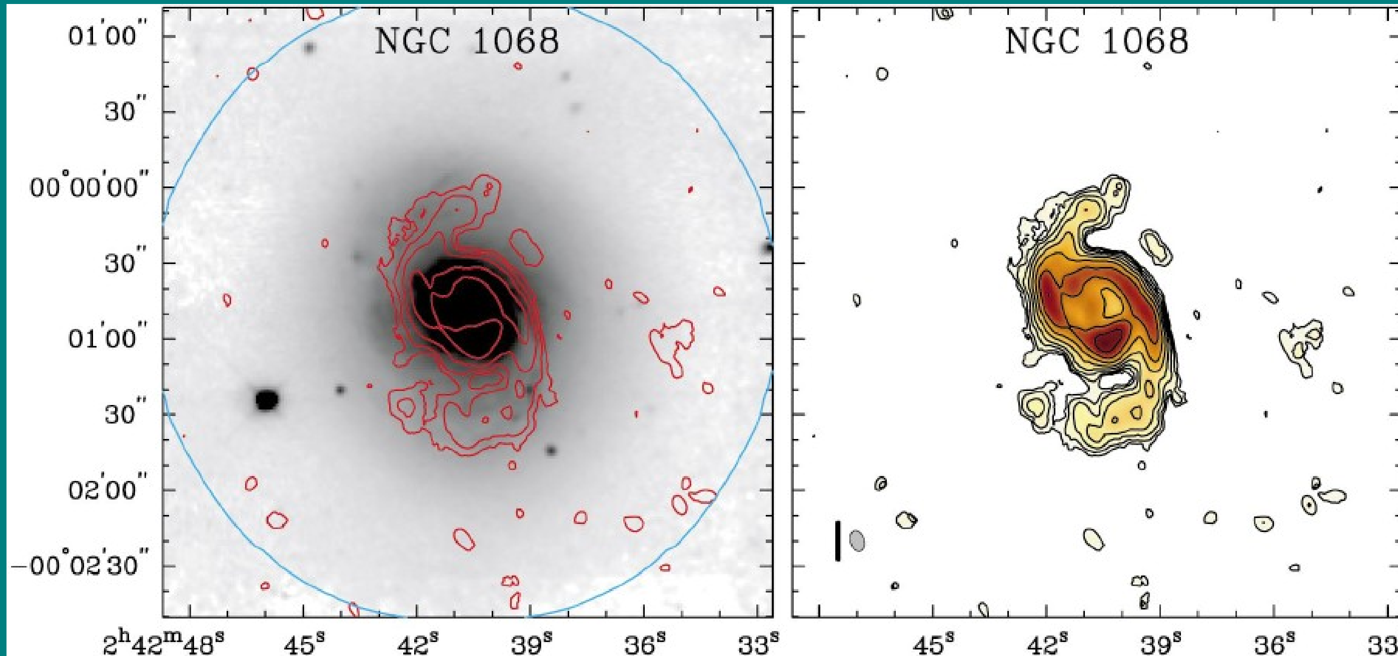
- Same as figure 2, except now
  - the average offset between the stars and the BIMA+12m profile has been subtracted
  - a simple $r^{1/4}$ bulge and exponential disk model has been fit to the stellar profile




NGC 0628
NGC 0628
49′00″
30″
48′00″
30″
47′00″
30″
46′00″
30″
15°45′00″
1h36m51s
48s
45s
42s
39s
36s
33s


NGC 0628
Stars R−band
BIMA+12m CO(1−0)
12m CO(1−0)
Stellar surface brightness (Mag)
10
15
20
1 kpc


NGC 0628
Offset Stars
BIMA+12m
12m
CO surface brightness
6
8
10
12
14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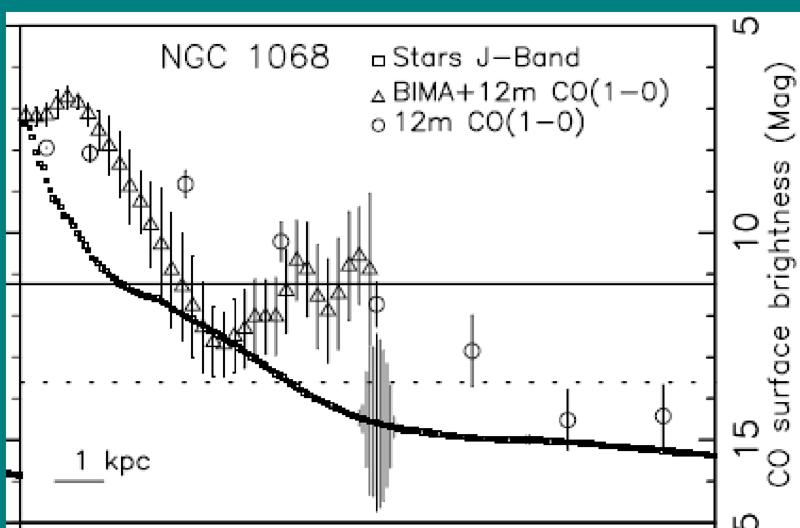
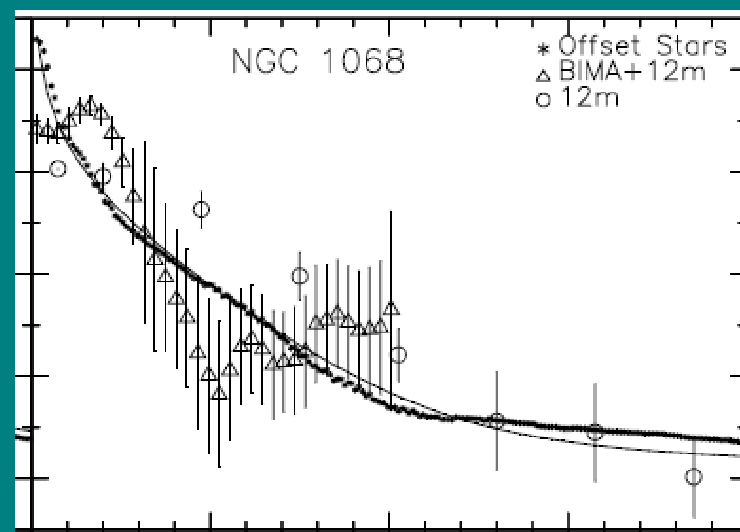
NGC 1068
01'00"
30"
00°00'00"
30"
01'00"
30"
02'00"
−00°02'30"
2h42m48s
45s
42s
39s
36s
33s


NGC 1068
Stars J−Band
BIMA+12m CO(1−0)
12m CO(1−0)
1 kpc
CO surface brightness (Mag)
5
10
15
5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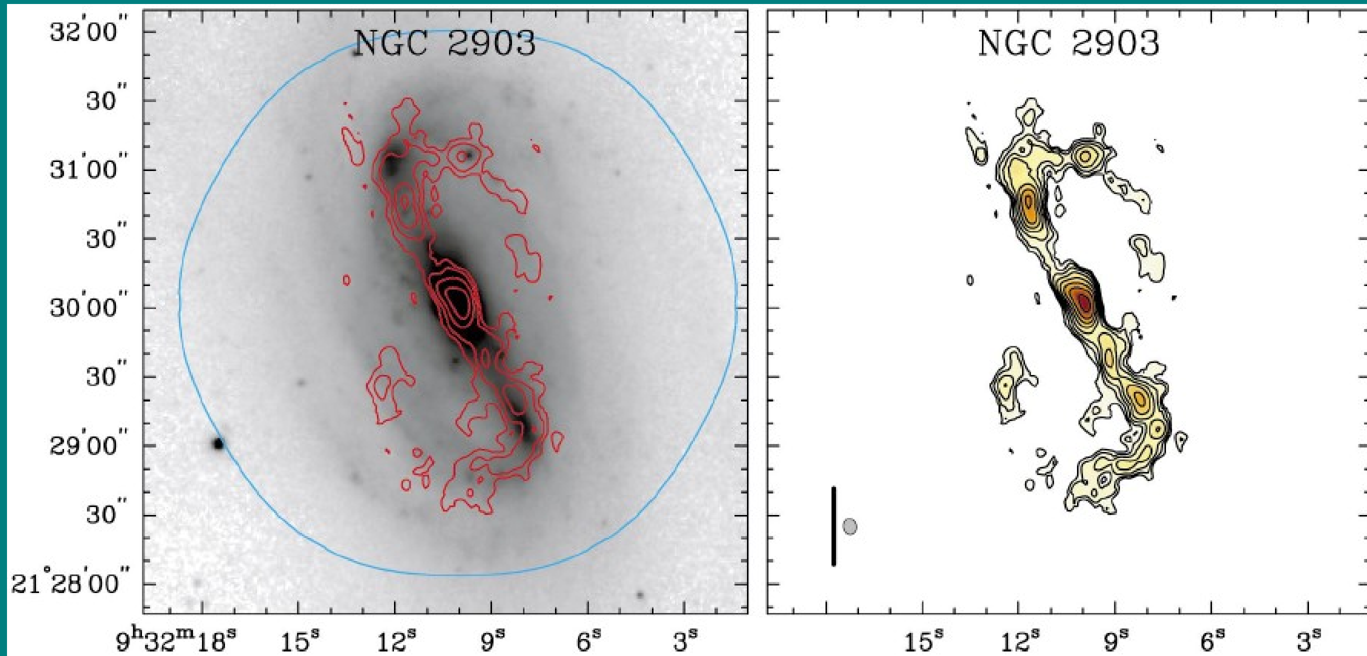
Offset Stars
BIMA+12m
12m


NGC 2903
NGC 2903
32'00"
30"
31'00"
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30"
29'00"
30"
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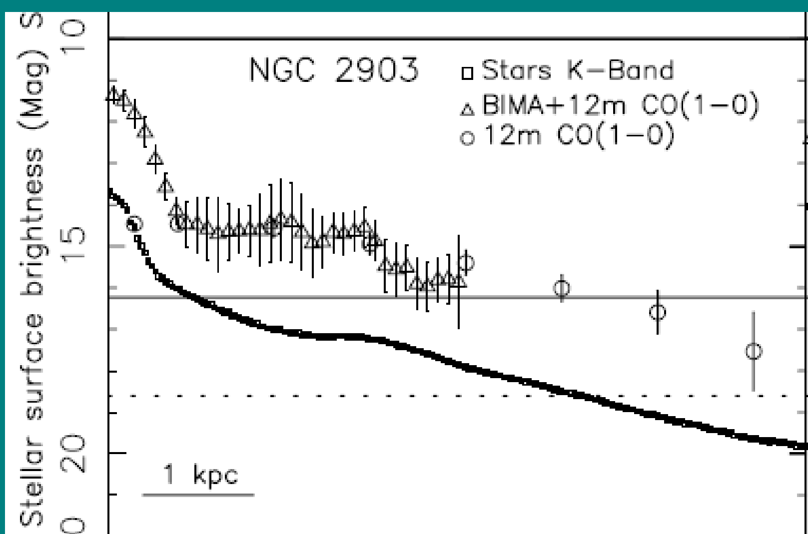
15s
12s
9s
6s
3s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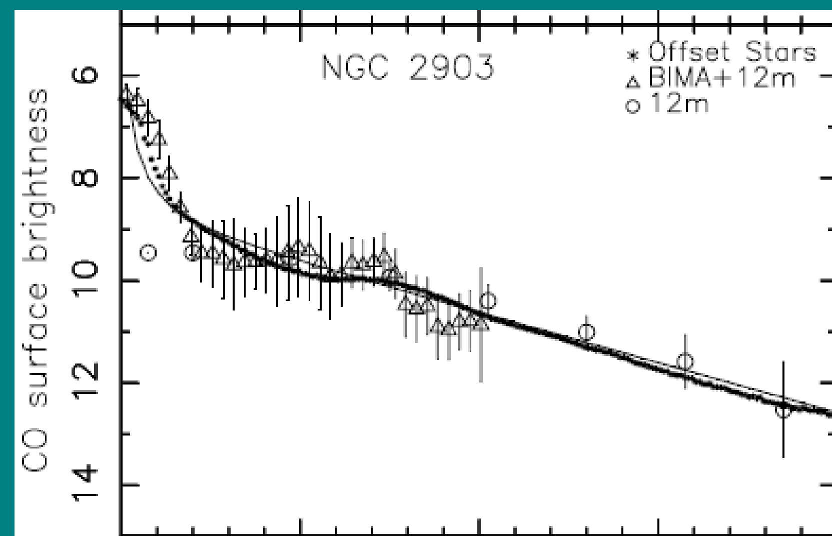
Stars K−Band
BIMA+12m CO(1−0)
12m CO(1−0)
Stellar surface brightness (Mag)
10
15
20
0
1 kpc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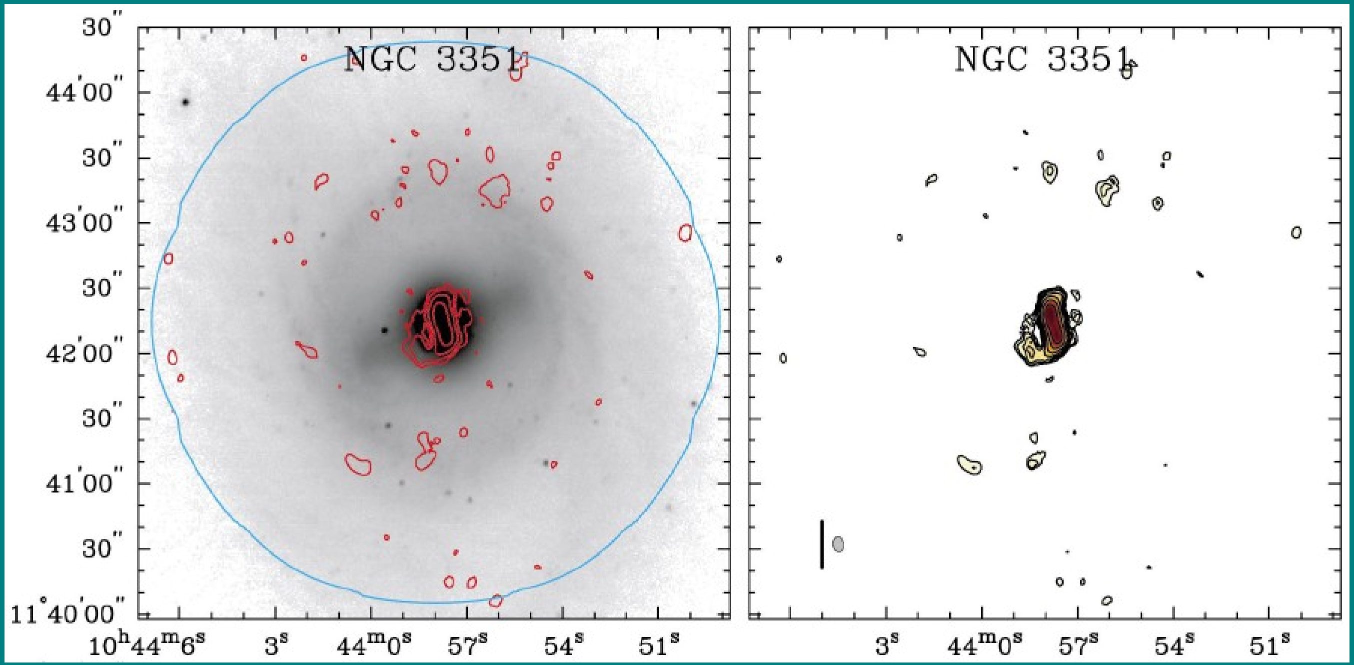
Offset Stars
BIMA+12m
12m
CO surface brightness
6
8
10
12
14


NGC 3351
NGC 3351
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30"
43'00"
30"
42'00"
30"
41'00"
30"
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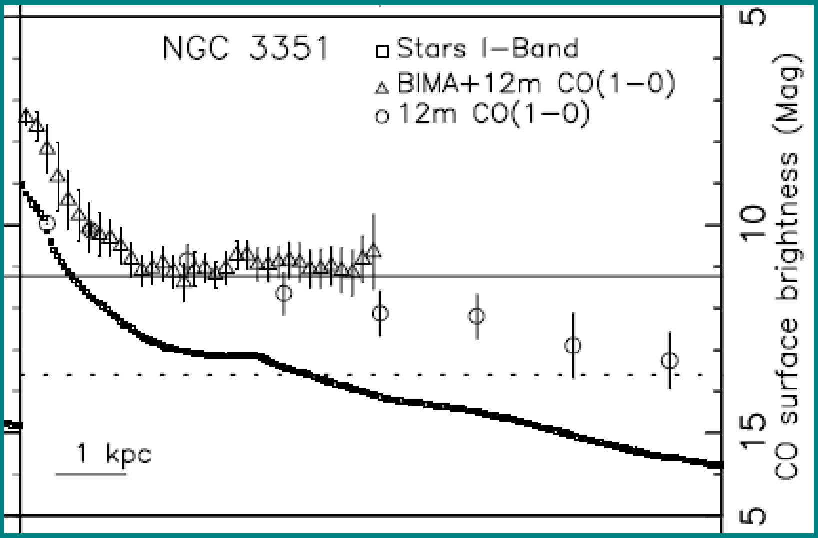
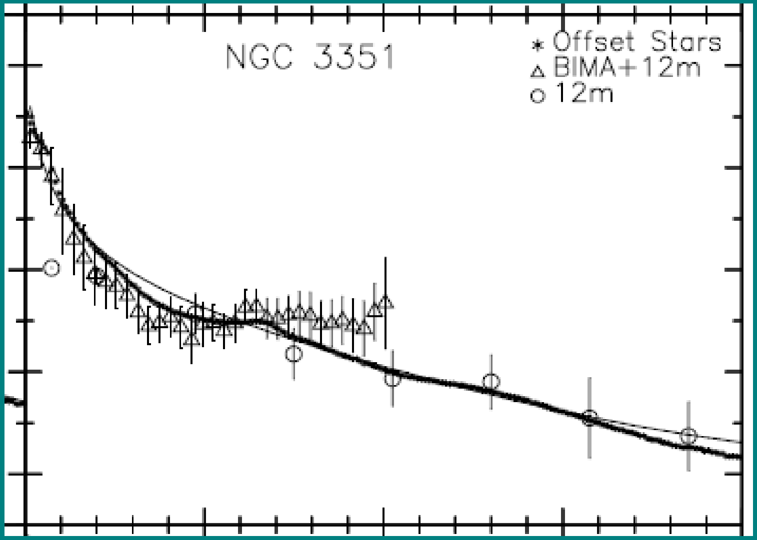
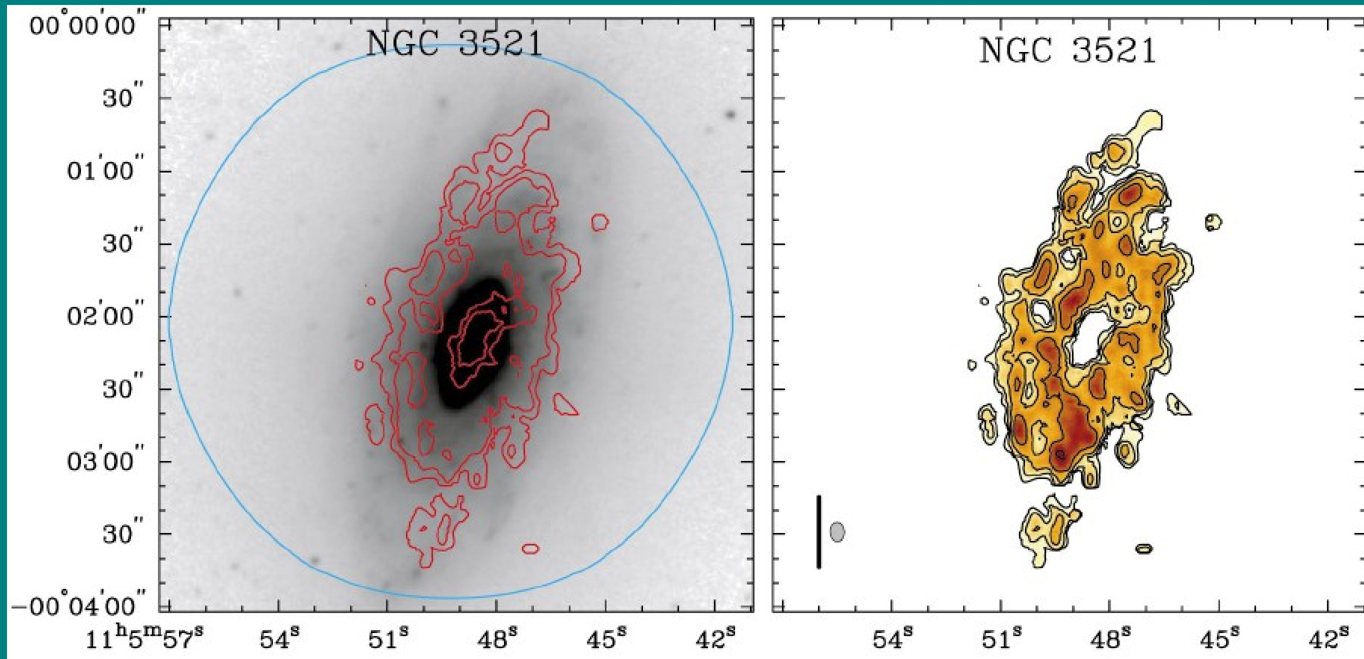
57s
54s
51s


NGC 3351
Stars I−Band
BIMA+12m CO(1−0)
12m CO(1−0)
1 kpc
CO surface brightness (Mag)
5
10
15
5


NGC 3351
Offset Stars
BIMA+12m
12m


NGC 3521
NGC 3521
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01'00"
30"
02'00"
30"
03'00"
30"
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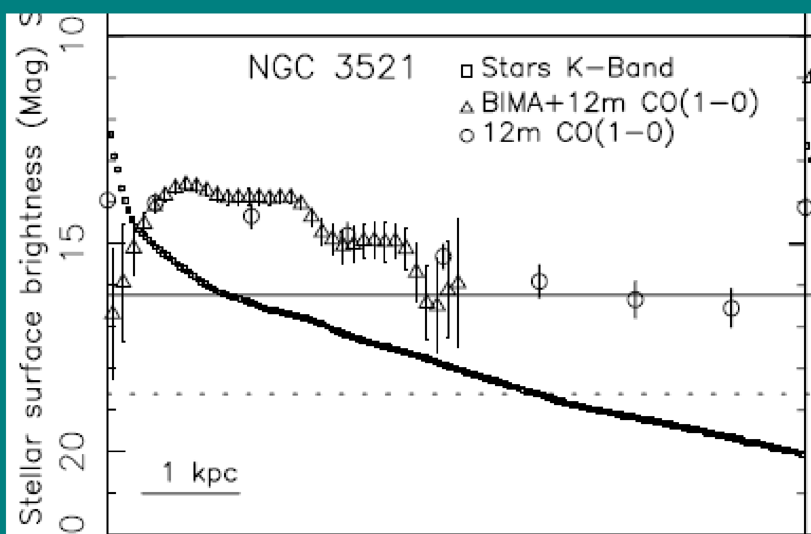
51s
48s
45s
42s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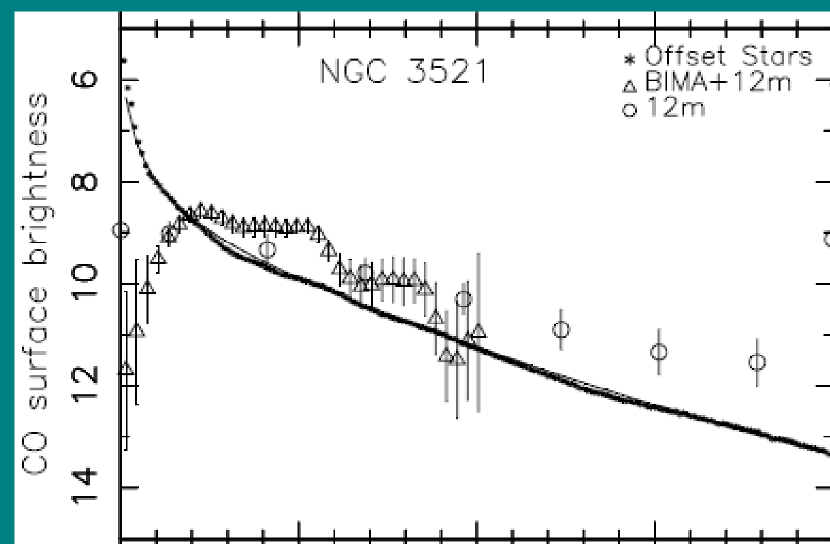
Stars K−Band
BIMA+12m CO(1−0)
12m CO(1−0)
Stellar surface brightness (Mag)
1 kpc
0
20
15
10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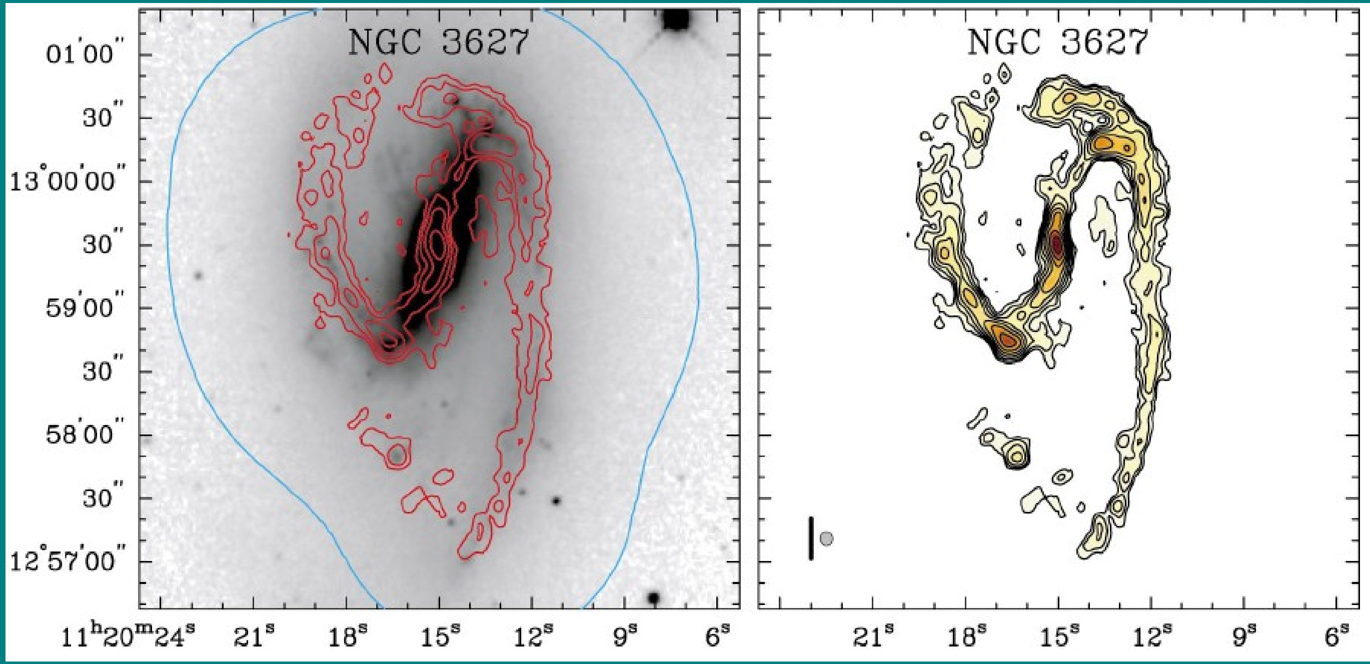
Offset Stars
BIMA+12m
12m
CO surface brightness
6
8
10
12
14


NGC 3627
NGC 3627
01′00″
30″
13°00′00″
30″
59′00″
30″
58′00″
30″
12°57′00″
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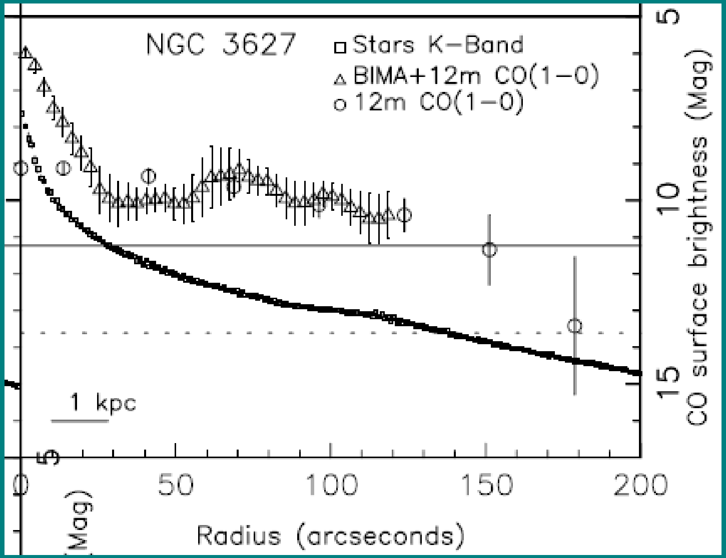
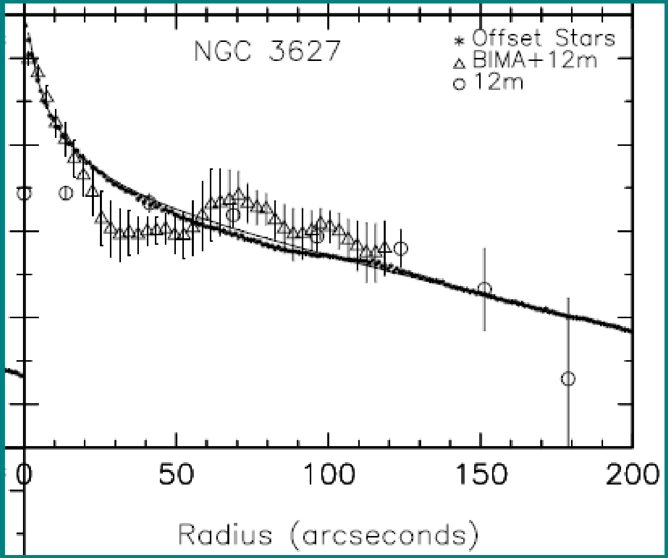
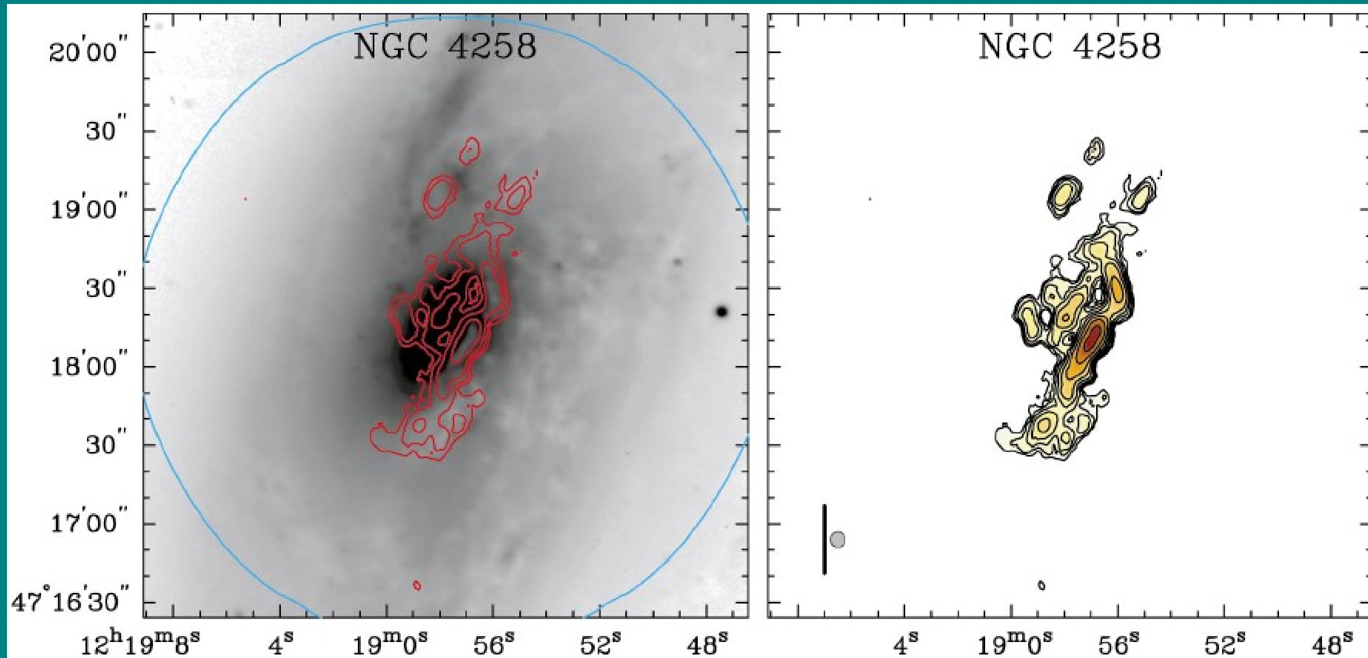
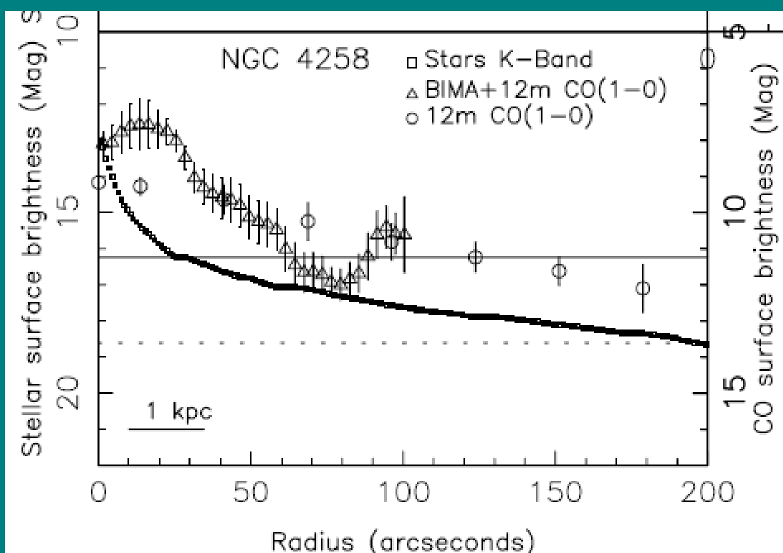
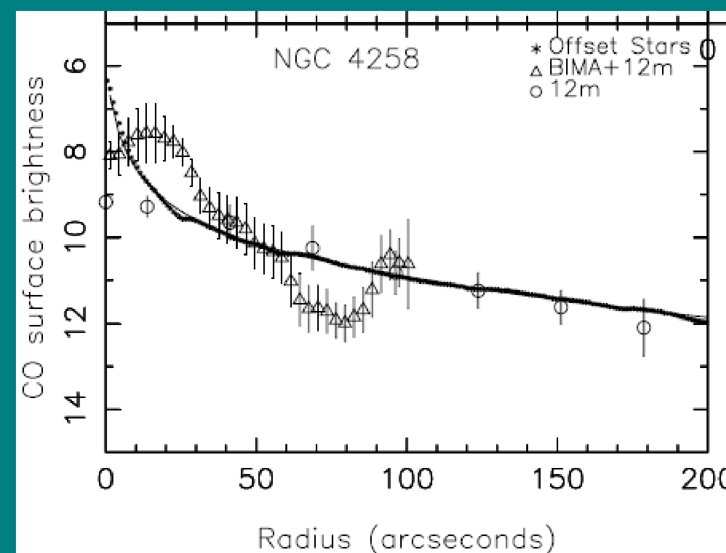
21s
18s
15s
12s
9s
6s

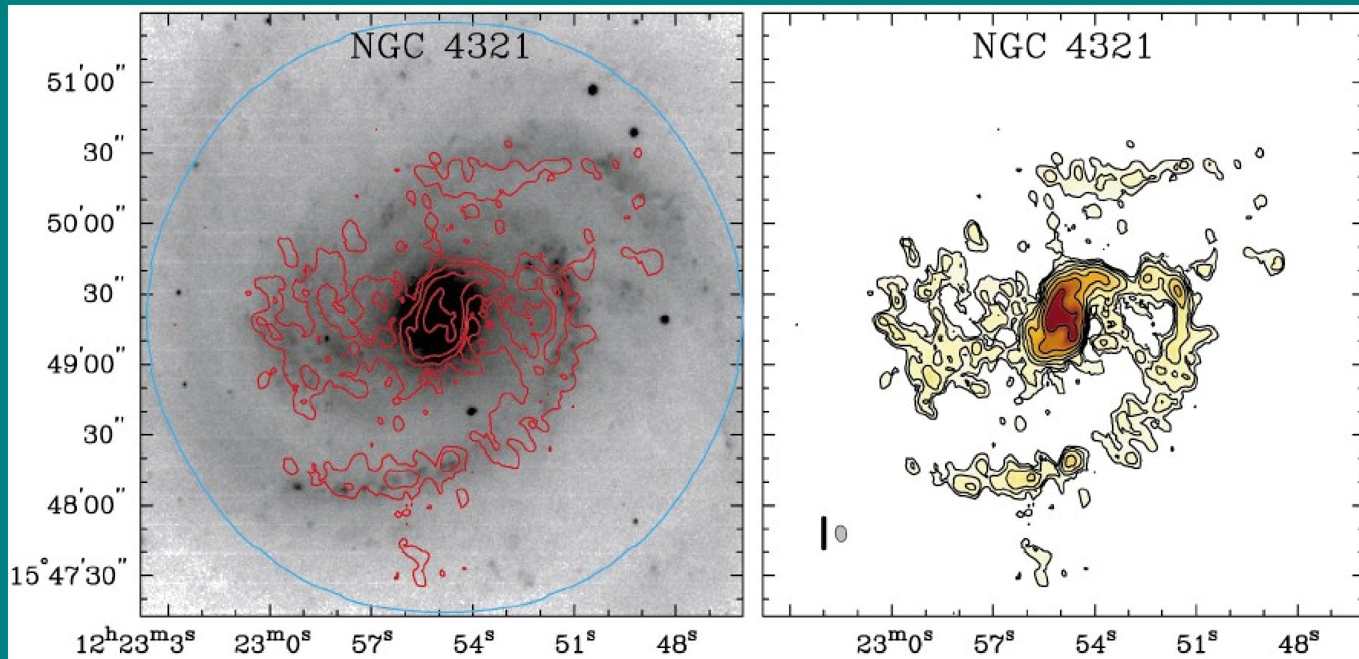

NGC 3627
□ Stars K−Band
△ BIMA+12m CO(1−0)
○ 12m CO(1−0)
1 kpc
CO surface brightness (Mag)
Radius (arcseconds)
0
50
100
150
200
5
10
15

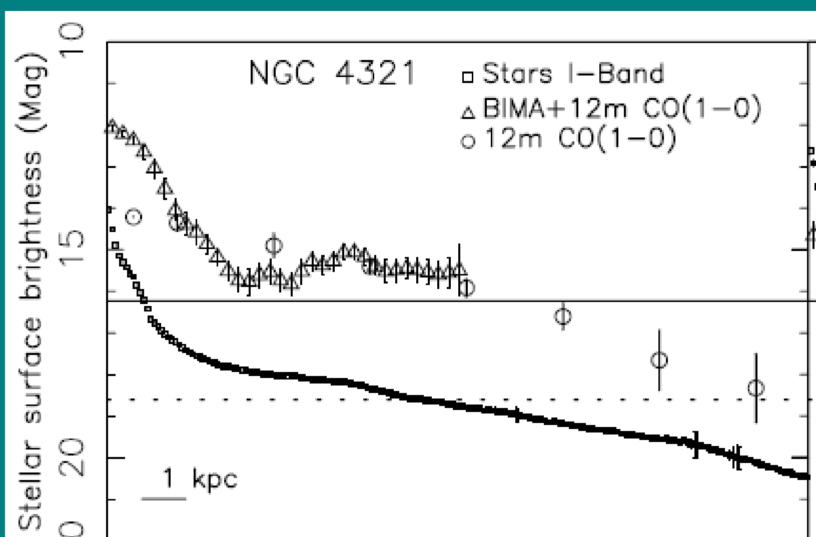

NGC 3627
∗ Offset Stars
△ BIMA+12m
○ 12m
Radius (arcseconds)
0
50
100
150
200

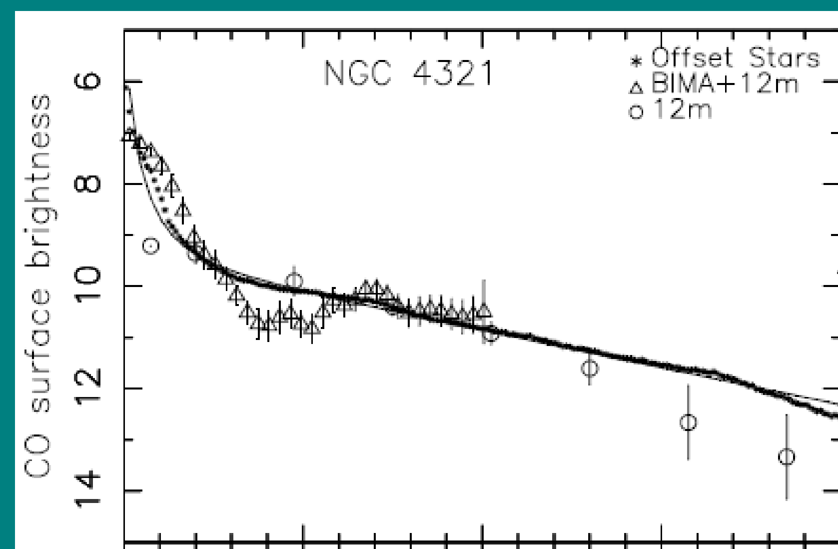

NGC 4258
20′00″
30″
19′00″
30″
18′00″
30″
17′00″
47°16′30″
$12^h19^m8^s$
4^s
19^m0^s
56^s
52^s
48^s
NGC 4258
4^s
19^m0^s
56^s
52^s
48^s

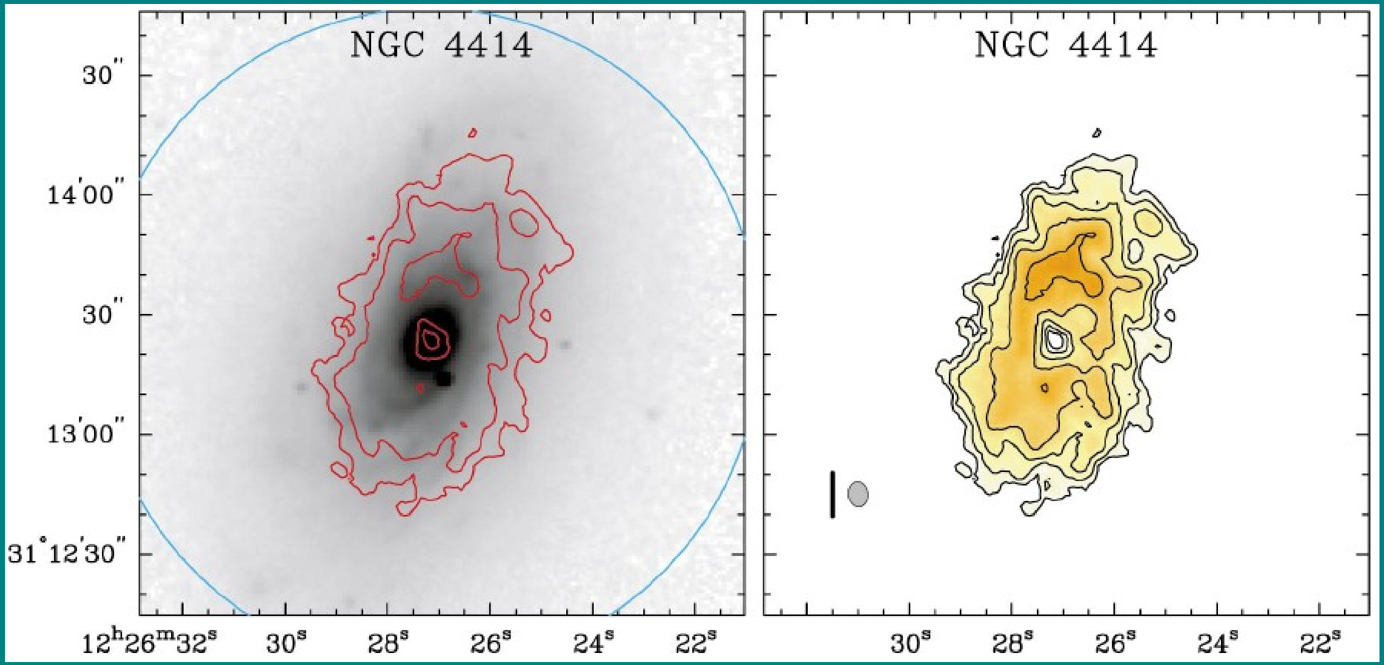

NGC 4258
Stars K−Band
BIMA+12m CO(1−0)
12m CO(1−0)
Stellar surface brightness (Mag)
CO surface brightness (Mag)
10
15
20
5
10
15
0
1 kpc
0
50
100
150
200
Radius (arcseconds)


NGC 4258
∗ Offset Stars
BIMA+12m
12m
CO surface brightness
6
8
10
12
14
0
50
100
150
200
Radius (arcseconds)

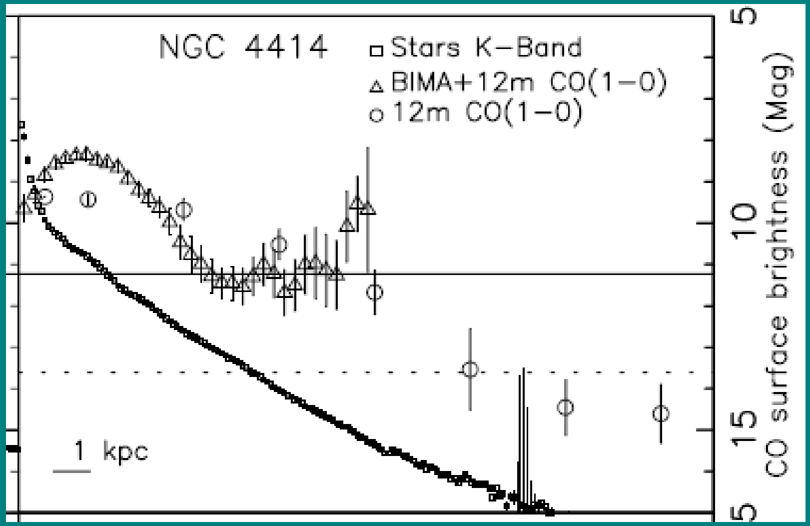

NGC 4321
51′00″
30″
50′00″
30″
49′00″
30″
48′00″
15°47′30″
12h23m3s
23m0s
57s
54s
51s
48s
NGC 4321
23m0s
57s
54s
51s
48s


NGC 4321
Stars I−Band
BIMA+12m CO(1−0)
12m CO(1−0)
Stellar surface brightness (Mag)
10
15
20
0
1 kpc

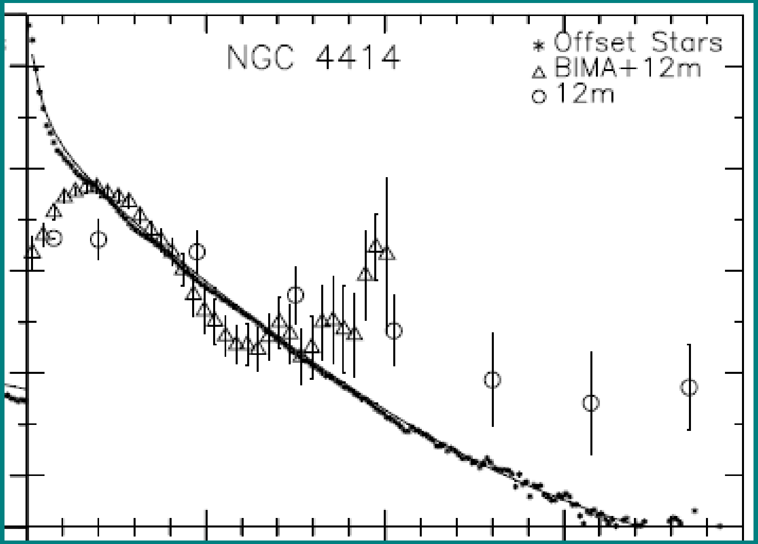

NGC 4321
∗ Offset Stars
BIMA+12m
12m
CO surface brightness
6
8
10
12
14



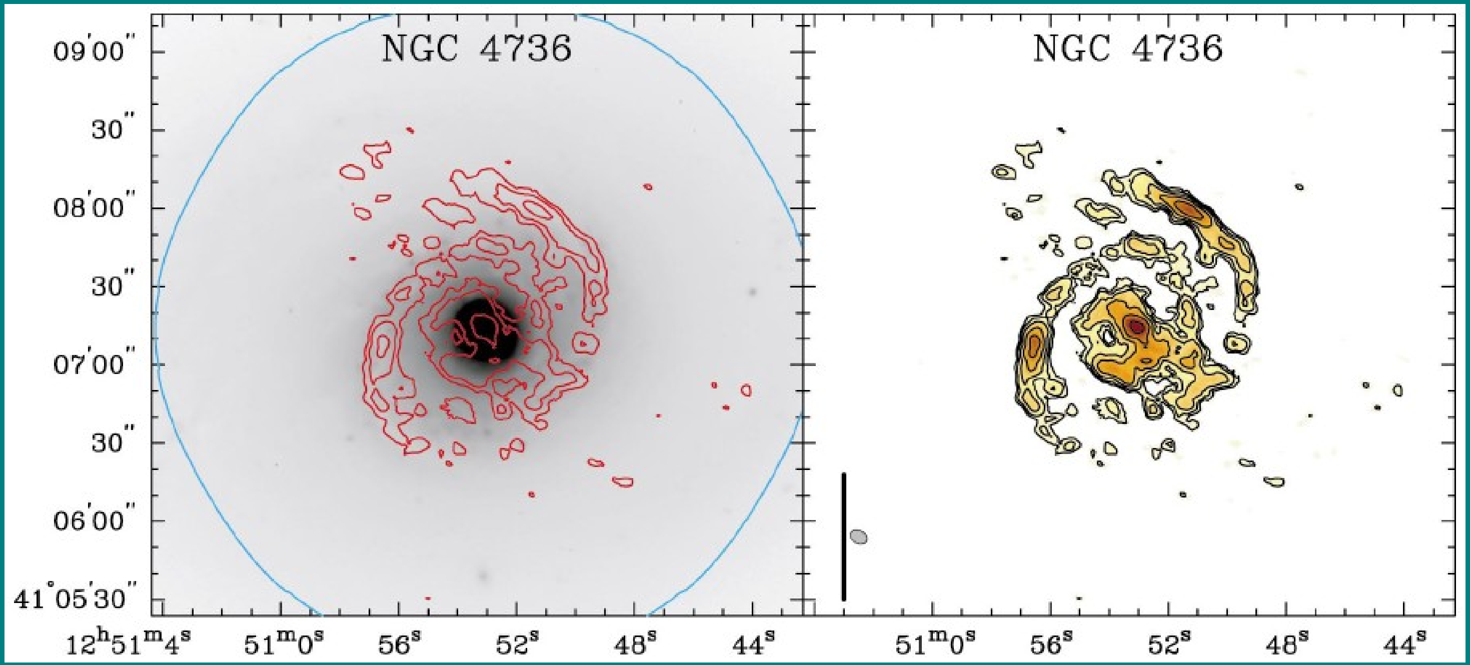
NGC 4414
NGC 4414
30″
14′00″
30″
13′00″
31°12′30″
12h26m32s
30s
28s
26s
24s
22s

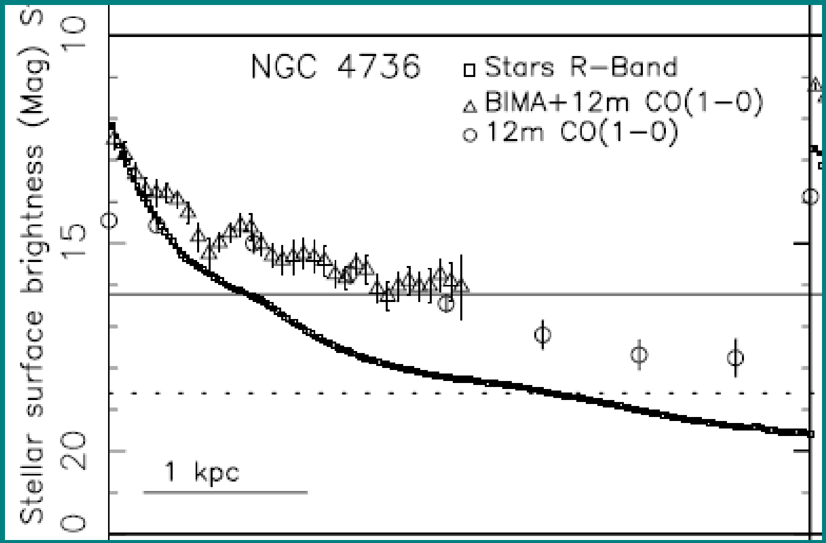


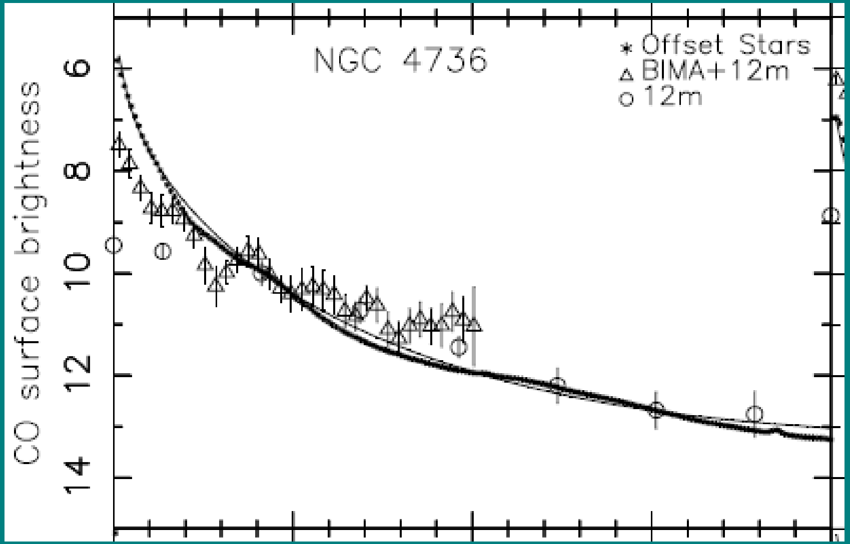
NGC 4414
Stars K−Band
BIMA+12m CO(1−0)
12m CO(1−0)
1 kpc
CO surface brightness (Mag)
5
10
15

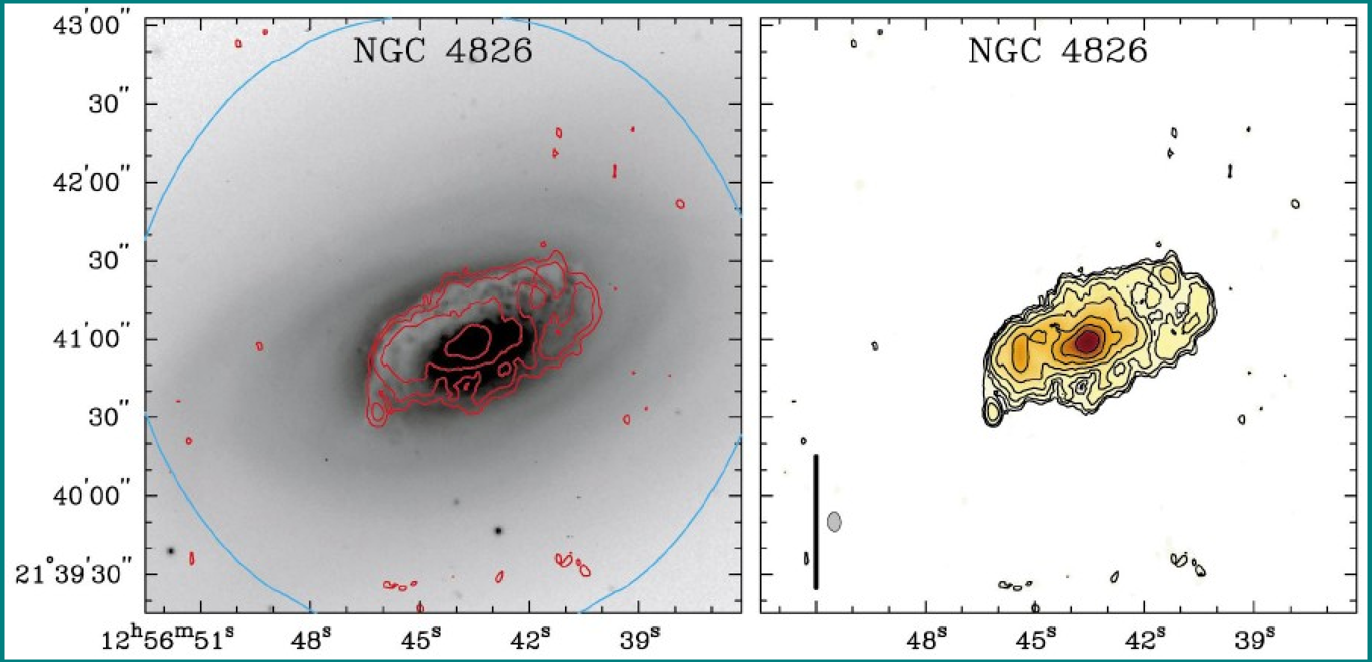


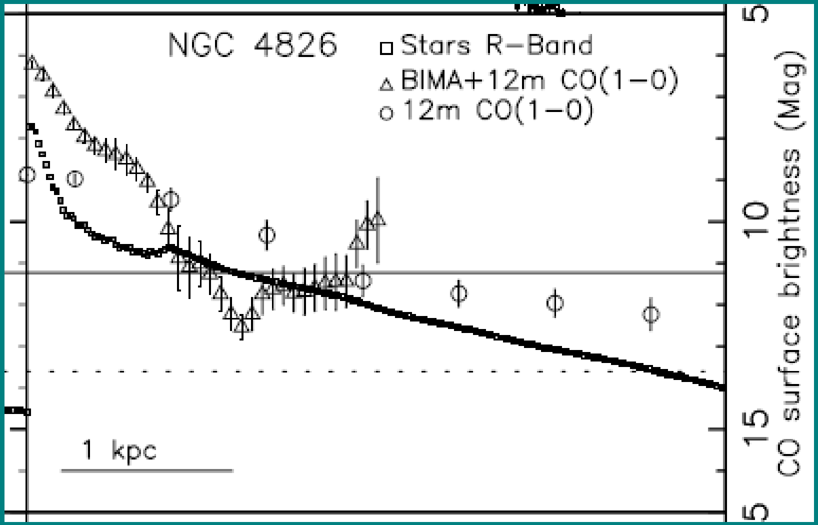
NGC 4414
Offset Stars
BIMA+12m
12m

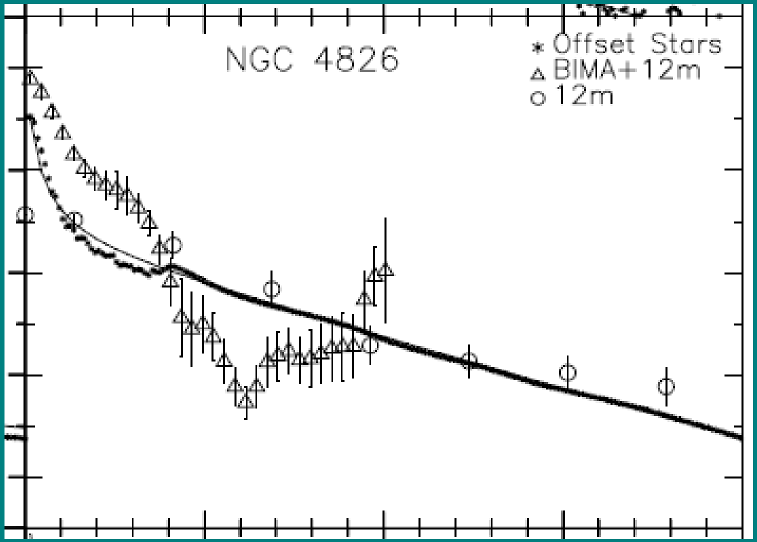

NGC 4736
NGC 4736
09'00"
30"
08'00"
30"
07'00"
30"
06'00"
41°05'30"
12h51m4s
51m0s
56s
52s
48s
44s

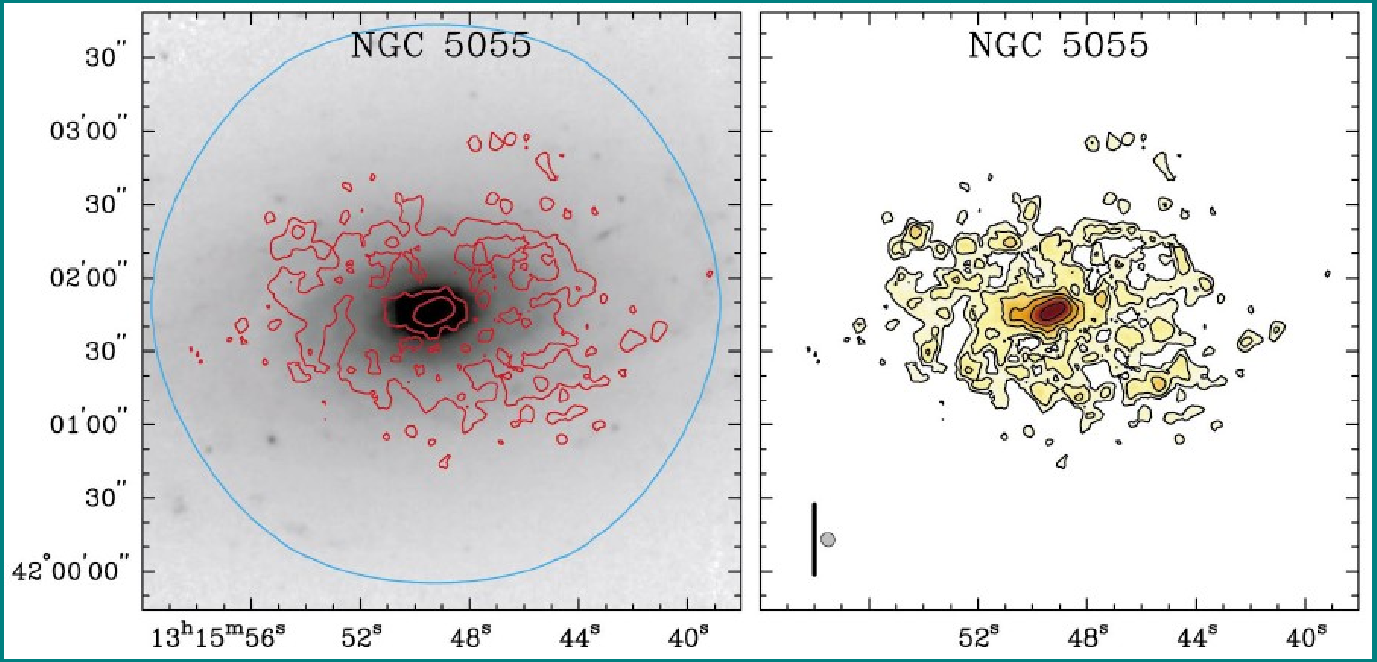

NGC 4736
Stars R-Band
BIMA+12m CO(1−0)
12m CO(1−0)
Stellar surface brightness (Mag)
1 kpc
10
15
20

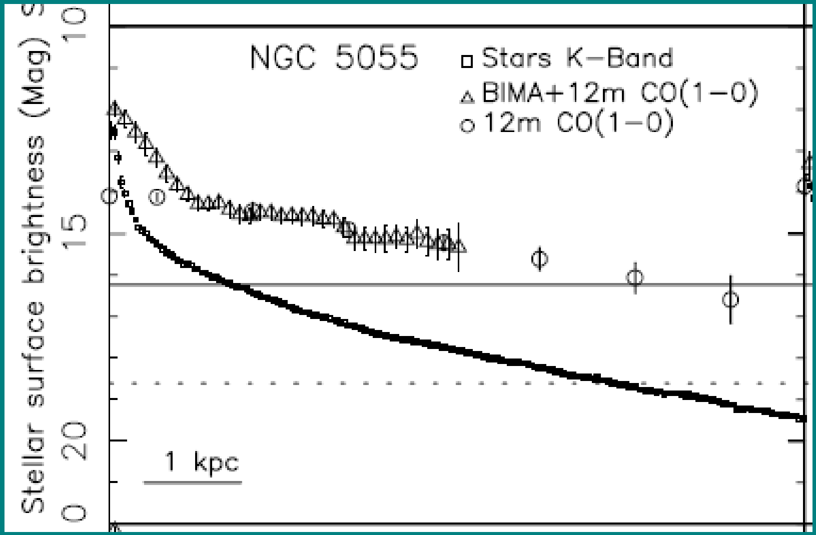

NGC 4736
Offset Stars
BIMA+12m
12m
CO surface brightness
6
8
10
12
14

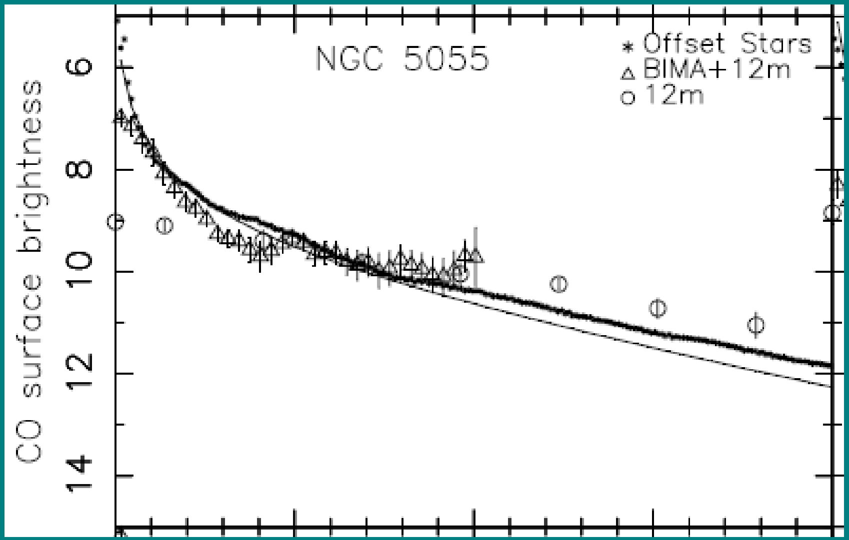

NGC 4826
NGC 4826
43'00"
30"
42'00"
30"
41'00"
30"
40'00"
21°39'30"
12h56m51s
48s
45s
42s
39s
48s
45s
42s
39s

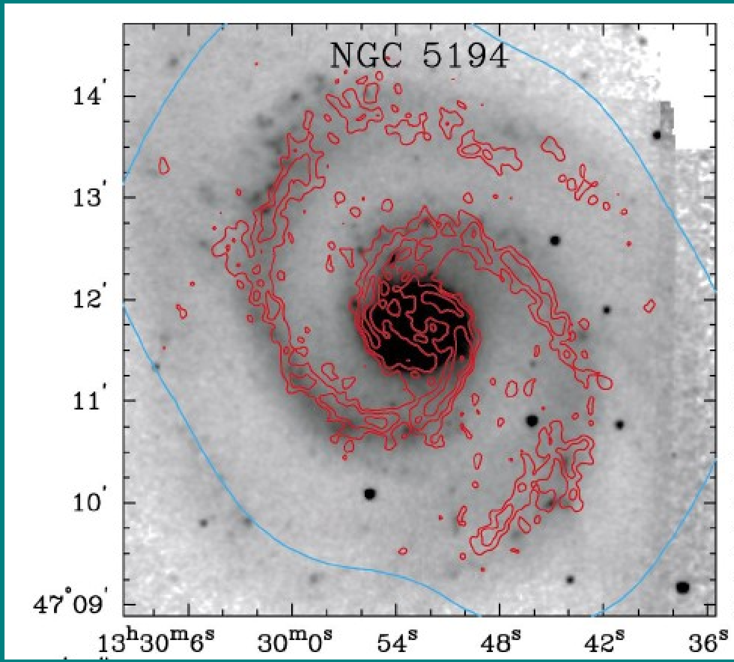

NGC 4826
Stars R−Band
BIMA+12m CO(1−0)
12m CO(1−0)
1 kpc
CO surface brightness (Mag)
5
10
15

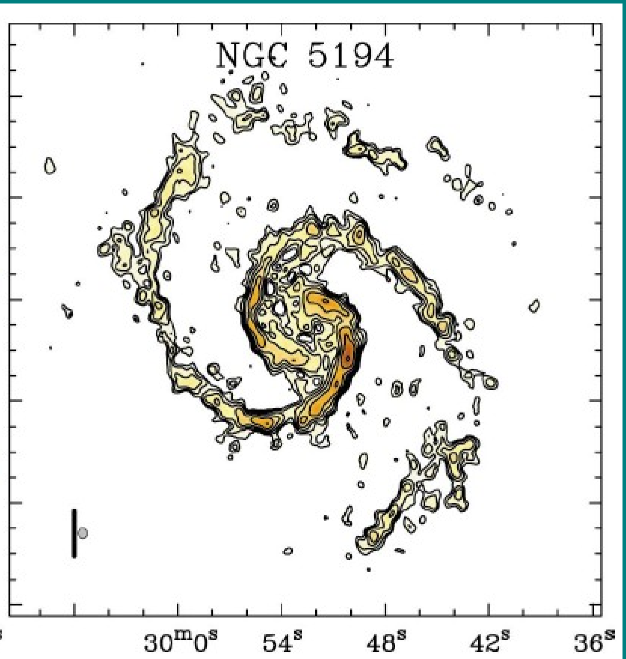

NGC 4826
Offset Stars
BIMA+12m
12m

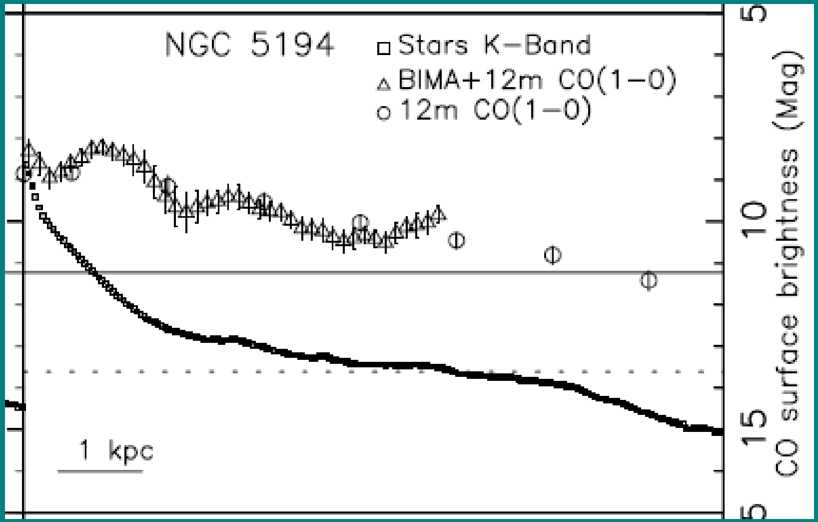

NGC 5055
NGC 5055
30"
03'00"
30"
02'00"
30"
01'00"
30"
42°00'00"
13h15m56s
52s
48s
44s
40s

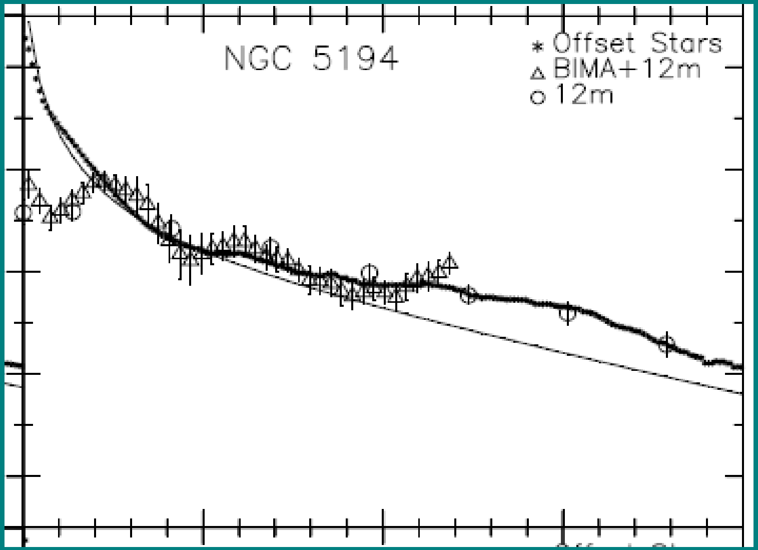

NGC 5055
Stars K–Band
BIMA+12m CO(1–0)
12m CO(1–0)
Stellar surface brightness (Mag)
1 kpc
0
20
15
10

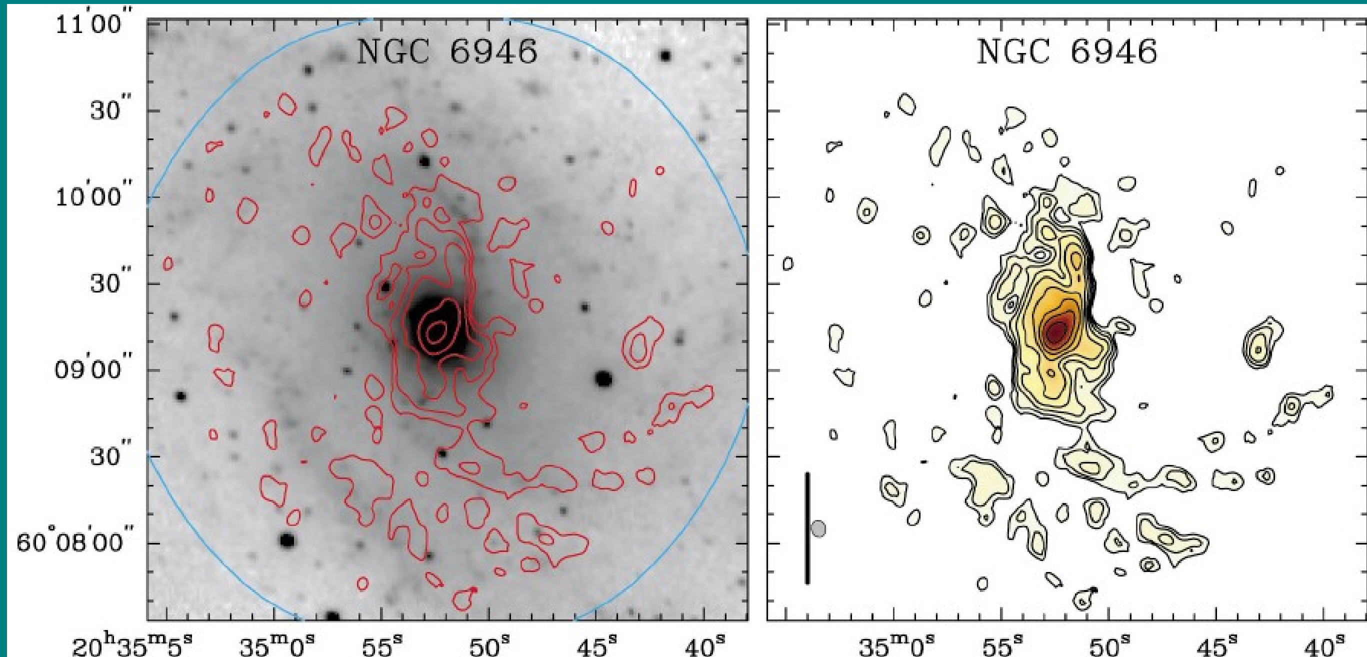

NGC 5055
Offset Stars
BIMA+12m
12m
CO surface brightness
6
8
10
12
14

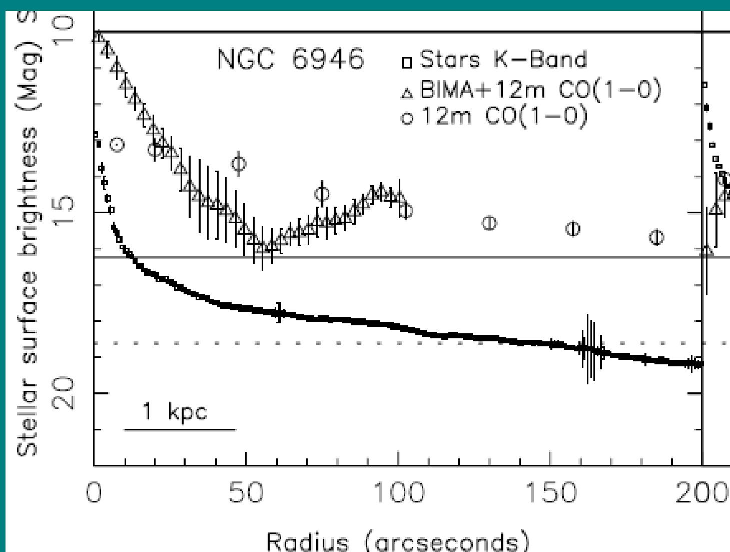

NGC 5194
14'
13'
12'
11'
10'
47°09'
13h30m6s
30m0s
54s
48s
42s
36s

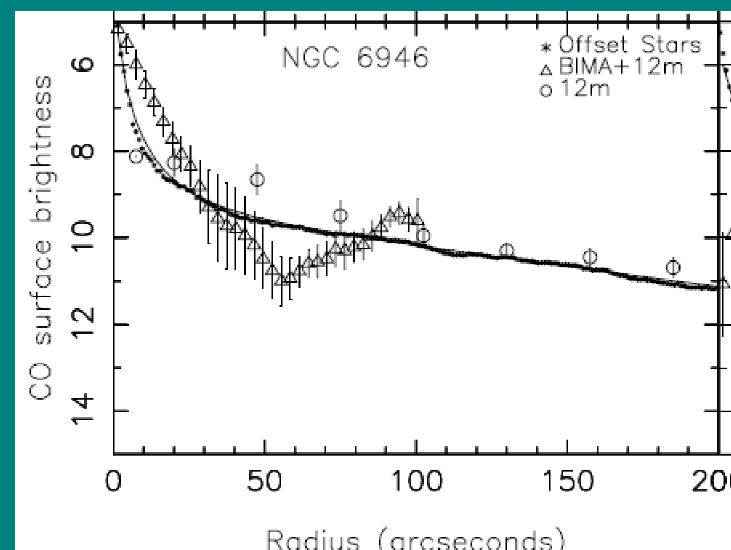

NGC 5194
30m0s
54s
48s
42s
36s

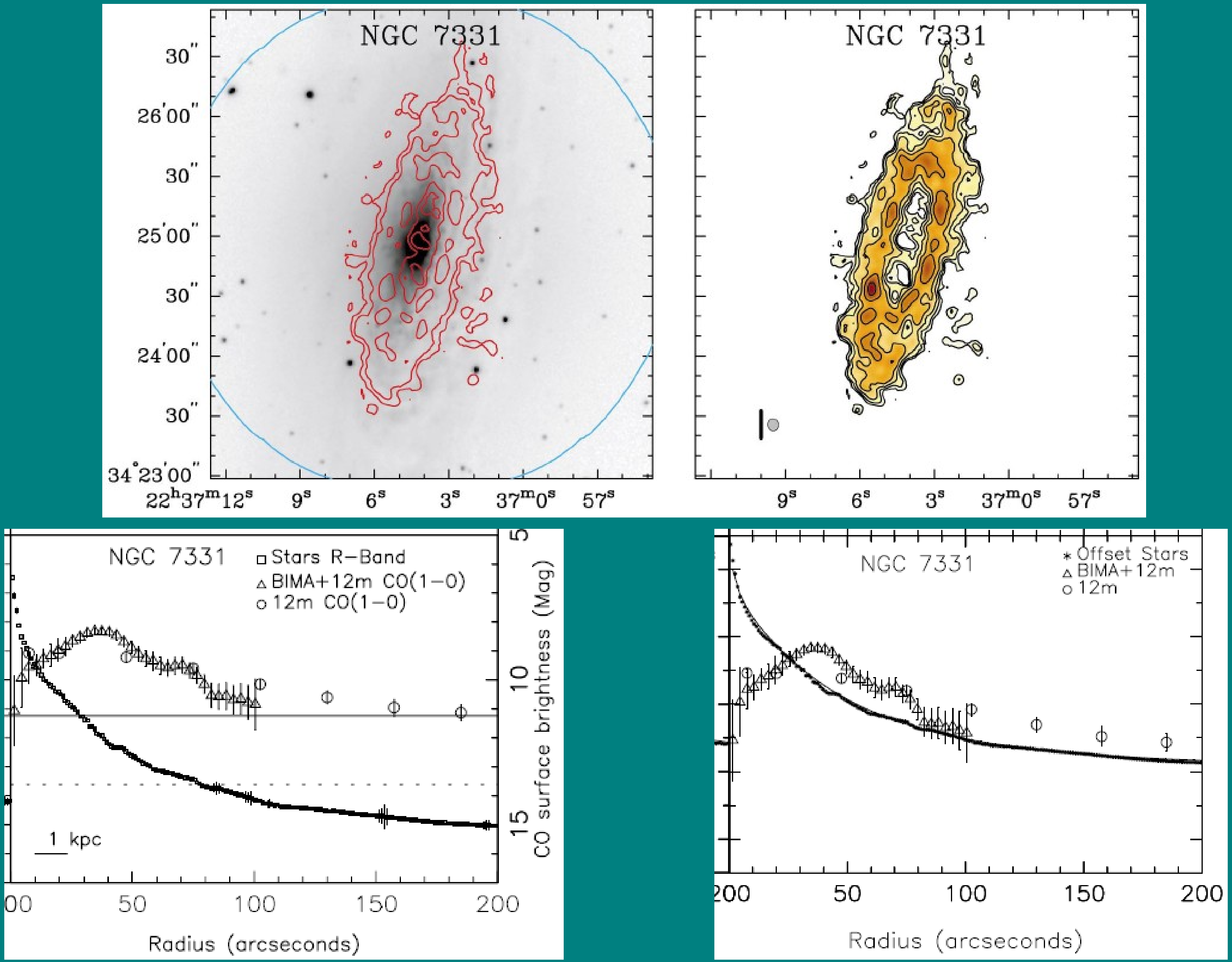

NGC 5194
Stars K-Band
BIMA+12m CO(1-0)
12m CO(1-0)
1 kpc
5
10
15
CO surface brightness (Mag)


NGC 5194
Offset Stars
BIMA+12m
12m


NGC 6946
11′00″
30″
10′00″
30″
09′00″
30″
60°08′00″
20h35m5s
35m0s
55s
50s
45s
40s
NGC 6946
35m0s
55s
50s
45s
40s


NGC 6946
Stars K−Band
BIMA+12m CO(1−0)
12m CO(1−0)
Stellar surface brightness (Mag)
1 kpc
10
15
20
0
50
100
150
200
Radius (arcseconds)


NGC 6946
Offset Stars
BIMA+12m
12m
CO surface brightness
6
8
10
12
14
0
50
100
150
200
Radius (arcseconds)


NGC 7331
30"
26'00"
30"
25'00"
30"
24'00"
30"
34°23'00"
22h37m12s
9s
6s
3s
37m0s
57s
NGC 7331
9s
6s
3s
37m0s
57s
NGC 7331
Stars R−Band
BIMA+12m CO(1−0)
12m CO(1−0)
1 kpc
CO surface brightness (Mag)
5
10
15
0
50
100
150
200
Radius (arcseconds)
NGC 7331
Offset Stars
BIMA+12m
12m
50
100
150
200
Radius (arcseconds)

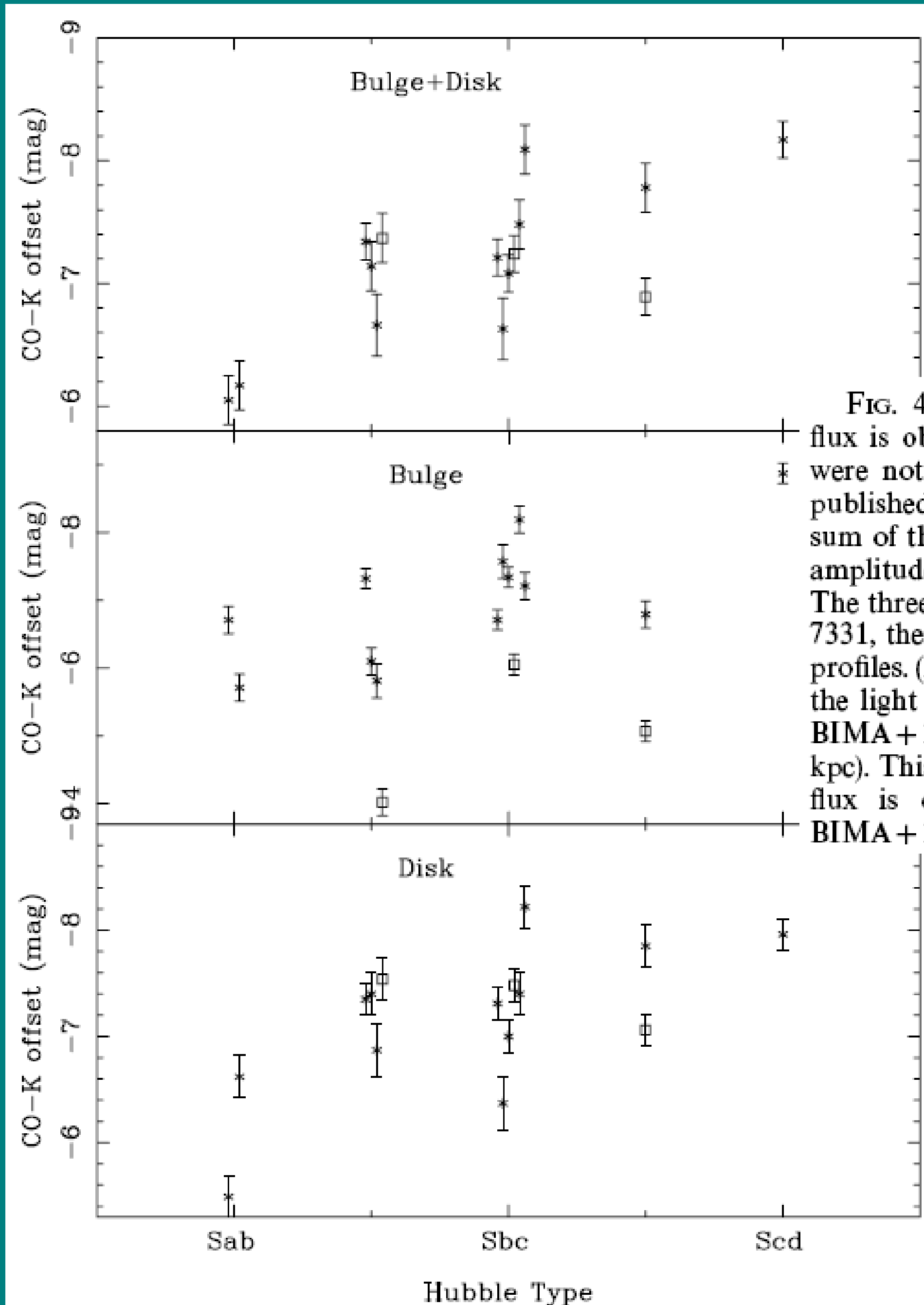


FIG. 4.—(*Top panel*) CO − *K* offsets of the inner 200″. The total CO flux is obtained from the single-dish map. The stellar observations that were not done in *K*-band were corrected to *K*-band magnitudes using published aperture photometry values. The error bars are the quadrature sum of the uncertainties in the *K*-band magnitudes and those of the CO amplitude calibration and are dominated by the uncertainties in the CO. The three galaxies plotted as boxes are NGC 4414, NGC 3521, and NGC 7331, the three with strong central depressions in their surface brightness profiles. (*Middle panel*) CO − *K* offsets of bulge region. This is the offset of the light inside a 1 kpc radius. The bulge CO flux is obtained from the BIMA + 12m map. (*Bottom panel*) CO − *K* offset of disk region ($r > 1$ kpc). This is the offset of the light outside of a 1 kpc radius. The disk CO flux is obtained by subtracting the bulge flux obtained from the BIMA + 12m map from the single-dish flux inside of 200″.

ott

- Slope of line is 0.53 +/- 0.03
- Intercept is 0.90 +/- 0.09
- “No systematic trend” for one scale length to be greater than the other because of nonzero intercept (?)
- More clear to me: mean ratio of CO to stellar scale length is 0.88 +/- 0.14 (consistent with 1).

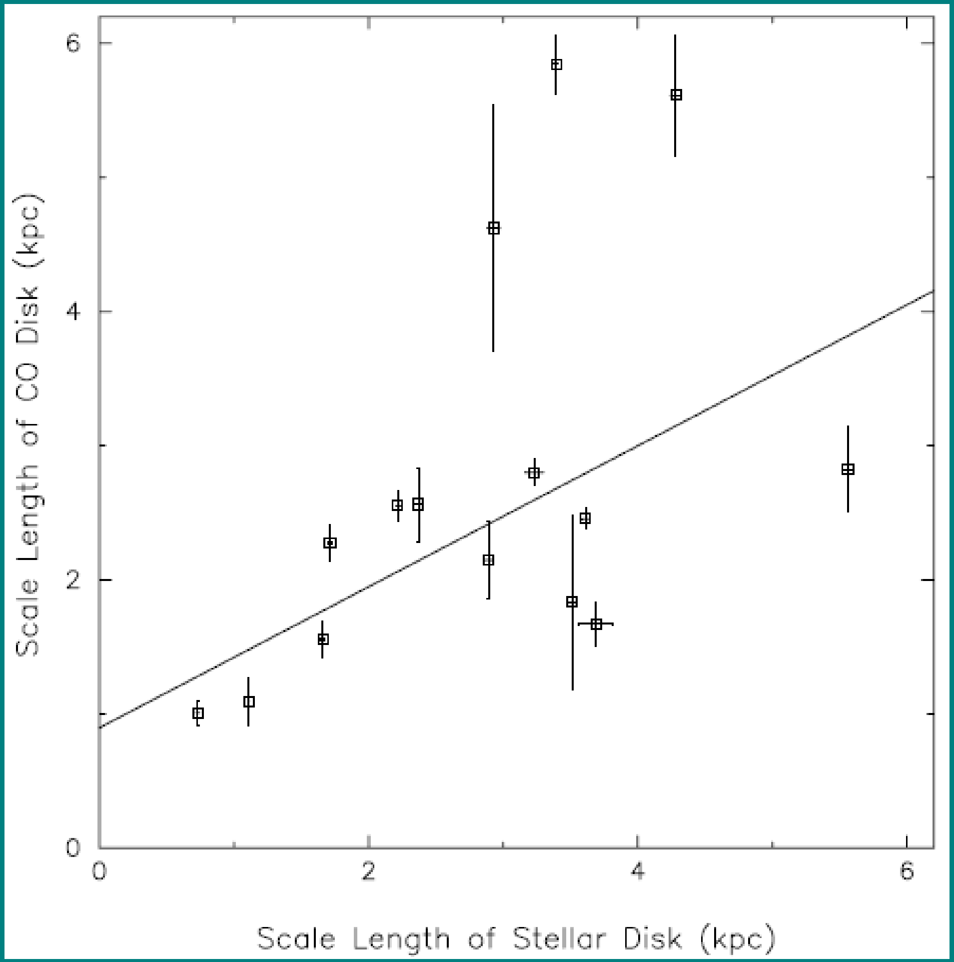


FIG. 5.—Scale lengths of CO and stellar disks. The error bars are the formal 1 σ uncertainties in the fitted scale lengths. The CO scale lengths are derived from the fully sampled single-dish maps. The solid line represents a linear least-squares fit.

Conclusions

- BIMA SONG maps show considerable variety in the distribution of molecular gas.
  - Much more heterogeneous on sub-kpc scales than the stellar images
- Radial brightness profiles of CO emission reflect the clumpy nature of CO gas on scales ~ few kpc.

Conclusions (cont'd)

- CO radial profiles cannot be discribed by a simple exponential disk model.
  - Fits a two-component bulge+disk model much better.
    - The scale lengths of the exponential disks for the stellar light and for the CO emission are roughly the same.
      - Variation from galaxy to galaxy
      - Authors suggest that the scale lengths may be the same when averaged over time.

Conclusions (cont'd)

- There is a weak relationship between Hubble type and the ratio of CO to *K*-band flux. This is true for:
  - The galaxies as a whole
  - The bulge regions
  - Bulge+disk regions
- Excess CO emission seen in the central regions of many of the galaxies may be due to:
  - An accumulation of molecular gas in the nuclear region
  - Or, an increase in the pressure in the bulge region due to hot diffuse gas.