

Fueling central activities in barred spiral galaxies

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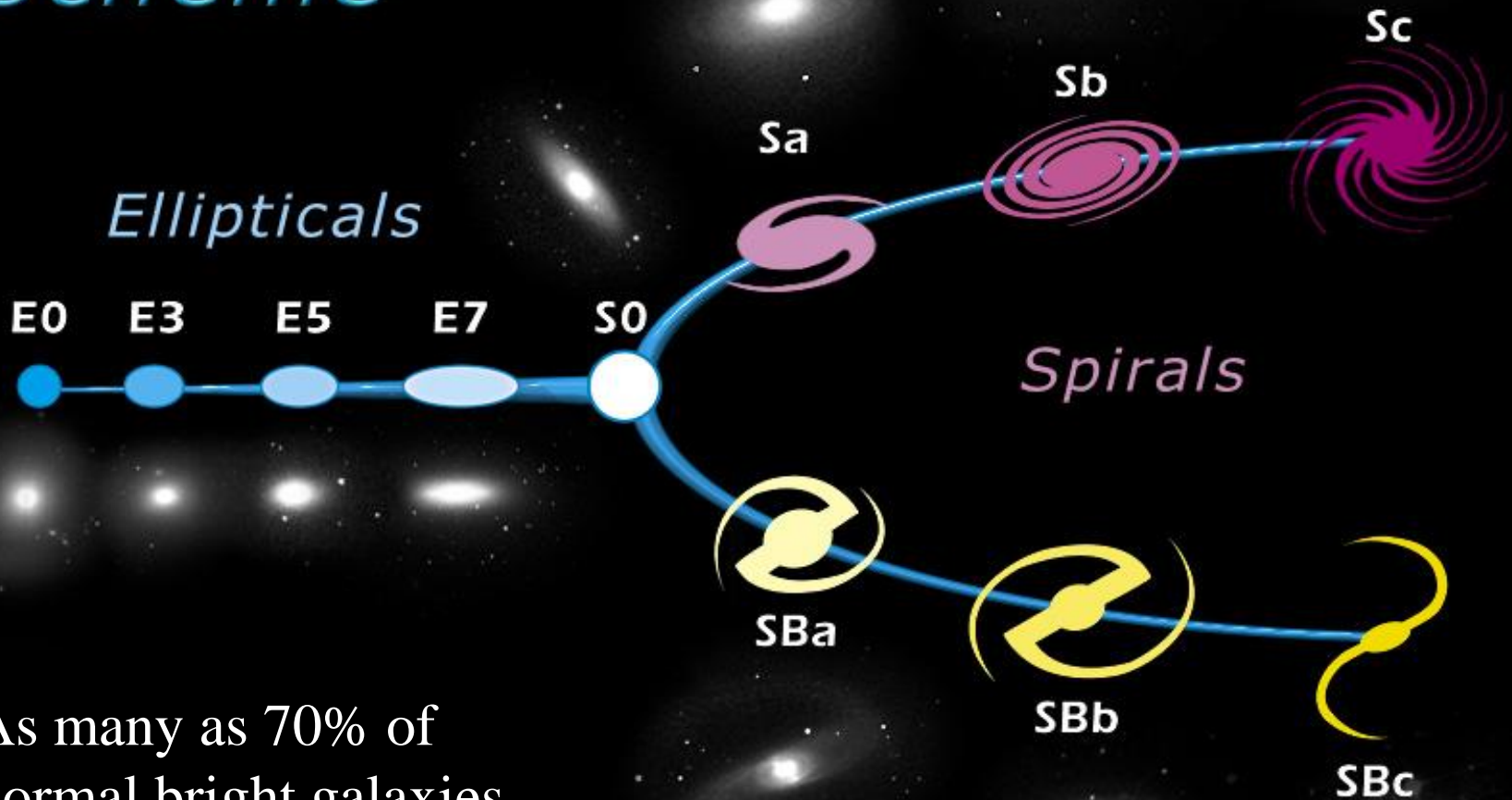
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S. Muller (Onsala Space Observatory)

Outline :

1. Introduction
2. Bar-driven Spiral Density Waves
3. Model for Numerical Simulation
4. Comparisons of Simulations and Observations
5. Conclusion

Edwin Hubble's Classification Scheme



As many as 70% of normal bright galaxies are barred at some level (Eskridge et al. 2002)

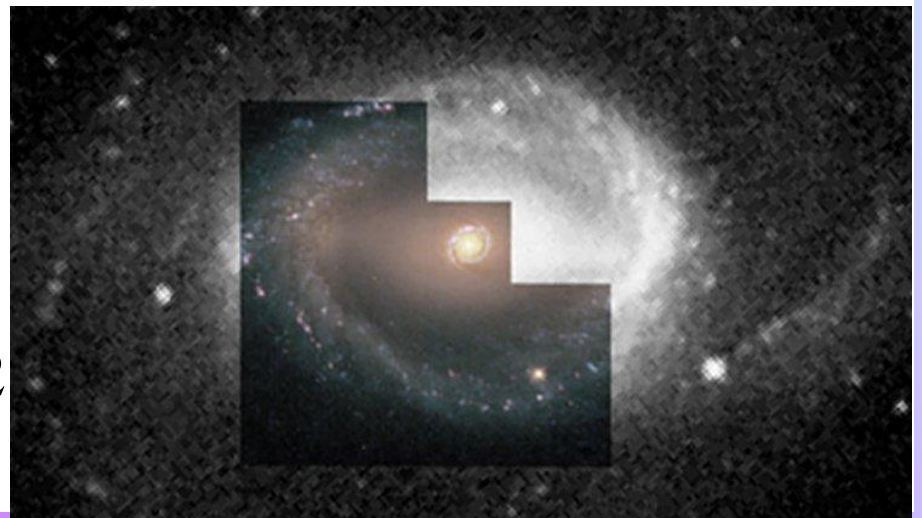
NGC 1300



NGC 1097 Sy1

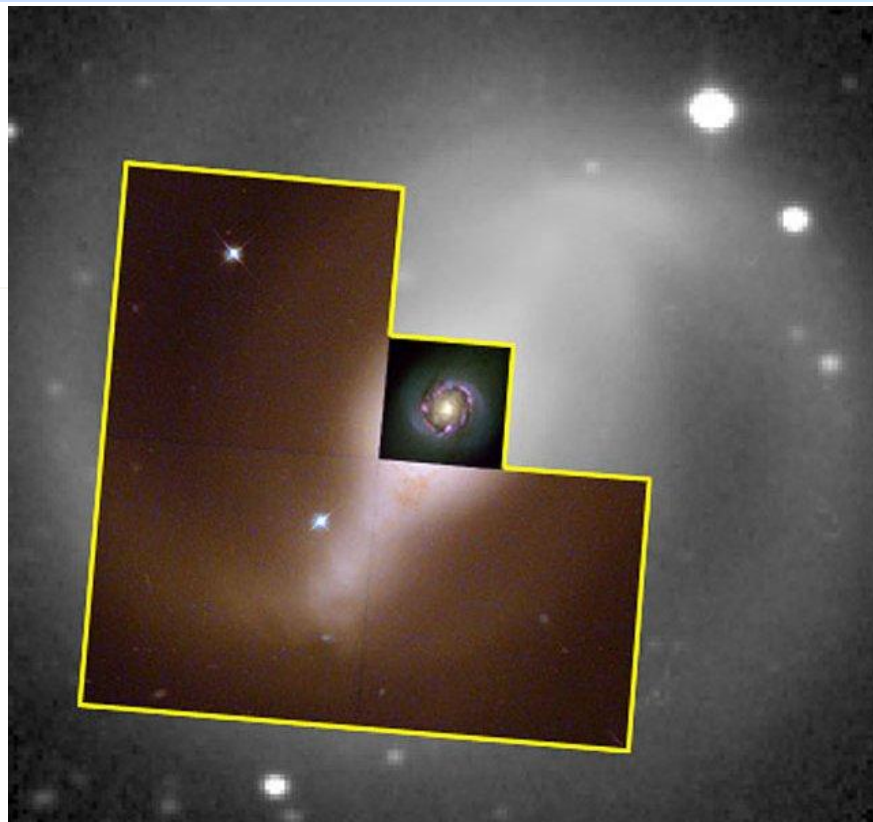
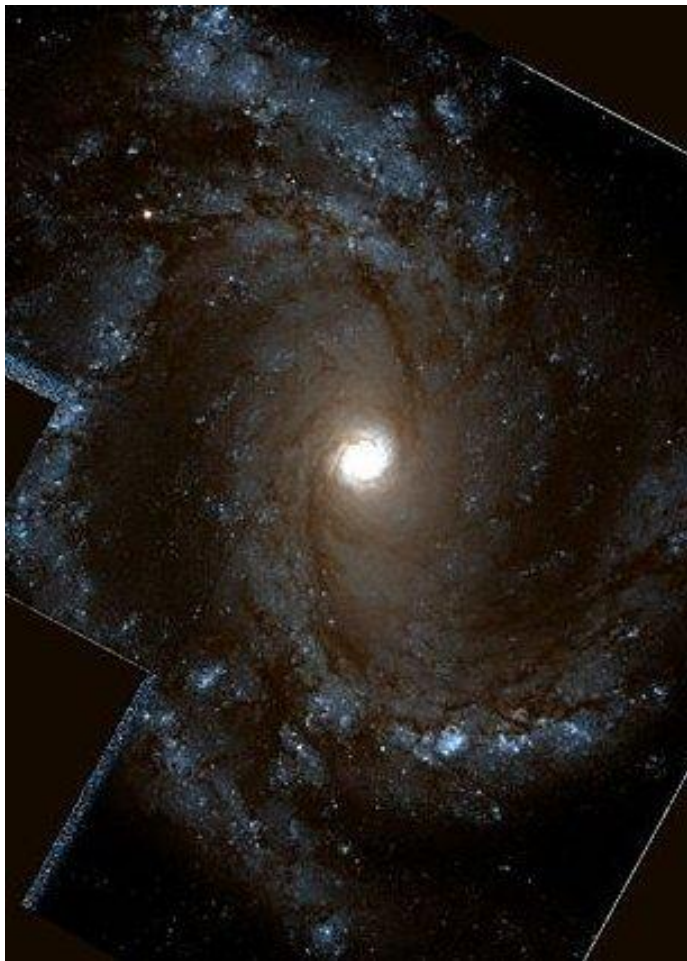


NGC 1512
AGN



NGC 4314

NGC 4303 Sy2



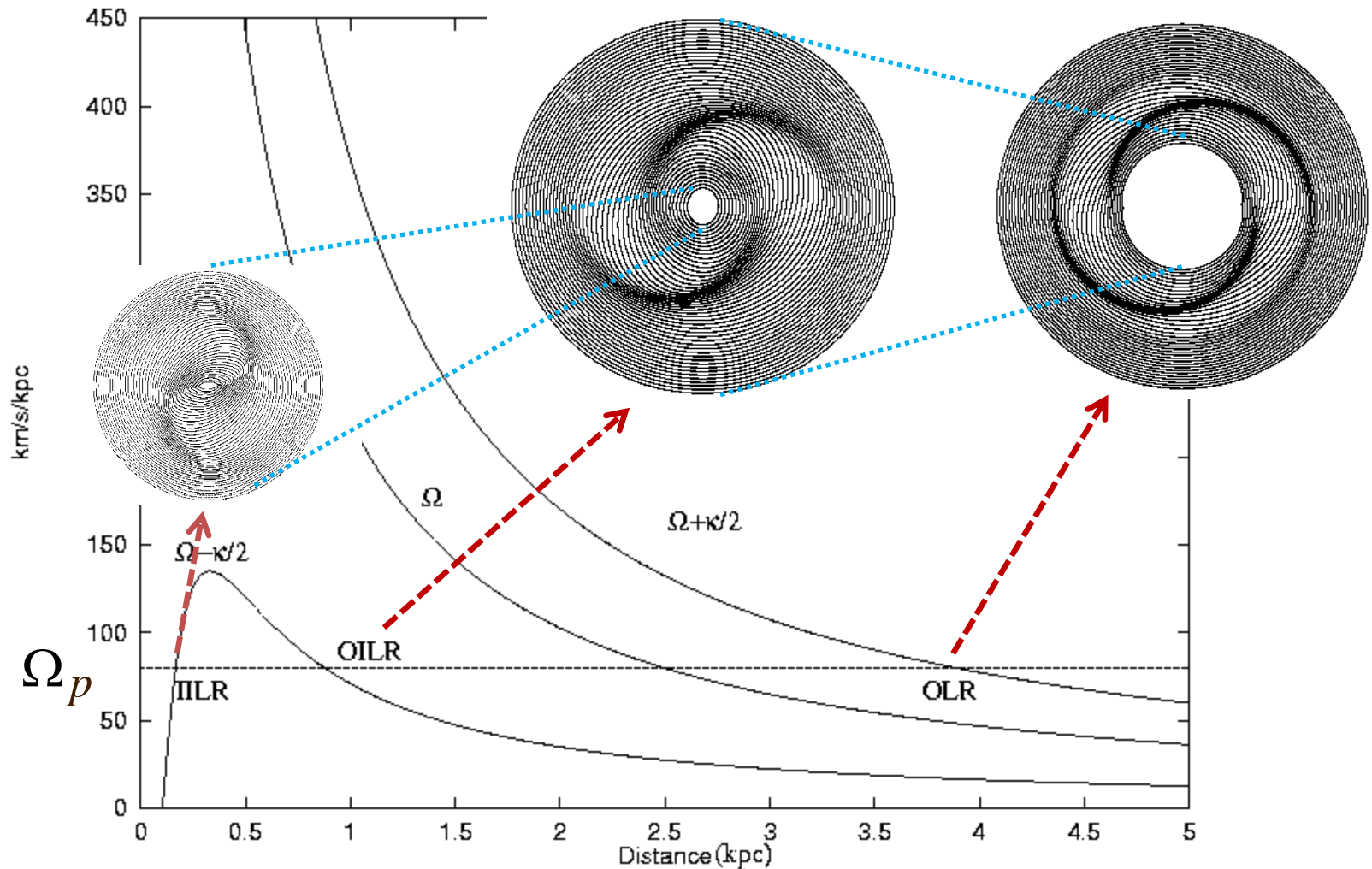
NGC 6782



Outline :

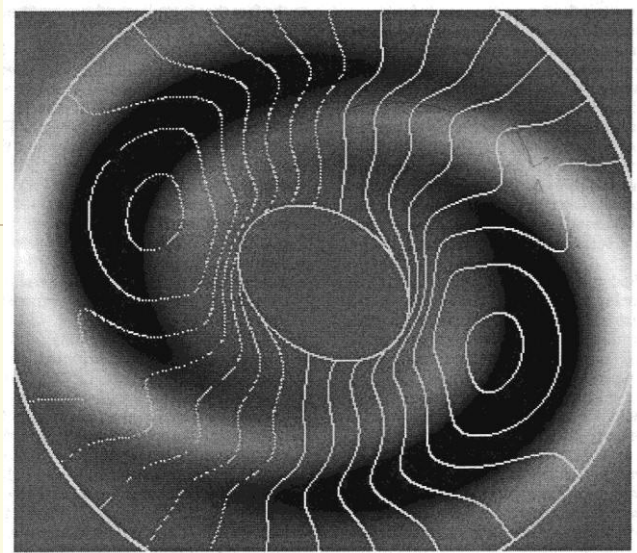
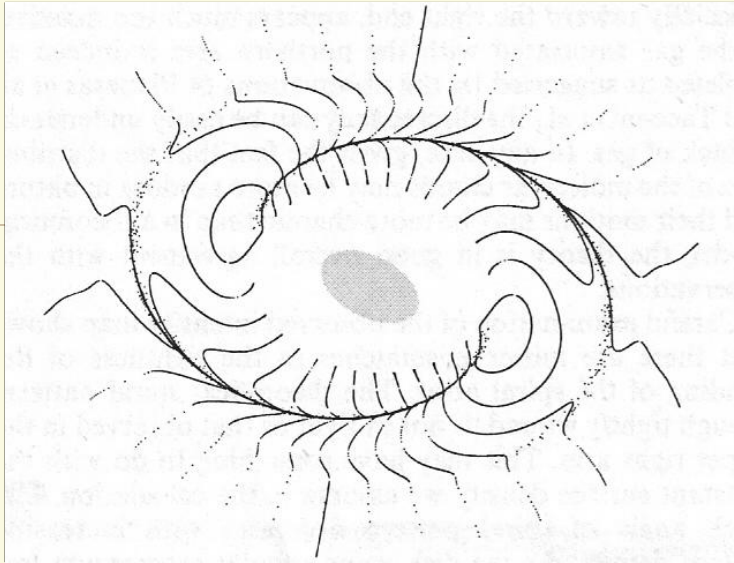
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Bar-driven spirals at Lindblad resonances according to asymptotic theory

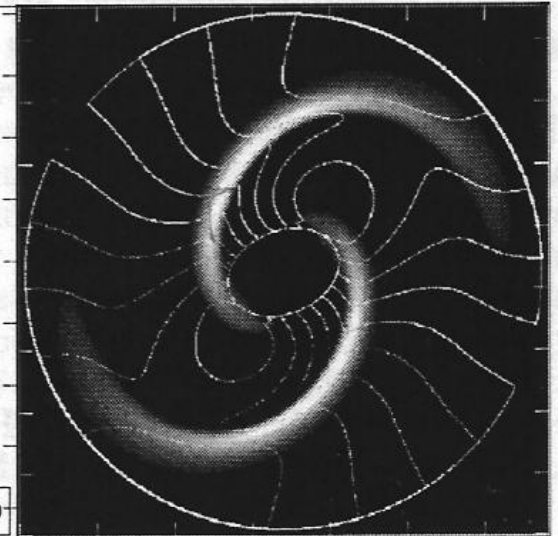
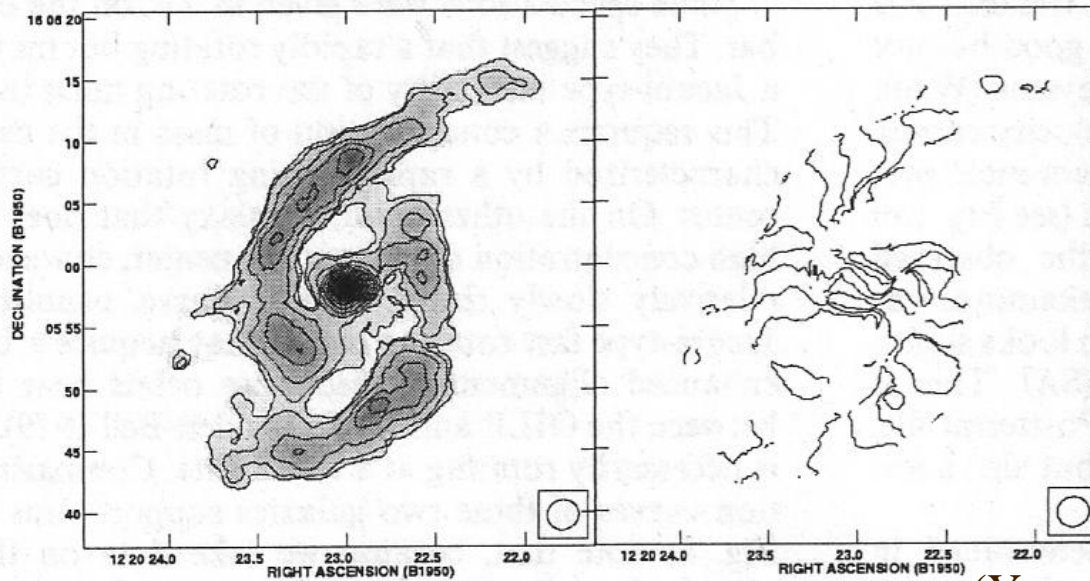


(Yuan & Kuo 1997)

Isovelocity curves bend inward along spirals excited at OLR

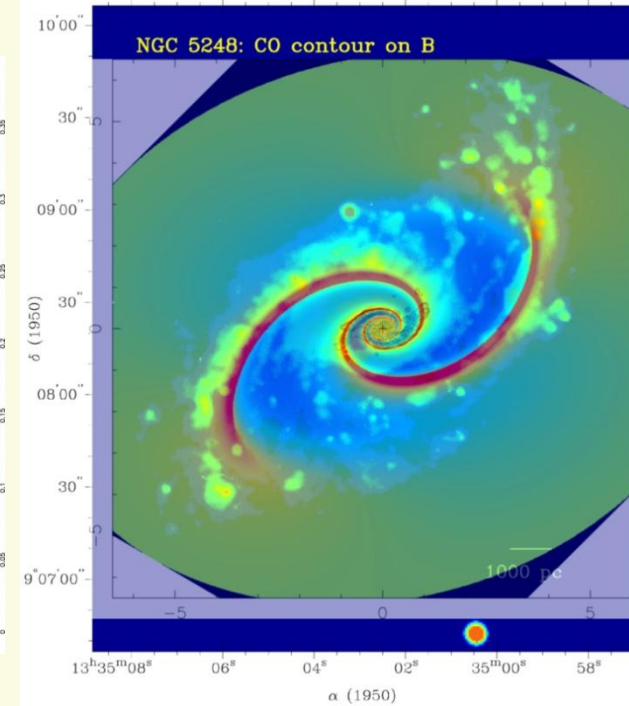
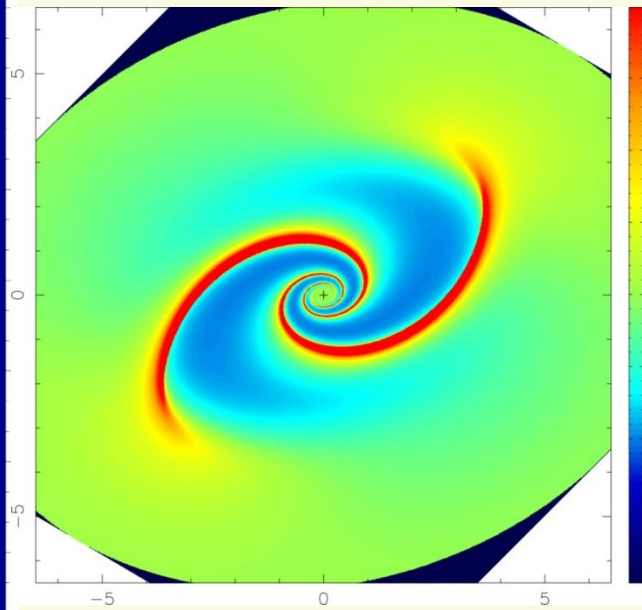
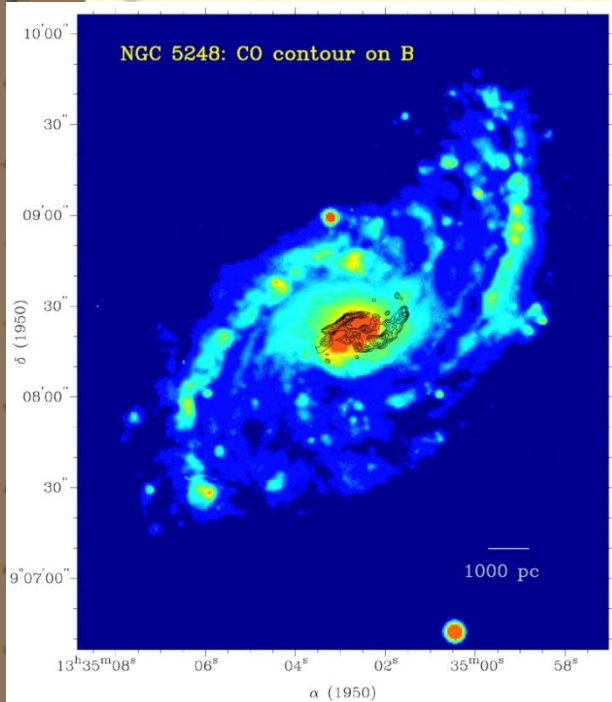


Isovelocity curves bend outward along spirals excited at OILR



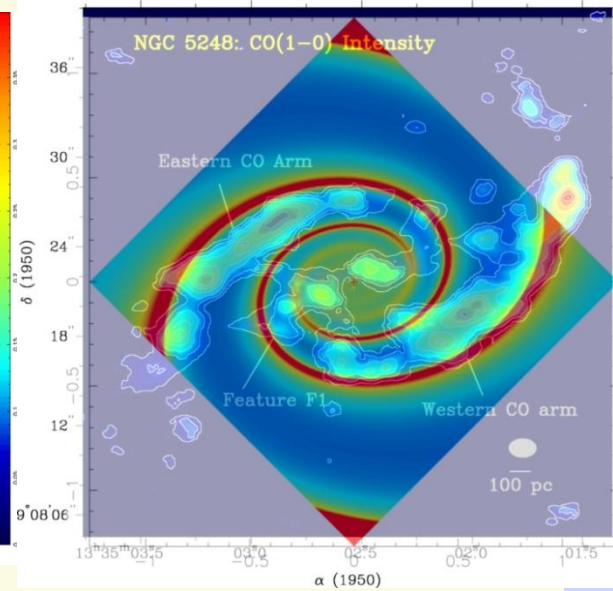
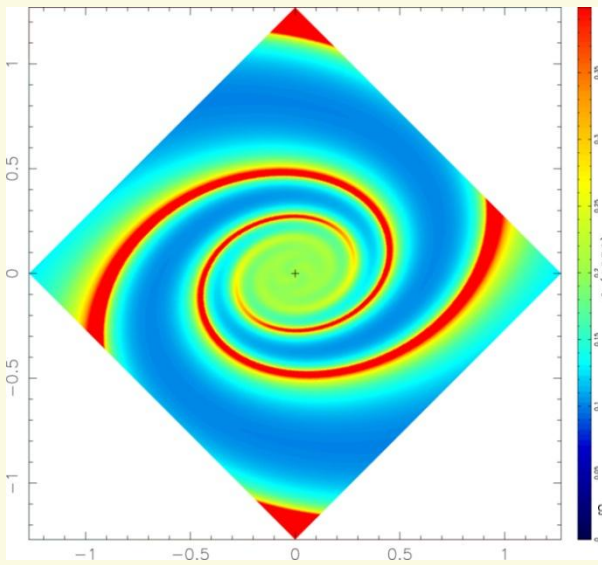
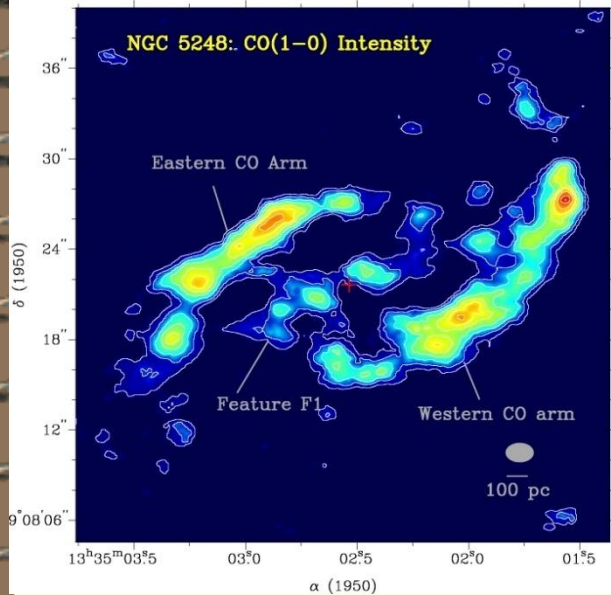
(Yuan & Kuo, 1998, ApJ, 497, 689)

NGC5248 : B-band vs Theory



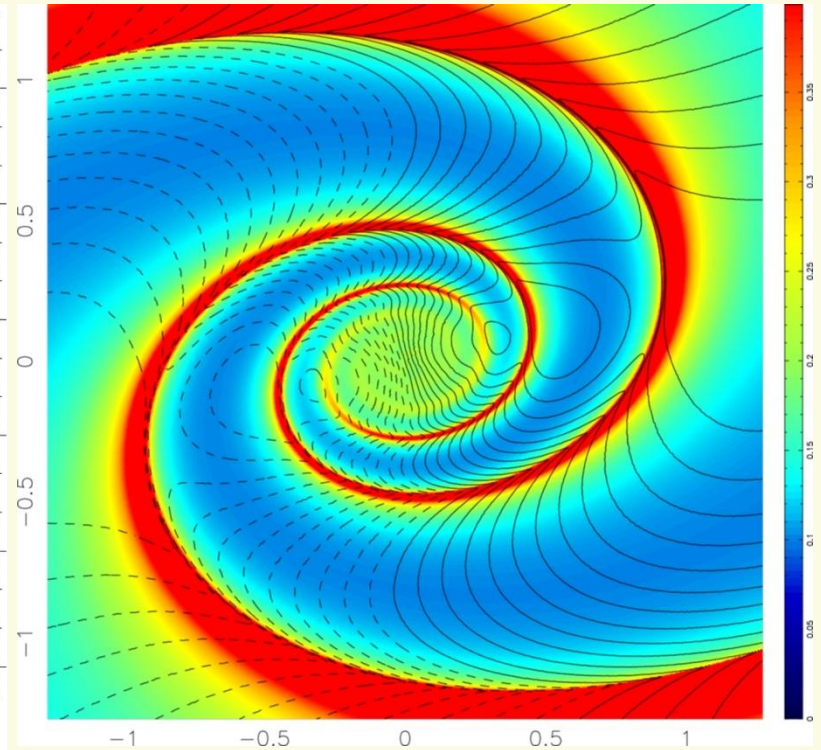
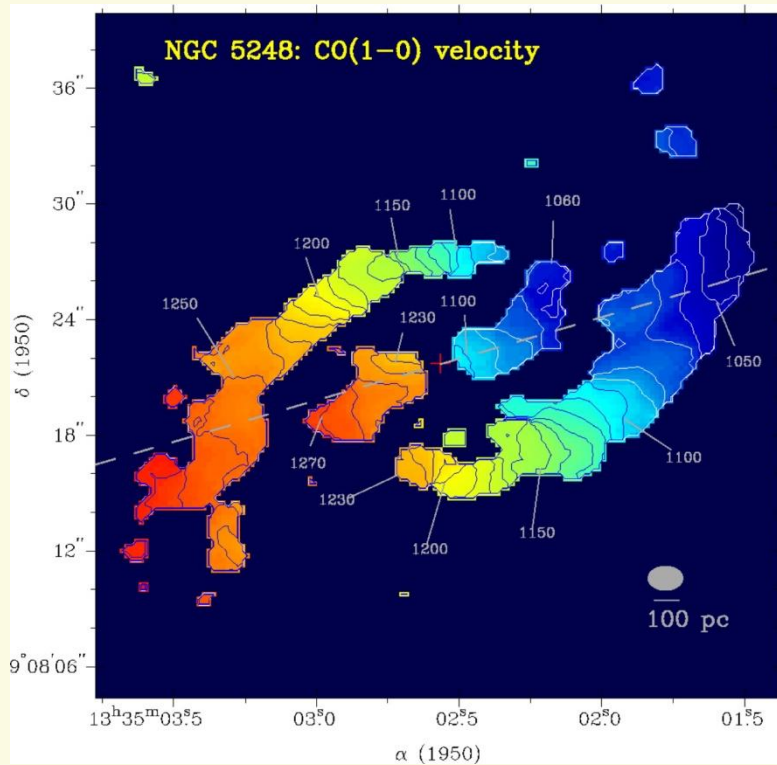
(Yuan & Yang 2006)

NGC5248 : CO vs Theory



(Yuan & Yang 2006)

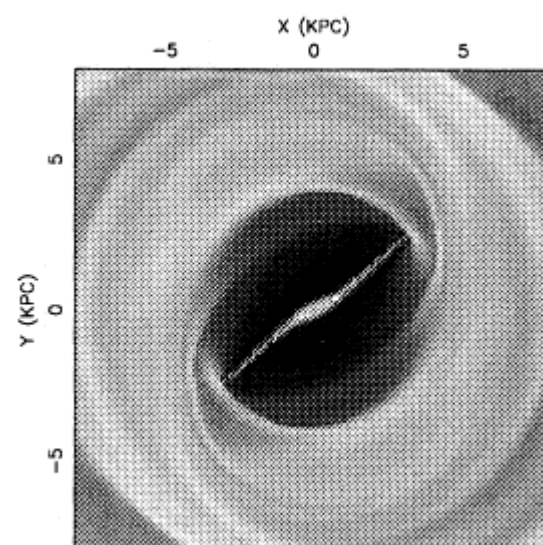
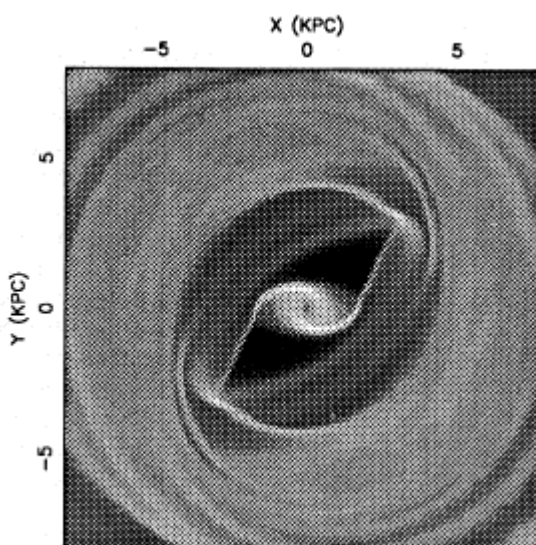
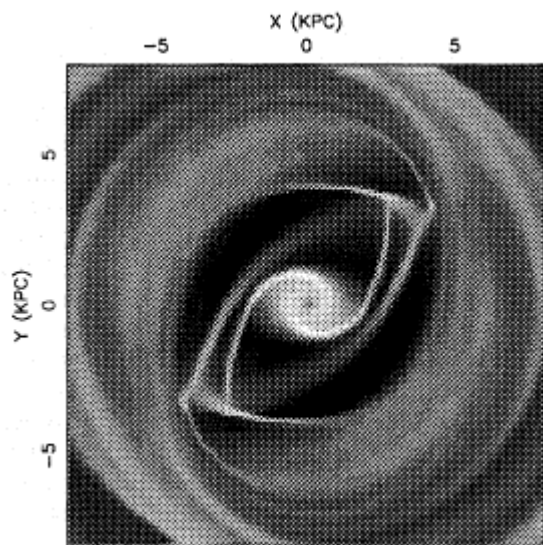
NGC5248 : Isovelocity Curves



(Yuan & Yang 2006)

Gas response in different bar models (Athanasoula, 1992)

Stronger bar

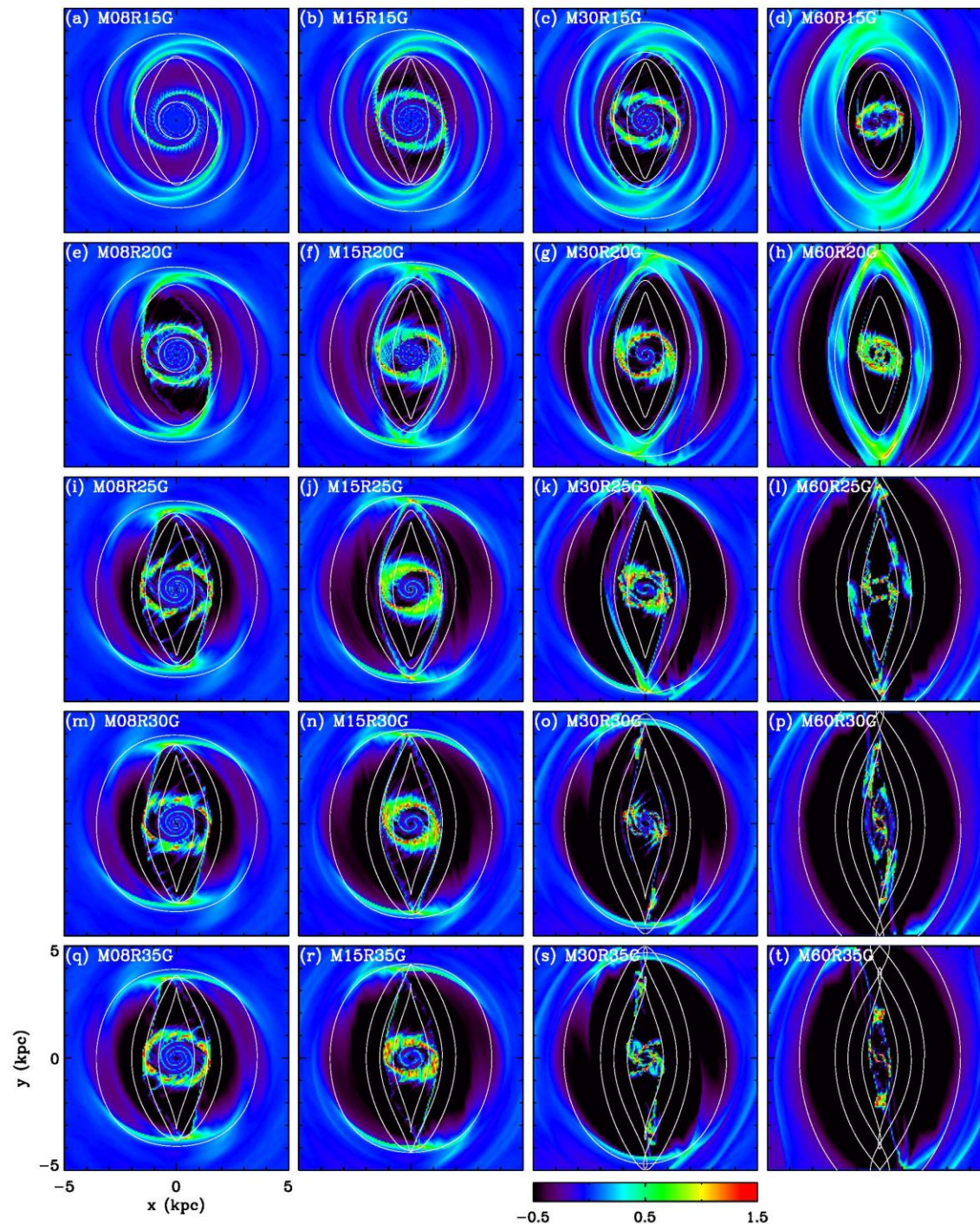


The gaseous disk is placed under an external gravitational potential which consists of three components: a stellar bulge, a Kuzmin/Toomre disk, and a Ferrers ellipsoid.

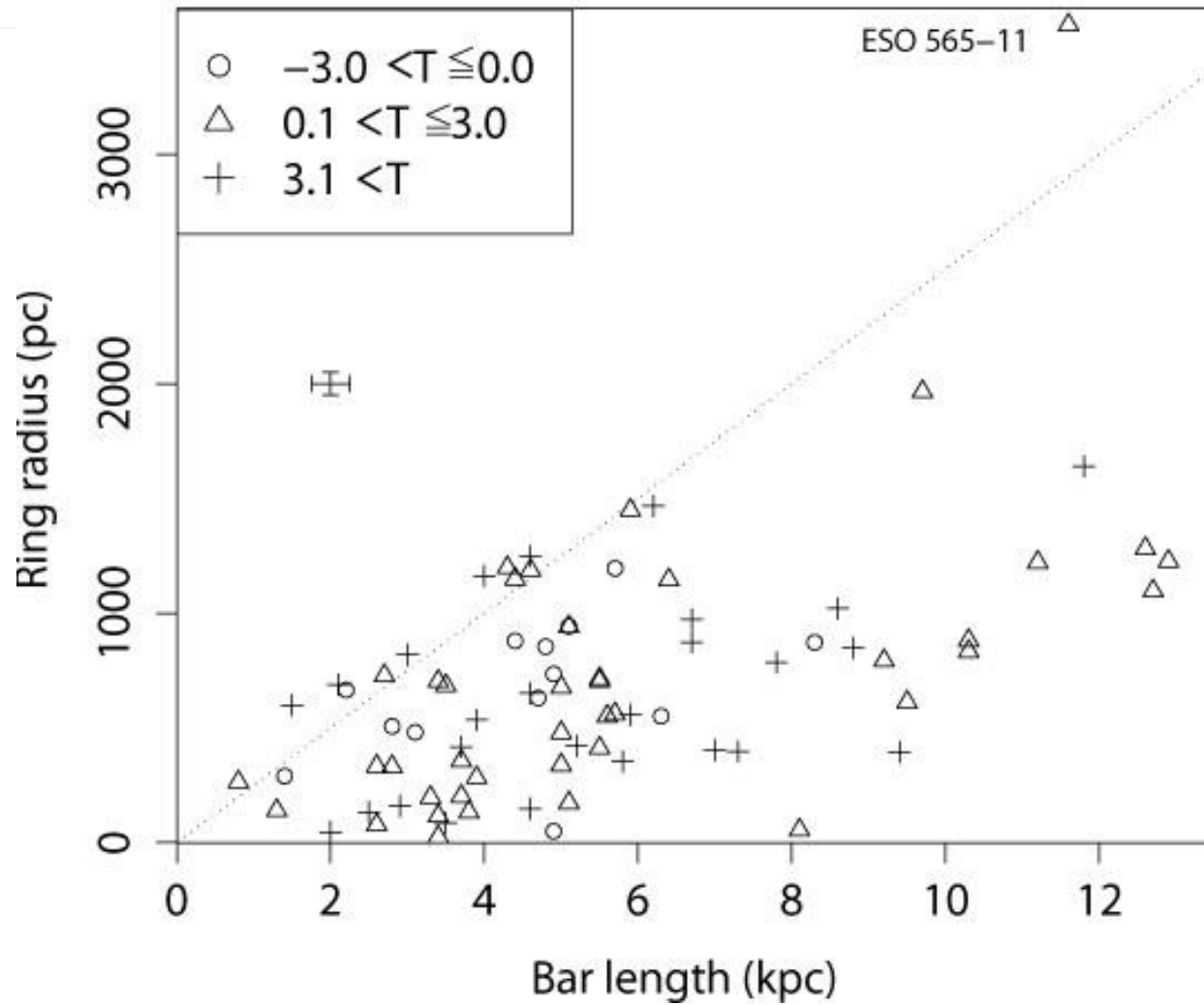
Kim et al. 2012

M : fraction of the mass of the bar relative to the spheroidal component

R : ratio of the bar semi-major axis to the semi-minor axis



Comerón et al. 2010



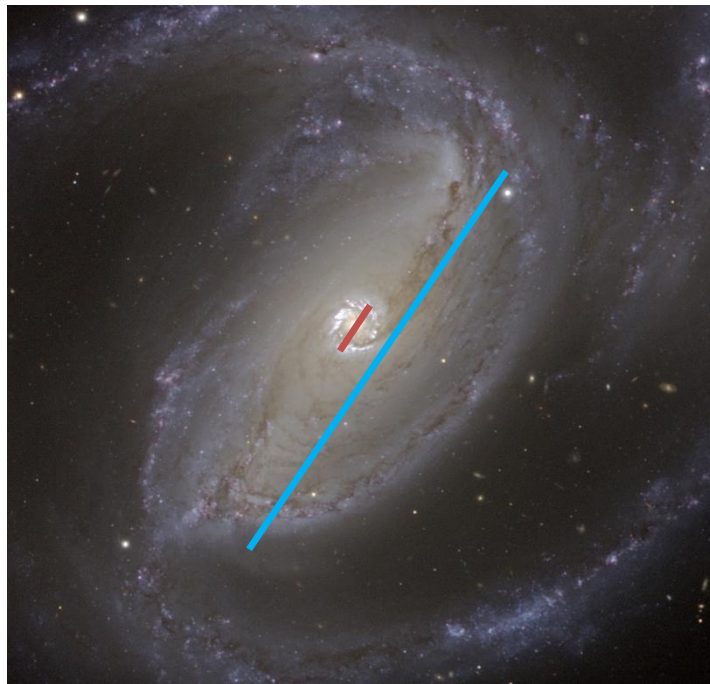
NGC 1300

0.84/16



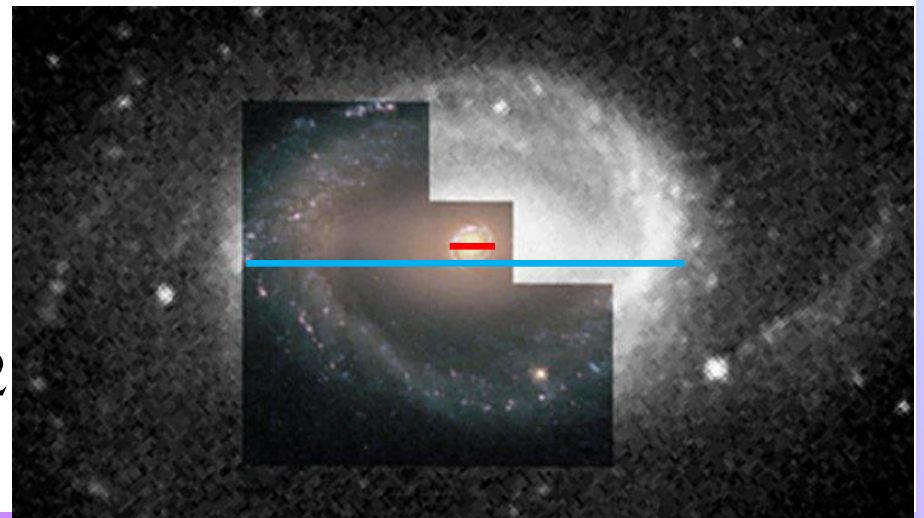
NGC 1097

1.4/16

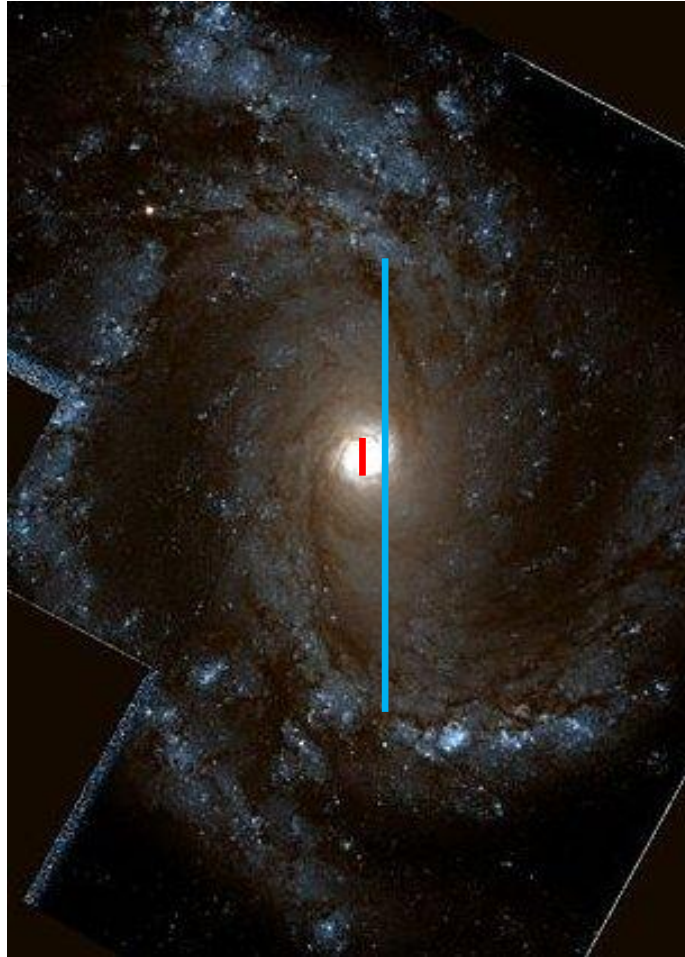


NGC 1512

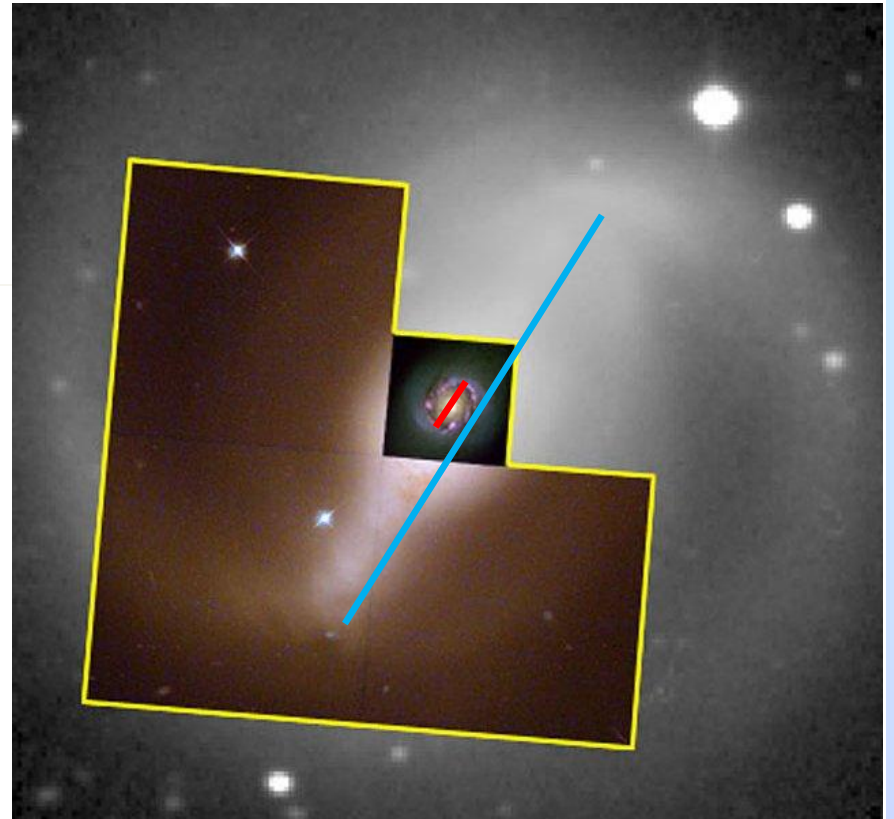
0.8/9.4



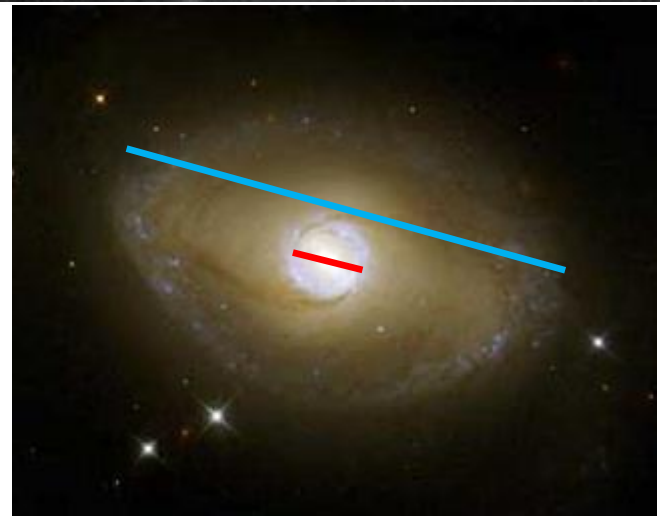
NGC 4303
0.85/8.5



NGC 4314
0.8/8.3



NGC 6782
2.5/15



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Governing Equations

(i) Equation of continuity

$$\frac{\partial \sigma}{\partial t} + \nabla \cdot (\sigma \mathbf{v}) = 0$$

(ii) Equation of motion

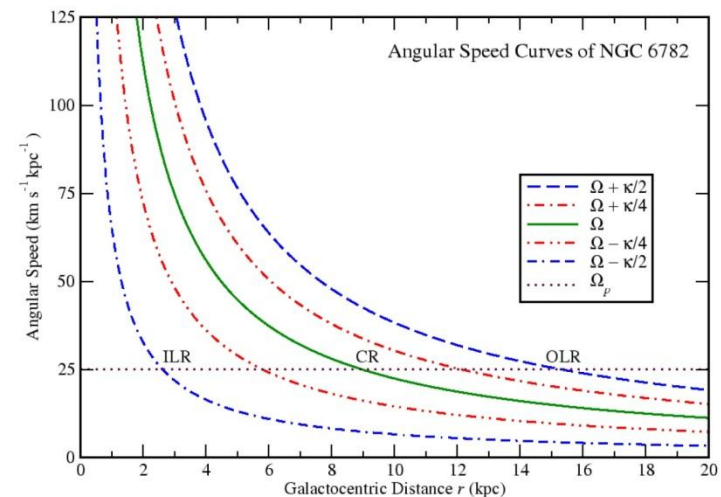
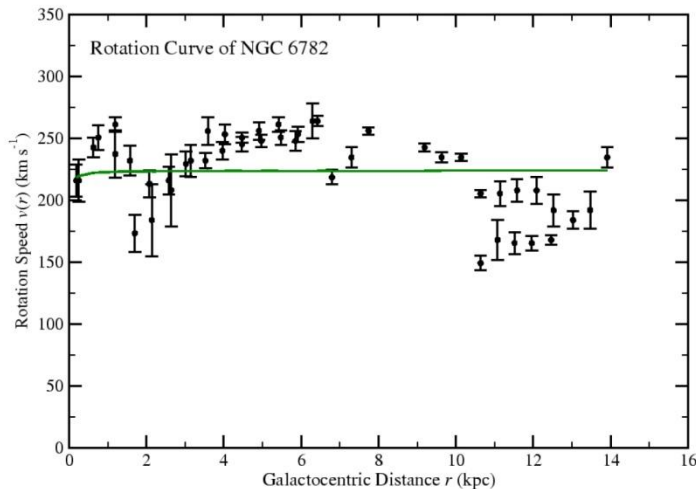
$$\frac{\partial(\mathbf{v})}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\frac{\nabla P}{\sigma} - \nabla V$$

$$V = V_0 + V_1 + V_g$$

$$\frac{dV_0}{dr} = r\Omega^2(r) = \frac{v(r)^2}{r}$$

$$V_1(R, \phi, t) = \Psi(R) \cos[2(\phi - \Omega_p t)]$$

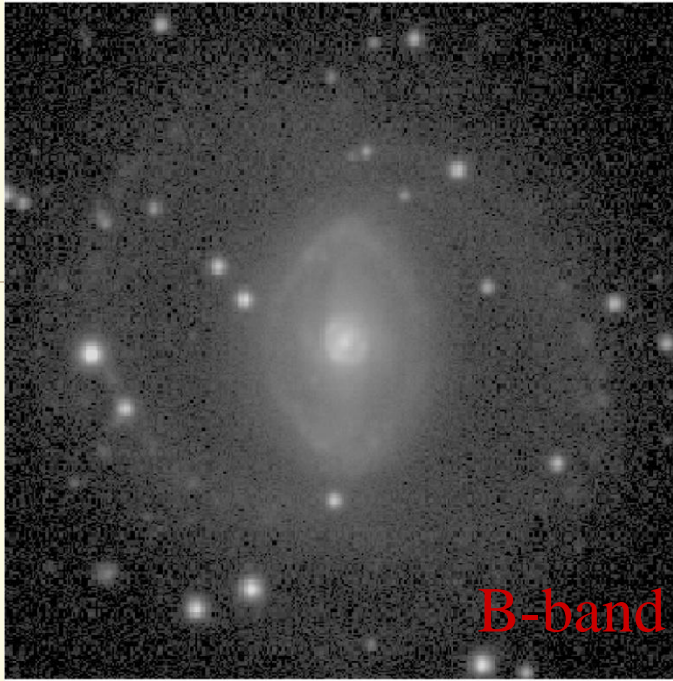
$$\Psi(R) = -\Psi_0 \frac{R^2}{r_A^2 + R^2 + D^2/2}$$



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NGC 6782



B-band image



Hubble Heritage image

SB(r)a

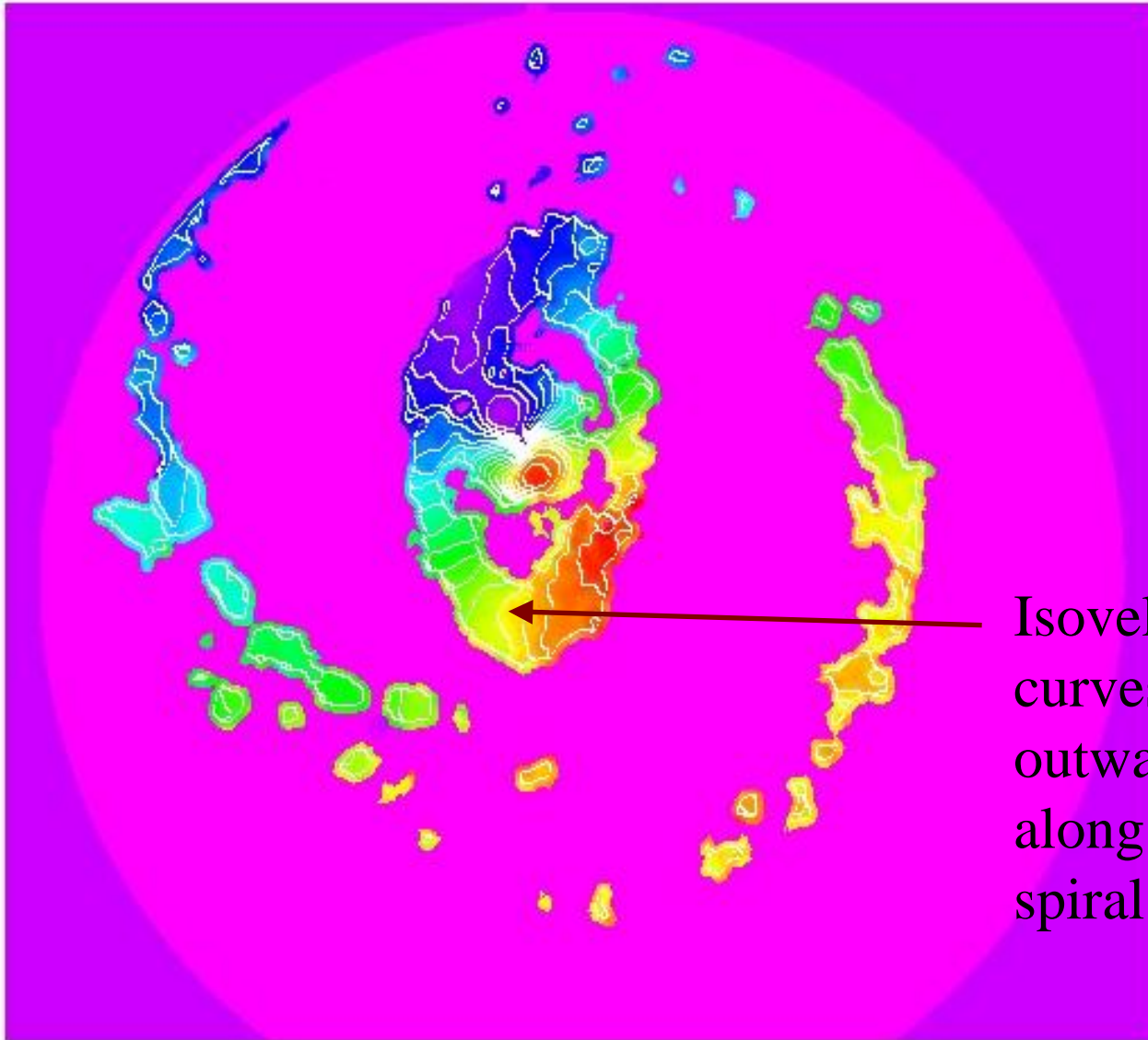
l.o.n = 35°

I.A. = 27°

P.A. = 177°

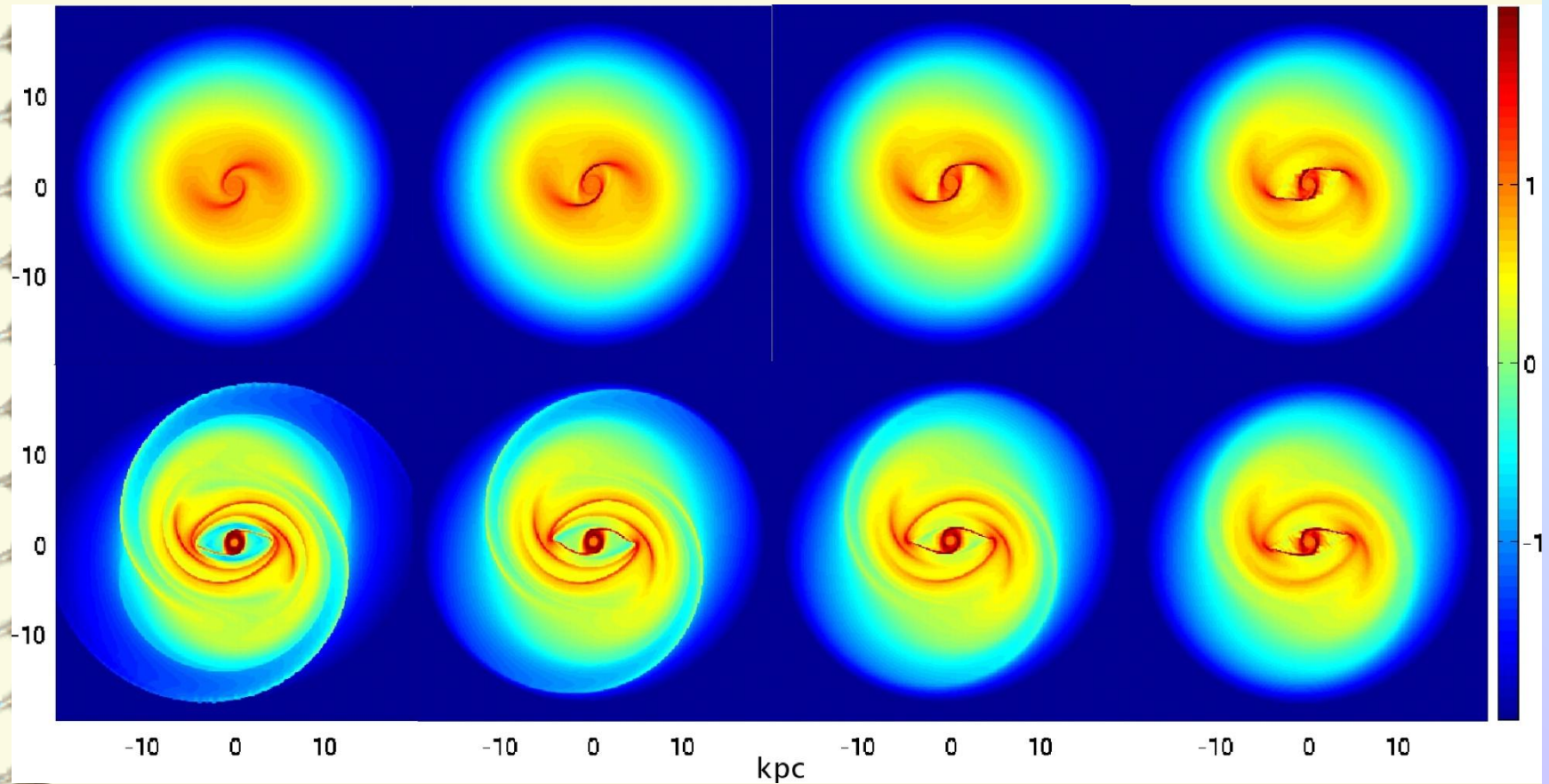
D = 39 Mpc

Velocity field of NGC 6782



Isovelocity curves bend outwards along the spiral arms

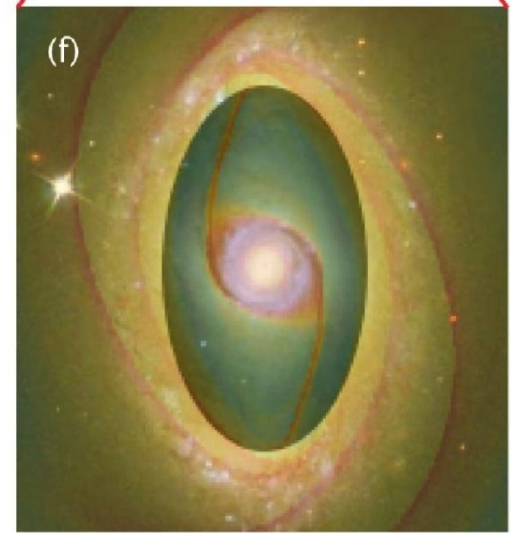
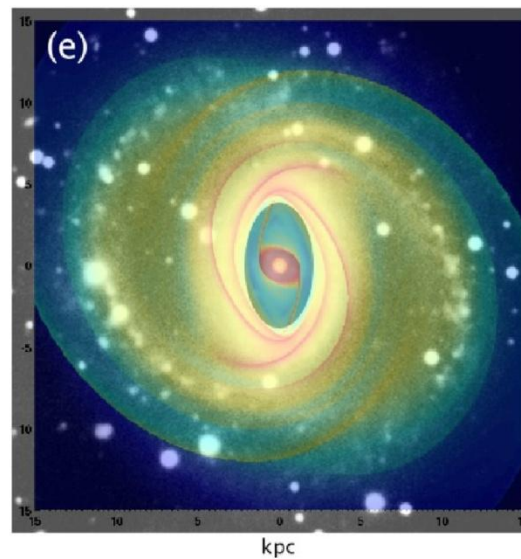
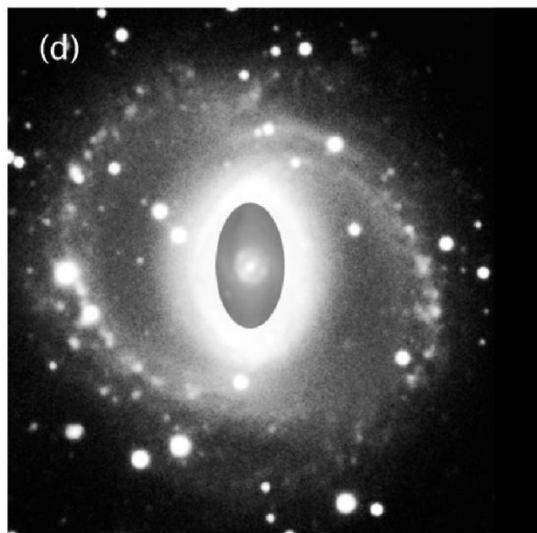
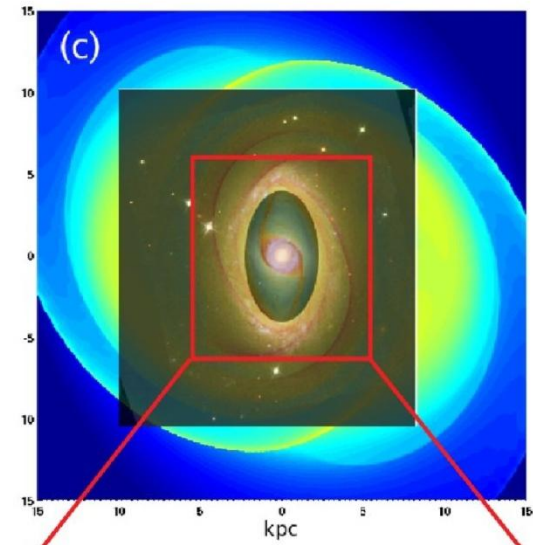
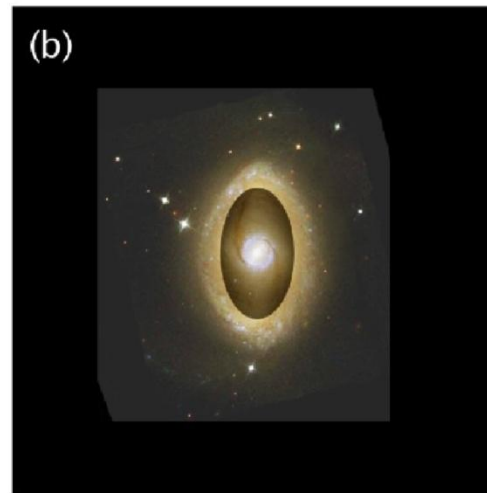
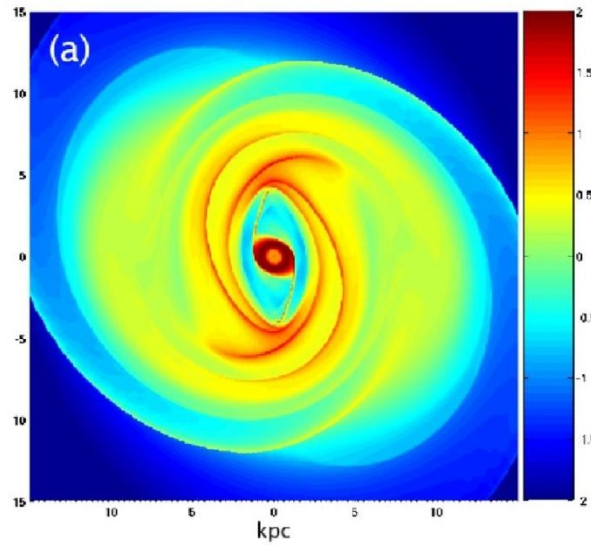
Evolution of the bar-driven gaseous disk for NGC 6782



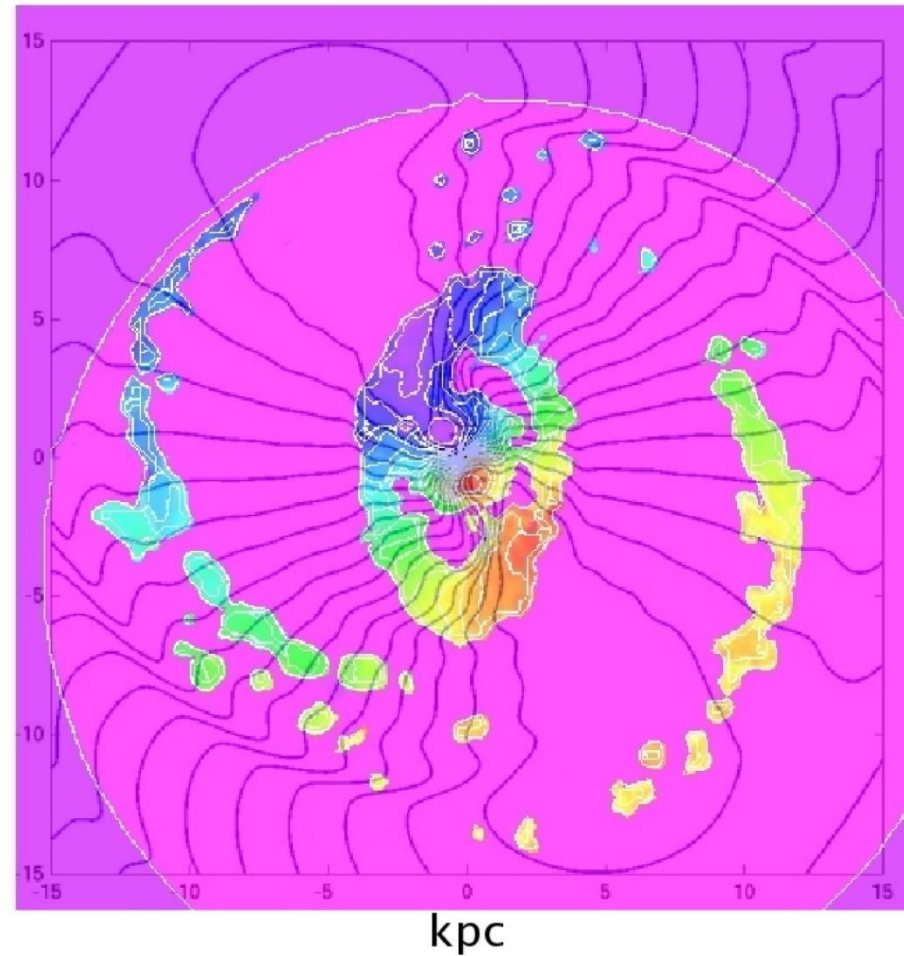
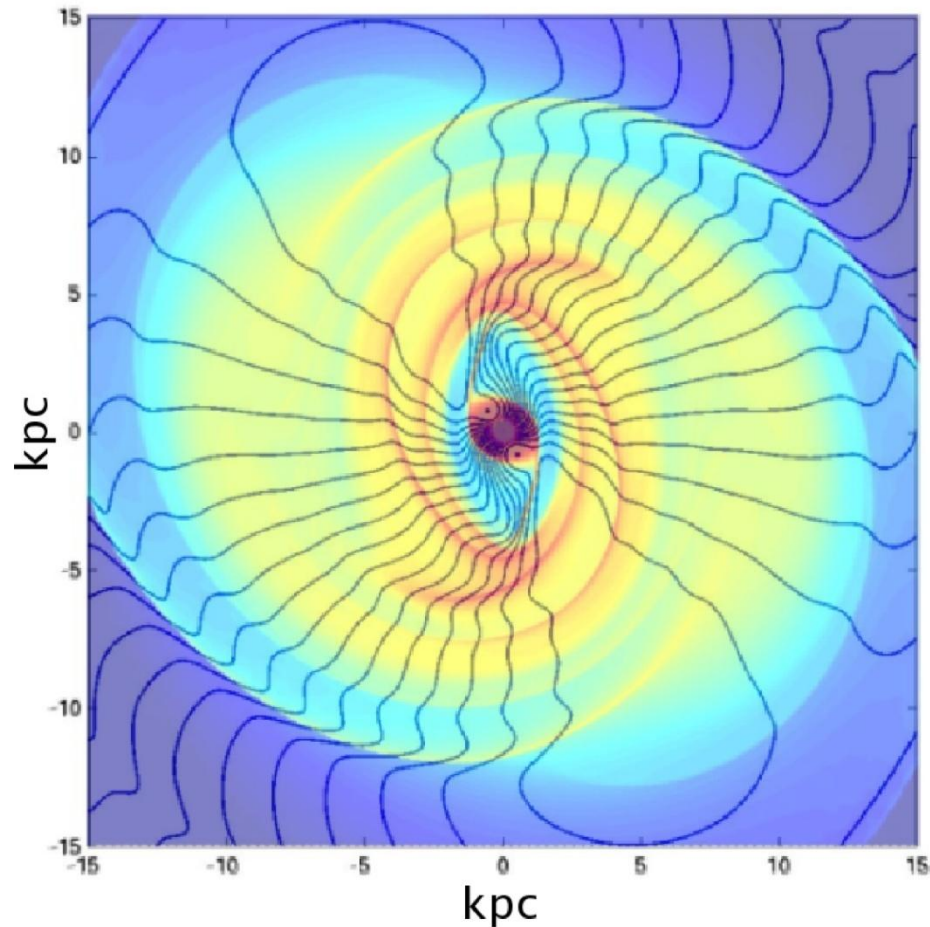
(Lin, Yuan, & Buta 2008)

Comparisons between the simulation and observations for NGC 6782

(Lin, Yuan, & Buta 2008)



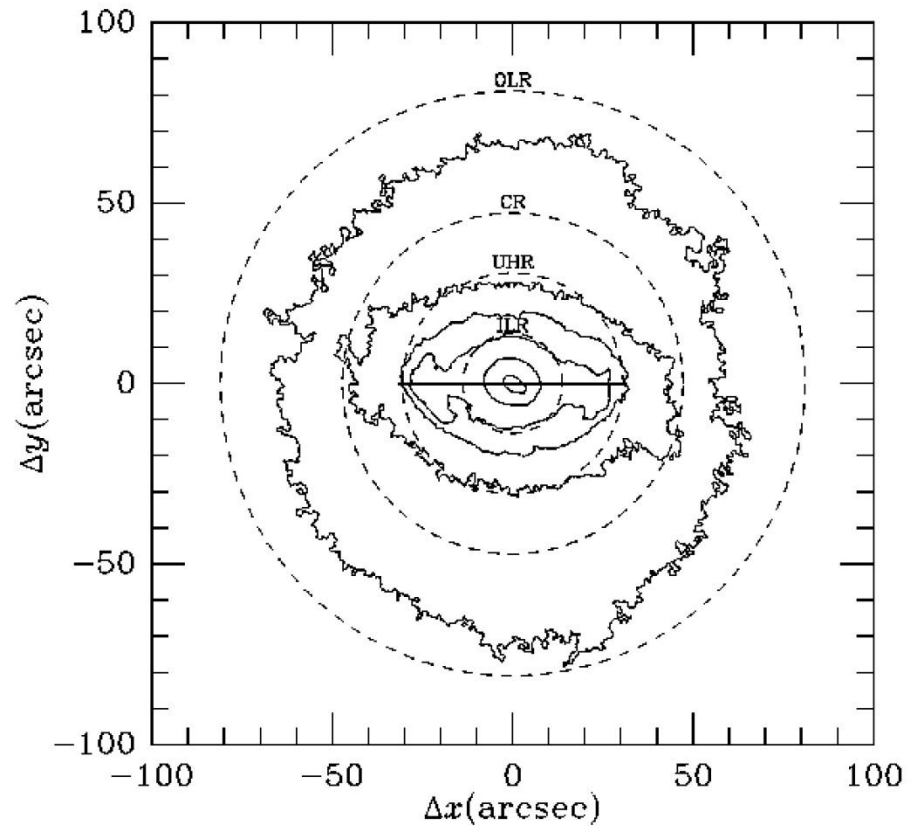
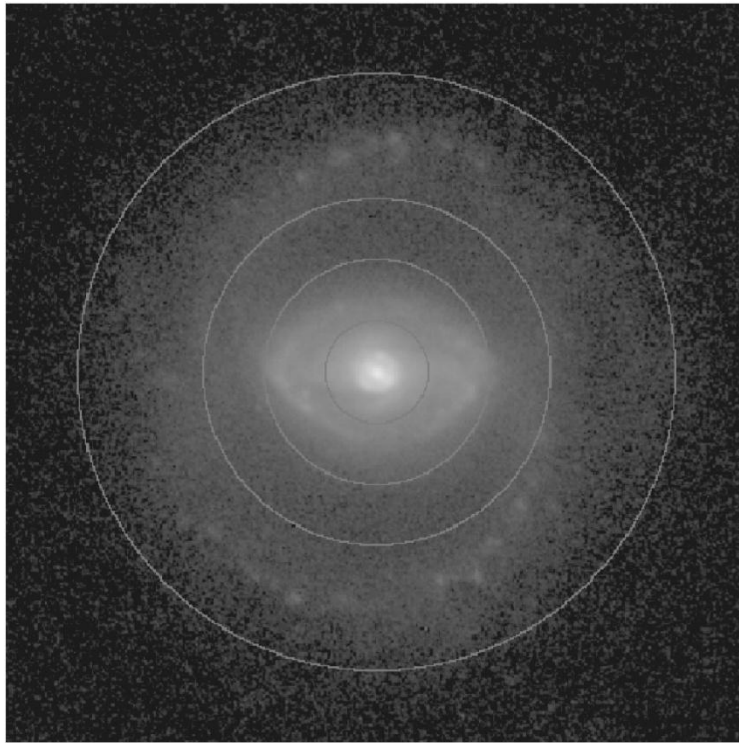
Simulated isovelocity curves plotted on top of the simulation density map (left) and the observed velocity field (right) for NGC 6782



(Lin, Yuan, & Buta 2008)

Locations of resonances in NGC 6782

(Lin, Yuan, & Buta 2008)



The solid horizontal line indicates the extent of the bar estimated by Rautiainen et al. (2005)

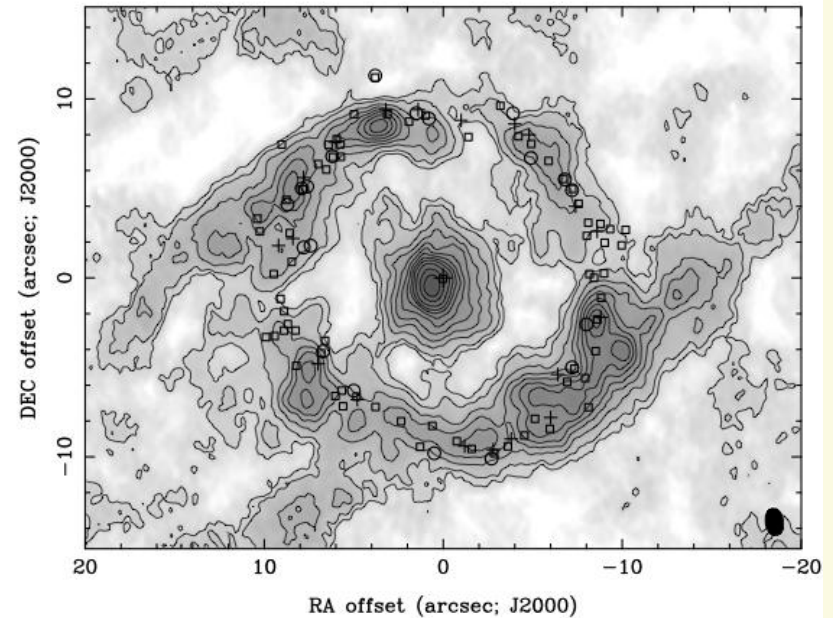
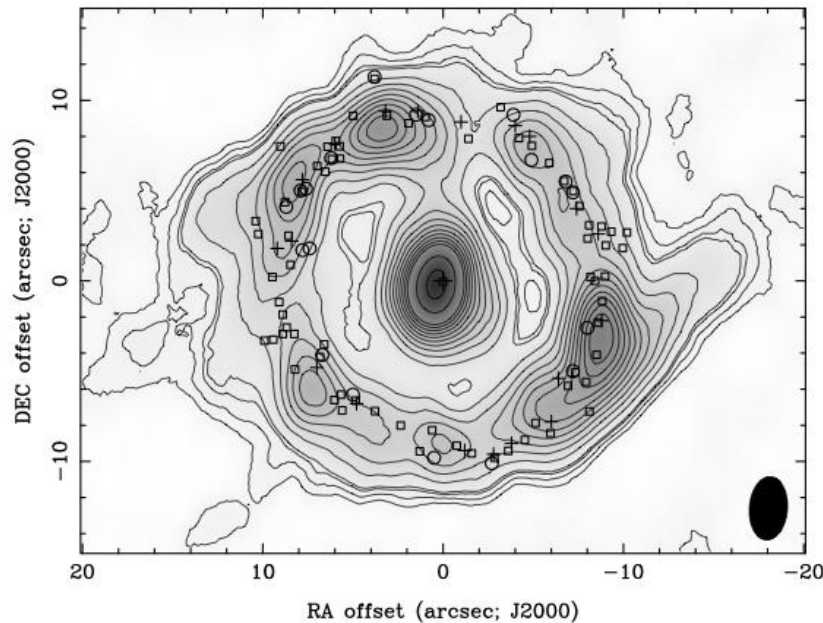
NGC 1097 [SB(s)b Seyfert 1]



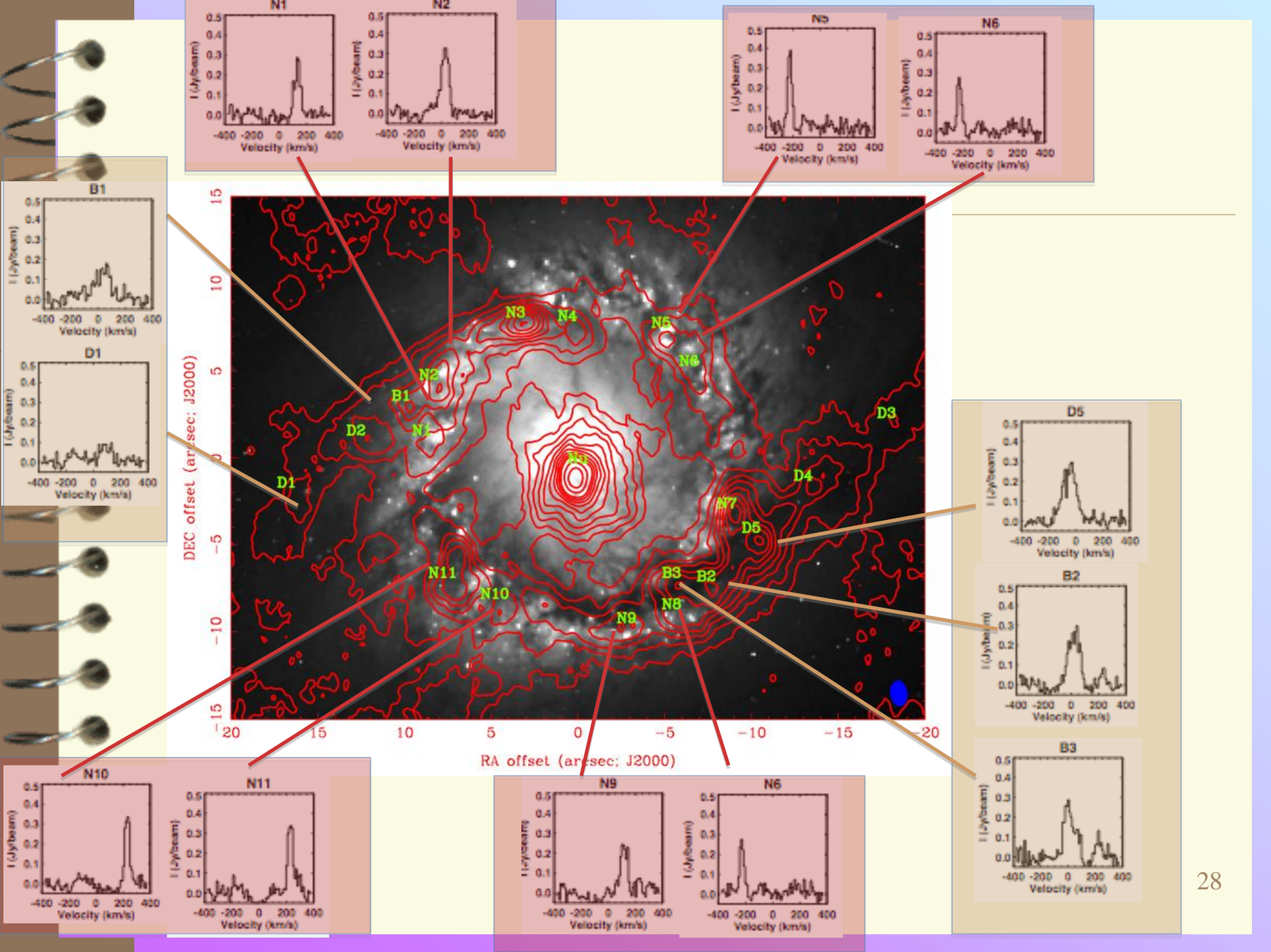
Nuclear starburst ring

Dust lanes

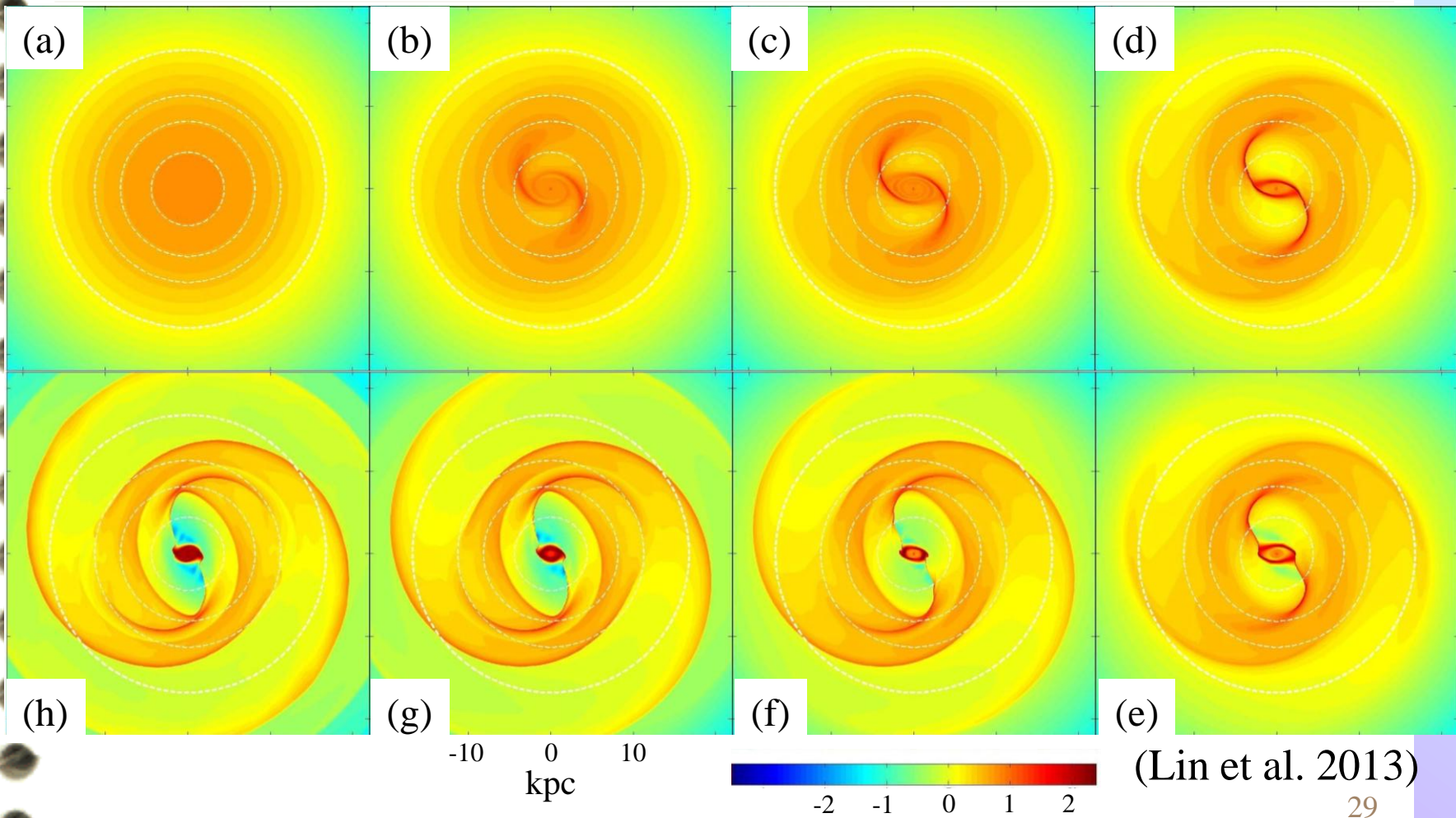
^{12}CO (J=2-1) intensity maps observed by SMA



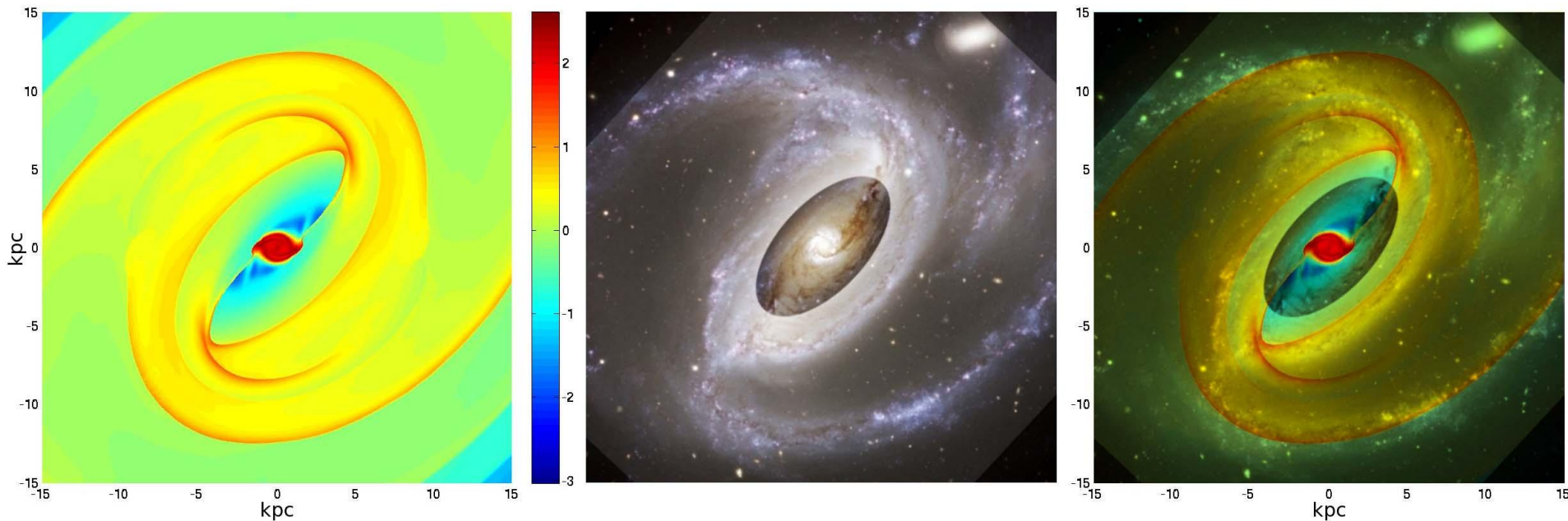
Hsieh et al. 2008 & 2011



Evolution of the gas disk for NGC 1097

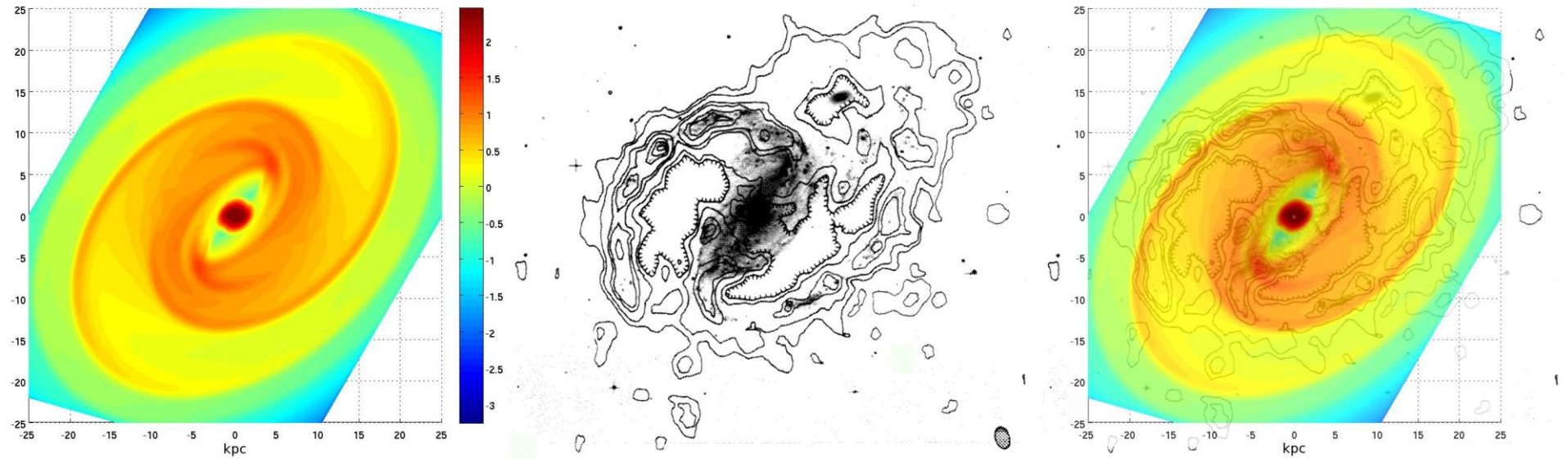


Comparison between the simulated density distribution and the optical image for NGC 1097



The bright nuclear starburst ring, dust lanes and the prominent spiral arms in the simulation match well with the observations.

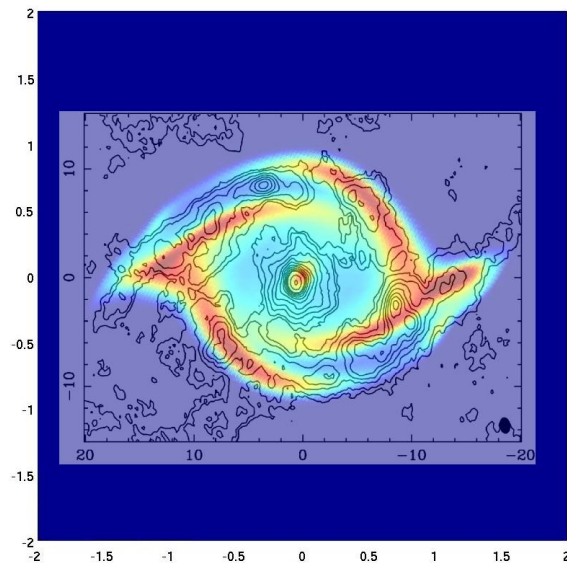
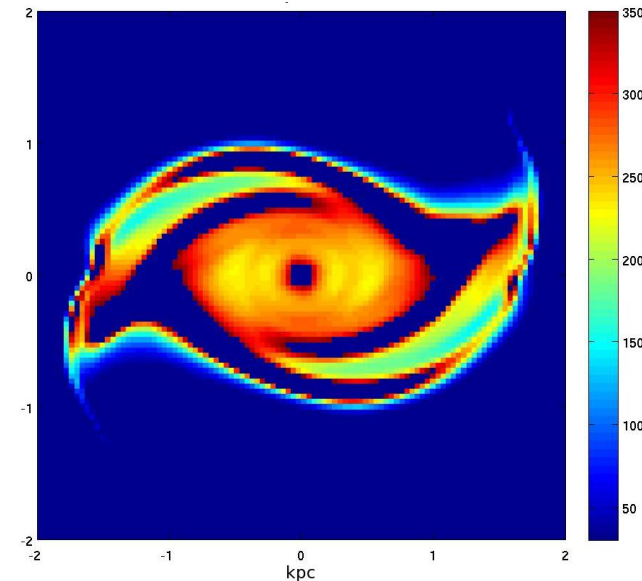
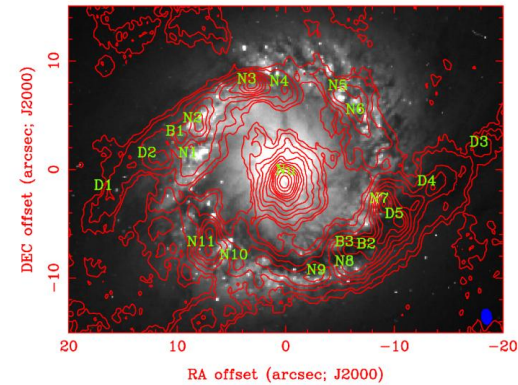
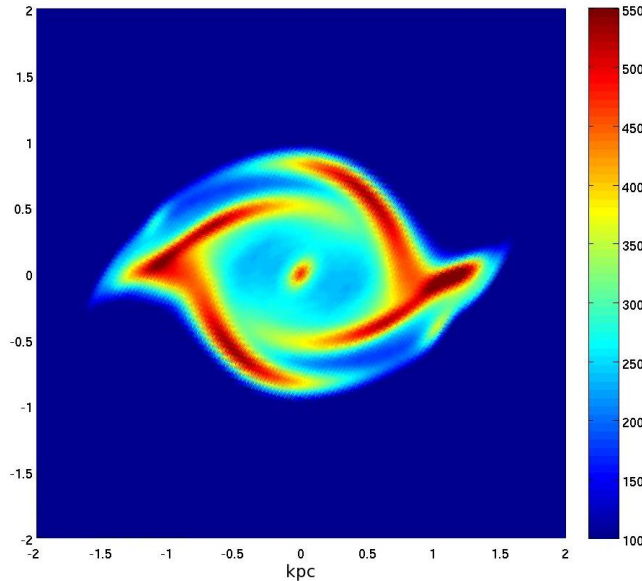
Comparison between the simulated density distribution and the HI surface density map for NGC 1097



(Lin et al. 2013)

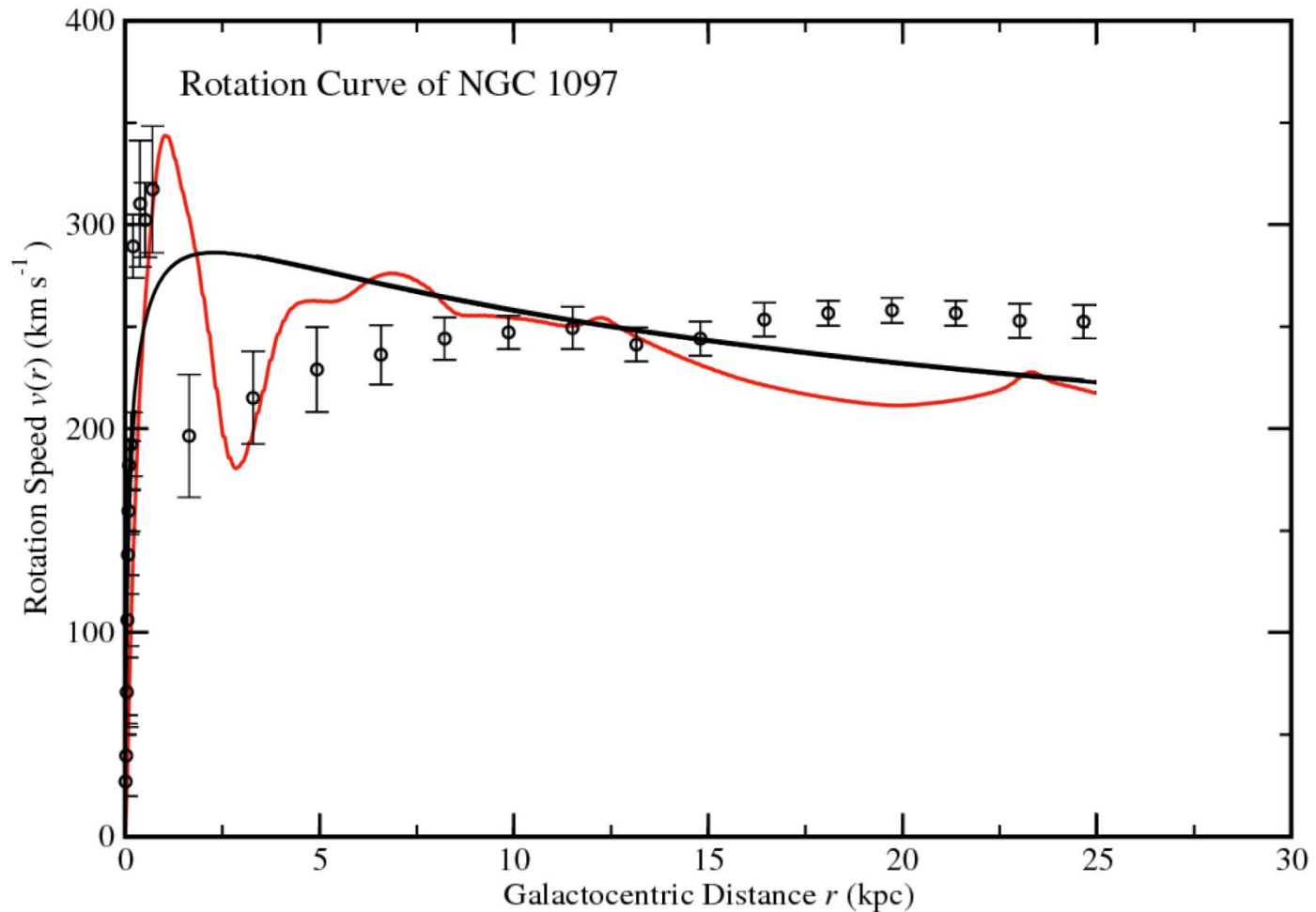
Comparison between the central part of the simulated density distribution and $^{12}\text{CO}(J=2-1)$ intensity map for NGC 1097

(Lin et al. 2013)

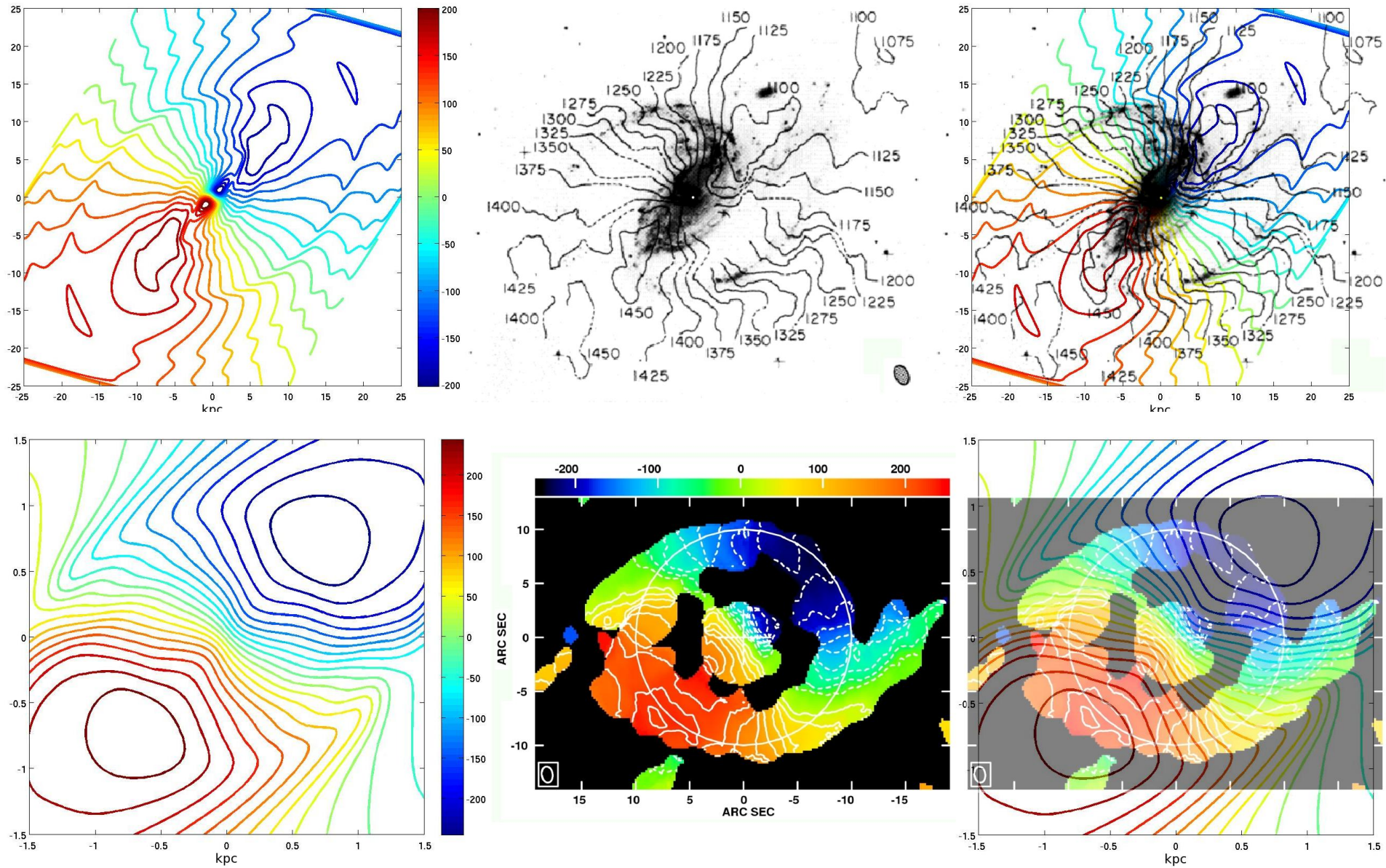


Comparison between the simulated and observed rotation curves for NGC 1097

(Lin et al. 2013)

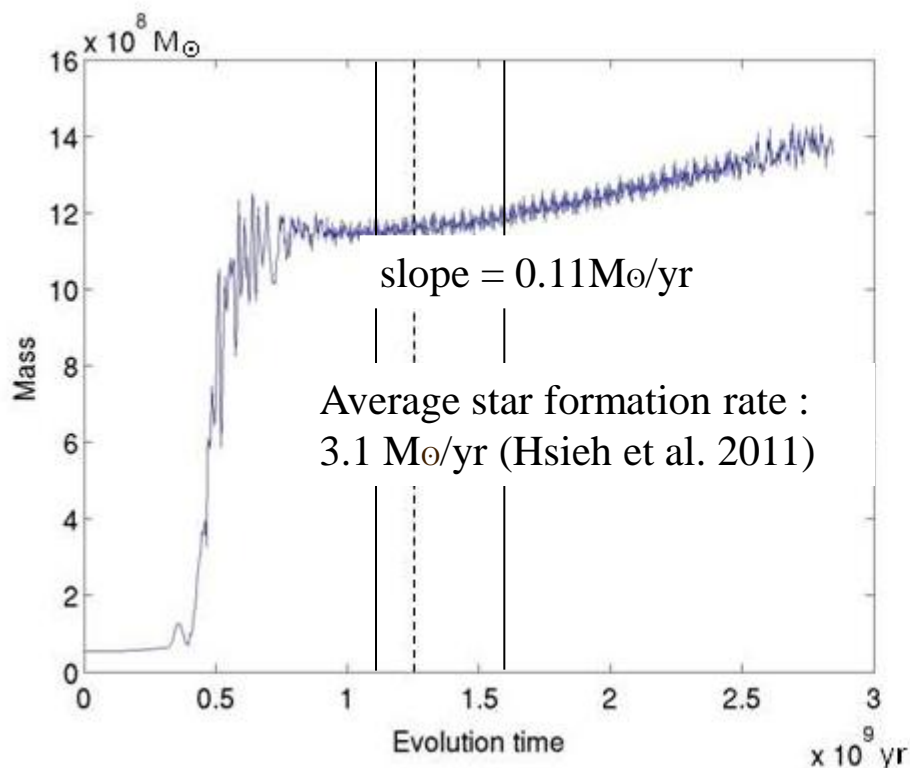


Comparison between the simulated and observed HI and $^{12}\text{CO}(J=2-1)$ velocity fields for NGC 1097



Mass inflow rates

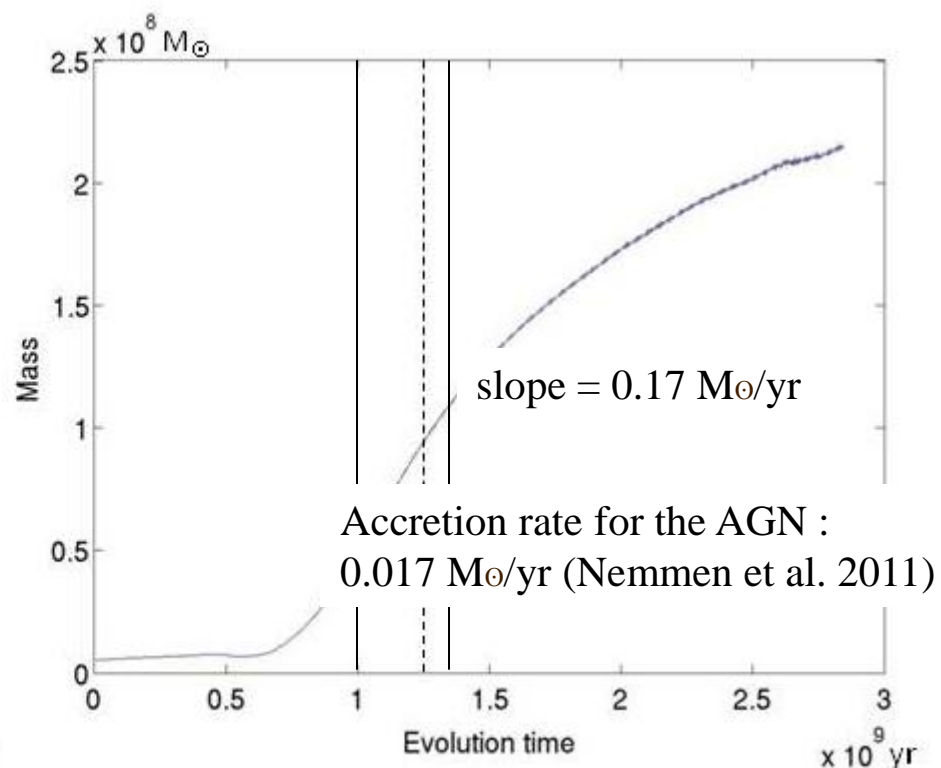
(Lin et al. 2013)



Mass in the starburst ring:

$11.6 \times 10^8 M_{\odot}$ (Sim.)

$5.8 \pm 0.6 \times 10^8 M_{\odot}$ (Hsieh et al. 2008)

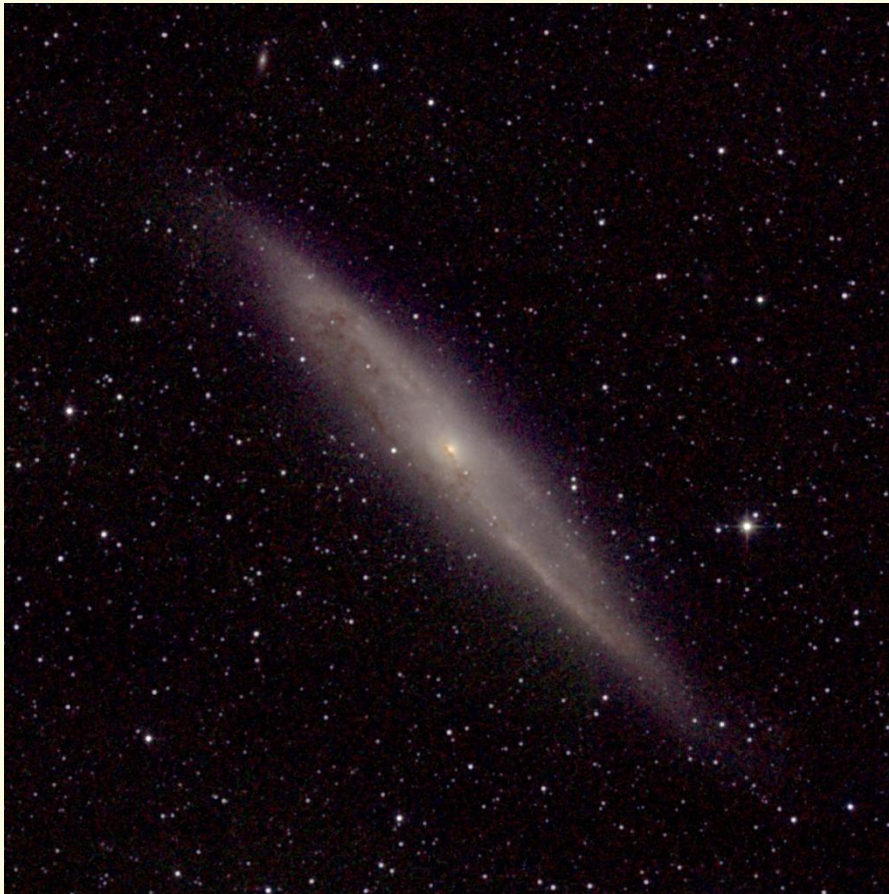


Mass in the circumnuclear disk:

$9.47 \times 10^7 M_{\odot}$ (Sim.)

$6.5 \times 10^7 M_{\odot}$ (Hsieh et al. 2008)

NGC 4945



SB(s)cd or SAB(s)cd
Sy2

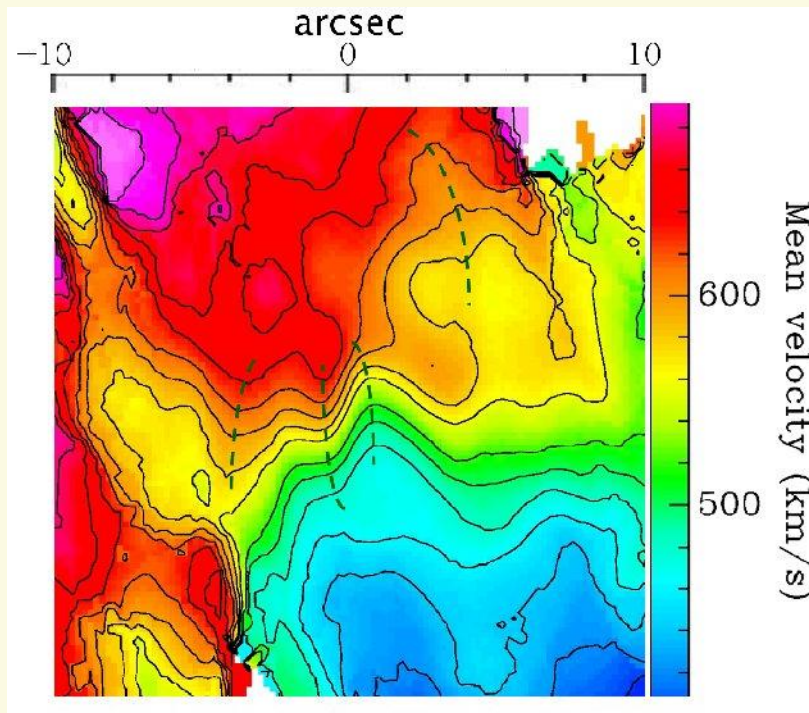
Distance : 3.82 Mpc

1" = 19 pc

Among the well-studied
AGNs, NGC 4945 is
closest to us.

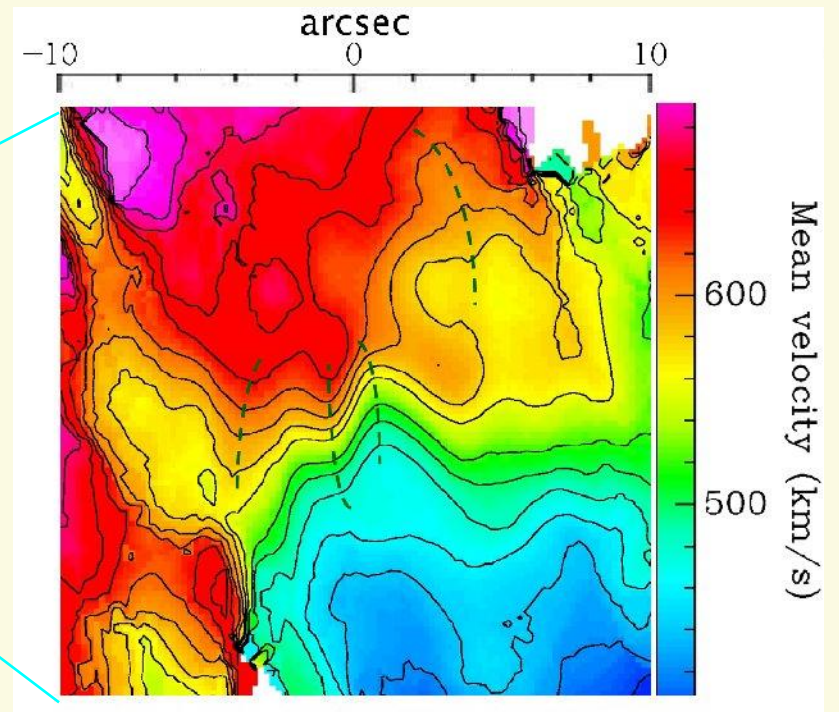
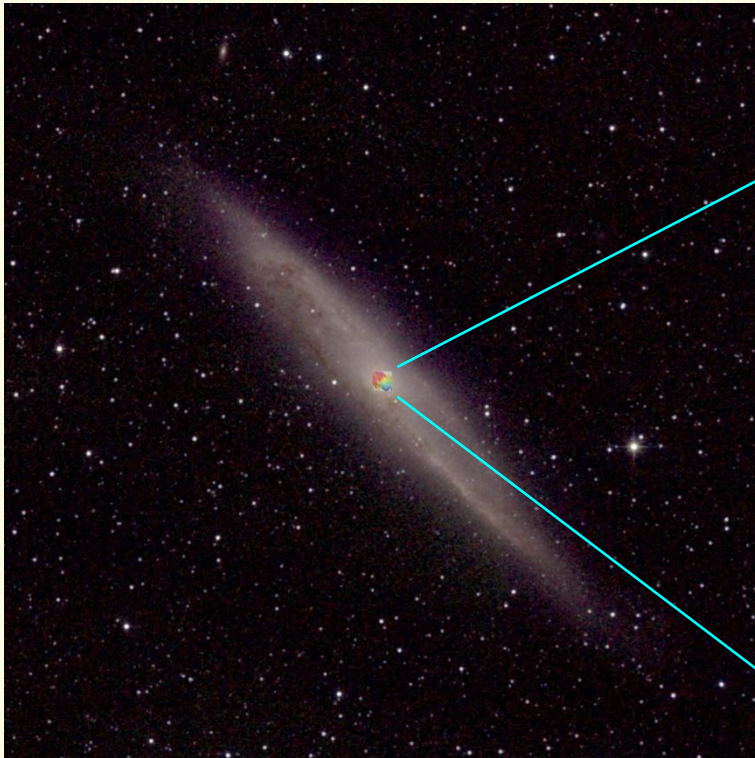
19.5' X 19.5'

NGC 4945

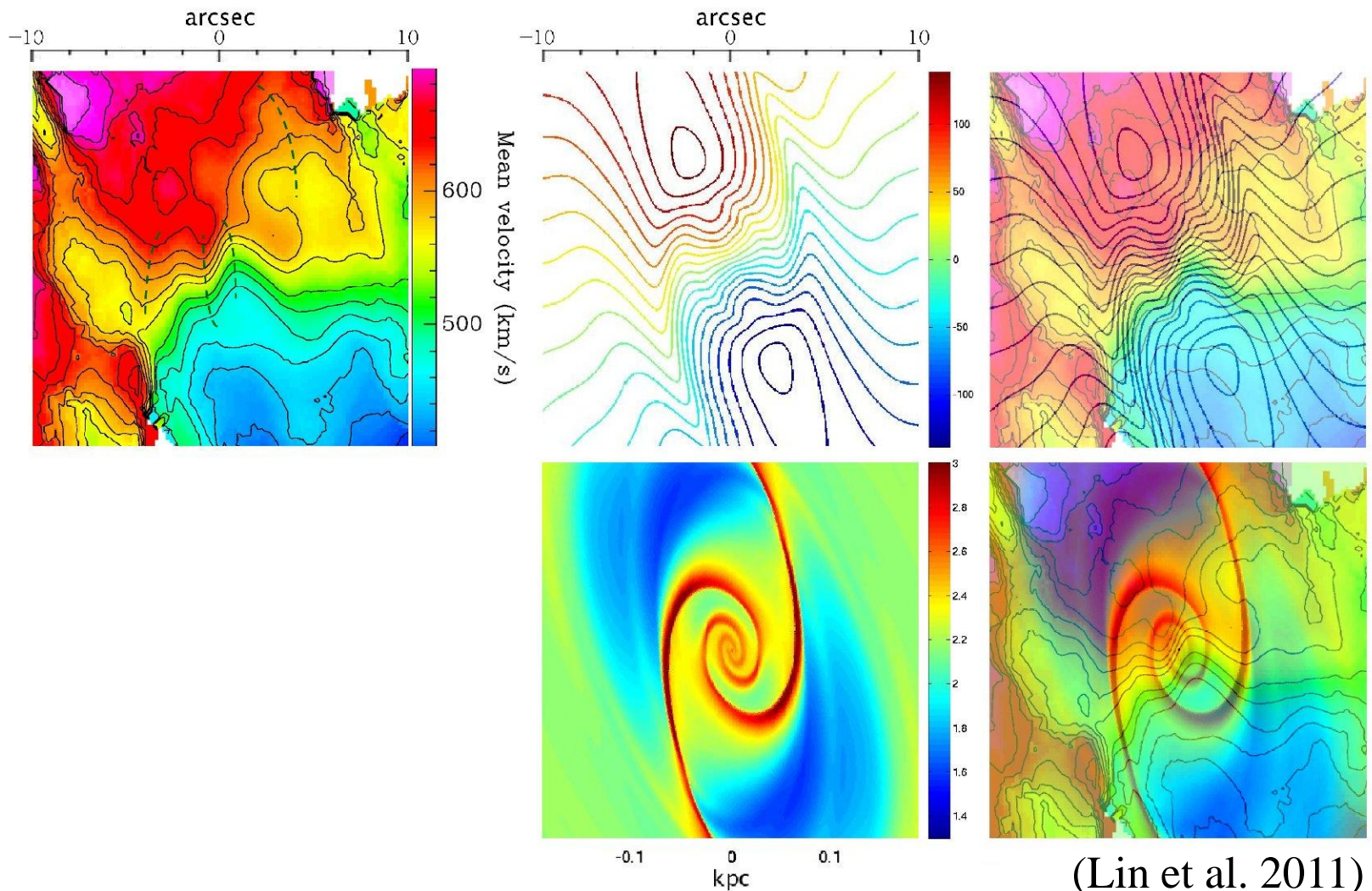


Intensity-weighted $^{12}\text{CO}(2-1)$ mean velocity map of the central region of the galaxy observed with the Submillimeter Array (SMA)

NGC 4945

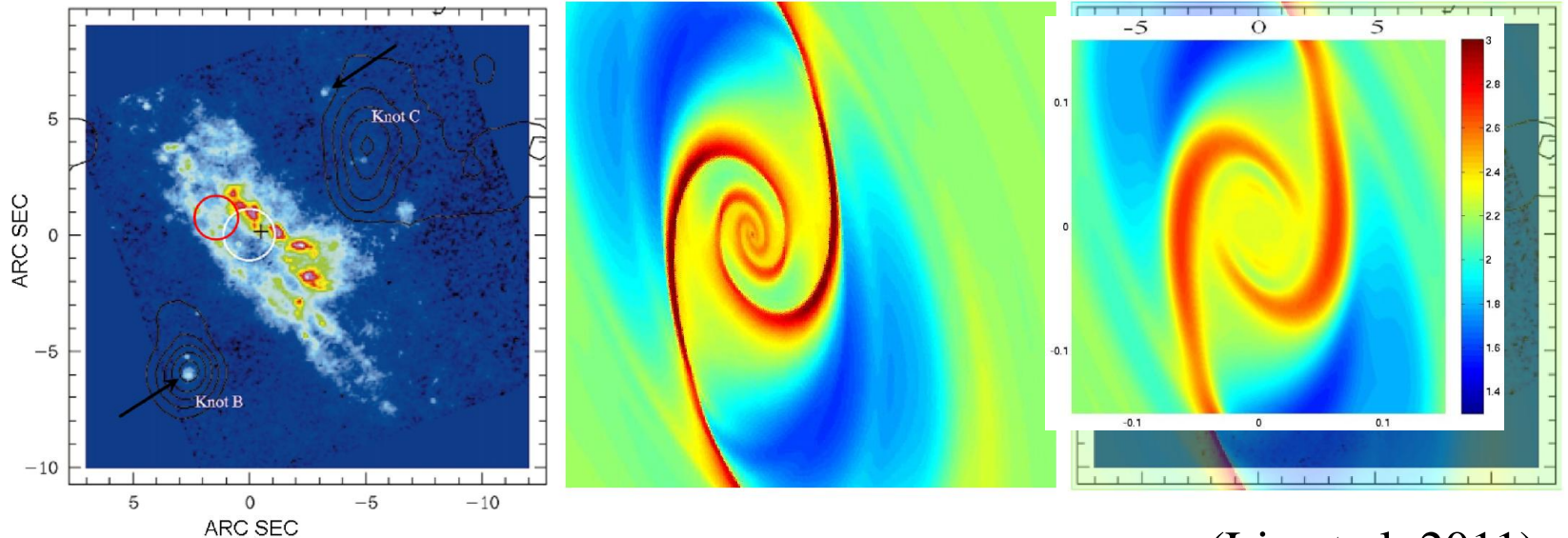


Comparison between $^{12}\text{CO}(2-1)$ observation and simulation



(Lin et al. 2011)

Comparison between Pa α image and simulation

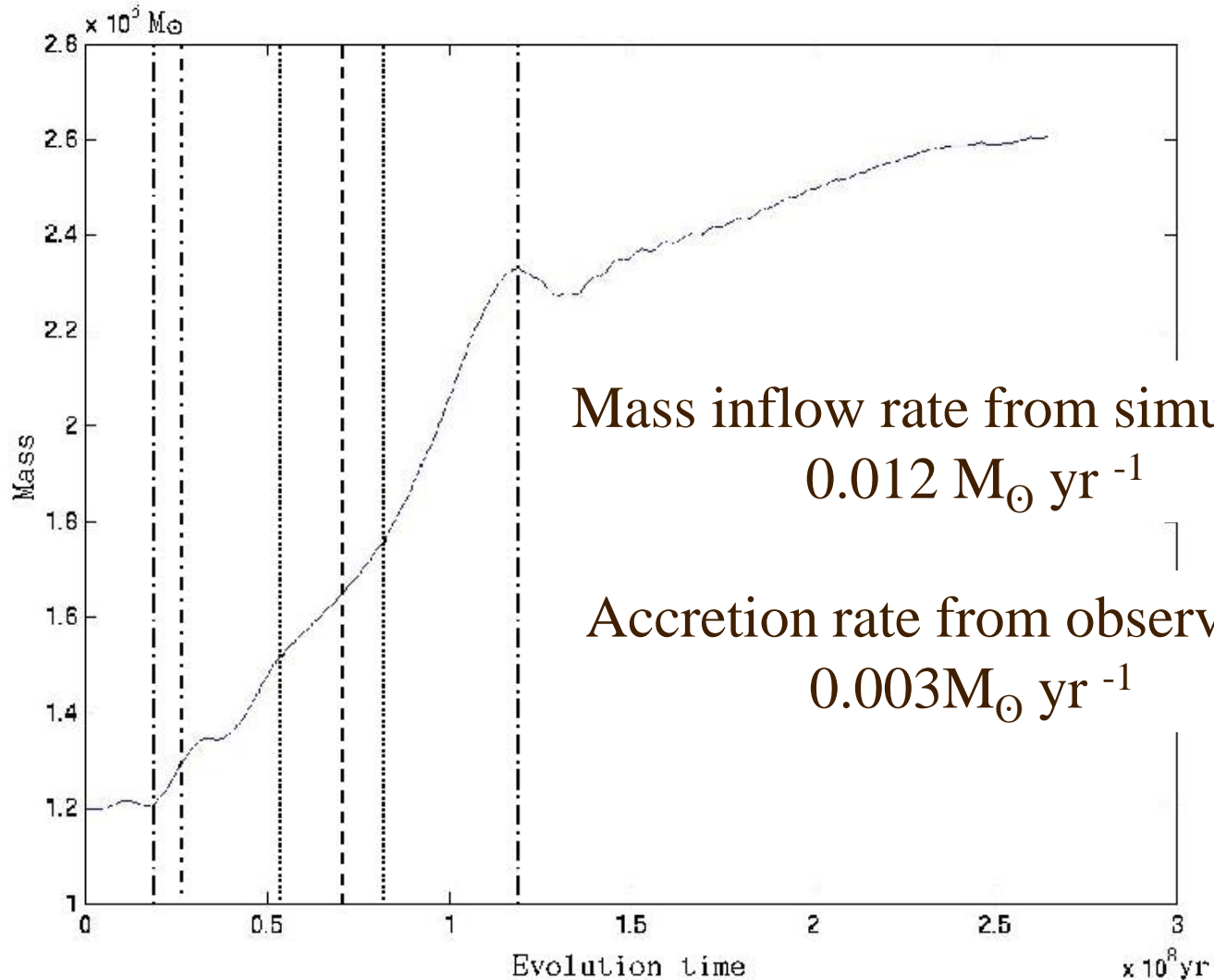


(Lin et al. 2011)

Continuum-subtracted Pa α image
(Marconi et al., 2000, A&A, 357, 24),
the black contours are from the
H α + [NII] image (Moorwood et al.,
1996, A&A, 308, L1)


Mass inflow rate at 50 pc

(Lin et al. 2011)



Conclusion

We examine how spiral density waves excited at the outer inner Lindblad resonances fuel central activities in NGC 6782, NGC 1097, and NGC 4945 by detailed comparisons of our hydrodynamical simulation results with observations. We find that bar potential can effectively transport gas into the central region of galaxies.



We dedicate this work with great affection to our teacher, colleague, and friend Prof. Chi Yuan, who continues to live in all our hearts as a man of the highest integrity, culture, and compassion—a person whose presence and company we miss every day more than we can say. A collaboration between theorists and observers at the ASIAA in extragalactic research is something Chi hoped for and encouraged, and we like to think that this is but a small step towards this realization.



A silver metal spiral binding is visible on the left side of the page, with the wire looping through a series of holes. The page is cream-colored and has a thin horizontal line near the top.

Thank you!