Evolution of a self-gravitating Gas Disk under the influence of a Rotating Bar Potential

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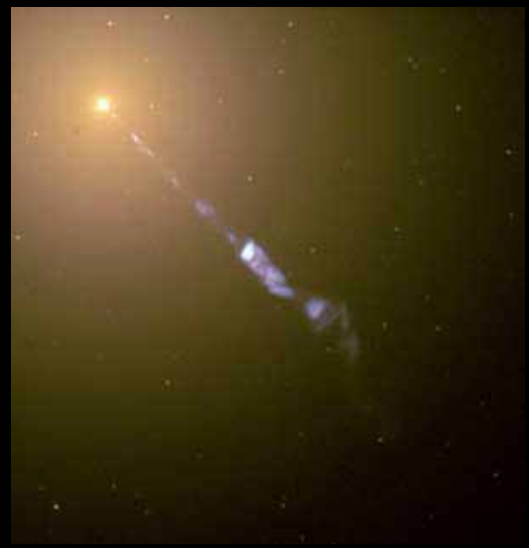
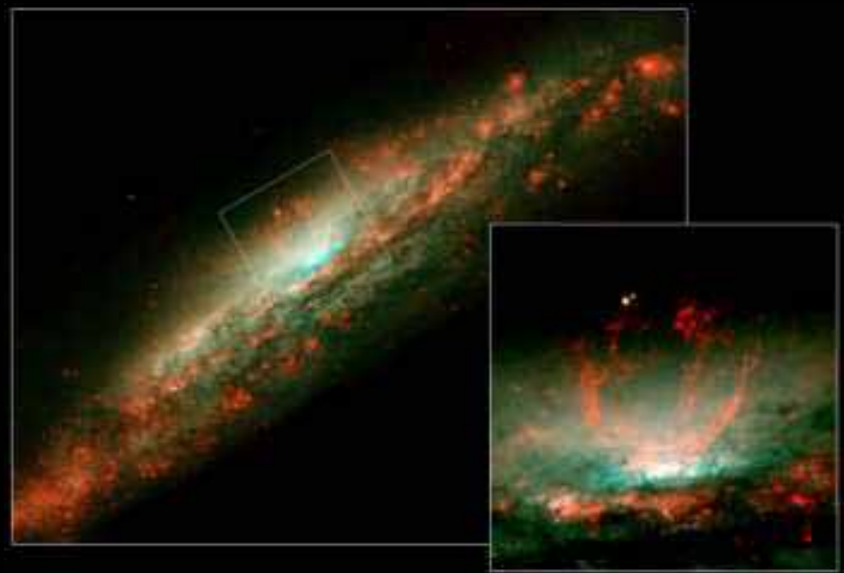
AGNs

NGC4438

M87



NGC3079



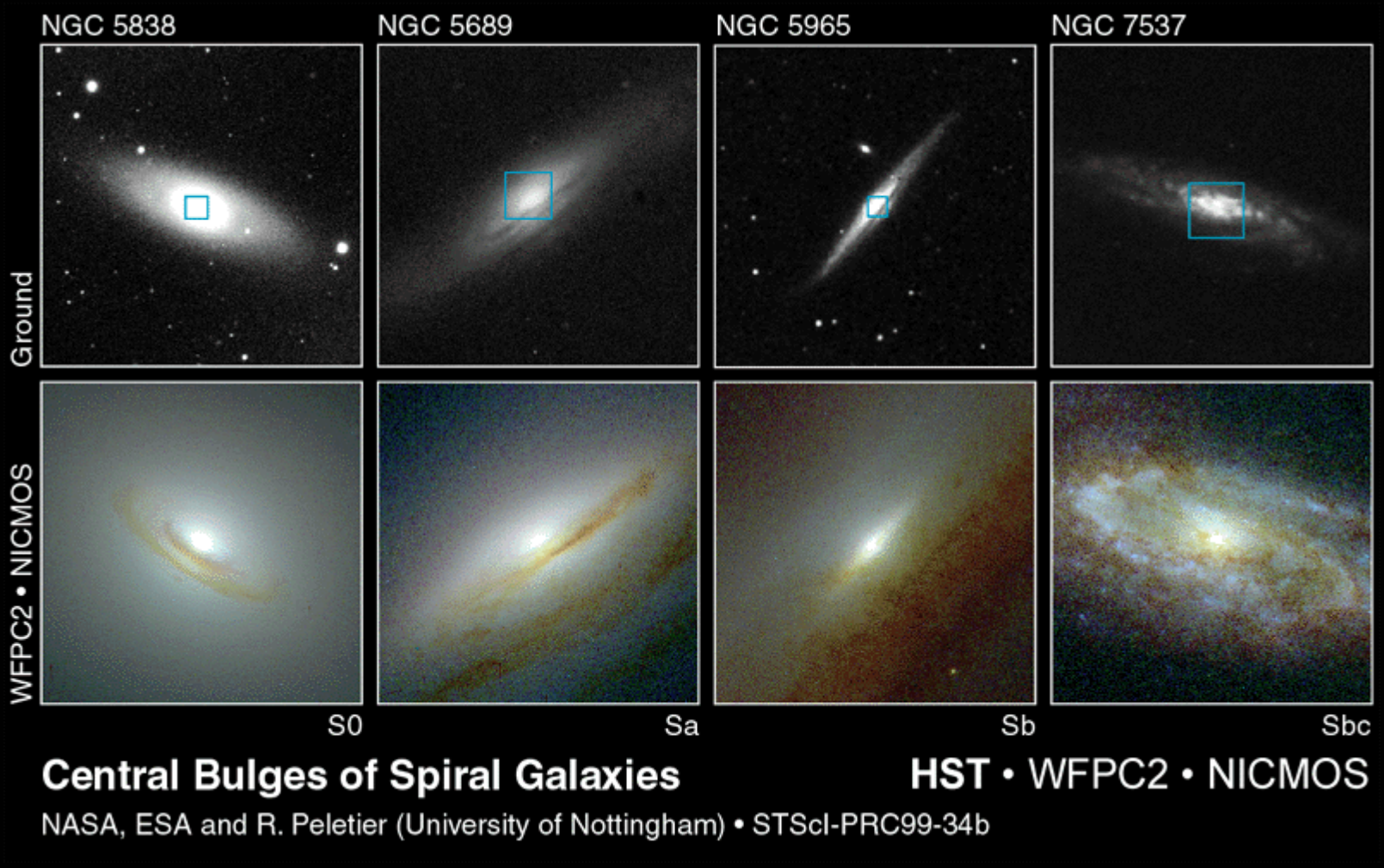
Starburst Rings

NGC4313

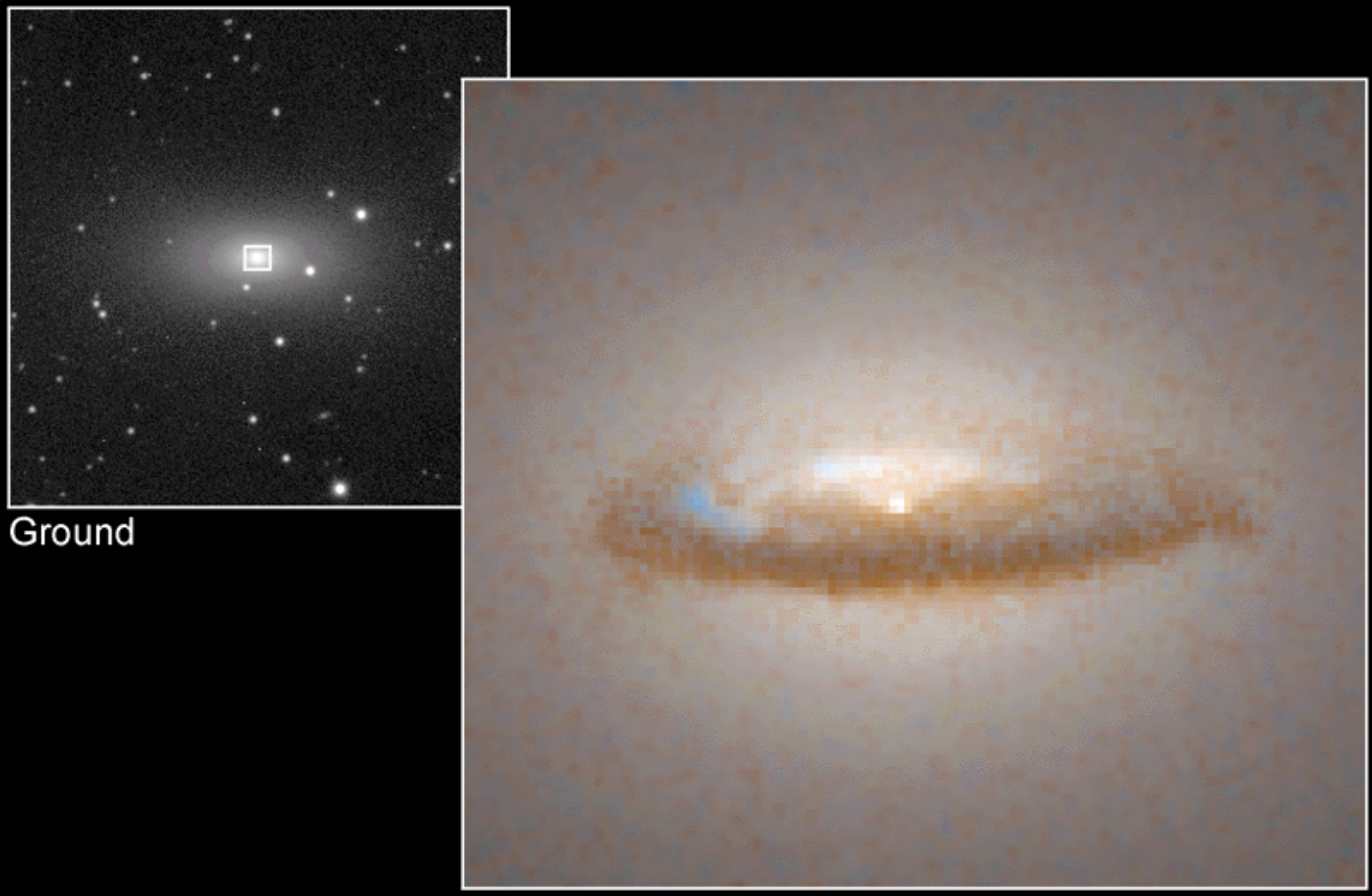
NGC1512

NGC6782

Gas-dust disks in galactic central region



Gas-dust disk in NGC7052

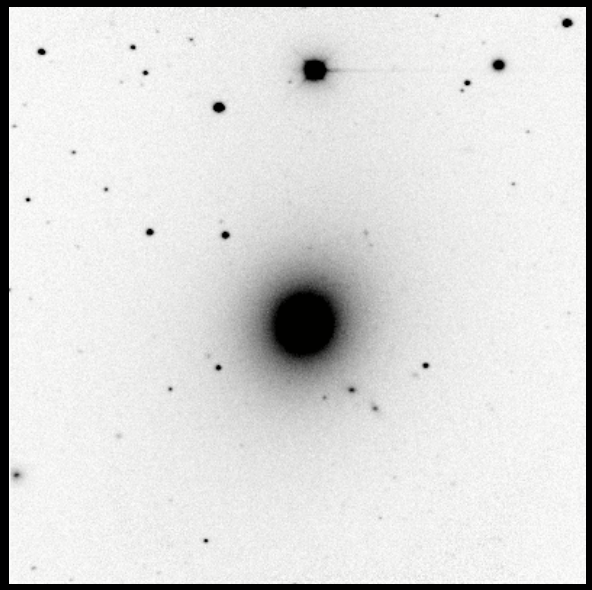


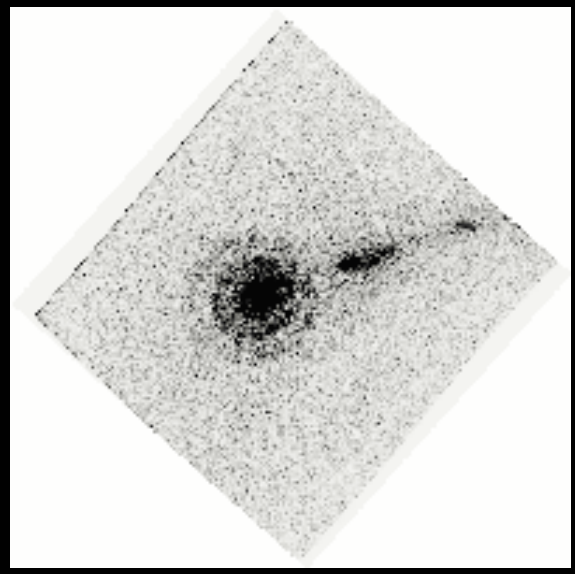
Disk in Galaxy NGC 7052

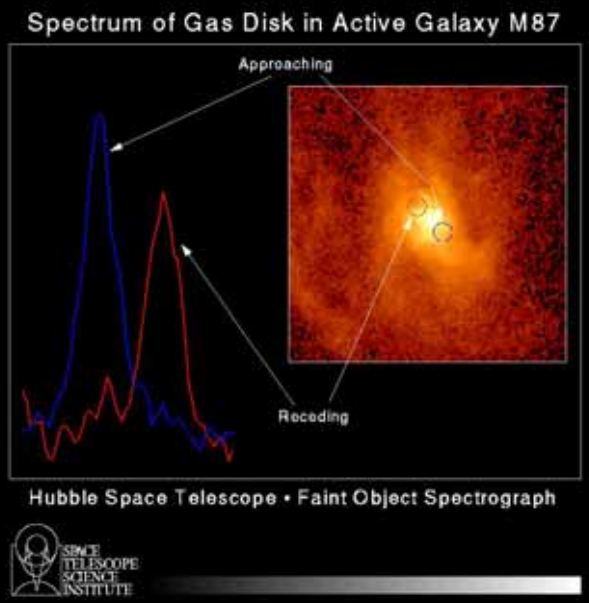
PRC98-22 • June 18, 1998 • ST ScI OPO

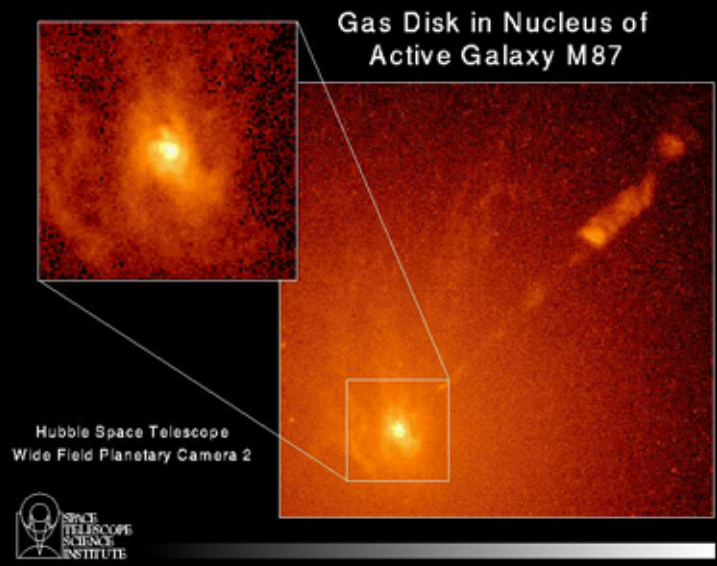
R. P. van der Marel (ST ScI), F. C. van den Bosch (University of Washington) and NASA

M87- Supermassive Black hole and Jet at the Center









Observations

- Central regions host two extraordinary events: AGNs and starburst ring activities
- Almost all galaxies are believed to have a supermassive blackhole (SMBH) in the nucleus
- AGNs are related to SMBHs, but not all SMBHs are AGNs
- Most galaxies have a gas-dust disk in the center
- Some have a dense circumnuclear molecular disk
- Often, the disks are characterized with spiral-bar structure, or ring structure.

Physical Issues

- Formation and evolution of supermassive blackholes
- Jets from the nucleus
- Origin of gas-dust disks
- Fueling of AGNs and starburst rings
- Origin of the central spiral structure
- Origin of the circumnuclear molecular disks

What I would like to show you

- Starburst rings can be formed by a rotating bar potential via a resonance excitation mechanism.
- Circumnuclear molecular disks can be formed at the same time, if there is an OILR at the center.
- Self-gravitation of the disk plays an important role in producing starburst rings, chaos, and instability.

Outline of My Talk

- 3-kpc arm of the Milky Way
- Probing central regions of nearby galaxies by wavelet method
- Resonance excitation mechanism and different types of spiral-ring structure
- Numerical simulation of disk evolution
- Stability, chaos, starburst rings

The 3-kpc Arm

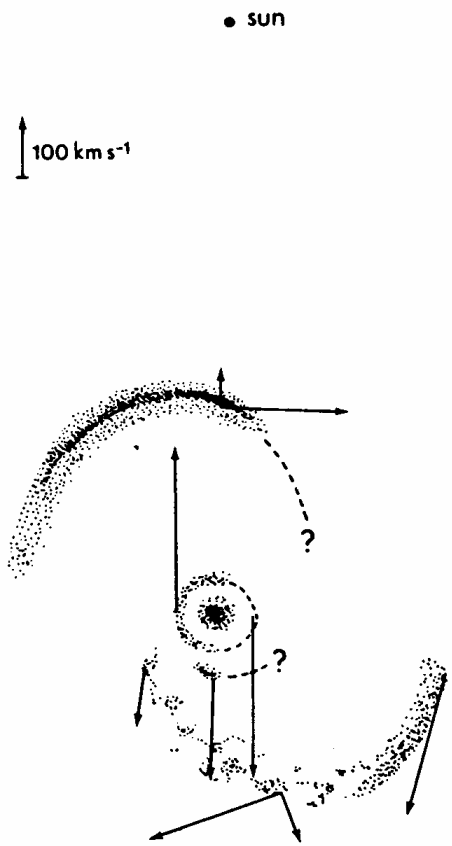


Figure 9 Sketch of the possible situation and motion of the 3-kpc arm, the +135 km sec^{-1} expanding arm, and the nuclear disk and ring (Rougoor & Oort 1960).

Bar-driven Spiral Density Waves
Theory by Yuan (1984)
Observation by Blitz & Spergel (1991)

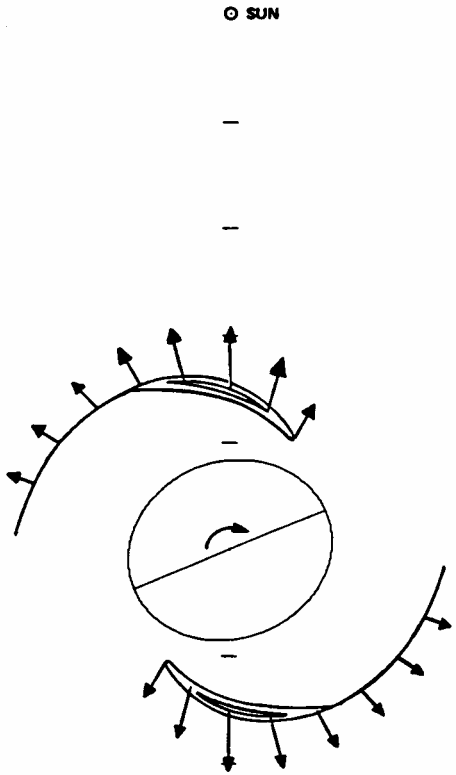
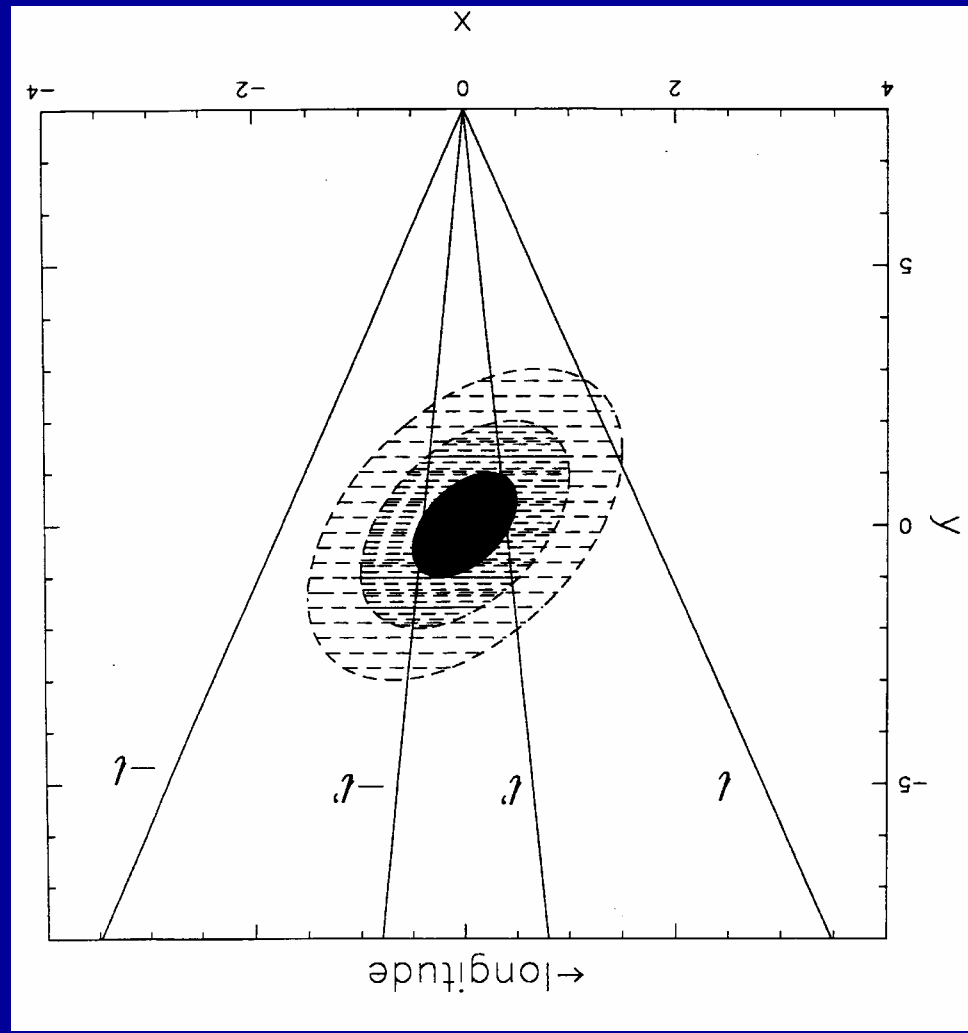
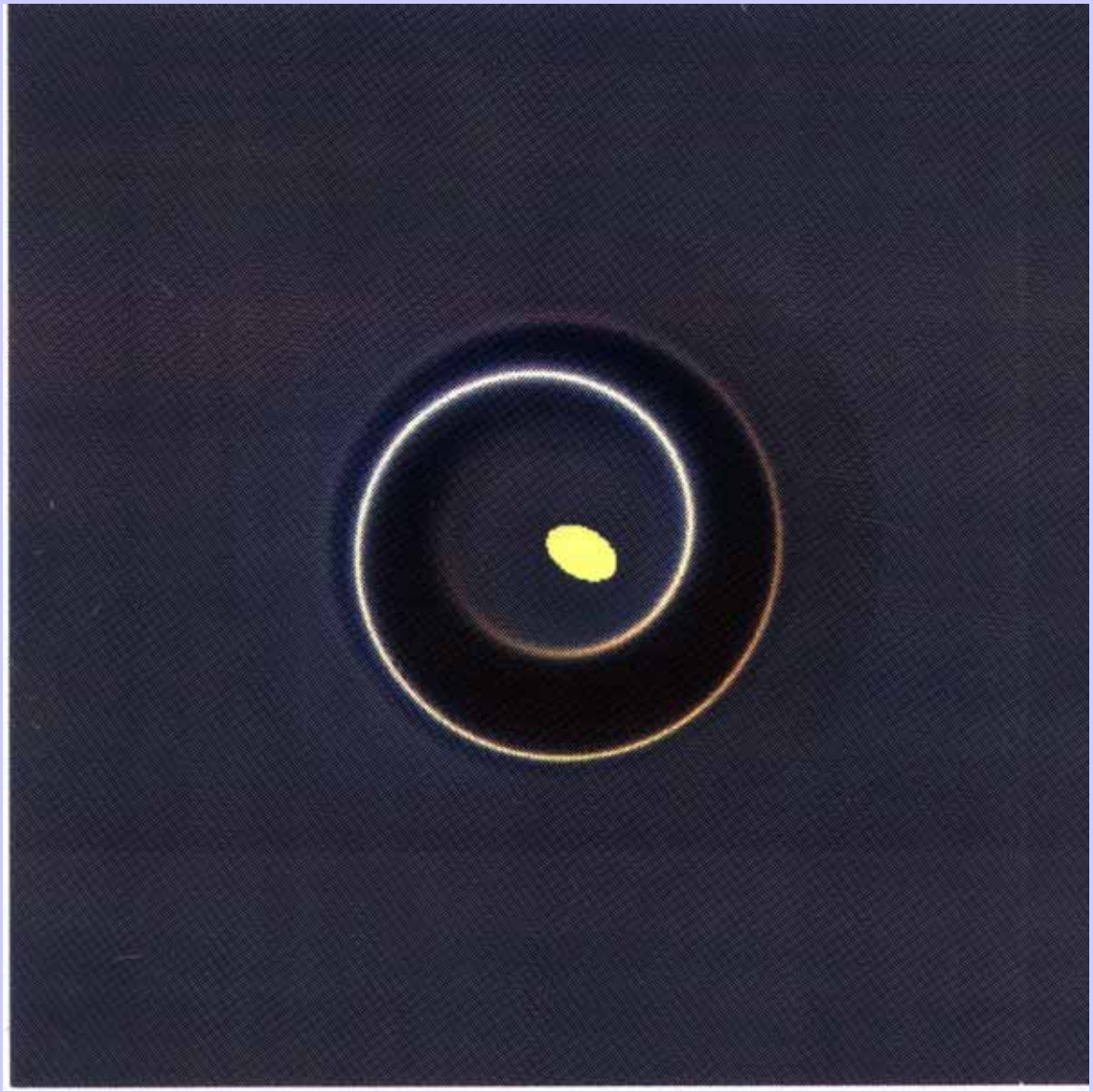


Figure 6.15

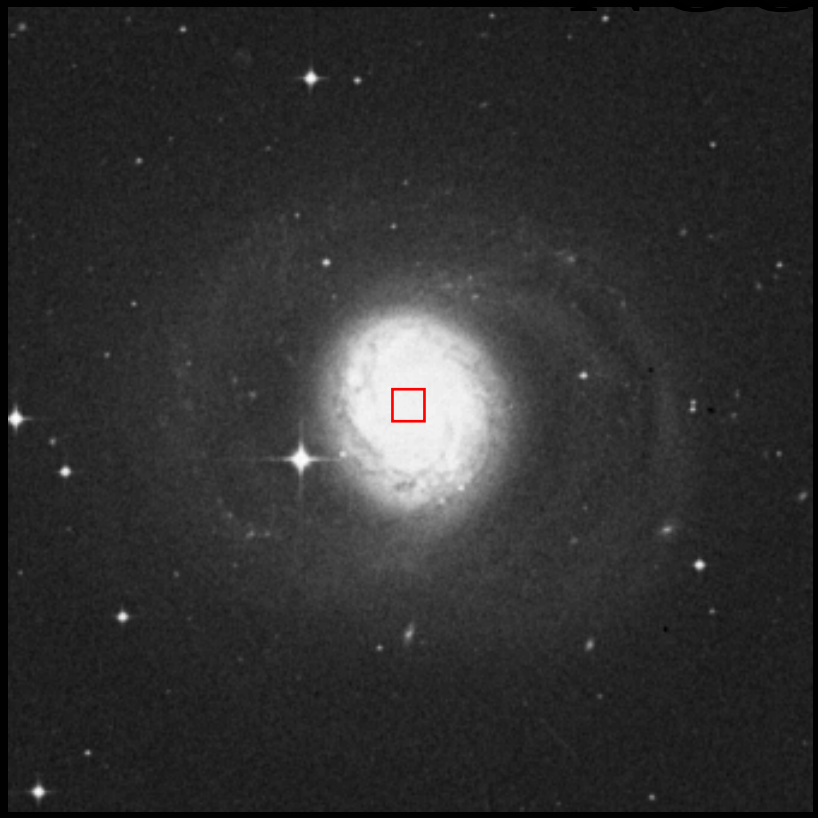


The 3-kpc Arm as Resonantly Excited by A Central Bar

The 3-kpc Arm as excited by an Unevenly Distributed Central Mass



NGC 1068

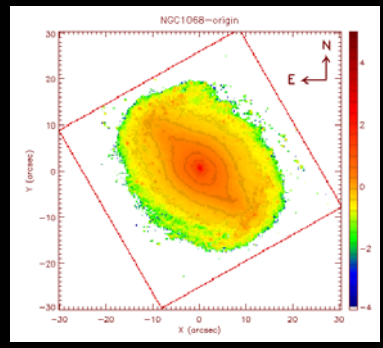


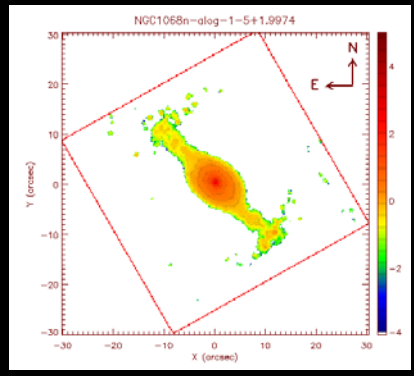
9.5 arcmin

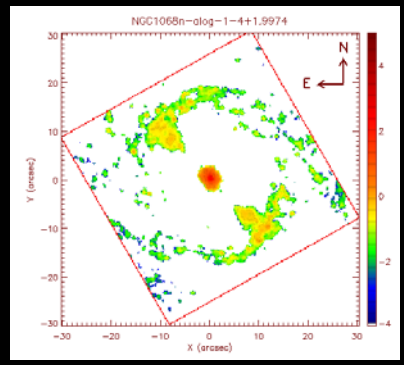
- Type : Sb / AGN
- Distance : 14.4 Mpc

  (H_0 = 75 km s^{-1} Mpc^{-1})

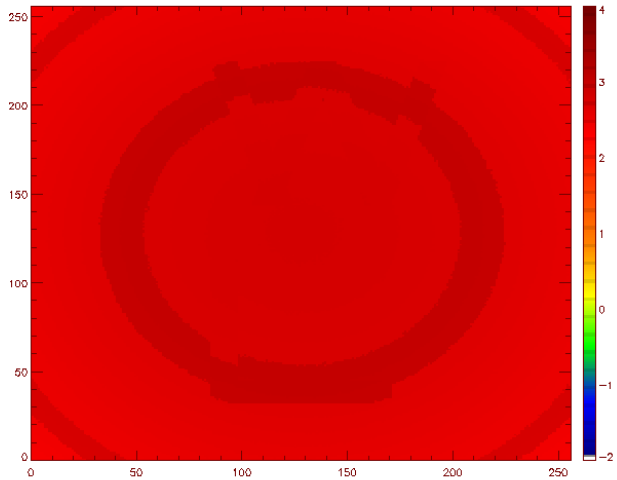
  1 arcsec = 74 pc

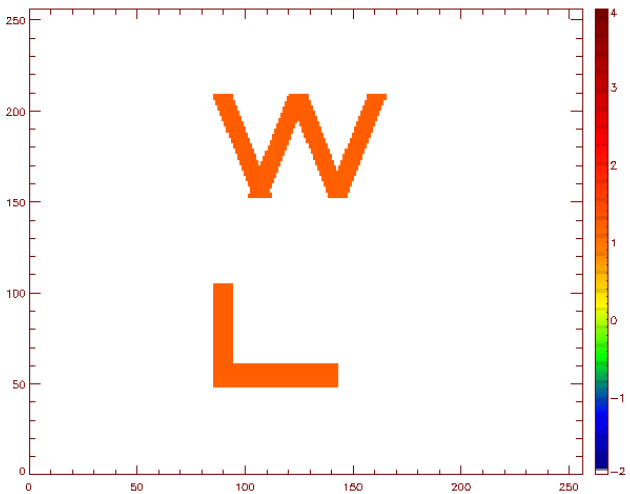


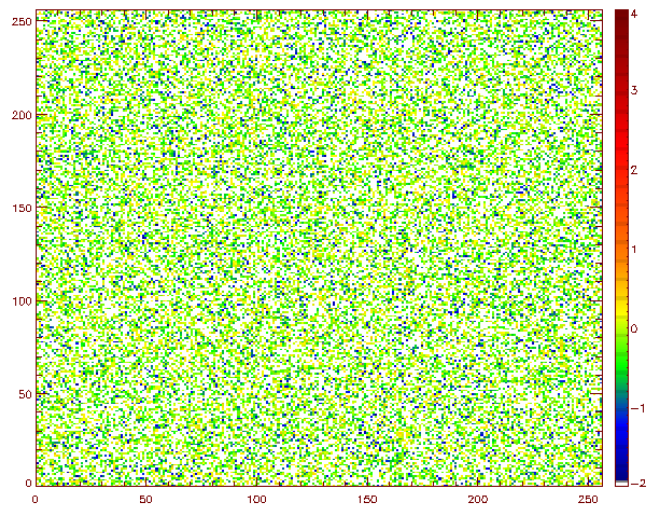




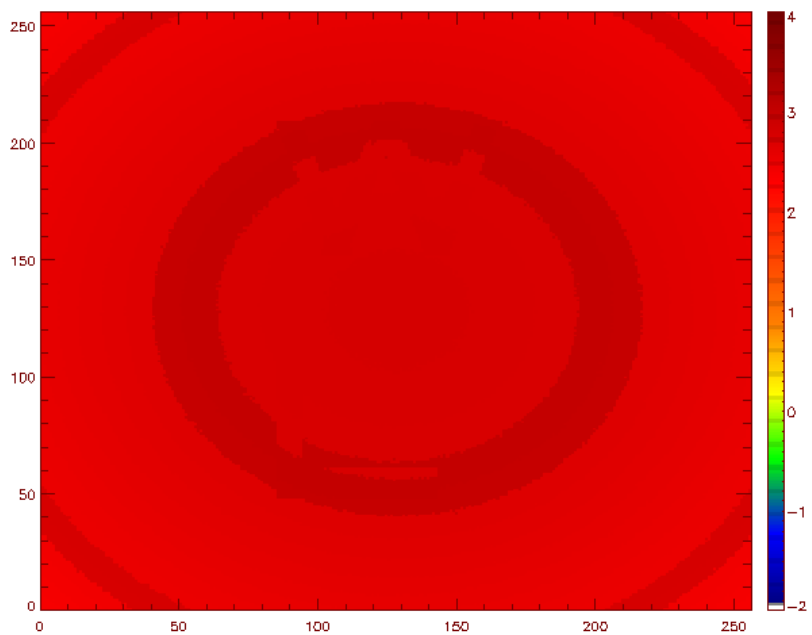
What is wavelet?

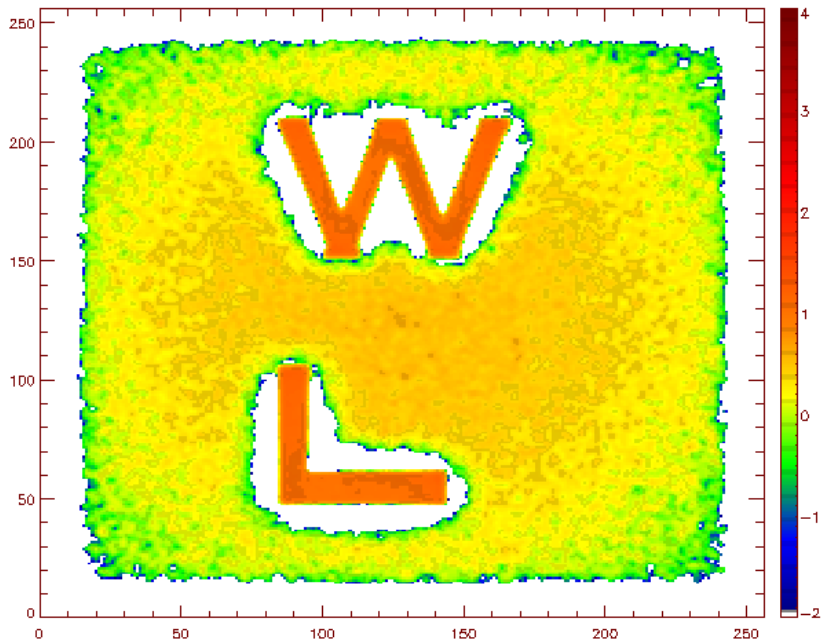






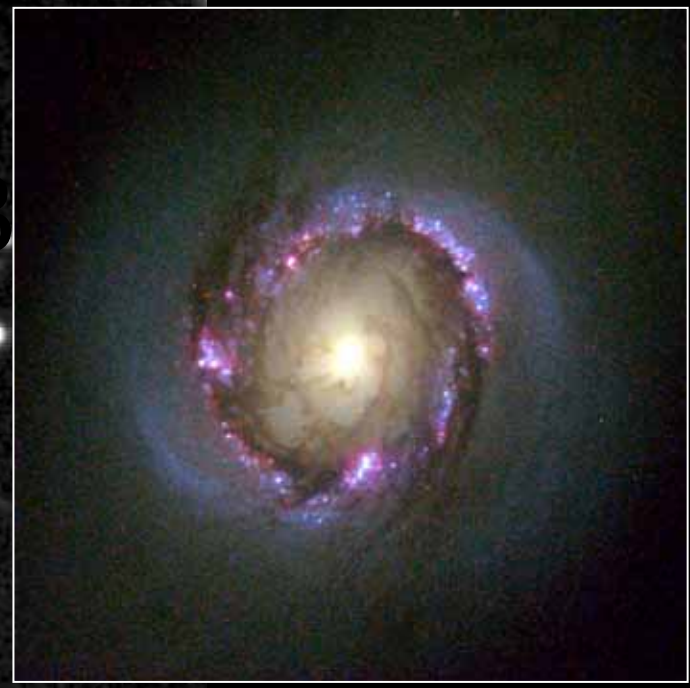
Wavelet Analysis

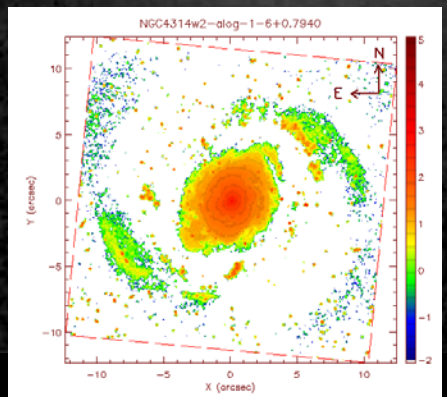


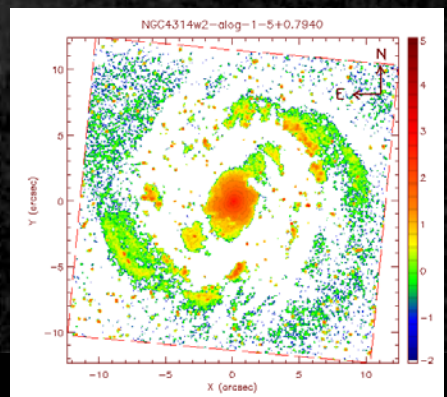


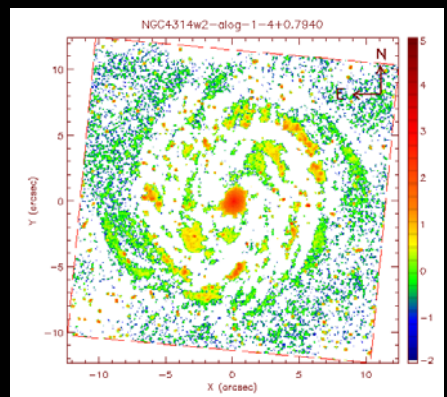
NGC4313

NGC4313





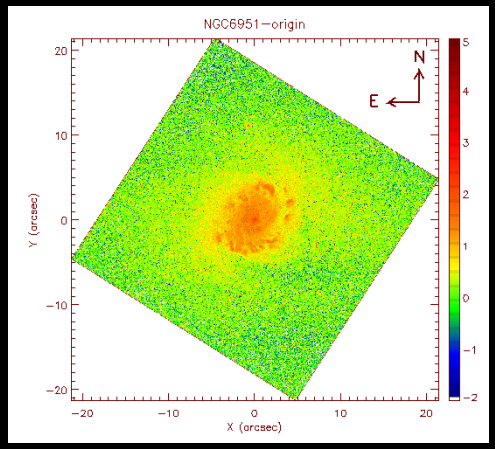


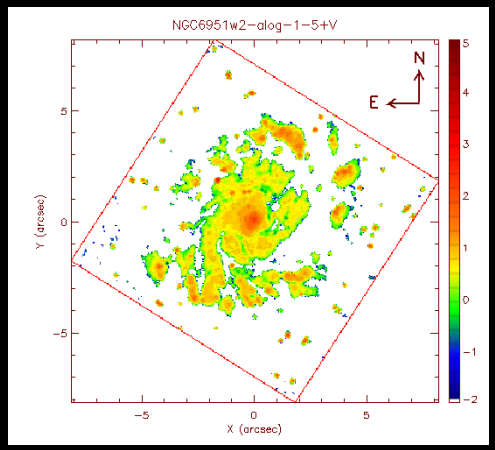


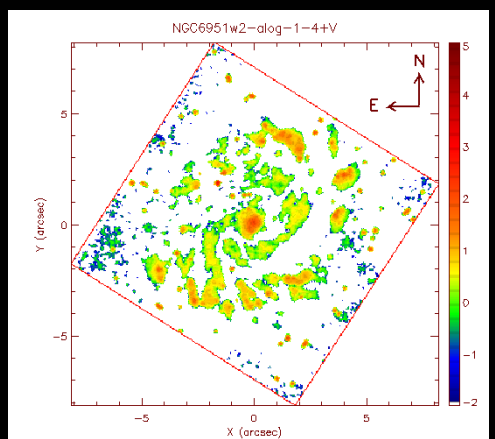
WFPC2

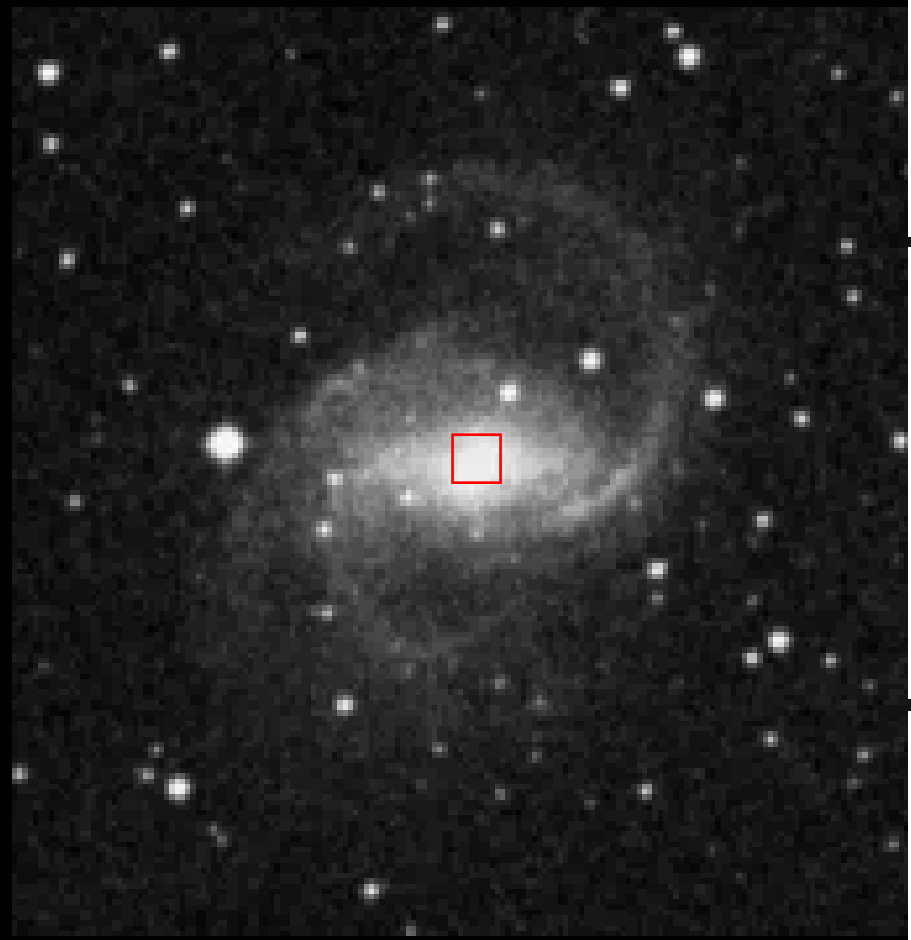
NICMOS

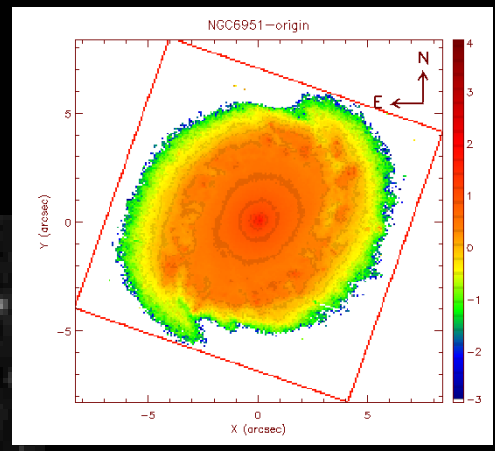
NGC6951

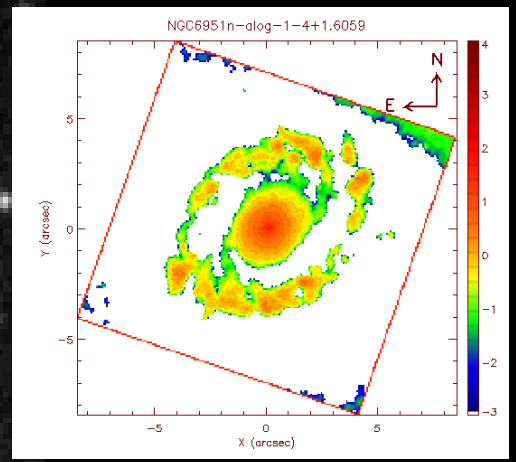


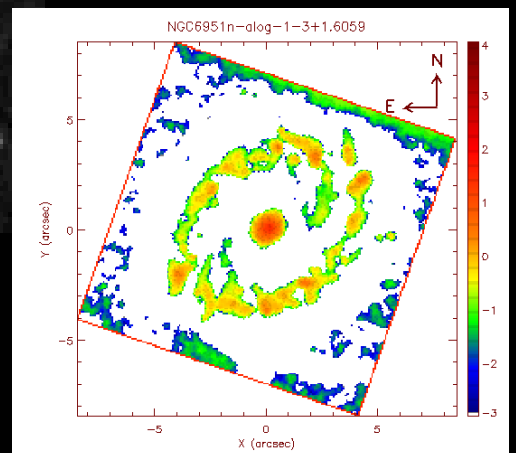




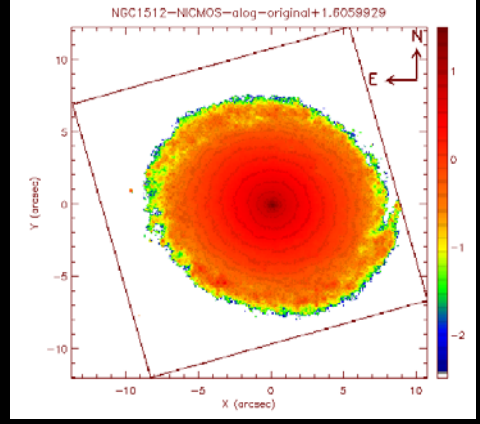








NGC1512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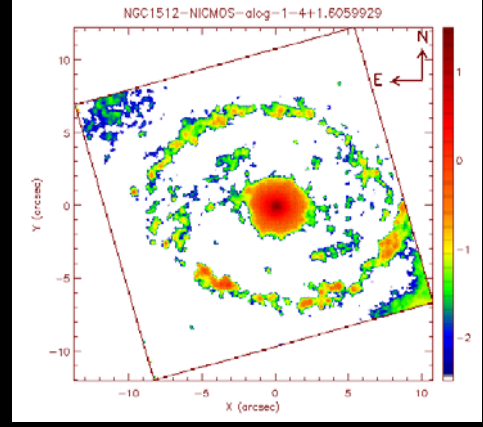
N
E
X (arcsec)
Y (arcsec)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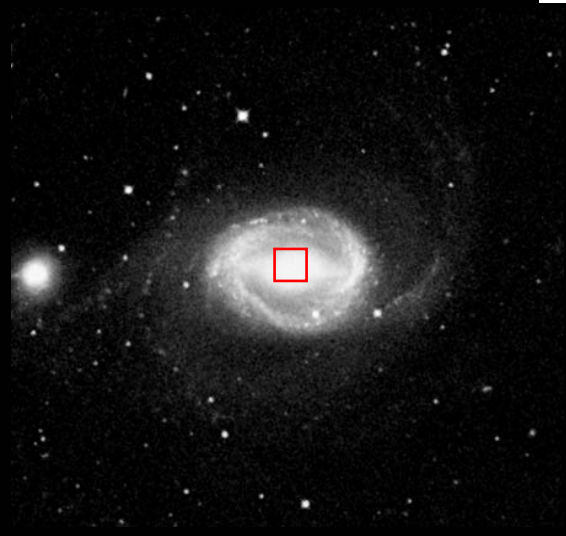

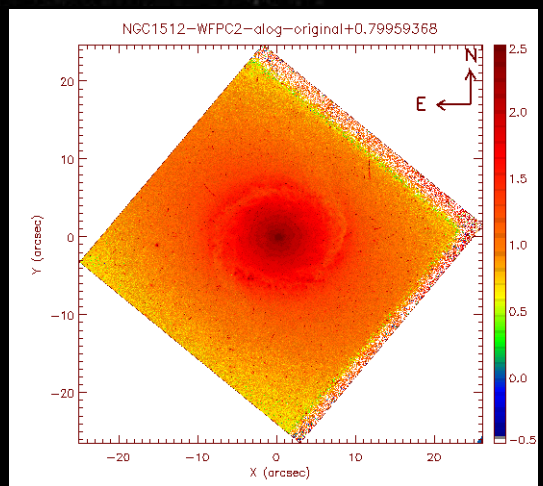
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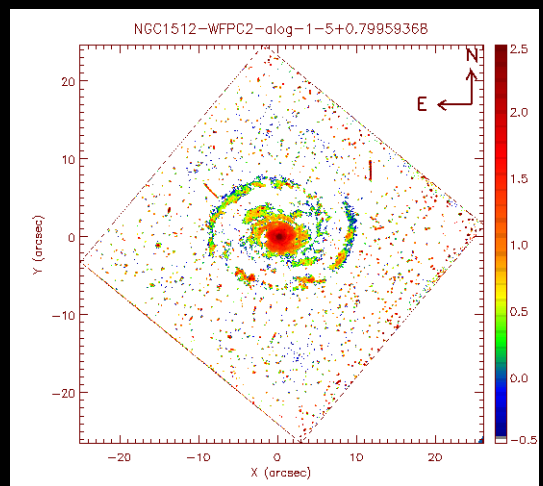
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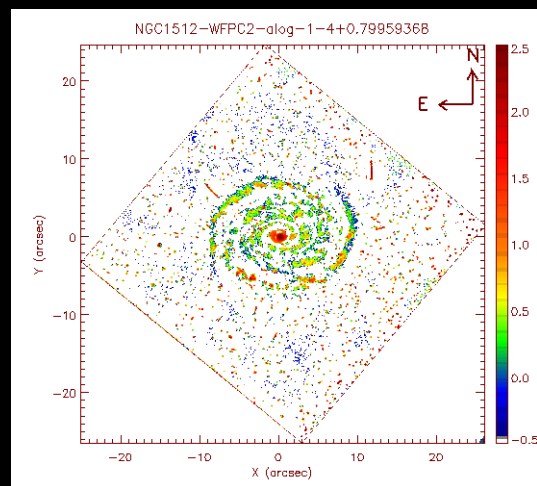
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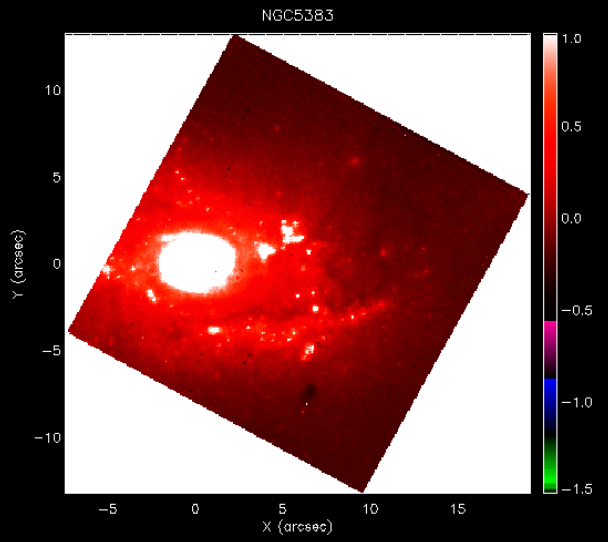
Y (arcsec)

NGC5383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−10
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5
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X (arcsec)
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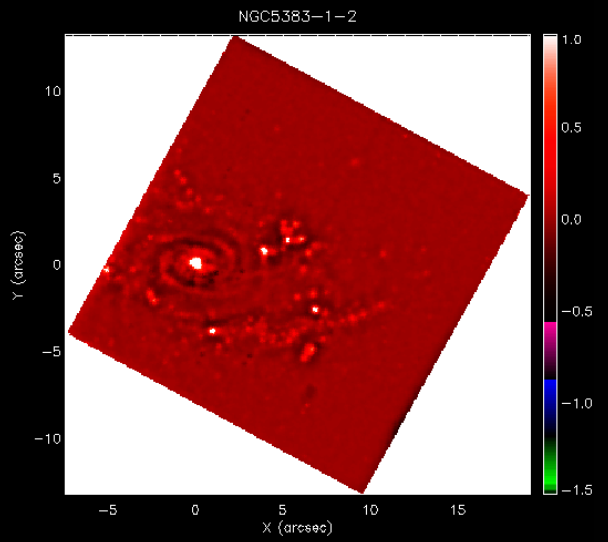
−1.0
−1.5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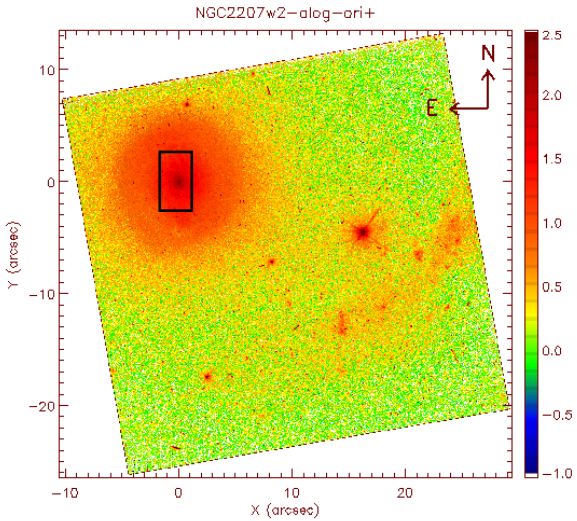
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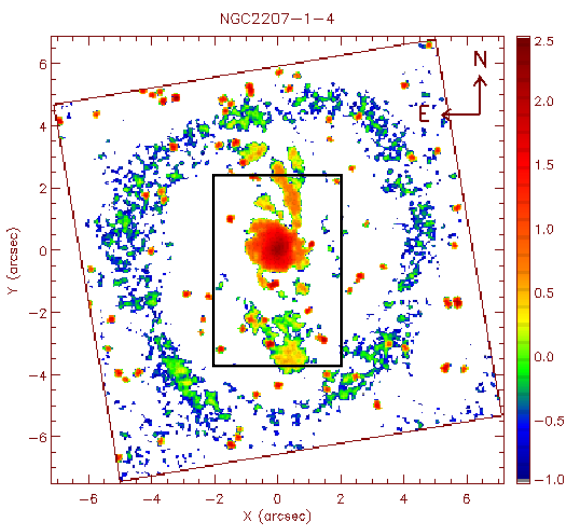
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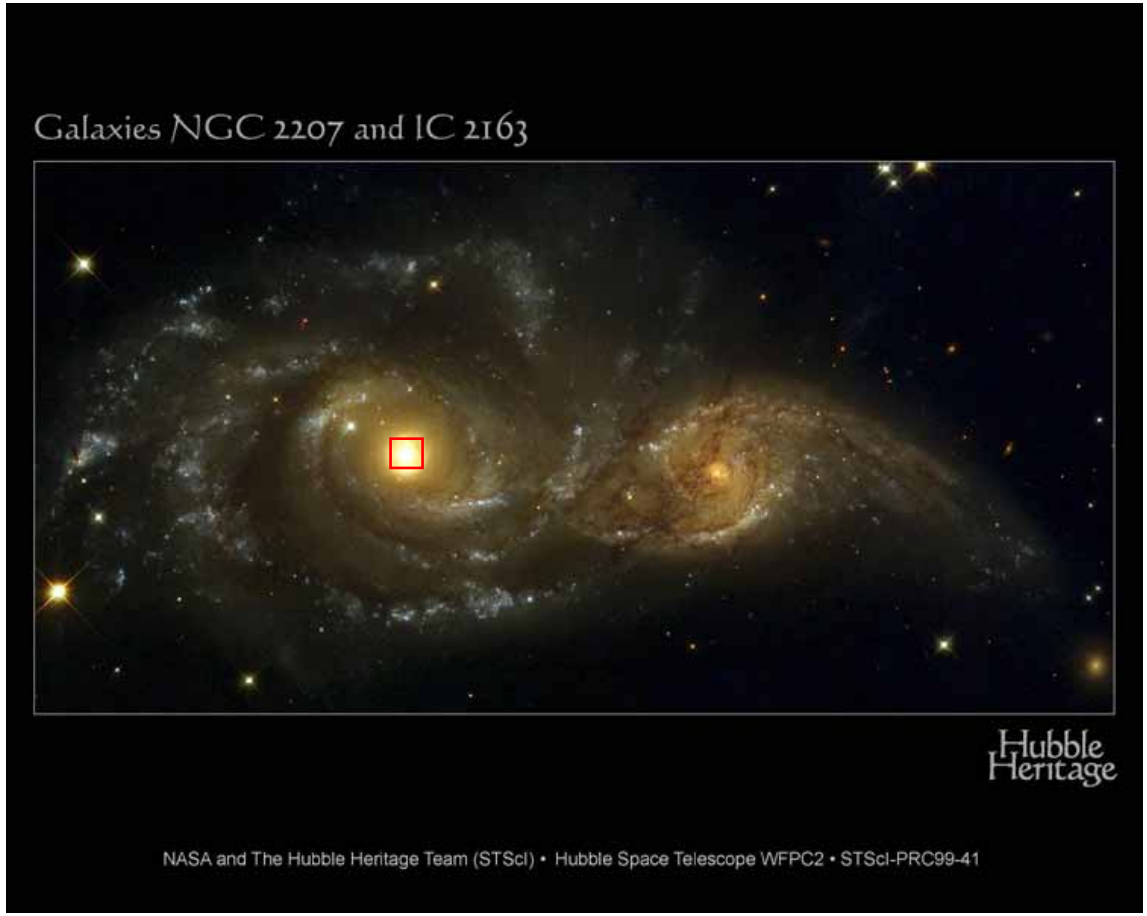
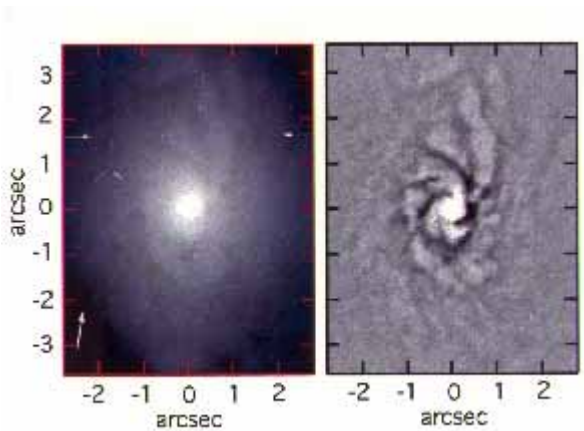
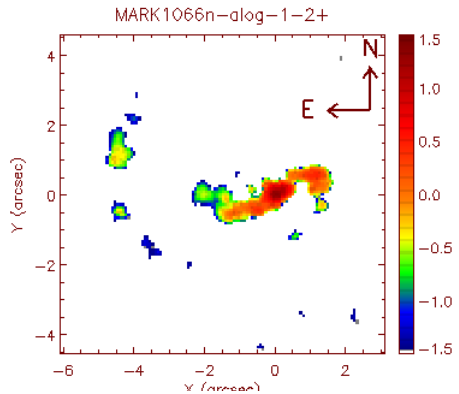
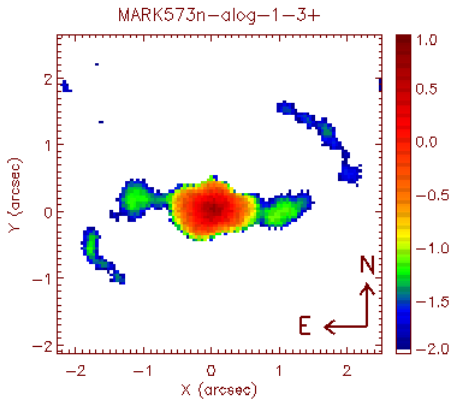
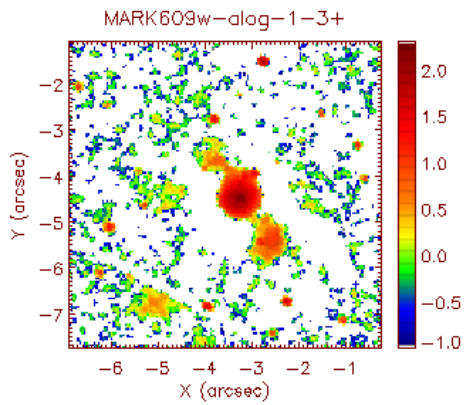

Galaxies NGC 2207 and IC 2163
Hubble Heritage
NASA and The Hubble Heritage Team (STScI) • Hubble Space Telescope WFPC2 • STScI-PRC99-41

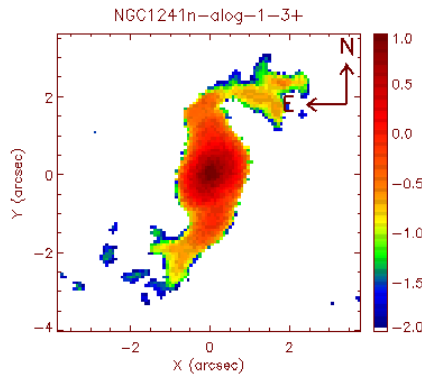

arcsec
arcsec
arcsec

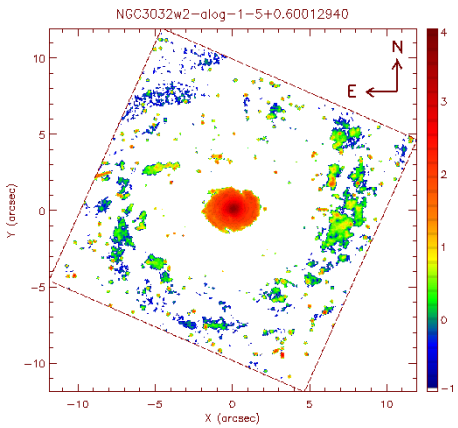
Bar-Oval Structure in the Center of Seyfert Galaxies:NICMOS

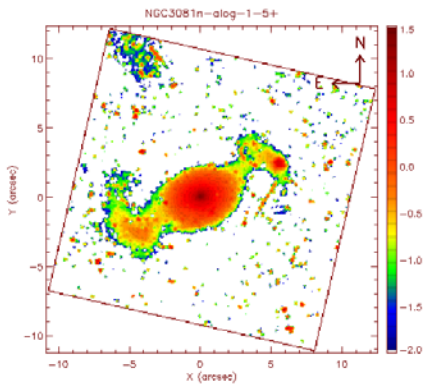


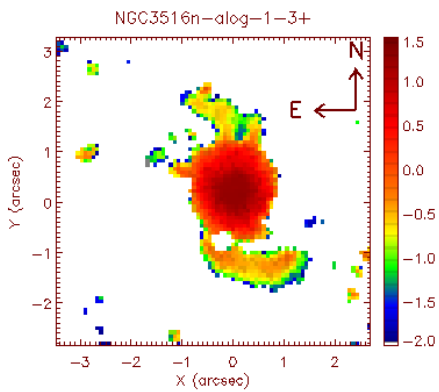


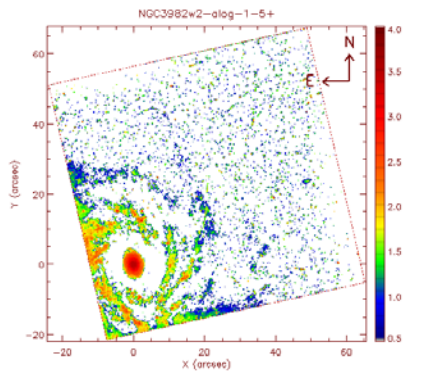


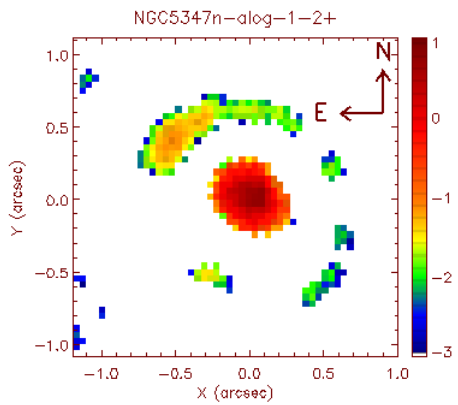


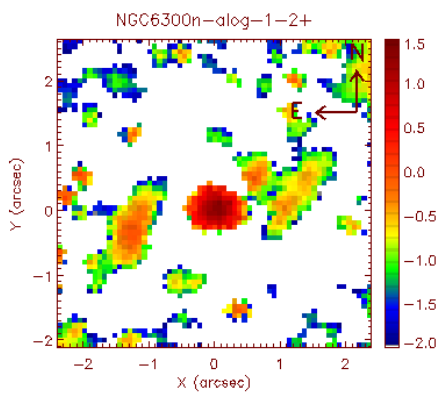


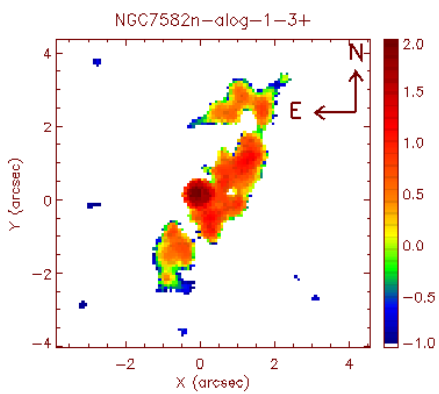


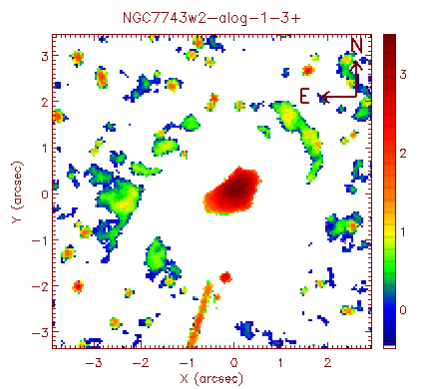








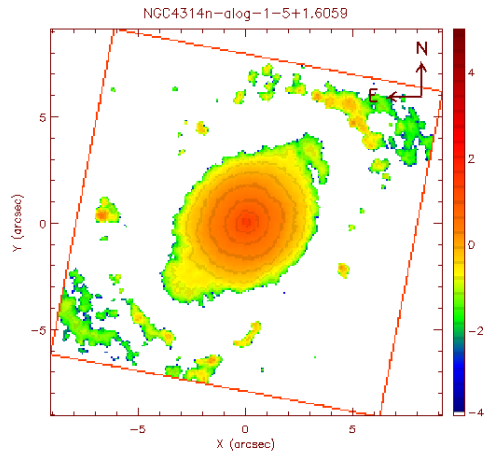


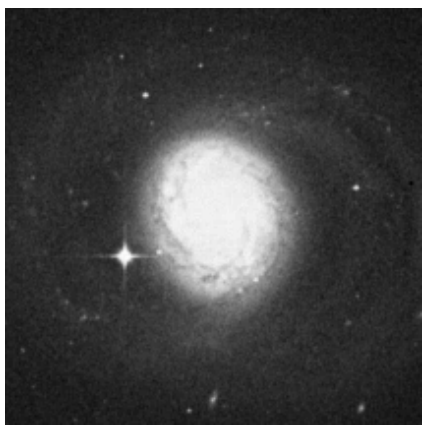


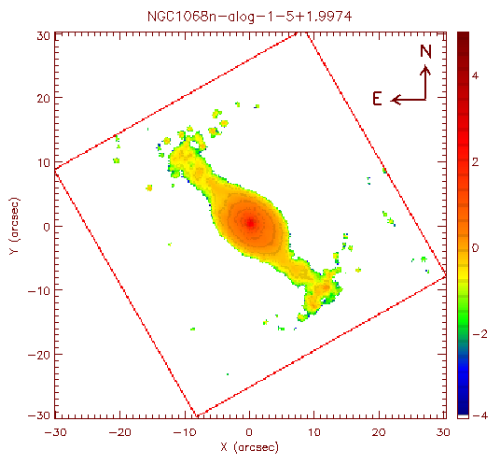
Conclusion of analyzing observational data

1. Bar structure is quite common in Galaxies. Some have major and others have central bars.

a. Galaxies, with or without a major bar, may have a central bar.



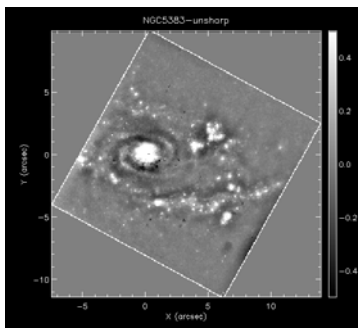


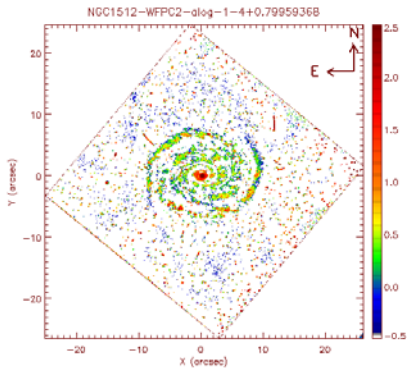


Conclusion of analyzing observational data

b. A galaxy with a major bar may not have a nuclear bar

NGC5383 NGC1512





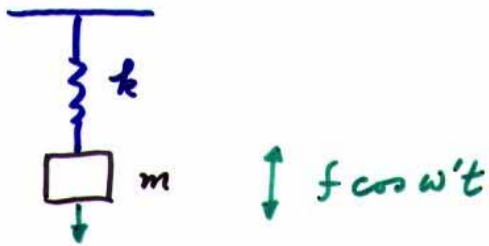
2. Spiral-ring structure in the galactic central regions is related to the bar in the system.

3. These spiral-rings are the sites of starburst rings.

4. Most of Seyfert galaxies have a central bar.

Simple Harmonic Oscillator

Resonance Excitation



$$\frac{d^2x}{dt^2} + \frac{k}{m}x = f\cos\omega' t$$

$$\omega^2 = \frac{k}{m}$$

$\omega = \omega'$ ⇒ Resonance

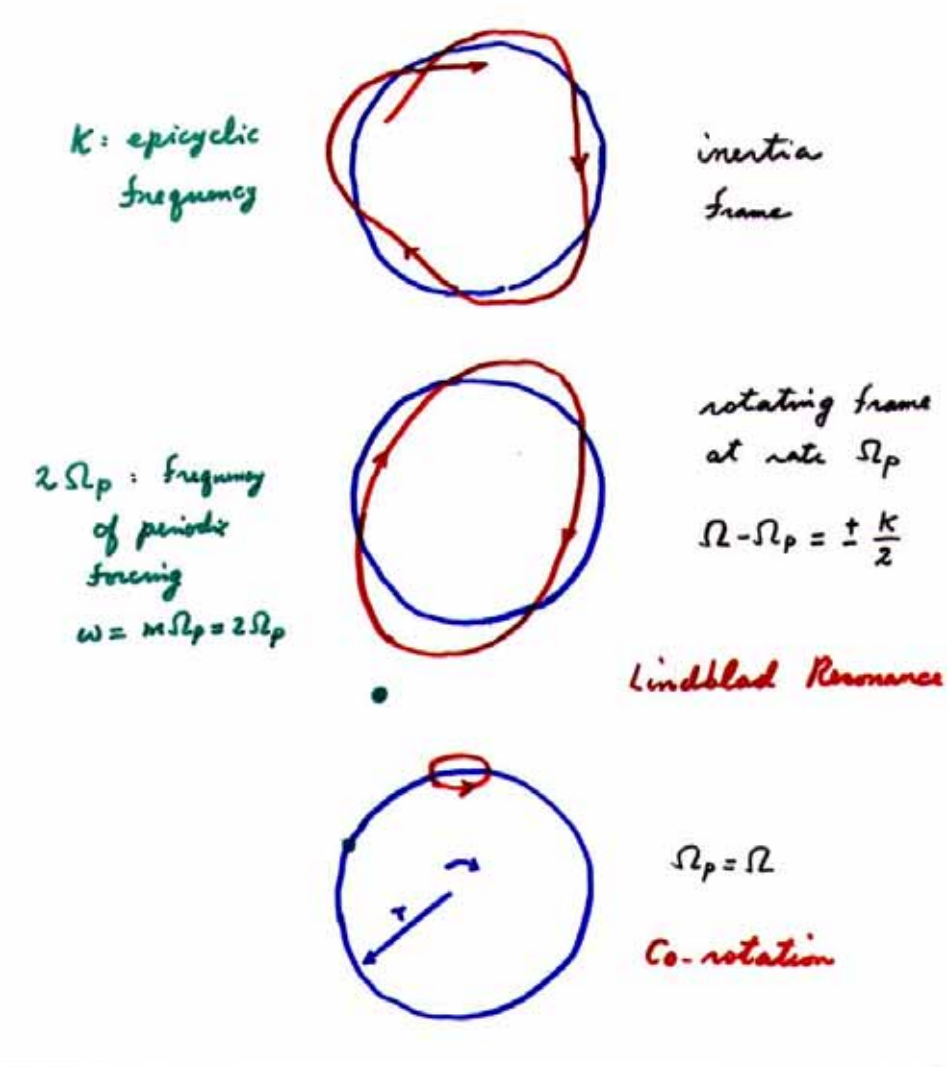
⇒ EXCITATION

⇒ non-linear

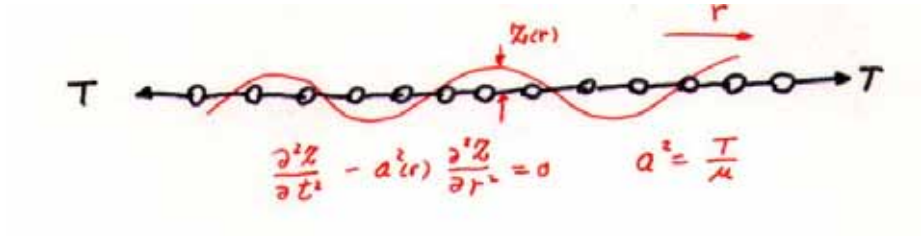
Oscillator (Simple harmonic)

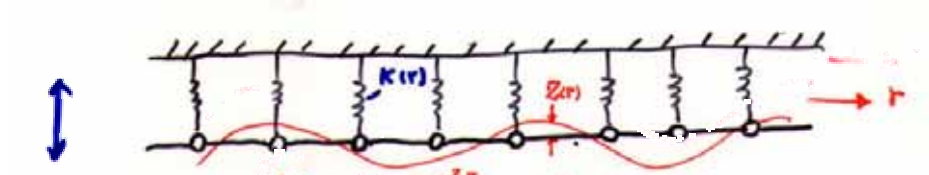
Periodic Forcing

Each Particle in a Disk is a harmonic Oscillator



Resonance Excitation: A Simple Analogy





$z \sim e^{i\omega' t}$

$\omega'^2 = \omega^2 - K^2$

$$\frac{\partial^2 z}{\partial t^2} - a^2(r)\frac{\partial^2 z}{\partial r^2} + K^2(r) z = f\cos\omega' t$$

ASTROPHYSICAL DISKS

self-gravity

viscosity

$$\frac{\partial^2 z}{\partial t^2} - [a^2 + i\kappa\nu]\frac{\partial^2 z}{\partial r^2} + i 2\pi G \sigma_0(r)\frac{\partial z}{\partial r} + K^2(r) z = f\cos[(\omega - m\Omega(r))t]$$

ω'

$-(\omega - m\Omega)^2 z$

$z \sim \hat{z}\, e^{i(\omega t - m\theta)}$, $\omega = m\Omega_p$

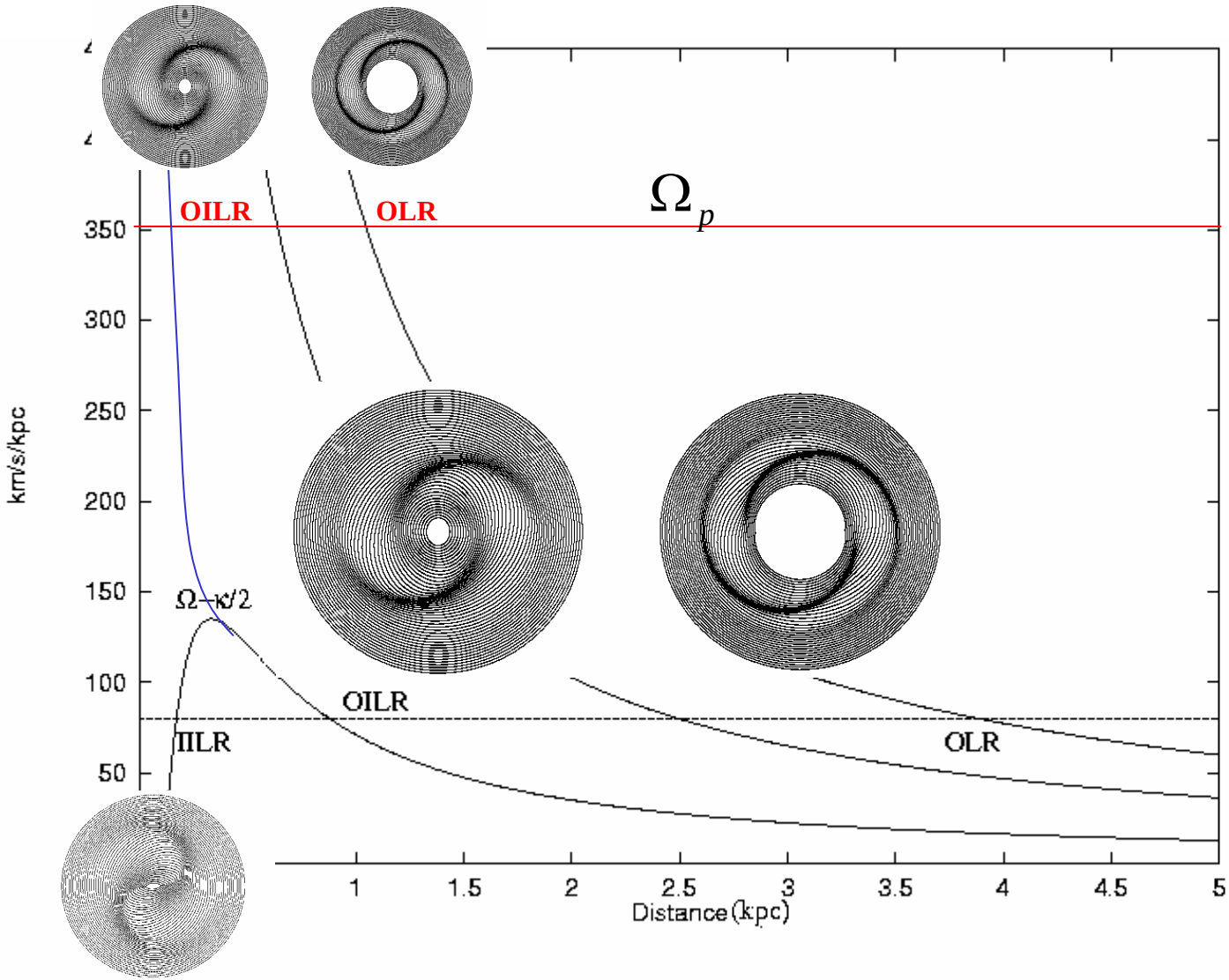
$$-[a^2 + i\kappa\nu]\frac{d^2\hat{z}}{dr^2} + i 2\pi G \sigma_0 \frac{d\hat{z}}{dr} + [K^2 - (\omega - m\Omega)^2]\hat{z} = f$$

$$a^2 k^2 + 2\pi G \sigma_0 |k| + \kappa^2(1 - \nu^2) = 0$$

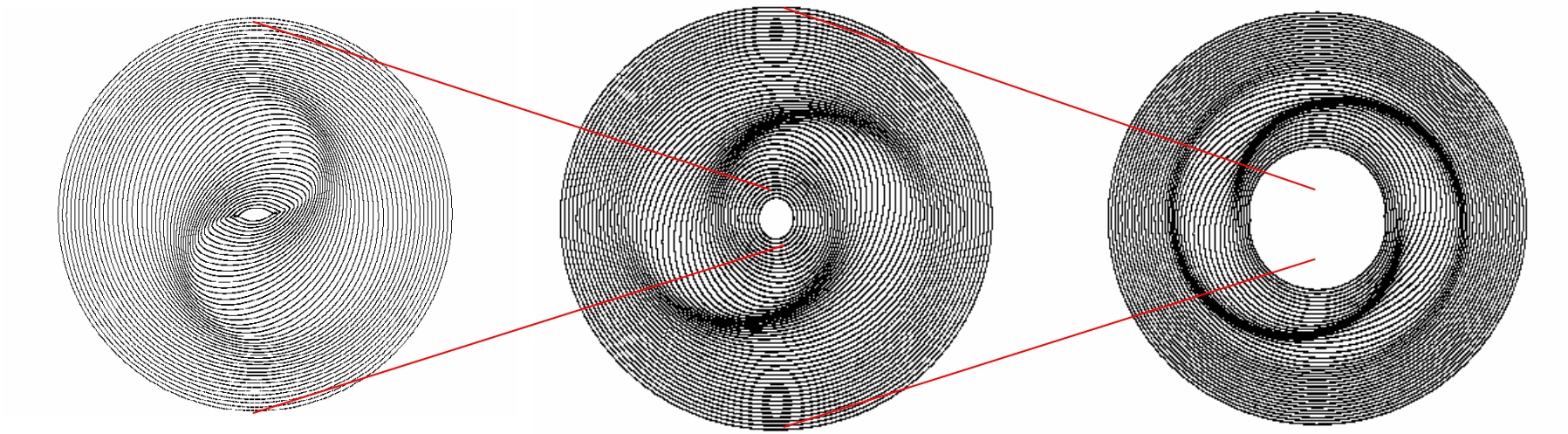
$\nu = \omega - \Omega/\kappa$

LIN-SHU DISPERSION RELATION

Rotation Curve and Lindblad Resonances

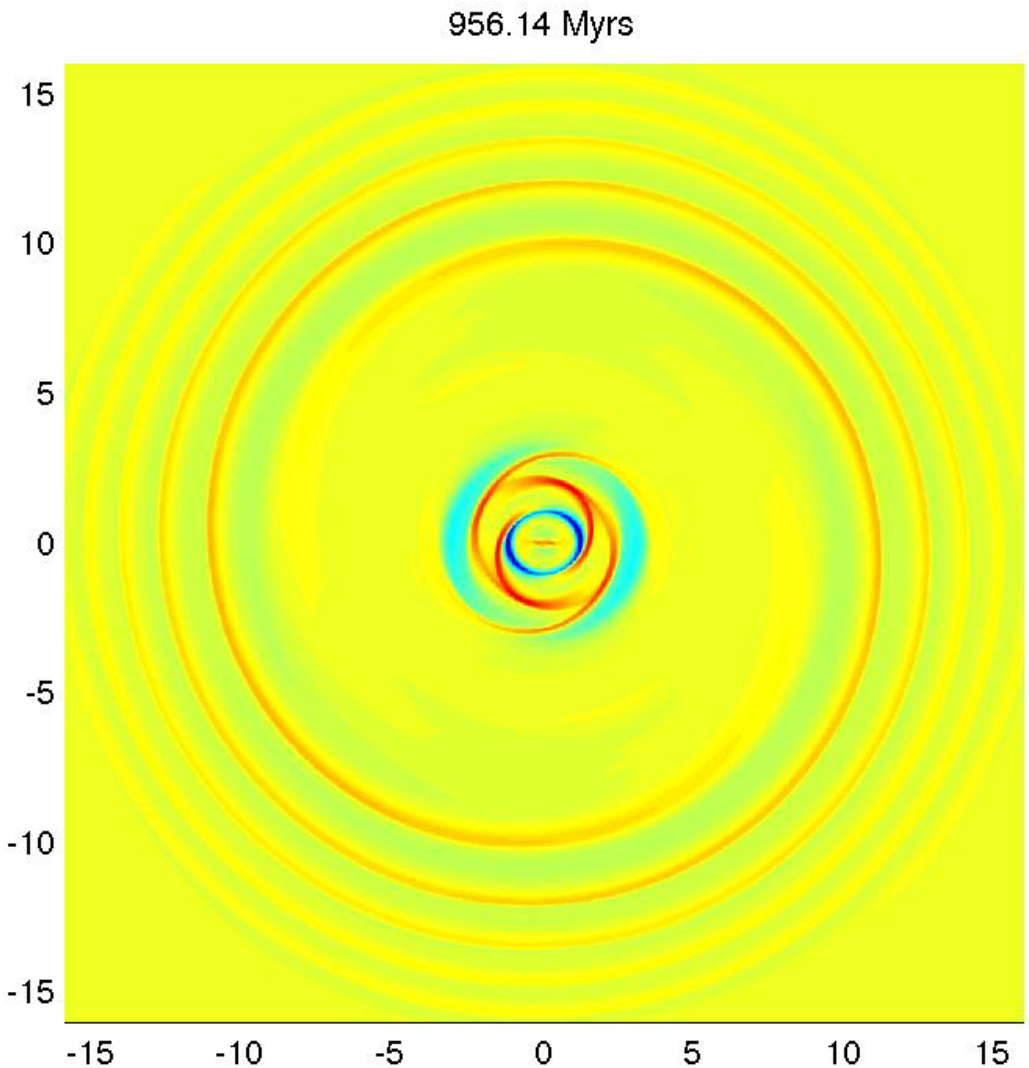


Bar-driven Spirals at Lindblad Resonances



IILR OILR OLR

Three Lindblad Resonances



Governing Equations

$$\frac{\partial \sigma}{\partial t} + \nabla \cdot \left(\sigma \, \mathrm{v} \right) = 0,$$

$$\frac{\partial \left(\sigma \, \mathrm{v} \right)}{\partial t} + \nabla \cdot \left(\sigma \, \mathrm{v} \, \mathrm{v} + \sigma a^2 \mathrm{I} \right) = -\sigma \nabla \Phi,$$

$$\nabla^2 V_\mathrm{d} = 4\pi G \sigma \delta \left(z \right),$$

$$\Phi = \Phi_0 + \Phi_\mathrm{d} + \Phi_\mathrm{b},$$

$$r\Omega^2 = \nabla \Phi_0$$

$$P = a^2 \sigma.$$

The Antares Code
大火程序

- A high-performance CFD-MHD code for astrophysics
- It is a second-order Godunov code (or codes) equipped with exact Riemann solver and the balance law correction. (2-D)
- It is also featured with the Poisson solver, to include the self-gravitation of the disk, and with characteristics decomposition on the boundary, to guarantee the true radiation (non-reflecting) boundary conditions.

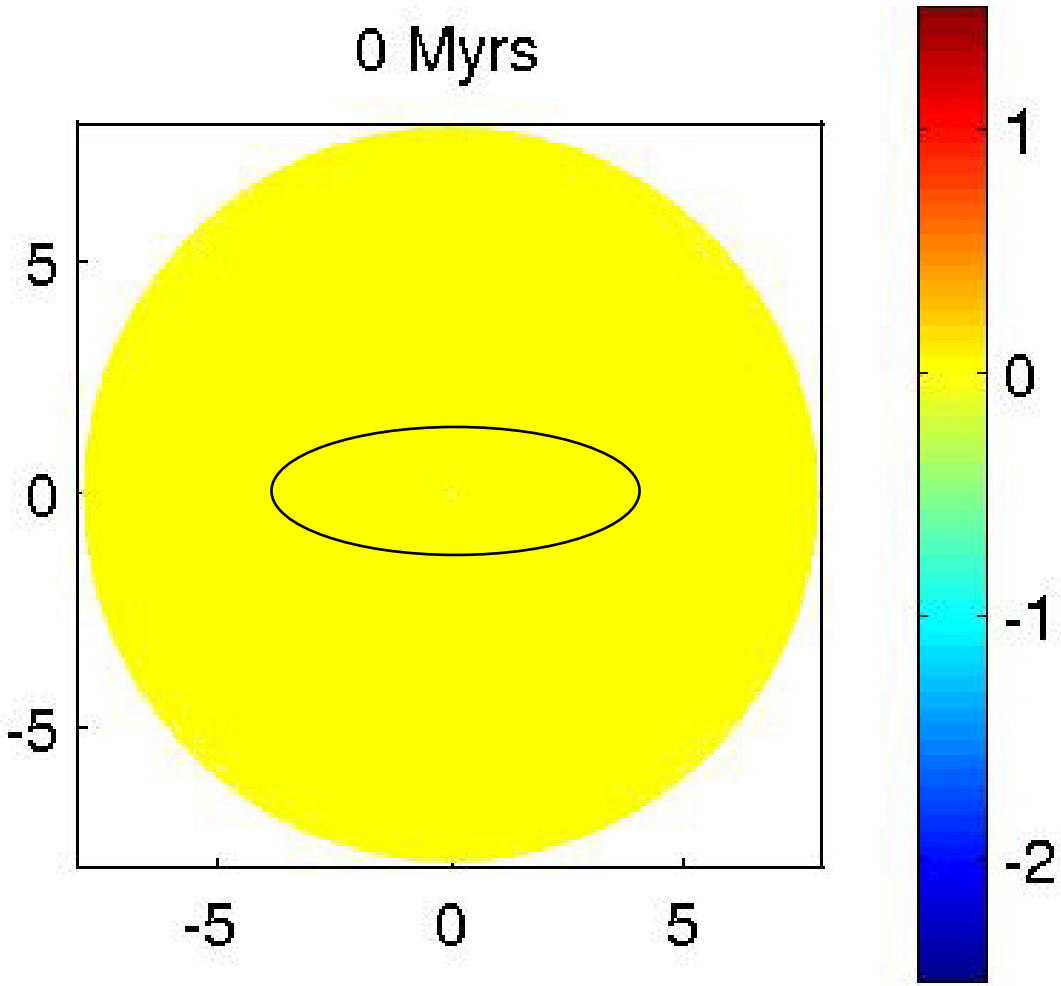
Code Development

- Coordinate System: Polar and Cartesian
- Spatial Discretization: High-order Godunov and relaxation
- Temporal Advancing: Unsplit and split
- Time Integrator: 2^{nd} order Runge-Kutta at least
- Van Leer type limiters
- FFT or Tree Code for Poisson Equation
- Boundary Condition: Radiation
- Testing: Several critical tests

Testing

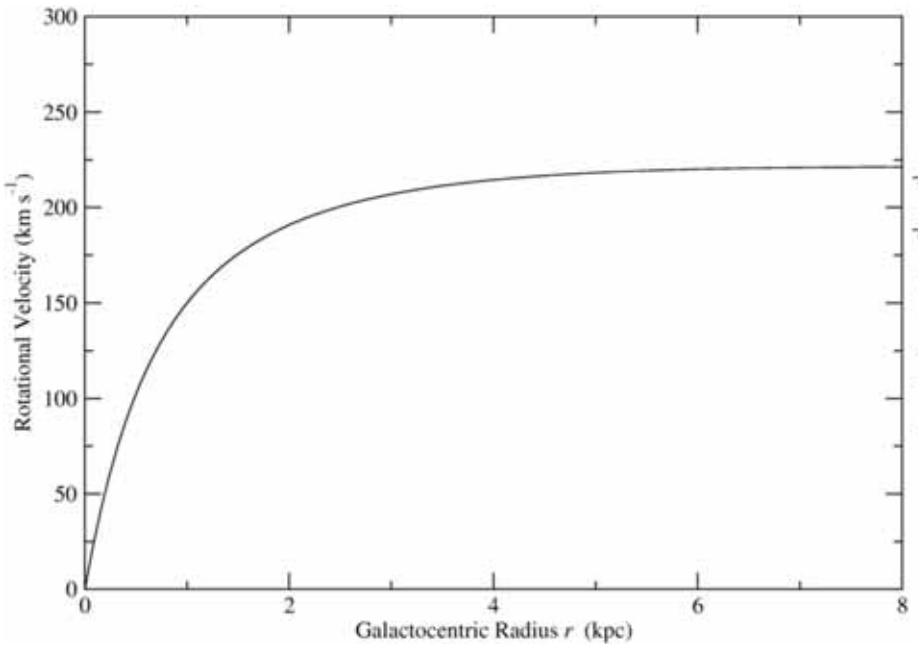
- Exact smooth solutions remain 2^{nd} order accuracy as long as our simulation requires
- Basic states remain unchanged for as long as our simulation runs
- Non-reflection boundary condition holds

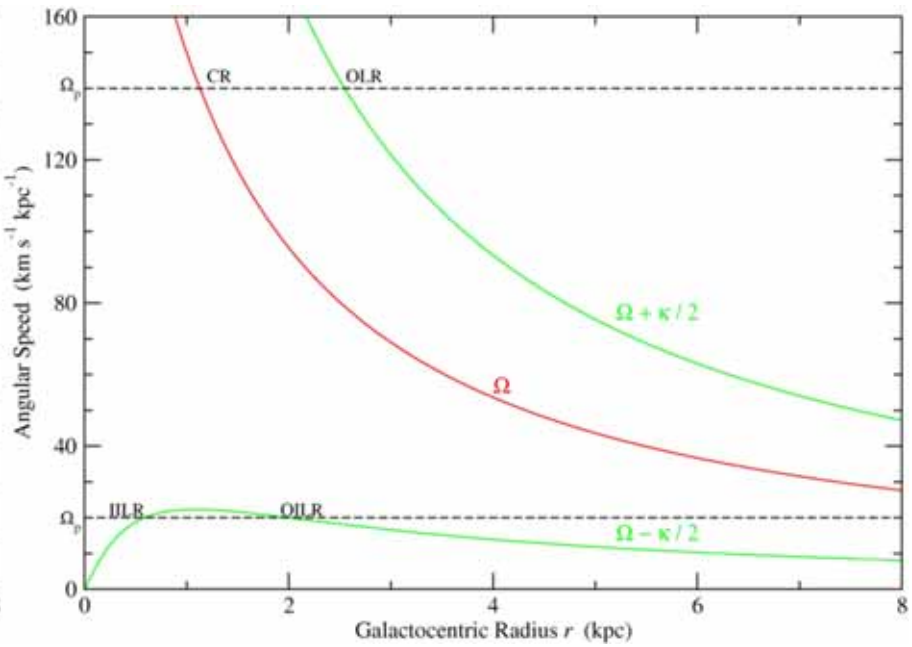
Schematic Picture of a Bar In Numerical Simulations



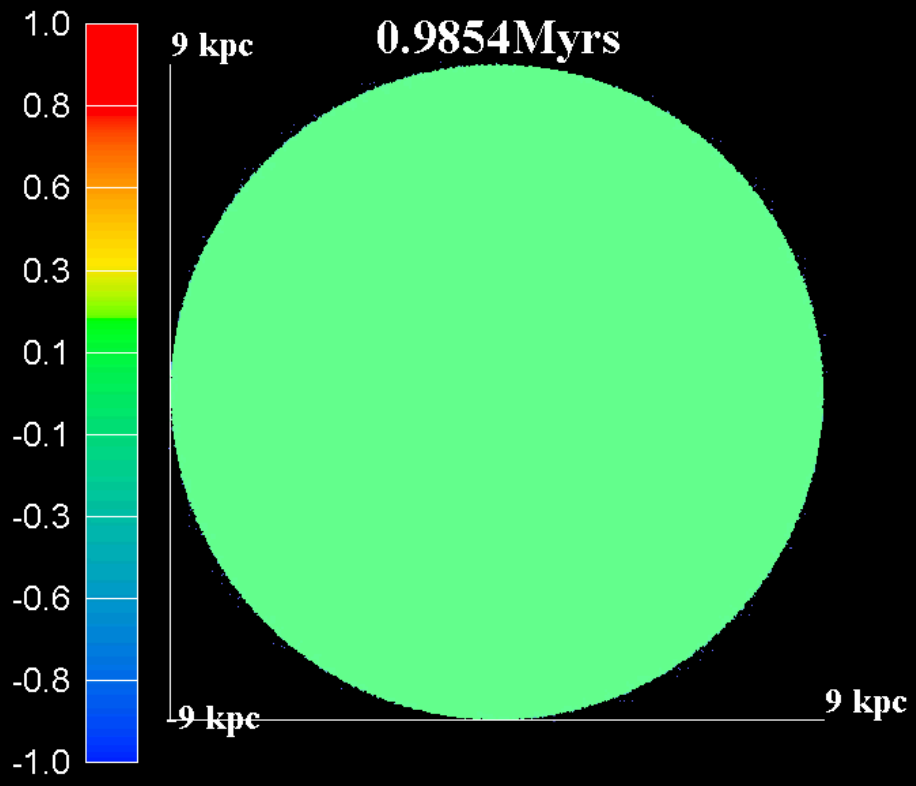
Elmegreen Rotation Curve

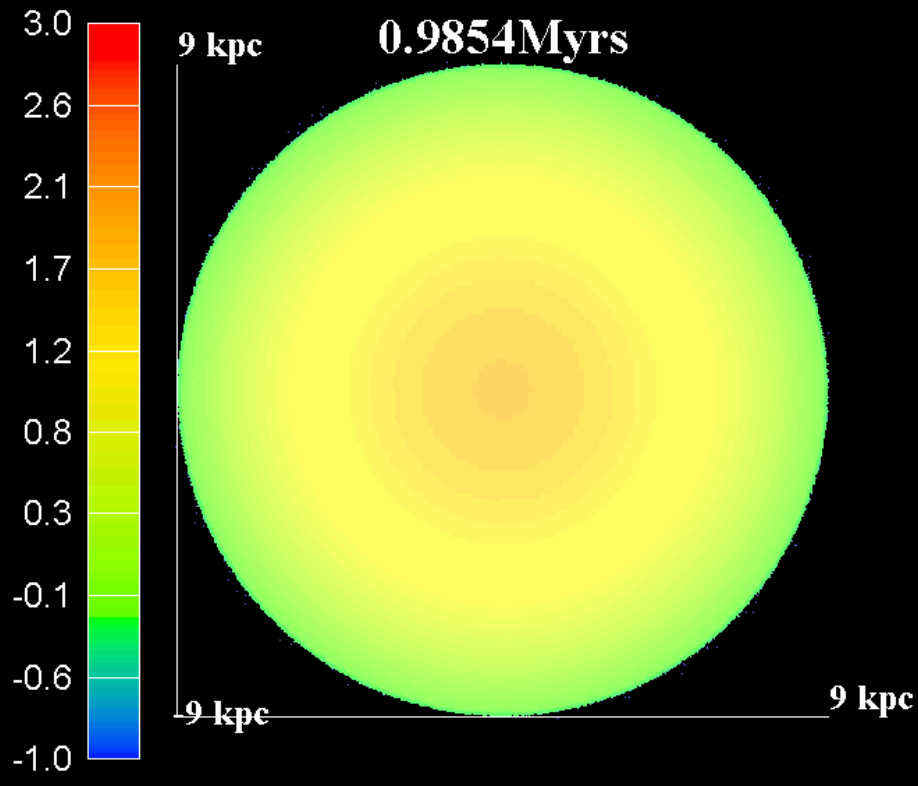
$$v = \frac{v_0 r}{r^B + r^{1-A}}, \; B = 0, \; A = -0.1$$





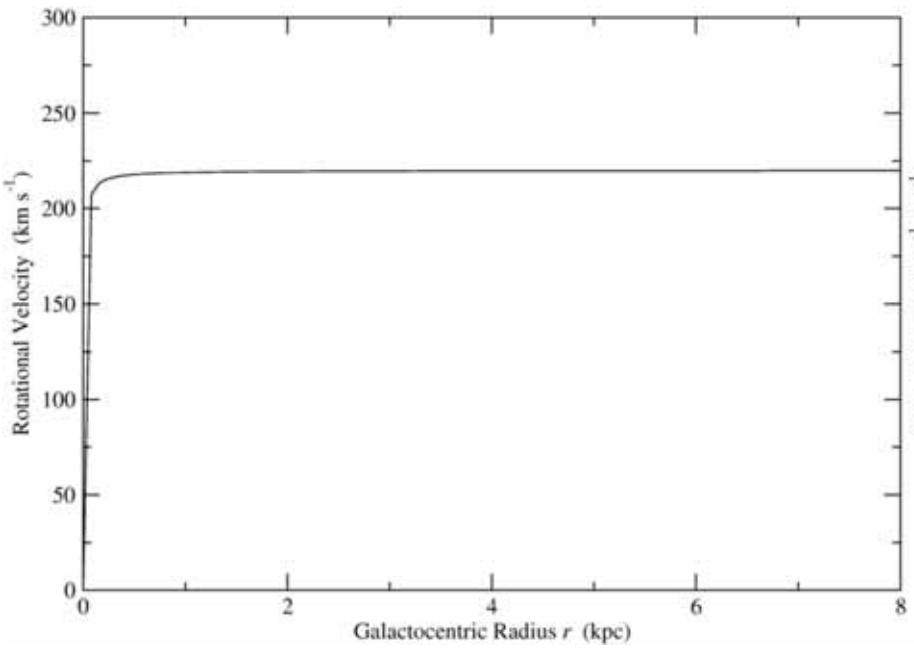
Cases for a Single OLR

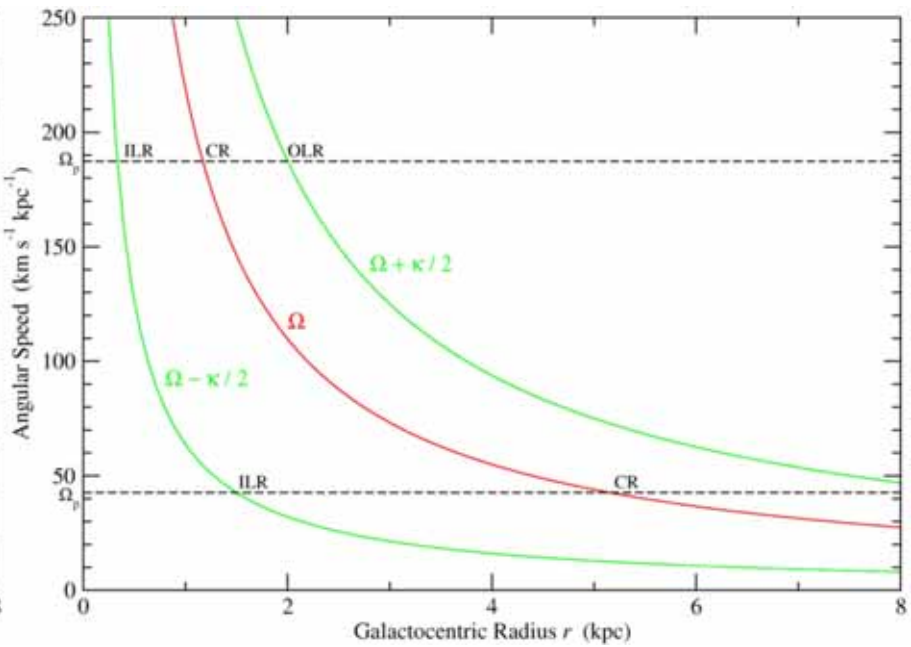




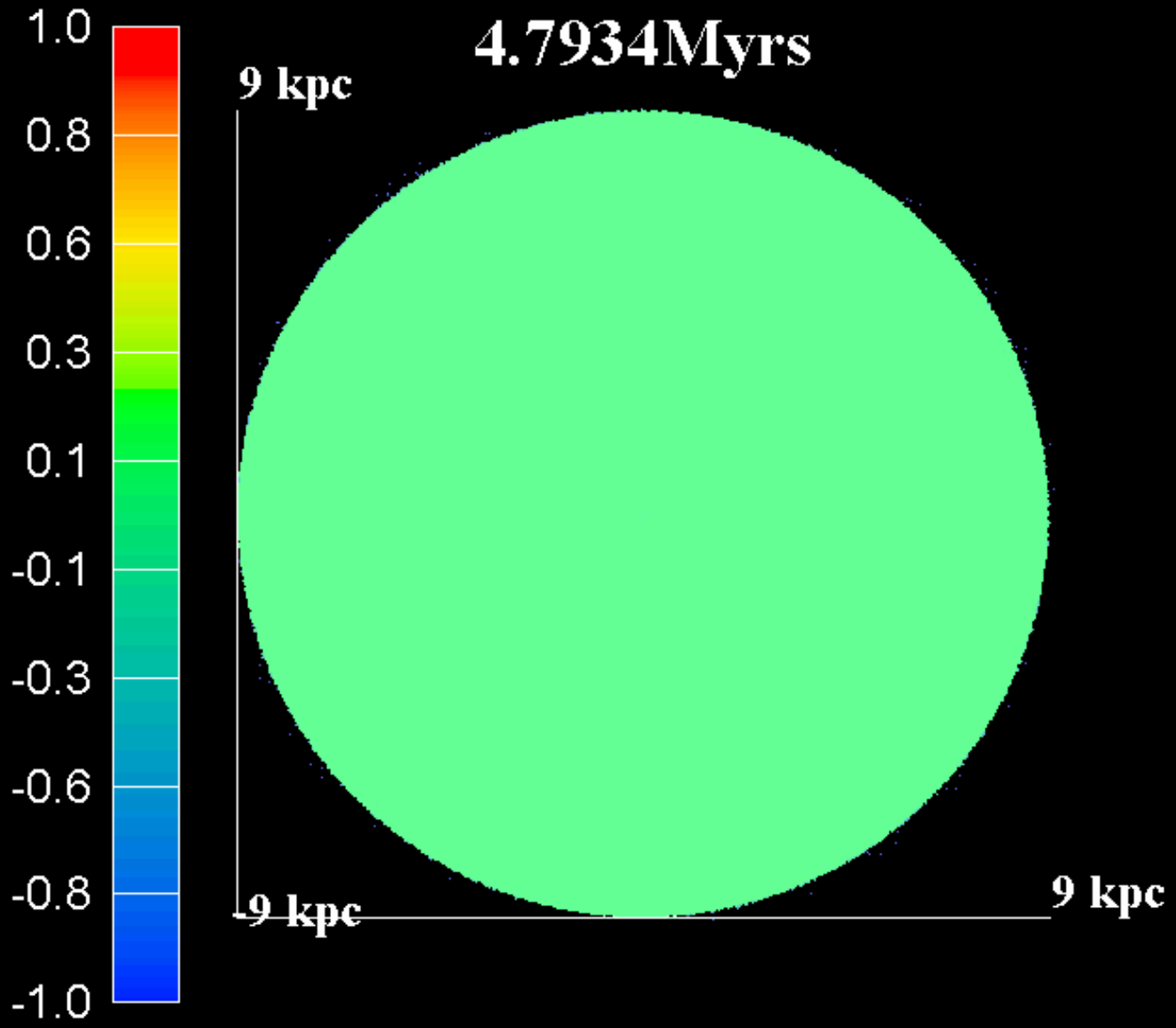
Nearly Flat Rotation Curve

$$v = v_0 \left(\frac{r}{r+\varepsilon}\right)^{\frac{1}{2}}, \varepsilon = 0.01$$

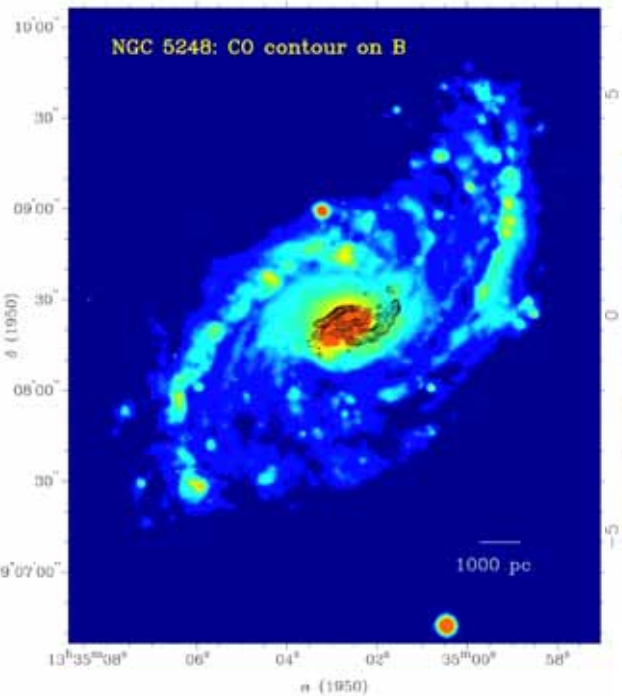


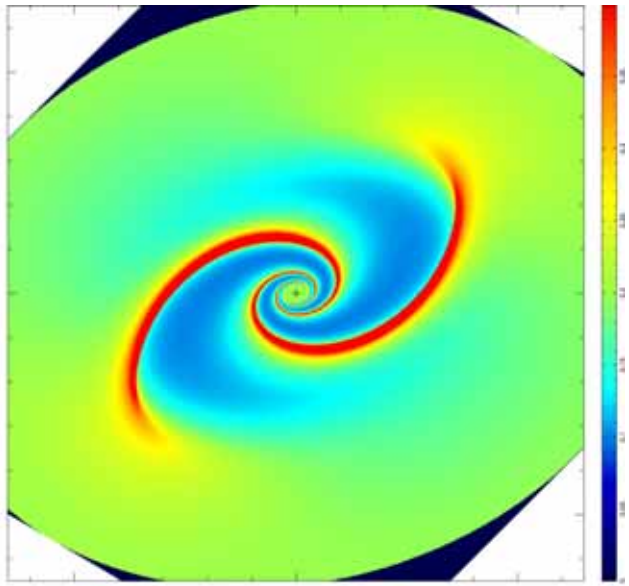


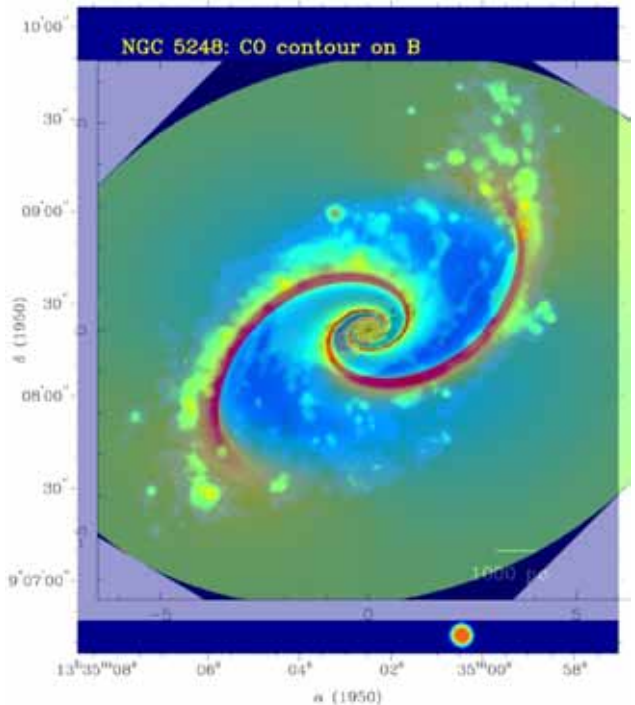
Case of a Single ILR



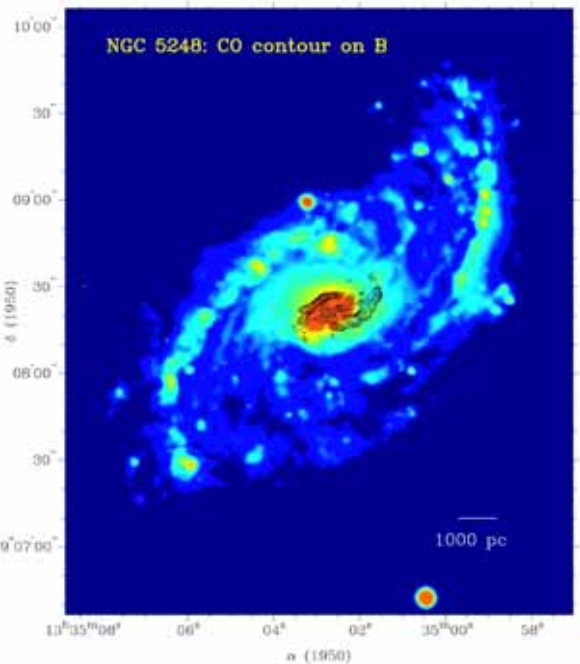
NGC5248

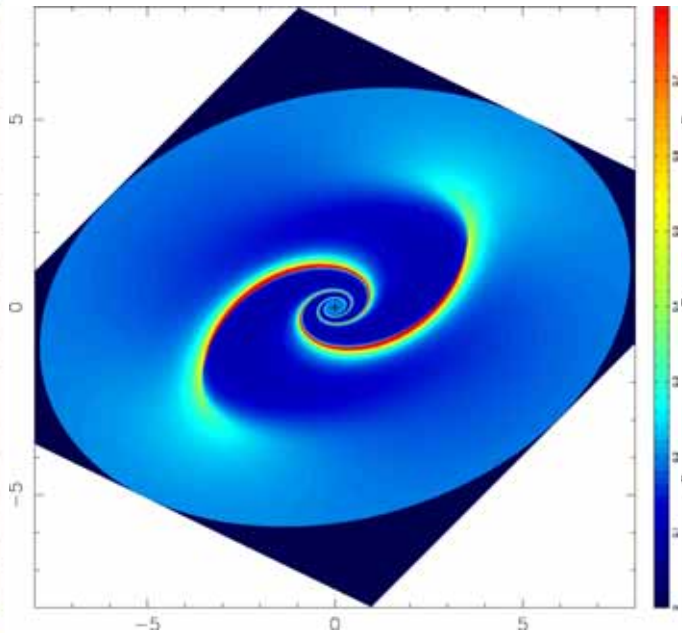

NGC 5248: CO contour on B
1000 pc
δ (1950)
α (1950)

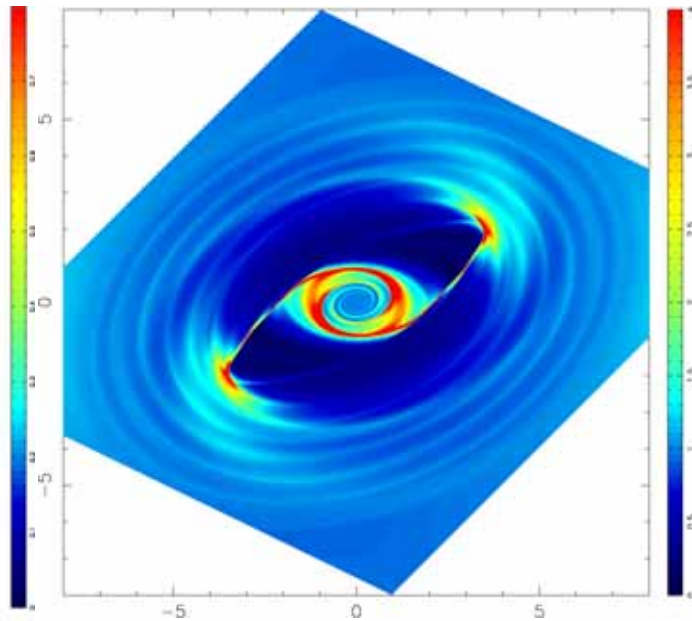



NGC 5248: CO contour on B
δ (1950)
α (1950)

NGC5248

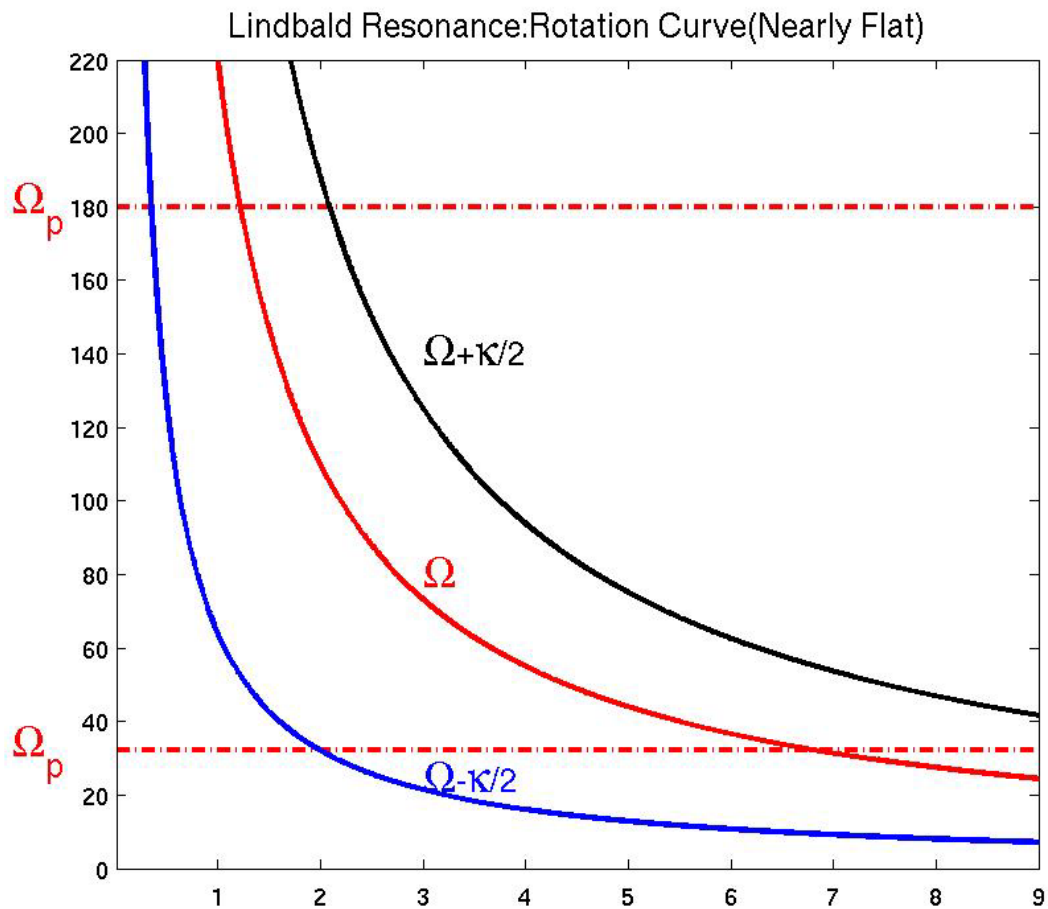




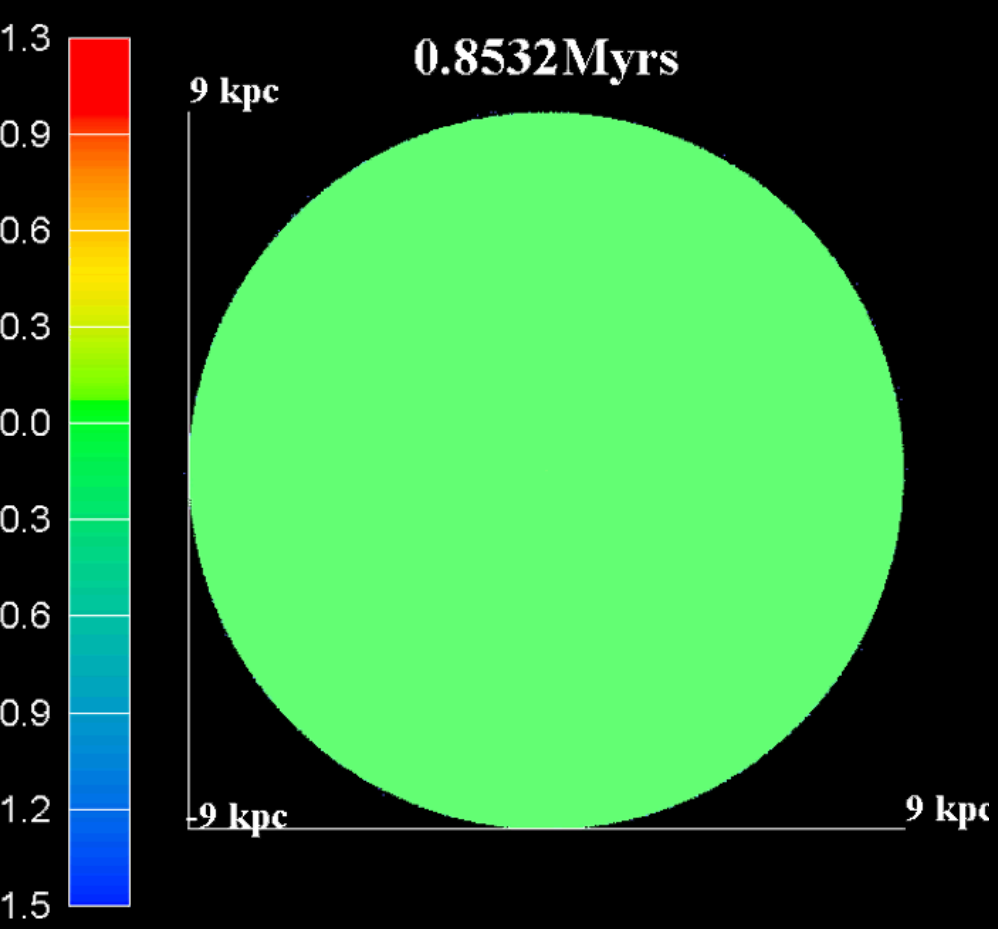


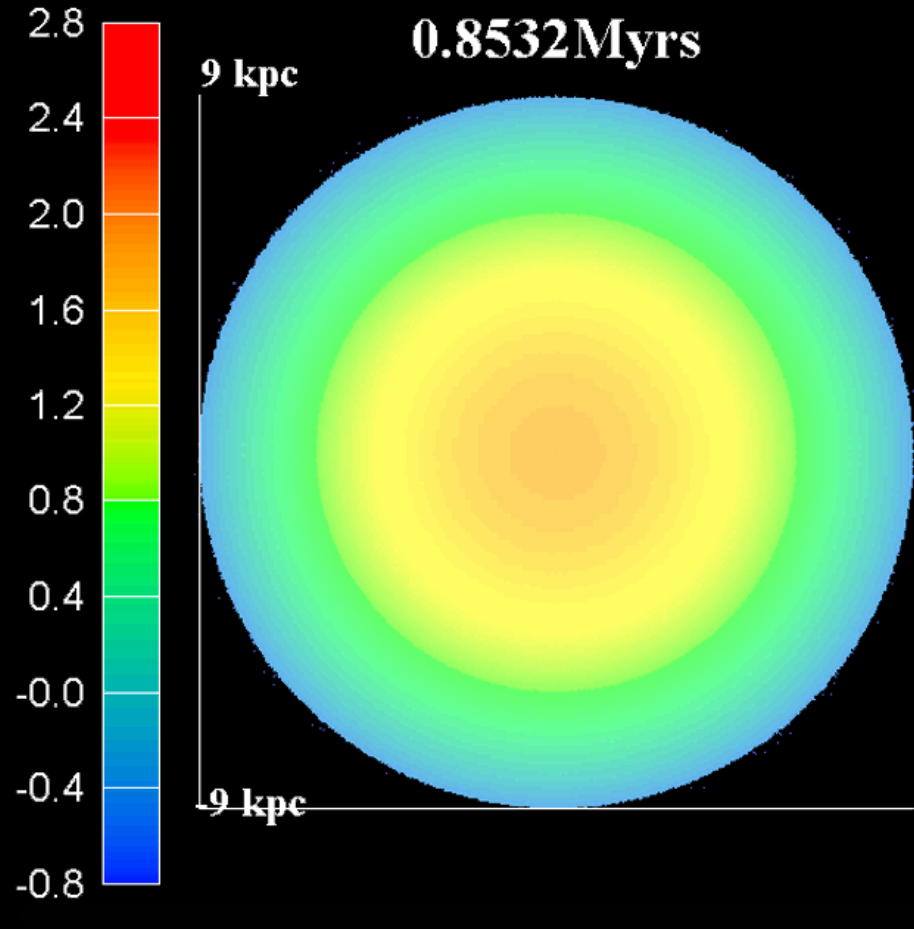
Nearly Flat Rotation Curve

$$v = v_0 \left(\frac{r}{r+\varepsilon}\right)^{\frac{1}{2}}, \varepsilon = 0.01$$

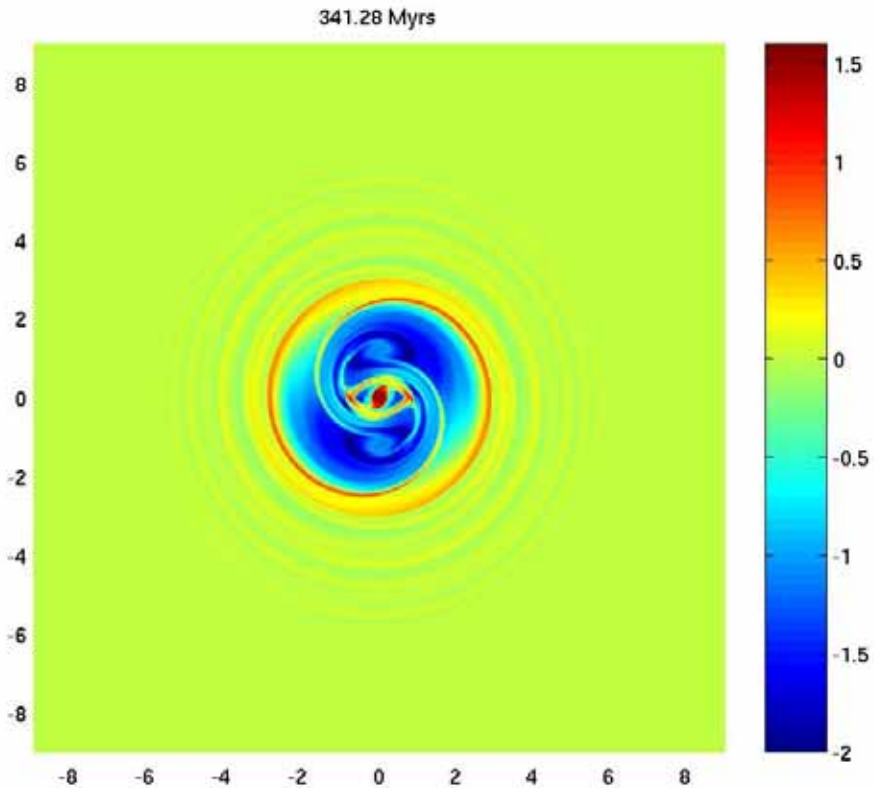


Cases of Double Resonances: OLR-OILR

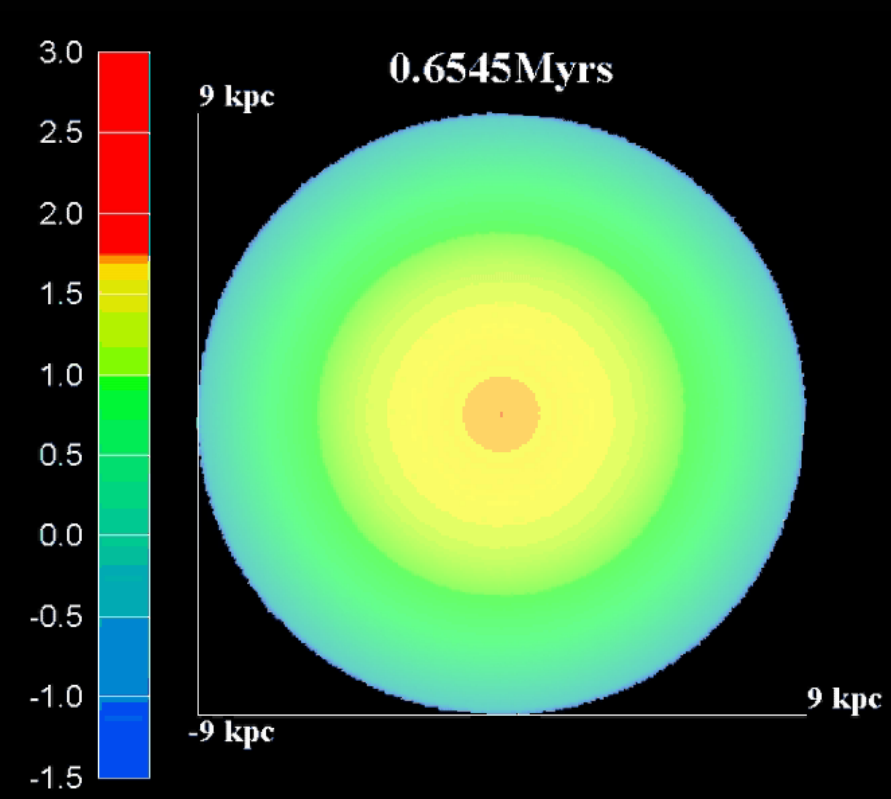


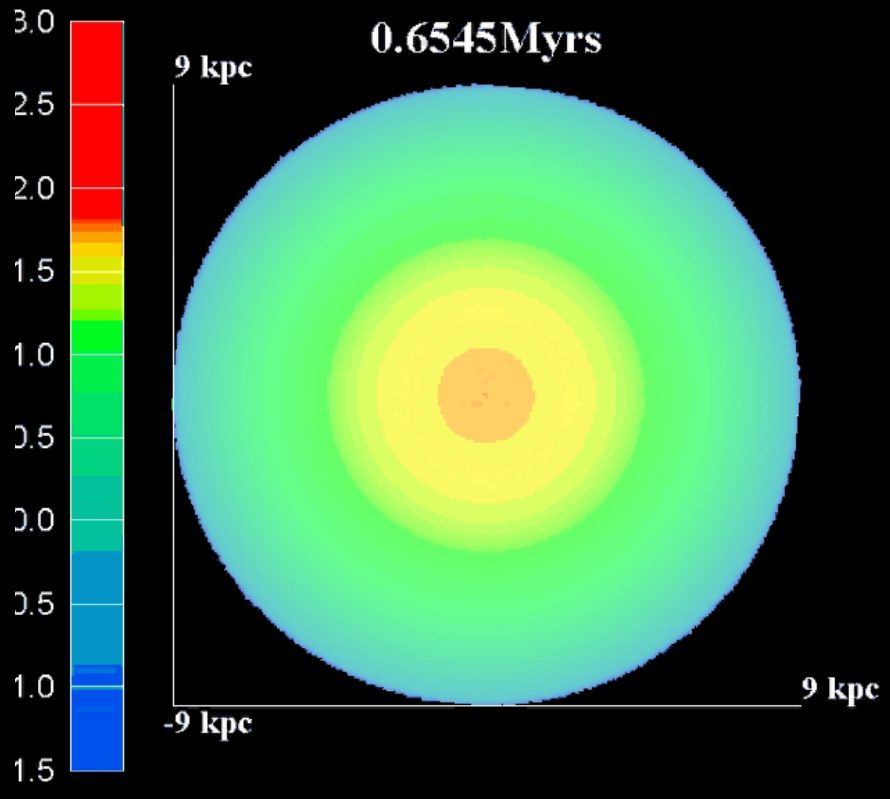


Double Ring Feature

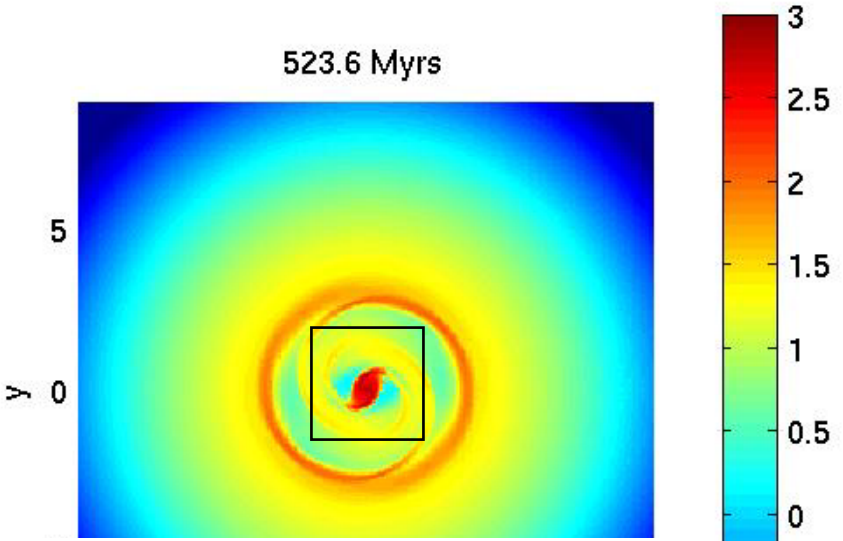


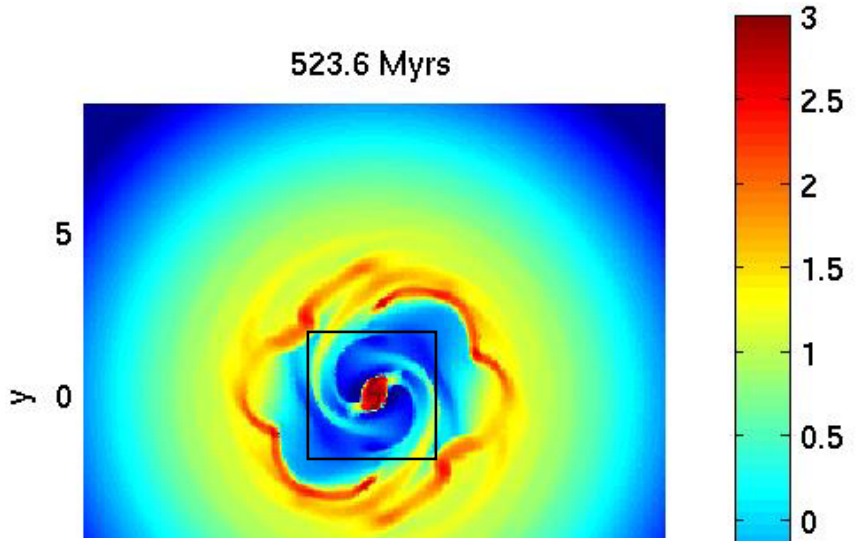
Evolution of the 3-kpc Arm with Self-gravitation

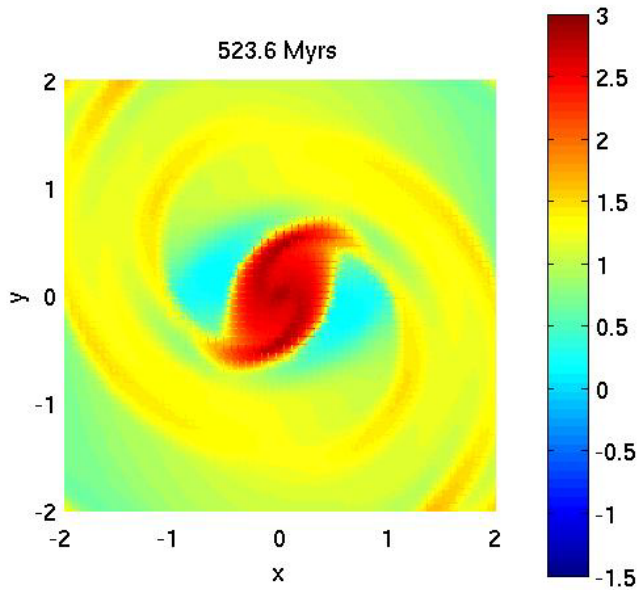


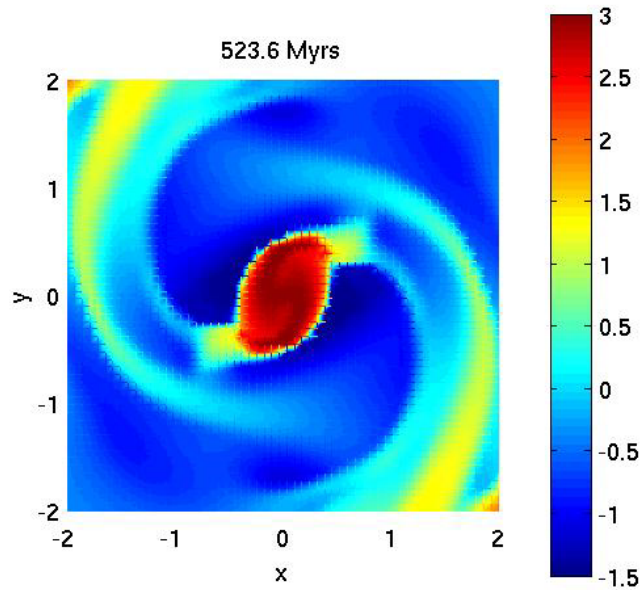


Double Rings and Central Spirals

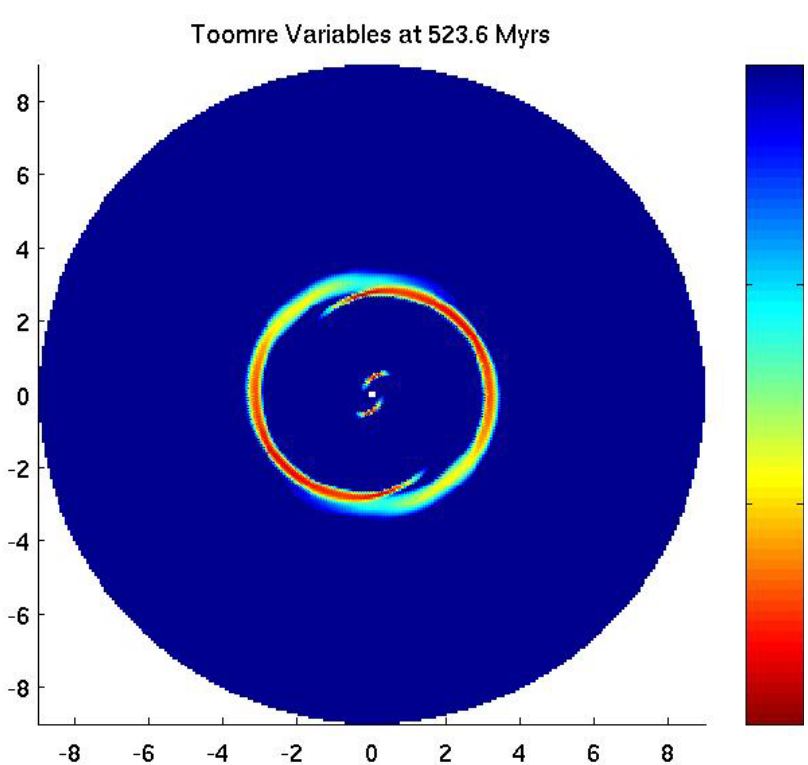


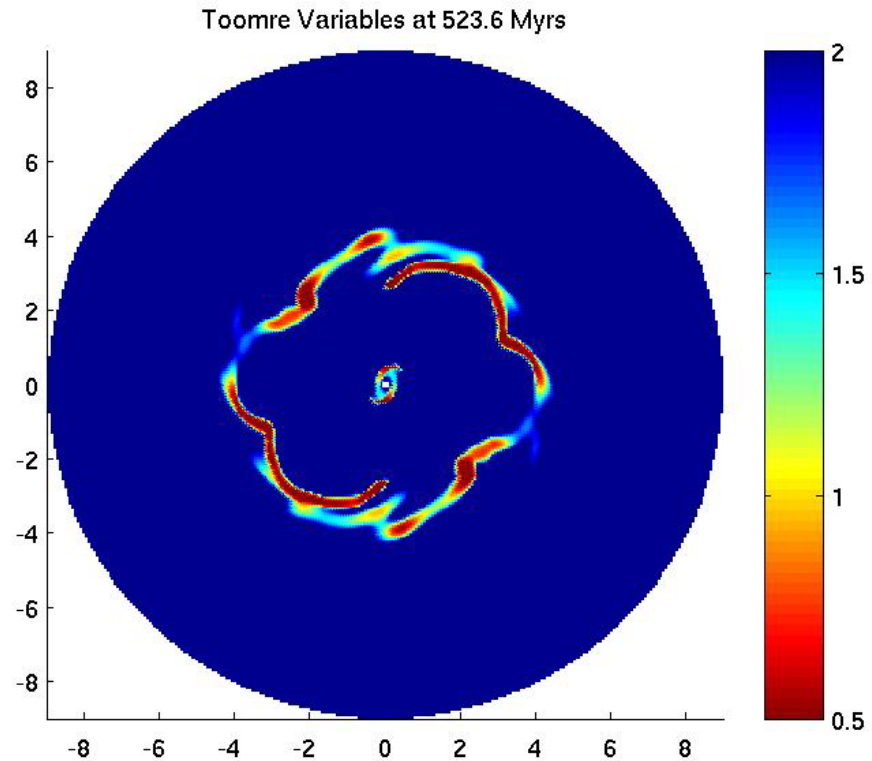




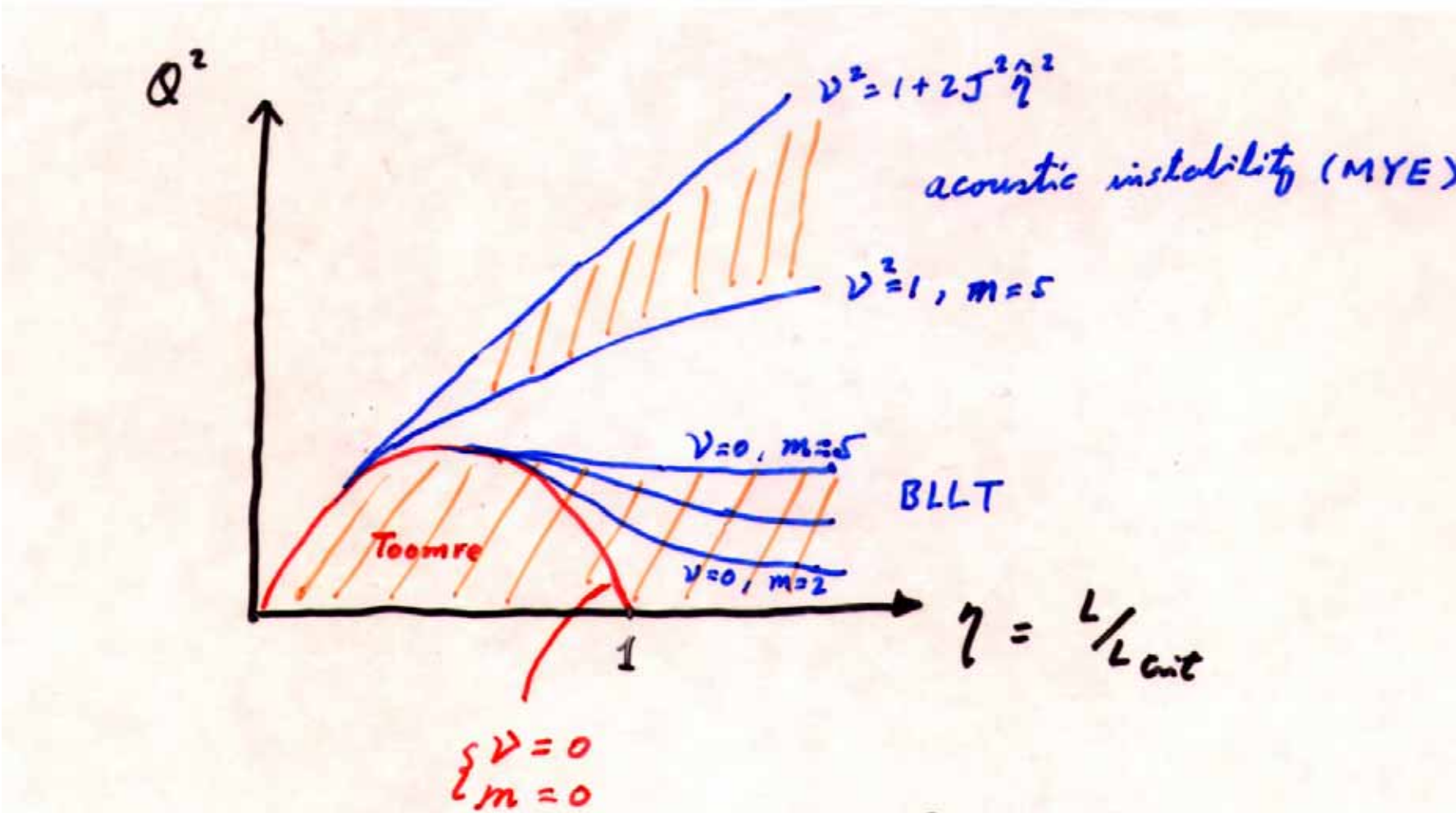


Q-value for Self-gravitating Disk



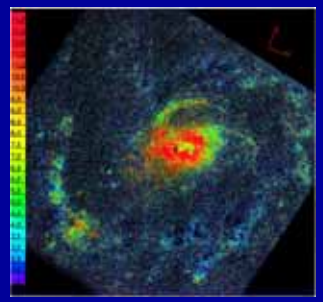
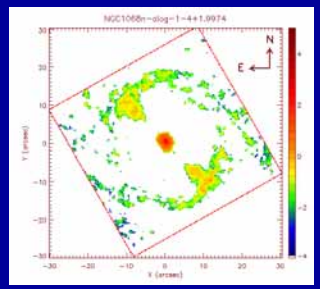
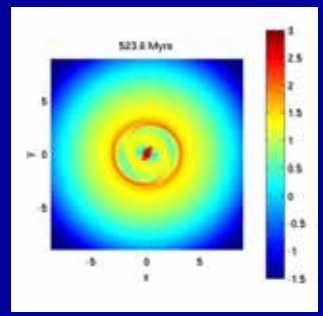
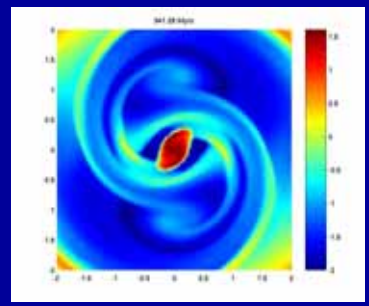


Disk Instability

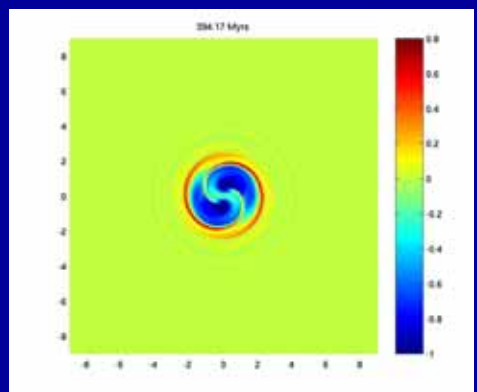


Conclusions

- Starburst rings are the results of a gaseous disk responding to a rotating bar potential. But, there are many possibilities.
- A fast nuclear bar like NGC1068 or the Milky Way (OLR and OILR)

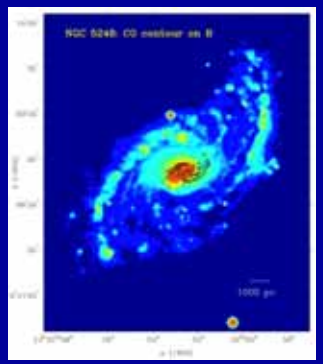
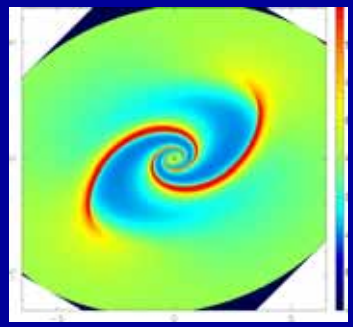
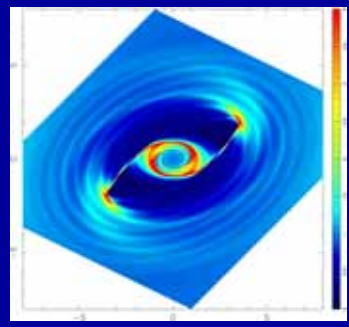





- A fast nuclear bar like possibly NGC4313 (OLR).

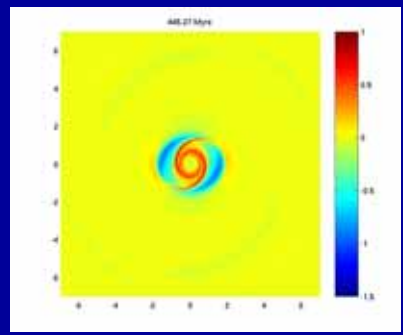



Conclusions cont.

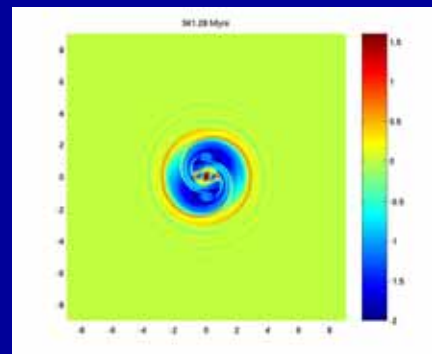
- A slow major bar like NGC5248 (OILR)

- A slow bar such as in NGC1512 after many turns (OILR)

- A double ring due slow bar like NGC6278 (OLR-OILR).

Conclusions cont.

- Interaction between IILR-OILR waves forms a bar configuration reinforcing the imposed bar potential.
- Due to high epicyclic frequency near center, the central surface density of the disk can be very high without gravitational collapse. This may be the origin of the circumnuclear molecular disks.
- Self-gravitation plays an important role. It leads to instability, chaos, and star formation
- Toomre's criterion Q=1 works extremely well.