Dynamics of warps in spiral galaxies

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❖ An outline of the talk :

1. Warp in galaxies and its observational facts.
2. Problems in warps.
3. Physics of symmetric warps.

PART-I

4. Making asymmetric warps in spirals.
5. Asymmetry and the dark matter halo?

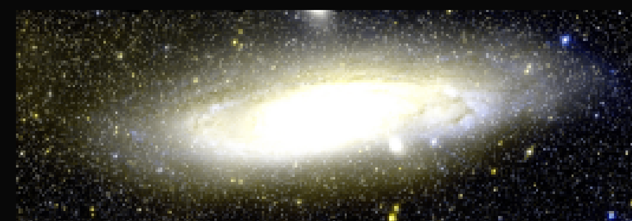
PART-II

6. Where does warp begin in the disk?
7. Preliminary results from Spitzer observations.

Warps: **Geometrical distortions of the galactic mid-plane in the vertical direction.**

Grand-design warps are anti-symmetric integral sign or 'S' shaped.

Disks of spiral galaxies refuse to stay flat



M31

ESO121 – G006

NGC7814

Observational facts:

- *Warps first observed in our own Galaxy, Kerr 1956*
- Warps are detected in Visible – IR - Radio
- Primarily and prominently seen in 21 cm
- The connection between optical and HI warps is not clear

Briggs rule: i). Warp develops between R_{25} and R_{HO}

ii). Line of node tends to be straight inside R_{HO}

iii). Outside R_{HO} LON curves so as to form a loosely wound leading spiral.

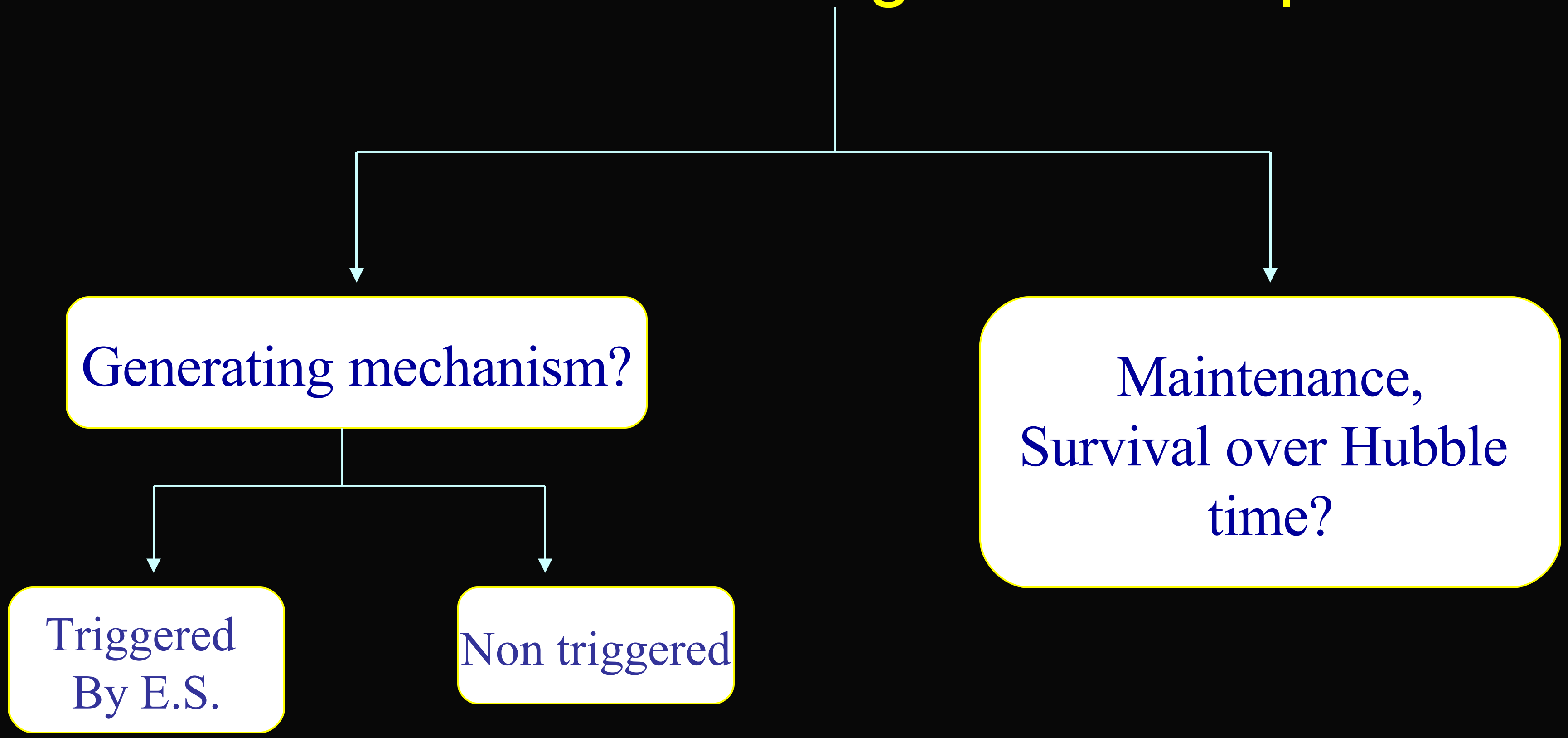
- No such established rules for optical warps!

- No connection between HI & optical warps!
- No warps found so far in Lenticulars!
- Warps are more frequent in late-type galaxies
- warps seem to be stronger in rich environment.
- Warps are best observed when viewed edge-on
- More than 50% of the Spiral galaxies are warped
  --- based on Statistical analysis.
- Most of the warps are asymmetric
  —based on recent observations

Almost all galaxies in the our Local group e.g. Milky Way, M31, M33 …… are Warped!

Warp is a common Phenomenon !

❖ Problems in galactic warps



Q. Is there a unique mechanism to generate warps in spiral galaxies?

Q. How does warp survive in spiral galaxies?

❖ Some mechanisms put forward so far:

1. Hydro-dynamical and Anisotropic Magnetic pressure of the IGM.
2. Tidal interaction with Satellites and companion galaxies.
3. Infall of intergalactic matter onto the disk
4. Cosmic infall and Angular momentum misalignment
5. Non-linear generation of warps through spirals
6. Galactic Bar as a possible source
7. Warp as Bending Instability

❖ Maintenance problem for warps:

1. Winding up problem due to Differential Precession in the disk.

   Typical winding up time ~ less than a Gyr!

2. Dynamical friction from the dark matter halo

   -May not be active indefinitely!

So major problem is due to winding!

➡ Solution: Normal mode?

❖ Governing dynamics of bending modes

Dynamical equation of small bending:

$$\left(\frac{\partial}{\partial t}+\Omega(r)\frac{\partial}{\partial \phi}\right)^2 z_m(r,\phi,t)=F^m_{self}(r,\phi,t)+F^m_{halo}(r,\phi,t) \quad \ldots(1)$$

Self force due to bent disk

Restoring force due to dark matter halo

$$z_m(r,\phi,t)=\Re\left(h_m(r)\,e^{i(\omega_m t-m\phi)}\right)$$

Bending mode of the disk with azimuthal wave number m

Q. How to solve the eqn. of bending?

- **Eq.(1) is an integral equation and is solved by recasting it into a Matrix-Eigenvalue problem.**
- **The galactic disk is approximated as a system of N uniformly spaced concentric rings.**
- **Resulting problem reduces to an N-dimensional Quadratic Eigenvalue Problem (QEP) :**

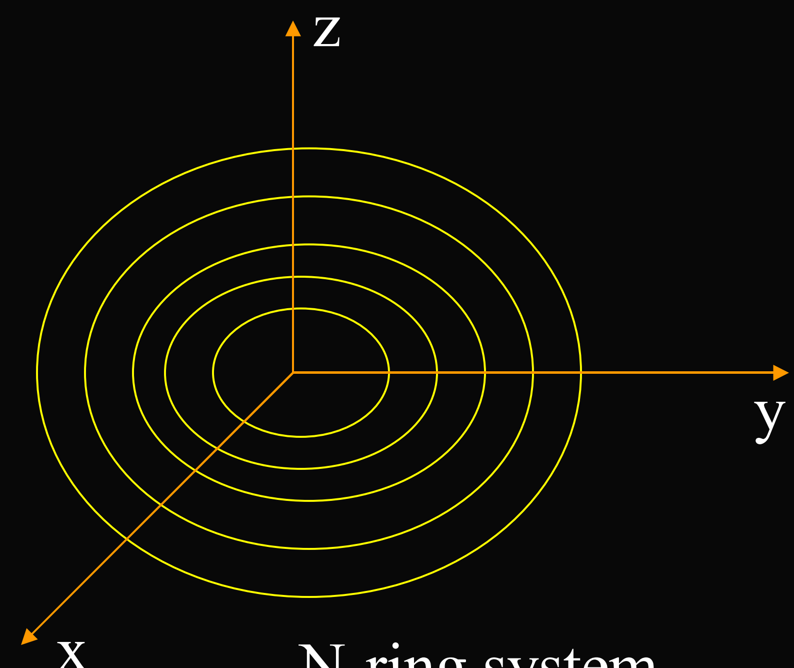
$$(I\omega_m^2 + D\omega_m + S)h_m = 0$$

Eigenvalue → ω_m

Physical state of the system

↓

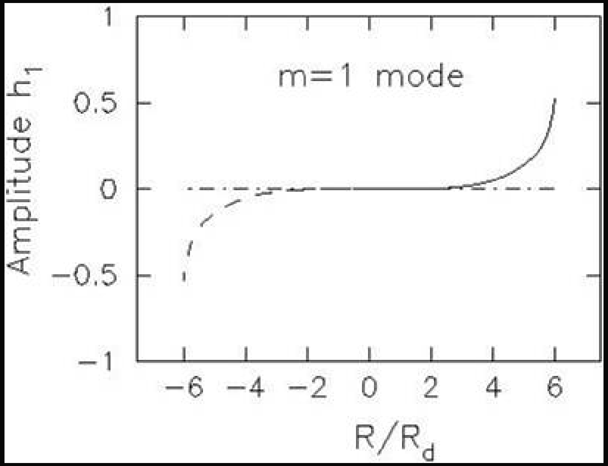
N-dimensional eigenvector h_m



N-ring system

❖ Integral-sign galactic warp (m=1)

- Warps are normal mode oscillation of the disk mid-plane
- Disk embedded in a dark matter halo and precessing with a pattern speed ω_1



- Warp mode is represented by:

$$z_1(r,\phi,t) = h_1(r)\cos(\omega_1 t - \phi)$$

Saha & Jog, A&A, 2006

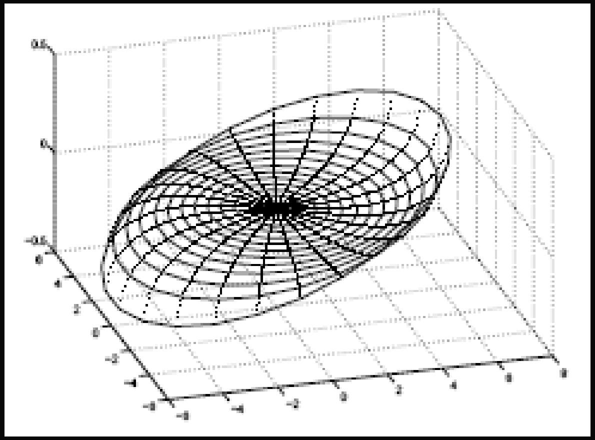
Parameters for the warping mode:

$q=0.7$; $R_c=2.0\ R_d$

$\rho_0 = 0.0117\ M_d/R_d^3$

$\omega_1 = -0.0109\sqrt{GM_d/R_d}$

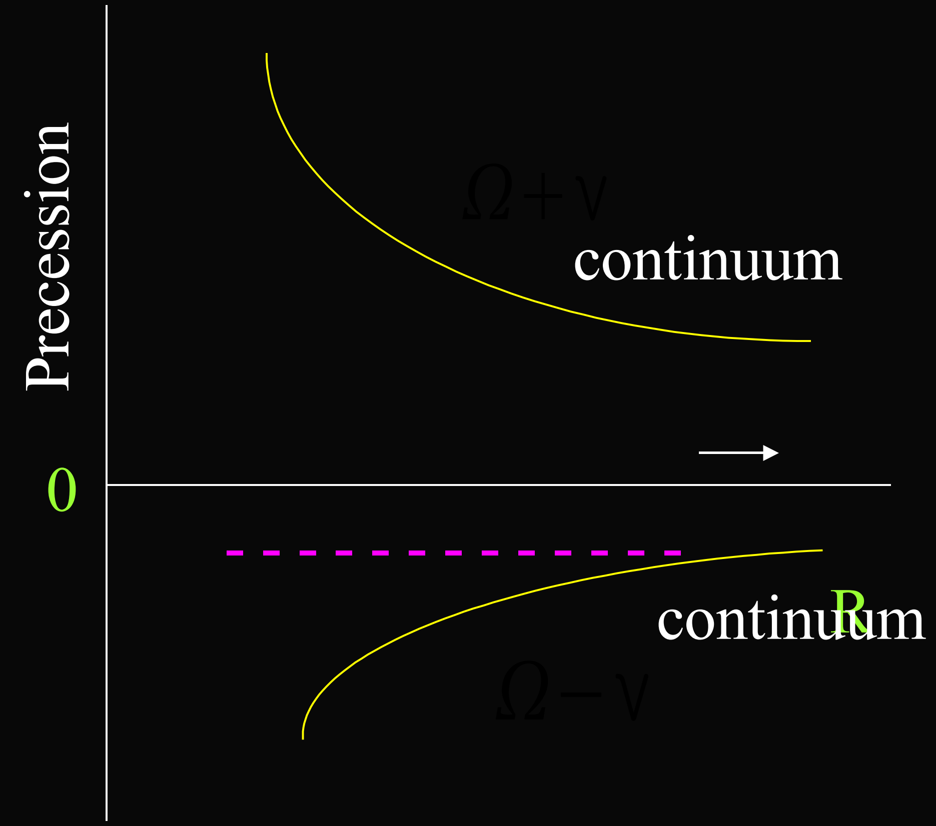
Warped surface



Physics of m=1 symmetric warp

WKB analysis with
no self-gravity of perturbation
Disk supports:

- Slow mode (m=1)
- Fast mode (m=1)



Disperses because of differential precession of the disk

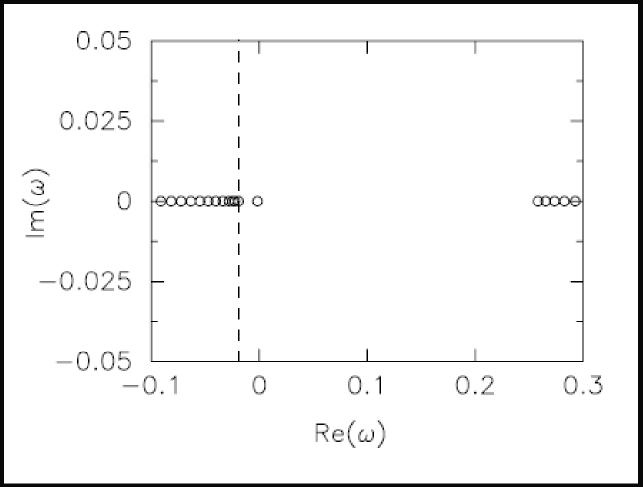
No solution in the gap!!

Global self-gravity of perturbation seems to be promising!

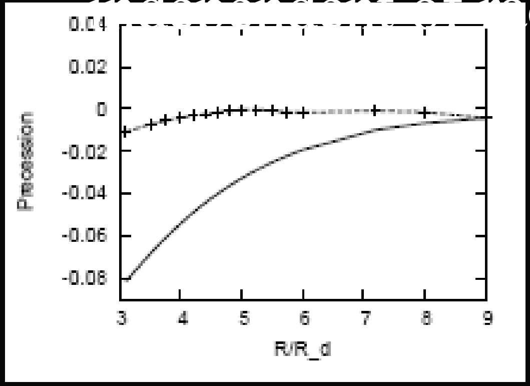
Complete global solution:

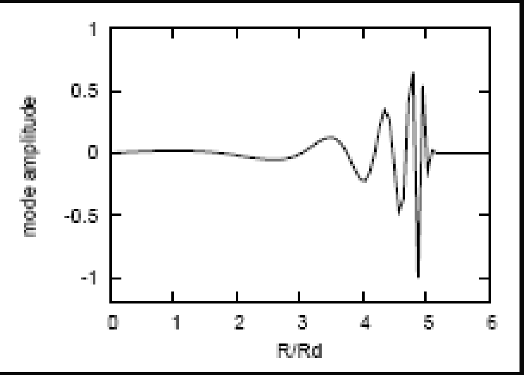
- self-gravity of perturbation helps

  synchronizing different rings
  so that the whole disk precesses
  uniformly with a single frequency
  independent of radii!!

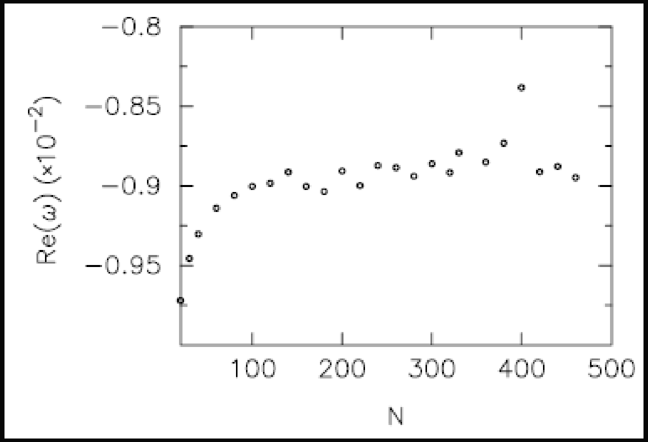


Eigen spectrum
Saha 2007 (submitted)





Continuum mode



Saha 2007 (submitted)

Symmetric Warps?

Some facts:

1. Symmetric warps are less in number
2. Its hard to understand a galactic disk represented by a pure single mode!

All kinds of modes are generated in the disk and they are likely to interact with each other --- whenever the disk is subjected to a perturbation

So understanding symmetric warp poses a greater difficulty!

Asymmetric Warps

- Warps in most disk galaxies are seen to be asymmetric.
- Asymmetry in warps may be the norm rather than exception !

Q. Are there any generic mechanism
to generate these asymmetries in warps ?

- Disks of Spiral galaxies are capable of
supporting various kinds of 'Bending modes'

- Warps and Bowl-shaped structures are such bending
modes in the disks of spiral galaxies

Bowl-shaped mode?

Bowl-shaped mode (m=0)

- Bowl-shaped mode ➡ Axisymmetric oscillations of the galactic disk

- Disk embedded in a dark matter halo :
  Oscillating from 'cupped upwards' to flat to 'cupped downwards' and back again with frequency ω_0

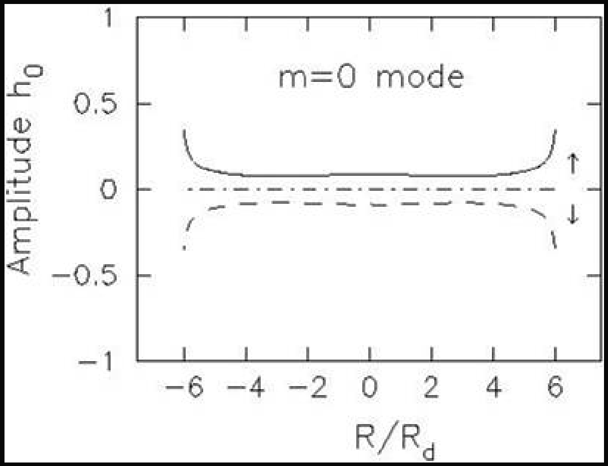
$$z_0(r,\phi,t) = h_o(r)\cos(\omega_o t)$$

Parameters for the bowl-shaped mode

$q=0.7$; $R_c=2.0\ R_d$

$$\rho_0 = 0.0117\, M_d / R_d^3$$

$$\omega_0 = 0.1315\sqrt{GM_d / R_d}$$



Saha & Jog, A&A, 2006

❖ Generating Asymmetric Warps

- **Principle:**

Linear and Time Dependent Superposition of

Bowl-shaped mode (m=0)
&
Integral-sign warping mode (m=1)

- According to the above principle asymmetric warps can be represented by:

$$Z_{asym}(r,\phi,t)=A_0 z_0(r,\phi,t)+A_1 z_1(r,\phi,t)$$

➢ **In the current picture the presence of Bowl-shaped mode (m=0) is the primary reason for various dynamical asymmetric warps in the disk.**

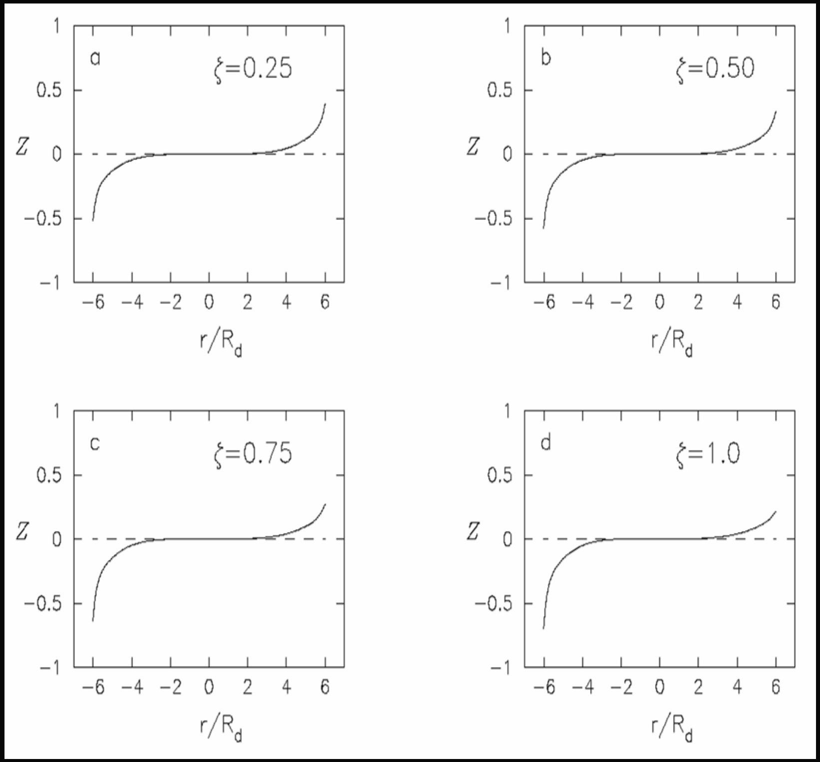
❖ Various Asymmetric Warps

➢ ***Asymmetric warp manifests itself as a classic example of dynamical wave interference in a self-gravitating media***

➢ **S-shaped asymmetric warps:**

ς ➡ Ratio of $A_0 \wedge A_1$

Fig-d shows the most asymmetry in warp

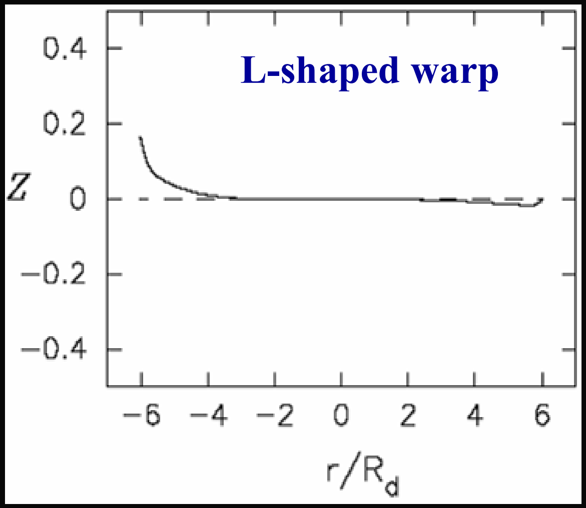


Saha & Jog, A&A, 2006

❖ Extreme Asymmetric Warps

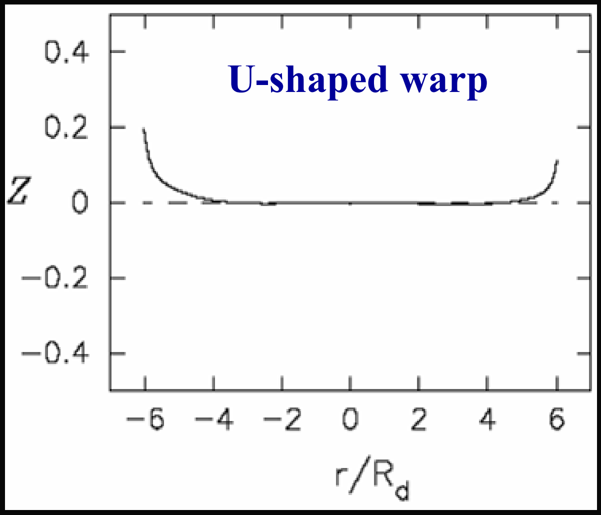
- Observations show that extreme asymmetries are less in nature

➡ May be they are very hard to make!



For the L-shaped asymmetric warp

A_0=0.55 & A_1=0.20



For the U-shaped asymmetric warp

A_0=1.0 & A_1=0.10

⬇

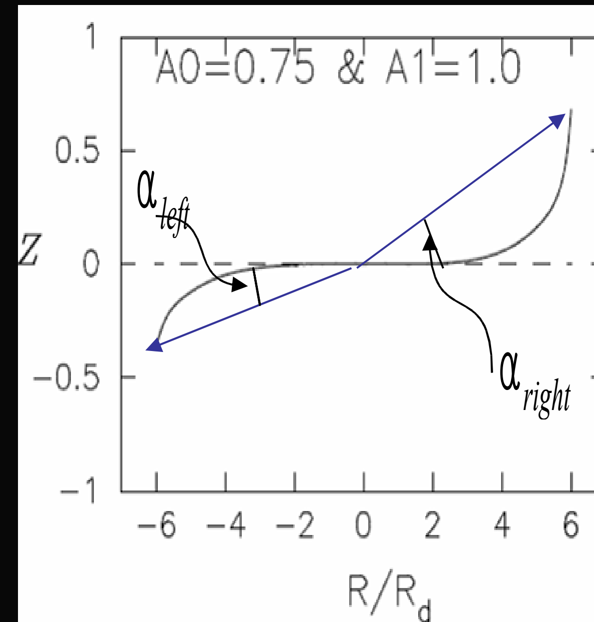
These numbers are contrived!

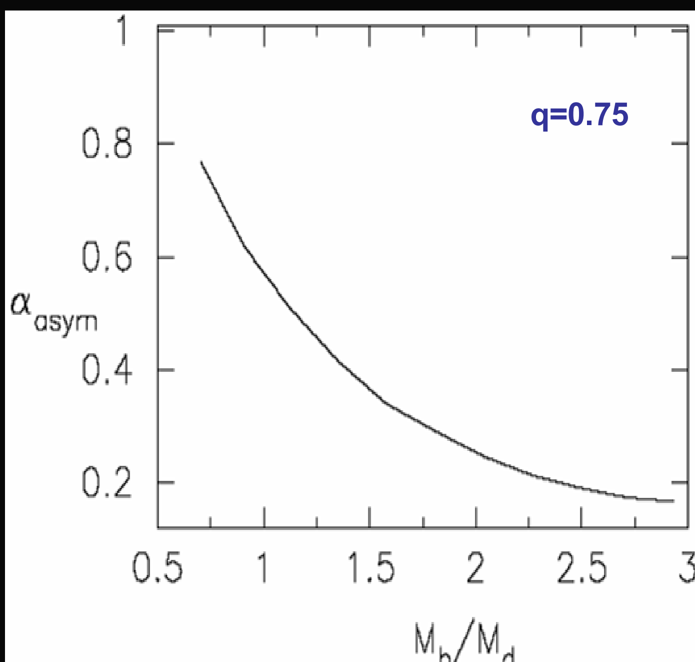
❖ Asymmetry & Dark matter halo

- Asymmetry-index :

$$\alpha_{asym} = \frac{|\alpha_{right} - \alpha_{left}|}{\alpha_{right} + \alpha_{left}}$$

Provided : $\alpha^2_{right} + \alpha^2_{left} \neq 0$





- So more the dark matter within the disk less is α_{asym}
- Disks with less dark matter are likely to show more asymmetry in warp

Saha & Jog, IAU235,2006

Where does warp begin?

- Warps are seen in the outer regions of galaxies typically ~ 4 – 6 disk scale lengths.

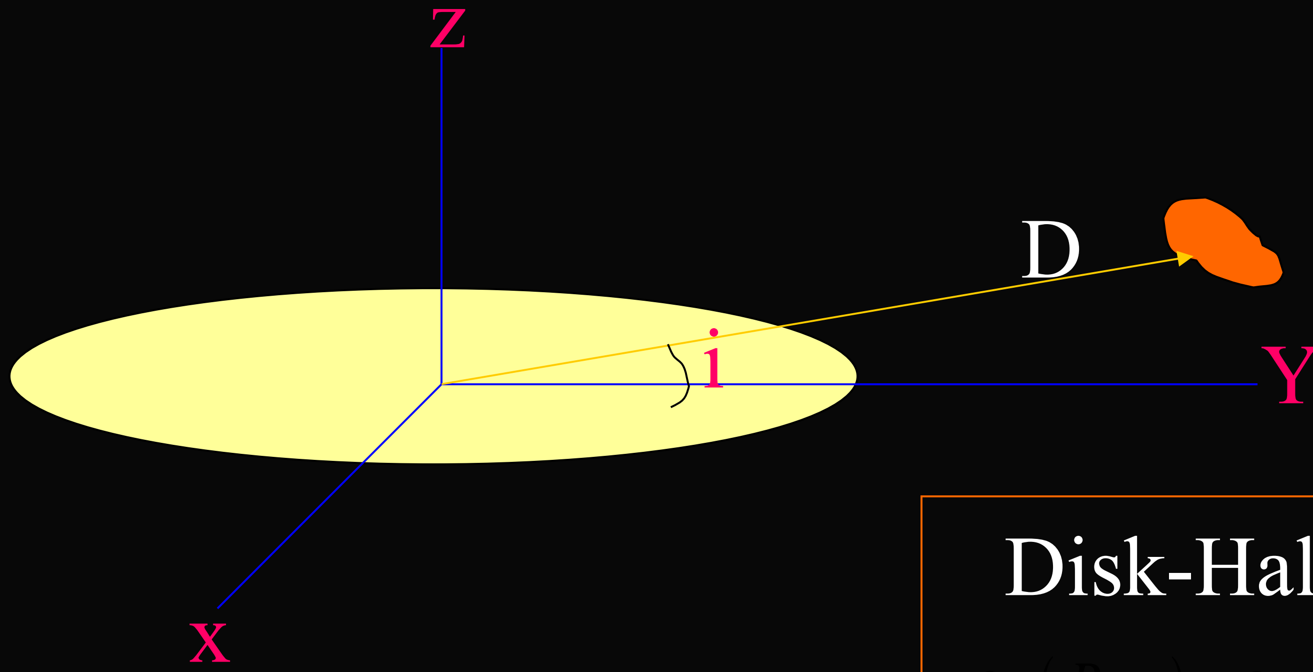
Remember Briggs rule

You can ask a question: why?

Or

What decides the actual radius for the onset of warps in the disk ?

Model for Tidal Interactions



Disk-Halo model

$$\rho_d(R,z)=\rho_{d0}\,e^{-R/R_d}\,e^{-|z|/z_0}$$

$$\rho_h(R,z)=\frac{\rho_{h0}}{1+(R^2+z^2/q^2)/R_c^2}$$

Perturbing Potential ¿ $\cos(m\phi)$

m=1 generates a well-defined integral-sign warp

Basic Physics to Calculate disk Response:

- Vertical equation of motion:

$$\frac{d^2 z_m}{dt^2} = -\nu_0^2 z_m + \frac{\partial \psi_1}{\partial z}\Big|_{(R_0, \phi_0, 0)}$$

- Linearized continuity equation:

$$\frac{\partial \rho_1}{\partial t} + \vec{\nabla}.(\rho_0 \vec{v}_1) + \vec{\nabla}.(\rho_1 \vec{v}_0) = 0$$

- Poisson equation:

$$\nabla^2 \psi_{resp}(R, \phi, z) = 4\pi G \rho_1 (R, \phi, z)$$

❖ We solve these eqs self-consistently and calculate the response potential by inverting the Poisson eq. using Green's function technique

Solution of the problem:

- The linear response potential corresponding to the m[th] order perturbations is given by the following relation:

$$\psi_{resp}(R,\phi,z=0)=\Re_m(R)\,\psi_1(R,\phi,z=0)$$

Dimensionless response of the disk galaxy

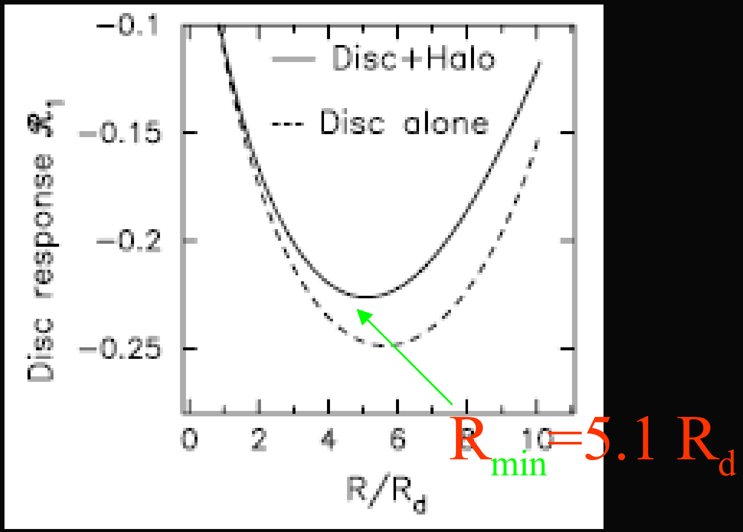
- **Nature of disk response:**

The galactic disk responds negatively to the external perturbation for two commonly used system:

i) Disk-alone system
ii) Disk + Oblate halo system

Onset of warps:

- We consider an oblate dark matter halo with parameters similar to that of our Galaxy.



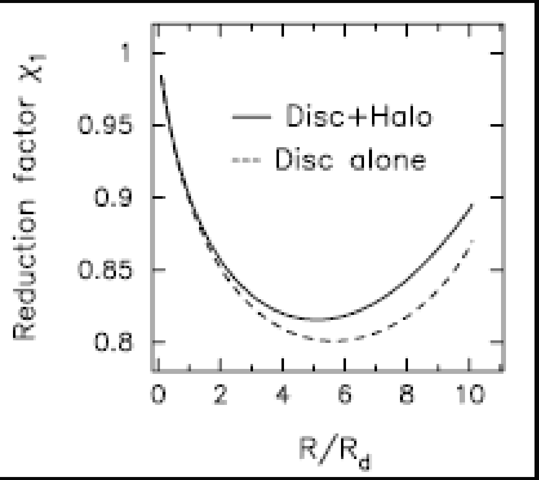
(Saha & Jog, MNRAS, 2006)

R_{min} depends primarily on the stiffness of the disk: measured by the thickness parameter.

Disk Reduction Factor :

$$\chi_m = \frac{1}{1 + |R_m|}$$

How the magnitude of the perturbing potential is reduced due to negative disk response

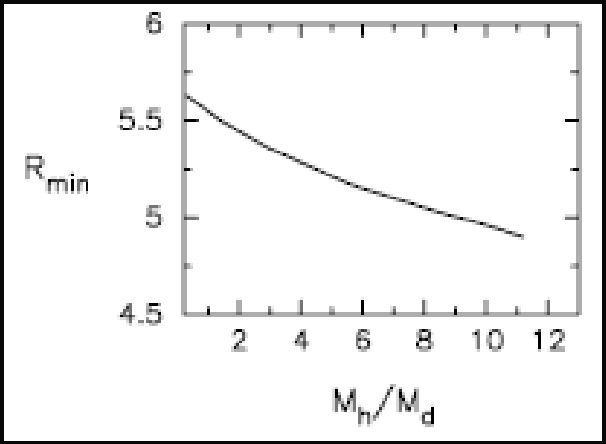


(Saha & Jog, MNRAS, 2006)

A relation between R_{min} and *Dark matter* content

- Ratio of dark matter to disk mass -- within 10 R_d
- *Dark matter halo* considered to be slightly *Oblate*

R_{min} ➡ Always within 4 – 6 R_d



(Saha & Jog, MNRAS, 2006)

Onset of warps in Spitzer/IRAC observations

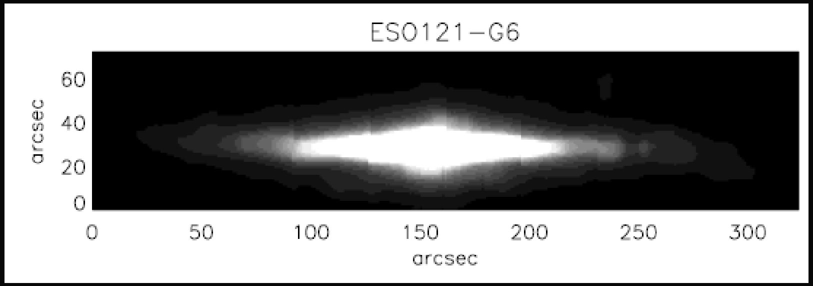
Galaxy	R_d	R_w^l	R_w^r	R_w^{obs}	ε_{on}
ESO 121 –G006	18.11	96.75	84.00	90.37	0.071
NGC 4565	84.22	405.75	378.75	392.25	0.034
NGC 4013	28.20	123.00	129.00	126.00	0.024
NGC 4157	29.40	145.50	135.75	140.60	0.035
NGC 4302	35.40	121.50	115.50	118.00	0.025
NGC 5907	56.90	233.25	228.00	230.90	0.012
NGC 7090	32.55	91.50	82.50	87.00	0.052
NGC 7814	23.06	135.00	121.50	128.25	0.053
NGC 4217	31.90	111.75	98.25	105.00	0.064
NGC 4244	89.35	242.25	264.75	253.50	0.044

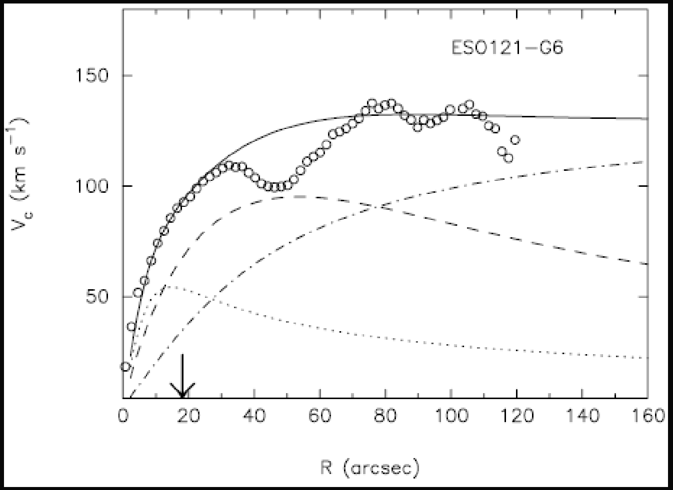
In collaboration with

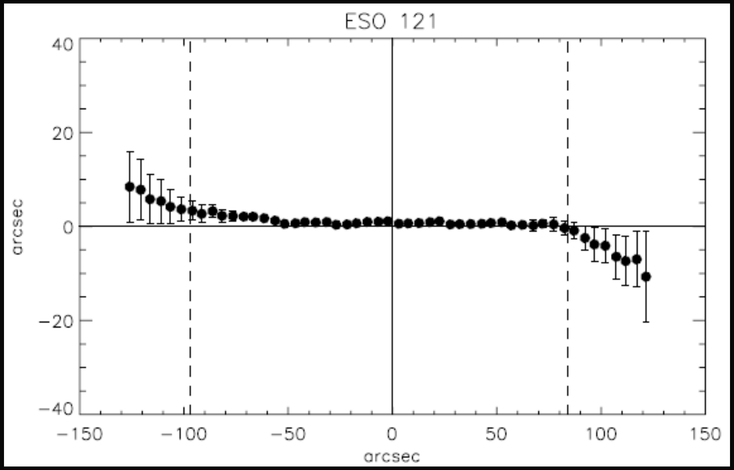
Roelof de Jong (STScI, USA)

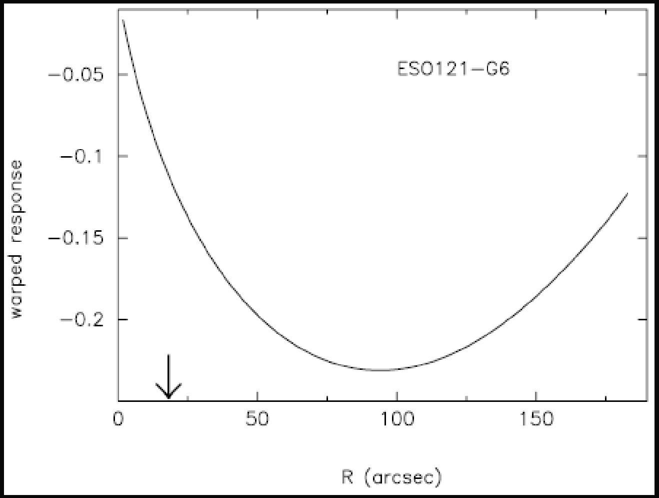
Benne Holwerda (STScI, USA)

ESO 121 – G006

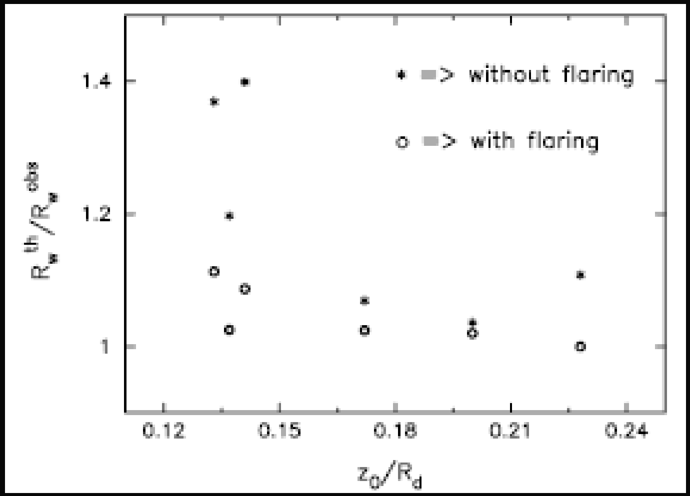

ESO121–G6
arcsec
arcsec

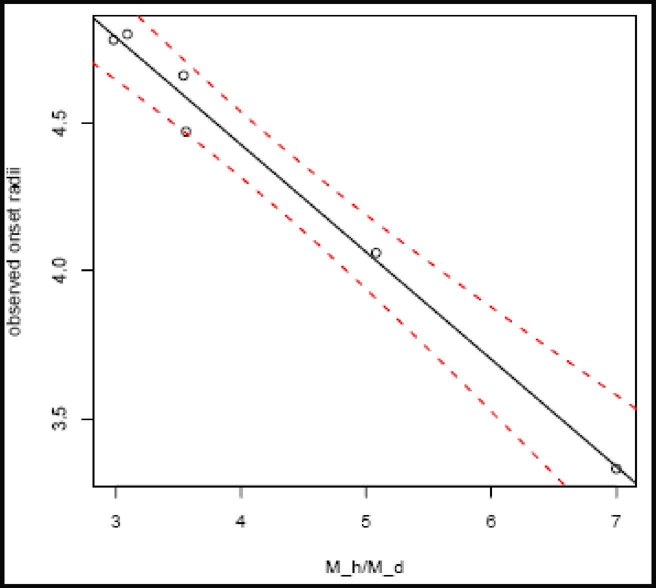

ESO121–G6
V_c (km s^{-1})
R (arcsec)

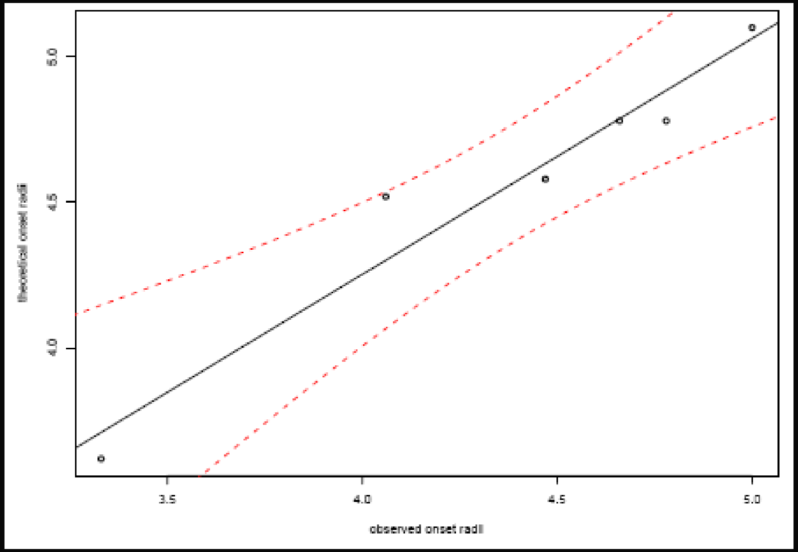

ESO 121
arcsec
arcsec

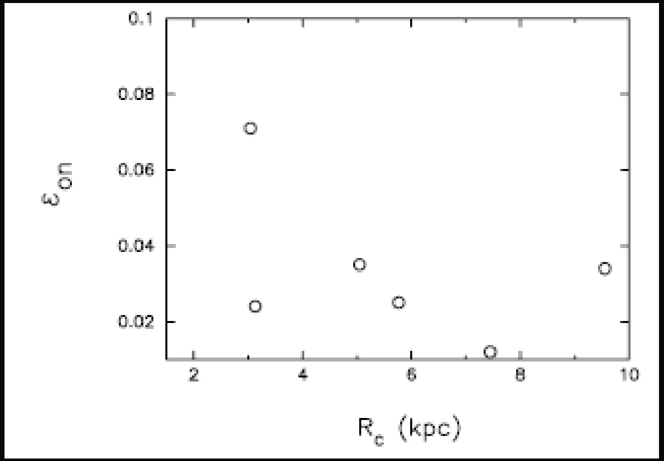

ESO121–G6
warped response
R (arcsec)

Analysis based on 6 galaxies from the Spitzer/IRAC obs :









Saha, de Jong & Holwerda 2007 (manuscript in prep.)

Summary:

- Understanding symmetric warp poses potential difficulty
- Maintenance of warp in low density region is really hard
- Most of the warps are asymmetric
- A generic mechanism to generate asymmetric warps is proposed.
- Disk with smaller sized dark matter halos are likely to show more asymmetry in warps.
- Inner parts of the galactic disks are robust to external perturbations
- Negative disk response is a general phenomenon in self-gravitating system
- Galactic warps begin around 4 – 6 disk scale lengths --- explaining the well-known Briggs rule for warps.
- Theoretically predicted warp onset radii matches quite well with Spitzer observations
- Onset-asymmetry seen in Spitzer/IRAC observations --- an indication of asymmetric dark matter potential!

References:

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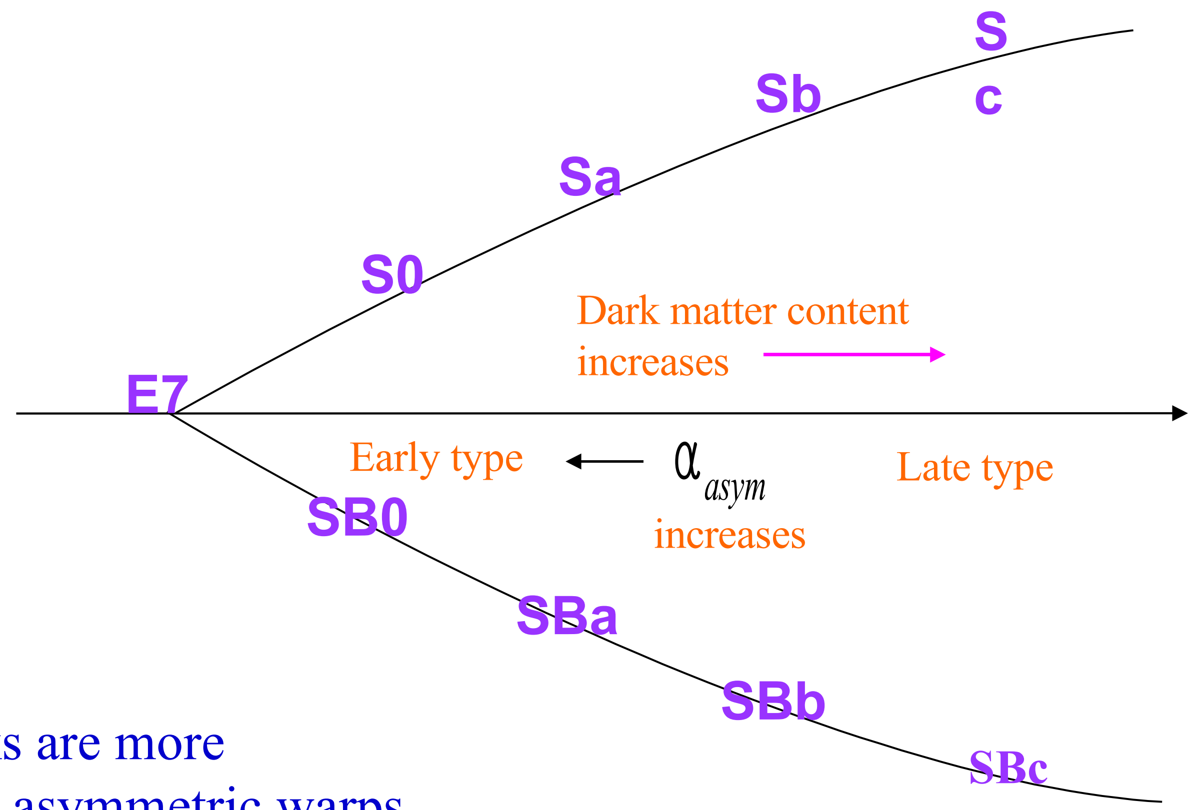
Asymmetry-index & Hubble Sequence

Hubble Tuning Fork diagram



Early type disks are more
Likely to show asymmetric warps