From Bar Formation to Dark Matter Detection: Implications of Halo Spin Distribution

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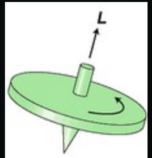
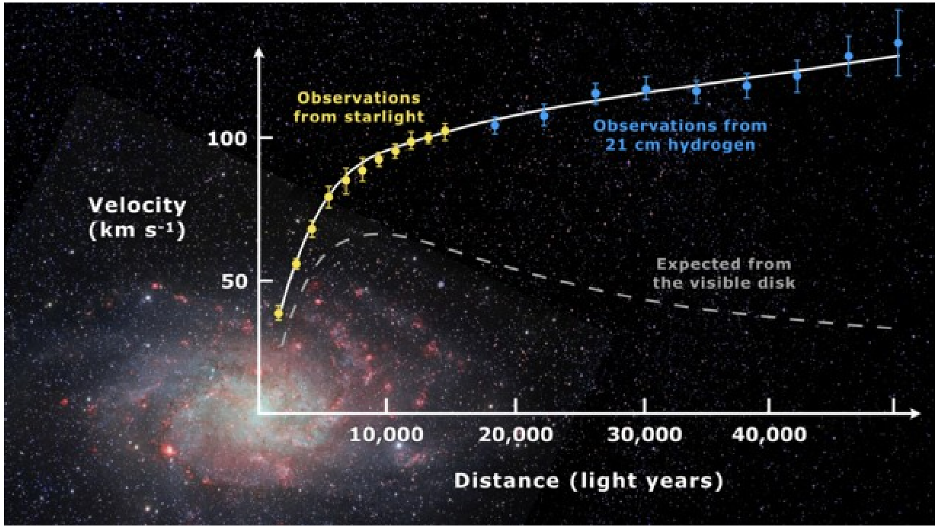


Introduction

Early Evidences of Dark Matter:

- 1933 ~ Fritz Zwicky
  (Coma Cluster)
- 1970s ~ Vera Rubin
  (Galaxy Rotation Curves)



Credits: E. Corbeli & Salucci 2000

Subsequent Evidences:

- Gravitational lensing, CMB, LSS

Ongoing Astroparticles Experiments

- Direct & Indirect (Discussed in plenary sessions)

Motivation

- Direct DM Detection Experiments (WIMP):

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int dv\, f(v) v \frac{d\sigma}{dE_R}(v, E_R)$$

- Detections are limited by **background noise & low energy recoiling events**.
- Therefore the knowledge of dark matter velocity distribution in the MW is very crucial (m=2 non-axisymmetric modes can provide crucial information).

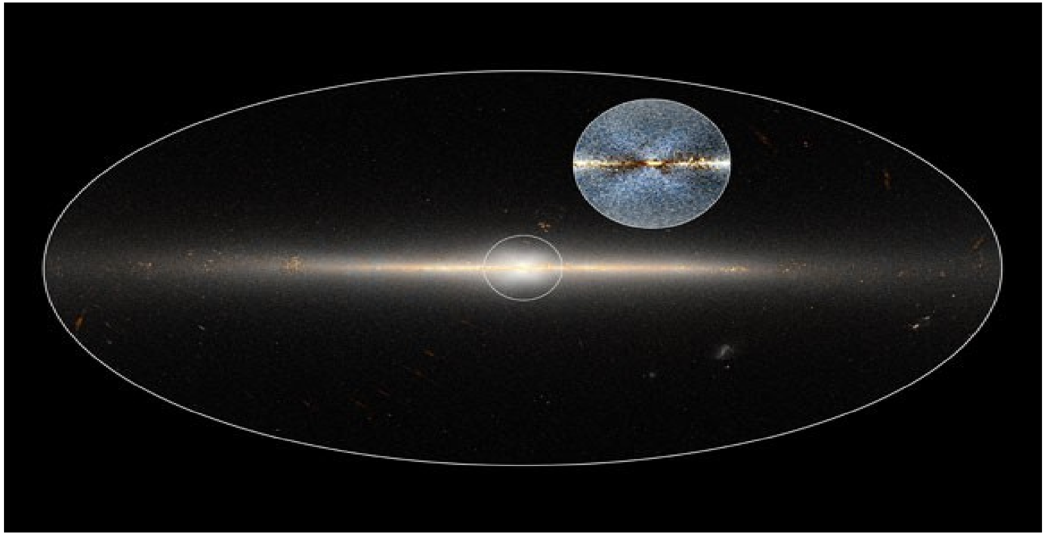
Milky Way

Weiland 1994

COBE image of Milky Way

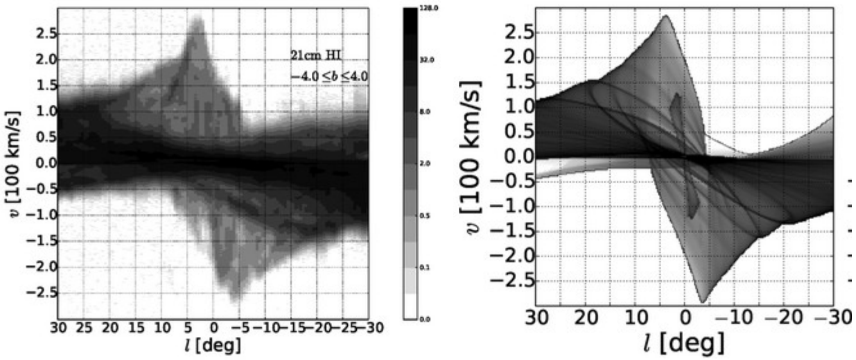
Ness & Lang 2016

Wise image of Milky Way

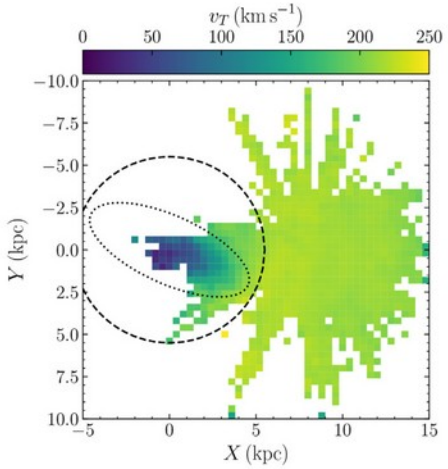


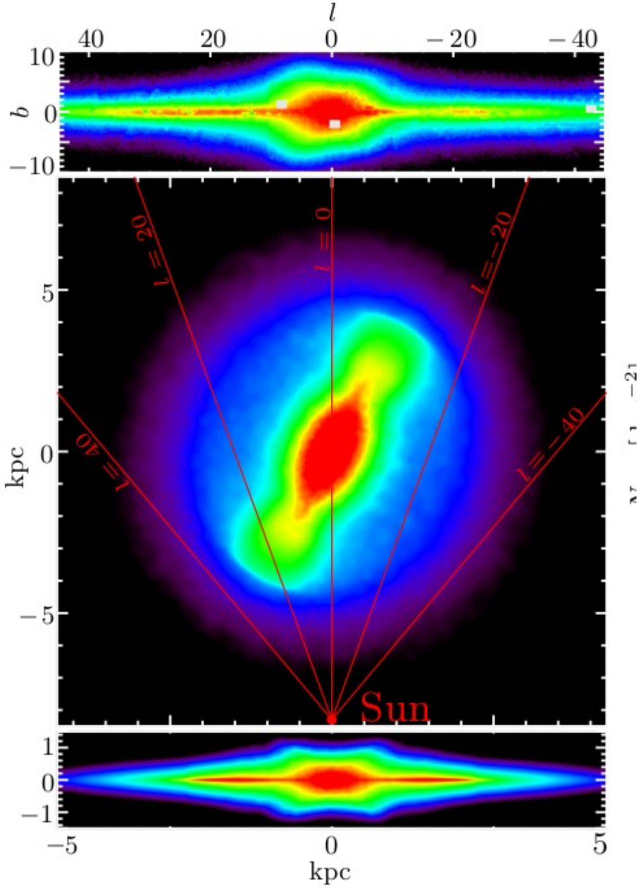
Barred Galaxies: Milky Way

Sormani et al. 2015



Bovy et al 2019





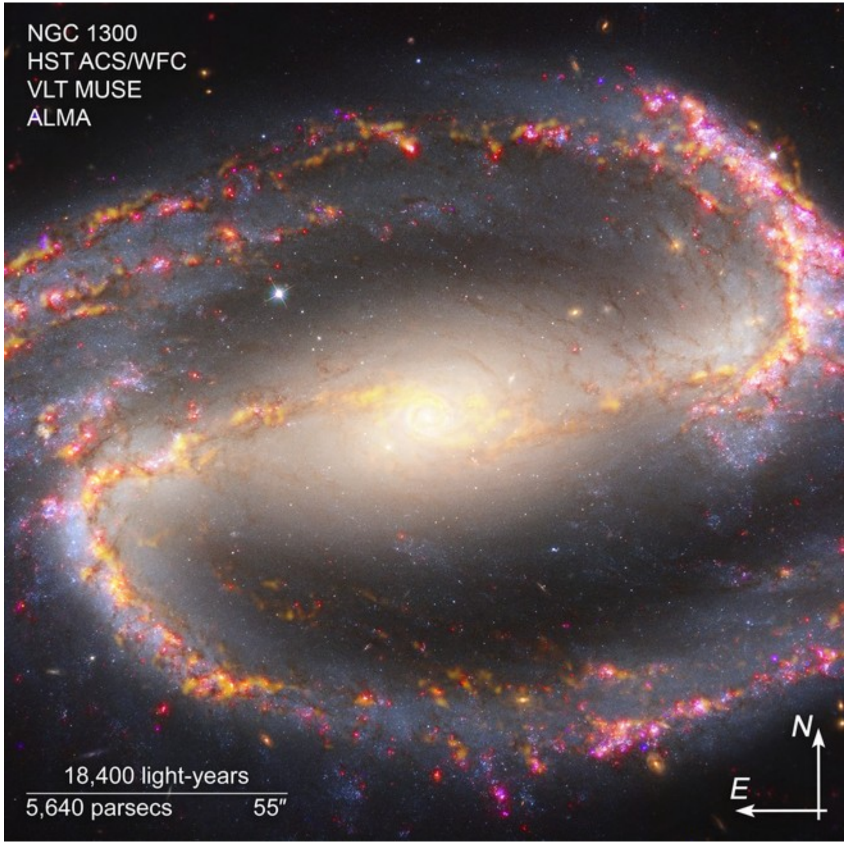
Wegg et al 2015

Barred Galaxies: A Brief Overview

Bars are **eccentric orbits of stars** (x1 orbits) in the central region of disk galaxies.

Nearly **2/3 of disk galaxies** in local universe contains bar (Weak + Strong Bars). (Eskridge+2000, Erwin+2018)

Bar fraction has been shown to **constant up to z~1** (Jogee+2004) **or z~2** (Simmons+2014); debated.



Halo Spin Distribution

Juntai Shen

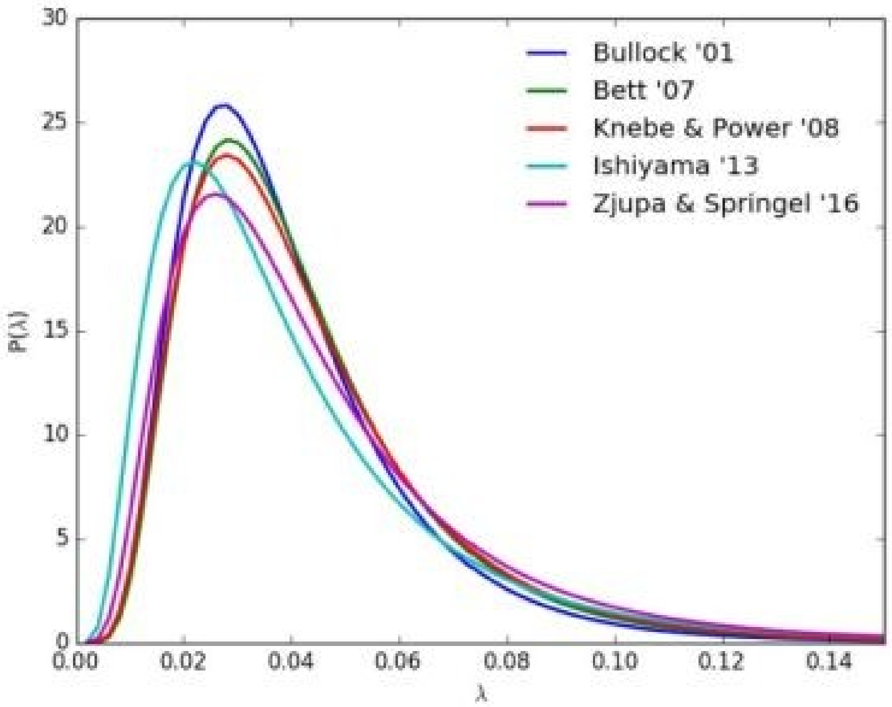
Halo spin in cosmological simulations

- Peebles 1969:

$$\lambda = \frac{JE^{1/2}}{GM^{5/2}}$$

- Bullock et al. 2001

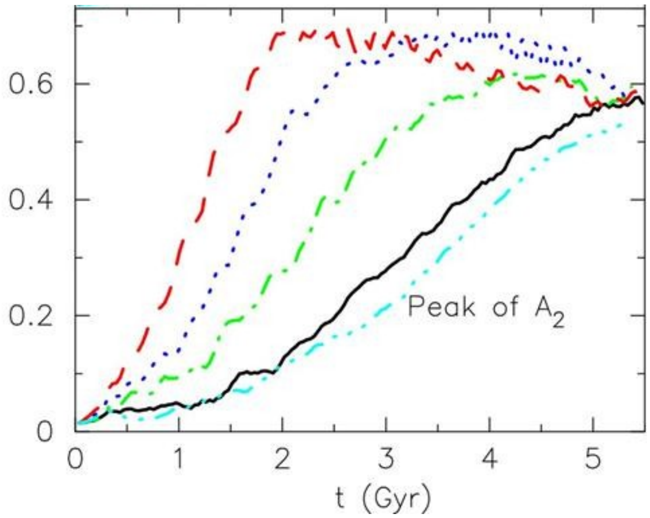
$$\lambda = \frac{J}{\sqrt{2}MVR}$$



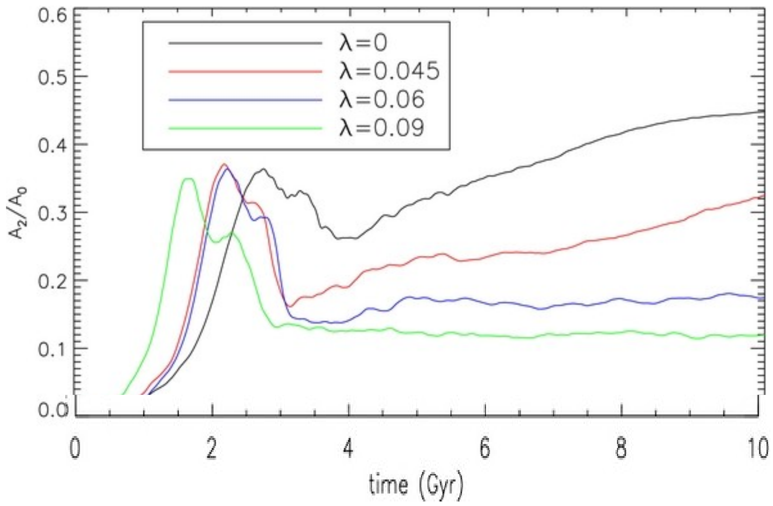
Role of the Inner Halo Angular Momentum ?

Bar grows in disk by **transferring angular momentum from inner disk** to outer disk as well as surrounding dark matter halo (Athanassoula+2003, Kataria & Das 2018, 2019).

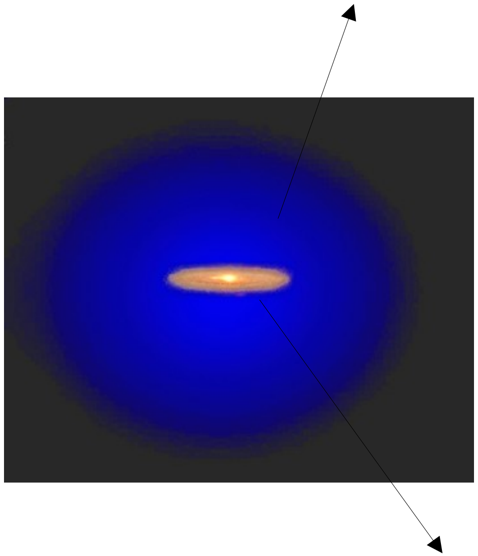
Saha & Naab 2013



Long, Shlosman & Hellen 2014



Role of the Inner Halo Angular Momentum ?



For a given spin of halo (or total angular momentum); various radial angular momentum distributions are possible (**not explored in previous studies**).

Big Questions:

1) How does inner halo AM distribution affects bar formation and evolution ?

2) How does the dynamical friction varies with dark matter AM ?

Initializing N-body Experiments

GalIC (Yurin & Springel 2014) to generate Initial Condition of MW-type disk galaxies. ($N_{disk} = N_{halo} = 10^6$)

- Halo:

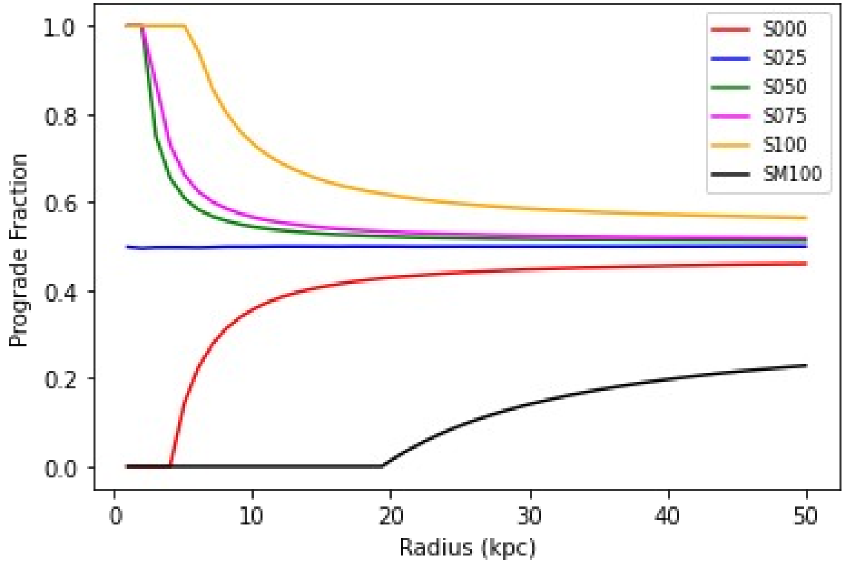
$$\rho_h = \frac{M_{dm}}{2\pi} \frac{a}{r(r+a)^3}$$

- Disc:

$$\rho_d = \frac{M_d}{4\pi z_0 h^2} exp\left(-\frac{R}{R_d}\right) sech^2\left(\frac{z}{z_0}\right)$$

Jean's idea (1919): Both counter-rotating and co-rotating particles are solutions to *Collisionless Boltzman Equation* (**CBE**).

Five increasing spin **co-rotating** model and one **counter-rotating** halo wrt disk.

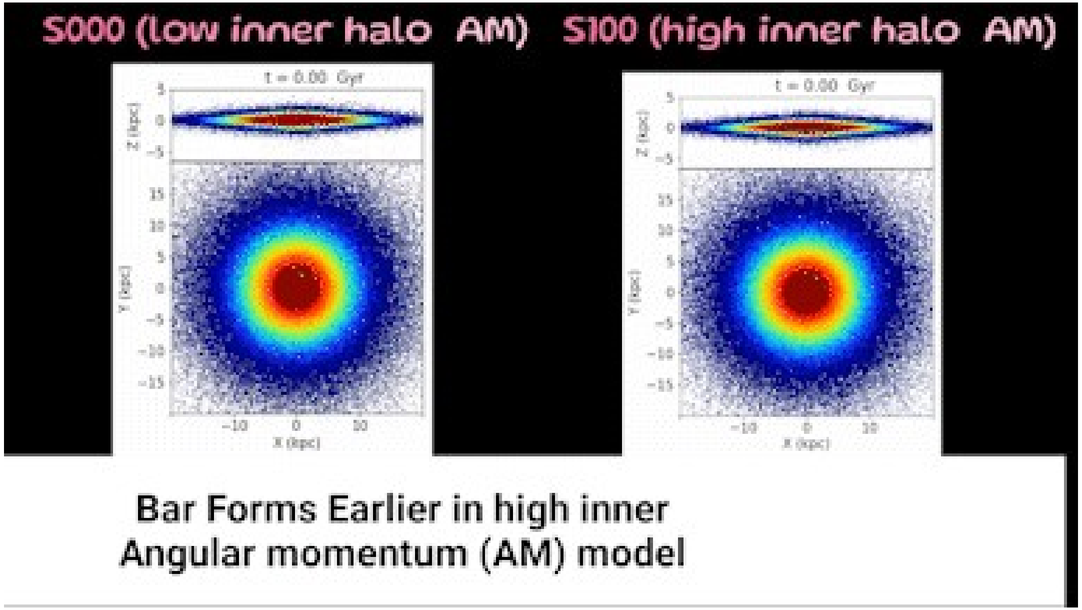


Simulating the Galaxy Models

We evolve our models up to 9.78 Gyr using **GADGET-2 code** (V. Springel, 2005).

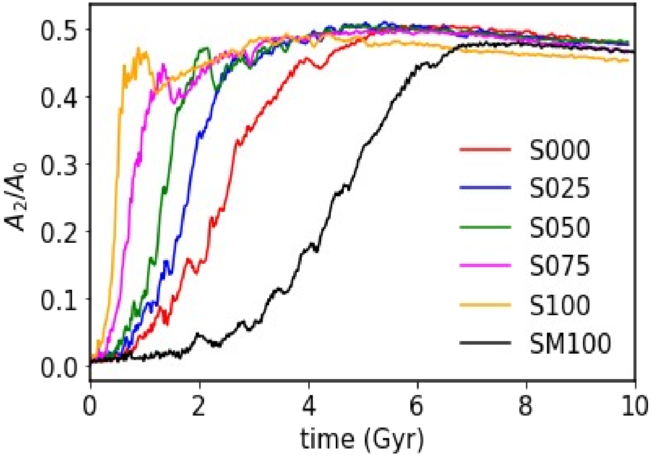
~40 K CPU hours per simulation.

Angular momentum and energy in our simulation is **conserved within 0.1%**.

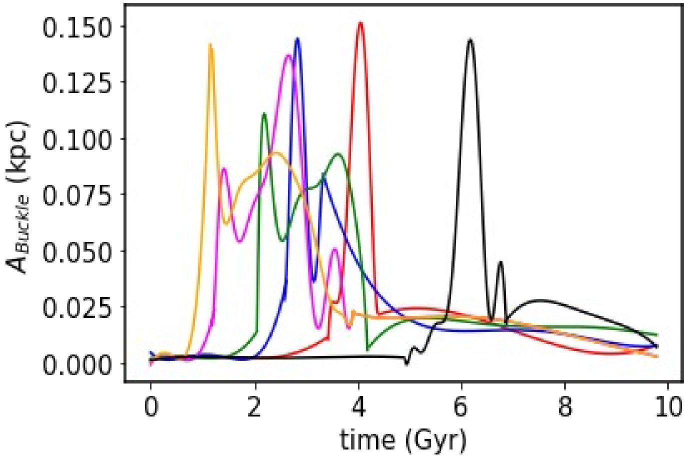


Results: Bar, Buckling, Box/Peanut/X-shaped bulges (BPX) Strength

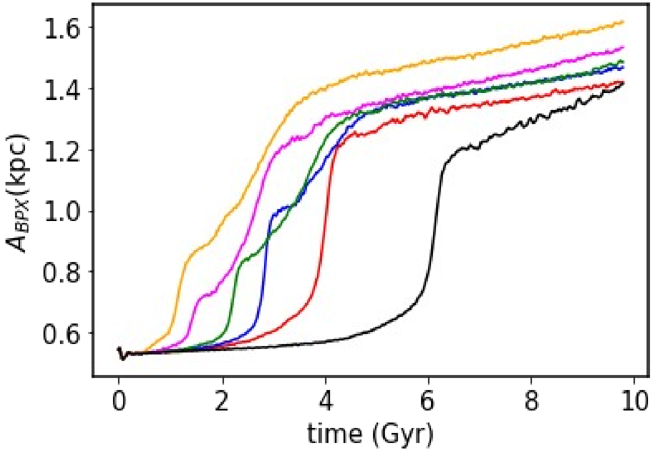
$$\frac{A_2}{A_0} = \frac{\sqrt{a_2^2 + b_2^2}}{\sum_{i=1}^{N} m_i}$$



$$A_{Buckle} = \left| \frac{\sum_{k=1}^{N} z_k m_k e^{2i\phi_k}}{\sum_{k=1}^{N} m_k} \right|$$



$$A_{BPX} = \sqrt{\frac{\sum_{k=1}^{N} m_k z_k^2}{\sum_{k=1}^{N} m_k}}$$

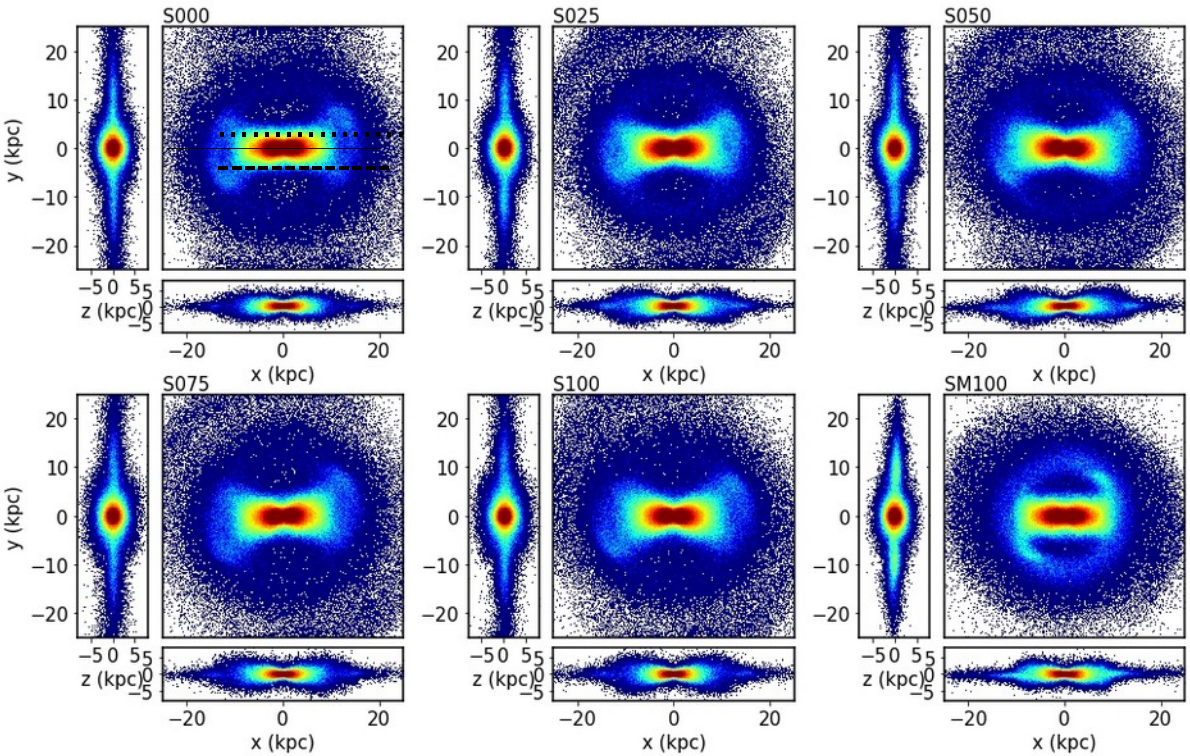


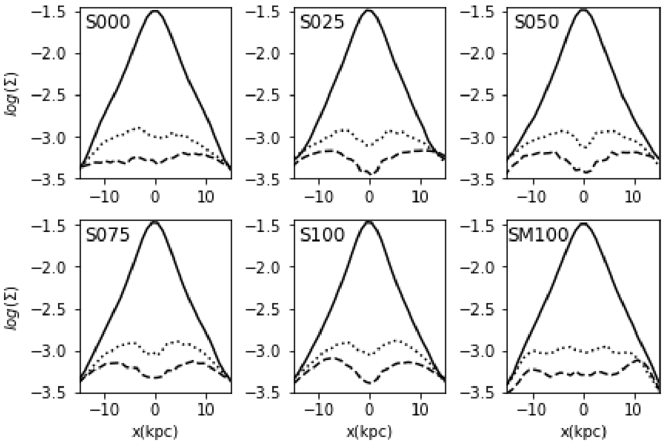
Bar triggers **earlier for high inner halo AM cases**, and its strength saturates in secular evolution for all models.

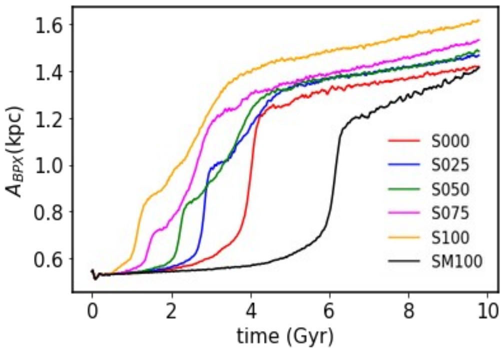
Bar buckles early for high inner halo AM models. For S075, **second buckling timescale goes to 1 Gyr much larger than first buckling event (~150-200 Myr)**.

BPX shape is prominent for **high inner halo models**.

Results: Face/Edge-on Shape of Bars







Face on shape changes from **rectangular to farfalle** as inner halo AM increases.

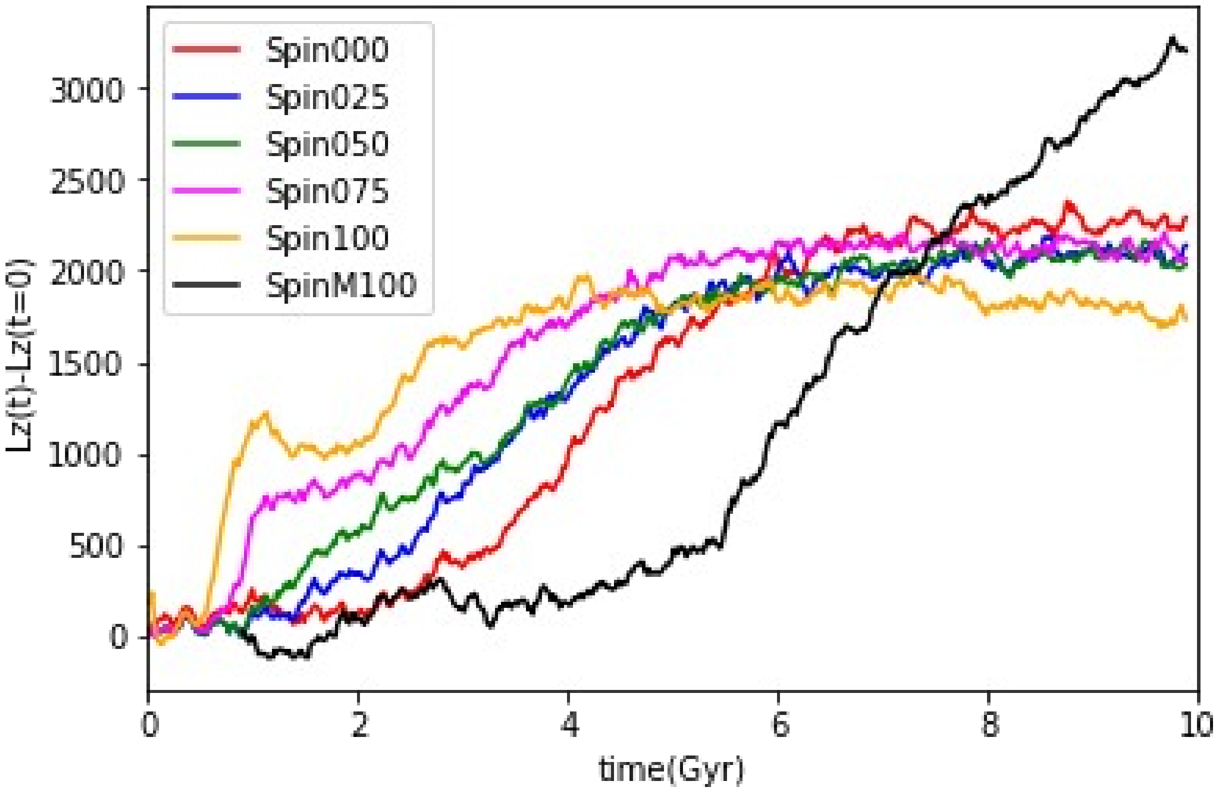
BPX Shape is more pronounced for higher spinning halos.

Kataria & Shen 2022; ApJ

Results: Angular Momentum Exchange

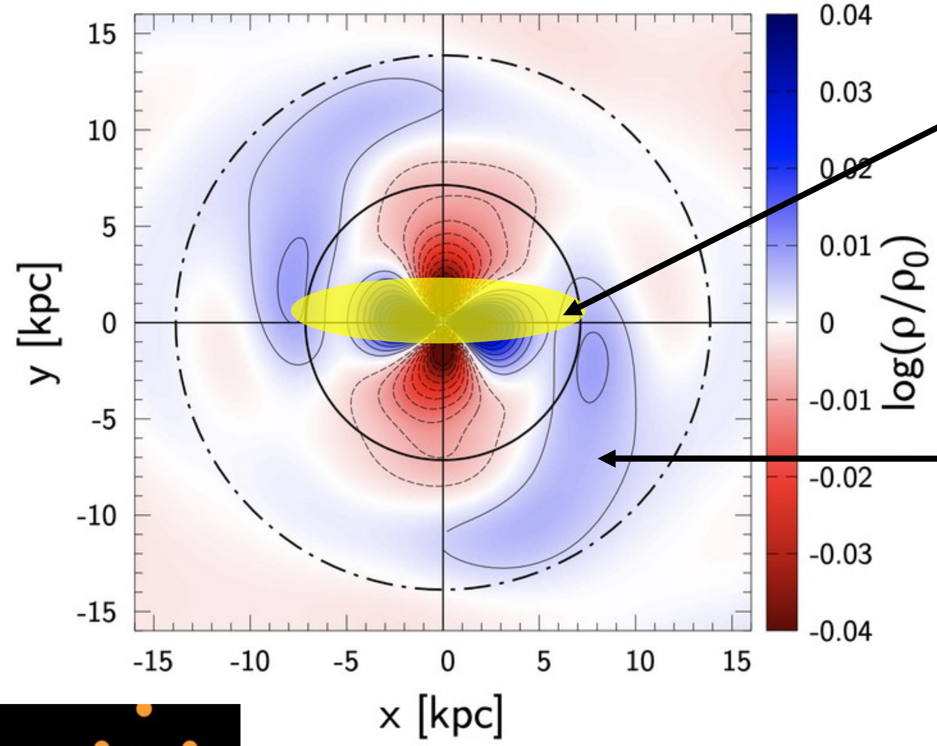
In the bar formation regime, angular mometum exchange to halo **enhances with increasing halo spin**.

In **secular evolution,** angular momentum exchange trend reverses.



2. Dynamical Friction on Galactic Bars

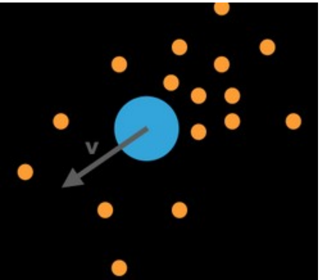
Rimpei Chiba



Galactic bar torques dark matter

Dark Matter Form Density Wakes

Dark matter wakes pulls bar
“**Dynamical Friction**”



$$M\frac{dv}{dt} = -\frac{4\pi G^2 M^2}{v^2}\ln\Lambda\,\rho(<v),$$

Similar theme to Chandrashekhar (1943) [Homogeneous system]

Dynamical Friction on Galactic Bars: Linear Theory

From the Lyndon Bell 1960

$$f(\boldsymbol{J}) = f_+(\boldsymbol{J}) + f_-(\boldsymbol{J}),$$

Density distribution

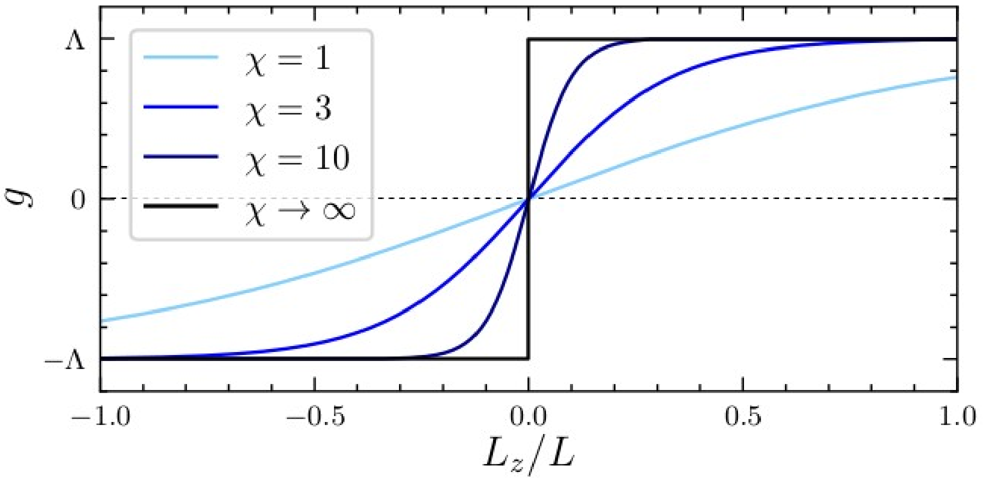
Net rotation

$$f_\pm(\boldsymbol{J}) \equiv [f(J_r, L, L_z) \pm f(J_r, L, -L_z)]/2$$

$$f_-(\boldsymbol{J}) = g(\boldsymbol{J}) f_+(\boldsymbol{J}), \longrightarrow f = (1+g) f_+ .$$

$$g(L_z) = \Lambda \, \mathrm{sgn}\,(L_z),$$

$\Lambda \in [-1, 1]$ Controls the halo rotation



$$g(L, L_z) = \Lambda \tanh\left(\frac{\chi L_z}{L}\right)$$

Dynamical Friction on Galactic Bars: Linear Theory

Lyndon-Bell and Kalnajs (LBK, 1972) torque formula

$$\tau_{\rm LBK} = (2\pi)^3 \sum_{\boldsymbol{n}} n_\varphi \int \mathrm{d}^3\boldsymbol{J}\, \boldsymbol{n}\cdot \frac{\partial f}{\partial \boldsymbol{J}} |\hat{\Phi}_{\boldsymbol{n}}(\boldsymbol{J})|^2 \pi\delta\left(\boldsymbol{n}\cdot\boldsymbol{\Omega} - n_\varphi \Omega_{\rm p}\right),$$

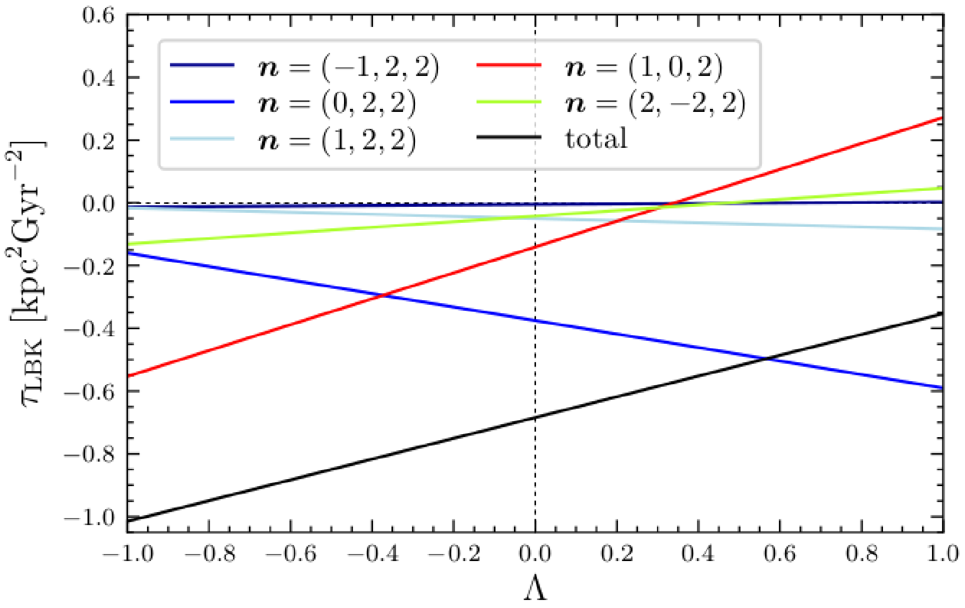
For spinning dark matter halo,

$$\tau_{\rm LBK} = (2\pi)^3 \sum_{\boldsymbol{n}} n_\varphi \int \mathrm{d}^3\boldsymbol{J}\, \boldsymbol{n}\cdot\left[(1+g)\frac{\partial f_+}{\partial \boldsymbol{J}} + f_+ \frac{\partial g}{\partial \boldsymbol{J}}\right] \times |\hat{\Phi}_{\boldsymbol{n}}(\boldsymbol{J})|^2 \pi\delta\left(\boldsymbol{n}\cdot\boldsymbol{\Omega} - n_\varphi \Omega_{\rm p}\right).$$

Gradient of introduced redistribution as a result of spinning τ_g

Gradient of original distribution function τ_{f_+}

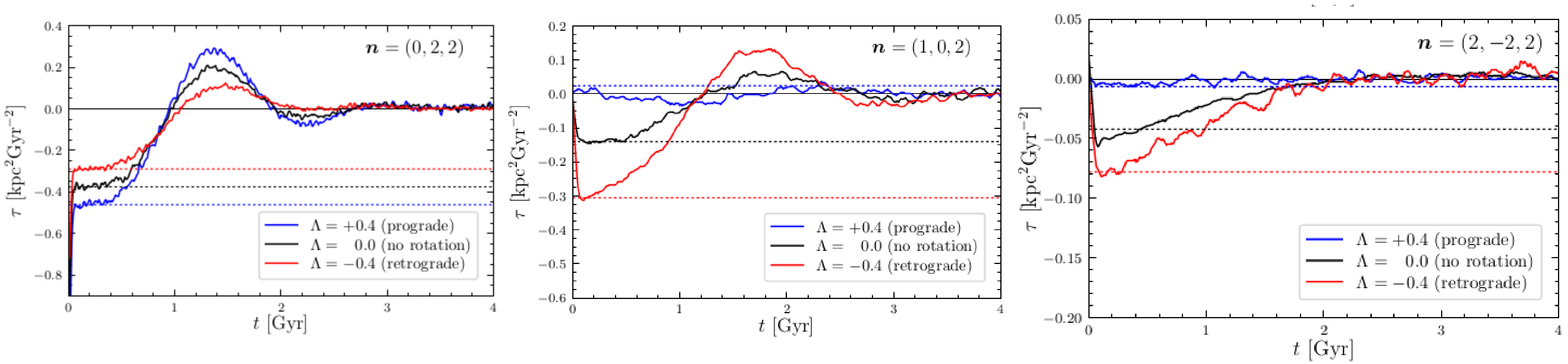
Dynamical Friction on Galactic Bars: Linear Theory



Net Rotation

The net torque experienced by the bar **decreases with increase in net roation** of dark matter halo.

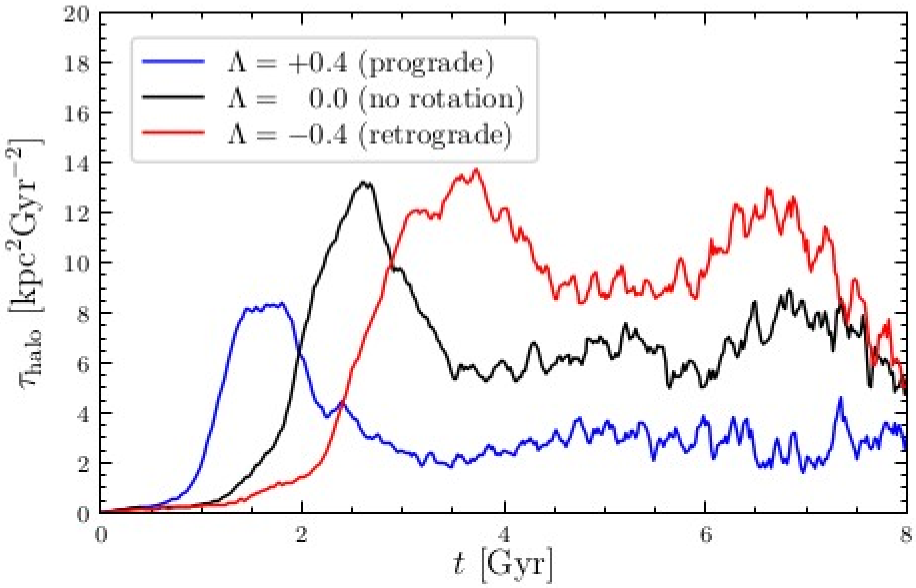
Dynamical Friction on Galactic Bars: Test Particle Simulations



Corotation (0,2,2) show opposite trend of torque compare to other two resonances as predicted by linear theory (LBK, dashed lines).

Results satuates in longer time, orbits phase mix and gradient disappear near the resonances.

Dynamical Friction on Galactic Bars: N-body Simulations



Chiba & Kataria 2024; MNRAS

N-body simulations also predicts the **reduction in torque as a result of net rotation (enhanced prograde fraction)** in agreement with **Linear Theory and Test Particle Simulations**.

Weinberg 1985 results are updated (didn't take account of gradient of the redistribution)

Take Home Message

1) How does the *inner angular momentum of halo* affects the bar formation and evoluion ?

- Face on shapes **rectangular to pronounced farfalle shape** with inner halo AM**.**
- BPX bulges are **more pronounced** in high inner halo AM models.
- Tendency to have **second buckling increases** with the increasing inner AM of halo. Time period for second buckling is much **higher (~ Gyr) compare to first buckling (~150-200 Myr)**.

2) How does dynamical friction varies with net rotation of halo ?

- Reduces with net rotation of halo (updates Weinberg 1985 prediction), confirmed with linear Theroy, test particle simulations and N-body simulations.

The properties of Milky Way bar provides a constrains on velocity distribution dark matter halo.