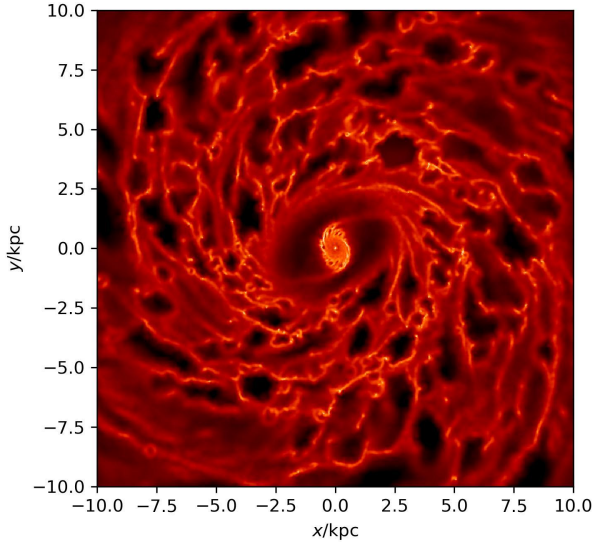
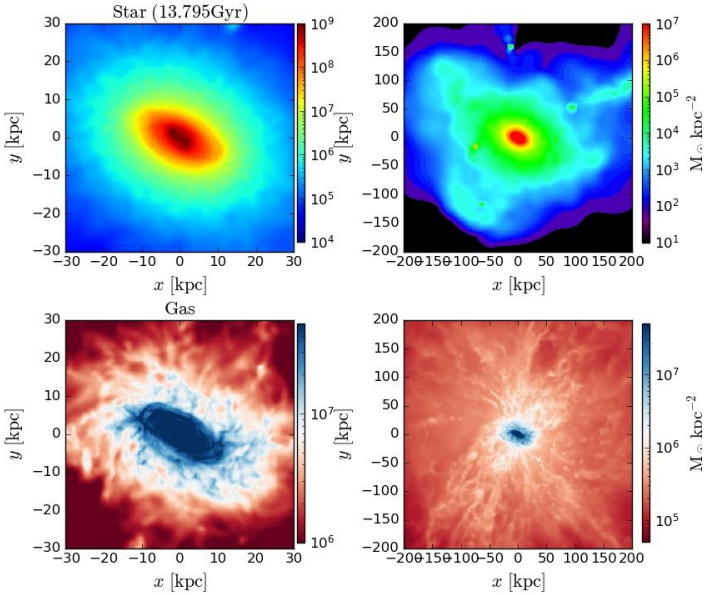
The Effects of Resolution and Disk Stability on the Multi-armed Spiral Formation

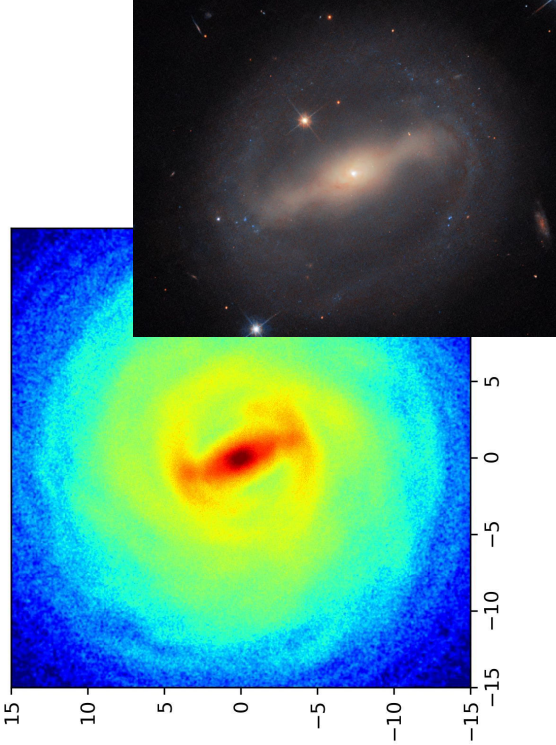
@EANAM10
SungWon Kwak

Leibniz-Institut für
Astrophysik Potsdam

What I'm working on…





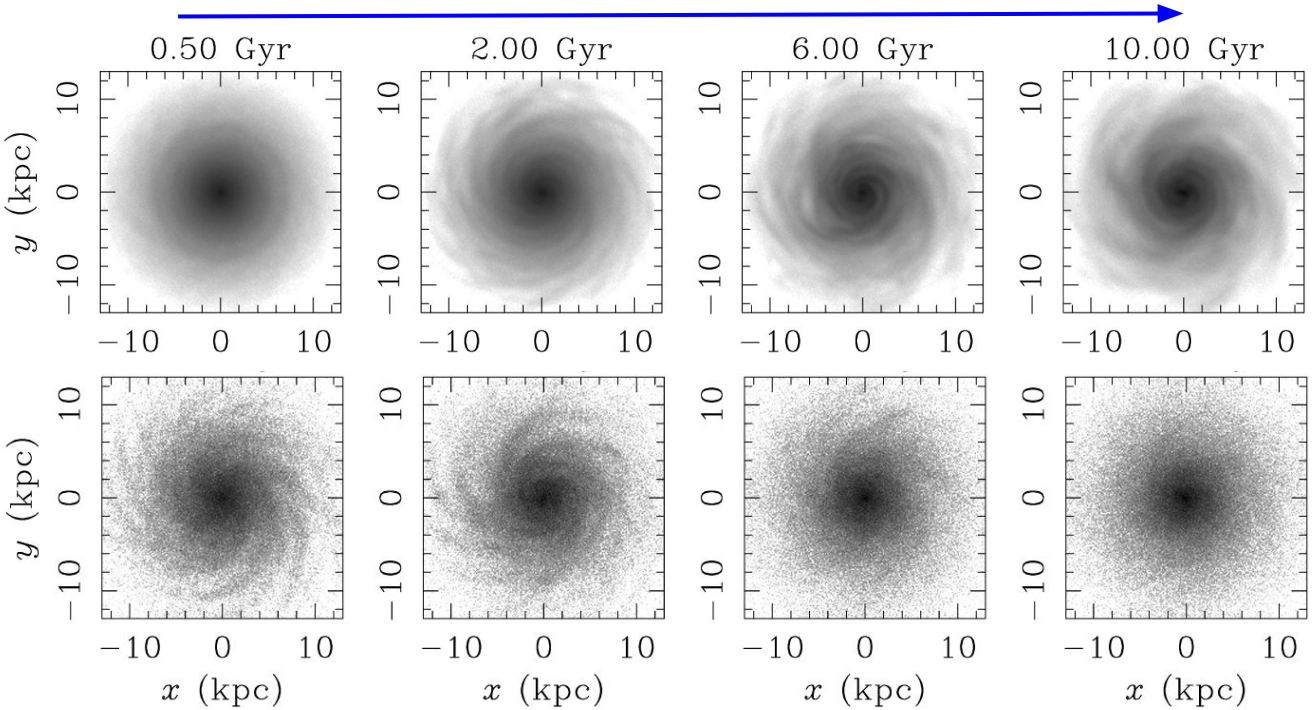


AREPO-SMUGGLE
Nuclear Ring
(+ 4MOST Survey)

AREPO-AURIGA
Old Stellar Halo

N-body
Bar and Spirals

Fujii et al. 2011



Increasing resolution lowers numerical heatings, which make spiral arms form later and last longer without additional cooling.

(Fixed potential models)

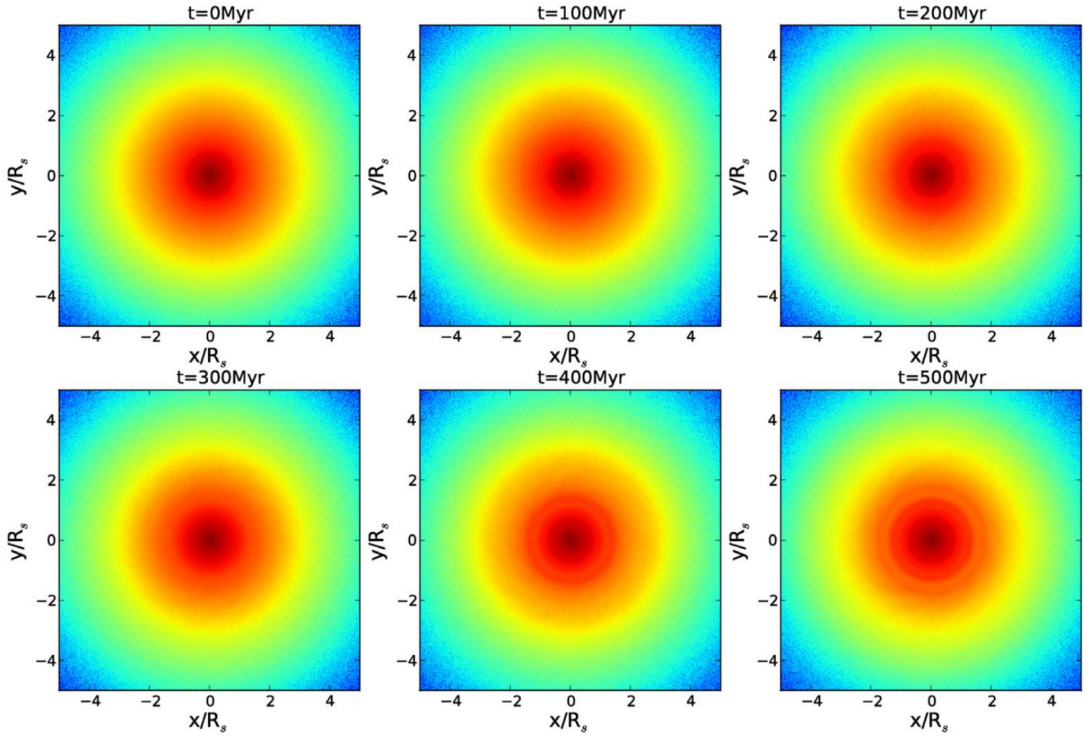
D’Onghia, Vogelsberger & Hernquist 2013

- After increasing resolution from 1M to 100M stellar particles, spirals are gone.

- Only ran for 0.5 Gyr.

- Need internal perturbers like giant molecular clouds (GMC) to trigger multi-spirals.

(Fixed potential models)



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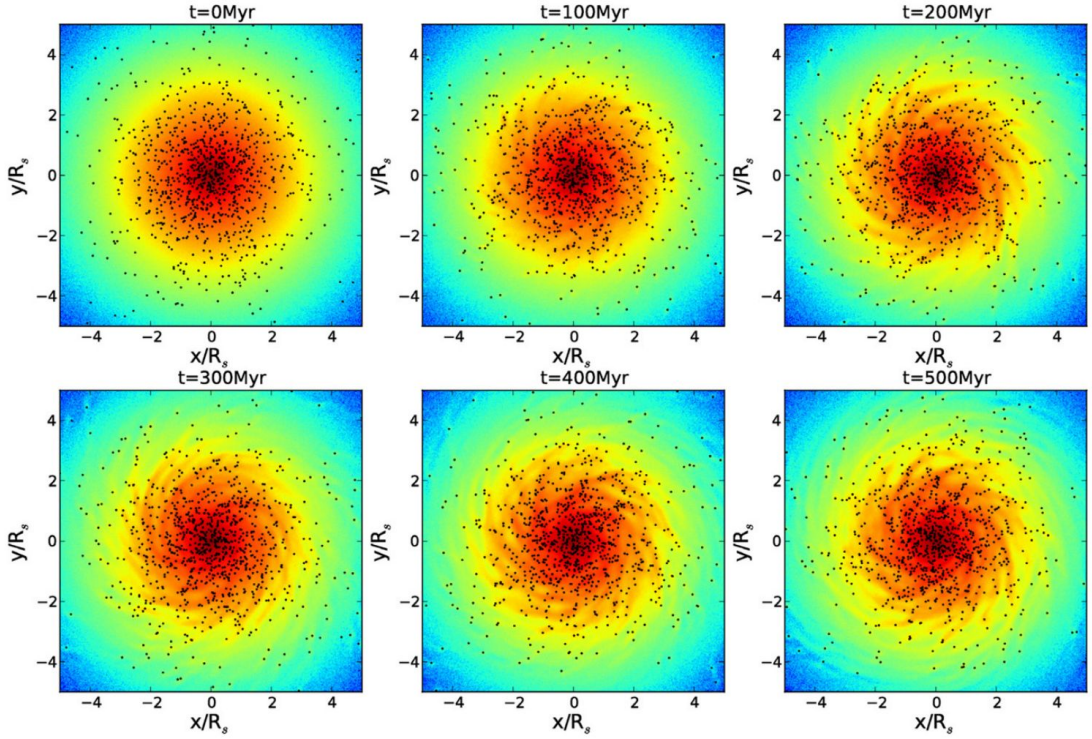


Questions

Questions

- Does increasing resolution really suppress the spiral arm formation?
- Does resolution matter more than disk stability?
- Is adopting a live halo really important? (instead of fixed potential)
- Should we care about the DM resolution as well?

Models

~~GPU N-body code (too much noise)~~

AREPO

IC by GALIC (Yurin & Springel 2014)

Milky Way-size 11 disk-halo system

- R_d = 3 kpc & z_d = 0.3 kpc
- M_d = 5e10 Msol
- M_dm = 1.14e12 Msol (Hernquist)
- **'c' halo concentration controls the stability of disk in our models.**

- r1: star 10000 Msol (5M, eps 0.03 kpc)
- r2: star 1000 Msol (50M, eps 0.01 kpc)

Evolved for 2 Gyr

Table 1: Initial Conditions

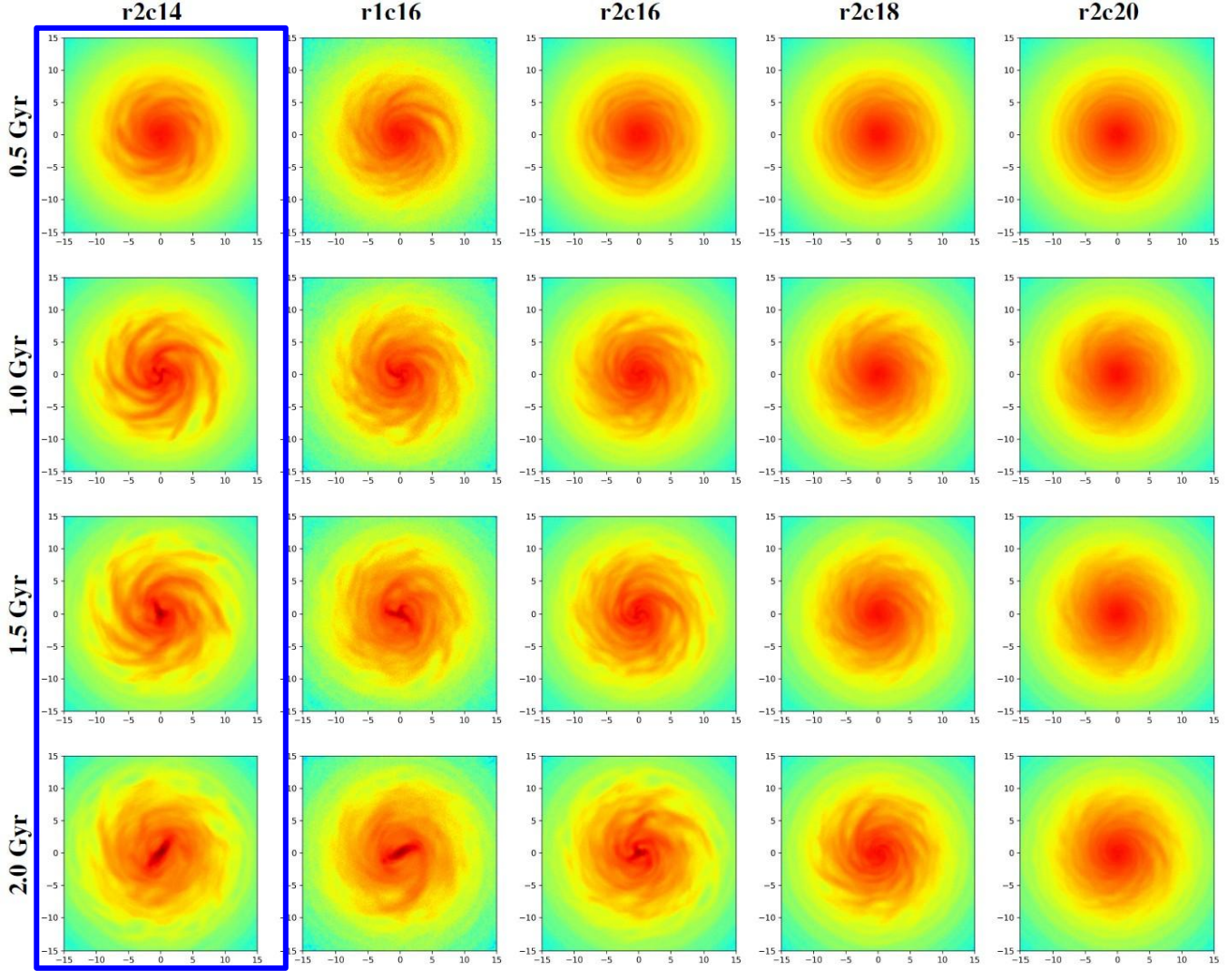
Model	c	$N_\star$	N_{DM}	$m_\star : m_{DM}$
r1c14	14	5e6	1.14e7	1:10
r1c16	16	5e6	1.14e7	1:10
r1c18	18	5e6	1.14e7	1:10
r1c20	20	5e6	1.14e7	1:10
r2c14	14	5e7	1.14e8	1:10
r2c16	16	5e7	1.14e8	1:10
r2c18	18	5e7	1.14e8	1:10
r2c20	20	5e7	1.14e8	1:10
r1c16hdm	16	5e6	1.14e8	1:1
r1c16ldm	16	5e6	1.14e6	1:100
r1c16fdm	16	5e6	Fixed	

Faceon image

High Resolution

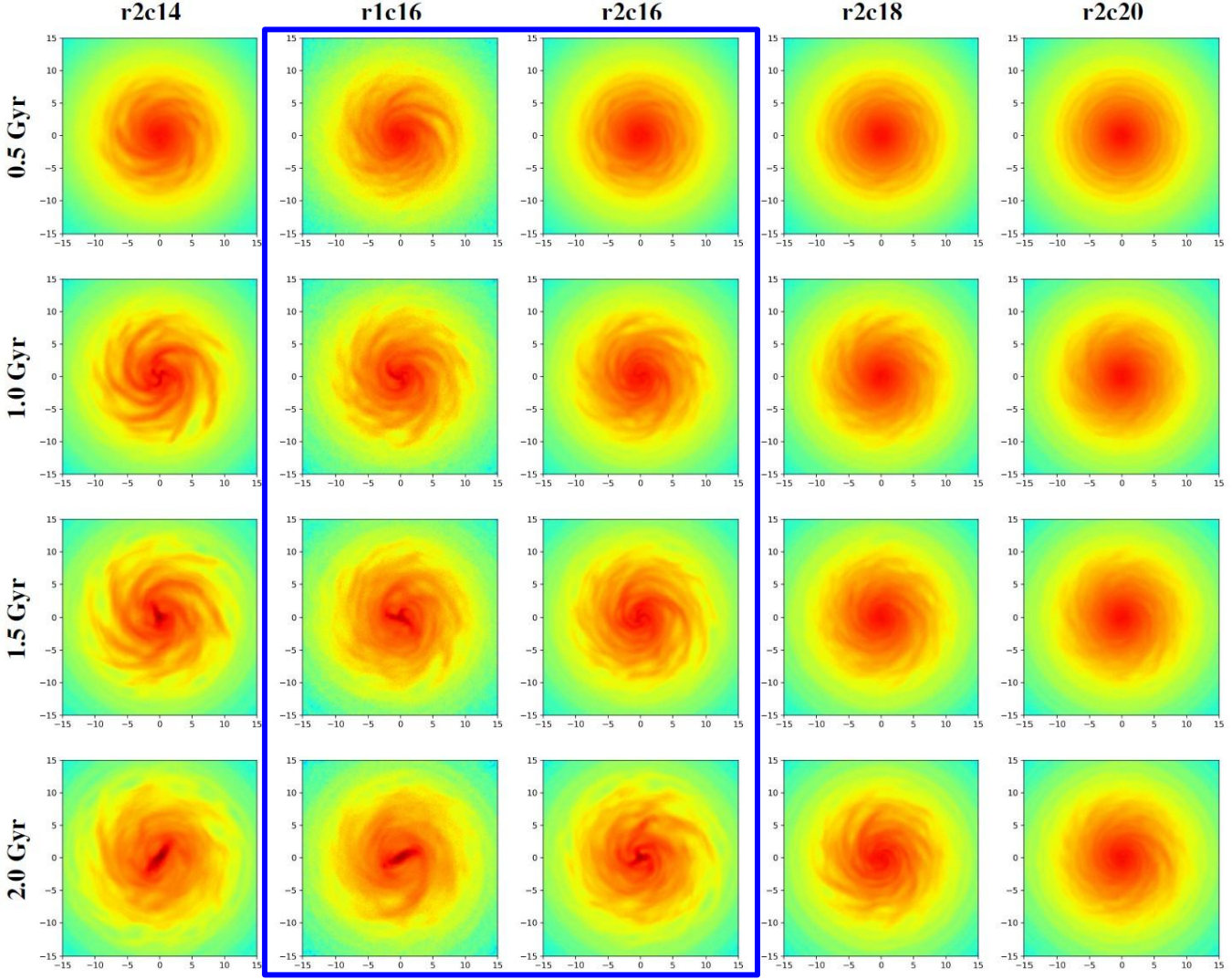
Unstable disk still forms spirals in the first 0.5 Gyr.

Small bar is formed in the end.



Faceon image

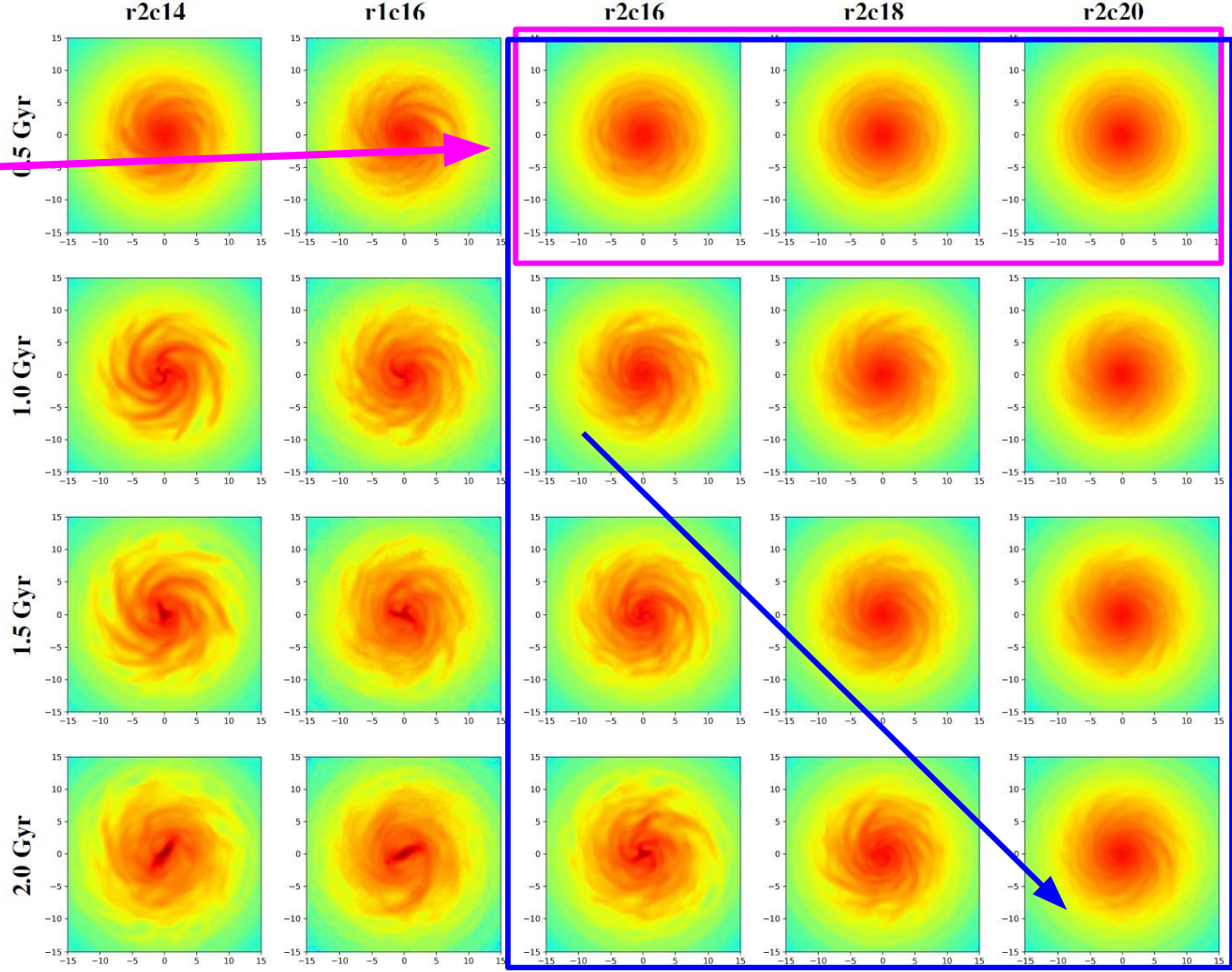
In c16 comparison (same stability), resolution delays spiral formation but still forms visible spirals after 0.5 Gyr.



Faceon image

No spirals at 0.5Gyr

but slowly forms spirals over time depending on disk stability.

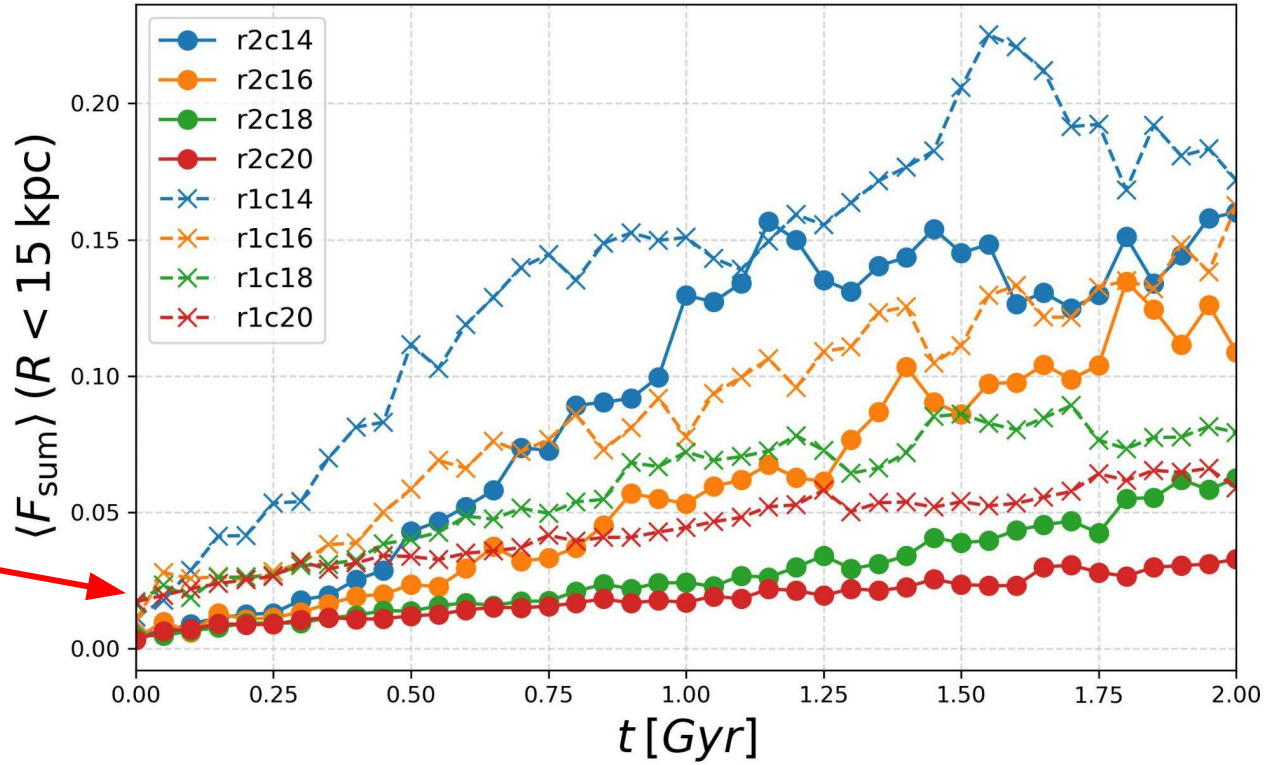


Fourier Amplitudes: Resolution Effects (<15kpc)

$$F_{\mathrm{sum}} = \frac{\sqrt{\sum_{m=1}^{6}(F_m(R))^2}}{F_0(R)}$$

Region dominant by higher Fourier modes ***(Spirals)***

- Lower resolution, 1~2% initial noise & earlier spiral formation.



Fourier Amplitudes: Resolution Effects (<3kpc)

$$F_{\mathrm{sum}} = \frac{\sqrt{\sum_{m=1}^{6}(F_m(R))^2}}{F_0(R)}$$

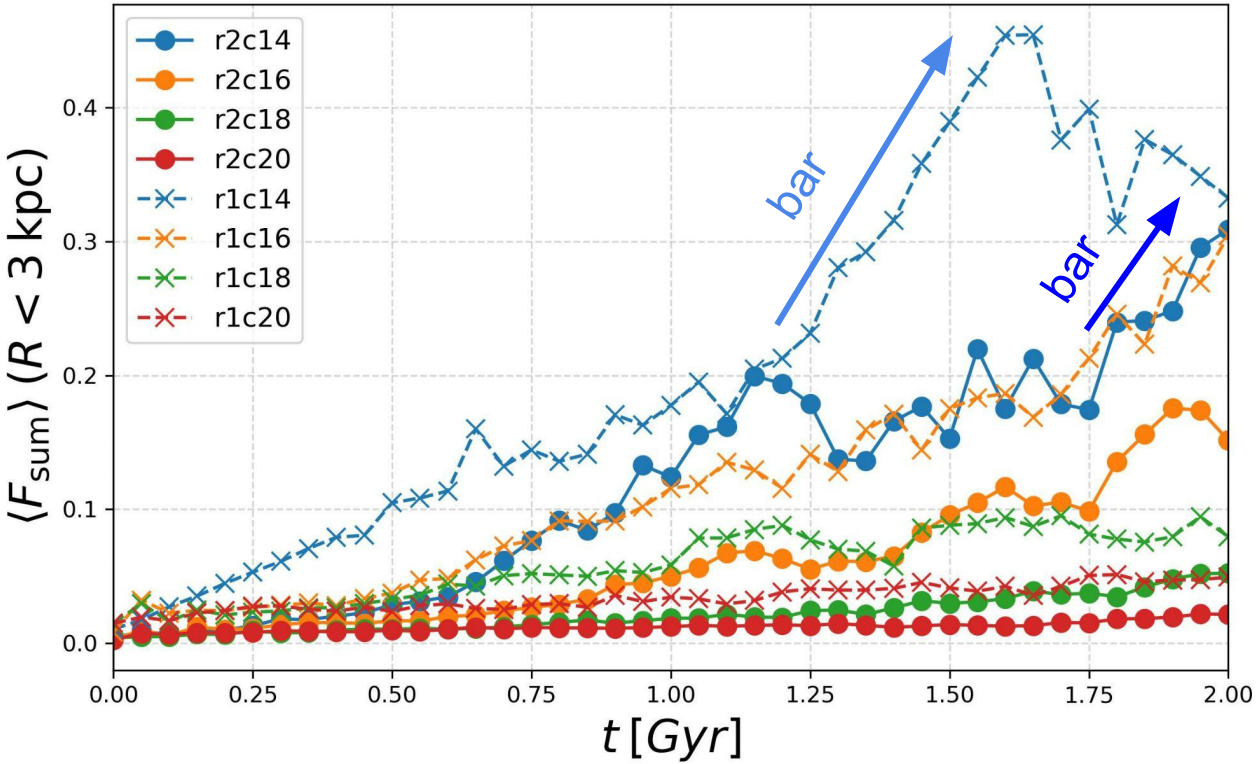
Region dominant by Fourier mode = 2,3 ***(Bar)***

- Bar formation (F_2>0.3) is delayed by

0.5 Gyr in r2c14

& 2 Gyr in r2c16.

- More unstable, shorter time delay.

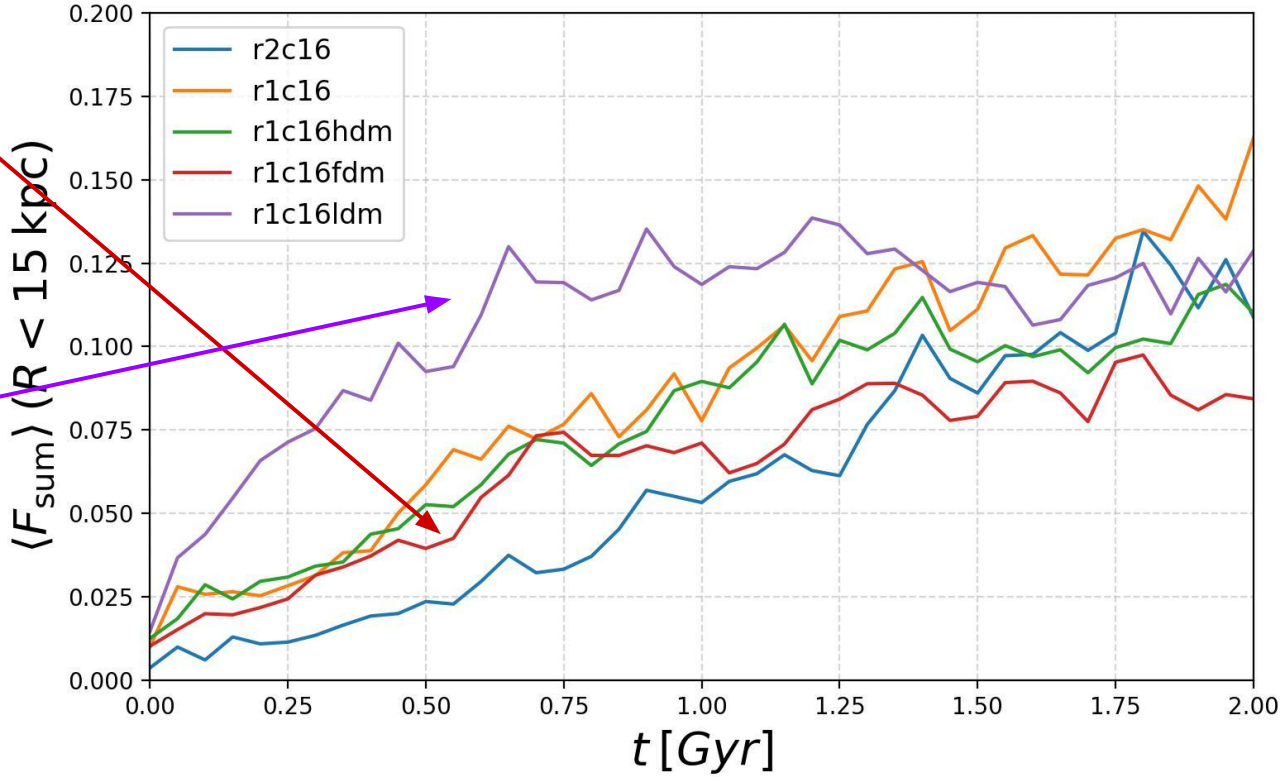


Fourier Amplitudes: DM Halo Effects (<15kpc)

fdm (fixed potential): divergence in the growth rate by lacking dynamical friction by live DM.

ldm (1:100): early heating by strong gravitational kicks from massive DM particles.

hdm (1:1): bar formation is delayed by 0.8 Gyr.



Fourier Map

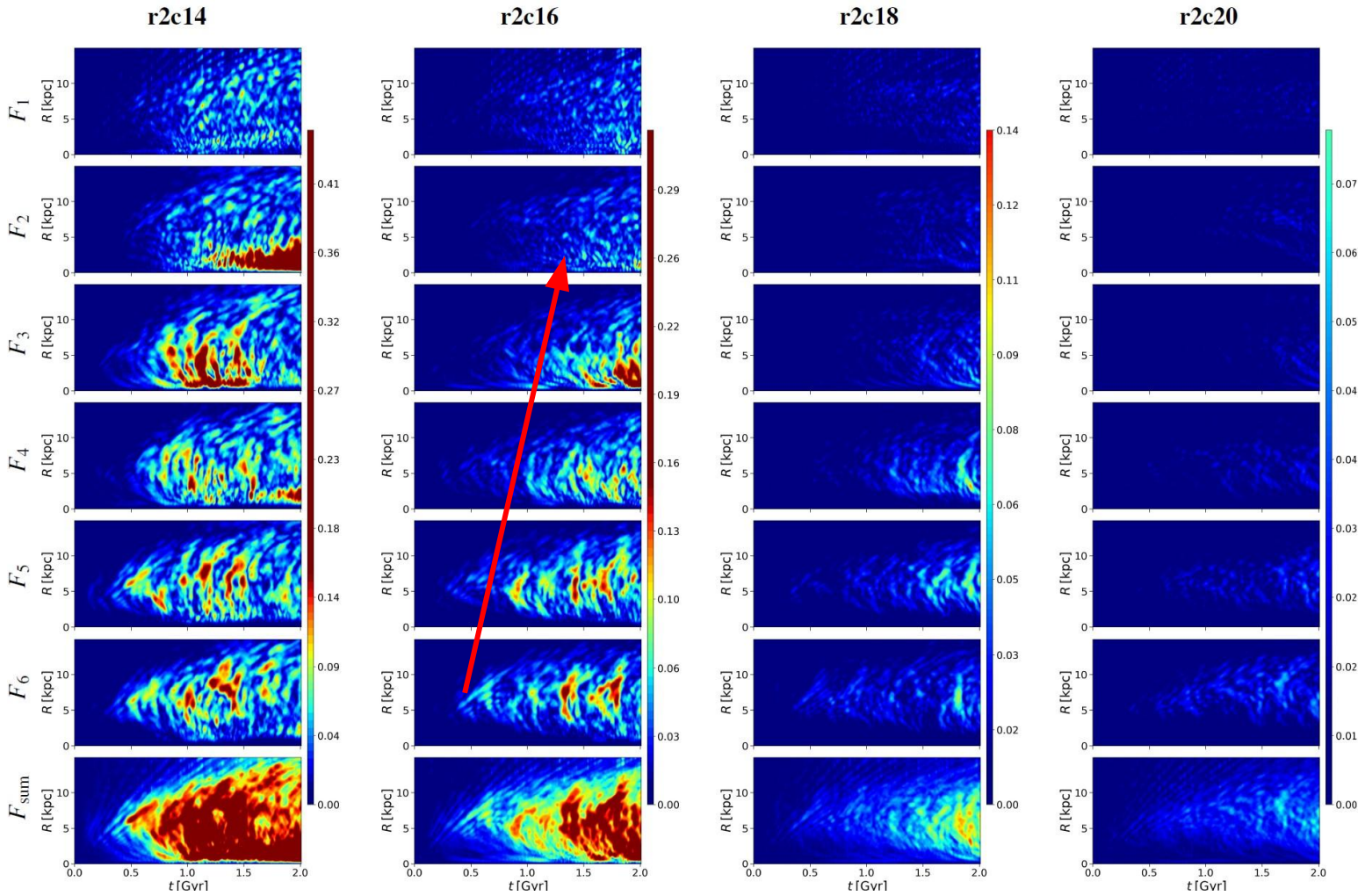
<u>High Resolution</u>

Spiral Formation
1) Higher modes to lower modes

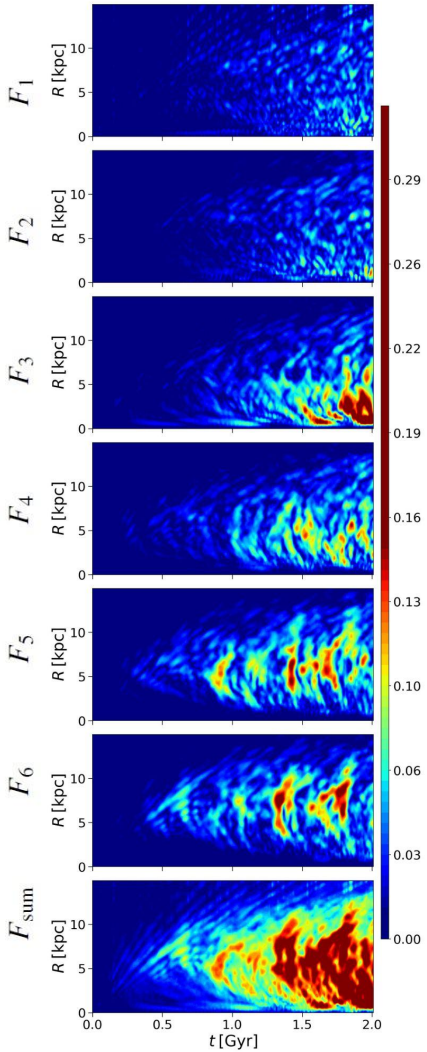
2) Outside to inside

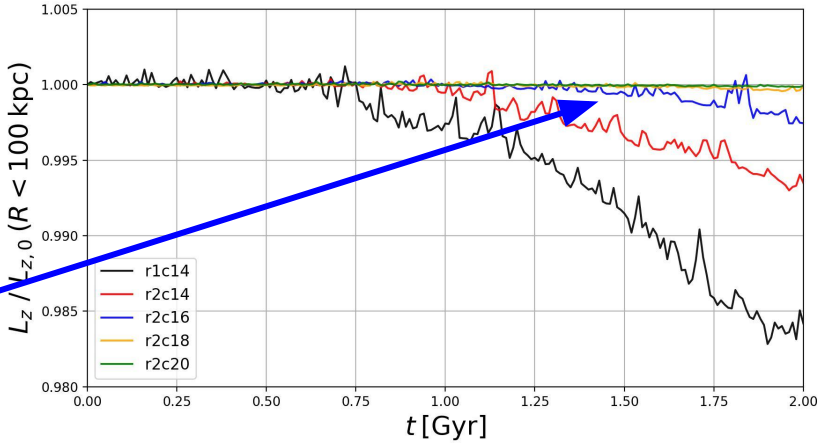
3) m=3 is bridge before m=2 bar formation.

In more stable one, this process is slower and more evident.



r2c16
(no bar)





The m=3 mode serves as a transitional phase where central amplification initiates disk angular momentum loss, transitioning to bar formation.
<u>This is absent in the fixed potential model!</u>

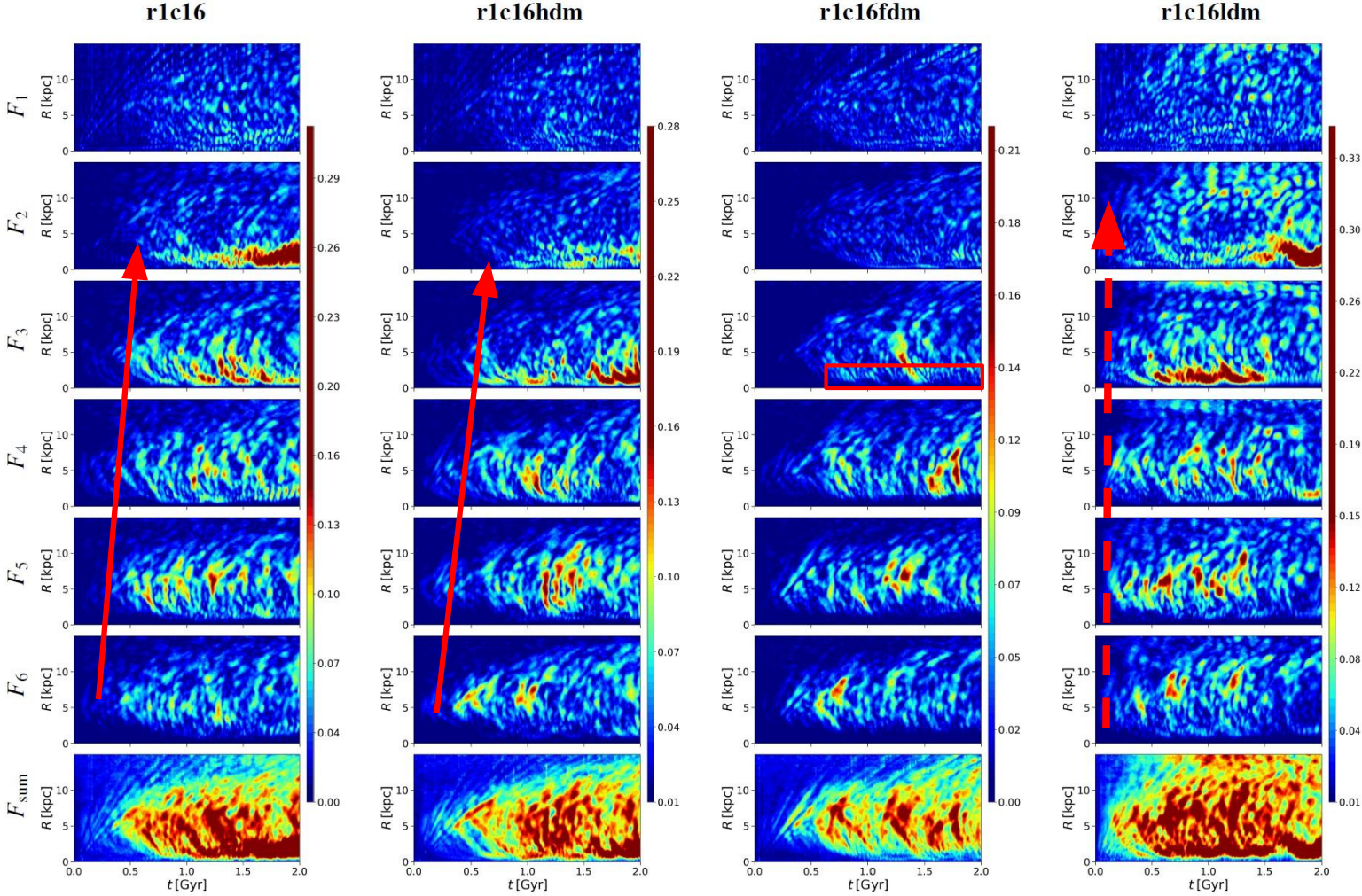
Fourier Map

DM Halo Effects

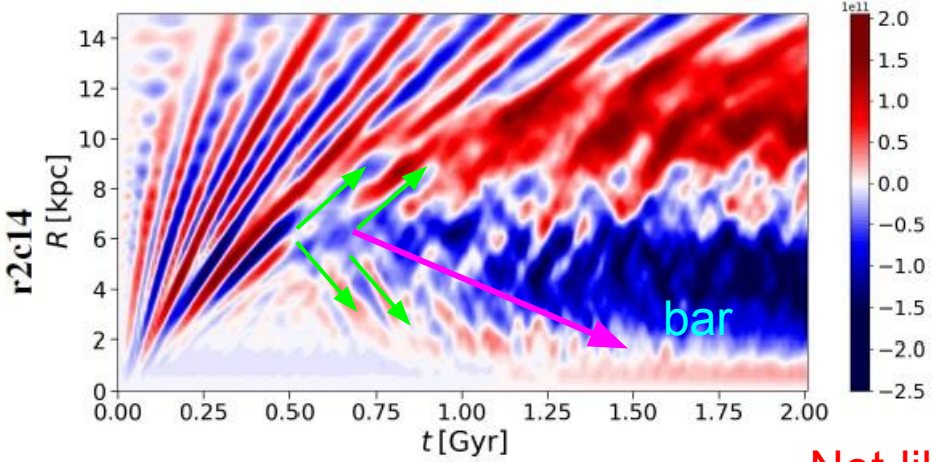
In general, more noisy and earlier formation in all modes.

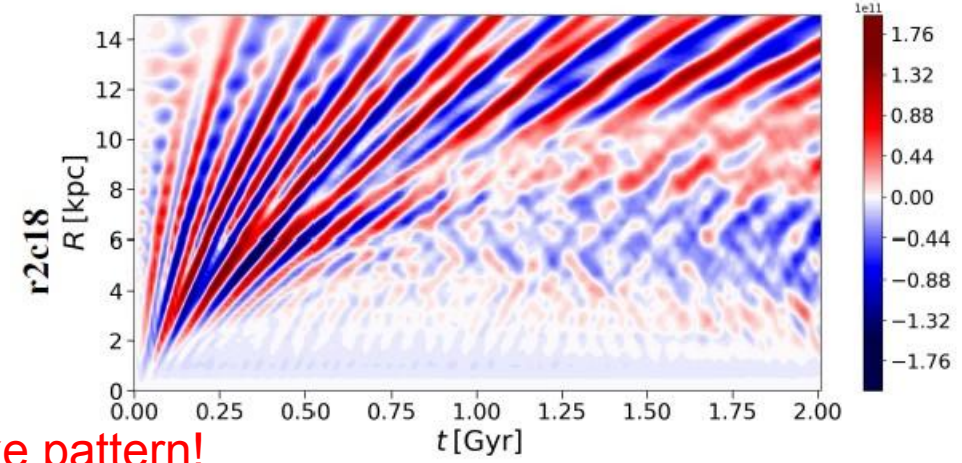
fdm (fixed potential): no central m=3 amplification & no bar.

ldm (1:100): soon after the evolution begins, numerical spirals appear in all modes.

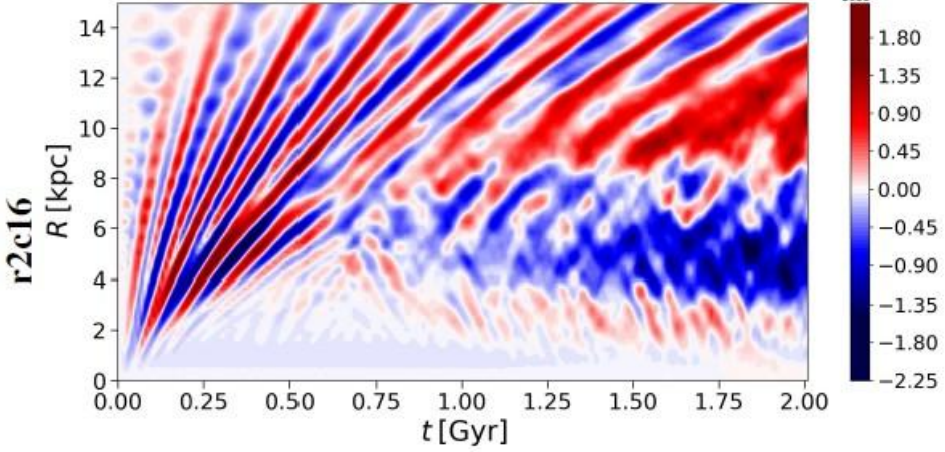


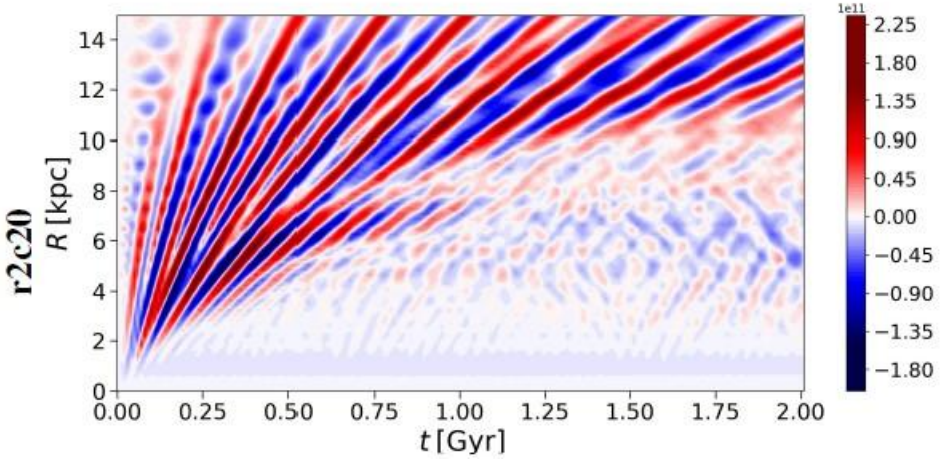
Disk Angular Momentum Distribution by Lz(t) - Lz(0)





Net-like pattern!





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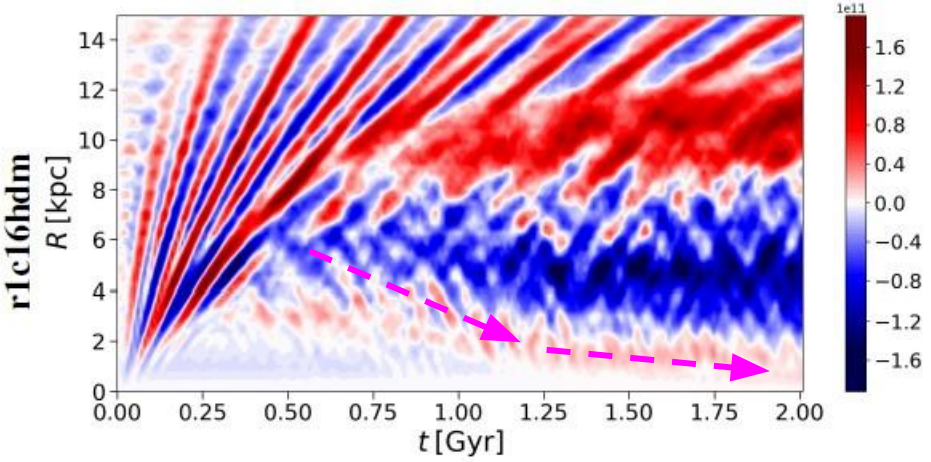
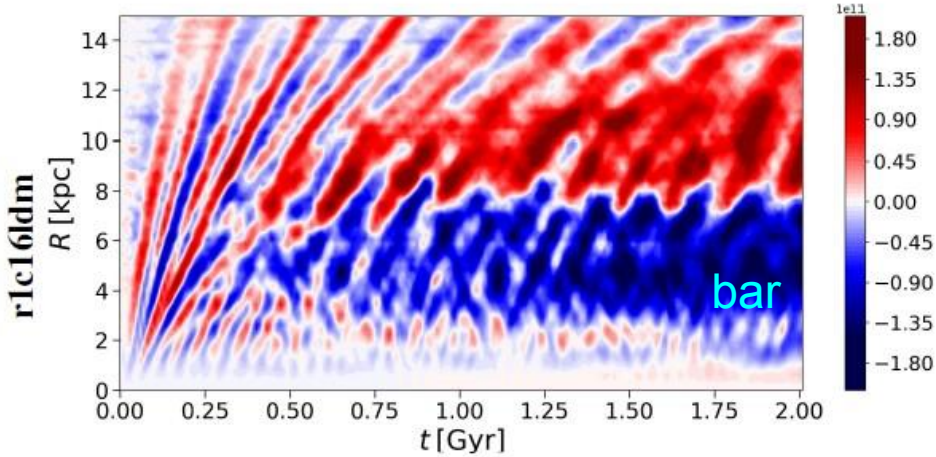




hdm (1:1) : the trace of spiral formation from outside to inside is clearly visible.

ldm (1:100) : not looking great

- Higher mode -> lower mode
- Outside -> Inside
- Leaving net-like pattern

Summary

1. Increasing the number of star and DM particles does not suppress the spiral formation by a factor of 10, but delays spiral and bar formation by 0.5 and 2.0 Gyr (c16). In more unstable disk, the delay becomes shorter.

2. Increasing halo resolution delays the bar formation as well. Decreasing halo resolution significantly affects spiral formation due to the strong gravitational kicks by massive DM particles.

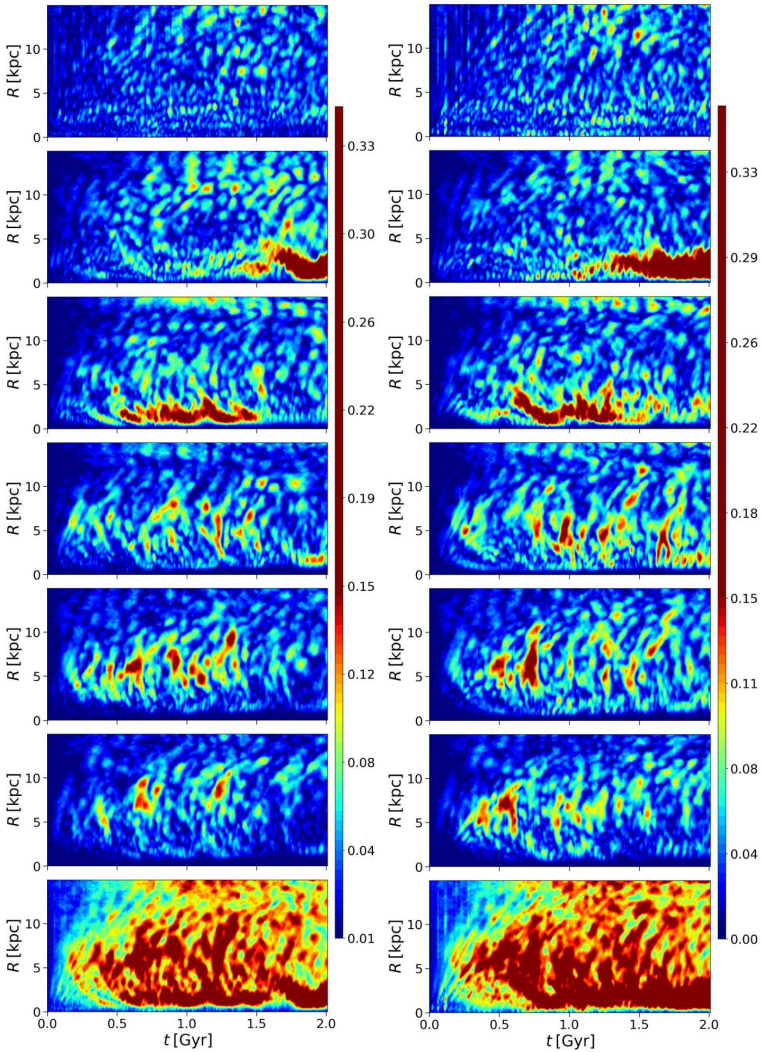
3. Angular momentum exchange between spirals and live DM halo is fractional, but still plays an important role in shaping the evolution of spiral arms.

4. The m=3 mode serves as a transitional phase where spiral amplification in the central region initiates disk angular momentum loss, transitioning to bar formation, which is absent in the fixed potential model.

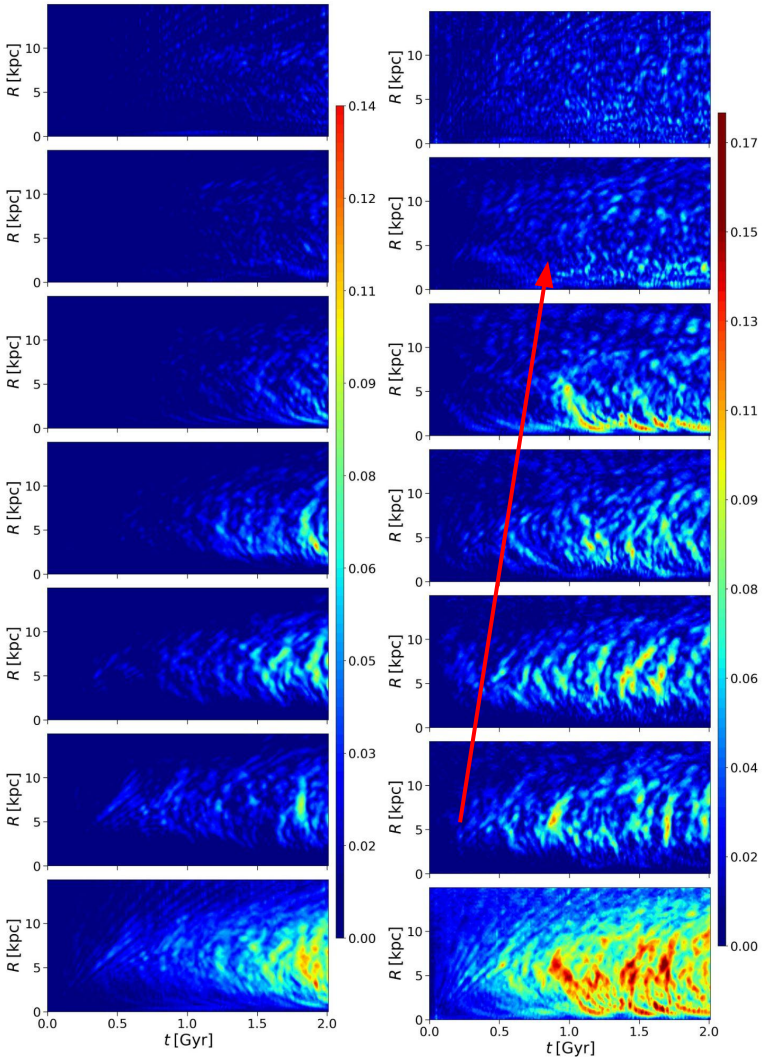
5. We find that spiral arms exhibit a cascading trend in Fourier modes and radial position: **higher-m modes** form and decay recurrently, followed by the emergence of **lower-m modes** with a delayed onset and **a radially inward-drifting epicenter**, creating a **net-like pattern** in the angular momentum distribution.

Proper setup in resolution and mass ratio (star:DM) is required to see the nature of spirals.

r1c16ldm (DM softening 0.03 kpc)
vs.
r1c16ldmsf06 (DM softening 0.6kpc)



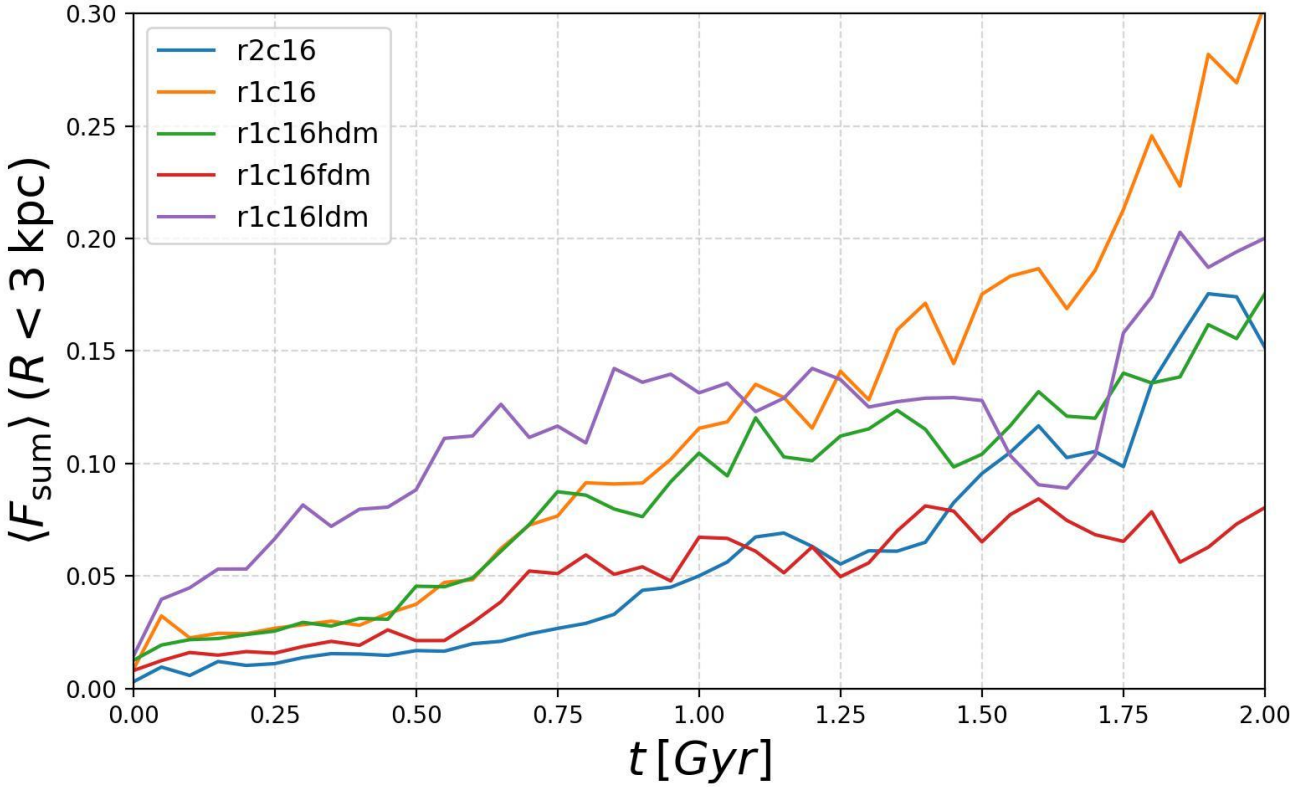
r2c18 vs r1c18

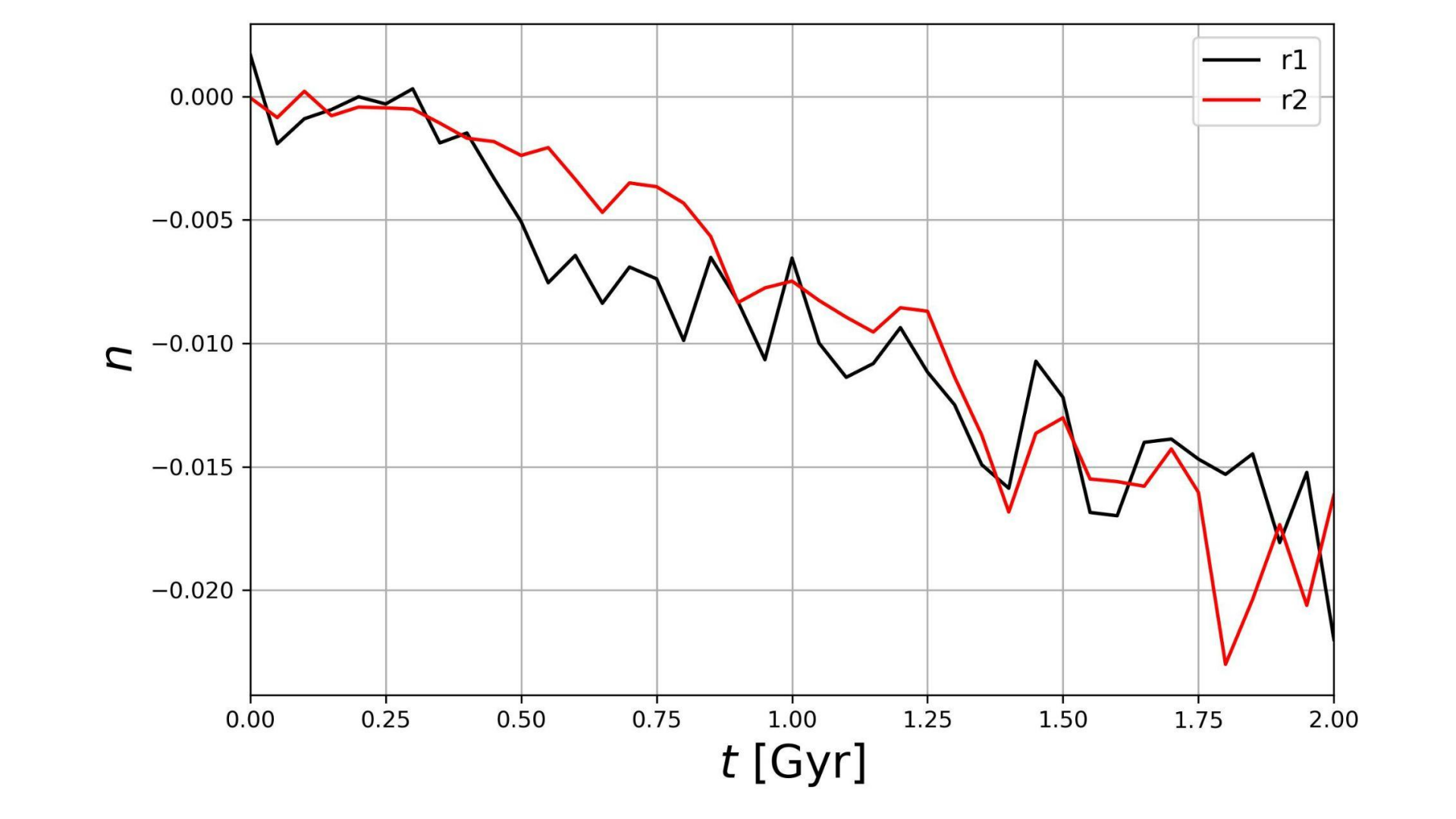


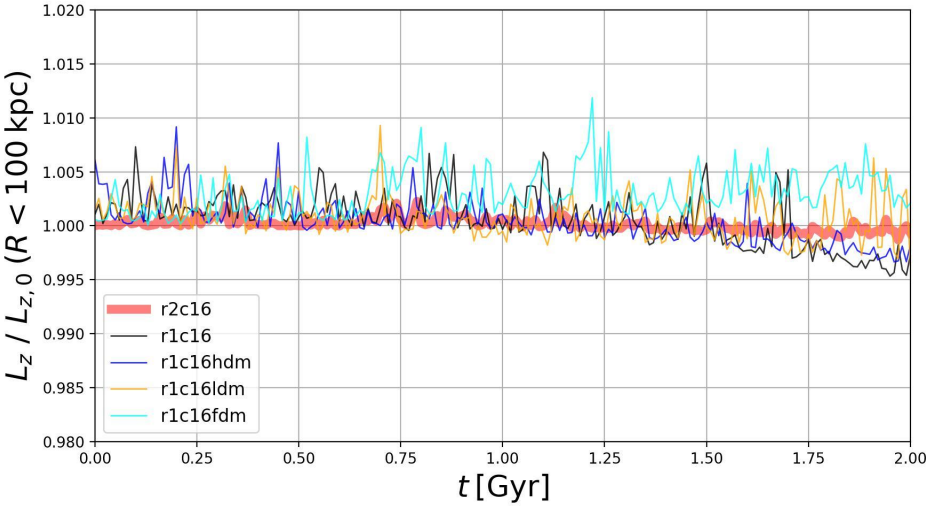
Fourier Amplitudes: Halo Effects (<3kpc)

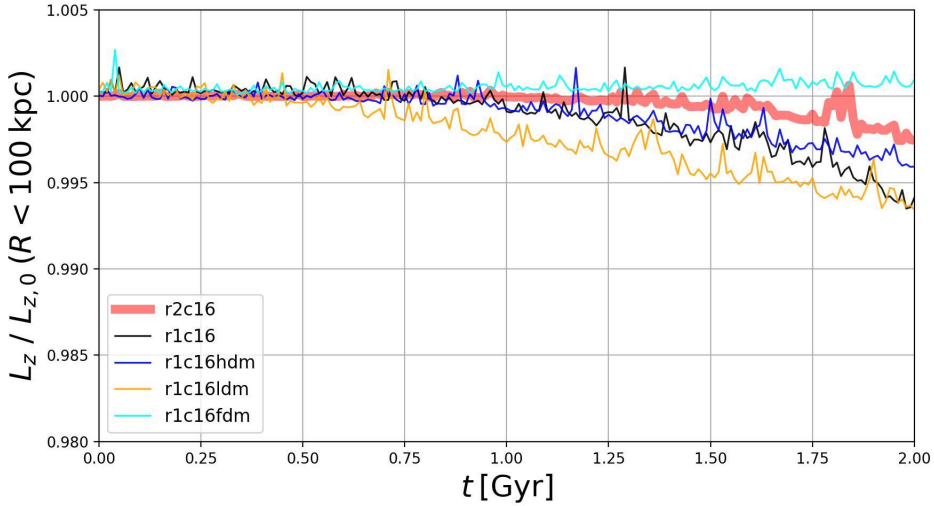
- Large divergence in the central region due to Fourier mode m=2,3 growth is significantly affected by live DM.

- Bar formation is delayed by 0.8 Gyr when increasing DM halo resolution by 10 times. (1:1 mass ratio)



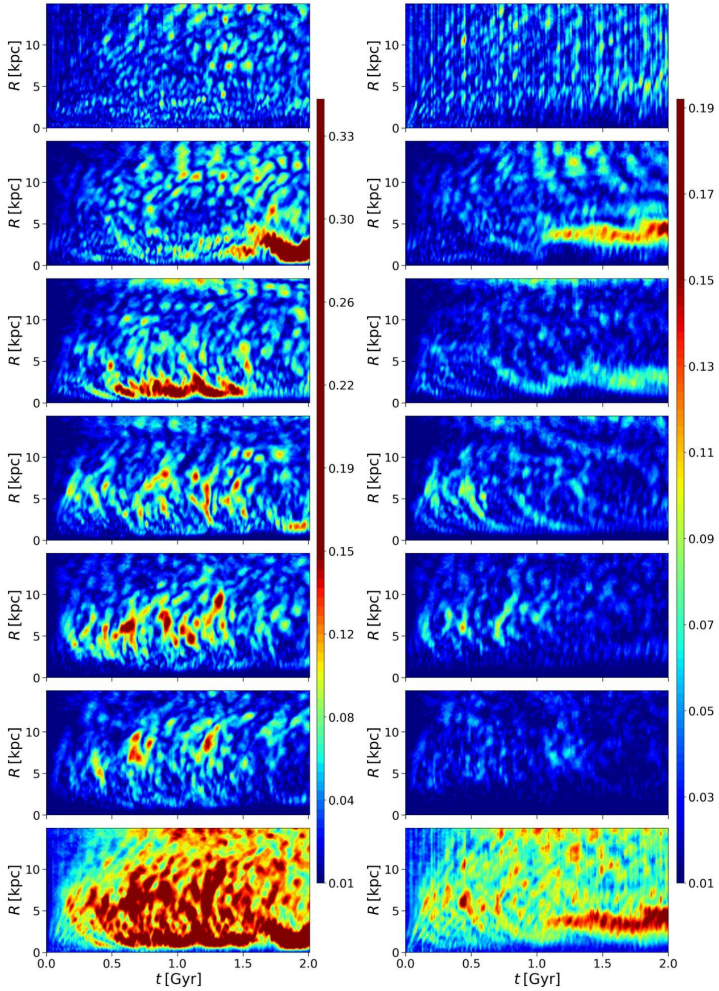

r1
r2
0.000
−0.005
−0.010
−0.015
−0.020
n
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
t [Gyr]

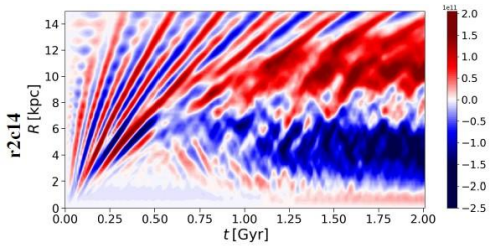

1.020
1.015
1.010
1.005
1.000
0.995
0.990
0.985
0.980
L_z / $L_{z,0}$ (R < 100 kpc)
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
t [Gyr]
r2c16
r1c16
r1c16hdm
r1c16ldm
r1c16fdm

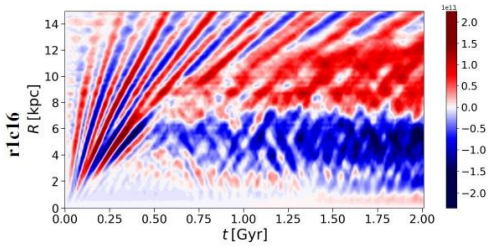

1.005
1.000
0.995
0.990
0.985
0.980
L_z / $L_{z,0}$ (R < 100 kpc)
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
t [Gyr]
r2c16
r1c16
r1c16hdm
r1c16ldm
r1c16fdm

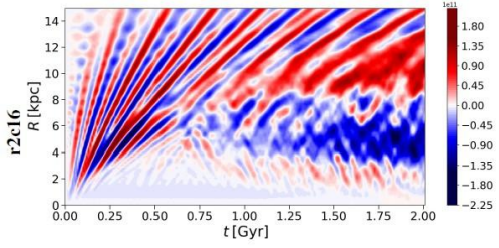
AREPO vs GPU

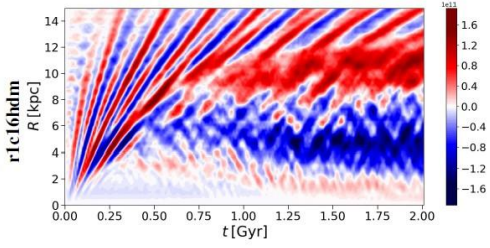
ldm (1:100) comparison

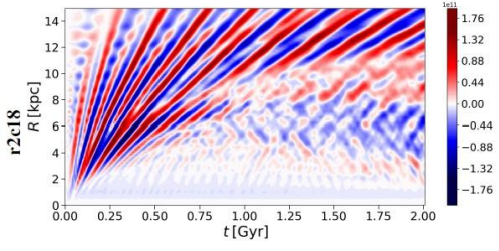


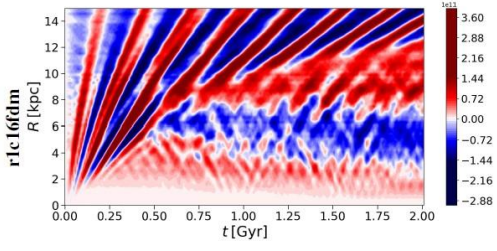

r2c14
R [kpc]
t [Gyr]
1e11

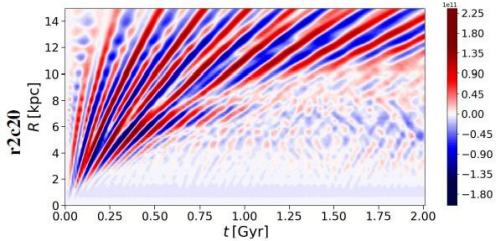

r1c16
R [kpc]
t [Gyr]
1e11

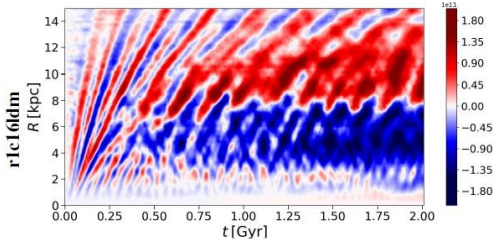

r2c16
R [kpc]
t [Gyr]
1e11


r1c16hdm
R [kpc]
t [Gyr]
1e11


r2c18
R [kpc]
t [Gyr]
1e11


r1c16fdm
R [kpc]
t [Gyr]
1e11


r2c20
R [kpc]
t [Gyr]
1e11


r1c16dm
R [kpc]
t [Gyr]
1e11