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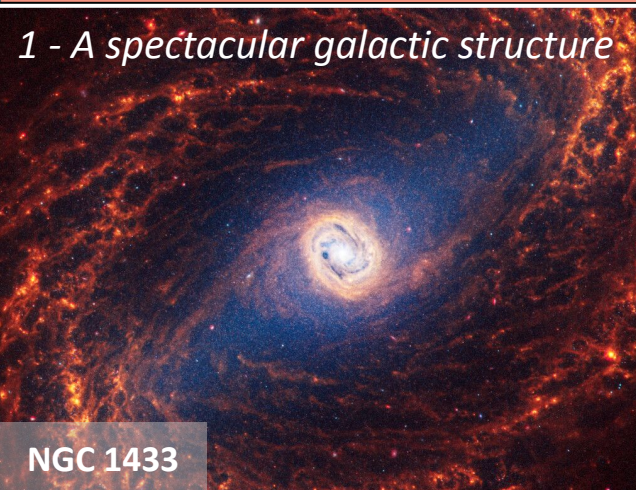
# ***Nuclear ring formation in barred galaxies with hydrodynamical simulations***

**Journées de la SF2A 2026 - S04 session  
June 22 2026**

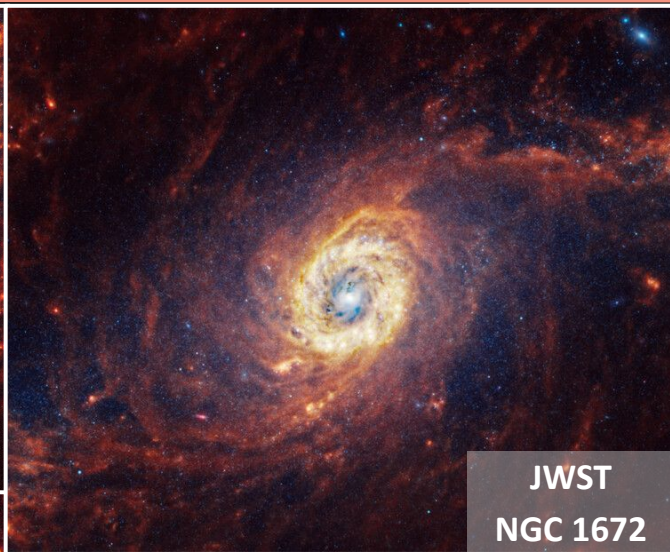
Supervised by Dr. Anaëlle Hallé and Pr. Françoise Combes

# *1/ Context: the role of nuclear rings in secular evolution*

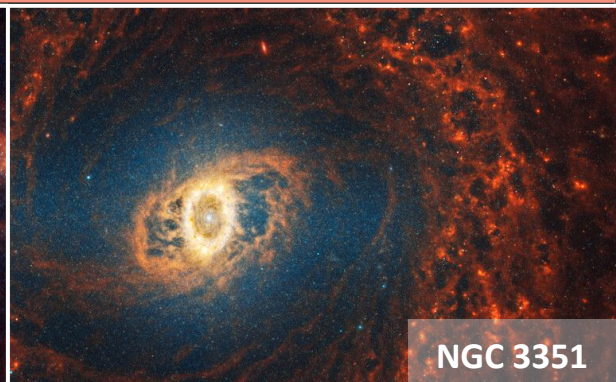
*1 - A spectacular galactic structure*



NGC 1433



JWST  
NGC 1672



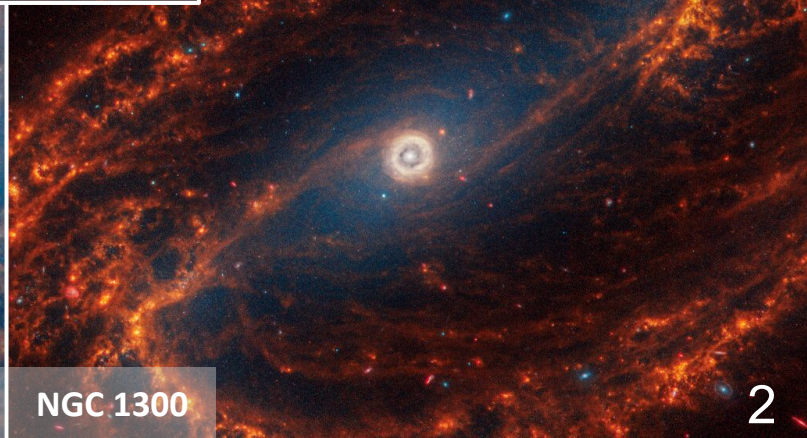
NGC 3351



NGC 1512



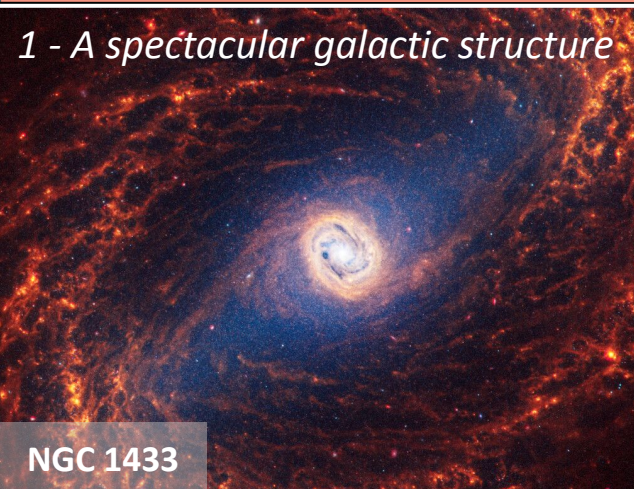
NGC 4303



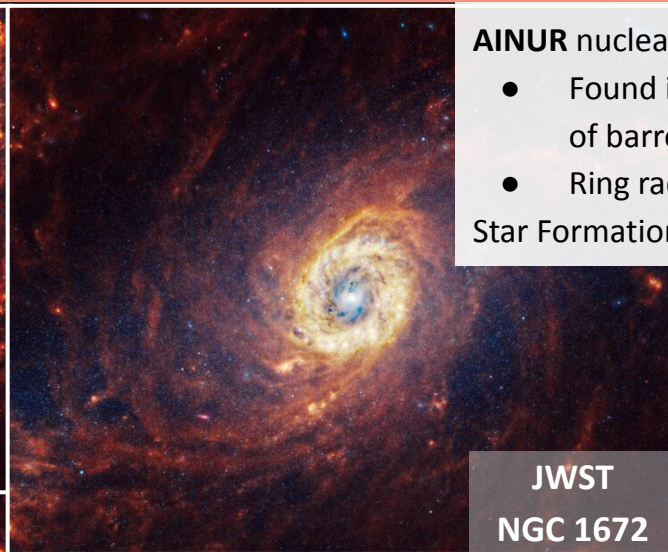
NGC 1300

# *I/ Context: the role of nuclear rings in secular evolution*

*1 - A spectacular galactic structure*



NGC 1433



JWST  
NGC 1672



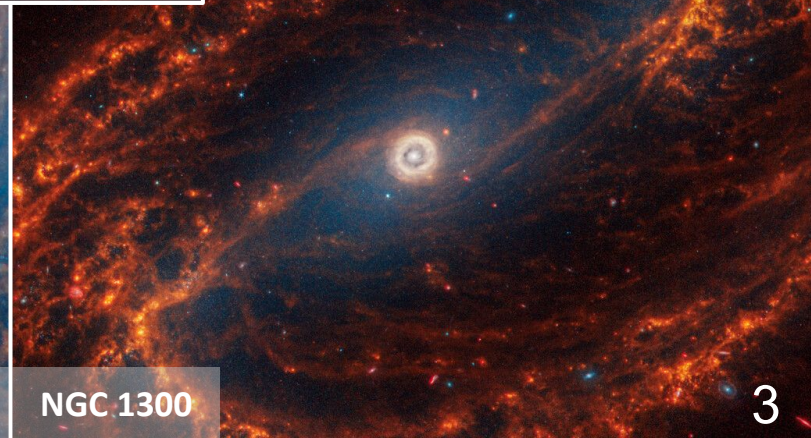
NGC 3351



NGC 1512



NGC 4303



NGC 1300

**AINUR** nuclear ring catalog ( $z = 0$ , Coméron et al. 2010):

- Found in  $\approx 20\%$  of disk galaxies, including  $\approx 75\%$  of barred galaxies
- Ring radii from  $\lesssim 100$  pc to  $\approx 3.5$  kpc

Star Formation Rates  $\sim 0.1$  to  $10 M_{\odot}/\text{yr}$  (Mazzuca+2008)

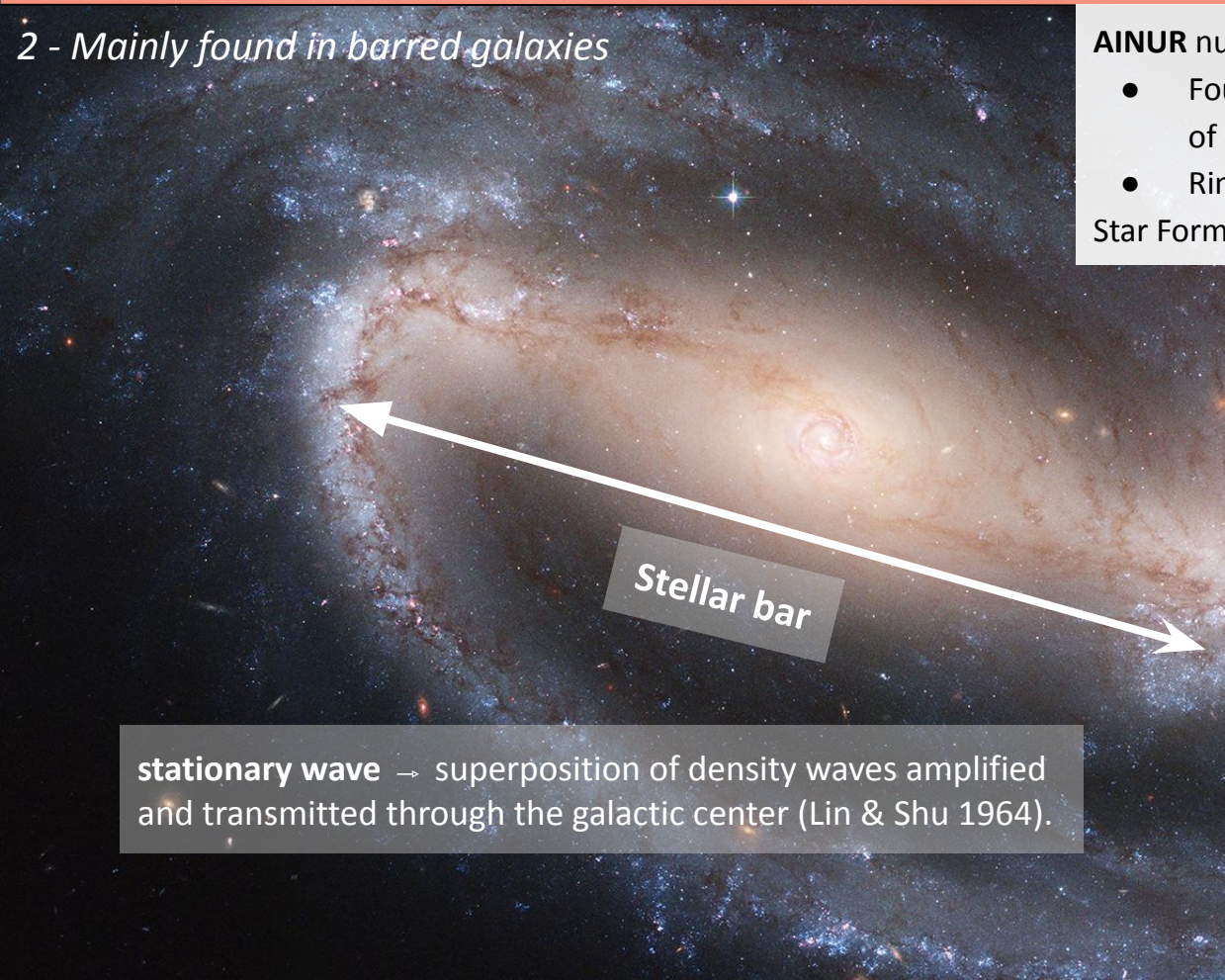
# 1/ Context: the role of nuclear rings in secular evolution

2 - Mainly found in barred galaxies

**AINUR** nuclear ring catalog ( $z = 0$ , Coméron et al. 2010):

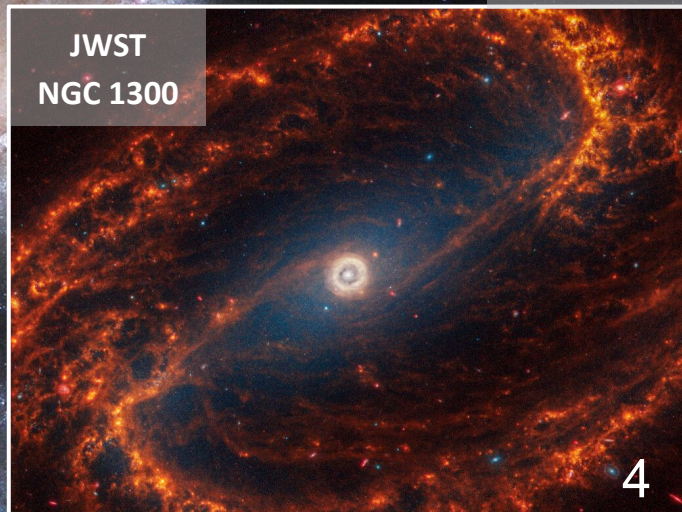
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HST  
NGC 1300

JWST  
NGC 1300

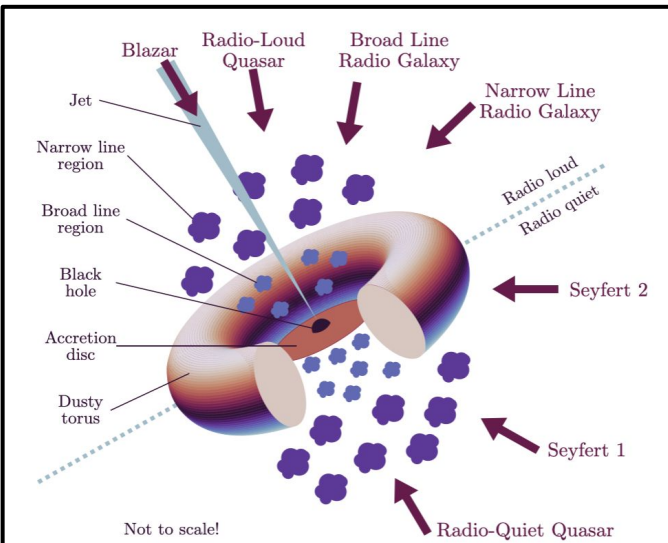


**stationary wave**  $\rightarrow$  superposition of density waves amplified and transmitted through the galactic center (Lin & Shu 1964).

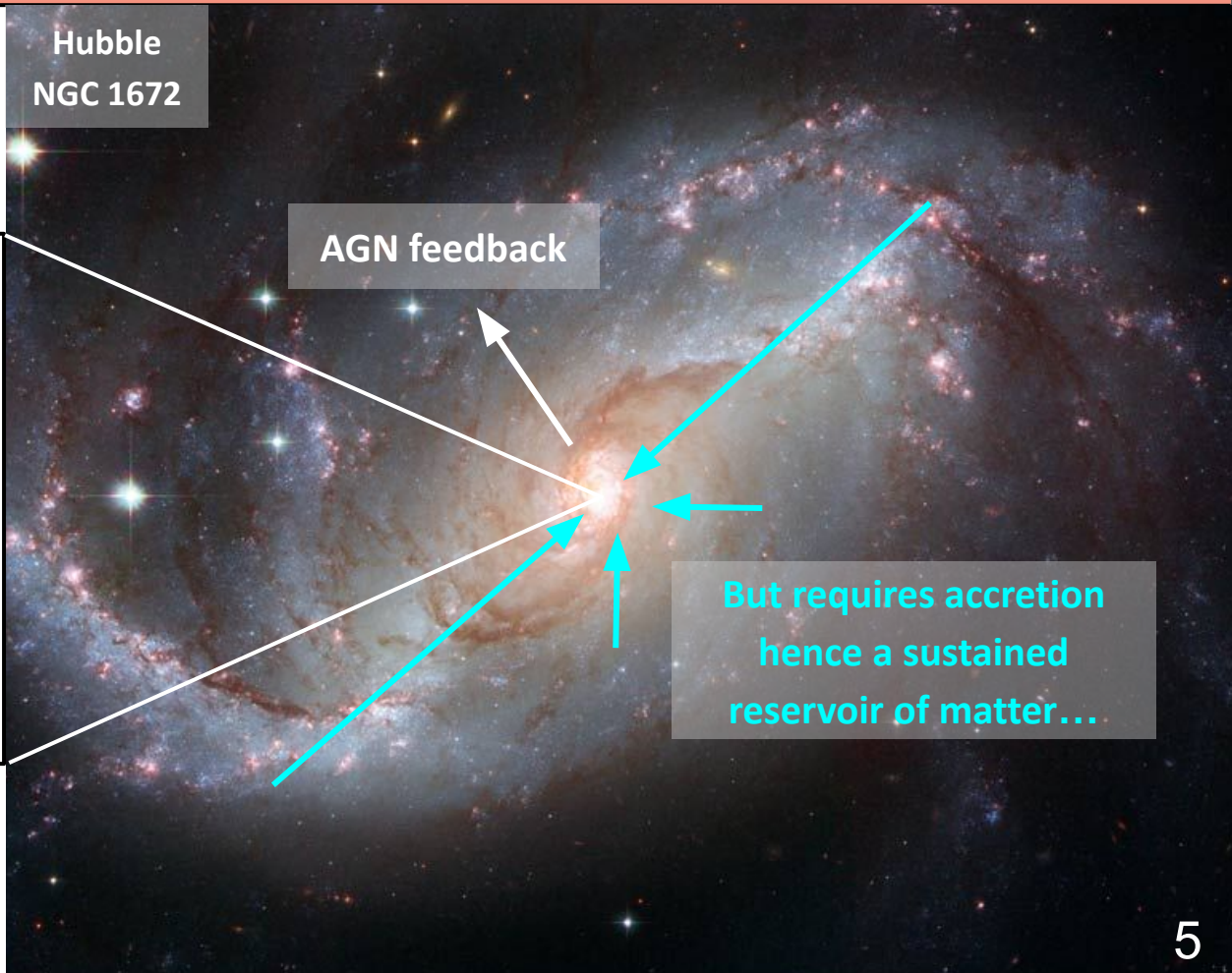
# 1/ Context: the role of nuclear rings in secular evolution

## 2 - Role in AGN fuelling in barred galaxies

Hubble  
NGC 1672



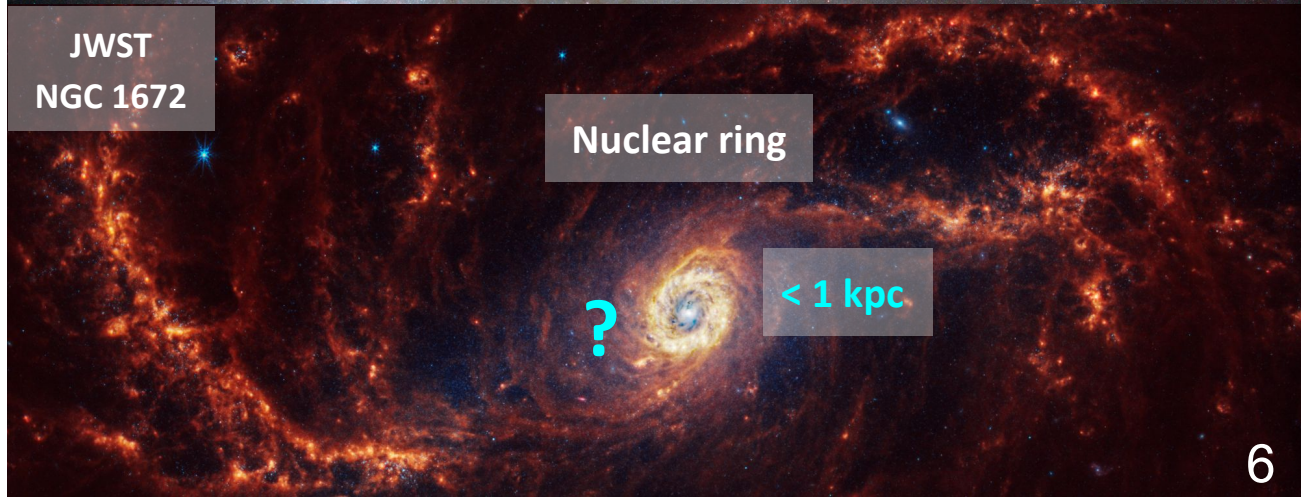
standard model of AGN  
Credit: Emma Alexander



# 1/ Context: the role of nuclear rings in secular evolution

## 2 - Role in AGN fuelling in barred galaxies

- AGN particularly found in barred galaxies.
- Stellar bars perturb the potential and **drive the gas inwards** up to  $\sim 1$  kpc from the center.
- On  $\sim 1$  kpc scales, gas accumulation in star-forming **nuclear rings**  $\rightarrow$  hinders the gas inflow and AGN feeding?



## II/ Context: formation process of nuclear rings?

### 1 - Connected to the existence of different orbit families

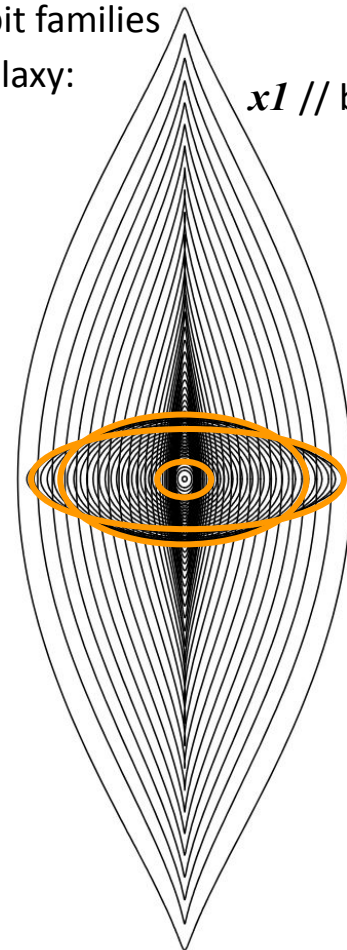
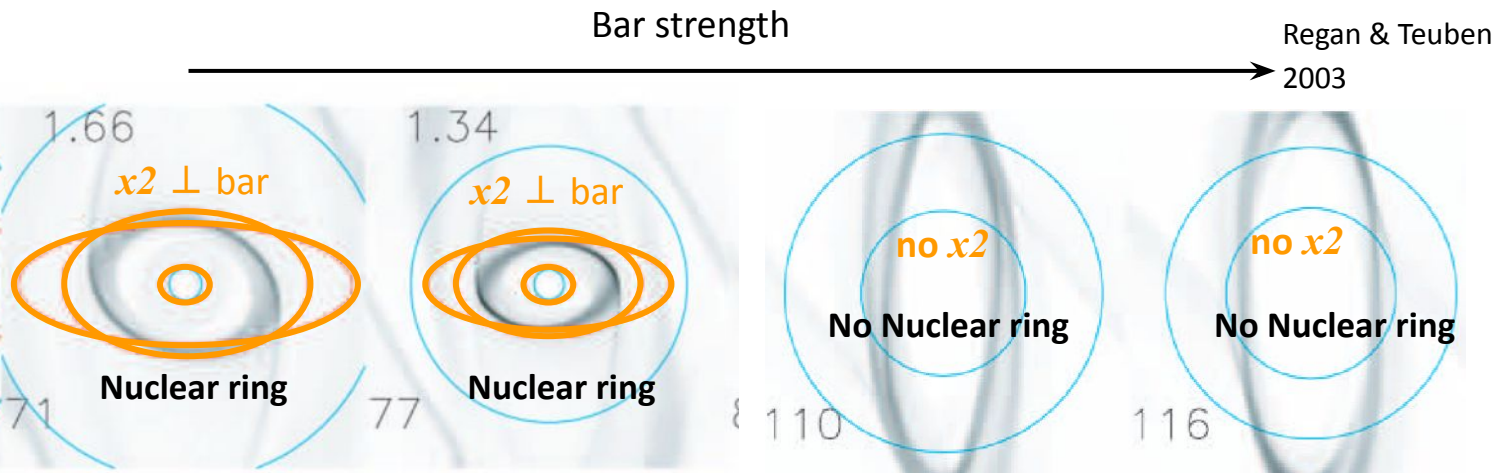
- Initially:  $x1$  orbits **parallel** to the bar.
- When bar slows down:  $x2$  orbits **perpendicular** to the bar appear.
- $x2$  orbits disappear in strong and thin bars.
- **General consensus: no nuclear ring when no  $x2$  orbits.**

$x1$  and  $x2$  orbit families  
in a barred galaxy:

$x1 // \text{bar}$

$x2 \perp \text{bar}$

Regan & Teuben  
2003





## II/ Context: formation process of nuclear rings?

### 2 - The epicyclic approximation

- weak potential perturbation → **epicyclic motion** (angular frequency  $\kappa$ )

#### - Bar Orbital Resonances :

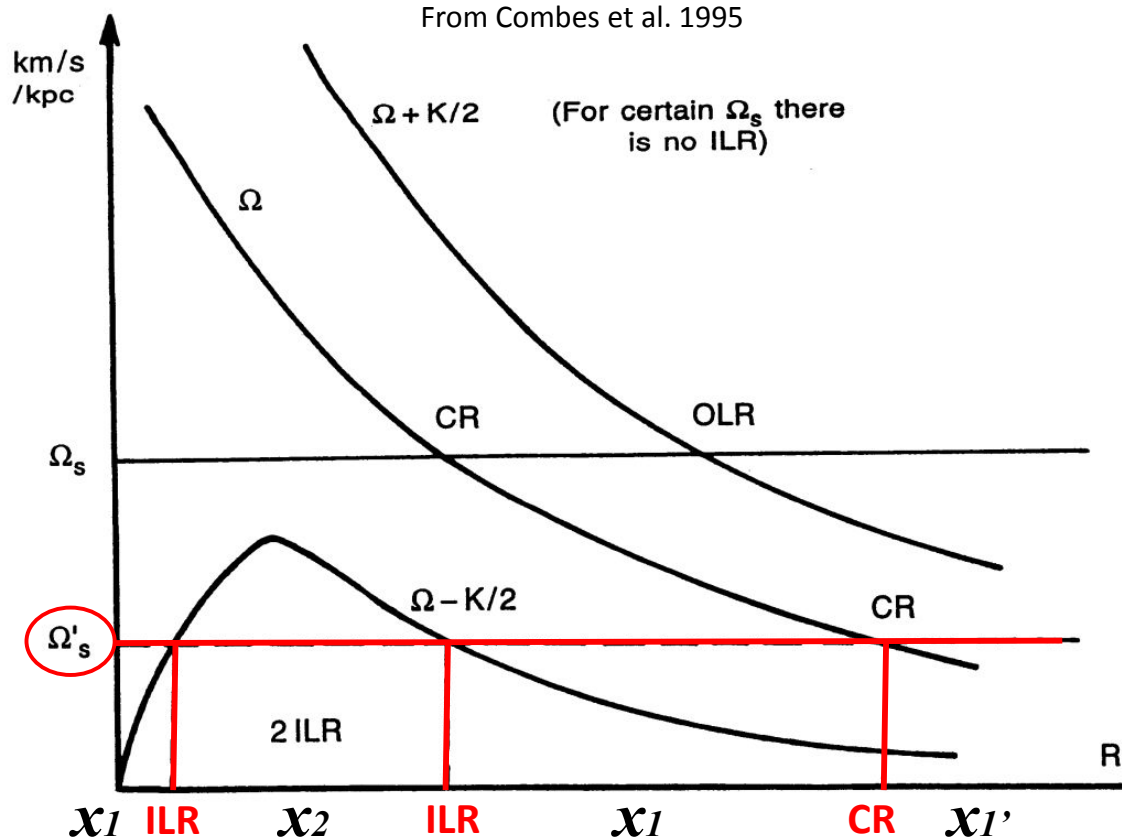
- Inner Lindblad Resonances (**ILRs**):  
 $\Omega_p = \Omega - \kappa/2$
- Corotation (**CR**):  
 $\Omega_p = \Omega$
- Outer Lindblad Resonance (**OLR**):  
 $\Omega_p = \Omega + \kappa/2$

- In weak bars, Lindblad Resonances



**transitions between orbit families**

(Contopoulos & Payyanopoulos 1980)



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### 2 - The epicyclic approximation

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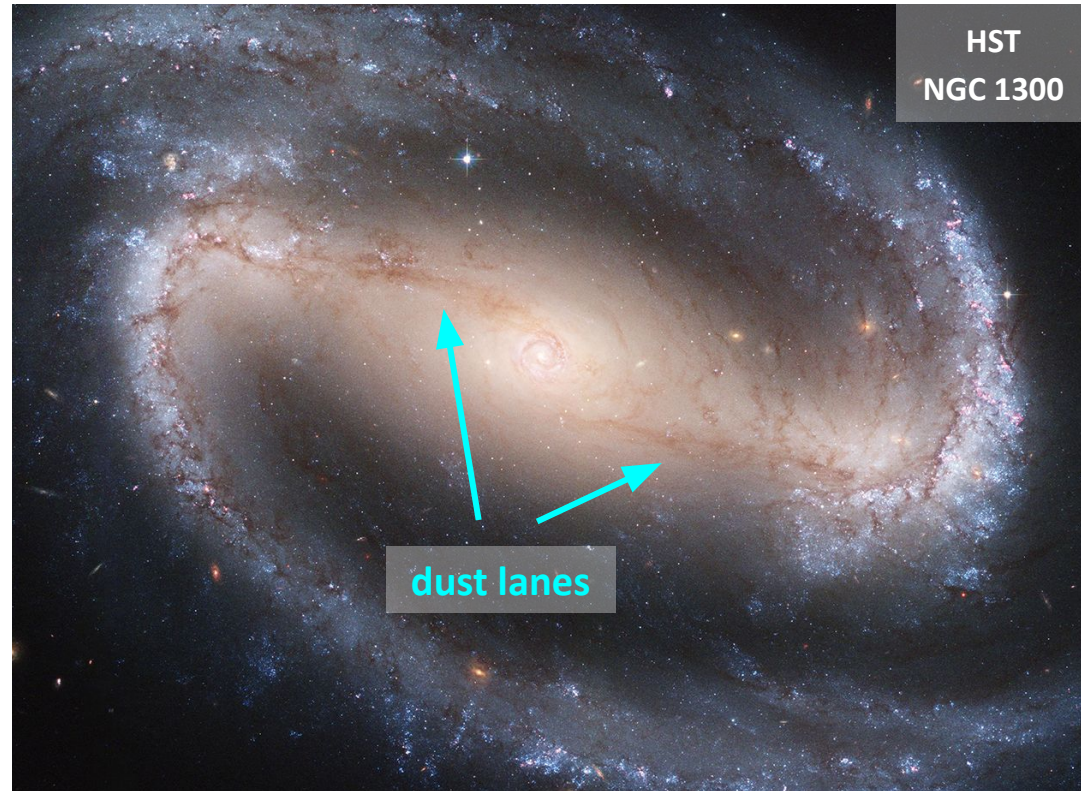


**transitions between orbit families**

(Contopolous & Payyanopoulos 1980)



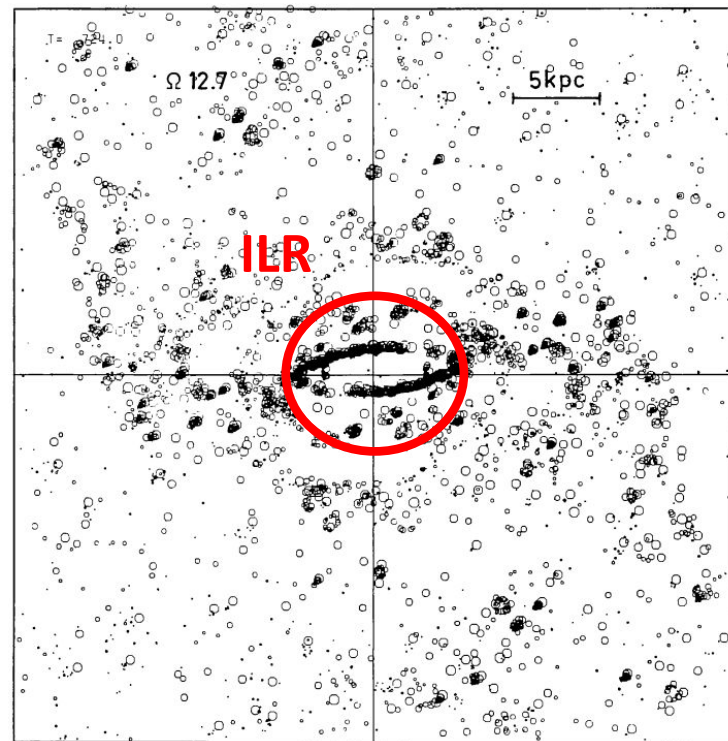
emergence of **inner gas spirals / dust lanes** (Athanasoula 1992)



## II/ Context: formation process of nuclear rings?

### 3 - Several scenarios...

- **Resonant Theory** (Buta & Combes 1996):  
Misalignment gas spirals / bar  $\Rightarrow$  average torque  $\neq 0 \Rightarrow$  gas accumulates to OLR and inner ILR  $\Rightarrow$  **nuclear ring**
  - $\rightarrow$  Depends only on gravity
  - $\rightarrow$  Tested in *Sticky Particle* simulations but **bad hydrodynamics**

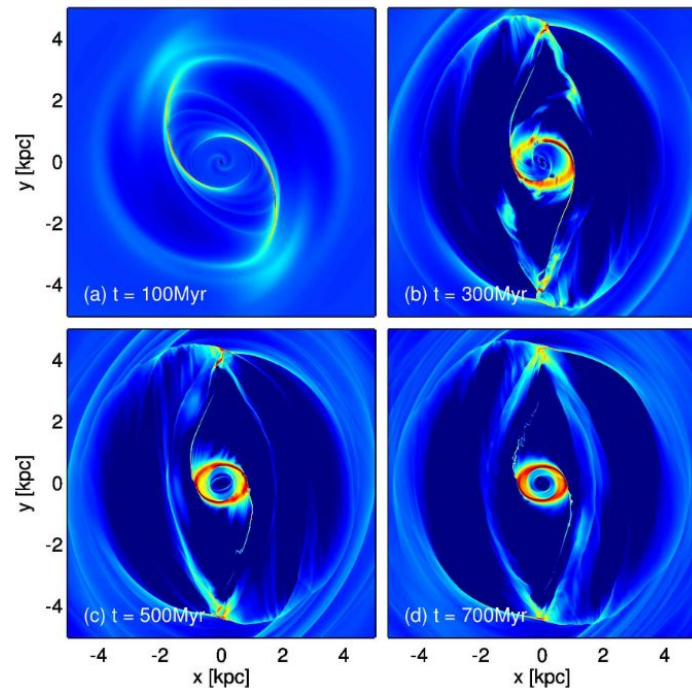


Sticky Particle simulation,  
from Combes and Gerin 1985

## II/ Context: formation process of nuclear rings?

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  - $\rightarrow$  Tested in *Sticky Particle* simulations but **bad hydrodynamics**
- Angular momentum transfer via **shocks** in the dust lanes (Regan & Teuben 2003, Li et al. 2015, Kobayashi et al. 2026):
  - $\rightarrow$  Hydrodynamical process, **not about** gravity torques
  - $\rightarrow$  Depends on gas properties
- etc.



Li et al. 2015

(2D grid-code, fixed bar potential,  
isothermal gas, no star formation)

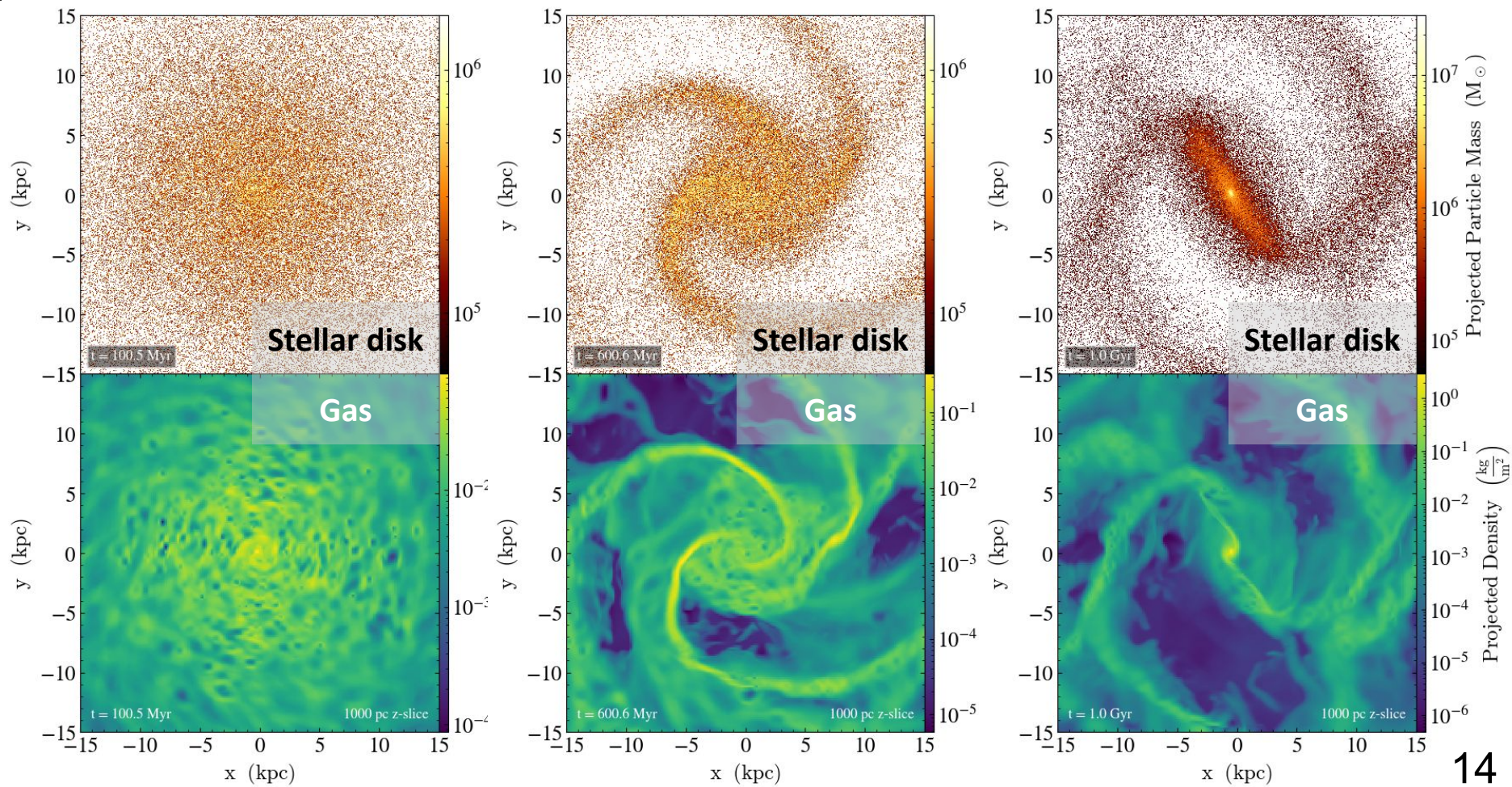
**Almost no numerical studies with “realistic” bar-forming galaxies (dynamical bar, star formation...)**

**$\Rightarrow$  my objective.**

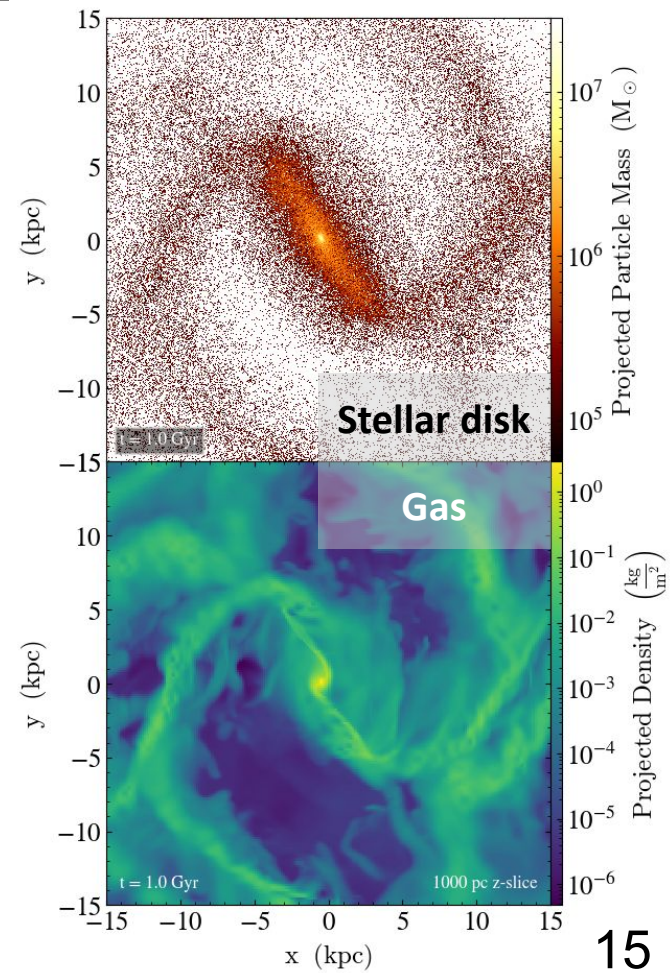


- The **RAMSES** code (Teyssier 2002, Ramses Team):
  - hydrodynamics + N-body (stars, cold dark matter) + physical processes (e.g. star formation, feedback).
  - **Adaptive Mesh Refinement** (grid code) -> density contrast, shocks, many refinement schemes.
- Initial conditions with **DICE** (Perret+2014).
- **Simple model:**
  - **Isolated galaxy** with 4 components: dark matter halo (NFW), stellar bulge (Sérsic), stellar and gaseous disks (exp-sech2).
  - Perfect gas  $\gamma = 5/3$ , metallicity  $Z = 0.1 Z_{\odot}$  (with metallic enrichment), gas cooling and heating, star formation, supernovae.
  - No AGN.

## IV/ Simulation of a bar-forming galaxy



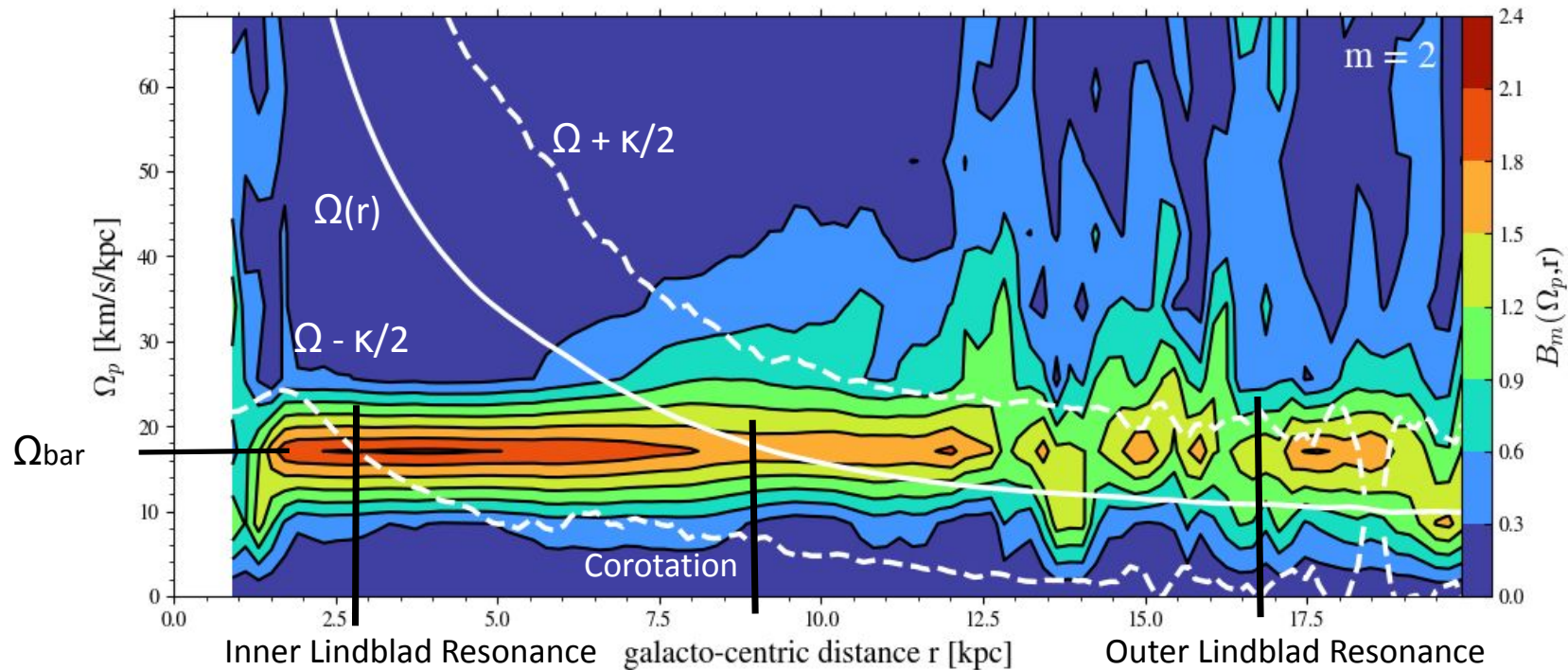
# IV/ Simulation of a bar-forming galaxy



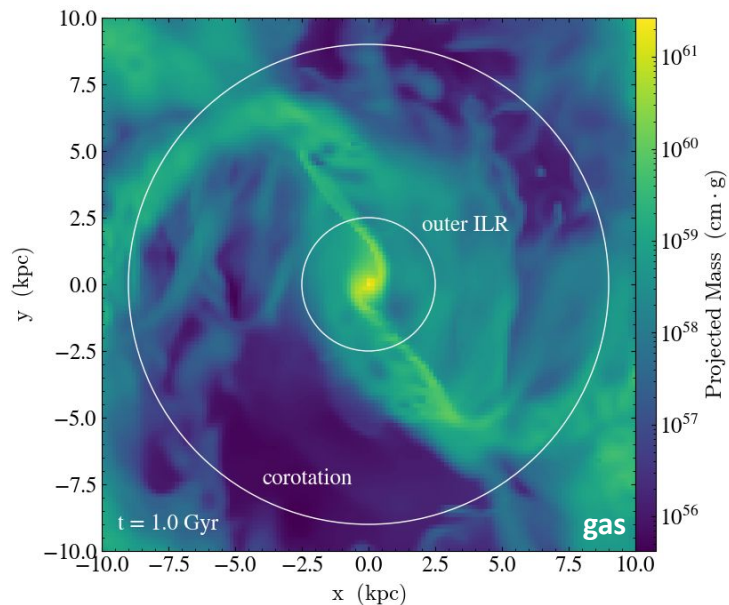
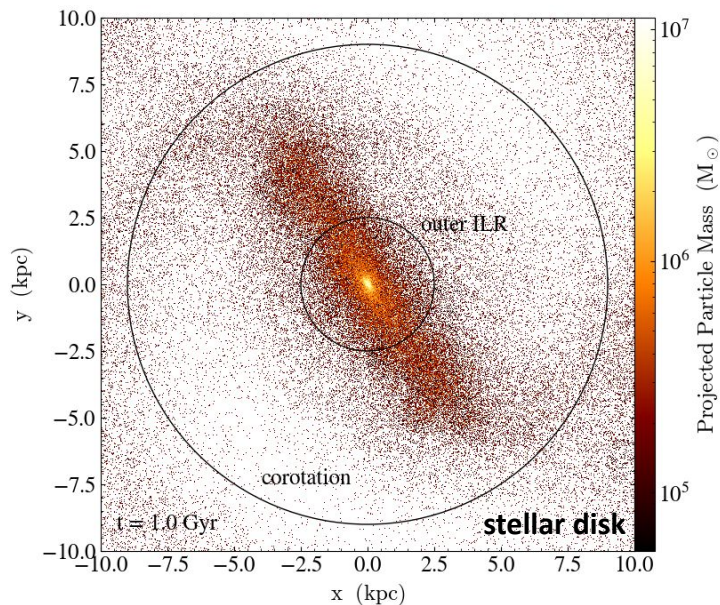
# V/ Fourier Analysis of the bar

Polar + Temporal FFT:  $B_m(\omega, r) = \frac{1}{\sqrt{2\pi}} \left| \int_{\mathbb{R}} \cos(\phi)(m, r, t) e^{-i\omega t} dt \right|$  and  $\Omega_p = \omega/m$

temporal FFT angular frequency  
polar FFT phase



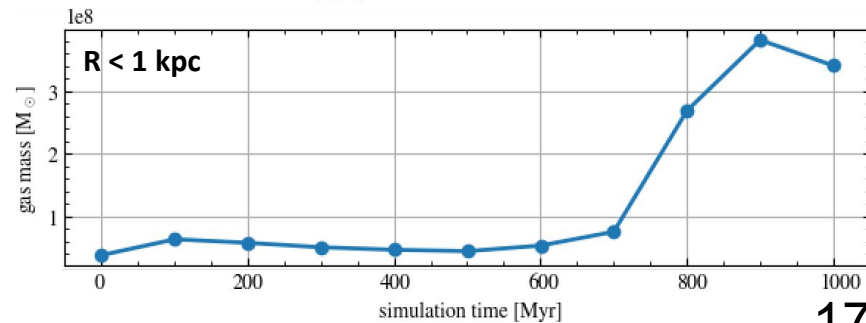
# V/ Fourier Analysis of the bar



## Consistent with classical picture:

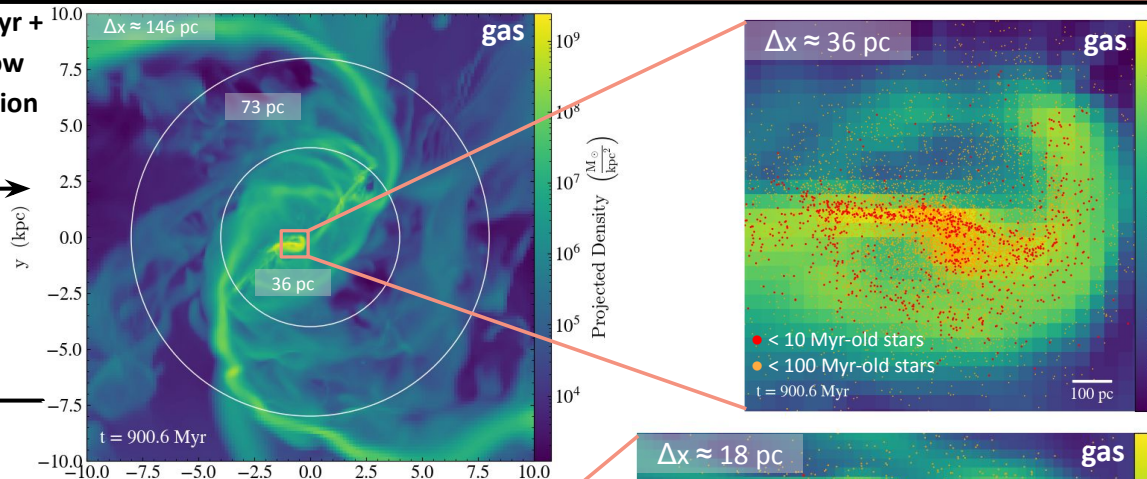
- Bar extends  $\sim$  up to corotation.
- Radial gas migration in the central kpc when bar + ILR.
- Accumulated gas mass  $\sim 10^8$  to  $10^9 M_{\odot}$  as observed (Sheth et al. 2005).

But no ring so far.



# V/ Zoom-in simulations and impact of star formation

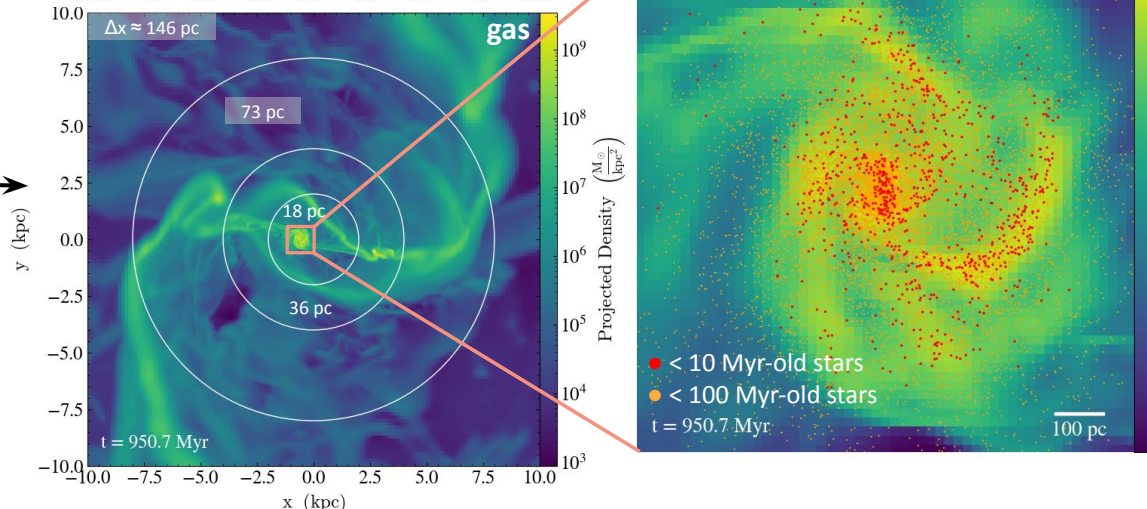
restart from 800Myr +  
zoom from the low  
resolution simulation



1 kpc

Still no ring but maybe  
dynamical **nuclear spirals?**  
Within 1kpc:  $f_{\star, disk} \approx 0.48$   
(close of that of bar-  
forming galactic disk!)

restart from 900  
Myr + zoom



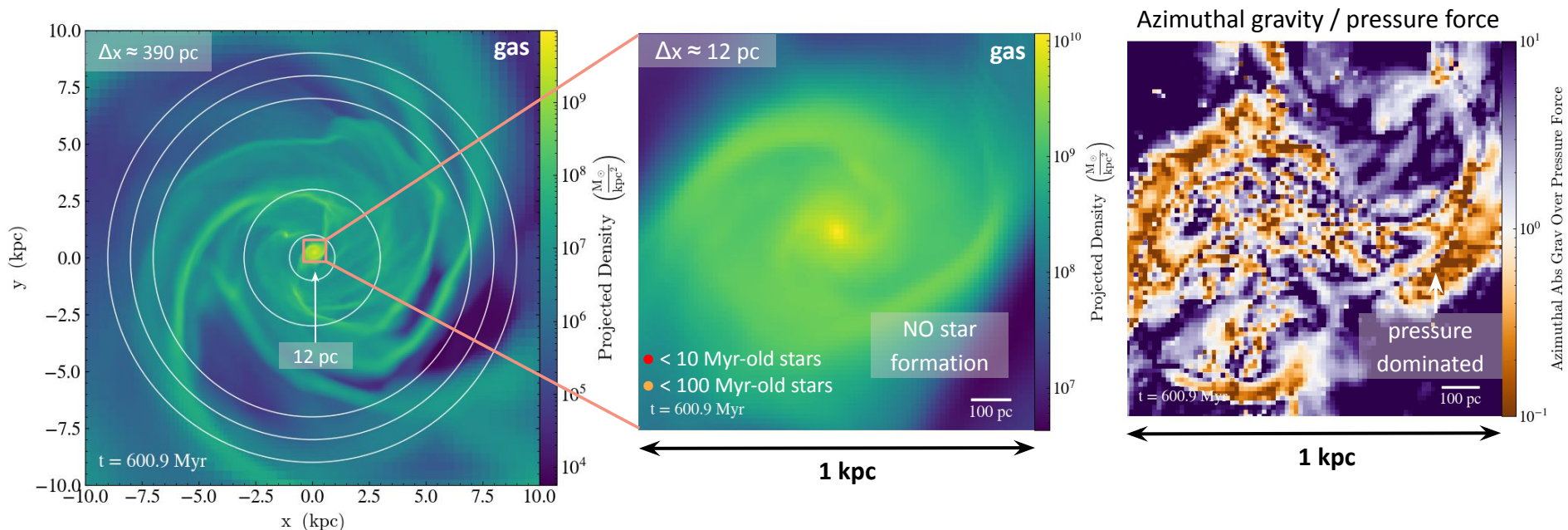
1 kpc

Sign of possible  
**nuclear bar?**

May highly depends on  
the star formation /  
feedback models (and gas  
properties!)

# V/ Zoom-in simulations and impact of star formation

Another problem of star formation in grid-based simulations: link with artificial fragmentation



Artificial fragmentation = **unresolved Jeans length**  $\Rightarrow$  at least 4 cells per Jeans length (Truelove 1997)

$\Rightarrow$  Minimum temperature  $T_{\min}(\rho, \Delta x)$  for density  $\rho$  = "Jeans polytrope"

If new star mass too large  $\Rightarrow$  star formation density threshold too large

no star formation, pressure-dominated inner region

Resonant Theory cannot be tested...

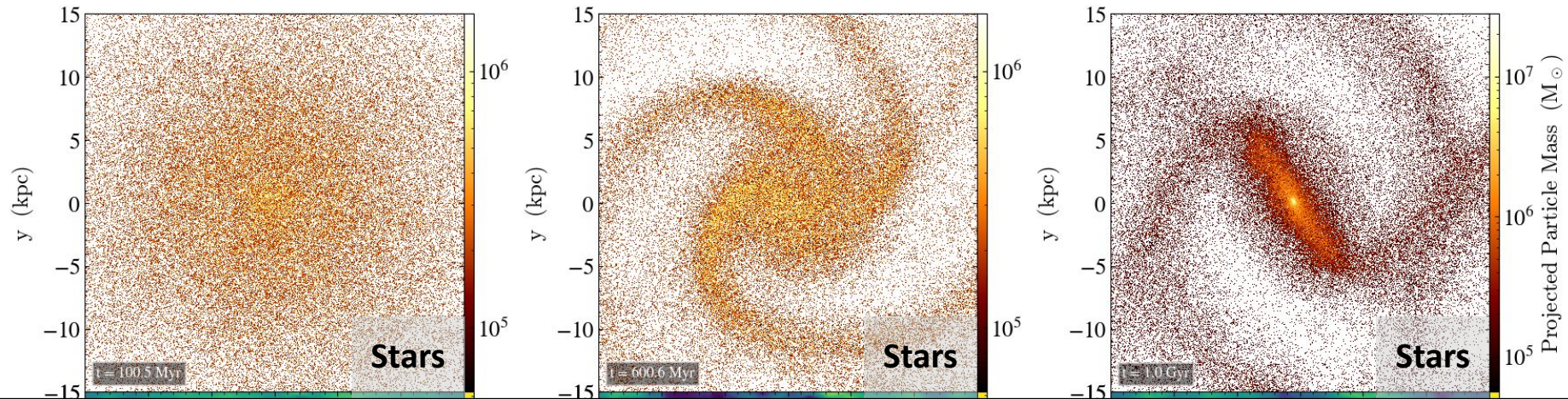
## Conclusion and perspectives

- Nuclear rings **important** for secular evolution and AGN fuelling.
- **Bar-forming isolated galaxies** with consistent large-scale physics can be simulated in RAMSES.
- Adaptive Mesh Refinement → **high spatial resolution** in the inner region, allowing to study nuclear ring formation.
- Nuclear rings are known to occur in very idealized simulations, but more complex formation in more physical contexts. Stellar nuclear spirals from dynamical origin may form more easily.
- **Next steps:** adaptation of subgrid models; orbital analysis to test the scenarios for nuclear ring / nuclear spiral formation.

Thank you for listening!

# Appendices

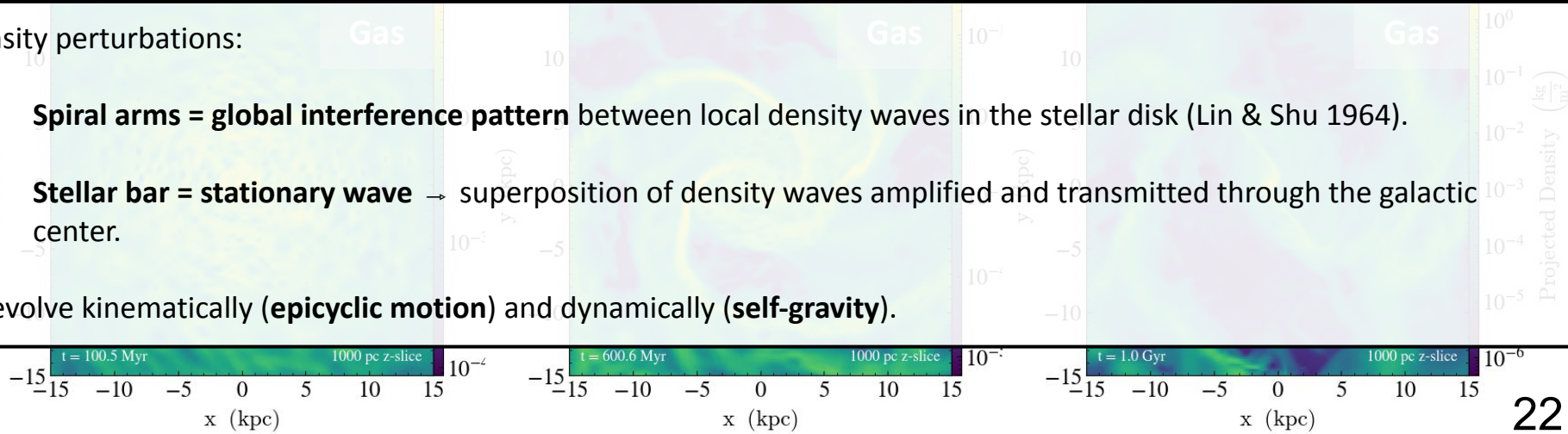
# A/ Simulation of a bar-forming galaxy



Density perturbations:

- **Spiral arms = global interference pattern** between local density waves in the stellar disk (Lin & Shu 1964).
- **Stellar bar = stationary wave** → superposition of density waves amplified and transmitted through the galactic center.

→ evolve kinematically (**epicyclic motion**) and dynamically (**self-gravity**).

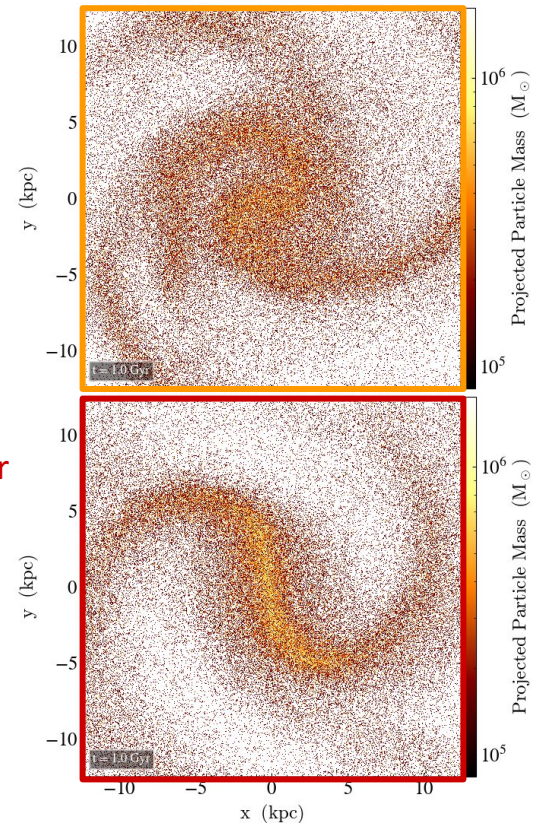
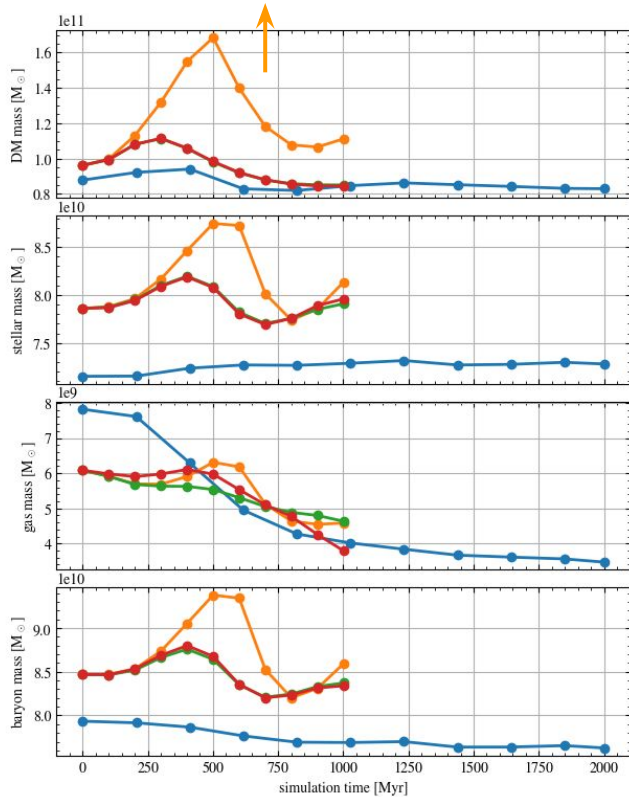
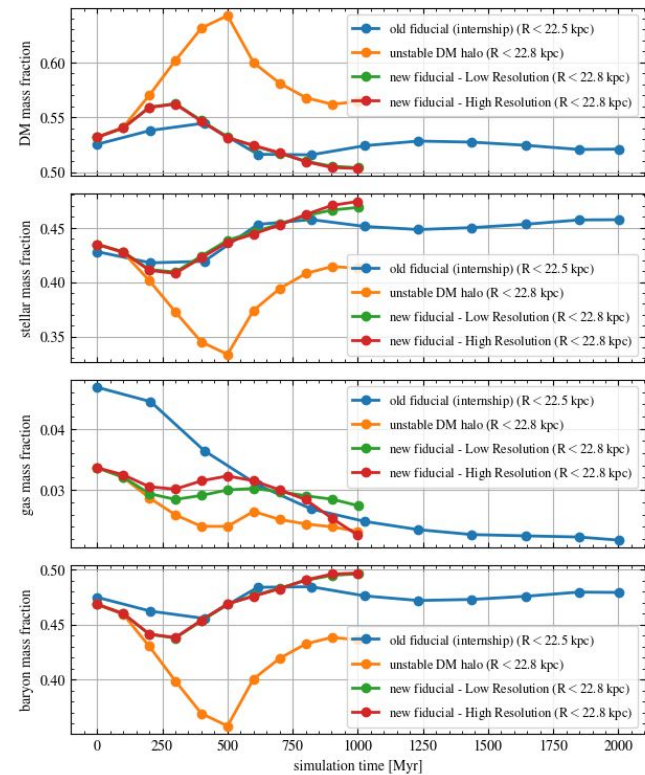


# B/ Bar formation

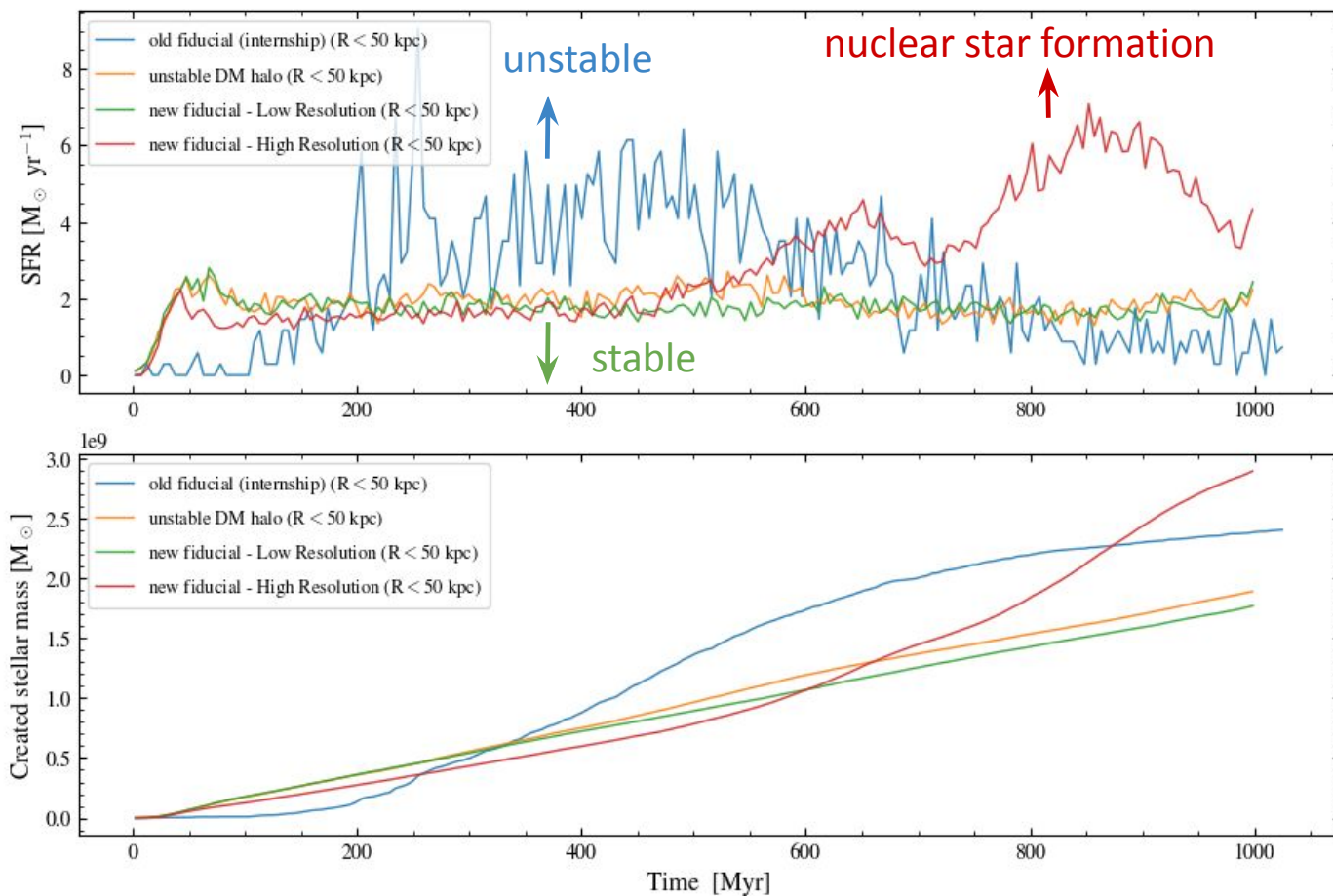
unstable halo  $\Rightarrow$  no bar formation

bar

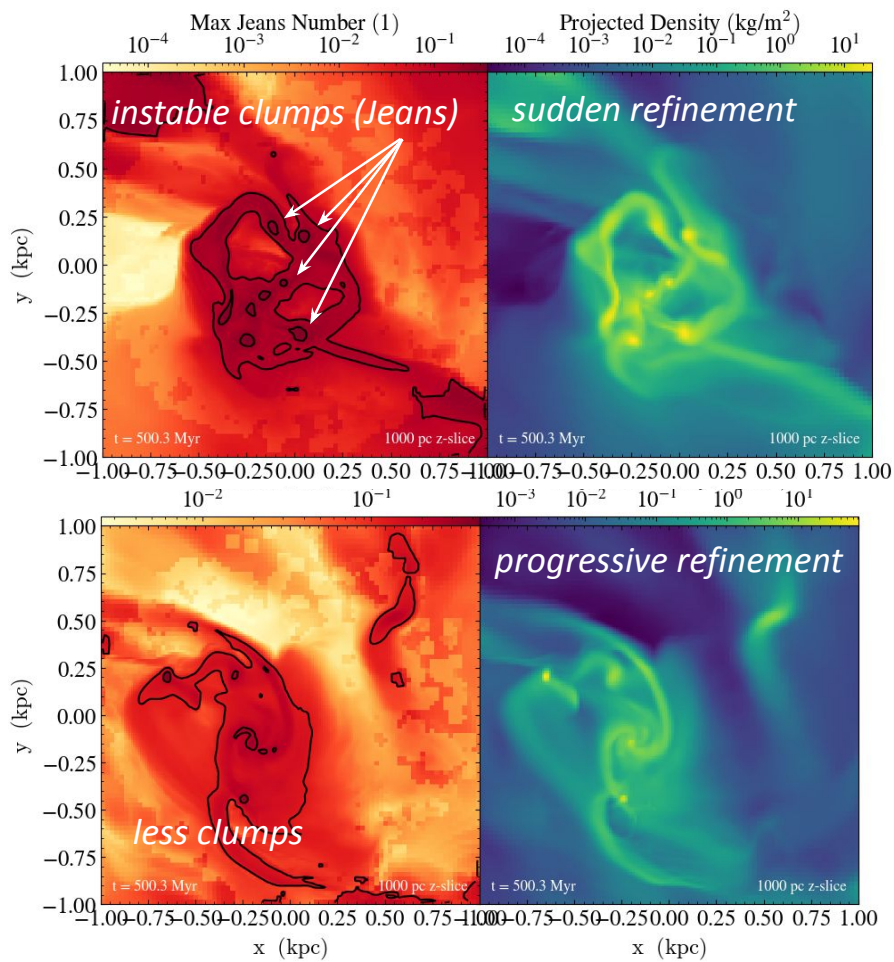
no bar



# C/ Subgrid mode: stable star formation rate

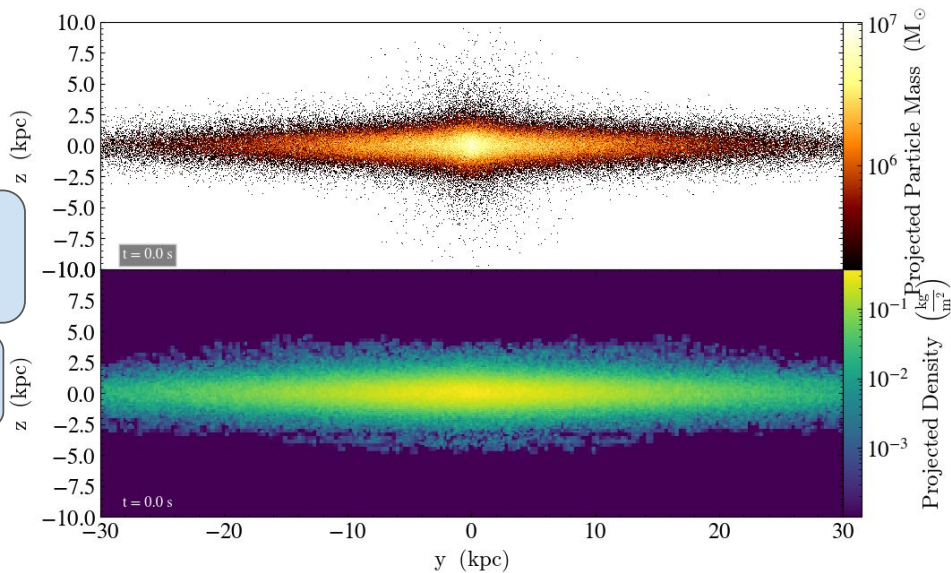
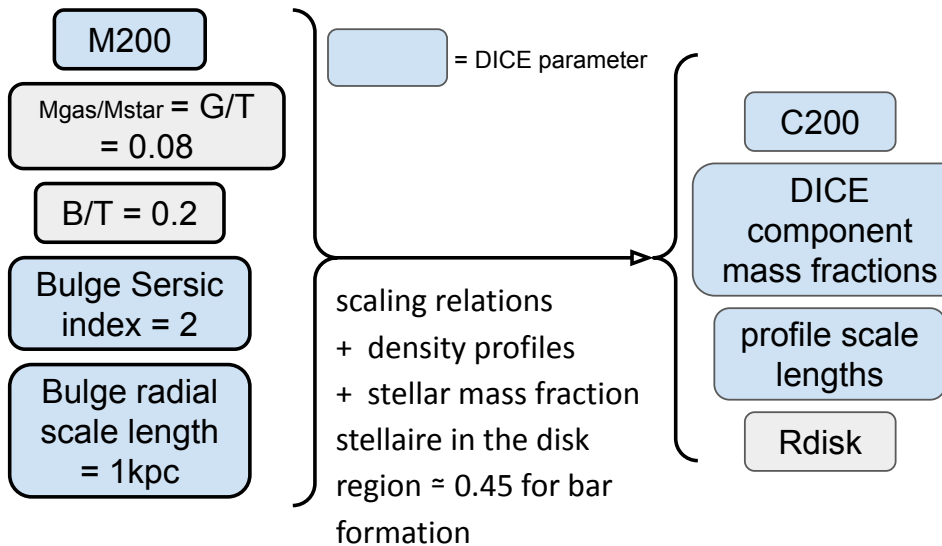


# D/ Progressive refinement rather than sudden refinement

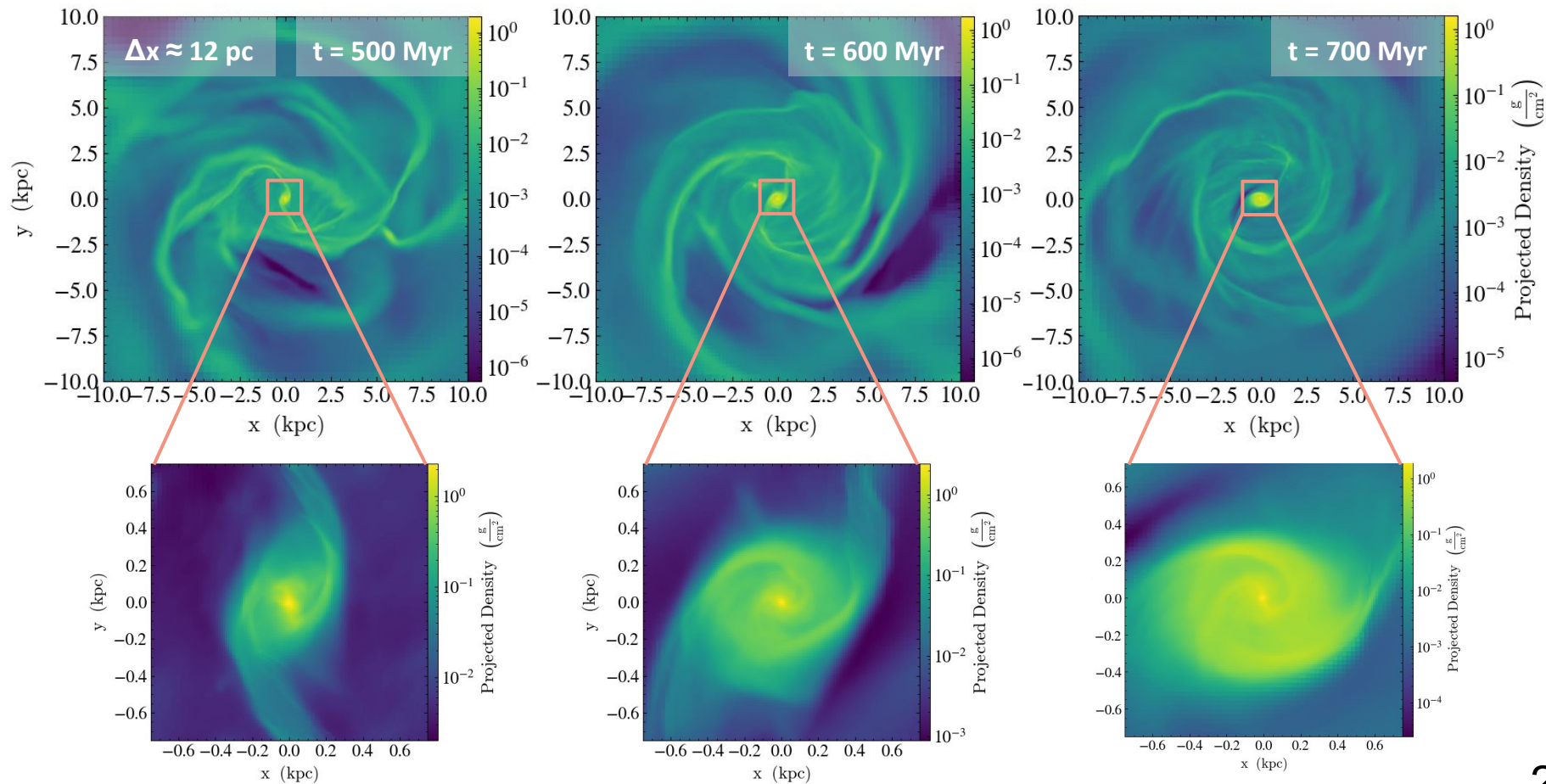


# E/ Initial conditions

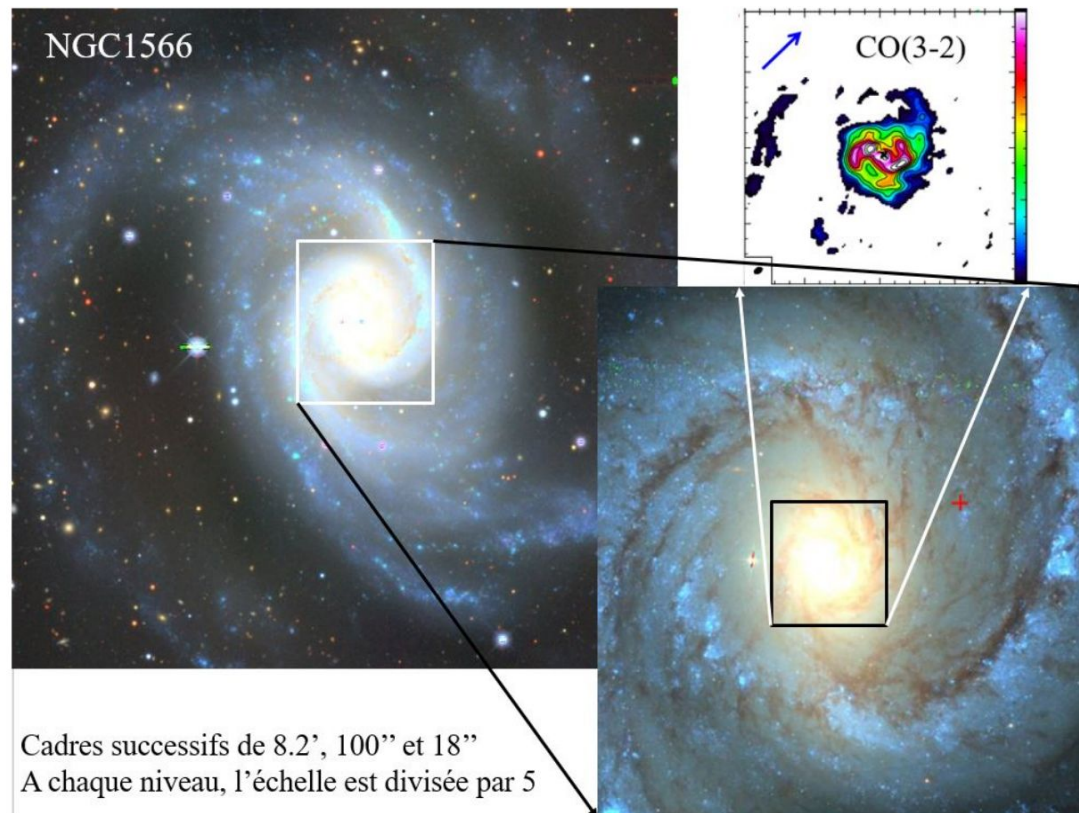
**Idea** : Initial conditions determined by a minimum number of free parameters and using published relations.



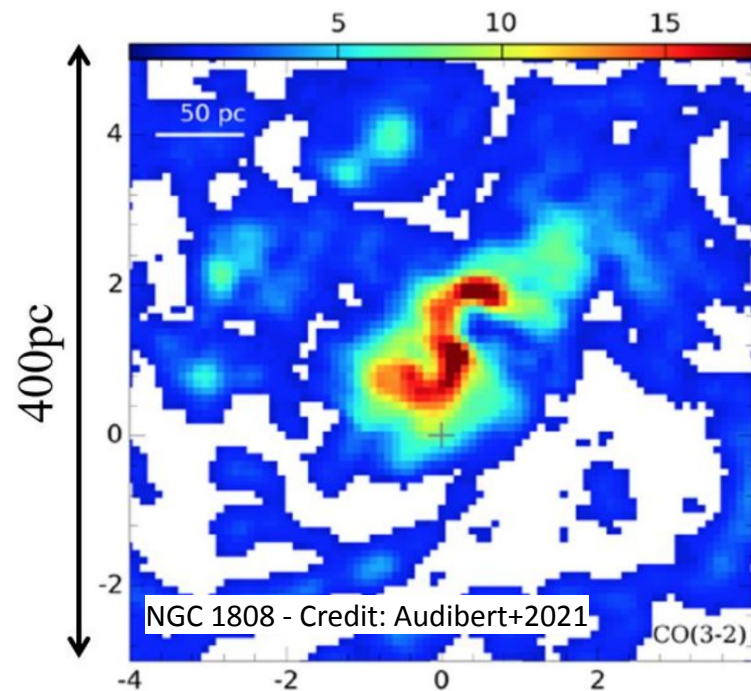
# F/ Zoom-in simulations and nuclear disk



# G/ Context: Nuclear spirals



Adapted from Combes+2014



# H/ N-body simulation of a bar-forming galaxy

## Bar formation from 800 Myr

