Timescales
Galaxy Dynamics

Eric Emsellem

The basics

Time as a velocity versus scale

At 1 km/s, 1 pc is covered in 1 Myr

At 100 km/s, 1kpc is covered in 10 Myr

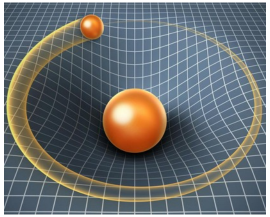
Object	Mass [M☉]	Radius [pc]	Crossing t_c [10^6 yr]	Virialisation t_d [10^6 yr]	Relaxation t_R [10^6 yr]	Evaporation t_e [10^6 yr]
Open cluster	500	1	1	1.6	7.5	240
Globular cluster	10^5	10	2	3.6	1,800	54,000
Galaxy	10^{12}	50,000	250	400	>> 10^{11}	>> 10^{12}
			t_c	$\sqrt{3} \cdot t_c$	$0.1 \times n / \ln(n) \cdot t_c$	$30 \cdot t_R$

[Grav. wave = 60kpc = 0.2 Myr]

Time
for
a change

Time for a change

Timescales set by a measure of change or gradient



Gradient of the gravitational potential $d\Phi/dx$ ⇒ Trajectory

Significant change, e.g. **dE/E** or **dV/V** or **dL/L >> 1**

⇒ timescale for dynamical processes

Time(scales) may be seen relative to either :

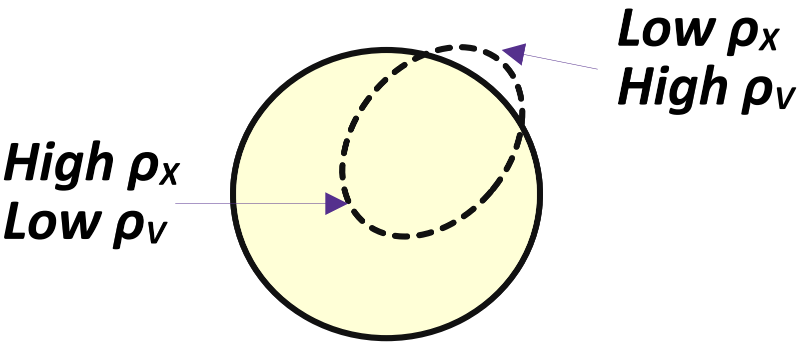
- the amplitude of change

  or

- a another time (another process)

reference timescale?

Time evolution

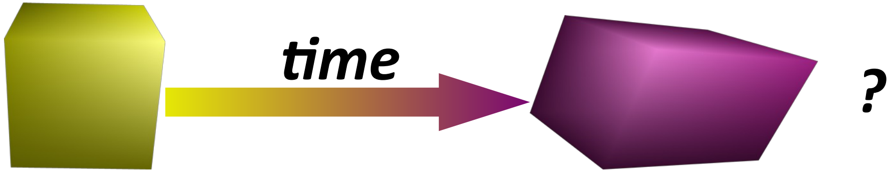


Constant phase-space density

df(X,V) = 0

f = integral of motion

Evolution of a patch of stars



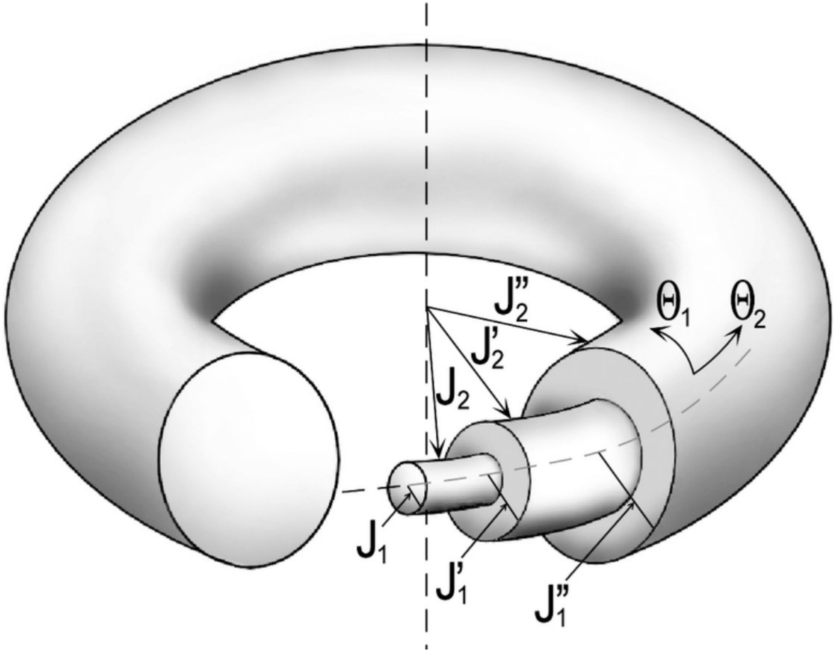
Liouville's theorem

⇒ evolving towards a uniform phase-space density

(within a region)

Mixing timescales

Merritt & Valluri 1996



In 2D

resonant tori when 2 frequencies ω_1, and ω_2 are commensurate [$l.\omega_1 = m.\omega_2$] ⇒ orbit is closed (1D)

In nD

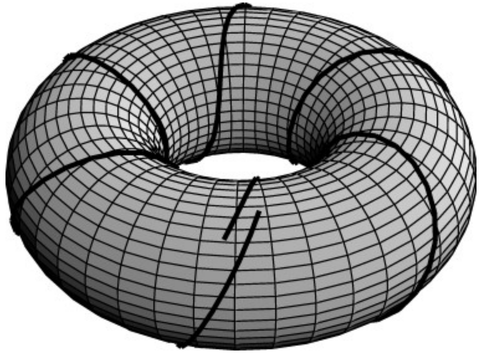
each relation ω_i vs ω_j decreases the dimensionality of the orbit

Trajectory in phase-space

Can be described as motion on a torus

⇒ dimensions defined by Actions (**J_i = cte**)

⇒ position defined as Angles ($\theta_i = \omega_i\, t$ + cte)



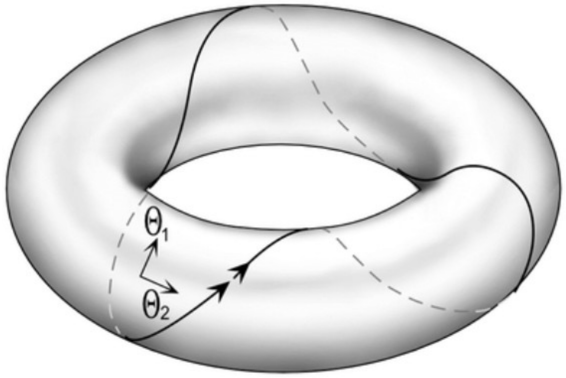
Phase and Chaotic mixing

Merritt & Valluri 1996

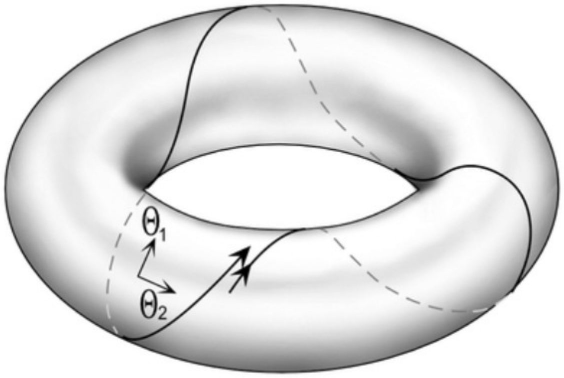
Resonant tori can be unstable

Fast vs slow motions (low vs high frequencies) : $\omega_1 << \omega_2$

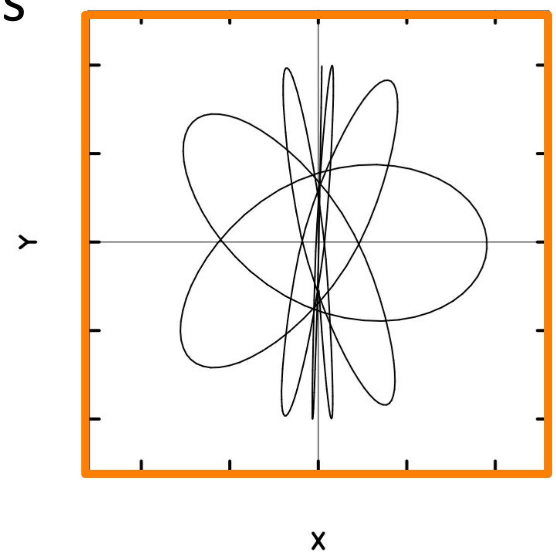
⇒ neighbouring resonances get very close to each others



Resonant torus



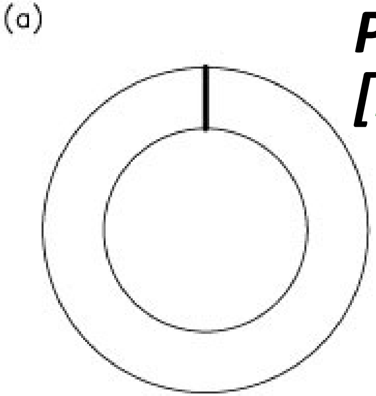
Non-resonant torus



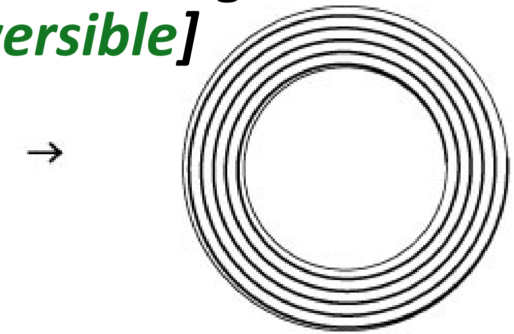
very complex motion ⇒ **exponential divergence**

Phase and Chaotic mixing

Merritt & Valluri 1996



Phase mixing
[reversible]

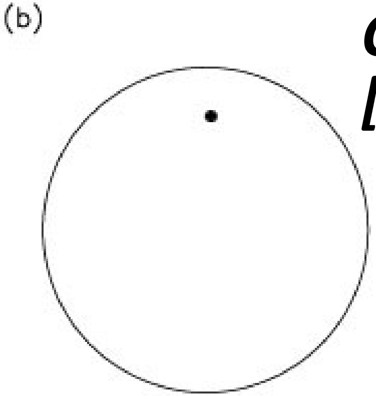


Linear evolution

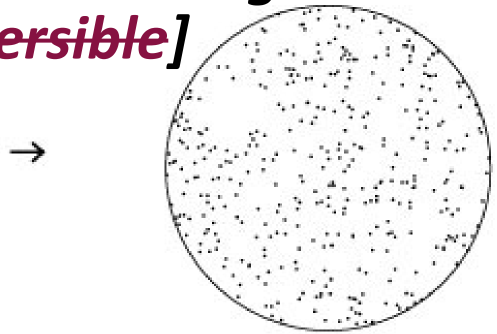
⇒ <u>no well-defined</u> timescale

[depends on 1 / ($\omega_{max} - \omega_{min}$)]

>> $t_{dynamical}$



Chaotic mixing
[~~reversible~~]

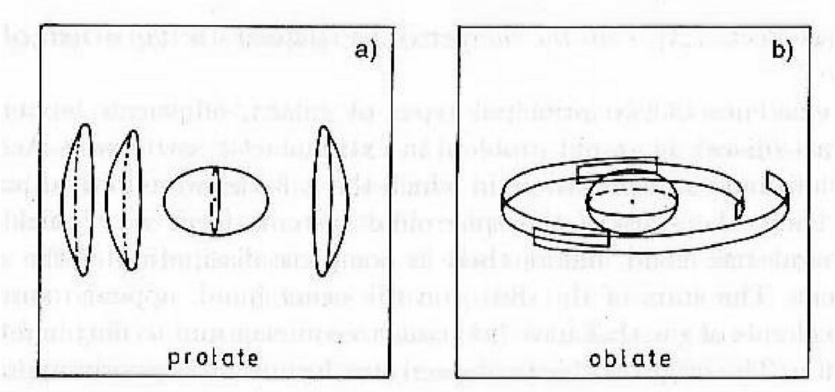


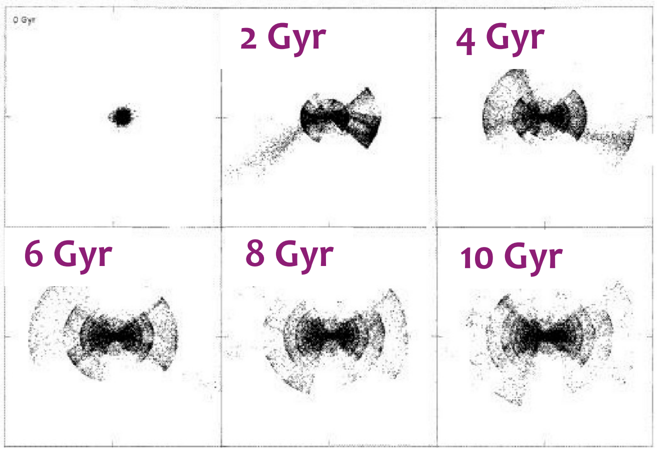
Exponential divergence

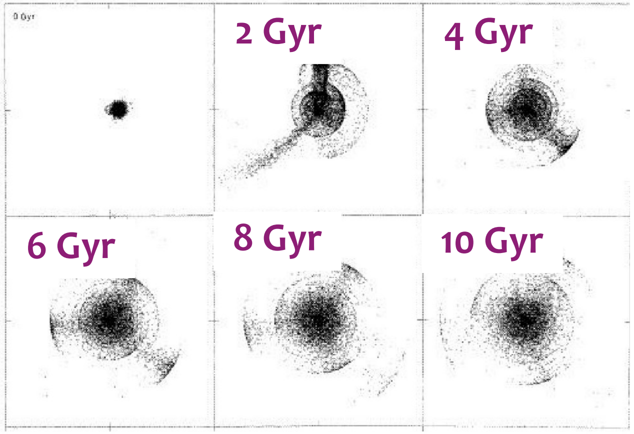
⇒ timescale defined by Lyapunov exponents

Phase mixing

Dupraz & Combes 1986





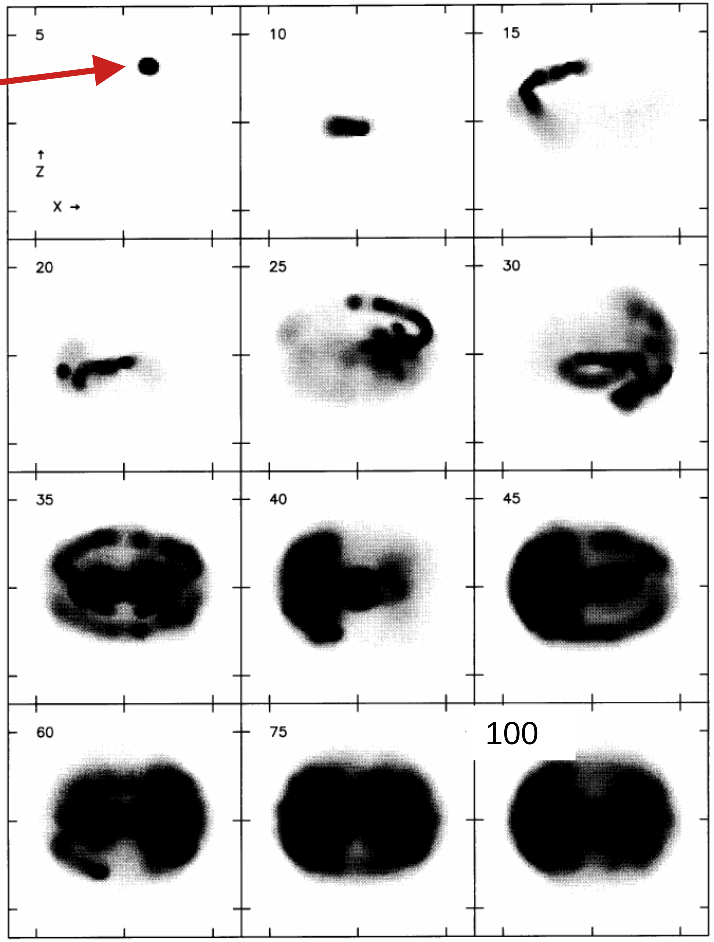


Long timescale (Gyr – Hubble time)

Chaotic mixing

Merrit & Valluri 1996

Initial patch of stars

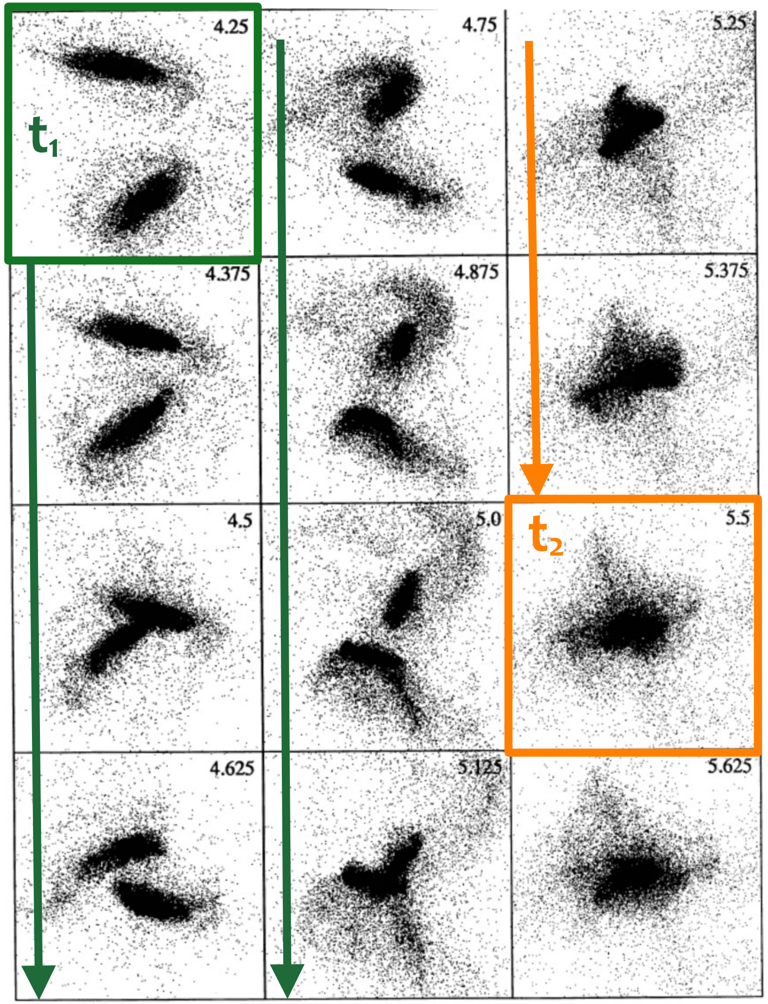


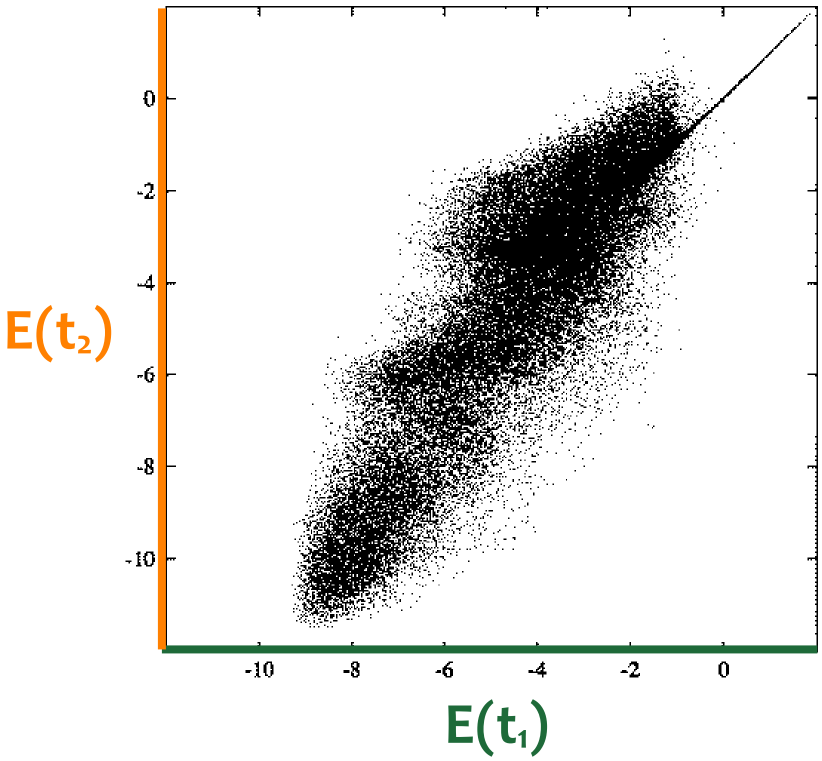
In units of Dynamical times

Mixed within the allowed phase-space volume in about **100 t_D**

Relaxation timescales (varying Φ)

Barnes 1992





A Hubble time perspective

Long timescales – small changes

Some processes have very long timescales

- Dynamical friction
- Mixing at large scale

⇒ Potential changes over the age of the universe
⇒ Difficult to observe / detect

Risk to mis-interpret observations to fit our Theories

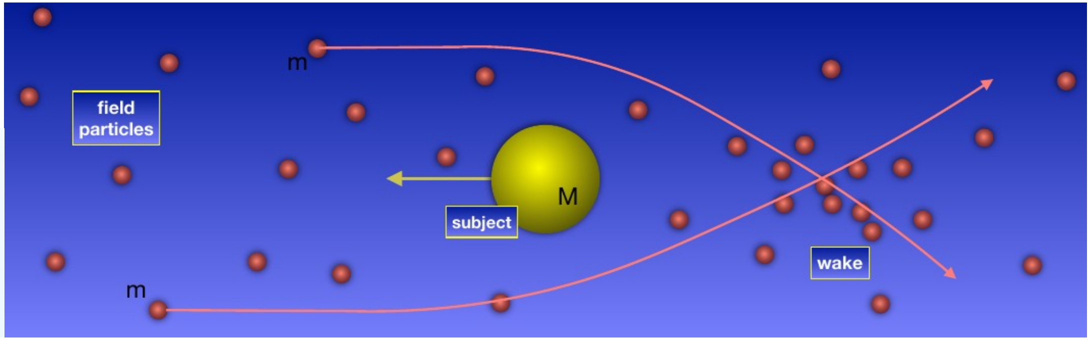
How do we consolidate the existence of such processes, predicted by Theory ?

Dynamical friction as an illustration

We think we understand it well

- Chandrasekhar formula !

$$t_{fric} \simeq \frac{v^3}{G^2 \rho m_0 \ln \Lambda}$$



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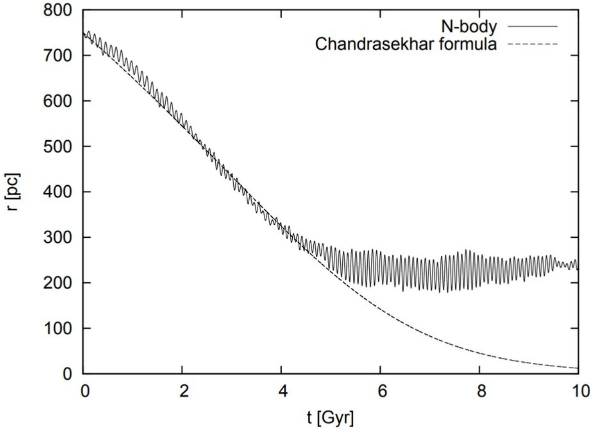
But…

- ✗ Perturber will be stripped ⇒ reduces mass ratio ⇒ increases t_{fric}
- ✗ Depends on orbit excentricities (e.g. van den Bosch et al. 1999)
- ✗ Potential will vary ⇒ ?

- ✗ Numerical experiments show a saturation…

  (Goerdt+06, Read+06, Inoue+11, Petts+16, Zelnikov+16, Dutta Chowdhury+19)

Inoue 2010



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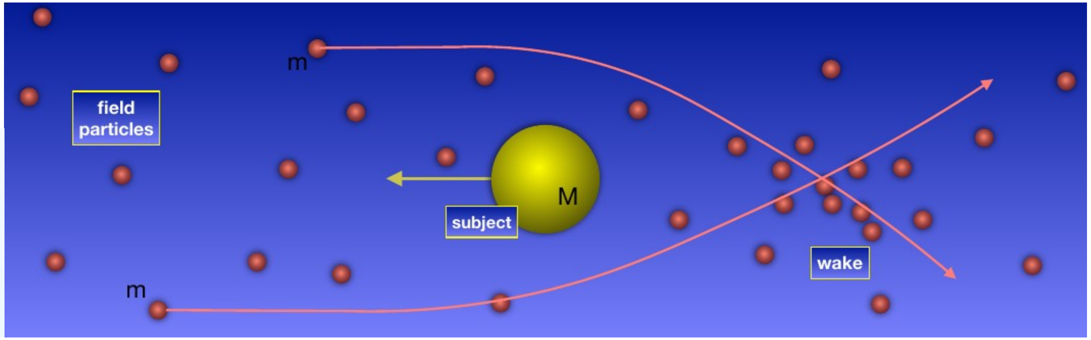

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And…

✗ Inside flattened cores, there is a potential ***dynamical buoyancy due to a specific set of orbits towards the centre***

Important implications for: nuclear clusters, BH binaries, group evolution ?

Testing theories

We do not understand it...

$$t_{fric} \simeq \frac{v^3}{G^2 \rho m_0 \ln \Lambda}$$

Can we robustly predict :

→ the decay of e.g., Milky Way satellites (Sagitarius dwarf) ?

Simple predictions = decay in a few Gyr

Also : a number of small satellites should already have mergedIs that consistent with what we observe ?

→ Evolution of galaxy group ?

→ Evolution of globular clusters in a dwarf ?

Merritt (2021) using Feyerabend's rule :

- falsification nearly impossible : hard to observe
- Highly problematic and questions the existence of dark matter ?

Testing theories

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Can we trust our numerical experiments ?

➔ Timescales depend on physics but also on numerics and set up (gas, dark matter, number of particles, etc)

Density Waves

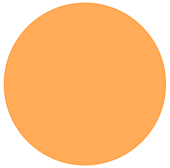
Density Waves = the cavity

Galactic disk ***seen as a cavity*** where waves can propagate

As they propagate (at group velocity)

- their properties (pitch angle, amplitude, …) change

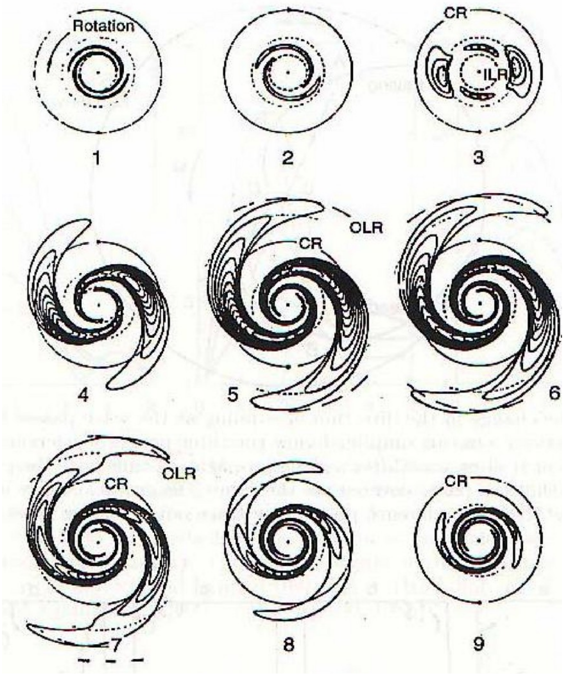
≡



Timescales for those waves to propagate:

- group velocity : 5 – 20 km/s

⇒ **in 100 Myr = 0.5 – 2 kpc**



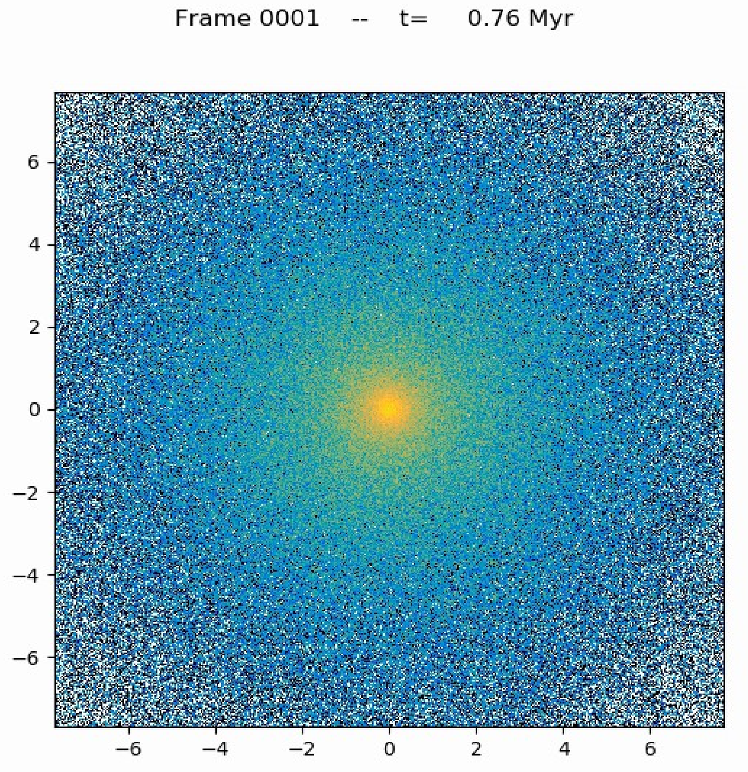
Galactic disk gravitational potential

= superposition of waves with varying scaling

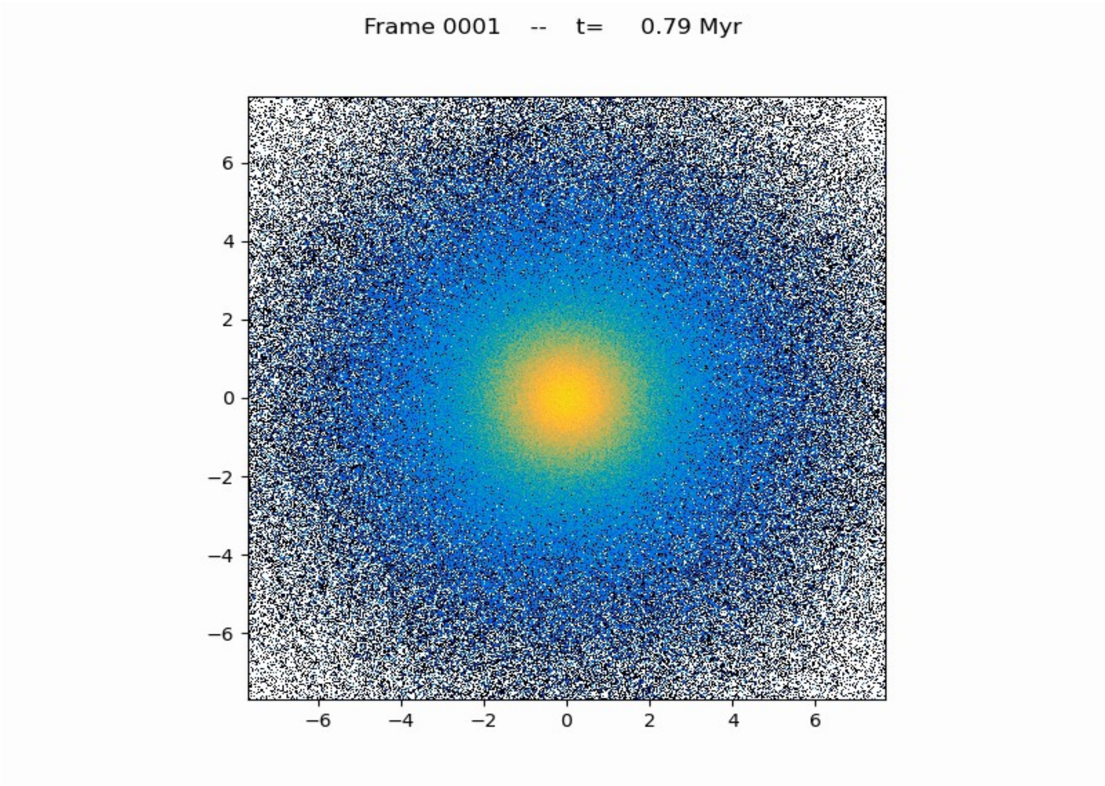
⇒ Some wave get amplified, some damped

Density Waves = the cavity

Steady state ?



Density Waves = the cavity



Testing theories

Can we trust our numerical experiments ?

→ Timescales depend on physics but also on numerics and set up
(gas, dark matter, stellar evolution, number of particles, binaries, etc)

e.g., Can (cosmological) simulations exhibit the right evolution timescales ?

(not even resolving discs ? Can we pls count/measure bars?)

Time and Phases

Phases

Formation of the bar

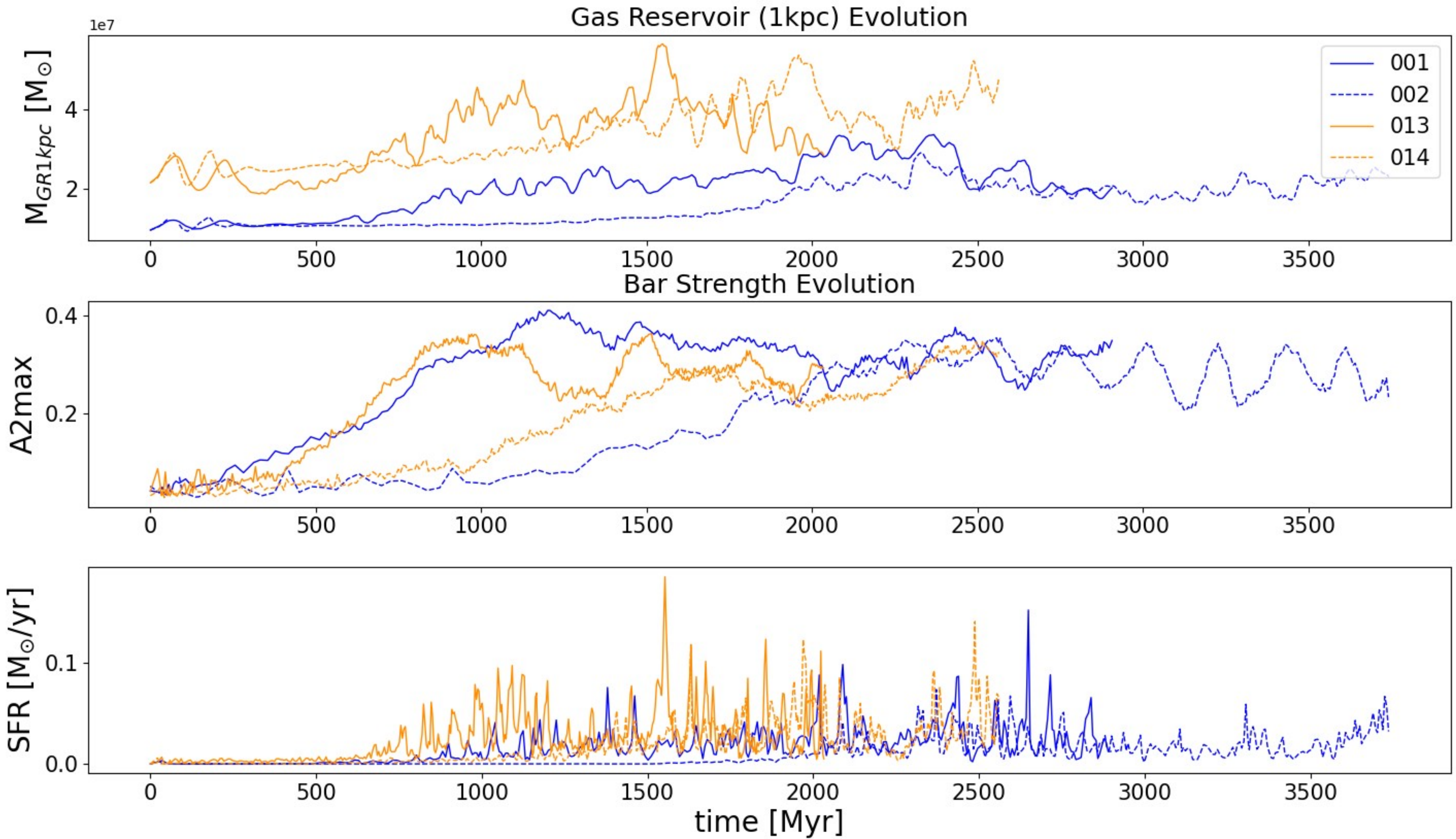
Plateau

Phase shift (spiral, bar)

Damping or self-destruction

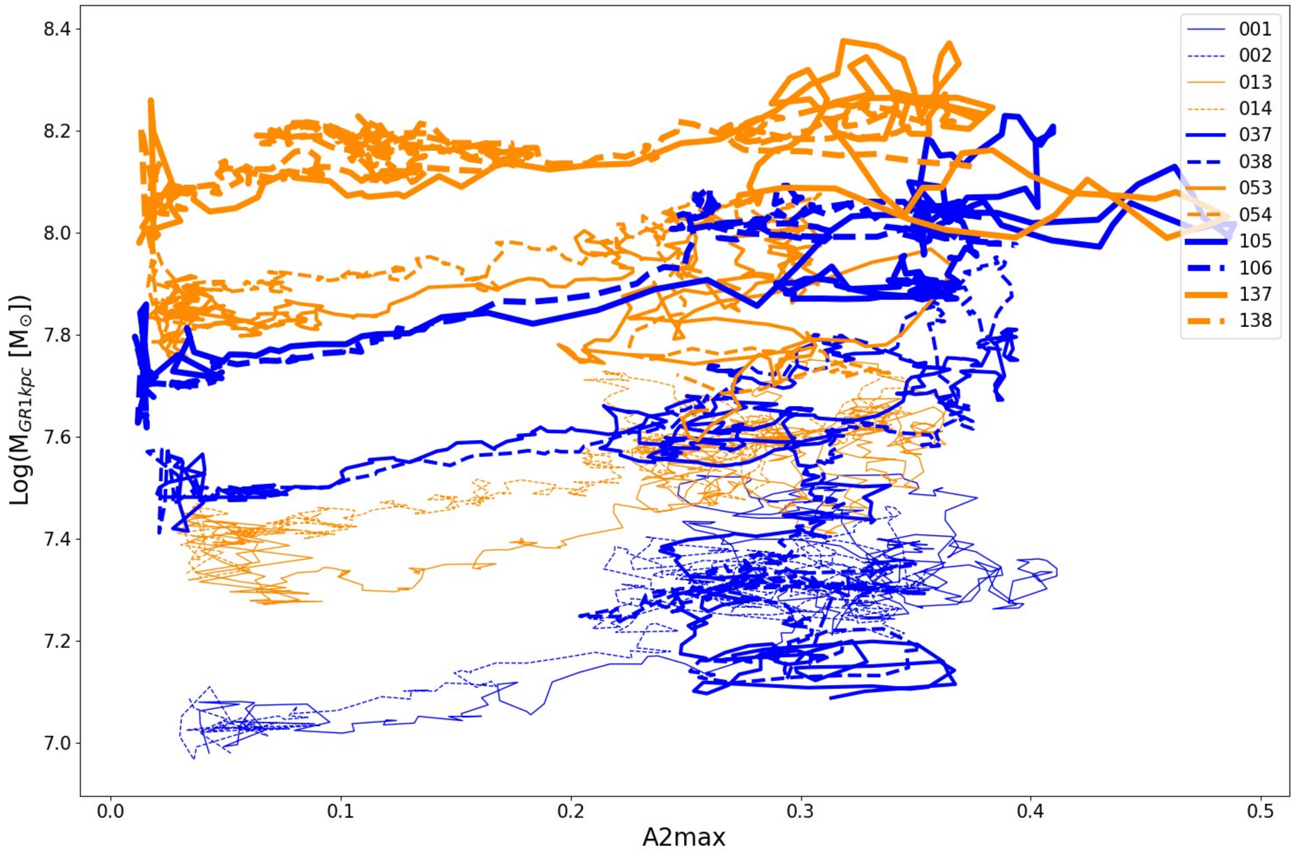
From birth to maturity

Verwilghen et al. In prep



Timescales

Verwilghen et al. In prep



- Gas fraction 10%
- Gas fraction 20%
- No bulge

-- Bulge 10%

Phases

- **How to determine the phase and associated timescales ?**
  - Formation
  - Plateau
  - Weakening / self-destruction

- Reversibility and Time direction: ***can we tell which way it goes ?***
  - formation or damping of bar ?
  - stabilising or destabilising ?

Stars+DM able to trigger high contrast structures ⇒ fast evolving

⇒ **Textbook Galactic dynamics barely exist = Importance/Relevance of**

Environment, interactions, replenishment of gas reservoir

Gas (re-)distribution, star formation, feedback

Coupling Galaxy potentials – Gas distribution / SF

Which sub-volume of “Tuples” (Potential/Gas-distrib) do galaxies occupy?

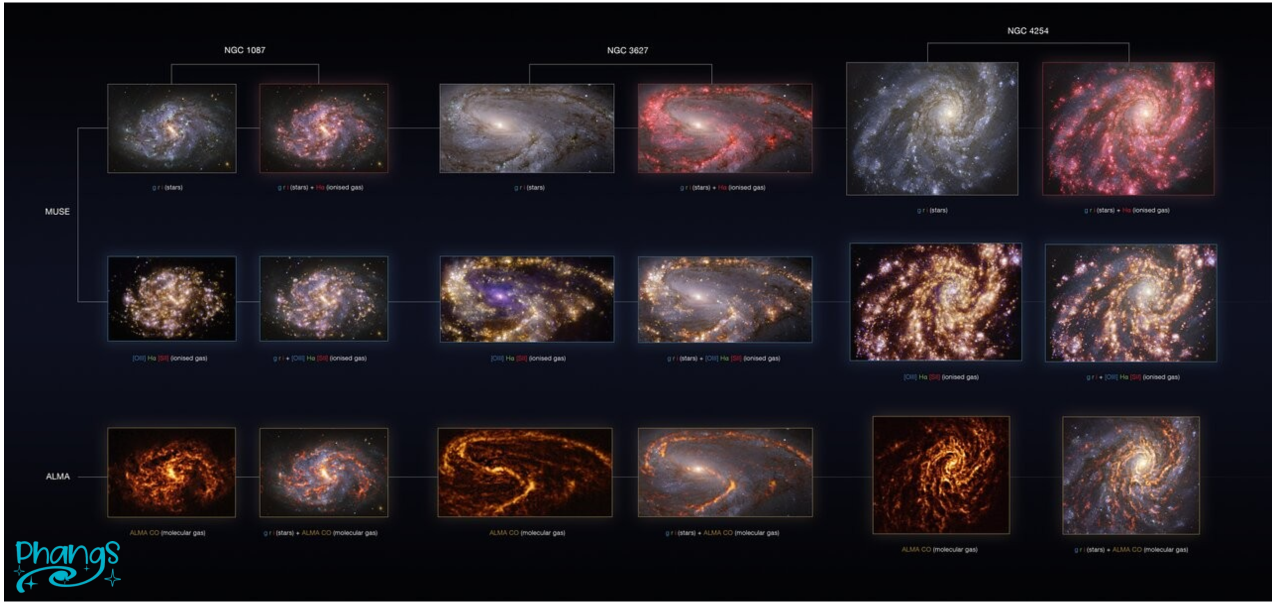
Why: Evolution? Physics?

Q 1 ⇒ A bar strengthens : gas flows change ⇒ potential change ⇒ Bar ?

Q 2 ⇒ Is a given gas flow a unique tracer of the galaxy potential ?

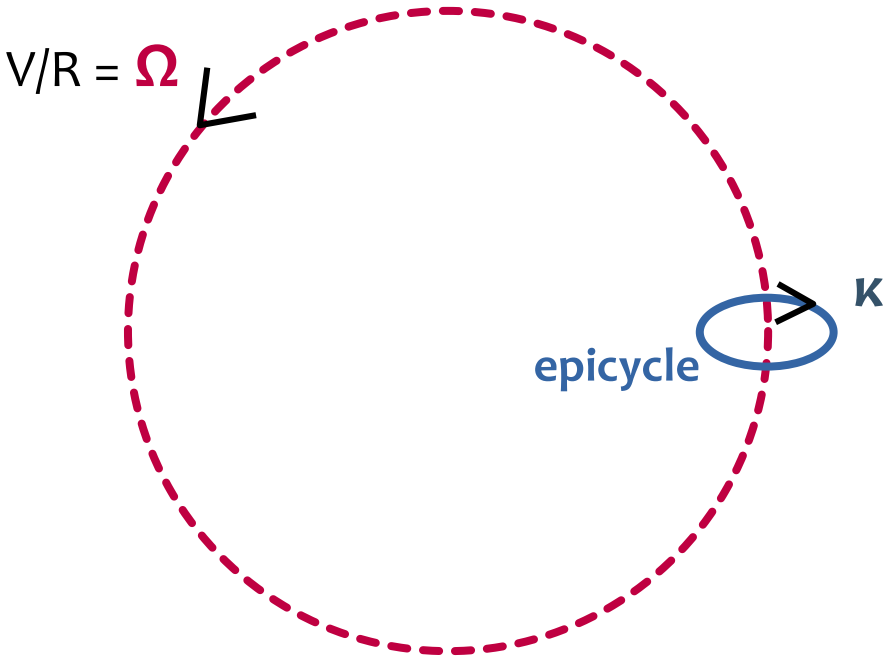
Q 3 ⇒ What can we predict from the gas distribution/flow alone ?

How can Simulations help?

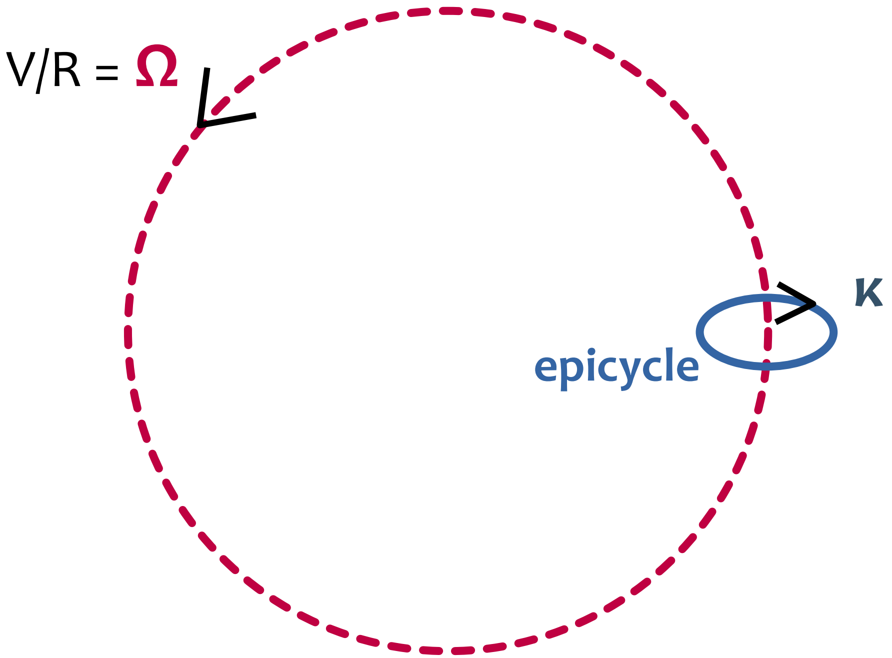


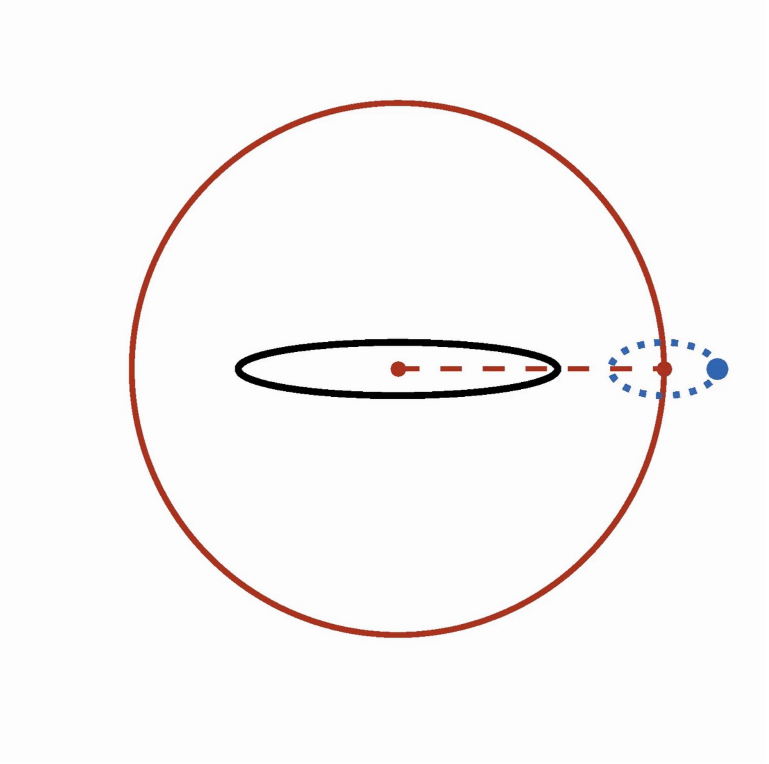
Timescales Conversations

Perturbed orbit → Epicycles



Perturbed orbit → Epicycles





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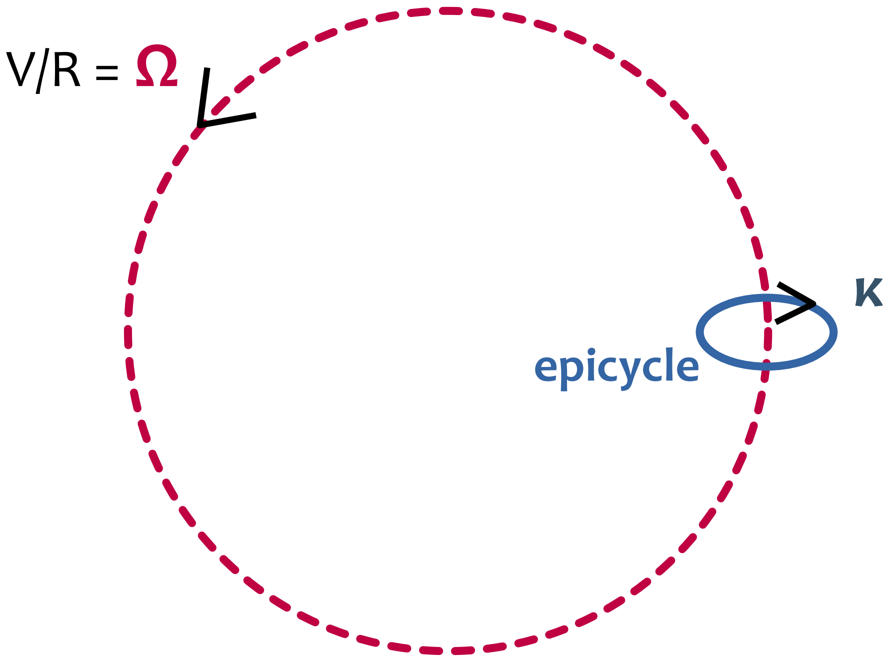
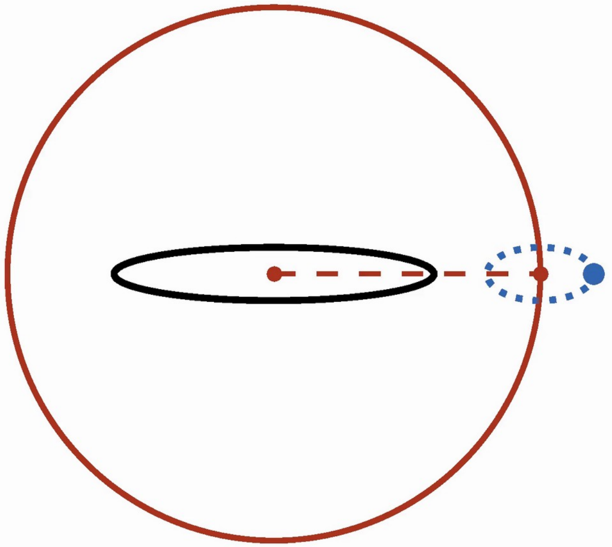




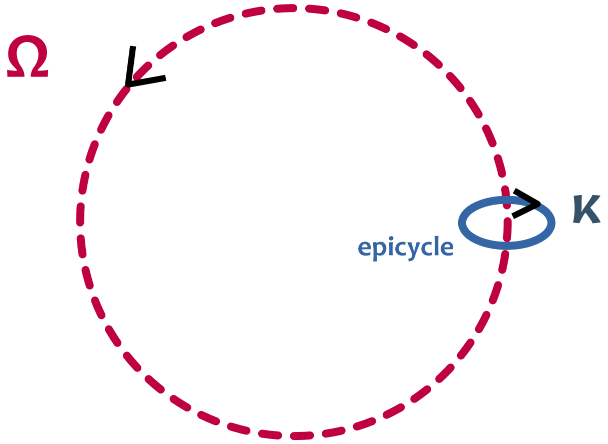
Resonating

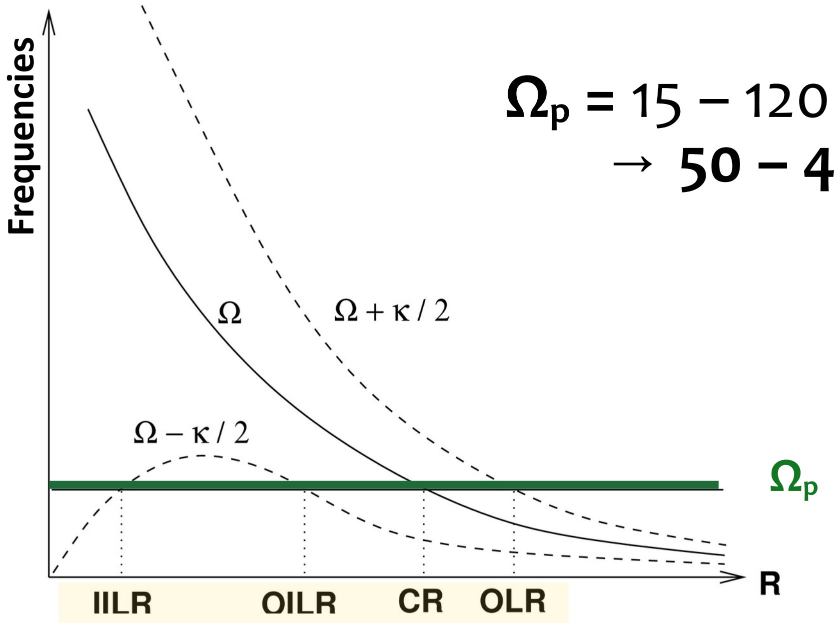
When two timescales are present

- Emergent processes

➔ Dynamical timescales versus [SF, feedback, …] timescales

➔ Disk frequencies (e.g., Ω, κ) versus Wave freq (Ω_p) → ***dynamical resonances***





Ω_p = 15 – 120 km/s/kpc

→ **50 – 400 Myr**

Dynamical resonances

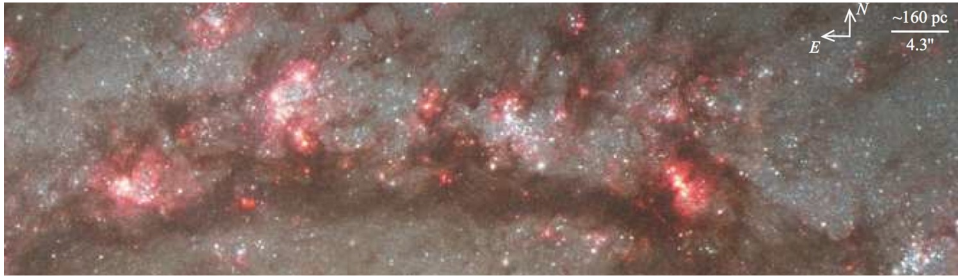
Locations of resonances

- Organise the gas distribution
- Determines where gas accumulates, form stars etc

  e.g., rings / central region

Generally speaking

Dynamics → determines where the energy is released !



2 examples

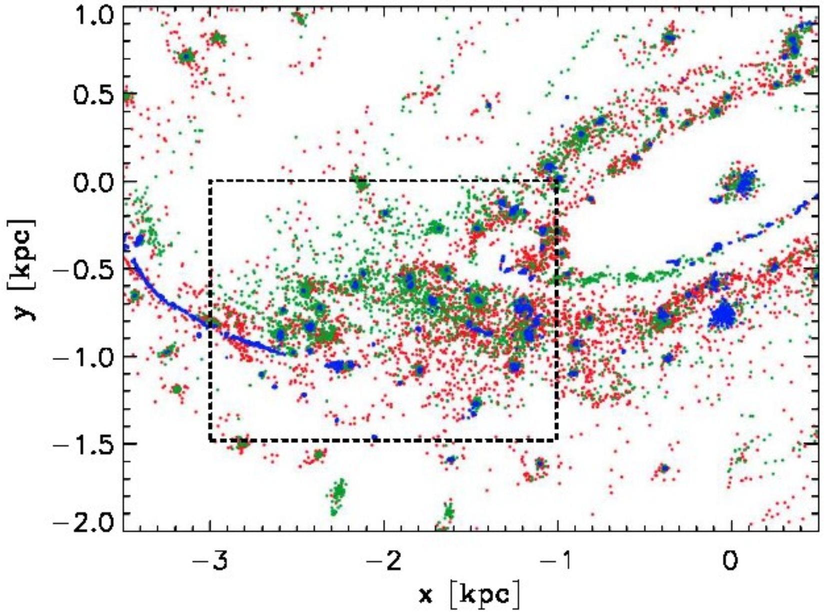
1- Bar ends → collisions

2- Clouds at corotation

Giving time

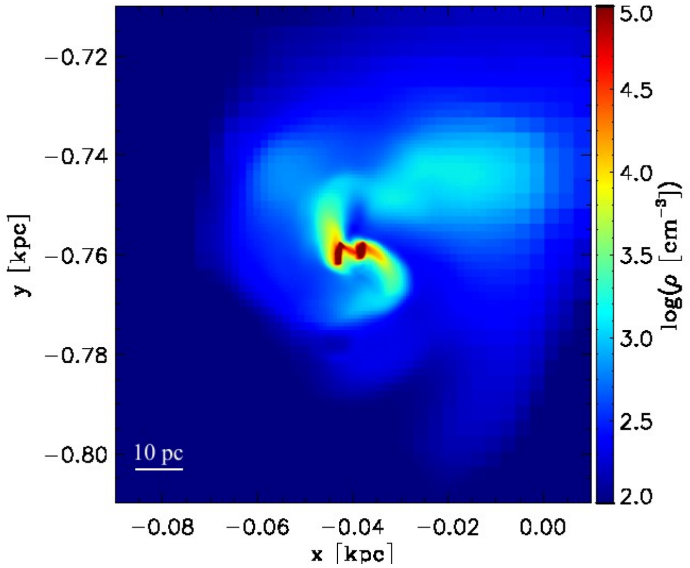
Renaud, Bournaud, Emsellem et al. 2015

Another way to have clouds collide



< 20 Myr
20 – 40 Myr
> 40 Myr

Forming 5 10^6 $M_\odot$ clusters (W43)



Cloud-cloud collisions boost the SFE

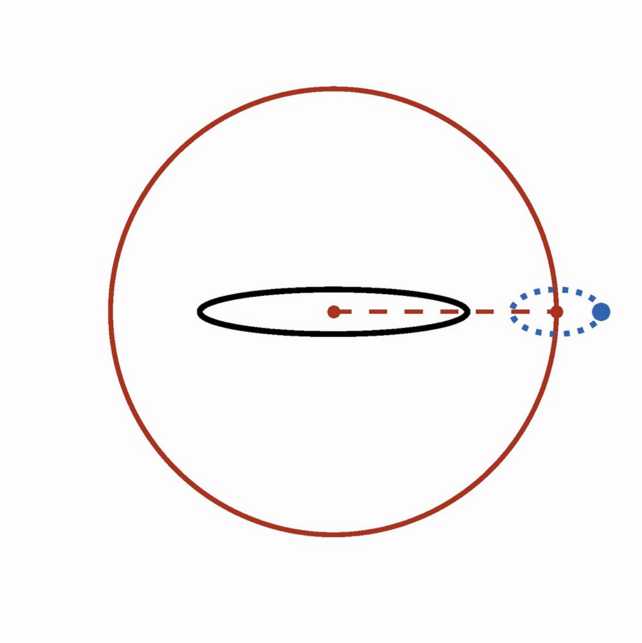
Just like galaxy collisions!

Star clusters witnessed far from their birth sites

Giving time

Forming large gas clouds at corotation

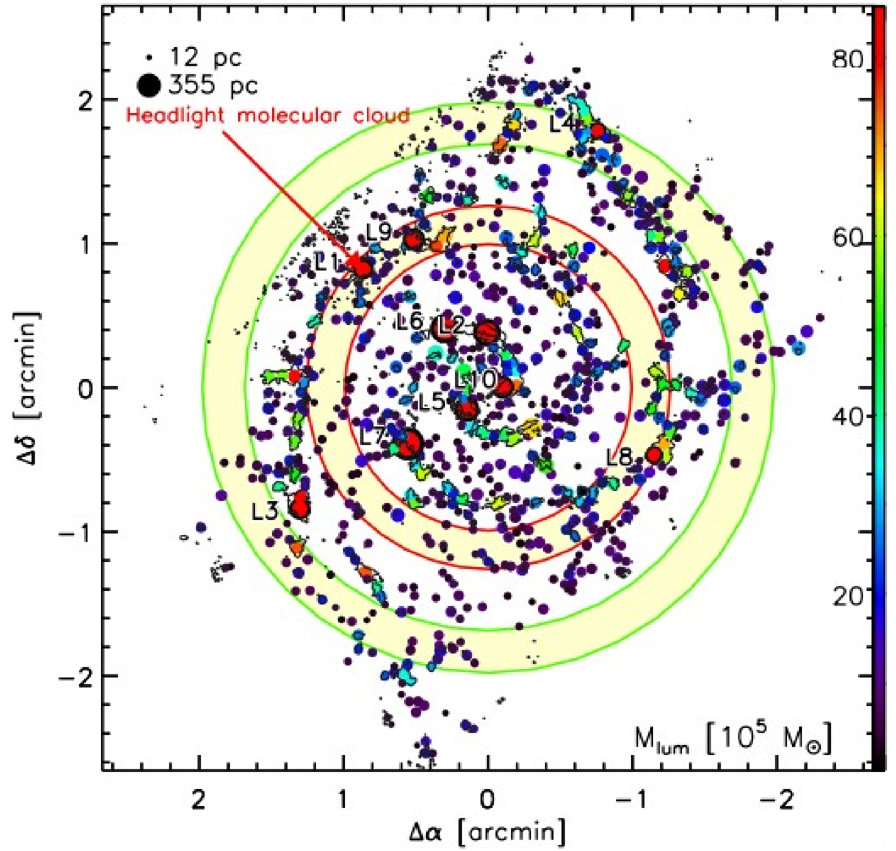
→ the headlight cloud in NGC 628

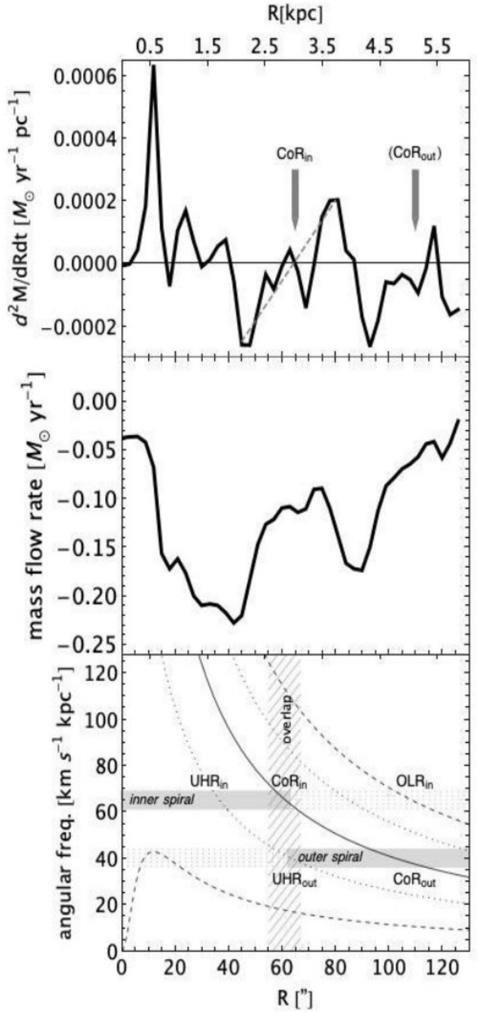


Giving time

Herrera et al. 2020

Forming large gas clouds → the headlight cloud in NGC 628

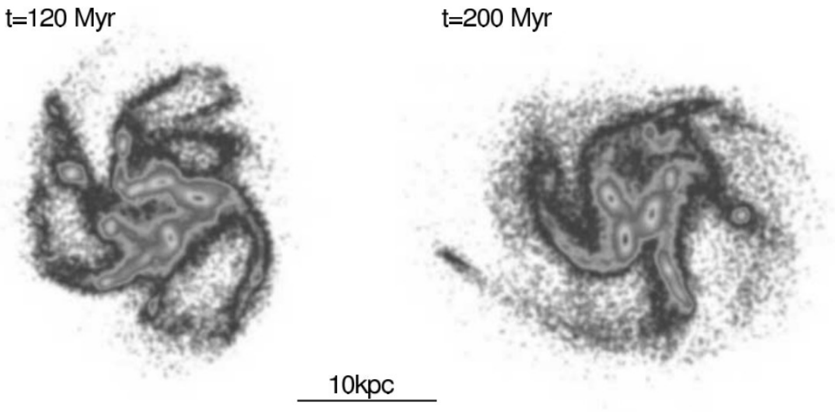




Giving time for seed Black Holes

Bournaud et al. 2007

Time for black holes to form before seeding the central region ?



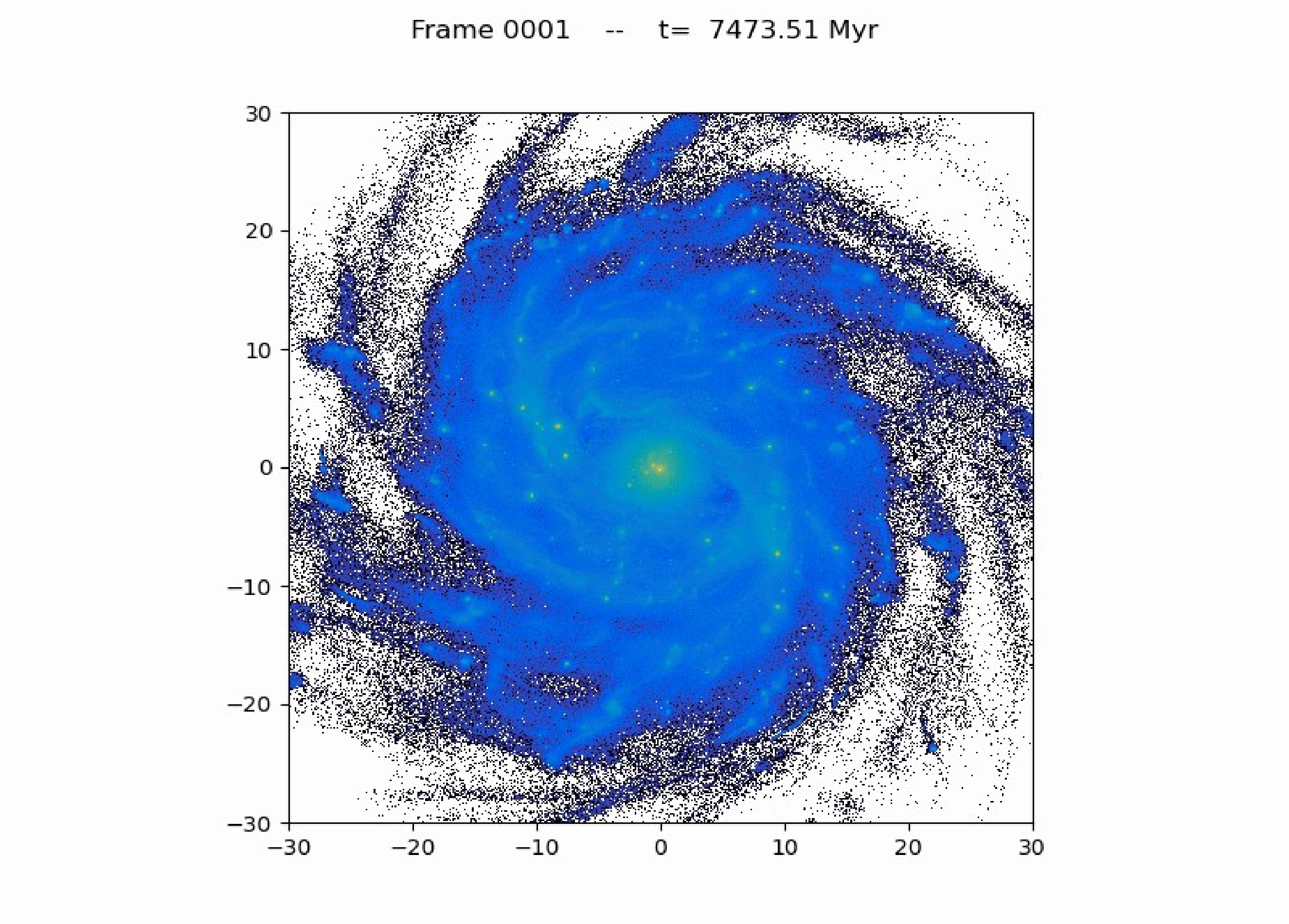
Uncertain timescales for clusters to evolve
Varying environments
Very complex interplay with gas and SF

Can we answer that question with numerical experiments? What else?

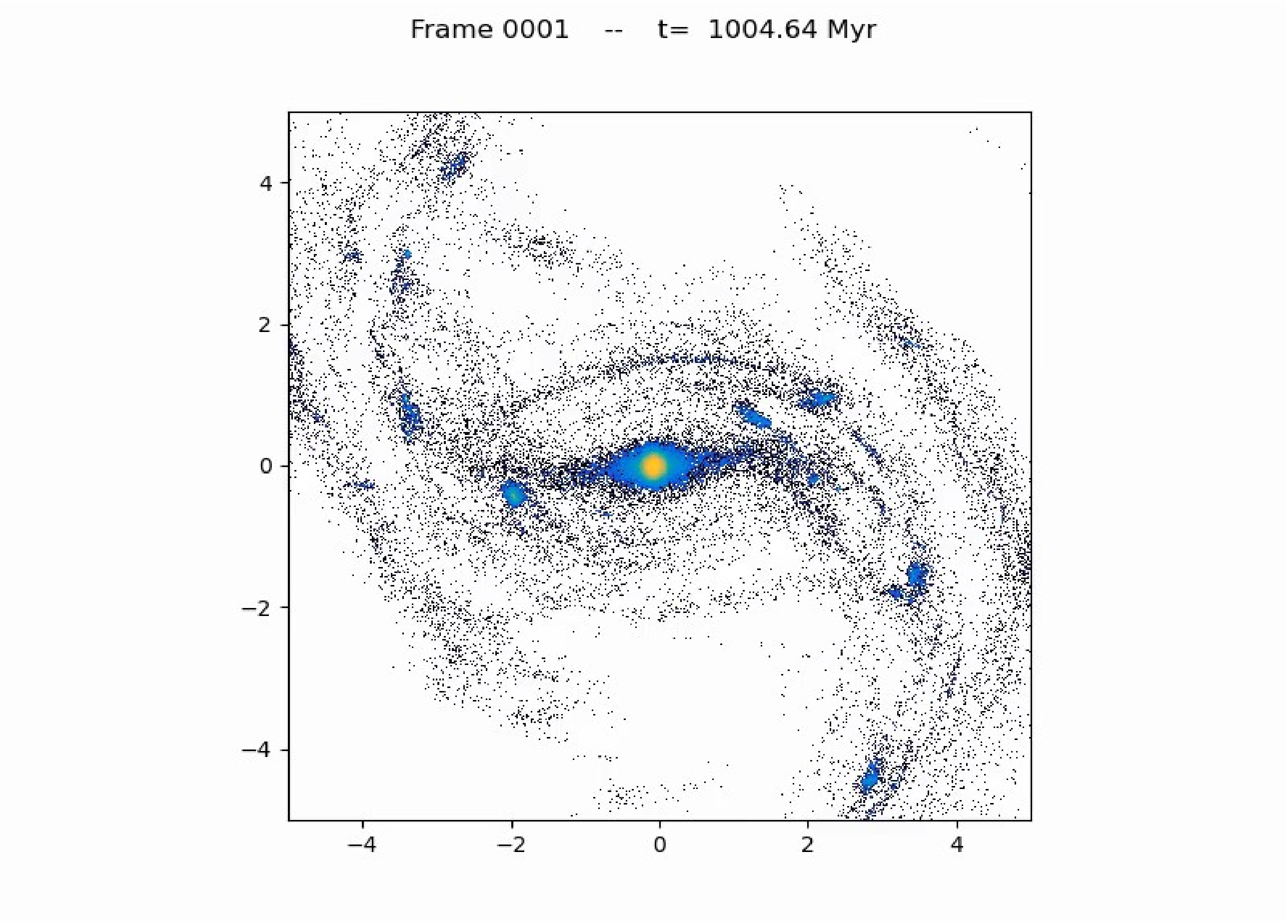
Time variation

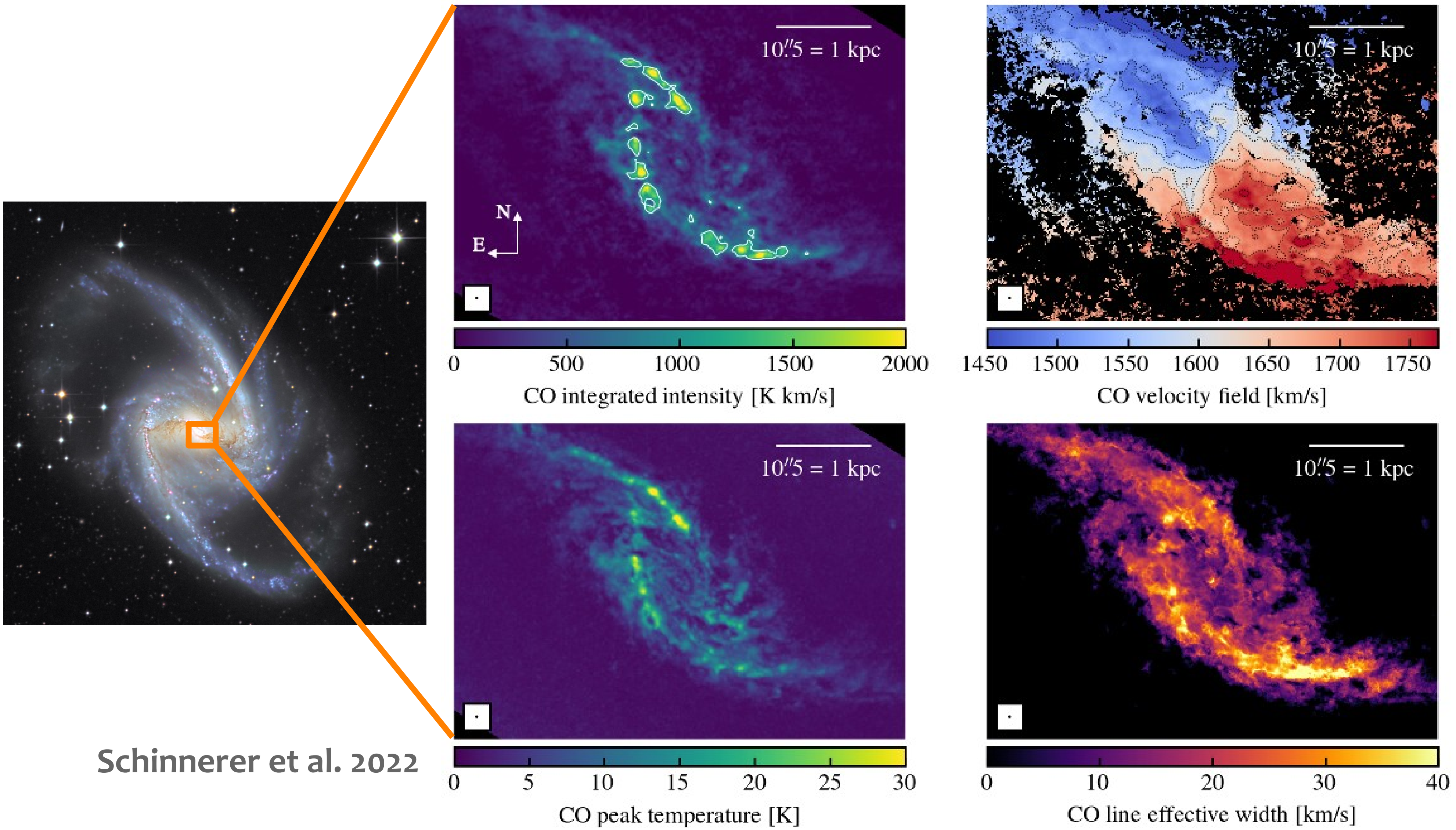
NGC 1365

NGC 1365-inspired sim



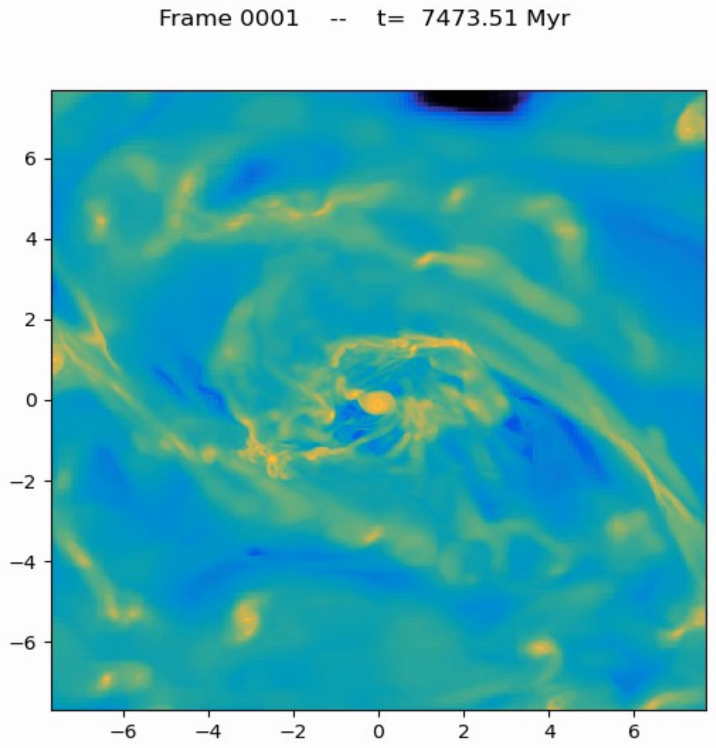
M83-inspired sim

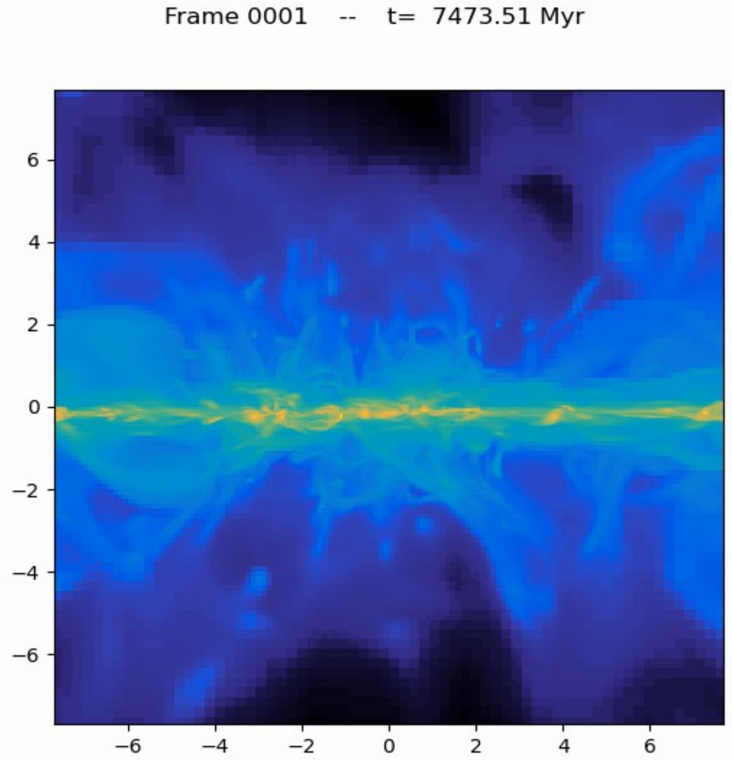




Schinnerer et al. 2022

NGC 1365-inspired sim





Schinnerer et al. 2022

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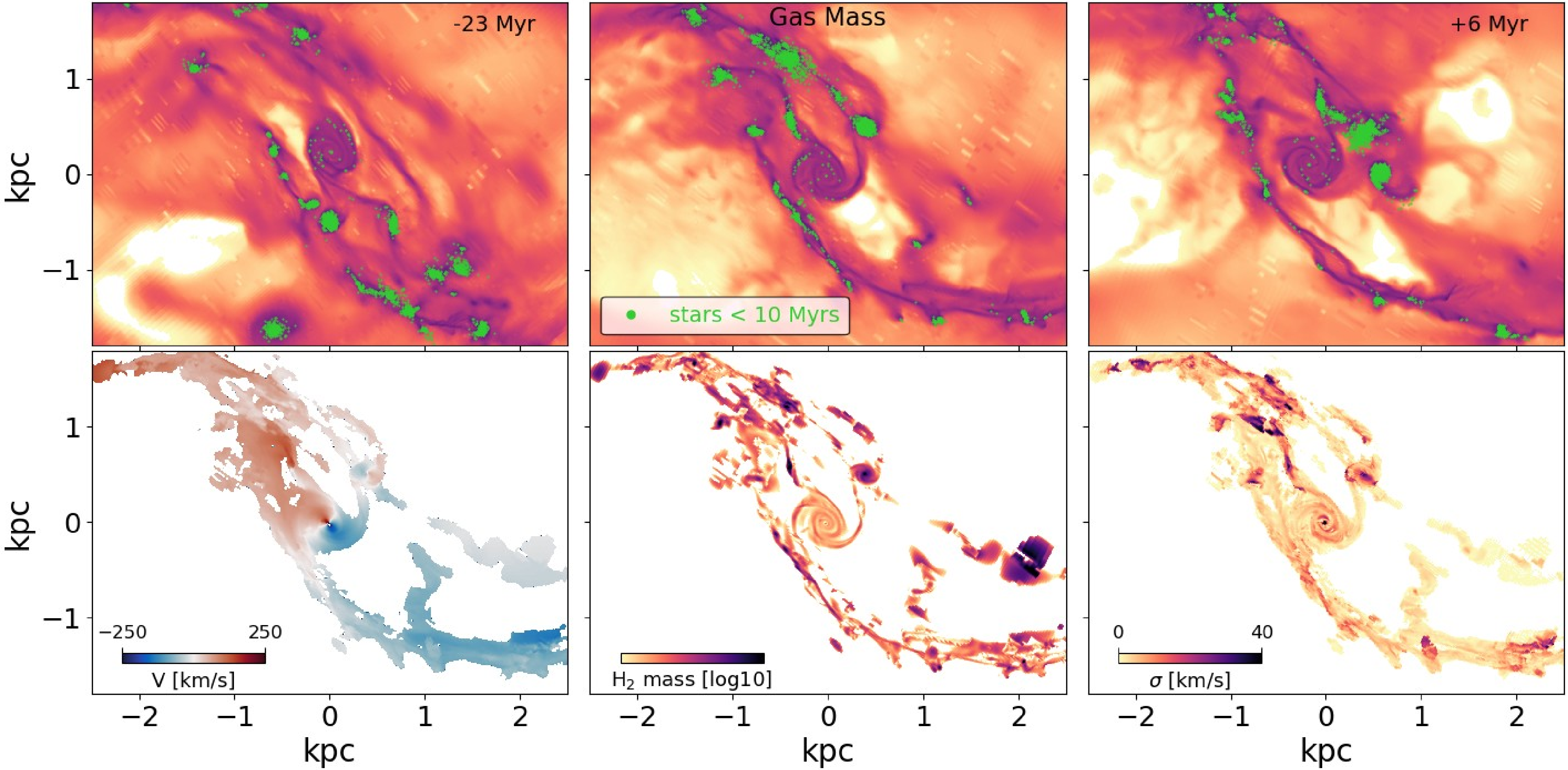
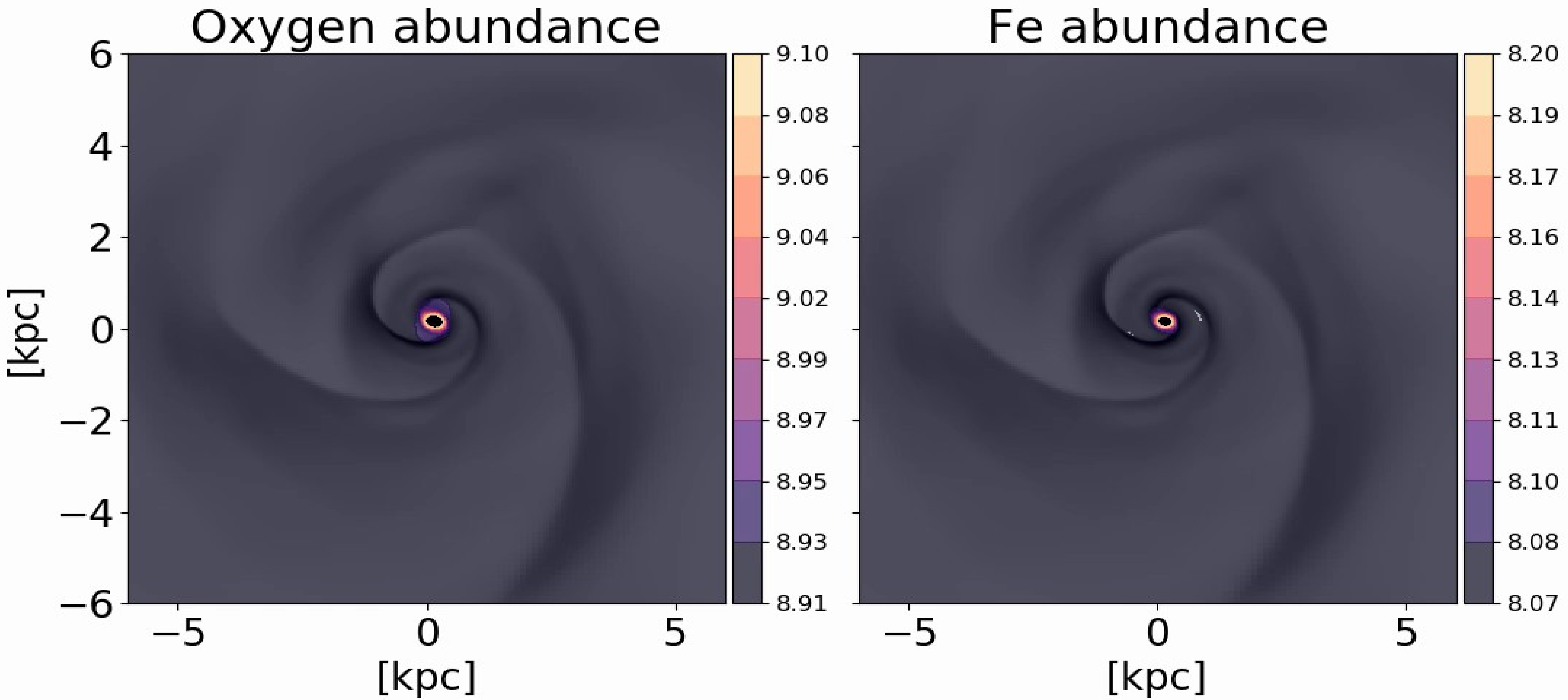


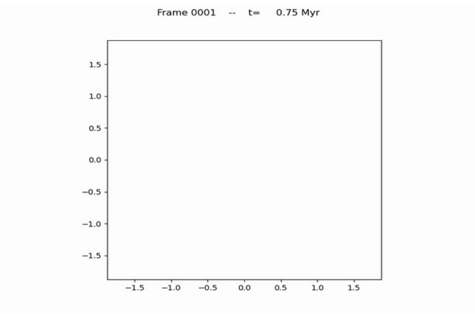

Oxygen abundance
Fe abundance
[kpc]
[kpc]
[kpc]
6
4
2
0
−2
−4
−6
−5
0
5
−5
0
5
9.10
9.08
9.06
9.04
9.02
8.99
8.97
8.95
8.93
8.91
8.20
8.19
8.17
8.16
8.14
8.13
8.11
8.10
8.08
8.07

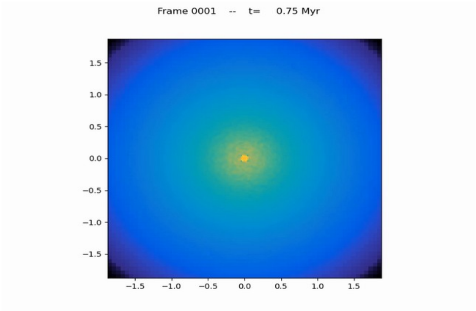
Time for changes

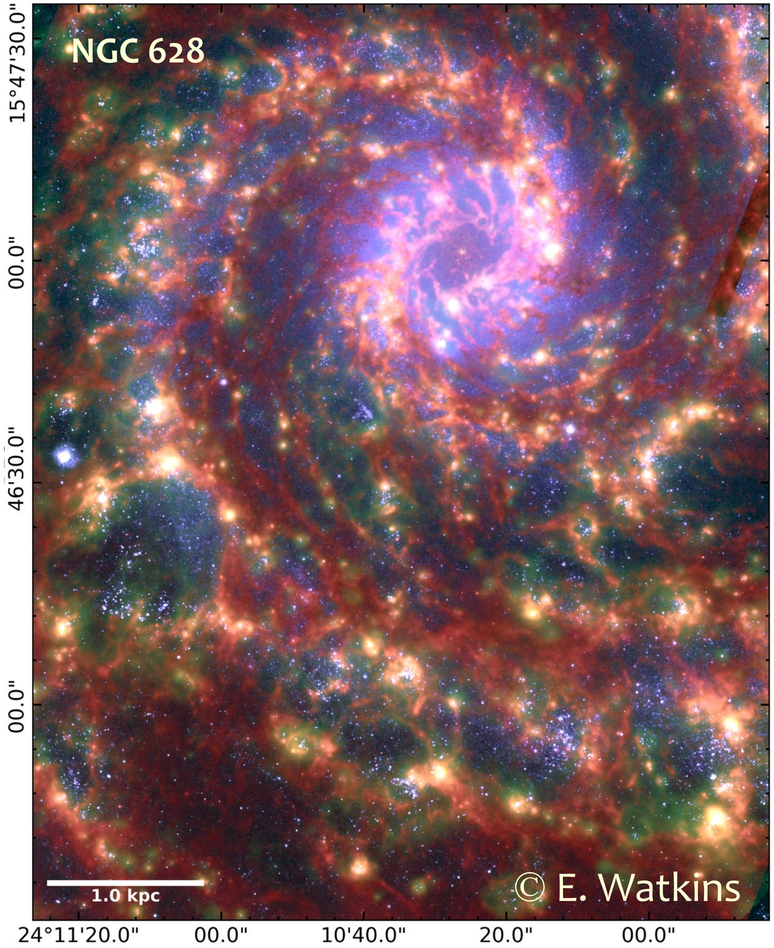
- ➔ **We take (galaxy dynamics) timescales for granted**
  - ➔ **Are we under-estimating time-variations?**

- ➔ Spiral structure
  - Vs Star formation
  - Vs Feedback (where the energy is released)
  - Vs Metallicity

  Is that all easy and clear?







JWST/MIRI 7μm, MUSE/VLT Hα, and HST B bands.

Wrap-up

- ➔ **We understand (many textbook) principles**
- ➔ **We do not understand real galaxies (yet)**

➔ **Galactic dynamics sets the skeleton of structures and orbits**

➔ Galactic timescales can be long

Some processes are « theoretical » and hard to calibrate

➔ Can we trust our numerical experiments (simulations)?

Baryonic processes can act quickly and impact the evolution

➔ Coupling has a profound impact

Dance between baryons and galaxy dynamics: multi-scale coupling

How can we use this coupling to determine the time arrow/timescale ?
Is there a sub-volume of parameter space used (physics or just evolution)?

Timescales
Galaxy Dynamics

Eric Emsellem