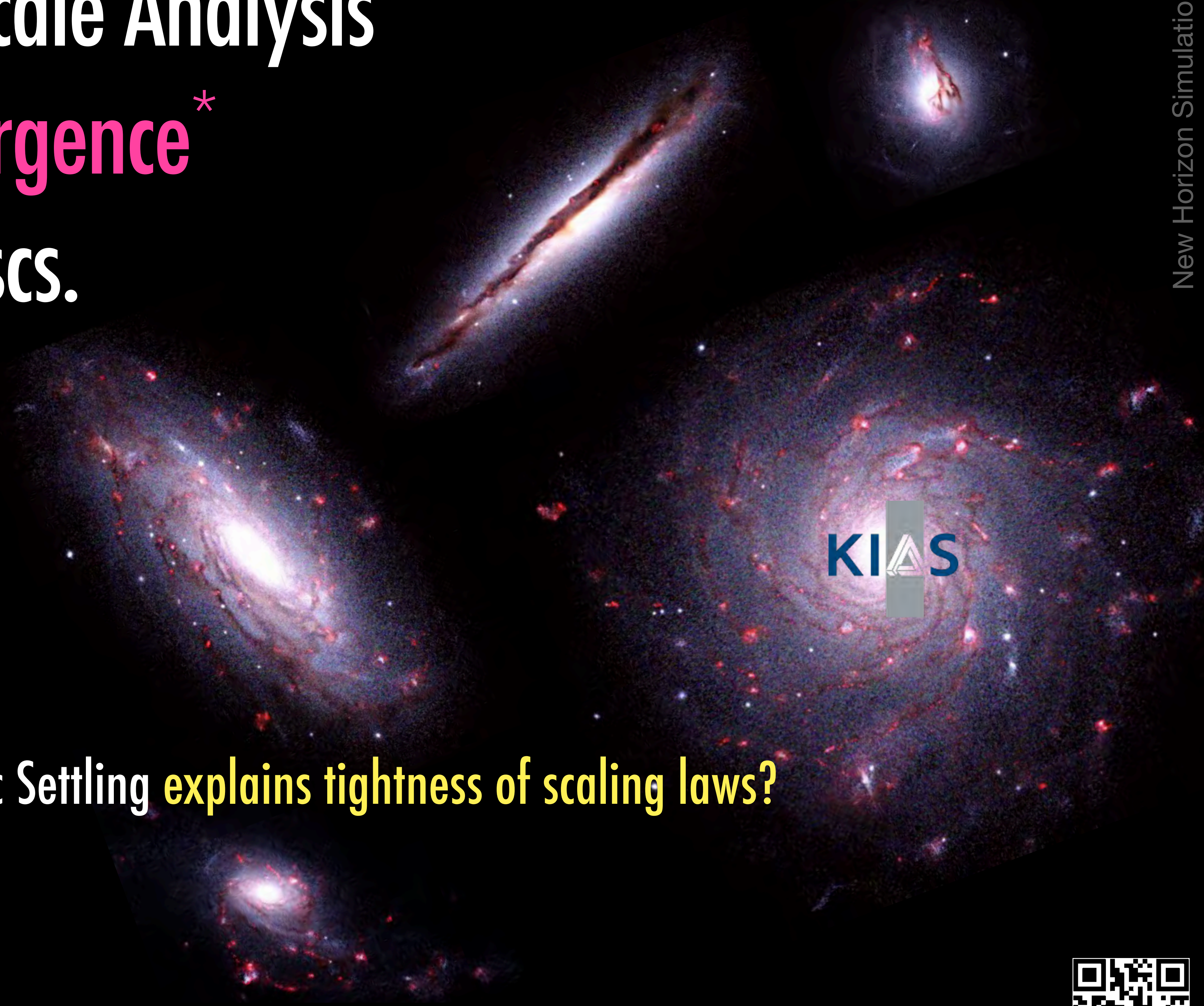
Gravity does it all:

A Top-Down Multiscale Analysis of the Cosmic Emergence* of Thin Galactic Discs.



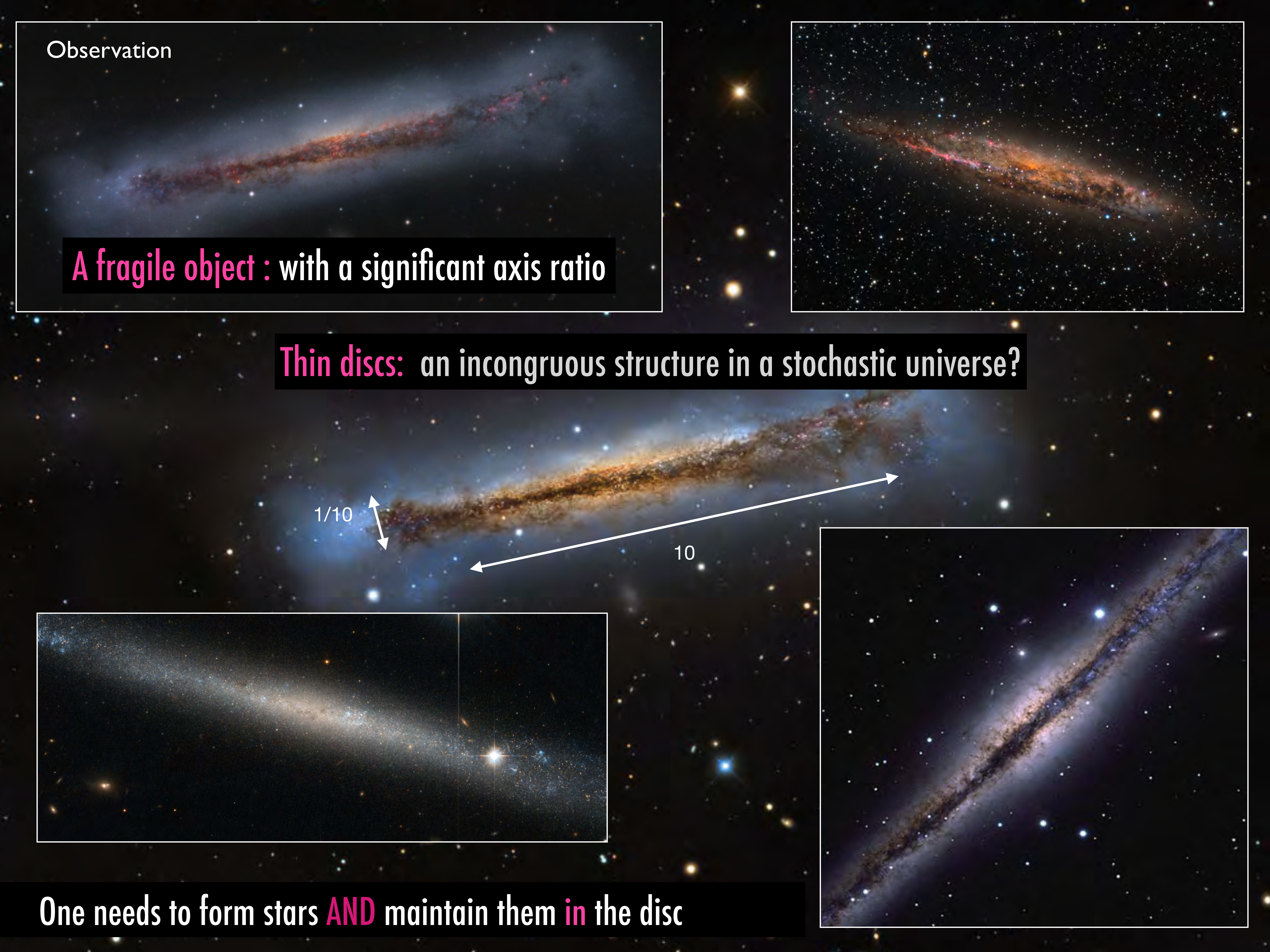
Order out of Chaos = Secular Disc Settling explains tightness of scaling laws?

* emergence = the arising of novel and coherent structures through self-**organization** in complex systems

Christophe Pichon + (Min-Jung Park, M. Roule, K Tep, JB Fouvry, Y Dubois, J. Devriendt++)

Context


NGC 5068
NGC 4303
NGC 1512
NGC 1365
NGC 4535
NGC 3351
NGC 4321
NGC 0628
IC 5332
NGC 4254
NGC 1300
NGC 1433
NGC 2835
NGC 7496
NGC 3627


Observation
A fragile object : with a significant axis ratio
Thin discs: an incongruous structure in a stochastic universe?
1/10
10
One needs to form stars AND maintain them in the disc

* Emergence: arising of novel coherent (unlikely) structures through self-organisation

*Near **phase transition** in **open dissipative** systems.*

The **whole** does **not** simply behave like the **sum** of its parts!

Emergence cf: self-steering Bike on slope of increasing steepness

Disc resilience is direct analog of self-steering bike on slope of increasing steepness.

remarkably,
the bike's analog
spontaneously emerges

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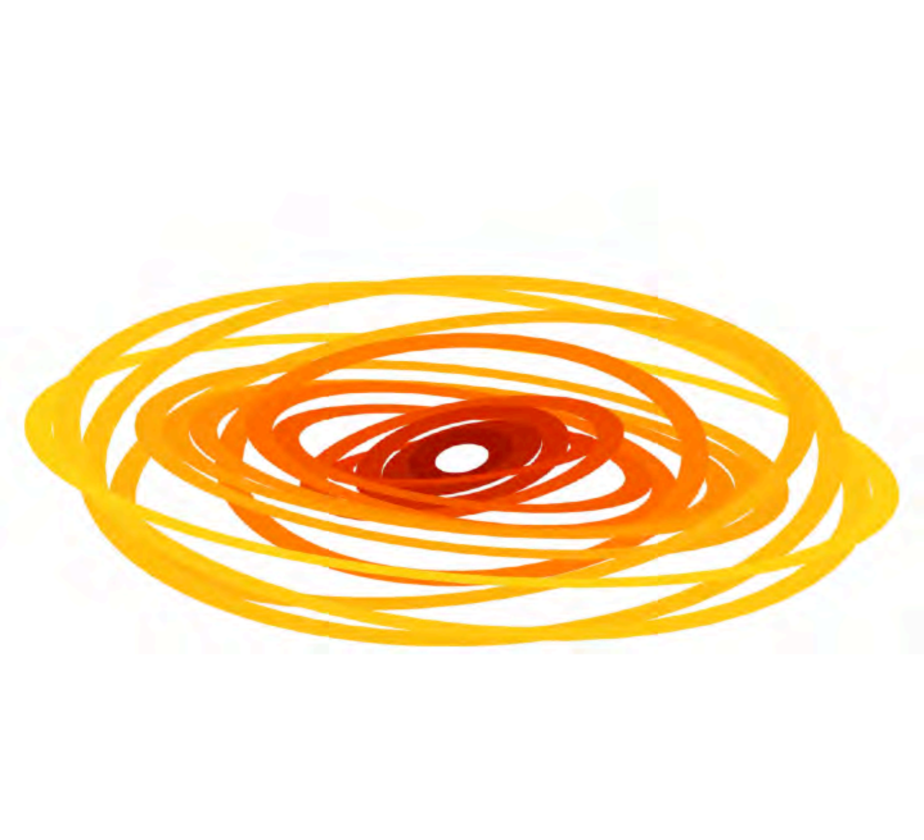
Synopsis of thin disc emergence: homeostasis

- Why do disc settle ? Because Q→1
- But Why does Q→1? Because tighter control loop ($t_{\rm dyn} \ll 1$) via wake
- But how does it impact settling? Because wake also stiffens coupling

New Horizon



Ring toy model

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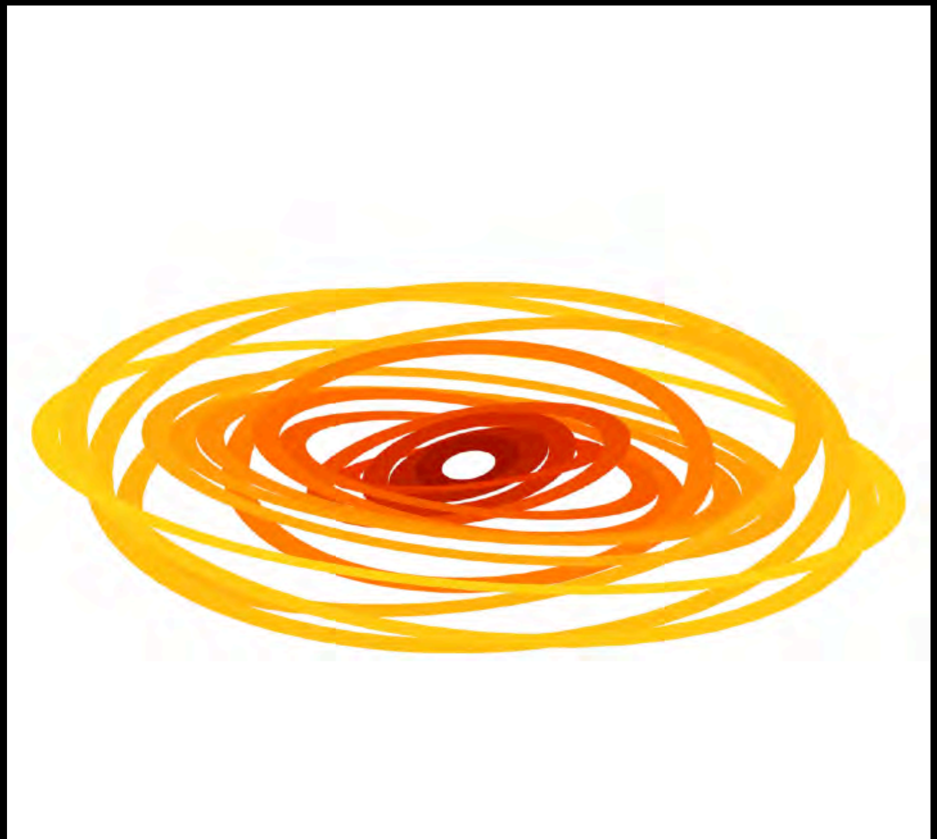
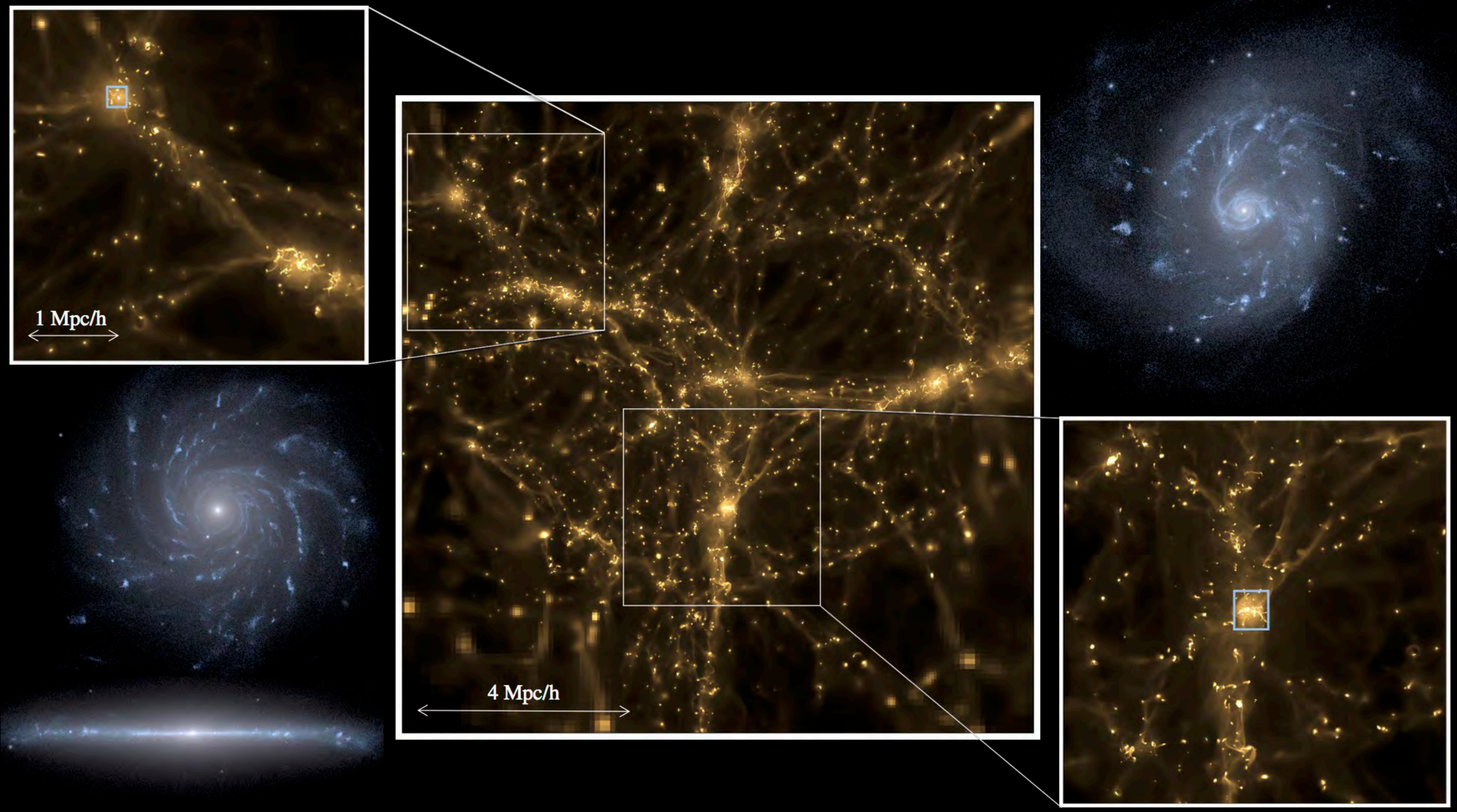

Ring toy model

Cosmological simulations produce thin discs/scaling laws

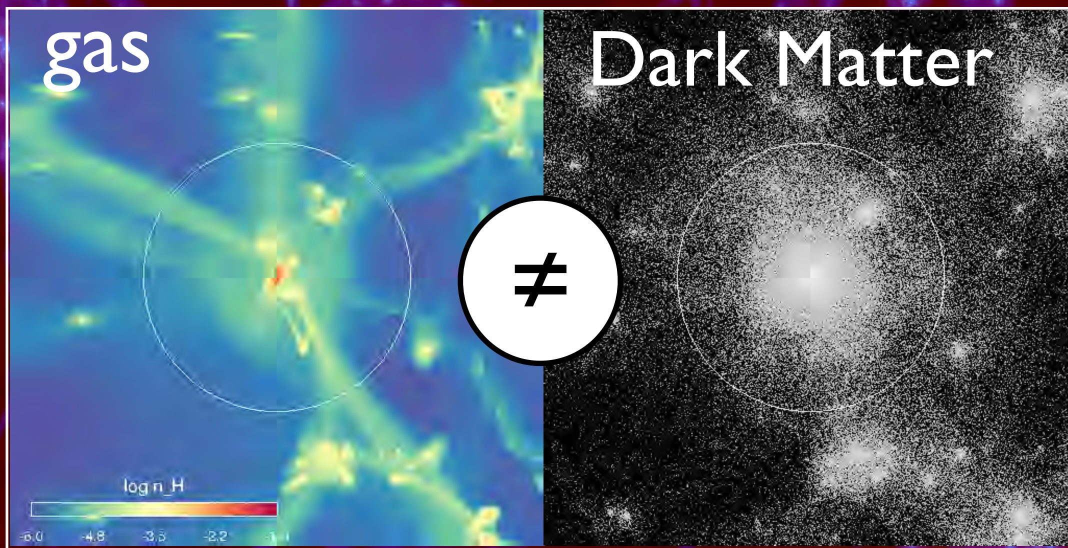


New Horizon Simulation

(c) M Park 2020

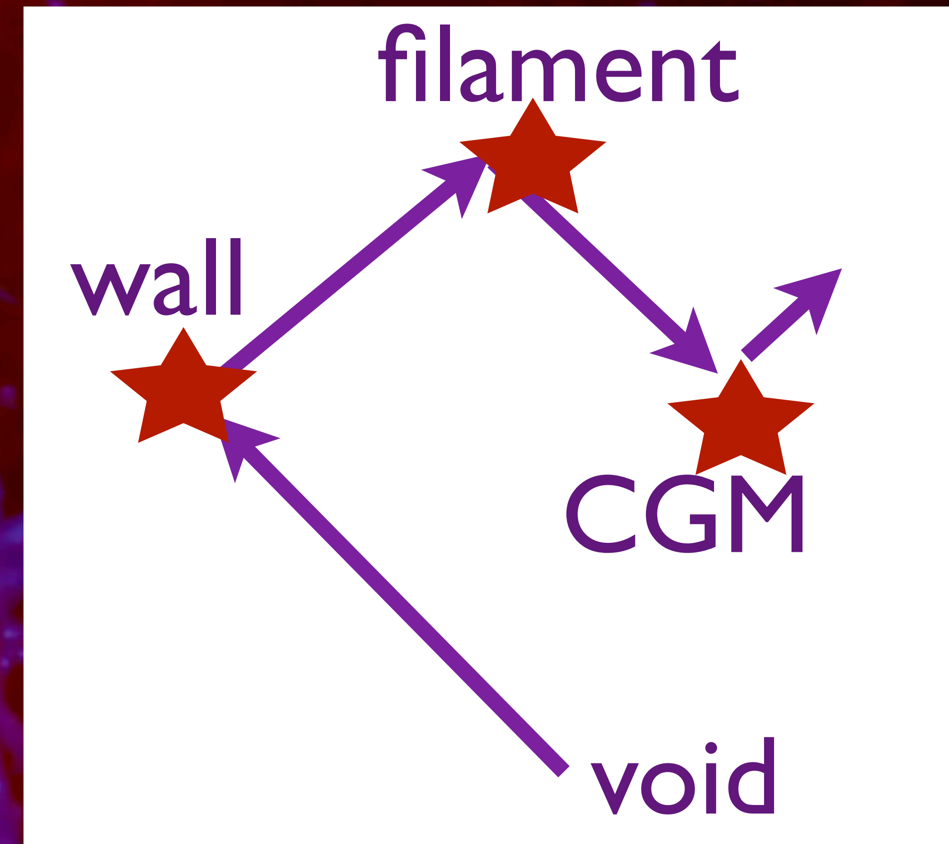
The impact of shocks in gaseous cosmic web

CW drives secondary infall :



$t_{\rm dyn} \sim 1/\sqrt{\rho}$

MILKY WAY



Disks (re)form because LSS are large (dynamically young) and (partially) an-isotropic : they induce persistent angular momentum advection of gas along filaments which stratifies accordingly.

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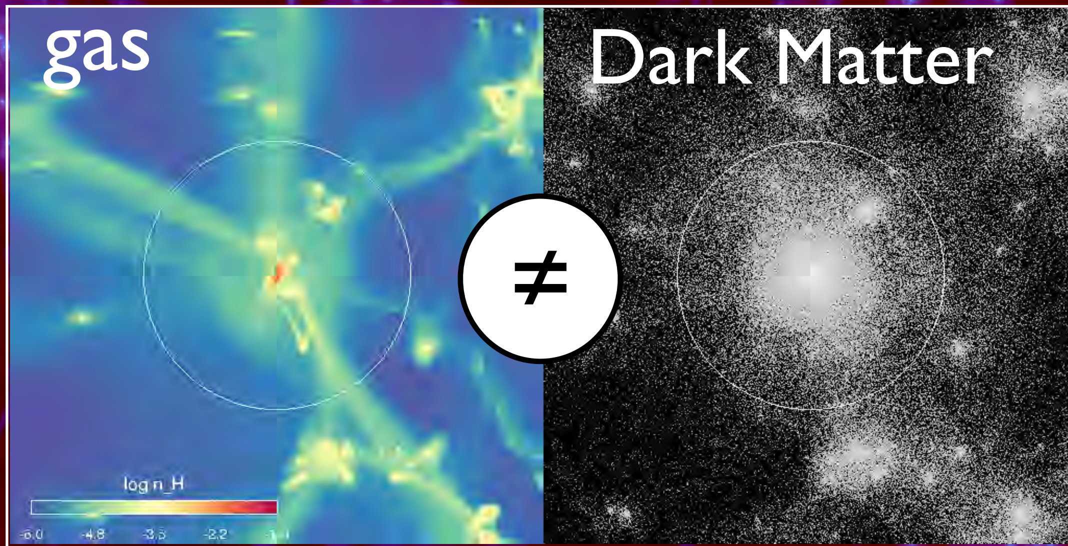

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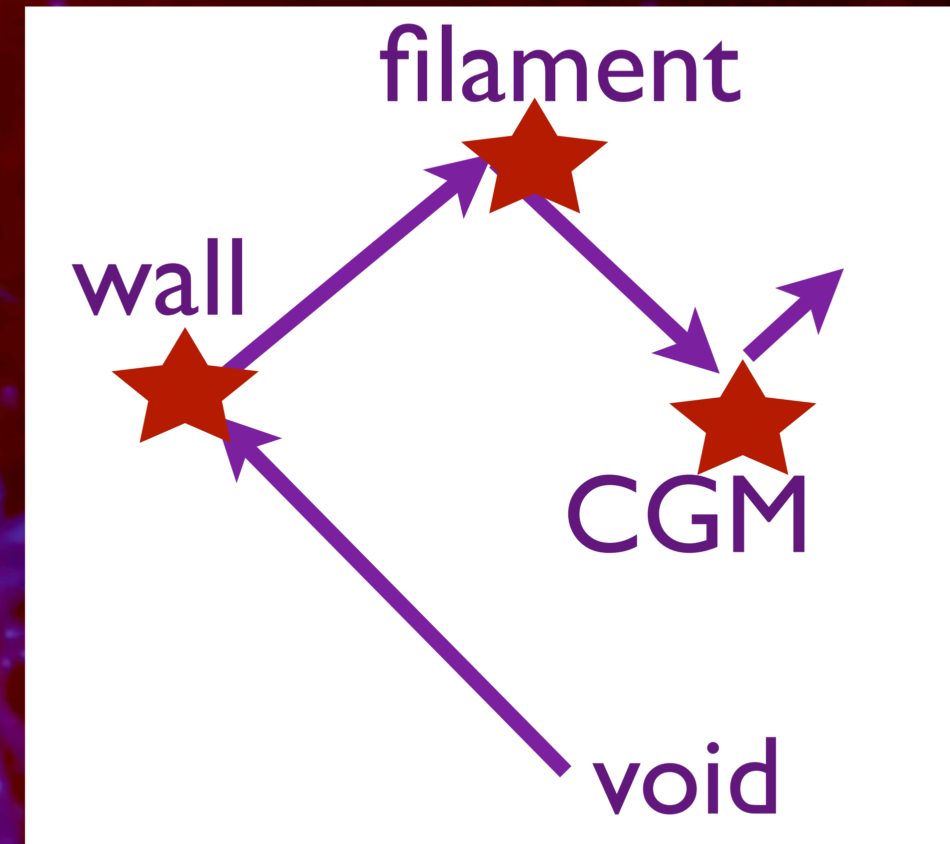

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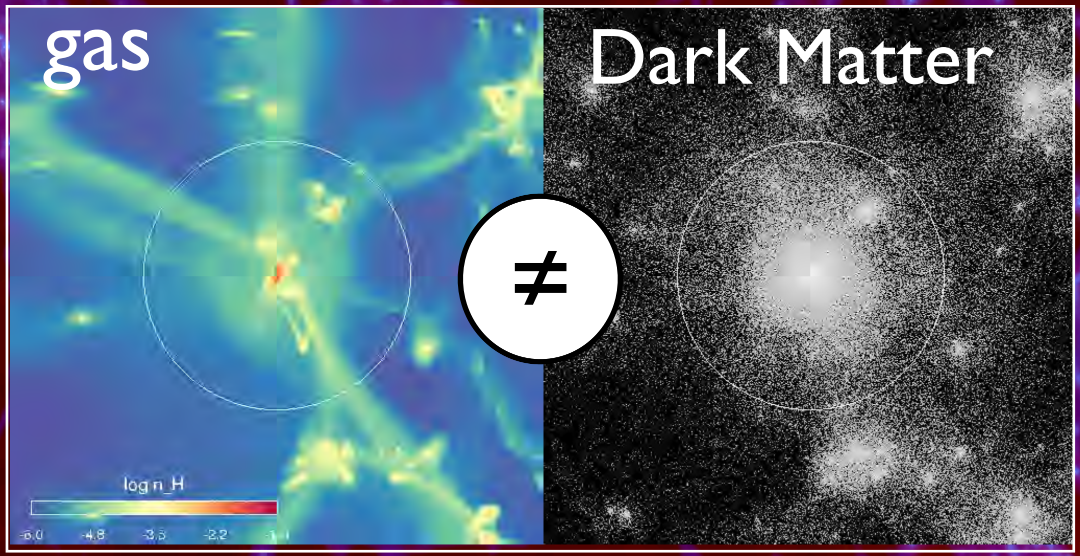

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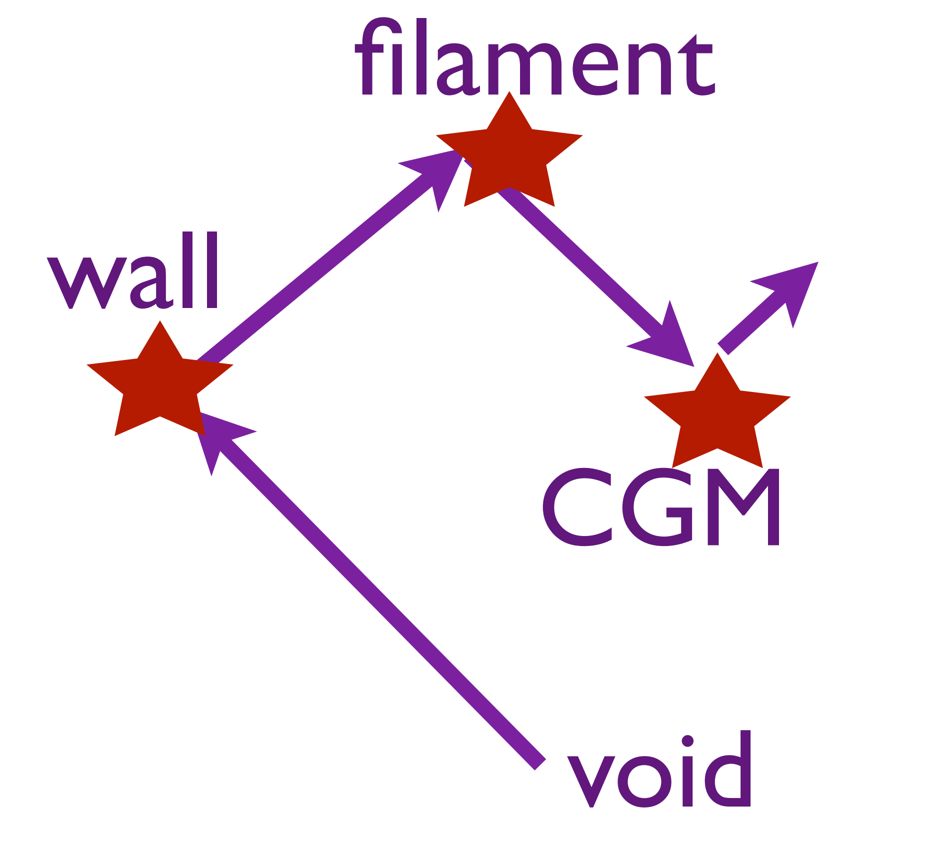

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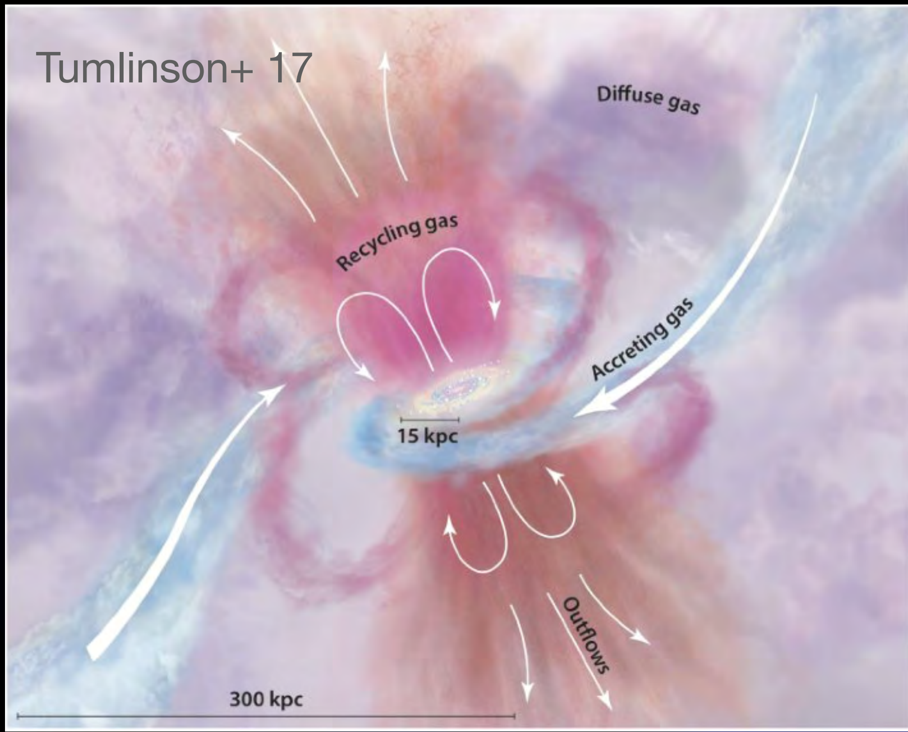
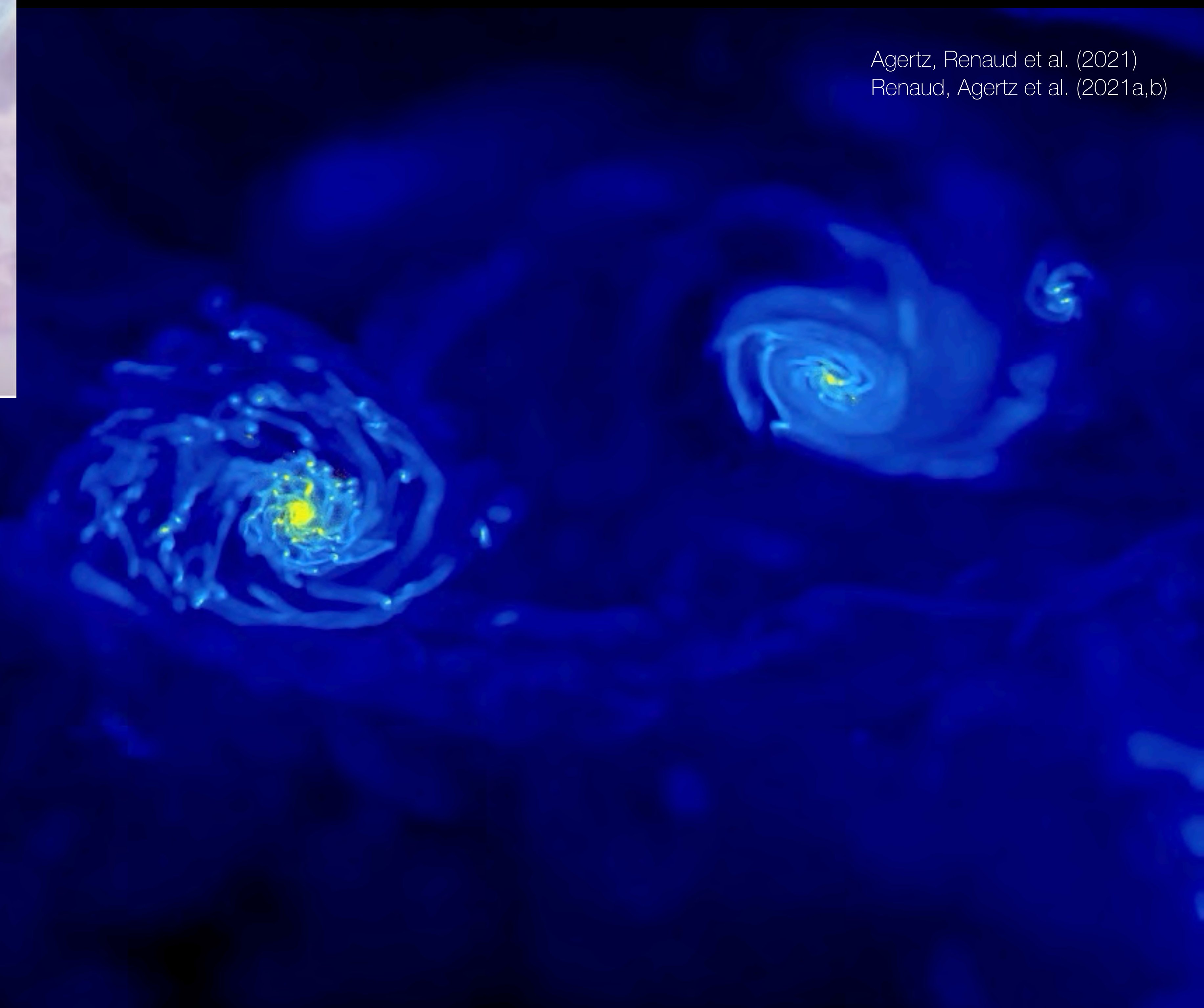
Shape of Circum Galactic Medium





Disc torqued by GCM

$$t_{\rm dyn} \sim 1/\sqrt{\rho}$$

Cosmic web sets up
reservoir of free energy in CGM = the fuel for thin disc emergence

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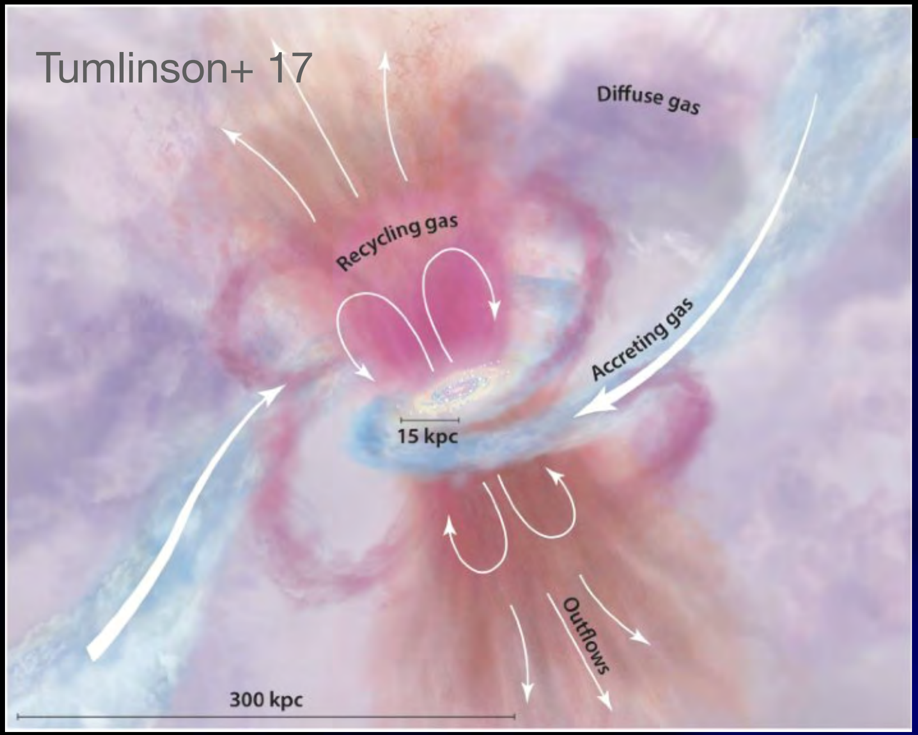

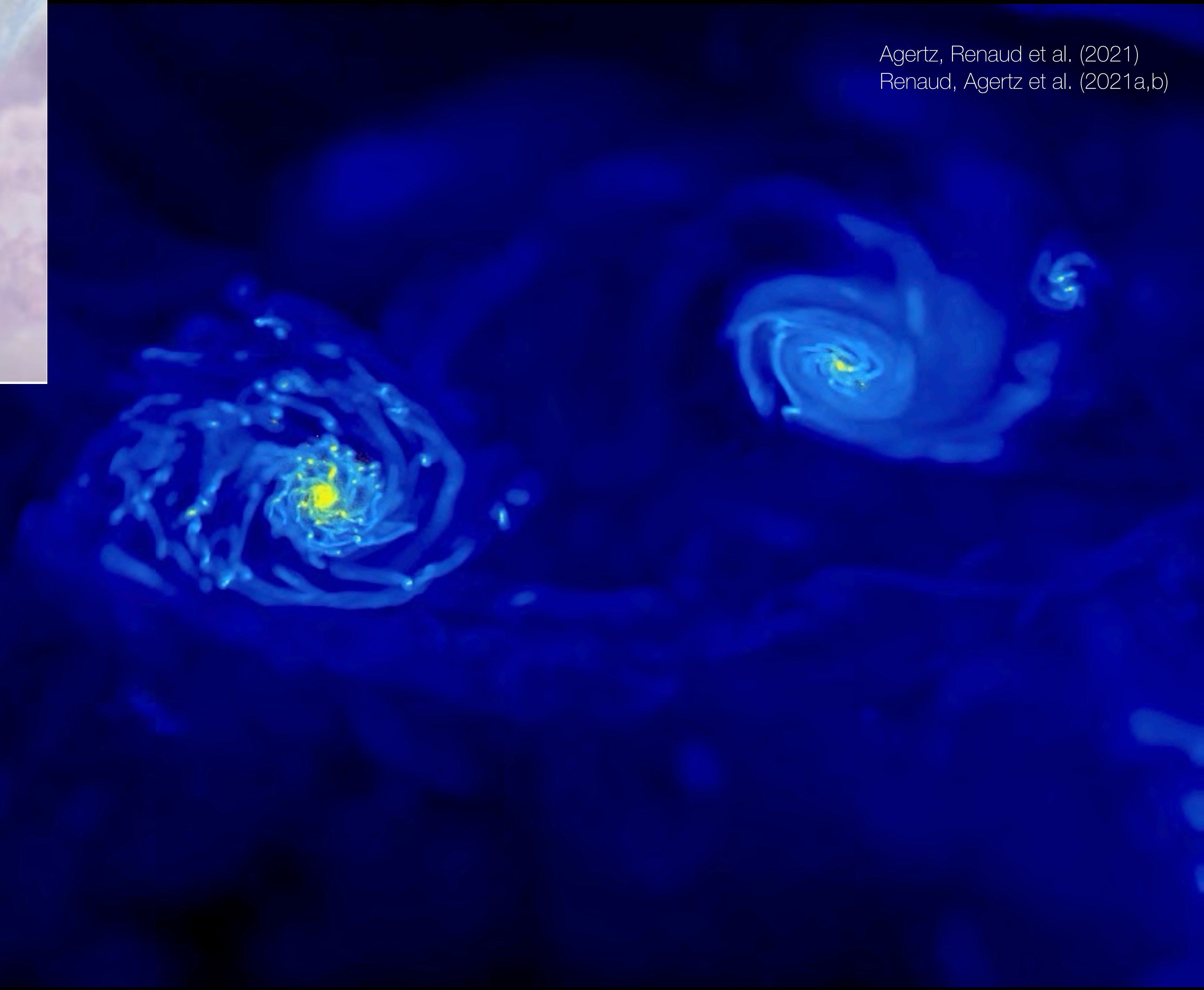

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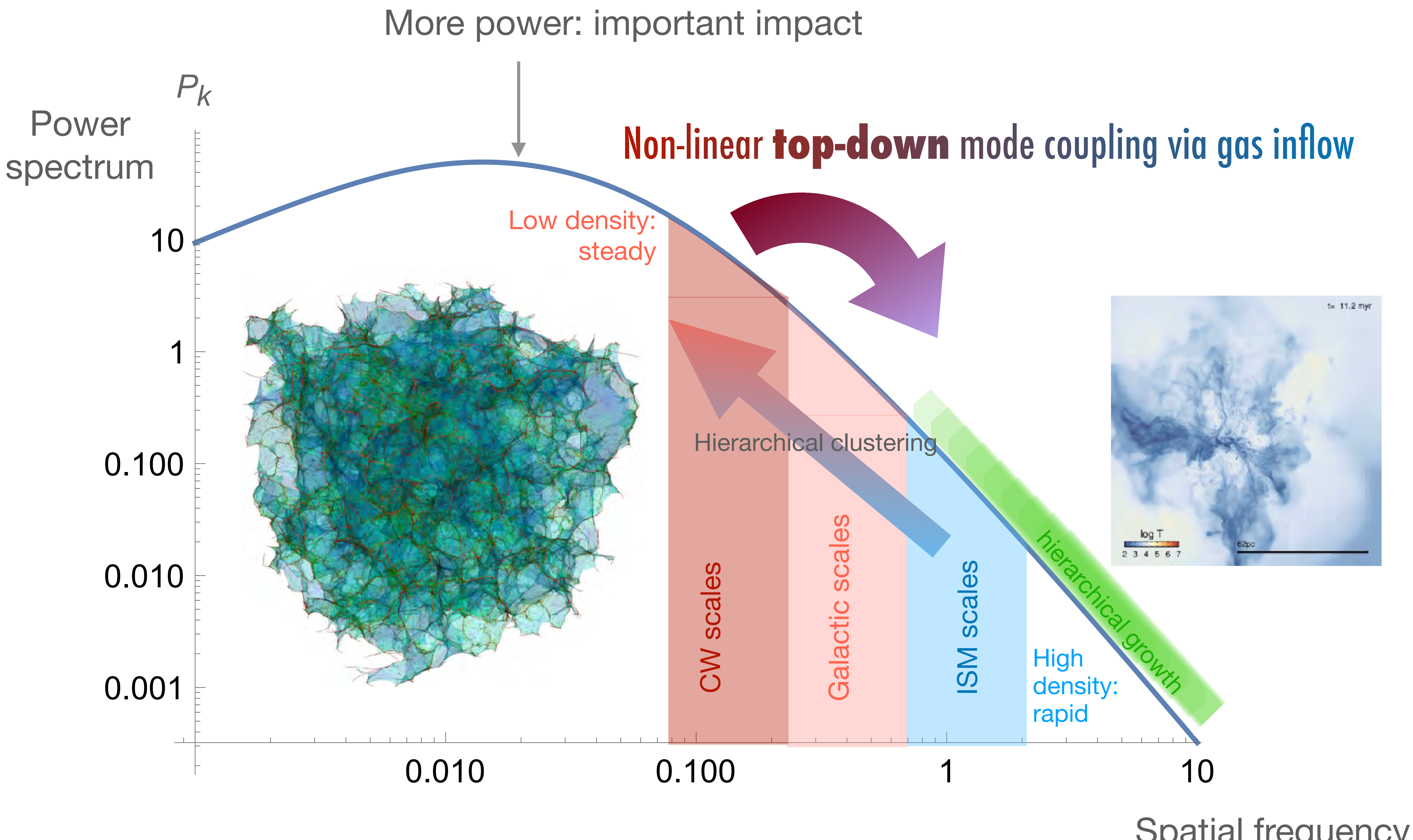
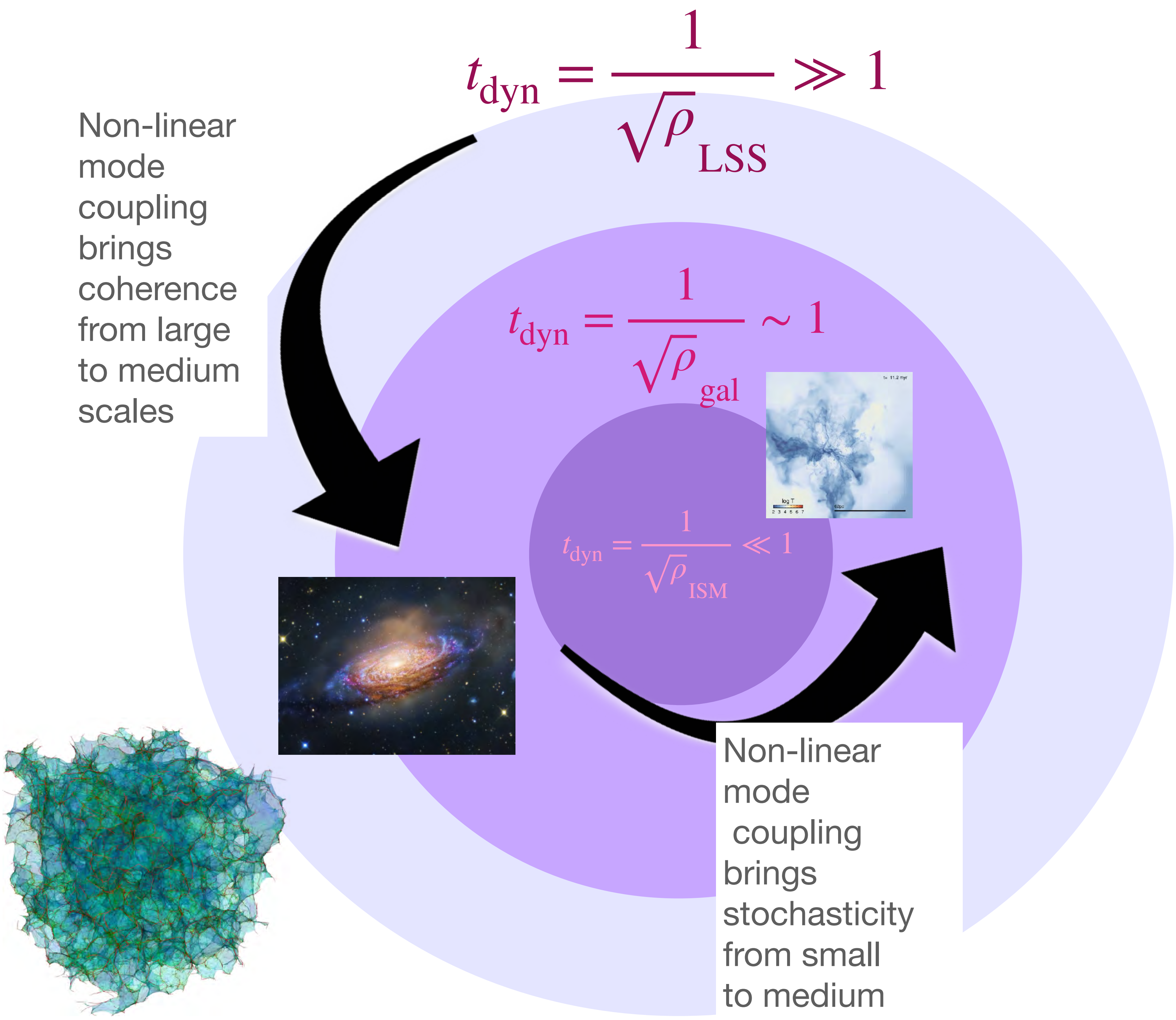
1. Impact of CW on non-linear dynamics is non linear & top down

On galactic scales, the Shape of initial P_k is such that galaxies inherit stability from LSS via cold flows



Galaxies are multi-scale non-linearly asymmetrically coupled systems



Why (naive) subgrid physics is a bad idea…

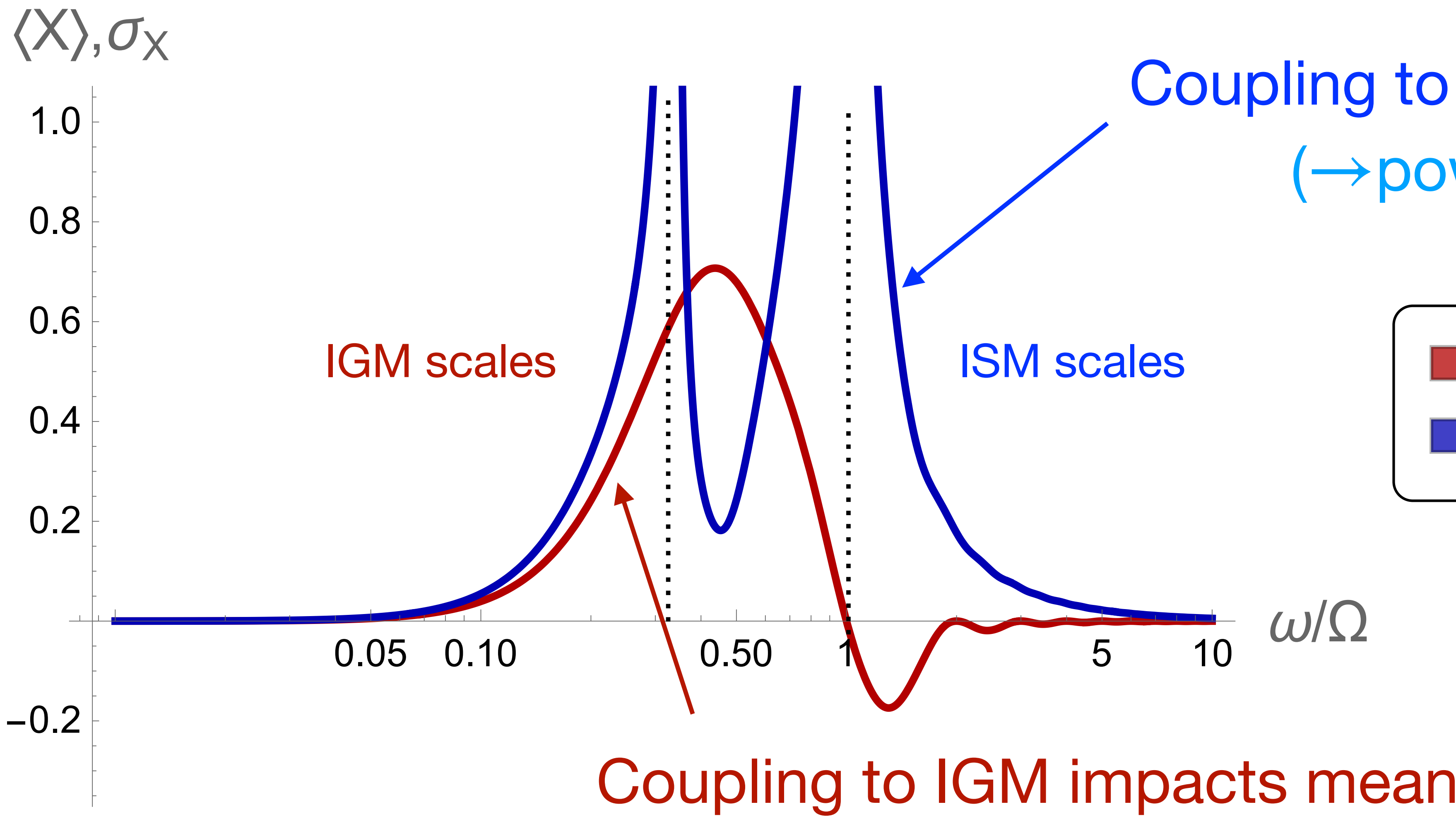
Galaxies are multi-scale non-linearly asymmetrically coupled systems

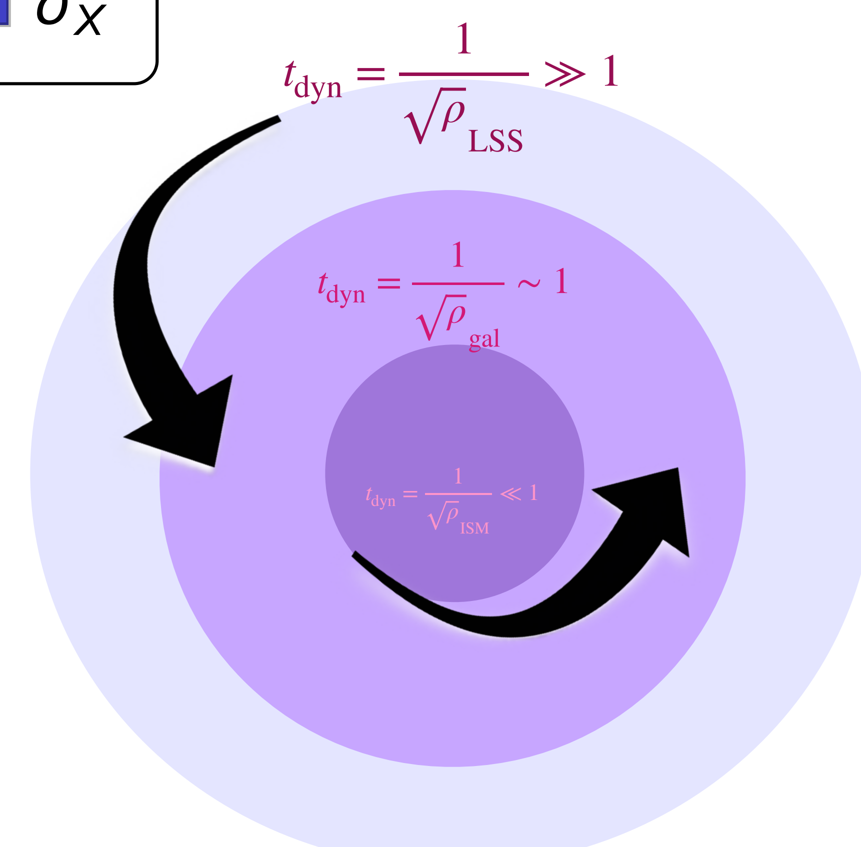
$$\ddot{X} + \Omega^2 X = \epsilon X_{\rm env}^3 \quad \text{given} \quad \ddot{X}_{\rm env} + \omega^2 X_{\rm env} = 0$$

Natural frequency of galaxy

perturbative coupling to environment

Natural frequency of environment





$$\langle X \rangle = \frac{\sin^2(3\pi\omega)}{12\pi\omega(3\omega-1)(3\omega+1)} - \frac{3\sin^2(\pi\omega)}{4\pi(\omega-1)\omega(\omega+1)}$$

$$\sigma_X = \frac{\sin^4(\pi\omega)\left(-75\omega^2 + 8\left(\omega^2-1\right)\cos(2\pi\omega) + 4\left(\omega^2-1\right)\cos(4\pi\omega) + 3\right)}{16\pi^2\omega^2\left(\omega^2-1\right)^2\left(9\omega^2-1\right)} - \frac{8\sin^4(3\pi\omega) + 3\pi\omega\sin(12\pi\omega)}{1152\pi^2\omega^2\left(1-9\omega^2\right)^2} + \frac{8\pi\omega\left(365\omega^4 - 82\omega^2 + 5\right) - 3\left(261\omega^4 - 74\omega^2 + 5\right)\sin(4\pi\omega) + 3\left(9\omega^4 - 10\omega^2 + 1\right)\sin(8\pi\omega)}{128\pi\omega\left(9\omega^4 - 10\omega^2 + 1\right)^2}$$

Why (naive) subgrid physics is a bad idea…

Upshot of the various processes operating on a galaxy

Destabilising effects

- supernovae
- Turbulence

————

- Minor merger
- accretion
- flybys

Stabilising effects

- Stellar formation
- Cooling
- Shocks

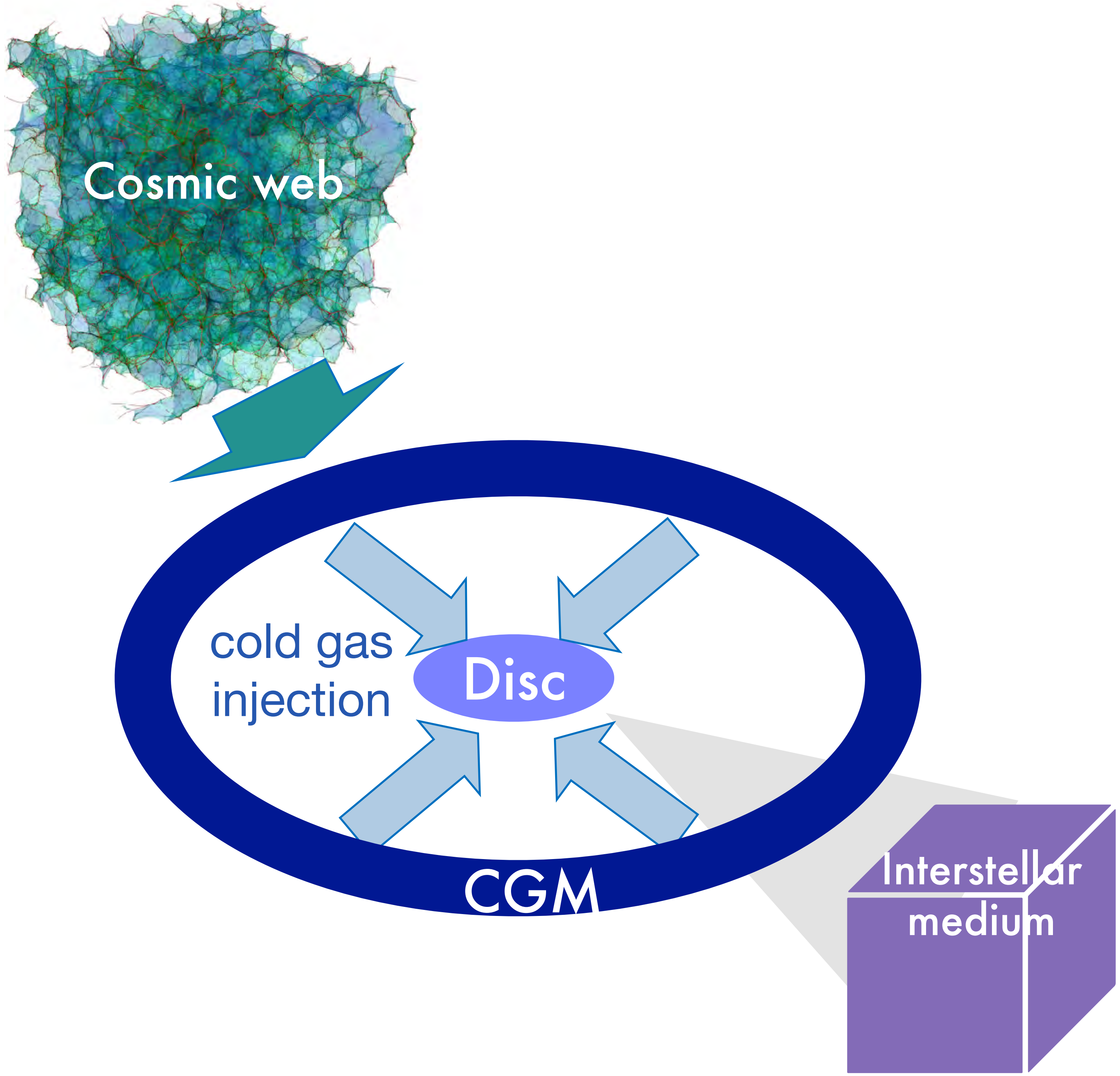
—————

- aligned accretion

Cosmic perturbation

Free energy reservoir in CGM

Synopsis of thin disc emergence induced by CW



Three components system coupled by gravitation.

- A CGM reservoir fed by the CW (top down *causation*)
- Convergence towards marginal stability : acceleration of dynamical control-loop by wakes
- Tightening of stellar disc by boosting of torques, & increased dissipation.

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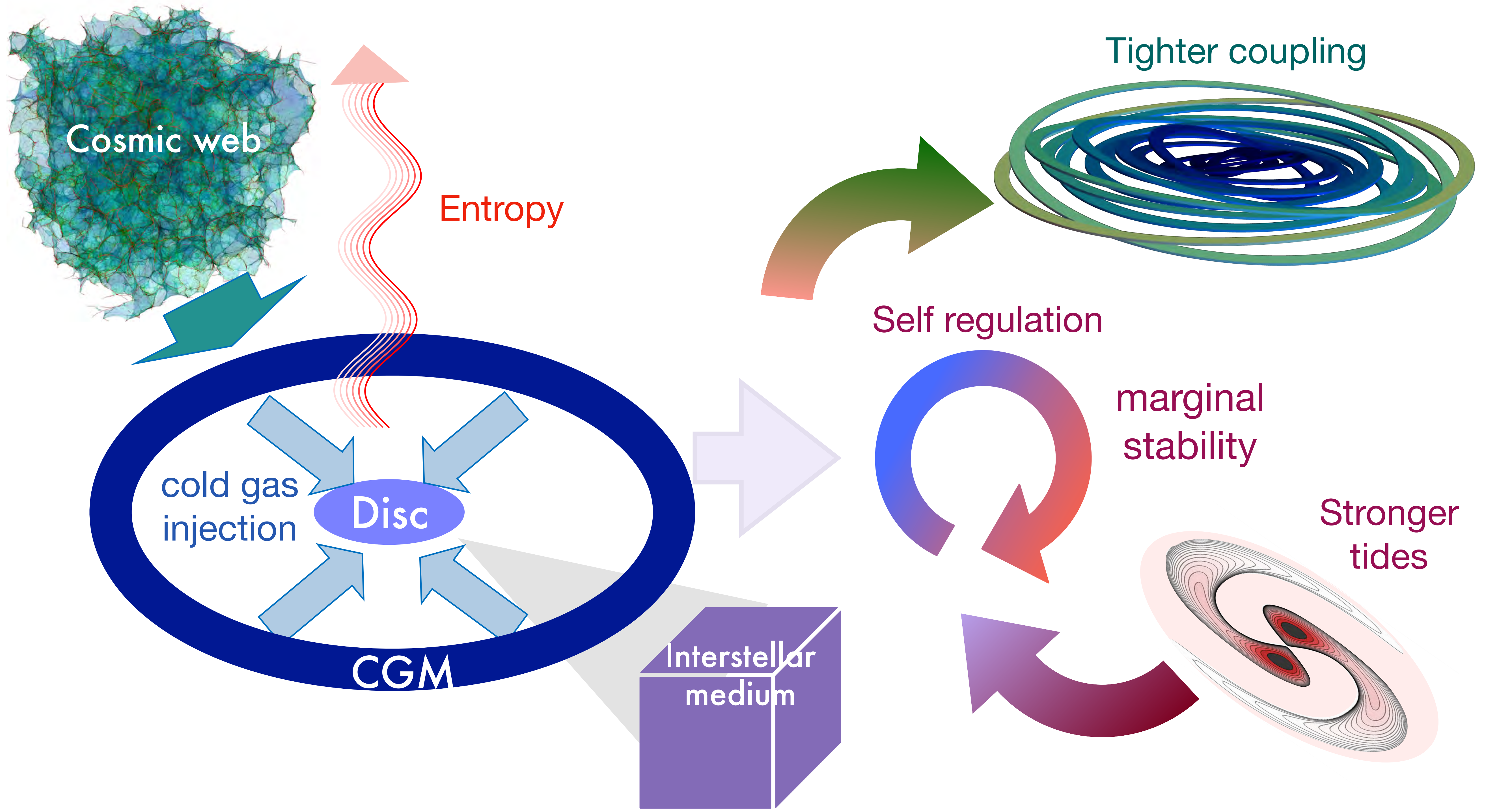

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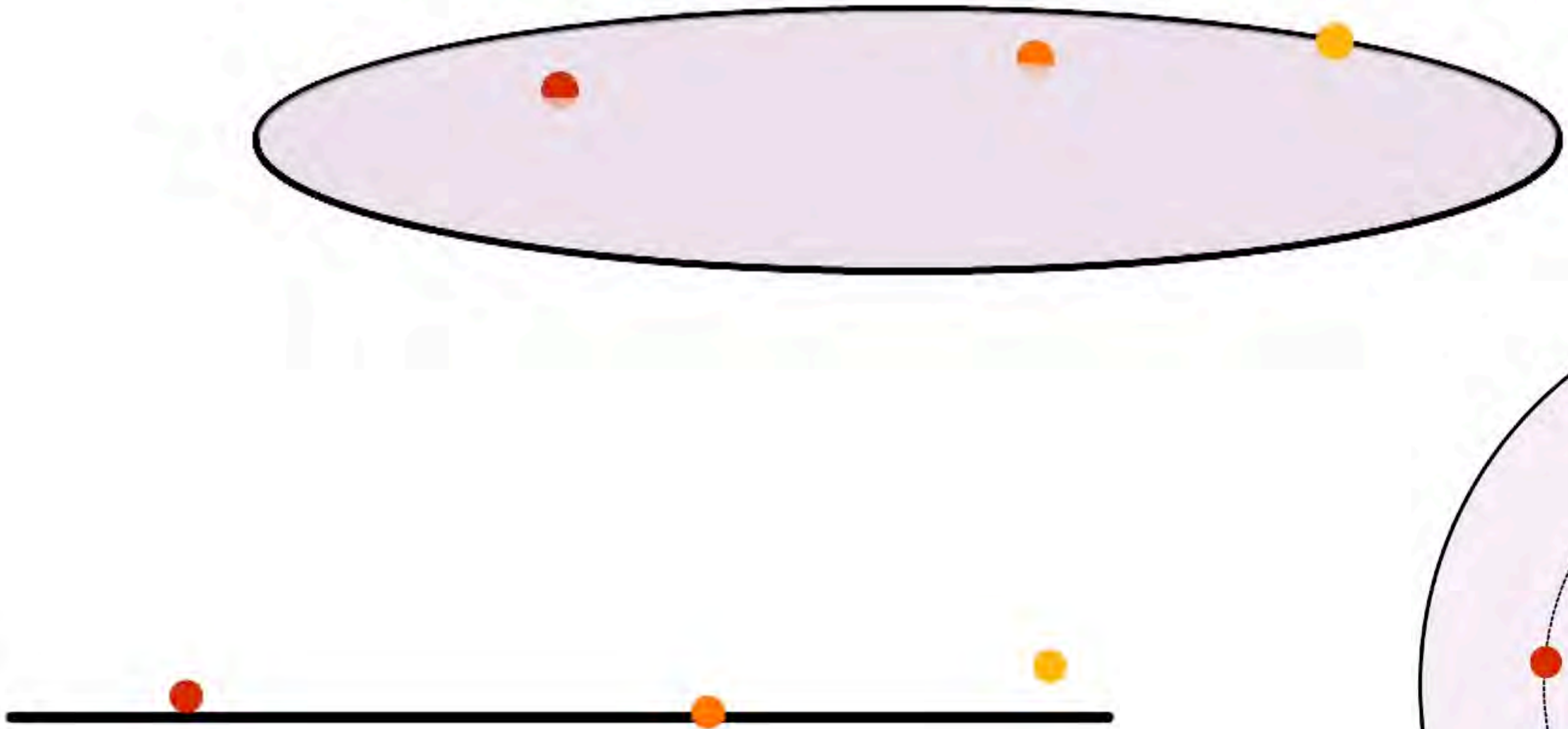
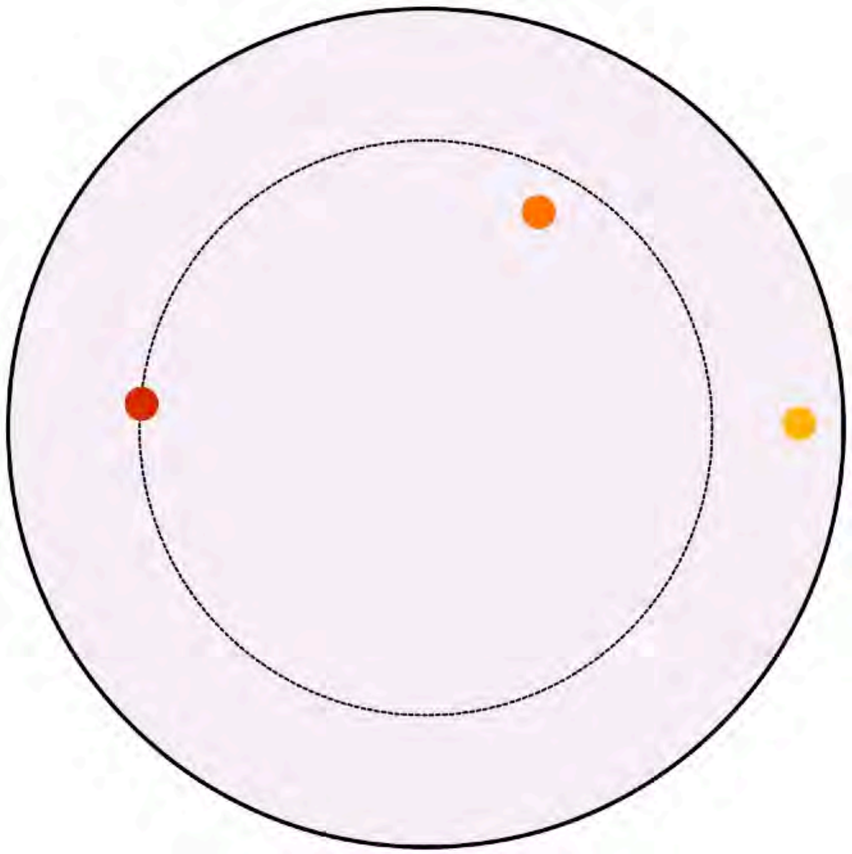
Gravity dominates stellar disc: linear response and diffusion

Gravity is long range ⇒ mean field is strong ⇒ perturbative treatment relevant





- Need a statistical representation of my system
  - **Distribution function F**

$$\mathrm{d}\boldsymbol{x}\mathrm{d}\boldsymbol{v} F(\boldsymbol{x},\boldsymbol{v}) \sim \text{Number of stars around } (\boldsymbol{x},\boldsymbol{v})$$

- What is the dynamics of F?
  - On short timescales?
  - On secular timescales?

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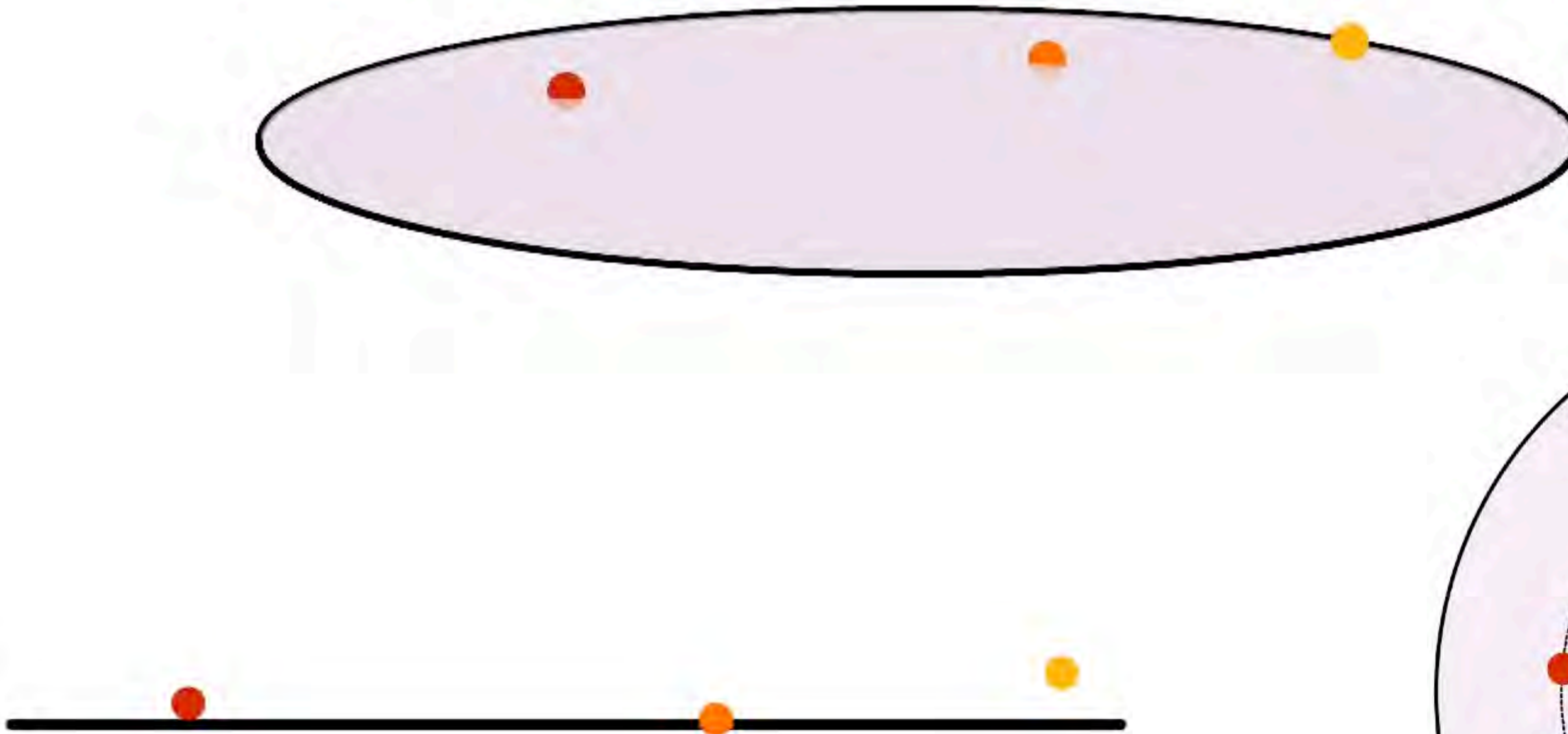

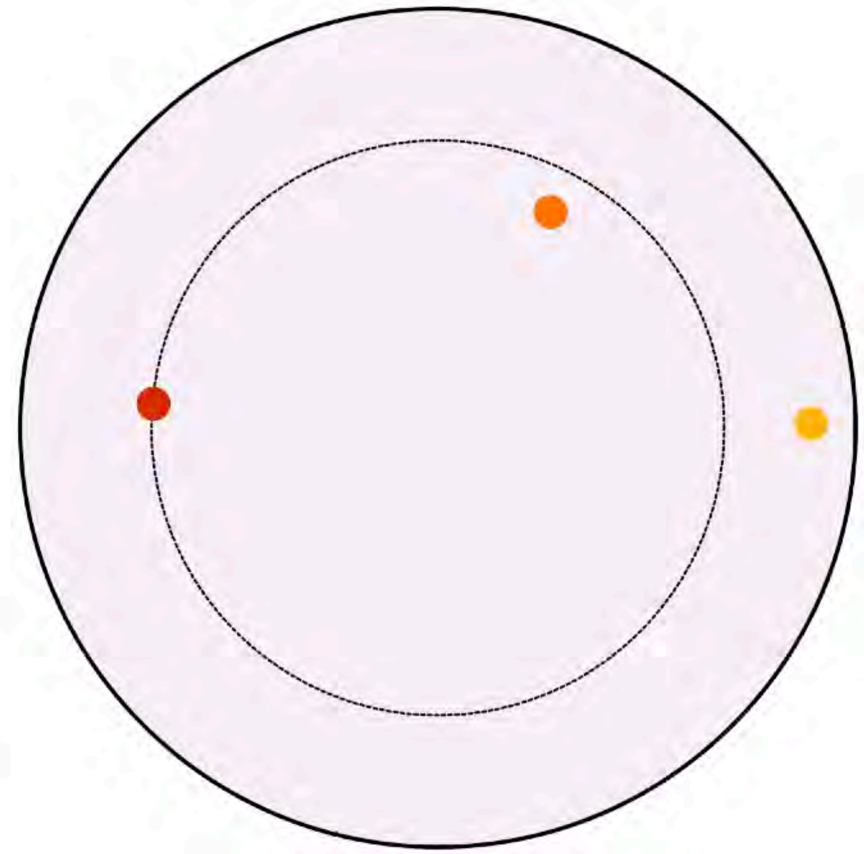

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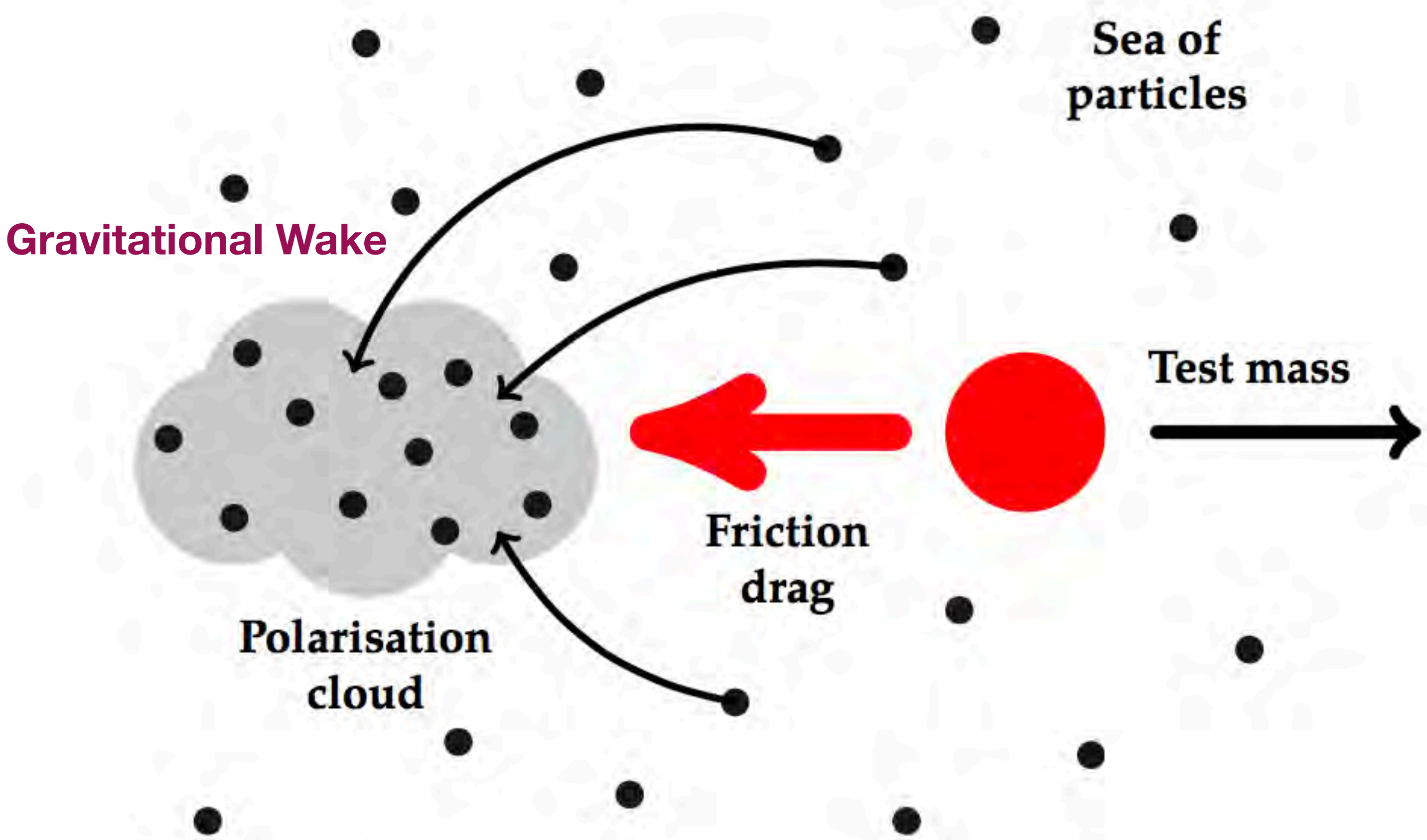
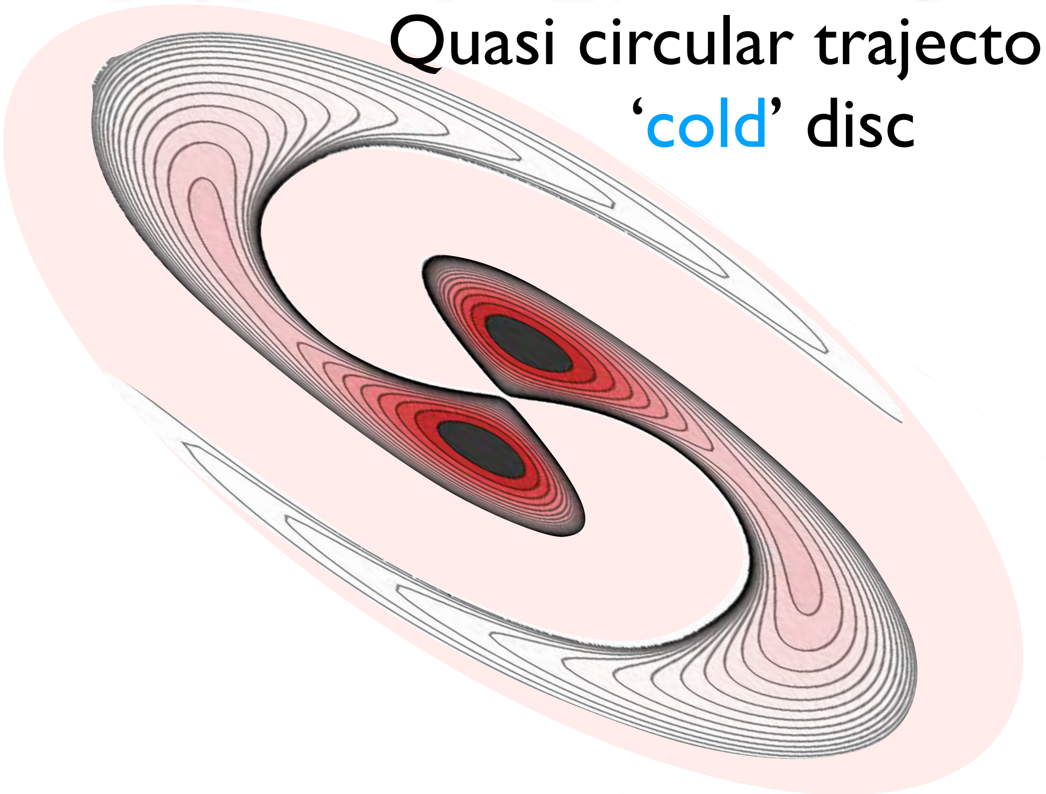
Chandrasekhar polarisation



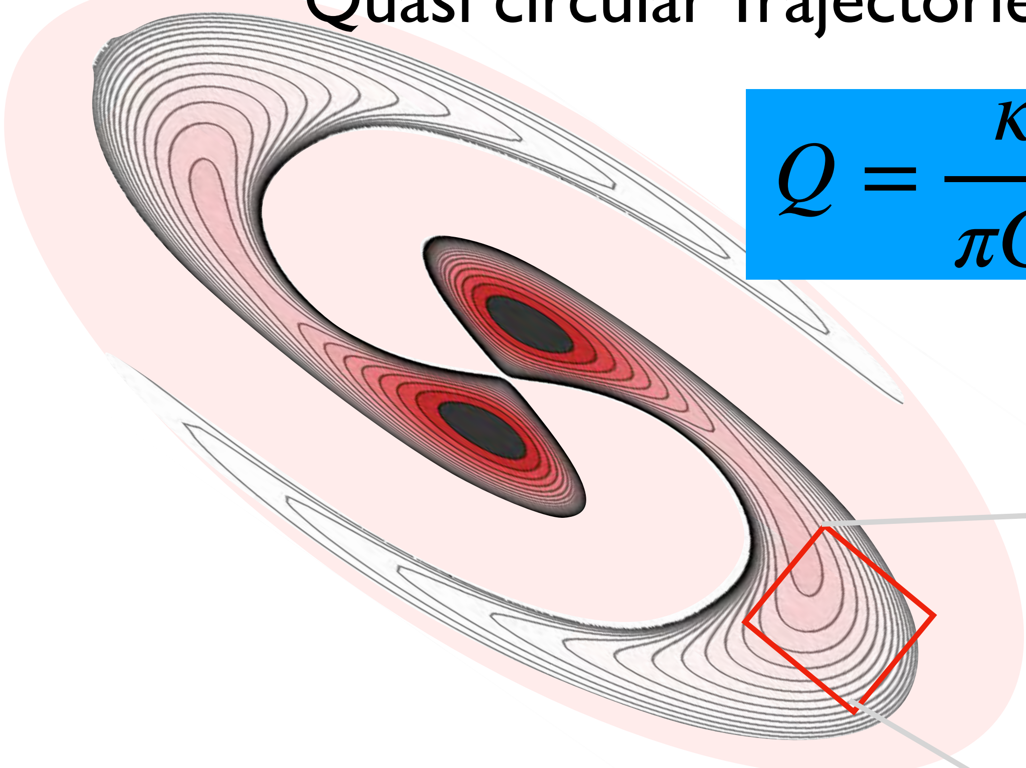
Quasi circular trajectories:
'cold' disc



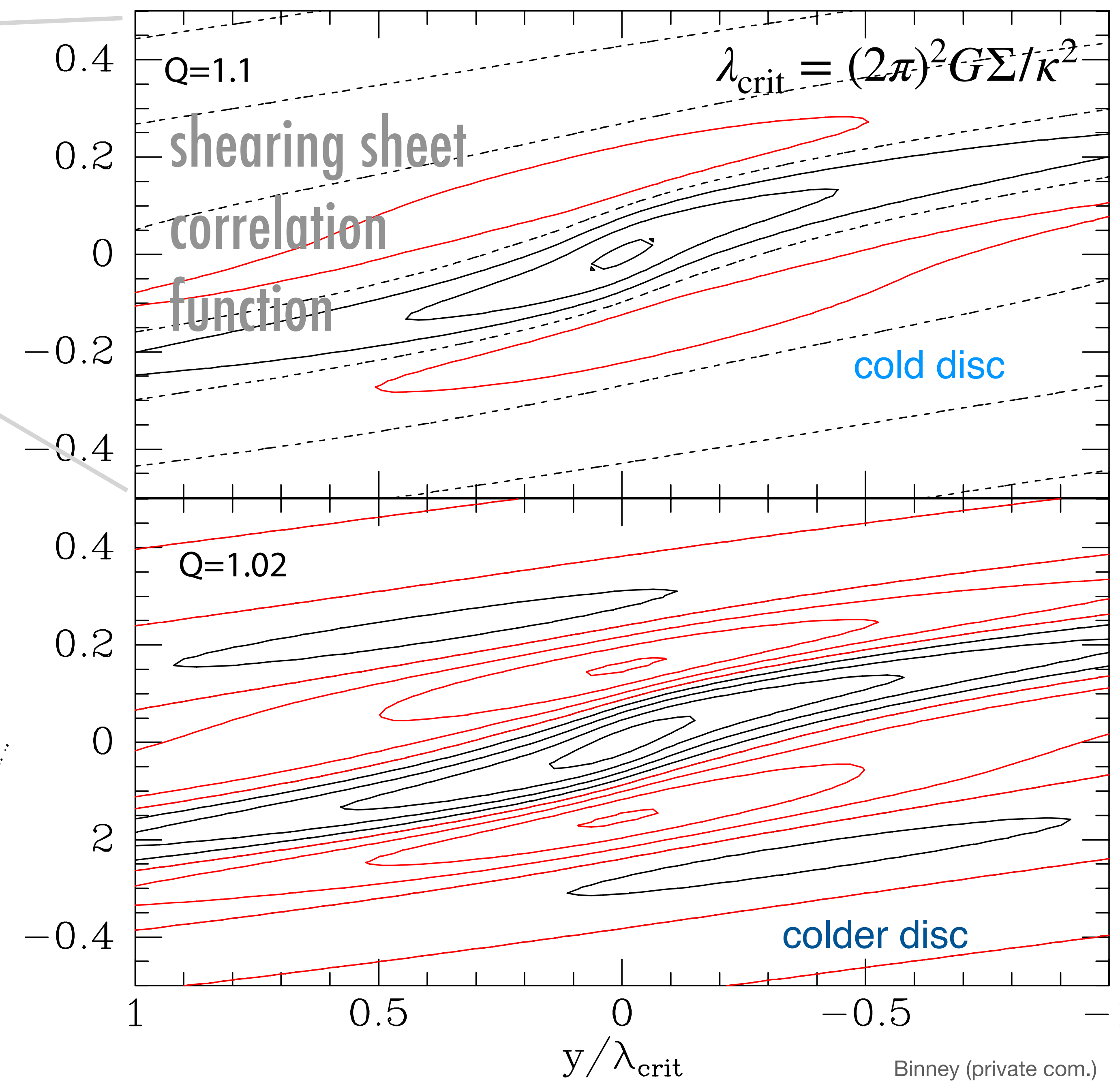
→ No significant relative motion to oppose gravitation

Quasi circular Trajectories: 'cold' disc

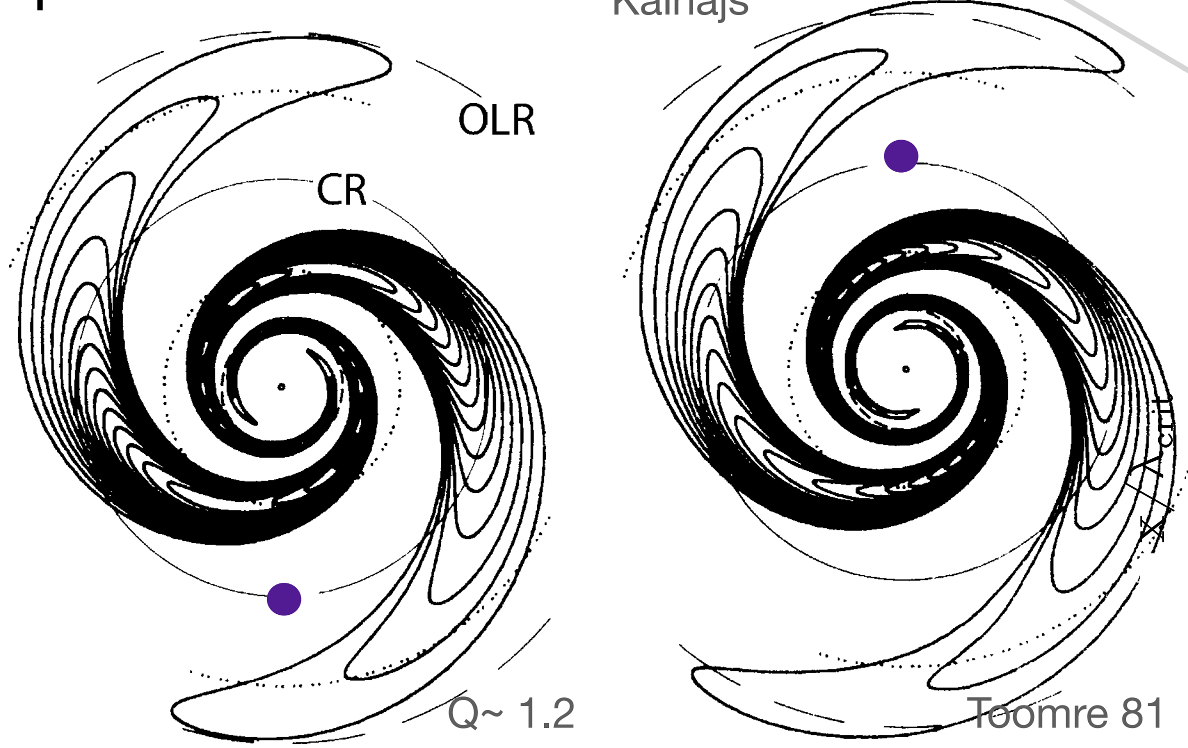
$$Q = \frac{\kappa\sigma}{\pi G \Sigma} \to 1$$



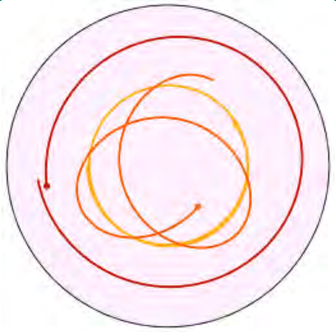
- colder disc means **larger** wake
- colder disc means **stronger** wake
- colder disc means **shorter** dynamical time



Mass in **wake** = mass in perturbation **X 30** !!

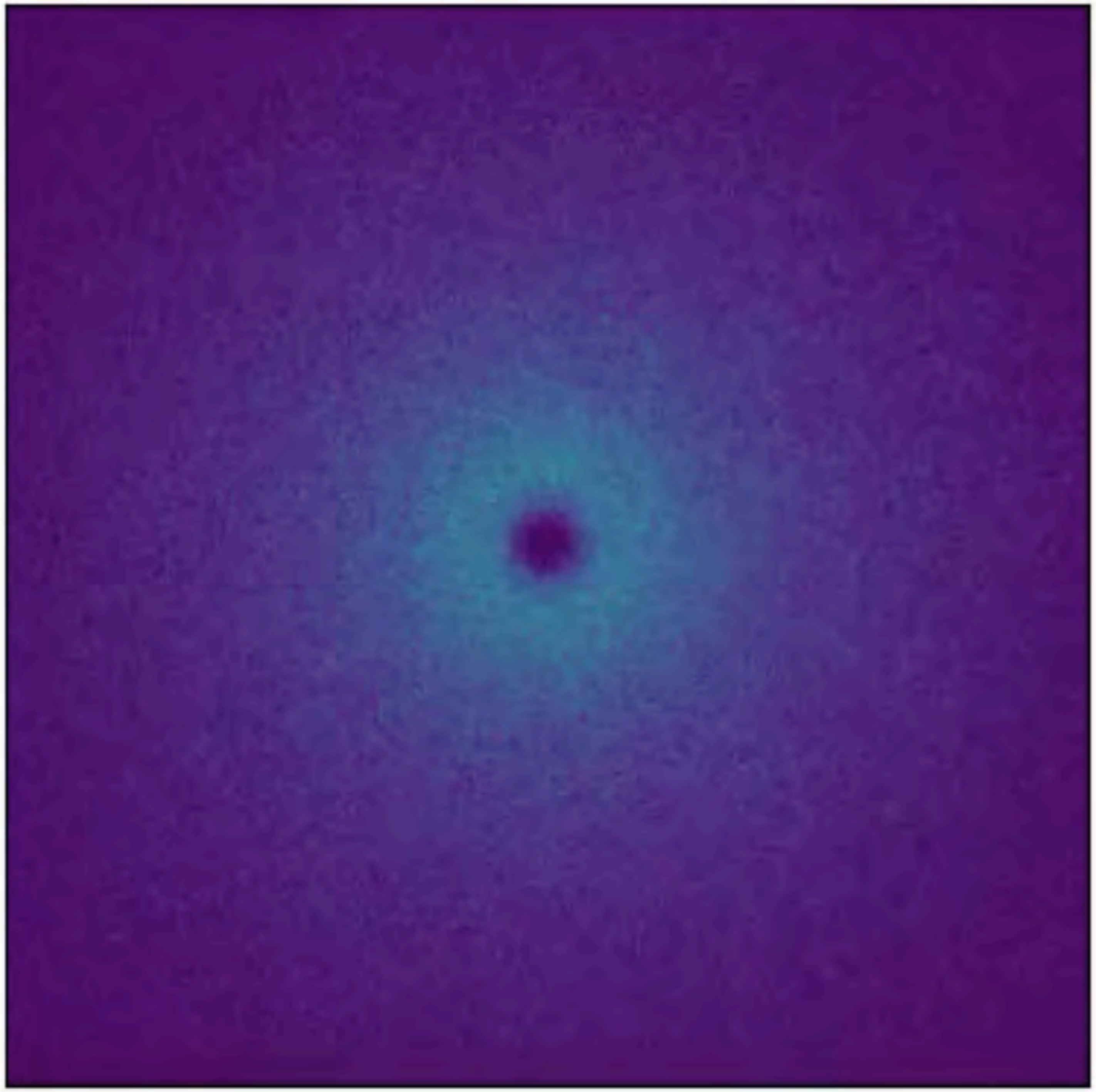


→ long range correlations



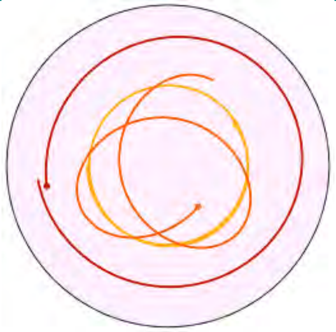
Linear instabilities

Massive **cold** disc



See also Zang (1976), Evans+(1998)

Collective effects drastically **amplify** wakes, in particular on **large scales**



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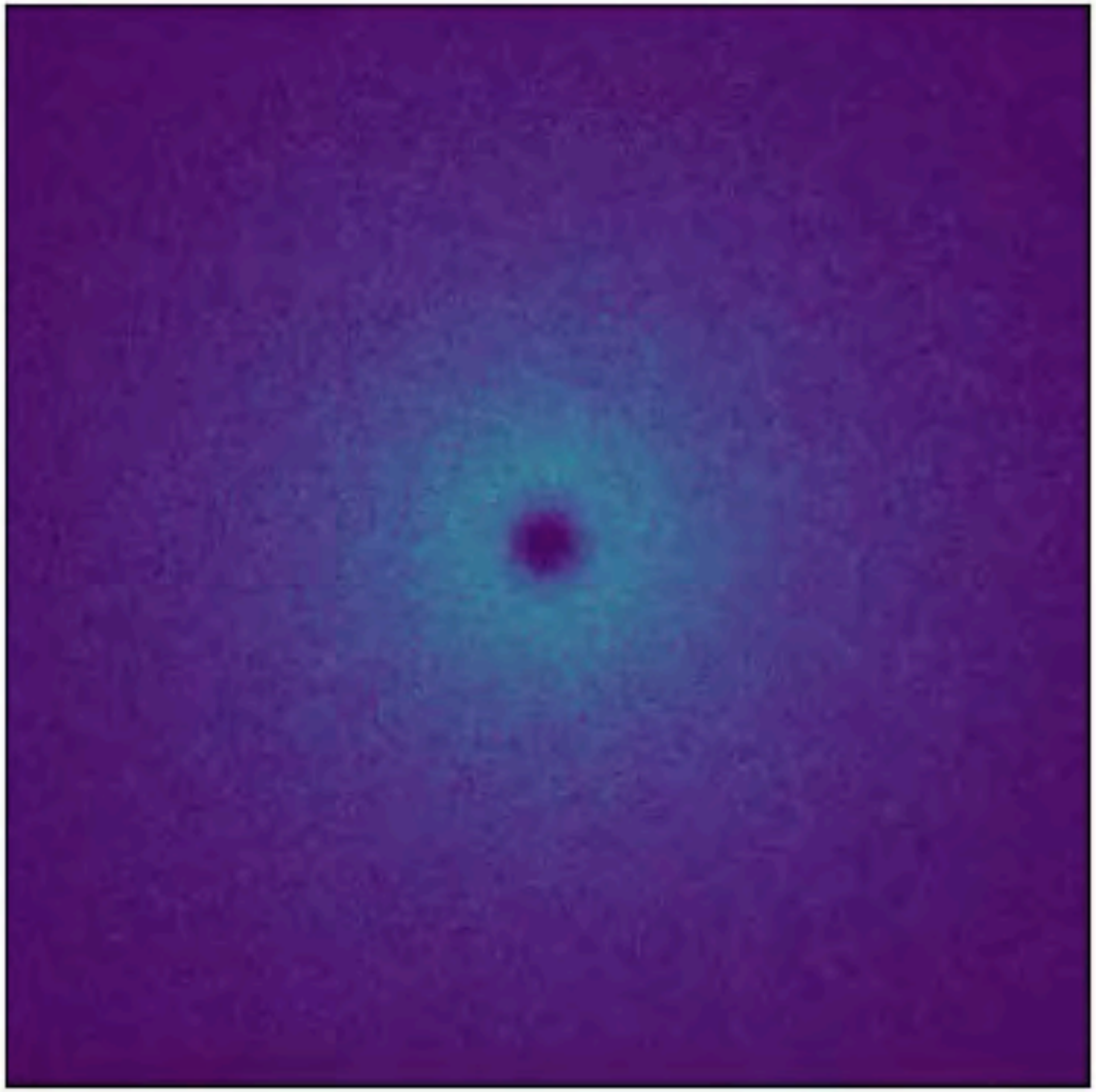

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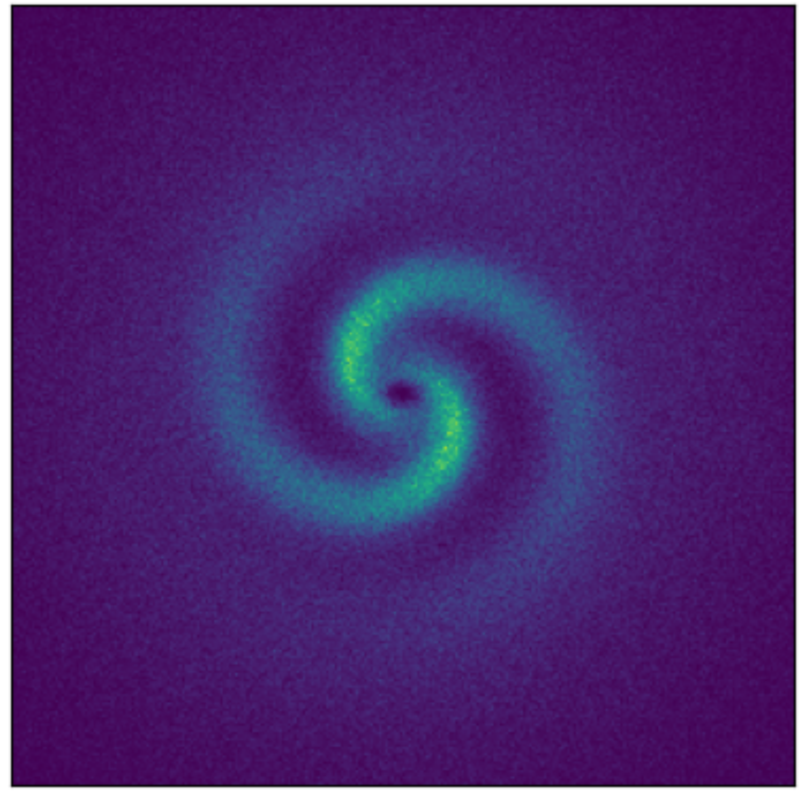
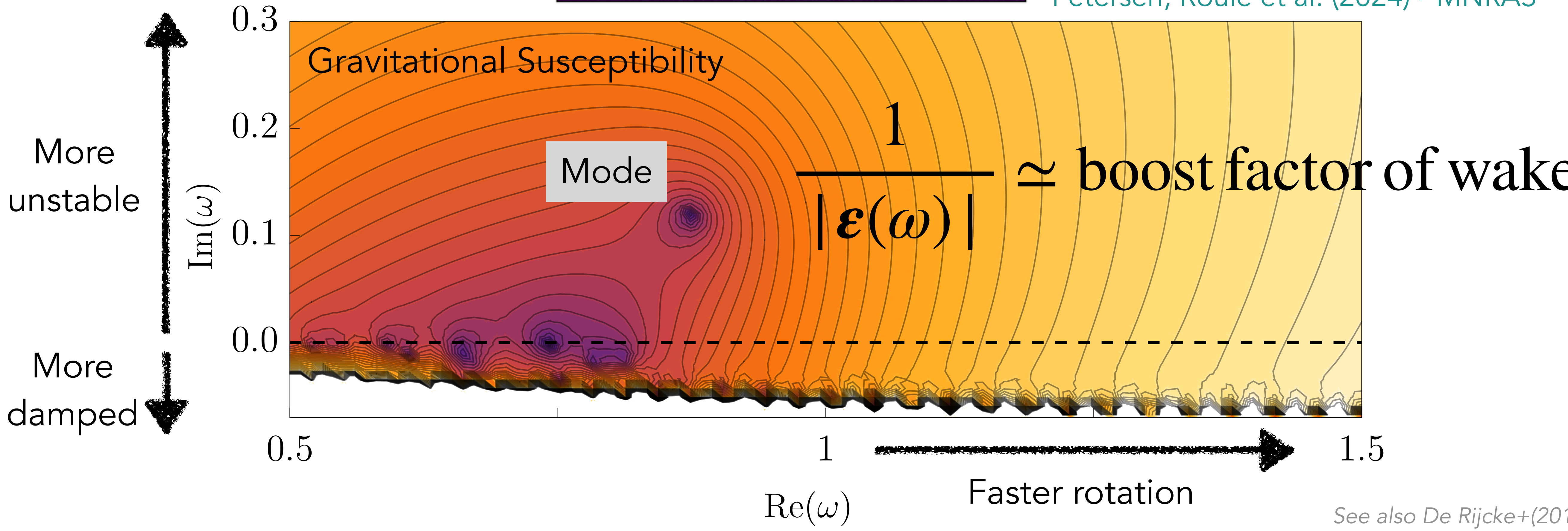
Linear instabilities: response theory matches simulations



Petersen, Roule et al. (2024) - MNRAS



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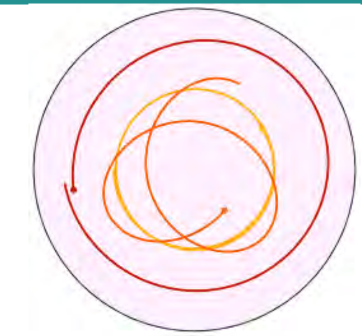

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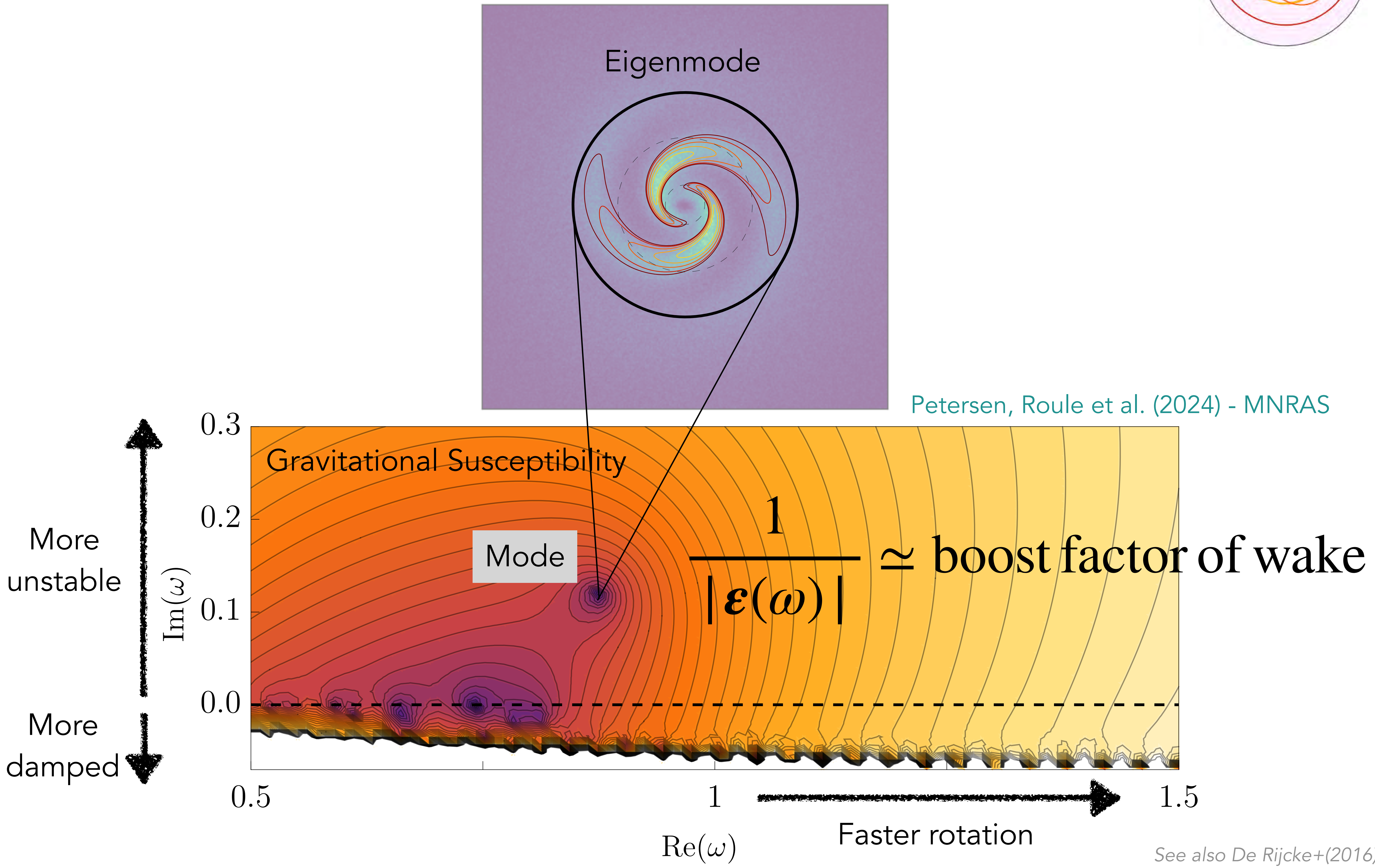

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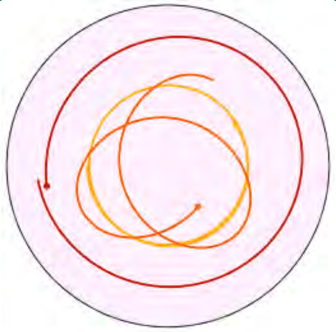
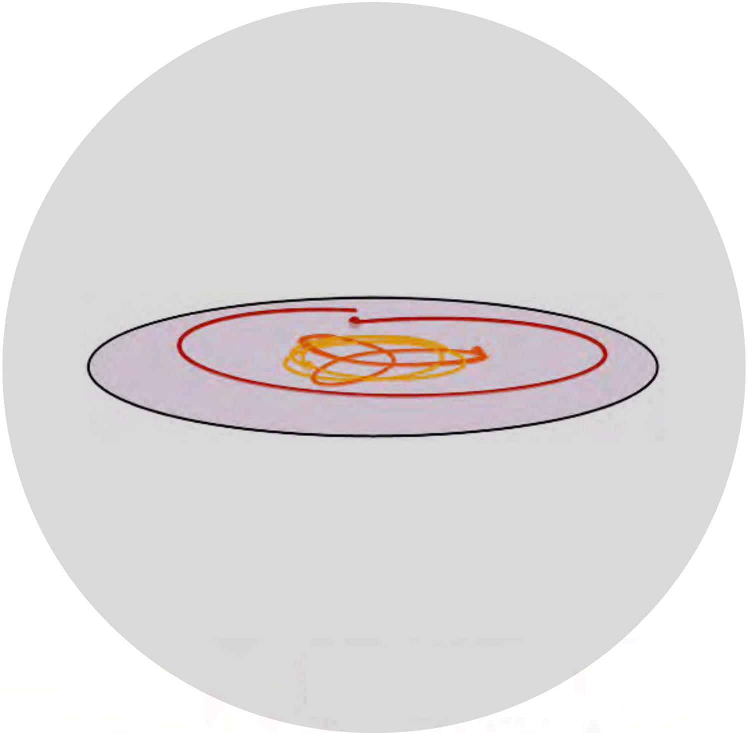
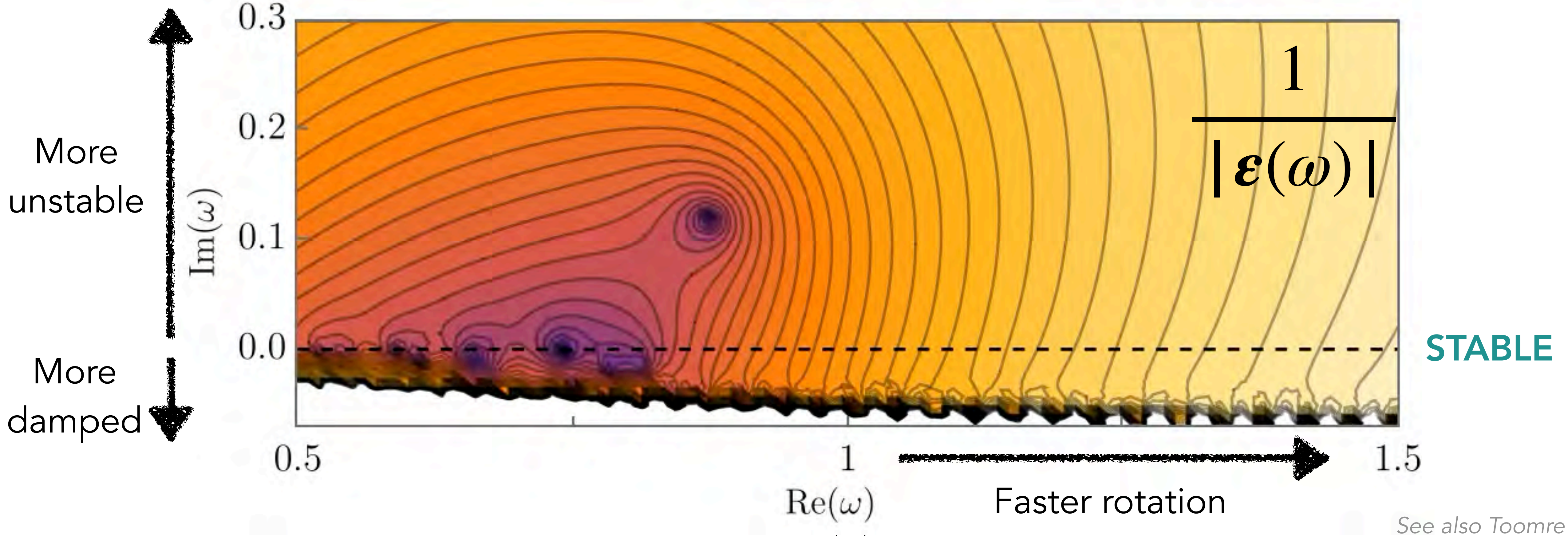
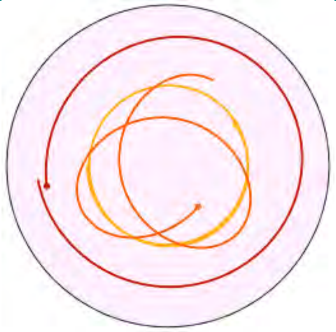


Halo and stability





See also Toomre (1981)



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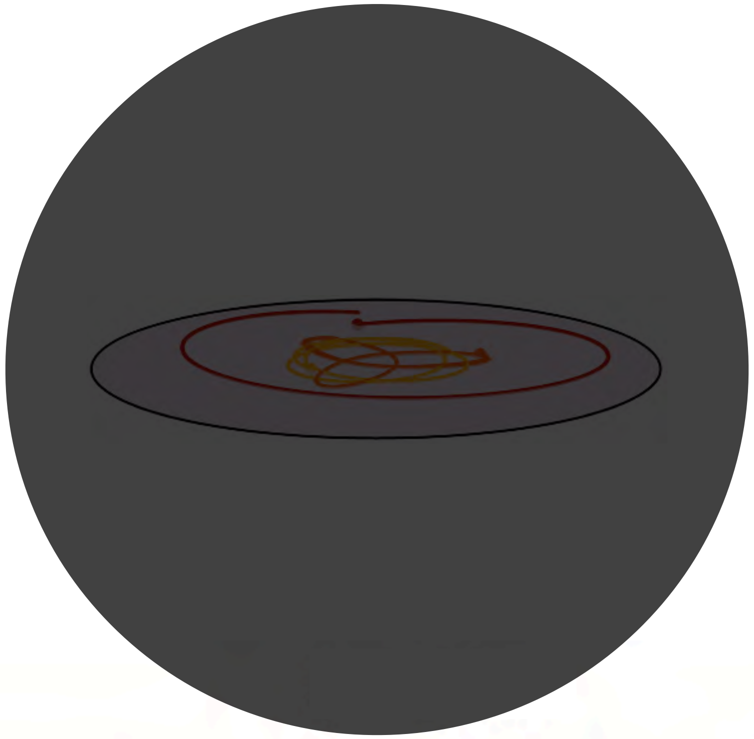
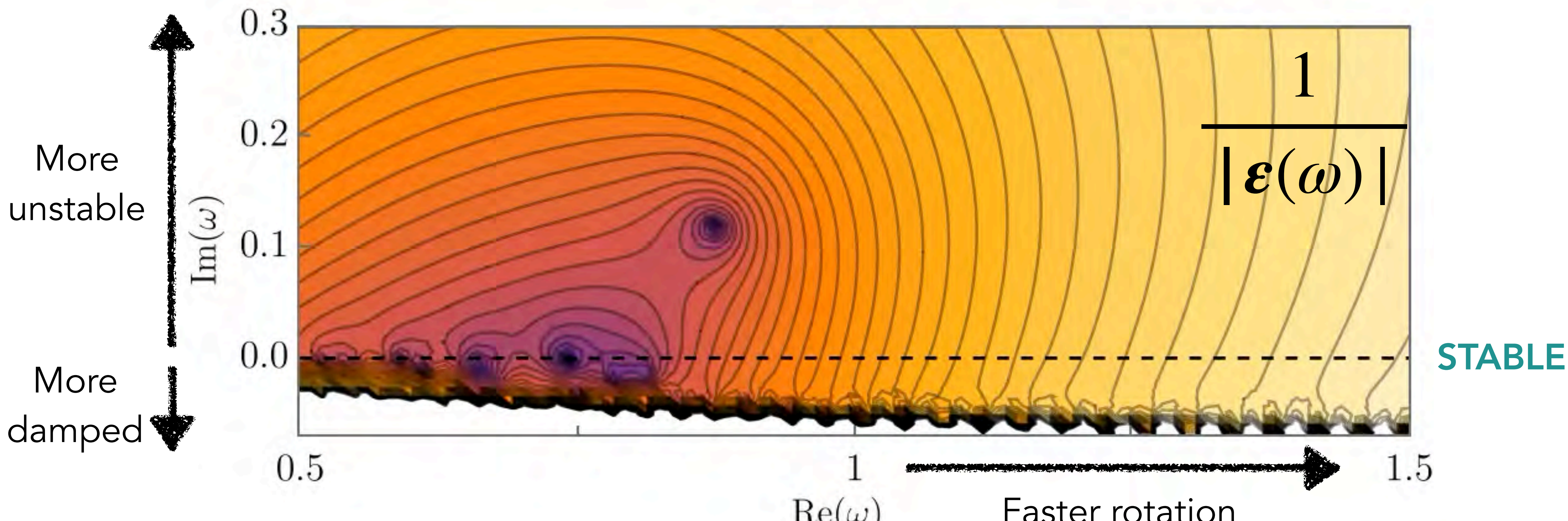




See also Toomre (1981)

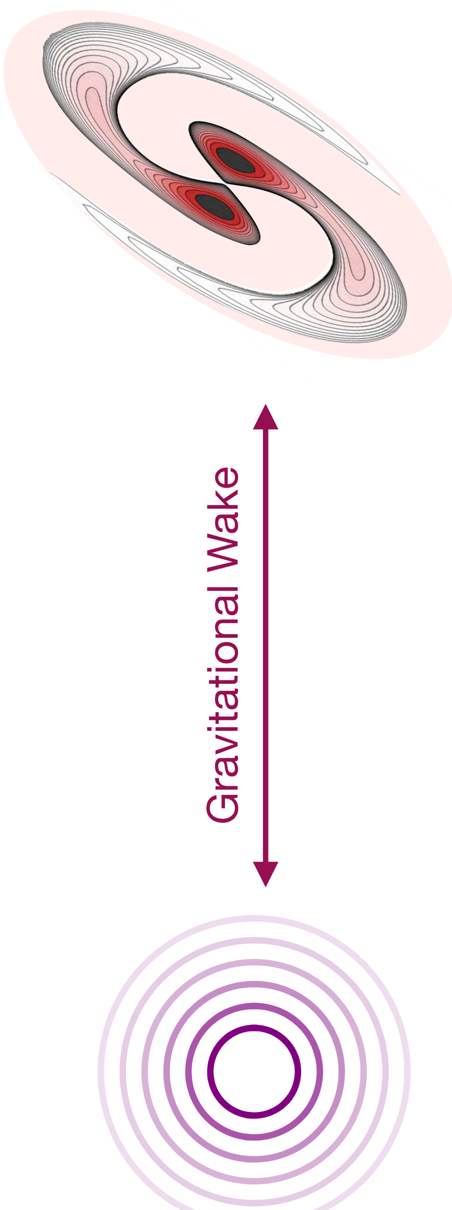
For cold discs…

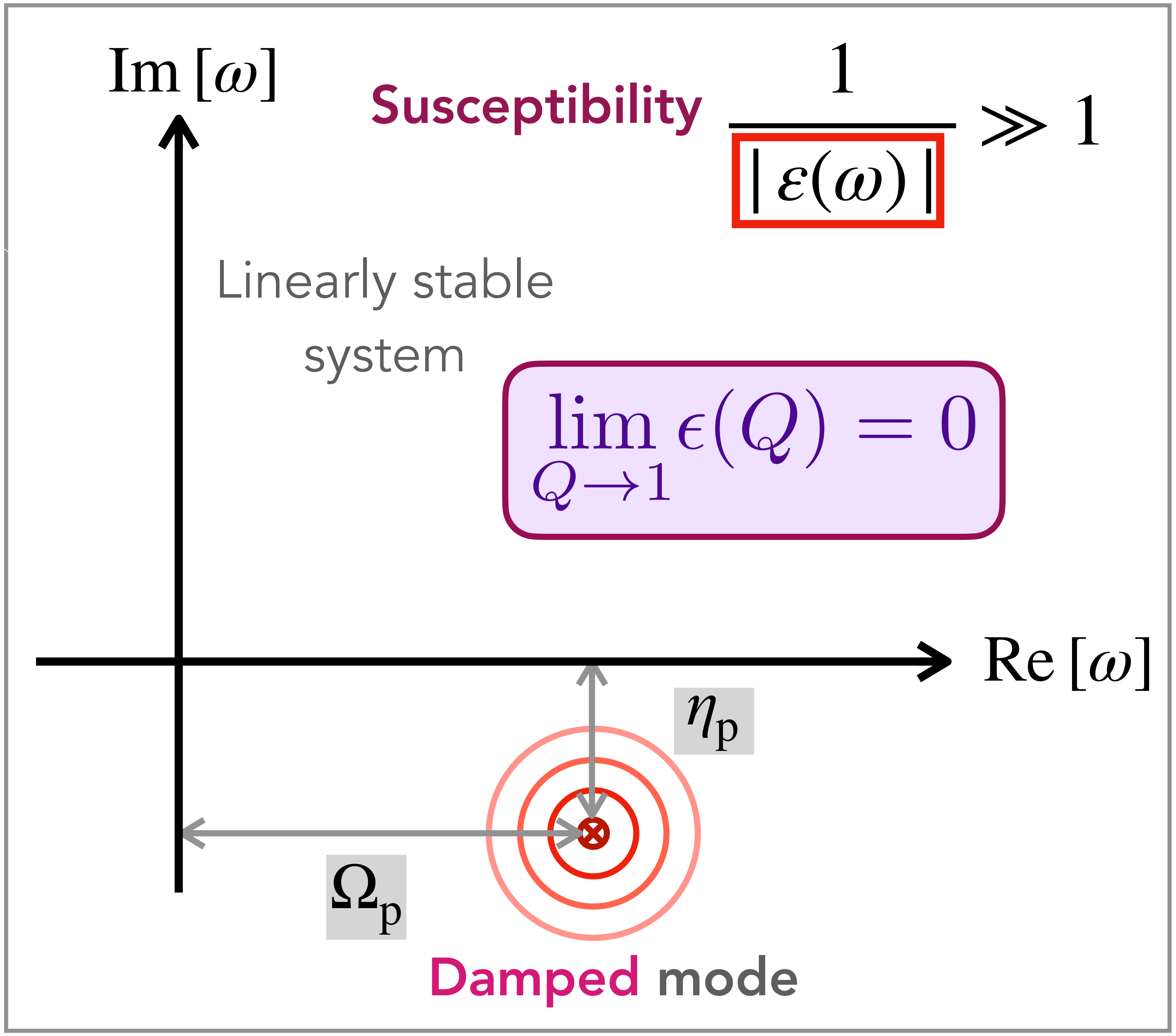
$$Q = \frac{\kappa\sigma}{\pi\Sigma} \to 1$$

Gravitational “*Dielectric*” function ϵ

$$\epsilon(Q) \equiv \mathcal{D}(\omega, k) = \det\big(1 - \mathbf{M}(\omega)\big)$$

Dispersion relation — Response matrix





$$\left[\delta\psi\right]_{\rm dressed} = \frac{\left[\delta\psi\right]_{\rm bare}}{|\,\varepsilon(\omega)\,|}$$

$$T_{\rm dressed} \simeq |\,\varepsilon\,|\, T_{\rm bare}$$

$$\Omega_{\rm dressed} \simeq \frac{1}{|\,\varepsilon\,|}\, \Omega_{\rm bare}$$

thanks to **cosmic web** which sets up cold disc

Wake drastically boost orbital frequencies, stiffening coupling/tightening control loops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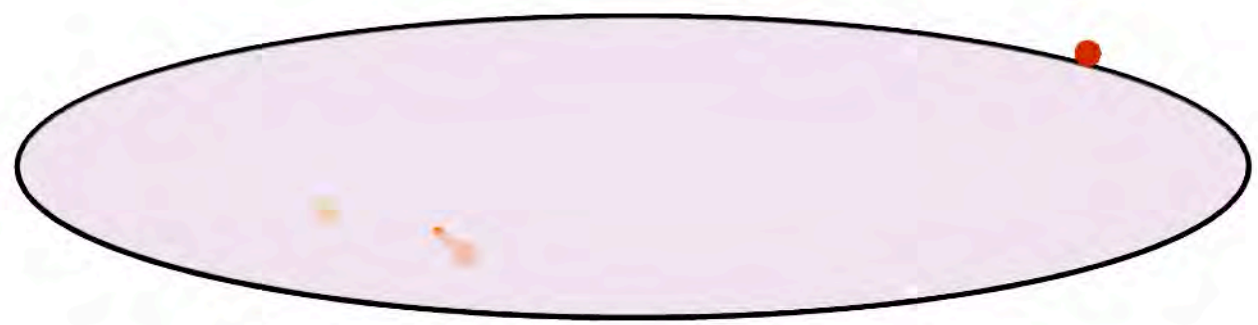
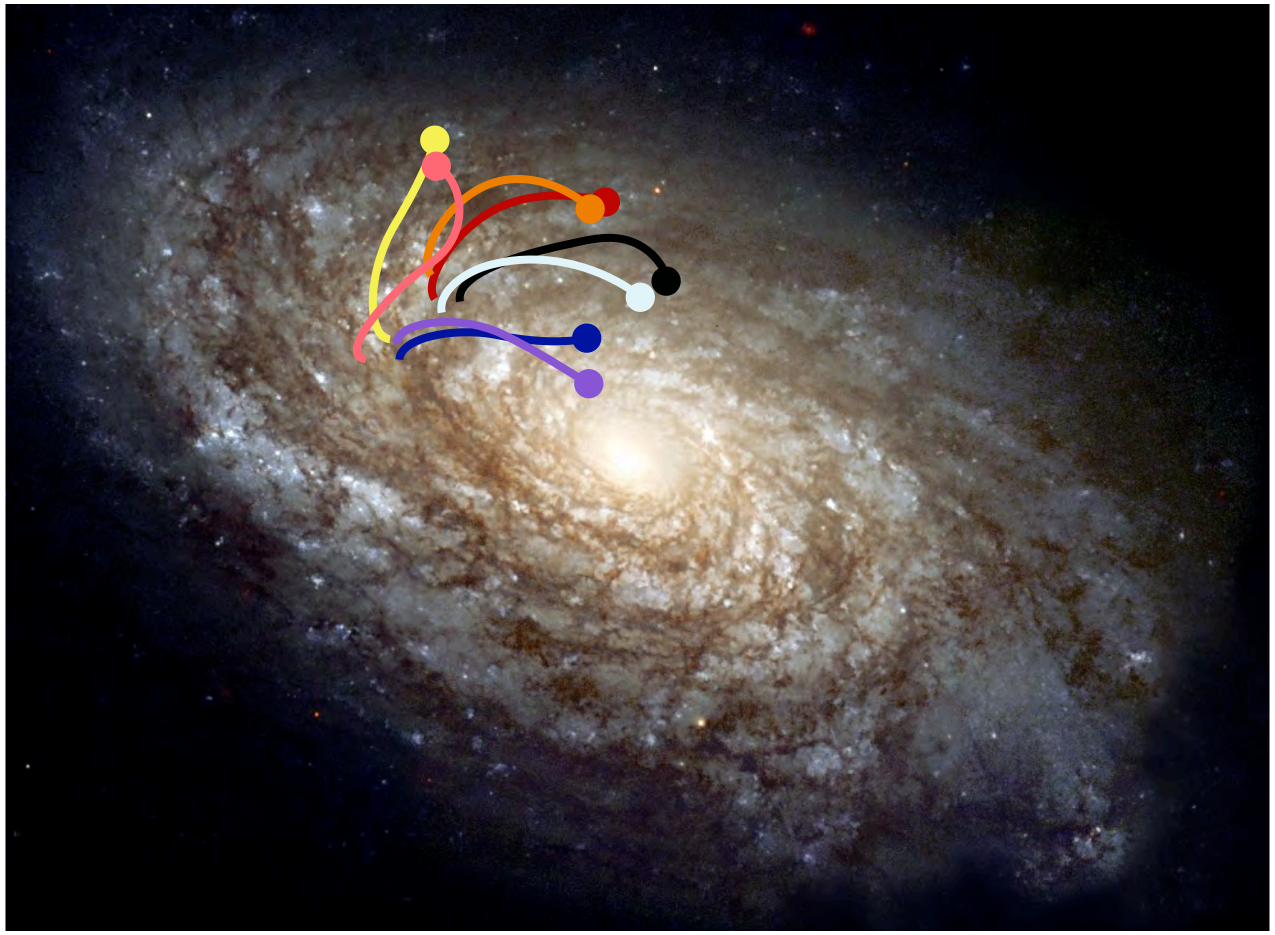
Quid of cumulative effect of swing amplified perturbations?



Fluctuation-Dissipation Theorem

Diffusion rate ⟷ **Power-spectrum of the fluctuations**



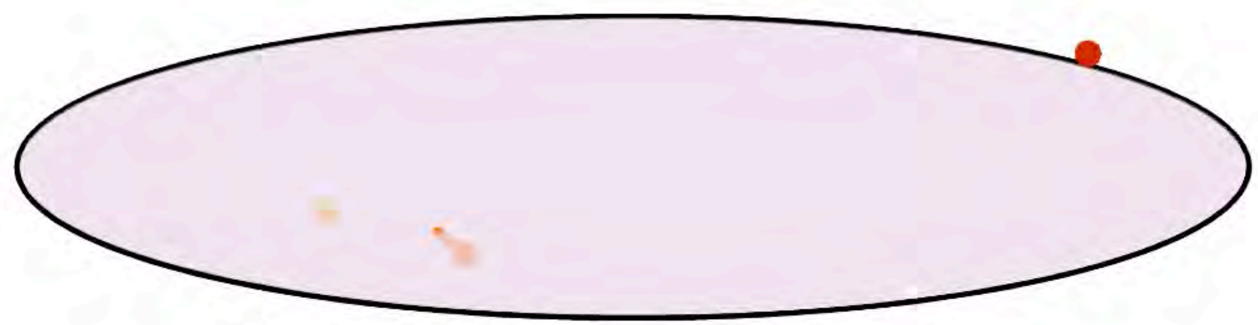
≈

Orbits in a galaxy

But temperature-driven wake : the colder the faster!

Ink in water

Quid of cumulative effect of swing amplified perturbations?



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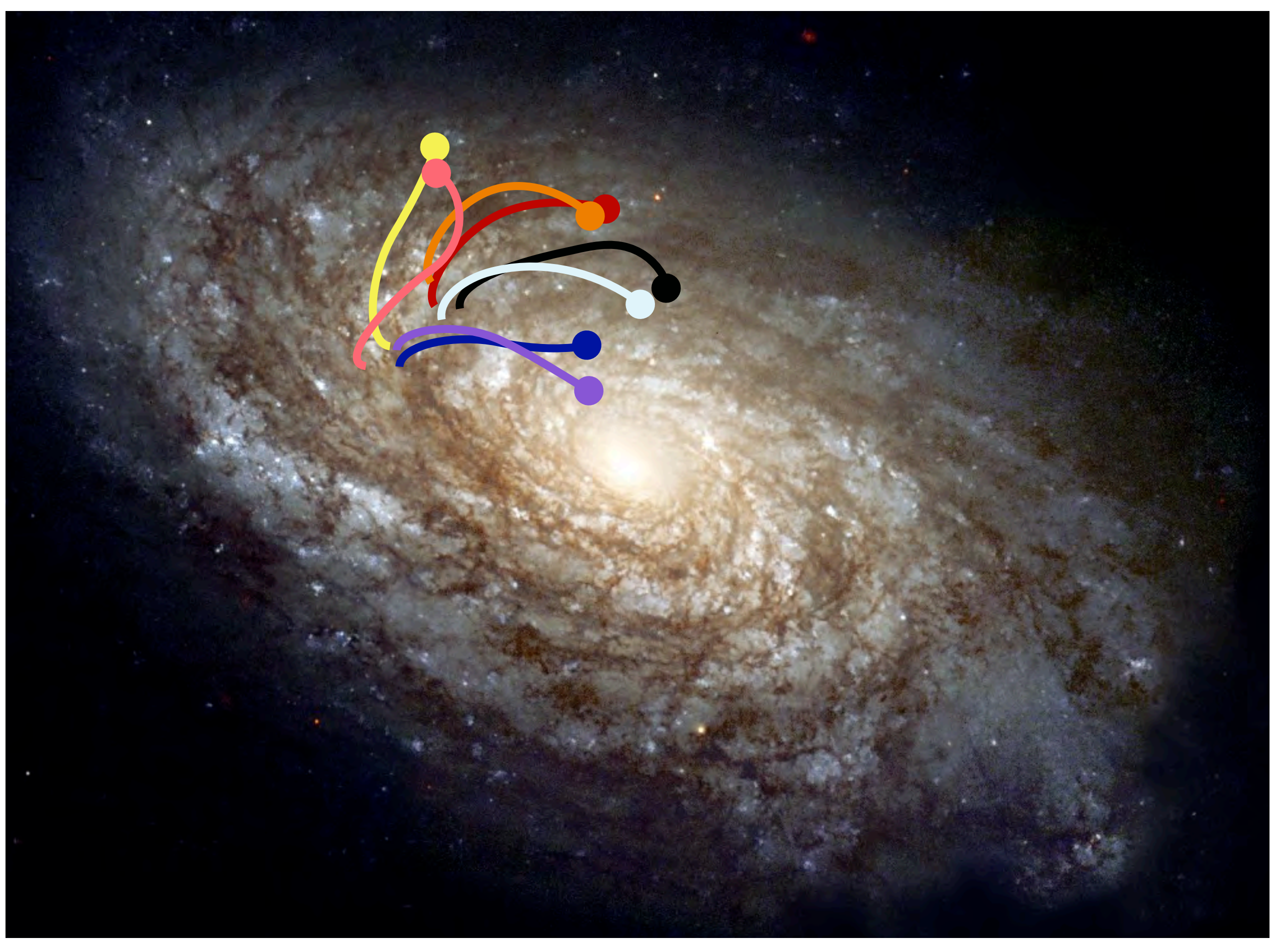

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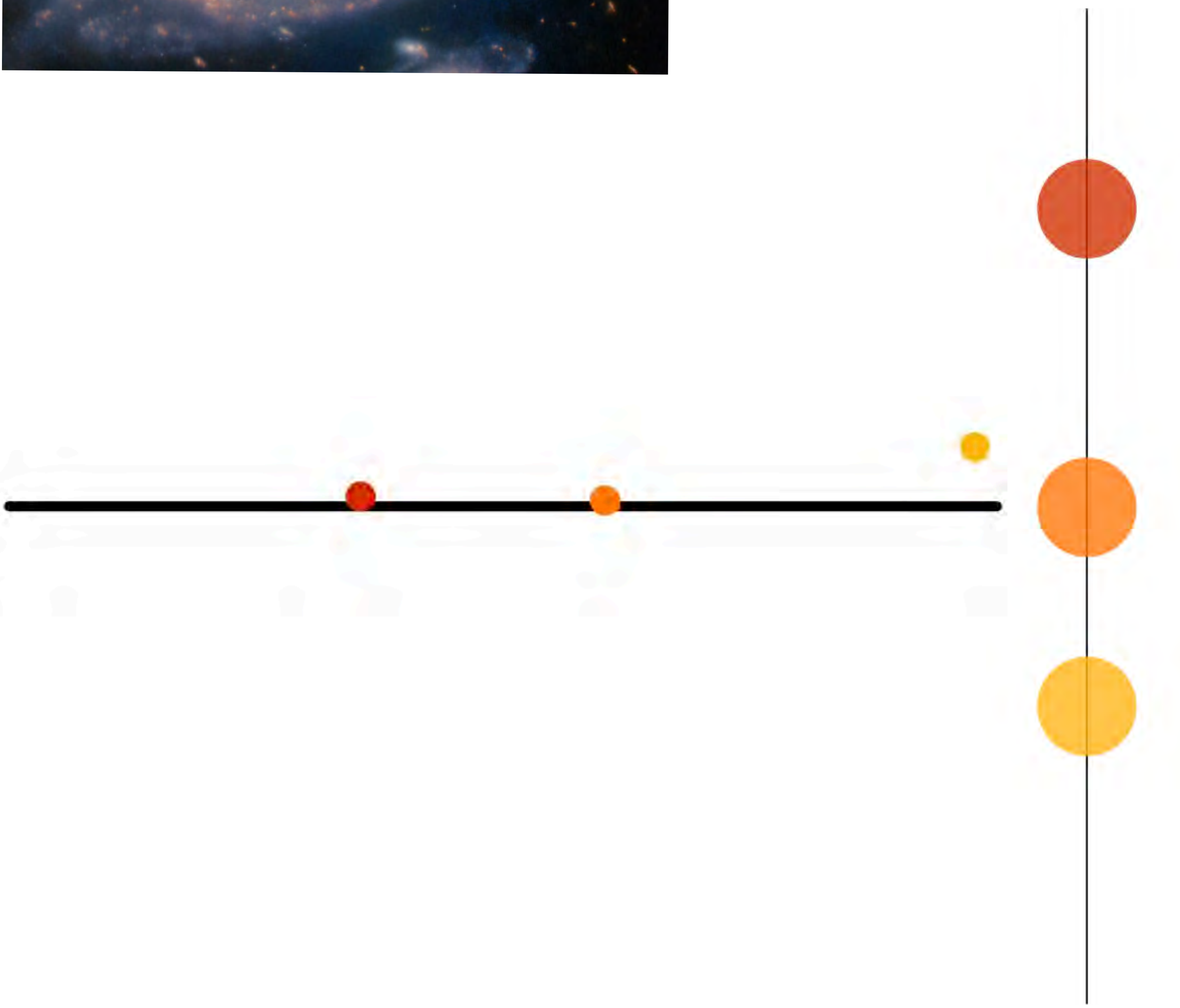
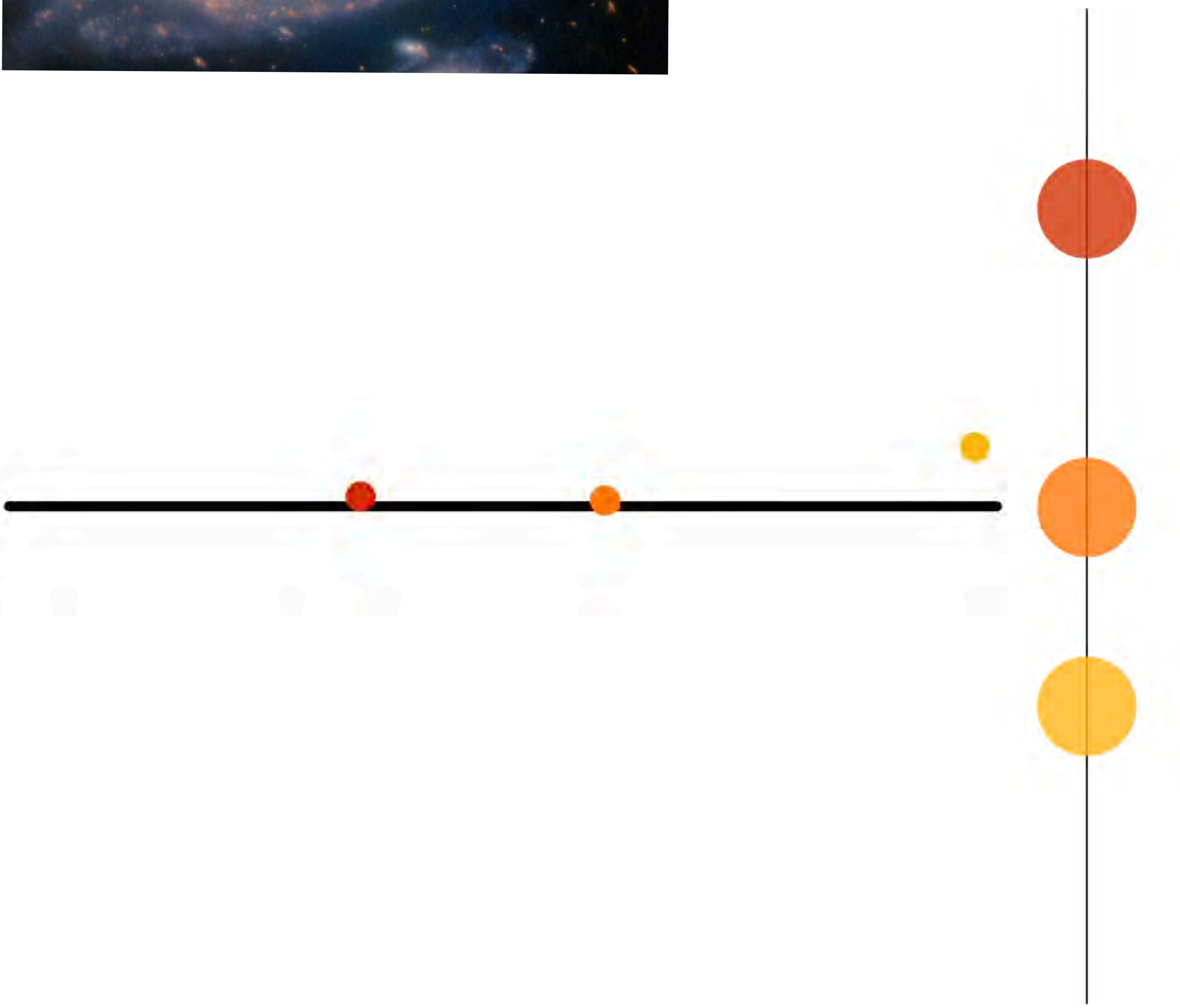


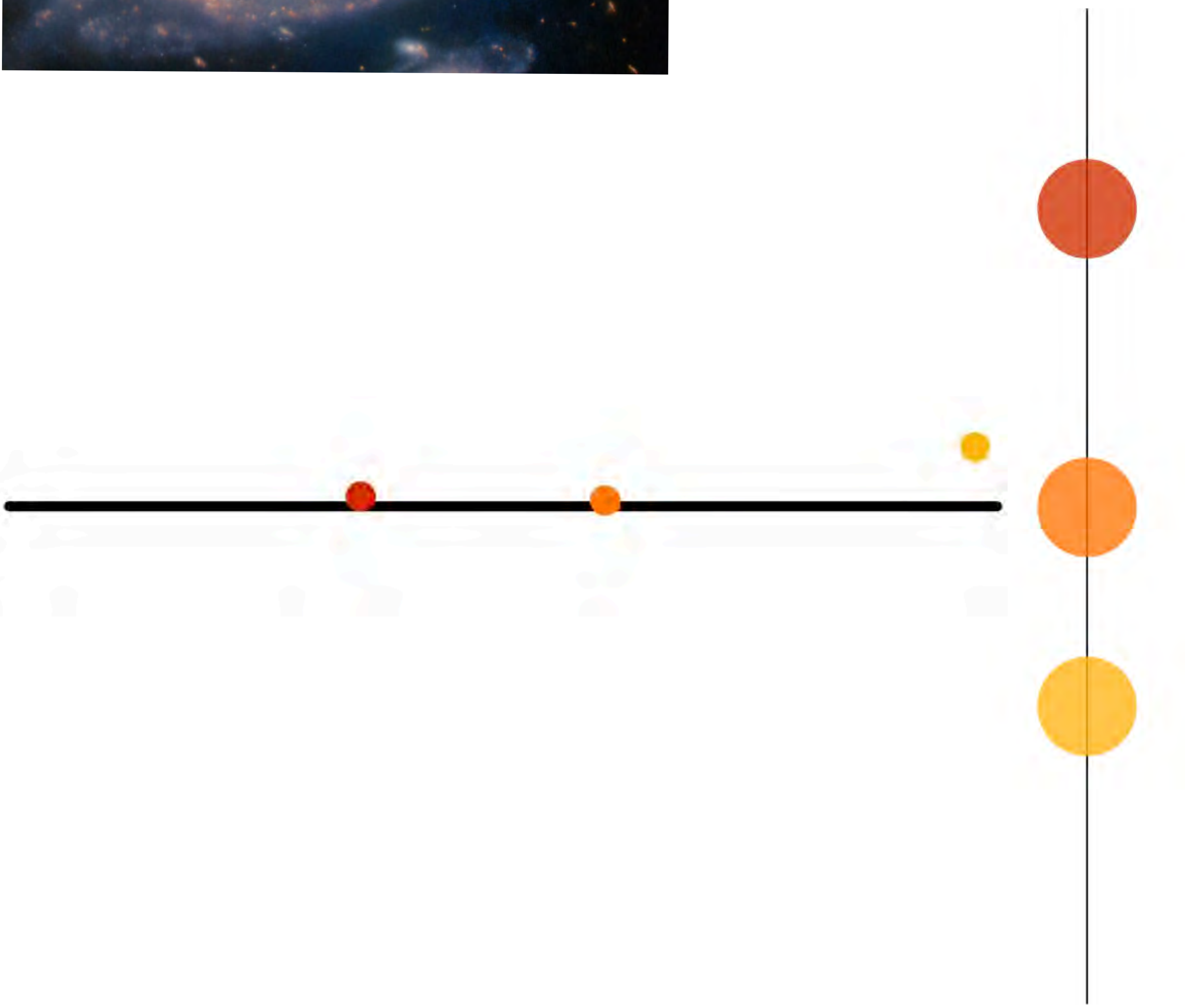
See also Joyce+(2010)

Vertical motion



See also Joyce+(2010)

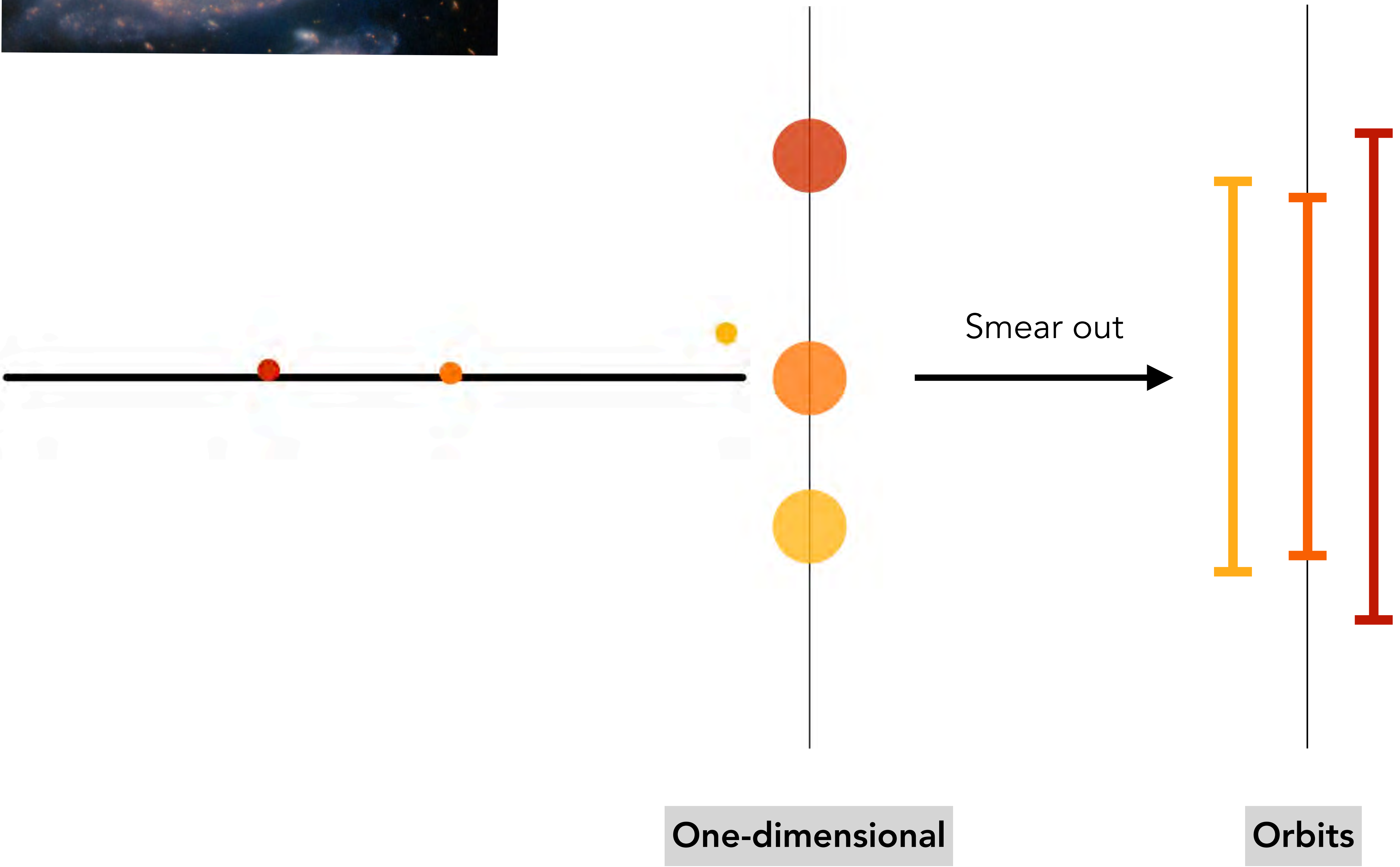
Vertical motion



One-dimensional

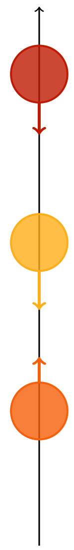
See also Joyce+(2010)

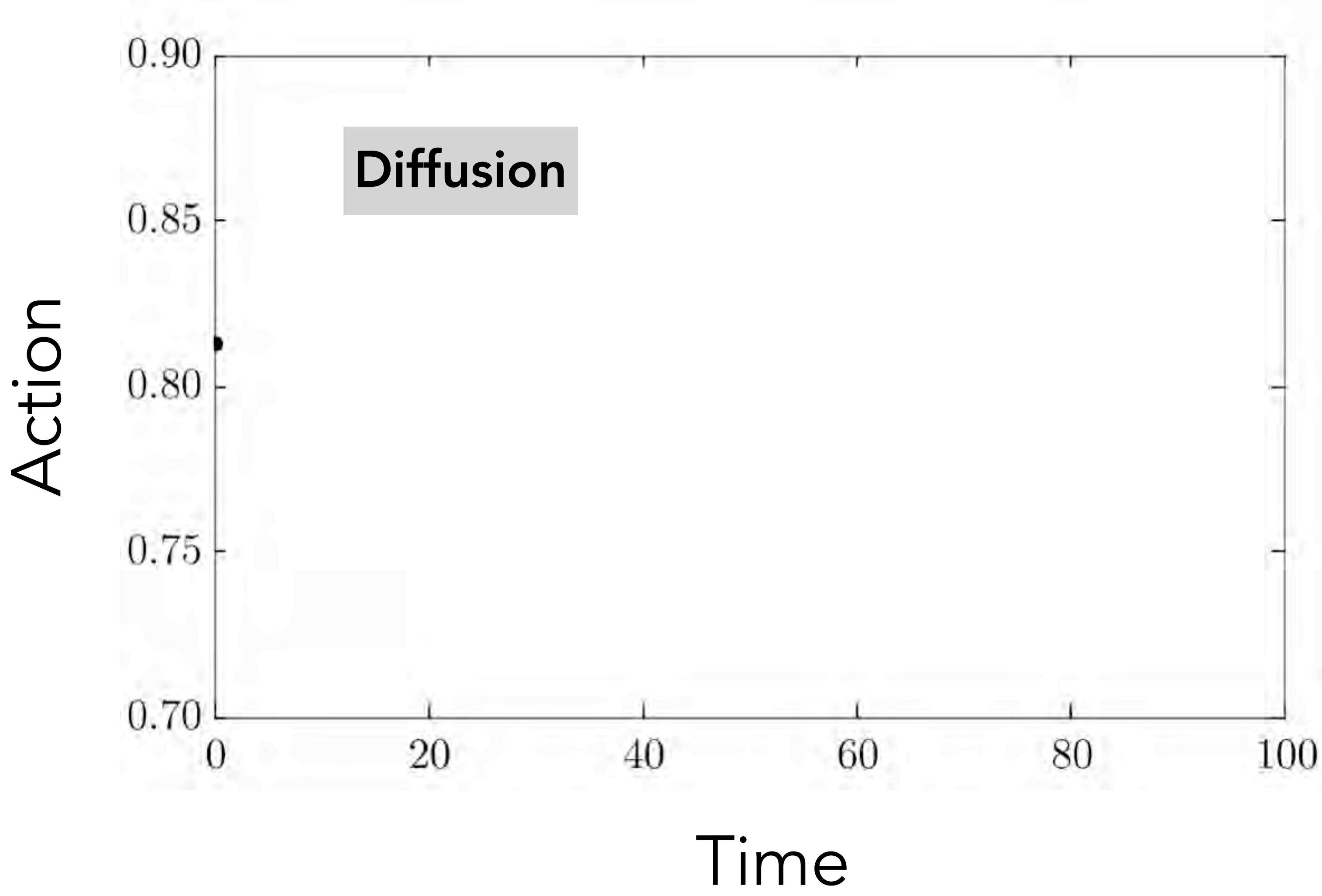
Vertical motion



See also Joyce+(2010)

Orbital diffusion

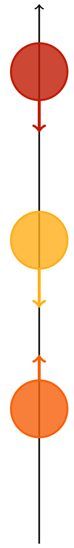


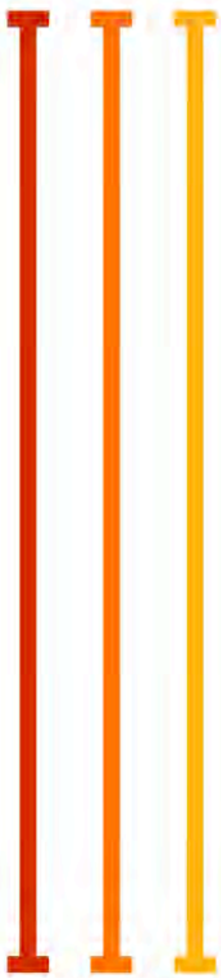


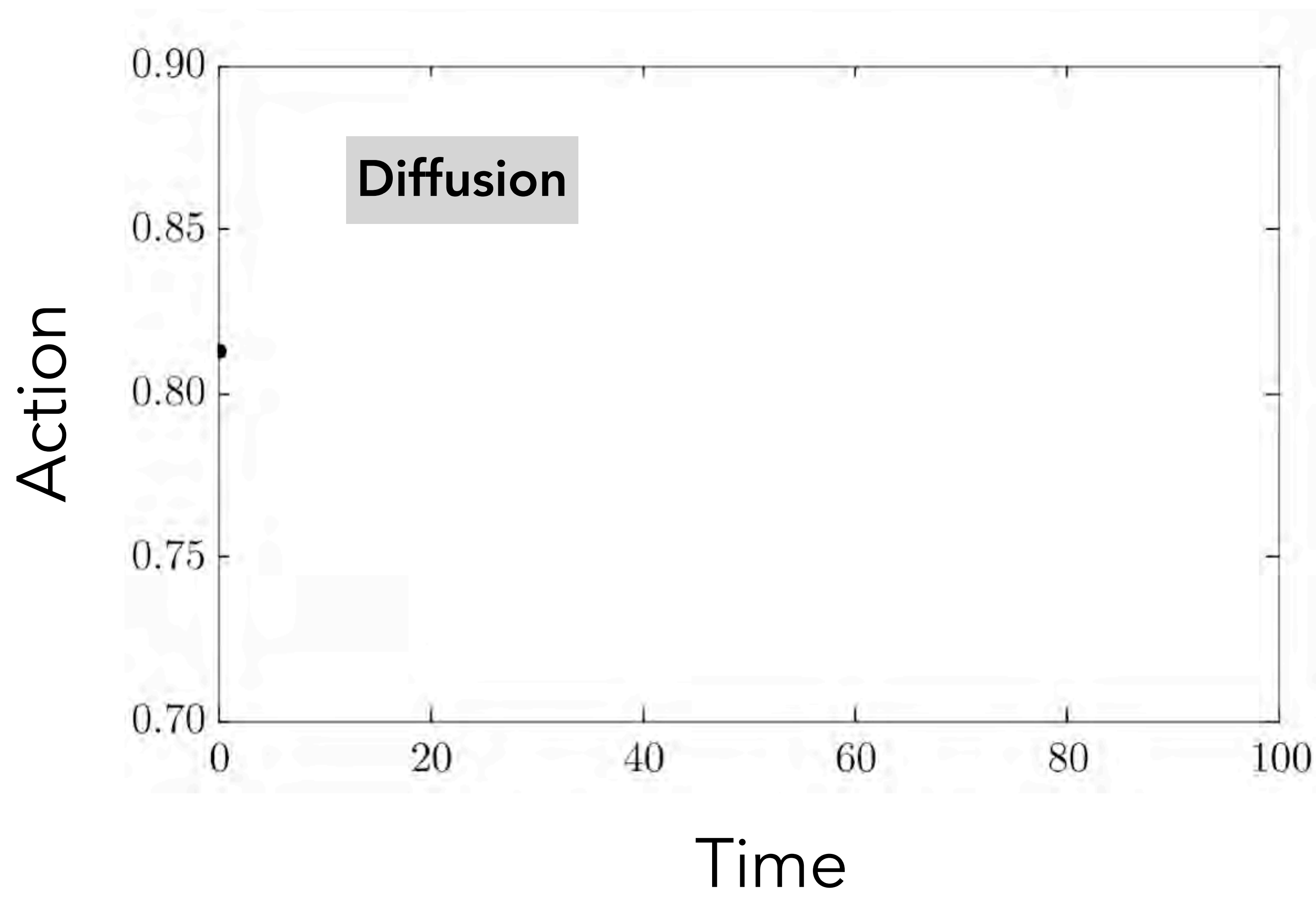
Perturbed

Disc **thickening**

Orbital diffusion







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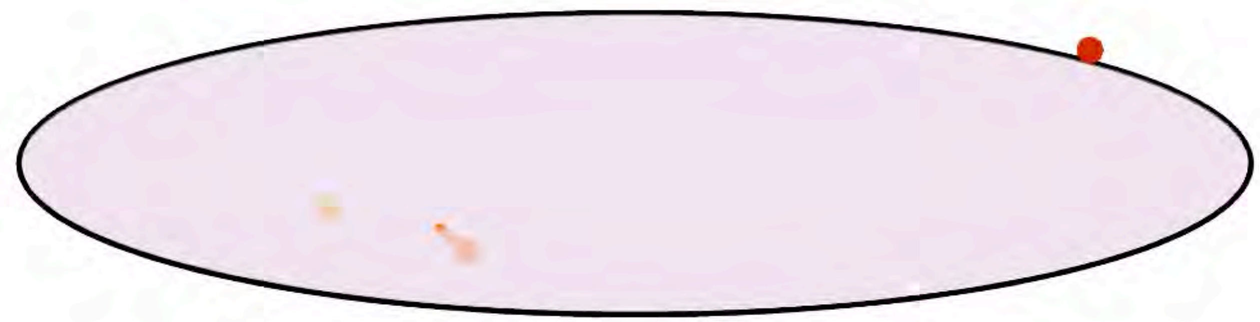
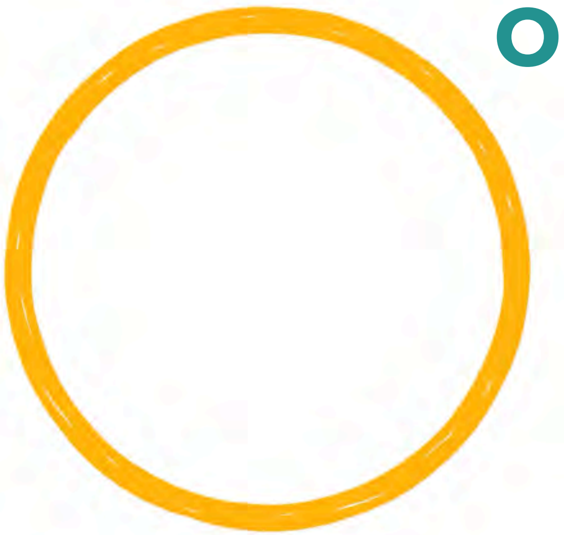
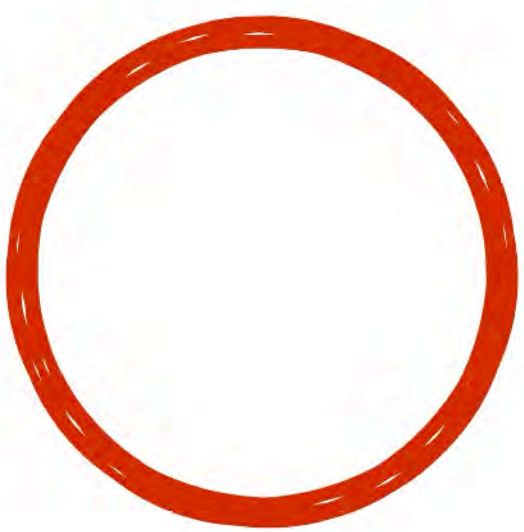


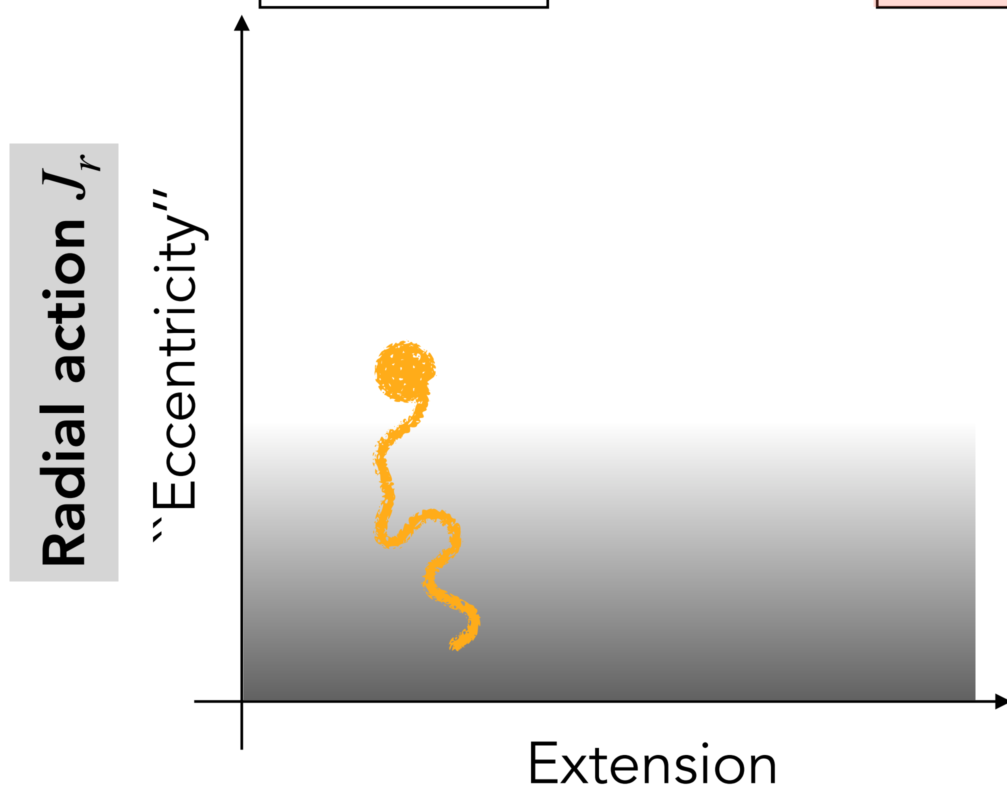
Orbital diffusion





Fluctuation-Dissipation Theorem

Diffusion rate ⟷ **Power-spectrum of the fluctuations**

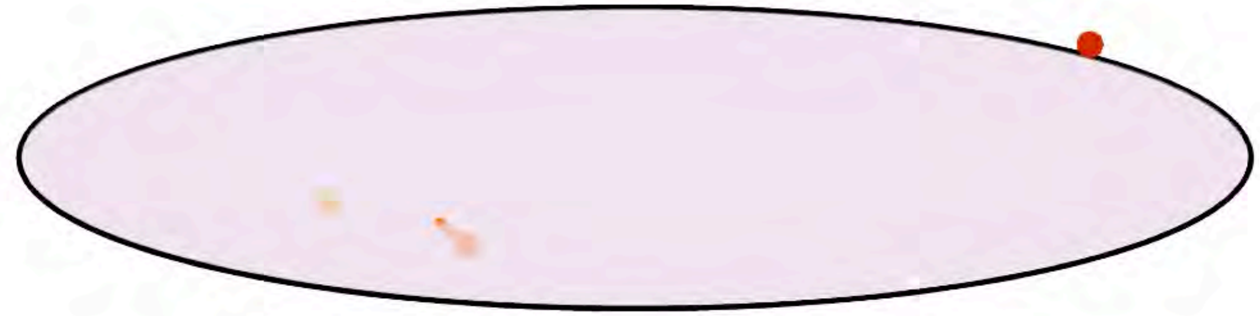


Angular momentum L

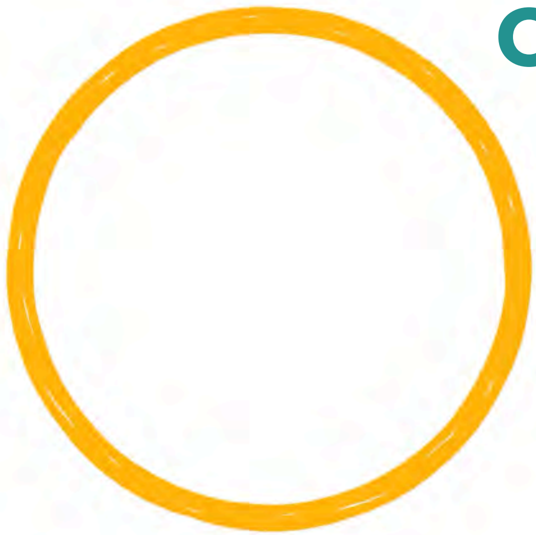
Initially **cold**

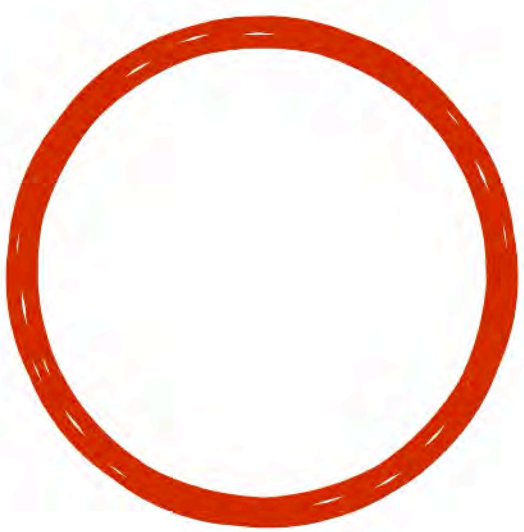
Fluctuations heat and statistically increase **radial oscillations**

See also Sellwood+(2002)



Orbital diffusion





Fluctuation-Dissipation Theorem

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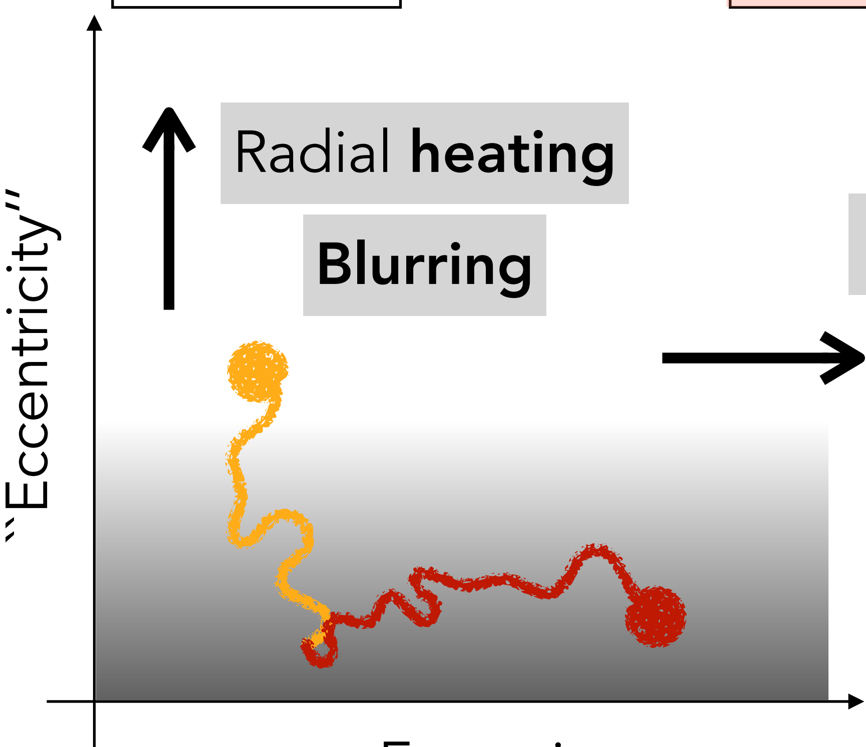


Fluctuations heat and statistically increase **radial oscillations**

See also Sellwood+(2002)

Perturbative quasi-linear/Kinetic theory

Exact **stochastic** equation | **Perturbative** expansion | mean field Quasi-stationary **equilibrium**

$$\left\langle \frac{\partial F_{\rm d}}{\partial t} + \left[F_{\rm d}, H_{\rm d}\right] = 0 \quad + \quad \begin{matrix} F_{\rm d} = \langle F \rangle + \delta F \\ H_{\rm d} = \langle H \rangle + \delta H \end{matrix} \quad + \quad \left[F, \langle H \rangle\right] = 0 \right\rangle$$

ensemble average

$$=$$

$$\frac{\partial \langle F \rangle}{\partial t} = - \left\langle \left[\delta F, \delta H\right] \right\rangle$$

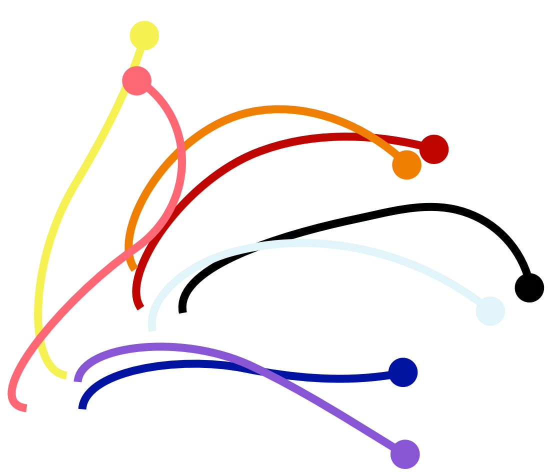
quadratic term

Fluctuations **correlations**

inertial time delay

Fluctuation-Dissipation Theorem

Diffusion rate ⟷ **Power-spectrum of the fluctuations**



Mean galaxy subject to **deterministic** orbital **diffusion**

Collective amplification

Secular evolution equation

$$\frac{\partial \langle F \rangle}{\partial t} = - \left\langle \left[\delta F, \delta H \right] \right\rangle$$

ensemble average

quadratic term

Dressing comes twice

$$M_{\mathrm{wake}} = \frac{M_{\mathrm{perturb}}}{|\,\varepsilon(\omega)\,|} \longrightarrow \frac{\partial F}{\partial t} \simeq \frac{M^2_{\mathrm{perturb}}}{|\,\varepsilon(\omega)\,|^2}$$

$$\frac{1}{|\,\varepsilon(\omega)\,|} \sim 30 \longrightarrow \frac{1}{|\,\varepsilon(\omega)\,|^2} \sim 1000$$

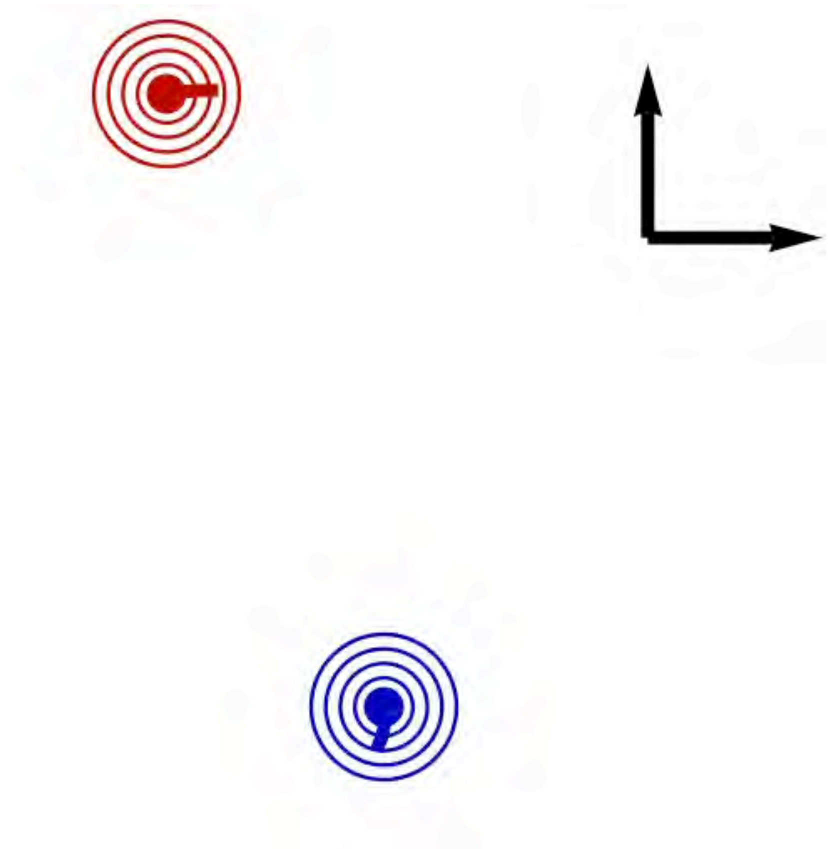
Toomre (1981)

Collective effects drastically **accelerate** orbital **heating**, in particular on **large scales**

Resonant encounters

- **Resonance condition** $\delta_{\mathrm{D}}(\boldsymbol{m}_1\cdot\boldsymbol{\Omega}_1-\boldsymbol{m}_2\cdot\boldsymbol{\Omega}_2) \Longrightarrow$ **Distant encounters.**

Here ● and ● resonate
in some rotating frame



The two (*blue* and *red*) sets of orbits satisfy the resonance condition **m**1·**Ω1=m2·Ω2**,
and therefore will interact consistently, driving a significant distortion of their shapes.

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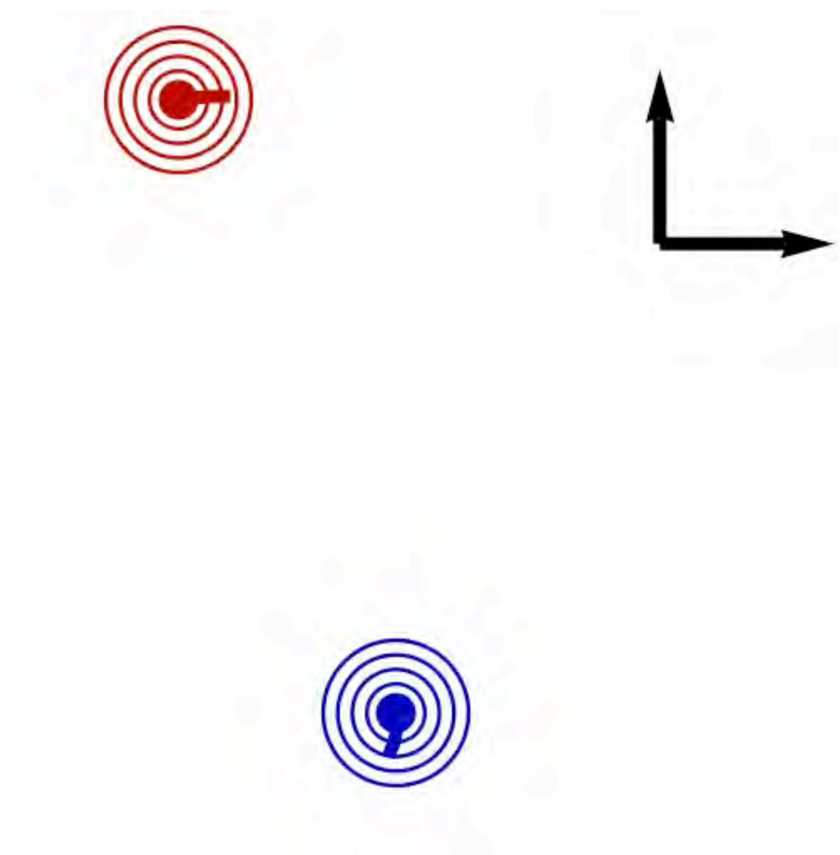


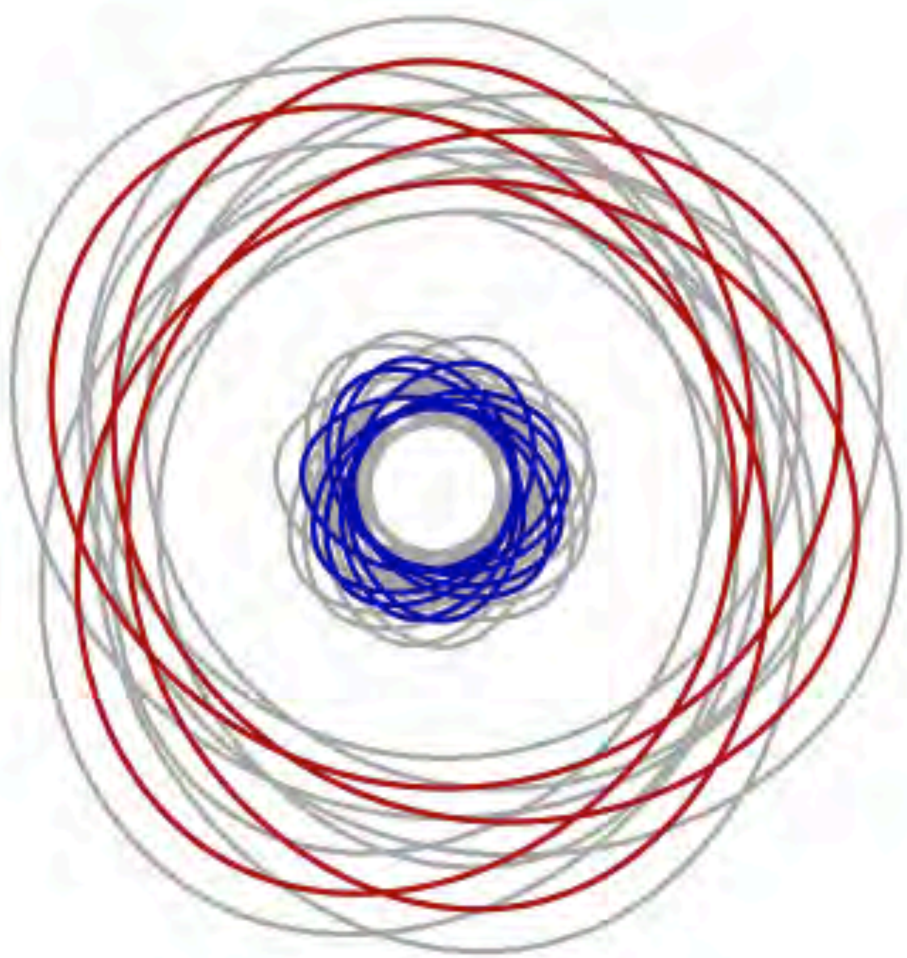
The two (*blue* and *red*) sets of orbits satisfy the resonance condition **m**1·**Ω1=m2·Ω2**,
and therefore will interact consistently, driving a significant distortion of their shapes.

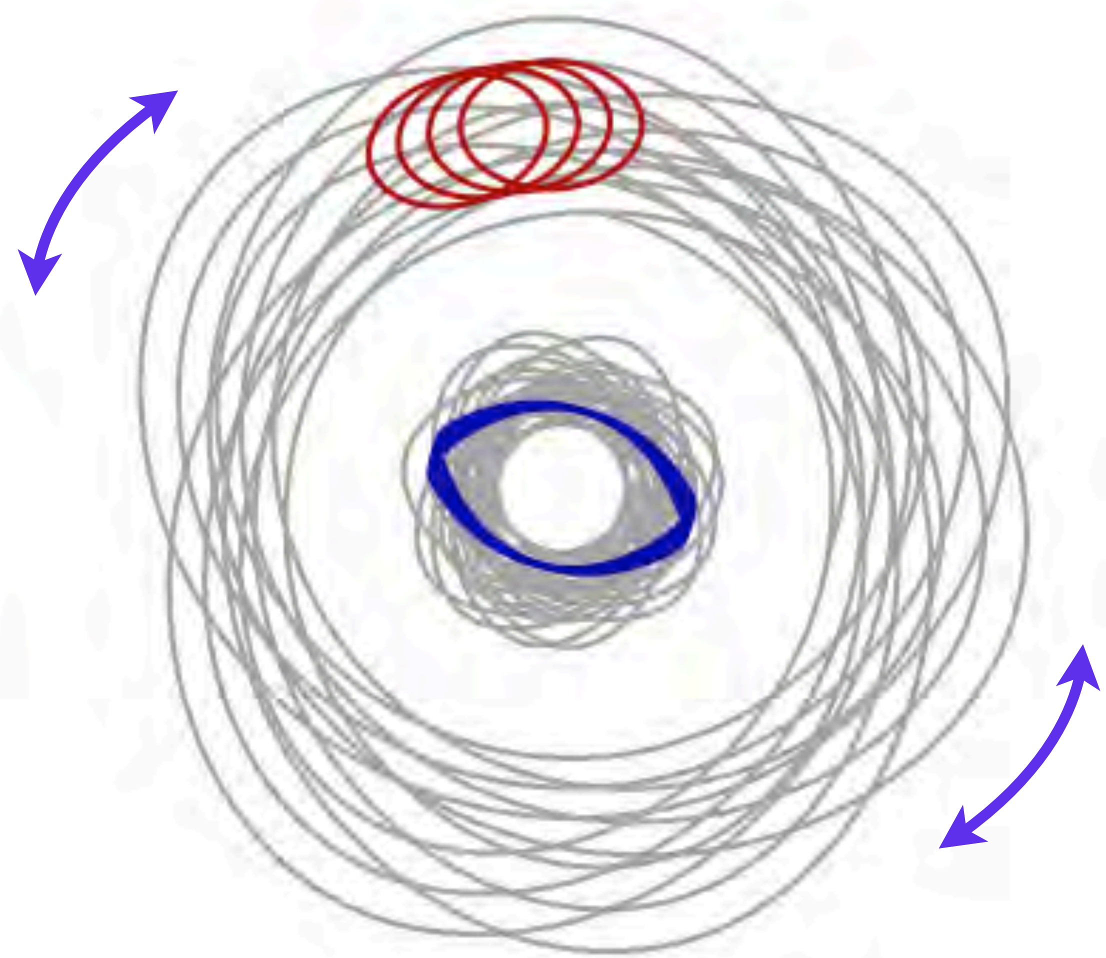
The idea behind resonant relaxation.

- **Resonance condition** $\delta_{\rm D}(\boldsymbol{m}_1 \cdot \boldsymbol{\Omega}_1 - \boldsymbol{m}_2 \cdot \boldsymbol{\Omega}_2) \Longrightarrow$ **Distant encounters.**

Here ● and ● resonate
in some rotating frame

Through resonances
departure from axial symmetry





No Torque

resonance drives recurrence

Net Torque

Fokker-Planck form

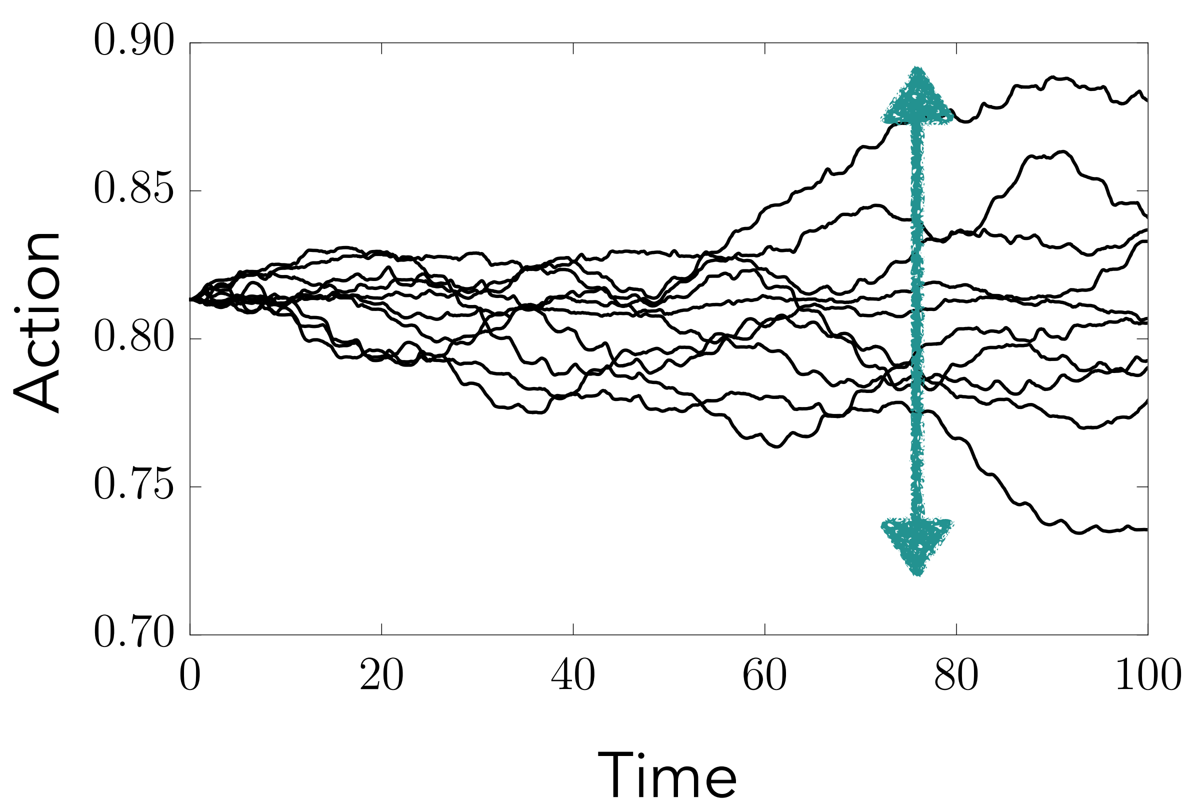
$$\frac{\partial F}{\partial t} = -\frac{\partial}{\partial \mathbf{J}} \cdot \left[\mathbf{A}(\mathbf{J}) F(\mathbf{J}) - \frac{1}{2} \mathbf{D}(\mathbf{J}) \cdot \frac{\partial F}{\partial \mathbf{J}} \right]$$

See also Lynden-Bell (1974), Tremaine+(1984)

Fokker-Planck form

$$\frac{\partial F}{\partial t} = -\frac{\partial}{\partial \mathbf{J}} \cdot \left[\mathbf{A}(\mathbf{J}) F(\mathbf{J}) - \frac{1}{2} \mathbf{D}(\mathbf{J}) \cdot \frac{\partial F}{\partial \mathbf{J}} \right]$$

Diffusion



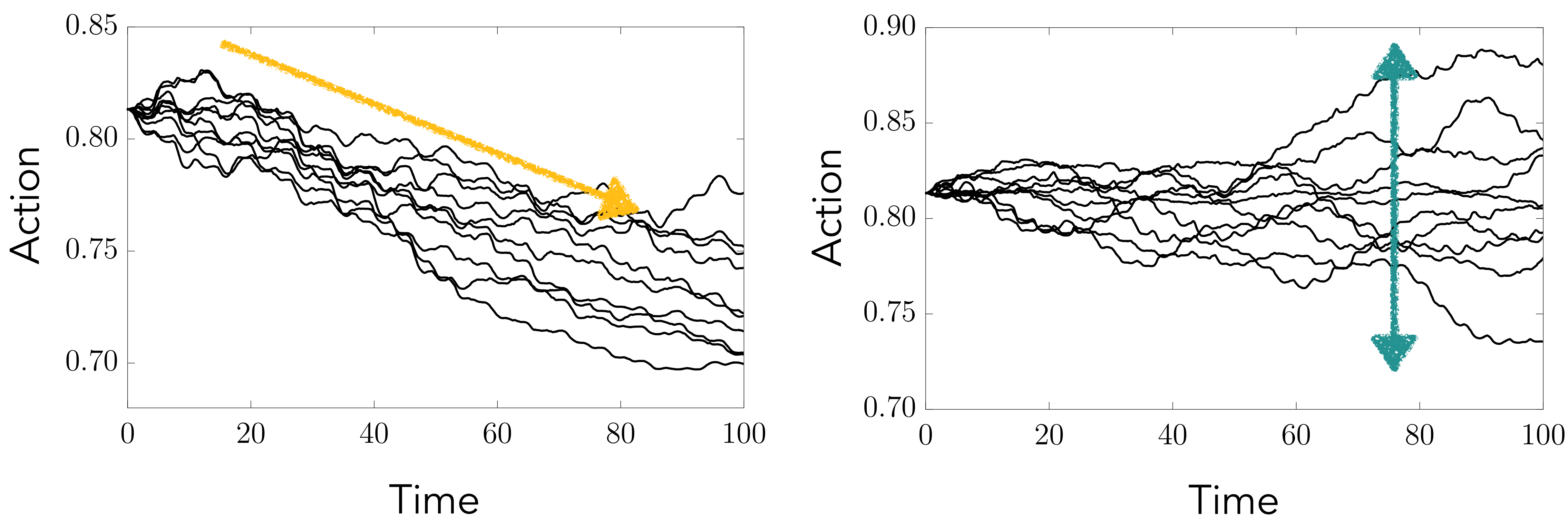
Stars spread

See also Lynden-Bell (1974), Tremaine+(1984)

Fokker-Planck form

$$\frac{\partial F}{\partial t} = -\frac{\partial}{\partial \mathbf{J}} \cdot \left[\mathbf{A}(\mathbf{J}) F(\mathbf{J}) - \frac{1}{2} \mathbf{D}(\mathbf{J}) \cdot \frac{\partial F}{\partial \mathbf{J}} \right]$$

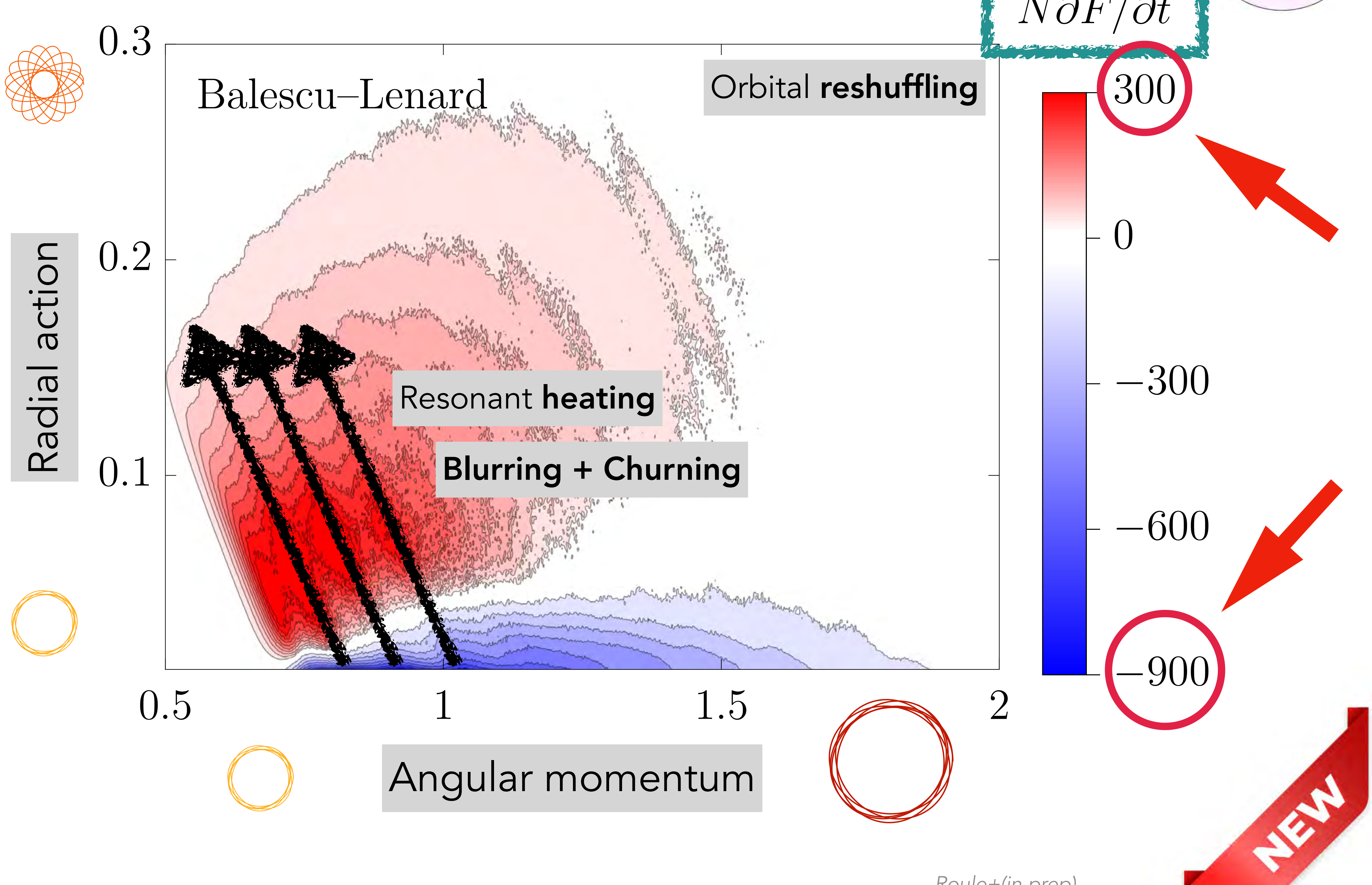
Dynamical friction **Diffusion**



Massive stars sink **Stars spread**

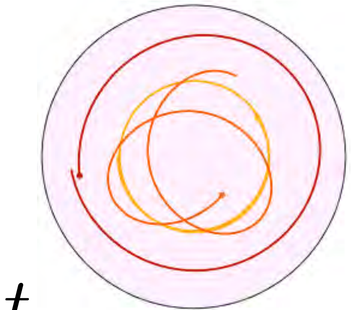
See also Lynden-Bell (1974), Tremaine+(1984)

Self induced secular prediction

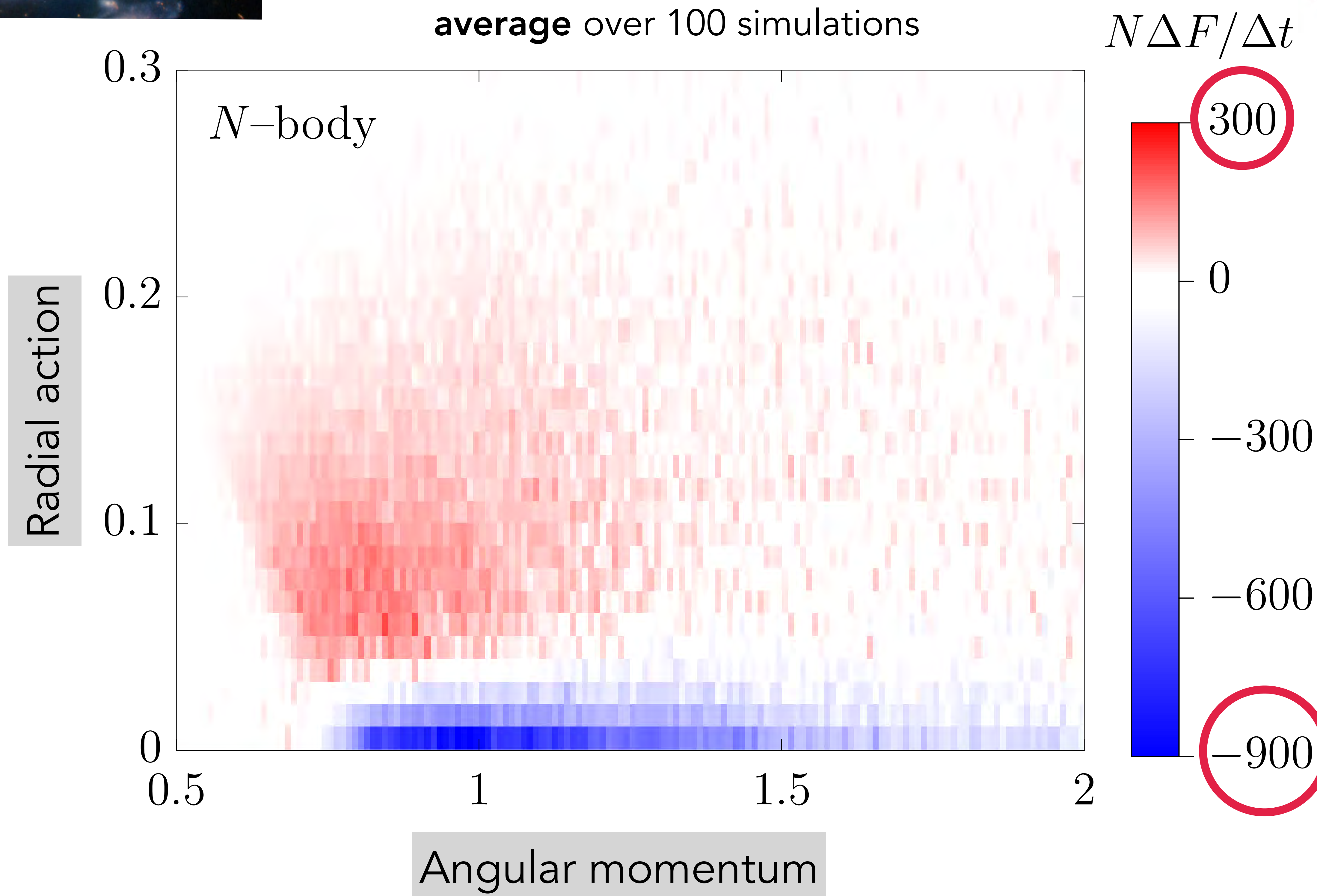


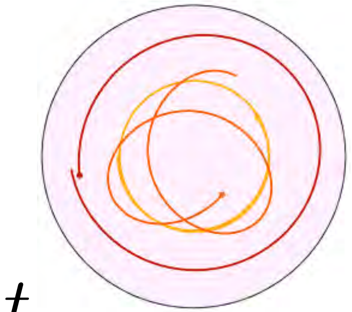
Roule+(in prep)

N–body measurements



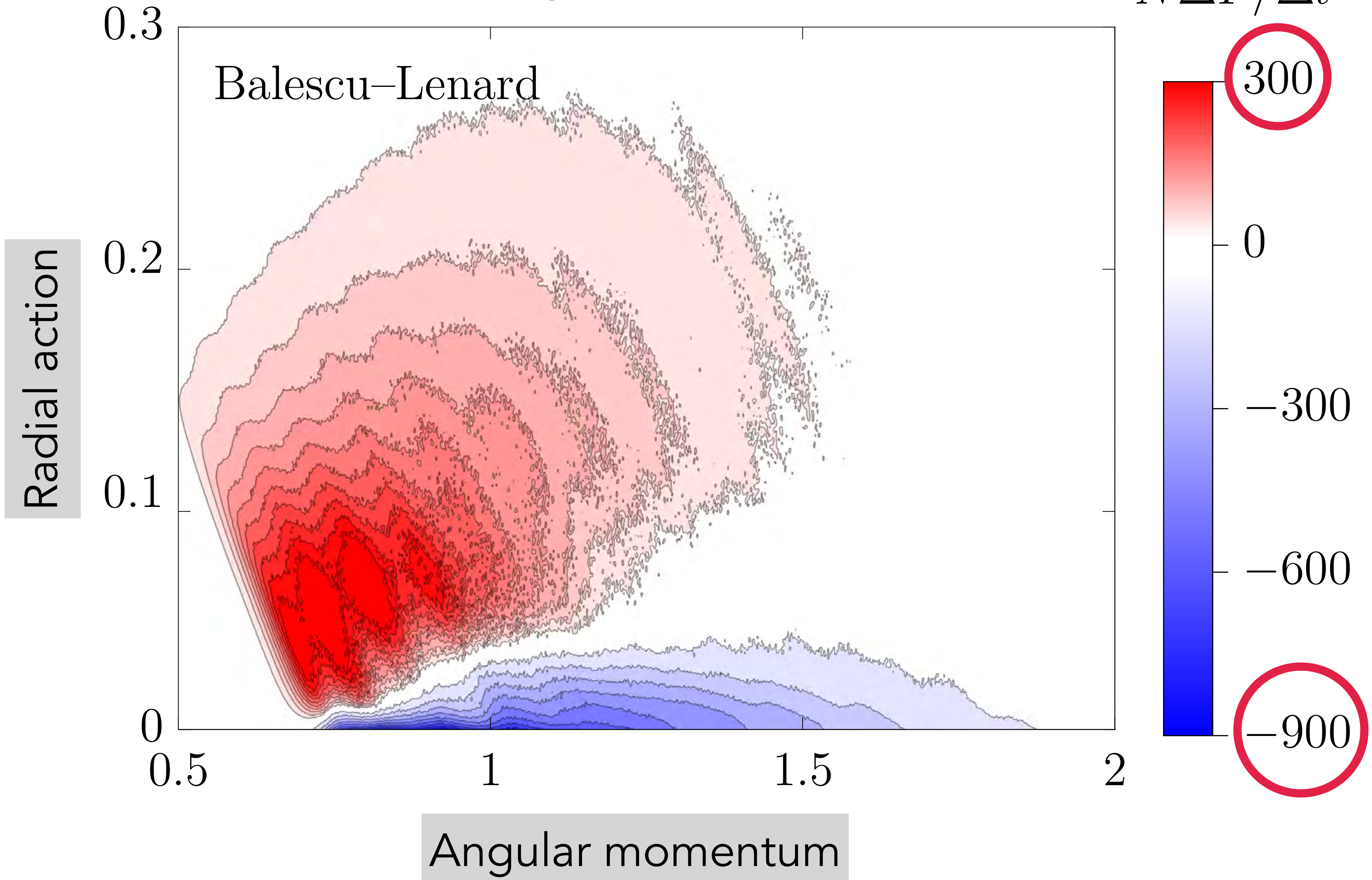
average over 100 simulations



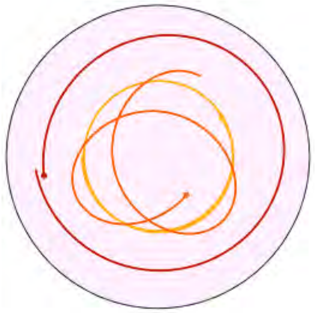


N–body measurements

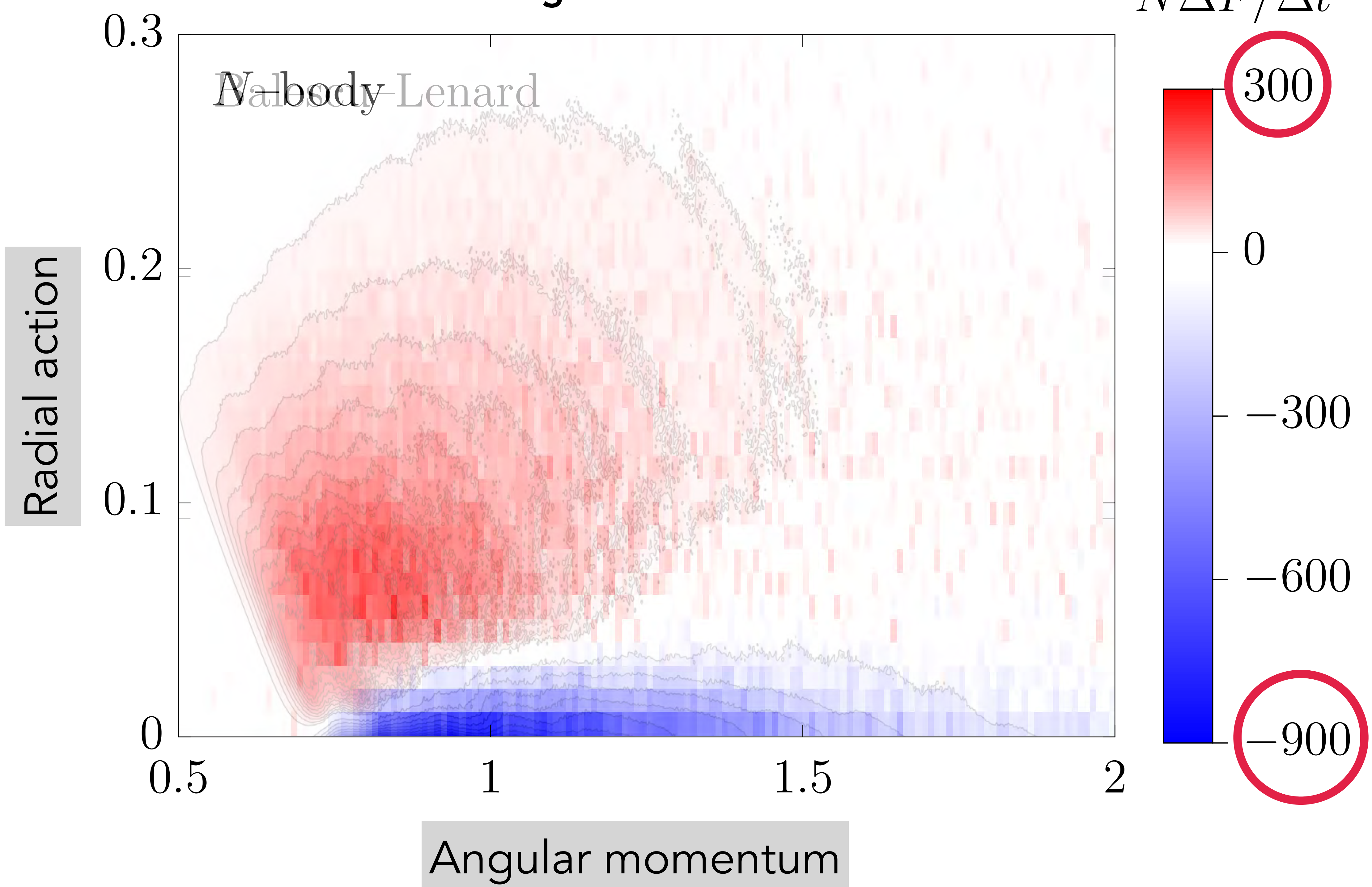
average over 100 simulations



$N-$body measurements

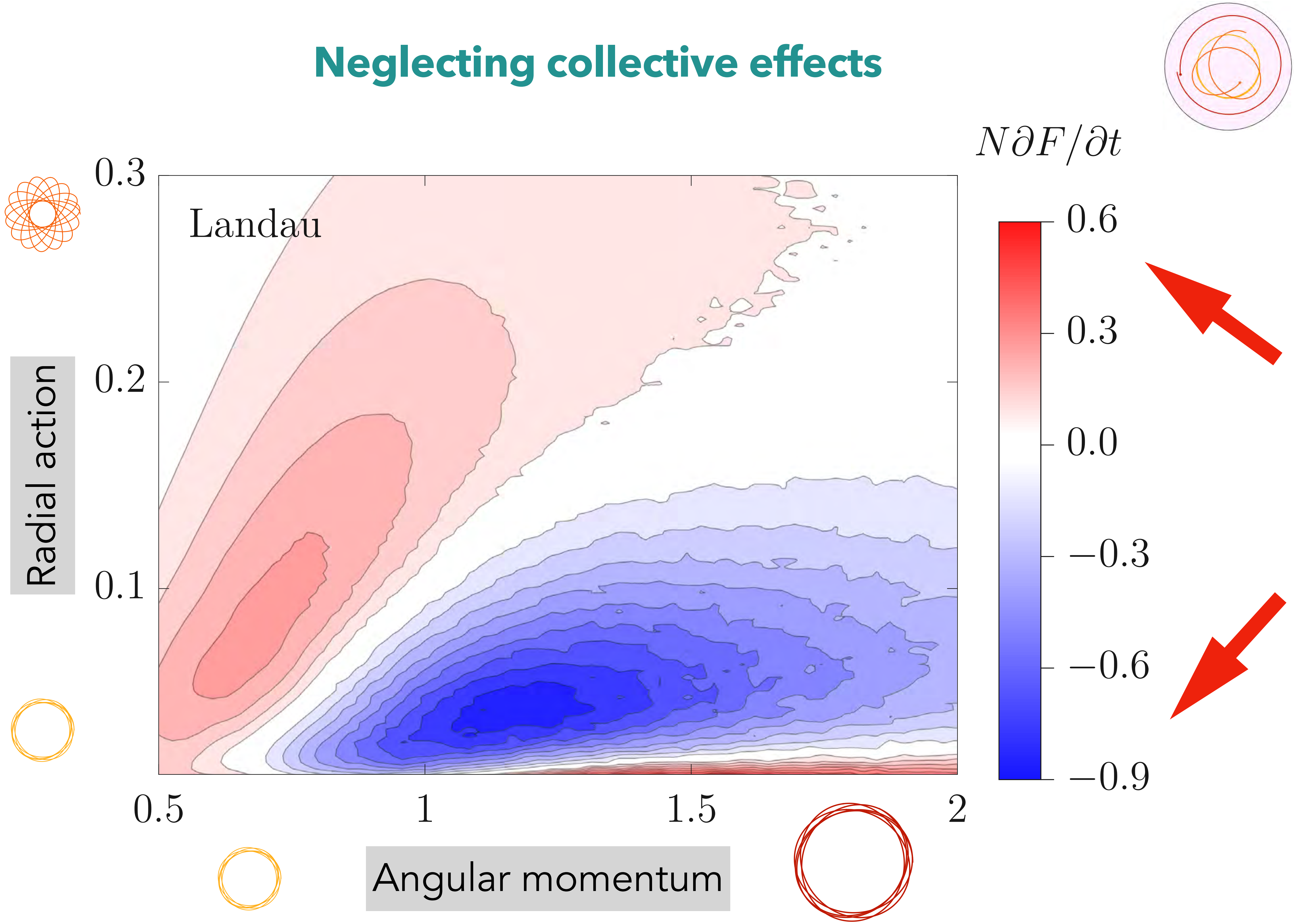


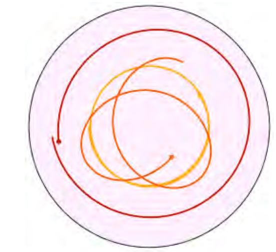
average over 100 simulations



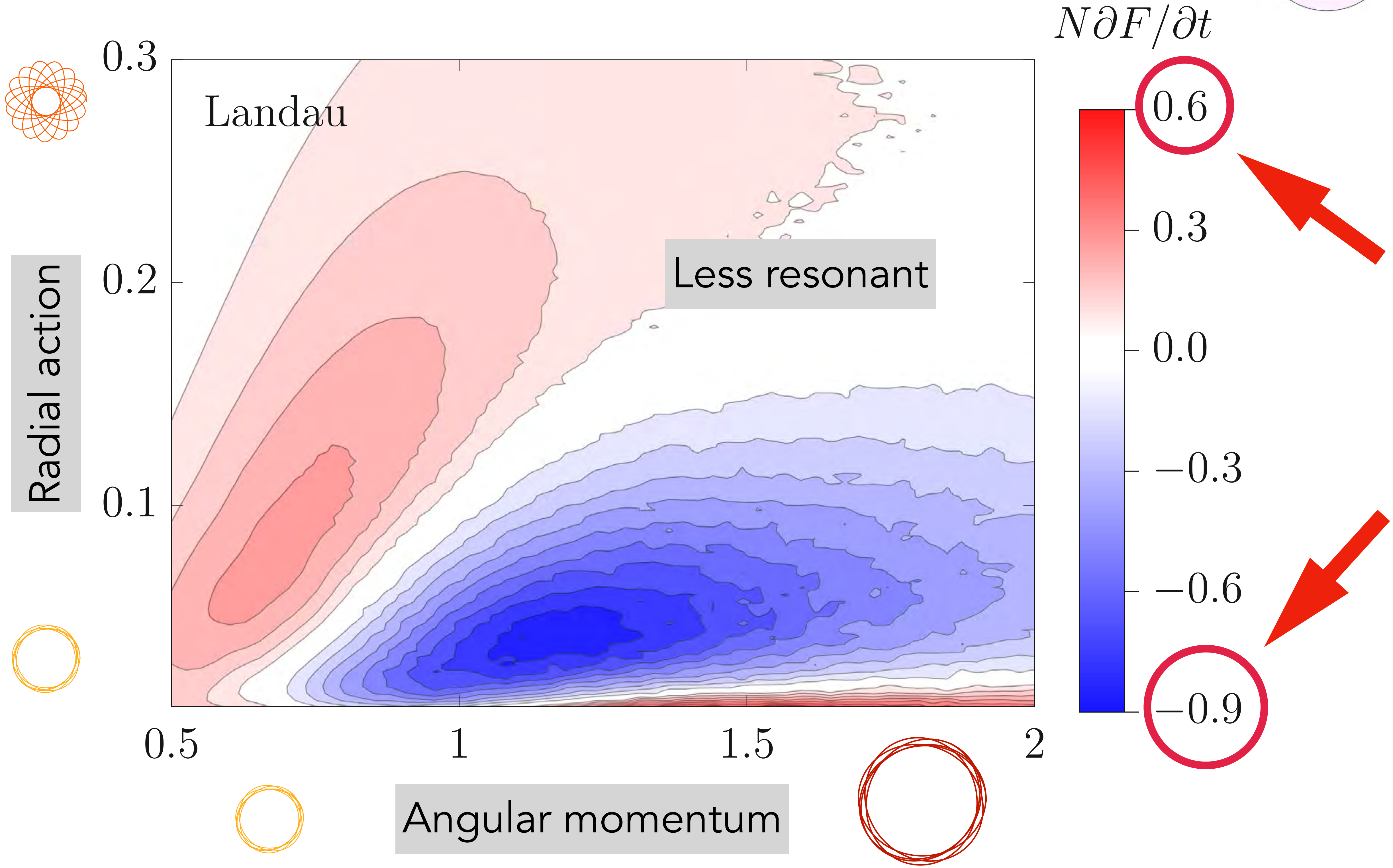
Kinetic theory quantitatively captures the long-term heating of isolated cold discs

Neglecting collective effects



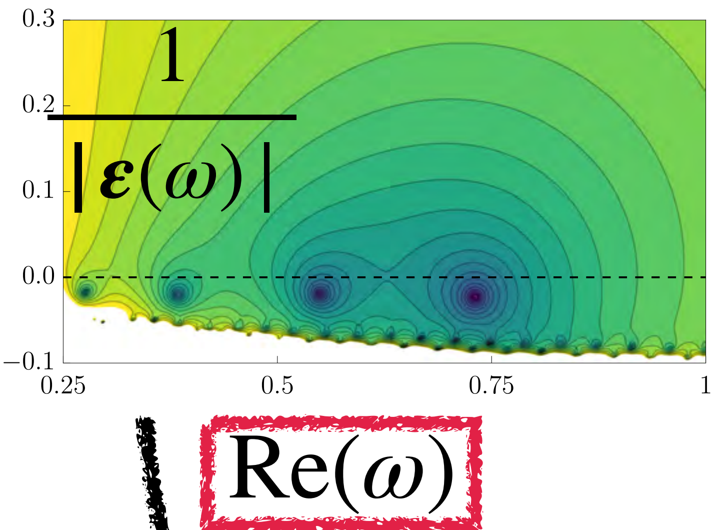


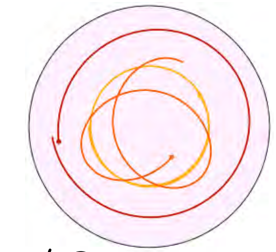
Neglecting collective effects

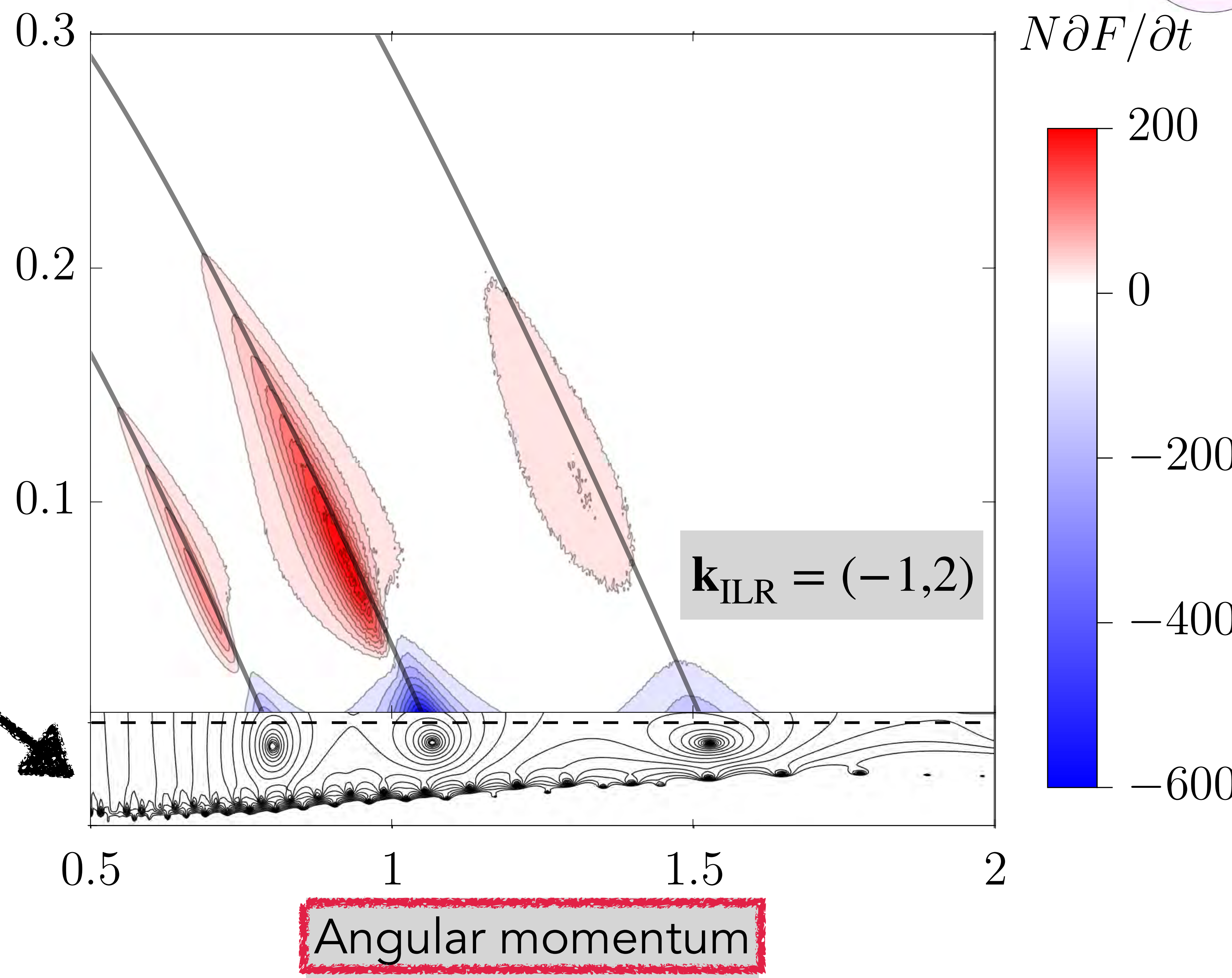


Collective effects strongly enhance radial heating in cold discs

Impact of weakly damped modes

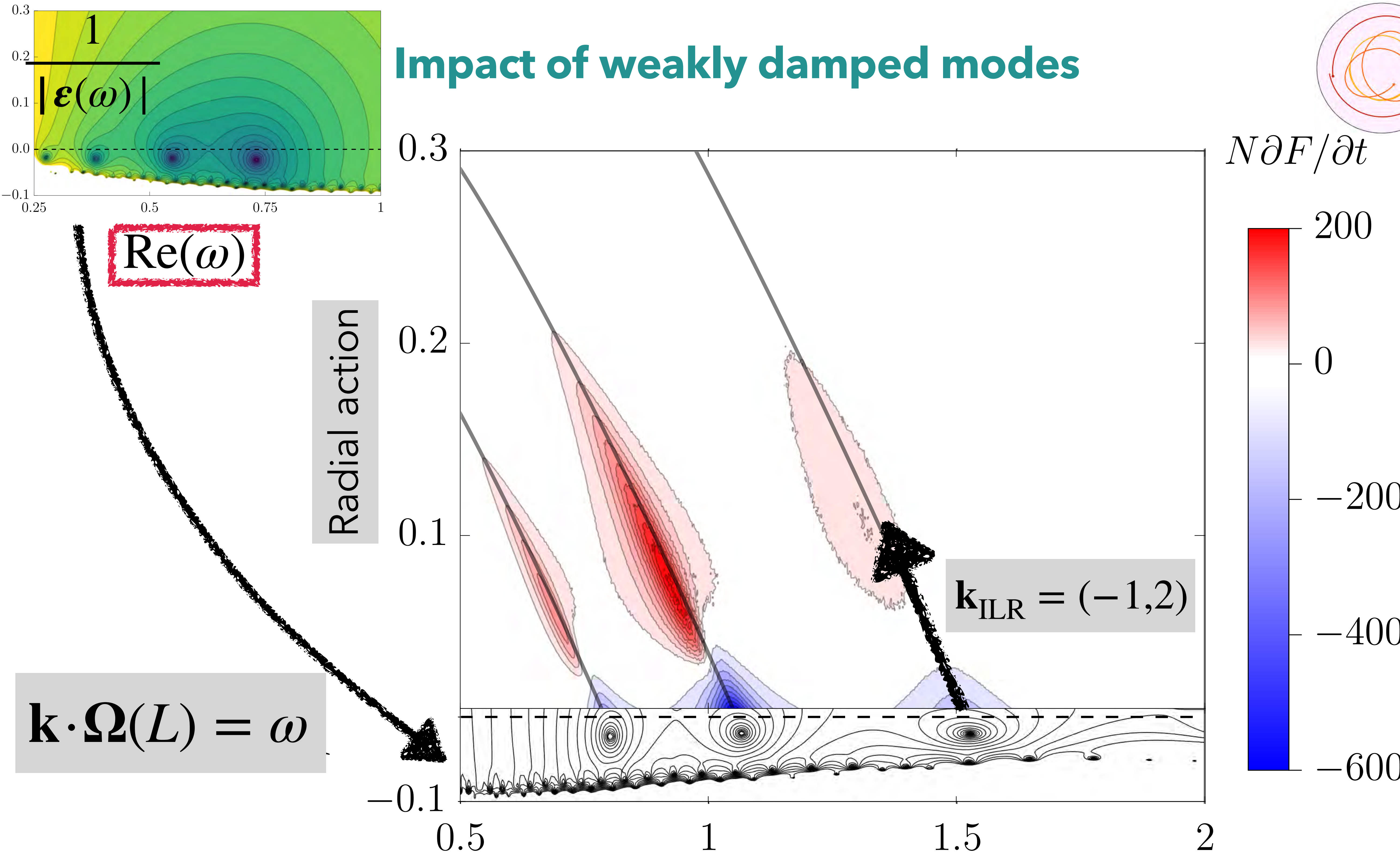






Heating is strongly enhanced at resonance with weakly damped modes

Impact of weakly damped modes

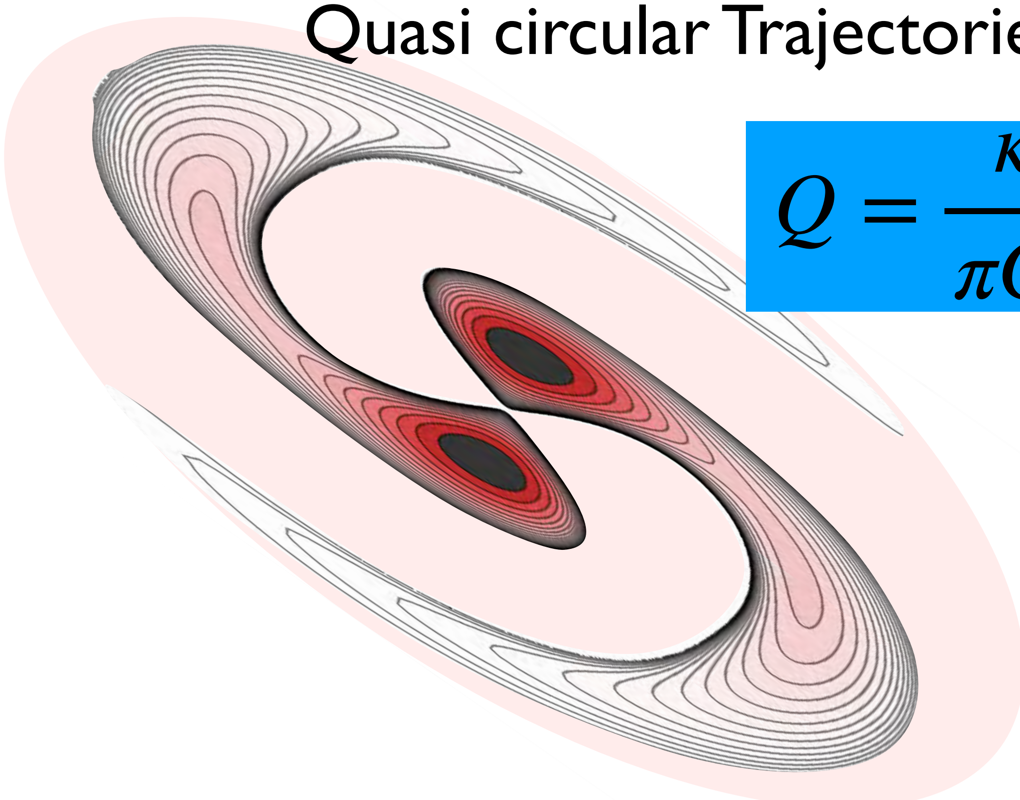


Heating is strongly enhanced at resonance with weakly damped modes


NGC 5068
NGC 4303
NGC 1512
NGC 1365
NGC 4535
NGC 3351
Cooling
NGC 4321
NGC 0628
IC 5332
NGC 4254
NGC 1300
NGC 1433
NGC 2835
NGC 7496
NGC 3627

$Q \sim 1$ leads to gas clumping and star formation

Quasi circular Trajectories: 'cold' disc

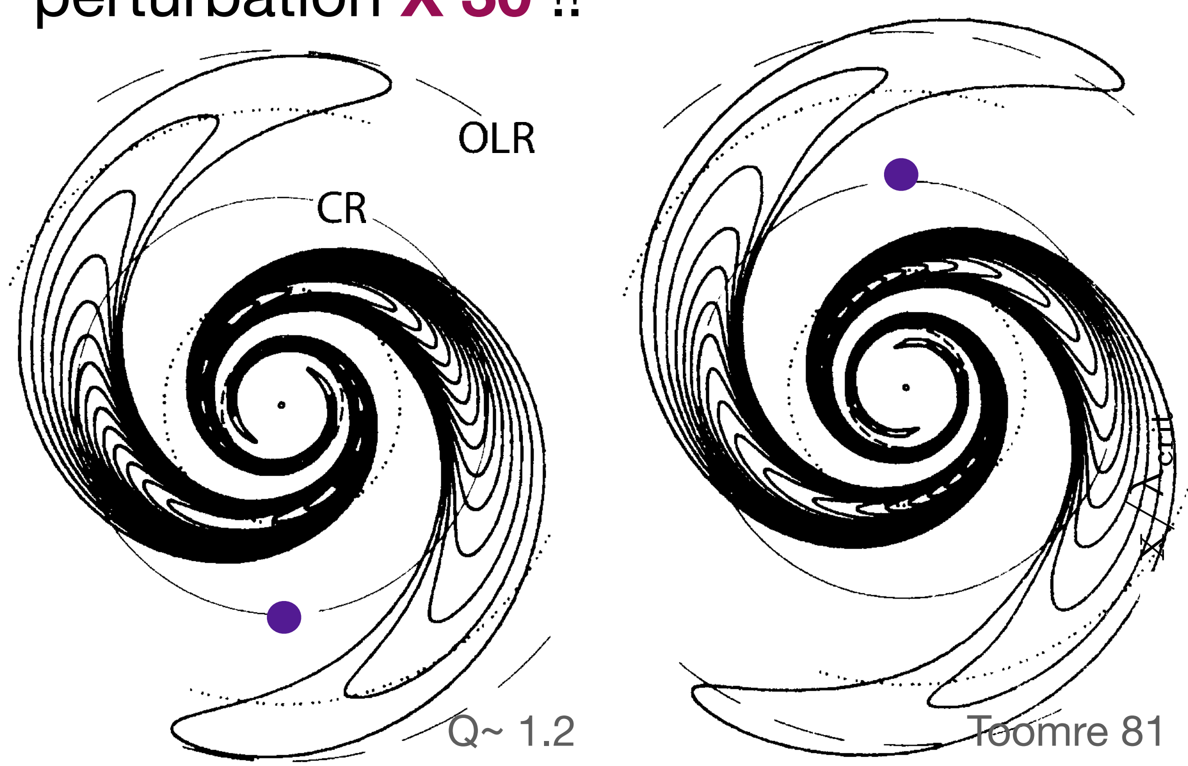


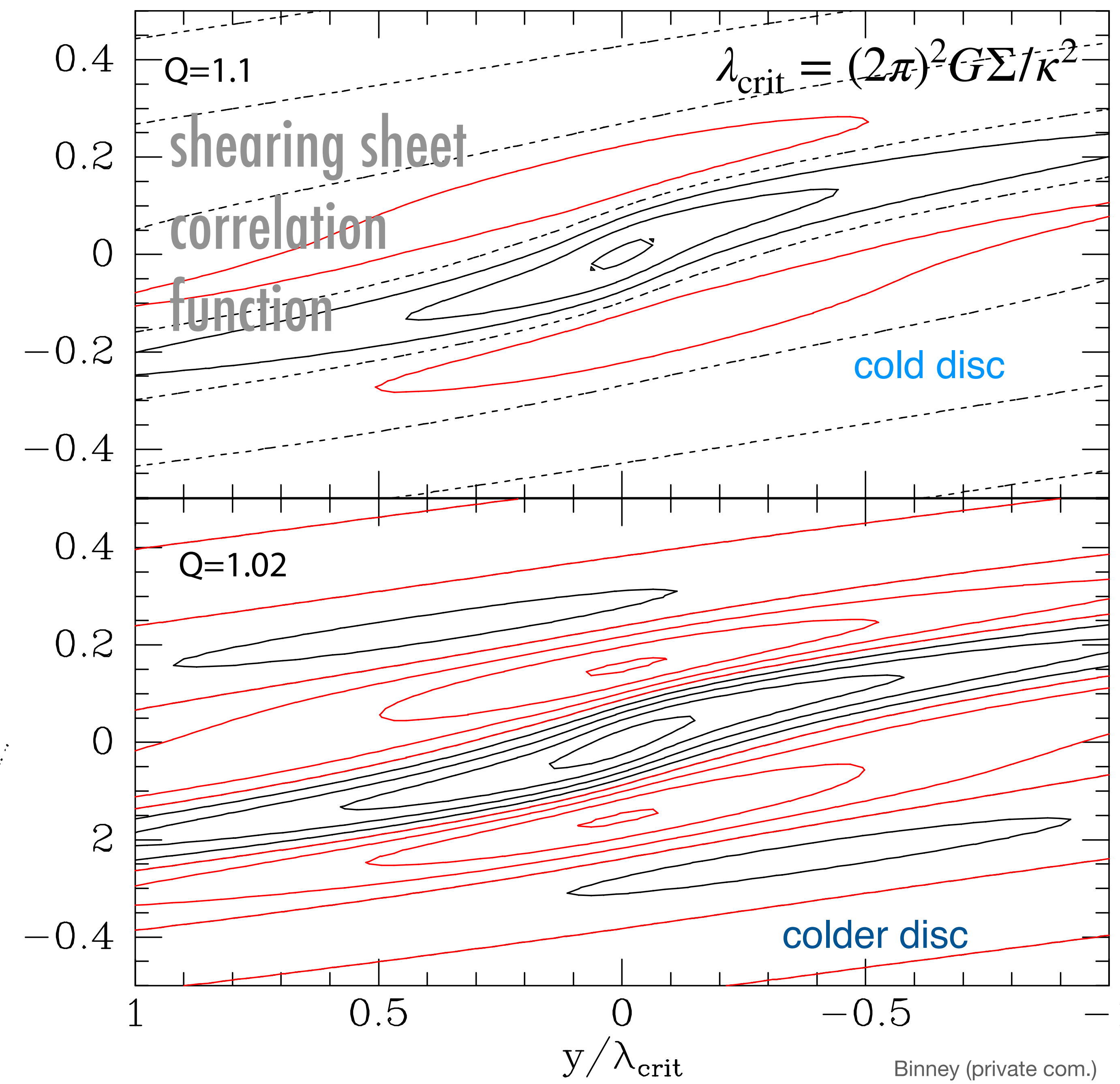
$$Q = \frac{\kappa\sigma}{\pi G \Sigma} \to 1$$

- colder disc means **larger** wake
- colder disc means **stronger** wake
- colder disc means **shorter** dynamical time

Mass in **wake** = mass in perturbation **X 30** !!

Kalnajs

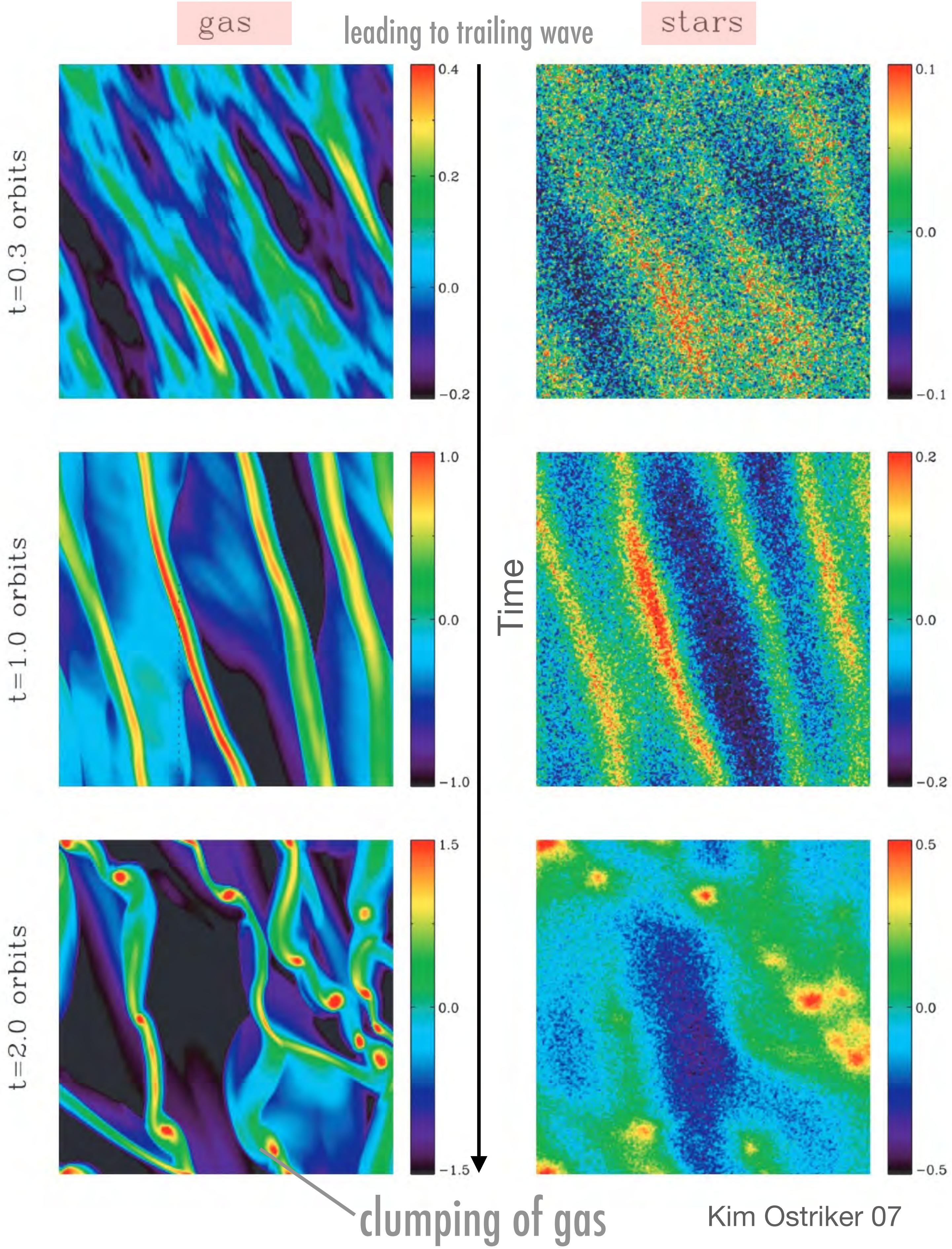




Binney (private com.)

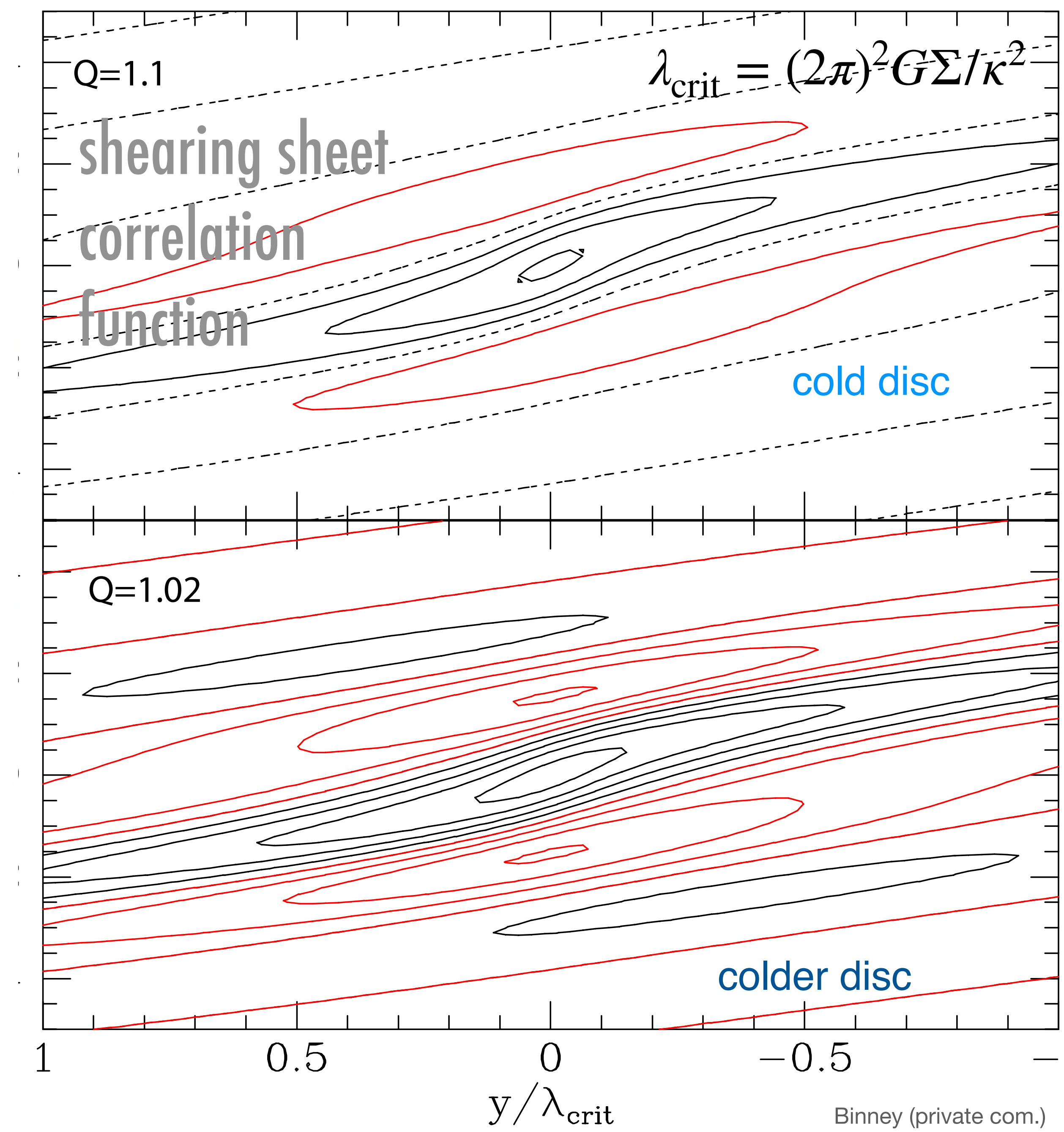
→ long range correlation

Q ∼ 1 leads to gas clumping and star formation



Kim Ostriker 07

- colder disc means **larger** wake
- colder disc means **stronger** wake
- colder disc means **shorter** dynamical time
- colder disc means **more star** formation



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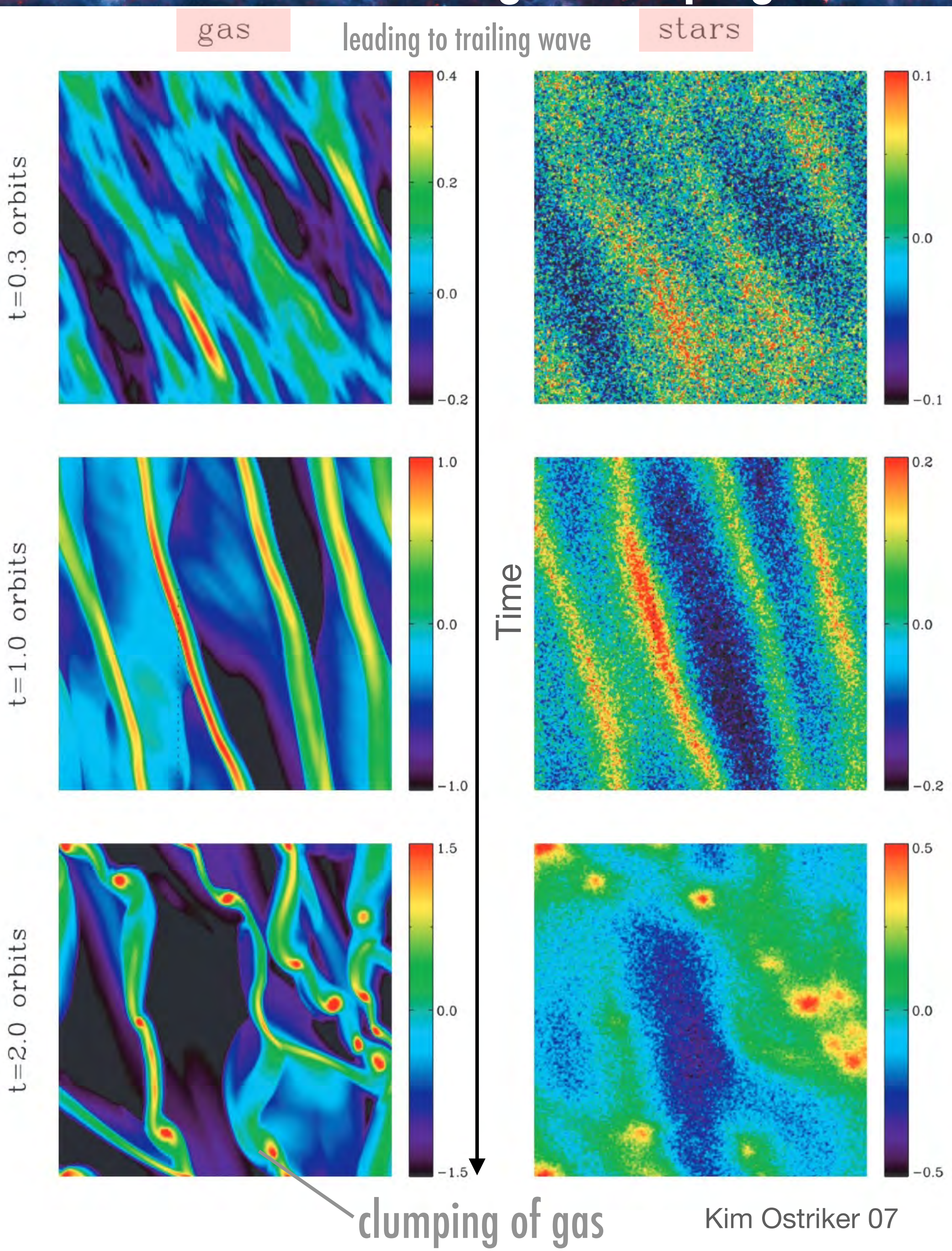

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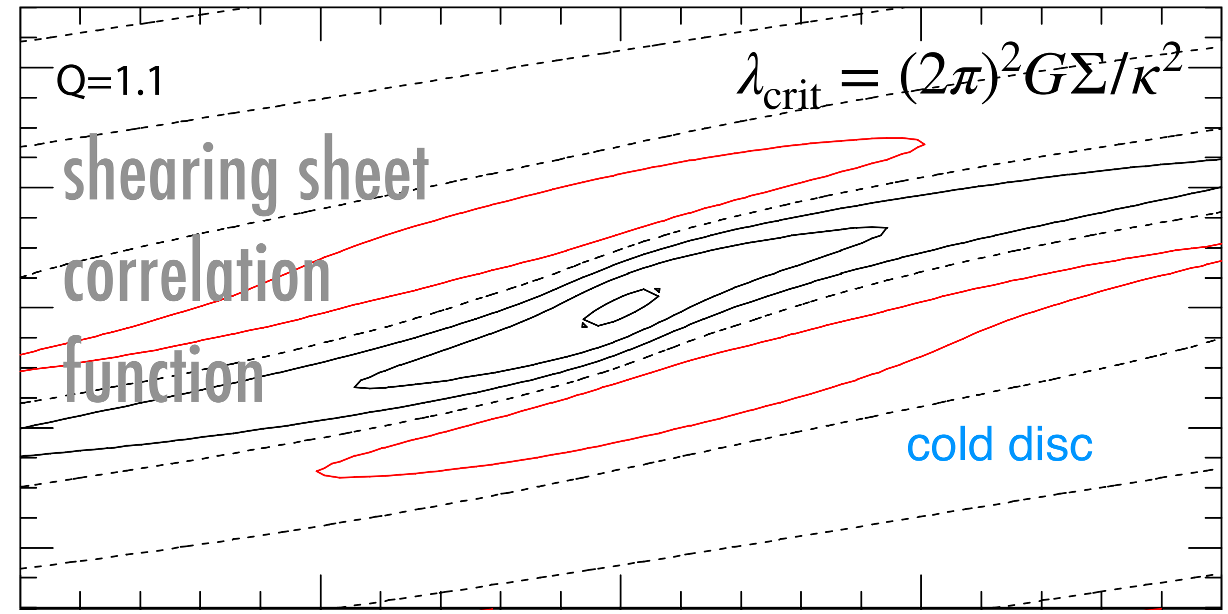
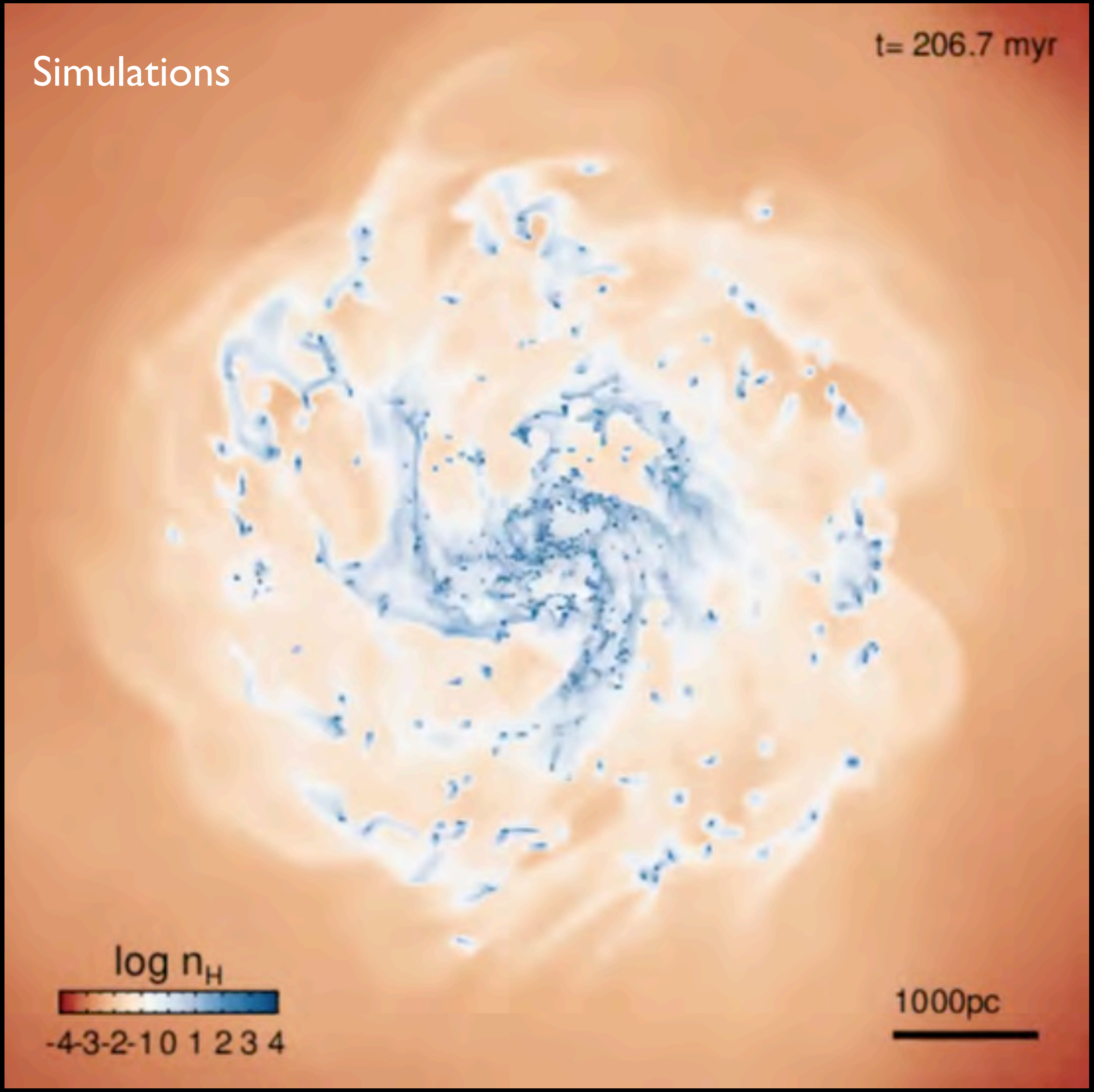
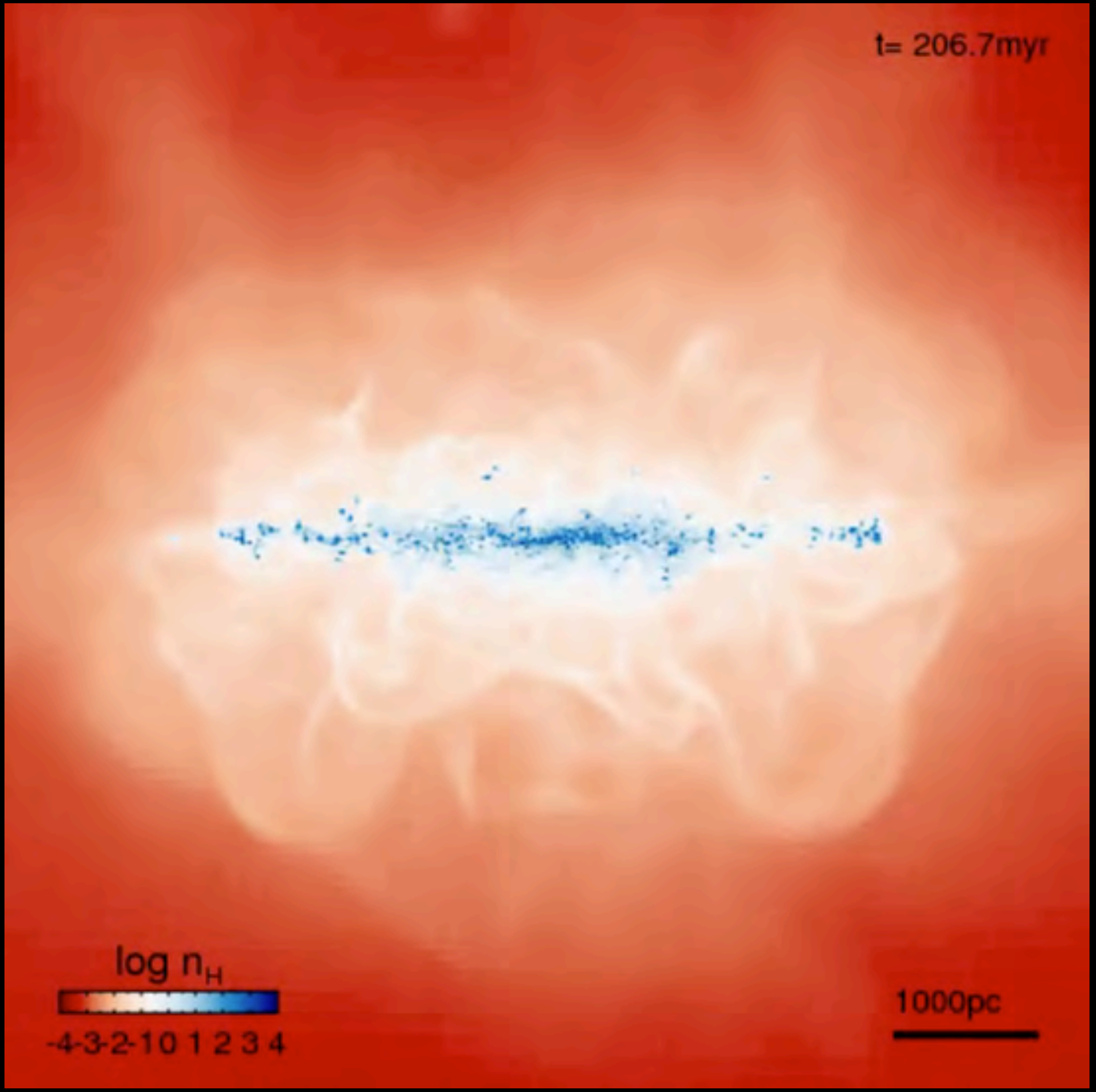


During each swing amplified cycle the gas clumps, form new stars with an efficiency $\propto$ proximity to (marginal stability)^2

Internal Structure of a simulated thin disc

State-of-the-art in modelling illustrates
the level of SFR/turbulence/feedback induced perturbation





(c)Taysun Kimm

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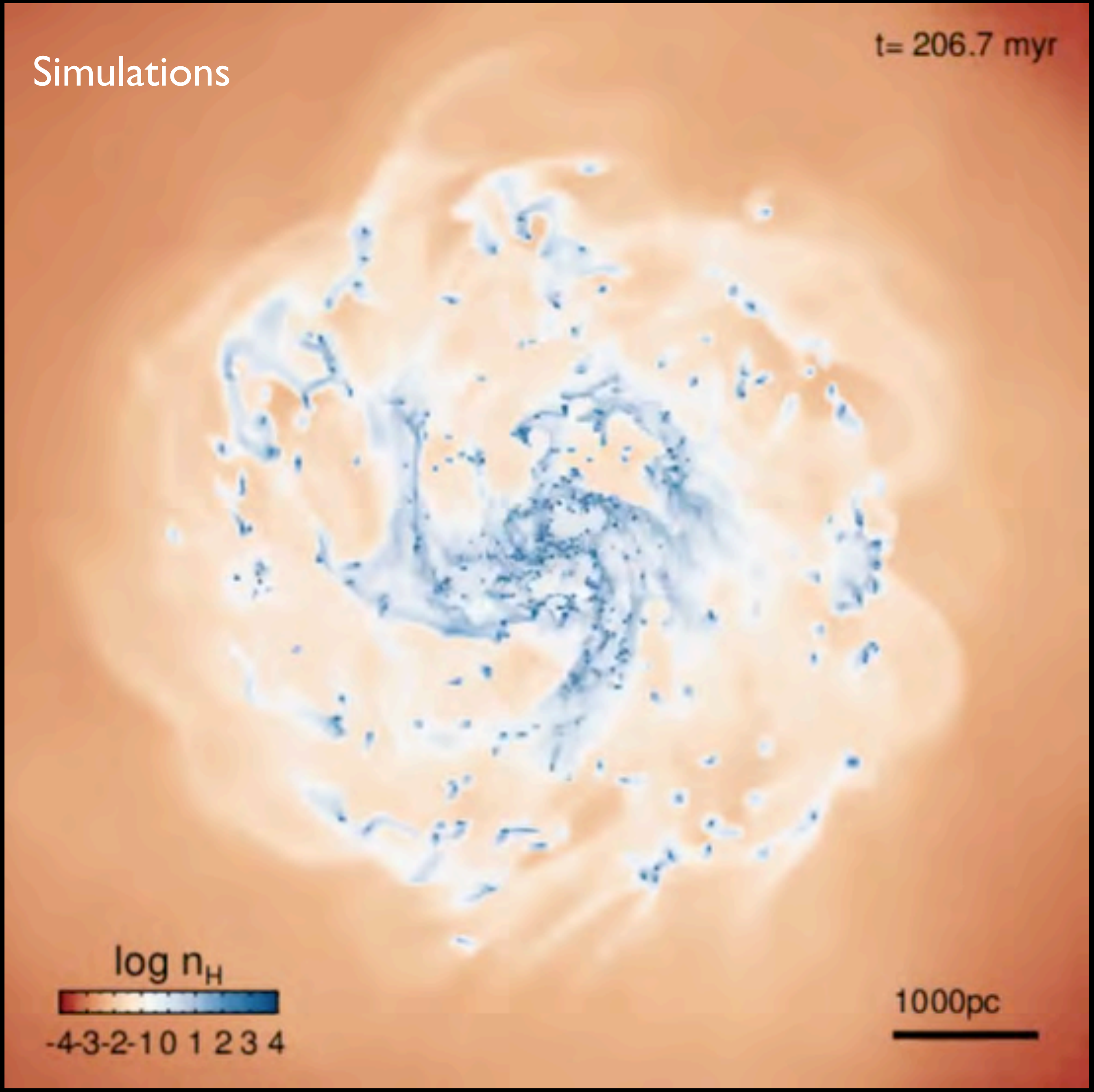
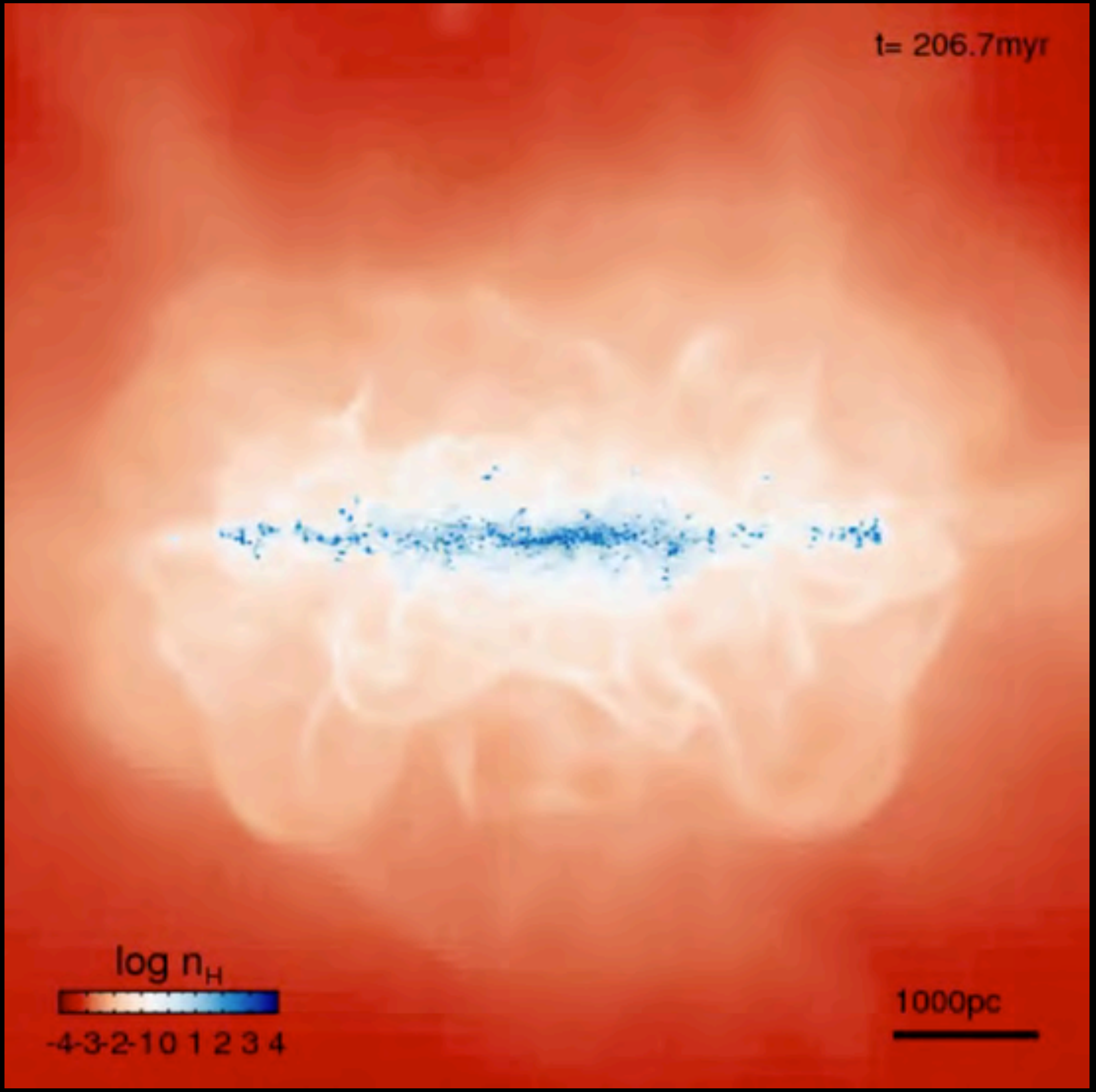
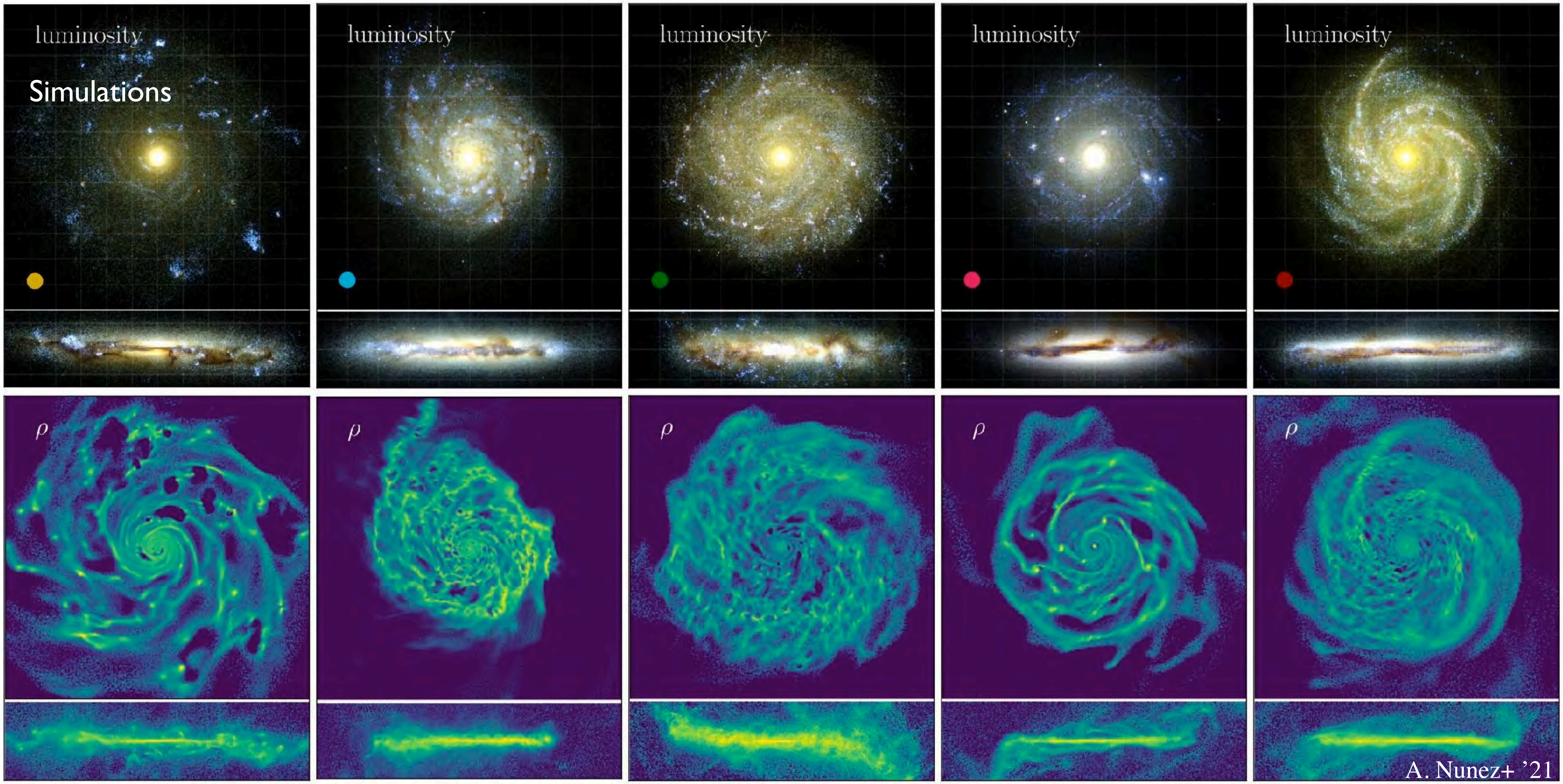




(c)Taysun Kimm

Internal Structure of a simulated thin disc: varying feedback model

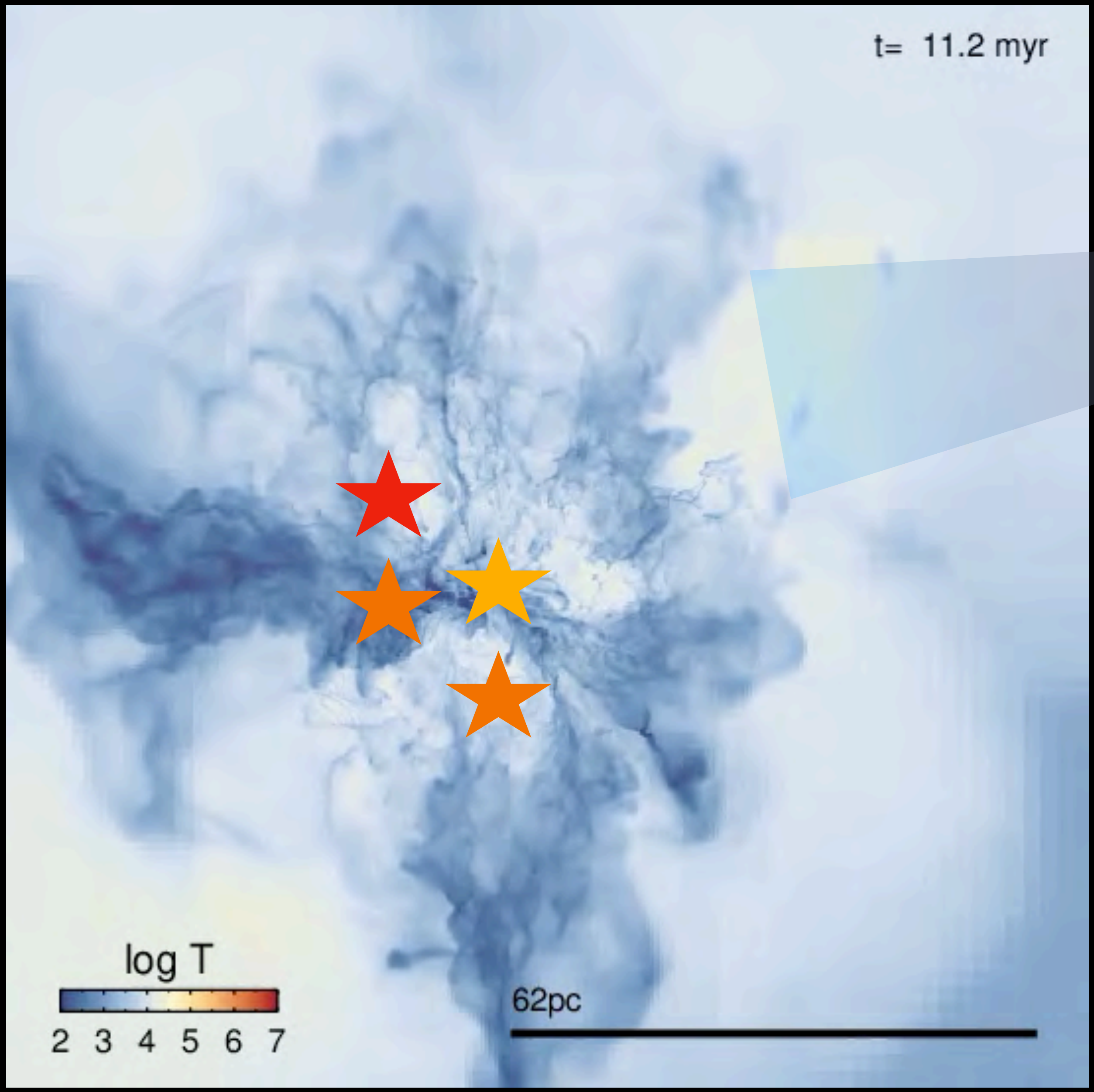


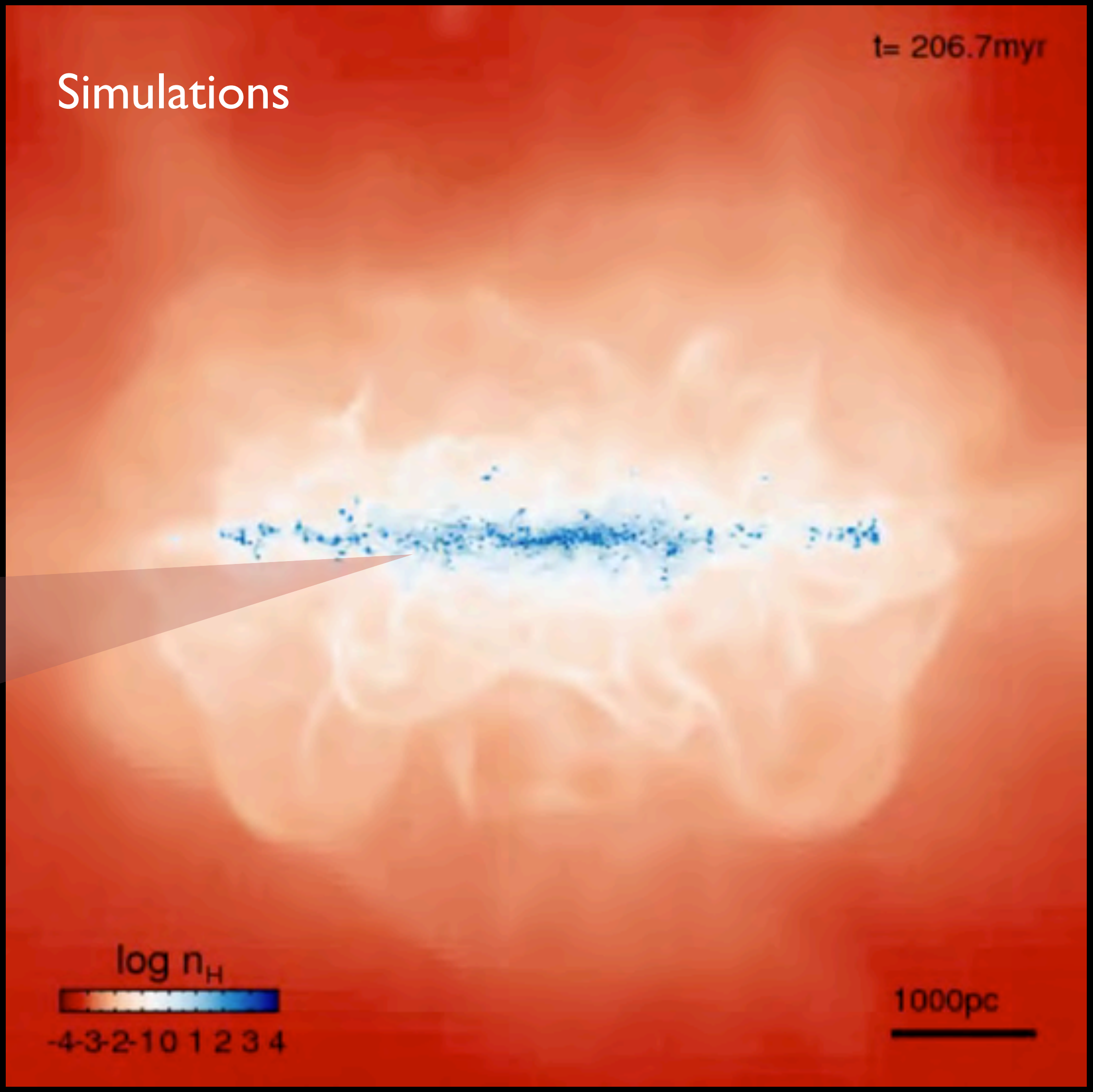
Note that the *exact* model of feedback impacts face-on view BUT does not impact much disc thickness.

No fine tuning required: something more fundamental operates

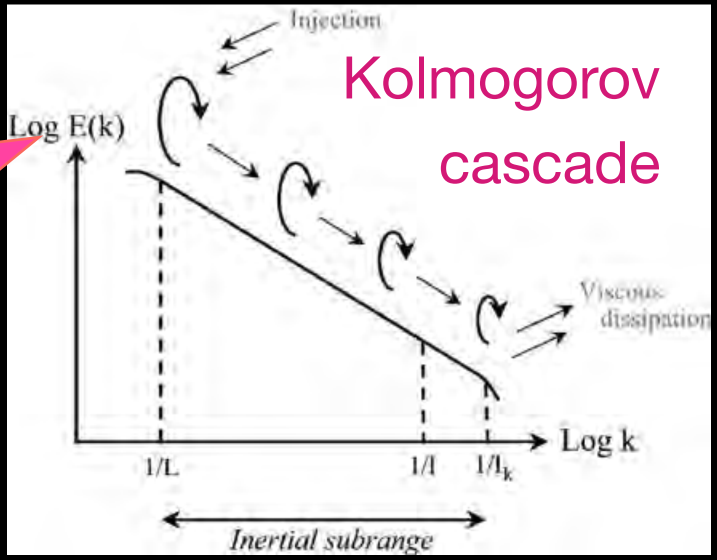
Internal Structure @ small scales: simulation & theory

State-of-the-art simulations also illustrates the level of perturbation on smaller (molecular cloud) scales





Turbulent cascade controlled by energy **injection** scale



(c)Taysun Kimm

Internal Structure @ small scales: simulation & theory

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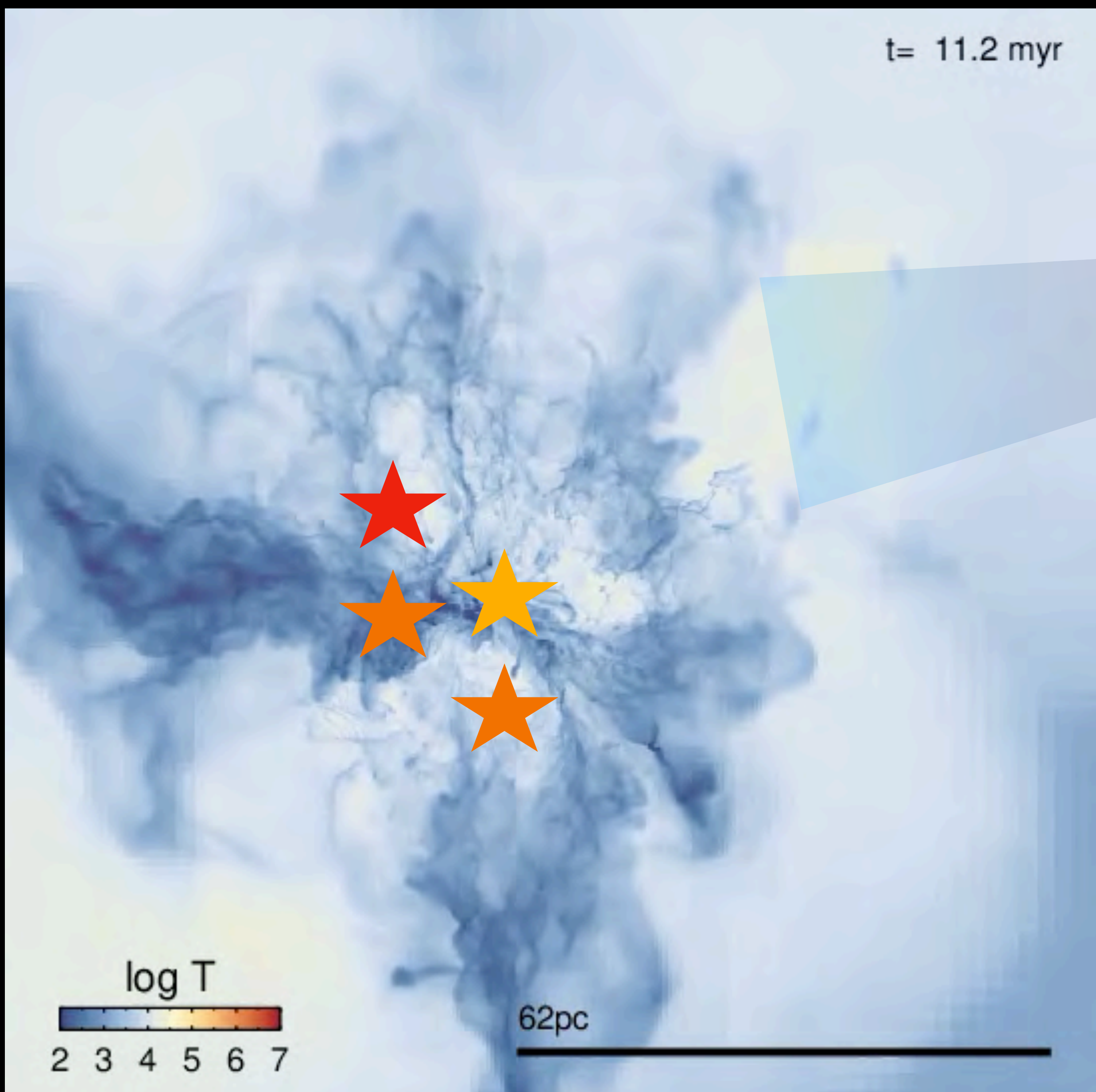
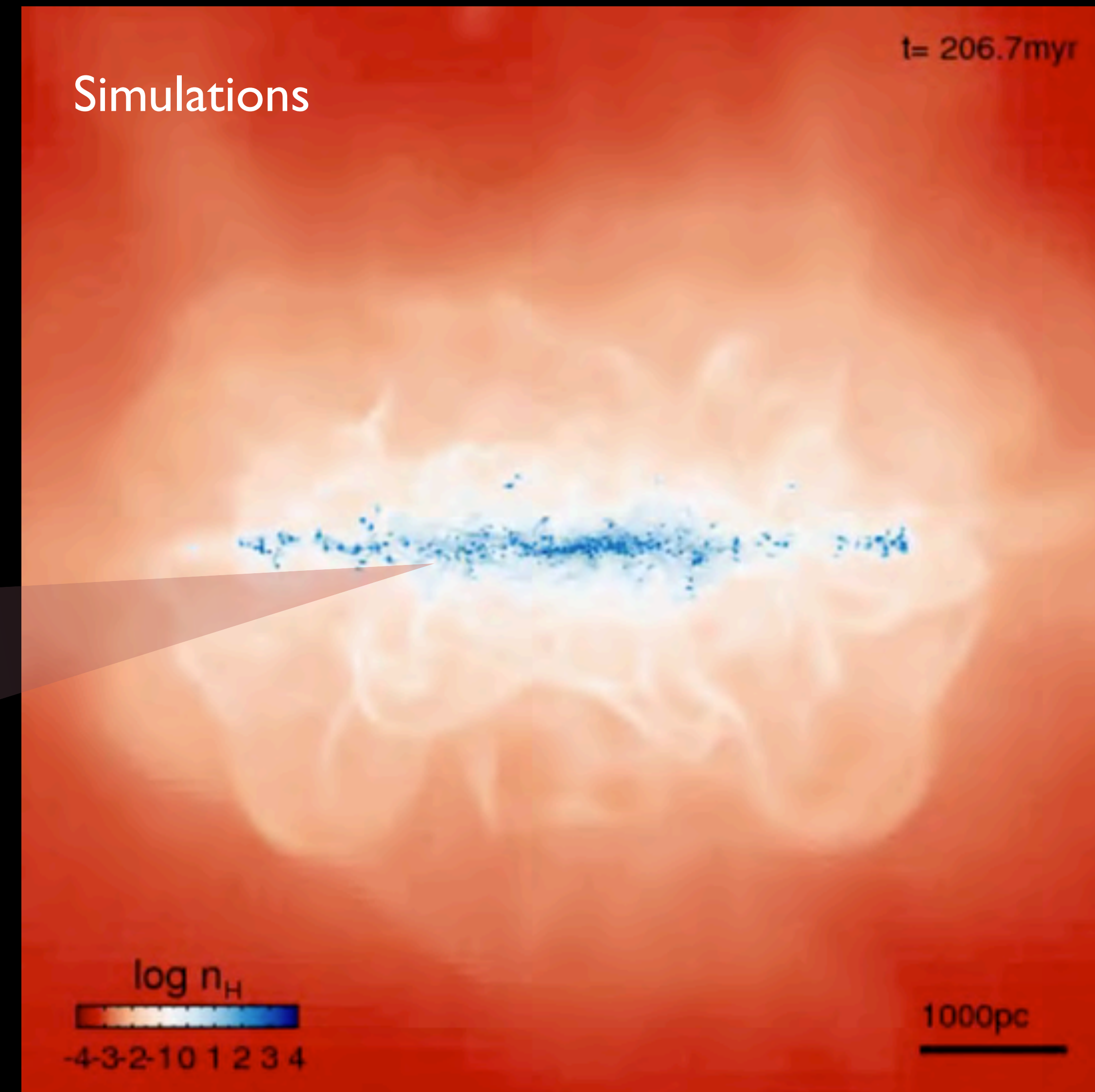
on smaller (molecular cloud) scales





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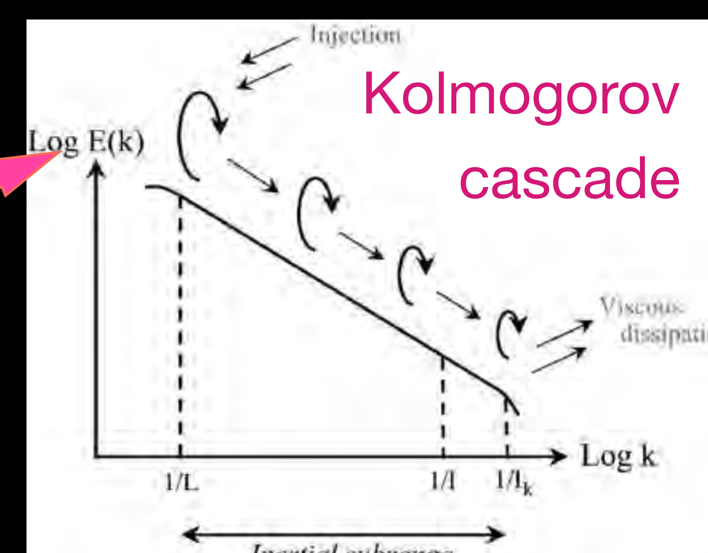

(c)Taysun Kimm

Internal Structure @ small scales: simulation & theory

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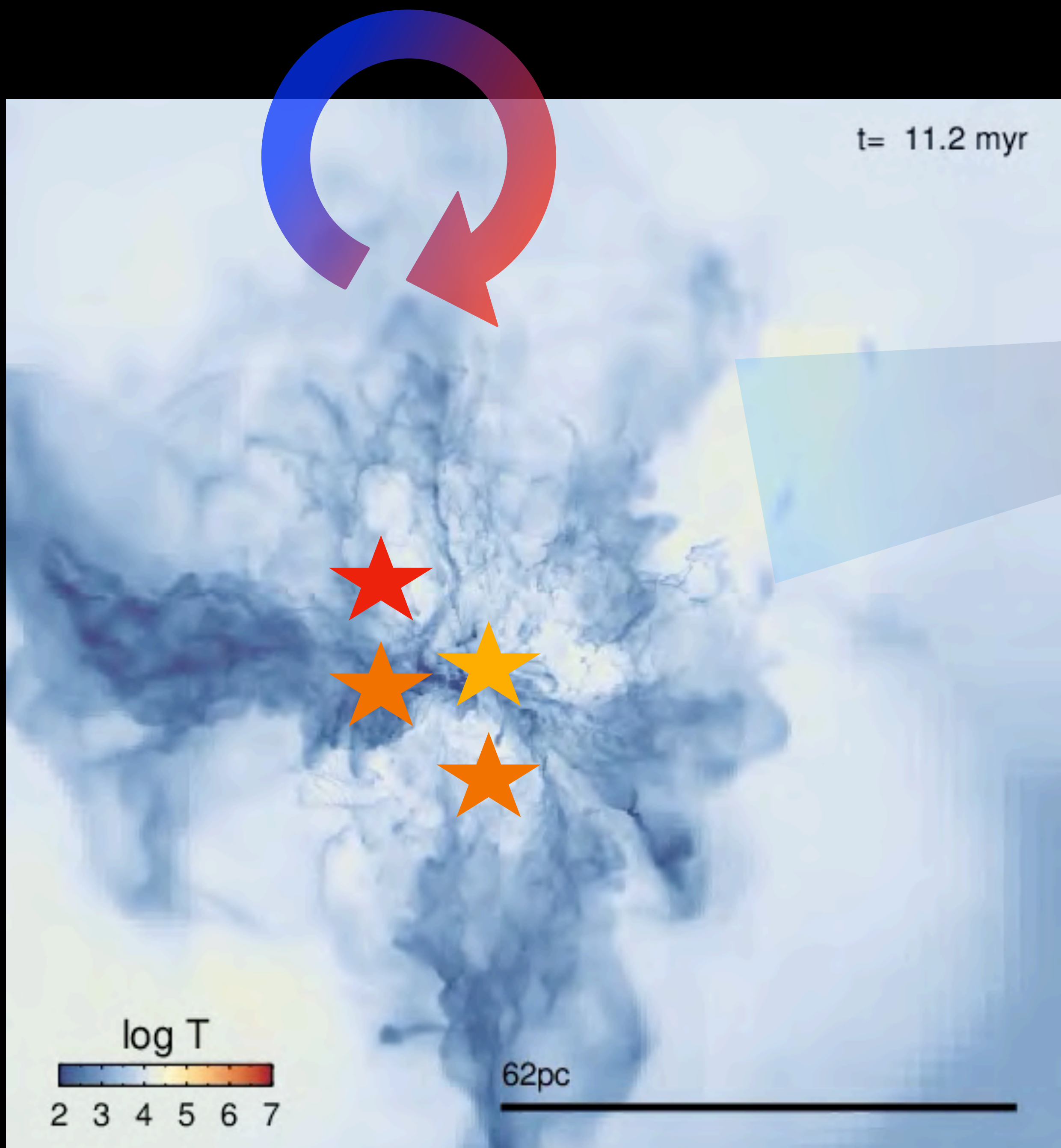
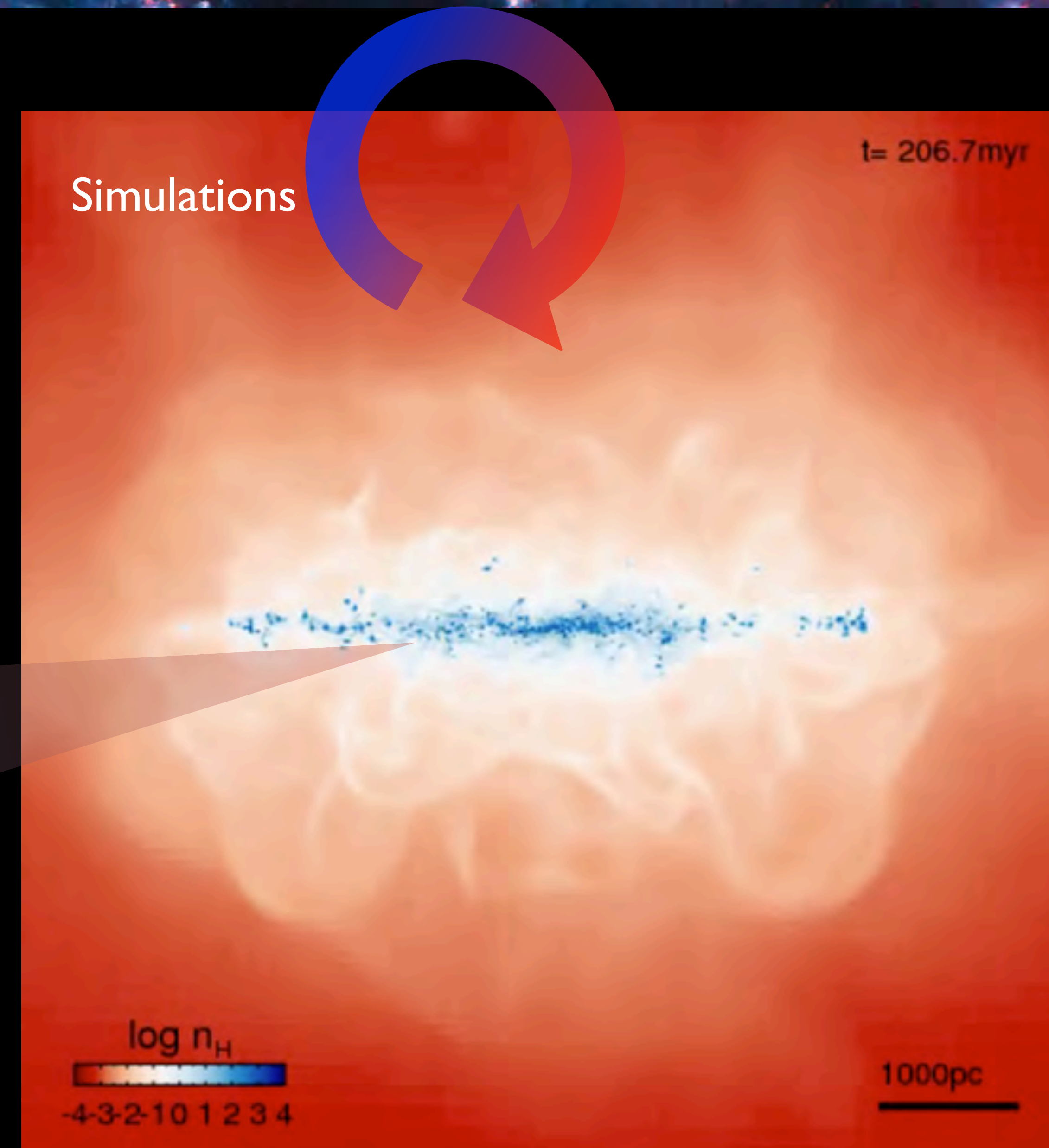
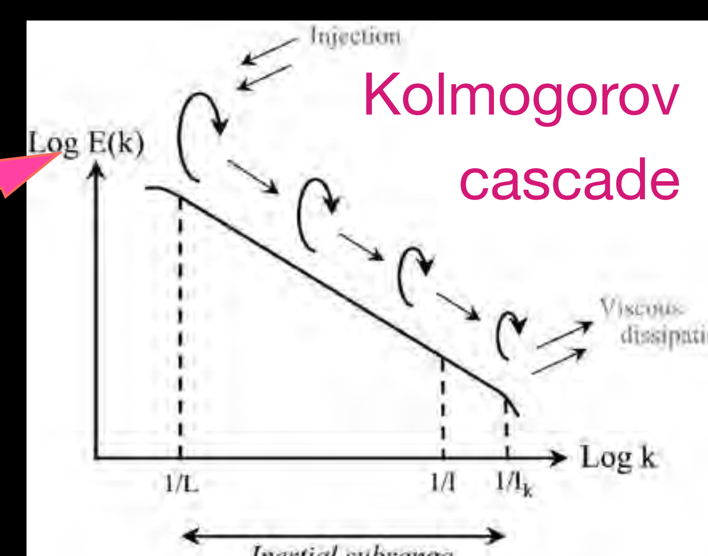




Turbulent cascade controlled by energy **injection** scale

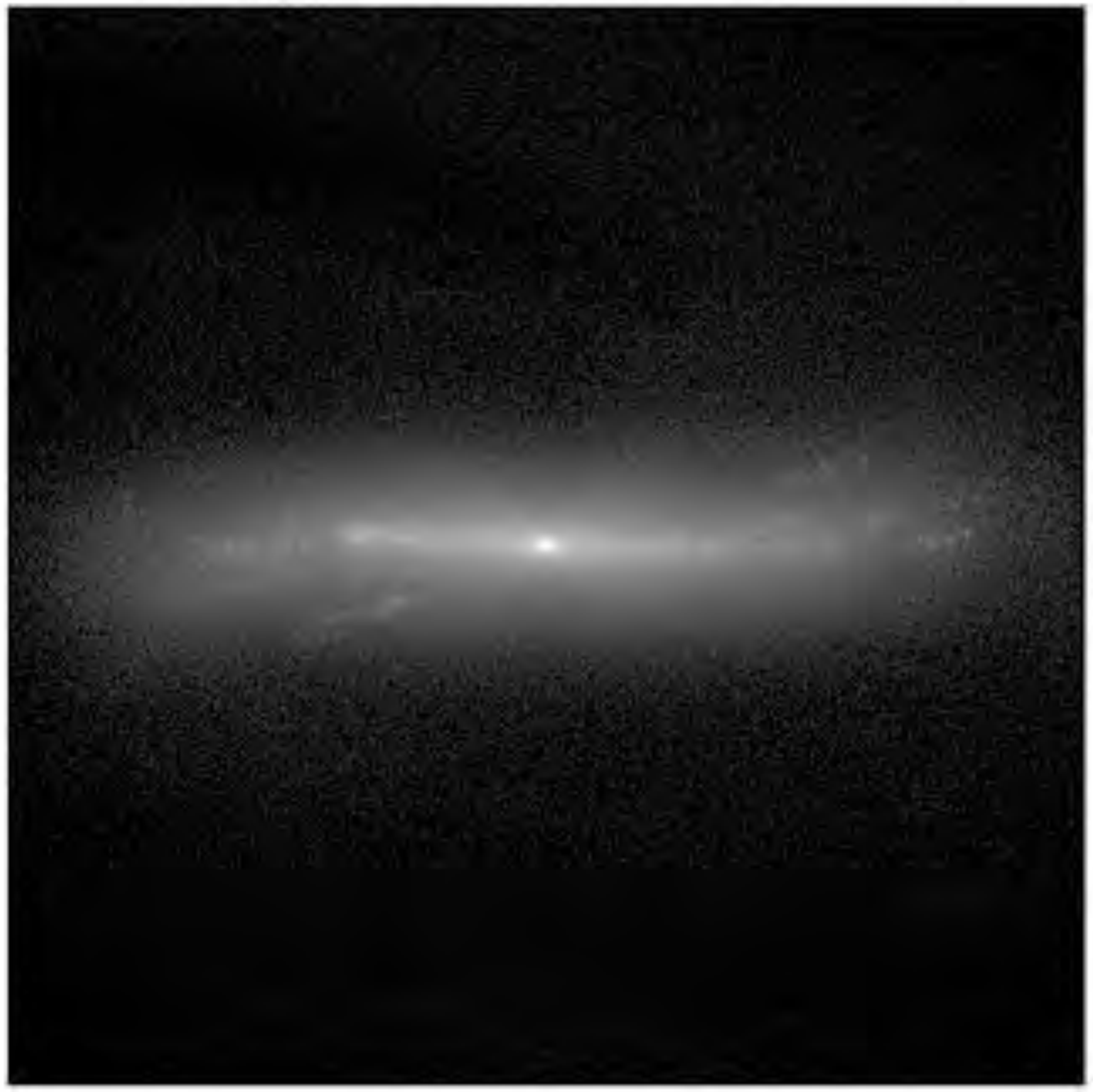


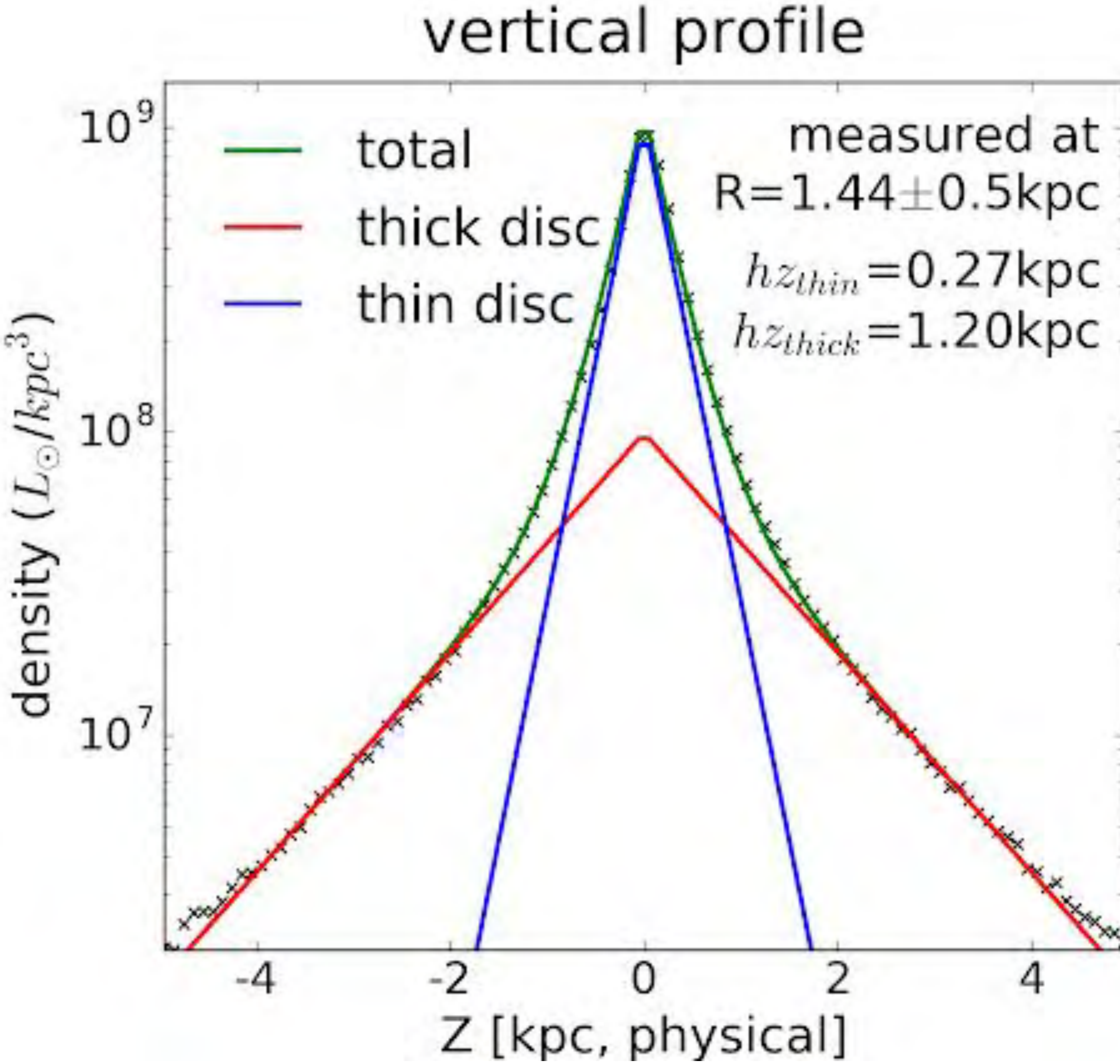
Quid of the effect of wakes on injection scale?

(c)Taysun Kimm

Q∼ 1 confounding factor for joint thick+thin growth

$M_{*,\,disc} = 4.53 \times 10^{10} M_\odot$

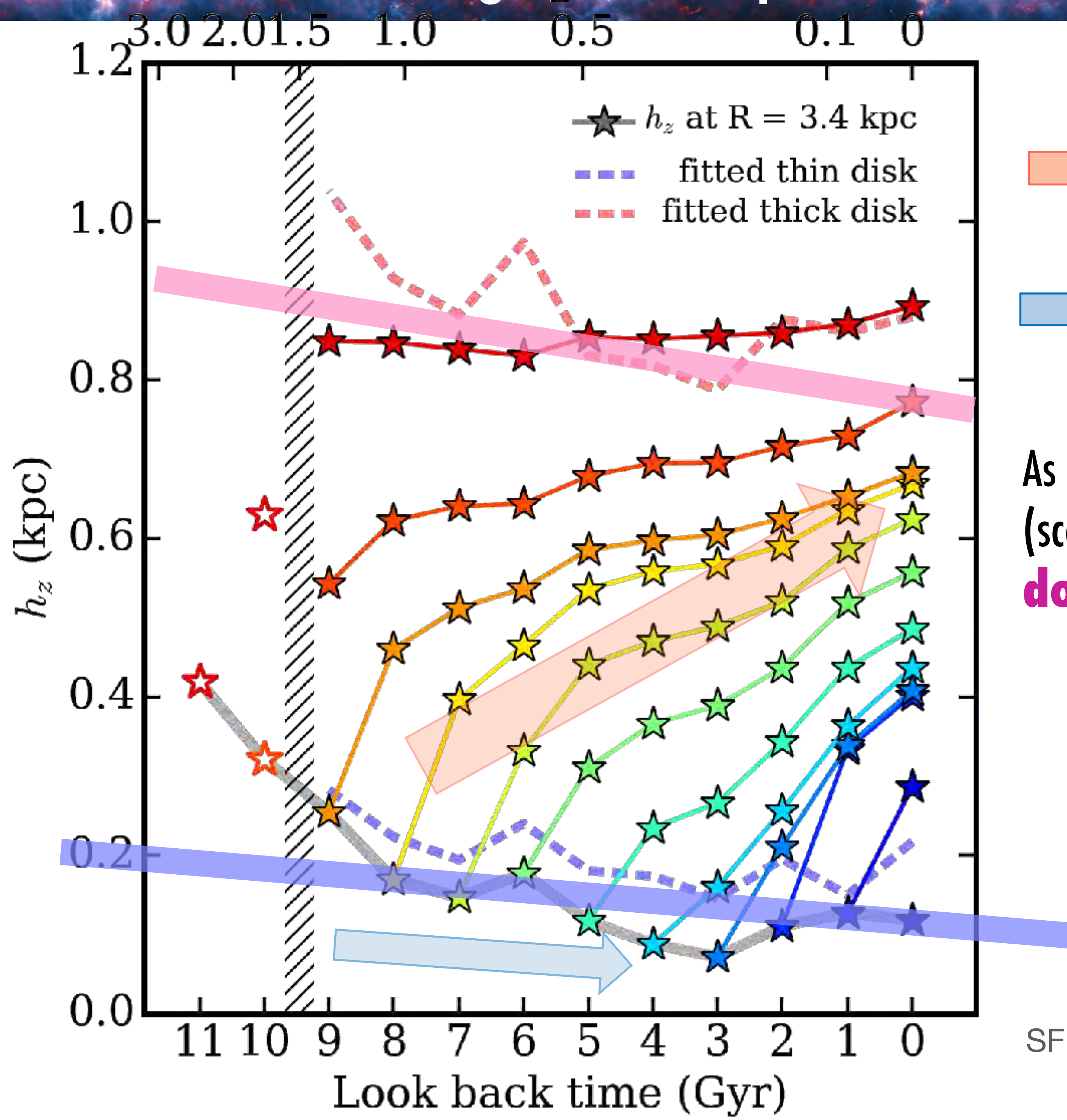




Both star formation and vertical orbital diffusion regulated by (Q $\rightarrow$ 1) **confounding** factor.

Stellar thick disc = **secular remnant** of (self regulated) disc settling process.

Q∼ 1 confounding factor for joint thick+thin growth



Pre-existing disk stars get thicker with time due to heating

Galaxy keeps forming in // young thin-disk stars

As a result, the vertical distribution (scale heights of the two components from fit) **do not change** since self-regulation controls both processes

Vertical orbital diffusion

$$D_{\mathrm{dressed}} \propto D_{\mathrm{raw}}/\epsilon^2(Q)$$

$$\eta_{\mathrm{dressed}} \propto \eta_{\mathrm{raw}}/\epsilon^2(Q)$$

SF efficiency

Both star formation and vertical orbital diffusion regulated by (Q $\to$ 1) **confounding** factor.

Stellar thick disc = **secular remnant** of (self regulated) disc settling process.

Emergence

NGC 5068
NGC 1365
NGC 4303
NGC 1512
NGC 4535
NGC 3351
NGC 4321
NGC 0628
IC 5332
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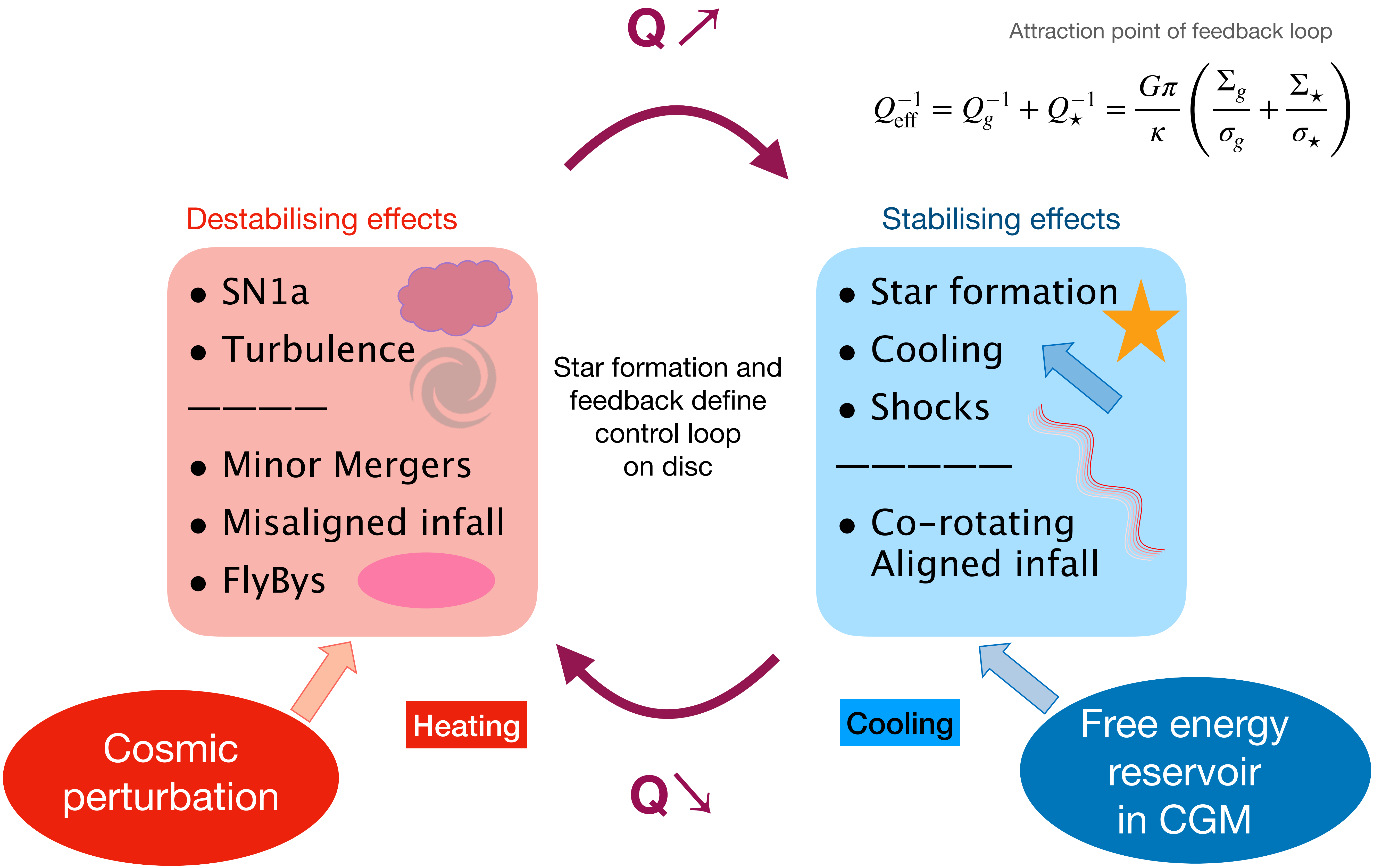
NGC 7496
NGC 3627

Self regulating loop boosted by wake

Transition to secularly-driven morphology promoting self-regulation around an effective Toomre $Q \sim 1$.



Self regulating loop boosted by wake

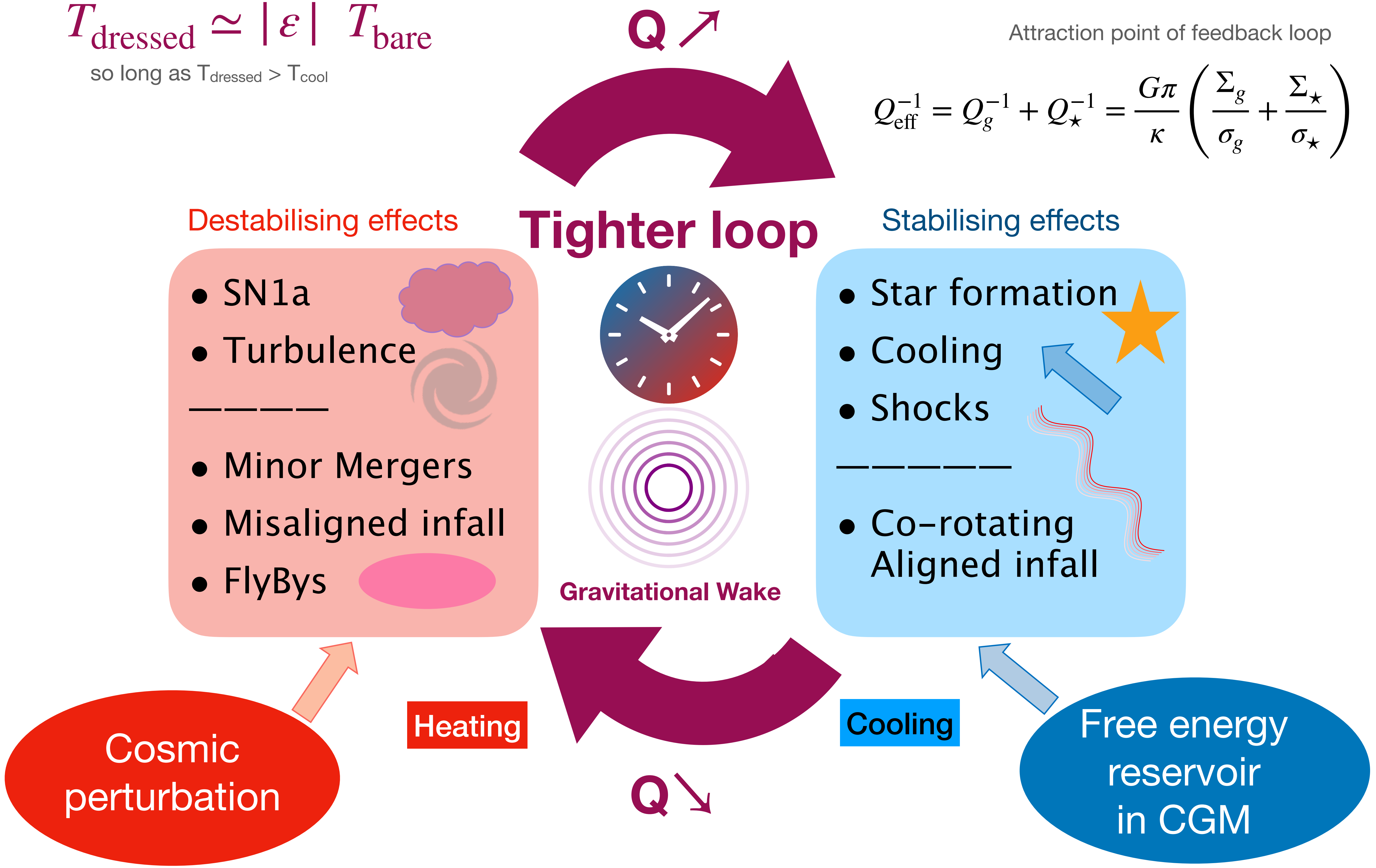
Transition to secularly-driven morphology promoting self-regulation around an effective Toomre $Q \sim 1$.

$$T_{\rm dressed} \simeq |\varepsilon| \; T_{\rm bare}$$

so long as $T_{\rm dressed} > T_{\rm cool}$

Attraction point of feedback loop

$$Q_{\rm eff}^{-1} = Q_g^{-1} + Q_\star^{-1} = \frac{G\pi}{\kappa}\left(\frac{\Sigma_g}{\sigma_g} + \frac{\Sigma_\star}{\sigma_\star}\right)$$



Open system with control loop generates complexity through self-organisation

Synopsis of thin disc emergence:

Gravity

Cosmic infall

Star formation

Feedback

Turbulence

Cartoon, drawn by Janet Sellwood in 1984, based on Toomre's assessment of the state of spiral structure theory in 1980. Apart from a few extra blindfolded individuals, this still seems appropriate today.

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Cosmic infall

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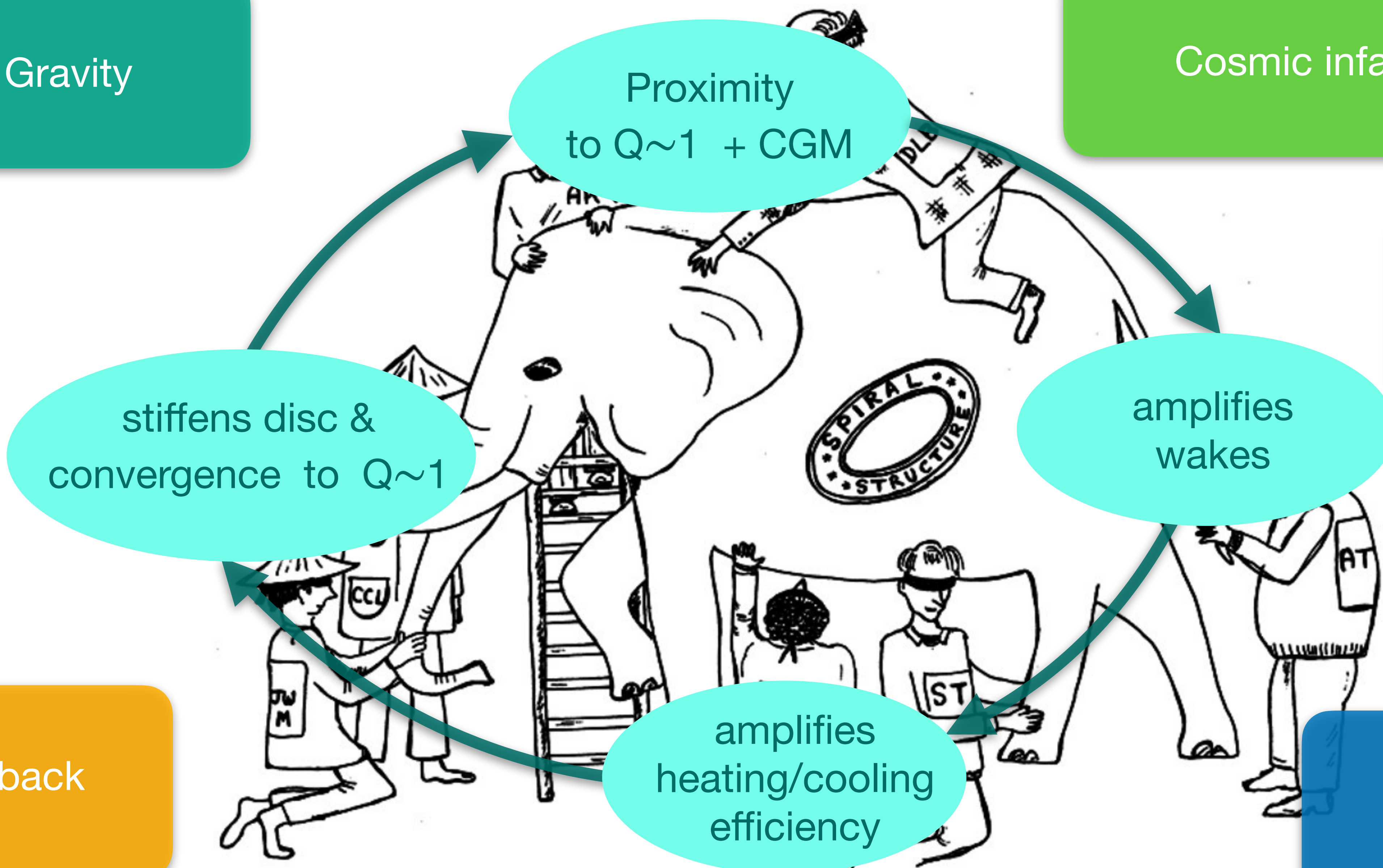

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Feedback

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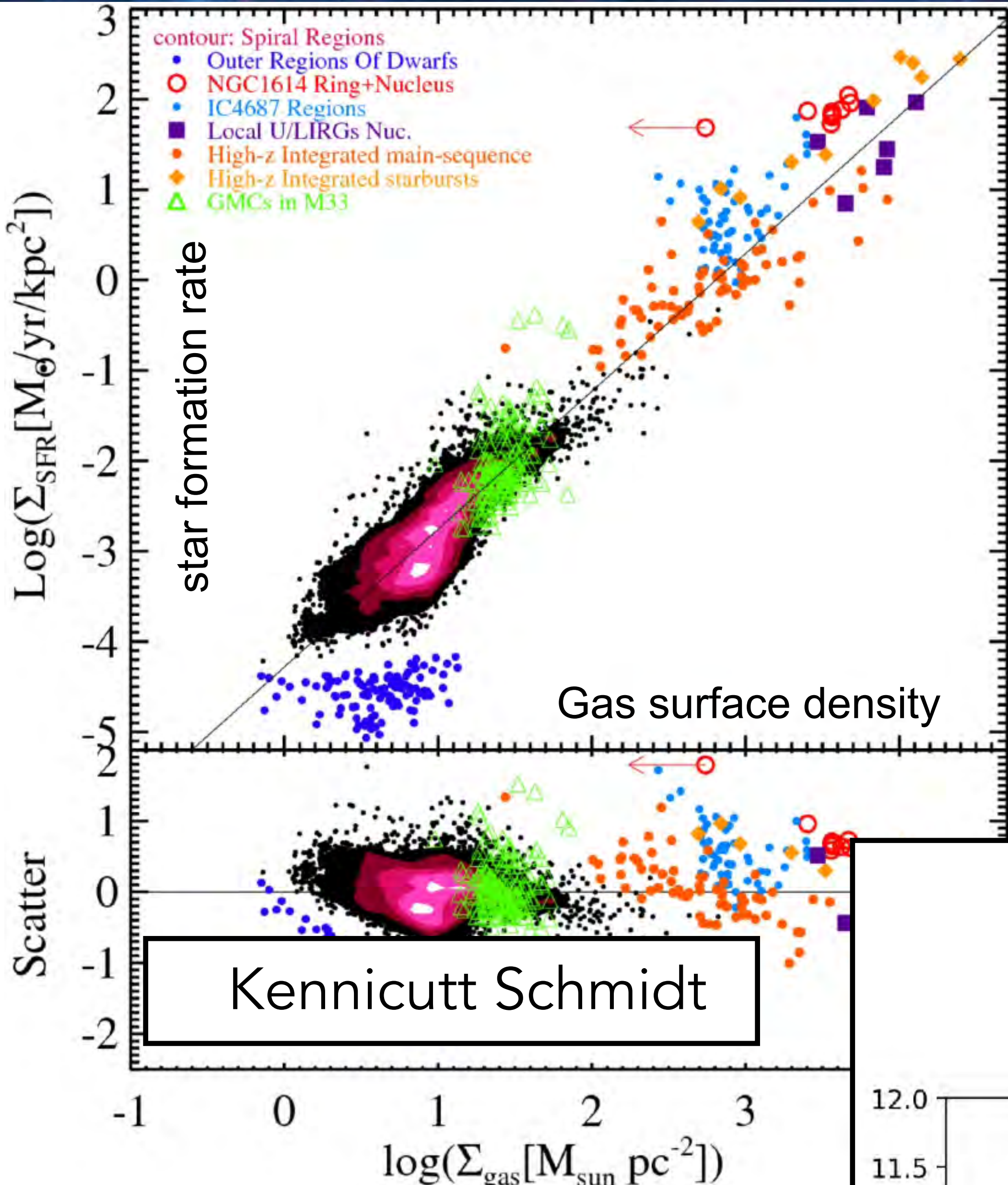
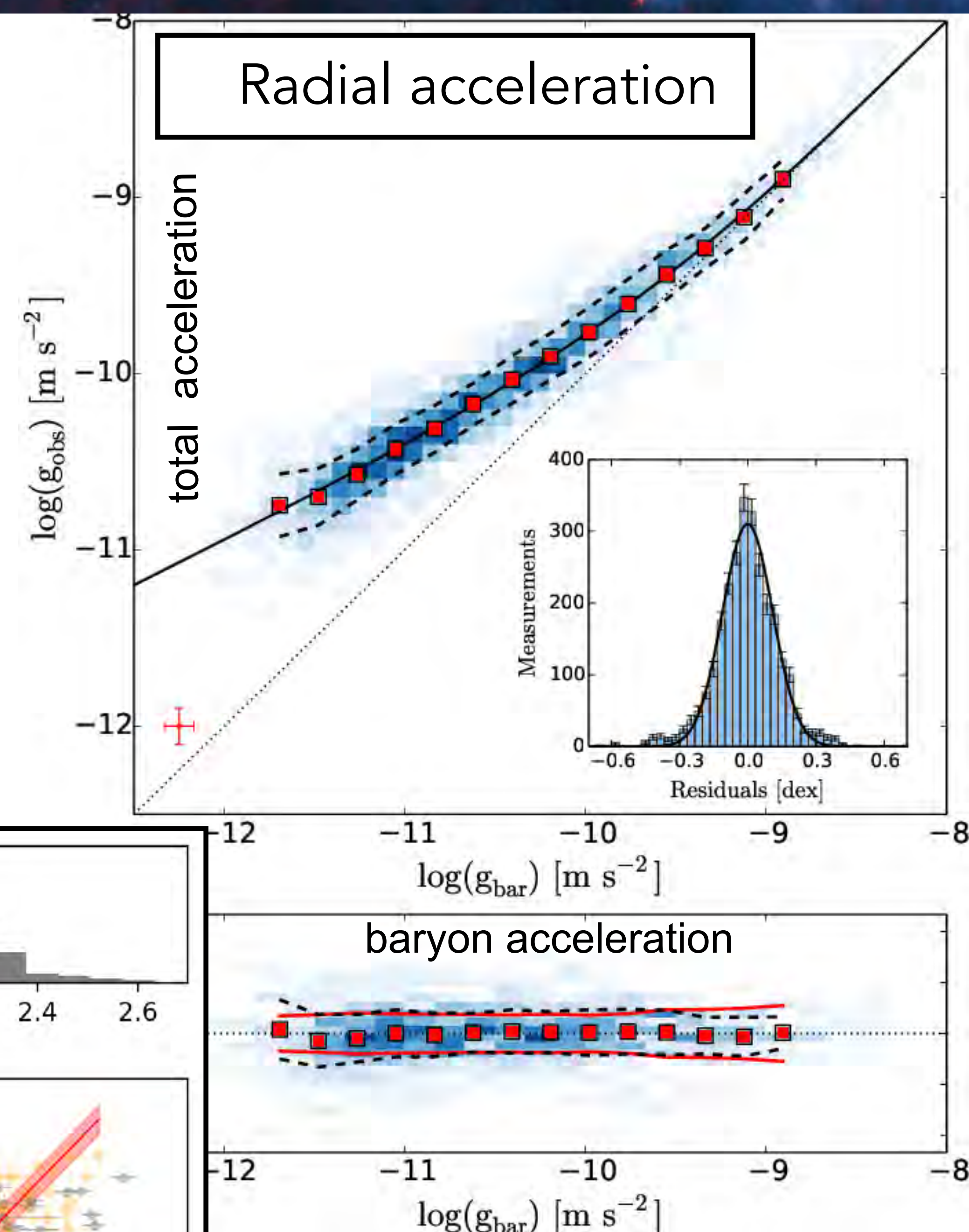
Scaling laws & Q=1 : origin of tight relations?

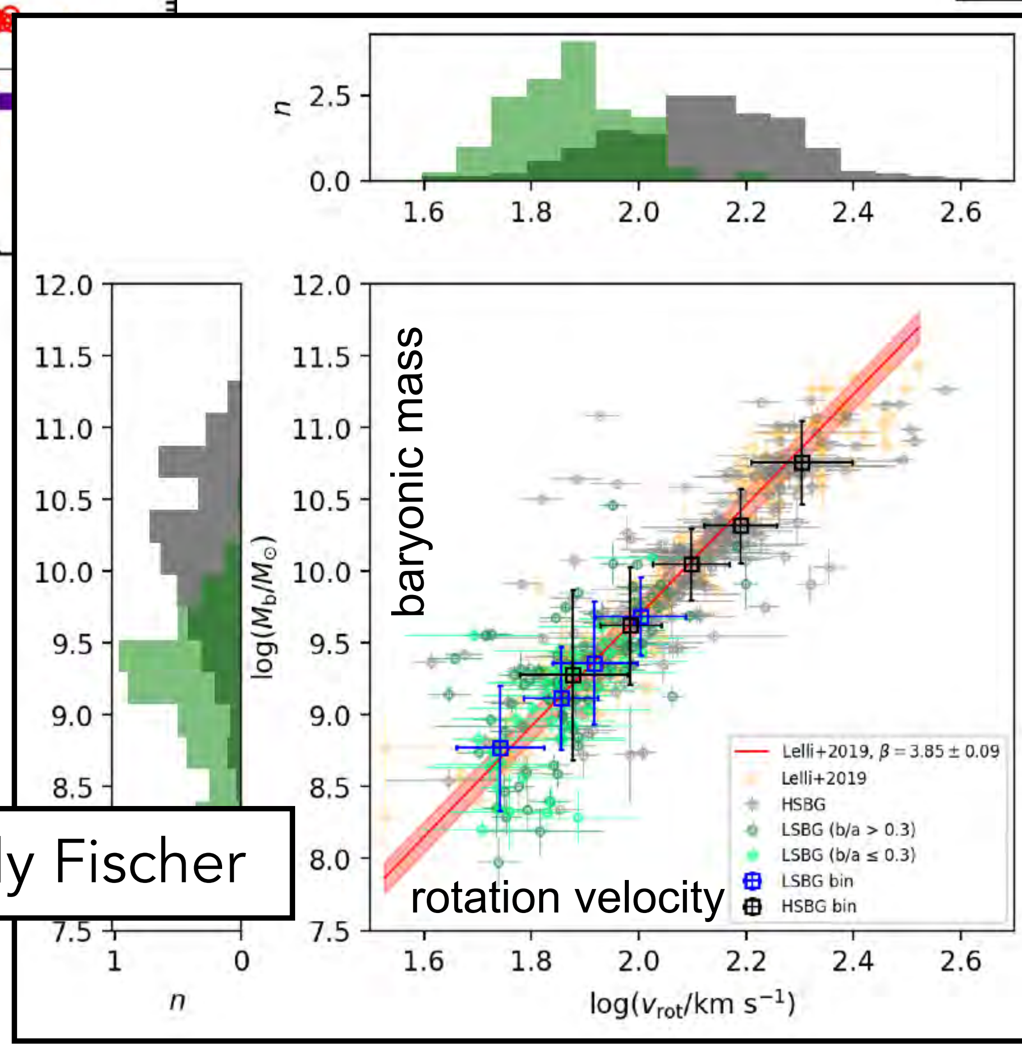


Kim Ostriker (2007)

Q~1 provides *dynamical* halo to disc link

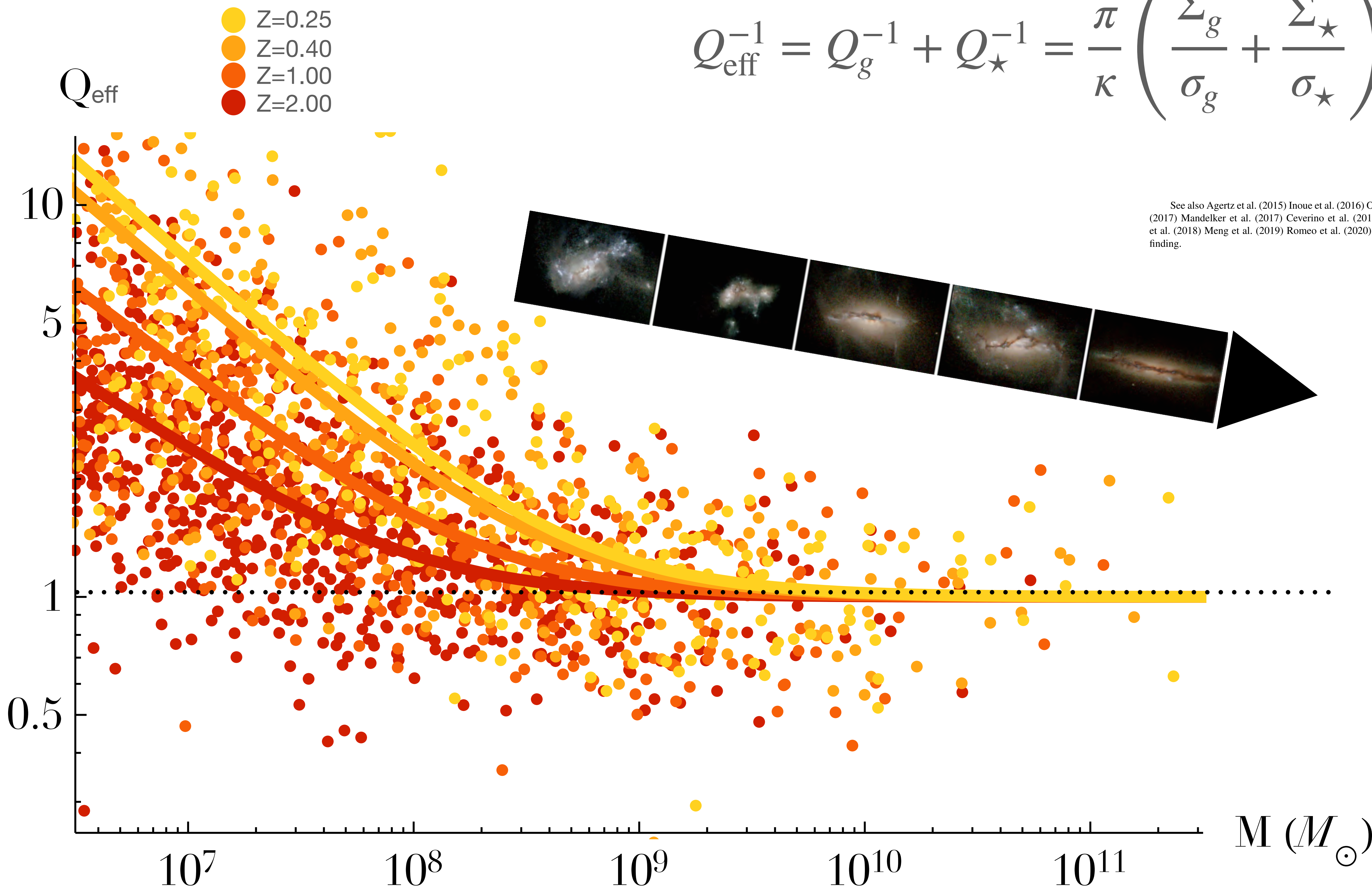
Tight Q~1 ⇒ Tight scaling relations





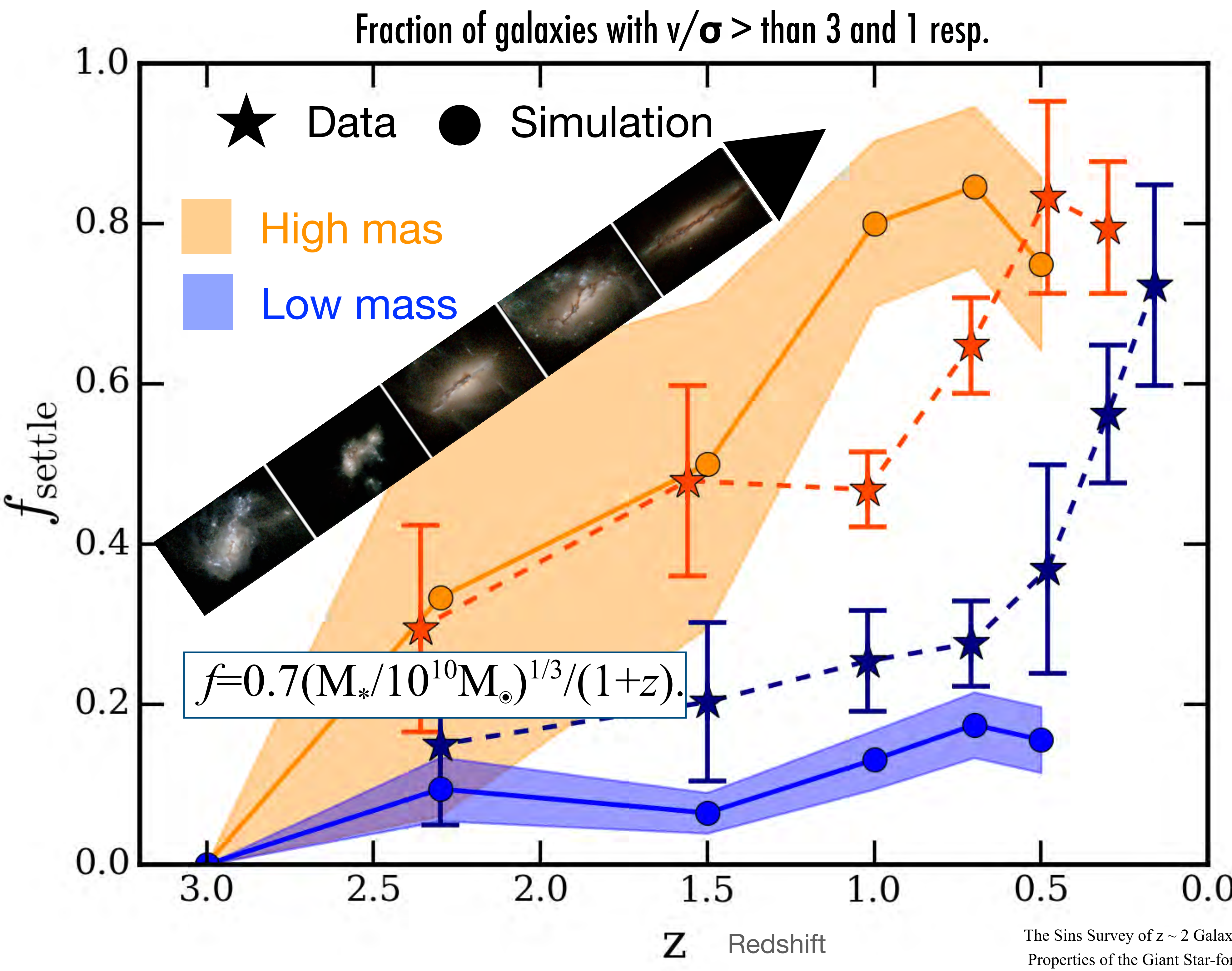
Toomre Q (★+gas) parameter convergence as a function of *both* mass and redshift

$$Q_{\rm eff}^{-1} = Q_g^{-1} + Q_\star^{-1} = \frac{\pi}{\kappa}\left(\frac{\Sigma_g}{\sigma_g} + \frac{\Sigma_\star}{\sigma_\star}\right)$$



See also Agertz et al. (2015) Inoue et al. (2016) Oklopčić et al. (2017) Mandelker et al. (2017) Ceverino et al. (2017) Krumholz et al. (2018) Meng et al. (2019) Romeo et al. (2020) for a similar finding.

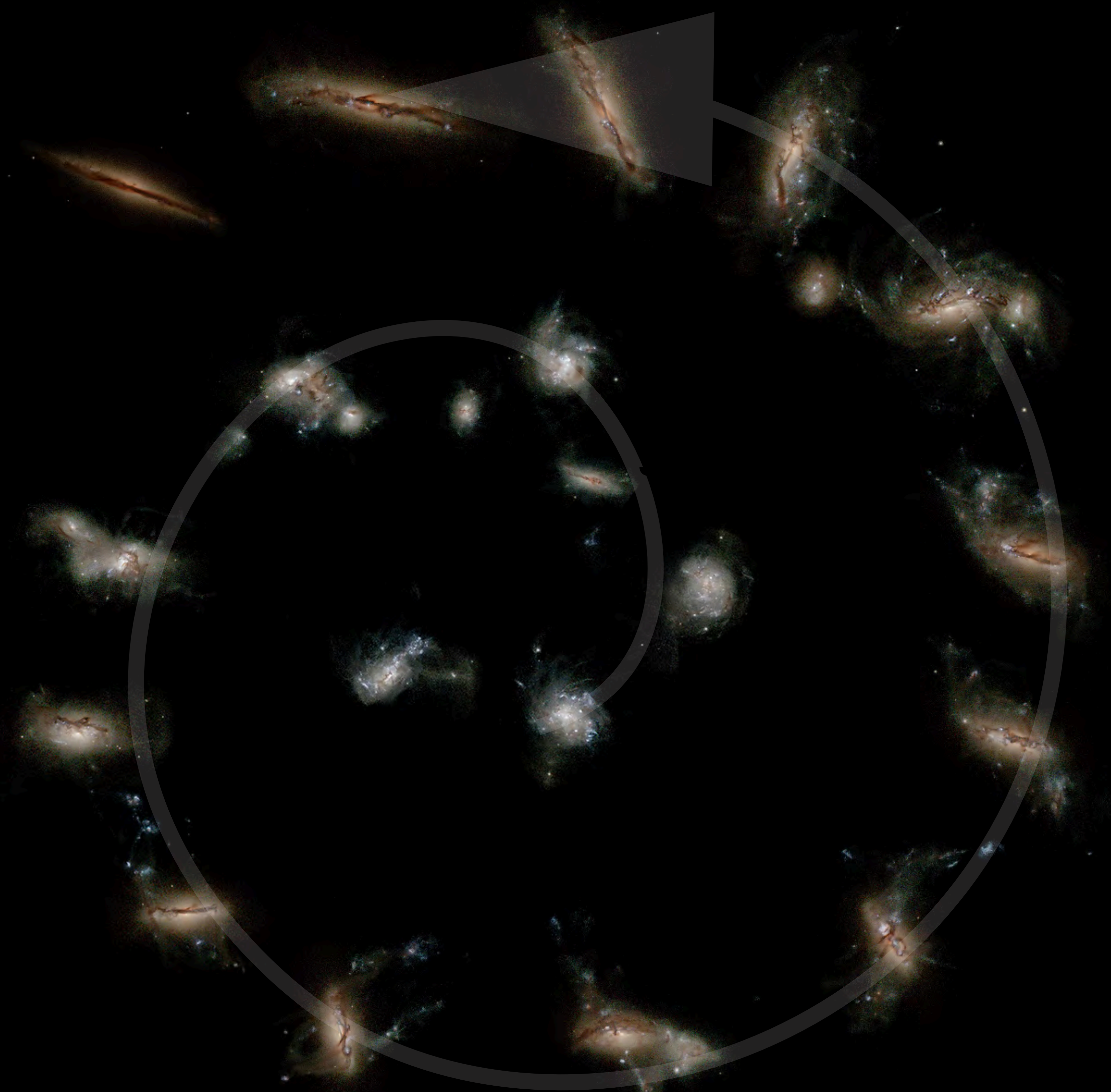
Match between simulation and observation as a function of *both* mass and redshift



The Sins Survey of z ~ 2 Galaxy Kinematics: Properties of the Giant Star-forming Clumps. Astrophys. J., 733, 101-130 (2011)

Disc settling: timeline of a thin galactic disc

New Horizon Simulation



morphological settling is suggestive of emergence

Disc settling: timeline of a thin galactic disc

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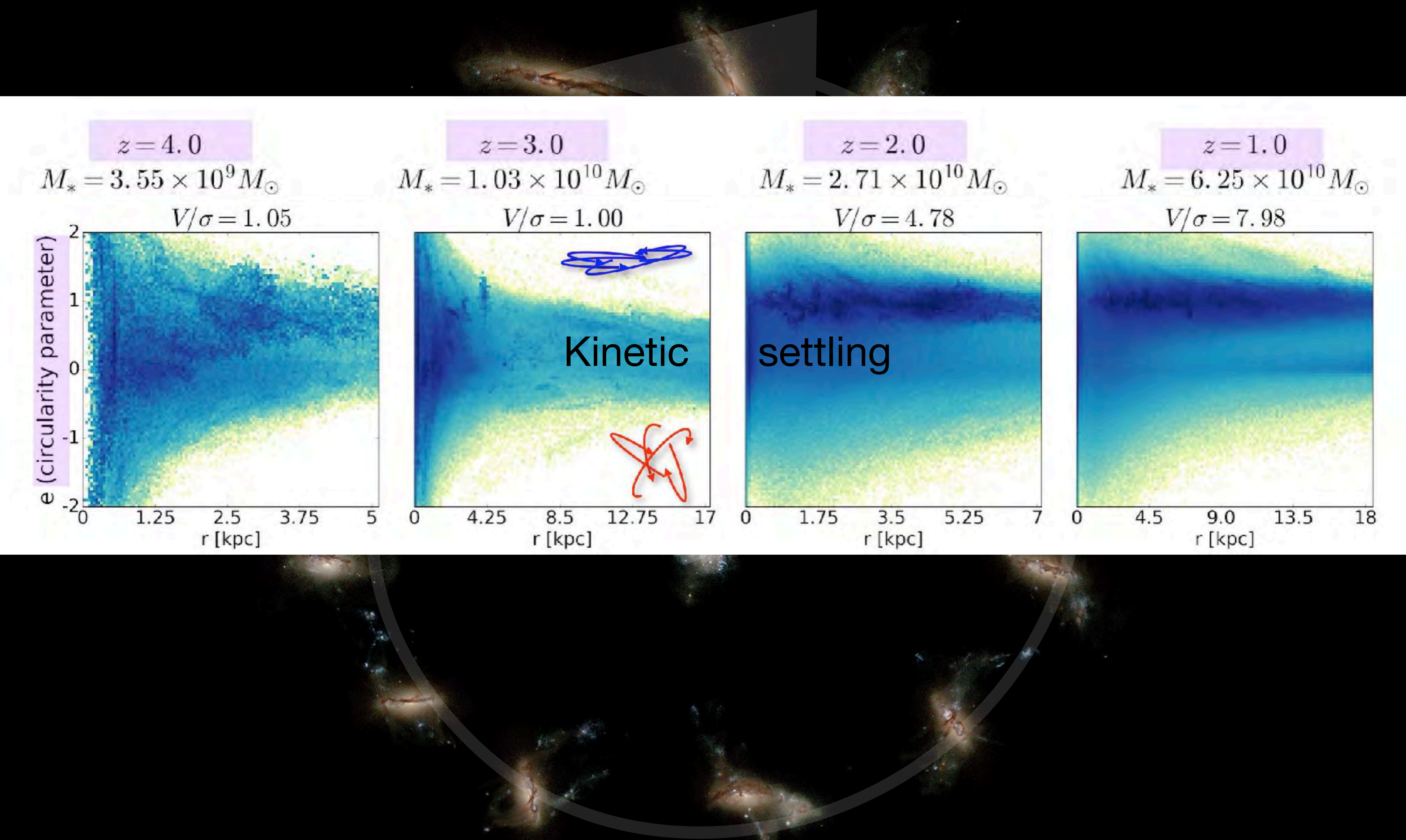
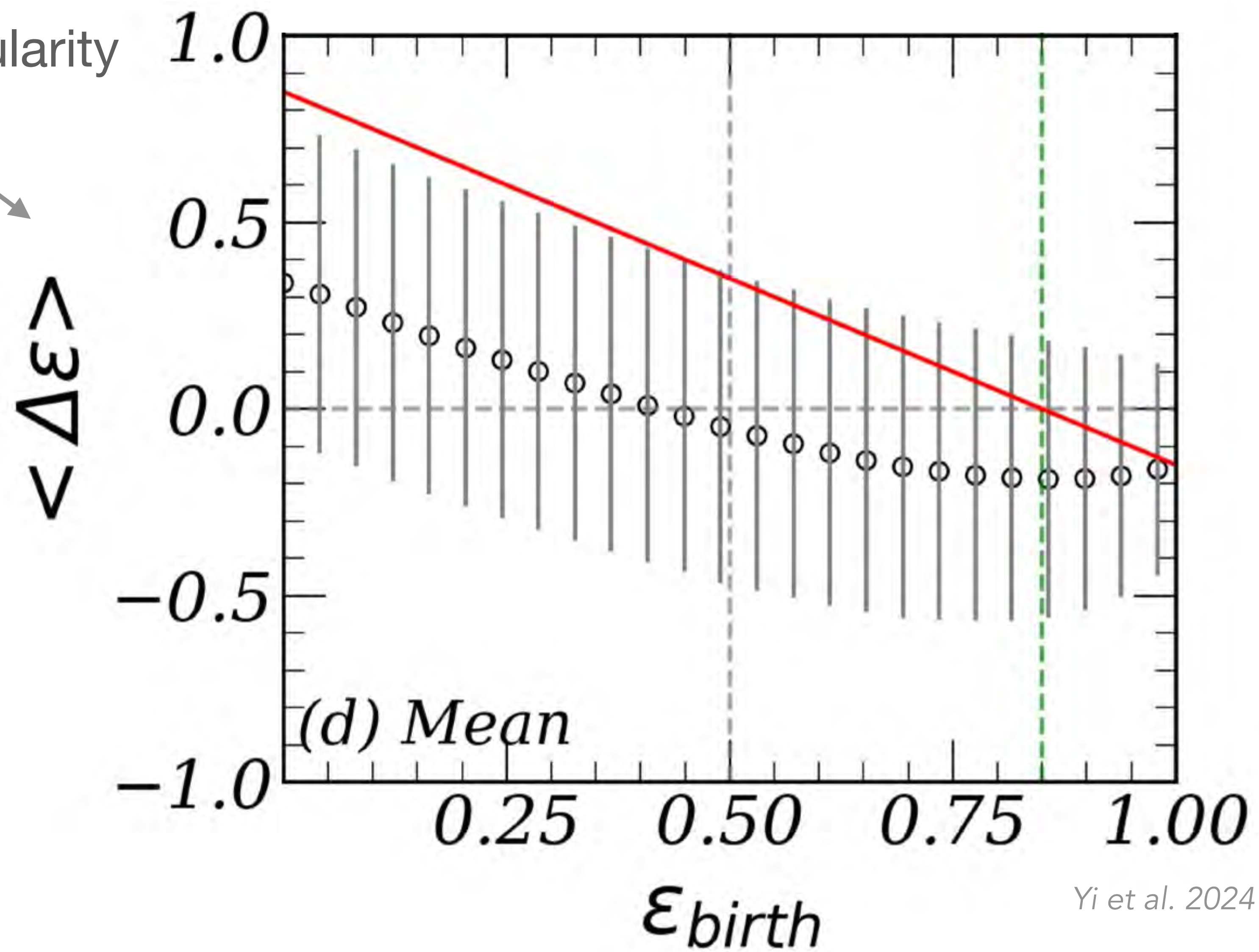


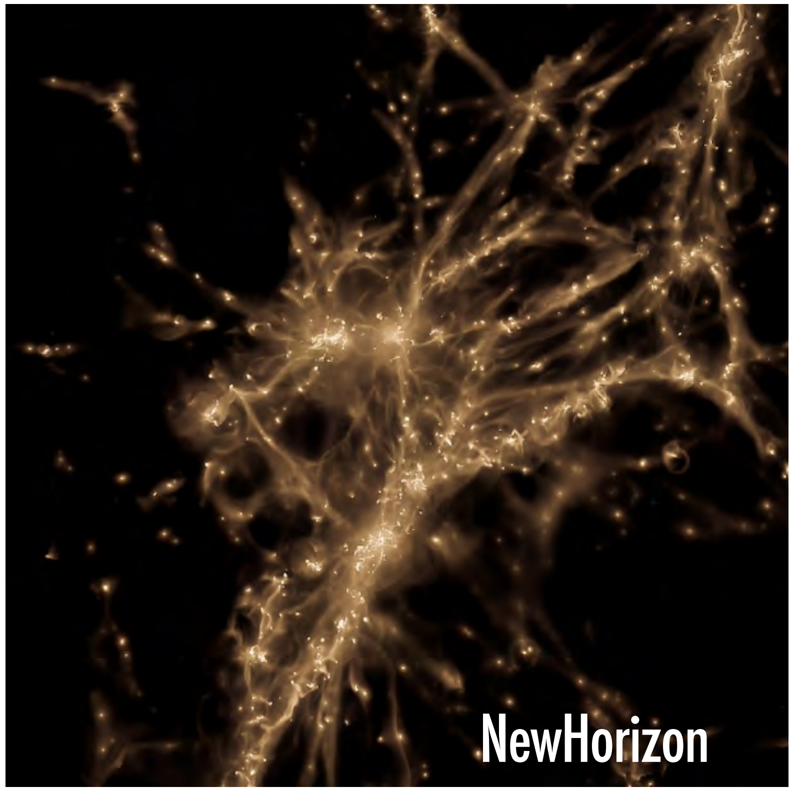
morphological settling is suggestive of emergence

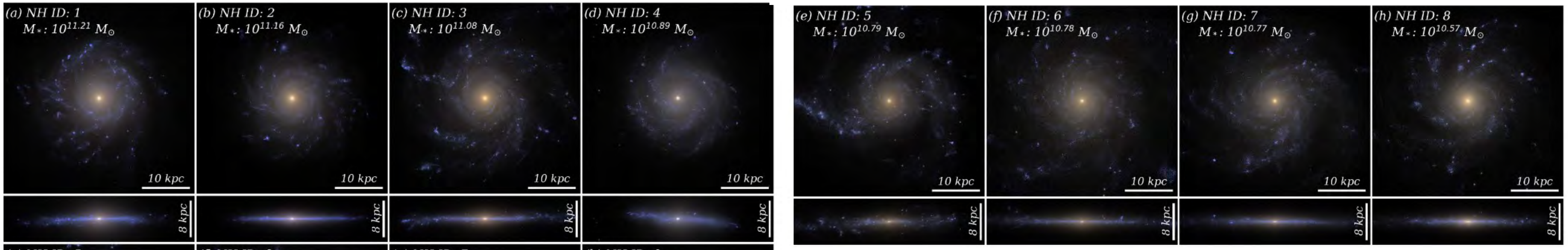
Measured orbital diffusion in cosmological simulation NewHorizon

Change in circularity



Circularity @ birth

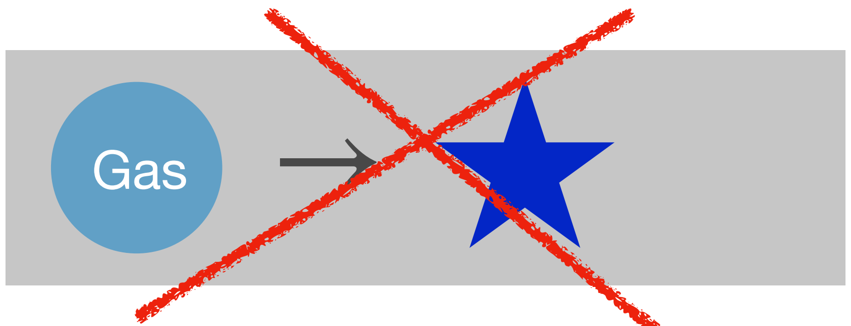




Why finite thickness? Chemistry of emergence

Let us write down effective (closed loop) production rate for cold stellar component

Auto-catalysis of the cold component (via wakes) converts kinetic evolution into a logistic differential equation.



Gas + ★ → ★ + ★

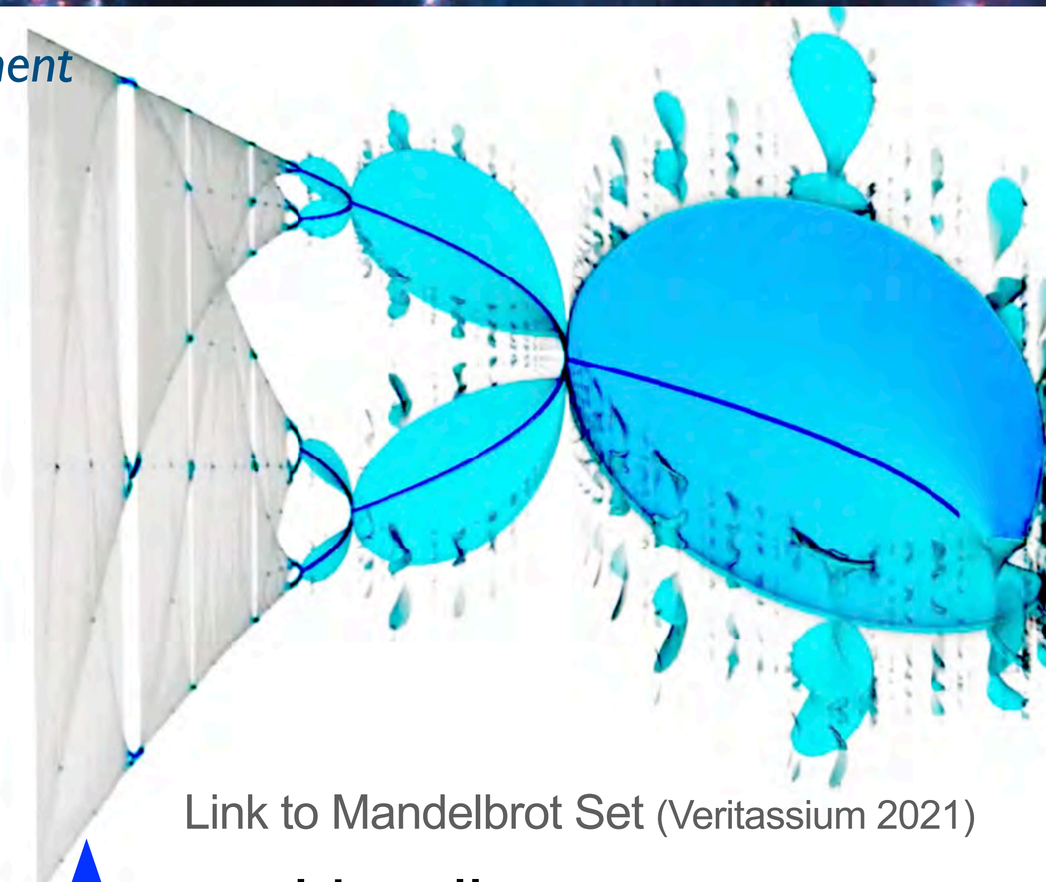
$$\frac{d}{dt}\star = r\star(1-\star)$$

control parameter

Logistic *ODE (cf Ecology, Chaos, Covid, Innovation etc..)*

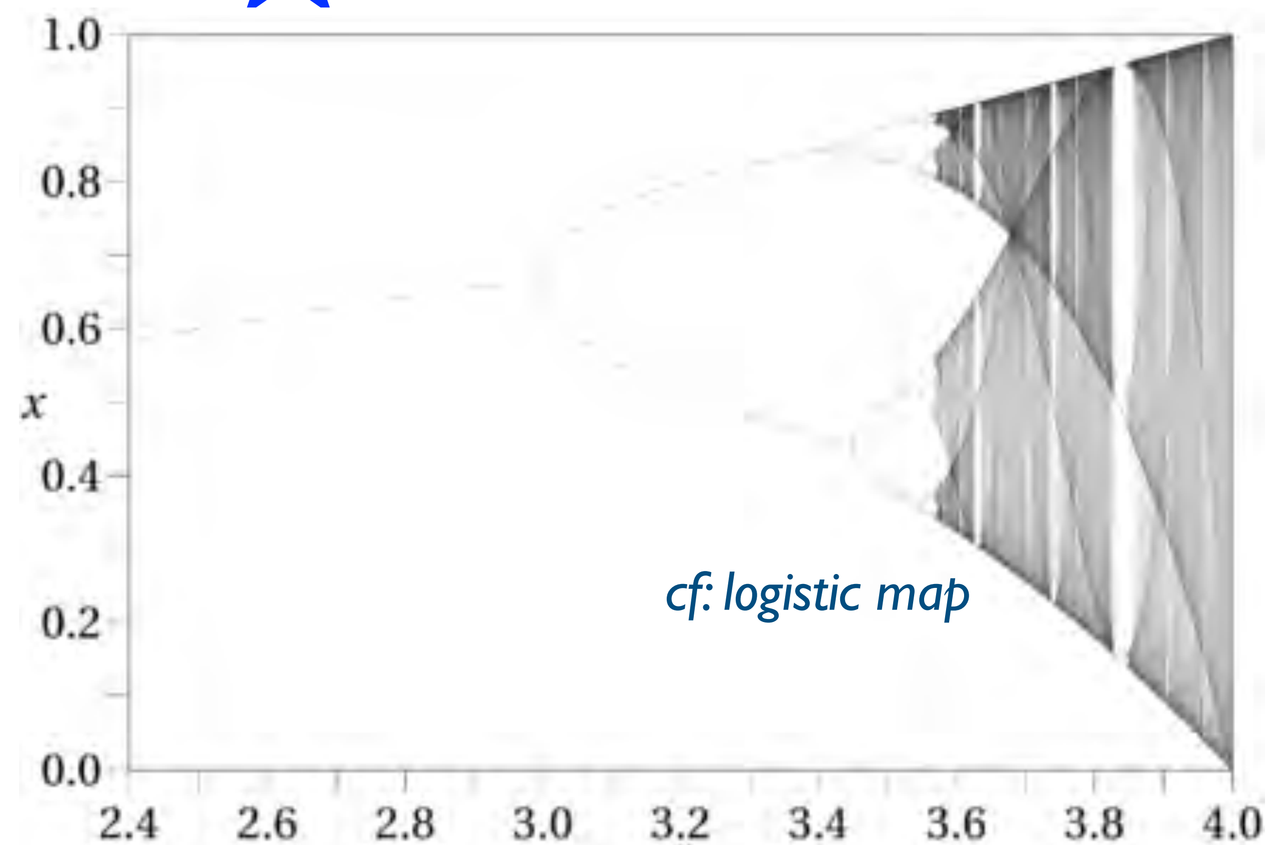
= Simplest **quadratic** model for self -regulation

= Taylor expansion of effective production rate



Link to Mandelbrot Set (Veritassium 2021)

★ = cold stellar component



r control parameter

Chemistry of emergence… introduce heating

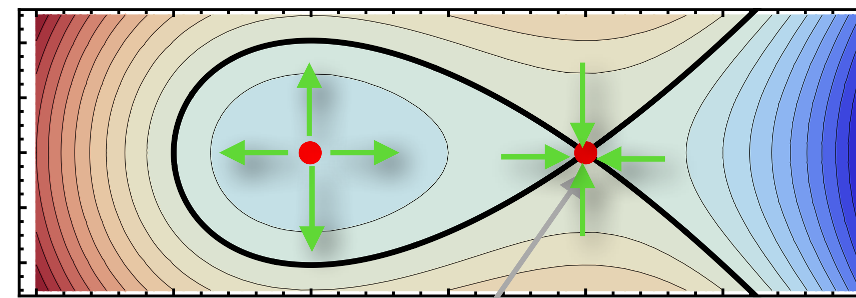
*Now let us take into account for the **vertical** secular diffusion of the cold component*

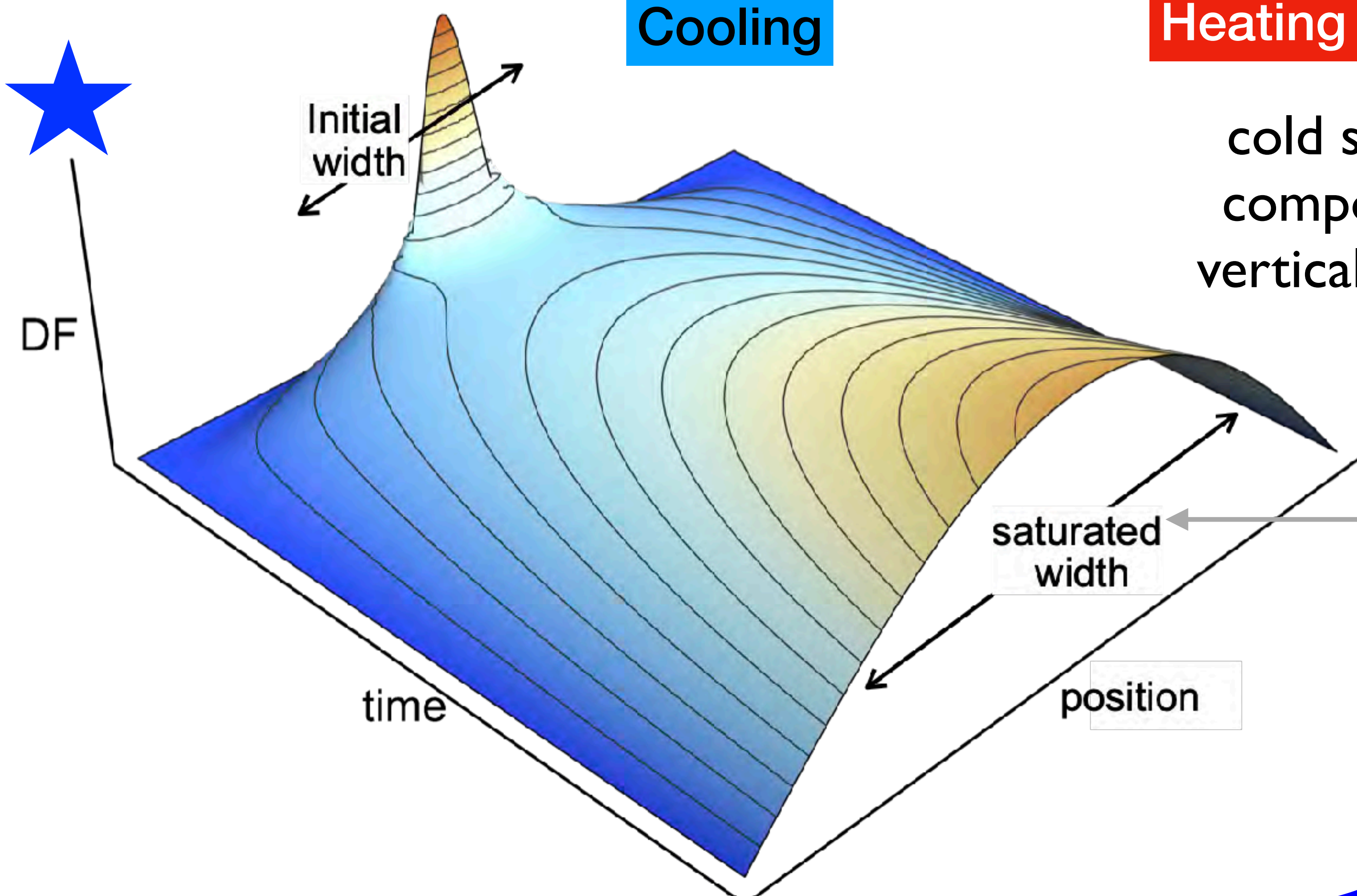
Dissipation converts kinetic instability point into an attractor.

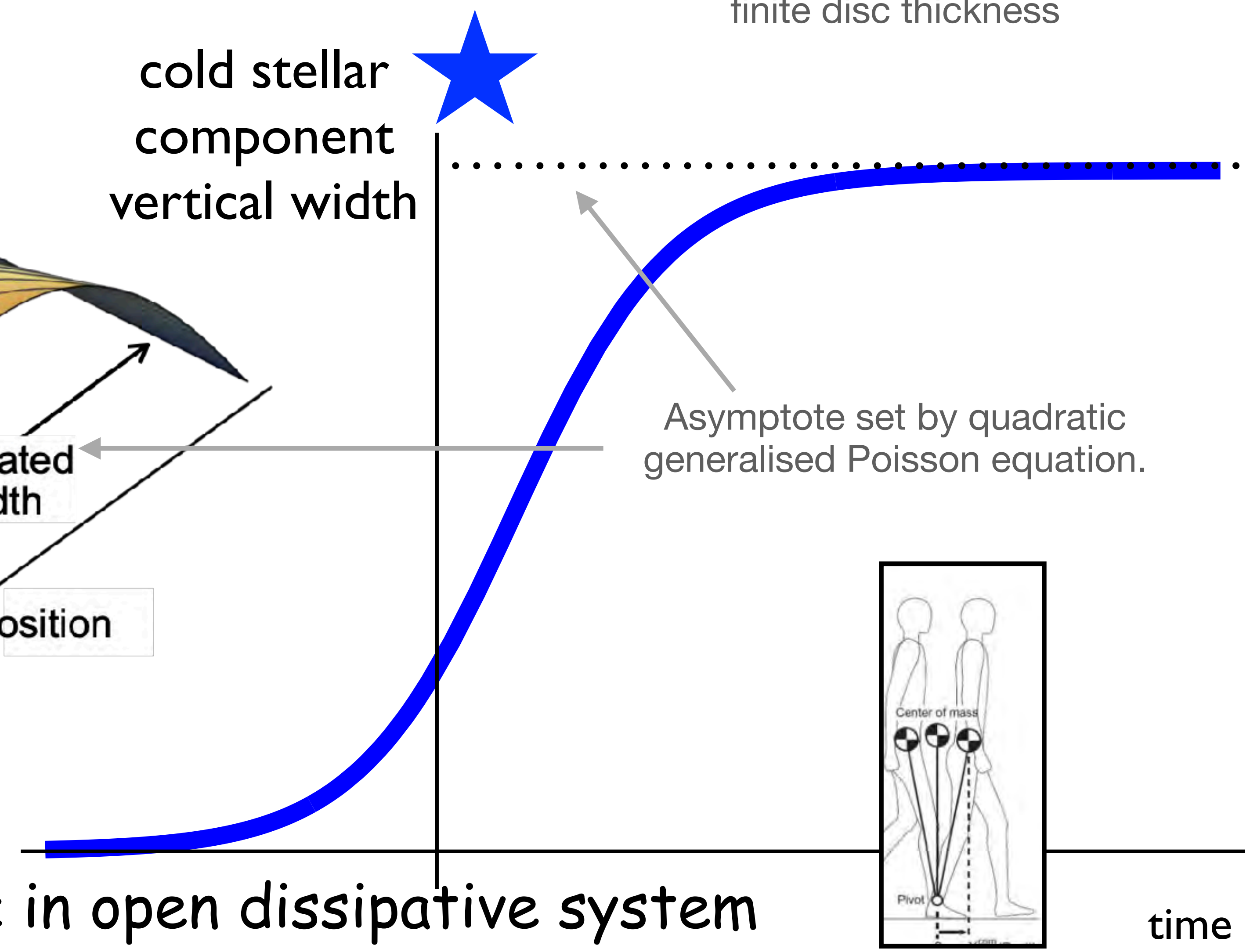
Reaction-Diffusion equation (cf morphogenesis)

$$\frac{d}{dt}\bigstar = \delta_D \bigstar (1 - \bigstar) + \Delta \bigstar$$

Cooling (under $\delta_D \bigstar (1 - \bigstar)$) · Heating (under $\Delta \bigstar$, Fokker Planck orbital diffusion)







→ **Emergence of thin fixed width disc in open dissipative system**

Chemistry of emergence... introduce tides

*Now let us take into account for the **vertical** secular diffusion of the cold component*

Dissipation converts kinetic instable point into an attractor.

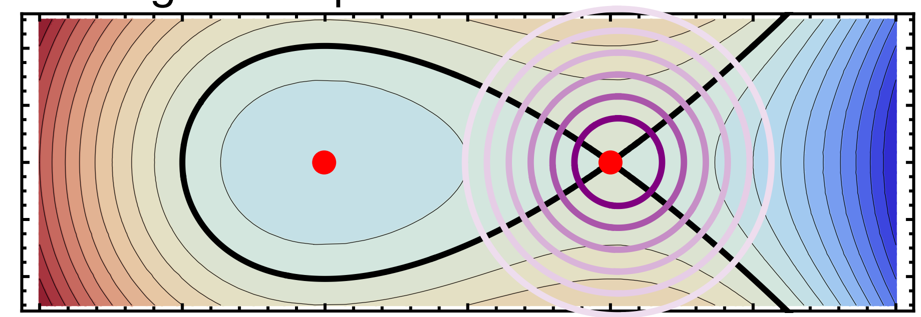
Dressed Reaction-Diffusion equation (cf morphogenesis)

$$\frac{d}{dt}\bigstar = \frac{\delta_D}{\epsilon^2}\bigstar(1-\bigstar) + \frac{1}{\epsilon^2}\Delta\bigstar$$

wake driven $\varepsilon(z) \to 0$ as $Q \to 1$

Gravitational Wake

Logistic map Hamiltonian



SF efficiency

$$\eta_{\rm dressed} \propto \eta_{\rm raw}/\epsilon^2(Q)$$

$$D_{\rm dressed} \propto D_{\rm raw}/\epsilon^2(Q)$$

$\sim$ quadratic in ε

Diffusion

$$\Longrightarrow \quad dt \to \epsilon^2 dt$$

Rapid correction

- $\to$ Cosmic resilience of thin disc driven by CW
- $\to$ Operates swiftly near self-organised Criticality
- $\to$ Robustness / feedback details

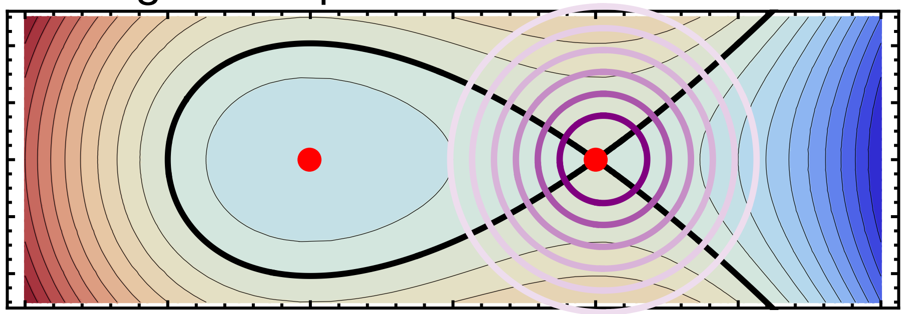
Chemistry of emergence... introduce tides

Now let us take into account for the ***vertical*** *secular diffusion of the cold component*

Dissipation converts kinetic instable point into an attractor.

Gravitational Wake

Logistic map Hamiltonian



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Diffusion

$$\Longrightarrow \quad dt \to \epsilon^2 dt$$

Rapid correction

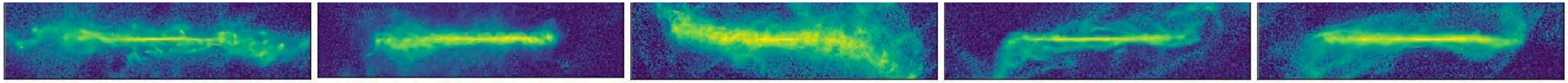
→ Cosmic resilience of thin disc driven by CW

→ Operates swiftly near self-organised Criticality

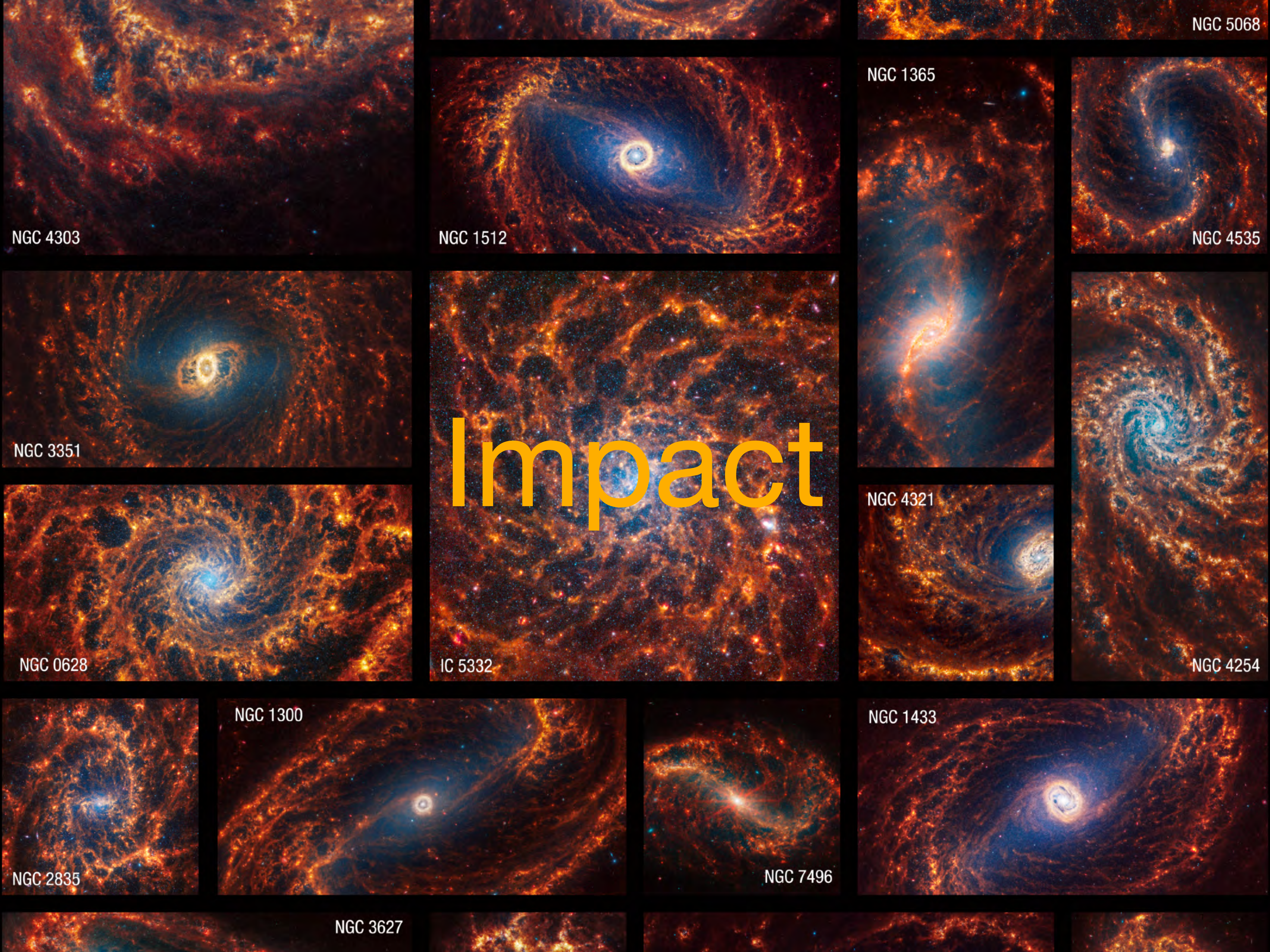
→ Robustness / feedback details

No fine tuning !

all discs are fairly thin whatever the feedback



Impact


NGC 5068
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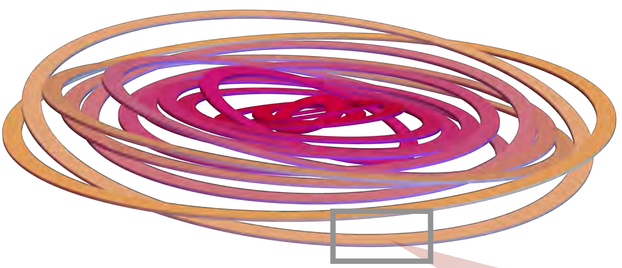
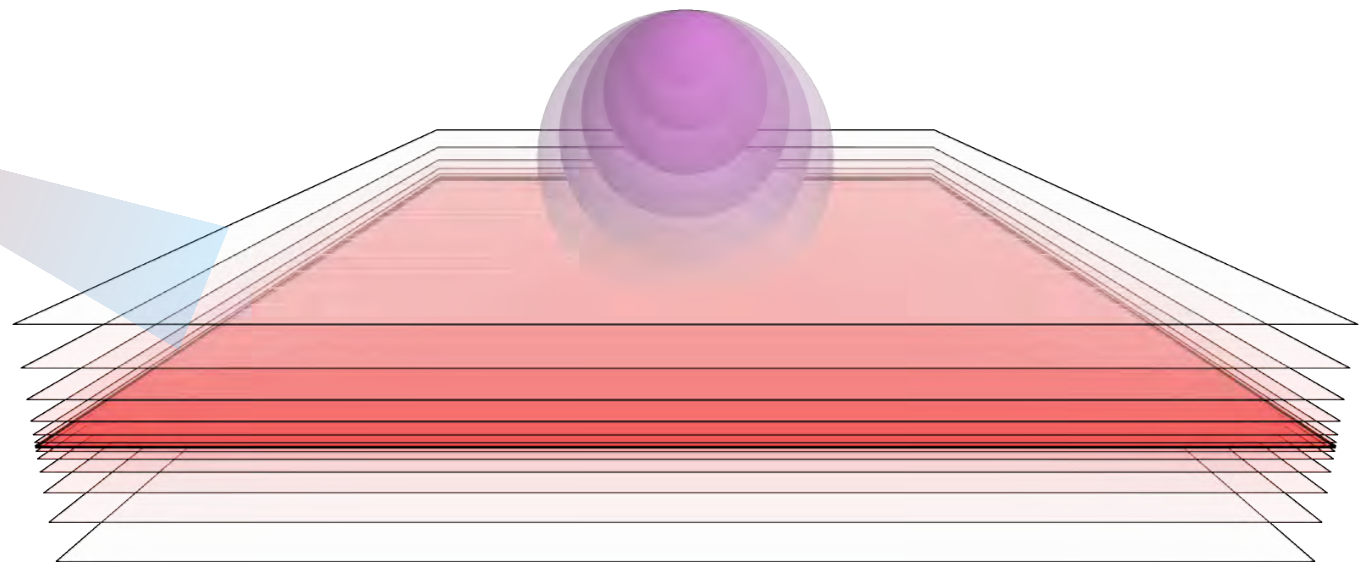
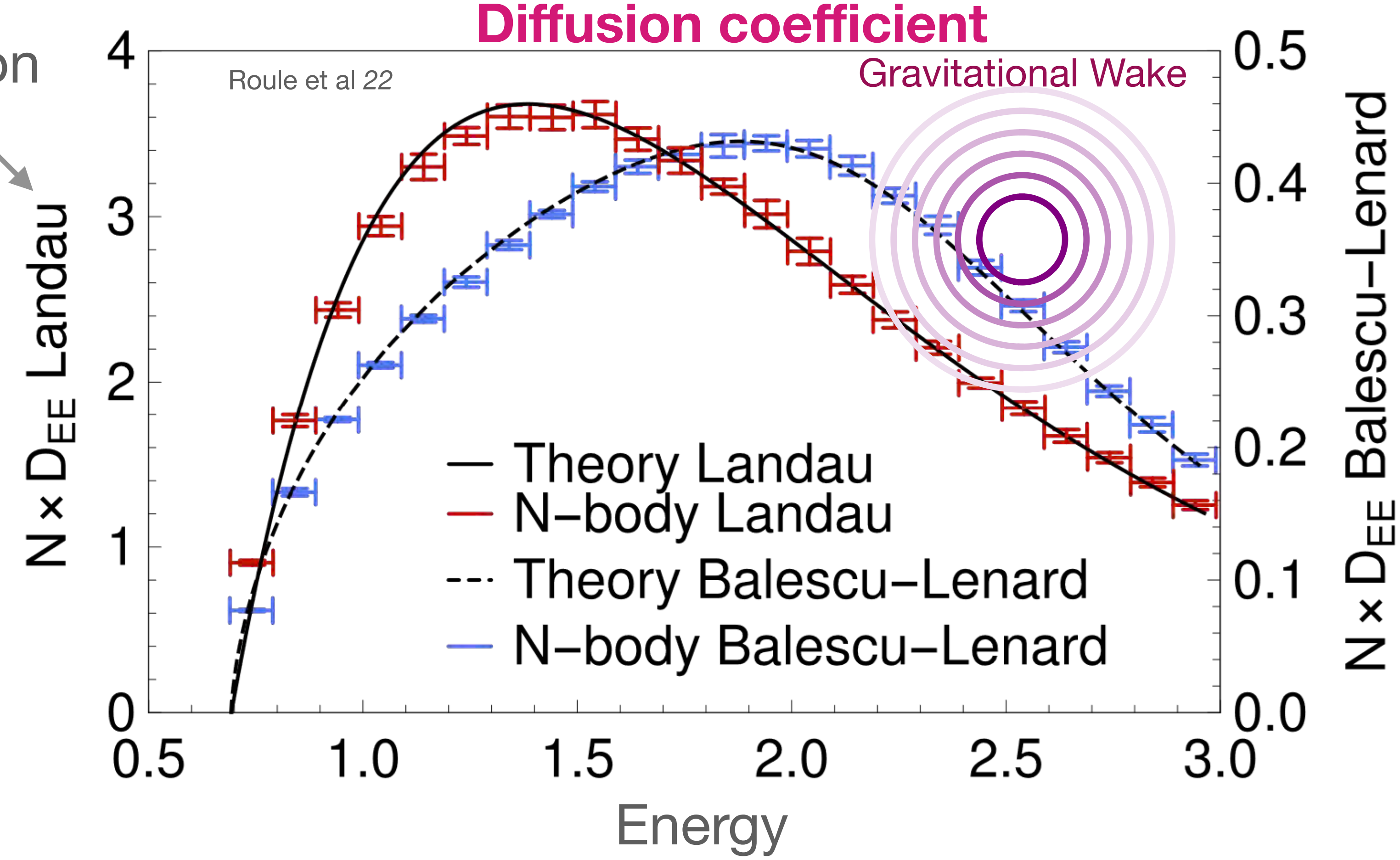


Kinetic theory of (toy model) parallel planes with and w/o dressing



Without polarisation



With polarisation:

rate of diffusion **x 1/ 10**

Polarisation stiffen coupling between planes → wakes stiffen disc

<u>Lagrange Laplace theory of rings</u> *(small eccentricity small inclinaison)*

x and y components of **angular momentum**

$$H(\mathbf{p},\mathbf{q}) = \frac{1}{2}\mathbf{p}^{\mathrm{T}}\cdot\mathbf{A}\cdot\mathbf{p} + \frac{1}{2}\mathbf{q}^{\mathrm{T}}\cdot\mathbf{A}\cdot\mathbf{q}\,,$$

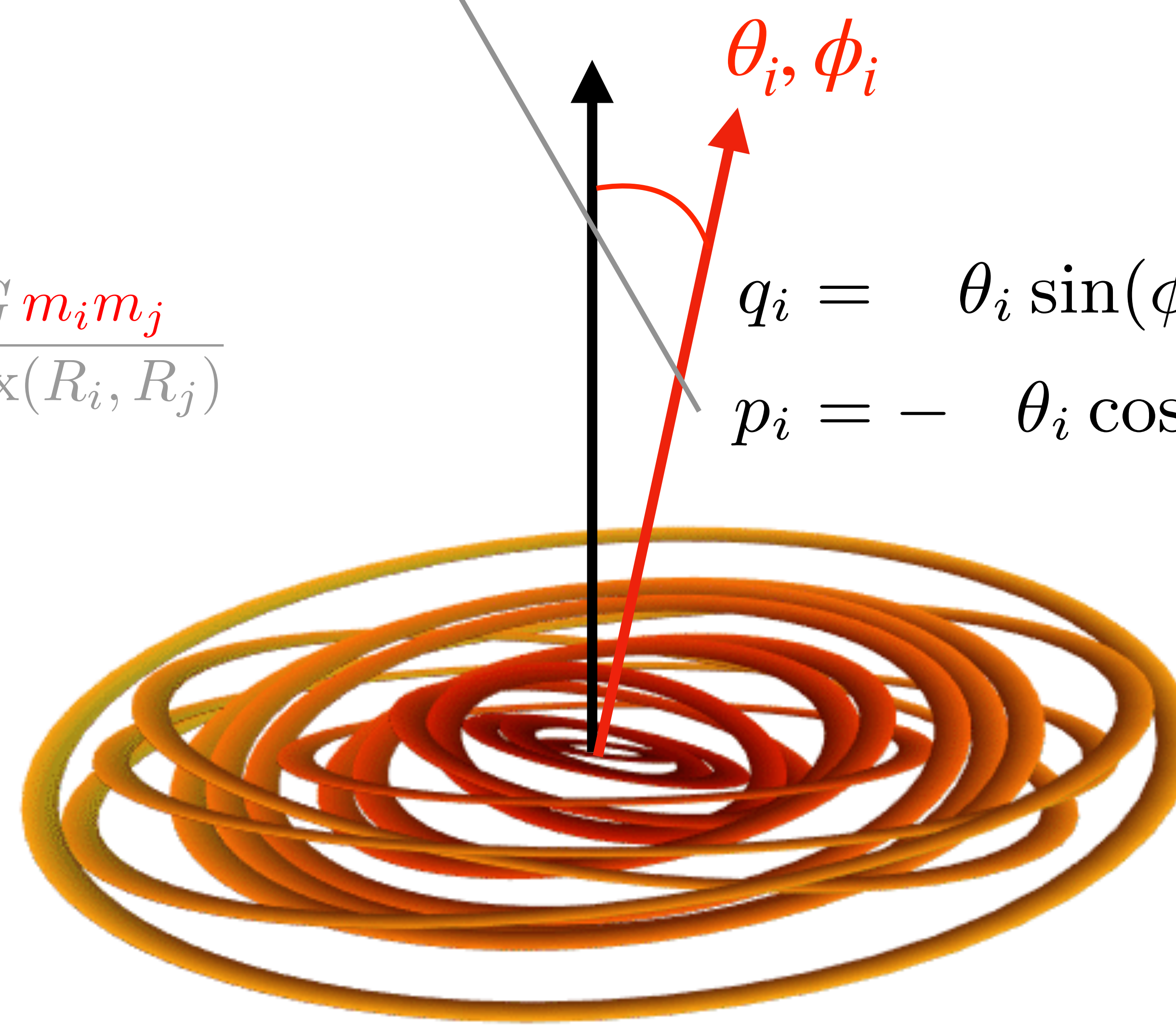
$$A_{ij} \propto -\frac{G\,m_i m_j}{\max(R_i, R_j)}$$

In eigenframe of A

Eigen frequency

$$\ddot{\hat{q}}_i + \omega_i^2(t)\hat{q}_i = \xi_i$$

forcing



$$q_i = \theta_i \sin(\phi_i)$$

$$p_i = -\theta_i \cos(\phi_i)$$

Ring Toy model: secular damping by wake growth

<u>Lagrange Laplace theory of rings</u> *(small eccentricity small inclinaison)*

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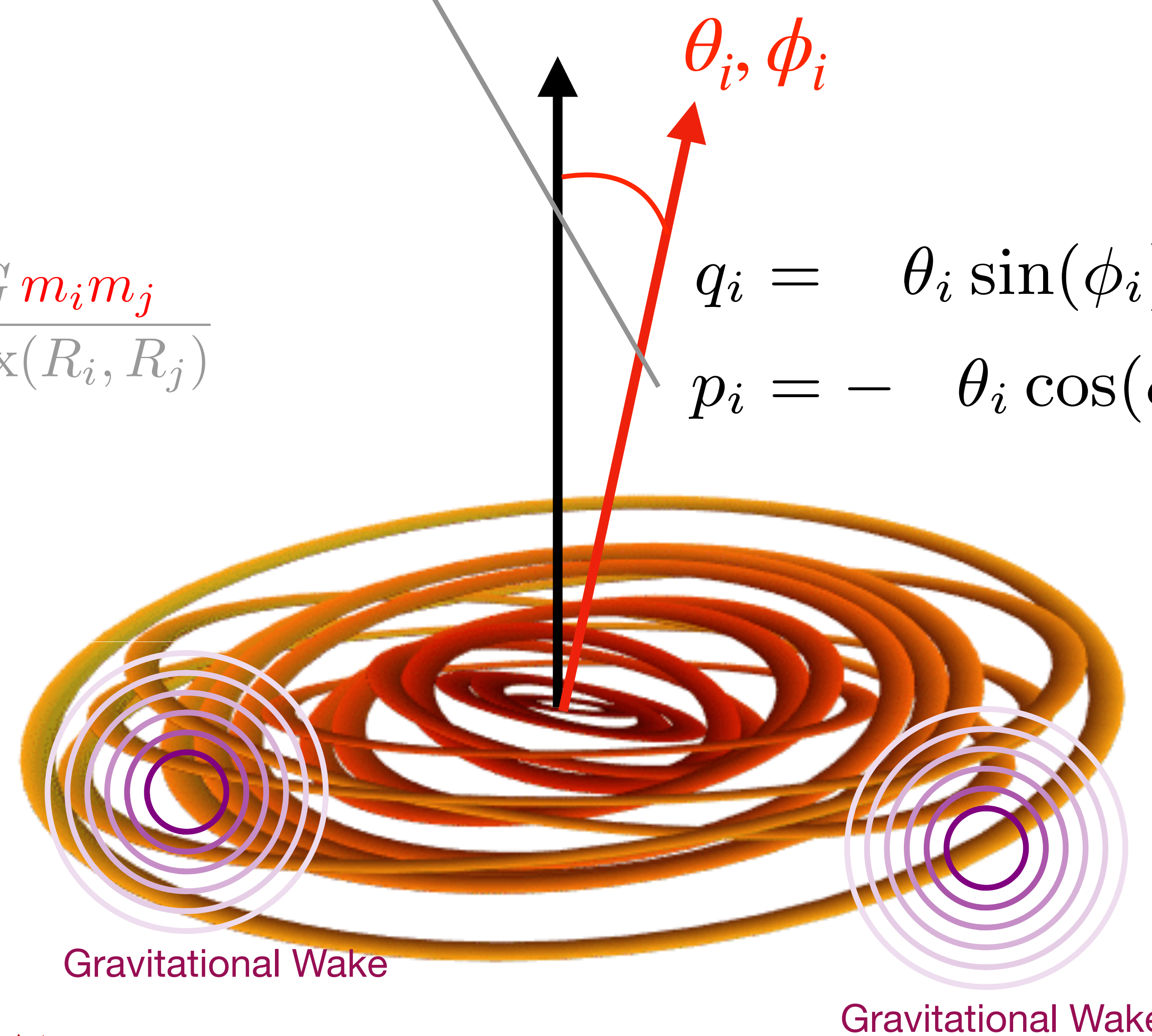

In eigenframe of A

Eigen frequency

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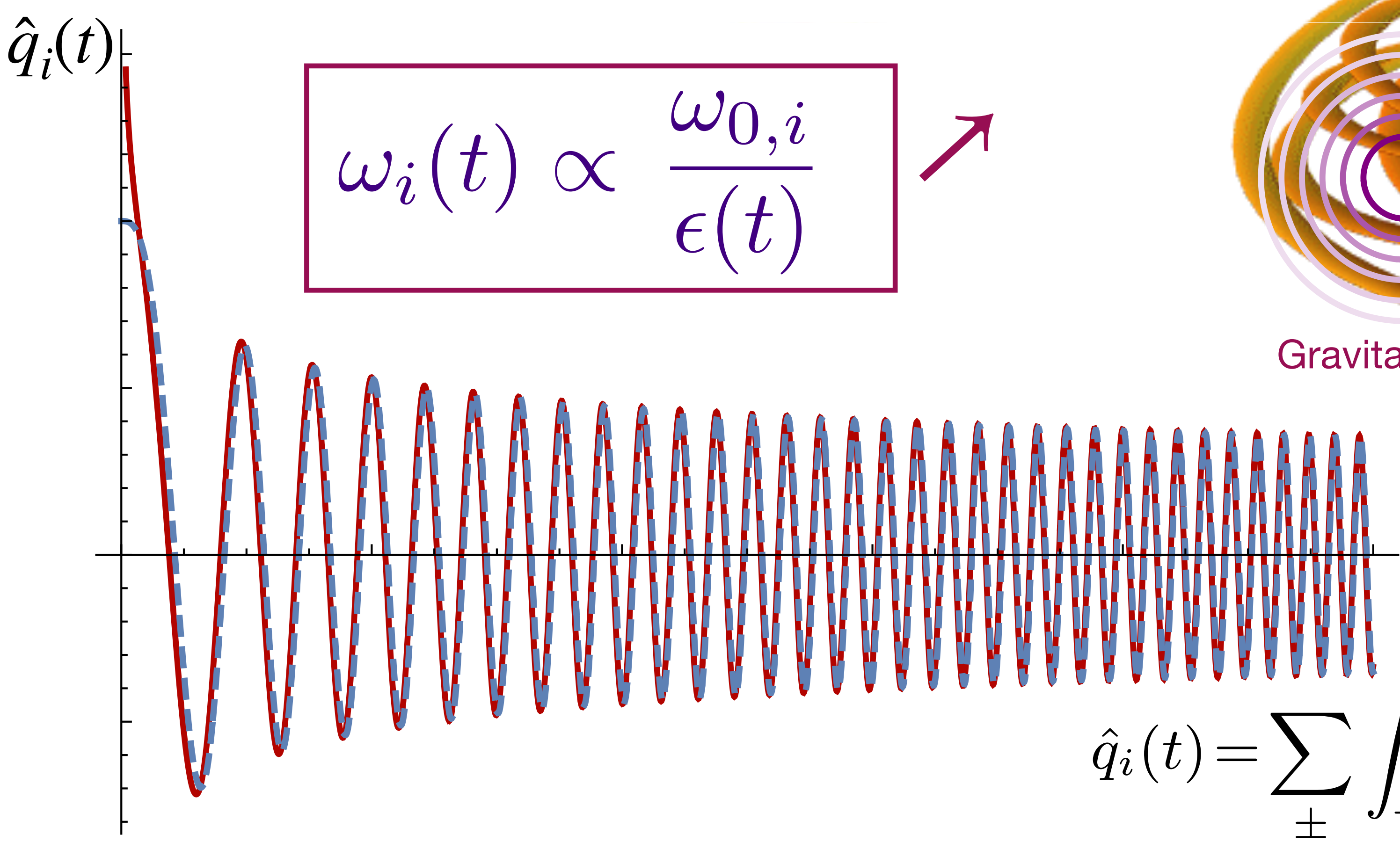
forcing

$$\omega_i(t) \propto \frac{\omega_{0,i}}{\epsilon(t)} \nearrow$$



Secular WKB solution

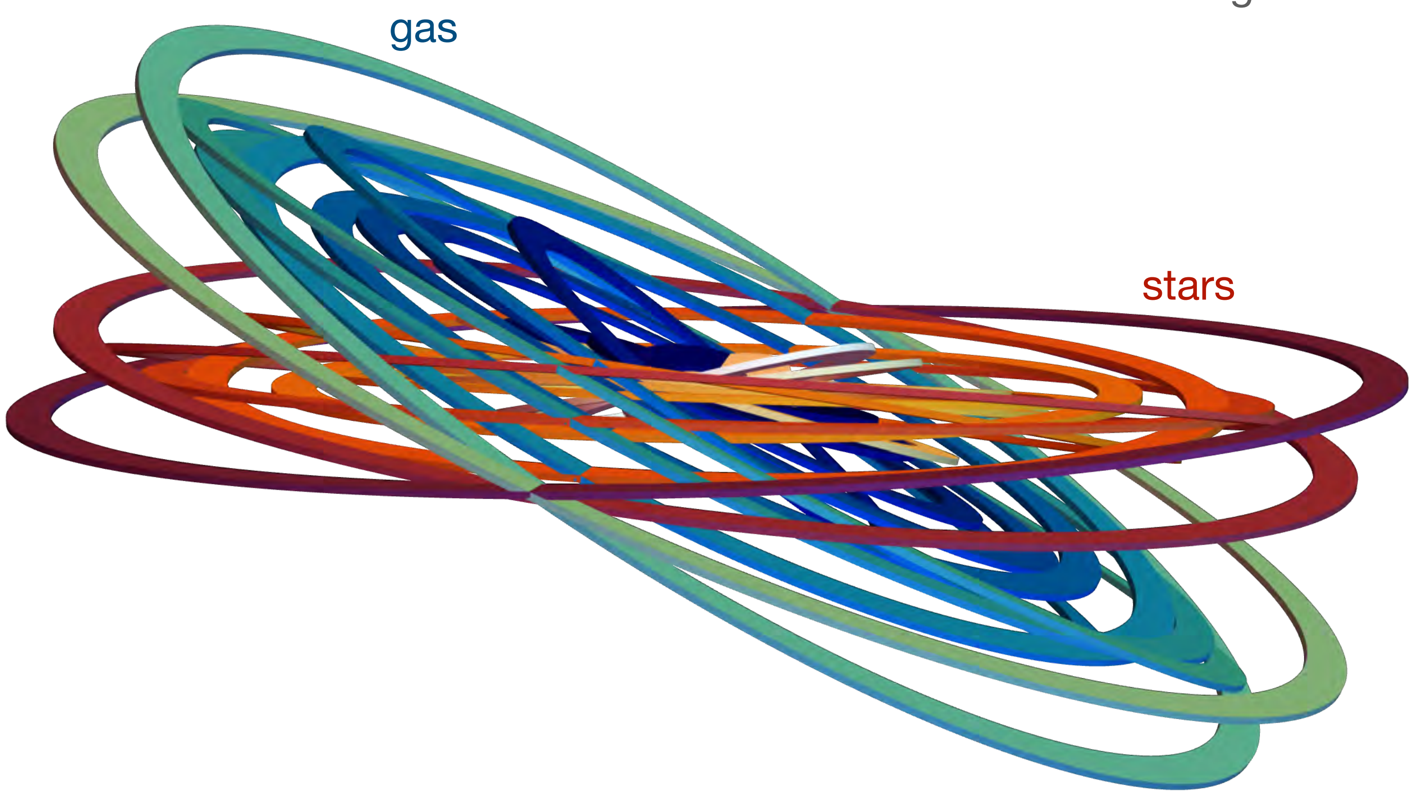
$$\hat{q}_i(t) = \sum_{\pm}\int_{-\infty}^{\infty}\frac{\hat{\xi}_i(t')}{\sqrt{\omega_i(t)\omega_i(t')}}\exp\left(\pm\imath\int_{t'}^{t}\omega_i(\tau)d\tau\right)dt'$$

Ring Toy model: gas + star coupling

gravitational coupling — damping

$$
\begin{aligned}
\ddot{q}_\star + \omega_\star^2 q_\star + \omega_{\star g}^2 q_g &= 0\,, \\
\ddot{q}_g + \omega_g^2 \hat{q}_g + \omega_{\star g}^2 q_\star + \eta \dot{q}_g &= \xi\,,
\end{aligned}
$$

forcing



See also Bertin Romeo (1988) 195, 105-113

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gravitational coupling — damping — forcing

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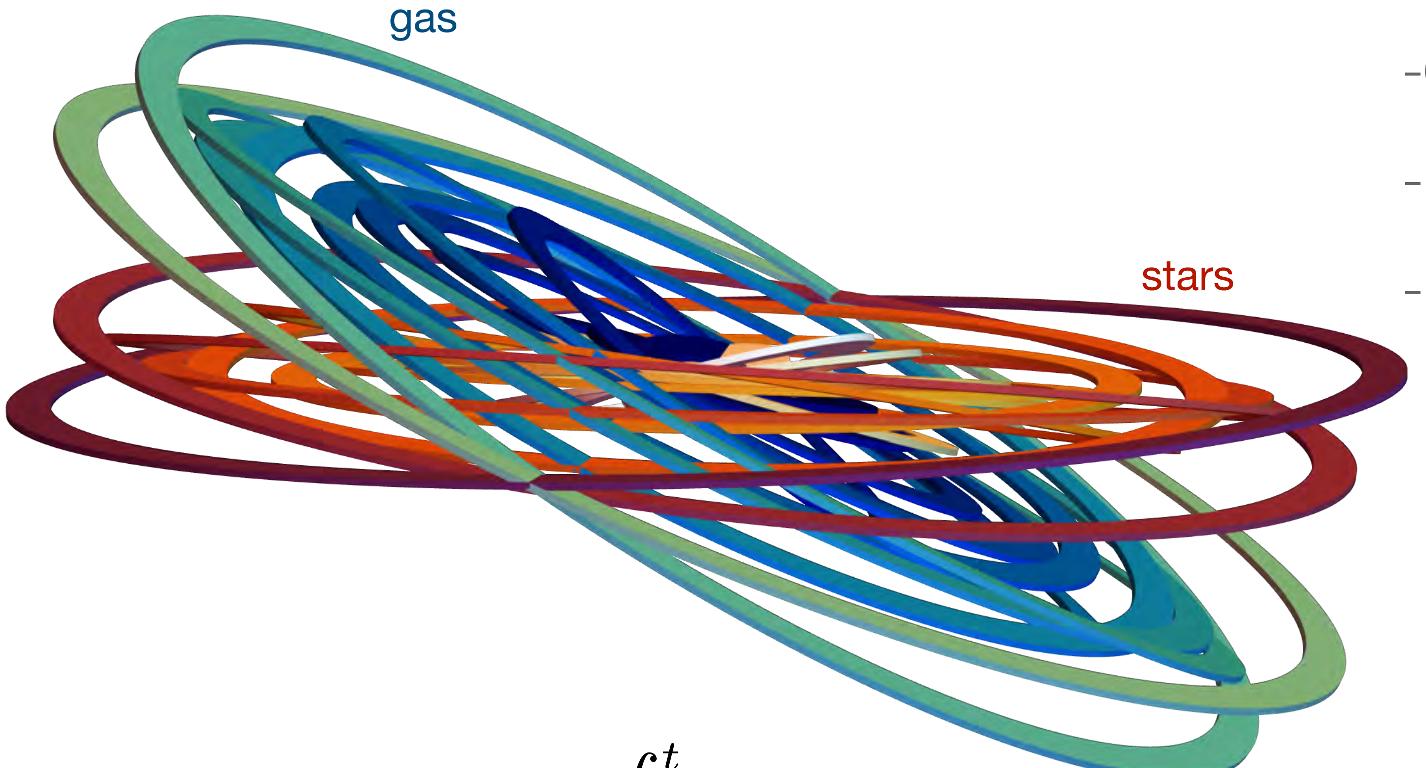
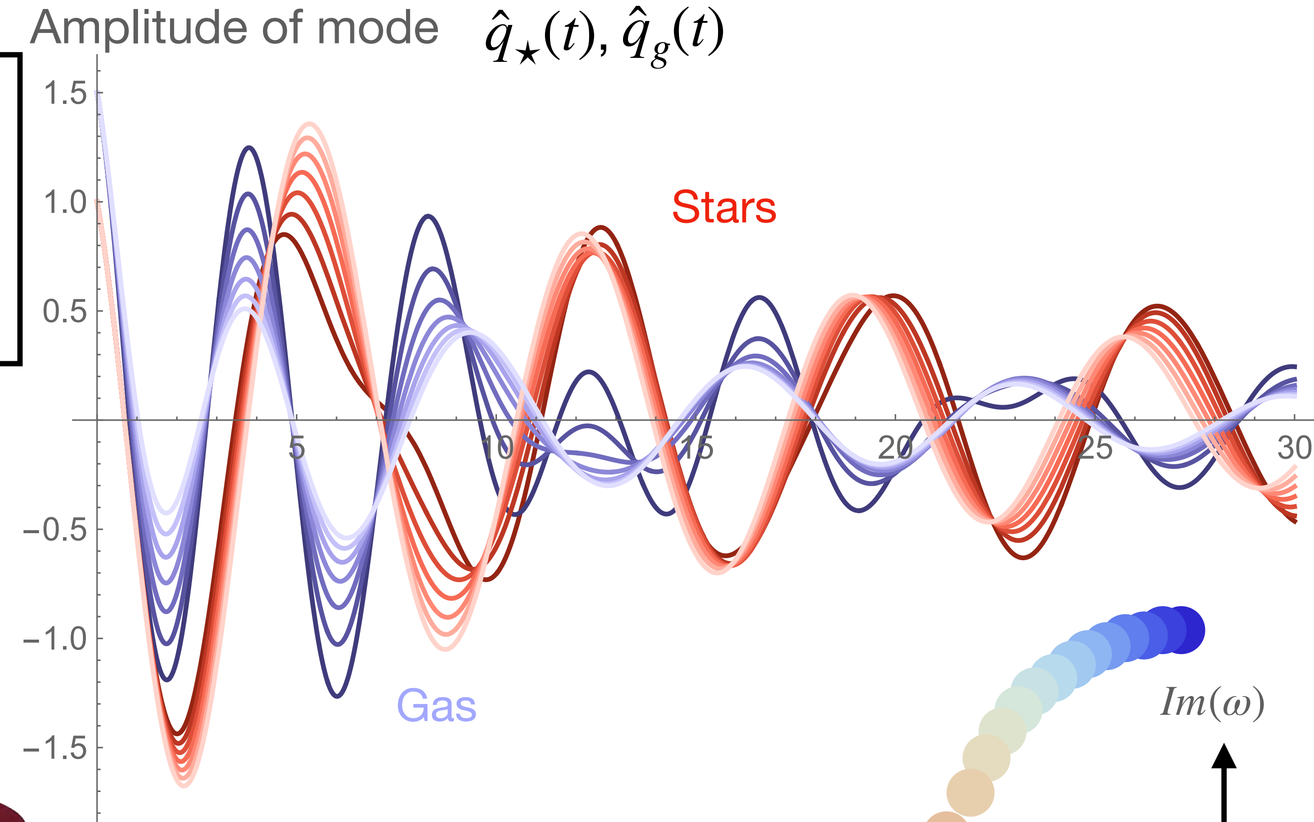
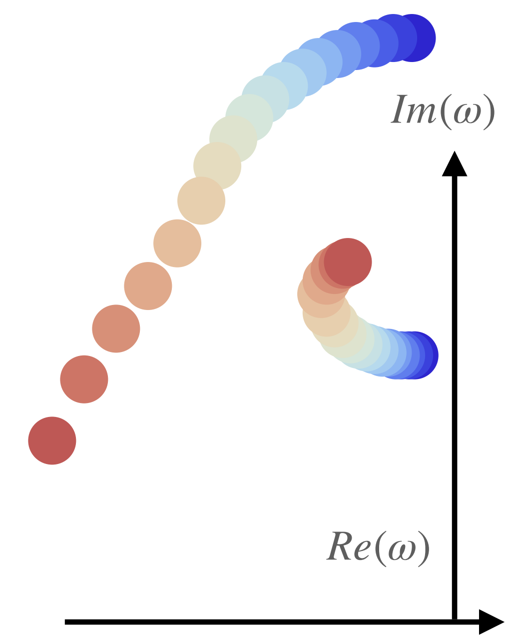


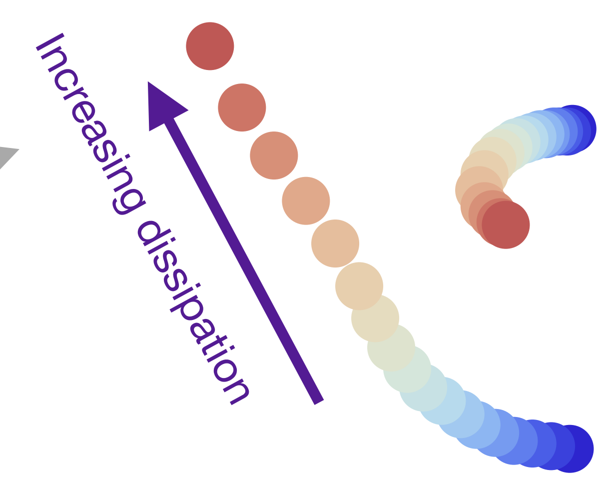


Nyquist diagram



$$q_\star(t) = -\sum_{\omega \in S_4} \frac{\omega_{g\star}^2 \int_{-\infty}^{t} \exp\left((t-\tau)\omega\right) \xi(\tau)\, d\tau}{\eta\left(3\omega^2 + \omega_\star^2\right) + 2\omega\left(2\omega^2 + \omega_g^2 + \omega_\star^2\right)}\,,$$

$$S_4 = \{\omega |\, \left(\omega^2 + \omega_\star^2\right)\left(\omega\left(\eta + \omega\right) + \omega_g^2\right) = \omega_{g\star}^4\},$$



*Dissipation in gas **also** brings down the ★ modes*

See also Bertin Romeo (1988) 195, 105-113

Impact of CGM growth

<u>Lagrange Laplace theory of rings</u> *(small eccentricity small inclinaison)*

x and y components of **angular momentum**

$$H(\mathbf{p},\mathbf{q}) = \frac{1}{2}\mathbf{p}^{\mathrm{T}}\cdot\mathbf{A}\cdot\mathbf{p} + \frac{1}{2}\mathbf{q}^{\mathrm{T}}\cdot\mathbf{A}\cdot\mathbf{q}\,,$$

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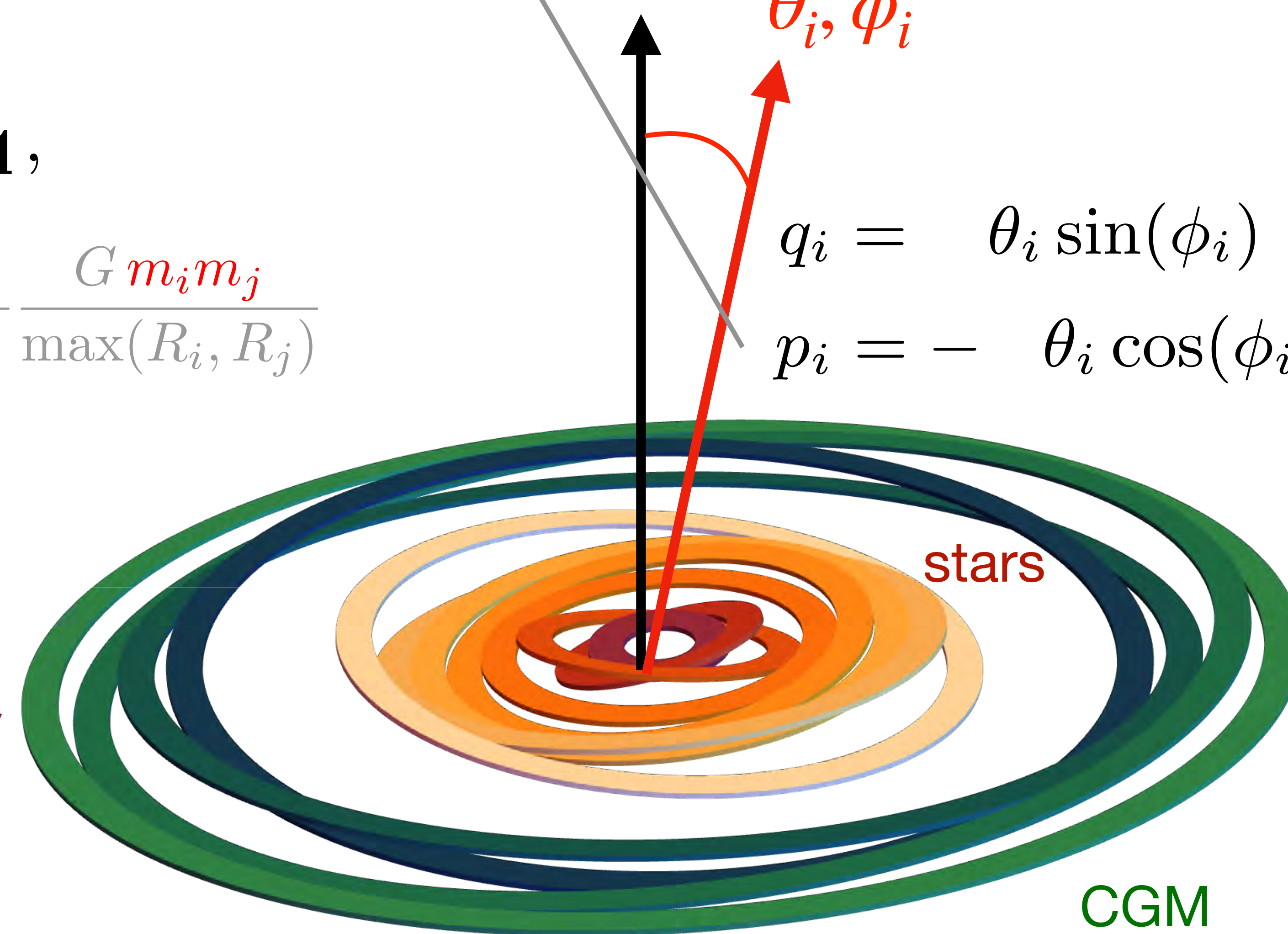


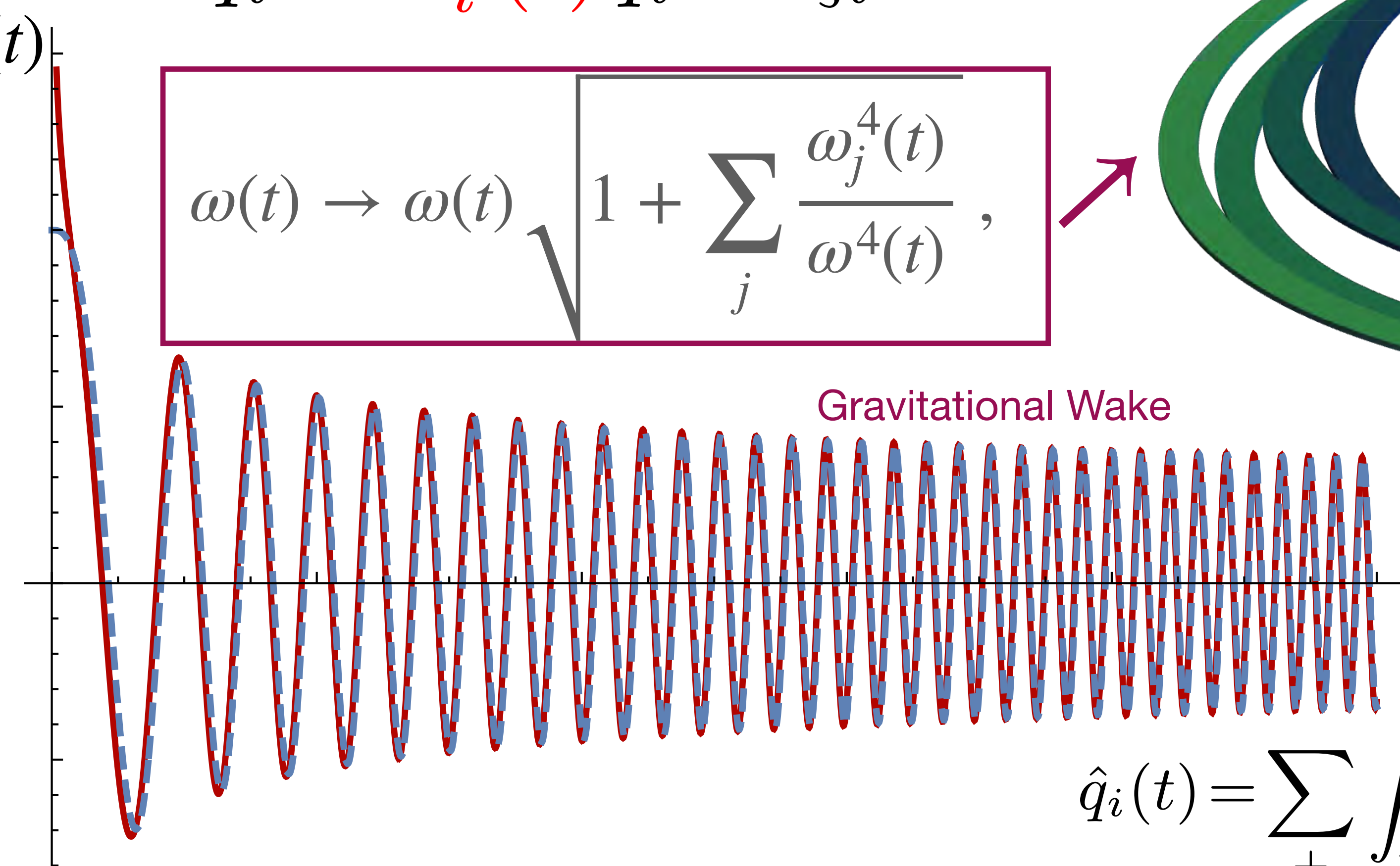
In eigenframe of A

Eigen frequency

$$\ddot{\hat{q}}_i + \omega_i^2(t)\hat{q}_i = \xi_i$$

forcing

$$\omega(t) \to \omega(t)\sqrt{1 + \sum_j \frac{\omega_j^4(t)}{\omega^4(t)}}\,,$$



Secular WKB solution

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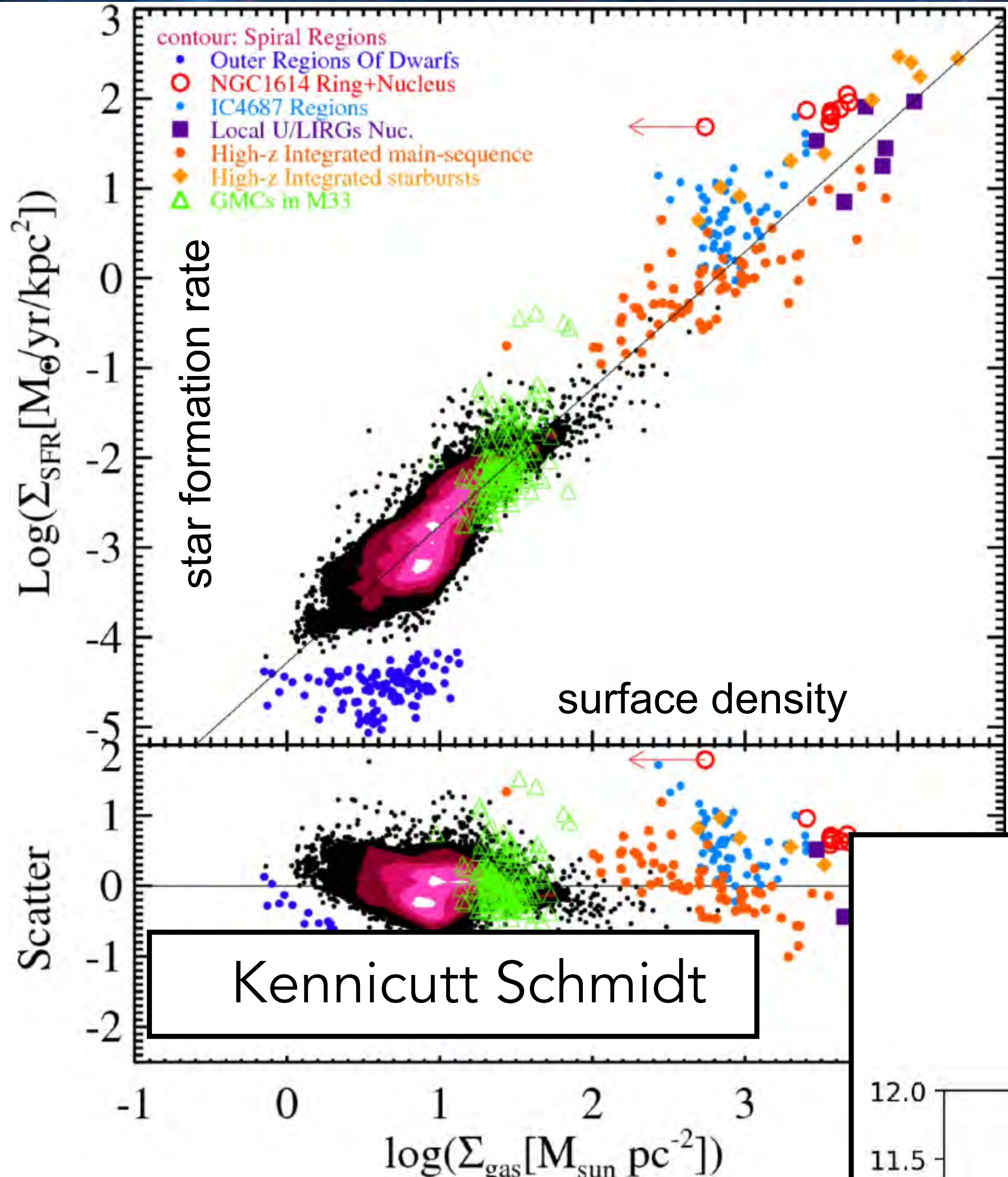
*Growth of CGM component **also** brings down the ★ modes*

Scaling laws & Q=1 : origin of tight relations?



Kim Ostriker (2007)

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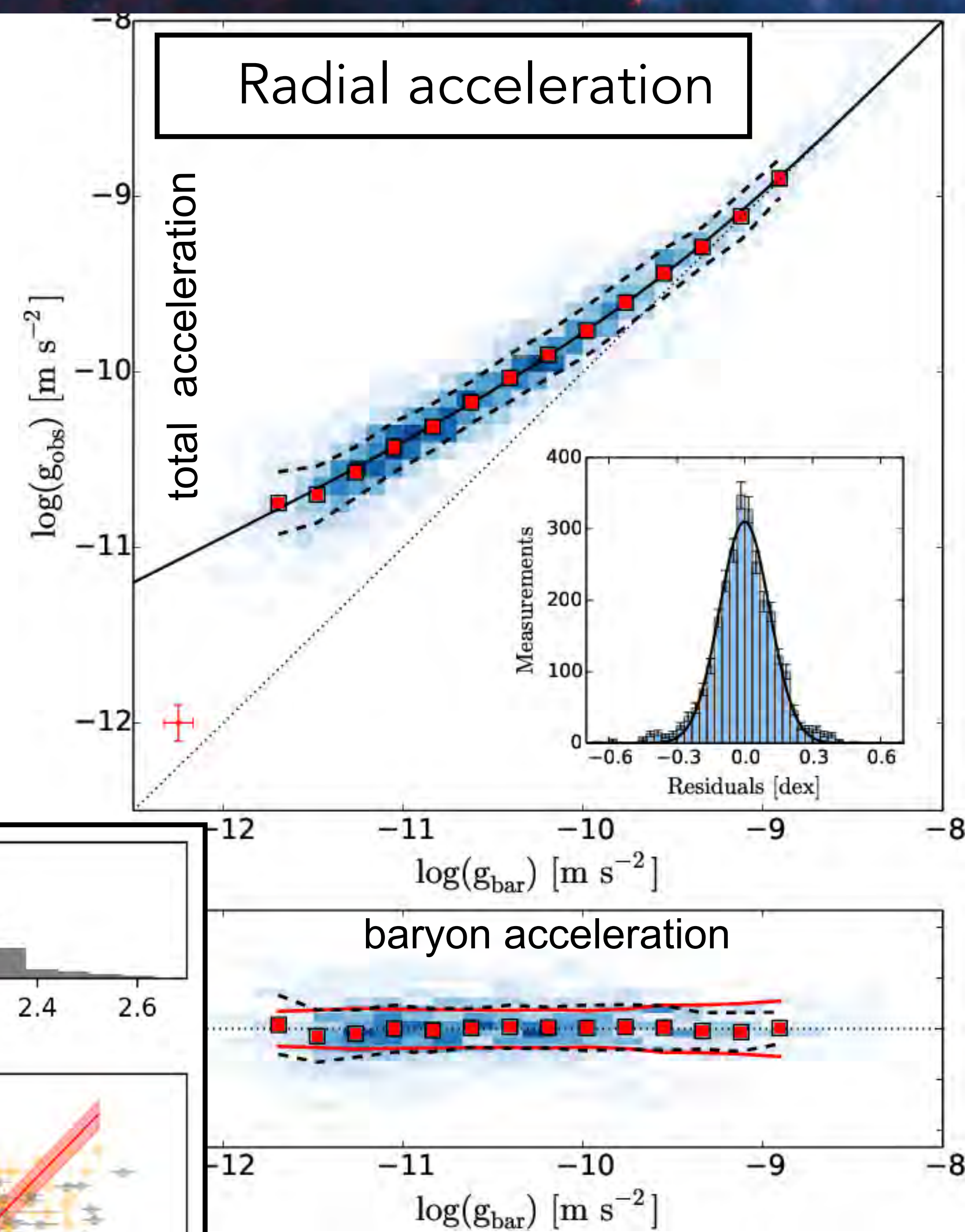
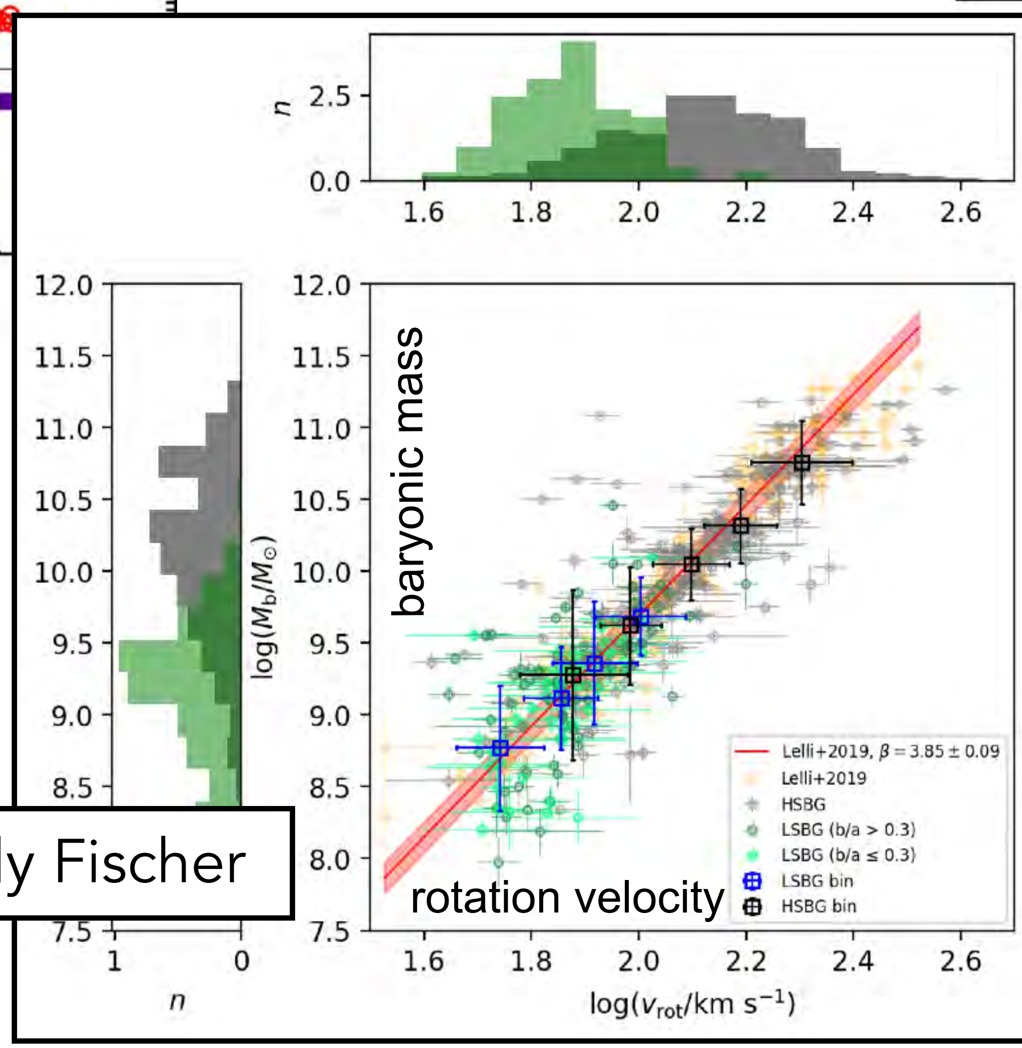
Tight Q~1 ⇒ Tight scaling relations



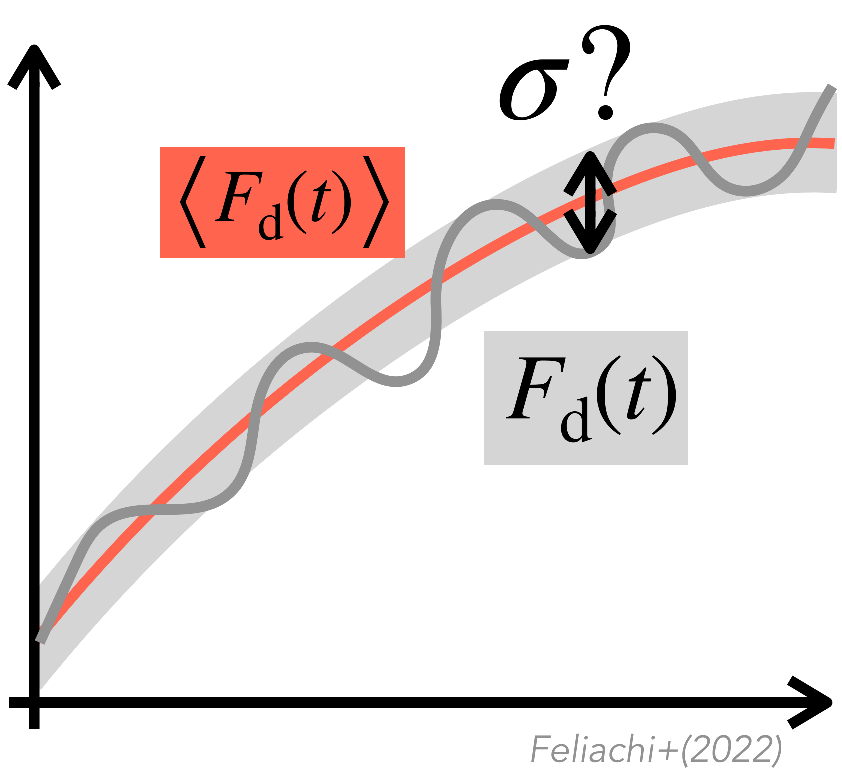


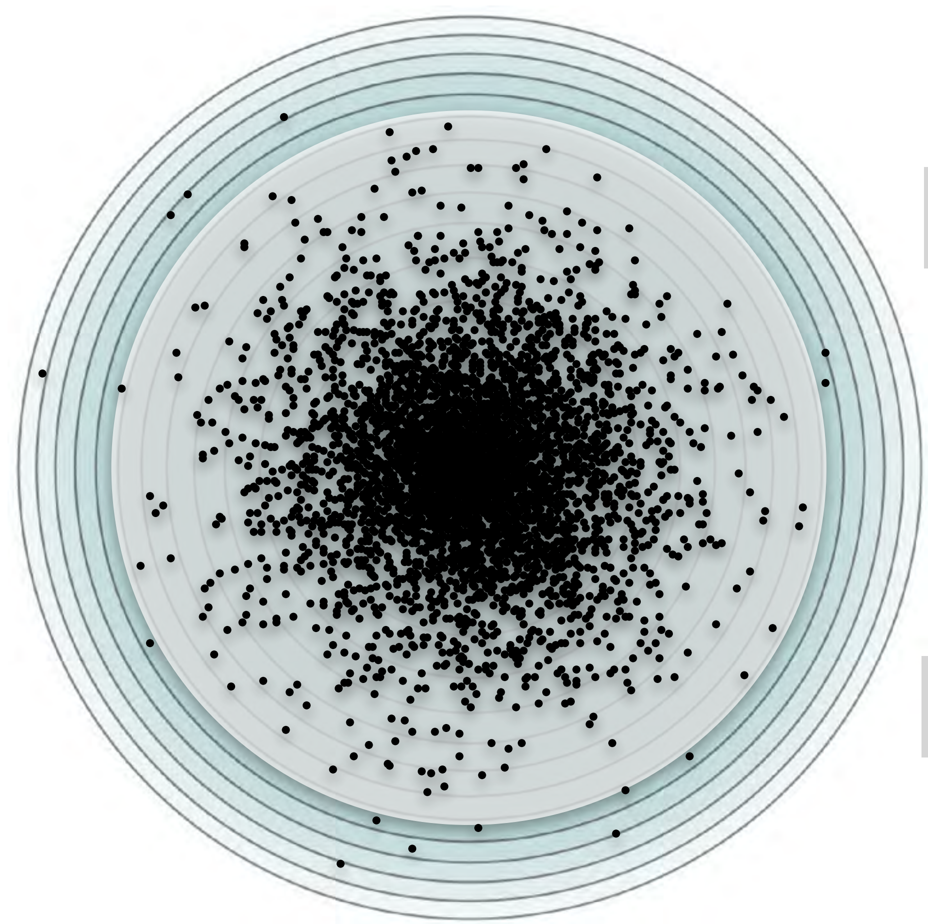
Access **full statistics** in the (least rare) small perturbation regime through **cumulant generating function**

$$\Phi[H] = \log\Bigg(\Bigg\langle \underbrace{\frac{\partial F_{\rm d}}{\partial t} + [F_{\rm d}, H_{\rm d}] = 0}_{\text{Exact Klimontovich equation}} + \underbrace{\begin{matrix} F_{\rm d} = F + \delta F \\ H_{\rm d} = H + \delta H \end{matrix}}_{\text{Perturbative expansion}} \times \exp\left(\int \mathrm{d}t\, \dot{F}_d\, H\right) \Bigg\rangle\Bigg)$$

Exact **Klimontovich** equation

Perturbative expansion





Weighted **Stack**

Predict **variance**

IN PROGRESS

Quantify tightness of scaling relations

CONCLUSIONS

Robust *gravity-driven* top-down causation : no fine tuning required

gravity-driven baryonic processes operate on **multiple anisotropic** scales, working to **spontaneously** set up a remarkably efficient level of **self-regulation**.

This regulation is responsible for disc emergence/resilience & the **tightness** of observed scaling laws (KS,bTF,RAR).

- recent perturbative modelling explains half of the loop;
- current efforts involve
  - → extend kinetic theory to sourced dissipative regime.
  - → model excursion using large deviation theory

CONCLUSIONS

Robust *gravity-driven* top-down causation : no fine tuning required

On galactic scales, the shape of initial powerspectrum is such that galaxies inherit **stability** from non-linear scale coupling to the LSS via cold flows, which sets up the circumgalactic engine.

When secular processes take over, gravitational **wakes** tightens a self-regulating loop, driving the discs towards marginal stability, while pumping free rotational energy from the CGM.

Homeostatic thin disks are **emerging** structures: They are made possible by shocks, star formation, feedback & turbulence controlled by **gravity**.

when the control loop fails → quantify morphological diversity

Merci !

Complement: is a disc alive? vaguely!

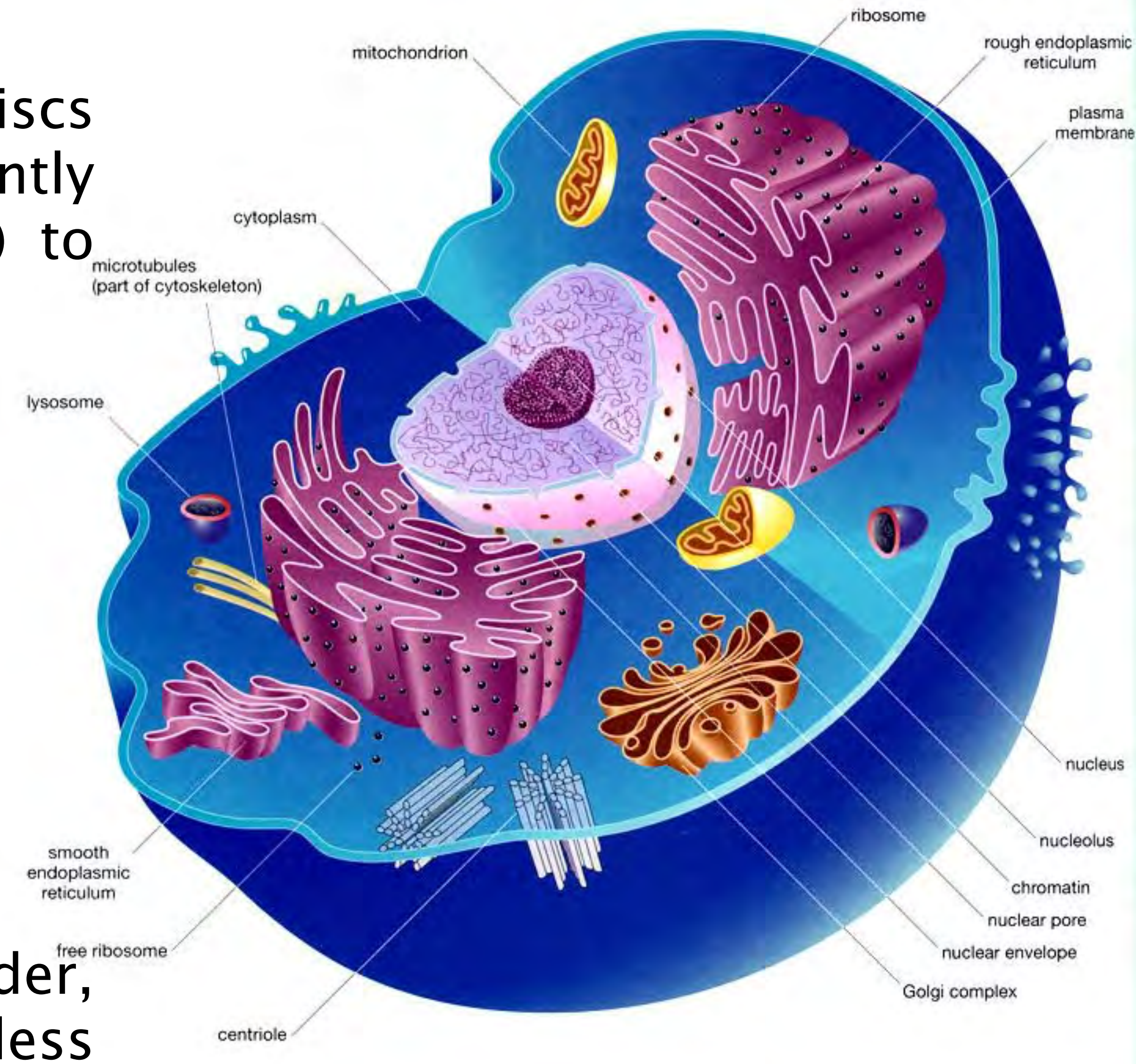
Interestingly, though anecdotical, the thin discs possesses at least three out of four pillars recently required by some authors (Wong & Bartlett 2020) to define **pre-biotic systems**:

i) they are open dissipative structures;

ii) auto-catalytic;

iii) homeostatic,

iv) but not (quite) learning.

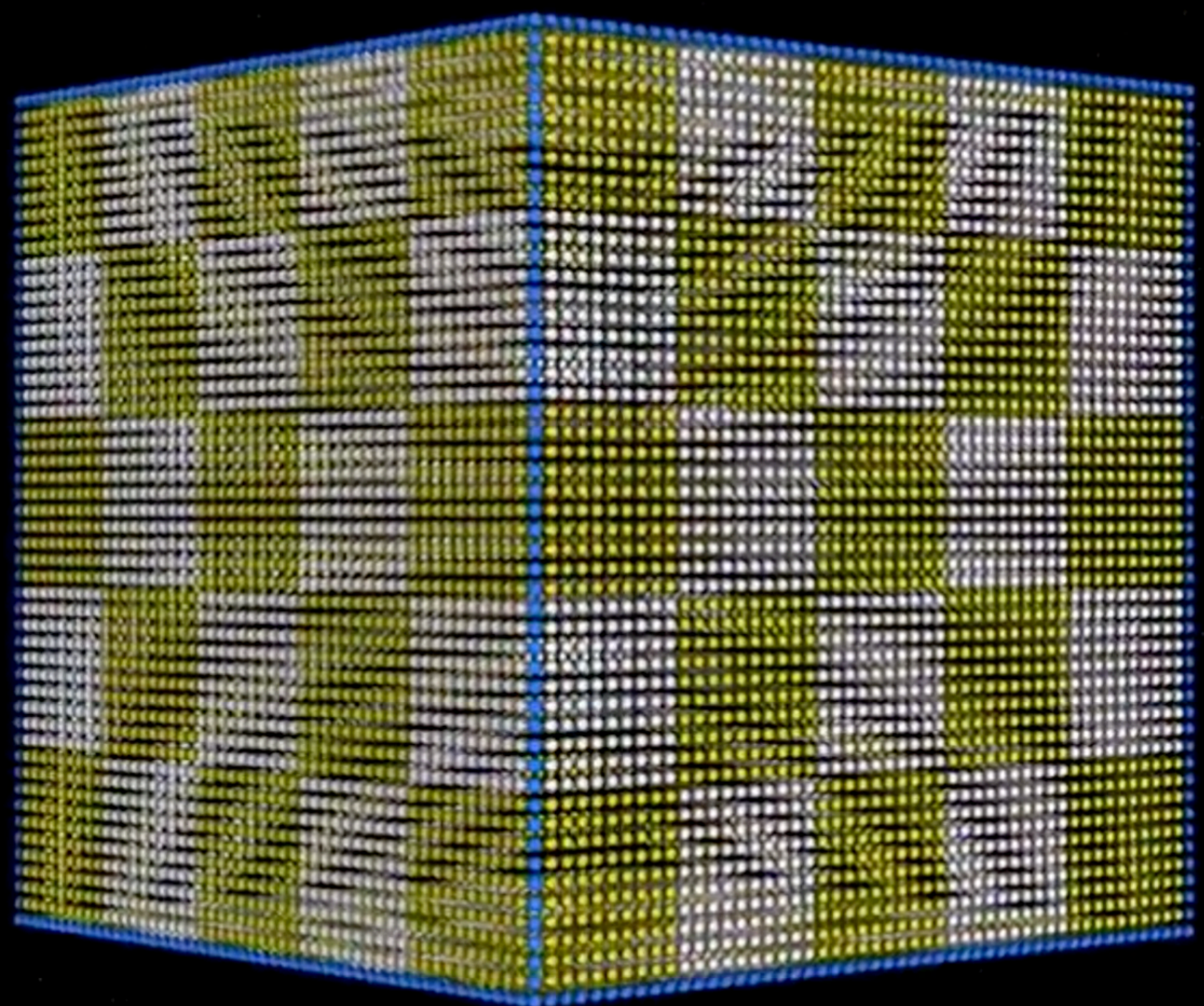


May be in a **neg-entropic** (information) sense:

as the stellar disc grows, it accumulates (stellar) order, which makes its **effective** Toomre parameter less sensitive to the environment: it has **learnt**!

Attractor for dissipative systems

$$\frac{dx}{dt} = \sigma(y - x) \quad \frac{dy}{dt} = x(\rho - z) - y \quad \frac{dz}{dt} = xy - \beta z$$



Lorenz attractor

https://www.youtube.com/watch?v=aAJkLh76QnM

Attractor for dissipative systems

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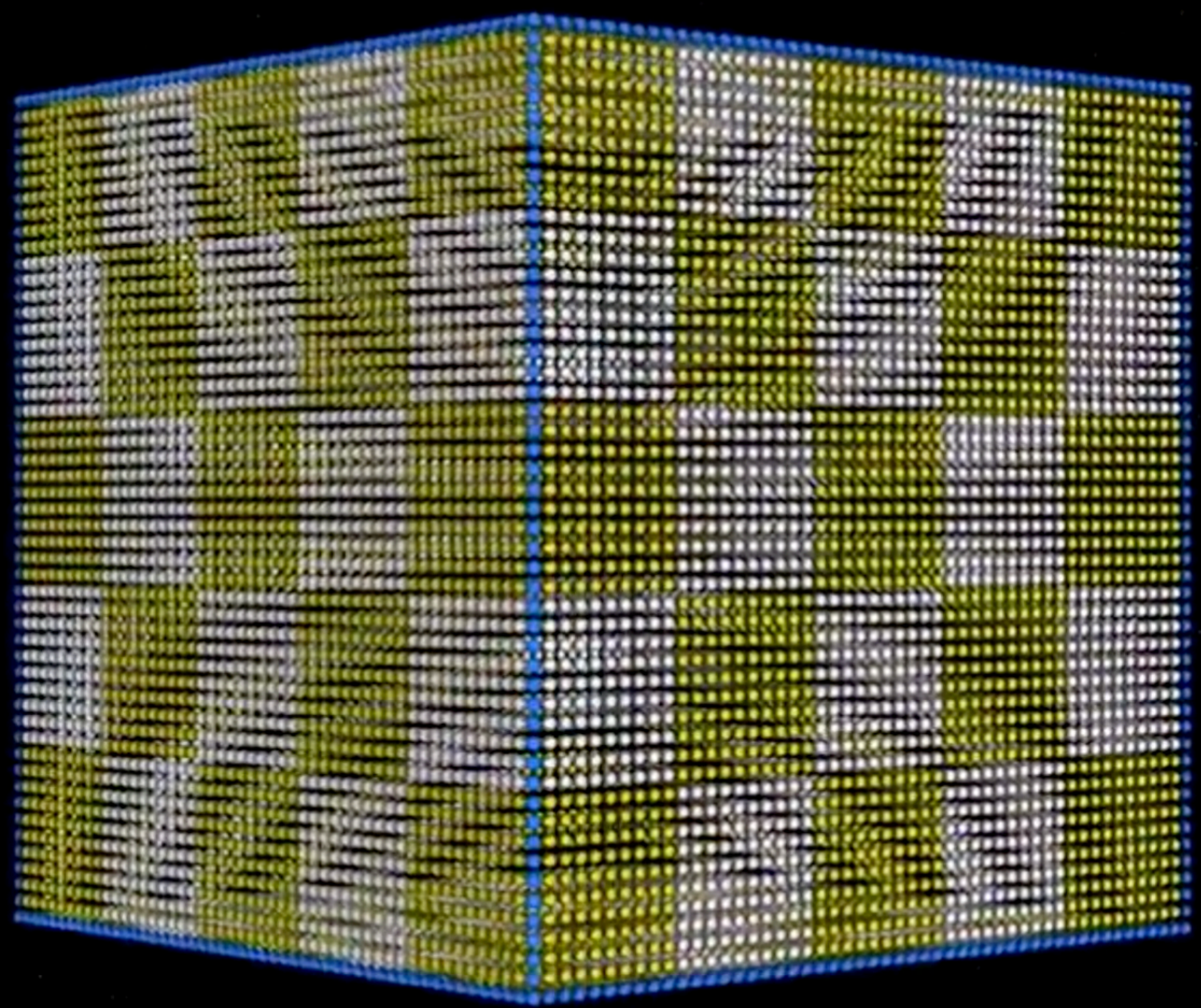
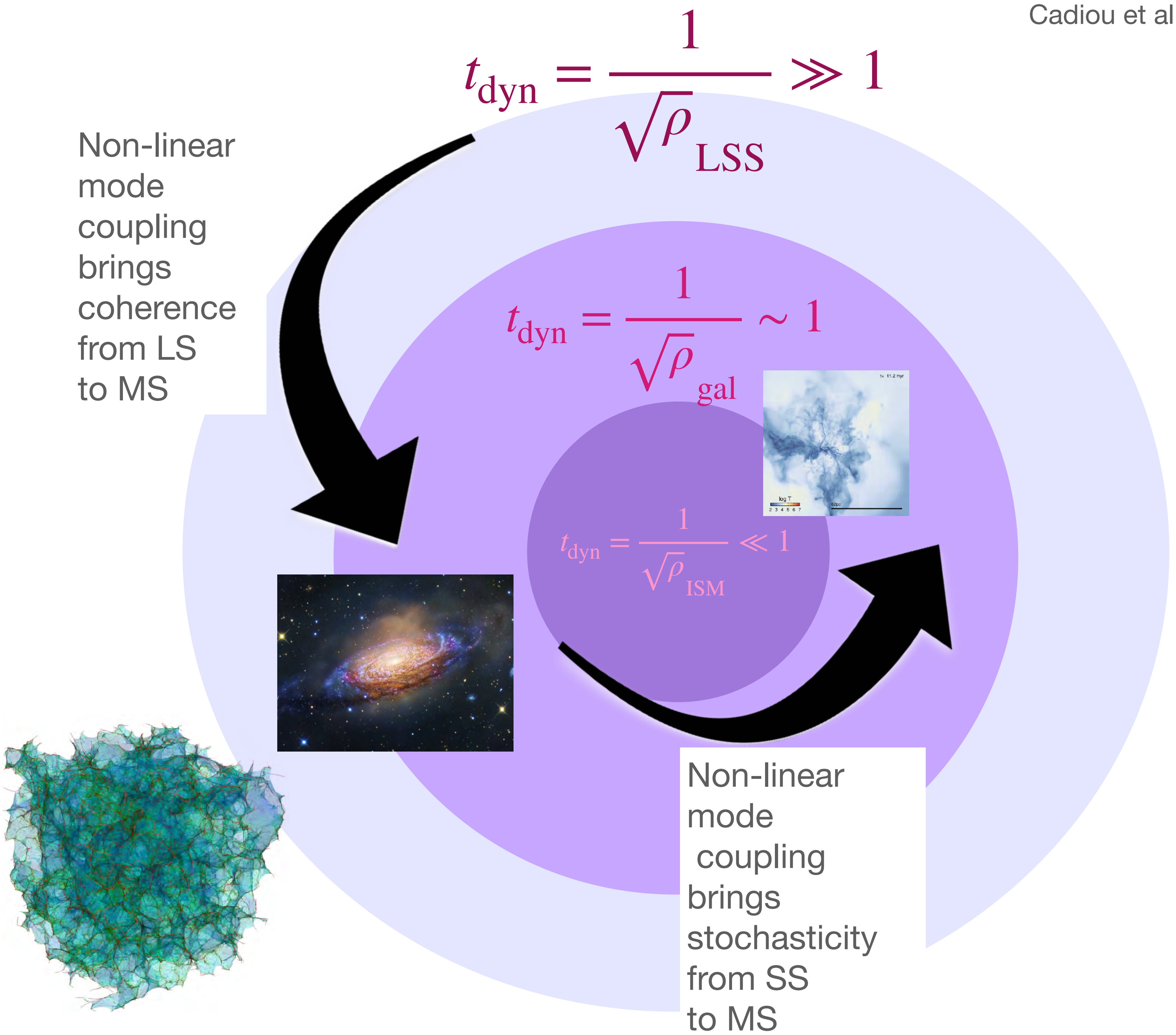


Lorenz attractor

https://www.youtube.com/watch?v=aAJkLh76QnM

Galaxies are multi-scale non-linearly asymmetrically coupled systems

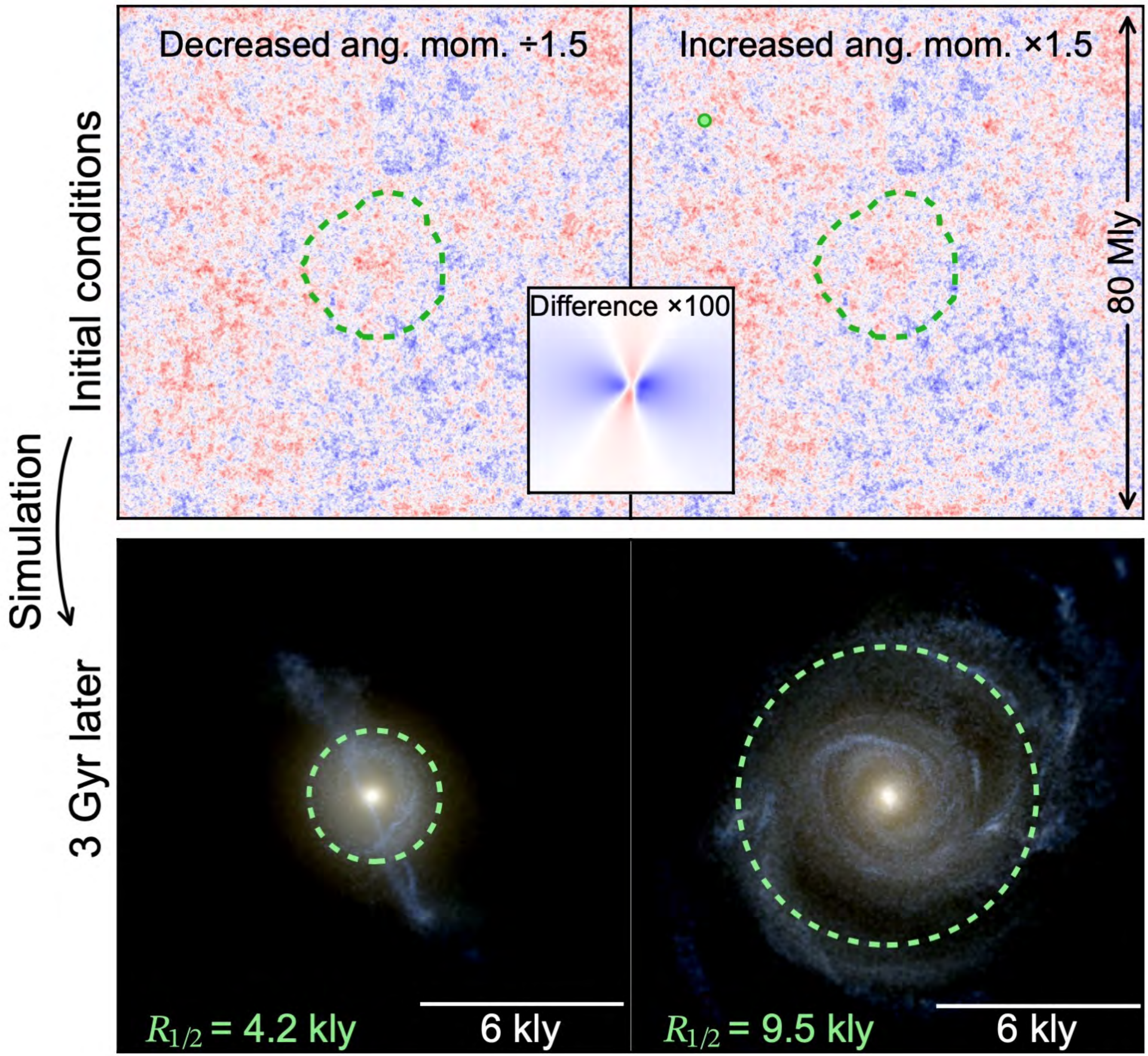
Cadiou et al 2023



Why (naive) subgrid physics is a bad idea…

Galaxies are multi-scale non-linearly asymmetrically coupled systems

Cadiou et al 2023



Why Secular Dynamics?

What happens to stable self-gravitating galactic discs on a Hubble time?

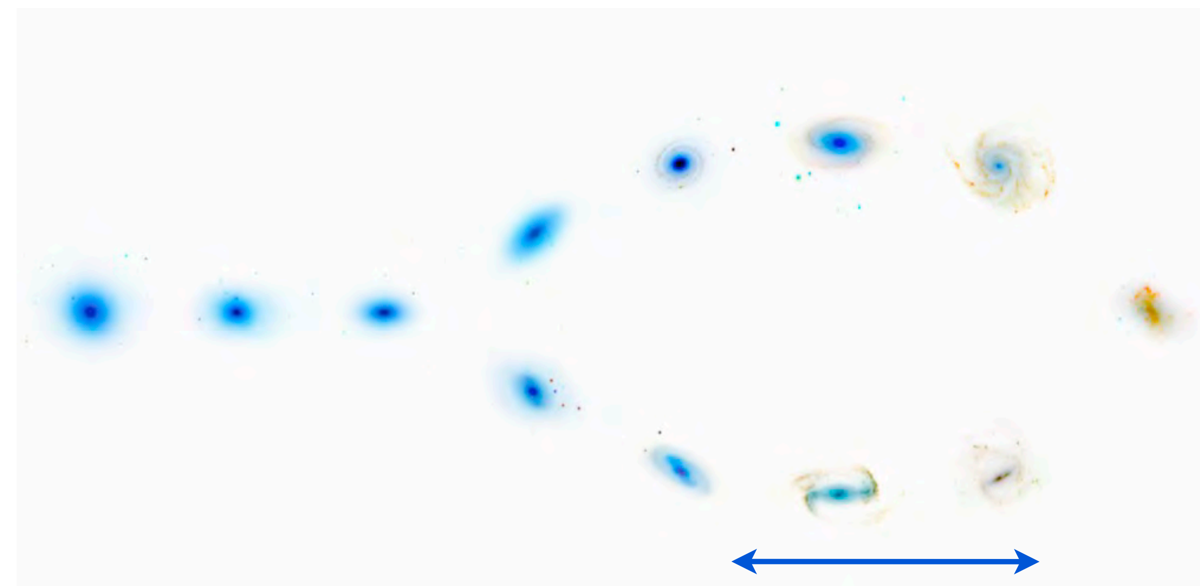
How does a galaxy respond

- *to its environment?* Nurture

  Dressed Fokker Planck diffusion

- *to its internal graininess?* Nature

  Balescu-Lenard diffusion



Move along Hubble Fork

- *Which process matters most on cosmic timescales?*

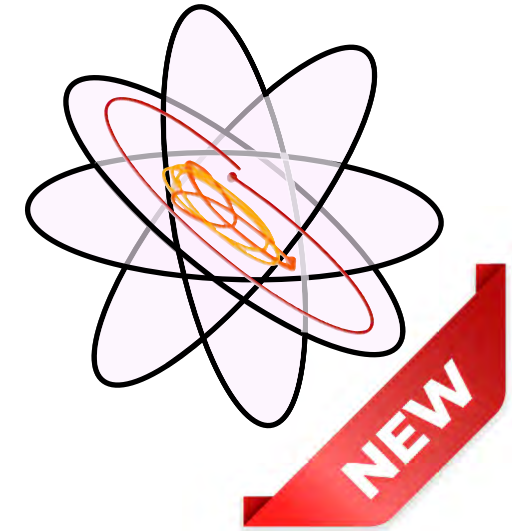
Of interest for galactic chemodynamics (GAIA), Galactic Centre, planetesimals, DM haloes...

Provide quasi-linear theories accounting for non-linear gravity for $t \gg t_{\rm dyn}$

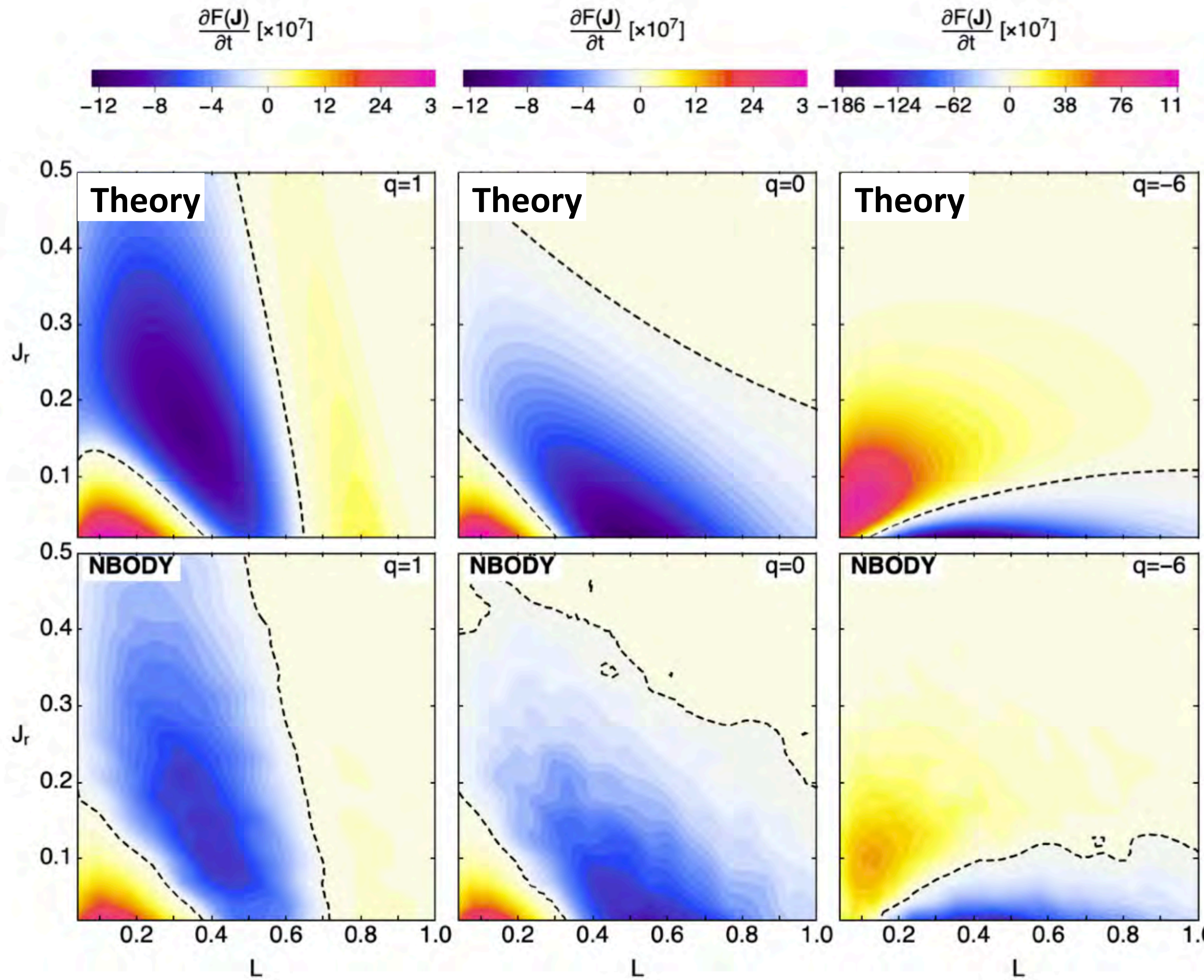
- **Resonant** effects $\Longrightarrow$ **Secular evolution**

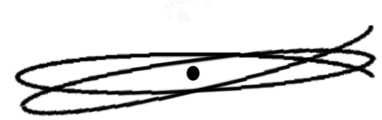
What happens to **orbital structures** on **cosmic age**?

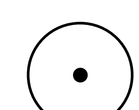
Dynamically hot systems : impact of **anisotropy**



$$\partial F/\partial t$$

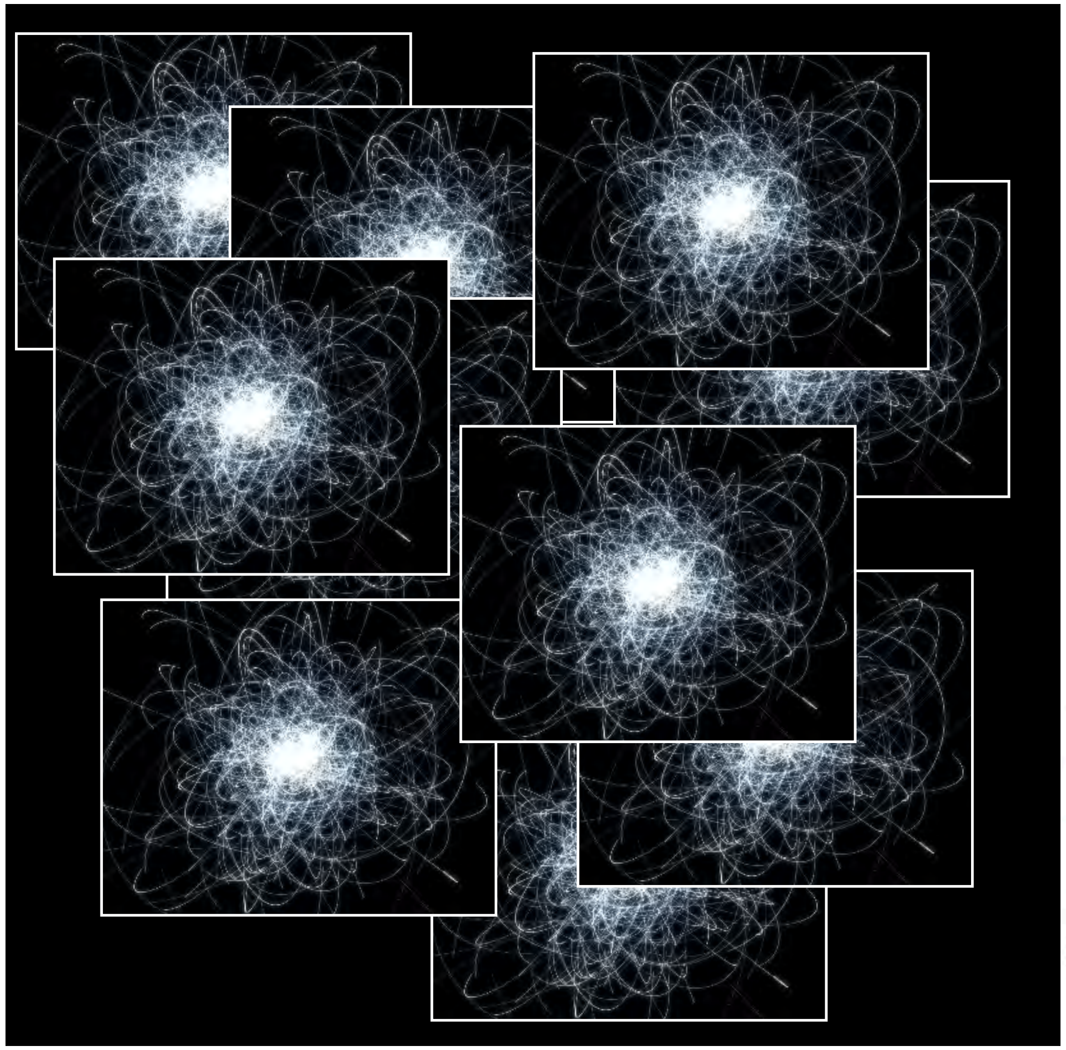


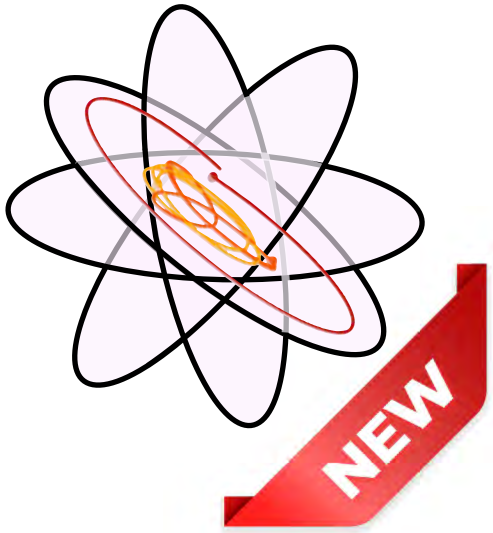




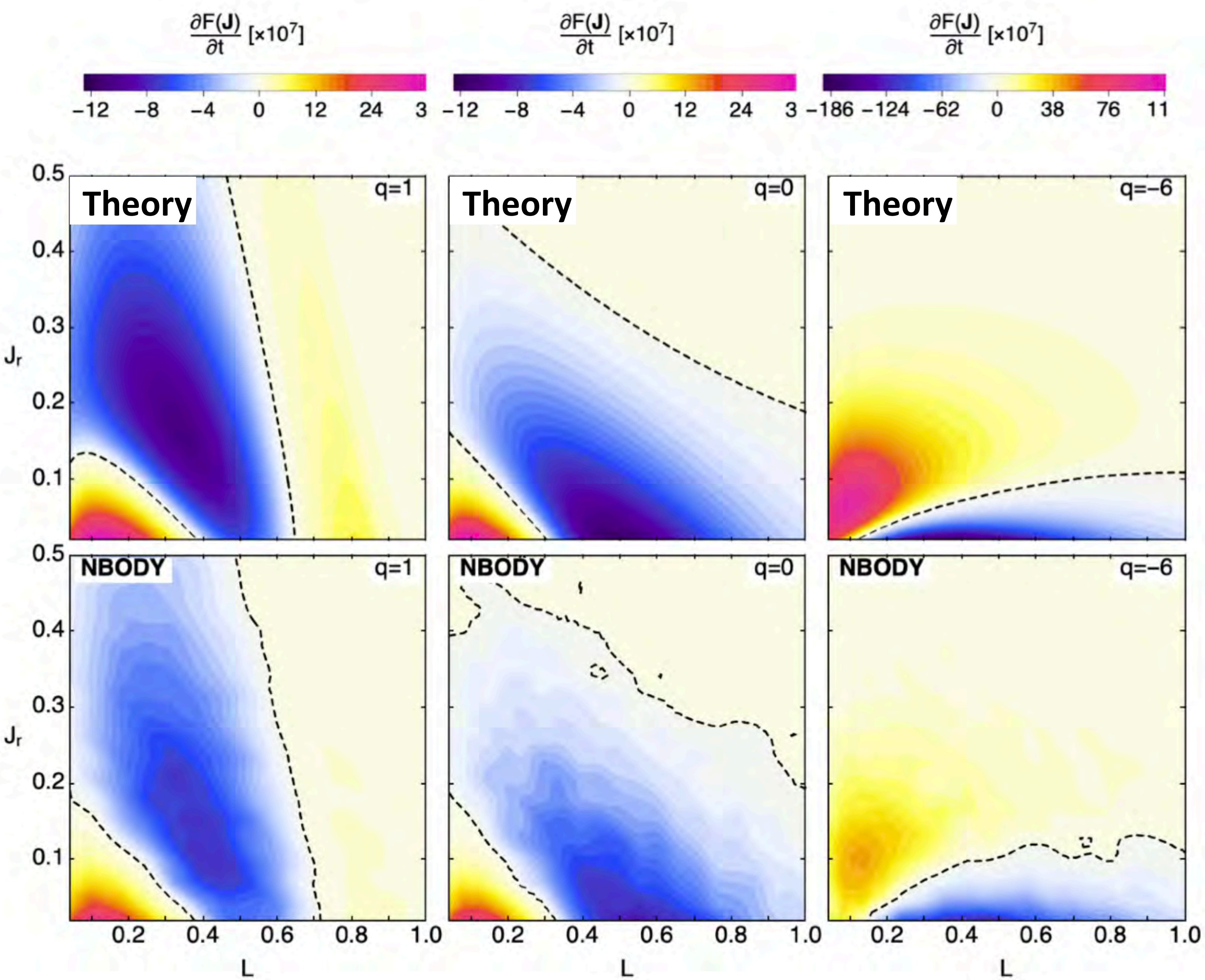
Tep+(24)

Dynamically hot systems : impact of **anisotropy**

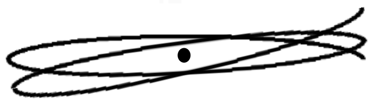


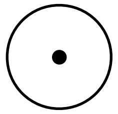


$\partial F/\partial t$



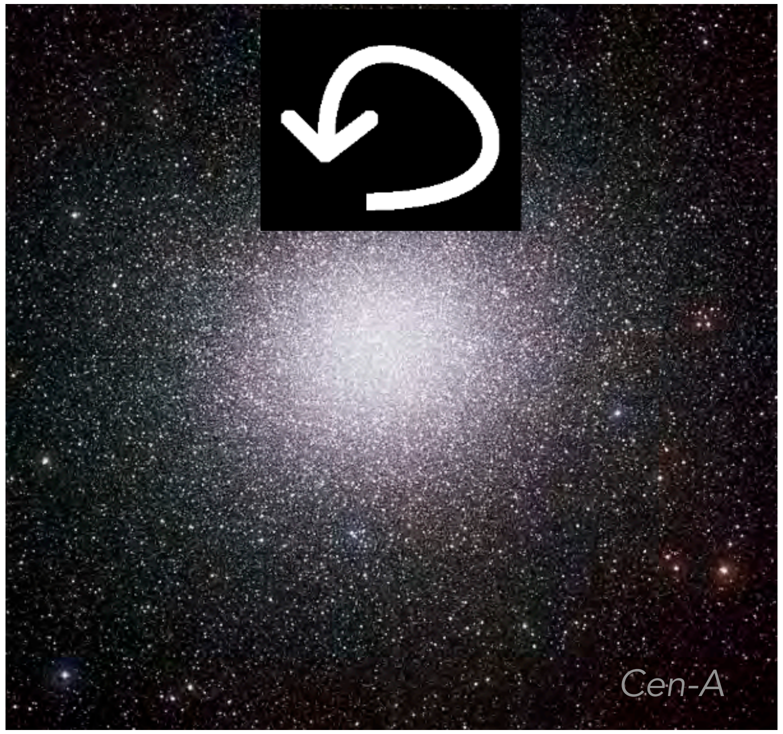
average over 100 simulations

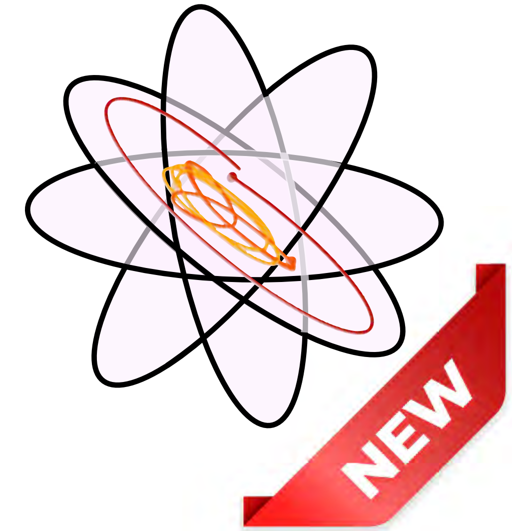




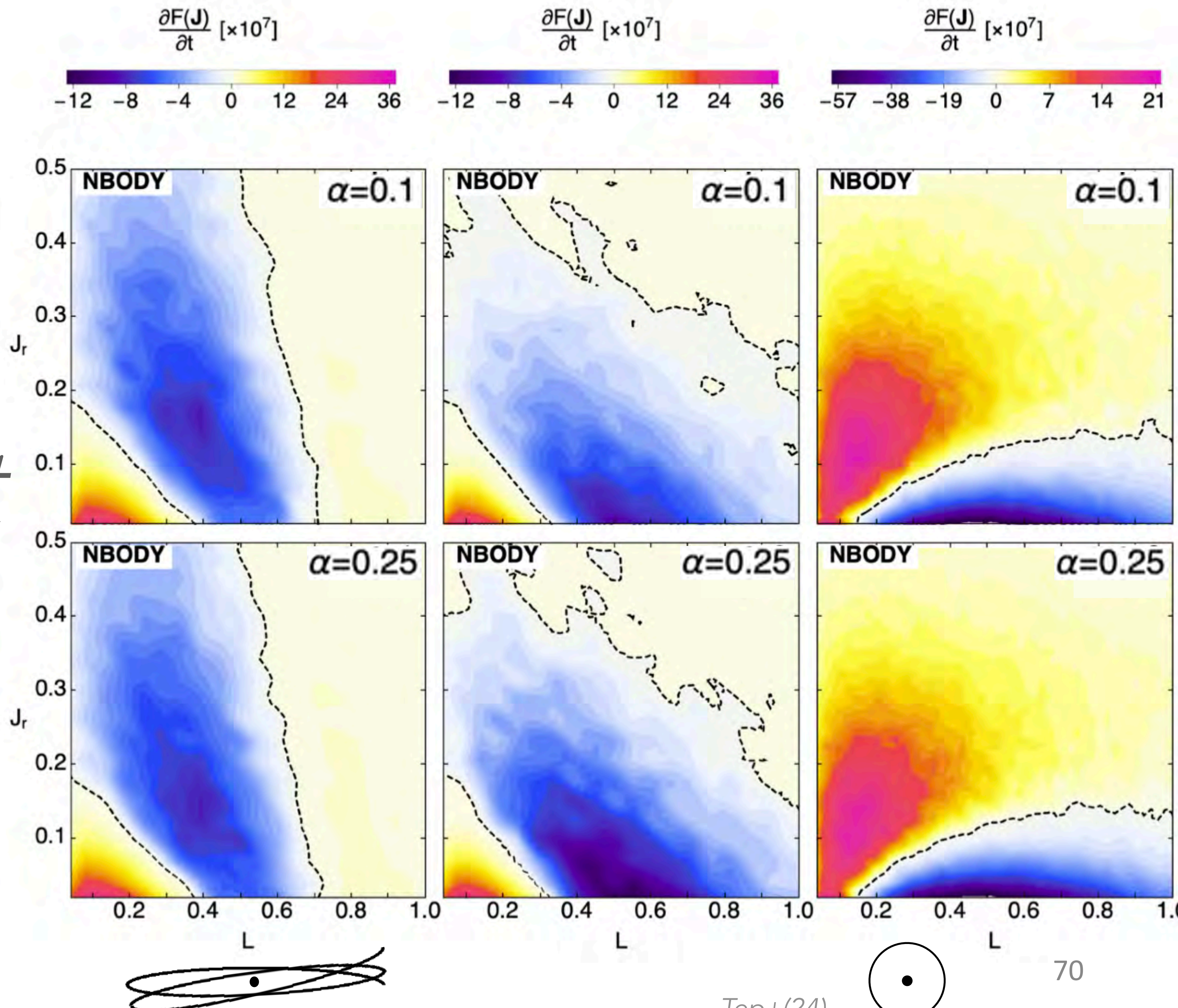
Tep+(24)

Dynamically hot systems : impact of **rotation**





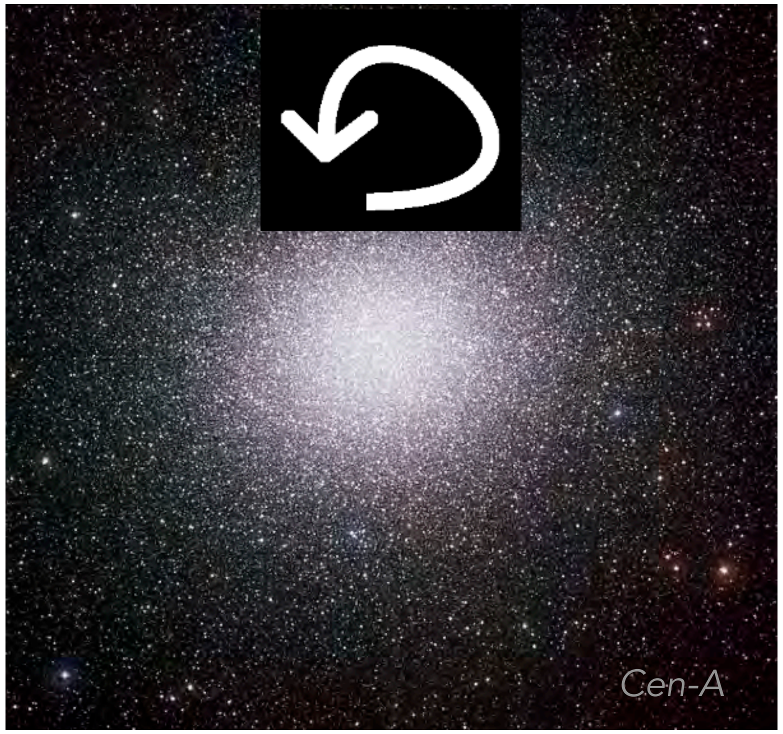
$\partial F / \partial t$

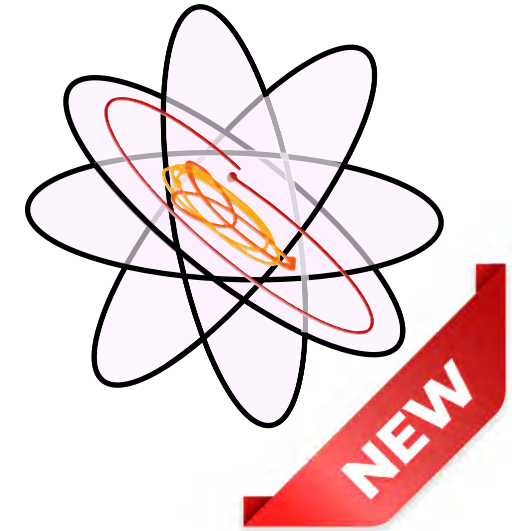


average over 100 simulations

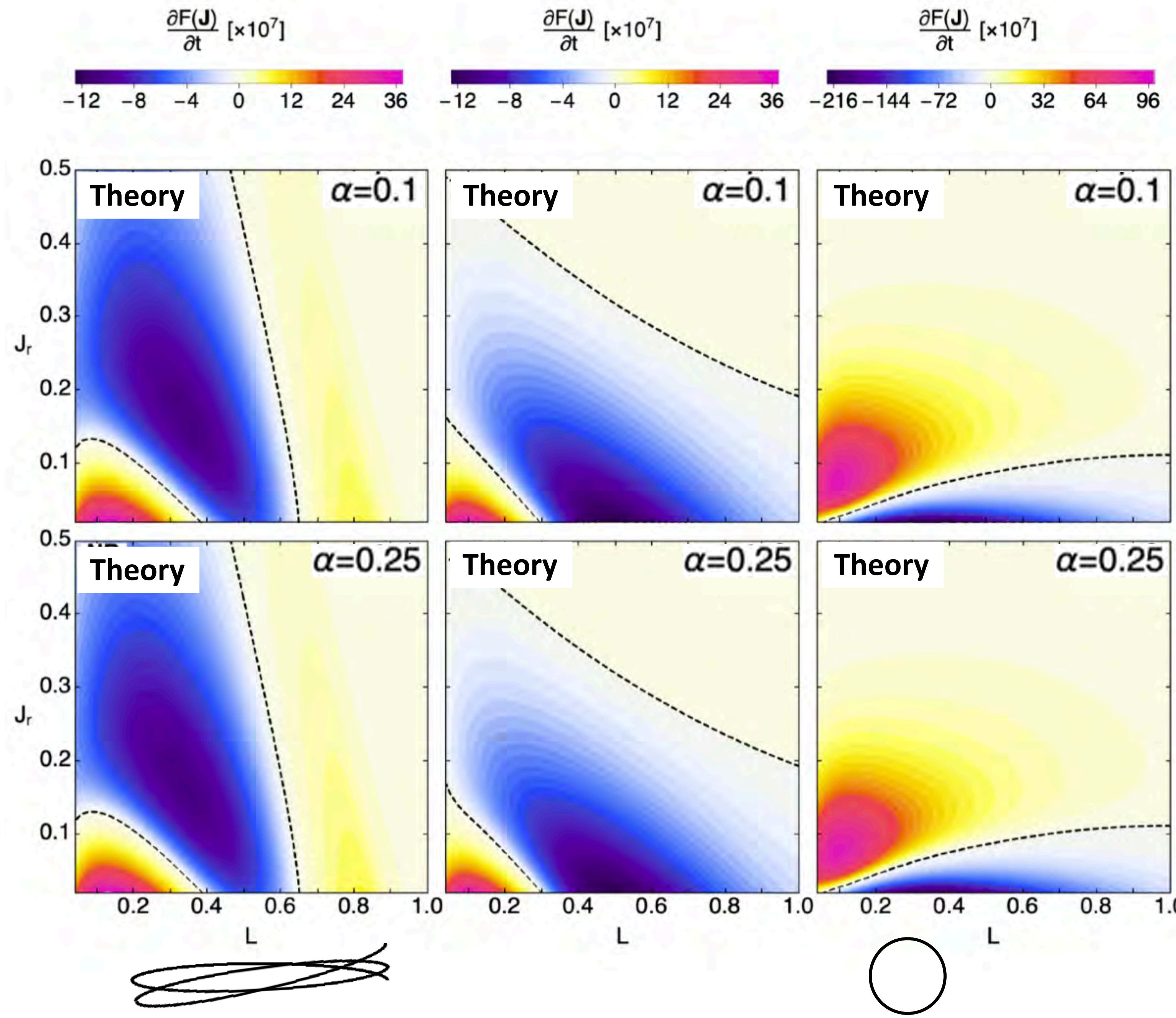
Tep+(24)

Dynamically hot systems : impact of **rotation**





$\partial F / \partial t$



average over 100 simulations

MNRAS **477,** 2716–2740 (2018)
Advance Access publication 2018 April 5
doi:10.1093/mnras/sty852

A unified model for galactic discs: star formation, turbulence driving, and mass transport

Mark R. Krumholz,[1★] Blakesley Burkhart,[2] John C. Forbes[2] and Roland M. Crocker[1]

The evolution of turbulent galactic discs: gravitational instability, feedback and accretion

Omri Ginzburg,[1★] Avishal Dekel[1,2] Nir Mandelker[1] and Mark R. Krumholz[3,4]
[1] *Racah Institute of Physics, The Hebrew University, Jerusalem 91904 Israel*
[2] *SCIPP, University of California, Santa Cruz, CA 95064, USA*
[3] *Research School of Astronomy and Astrophysics, Australian National University, Canberra, ACT 2611, Australia*
[4] *Australian Research Council Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), Australia*

Regulation of star formation by large scale gravito-turbulence

Adi Nusser[1] and Joseph Silk[2,3,4]

open (*spherical*) box where free energy driven by **contraction** induced by **unstable** disc

this induces radial transport and generates the energy to feed the turbulence which regulates star formation

Fluctuations and dissipation

- Einstein (1905) and Perrin (1908): we know how ink diffuses in water.

- **Fluctuation-Dissipation Theorem**

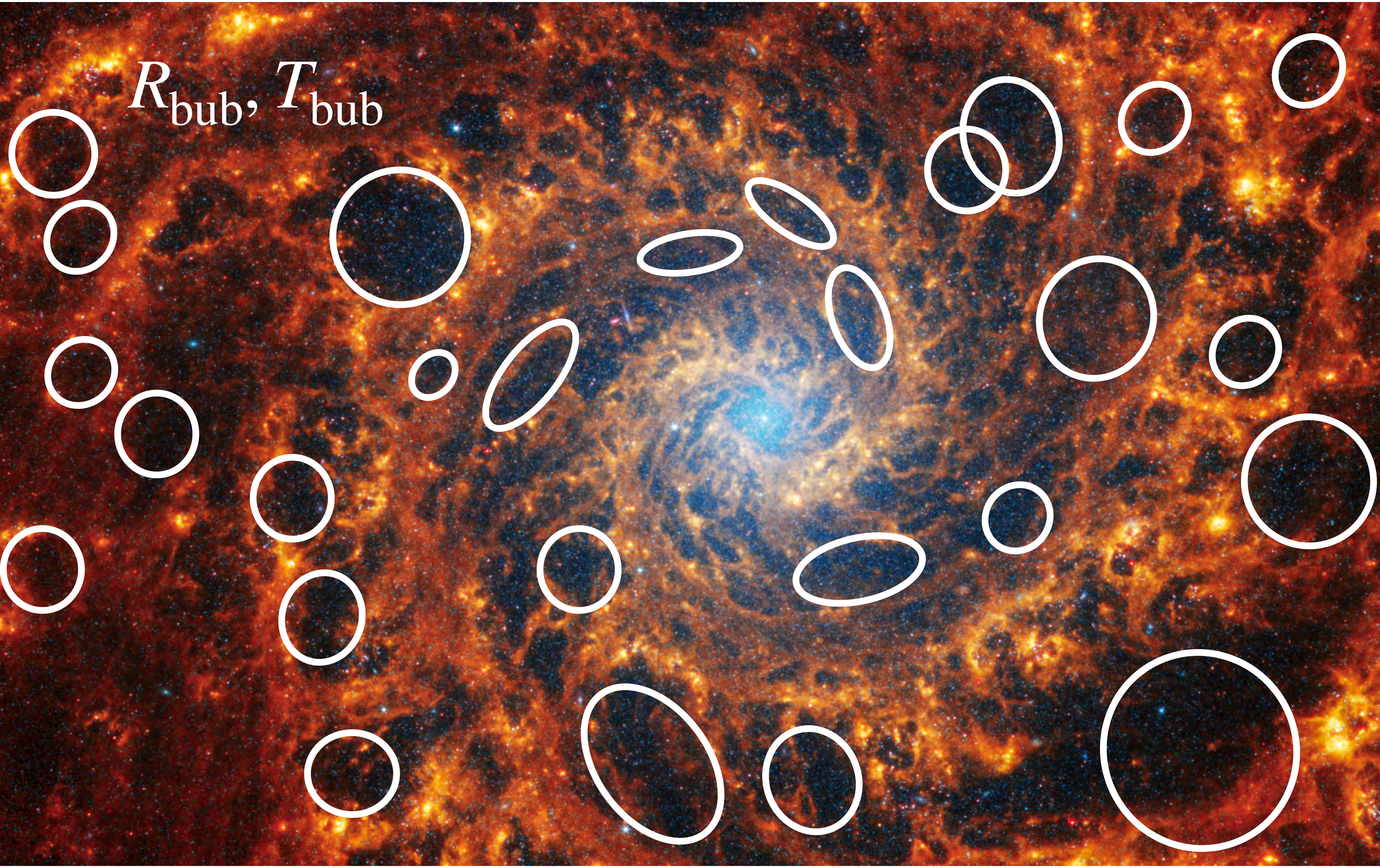
Diffusion rate	$\Longleftrightarrow$	Power spectrum **fluctuating forces**

- Stars in cold galaxies undergo the same process
  $\Longrightarrow$ But, gravity is a **long-range interaction**.
  - To diffuse, stars need to **resonate**, otherwise follow the **mean field**.
  - Fluctuations are boosted by **collective effects**.

How do stars' orbits distort on cosmic times?

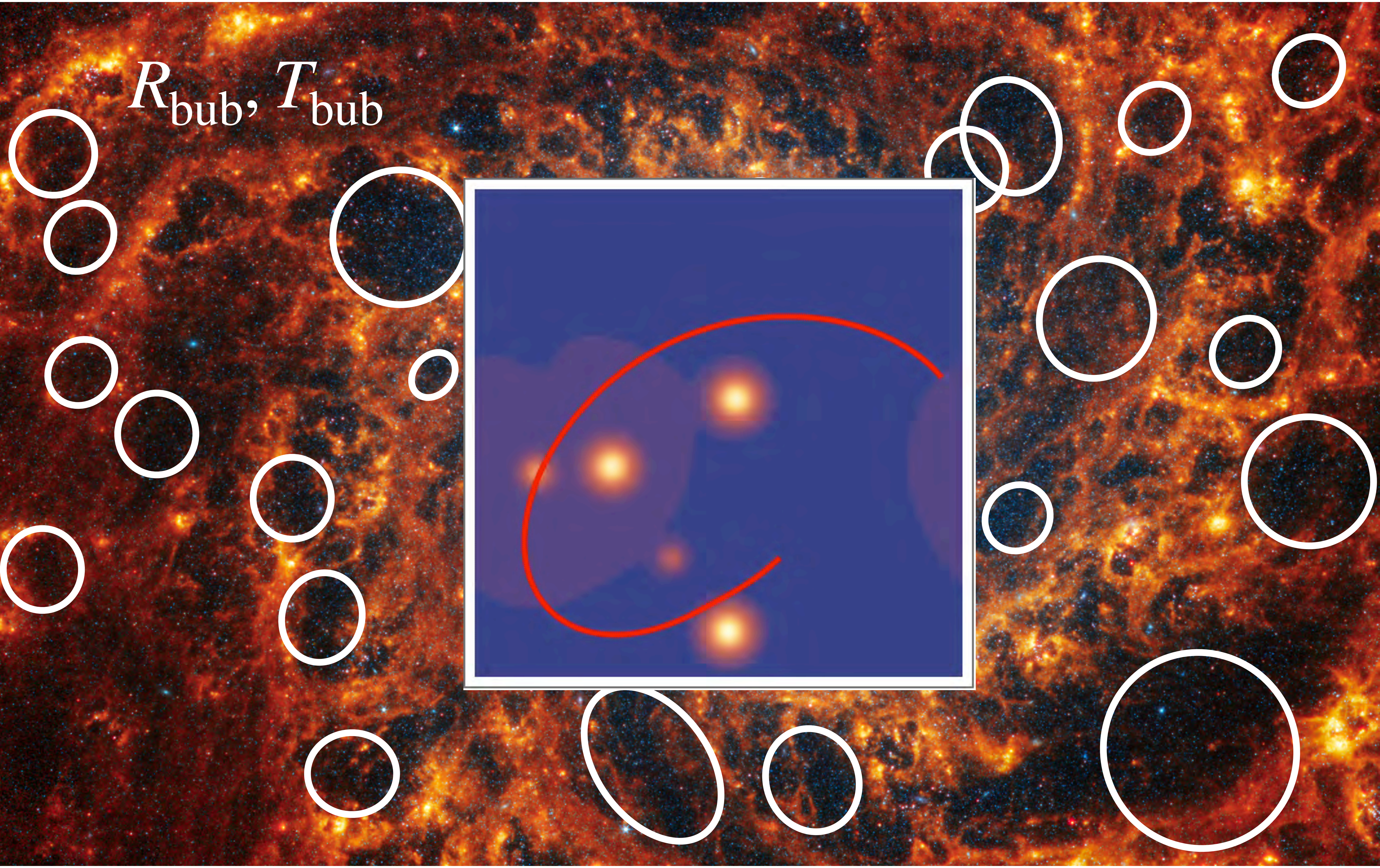
→ Morphological transformation of mean galaxy

2.4 Example of external fluctuations: SN driven bubbles disolve DM cusps?

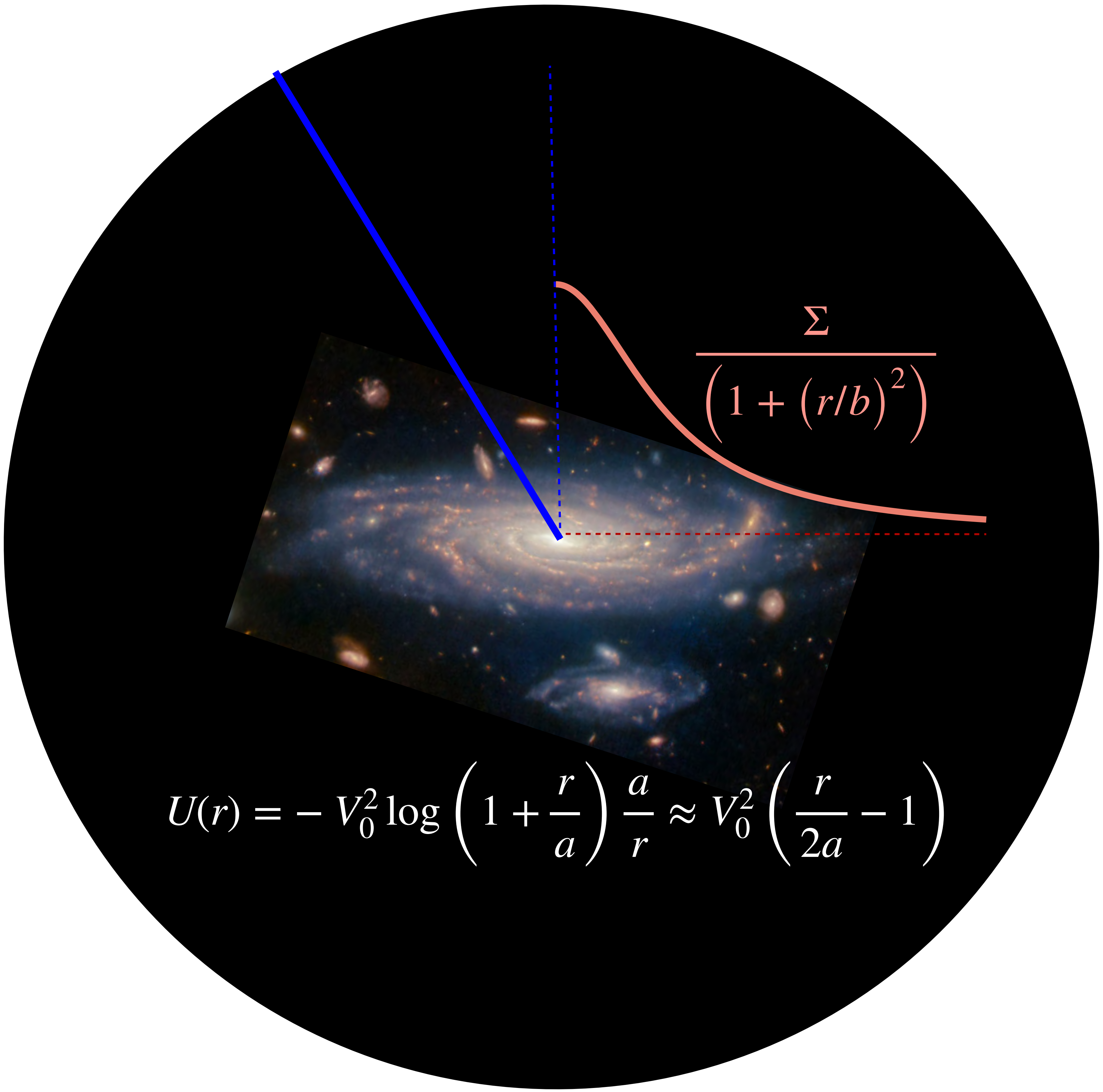


Toy model accounting for impact of baryons on orbital structure

2.4 Example of external fluctuations: SN driven bubbles disolve DM cusps?

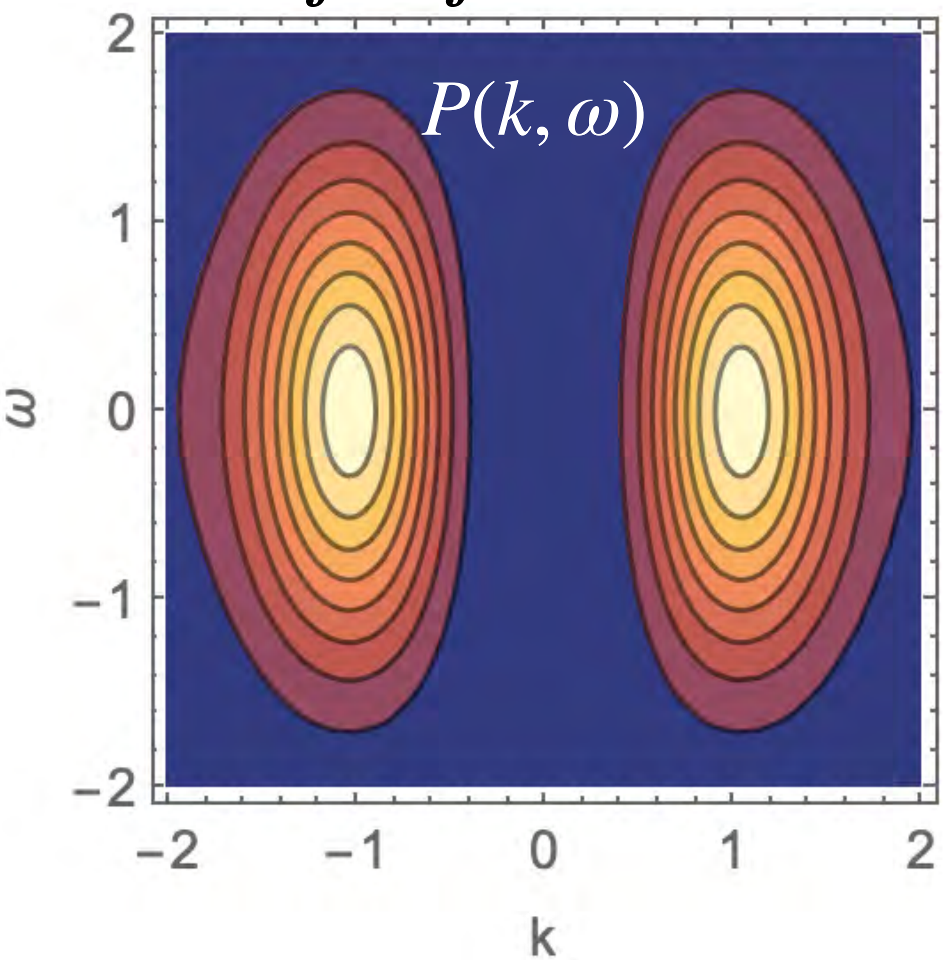


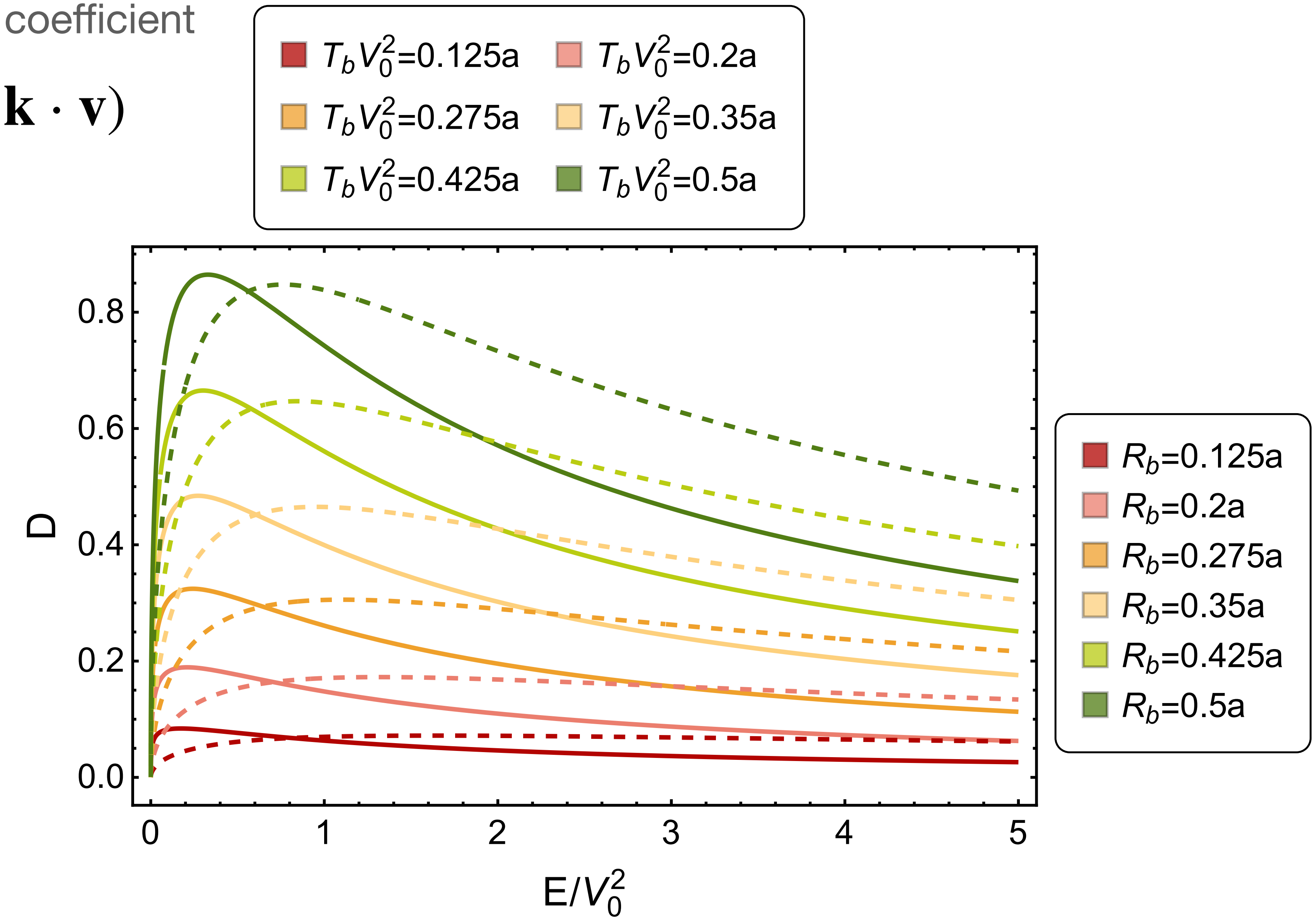
Toy model accounting for impact of baryons on orbital structure


$\frac{\Sigma}{\left(1+\left(r/b\right)^2\right)}$
$U(r) = -V_0^2 \log\left(1+\frac{r}{a}\right)\frac{a}{r} \approx V_0^2\left(\frac{r}{2a}-1\right)$

Chandrasekhar phase averaging Diffusion coefficient

$$D(\mathbf{J}) \propto \int \mathrm{d}\phi \int \mathrm{d}\mathbf{k}\mathbf{k} \otimes \mathbf{k} P_k(\omega = \mathbf{k} \cdot \mathbf{v})$$





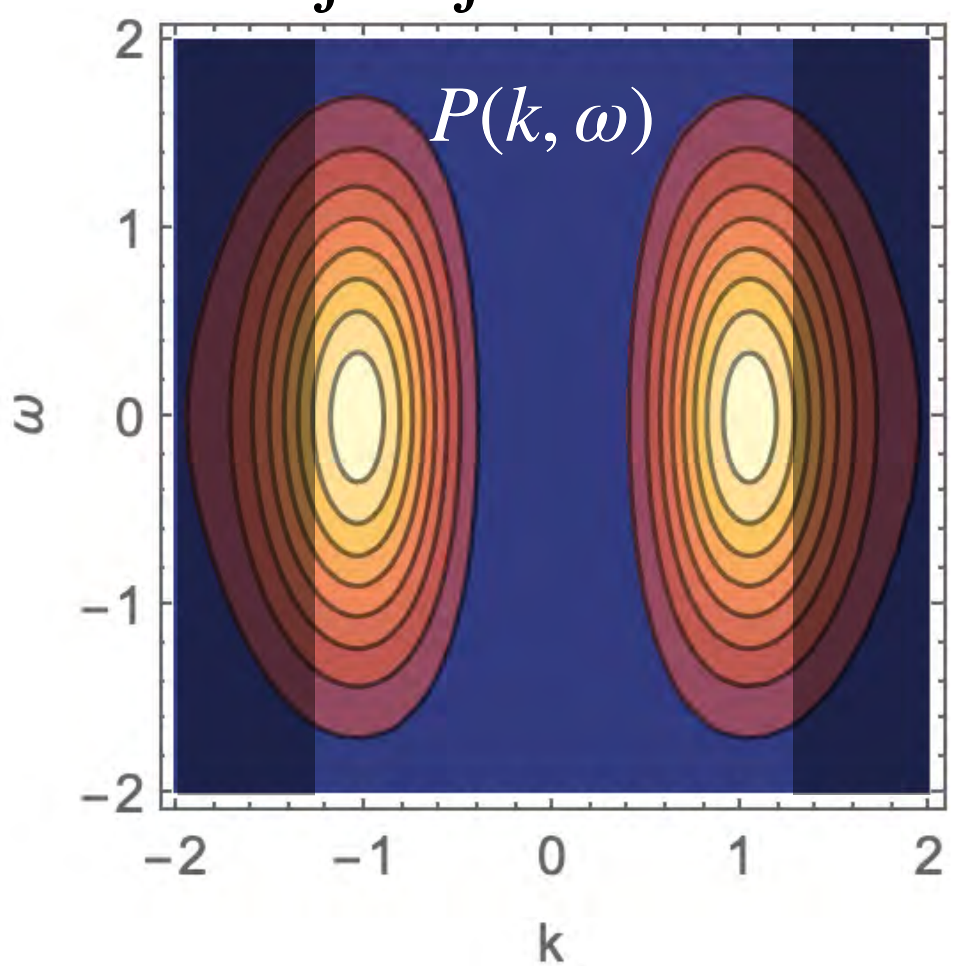
rate of bubble explosion; bubble lifespan; bubble size; energy

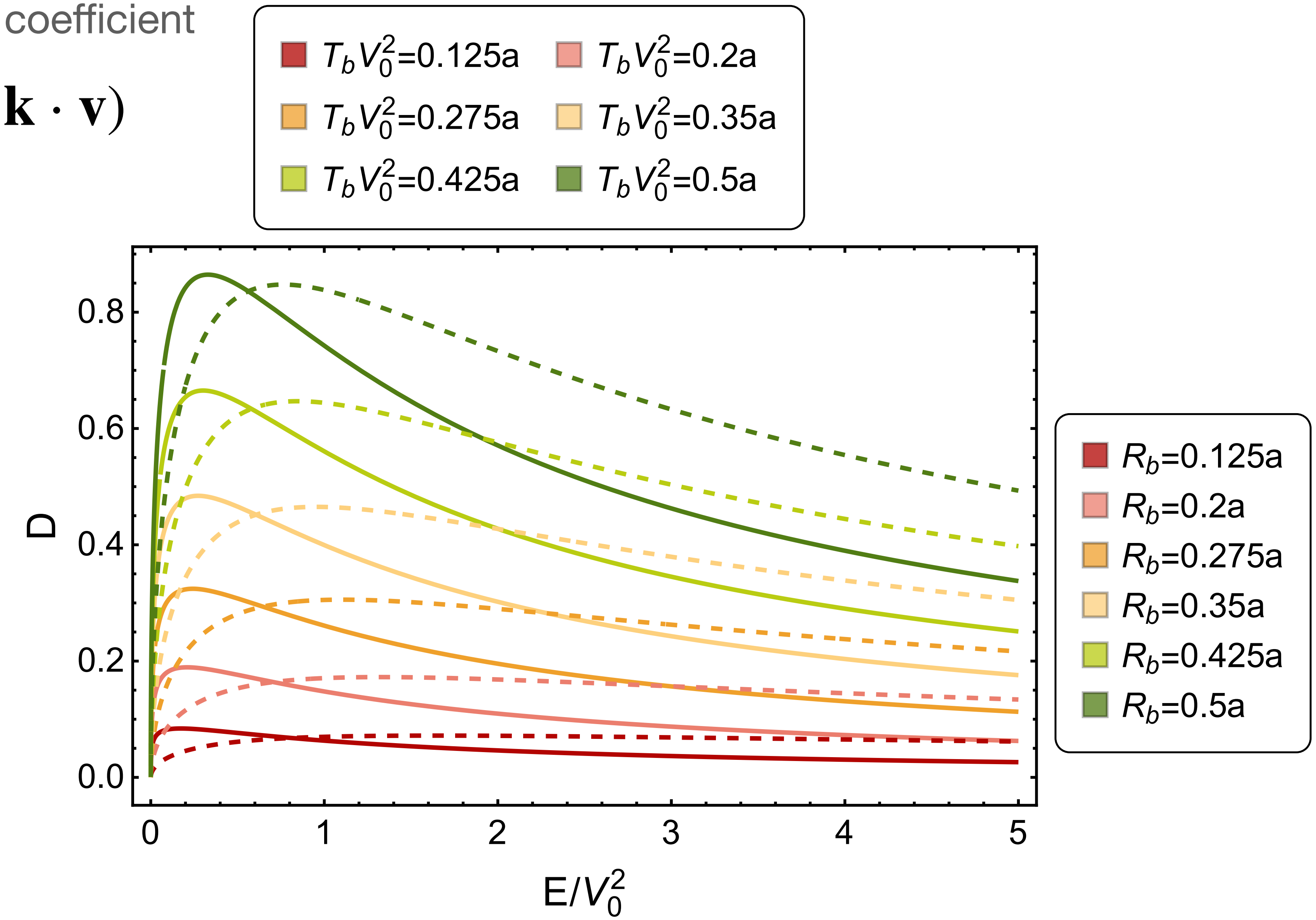
$$D_E = 5\sqrt{2}\pi\Sigma \frac{T_{\rm bub}^2 V_0^2 R_{\rm bub}}{3a^3} \sqrt{\frac{E}{V_0^2}} \left(1 - \frac{2}{3}\frac{a}{b}\frac{E}{V_0^2}\right)$$

potential scale length; potential amplitude; bubble distribution scale length

Chandrasekhar phase averaging Diffusion coefficient

$$D(\mathbf{J}) \propto \int \mathrm{d}\phi \int \mathrm{d}\mathbf{k}\mathbf{k} \otimes \mathbf{k} P_k(\omega = \mathbf{k} \cdot \mathbf{v})$$





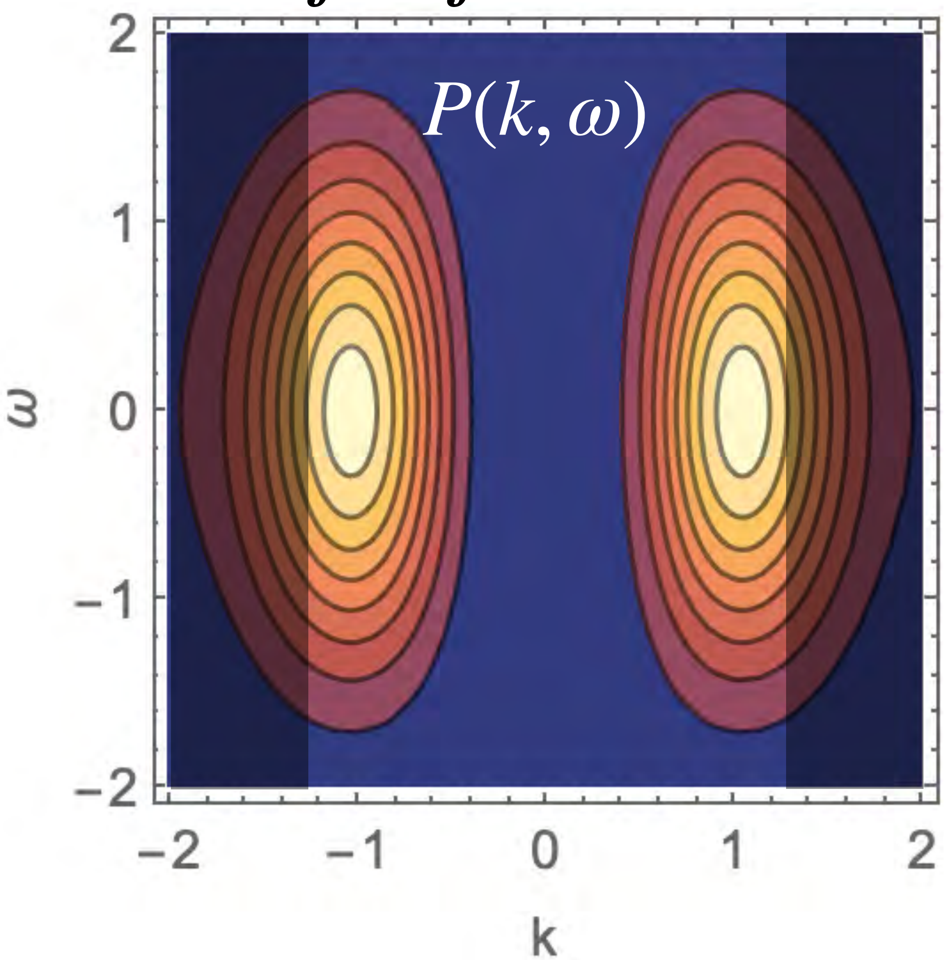
$$D_E = 5\sqrt{2}\pi\Sigma \frac{T_{\mathrm{bub}}^2 V_0^2 R_{\mathrm{bub}}}{3a^3} \sqrt{\frac{E}{V_0^2}} \left(1 - \frac{2}{3}\frac{a}{b}\frac{E}{V_0^2}\right)$$

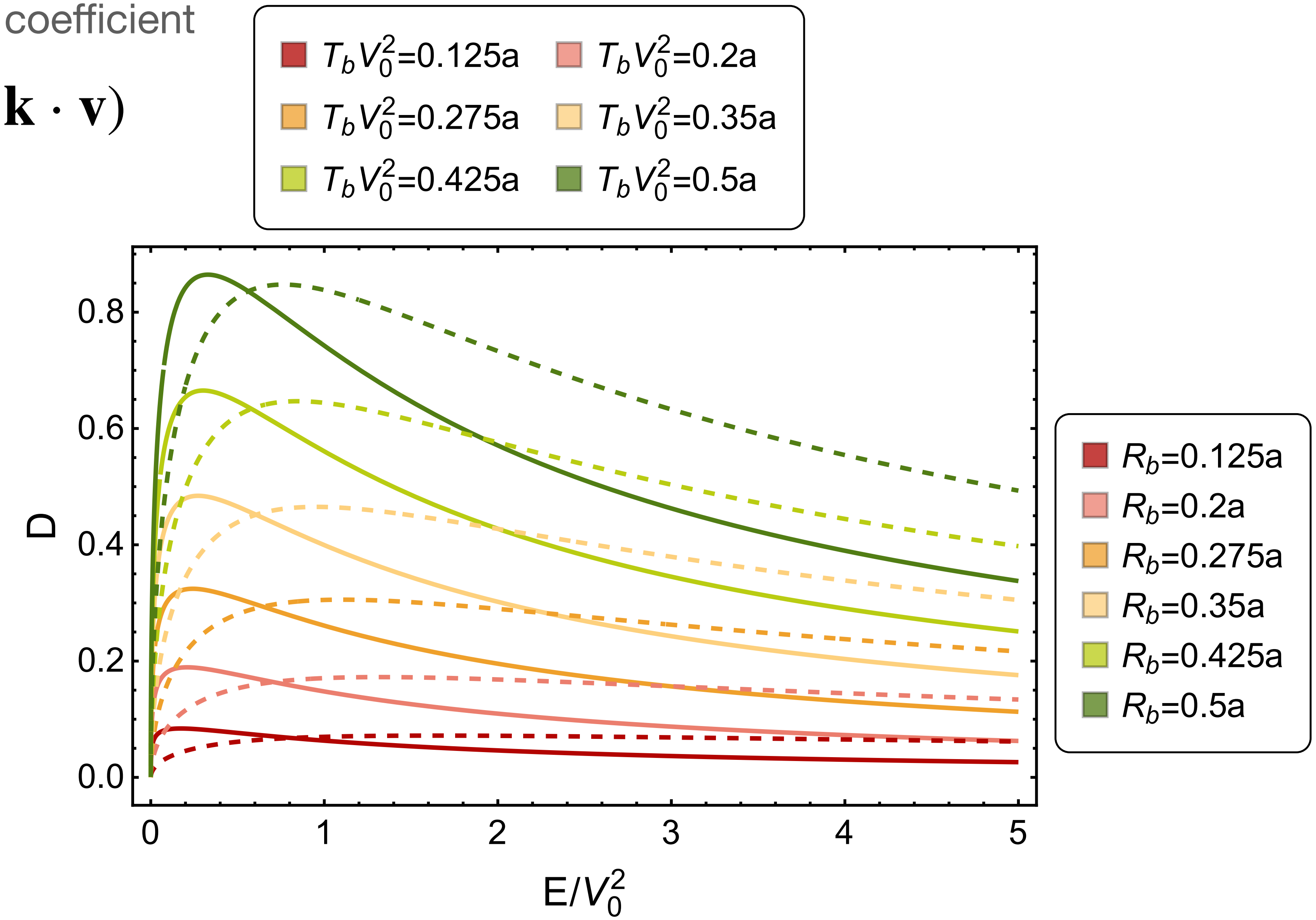
- rate of bubble explosion → Σ
- bubble lifespan → T_{bub}
- bubble size → R_{bub}
- energy → E
- potential scale length → a
- potential amplitude → V_0
- bubble distribution scale length → b

2.4 Bubble induced orbital diffusion

Chandrasekhar phase averaging Diffusion coefficient

$$D(\mathbf{J}) \propto \int \mathrm{d}\phi \int \mathrm{d}\mathbf{k}\mathbf{k} \otimes \mathbf{k} P_k(\omega = \mathbf{k} \cdot \mathbf{v})$$





$$D_E = 5\sqrt{2}\pi\Sigma \frac{T_{\mathrm{bub}}^2 V_0^2 R_{\mathrm{bub}}}{3a^3} \sqrt{\frac{E}{V_0^2}} \left(1 - \frac{2}{3}\frac{a}{b}\frac{E}{V_0^2}\right)\left(1 - \frac{3}{5R_{\mathrm{bub}}k_{\mathrm{max}}}\right).$$

rate of bubble explosion (Σ)

bubble lifespan (T_{bub})

bubble size (R_{bub})

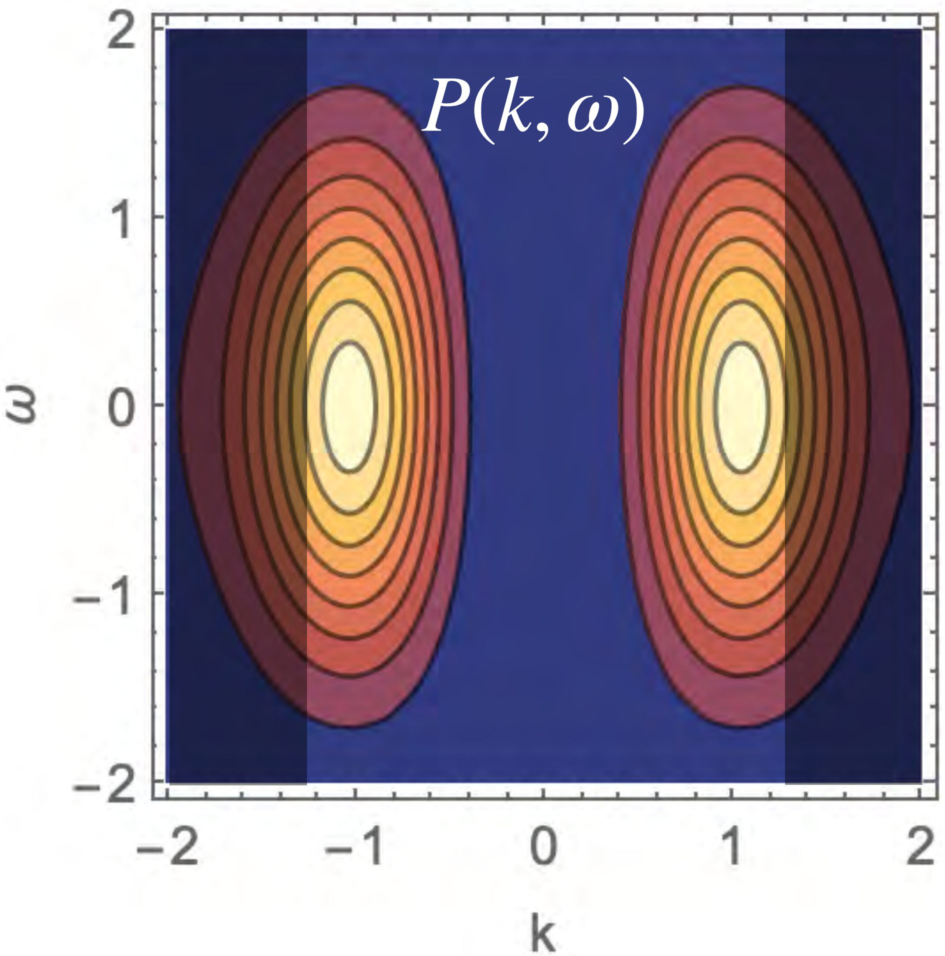
energy (E)

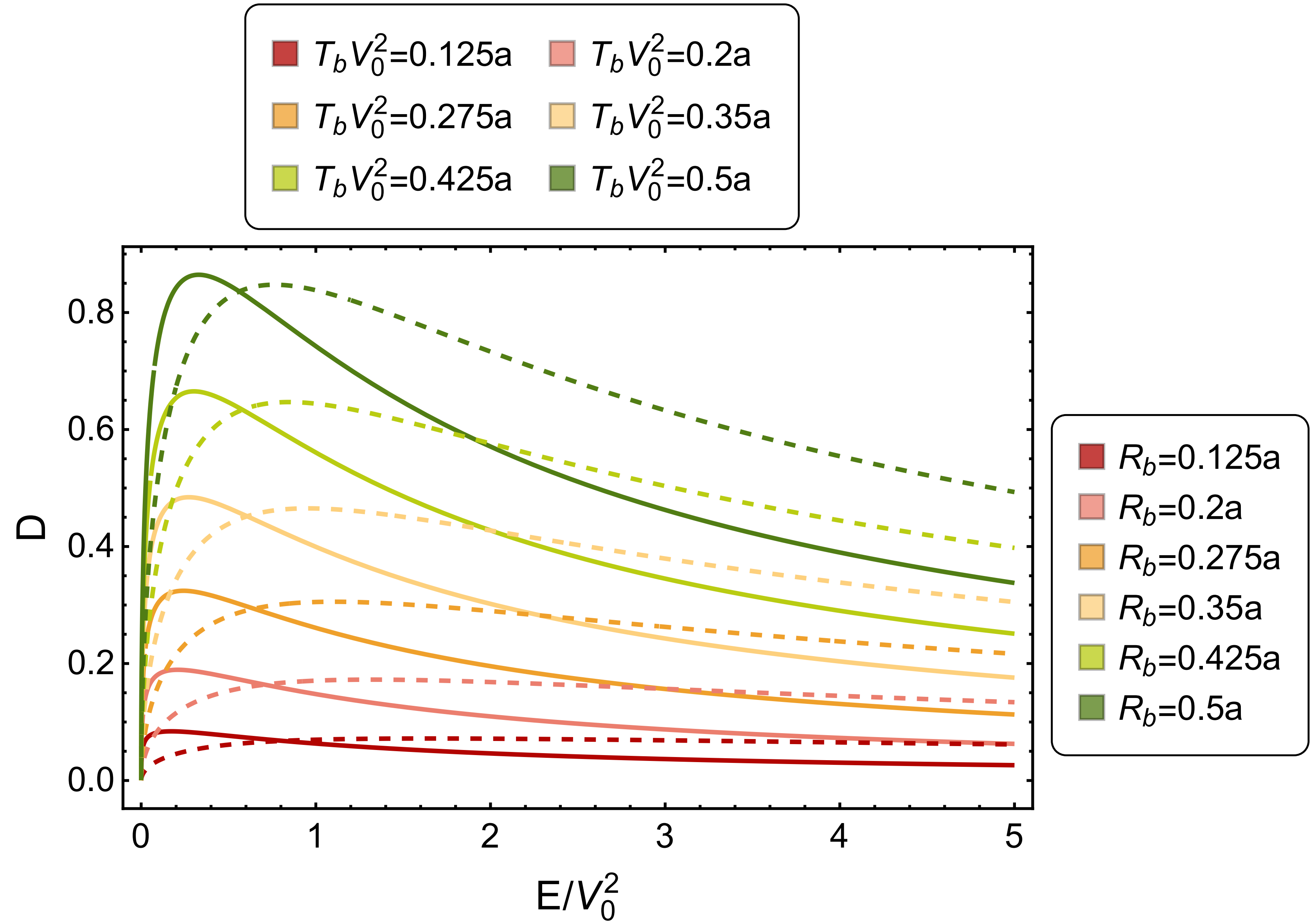
cutoff frequency (k_{max})

potential scale length (a)

potential amplitude (V_0)

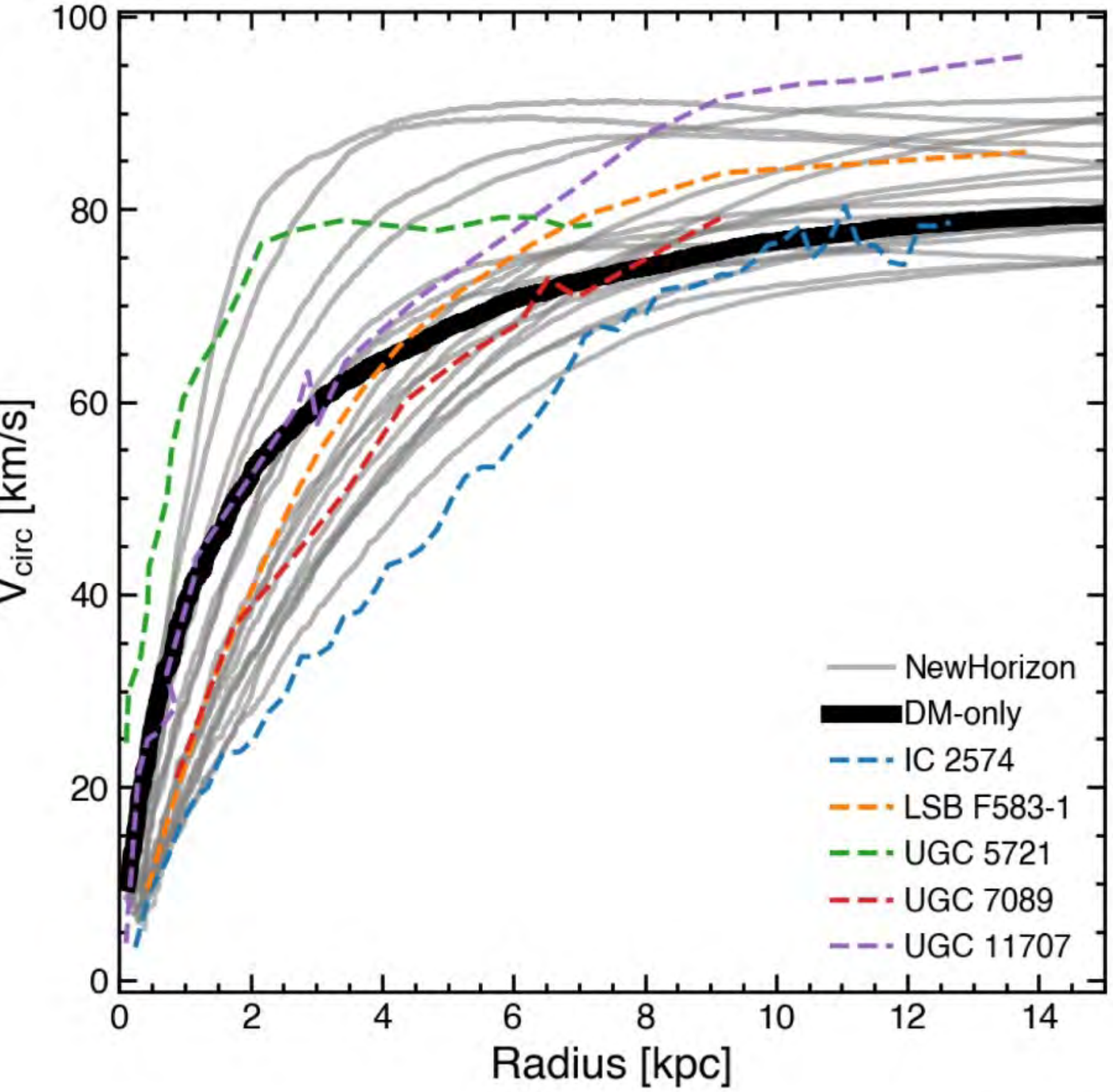
bubble distribution scale length (b)

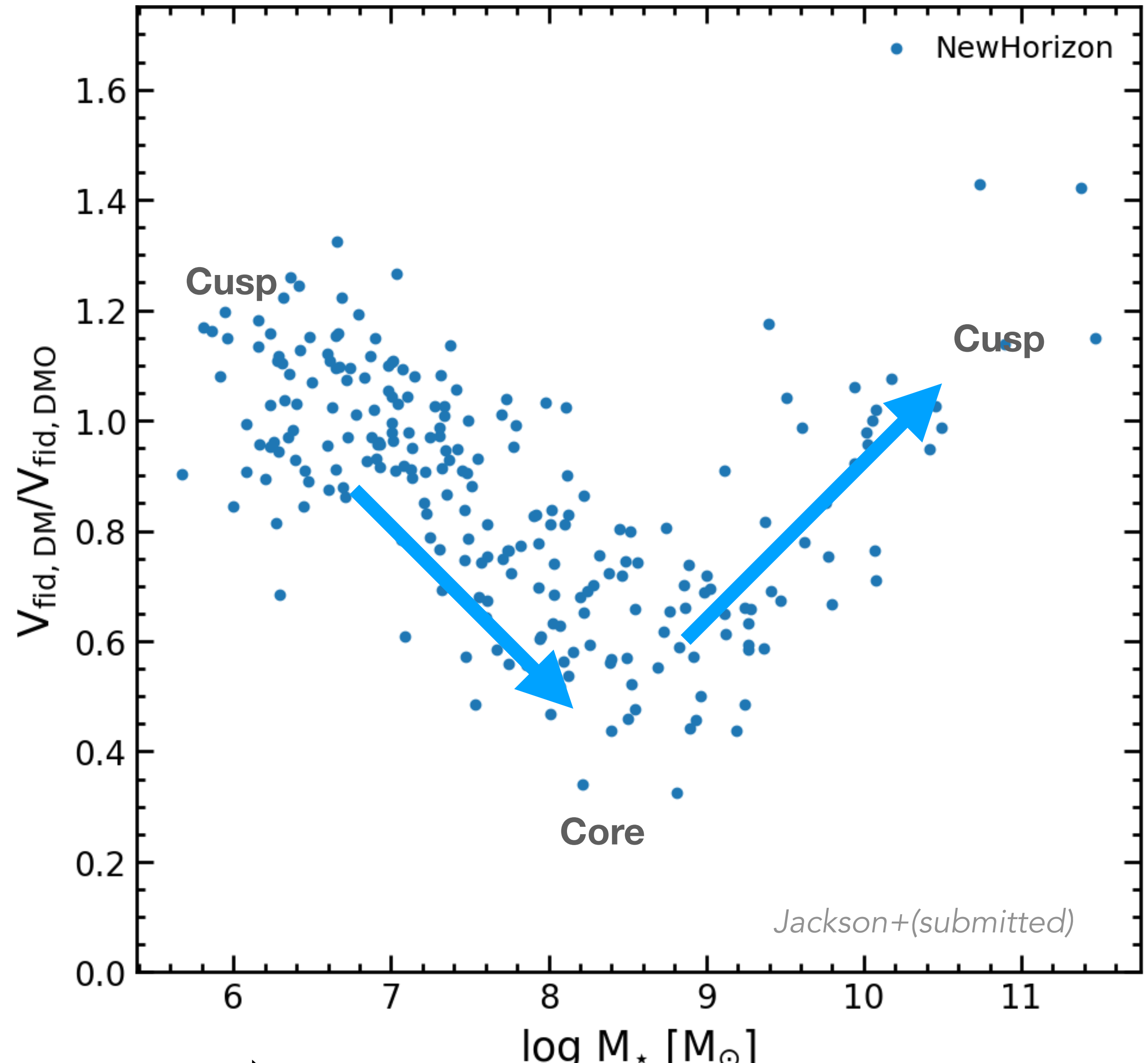




$$D_{\max} = \frac{10\pi}{9}\Sigma\sqrt{\frac{b}{a}}\frac{R_{\rm bub}}{a}\frac{V_0^2 T_{\rm bub}^2}{a^2}\left(1 - \frac{3}{5R_{\rm bub}k_{\max}}\right) \quad \text{at} \quad E = V_0^2\frac{b}{3a}$$

- **Smaller scales** impact galactic scales through **fluctuations**
- Diffusion only effective when processes are commensurable



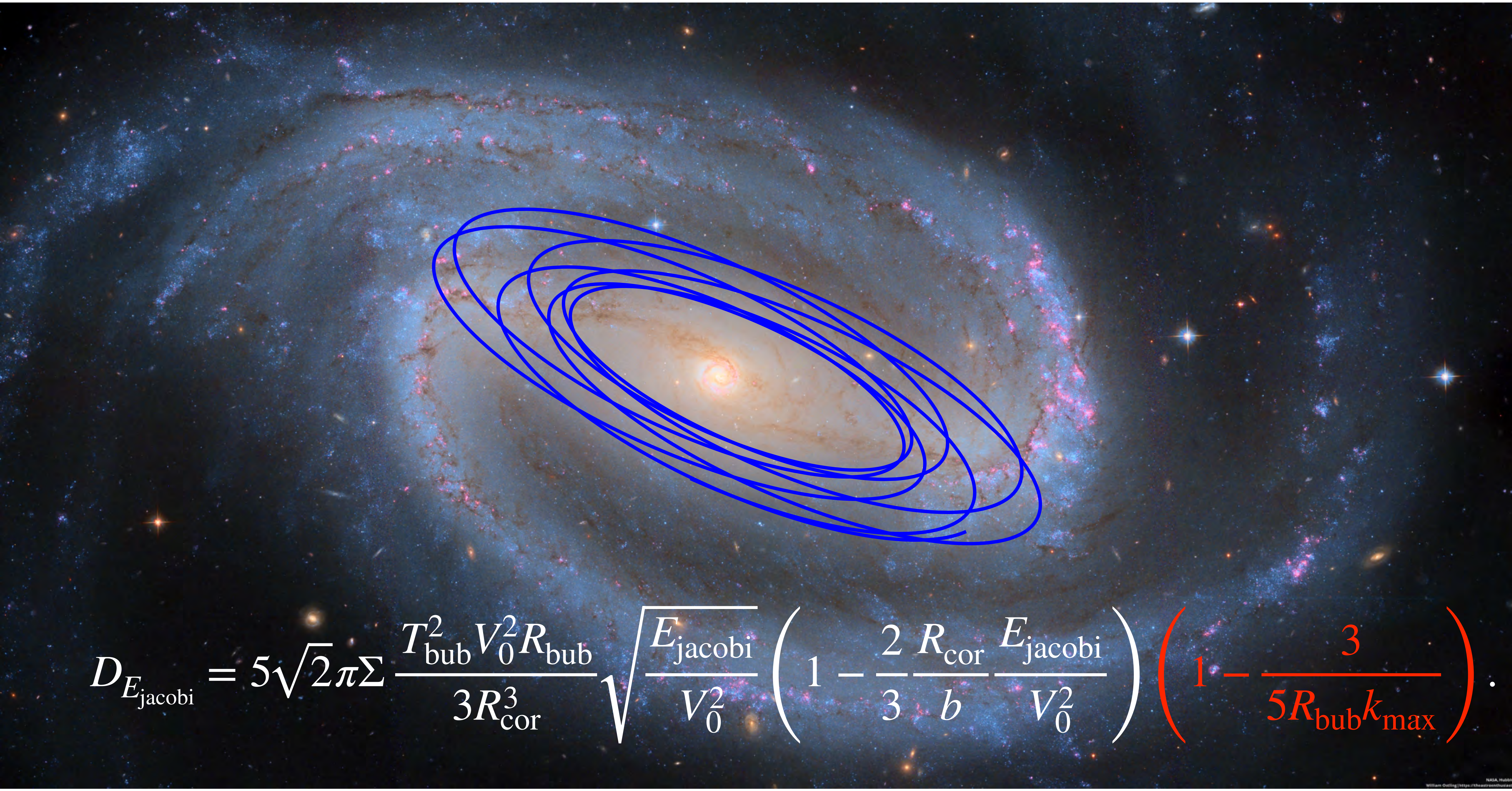


$$D_{\max} = \frac{10\pi}{9}\Sigma\sqrt{\frac{b}{a}}\frac{R_{\rm bub}}{a}\frac{V_0^2 T_{\rm bub}^2}{a^2}\left(1-\frac{3}{5R_{\rm bub}k_{\max}}\right) \quad \text{at} \quad E = V_0^2\frac{b}{3a}$$

- Why galaxy centres go through cusp → core → cusp

IN PROGRESS

Diffusion only effective when processes are commensurable



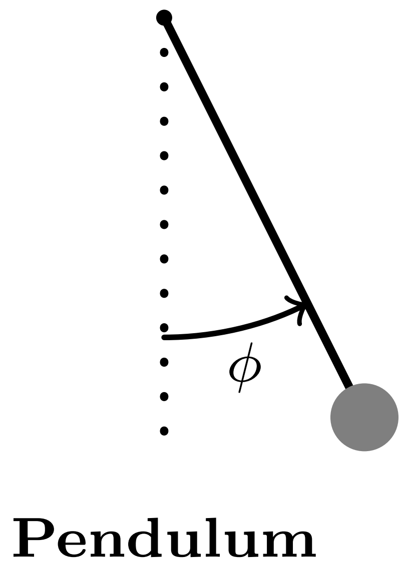
$$D_{E_{\rm jacobi}} = 5\sqrt{2}\pi\Sigma \frac{T_{\rm bub}^2 V_0^2 R_{\rm bub}}{3R_{\rm cor}^3}\sqrt{\frac{E_{\rm jacobi}}{V_0^2}}\left(1-\frac{2}{3}\frac{R_{\rm cor}}{b}\frac{E_{\rm jacobi}}{V_0^2}\right)\left(1-\frac{3}{5R_{\rm bub}k_{\rm max}}\right).$$

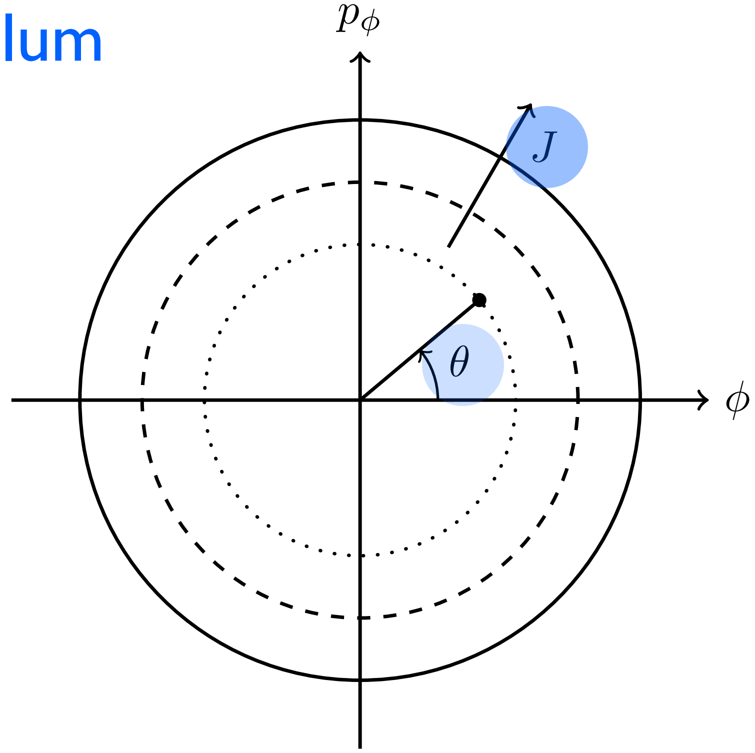
- Why resolution impacts bar resilience ($k_{\rm max}R_{\rm bub} \neq \infty$) IN PROGRESS

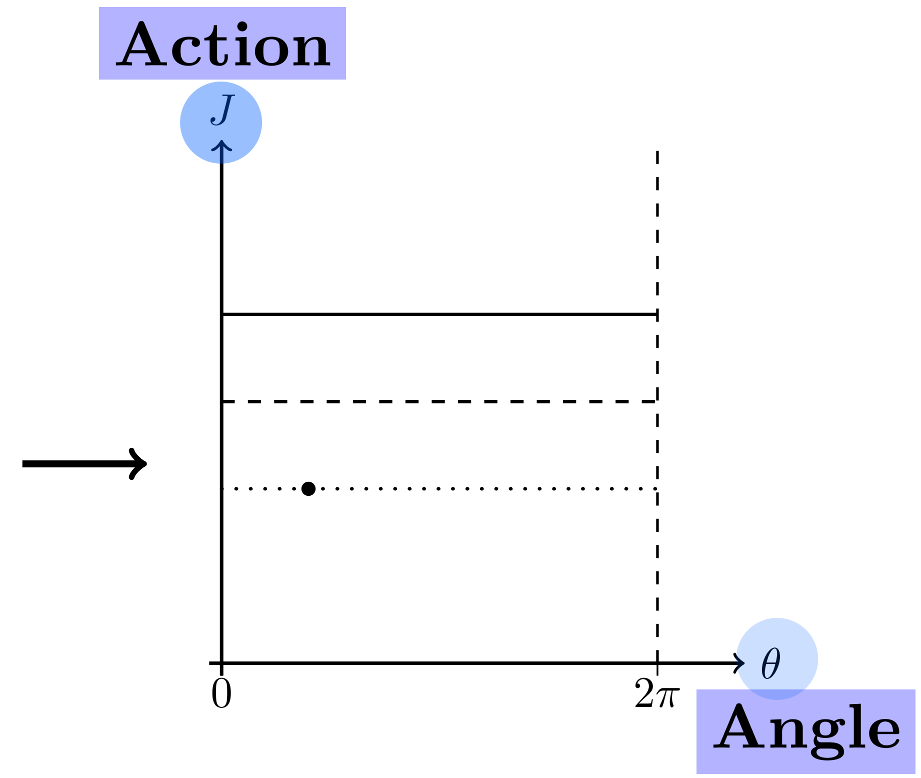
Angle-action coordinates

- Label orbits using integrals of motion

1 d.o.f. pendulum







- **Angle-action coordinates**

$$\begin{cases} \boldsymbol{\theta}(t) = \boldsymbol{\theta}_0 + t\,\boldsymbol{\Omega}\,, \\ \boldsymbol{J}(t) = \mathrm{cst.} \end{cases}$$

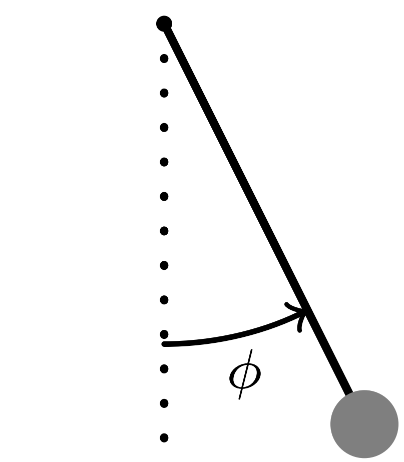
$\Longrightarrow$ **Straight lines.**

$$\begin{cases} H(\boldsymbol{q},\boldsymbol{p}) = H(\boldsymbol{J})\,, \\ \textbf{Frequencies:}\ \boldsymbol{\Omega}(\boldsymbol{J}) = \dfrac{\partial H}{\partial \boldsymbol{J}}\,. \end{cases}$$

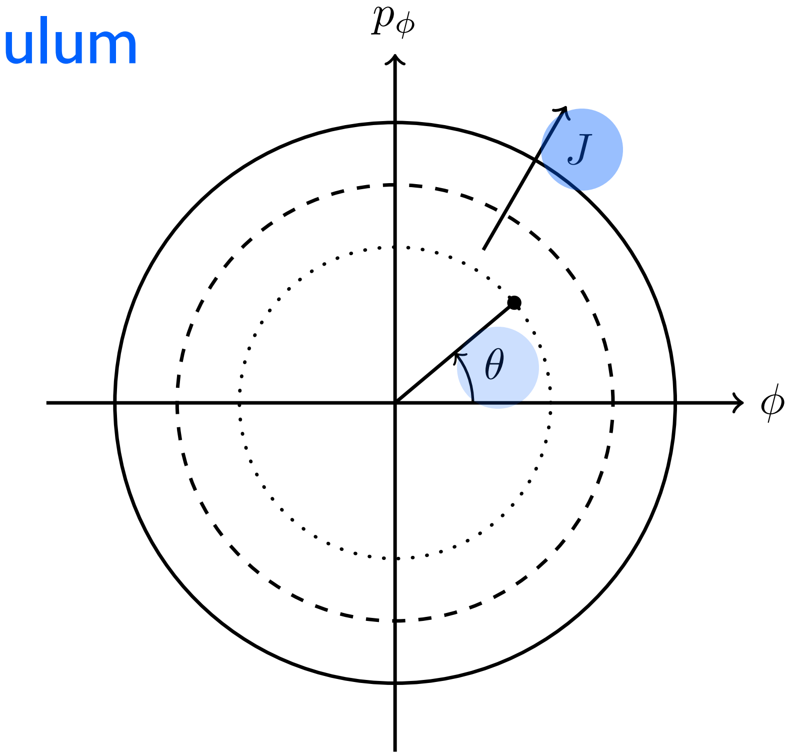
Angle-action coordinates

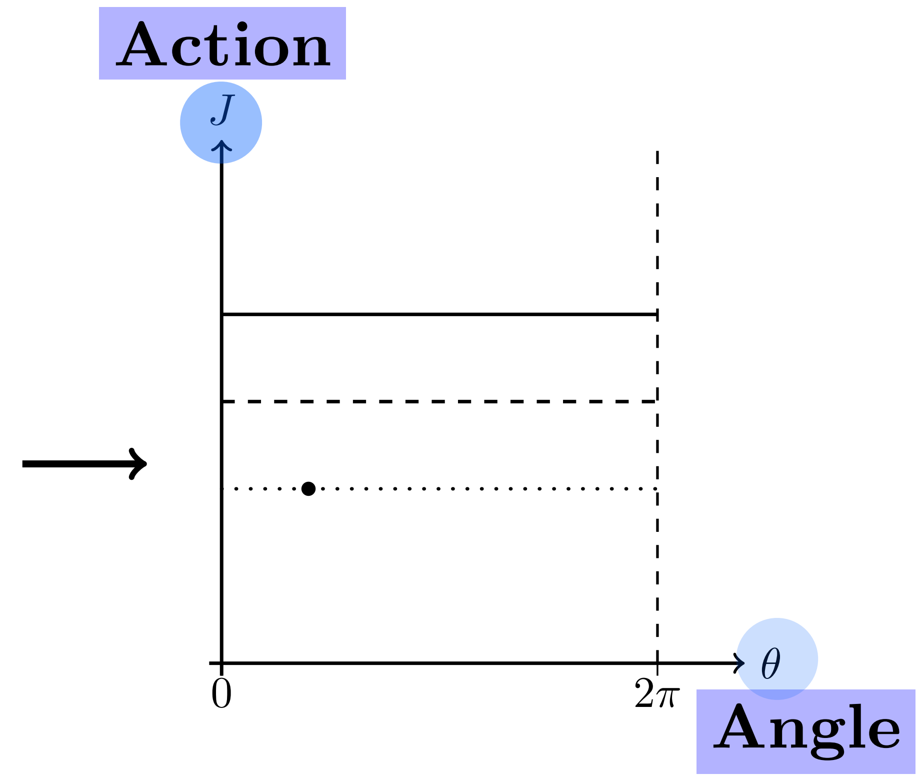
- Label orbits using integrals of motion

1 d.o.f. pendulum

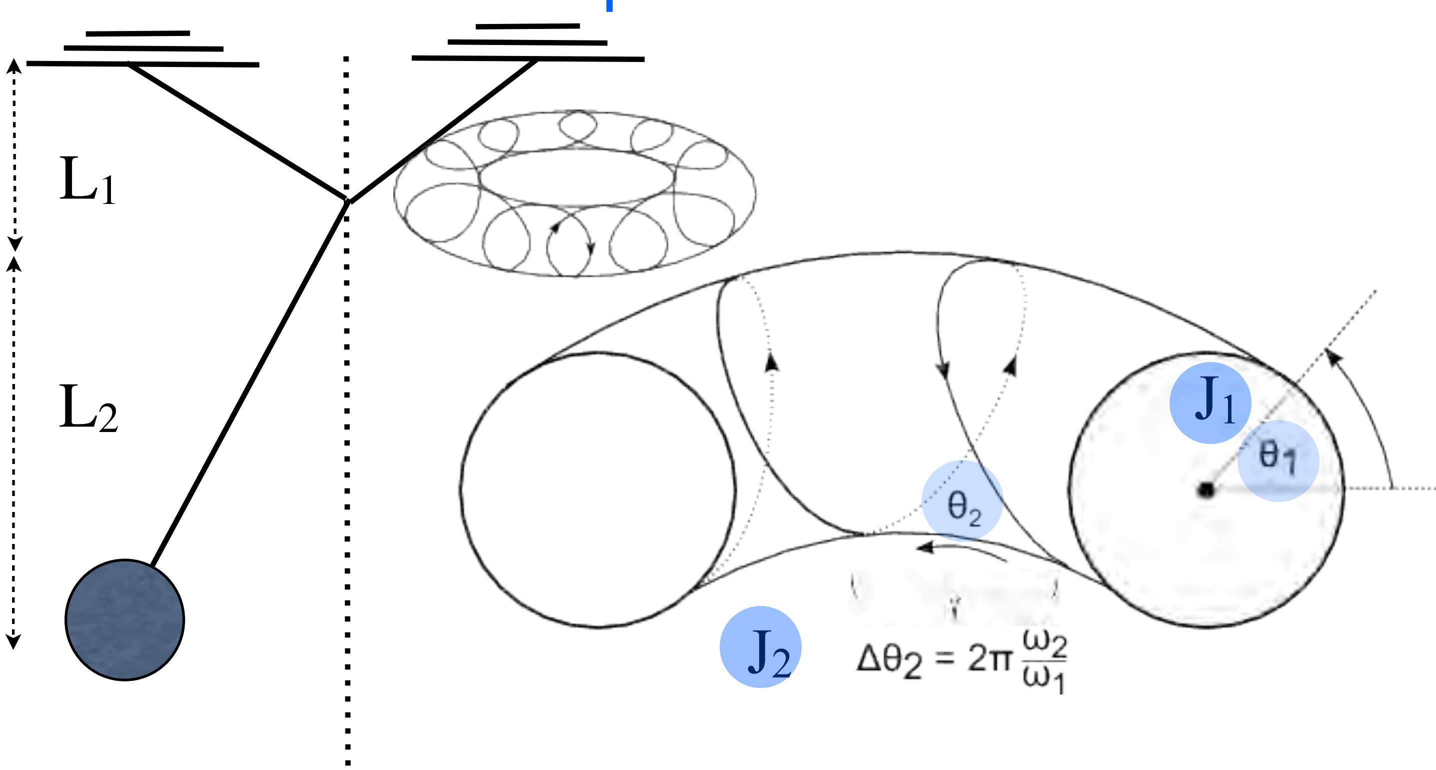


Pendulum





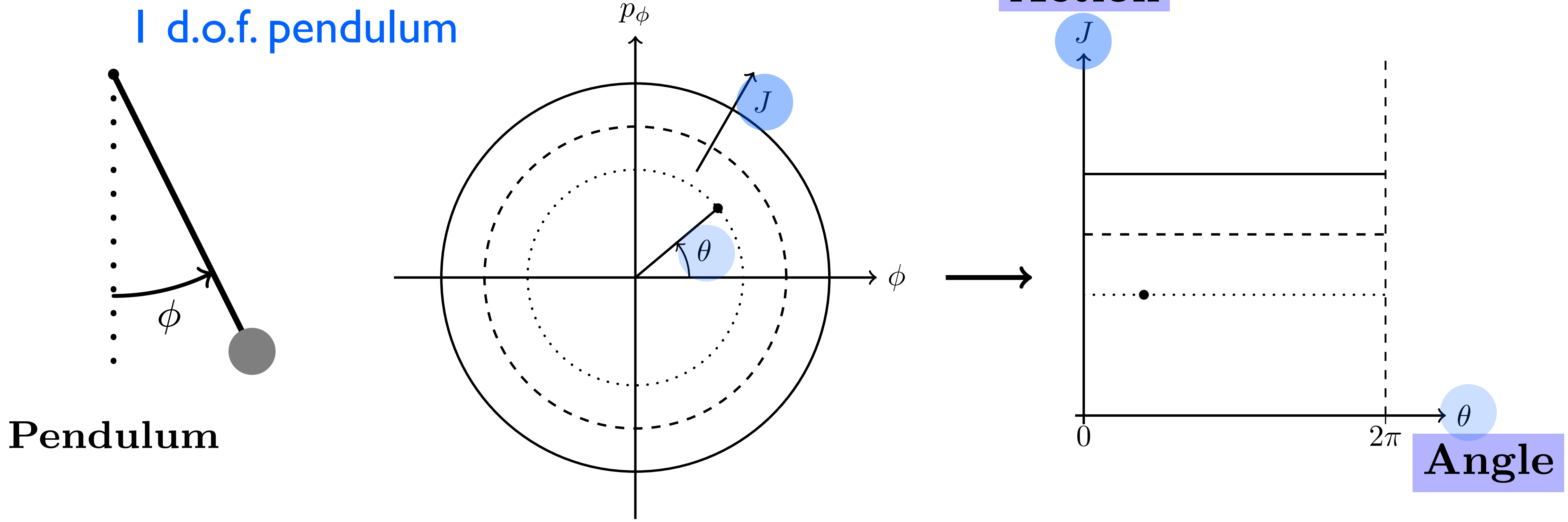
2 d.o.f. pendulum



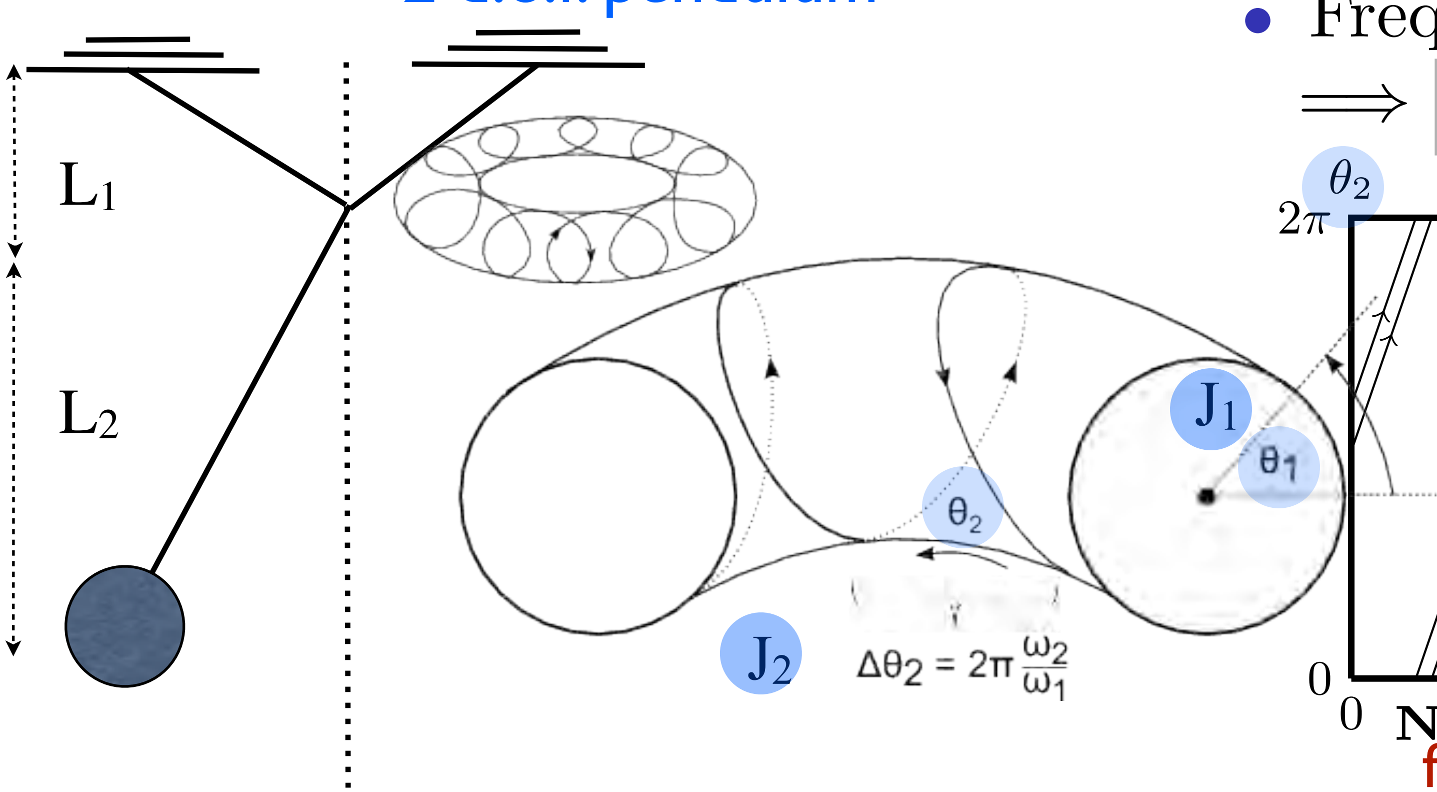
Angle-action coordinates

- Label orbits using integrals of motion

1 d.o.f. pendulum

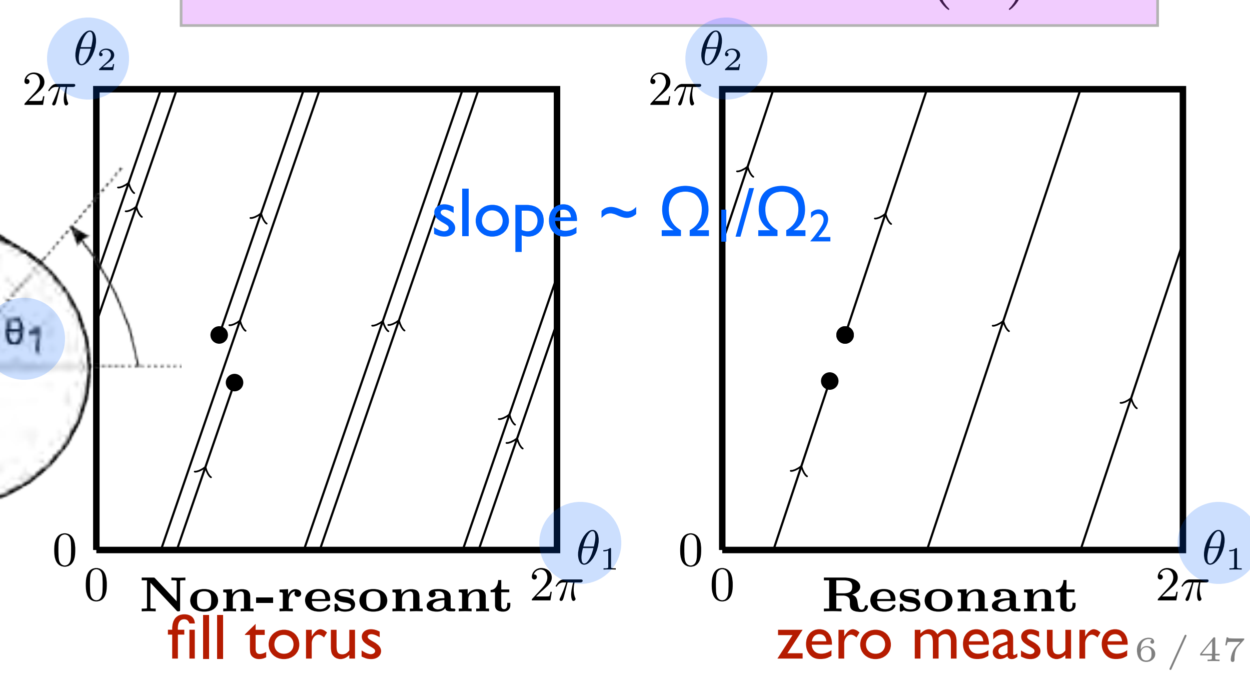


2 d.o.f. pendulum

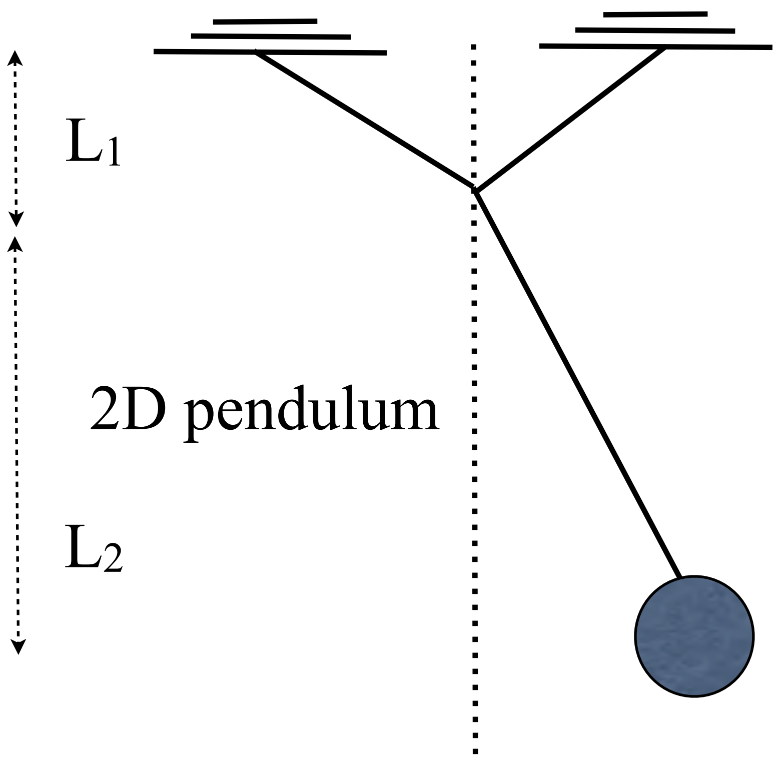


- Frequency **commensurability**

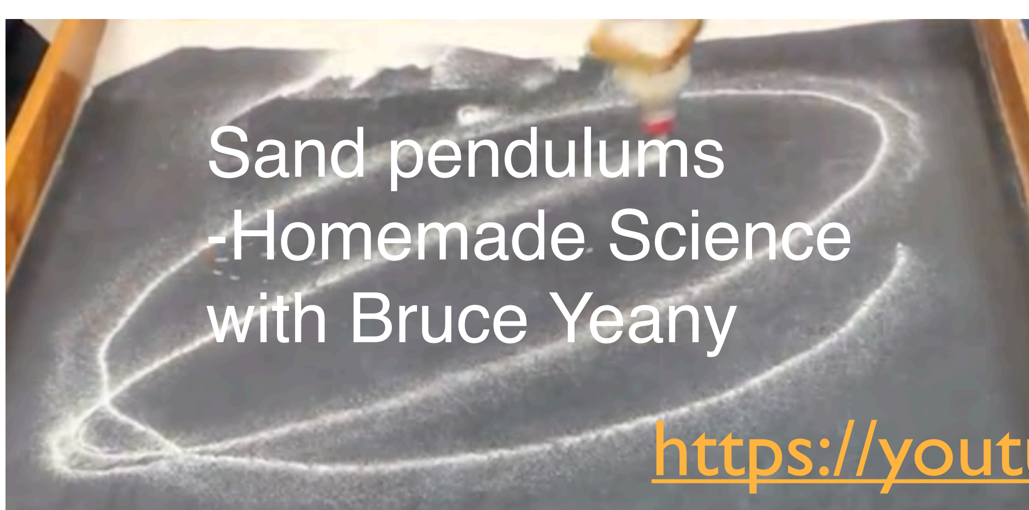
$\Longrightarrow$ Resonant orbits: $\boldsymbol{n}\cdot\boldsymbol{\Omega}(\boldsymbol{J}) = 0$.



Why resonance matters ?

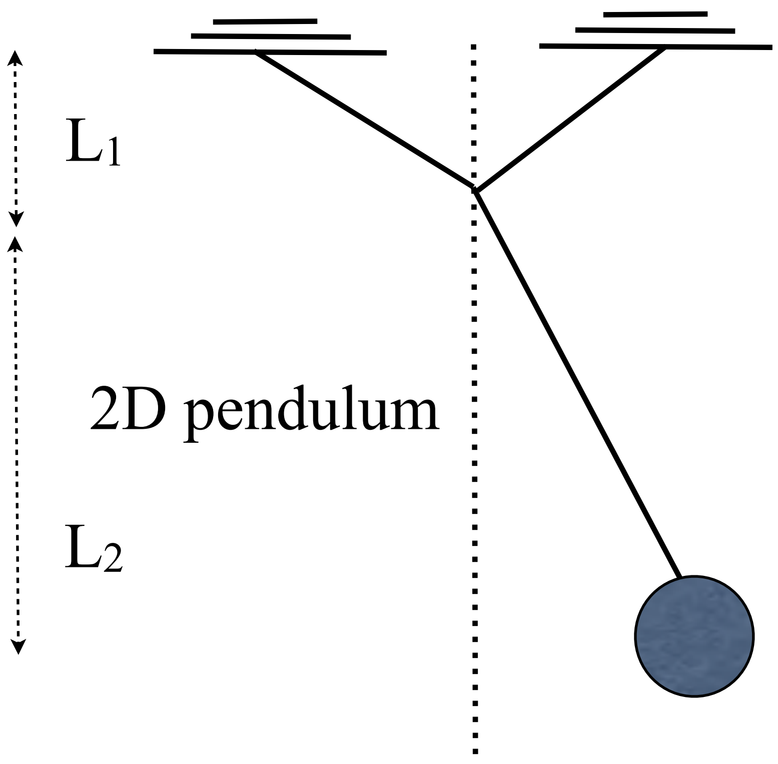


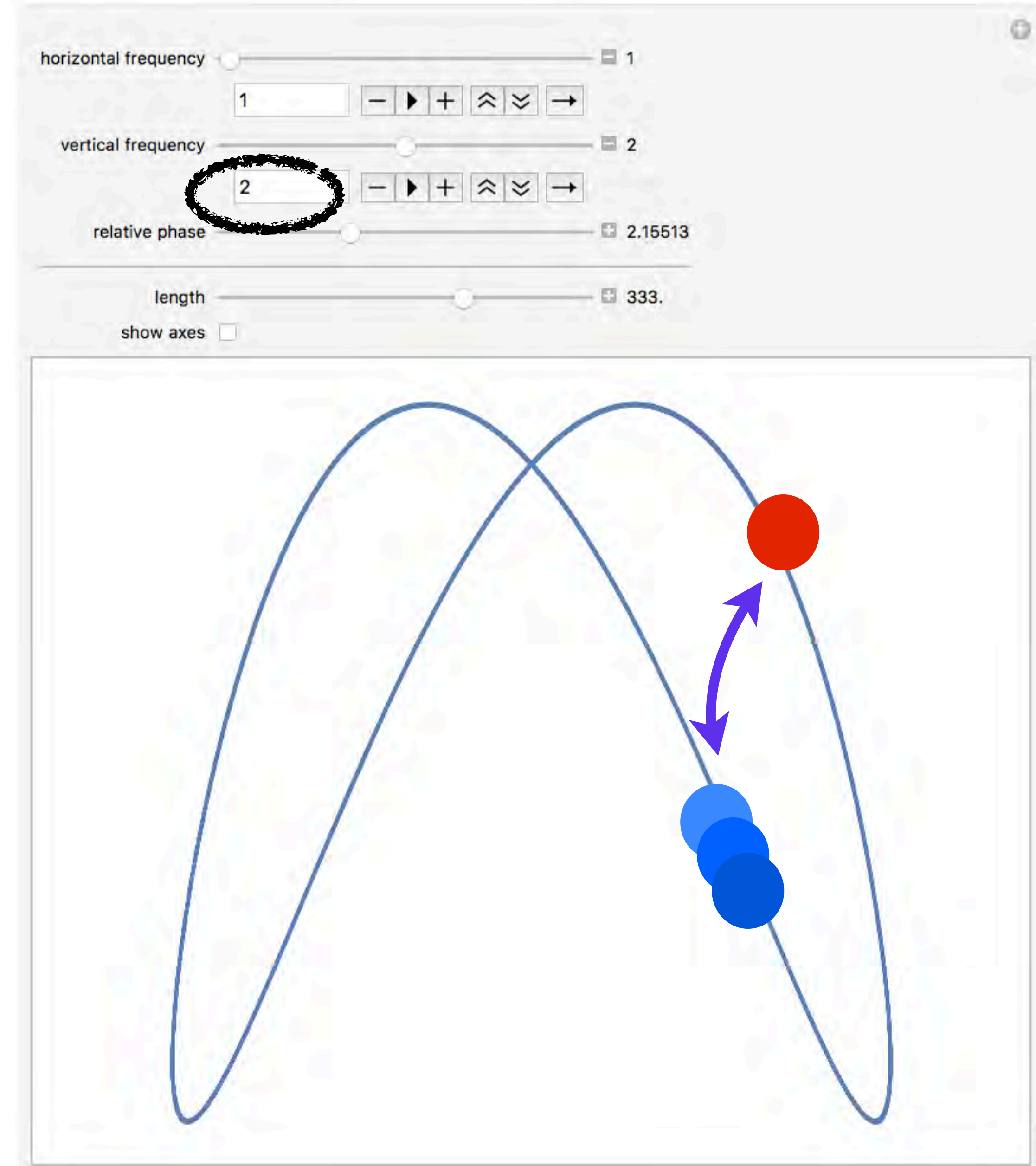
when and talk?



https://youtu.be/uPbzhxYTioM

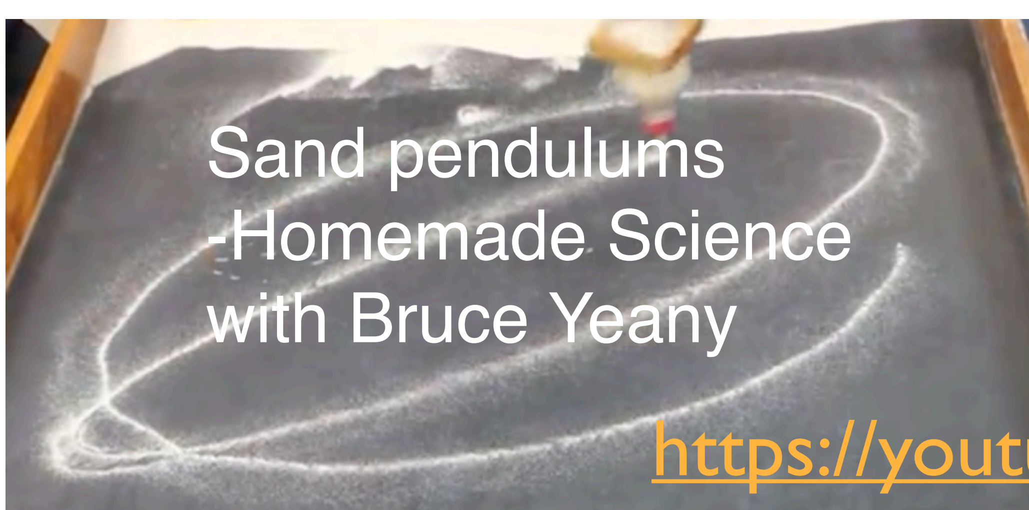
Why resonance matters ?





resonant

when ● and ● talk?



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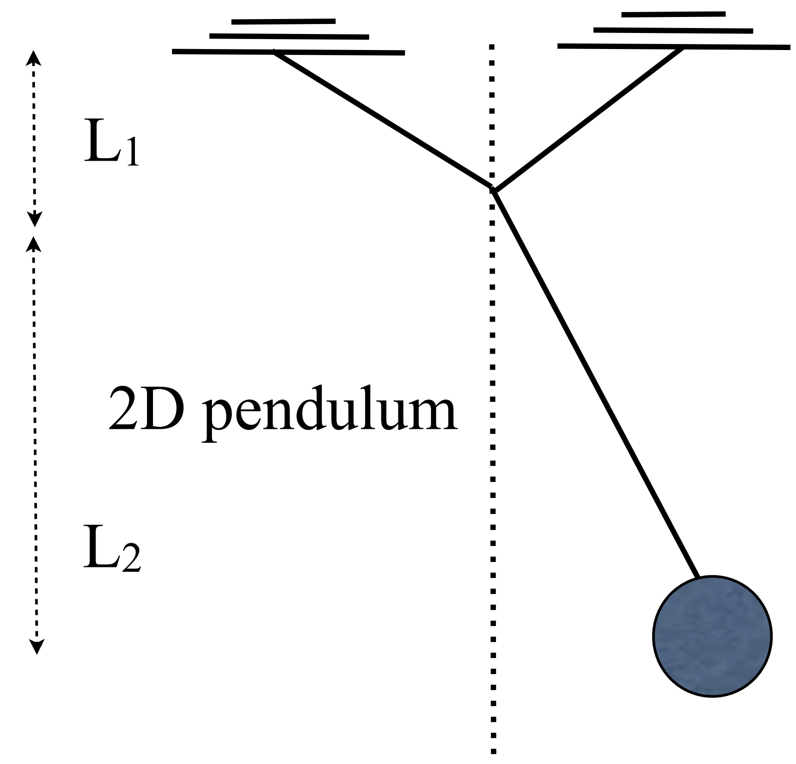
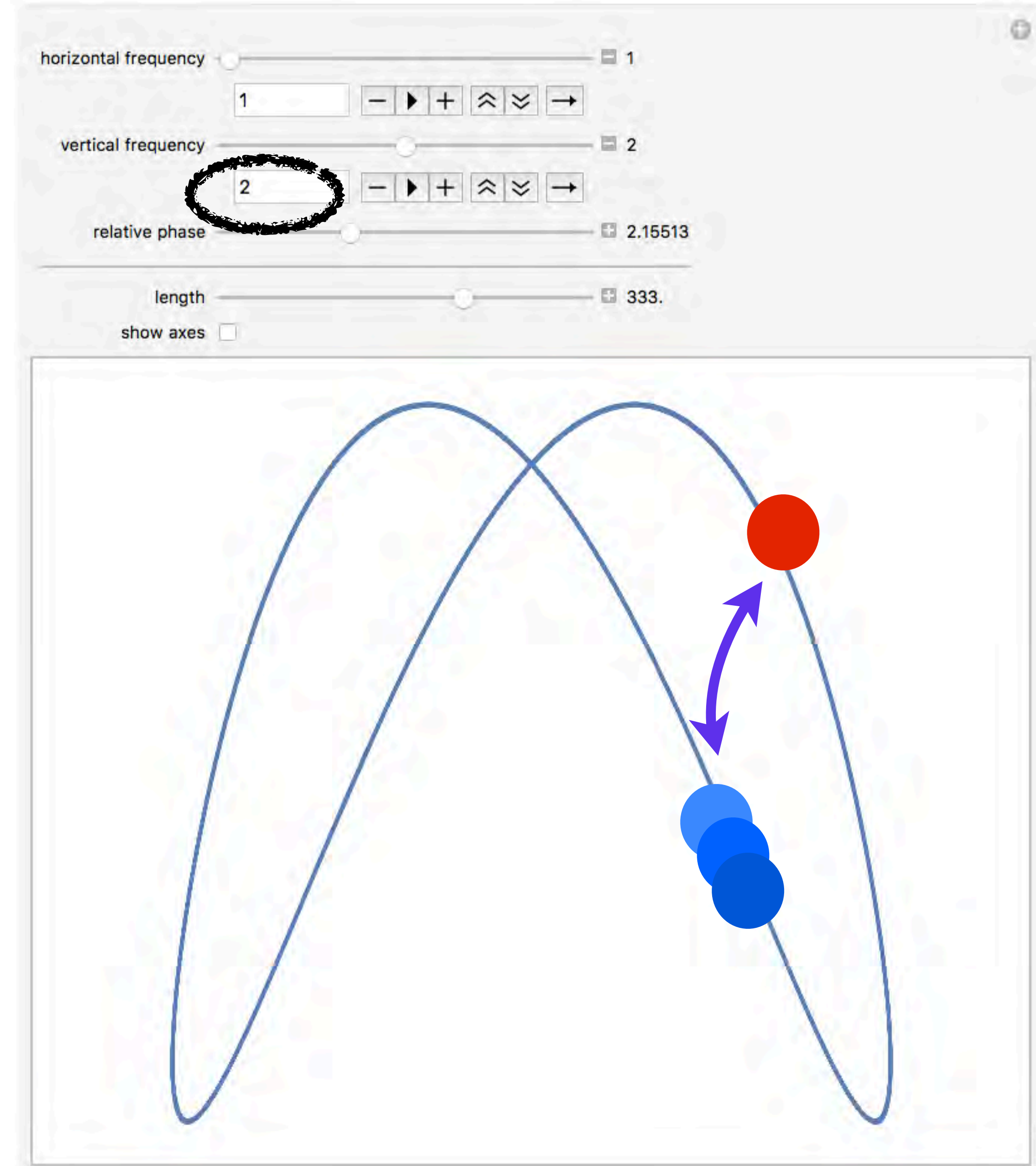
Why resonance matters ?

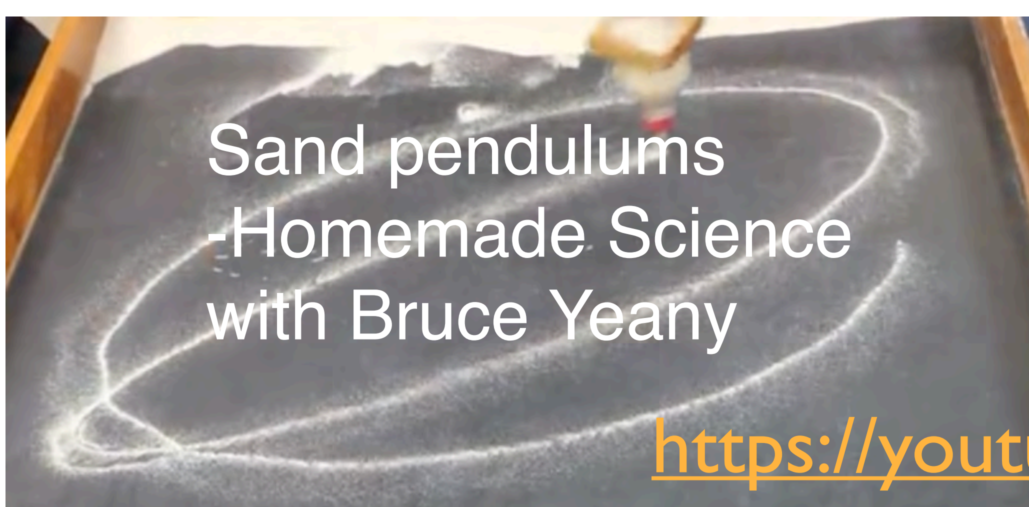




resonant

when ● and ● talk?

resonance drives recurrence



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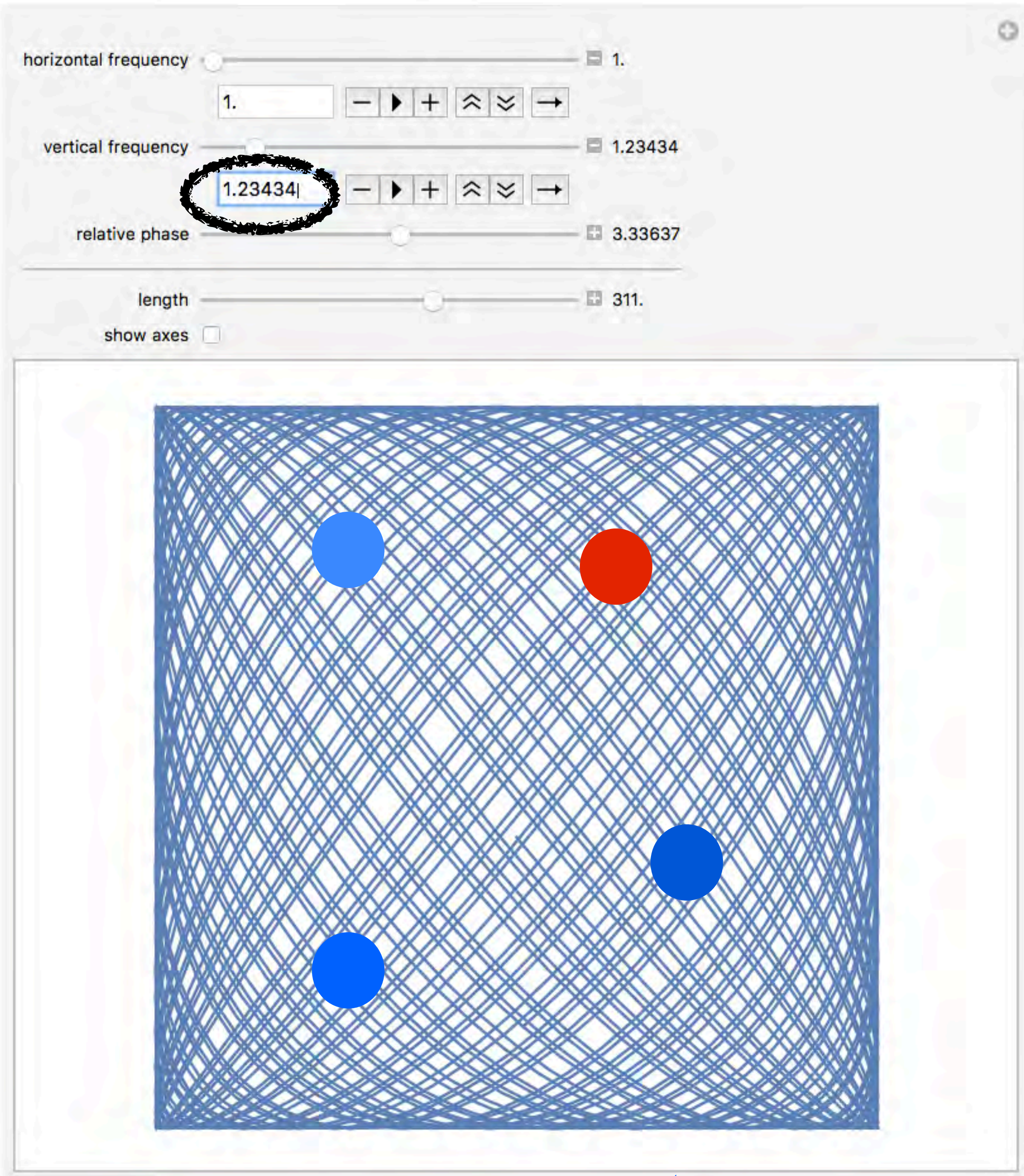
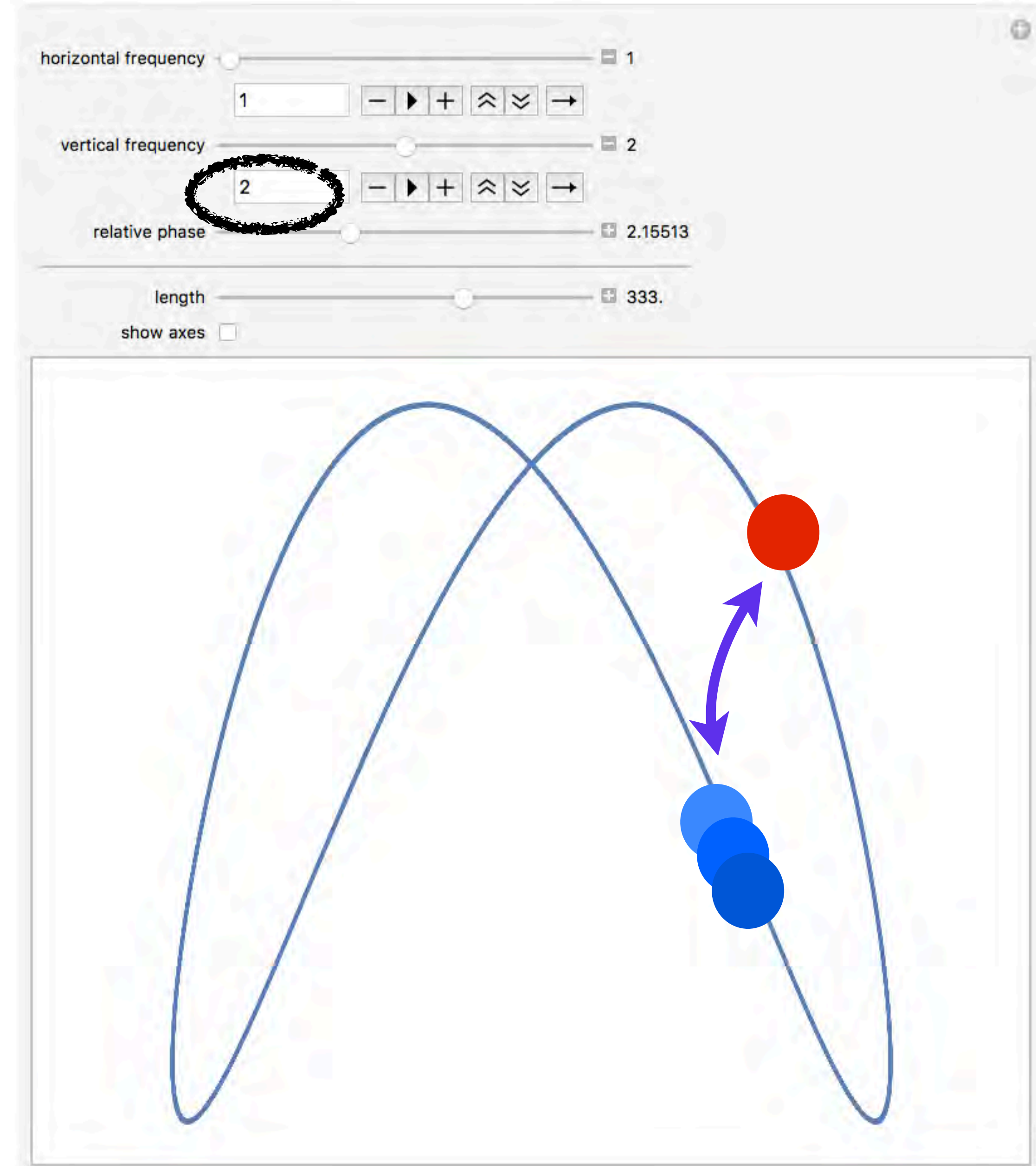
Why resonance matters ?



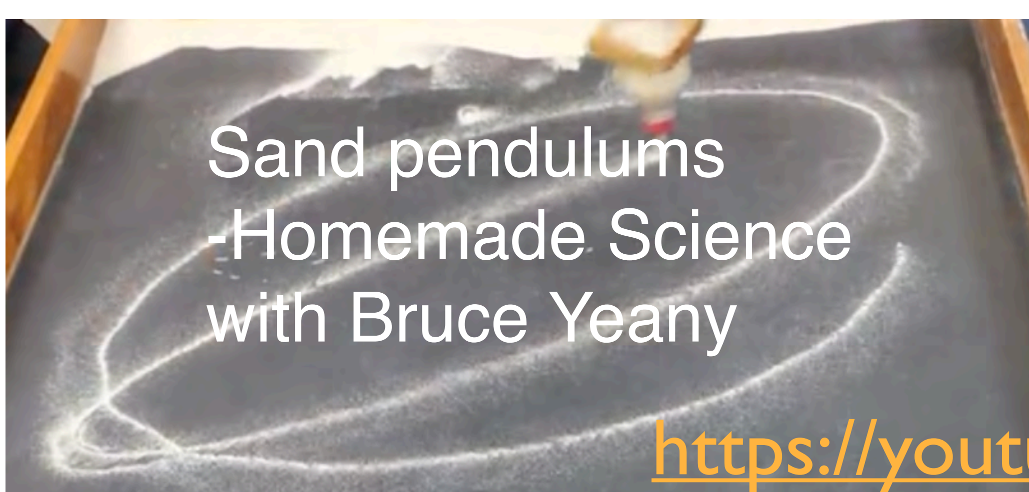
non resonant



resonant

when ● and ● talk?

resonance drives recurrence



https://youtu.be/uPbzhxYTioM

In order to turn left driver must turn right!

Bike counter-steering: casper+ gyroscopic effect

In order to turn left driver must turn right!

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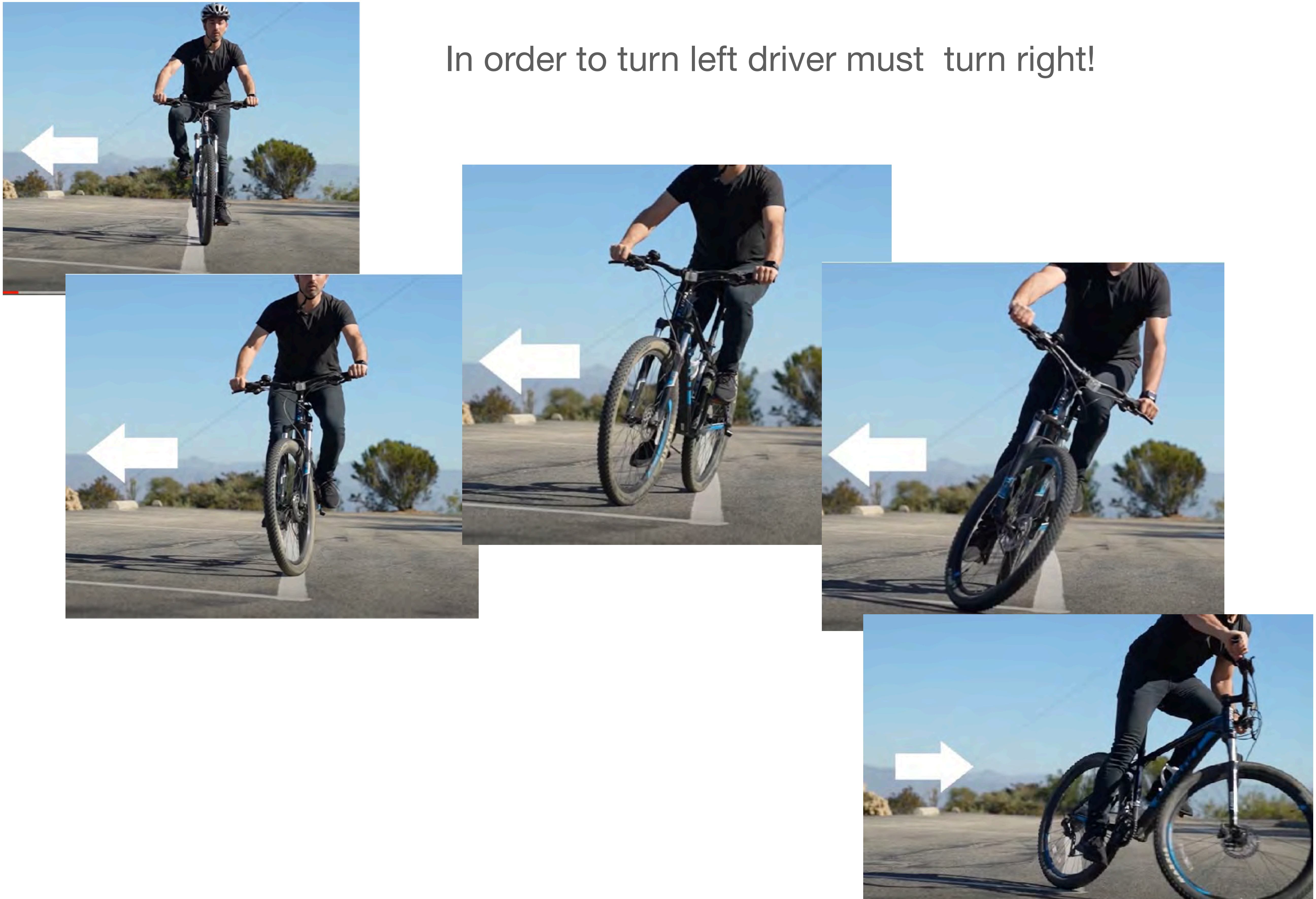
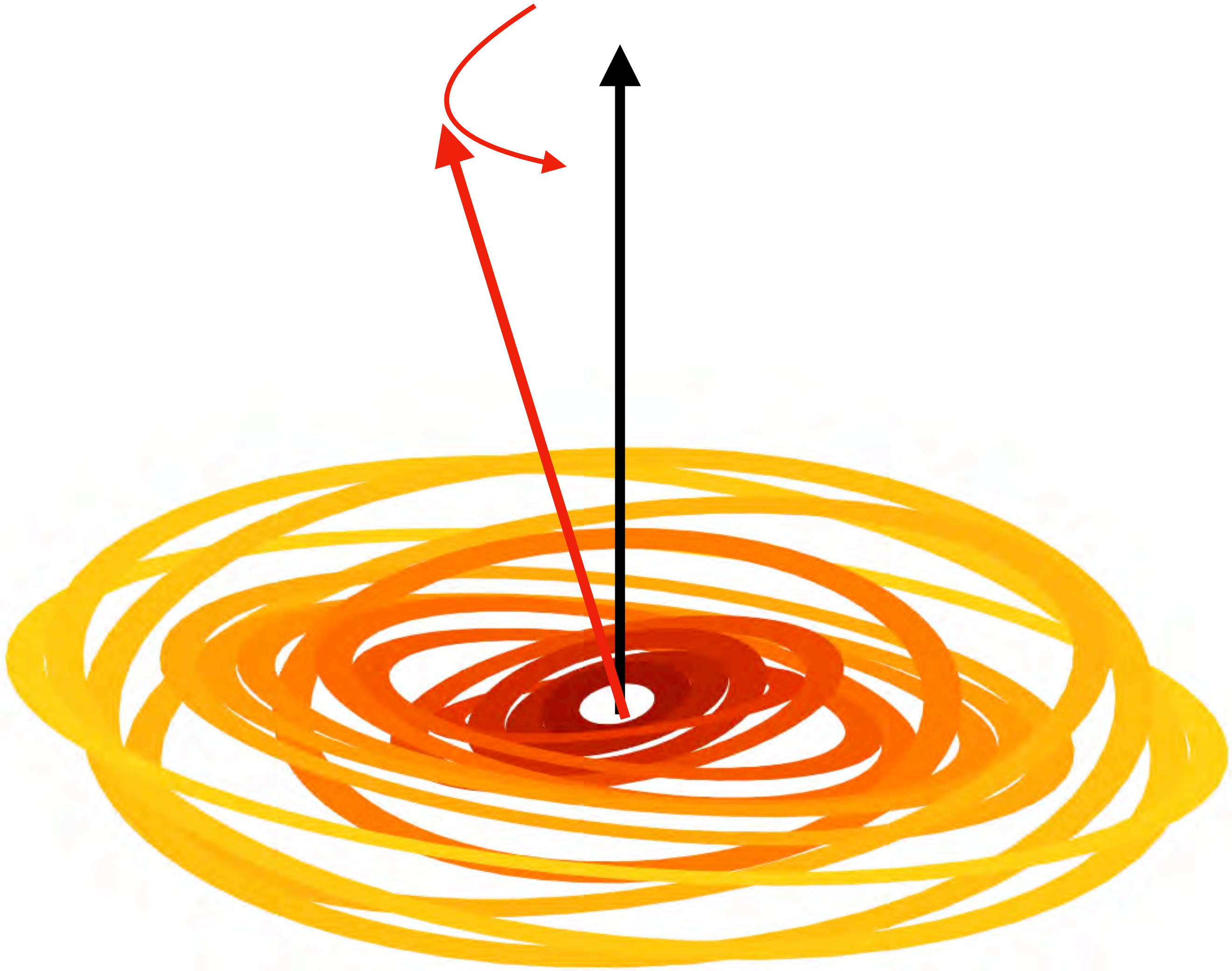
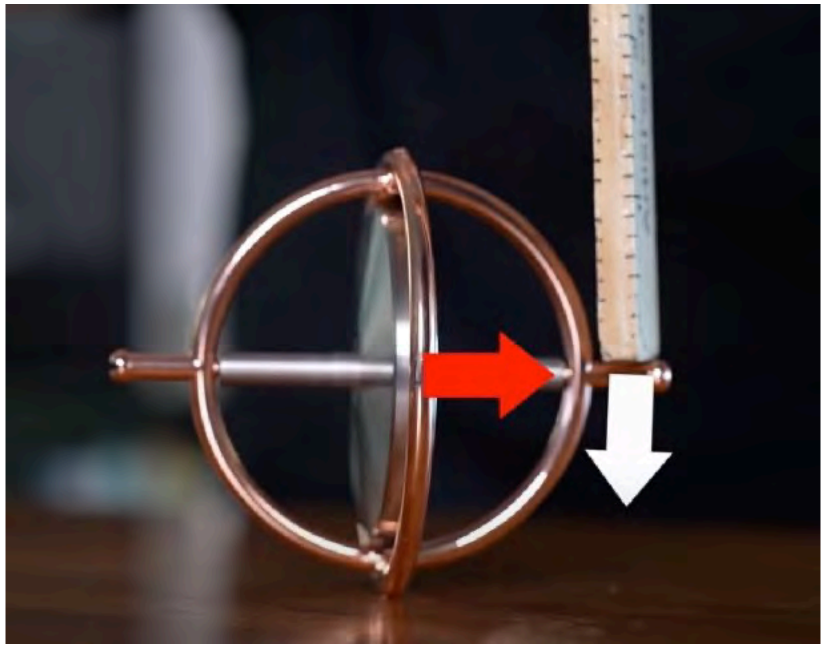


(c) veritassium 22

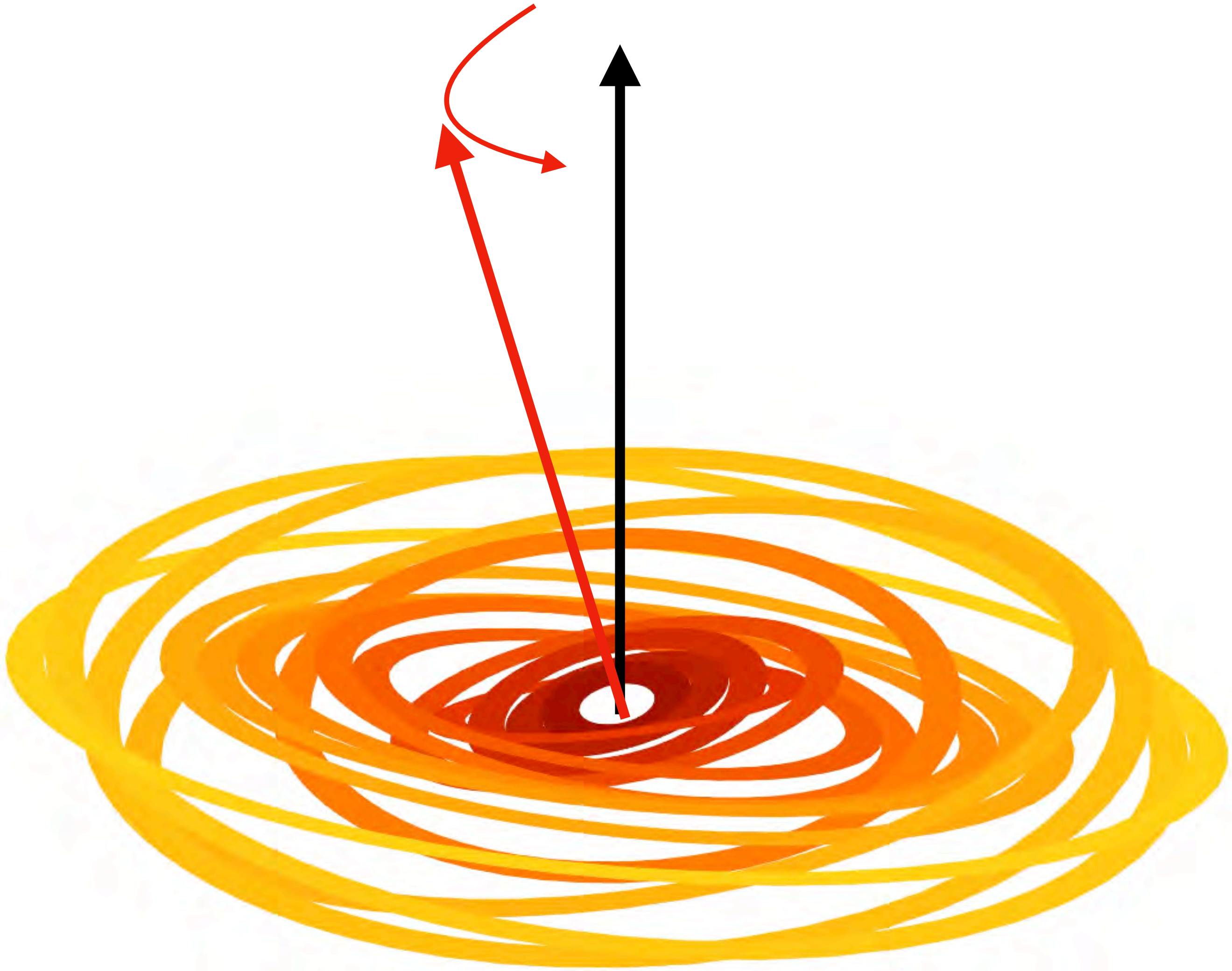
$$\dot{\mathbf{n}}_i = \boldsymbol{\Omega}(\{\mathbf{n}_j\}) \times \mathbf{n}_i \,, \quad \text{with} \quad \boldsymbol{\Omega}(\{\mathbf{n}_j\}) = \sum_{j,\ell} P_\ell\,(\mathbf{n}_i \cdot \mathbf{n}_j)\,\mathbf{n}_j \left(\frac{r_<}{r_>}\right)^{\ell}_{i,j}$$

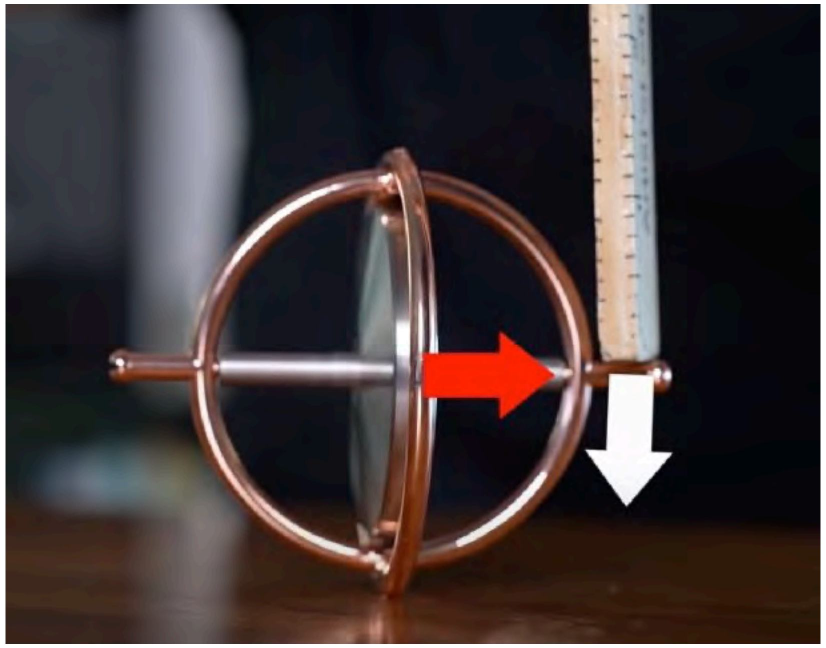




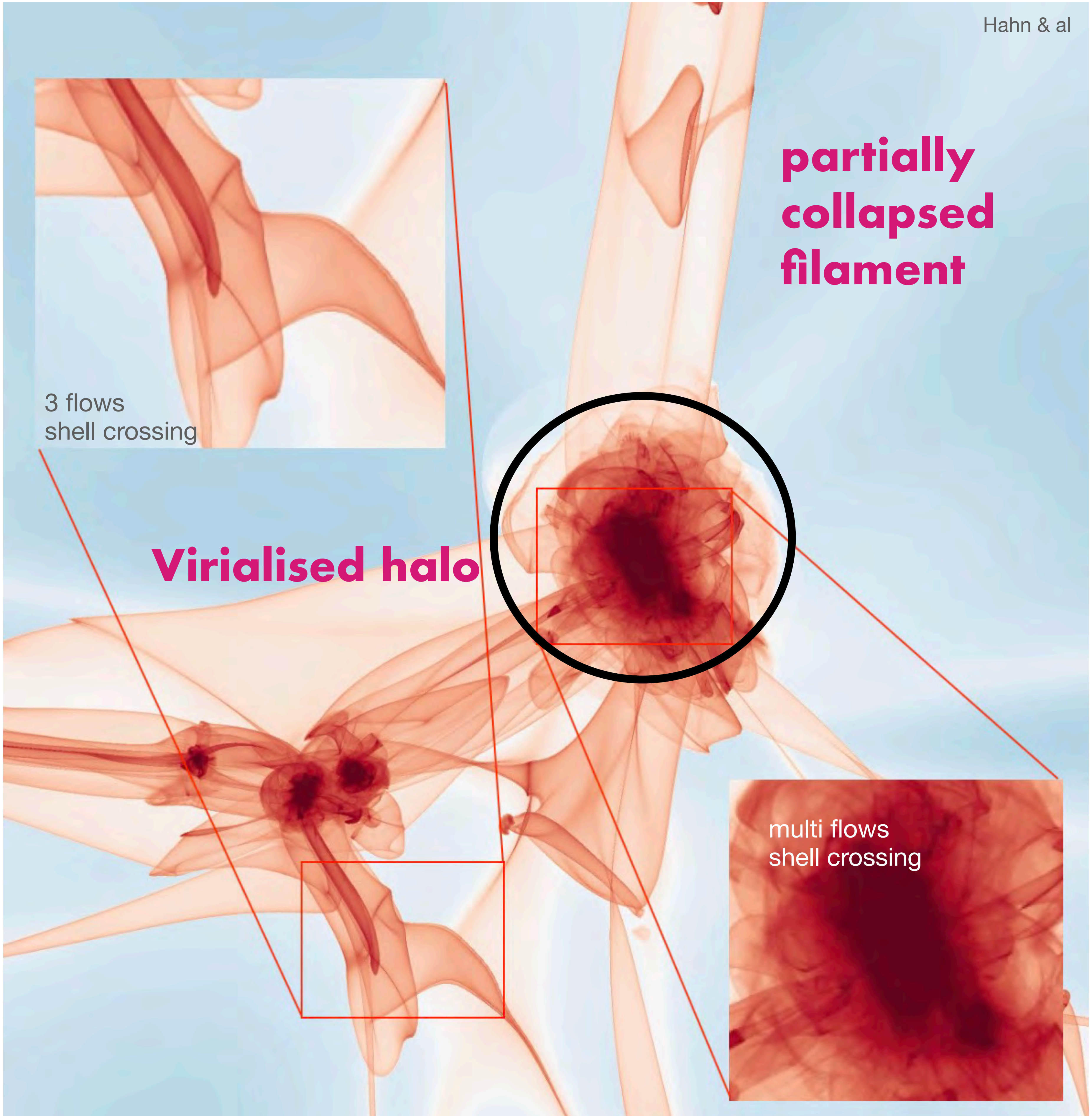
Gyroscopic equation

$$\dot{\mathbf{n}}_i = \boldsymbol{\Omega}(\{\mathbf{n}_j\}) \times \mathbf{n}_i\,, \quad \text{with} \quad \boldsymbol{\Omega}(\{\mathbf{n}_j\}) = \sum_{j,\ell} P_\ell\,(\mathbf{n}_i \cdot \mathbf{n}_j)\,\mathbf{n}_j \left(\frac{r_<}{r_>}\right)_{i,j}^{\ell}$$

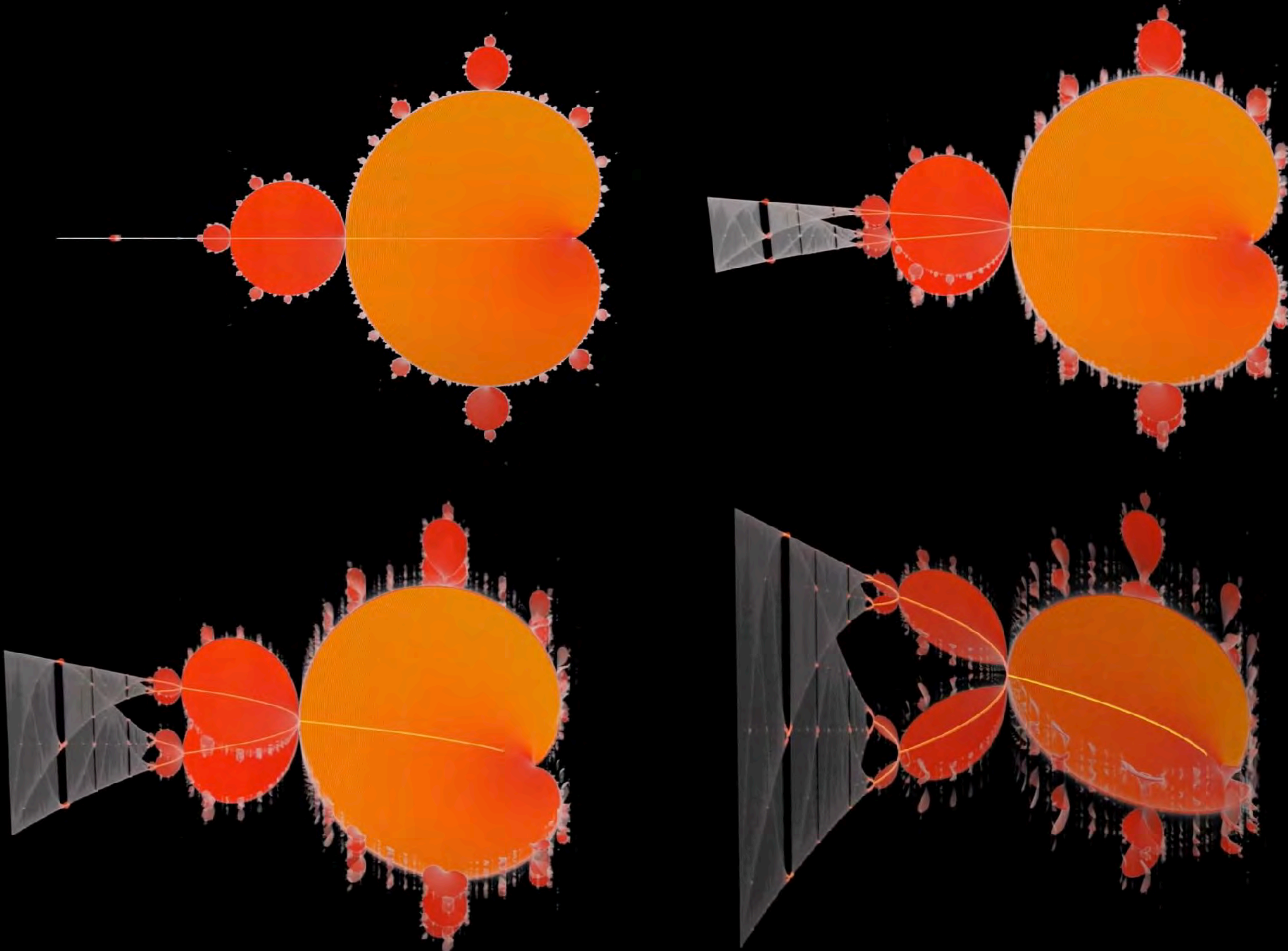




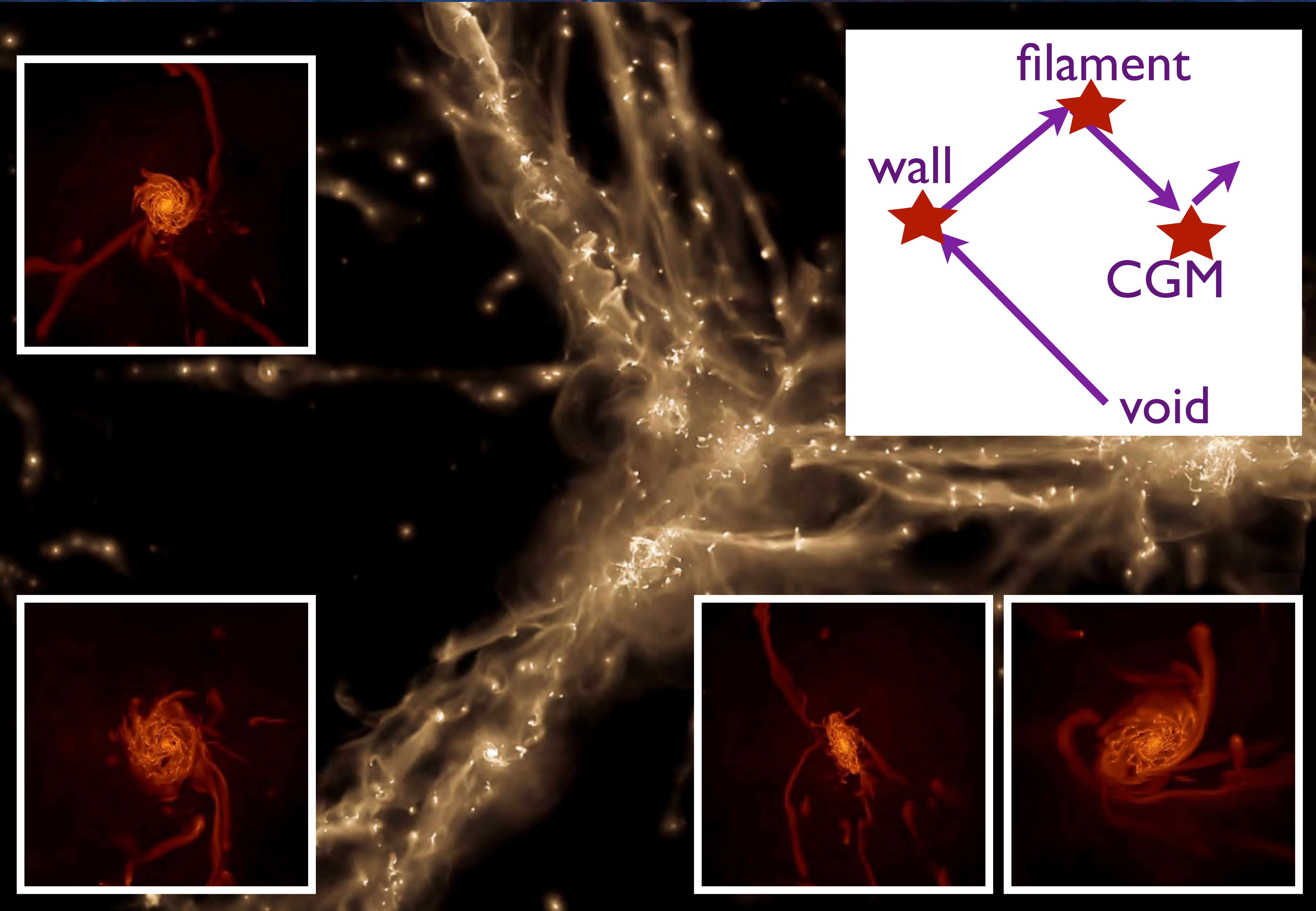
Spherical versus partial collapse



Link to Mandelbrot Set (Veritassium 2021)



Geometry of flow: Eulerian view @ high resolution.



2.4 Observable: morphology change within saddle frame

$$\frac{\partial f_R}{\partial t} = \frac{\partial}{\partial \mathbf{J}} \cdot \mathbf{D}_R \cdot \frac{\partial f_R}{\partial \mathbf{J}} + s_R(\mathbf{J})\,,$$

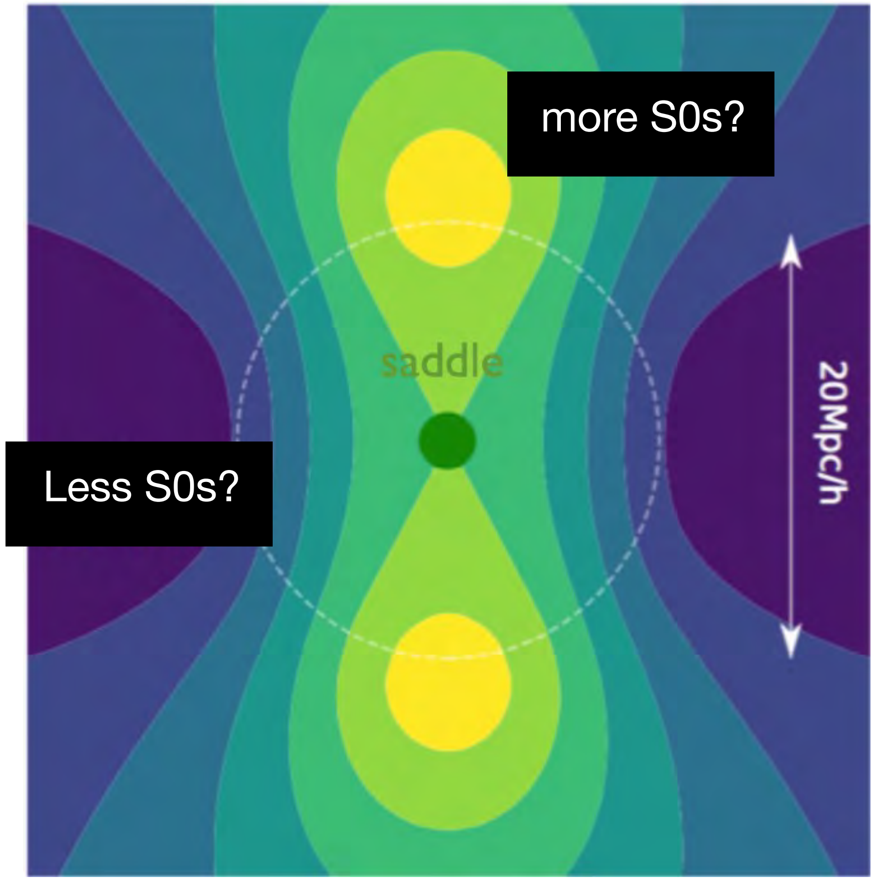
source of new stars

possibly subject to environmental variation labelled by R= $(r, \mathcal{Q})$

IN PROGRESS

Green function

$$G_R(\mathbf{J}, t\,|\,\mathbf{J}', t') \approx \frac{\exp\left(-\frac{(\mathbf{J}-\mathbf{J}')^{\mathrm{T}}\,\mathbf{D}_R^{-1}\,(\mathbf{J}-\mathbf{J}')}{4\,(t-t')}\right)}{\sqrt{(4\pi\,(t-t'))^3\,\det(\mathbf{D}_R)}}\,.$$



predict **morphology** (subject to R?)

$$f_R(\mathbf{J}, t) = \int \mathrm{d}\mathbf{J}'\mathrm{d}t' G_R(\mathbf{J}, t\,|\,\mathbf{J}', t') s_R(\mathbf{J}', t')\,,$$

Differential competition between

- Heating by orbital diffusion
- Cooling by star formation on circular orbits
- Quenching of gas inflow

Diffusion coefficient

$$\mathbf{D}_R \propto \left\langle \left| \delta\psi(k, \omega) \right|^2 \right\rangle_R$$

potential fluctuations

$$\Sigma_R(r, t) = \int \mathrm{d}^3 v\, \mathrm{d}z\, f_R(\mathbf{J}, t)\,,$$

Surface density

$$1/n_s(R, t) \equiv -\left\langle \mathrm{d}\log \Sigma_R / \mathrm{d}\log r \right\rangle_r$$

Sérsic index

$$\frac{\partial f_R}{\partial t} = \frac{\partial}{\partial \mathbf{J}} \cdot \mathbf{D}_R \cdot \frac{\partial f_R}{\partial \mathbf{J}} + s_R(\mathbf{J}) \,,$$

source of new stars

possibly subject to environmental variation labelled by R= $(r, \mathcal{Q})$

Green function IN PROGRESS

$$G_R(\mathbf{J}, t \,|\, \mathbf{J}', t') \approx \frac{\exp\left(-\frac{(\mathbf{J}-\mathbf{J}')^{\mathrm{T}}\mathbf{D}_R^{-1}(\mathbf{J}-\mathbf{J}')}{4(t-t')}\right)}{\sqrt{(4\pi(t-t'))^3 \det(\mathbf{D}_R)}} \,.$$

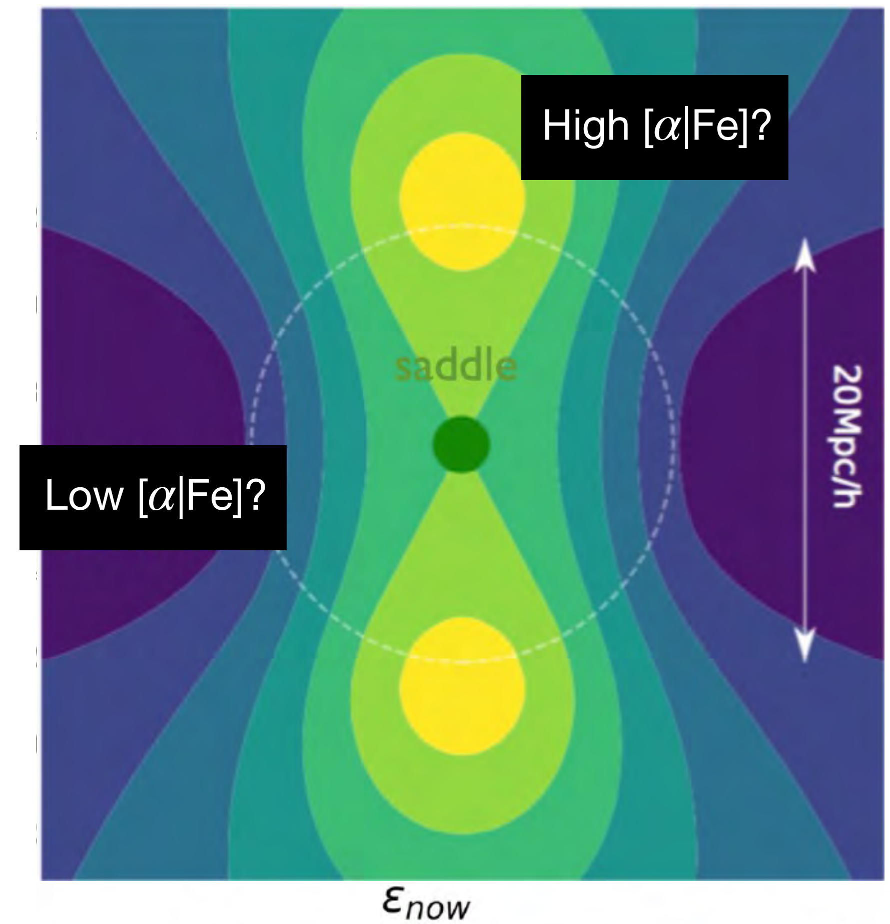
Diffusion coefficient

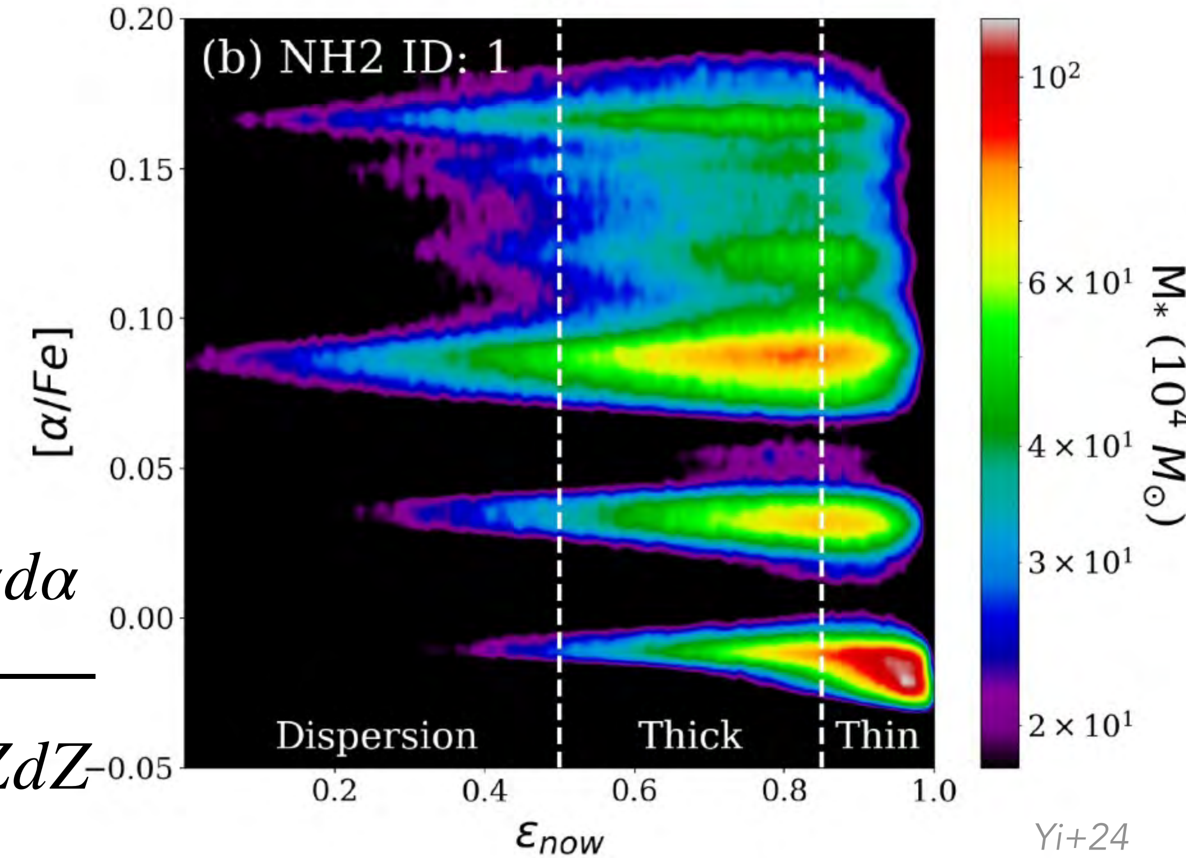
$$\mathbf{D}_R \propto \left\langle \left| \delta\psi(k,\omega) \right|^2 \right\rangle_R$$

potential fluctuations

predict element abundance ratio (subject to R?)

$$[\alpha/Z](\mathbf{I}, t) = \log \frac{\int \dot{\Sigma}_*(t_0(\alpha)) G(\mathbf{I}, t \,|\, \mathbf{I}_0, t_0(\alpha)) \left| dt_0/d\alpha \right| \alpha d\alpha}{\int \dot{\Sigma}_*(t_0(Z)) G(\mathbf{I}, t \,|\, \mathbf{I}_0, t_0(Z)) \left| dt_0/dZ \right| Z dZ}$$





Yi+24

Perturbative (quasi-linear) expansion

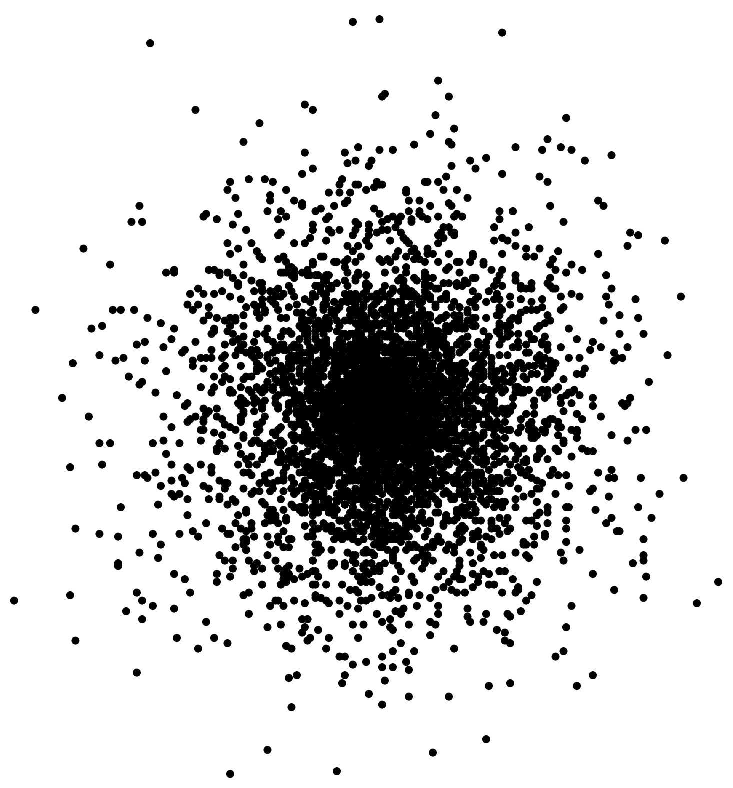
$$F_\mathrm{d} = F + \delta F$$

$$F = \langle F_\mathrm{d} \rangle$$

One galaxy

$$H_\mathrm{d} = H + \delta H$$

$$H = \langle H_\mathrm{d} \rangle$$



Predicts the secular evolution of the **mean** galaxy

Perturbative (quasi-linear) expansion

$$F_{\mathrm{d}} = F + \delta F$$

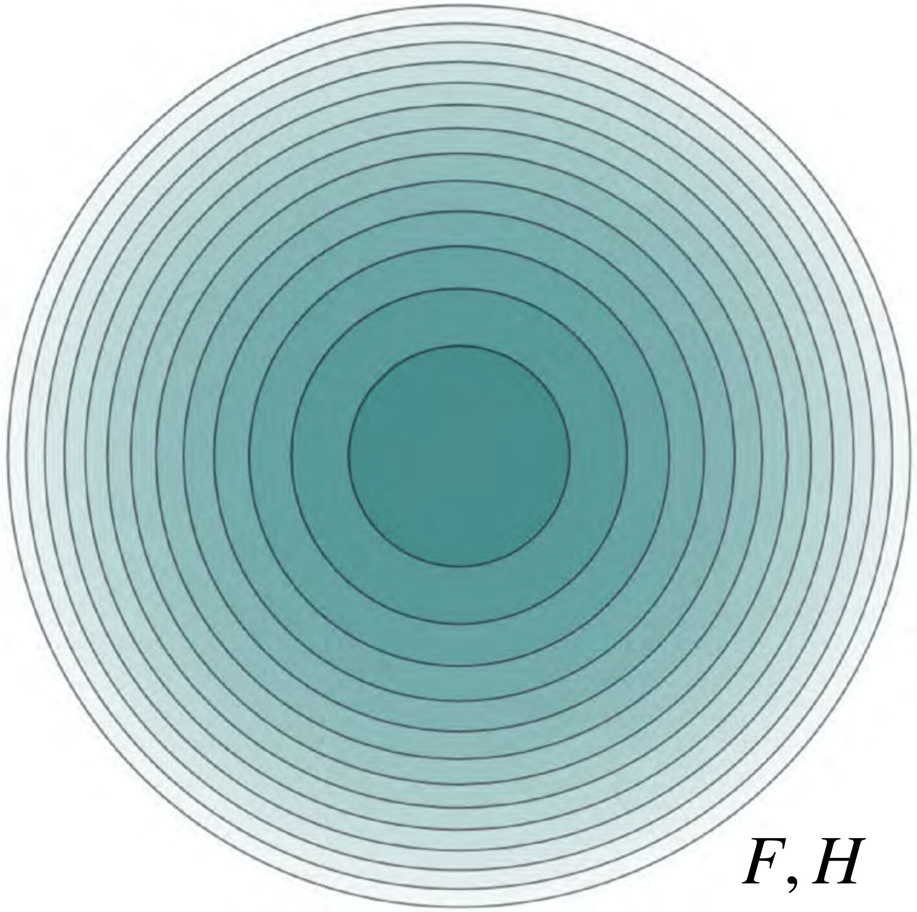
$$F = \langle F_{\mathrm{d}} \rangle$$

Smooth ensemble average

One galaxy

$$H_{\mathrm{d}} = H + \delta H$$

$$H = \langle H_{\mathrm{d}} \rangle$$



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$$F = \langle F_{\rm d} \rangle$$

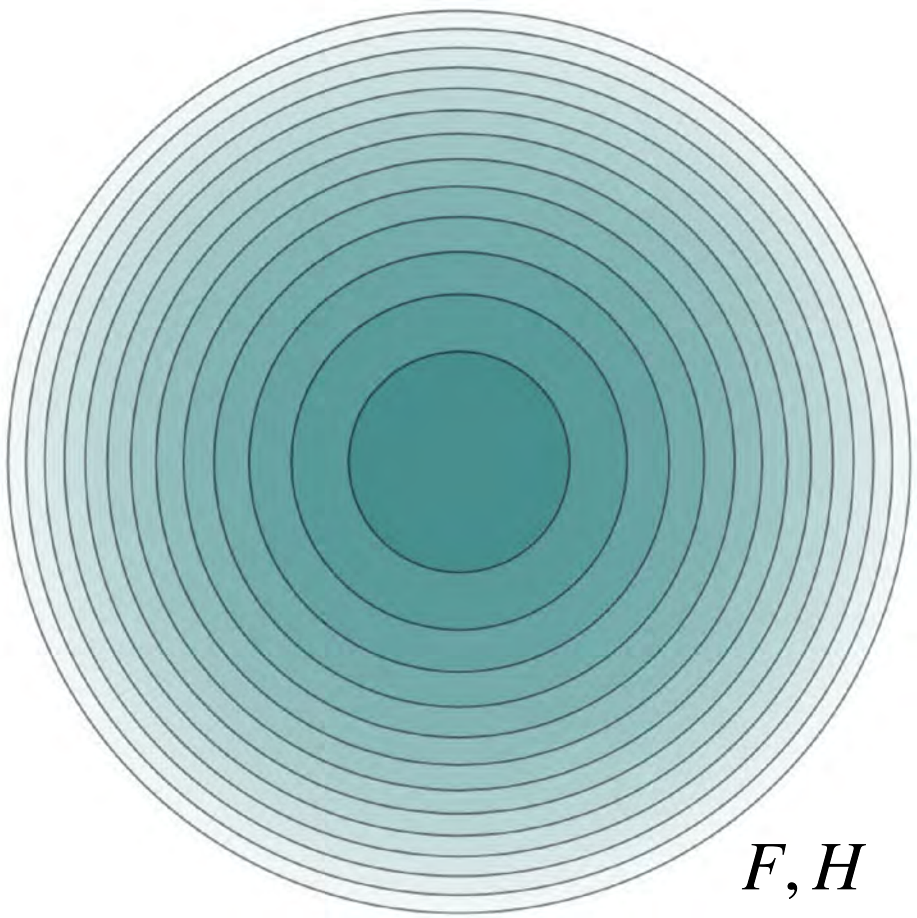
Smooth ensemble average

One galaxy

Stacking galaxies

$$H_{\rm d} = H + \delta H$$

$$H = \langle H_{\rm d} \rangle$$



F, H

Predicts the secular evolution of the **mean** galaxy

Perturbative (quasi-linear) expansion

$$F_{\mathrm{d}} = F + \delta F$$

One galaxy

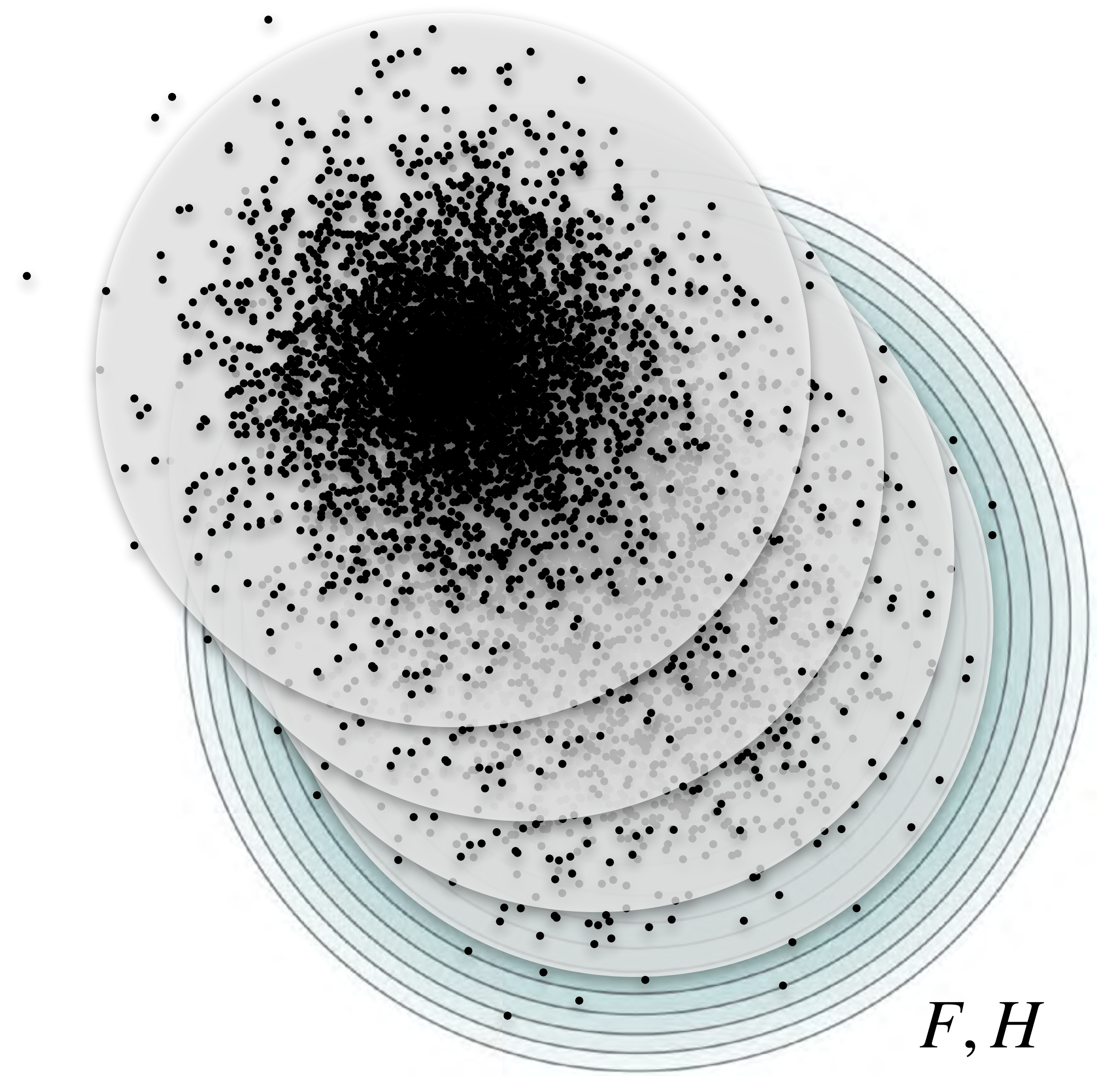
$$H_{\mathrm{d}} = H + \delta H$$

$$F = \langle F_{\mathrm{d}} \rangle$$

Smooth ensemble average

Stacking galaxies

$$H = \langle H_{\mathrm{d}} \rangle$$



Predicts the secular evolution of the **mean** galaxy

Perturbative (quasi-linear) expansion

$$F_{\mathrm{d}} = F + \delta F$$

$$F = \langle F_{\mathrm{d}} \rangle$$

What ensemble?

Smooth **ensemble** average

Stacking galaxies

One galaxy

Density fluctuations

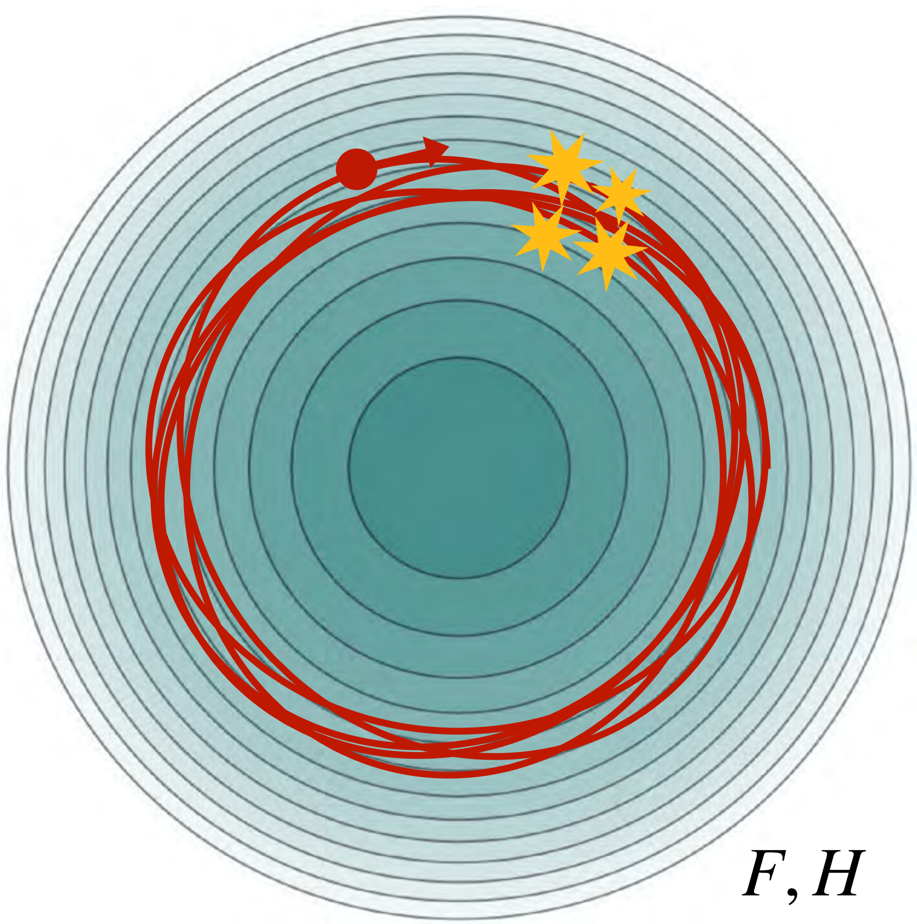
$$H_{\mathrm{d}} = H + \delta H$$

$$H = \langle H_{\mathrm{d}} \rangle$$

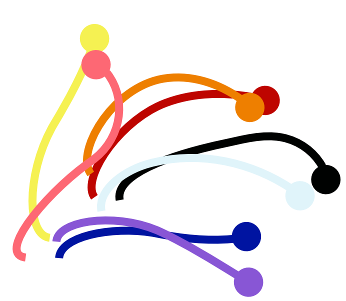
mean field **Orbits**

Potential fluctuations

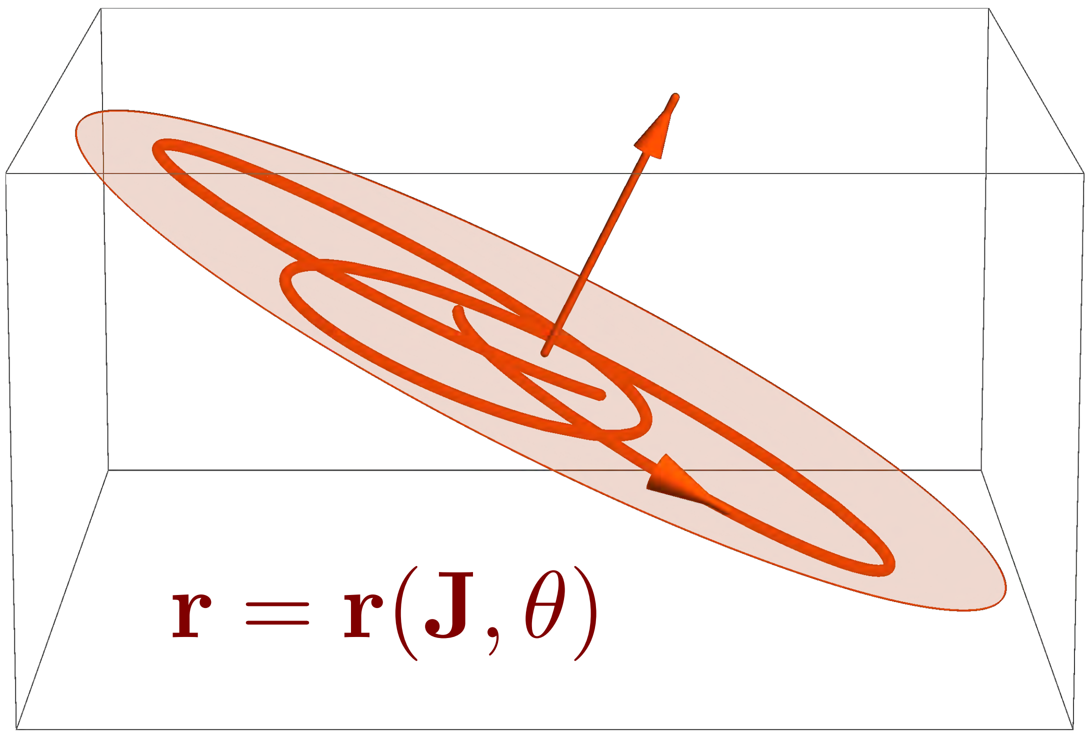
Diffusion



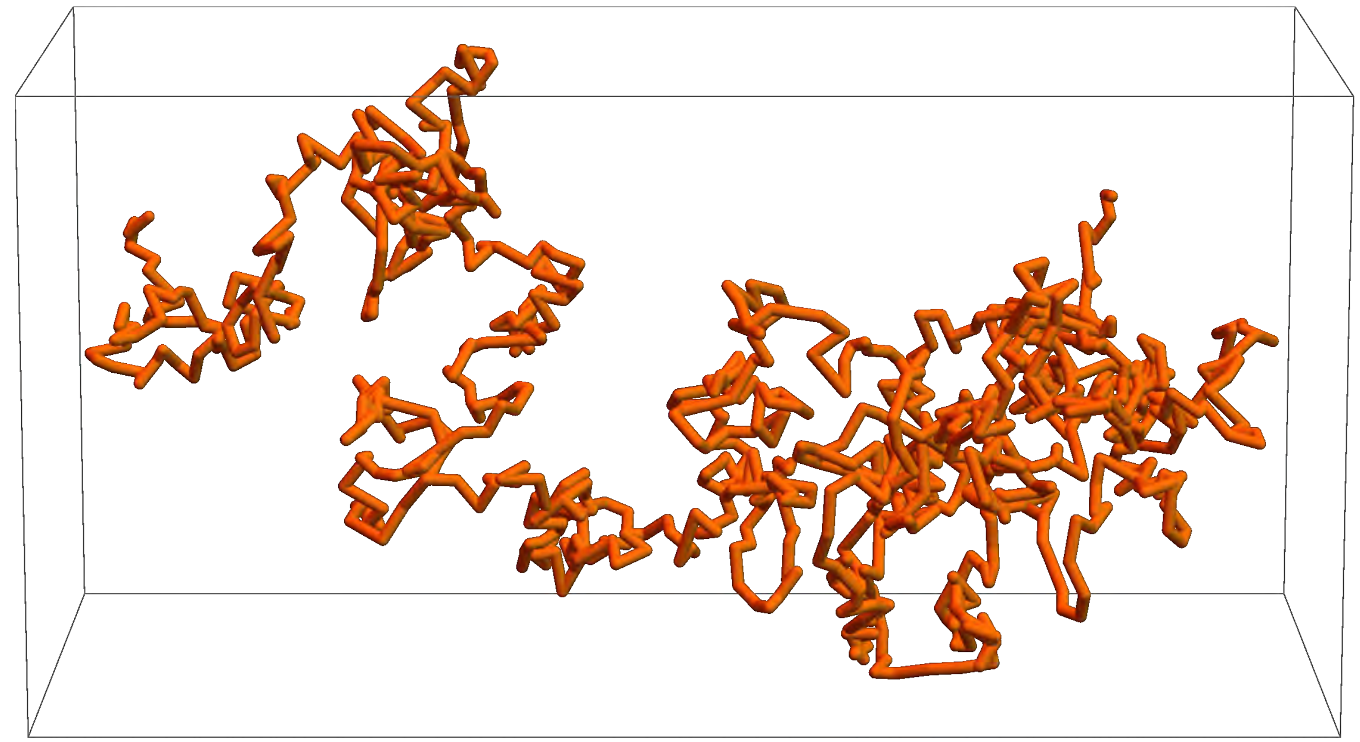
F, H



Along the unperturbed orbit



Potential fluctuate (stronger if resonances)

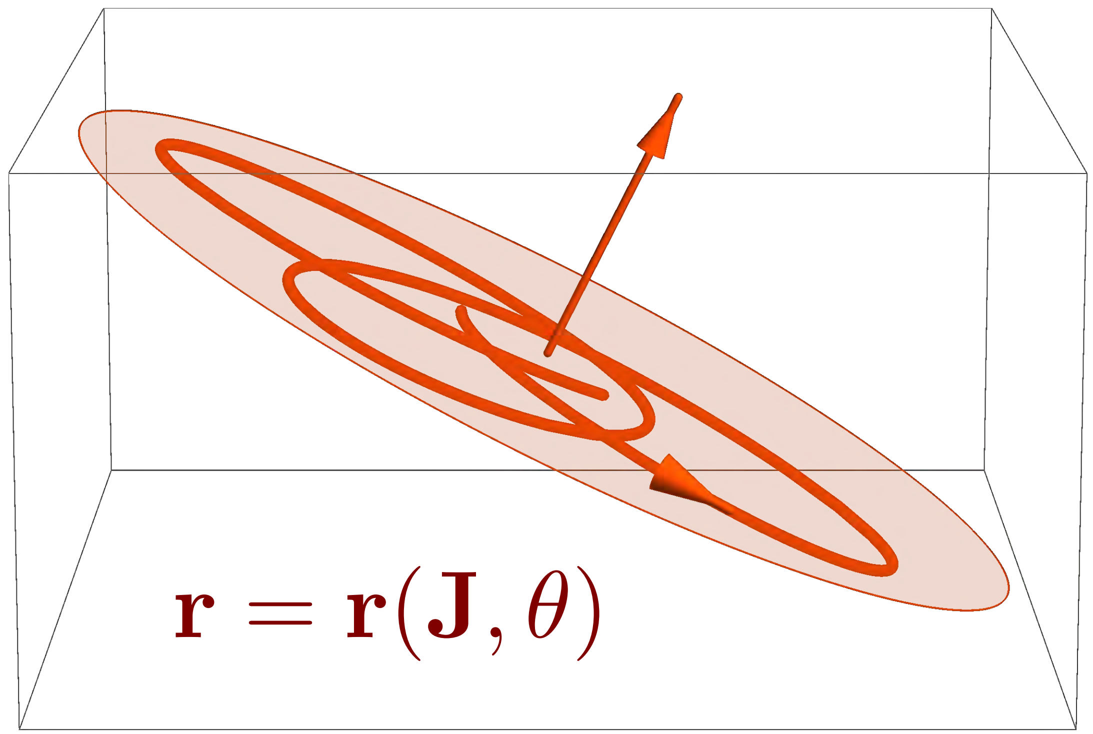


$$\delta\psi(\mathbf{r},t) \rightarrow \sum_{\mathbf{m}} \delta\hat{\psi}_{\mathbf{m}}(\mathbf{J},\omega)\exp\left(i\mathbf{m}\cdot\theta-\omega t\right)$$

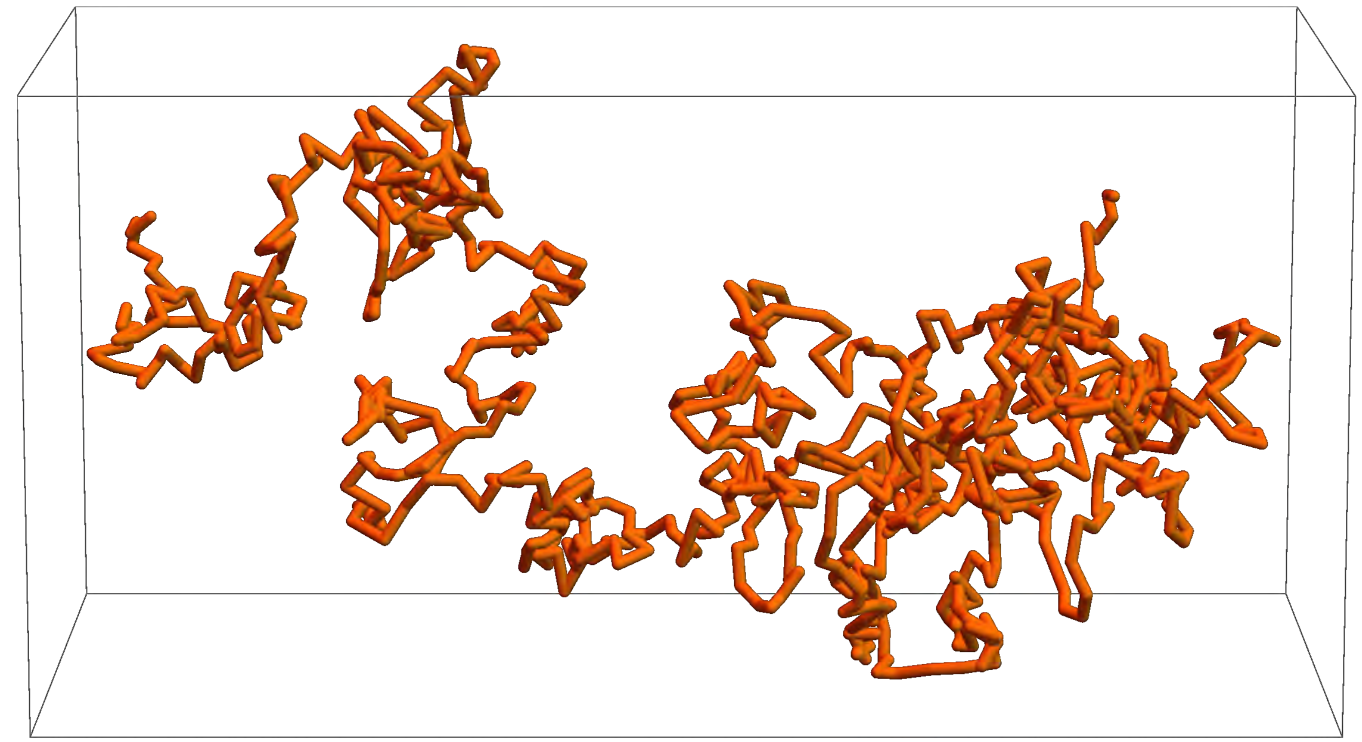
Fluctuating potential

Harmonic component

Along the unperturbed orbit



Potential fluctuate (stronger if resonances)

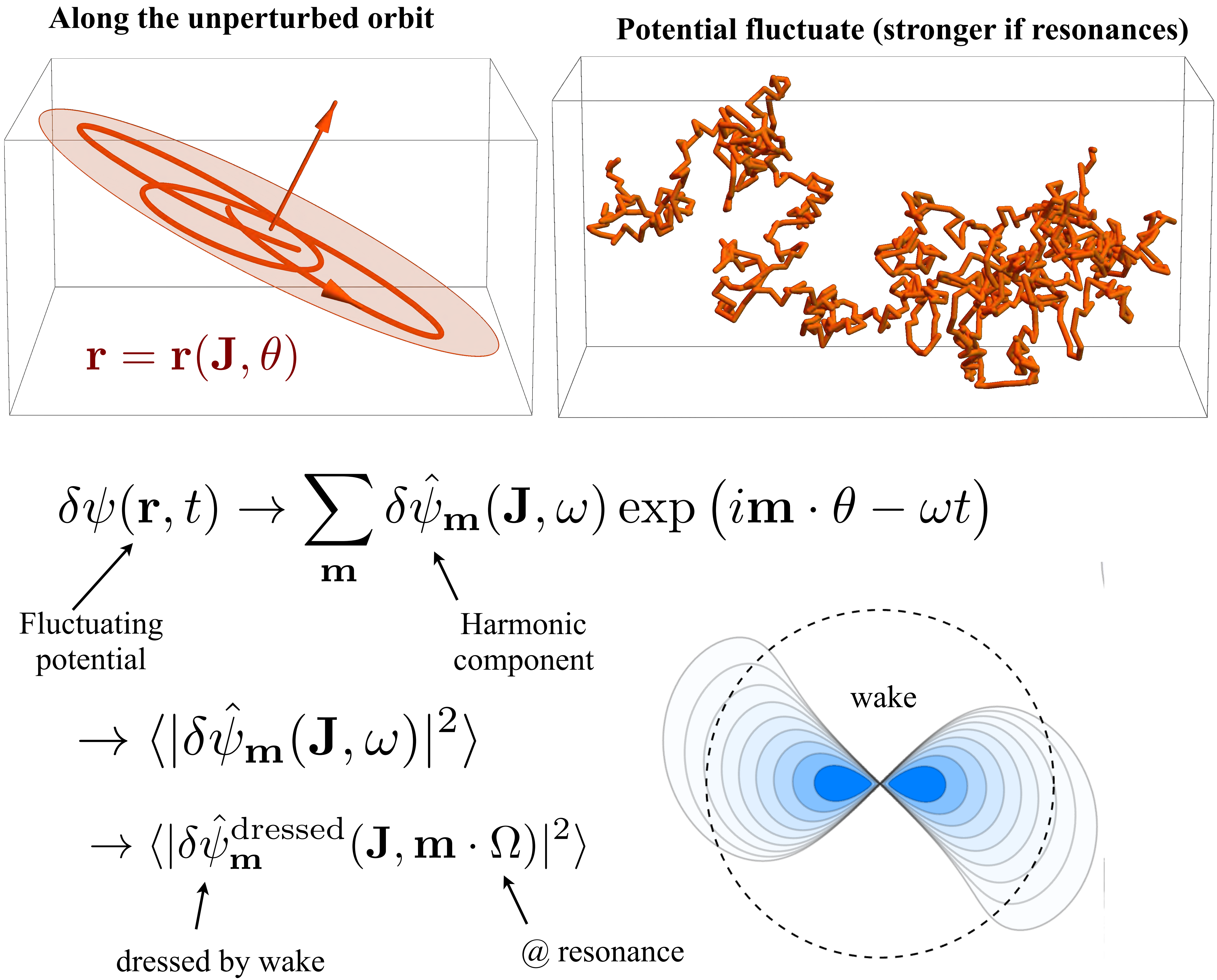


$$\delta\psi(\mathbf{r}, t) \rightarrow \sum_{\mathbf{m}} \delta\hat{\psi}_{\mathbf{m}}(\mathbf{J}, \omega) \exp\left(i\mathbf{m}\cdot\theta - \omega t\right)$$

Fluctuating potential

Harmonic component

$$\rightarrow \langle |\delta\hat{\psi}_{\mathbf{m}}(\mathbf{J}, \omega)|^2 \rangle$$



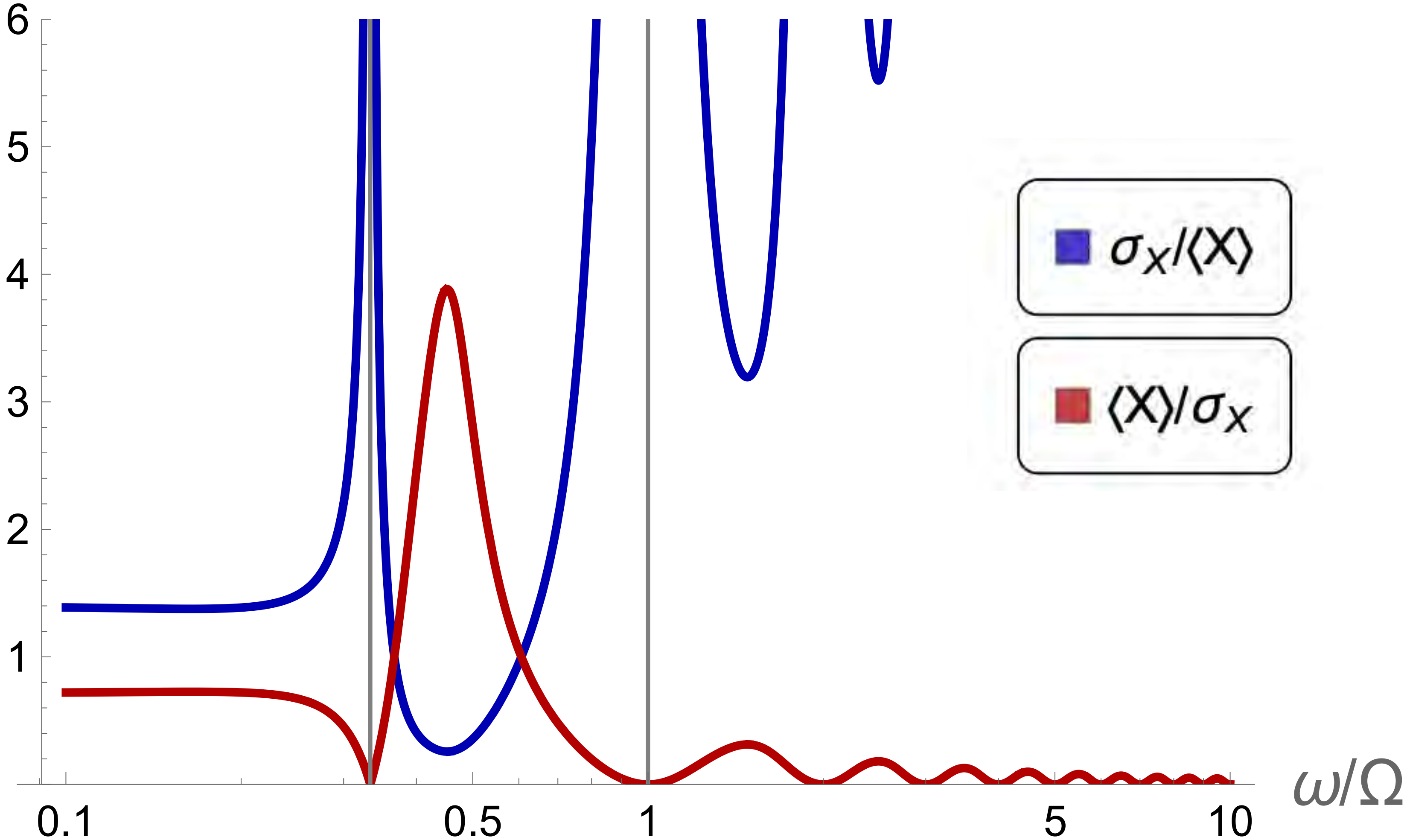
Along the unperturbed orbit
Potential fluctuate (stronger if resonances)
$\mathbf{r} = \mathbf{r}(\mathbf{J}, \theta)$
$\delta\psi(\mathbf{r}, t) \to \sum_{\mathbf{m}} \delta\hat{\psi}_{\mathbf{m}}(\mathbf{J}, \omega) \exp\left(i\mathbf{m}\cdot\theta - \omega t\right)$
Fluctuating potential
Harmonic component
$\to \langle|\delta\hat{\psi}_{\mathbf{m}}(\mathbf{J}, \omega)|^2\rangle$
$\to \langle|\delta\hat{\psi}^{\mathrm{dressed}}_{\mathbf{m}}(\mathbf{J}, \mathbf{m}\cdot\Omega)|^2\rangle$
dressed by wake
@ resonance
wake

Galaxies are multi-scale non-linearly asymmetrically coupled systems

$$\ddot{X} + \Omega^2 X = \epsilon X_{\rm env}^3 \quad \text{given} \quad \ddot{X}_{\rm env} + \omega^2 X_{\rm env} = 0$$

SNR, 1/SNR

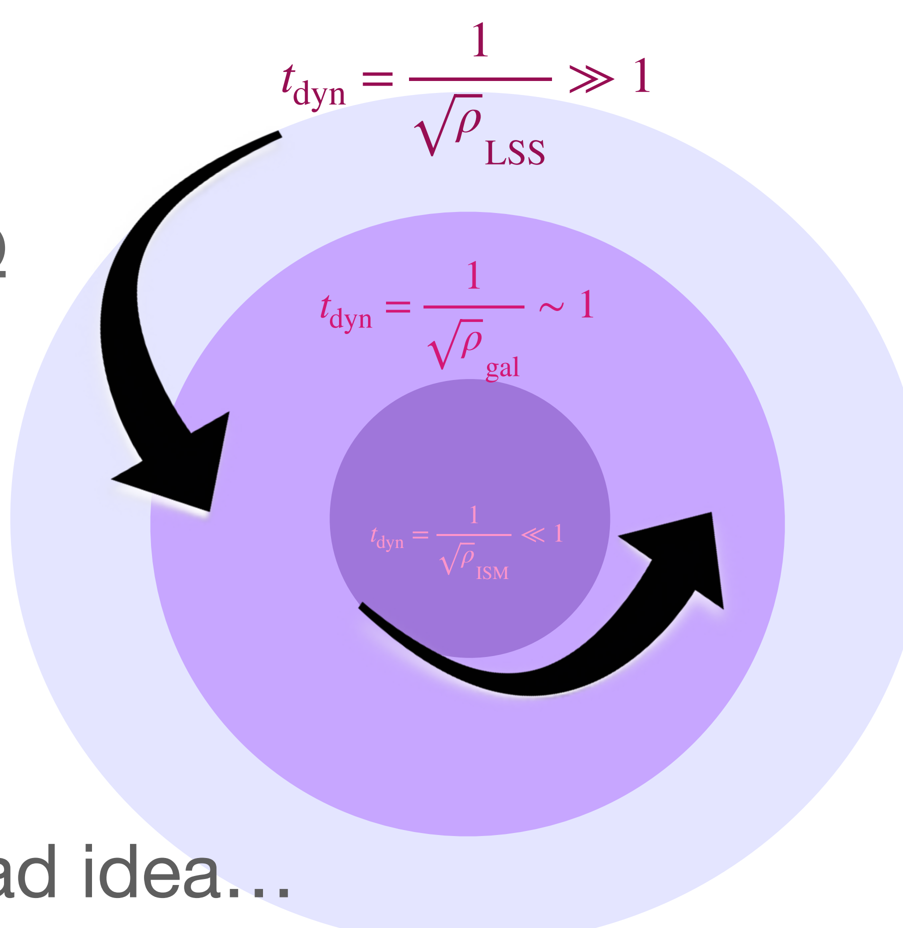
Coupling to ISM impact RMS



Coupling to IGM impacts mean

$$\langle X \rangle = \frac{\sin^2(3\pi\omega)}{12\pi\omega(3\omega-1)(3\omega+1)} - \frac{3\sin^2(\pi\omega)}{4\pi(\omega-1)\omega(\omega+1)}$$

$$\sigma_X = \frac{\sin^4(\pi\omega)\left(-75\omega^2 + 8\left(\omega^2-1\right)\cos(2\pi\omega) + 4\left(\omega^2-1\right)\cos(4\pi\omega) + 3\right)}{16\pi^2\omega^2\left(\omega^2-1\right)^2\left(9\omega^2-1\right)} - \frac{8\sin^4(3\pi\omega) + 3\pi\omega\sin(12\pi\omega)}{1152\pi^2\omega^2\left(1-9\omega^2\right)^2} + \frac{8\pi\omega\left(365\omega^4 - 82\omega^2 + 5\right) - 3\left(261\omega^4 - 74\omega^2 + 5\right)\sin(4\pi\omega) + 3\left(9\omega^4 - 10\omega^2 + 1\right)\sin(8\pi\omega)}{128\pi\omega\left(9\omega^4 - 10\omega^2 + 1\right)^2}$$



Why (naive) subgrid physics is a bad idea…

Discussion

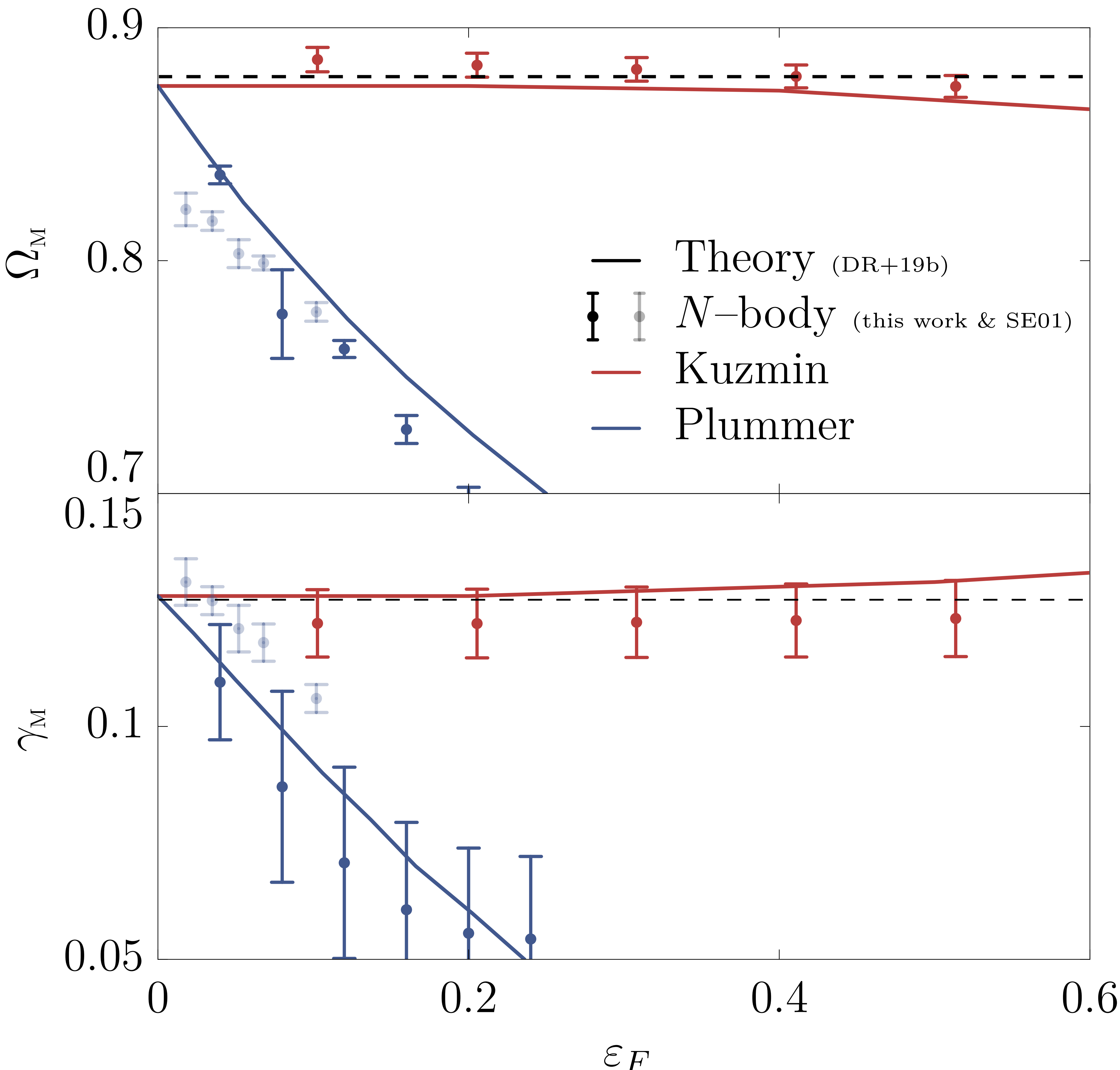
Bring home message

- Feedback+SF physics transpires to self-regulated disc geometry via wake!
- Gas inflow yields emergence via homeostasis: rotation matters!
- CGM = free energy reservoir: top down causation from cosmic coherence
  - regulation can be broken via change in vorticity and mass content of CGM.

- Proximity to *cliff* (Q<1) essential
- Close link to self-organised criticality/Maximum entropy production
- No absolute transition mass

- Variation of inflow that the disc's tolerate
  before instability /contraction ? (cf red giants)

- Assumes disc can respond thermally fast enough
- Leap of faith in dynamical range (SF controlled by turbulent injection scale)
- Ignore extension of disc + bars /bulge + life halo (locality)



0.9
0.8
0.7
Ω_M
Theory (DR+19b)
N–body (this work & SE01)
Kuzmin
Plummer
0.15
0.1
0.05
γ_M
0
0.2
0.4
0.6
ε_F

Heuristic derivation

$$\frac{\partial F}{\partial t} + [H, F] = 0 \quad \text{with} \quad H = \frac{v}{2} + \psi$$

$$F = f(\mathbf{I}, t) + \delta f(\mathbf{I}, \theta, t) \quad \text{with} \quad \frac{\partial \delta f}{\partial t} \gg \frac{\partial f}{\partial t}$$

Easy to derive

$$\frac{\partial f}{\partial t} = -\langle [\delta f, \delta\Phi] \rangle$$

where $[,]$ a Poisson bracket and $\langle . \rangle$ is ensemble average

f evolves because fluctuations in f and Φ correlated

- δf depends on $\delta\phi$ through eqns of motion
- $\delta\Phi$ depends on δf through Poisson eqn

Heuristic derivation

$$\frac{\partial F}{\partial t} + [H, F] = 0 \quad \text{with} \quad H = \frac{v}{2} + \psi$$

$$F = f(\mathbf{I}, t) + \delta f(\mathbf{I}, \theta, t) \quad \text{with} \quad \frac{\partial \delta f}{\partial t} \gg \frac{\partial f}{\partial t}$$

Diffusion Tensor

$$\frac{\partial f(\mathbf{J}, t)}{\partial t} = \frac{\partial}{\partial \mathbf{J}} \cdot \left(\mathbf{D} \cdot \frac{\partial f}{\partial \mathbf{J}} \right) \quad \text{where} \quad \mathbf{D} = \sum_{\mathbf{m}} D_{\mathbf{m}} \, \mathbf{m} \otimes \mathbf{m}$$

Dressed fluctuations | **Nurture** | At **resonance**

$$D_{\boldsymbol{m}}(\boldsymbol{J}) = \left\langle \left| \psi_{\boldsymbol{m}}^{\mathrm{tot}}(\omega) \right|^2 \right\rangle (\omega = \boldsymbol{m} \cdot \boldsymbol{\Omega}) = \frac{\left\langle \left| \psi_{\boldsymbol{m}}^{\mathrm{ext}}(\omega) \right|^2 \right\rangle}{\left| \varepsilon_{\boldsymbol{m}}(\boldsymbol{J}, \omega) \right|^2} (\omega = \boldsymbol{m} \cdot \boldsymbol{\Omega})$$

Nature

Context: explain the emergence of galactic discs and scaling laws to motivate
what is observed in simulations & JWST

Upshot: galactic discs are attractors: no fine tuning required. Explains tightness of galactic scaling laws

Why:
- disc & halo form together
- disc self regulates towards attractor in frame set up by halo (dynamical response)

Beyond speculation: what can we do?
+ kinetic theory= perturbative theory of (dynamical) heating;
→ extend to sourced dissipative regime.
+ perturbative theory of dynamical cooling= model for sourcing.
+ large deviation theory = quantify the expected spread in scaling laws.
+ laplace-lagrange theory: explain disc stiffening.

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