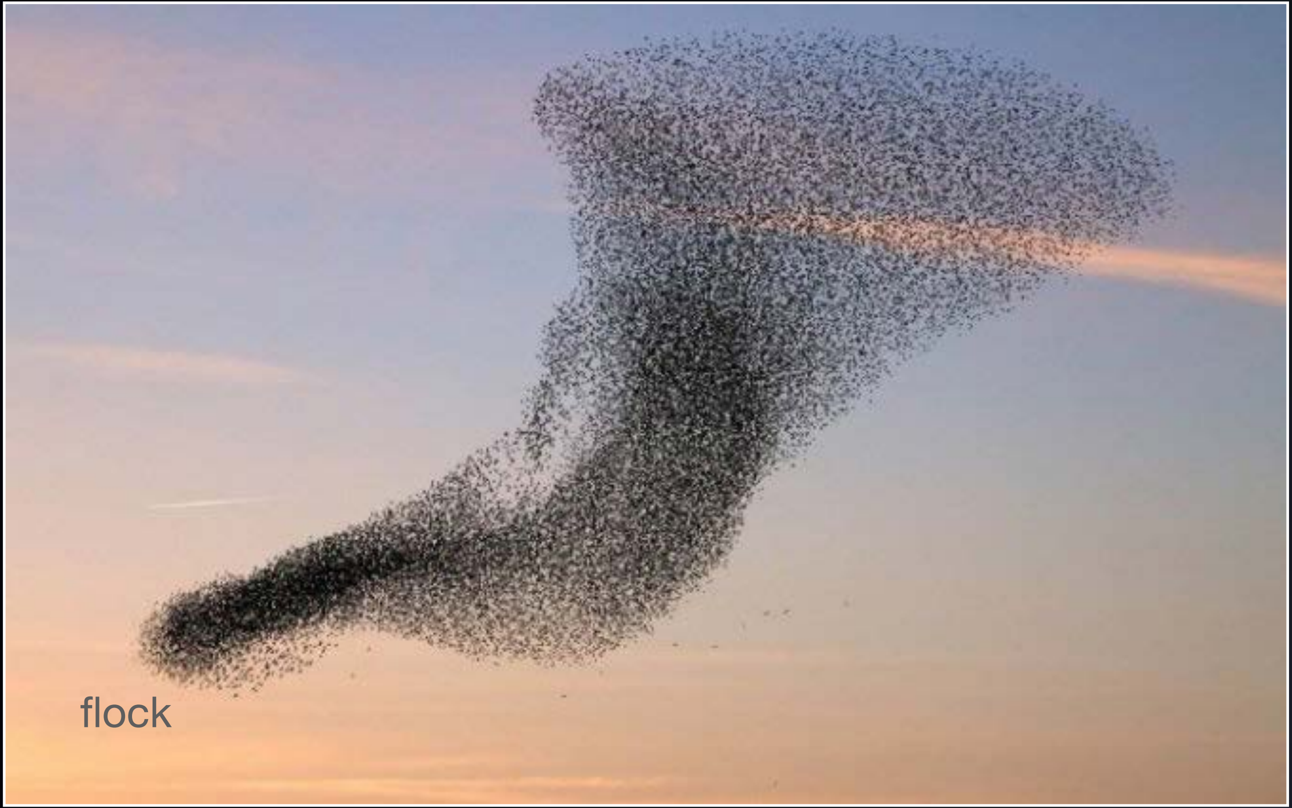
Gravity does it all:
A Top-Down Multiscale Analysis of the Cosmic Emergence of Thin Galactic Discs.

Order out of Chaos: Secular Disc Settling

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

Christophe Pichon & The NewHorizon Collaboration (Min-Jung Park, M. Roule, Y Dubois, J. Devriendt++)



* **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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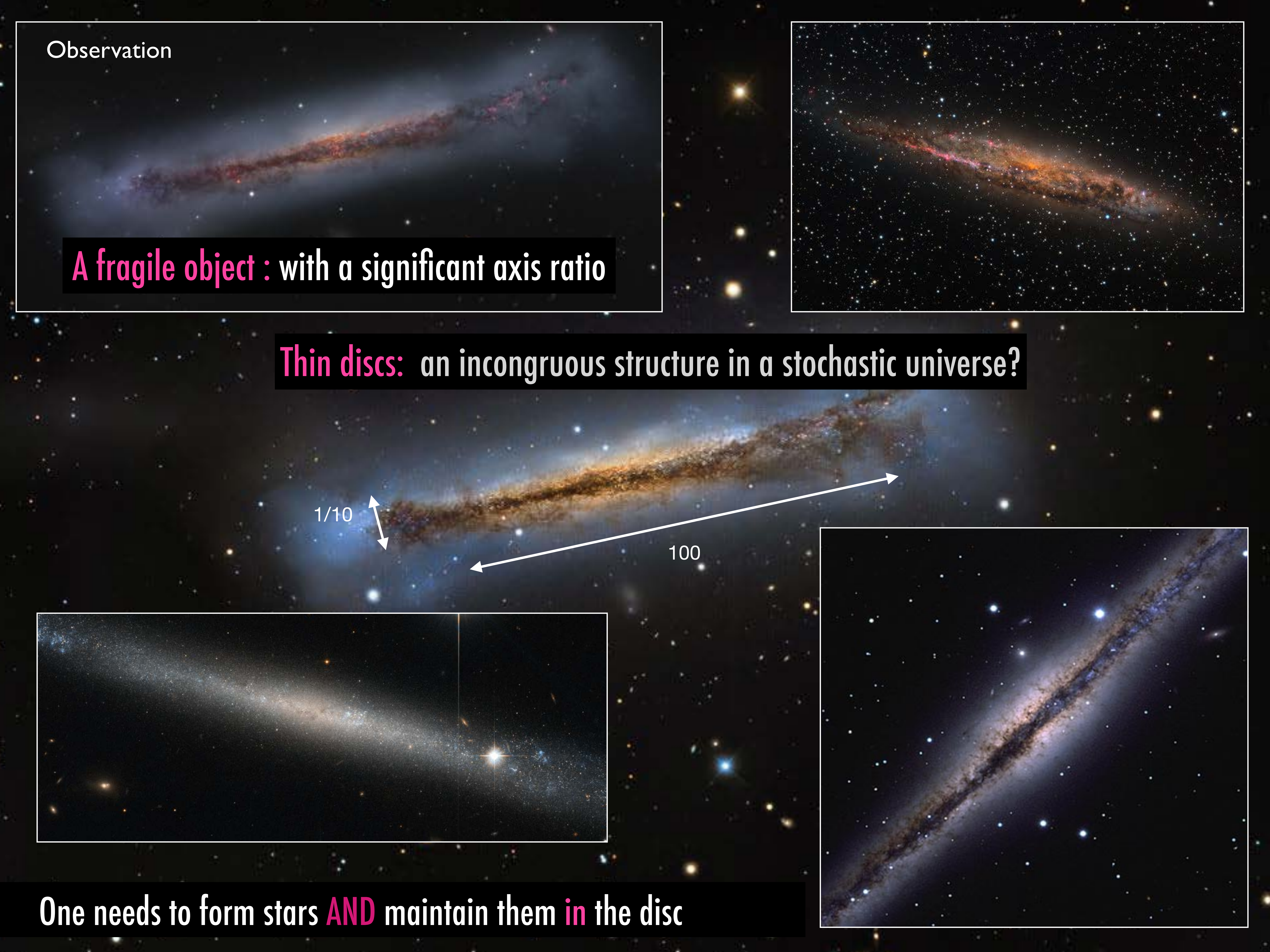
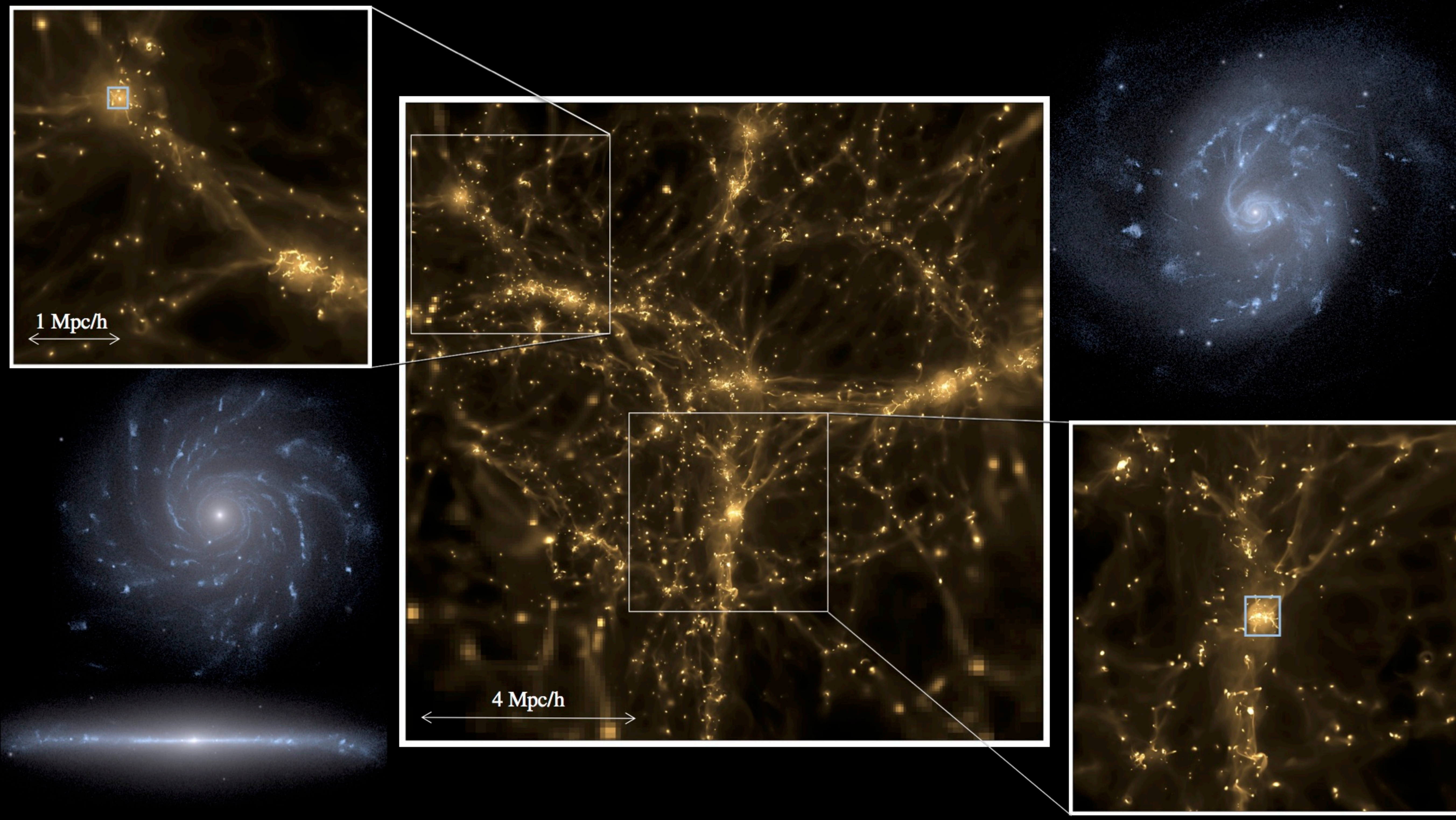

Observation
A fragile object : with a significant axis ratio
Thin discs: an incongruous structure in a stochastic universe?
1/10
100
One needs to form stars AND maintain them in the disc

Cosmological simulations produce thin discs



New Horizon Simulation

(c) M Park 2020

Question raised by emergence of thin disc

- Environment need to detune & stellar component to dominate: secular mode

- **Where is the coherence coming from?** The CGM acts like a free energy reservoir
- **Why do disc settle ?** Because they converge towards marginal stability
- **What is the role of Q ~ 1?** Because tighter control loop ($t_{\rm dyn} \ll 1$) via wake
- **How does it impact settling?** Because wake also stiffens coupling

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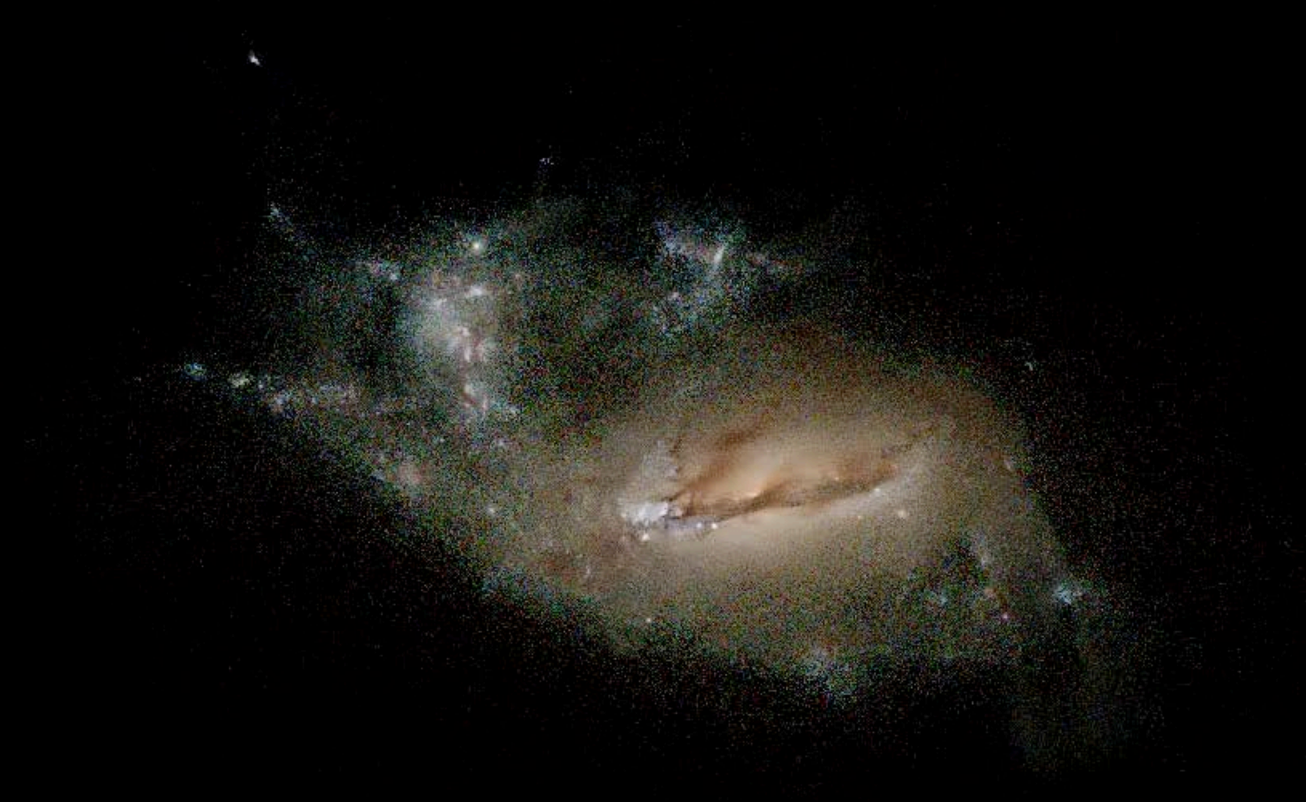
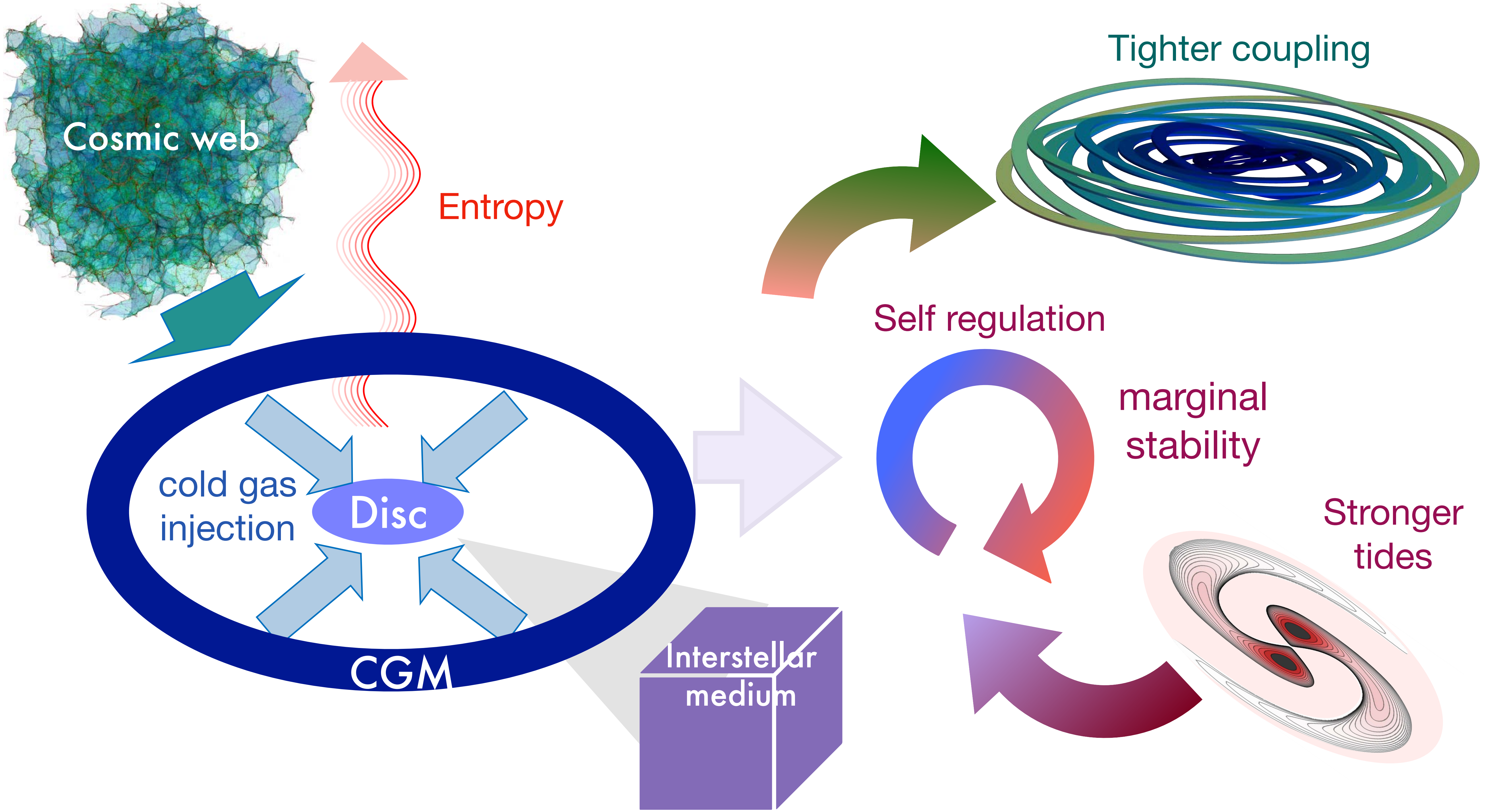


New Horizon

Synopsis of thin disc emergence



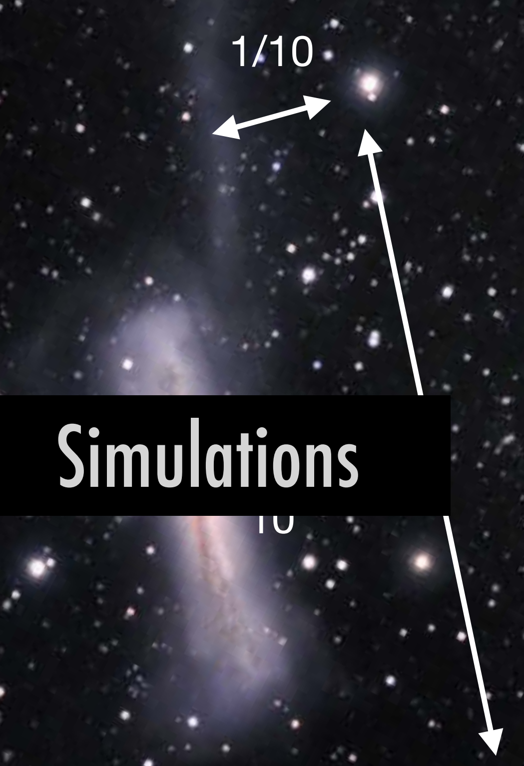
- Three components system coupled by gravitation.
- A CGM reservoir fed by the large scale structures (top down *causation*)
- Convergence towards marginal stability : acceleration of dynamical control-loop by wakes
- Tightening of stellar disc by boosting of torques, & increased dissipation.

Chicken or the egg ...

How to **find** the galaxy?
How to **collimate** accretion?
How to **sustain** thinness?

- warps
- thick disks

Both **know** about infall direction!



Simulations

Clue? circumgalactic medium geometry

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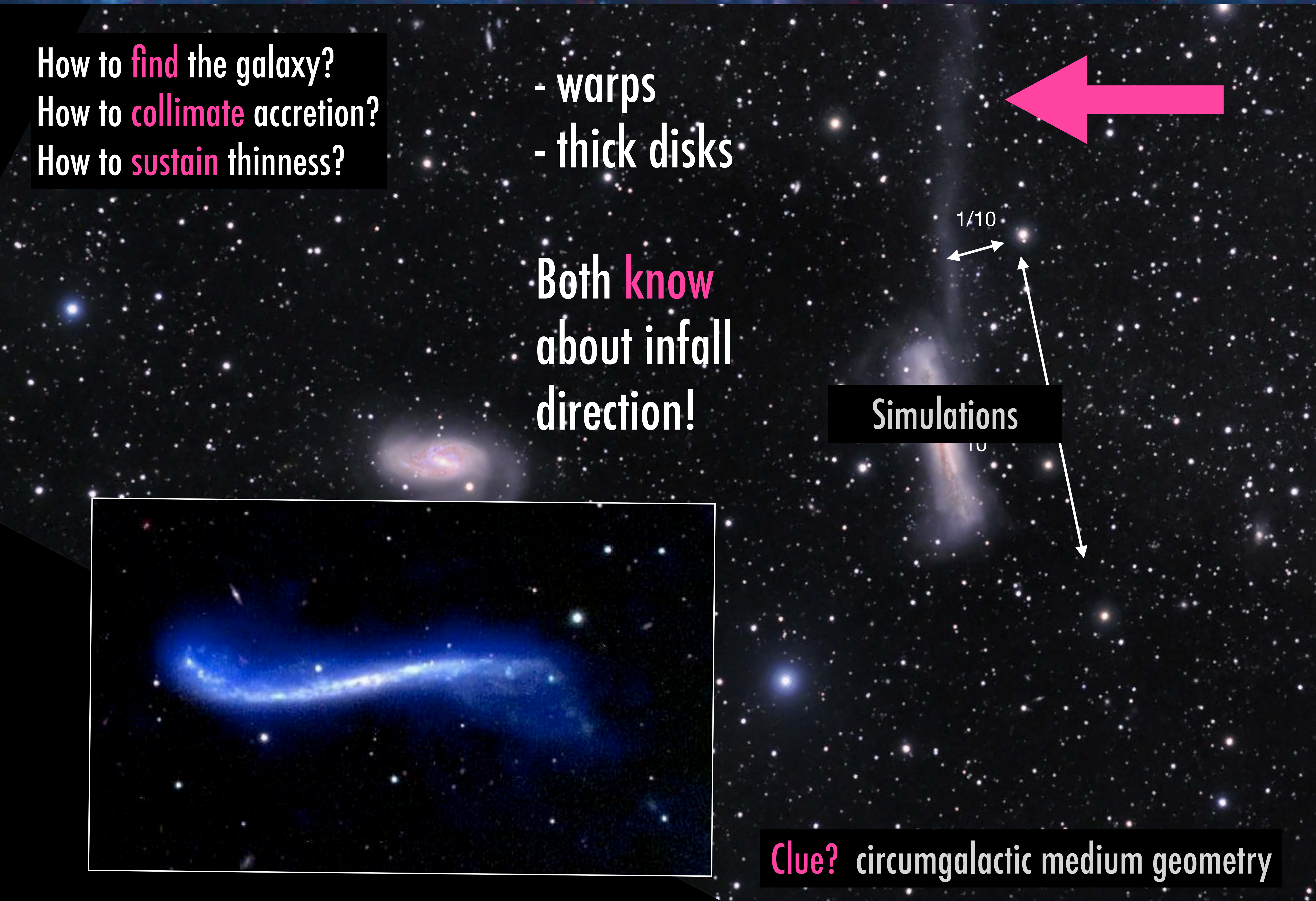

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1/10

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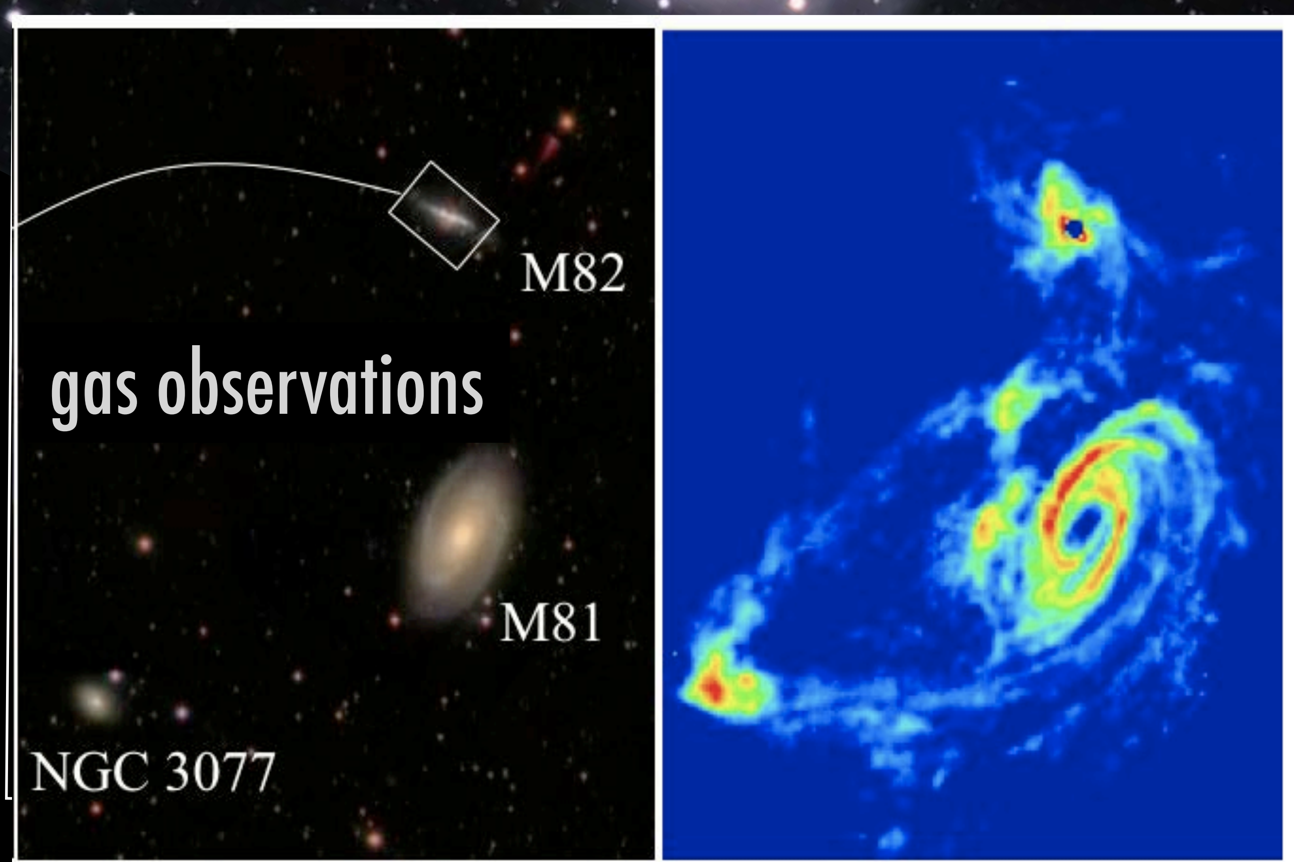

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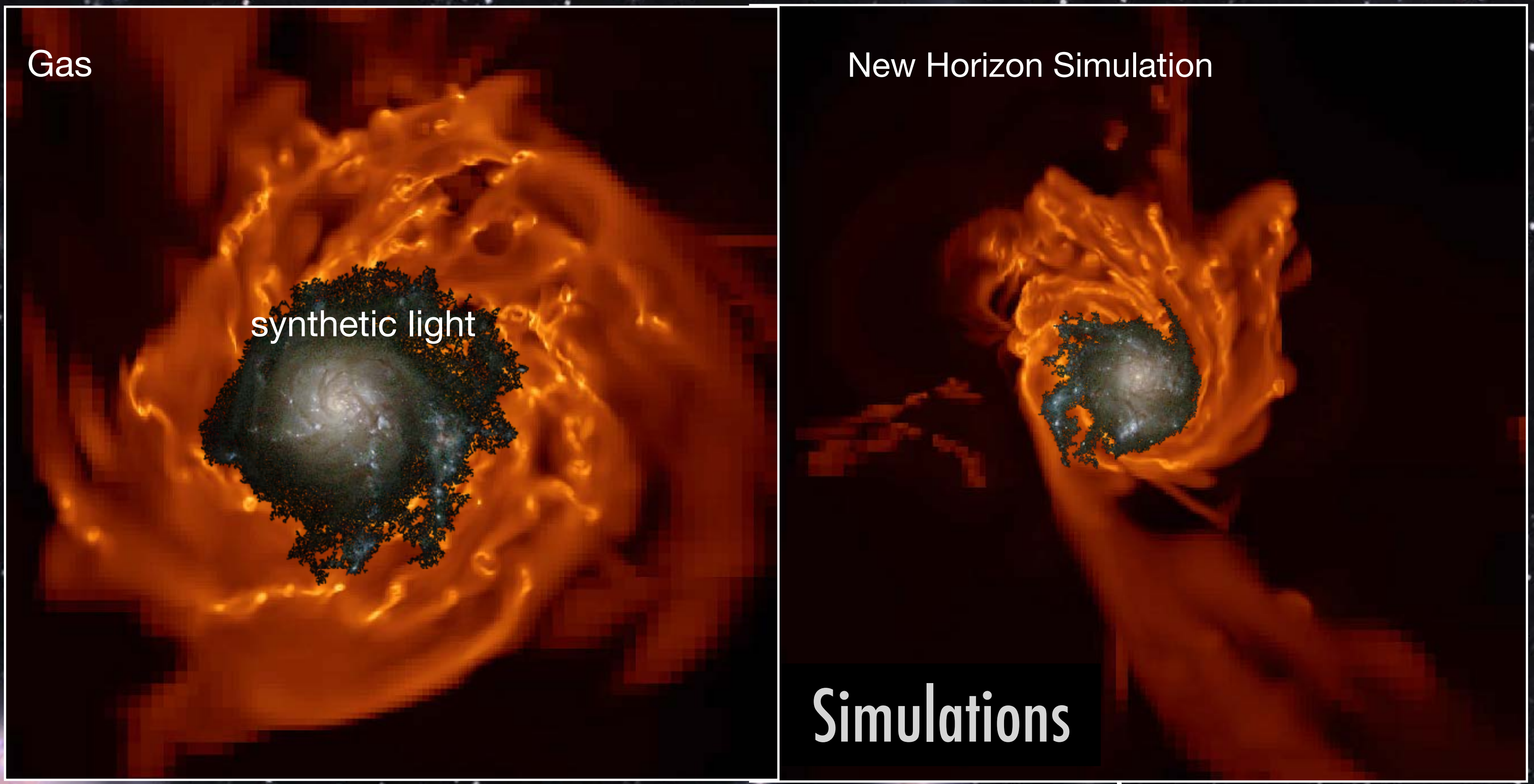
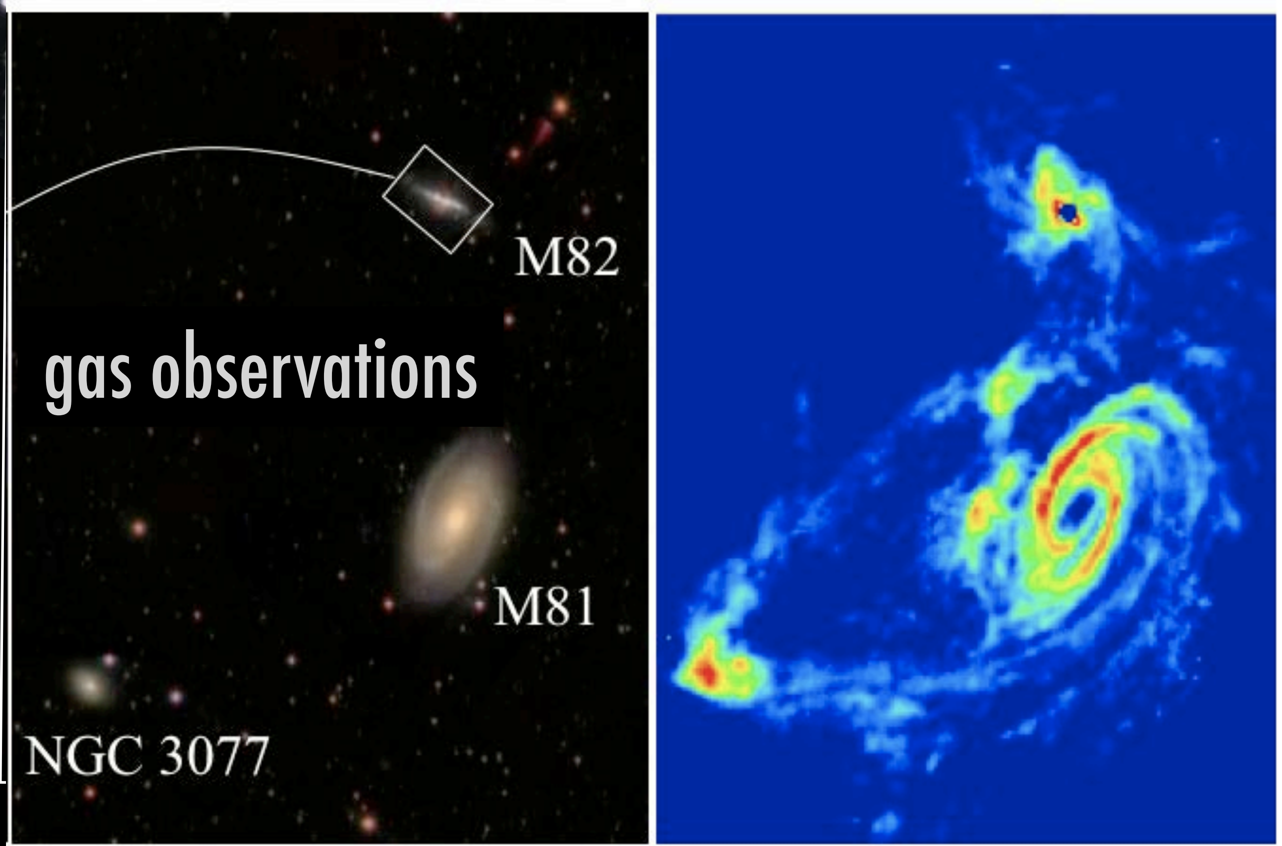
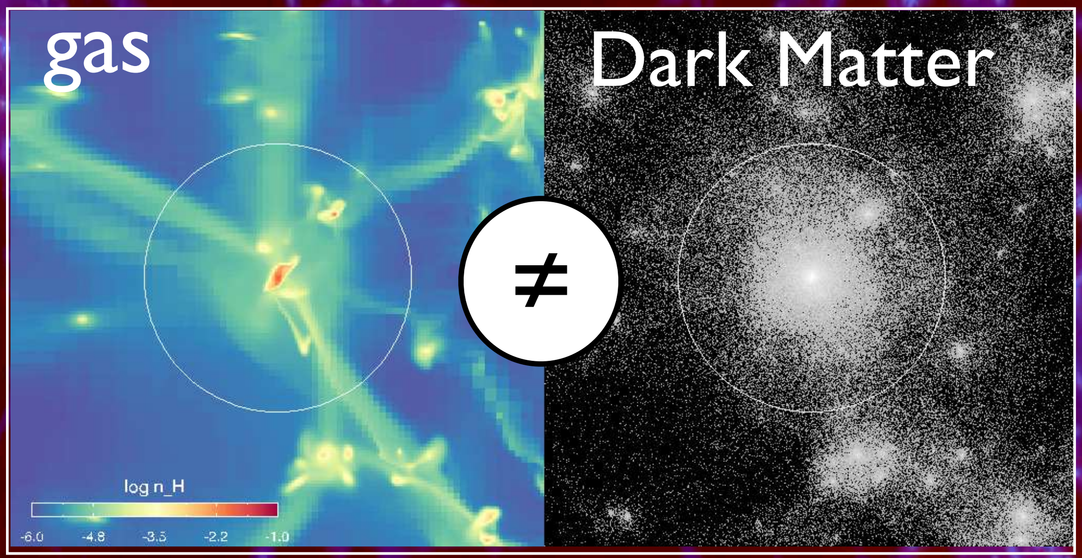




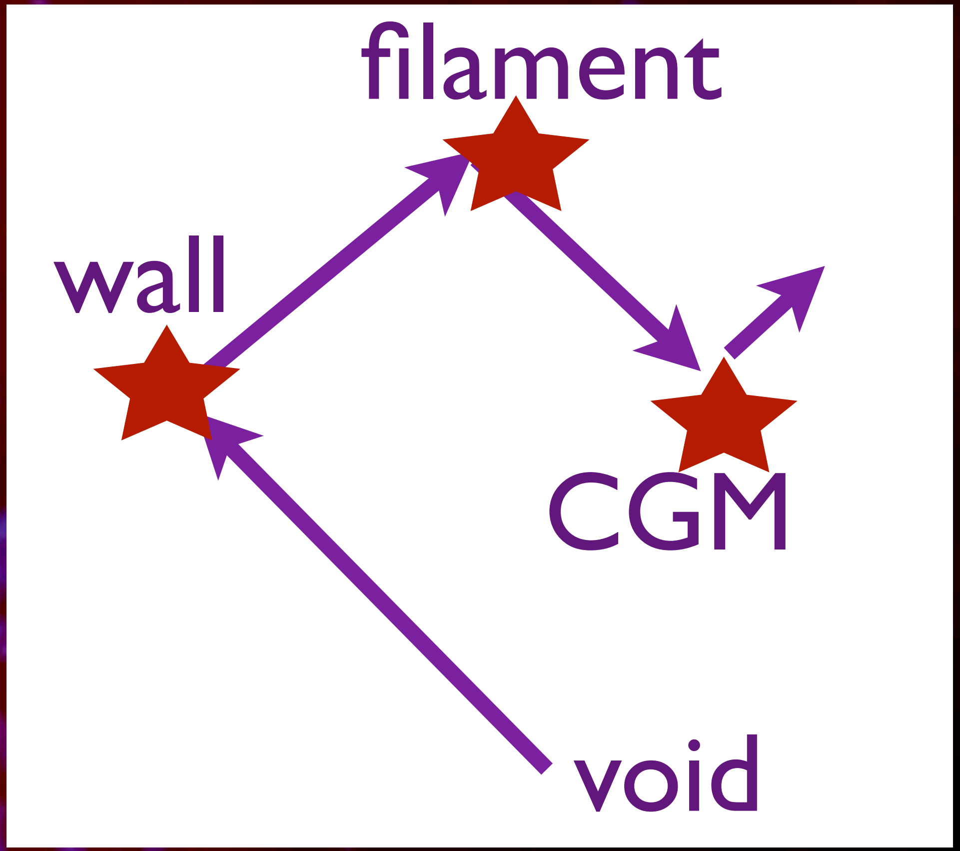
Clue? circumgalactic medium geometry

The impact of shocks in gaseous cosmic web

LSS drives secondary infall :



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



MILKY WAY

IRON
STARS
GAS
DARK MATTER

Z = 6
12.9 GYR AGO

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

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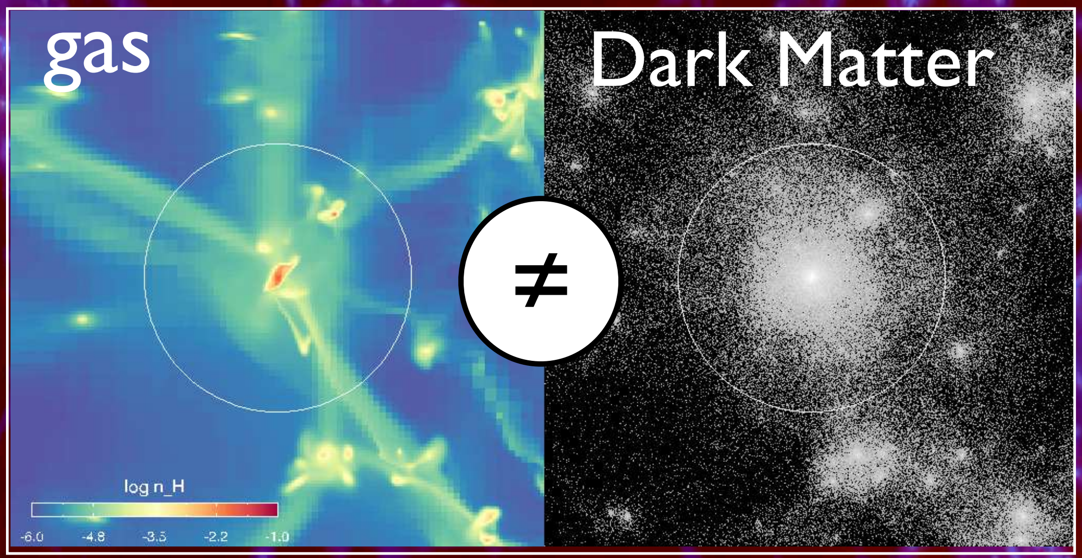

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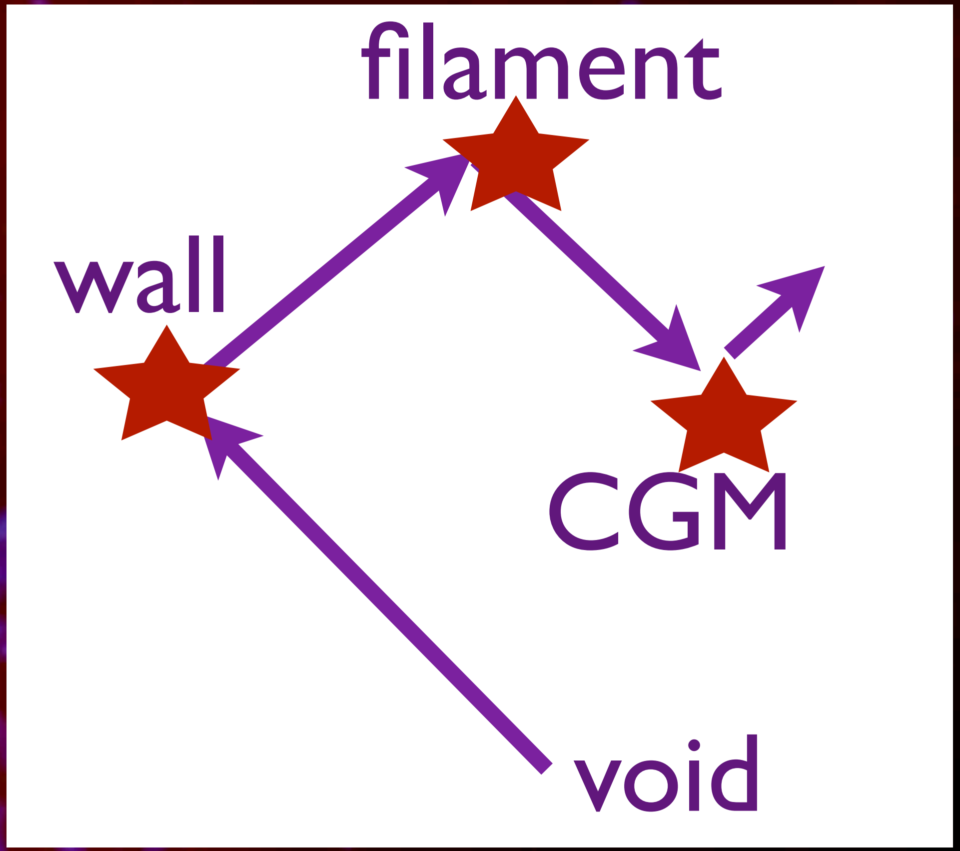

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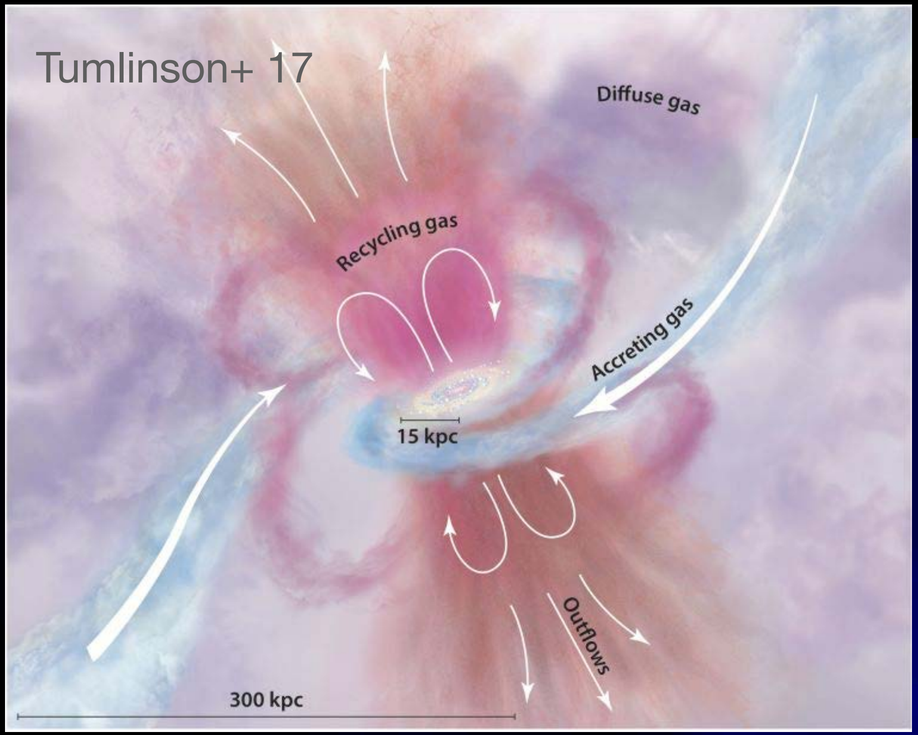
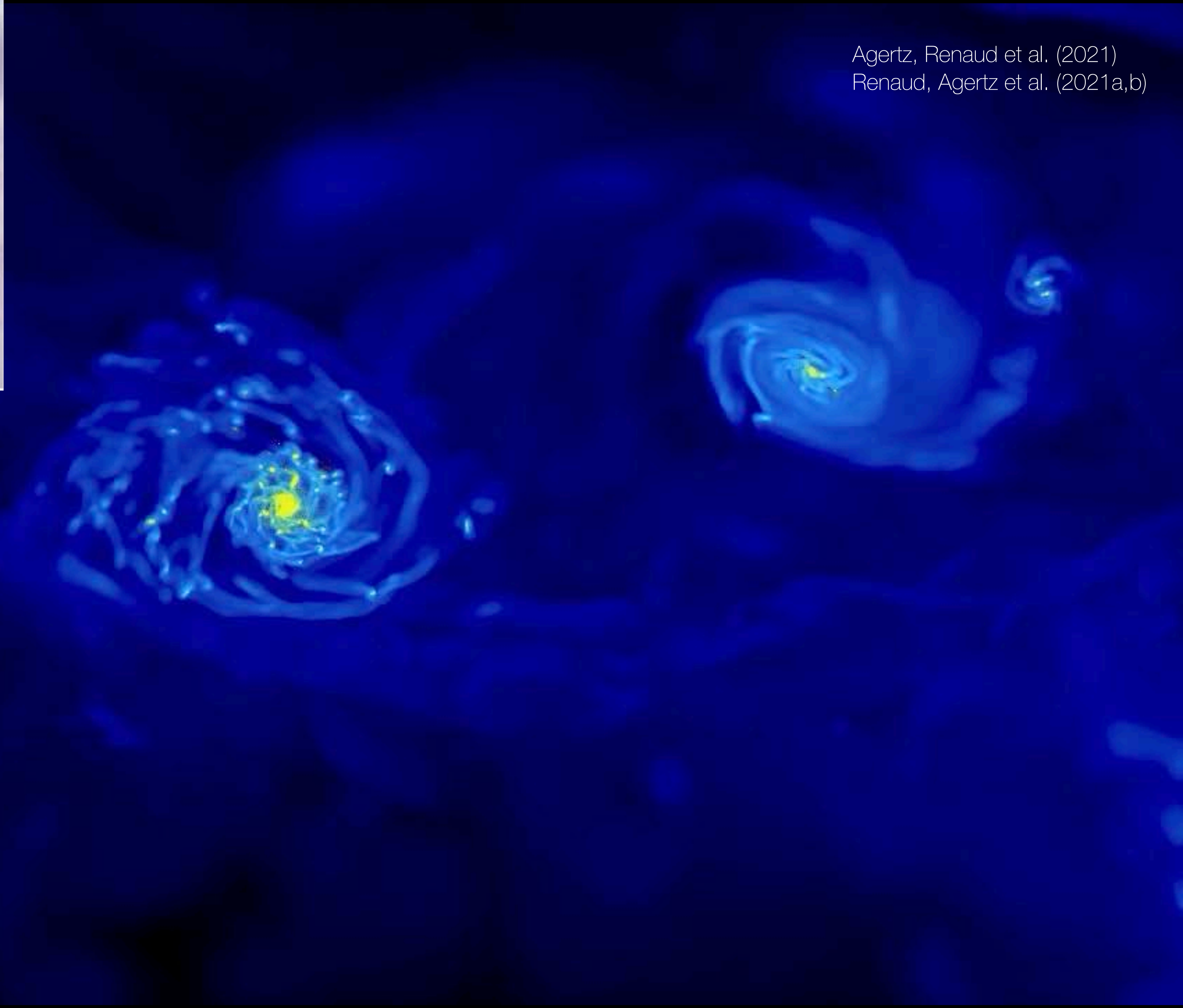
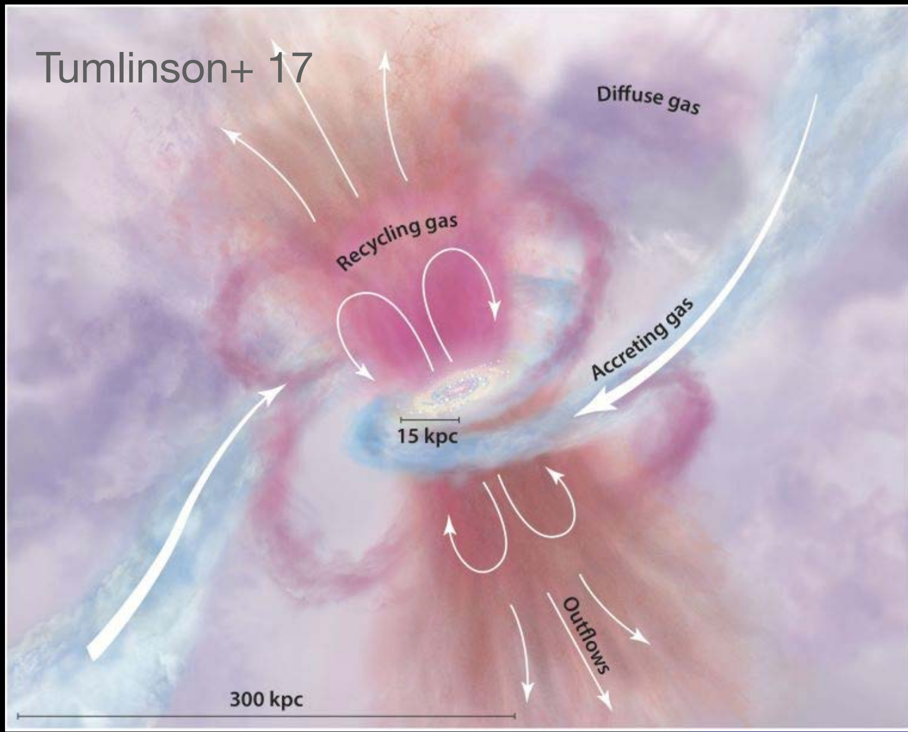
Shape of Circum Galactic Medium

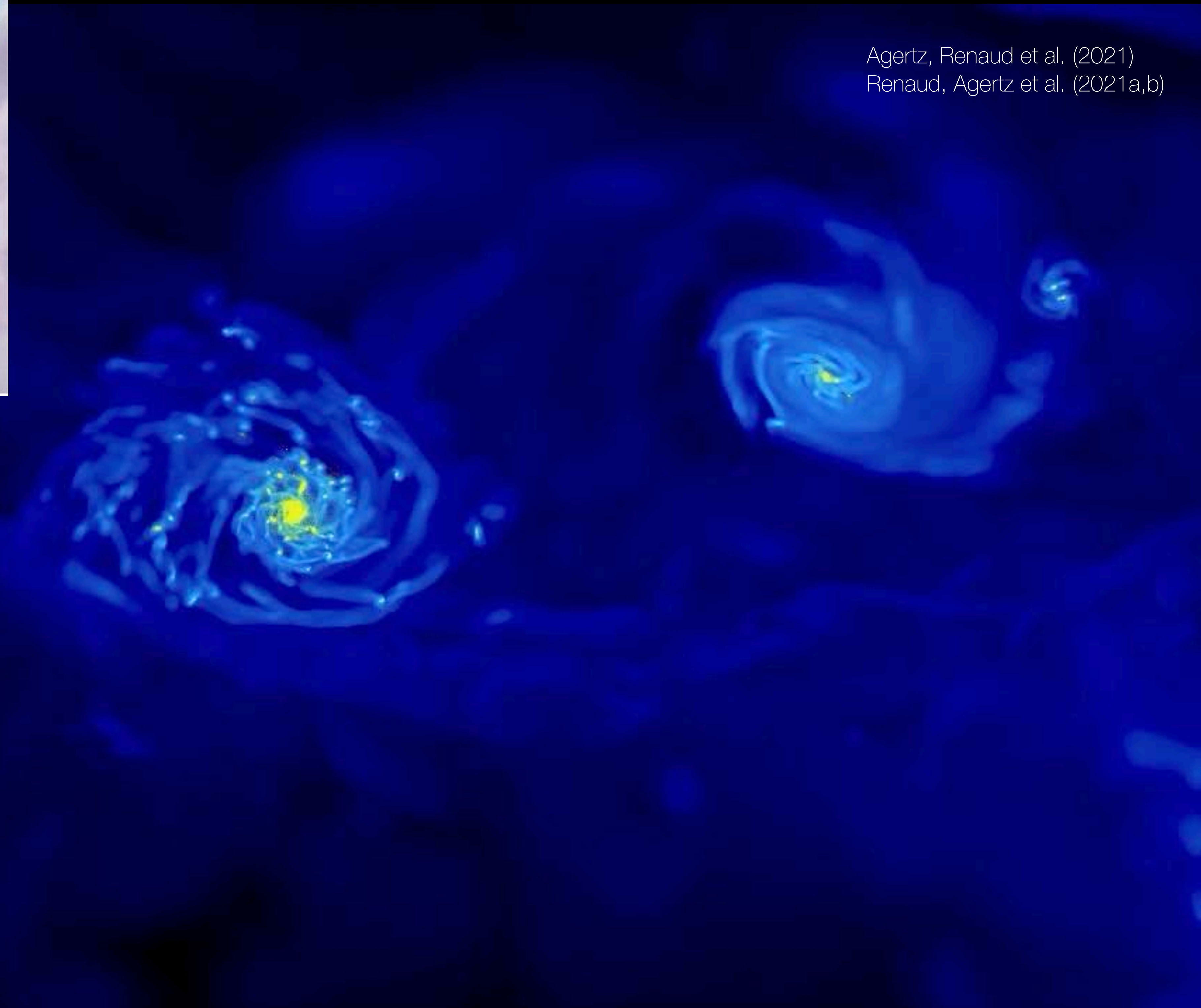




Disc torqued by GCM

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





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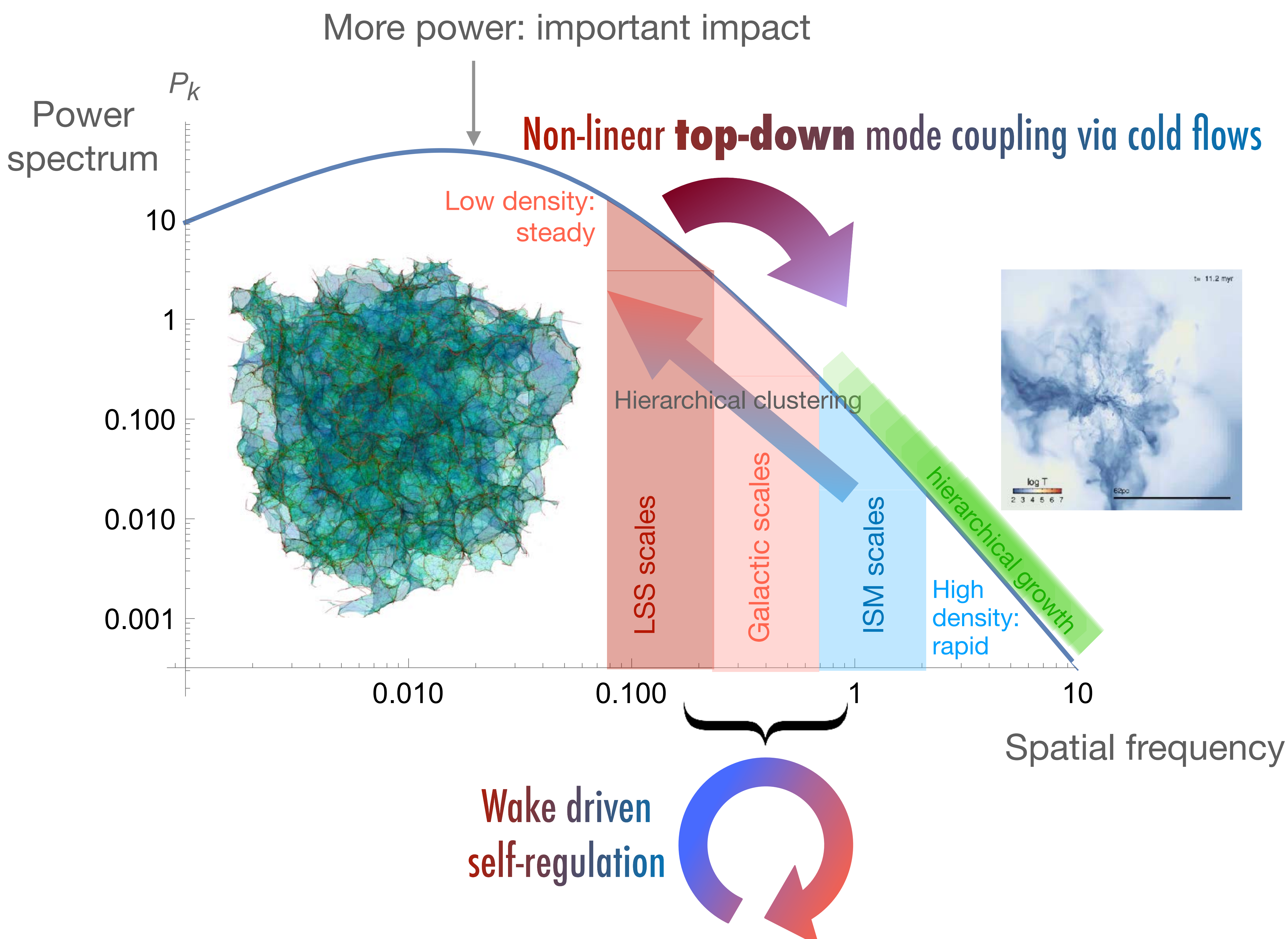
Impact of LSS on non-linear dynamics is top down

On galactic scales, the Shape of initial P_k is such that galaxies inherit stability from LSS via cold flows, which, in turn, sets up CGM engine/reservoir.



Upshot of the various processes in the intra galactic medium

Destabilising effects

- supernovae
- Turbulence

————

- Minor merger
- accretion
- flybys

Stabilising effects

- Stellar formation
- Cooling
- Shocks

—————

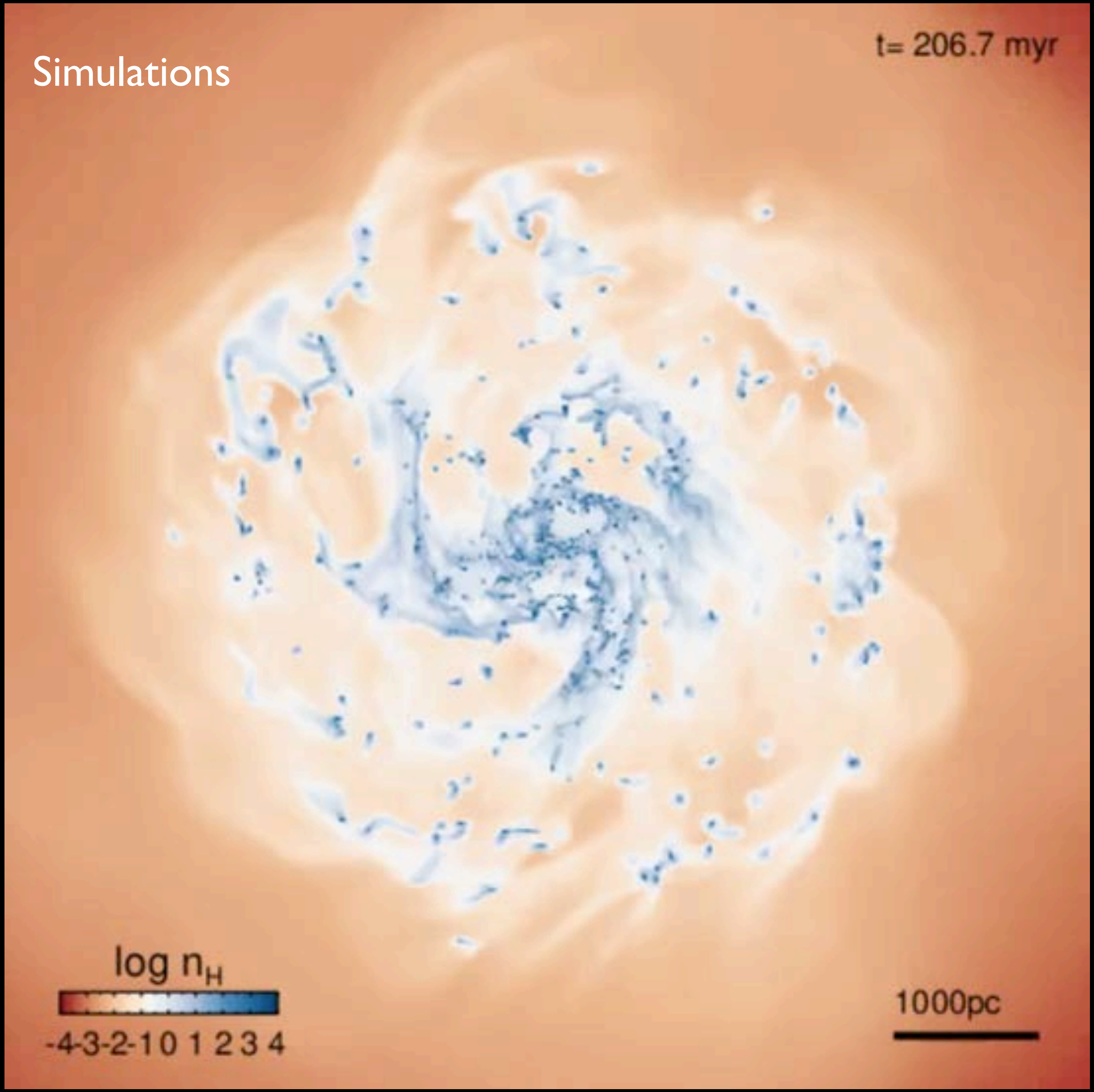
- aligned accretion

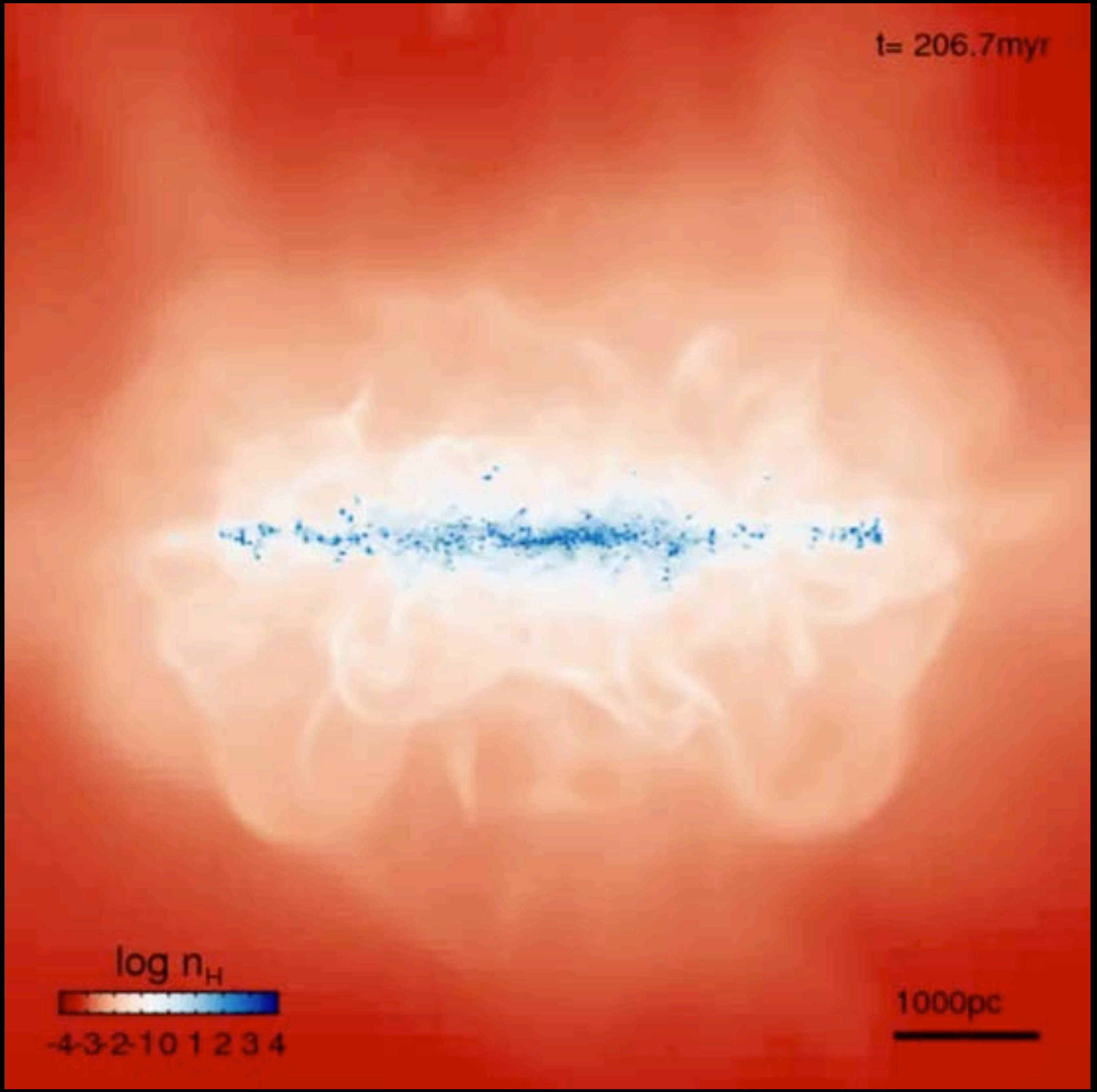
Cosmic perturbation

Free energy reservoir in CGM

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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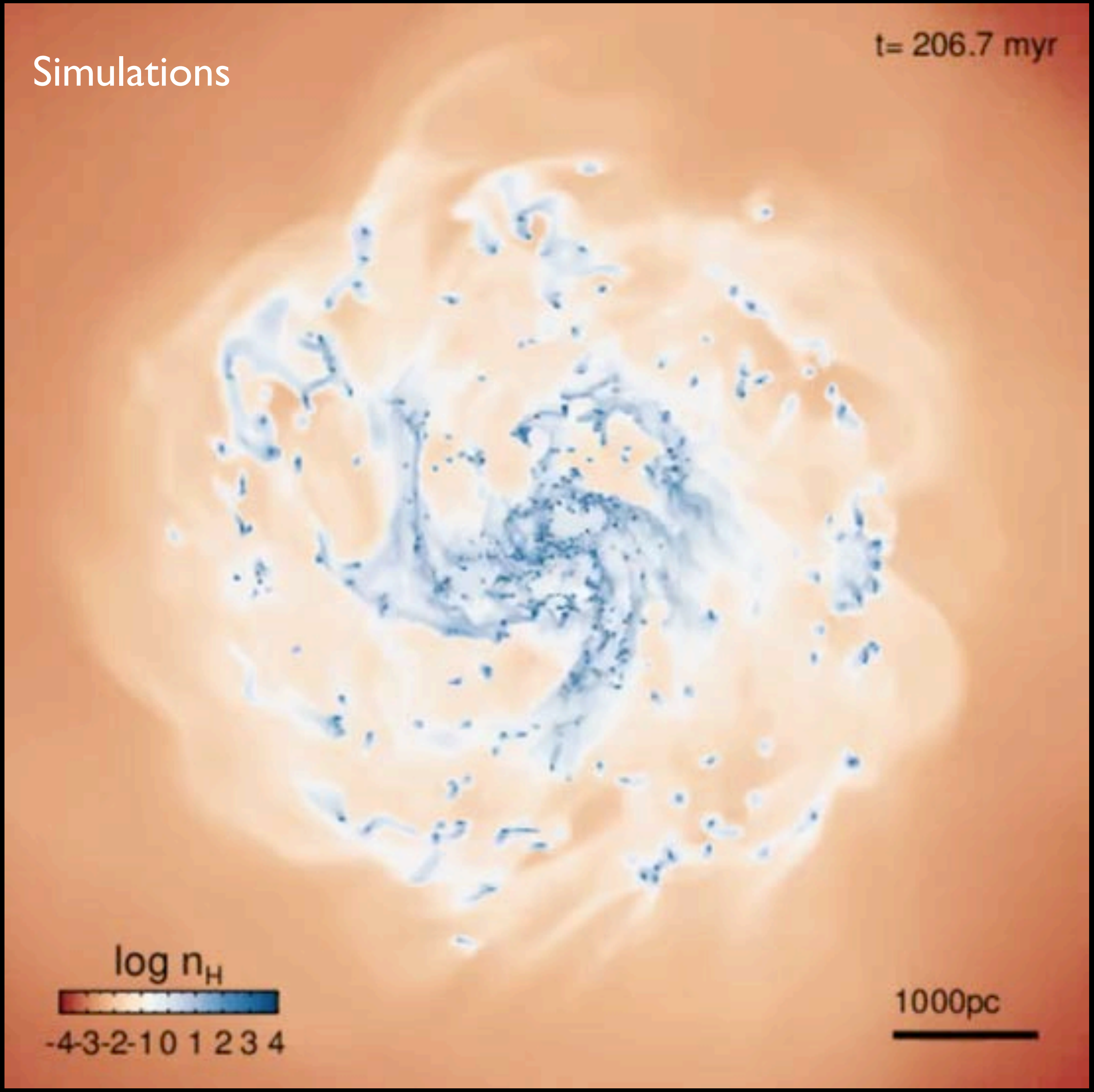
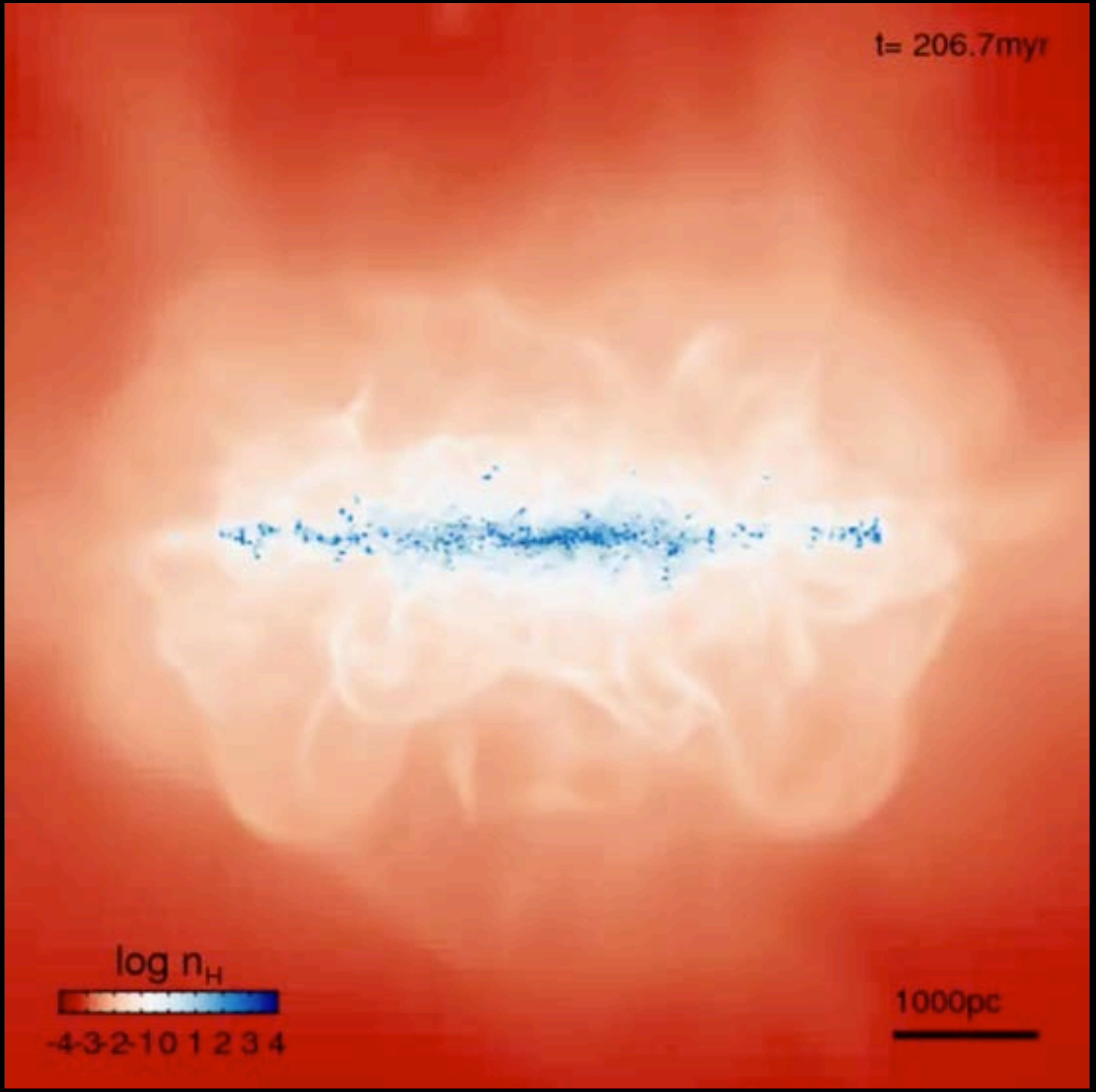
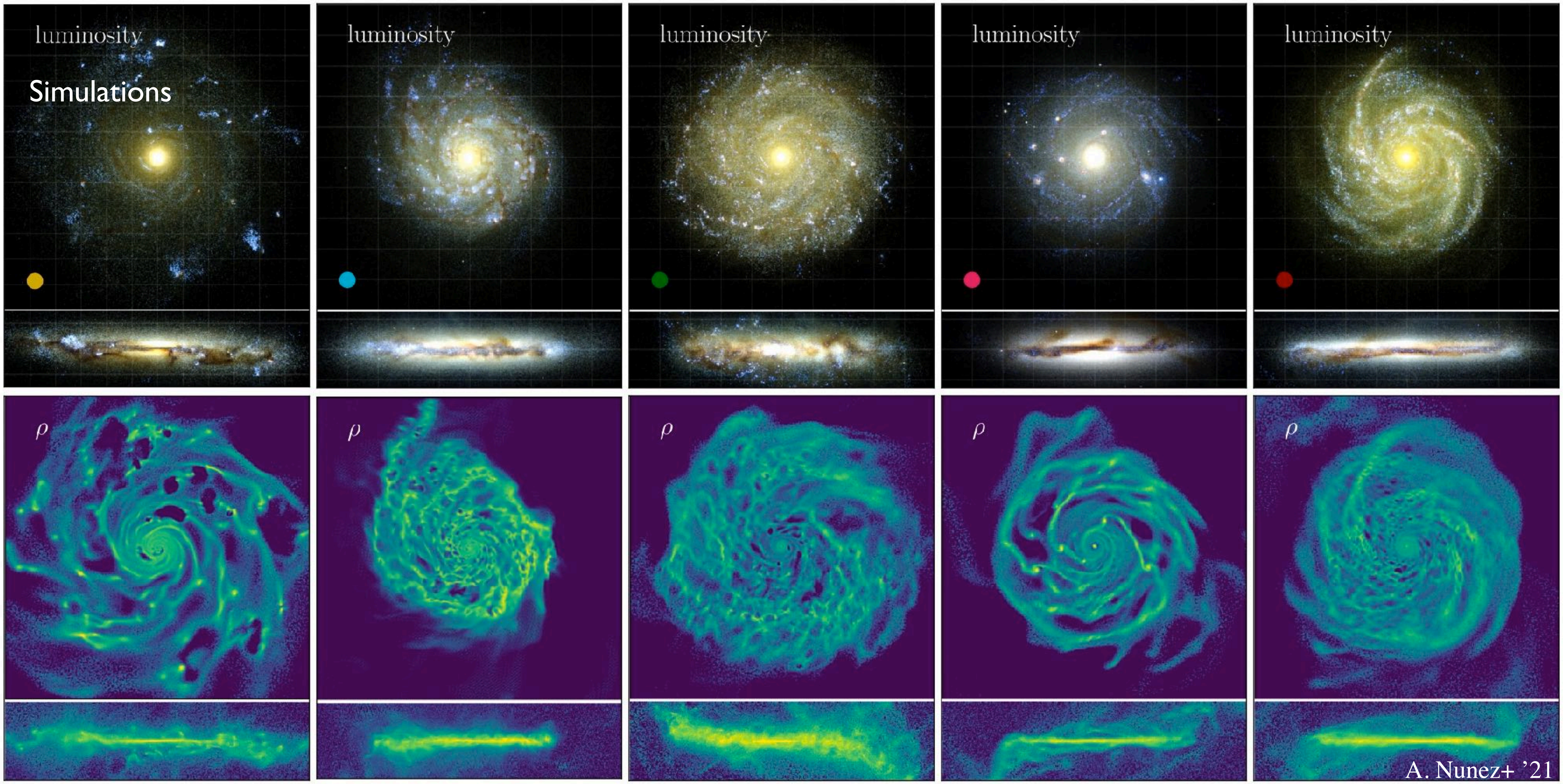




(c)Taysun Kimm

Internal Structure of a simulated thin disc: varying feedback model

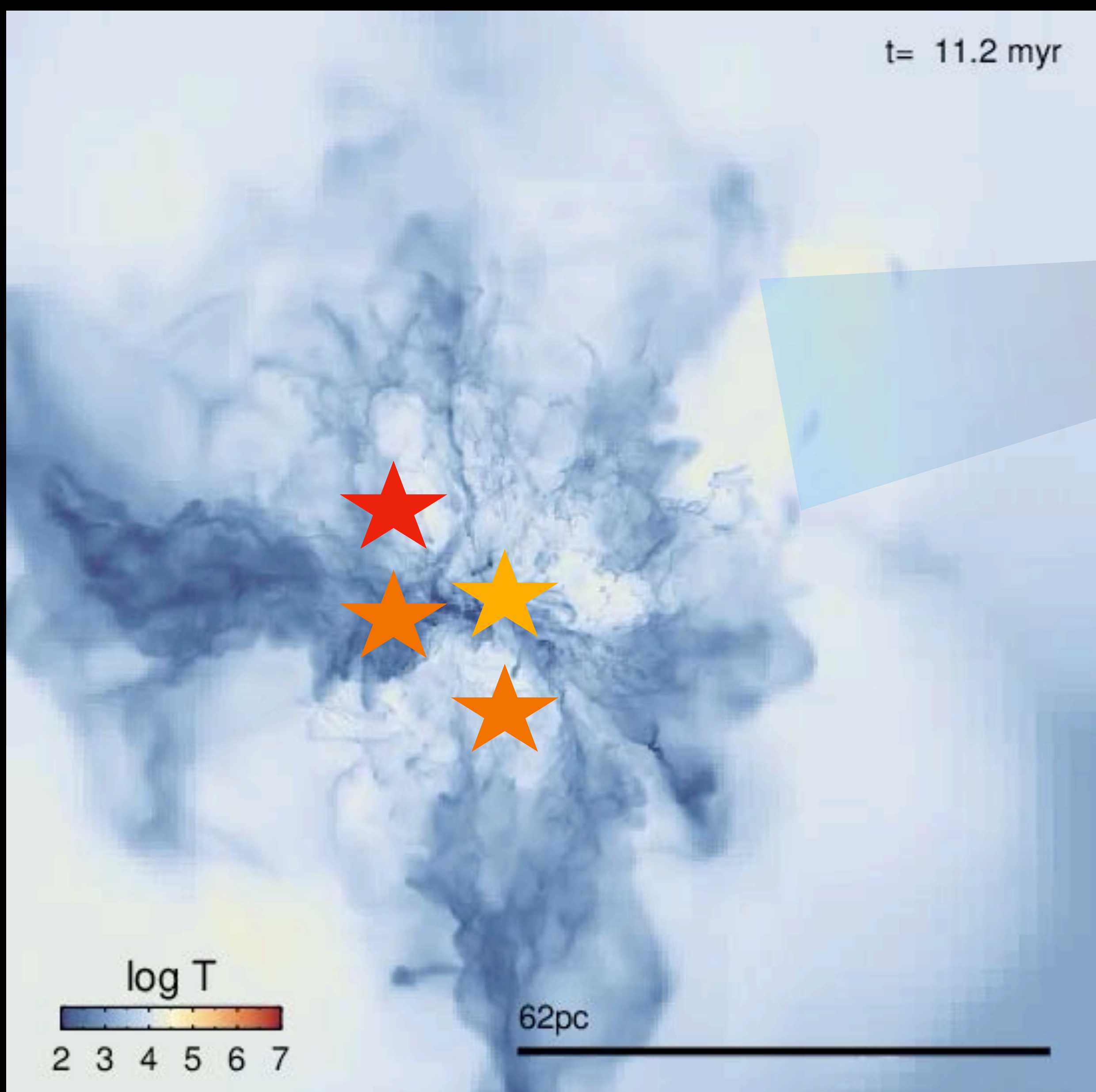


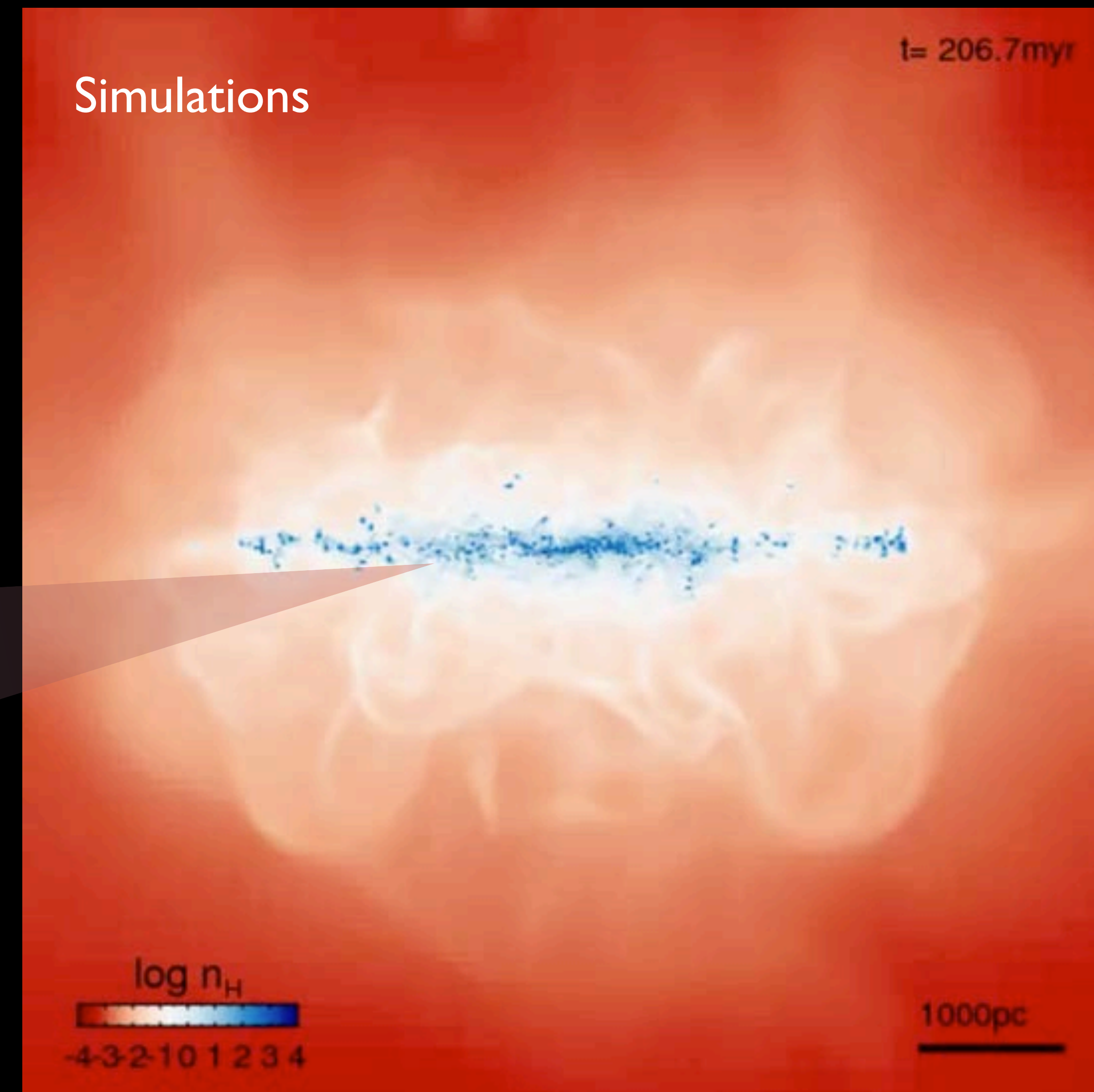
Note that the *exact* model of feedback impacts face-on view BUT does not impact disc thickness.

No fine tuning required: something more fundamental operates

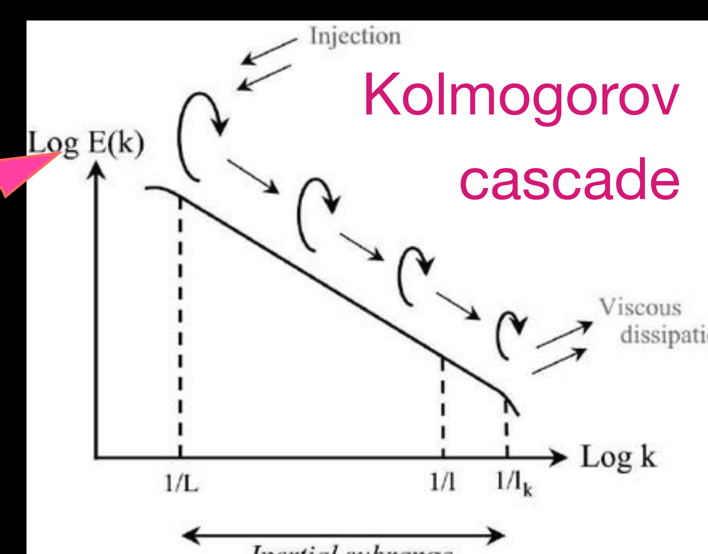
Internal Structure @ small scales: simulation & theory

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





Turbulent cascade
controlled by
energy **injection** scale



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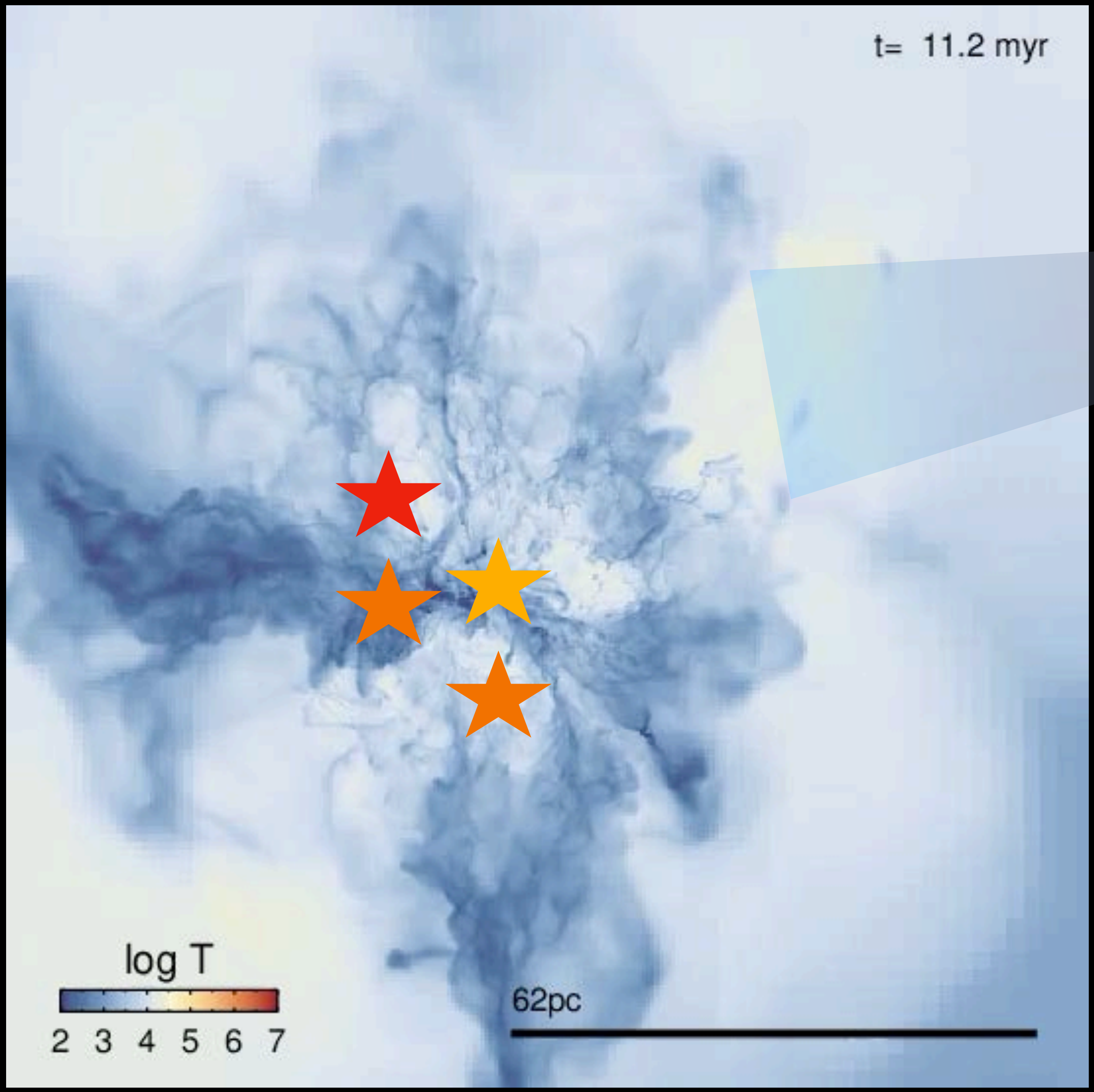

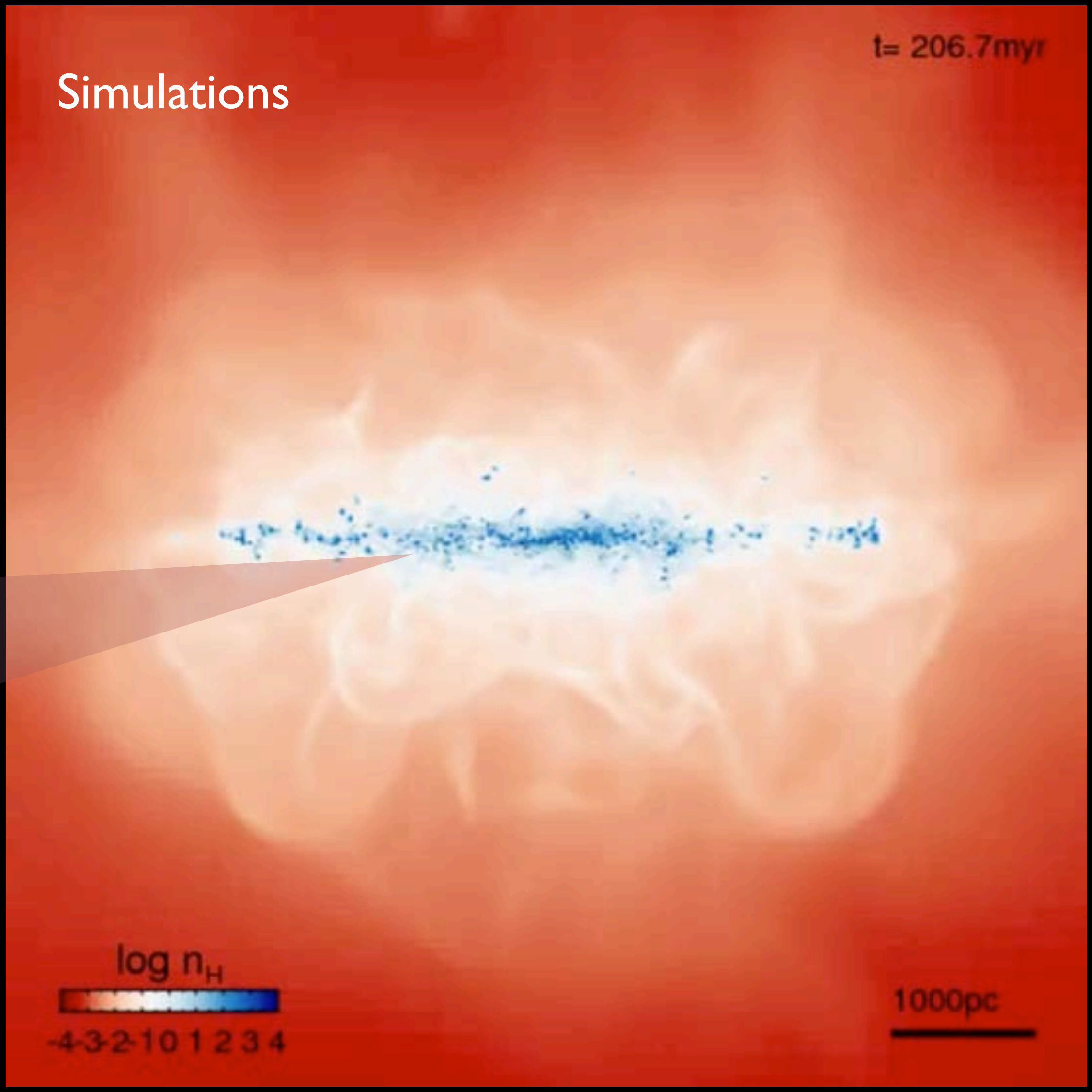

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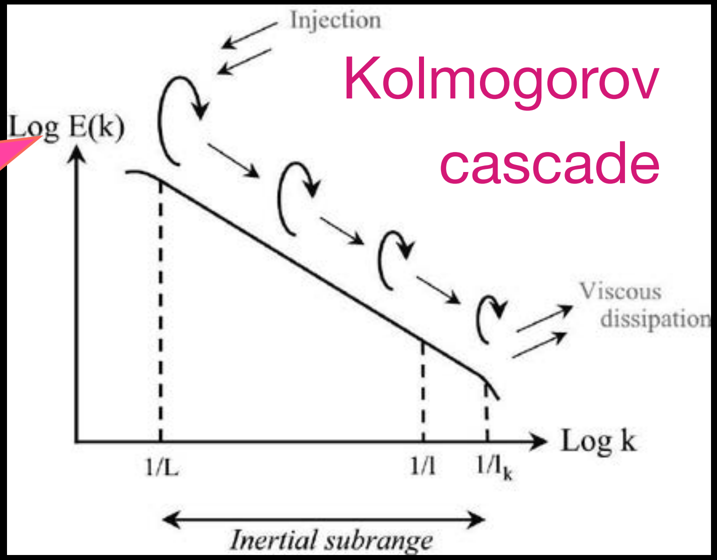

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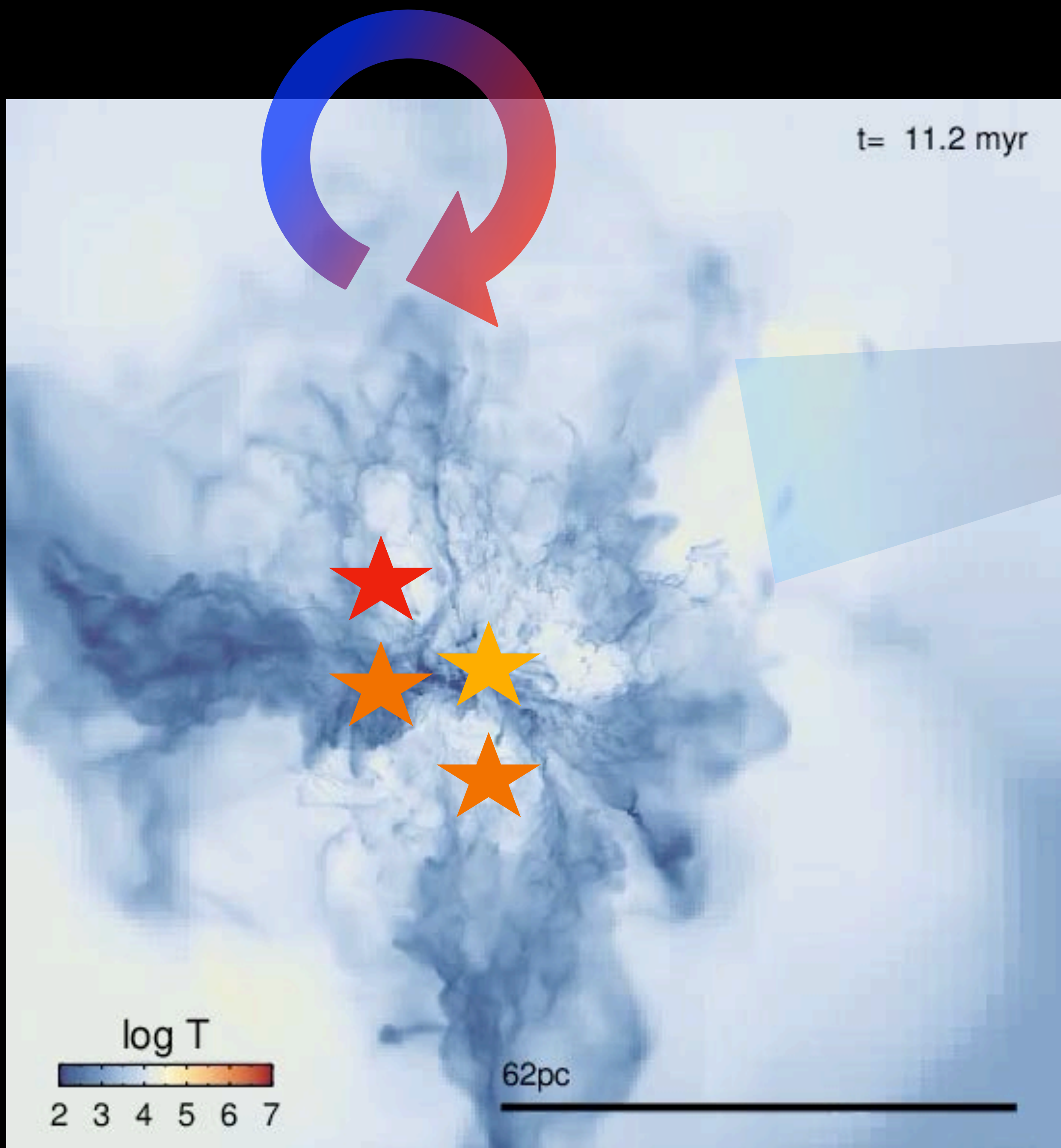

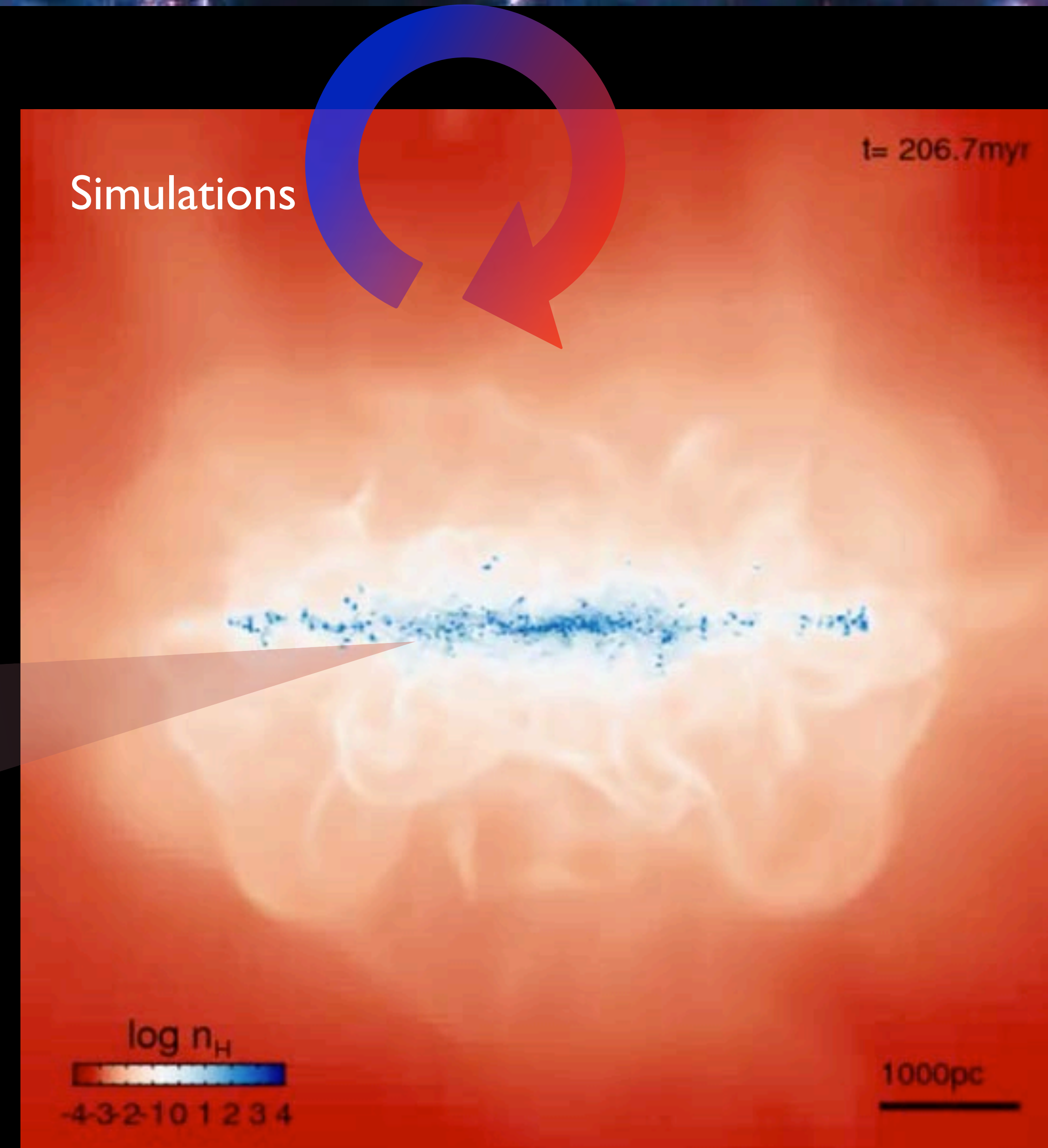

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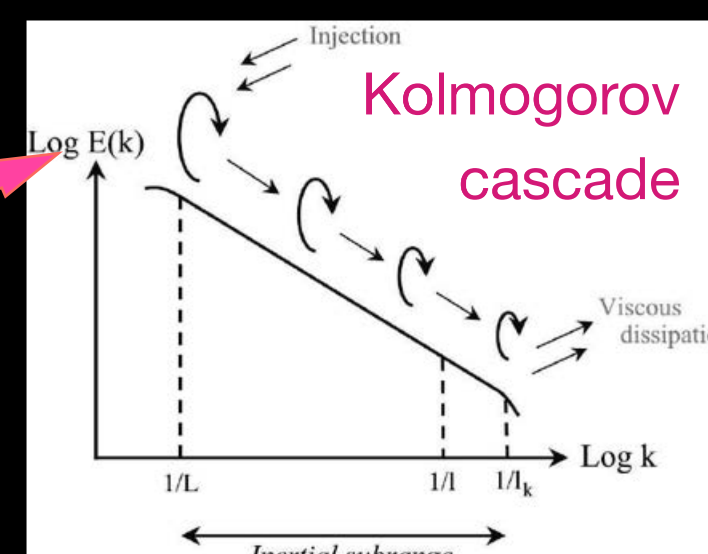
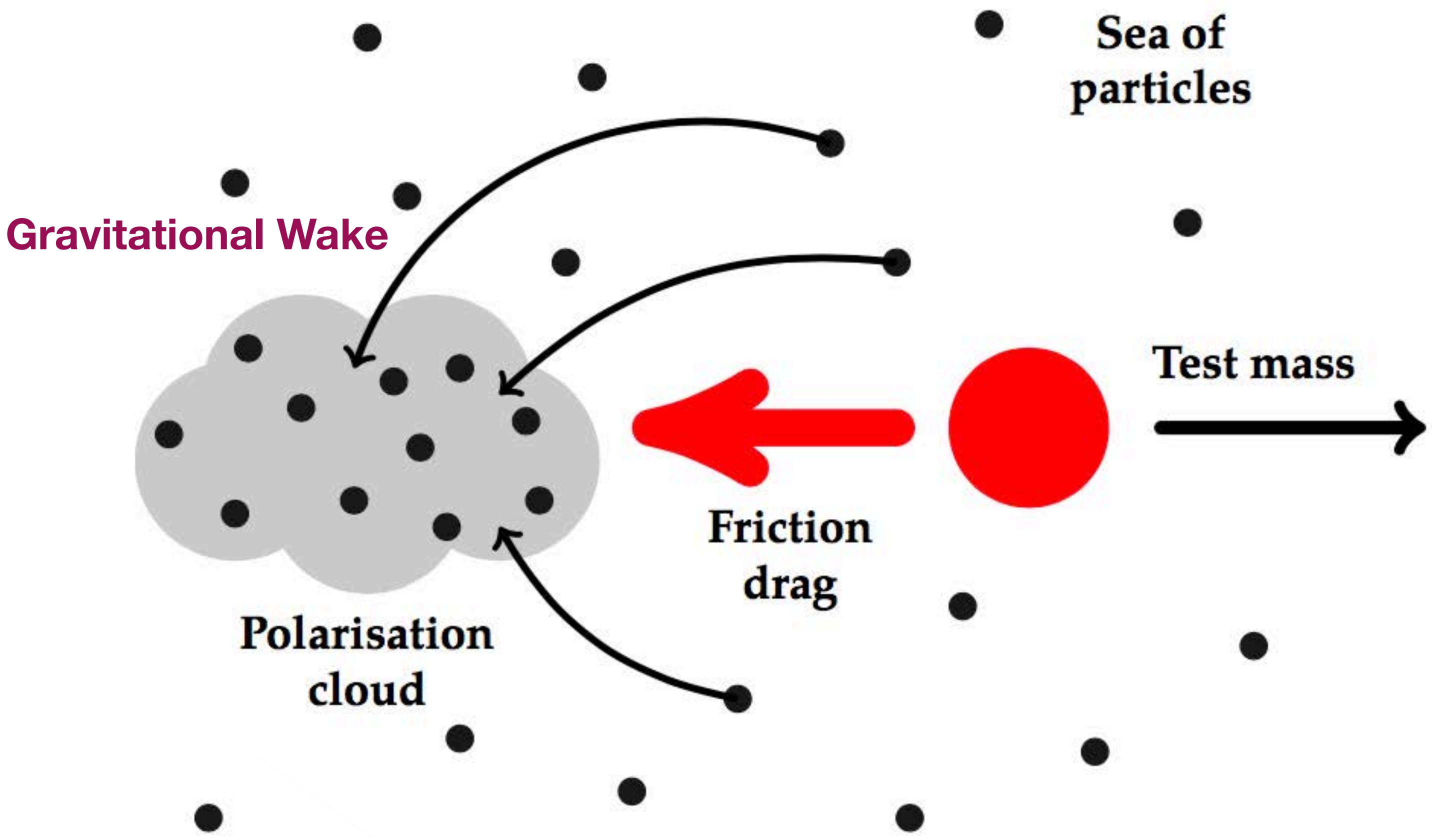
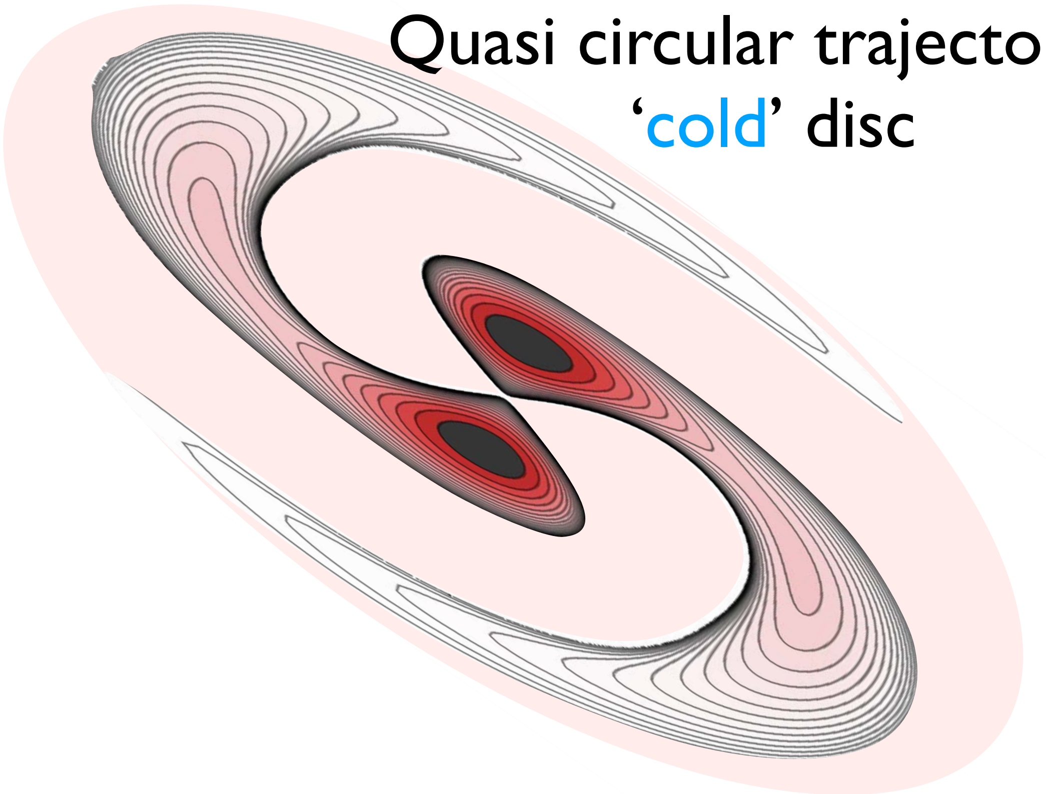


Quid of the effect of wakes on injection scale?

Chandrasekhar polarisation



Quasi circular trajectories:
'cold' disc



→ No significant relative motion to oppose gravitation

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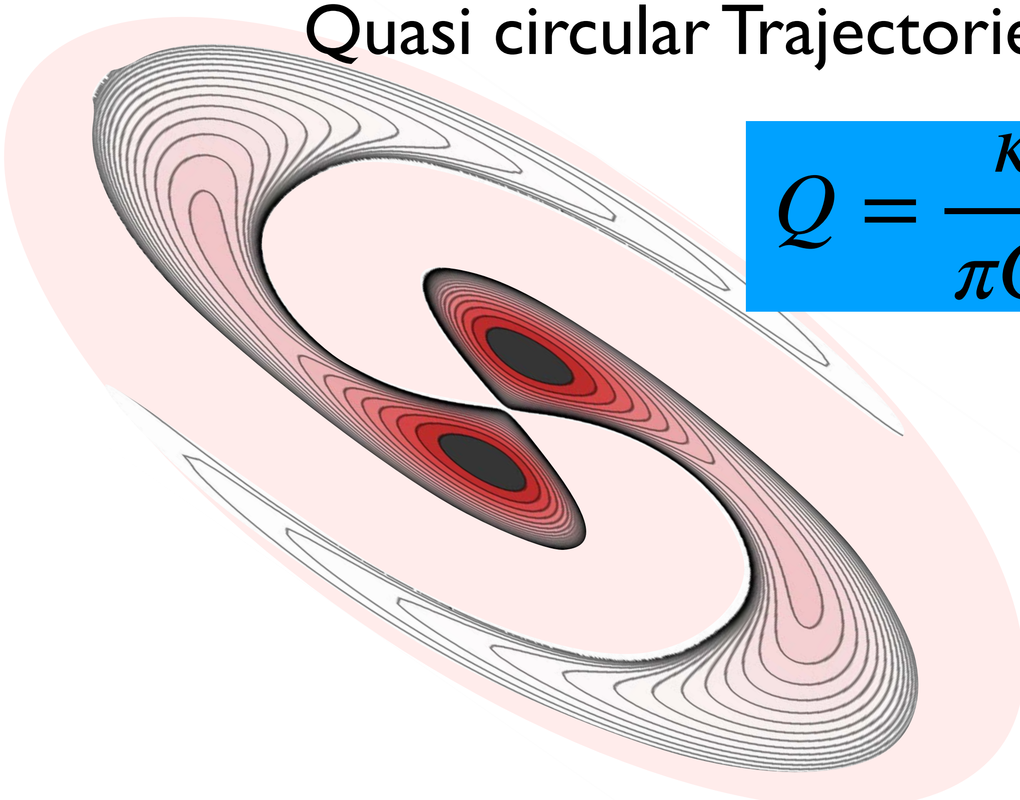
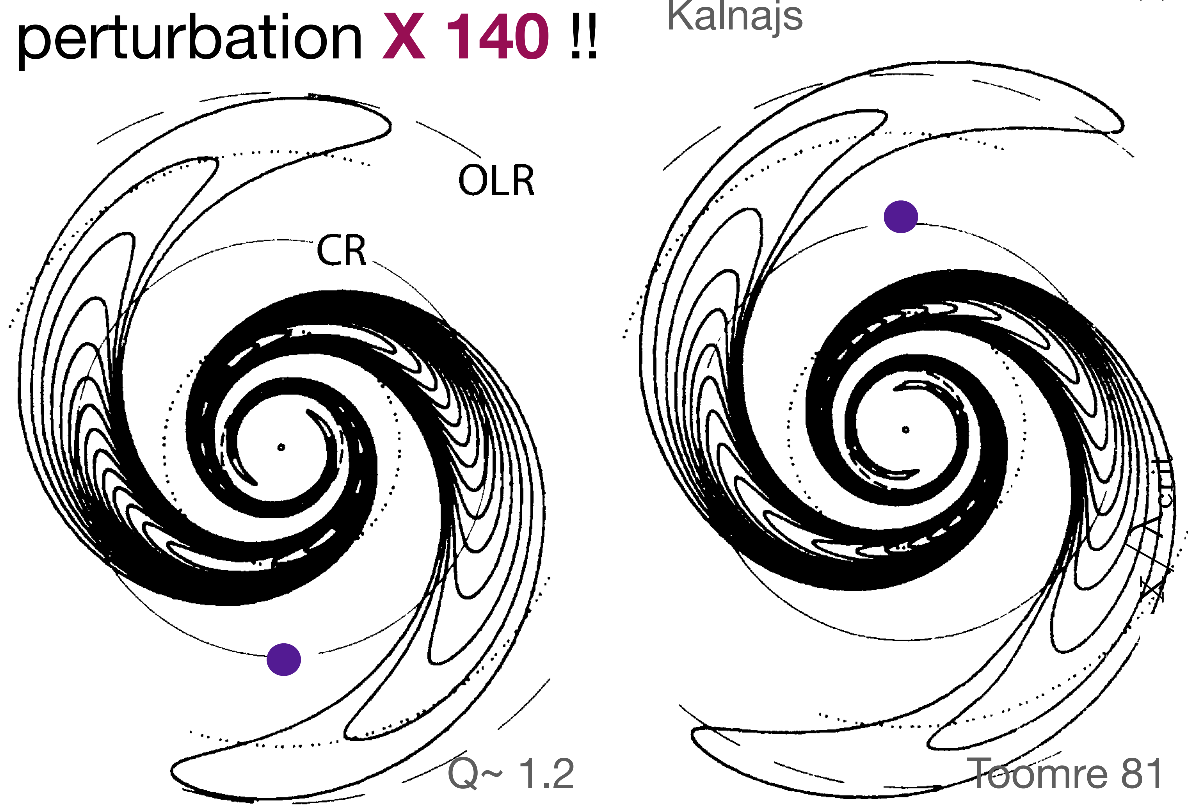
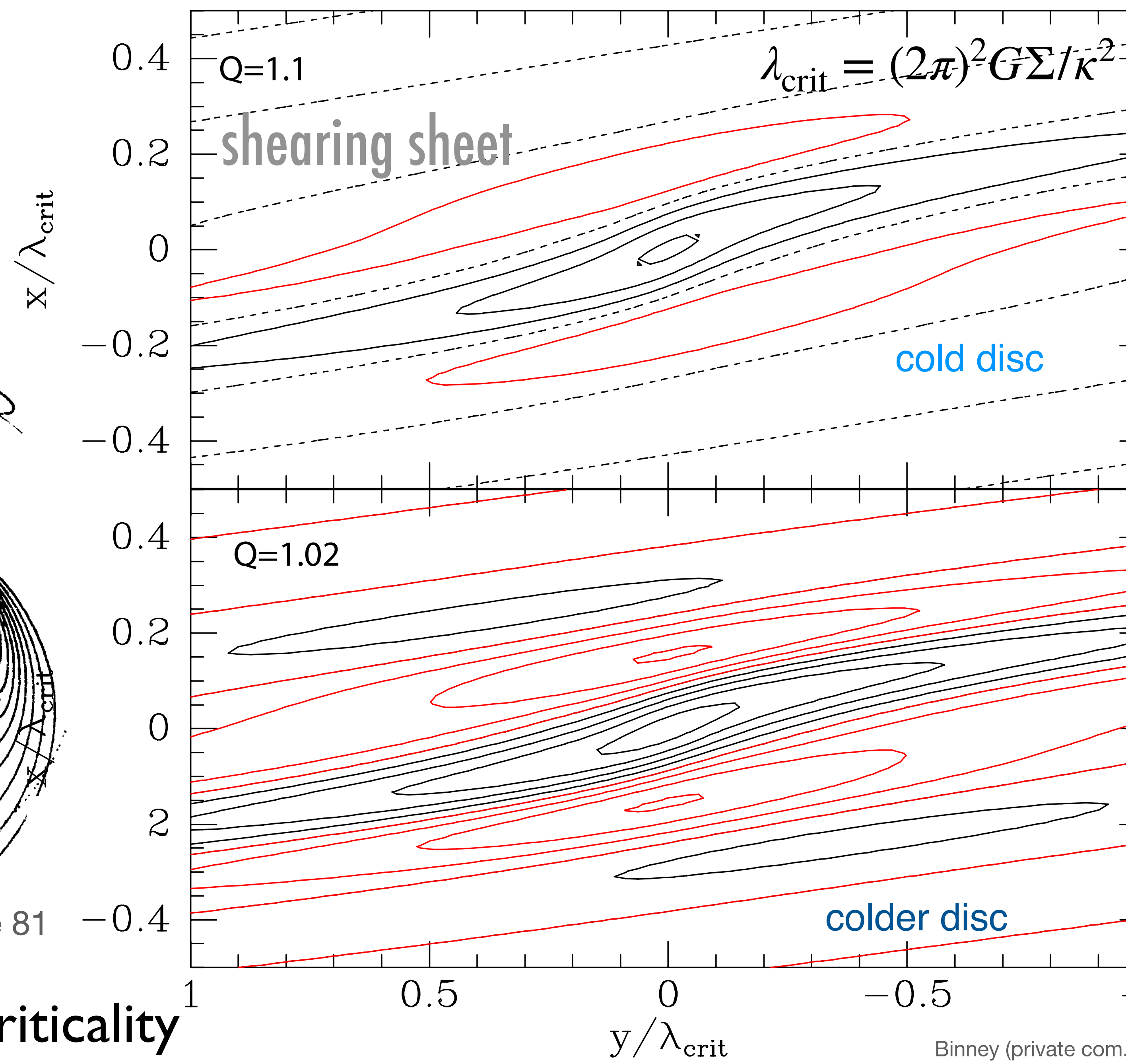


$$Q = \frac{\kappa\sigma}{\pi G \Sigma} \rightarrow 1$$

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

Mass in **wake** = mass in perturbation **X 140** !!





Binney (private com.)

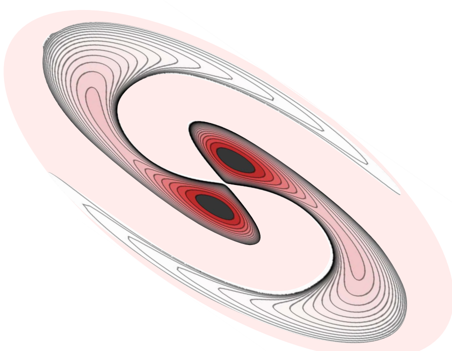
→ long range correlation: self organised criticality

Gravitational "*Dielectric*" function ϵ

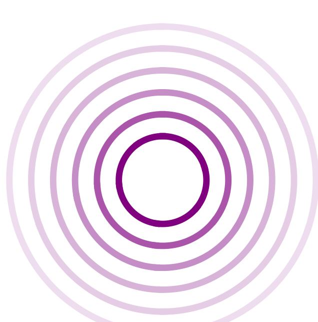
For cold discs…

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

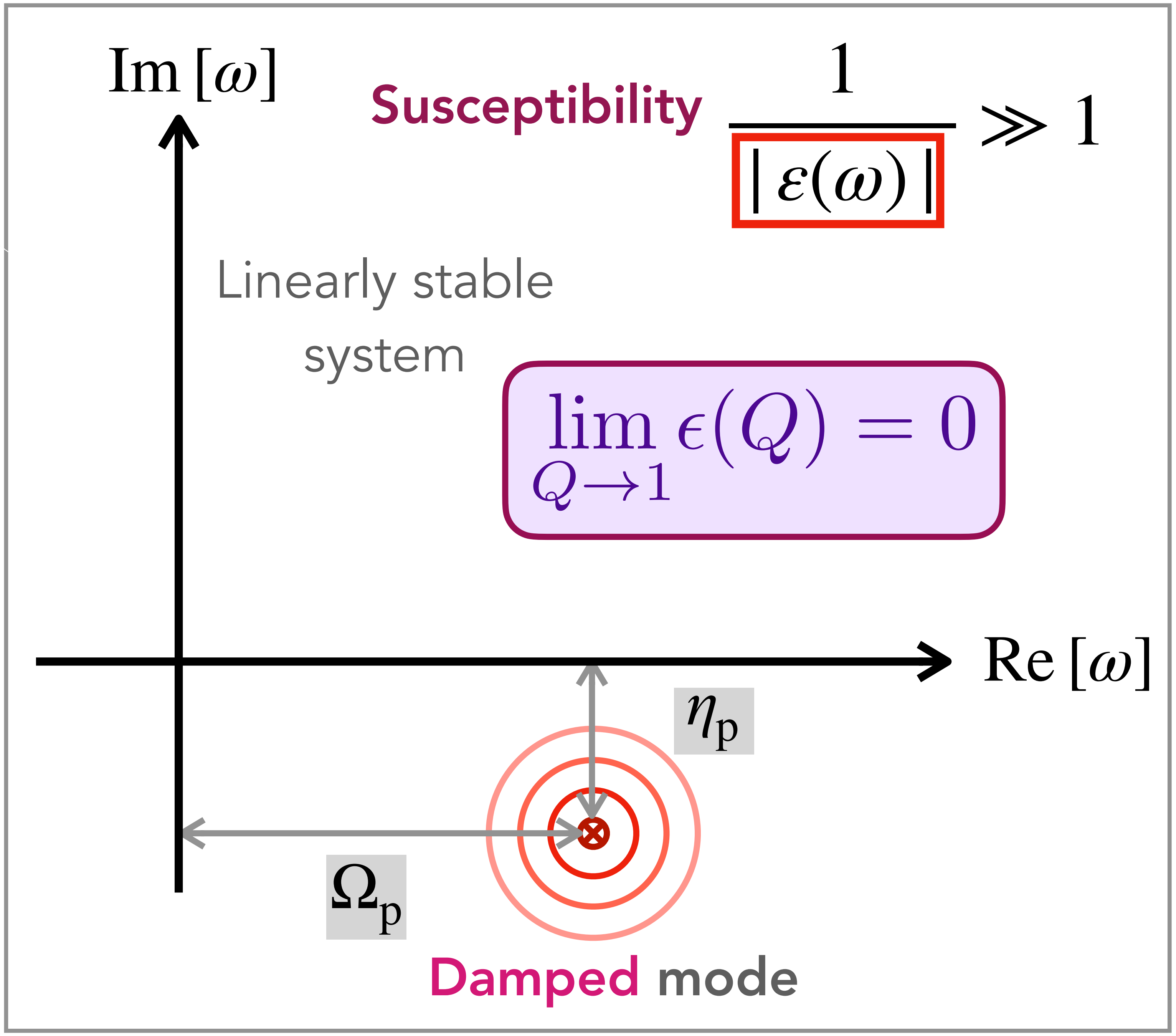
$$\epsilon(Q) \equiv \underbrace{\mathcal{D}(\omega, k)}_{\text{Dispersion relation}} = \det\big(1 - \underbrace{\mathbf{M}(\omega)}_{\text{Response matrix}}\big)$$



Gravitational Wake



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



$$[\delta\psi]_{\mathrm{dressed}} = \frac{[\delta\psi]_{\mathrm{bare}}}{\boxed{|\varepsilon(\omega)|}}$$

$$T_{\mathrm{dressed}} \simeq \boxed{|\varepsilon|}\, T_{\mathrm{bare}}$$

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

Wake drastically boost orbital frequencies, stiffening coupling/tightening control loops

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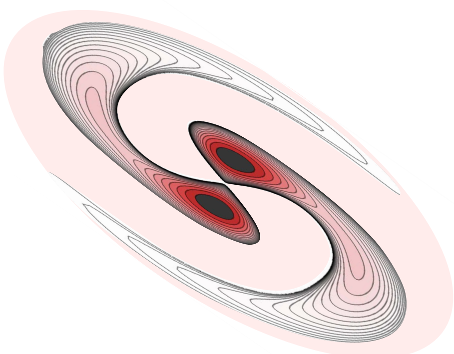
Dispersion relation — Response matrix



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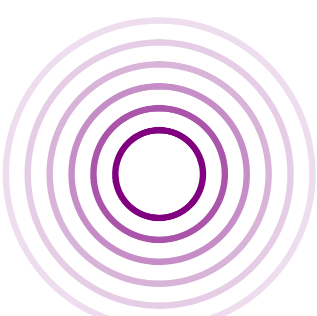

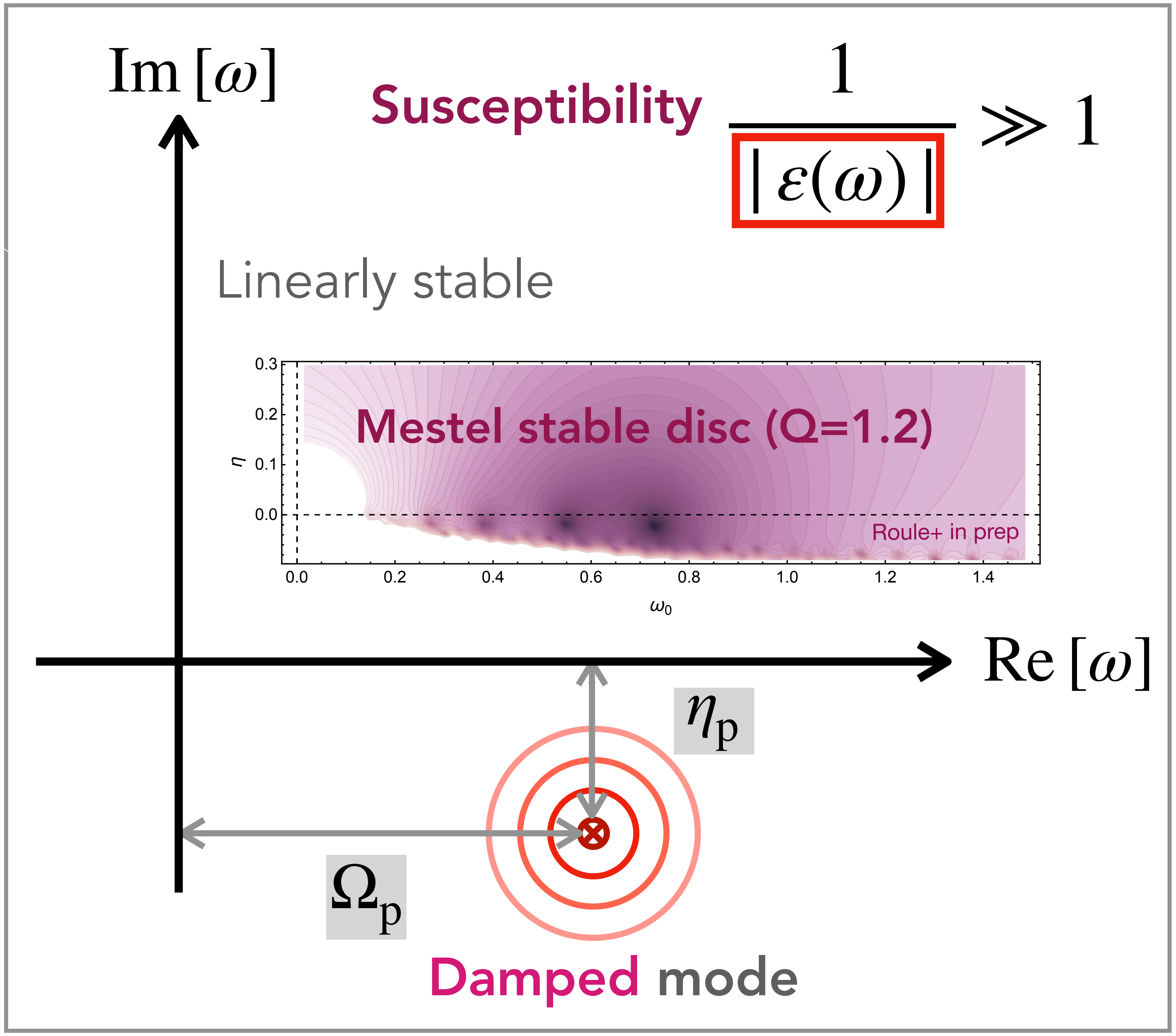

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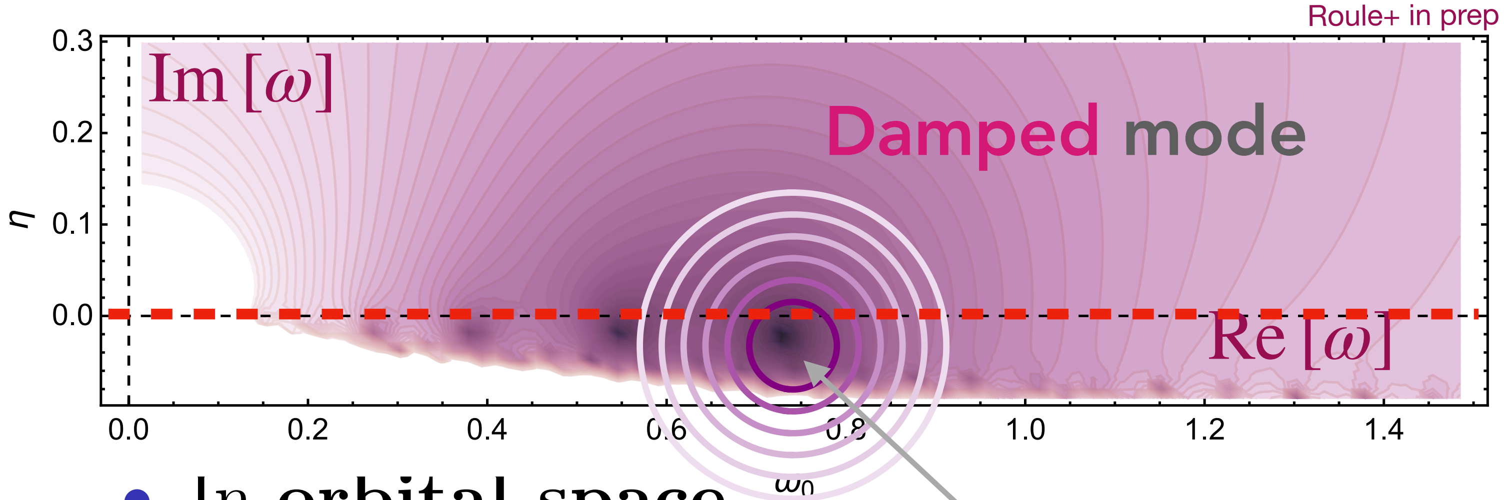
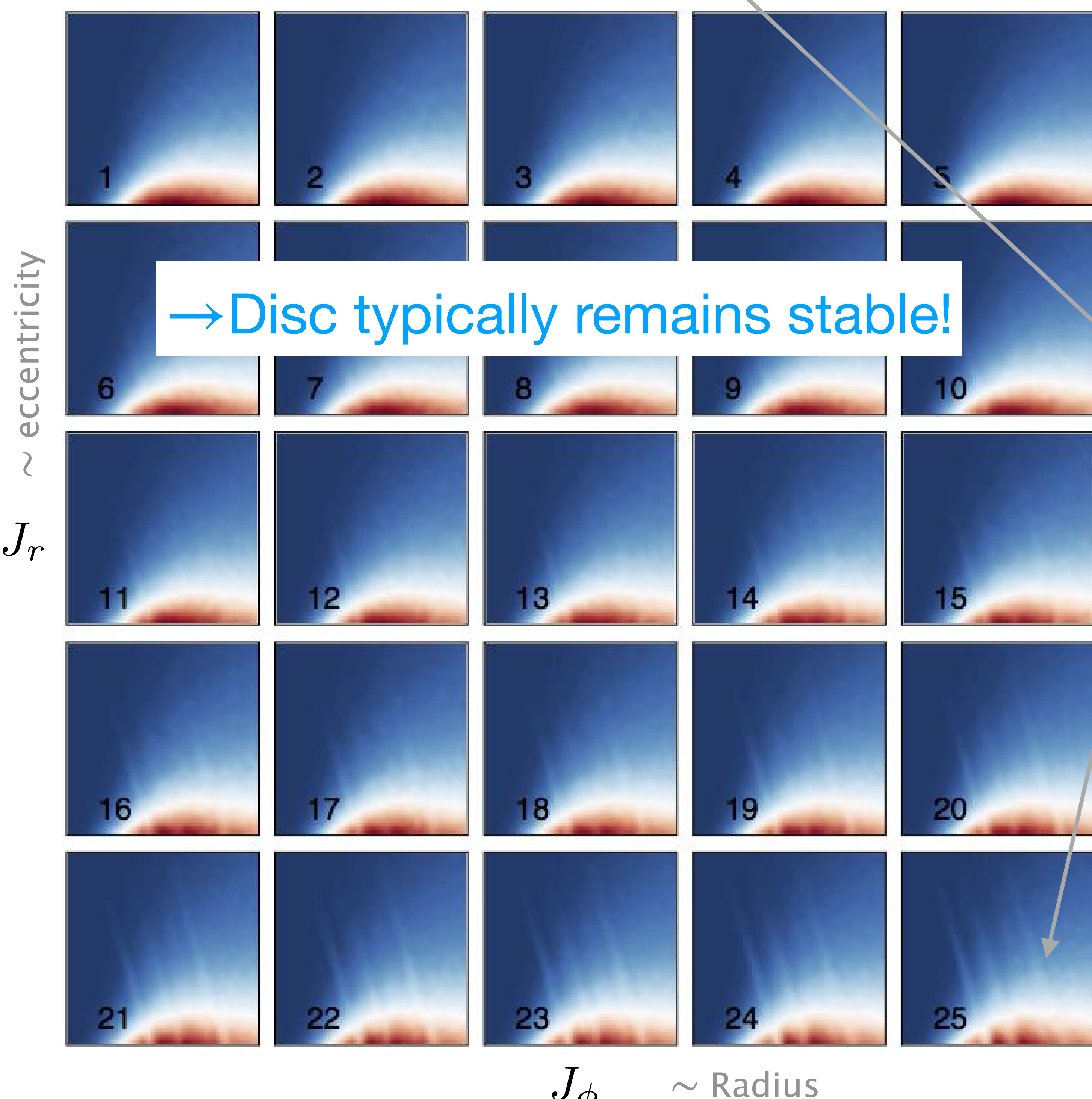


• **In orbital space**



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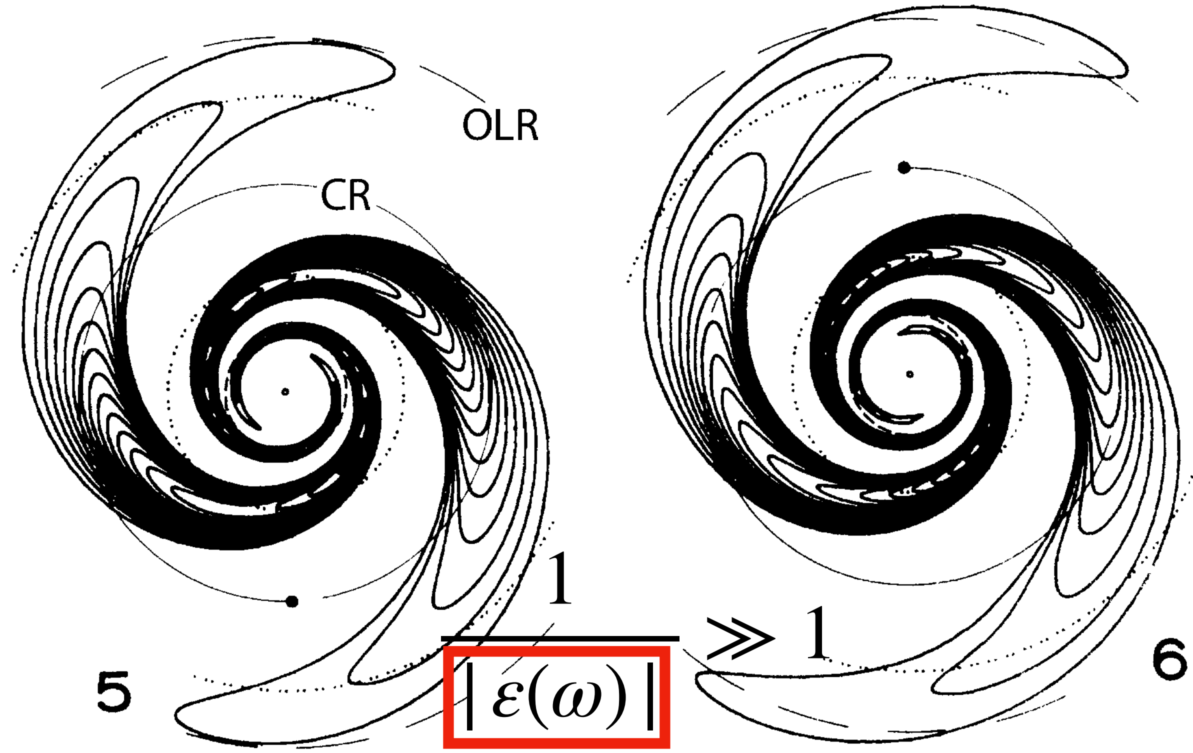
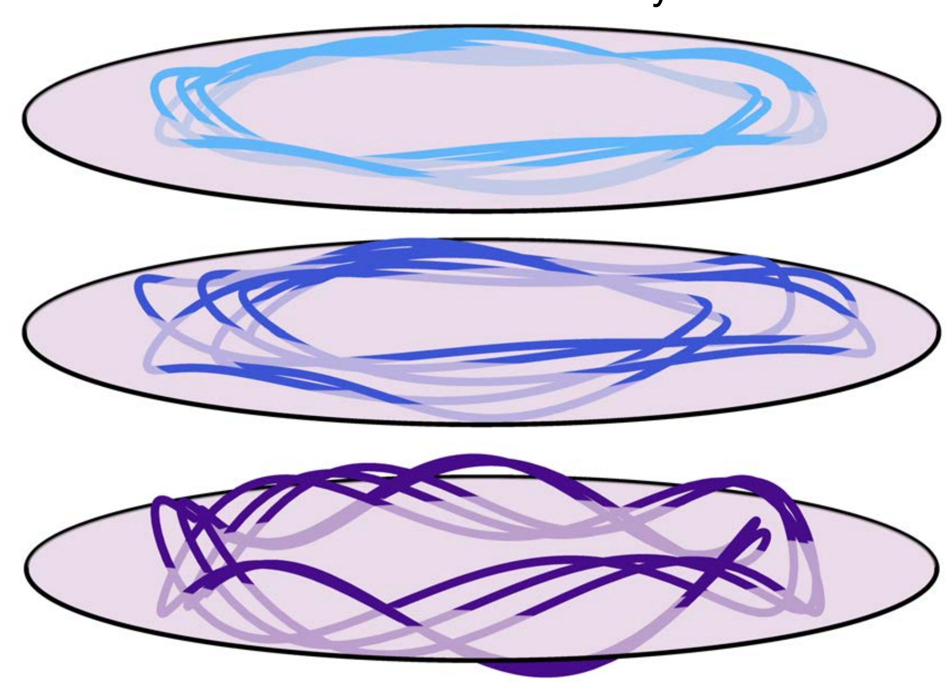


One-to-one correspondance between **position** of 4 **weakly damped** mode and position of **ridges**

Orbital diffusion time = $t_{\rm dyn}$ **/ 140x 140**

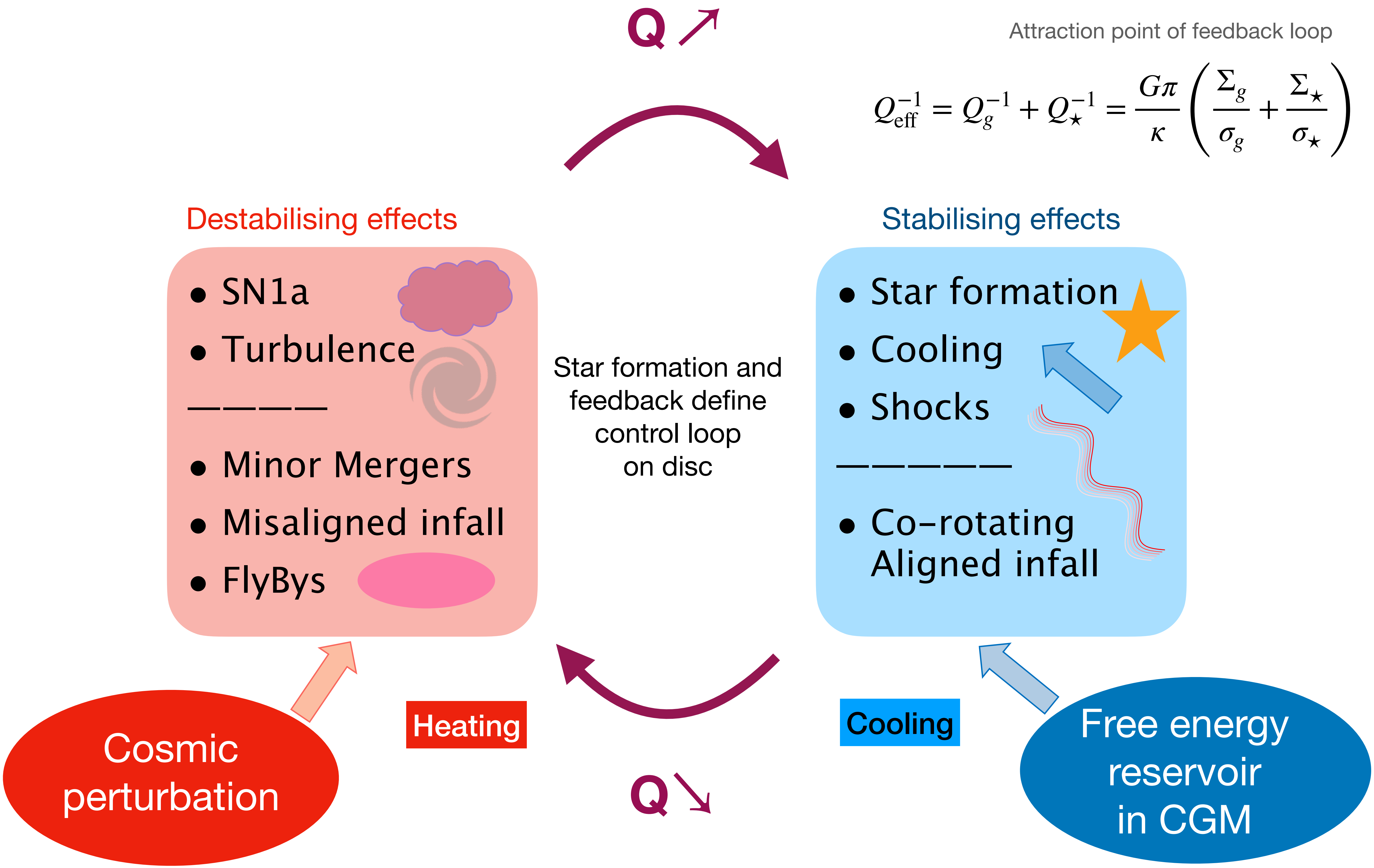


Self regulating loop boosted by wake

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

Attraction point of feedback loop

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



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

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

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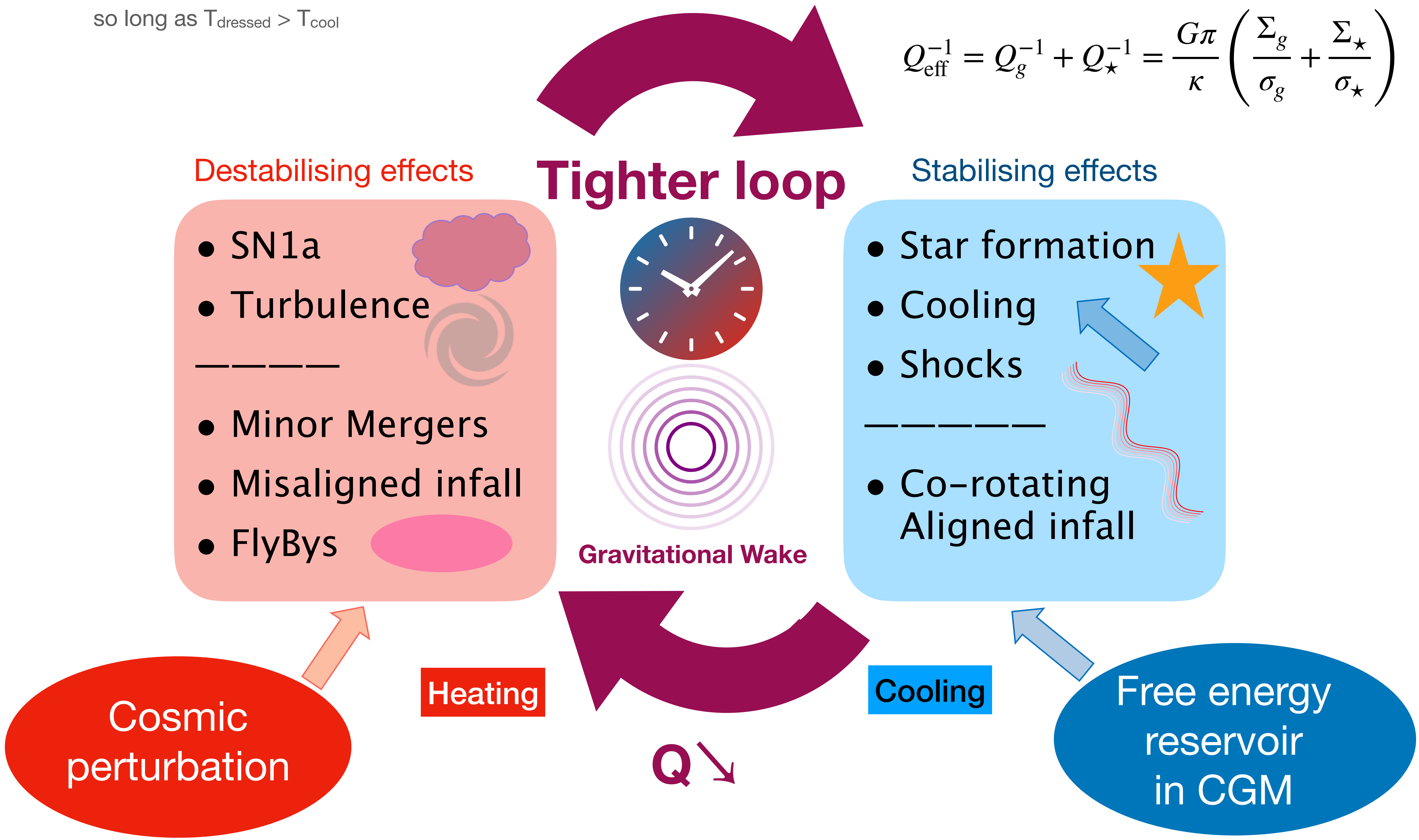
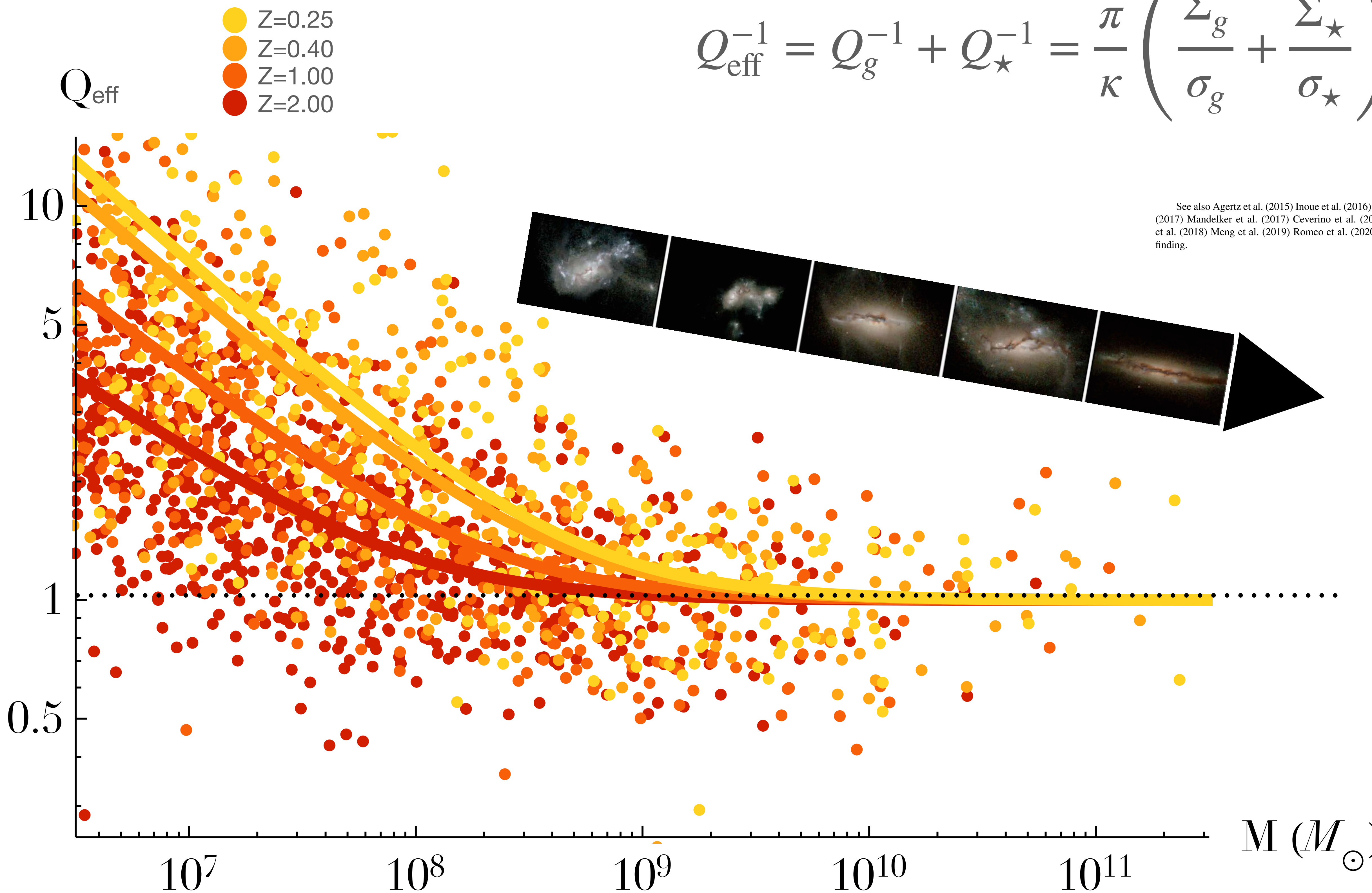


Open system with control loop generates complexity through self-organisation

Toomre Q convergence with mass and z

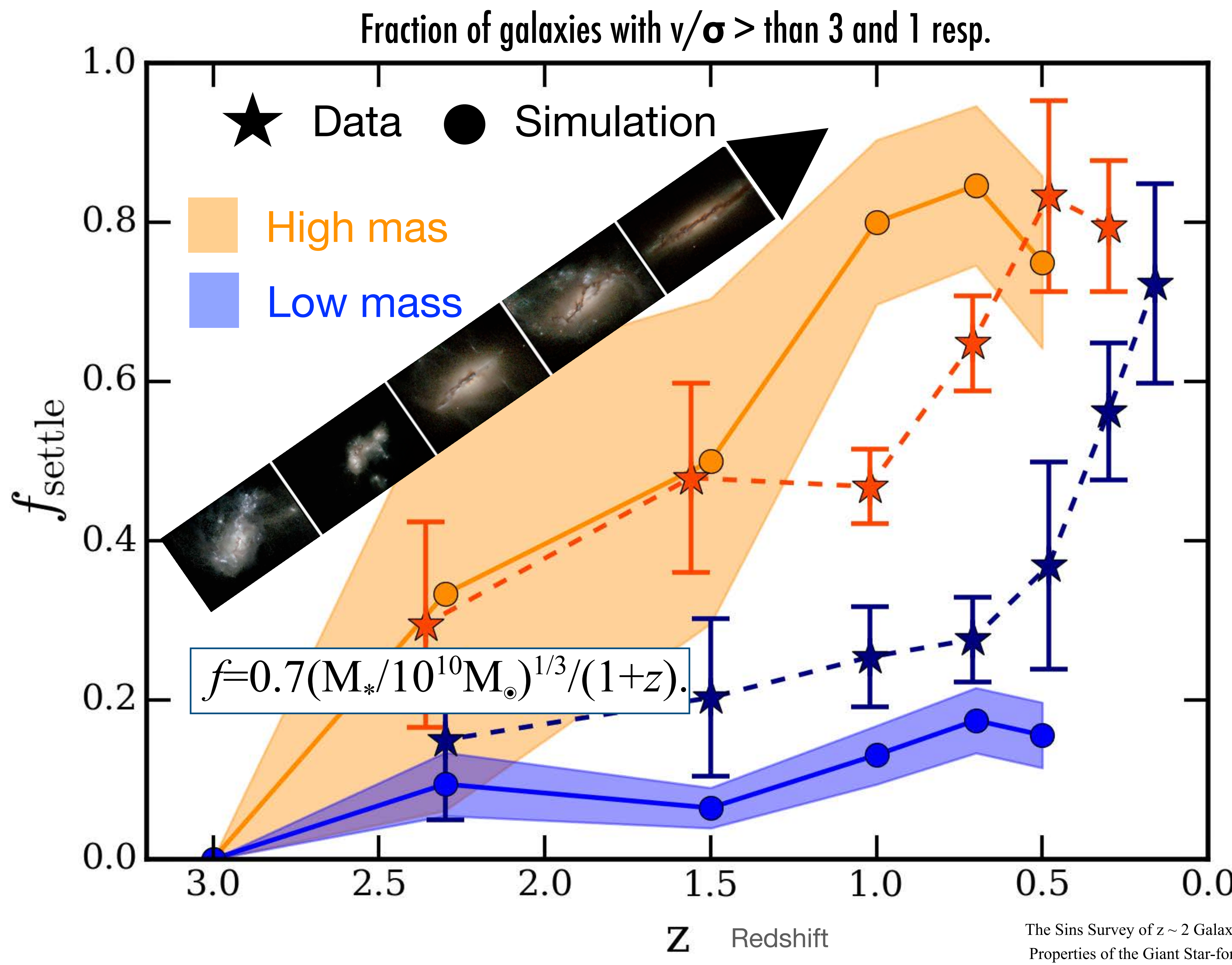
Toomre Q (★+gas) parameter convergence as a function of *both* mass and redshift

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



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)

Ring Toy model: secular damping by wake growth

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

x and y components of **angular momentum**

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

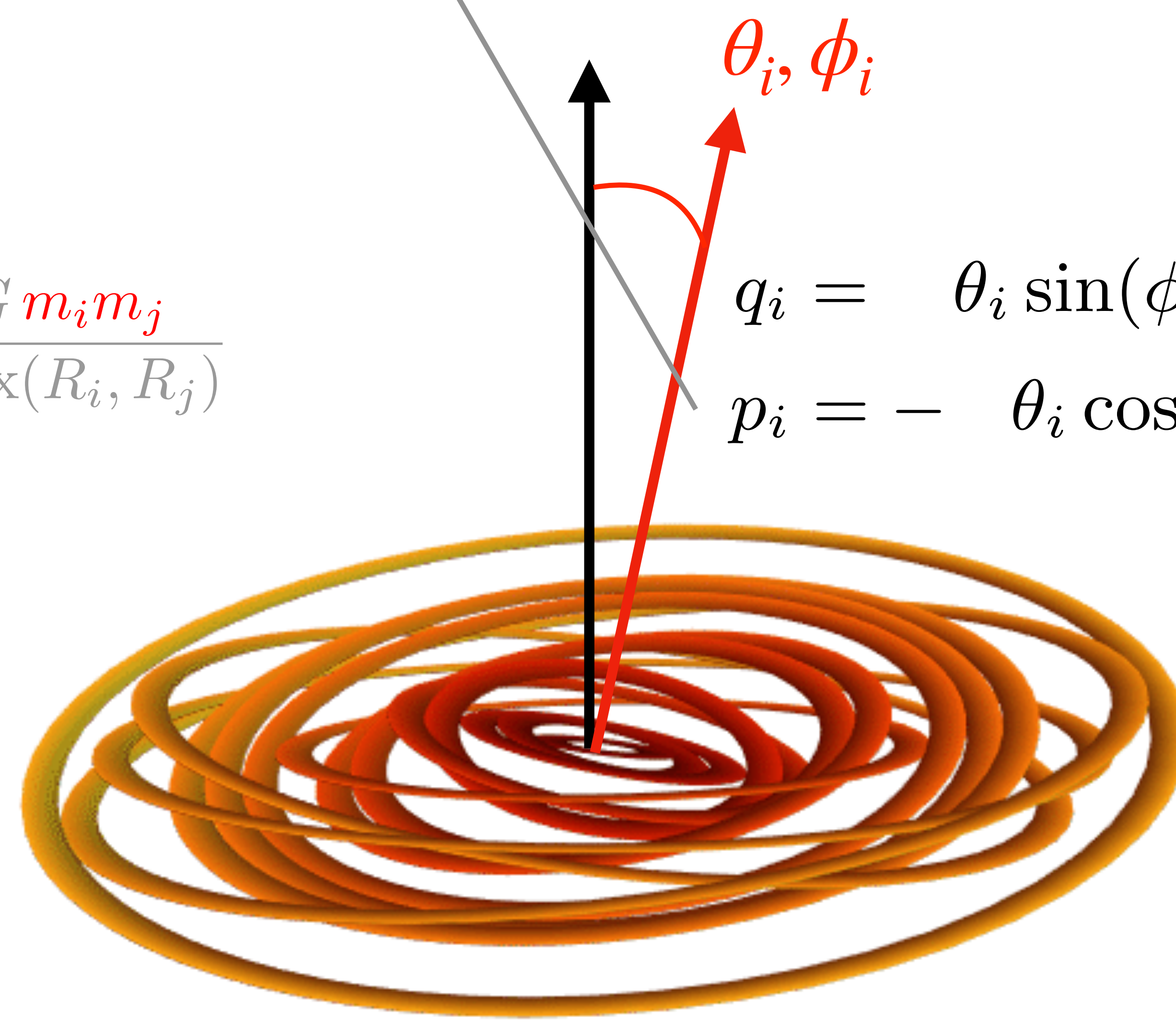
$$A_{ij} \propto -\frac{G\, m_i m_j}{\max(R_i, R_j)}$$

In eigenframe of A

Eigen frequency

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

forcing



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

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

Ring Toy model: secular damping by wake growth

Lagrange Laplace theory of rings *(small eccentricity small inclinaison)*

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θ_i, ϕ_i

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

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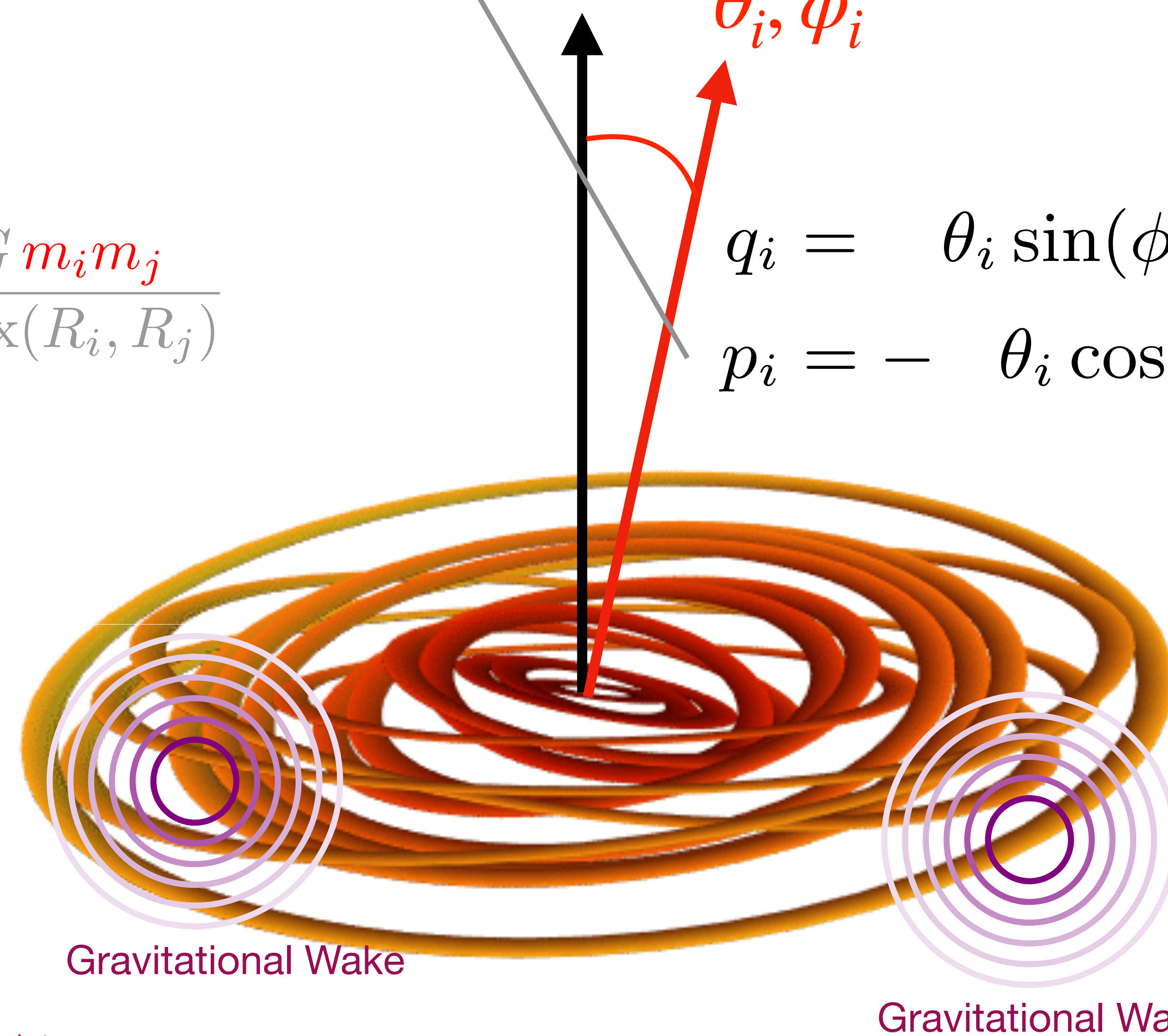


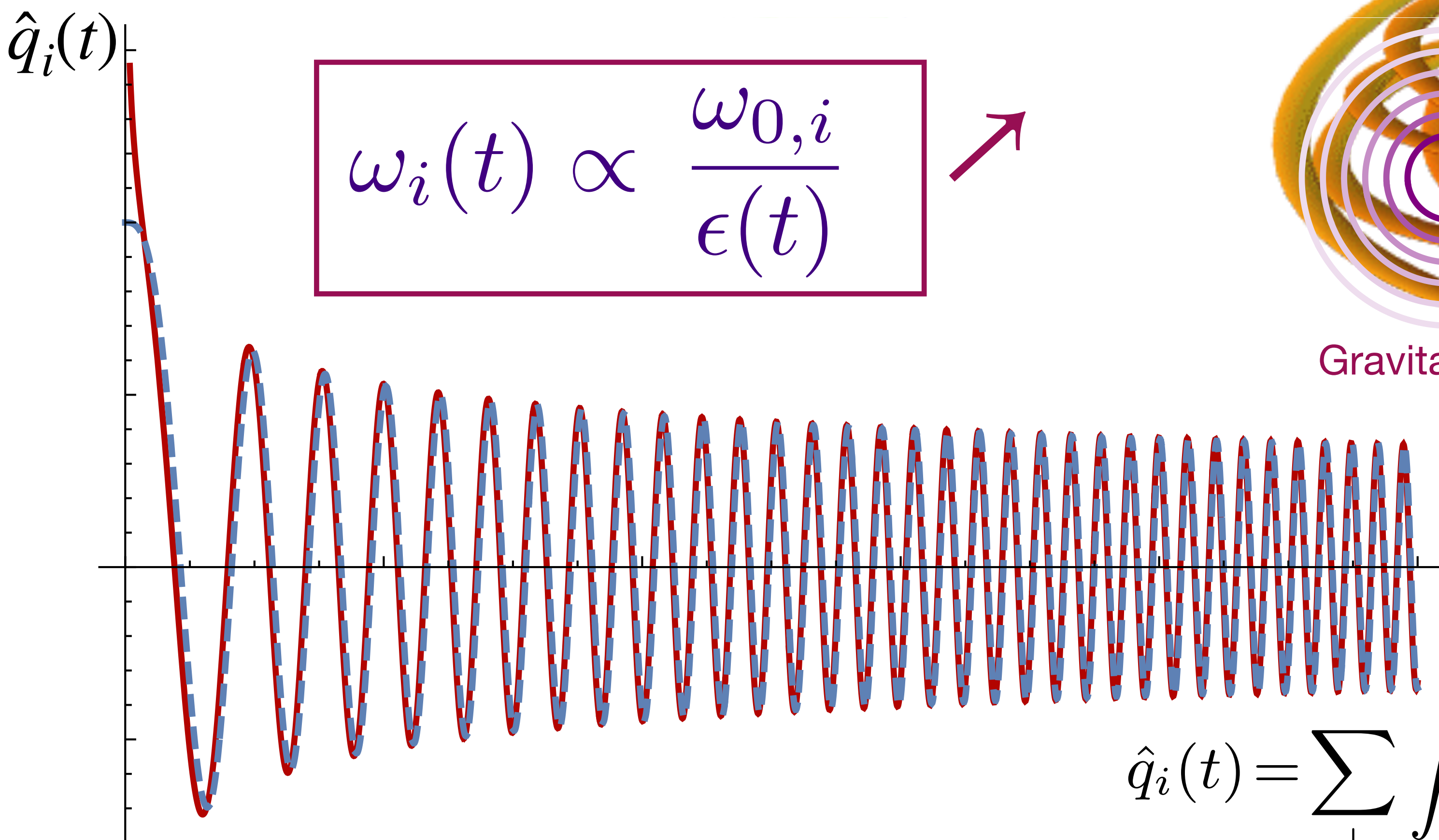
In eigenframe of A

Eigen frequency

forcing

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

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

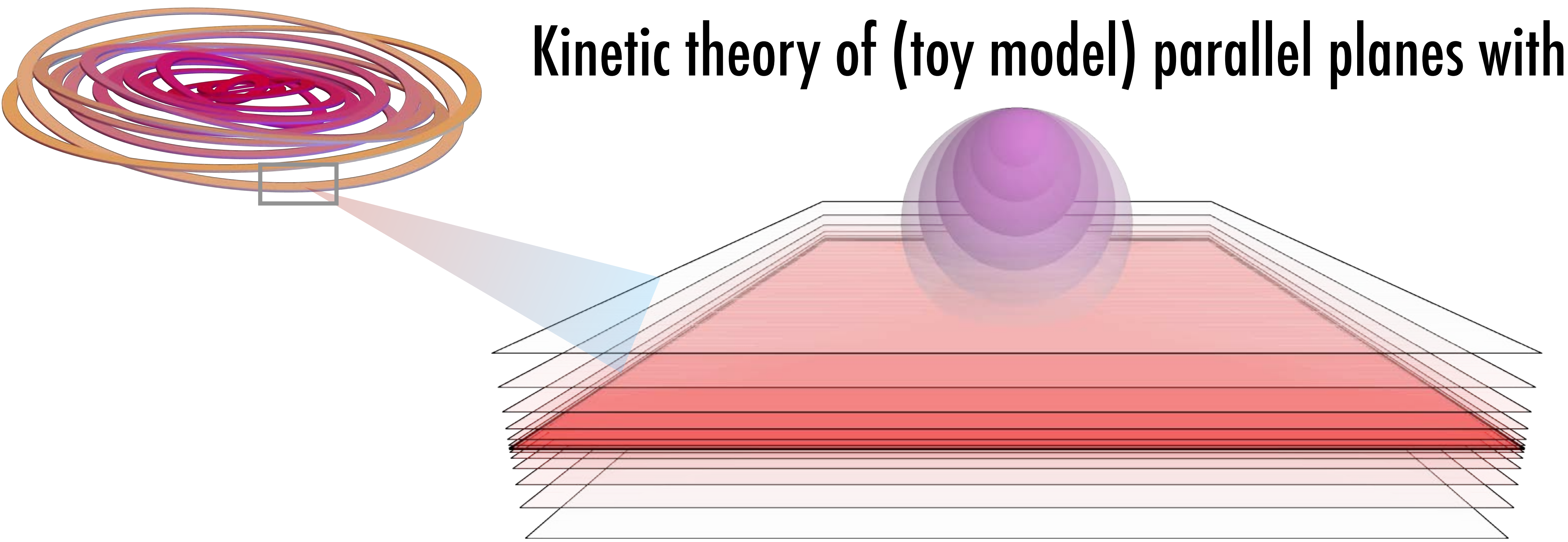


Secular WKB solution

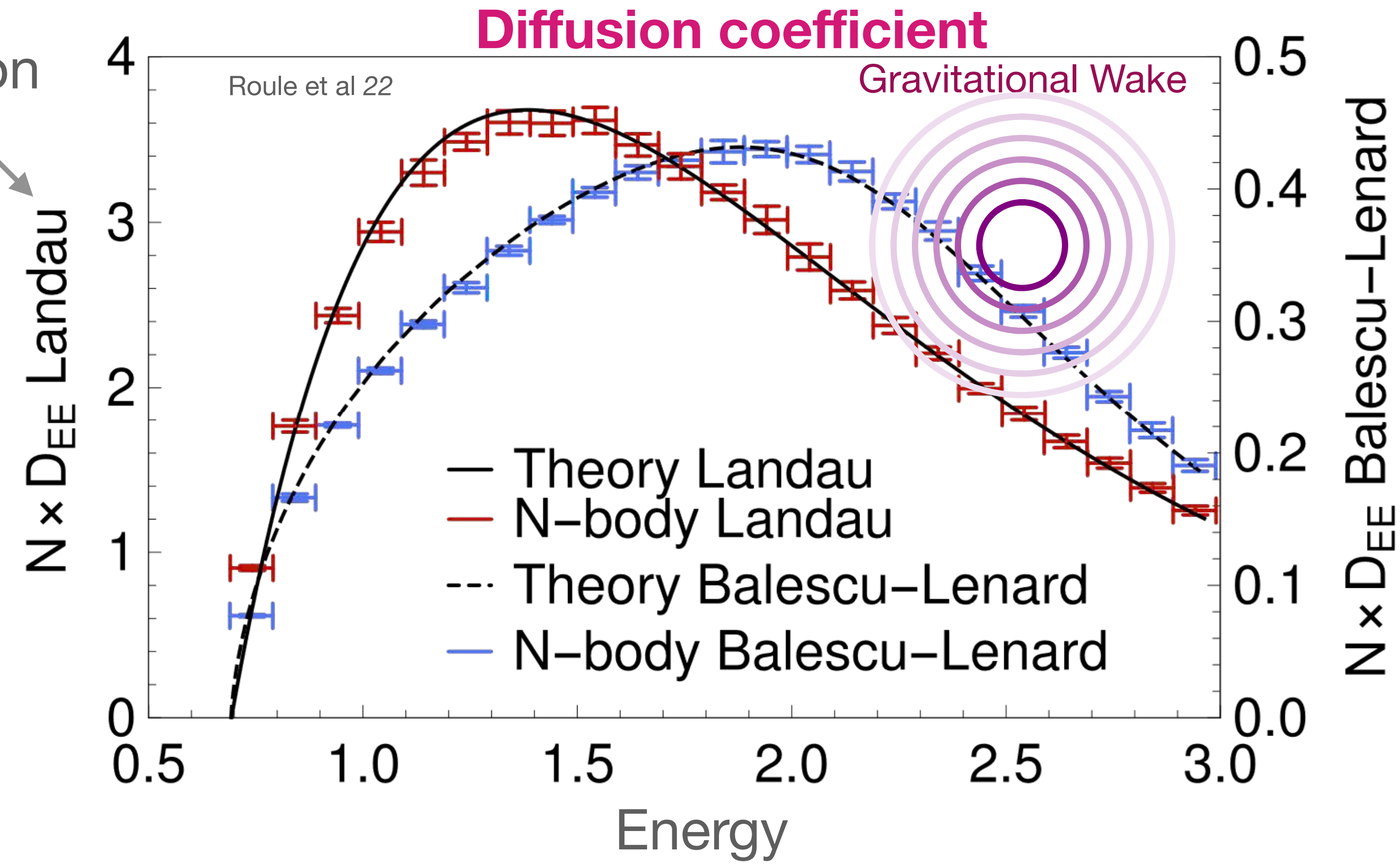
$$\hat{q}_i(t) = \sum_{\pm}\int_{-\infty}^{\infty}\frac{\hat{\xi}_i(t')}{\sqrt{\omega_i(t)\omega_i(t')}}\exp\left(\pm\imath\int_{t'}^{t}\omega_i(\tau)d\tau\right)dt'$$

Plane Toy model: dressing damps vertical diffusion

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

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 → ★~~

Gas + ★ → ★ + ★

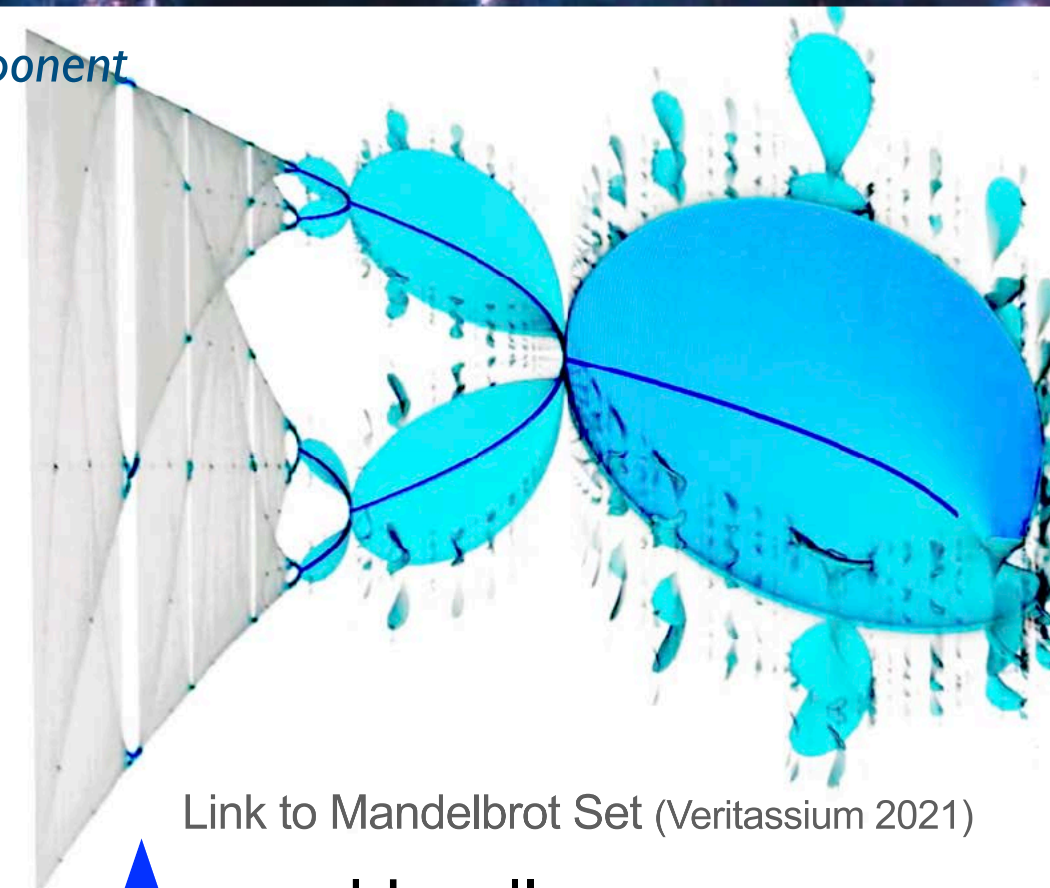
$$\frac{d}{dt}\bigstar = r\bigstar(1-\bigstar)$$

control parameter

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

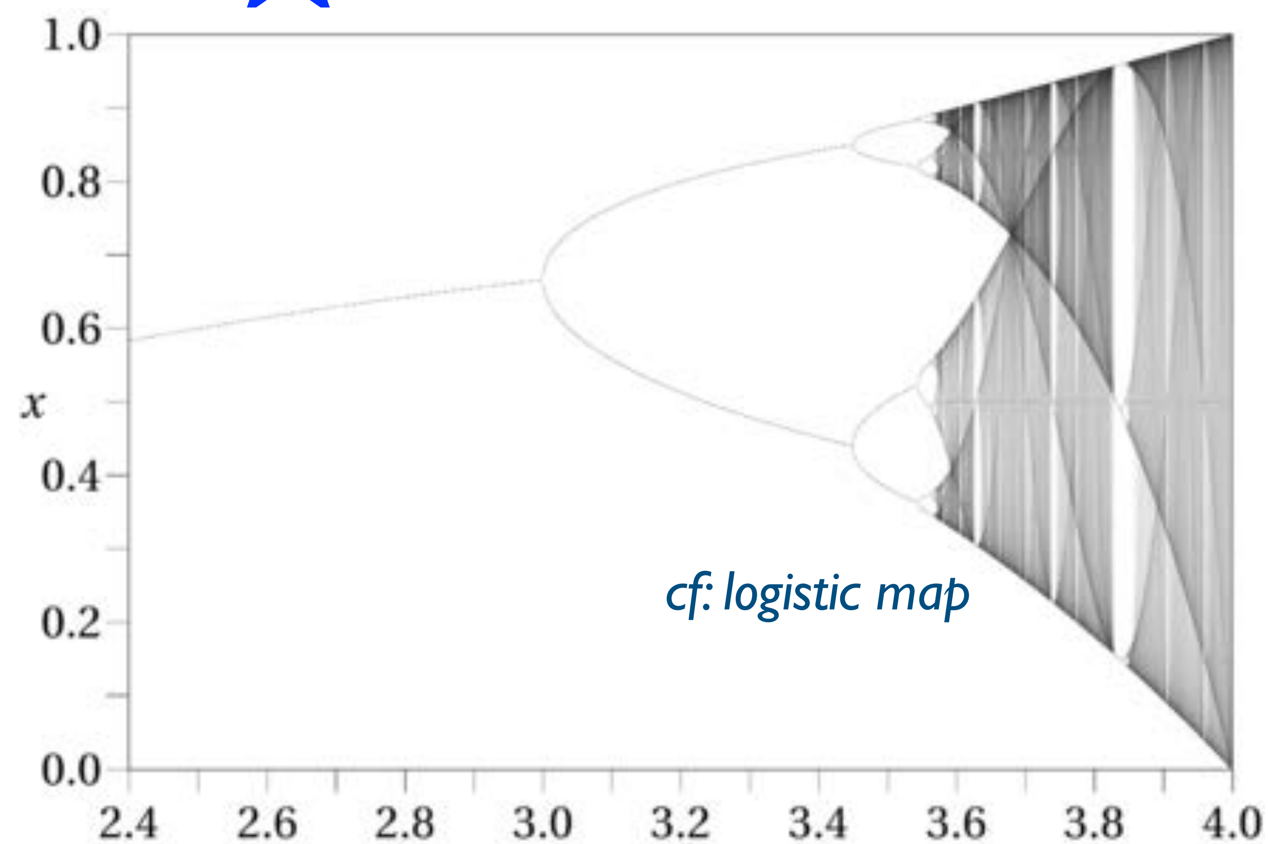
= Simplest **quadratic** model for self -regulation

= 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*

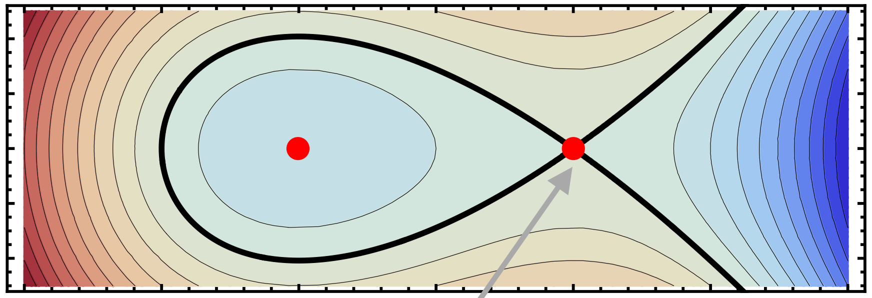
Dissipation converts kinetic instability point into an attractor.

Reaction-Diffusion equation (cf morphogenesis)

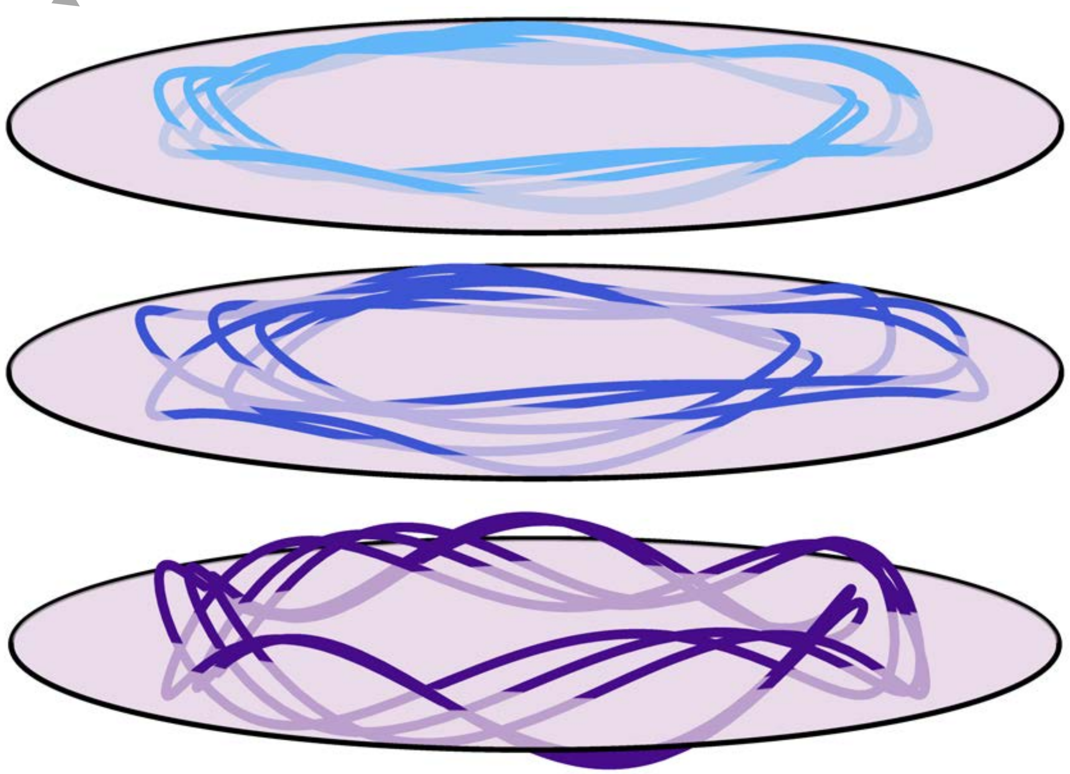
Fokker Planck orbital diffusion

$$\boxed{\frac{d}{dt}\bigstar = \underbrace{\delta_D \bigstar (1- \bigstar)}_{\text{Cooling}} + \underbrace{\Delta \bigstar}_{\text{Heating}}}$$

Logistic map Hamiltonian



New point of equilibrium with finite disc thickness



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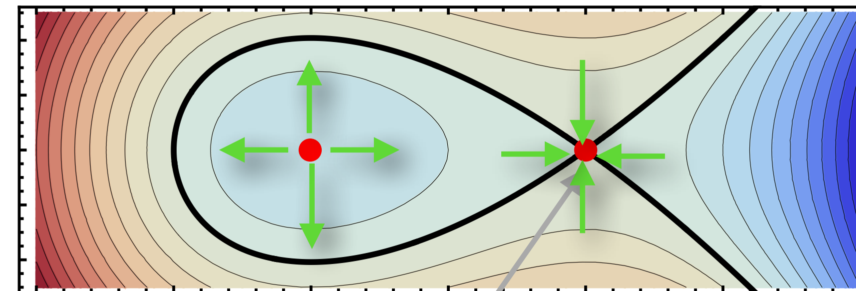

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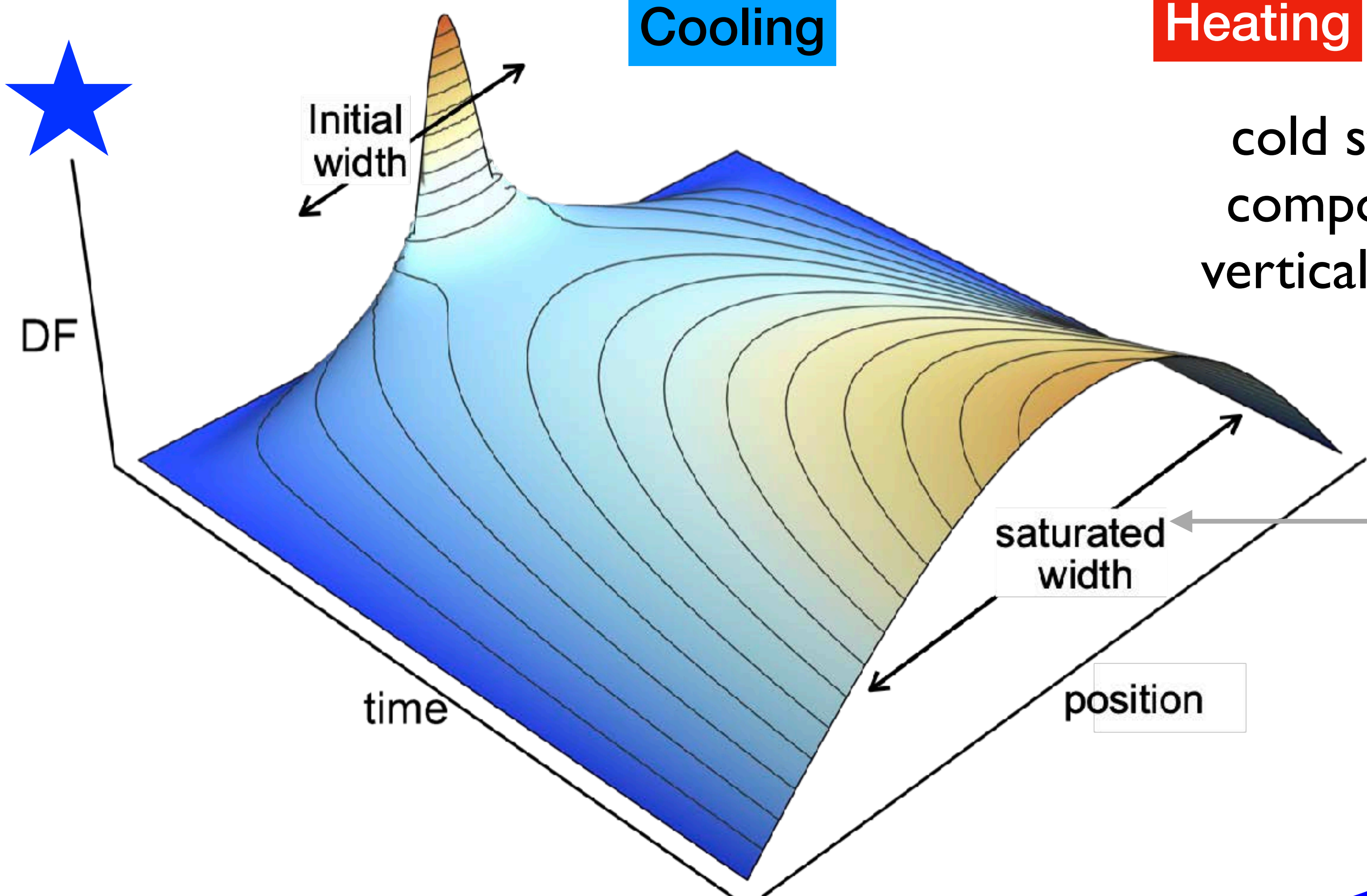
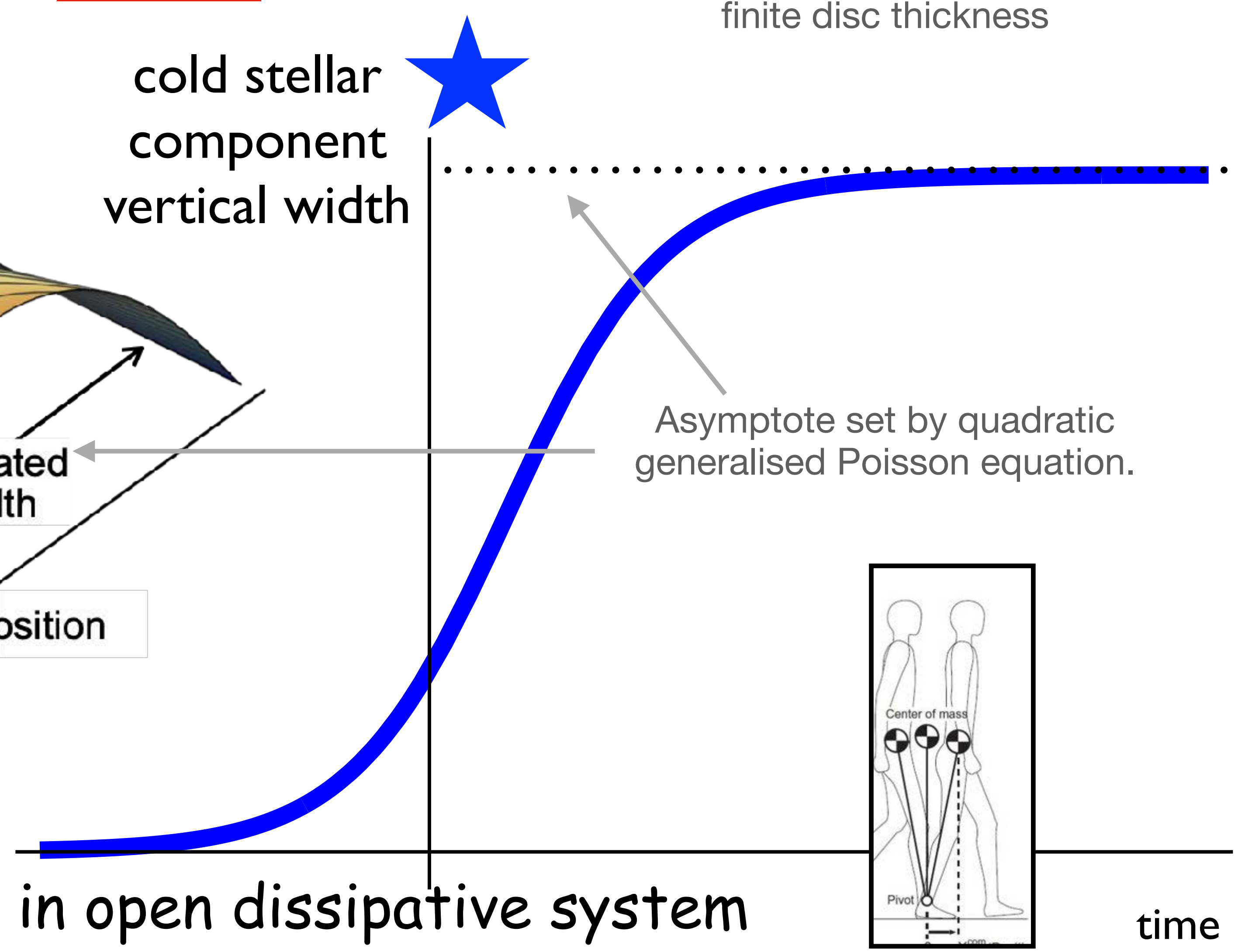




→ Emergence of thin **fixed width** disc in open dissipative system

Chemistry of emergence… introduce tides

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

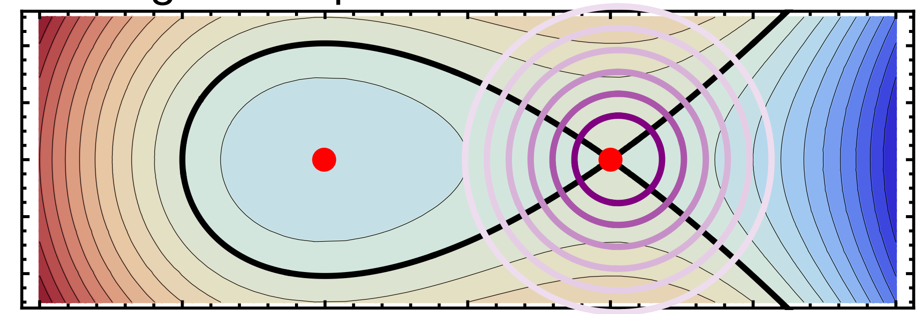
Dissipation converts kinetic instability point into an attractor.

Dressed Reaction-Diffusion equation (cf morphogenesis)

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

Gravitational Wake

Logistic map Hamiltonian



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

SF efficiency

$$\left.\begin{aligned}\eta_{\rm dressed} &\propto \eta_{\rm raw}/\epsilon^2(Q)\\ D_{\rm dressed} &\propto D_{\rm raw}/\epsilon^2(Q)\end{aligned}\right\} \sim \text{quadratic in } \varepsilon \qquad \Longrightarrow \quad dt \to \frac{dt}{\epsilon^2}$$

Diffusion

Rapid correction

→ Cosmic resilience of thin disc

→ Operates swiftly near self-organised Criticality

→ Robustness / feedback details

Chemistry of emergence… introduce tides

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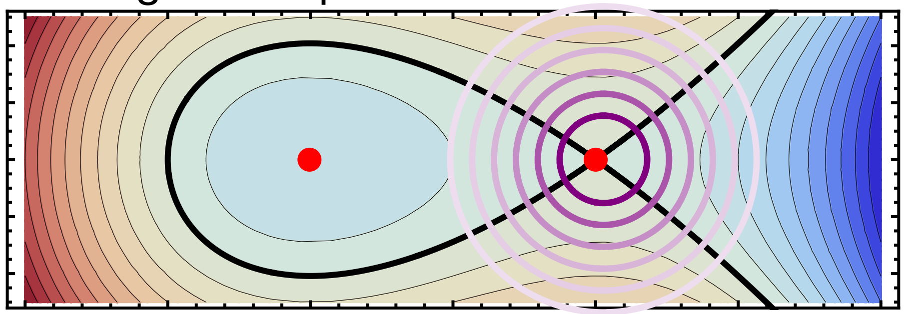

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Diffusion

Rapid correction

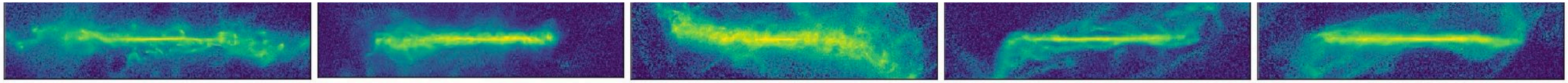
→ Cosmic resilience of thin disc

→ Operates swiftly near self-organised Criticality

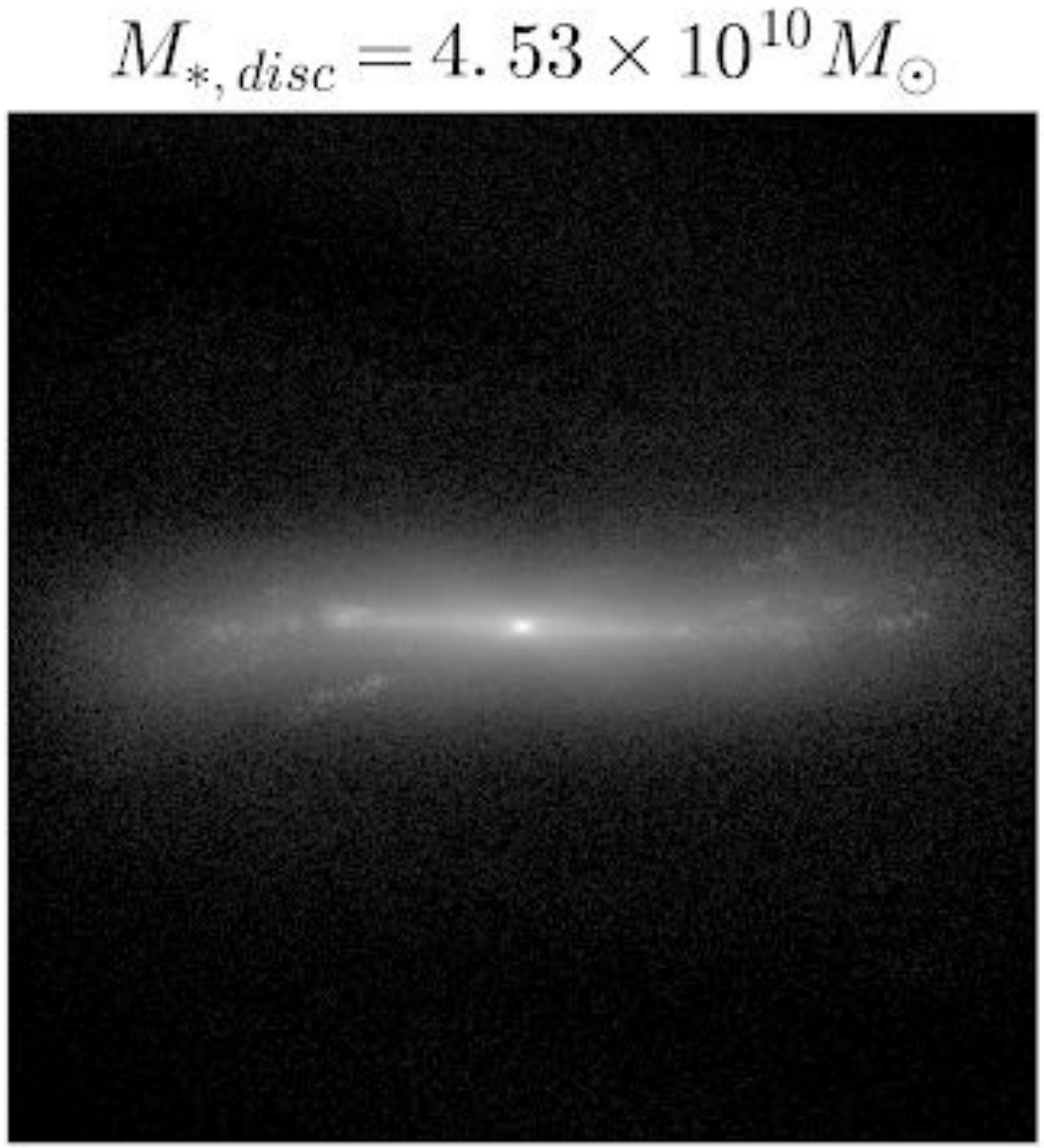
→ Robustness / feedback details

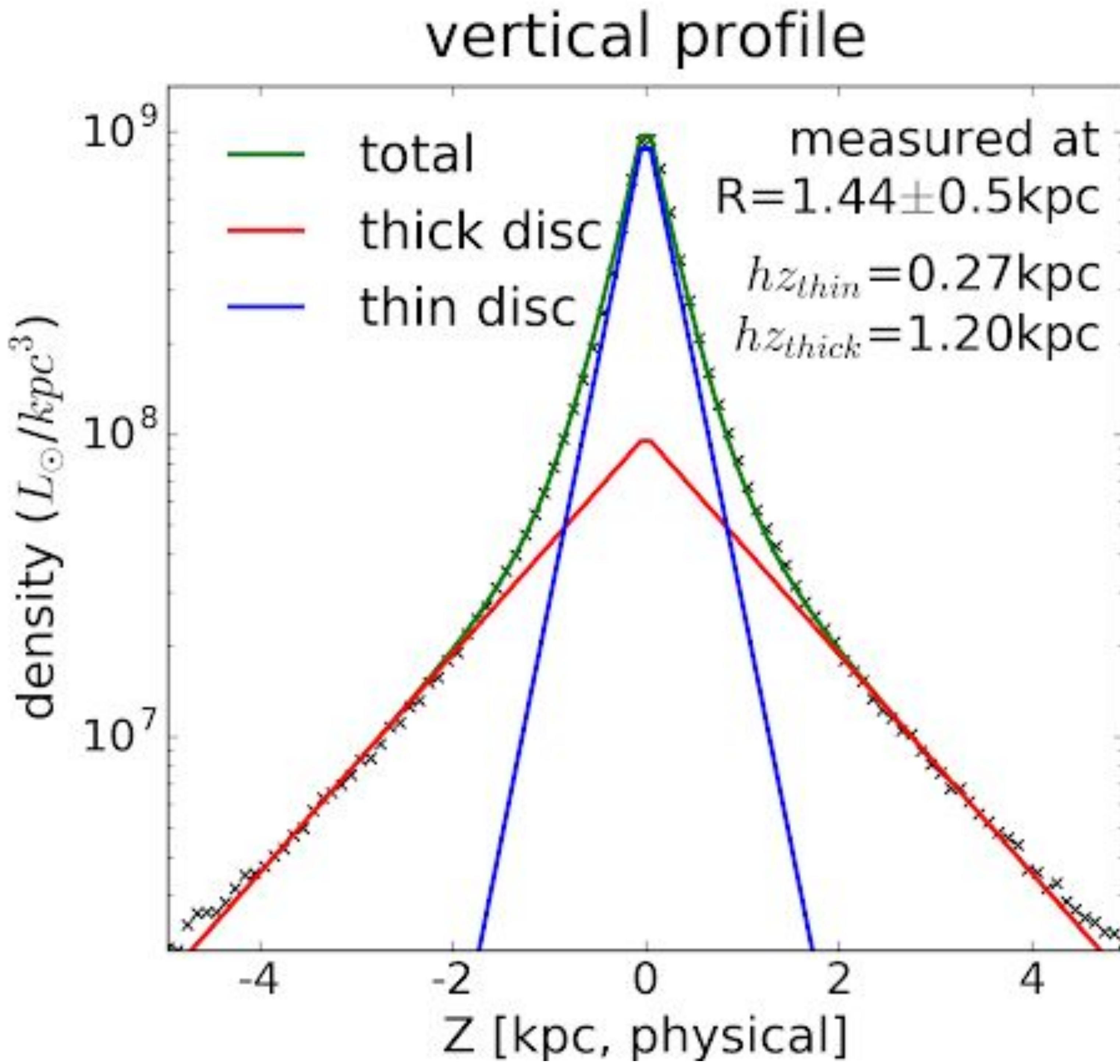
No fine tuning !

all discs are fairly thin whatever the feedback



Q∼ 1 confounding factor for joint thick+thin growth





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.

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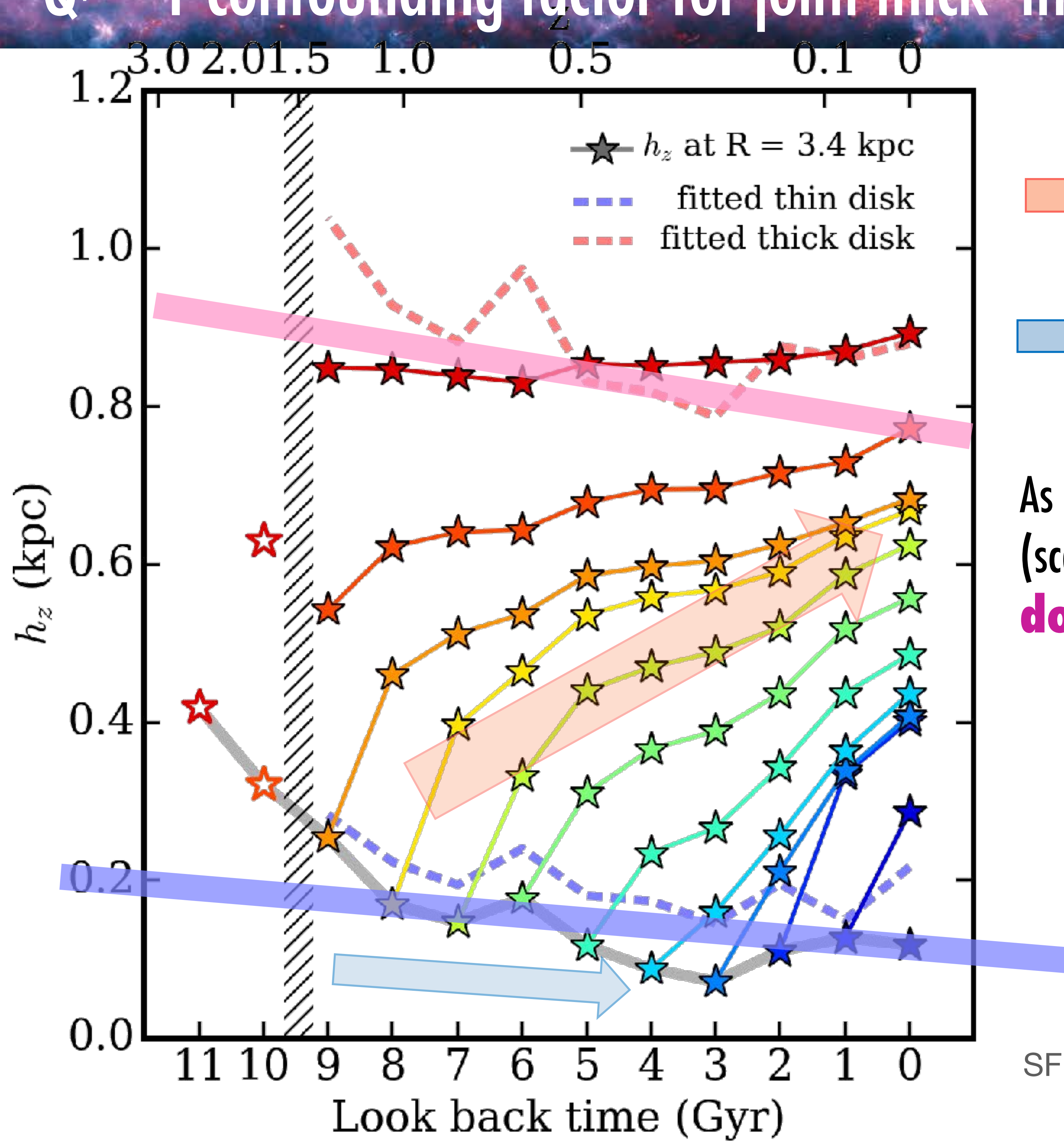


Pre-existing disk stars get thicker with time due to heating

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

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

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

SF efficiency

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.

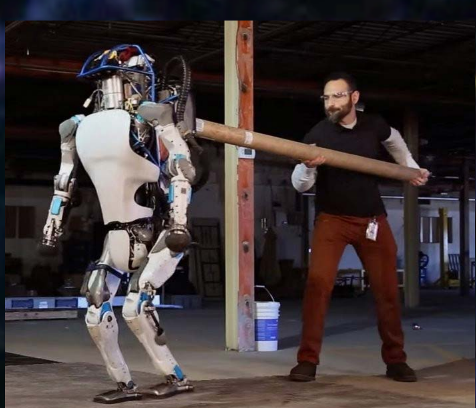
CONCLUSIONS

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

upcoming KITP programme/conference

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The Co-evolution of the Cosmic Web and Galaxies across Cosmic Time

Feb 6, 2023 - Feb 9, 2023

Programme
Conference
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Cosmic Web 2023 conference @KITP

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The Co-evolution of the Cosmic Web and Galaxies across Cosmic Time

Coordinators: Joanne Cohn, Nick Kaiser, Katarina Kraljic, and Dmitri Pogosyan

Date: Feb 6, 2023 - Feb 9, 2023

REGISTER

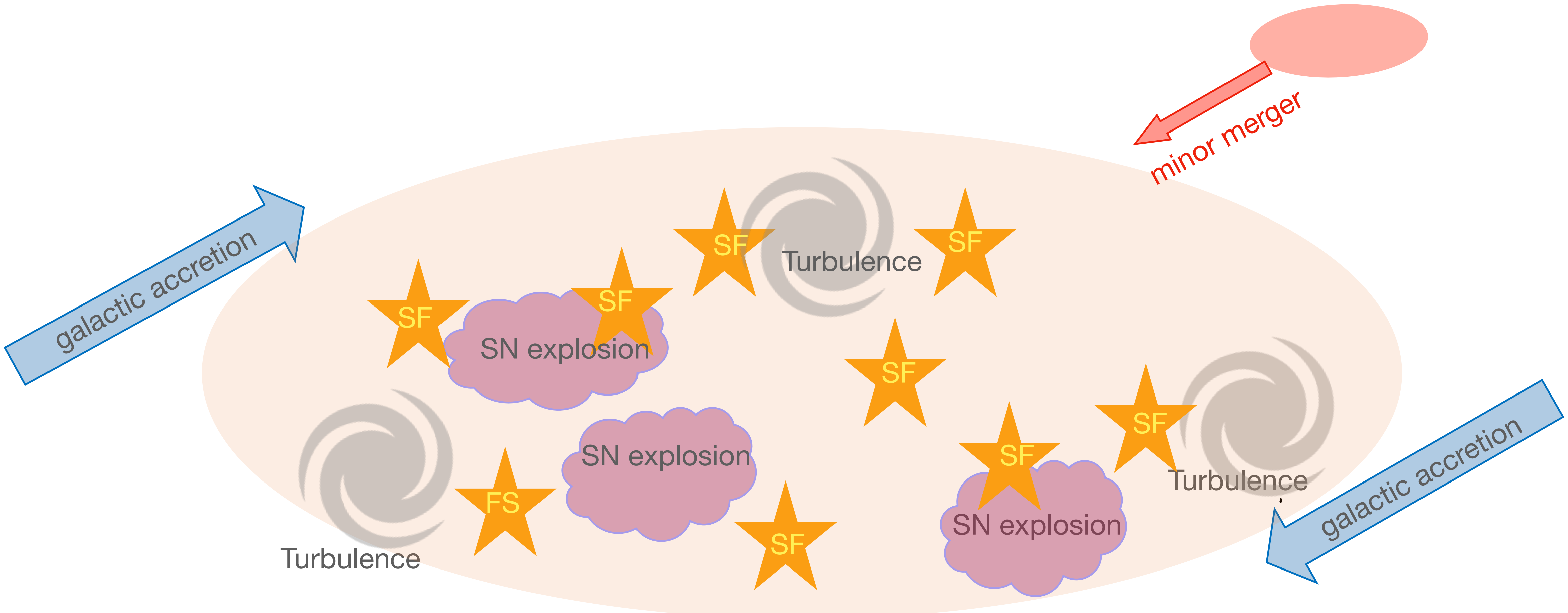
Registration **deadline** is: Jan 8, 2023.
Registration Fee: $330
Fee Due: Jan 8, 2023
Late Registration Fee: $380
Conference begins (with registration): Feb 6, 2023 at 08:50 am

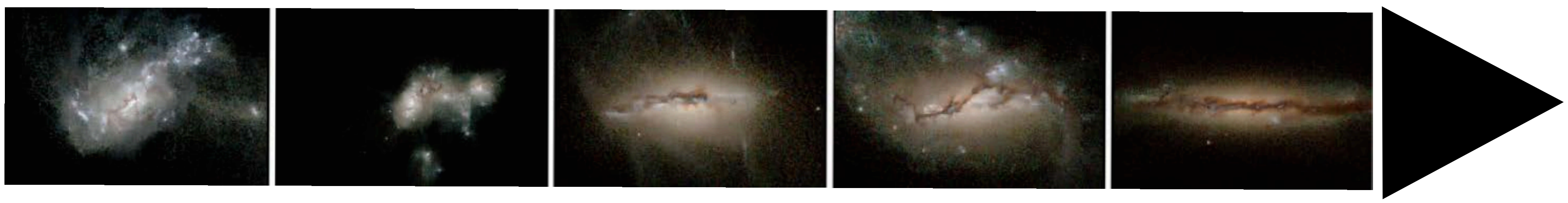
https://conference.cosmicweb23.org

The cosmic web of the matter distribution in the universe provides the framework for the formation and evolution of galaxies and is fundamental to connect galactic properties to cosmology. This conference will address the effects of the cosmic web upon galaxies and vice versa. The aim is to create both a broad-brush and then, for some aspects, a more detailed, early to late time joint history of the web and galaxies. Indeed, the web reflects what the universe is on intermediate scales, which are informative, both in terms of cosmic evolution and quantity of data. It acts as a dynamically relevant intermediate-density bridge (easier to model) between cosmology and galaxies. It is also the source of all anisotropy, critical for angular momentum acquisition, which is the number two parameter in galaxy formation.

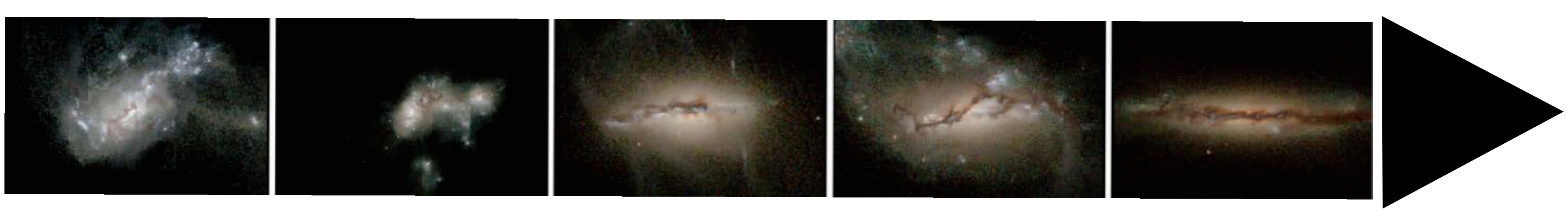
Merci !

Bring home message: dressing redefine clocks





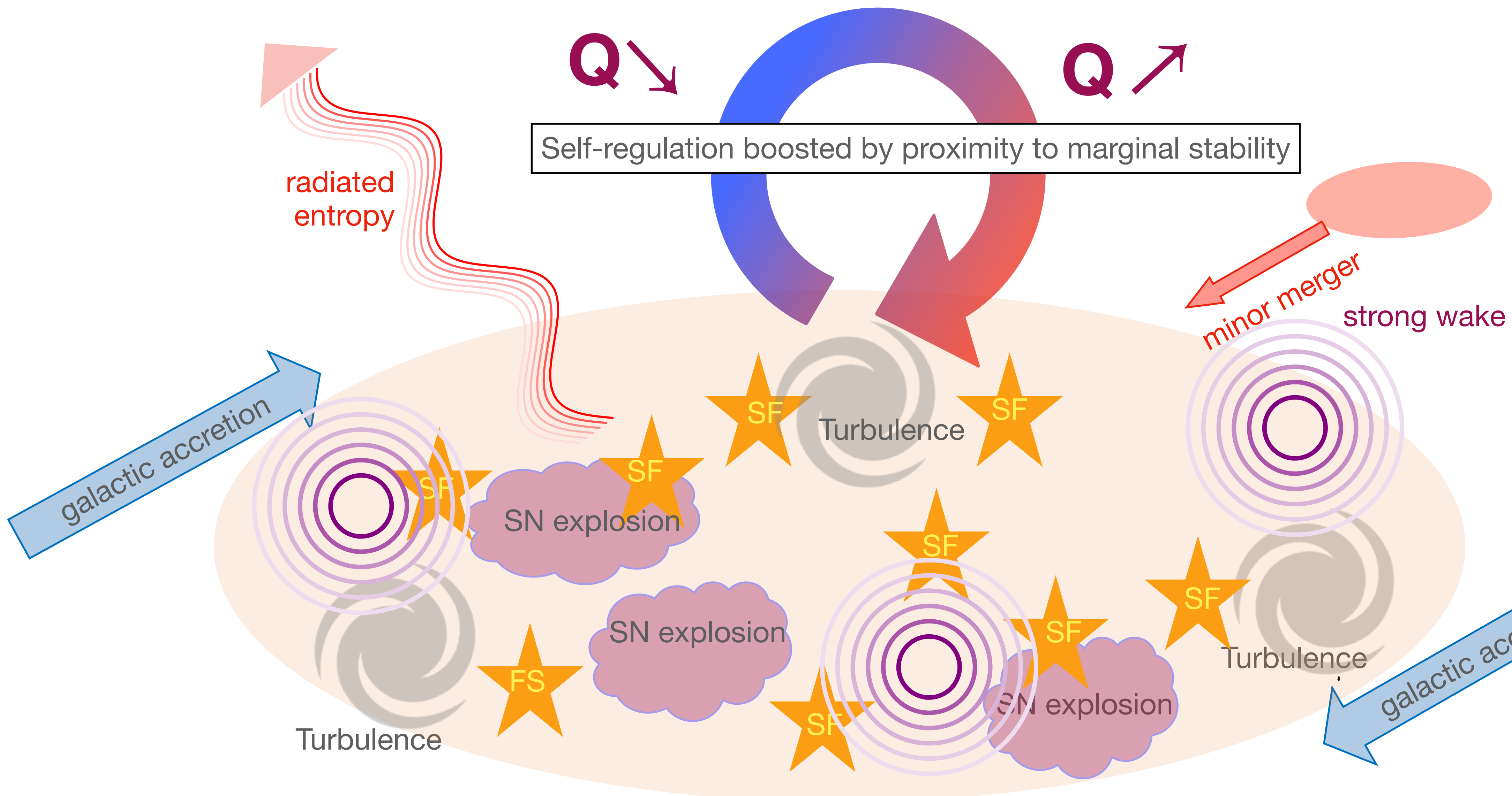
Bring home message: dressing redefine clocks

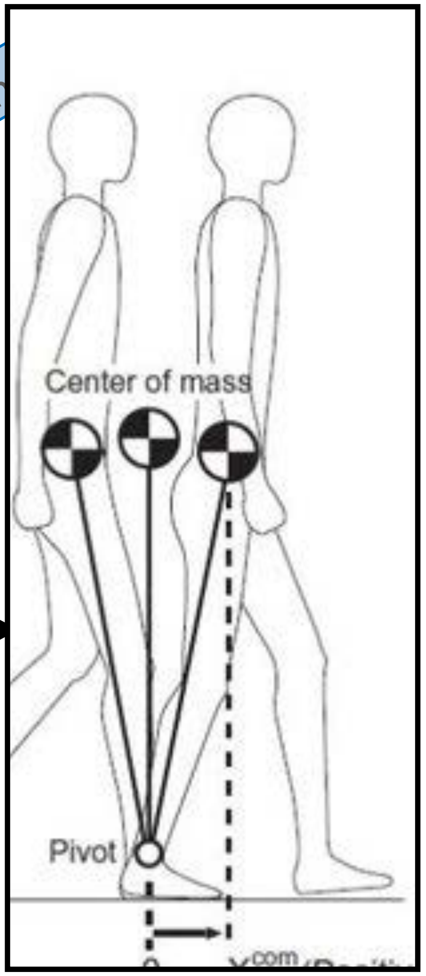


Wake drastically boost orbital frequencies,
tightening control loops

Bring home message: dressing redefine clocks

New dynamical equilibrium





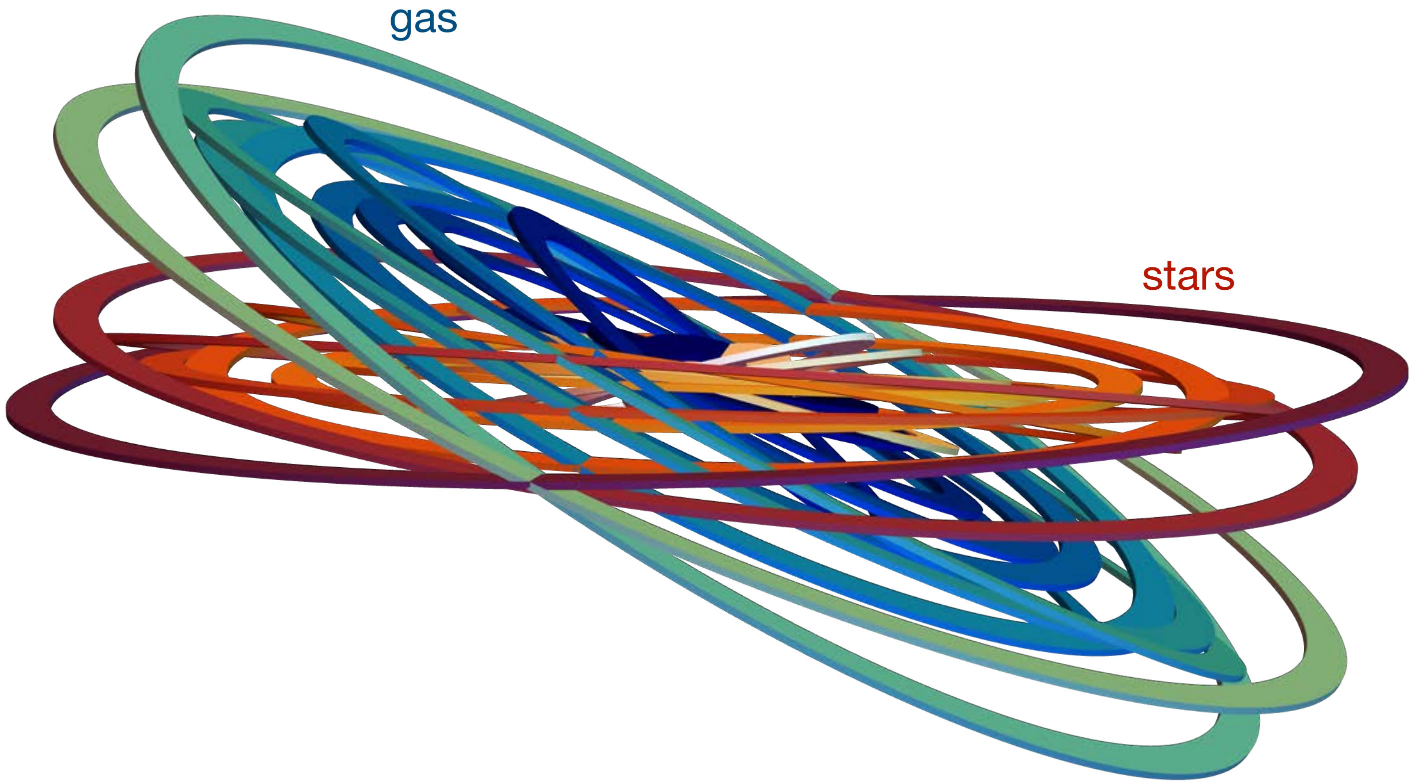
Wake drastically boost orbital frequencies,
tightening control loops

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

$$
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\ddot{q}_\star + \omega_\star^2 q_\star + \omega_{\star g}^2 q_g &= 0\,, \\
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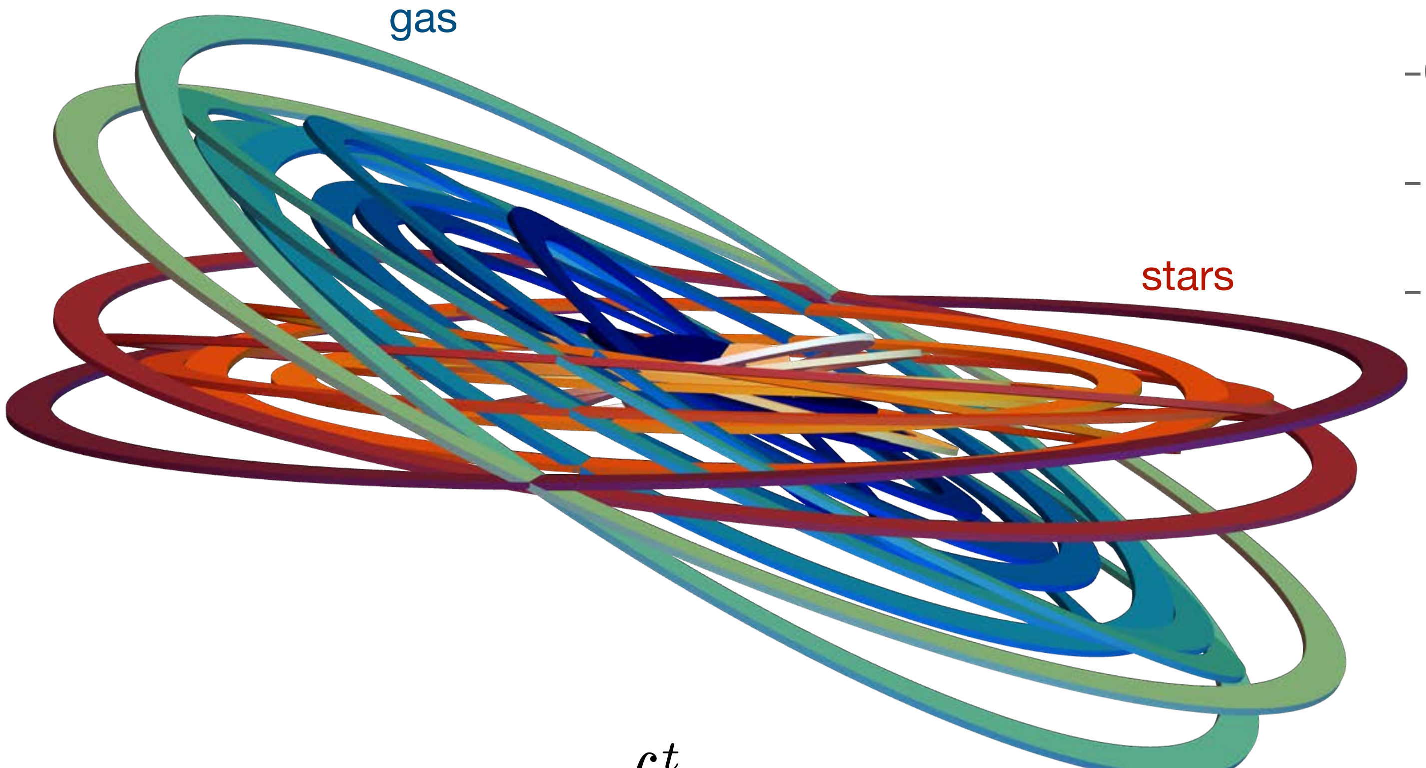
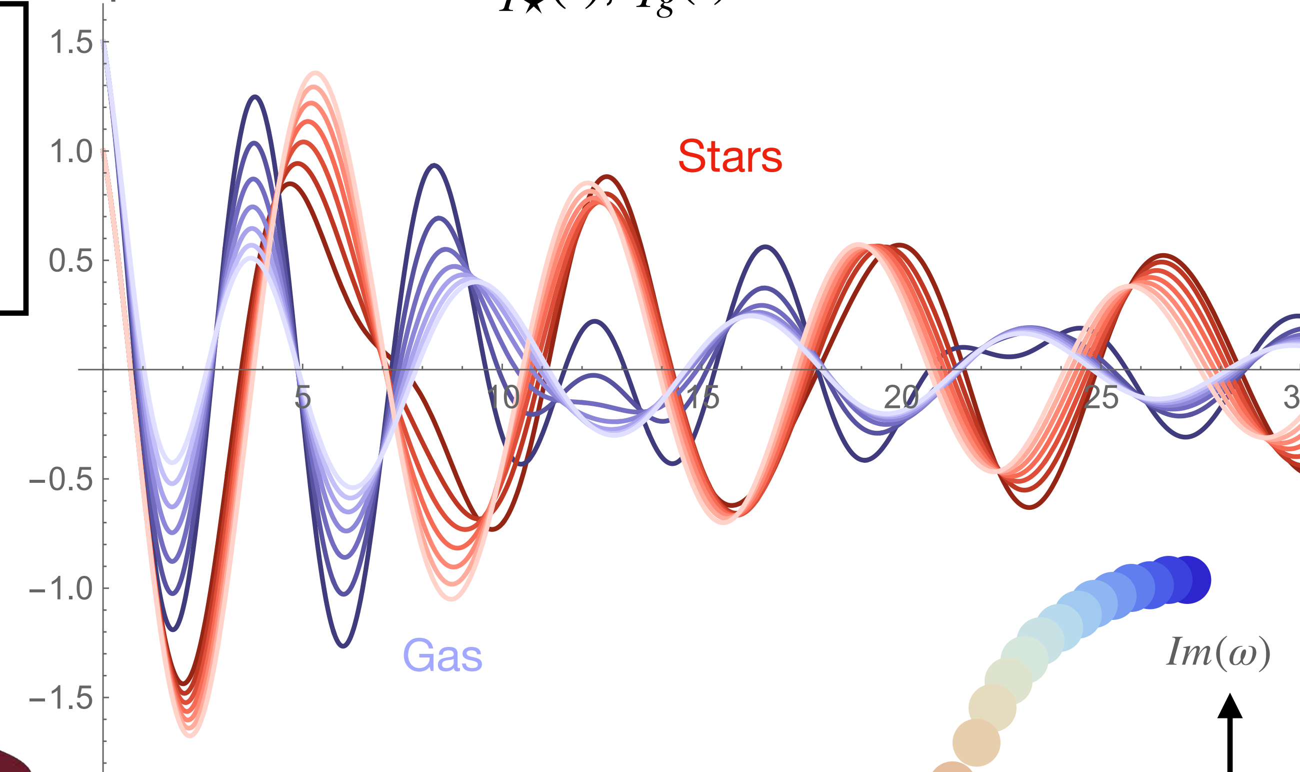
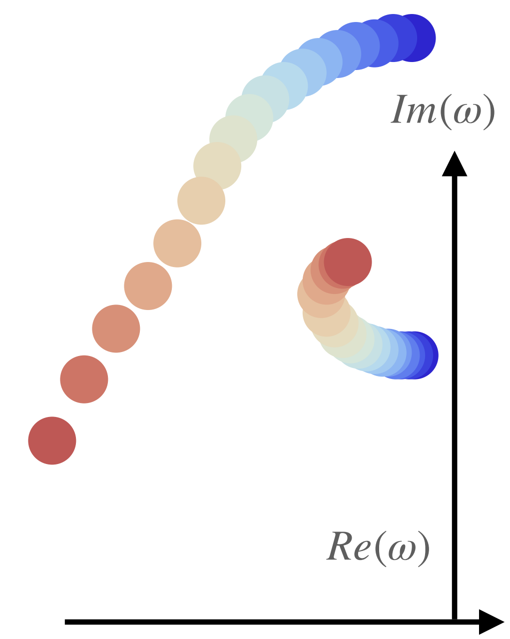


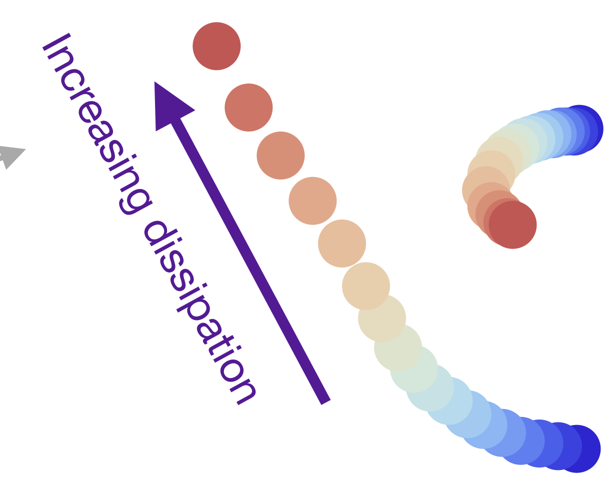


Nyquist diagram



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

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



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

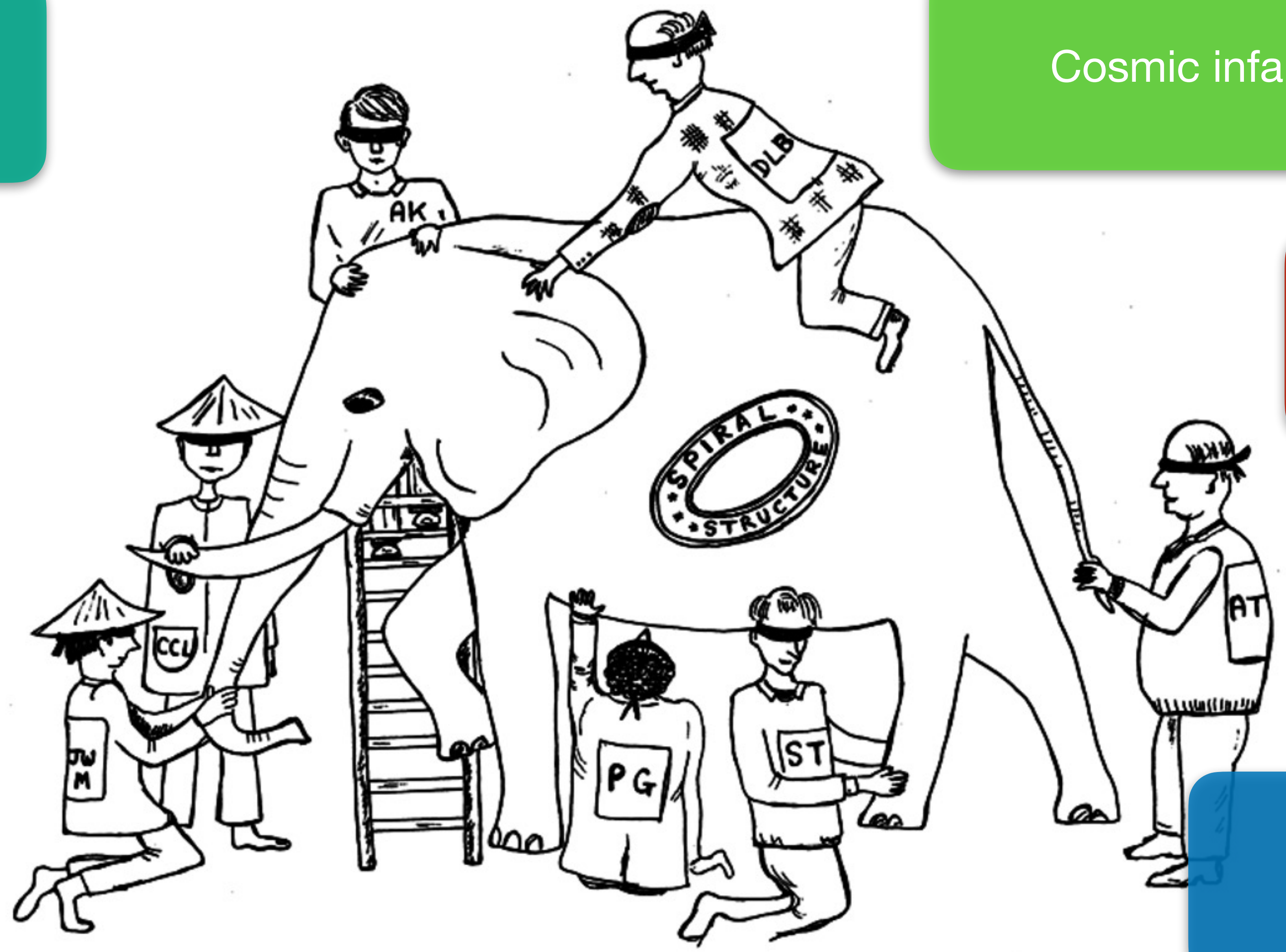
See also Bertin Romeo (1988) 195, 105-113

Synopsis of thin disc emergence: 0/2

Gravity

Cosmic infall

Star formation

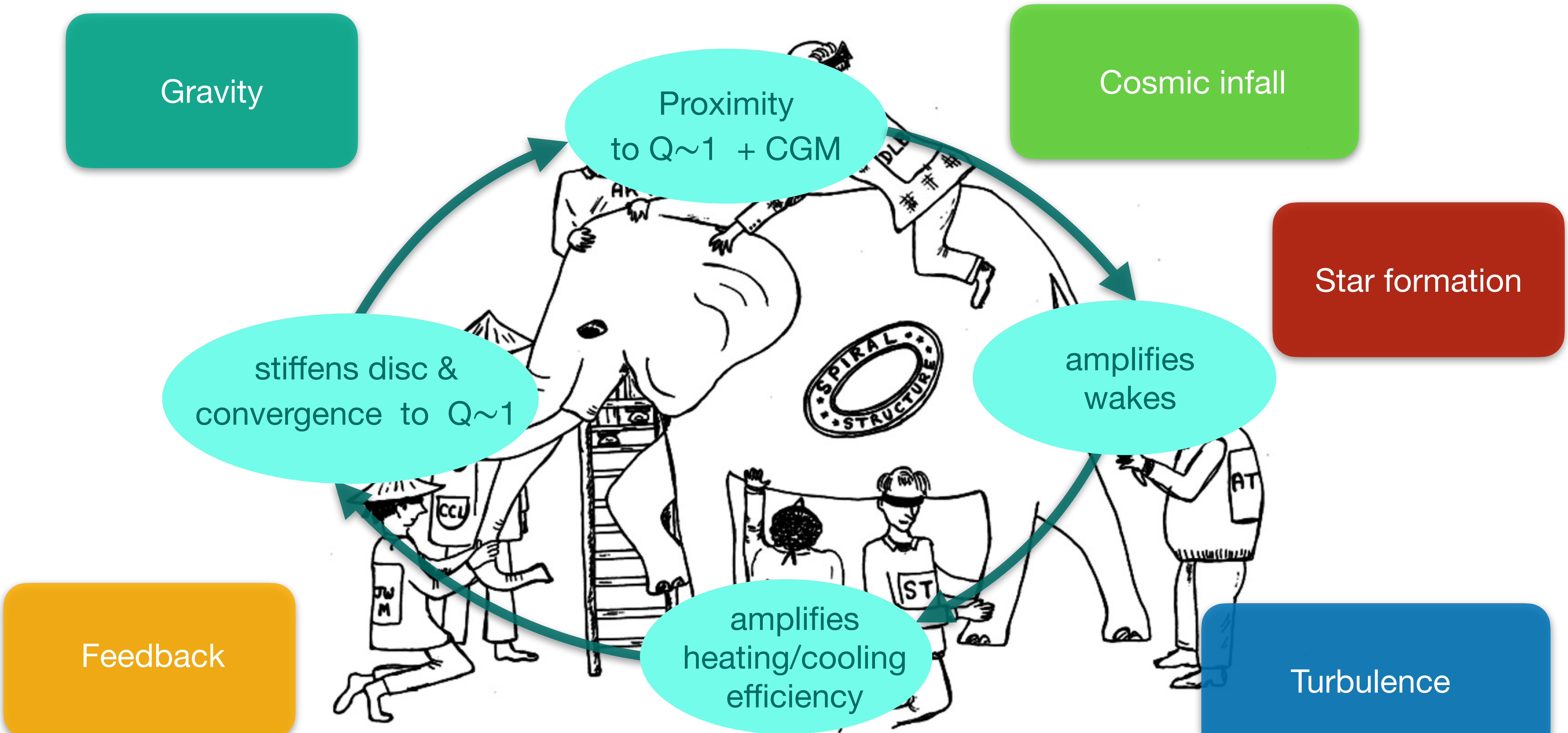


Cartoon, drawn by Janet Sellwood in 1984, based on Toomre's assessment of the state of spiral structure theory in 1980. Apart from a few extra blindfolded individuals, this still seems appropriate today.

Feedback

Turbulence

Synopsis of thin disc emergence: 0/2



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Recent aternative views

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

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;

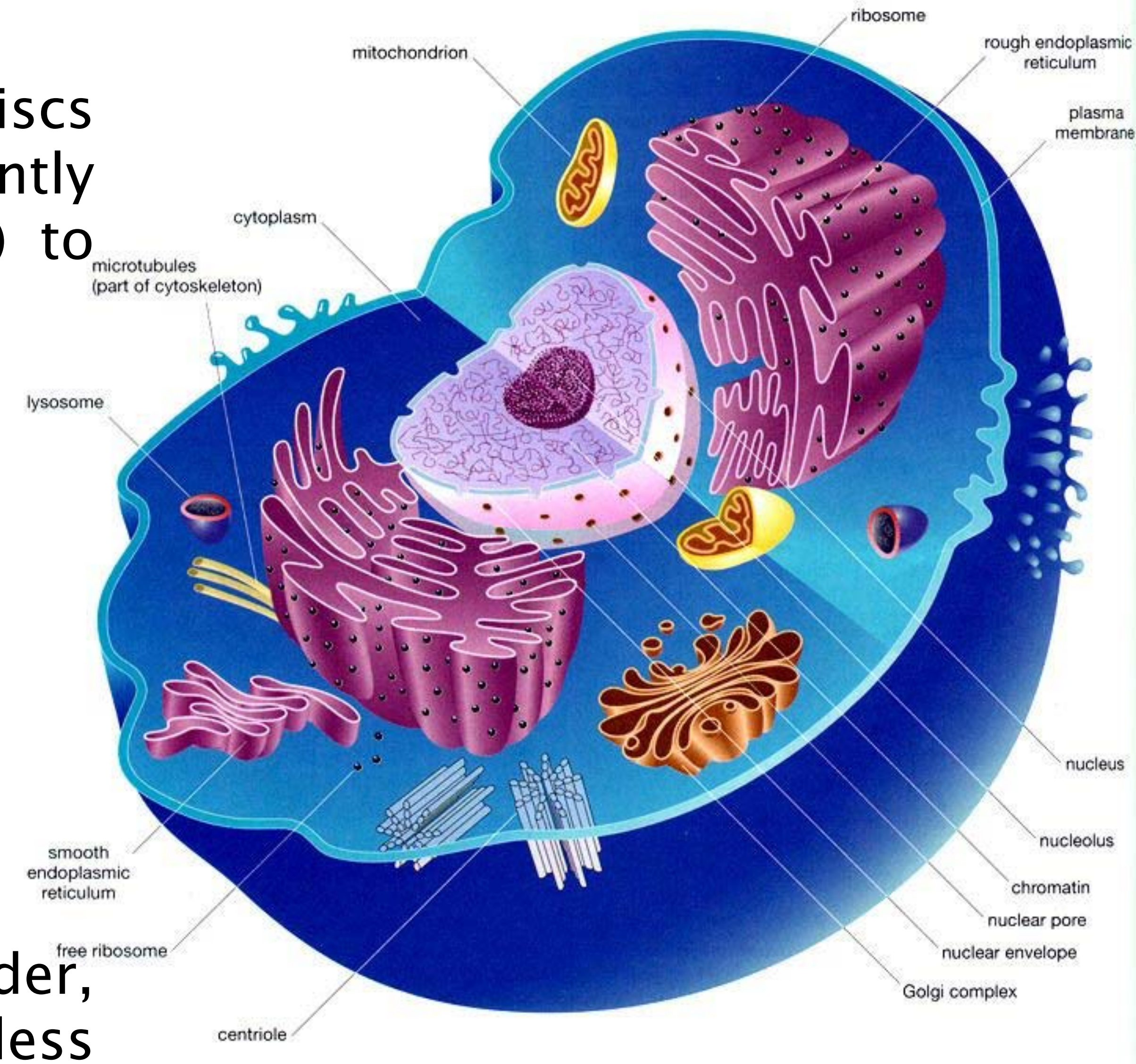
ii) auto-catalytic;

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**!



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)

Fokker Planck orbital diffusion

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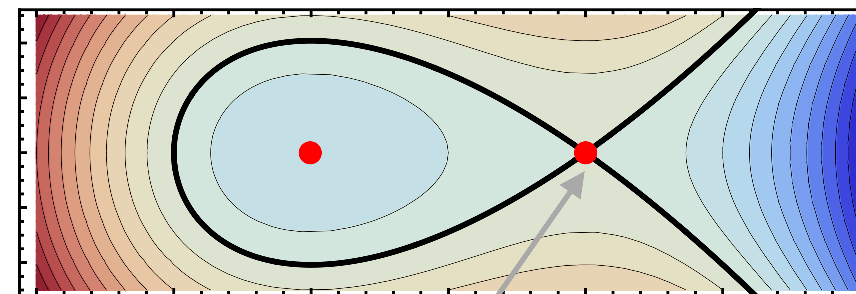
Logistic map Hamiltonian



New point of equilibrium with finite disc thickness

Alternative derivation: heating versus cooling in-balance

$$\frac{d}{dt}\bigstar = \mathscr{C}(\bigstar)+\mathscr{H}(\bigstar)$$

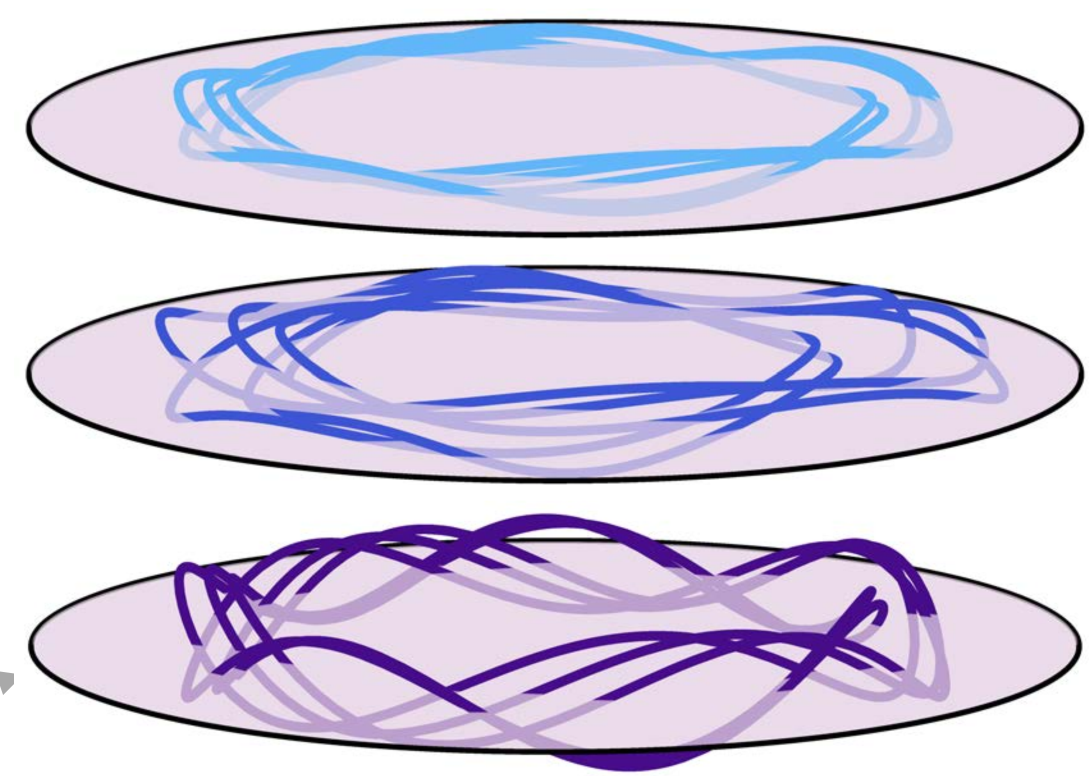
$$\mathscr{C}(\bigstar) = \mathscr{C}'\bigstar - \frac{1}{2}|\mathscr{C}''|(\bigstar)^2$$

star formation

stellar feedback

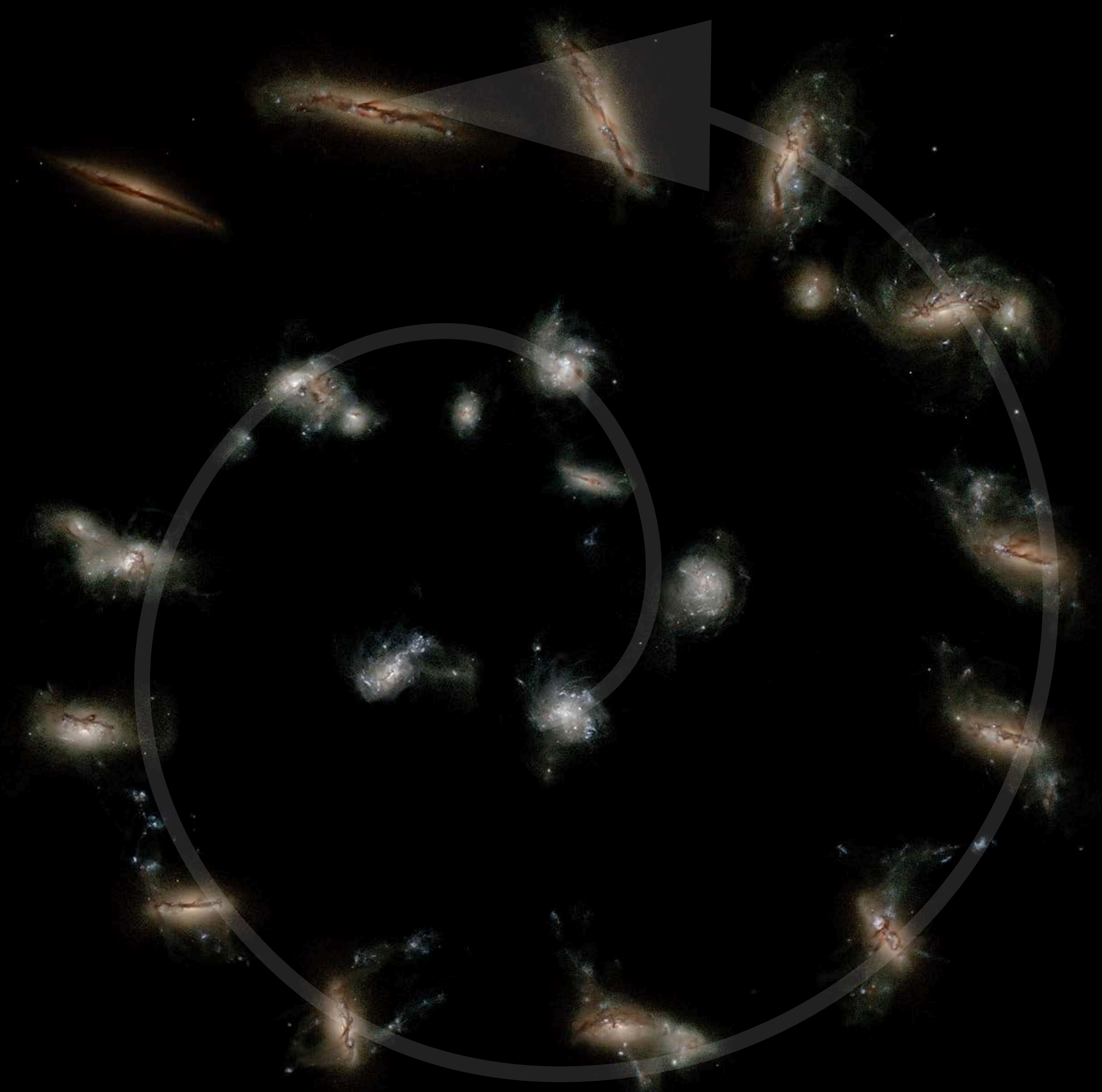
$$\mathscr{H}(\bigstar) = \nabla^2\bigstar$$

orbital diffusion
(blurring/churning/heating)



Disc settling: timeline of a thin galactic disc

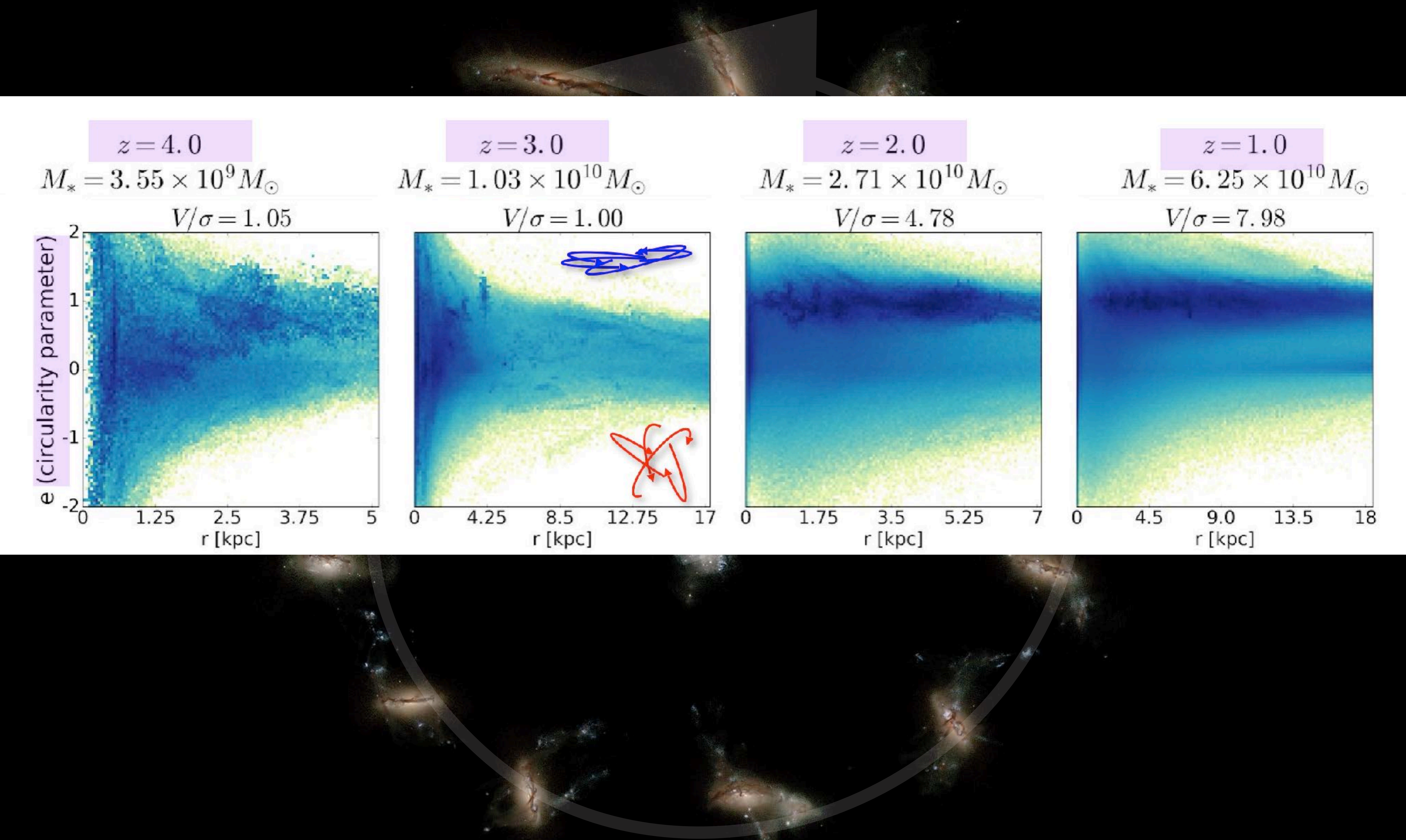
New Horizon Simulation



Thin discs in cosmological simulations operate as though they are isolated: this needs explaining.

Disc settling: timeline of a thin galactic disc

New Horizon Simulation



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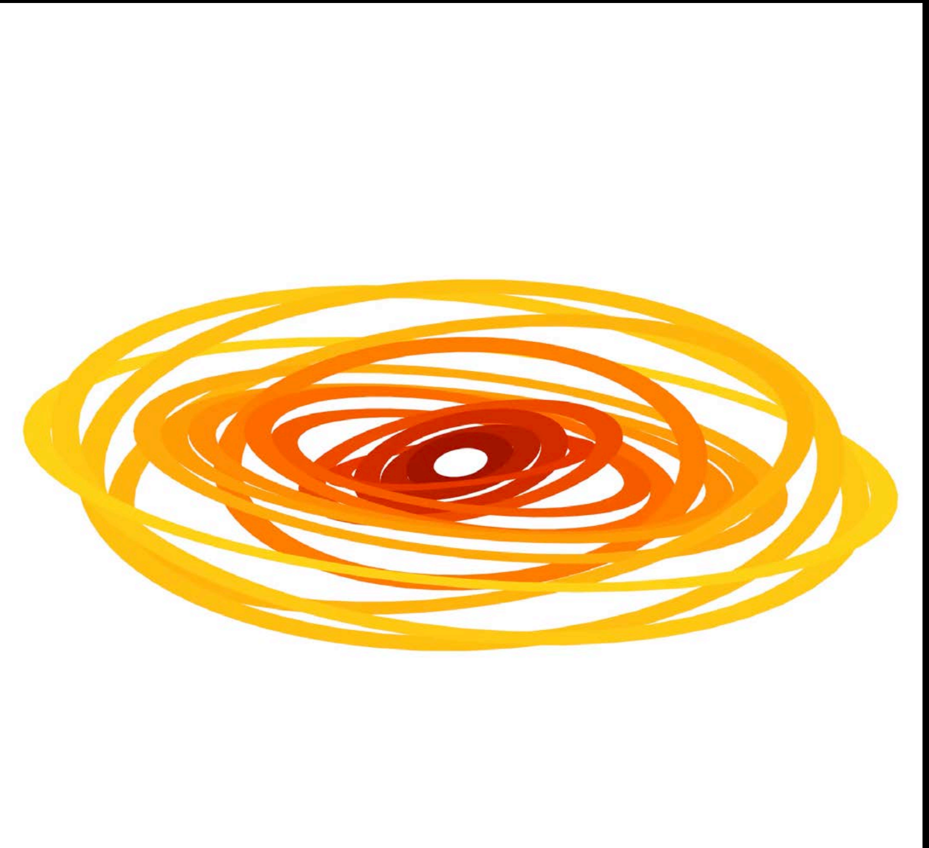
Synopsis of thin disc emergence: 1/2

- 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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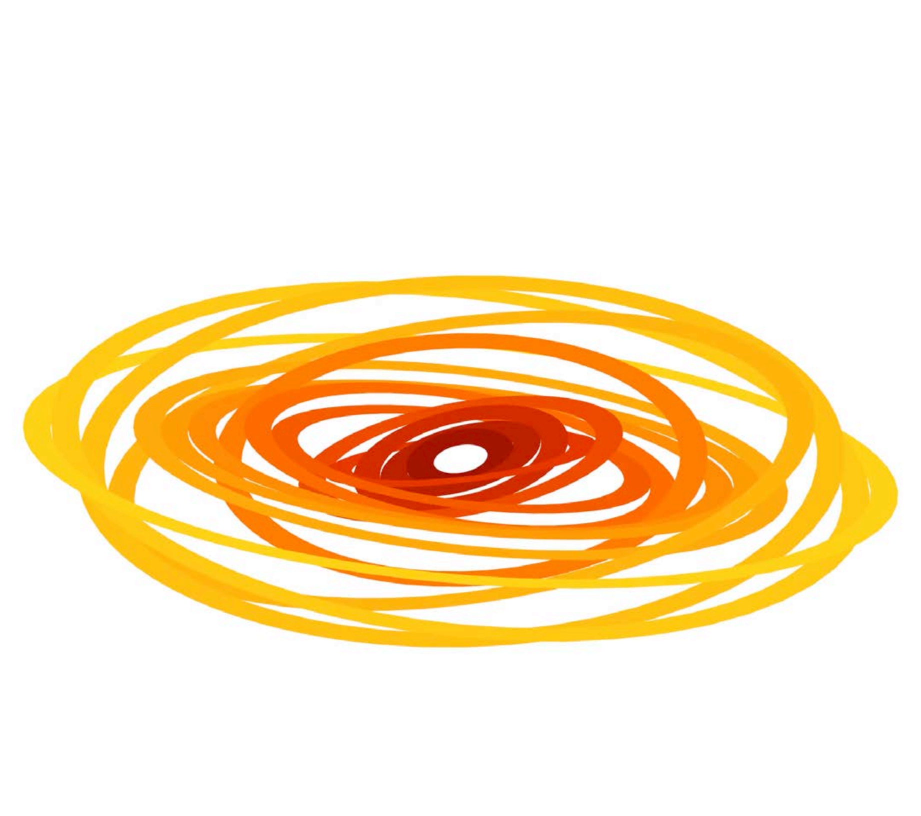
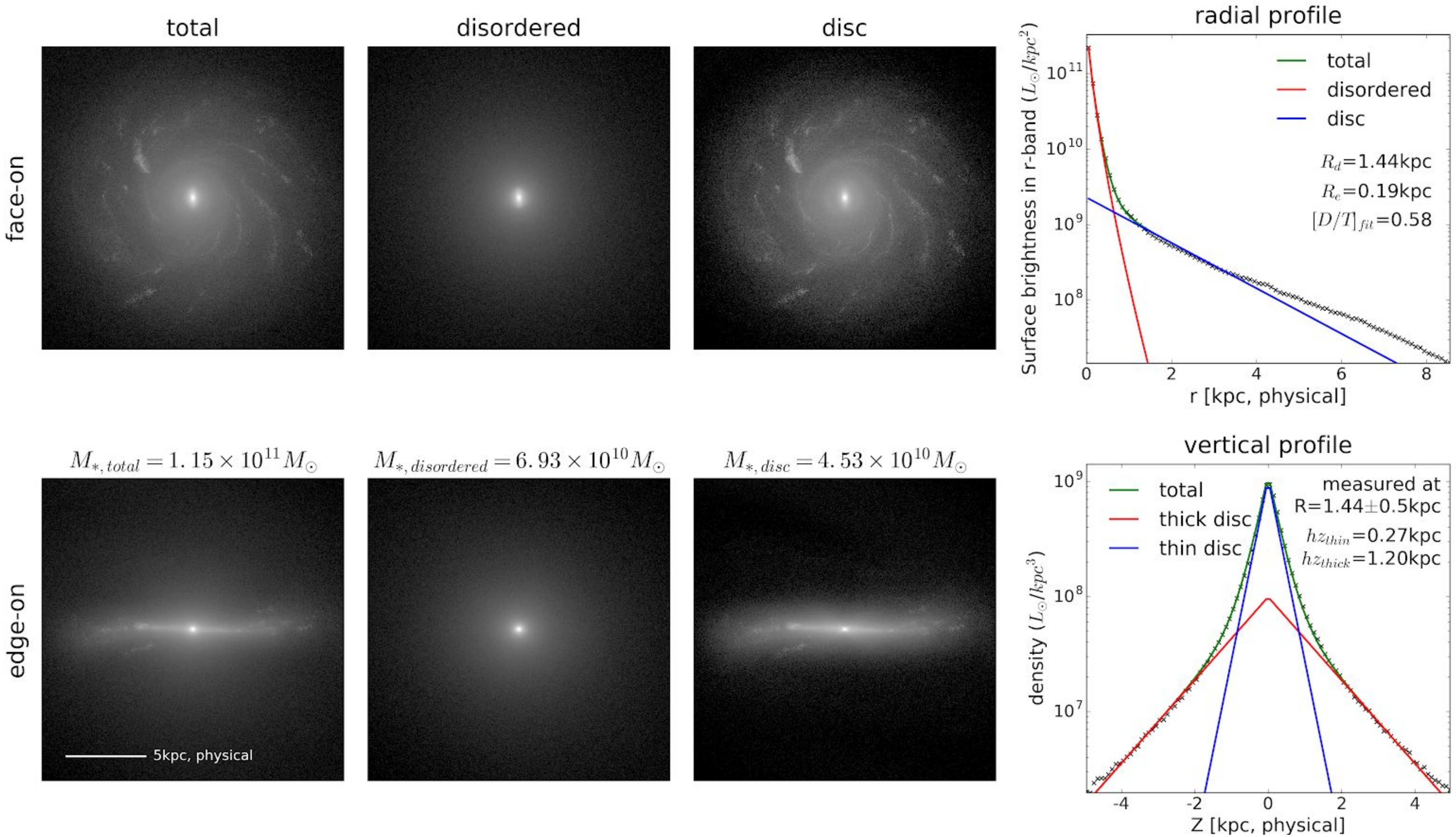


Ring toy model

Disc settling preserves double thick/thin profile



Once in secular mode, the self regulated loop

stratifies vertically stars by age, while preserving the total double sech^2 profile

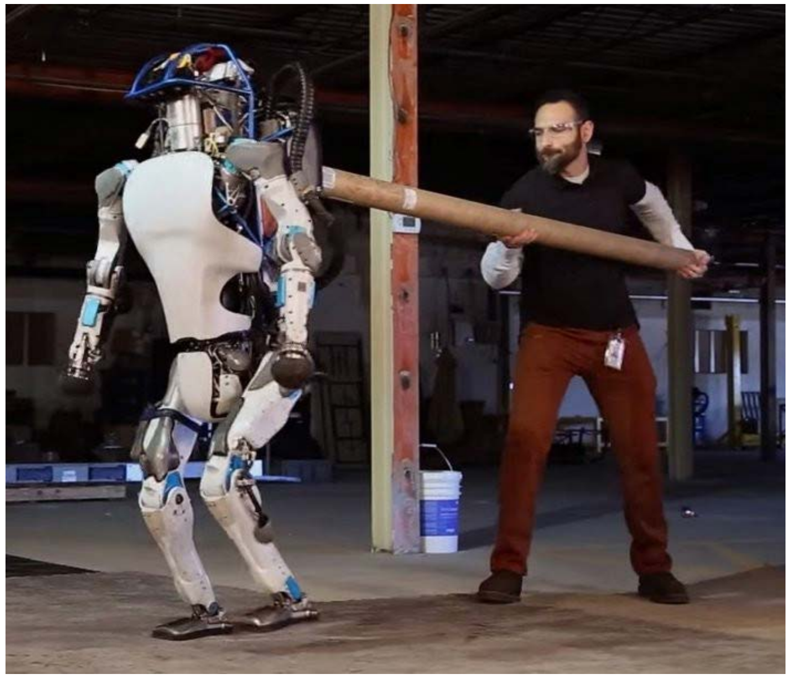
Discussion

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

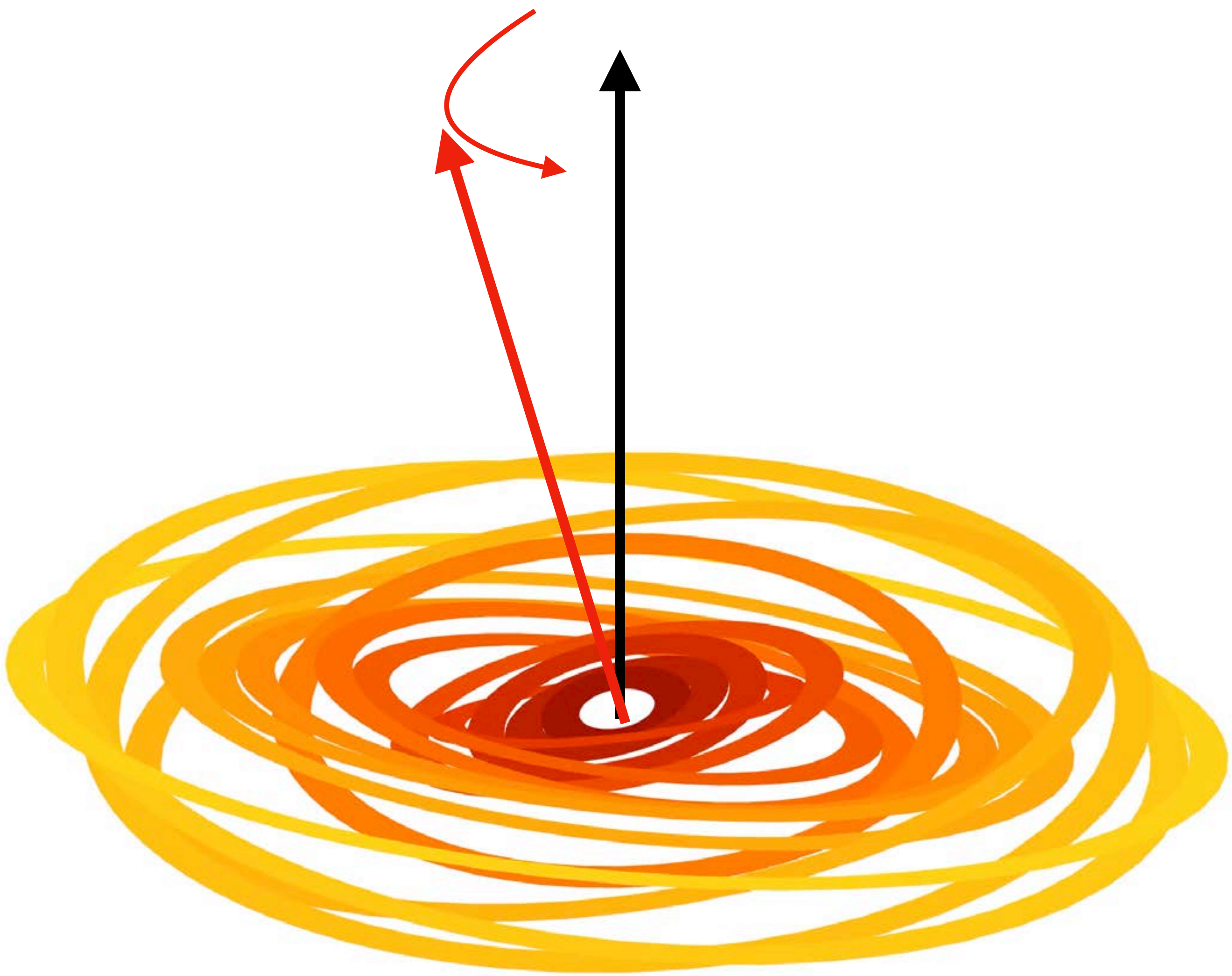
- Variation of inflow that the disc's tolerate before instability /contraction ? (cf red giants)

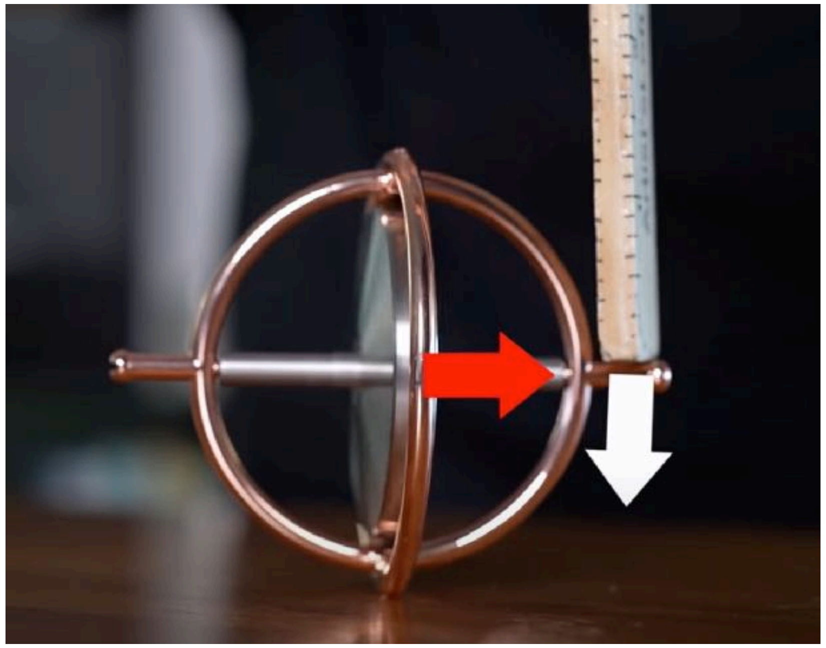


- Assumes disc can respond thermally fast enough
- Leap of faith in dynamical range (SF controlled by turbulent injection scale)
- Ignore extension of disc + bars /bulge + life halo (locality)

Gyroscopic equation

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





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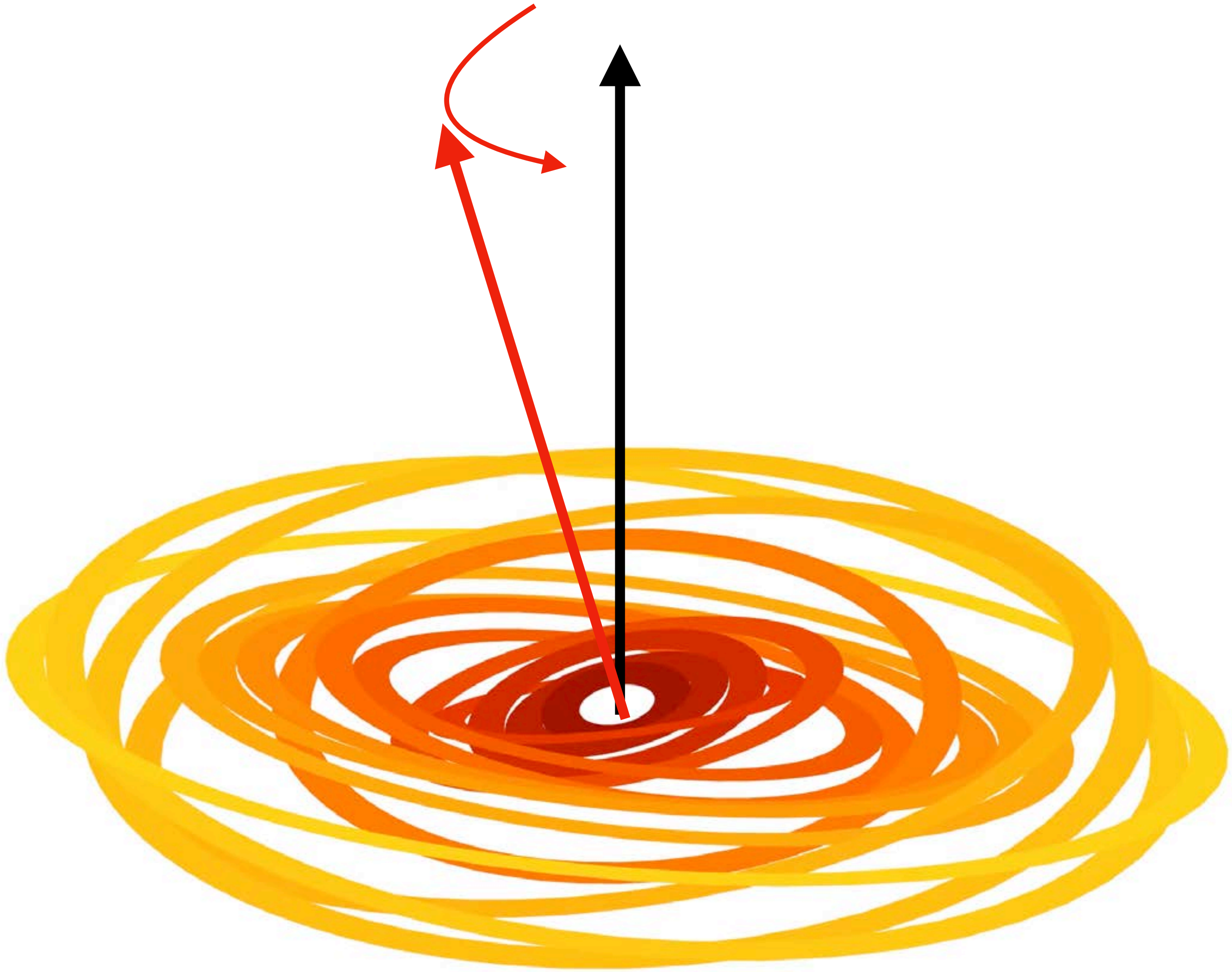
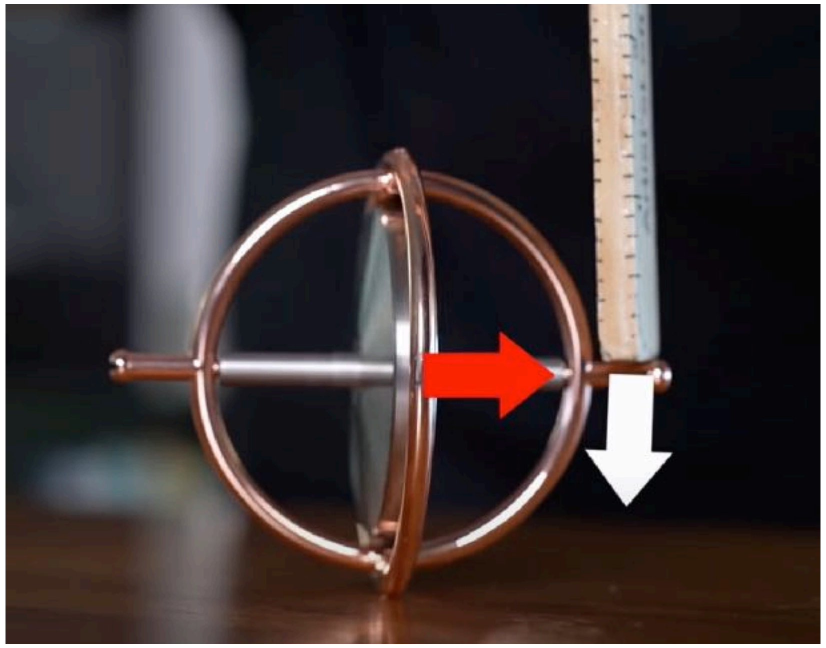




★ **Revisit paradigm**: impact of large scale anisotropy

- Galaxy properties driven by past lightcone of tidal tensor $\partial^2\psi/\partial x_i \partial x_j$
- Non-linear evolution impacted by *scale coupling* /shocks/ differential *delays*

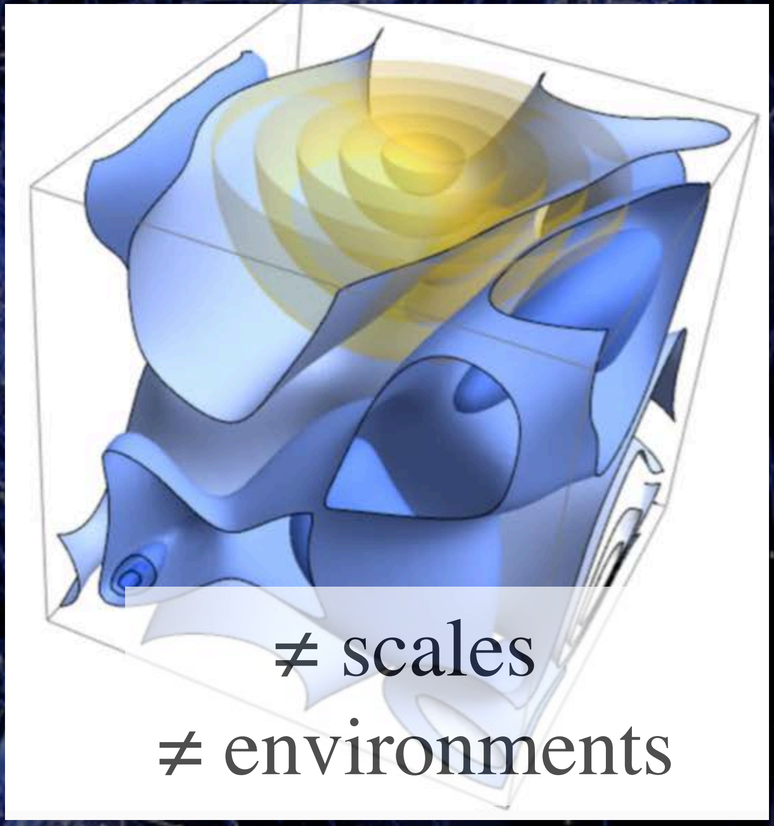
$$\langle f_{\rm NL}(IC)\rangle \neq f_{\rm NL}(\langle IC\rangle)$$

$$\langle f_{\rm NL}(IC)\rangle_{\theta,\phi} \neq f_{\rm NL}(\langle IC\rangle_{\theta,\phi})$$

Spherical collapse does not capture filamentary tides...

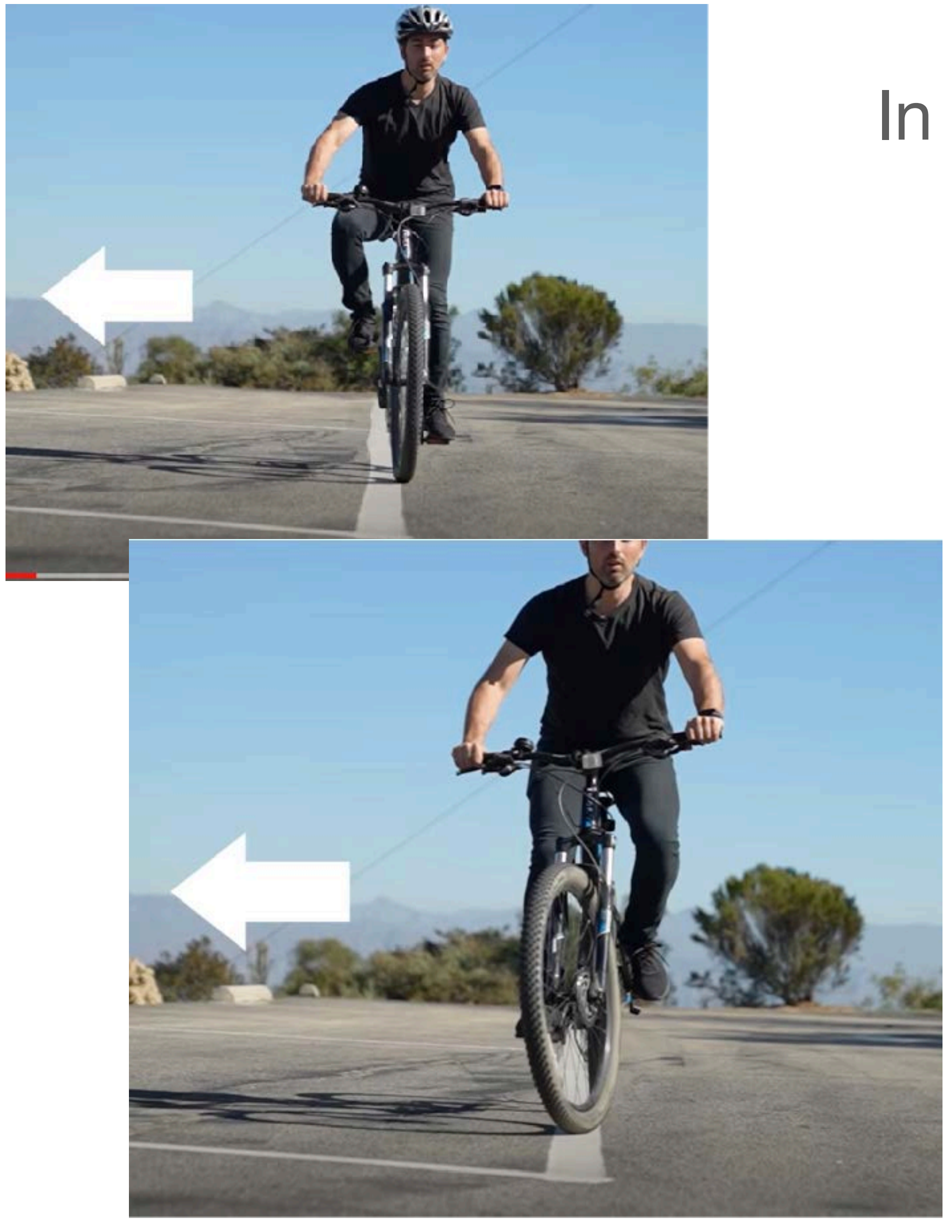
galaxy growth will be impacted by **all** components of Tidal tensor (not just trace, also eigenvectors+other minors)

All the more true for the gas



In order to turn left driver must turn right!

Bike counter-steering: casper+ gyroscopic effect



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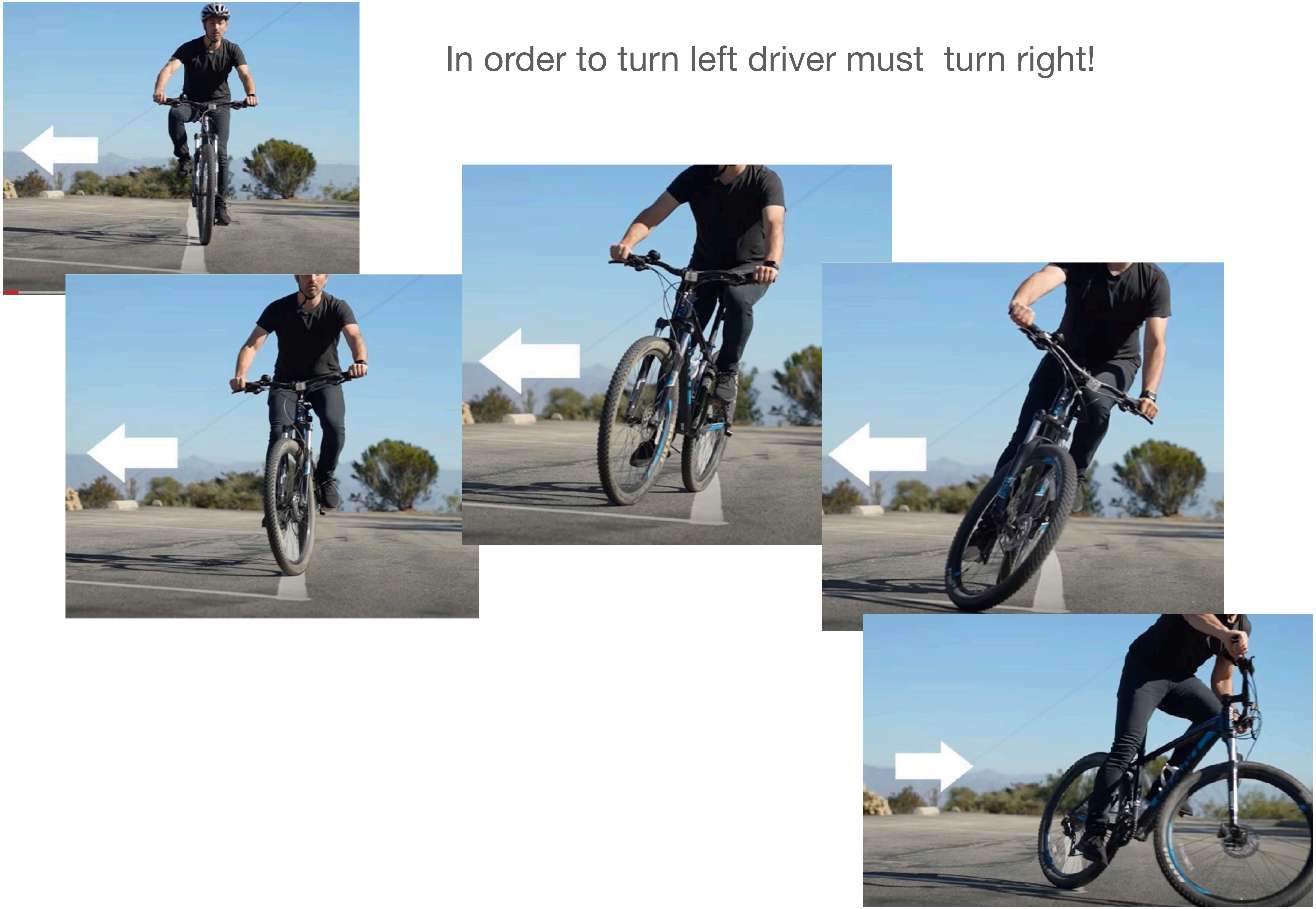
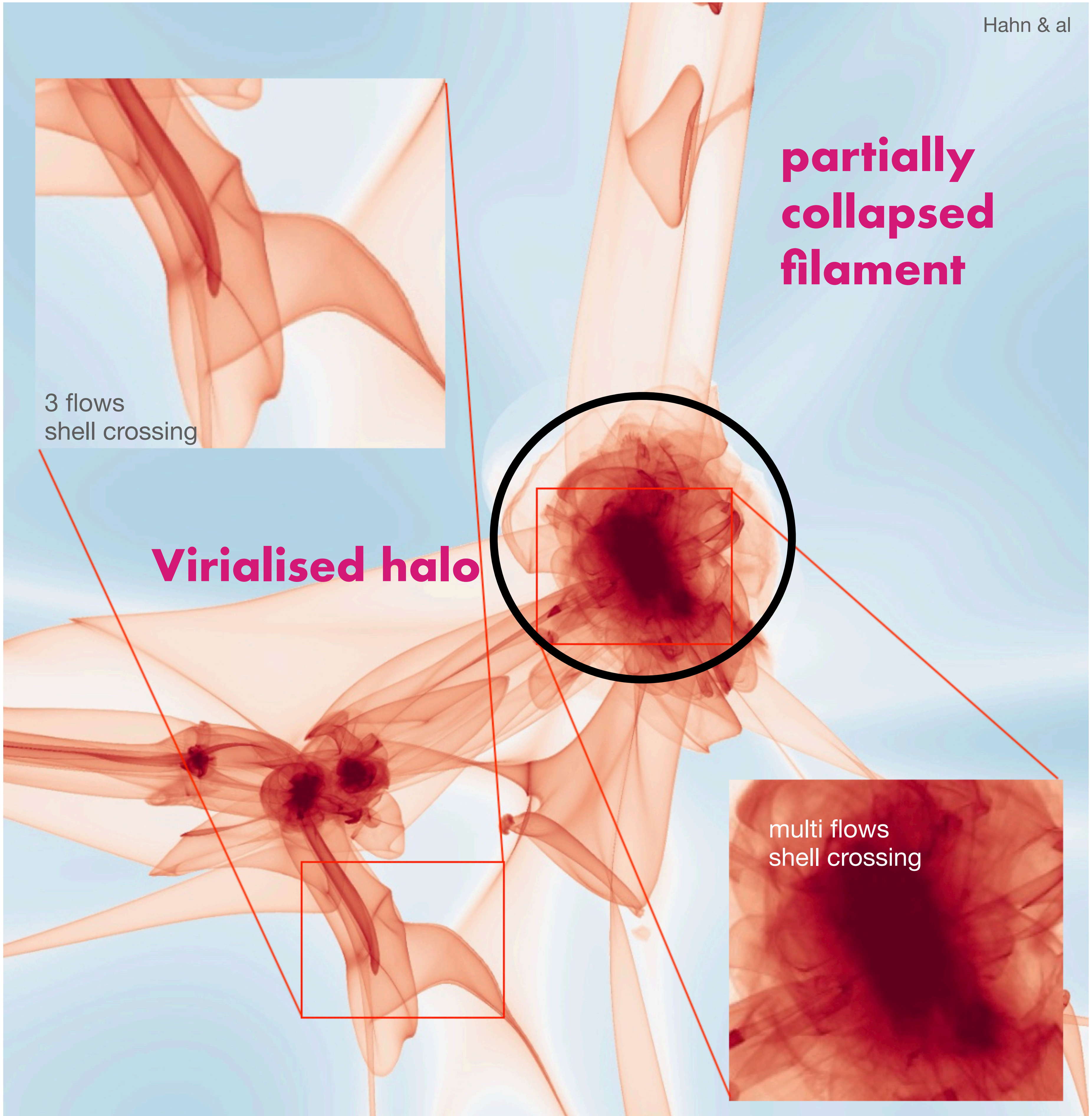
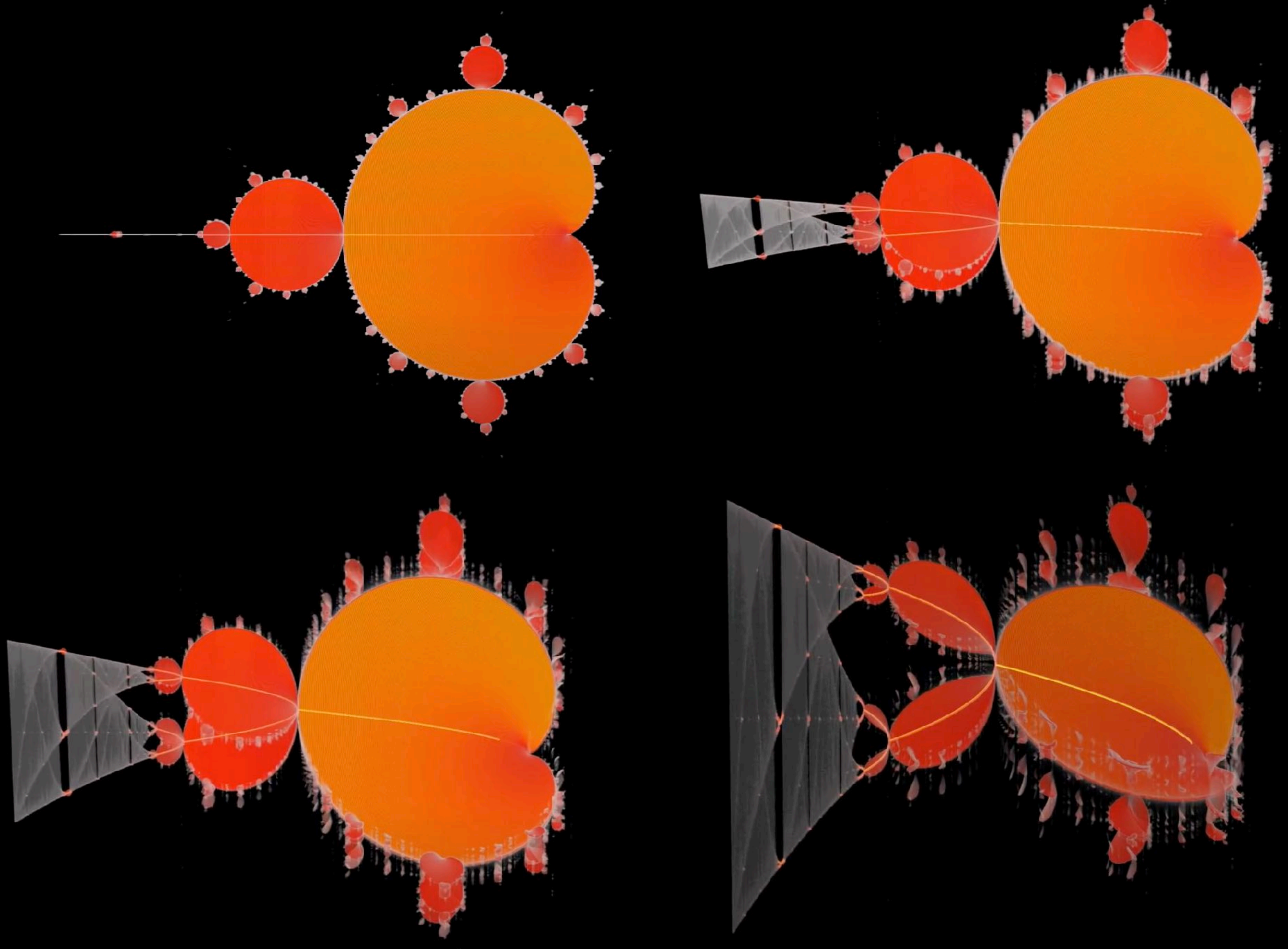


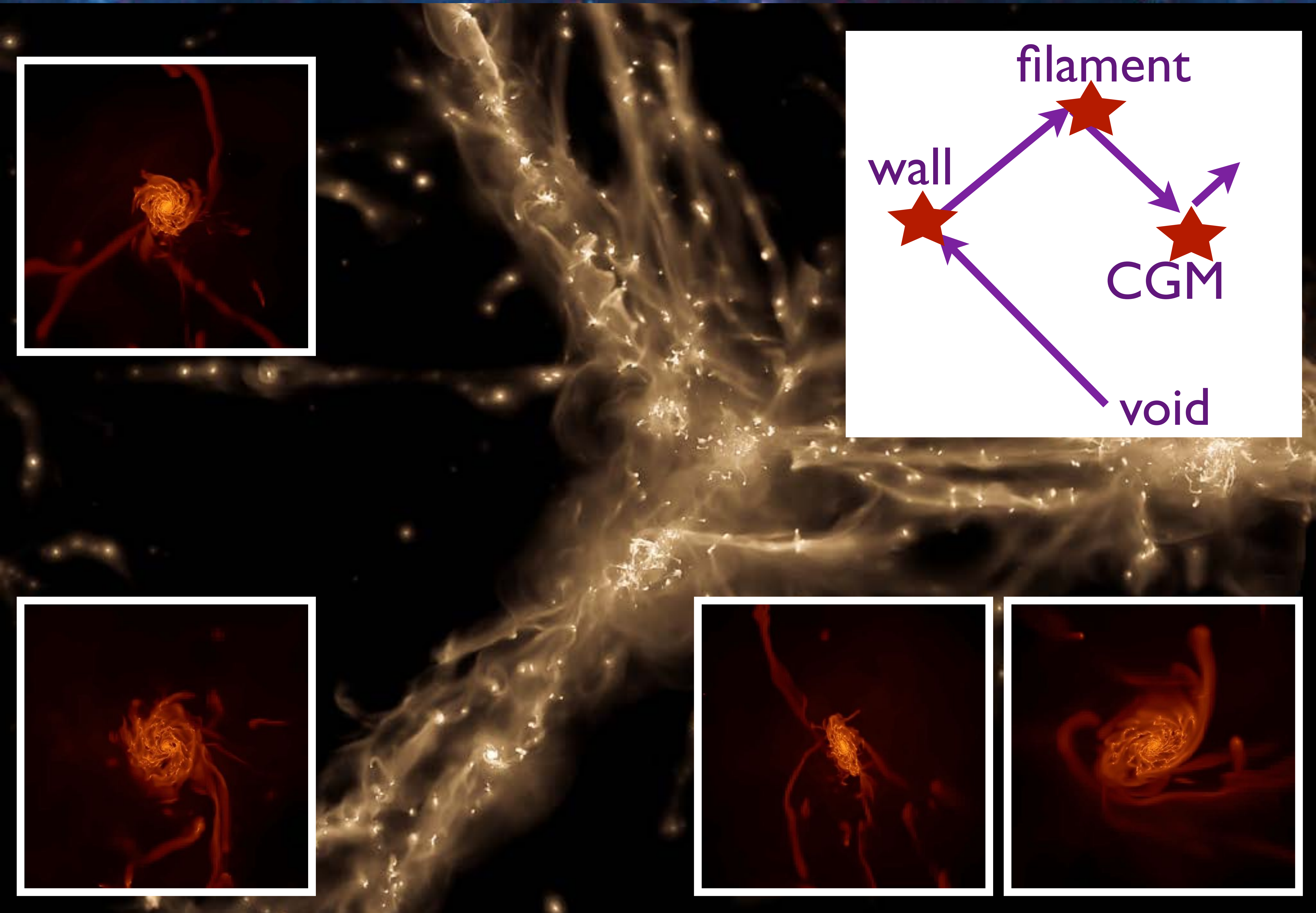
Spherical versus partial collapse



Link to Mandelbrot Set (Veritassium 2021)



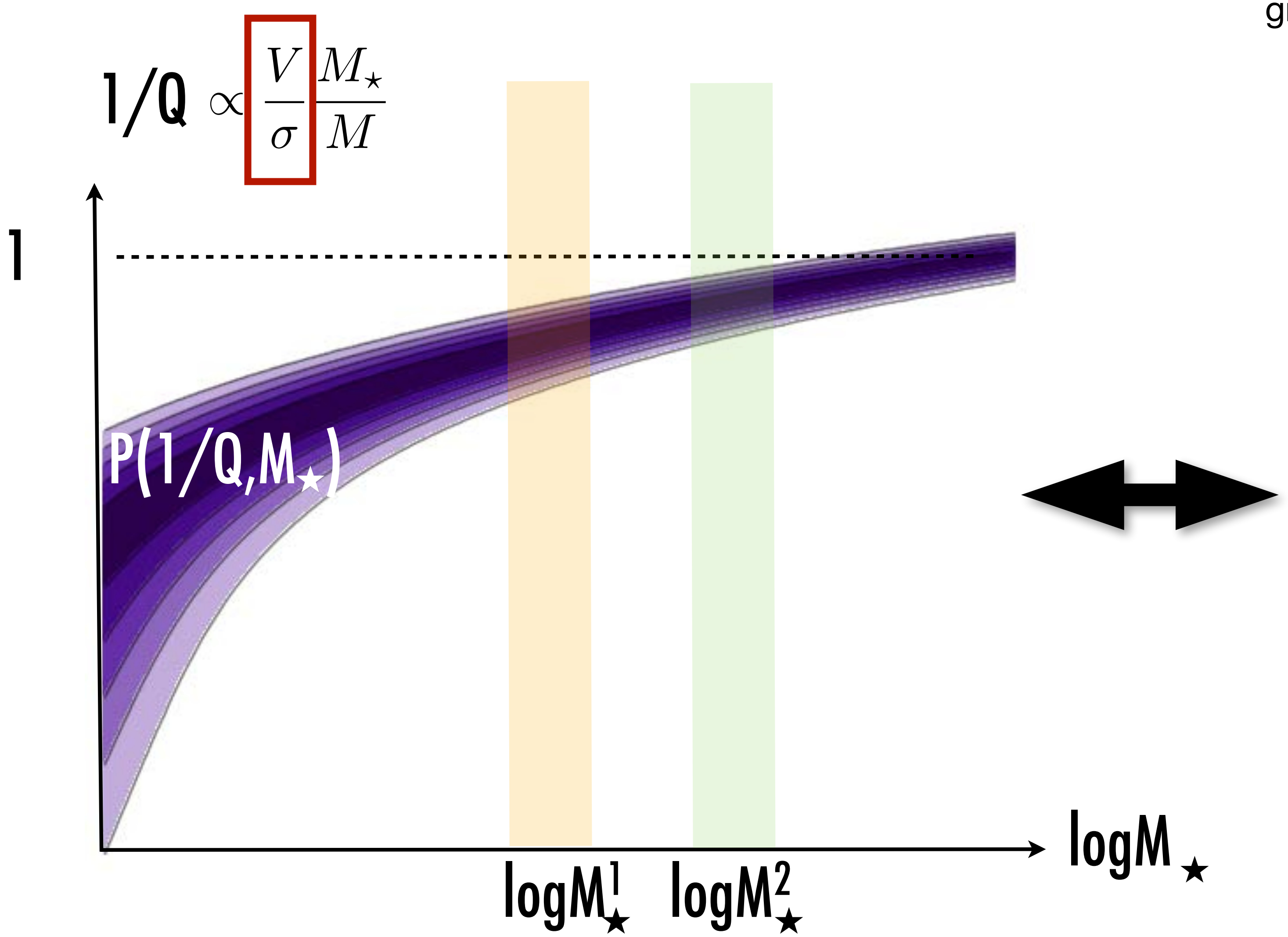
Geometry of flow: Eulerian view @ high resolution.

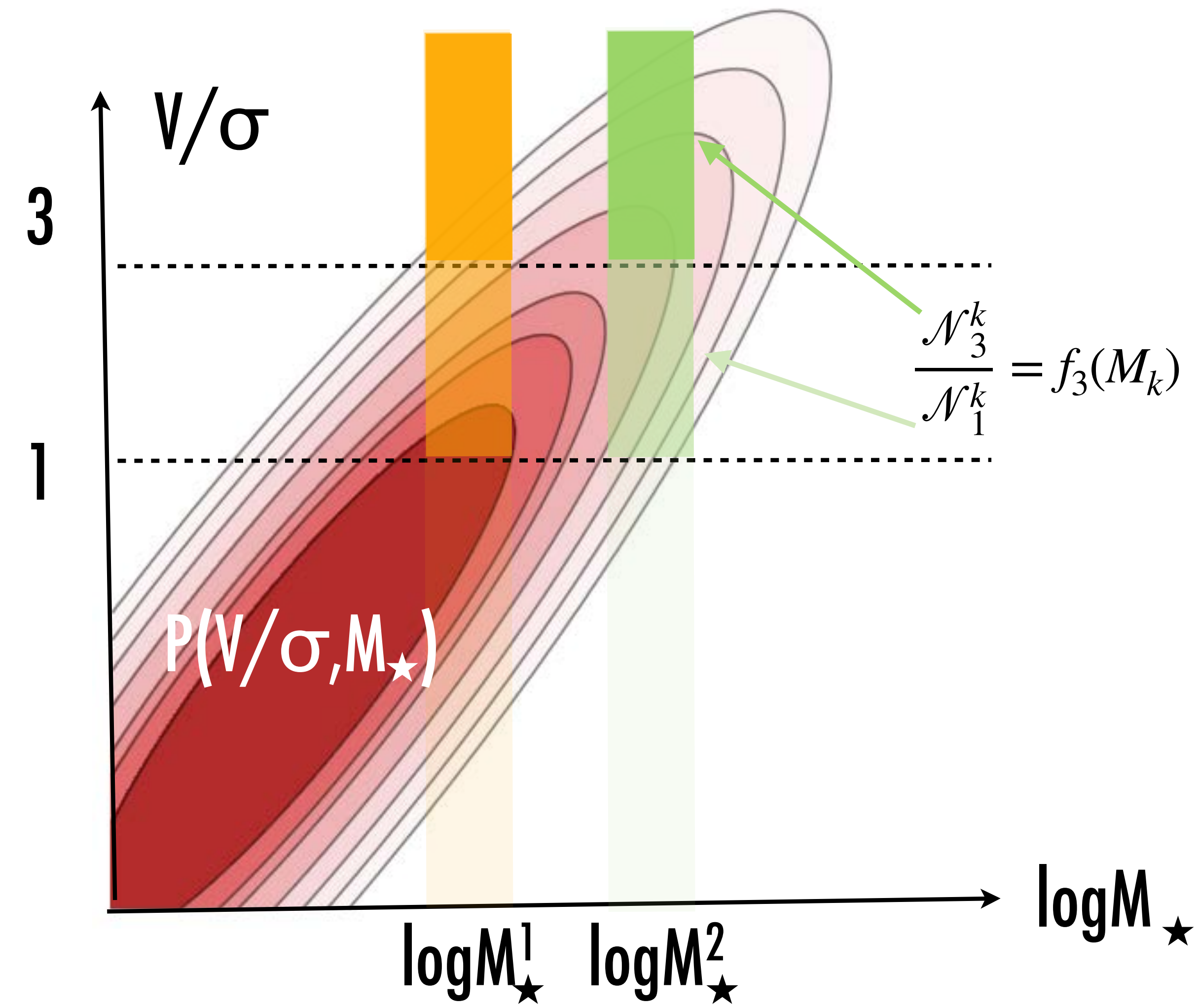


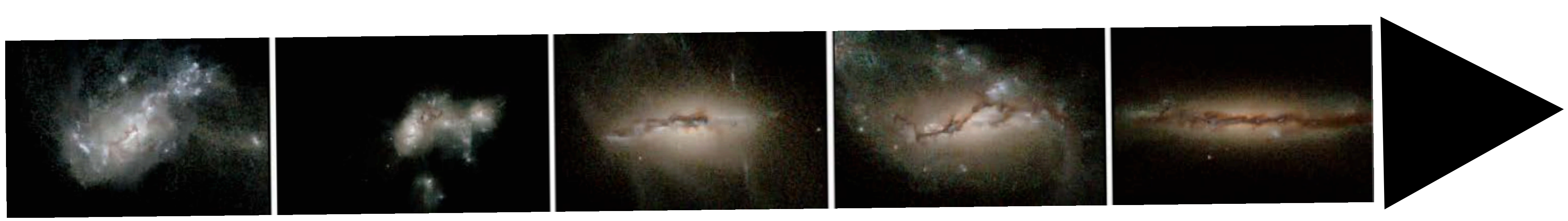
Numerical equivalence, given Toomre(v/σ)

Correspondance best expressed while looking at PDF(Q , $M_\star$) and PDF(V/σ , $M_\star$)

f_{settle} = Ratio of the integral of the galactic counts over dark (orange or green) regions to that over the light region increases with $M_\star$







Inhomogeneous Balescu-Lenard equation

- **Inhomogeneous Balescu-Lenard equation**
  Heyvaerts (2010), Chavanis (2012)

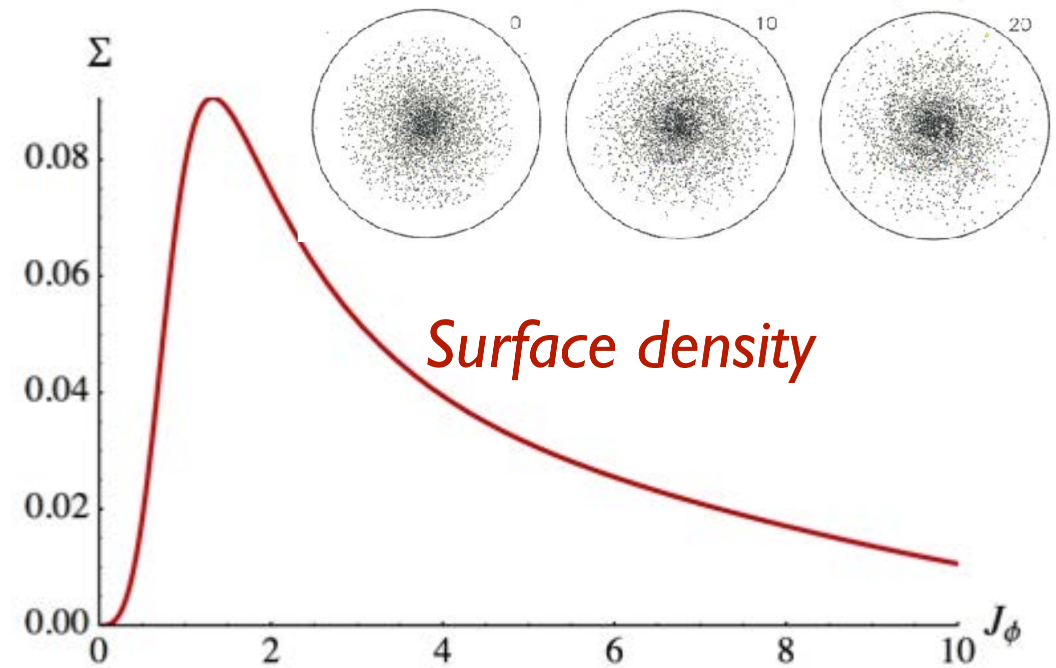
$$\frac{\partial F(\boldsymbol{J}_1,t)}{\partial t} = \pi(2\pi)^d \frac{M_{\mathrm{tot}}}{N} \frac{\partial}{\partial \boldsymbol{J}_1} \cdot \bigg[\sum_{\boldsymbol{m}_1,\boldsymbol{m}_2} \boldsymbol{m}_1 \int \mathrm{d}\boldsymbol{J}_2 \, \frac{\delta_{\mathrm{D}}(\boldsymbol{m}_1 \cdot \boldsymbol{\Omega}_1 - \boldsymbol{m}_2 \cdot \boldsymbol{\Omega}_2)}{|\mathcal{D}_{\boldsymbol{m}_1,\boldsymbol{m}_2}(\boldsymbol{J}_1,\boldsymbol{J}_2,\boldsymbol{m}_1 \cdot \boldsymbol{\Omega}_1)|^2} \left[\boldsymbol{m}_1 \cdot \frac{\partial}{\partial \boldsymbol{J}_1} - \boldsymbol{m}_2 \cdot \frac{\partial}{\partial \boldsymbol{J}_2} \right] F(\boldsymbol{J}_1,t)\, F(\boldsymbol{J}_2,t) \bigg] .$$

- Some properties:
  - $F(\boldsymbol{J},t)$: **Orbital distorsion** in action space.
  - $1/N$: Driven by **finite$-N$ effects**.
  - $\partial/\partial \boldsymbol{J}_1 \cdot$: **Divergence of a flux**, i.e. conservation.
  - $\boldsymbol{m}_1$: **Discrete** Fourier vectors - **Anistropic** diffusion.
  - δ_{D}: **Resonance condition** for distant encounters.
  - $1/\mathcal{D}_{\boldsymbol{m}_1,\boldsymbol{m}_2}$: **Self-gravitating dressing** (squared).
  - $\boldsymbol{m}_1 \cdot \boldsymbol{\Omega}_1$: Secular diffusion **at resonance**.

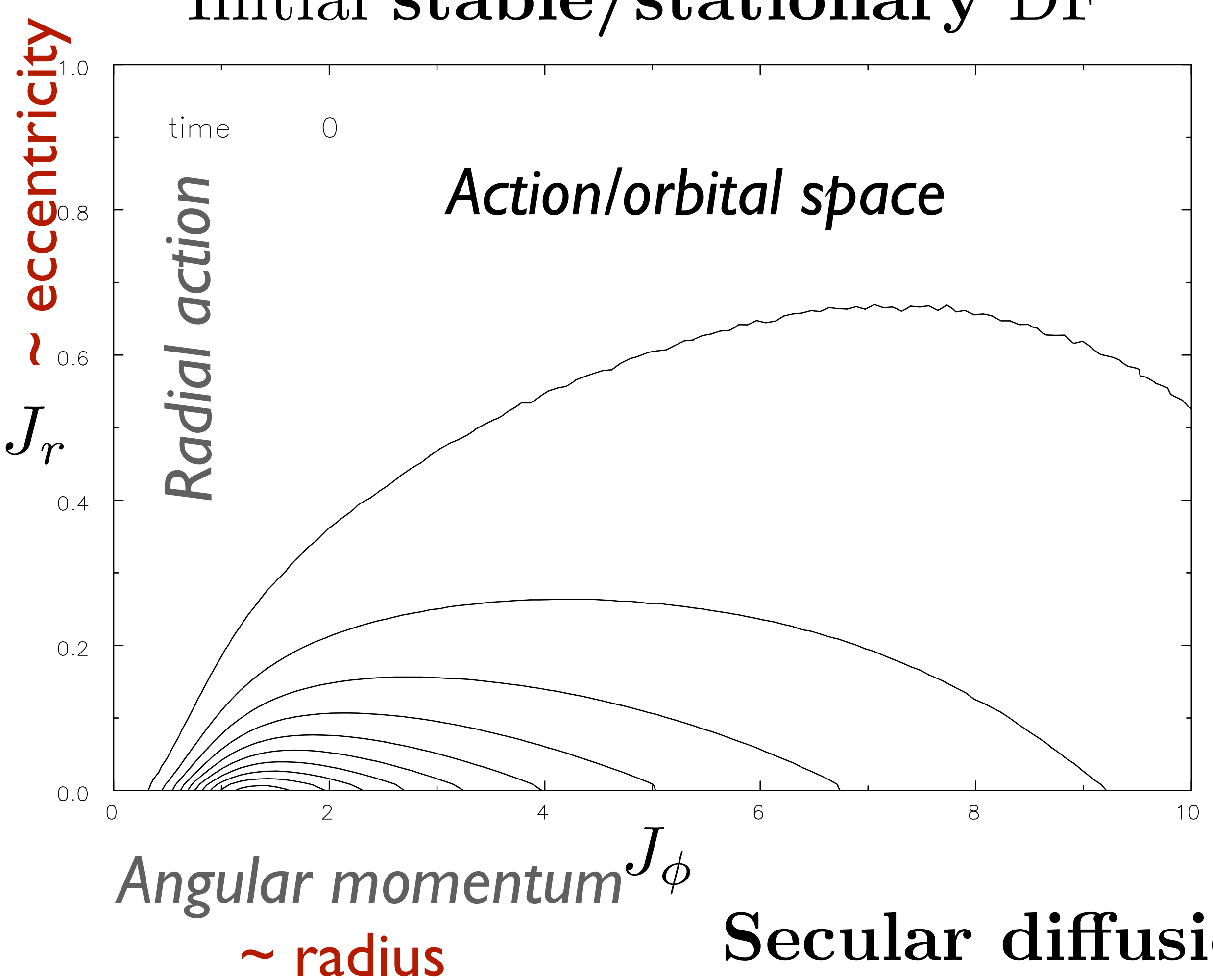
$\Longrightarrow$ **Master equation for self-induced orbital distortion.**

An example of secular evolution

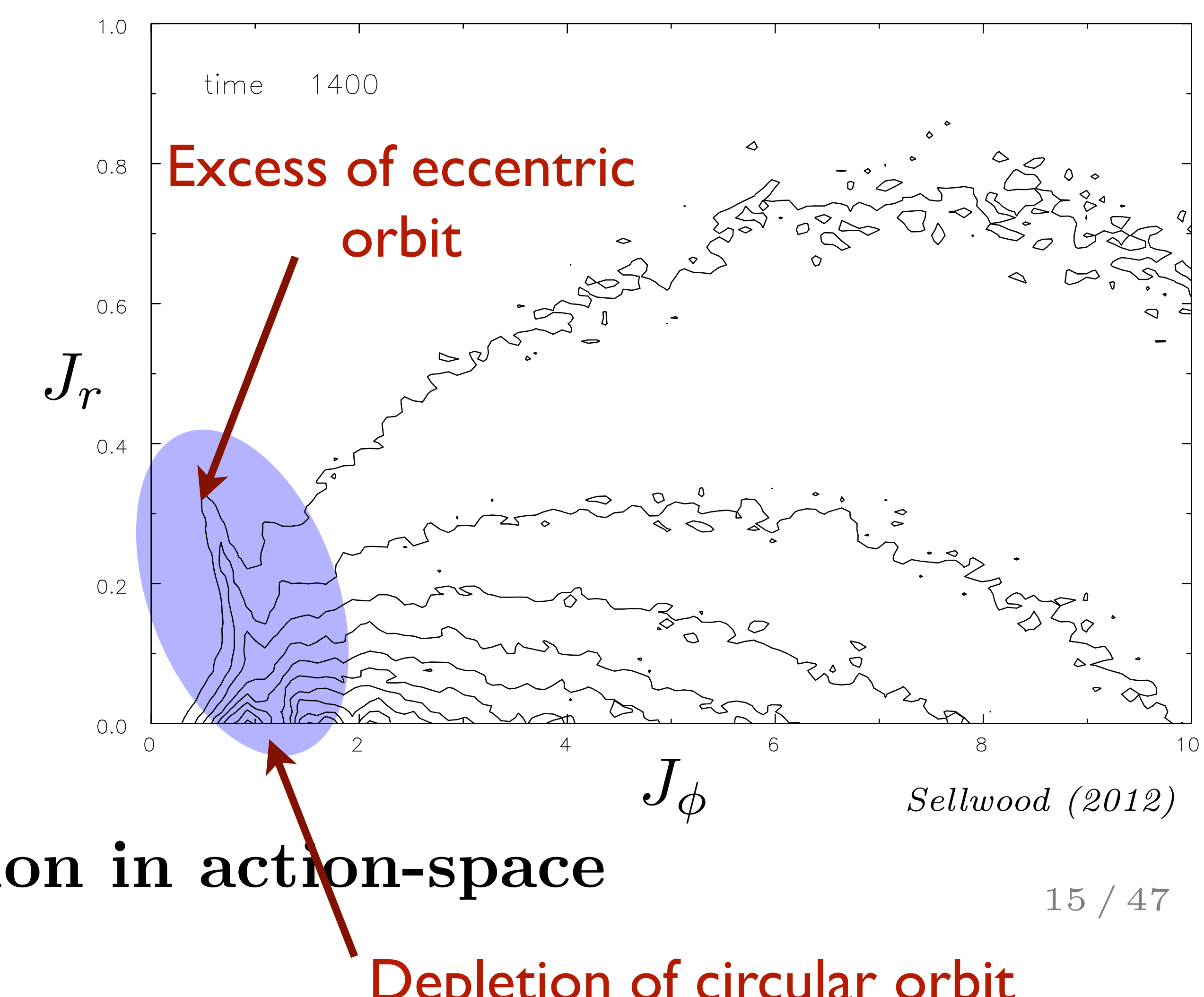
- Sellwood's 2012 numerical experiment
  - Stationnary **stable** tapered *Mestel disc*
  - $N-$body code with 500M particles
  - Appearance of **transient spiral waves**
  - Archetype of **radial migration**



Initial **stable/stationary** DF



Evolved DF



Sellwood (2012)

Secular diffusion in action-space

The fact that thin discs in cosmological simulations operate essentially as though they are isolated is quite remarquable and needs explaining.

• We measure that $Q \sim 1$ is an attractor for disc settling. It is an attractor because polarisation (near marginal stability) yields a tighter (faster) control loop for self regulating processes (turbulence, SN, star formation), and efficient entropy radiation. The tightness of this loop controlled by the amplitude of the fluctuating gravitational potential. Since these fluctuations are dressed by gravitational wakes, the closer the disc is to marginal stability the stronger the wake, the shorter the effective dynamical time, the tighter the loop, the closer the disc to marginal stability.

• The transition mass appearing in the fit of Q scales likes the mass of non-linearity, which defines the local dynamical clock, reflecting the idea that for more massive discs (in units of that mass) secular processes can operate more swiftly and efficiently. This transition translates into a fraction of settled discs as a function of stellar mass and redshift which match the observed one.

• The closer the disc to $Q \sim 1$, the stronger the gravitational coupling between rings, the more damped out of plane oscillation, the more settled the disc.

• The gravitational torquing between the gas and stellar components and dissipation within the former component can be accounted for via a two set of rings or two sets of WKB wave model. Both models provide means to understand how the stellar can converge towards low entropy states.

• Once in secular mode, the self regulated loop also stratifies vertically stars by age, while preserving the sech profile of the existing thick disc. This is achieved because both star formation and vertical orbital diffusion are regulated by the same confounding factor which stirs cold gas and diffuse the stellar orbital structure. As such, the stellar thick disc is simply the secular remnant of the disc settling process.

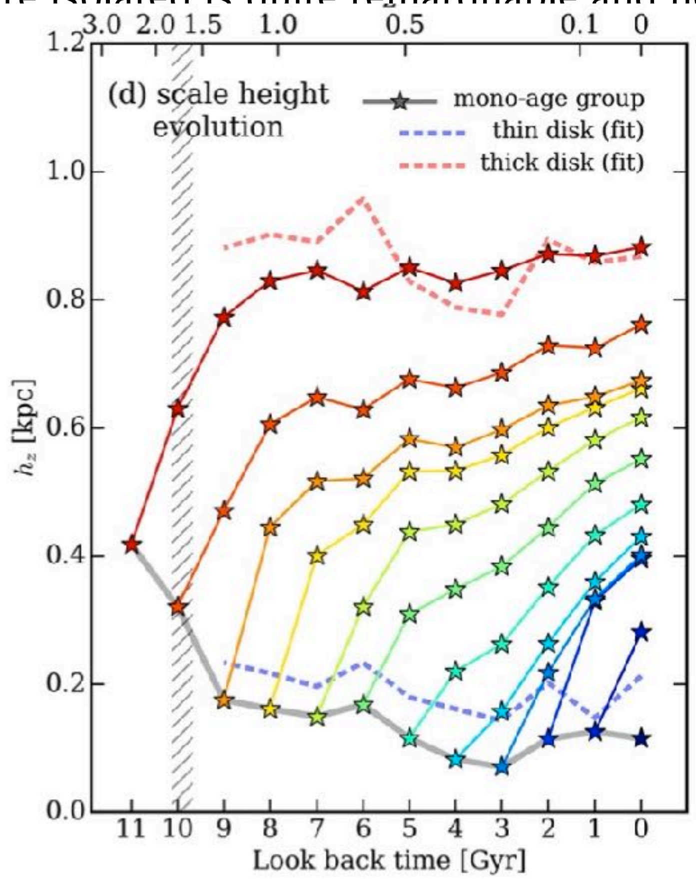


Figure 10. Evolution of the vertical distribution of the disk in the GALACTICA galaxy. (a) The instantaneous SFR as a function of redshift. (b) The evolution of the V/σ of the cold gas in the galaxy. (c) The evolution of disk scale length (R_d) of the galaxy. (d) The scale height evolution of mono-age groups of stellar particles indicated as different colors from red to blue with age bin of 1 Gyr (the same color key in Figure 9). The vertical distribution is measured at $2\,R_d$ of the galaxy at each epoch. The gray solid line connects to the scale height of the youngest stellar particles at each epoch. The dashed blue and red lines are the scale heights (h_z) of the thin and thick disks derived from the double-component fit to the vertical profile measured at each epoch. The vertical hatched band points to $z \sim 1.7$, the time at which the disk structure begins to appear in this galaxy. As the combined result of the thickening of the existing disk stars and the continued formation of young thin disk stars, the vertical distribution (and the scale heights of the thin and thick disks obtained as a result of the fit) does not change much since disk settling. This conspiracy points towards a confounding factor regulating simultaneously star formation and vertical diffusion.