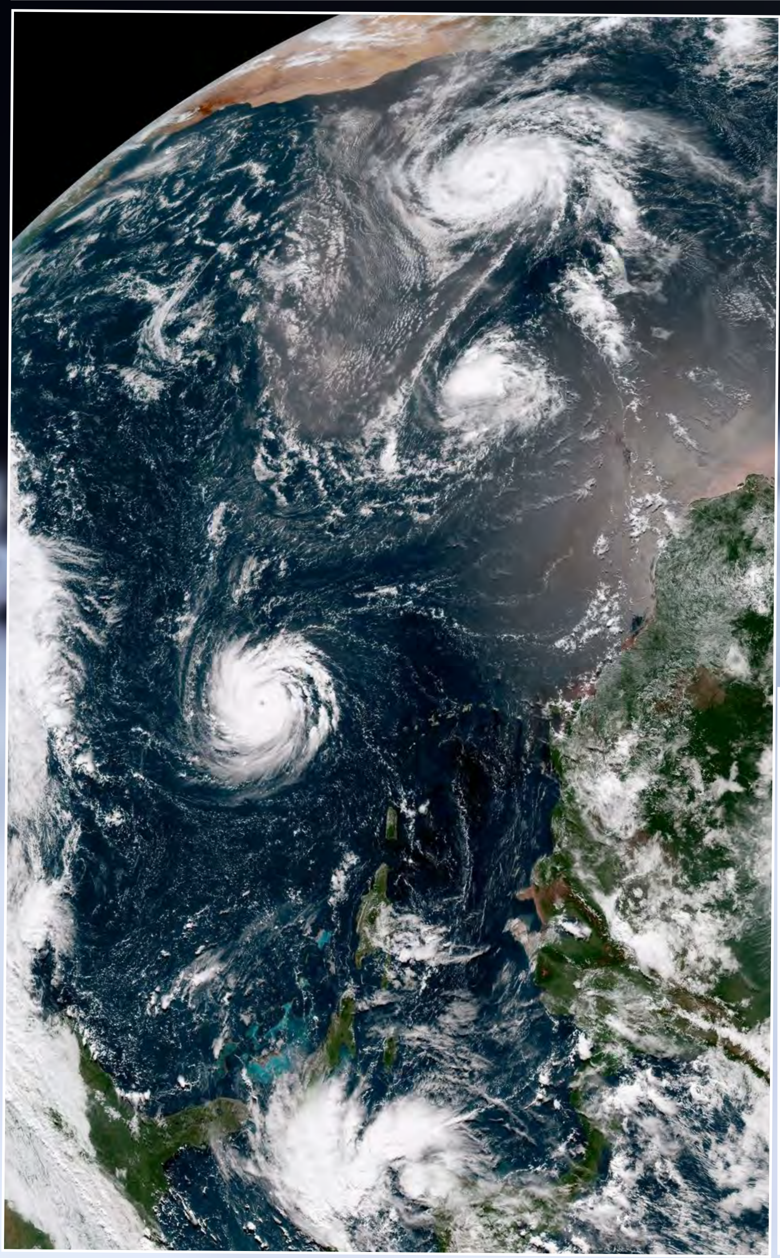
The cosmic emergence* of thin discs

Order out of Chaos:
Secular Disc Settling driven by the Cosmic Web

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

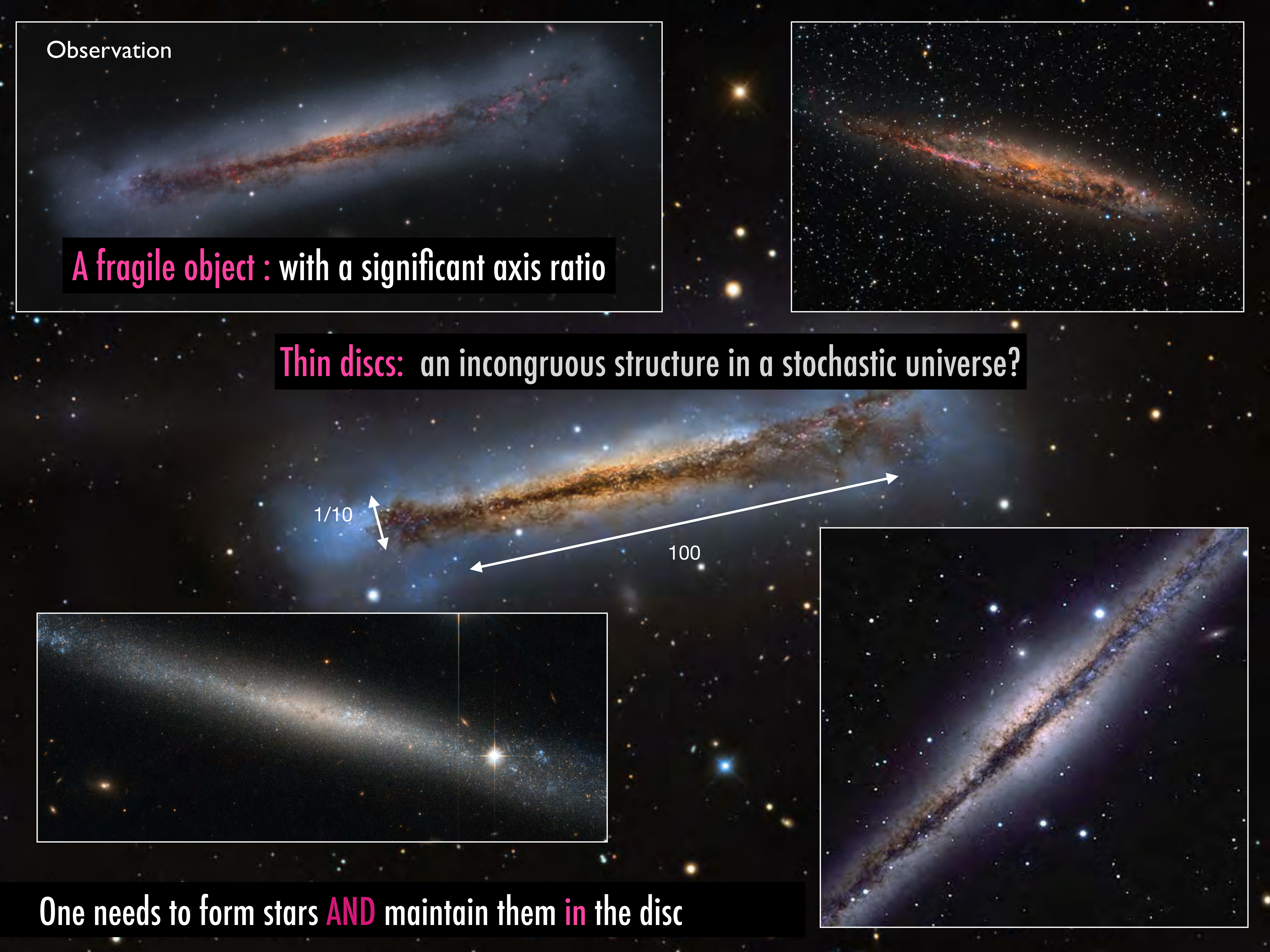
Christophe Pichon & The NewHorizon Collaboration (Min-Jung Park, Y Dubois, J. Devriendt++)

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



Near phase transition in open dissipative systems.

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



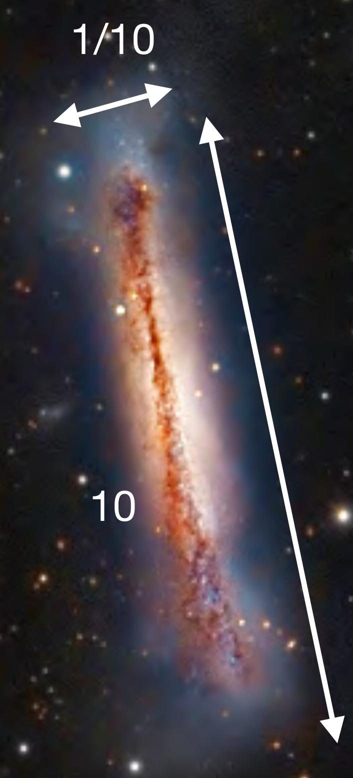
Observation
A fragile object : with a significant axis ratio
Thin discs: an incongruous structure in a stochastic universe?
1/10
100
One needs to form stars AND maintain them in the disc

Clues from the 90s

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

- warps
- thick disks

Both know about infall direction!



Clue? circumgalactic medium geometry

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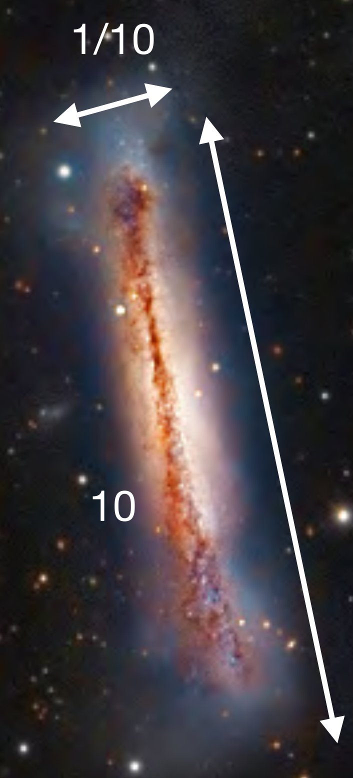

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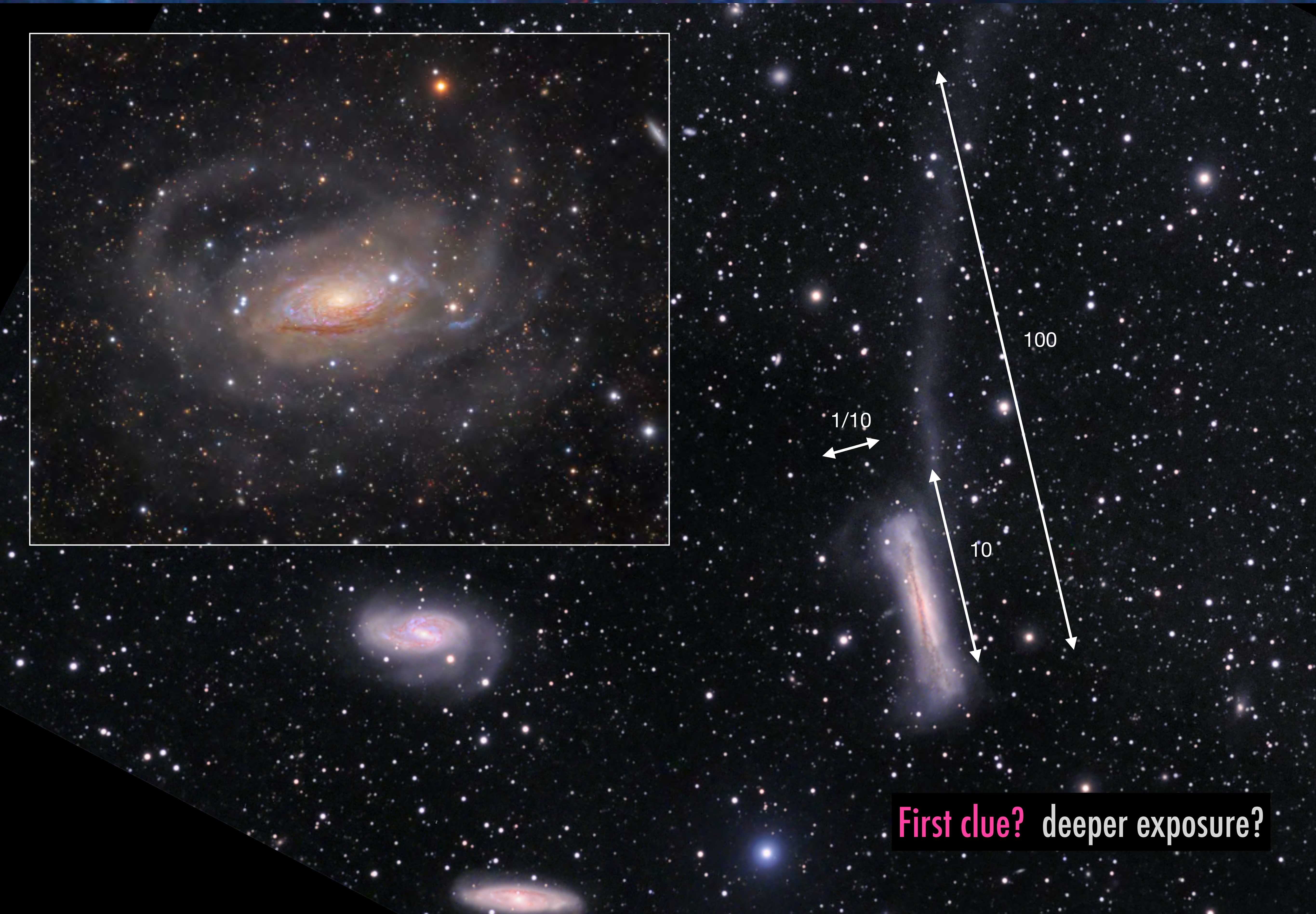
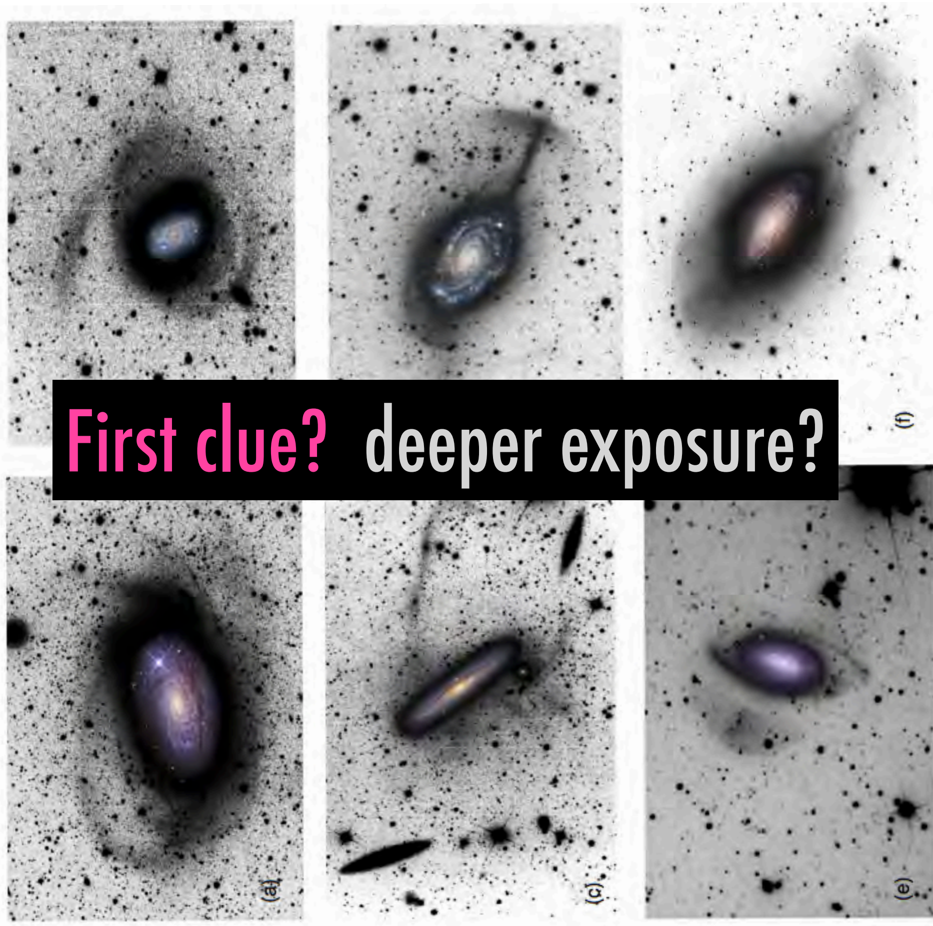
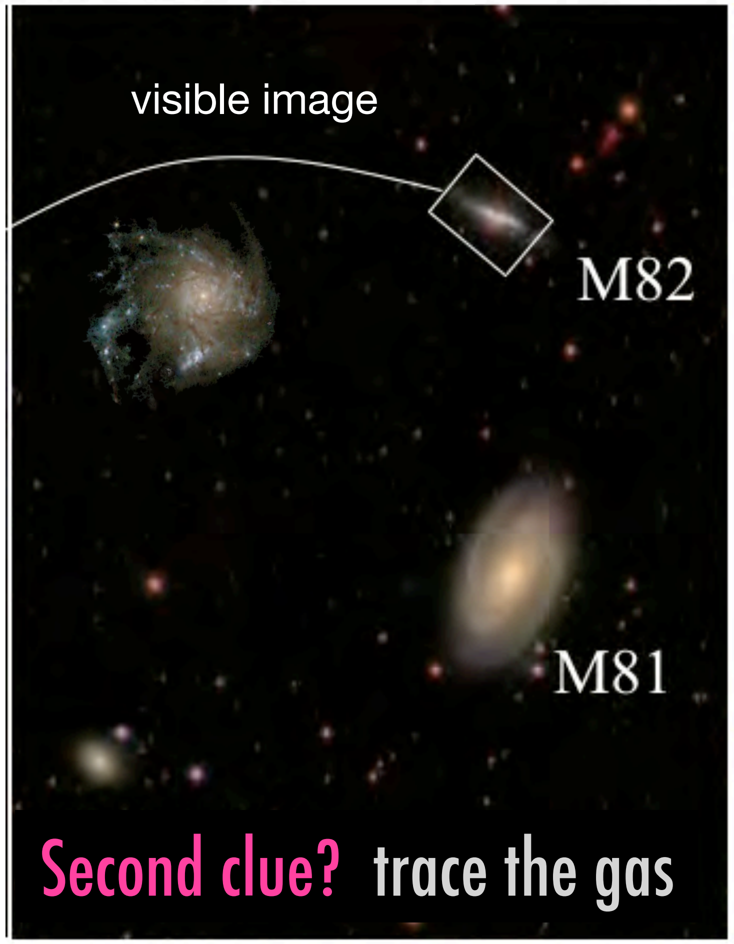
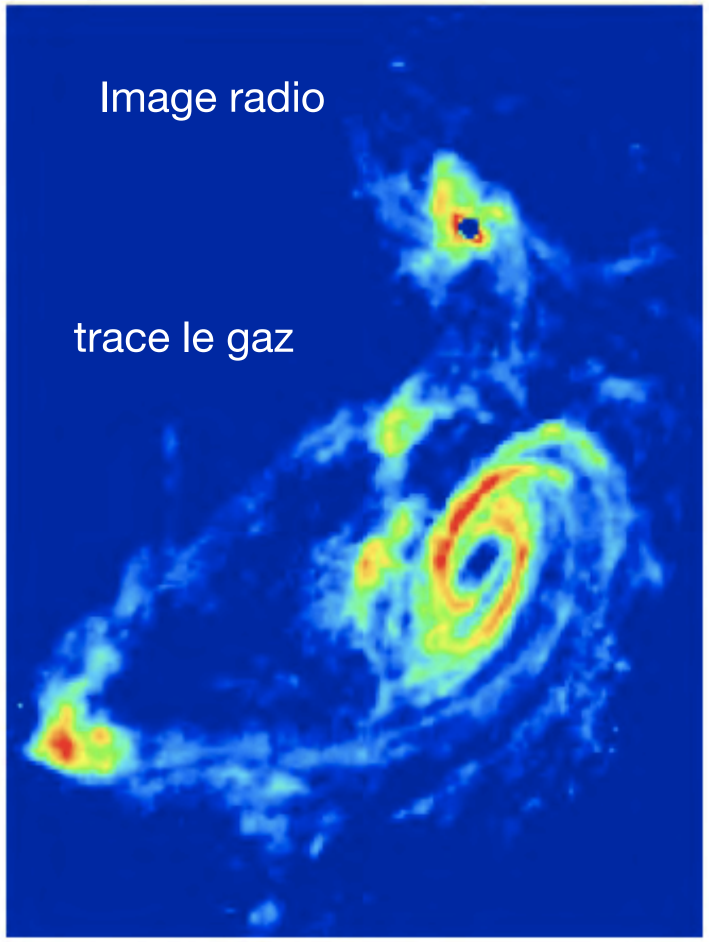
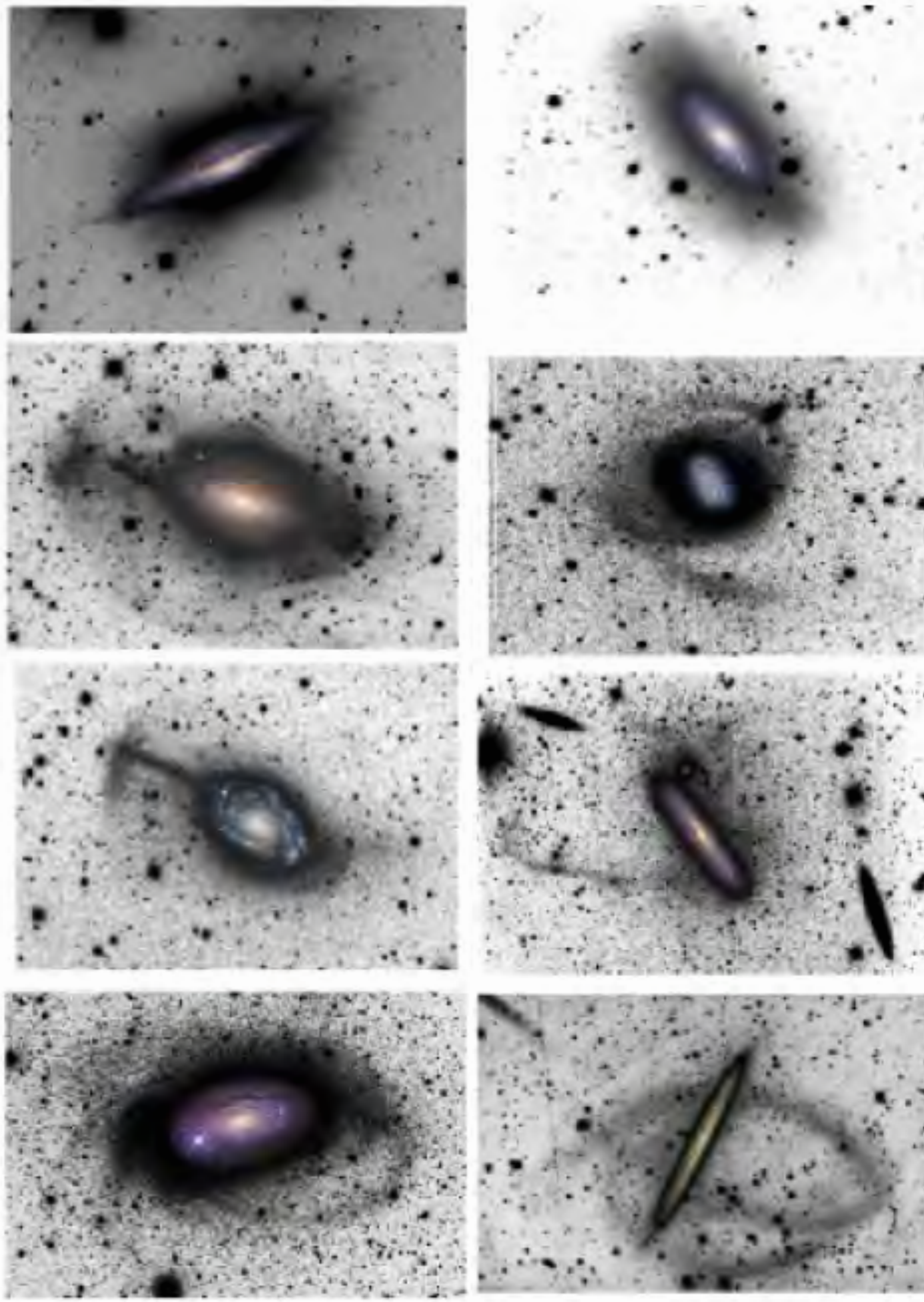


Geometry of circum-galactic medium









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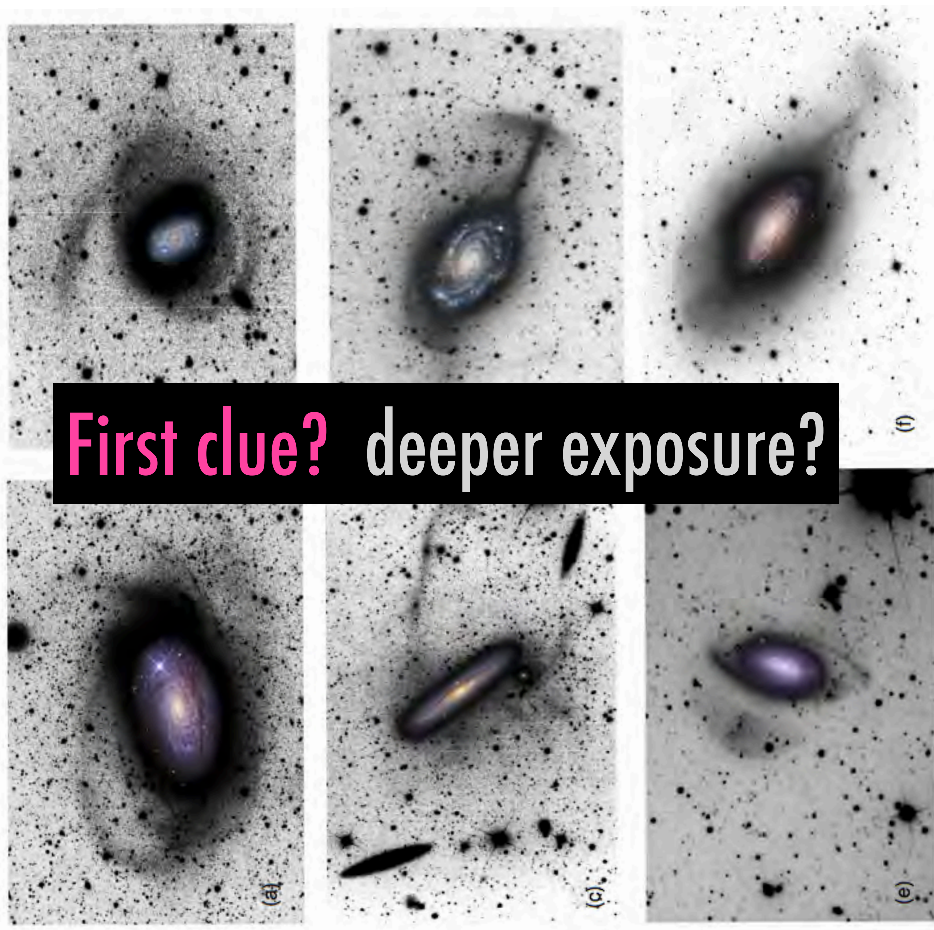

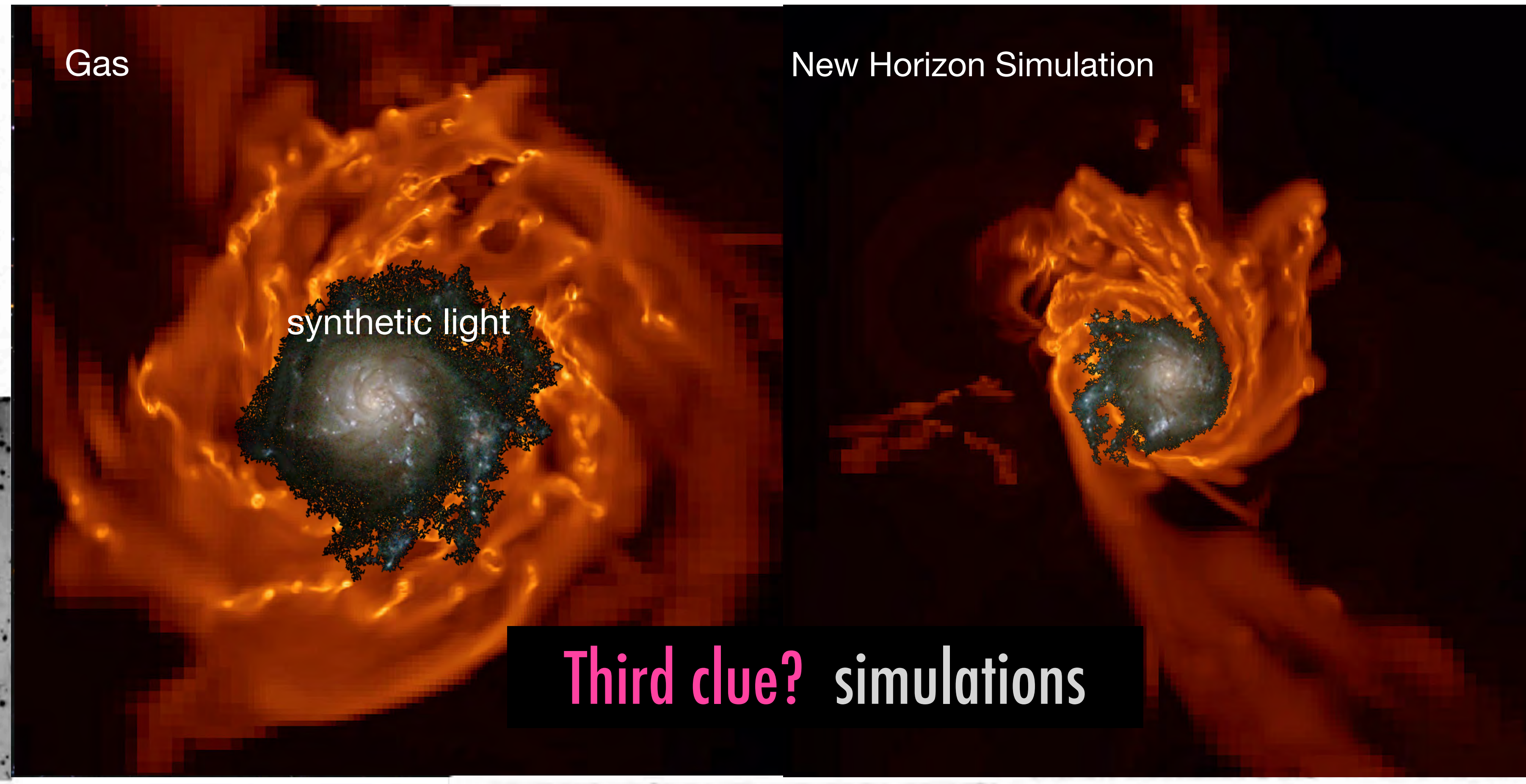

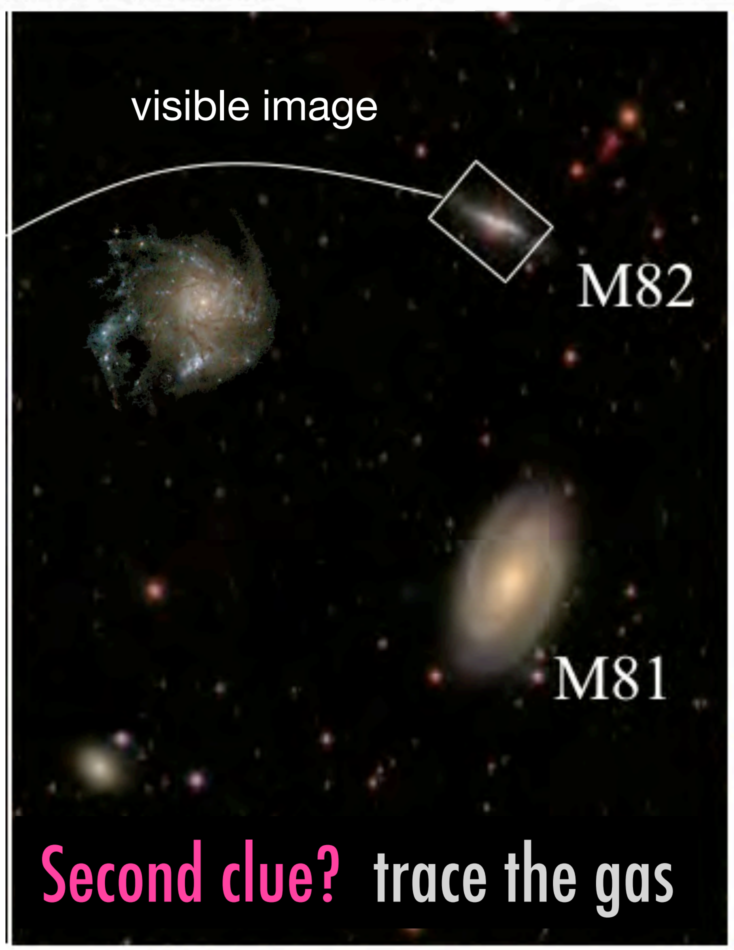

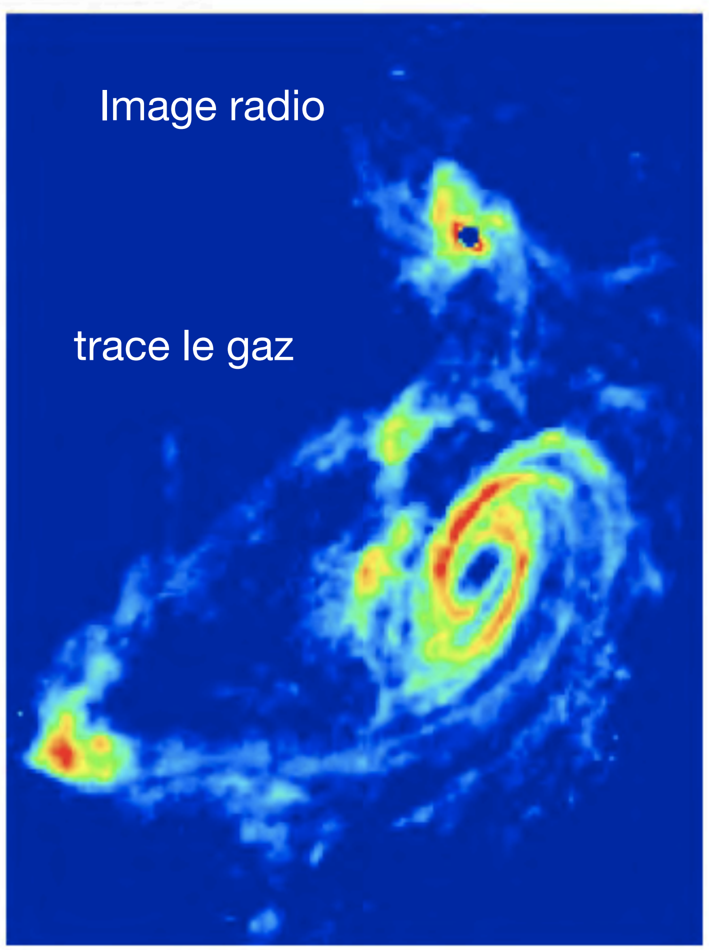

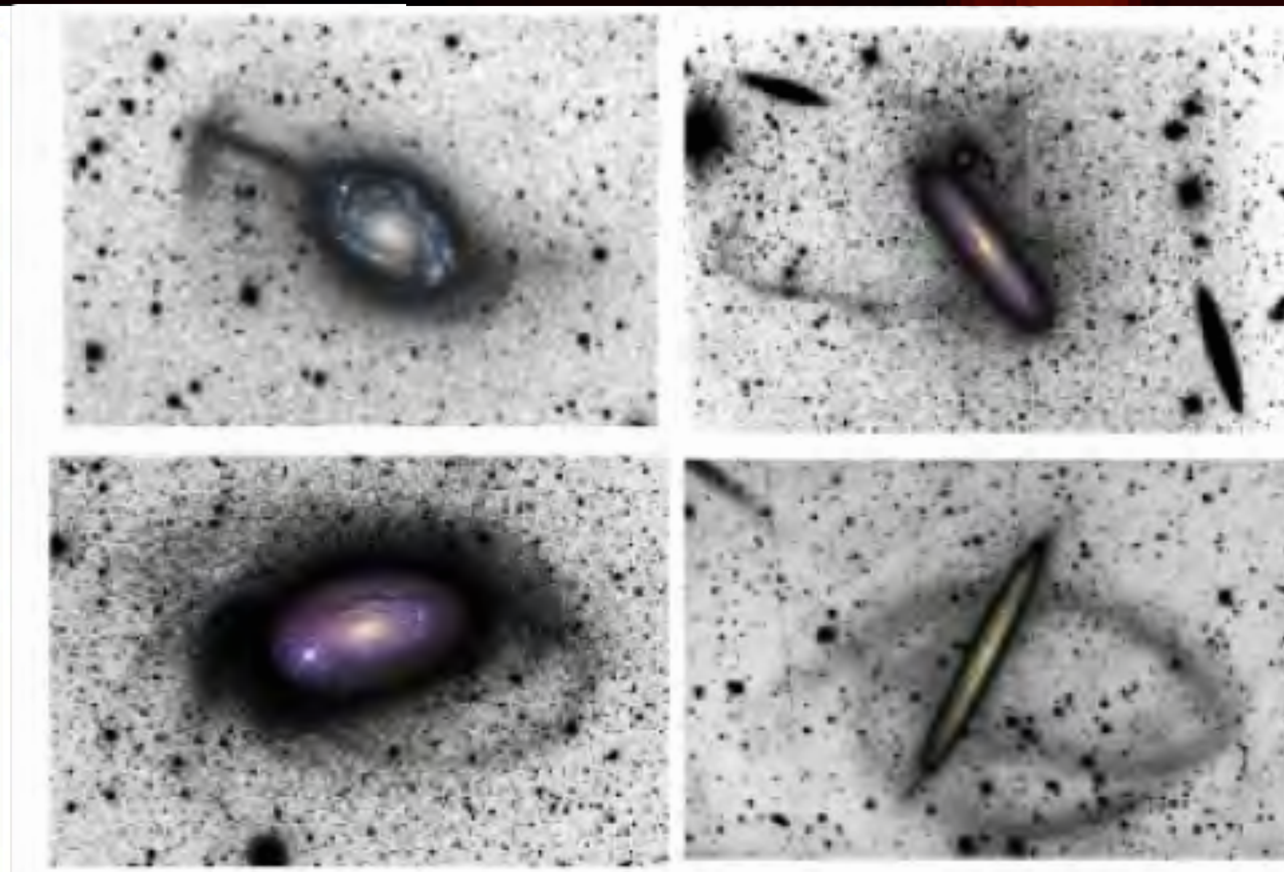

How thin discs build up-from persistent cosmic web?

Part I (2010)

Disc morphology is driven by AM acquisition through ***anisotropic*** *secondary infall, coming from larger scales, which are* ***less dense****, hence more steady; NL baryonic flows provide the link.*

An illustration of top-down causation

Part II (2020)

Thin disks are ***emerging*** *structures when secular processes take over. They are made possible by shocks, feedback and turbulence. Gravitational* ***wakes*** *tightens a self-regulating loop towards marginal stability, pumping free (rotational) energy from the CGM.*

An illustration of emergence/SOC


The *Virtual (dark matter)* universe
Voids become more void
Filaments drifts...
Log density
... and get **distorted**
$t_{\rm dyn} \sim 1/\sqrt{\rho}$
not much happens on LS: which is good & expected


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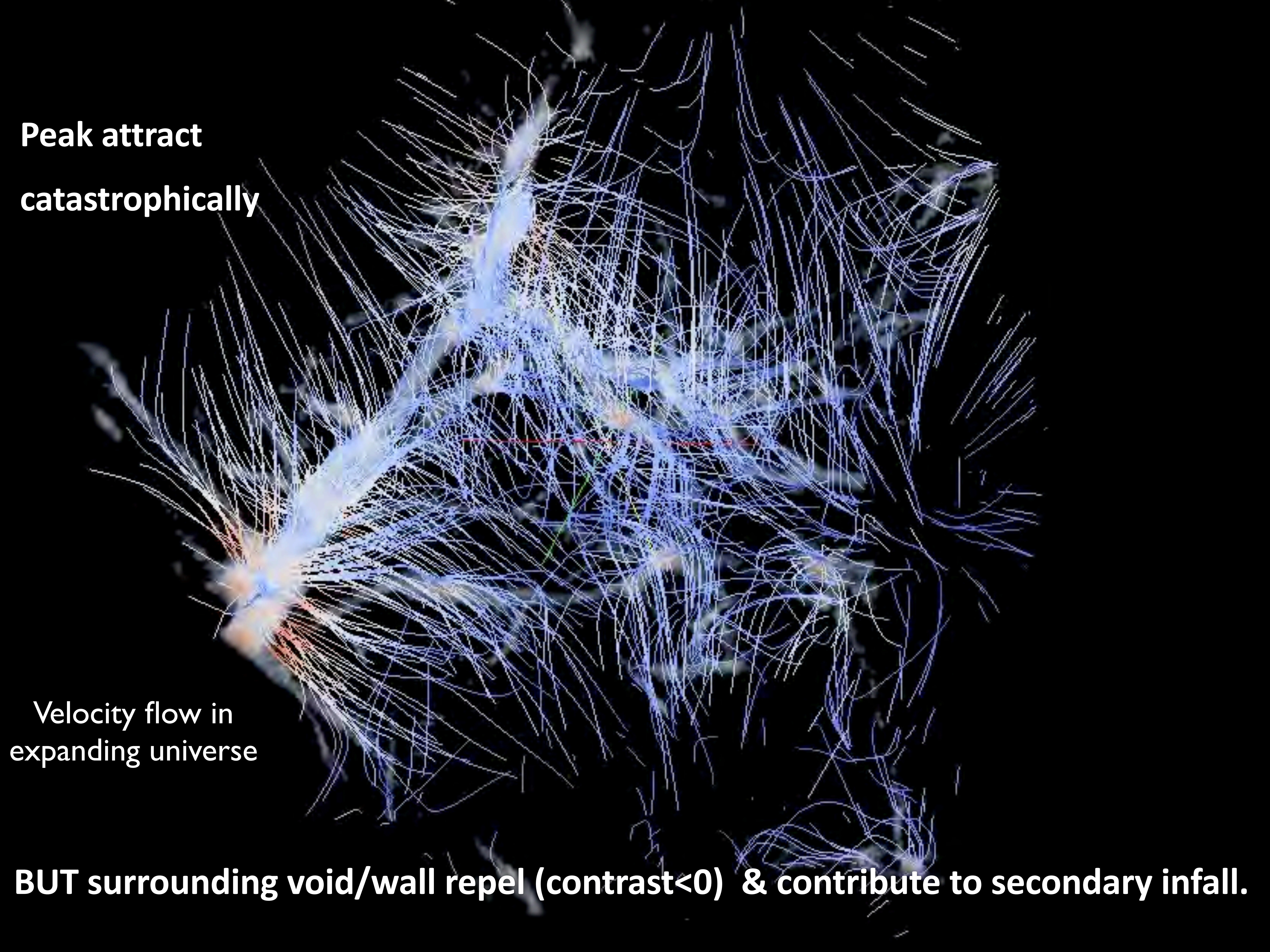
Peak attract
catastrophically
Velocity flow in
expanding universe
BUT surrounding void/wall repel (contrast<0) & contribute to secondary infall.

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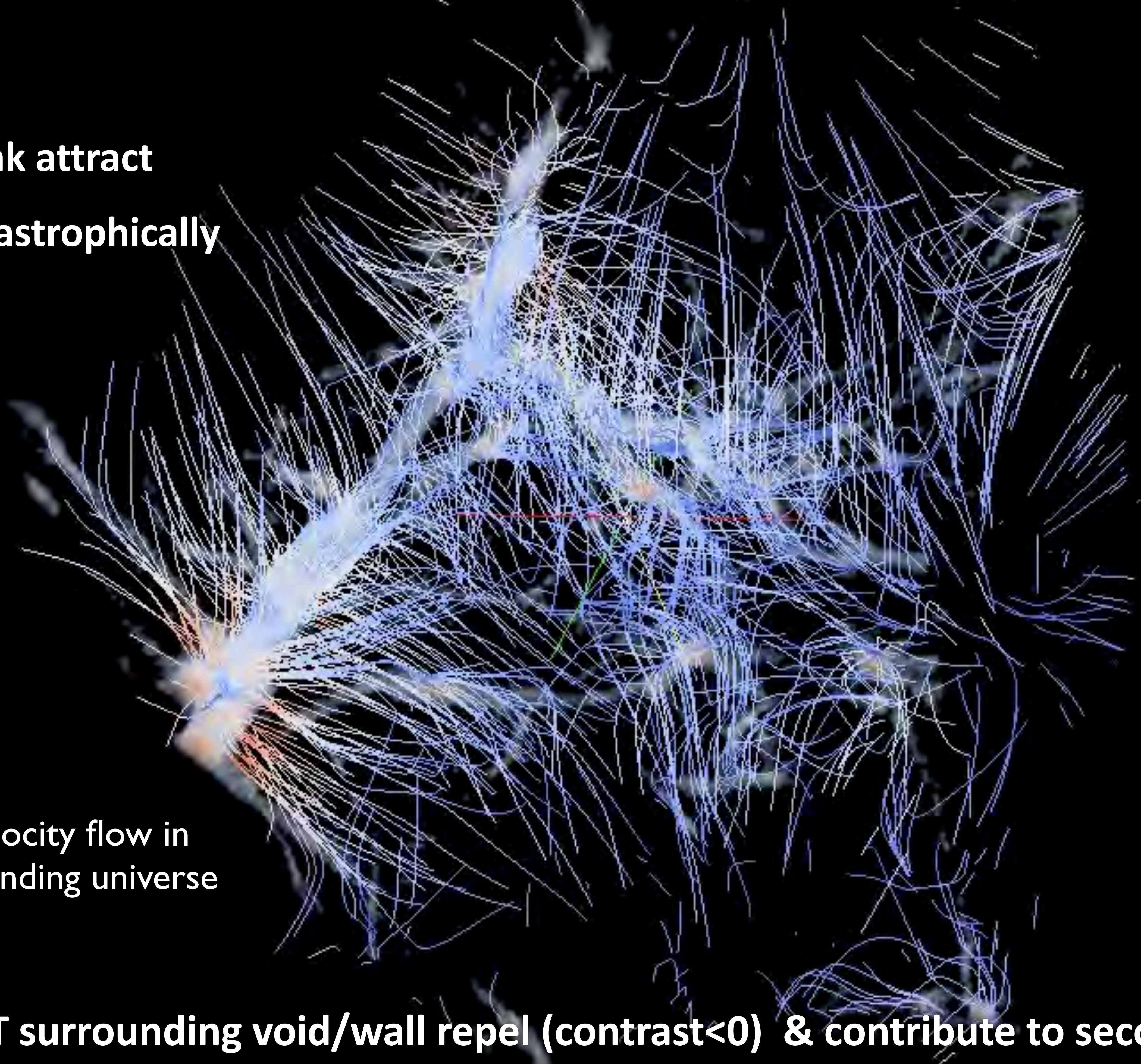

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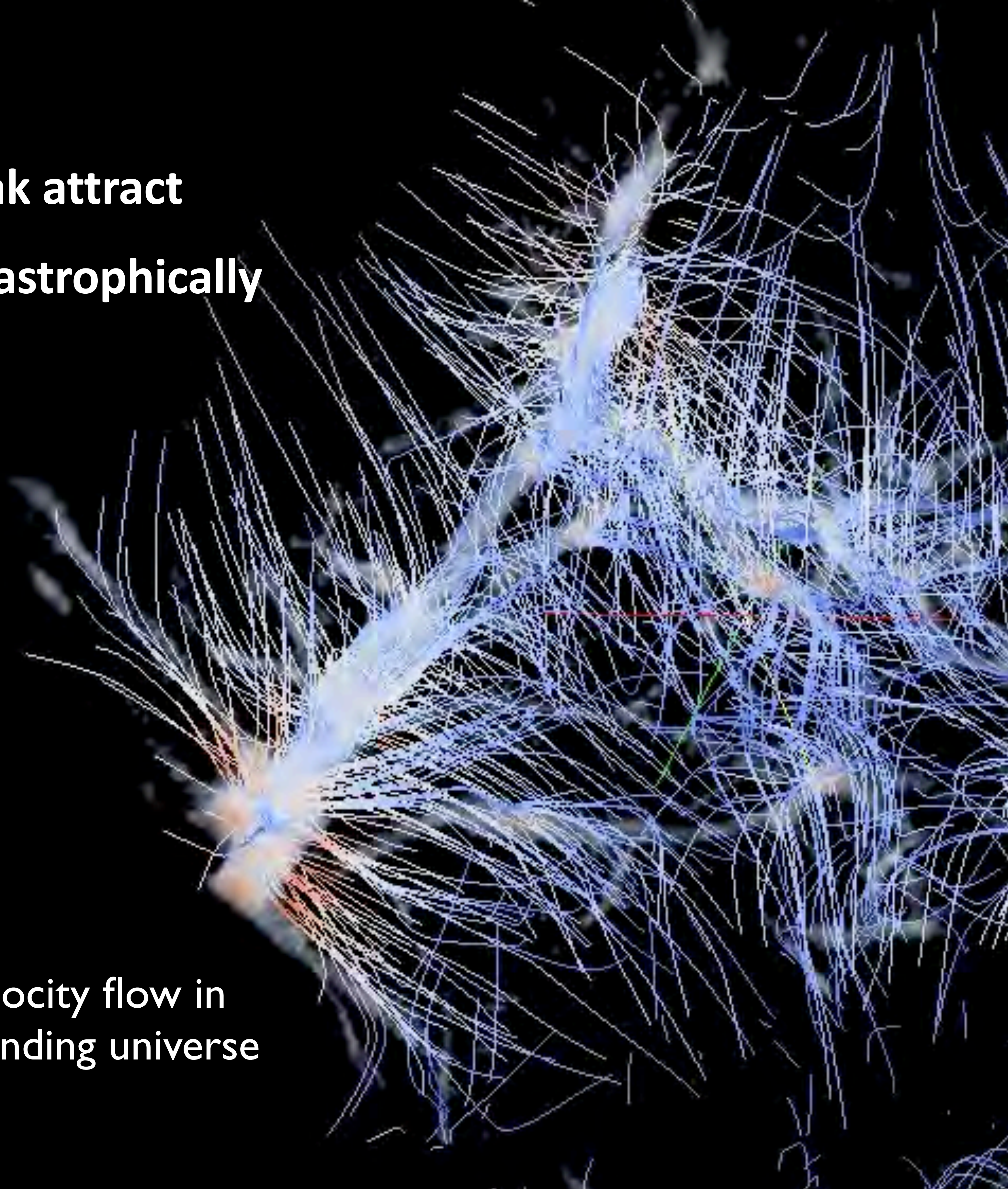

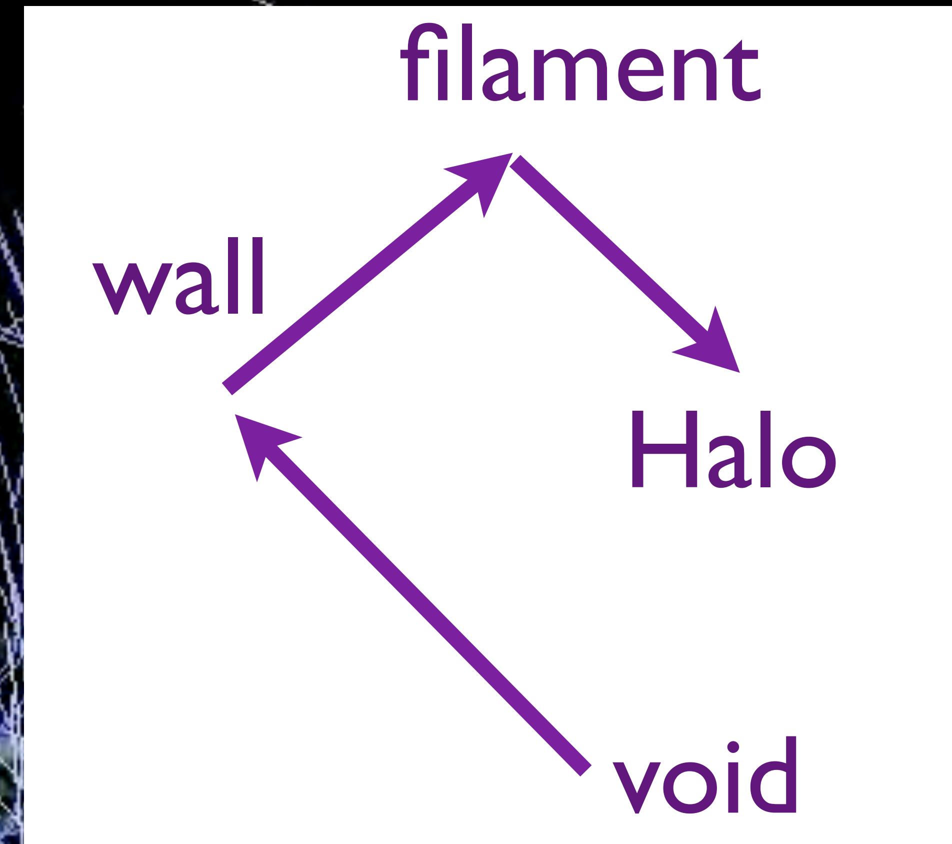

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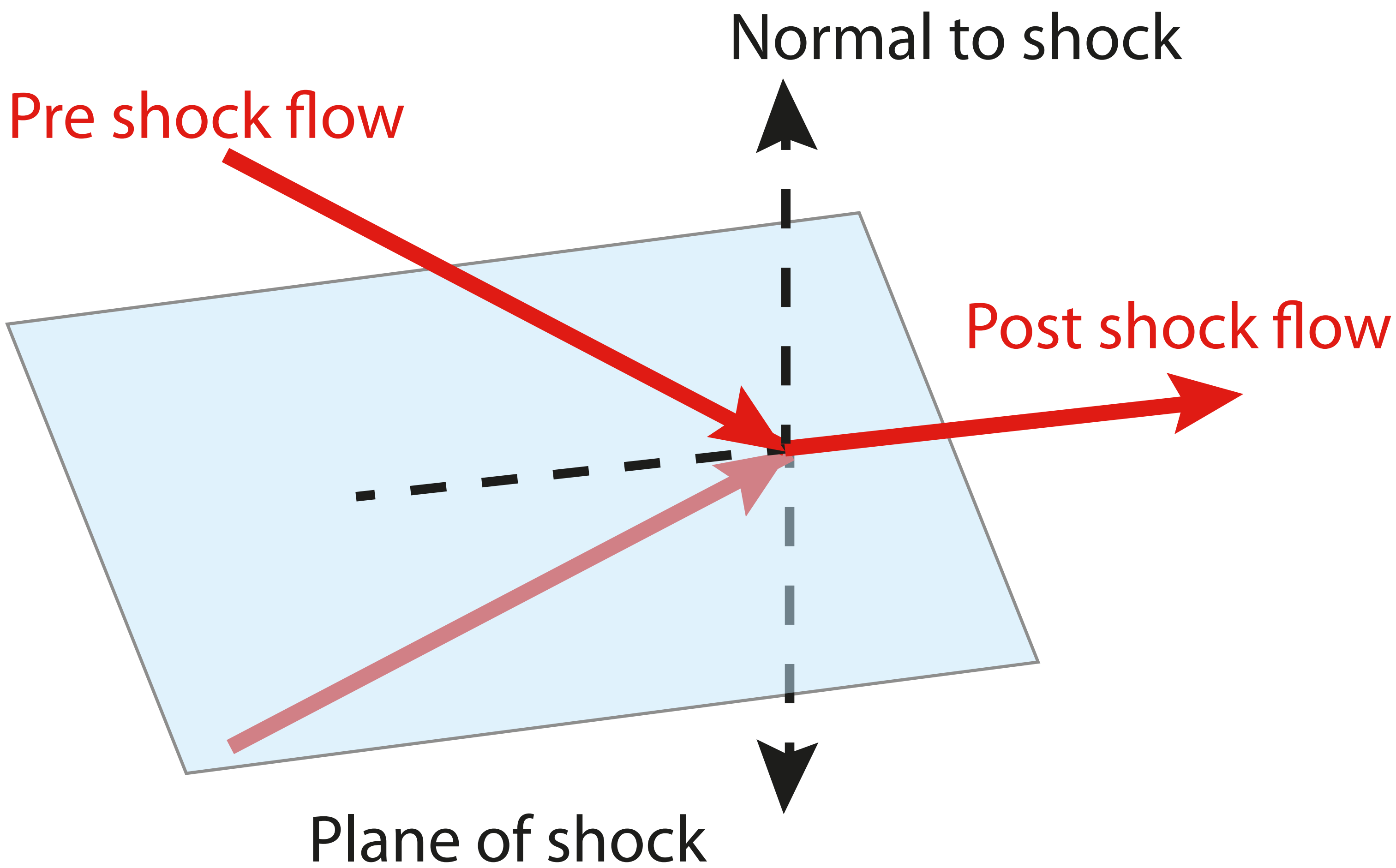

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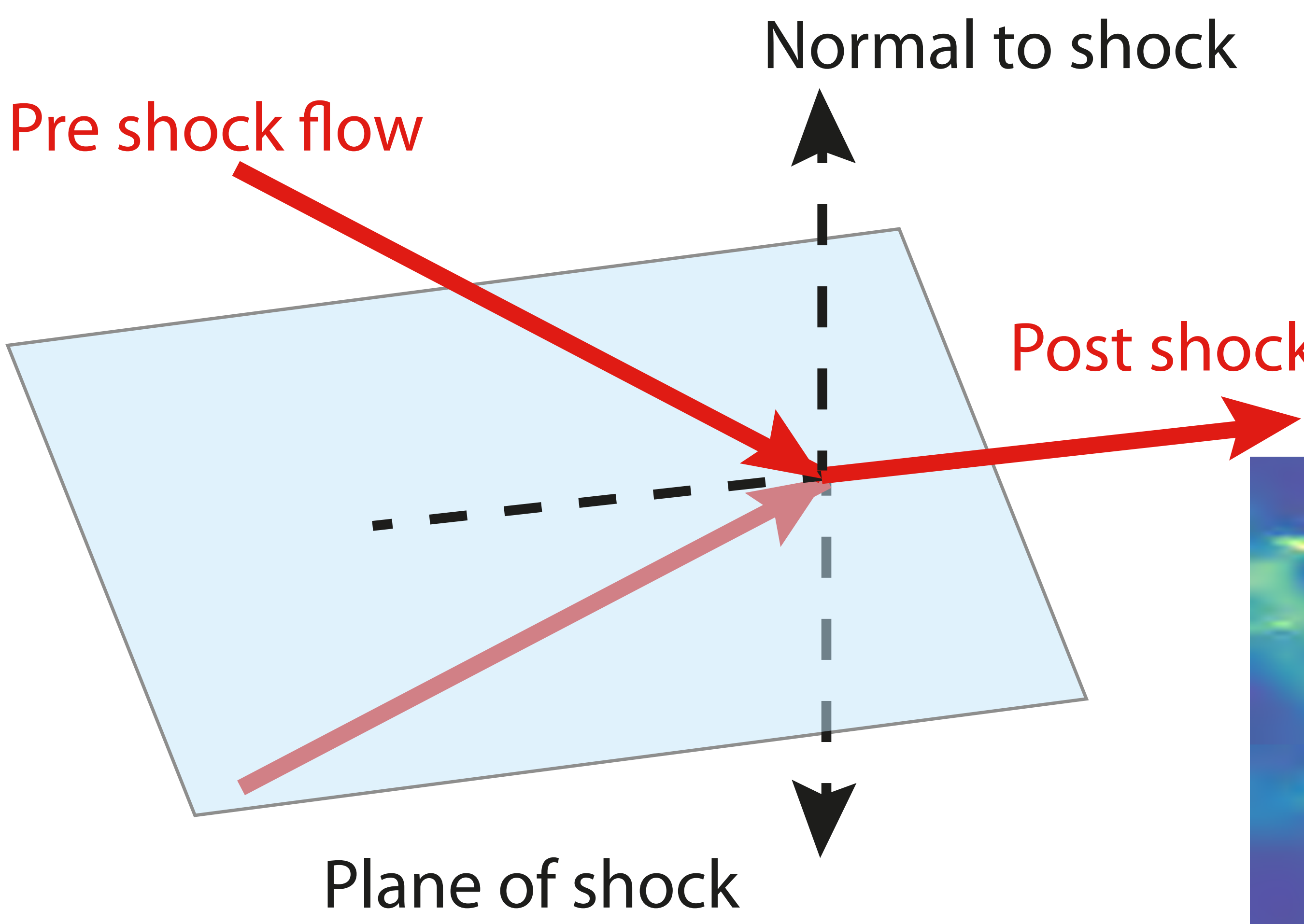

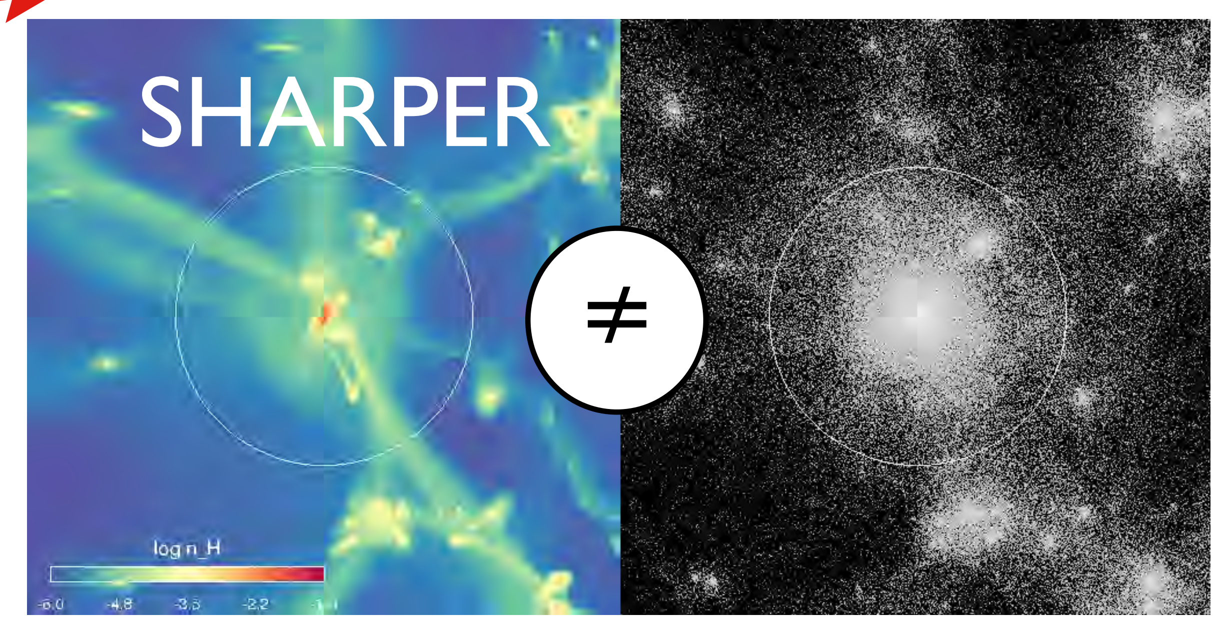

Gas, unlike dark matters, shocks (iso-T) and

follows closely the cosmic web

cosmic web is important **for galaxy morphology**

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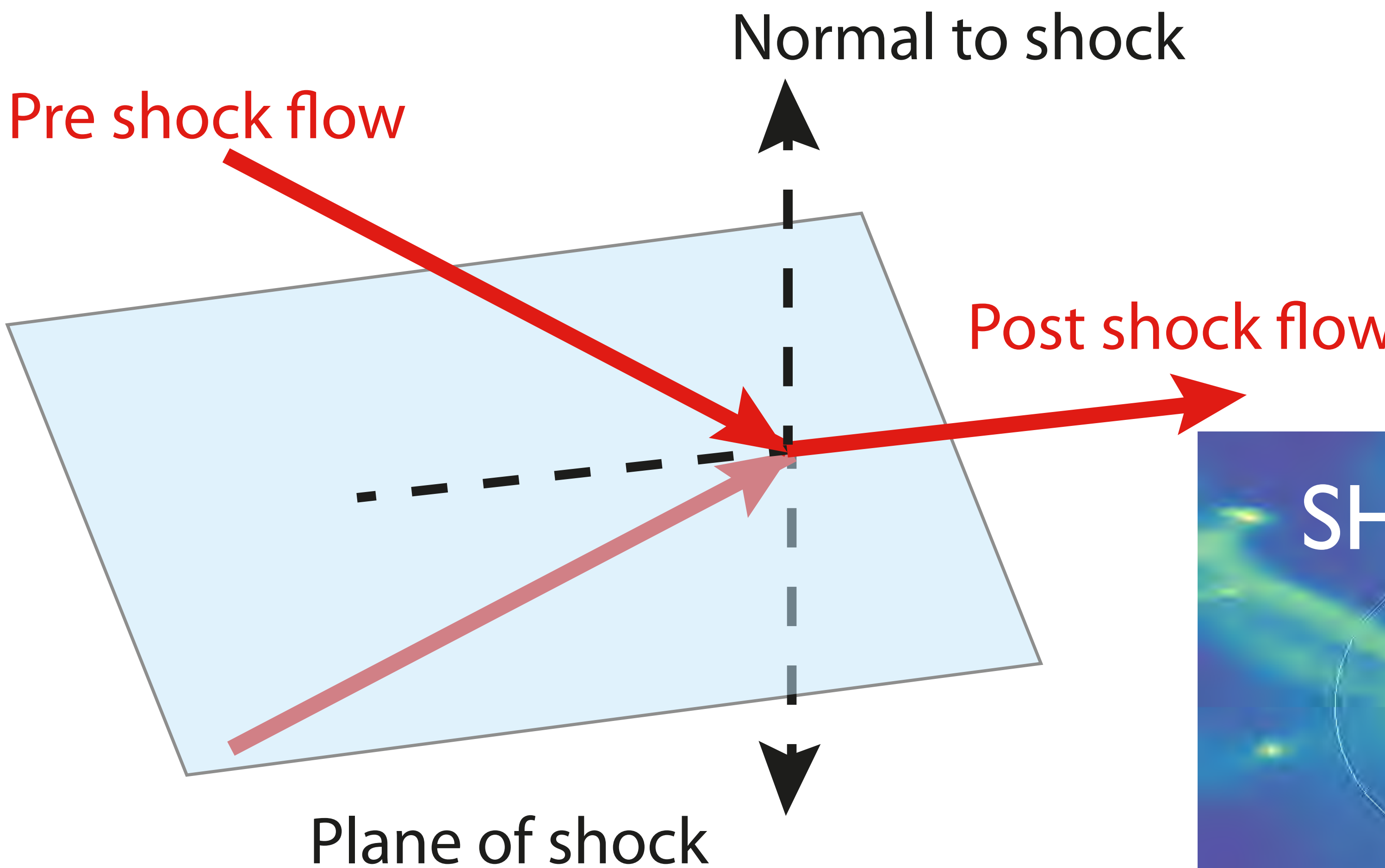

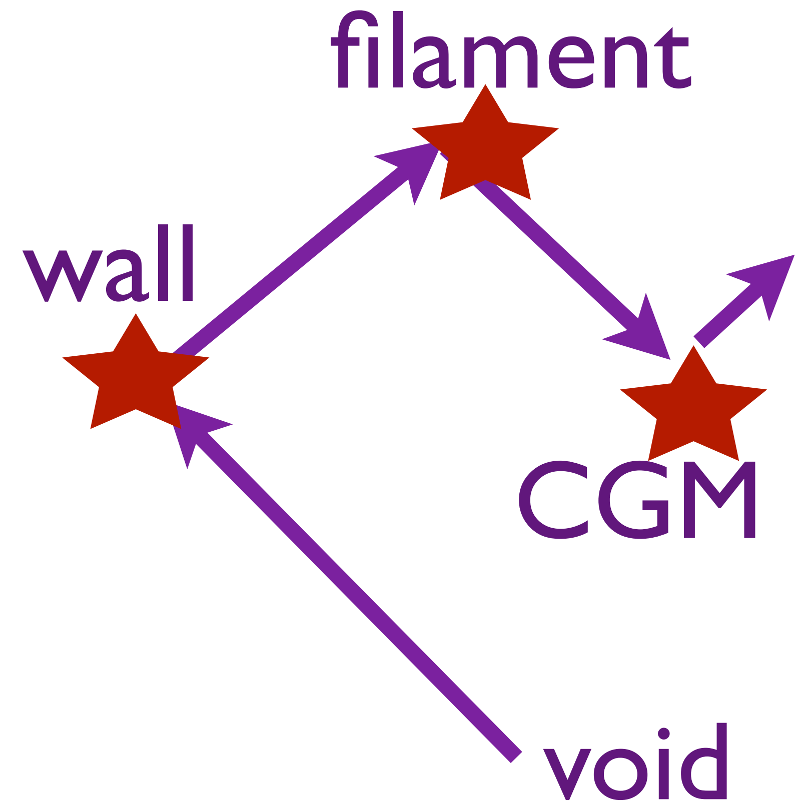

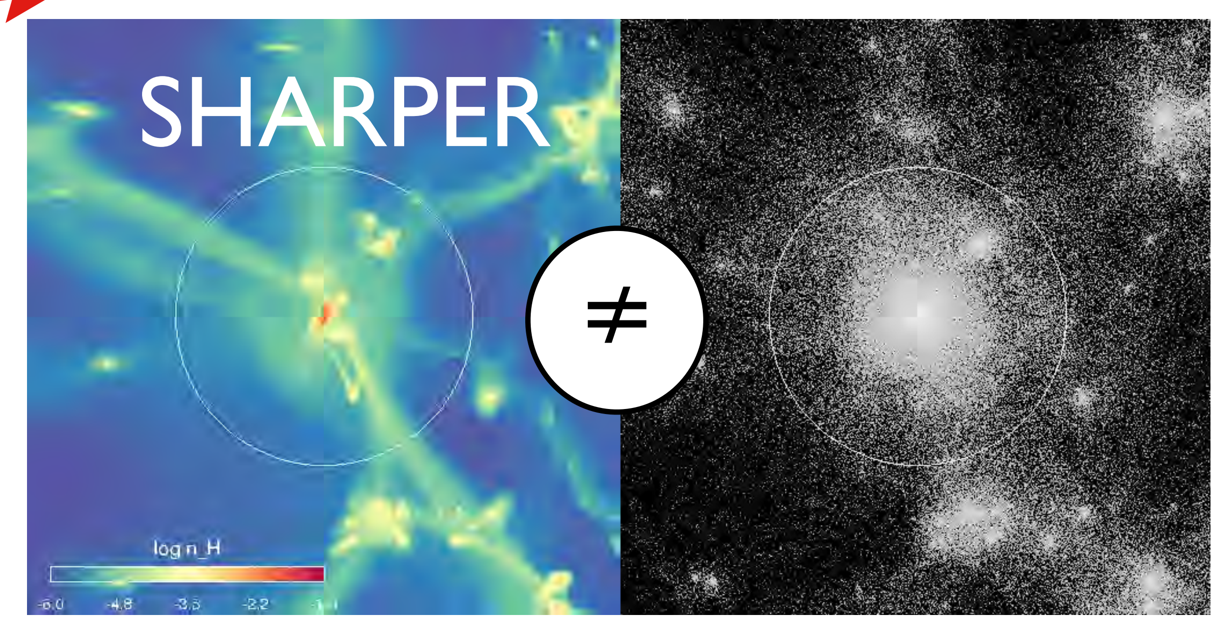

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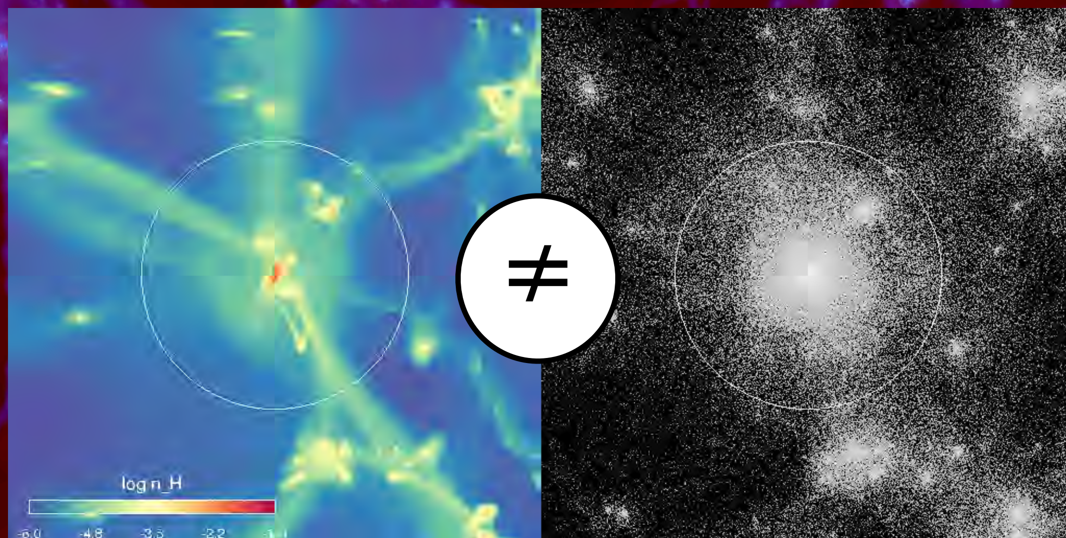
The *Virtual (hydrodynamical)* universe

Agertz, Renaud et al. (2021)
Renaud, Agertz et al. (2021a,b)



Gas cosmic web SHARPER

we see cold flows + recurrent disk reformation

LSS drives secondary infall

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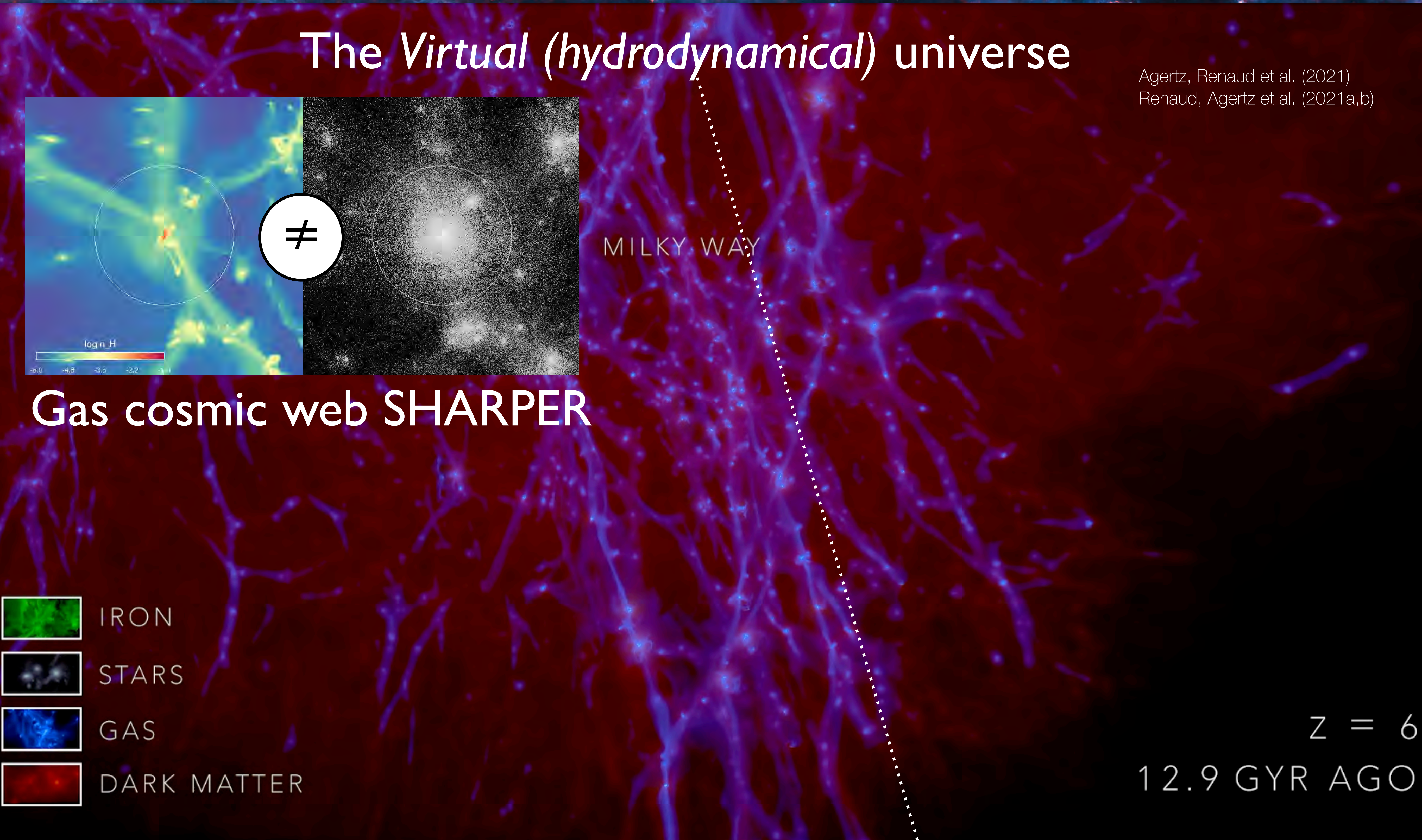

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LSS drives secondary infall

Cosmic web dynamics on galactic scales

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 so as to (re)build discs
continuously.

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

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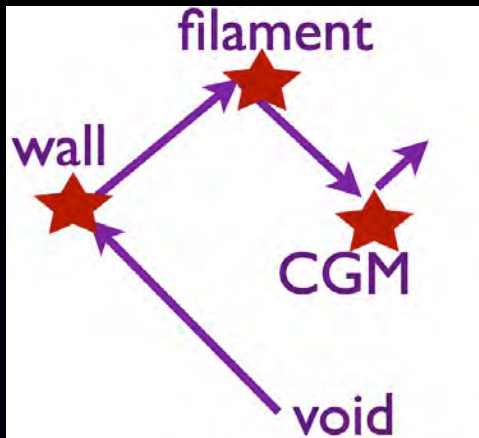

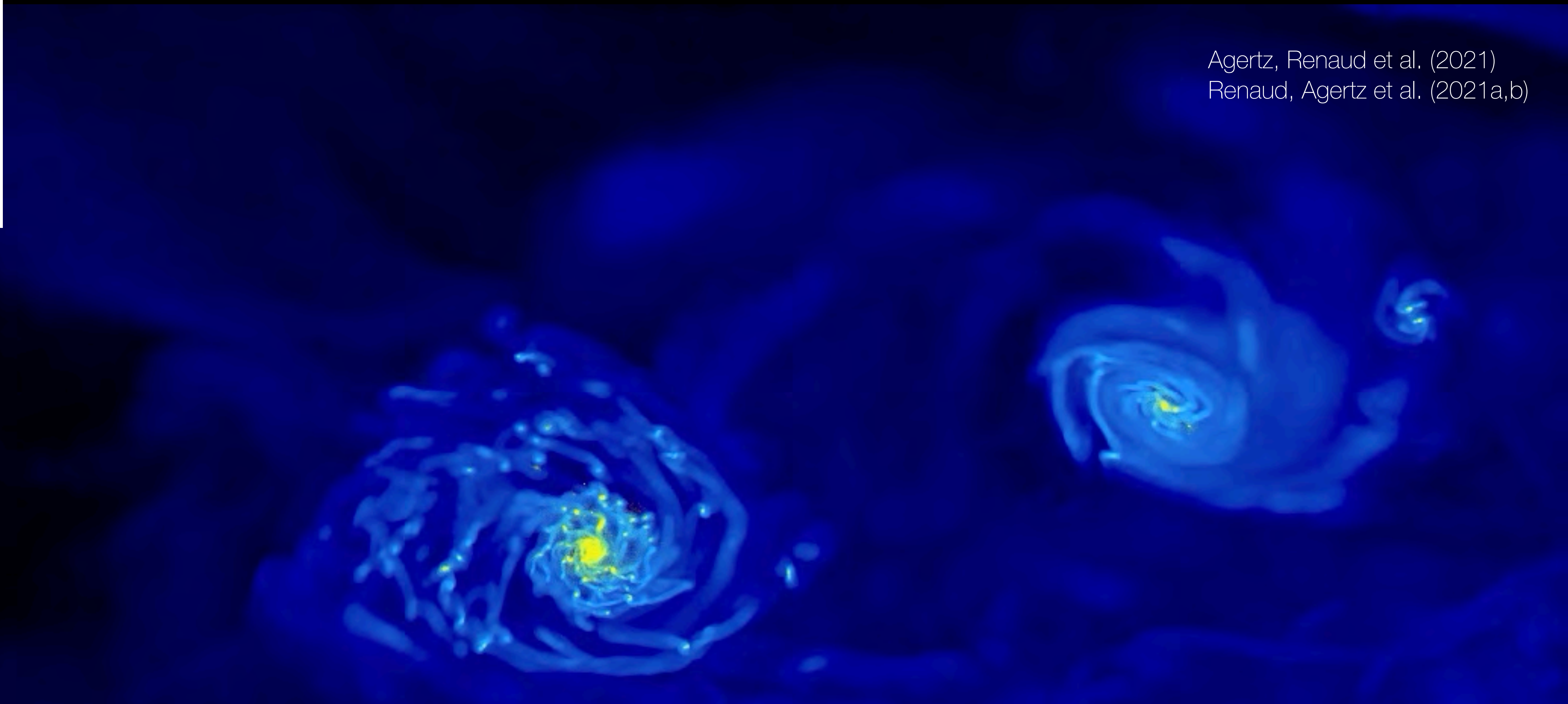

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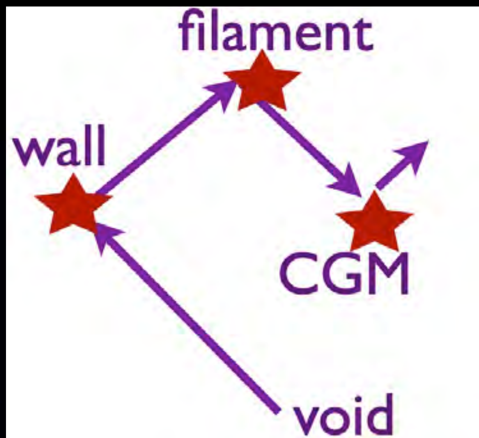
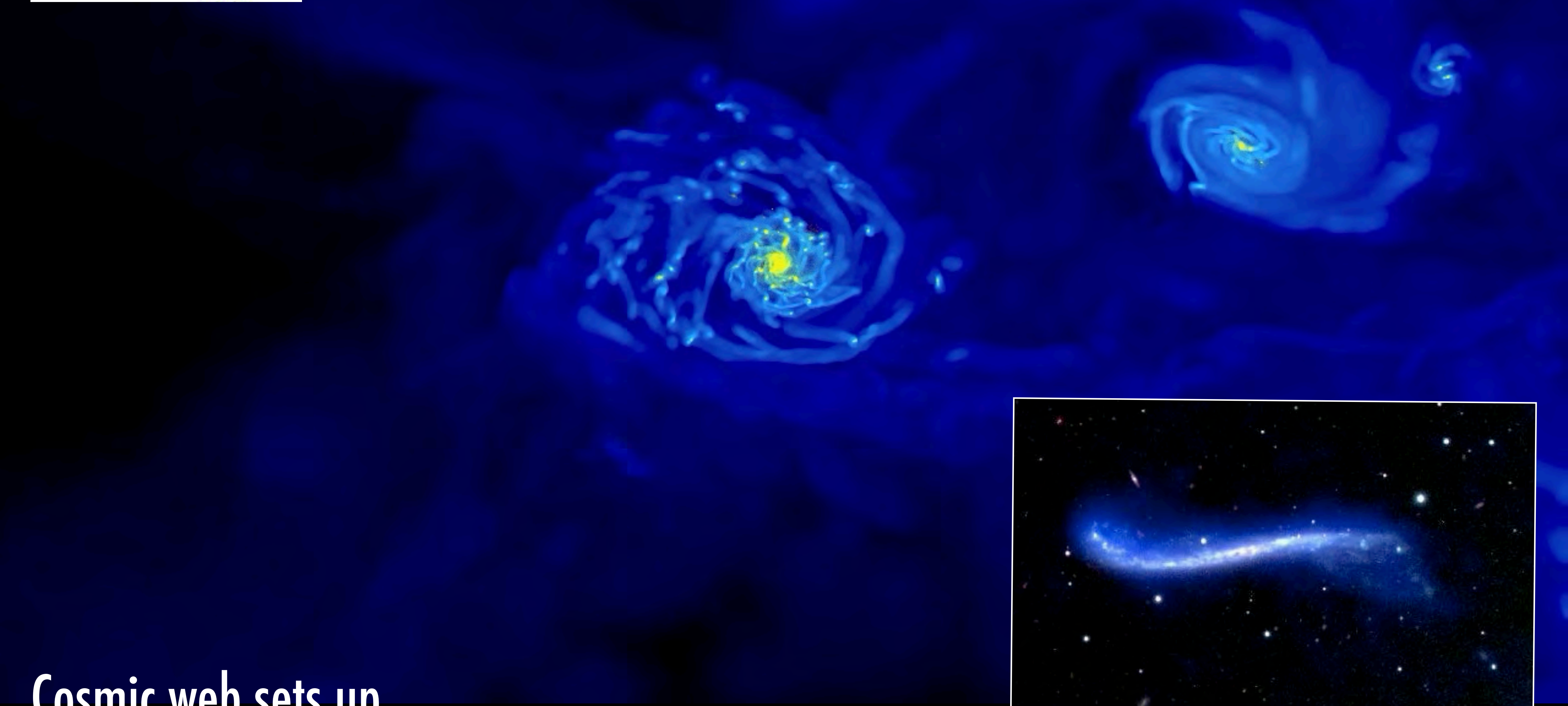
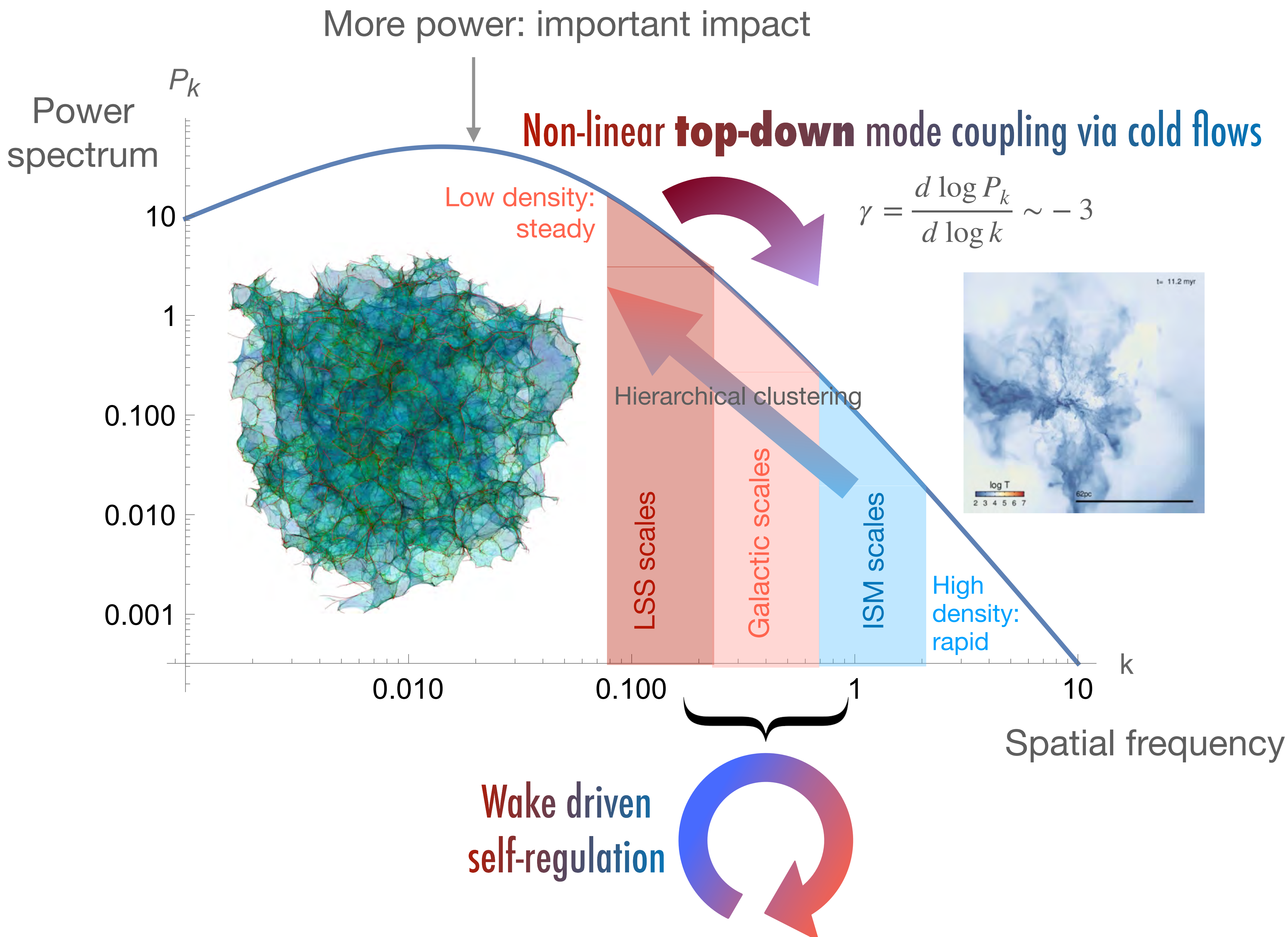




Cosmic web sets up
reservoir of free energy in CGM = the fuel for emergence

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.



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Part II

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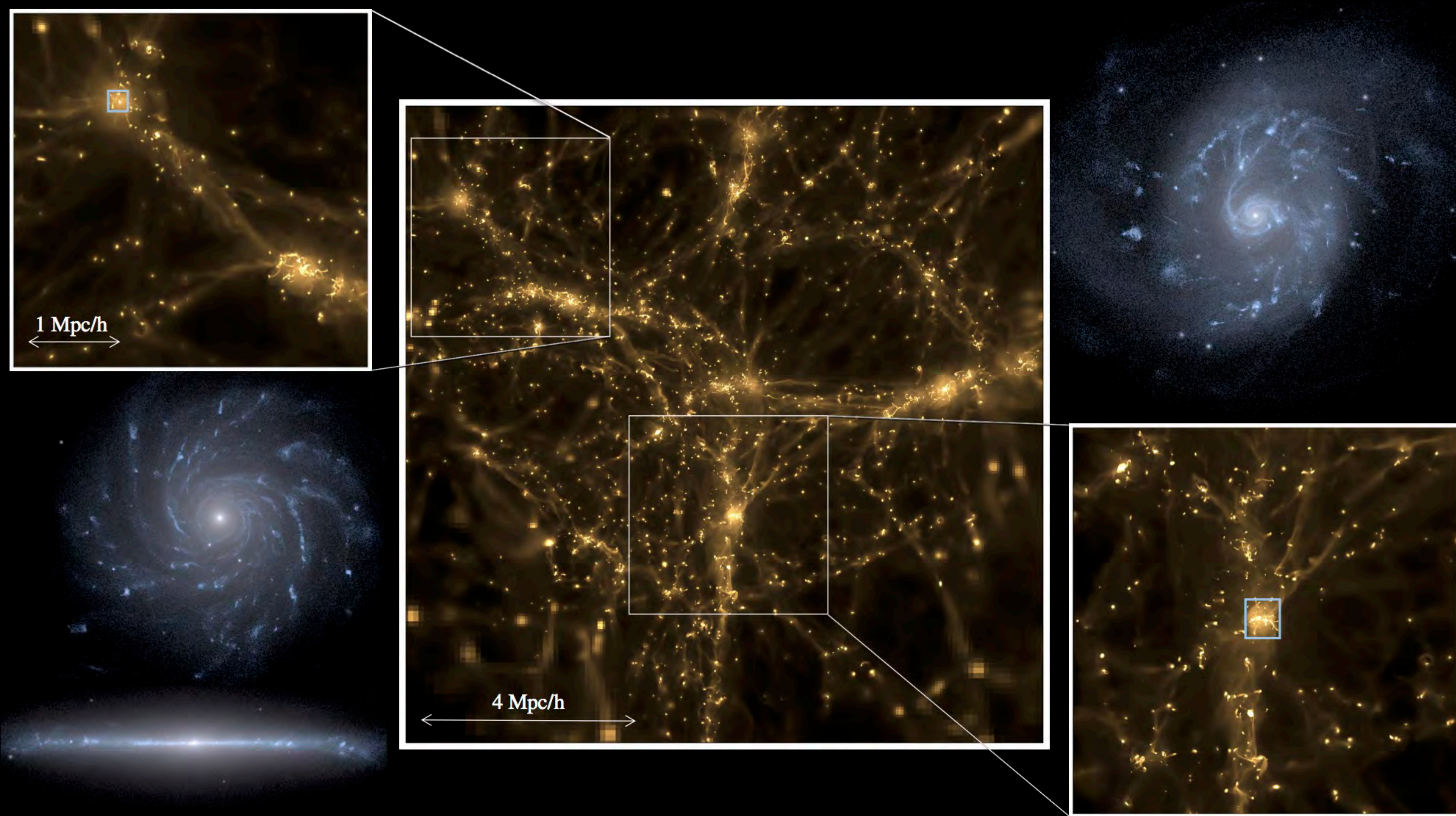
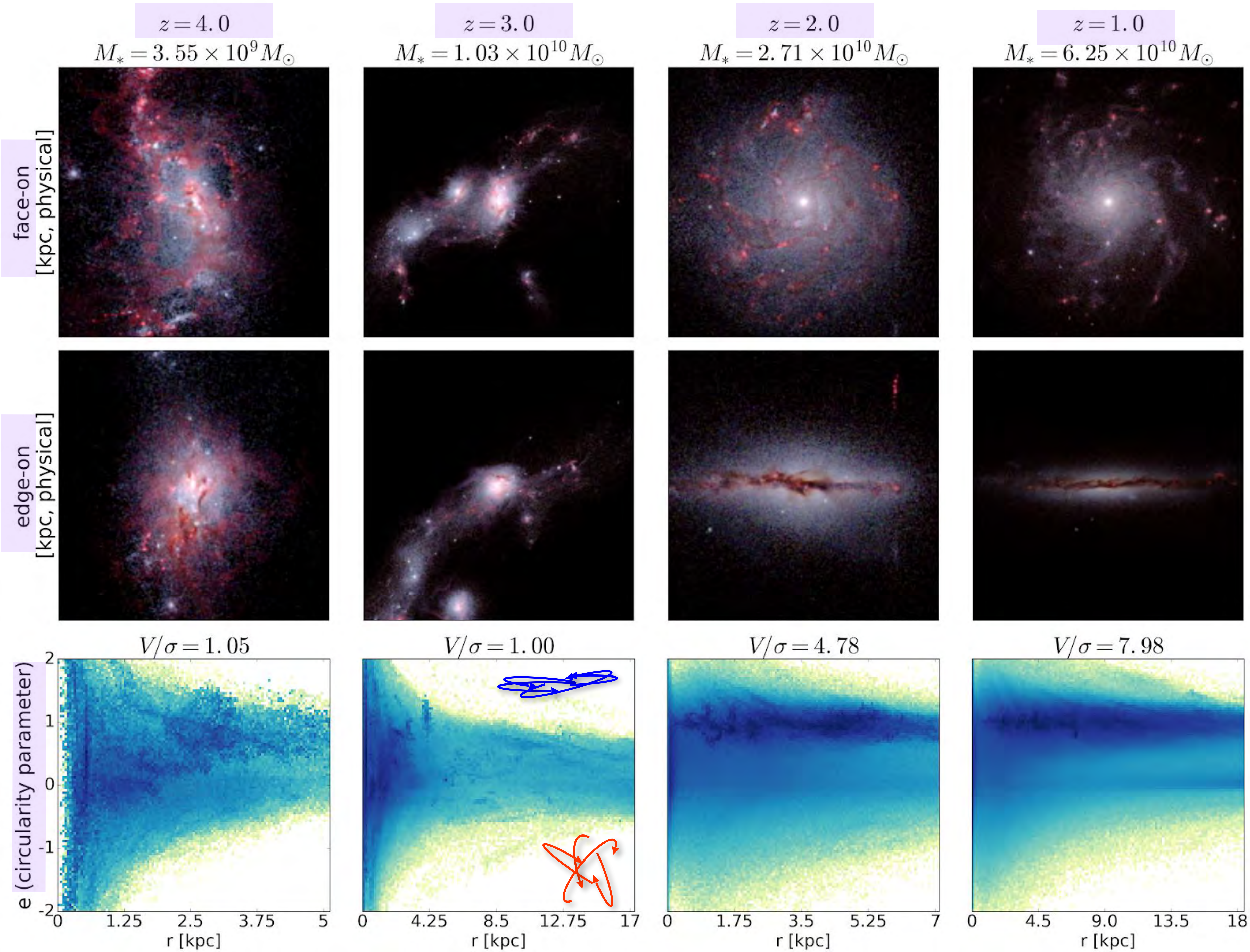
An illustration of emergence

The New Horizon simulation

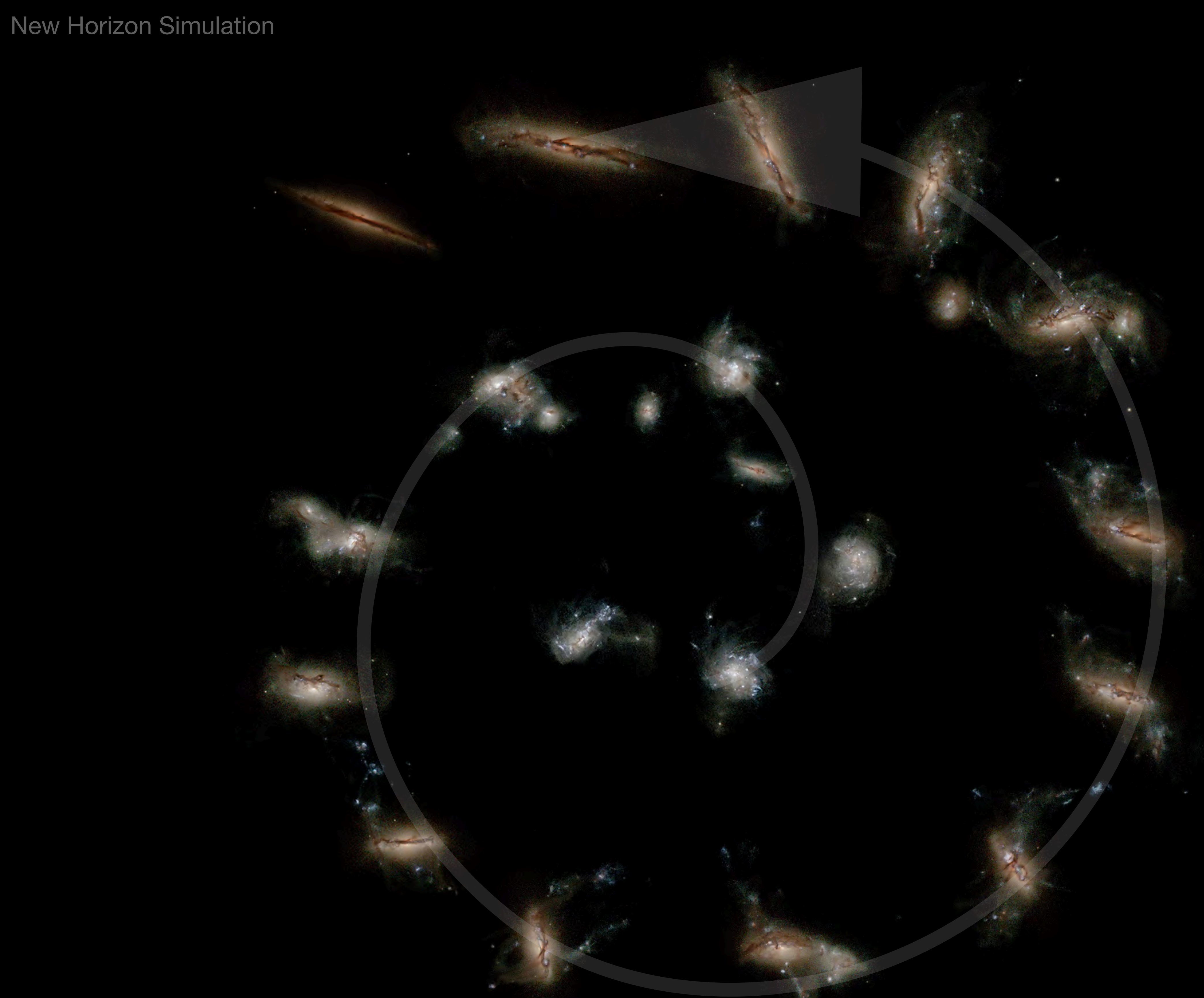


New Horizon Simulation

Disc settling: numerical evidence



Disc settling: timeline of a thin galactic disc

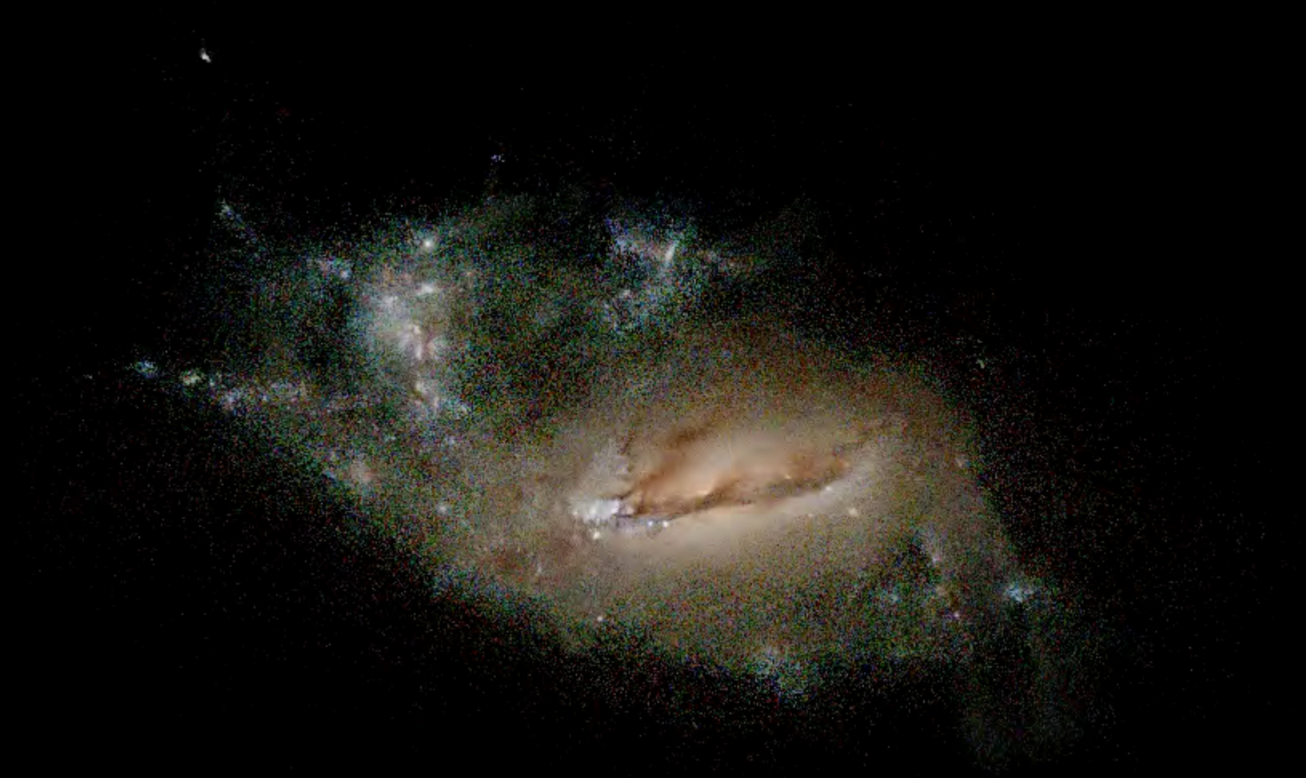


Thin discs in cosmological simulations operate as though they are isolated: this needs explaining.

Synopsis of thin disc emergence

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

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



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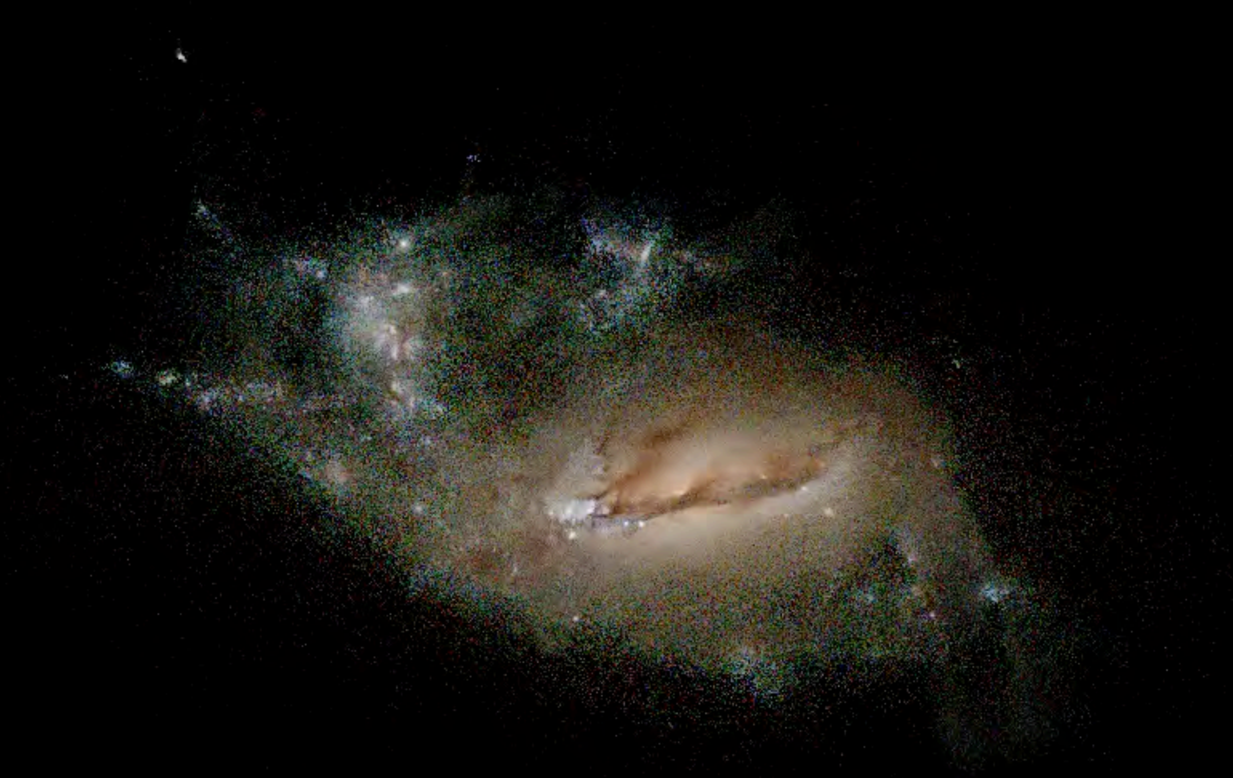


New Horizon

Various processes in the intra galactic medium

Destabilising effects

- supernovae
- Turbulence

————

- Minor merger
- accretion
- flybys

Stabilising effects

- Stellar formation
- Cooling
- Shocks

—————

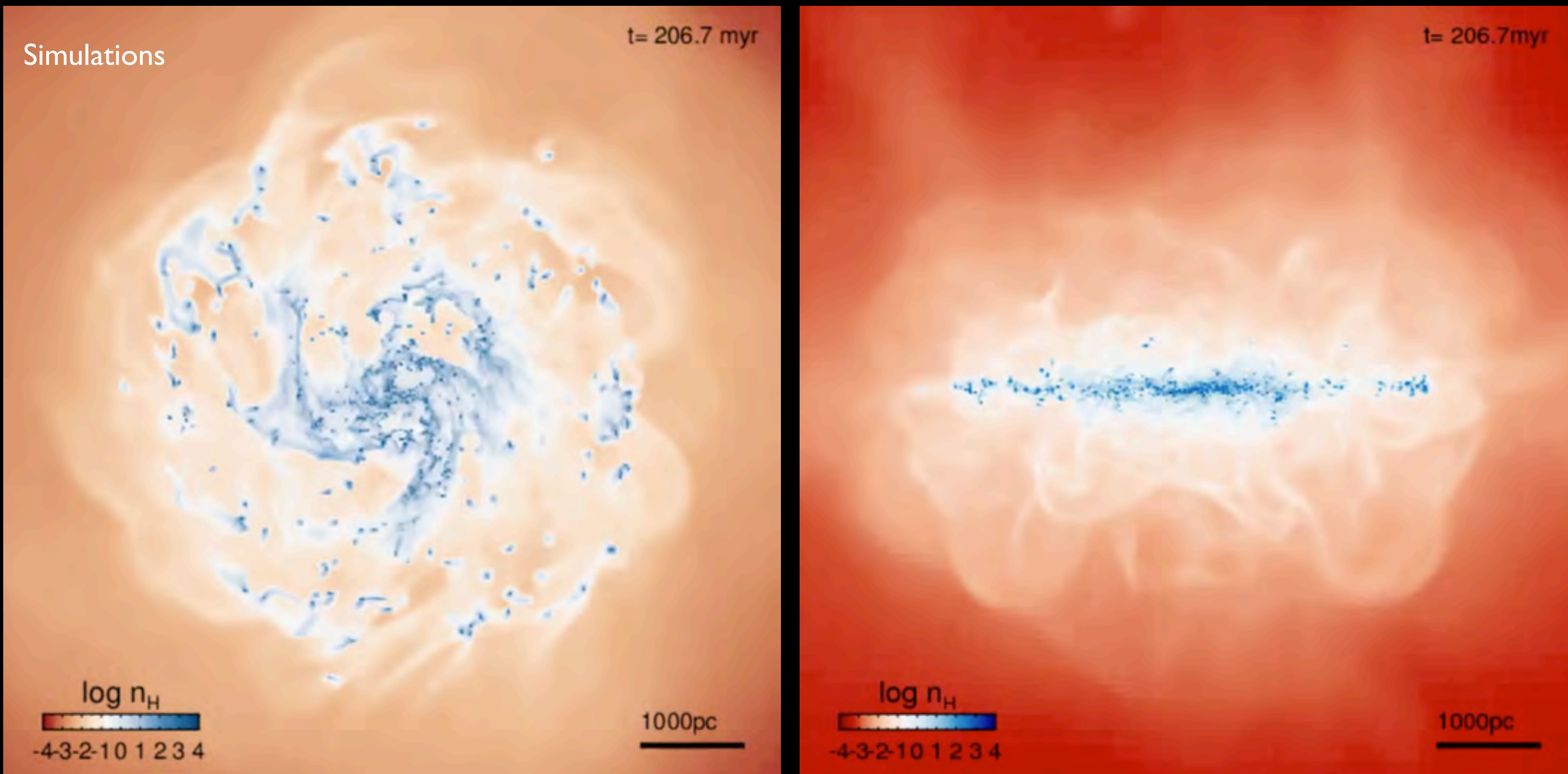
- aligned accretion

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



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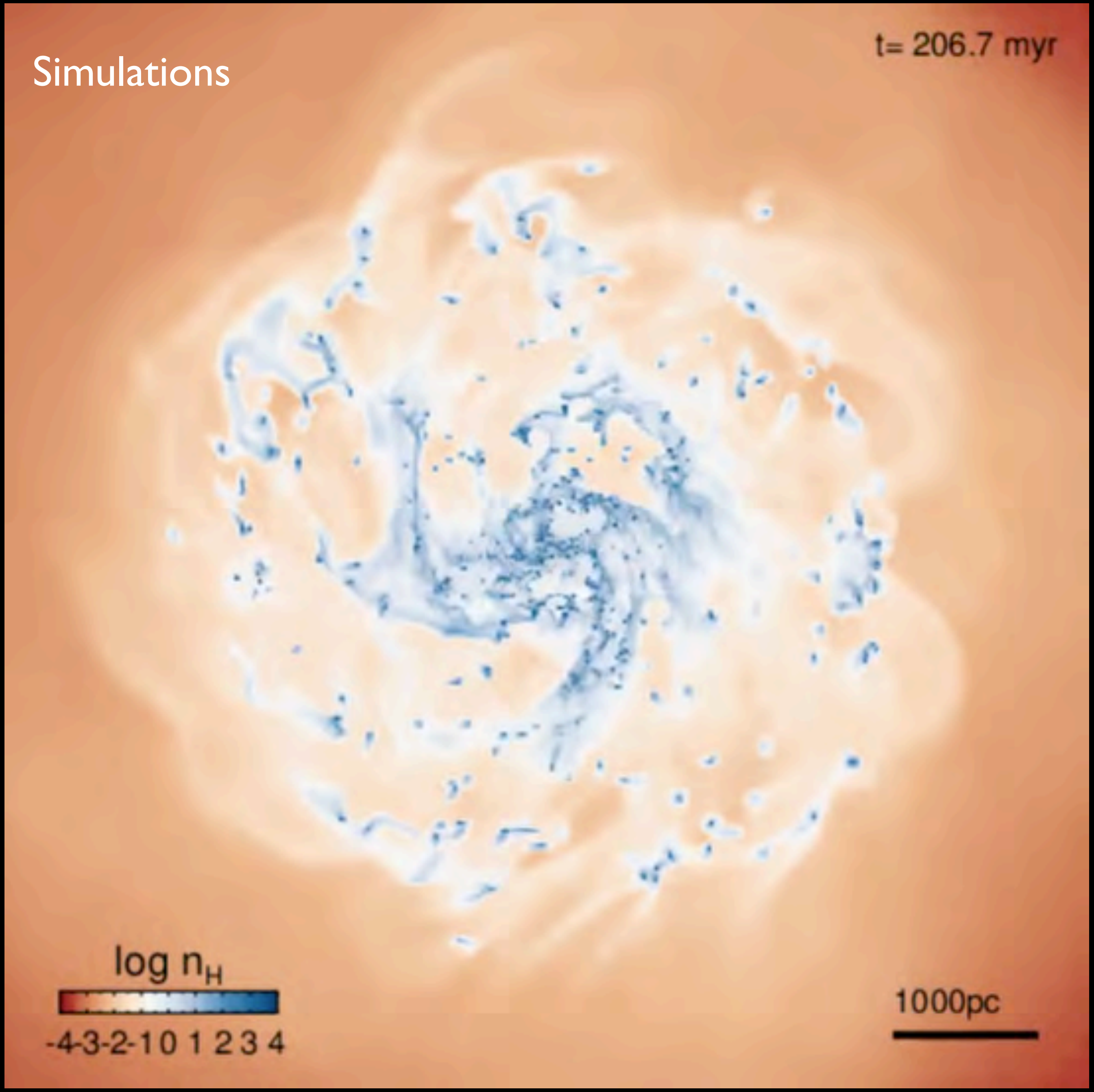
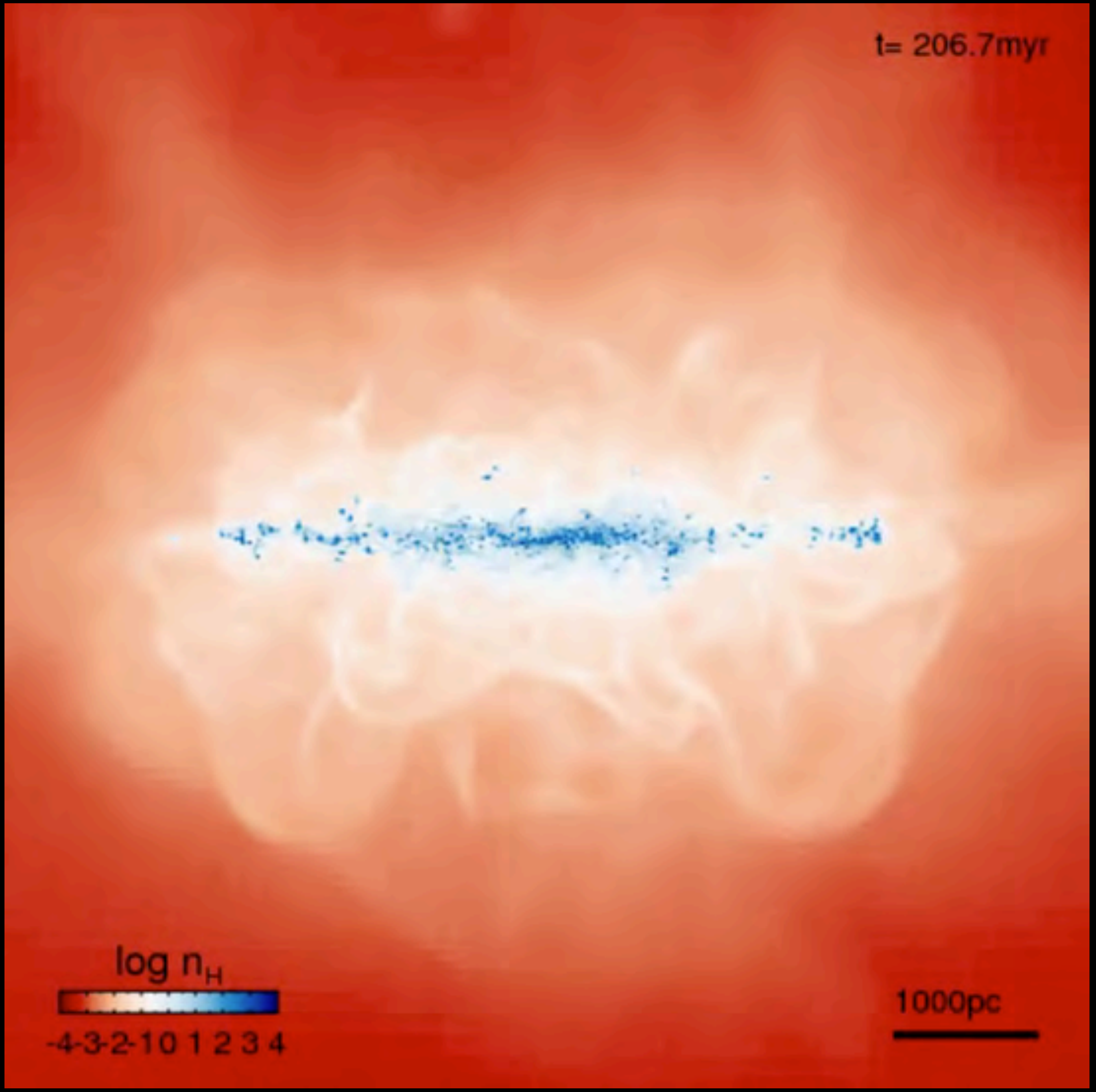
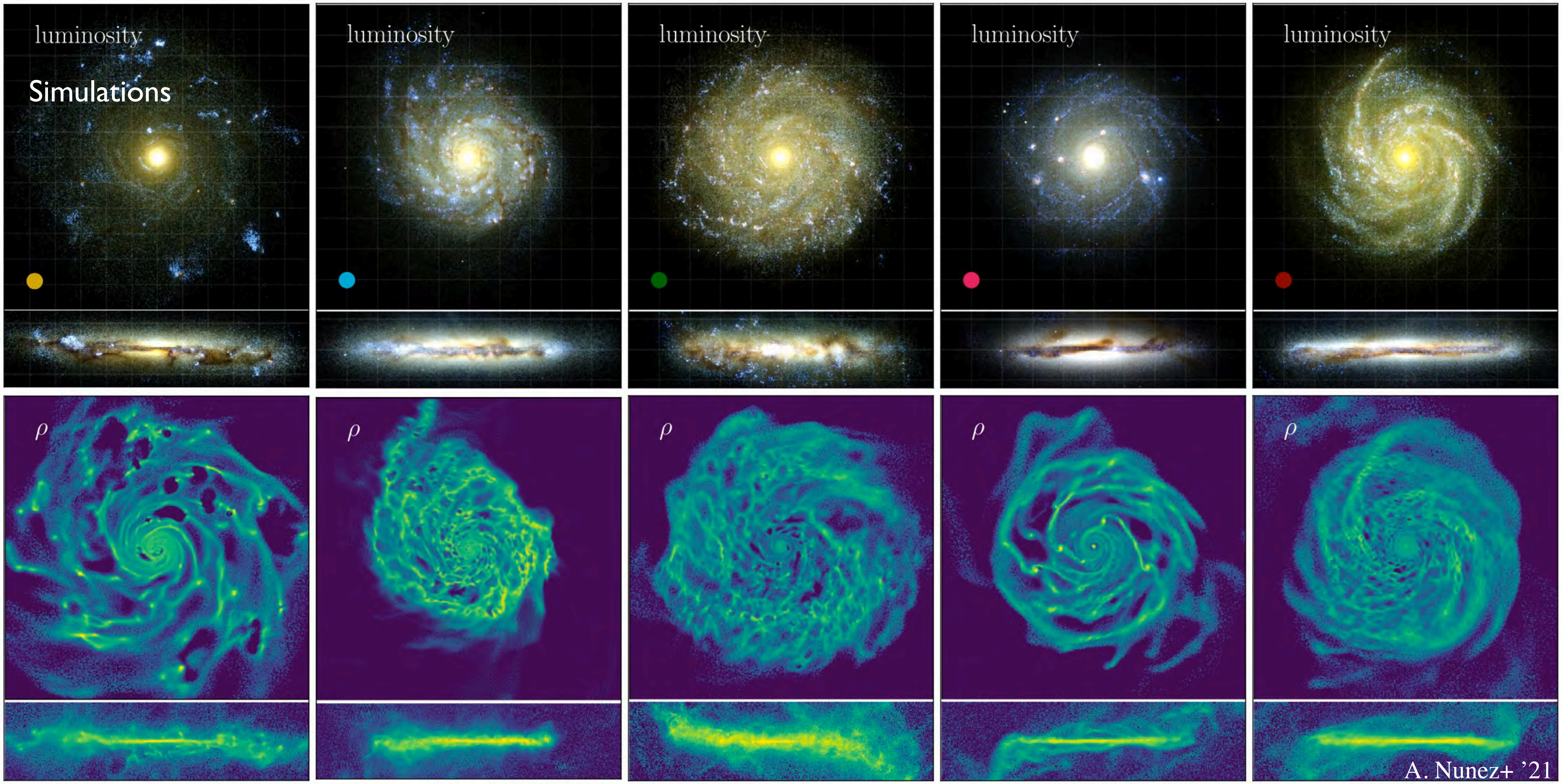




(c)Taysun Kimm

Internal Structure of a simulated thin disc: varying feedback model

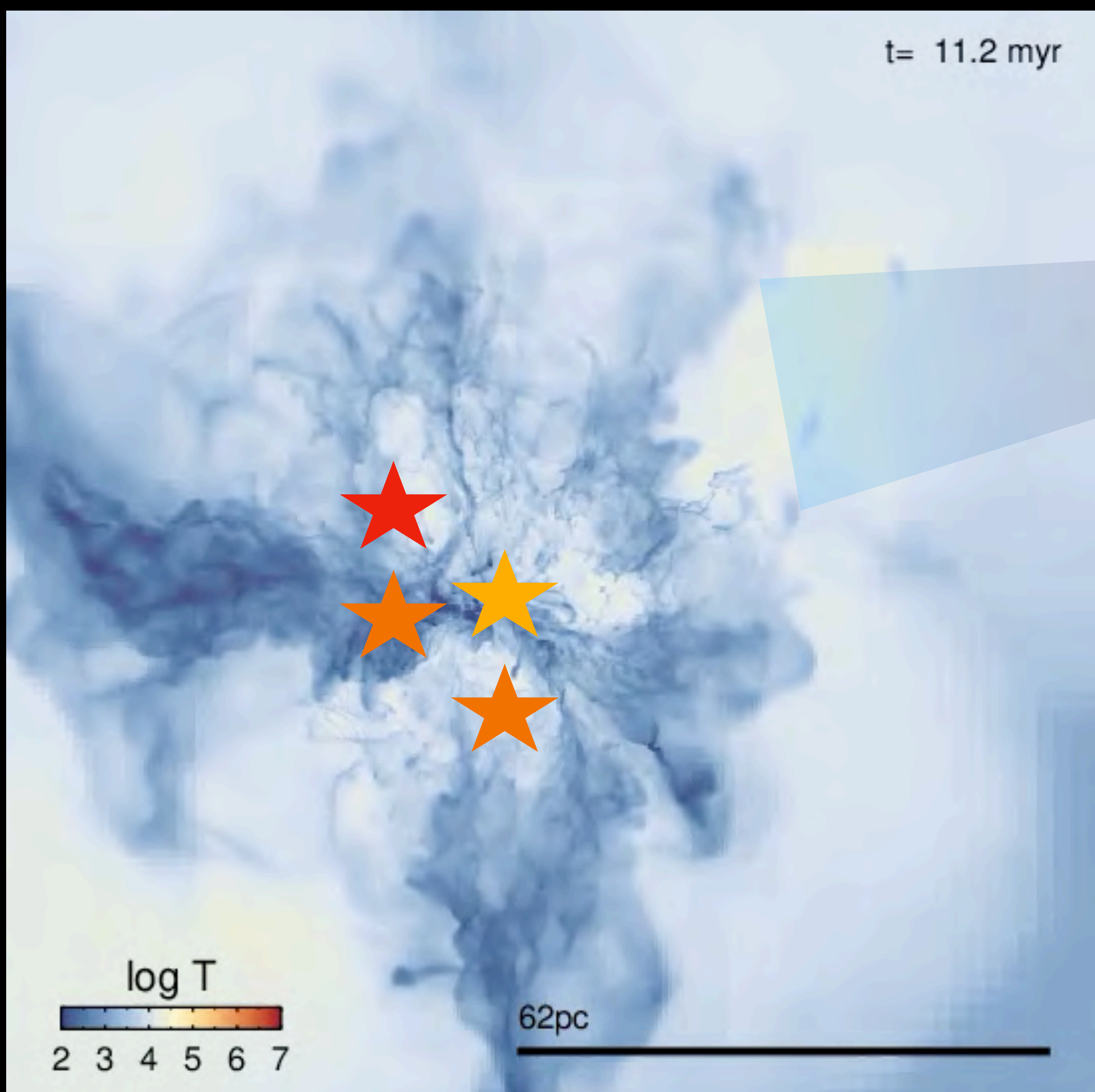


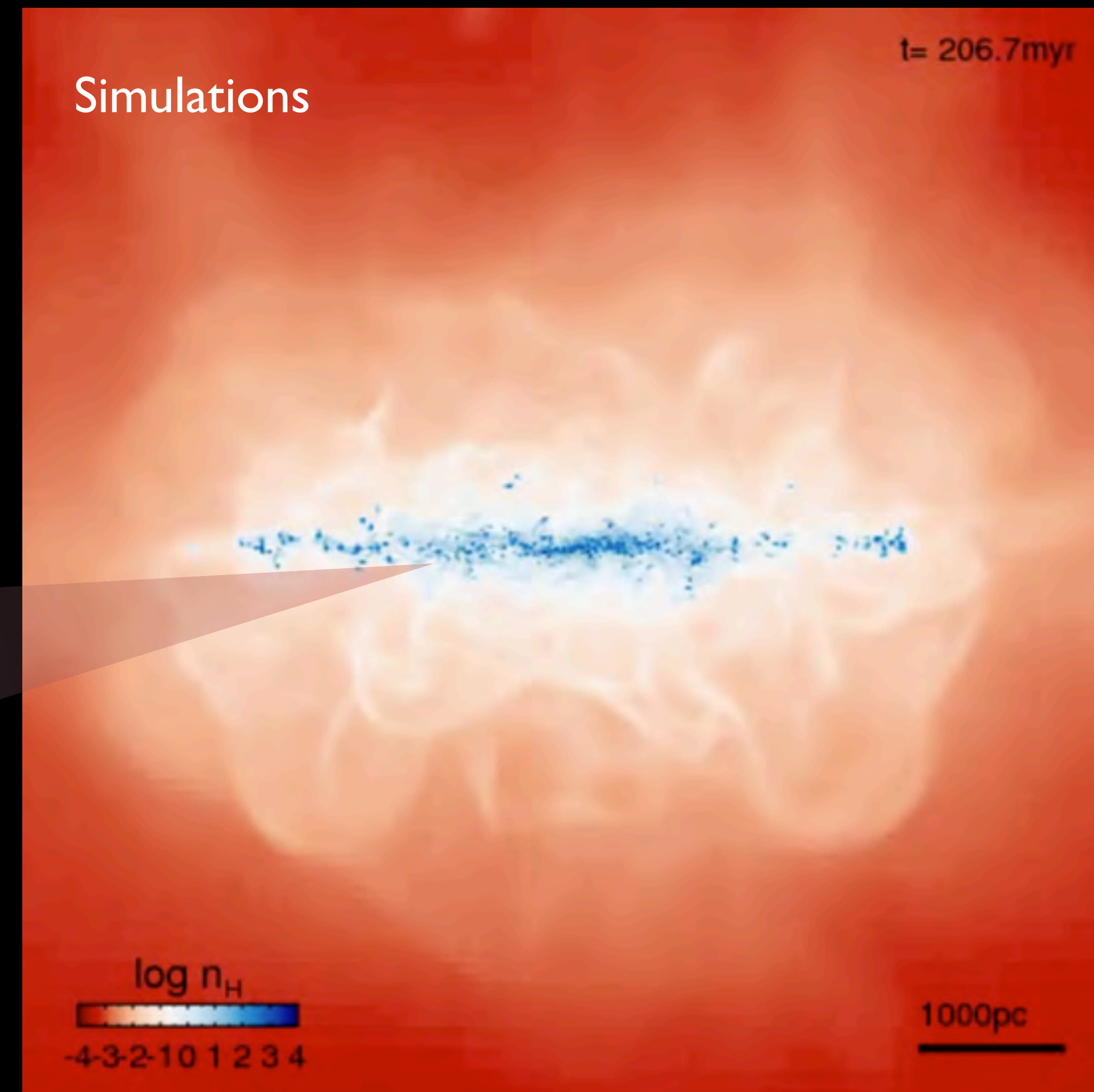
Note that the exact model of feedback impacts face one view BUTdoes not impact disc thickness.

No fine tuning required: something more fundamental operates

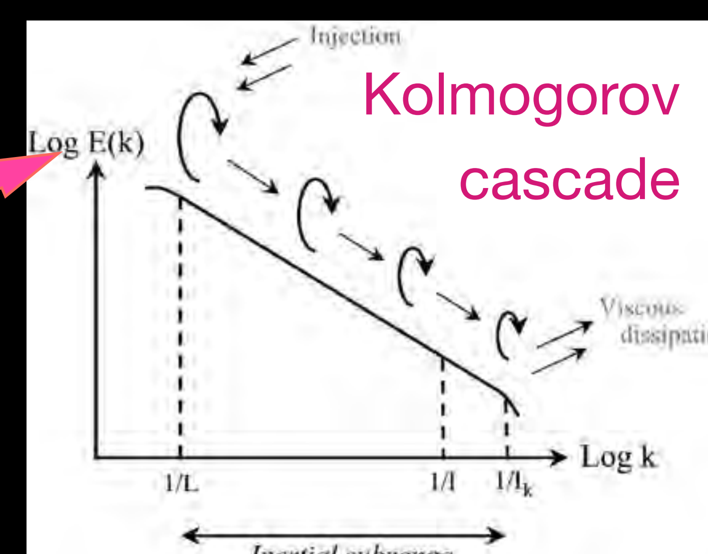
Internal Structure @ small scales

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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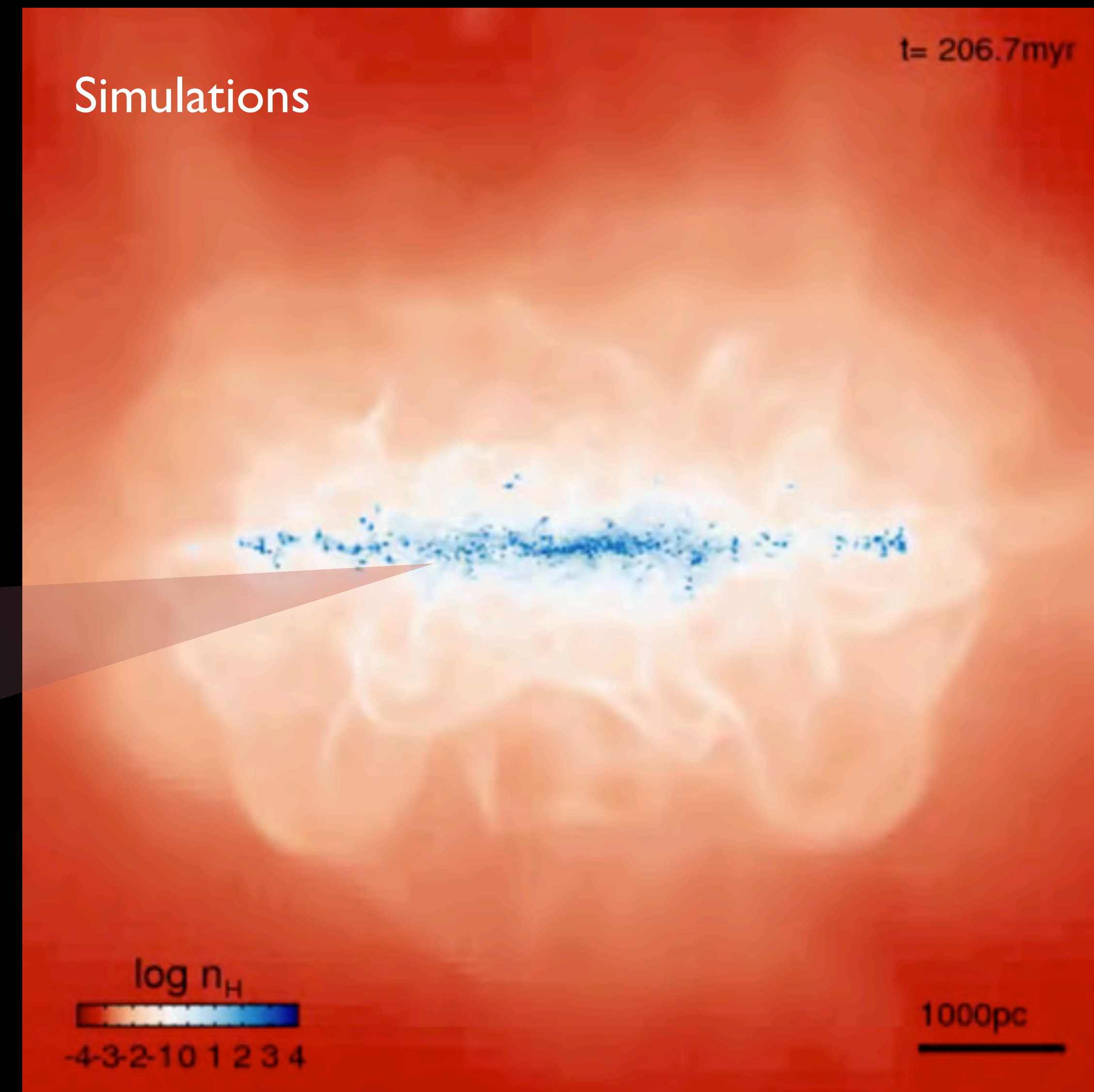

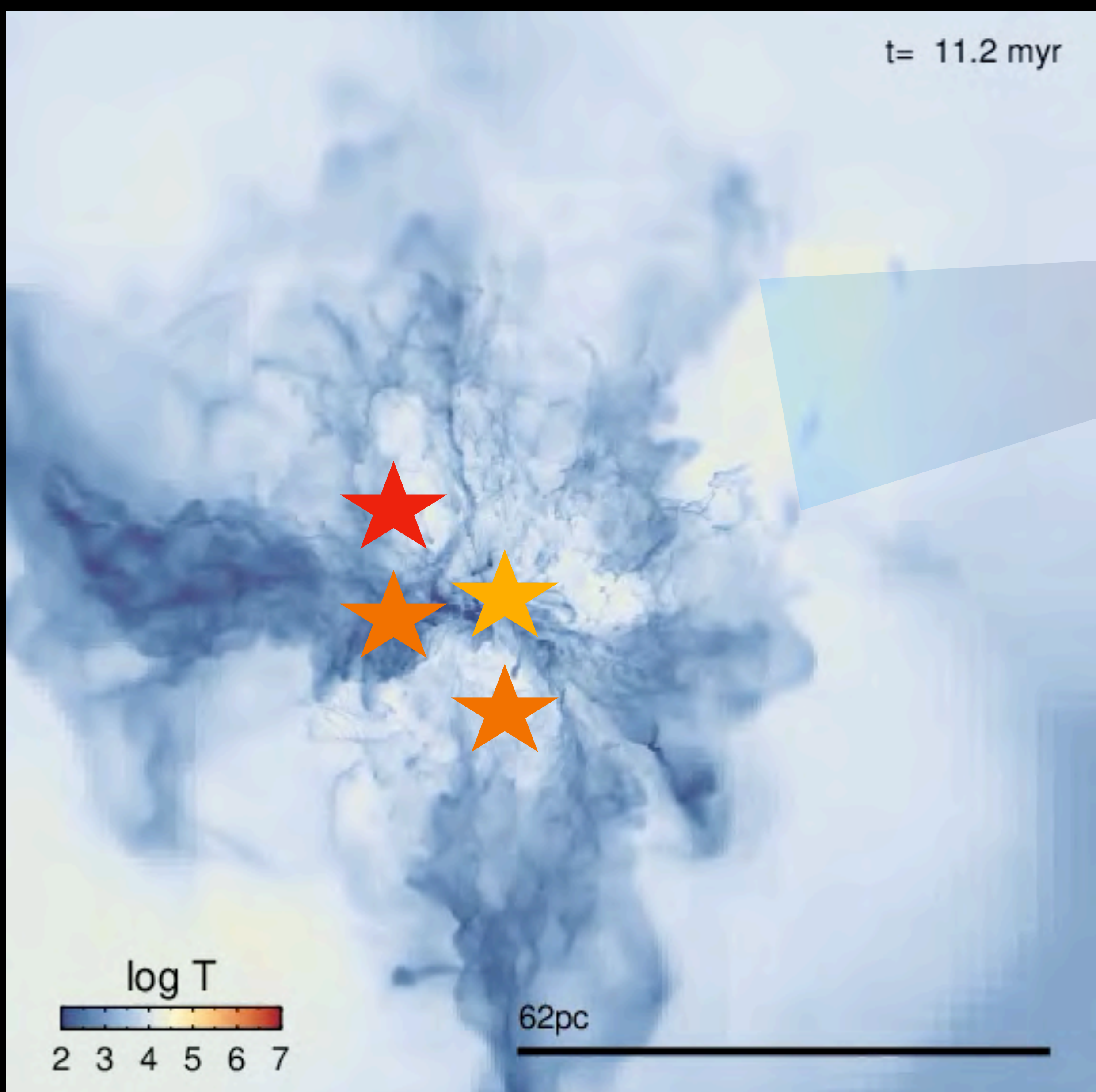

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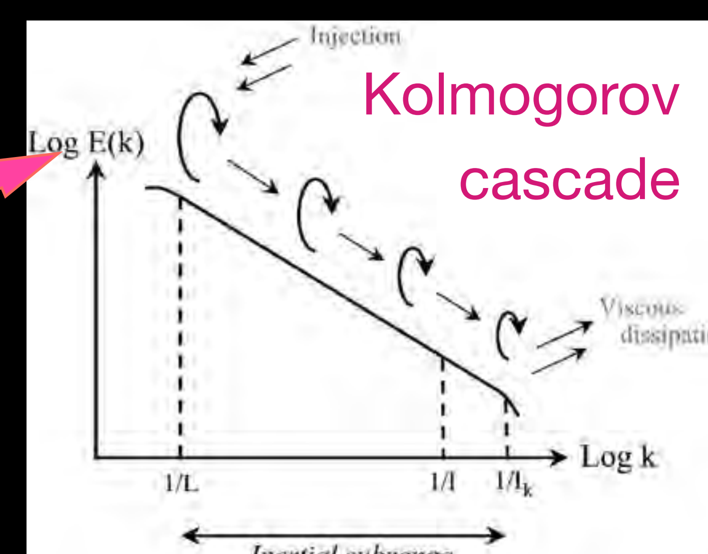

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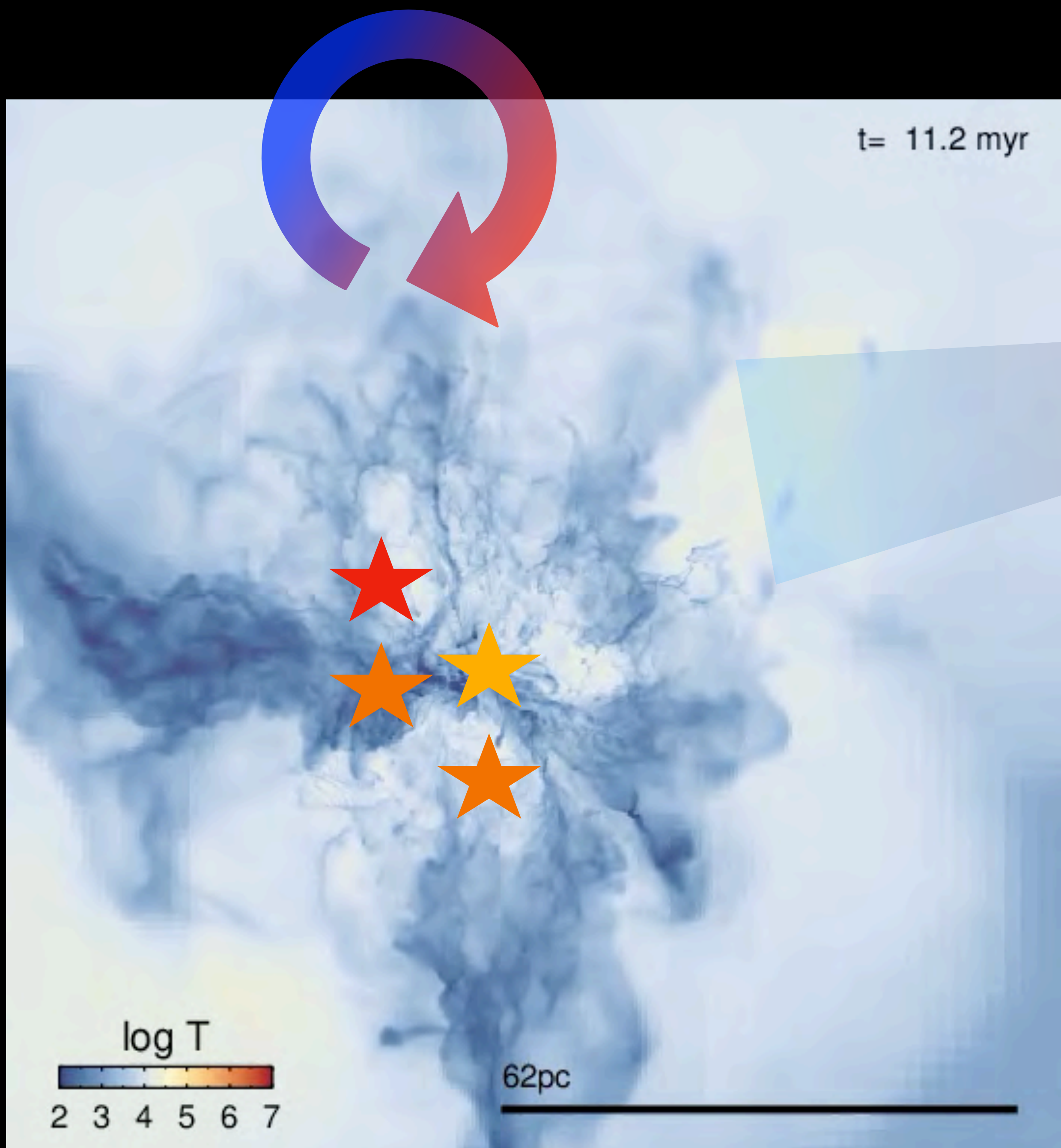

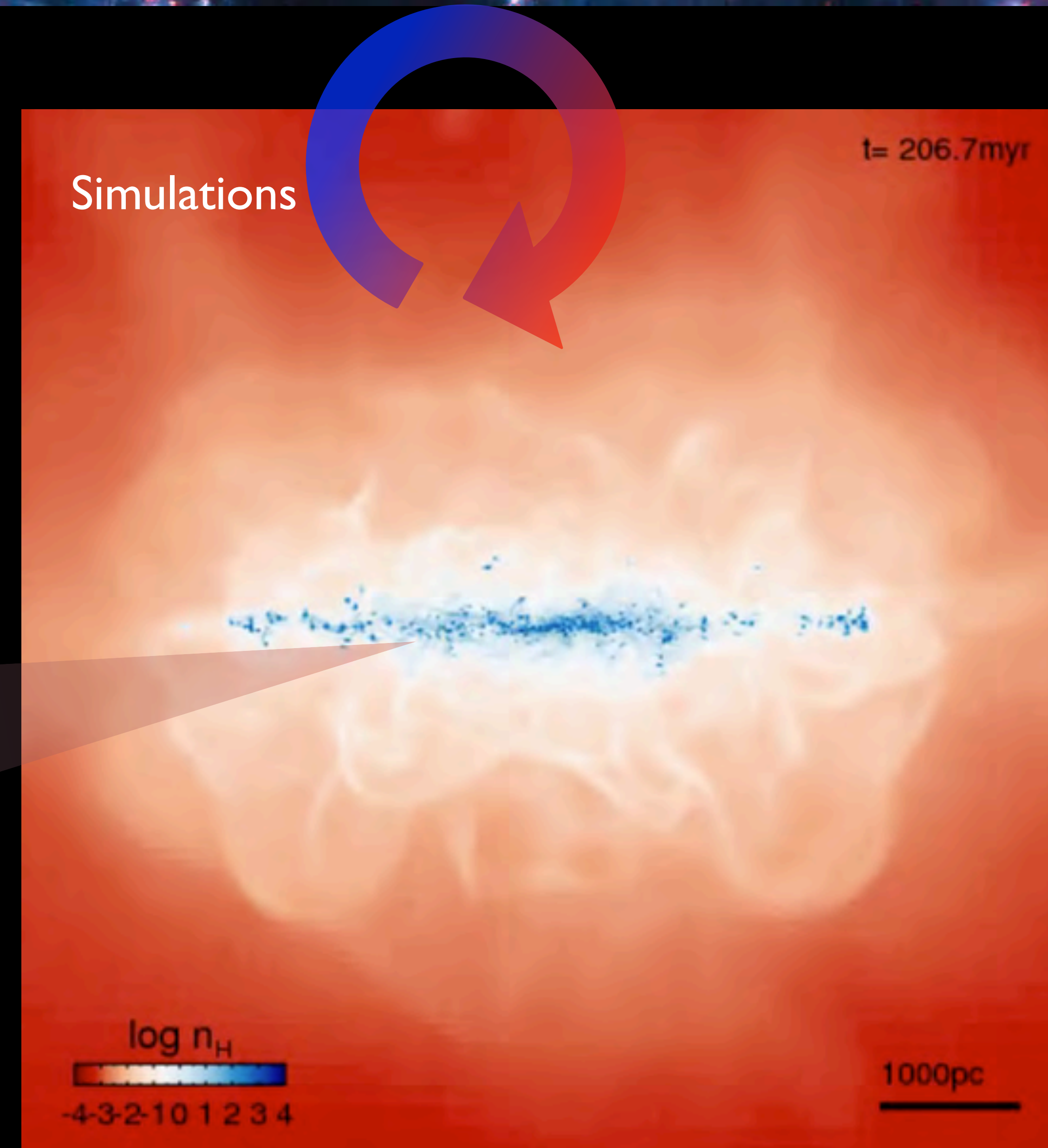

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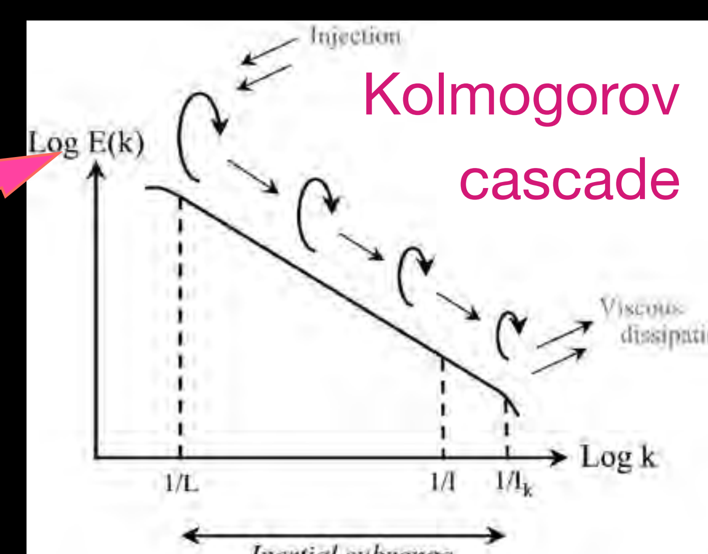
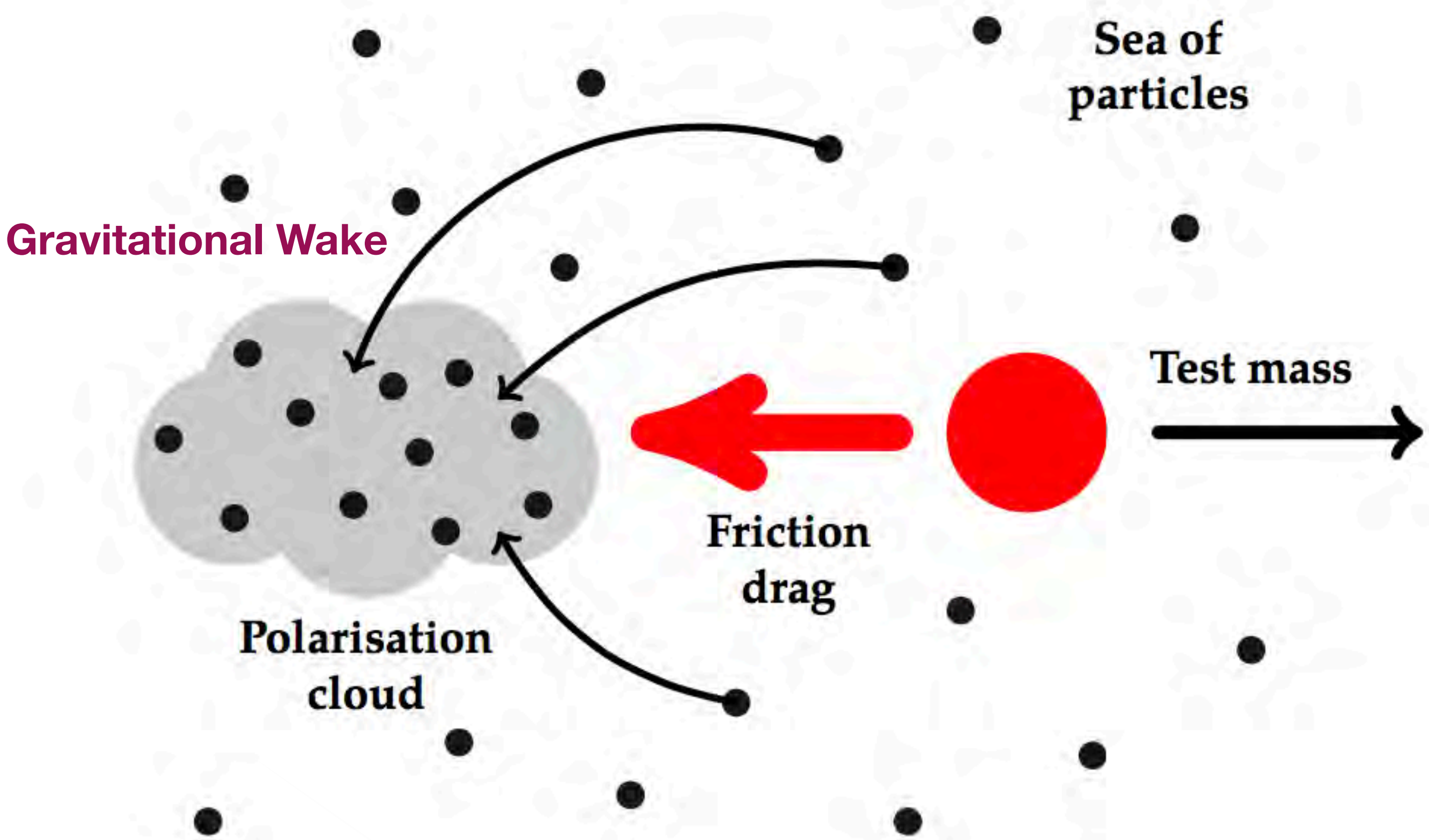
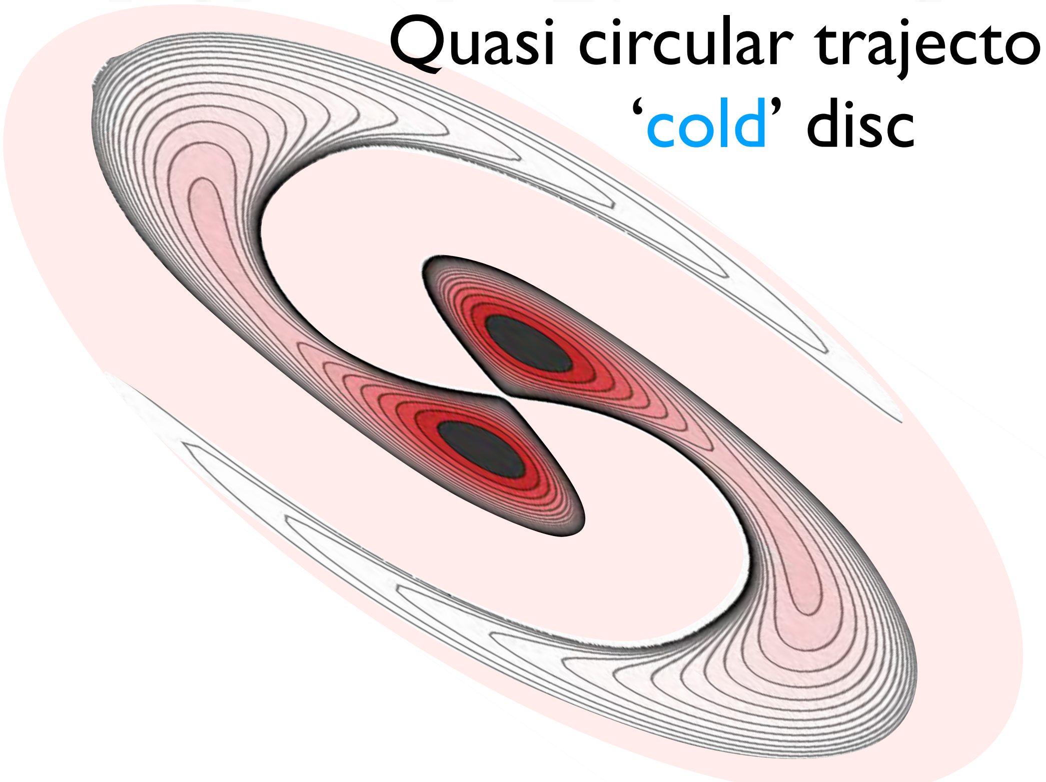


Quid of the effect of wakes on injection scale?

Chandrasekhar polarisation



Quasi circular trajectories:
'cold' disc



→ No significant relative motion
to oppose gravitation

Gravitational wake/polarisation/dressing

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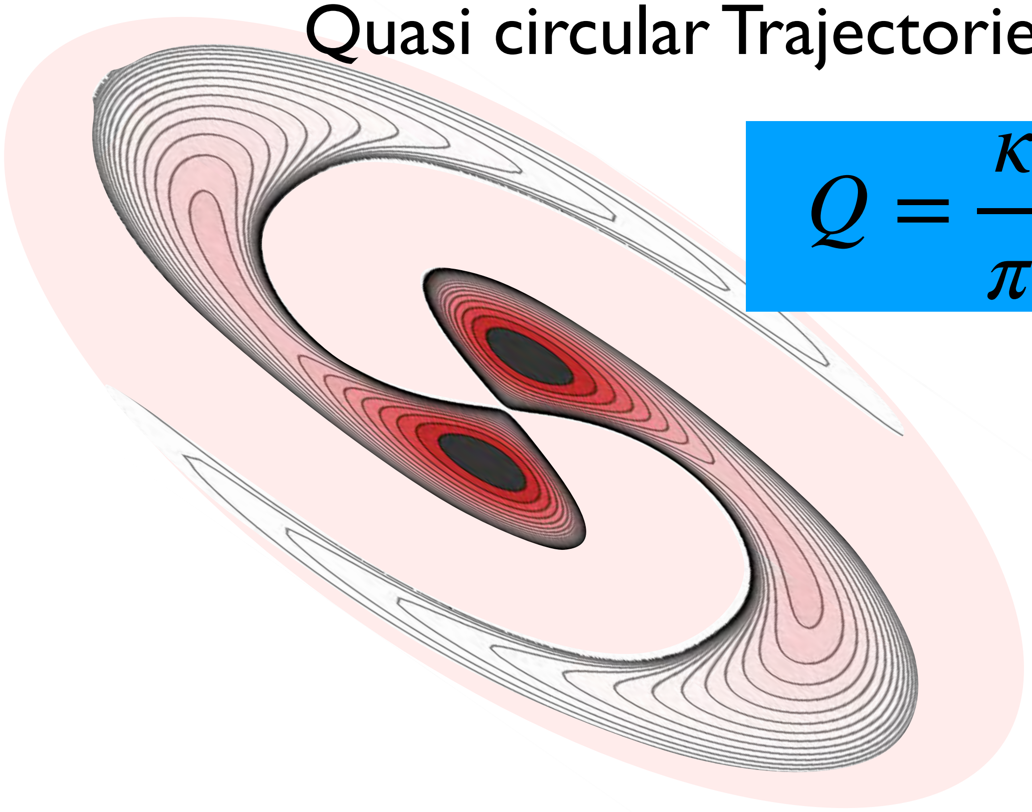
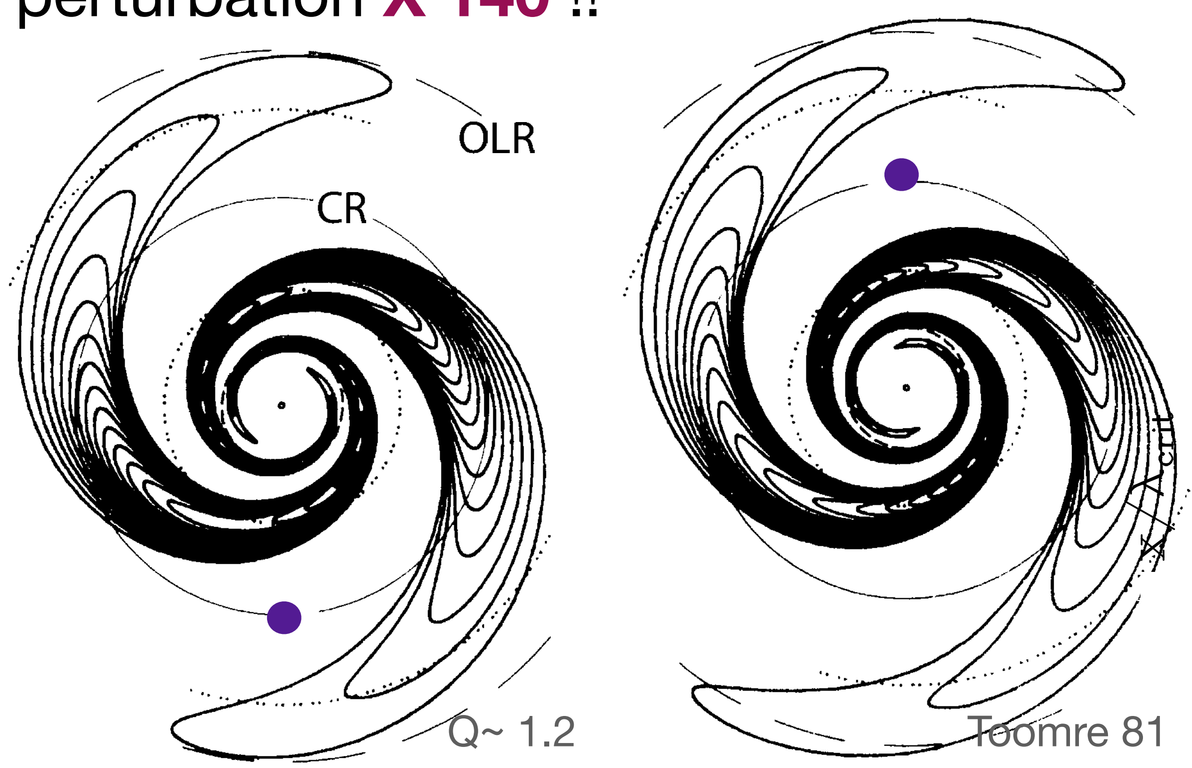
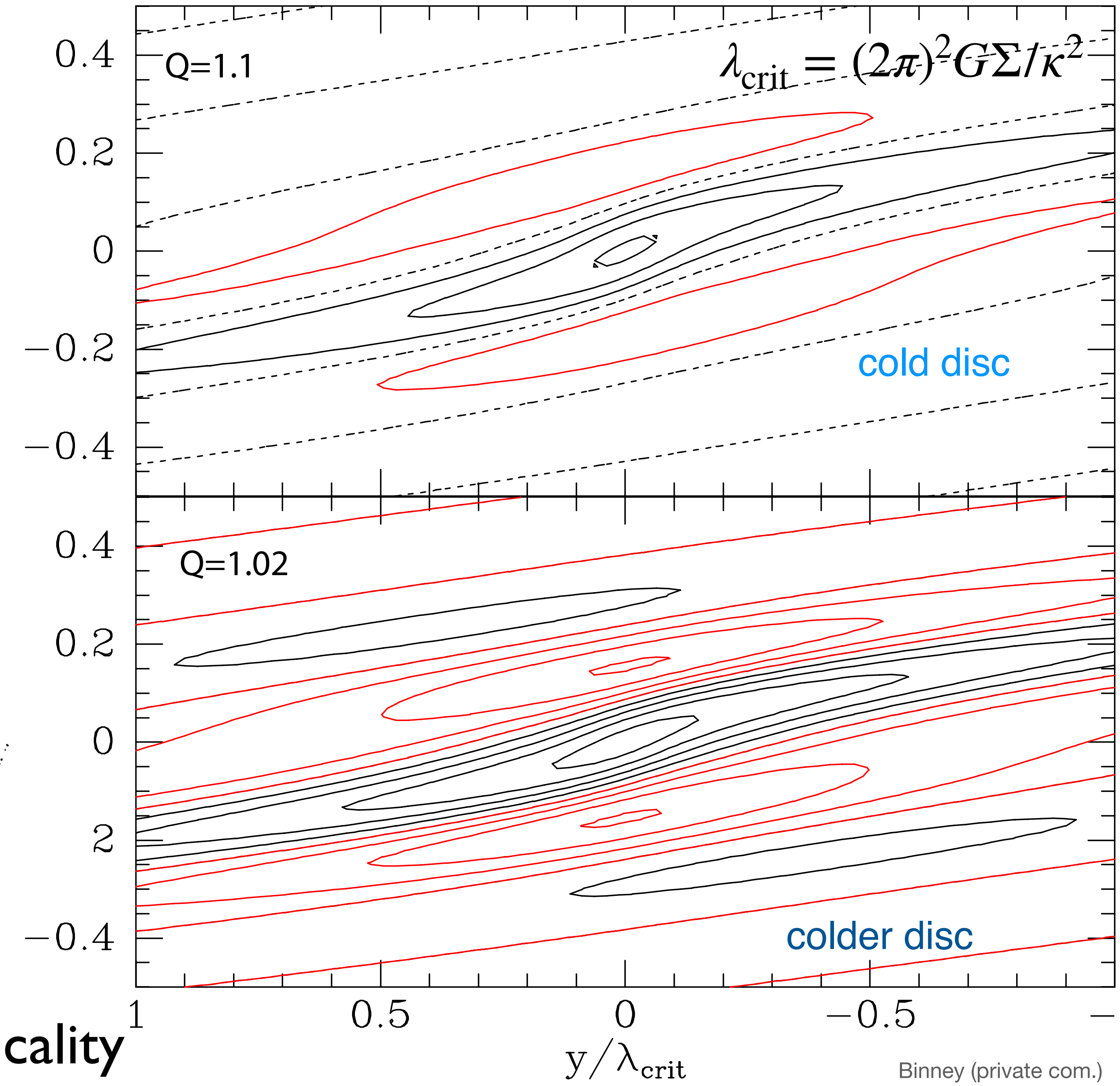


$$Q = \frac{\kappa\sigma}{\pi\Sigma} \to 1$$

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

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





Binney (private com.)

→ long range correlation: self organised criticality

On the importance of *gravitational* dressing

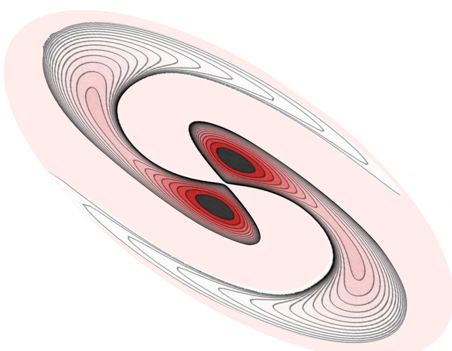
For cold discs…

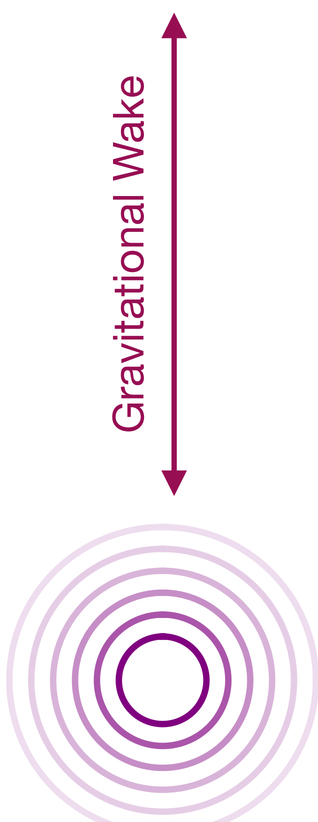
$$Q = \frac{\kappa \sigma}{\pi \Sigma} \to 1$$

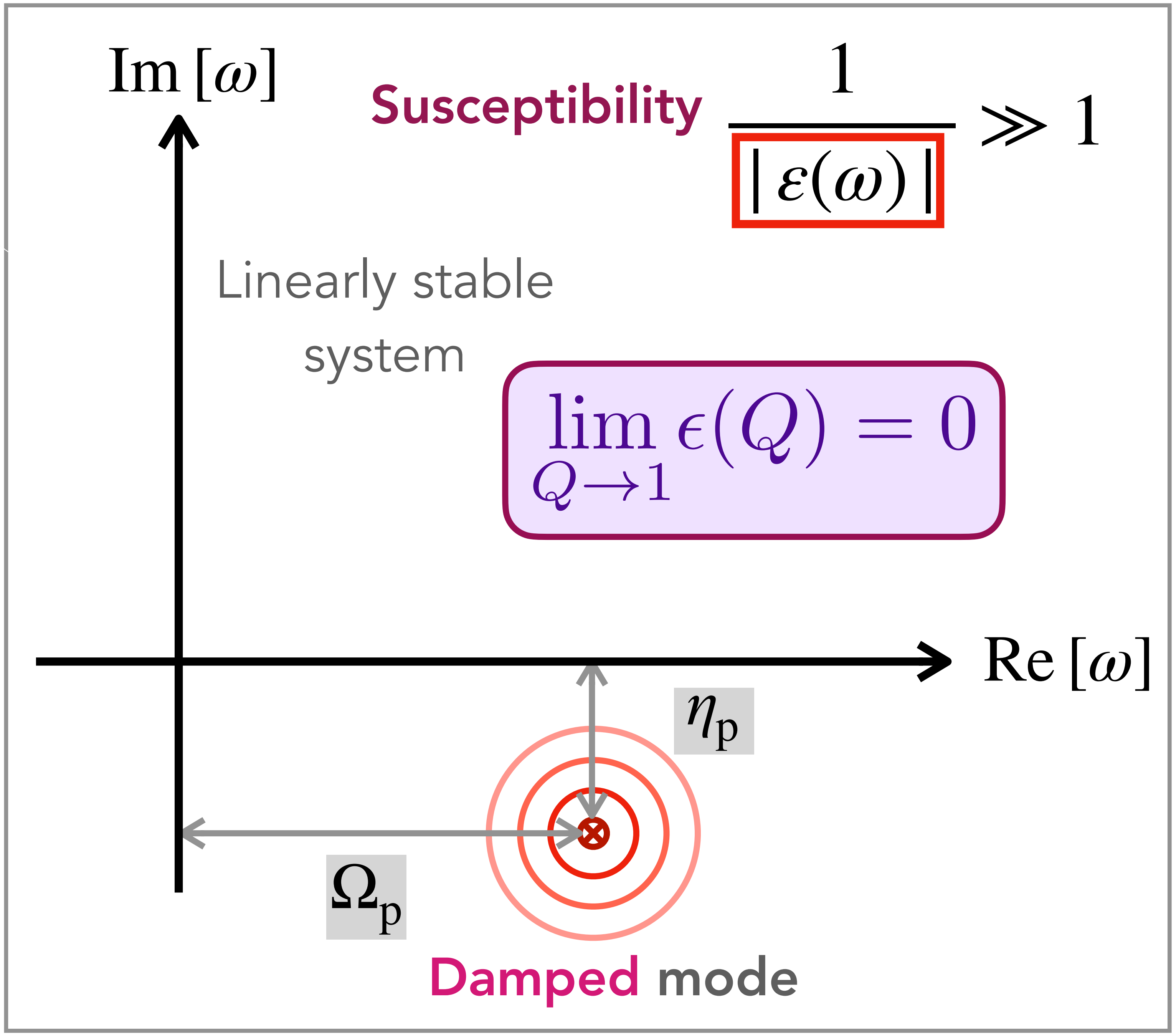
Gravitational "*Dielectric*" function ϵ

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

Dispersion relation | Response matrix







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

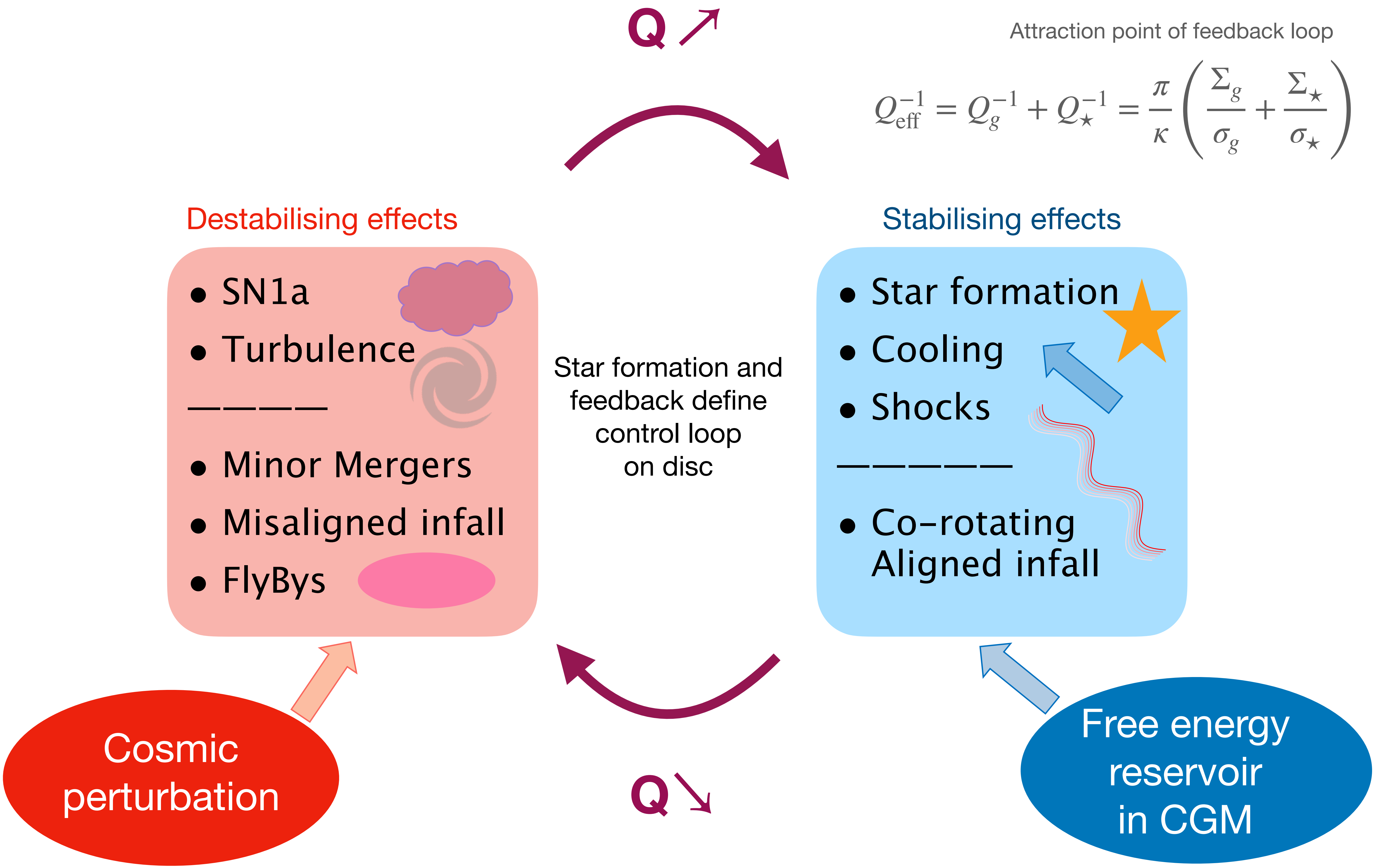
$$T_{\mathrm{dressed}} \simeq |\varepsilon| \, T_{\mathrm{bare}}$$

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

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

Self regulating loop boosted by wake

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



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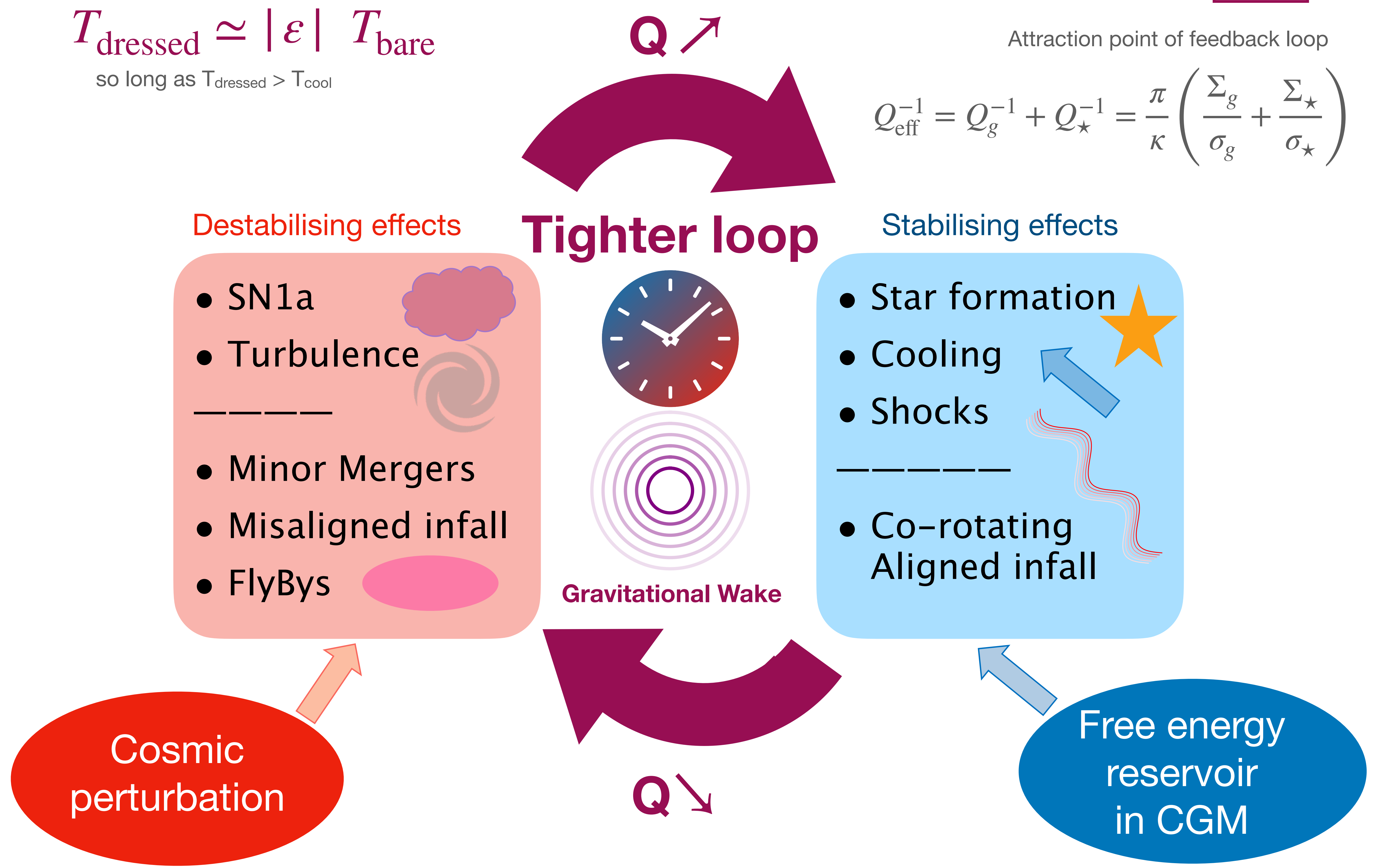
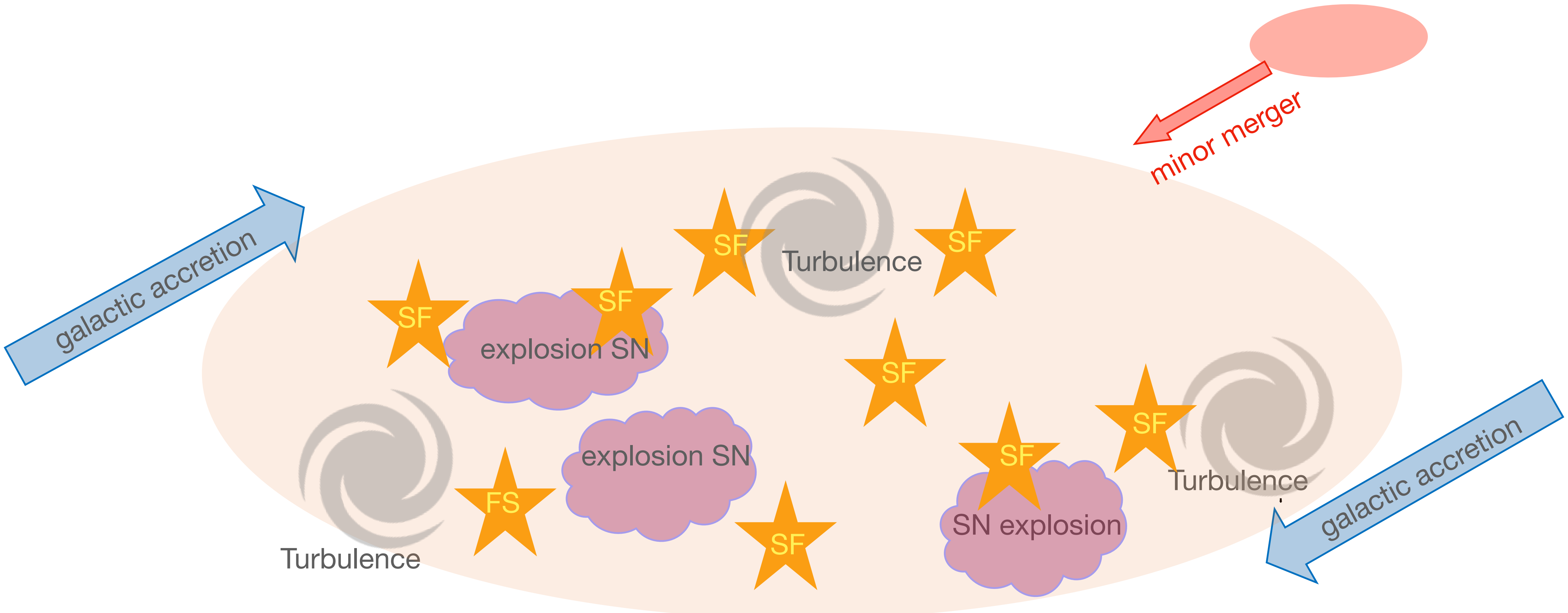


Open system with control loop generates complexity through self-organisation


minor merger
galactic accretion
galactic accretion
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Turbulence
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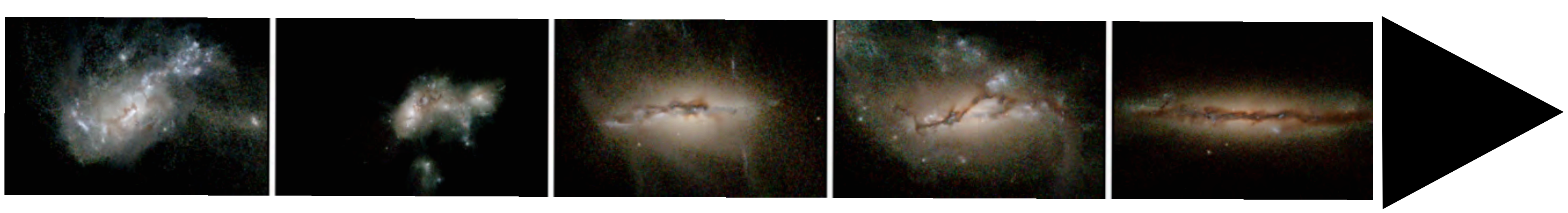
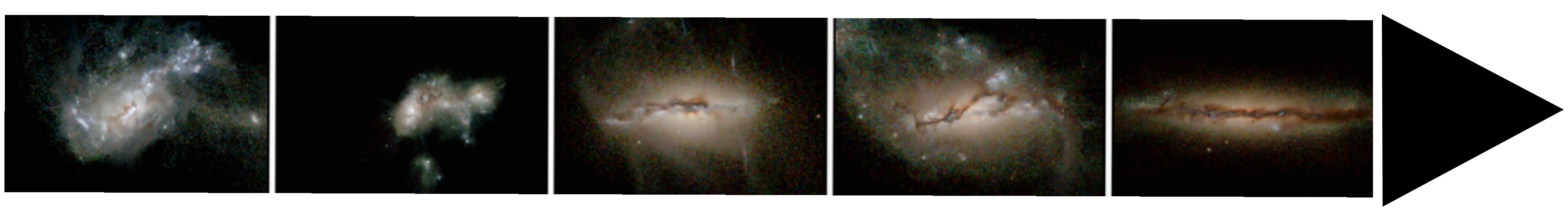
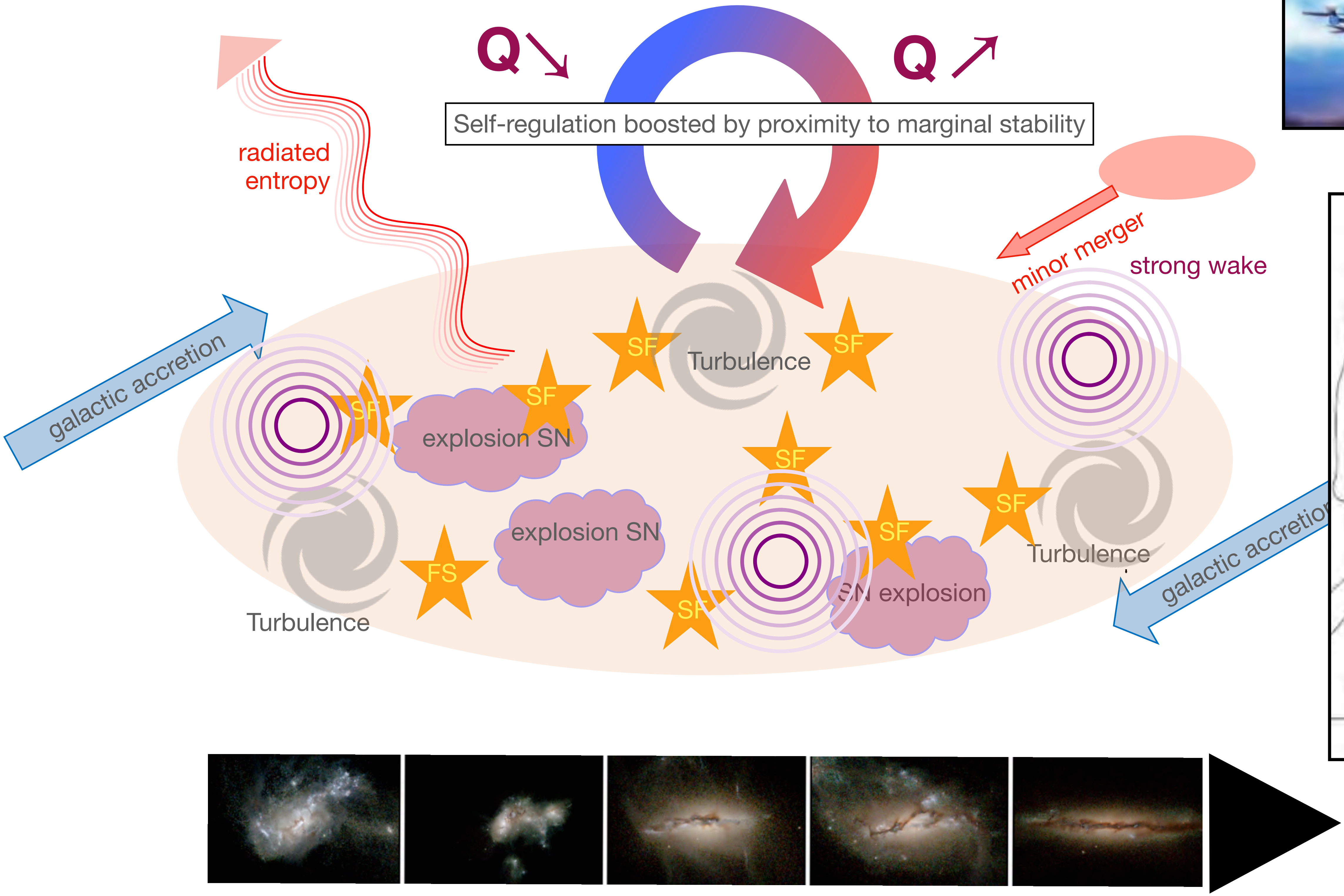
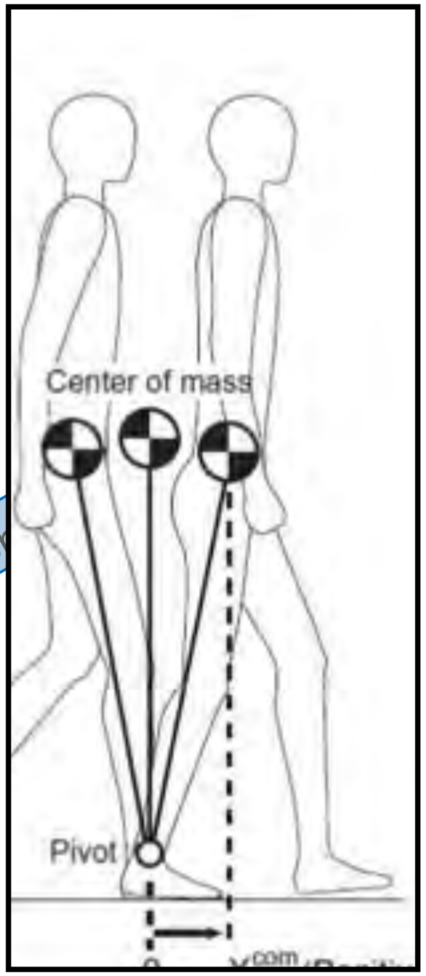




Wake drastically boost orbital frequencies,
tightening control loops

Bring home message: dressing redefine clocks



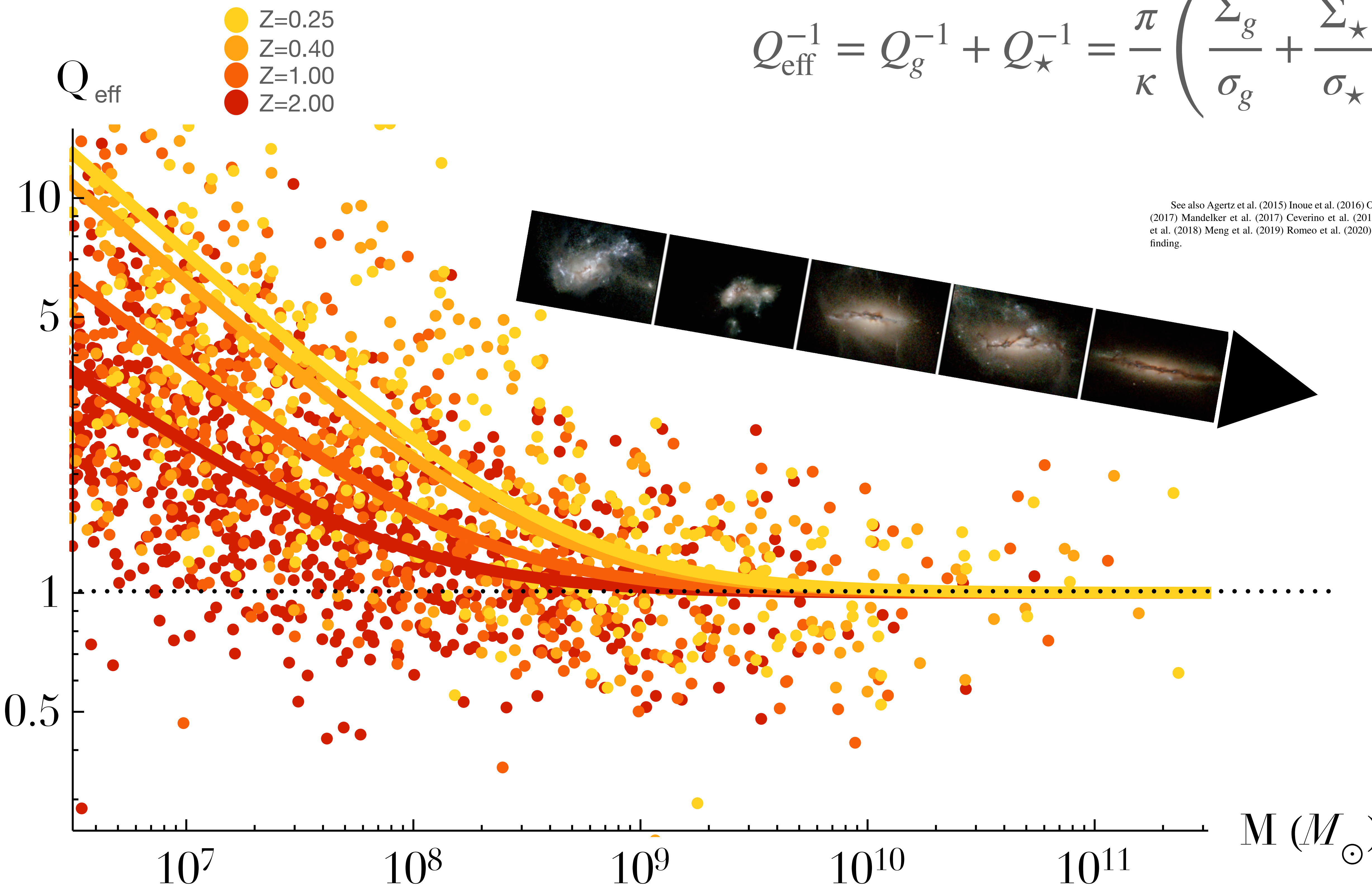


Wake drastically boost orbital frequencies,
tightening control loops

Toomre Q convergence with mass and z

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

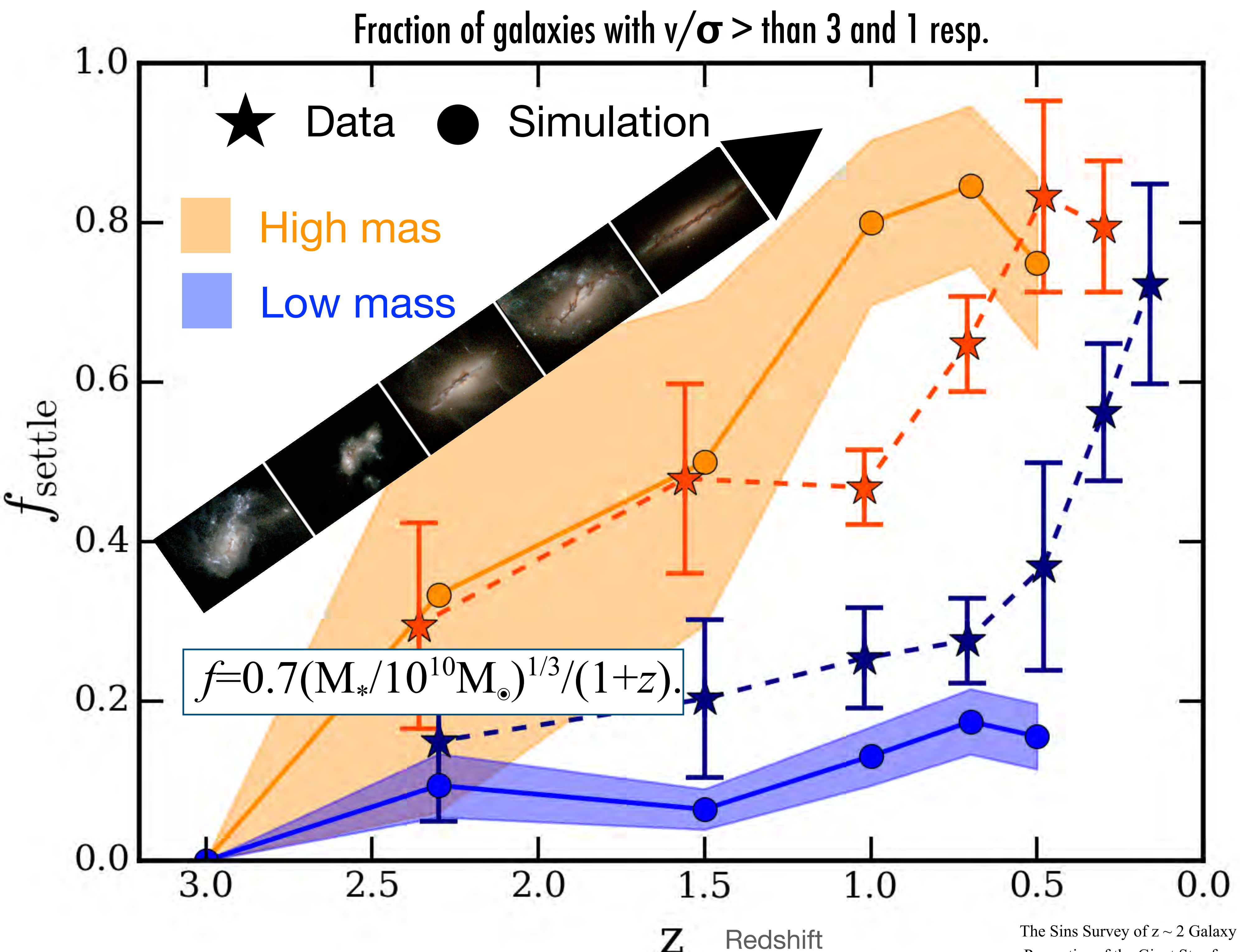
$$Q_{\rm eff}^{-1} = Q_g^{-1} + Q_\star^{-1} = \frac{\pi}{\kappa}\left(\frac{\Sigma_g}{\sigma_g} + \frac{\Sigma_\star}{\sigma_\star}\right)$$



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.

Disc settling : fraction of settled discs

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

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

x and y components of **angular momentum**

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

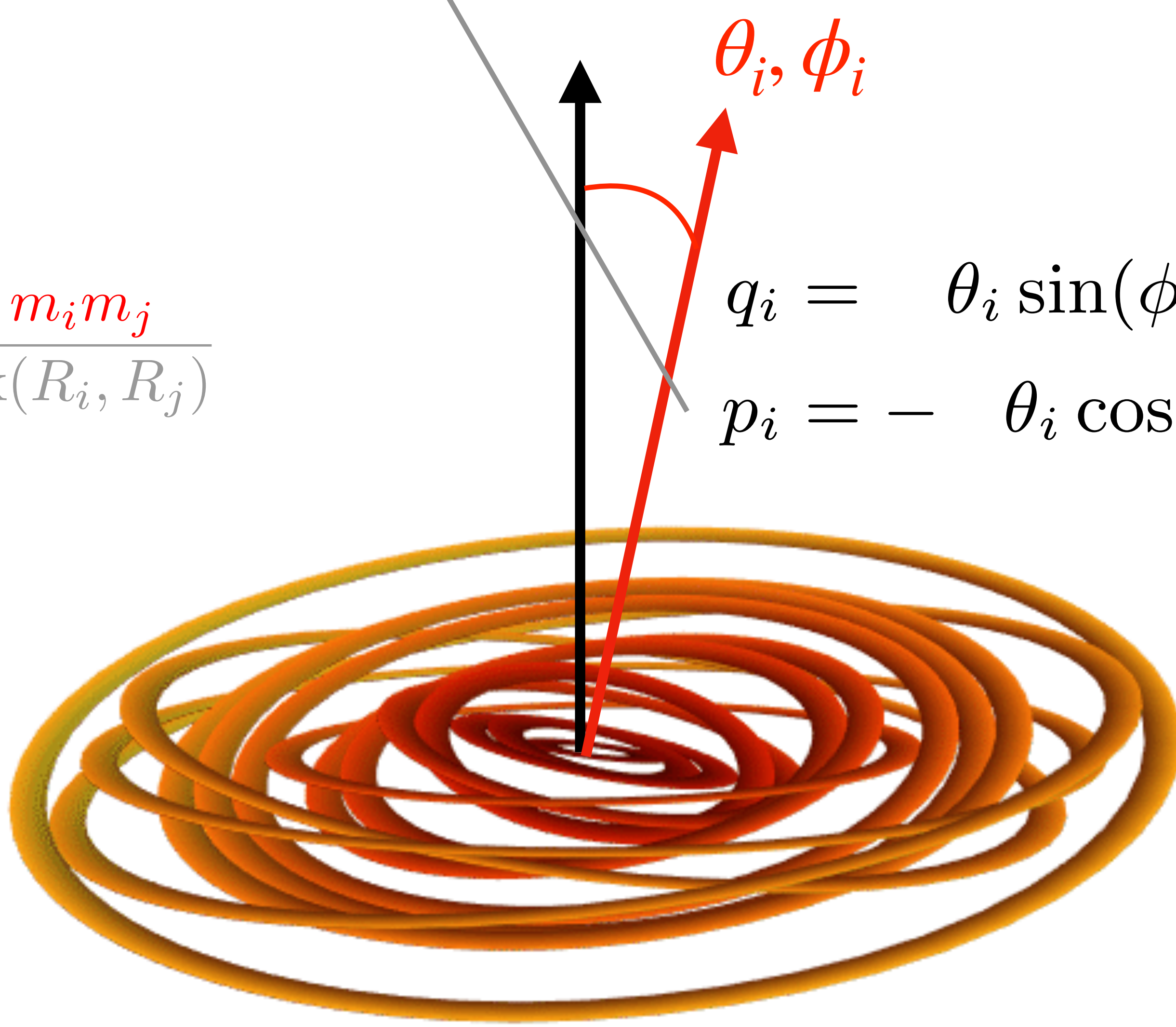
$$A_{ij} \propto -\frac{G\, m_i m_j}{\max(R_i, R_j)}$$

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

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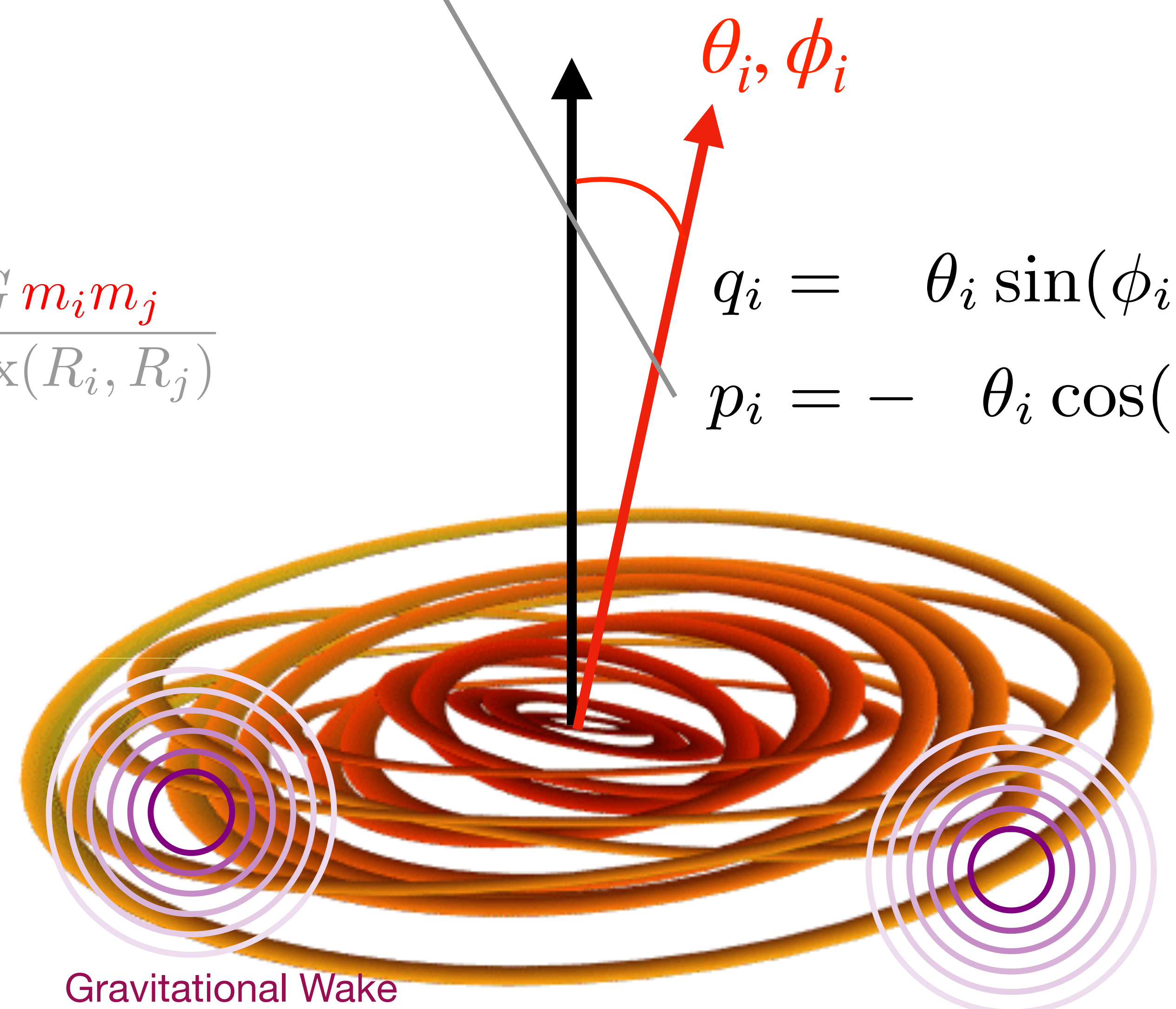
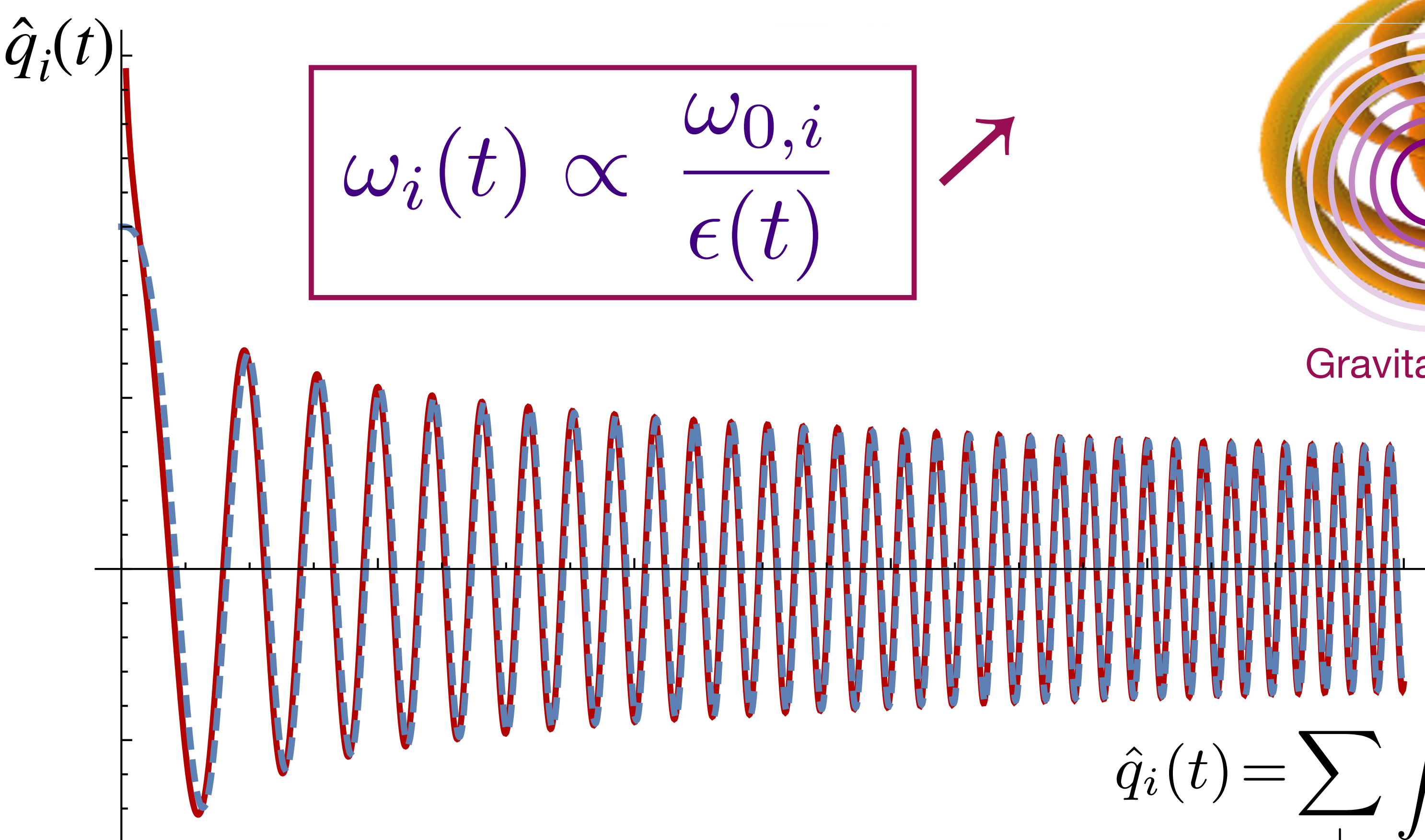


In eigenframe of A

Eigen frequency

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

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

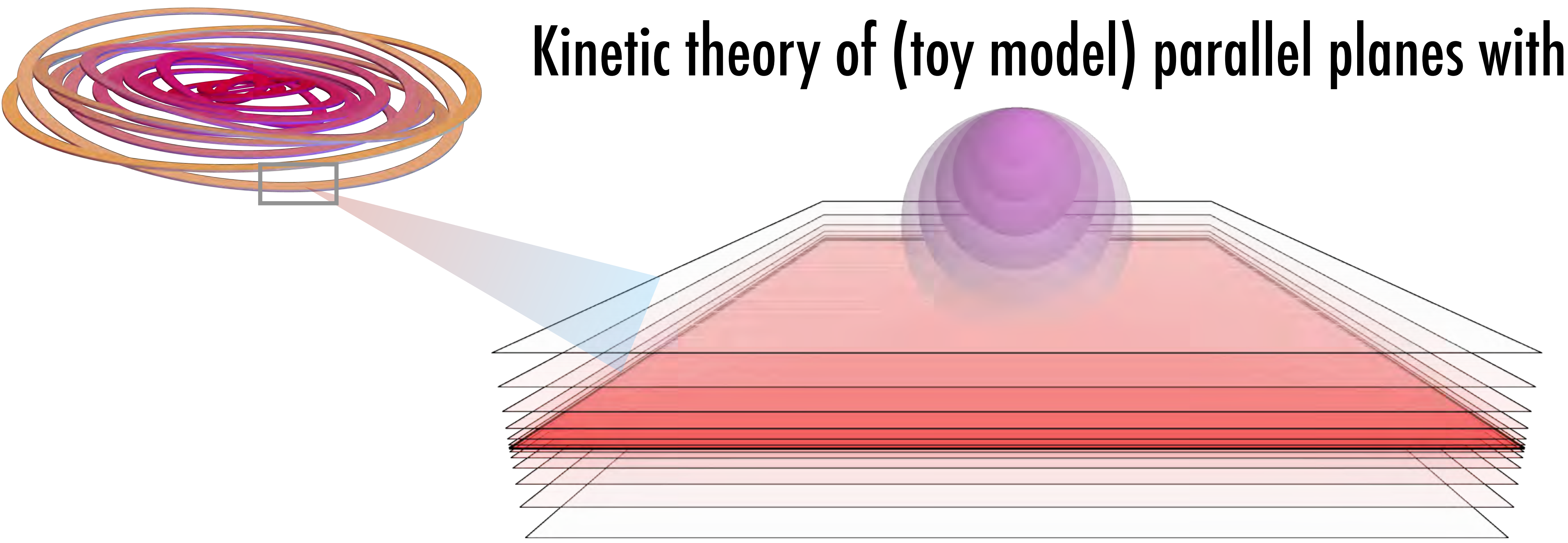


Secular WKB solution

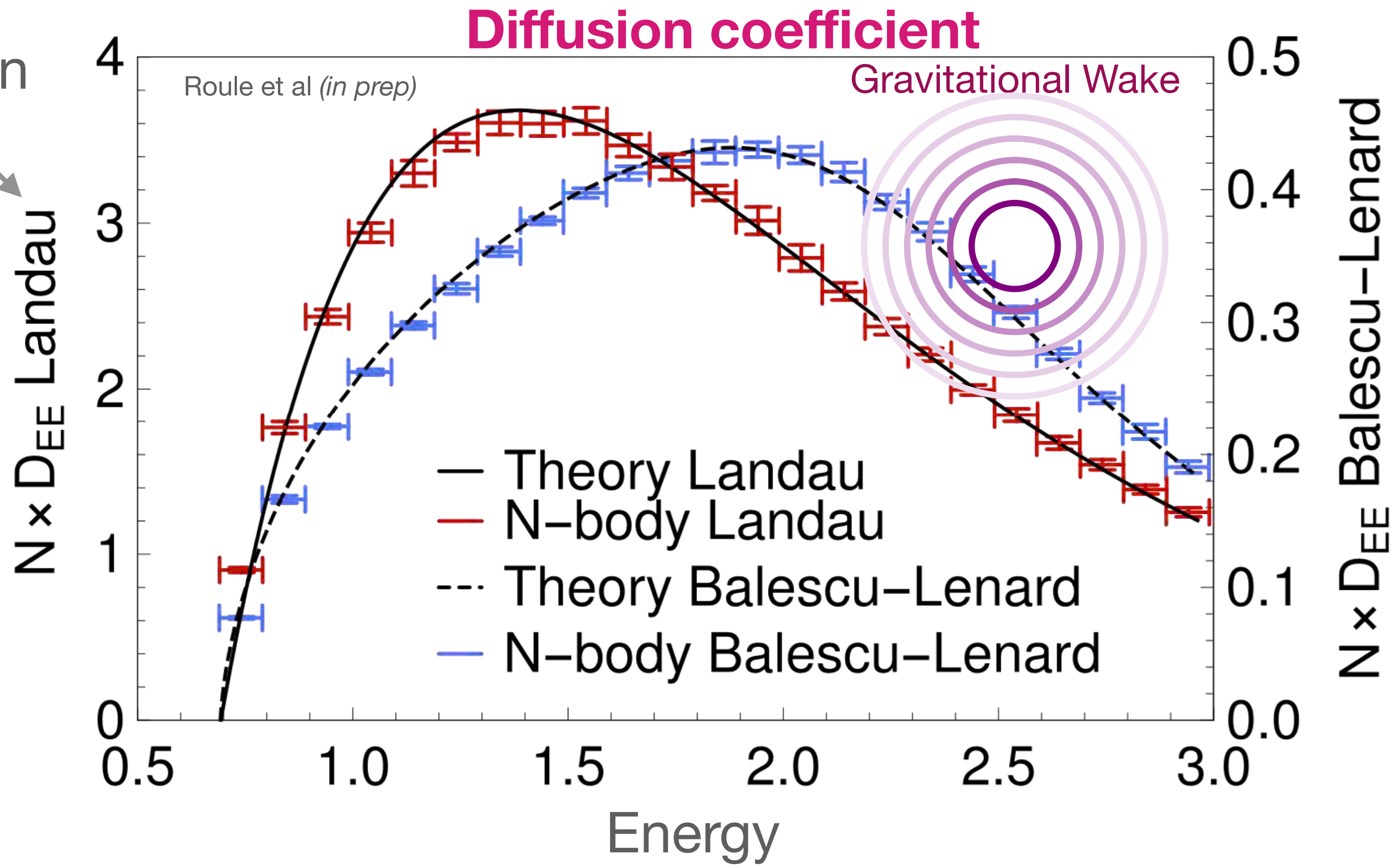
$$\hat{q}_i(t) = \sum_{\pm}\int_{-\infty}^{\infty}\frac{\hat{\xi}_i(t')}{\sqrt{\omega_i(t)\omega_i(t')}}\exp\left(\pm\imath\int_{t'}^{t}\omega_i(\tau)d\tau\right)dt'$$

Plane Toy model: dressing damps vertical diffusion

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



Without polarisation



With polarisation:

rate of diffusion x 1/ 10

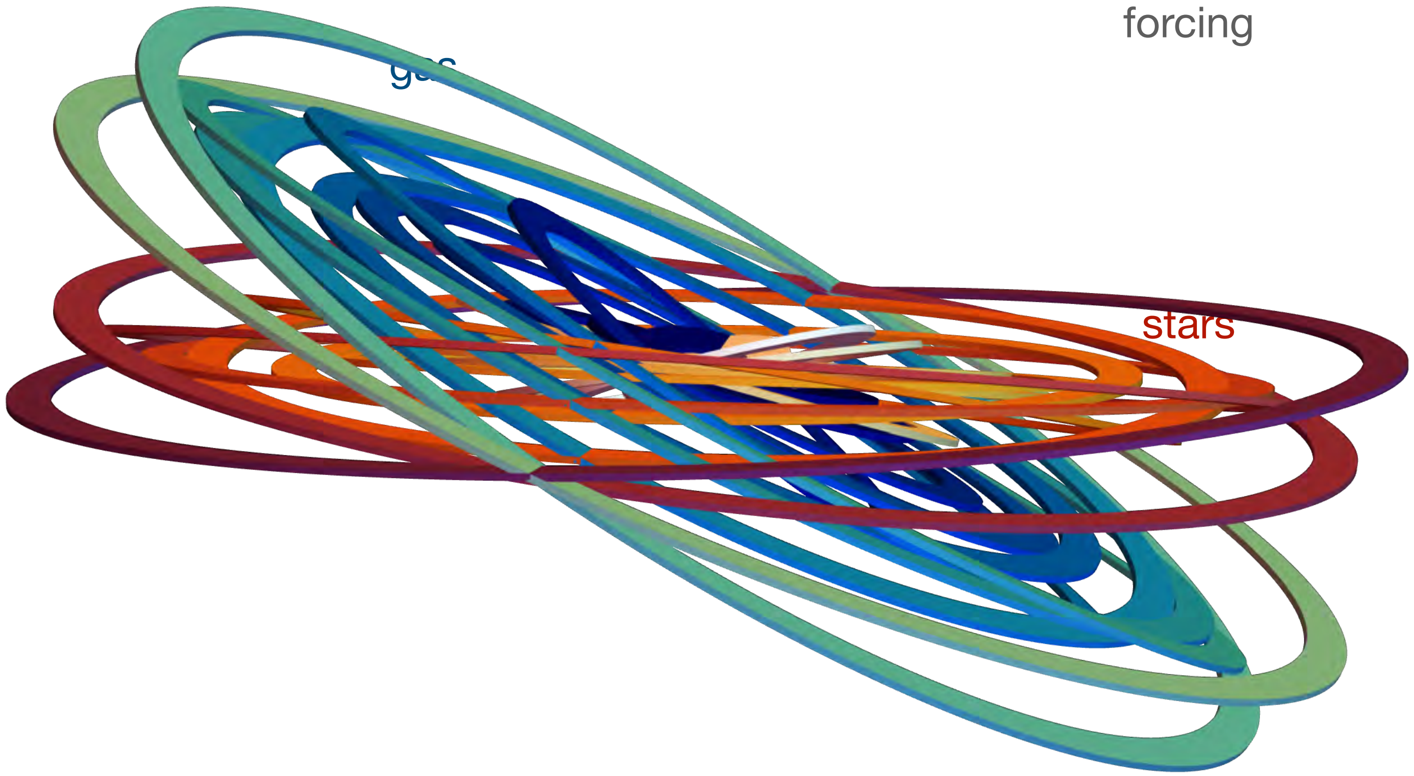
Polarisation stiffen coupling between planes

Ring Toy model: gas + star coupling

gravitational coupling — damping

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

forcing



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

Ring Toy model: gas + star coupling

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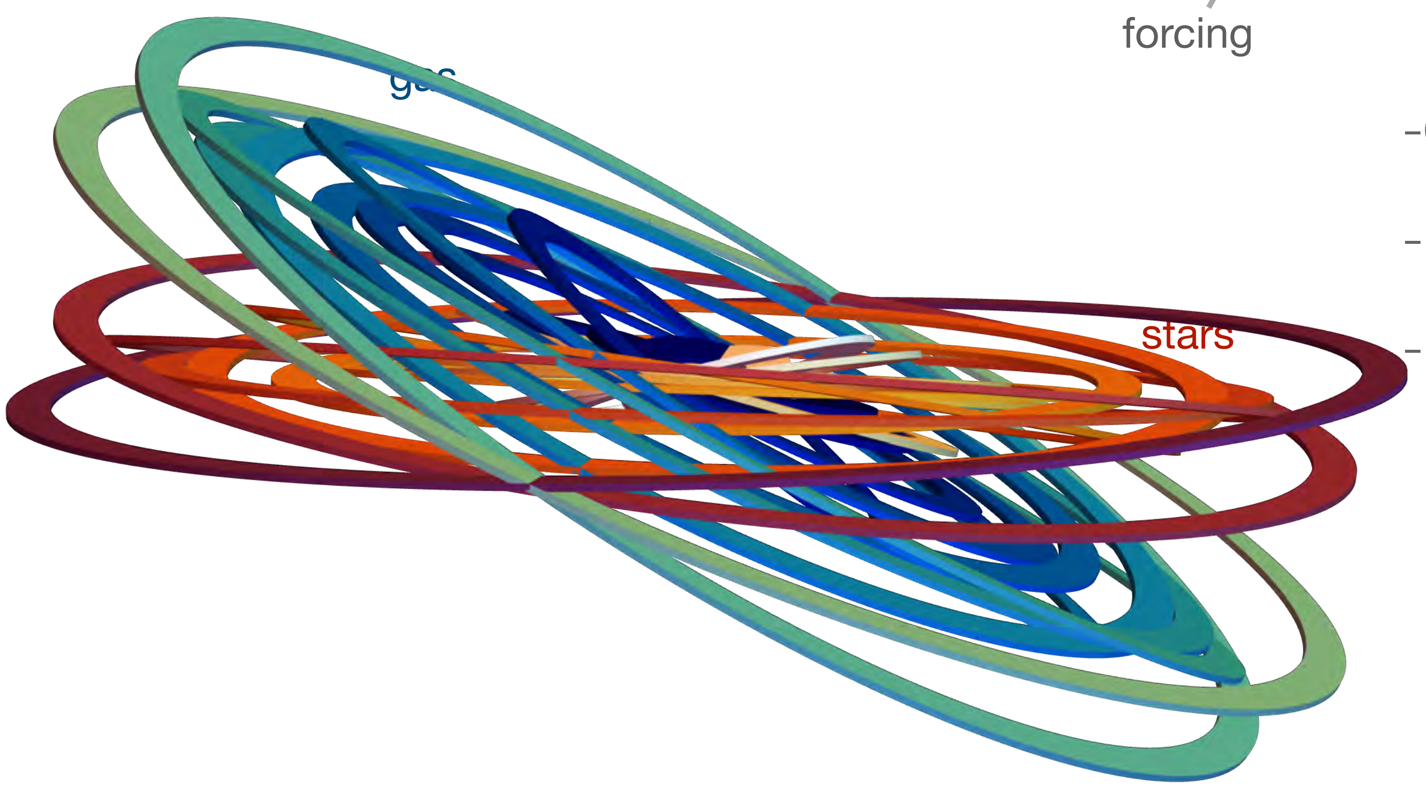
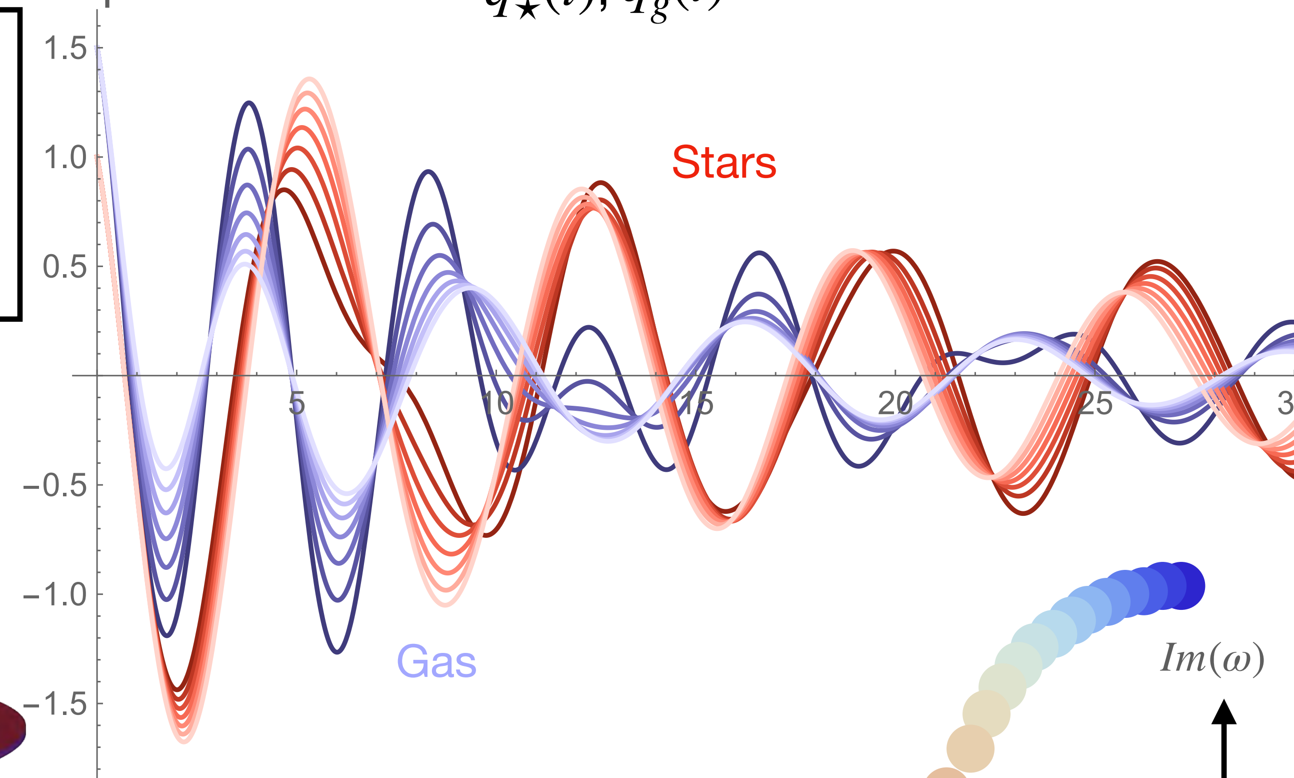
forcing

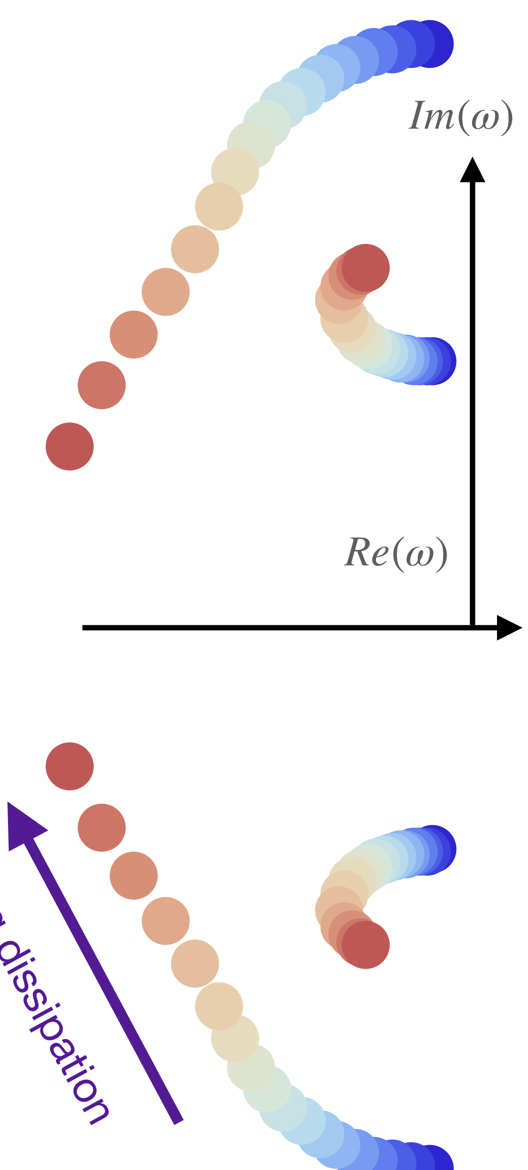




$$q_\star(t) = -\sum_{\omega \in S_4} \frac{\omega_{g\star}^2 \int_{-\infty}^{t} \exp\left((t-\tau)\omega\right)\xi(\tau)\,d\tau}{\eta\left(3\omega^2+\omega_\star^2\right)+2\omega\left(2\omega^2+\omega_g^2+\omega_\star^2\right)}\,,$$

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

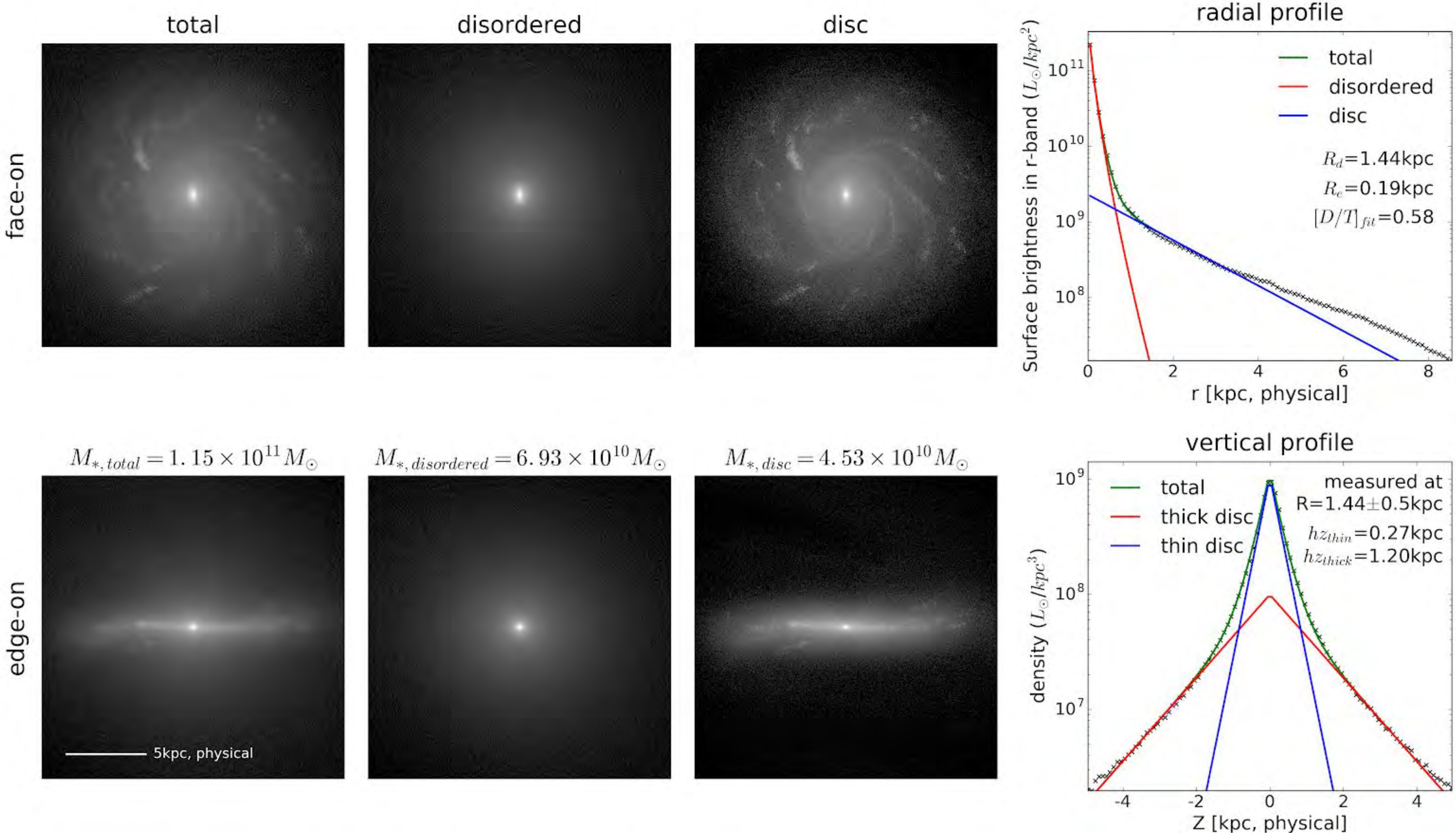
Nyquist diagram



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

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

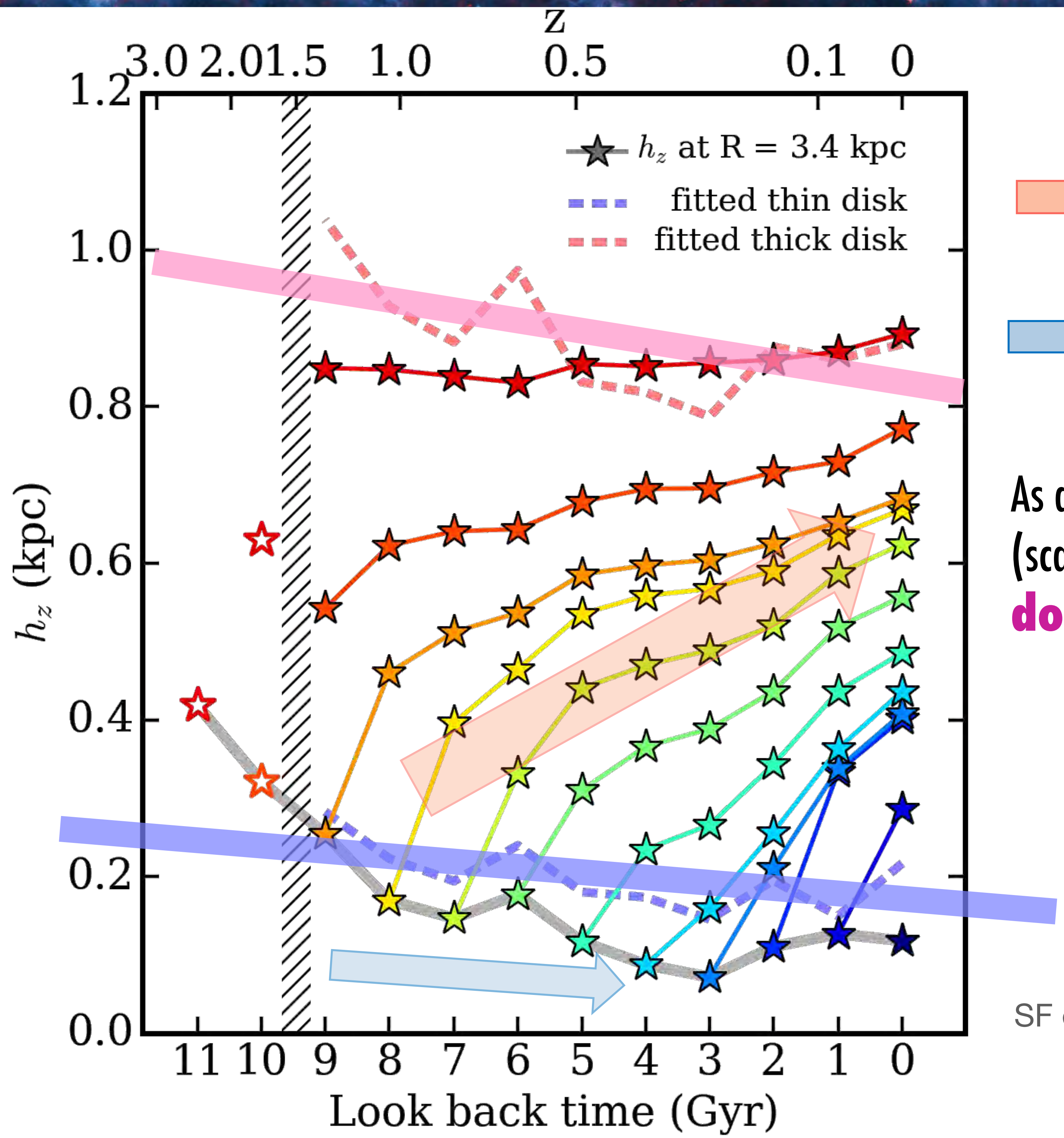
Disc settling preserves double thick/thin profile



Once in secular mode, the self regulated loop

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

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

$$D_{\rm diff,dressed} = \frac{D_{\rm diff,bare}}{\varepsilon(Q)^2}$$

SF efficiency

$$\frac{\partial \eta_{\rm SF}}{\partial Q} < 0$$

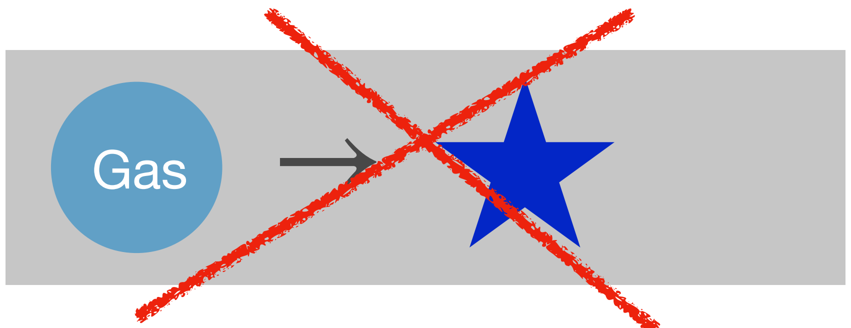
Both star formation and vertical orbital diffusion are regulated by same (Q $\rightarrow$ 1) **confounding** factor which produce stars and diffuse the stellar orbital structure.

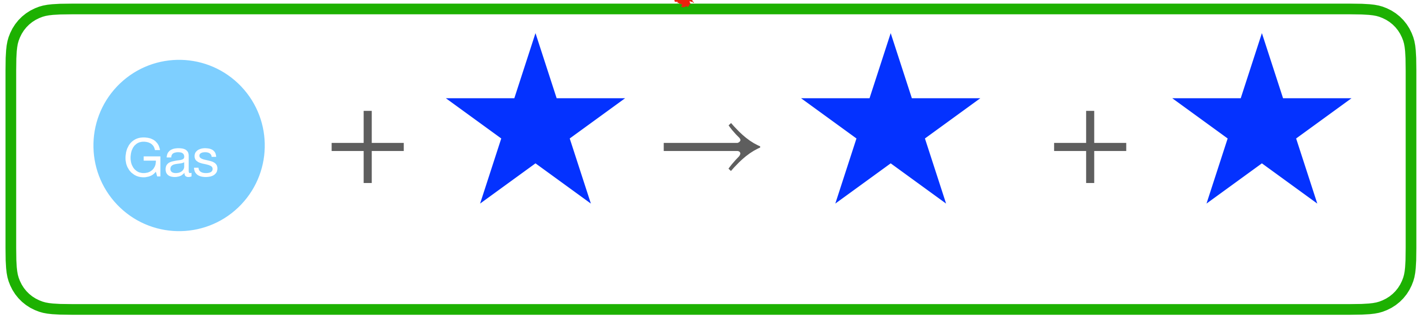
The stellar thick disc is simply the **secular remnant** of the (self regulated) disc settling process.

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**.





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

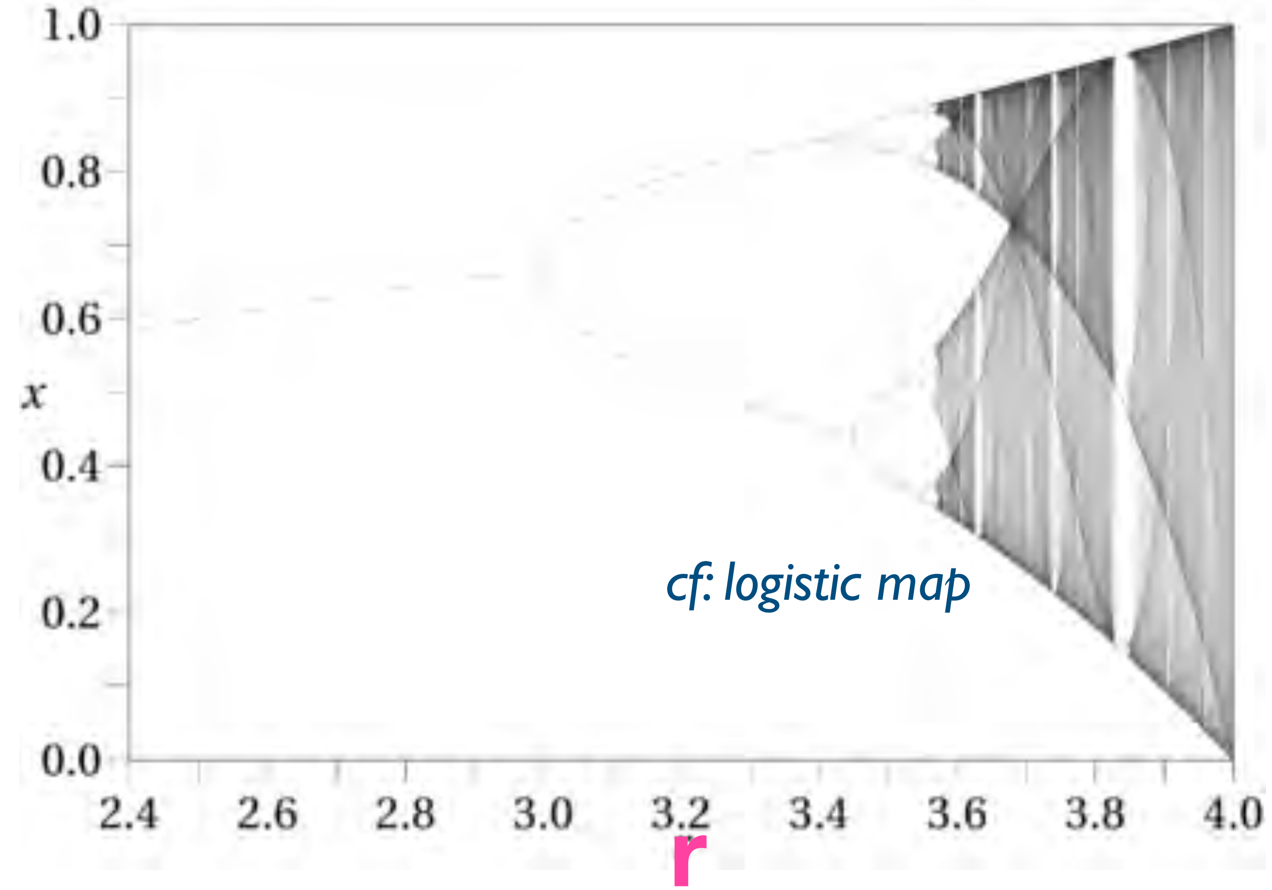
control parameter

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

= Simplest quadratic model for self -regulation

= Taylor expansion of effective production rate

★= cold stellar component



Why finite thickness: chemistry of emergence

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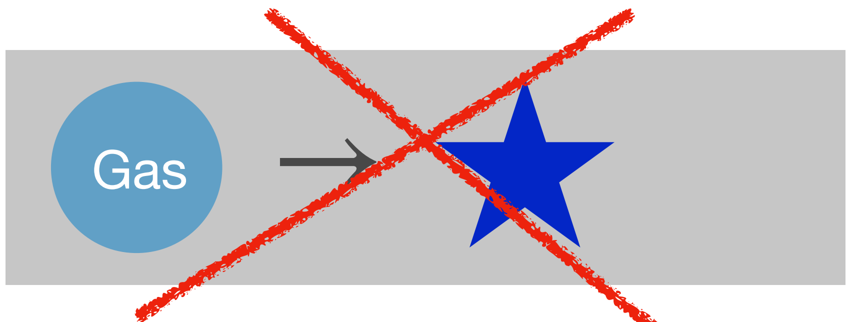


Gas + ★ → ★ + ★

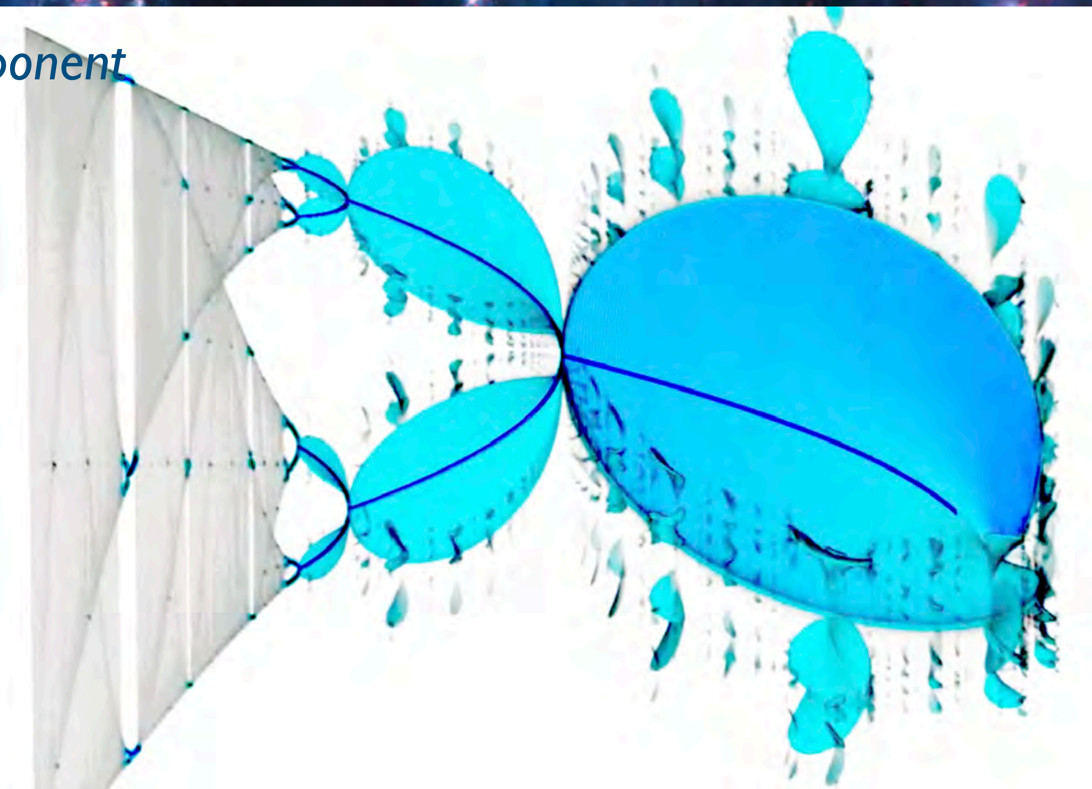
$$\frac{d}{dt}\star = r\star(1-\star)$$

control parameter

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

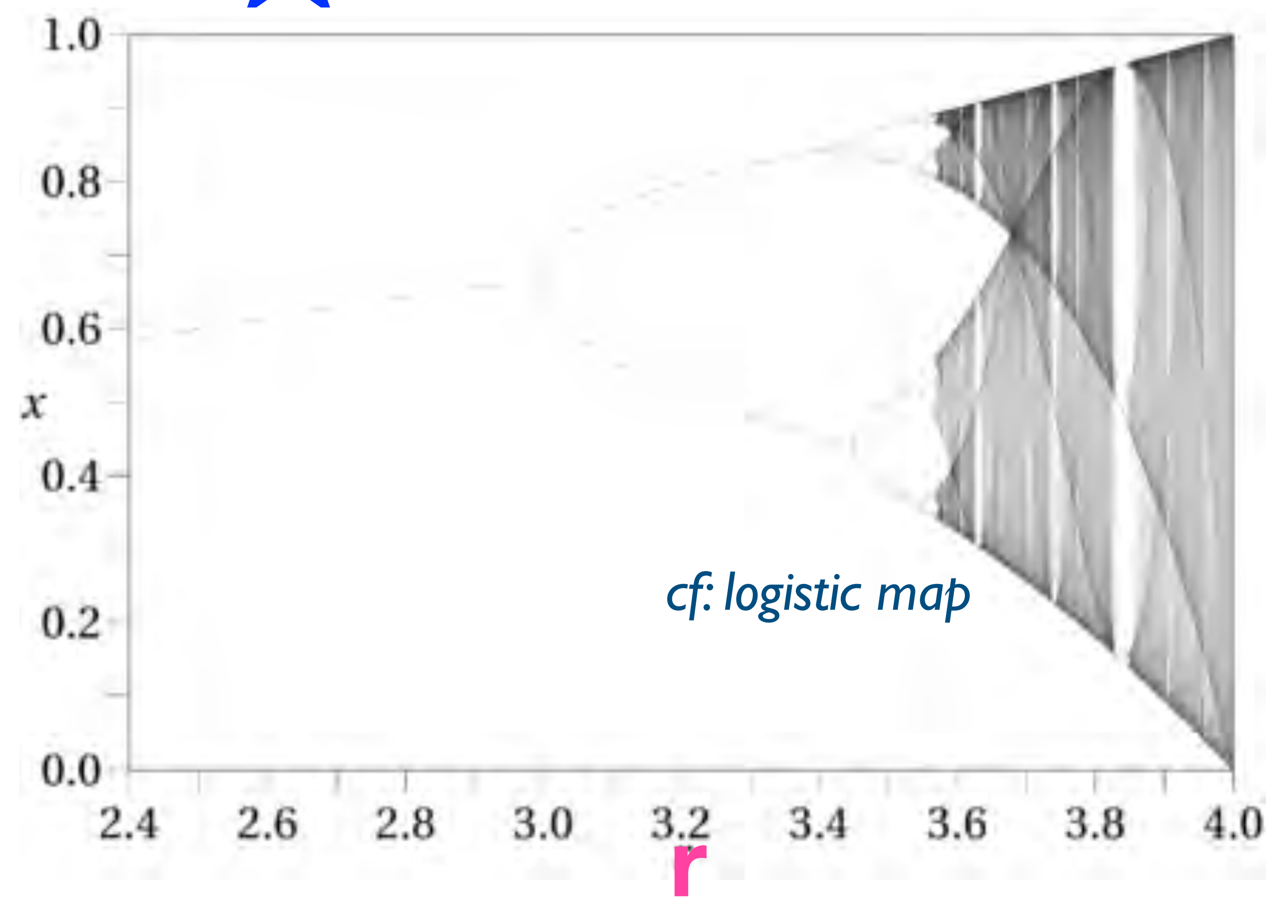
= Simplest quadratic model for self -regulation

= Taylor expansion of effective production rate



Link to Mandelbrot Set (Veritassium 2021)

★ = cold stellar component



Chemistry of emergence… (cont')

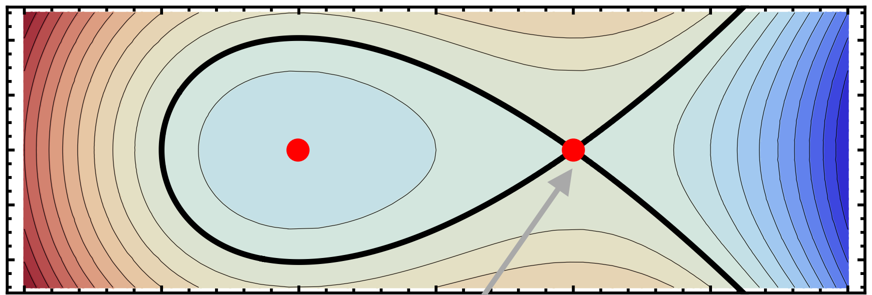
*Now let us take into account for the **vertical** secular diffusion of the cold component*

Dissipation converts **kinetic instability** point into an **attractor**.

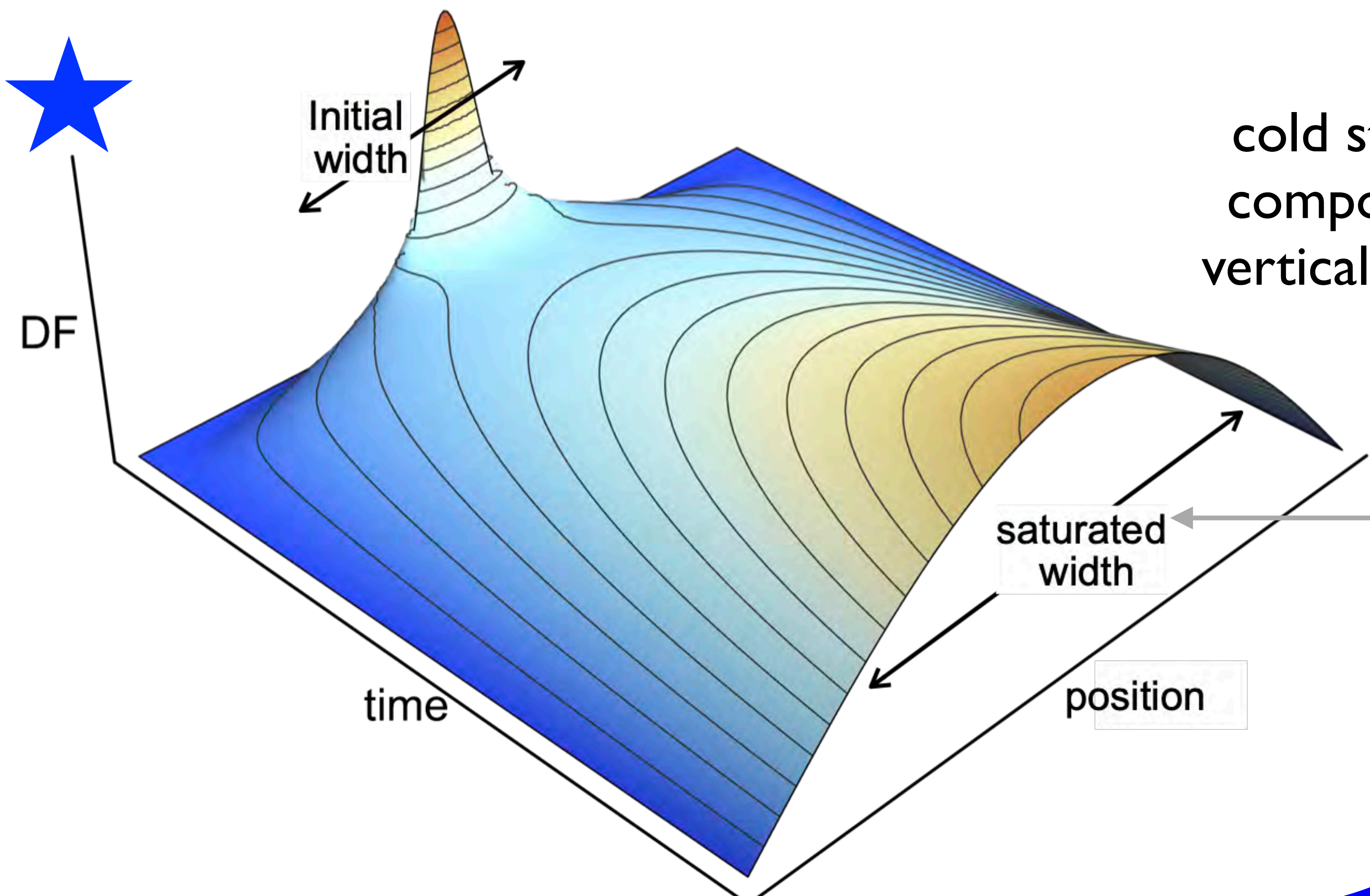
$$\frac{d}{dt}\bigstar = \bigstar(1-\bigstar) + \Delta\bigstar$$

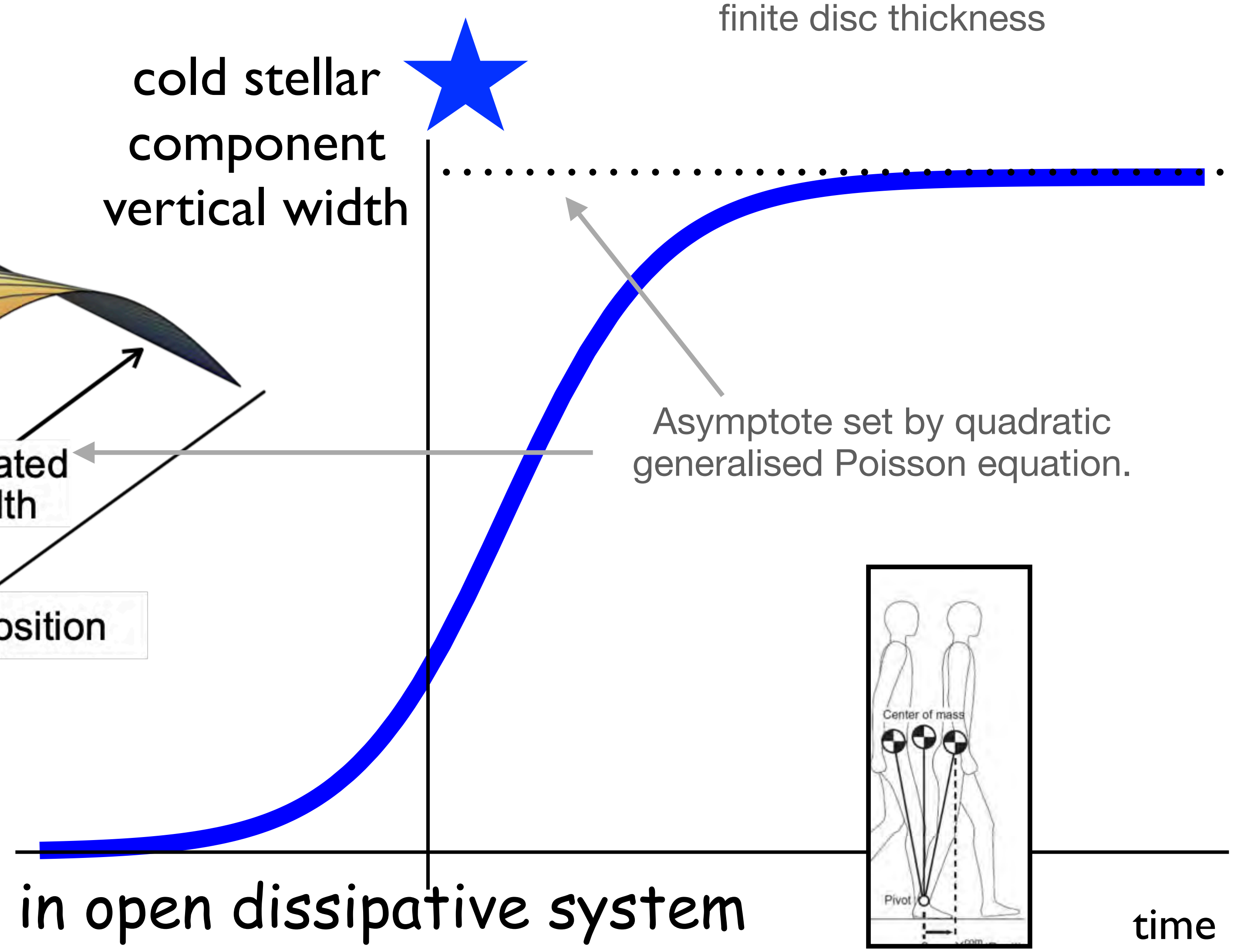
Reaction-Diffusion equation

Logistic map Hamiltonian



New point of equilibrium with finite disc thickness





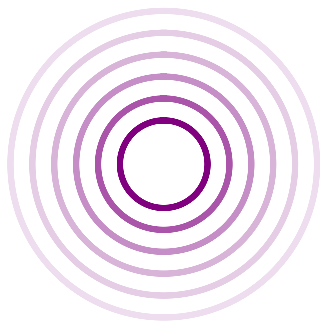
→**Emergence** of thin **fixed width** disc in open dissipative system

Chemistry of emergence… (cont')

Now let us study its cosmic evolution via the growing boosting impact of wakes

Auto-catalysis of the cold component (via **wakes**) and **dissipation** converts **dynamical instability** point into a robust **attractor**.

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


Gravitational Wake

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

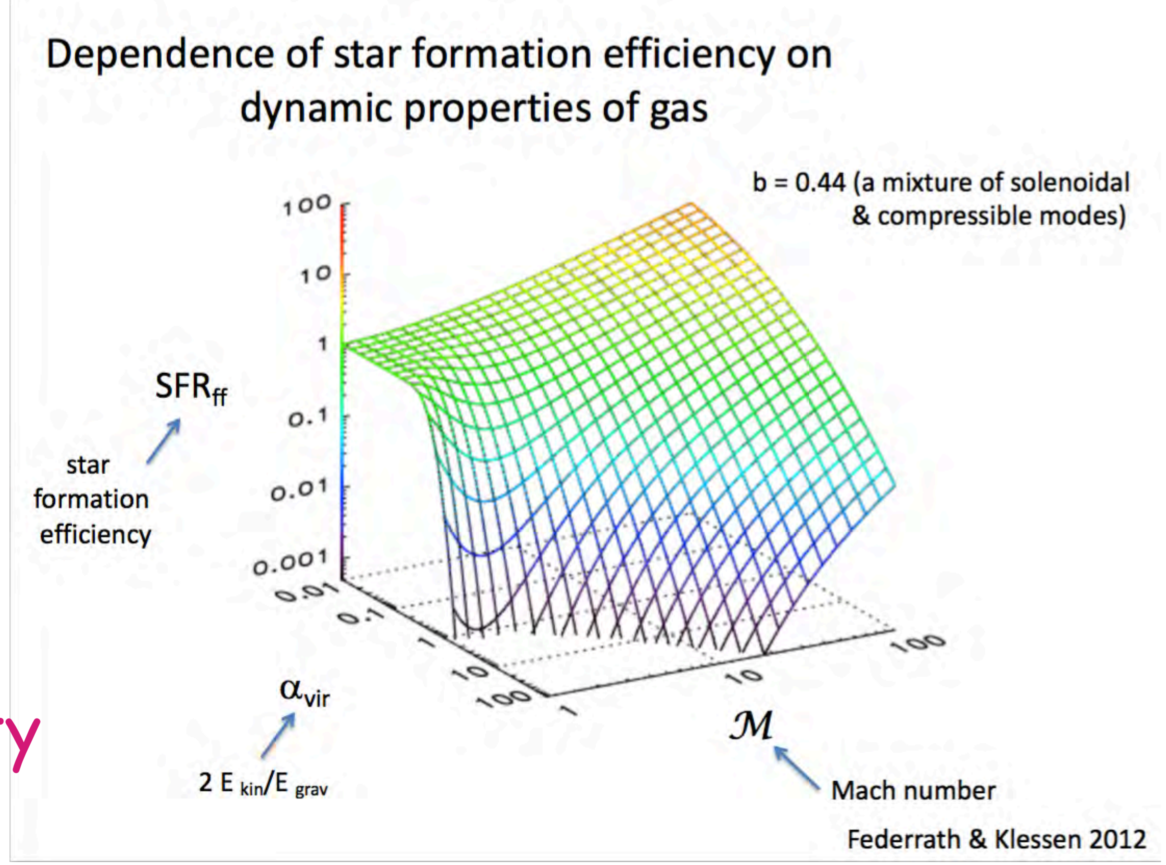
SF efficiency

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

$\sim$ quadratic in ε

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

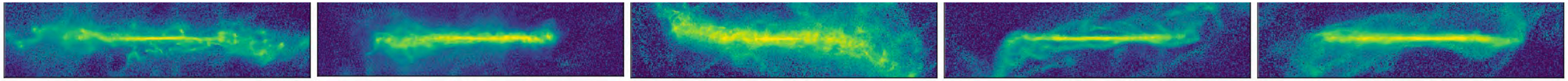
Diffusion



→cosmic Emergence of thin disc

→Operates swiftly via self-organised Criticality

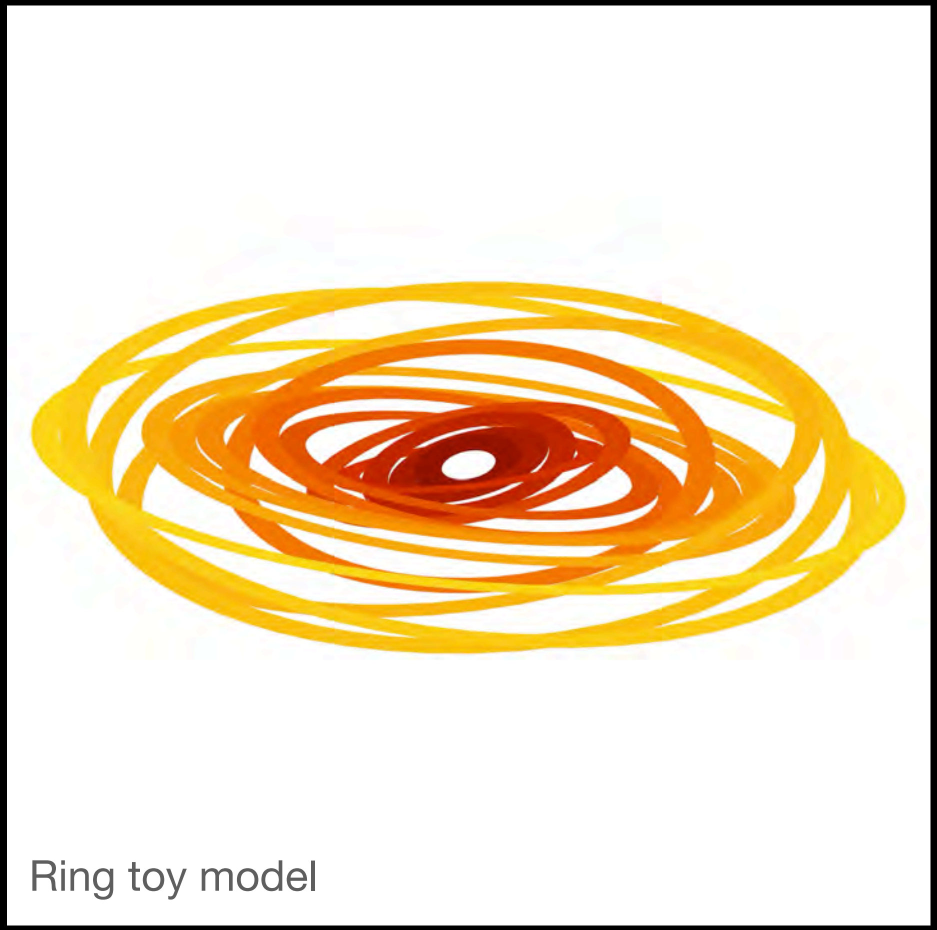
→Robustness / feedback details No fine tuning !



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

- Convergence towards Q~1
  — is dual to settled fraction of discs increasing with mass and cosmic time
  — sets a robust & fast reaction-diffusion kinetic process controlling the disc's thickness
  — implies that thick and thin discs grow together

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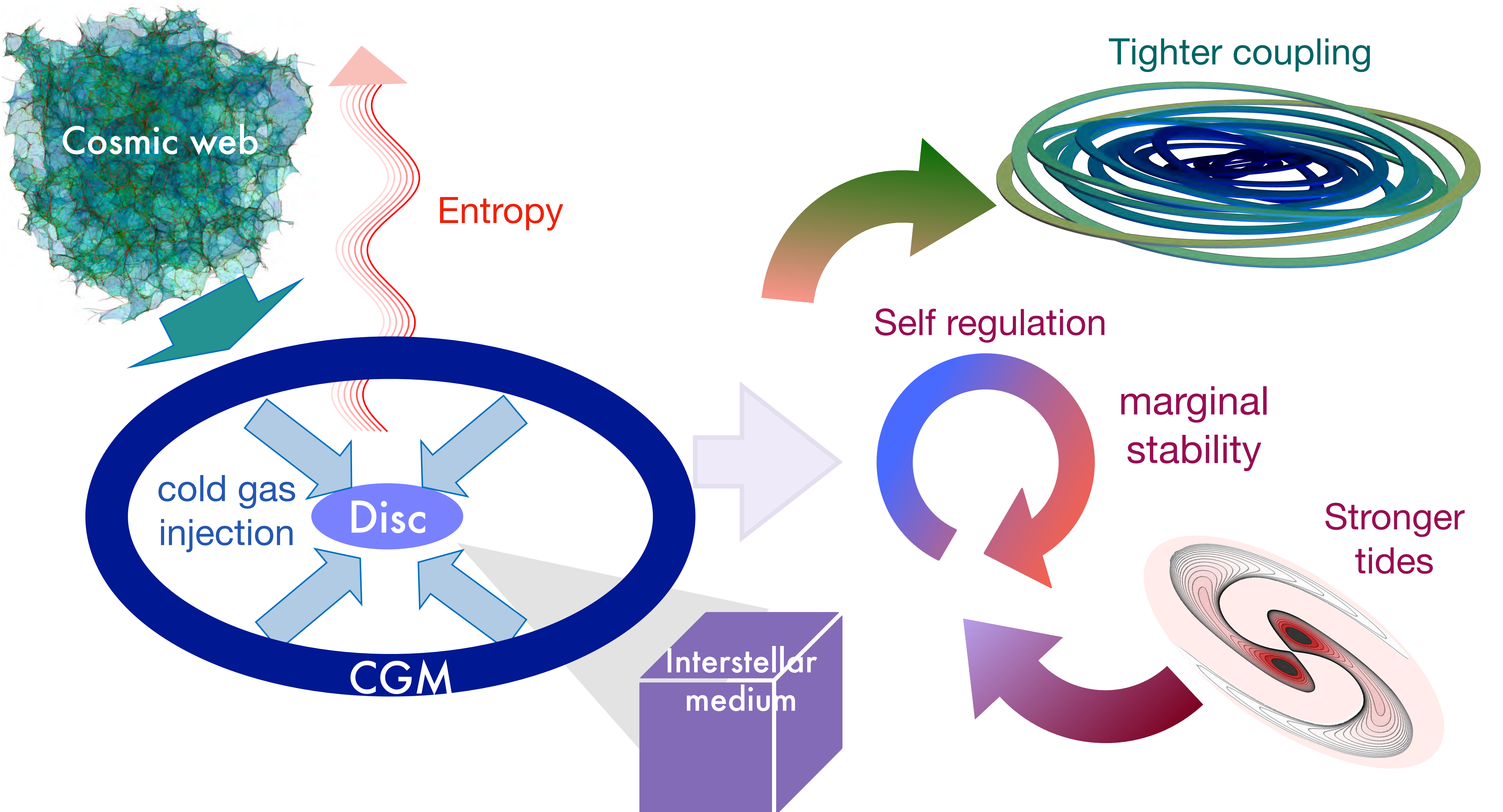
  — sets a robust & fast reaction-diffusion kinetic process controlling the disc's thickness
  — implies that thick and thin discs grow together

Synopsis of thin disc emergence 2/2

- 3 components system coupled by gravitation.
- A CGM reservoir fed by the large scale structures
- Convergence towards marginal stability : acceleration of dynamical control-loop by wakes
- Tightening of stellar disc by amplification of relative torque & increased dissipation.



CONCLUSION

★ *Revisited galaxy formation theory subject to cosmic filaments*

- because it's interesting (most galaxies are born in filaments)
  - ✳ to understand LSS surveys (morphology, orientation)
  - ✳ to understand emergence of razor thin galactic discs @ $z \sim 0$
- LSS impact non-linearly gas flows (what galaxies are made of!)
  - ✳ build up of discs/CGM via stratified AM-rich gas inflow
  - ✳ provide engine for emergence of homeostatic thin discs

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

Dynamical marginal stability is an attractor for open dissipative systems.
Failure of loop will allows us to quantify morphological diversity.

upcoming KITP programme/conference

Recent Changes Search: Go

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

Feb 6, 2023 - Feb 9, 2023

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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 !

Complement: is a disc alive? vaguely!

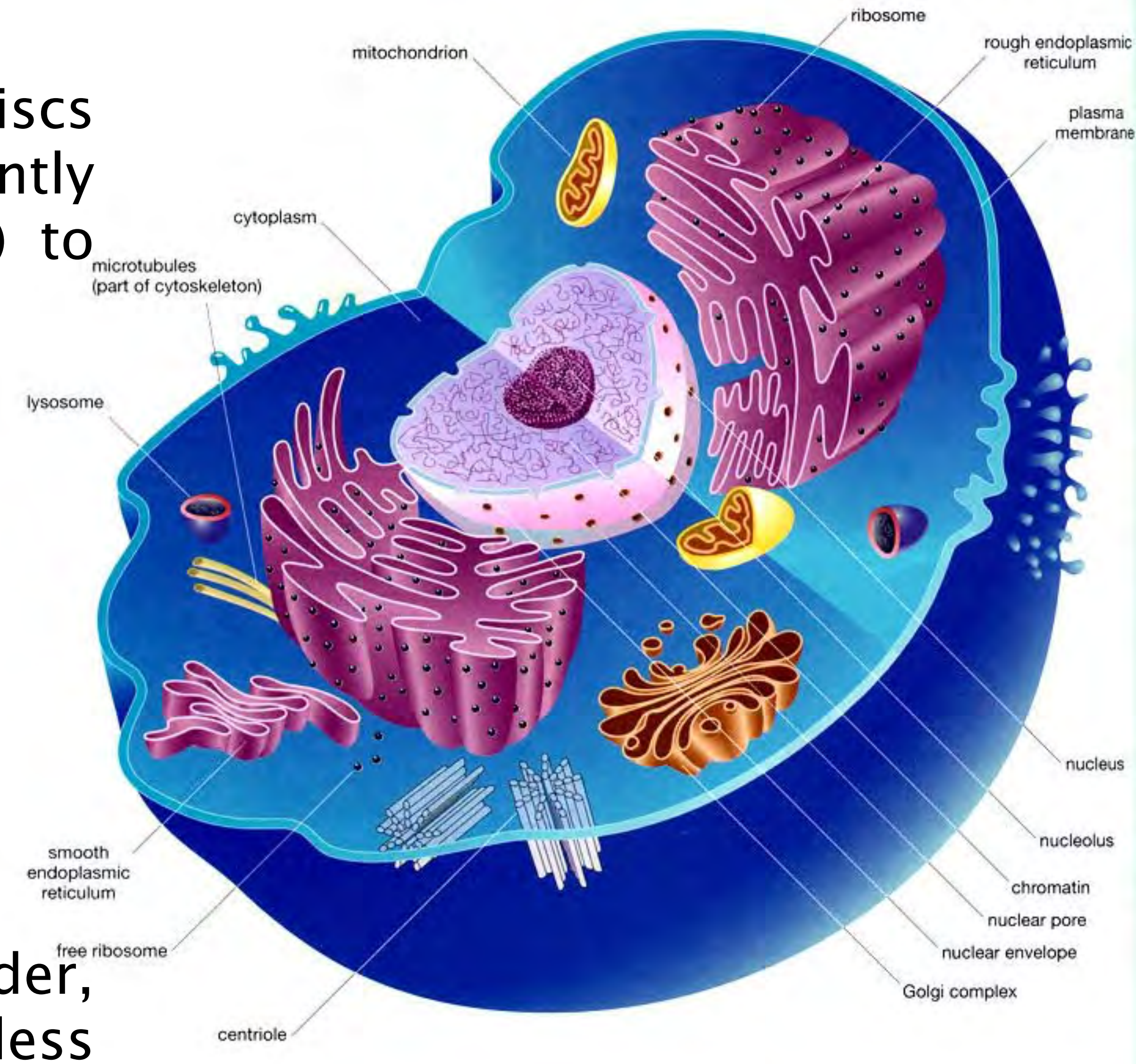
Interestingly, though anecdotical, the thin discs possesses at least three out of four pillars recently required by some authors (Wong & Bartlett 2020) to define **pre-biotic systems**:

i) they are 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**!

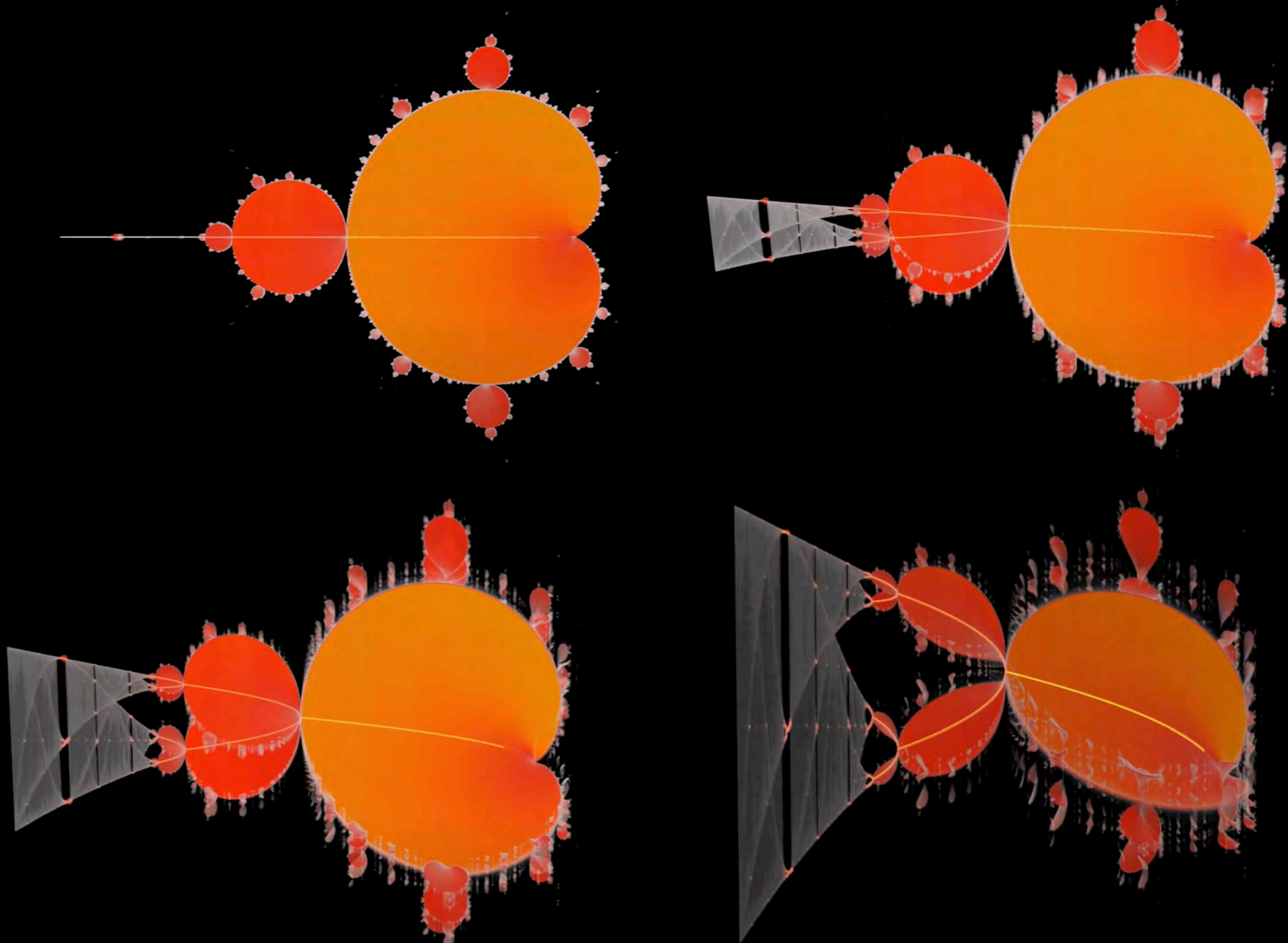
Bring home message

- 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.

- Variation of inflow that the disc's tolerate before instability
- Proximity to *cliff* (Q<1) essential
- Link to self-organised criticality/Maximum entropy production
- No absolute transition mass

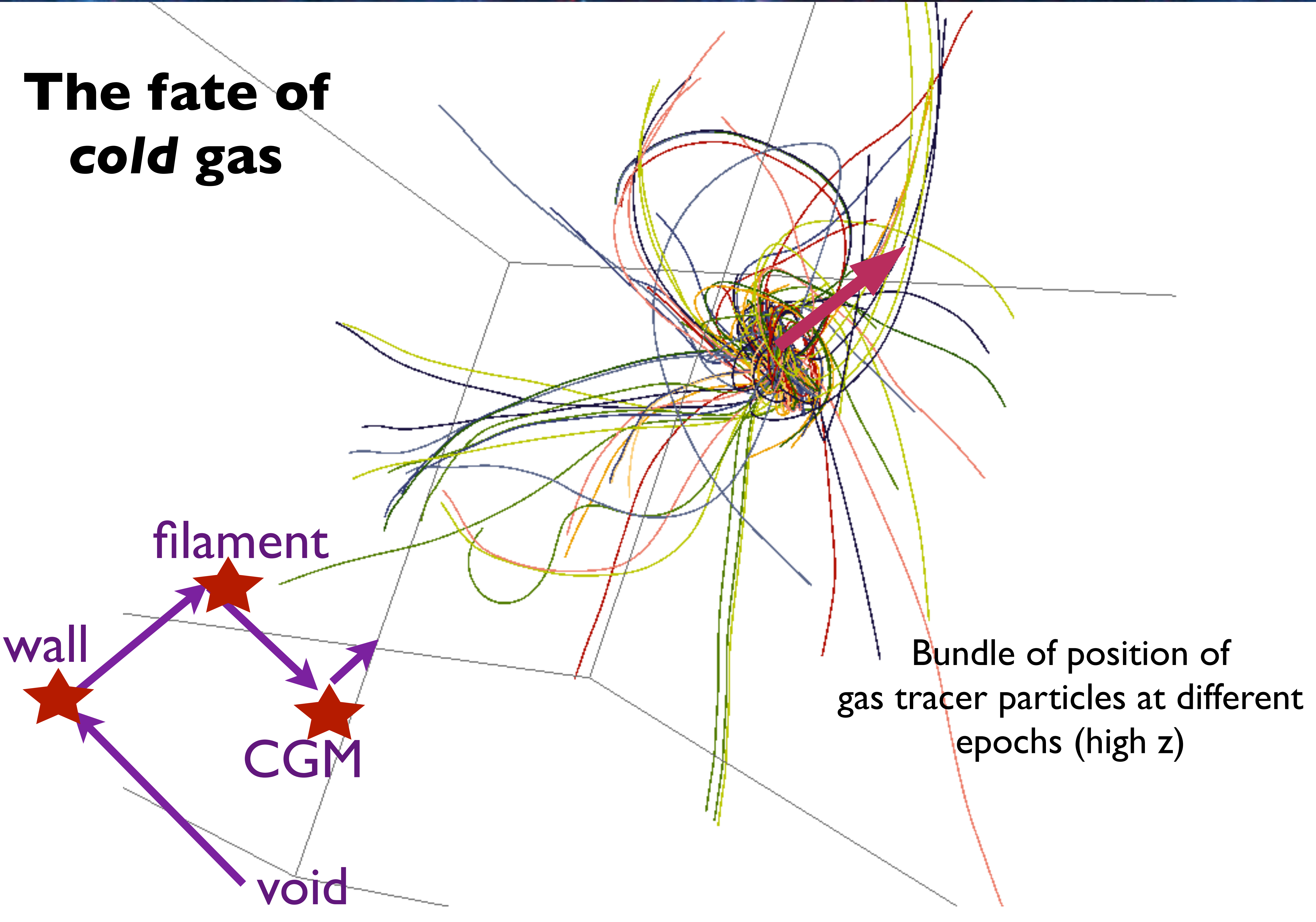
- Assumes disc can respond dynamically fast enough
- Leap of faith in dynamical range (SF controlled by turbulent injection scale)
- Ignore extension of disc + bars /bulge + life halo (locality)

Link to Mandelbrot Set (Veritassium 2021)

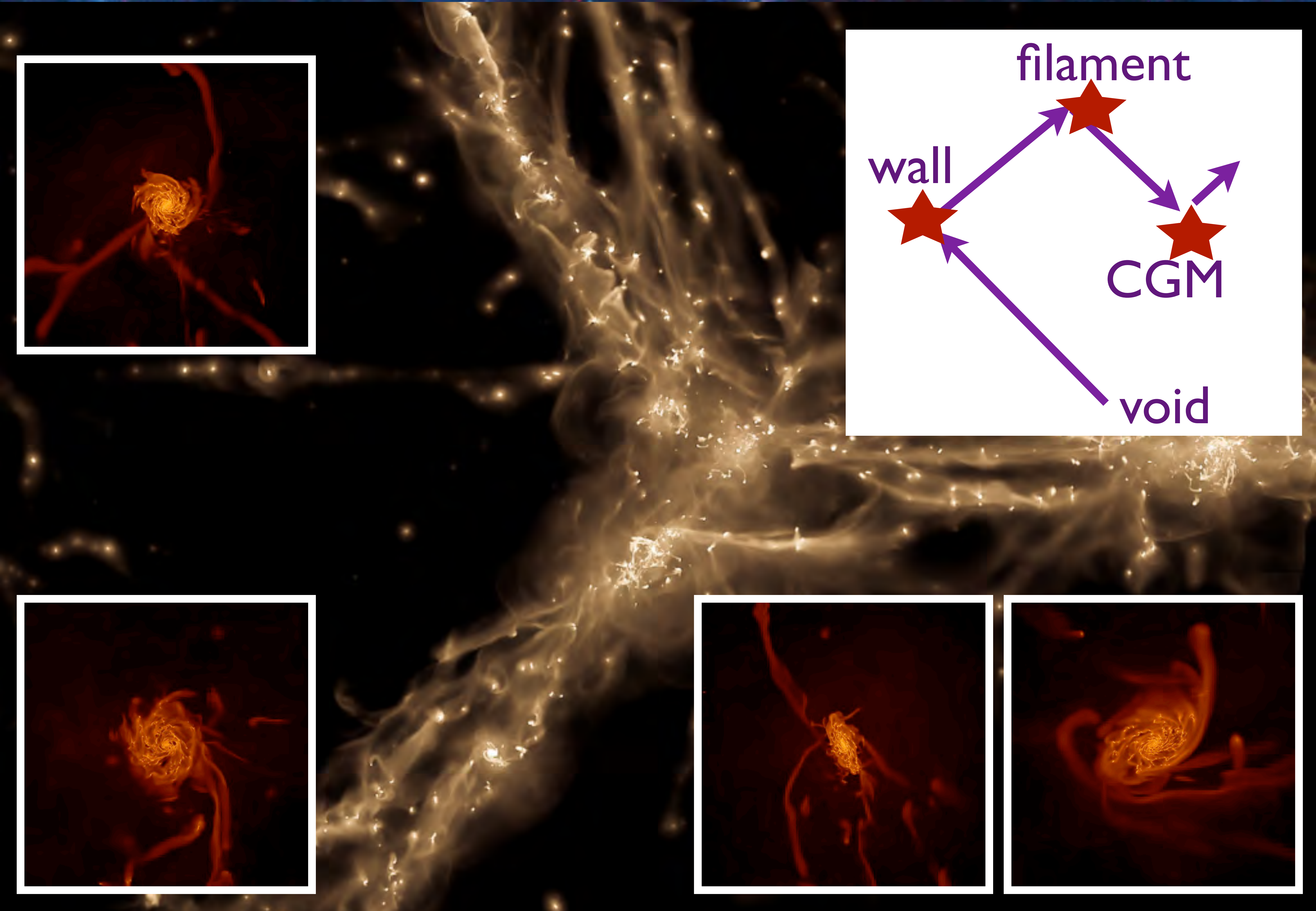


Geometry of gas flow: Lagrangian timeline

The fate of *cold* gas

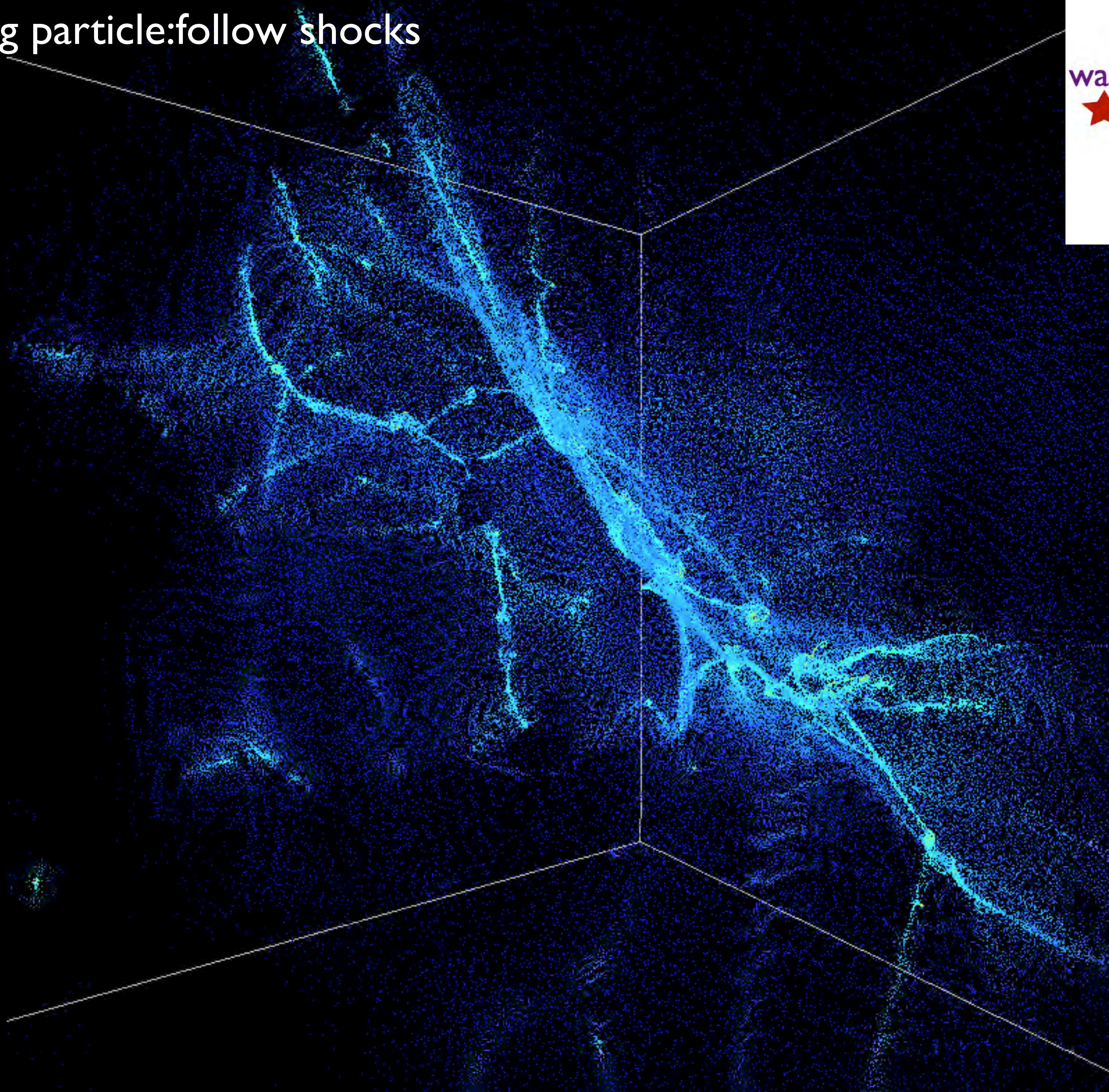


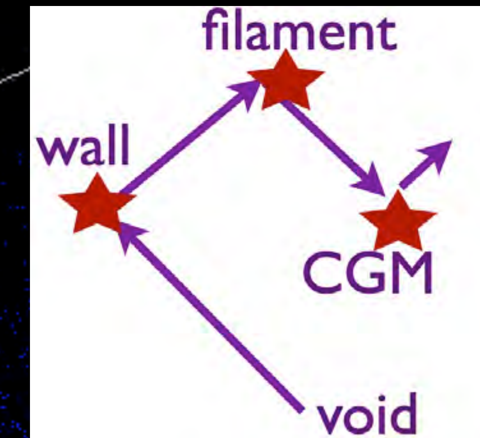
Geometry of flow: Eulerian view @ high resolution.



Geometry of gas flow: Tracer particle

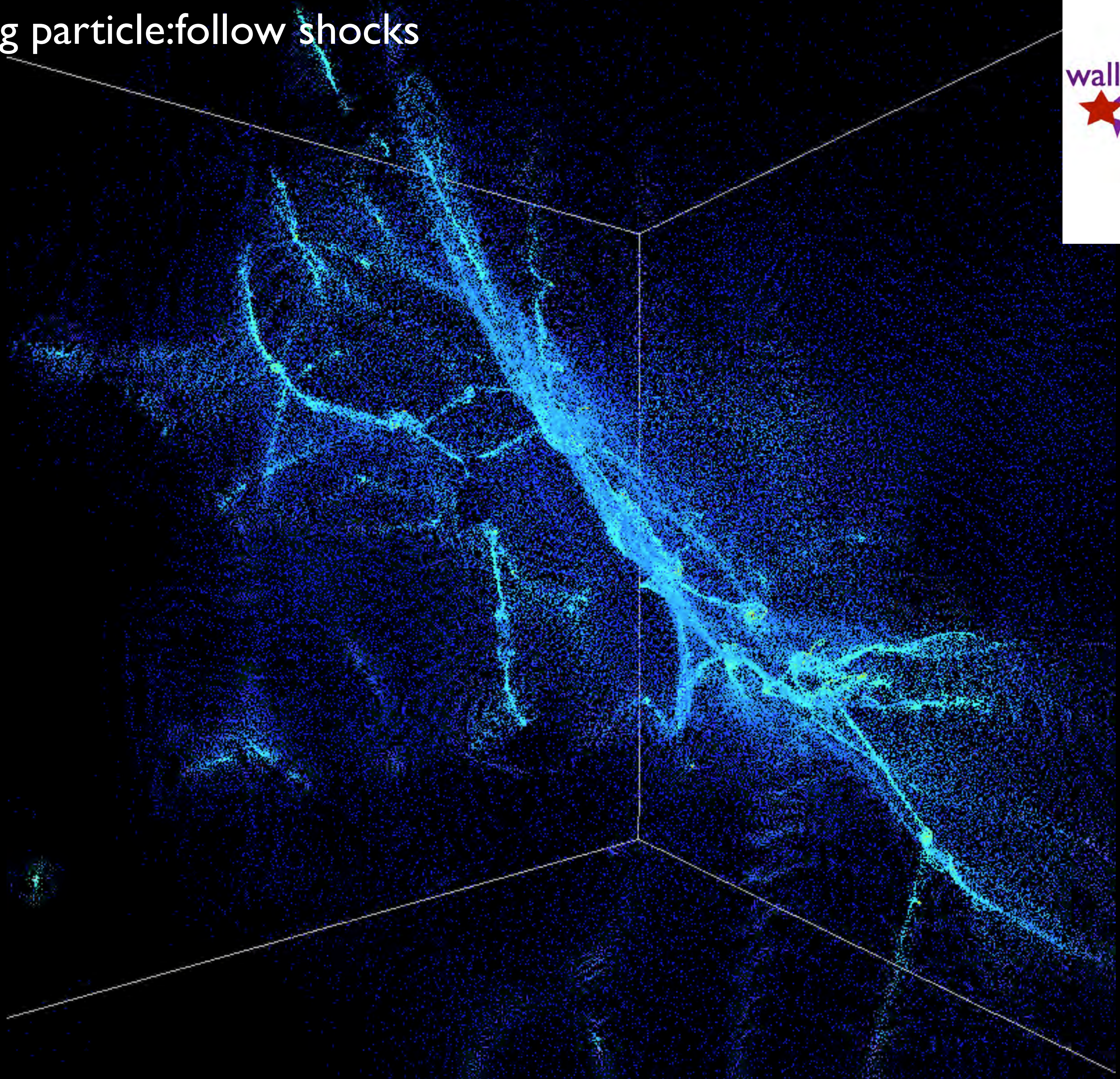
gas tracing particle:follow shocks

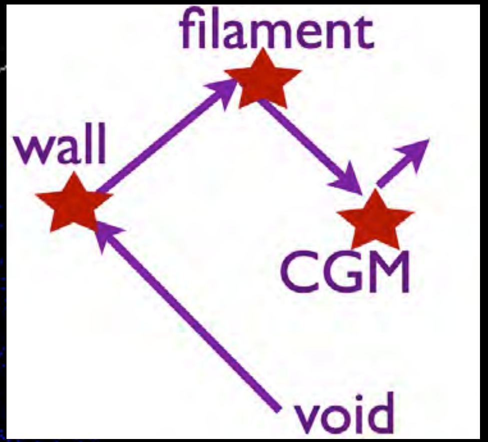




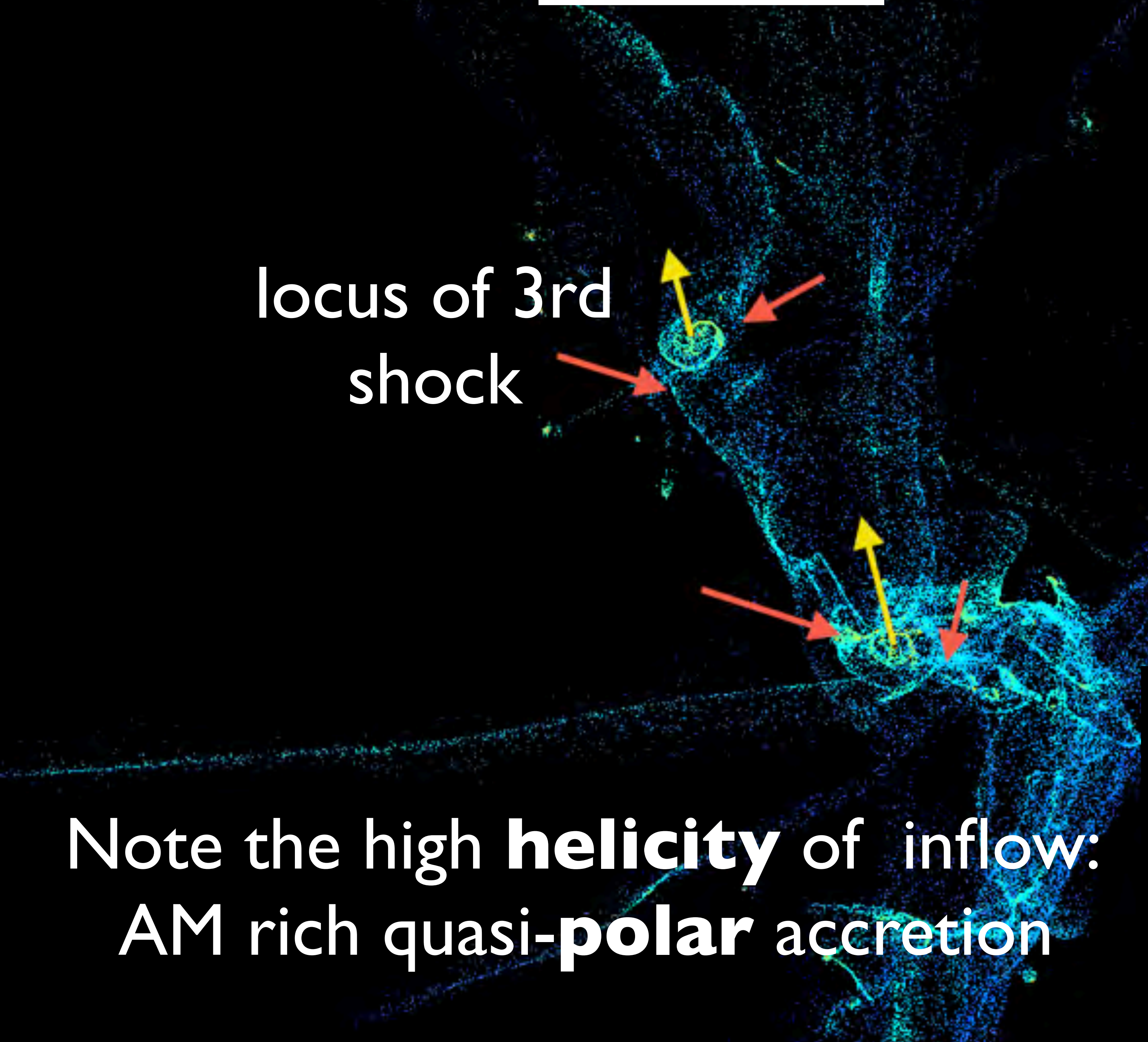
Geometry of gas flow: Tracer particle

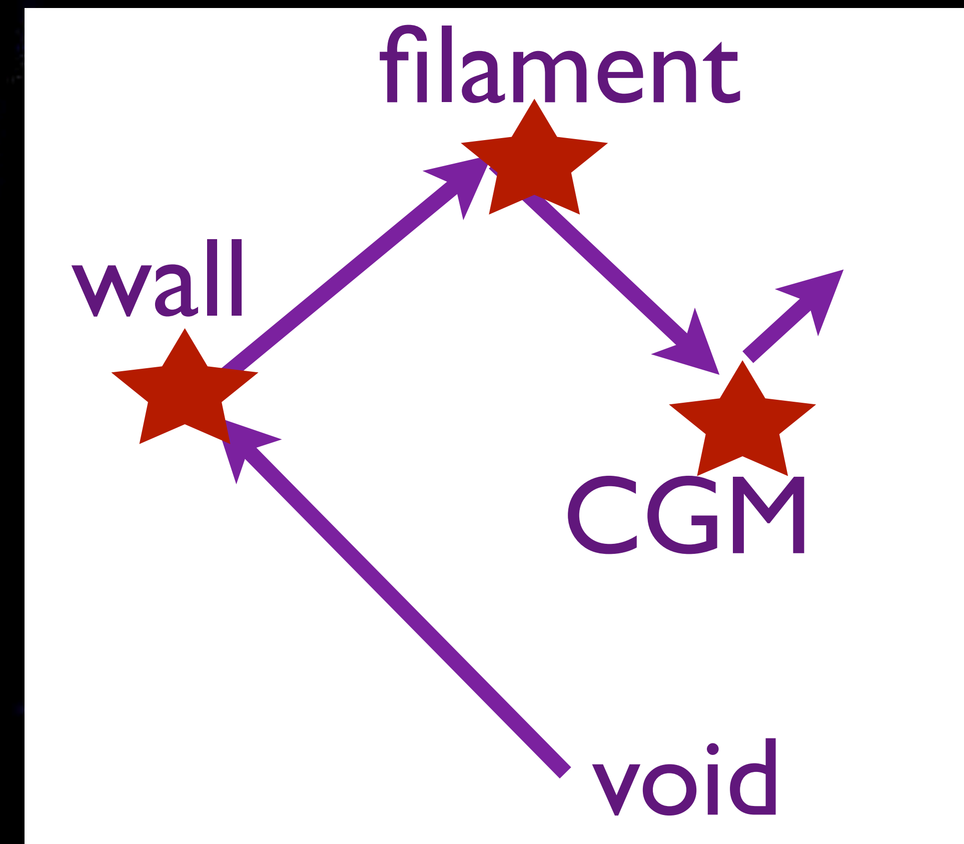
gas tracing particle:follow shocks





Geometry of gas flow: Tracer particle

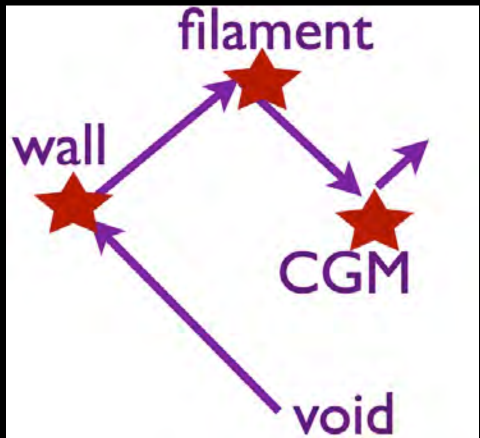


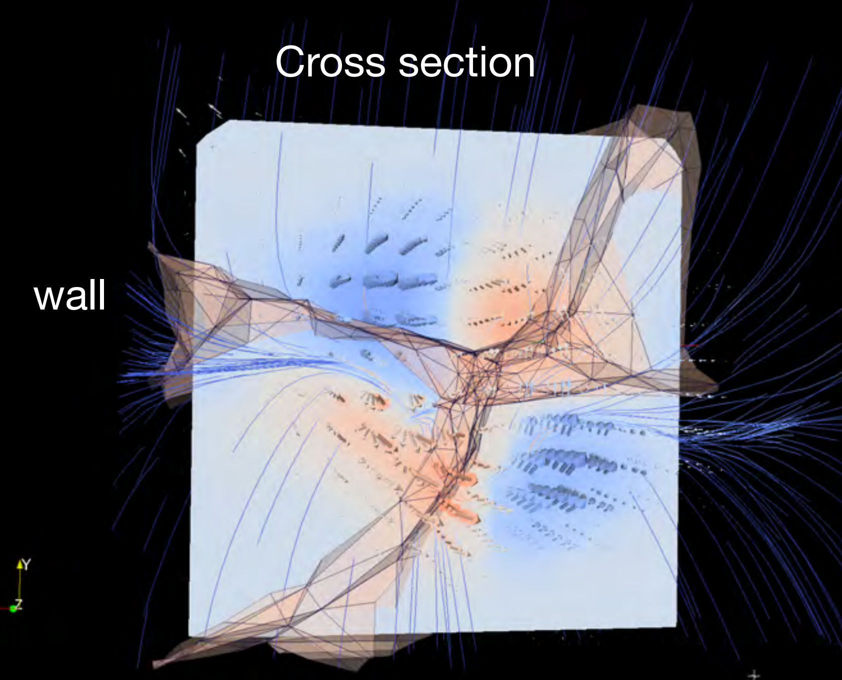


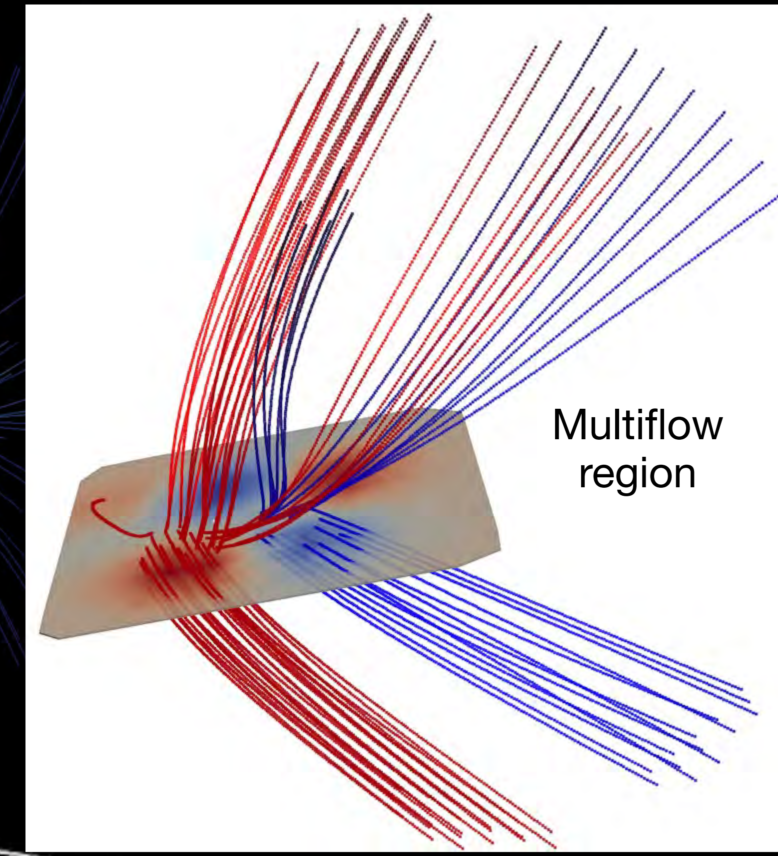
Note the high **helicity** of inflow:
AM rich quasi-**polar** accretion

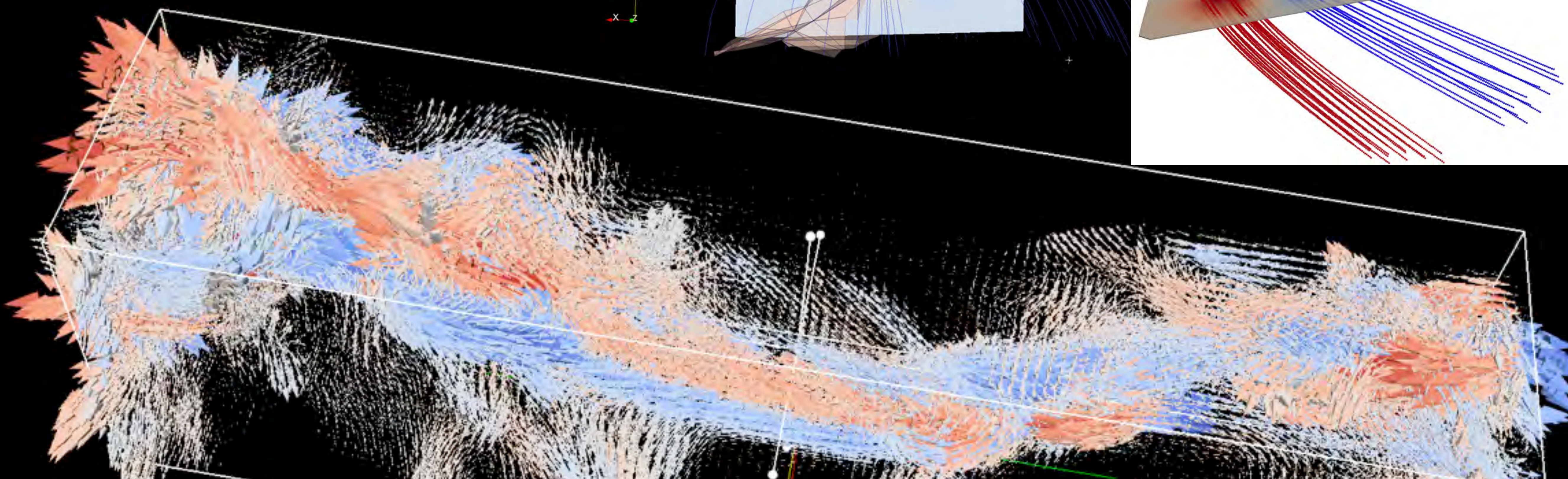
Danovich+'15

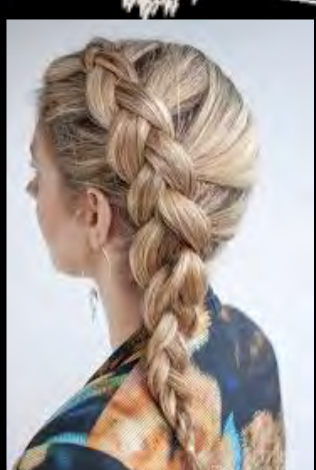
Geometry of flow: Alignement of vorticity with cosmic web











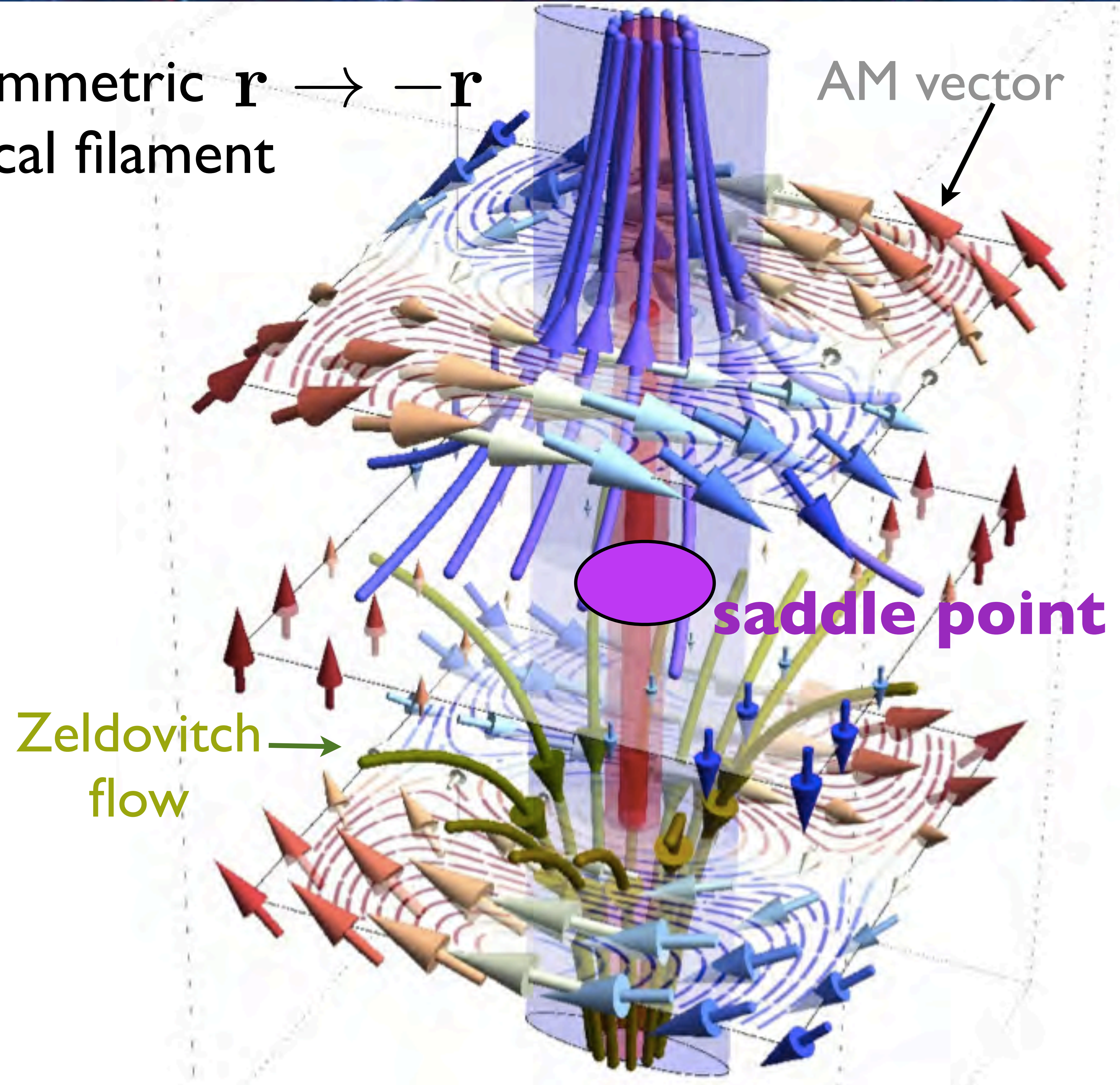
Spin structure near Saddle: conditional TTT

- point reflection symmetric $\mathbf{r} \to -\mathbf{r}$
- vanishes if cylindrical filament

spin perp. = along e_φ

spin // to filament

spin perp = along e_φ



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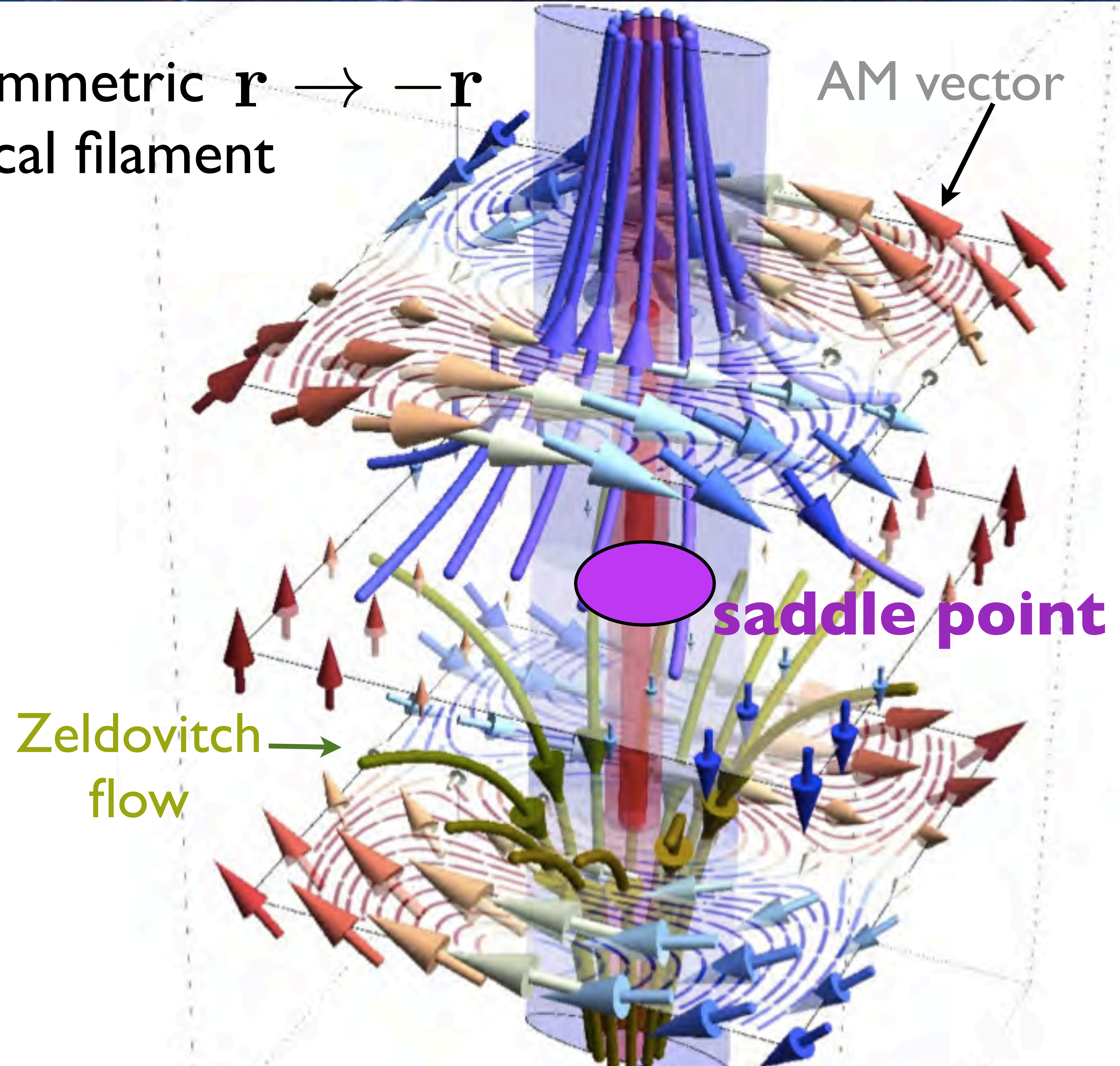
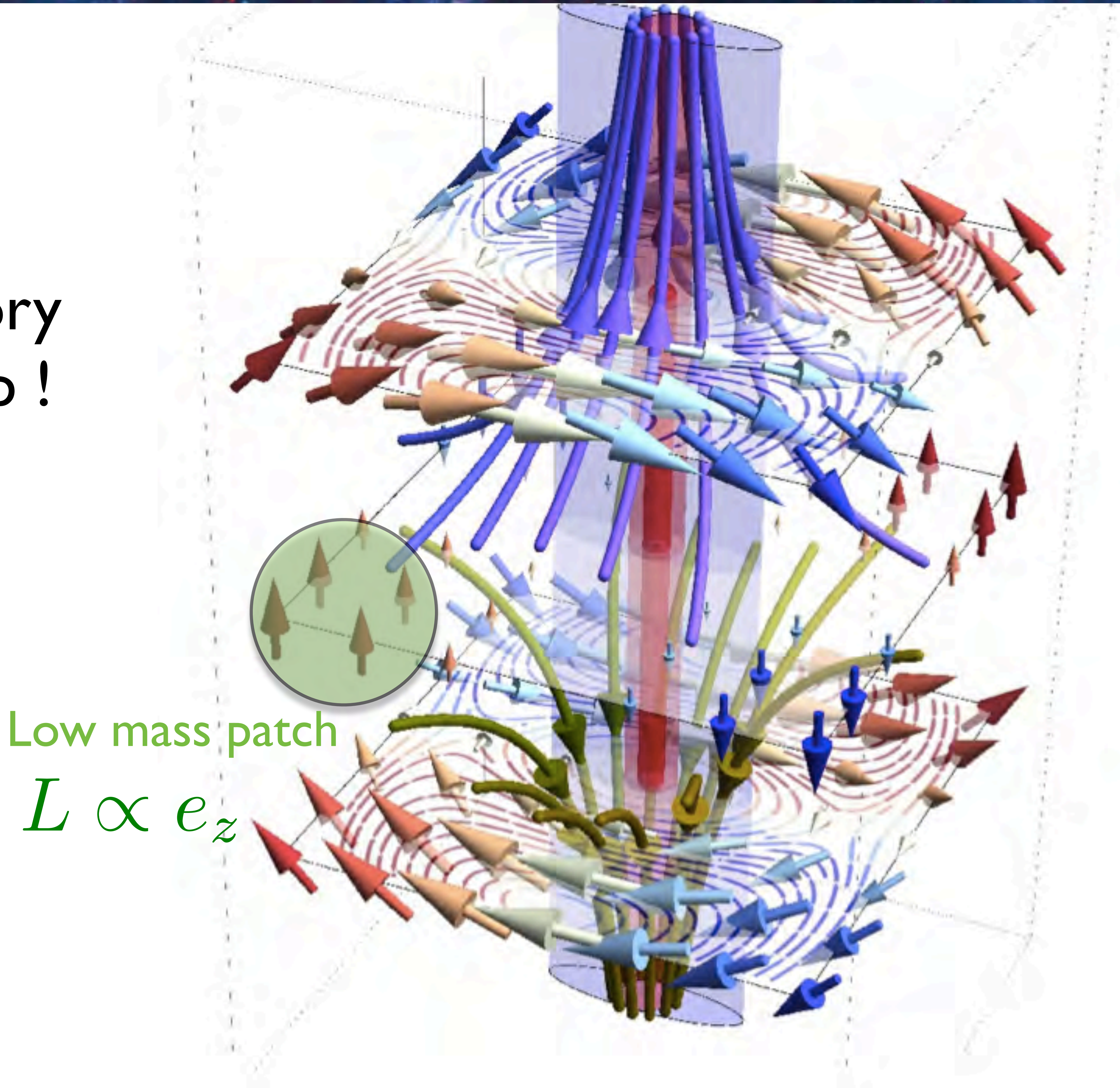


spatial transition+ **ROI smaller**

Spin flip along filament: transition mass

Lagrangian theory capture spin flip !

Transition mass associated with **size** of quadrant



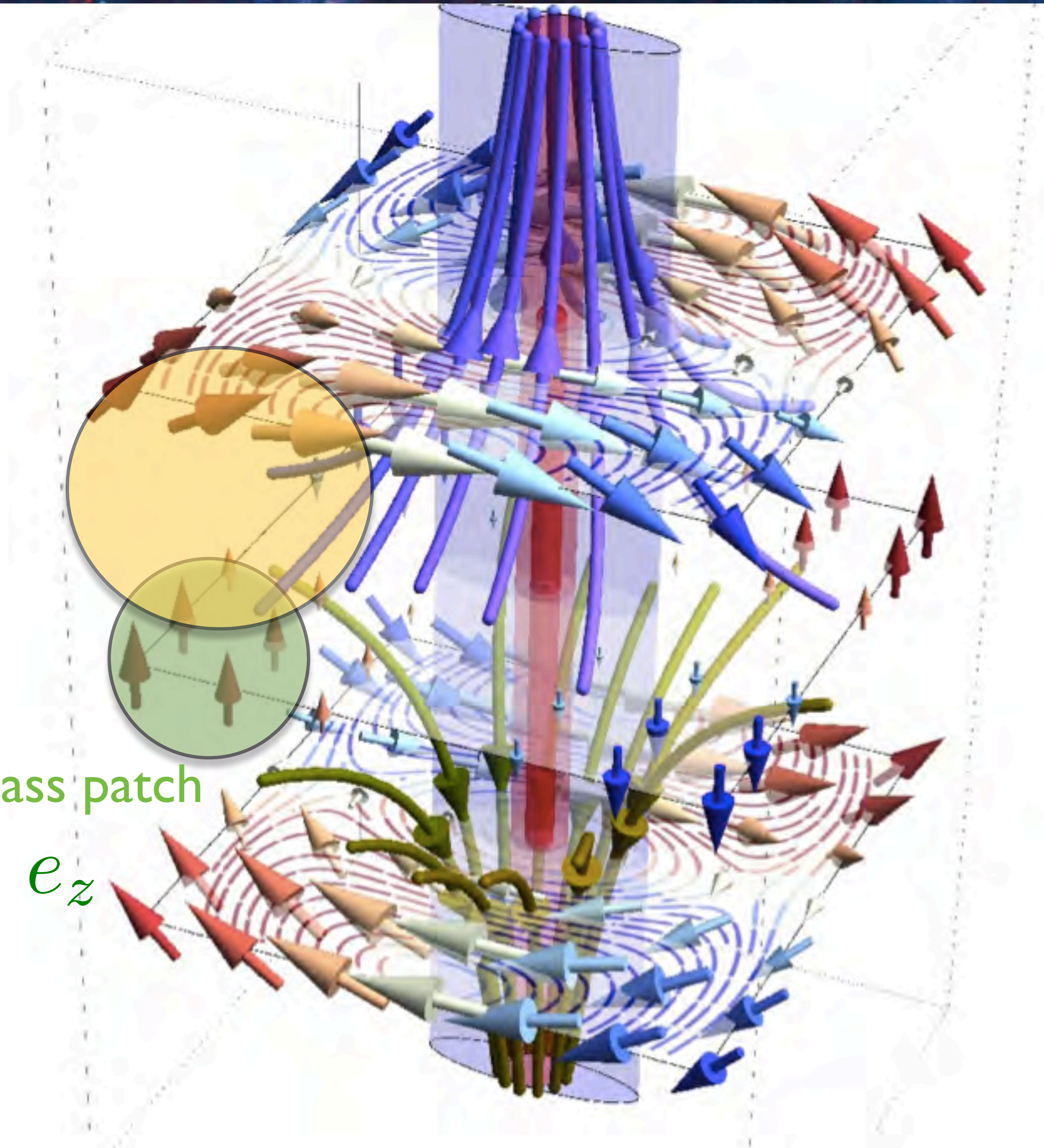
Spin flip along filament: transition mass

Lagrangian theory capture spin flip !

Transition mass associated with **size** of quadrant

Low mass patch

$L \propto e_z$



Spin flip along filament: transition mass

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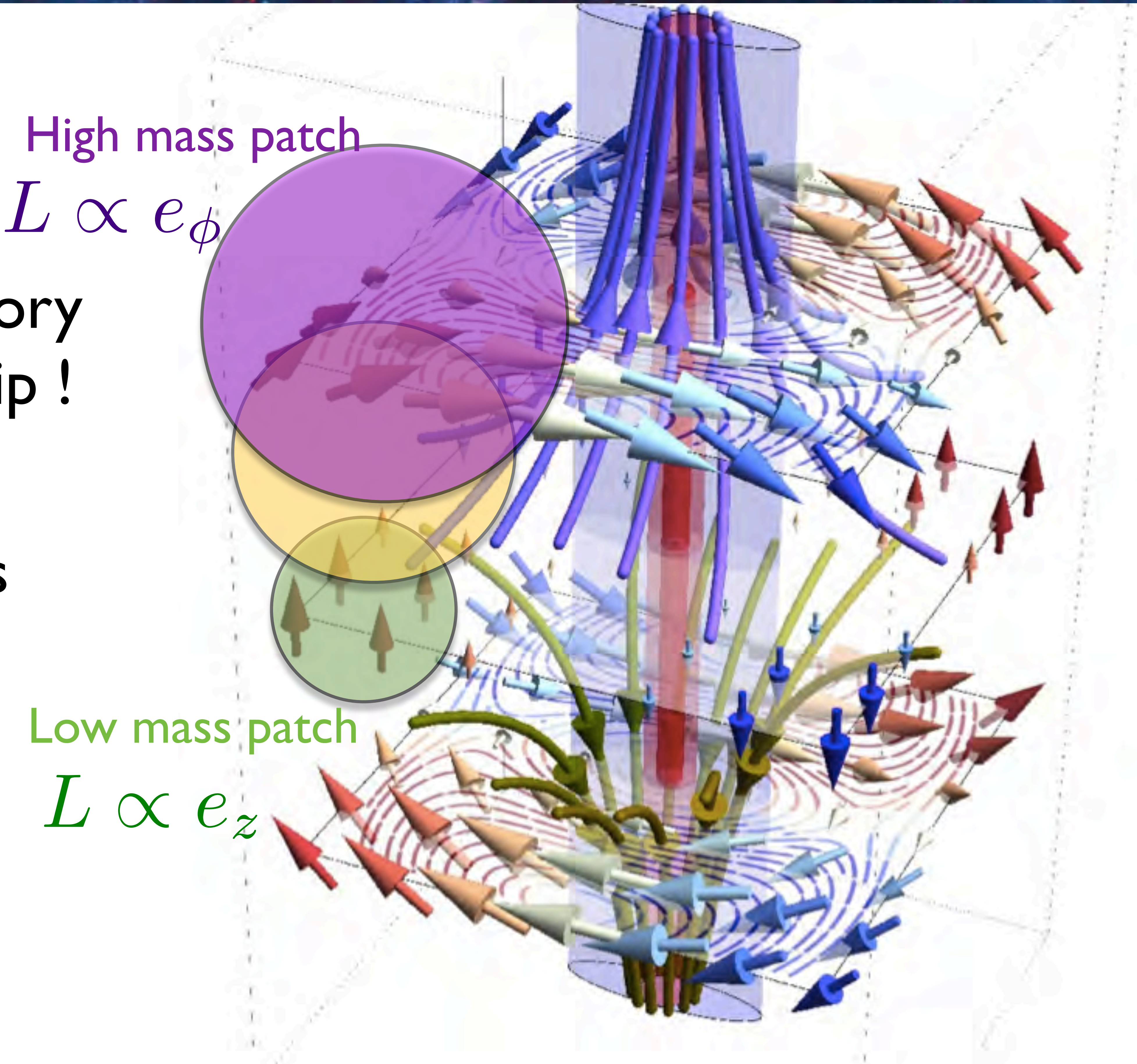
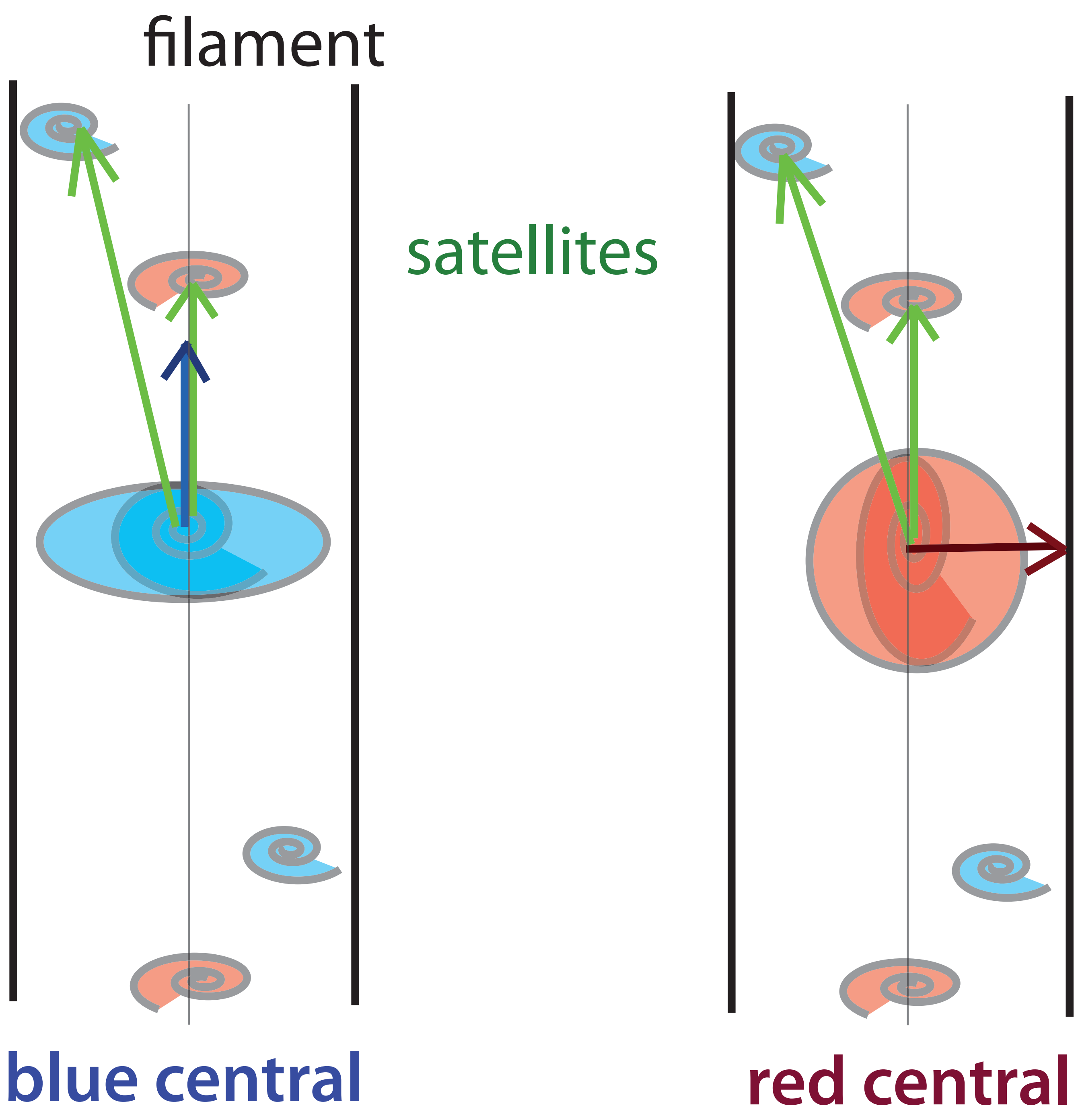
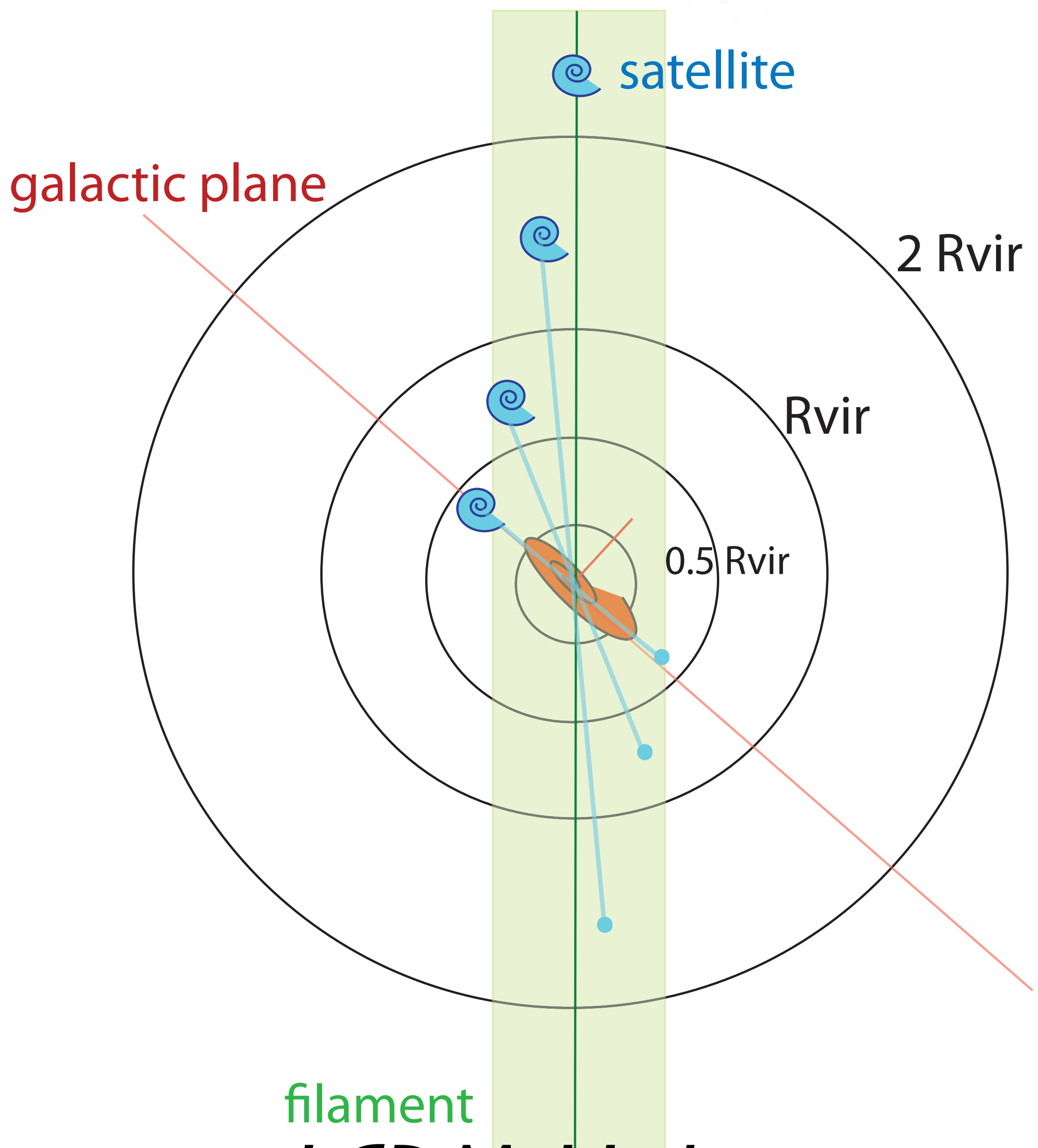


Geometry of flow: Satellite view

Helicity rich satellite distribution consistent with filamentary polar accretion towards flipped central





LCDM: Hydro

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.

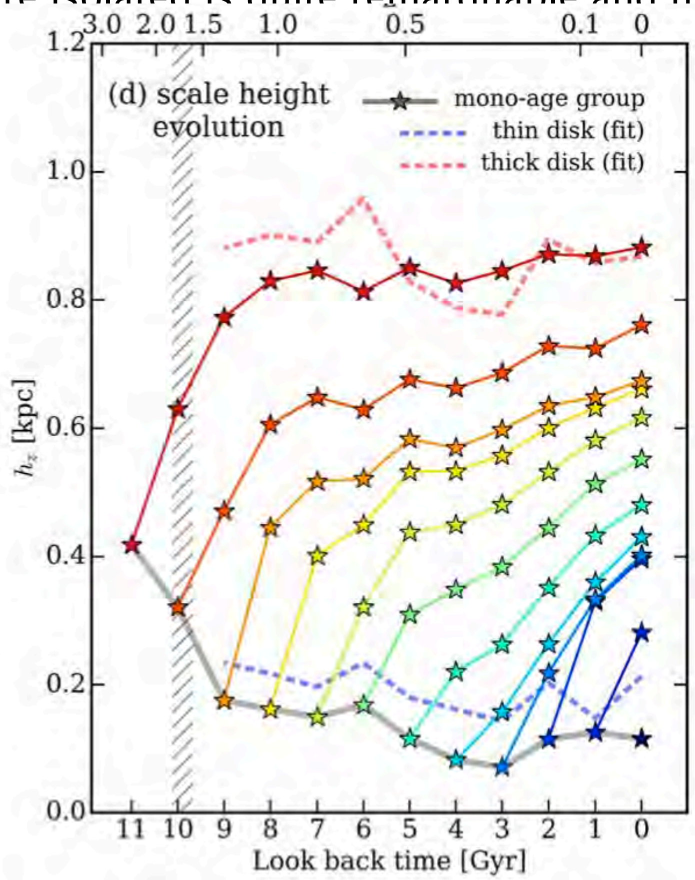


Figure 10. Evolution of the vertical distribution of the disk in the GALACTICA galaxy. (a) The instantaneous SFR as a function of redshift. (b) The evolution of the V/σ of the cold gas in the galaxy. (c) The evolution of disk scale length (R_d) of the galaxy. (d) The scale height evolution of mono-age 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.