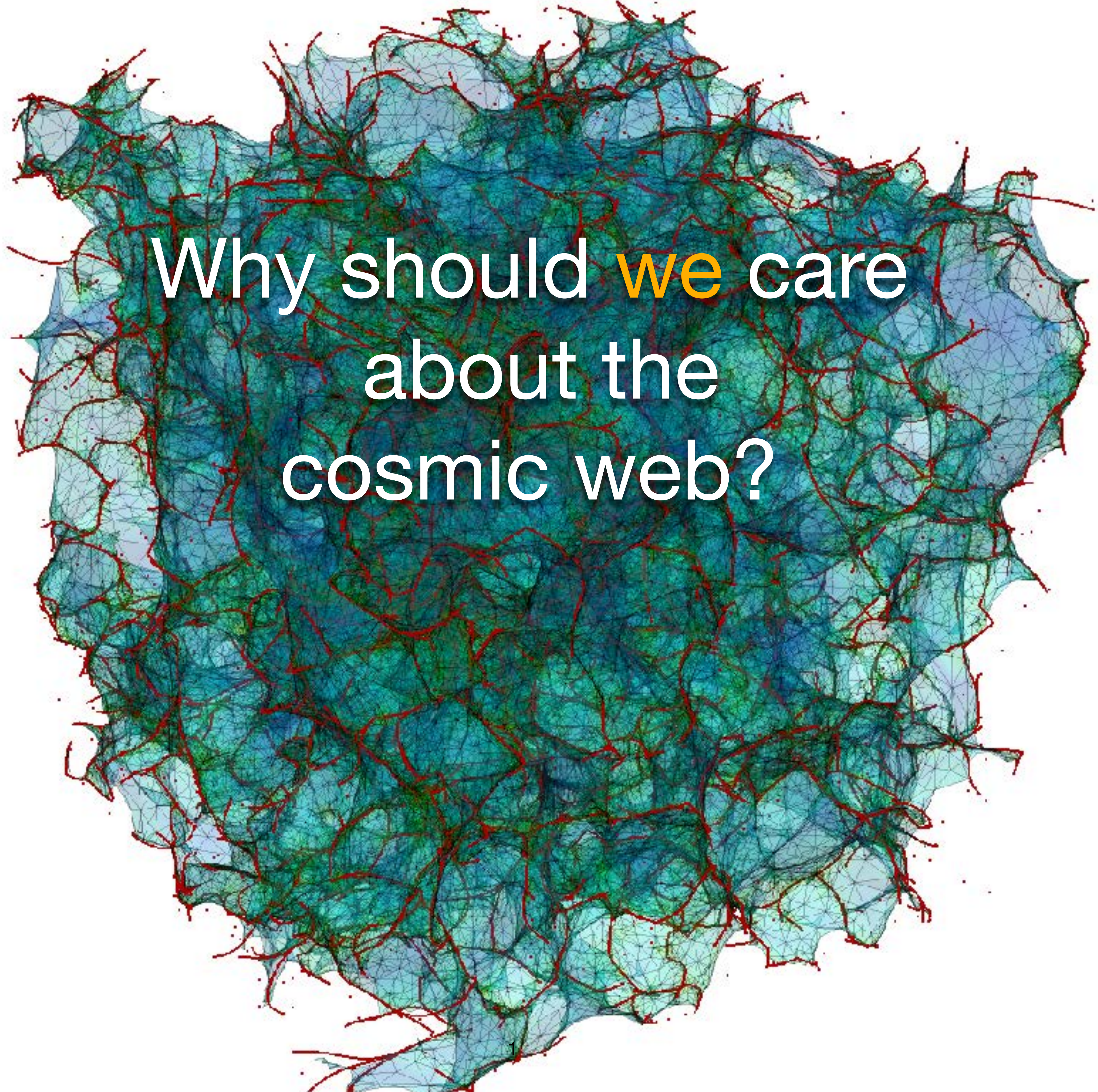
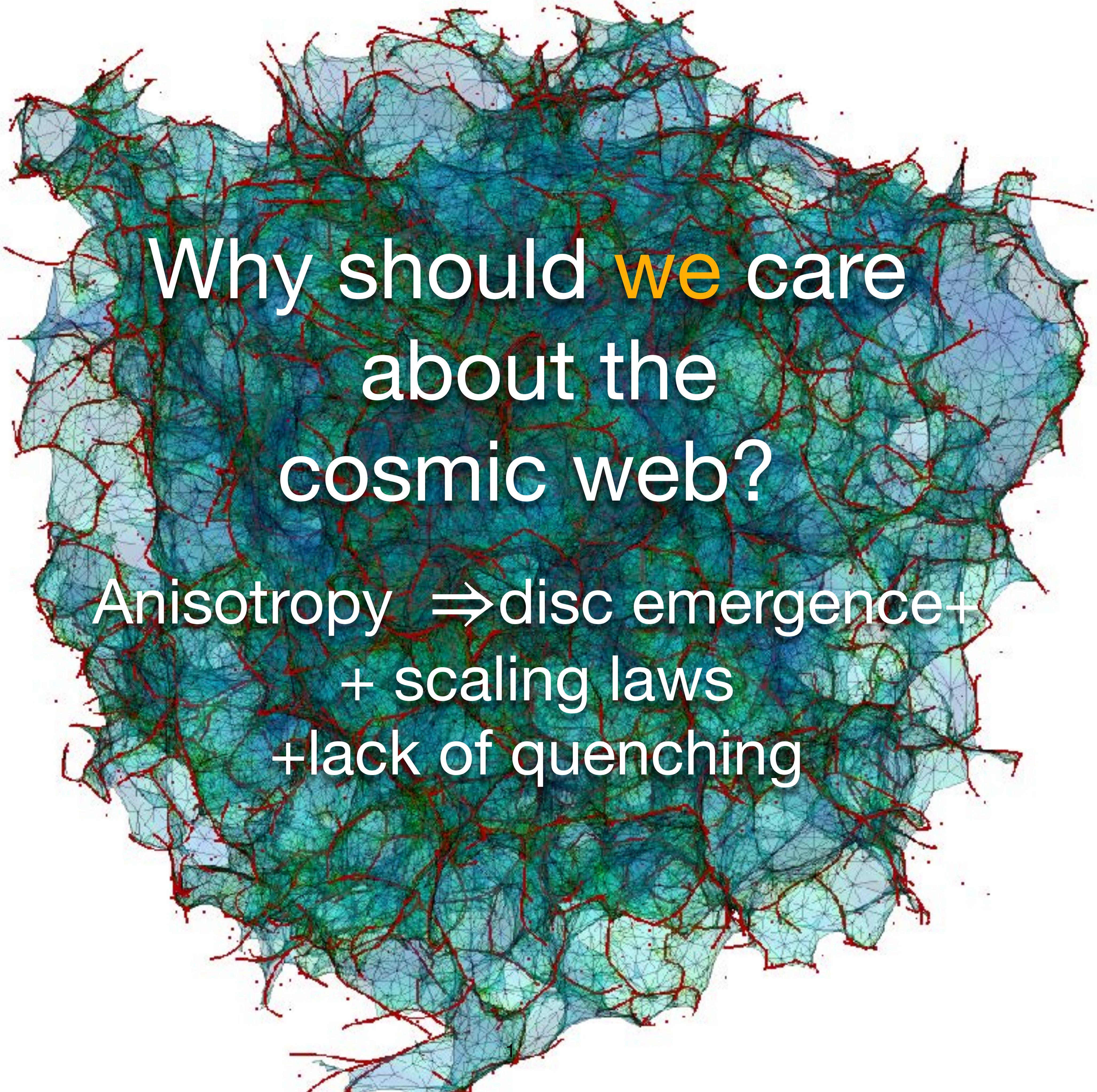
Why should we care about the cosmic web?



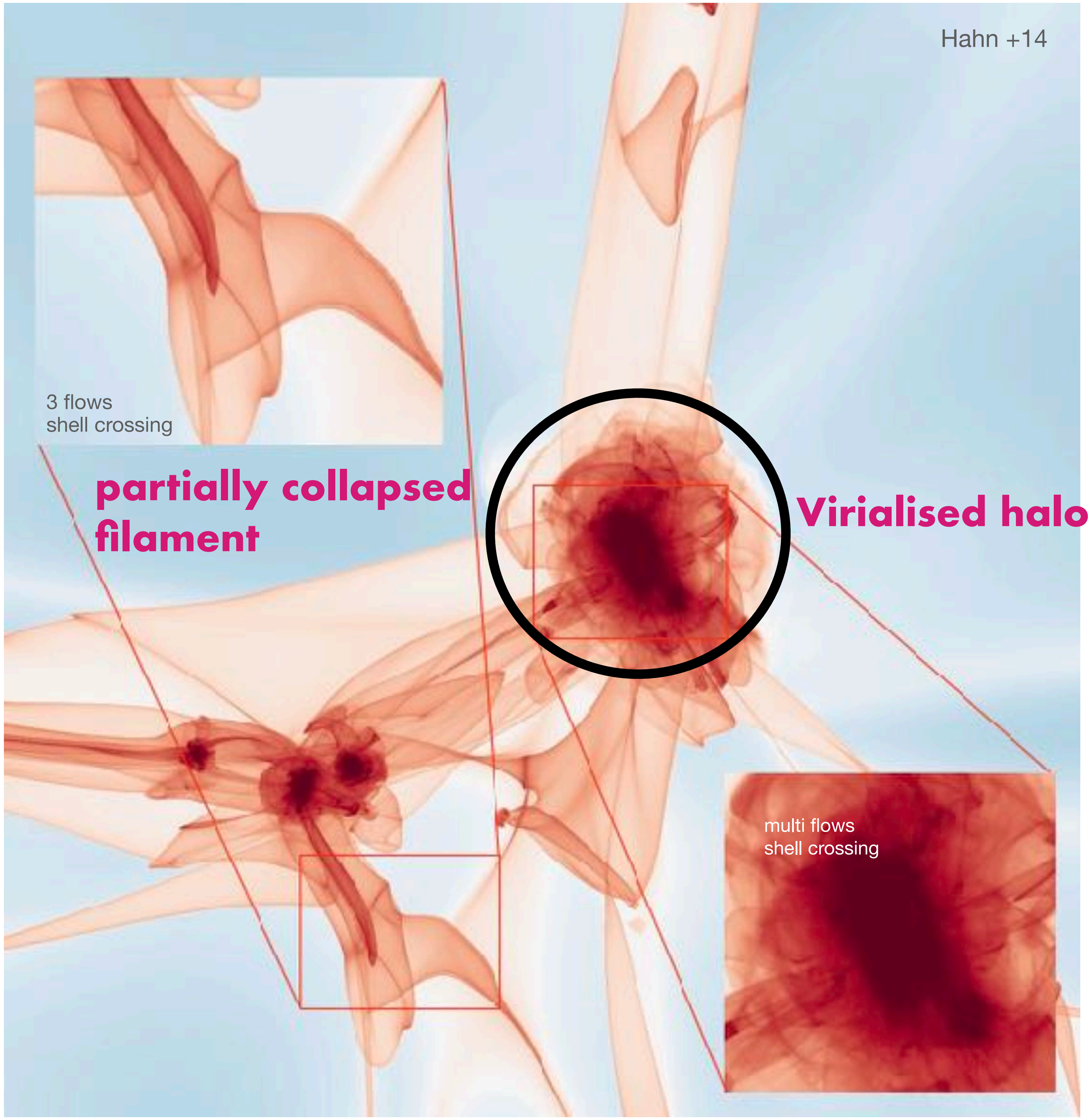


Why should we care about the cosmic web?

Anisotropy ⇒disc emergence+
+ scaling laws
+lack of quenching

1. What is the cosmic web?

The cosmic web is a dynamically relevant intermediate-density boundary between cosmology and galaxy formation.



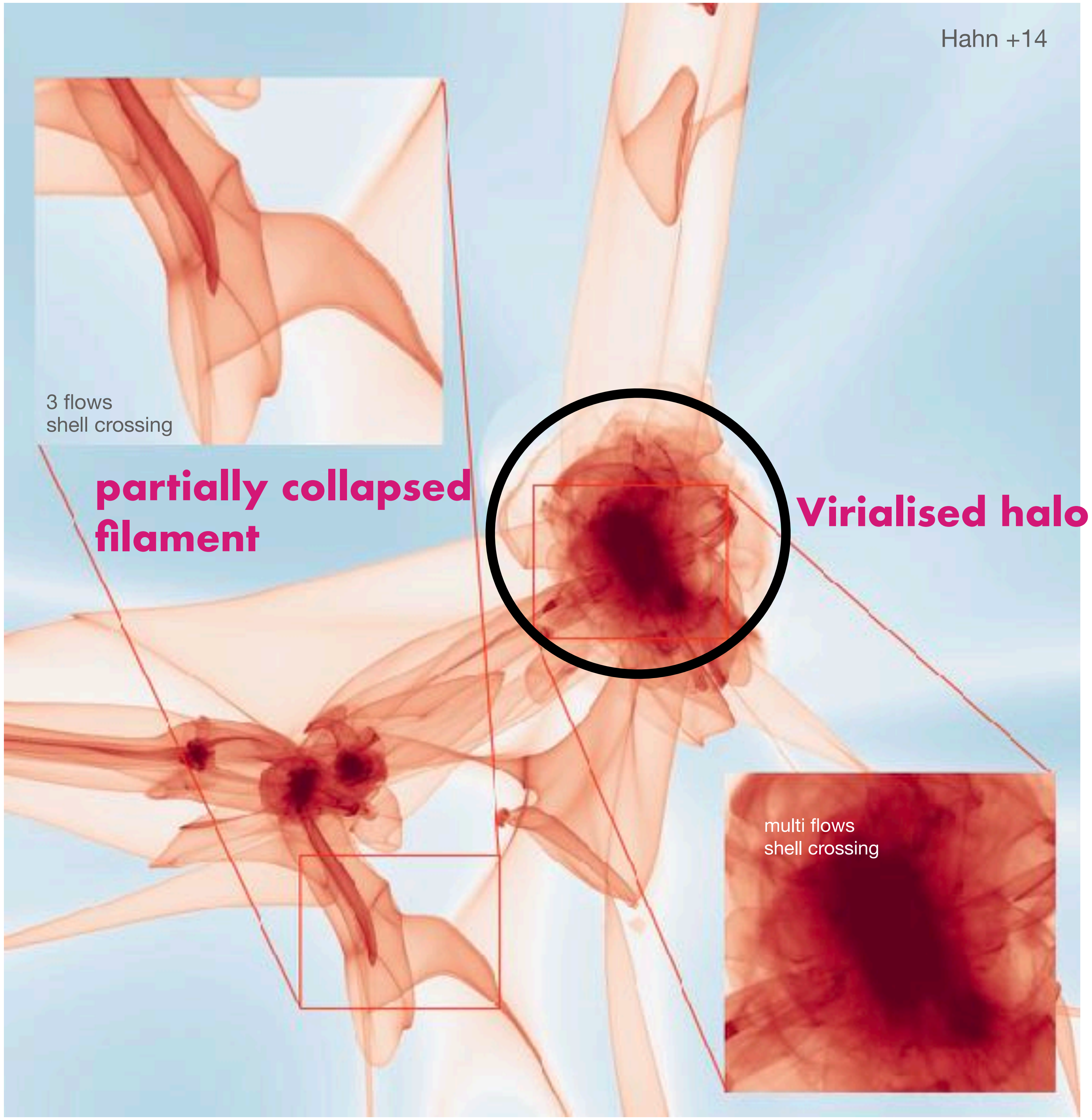
When halo collapse, neighbouring filaments+walls are in place.

1. What is the cosmic web?

~~The cosmic web is a dynamically relevant intermediate-density boundary between cosmology and galaxy formation.~~

Since it exists on many scales

The cosmic web is a dynamically relevant anisotropic (=spin 2) boundary between a given scale and a larger scale.



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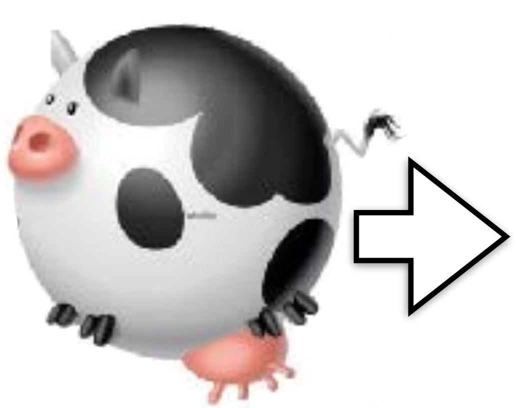
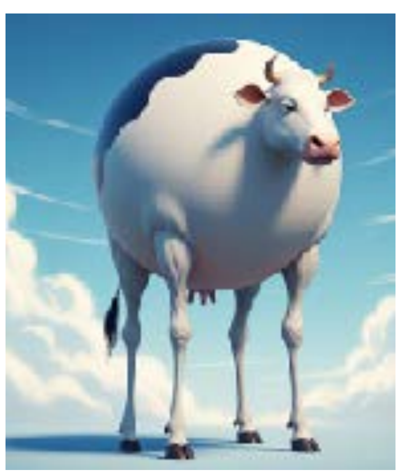
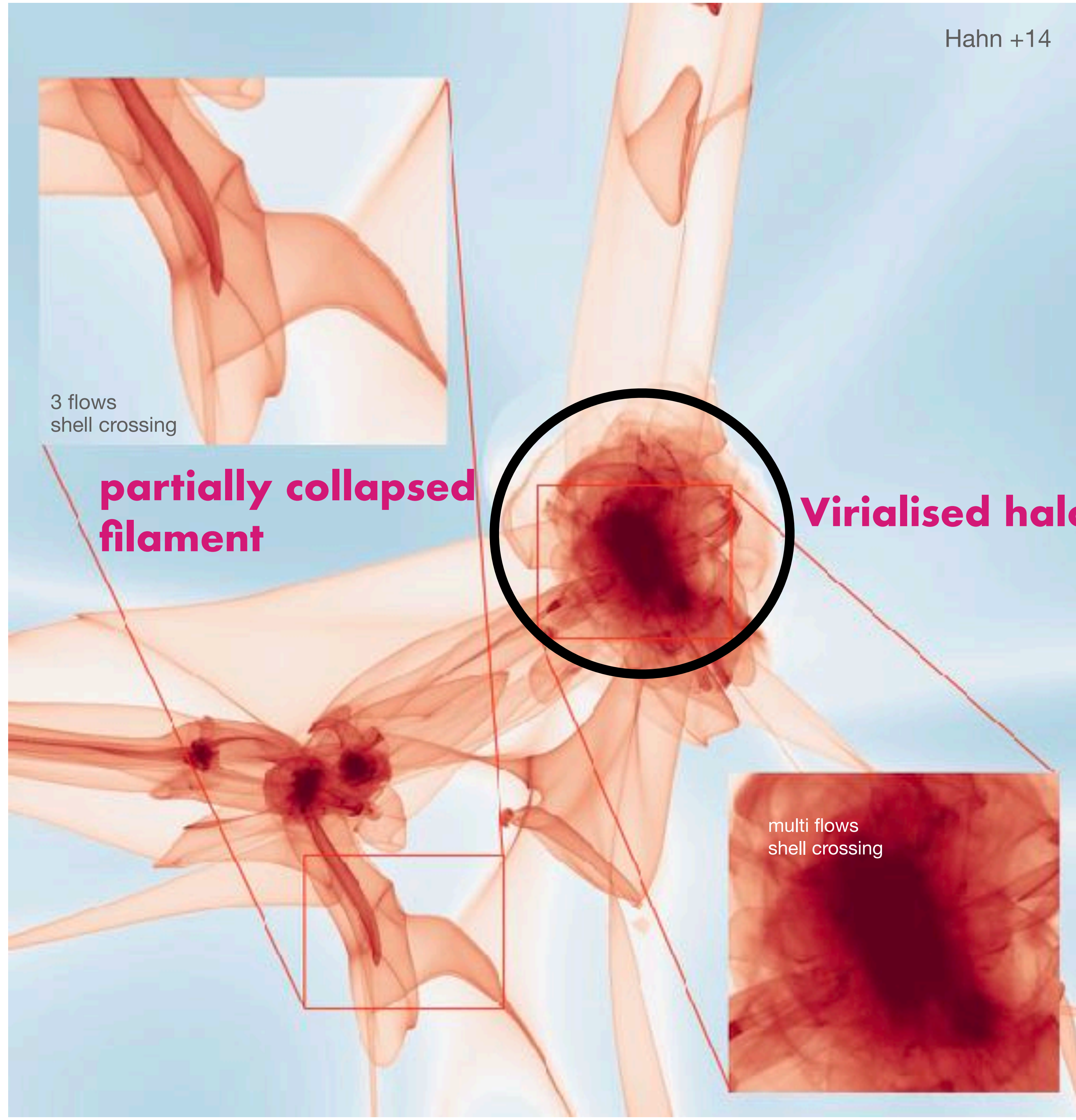




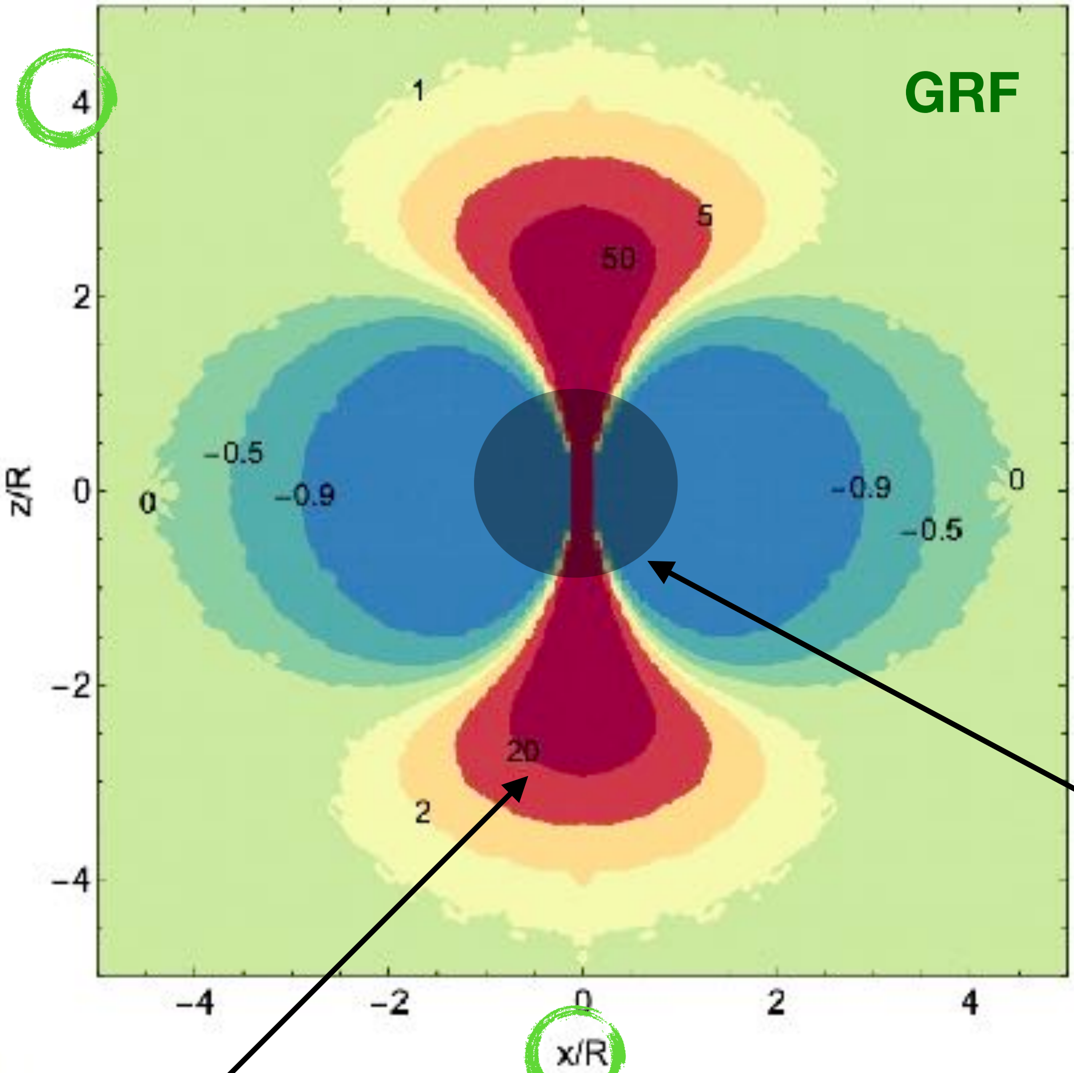


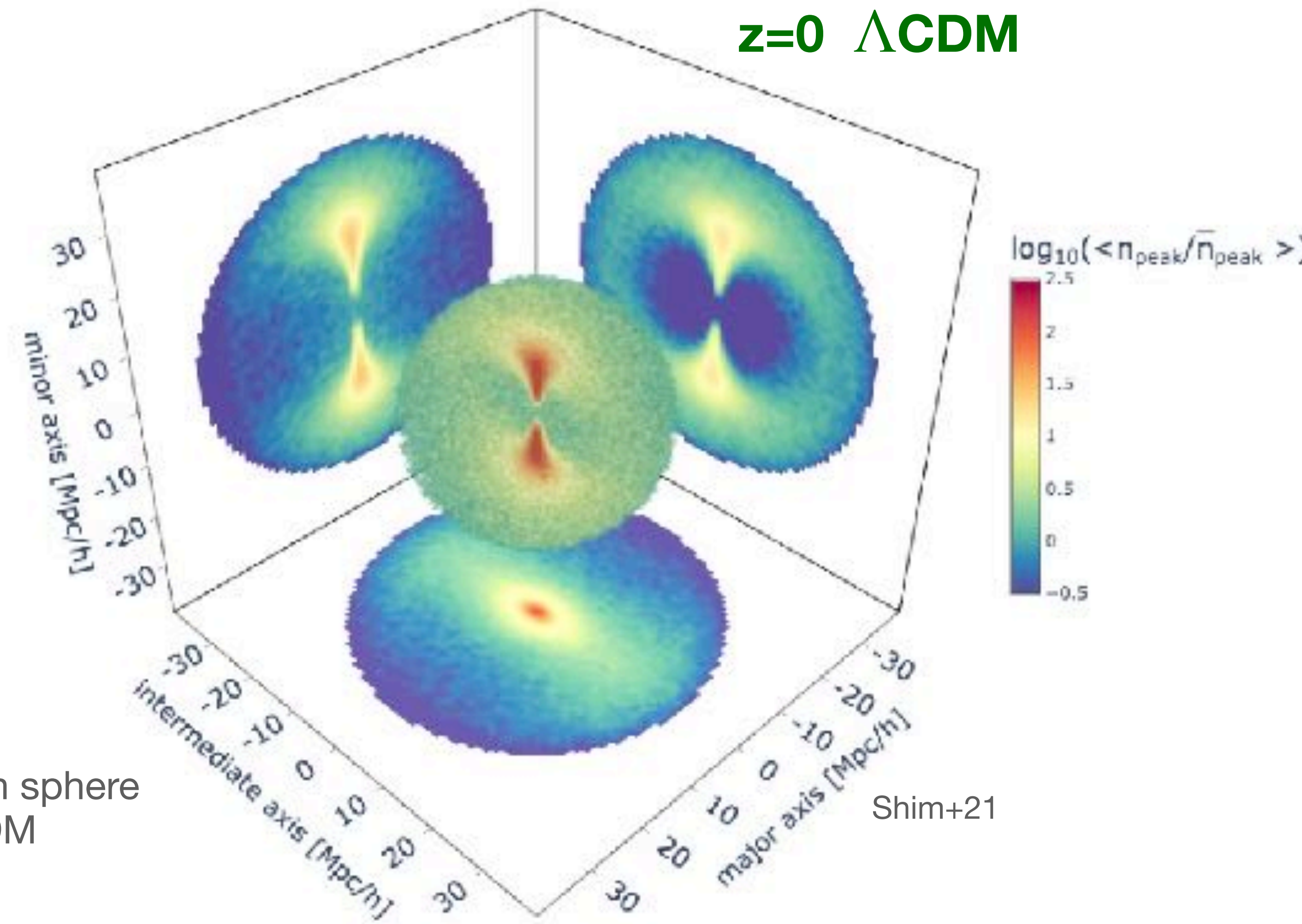
We must consider peaks dressed by their sets of (wall + filament) saddle critical pts.

1. What is the cosmic web? a spin-2 one-point process

$$\textbf{cosmic web} \approx \text{metric set by eigframe} \left[\frac{\partial^2\rho}{\partial x_i \partial x_j}\right]_{\rm sad}$$

More recently, alignment w.r.t. (filament or wall) saddle eigen-frame = spin-2 one-point process.





Cross correlation of peaks relative to a given saddle

long range: one should consider peaks dressed by neighbouring critical pts.

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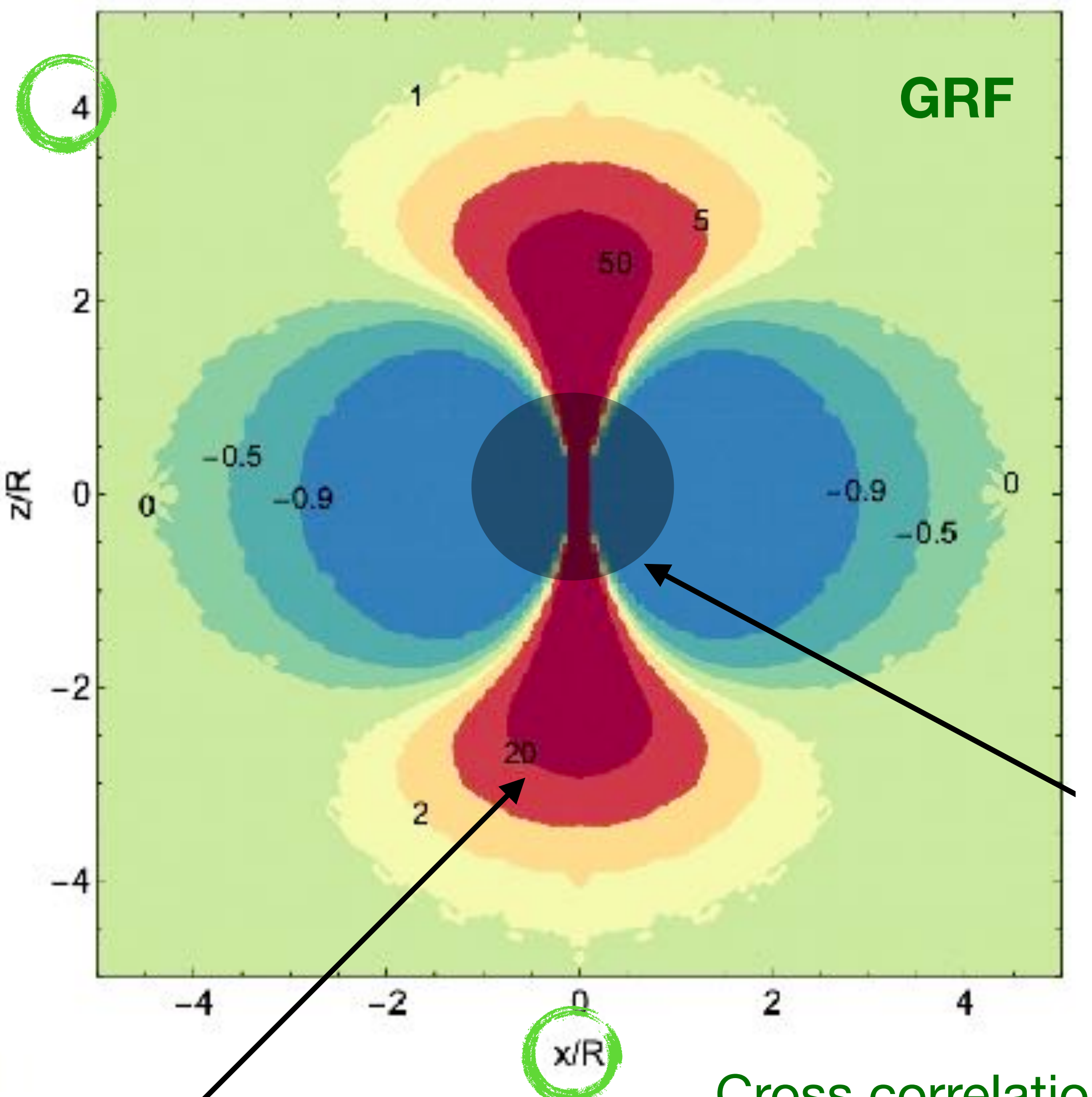

Correlation zone of saddle

upshot of talk: similar maps for

- tidal torque theory
- excursion set theory
- critical event theory
- **morphology theory**

Cross correlation of peaks relative to a given saddle

long range: one should consider peaks dressed by neighbouring critical pts.

revisit

- tidal torque theory
- excursion set theory
- critical event theory
- morphology theory

- CW metric changes (=biases) anisotropically the mean and variance of infall+fluctuations = specific signature of CW
- implication for Galaxy morphology/metallicity?
- implication for tightness of scaling laws?

Morphology = orbital structure of the stellar component

On secular timescales, morphological transformation = change of orbital structure

Level of noise depends on environment → morphology depends on environment

revisit

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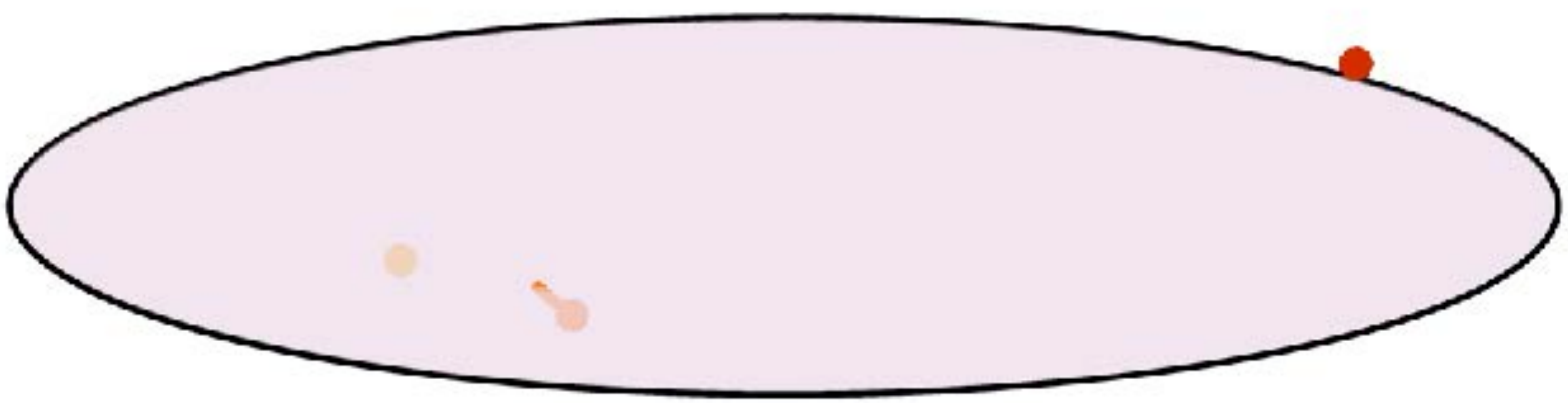

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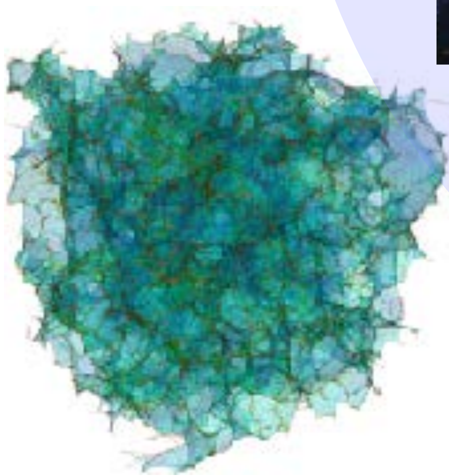
Galaxies are multi-scale non-linearly asymmetrically coupled systems

$$t_{\rm dyn} = \frac{1}{\sqrt{\rho}_{\rm LSS}} \gg 1$$

Non-linear mode coupling brings coherence from LS to MS

$$t_{\rm dyn} = \frac{1}{\sqrt{\rho}_{\rm gal}} \sim 1$$

$$t_{\rm dyn} = \frac{1}{\sqrt{\rho}_{\rm ISM}} \ll 1$$



Non-linear mode coupling brings stochasticity from SS to MS

Why (naive) subgrid physics is a bad idea…

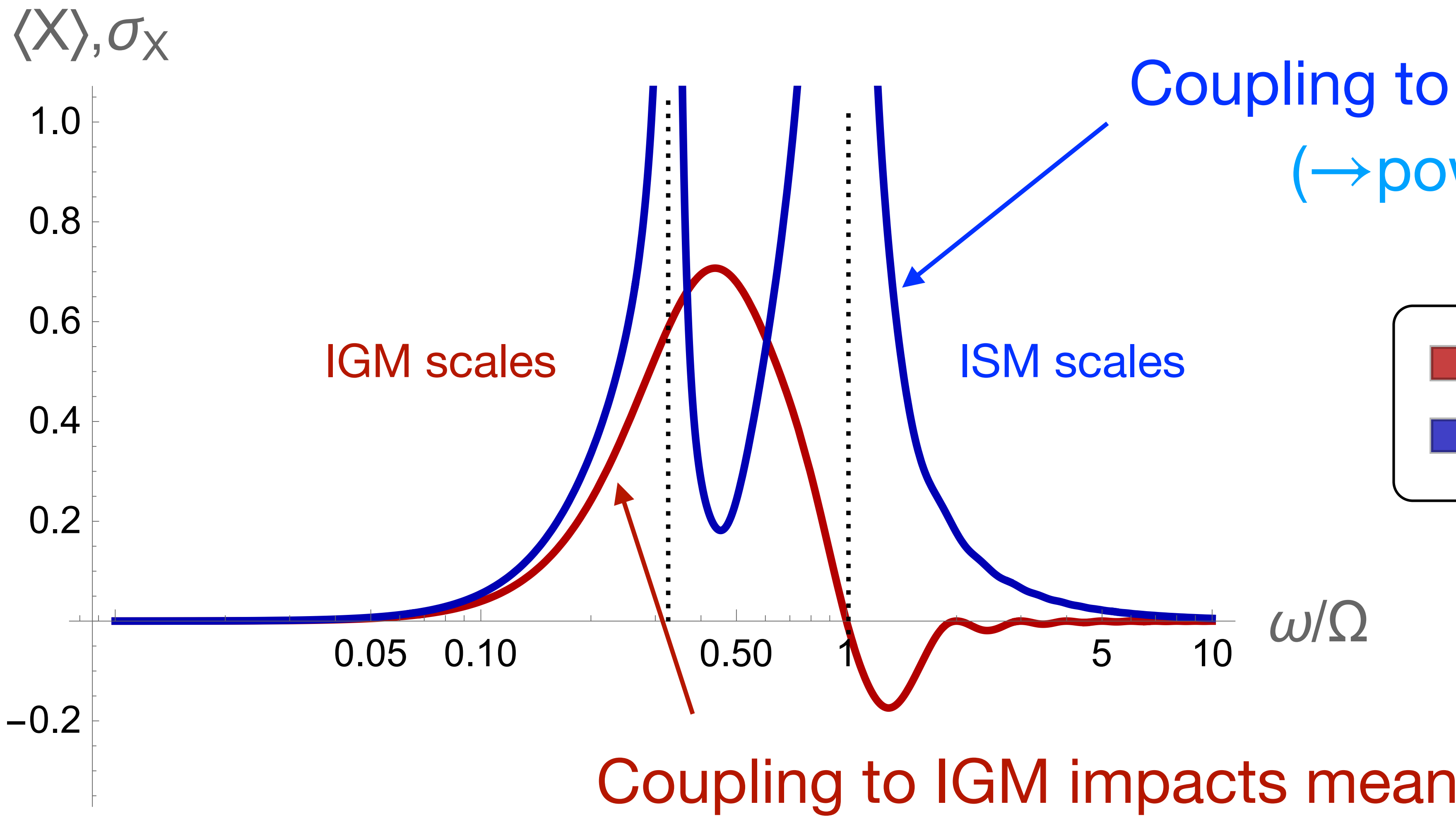
Galaxies are multi-scale non-linearly asymmetrically coupled systems

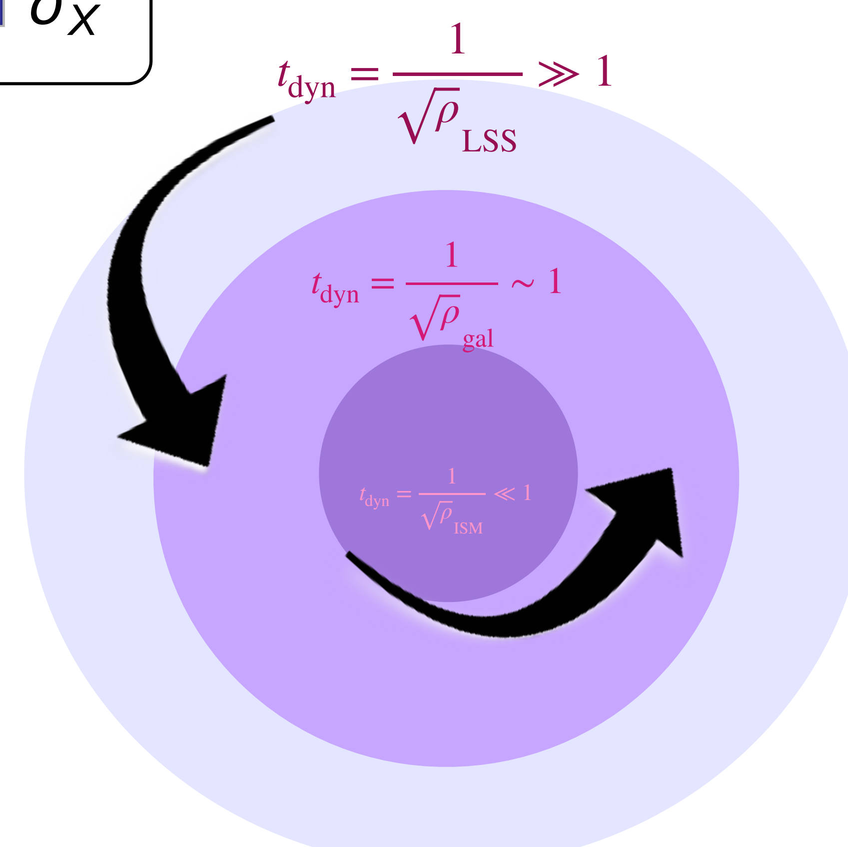
$$\boxed{\ddot{X} + \Omega^2 X = \epsilon X_{\rm env}^3} \quad \text{given} \quad \ddot{X}_{\rm env} + \omega^2 X_{\rm env} = 0$$

Natural frequency of galaxy

perturbative coupling to environment

Natural frequency of environment



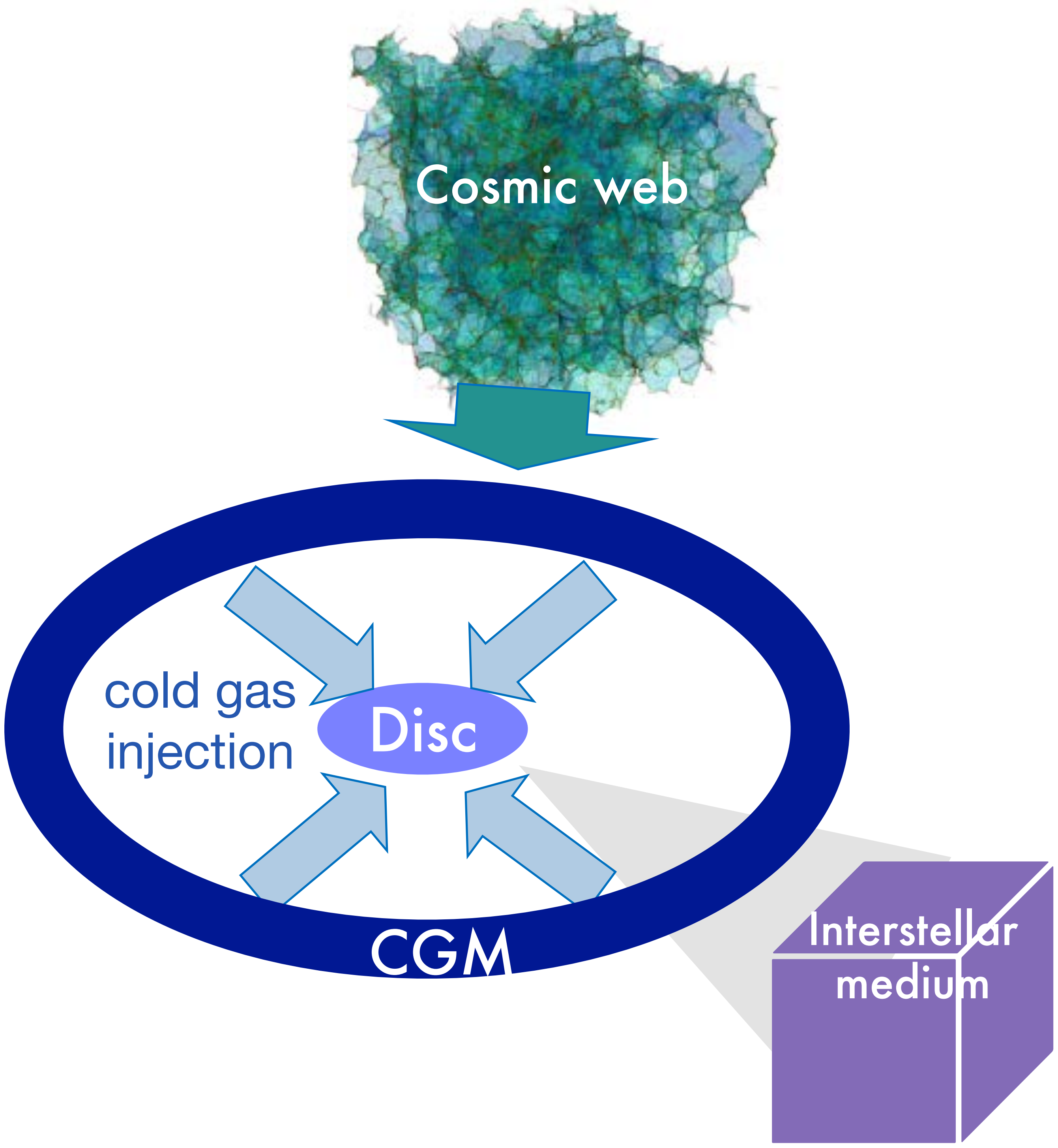


$$\langle X \rangle = \frac{\sin^2(3\pi\omega)}{12\pi\omega(3\omega-1)(3\omega+1)} - \frac{3\sin^2(\pi\omega)}{4\pi(\omega-1)\omega(\omega+1)}$$

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

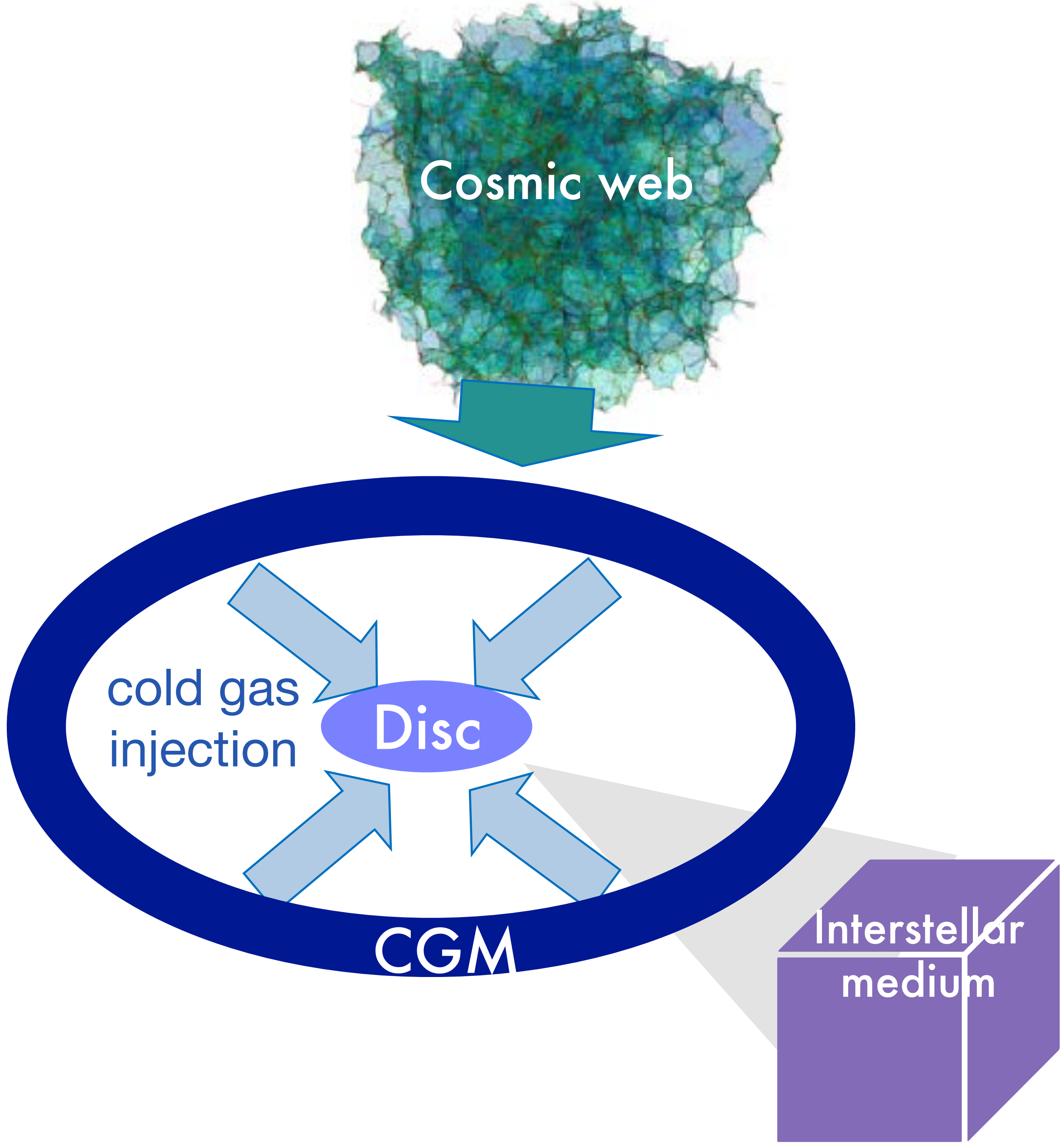
Why (naive) subgrid physics is a bad idea…

Impact of coupling to small scale on orbital structure: heating +cooling



Three components system coupled by gravitation.

Impact of coupling to small scale on orbital structure: heating +cooling



Heating

Stabilising effects

- SN1a
- Turbulence

———–

- Minor Mergers
- Misaligned infall
- FlyBys

Three components system coupled by gravitation.

Impact of coupling to small scale on orbital structure: heating +cooling

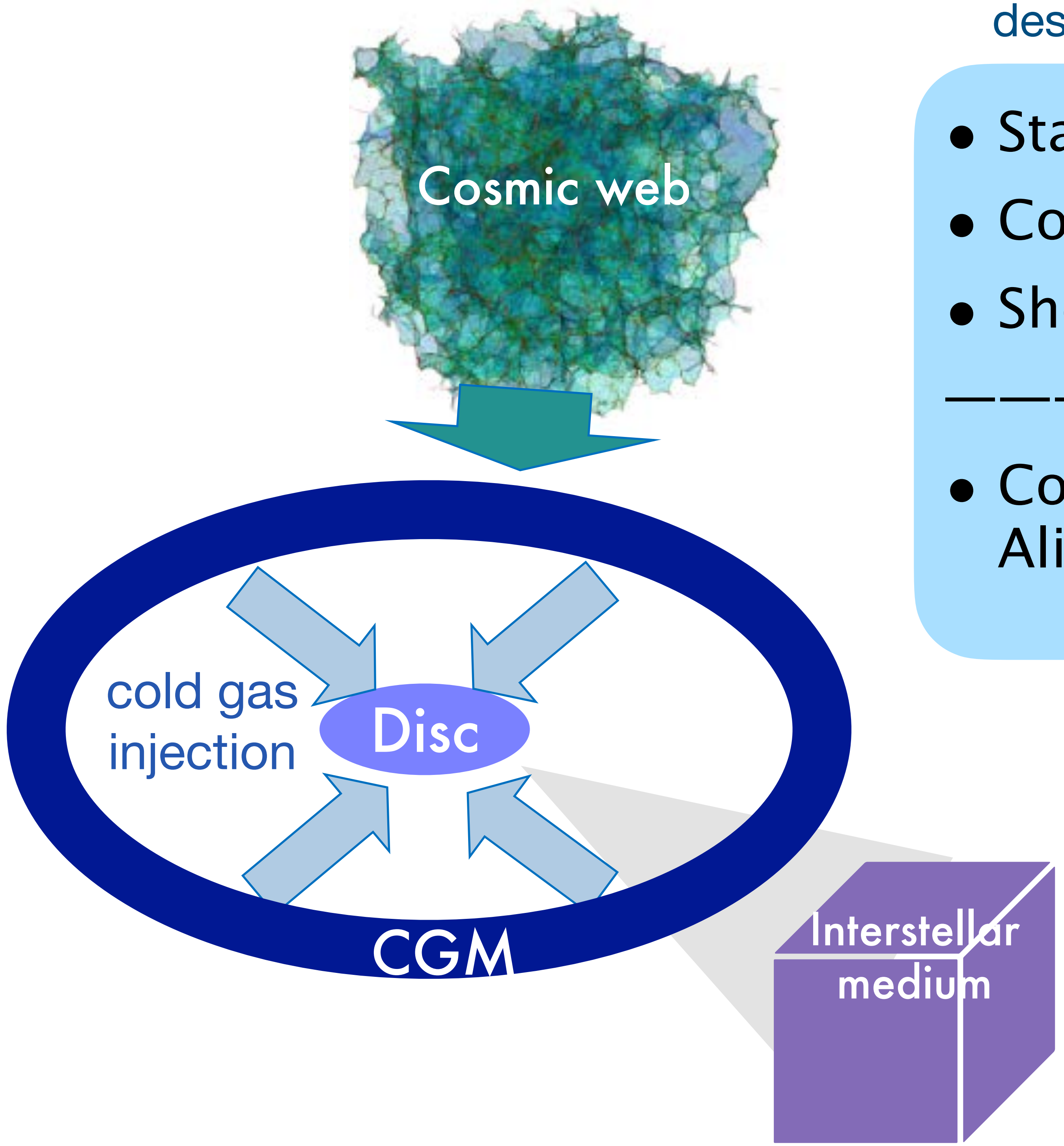
destabilising effects

- Star formation
- Cooling
- Shocks

———————

- Co-rotating Aligned infall

Cooling



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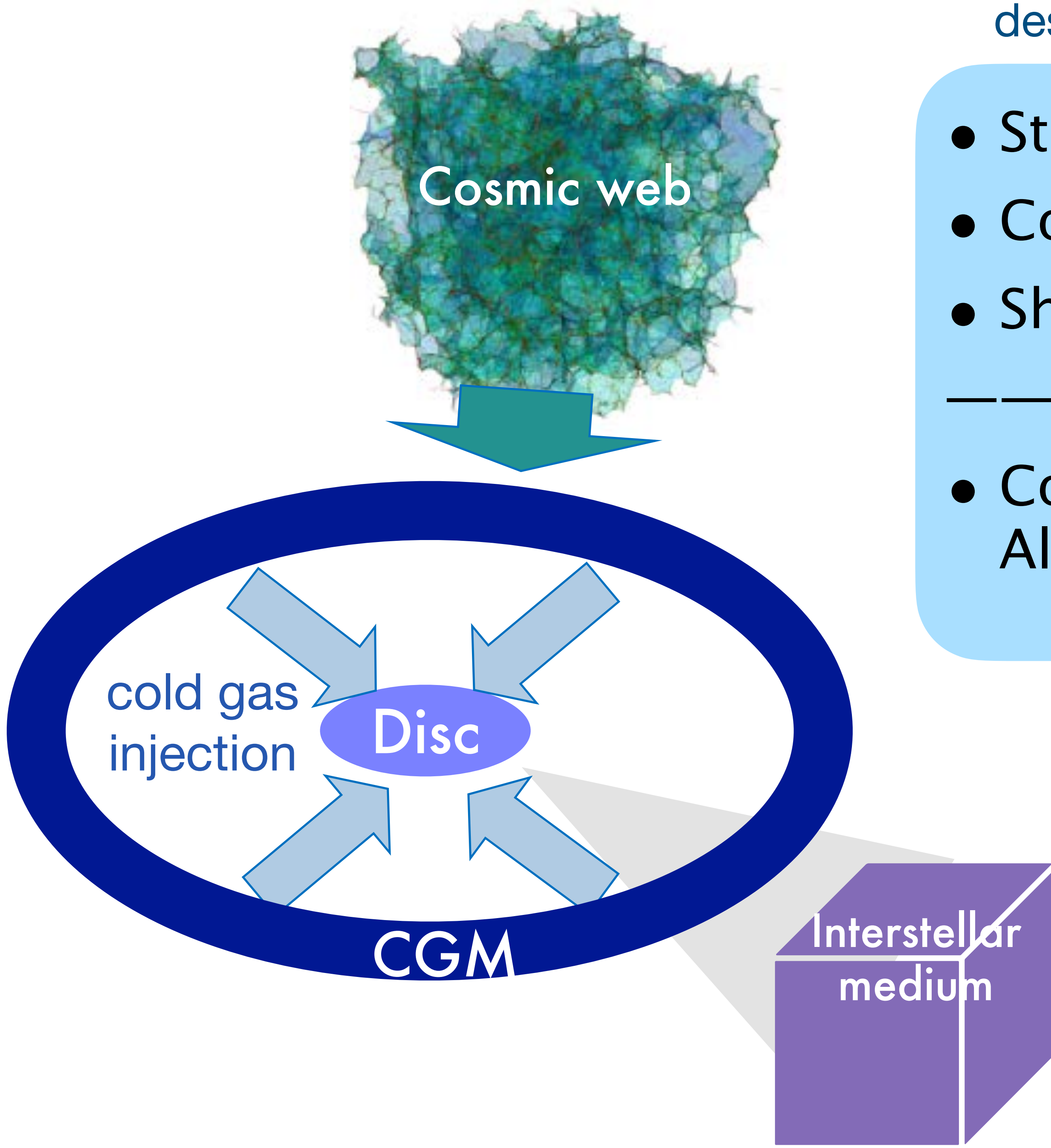

Heating

Stabilising effects

- SN1a
- Turbulence

————

- Minor Mergers
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Three components system coupled by gravitation.

Let us focus on heating…

Heating


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

revisit

- tidal torque theory
- excursion set theory
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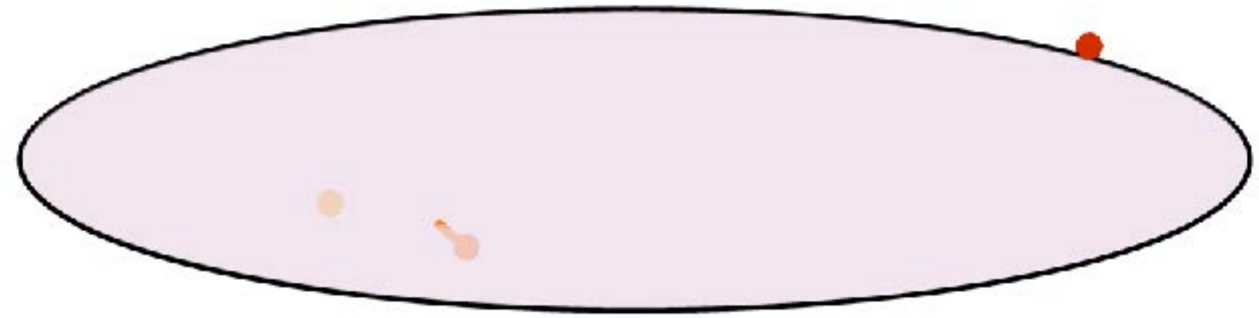
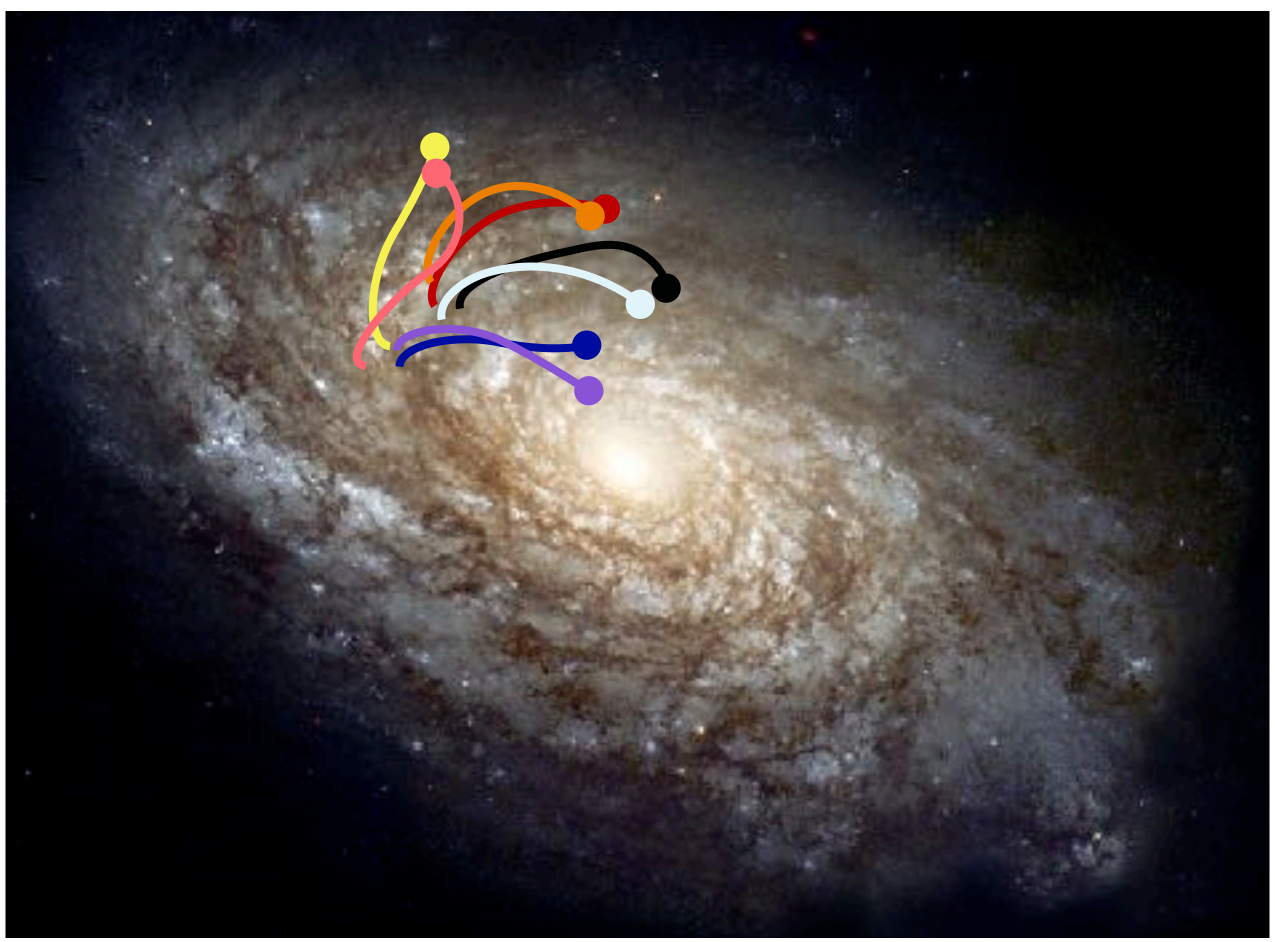
- morphology theory



Fluctuation-Dissipation Theorem

Diffusion rate	⟷	Power-spectrum of the fluctuations



$\approx$

Orbits in a galaxy

But temperature-driven wake : the colder the faster!

Ink in water

revisit

- tidal torque theory
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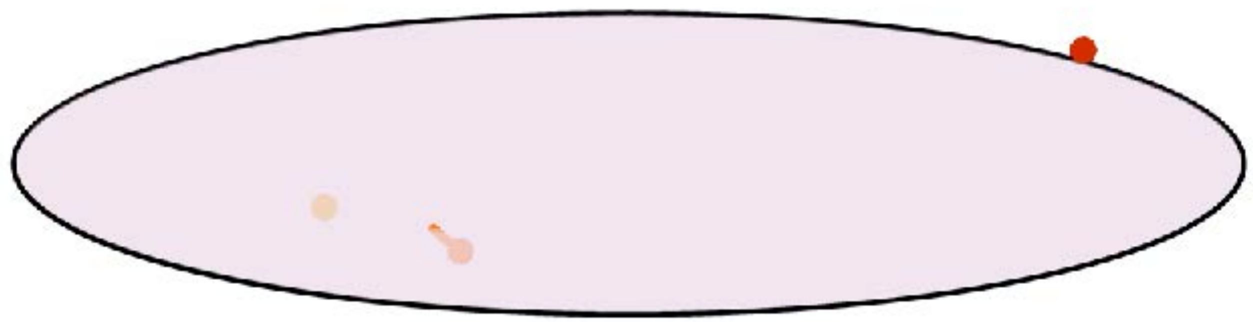

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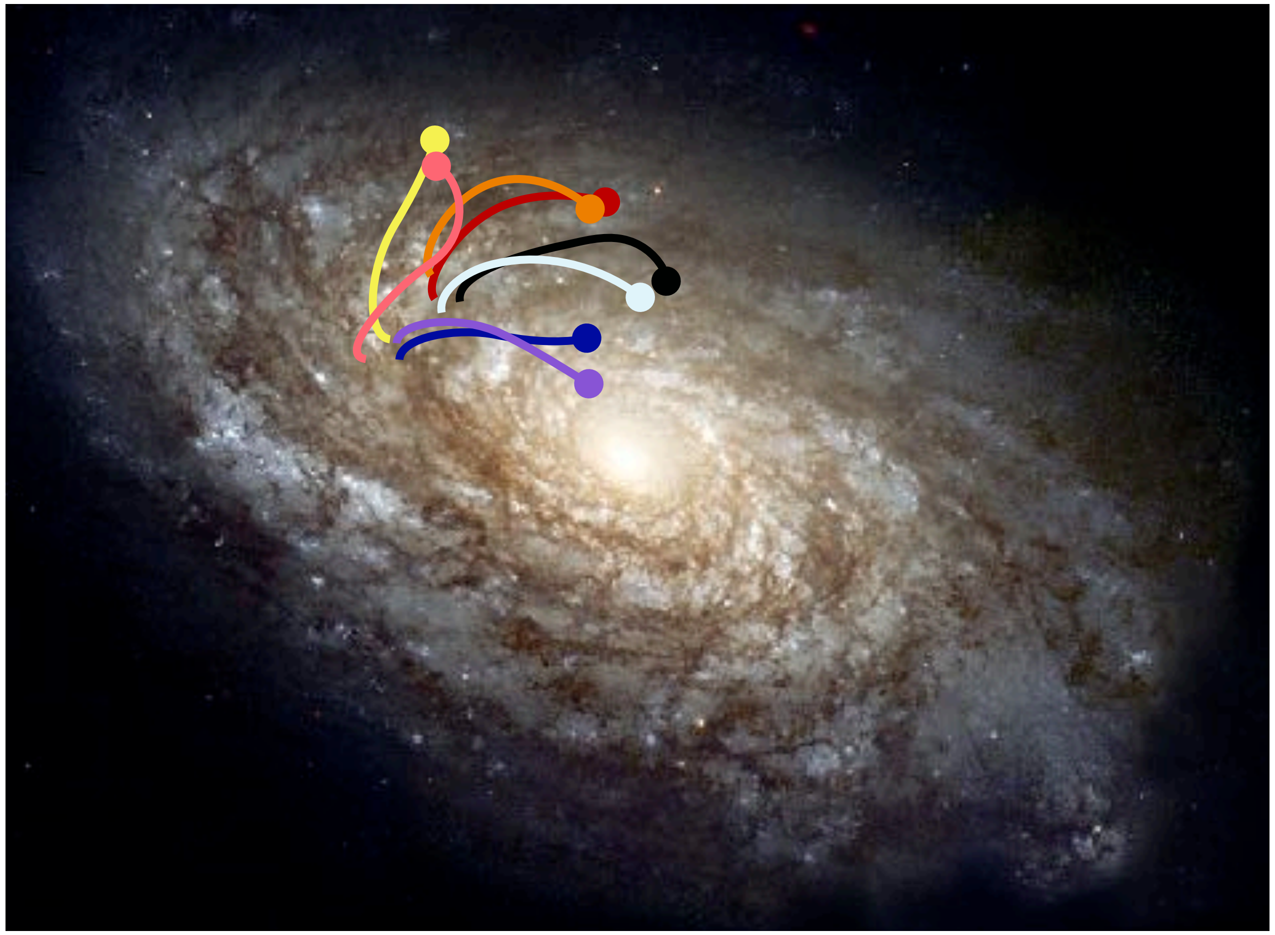

≈

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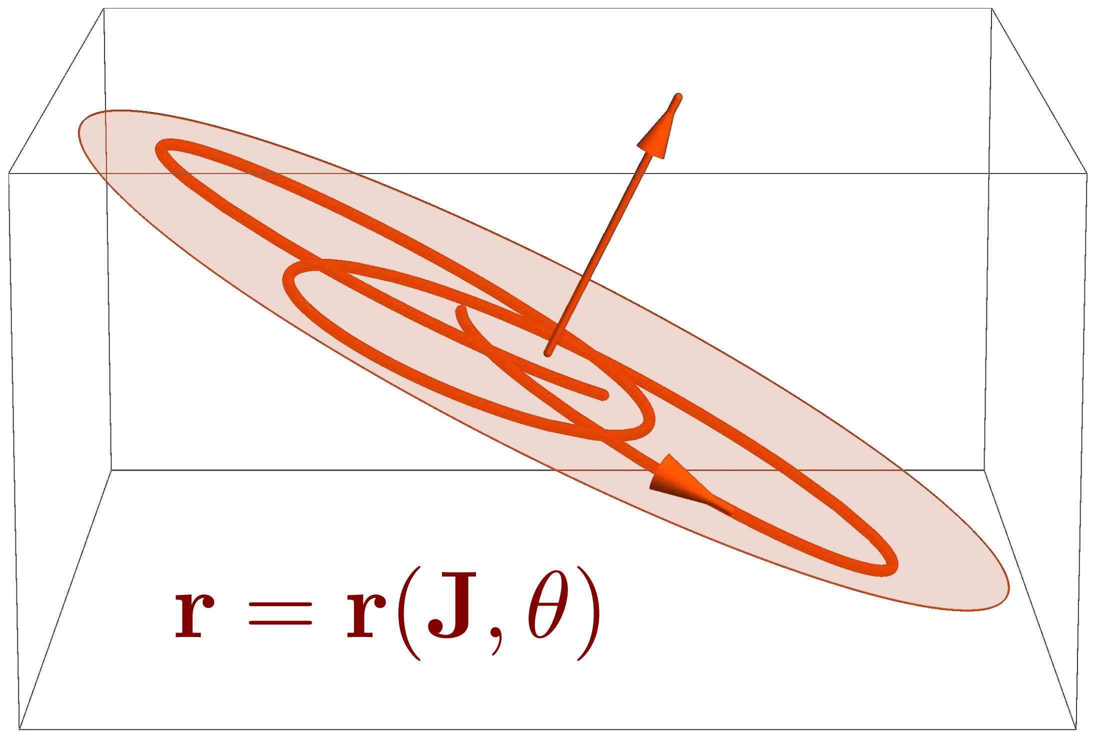
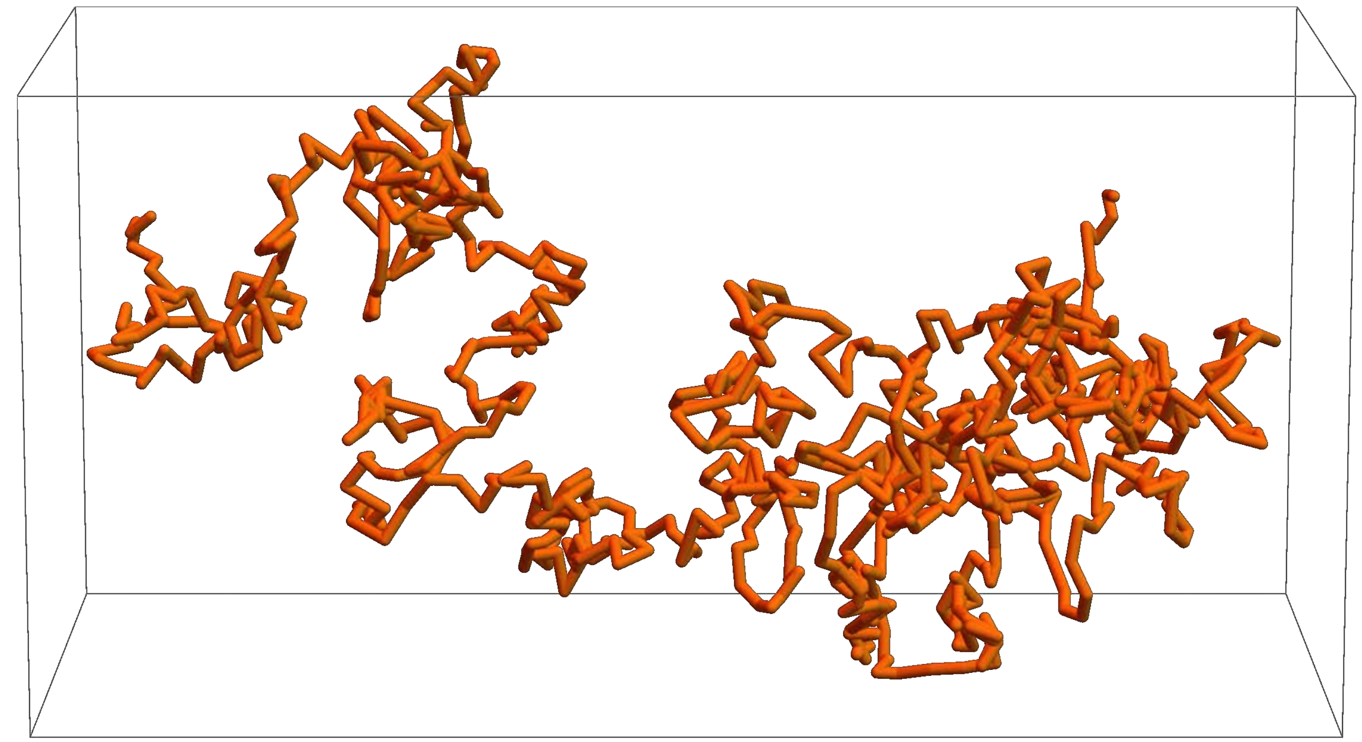
Along the unperturbed orbit



Potential fluctuate (stronger if resonances)

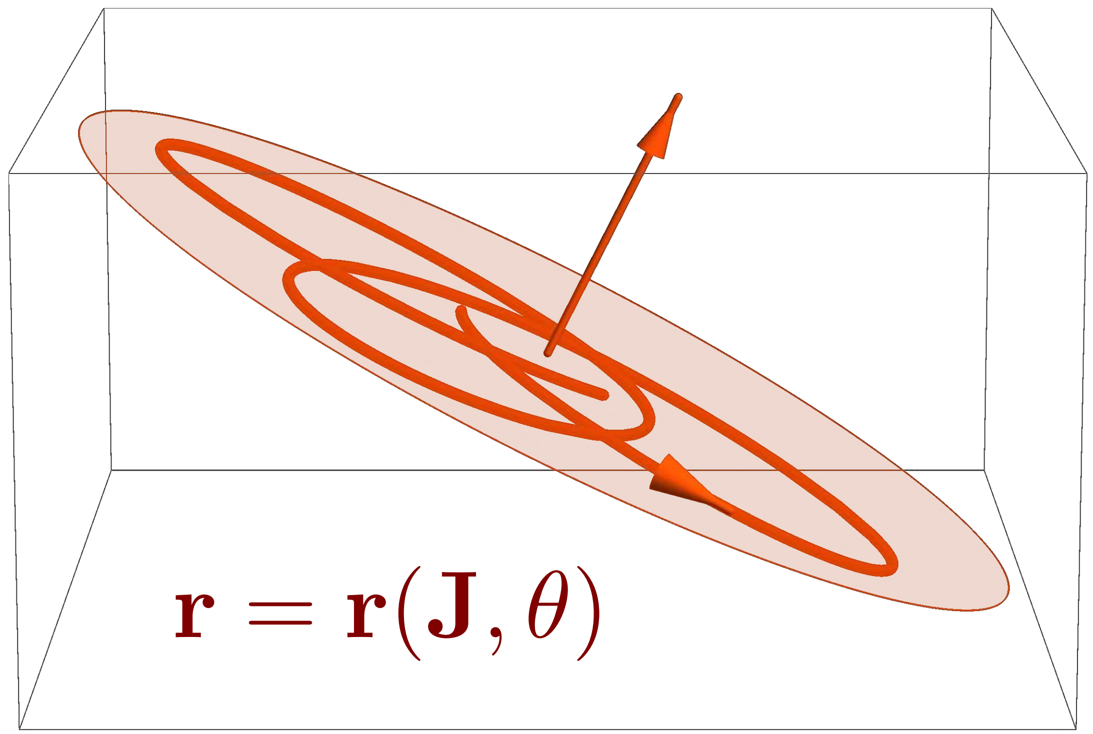


$$\delta\psi(\mathbf{r}, t) \rightarrow \sum_{\mathbf{m}} \delta\hat{\psi}_{\mathbf{m}}(\mathbf{J}, \omega) \exp\left(i\mathbf{m}\cdot\theta - \omega t\right)$$

Fluctuating potential

Harmonic component

Along the unperturbed orbit



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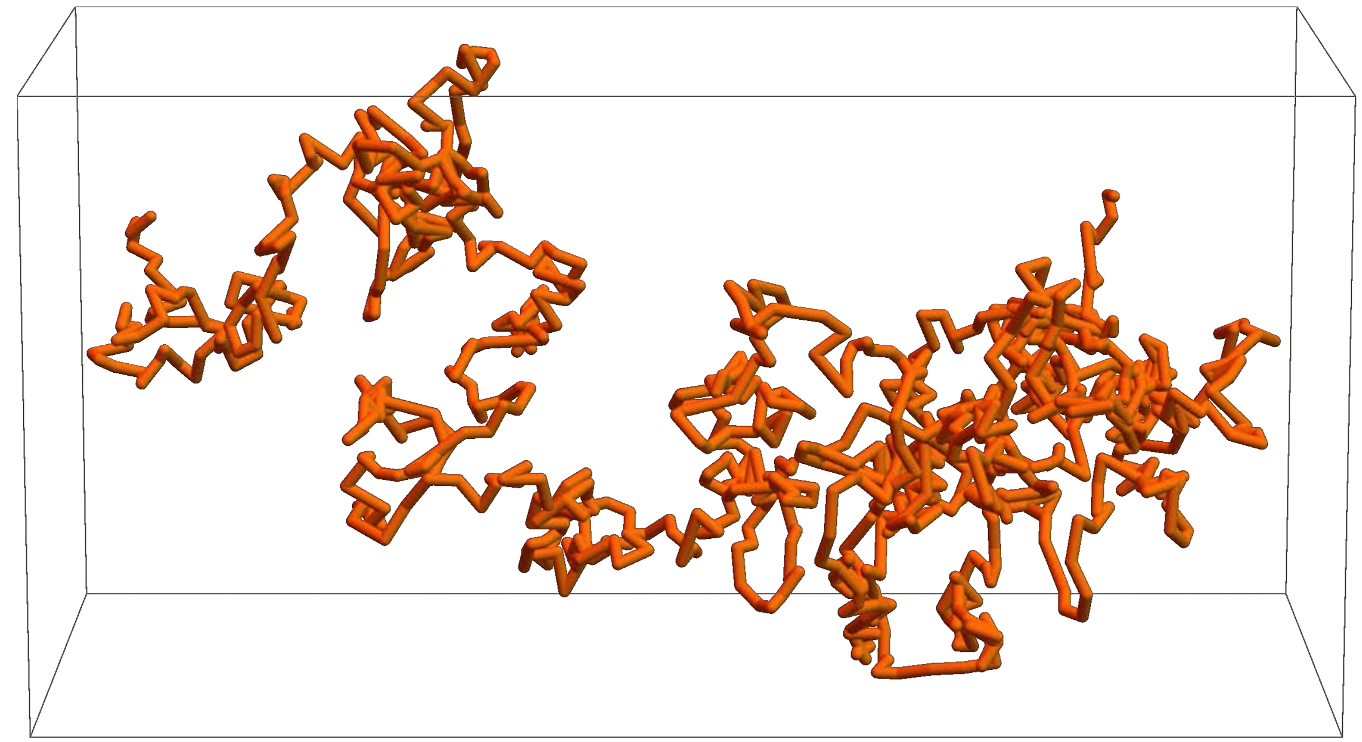

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Harmonic component

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

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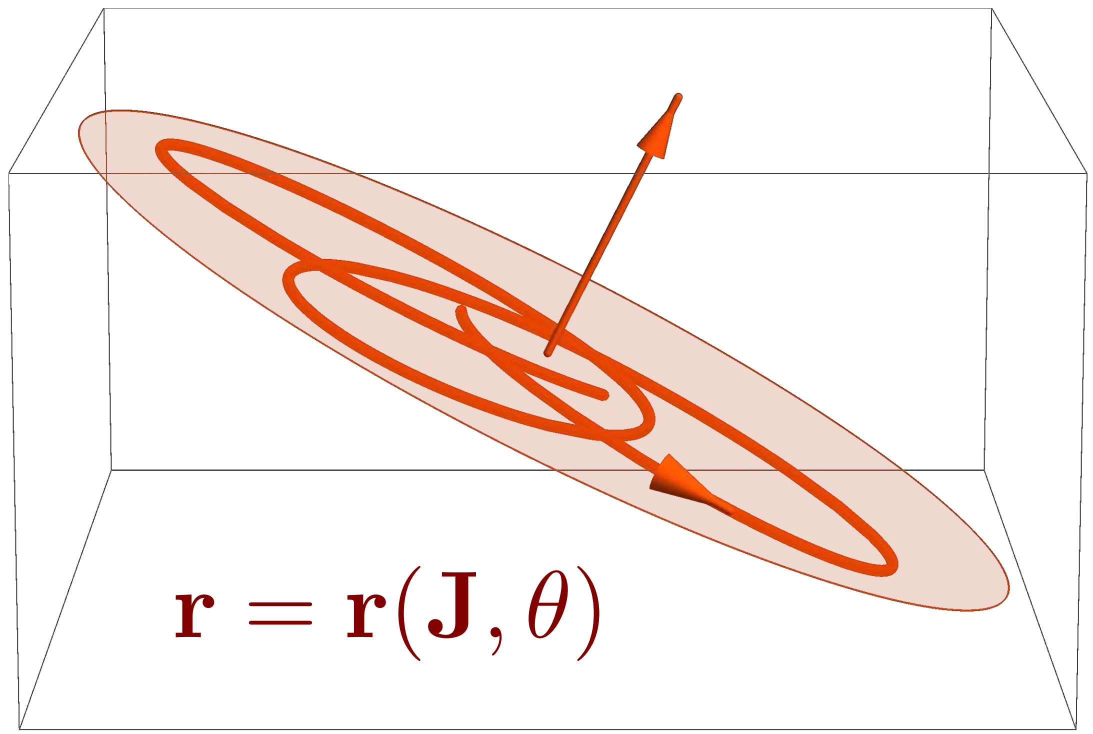

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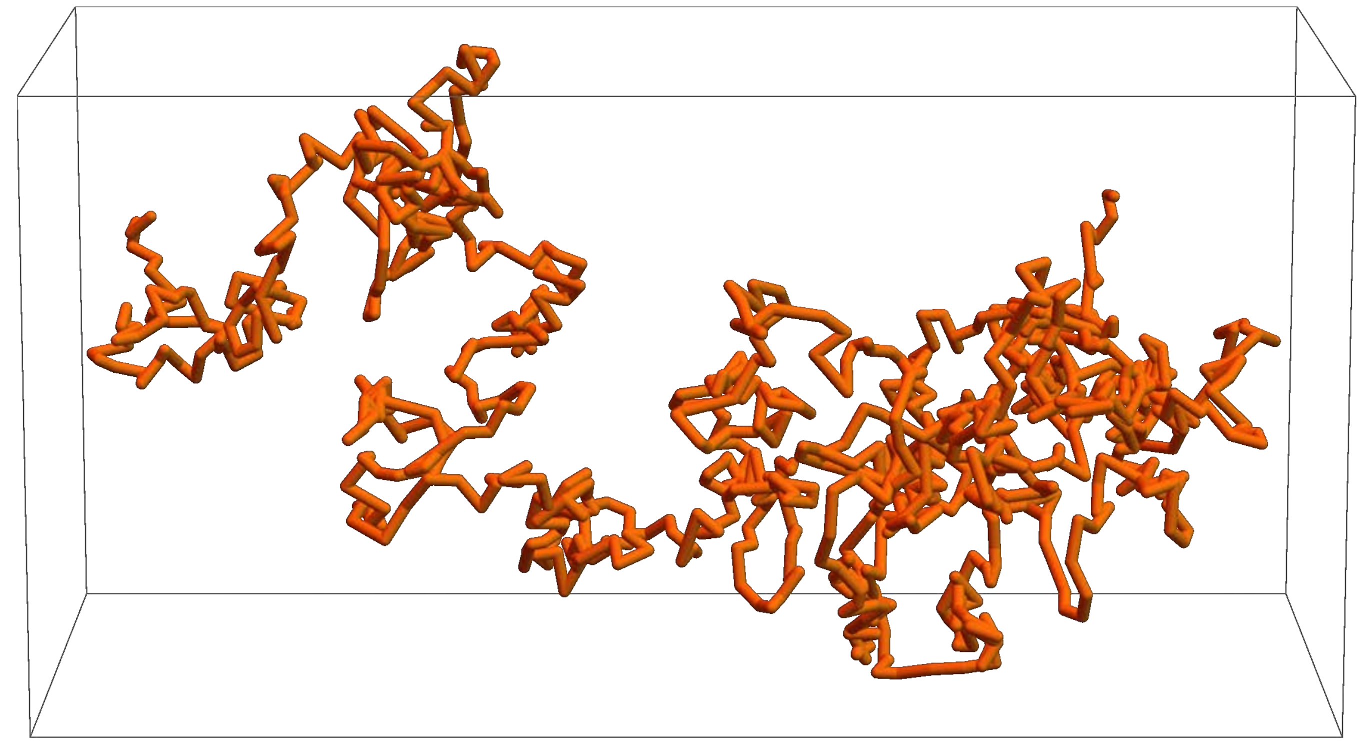


$$\delta\psi(\mathbf{r}, t) \to \sum_{\mathbf{m}} \delta\hat{\psi}_{\mathbf{m}}(\mathbf{J}, \omega) \exp\left(i\mathbf{m}\cdot\theta - \omega t\right)$$

Fluctuating potential

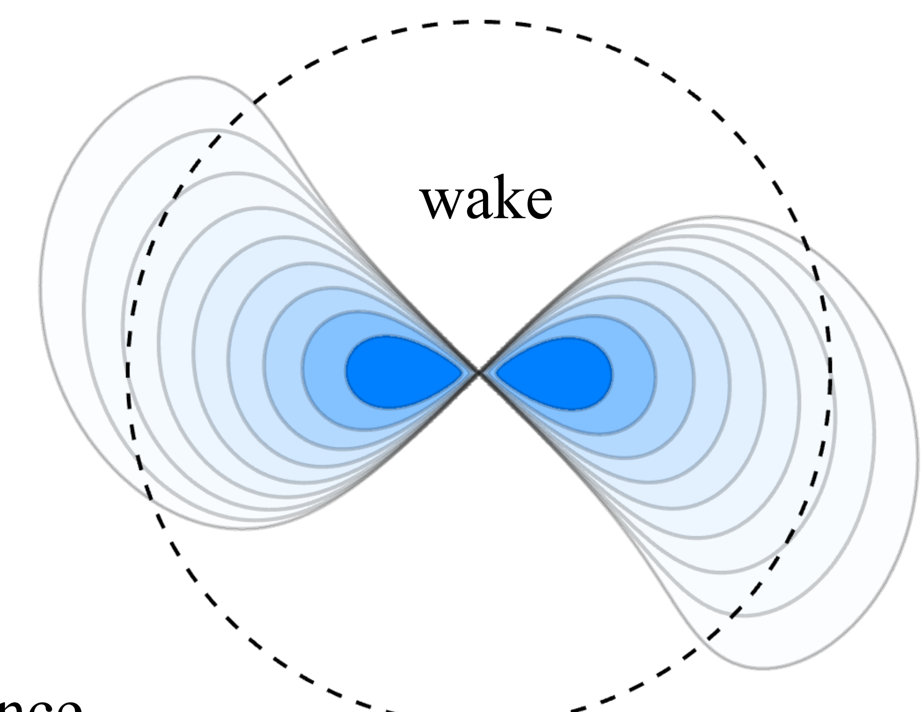
Harmonic component

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

$$\to \langle|\delta\hat{\psi}^{\mathrm{dressed}}_{\mathbf{m}}(\mathbf{J}, \mathbf{m}\cdot\Omega)|^2\rangle$$

dressed by wake

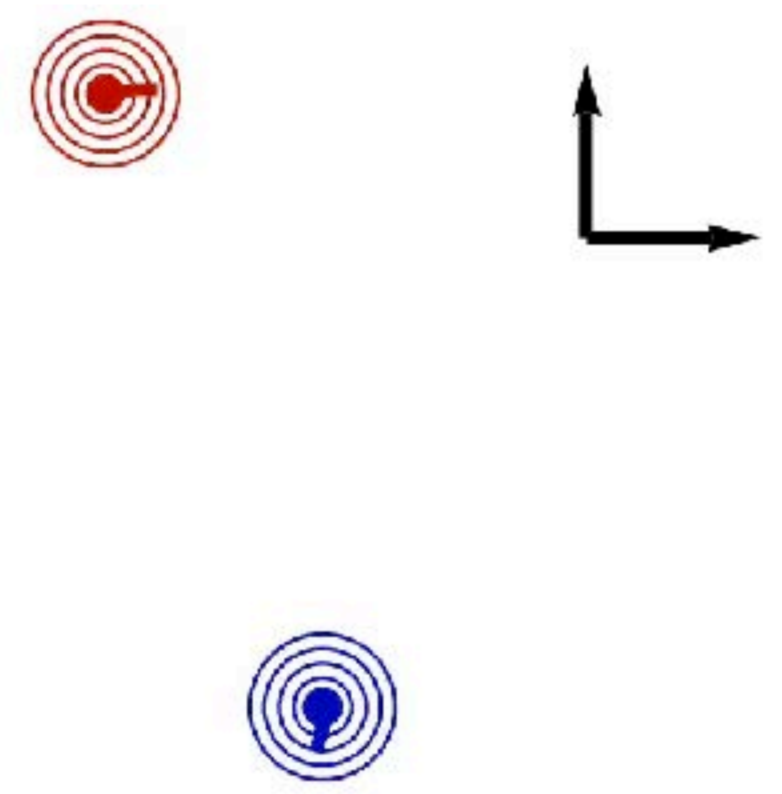
@ resonance



Resonant encounters

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

Here ● and ● resonate
in some rotating frame



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

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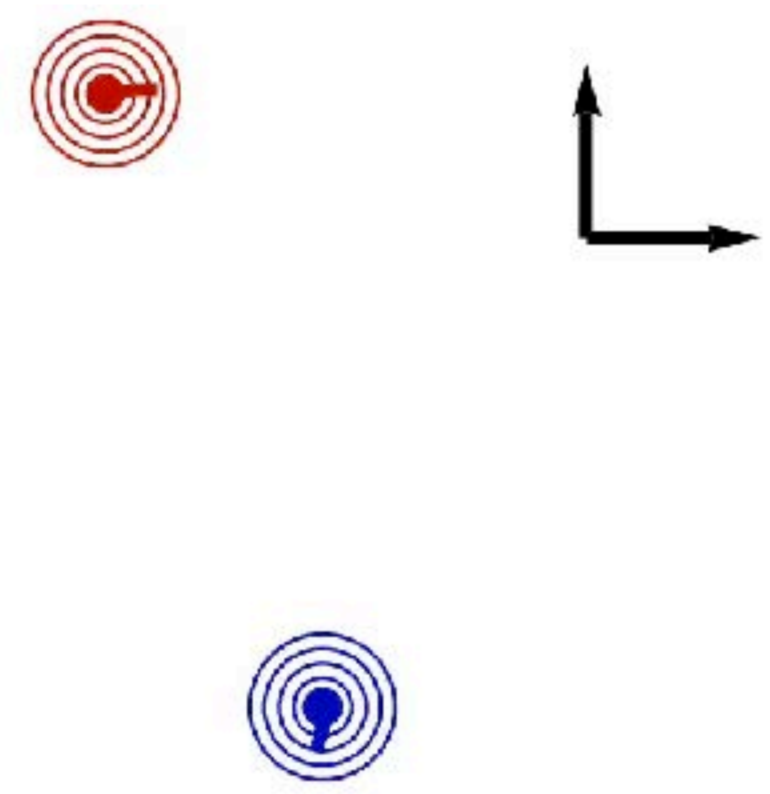

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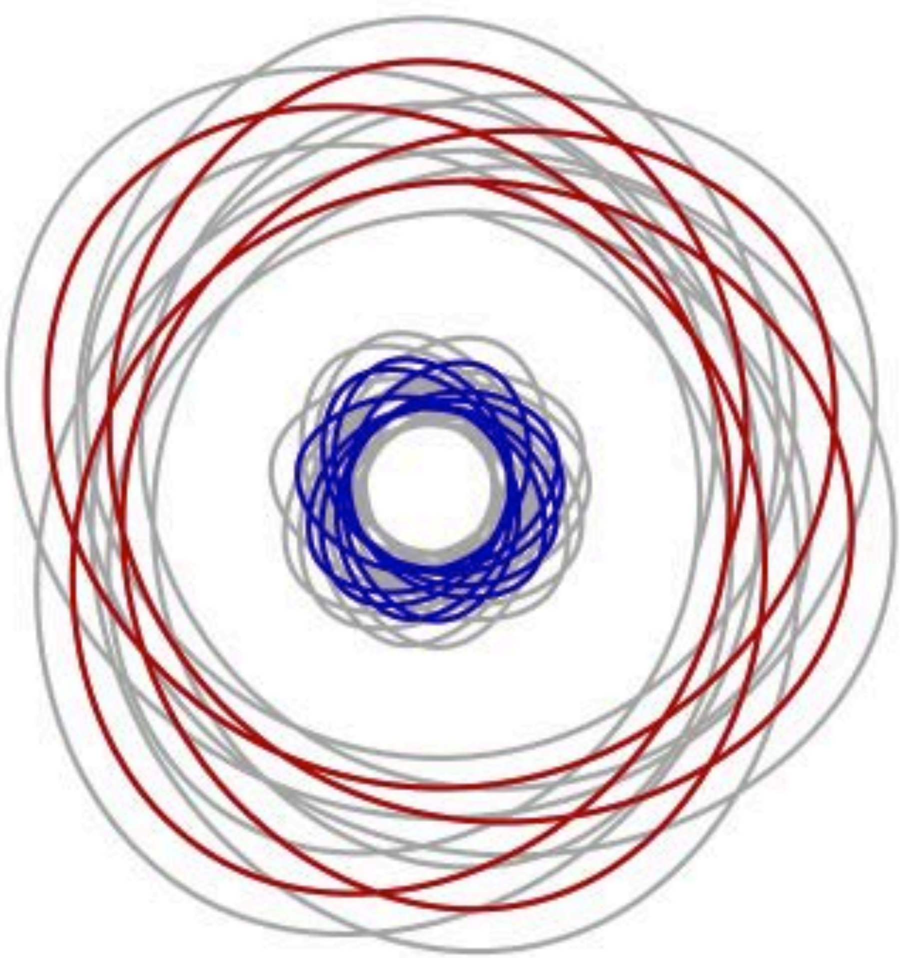
The idea behind resonant relaxation.

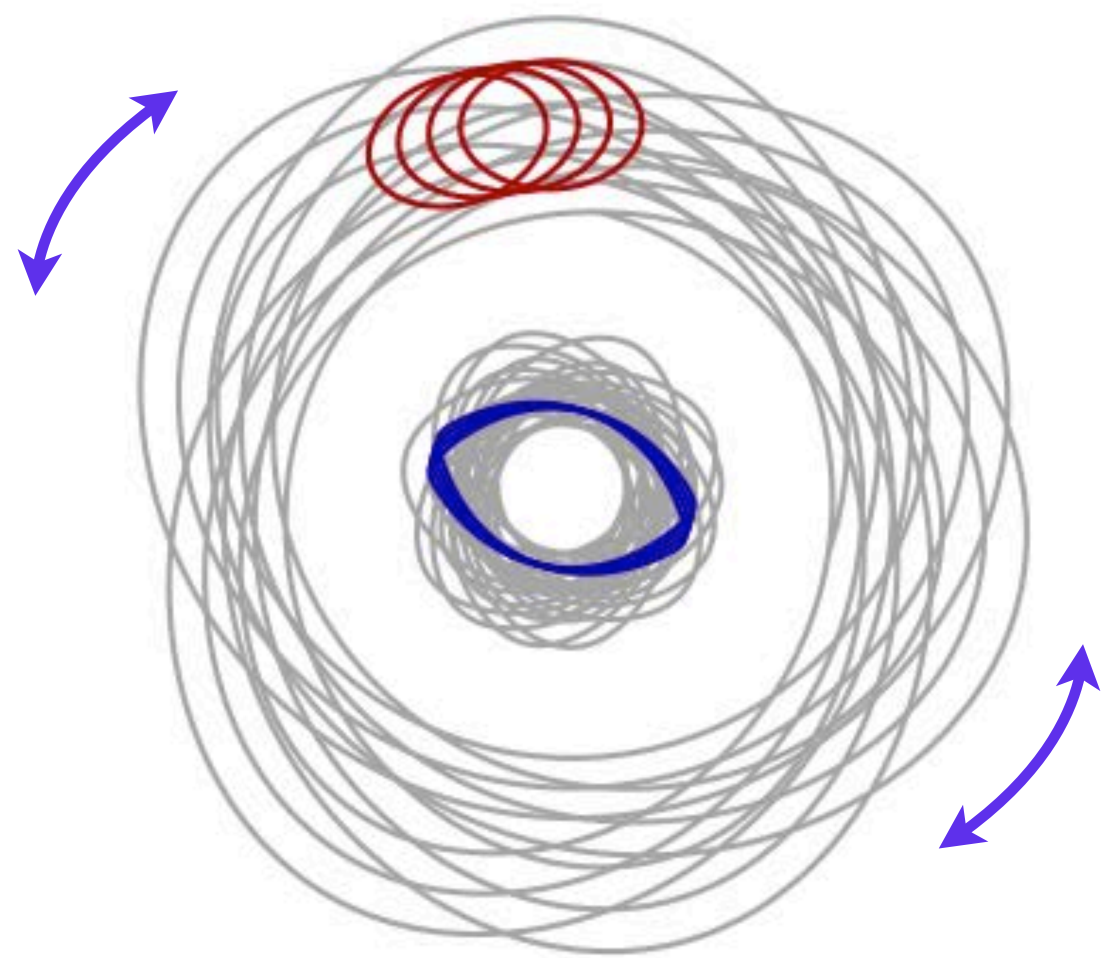
- Resonance condition $\delta_{\mathrm{D}}(\boldsymbol{m}_1 \cdot \boldsymbol{\Omega}_1 - \boldsymbol{m}_2 \cdot \boldsymbol{\Omega}_2) \Longrightarrow$ Distant encounters.

Here ● and ● resonate in some rotating frame

Through resonances departure from axial symmetry



No Torque



Net Torque

resonance drives recurrence

Perturbative quasi-linear/Kinetic theory

Exact **stochastic** equation

Perturbative expansion

mean field

Quasi-stationary **equilibrium**

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

ensemble average

$$=$$

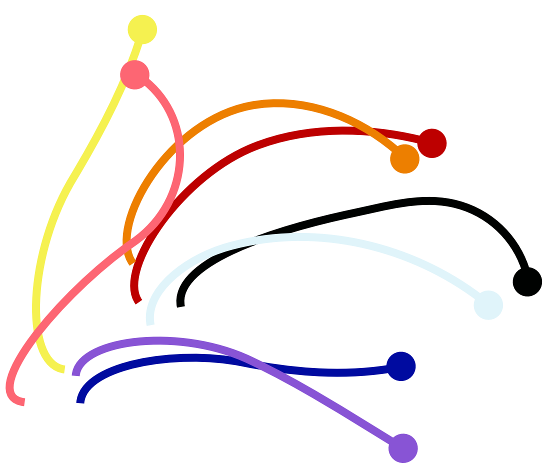
$$\frac{\partial \langle F \rangle}{\partial t} = - \left\langle \left[\delta F, \delta H\right] \right\rangle$$

quadratic term

Fluctuations **correlations**

inertial
time delay

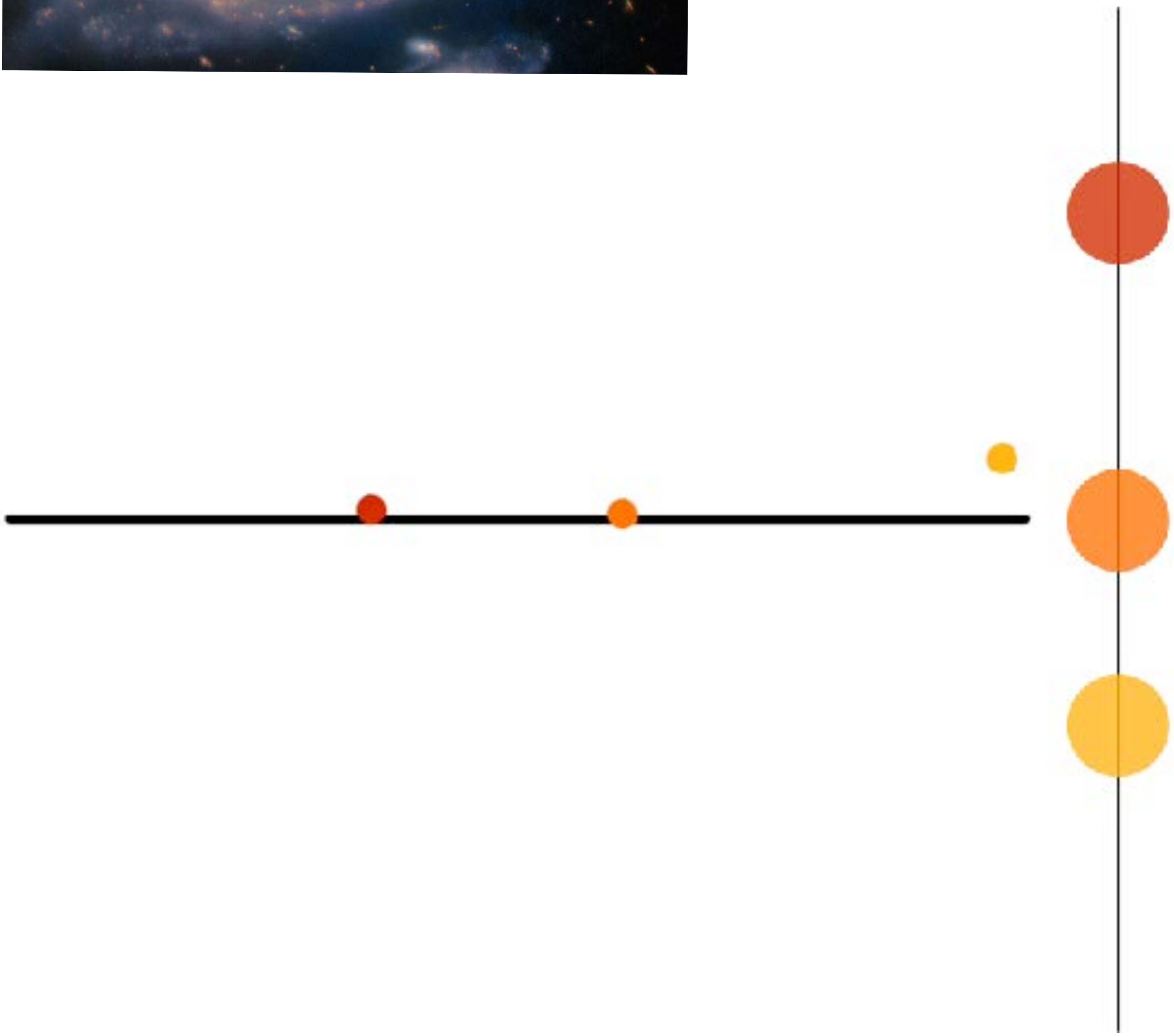
Fluctuation-Dissipation Theorem



Diffusion rate	$\longleftrightarrow$ $\longleftrightarrow$	**Power-spectrum of the fluctuations**

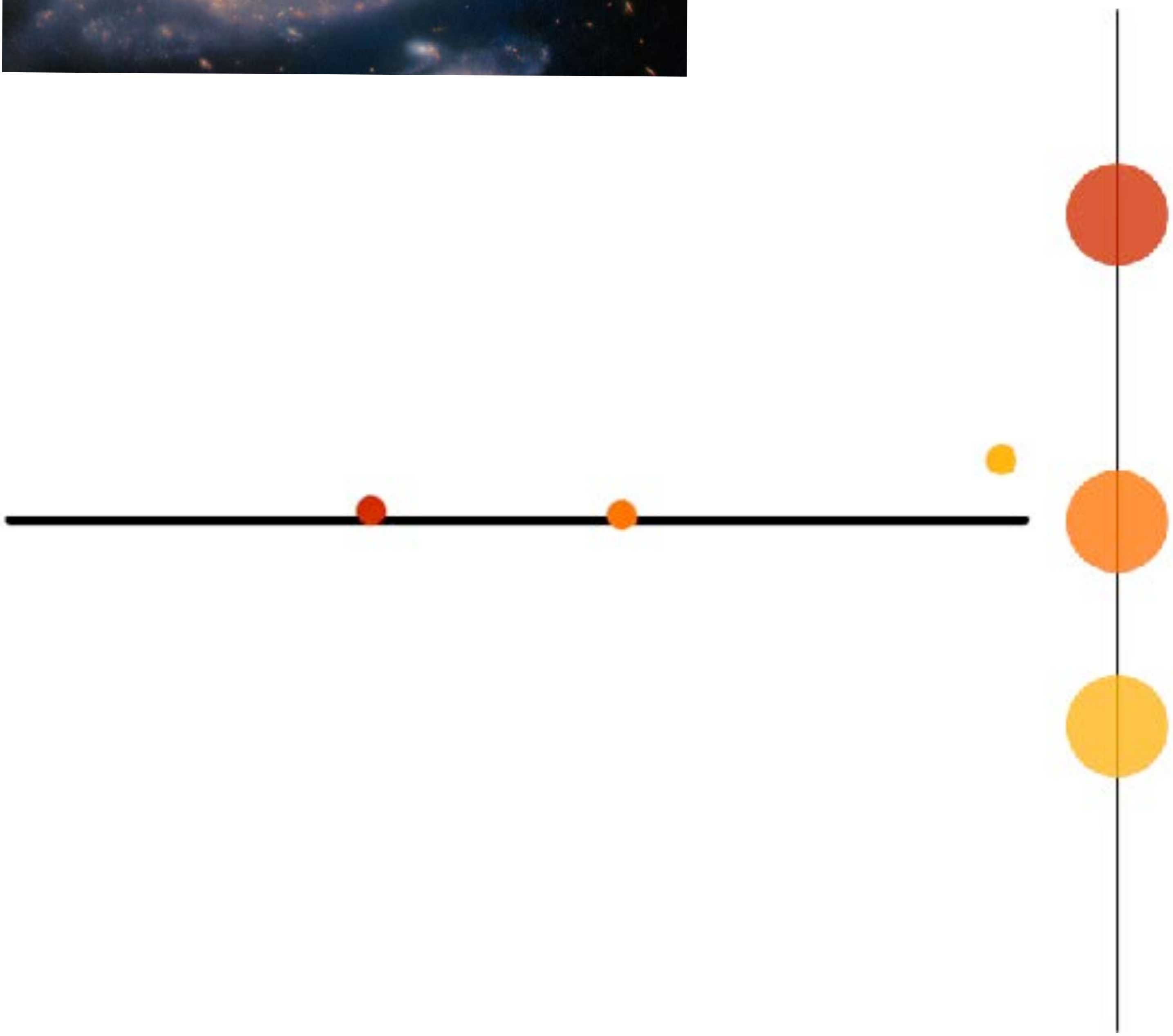
Mean galaxy subject to **deterministic** orbital **diffusion**

Vertical motion



See also Joyce+(2010)

Vertical motion



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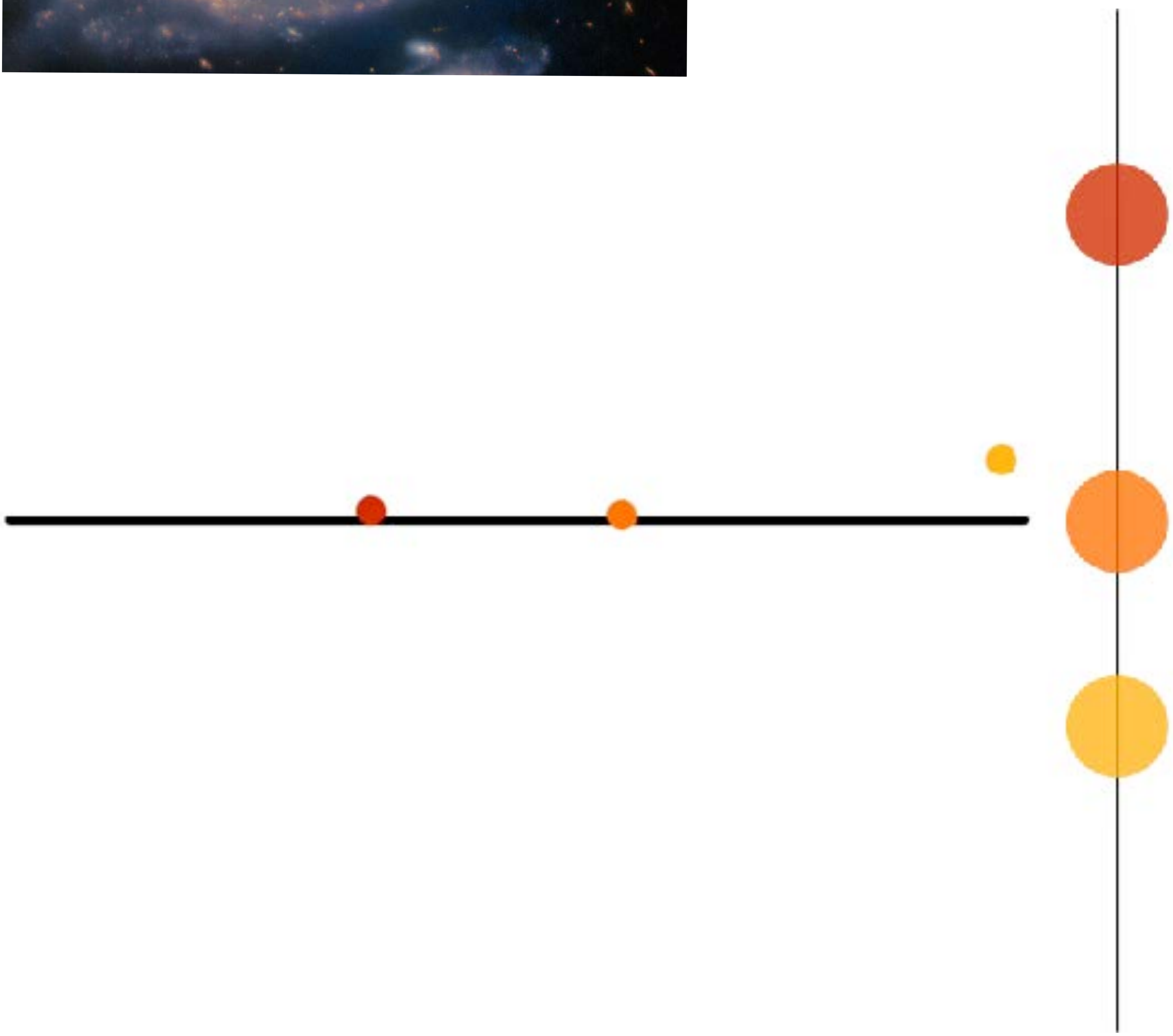
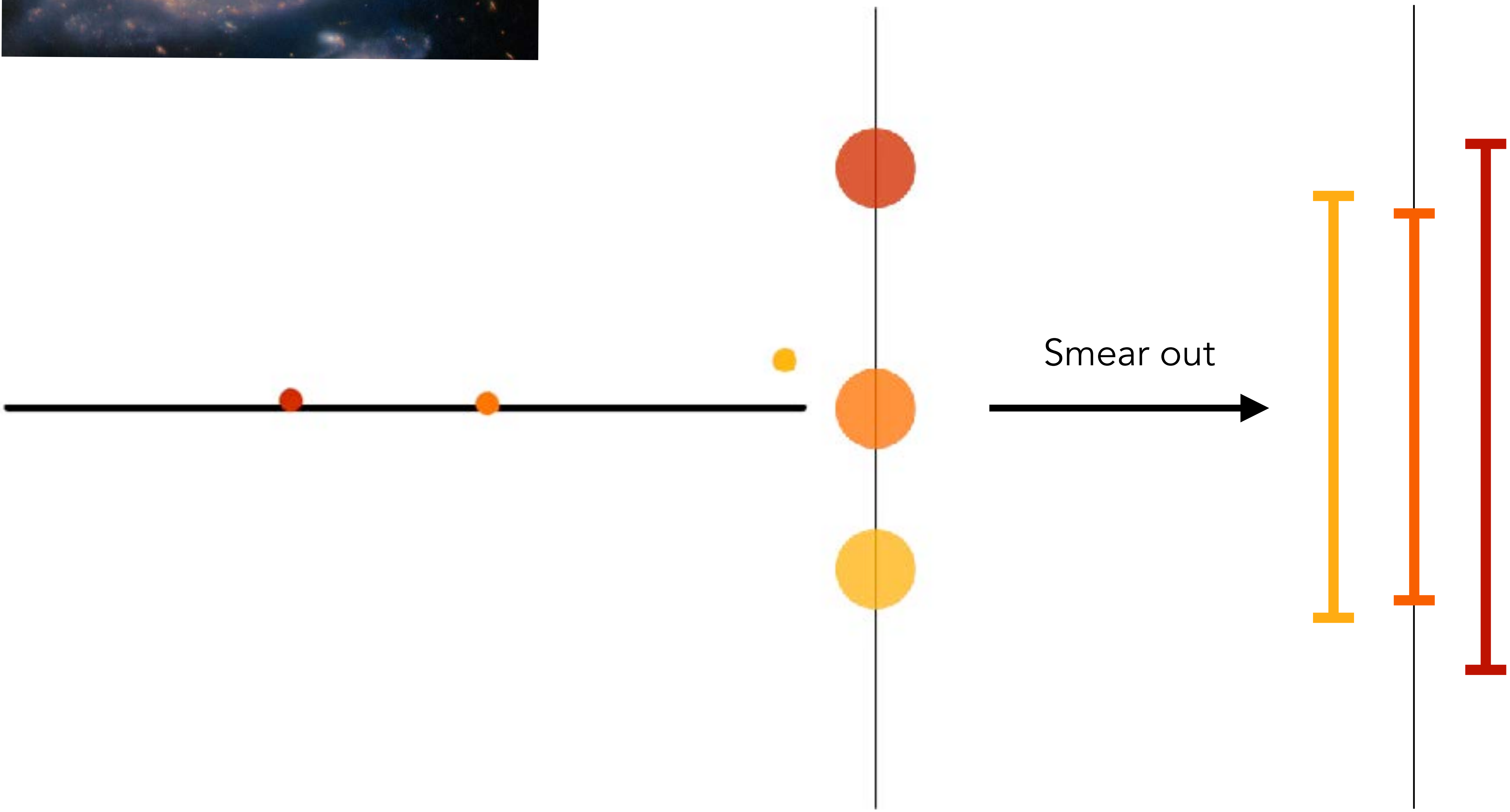


One-dimensional

See also Joyce+(2010)

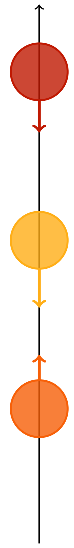
Vertical motion

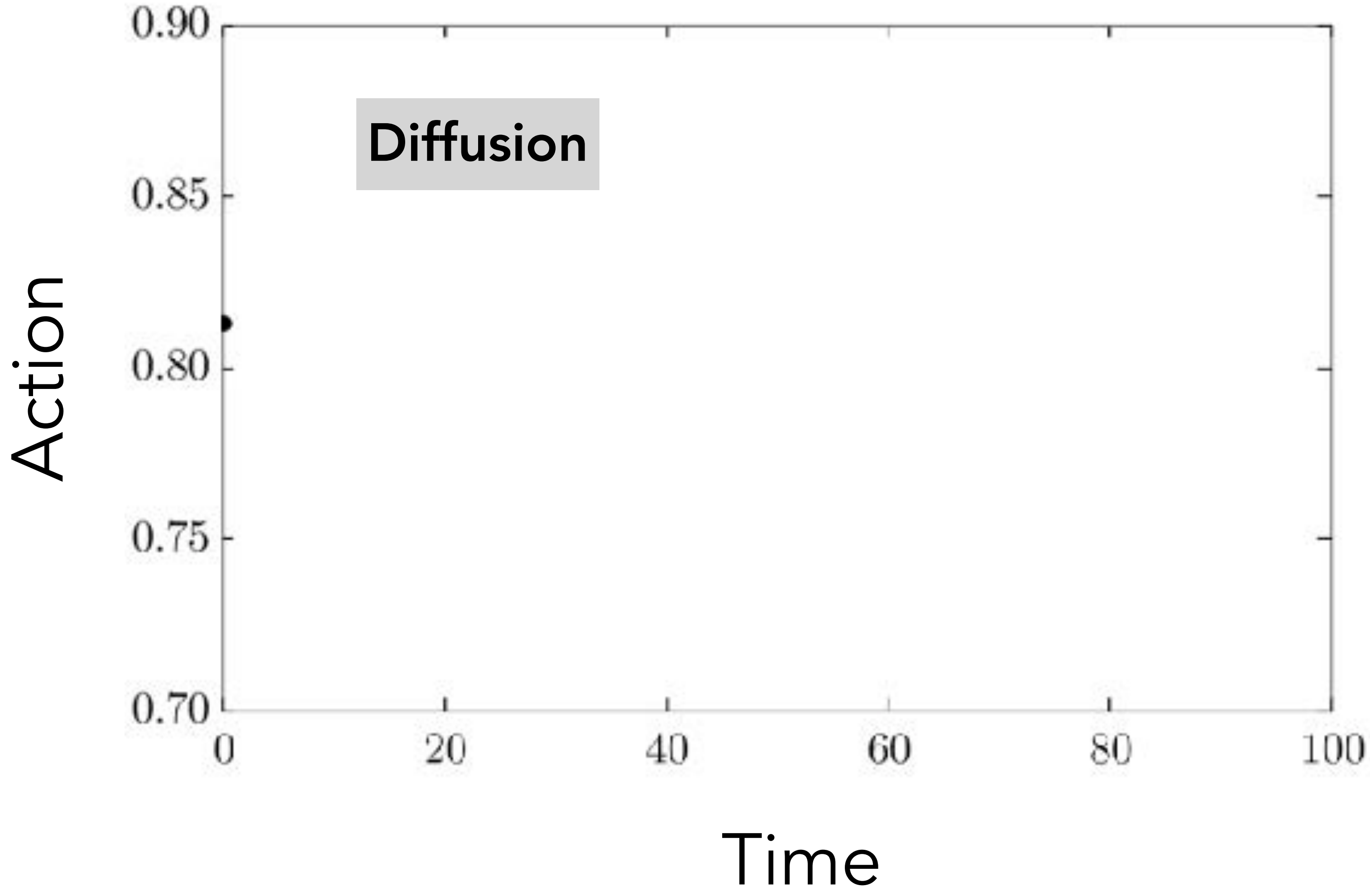


One-dimensional **Orbits**

See also Joyce+(2010)

Orbital diffusion

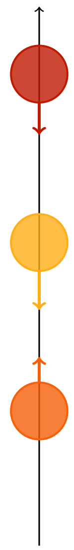


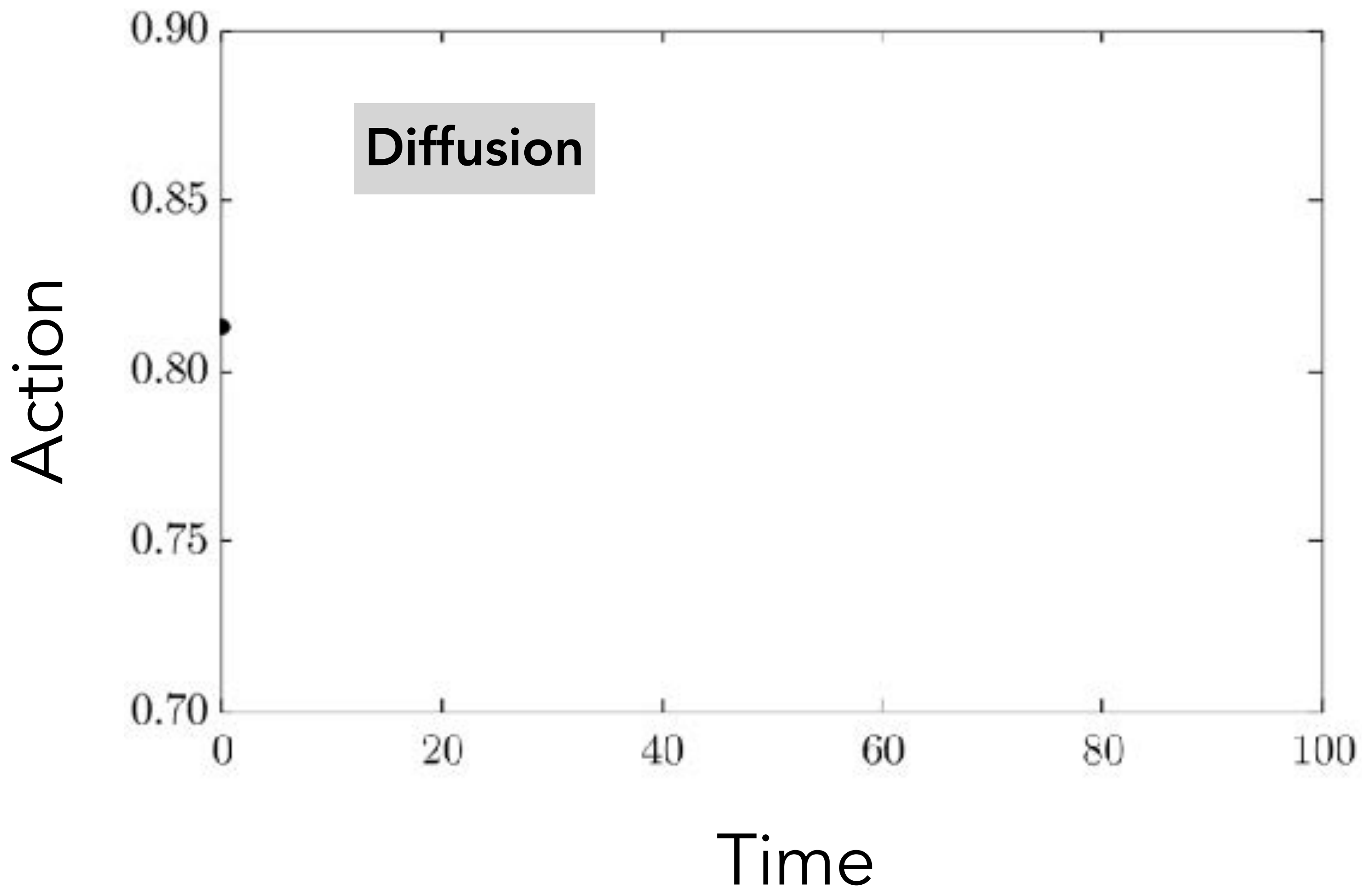


Perturbed

Disc **thickening**

Orbital diffusion





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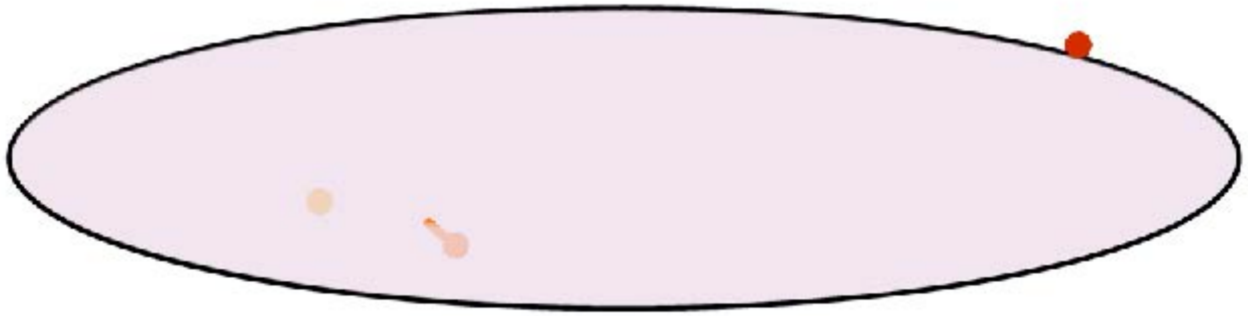
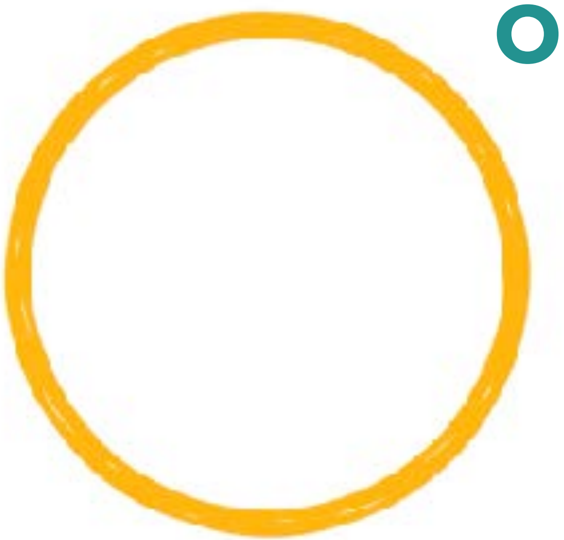
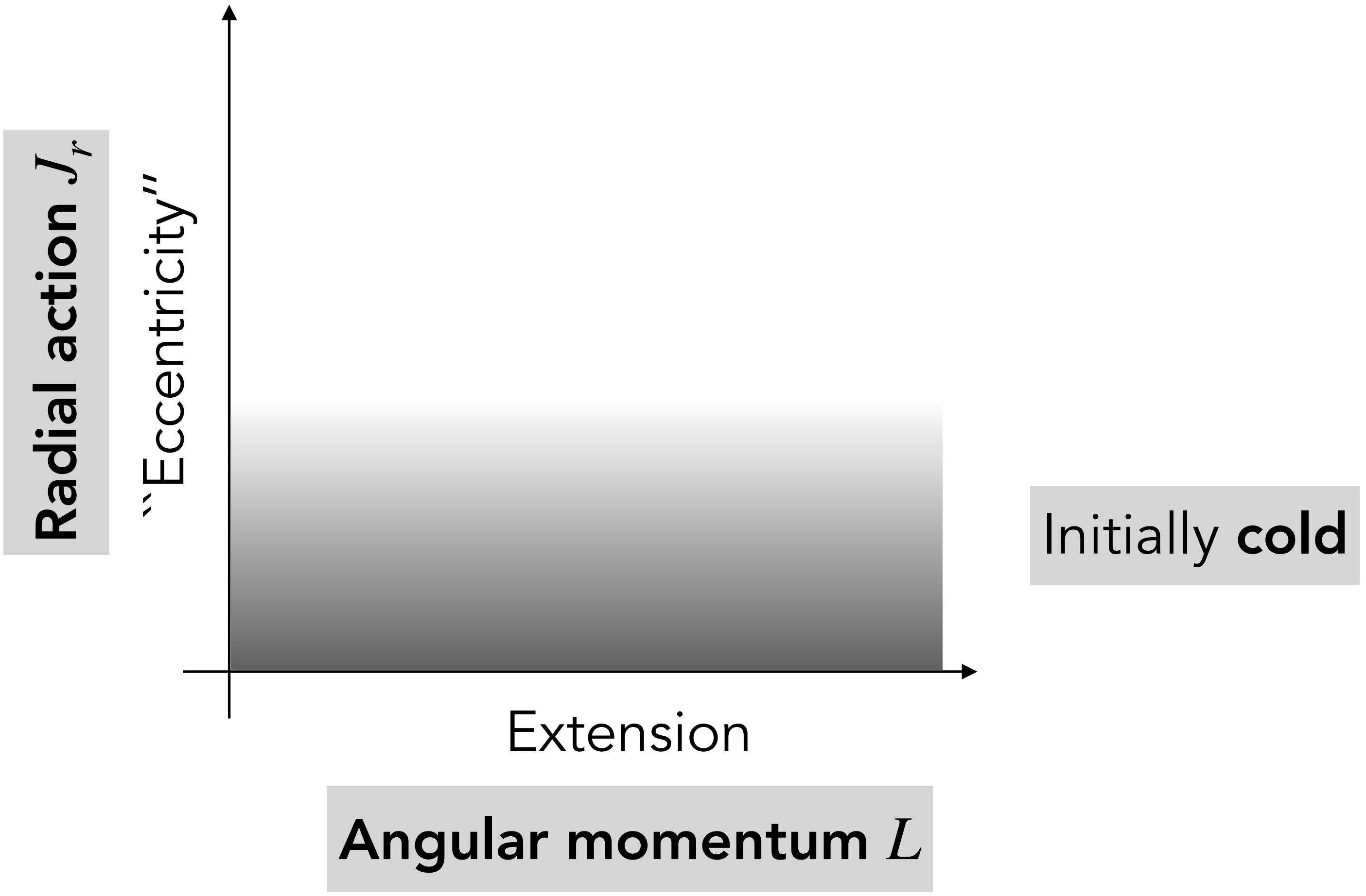


Orbital diffusion



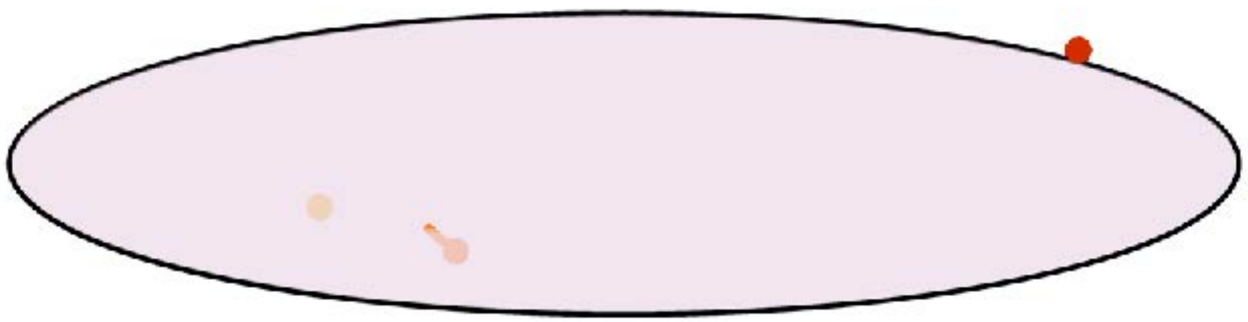
Fluctuation-Dissipation Theorem

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



Fluctuations heat and statistically increase **radial oscillations**

See also Sellwood+(2002)



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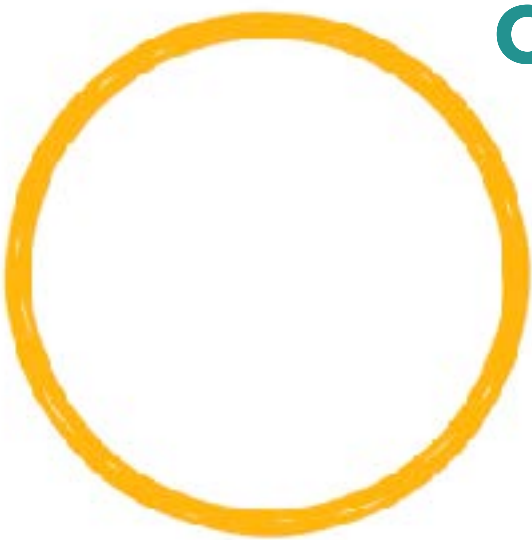
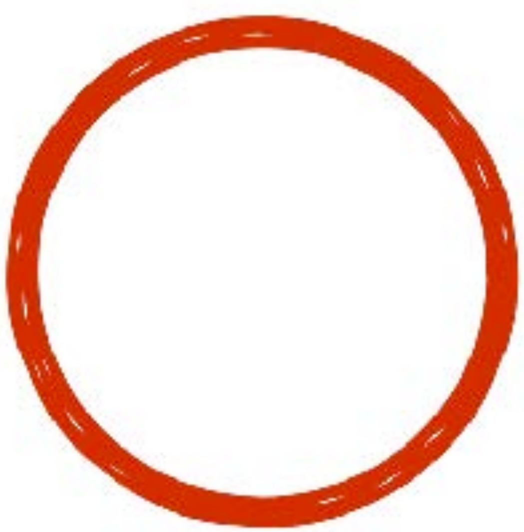
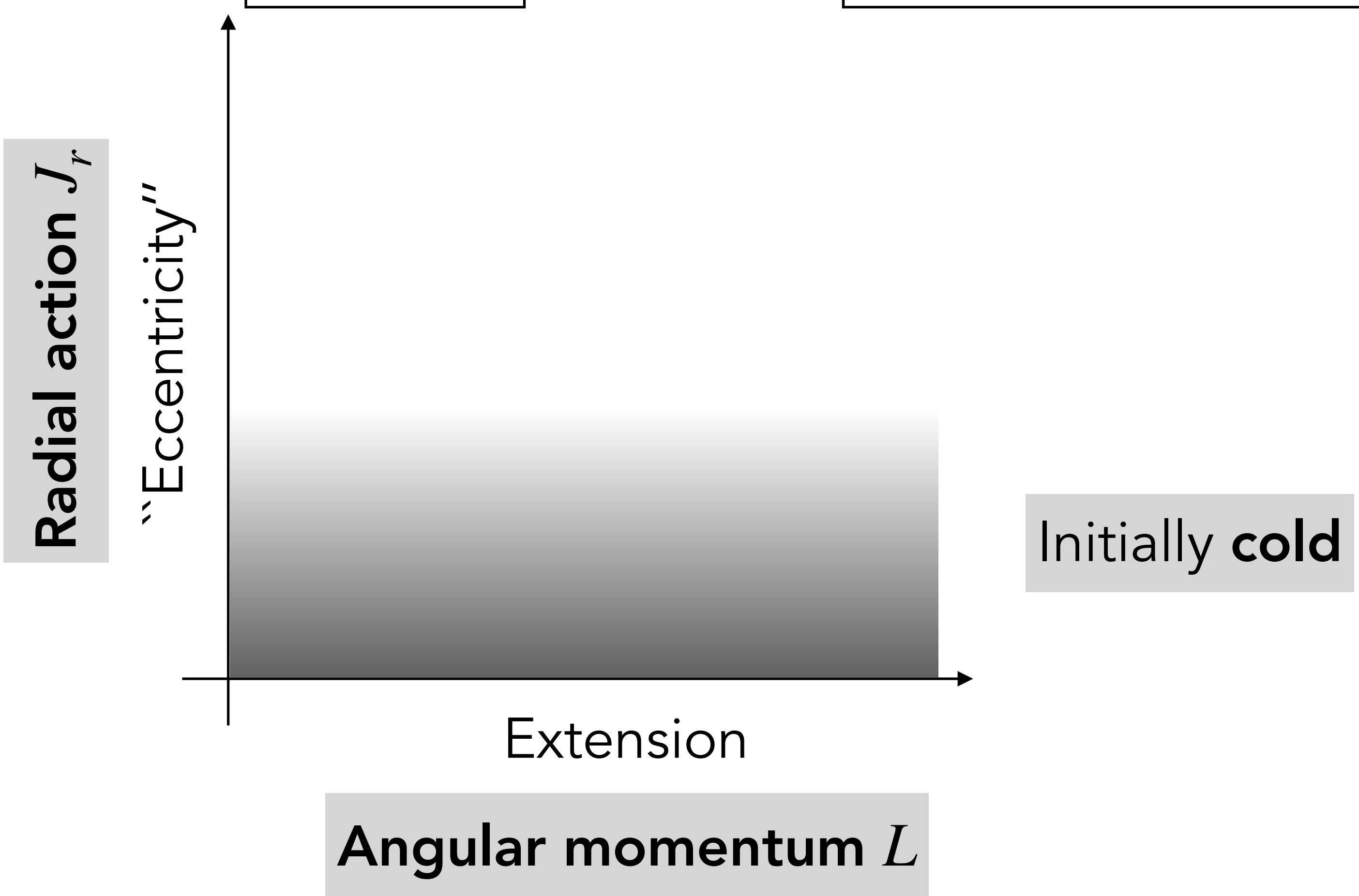




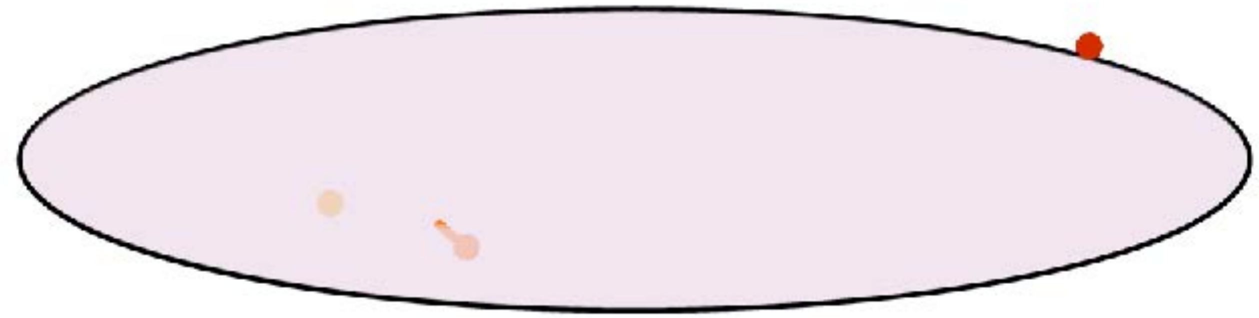
Fluctuation-Dissipation Theorem

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

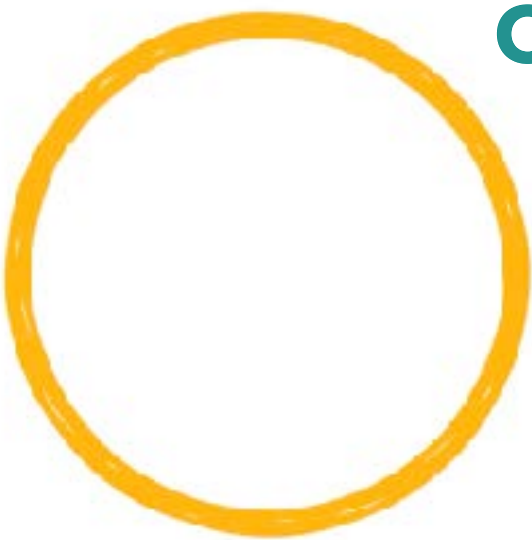


Fluctuations heat and statistically increase **radial oscillations**

See also Sellwood+(2002)



Orbital diffusion



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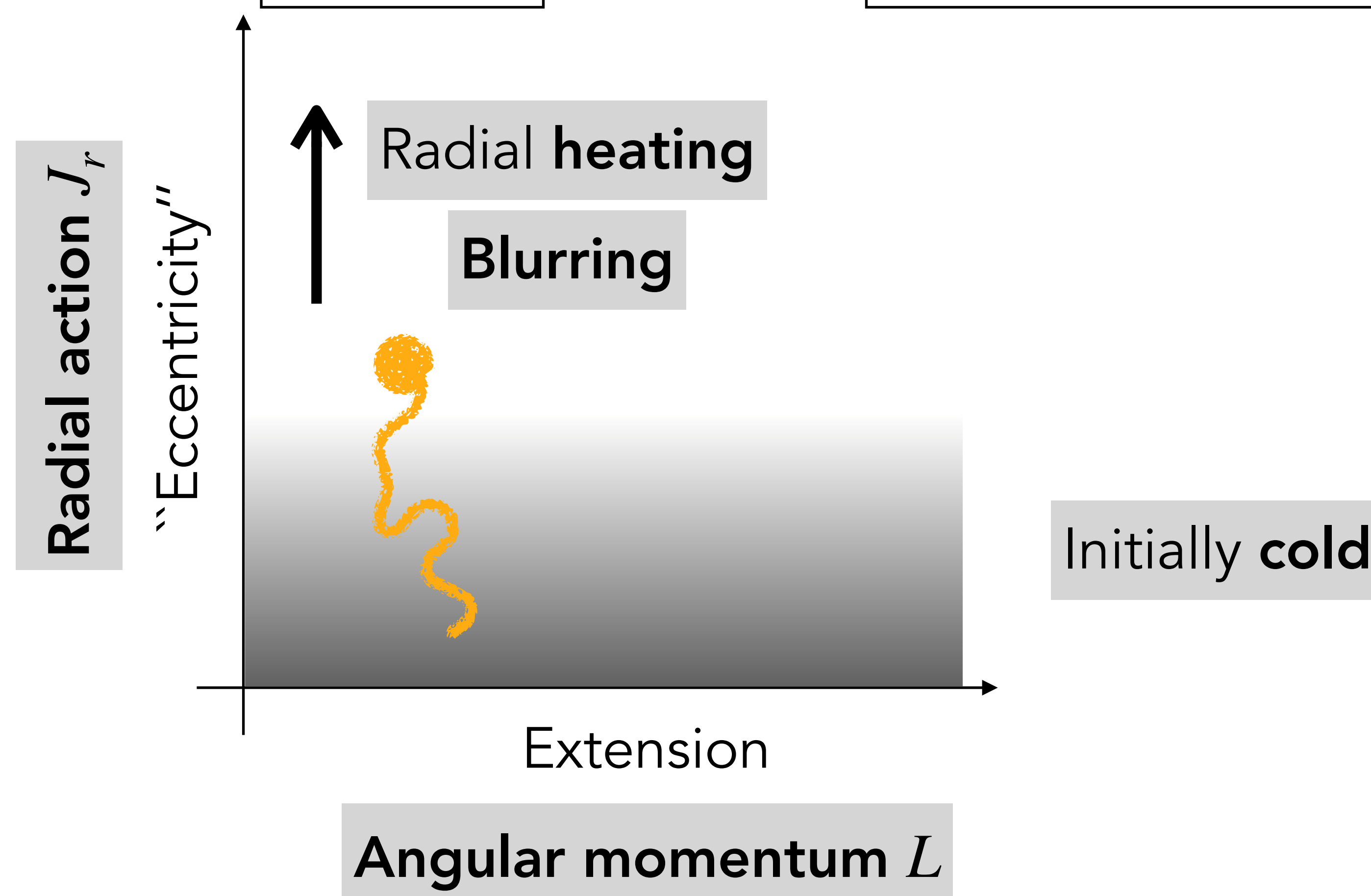

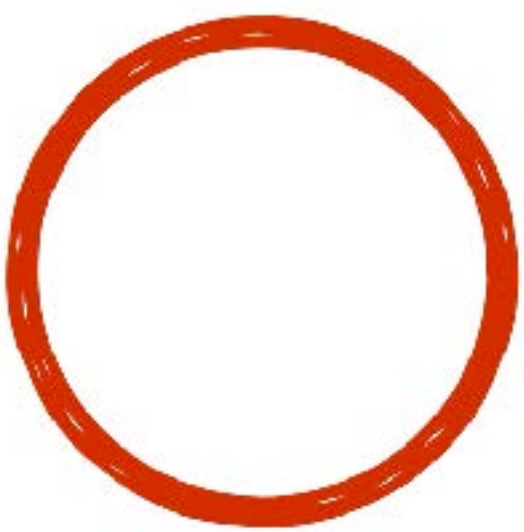

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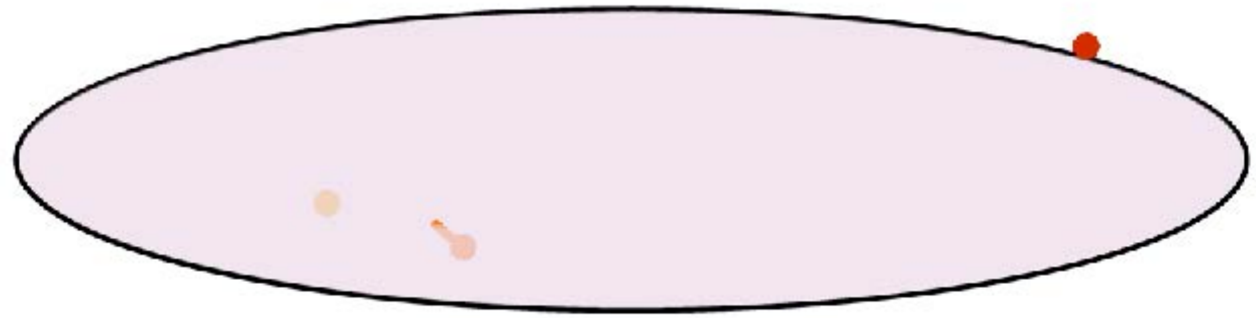

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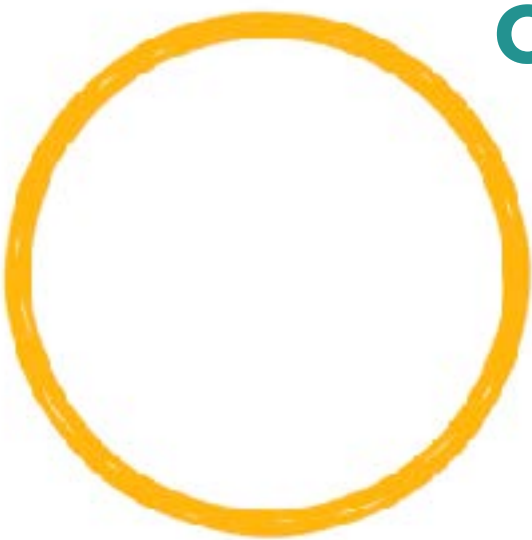
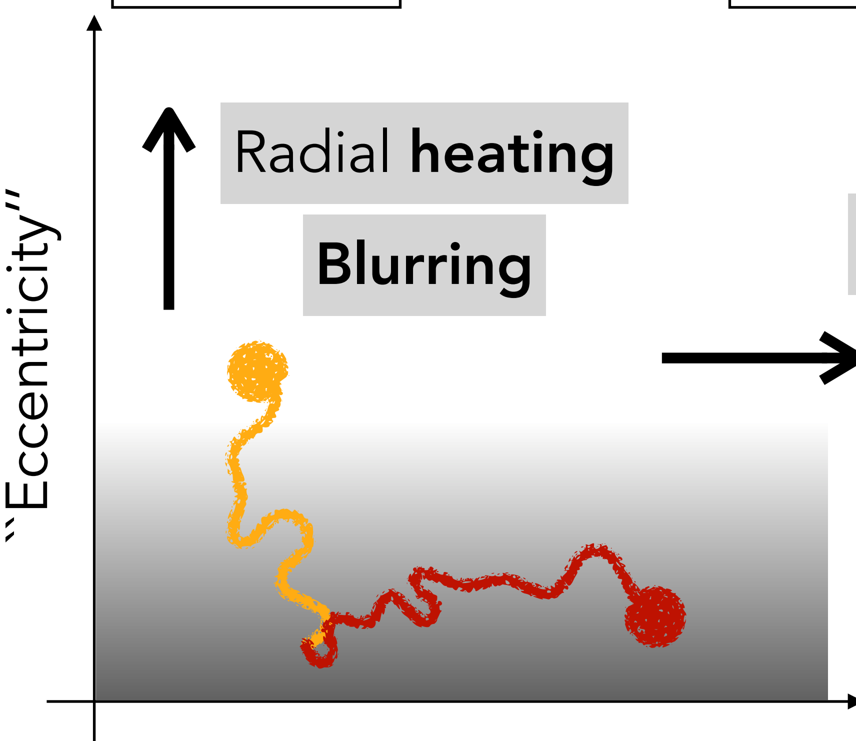


Fluctuation-Dissipation Theorem

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

Radial action J_r

"Eccentricity"



Extension

Angular momentum L

Radial **migration**

Churning

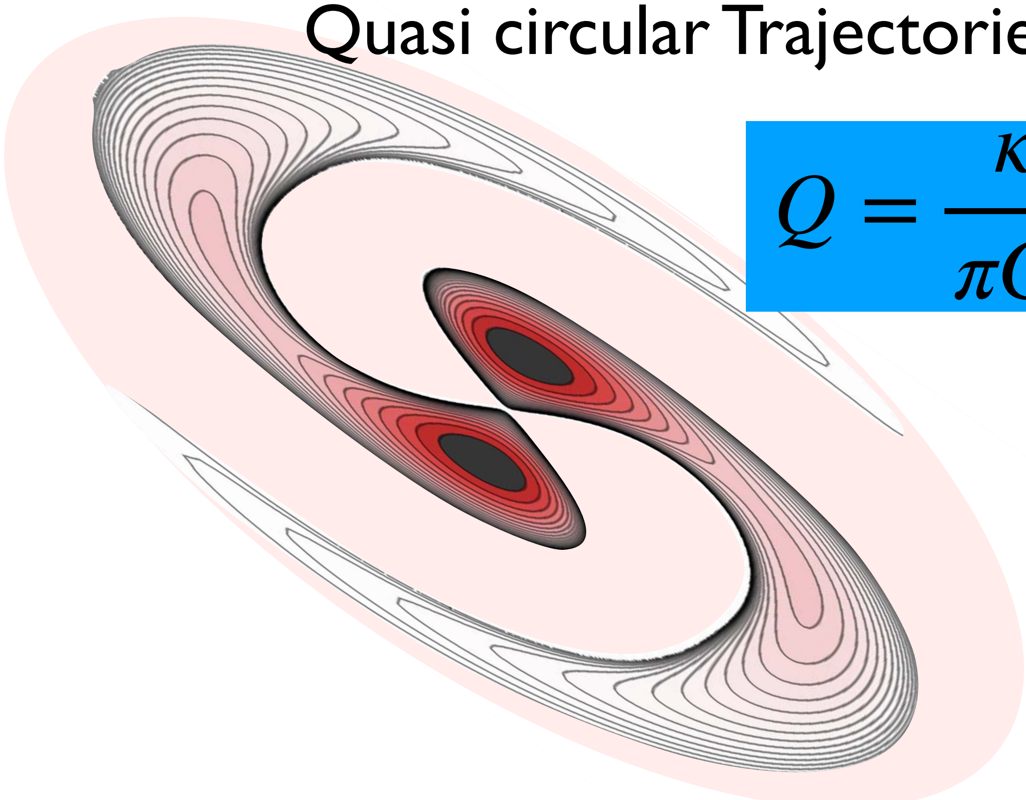
Initially **cold**

Fluctuations heat and statistically increase **radial oscillations**

See also Sellwood+(2002)

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

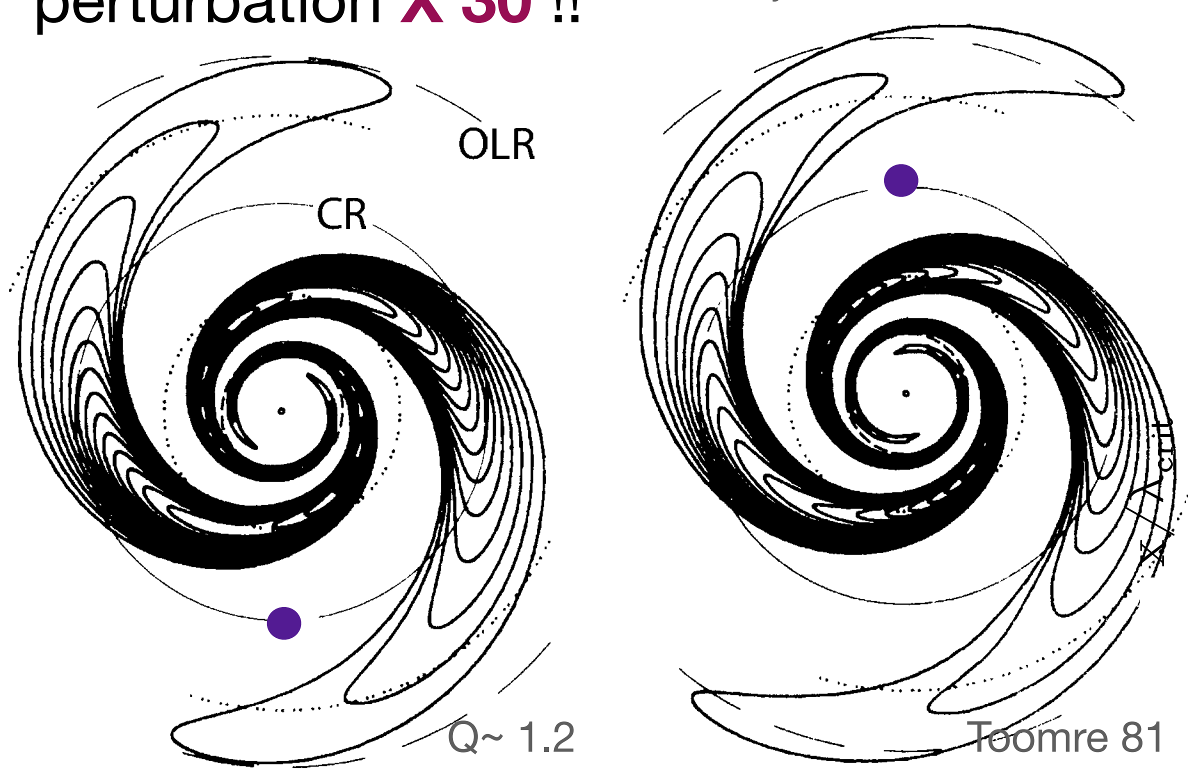
Quasi circular Trajectories: 'cold' disc

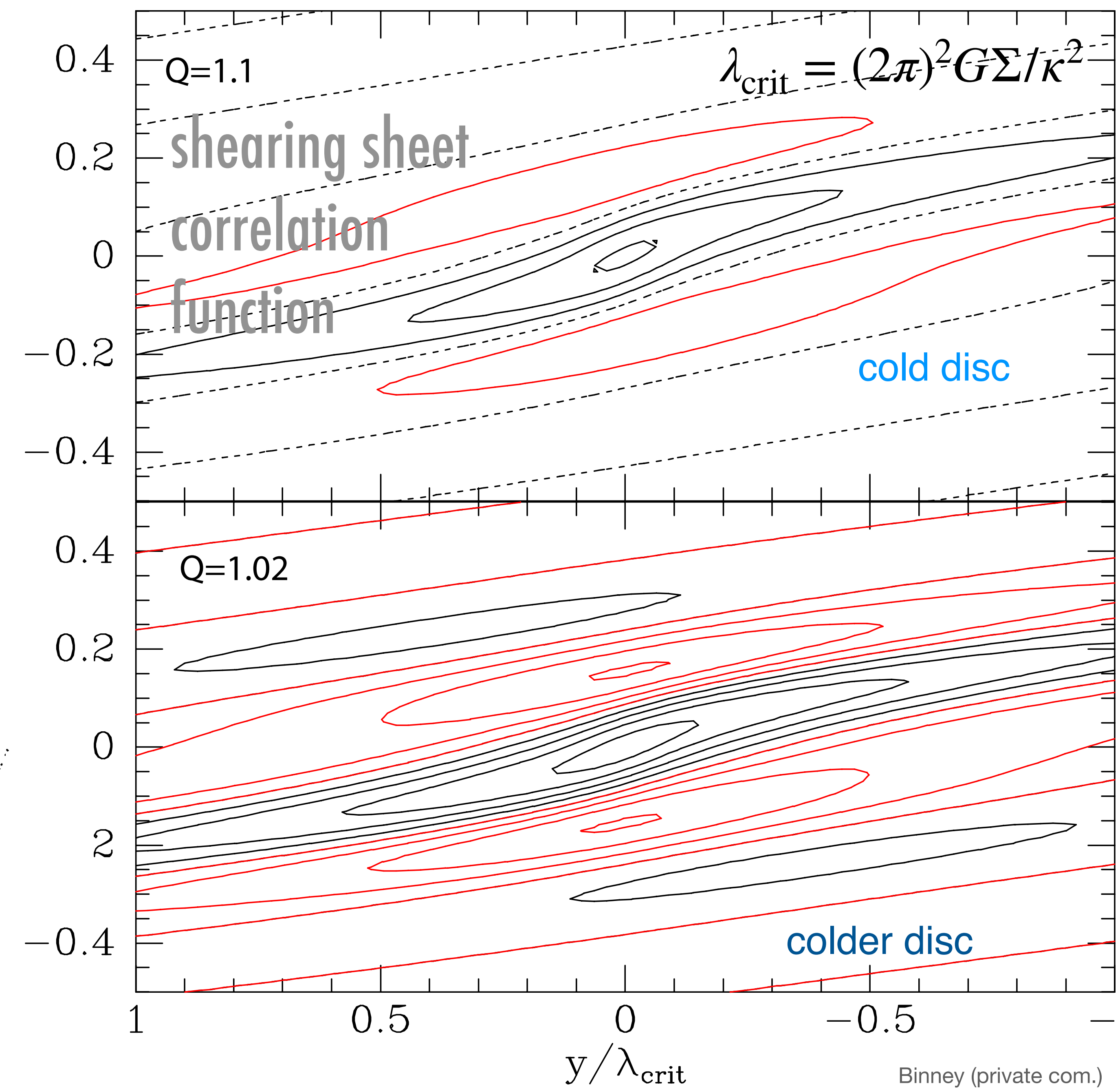


$$Q = \frac{\kappa\sigma}{\pi G \Sigma} \to 1$$

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

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





→ long range correlation

Binney (private com.)

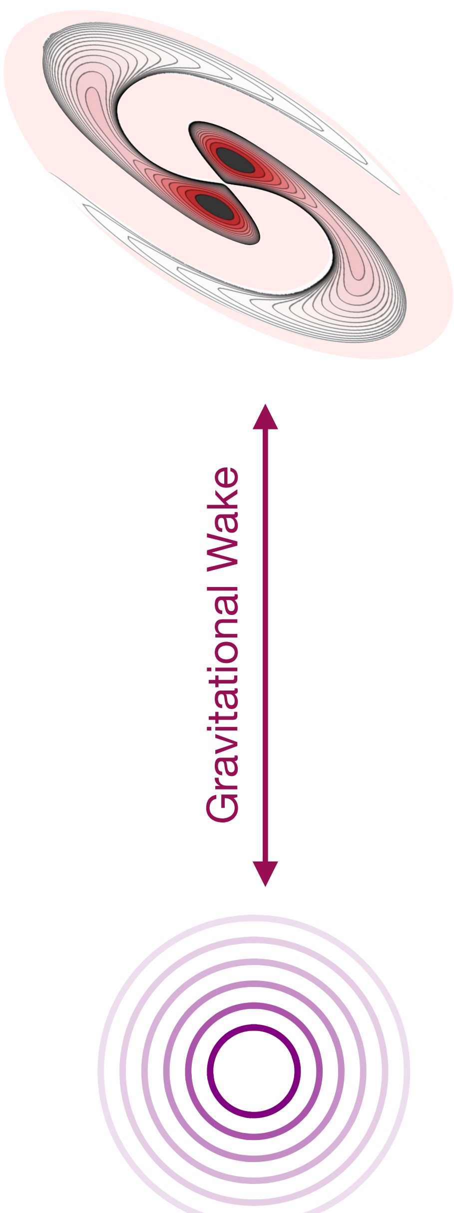
For cold discs…

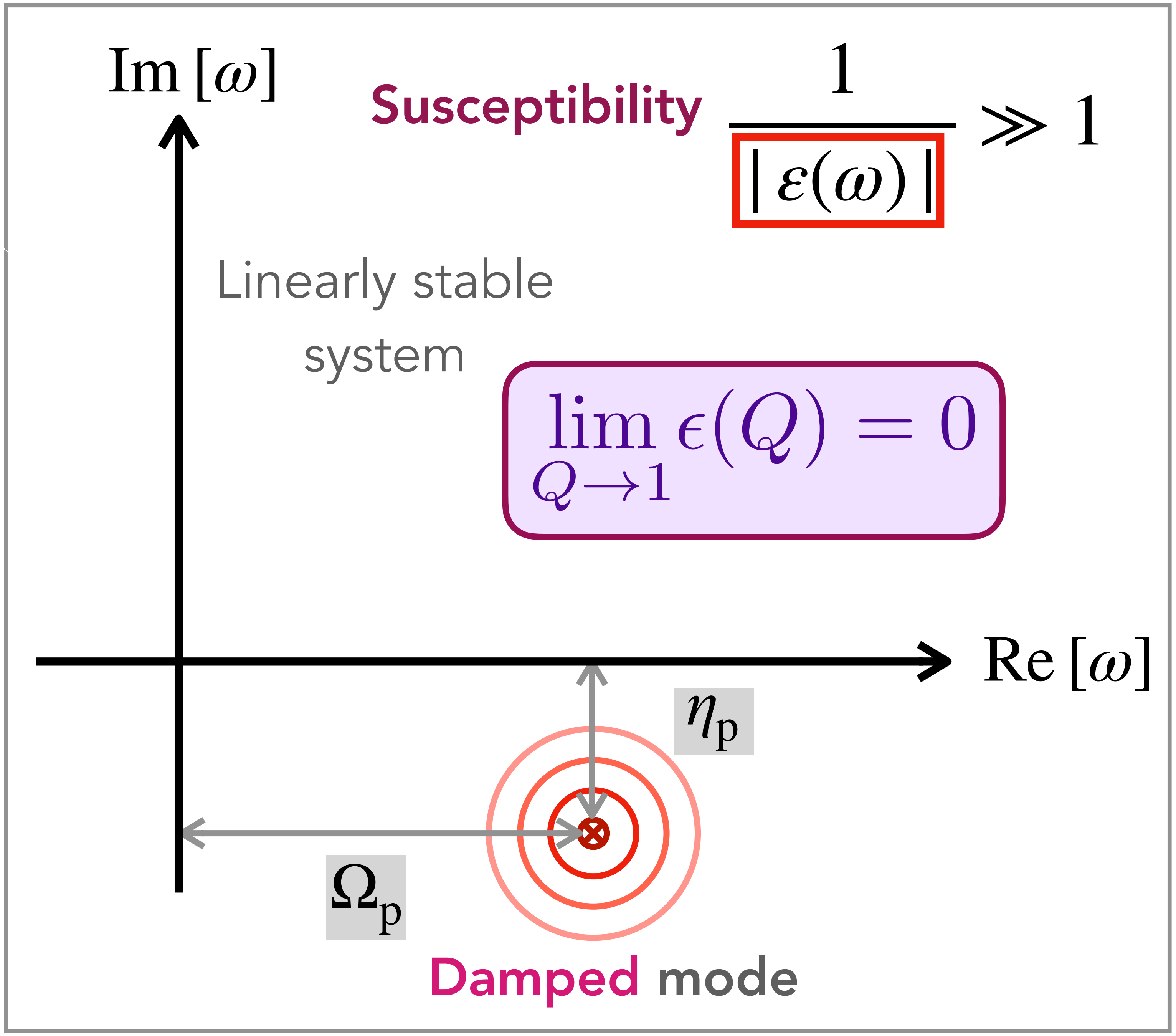
$$Q = \frac{\kappa\sigma}{\pi\Sigma} \to 1$$

Gravitational "*Dielectric*" function ϵ

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

Dispersion relation   Response matrix





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

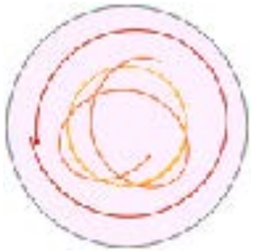
$$T_{\rm dressed} \simeq \boxed{|\,\varepsilon\,|}\, T_{\rm bare}$$

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

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

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

Collective amplification



Secular evolution equation

ensemble average

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

Dressing comes twice

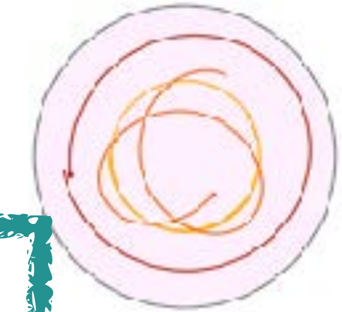
$$M_{\mathrm{wake}} = \frac{M_{\mathrm{perturb}}}{\boxed{|\,\varepsilon(\omega)\,|}} \quad\longrightarrow\quad \frac{\partial F}{\partial t} \simeq \frac{M_{\mathrm{perturb}}^2}{\boxed{|\,\varepsilon(\omega)\,|^2}}$$

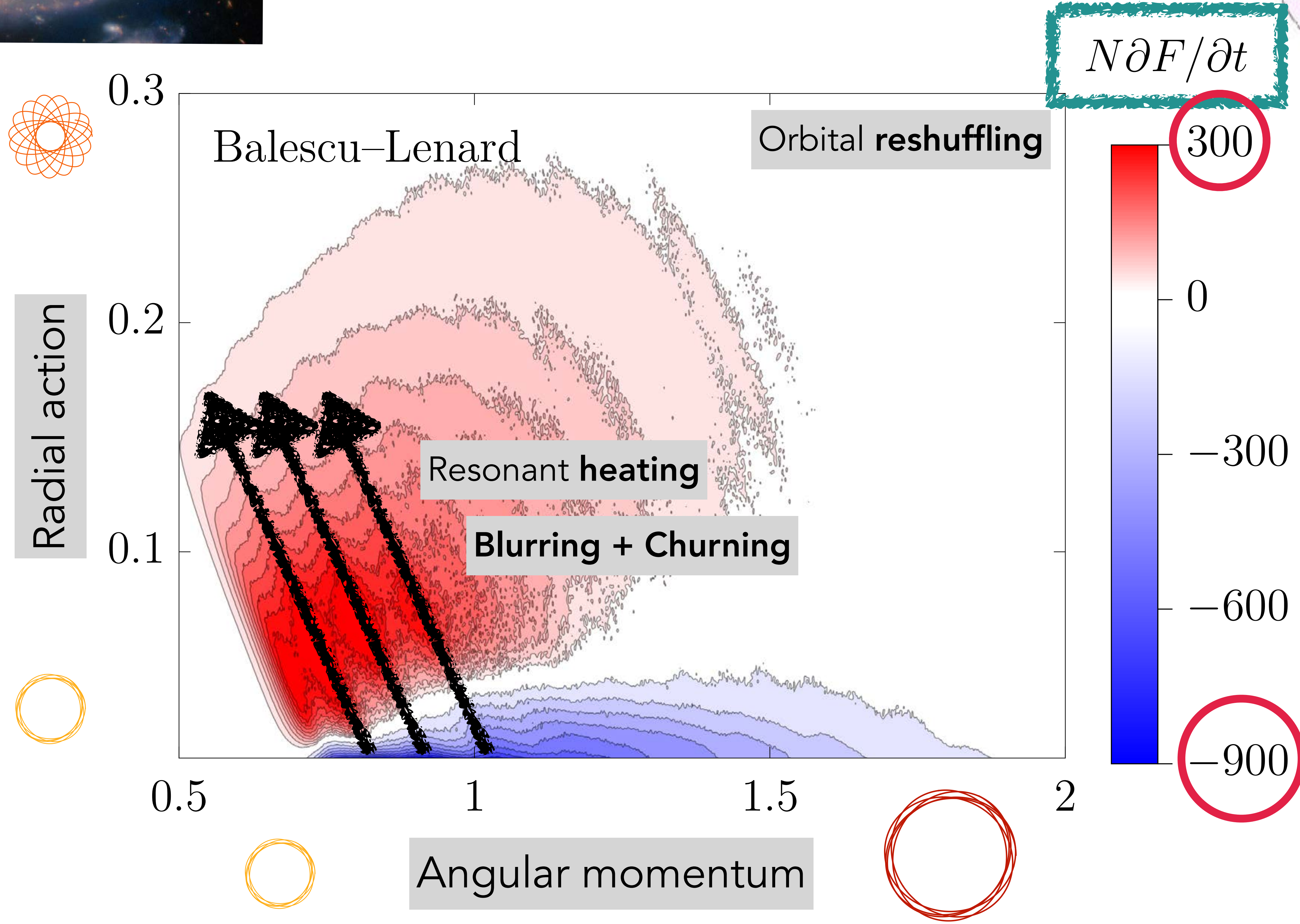
$$\frac{1}{\boxed{|\,\varepsilon(\omega)\,|}} \sim 30 \quad\longrightarrow\quad \frac{1}{\boxed{|\,\varepsilon(\omega)\,|^2}} \sim 1000$$

Toomre (1981)

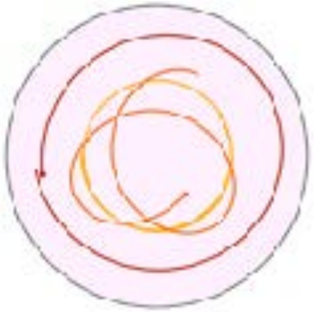
Collective effects drastically **accelerate** orbital **heating**, in particular on **large scales**

Self induced secular prediction



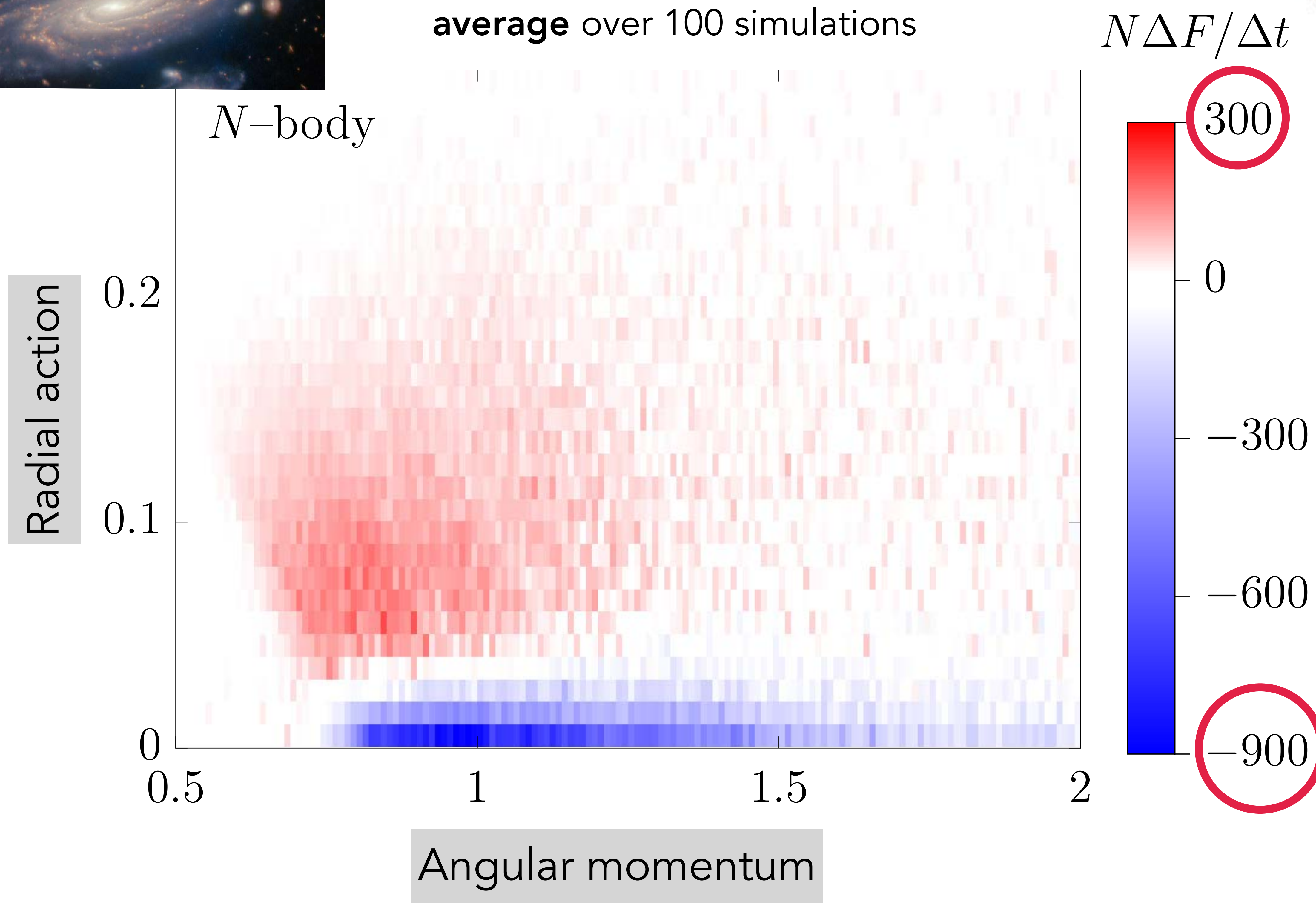


Roule+(in prep)



N–body measurements

average over 100 simulations



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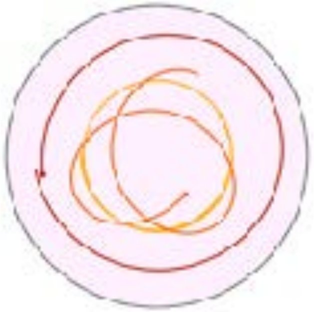

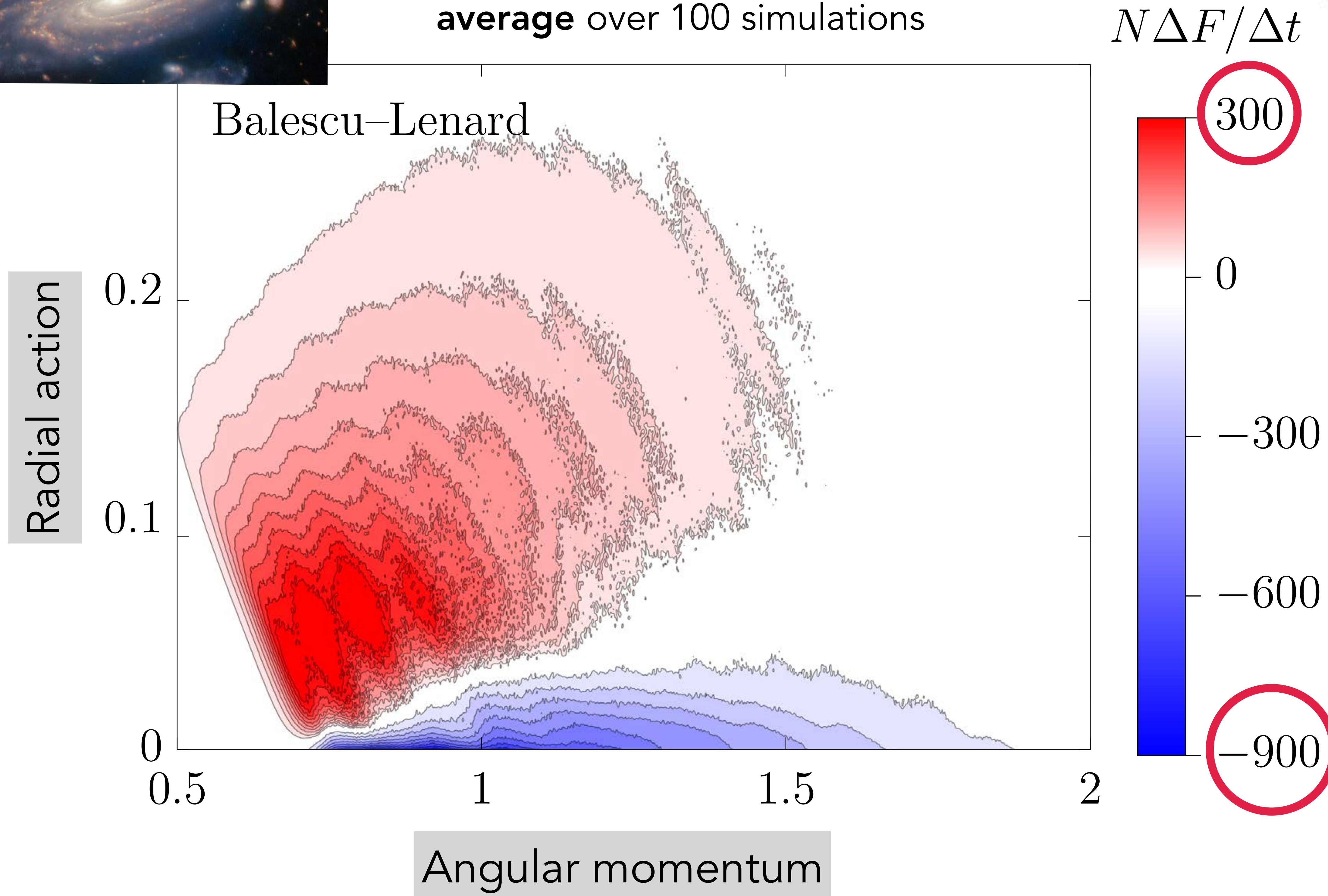

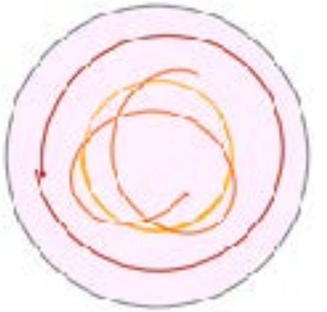

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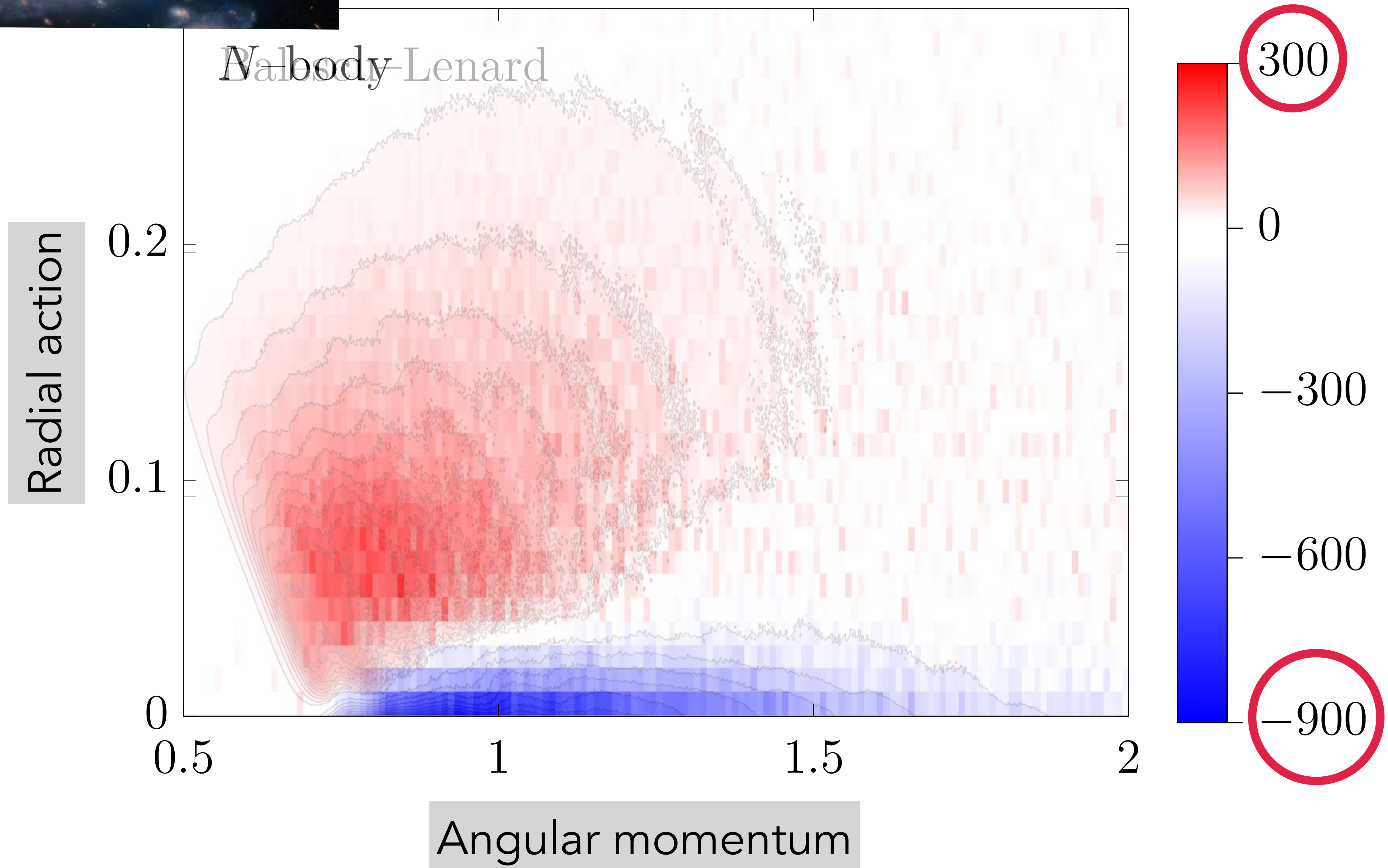
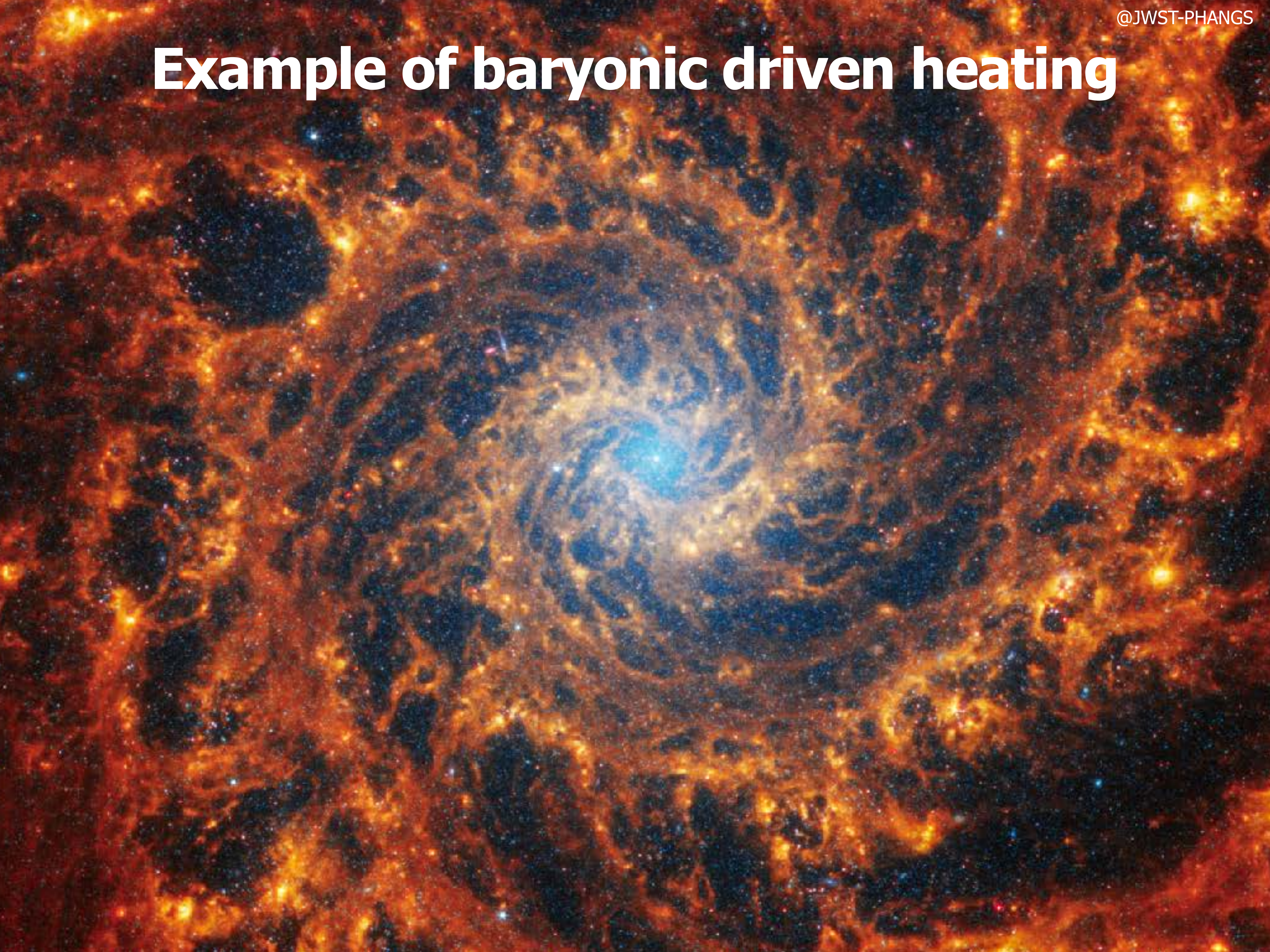
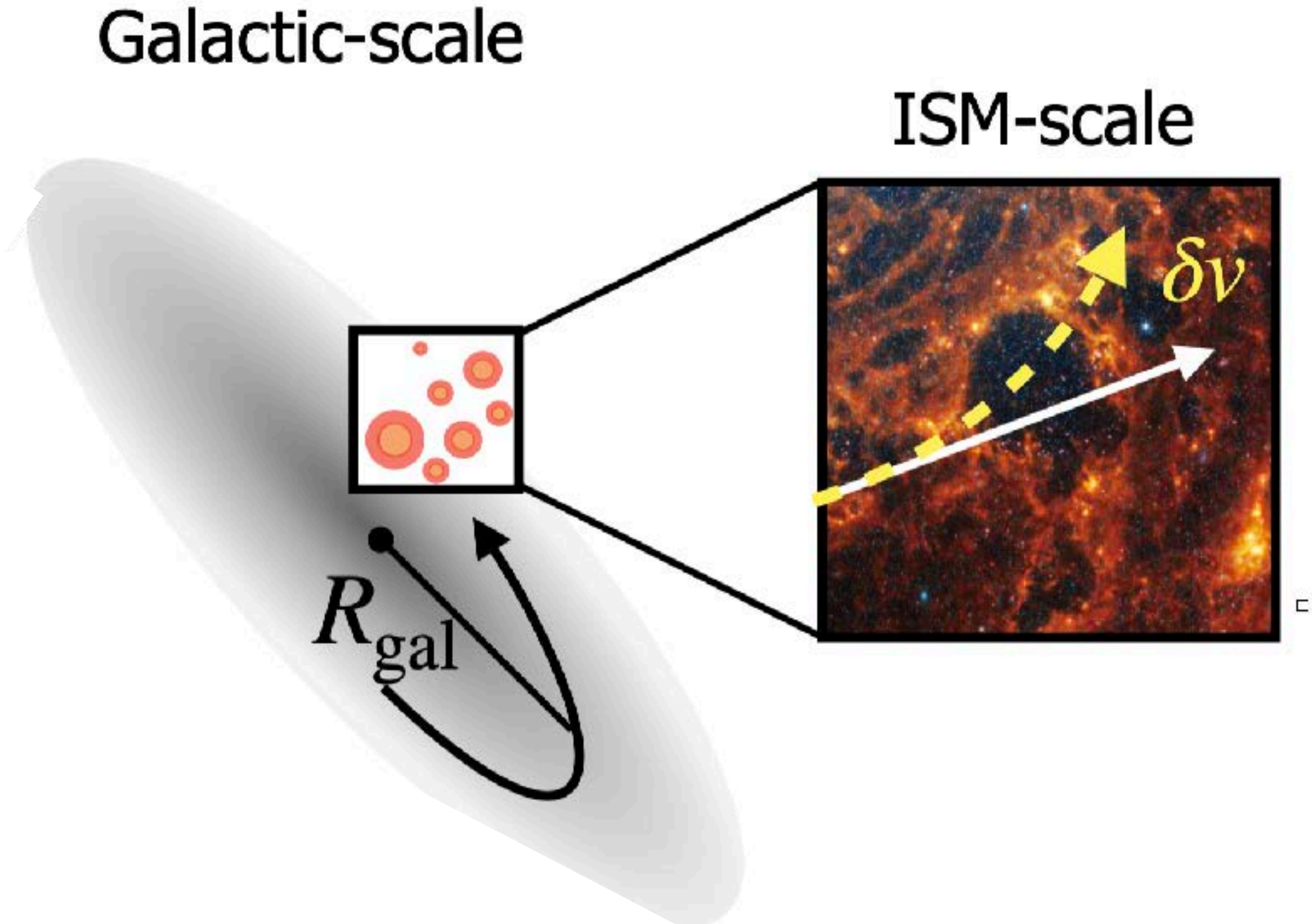


Kinetic theory satisfactorily captures the long-term heating of isolated cold discs

Example of baryonic driven heating

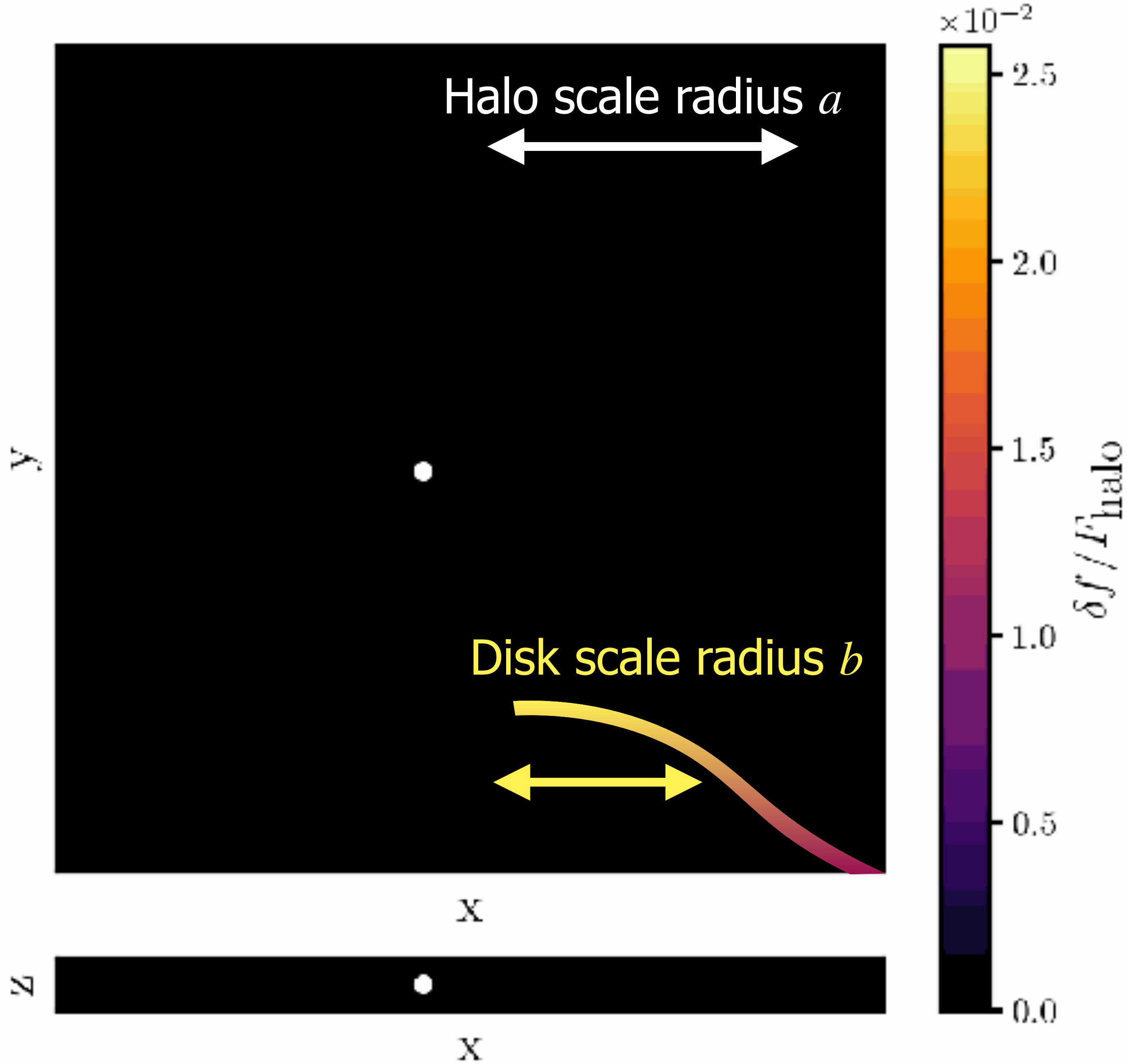


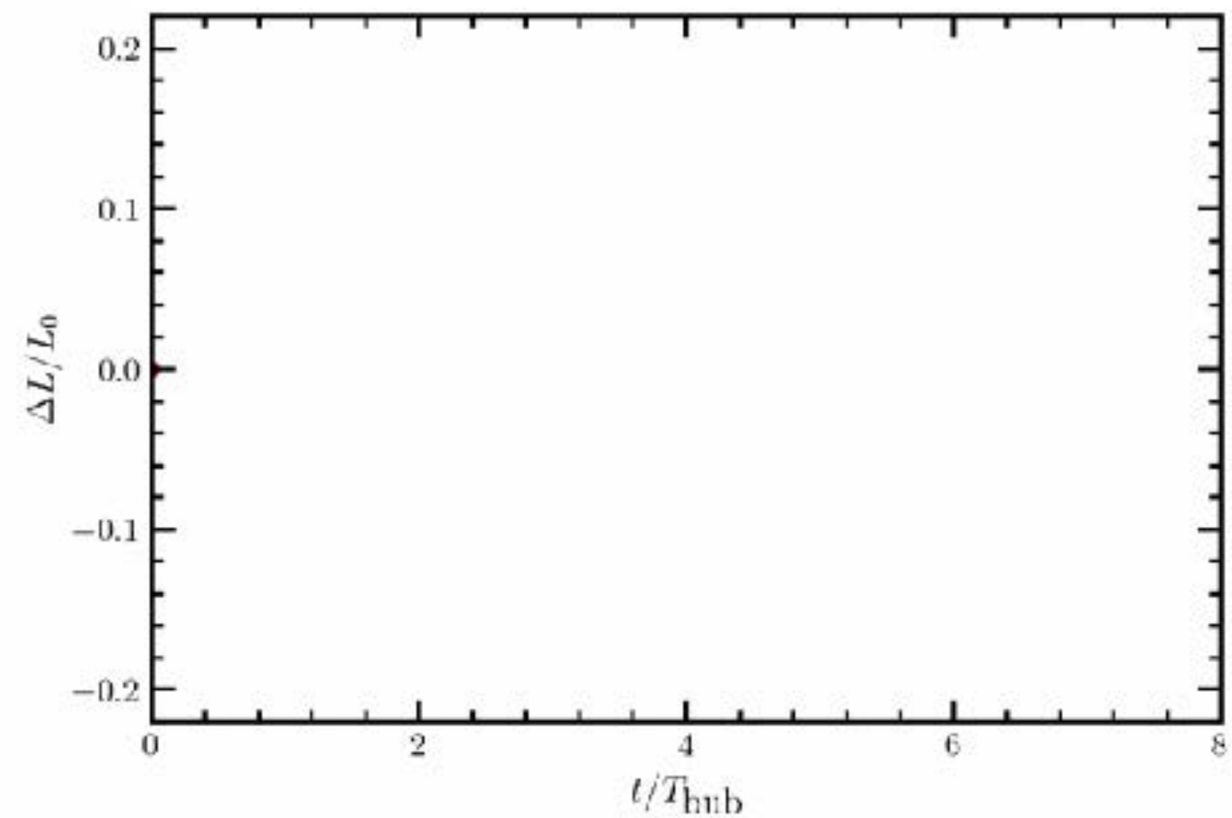
@JWST-PHANGS



with E Ko, JB Fouvry, K Tep

Superbubble (SB) as a dynamical heating source





Quantitative understanding in orbital diffusion in the context of **stochasticities & resonance**

Evolution of superbubble		DM halo		Gaseous disk
$R_{\rm bub}, T_{\rm bub}$	↭	a, V_0	↭	b

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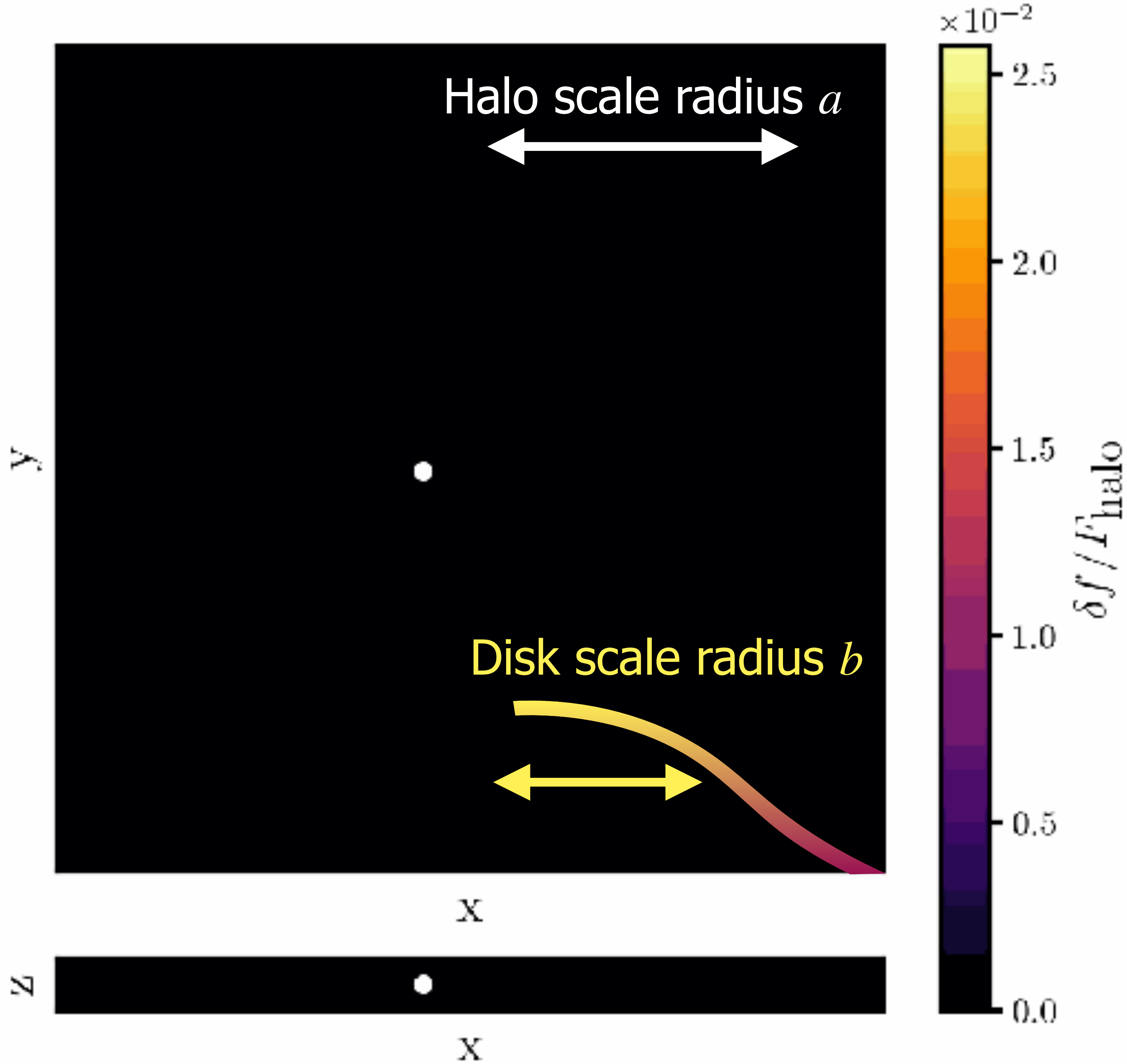

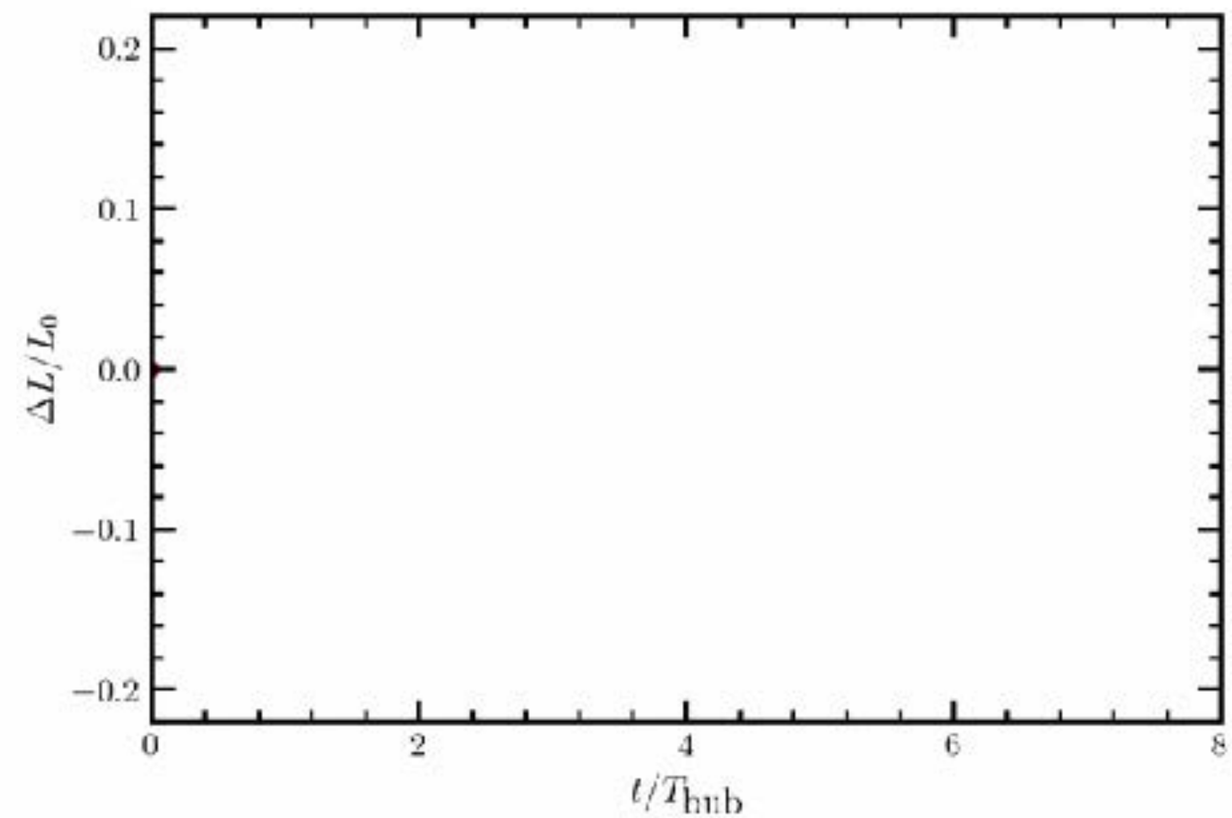

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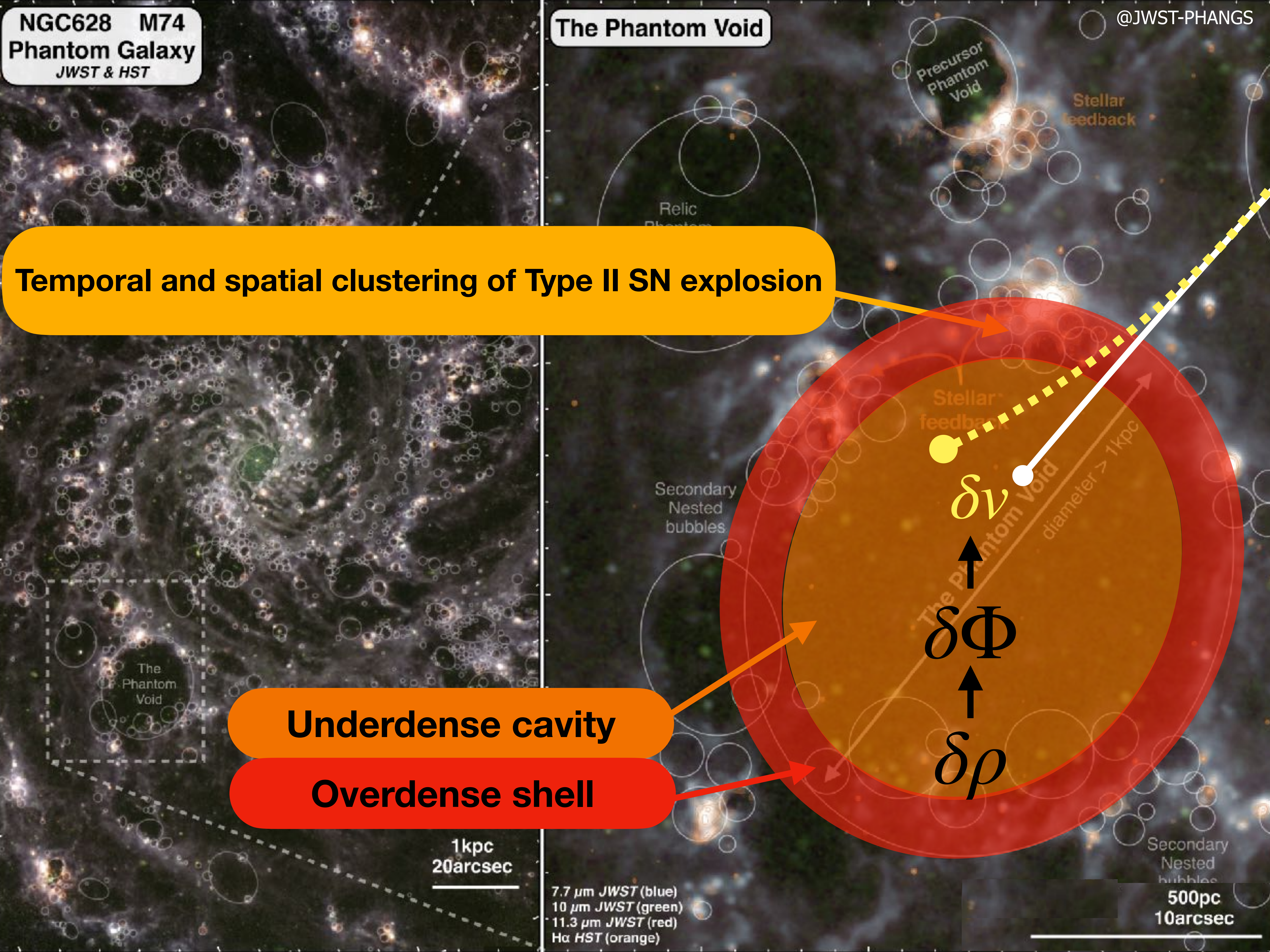


NGC628 M74
Phantom Galaxy
JWST & HST
The Phantom Void
@JWST-PHANGS
Precursor Phantom Void
Stellar feedback
Relic
Temporal and spatial clustering of Type II SN explosion
Stellar feedback
δv
The Phantom Void
diameter > 1kpc
Secondary Nested bubbles
$\delta\Phi$
$\delta\rho$
The Phantom Void
Underdense cavity
Overdense shell
1kpc
20arcsec
7.7 μm JWST (blue)
10 μm JWST (green)
11.3 μm JWST (red)
Hα HST (orange)
Secondary Nested
500pc
10arcsec

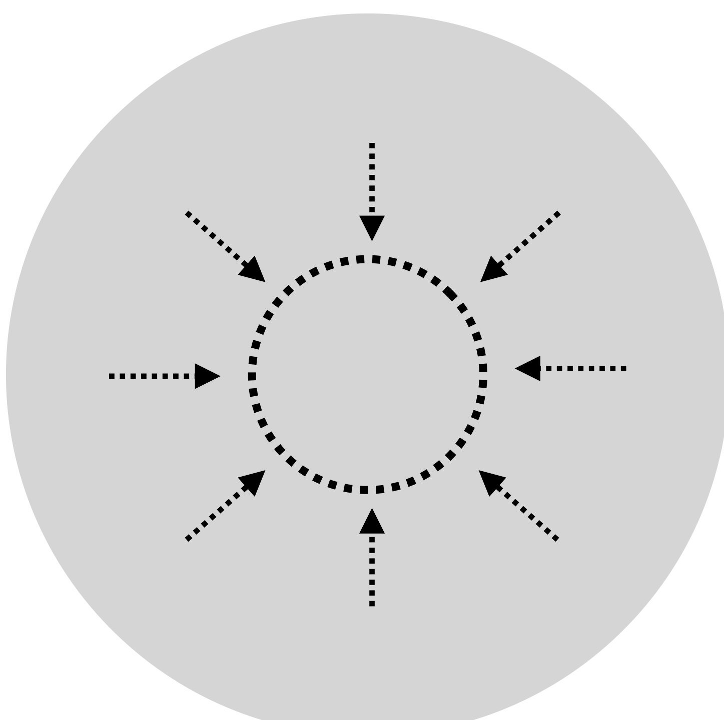
Cusp-core transformation driven by stochasticity

α: inner DM density profile slope

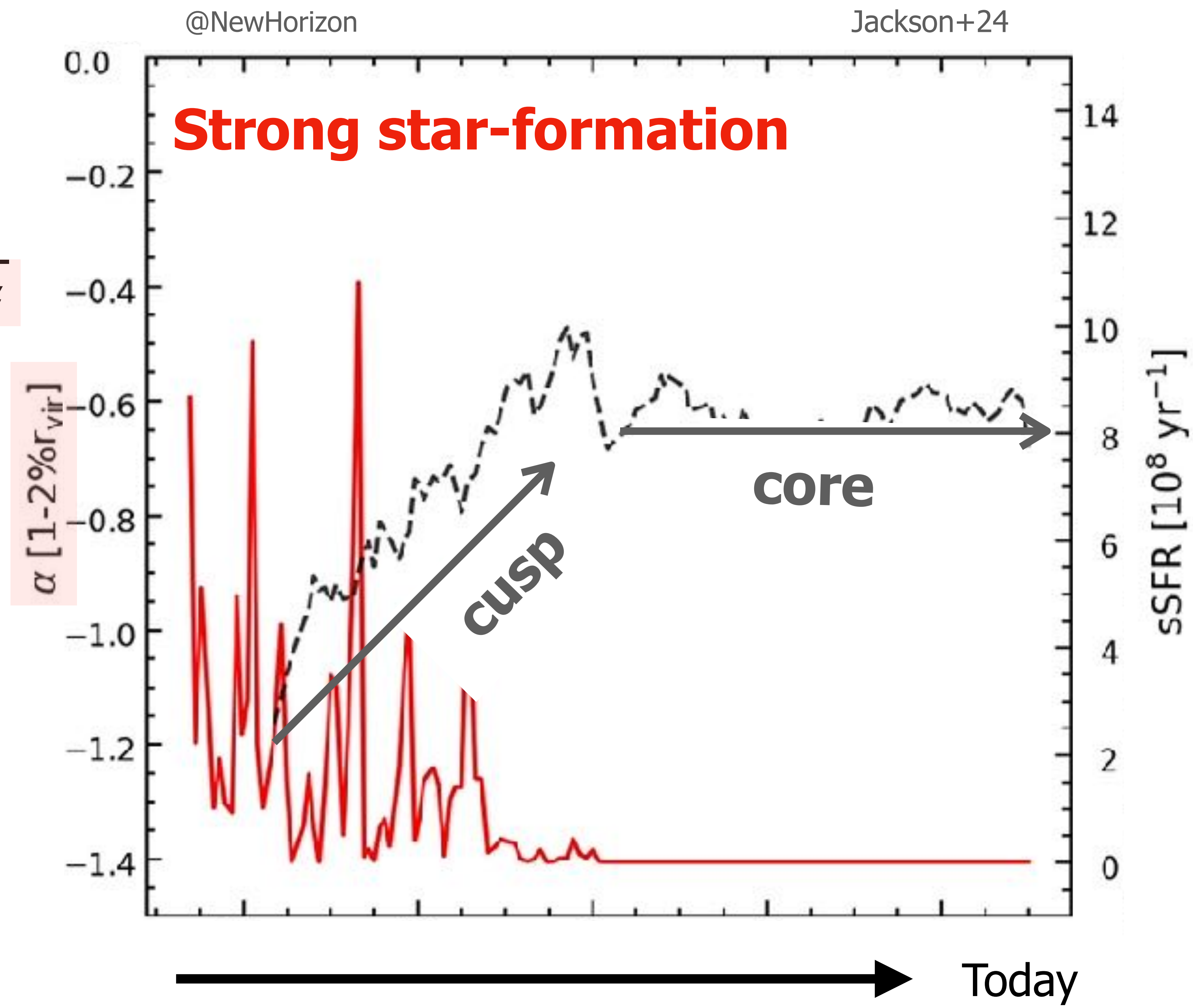
$$\Phi_{\mathrm{NFW}} = V_0^2 \frac{a}{r} \log\left(1 + \frac{r}{a}\right)$$

$$\rho_{\mathrm{NFW}} = \frac{\rho_0}{\left(\frac{r}{a}\right)^{-\alpha}\left(1 + \frac{r}{a}\right)^{-\beta+\alpha}}$$

Cusp



Quasi-stationary state of ΛCDM



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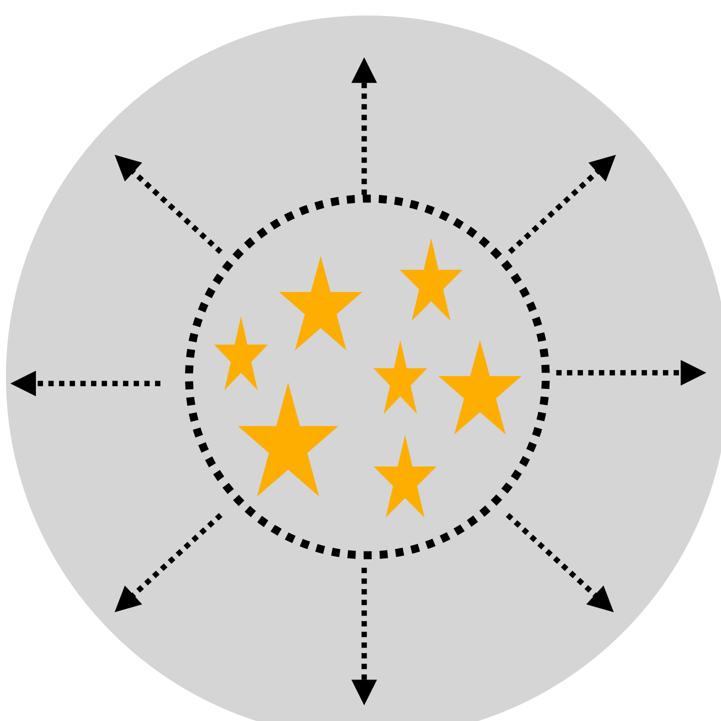
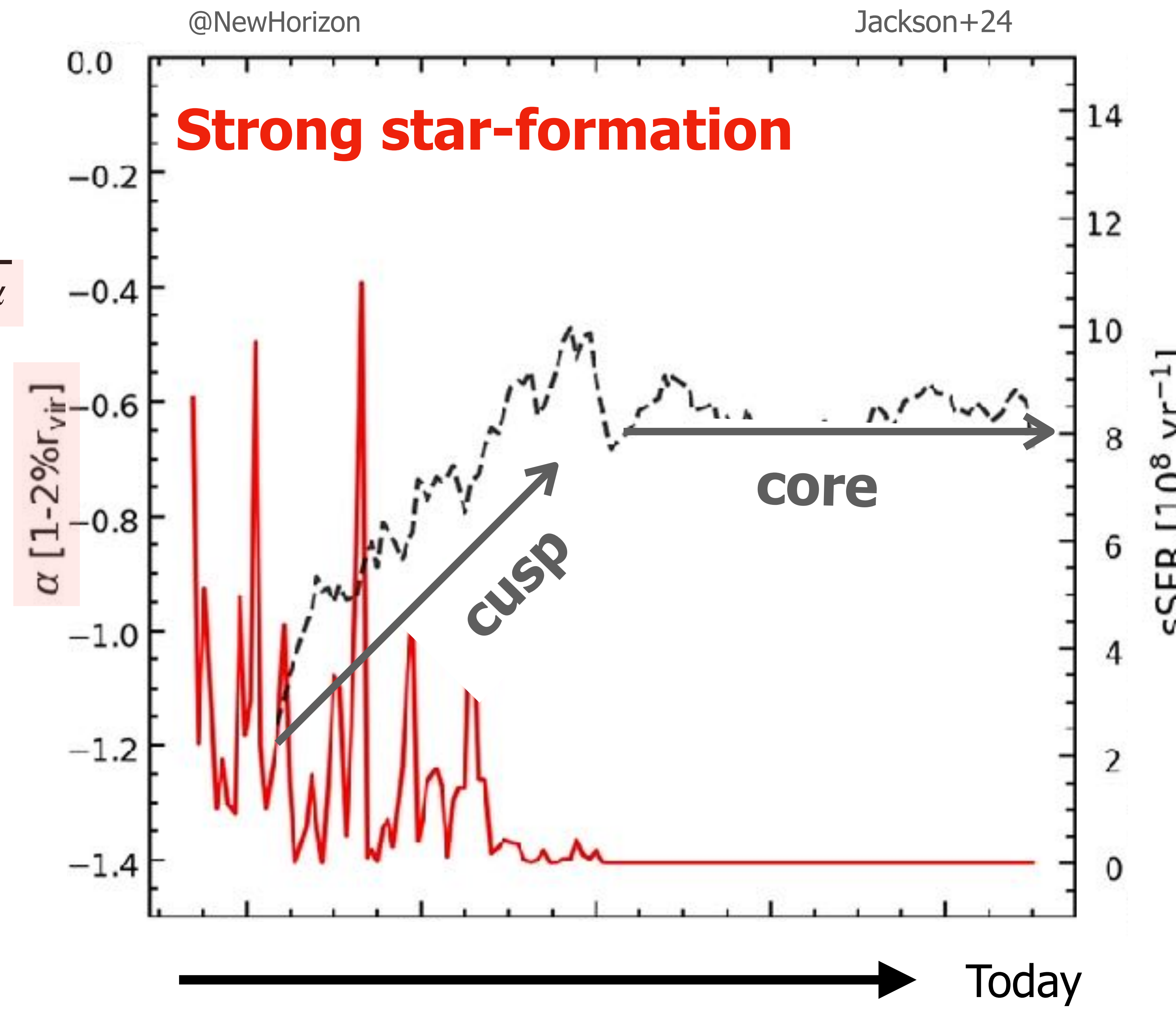
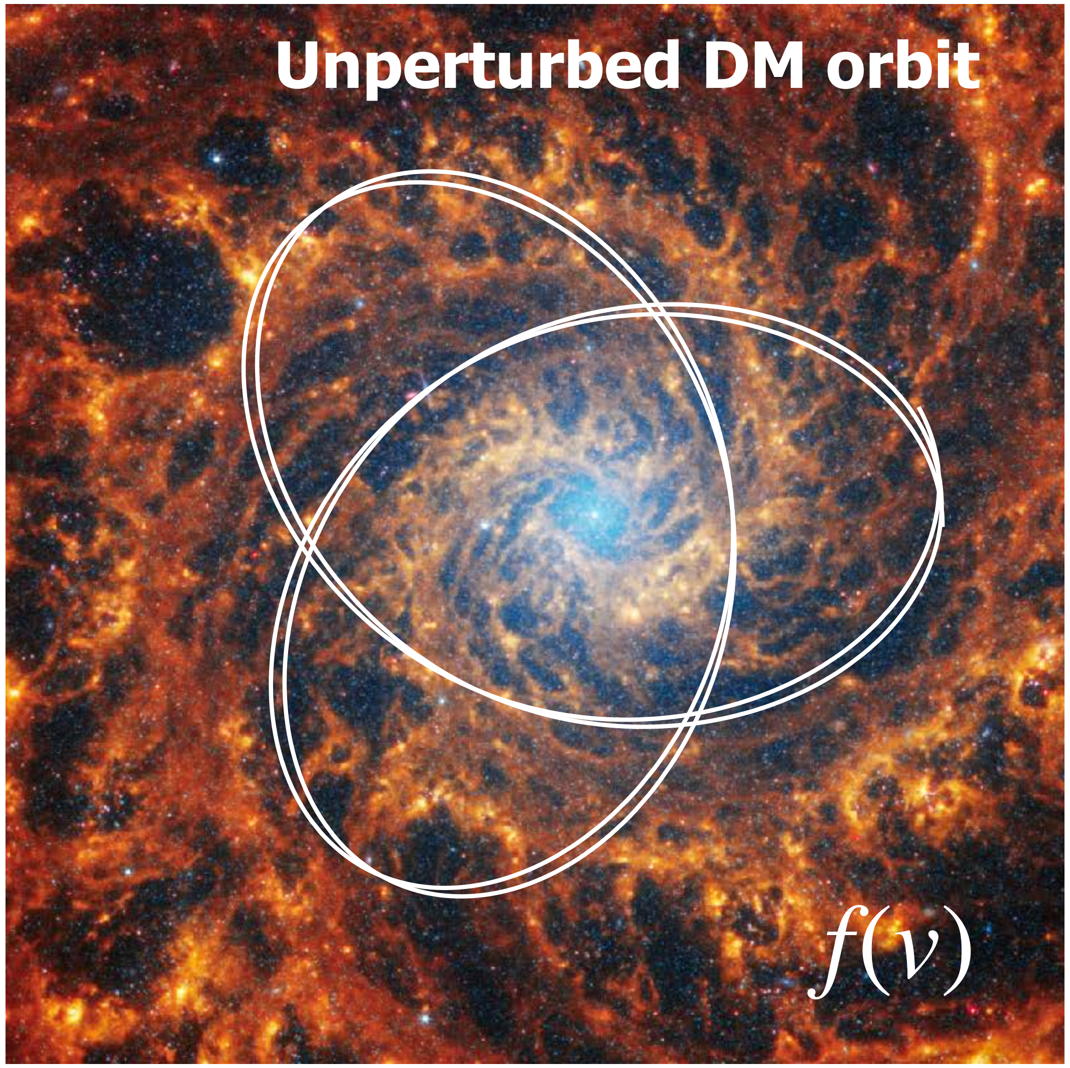


Orbital diffusion sourced by feedback-driven stochasticity



Orbit-Averaged Fokker-Planck Equation

Kinetic equation for secular evolution



$f(v)$: DM distribution function

δv: Velocity deflection by bubbles

Diffusion coefficient

$$\frac{\partial f}{\partial t} = \frac{1}{2}\frac{\partial}{\partial v_i}\left(\overbrace{D^{(2)}_{v_i v_j}}\frac{\partial f}{\partial v_j}\right)$$

Key assumptions

(1) Diffusion by series of **stochastic**, **weak**, **local**, and **short-timescale** perturbations

(2) **Accumulation** the local deflections along the **unperturbed** trajectory

(3) Locally homogenous but **globally inhomogeneous** superbubble distribution

(4) Alignment of DM orbit and gaseous disk

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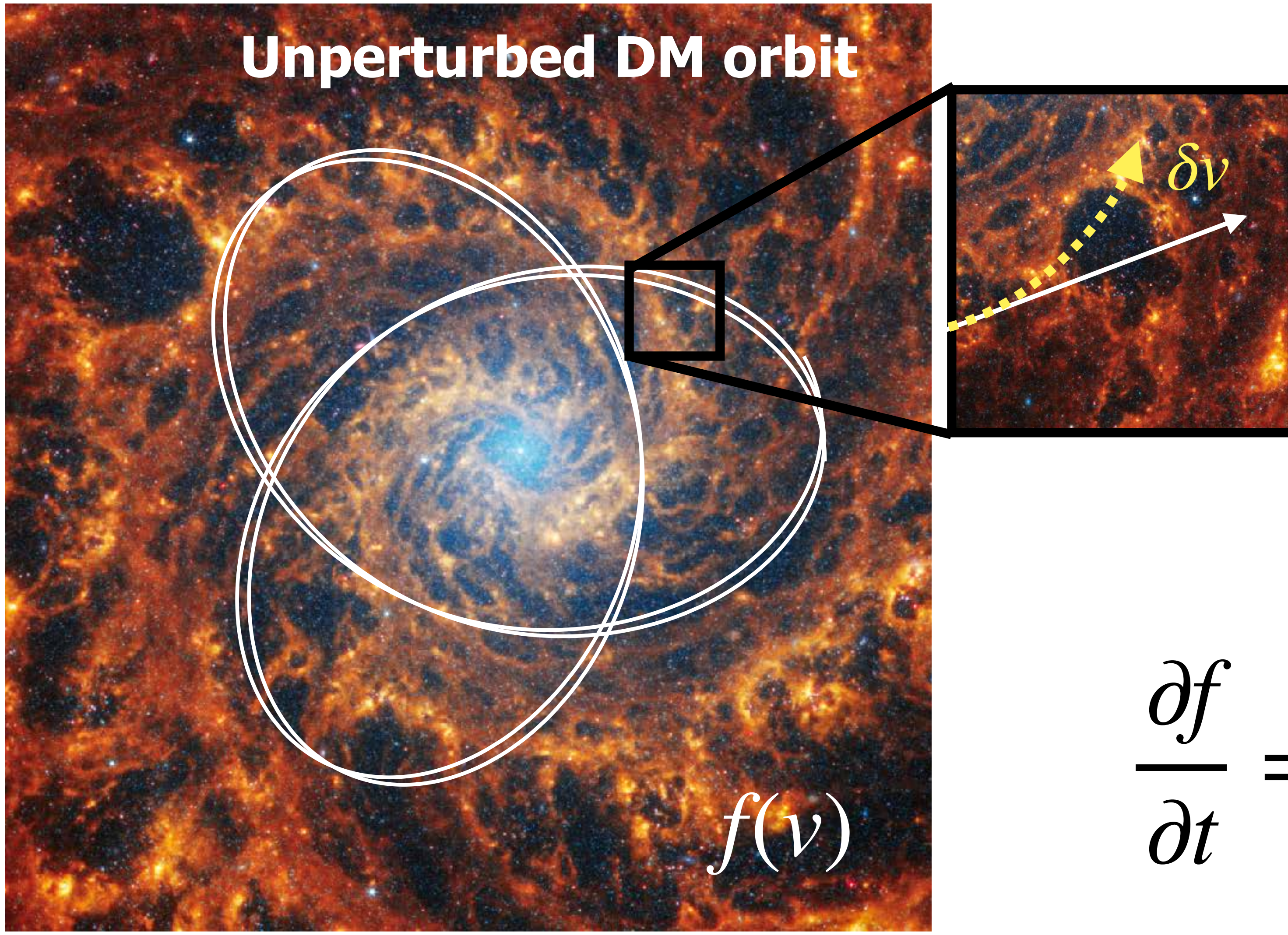

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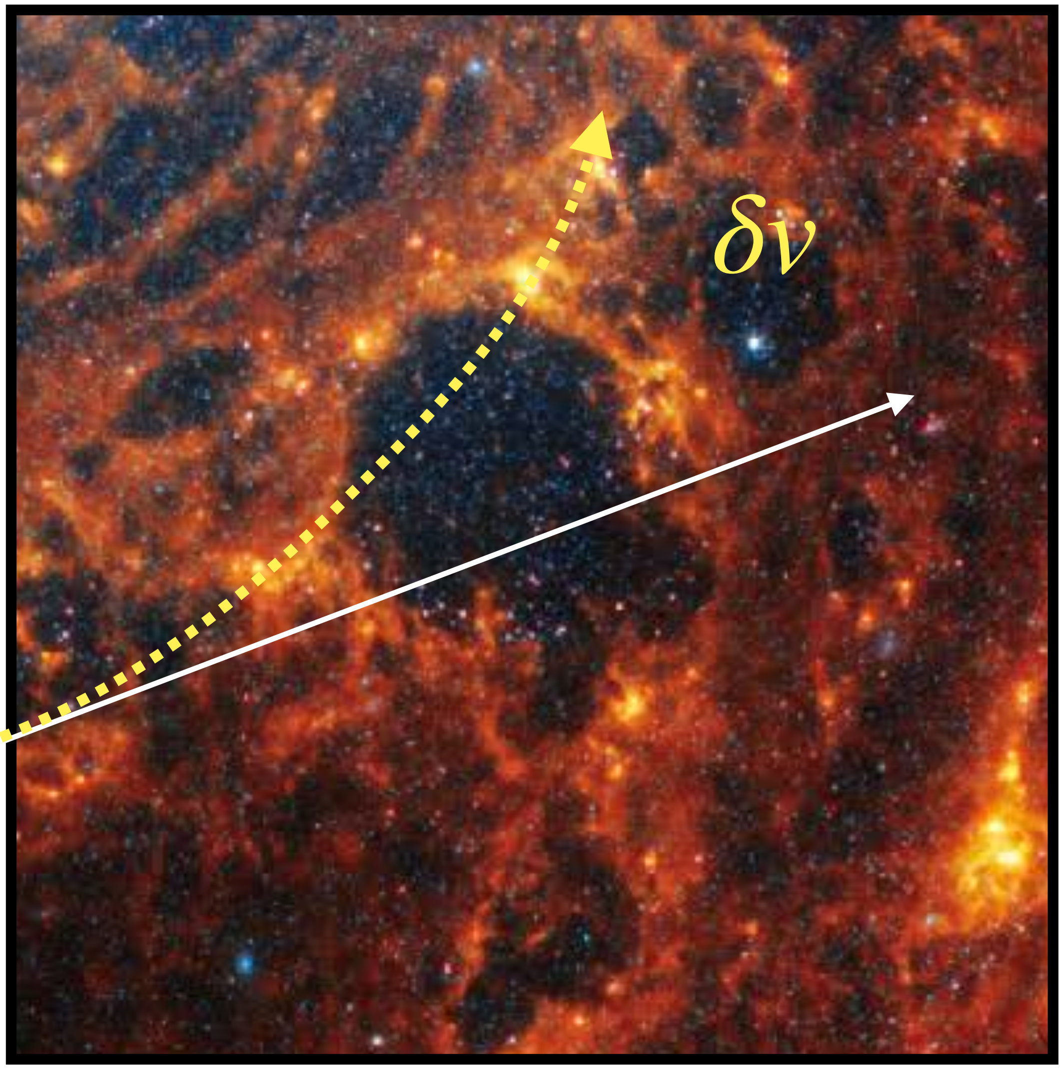

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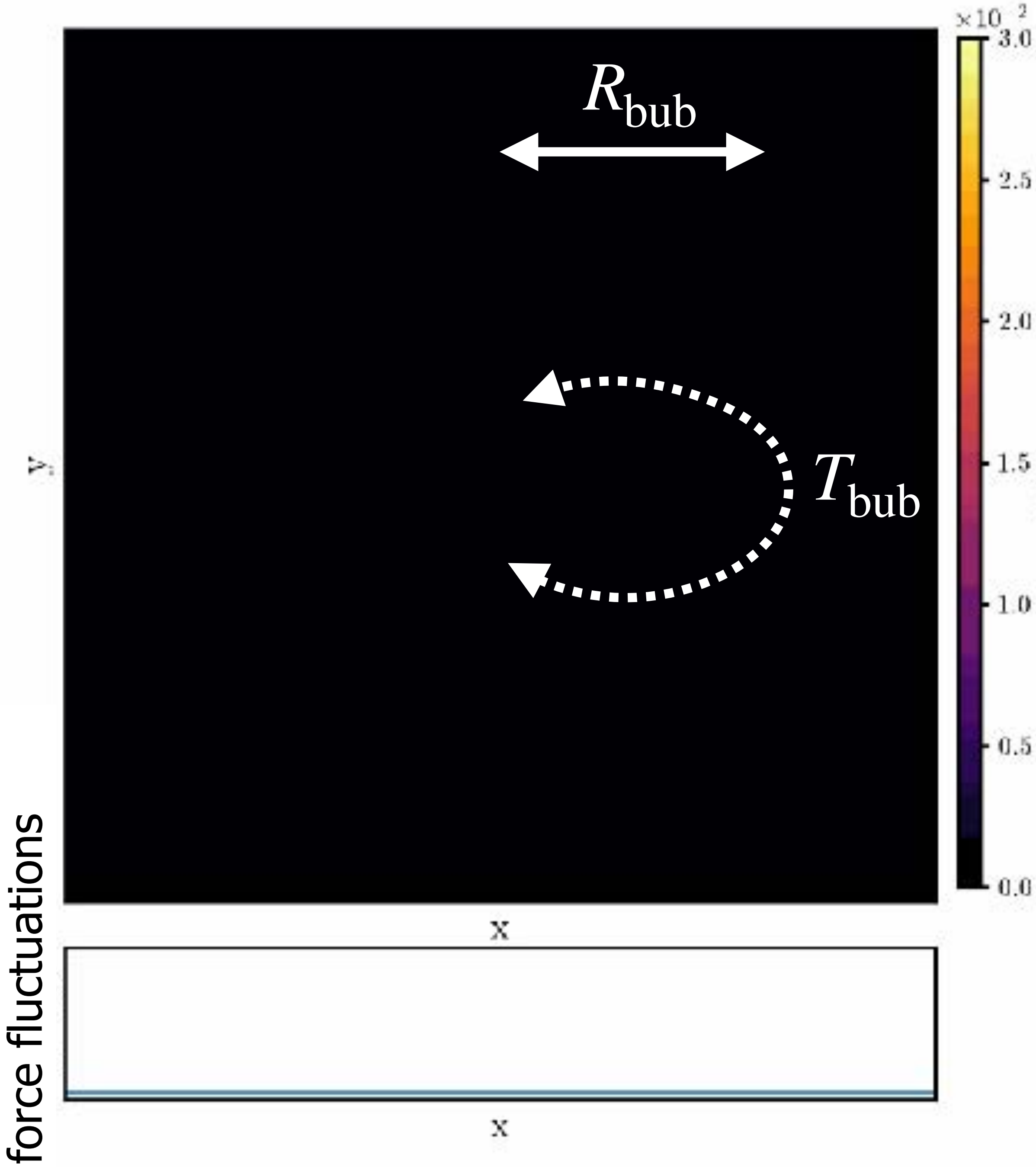
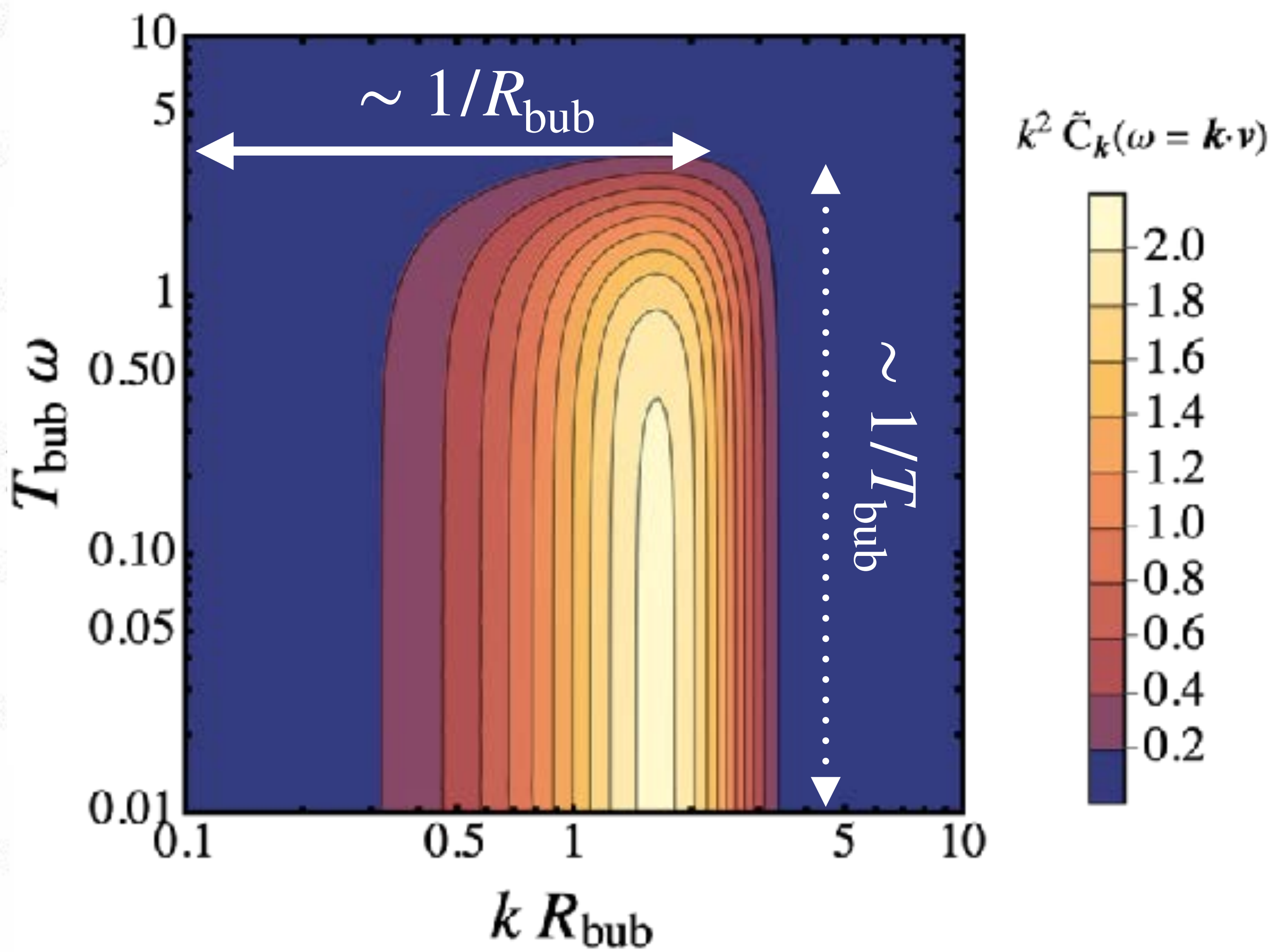
Bubble power spectrum





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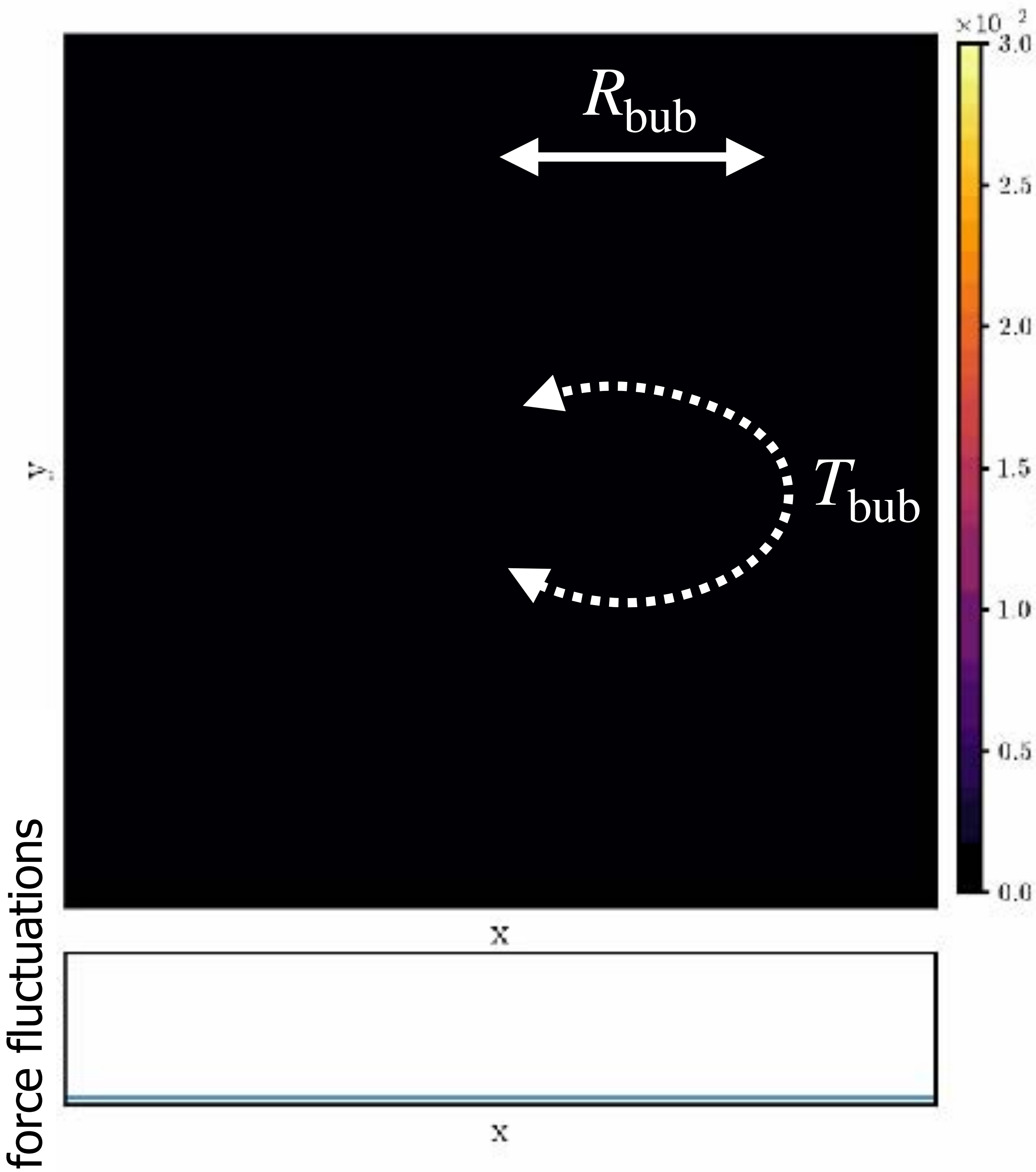
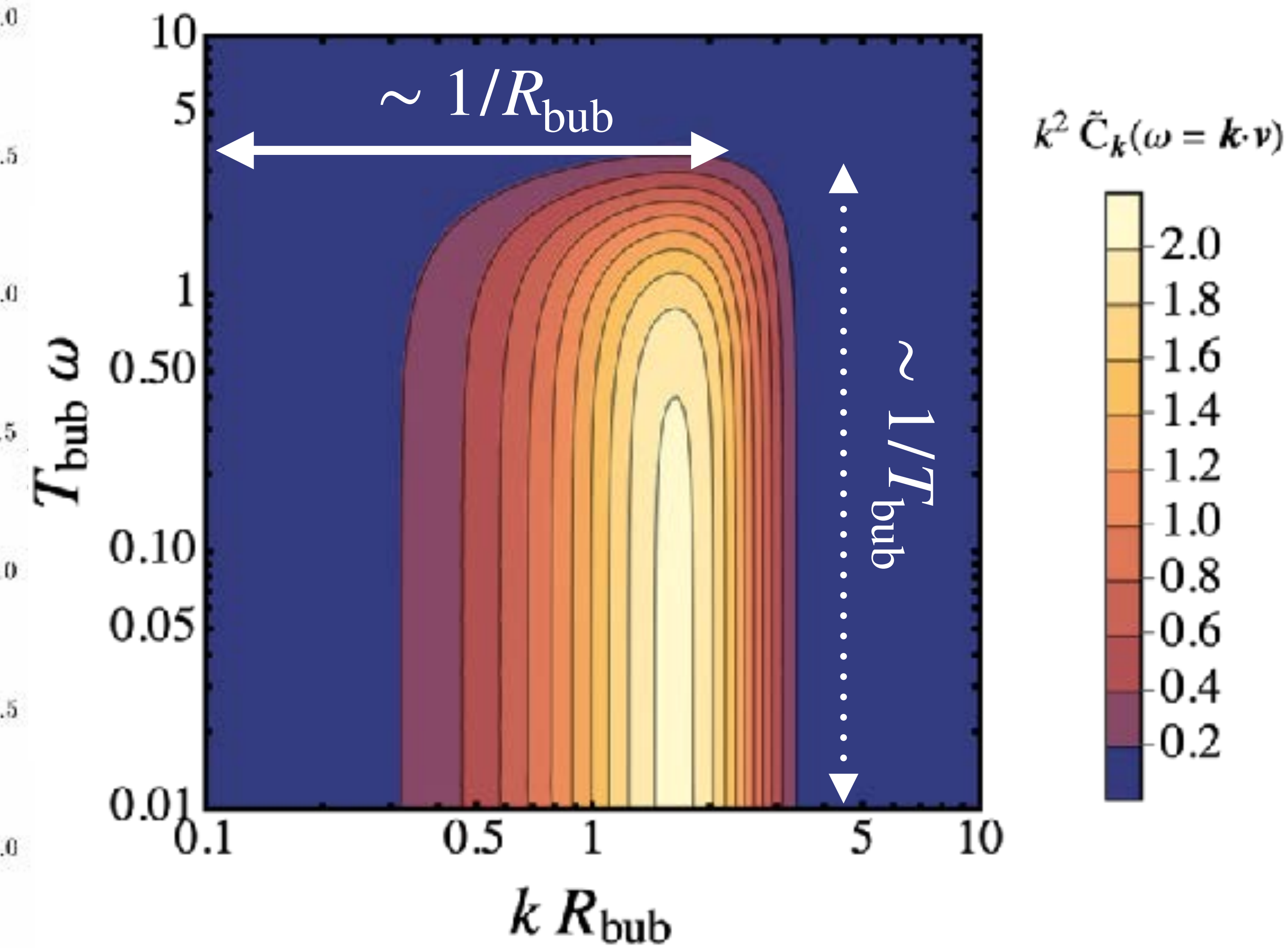
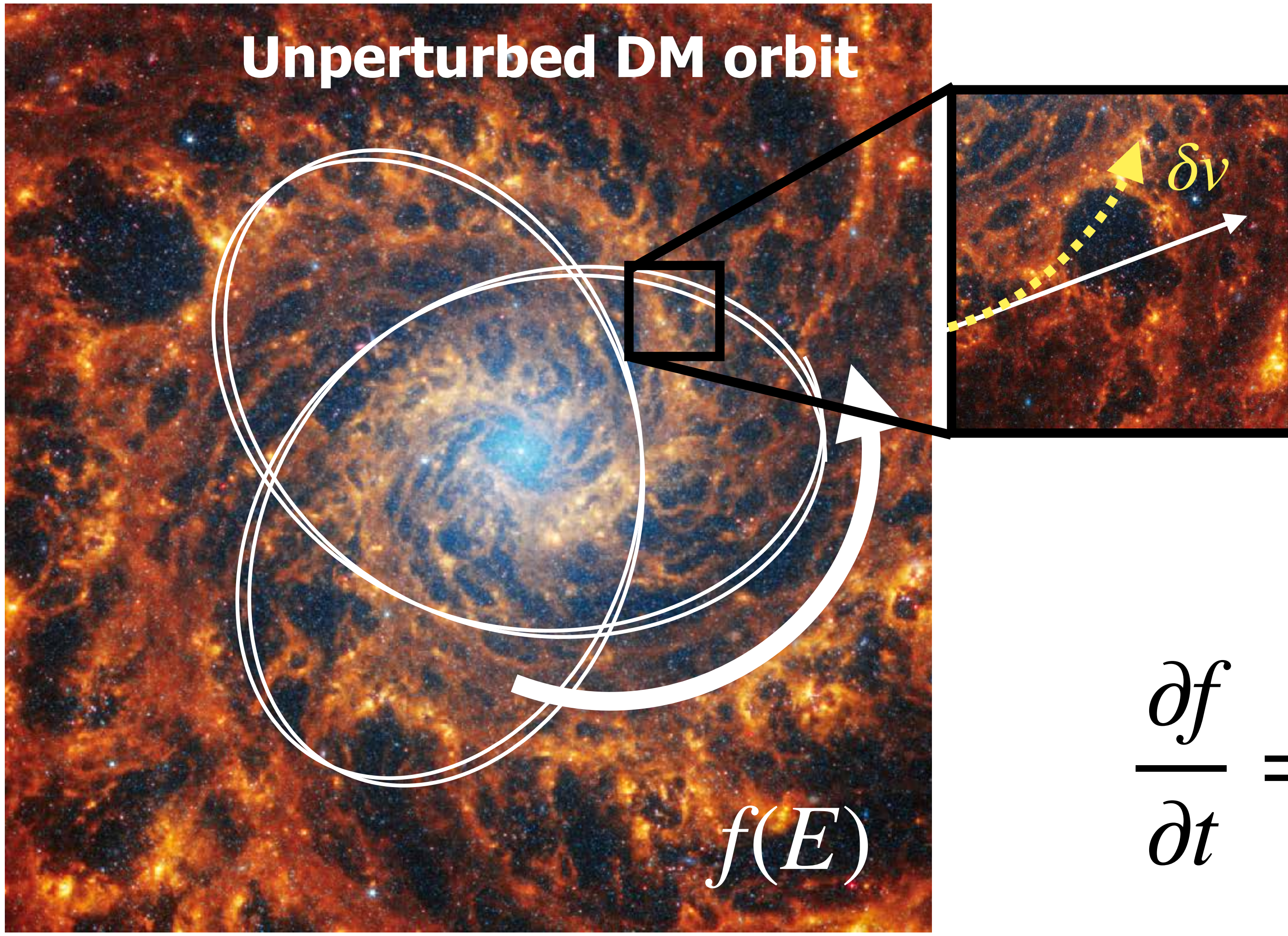




Orbit-Averaged Fokker-Planck Equation

Kinetic equation for secular evolution



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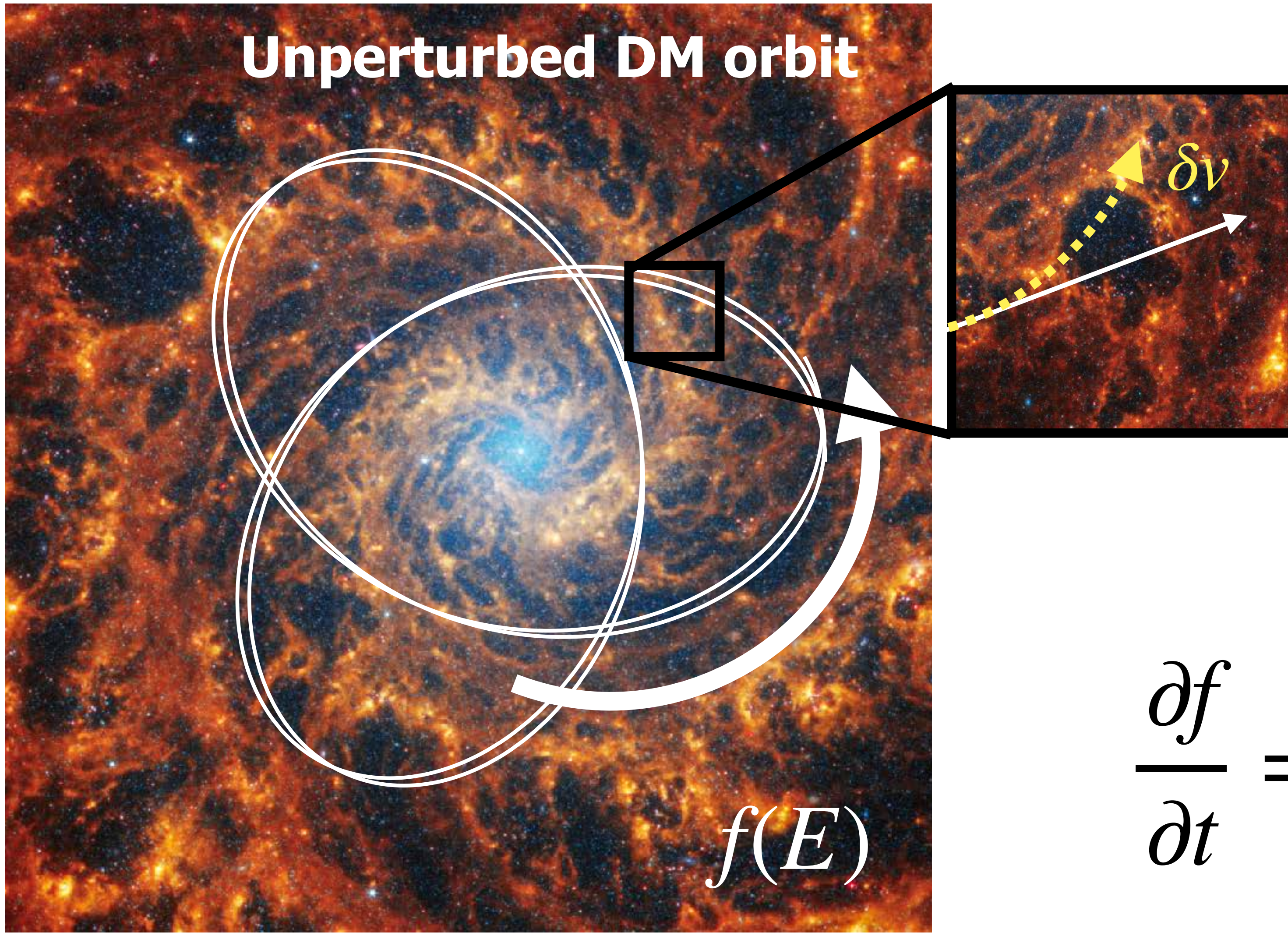

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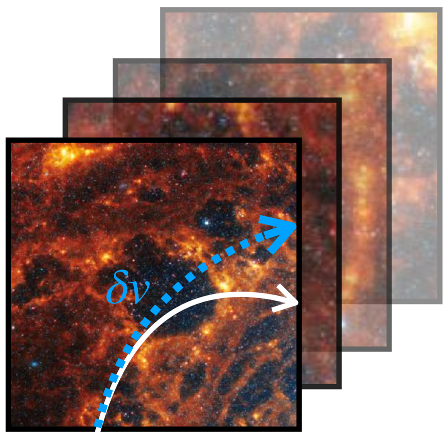
Orbit-Averaged Fokker-Planck Equation

(1) **Local** diffusion by stochastic perturbations

Local velocity deflection δv due to potential fluctuation $\delta\Phi$ by superbubbles: $\delta v = -\nabla\delta\Phi$



Average over different realizations of $\begin{cases}\text{random position and birth time}\\ \text{initial phases of orbits}\end{cases}$

Local diffusion coefficient

Power spectrum

$$\tilde{C}_{\boldsymbol{k}} = \lim_{T\to\infty}\frac{\langle\overline{\delta\Phi_{\boldsymbol{k}}\delta\Phi^*_{\boldsymbol{k}}}\rangle}{T}$$

$$d^{(2)}_{v_iv_j}(v_0) \equiv \lim_{T\to\infty}\frac{\langle\overline{\delta v_i\delta v_j}\rangle}{T}$$

$$= \dot{n}_{\rm bub}\int\frac{\mathrm{d}^3\boldsymbol{k}}{(2\pi)^3}k_ik_j\tilde{C}_{\boldsymbol{k}}(\overbrace{\omega = \boldsymbol{k}\cdot\boldsymbol{v}_0}^{\textbf{Resonance}})$$

number density rate

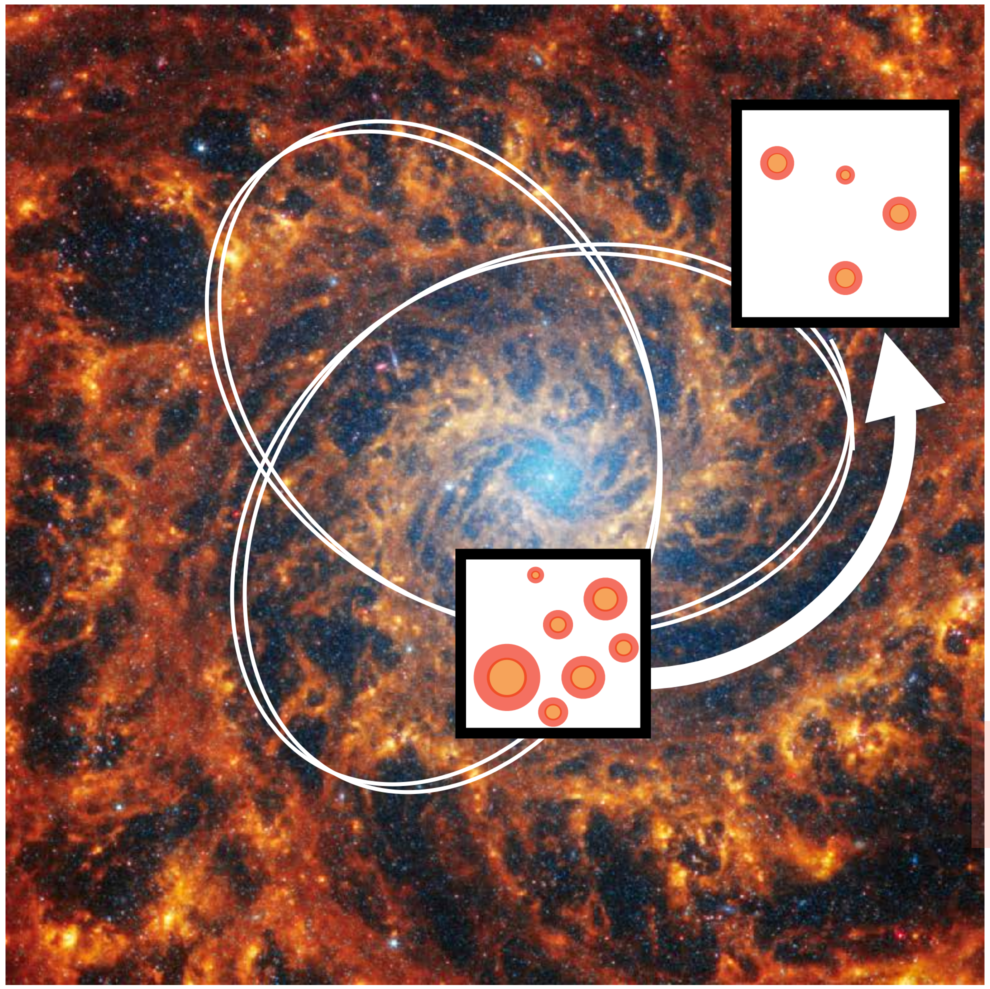
temporal freq.

spatial freq.

unperturbed velocity

Orbit-Averaged Fokker-Planck Equation

(2) **Accumulation** of local deflection **along the unperturbed orbit**



Orbit-averaged diffusion coefficient

$$D^{(2)}_{v_i v_j} = \frac{\Omega_r}{\pi} \oint_{r_a}^{r_p} \frac{\mathrm{d}r}{v_r} \Sigma_{\mathrm{bub}}(r)\, d^{(2)}_{v_i v_j}(\mathbf{v}[r])$$

radial orbital freq.

radial velocity

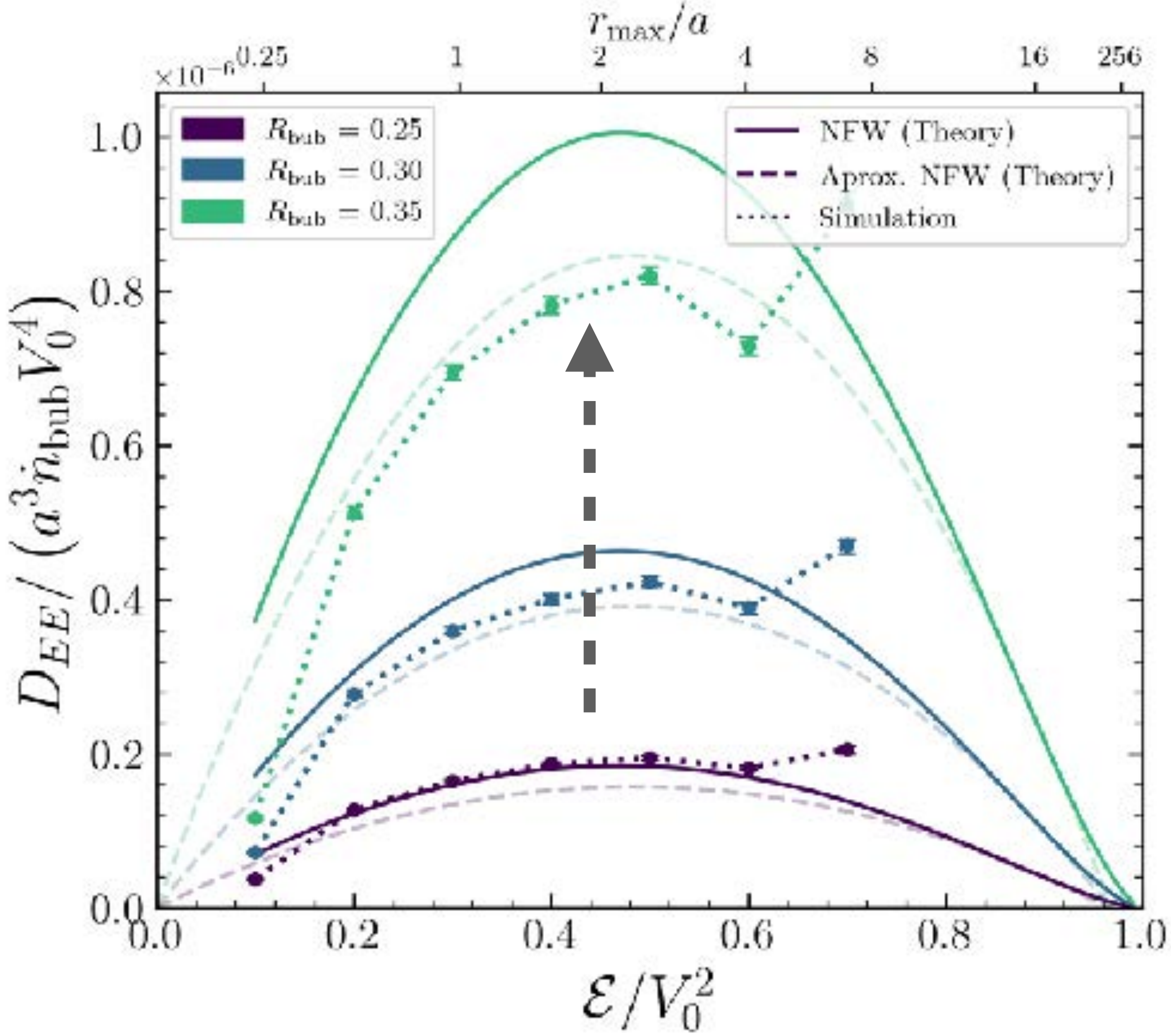
Bubble distribution

$$\Sigma_{\mathrm{bub}}(r) = \frac{1}{1 + r/b}$$

Local diffusion coefficient

Globally inhomogeneous superbubble on the disk:

Resonance between DM orbit and superbubble distribution



*SB = Superbubbles

$$\mathscr{E}_{\max} = \frac{V_0^2}{2}\left(1 - \frac{1}{2}\frac{a}{b}\right)$$

Scaling relation for diffusion coefficient for $E \ll V_0^2, R_{\rm bub} \ll a, T_{\rm bub} \ll a/V_0$

$$D_{EE}^{(2)} = \pi^{5/2}\frac{1536}{15625}\sqrt{\frac{7}{5}}\left(a^3\dot{n}_{\rm bub}V_0^4\right)\left(\frac{4\pi}{3}\frac{a^2\rho_{\rm bub}}{V_0^2/(4\pi G)}\right)^2\left(\frac{R_{\rm bub}}{a}\right)^5\left(\frac{T_{\rm bub}V_0}{a}\right)^2\left(\frac{\mathscr{E}}{V_0^2}\right)\left[1 - \frac{V_0^2}{2\mathscr{E}_{\max}}\left(\frac{\mathscr{E}}{V_0^2}\right)\right]$$

Number of SB

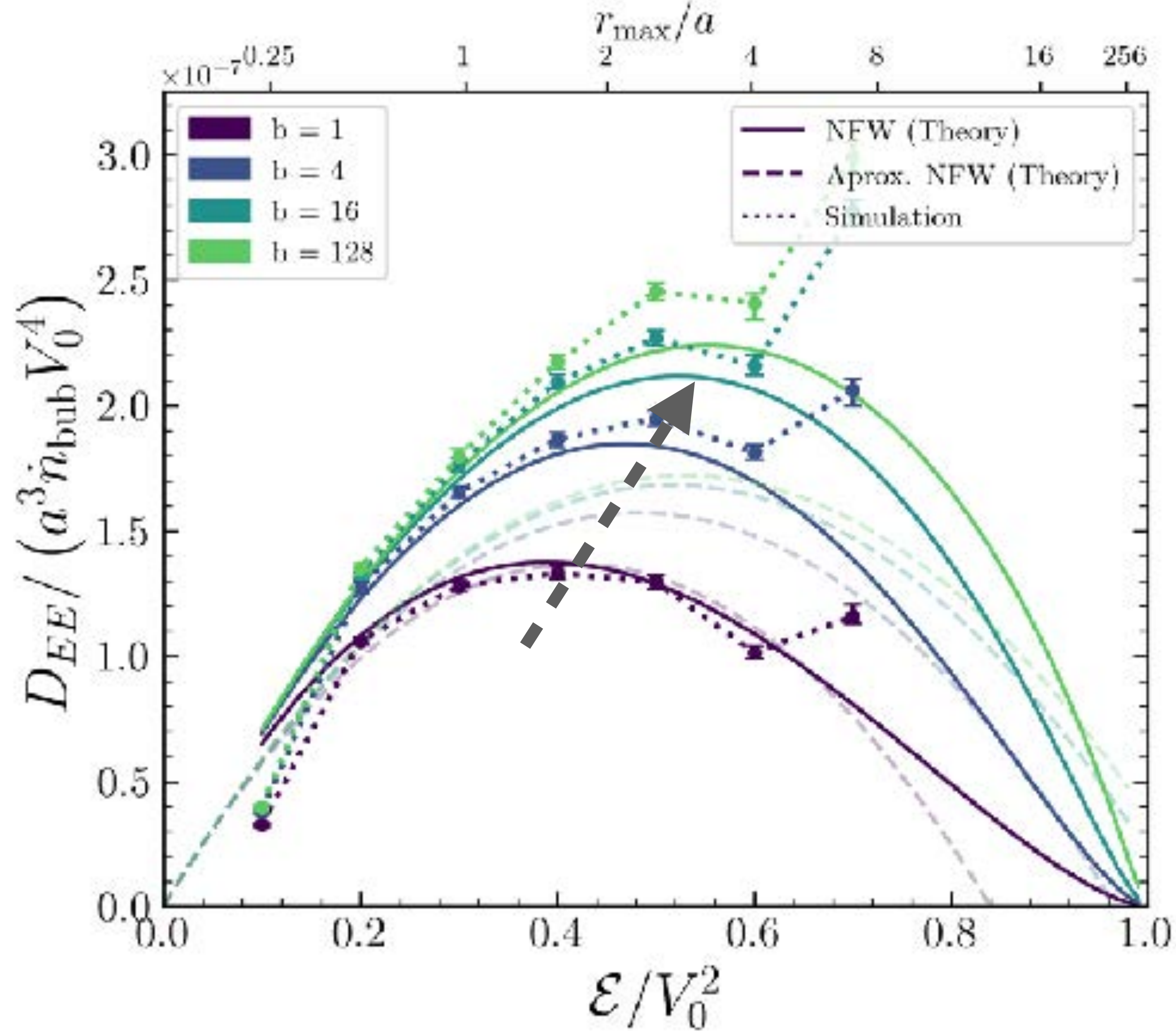
Mass density: SB vs. halo

Scale radius: SB vs. halo

Dynamical timescale: SB vs. halo

Energy: orbit vs. halo

Scale radius: halo vs. disk



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$$\mathscr{E}_{\max} = \frac{V_0^2}{2}\left(1 - \frac{1}{2}\frac{a}{b}\right)$$

Scaling relation for diffusion coefficient for $E \ll V_0^2, R_{\rm bub} \ll a, T_{\rm bub} \ll a/V_0$

$$D^{(2)}_{EE,\max} = \pi^{5/2}\frac{768}{15625}\sqrt{\frac{7}{5}}\left(a^3\dot{n}_{\rm bub}V_0^4\right)\left(\frac{4\pi}{3}\frac{a^2\rho_{\rm bub}}{V_0^2/(4\pi G)}\right)^2\left(\frac{R_{\rm bub}}{a}\right)^5\left(\frac{T_{\rm bub}V_0}{a}\right)^2\left(\frac{\mathscr{E}_{\max}}{V_0^2}\right)$$

Number of SB

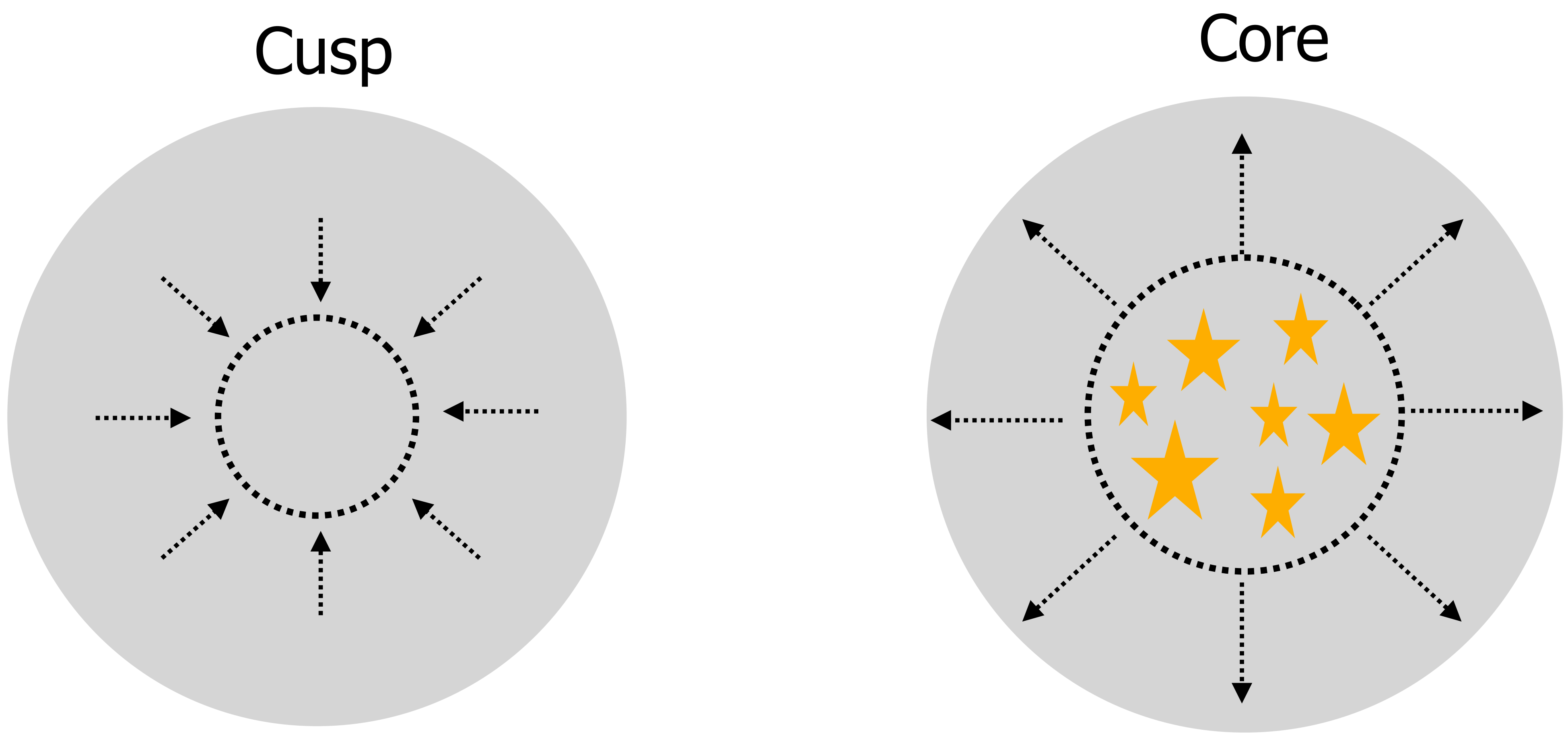
Scale radius: SB vs. halo

Energy: orbit vs. halo

Mass density: SB vs. halo

Dynamical timescale: SB vs. halo

Summary

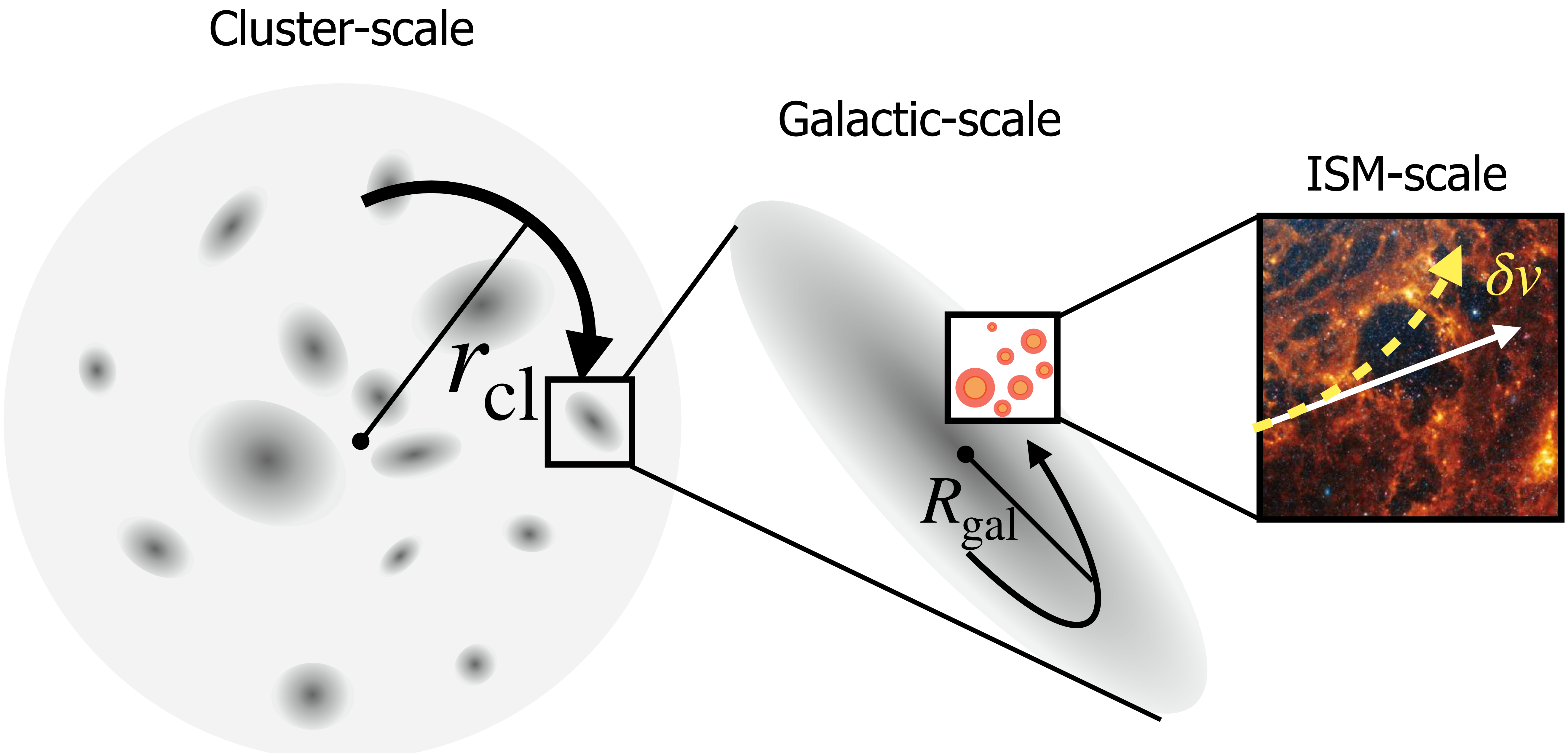


Dynamical heating sourced by {
Stochastic power spectrum
Resonance between different scales

↓

Bar dissolution / Disk heating / Giant Molecular Clouds

Perspective: multi-scale orbit-averaging



Orbit-averaging

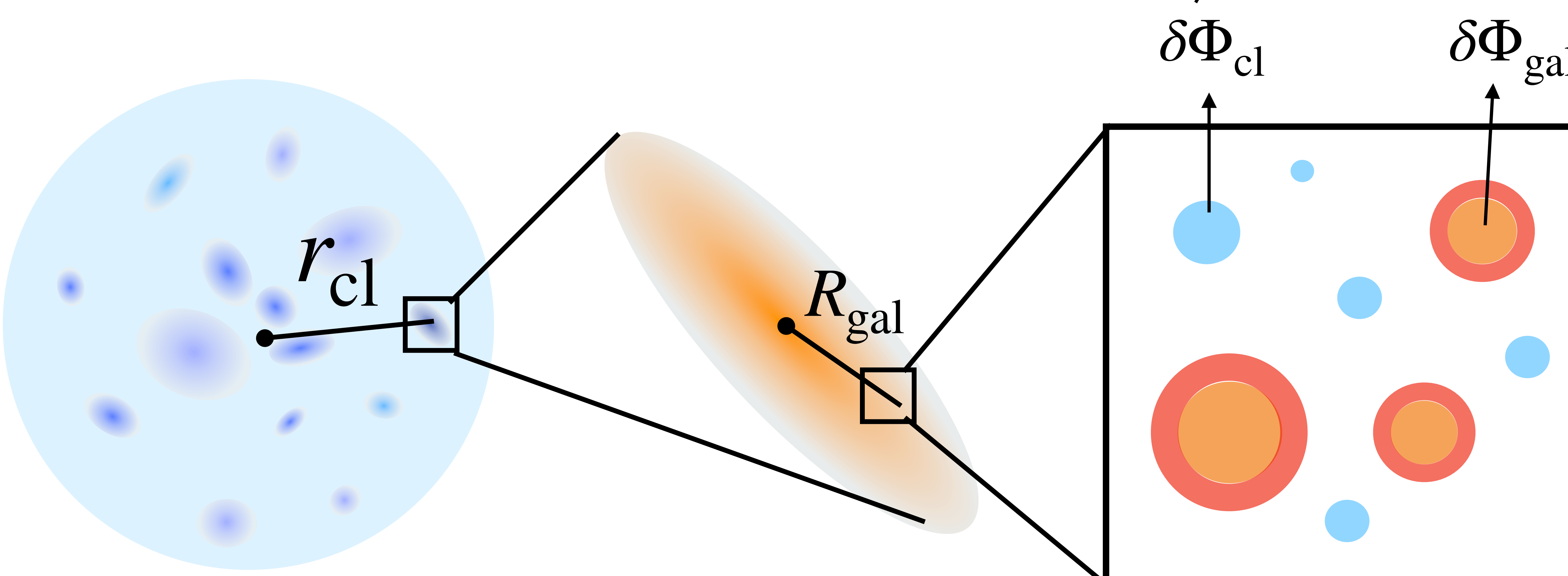
Stochastic perturbations

$$D^{(2)}_{v_i v_j} \propto \frac{1}{T_{\mathrm{cl}}}\int_0^{T_{\mathrm{cl}}} \mathrm{d}t\, \overbrace{\Sigma_{\mathrm{cl}}(r[t])}^{\text{Cluster substructures}}\, \frac{1}{T_{\mathrm{gal}}}\int_0^{T_{\mathrm{gal}}} \mathrm{d}t'\, \overbrace{\Sigma_{\mathrm{gal}}(R[t'])}^{\text{Bubble distribution}} \int \mathrm{d}^3\mathbf{k}\, k_i k_j\, \overbrace{\tilde{C}_{\mathrm{tot}}(\omega = \mathbf{k}\cdot\mathbf{v}_{\mathrm{tot}})}^{\text{Stochastic perturbations}}$$

Morphological transformation as a diffusion process

Orbit-averaged diffusion coefficient

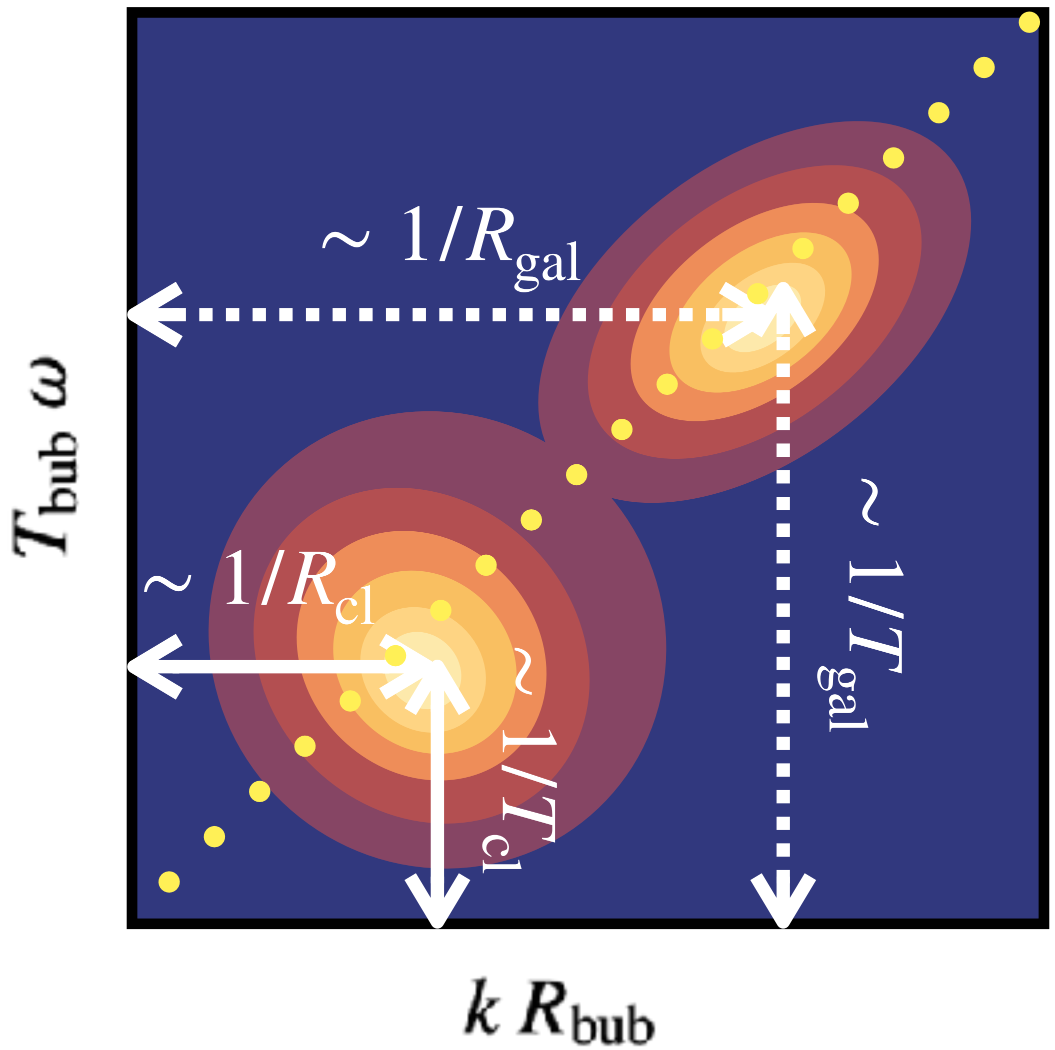
$$D^{(2)}_{v_i v_j}(r_{\mathrm{cl}}, R_{\mathrm{gal}}) \propto \underbrace{\oint_{r_{\mathrm{p}}}^{r_{\mathrm{a}}} \frac{\mathrm{d}r}{v_r} \Sigma_{\mathrm{cl}}(r)}_{\Sigma_{\mathrm{cl}}(r[r_{\mathrm{cl}}, \varphi_{\mathrm{cl}}])} \underbrace{\oint_{R_{\mathrm{p}}}^{R_{\mathrm{a}}} \frac{\mathrm{d}R}{v_R} \Sigma_{\mathrm{gal}}(R)}_{\Sigma_{\mathrm{gal}}(R[R_{\mathrm{gal}}, \varphi_{\mathrm{gal}}])} \int \mathrm{d}^3\mathbf{k}\, k_i k_j\, \underbrace{\tilde{C}_{\mathrm{tot}}(\omega = \mathbf{k} \cdot \mathbf{v}_{\mathrm{tot}})}_{n_{\mathrm{cl}} \tilde{C}_{\mathrm{cl}} + n_{\mathrm{gal}} \tilde{C}_{\mathrm{gal}}}$$



Expected main result

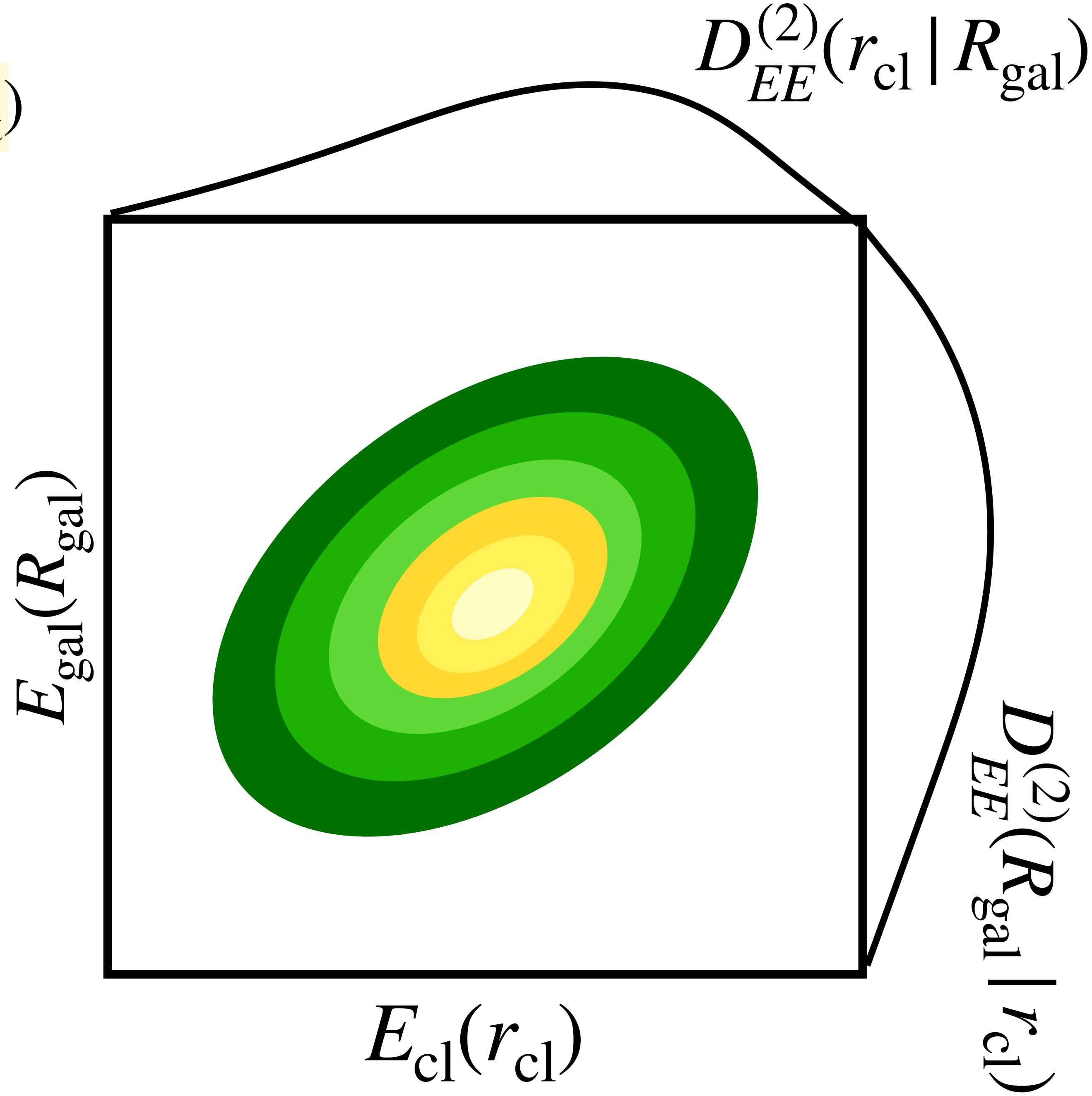
Additive power spectrum

$$n_{\rm cl}\tilde{C}_{\rm cl}(\omega = \mathbf{k}\cdot\mathbf{v}_{\rm tot}) + n_{\rm gal}\tilde{C}_{\rm gal}(\omega = \mathbf{k}\cdot\mathbf{v}_{\rm tot})$$



multi-scale coupling — slope $\mathbf{v}_{\rm tot}$

Conditional diffusion coefficient

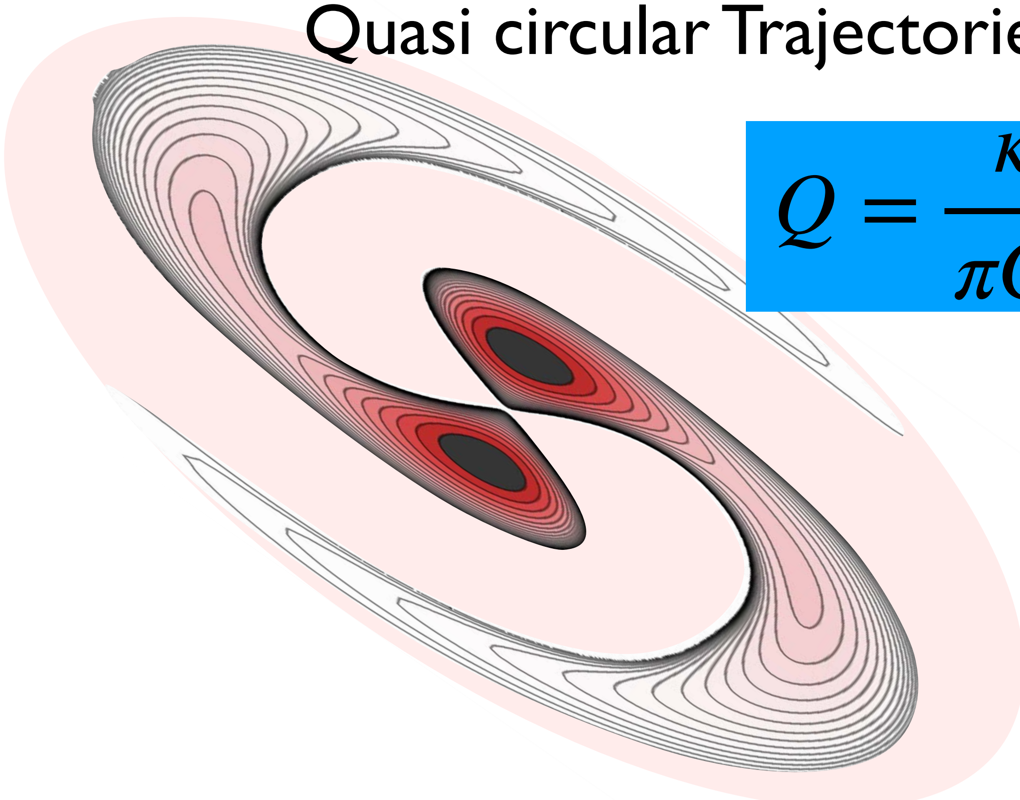


Cooling


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

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

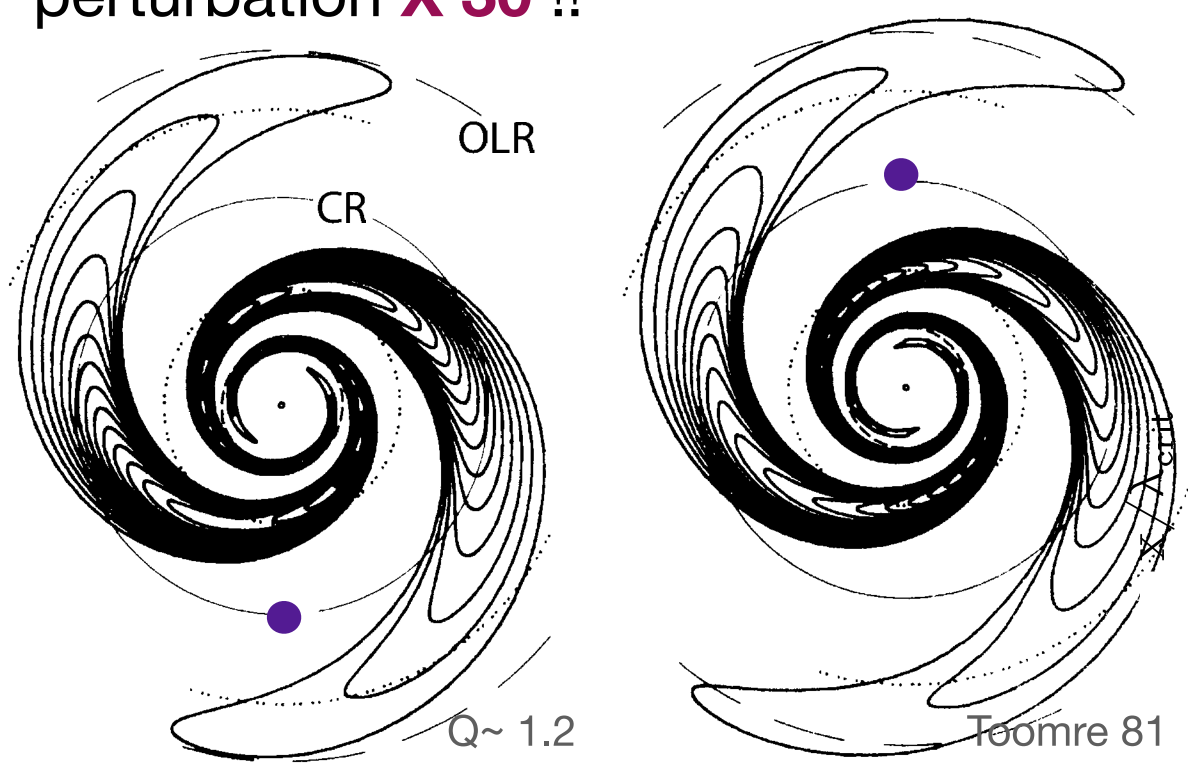
Quasi circular Trajectories: ‘cold’ disc



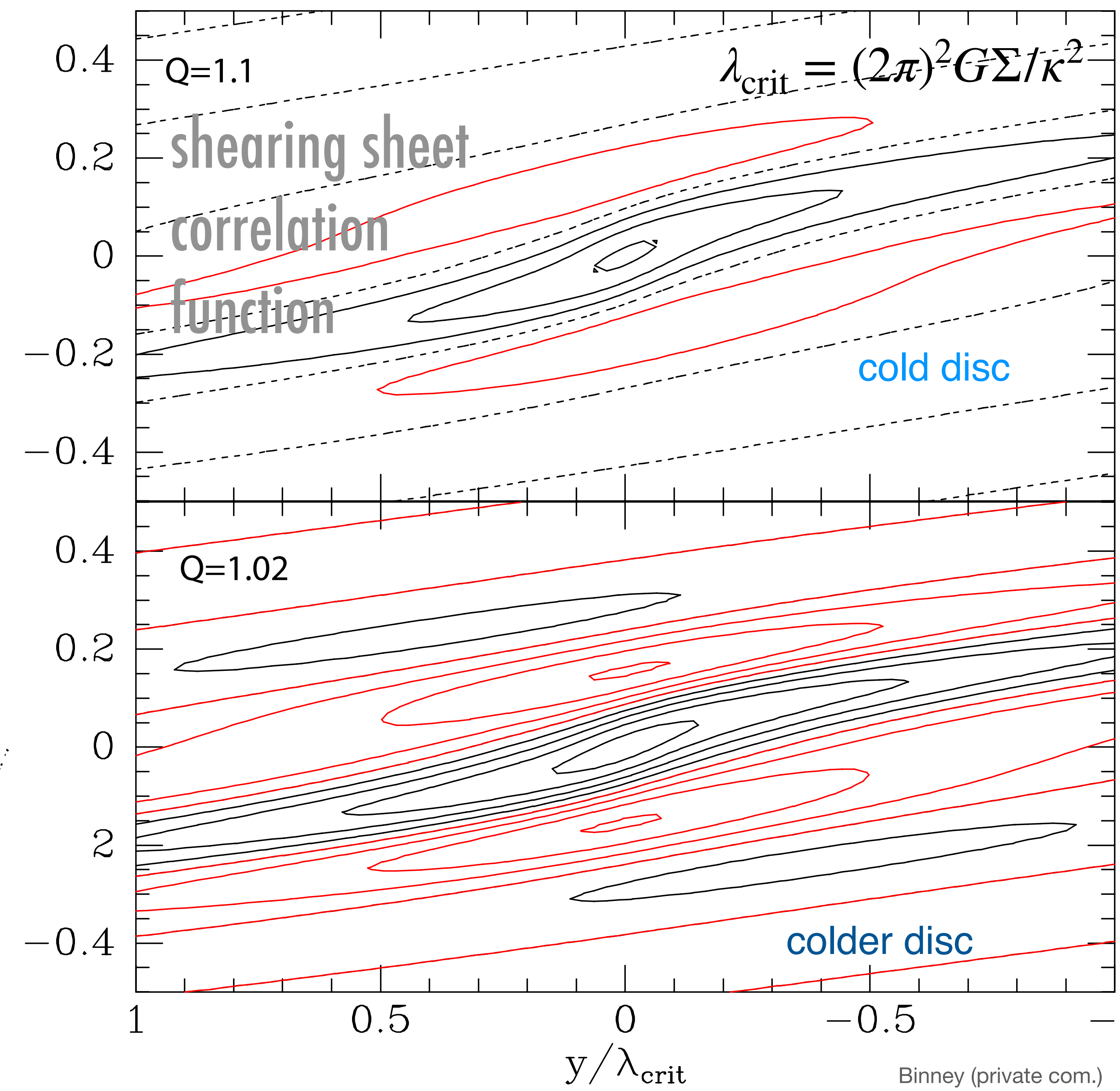
$$Q = \frac{\kappa\sigma}{\pi G\Sigma} \to 1$$

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

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

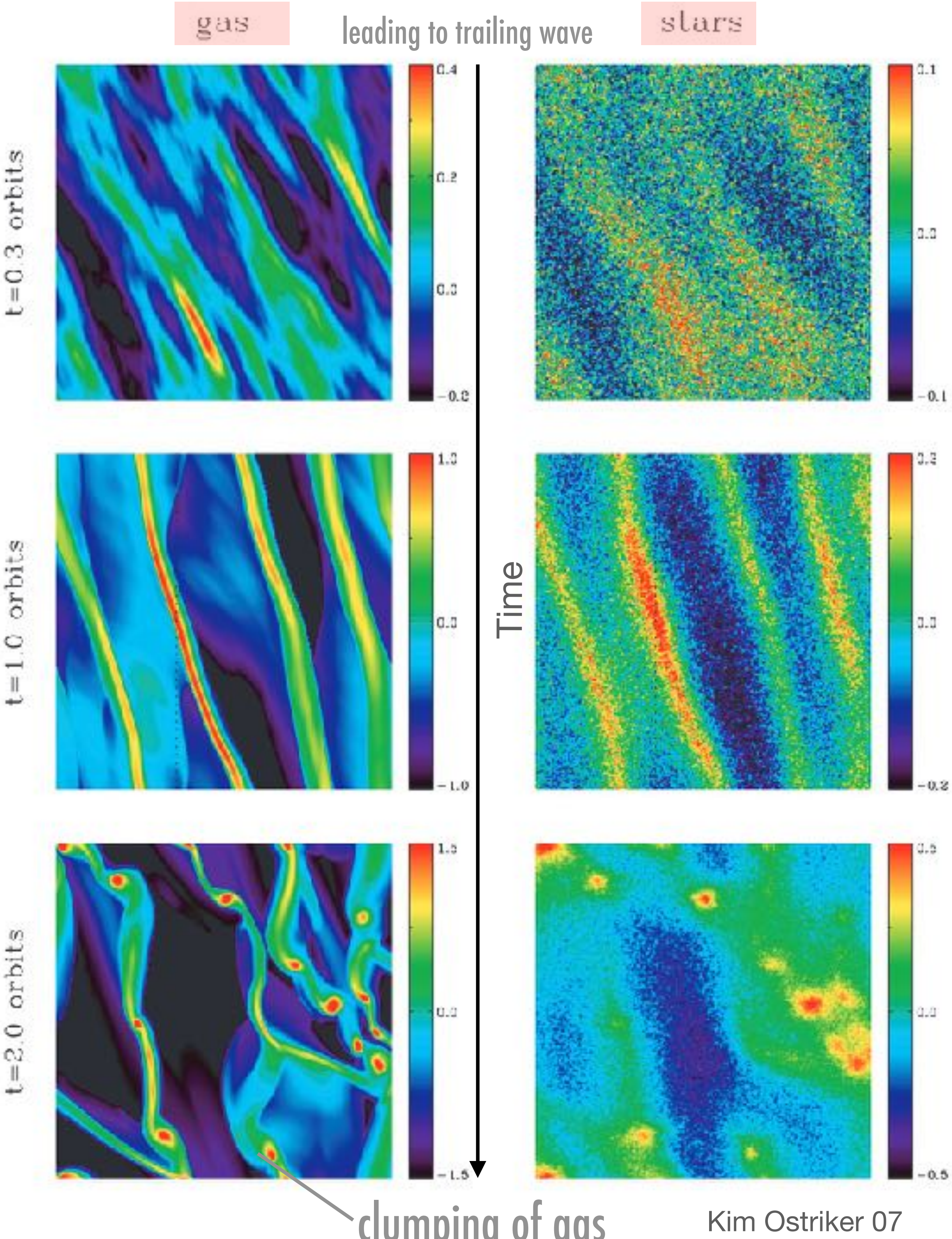


→ long range correlation

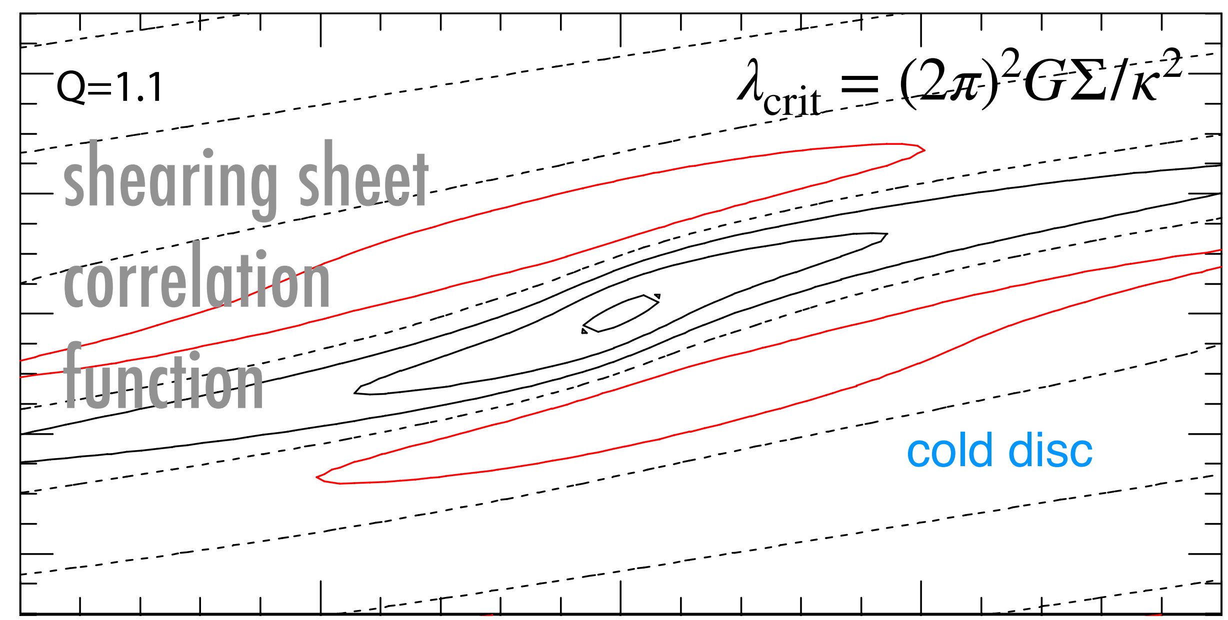


Binney (private com.)

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



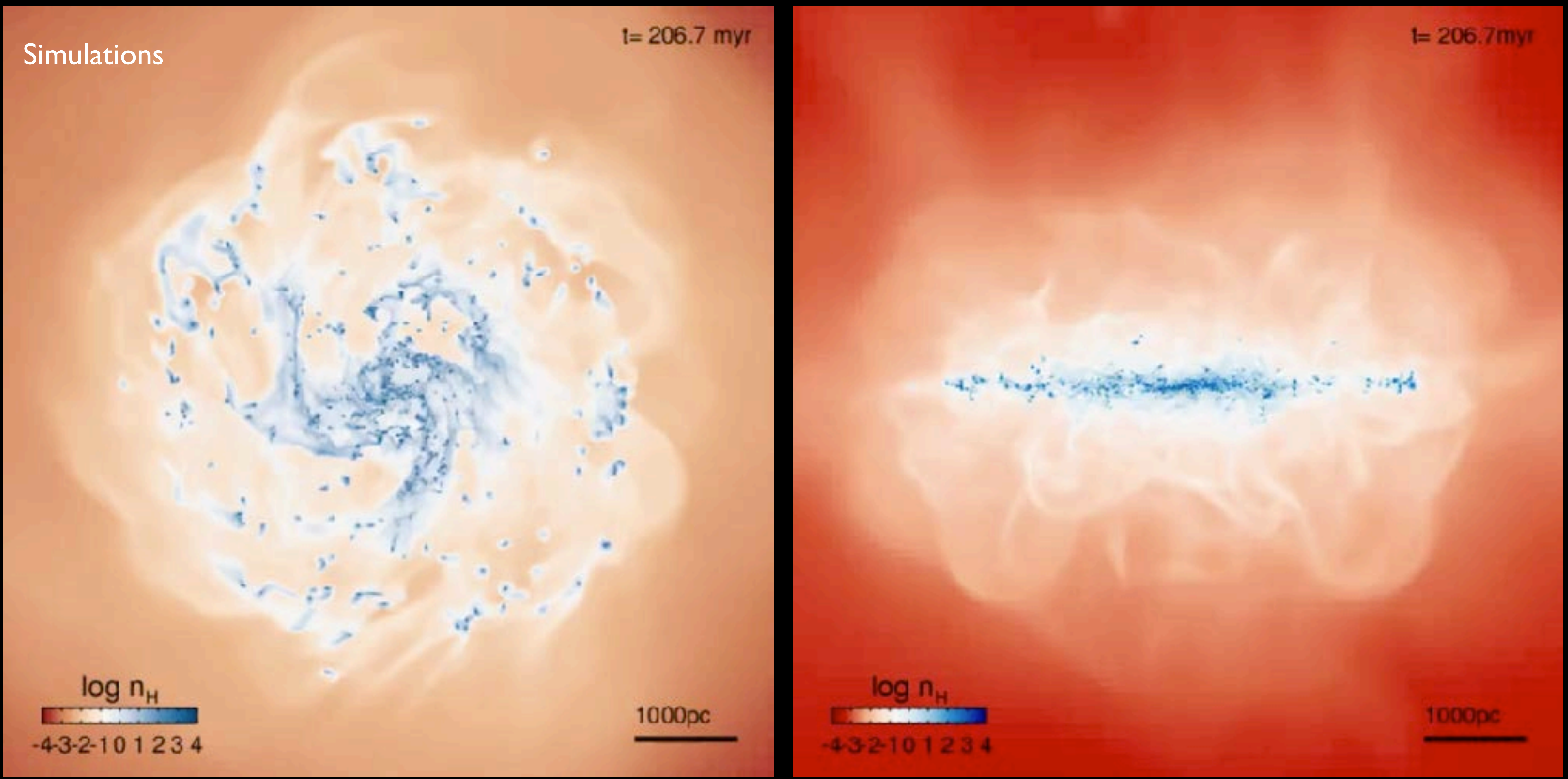
- colder disc means **larger** wake
- colder disc means **stronger** wake
- colder disc means **shorter** dynamical time
- colder disc means **more star** formation



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

Internal Structure of a simulated thin disc

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



(c)Taysun Kimm

Internal Structure of a simulated thin disc

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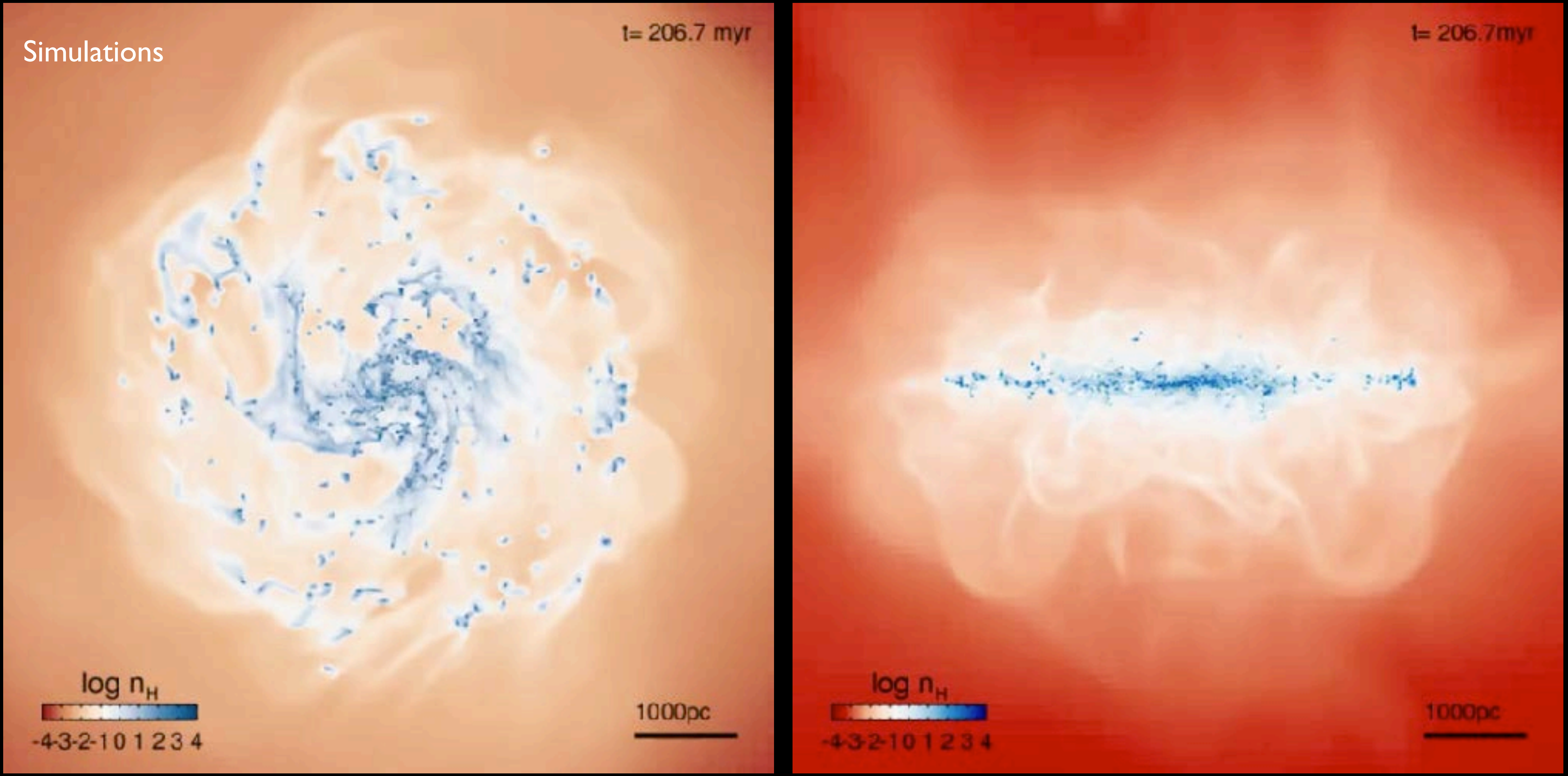
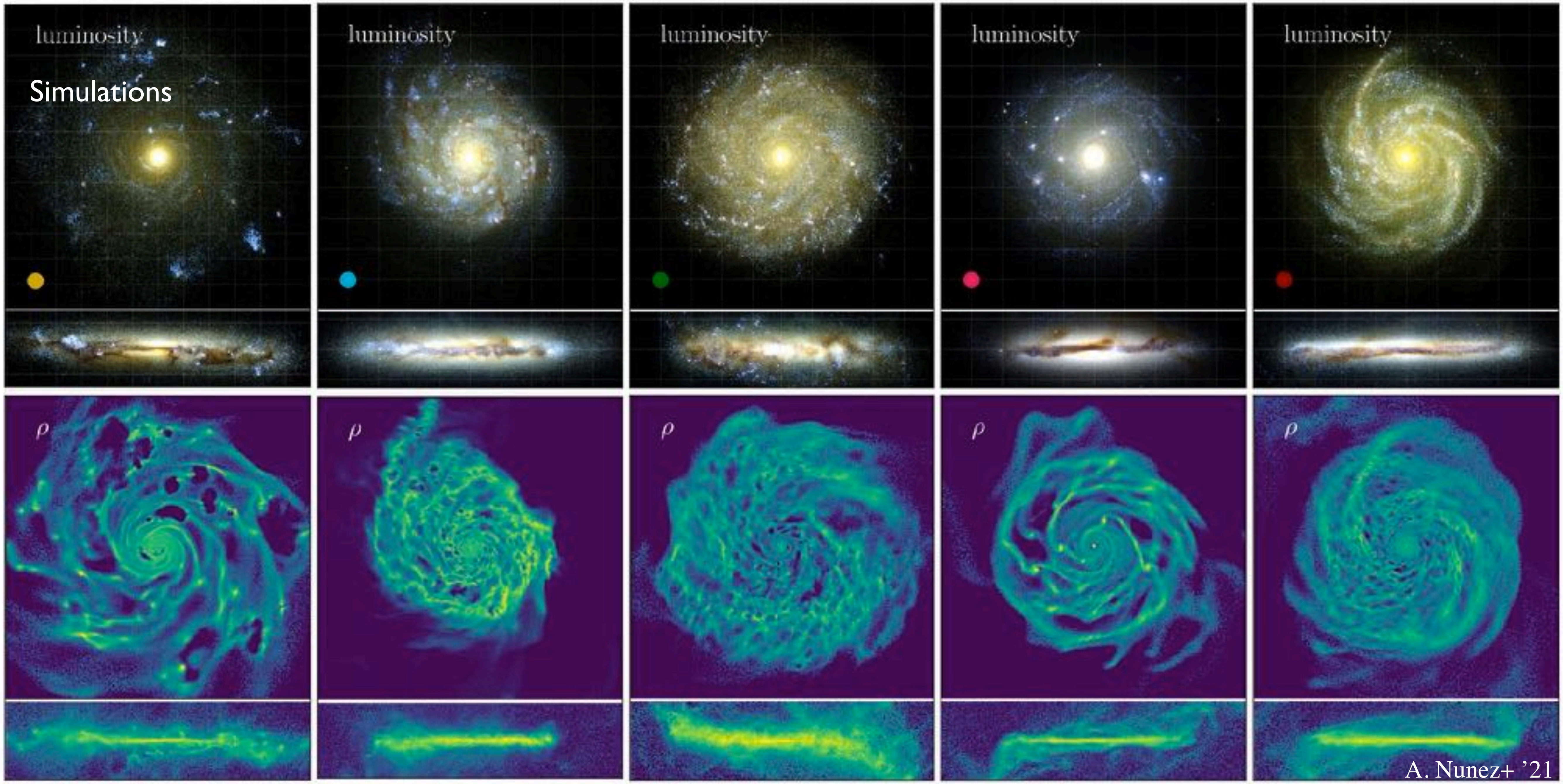


(c)Taysun Kimm

Internal Structure of a simulated thin disc: varying feedback model

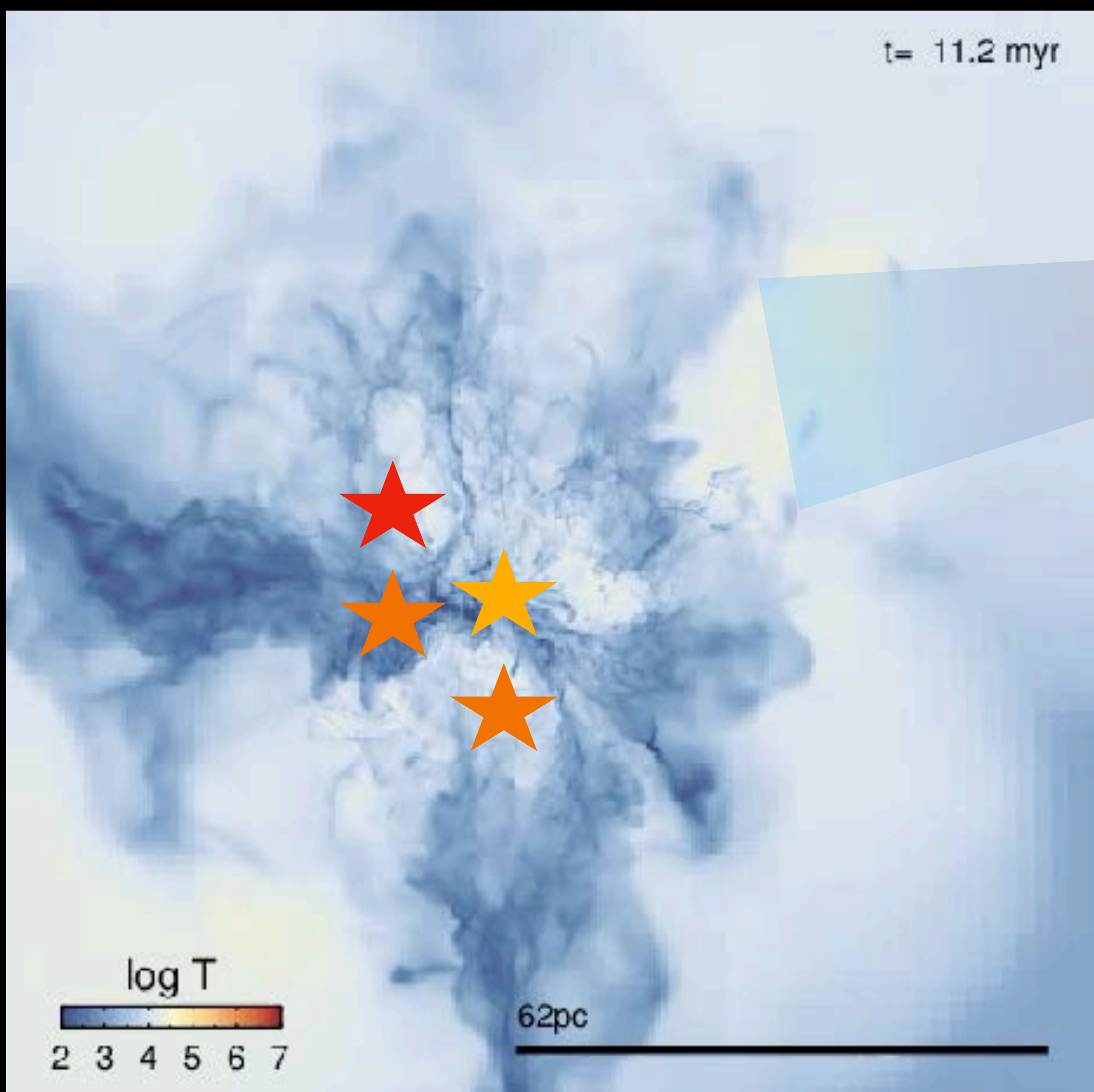


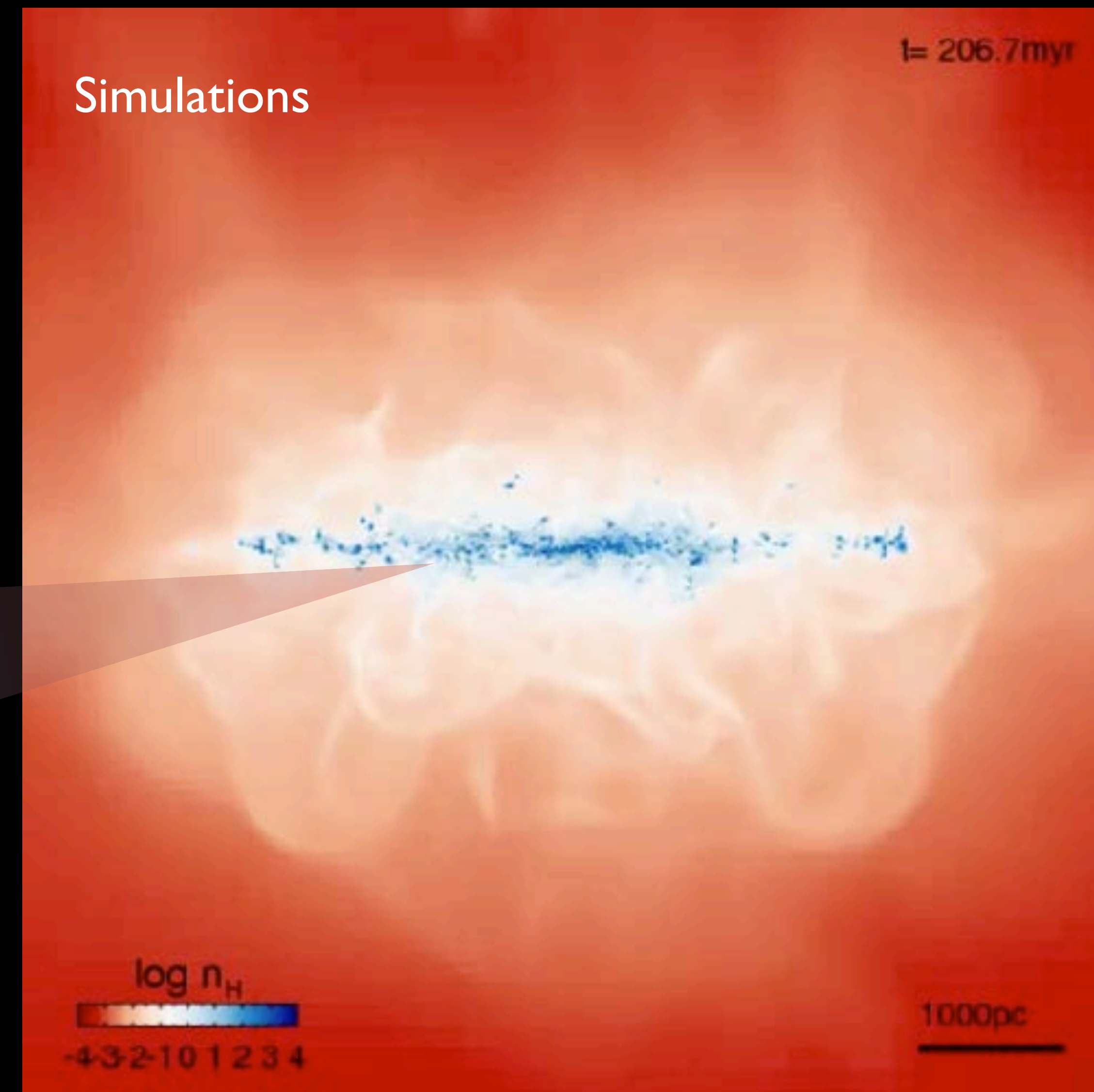
Note that the exact model of feedback impacts face-on view BUT does not impact much disc thickness.

No fine tuning required: something more fundamental operates

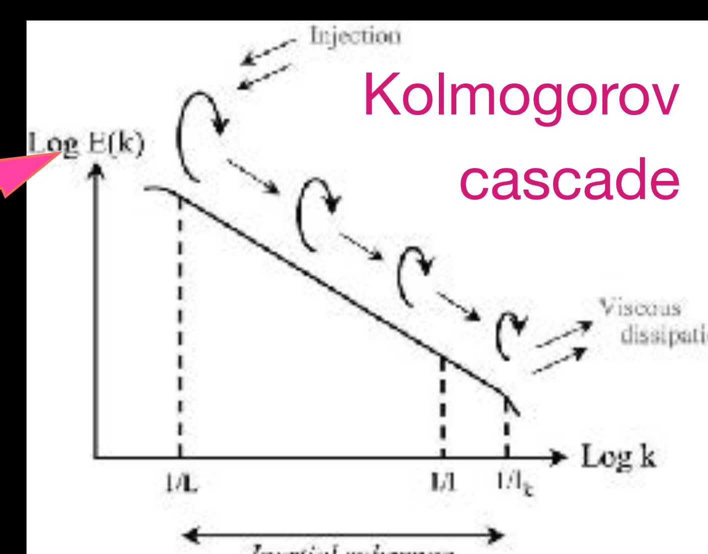
Internal Structure @ small scales: simulation & theory

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





Turbulent cascade controlled by energy **injection** scale



(c)Taysun Kimm

Internal Structure @ small scales: simulation & theory

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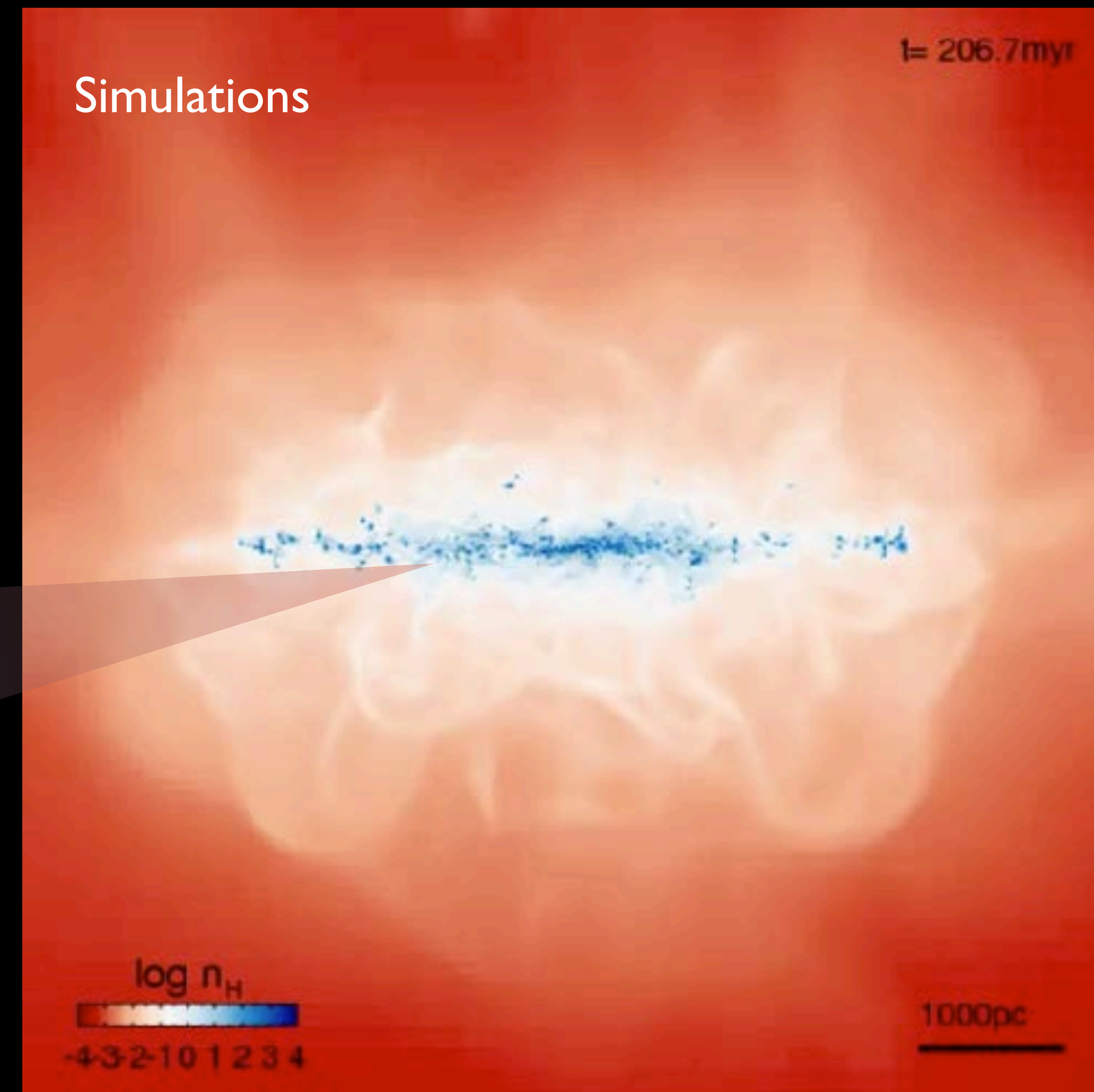

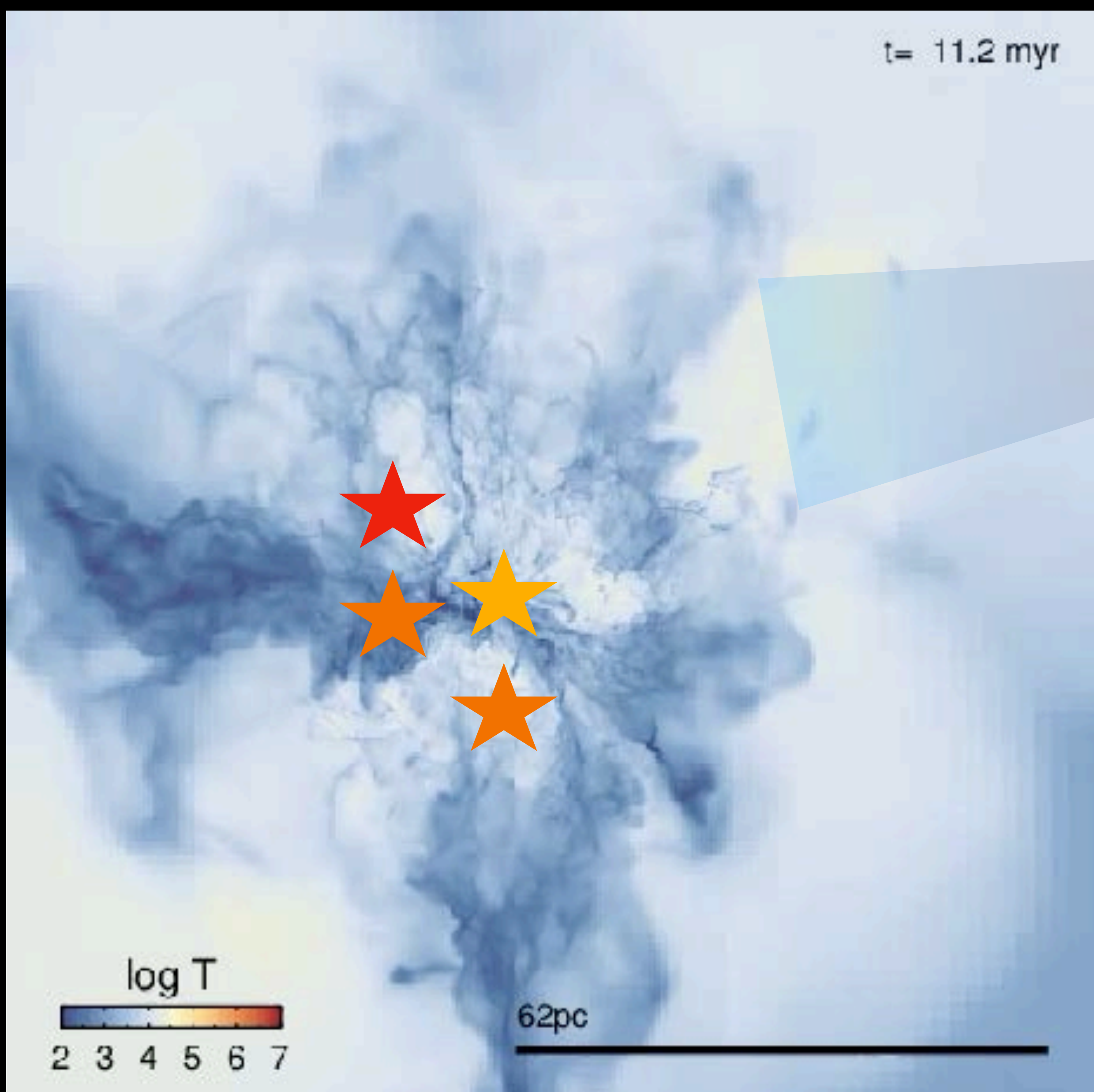

Turbulent cascade
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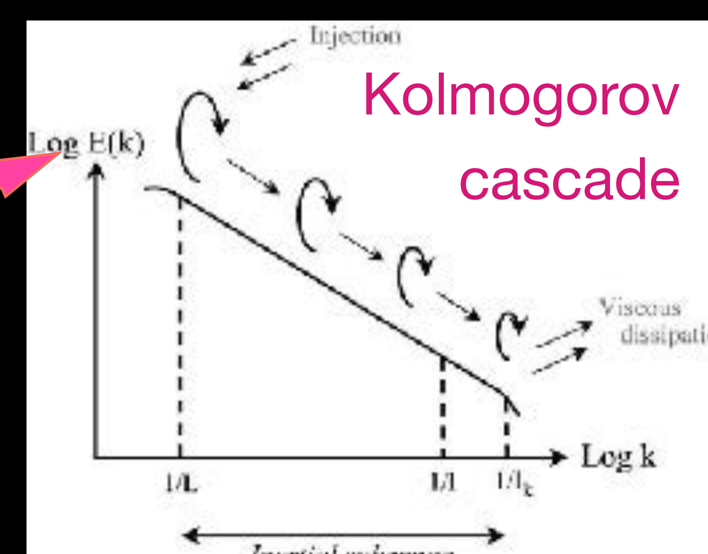

(c)Taysun Kimm

Internal Structure @ small scales: simulation & theory

State-of-the-art simulations also illustrates
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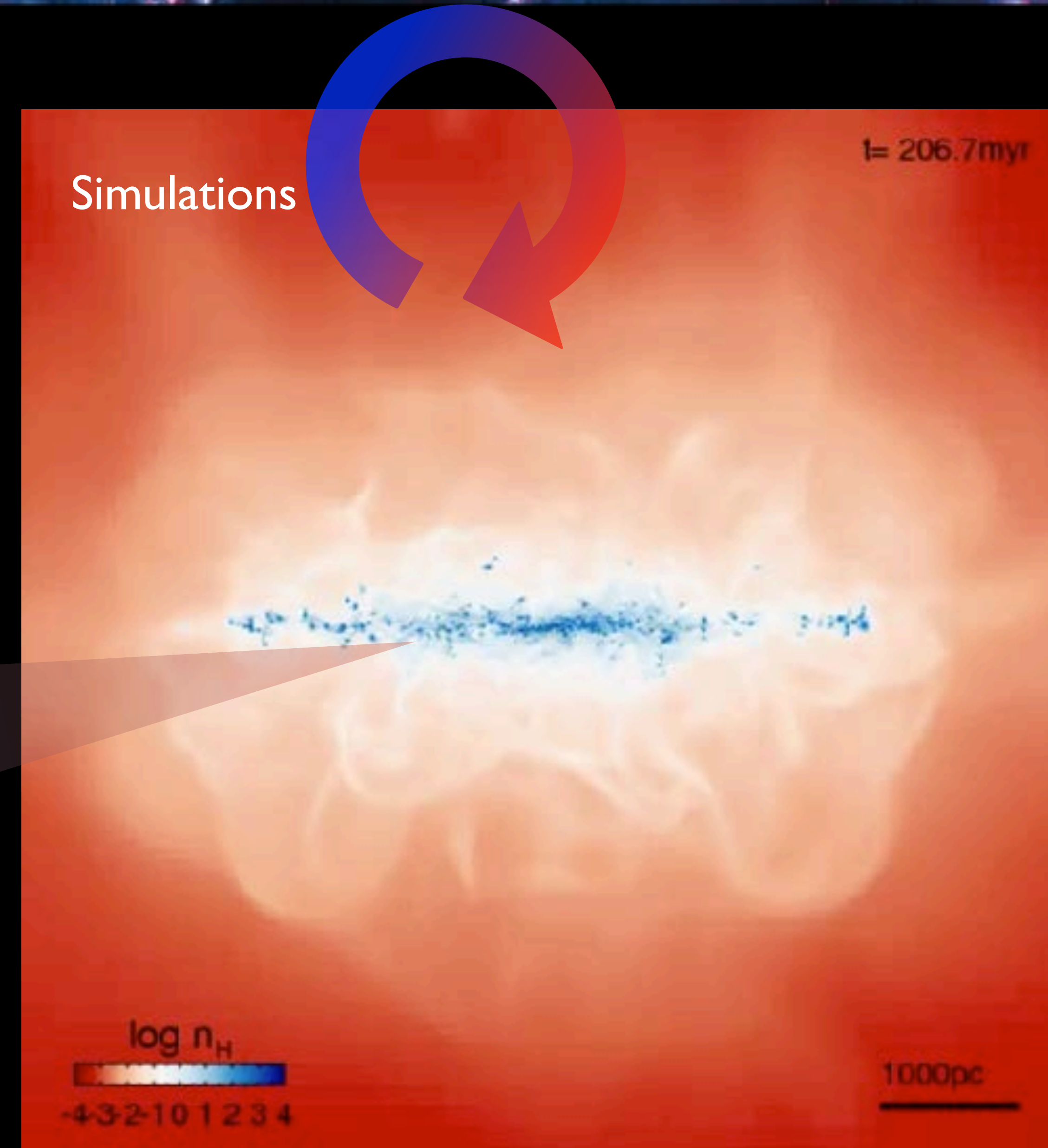

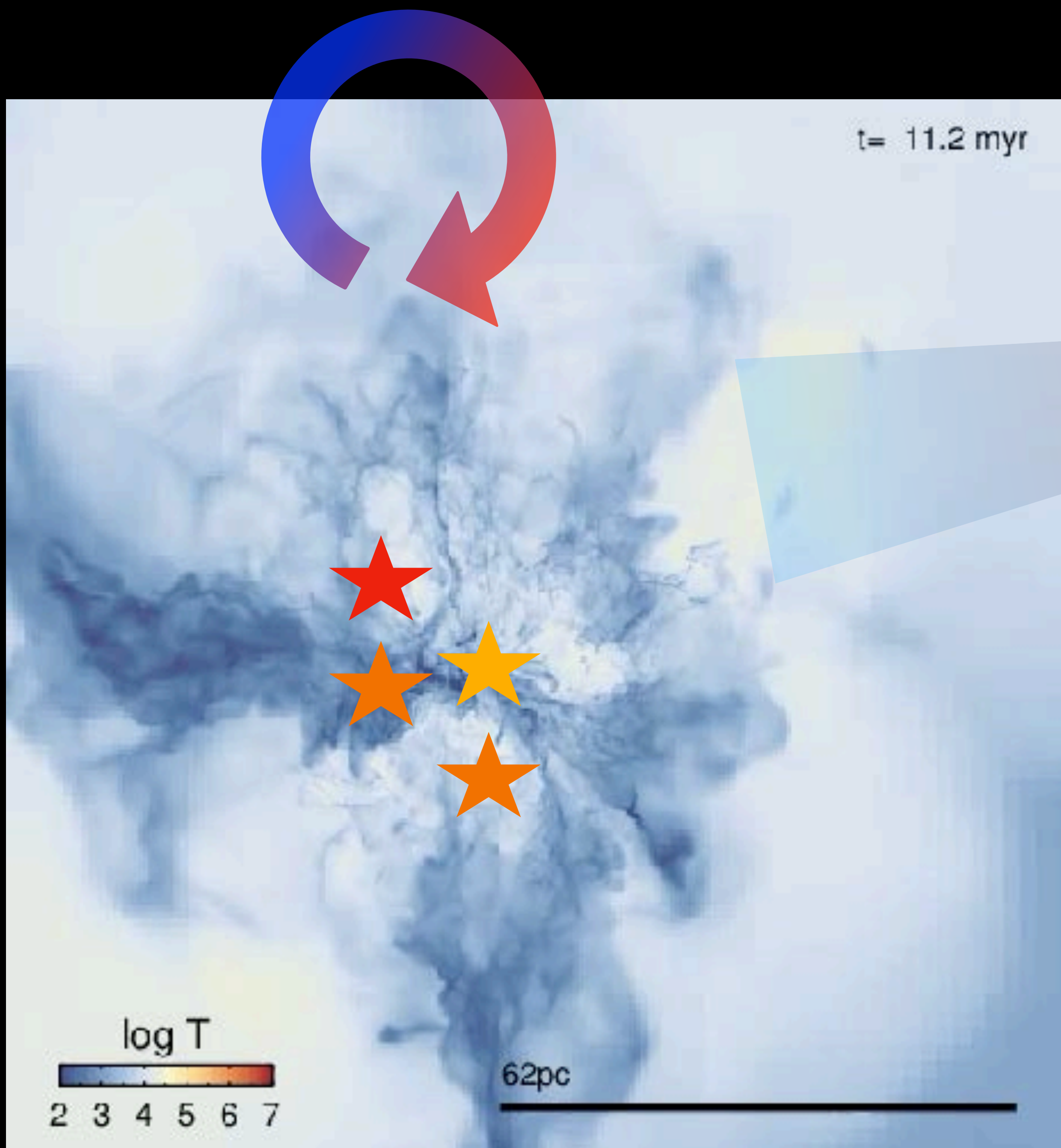

Turbulent cascade
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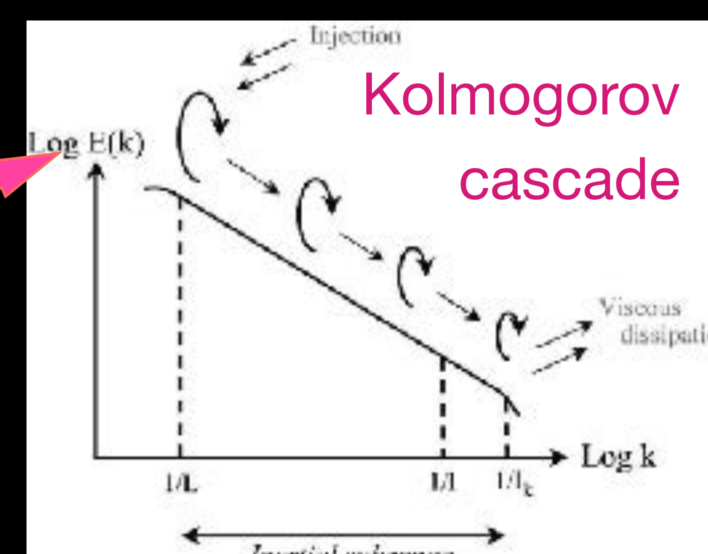


Quid of the effect of wakes on injection scale?

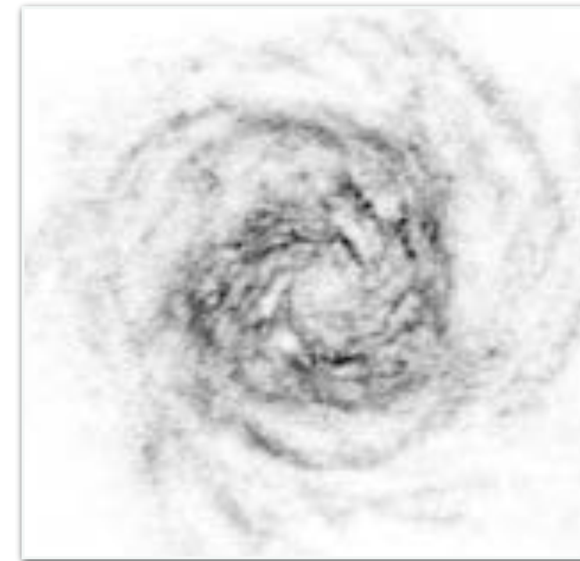
(c)Taysun Kimm

Feedback + gravity match cascade

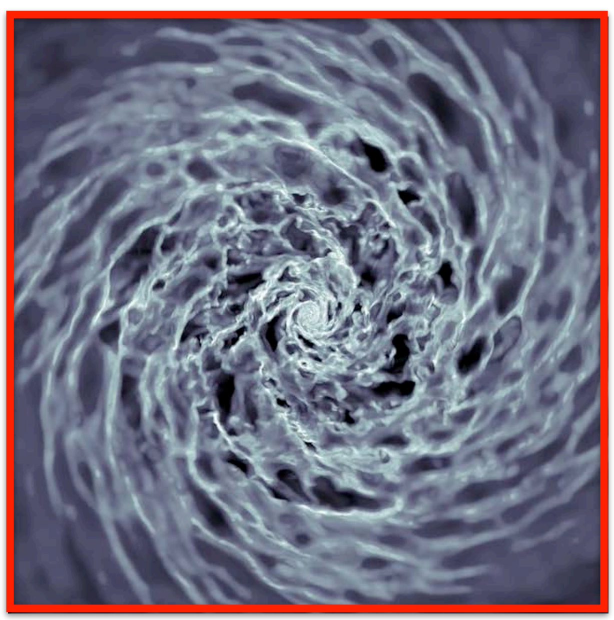
Disc instabilities and gas turbulence in local spiral galaxies

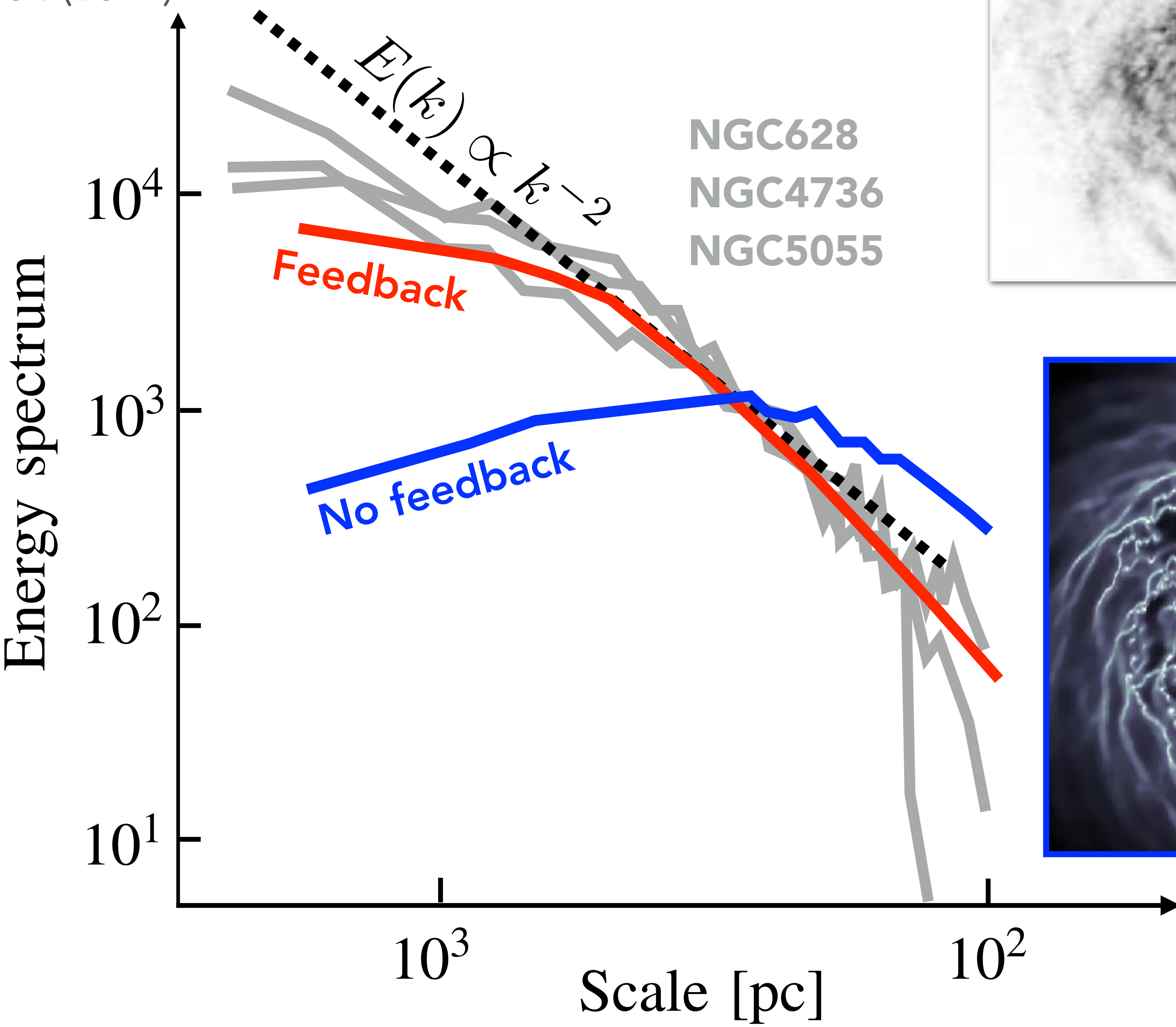
Kinetic energy spectrum of neutral hydrogen

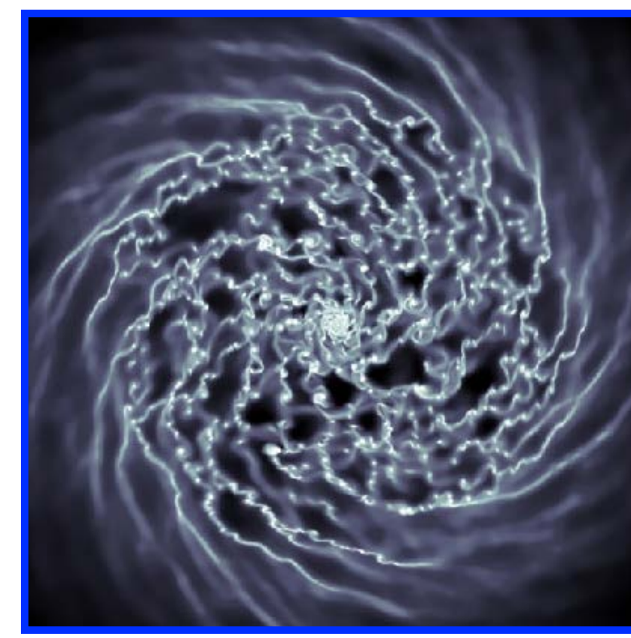
Grisdale, Agertz, Renaud et al. (2017)



Walter et a
(2008)







Agertz+ collaboration

Feedback + gravity explain energy injection scale

On what scale is ISM turbulence injected?

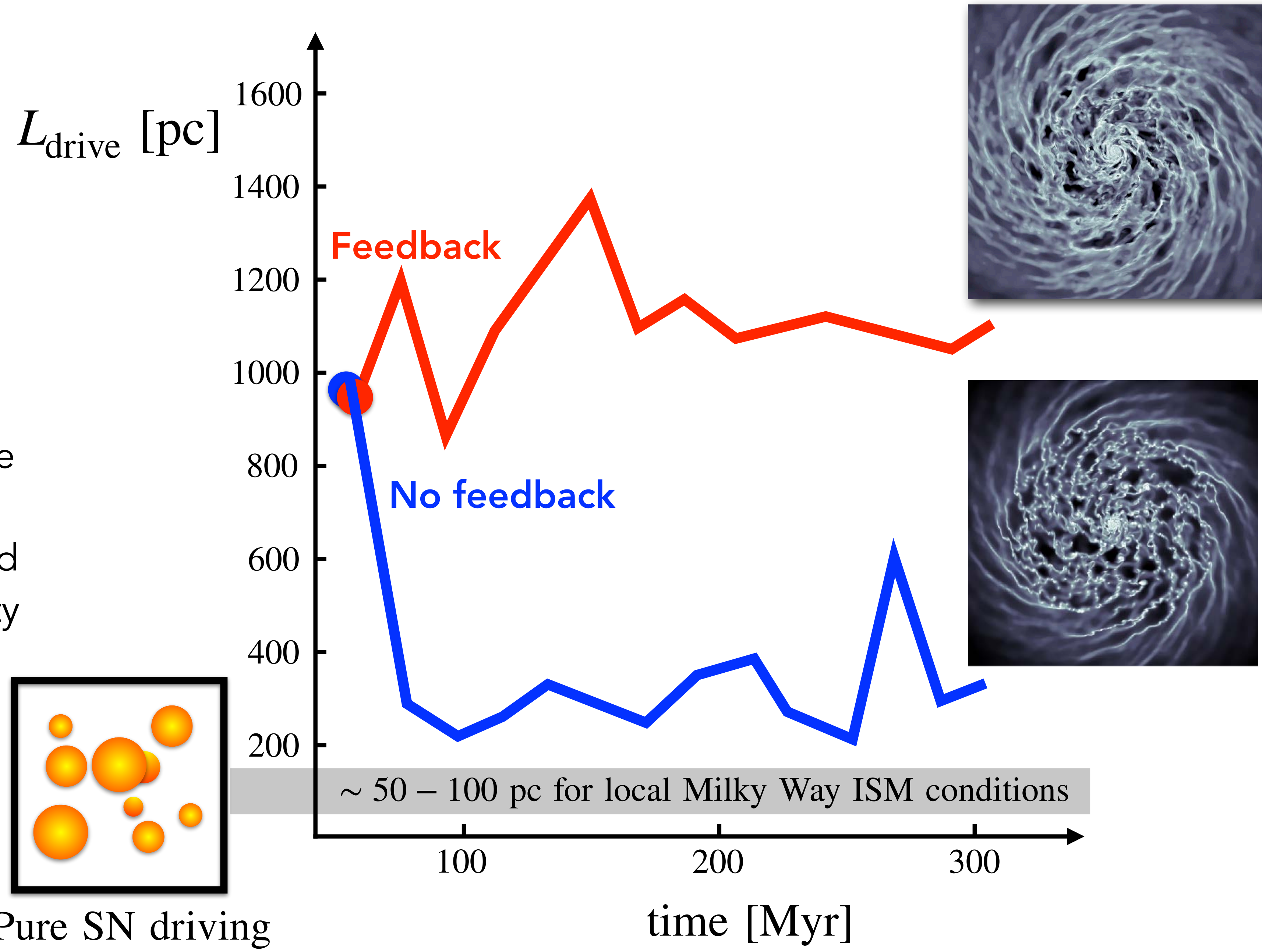
Agertz et al. (in prep since way too long!)

$$L_{\rm drive} \equiv \frac{\int k^{-1} E(k)\, \mathrm{d}k}{\int E(k)\, \mathrm{d}k}$$

Joung, Mac Low & Bryan (2009)
Padoan et al. (2016)

- Stellar feedback allows for a (counterintuitively?) large driving scale

- Large scale coupling between gas and stars is crucial. Driven by the instability of the stars



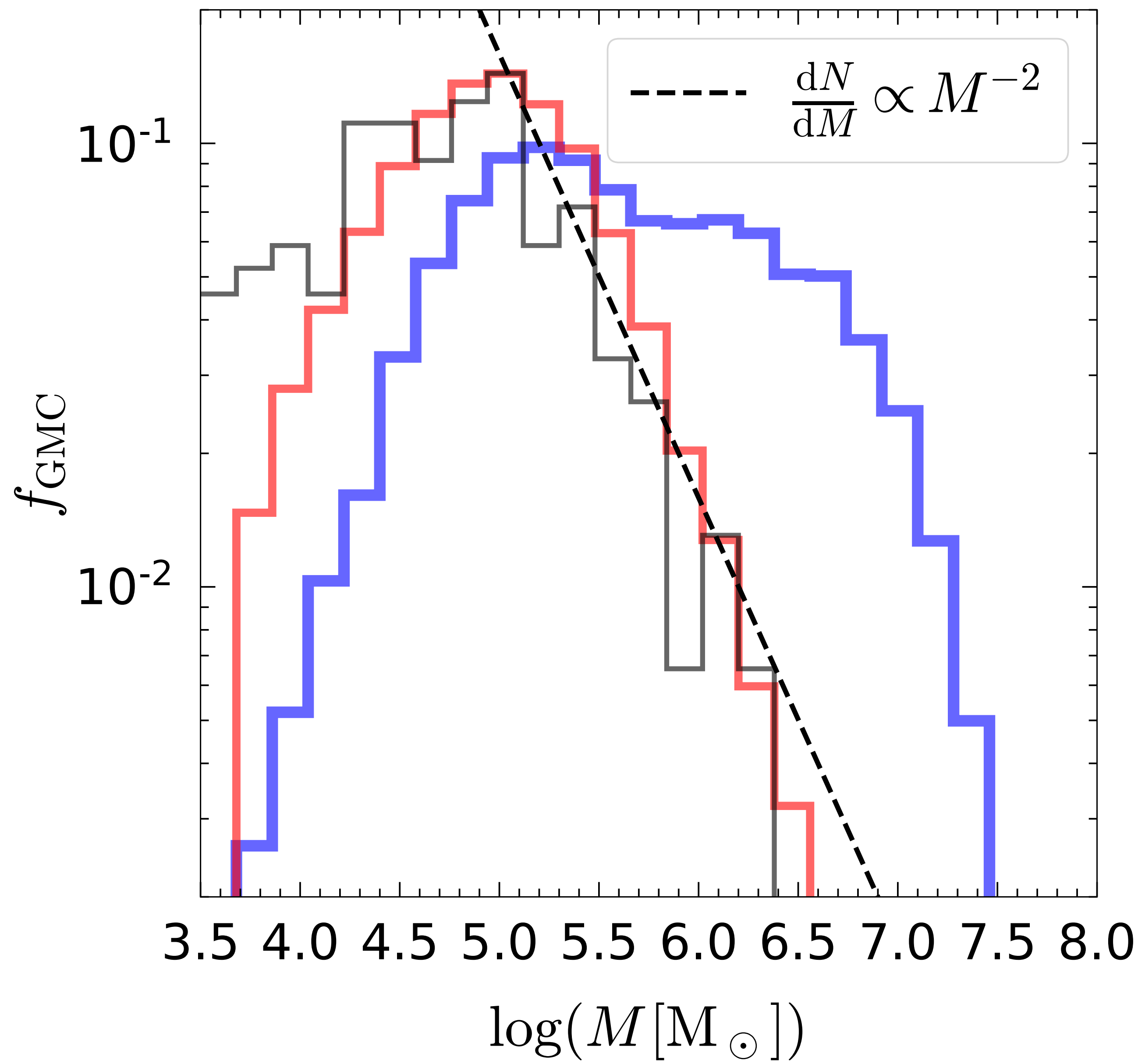
Agertz+ collaboration

Molecular cloud formation - when turbulence and cloud dissolution is“right”

(Gravitational instabilities and stellar feedback in tandem)

Grisdale, Agertz, Renaud et al. (2018)

$$\frac{dN}{dM}$$



The Milky Way (Heyer et al. 200

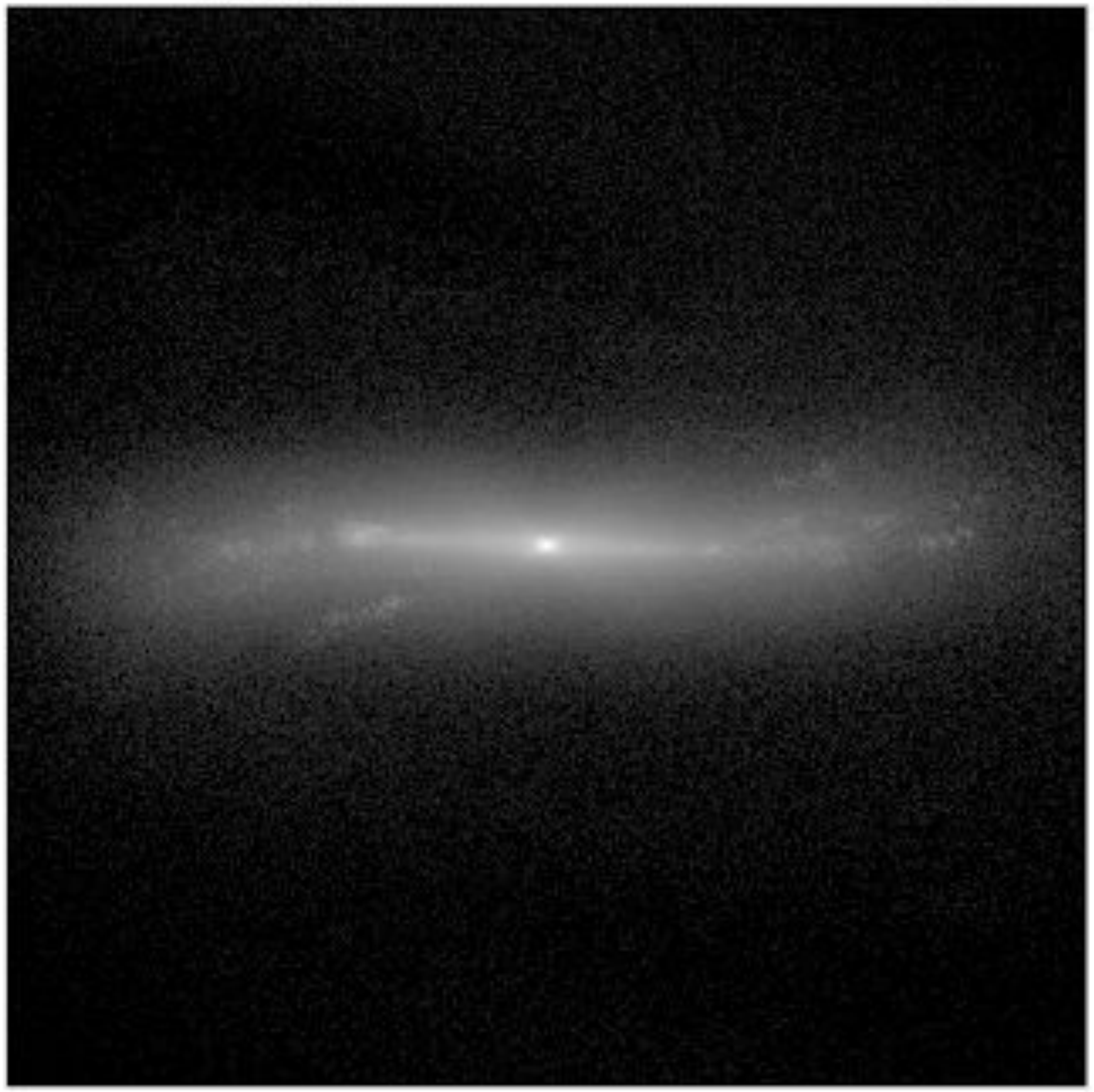
No feedback

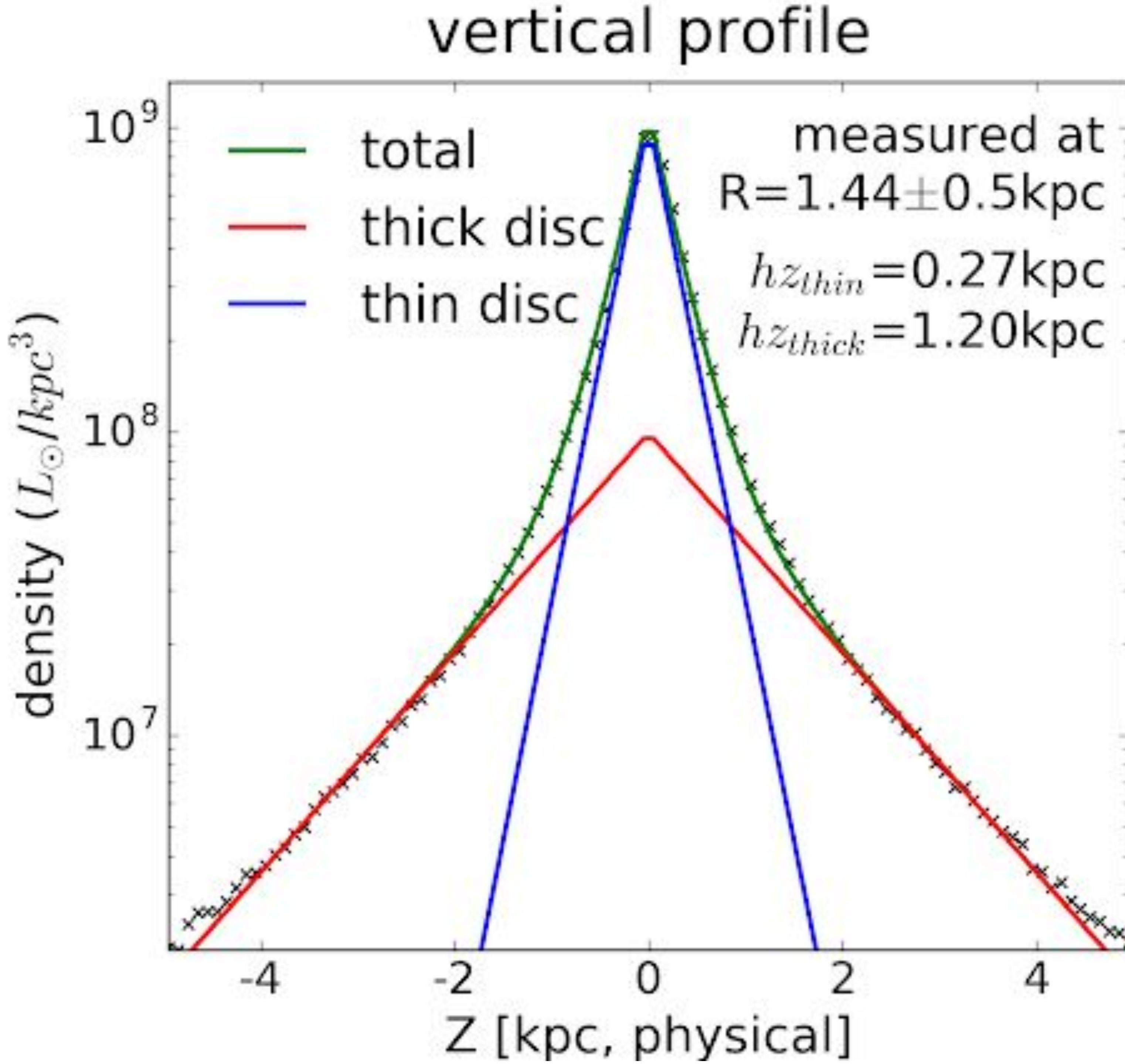
Feedback

Agertz+ collaboration

Q∼ 1 confounding factor for joint thick+thin growth

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

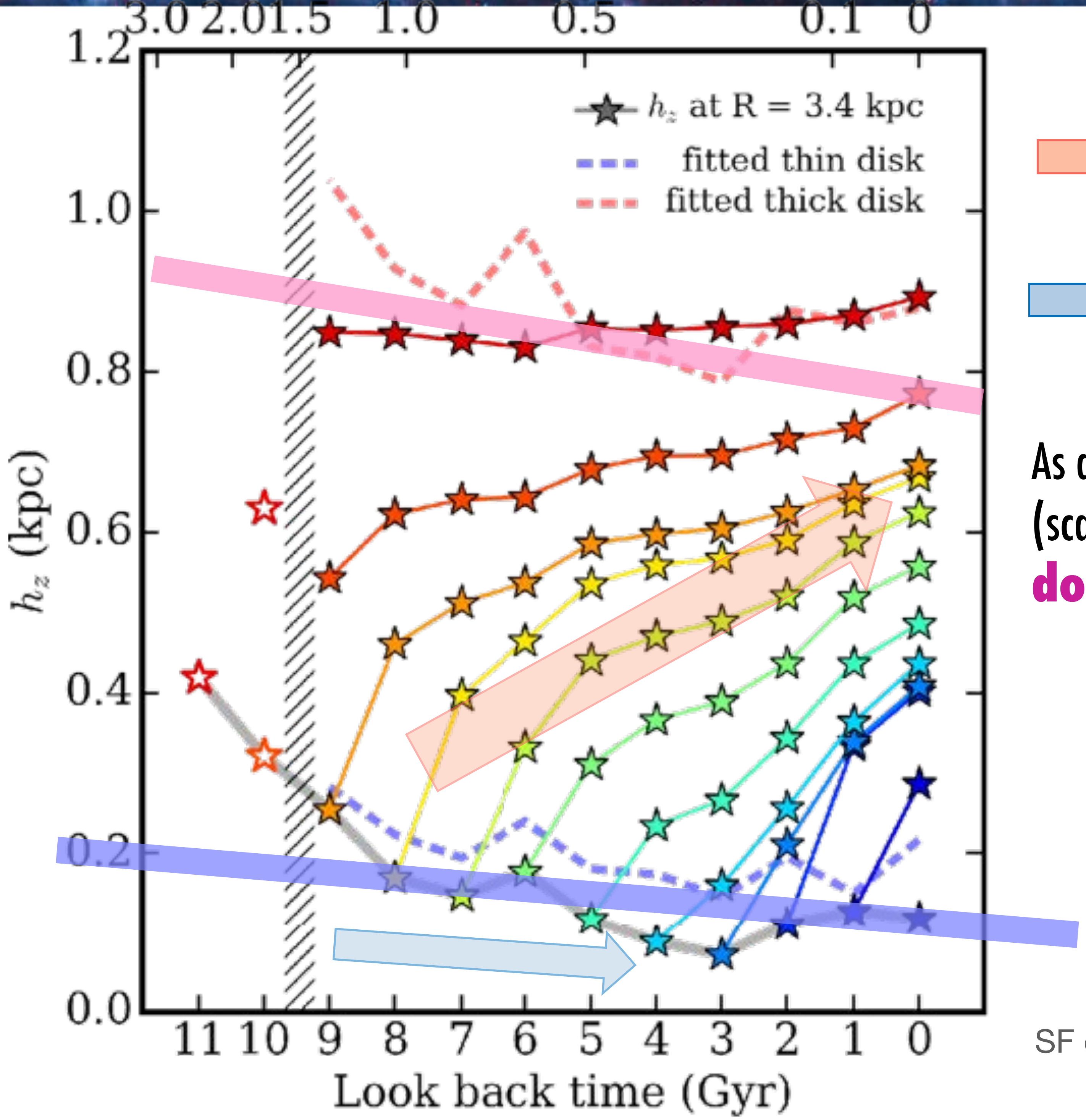




Both star formation and vertical orbital diffusion regulated by (Q $\rightarrow$ 1) **confounding** factor.

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

Q∼ 1 confounding factor for joint thick+thin growth



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

Galaxy keeps forming in // young thin-disk stars

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

Vertical orbital diffusion

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

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

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.

Emergence


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

* 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

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

remarkably,
the bike's analog
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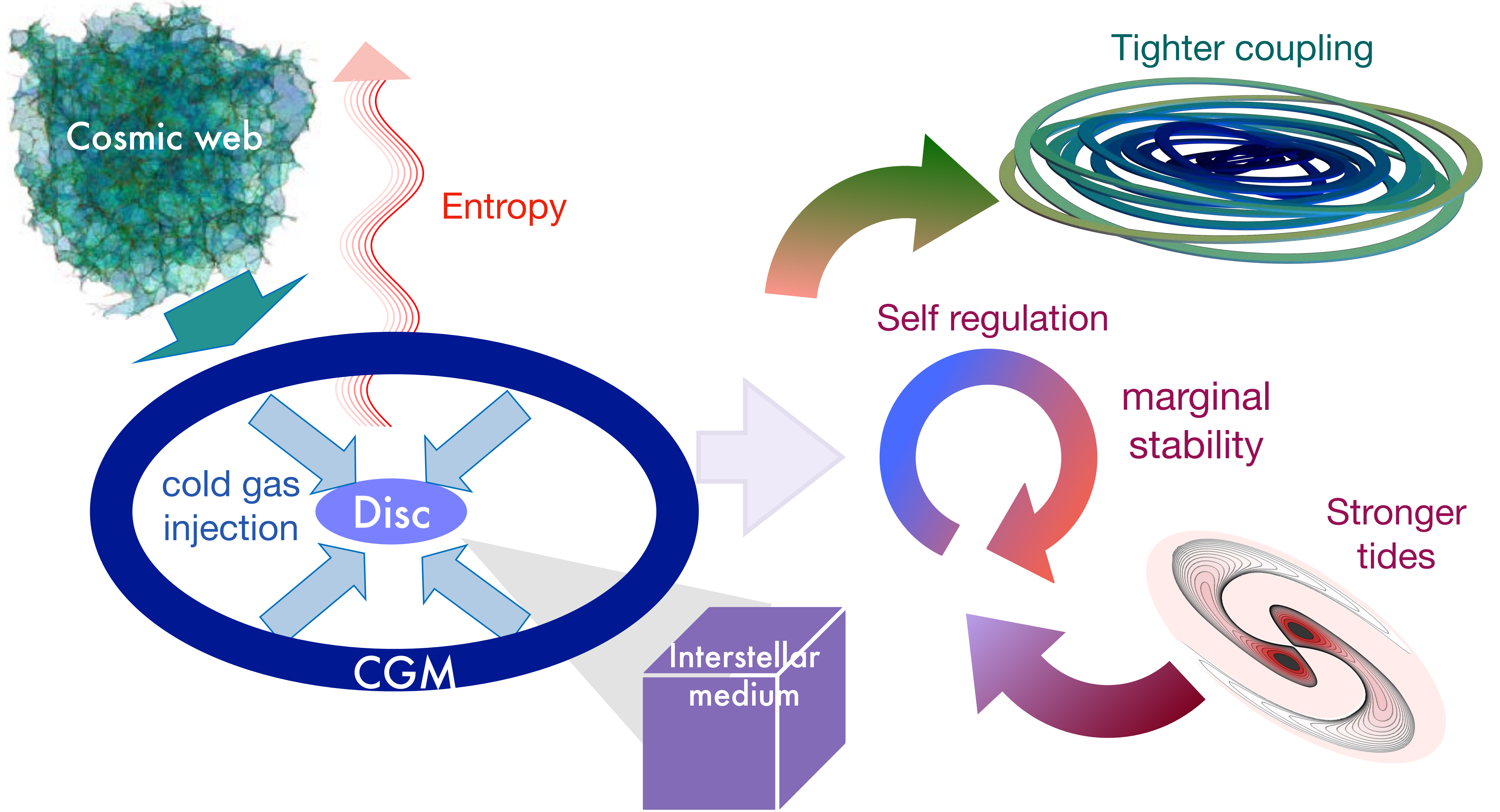
Synopsis of thin disc emergence



Three components system coupled by gravitation.

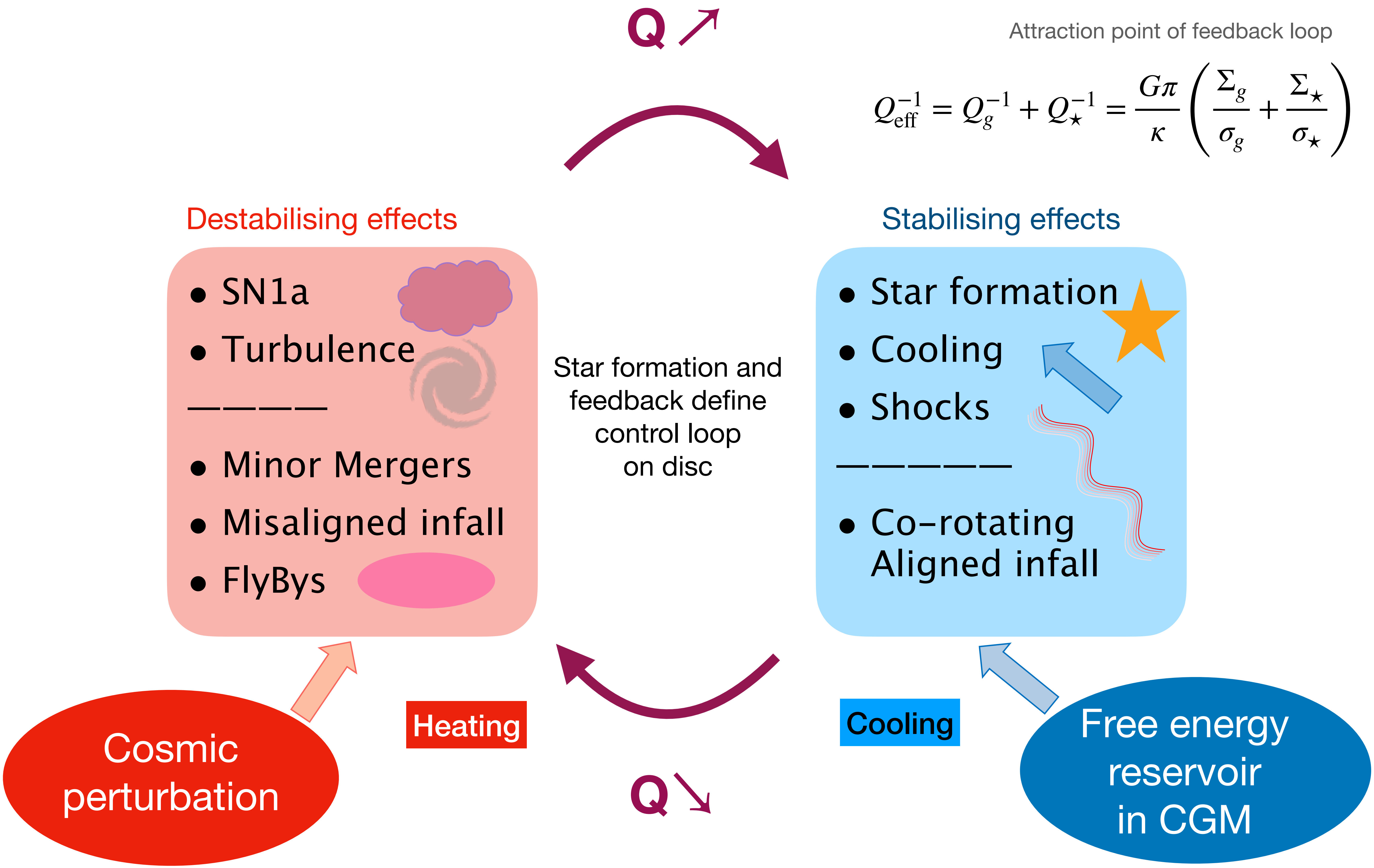
- A CGM reservoir fed by the CW (top down *causation*)
- Convergence towards marginal stability : acceleration of dynamical control-loop by wakes
- Tightening of stellar disc by boosting of torques, & increased dissipation.

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

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



Self regulating loop boosted by wake

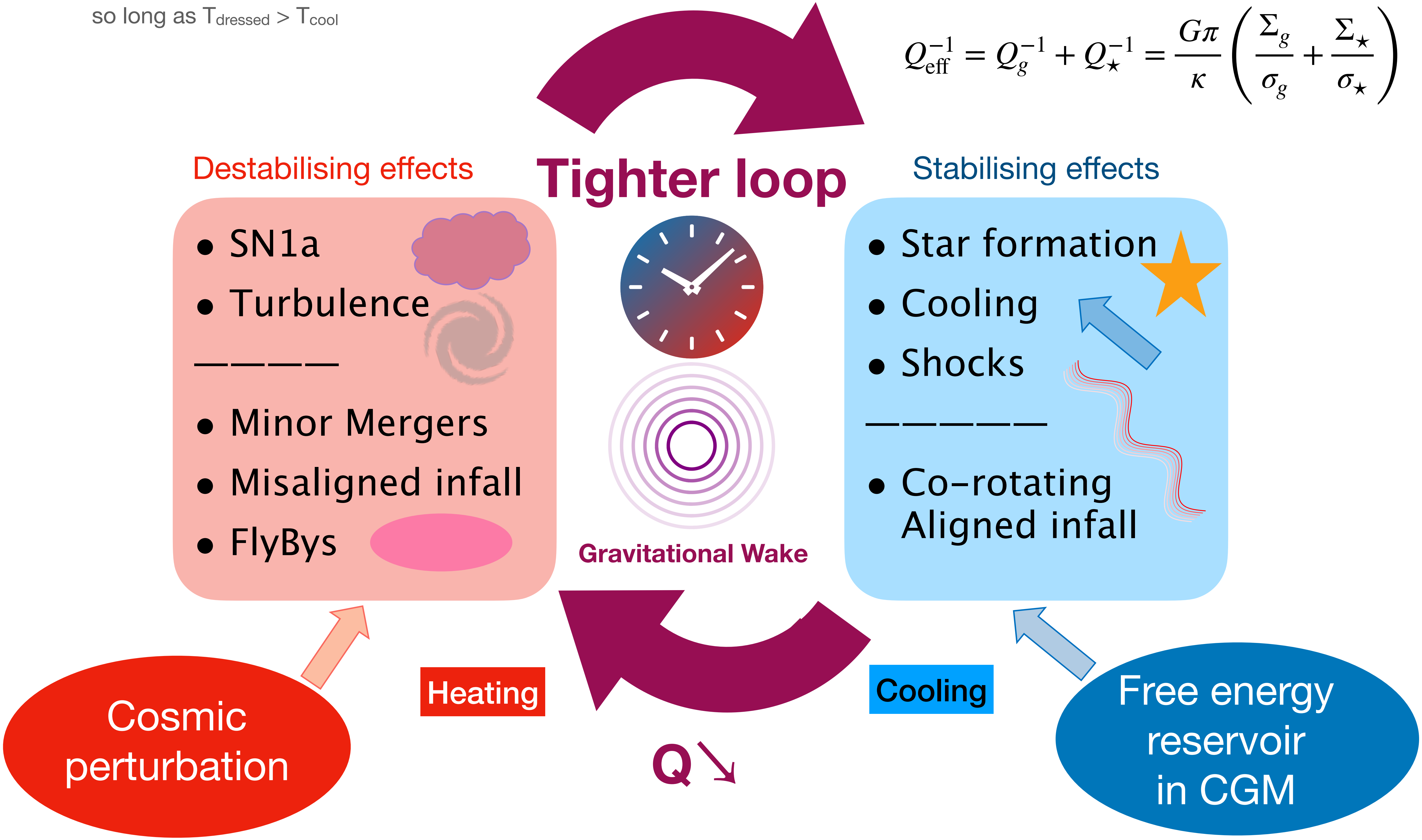
Transition to secularly-driven morphology promoting self-regulation around an effective Toomre $\boxed{Q \sim 1.}$

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

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

Attraction point of feedback loop

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



Open system with control loop generates complexity through self-organisation

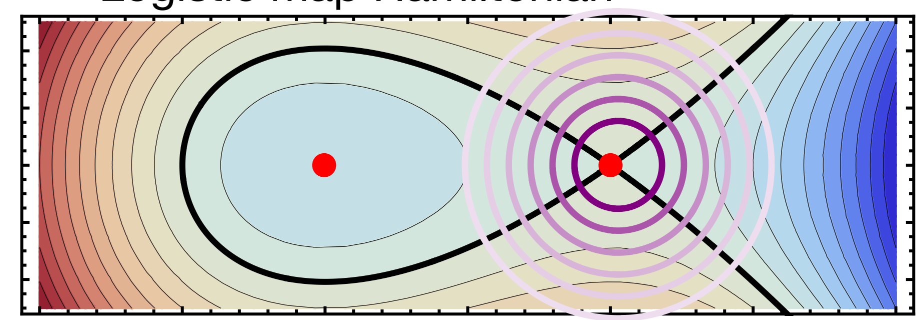
Chemistry of emergence... introduce tides

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

Dissipation converts kinetic instable point into an attractor.

Gravitational Wake

Logistic map Hamiltonian



Dressed Reaction-Diffusion equation (cf morphogenesis)

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

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

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

$$\Longrightarrow \quad dt \to \frac{dt}{\epsilon^2}$$

Rapid correction

→ Cosmic resilience of thin disc driven by CW

→ Operates swiftly near self-organised Criticality

→ Robustness / feedback details

Chemistry of emergence... introduce tides

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

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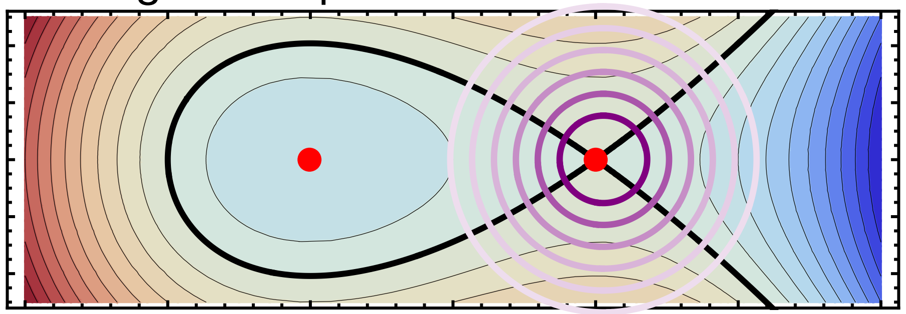


Dressed Reaction-Diffusion equation (cf morphogenesis)

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

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

SF efficiency

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

Diffusion

Rapid correction

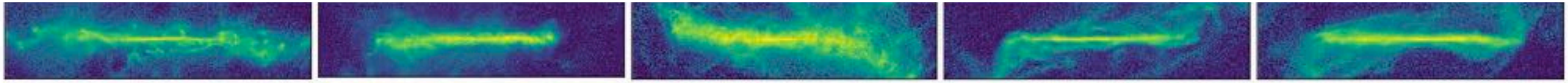
→ Cosmic resilience of thin disc driven by CW

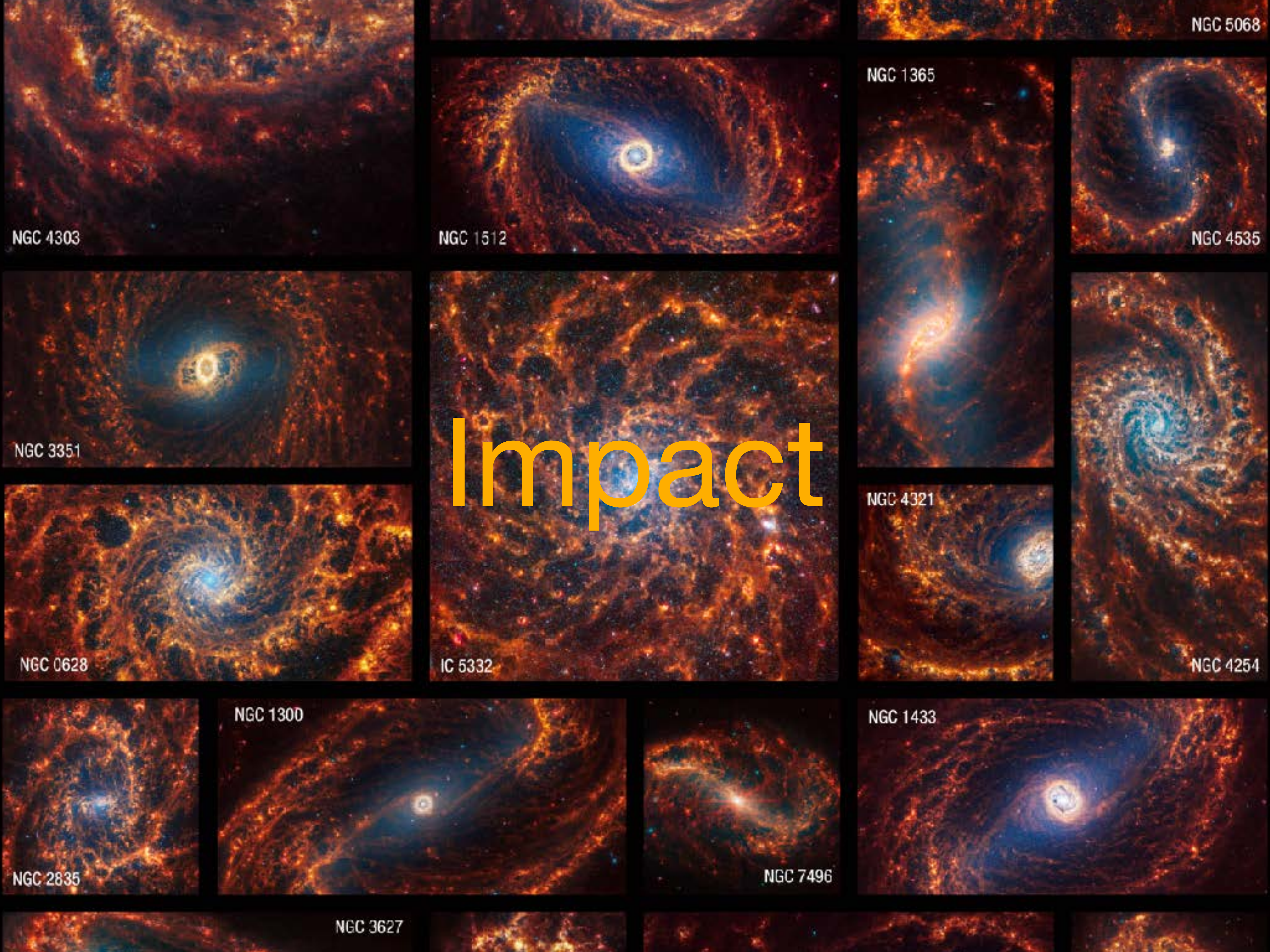
→ Operates swiftly near self-organised Criticality

→ Robustness / feedback details

No fine tuning !

all discs are fairly thin whatever the feedback




NGC 5068
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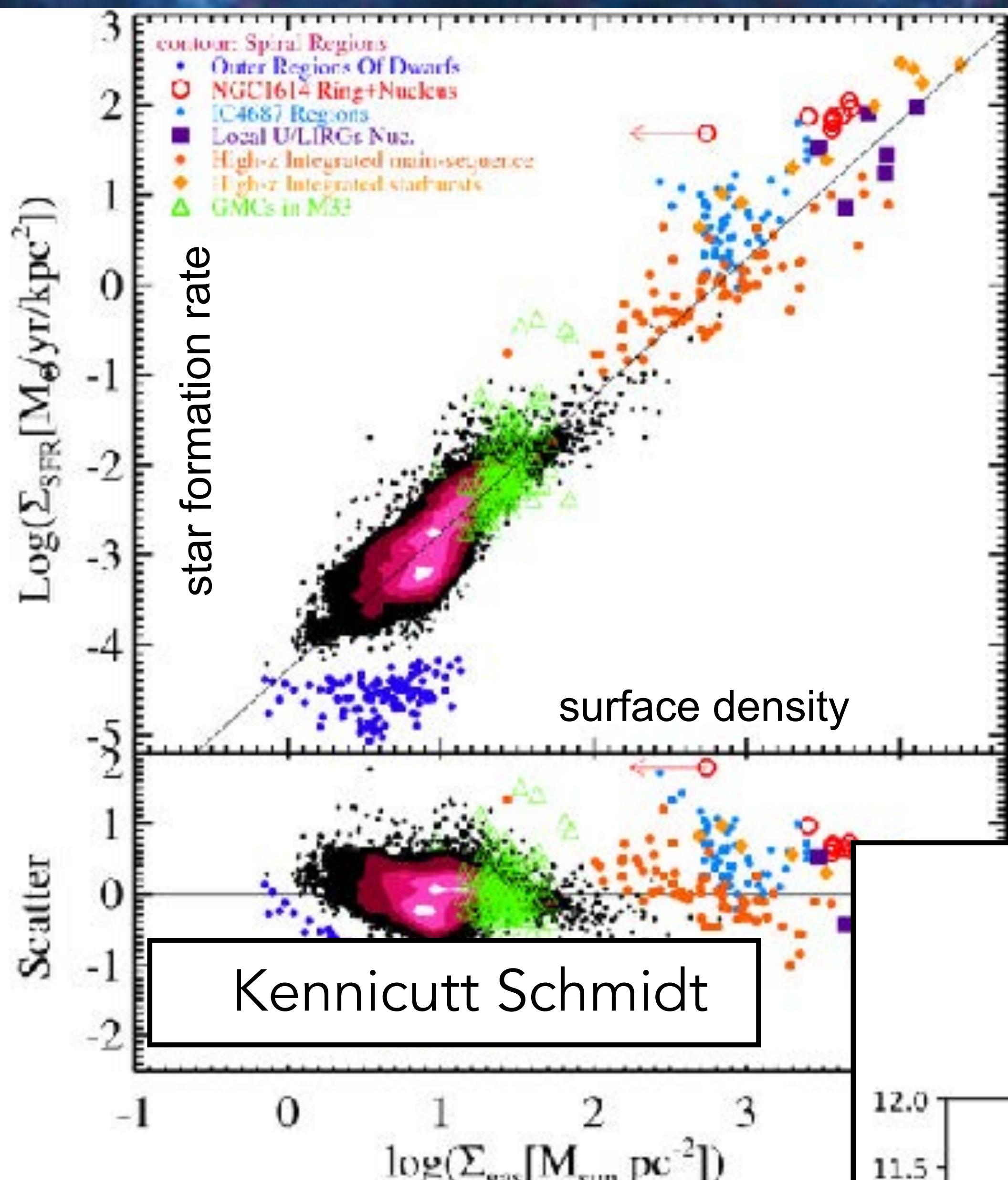
NGC 7496
NGC 3627

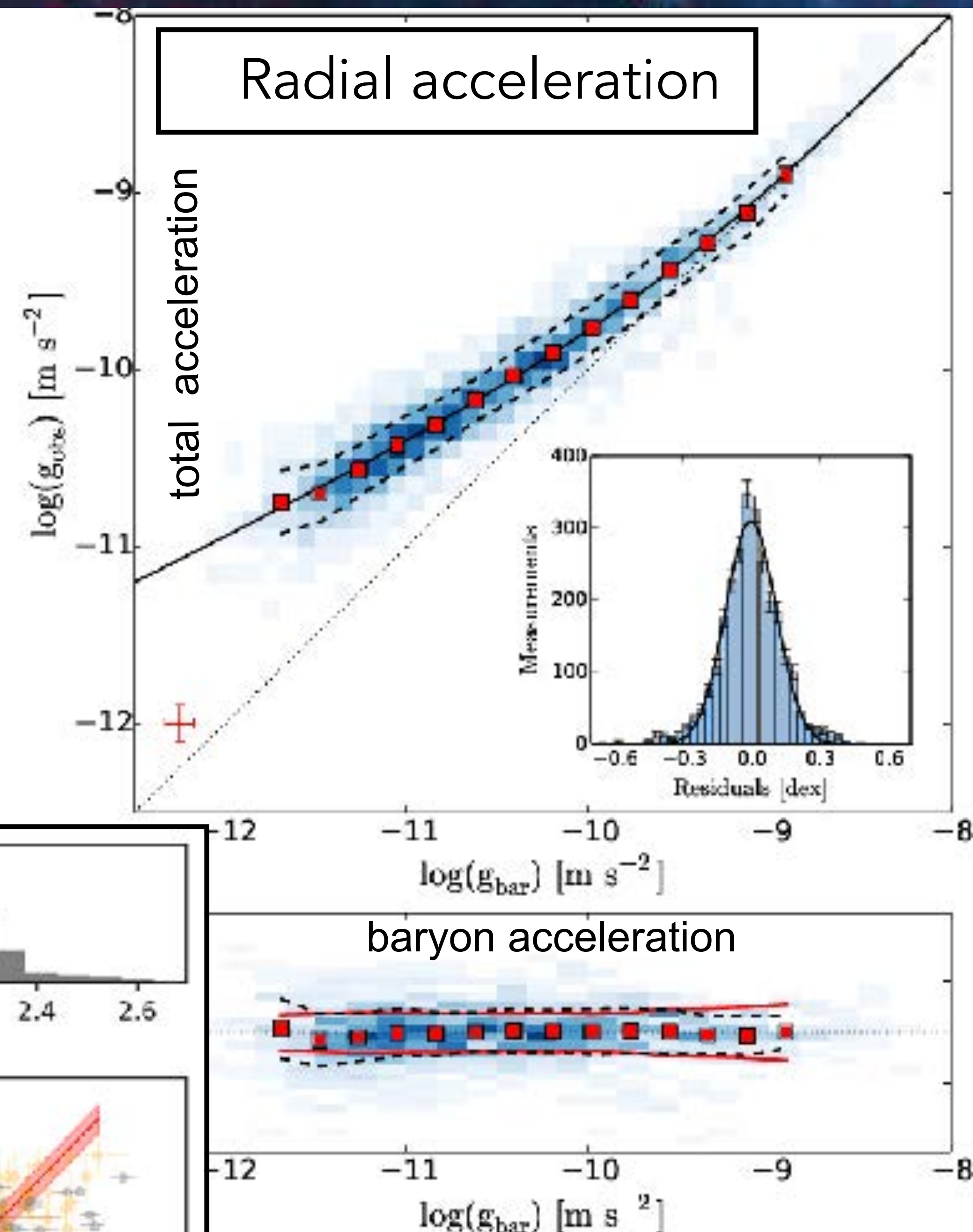
Scaling laws & Q=1 : origin of tight relations?

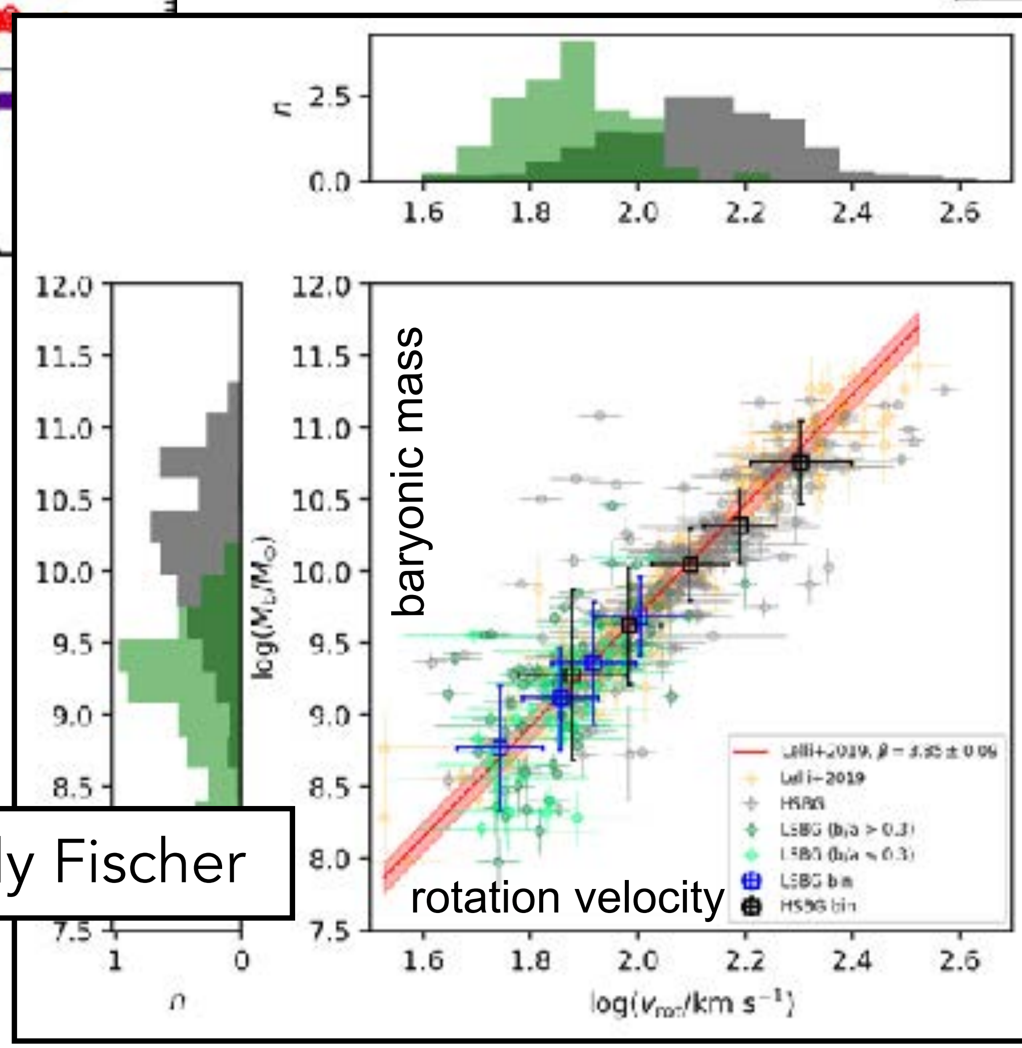


Kim Ostriker (2007)

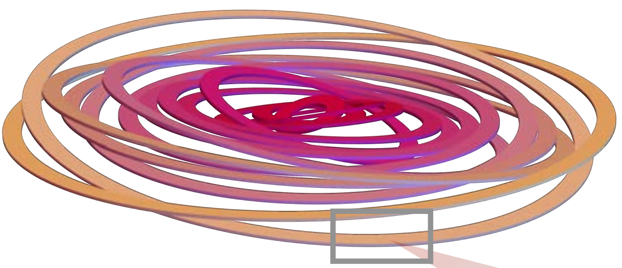
Q~1 provides *dynamical* halo to disc link

Tight Q~1 ⇒ Tight scaling relations

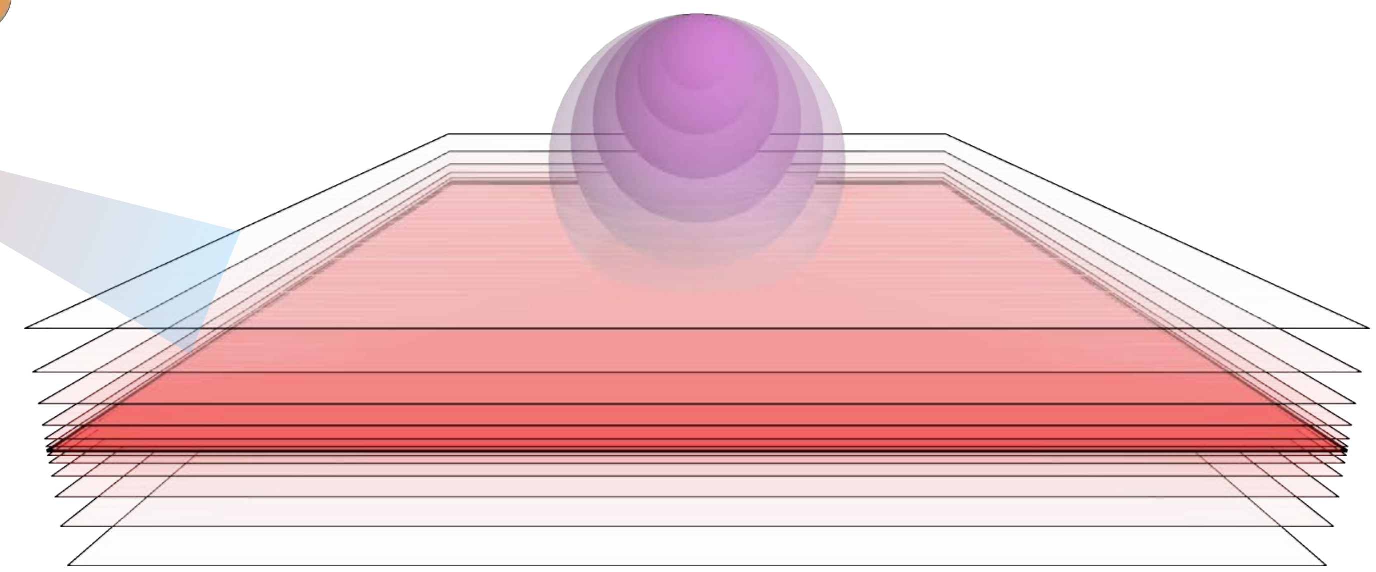




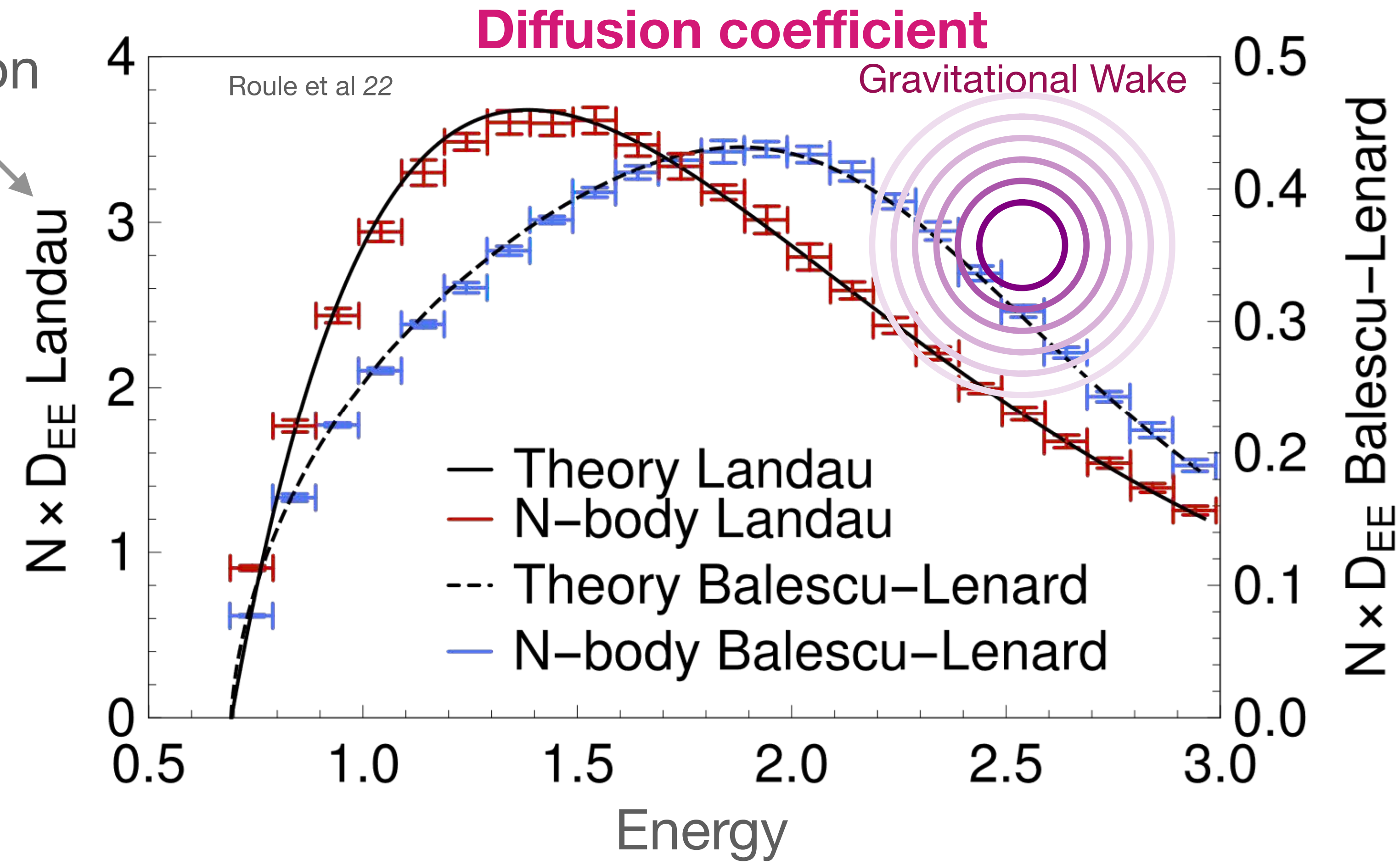
Plane Toy model: dressing damps vertical diffusion



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

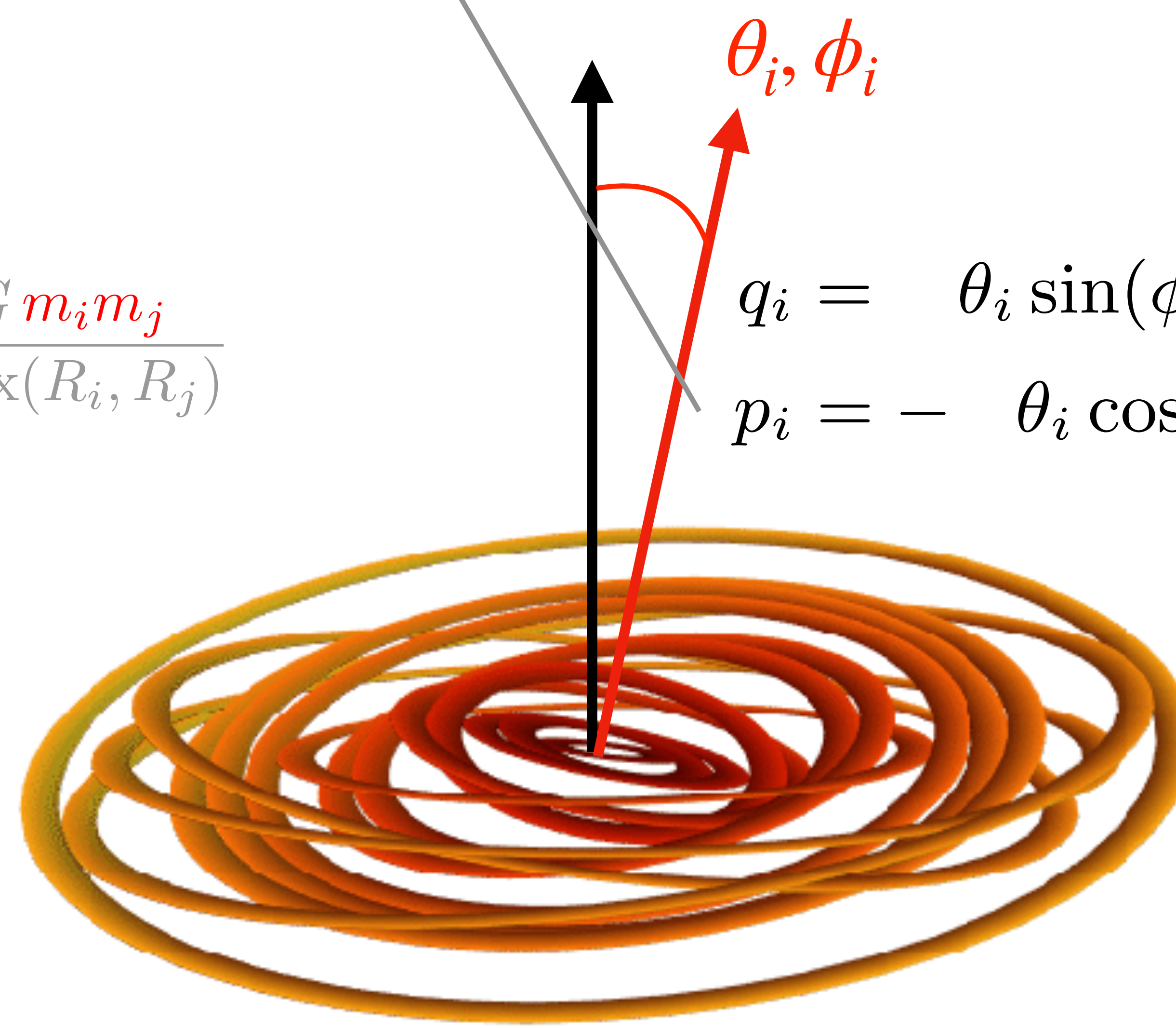
Ring Toy model: secular damping by wake growth

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

x and y components of **angular momentum**

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

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



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

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

In eigenframe of A

Eigen frequency

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

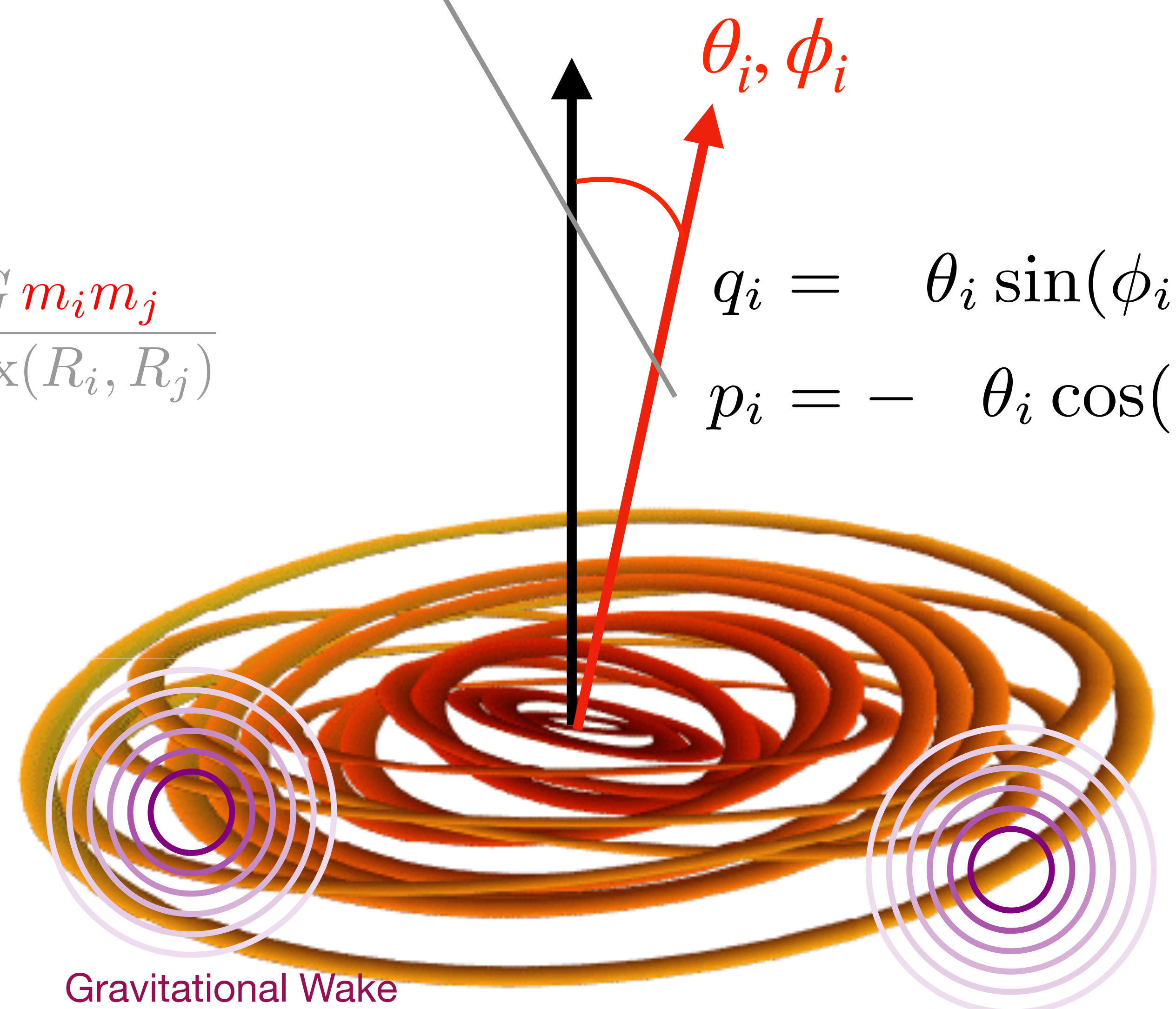
forcing

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

x and y components of **angular momentum**

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

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



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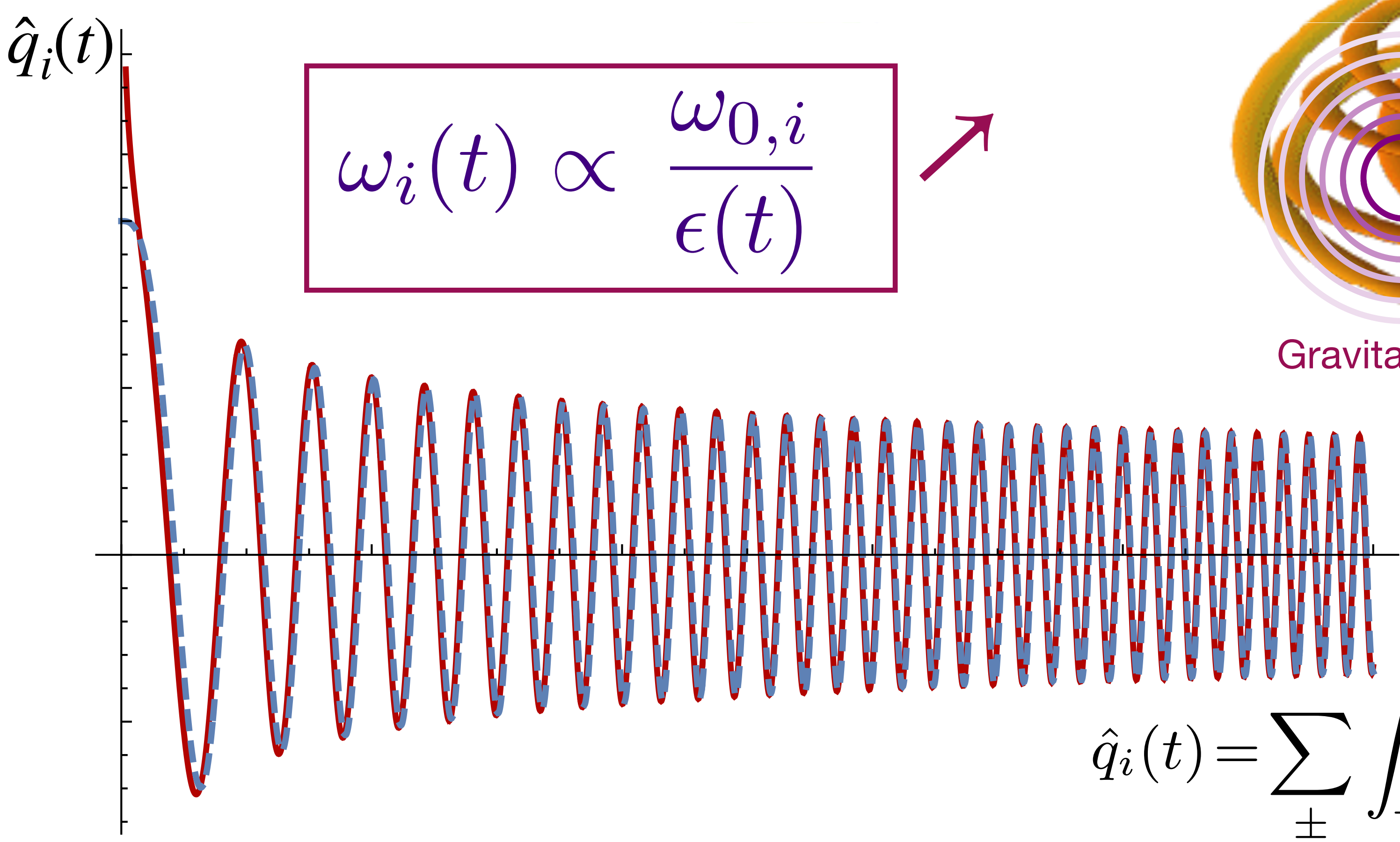


$$\boxed{\omega_i(t) \propto \frac{\omega_{0,i}}{\epsilon(t)}} \nearrow$$

Secular WKB solution

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

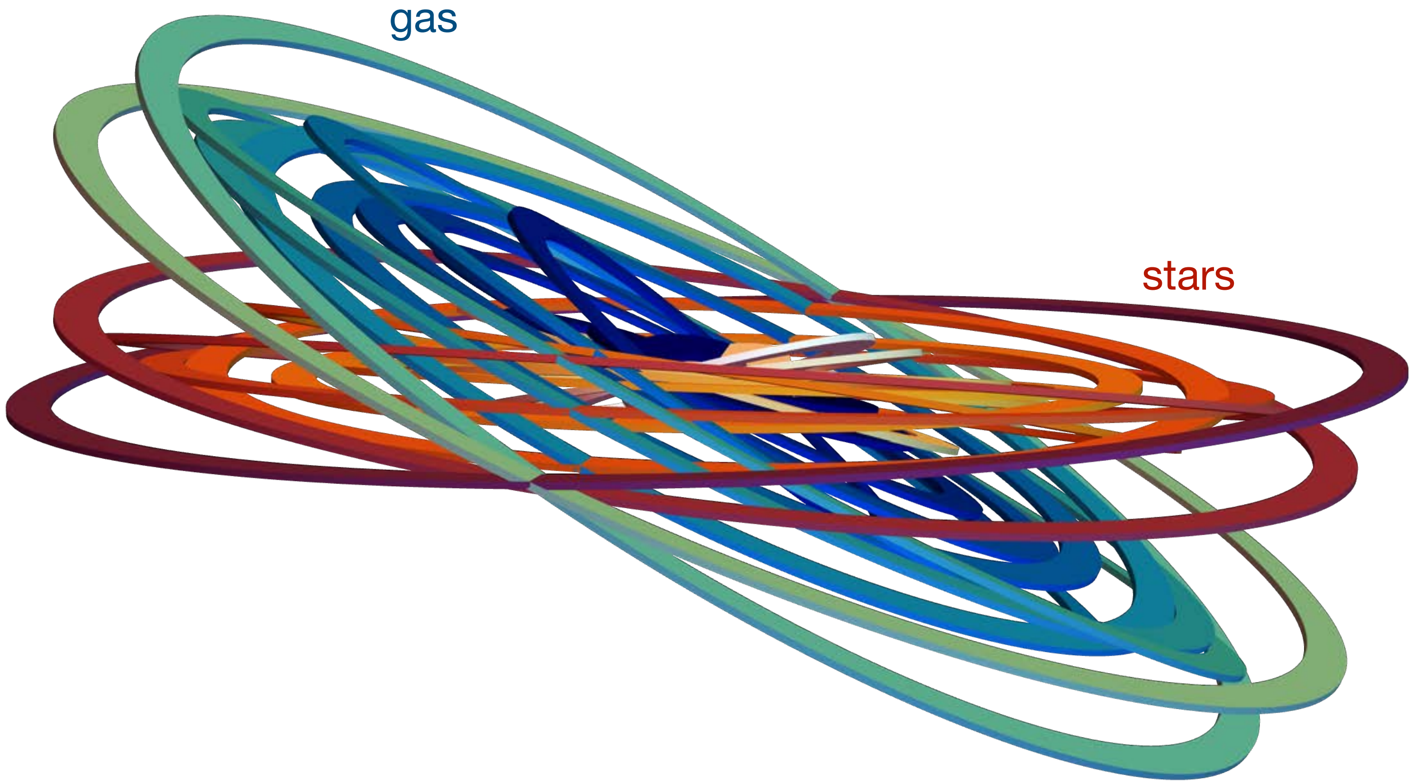
Ring Toy model: gas + star coupling

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



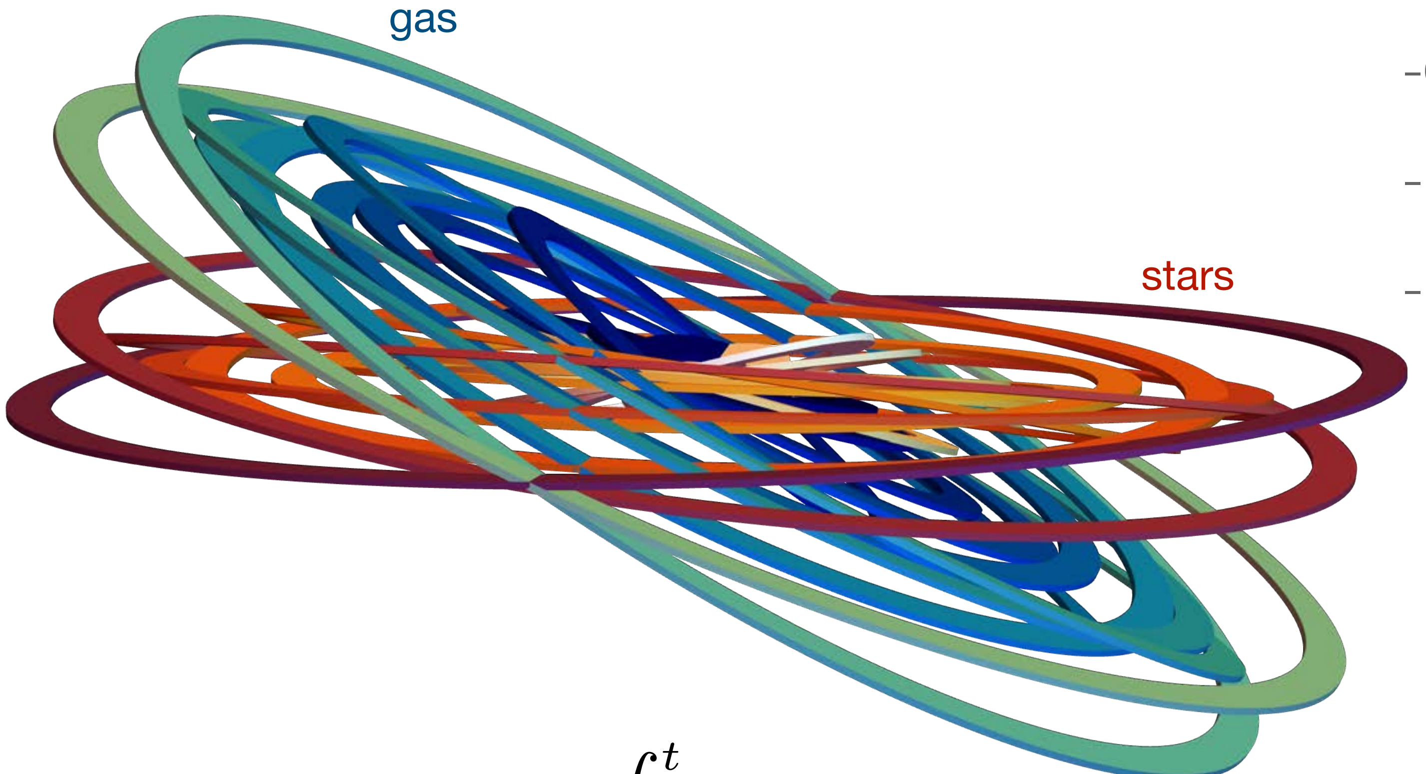
See also Bertin Romeo (1988) 195, 105-113

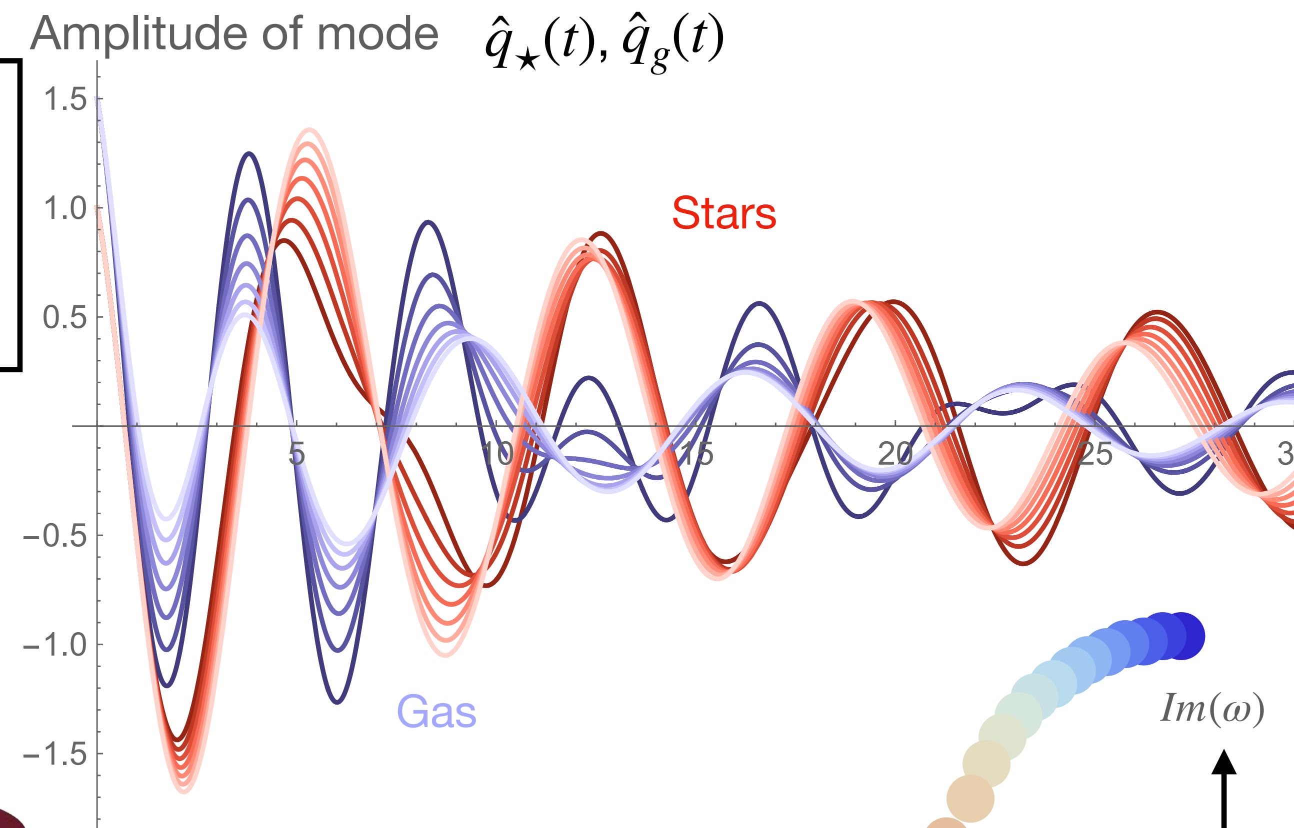
Ring Toy model: gas + star coupling

gravitational coupling   damping

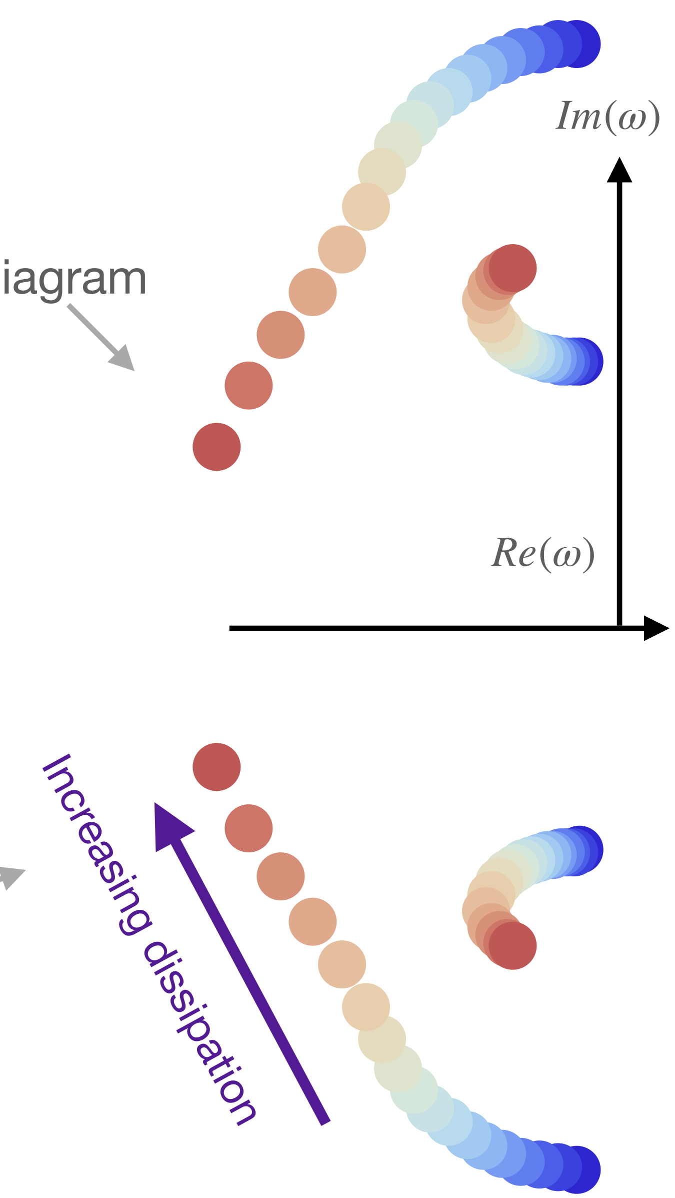
$$\boxed{\begin{aligned}\ddot q_\star + \omega_\star^2 q_\star + \omega_{\star g}^2 q_g &= 0\,,\\ \ddot q_g + \omega_g^2 \hat q_g + \omega_{\star g}^2 q_\star + \eta \dot q_g &= \xi\,,\end{aligned}}$$

forcing





Nyquist diagram



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

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

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

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

Lagrange Laplace theory of rings (small eccentricity small inclinaison)

x and y components of **angular momentum**

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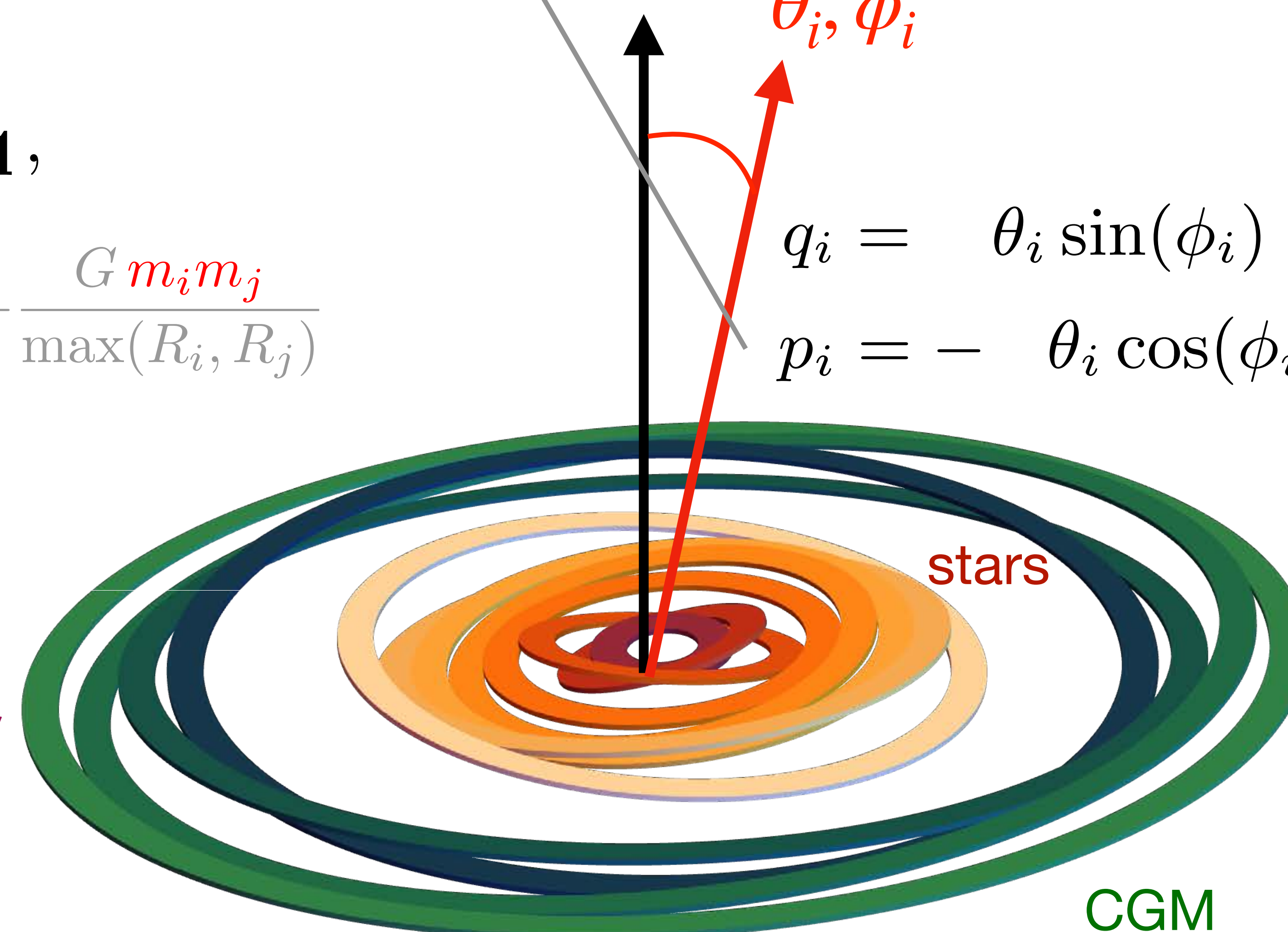

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$$p_i = -\theta_i \cos(\phi_i)$$

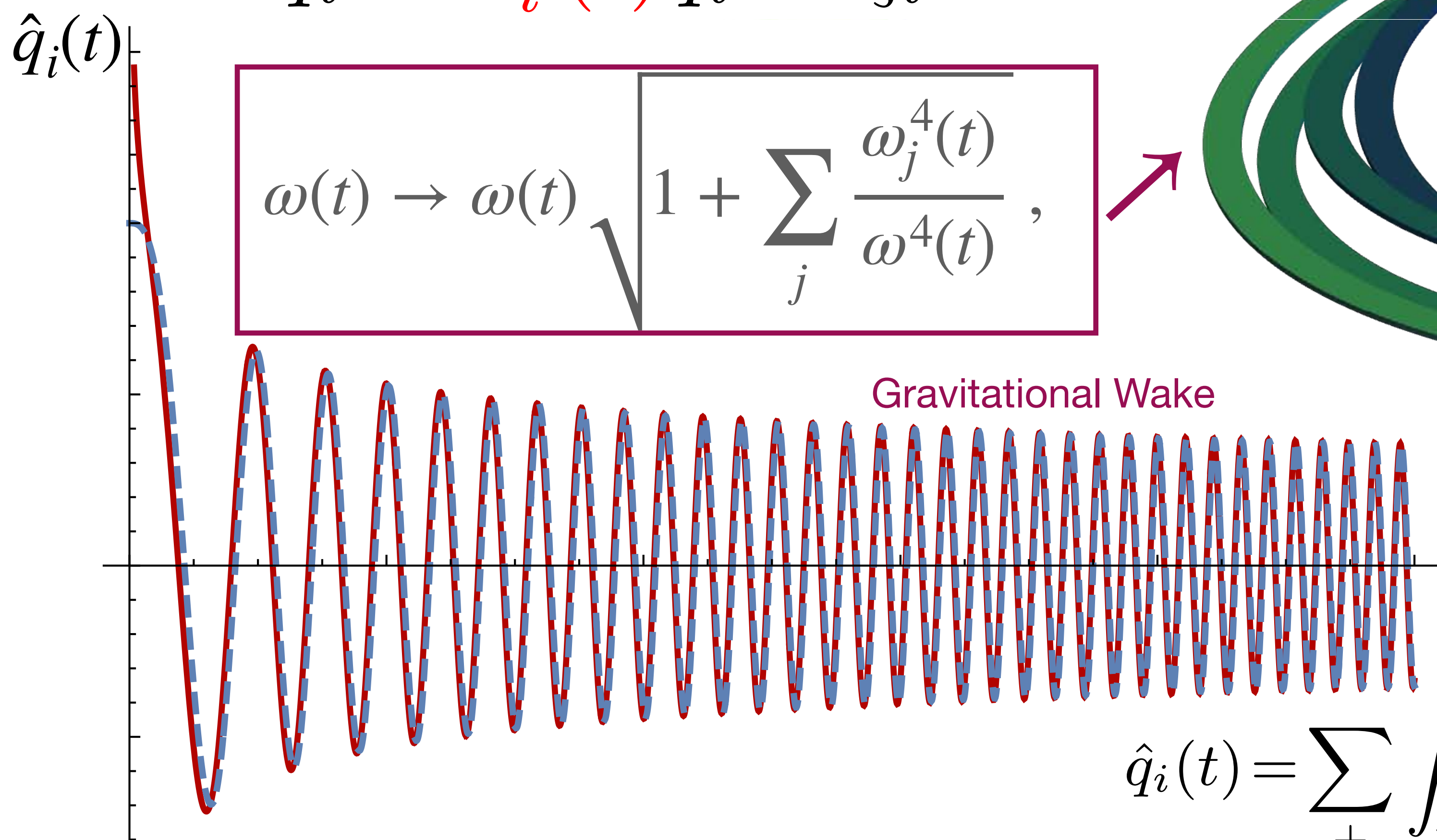
In eigenframe of A

Eigen frequency

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

forcing

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



Secular WKB solution

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

CONCLUSIONS

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

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

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

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

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

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

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