The cosmic emergence* of thin discs

New Horizon Simulation

Order out of Chaos:
secular thick and thin disc settling

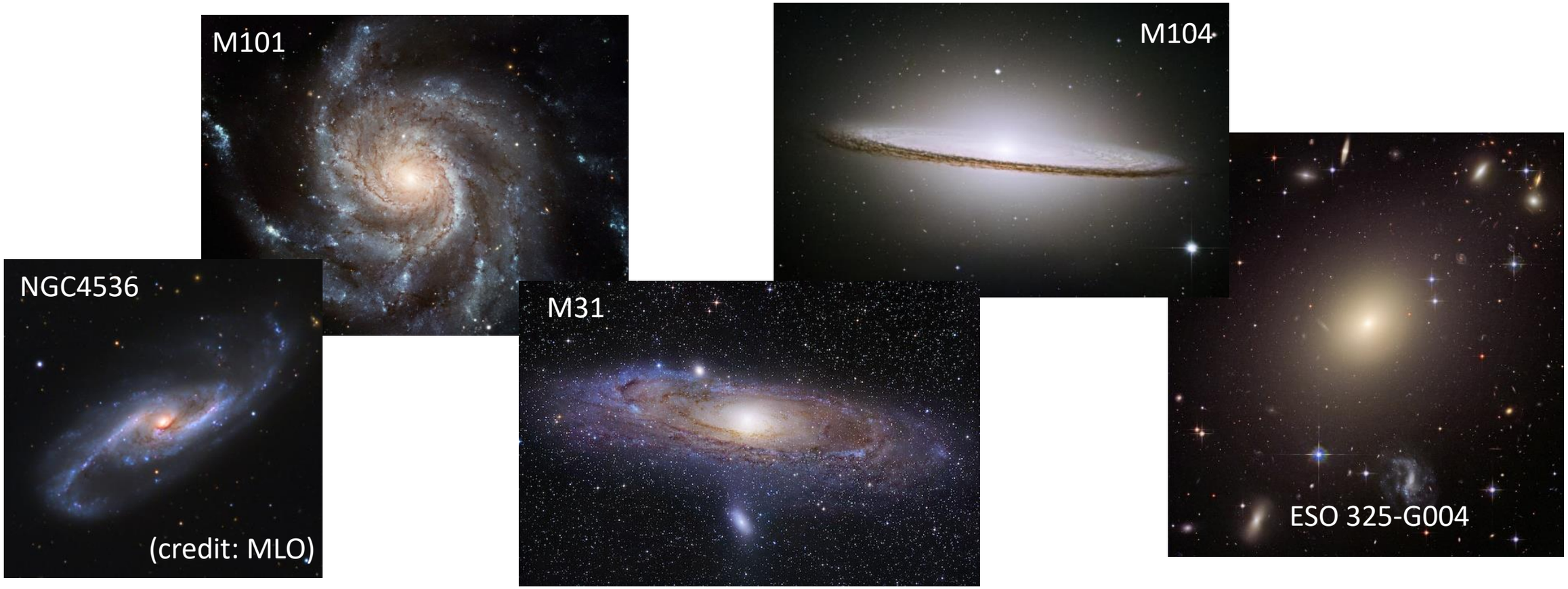
* emergence = the arising of novel and coherent structures through self-organization in complex systems

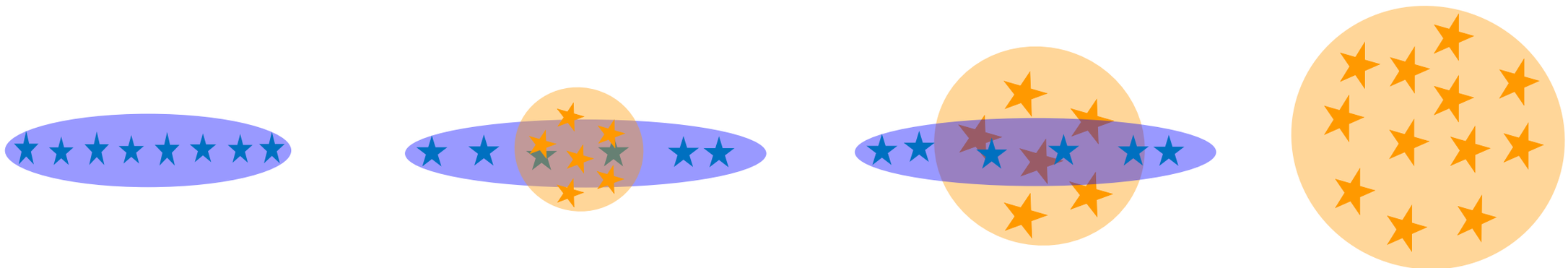
Christophe Pichon & The NewHorizon Collaboration (Min-Jung Park++)

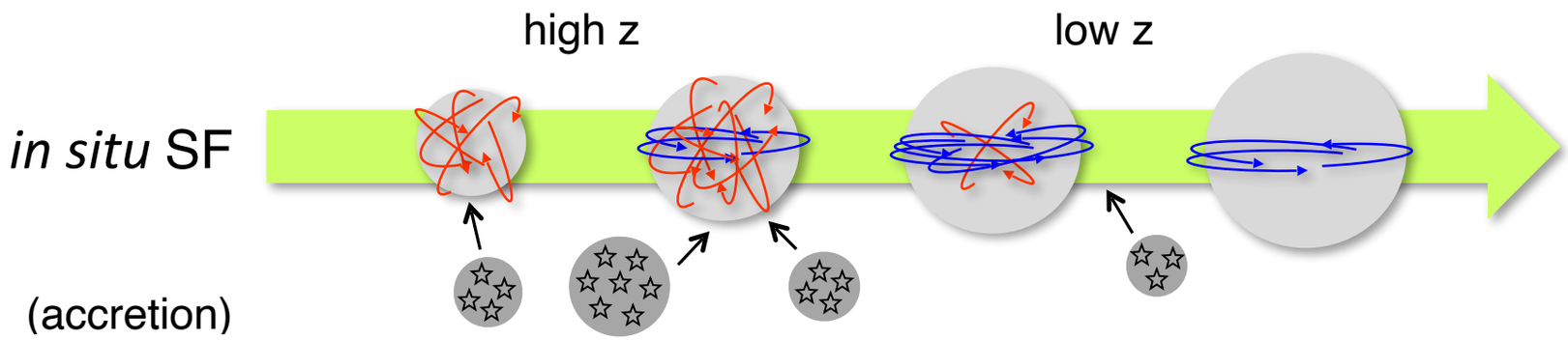
Understanding formation of massive thin discs?

Diverse morphologies of galaxies

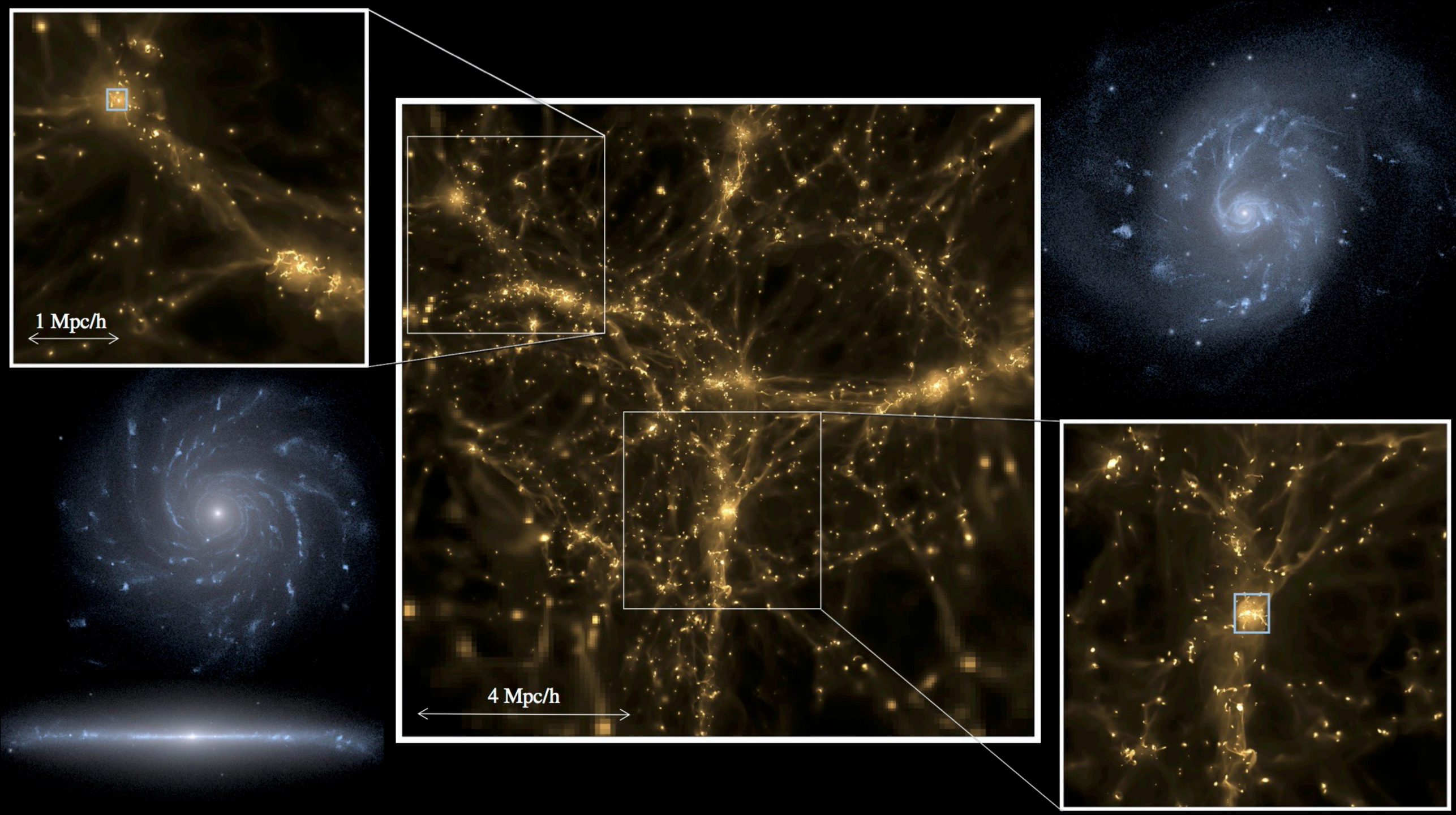
(Credit: NASA, ESA and STScI)





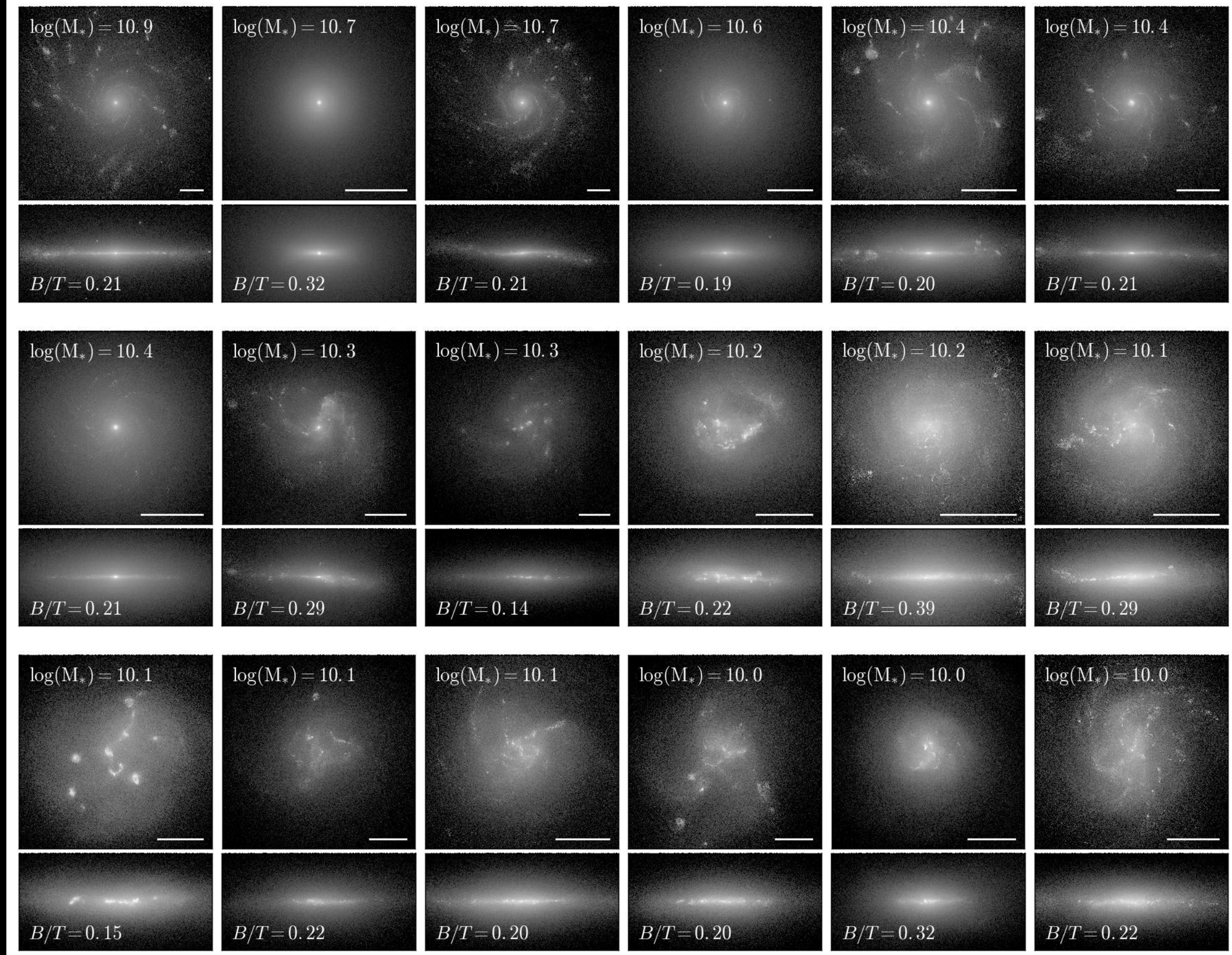


The New Horizon simulation

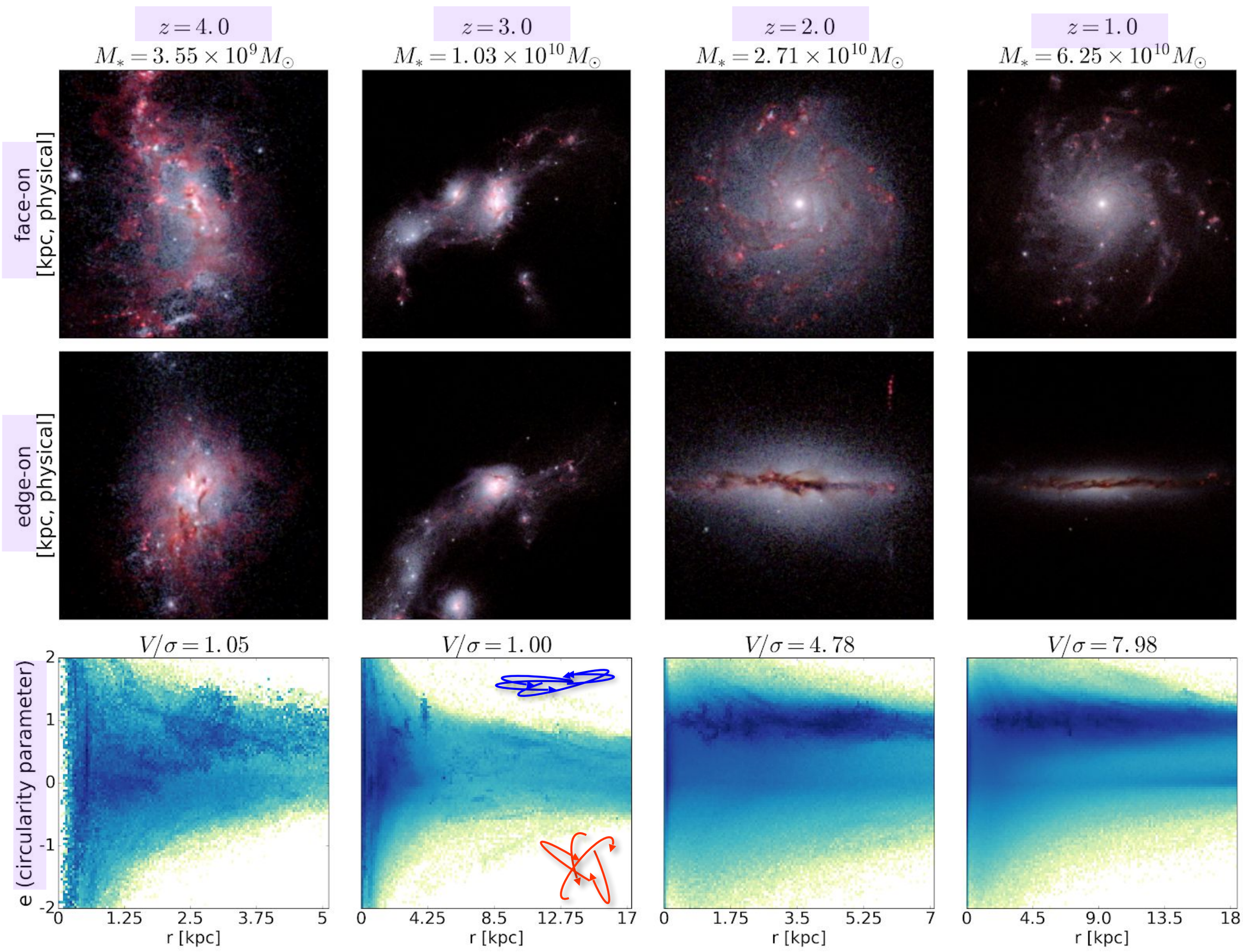


New Horizon Simulation

Other examples (out of 1000s)

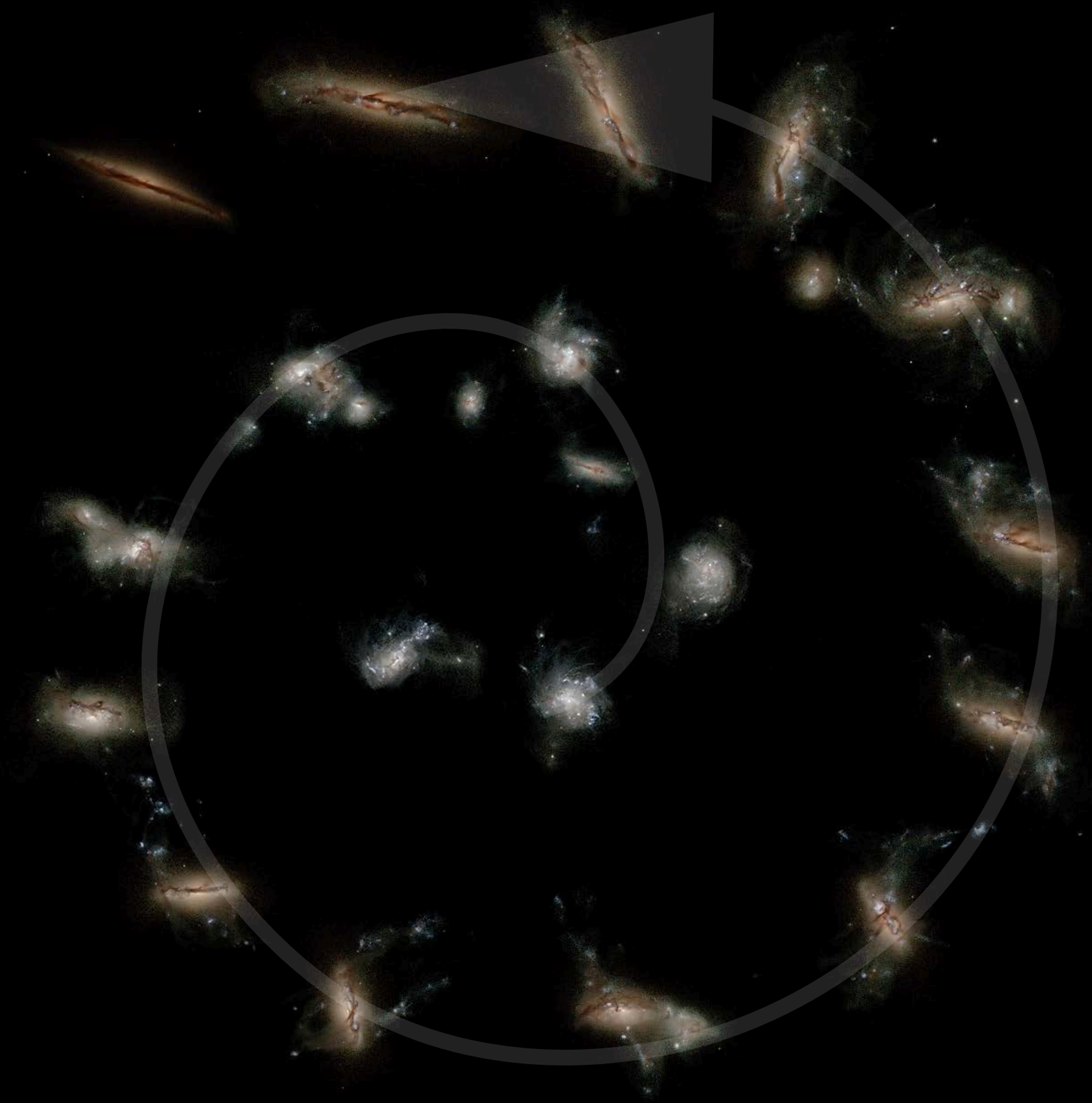


Disc settling: numerical evidence



Disc settling: timeline of a thin galactic disc

New Horizon Simulation



Synopsis of presentation

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

- 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
  - implies that thick and thin discs grow together

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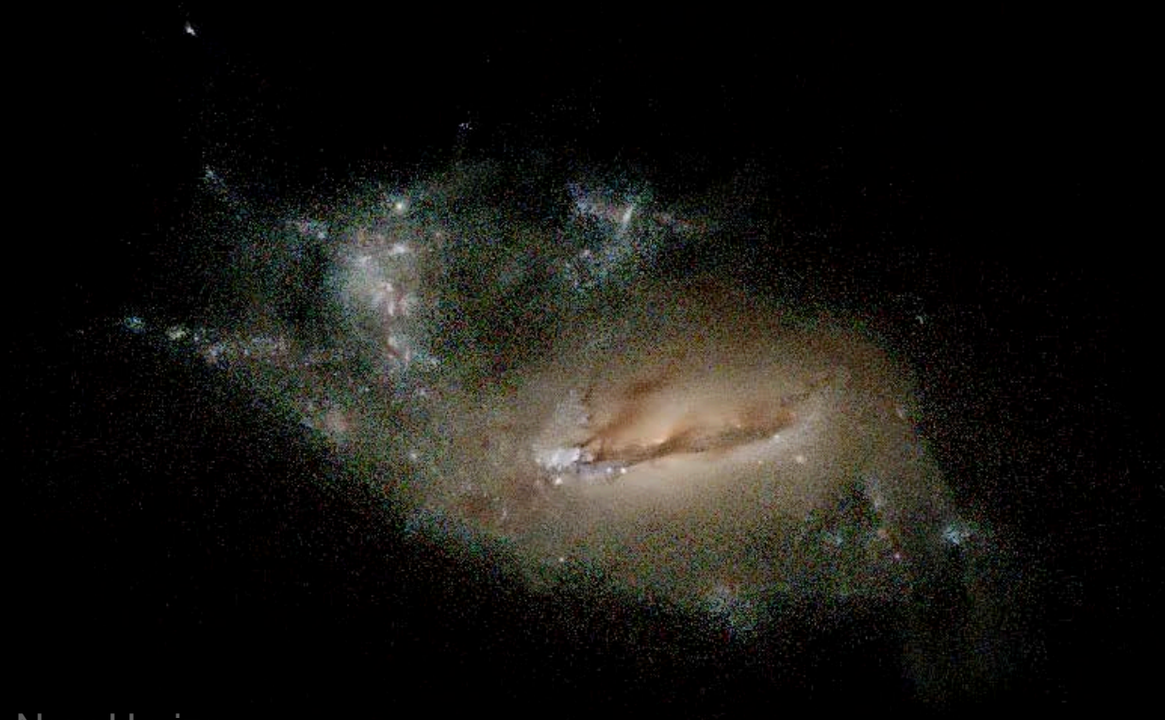

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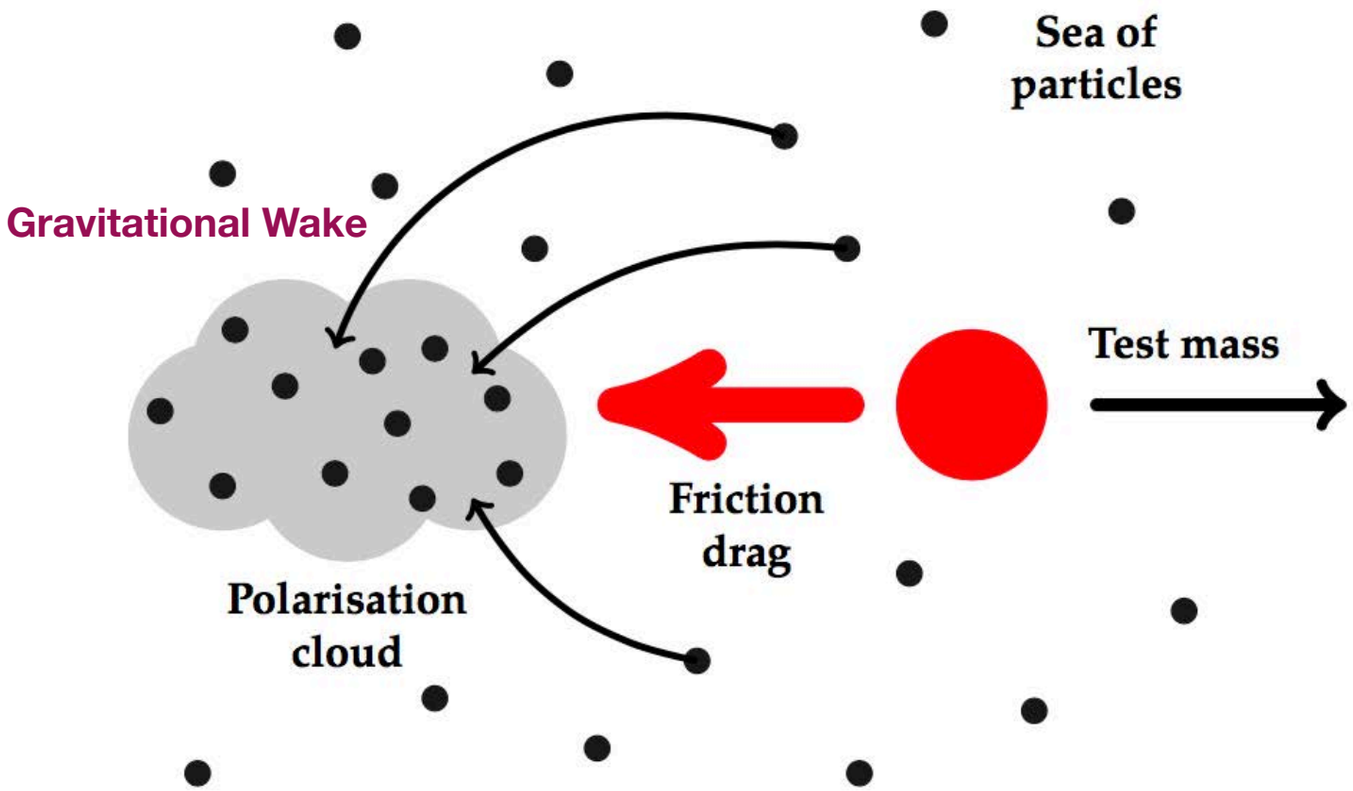
Gravitational wake/polarisation/dressing

Chandrasekhar polarisation

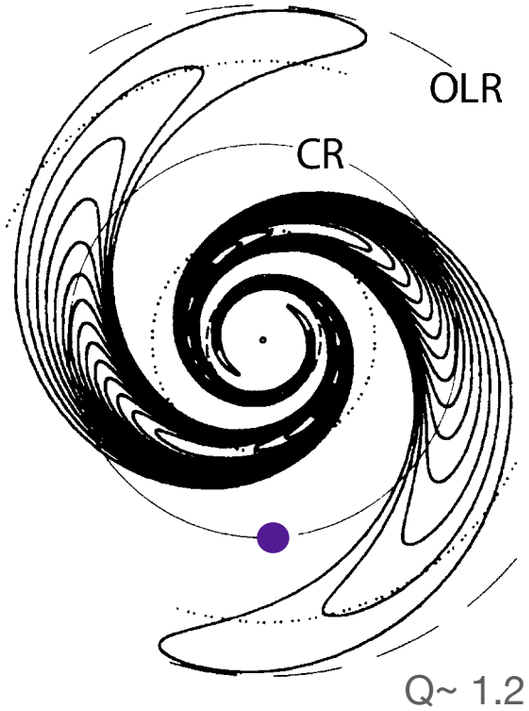


$$[\delta\psi]_{\text{dressed}} = \frac{[\delta\psi]_{\text{bare}}}{|\,\varepsilon(\omega)\,|}$$

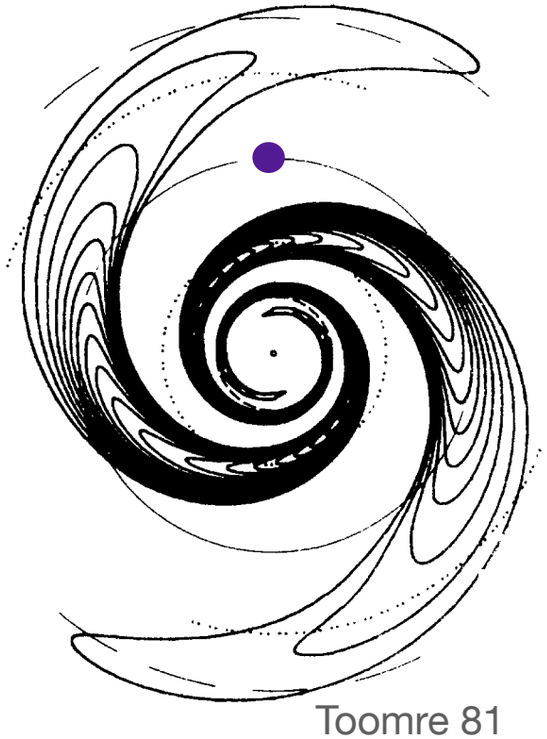
$$T_{\text{dressed}} \simeq |\,\varepsilon\,|\; T_{\text{bare}}$$

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

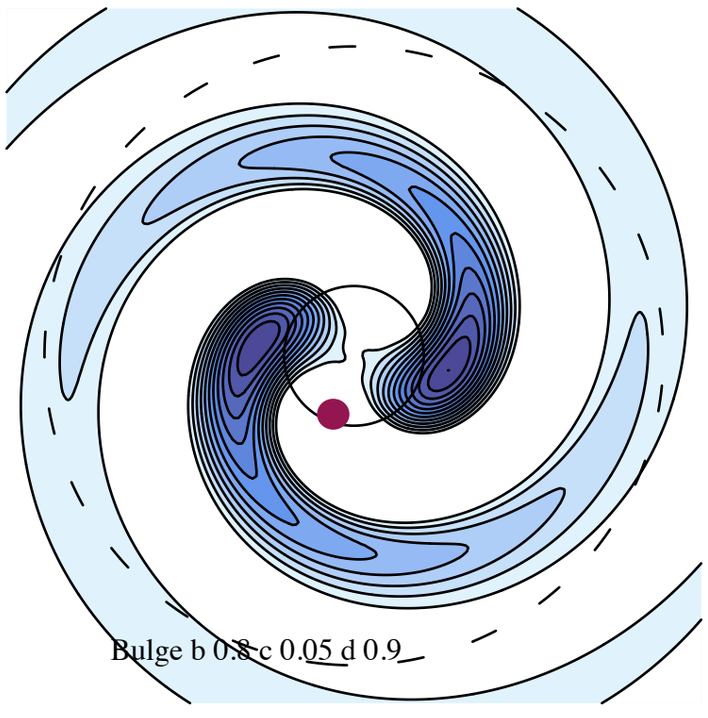
Mass in **wake** = mass of perturbation **X 140** !! ≠ 1.8 for sphere



Q~ 1.2



Toomre 81



Bulge b 0.8 c 0.05 d 0.9

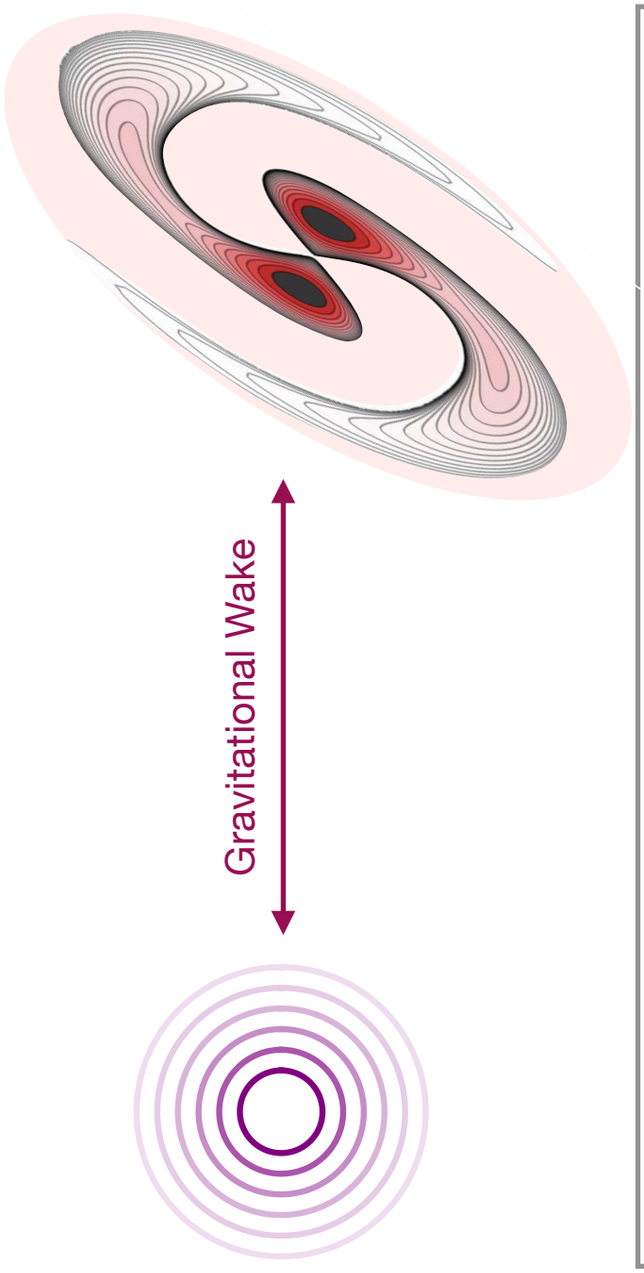
On the importance of *gravitational* wakes

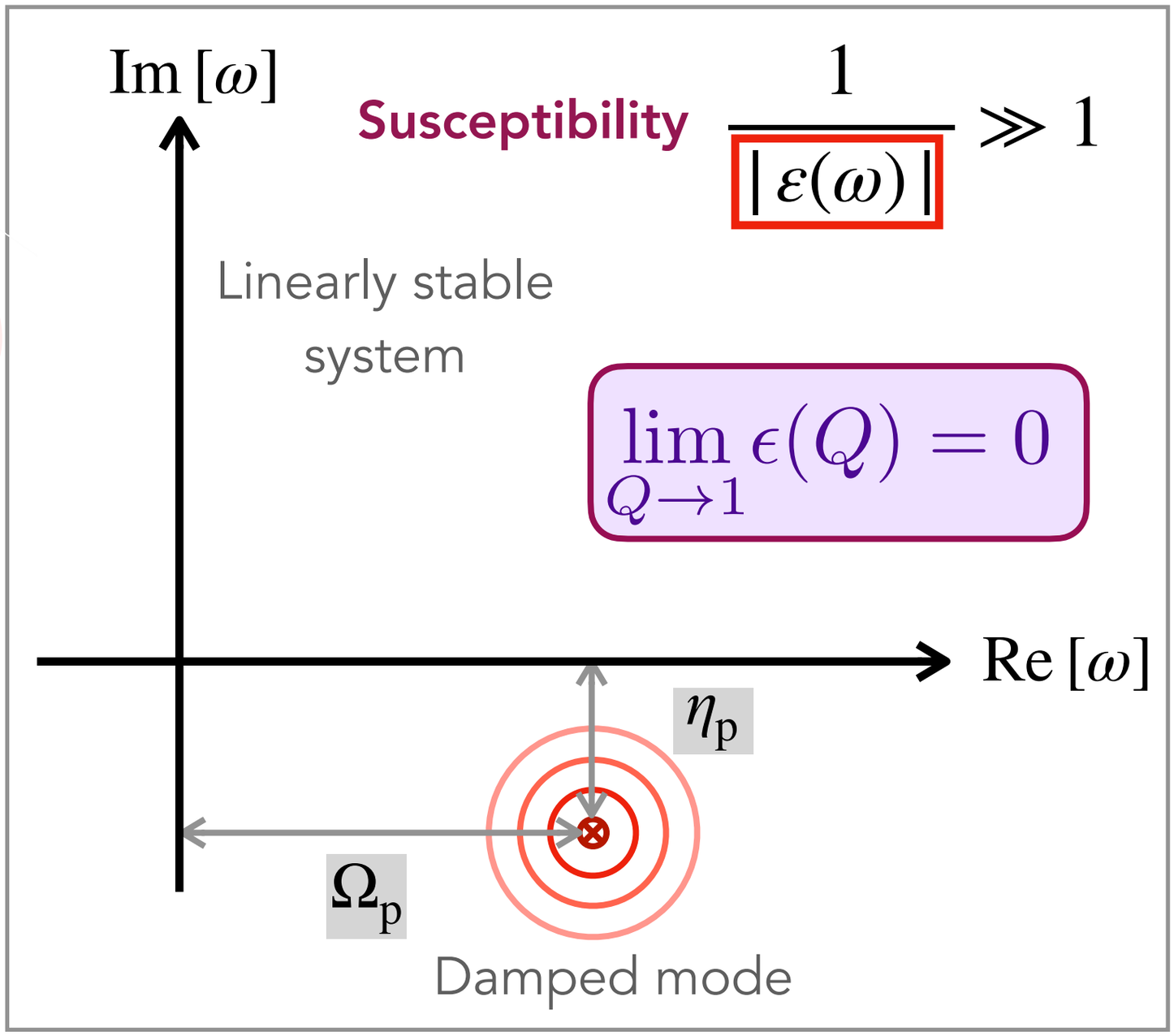
For cold discs…

Gravitational "*Dielectric*" function ϵ

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

Dispersion relation — Response matrix





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 $Q \sim 1$.

Attraction point of feedback loop

$$Q_{\rm eff}^{-1} = Q_g^{-1} + Q_\star^{-1}$$

Q ↗

Destabilising effects

- SN1a
- Turbulence

———

- Minor Mergers
- Misaligned infall
- FlyBys

Star formation and feedback define control loop on disc

Stabilising effects

- Star formation
- Cooling
- Shocks

———

- Co-rotating Aligned infall

Cosmic perturbation

Free energy reservoir in CGM

Q ↘

Self regulating loop boosted by wake

Transition to secularly-driven morphology promoting self-regulation around an effective Toomre **Q ~1.**

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

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

Attraction point of feedback loop

$$Q_{\rm eff}^{-1} = Q_g^{-1} + Q_\star^{-1}$$

Q ↗

Tighter loop

Destabilising effects

- SN1a
- Turbulence

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Gravitational Wake

Stabilising effects

- Star formation
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Cosmic perturbation

Free energy reservoir in CGM

Q ↘

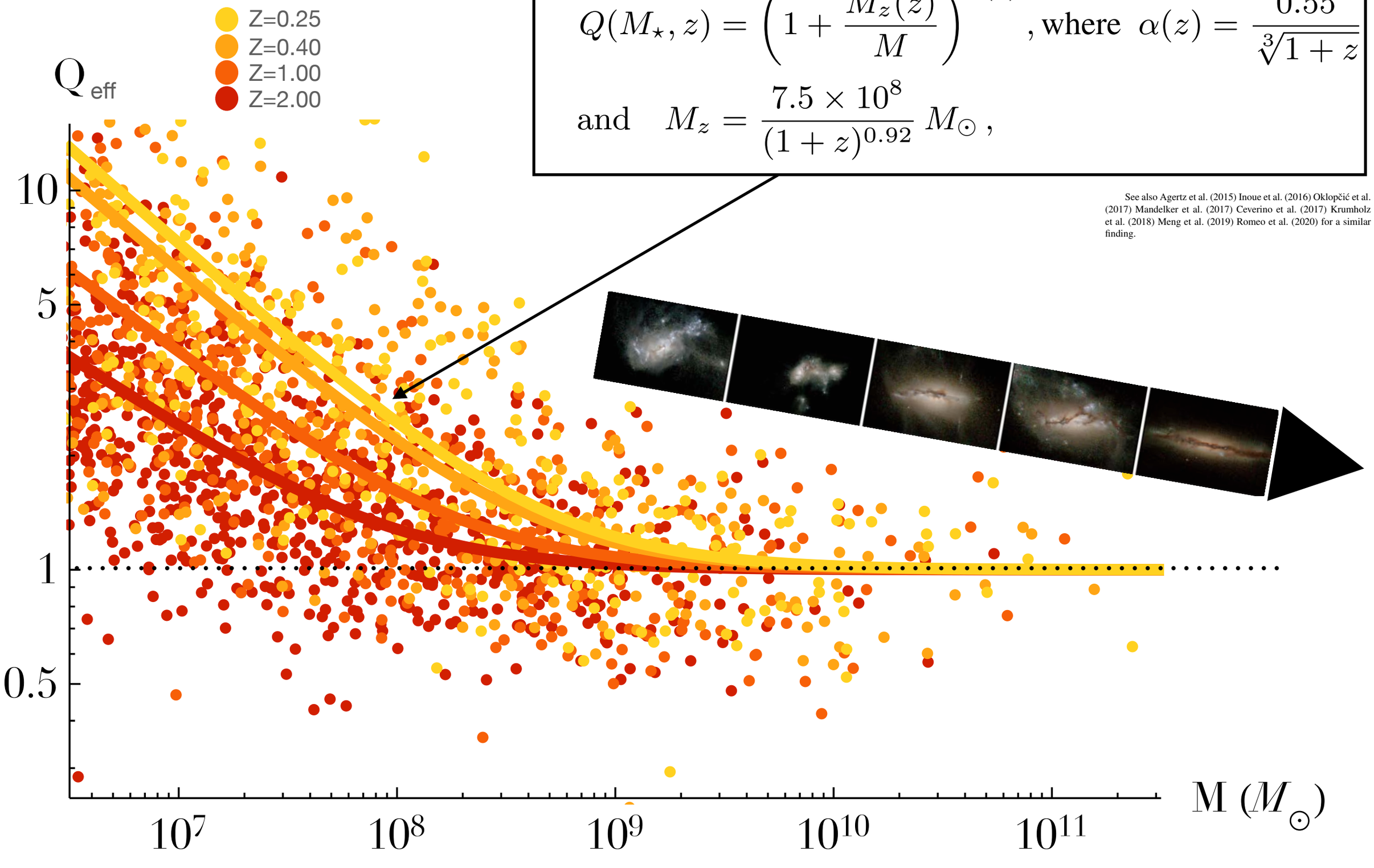
Open system with control loop generates complexity through self-organisation

Toomre Q convergence with mass and z

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

$$Q(M_\star, z) = \left(1 + \frac{M_z(z)}{M}\right)^{\alpha(z)}, \text{where } \alpha(z) = \frac{0.55}{\sqrt[3]{1+z}}$$

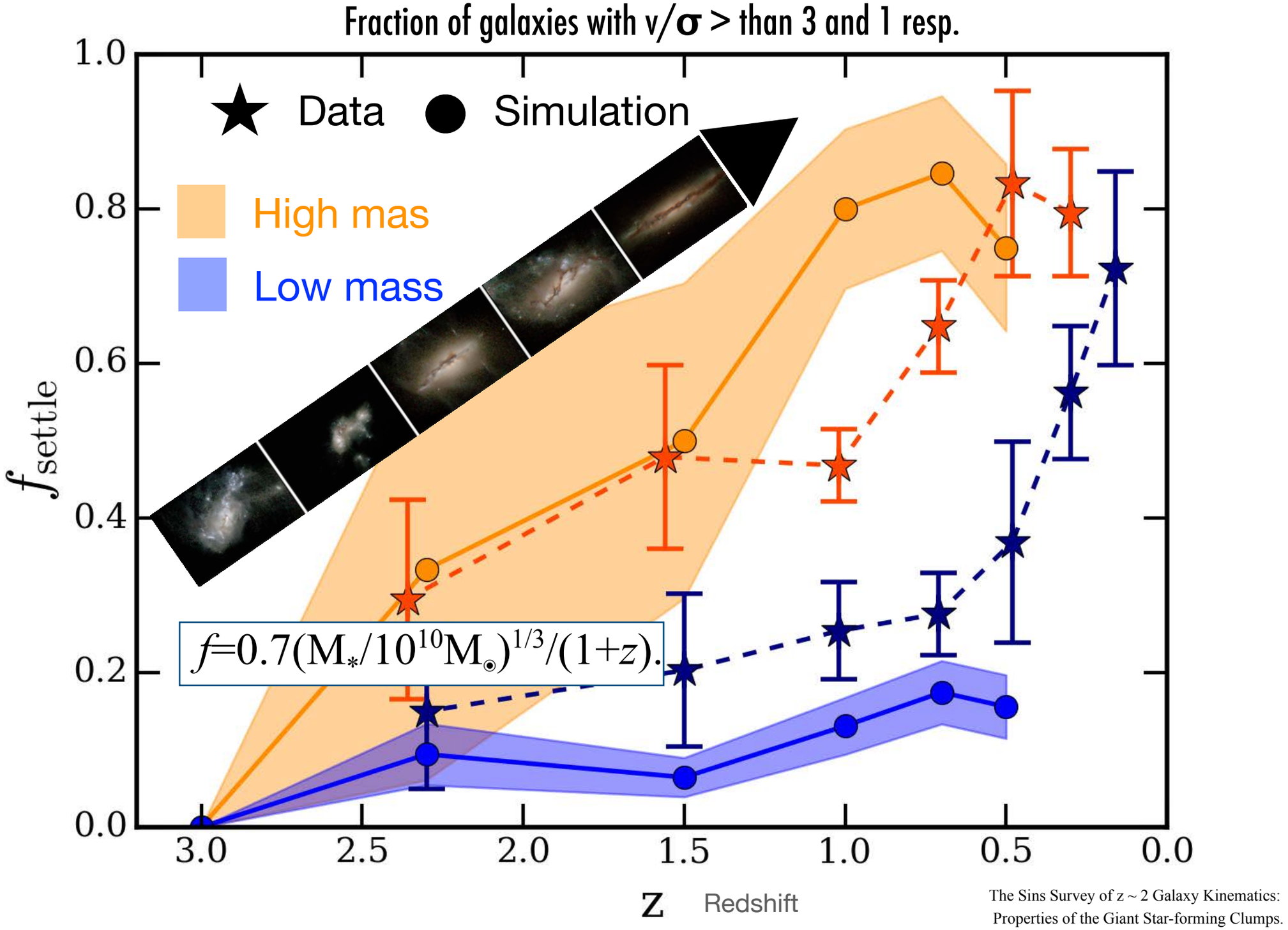
$$\text{and} \quad M_z = \frac{7.5 \times 10^8}{(1+z)^{0.92}} M_\odot ,$$



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

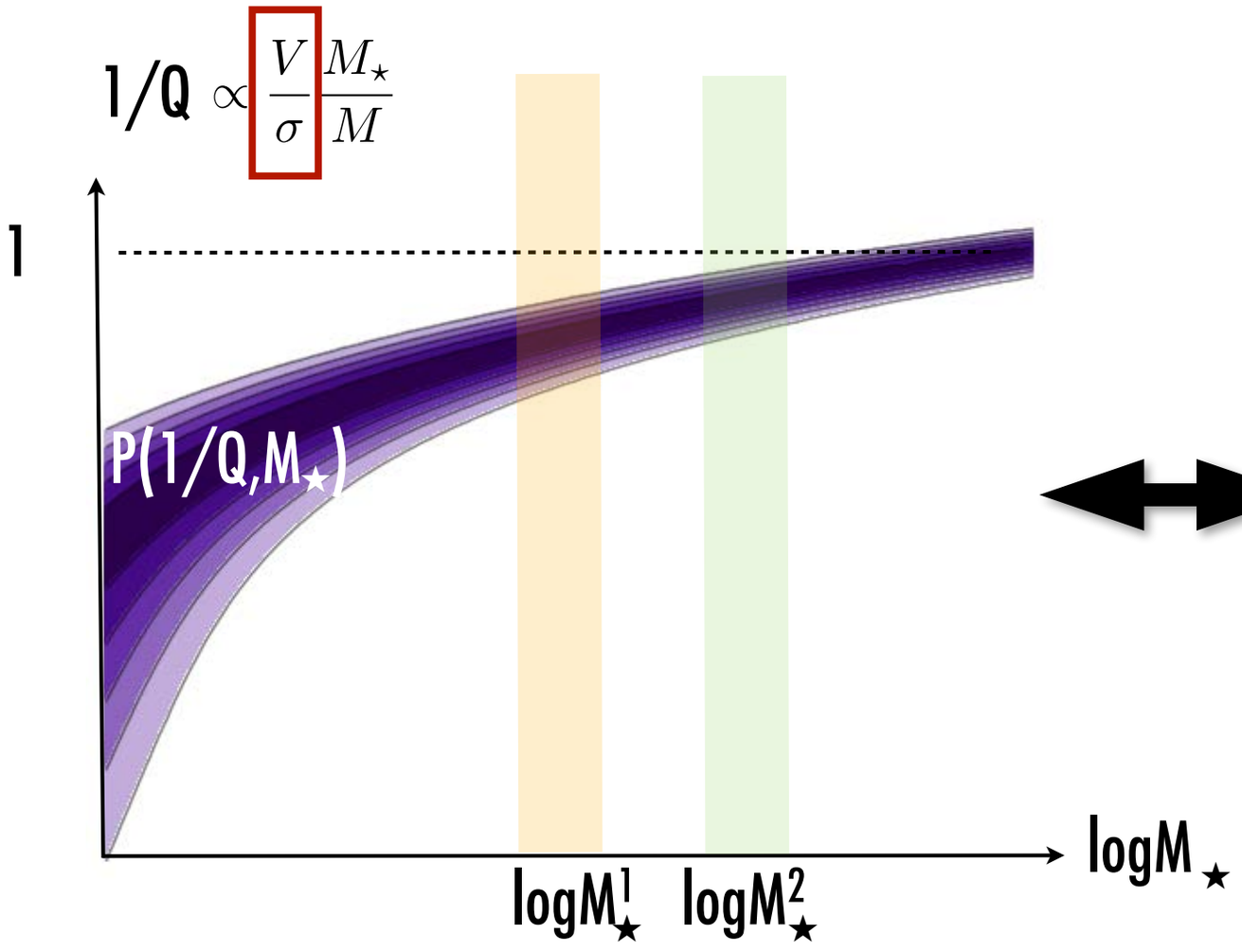


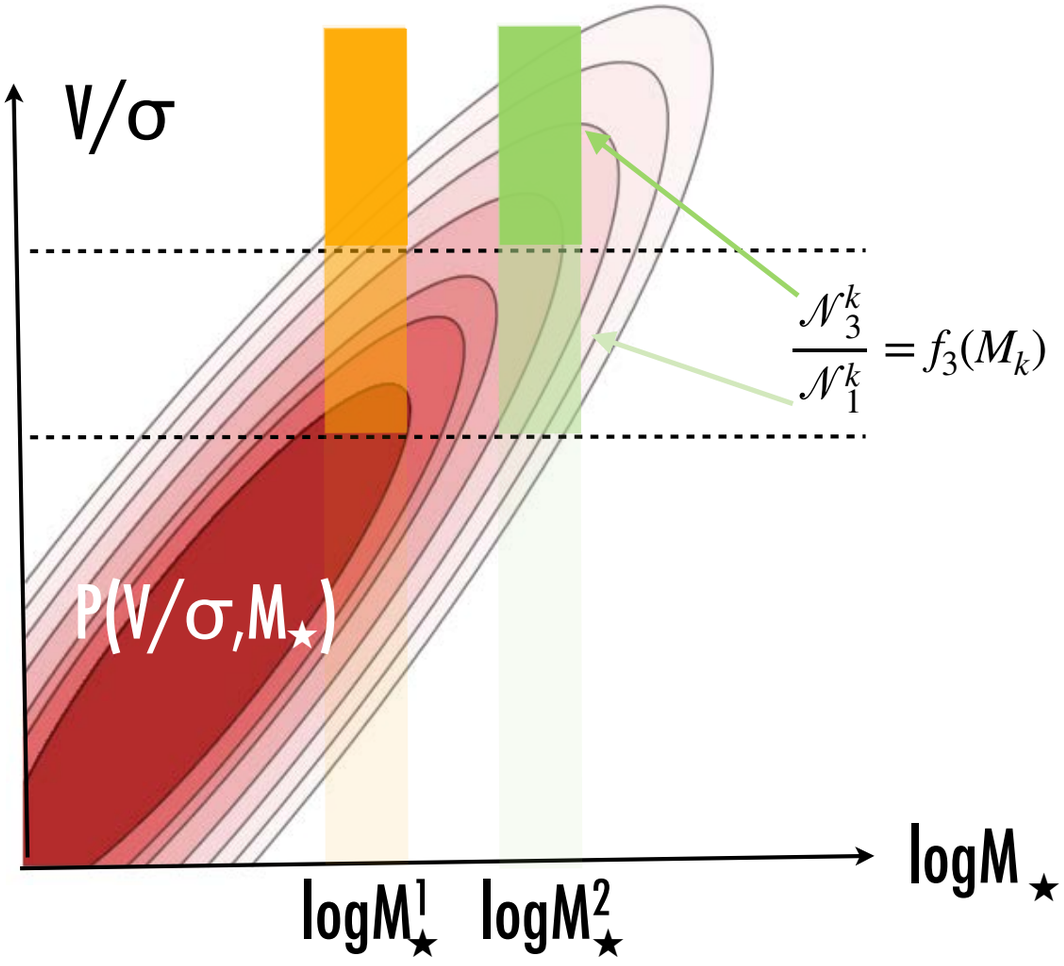
The Sins Survey of z ~ 2 Galaxy Kinematics: Properties of the Giant Star-forming Clumps. Astrophys. J., 733, 101-130 (2011)

Numerical equivalence given Toomre(V/σ)

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

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





Can this be also explained qualitatively ?

Ring Toy model: secular damping by wake growth

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

x and y components of angular momentum

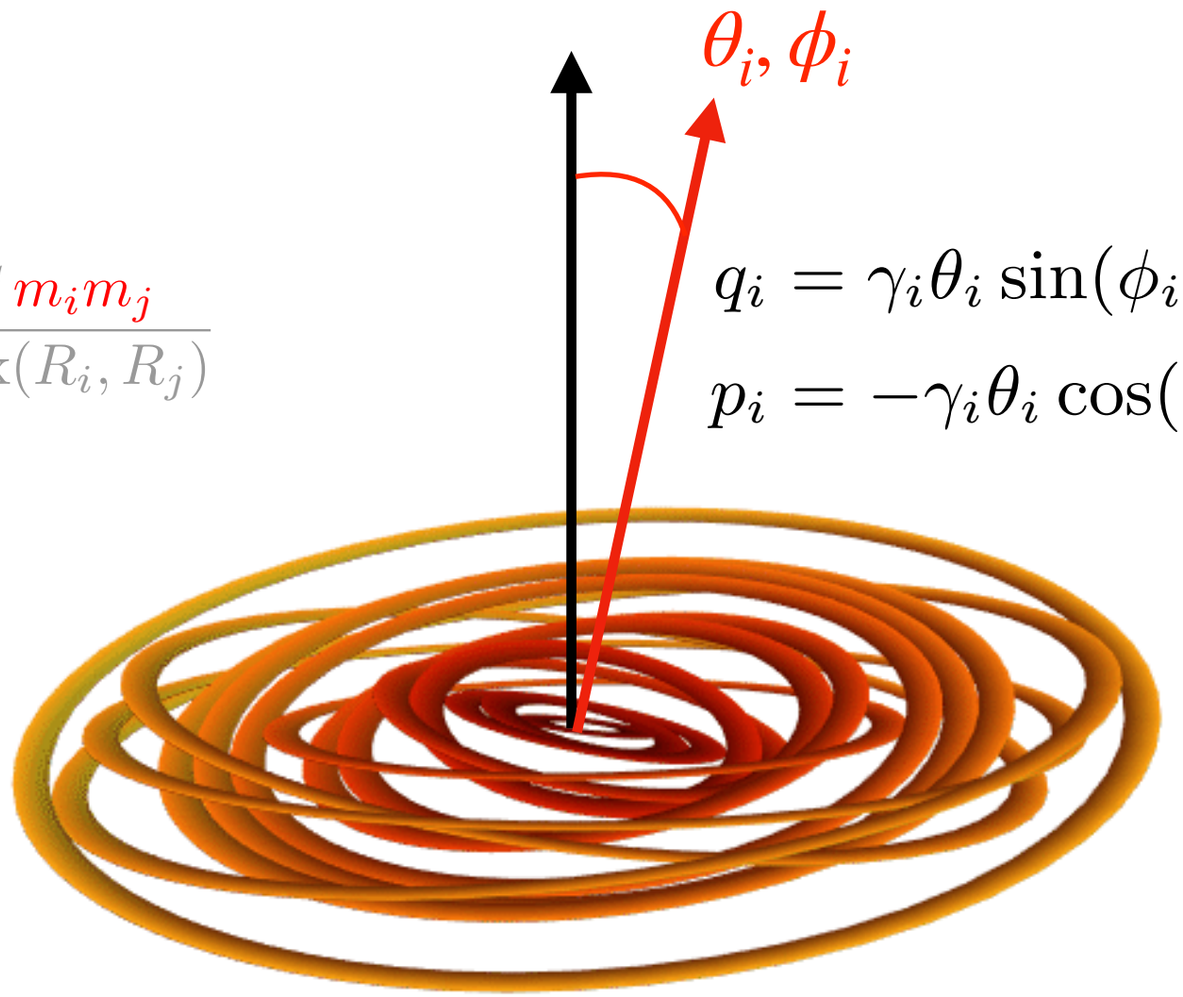
$$H(\mathbf{p},\mathbf{q}) = \frac{1}{2}\mathbf{p}^{\mathrm{T}}\cdot\mathbf{A}\cdot\mathbf{p} + \frac{1}{2}\mathbf{q}^{\mathrm{T}}\cdot\mathbf{A}\cdot\mathbf{q},$$

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

In eigenframe of A

Eigen frequency

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



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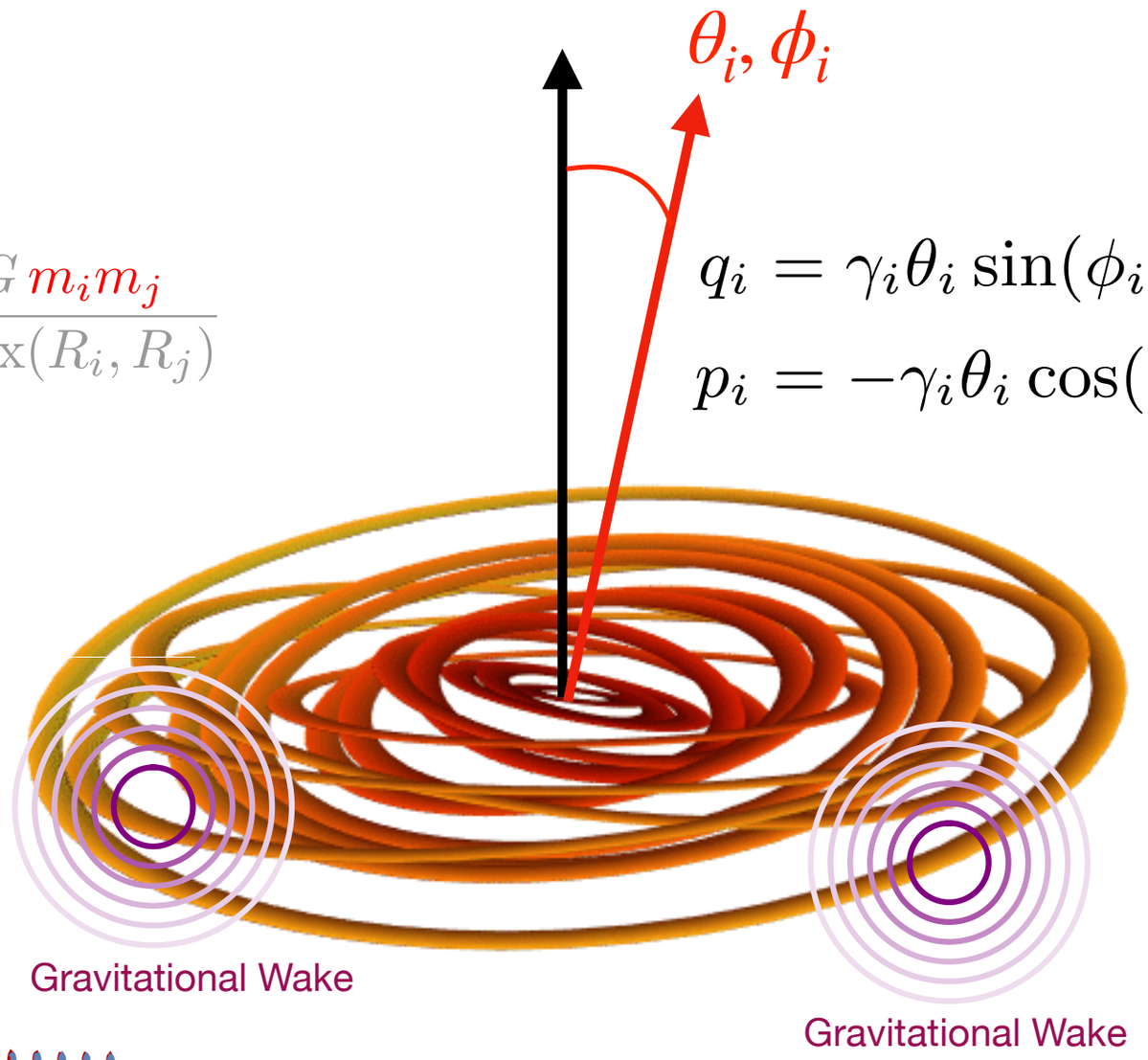
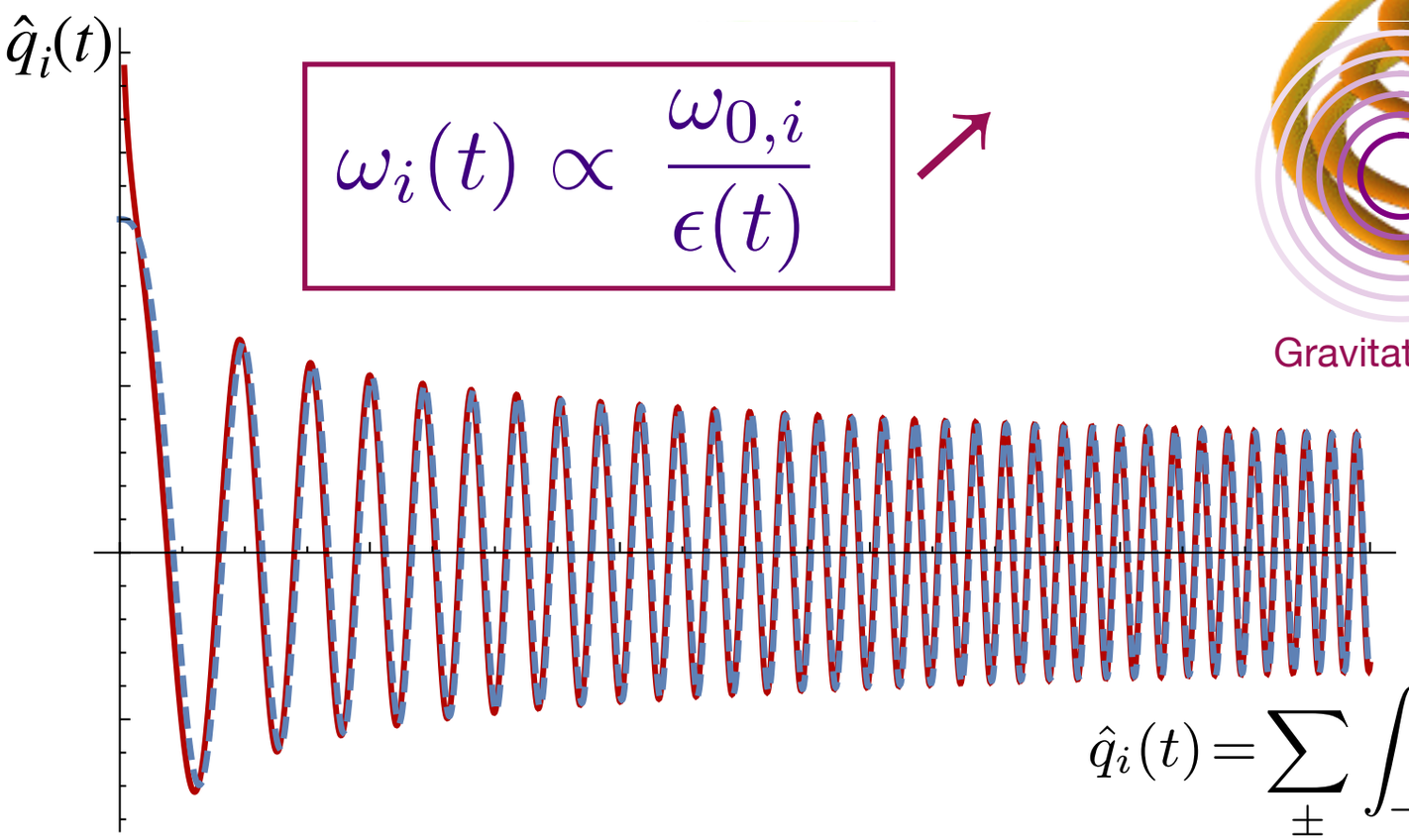


In eigenframe of A

Eigen frequency

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

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



Secular WKB solution

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

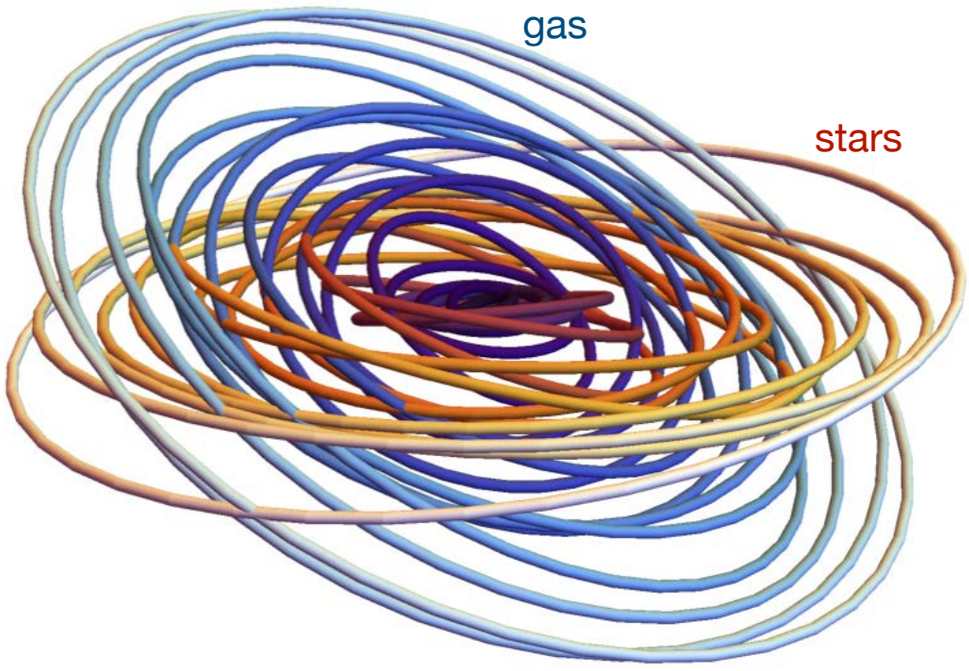
Ring gas + star coupling

gravitational coupling

damping

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

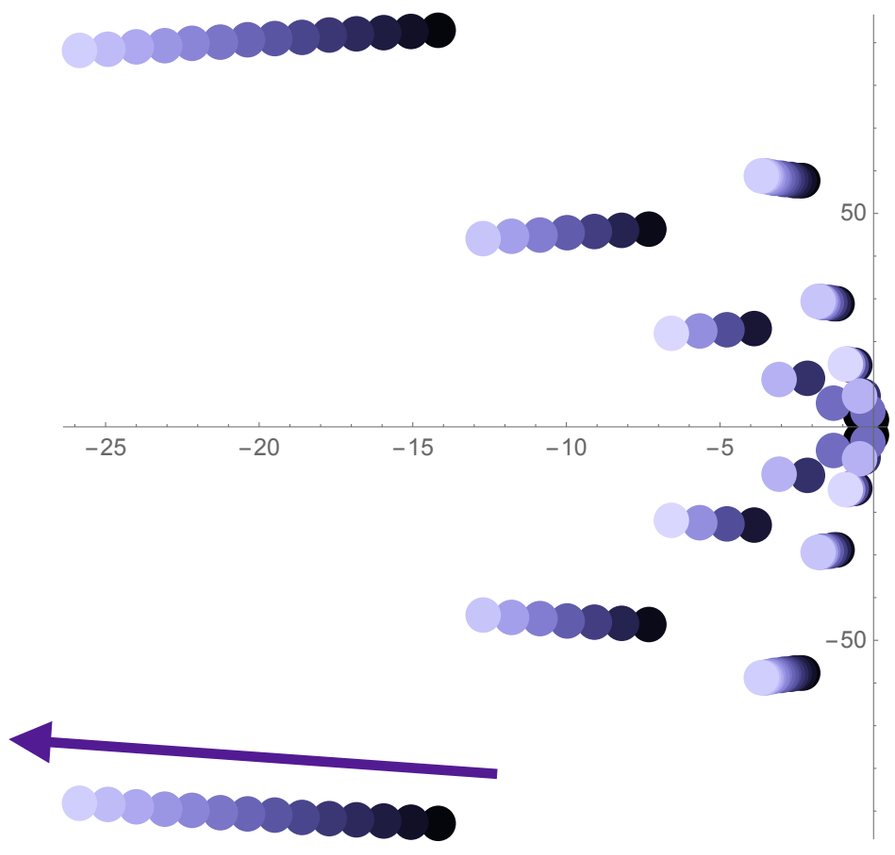
forcing



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

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

Nyquist diagram



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

Ring gas + star coupling

gravitational coupling damping

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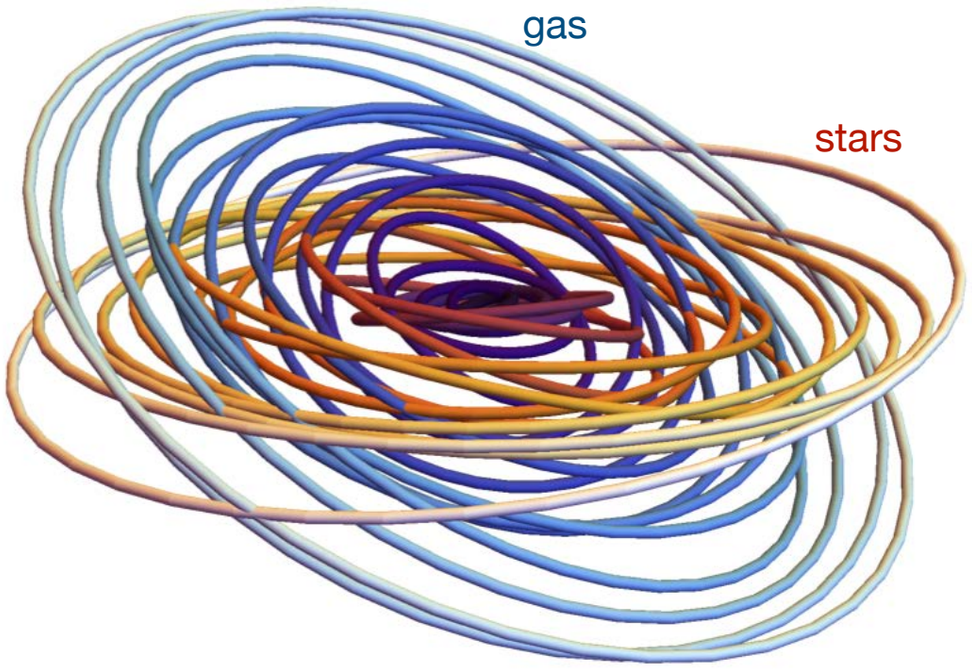
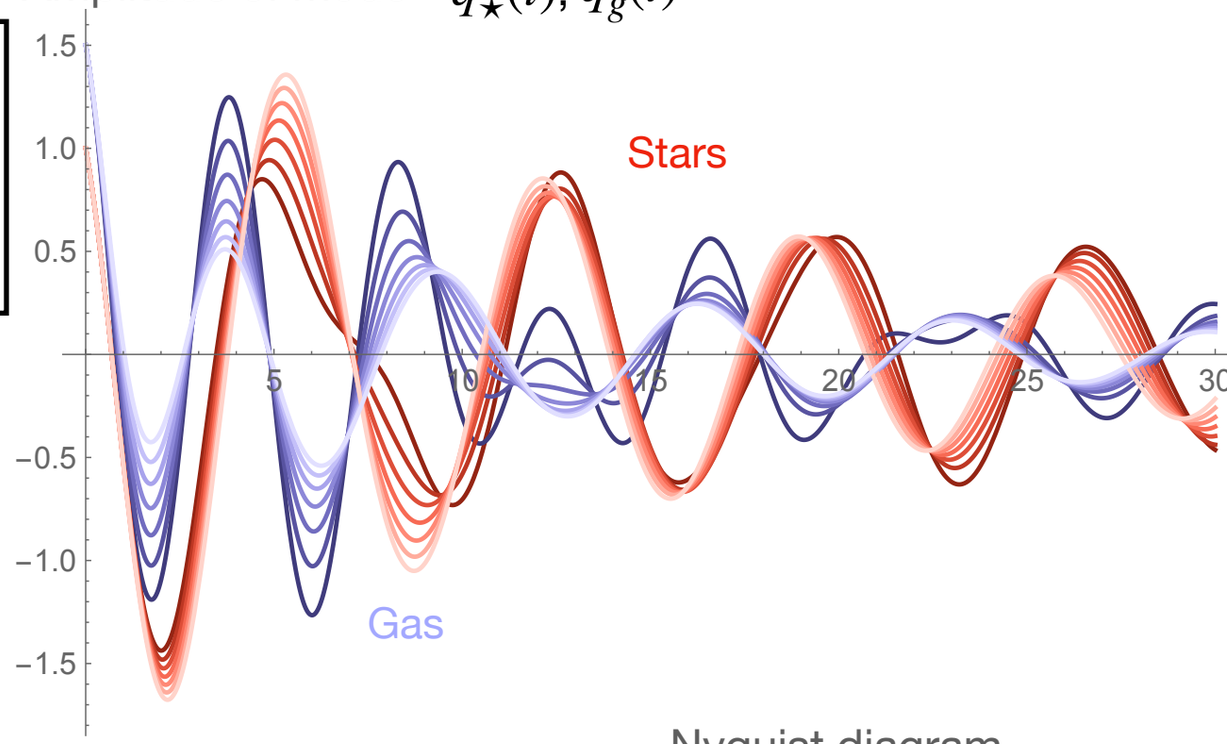


Amplitude of mode $\hat{q}_\star(t), \hat{q}_g(t)$



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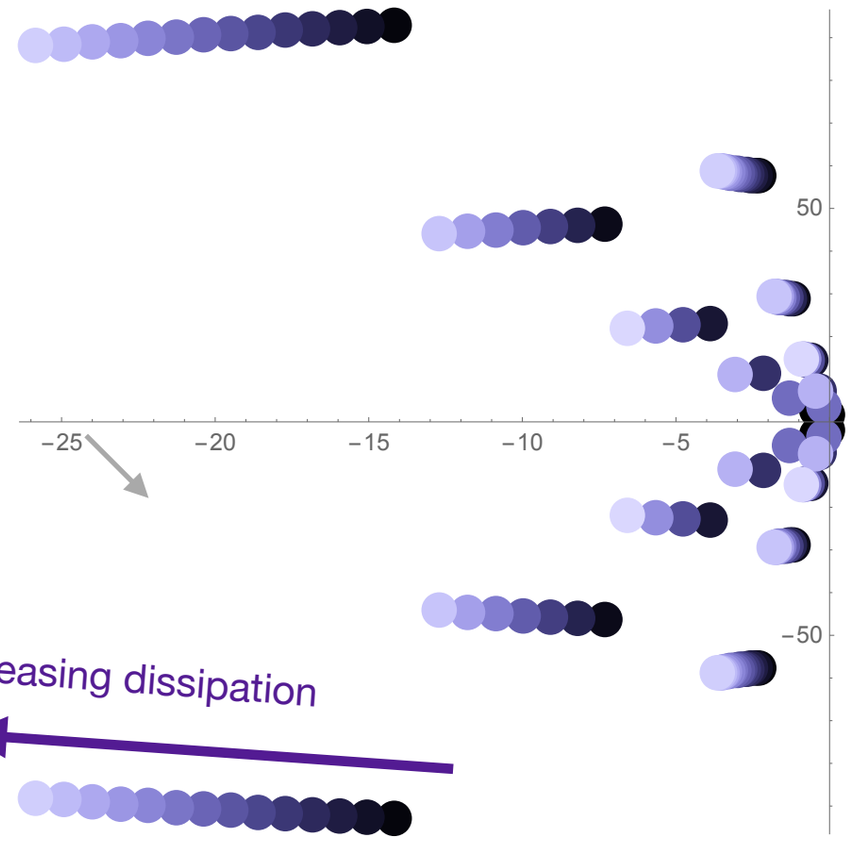

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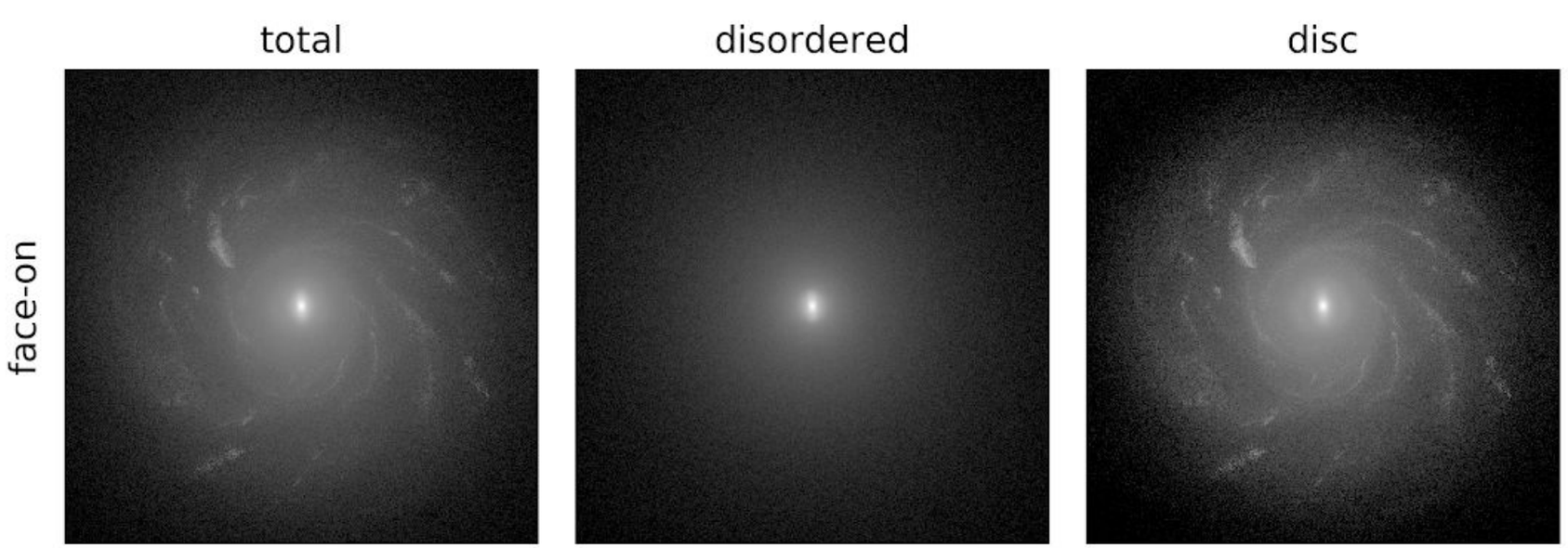
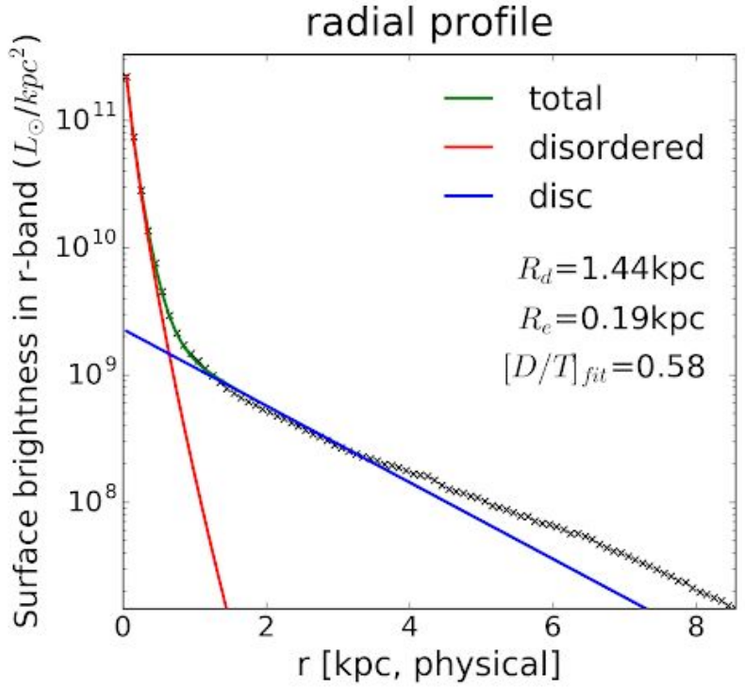
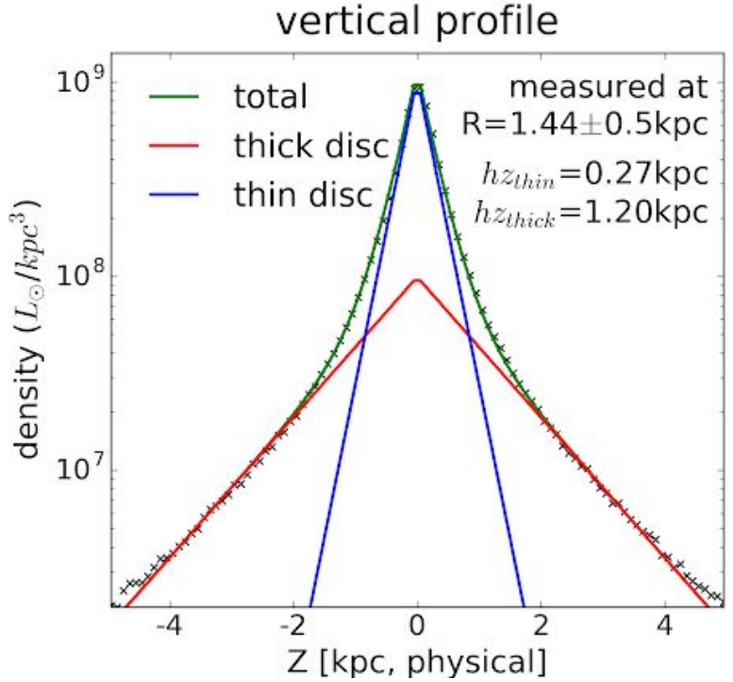
*Dissipation in gas **also** brings down the ★ modes*

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

Result from S.K.Y. ' talk.



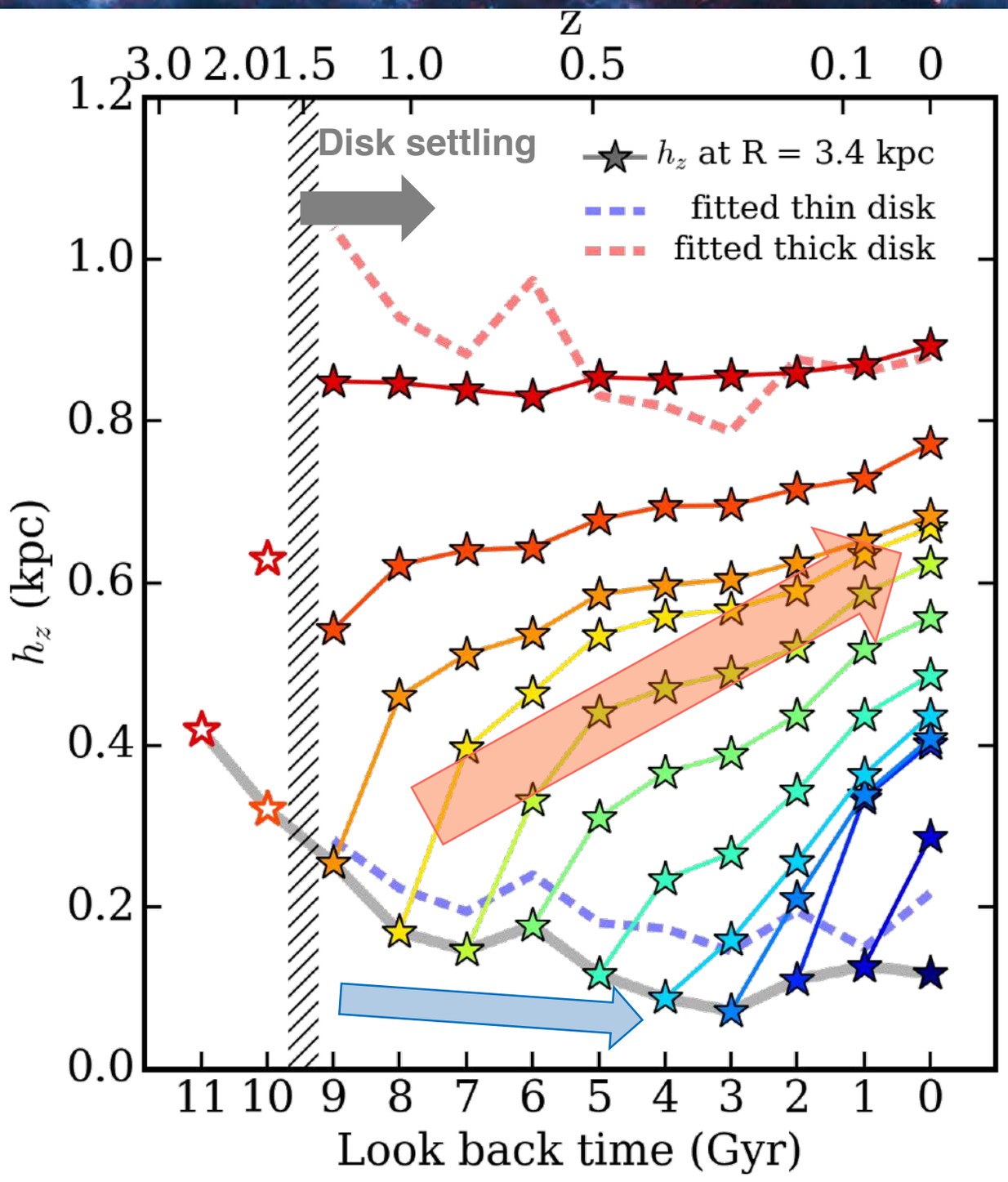




Once in secular mode, the self regulated loop

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 disk settling

Vertical orbital diffusion

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

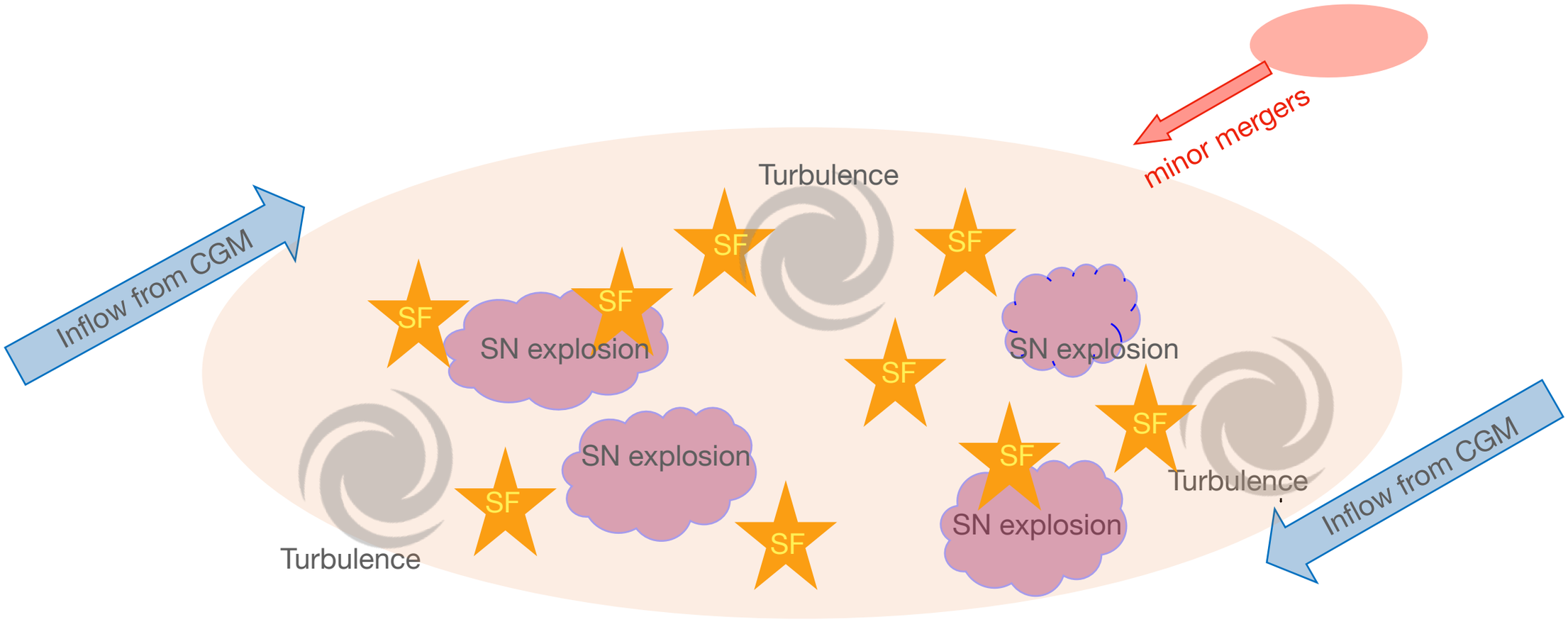
SF efficiency

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

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.

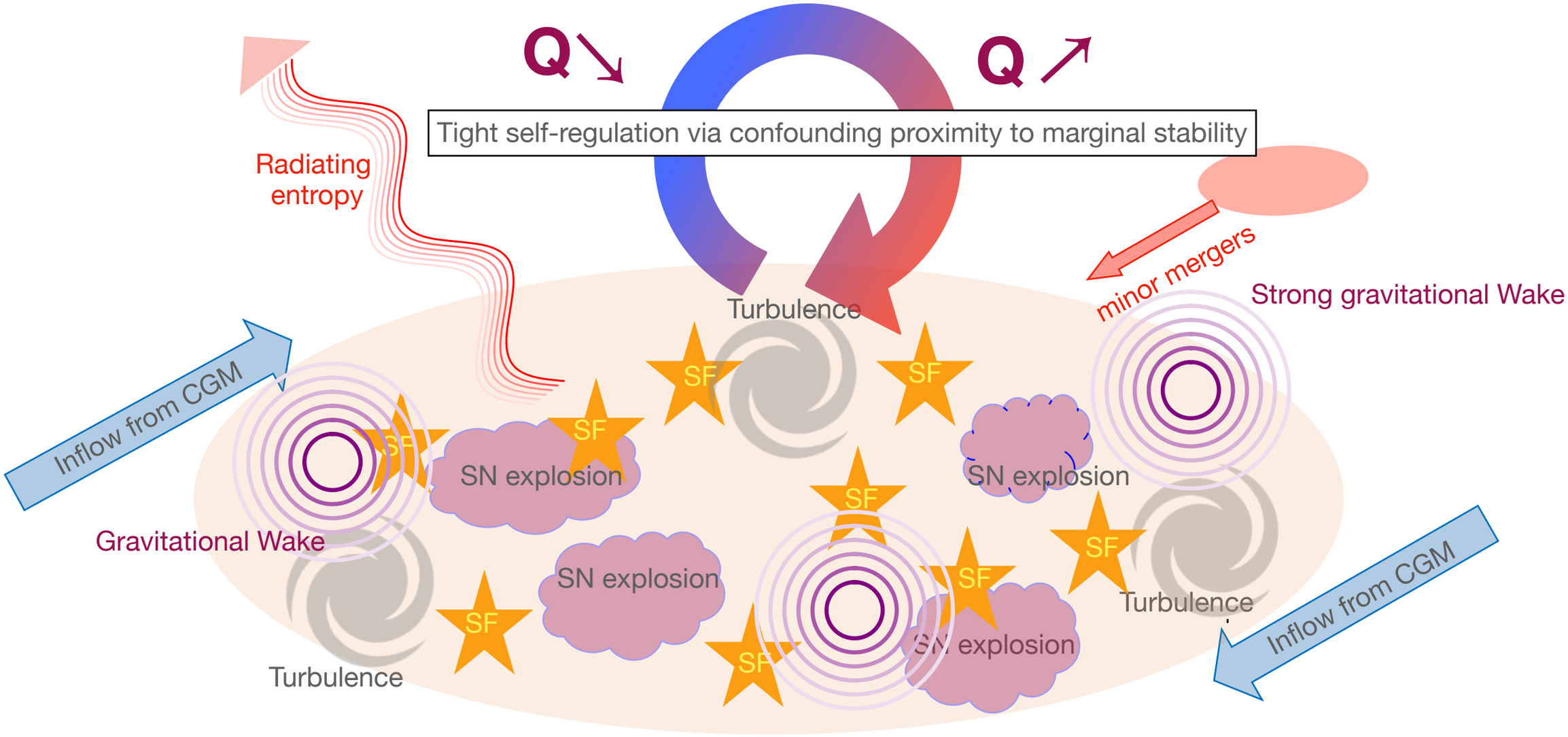
The stellar thick disc is simply the **secular remnant** of the disc settling process.

Conclusion: wakes redefines clocks



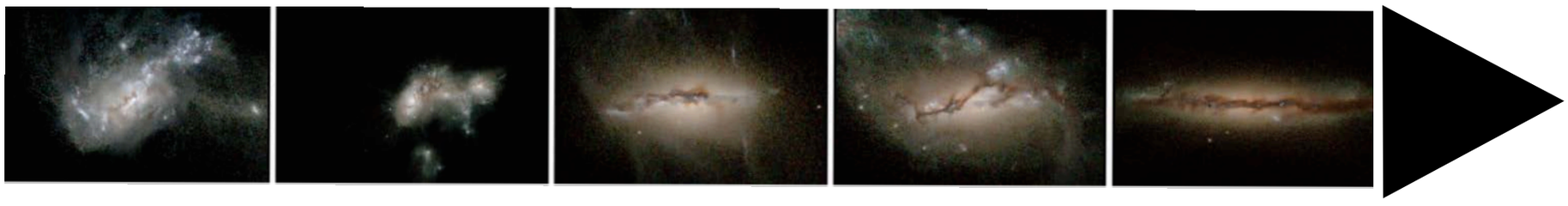
From a complex picture…

Conclusion: wakes redefines clocks



From a complex picture…

… to a clear one! :-)



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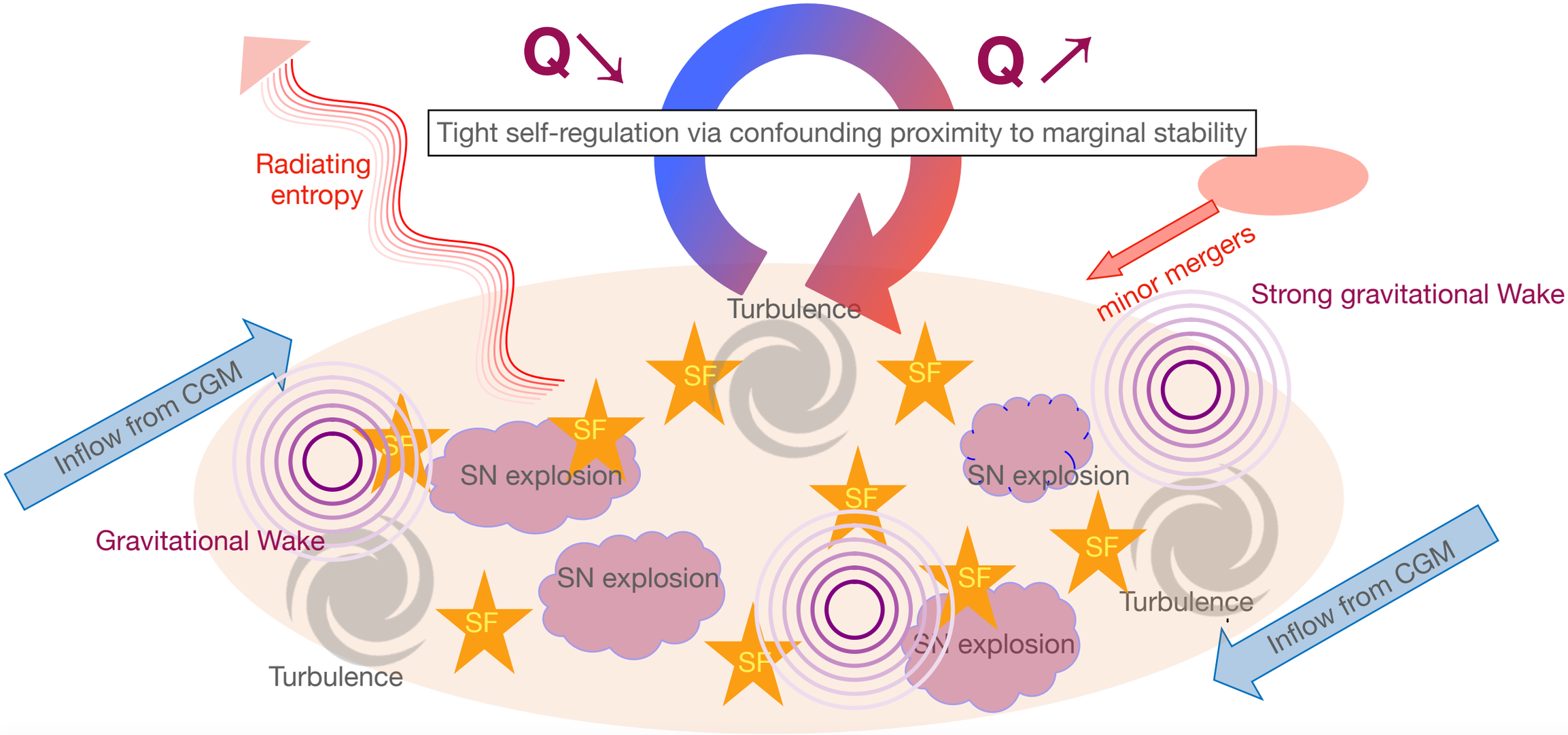

From a complex picture…

… to a clear one! :-)

Thin galactic disks are **emerging** structures of hierarchical clustering when secular processes take over.

Appearance of improbable structure is **paradoxically** made possible by shocks, feedback and turbulence in disc.

Processes **radiates** entropy, and **wakes** tightens a **self-regulating** loop towards **marginal stability**, pumping free (rotational) energy from the CGM. **Wake** also tightens re-alignment.

Link to maximum entropy production??

Proximity to marginal stability acts as **confounding** factor for thickening and star formation, explaining stratification of thin and **thick** disc (Yi's talk).