The cosmic emergence* of thin discs

Order out of Chaos: secular thick and thin disc settling

*emergence = the arising of novel and coherent structures through self-organization in complex systems
Understanding formation of massive thin discs?

Diverse morphologies of galaxies

Key Question:
How does each kinematic component (disk / spheroid) form?

Kinematic morphology of galaxies evolve?

ESO 325-G004

M101

M104

NGC4536

M31

Diverse morphologies of galaxies

Pure disks
Ellipticals

Needle galaxy

How to explain razor thin discs?
in situ
SF
(accretion)

in situ SF

Needle galaxy

high z

low z
The New Horizon simulation

(c) M Park 2020
Figure 1. The r-band face-on and edge-on images of the 18 selected NH galaxies at $z = 0.3$, in descending order of stellar mass of galaxies. The extent of each box for the face-on image is 2 $R_{90}$ of each galaxy, while the height of the box for the edge-on image is $R_{90}$. The $R_{90}$ is the 3D radius containing 90% of the total stellar mass of a galaxy. The white bar represents 5 kpc.

The kinematic bulge-to-total ratio ($B/T$) of each galaxy is presented at the bottom.

3.1. The two-component fits to the vertical profiles

3.1.1. The Galactica galaxy

First, we check the radial and vertical profile of the Galactica galaxy at $z = 0$. The top panels of Figure 2 show the face-on and edge-on r-band images of the Galactica galaxy. The r-band flux of each stellar particle is calculated based on its age and metallicity following the Bruzual & Charlot (2003) stellar population model, without dust extinction. The galaxy's stellar mass and size are about half that of the MW; the stellar mass of this galaxy is $2.75 \times 10^{10} M_\odot$, and the half-mass radius ($R_{50}$) and $R_{90}$, the radius within which 90% of the total stellar mass is contained, are 1.9 kpc and 8.0 kpc, respectively. We measure the radial and vertical profiles of this galaxy in both mass and r-band luminosity. The radial profile is measured from the face-on images and the combination of the Sersic (S´ersic 1963) and exponential disk profiles is applied to the radial profile, which gives the bulge-to-total ratios, $[B/T]$, of 0.38 (mass) and 0.18 (r-band). To measure the vertical distribution, we use

Other examples (out of 1000s)
Disc settling: numerical evidence

$z = 4.0$
$M_*= 3.55 \times 10^9 M_\odot$

$z = 3.0$
$M_*= 1.03 \times 10^{10} M_\odot$

$z = 2.0$
$M_*= 2.71 \times 10^{10} M_\odot$

$z = 1.0$
$M_*= 6.25 \times 10^{10} M_\odot$
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 $Q \rightarrow 1$
- But Why does $Q \rightarrow 1$? Because tighter control loop ($t_{\text{dyn}} \ll 1$) via wake
- But how does it impact settling? Because wake also stiffens coupling

New Horizon

- Convergence towards $Q \sim 1$
  - is dual to settled fraction of discs increasing with mass and cosmic time
  - implies that thick and thin discs grow together
Synopsis of presentation

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

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

- Convergence towards $Q \sim 1$
  — is dual to settled fraction of discs increasing with mass and cosmic time
  — implies that thick and thin discs grow together
Synopsis of presentation

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

• Why do disc settle? Because $Q \to 1$

• But Why does $Q \to 1$? Because tighter control loop ($t_{\text{dyn}} \ll 1$) via wake

• But how does it impact settling? Because wake also stiffens coupling

• Convergence towards $Q \sim 1$
  — is dual to settled fraction of discs increasing with mass and cosmic time
  — implies that thick and thin discs grow together
Chandrasekhar polarisation

\[
\begin{align*}
\left[ \delta \psi \right]_{\text{dressed}} &= \frac{\left[ \delta \psi \right]_{\text{bare}}}{|\varepsilon(\omega)|} \\
T_{\text{dressed}} &\sim |\varepsilon| T_{\text{bare}} \\
\Omega_{\text{dressed}} &\sim \frac{1}{|\varepsilon|} \Omega_{\text{bare}}
\end{align*}
\]

Mass in wake = mass of perturbation $X$ 140 !! ≠ 1.8 for sphere
For cold discs...

Gravitational “Dielectric” function $\epsilon$

$$\epsilon(Q) \equiv D(\omega, k) = \det(1 - M(\omega))$$

Dispersion relation

Response matrix

Susceptibility

$$\lim_{Q \to 1} \epsilon(Q) = 0$$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$

$\lim_{Q \to 1} \epsilon(Q) = 0$
Self regulating loop boosted by wake

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

Destabilising effects
- SN1a
- Turbulence
- Minor Mergers
- Misaligned infall
- FlyBys

Stabilising effects
- Star formation
- Cooling
- Shocks
- Co-rotating Aligned infall

Star formation and feedback define control loop on disc

Free energy reservoir in CGM

Cosmic perturbation

Attraction point of feedback loop

$Q_{\text{eff}}^{-1} = Q_g^{-1} + Q_x^{-1}$
Transition to secularly-driven morphology promoting self-regulation around an effective Toomre $Q \sim 1$.

$T_{\text{dressed}} \sim |\varepsilon| T_{\text{bare}}$

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

Attraction point of feedback loop

$Q_{\text{eff}}^{-1} = Q_g^{-1} + Q_x^{-1}$

Destabilising effects

- SN1a
- Turbulence
- Minor Mergers
- Misaligned infall
- FlyBys

Tighter loop

Gravitational Wake

Stabilising effects

- Star formation
- Cooling
- Shocks
- Co-rotating Aligned infall

Free energy reservoir in CGM

Cosmic perturbation

Open system with control loop generates complexity through self-organisation
Let us revisit the issue of disc settling based on Toomre's criterion. The epoch of cosmic environment settling allows secular res-...
Disc settling: fraction of settled discs

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

\[ f = 0.7 \left( \frac{M_*}{10^{10} M_\odot} \right)^{1/3} / (1+z) \]

The fraction of galaxies with \( v/\sigma > \) than 3 and 1 resp.

\[ f_{\text{settle}} \]

Redshift

High mas

Low mass

Data

Simulation

\( \sigma \)

\( M \)

\( z \)

\( N \)

\( L \)

\( \mu \)

\( I \)

\( H \)

\( G \)

\( D \)

\( 
\)

\( < \)

\( > \)

\( \approx \)

\( \phi \)

\( \chi \)

\( \psi \)

\( \theta \)

\( \epsilon \)

\( \delta \)

Numerical equivalence given $\text{Toomre}(\nu/\sigma)$

Correspondance best expressed while looking at $\text{PDF}(Q, M_\star)$ and $\text{PDF}(V/\sigma, M_\star)$

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

Can this be also explained qualitatively?
Lagrange Laplace theory of rings \textit{(small eccentricity small inclinaison)}

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

$x$ and $y$ components of angular momentum

In eigenframe of $A$

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

Eigen frequency

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

$$p_i = -\gamma_i \theta_i \cos(\phi_i)$$
**Lagrange Laplace theory of rings** *(small eccentricity small inclinaison)*

\[ H(p, q) = \frac{1}{2} p^T \cdot A \cdot p + \frac{1}{2} q^T \cdot A \cdot q, \]

**In eigenframe of A**

\[ \ddot{q}_i + \omega_i^2(t) \dot{q}_i = \xi_i \]

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

**Secular WKB solution**

\[ \hat{q}_i(t) = \sum_{\pm} \int_{-\infty}^{\infty} \frac{\hat{\xi}_i(t')}{\sqrt{\omega_i(t)\omega_i(t')}} \exp \left( \pm i \int_{t'}^{t} \omega_i(\tau) d\tau \right) dt' \]
\[ \ddot{q}_* + \omega_*^2 q_* + \omega_*^2 q_g = 0, \]
\[ \ddot{q}_g + \omega_g^2 \hat{q}_g + \omega_*^2 q_* + \eta \dot{q}_g = \xi, \]

\[
q_*(t) = -\sum_{\omega \in S_4} \frac{\omega_*^2 \int_{-\infty}^{t} \exp((t - \tau)\omega) \xi(\tau) d\tau}{\eta(3\omega^2 + \omega_*^2) + 2\omega(2\omega^2 + \omega_g^2 + \omega_*^2)},
\]

\[
S_4 = \{ \omega \mid (\omega^2 + \omega_*^2)(\omega(\eta + \omega) + \omega_g^2) = \omega_g^4 \},
\]
Dissipation in gas also brings down the ★ modes

\[
\ddot{q}_* + \omega_*^2 q_* + \omega_*^2 \dot{q}_g = 0, \\
\ddot{q}_g + \omega_g^2 \dot{q}_g + \omega_*^2 q_* + \eta \dot{q}_g = \xi,
\]

\[
q_*(t) = - \sum_{\omega \in S_4} \frac{\omega_g^2}{\eta (3\omega^2 + \omega_*^2) + 2\omega (2\omega^2 + \omega_g^2 + \omega_*^2)} \int_{-\infty}^{t} \exp ((t - \tau)\omega) \xi(\tau) \, d\tau,
\]

\[
S_4 = \{ \omega \mid (\omega^2 + \omega_*^2) (\omega (\eta + \omega) + \omega_g^2) = \omega_g^4 \}.
\]
Once in secular mode, the self regulated loop stratifies vertically stars by age, while preserving the total double sech^2 profile.
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.

Both star formation and vertical orbital diffusion are regulated by same (Q → 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

Tight self-regulation via confounding proximity to marginal stability

Radiating entropy

Inflow from CGM

Gravitational Wake

Turbulence

SN explosion

SF

Strong gravitational Wake

minor mergers

… to a clear one! :-)

From a complex picture…
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).