Data Science Course
Understanding swarm behaviour

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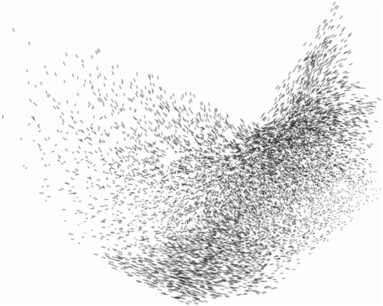
August 4, 2017



Presentation Overview

- Introductory models: simple speed coupling, couzin model, vicsek model
- Module 1: Effective leadership and decision-making in animal groups on the move (Couzin et al)
- Module 2: Self-Propelled Particles with Soft-Core Interactions: Patterns, Stability, and Collapse (D'Orsogna et al)

Introductory models (Speed coupling & Vicsek)

Simple speed coupling: weighted speed
Particle adapts a fraction of its nearest neighbour's speed

Vicsek model: alignment of directions

- introduce interaction zones: repulsion ($r < R_{rep}$) and orientation ($R_{rep} < r < R_{orient}$)
- add noise term

Couzin model

- different zones of neighbourhoods: repulsion, orientation, attraction

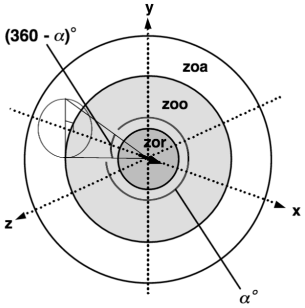


Figure: Zone scheme: *zor* = zone of repulsion, *zoo* = zone of orientation, *zoa* = zone of attraction. α = field of perception

Module 1: Effective leadership and decision-making in animal groups on the move (Couzin et al): `czn2`

- introduce a bias: orientation of ≥ 1 particle ("scout")
- merge orientation and attraction zone

THEORY

New parameters: bias direction $\vec{g}$, weight of bias ω, proportion of bias *prop*
Goal: Which parameter sets give a nice group movement, and how does the behaviour change when we change the parameters?
Direction update in each zone:

$$\mathbf{d}_i(t+\Delta t) = -\sum_{j \neq i} \frac{\mathbf{c}_j(t) - \mathbf{c}_i(t)}{|(\mathbf{c}_j(t) - \mathbf{c}_i(t))|} \qquad \mathbf{d}_i(t+\Delta t) = \sum_{j \neq i} \frac{\mathbf{c}_j(t) - \mathbf{c}_i(t)}{|(\mathbf{c}_j(t) - \mathbf{c}_i(t))|} + \sum_{j=1} \frac{\mathbf{v}_j(t)}{|\mathbf{v}_j(t)|}$$

$$\mathbf{d}_i{}'(t+\Delta t) = \frac{\hat{\mathbf{d}}_i(t+\Delta t) + \omega \mathbf{g}_i}{|\hat{\mathbf{d}}_i(t+\Delta t) + \omega \mathbf{g}_i|}$$

with position vector $c_i(t)$, direction vector $v_i(t)$

Module 1: Effective leadership and decision-making in animal groups on the move (Couzin et al): `czn2`

IMPLEMENTATION

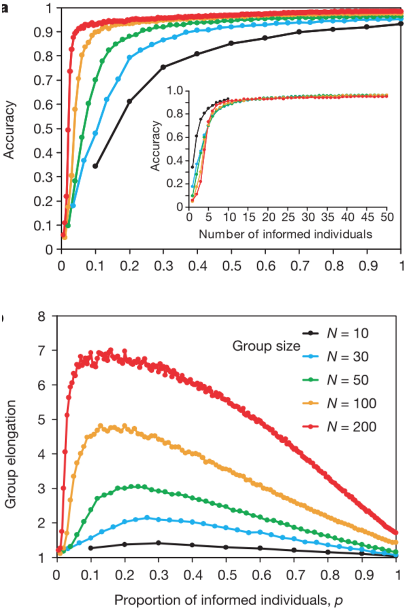
- periodic boundary conditions
- virtual interaction of agents
- explicit Euler method: $v_{n+1} = v_n + \tau \cdot \frac{dv_n}{dt}$
- $\frac{dv_n}{dt} = s \cdot d_i$ (with s constant)

Effective leadership and decision-making

QUANTIFICATION

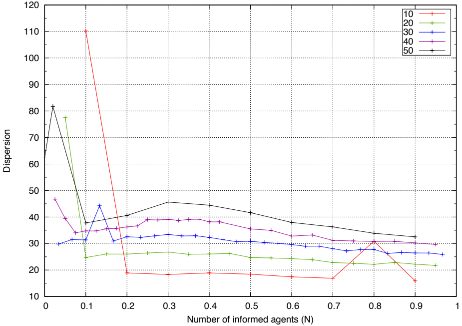
- Agents dispersion - Did a proper swarm form?
- Accuracy - Do the leaders influence the group?
- Elongation - Does the movement deform the group?

What to expect



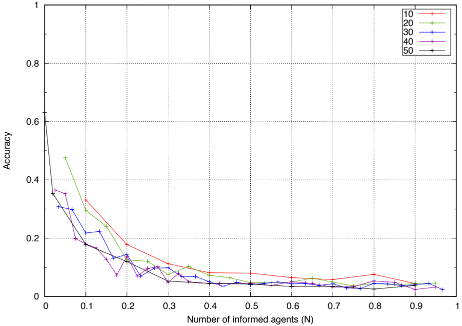
Effective leadership and decision-making

Dispersion



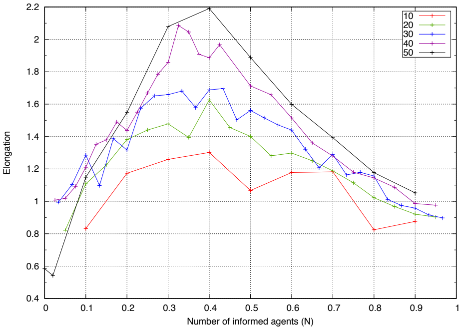
Effective leadership and decision-making

Accuracy



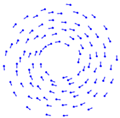
Effective leadership and decision-making

Elongation



Module 2: Self-Propelled Particles with Soft-Core Interactions: Patterns, Stability, and Collapse (D'Orsogna et al)

Motivation: Simulate multiagent interaction under a model which shows **milling** behaviour
(observed in *M. xanthus* cells)



The model consists of:

- self-propulsion (α)
- friction (β)
- interaction between particles: repulsion and attraction ($\vec{\nabla} U$)

Module 2: Self-Propelled Particles with Soft-Core Interactions: Patterns, Stability, and Collapse (D'Orsogna et al)

Consider N interacting, self-propelled particles governed by the following equations of motion

$$F = m\frac{d\vec{v}_i}{dt} = (\alpha - \beta|\vec{v}_i|^2)\vec{v}_i - \vec{\nabla}_i U(\vec{x}_i) \tag{1}$$

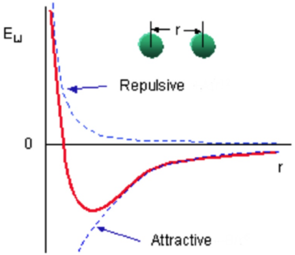
where U is a pairwise interaction potential and $\alpha, \beta > 0$ are values for propulsion and friction forces.

Module 2: Self-Propelled Particles with Soft-Core Interactions: Patterns, Stability, and Collapse (D'Orsogna et al)

For U we choose the *Morse potential*

$$U(\vec{x}_i) = \sum_{j \neq i} [\underbrace{-C_a e^{-|\vec{x}_i - \vec{x}_j|/l_a}}_{\text{attraction}} + \underbrace{C_r e^{-|\vec{x}_i - \vec{x}_j|/l_r}}_{\text{repulsion}}] \tag{2}$$

where C_a, C_r denote attractive and repulsive strengths and l_a, l_r their respective length scales.



Module 2: Self-Propelled Particles with Soft-Core Interactions: Patterns, Stability, and Collapse (D'Orsogna et al)

IMPLEMENTATION

- rigid boundary conditions (no virtual interactions)
- initial conditions of random distribution
- explicit Euler method: $\vec{v}_{n+1} = \vec{v}_n + \frac{d\vec{v}_n}{dt} \cdot \tau$
- $\frac{d\vec{v}_n}{dt} = \frac{1}{m}(propulsion - friction - \vec{\nabla} U)$

Module 2: Self-Propelled Particles with Soft-Core Interactions: Patterns, Stability, and Collapse (D'Orsogna et al)

SIMULATION

Milling Ring formed out of proper choice of parameters

Module 2: Self-Propelled Particles with Soft-Core Interactions: Patterns, Stability, and Collapse (D'Orsogna et al)

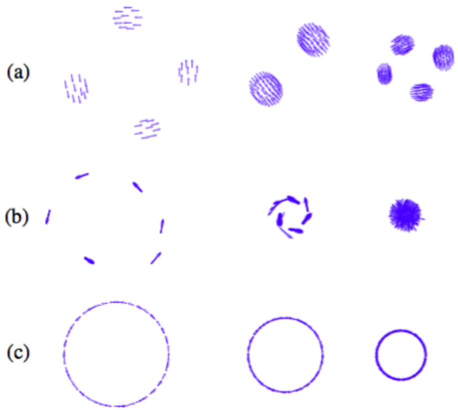


Figure: Catastrophic geometry.
(a) Clumps. (b) Ring Clumping. (c) Rings.

Module 2: Self-Propelled Particles with Soft-Core Interactions: Patterns, Stability, and Collapse (D'Orsogna et al)

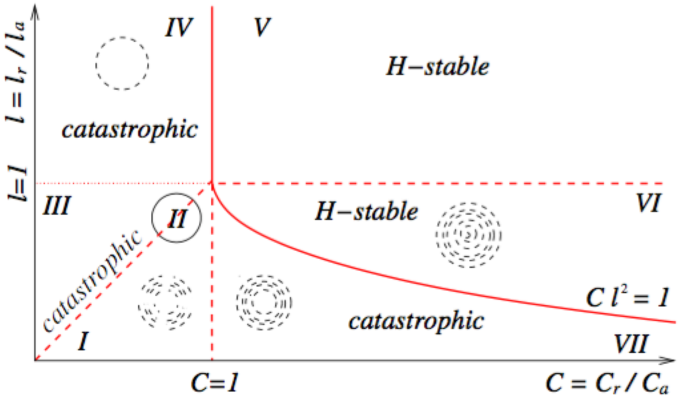


Figure: H-stability phase diagram of the Morse potential

Module 2: Self-Propelled Particles with Soft-Core Interactions: Patterns, Stability, and Collapse (D'Orsogna et al)

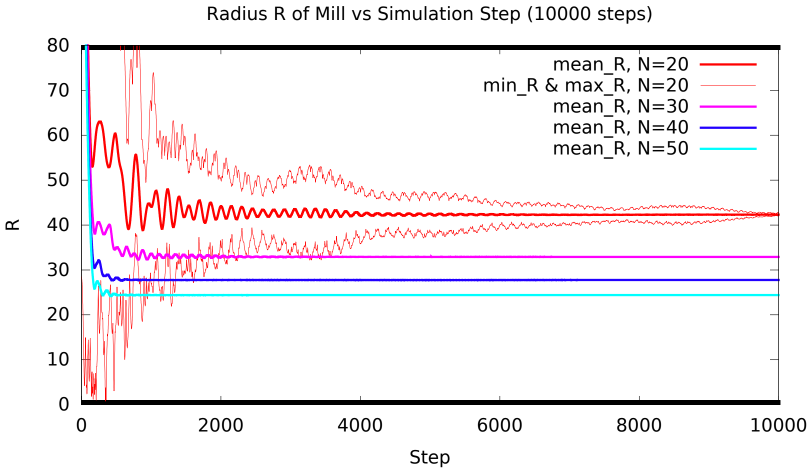
SIMULATION:
Region I, Region IV, Region VI, Region VII

Module 2: Self-Propelled Particles with Soft-Core Interactions: Patterns, Stability, and Collapse (D'Orsogna et al)

QUANTIFICATION (Goals of Observation)

- Parameter Sets for different Stability Regions
- Confirming Ring formation:
  - $R_{max}, R_{mean}, R_{min}$ converge to same value
  - $v_{radial} \to 0$ and $v_{tangential} \to |v_i|$ for $t \to \infty$

Quantification `mill` (Region II: Convergence to Ring)



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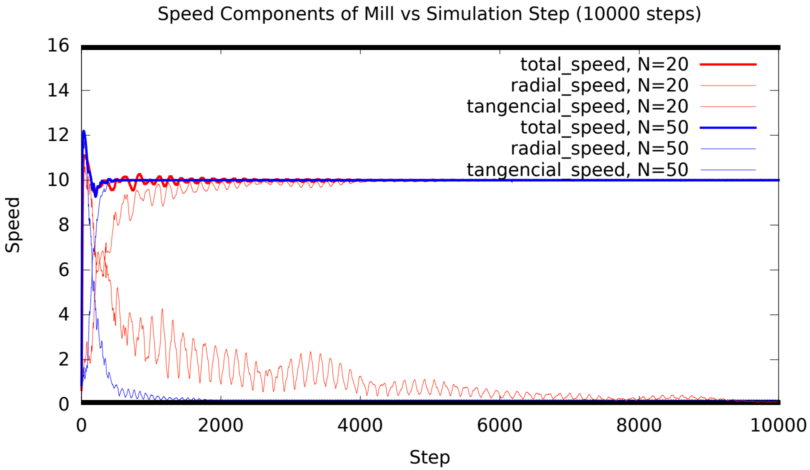
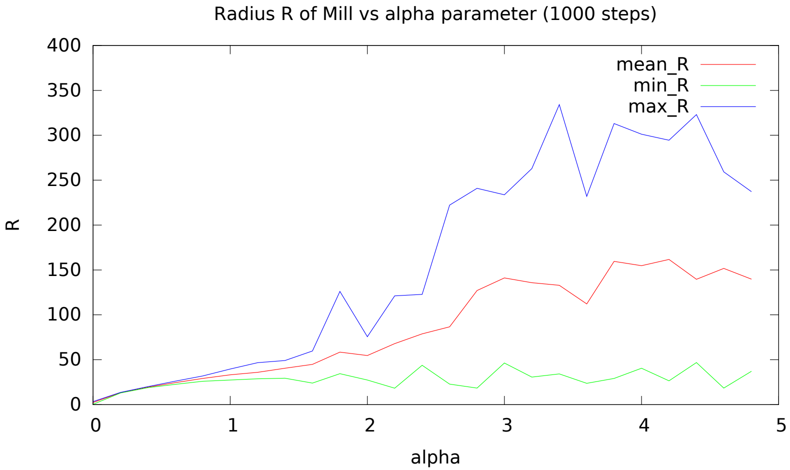


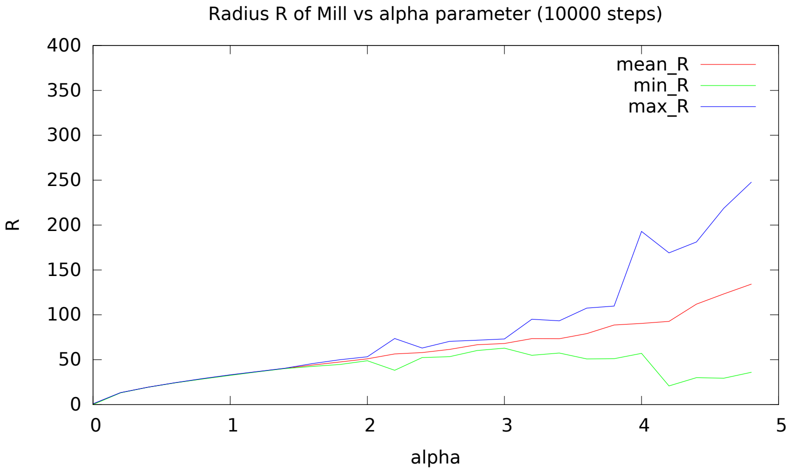
Quantification `mill` (Goals of Observation)

- Parameter Sets for different Stability Regions
- Confirming Ring formation:
  - $R_{max}, R_{mean}, R_{min}$ converge to same value
  - $v_{radial} \to 0$ and $v_{tangential} \to |v_i|$ for $t \to \infty$
- $R \propto \frac{\alpha m}{\beta}$ (from $F_{centrifugal} = F_{centripetal}$)

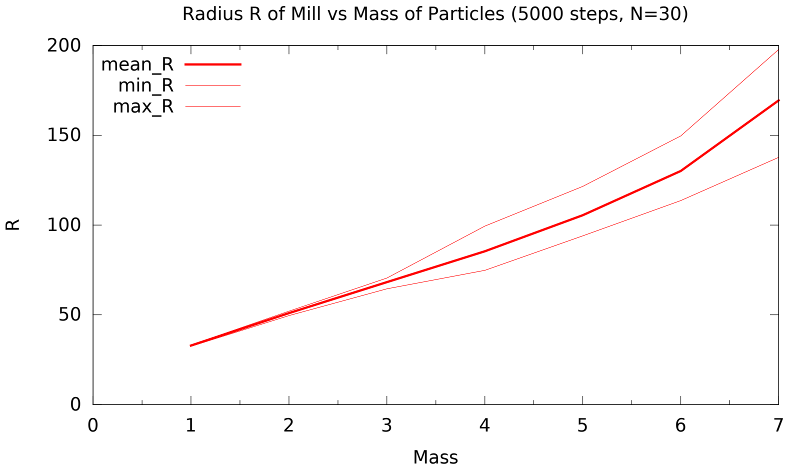
Quantification `mill` (Region II: Effect on Radius of Ring)



Quantification `mill` (Region II: Effect on Radius of Ring)



Quantification `mill` (Region II: Effect on Radius of Ring)



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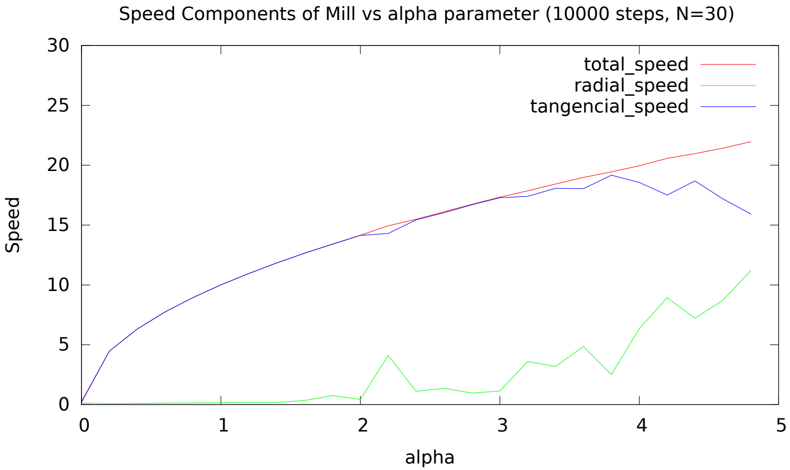
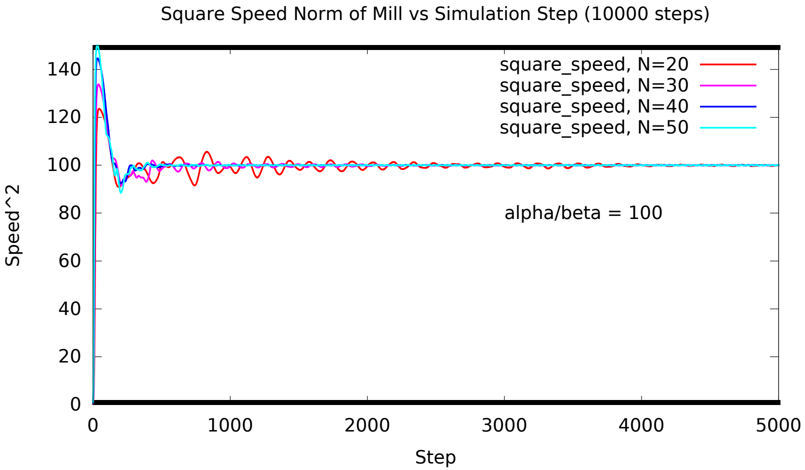


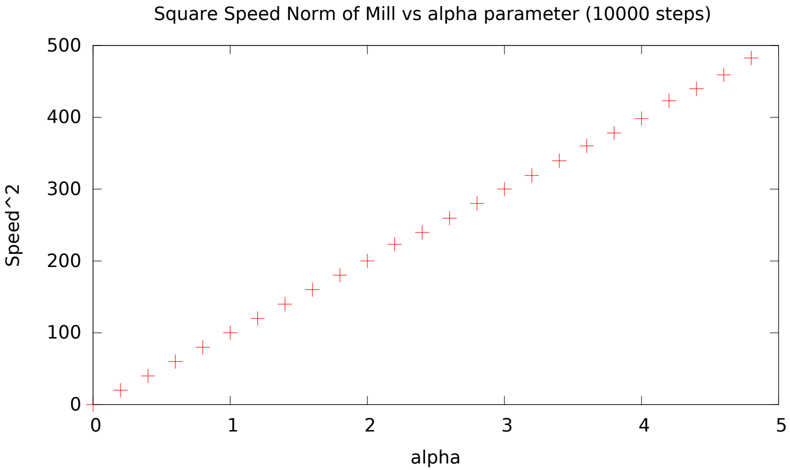
Quantification `mill` (Goals of Observation)

- Parameter Sets for different Stability Regions
- Confirming Ring formation:
  - $R_{max}, R_{mean}, R_{min}$ converge to same value
  - $v_{radial} \rightarrow 0$ and $v_{tangential} \rightarrow |v_i|$ for $t \rightarrow \infty$
- $R \propto \frac{\alpha m}{\beta}$ (from $F_{centrifugal} = F_{centripetal}$)
- $|\vec{v}|^2 \xrightarrow{t \rightarrow \infty} \alpha/\beta$ (at steady state $(\alpha - |\vec{v}|^2\beta)\vec{v} = 0$)

Quantification `mill` (Region II: Influence of α)



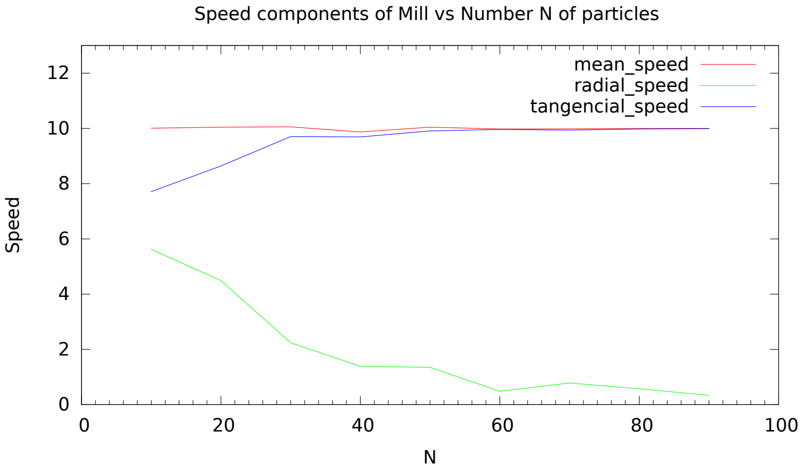
Quantification `mill` (Region II: Influence of α)



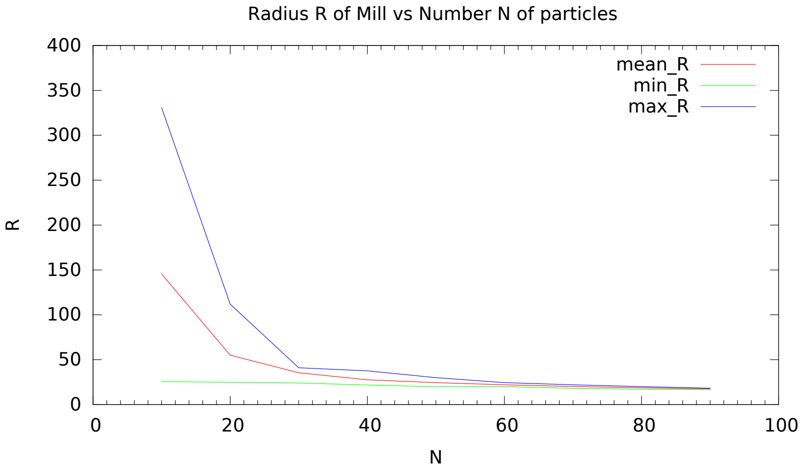
Quantification `mill` (Goals of Observation)

- Parameter Sets for different Stability Regions
- Confirming Ring formation:
  - $R_{max}, R_{mean}, R_{min}$ converge to same value
  - $v_{radial} \to 0$ and $v_{tangential} \to |v_i|$ for $t \to \infty$
- $R \propto \frac{\alpha m}{\beta}$ (from $F_{centrifugal} = F_{centripetal}$)
- $|\vec{v}|^2 \xrightarrow{t \to \infty} \alpha/\beta$ (at steady state $(\alpha - |\vec{v}|^2 \beta)\vec{v} = 0$)
- influence of increasing N

Quantification `mill` (Region II: influence of N)



Quantification `mill` (Region II: influence of N)



Quantification `mill` (Region VII: Torus Ring)