Bottleneck flow of macroscopic active matter

(pedestrians, grains, sheep, robots, hexbugs…)

Iker Zuriguel

iker@unav.es

Collective Motions of Animals and Robots
Cargèse. 2024, May 27 – 31.

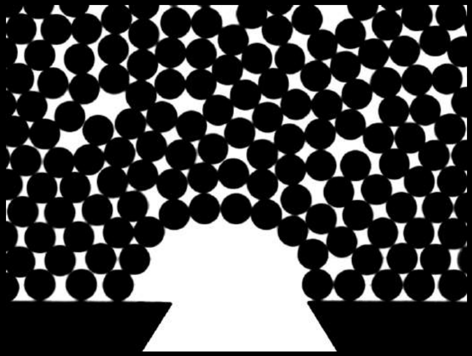
Granular Lab

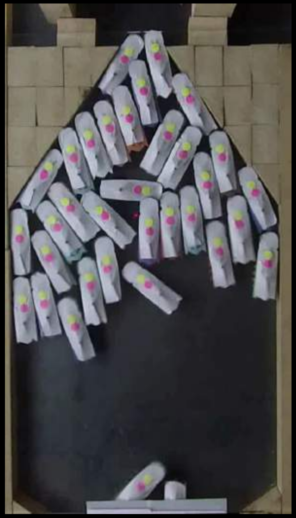
Department of Physics and Applied Mathematics

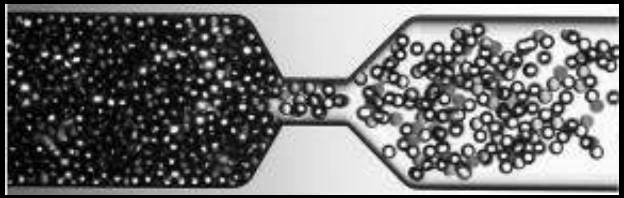
Universidad de Navarra

Outline.

- Why going from grains to sheep… and beyond?







Outline.

- Why going from grains to sheep… and beyond?
- Sheep
- Grains
- Other (colloids & electronic bugs)
- Humans (pedestrians)
- Robots

- Other experiments with robots and humans

The beginning.

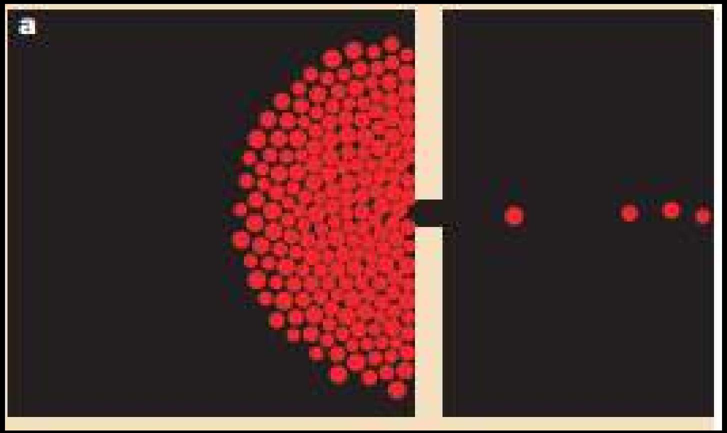
letters to nature

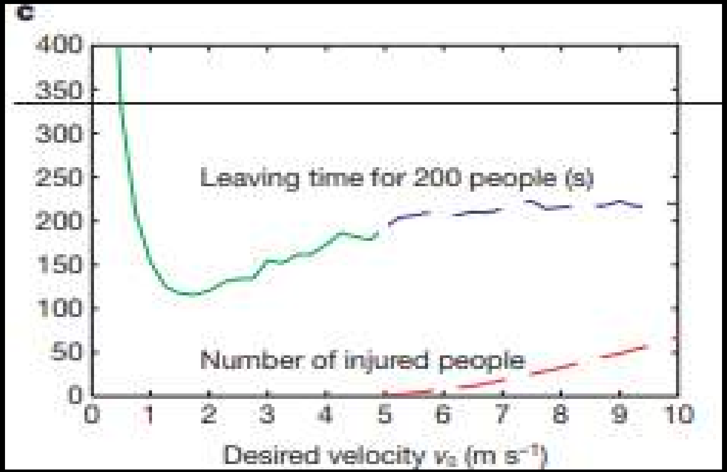
Simulating dynamical features of escape panic

Dirk Helbing*†, Illés Farkas‡ & Tamás Vicsek*‡

At exits, arching and clogging are observed. Jams build up. The physical interactions in the jammed crowd add up and cause dangerous pressures.

Improved outflows can be reached by columns placed asymmetrically in front of the exits, which also prevent the build up of fatal pressures.





Faster Is Slower!

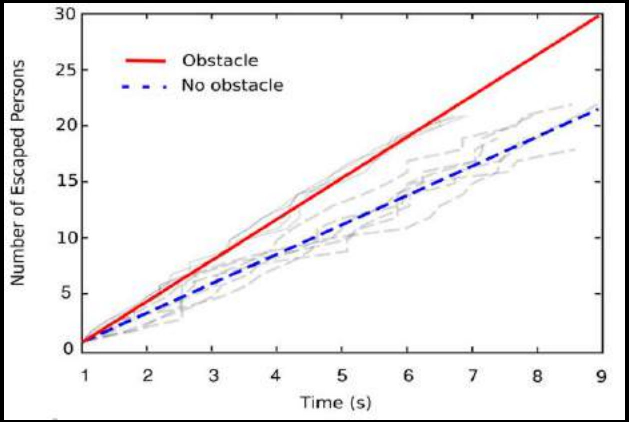
D. Helbing, I. Farkas, & T. Vicsek, *Nature* **407** (2000)

D. Helbing, L. Buzna, A. Johansson, T. Werner, *Transportation Science* **39** (2005)

The obstacle.

6 tests without obstacle
4 tests with an obstacle
30 people

The participants were asked to rush toward the door and behave in a pushy way. Without an obstacle, the experiment showed clogging effects and a tendency of people to fall (left). In another setup, a board served as an obstacle (right). Despite of the strong forces in the crowd (the board was shaking), the clogging effect could be significantly reduced.



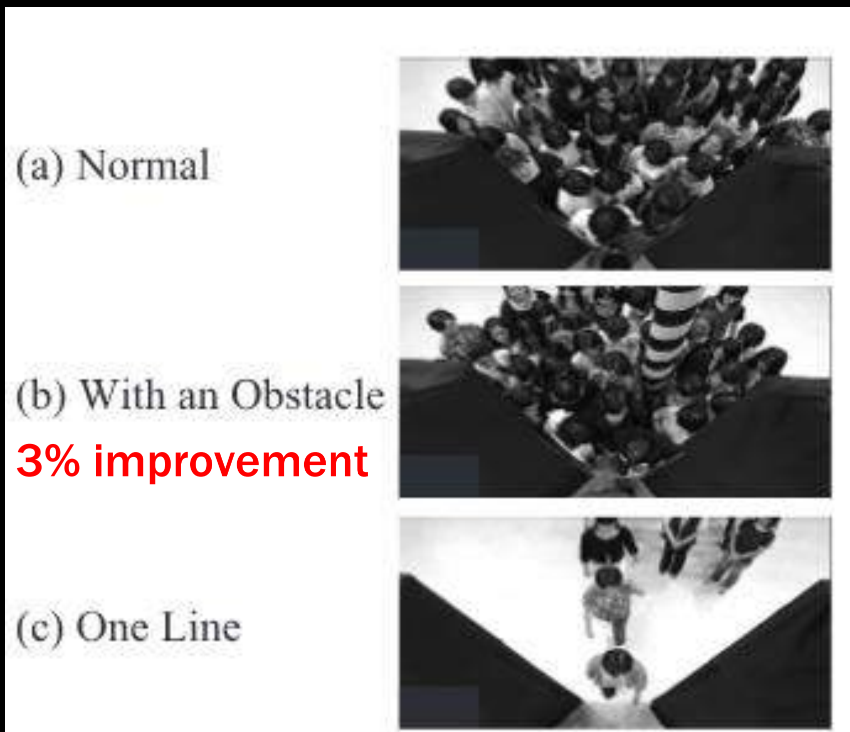
D. Helbing, I. Farkas, & T. Vicsek, *Nature* **407** (2000)
D. Helbing, L. Buzna, A. Johansson, T. Werner, Transportation Science 39 (2005)

The obstacle became controversial.

- Physical Vs psychological effect.

The obstacle became controversial.

- Physical Vs psychological effect.



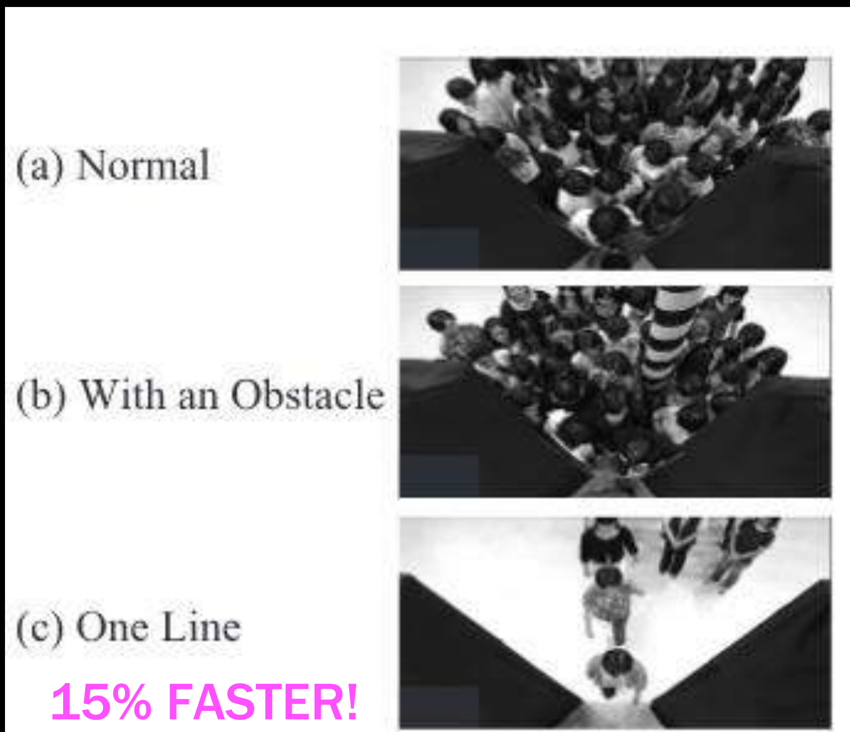
No experiments with competition!

$$\langle q_{\mathrm{exp}} \rangle = \begin{cases} 2.80 \text{ [persons / (m} \cdot \text{sec)]} & \text{(case (a))}, \\ 2.92 \text{ [persons / (m} \cdot \text{sec)]} & \text{(case (b))}, \\ 3.23 \text{ [persons / (m} \cdot \text{sec)]} & \text{(case (c))}. \end{cases}$$

D. Yanagisawa et al. *SICE Journal of Control, Measurement, and System Integration*, *3*(6), 395 (2010).

The obstacle became controversial.

- Physical Vs psychological effect.



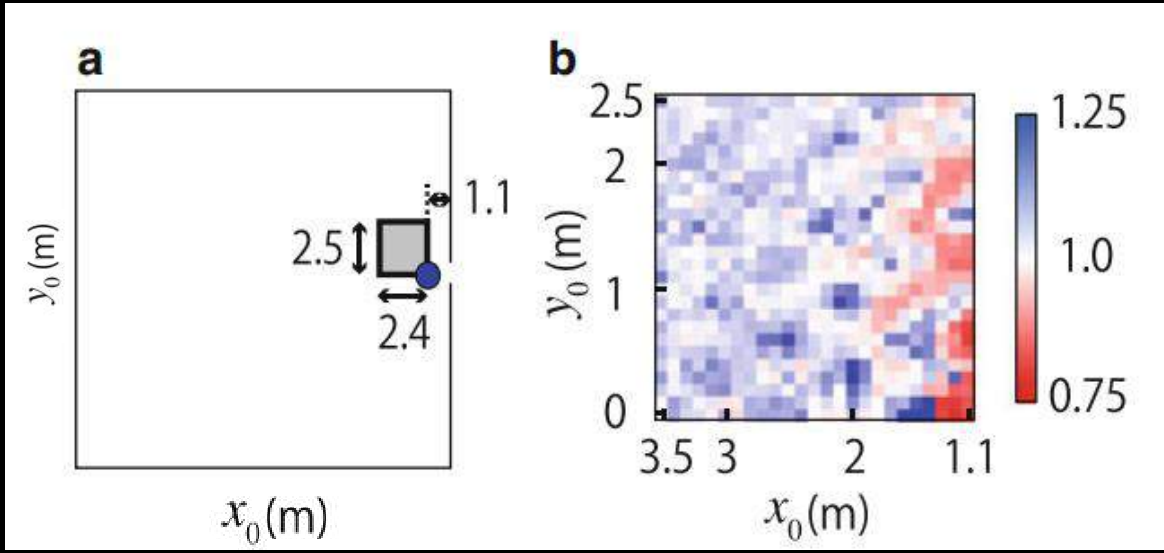
No experiments with competition!

$$\langle q_{\text{exp}} \rangle = \begin{cases} 2.80 \text{ [persons / (m} \cdot \text{sec)]} & \text{(case (a))}, \\ 2.92 \text{ [persons / (m} \cdot \text{sec)]} & \text{(case (b))}, \\ 3.23 \text{ [persons / (m} \cdot \text{sec)]} & \text{(case (c))}. \end{cases}$$

D. Yanagisawa et al. *SICE Journal of Control, Measurement, and System Integration*, *3*(6), 395 (2010).

The obstacle became controversial. (but there was consensus on its beneficial role)

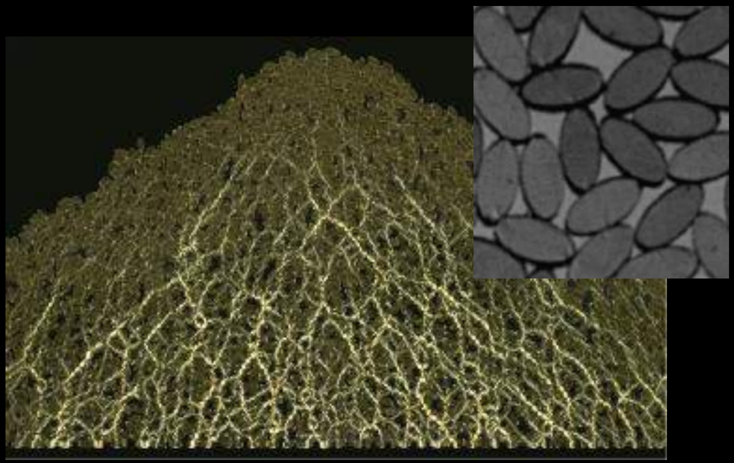
- Physical Vs psychological effect.
- If the position is carefully chosen, always benefitial.

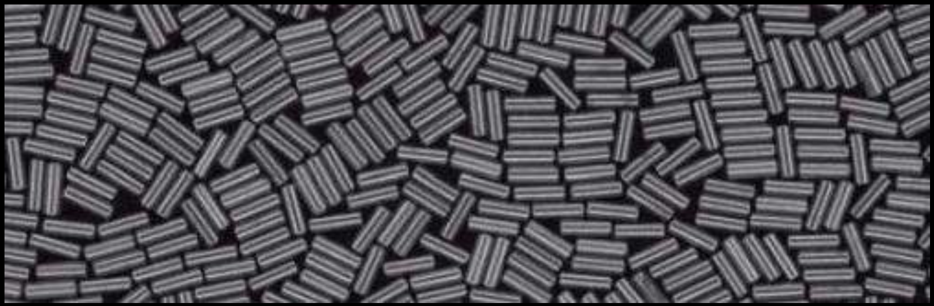


Many numerical works

T. Matsuoka et al. In:
Traffic and Granular Flow '13.
Springer (2015)

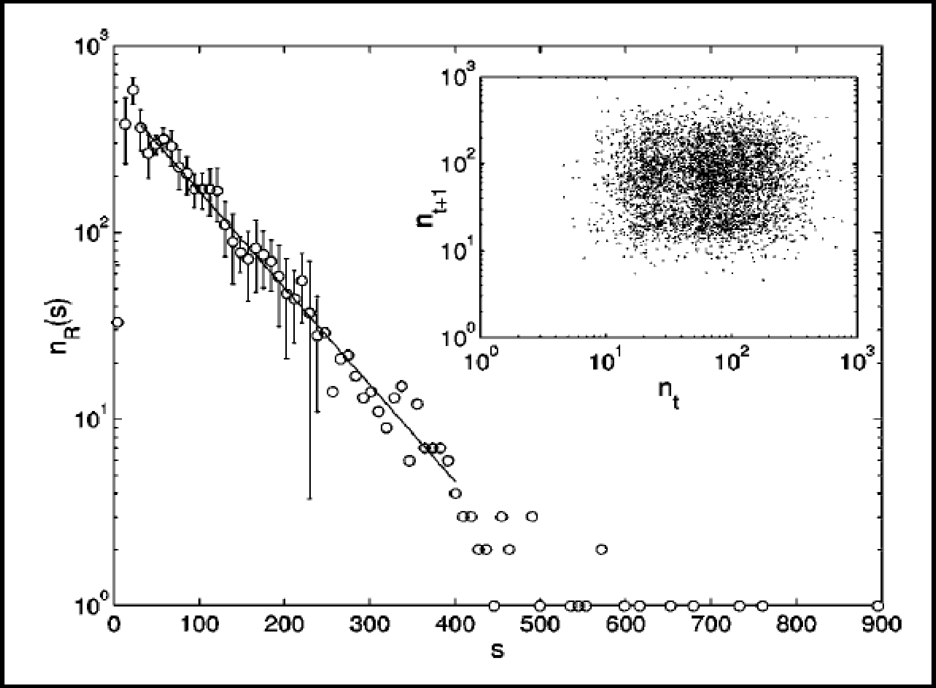
2005-2010 At that time…

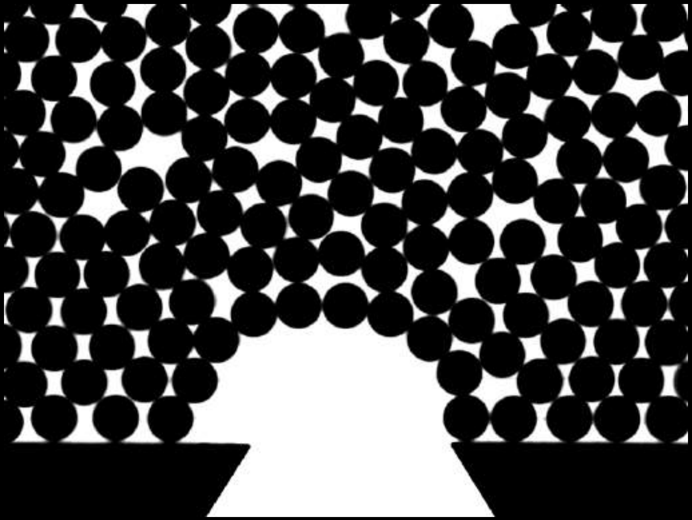




…I was investigating particle shape effects trying to distance myself from my thesis topic… but I decided to do an experiment in a "lab corner".

Clogging in silos (my thesis research topic)





s : avalanche size (number of beads)

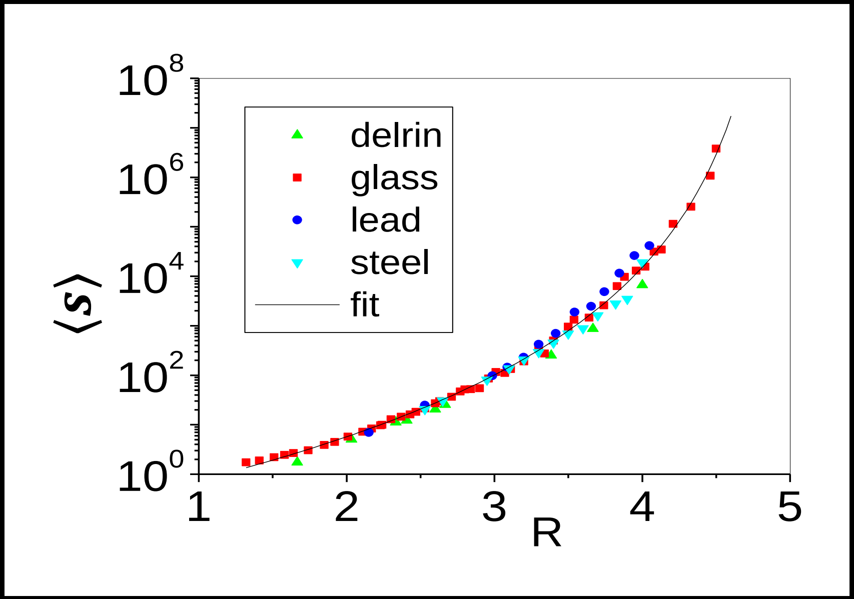
$$n_R(s) = p^s\ (1-p)$$

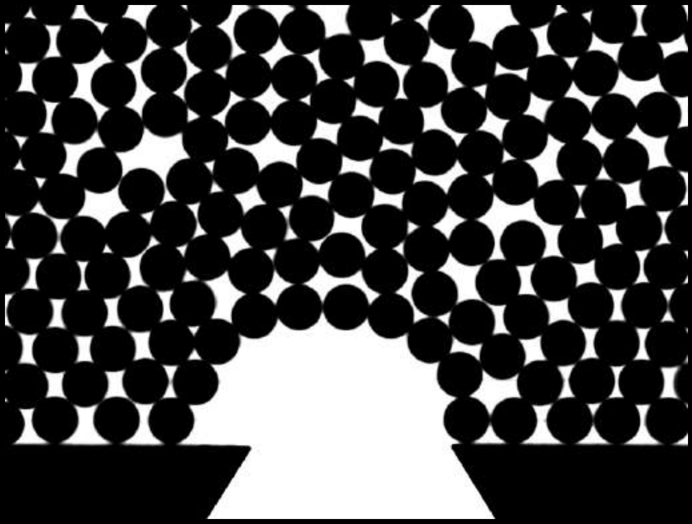
No memory

Constant clogging probability (p) over the whole avalanche process

I. Zuriguel et al PRE 2003 & PRE 2005

Clogging in silos (my thesis research topic)





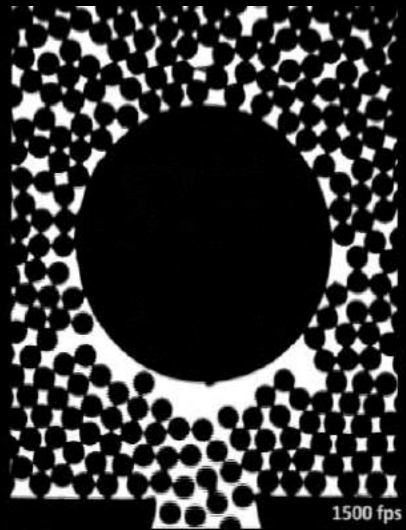
Does the mean avalanche size ⟨s⟩ diverges for a critical outlet size?

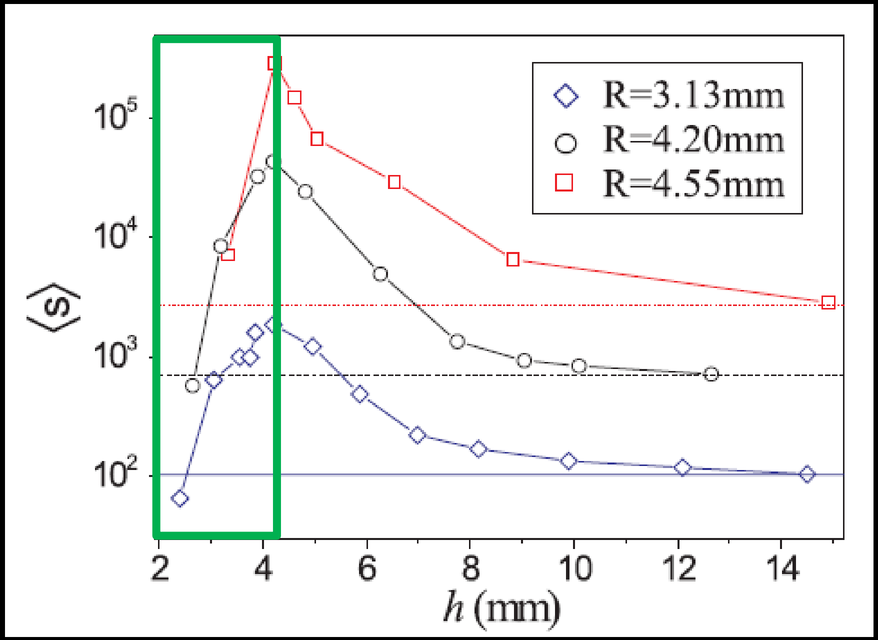
(A robust answer is still pending)

I. Zuriguel et al PRE 2003 & PRE 2005

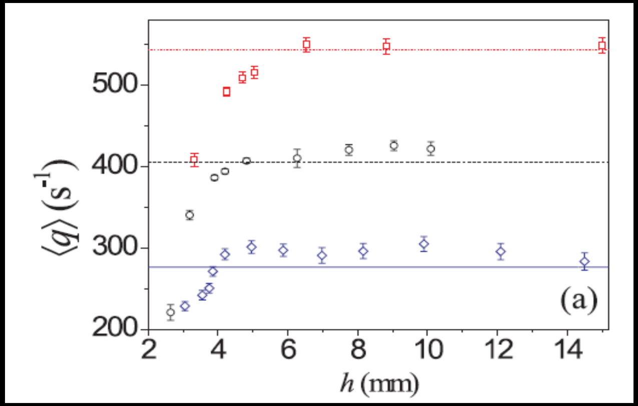
The obstacle & the silo (the experiment at the “lab corner”)

beads
psychology
is simple





The mean avalanche size can be increased more than 100 times!



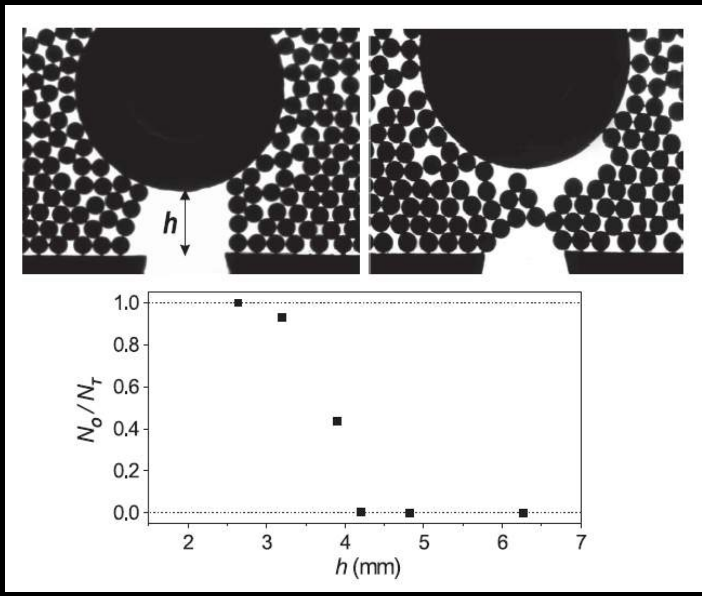
While the flow is almost unaltered

I. Zuriguel et al PRL 2011 & PRE 2012

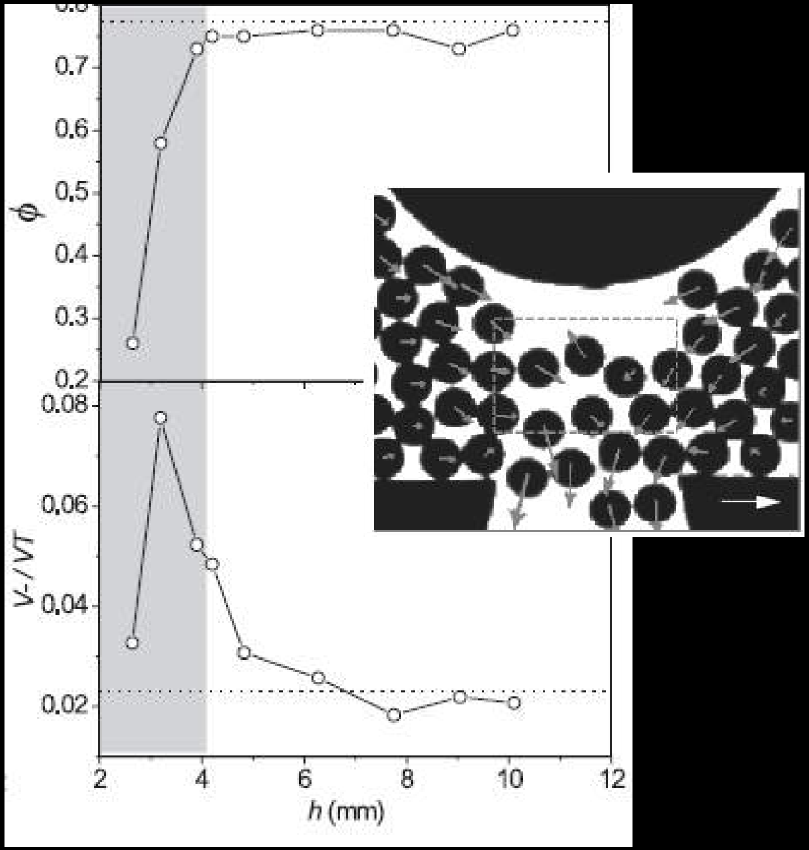
The obstacle & the silo

(the experiment at the "lab corner")

(beads psychology is simple)



If the obstacle is too close, clogging develops on the sides



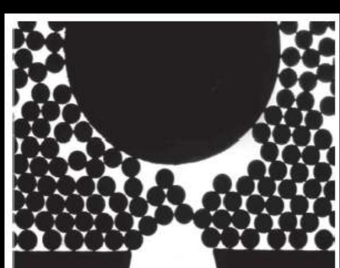
Pressure? Confinement?
From contacts to colisions?

I. Zuriguel et al PRL 2011 & PRE 2012

The obstacle & the sheep (sheep psychology is..)

My grandpa:

"Of all animals I know, the dumbest one is the sheep.“



The obstacle & the sheep (sheep psychology is..)

Tomás (farmer)

Veterinarians
UniZar

Luisfer
(our technician)

The obstacle & the sheep

- ✓ Daily, around 100 sheep are taken out of the yard.
- ✓ The yard is cleaned and food is placed inside it.
- ✓ When the yard is opened again, all the sheep enter crowding together in front of the door.

- Sheep width ~ 35 cm (soft 😛)
- Door width = 77 & 94 cm
- Obstacle of 117 cm diameter placed at different positions in front of the door.
- Inside and outside recordings.
- 20 tests for every experimental condition. One per day.

The obstacle & the sheep

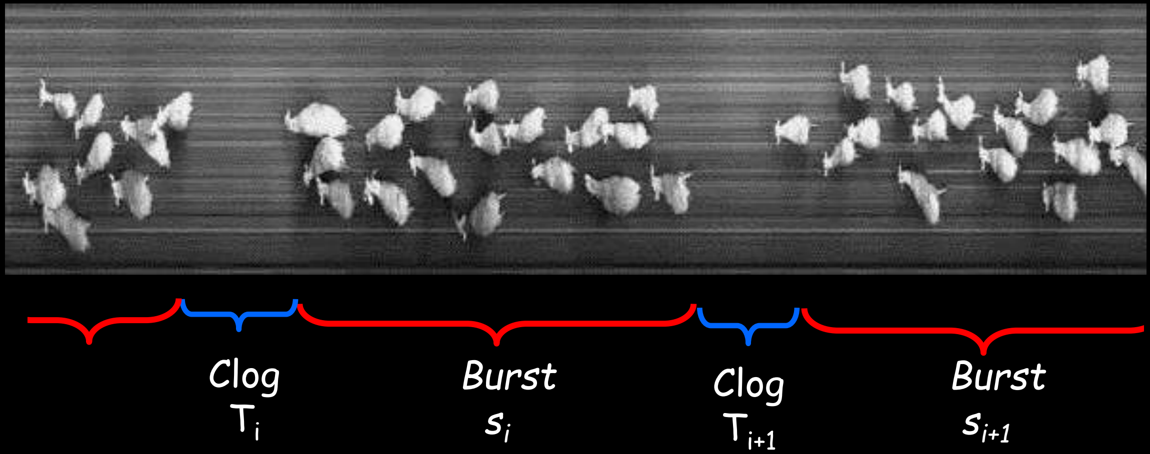
The obstacle & the sheep

The obstacle works but not really as expected:

- the total evacuation time is marginally improved (reduced)
- jams are reduced

Department of Physics and Applied Mathematics
Universidad de Navarra

The obstacle & the sheep

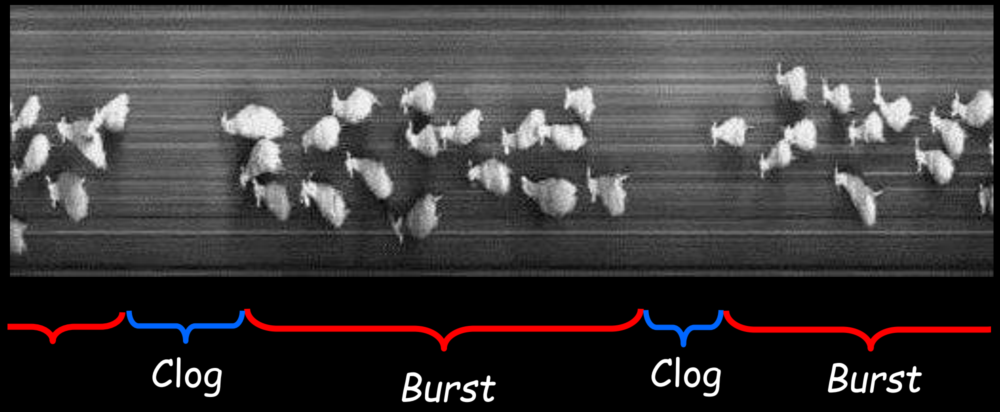


s → depends on what is considered a clog

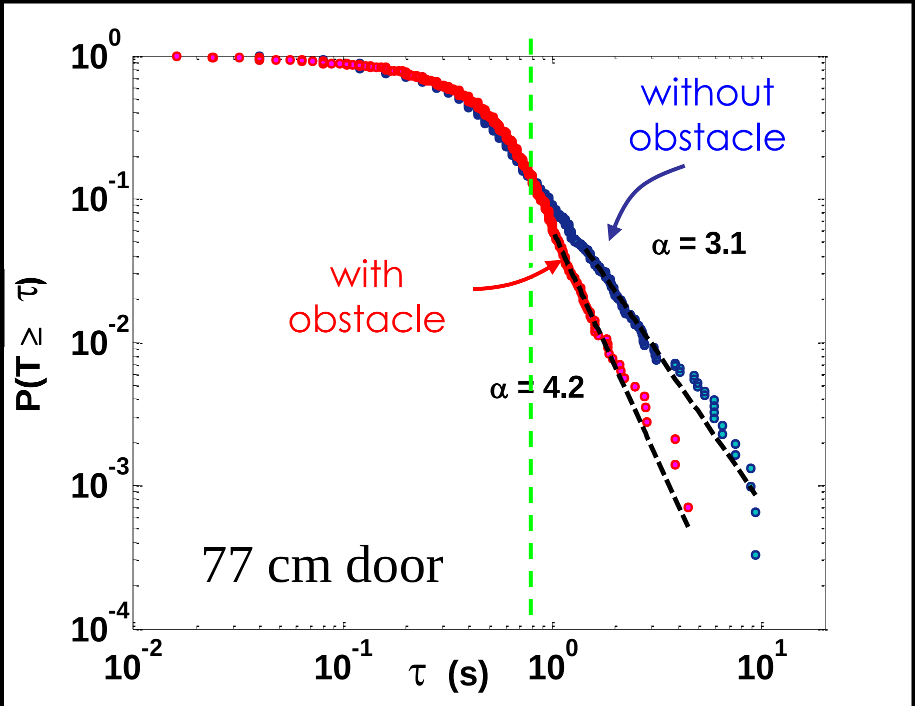
T → we can measure all the clogging times (heading times)

(N-1) R heading times
- **N: number of animals**
- **R: number of runs in the same conditions**

The obstacle & the sheep

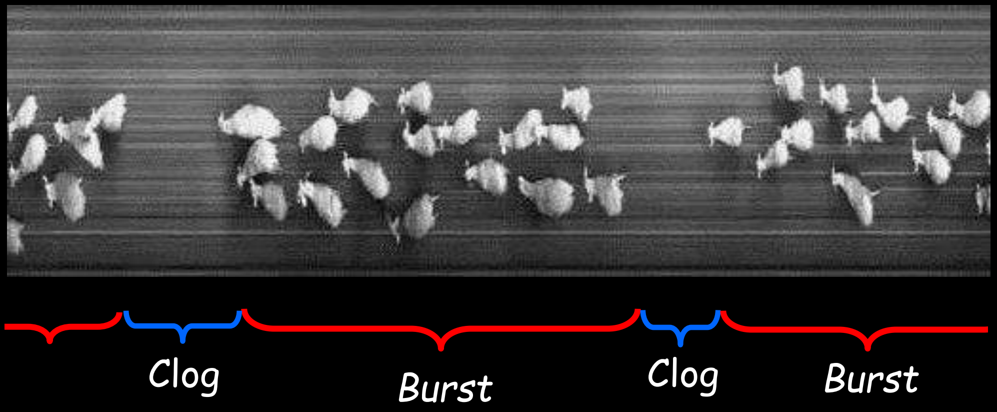


Clogging time survival function

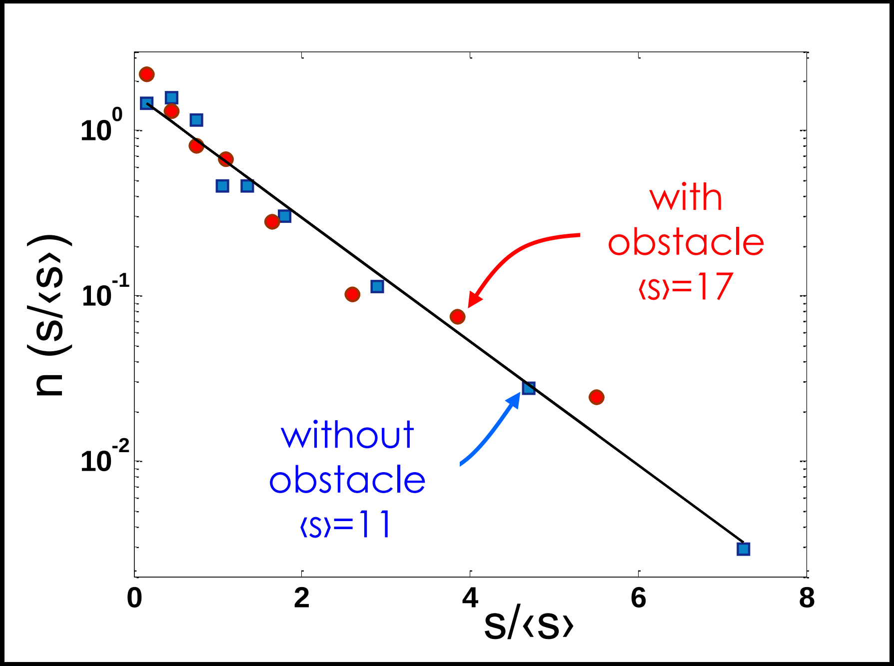


- Power-law tail of clogging times
- Differences appear for long-lasting clogs
- The obstacle reduces their duration

The obstacle & the sheep



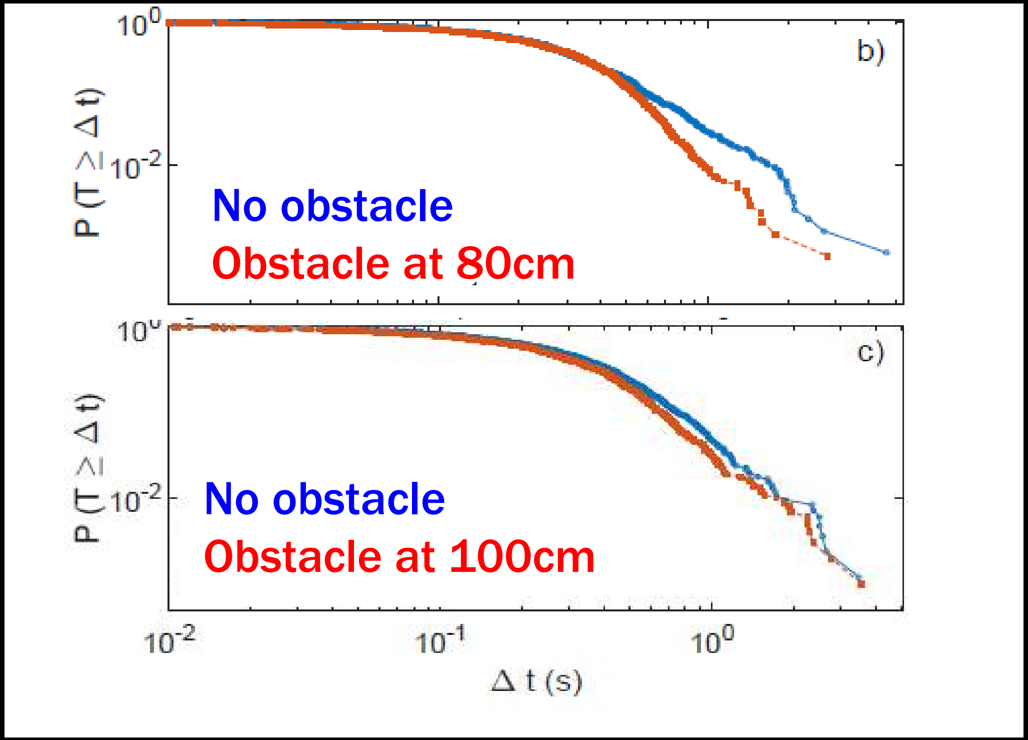
Burst sizes (T_{thres}=0.5s)



- Exponential tails (like avalanches in silos)
- Of course ⟨s⟩ depends on T_{thres}
- For the same T_{thres} bursts are longer in the obstacle presence

The obstacle & the sheep

Obstacle Position



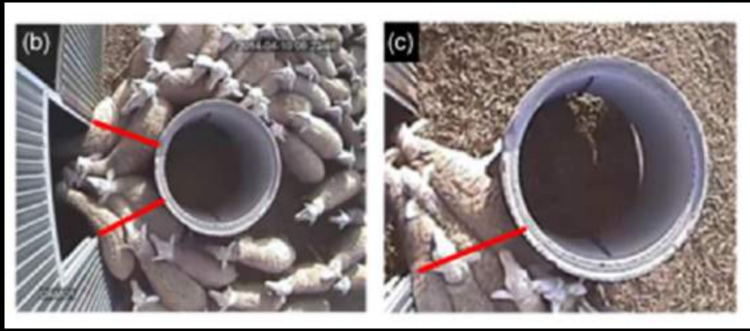
Too far → no effect

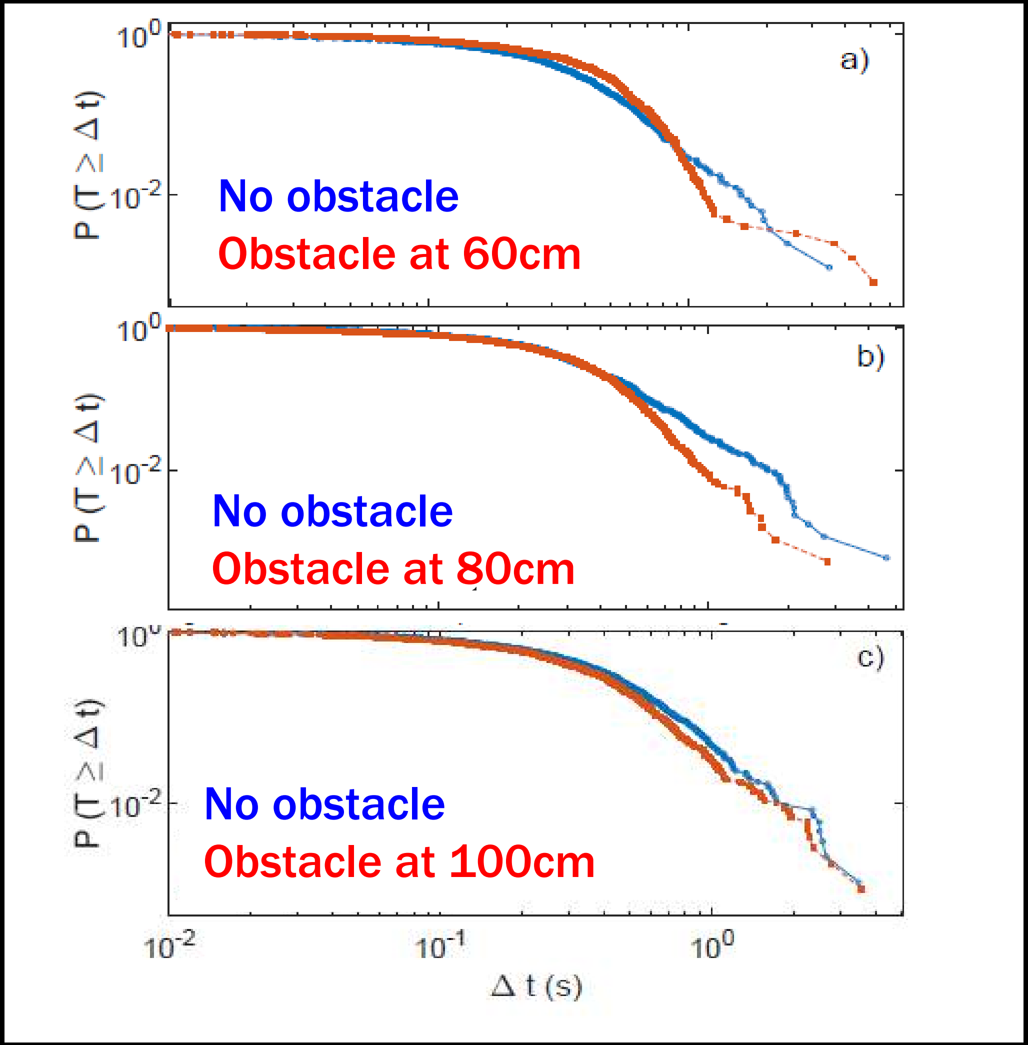
I. Zuriguel et al. PRE 2016

The obstacle & the sheep

Obstacle Position

Too close → prejudicial



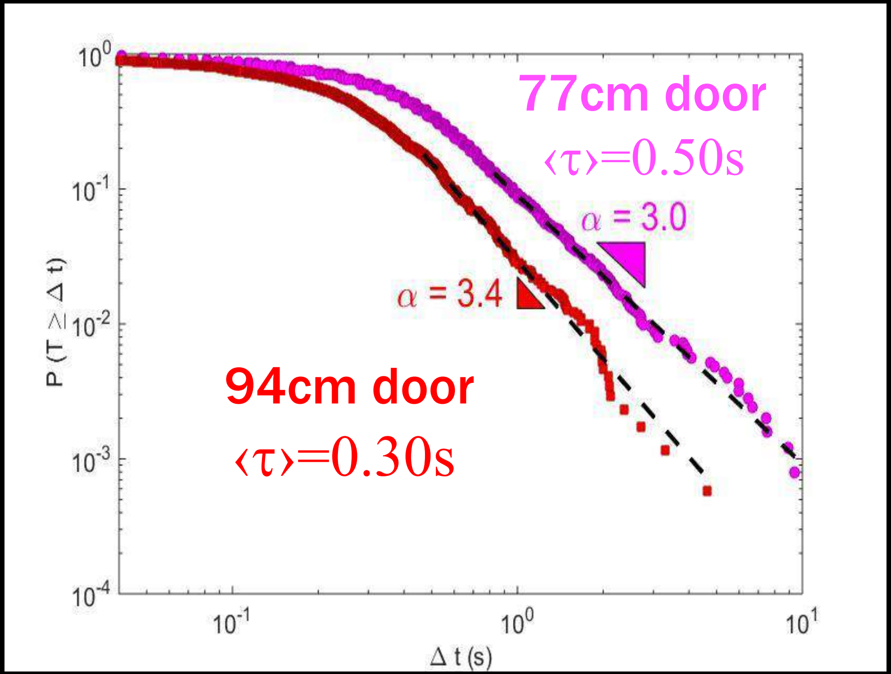


Too far → no effect

I. Zuriguel et al. PRE 2016

The obstacle & the sheep

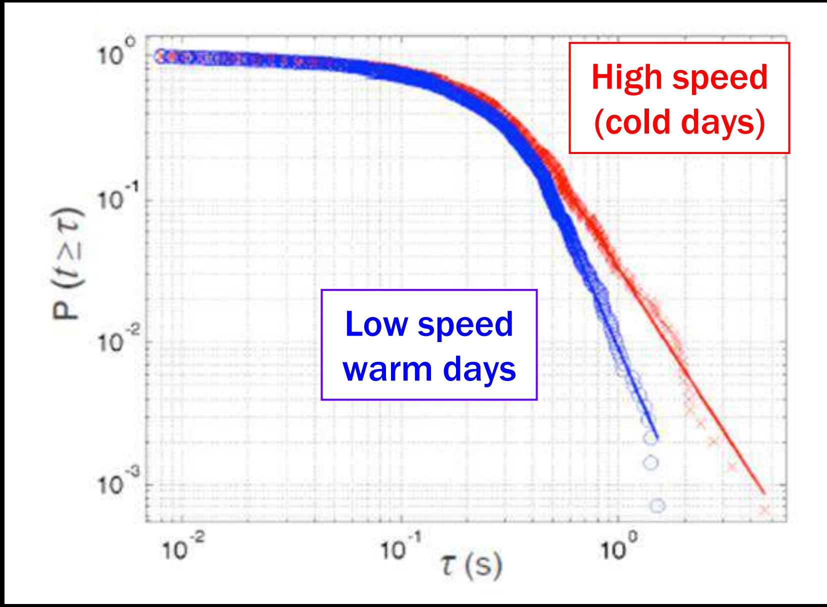
Door size

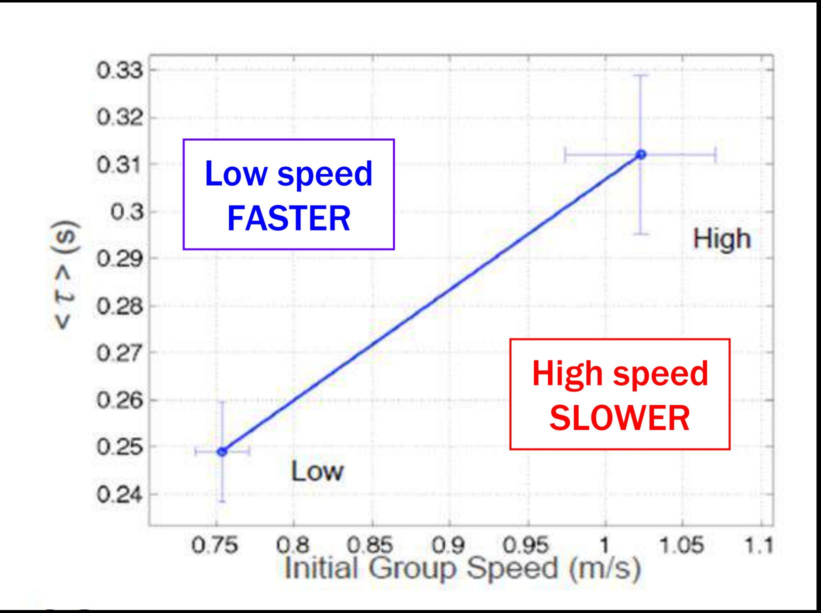


The obstacle & the sheep

Competitiveness

Warm days (T = 25±2ºC) Vs Cool days (T = 10±5ºC).





Faster is slower

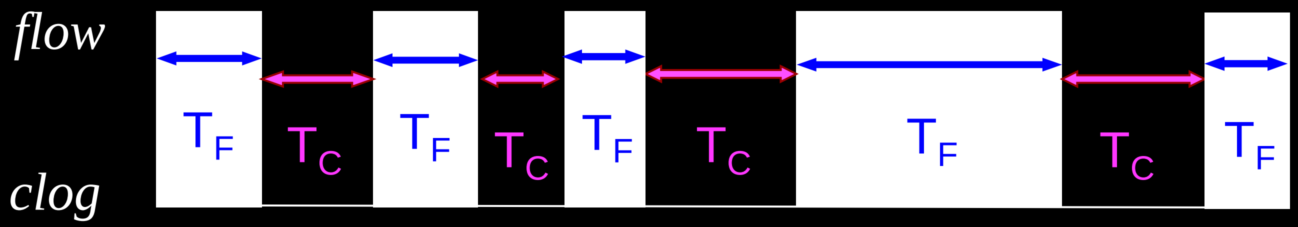
J.M. Pastor et al. *PRE* 2015

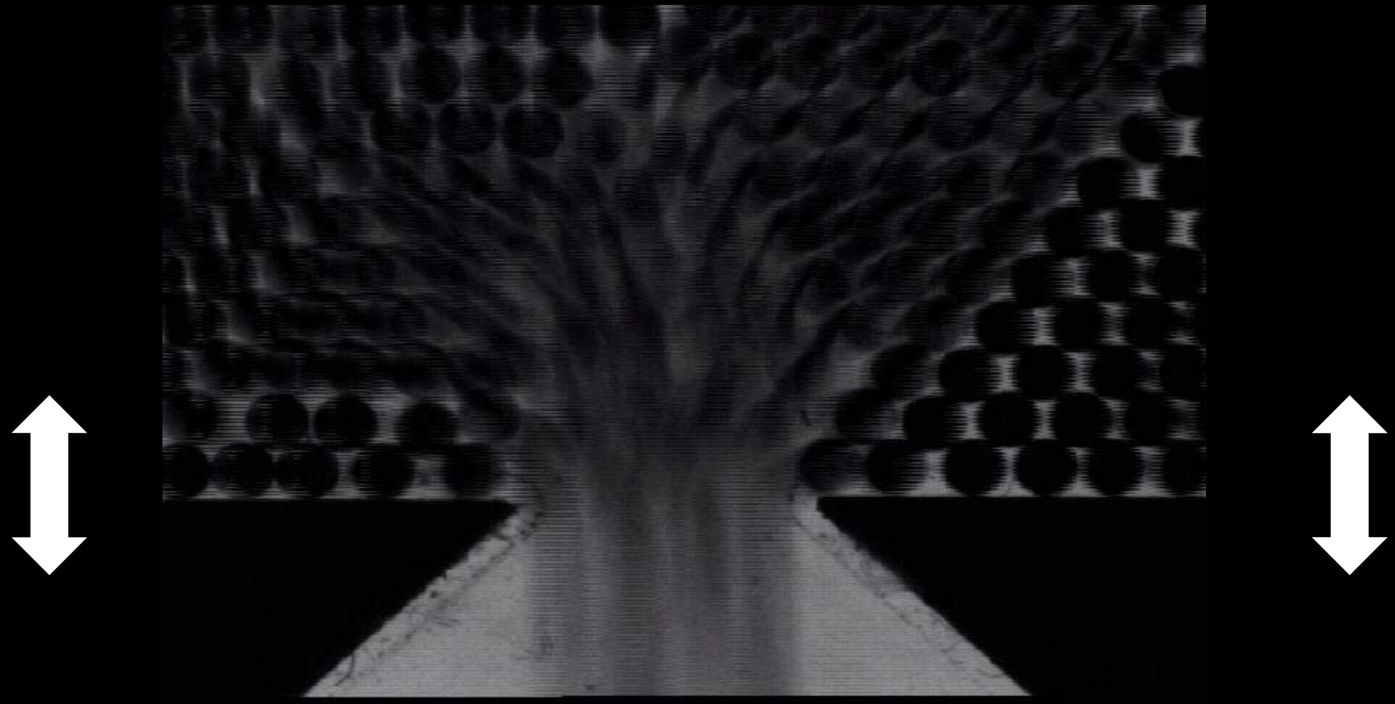
The obstacle & the sheep

Summarizing

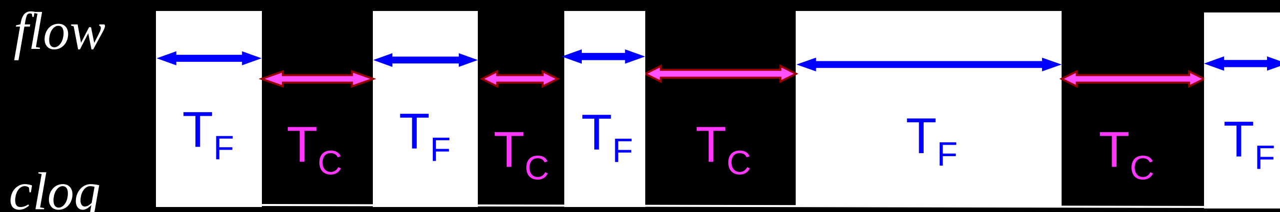
- The obstacle works (but not really as expected)
- There is an optimal position
- There is Faster is Slower
- The larger the door, the better the flow
- Bursts are exponentially distributed (like in granular silos)
- Clog durations display broad tails (power laws?)

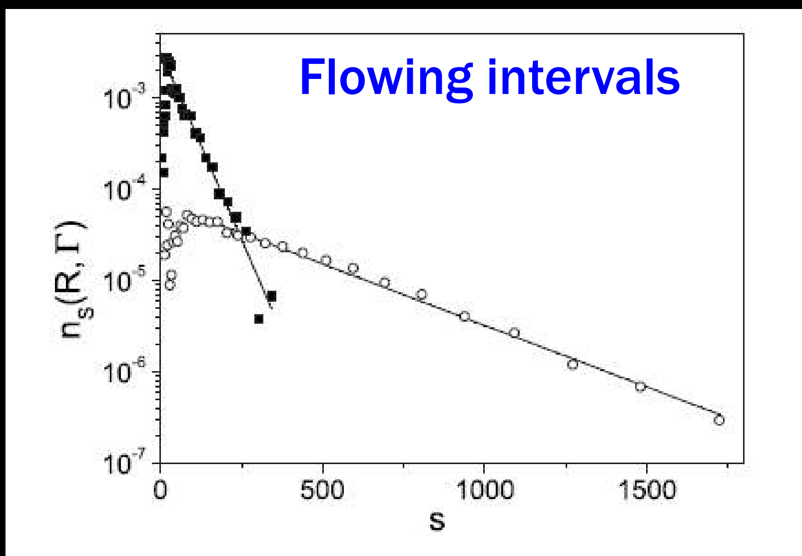
Broad tails of unclogging times (the vibrated silo)

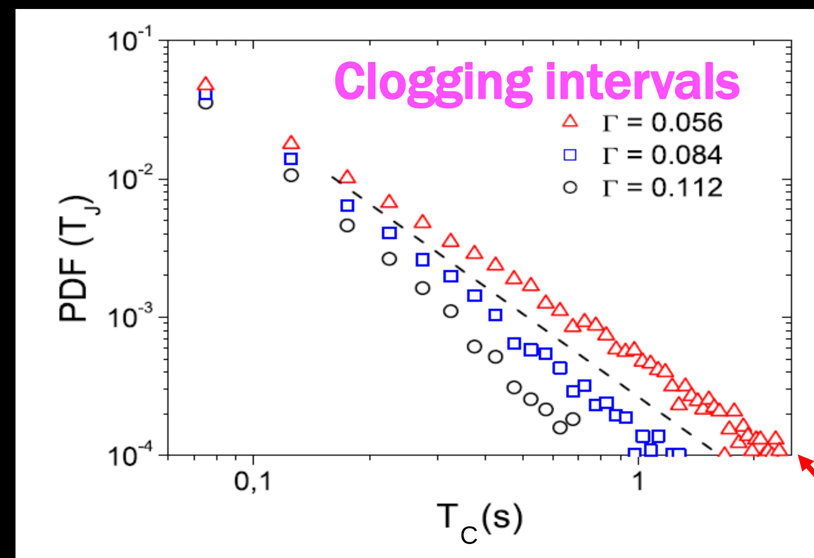




Broad tails of unclogging times (the vibrated silo)







Exponential distribution of T_F

C. Mankoc et al PRE 2009

Power law distribution of T_C

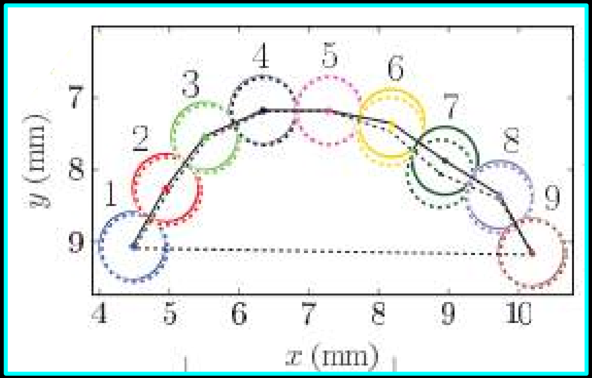
$P(T_C) \sim T_C^{-\alpha}$ with α sometimes below 2

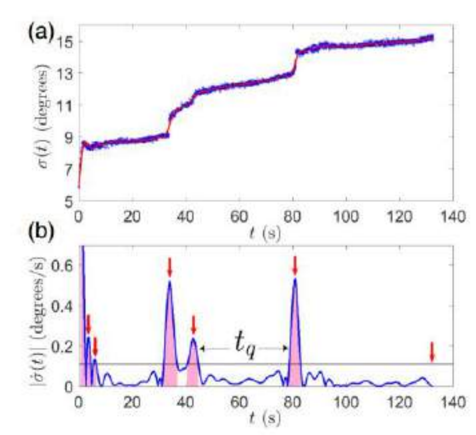
A. Janda et al EPL 2009

Broad tails of unclogging times

Physical origin?

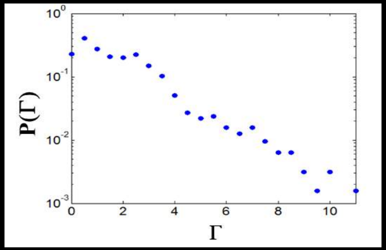
Option 1. Aging in the arch destabilization dynamics.

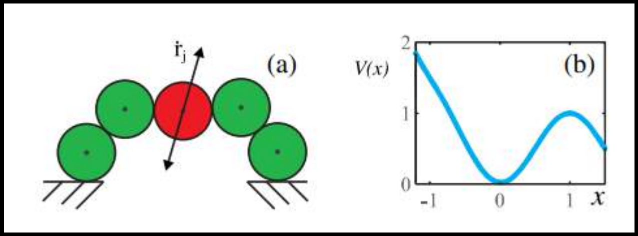


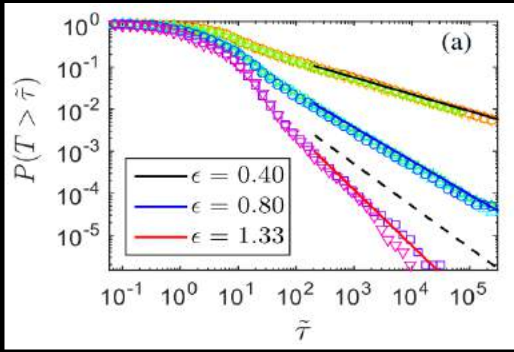


B. V. Guerrero et al. PRE 2018
C. Merrigan et al. PRE(R) 2018
B. V. Guerrero et al. PRE 2019

Option 2. Heterogeneous stability of the arches that clog a given orifice.







Hopping rate:

$$k \equiv \langle \tau \rangle^{-1} = \nu e^{-\beta E_b},$$

A. Nicolas et al. PRL 2018

Clogging and unclogging in vibrated silos

The flowing parameter

Fraction of time that the grains are flowing

$$\Phi = \frac{\langle T_F \rangle}{\langle T_F \rangle + \langle T_C \rangle}$$

$\langle T_F \rangle$ always defined in an intermittent flow

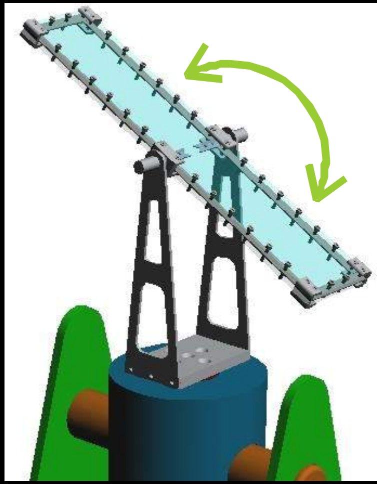
$\langle T_C \rangle$ only well defined if α higher than 2 as **$P(T_C) \sim T_C^{-\alpha}$**

→ Otherwise the average does not converge

$\alpha \leq 2$ → $\Phi = 0$ (clogged)

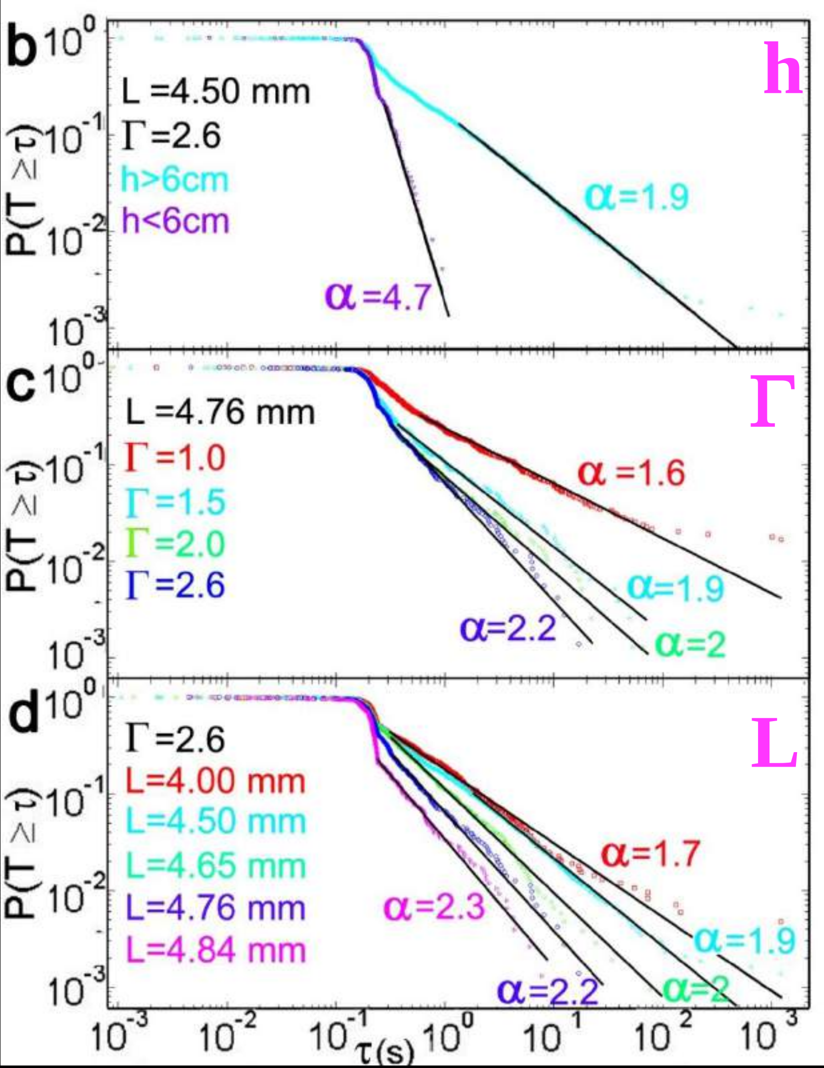
$\alpha > 2$ → $\Phi > 0$ (unclogged)

Broad tails of unclogging times (the vibrated silo)



2D SILO
Vibrated as a whole
1 mm particles

Lozano et al, PRL 2012



h: height of the layer of grains above the outlet

Γ: acceleration of the external vibration

L: outlet size

The system can be unclogged

↓h ↑Γ ↑L

Broad tails of unclogging times (the vibrated silo)

The flowing parameter

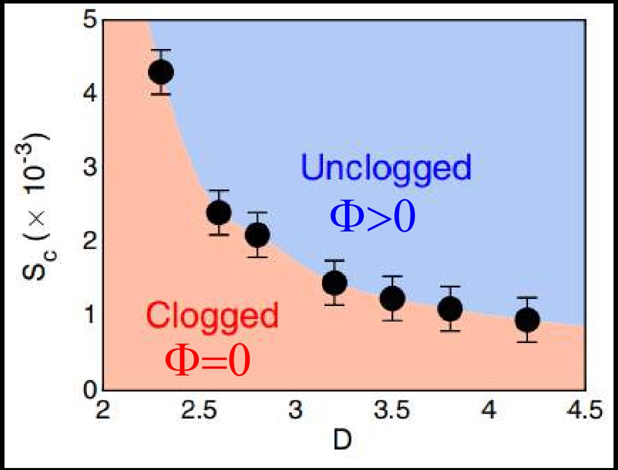
Fraction of time that the grains are flowing

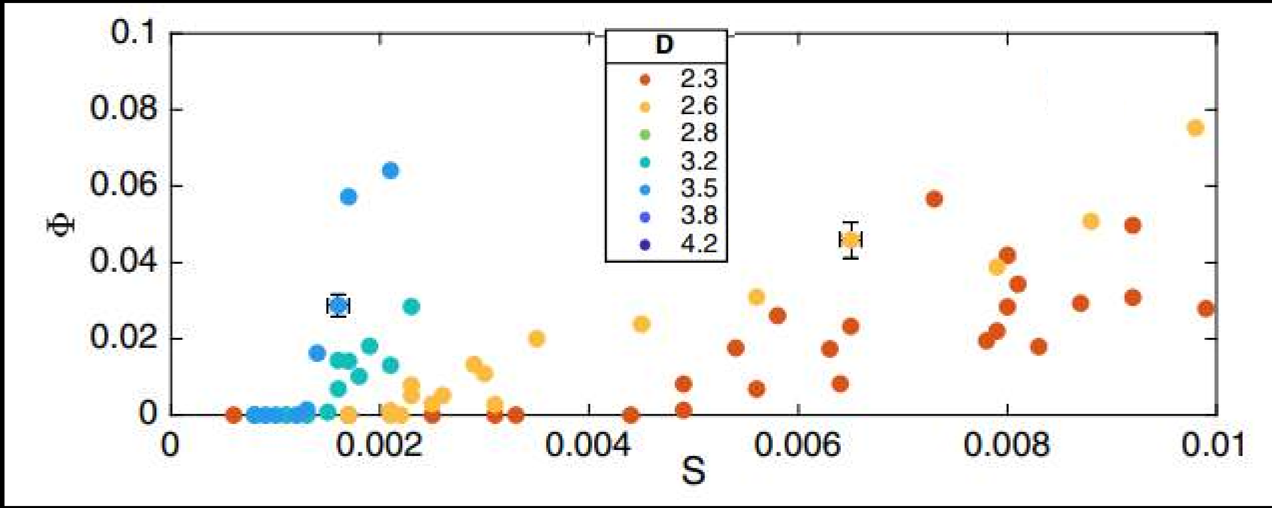
$$\Phi = \frac{\langle T_F \rangle}{\langle T_F \rangle + \langle T_C \rangle}$$

The control parameter

Square root of kinetic and potential energy ratio

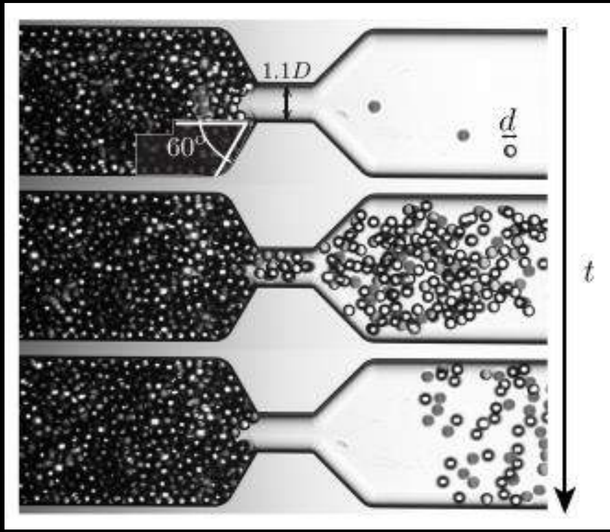
$$S = A\,\omega / \sqrt{gl}$$

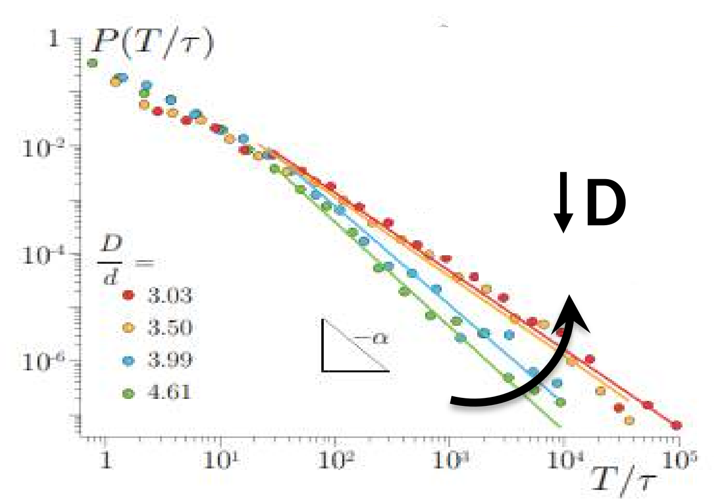


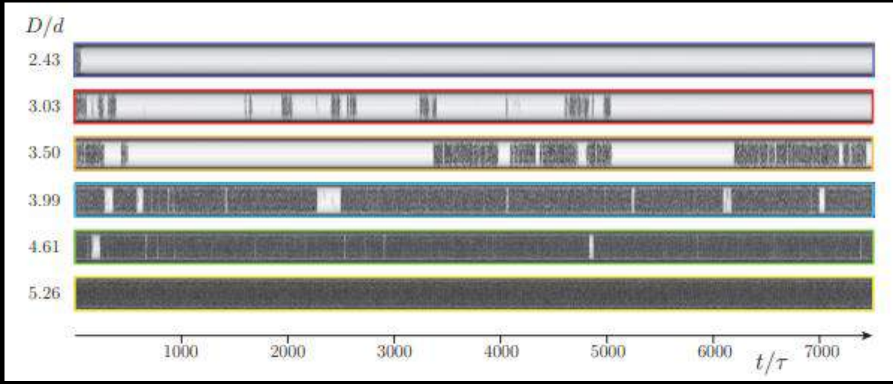


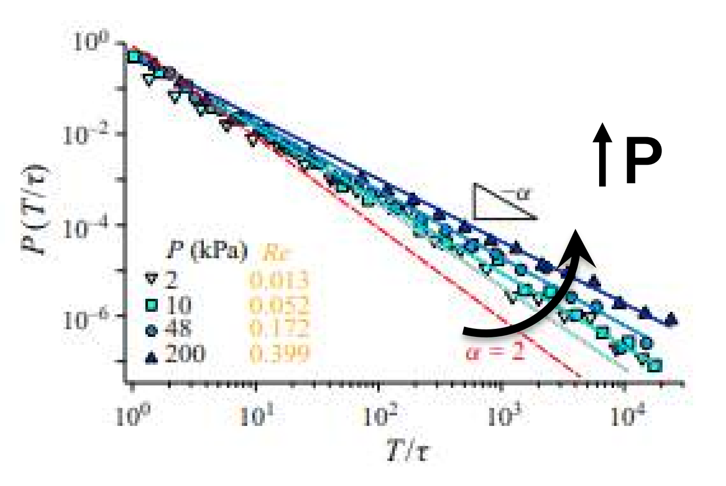
R Caitano et al.
PRL 127, 148002 (2021)

Broad tails of unclogging times: other systems (colloids)









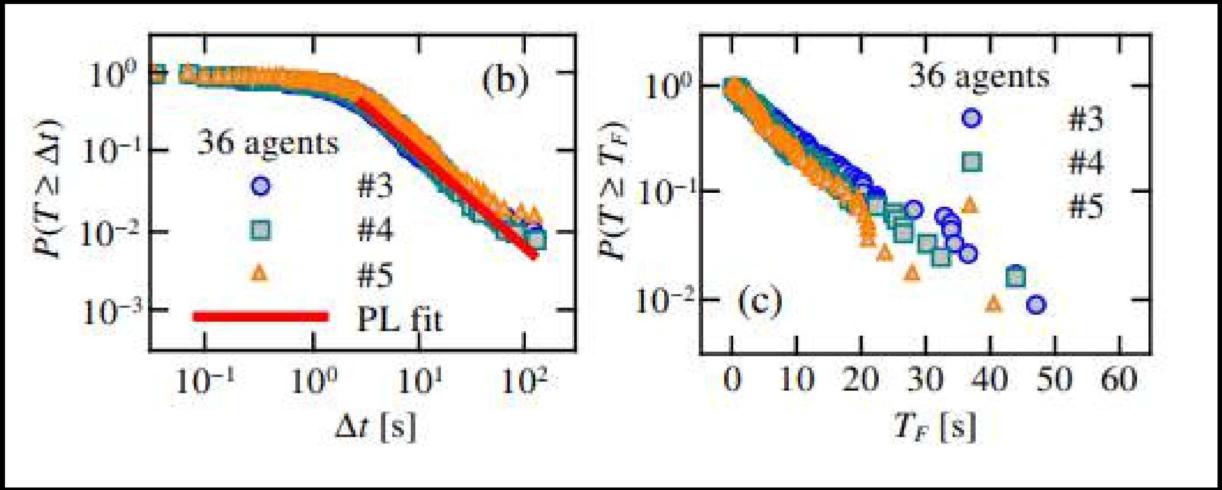
M. Souzy, A. Marin et al.
PRE **101**, 060901(R) (2020), JFM 953, A40 (2022)

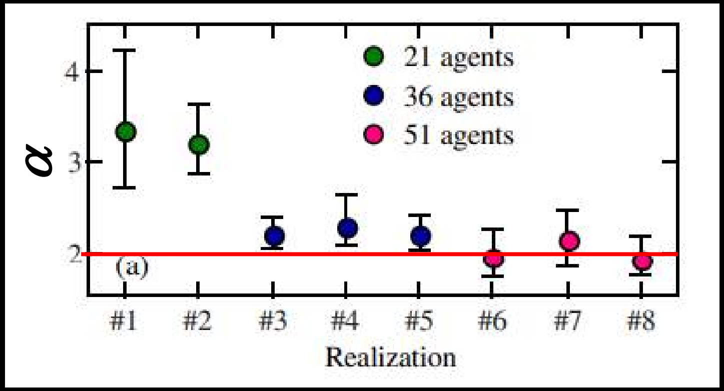
Broad tails of unclogging times: other systems (hexbugs)

G. Patterson et al. PRL 2017

Clogging times

Flowing times





The unclogging transition

gran. silo	↓ *layer of grains*	↑ *External vibration*	↑ *Outlet size*
sheep	↓ *Competitiveness (summer Vs winter exp.)*		↑ *Door size*
colloids	↓ *Pressure*	↑ *T*	↑ *Neck size*
hexbugs	↓ *Crowd size*		

The unclogging transition ($\alpha \leq 2$ to $\alpha > 2$) is observed

The value of α is increased

The unclogging transition

	↓ ***Compatible load***	↑ ***Incompatible load***	↑ ***Length scale***
gran. silo	↓ *layer of grains*	↑ *External vibration*	↑ *Outlet size*
sheep	↓ *Competitiveness* *(summer Vs winter exp.)*		↑ *Door size*
colloids	↓ *Pressure*	↑ *T*	↑ *Neck size*
hexbugs	↓ *Crowd size*		

The unclogging transition ($\alpha \leq 2$ to $\alpha > 2$) is observed

The value of α is increased

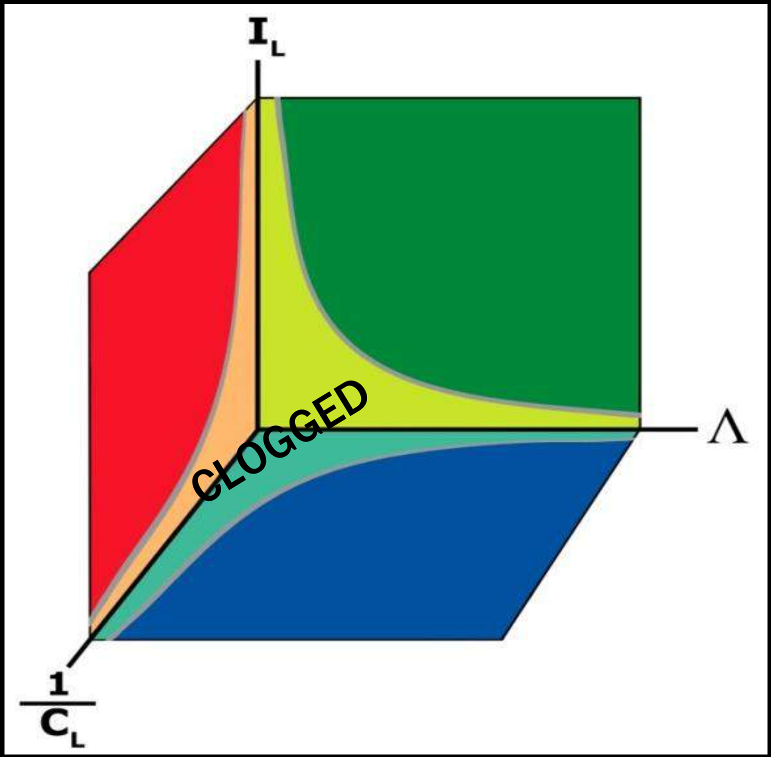
The unclogging transition

The system becomes unclogged when:

↓ *Compatible load* C_L

↑ *Incompatible load (temperature)* I_L

↑ *Neck size* Λ

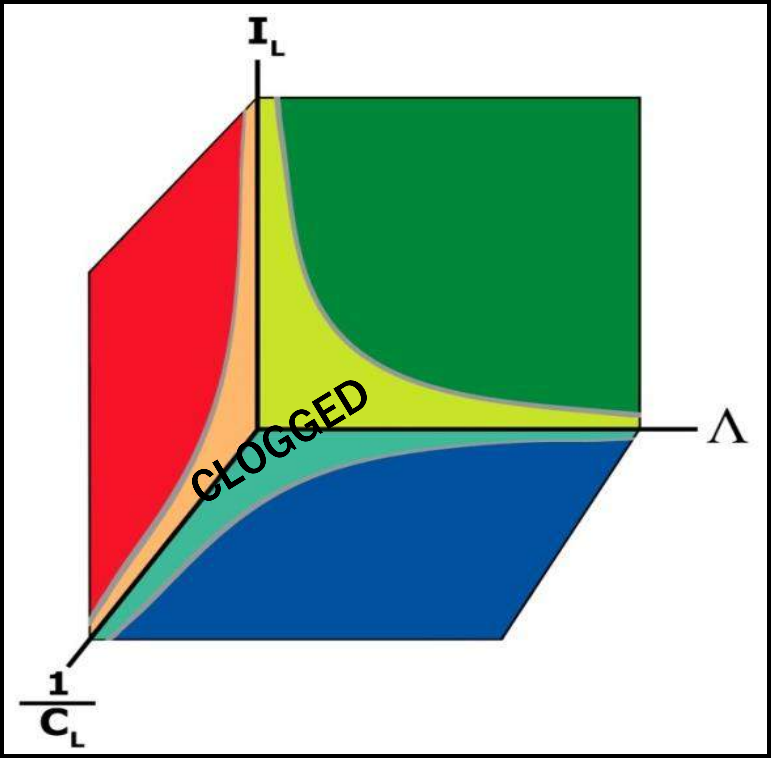


I. Zuriguel et al, *Scientific Reports* (2014)

The unclogging transition

- *Can pedestrian behavior be explained with this framework?*
- *How the obstacle role fits within this idea?*

  (in pricinciple OK, it reduces Compatible Load or it increases Incompatible Load)



I. Zuriguel et al, *Scientific Reports* (2014)

Can pedestrian behavior be explained with this framework?

Pedestrians

Four series of test (~ 30 evacuations each)

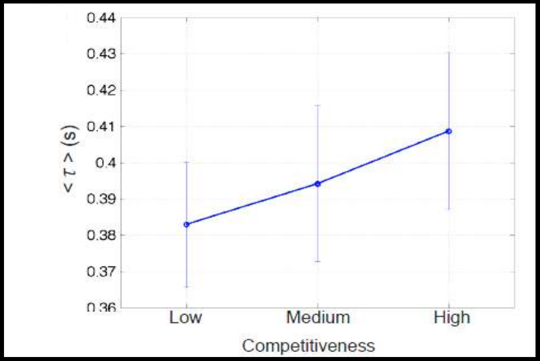
90 -100 volunteers (series 1-3)
180 soldiers (series 4)

Door sizes (69 and 75 cm)
Obstacle effect
Different competitiveness. Pushing allowed!!

10 evacuations for each experimental condition!

Pressure sensors at the door
Two cameras: 1 outside and 1 inside (4K)

Pedestrians: Faster is Slower



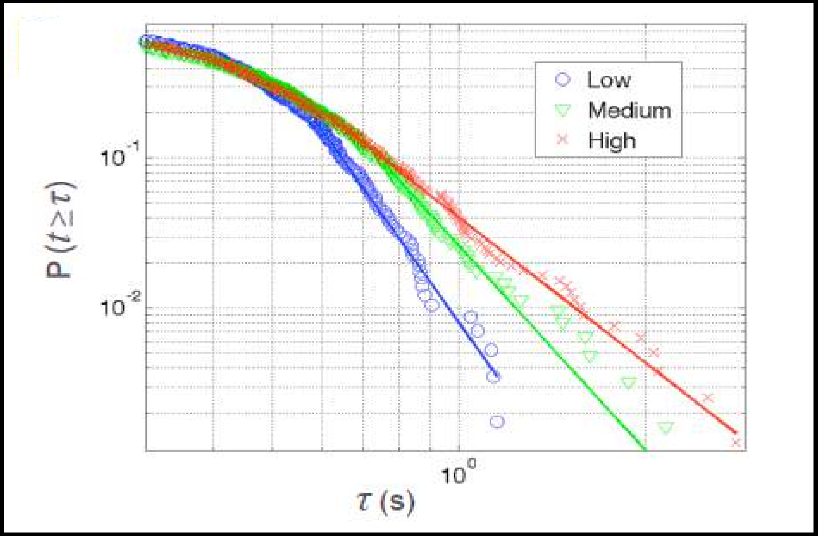
Try to evacuate the room as fast as possible and:

(3 competitiveness levels)

Low: No touch

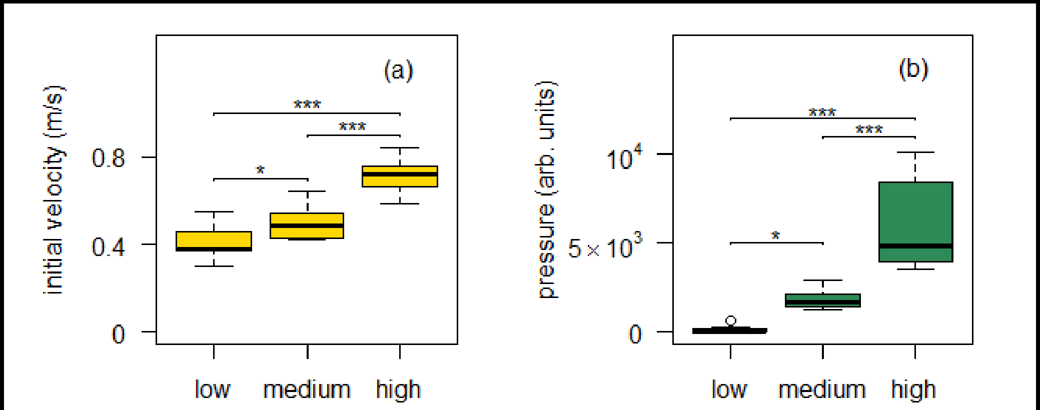
Medium: Touching allowed

High: You can push

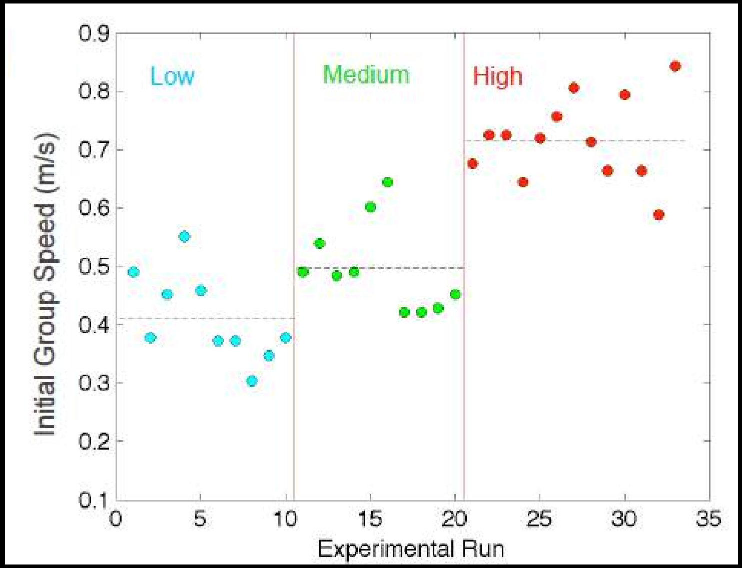


Faster? is slower

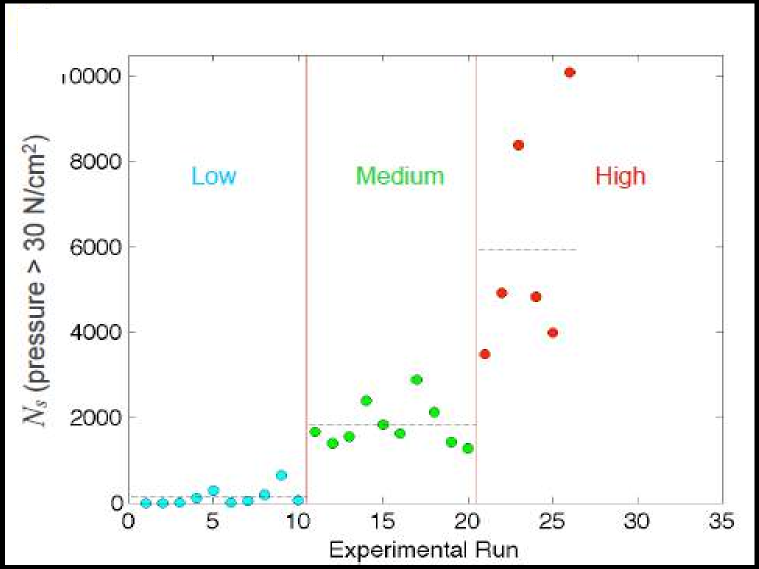
<u>Pedestrians:</u> Faster is Slower



Initial group speed



Pressure



Faster
(or stronger)
is slower

$\downarrow C_L$

Shorter Clogs

The unclogging transition

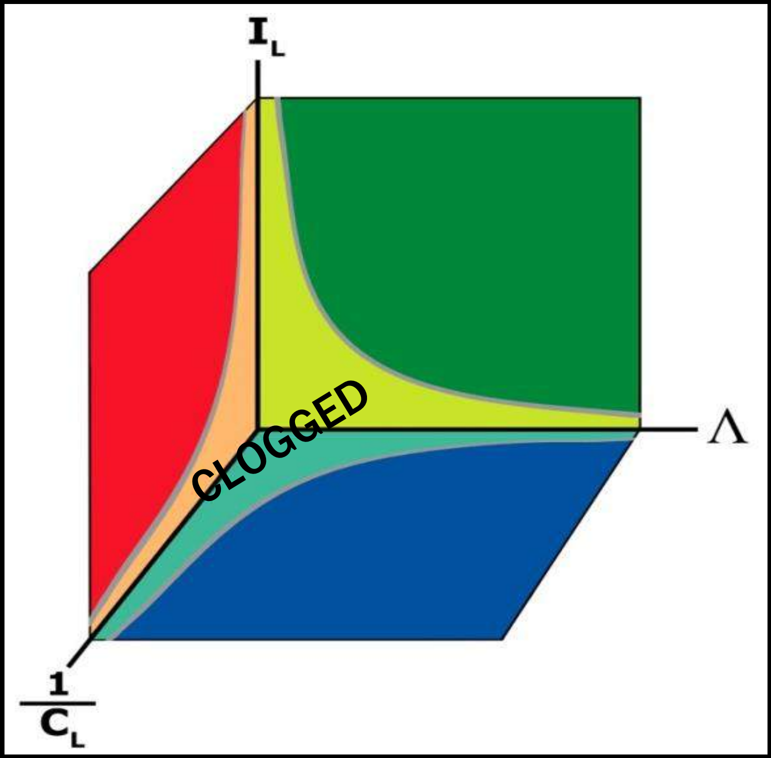
	↓ ***Compatible load***	↑ ***Incompatible load***	↑ ***Length scale***
gran. silo	↓ *layer of grains*	↑ *External vibration*	↑ *Outlet size*
sheep	↓ *Competitiveness* *(summer Vs winter exp.)*		↑ *Door size*
colloids	↓ *Pressure*	↑ *T*	↑ *Neck size*
hexbugs	↓ *Crowd size*		
pedestrians	↓ *Competitiveness*		↑ *Door size*

The unclogging transition ($\alpha \leq 2$ to $\alpha > 2$) is observed
The value of α is increased

The unclogging transition

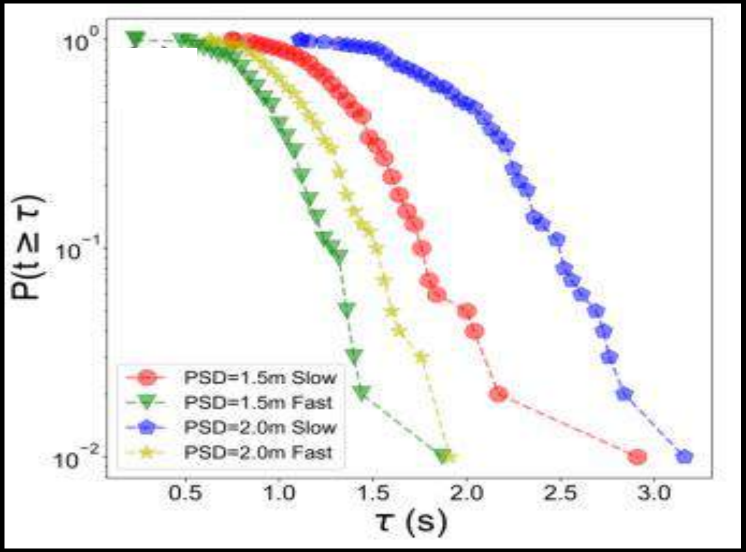
- *Can pedestrian behavior be explained with this framework?*

Yes, provided that the density is high (all is about clogs)



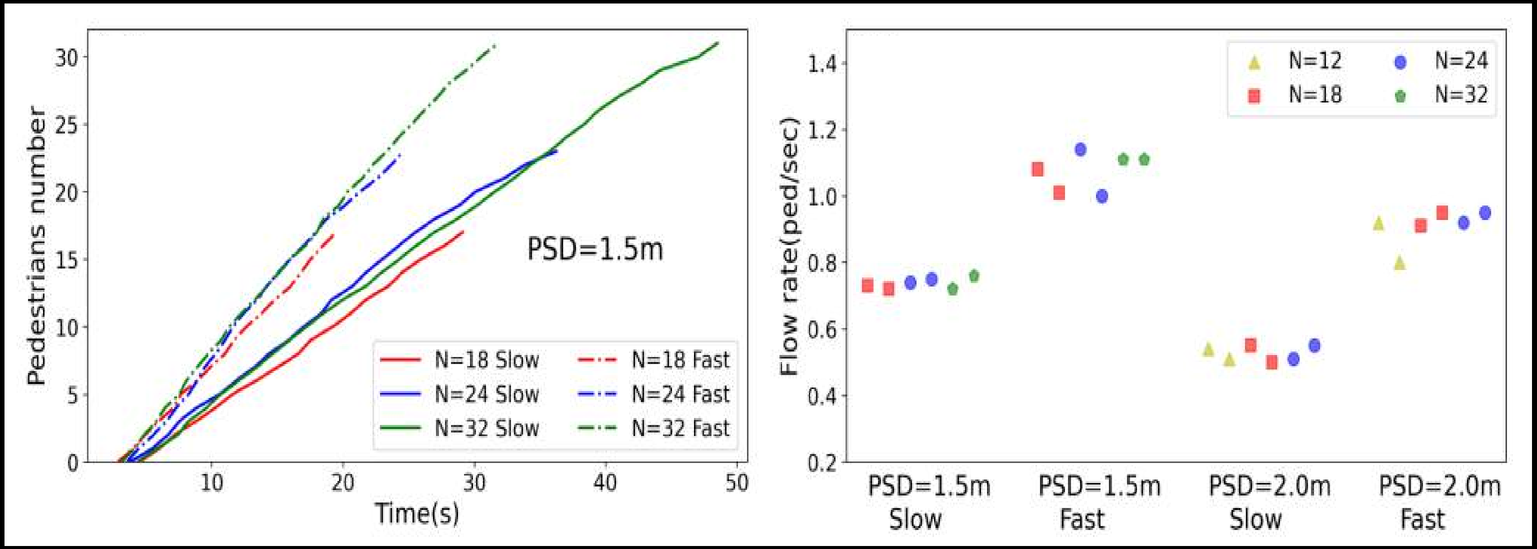
The exception that proves the rule…

Pedestrian evacuations keeping social distancing



- Exponential distribution of heading times (no competition, no contacts, no clogs, no broad tails)

Pedestrian evacuations keeping social distancing



- Exponential distribution of heading times (no contacts, no competition, no clogging, no broad tails)
- No effect of crowd size (there is no pressure)
- Faster is faster
- The higher the prescribed distance the slower the evacuation

Pedestrians: The obstacle

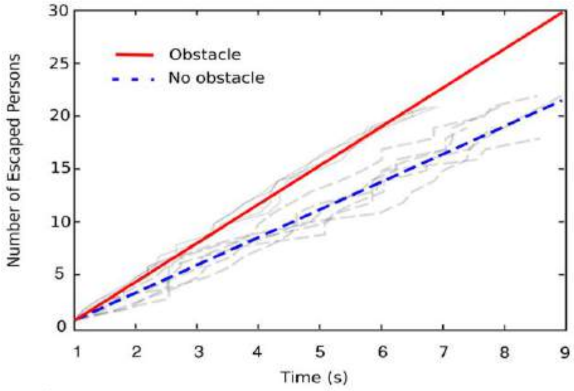
Pedestrians: The obstacle

First run ~ 90 volunteers
1 meter diameter
2 meters high
300 Kg obstacle

1m distance but displaced backwards
No apparent effect on the flow
But only 5 evacuations

The participants were asked to rush toward the door and behave in a pushy way.

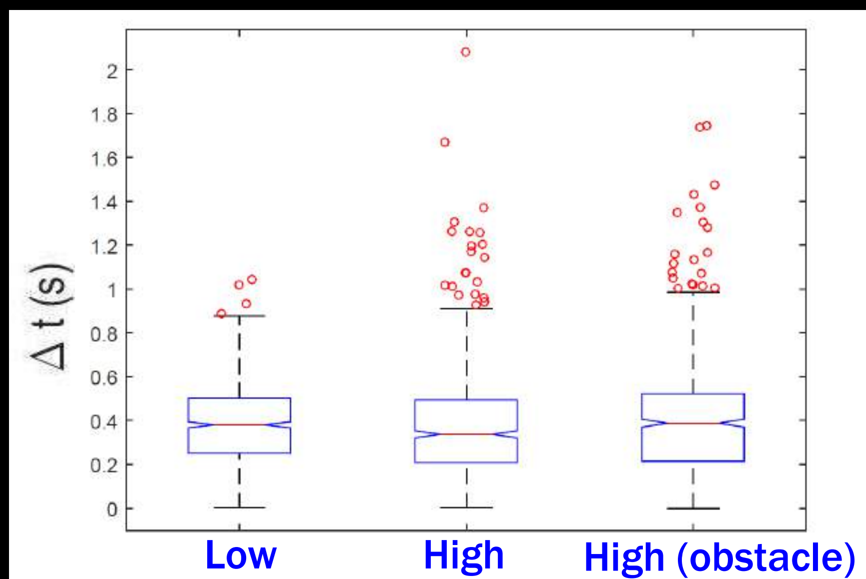
30 people
4 tests with obstacle / 6 without



D. Helbing et al., *Transportation Science* **39** (2005)

Pedestrians: The obstacle

Second run ~ 90 volunteers
1 meter diameter
2 meters high
1Ton obstacle
At 80cm



Pedestrians: The obstacle

Third run

~ 180 soldiers
several positions

Granular Lab

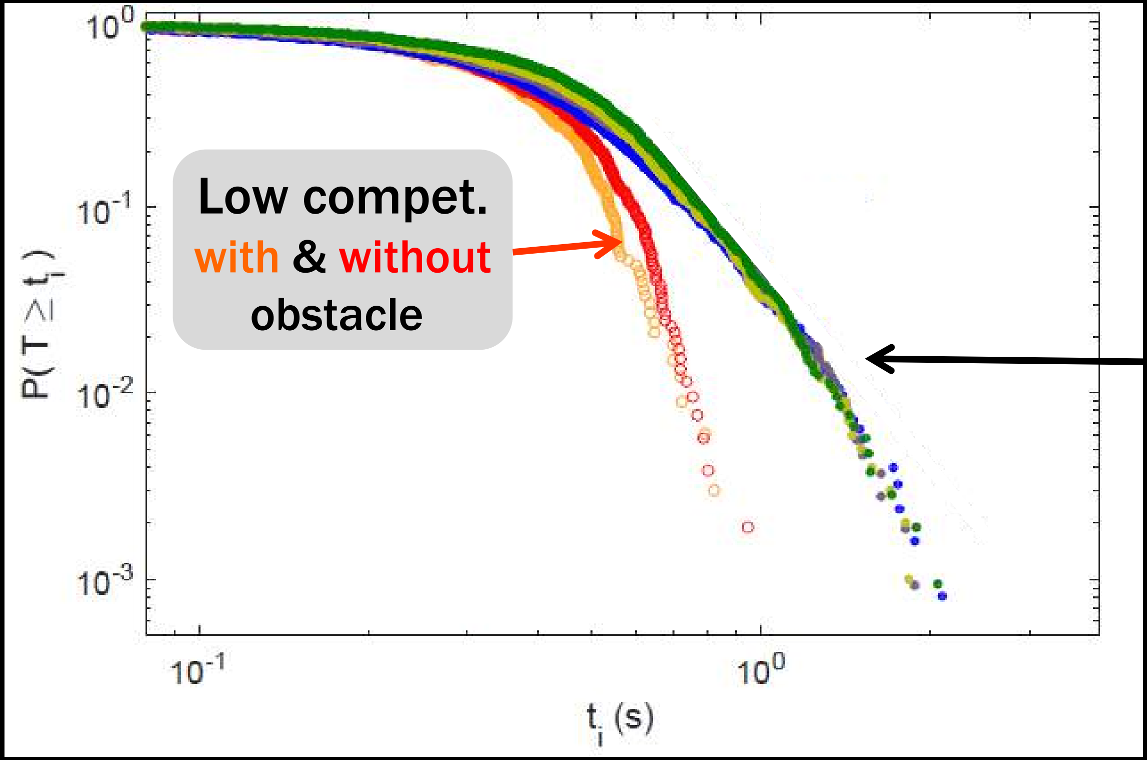
Department of Physics and Applied Mathematics

Universidad de Navarra

Pedestrians: The obstacle

Third run

~ 180 soldiers
several positions



High compet.

Without obstacle

With obstacle at:
50 cm
60 cm
70 cm

MODELS SHOULD BE REVISITED!!!

Pedestrians: The obstacle

Third run

~ 180 soldiers several positions

Polarization Φ

$\vec{v}_i \rightarrow$ pedestrian velocity

$\vec{u}_i \rightarrow$ unitary vector pointing in the exit direction

$$\Phi = \left\| \frac{1}{N} \sum_{i=1}^{N} \frac{\vec{v}_i}{\|v_i\|} \right\|$$

$$\Phi_d = \left\| \frac{1}{N} \sum_{i=1}^{N} \frac{\vec{v}_i}{\|v_i\|} \cdot \vec{u}_i \right\|$$

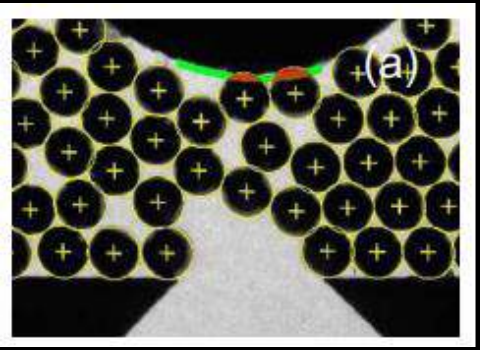
The obstacle and the vibrated silo

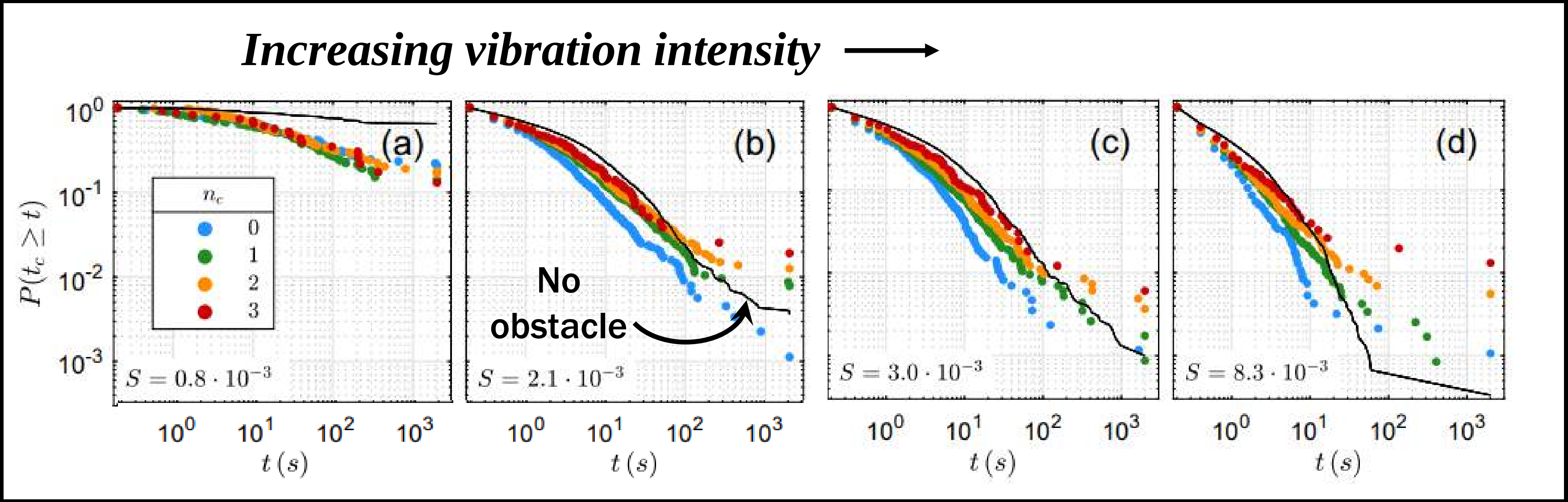
Perhaps the analogy with a static silo was not the best choice

The obstacle and the vibrated silo

Anchoring Effect of an Obstacle in the Silo Unclogging Process

PRL 131, 098201 (2023)

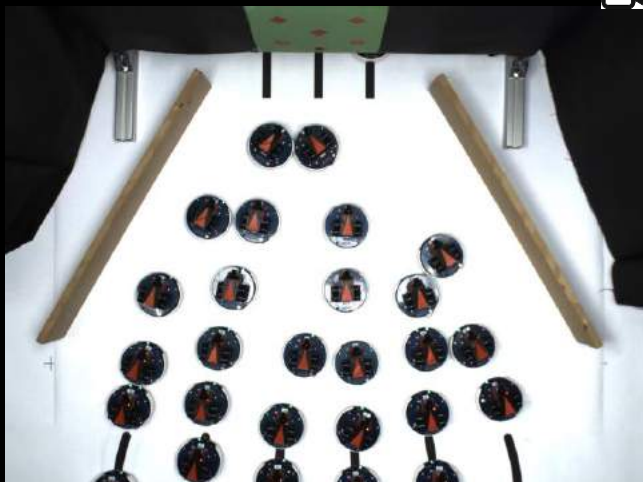


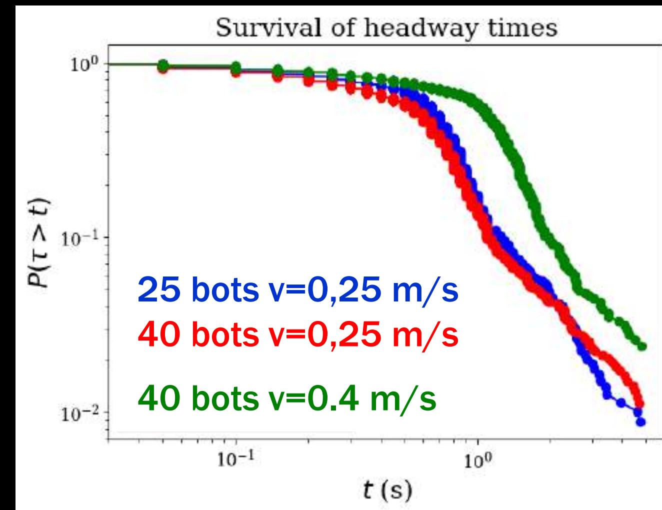


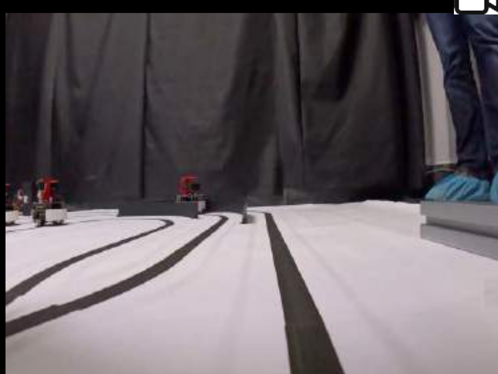
Overall, the obstacle is benefitial... but some configurations emerge that are very stable

Robot evacuations

Ongoing Project (very preliminary)

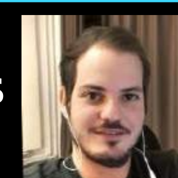






- Power laws (clogs?)
- No effect of crowd size (no pressure)
- Faster is faster (no pushing)

Laciel Alonso-Llanes
(see poster)



Summarizing

- Bottleneck Flow of different many-body systems presents interesting analogies
  - Exponential tails of bursts sizes distributions
  - Broad tails of clogging times (only in dense scenarios)
  - Stronger (Faster) is Slower driven by clogs
  - Faster is faster in diluted scenarios (without pressure)

Summarizing

- Bottleneck Flow of different many-body systems presents interesting analogies
  - Exponential tails of bursts sizes distributions
  - Broad tails of clogging times (only in dense scenarios)
  - Stronger (Faster) is Slower driven by clogs
  - Faster is faster in diluted scenarios (without pressure)
- A qualitative phase diagram seems to encompass the role of Compatible Load, Incompatible Load and Neck Size

Summarizing

- Bottleneck Flow of different many-body systems presents interesting analogies
  - Exponential tails of bursts sizes distributions
  - Broad tails of clogging times (only in dense scenarios)
  - Stronger (Faster) is Slower driven by clogs
  - Faster is faster in diluted scenarios (without pressure)
- A qualitative phase diagram seems to encompass the role of Compatible Load, Incompatible Load and Neck Size
- The obstacle role is still a conundrum (a mystery for pedestrians)

Summarizing

- Bottleneck Flow of different many-body systems presents interesting analogies
  - Exponential tails of bursts sizes distributions
  - Broad tails of clogging times (only in dense scenarios)
  - Stronger (Faster) is Slower driven by clogs
  - Faster is faster in diluted scenarios (without pressure)
- A qualitative phase diagram seems to encompass the role of Compatible Load, Incompatible Load and Neck Size
- The obstacle role is still a conundrum (a mystery for pedestrians)
- Working with different systems is helpful (sharing methodologies, ideas, learning from similarities and differences, etc.)

Granular Lab

Department of Physics and Applied Mathematics

Universidad de Navarra




Angel Garcimartín, Diego Maza, Raúl Cruz Hidalgo, Iñaki Echeverría.
University of Navarra, Spain.

Daniel R. Parisi
ITBA Argentina

Alexandre Nicolas
CNRS / Univ. Lyon

Ignacio Pagonabarraga
University of Barcelona

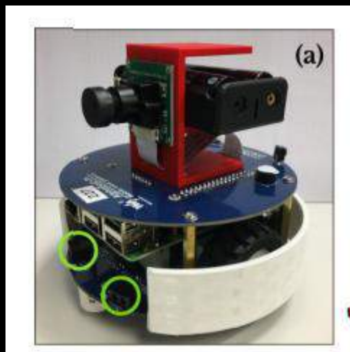
Eric Clément
ESPCI París

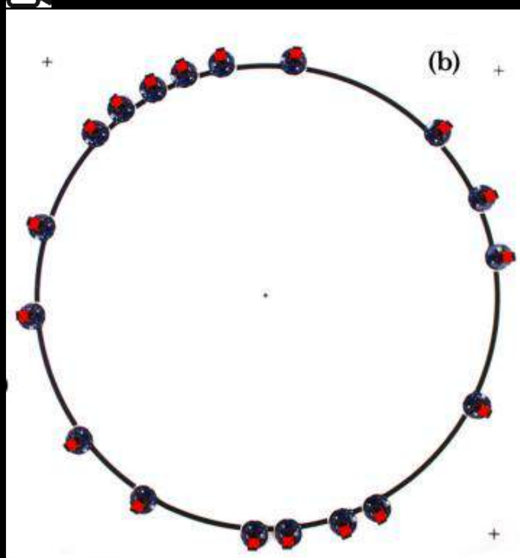
Luis Pugnaloni
UTN La Plata, Argentina

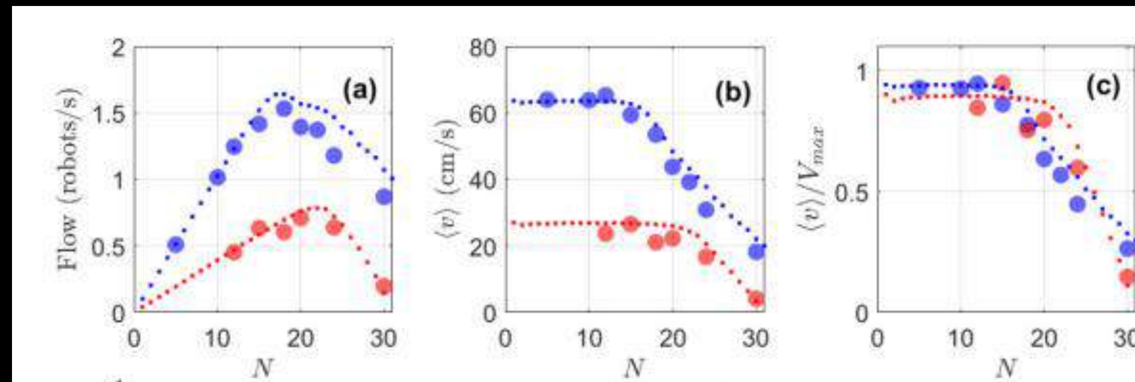
Other works (robots and pedestrians)

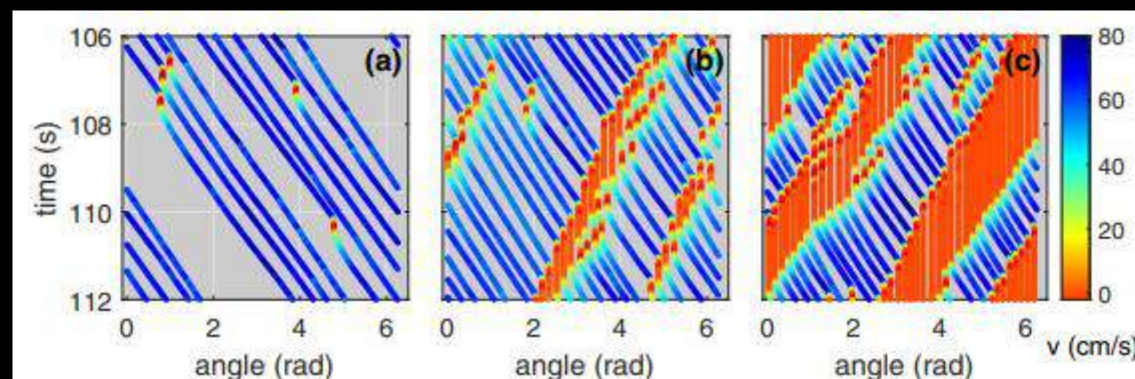
Department of Physics and
Applied Mathematics

Single file motion of robot swarms

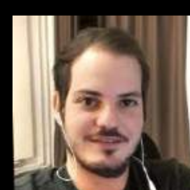








Phys. Rev. Research 6, L022037 (2024)



Laciel Alonso-Llanes (see poster)

Pedestrian motion keeping social distancing:

When moving, are we really able to respect a physical distance?
(even being aware of having to do so)

The experiment: Walk inside an enclosure with other pedestrians (don't stop) while paying attention to keep a prescribed safety distance

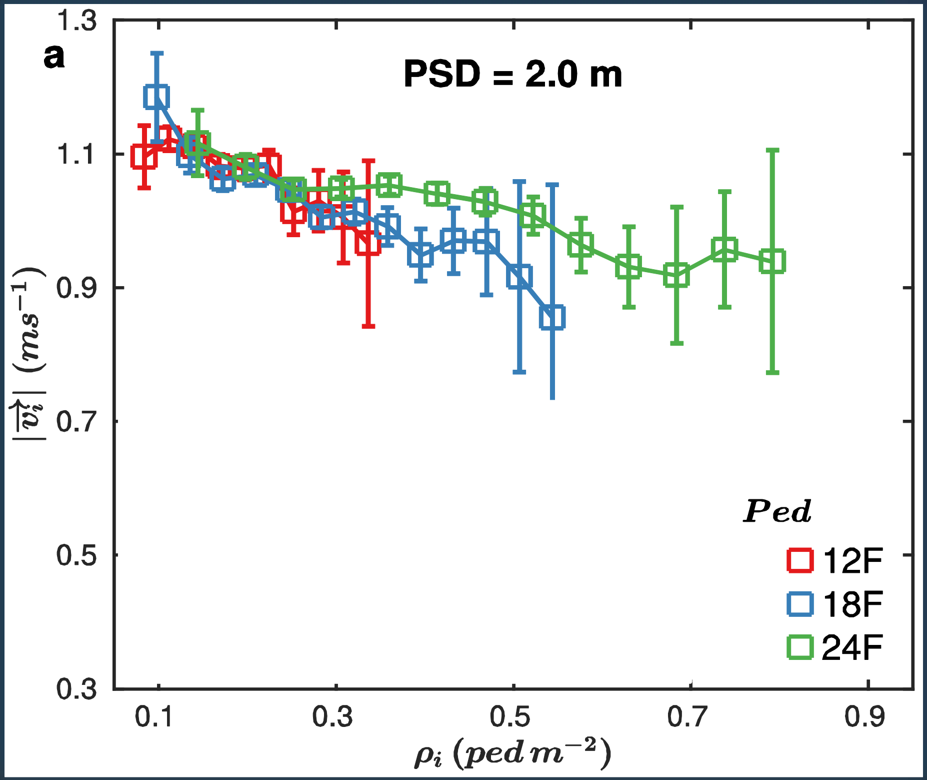
Parameters explored

Walking speed → Slow and fast

Global density → from 12 to 32 ped (in 76m²)

Prescribed safety distance → 1.5 and 2 m

Pedestrian motion keeping social distancing:

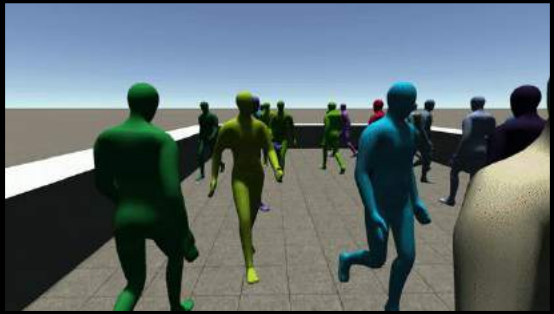


Fast walking speed

- Slight decreasing trend.
- Speed is only afected by local density values.

Slow walking speed

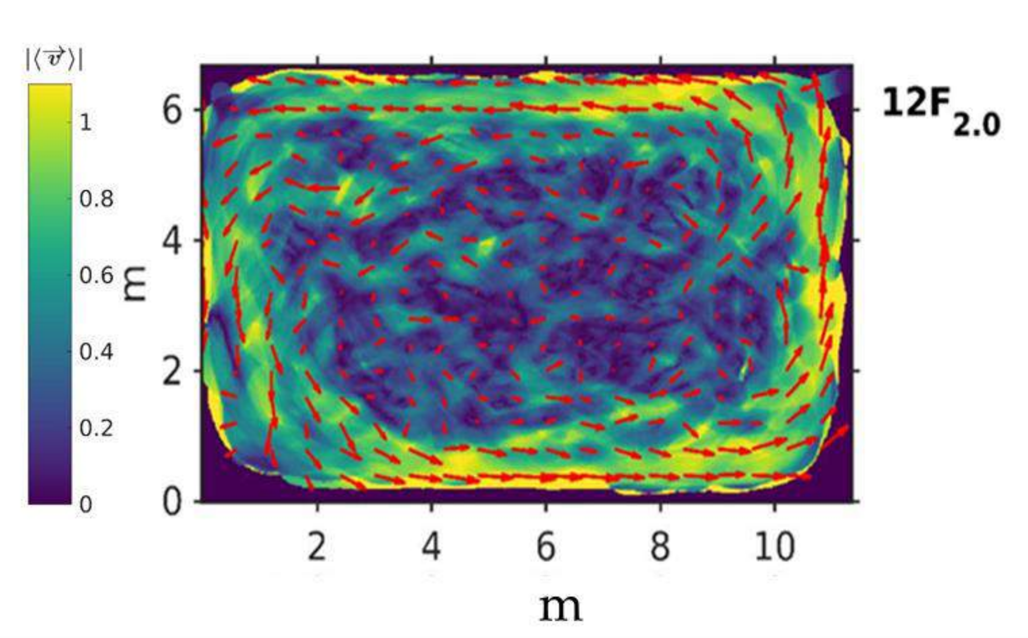
- Slight decreasing trend.
- Speed is afected by local and **global density** values.



Global perception at **slow** walking speed but not at fast?

Pedestrian motion keeping social distancing:

A serendipitous discovery: always counterclockwise rotation.



- ➢ Turning preference when facing a wall
- ➢ Lane forming (right side preference)
- ➢ Social convention
- ➢ Hand/foot/eye dominance

Robot analogy?

András Libál & Levente Varga
Babeș-Bolyai University, Romania

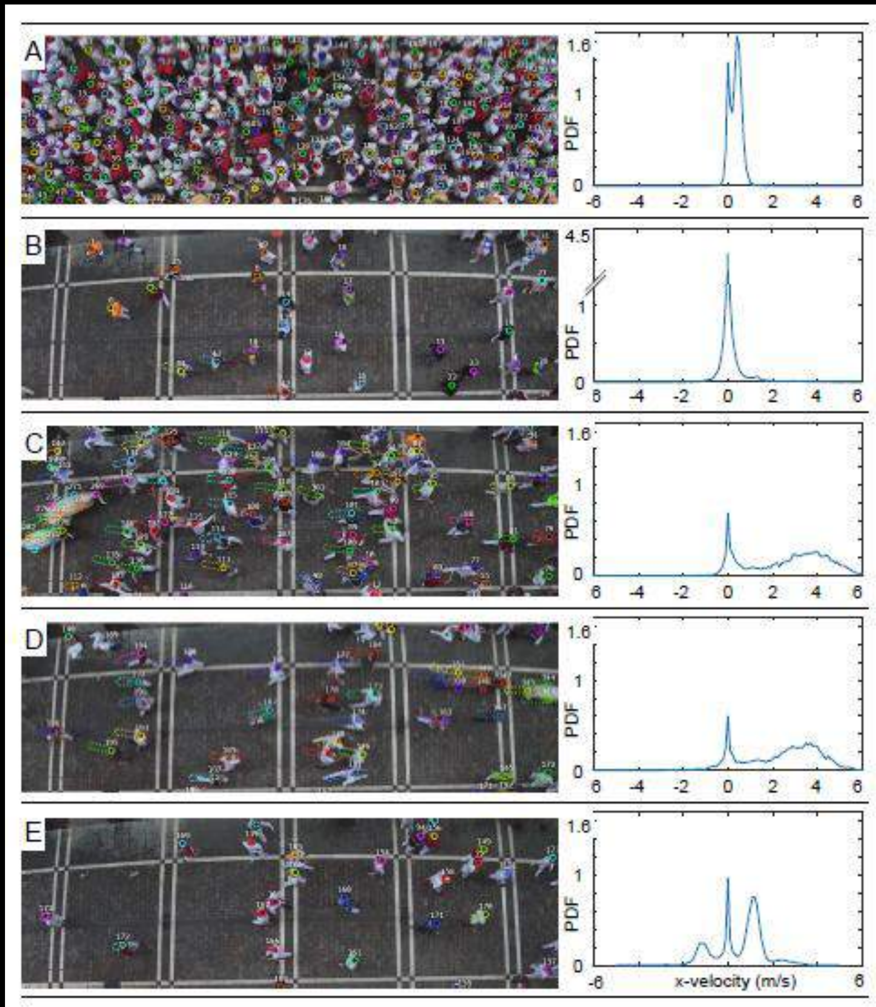
Emergent collective oscillations in massive crowds

Pamplona (Navarra) 6th July

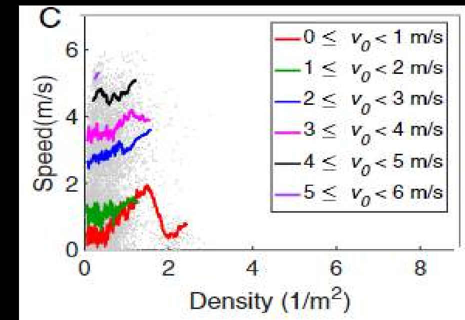
2019
X
X
2022
2023
2024 (TBD)
…

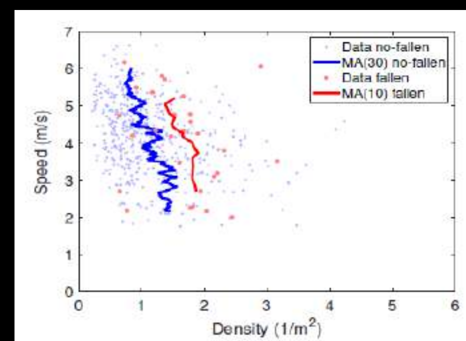
Francois Gu, Benjamin Guiselin, Nicolas Bain, Denis Bartolo
Univ. Lyon, ENS de Lyon

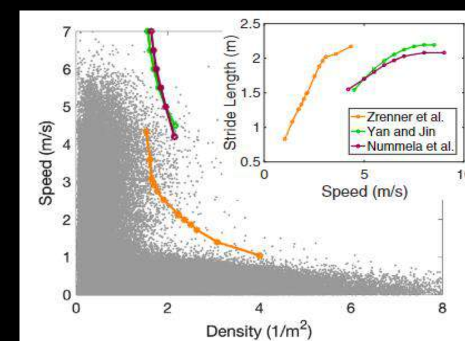
Pedestrian dynamics at the running of the bulls



2019







PNAS 2021 Vol. 118 No. 50 e2107827118

Daniel R. Parisi.
Universidad de Buenos Aires

Angel Garcimartín, Diego Maza, Raúl Cruz Hidalgo, Iñaki Echeverría.
University of Navarra, Spain.

Daniel R. Parisi
ITBA Argentina

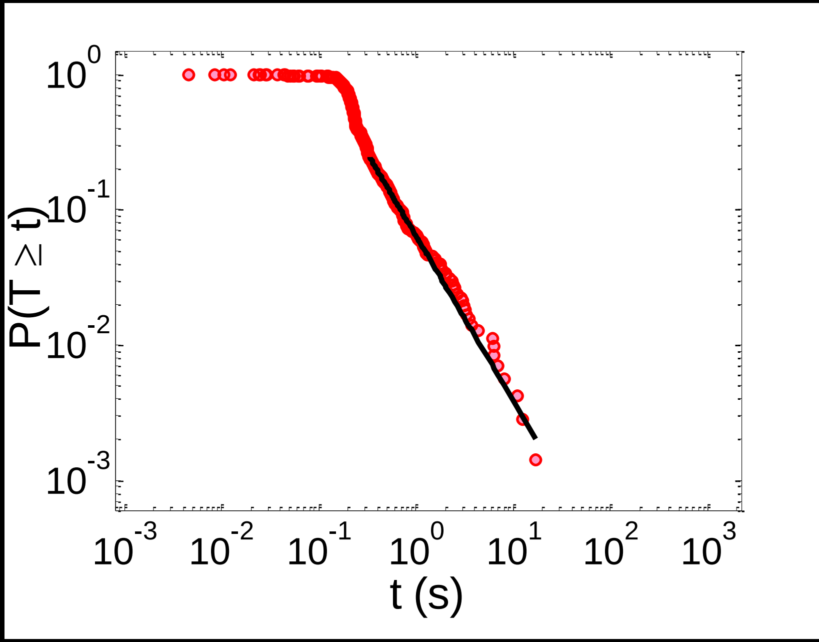
Alexandre Nicolas
CNRS / Univ. Lyon

Ignacio Pagonabarraga
University of Barcelona

Eric Clément
ESPCI París

Luis Pugnaloni
UTN La Plata, Argentina

Power-law tail



$$P \sim x^{-\alpha}$$

$$P(x) = \int_x^\infty p(x')\,\mathrm{d}x'.$$

$$p(x) = Cx^{-\alpha},$$

$$P(x) = C\int_x^\infty x'^{-\alpha}\,\mathrm{d}x' = \frac{C}{\alpha-1}x^{-(\alpha-1)}.$$

The mean value of x in our power law is given by

$$\langle x\rangle = \int_{x_{\min}}^\infty x p(x)\mathrm{d}x = C\int_{x_{\min}}^\infty x^{-\alpha+1}\mathrm{d}x$$
$$= \frac{C}{2-\alpha}\left[x^{-\alpha+2}\right]_{x_{\min}}^\infty.$$