Experiments on Granular Gases in Zero Gravity

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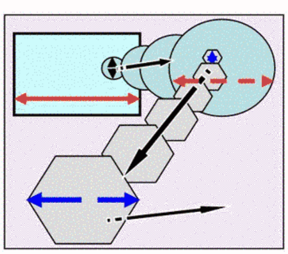
Accurate comparaisons lead to a series of puzzling questions for theorists of hydrodynamics and of disordered systems

However it requires to look to what does not work

Poudres & grains: http://www.mssmat.ecp.fr/sols/Poudres&Grains/poudres-index.htm ;

Recall: classic gas : thermodynamics behaviour

Role of scale change



Scale invariance ?

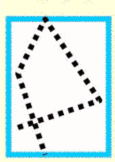
Classic gas of molecules and atoms:

$pV=Nk_BT$ applies always, i.e. $\forall$ L because the gas is homogeneous

good variables: statistics: T, N, p,….

Role of **collisions** and interaction: continuum mech. + (liquid-gas transition (phase Transition)

Role of **mean free path** l_c :



$L>l_c$: continuous mechanics

$L\leq l_c$: **Knudsen** gas => no $C_{ont}M_{ed}M_{ech}$ description

$L<<l_c$: billiard, chaos but ergodicity

=> **pv=nRT**

Important Remark :

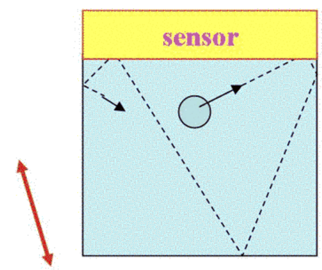
When $L<l_c$ => no sound propagation

Experimental Physics on dissipative granular gases.

Goals:

Test ergodicity assumption
Test extensivity
Test of the extension of statistical concepts (temperature, pressure,…)
Test of the validity of simulations (most of them do not take care of rotation)
Do simulations predict, with which accuracy
Test of the hydrodynamics approach

Dissipative granular gases, Dissipative Billiard



But who wants to test ask what is not working.

Outline

Question 1: Maxwell Demon on earth

1.1 Obvious that $f \neq n^2$ (predicted by Eggers)
1.2 Importance: of the shape of the flow f(n) on the nature of the transition

Question 2: Granular gas in 0g ($l_c < L/5$)

2.1 is the temperature a good measure of the pressure on a wall
2.2 Why getting an $\exp(-v/v_o)$ distribution of impacts => $f(v) \propto 1/v \exp(-v/v_o)$ => ???
Airbus A300-Og Maxus 5

Question 3: limit of non interacting particles (1 or 2 particles)

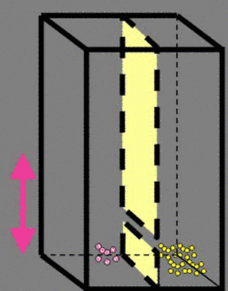
3.1 is the dynamics ergodic?

Models : $f(v) \propto 1/v \exp(-v/v_o)$ what is T
m1: boundary is a velostat or an impact generator
m2: gas with large internal dissipation

Have these behaviours been predicted by theory and/or simulations

Why not ? (1, 10, 50 balls, 500 balls)

Maxwell Demon on earth



Model : with **T(z) , n(z)** and **continuous diff. eqs.**

Model: J. Eggers, "Sand as a Maxwell demon", *Phys. Rev. Lett.* **83**, 5322-25, (1999)
J. Brey et al. (2001) , g=0,…. *PRL* **65**, , 011305 (2001)
Disc sur Phys. Stat : J. Maddox, "Slamming the door", *Nature* **247**, 903, (2002)

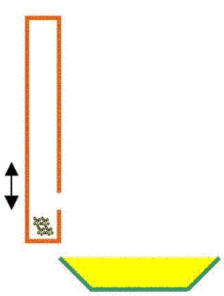
the Literature: Experiments look the same as prediction

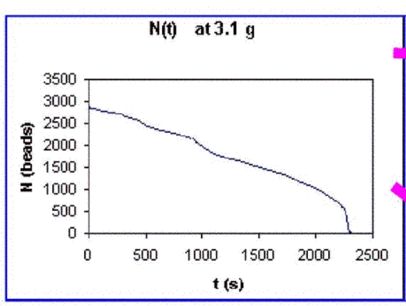
P. Evesque - ESA TT « Non Equilibrium complex matter » ; Alpe d'Huez , April 4-6, 2005 5

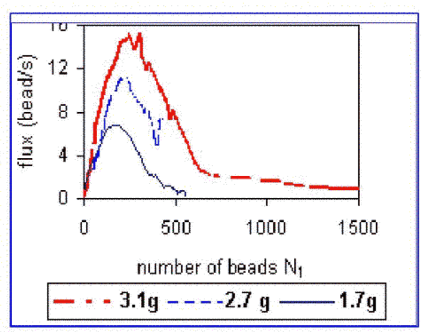
Maxwell's Demon in granular gases :

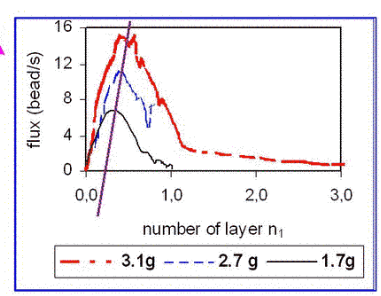
Prediction: Flow from box : $F = S\, n(z=h)\, T^{1/2}$ $F_{l\to r}=F_o N_l^2 \exp(-aN_l^2)$ with $a=4\pi g h r^2(1-e^2)/v_b^2$
(From Eggers)

From P. Jean, et al. : Poudres&Grains **13** (2002), *27*



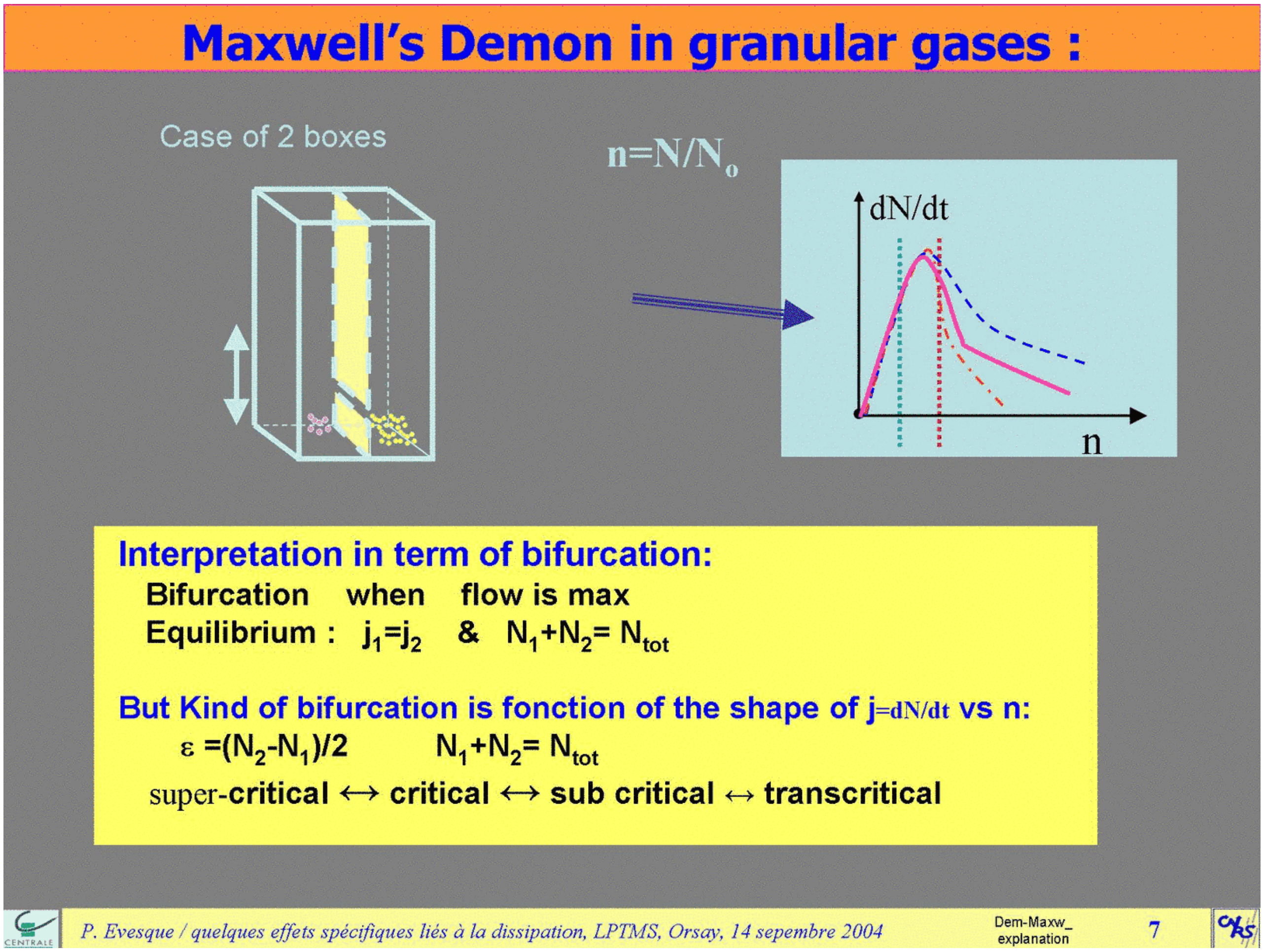






- F starts linearly and not as n² **WHY?**
- Is the shape of the ball important?
- Is the maximum varying as Γ (or as v) ?

P. Evesque / KITP – UCSB, (June 8 2005) 6


Maxwell's Demon in granular gases :
Case of 2 boxes
n=N/No
dN/dt
n
Interpretation in term of bifurcation:
Bifurcation when flow is max
Equilibrium : j1=j2 & N1+N2= Ntot
But Kind of bifurcation is fonction of the shape of j=dN/dt vs n:
ε =(N2-N1)/2 N1+N2= Ntot
super-critical ↔ critical ↔ sub critical ↔ transcritical
P. Evesque / quelques effets spécifiques liés à la dissipation, LPTMS, Orsay, 14 sepembre 2004
Dem-Maxw_ explanation
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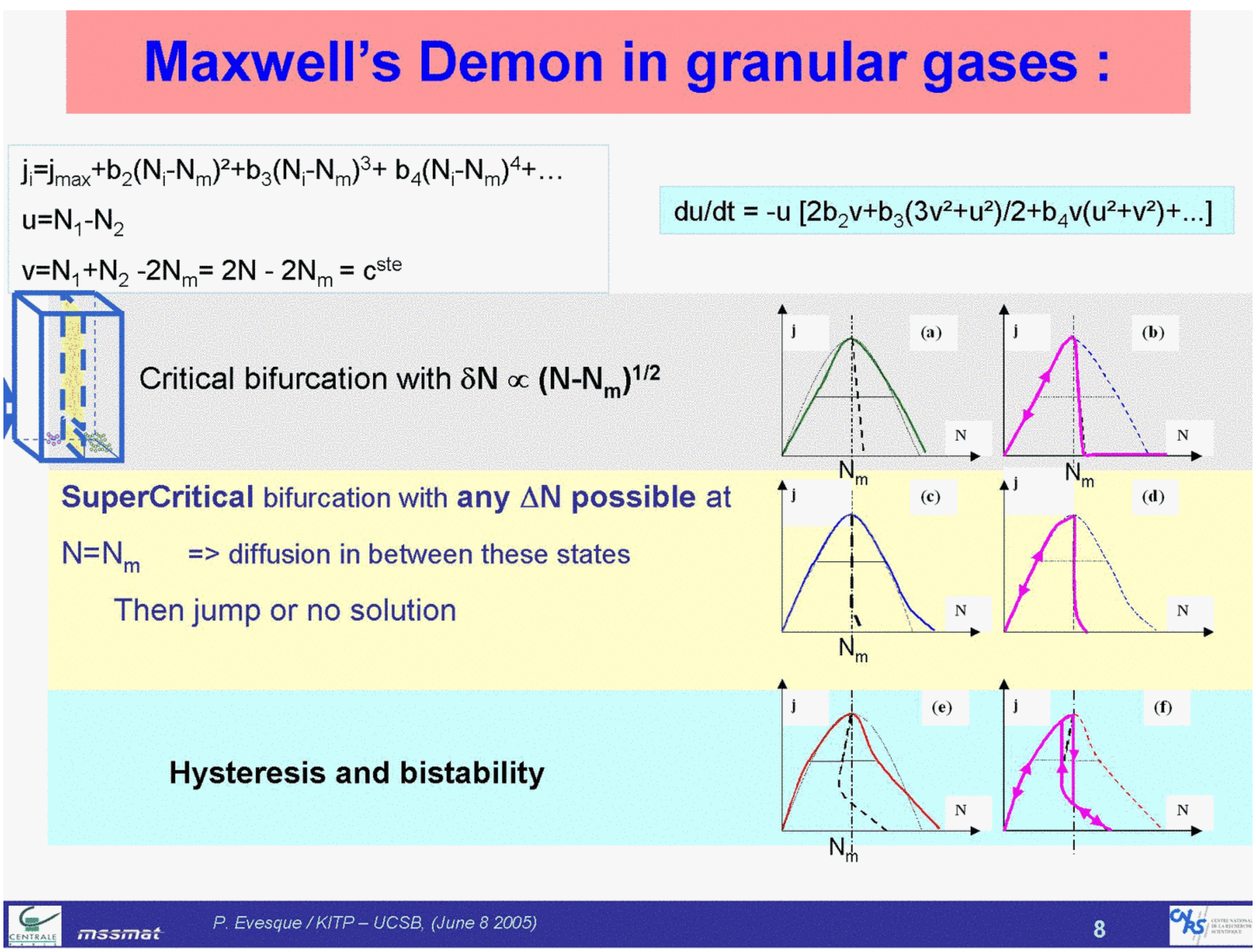
Maxwell's Demon in granular gases :
ji=jmax+b2(Ni-Nm)²+b3(Ni-Nm)³+ b4(Ni-Nm)⁴+…
u=N1-N2
v=N1+N2 -2Nm= 2N - 2Nm = cste
du/dt = -u [2b2v+b3(3v²+u²)/2+b4v(u²+v²)+…]
Critical bifurcation with δN ∝ (N-Nm)1/2
SuperCritical bifurcation with any ΔN possible at
N=Nm => diffusion in between these states
Then jump or no solution
Hysteresis and bistability
(a)
(b)
(c)
(d)
(e)
(f)
j
N
Nm
P. Evesque / KITP – UCSB, (June 8 2005)
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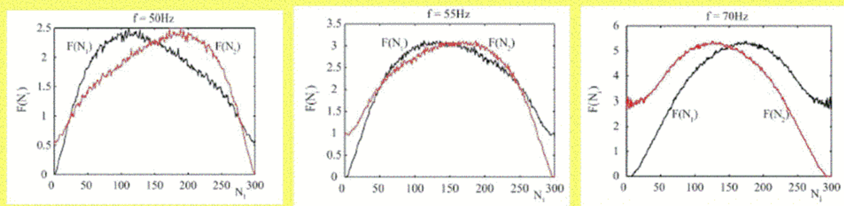
MD : Bifurcation nature:

Experiments of ***Mikkelsen et al.*** show large fluctuations, but they show also the following flow:

Flow from a compartment



*From fig.5 of R. Mikkelsen, K. vd Weele, D. vdMeer, M. v.Hecke, and D. Lohse: PHYS. REV. E **71**, 041302 (2005)*

1) Change of shape => change of bifurcation nature

2) When completely symmetric => enhancment of fluctuations due to a series of stable states

3) Interpretation proposed in the paper due to fluctuations is probably erroneous (discussion with vdMeer in progress)

But, are these variations of shapes described by theories? **No? => work**

Granular Gas in 0g

MiniTexus 5 (recalls) (1998)

Airbus A300-0g (2000-2004)

Maxus 5 (2003)

Thanks to ESA and CNES

The flights:

Start	Mini Texus 5	Airbus A300 0g	Maxus 5	Maxus 7	VIP-Crit / VIP-Gran
1992	1998	2000-2005	2003	2006	ISS?

The team :

A good experiment starts with a good complementary team

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Y. Garrabos, F. Palencia & C. Lecoutre ICM-Bordeaux-CNRS

D. Beysens, ESPCI-CEA

S. Fauve, ENS Paris

E. Falcon, ENS Lyon- CNRS

Introduction:

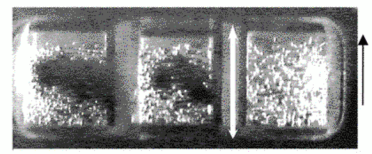
Some results from The MiniTexus 5 experiment

miniTexus 5 : Granular Gas and clustering in micro-g

Dissipative gas of real spheres or particles:

« Cluster » forms as soon as L≈ l_c

n=3 n=2 n=1



f = 60 Hz a =1mm

A good photo is better than a pressure measurement

n >1 =>L>l_c
- **Supersonic** excitation, i.e. V_{bead}<aω
- **Hyperbolic** equation for classic gas
- **Cluster** forms as soon as L>l_c
- System becomes **inhomogeneous** as soon as local **p** could have been defined

n <1 =>L<l_c
- **Supersonic** Excitation => V_{bead}< aω
- Granular gas in Knudsen regime
- no sound

Does one see shock waves ?

n<<1 ?

Does the transition exist always? even on Earth?
- **No, because gravity forces the cluster to collide with the bottom.**
- **Problem of g-jitter in micro-gravity** of Airbus **explosion of the cluster.**

=> pure micro-g result

Falcon et al. PRL (1999)

Poudres & grains **12** , 60-82 (2001); http://www.mssmat.ecp.fr/sols/Poudres&Grains/poudres-index.htm ;

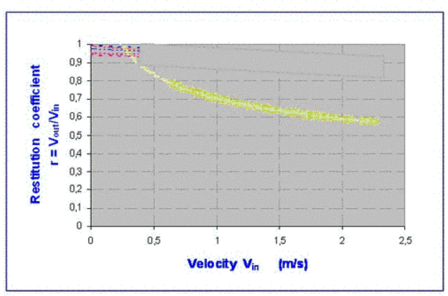
P. Evesque / Dissipative granular gases, USA, May 2004 miniT5 13

Granular Gas and clustering in micro-g :

Case n=1: δp ∝exp- {v/(aω)}$^{3/2}$ **Why?**

Rest coef used in simulations to Mimic MiniTexus5

Falcon-Mac Namara



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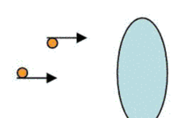
Other possible explanations:

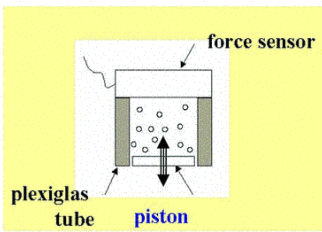


- gauge used does not work correctly (limit of sensitivity)
- crossover due to response time τ of gauge vs time between 2 collisions

Poudres & grains **12** , 60-82 (2001); http://www.mssmat.ecp.fr/rubrique.php3?id_rubrique=402;

P. Evesque / PMMH – ESPCI, Paris, (13 Mai 2004) Pressure-MiniT 14

Airbus A300-0g (& Maxus 5) experiments with n balls



Experimental condition: cylindrical cell with a piston

D=12.7mm, H=10mm, d_{ball}=2mm, N={12, 24, 36, 48};

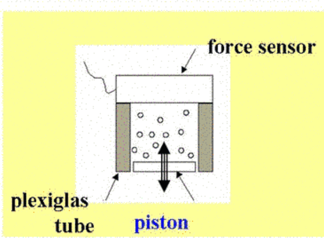
=> $l_c=HD^2/(4Nd^2)$ or

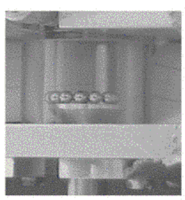
$H/l_c=N(2d/D)^2$ = {1.2 ; 2.4 ; 3.6 ; 4.75}

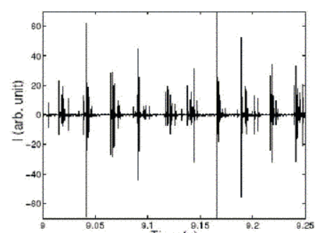
Few balls dynamics N=12-48

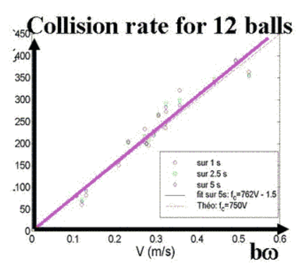
Airbus A300 mg

Poudres & grains **14** , 8-53 (2004);









Statistics on :

- Waiting times
- Amplitude of impacts
- Nb of collisions with (bω), N

results:

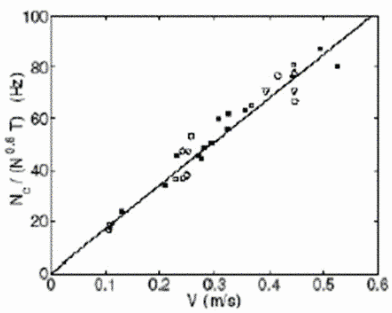
- $<V_{bead}> \approx b\omega$. For N=12
- 3d chaotic motion => looks ergodic

$N_c(T) \propto T\,(b\omega)\,N^{0.6}$

Few balls dynamics N=12-48

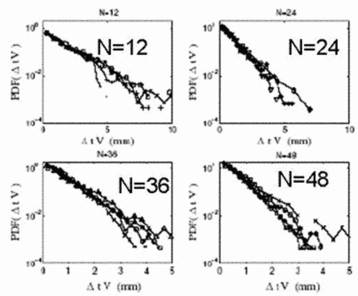
Airbus A300 mg

Poudres & grains **14** , 8-53 (2004);



Rescaling of $N_{coll}/(N^{0.6} T b\omega)$

N_{beads}=12,24,36,48



Waiting time distribution

If Randomness :

$\exp(-\Delta t/\tau_c)$

Distribution of impacts

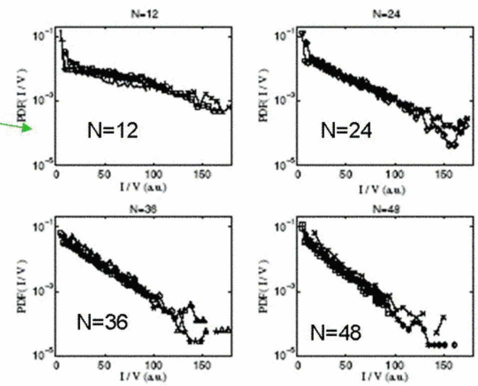


FIG. 9: functions amplitude sensor, for parameters gravity and of balls: N N=48. Symbols are 8. From [11]

distribution : $p(v) \propto e^{-v/v_o}$ (when N>12)

with $v_o \propto N_b^{0.8}(b\omega)$

$f(v) \propto (1/v) \exp[-v/(Nb\omega)]$

Is it a Boltzmann's distribution?

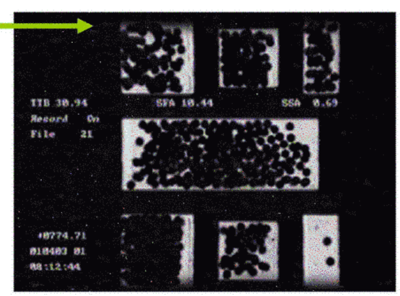
P. Evesque / Gaz Granulaires en Micro-g,GDR-MAF, Carry-le-Rouet, 18 novembre 2004 17

Confirmation by Maxus 5 exper. of the $1/v \exp(-v/v_o)$ distribution

N=50 balls

$P(I) \propto \exp[-v/(b\omega)]$

$f(v) \propto (1/v) \exp[-v/(b\omega)]$



- **Is this trend explained by classic approach?** **No**
  It contradicts the **hydrodynamics** model of Brey et al => **in discussion;**
- **∃ few attractors?** **(no motion, …, hydrodynamics?)**
- This attractor indicates a condensation at v=0 => ???

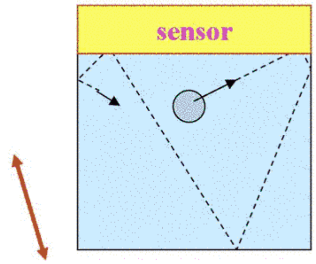
I will give a possible explanation later…..

Poudres & grains **14** , 8-53 (2004); *ib.* **15**, 1-34 (2005)

P. Evesque / PMMH – ESPCI, Paris, (13 Mai 2004) 18

1 ball experiment in 0g

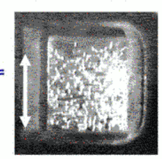
- Test of extensivity
- Limit of infinitely dilute gas
- Limit of non interacting particles
- Billiard
- In 1d: → Fermi problem



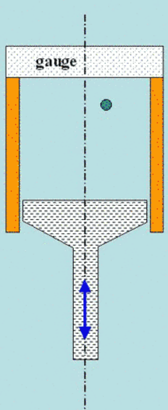
In fact this experiment has been performed to calibrate the gauge !!

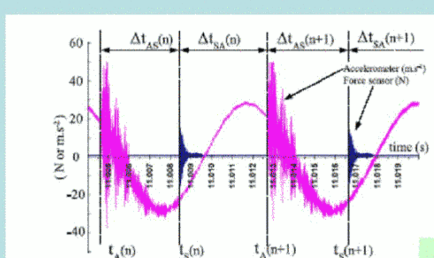
1-ball experiment

When few grains are vibrated one get a « granular gas »



f = 60 Hz ; a =1mm



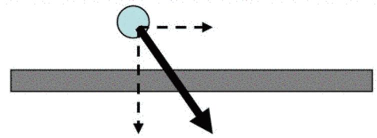


Periodic **linear** motion

1-d motion

One observes : $t_A(n) = t_A(n-1)+T$ and $t_s(n)=t_s(n-1)+T$

Collision rules



Restitution coefficient :

$v_n^+ = -\varepsilon\, v_n^-$ → periodic

During contact: Solid friction :

$F_t = k\, F_n$ → 1-d

1 sphere in a vibrated box in 1d

Periodic motion vs. Erratic motion

Collision rules in 1d:

$v_{n+1} - b_p\omega \sin(\omega t_n) = -\varepsilon_p [v_n - b_p\, \omega \sin(\omega t_n)]$

$v_{n+2} = -\varepsilon_g v_{n+1}$

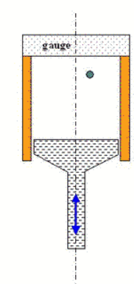
Periodic conditions:

$v_{n+2} = \varepsilon_p\, \varepsilon_g v_n \;+ (1+\varepsilon_p)\, b_p\, \omega \sin(\omega t_{n+1}) = v_n$

$L(\varepsilon_g+1) + b_p\, \varepsilon_g \cos(\omega t_n) + b_p \cos(\omega t_{n+1}) = \varepsilon_g v_n\, (t_{n+1} - t_n)$

Solution:

$V = L\omega/\pi = \; b_p\, \omega\, (1+\varepsilon_p) \sin(\chi)/[1-\varepsilon_p\, \varepsilon_g]$



Periodic motion :

$b/L > [1-\varepsilon_p\, \varepsilon_g] / [\pi\, (1+\varepsilon_p)]$

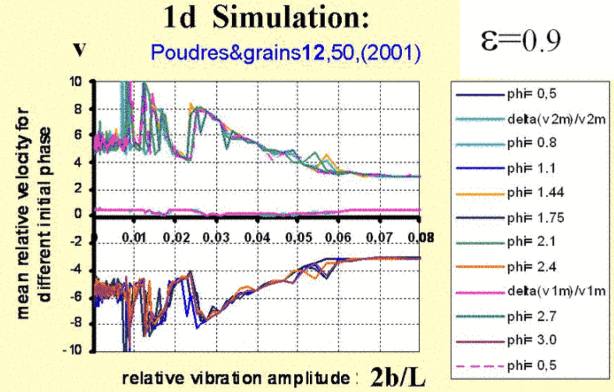
Erratic motion :

$b/L < [1-\varepsilon_p\, \varepsilon_g] / [\pi\, (1+\varepsilon_p)]$

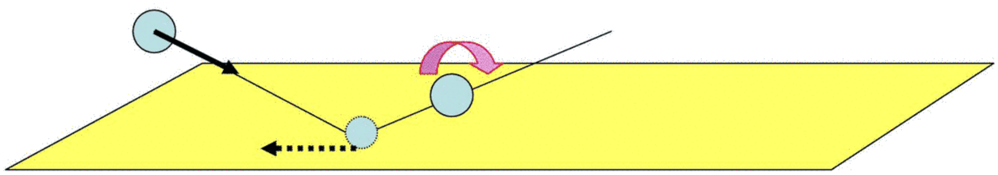
1d Simulation:

Poudres&grains12,50,(2001)

$\varepsilon = 0.9$



Why 1-d linear dynamics ?



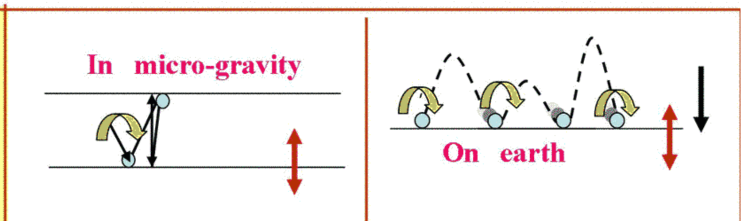
After the collision the ball rotates

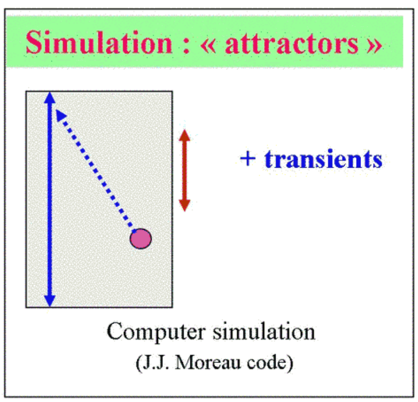
Speed of contact

One single sphere in a vibrated box

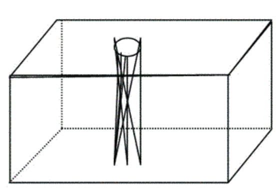
Why the 1d motion is stabilised:

Rotation is inhibited, because it dissipates due to alternate condition on rotation rules at top and bottom during a round trip.





Question : Stability of this « eigen » mode ?



⇒ **Surface density n<3%**

⇒ **reduction of the space dimensionality** of the degrees of freedom from

13-d → 1-d + random noise

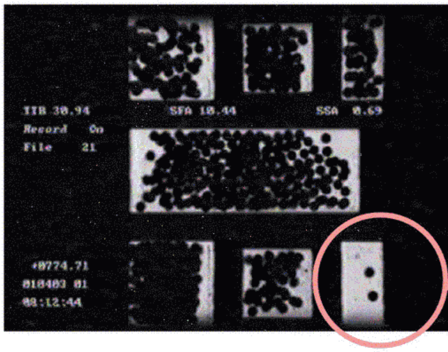
[(3+3 (for rotation) + 3+3 (translation) + 1 (time excitation)] to (x,y) **+random noise**.

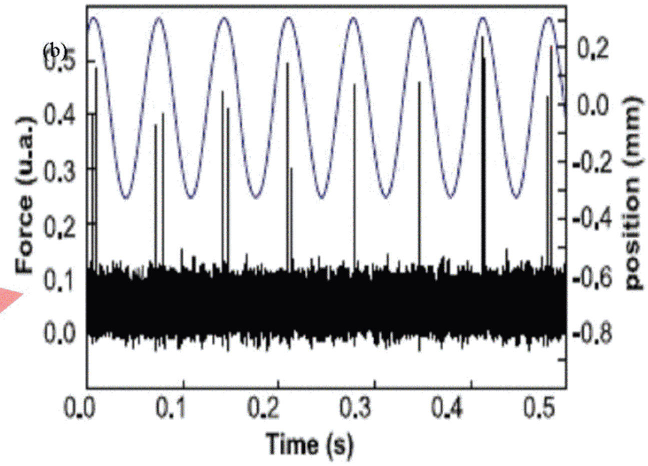
- The largest path is stabilised

Conclusion: Non ergodicity; regular rule in dissipative systems.
Parallel with: Classic billiard, quantum well electronics
=> Here: also **usefull to calibrate a gauge**

2-ball synchronisation in a vibrated box

From Maxus 5 (1st April 2003)





Better synchonised than the 1-ball case

Partial synchronisation in a vibrated box

From Airbus milli-g and ground-based experiments

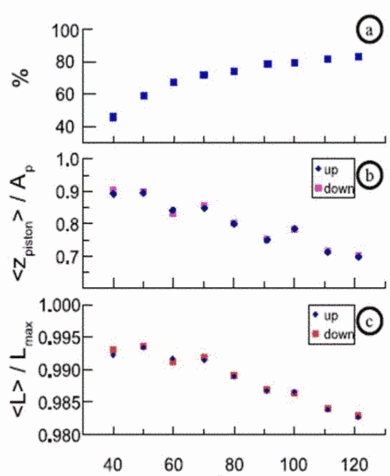
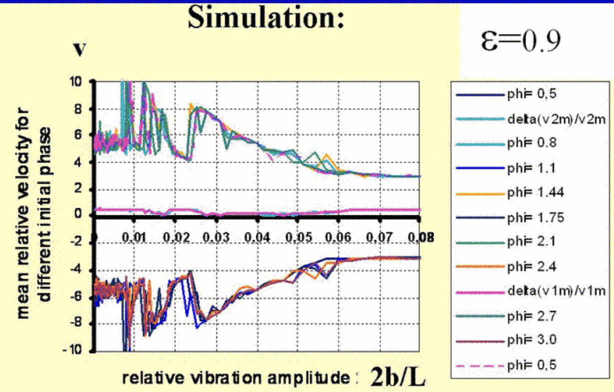


Figure : (a) Resonant rate (%); (b) Relative piston position; and (c) Relative cavity length, as a function of frequency, where L_{max} = L-d+ A_p. A_p=b is the amplitude of vibration. In part b and c, the up and down trajectories of the ball are hardly distinguished at this scale.

Better synchronisation at :

- large Frequency
- large Speed
- when phase is near $\pi/2$

Simulation: ε=0.9



Conclusion of 1-ball exp: thanks to ESA and CNES

1-ball experiment and 2-ball experiment

- Role of micro-g — 1g-bouncing/0g-bouncing
- Role of rotation — (micro-g result)
- Synchronistation for b/L> α — (to be tested) — (simulated by M. Leconte)
- Reduction of the efficient phase space — (dissipation) — 1-d simulation
- Rate of synchronisation — (simulated by M. Leconte)
- Restitution coefficient depends little on v — (micro-g result)
- bω is subsonic => 1d simul are correct — (micro-g result)

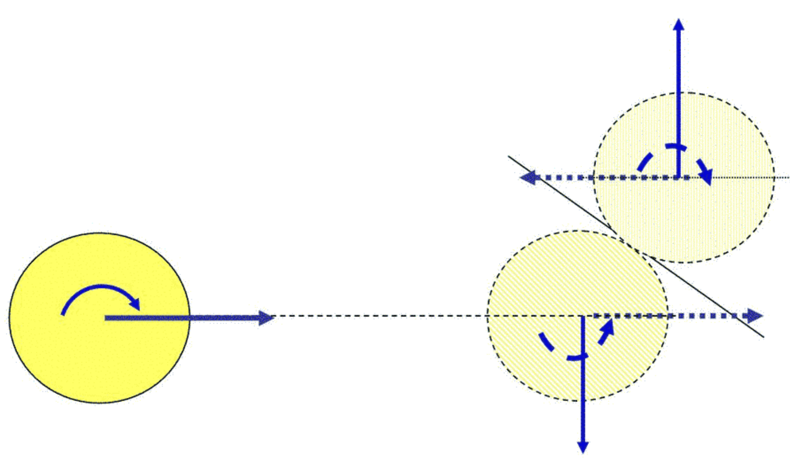
Revisiting billiard — shape of the container, of the ball….

parallel with other pb: microfluidic, electron,…

Fermi problem — sensitivity to $\varepsilon_{restitution}$

What are the consequences of dissipation due to rotation for larger density of grains ?

Dissipition in ball-ball collisions due to solid friction



Freezing of 1 or 2 degrees of freedom at each collision

Possible Interpretations

of the distribution

$f(v) \propto (1/v) \exp(-v/v_o)$

2 models:

- Boundary condition: velostat instead of thermostat
- Simple dissipative model

Another Statistical modelling of speed in granular gas

N_1 N_2 … N_i N_{i+1} … E or mv

(1) **Number of complexions:** $W(N, N_1, .., N_i, \ldots) = N! / [\pi_i(N_i!)]$

Preservation rules:

(2) Energy is given: => $U = cste = E_1N_1 + E_2N_2 + \ldots E_iN_i + \ldots$ Or $m(v_1N_1 + \ldots v_iN_i + \ldots) = cste$

Nb of particles given: => $N = cste = N_1 + N_2 + \ldots N_i + \ldots$

Max of disorder=> W is Max => $dW = 0$

Stirling formula: $n! = n \, Log(n) - n$

(3) **Lagrange multipliers:** $\lambda_1, \lambda_2, \lambda_3$

=> $\lambda_1 dU + \lambda_2 dN + \lambda_3 dW = 0 = \Sigma_i [\lambda_1 E_i + \lambda_2 + \lambda_3 Log(N_i)] \, dN_i$

=> $N_i = A e^{-\beta E_i}$ with $\beta = -\lambda_1/\lambda_2 = 1/(kT)$ — or $N_i = A e^{-\beta' v_i}$

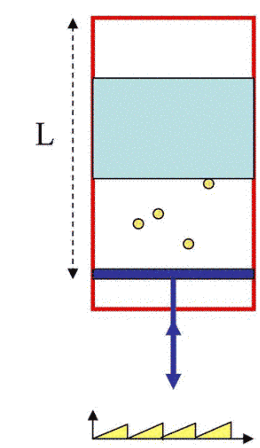
thermostat — *poudres & grains* 13 (2), 20-26 (2002) — velostat

2^{nd} attempt of a simple granular gas modelling with strong dissipation

At medium concentration $l_c<2L$

$n > \approx 0.5$

The model:



Excitation:

T ; $V_2 >> V_p$; $b << L$

ASSUMPTIONS:

- **ball-ball Collisions** :
  either interchange speeds **(1-p)** or dissipate completely **(p)**
- $\varepsilon_{wall}=1$ => $v'=v+2V_p$
- $l_c=L/(4n)$ with $n=Nd^2/D^2$

Questions: P(v) = probability of impact at speed v (?)
f(v) = distribution of speed v (?)

SOLUTION :

- $P(v_o+v) = P(v_o) \exp-[(v/(2V_p))*(2Lp/l_c)]$
  => $P(v) \approx \exp(-4npv/V_p)$
- As a roundtrip lasts $\tau=2L/v$ => Time averaging
  => $f(v) \propto (1/v) \exp(-4npv/V_p)$

Prediction

The result: $P(v) \approx \exp(-4npv/V_p)$ => $\langle v \rangle = V_p/(4np)$

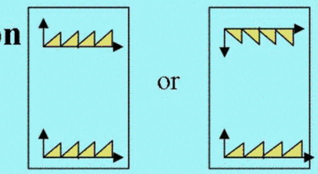
1) Supersonic excitation or $\langle v \rangle = v_o < V_p$ => $4np > 1$ => **$n > 1/4$** **(observed)**

2) Difference between 1g vs. 0g => $\tau = v/g$ *vs.* **$\tau = L/v$** (observed?)

Normal scaling; $f(v) \propto v \exp(-v/v_o)$ *vs.* Anomalous scaling $f(v) \propto (1/v) \exp(-v/v_o)$

3) Vibrating box *vs.* **2 pistons working in opposite direction**

No net gain after a roundtrip *vs.* A gain



4) In 3d : p=1

5) Link with Boltzmann equation formalism

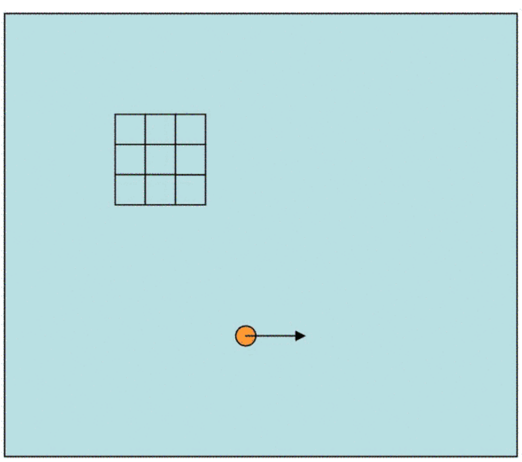
Diffusive ↔ propagative (non local)

poudres & grains **14** (2) pp 8-53 (Mai 2004); *ibid* **15** (1) pp 1-16 (février 2005).); *ibid* **15** (2) pp 18-34 (mars 2005).
http://www.mssmat.ecp.fr/sols/Poudres&Grains/poudres-index.htm
And to appear in Powders & Grains 05

P. Evesque - ESA TT « Non Equilibrium complex matter » ; Alpe d'Huez , April 4-6, 2005 33

Propagative *vs.* diffusive Boltzmann Equation

$\partial f_{coll} / \partial t = - \int \sigma(p_1,p_2) + \int \sigma(p'_1,p'_2)$ f enters in σ



In general

When ∃ good local means => T(f), P(f)…

⇒ Diffusion of f (T,P) :

$\partial f/\partial x$ = interchange of particles from adjacent volumes

Here:

$f(v,x+vdt,t+dt) = f(v,x,t)$ => f propagates far,

then ball collides and dissipates, even for $L/l_c=4$

P. Evesque / PMMH – ESPCI, Paris, (13 Mai 2004) 34

Conclusion

Are these results described in literature ? (no)

Are these results obtained with simulations ? (no)

Maxwell Demon:

- effect of shape of flow curve with n => fluctuations, (in discussion with vdMeer)

1 ball case:

- related to other important problems: dissipative Billiard , Fermi problem , particle dynamics in a quantum well…
- strong effect of rotation + friction: improve the dissipation
- large reduction of the number of freedom degrees (13 → 1)
- Has it been studied numerically ?

Granular gas in 0g : Experiments concern N<50 balls

♦ Anomalous distribution of speed $f(v) \propto (1/v) \exp(-v/v_o)$ where is T_{empera}

- Are rotations involved and how ? + friction => improve the dissipation
- short range effect (few lc)
- ∃ an uncoupled « immobile » gas ?
- ∃ few attractors? (discussion with Brey on conditions to observe hydrodynamics gas)

Thanks to

ESA

&

CNES

Conclusion

Evaluating the relative difficulty between statics and flows

When I started granular physics (1987):

statics: single configuration with no mixing => large memory effect,

flows: good mixing of configurations => good averaging

=> I thought statics is more complicated than flows

Now: due to rotations

statics: lot of internal degrees of freedom => good averaging,

flows: large dissipation controlled by uncontrolled degrees of freedoms

=> I think flows are more complicated than statics

Thanks to ESA and CNES

The flights:

Start	Mini Texus 5	Airbus A300 0g	Maxus 5	Maxus 7	{VIP-Crit, VIP-Gran}
1992	1998	2000-2005	2003	2006	ISS

The team :

A good experiment starts with a good complementary team

P. Evesque, ECP-CNRS

Y. Garrabos, F. Palencia & C. Lecoutre ICM-Bordeaux-CNRS

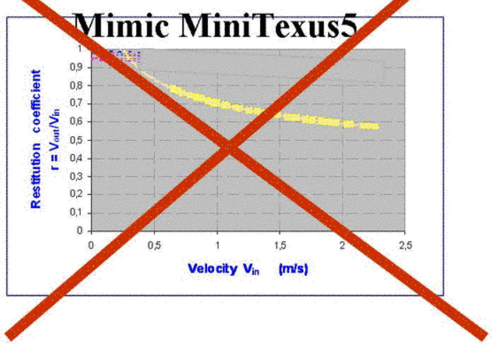
D. Beysens, ESPCI-CEA

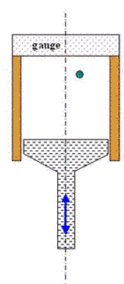
S. Fauve, ENS Paris

E. Falcon, ENS Lyon- CNRS

Measure of the restitution coefficient

Rest coef used in simulations to Mimic MiniTexus5





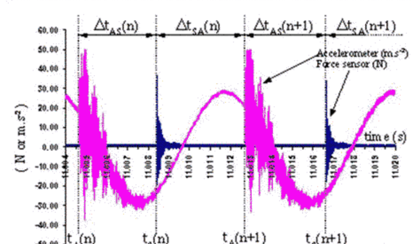
The modelling with ε which depends on V as V^{α} is not good.

=> new modelling

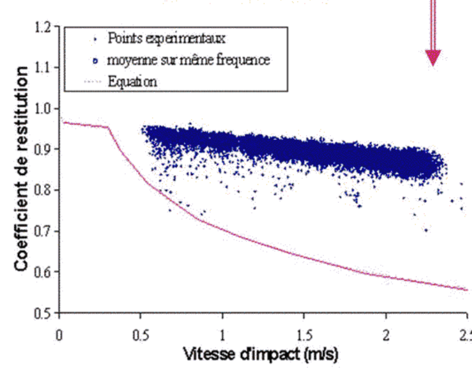
(Hertz law + viscous damping)

Most simulations do not take into account rotation (micro-g result)

Stainless steel ball : d= 2mm



$(\ldots, t_n, \varphi_n, t_{n+1}, \varphi_{n+1} \ldots)$



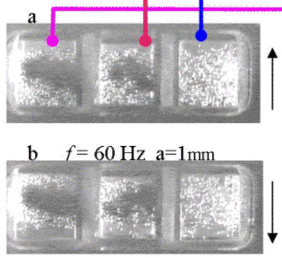
Granular Gas and clustering in micro-g :

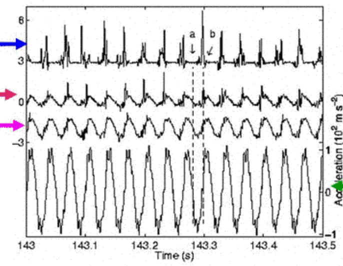
MiniTexus 5, Fév. 1998 :

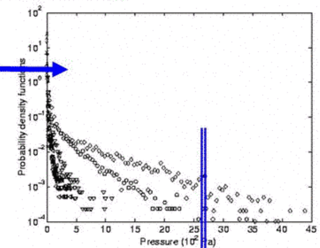
image recording + pressure recording + acceleration recording

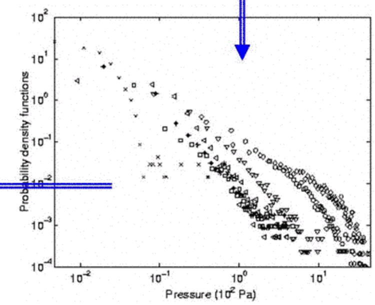
n=1 , n=2, n=3

a, ω









Renormalisation

$\Rightarrow p \propto (a\omega)^{3/2}$

Why?

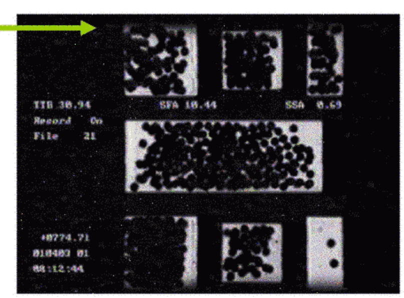
Falcon et al. PRL (1999)

Confirmation by Maxus 5 exp of the 1/v exp(-v/v$_o$) distribution?

P(I) ∝ exp [-v/(bω)]

N=50 balls

f(v) ∝ (1/v) exp [-v/(bω)]



So Airbus exp have found : p(I) ∝ exp[-I/I$_o$] with $I_o \propto (b\omega)N^{0.8}$

Dissipative model predicts : p(I) varies as p(I=mv)=exp(-v/v$_o$) with $v_o = Nb\omega$

2 problems remain:

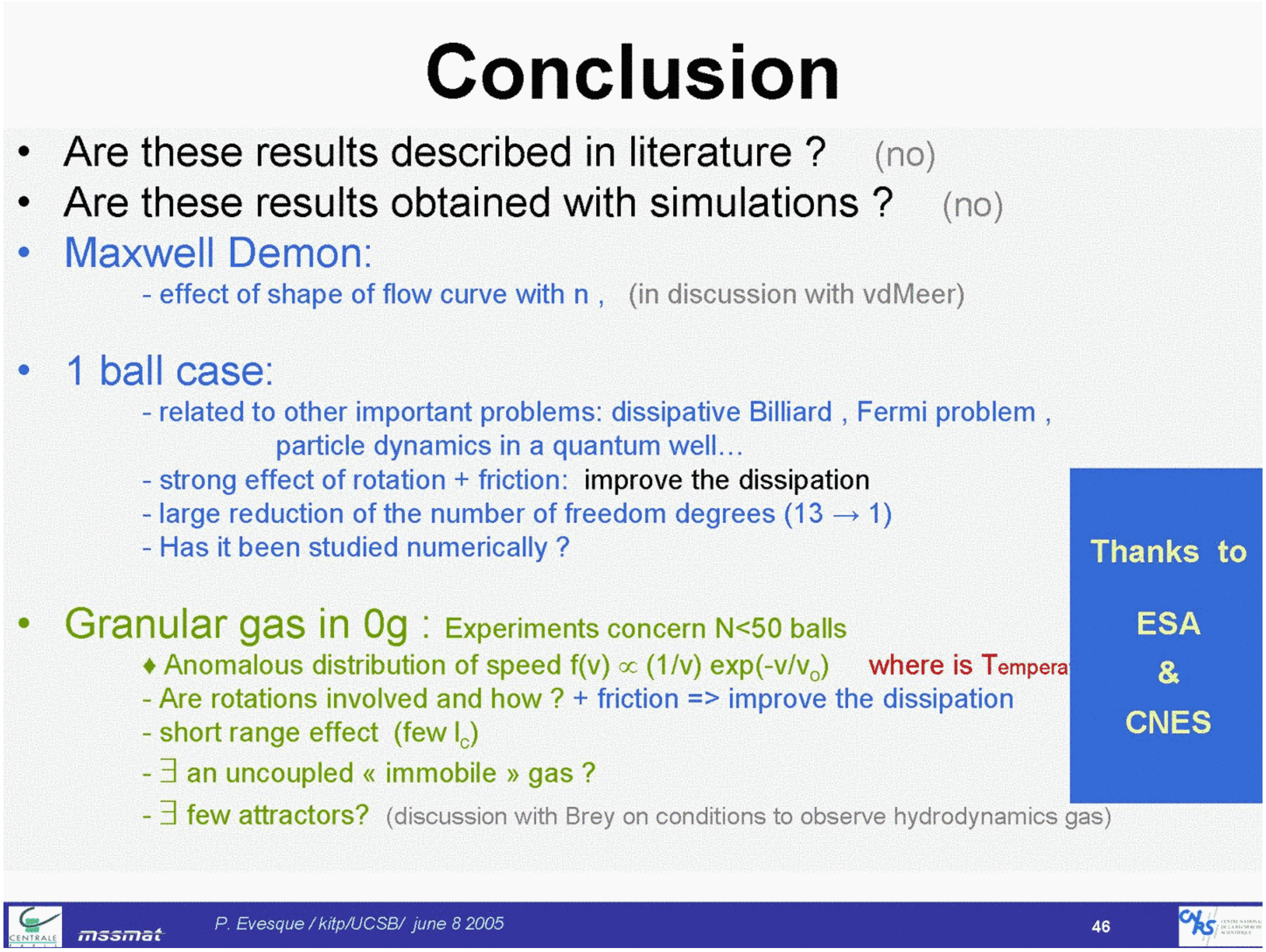
(i) total collisions $N_c \propto T(b\omega)N^{0.6}$ (but due likely to a change of normalisation prefactor)?

(ii) gauge calibration: $I \propto v^{6/5}$ instead of $I \propto v$

Conclusion: Range for Granular gas with e^{-v/v_o} behaviour: $n \approx$ 0.03-to-1-3

It is not a Boltzmann's distribution? => ≠(i) Caravelle exp

∃ An other modelling: vibrator is a velostat or an impact generator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P. Evesque / kitp/UCSB/ june 8 2005
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