On the effectiveness of the collapse in the Diósi-Penrose model

Laria Figurato
University of Trieste
INFN- Trieste Section

ECT* workshop
"Modern Odyssey: Quantum Gravity meets Quantum Collapse at Atomic and Nuclear physics energy scales in the Cosmic Silence"
Trento, Jun 3-7

01.

Introduction

Introduction

- Measurement problem

length parameter R_0

DP model

F. Karolyhazy, Il Nuovo Cimento A (1965-1970) **42**, 390 (1966).

A. Tilloy and L. Diósi, Physical Review D **93**, 024026 (2016).

Introduction

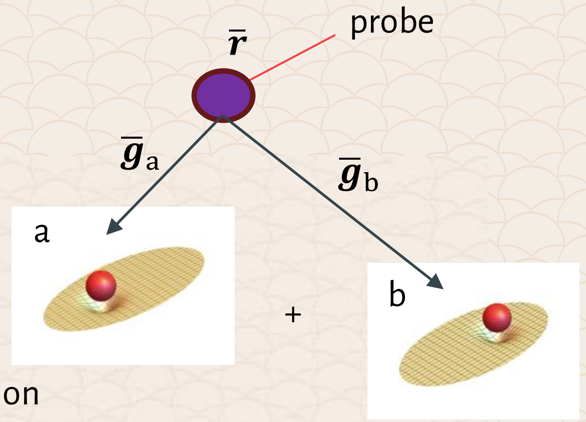
- Measurement problem

length parameter R_0

DP model

$$\int d\bar{r}\,[g_a(\bar{r}) - g_b(\bar{r})]^2 \sim \Delta E$$

particle in a spatial superposition



Penrose proposal
(badly sketched)

Introduction

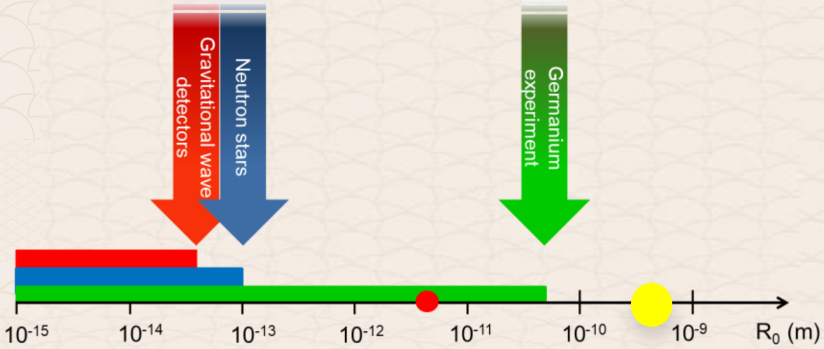
- Measurement problem

length parameter R_0

DP model

Different predictions of DP with respect to QM experimental bounds

lower bounds



I. J. Arnquist, et al. (Majorana Collaboration), Phys. Rev. Lett. 129, 080401 (2022)

Introduction

- Measurement problem

length parameter R_0

DP model

Different predictions of DP with respect to QM experimental bounds

lower bounds

- Theoretical
- if R_0 too large

collapse effect too weak

collapse not sufficiently strong to collapse macro objects

upper bound

request the collapse

the smallest visible object in a spatial superposition on a time scale that is comparable with the time resolution of the human eye

02

The DP model

L. Diosi, Physics letters A **120**, 377 (1987).
L. Diósi, Physical Review A **40**, 1165 (1989).
R. Penrose, Gen. Rel. Grav. 28: 581-600 (1996).

$$\frac{\mathrm{d}}{\mathrm{d}t}\hat{\rho}(t) = -\frac{i}{\hbar}\left[\hat{H}_N, \hat{\rho}(t)\right] + \mathcal{D}[\hat{\rho}(t)]$$

DP master equation

$$\mathcal{D}[\hat{\rho}(t)] = -\frac{4\pi G}{\hbar}\int \mathrm{d}\mathbf{r}\int \mathrm{d}\mathbf{r}'\,\frac{1}{|\mathbf{r}-\mathbf{r}'|}\,[\hat{\mu}(\mathbf{r}'),[\hat{\mu}(\mathbf{r}),\hat{\rho}(t)]]$$

DP non-unitary term responsible for the collapse

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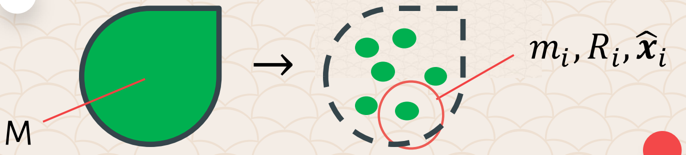
DP master equation



rigid body approximation

$$\mathcal{D}[\hat{\rho}(t)] = -\frac{4\pi G}{\hbar}\int \mathrm{d}\mathbf{r}\int \mathrm{d}\mathbf{r}'\,\frac{1}{|\mathbf{r}-\mathbf{r}'|}\,[\hat{\mu}(\mathbf{r}'),[\hat{\mu}(\mathbf{r}),\hat{\rho}(t)]]$$

DP non-unitary term responsible for the collapse

$$\hat{\mu}(\mathbf{r}) = \sum_{i=1}^{N}\frac{m_i}{(2\pi R_{\mathrm{eff},i}^2)^{3/2}}e^{-\frac{(\mathbf{r}-\hat{\mathbf{x}}_i)^2}{2R_{\mathrm{eff},i}^2}}$$

mass density

free parameter

radius of the particle

$$R_{\mathrm{eff},i} = \sqrt{R_0^2 + R_i^2}$$

effective radius

Aim

Upper bound on R_0

Dynamics of the CM degrees of freedom

interested in the collapse dynamics
→ neglect the free evolution

Aim

Upper bound on R_0

Dynamics of the CM degrees of freedom

interested in the collapse dynamics
→ neglect the free evolution

$$\langle \mathbf{x}|\hat{\rho}(t)|\mathbf{y}\rangle = \langle \mathbf{x}|\hat{\rho}(0)|\mathbf{y}\rangle \exp\left[-t/\tau(\mathbf{x}-\mathbf{y})\right]$$

CM density matrix

Aim

Upper bound on R_0

Dynamics of the CM degrees of freedom

interested in the collapse dynamics
→ neglect the free evolution

$$\langle \mathbf{x}|\hat{\rho}(t)|\mathbf{y}\rangle = \langle \mathbf{x}|\hat{\rho}(0)|\mathbf{y}\rangle \exp\left[-t/\tau(\mathbf{x}-\mathbf{y})\right]$$

CM density matrix

$$\tau(\mathbf{d}) = \hbar/\Delta E(\mathbf{d})$$

collapse timescale

$$\Delta E(\mathbf{d}) = -8\pi G \int \mathrm{d}\mathbf{r} \int \mathrm{d}\mathbf{r}' \, \frac{\mu(\mathbf{r})\left[\mu(\mathbf{r}'+\mathbf{d}) - \mu(\mathbf{r}')\right]}{|\mathbf{r}-\mathbf{r}'|}$$

$$\Delta E(\mathbf{d}) = 8\pi G m^2 \sum_{i=1}^{N} \sum_{j=1}^{N} f(\mathbf{r}_{ij}, R_0, \mathbf{d})$$

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CM system in a spatial superposition **d**

compute the **collapse time** $\tau(\mathbf{d})$

time-scale after which the collapse is effective

$$\Delta E(\mathbf{d}) = 8\pi G m^2 \sum_{i=1}^{N} \sum_{j=1}^{N} f(\mathbf{r}_{ij}, R_0, \mathbf{d})$$

CM system in a spatial superposition $\mathbf{d}$
compute the **collapse time** $\tau(\mathbf{d})$

time-scale after which the collapse is effective

exp

if after t the system is still observed
in a superposition
R_0 determining τ is exp excluded

lower bound on R_0

$$\Delta E(\mathbf{d}) = 8\pi G m^2 \sum_{i=1}^{N}\sum_{j=1}^{N} f(\mathbf{r}_{ij}, R_0, \mathbf{d})$$

CM system in a spatial superposition $\mathbf{d}$
compute the **collapse time** $\tau(\mathbf{d})$

time-scale after which the collapse is effective

theo

We don't have to see
macro quantum superpositions

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ambiguity

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lower bound on R_0

theo

ambiguity

We don't have to see macro quantum superpositions

DP model must collapse any macroscopical object within the observational time-scale τ_{obs}

$$\tau(\mathbf{d}) < \tau_{obs}$$

upper bound on R_0

03

Application

P. Blake, E. Hill, A. Castro Neto, K. Novoselov, D. Jiang, R. Yang, T. Booth, and A. Geim, Applied physics letters **91** (2007).

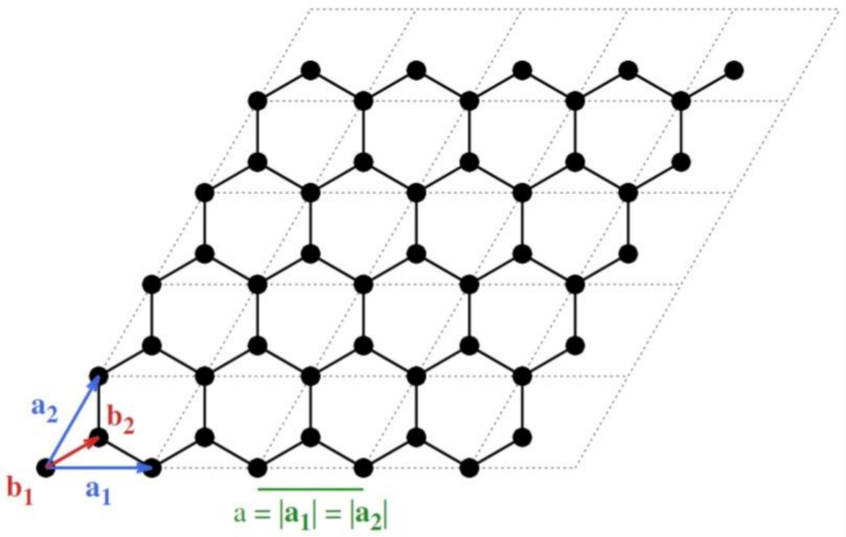
G. H. Jacobs, *Comparative psychology of vision* (Wiley Online Library, 2003) pp. 47–70.

Fix the system of interest

The measurement is performed with the **human eye**

$$\tau_{obs} = 0.01s$$

Fix the system of interest



The measurement is performed with the **human eye**

$\tau_{obs} = 0.01s$

$L_{obs} = 25\mu m$

$N = 2 \times 10^{10}$

Plate made of a single layer of graphene

Fix the system of interest

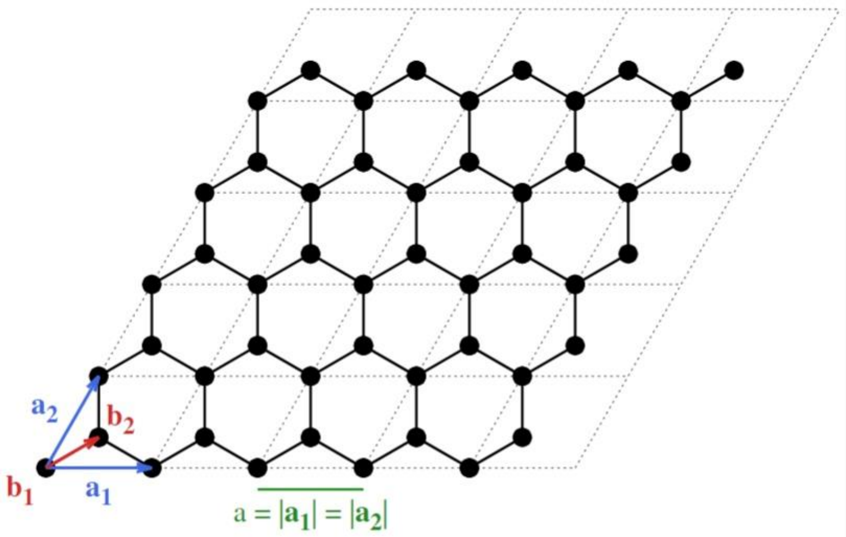


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Plate made of a single layer of graphene

$(|\mathbf{x}\rangle + |\mathbf{x}+\mathbf{d}\rangle)/\sqrt{2}$

CM spatial superposition

$d = 4L = 100\mu m$

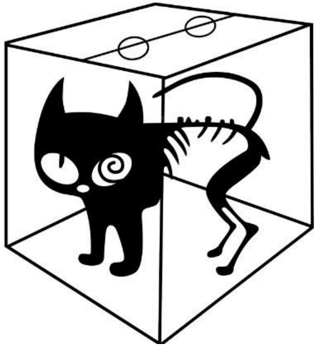
superposition distance

here

+

there

cat state



Quantify $\tau(\mathbf{d})$ by explicitly computing $\Delta E(\mathbf{d})$

sum of N^2 terms

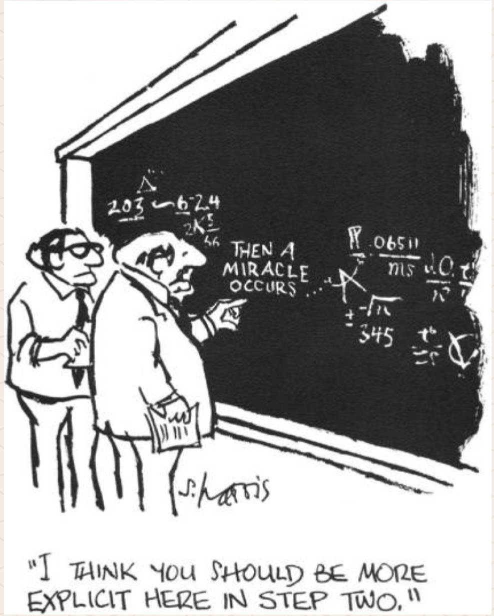
$$\sum_{i=1}^{N}\sum_{j=1}^{N} f(\mathbf{r}_{ij}, R_0, \mathbf{d})$$

Quantify $\tau(\mathbf{d})$ by explicitly computing $\Delta E(\mathbf{d})$

sum of N^2 terms

$f(\mathbf{r}_{ij}, R_0, \mathbf{d})$ depends only on $\mathbf{r}_{ij}$

$$\sum_{i=1}^{N}\sum_{j=1}^{N} f(\mathbf{r}_{ij}, R_0, \mathbf{d}) = \sum_{\mathbf{r}\in\mathcal{D}} \omega(\mathbf{r}) f(\mathbf{r}, R_0, \mathbf{d})$$



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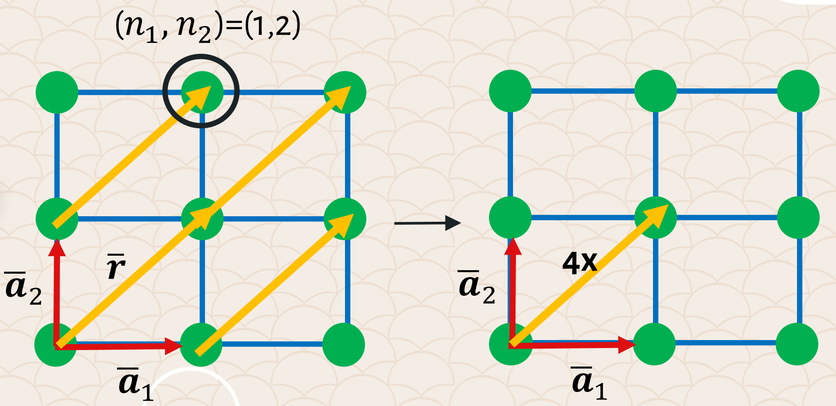
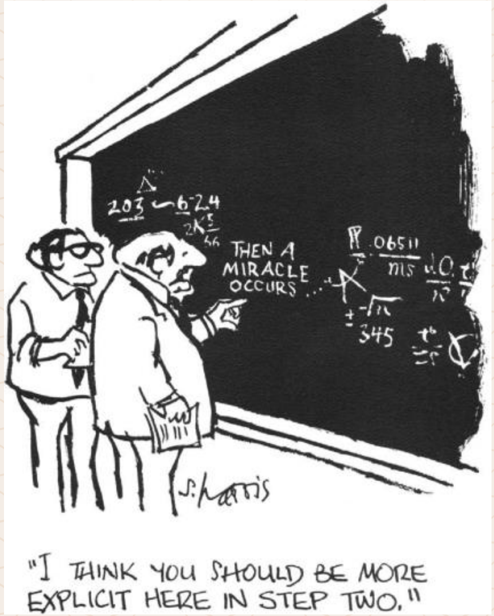
the atoms lie in a periodic lattice
$\mathbf{r}$ is a function of the basis vector $\boldsymbol{a}_i$
and lattice index $\boldsymbol{n}_i$



$$\bar{\boldsymbol{r}} = n_1\bar{\boldsymbol{a}}_1 + n_2\bar{\boldsymbol{a}}_2$$
$$n_i \in \mathbb{N}$$

sum of $O(N)$ terms



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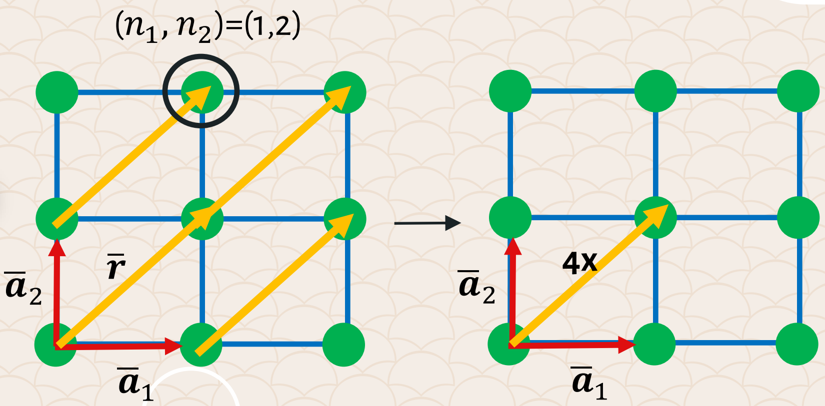

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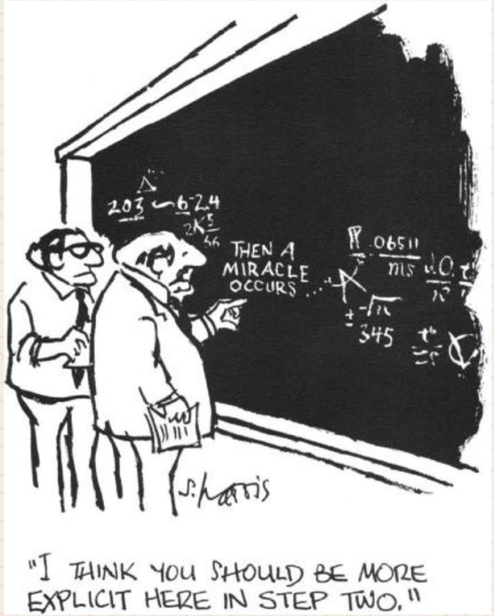
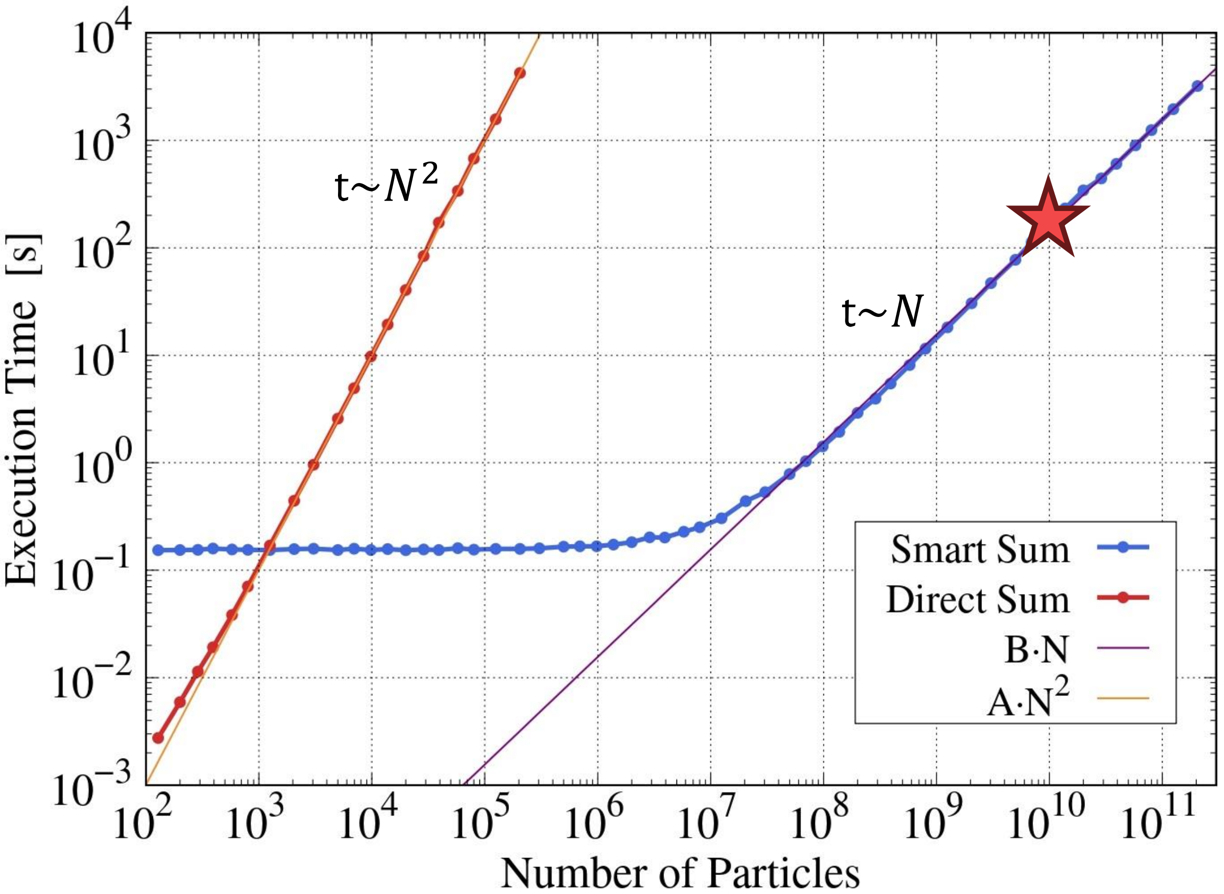


this sum and thus $\tau(\mathbf{d})$
are **computed numerically**
for different values of R_0 and N

Computational time
$(R_0 = 10^{-5}$Å$)$



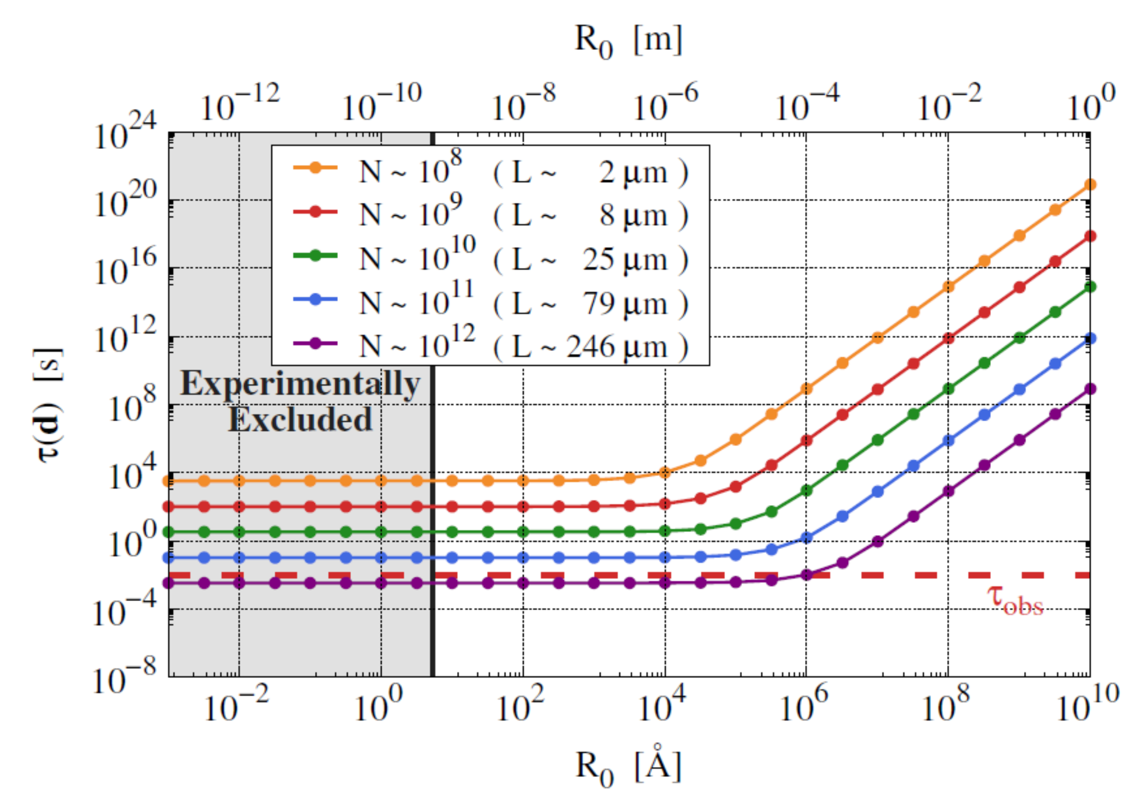
$N = 2 \times 10^{10}$

Smart ~ 5 min
Direct ~ 12817 centuries!!

Marco's PC
processor Intel Core i7-8750H
computation on CPU
parallelized on 12 threads

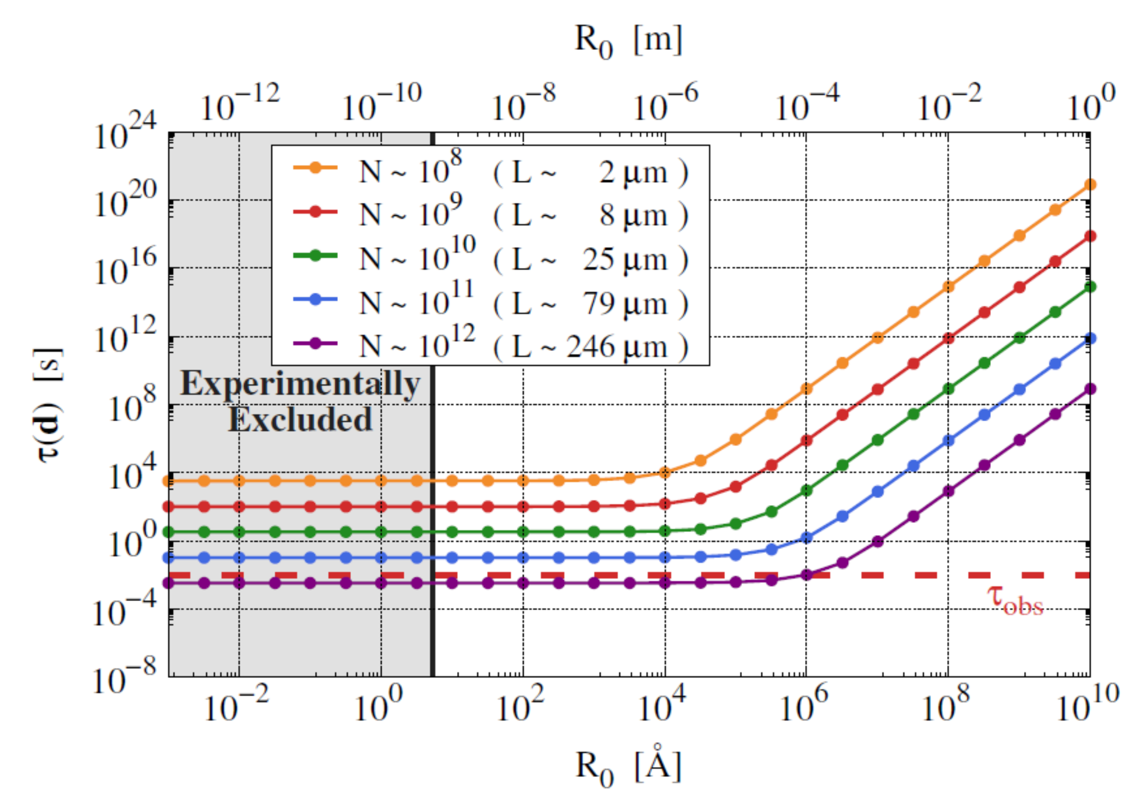
Behaviour of $\tau(\mathbf{d})$ varying R_0 for different number of atoms *N* (and thus length *L*) of the graphene plate in a superposition of d=4*L*

Comparison of $\tau(\mathbf{d})$ with τ_{obs}



Behaviour of $\tau(\mathbf{d})$ varying R_0 for different number of atoms N (and thus length L) of the graphene plate in a superposition of d=4L

Comparison of $\tau(\mathbf{d})$ with τ_{obs}



values of R_0 for which $\tau(\mathbf{d}) > \tau_{obs}$ are excluded

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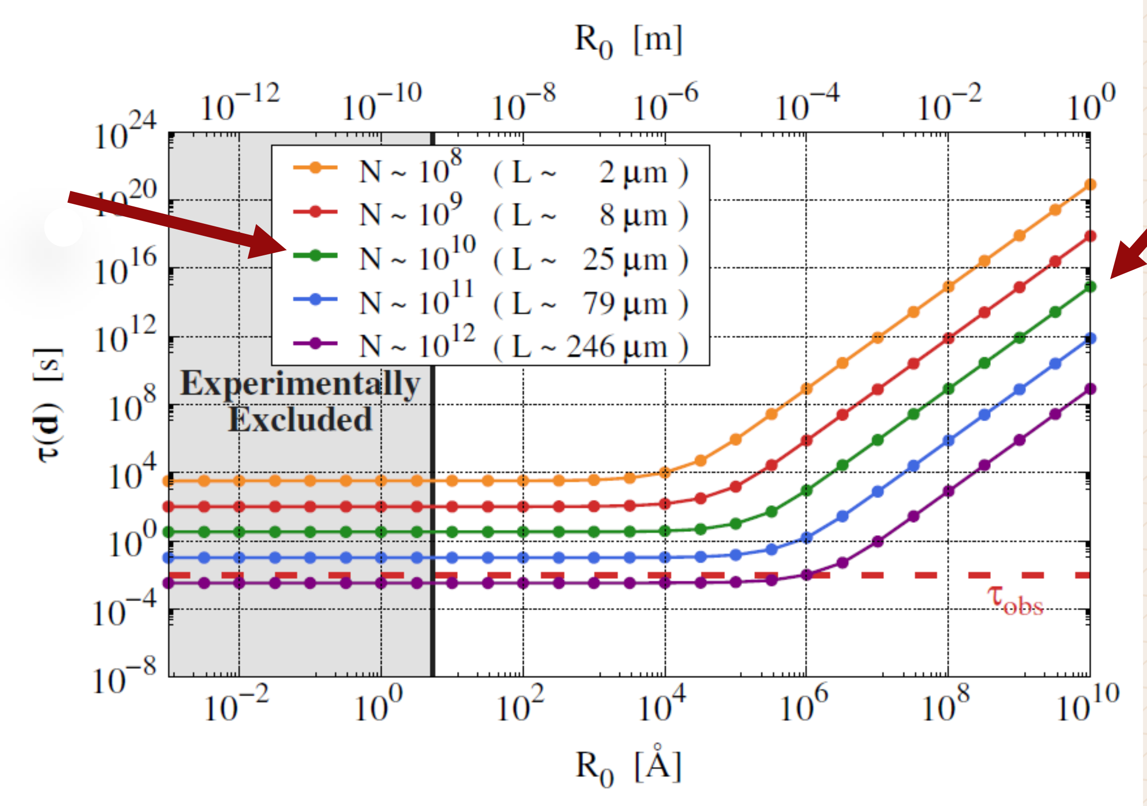

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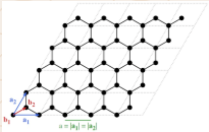
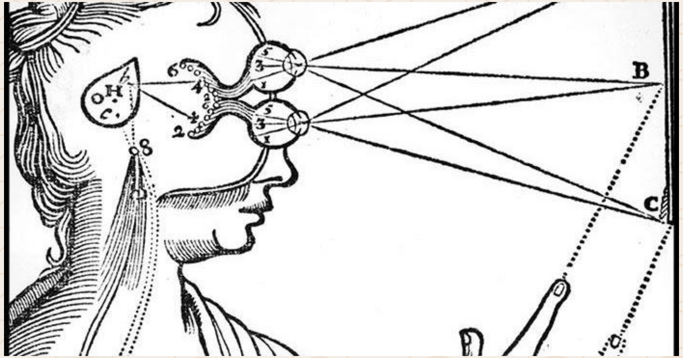


DP model does not collapse the graphene plate fast enough

Arbitrarity

choice of measurement system

human eye as the measurement apparatus



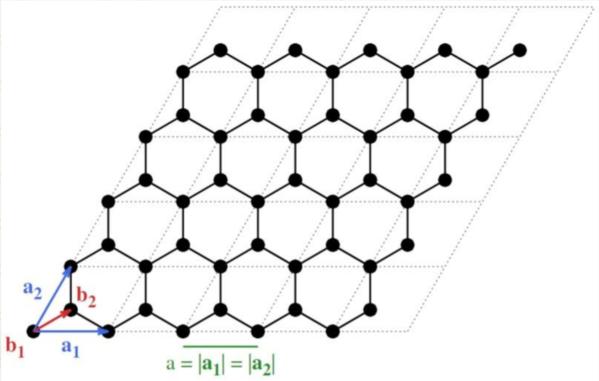


plate made
of a single layer of graphene

$\tau_{obs} = 0.01s$

$L_{obs} = 25\mu m$

$d = 4L$

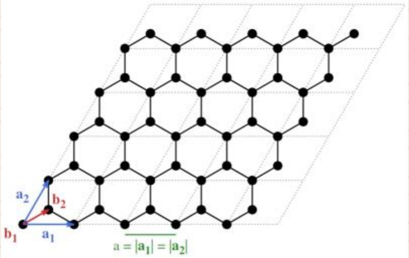
DP model → $\tau(\mathbf{d})$
$\tau(\mathbf{d}) > \tau_{obs}$

About the time

time τ_{obs}

Taking longer τ_{obs} allows the collapse of smaller systems

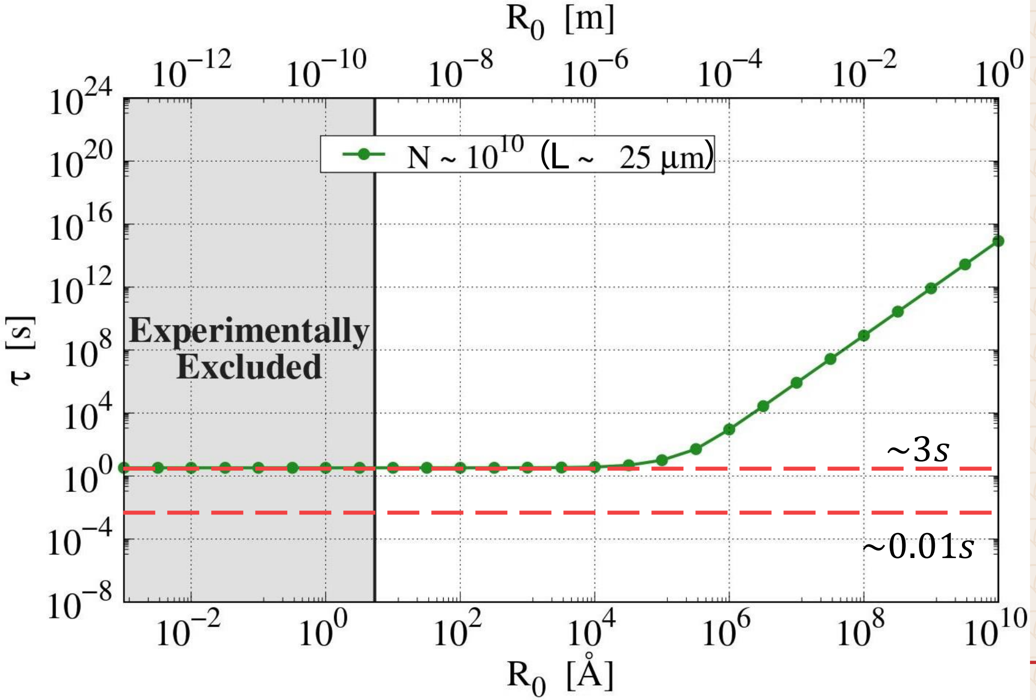
L fixed
25μm



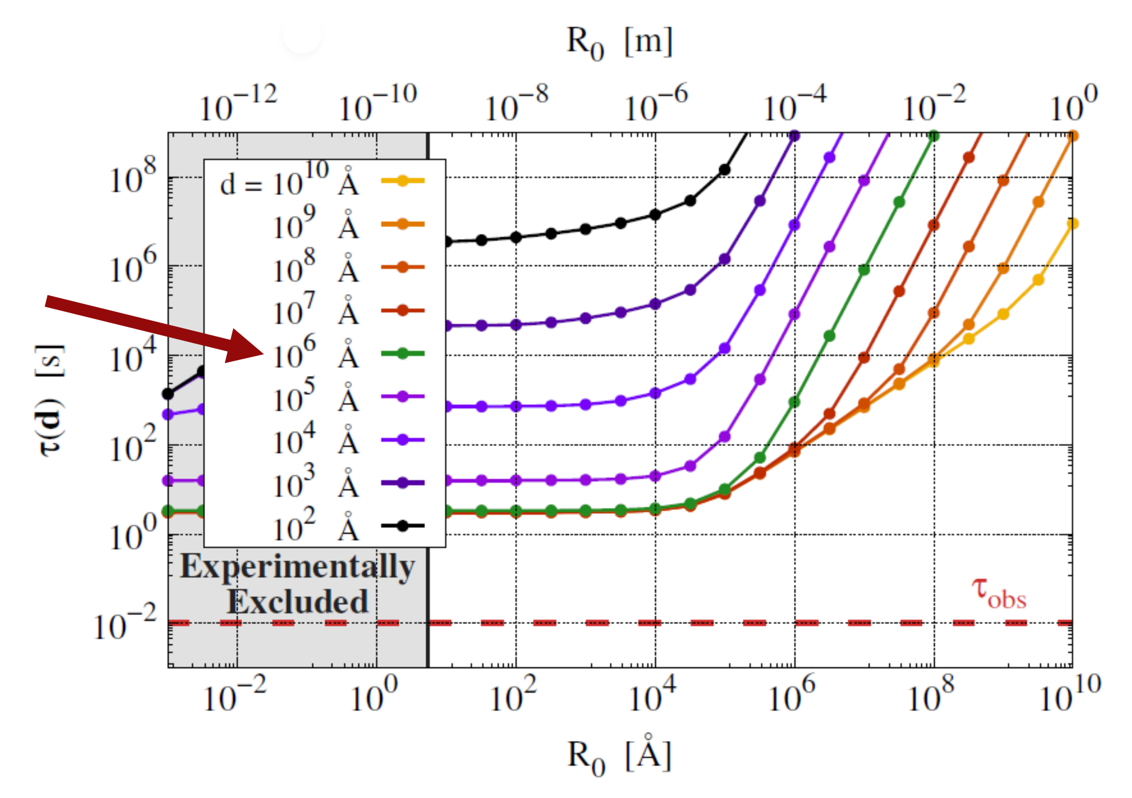
$\tau(\mathbf{d}) \sim 3s$
collapse

$\tau(\mathbf{d}) \sim 0.01s$
no collapse

macroscopic!!



Behaviour of $\tau(\mathbf{d})$ varying R_0 for **different superposition distances *d***
$(L = 25\mu m, \;\; N = 2 \times 10^{10})$



$R_0 > L$
the collapse effect becomes stronger for larger values of d

$d < L$
the collapse effect loses strength $\forall \, R_0$

The collapse is not fast enough to occur before τ_{obs}

About the system

dimension $L \to d$

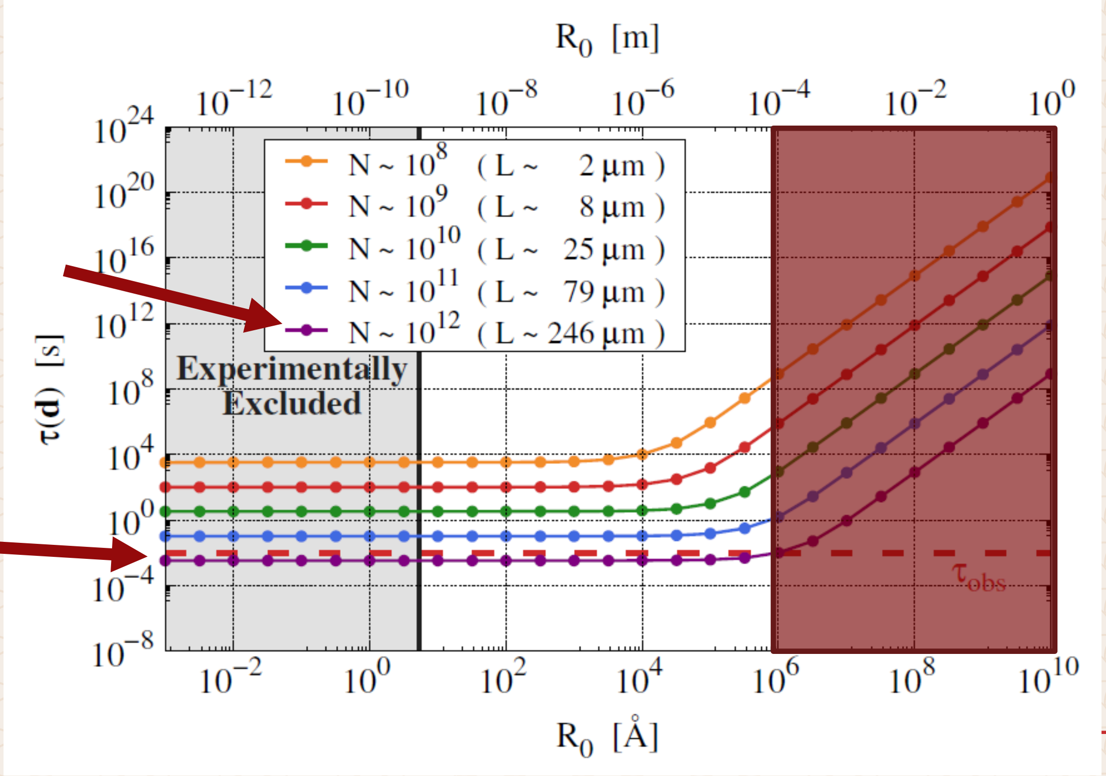
Changing L_{obs} allows changing L

A system collapsing fast enough

$\mathrm{L} \sim 1/5\,mm$

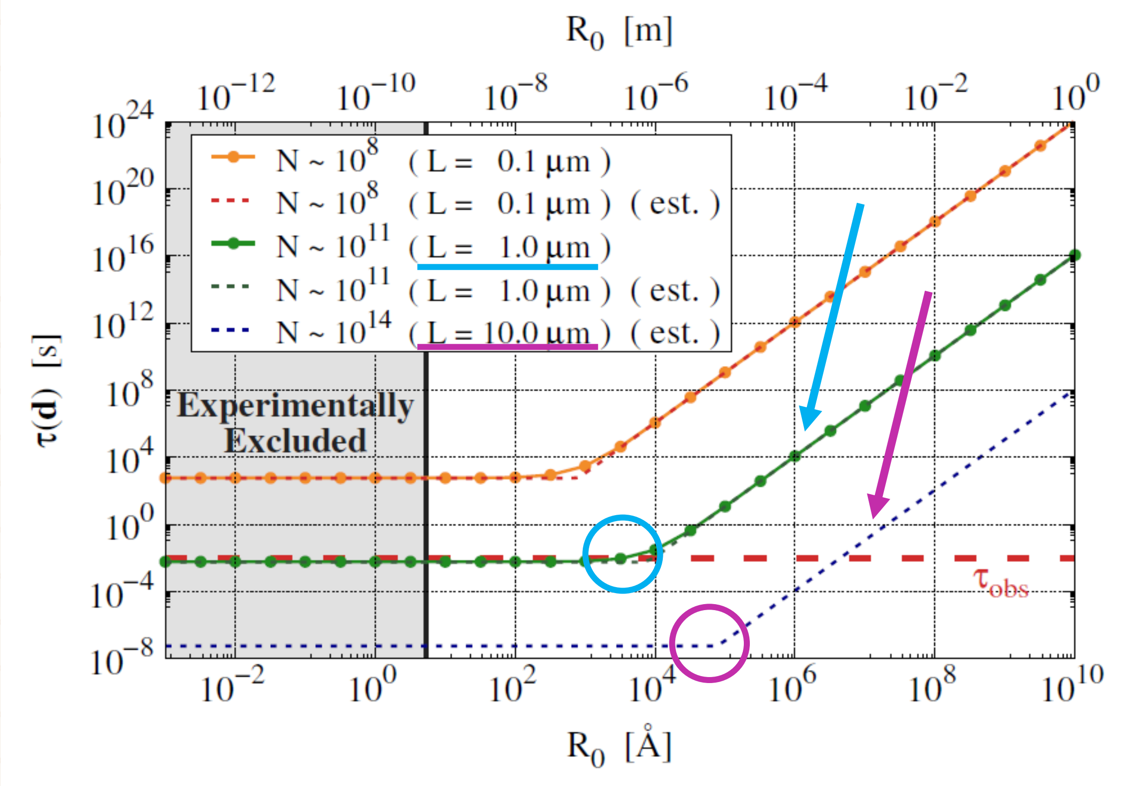
$\mathrm{L} \sim 10\, L_{obs}$

excluded
$R_0 > 10^6$Å
upper bound



3d

Comparison of $\tau(\mathbf{d})$ with τ_{obs} varying R_0
for different number of atoms *N* (and thus length *L*)
of a cubic graphene system with d=4L



$\tau(\mathbf{d}) = \tau_{obs}$
cubic system
made of stacked layers
of graphene

3d system
collapses faster
than a 2d one

same length L
3d has much **more** atoms involved

same number of atoms N
3d atoms are **more densily disposed**
the Newtonian interaction is stronger

05

Conclusions

conclusions

Experimental verification on DP model
→ how effective the DP collapse is in predicting the emergence of a macroscopic classical world from an underlying quantum structure

Not all macroscopic objects collapse effectively

Our analysis shows that the quantum-to-classical transition occurs roughly at the border ($10^{10} - 10^{12}$ atoms) between macro/micro

The collapse is roughly independent from R_0 for a large range of values ($1 - 10^6$Å)

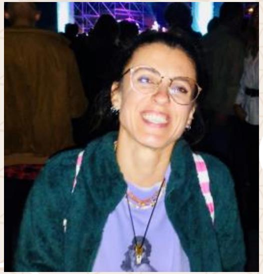
relevant

Various are the theories
but Beauty is all one however
which brings them out

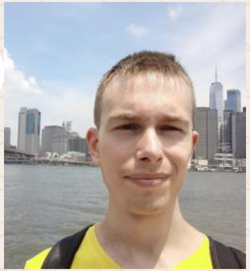
paraphrasing the

Orlando Furioso
XXIV,2, first verses
Ludovico Ariosto

the Team



Caria Figurato



Marco Dirindin

José Luis Gaona Reyes

Matteo Carlesso

Angelo Bassi

Sandro Donadi

Thanks!

INFN TRIESTE

NQSTI National Quantum Science and Technology Institute

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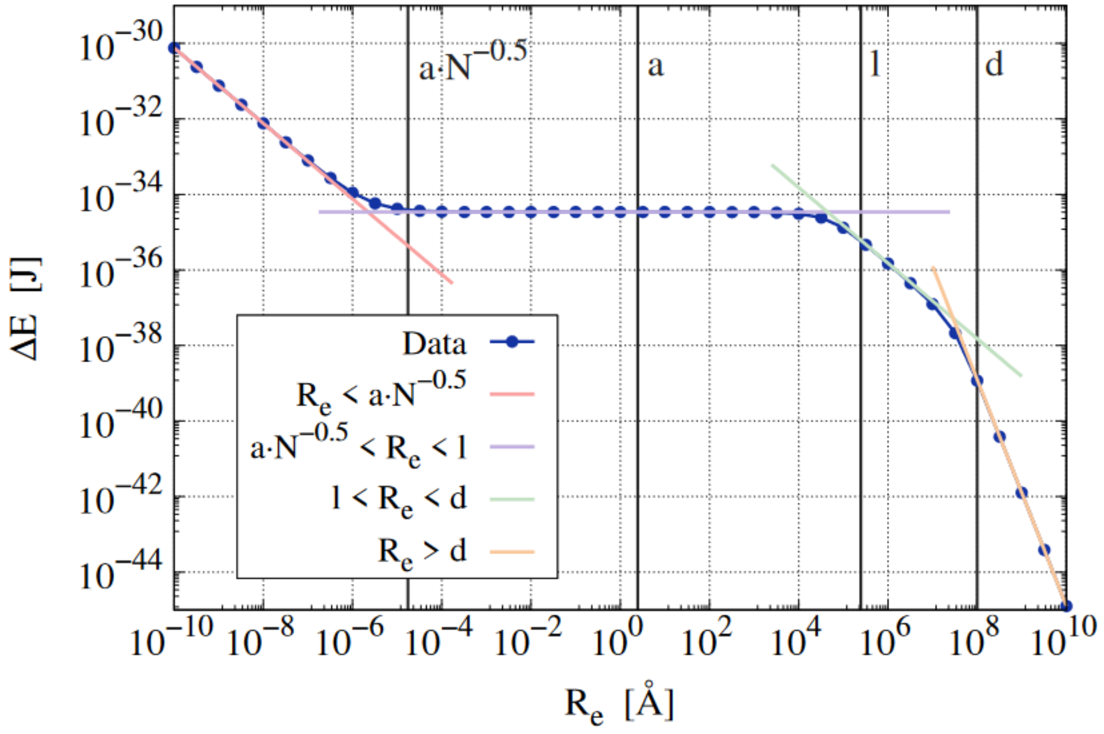
relevant

Backup slides

Behaviour of ΔE as a function of R_0 in a logarithmic plot



ΔE can be well approximated by **4 linear functions** for different values of R_{eff}

$$\Delta E(\mathbf{d}) = 8\pi G m^2 \sum_{i=1}^{N} \sum_{j=1}^{N} f(\mathbf{r}_{ij}, R_0, \mathbf{d})$$

$$f(\mathbf{r}_{ij}, R_0, \mathbf{d}) = \frac{\operatorname{erf}\left(\frac{r_{ij}}{2R_{\text{eff}}}\right)}{r_{ij}} - \frac{\operatorname{erf}\left(\frac{|\mathbf{d}-\mathbf{r}_{ij}|}{2R_{\text{eff}}}\right)}{|\mathbf{d}-\mathbf{r}_{ij}|}$$

04

Modifications

Colored version of the DP model

Neglecting the free evolution

$\delta(t) \to f(t)$

non-trivial two-time correlation function

$$\langle \mathbf{x}|\hat{\rho}(t)|\mathbf{y}\rangle = \langle \mathbf{x}|\hat{\rho}(0)|\mathbf{y}\rangle \exp\left[-t/\tau(\mathbf{x}-\mathbf{y})\right]$$

CM density matrix evolves with a time-dependent timescale $\tau(\mathbf{d},t)$

$$\tau(\mathbf{d},t) = \frac{\hbar}{2\Delta E(\mathbf{d})}\frac{t}{g(t)}$$

$$g(t) = 2\int_0^t \mathrm{d}s \int_0^s \mathrm{d}s'\, f(s-s')$$

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$$f(t) = \Omega_{\mathrm{C}} e^{-\Omega_{\mathrm{C}}|t|}/2$$

$$g(t>0) = \frac{t}{2}\left[1 - \frac{1}{\Omega_{\mathrm{C}} t}\left(1 - e^{-\Omega_{\mathrm{C}} t}\right)\right]$$

cutoff frequency of the noise

parameter of the DP model

Colored version of the DP model

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$$g(t>0) = \frac{t}{2}\left[1 - \frac{1}{\Omega_C t}\left(1 - e^{-\Omega_C t}\right)\right]$$

cutoff frequency of the noise parameter of the DP model

$$g(t) < t$$

$\tau(\mathbf{d},t)$ longer than that of the standard DP

the collapse requires **more time** to become effective $\forall\ \Omega_C$