Techniques to enhance reaction rates of nuclear fusion

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- I am in a ‘study’ mode in plasma and fusion physics since about three years (formerly various topics, among which more recently statistical mechanics of ultracold atoms)

- Nuclear energy is the way to free up the Planet from fossil fuel wherever high anthropic densities are present

- It has the potential to revolutionize international relationships (ALL wars of XX century are oil-motivated, read ‘The Prize’ by Daniel Yergin). <u>Priority number 1 for Italy’s future</u>

- Enough of Hilbert spaces and linear structures, the real world is nonlinear and eventually I believe that even the standard model of particle physics (as well as quantum physics at large) will be superseded by nonlinear theories

In this context, as a beginner, I started tackling some simple exercises to gain knowledge, and today I will show a couple of examples

Enhancing the reaction rate for nuclear fusion

a) Standard estimates based on Maxwell-Boltzmann distribution for involved nuclei

b) Coulomb barrier is ‘bare’, there is no tailored screening

Is it possible to relax a) and/or b) in the realistic setting of confined fusion plasma?

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Concepts for a Deuterium–Deuterium Fusion Reactor[1]

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Abstract—We revisit the assumption that reactors based on deuterium–deuterium (D–D) fusion process have to be necessarily developed after the successful completion of experiments and demonstrations for deuterium–tritium (D–T) fusion reactors. Two possible mechanisms for enhancing the reactivity are discussed. Hard tails in the energy distribution of the nuclei, through the so-called κ-distribution, allow to boost the number of energetic nuclei available for fusion reactions. At higher temperatures than usually considered in D–T plasmas, vacuum polarization effects from real e^+e^- and $\mu^+\mu^-$ pairs may provide further speed-up due to their contribution to screening of the Coulomb barrier. Furthermore, the energy collection system can benefit from the absence of the lithium blanket, both in simplicity and compactness. The usual thermal cycle can be bypassed with comparable efficiency levels using hadron calorimetry and third-generation photovoltaic cells, possibly allowing to extend the use of fusion reactors to broader contexts, most notably maritime transport.

In space plasma physics and astrophysics use of kappa-distributions is rather common

These form a family of power-law distributions

$$P(E) = \frac{C(\kappa)}{(k_B T_U)^{3/2}} \frac{E^{1/2}}{\left[1 + \frac{E}{(\kappa - 3/2) k_B T_U}\right]^{\kappa+1}}$$

$$C(\kappa) = \frac{2\Gamma(\kappa+1)}{\pi^{1/2}(\kappa - 3/2)^{3/2}\Gamma(\kappa - 1/2)}$$

In the limit of kappa going to infinity, they reproduce a Maxwell-Boltzmann

They are characterized by a 'hard' high-energy tail and a peak at lower energy than the corresponding Maxwell-Boltzmann

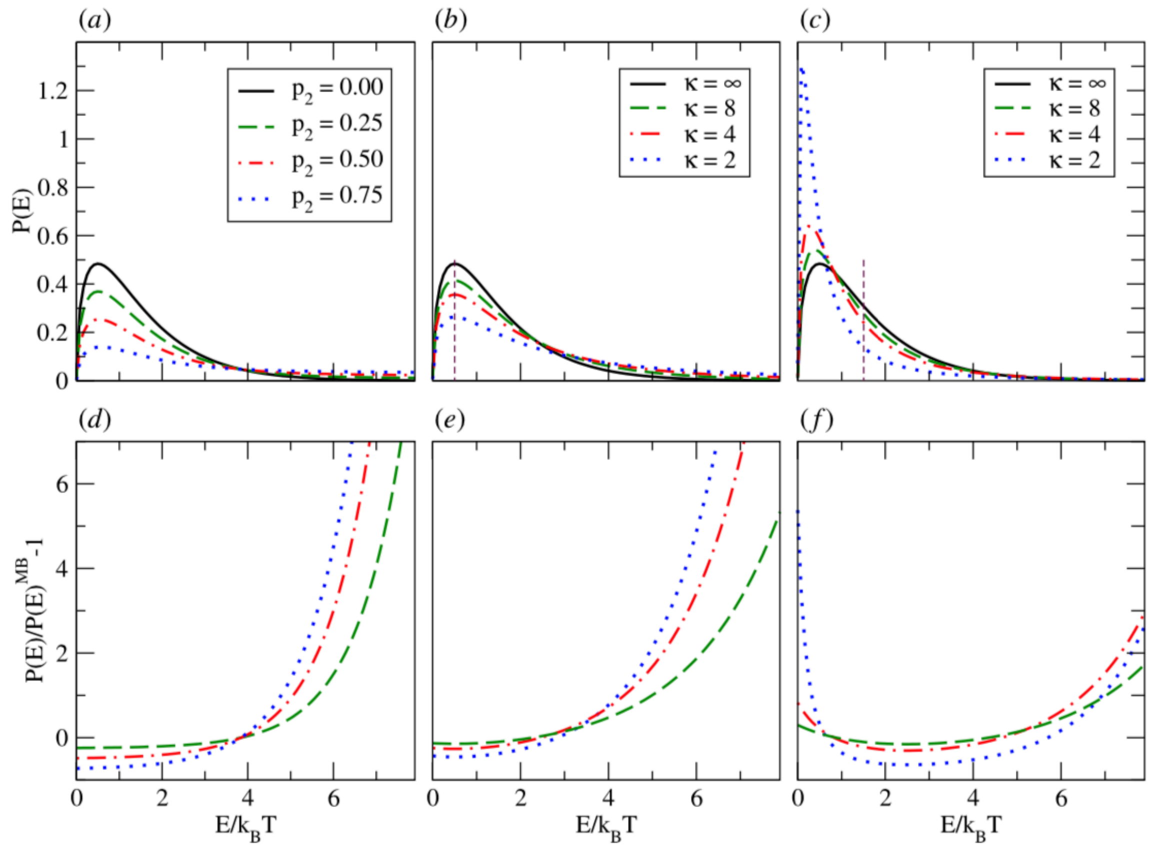


FIGURE 1. Absolute (a–c) and relative (d–f) comparison of bMB and κ-distributions to MB distributions. The solid lines in the top panels represent the limiting cases for the MB distributions, i.e. $p_2 = 0$, and $\kappa \to \infty$ for the κ-distributions: (a) bMB distributions with increasing weight p_2 of the high-temperature component, and $T_2 = 10\,T_1$; (b) κ-distributions for $\eta = 1/2$ have maxima at $\langle E \rangle = \frac{1}{2} k_B T$, indicated by vertical dashed lines; (c) κ-distributions for $\eta = -3/2$ have average energy given by $\langle E \rangle = \frac{3}{2} k_B T$, indicated by vertical dashed lines. Panels (d–f) show more clearly the relative deviations from a MB energy distribution for the corresponding top panels, especially in the high-energy tails. Notice that the κ-distributions for $\eta = 1/2$ resemble more closely the bMB distributions, compared to the corresponding κ-distributions for $\eta = -3/2$. In the latter, the deviations from a MB distribution at high energy are less pronounced, while significant deviations instead occur at low energy. The case of $\eta = 0$, not depicted for graphical reasons, has a behaviour close to the $\eta = 1/2$ case.

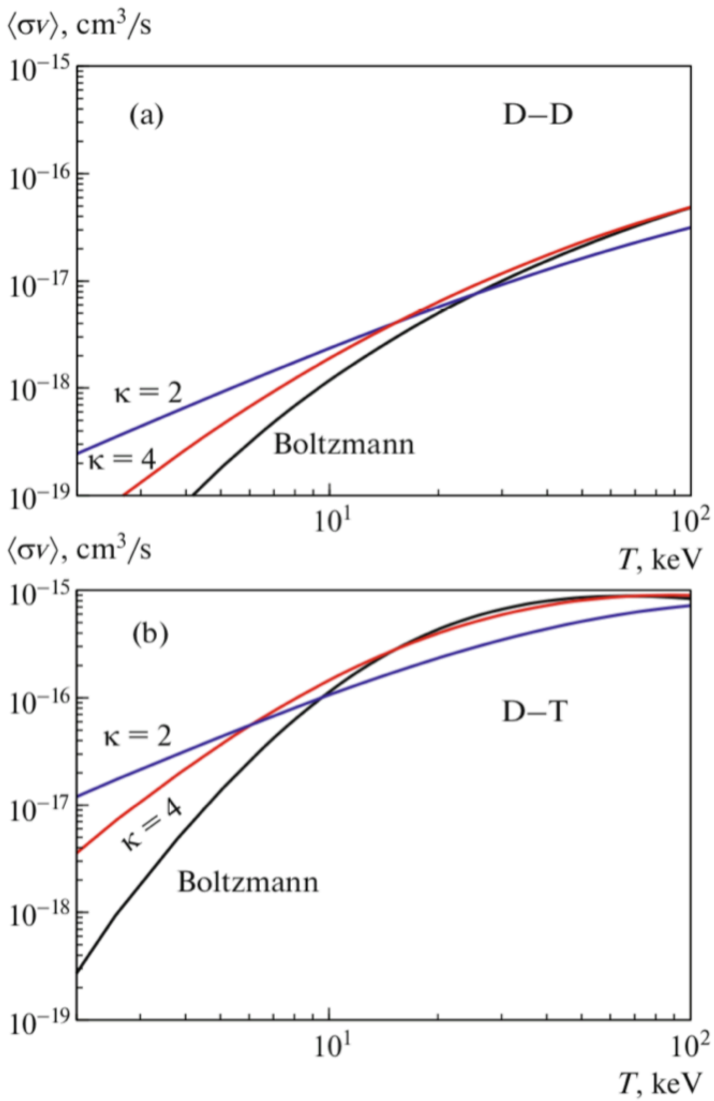


Fig. 1. (Color online) Reactivities for D–D (a) and D–T (b) fusion processes averaged over Boltzmann energy distributions (black) and over two κ-distributed energies, κ = 2 (blue) and κ = 4 (red), in the 2–100 keV temperature range. Reactivities and temperatures in the two plots are expressed with the same scales allowing for an easier comparison. The D–D reactivity is obtained summing over both reaction channels, $D(d, p)T$ and $D(d, n)^3He$.

Parameterizing the cross-section for fusion and inserting kappa-distributions with various values one can evaluate the gain or loss with respect to the corresponding MB distribution

There is a range of temperatures for which kappa-distributions can yield a couple of orders of magnitude higher reactivity for both D-D and D-T fusion processes

Due to the shift of the peak towards lower energy values, it is not always convenient to use kappa-distributions

It is unclear how to generate ‘on demand’ kappa-distributions. They seem related to steady state situations in which energy is pumped into the system at a rate larger than the dissipation rate within the system (for instance, NBI at high temperature?)

We need a dynamical model for thermalization of different species

If possible, this should not reflect coarse graining in the dynamics like with Boltzmann or Fokker-Planck approaches, to fully study the exact dynamics including fluctuations.

Closest inspiration is the Caldeira-Leggett open system approach

$$H = \frac{P^2}{2M} + \frac{1}{2}M\Omega^2 Q^2 + \sum_{n=1}^{N}\left[\frac{p_n^2}{2m} + \frac{1}{2}m\omega_n^2(q_n - Q)^2\right]$$

We know that in the limit of <u>infinite</u> bath oscillators and <u>infinite</u> bandwidth the dynamics of a test particle is described by a Langevin equation leading to relaxation/thermalization.
The model incorporates translational invariance.

We work with a finite number of particles
The bandwidth is zero, particles oscillates around equilibrium with a finite bandwidth
The system is not translational invariant due to confinement

$$H = \frac{P^2}{2M} + \frac{1}{2}M\Omega^2 Q^2 + \sum_{n=1}^{N}\left(\frac{p_n^2}{2m} + \frac{1}{2}m\omega_n^2 q_n^2\right) + H_{int}$$

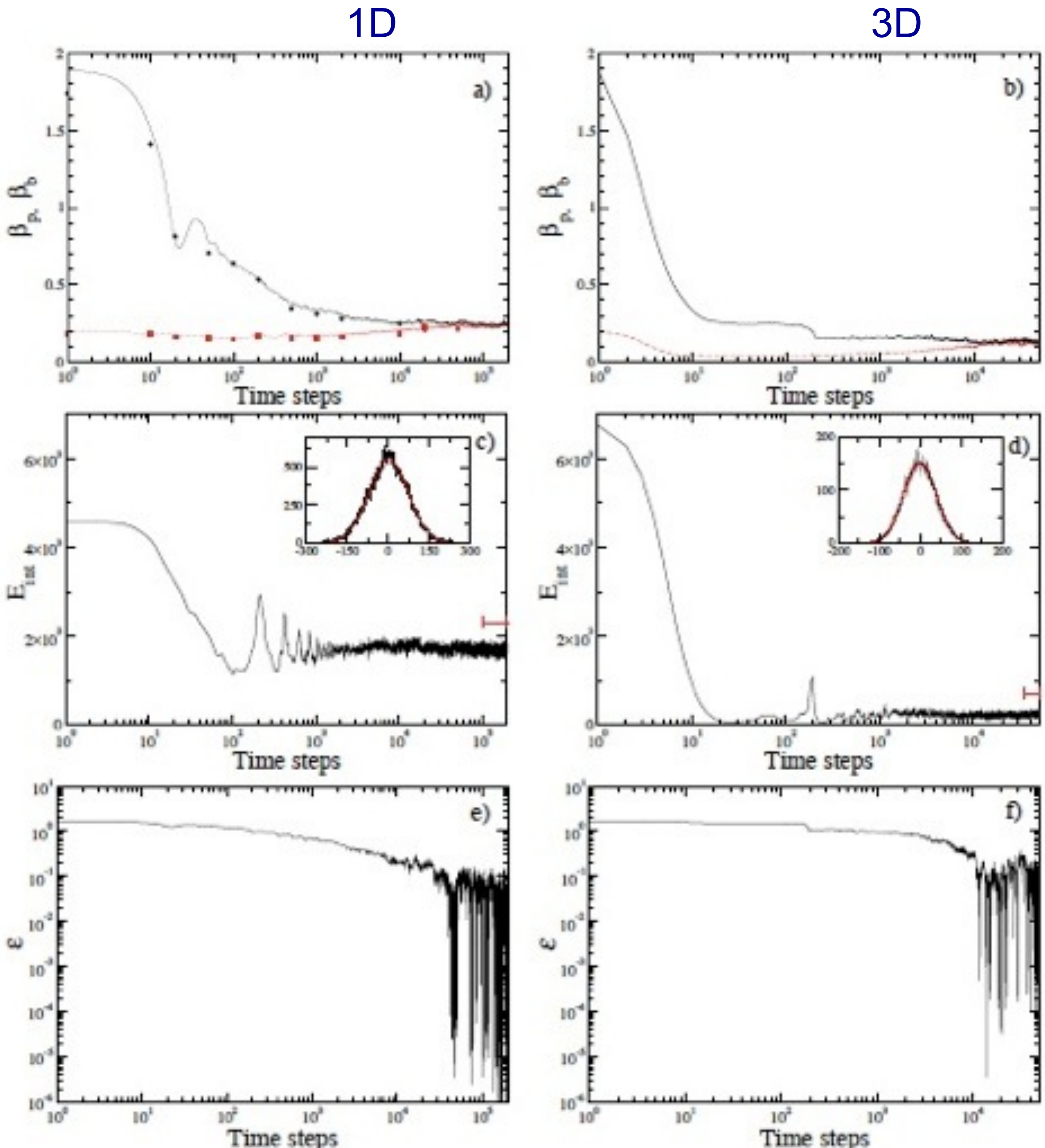
$$H_{int} = \gamma_E \sum_{n=1}^{N} \exp\left[-\frac{(q_n - Q)^2}{\lambda^2}\right]$$

[R.O. and B. Sundaram, PRA 92, 033422 (2015)]

The analysis can be extended to two many-body systems initially at different temperatures, rather than a test particle interacting with a heat bath

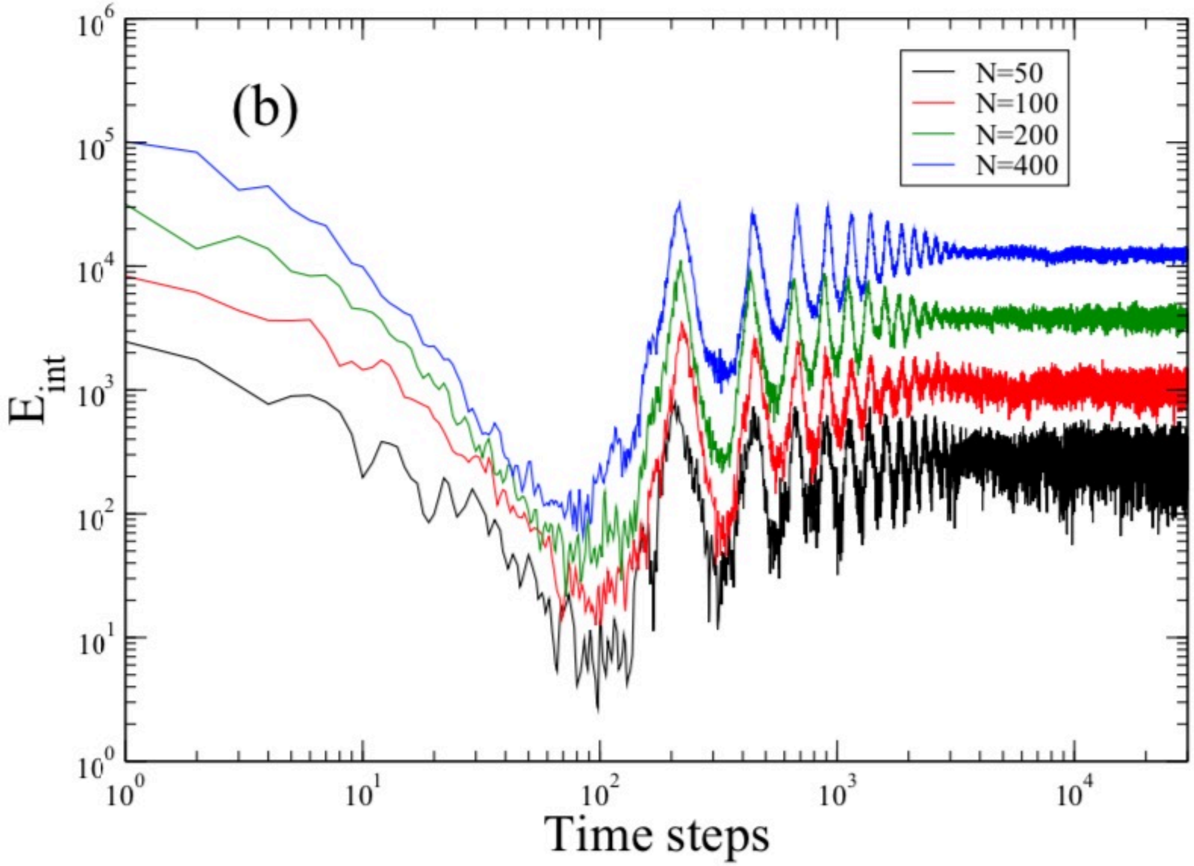
Codes for 1, 2 3 D, up to 800 particles/bath, repulsive and attractive interactions

Long-time equilibration, seen also in the interaction energy



$$\epsilon = 2\frac{|\beta_p - \beta_b|}{\beta_p + \beta_b}$$

Scaling of the total interaction energy at equilibrium with N (balanced mixture)



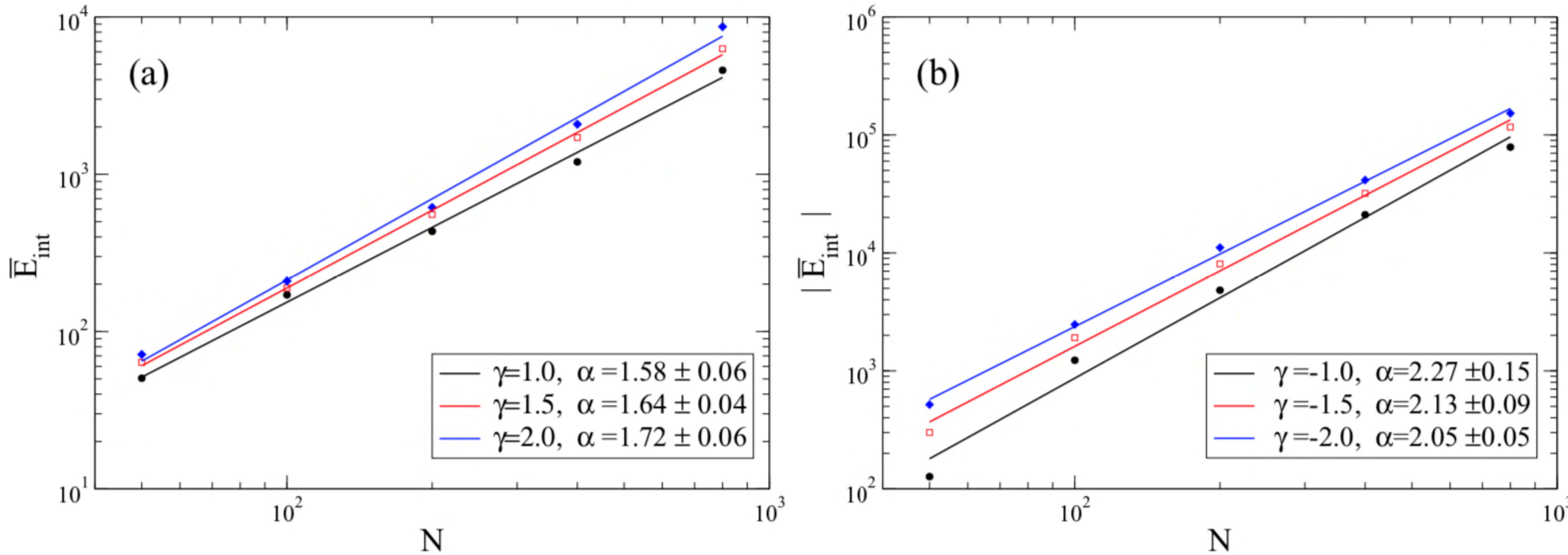


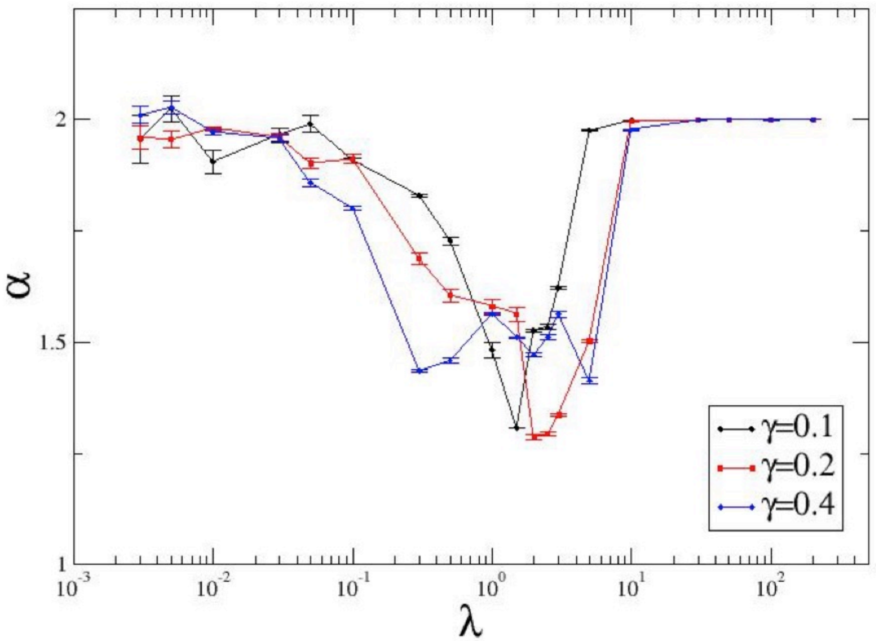
FIG. 3. Scaling of the total interaction energy with system size ($N_A = N_B = N$) for both repulsive (left) and attractive (right) cases. The strength γ is specified while $m_A = m_B = 1.0$, $\lambda = 0.1$, $\omega_A = 1.0$, $\omega_B = 144/89$, $\beta_A = 0.2$, and $\beta_B = 2.0$.

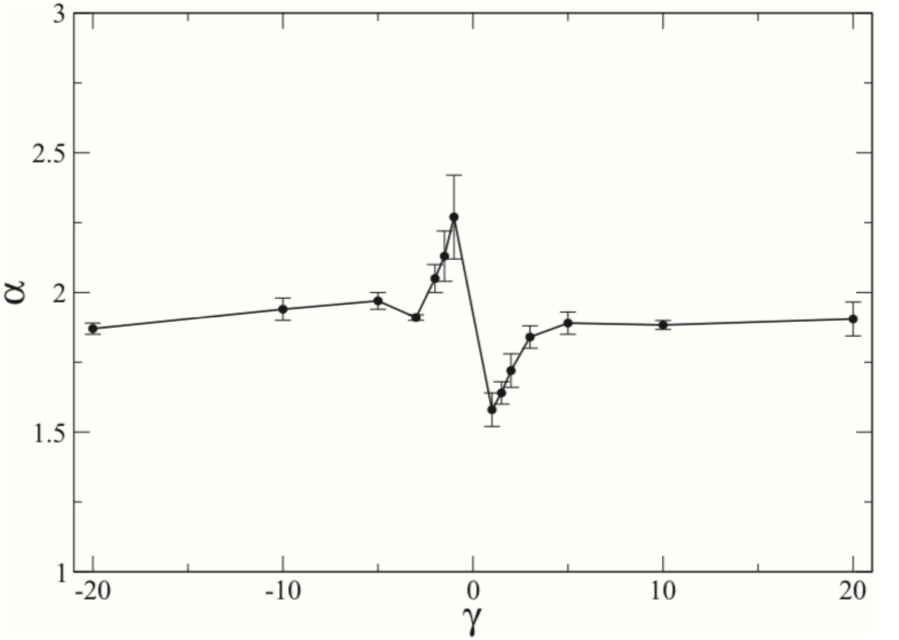
Power-law dependence of the total interaction energy, proportional to N^α

Scaling exponent compatible with 2 for attractive interactions,
less than 2 for repulsive interactions, and close to 5/3: Kolmogorov-like regime

F. Jauffred, R.O. and B. Sundaram, PRE 99, 022116 (20159]

The scaling exponent depends on interaction range and coupling strength





In an intermediate interaction range and coupling strength, there is anomalous scaling of the total interaction energy at equilibrium. Similar to nonextensive thermodynamics developed by Constantino Tsallis and collaborators.

In the Tsallis approach to thermodynamics, a q-parameter appears which is 1 for MB states, but assumes a different value for more general distributions. These distributions are precisely the kappa-distributions, and the relationship between kappa and q is kappa=1/(q-1)

We do expect generation of Tsallis-kappa equilibrium states in our model, to be tested with large number of particles simulations. We can also impose an external driving to the energy of the particles

No time to discuss the second possibility to enhance fusion rates, but just a snapshot

D-D fusion has advantages with respect to D-T (no need for T, neutrons at lower energy, it contains D-T reactions in the chain anyway) but it must occur at higher temperatures, order of 100 keV

The electron mass is 511 keV. Even at a temperature of 100 keV, there is the possibility to create electron-positron pairs via the high-energy tail

Those pairs create a ‘dielectric medium’ partially screening the Coulomb repulsion (see again JETP for some details)

Unfortunately density of pairs too low, need further amplification mechanisms

Collaborations with:

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(simulations for mixtures and anomalous scaling)

Hossein R. Sadeghpour,
ITAMP, Harvard-Smithsonian Center for Astrophysics
&
Daniel Vrinceanu, SouthernTexas University, Houston
(plasma astrophysics, electron and proton scattering on Rydberg atoms)
Contribution to JPP special issue

Ben I. Squarer, undergraduate student at Dartmouth (just started, on QFT effects)

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Thank you!