Modelling flocks and prices: jumping particles with an attractive interaction

Joint work with Miklós Zoltán Rácz and Bálint Tóth

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Budapest University of Technology and Economics
MTA-BME Stochastics Research Group

Particle systems and PDE's
U do Minho, December 5, 2012.

[1] Bolyai Scholarship of the HAS; OTKA K100473;TAMOP422

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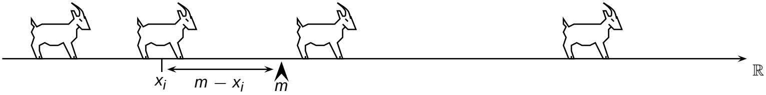

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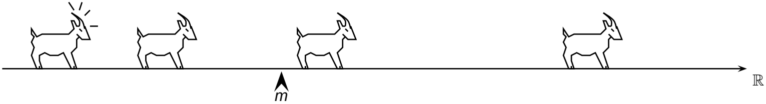

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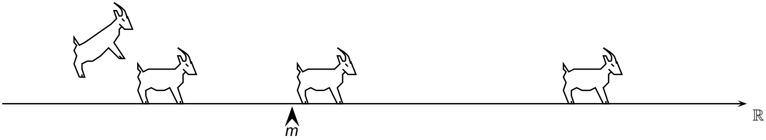

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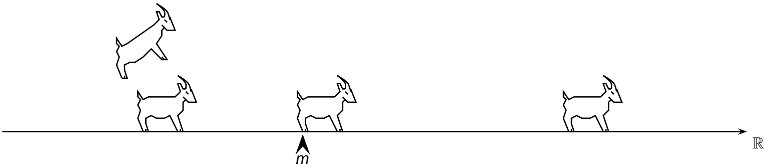

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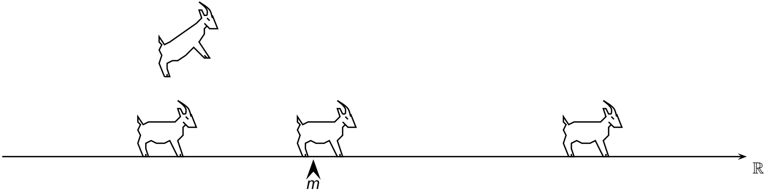

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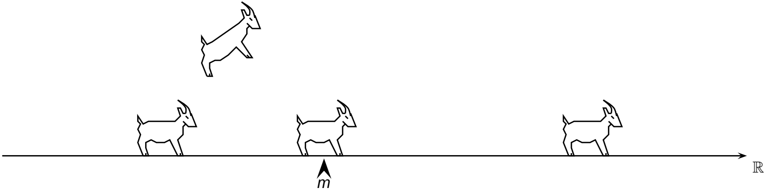

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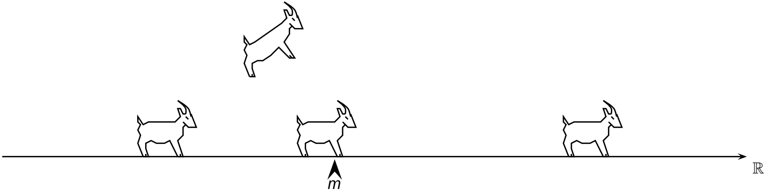

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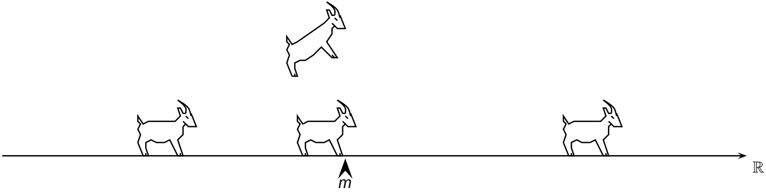

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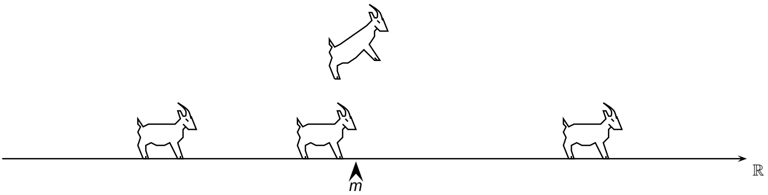

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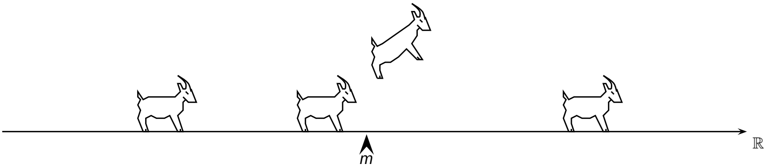

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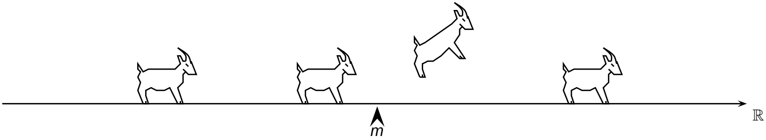

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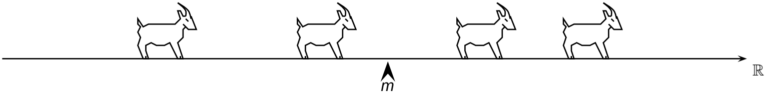

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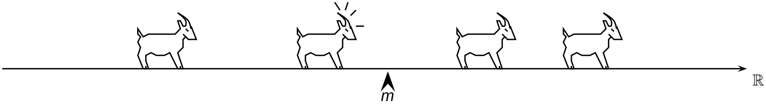

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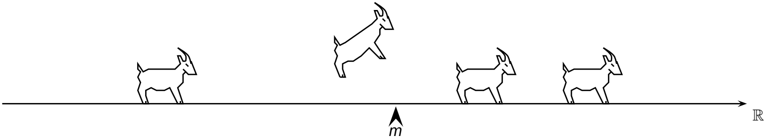

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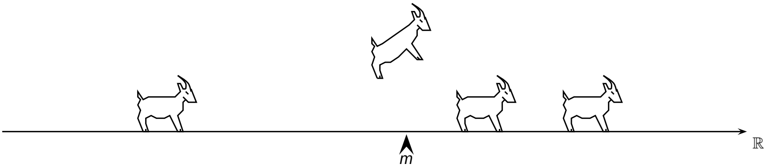

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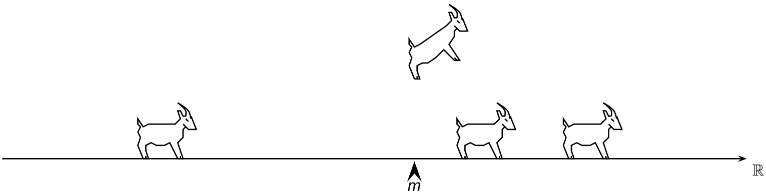

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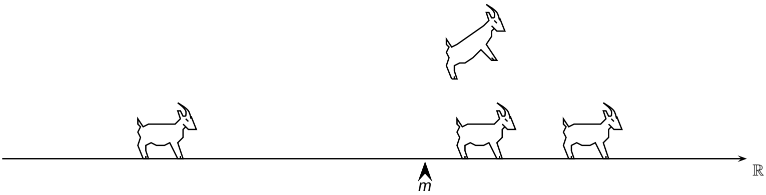

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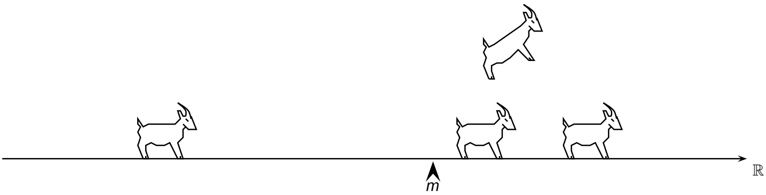

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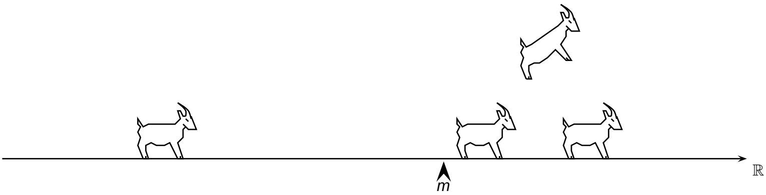

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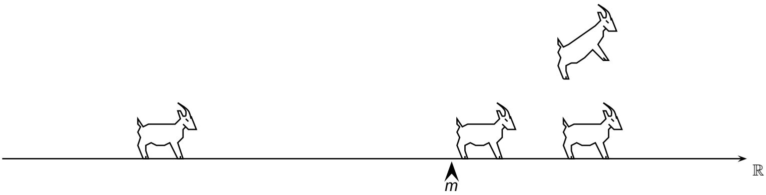

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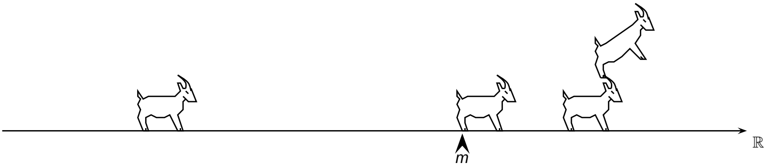

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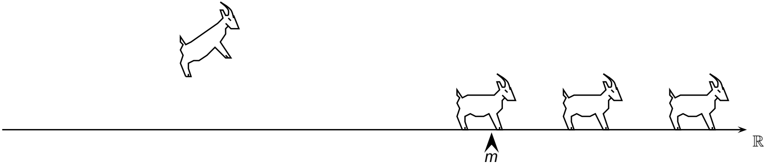

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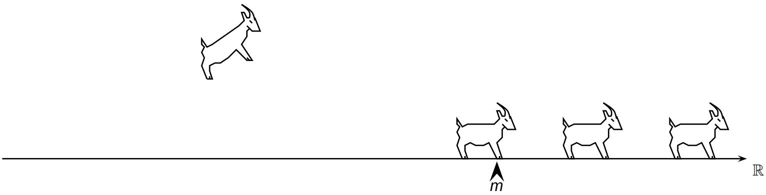

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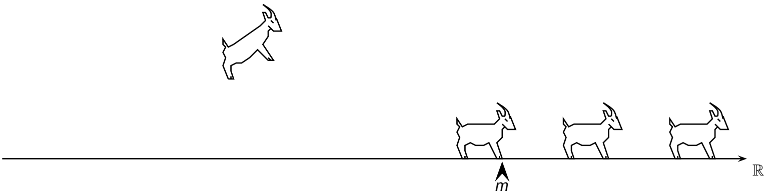

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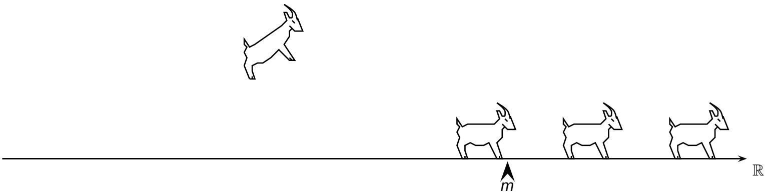

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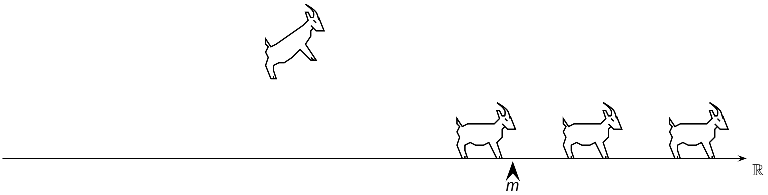

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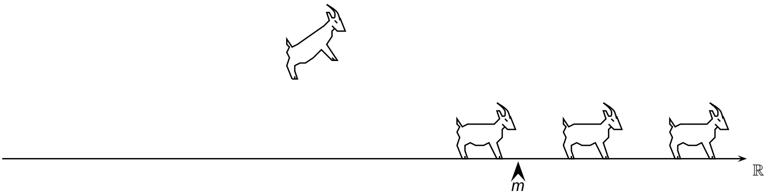

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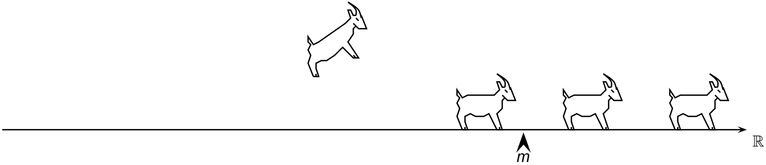

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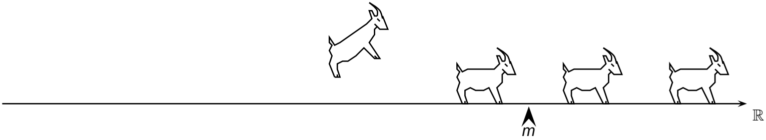

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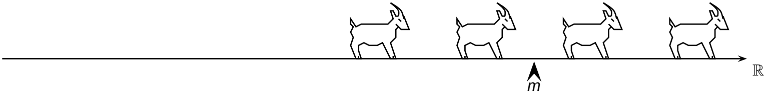

- n goats jump on $\mathbb{R}$ (state space is $\mathbb{R}^n$).
- Given a configuration $x_1, x_2, \ldots, x_n$ of goats the center of mass is $m = \frac{1}{n}\sum_{i=1}^{n} x_i$.
- Goat i jumps with rate $w(x_i - m)$, where w is the jump rate function: $\mathbb{R} \to \mathbb{R}^+$, decreasing.
- Jumps are positive, random, independent of everything, and are of density φ, mean one.

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Found results of the types:

- rat race model (D. ben-Avraham, S.N. Majumdar, S. Redner 2007)
- interacting diffusions with linear drift (A. Greven et. al.),
- rank dependent drift of Brownian motions (S. Pal, J. Pitman 2008, S. Chatterjee, S. Pal 2009),
- relocation of random walking particles (A. Manita, V. Shcherbakov 2005),
- interacting jump processes (A. Greenberg, V.A. Malyshev, S.Yu. Popov 1995)
- multiplicative steps as well (I. Grigorescu, M. Kang 2010).

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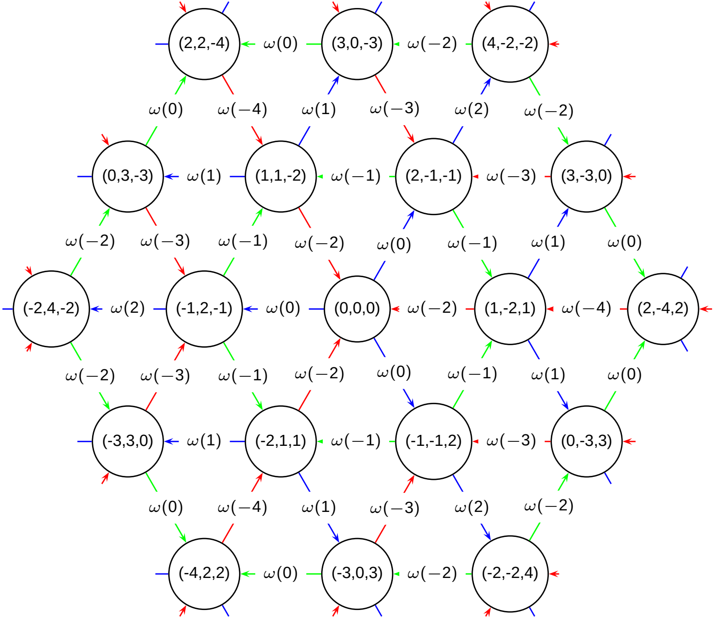
$n = 3$ particles: already seems hopeless. The process is "very irreversible".

$n = 3$ particles, jump lengths are deterministically 1



Fluid limit: a mean field equation

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$$+\int_{-\infty}^{x} w(y-m(t)) \cdot \varrho(y,t) \cdot \varphi(x-y) \, \mathrm{d}y,$$

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jump rate at x — density at x

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jump rate at y — density at y — prob to jump to x

$$+ \int_{-\infty}^{x} w(y - m(t)) \cdot \varrho(y,t) \cdot \varphi(x-y) \, \mathrm{d}y,$$

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$$m(t) = \int_{-\infty}^{\infty} x \varrho(x,t) \, \mathrm{d}x.$$

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$$m(t) = \int_{-\infty}^{\infty} x\,\varrho(x,t)\,\mathrm{d}x.$$

These equations conserve $1 = \int \varrho(x,t)\,\mathrm{d}x$ and give $\dot{m}(t) = \int w(x-m(t)) \cdot \varrho(x,t)\,\mathrm{d}x$.

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We look for stationary solution of this equation as seen from the center of mass.

Idea: as $n \to \infty$, in a stationary distribution $m(t)$ would stabilize. So assume

$$m(t) = ct \qquad \text{and}$$
$$\varrho(x, t) = \varrho(x - ct).$$

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Plug this in to get

$$-c\varrho'(x) = -w(x)\varrho(x) + \int_{-\infty}^{x} w(y)\varrho(y)\varphi(x-y)\,\mathrm{d}y,$$
$$0 = \int_{-\infty}^{\infty} y\varrho(y)\,\mathrm{d}y.$$

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When the jumps are Exp(1): $\varphi(x) = \mathrm{e}^{-x}$,
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Between t and $t+\mathrm{d}t$, $\mathrm{d}N(t) = \mathrm{e}^{ct}\,\mathrm{d}t$ many new Exp(1) particles try to break the record. So the probability that $Y(t)$ jumps is

$$1-\left(1-\mathrm{e}^{-Y(t)}\right)^{\mathrm{e}^{ct}\,\mathrm{d}t} \simeq \mathrm{e}^{ct-Y(t)}\,\mathrm{d}t \qquad \text{(for large } Y(t)\text{)}.$$

And when it jumps, it jumps Exp(1). But we know that $Y(t)-ct+\log c$ converges to standard Gumbel.

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$$ci\tau\widehat{\varrho}(\tau) = \big(\widehat{\varphi}(\tau) - 1\big) \cdot \widehat{\varrho}(\tau + i\beta).$$

  Hope to solve the recurrence relation on the $\mathfrak{Im}$ line, then analytic continuation gives a hint on the form of $\widehat{\varrho}$, to be verified.

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  - Method tested when $\varphi(x) = \mathrm{e}^{-x}$ (also seen before), hope to work with other φ's too.

Taking the fluid limit

Recall the original mean field equation:

$$\frac{\partial \varrho(x,t)}{\partial t} = -w(x - m(t)) \cdot \varrho(x,t) + \int_{-\infty}^{x} w(y - m(t)) \cdot \varrho(y,t) \cdot \varphi(x-y) \, \mathrm{d}y,$$

or, for all f test functions:

$$\langle f, \mu(t) \rangle - \langle f, \mu(0) \rangle = \int_0^t \left\langle \left\{ \mathbf{E}[f(x+Z)] - f(x) \right\} w(x - m(s)), \, \mu(s) \right\rangle \, \mathrm{d}s,$$

$$m(s) = \langle x, \, \mu(s) \rangle.$$

Here **E** refers to expectation of Z w.r.t. the jump length distribution.

Taking the fluid limit

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Problem: bounded functions and “just measures” are not enough!

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Goal: convergence of the n-particle empirical measures $\mu_n(t)$ in the Skohorod space $D([0, \infty), \mathcal{P}_1)$.

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$\Big\}$ *C-relative compactness*

Method for these bounds: introduce *ghost goats*: they jump with rate $\sup_x w(x)$, they have the same jump length distribution as their planetary counterparts. Couple such that ghost goat$_i$ can jump without goat$_i$, but not vice-versa. $\rightsquigarrow$ increments of ghosts dominate increments of the planetary goats.

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  - Generalize Perkins' theorem (Perkins, St.-Flour notes, 1999) to include measures with first moments, not only bounded ones.

1. Tightness

- Step 3: C-relative compactness of $\mu_n(t)$ in $D([0, \infty], \mathcal{P}_1)$.
  - Generalize Perkins' theorem (Perkins, St.-Flour notes, 1999) to include measures with first moments, not only bounded ones.

For the compactness-type conditions, use again the ghost goats.

2. The limit solves the mean field eq.

Let

$$
\begin{aligned}
A_{t,f}(\mu) :&= \langle f, \mu(t)\rangle - \langle f, \mu(0)\rangle \\
&\quad - \int_0^t \Big\langle \big\{ \mathbf{E}[f(x+Z)] - f(x) \big\} w(x - m(s)),\, \mu(s) \Big\rangle \,\mathrm{d}s \\
&= \langle f, \mu(t)\rangle - \langle f, \mu(0)\rangle - \int_0^t L\langle f, \mu(s)\rangle \,\mathrm{d}s, \\
m(s) &= \langle x,\, \mu(s)\rangle.
\end{aligned}
$$

Recall that the mean field equation was

$$
A_{t,f}(\mu) = 0.
$$

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- Step 2: If $\mu_n \Rightarrow \mu$ in $D([0, \infty], \mathcal{P}_1)$, then

$$A_{s,f}(\mu_n) \Rightarrow A_{s,f}(\mu)$$

  in $\mathbb{R}$.

3. Uniqueness of solutions of the mean field eq.

- Step 1: Look at the distance

$$d_H(\mu, \nu) := \sup_f |\langle f, \mu \rangle - \langle f, \nu \rangle|,$$

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$$\langle f, \mu(t)\rangle = \langle f, \mu(0)\rangle + \int_0^t \left\langle \left\{ \mathbf{E}[f(x+Z)] - f(x) \right\} w(x - m(s)), \mu(s) \right\rangle \mathrm{d}s.$$

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$\rightsquigarrow d_H(\mu(t), \nu(t)) \le d_H(\mu(0), \nu(0)) + c \int_0^t d_H(\mu(s), \nu(s)) \, \mathrm{d}s$, apply Grönwall's inequality.

Questions

- Variance of the center of mass should scale:

$$\mathbf{Var}(m_n(t)) \sim \frac{t^\gamma}{n^\alpha}.$$

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Thank you.