Nonlinear Diffusion. The Porous Medium Equation. From Analysis to Physics and Geometry

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  + M. Crandall, L. Evans, A. Friedman, C. Kenig,...

I. Diffusion

populations diffuse, substances (like particles in a solvent) diffuse, heat propagates, electrons and ions diffuse, the momentum of a viscous (Newtonian) fluid diffuses (linearly), there is diffusion in the markets, ...

- *what is diffusion anyway?*
- *how to explain it with mathematics?*
- *is it a linear process?*

The heat equation origins

- We begin our presentation with the Heat Equation $\boxed{u_t = \Delta u}$ and the analysis proposed by Fourier, 1807, 1822 (Fourier decomposition, spectrum). The mathematical models of heat propagation and diffusion have made great progress both in theory and application. They have had a strong influence on the 5 areas of Mathematics already mentioned.

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- The heat flow analysis is based on two main techniques: integral representation (convolution with a Gaussian kernel) and mode separation:

$$u(x,t) = \sum T_i(t) X_i(x)$$

where the $X_i(x)$ form the spectral sequence

$$-\Delta X_i = \lambda_i \, X_i.$$

This is the famous linear eigenvalue problem

Linear heat flows

- From 1822 until 1950 the heat equation has motivated
  (i) Fourier analysis decomposition of functions (and set theory),
  (ii) development of other linear equations
  $\Longrightarrow$ Theory of Parabolic Equations

$$u_t = \sum a_{ij}\partial_i\partial_j u + \sum b_i\partial_i u + cu + f$$

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- Main inventions in Parabolic Theory:
  (1) a_{ij}, b_i, c, f regular $\Rightarrow$ Maximum Principles, Schauder estimates, Harnack inequalities; C^α spaces (Hölder); potential theory; generation of semigroups.
  (2) coefficients only continuous or bounded $\Rightarrow W^{2,p}$ estimates, Calderón-Zygmund theory, weak solutions; Sobolev spaces.

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- The probabilistic approach: Diffusion as an stochastic process: Bachelier, Einstein, Smoluchowski, Wiener, Levy, Ito,...

$$dX = b\,dt + \sigma dW$$

Nonlinear heat flows

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  I will present an overview and recent results in the theory mathematically called Nonlinear Parabolic PDEs. General formula

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- Typical nonlinear diffusion: $u_t = \Delta u^m$

  Typical reaction diffusion: $u_t = \Delta u + u^p$

The Nonlinear Diffusion Models

- The Stefan Problem (Lamé and Clapeyron, 1833; Stefan 1880)

$$SE: \begin{cases} u_t = k_1 \Delta u & \text{for } u > 0, \\ u_t = k_2 \Delta u & \text{for } u < 0. \end{cases} \quad TC: \begin{cases} u = 0, \\ \mathbf{v} = L(k_1 \nabla u_1 - k_2 \nabla u_2). \end{cases}$$

  Main feature: the free boundary or moving boundary where $u = 0$. TC= Transmission conditions at $u = 0$.

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- The Hele-Shaw cell (Hele-Shaw, 1898; Saffman-Taylor, 1958)

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$$u_t = \Delta u^m, \quad m > 1.$$

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- The p-Laplacian Equation, $u_t = \text{div}\,(|\nabla u|^{p-2} \nabla u)$.

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- The Standard Blow-Up model (Kaplan, 1963; Fujita, 1966)

$$u_t = \Delta u + u^p$$

Main feature: If $p > 1$ the norm $\|u(\cdot,t)\|_\infty$ of the solutions goes to infinity in finite time. Hint: Integrate $u_t = u^p$.

Problem: *what is the influence of diffusion / migration?*

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- The geometrical models: the Ricci flow: $\partial_t g_{ij} = -R_{ij}$.

An opinion of John Nash, 1958:

The open problems in the area of nonlinear p.d.e. are very relevant to applied mathematics and science as a whole, perhaps more so that the open problems in any other area of mathematics, and the field seems poised for rapid development. It seems clear, however, that fresh methods must be employed...

Little is known about the existence, uniqueness and smoothness of solutions of the general equations of flow for a viscous, compressible, and heat conducting fluid...

"Continuity of solutions of elliptic and parabolic equations",

paper published in Amer. J. Math, 80, no 4 (1958), 931-954

II. Porous Medium Diffusion

$$u_t = \Delta u^m = \nabla \cdot (c(u)\nabla u)$$

density-dependent diffusivity

$$c(u) = mu^{m-1}[= m|u|^{m-1}]$$

degenerates at $u = 0$ if $m > 1$

Applied motivation for the PME

- Flow of gas in a porous medium (Leibenzon, 1930; Muskat 1933) $m = 1 + \gamma \geq 2$

$$\begin{cases} \rho_t + \text{div}\,(\rho \mathbf{v}) = 0, \\ \mathbf{v} = -\frac{k}{\mu}\nabla p, \quad p = p(\rho). \end{cases}$$

Second line left is the Darcy law for flows in porous media (Darcy, 1856). *Porous media flows are potential flows due to averaging of Navier-Stokes on the pore scales.*

To the right, put $p = p_o\,\rho^\gamma$, with $\gamma = 1$ (isothermal), $\gamma > 1$ (adiabatic flow).

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- Underground water infiltration (Boussinesq, 1903) $m = 2$

Applied motivation II

- Plasma radiation $m \geq 4$ (Zeldovich-Raizer, < 1950)

  Experimental fact: diffusivity at high temperatures is not constant as in Fourier's law, due to radiation.

$$\frac{d}{dt}\int_\Omega c\rho T\,dx = \int_{\partial\Omega} k(T)\nabla T\cdot \mathbf{n}dS.$$

  Put $k(T)=k_oT^n$, apply Gauss law and you get

$$c\rho\frac{\partial T}{\partial t} = \text{div}(k(T)\nabla T) = c_1\Delta T^{n+1}.$$

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This is not parabolic, but hyperbolic (propagation along characteristics). Mixed type, mixed properties.

- No big problem when $m > 1$, $m \neq 2$. The pressure transformation gives:

$$v_t = (m-1)v\Delta v + |\nabla v|^2$$

where $v = cu^{m-1}$ is the pressure; normalization $c = m/(m-1)$.

This separates $m > 1$ PME - from - $m < 1$ FDE

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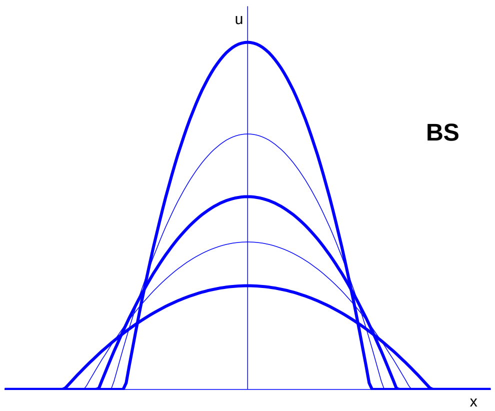

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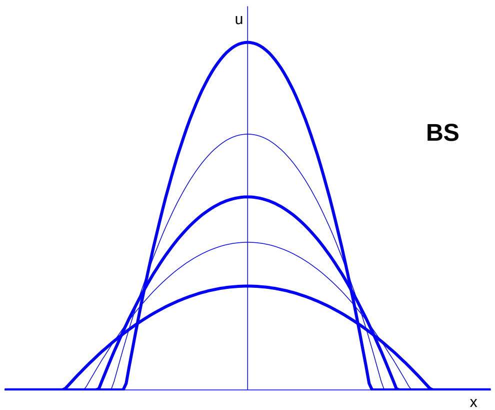

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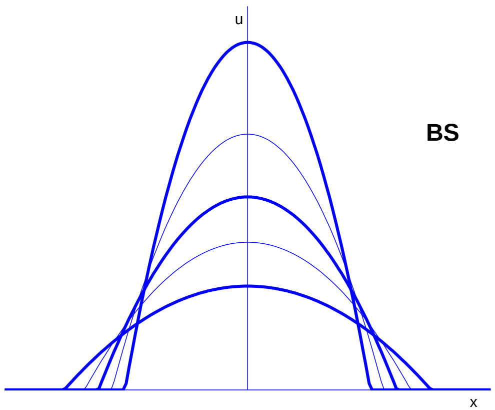

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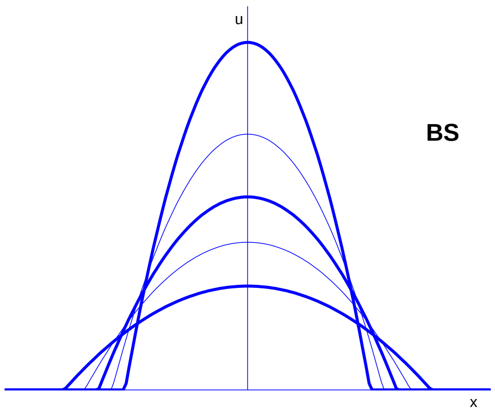

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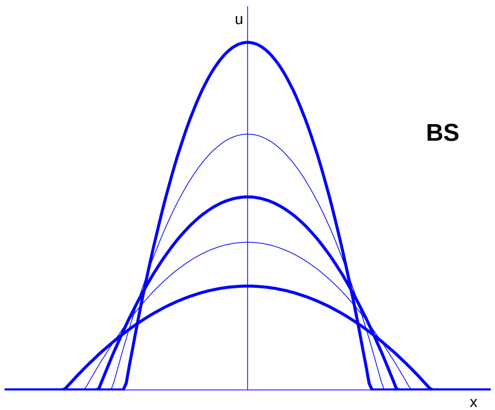
$$\mathbf{B}(x,t;M) = t^{-\alpha}\mathbf{F}(x/t^{\beta}), \quad \mathbf{F}(\xi) = \left(C - k\xi^2\right)_+^{1/(m-1)}$$



Height $u = Ct^{-\alpha}$ Free boundary at distance $|x| = ct^{\beta}$

Scaling law; anomalous diffusion versus Brownian motion

FDE profiles

- We again have explicit formulas for $1 > m > (n-2)/n$:

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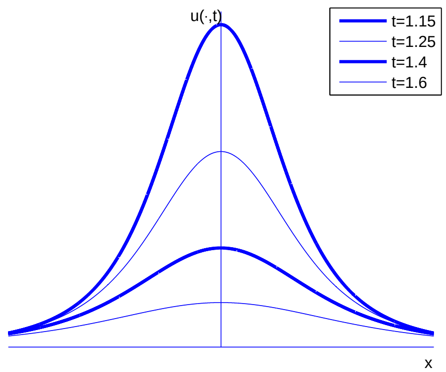

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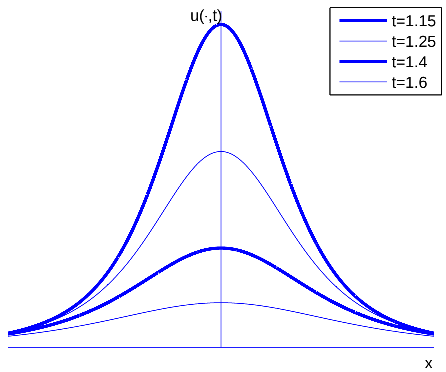

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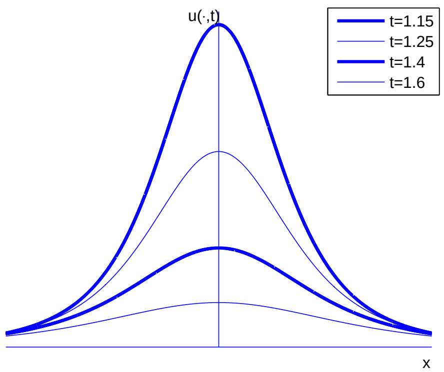

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- Weak solution Test against smooth functions and eliminate derivatives on the unknown function; it is the mainstream; (Oleinik, 1958)

$$\int\int (u\,\eta_t - \nabla u^m \cdot \nabla \eta)\,dxdt + \int u_0(x)\,\eta(x,0)\,dx = 0.$$

Very weak

$$\int\int (u\,\eta_t + u^m\,\Delta\eta)\,dxdt + \int u_0(x)\,\eta(x,0)\,dx = 0.$$

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Solutions of more complicated equations need new concepts:

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$$\int u_t\, h(w)\,dx = \int \Delta w\, h(w)\,dx = -\int h'(w)|\nabla w|^2\,dx \le 0.$$

Now let $h_\epsilon \to h = \text{sign}^+$. Observe that $\text{sign}\,(u_1-u_2) = \text{sign}\,(u_1^m - u_2^m)$. Then

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- Contraction is also true in H^{-1} and in the Wasserstein W_2 space

The standard solutions

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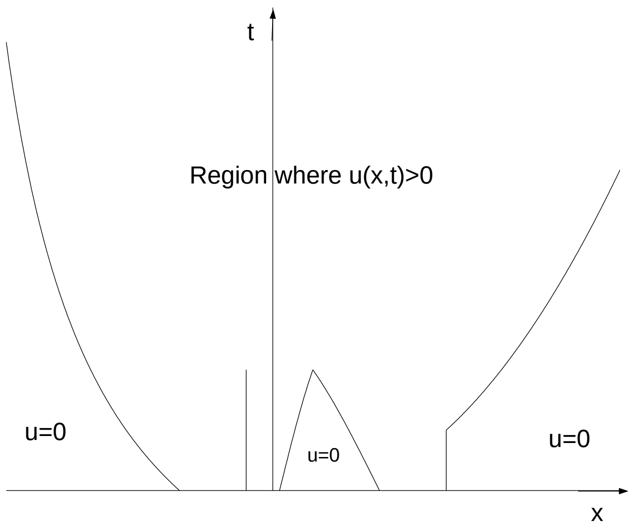
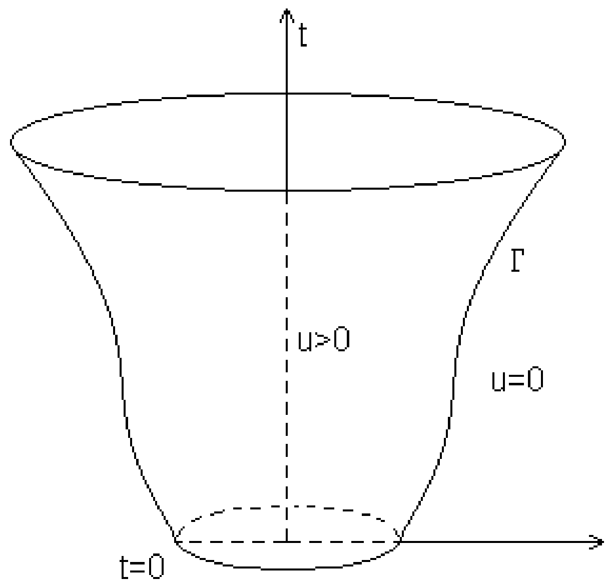
Free Boundaries in several dimensions



A complex free boundary in 1-D



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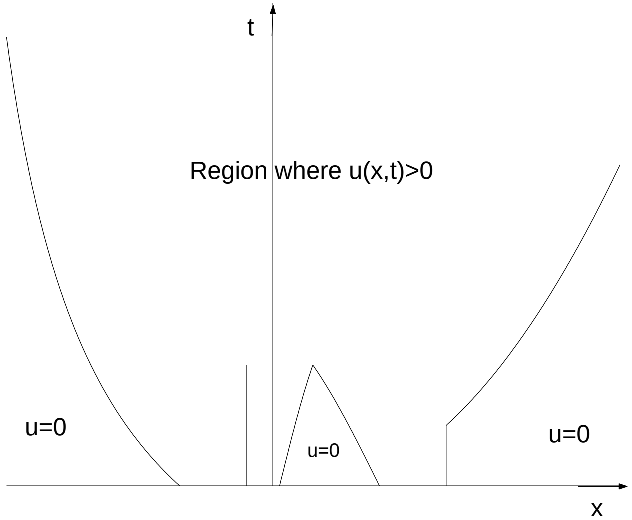

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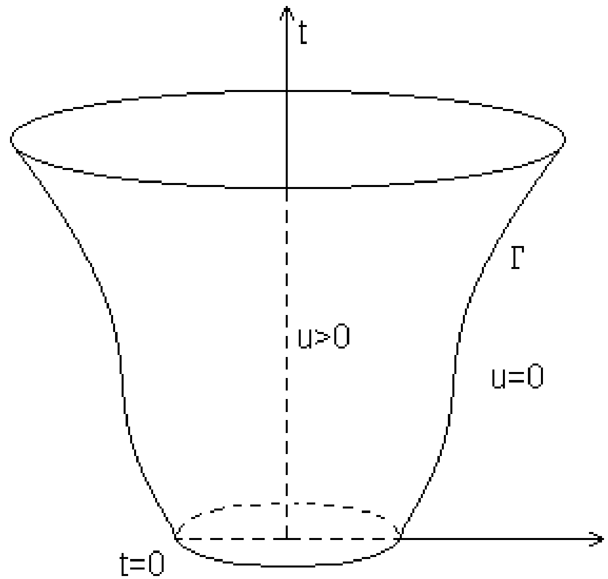

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- (Koch, thesis, 1997) If u_0 is transversal then FB is C^∞ after T. Pressure is “laterally" C^∞. *it is a broken profile always when it moves.*

Free Boundaries II. Holes

- A free boundary with a hole in 2D, 3D is the way of showing that focusing accelerates the viscous fluid so that the speed becomes infinite. This is blow-up for $\mathbf{v} \sim \nabla u^{m-1}$.
  The setup is a viscous fluid on a table occupying an annulus of radii r_1 and r_2. As time passes $r_2(t)$ grows and $r_1(t)$ goes to the origin. As $t \to T$, the time the hole disappears, the speed $r_1'(t) \to -\infty$.

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- There is a semi-explicit solution displaying that behaviour

$$u(x,t) = (T-t)^{\alpha} F(x(T-t)^{\beta}).$$

  The interface is then $r_1(t) = a(T-t)^{\beta}$. It is proved that $\beta < 1$. Aronson and Graveleau, 1993. later Angenent, Aronson,..., Vazquez,

III. Asymptotics

Asymptotic behaviour

Nonlinear Central Limit Theorem

- Choice of domain: $I\!R^n$. Choice of data: $u_0(x) \in L^1(I\!R^n)$. We can write

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- Starting result by FK takes $u_0 \ge 0$, compact support and $f = 0$

Asymptotic behaviour. Picture

- + The rate cannot be improved without more information on u_0
  + m also less than 1 but supercritical ($\rightarrow$ with even better convergence called relative error convergence)
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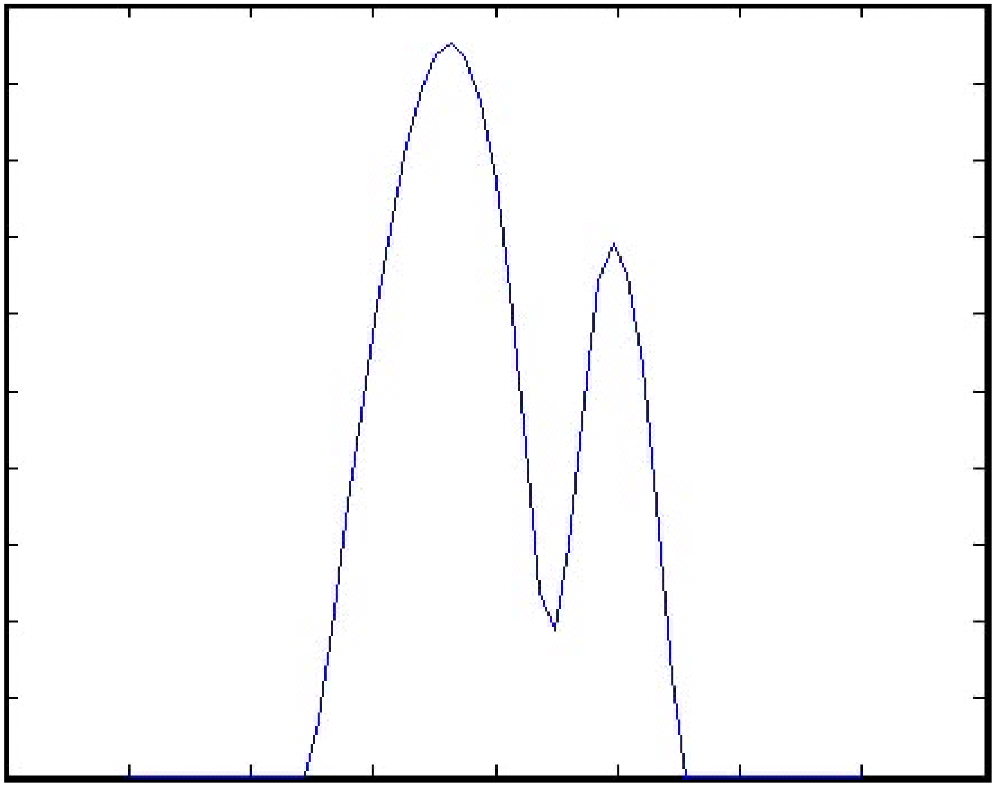
- *Click to see animation* $\Rightarrow$



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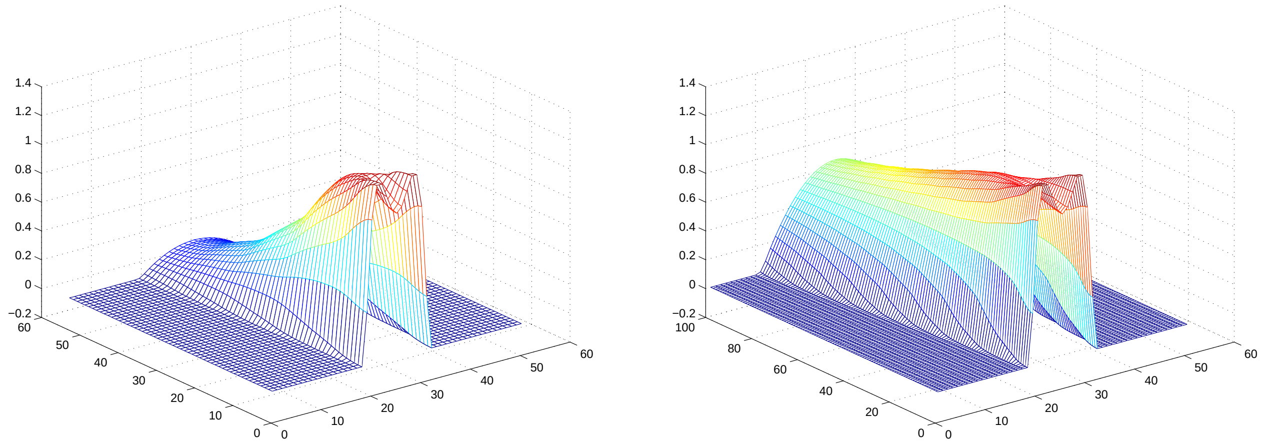
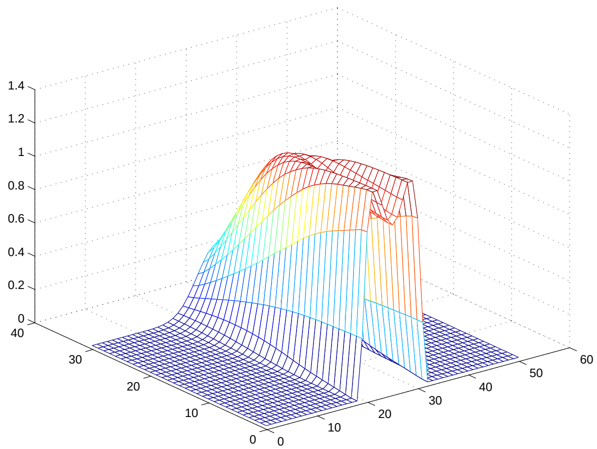
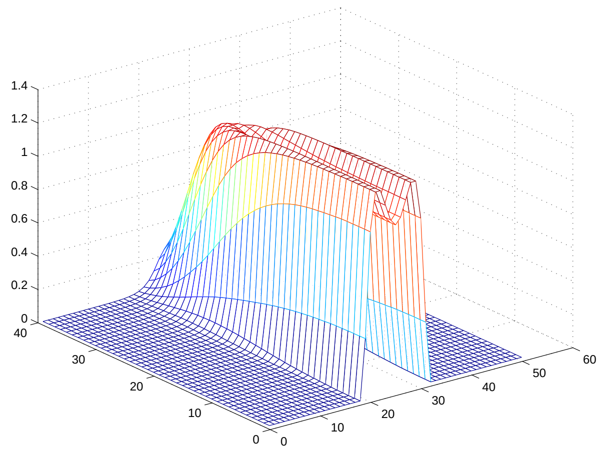


Eventual concavity for PME in 3D and in 1D





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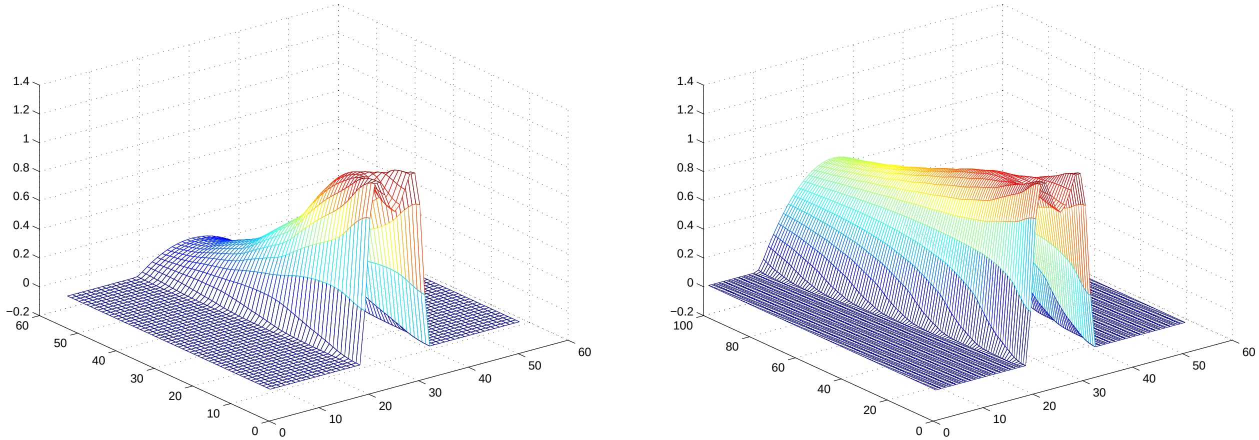

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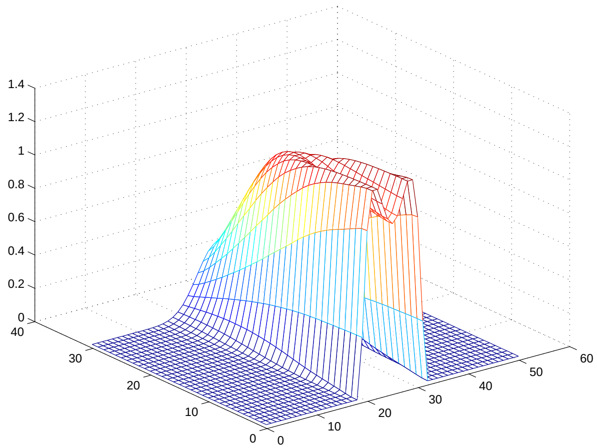

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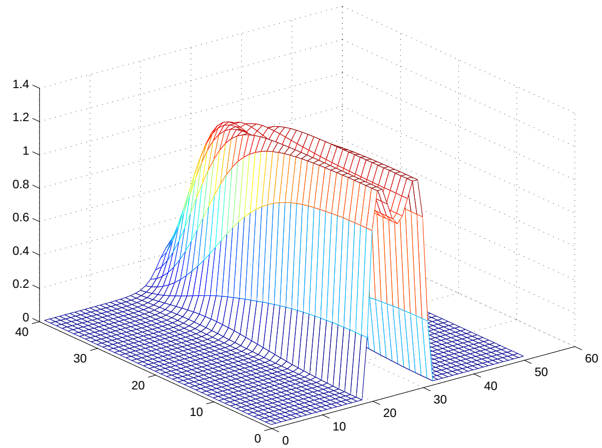

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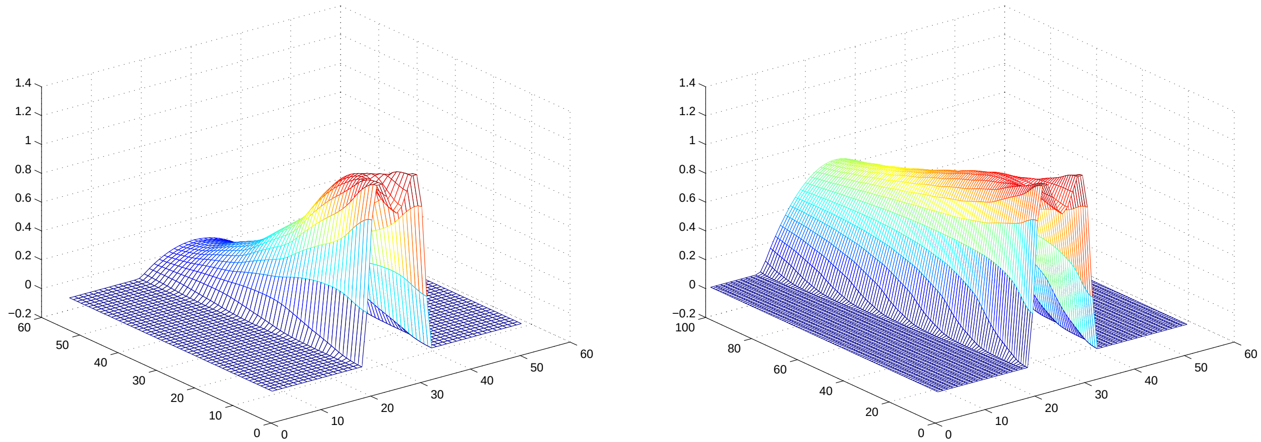

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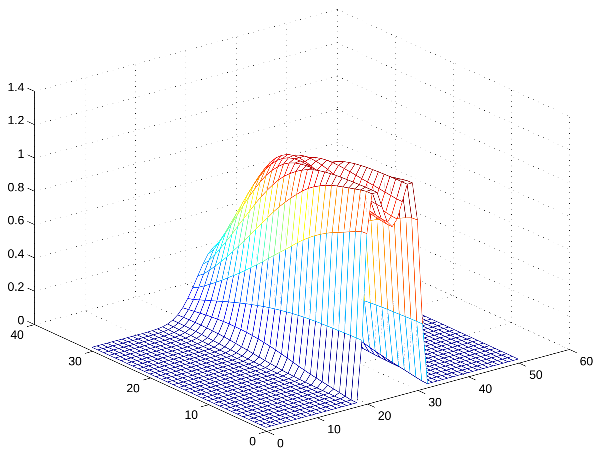

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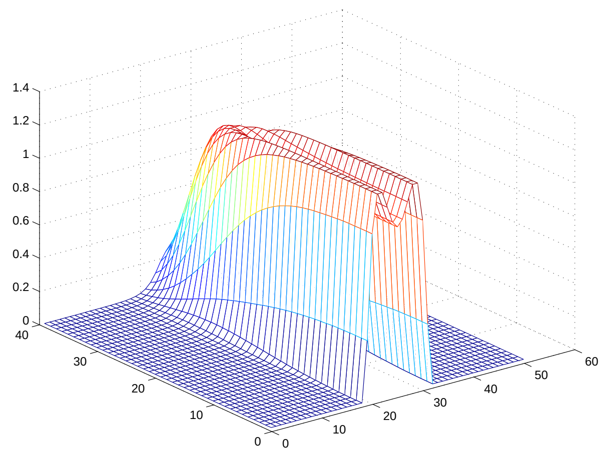

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Probabilities. Wasserstein

- Definition of Wasserstein distance.

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  Technically, this means that π is a probability measure on the product space $\mathbb{R}^n \times \mathbb{R}^n$ that has marginals μ_1 and μ_2. It can be proved that we may use transport functions $y = T(x)$ instead of transport plans (this is Monge's version of the transportation problem).

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- The metric d_∞ plays an important role in controlling the location of free boundaries. Definition $d_\infty(\mu_1, \mu_2) = \inf_{\pi \in \Pi} d_{\pi,\infty}(\mu_1, \mu_2)$, with

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J. L. Vázquez, *Evolution of point masses by planar logarithmic diffusion. Finite-time blow-down,* Preprint, 2006.

Pictures

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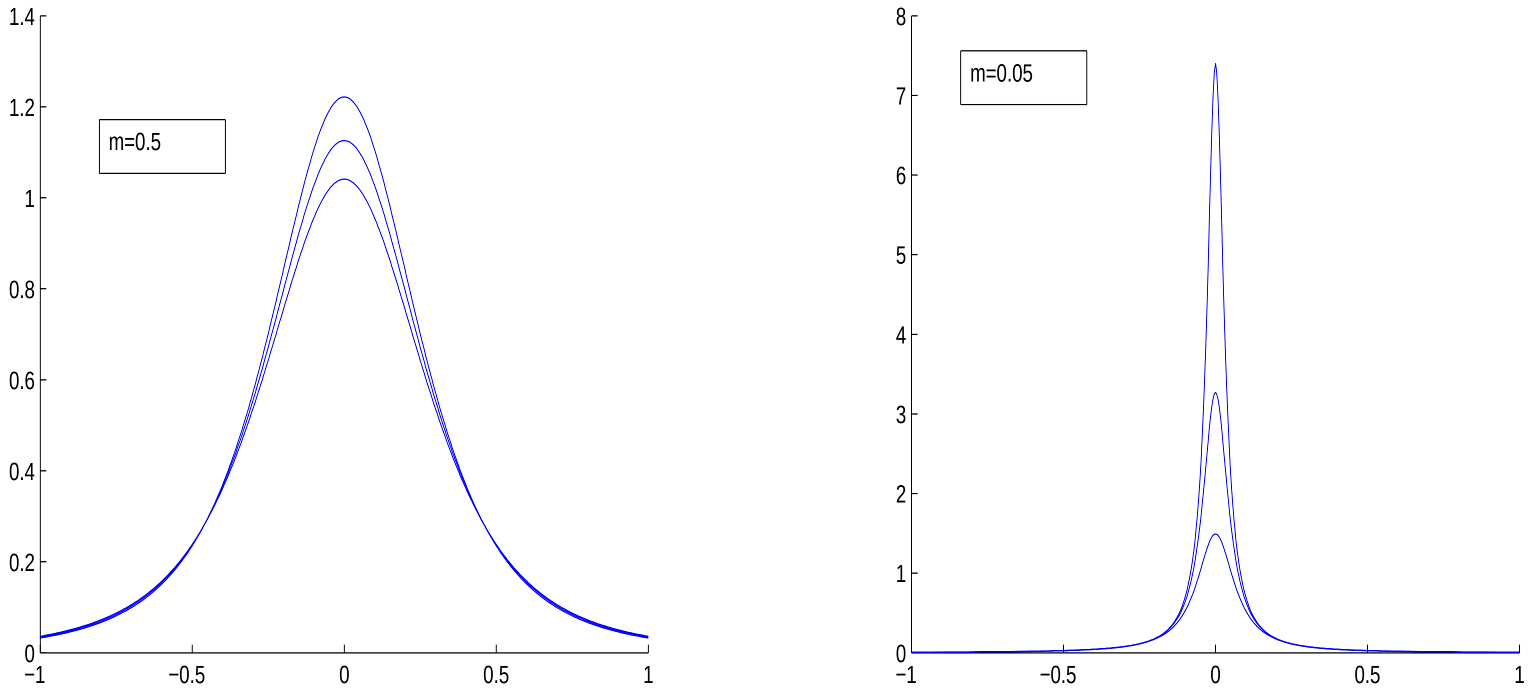

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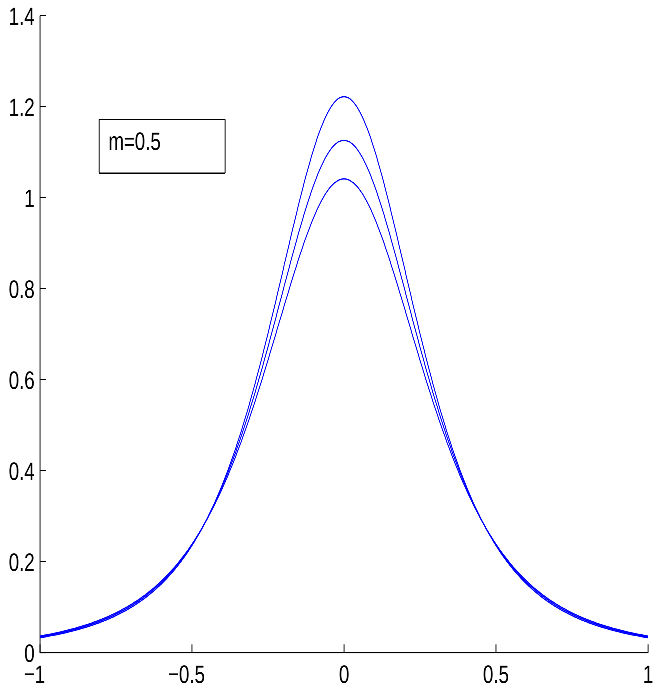

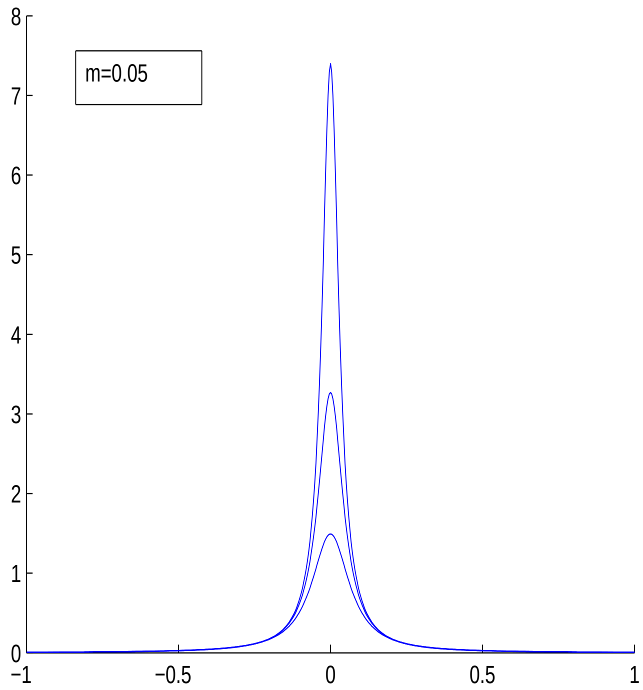

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  Left: intermediate fast diffusion exponent. Right: exponent near $m = 0$

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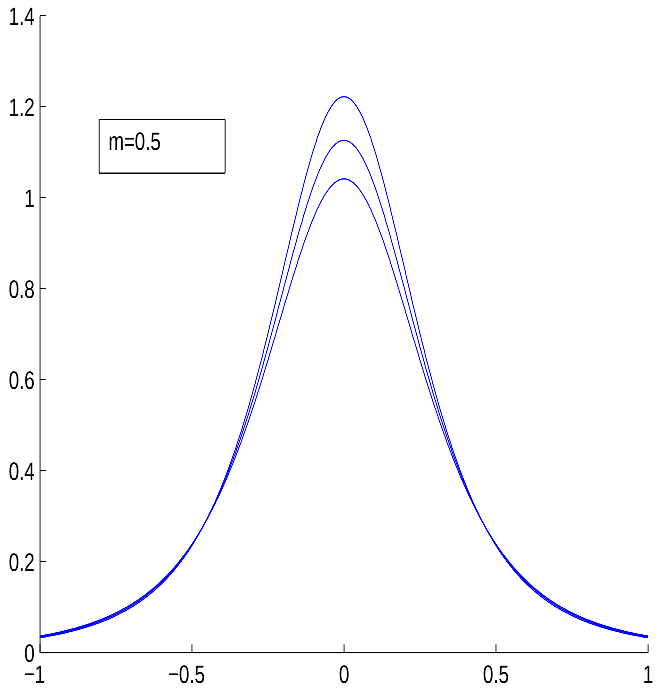

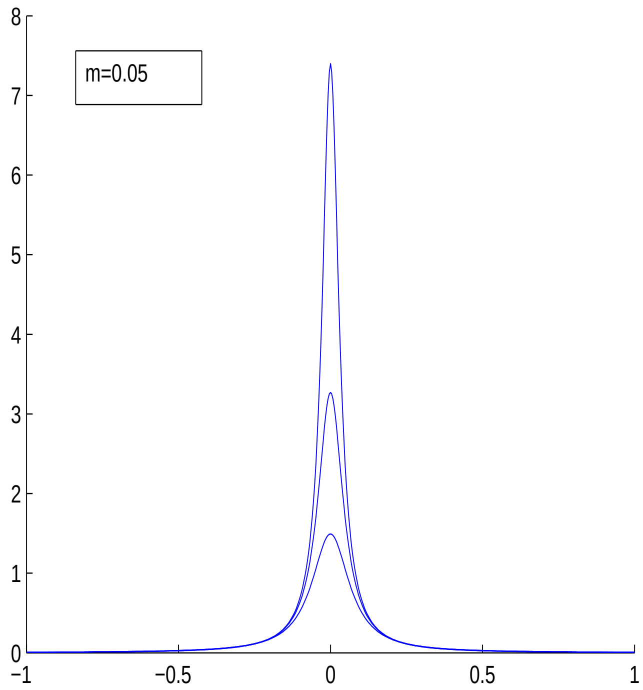

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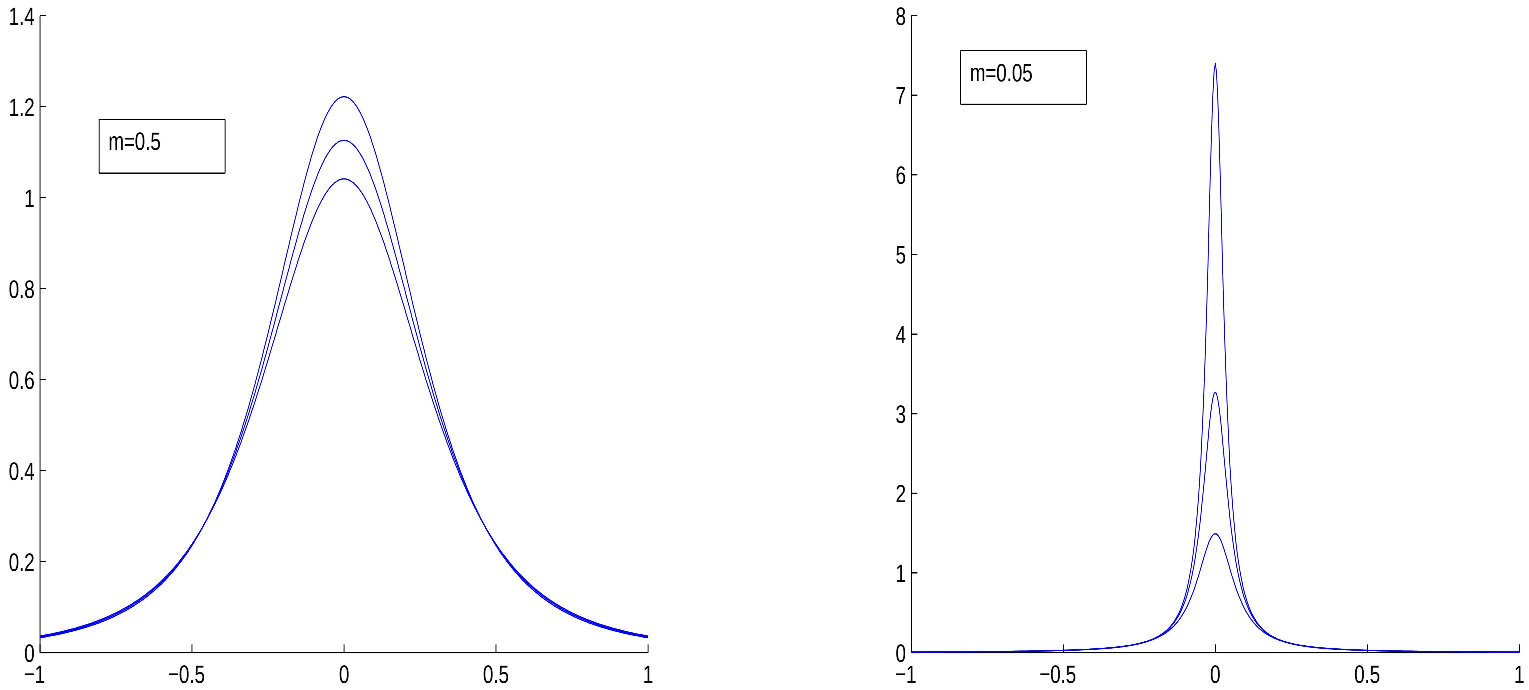

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