

Nonlinear Diffusion. Porous Medium and Fast Diffusion. From Analysis to Physics and Geometry

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The 3rd Symposium on Analysis and PDEs



Introduction

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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?*
- *A main question is: how much of it can be explained with **linear models**, how much is **essentially nonlinear**?*
- *The stationary states of diffusion belong to an important world, **elliptic equations**. Elliptic equations, linear and nonlinear, have many relatives: diffusion, fluid mechanics, waves of all types, quantum mechanics, ...*

The heat equation origins

- We begin our presentation with the Heat Equation $u_t = \Delta u$ 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
- ⇒ 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** \implies Maximum Principles, Schauder estimates, Harnack inequalities; C^α spaces (Hölder); potential theory; generation of semigroups.
 - (2) **coefficients only continuous or bounded** $\implies W^{2,p}$ 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,...

$$dX = bdt + \sigma dW$$

Nonlinear heat flows

- In the last 50 years emphasis has shifted towards the **Nonlinear World**. Maths more difficult, more complex and more realistic. My group works in the areas of **Nonlinear Diffusion** and **Reaction Diffusion**.

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

$$u_t = \sum \partial_i A_i(u, \nabla u) + \sum B(x, u, \nabla u)$$

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

The Reaction Diffusion Models

- 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 than 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

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

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

Applied motivation for the PME

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

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

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).

$$\rho_t = \operatorname{div}\left(\frac{k}{\mu} \rho \nabla p\right) = \operatorname{div}\left(\frac{k}{\mu} \rho \nabla(p_o \rho^\gamma)\right) = c \Delta \rho^{\gamma+1}.$$

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

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

→ When k is not a power we get $T_t = \Delta \Phi(T)$ with $\Phi'(T) = k(T)$.

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- Many more (boundary layers, geometry).

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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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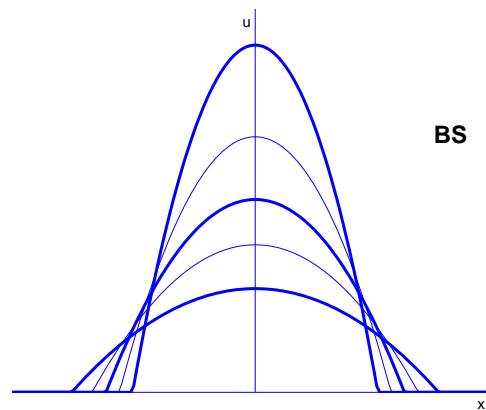
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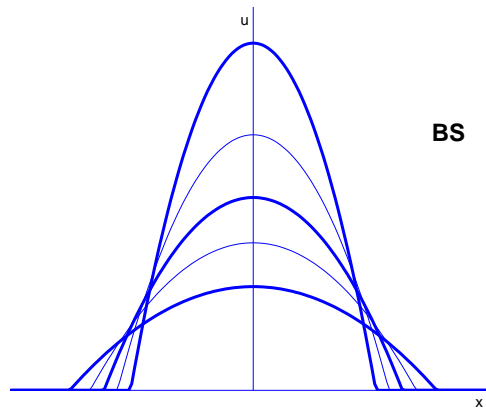
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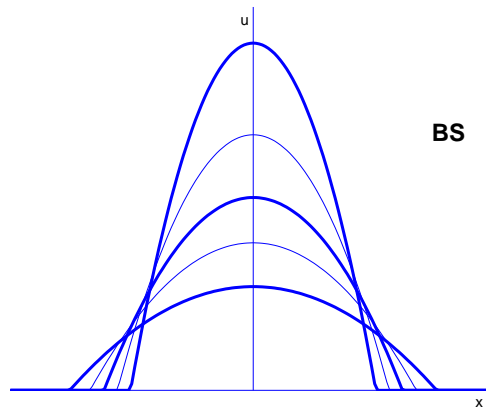
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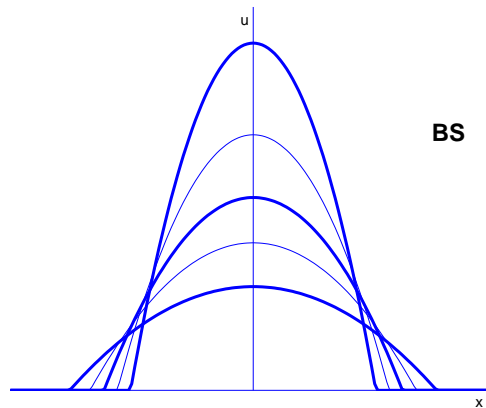
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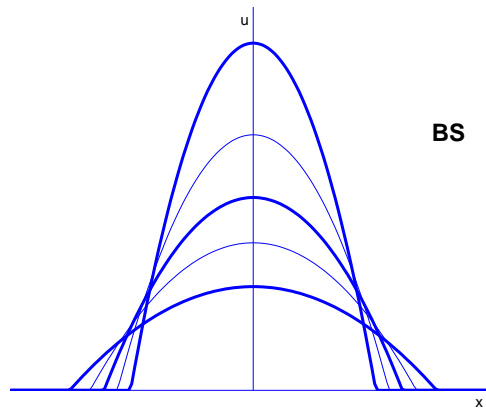
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- Explicit formulas (1950): $\left(\alpha = \frac{n}{2+n(m-1)}, \beta = \frac{1}{2+n(m-1)} < 1/2 \right)$

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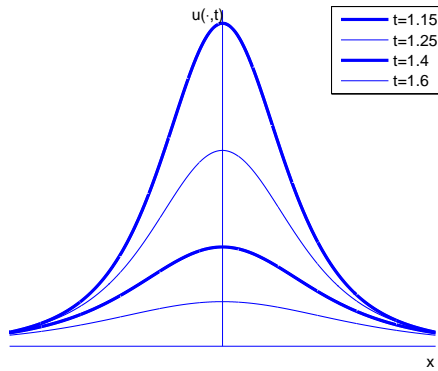
Height $u = Ct^{-\alpha}$ Free boundary at distance $|x| = ct^\beta$

Scaling law; anomalous diffusion versus Brownian motion

FDE profiles

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

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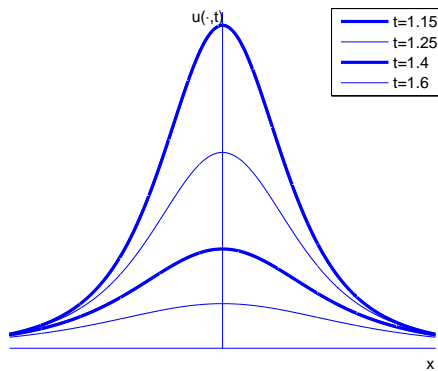
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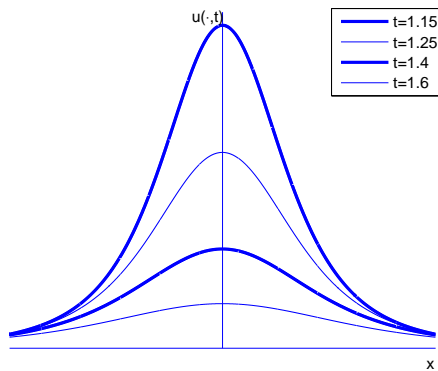
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- **Weak solution** Test against smooth functions and eliminate derivatives on the unknown function; it is the mainstream; (Oleinik, 1958)

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

Very weak

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

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

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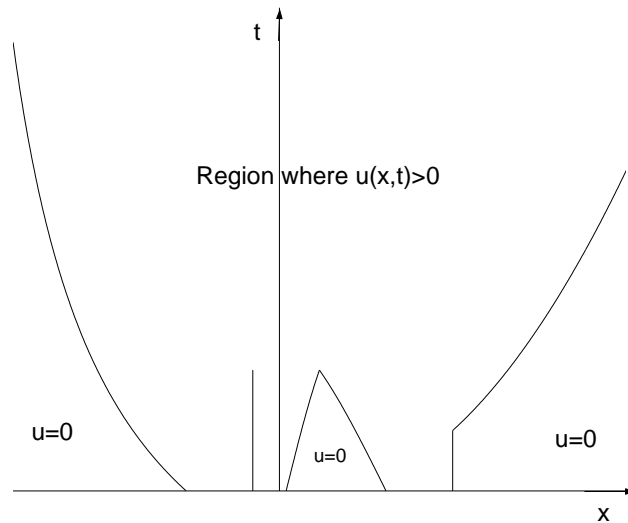
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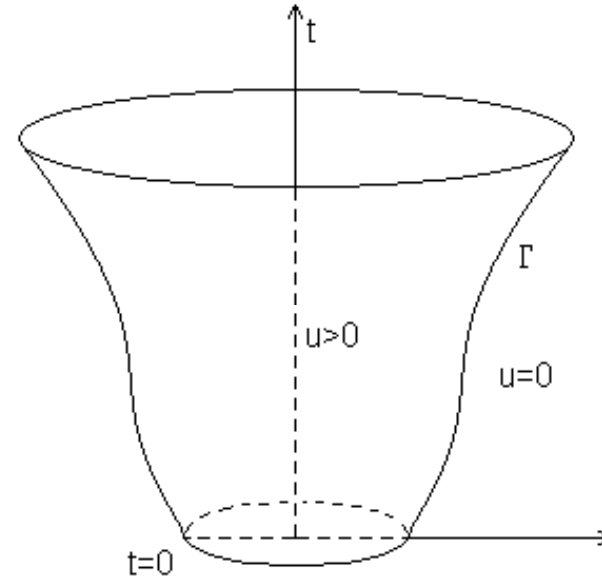
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Free Boundaries in several dimensions



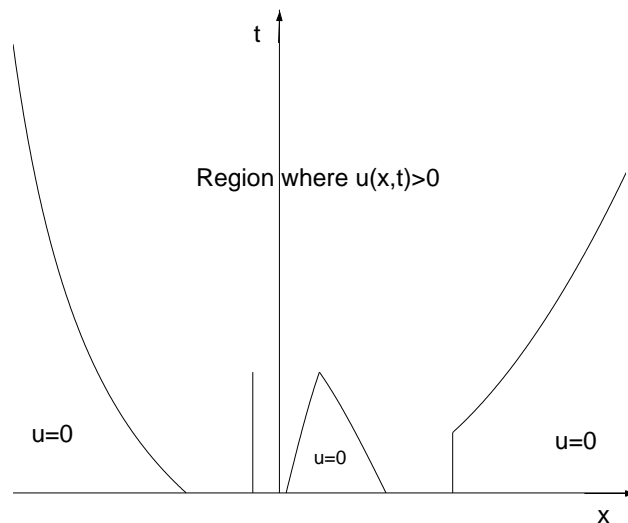
A complex free boundary in 1-D



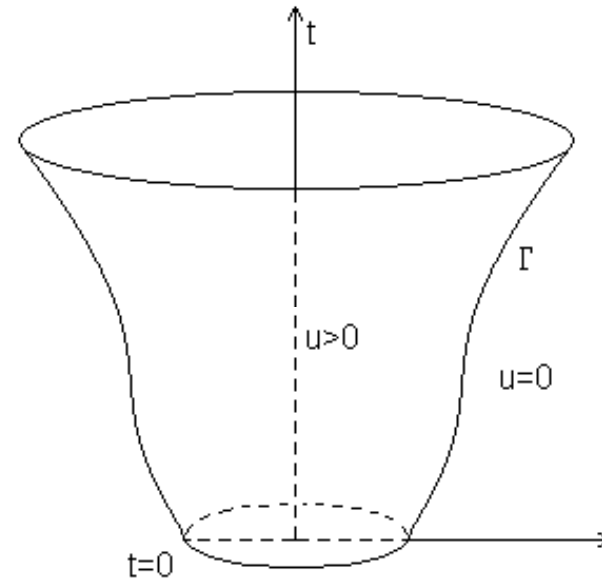
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- (Koch, thesis, 1997) If u_0 is transversal then FB is C^∞ after T . Pressure is “laterally” C^∞ . *it is a broken profile always when it moves.*

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 $t \rightarrow T$, the time the hole disappears, the speed $r_1'(t) \rightarrow -\infty$.

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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: \mathbb{R}^n . Choice of data: $u_0(x) \in L^1(\mathbb{R}^n)$. We can write

$$u_t = \Delta(|u|^{m-1}u) + f$$

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- Asymptotic Theorem** [Kamin and Friedman, 1980; V. 2001] *Let $B(x, t; M)$ be the Barenblatt with the asymptotic mass M ; u converges to B after renormalization*

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- Starting result by FK takes $u_0 \geq 0$, 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**)

$m < (n - 2)/n$ has big surprises;

$m = 0 \rightarrow u_t = \Delta \log u \rightarrow$ Ricci flow with strange properties;

Proof works for p -Laplacian flow

Asymptotic behaviour. II

- **The rates.** Carrillo-Toscani 2000. Using entropy functional with entropy dissipation control you can prove decay rates when $\int u_0(x)|x|^2 dx < \infty$ (finite variance):

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- **Eventual geometry, concavity and convexity** Result by Lee and Vazquez (2003): Here we assume compact support. There exists a time after which the **pressure is concave, the domain convex, the level sets convex** and

$$t \| (D^2 v(\cdot, t) - k\mathbf{I}) \|_\infty \rightarrow 0$$

uniformly in the support. The solution has only one maximum. Inner Convergence in C^∞ .

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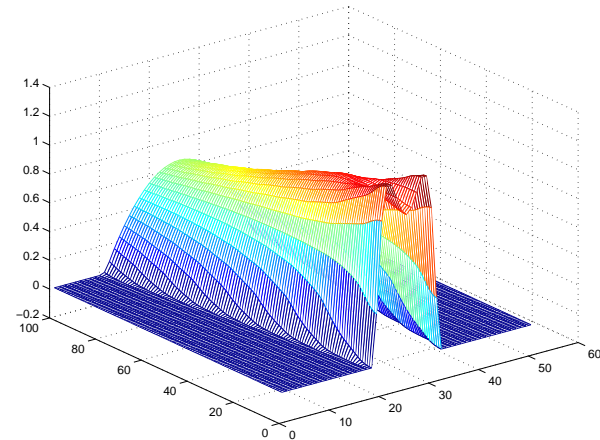
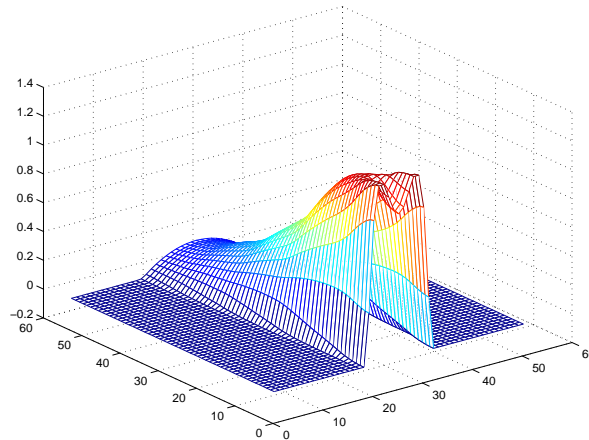
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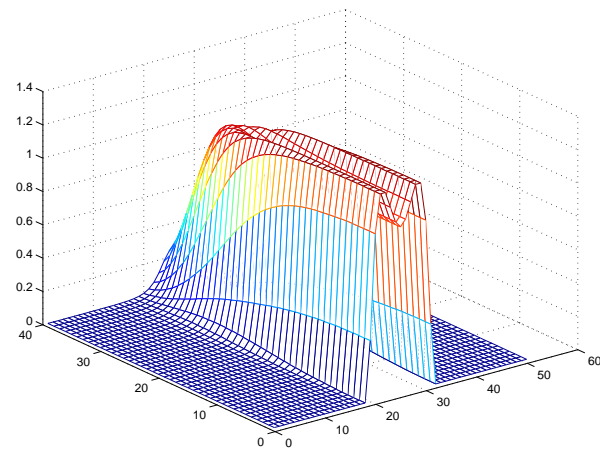
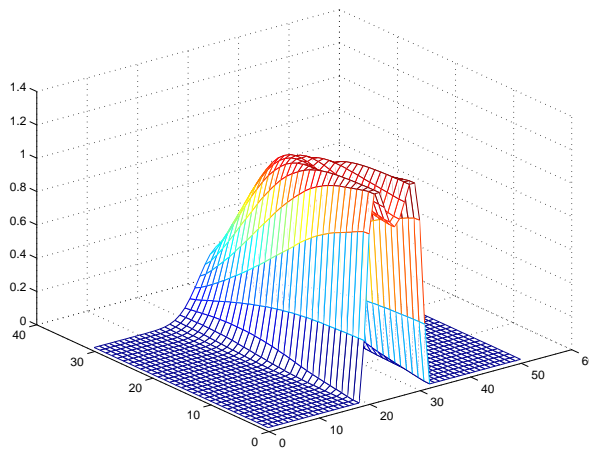
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Asymptotics IV. Concavity

- The eventual concavity results of Lee and Vazquez



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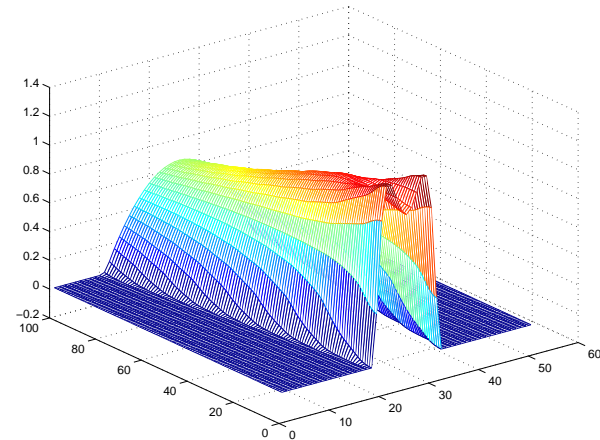
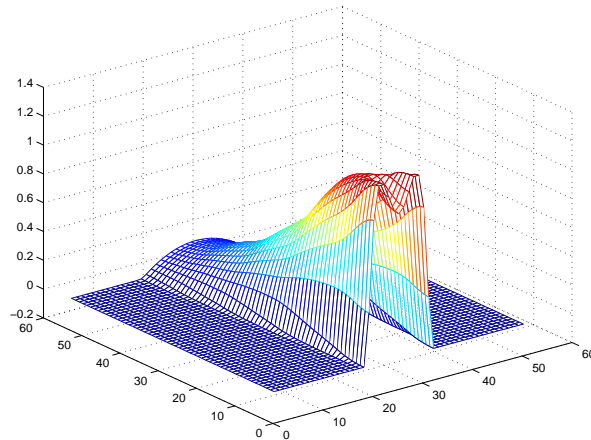


Eventual concavity for HE

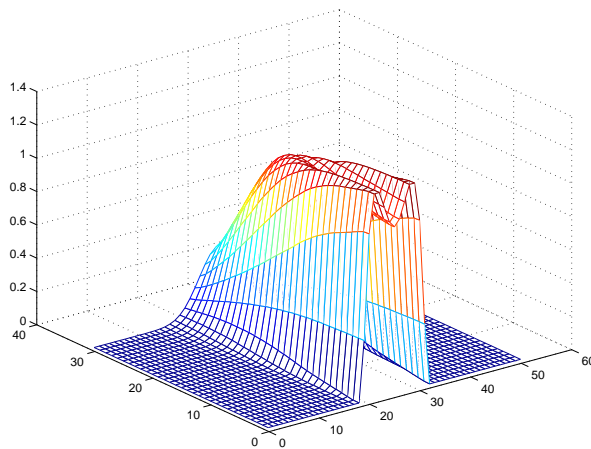
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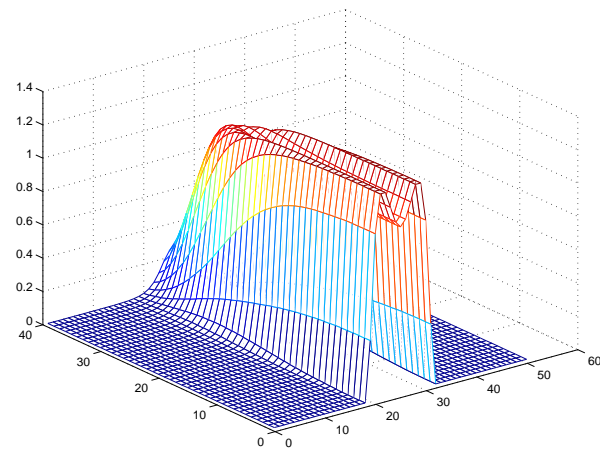
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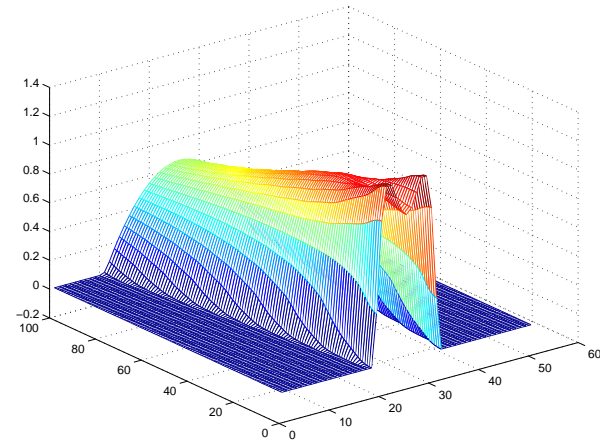
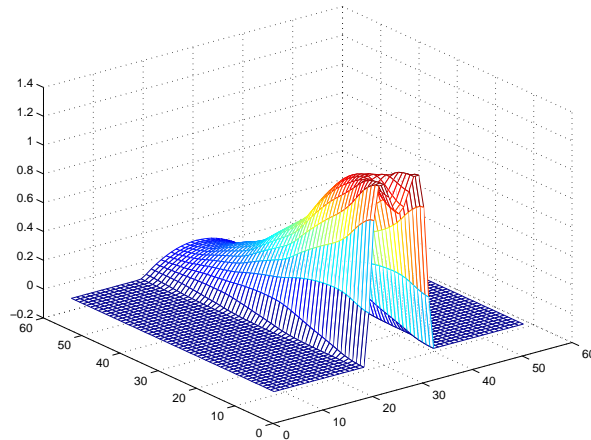
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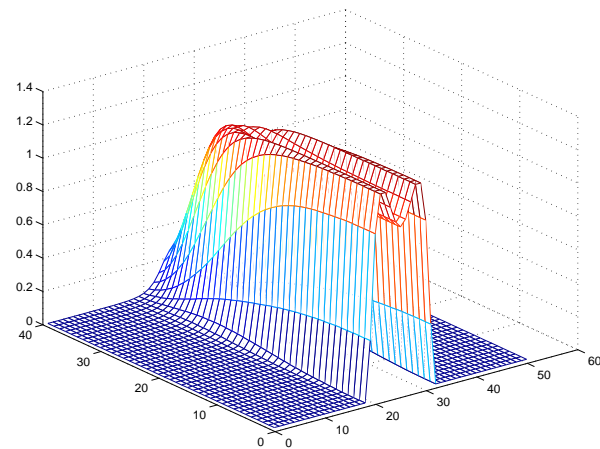
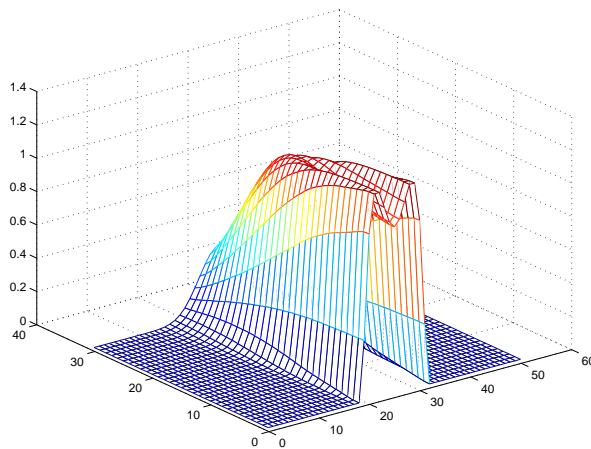
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Probabilities. Wasserstein

● Definition of Wasserstein distance.

Let $\mathcal{P}(\mathbb{R}^n)$ be the set of probability measures. Let $p > 0$. μ_1, μ_2 probability measures.

$$(d_p(\mu_1, \mu_2))^p = \inf_{\pi \in \Pi} \int_{\mathbb{R}^n \times \mathbb{R}^n} |x - y|^p d\pi(x, y),$$

$\Pi = \Pi(\mu_1, \mu_2)$ is the set of all transport plans that move the measure μ_1 into μ_2 . This is a distance.

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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- In principle, for any two probability measures, the infimum may be infinite. But when $1 \leq p < \infty$, d_p defines a metric on the set \mathcal{P}_p of probability measures with finite p -moments, $\int |x|^p d\mu < \infty$. A convenient reference for this topic is Villani's book, "[Topics in Optimal Transportation](#)", 2003.

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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

$$d_{\pi, \infty}(\mu_1, \mu_2) = \sup\{|x - y| : (x, y) \in \text{support}(\pi)\}.$$

In other words, $d_{\pi, \infty}(\mu_1, \mu_2)$ is the maximal distance incurred by the transport plan π , i.e., the supremum of the distances $|x - y|$ such that $\pi(A) > 0$ on all small neighbourhoods A of (x, y) . We call this metric the [maximal transport distance](#).

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- The contraction properties in $n = 1$

Theorem (Vazquez, 1983, 2004) *Let μ_1 and μ_2 be finite nonnegative Radon measures on the line and assume that $\mu_1(\mathbf{R}) = \mu_2(\mathbf{R})$ and $d_\infty(\mu_1, \mu_2)$ is finite. Let $u_i(x, t)$ the continuous weak solution of the PME with initial data μ_i . Then, for every $t_2 > t_1 > 0$*

$$d_\infty(u_1(\cdot, t_2), u_2(\cdot, t_2)) \leq d_\infty(u_1(\cdot, t_1), u_2(\cdot, t_1)) \leq d_\infty(\mu_1, \mu_2).$$

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New fields

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Geometrical applications: Yamabe flow, $m = (n - 2)/n$. Extinction.

see our book Smoothing

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where $f \geq 0$ is an integrable function in \mathbb{R}^2 , the $x_i, i = 1, \dots, n$, are a finite collection of (different) points on the plane, and we are given masses

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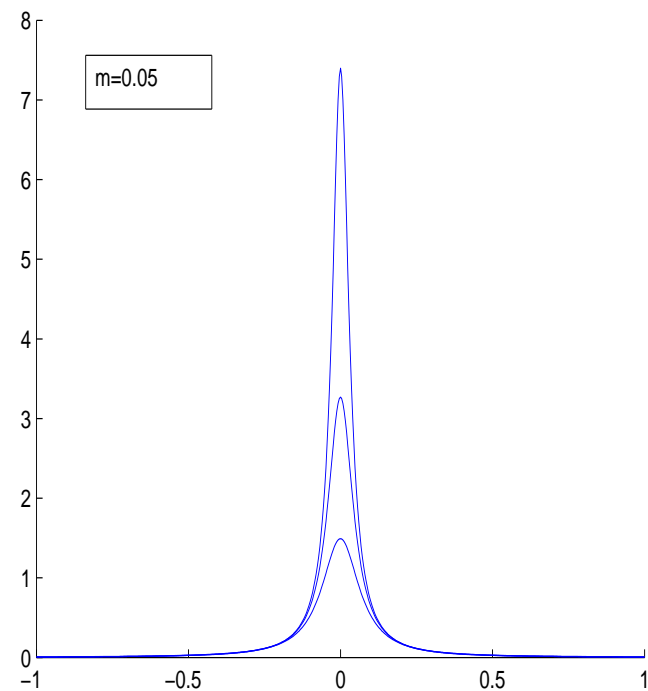
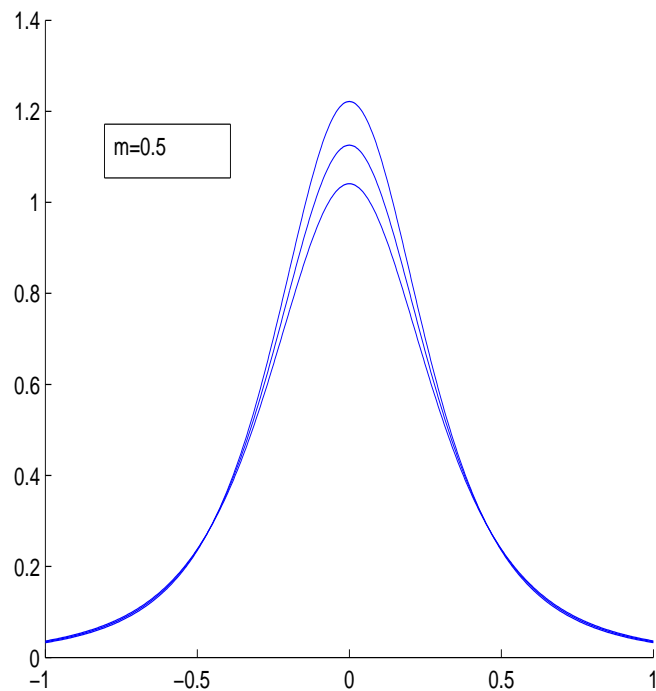
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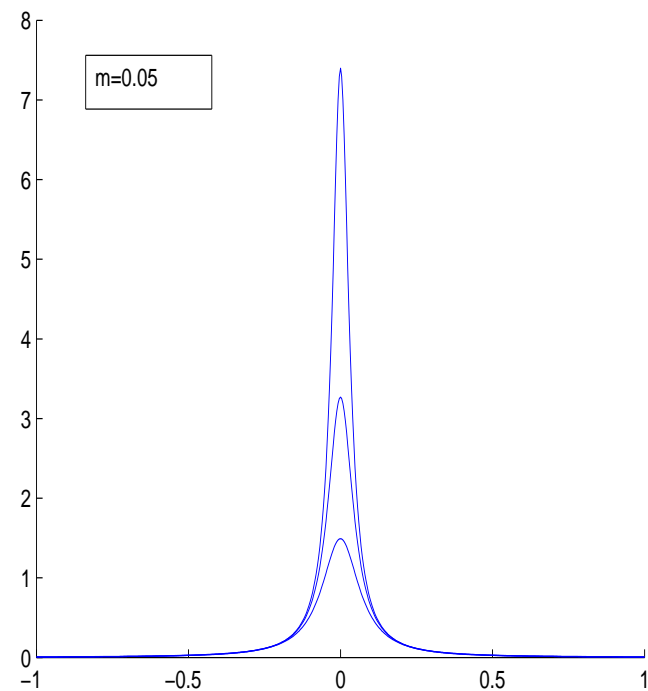
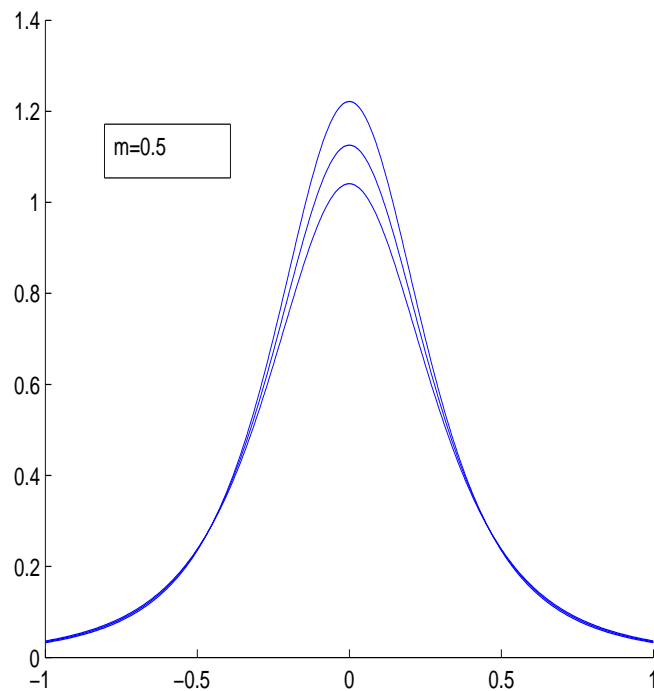
Pictures

About fast diffusion in the limit



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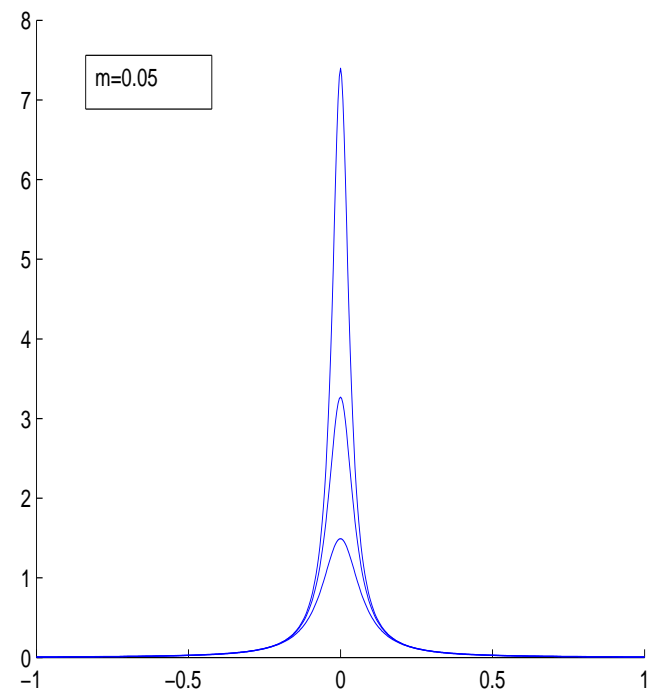
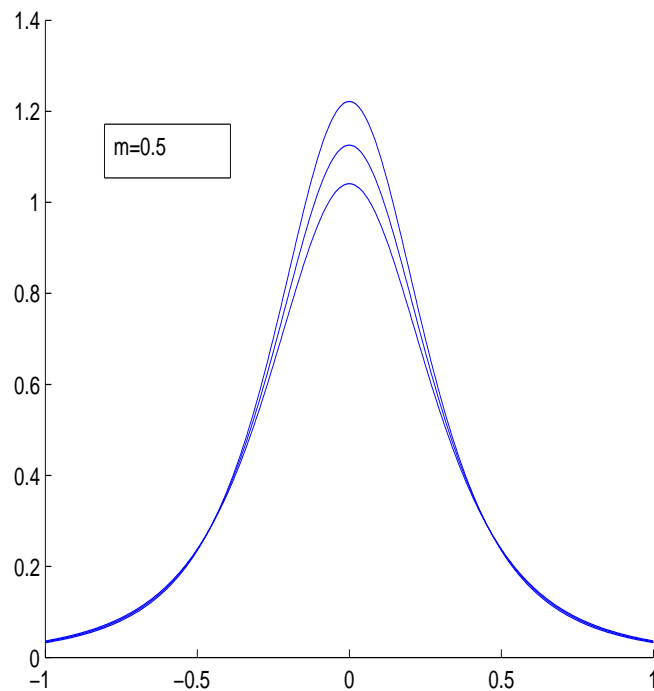


Evolution of the ZKB solutions; dimension $n = 2$.

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

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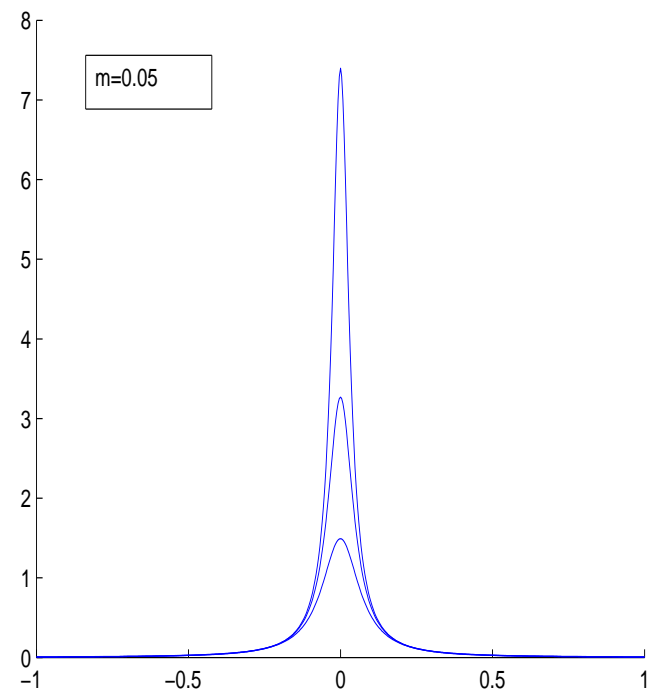
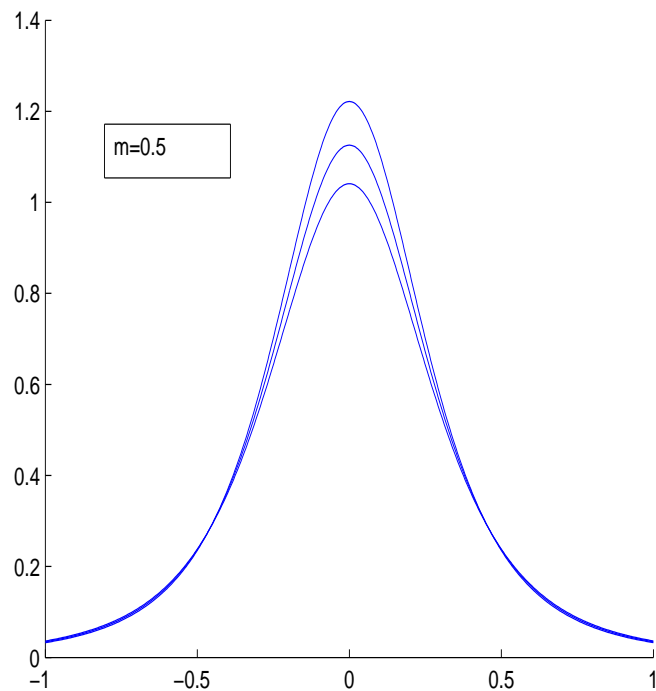


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 **Theorem** *Under the stated conditions, there exists a limit solution of the log-diffusion Cauchy problem posed in the whole plane with initial data μ_0 . It exists in the time interval $0 < t < T$ with $T = M/2\pi$. It satisfies the conditions of maximality at infinity (\rightarrow uniqueness). The solution is **continuous into the space of Radon measures**, $u \in C([0, T] : \mathcal{M}(\mathbb{R}^2))$, and it has two components, singular and regular.*

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- *The singular part amounts to a collection of (shrinking in time) point masses concentrated at $x = x_i$:*

$$u_{sing} = \sum (M_i - 4\pi t)_+ \delta(x - x_i).$$

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