Spectral theory for non-self-adjoint Lévy operators in the half-line

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Toronto, October 14, 2021

Starting point

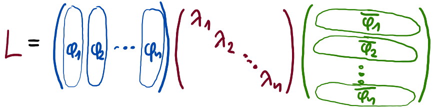
If L is a self-adjoint operator on a finitely-dimensional vector space, then

$$\langle Lu, v\rangle = \sum_{j=1}^{N} \lambda_j \langle u, \varphi_j\rangle \langle \varphi_j, v\rangle \tag{EE}$$

for a complete orthogonal set of eigenvectors φ_j:

$$L\varphi_j = \lambda_j \varphi_j$$

EE stands for 'eigenfunction expansion'.



Hilbert–Schmidt theory

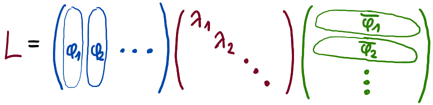
If L is a compact self-adjoint operator on a Hilbert space, then

$$\langle Lu, v\rangle = \sum_{j=1}^{\infty} \lambda_j \langle u, \varphi_j\rangle \langle \varphi_j, v\rangle \tag{EE}$$

for a complete orthogonal set of eigenvectors φ_j:

$$L\varphi_j = \lambda_j \varphi_j$$

EE stands for 'eigenfunction expansion'.



Spectral theorem

If L is a self-adjoint operator on a Hilbert space, then

$$\langle Lu, v\rangle = \int_Z \lambda d\langle E_\lambda u, v\rangle$$

for a resolution of identity E_λ.

Spectral theorem for Carleman's operators (Gårding, 1954)

If L is a self-adjoint Carleman operator on $L^2(X)$, then

$$\langle Lu, v\rangle = \int_Z \lambda_r \langle u, \varphi_r\rangle\langle \varphi_r, v\rangle dr \qquad \text{(GEE)}$$

for a set of generalised eigenfunctions φ_r:

$$L\varphi_r(x) = \lambda_r \varphi_r(x)$$

Note: typically $\varphi_r \notin L^2(X)$

Carleman operators have 'nice' kernels:

$$Lu(x) = \int K(x,y)u(y)dy$$

with $\|K(x,\cdot)\|_2 < \infty$ for almost all x.

Non-normal case

If L is an arbitrary operator on a finitely-dimensional vector space, then

L can be written in a Jordan normal form.

Optimistic scenario

If we are lucky:

$$L = \begin{pmatrix} \varphi_1 & \varphi_2 & \cdots & \varphi_n \end{pmatrix} \begin{pmatrix} \lambda_1 & & & \\ & \lambda_2 & & \\ & & \ddots & \\ & & & \lambda_n \end{pmatrix} \begin{pmatrix} \overline{\psi_1} \\ \overline{\psi_2} \\ \vdots \\ \overline{\psi_n} \end{pmatrix}$$

$$\langle Lu, v\rangle = \sum_{j=1}^{N} \lambda_j \langle u, \psi_j\rangle\langle \varphi_j, v\rangle \tag{EE}$$

for a complete set of eigenvectors φ_j and co-eigenvectors ψ_j:

$$L\varphi_j = \lambda_j\varphi_j, \qquad L^*\psi_j = \overline{\lambda}_j\psi_j$$

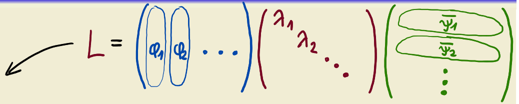
F. Riesz's theory

If L is a compact operator on a Hilbert space, then

L can be 'written' in a Jordan normal form.

Optimistic scenario

If we are lucky:



$$\langle Lu, v\rangle = \sum_{j=1}^{\infty} \lambda_j \langle u, \psi_j\rangle\langle \varphi_j, v\rangle \tag{EE}$$

for a complete set of eigenvectors φ_j and co-eigenvectors ψ_j:

$$L\varphi_j = \lambda_j\varphi_j, \qquad L^*\psi_j = \overline{\lambda}_j\psi_j$$

Overly optimistic scenario?

If L is an appropriate operator on $L^2(X)$, we hope for

$$\langle Lu, v\rangle = \int_Z \lambda_r \langle u, \psi_r\rangle\langle \varphi_r, v\rangle dr \tag{GEE}$$

for a set of generalised eigenfunctions φ_r and generalised co-eigenfunctions ψ_r:

$$L\varphi_r = \lambda_r\varphi_r, \qquad L^*\psi_r = \overline{\lambda}_r\psi_r$$

Markov chains

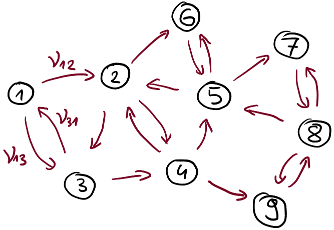
The generator of a continuous-time Markov chain:

$$L = \begin{pmatrix} -\nu_1 & \nu_{12} & \nu_{13} & \cdots & \nu_{1n} \\ \nu_{21} & -\nu_2 & \nu_{23} & \cdots & \nu_{2n} \\ \nu_{31} & \nu_{32} & -\nu_3 & \cdots & \nu_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \nu_{n1} & \nu_{n2} & \nu_{n3} & \cdots & -\nu_n \end{pmatrix}$$

with $\nu_{ij} \geqslant 0$ and $\nu_i = \sum_{j \neq i} \nu_{ij}$.

Its transition probabilities:

$$P_t = \exp(tL)$$



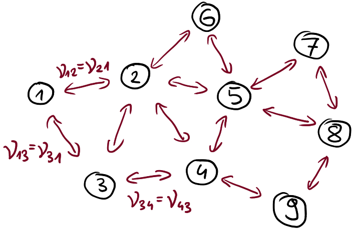
Symmetric Markov chains

For a symmetric Markov chain:

$$\langle Lu, v\rangle = \sum_{j=1}^{N} (-\lambda_j)\langle u, \varphi_j\rangle\langle \varphi_j, v\rangle$$

$$\langle P_t u, v\rangle = \sum_{j=1}^{N} e^{-t\lambda_j}\langle u, \varphi_j\rangle\langle \varphi_j, v\rangle \qquad \text{(EE)}$$

with $\lambda_j \geqslant 0$.



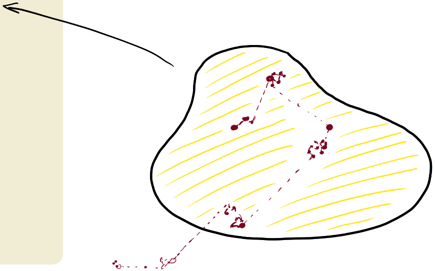
Markov processes

The generator of a Markov process, e.g.:

$$Lu(x) = \Delta u(x) \quad \text{(Laplace operator)}$$

or

$$Lu(x) = \int (u(y) - u(x))\nu(x,y)dy$$



Its transition operators:

$$P_t u(x) = \exp(tL)u(x) = \int p_t(x,y)u(y)dy$$

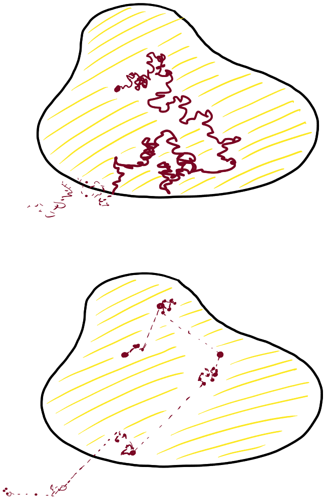
Symmetric Markov processes

If P_t are compact operators:

$$\langle Lu, v\rangle = \sum_{j=1}^{\infty} (-\lambda_j)\langle u, \varphi_j\rangle\langle \varphi_j, v\rangle$$

$$\langle P_t u, v\rangle = \sum_{j=1}^{\infty} e^{-t\lambda_j}\langle u, \varphi_j\rangle\langle \varphi_j, v\rangle \qquad \text{(EE)}$$

with $\lambda_j \geqslant 0$.



Symmetric Markov processes (Getoor, 1959)

If P_t are Carleman operators:

$$\langle Lu, v\rangle = \int_Z (-\lambda_r)\langle u, \varphi_r\rangle\langle \varphi_r, v\rangle dr$$

$$\langle P_t u, v\rangle = \int_Z e^{-t\lambda_r}\langle u, \varphi_r\rangle\langle \varphi_r, v\rangle dr \qquad \text{(GEE)}$$

with $\lambda_r \geqslant 0$

Non-symmetric Markov processes

For a non-symmetric Markov process, if P_t are compact operators:

we only know what follows from F. Riesz's theory.

Optimistic scenario

If we are lucky:

$$\langle Lu, v \rangle = \sum_{j=1}^{\infty} (-\lambda_j) \langle u, \psi_j \rangle \langle \varphi_j, v \rangle$$

$$\langle P_t u, v \rangle = \sum_{j=1}^{\infty} e^{-t\lambda_j} \langle u, \psi_j \rangle \langle \varphi_j, v \rangle$$

with $\operatorname{Re} \lambda_j \geqslant 0$.

Non-symmetric case

For a general non-symmetric Markov process:

we know virtually nothing.

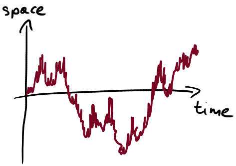
Self-adjoint example

The 1-D Brownian motion:

$$Lu(x) = u''(x)$$

Plancherel's formula:

$$\langle Lu, v\rangle = \frac{1}{2\pi}\int_{-\infty}^{\infty} (-\xi^2)\hat{u}(\xi)\overline{\hat{v}(\xi)}d\xi$$



Equivalently:

$$Lu(x) = \frac{1}{2\pi}\int_{-\infty}^{\infty} (-\xi^2)\langle u, \varphi_\xi\rangle\langle \varphi_\xi, v\rangle d\xi \qquad \text{(GEE)}$$

with $\varphi_\xi(x) = e^{i\xi x}$.

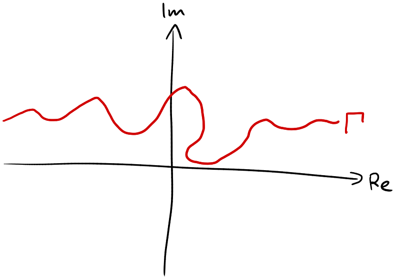
Non-uniqueness of GEE

By contour deformation:

$$Lu(x) = \frac{1}{2\pi} \int_{\Gamma} (-\xi^2) \langle u, \psi_\xi \rangle \langle \varphi_\xi, v \rangle d\xi \qquad \text{(GEE)}$$

with $\varphi_\xi(x) = e^{i\xi x}$, $\psi_\xi(x) = e^{i\bar{\xi} x}$, as long as Γ goes 'from $-\infty$ to $+\infty$'.

It is clear that $\Gamma = (-\infty, \infty)$ is 'optimal'.



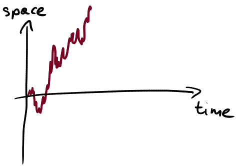
Normal example

The 1-D Brownian motion with drift:

$$Lu(x) = u''(x) + 2bu'(x)$$

Plancherel's formula:

$$\langle Lu, v\rangle = \frac{1}{2\pi}\int_{-\infty}^{\infty} (-\xi^2 + 2bi\xi)\hat{u}(\xi)\overline{\hat{v}(\xi)}d\xi$$



Equivalently:

$$Lu(x) = \frac{1}{2\pi}\int_{-\infty}^{\infty} (-\xi^2 + 2bi\xi)\langle u, \varphi_\xi\rangle\langle \varphi_\xi, v\rangle d\xi \tag{GEE}$$

with $\varphi_\xi(x) = e^{i\xi x}$.

Non-uniqueness of GEE

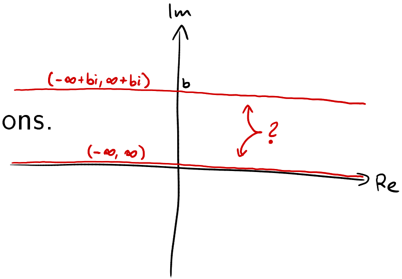
By contour deformation:

$$Lu(x) = \frac{1}{2\pi} \int_\Gamma (-\xi^2 + 2bi\xi)\langle u, \psi_\xi \rangle \langle \varphi_\xi, v \rangle d\xi \qquad \text{(GEE)}$$

with $\varphi_\xi(x) = e^{i\xi x}$, $\psi_\xi(x) = e^{i\bar{\xi} x}$, as long as Γ goes 'from $-\infty$ to $+\infty$'.

The choice of Γ is no longer clear:

- $\Gamma = (-\infty, \infty)$ leads to $\psi_\xi = \varphi_\xi$ bounded;
- $\Gamma = (-\infty + bi, \infty + bi)$ leads to real-valued expressions.



Non-normal example

The killed 1-D Brownian motion with drift in $(0, \infty)$:

$$Lu(x) = u''(x) + 2bu'(x) \qquad x \in (0, \infty)$$

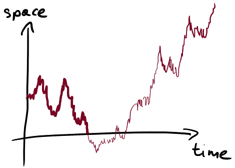
with Dirichlet boundary condition $u(0) = 0$.

The solution of the eigenvalue problem:

$$L\varphi = (-\xi^2 + 2ib\xi)\varphi$$

is given by

$$\varphi_\xi(x) = e^{i\xi x} - e^{i(-\xi+2ib)x}$$



Non-normal GEE

After an elementary calculation:

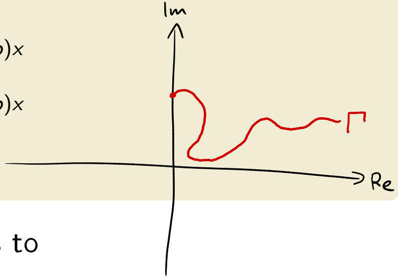
$$Lu(x) = \frac{1}{\pi} \int_\Gamma (-\xi^2 + 2bi\xi) \langle u, \psi_\xi \rangle \langle \varphi_\xi, v \rangle d\xi \tag{GEE}$$

with

$$\varphi_\xi(x) = e^{i\xi x} - e^{i(-\xi + 2ib)x}$$

$$\psi_\xi(x) = e^{i\bar{\xi} x} - e^{i(-\bar{\xi} - 2ib)x}$$

as long as Γ goes 'from a point on $i\mathbb{R}$ to $+\infty$'.



The choice of Γ clear again: $\Gamma = (bi, \infty + bi)$ leads to

- φ_ξ, ψ_ξ as small as possible,
- all expressions real-valued.

Goal

Study generalised eigenfunction expansions for generators L of other Markov processes

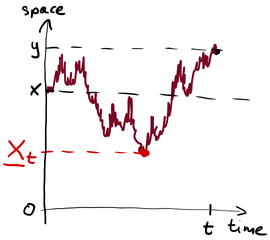
Applications so far:

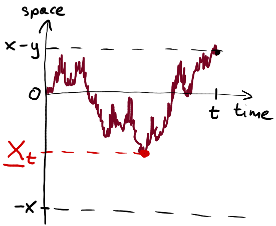
- expression for the heat kernel in $(0, \infty)$:

$$p_t^+(x,y) = \int_0^\infty \lambda_r \psi_r(x) \varphi_r(y) dr \qquad \text{(GEE)}$$

- supremum and infimum functionals:

$$\mathbb{P}(\underline{X}_t < -x) = \int_0^\infty p_t^+(x,y) dy.$$





Lévy process

A 1-D Lévy process is a translation-invariant Markov process on $\mathbb{R}$.

Lévy operators

A 1-D Lévy operator is the generator of a 1-D Lévy process:

$$Lu(x) = au''(x) + ibu'(x) + \int_{-\infty}^{\infty} (u(y) - u(x) - (\dots))\nu(y-x)dy$$

Lévy–Khinchin theorem

A Lévy operator L is a Fourier multiplier:

$$\widehat{Lu}(\xi) = -f(\xi)\hat{u}(\xi)$$

where the characteristic exponent is given by:

$$f(\xi) = a\xi^2 - ib\xi + \int_{-\infty}^{\infty} (1 - e^{i\xi z} - (\ldots))\nu(z)dz$$

Transition operators $P_t = \exp(tL)$ are Fourier multipliers with symbol $e^{-tf(\xi)}$.

Bernstein's theorem

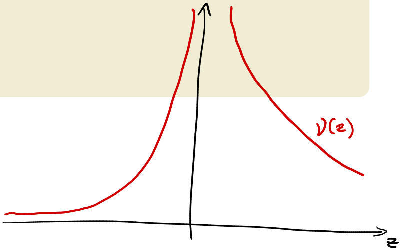
The following are equivalent:

- ν is completely monotone (or CM): $(-1)^n \nu(z) \geqslant 0$ for $z > 0$;
- ν is the Laplace transform of a non-negative measure.

CM jumps

A Lévy process has CM jumps if

$$\nu(z) \text{ and } \nu(-z) \text{ are CM.}$$



Rogers functions

A Rogers function is a holomorphic function in $\{\operatorname{Re} \xi > 0\}$ such that $\operatorname{Re} \dfrac{f(\xi)}{\xi} \geqslant 0$.

Equivalently: $\dfrac{f(\xi)}{\xi}$ is a Nevanlinna–Pick function.

Theorem (Rogers, 1983)

For a Lévy process, the following are equivalent:

- it has CM jumps;
- $f(\xi)$ extends to a Rogers function.

Spine

The spine of a Rogers function $f(\xi)$ is the curve

$$\Gamma = f^{-1}((0,\infty)) = \{\xi : f(\xi) \in (0,\infty)\}$$

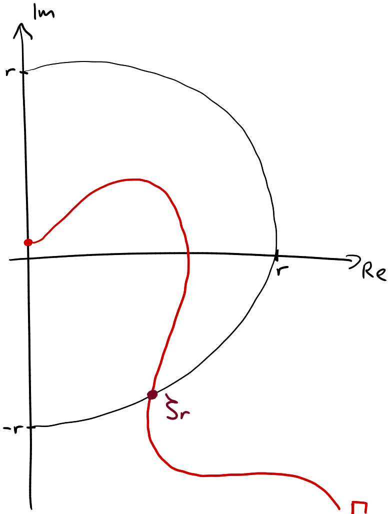
Lemma (K, 2019, 2021$^+$)

The spine intersects centred circles at most once:

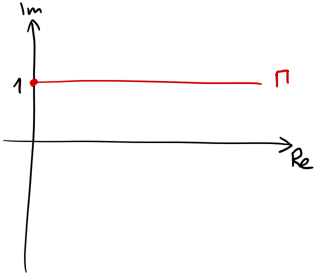
$$\Gamma = \{\zeta_r : r \in Z\}$$

with $|\zeta_r| = r$ and $Z \subseteq (0,\infty)$. Furthermore:

- ζ_r is $\frac{1}{30}$-Hölder continuous.
- $\lambda_r = f(\zeta_r)$ is $\frac{1}{3}$-Hölder continuous.



Sample spines:

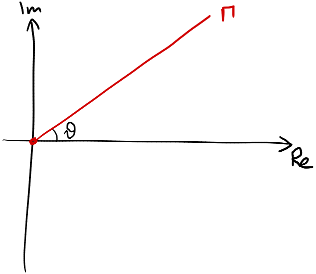


BM + drift

$$f(\xi) = \xi^2 - 2i$$

$$\zeta_r = \sqrt{r^2 - 1} + i$$

$$\lambda_r = r^2 + 1$$

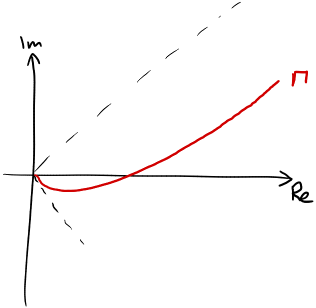


stable

$$f(\xi) = a\xi^\alpha$$

$$\zeta_r = re^{i\vartheta}$$

$$\lambda_r = |a|r^\alpha$$



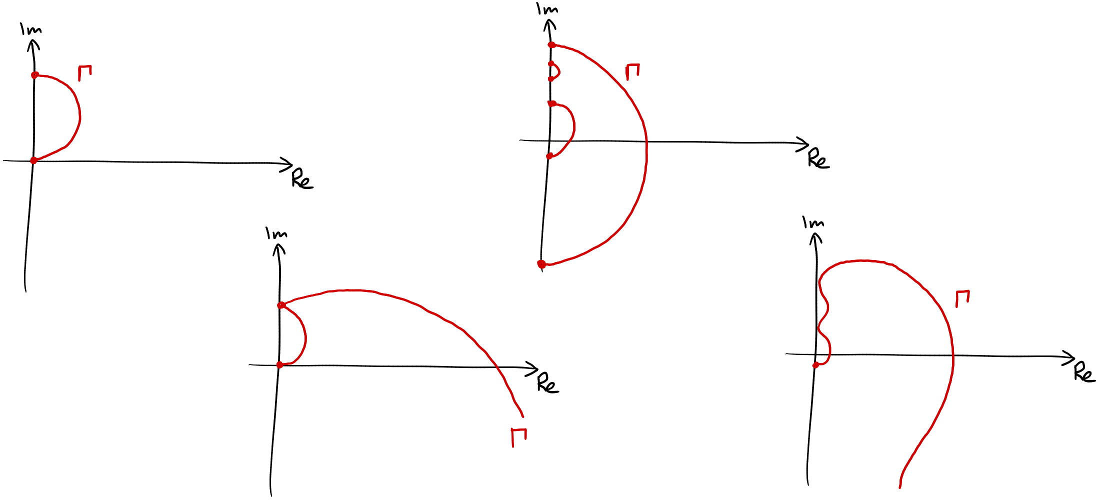
mixed stable

$$f(\xi) = a\xi^\alpha + b\xi^\beta$$

$$\zeta_r \sim re^{i\vartheta}$$

$$\zeta_r \sim |a|r^\alpha + |b|r^\beta$$

Sample spines for various meromorphic Rogers functions:



Lévy operators in half-line

A Lévy operator L restricted to $(0, \infty)$:

$$\langle L^+ u, v \rangle = \int_0^\infty Lu(x) \overline{v(x)} dx$$

Proabilistically: killing the process as soon as it exits $(0, \infty)$.

Transition operators: $P_t^+ = \exp(tL^+)$.

Theorem (K, 2011; K–Małecki–Ryznar, 2013)

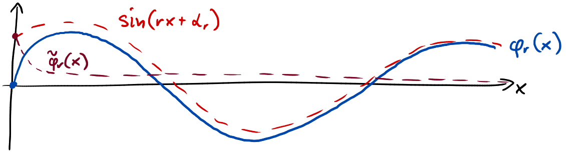
For a symmetric Lévy process with CM jumps and $u, v \in C_c((0,\infty))$:

$$\langle P_t^+ u, v\rangle = \frac{2}{\pi}\int_0^\infty e^{-tf(r)}\langle u, \varphi_r\rangle\langle \varphi_r, v\rangle dr \qquad \text{(GEE)}$$

where

$$\varphi_r(x) = \sin(rx + \alpha_r) - \tilde{\varphi}_r(x)$$

with explicit α_r and 'explicit' CM correction $\tilde{\varphi}_r(x)$.



Theorem (K, 2019, 2021$^+$)

For a Lévy process with CM jumps such that:

$$\limsup_{r \to \infty} |\operatorname{Arg} \zeta_r| < \frac{\pi}{2}$$

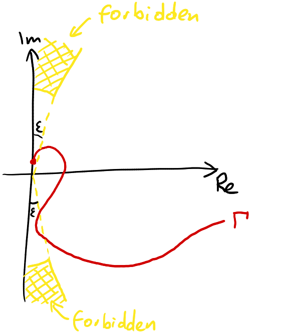
and admissible u and v we have:

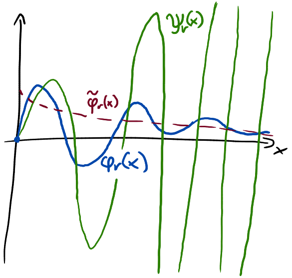
$$\langle P_t^+ u, v \rangle = \frac{2}{\pi} \int_Z e^{-t\lambda_r} \langle u, \psi_r \rangle \langle \varphi_r, v \rangle |\zeta_r'| dr \qquad \text{(GEE)}$$

where

$$\varphi_r(x) = e^{-x \operatorname{Im} \zeta_r} \sin(x \operatorname{Re} \zeta_r + \alpha_r) - \tilde{\varphi}_r(x)$$
$$\psi_r(x) = e^{x \operatorname{Im} \zeta_r} \sin(x \operatorname{Re} \zeta_r + \beta_r) - \tilde{\psi}_r(x)$$

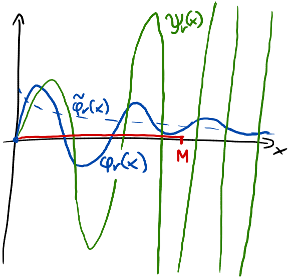
with explicit α_r, β_r and 'explicit' CM corrections $\tilde{\varphi}_r(x)$, $\tilde{\psi}_r(x)$.





If $f(\xi) = a\xi^\alpha$ (and in many other examples), we have:

$$\varphi_r(x) \approx e^{-arx} \sin(brx + \alpha_r)$$
$$\psi_r(x) \approx e^{arx} \sin(brx + \beta_r)$$



If $a > 0$ and $u, v \in C_c((0, \infty))$, then

$$\langle u, \psi_r \rangle = O(e^{arM}),$$
$$\langle \varphi_r, v \rangle = O(1)$$

Hence, the integral in

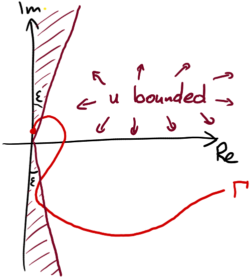
$$\langle P_t^+ u, v \rangle = \frac{2}{\pi} \int_Z e^{-t\lambda_r} \langle u, \psi_r \rangle \langle \varphi_r, v \rangle |\zeta_r'| dr \qquad \text{(GEE)}$$

need not even converge!

Admissible functions

A function u is admissible if

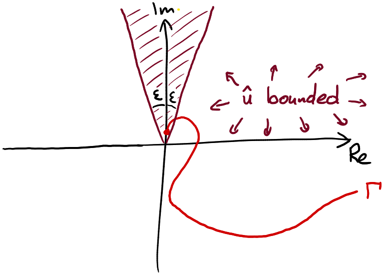
- it is a holomorphic function in $\{|\operatorname{Arg}\xi| < \frac{\pi}{2} - \varepsilon\}$;
- $|u(\xi)| \leqslant C\exp(-C|\xi|\log|\xi|)$ in this sector.



The Laplace transform of u is entire and

$$\left|\int_0^\infty e^{-\xi x} u(x) dx\right| \leqslant \frac{C}{1+|\xi|}$$

in $\{|\operatorname{Arg}\xi| \leqslant \pi - \varepsilon\}$.



Dense in $L^2((0,\infty))$: $e^{-r\xi\log(1+\xi)}$ is admissible.

Corollary (K, 2019, 2021$^+$)

For $\beta > 1$ and a Lévy process with CM jumps such that:

$$\limsup_{r\to\infty} |\operatorname{Arg} \zeta_r| < \frac{\pi}{2\beta}$$

and

$$\int_Z e^{-t\lambda_r} e^{s|\operatorname{Im} \zeta_r|} |\zeta_r'| dr \leqslant A e^{s^\beta}$$

we have

$$p_t^+(x, y) = \frac{2}{\pi} \int_Z e^{-t\lambda_r} \psi_r(x) \varphi_r(y) |\zeta_r'| dr \qquad \text{(GEE)}$$

Note: not quite optimal for L-fract. deriv. (stable Lévy proc.)

History

- $L = \partial^2$, $f(\xi) = \xi^2$: Laplacian or Brownian motion
  — classical (Fourier sine transform)
- $L = \partial^2 + 2b\partial$, $f(\xi) = \xi^2 - 2ib\xi$: Brownian motion with drift
  — also classical (Doob's h-transform)
- symmetric L: complete Bernstein functions of Δ or subordinate BM
  — K, 2011; K–Małecki–Ryznar, 2013
- $L = \partial^\beta(-\partial)^\gamma$, $f(\xi) = a\xi^\alpha$: fractional derivatives or stable Lévy processes
  — K–Kuznetsov, 2018
- general L — K, 2019; K, 2021$^+$

Elements of the proof:

- integral expression for

$$\int_0^\infty \int_0^\infty \int_0^\infty e^{-\tau t - \xi x - \eta y} p_t^+(x, y) dx dy dt$$

  (Baxter–Donsker, Fristedt, Pecherski–Rogozin)
- inversion of Laplace transforms
- lots of contour deformations
- even more auxiliary estimates
- boundary geometry of level lines of 2-D harmonic functions
- regularity of the Hilbert transform