59th Annual Meeting of
the Australian Mathematical Society
Flinders University, Adelaide, 28 Sep.-1 Oct. 2015

A simplified approach to the regularising effect of nonlinear semigroups

A joint work with Prof Thierry Coulhon (PSL/ANU)

Daniel Hauer

THE UNIVERSITY OF SYDNEY

Recent Trends in Nonlinear Evolution Equations

Workshop

4th & 5th November 2015
Lecture Room 5
Physics Building
University of Sydney

http://www.maths.usyd.edu.au/u/dhauer/nonlinear-evolution/

Speakers:

- Ben Andrews (ANU)
- Julie Clutterbuck (Monash)
- James McCoy (UoW)
- EN Dancer (USyd)
- Daniel Daners (USyd)
- Darek Robinson (ANU)
- Jérôme Droniou (Monash)
- Yihong Du (UNE)
- David Galloway (USyd)
- Pierre Portal (ANU)
- Neil Trudinger (ANU)
- Fernando Quirós (Spain)
- Xu-Jia Wang (ANU)
- Glen Wheeler (UoW)

Organisers:

- Daniel Hauer (USyd)
- Valentina-Mira Wheeler (UoW)

The framework of this talk

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Let (Σ, μ) be a σ-finite measure space,

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Let (Σ,μ) be a σ-finite measure space,
$X = L^q(\Sigma,\mu)$ for some $1 \le q \le \infty$,
A an operator on X with domain $D(A)$.

For given $u_0 \in X$ let $u : [0,\infty) \to X$ be a solution of (in some sense)

$$(\mathcal{CP}) \quad \begin{cases} \frac{du}{dt}(t) + Au(t) \ni 0 & \text{for } t > 0, \\ u(0) = u_0. \end{cases}$$

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Suppose A is m-accretive in X, that is,

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(Accretive) for every $\lambda>0$ the resolvent oper. $J_\lambda := (1+\lambda A)^{-1}$ is X-contractive,

$$\|J_\lambda u - J_\lambda \hat{u}\|_X \le \|u-\hat{u}\|_X \quad \forall u,\hat{u}\in Rg(1+\lambda A)$$

(Rg-cond.) there is (for all) $\lambda>0$, $Rg(1+\lambda A) = X$.

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Then by Crandall–Liggett '71,

$$(\mathrm{CP}) \begin{cases} \frac{du}{dt}(t) + Au(t) \ni 0 & \text{for } t>0, \\ u(0) = u_0 \in \overline{D(A)} \end{cases}$$

is well-posed in the sense of mild solutions.

The framework of this talk

Now, for given $u_0 \in X$ a function $u \in C([0,\infty);X)$ is called a mild solution of (EP) if for every $T>0$, $\varepsilon>0$ and partition $0=t_0<t_1<\dots<t_N=T$ of $[0,T]$ s.th. $t_i - t_{i-1} < \varepsilon$ $\forall i=1,\dots,N$

there is a piecewise constant function $u_{\varepsilon,N}(t) := \sum_{i=1}^{N} u_{\varepsilon,i}\, \mathbb{1}_{(t_{i-1},t_i]}(t) + u_0$, where $u_{\varepsilon,i}$ on $(t_{i-1},t_i]$ solves "recursively" the finite difference equation $u_{\varepsilon,i} + (t_i - t_{i-1}) A u_{\varepsilon,i} \ni u_{\varepsilon,i-1}$ $\forall i=1,\dots,N$

such that $\sup_{t\in[0,T]} \|u_{\varepsilon,N}(t) - u(t)\|_X \leq \varepsilon$.

The framework of this talk

By the celebrated Crandall-Liggett Thm (1971),
if A is m-accretive in X, then for every $u_0 \in \overline{D(A)}$
there is a unique mild solution of (EP) and the
solution is given by the exponential formula

$$u(t) := \lim_{n\to\infty} \left(1 + \tfrac{t}{n} A\right)^{-n} u_0$$ unif. on comp. subintev. of $[0,\infty)$.

The framework of this talk

For given $u_0 \in X$, we call a function $u \in C([0,\infty);X)$ a strong solution of (EP) if $u \in W^{1,1}_{loc}((0,\infty);X)$, $u(0) = u_0$ in X and for a.e. $t > 0$ one has

$$u(t) \in D(A) \quad \& \quad -\frac{du}{dt}(t) \in Au(t).$$

The framework of this talk

For given $u_0 \in \overline{D(A)}$, let $u : [0,\infty) \to X$ be the the mild solution of (EP), then set

$$T_t u_0 := u(t) \quad \forall t \geq 0.$$

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Then the family $\{T_t\}_{t\geq 0}$ of mappings $T_t : \overline{D(A)} \to \overline{D(A)}$ satisfies:

- ▷ $T_t \circ T_s = T_{t+s} \quad \forall t, s \geq 0$ (semi-group)
- ▷ $\lim_{t\to 0+} \|T_t u - u\|_X = 0 \quad \forall u \in \overline{D(A)}$ (Strong cont.)
- ▷ $\|T_t u - T_t \hat{u}\|_X \leq \|u - \hat{u}\|_X \quad \forall u, \hat{u} \in \overline{D(A)}$ (X-con-tractive)

The framework of this talk

The abstract framework

$$(\mathrm{EP})\quad \begin{cases} \frac{du}{dt}(t) + Au(t) \ni 0 & \text{for } t>0,\\ u(0) = u_0 \in \overline{D(A)} \end{cases}$$

allows to establish existence, uniqueness & cont. dependence on u_0 of many important parabolic bdry-value problems:

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allows to establish existence, uniqueness & cont. dependence on u_0 of many important parabolic bdry-value problems:

▷ $X = L^2(\Omega)$: $\quad A = -\mathrm{div}(a(x,\nabla u))$

$\Omega \subseteq \mathbb{R}^d$ domain $\quad$ or $\quad A = -\mathrm{div}\left(\frac{\nabla u}{|\nabla u|}\right)$

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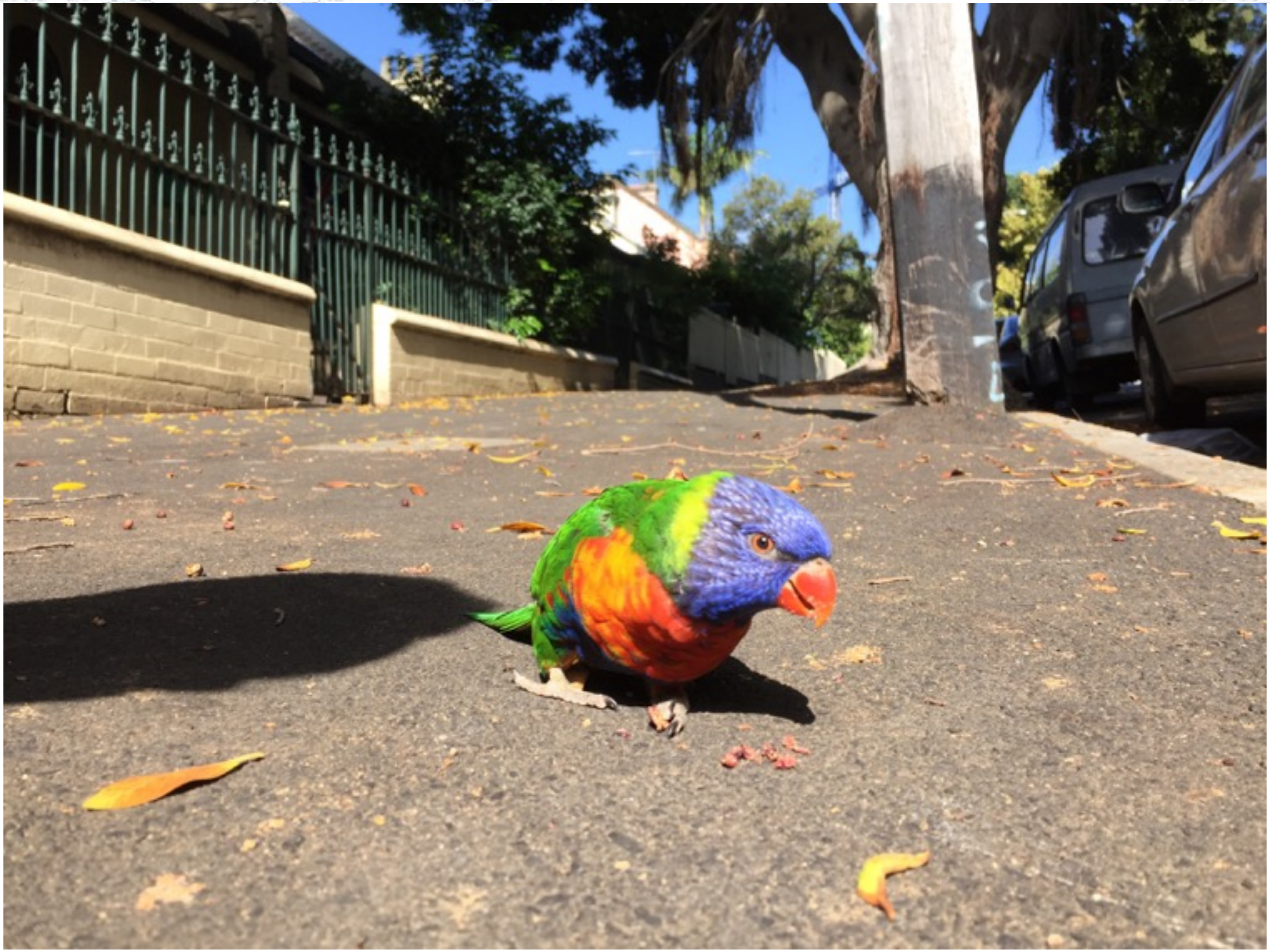
allows to establish existence, uniqueness & cont. dependence on u_0 of many important parabolic bdry-value problems:

▷ $X = L^1(\Omega)$: $\quad A = -\Delta_p^D u^m \quad , \; u^m := |u|^{m-1}u \quad m>1$



Main subject of this talk

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To investigate the "regularising effect":

For given $u \in L^q(\Sigma,\mu)$ for some $q \geq 1$,

$$T_t u \in L^r(\Sigma,\mu) \quad \forall t>0 \ \& \text{ some } q<r\leq\infty$$

+ uniform bdds/decay rates as $t \to \infty$.

Outline of this talk

1. Log-Sobolev is not always the direct & simplest way
2. Other results to this subject
3. Our motivation / AIM
4. Main theorems
5. Applications

1 Log-Sobolev is not always the direct & simplest way

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The approach:

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① Log-Sobolev is not always the direct & simplest way

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1. By using a **known** Sobolev inequality, one derives a Log-Sobolev inequality.

2. When $r:[0,\infty)\to[p_0,\infty)$ is nondecreasing & C^1, then one shows by using the Log-Sobolev inequality that
$$s\mapsto y(s):=\log\|u(s)\|_{r(s)}$$
satisfies a differential inequality.

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satisfies a differential inequality.

$\Longrightarrow$ L^q-L^r-regularising effect of $u(0)\mapsto u(t)$, $t>0$.

2 Other results to this subject

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- Véron '1979 (Moser simplified) more general
- Porzio '2009 (for Leray-Lions)

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- Bénilan '1978 (Truncation & Moser-ites.)
- Véron '1979 (Moser more general simplified)
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-
-
-

Many others but for more specific situations.

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$q \geq p$

$$\langle -\Delta_p u, |u|^{q-p} u \rangle = (q-p+1) \int_\Omega |\nabla u|^p |u|^{q-p} dx$$

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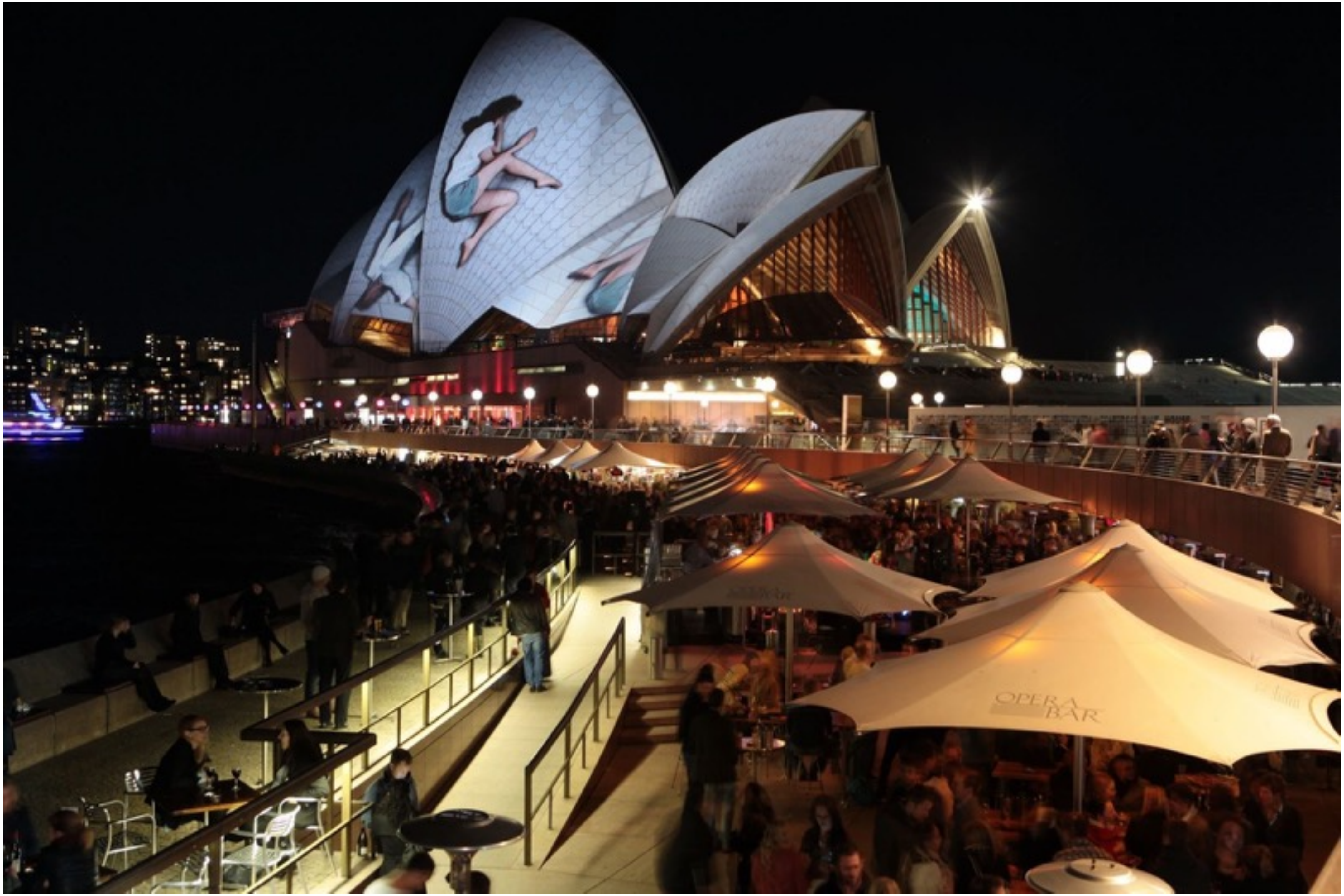
$$= \frac{(q-p+1)}{\left(\frac{q-p}{p}+1\right)^p} \int_\Omega \left| \nabla \left(|u|^{\frac{q-p}{p}} u \right) \right|^p dx$$

$$\geq C_{qp} \left(\int_\Omega \left| |u|^{\frac{q-p}{p}} u \right|^{p^*} dx \right)^{\frac{p}{p^*}}$$

2 Other results to this subject

Main tool in all these approaches (including Log-Sobolev appr.):

On builds a "one parameter family" of (Log-) Sobolev inequalities.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3 Our motivation / AIM

To develope a unified machinery,

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To develope a unified machinery, which avoids:

- the construction of one-parameter families of (Log-) Sobolev ineq.
- too much regularity.

③ Our motivation / AIM

To develope a unified machinery, which concerns

▷ completely accretive operators A,

i.e., $\forall \lambda > 0$ the resolvent J_λ is L^q-contractive $\forall\, 1 \le q \le \infty$

+ order preserving

③ Our motivation / AIM

To develope a unified machinery, which concerns

▷ completely accretive operators A, i.e., $\forall \lambda > 0$ the resolvent J_λ is L^q-contractive $\forall\, 1 \le q \le \infty$ + order preserving

▷ accretive operators A non-increasing resolvent J_λ in L^q $\forall\, 1 \le q \le \infty$ (i.e. $\|J_\lambda u\|_q \le \|u\|_q$)

4 Main theorems

Theorem [Coulhon, H. '15] Sobolev $\Rightarrow L^2$-L^r-reg

Let A be m-completely accretive in $L^2(\Sigma,\mu)$ with dense domain & $0 \in A0$.

If there are $2 \le r \le \infty$, $\sigma > 0$ & $c > 0$ s.th.

(Sob) $$\|u-\hat{u}\|_r^\sigma \le c\,\langle u-\hat{u}, v-\hat{v}\rangle_2$$

for all $(u,v),(\hat{u},\hat{v}) \in A$, then $\{T_t\}_{t\ge0} \sim -A$ satisfies

$$\|T_t u - T_t \hat{u}\|_r \le \left(\frac{c}{2}\right)^{\frac{1}{\sigma}} t^{-\frac{1}{\sigma}} \|u-\hat{u}\|_2^{\frac{2}{\sigma}} \quad \forall u,\hat{u} \in L^2.$$

④ Main theorems

1* Theorem [Coulhon, H. '15] Sobolev $\Rightarrow L^2$–L^r-reg

Let A be m-accretive in $L^1(\Sigma,\mu)$ with non-increas-resolvent in all L^q & dense domain.

If there are $2 \leq r \leq \infty$, $\sigma > 0$ & $c > 0$ s.th.

(Sob) $$\|u\|_r^\sigma \leq c \, \langle u, v\rangle_2$$

for all $(u,v) \in A \cap (L^2 \times L^2)$, then $\{T_t\}_{t\geq 0} \sim -A$ satisfies

$$\|T_t u\|_r \leq \left(\frac{c}{2}\right)^{\frac{1}{\sigma}} t^{-\frac{1}{\sigma}} \|u\|_2^{\frac{2}{\sigma}} \qquad \forall u \in L^2.$$

④ Main theorems

2 Theorem [Coulhon, H. '15] Sobolev $\Rightarrow L^q$–L^∞-reg.

Let A be m-completely accretive in $L^2(\Sigma,\mu)$ with dense domain & $0\in A0$.

If there are $2<r<\infty$, $\sigma>0$ & $c>0$ s.th. $\frac{r}{\sigma}>1$ &

$$\text{(Sob)}\qquad \|u-\hat{u}\|_r^\sigma \le C\,\langle u-\hat{u}, v-\hat{v}\rangle_2$$

for all $(u,v),(\hat{u},\hat{v})\in A$, then $\{T_t\}_{t\ge 0}\sim -A$ satisfies

$$\|T_t u - T_t\hat{u}\|_\infty \lesssim t^{-\delta}\,\|u-\hat{u}\|^{\gamma}_{\frac{r}{\sigma}m_0}\quad\forall u,\hat{u}\in L^{\frac{r}{\sigma}m_0},$$

for any $m_0>\sigma$ satisfying $(\frac{r}{\sigma}-1)m_0+\sigma-2>0$ with

$$\delta=\frac{1}{(\frac{r}{\sigma}-1)m_0+\sigma-2},\quad \gamma=\frac{(\frac{r}{\sigma}-1)m_0}{(\frac{r}{\sigma}-1)m_0+\sigma-2}.$$

④ Main theorems

3 Theorem [Coulhon, H. '15] **Extrapolation towards L^1**

For $1 \le q < r \le \infty$, let $\{T_t\}_{t\ge0}$ be L^1-contractive semigroup on $L^1 \cap L^r(\Sigma,\mu)$, $T_t 0 \equiv 0$ & suppose, there are $\delta, \gamma > 0$ s.th.

$$\|T_t u - T_t \hat{u}\|_r \le C\, t^{-\delta} \|u-\hat{u}\|_q^{\gamma} \quad \forall t>0 \ \& \ \forall u,\hat{u} \in L^1 \cap L^r$$

For $\Theta_r := \frac{r-q}{q(r-1)} > 0$ if $r<\infty$ & $\Theta_\infty := \frac{1}{q}$ if $r=\infty$

assume that $\gamma(1-\Theta_r) < 1$.

Then
$$\|T_t u - T_t \hat{u}\|_r \le (2^\delta C)^{1/\theta}\, t^{-\frac{\delta}{\theta}} \|u-\hat{u}\|_1^{\gamma\frac{\Theta_r}{\theta}} \quad \forall u,\hat{u} \in L^1(\Sigma,\mu)$$

with $\theta := 1-\gamma(1-\Theta)$.

5 Applications

5 Applications

1. Total variational flow in $\mathbb{R}^d$

$$A := \left\{ (u,v) \in L^2(\mathbb{R}^d) \times L^2(\mathbb{R}^d) \;\middle|\; \begin{array}{l} u \in BV(\mathbb{R}^N) \;\&\; \exists z \in L^\infty(\mathbb{R}^d,\mathbb{R}^d),\ \|z\|_\infty \leq 1, \\ v = -\operatorname{div} z \text{ in } \mathcal{D}' \;\&\; (z, Du) = |Du| \end{array} \right\}$$

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is the total variation flow operator $-\operatorname{div}\left(\frac{\nabla u}{|\nabla u|}\right) = \Delta_1$ (1-Laplace op.)
in $L^2(\mathbb{R}^d)$.

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$\Longrightarrow$ A is m-completely accretive in $L^2(\mathbb{R}^d)$ & $0 \in A0$.

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$\Rightarrow$ A is m-completely accretive in $L^2(\mathbb{R}^d)$ & $0 \in A0$.

Sobolev in

$$\|u\|_{L^{\frac{d}{d-1}}} \leq C\, |Du|(\mathbb{R}^d)$$

5 Applications

1. Total variational flow in $\mathbb{R}^d$

$\Rightarrow \forall (u,v) \in A, \quad \langle u, v\rangle_2 = \int_{\mathbb{R}^d} -\mathrm{div}(z)\cdot u \, dx$

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Green's formula (Anzelotti)
$$\overset{\Leftrightarrow}{=} \int_{\mathbb{R}^d} (z, Du)$$

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Green's formula (Auzelotti)

$$\overset{\text{Green's formula (Auzelotti)}}{=} \int_{\mathbb{R}^d} (z, Du)$$

$$= \int_{\mathbb{R}^d} |Du|$$

$$\geq C^{-1} \, \|u\|_{L^{\frac{d}{d-1}}}$$

⑤ Applications

1. Total variational flow in $\mathbb{R}^d$

Thm 1* $\Longrightarrow$

$$\|T_t u\|_{\frac{d}{d-1}} \leqslant \frac{c}{2}\, t^{-1} \|u\|_2^2 \quad \forall t>0$$
$$\& \ \forall u \in L^2(\mathbb{R}^d)$$

5 Applications

1. Total variational flow in $\mathbb{R}^d$

$\overset{\text{Thm 1}^*}{\Longrightarrow}$ $\|T_t u\|_{\frac{d}{d-1}} \leq \frac{c}{2}\, t^{-1} \|u\|_2^2 \quad \forall t>0$
$\& \ \forall u \in L^2(\mathbb{R}^d)$

Since $d/_{d-1} > 1$,

$\overset{\text{Thm 2}^*}{\Longrightarrow}$ $\|T_t u\|_\infty \lesssim t^{-\frac{1}{(d/(d-1)-1)m_0-1}} \|u\|_{\frac{d m_0}{d-1}}^{\frac{(\frac{d}{d-1}-1)m_0}{(d/(d-1)-1)m_0-1}} \quad \forall u \in L^{\frac{d m_0}{d-1}}$

for any $m_0 > 1$ s.th. $(\frac{d}{d-1}-1)m_0 - 1 > 0$

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Thank You!

Recent Trends in Nonlinear Evolution Equations

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