QUANTUM GENERALIZED HYDRODYNAMICS

PAOLA RUGGIERO

With: P. Calabrese, B. Doyon, J. Dubail

Based on: *Phys. Rev. Lett. 124, 140603 (2020)*

June 11th, 2020

UNIVERSITÉ DE GENÈVE

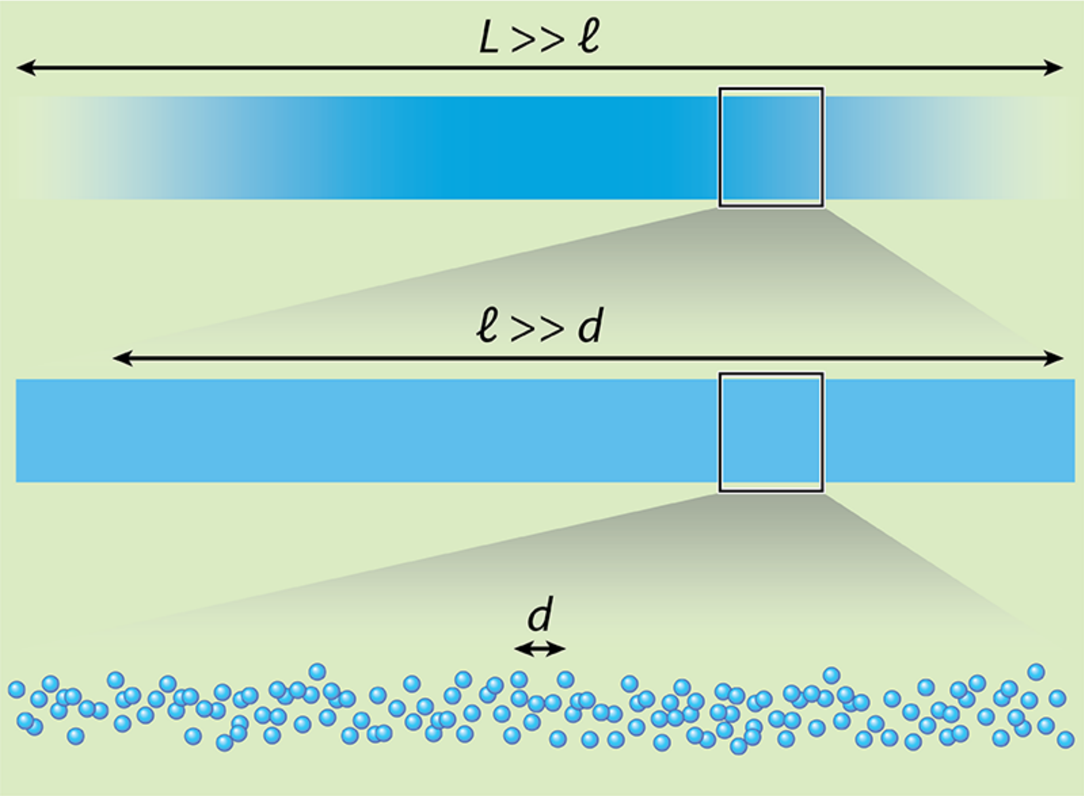
HYDRODYNAMICS: THE EULER SCALE

SEPARATION OF *LENGTH* SCALES

- Macroscopic scale : $L = \rho / \partial_x \rho$
- Microscopic scale : d
- MESOSCOPIC scale: $d \ll \ell \ll L$

SEPARATION OF *TIME* SCALES

- Macroscopic time : $T = \rho / \partial_t \rho$
- Microscopic time : τ_{relax}
- MESOSCOPIC time: $\tau_{relax} \ll t \ll T$



[PICTURE FROM: DUBAIL, PHYSICS 9, 153]

H. SPOHN, *Large Scale Dynamics of Interacting Particles* (1991)

(CONVENTIONAL) HYDRODYNAMICS

$$\langle O(x)\rangle_t = \langle O(x)\rangle_{\rho_{Gibbs}}, \quad \rho_{Gibbs} = \rho_{Gibbs}(x,t)$$

CONSERVATION LAWS:

- Mass
- Momentum
- Energy

→

CONTINUITY EQUATIONS:

$$\begin{cases} \partial_t \rho + \partial_x j &= 0 \\ \partial_t \rho_P + \partial_x j_P &= 0 \\ \partial_t \rho_E + \partial_x j_E &= 0. \end{cases}$$

GENERALIZED HYDRODYNAMICS (*GHD*)

CONSERVATION LAWS:

$$Q_i = \int q_i(x)\,dx \quad i = 1,2,\cdots$$

→

CONTINUITY EQUATIONS:

$$\partial_t q_i + \partial_x j_i = 0 \quad i = 1,2,\cdots$$

Castro-Alvaredo, Doyon, Yoshimura, PRX 6, 041065 (2016)
Bertini, Collura, De Nardis, Fagotti, PRL 117, 207201 (2016)

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EIGENSTATES: $|\theta_1, \cdots, \theta_N\rangle$ $\xrightarrow{\text{TDL}}$ $n(\theta)$

"Rapidities" "Occupation function"

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BERTINI, COLLURA, DE NARDIS, FAGOTTI, PRL 117, 207201 (2016)

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$$\langle O(x)\rangle_t = \langle O(x)\rangle_{stat,\rho_{GGE}}, \quad \rho_{GGE} = \rho_{GGE}(x,t)$$

$$\partial_t n(\theta) + v^{eff}(\theta)\partial_x n(\theta) = 0 \quad + \quad v^{\mathrm{eff}}(\theta) = \frac{(E')^{\mathrm{dr}}(\theta)}{(p')^{\mathrm{dr}}(\theta)}$$

$$f^{\mathrm{dr}}(\theta) = f(\theta) + \int \frac{d\theta'}{2\pi} \frac{d\phi(\theta-\theta')}{d\theta} n(\theta') f^{\mathrm{dr}}(\theta')$$

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"C

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"FREE" GHD

$$\theta \to p, \qquad v^{eff} \to p,$$

$$n(x,\theta;t) \to n(x,p;t)$$

GHD $\equiv$ *Evolution Wigner function*

Bettelheim, Abanov, Wiegmann, PRL 97, 246402 (2006)
Bettelheim, Abanov, Wiegmann, J.Phys.A 41 392003 (2008)
Bettelheim, Wiegmann, Phys. Rev. B 84, 085102 (2011)
Bettelheim, Glazman, PRL 109, 260602 (2012)
Protopopov, Gutman, Schmitteckert, Mirlin, PRB 87, 045112 (2013)

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ZERO-ENTROPY GHD

Doyon, Dubail, Konik, Yoshimura, PRL119, 195301 (2017)

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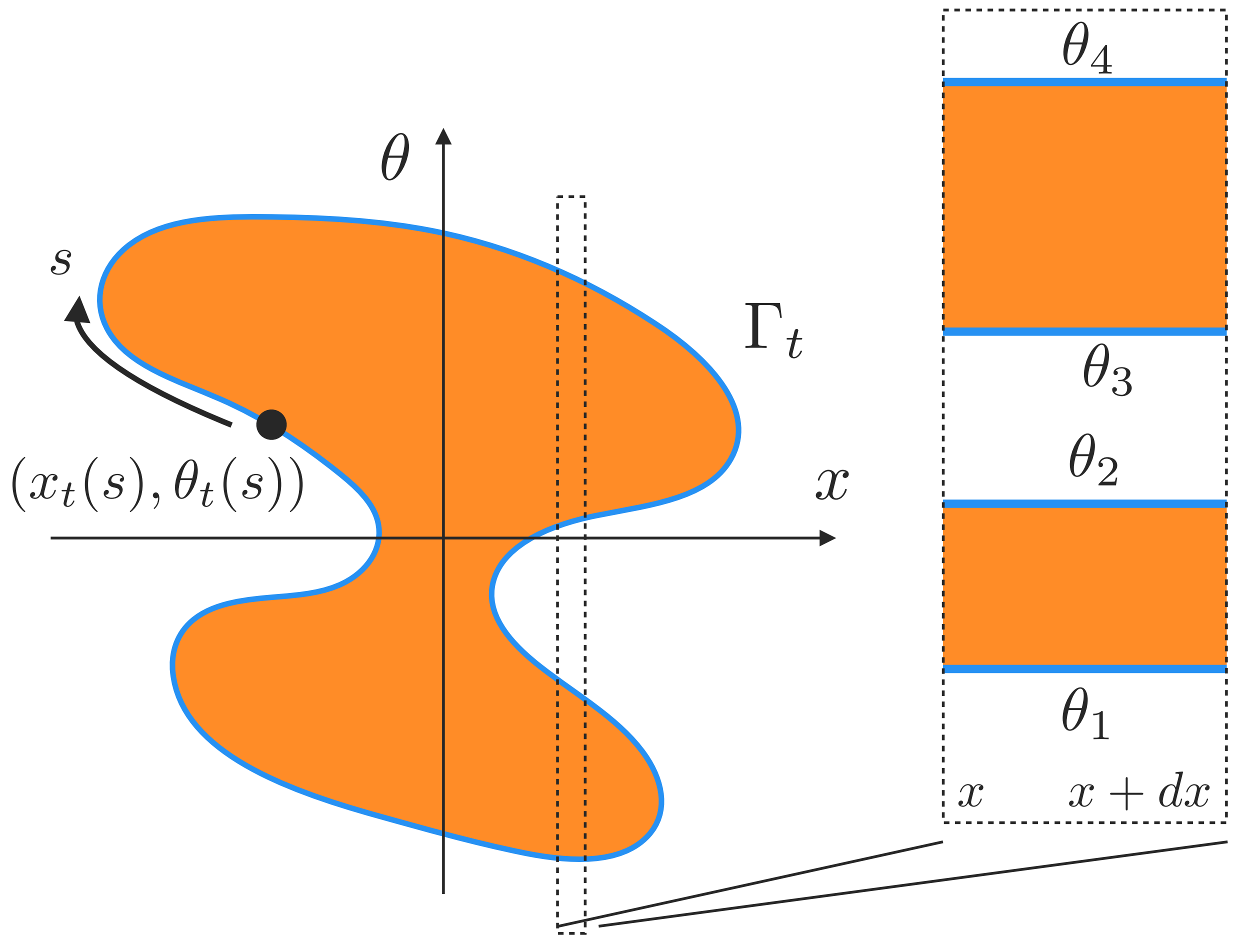

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EXAMPLES:
Ground states within inhomogeneous potentials

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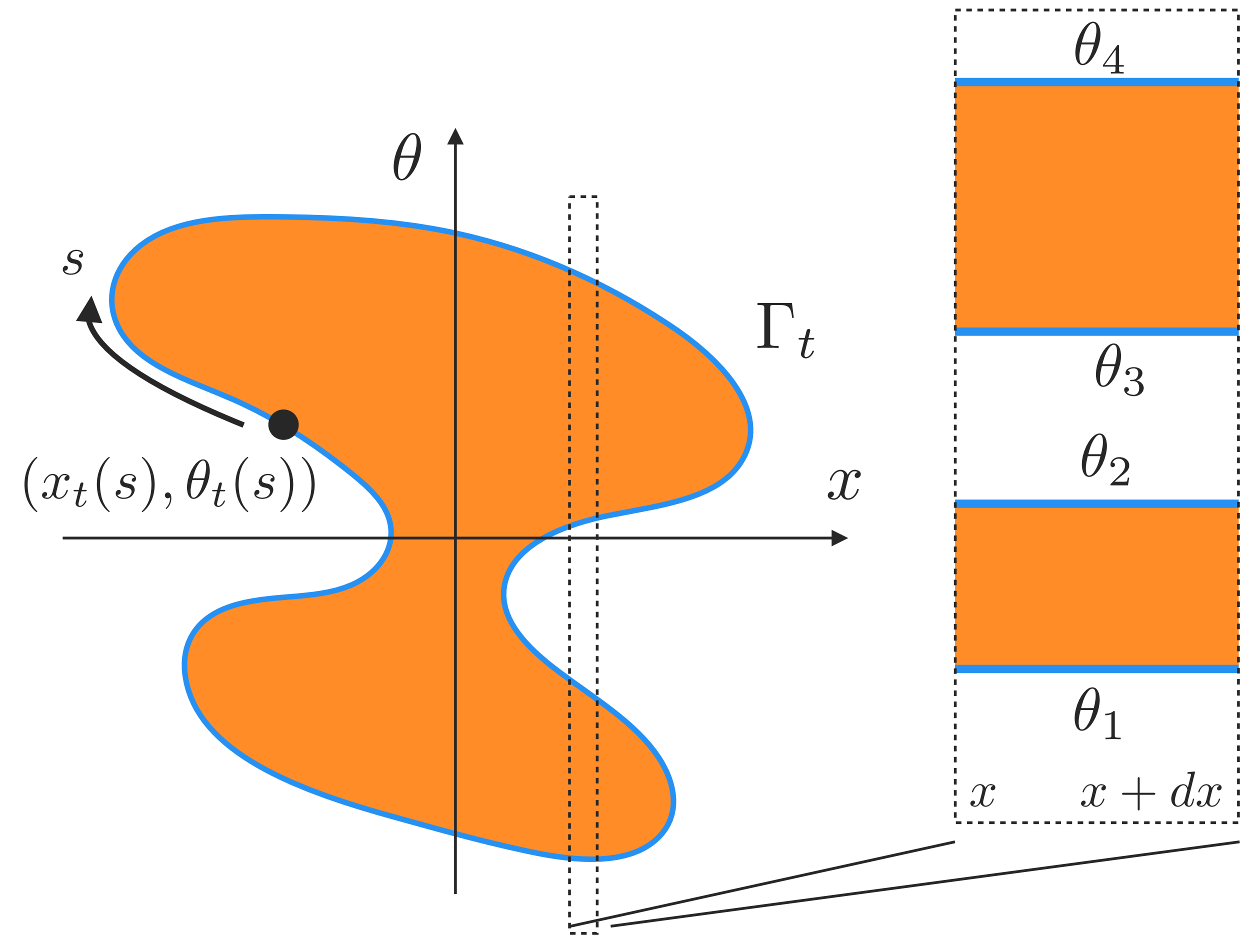

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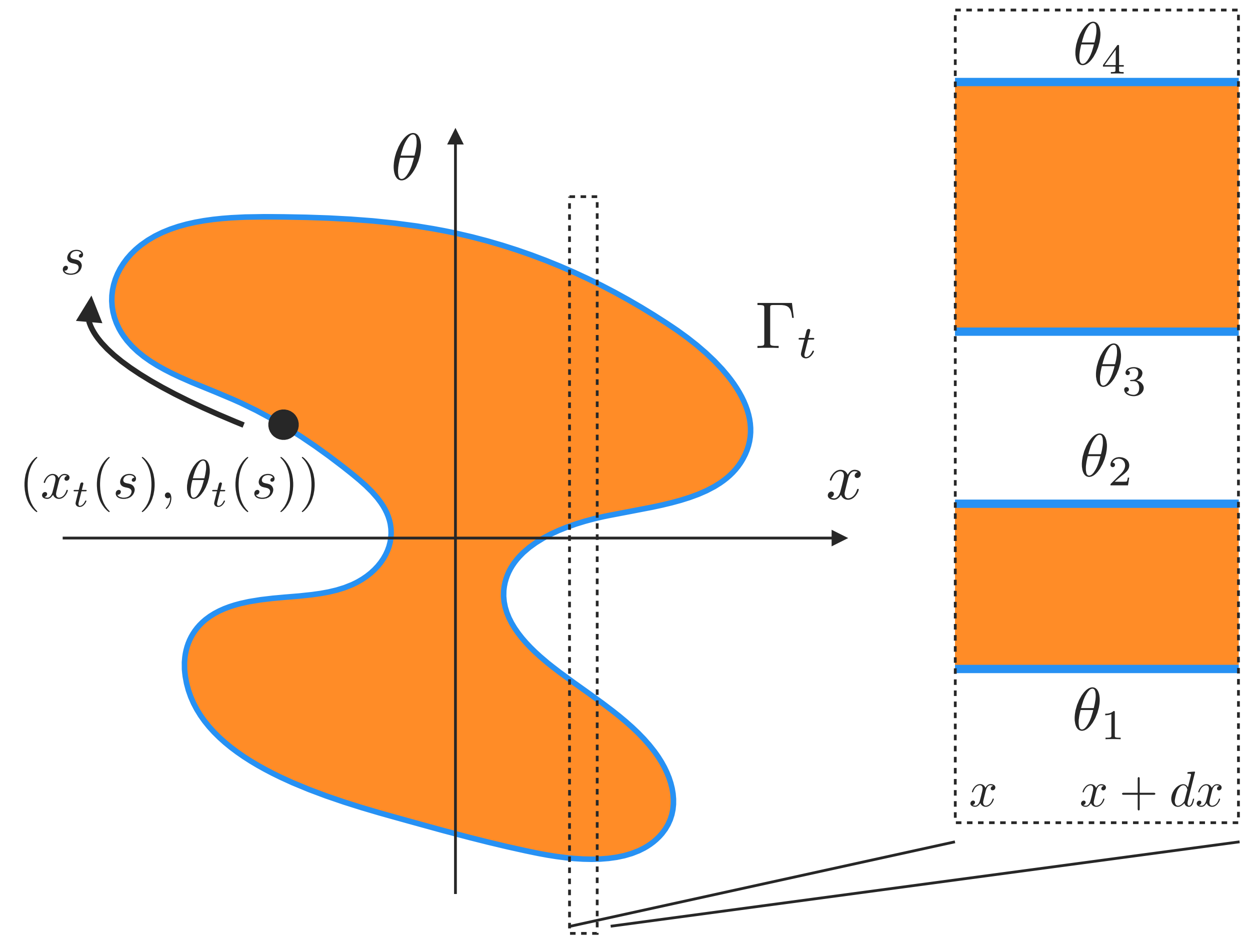

"Split Fermi seas"

Fokkema, Eliens, Caux, PRA 89, 033637 (2014)
Eliens, Caux, J.Phys.A 49, 495203 (2016)
Vlijm, Eliens, Caux, SciPost 1, 008 (2016)

$$\theta \in [\theta_1, \theta_2] \cup \ldots \cup [\theta_{2q-1}, \theta_{2q}]$$

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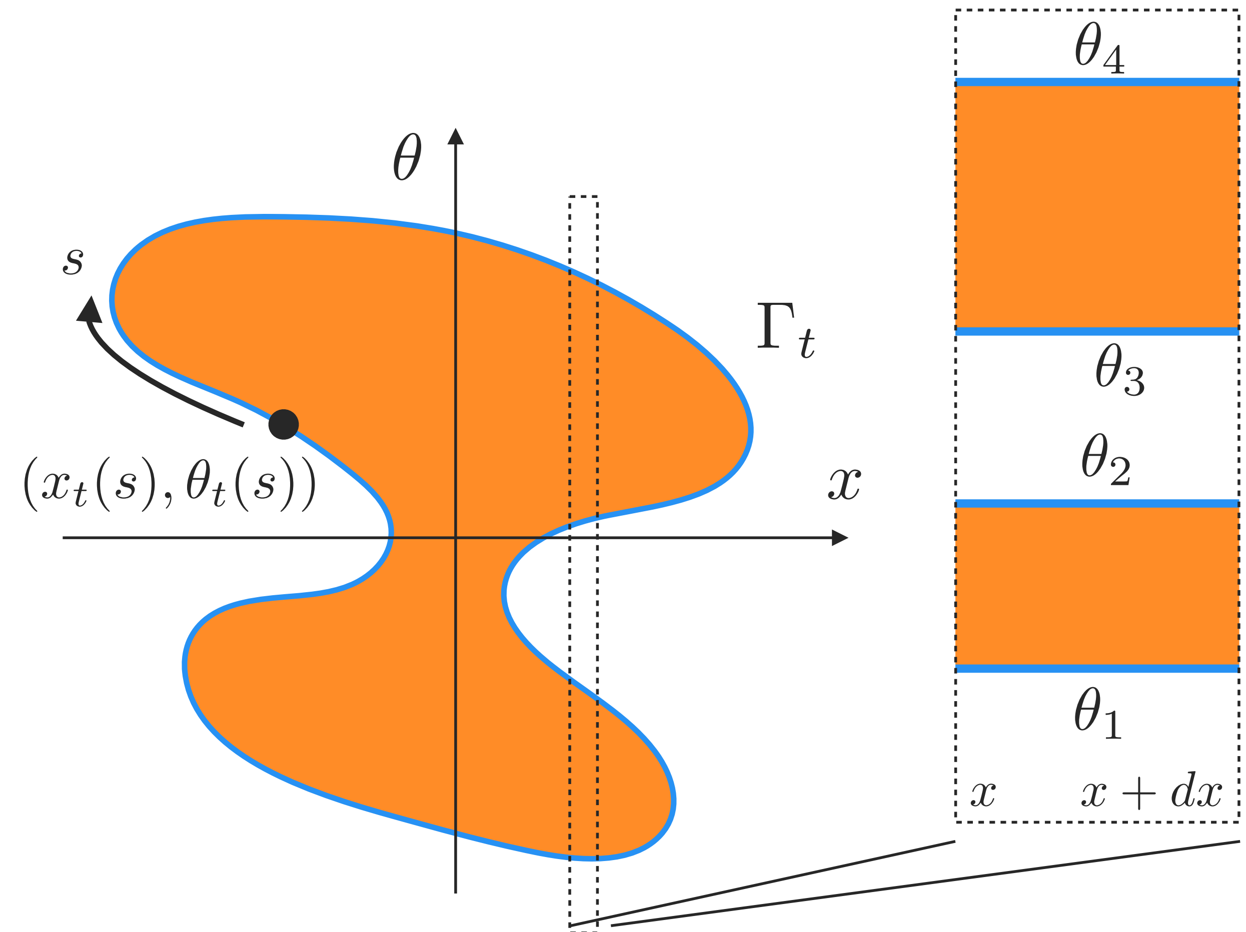

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FINITE-DIMENSIONAL GHD

$$\partial_t \theta_j + v^{eff}_{\{\theta\}}(\theta_j)\, \partial_x \theta_j = 0$$

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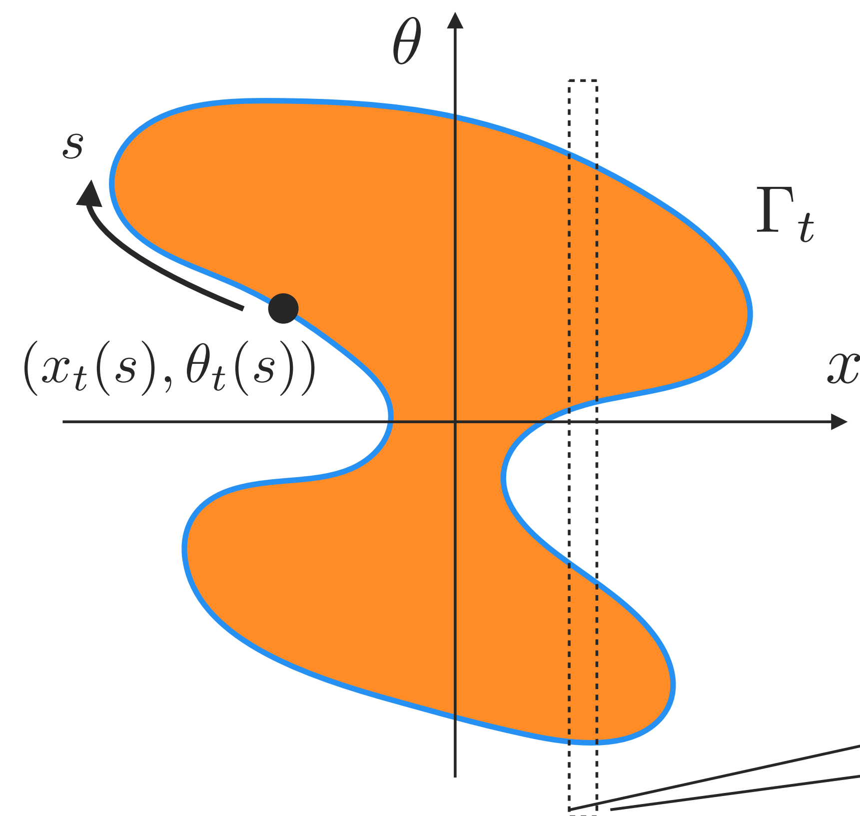

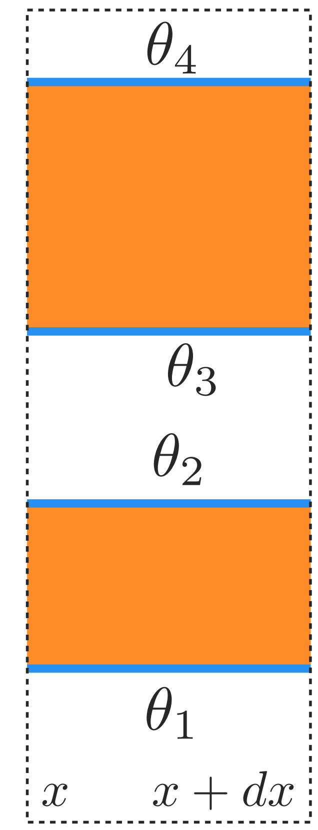

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FINITE-DIMENSIONAL **GHD**

$$\partial_t \theta_j + v^{eff}_{\{\theta\}}(\theta_j)\, \partial_x \theta_j = 0$$

$j = 1,2$

Conventional HD!

Doyon, Dubail, Konik, Yoshimura, PRL119, 195301 (2017)

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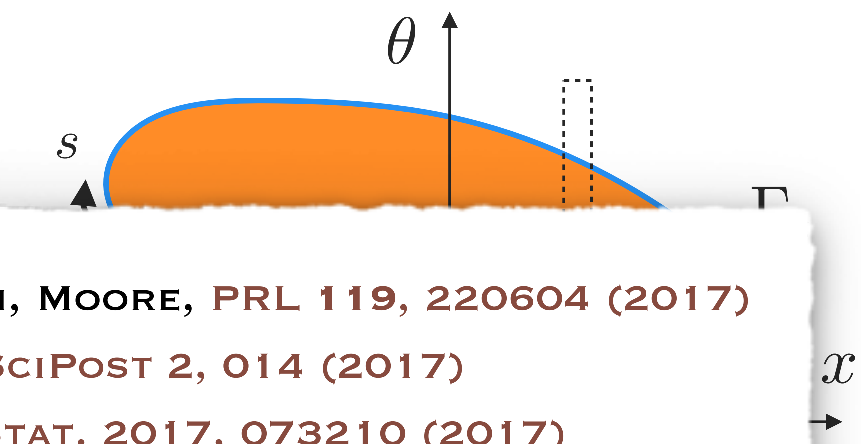

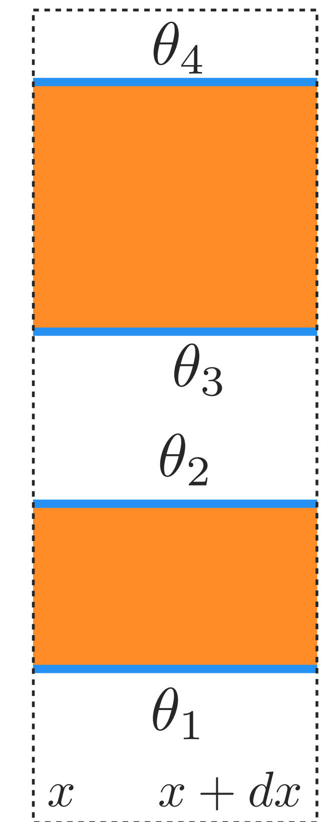

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Bulchandani, Vasseur, Karrasch, Moore, PRL 119, 220604 (2017)

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Doyon and H. Spohn, J. Stat. 2017, 073210 (2017)

Fagotti, PRB 96, 220302 (2017)

Gopalakrishnan, Huse, Khemani, Vasseur, PRB 98, 220303 (2018)

De Nardis, Bernard, Doyon, PRL 121,160603 (2018)

Bertini, Fagotti, Piroli, Calabrese, J. Phys. A 51, 39LT01 (2018)

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Bastianello, Alba, Caux, PRL 123, 130602 (2019)

Panfil, Pawelczyk, SciPost Core 1, 002 (2019)

Schemmer, Bouchoule, Doyon, Dubail, PRL122, 090601 (2019)

Moller, Schmiedmayer, SciPost 8, 041 (2020)

Fagotti, SciPost Phys. 8, 048 (2020)

...

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"QUANTUM" HYDRODYNAMICS ?

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CLASSICAL EQUATIONS → QUANTIZE THEM

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- Superfluidity — Landau, Phys. Rev. 60, 356 (1941)
- Bose-Einstein condensates — Bogolyubov, J. Phys. 11 (1947), 23
- Superconductivity — Bardeen, Cooper, Schrieffer, Phys Rev.. **104** (4)
- Hall liquids — Wiegmann, Abanov, PRL 113, 034501 (2014)
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Different problem:
Corrections
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FAGOTTI,
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DEAN, LE DOUSSAL, MAJUMDAR, SCHEHR,
EPL, 126 20006 (2019)

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$\neq$

HERE:

Look at propagation of linear sound waves on top of GHD and quantise them:

! We talk about "***quantum fluids***" in the same sense in which a Luttinger Liquid is a quantum fluid **!**

QUANTUM GENERALIZED HYDRODYNAMICS

$$H = \sum_{i=1}^{N} [-\frac{\hbar^2}{2}\partial_{x_i}^2 + V(x_i)] + g\sum_{i<j}\delta(x_i - x_j)$$

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PR, Calabrese, Doyon, Dubail, PRL 124, 140603 (2020)

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PLAN:
1. Look at *fluctuations* around a (zero-entropy) GHD background
2. *Quantize* them in a semiclassical fashion.

PR, Calabrese, Doyon, Dubail, PRL 124, 140603 (2020)

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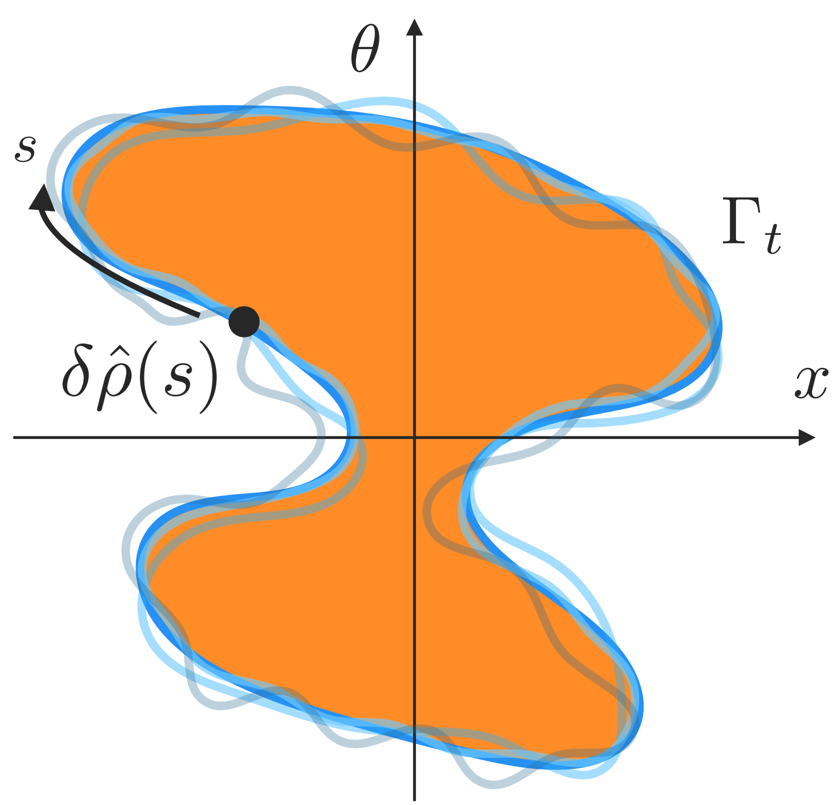

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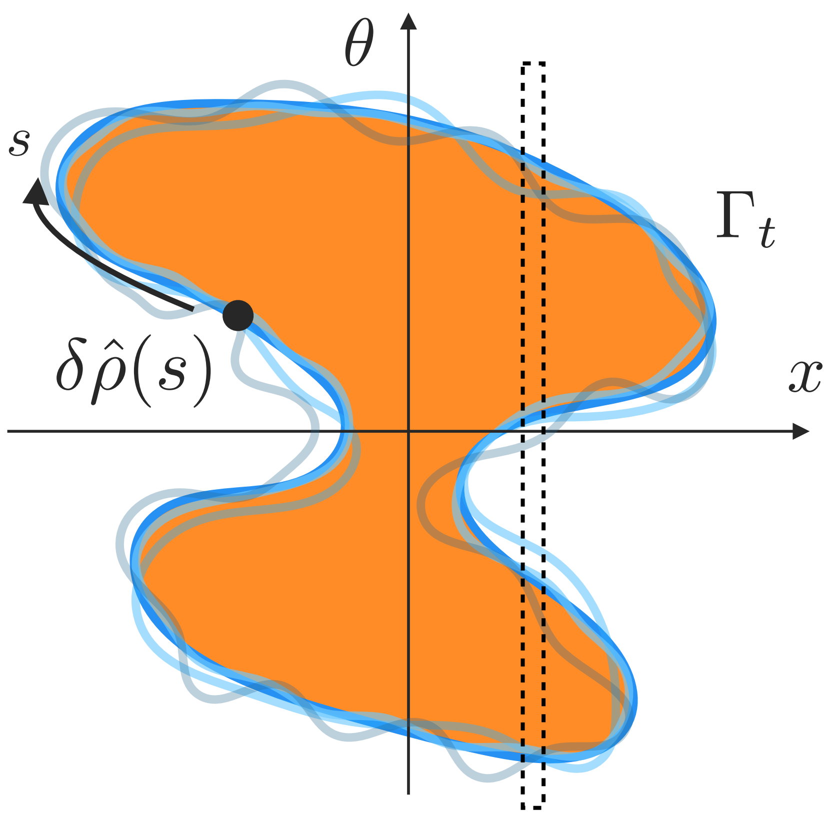

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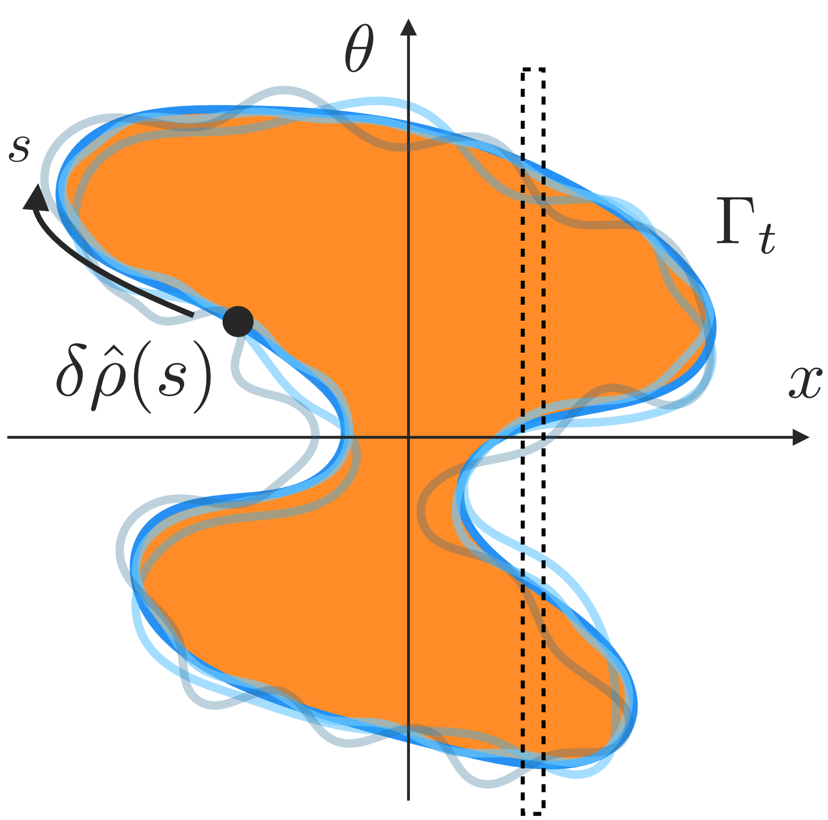

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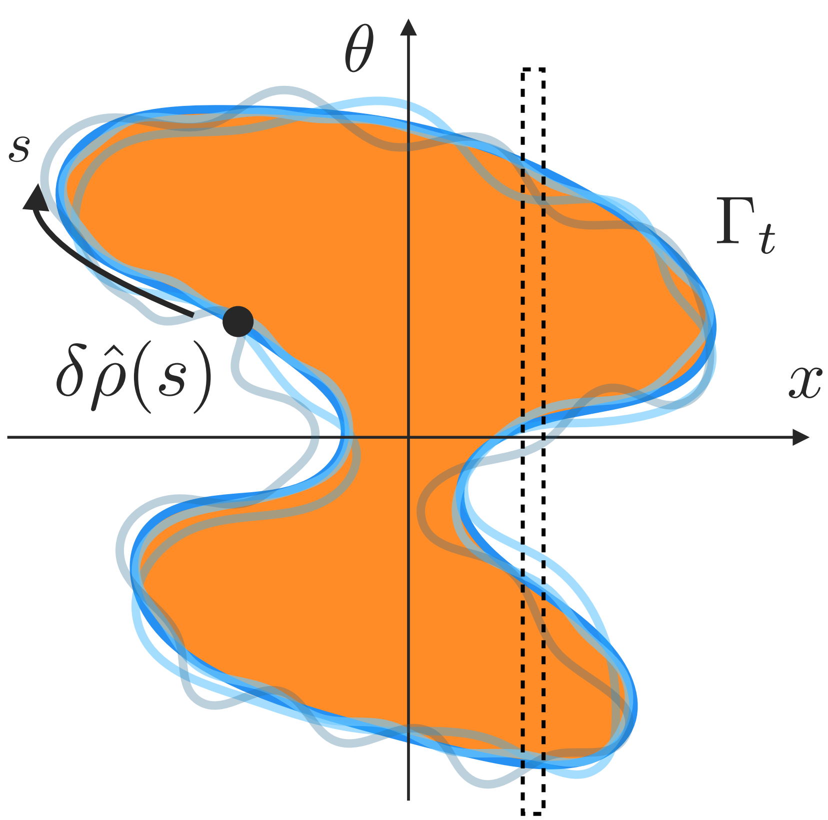

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$$\partial_t p_a + \partial_x \epsilon_a = 0$$

$$\partial_t \delta p_a + \sum_b \partial_x [\mathsf{A}_a{}^b \delta p_b] = 0\,, \quad \mathsf{A}_a^{\ b} = \partial\epsilon_a / \partial p_b$$

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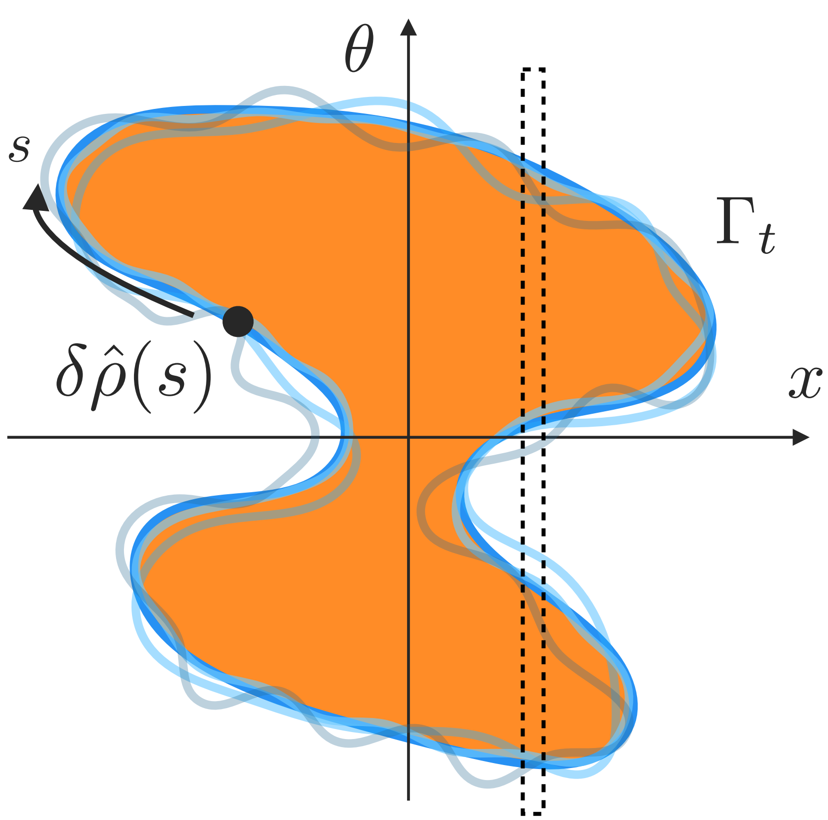

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2. $\delta p_a \to \delta\hat{p}_a : \quad e^{iS} \approx e^{iS_{\text{classical}} + i\sum_{ab} S^{(2)}_{ab}\delta p_a \delta p_b}$

PR, Calabrese, Doyon, Dubail, PRL 124, 140603 (2020)

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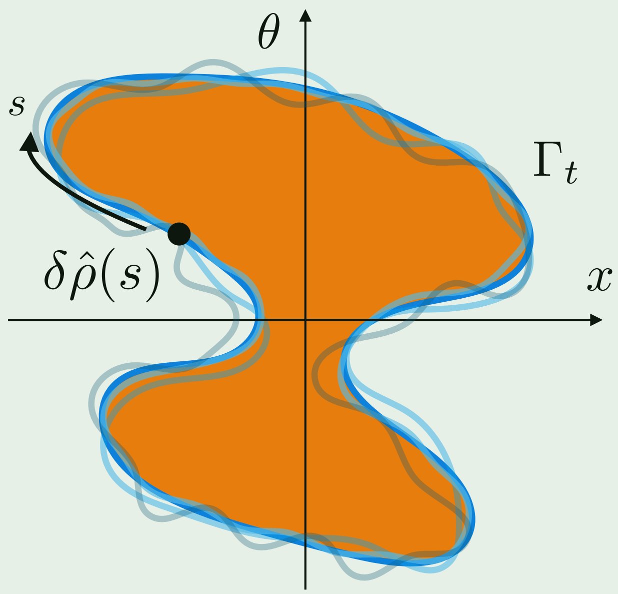
"QGHD HAMILTONIAN"

$$\hat{H}[\Gamma_t] = \frac{1}{4\pi\hbar}\int dx \sum_{a,b} \delta\hat{p}_a(x) \mathsf{A}^{ab} \delta\hat{p}_b(x)$$

$$\left[\delta\hat{p}_a(x), \delta\hat{p}_b(y)\right] = -i\sigma_a 2\pi\hbar^2 \delta_{ab}\,\delta'(x-y)$$



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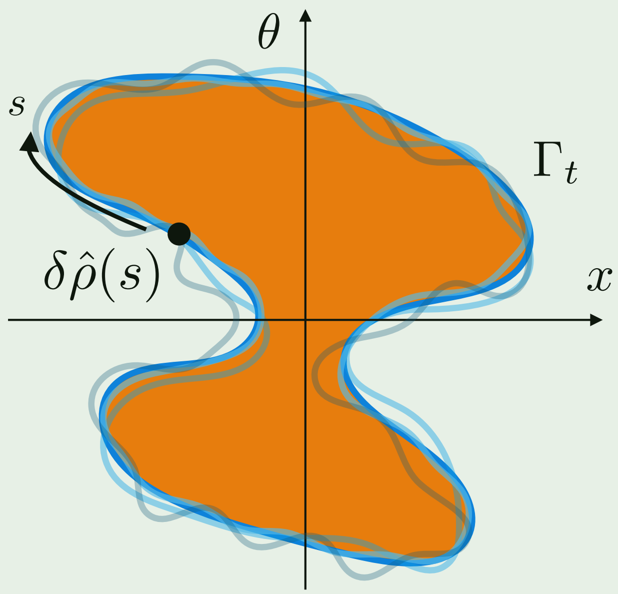


Time-dependent, spatially inhomogeneous, multicomponent
LUTTINGER LIQUID

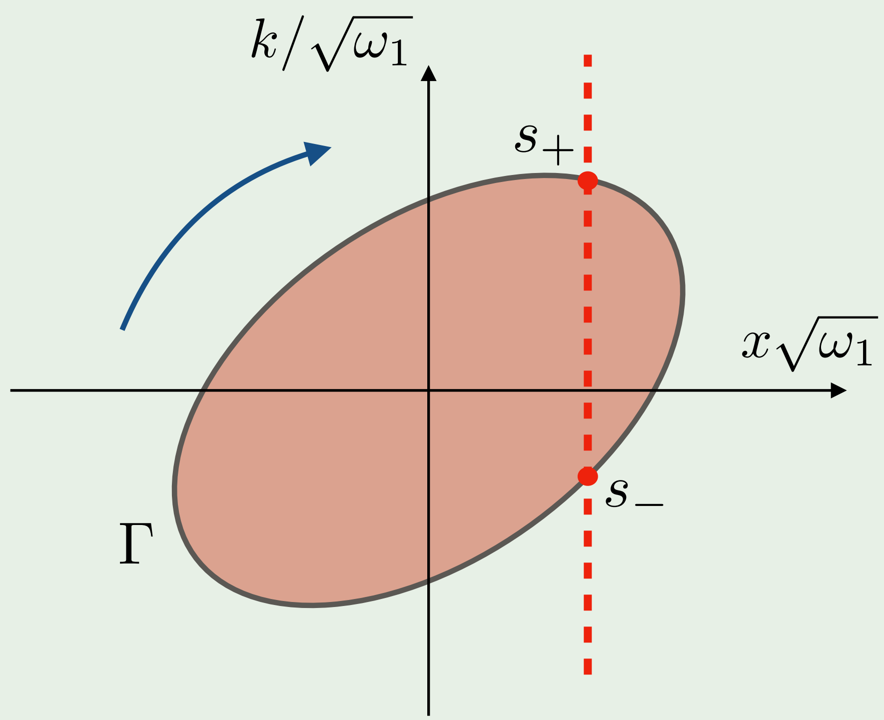
PR, Calabrese, Doyon, Dubail, PRL 124, 140603 (2020)

QUANTUM (conventional) HYDRODYNAMICS

$$H = \sum_{i=1}^{N} [-\frac{\hbar^2}{2}\partial_{x_i}^2 + V(x_i)] + g\sum_{i<j}\delta(x_i - x_j), \quad g \to \infty$$

$$V(x) = \frac{\omega^2 x^2}{2}, \quad \omega_0 \to \omega_1$$

PLAN:
1. Look at fluctuations around hydrodynamics
2. *Quantize* them in a semiclassical fashion.



$$n(x,p;t) \equiv \Gamma_t$$

$$p_+(x,t),\ p_-(x,t)$$

$$\equiv$$

$$\rho(x,t),\ j(x,t)$$

1. $(\rho, j) \to (\rho + \delta\rho, j + \delta j)$

2. $(\delta\rho, \delta j) \to (\delta\hat{\rho}, \delta\hat{j}) : \quad e^{iS} \approx e^{iS^{(0)} + iS^{(2)} + \cdots}$

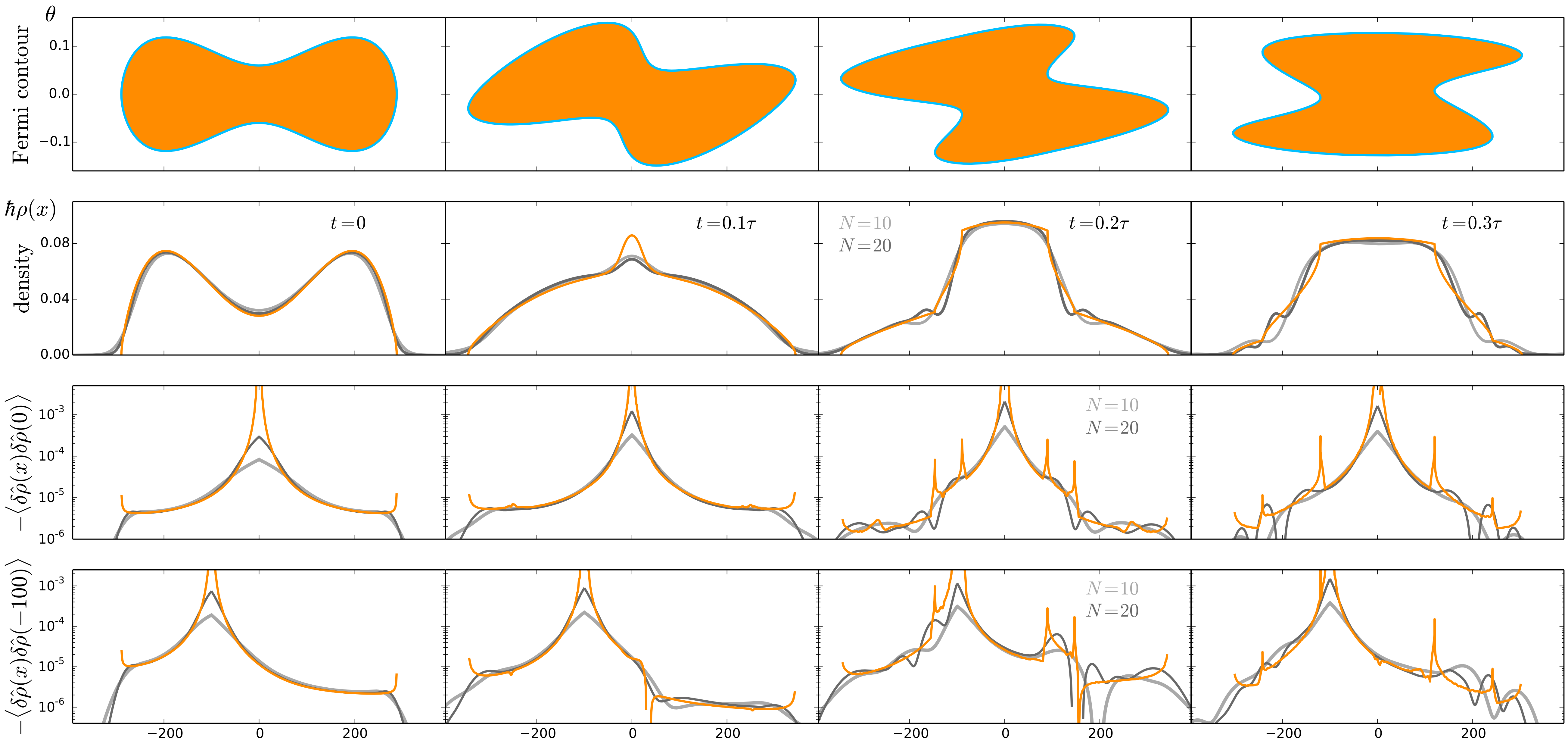
$$S^{(2)} = \frac{1}{8\pi}\int dxdt \left[\frac{m}{\pi\rho}\,\delta j^2 - 2\frac{mj}{\pi\rho^2}\,\delta\rho\delta j + (\frac{mj^2}{\pi\rho^3} - \frac{1}{\pi}\partial_\rho^2\varepsilon)\,\delta\rho^2\right]$$

Time-dependent, inhomogeneous **LUTTINGER LIQUID**

PR, Brun, Dubail, SciPost Phys. 6, 051 (2019)

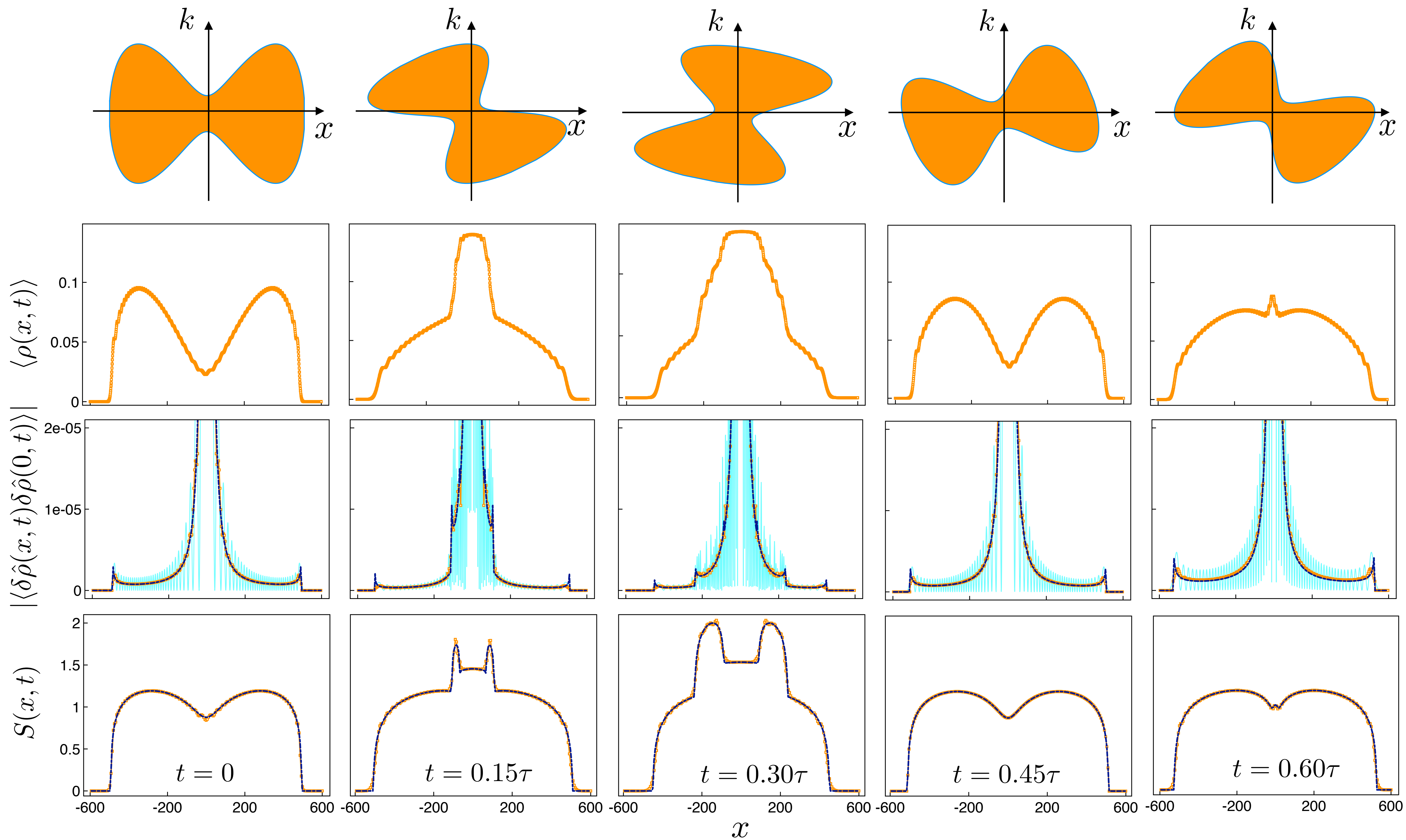
QGHD: Numerical check in the Lieb-Liniger model

Quench: $V_0(x) = a_4 x^4 - a_2 x^2 \quad \rightarrow \quad V(x) = \omega^2 x^2/2$



PR, Calabrese, Doyon, Dubail, PRL 124, 140603 (2020)

FREE QGHD: checks in the Tonks-Girardeau limit



PR, Calabrese, Doyon, Dubail, In Preparation

SUMMARY

1. GHD provides a more efficient way to describe interacting quantum particles in 1D

2. Still, it misses important quantum effects

3. QGHD gives a way to construct quantum fluctuations around GHD

4. This is not the end of the story…

THANK YOU.