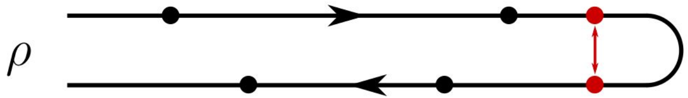
Schwinger-Keldysh EFTs for Precision Physics and Discovery

Luca Delacrétaz | U Chicago

Contours 2026 in Cambridge
30 June 2026

Schwinger-Keldysh EFTs have allowed for unprecedented control in otherwise strongly coupled quantum many-body systems



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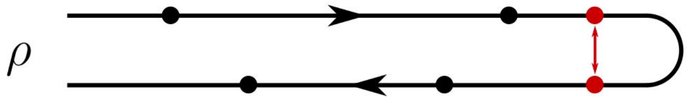
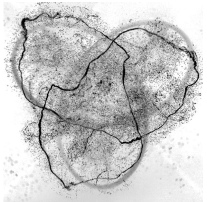
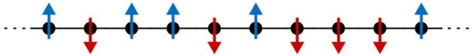
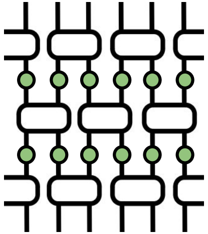




$$S = \int \bar{\psi} i \not{D} \psi + \frac{1}{4g^2} \mathrm{Tr}(F^2)$$

$$S = S_{\mathrm{CFT}} + \lambda \int \mathcal{O}$$





$$H = \sum_i \sigma_i^z \sigma_{i+1}^z + g \sigma_i^z + g' \sigma_i^x$$

$$H = -t \sum_{\langle ij \rangle} c_i^\dagger c_j + U \sum_i n_i^\uparrow n_i^\downarrow$$

Fluctuating hydrodynamics is arguably the most universal EFT in physics

Locality + symmetry ⇒ hydrodynamics

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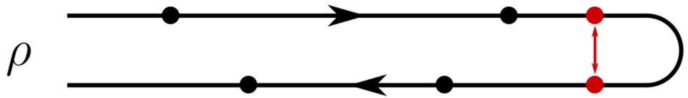

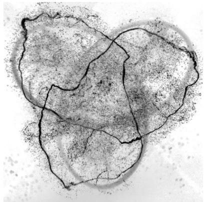

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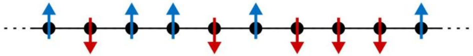

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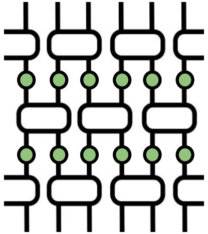

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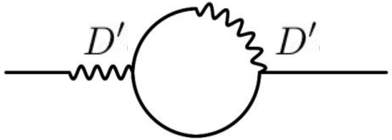

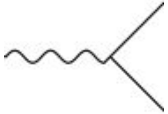

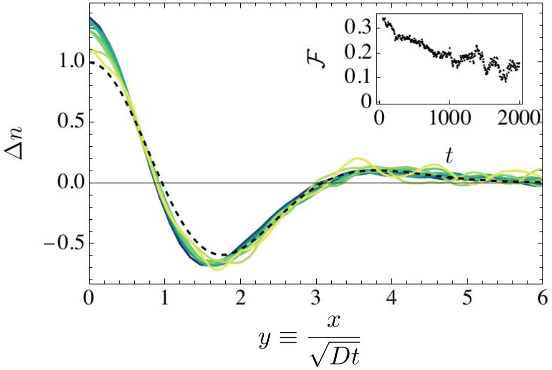

Inspired by $T = 0$ EFTs, it is possible to measure loop effects, nonlinear effects, …

What is this control good for?..

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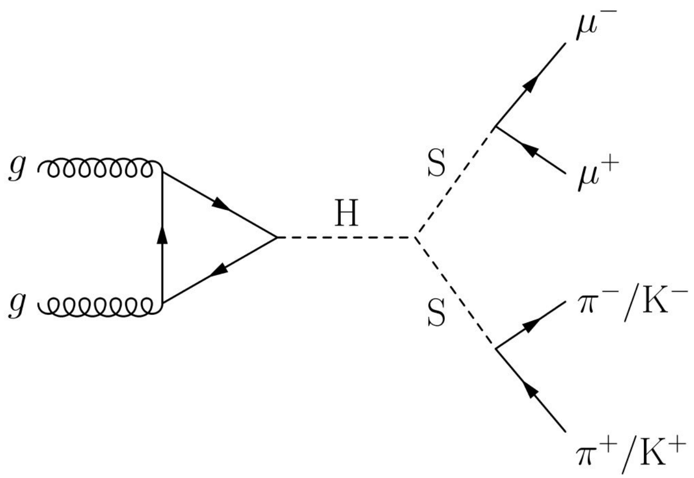
In SMEFT: find new (BSM) physics



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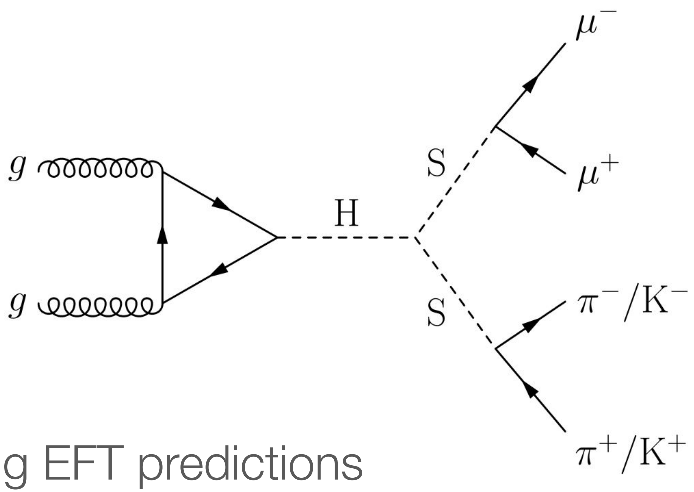
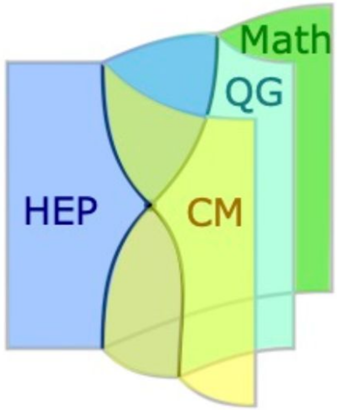


In SMEFT: find new (BSM) physics

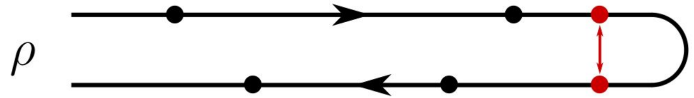
Search for many-body systems (numerics) violating EFT predictions

Because [Hydrodynamics ⇔ Symmetry], finding systems exhibiting "beyond hydro" behavior ≈ generalizing notions of symmetry

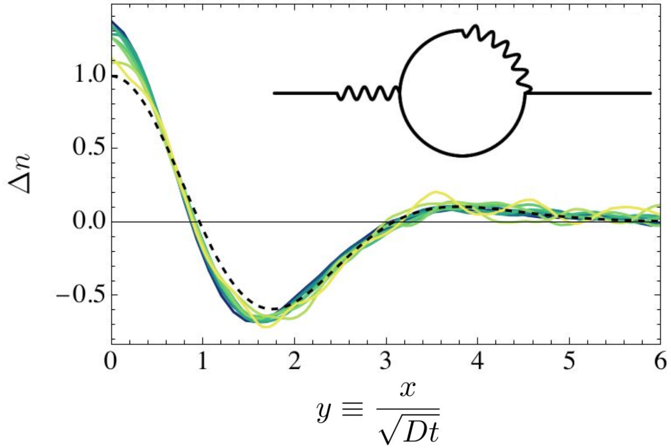
Connect to formal effort to generalize notion of symmetry.



Tools: Precision physics in thermalizing systems



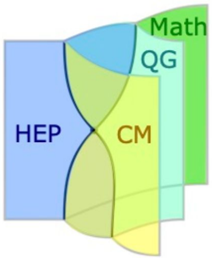
$$Z = \int D\phi_a D\mu_r e^{iS_{\text{eff}}[\phi_a,\mu_r]}$$

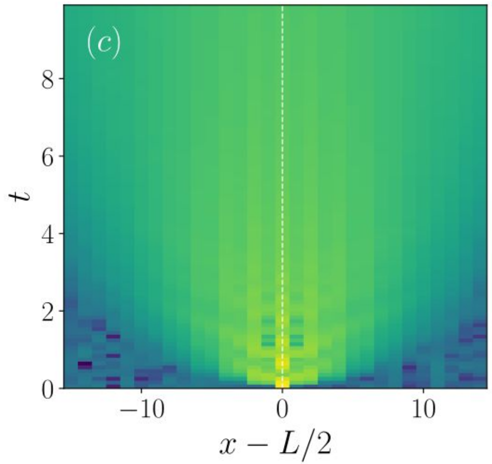


Discovery: Hydrodynamics beyond conventional symmetry

$$S^{\pm} = \sum_i \cdots \otimes q^{\sigma_z} \otimes q^{\sigma_z} \otimes \sigma_i^{\pm} \otimes \mathbb{1} \otimes \mathbb{1} \otimes \cdots$$

$z < 2$
universality





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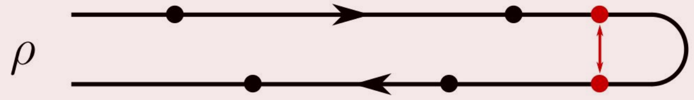

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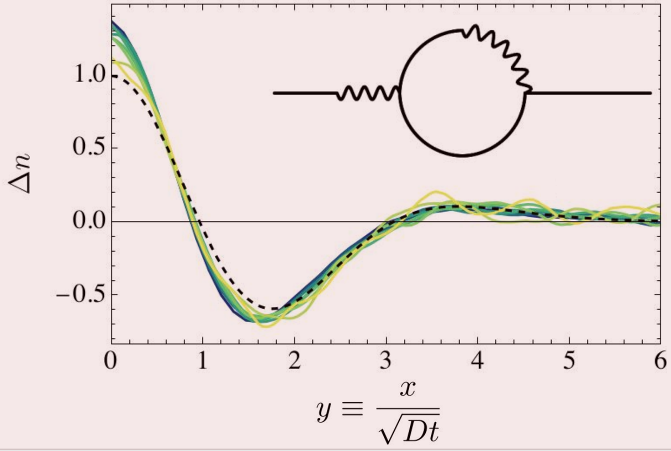

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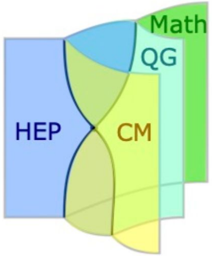
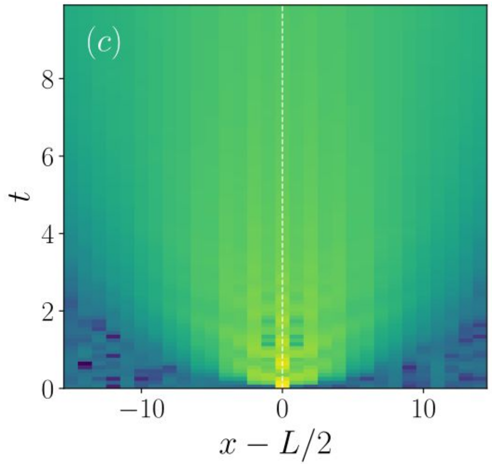




Schwinger-Keldysh EFT for Fluctuating Hydrodynamics

Martin Siggia Rose ‘73 De Dominicis ‘76 Janssen ‘76 ...

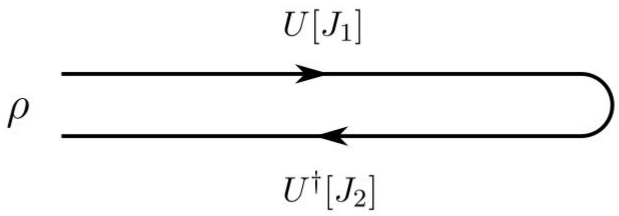
Hydrodynamics as an EFT on a Keldysh contour

Grozdanov Polonyi ‘14, Haehl Loganayagam Rangamani ‘15, Crossley Glorioso Liu ‘15, Jensen Pinzani-Fokeeva Yarom ‘17 …

Hydro = Nambu-Goldstone modes of strong to weak SSB

Ogunnaike Feldmeier Lee ‘23, Akyuz Goon Penco ‘23, Gu Wang Wang ‘24, Huang Qi Zhang Lucas ‘24, Firat Gomes Nardi Penco Rattazzi ‘25 …

Symmetries of mixed state evolution



Buca Prosen '12

Natural notion of doubled symmetries on mixed states

$$\rho \to e^{-i\alpha_1 Q} \rho e^{i\alpha_2 Q} \qquad U(1) \times U(1)$$

Useful in the context of *open* dynamics, where Lindblad evolution can break either symmetry

$$\partial_t \rho = \mathcal{L}\rho \equiv -i[H, \rho] + \sum \left(2L_i \rho L_i^\dagger - L_i^\dagger L_i \rho - \rho L_i^\dagger L_i\right)$$

If L_i is charged, dynamics only has "weak" symmetry $U(1)_{\rm diag}$

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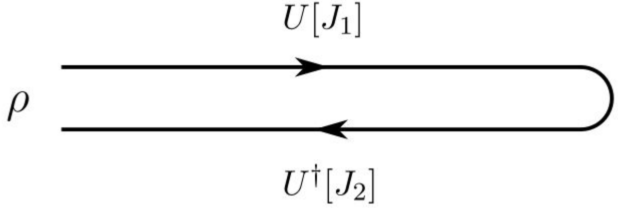

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Why care for closed systems? Thermal states have "strong to weak" SSB

$$\text{Tr}\left(\rho \psi^\dagger \psi\right) = \langle \psi_2^\dagger \psi_1 \rangle \neq 0 \qquad U(1) \times U(1) \to U(1)_{\text{diag}}$$

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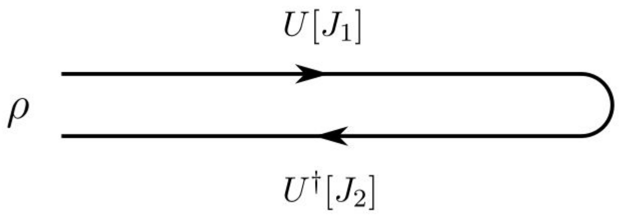

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Hydrodynamics

“Goldstone modes for strong to weak SSB”

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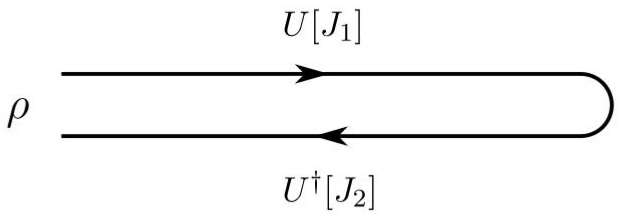

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Hydrodynamics

"Goldstone modes for strong to weak SSB"

Unifying description for open systems [review: Sieberer Buchhold Diehl '16]

Builds on previous SK EFTs Haehl Loganayagam Rangamani '15, Crossley Glorioso Liu '15, Jensen Marjieh Pinzani-Fokeeva Yarom '17

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Algorithm: double global symmetry group G and SSB to diagonal

$$G \times G \to G$$

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Works for symmetries that are non-abelian, spacetime, higher-form, anomalous, …

MHD, …

Navier-Stokes, …

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Simplest example: $G = U(1)$

$$\phi_a \,, \qquad \mu_r$$

Goldstone
(historically: "noise field")

$\mu_r \sim \dot{\phi}_r$

KMS multiplet: $\begin{cases} \phi_a \to -(\phi_a + i\beta\mu_r + \cdots) \\ \mu_r \to \mu_r + \frac{1}{4} i\beta\ddot{\phi}_a + \cdots \end{cases}$

EFT of diffusion

$$S[\phi_a, \mu_r] = \int \dot{\phi}_a n(\mu_r) + iT\sigma(\mu_r)\nabla\phi_a\left(\nabla\phi_a + i\beta\nabla\mu_r\right) + \cdots$$

Wilson coefficients (functions) of the EFT

EFT of diffusion

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Higher derivative, nonlinear in noise ϕ_a

Identify $U(1)$ density: $\delta S/\delta\dot{\phi}_a \simeq n(\mu_r) = n + \chi\delta\mu_r + \frac{1}{2}\chi'(\delta\mu_r)^2 + \cdots$

(equation of state)

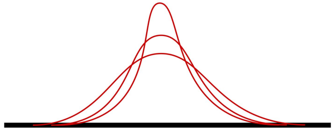
Linearized action predicts diffusion

$$S = \chi \int \dot{\phi}_a \mu_r + iTD\partial_i\phi_a \left(\partial_i\phi_a + i\beta\partial_i\mu_r\right)$$

$$G^R_{nn}(\omega, k) = \frac{\chi D k^2}{Dk^2 - i\omega} + \cdots$$

$$D = \sigma/\chi$$

$$\langle n(t,x) n\rangle = \frac{\chi T}{(4\pi D t)^{d/2}} e^{-x^2/4Dt} + \cdots$$



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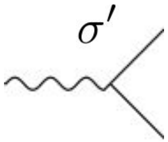
Leading nonlinearities come from $n(\mu)$ and $\sigma(\mu)$ (scaling argument)

⇒ Nonlinear response tied to linear response!

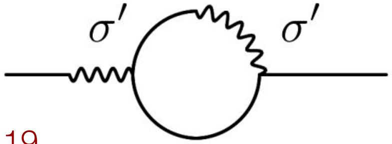
$$S^{(3)} \supset \int \sigma' \mu_r \nabla\mu_r \cdot \nabla\phi_a$$

… as are corrections to transport!



LVD Mishra ‘23

Chen-Lin LVD Hartnoll ‘19
Michailidis Abanin LVD ‘23



EFT systematics

$$y \equiv \frac{x}{\sqrt{Dt}}$$

$$\begin{aligned}\langle n(t,x)n\rangle = \frac{\chi T}{(4\pi D t)^{d/2}}\Bigg[\quad & F_{0,0}(y) + \frac{1}{t}F_{0,1}(y) + \frac{1}{t^2}F_{0,2}(y) + \cdots \\ & + \frac{1}{t^{d/2}}\left(F_{1,0}(y) + \frac{1}{t}F_{1,1}(y) + \frac{1}{t^2}F_{1,2}(y) + \cdots\right) \\ & + \frac{1}{t^{d}}\left(F_{2,0}(y) + \frac{1}{t}F_{2,1}(y) + \frac{1}{t^2}F_{2,2}(y) + \cdots\right) + \cdots \Bigg]\end{aligned}$$

Michailidis Abanin LVD ‘23

EFT systematics

Derivative expansion →

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Loop expansion ↓

Up to a handful of Wilson coefficients, EFT predicts entire *scaling functions* $F_{\ell,n}$

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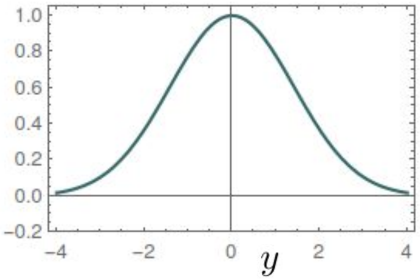

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$$F_{0,0}(y) = e^{-y^2/4}$$

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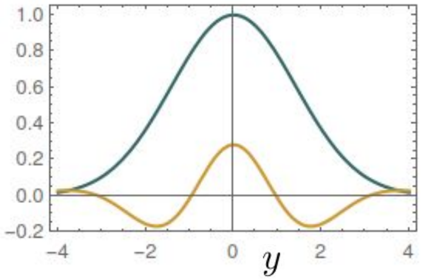

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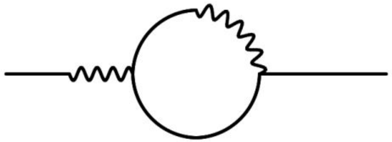
$$F_{1,0}(y) = \frac{\chi D'^2}{D^{5/2}}\left[\frac{4+y^2}{8\sqrt{\pi}}e^{-y^2/2} + \frac{y(y^2-10)}{16}e^{-y^2/4}\mathrm{Erf}(y/2)\right]$$

(d=1)

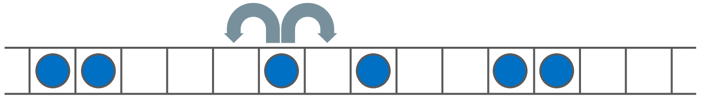


Michailidis Abanin LVD ‘23

Precision tests of thermalization

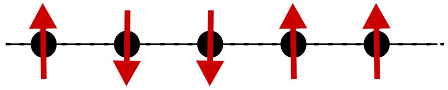
Can test these predictions numerically in many systems:

1. Classical lattice gas

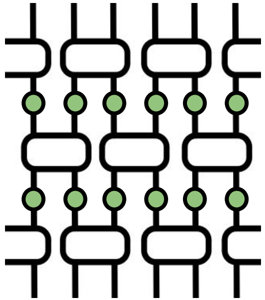


2. Hamiltonian spin chains

$$H = \sum_i \sigma_i^z \sigma_{i+1}^z + g\sigma_i^z + g'\sigma_i^x$$



3. Floquet quantum systems



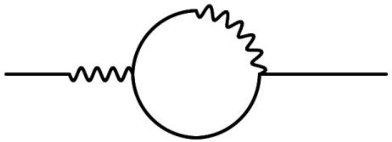
LVD Mishra '23

Michailidis Abanin LVD '23

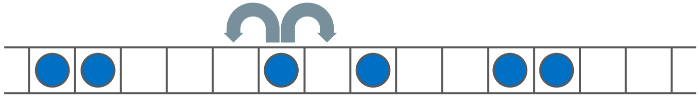
Precision test of thermalization:

Universal 1-loop correction to diffusion

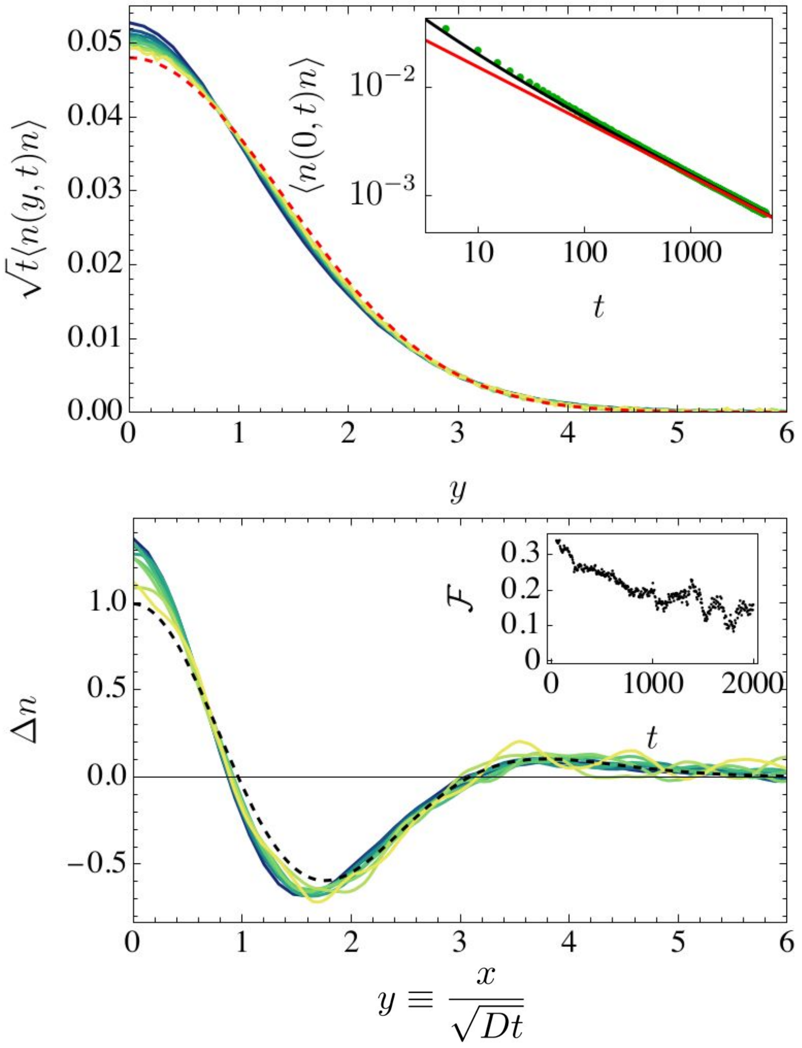
$$\langle n(x,t)n\rangle = \frac{1}{\sqrt{t}}\left[e^{-x^2/4Dt} + \frac{1}{\sqrt{t}}F_{1,0}\left(\frac{x^2}{Dt}\right) + \cdots\right]$$



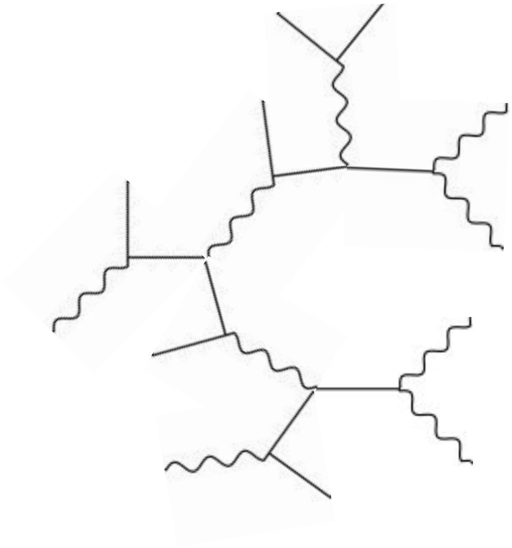
Test in a classical lattice gas [Spohn '12]



($D(n)$ known analytically → no fitting parameter!)



Non-linear response in diffusive systems



$$\langle n(x_N, t_N) \cdots n(x_2, t_2) n(x_1, t_1) \rangle$$

All leading order higher point functions fixed by $n(\mu)$ and $\sigma(\mu)$

Non-linear response in diffusive systems

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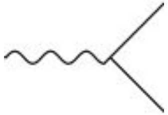
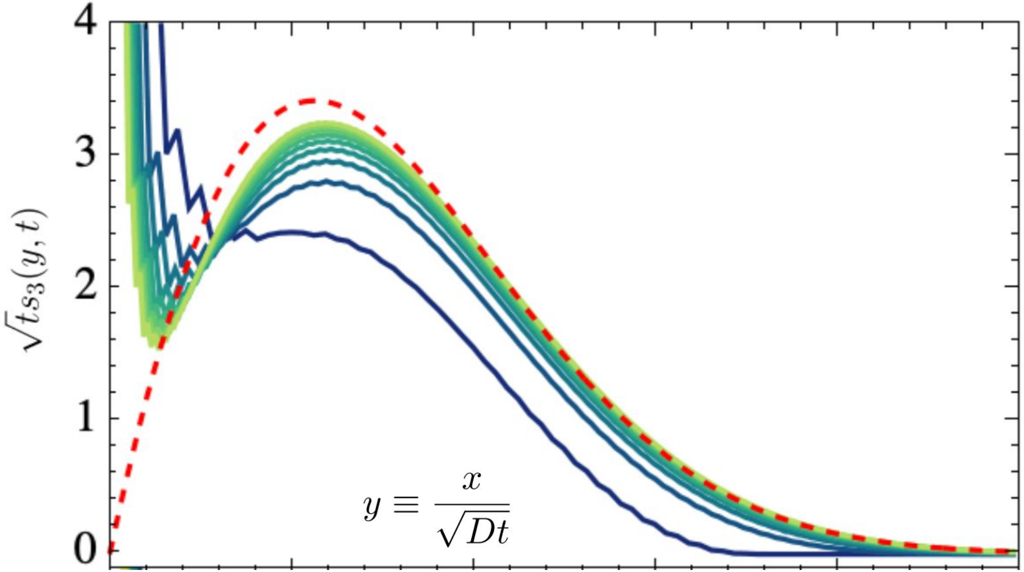
Higher point functions fixed by the same vertex:

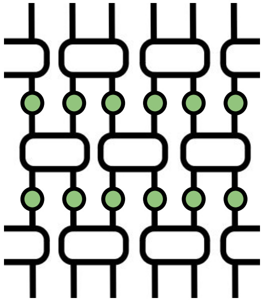


$$\langle n(t,x)n(t,0)n(0,0)\rangle = \frac{1}{\sqrt{t}}\frac{D'\chi}{8\sqrt{D^3\pi}}\left(e^{-y^2/4} + \mathrm{Erf}(y/2) - 1\right)$$

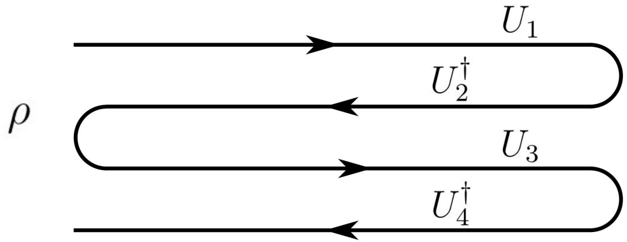


Numerics:

Floquet quantum spin chain



More exotic observables



EFTs can be extended to capture OTOCs

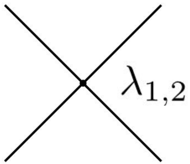
$$G \times G \times G \times G \to G_{\text{diag}}$$

3 Goldstones, one conjugate field: $\phi,\ \phi,\ \phi,\ \mu$

New EFT contains all the information from previous EFT $n(\mu),\ \sigma(\mu),\ \cdots$

Also contains two new parameters at leading order – “OTO-Transport”

$$S_{(4)} = \int dt d^d x\, \lambda_1 \mathcal{L}_1 + \lambda_2 \mathcal{L}_2$$



Mishra Wang Pappalardi LVD ‘25

Testing OTOC predictions

Mishra Wang Pappalardi LVD ‘25

Trace cyclicity ⇒ 3 independent 4pt functions

$$g_0 = \mathrm{Tr}\left(\rho O(t_4) O(t_3) O(t_2) O(t_1)\right)$$
$$g_1 = \mathrm{Tr}\left(\rho O(t_3) O(t_4) O(t_2) O(t_1)\right)$$
$$g_2 = \mathrm{Tr}\left(\rho O(t_4) O(t_2) O(t_3) O(t_1)\right)$$

Wang Heinz ‘98, Haehl Loganayagam Narayan Nizami Rangamani ‘17

Scaling in the EFT $\mu^R \sim \phi^A \sim \dot{\phi}^- \sim \phi^+ \sim q^{d/2}$ implies:

$$g_0 \sim \frac{1}{t^{3/2}} + \frac{i}{t^{5/2}}$$
$$g_1 - g_0 \sim \frac{1}{t^{7/2}} + \frac{i}{t^{5/2}}$$
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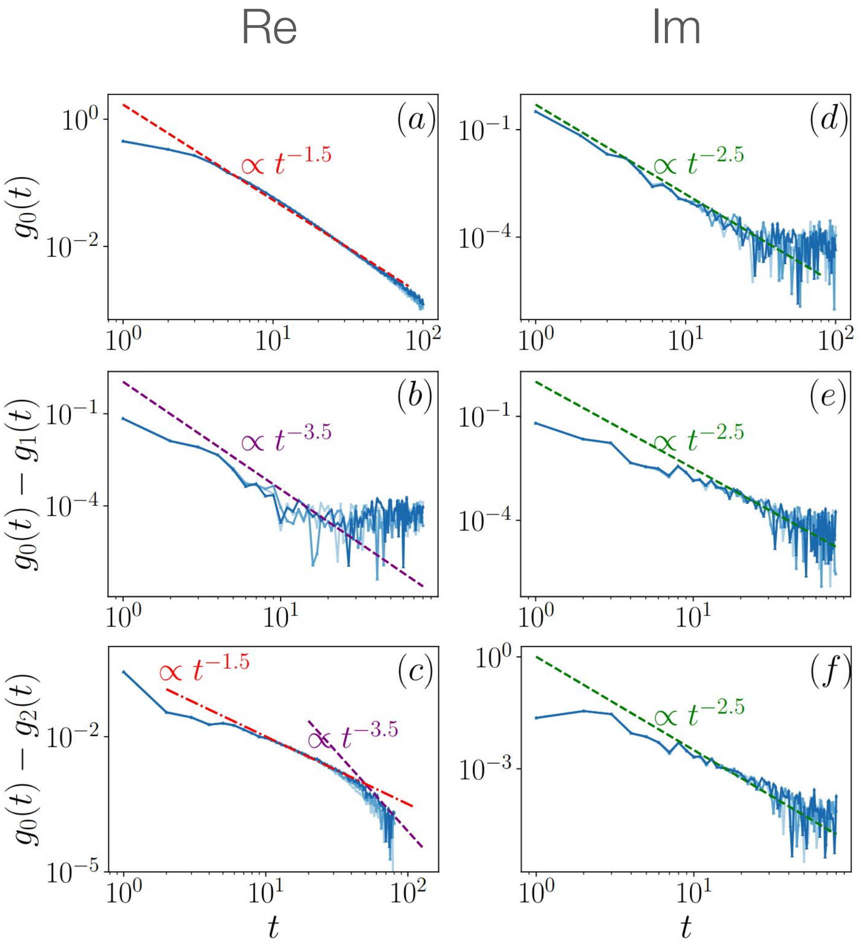

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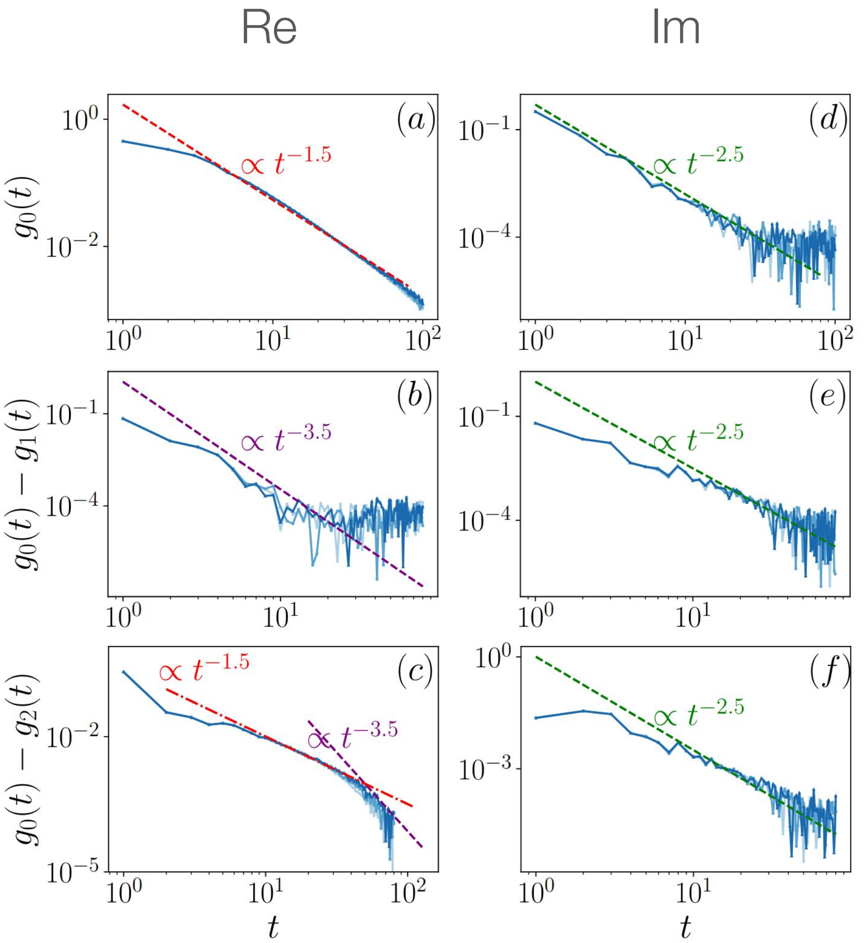
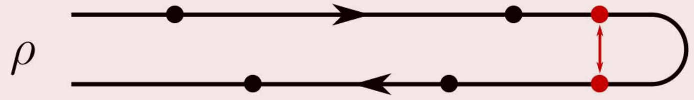
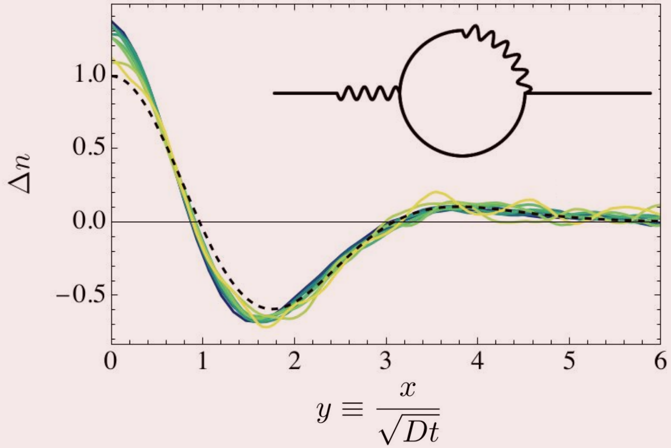
$\lambda_1,\ \lambda_2$



Tools: Precision physics in thermalizing systems



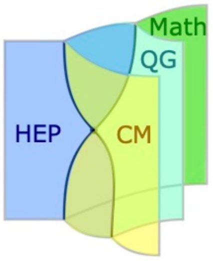
$$Z = \int D\phi_a D\mu_r e^{iS_{\text{eff}}[\phi_a, \mu_r]}$$

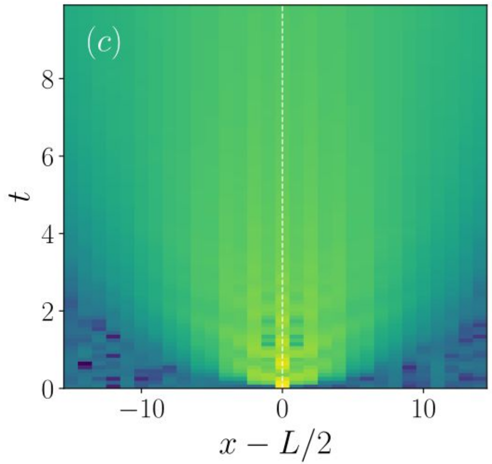


Discovery: Hydrodynamics beyond conventional symmetry

$$S^{\pm} = \sum_i \cdots \otimes q^{\sigma_z} \otimes q^{\sigma_z} \otimes \sigma_i^{\pm} \otimes \mathbb{1} \otimes \mathbb{1} \otimes \cdots$$

$z < 2$
universality





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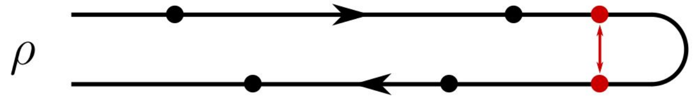

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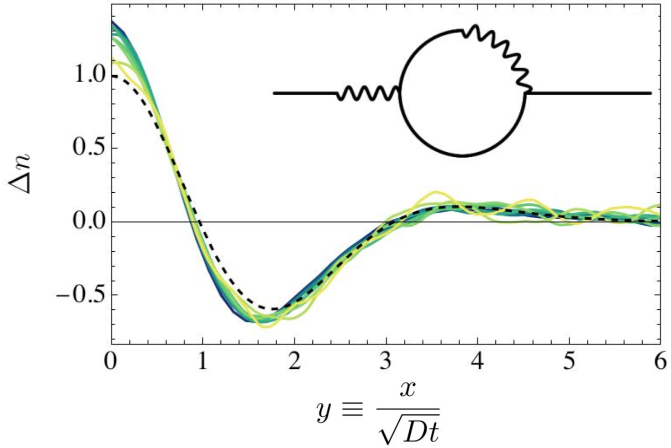

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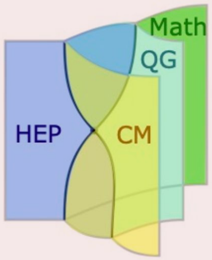
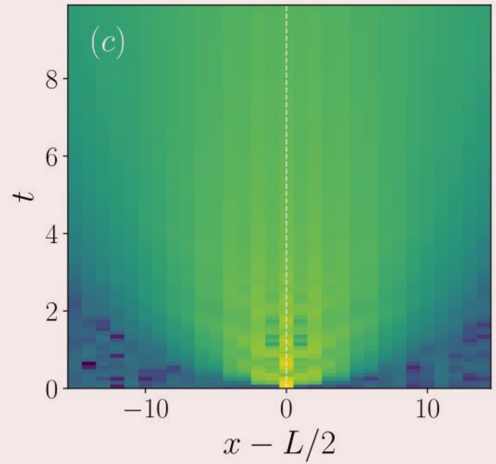
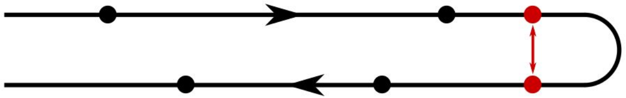




Tools: Precision physics in thermalizing systems

ρ



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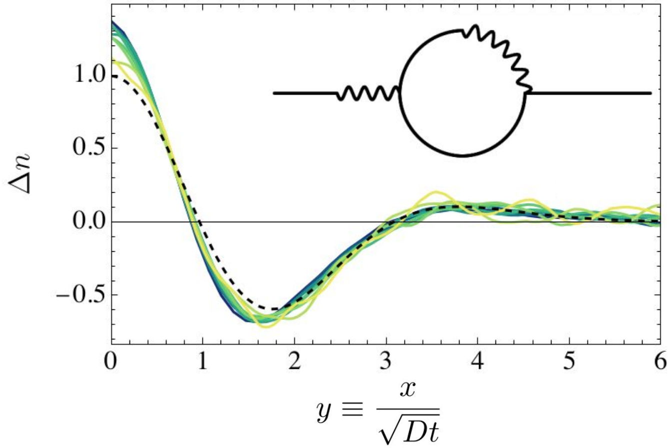

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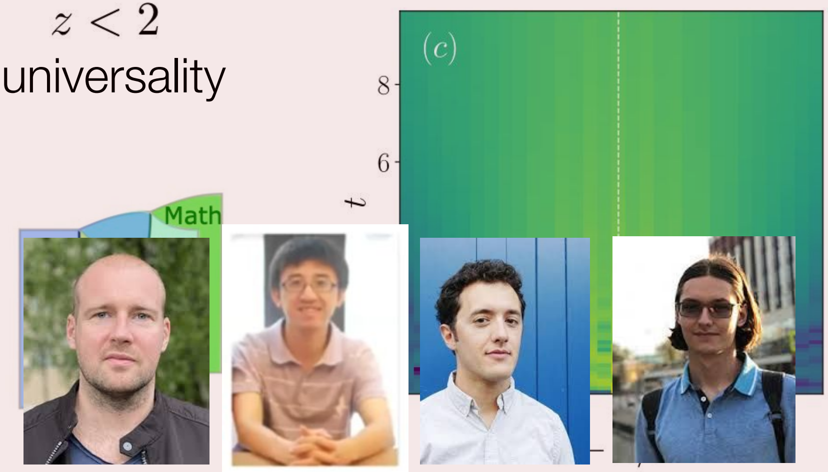
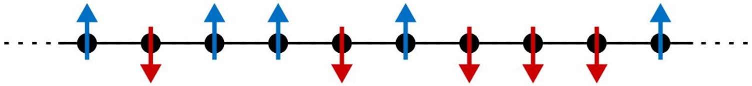


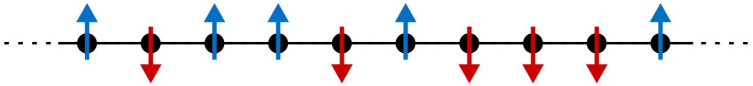
2606.20850 with Gorbenko, Wang, Zan, Zhabin

XXZ model



$$H = \sum_i \sigma_i^x \sigma_{i+1}^x + \sigma_i^y \sigma_{i+1}^y + \Delta \sigma_i^z \sigma_{i+1}^z$$

XXZ model



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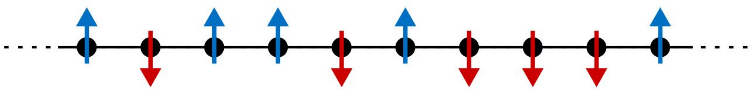
with, e.g., $V_i^{\mathrm{nnn}} = \sigma_i^x \sigma_{i+2}^x + \sigma_i^y \sigma_{i+2}^y + \sigma_i^z \sigma_{i+2}^z$

XXZ model



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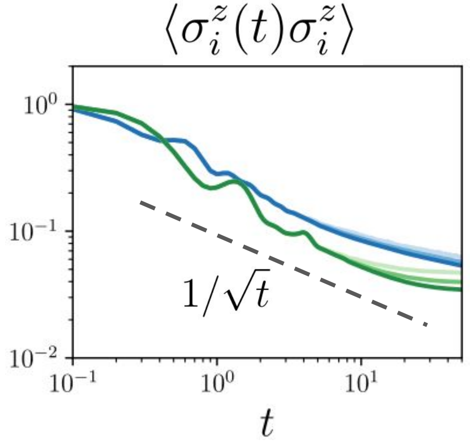
Symmetries: $U(1)$ and energy conservation.
Expect two diffusive modes: σ_i^z and h_i



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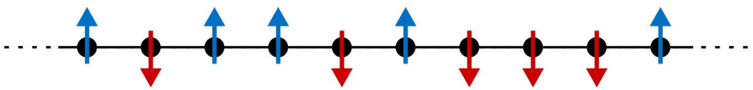

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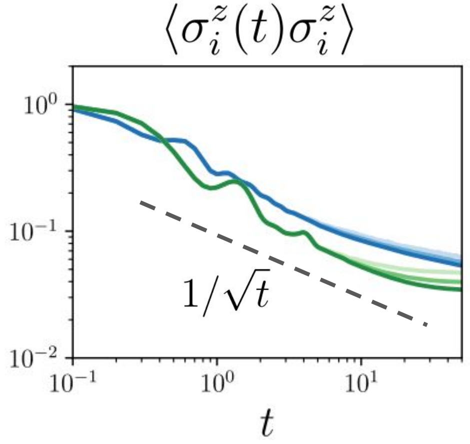

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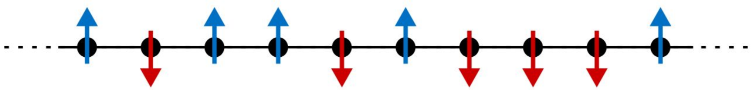
In contrast, transverse spin σ^x or σ^y
should decay fast, because $U(1)$ charge of
$\sigma^\pm = \sigma^x \pm i\sigma^y$ forbids overlap with hydro modes

XXZ model



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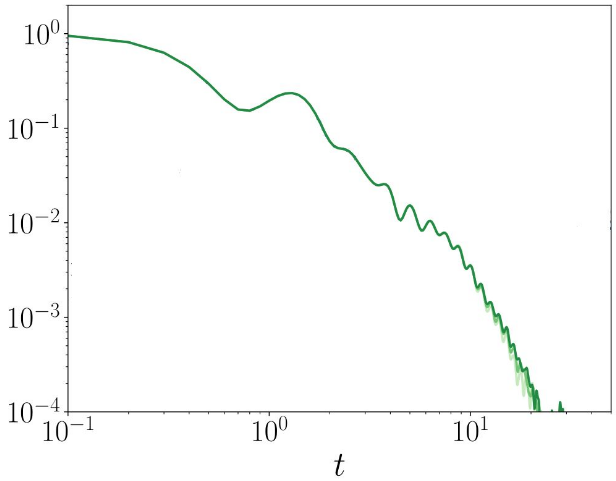
$\langle \sigma_i^x(t) \sigma_i^x \rangle$



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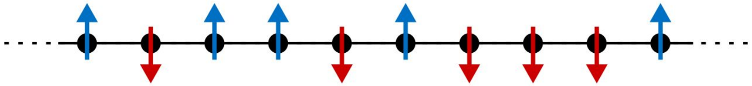
XXZ-like model



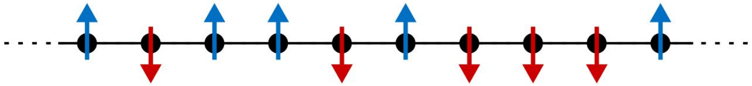
$$\tilde{H} = \sum_i \sigma_i^x \sigma_{i+1}^x + \sigma_i^y \sigma_{i+1}^y + \Delta \sigma_i^z \sigma_{i+1}^z + V_i$$

with $V_i = V_i^{\mathrm{nnn}} + A_i + B_i$

$$A_i = \frac{1}{4}(q - q^{-1})^2 \left(\sigma_i^z \sigma_{i+1}^z + \sigma_{i+1}^z \sigma_{i+2}^z\right)$$

$$B_i = \frac{1}{2}(q - q^{-1})\Big(\sigma_i^x \sigma_{i+1}^x \sigma_{i+2}^z + \sigma_i^y \sigma_{i+1}^y \sigma_{i+2}^z - \sigma_i^z \sigma_{i+1}^x \sigma_{i+2}^x - \sigma_i^z \sigma_{i+1}^y \sigma_{i+2}^y\Big)$$

XXZ-like model



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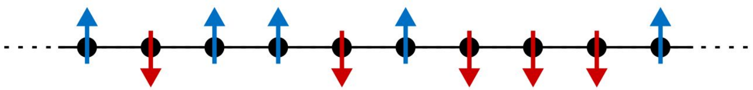
entirely different transverse spin dynamics!

XXZ-like model



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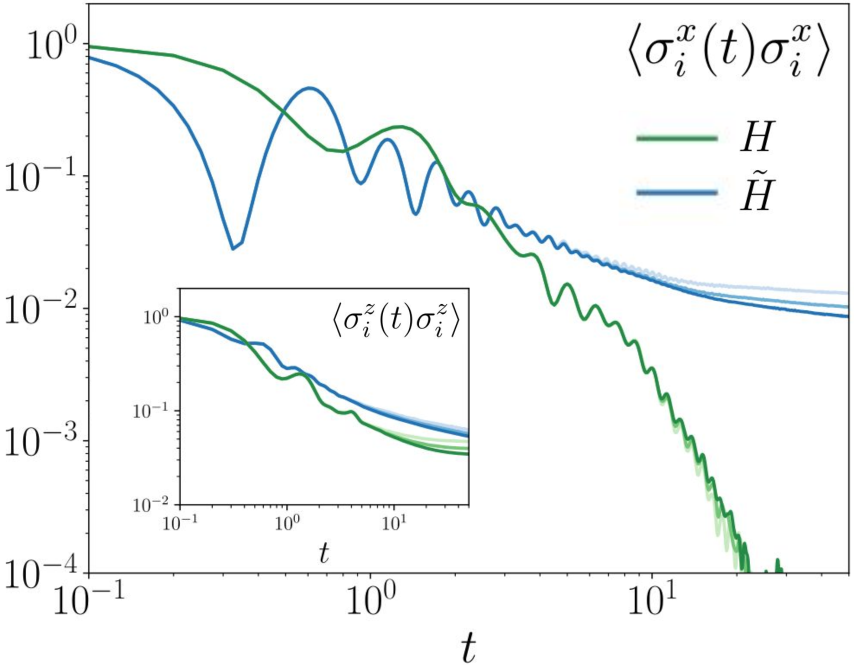
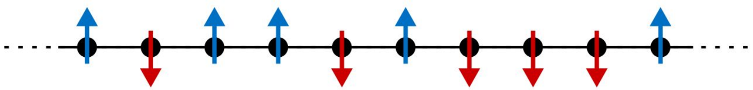
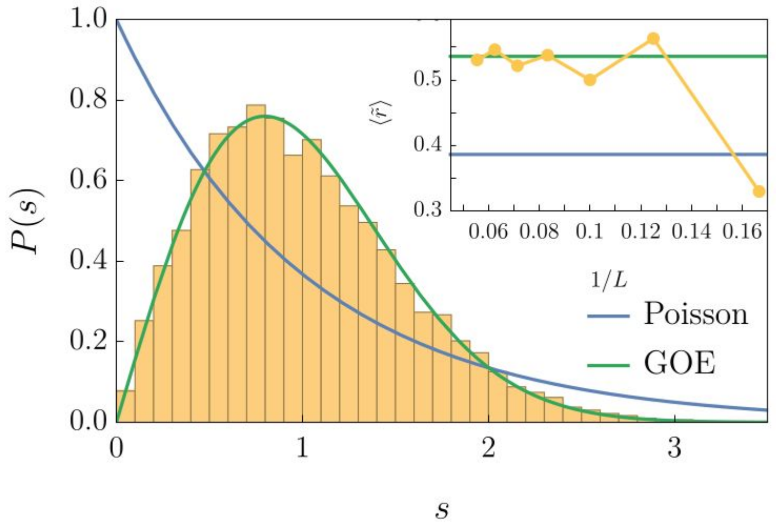


XXZ-like model

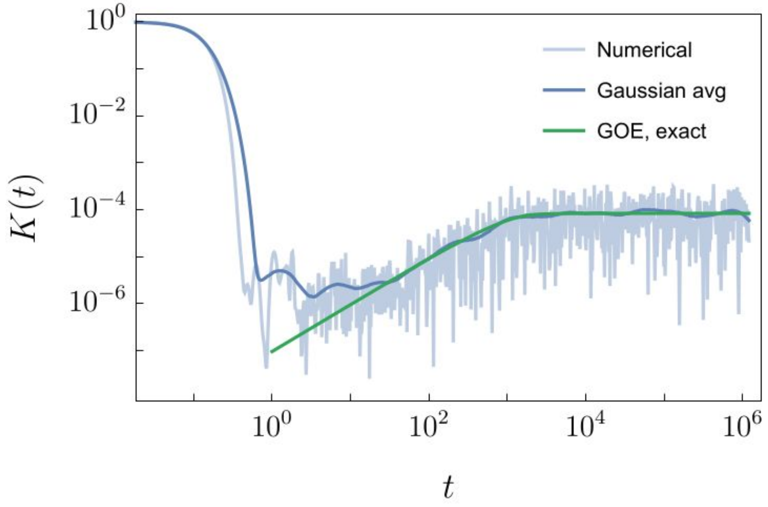


What explains the slow transverse spin dynamics? Integrability? No.

Level spacing statistics



Spectral form factor



$\tilde{H}$ has “quantum group” symmetry

Quantum group symmetry of XXZ model

$$H_0 = \sum_i \left(\sigma_i^x \sigma_{i+1}^x + \sigma_i^y \sigma_{i+1}^y + \frac{1}{2}(q+q^{-1})\sigma_i^z \sigma_{i+1}^z\right)$$

where $\Delta = \frac{1}{2}(q+q^{-1})$ has the quantum group symmetry $U_q(SU(2))$ [Pasquier Saleur '90]

when $q \to 1$, recover $SU(2)$ [which also protects transverse spin!] with densities:

$$S^z = \sum_i \sigma_i^z$$

$$S^\pm = \sum_i \sigma_i^\pm$$

Quantum group symmetry of XXZ model

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$$S^{\pm} = \sum_i \cdots \otimes q^{\sigma_z} \otimes q^{\sigma_z} \otimes \sigma_i^{\pm} \otimes \mathbb{1} \otimes \mathbb{1} \otimes \cdots \xrightarrow{q \to 1} S^{\pm} = \sum_i \sigma_i^{\pm}$$

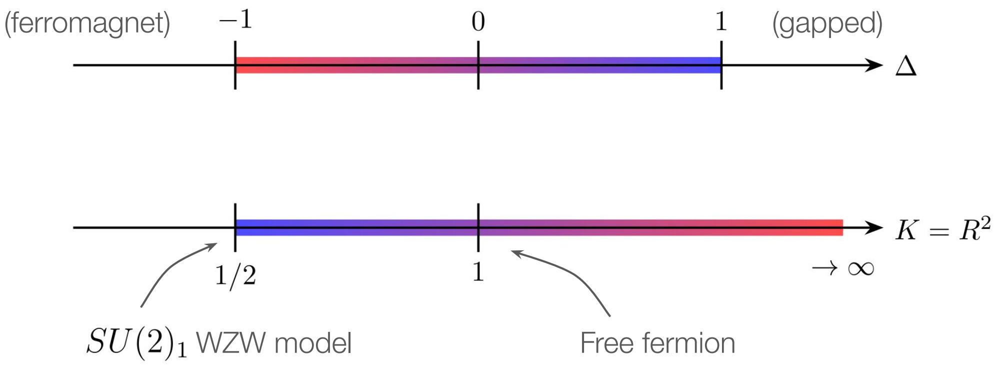
QG-symmetric Hamiltonians commute with charges whose densities are nonlocal

Quantum group symmetry of XXZ model

Continuum intuition for nonlocal density:

XXZ model $H = \sum_i \sigma_i^x \sigma_{i+1}^x + \sigma_i^y \sigma_{i+1}^y + \Delta \sigma_i^z \sigma_{i+1}^z$ flows to compact boson CFT with:

$$R^2 = \frac{\pi/2}{\pi - \cos^{-1}\Delta}$$



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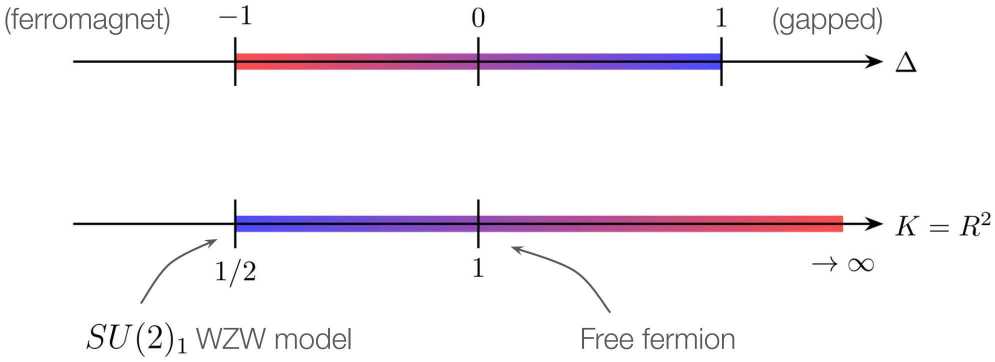
XXZ model $H = \sum_i \sigma_i^x \sigma_{i+1}^x + \sigma_i^y \sigma_{i+1}^y + \Delta \sigma_i^z \sigma_{i+1}^z$ flows to compact boson CFT with:

$$R^2 = \frac{\pi/2}{\pi - \cos^{-1}\Delta}$$



At $SU(2)$ point, vertex operator becomes an additional current:

$$e^{\pm i\phi} = j^{\pm}$$

Away from that point, that operator still exists, but is non-local, because ill-quantized ($\phi \sim \phi + 2\pi R$)

Constructing chaotic QG symmetric models

The Hamiltonian density of the XXZ model is a QG singlet: ("Hecke algebra element")

$$h_i = \frac{1}{2}\Big[\sigma_i^x\sigma_{i+1}^x + \sigma_i^y\sigma_{i+1}^y + \tfrac{q+q^{-1}}{2}\big(\sigma_i^z\sigma_{i+1}^z + \underbrace{1}_{\text{(const)}}\big) - \tfrac{q-q^{-1}}{2}\big(\underbrace{\sigma_i^z - \sigma_{i+1}^z}_{\text{(total derivative)}} \underbrace{-\,2}_{\text{(const)}}\big)\Big]$$

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$H_{\text{XXZ}} = \sum_i h_i$ is thus QG invariant

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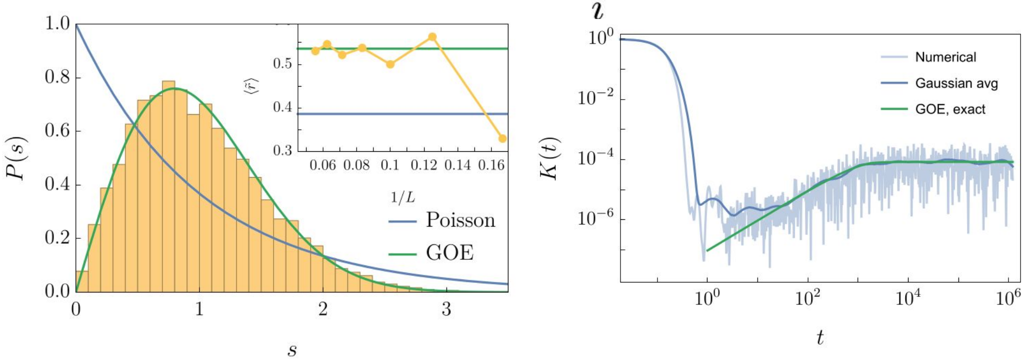
Can easily generate further QG invariants using h_i, e.g.: $\tilde{H} = \sum_i h_i + \lambda h_i h_{i+1}$

$\tilde{H}$ still has $U_q(SU(2))$ symmetry, but is chaotic!

(QG symmetry sectors must be taken into account before comparing statistics to RMT)



Is QG a good generalization of continuous symmetry?

[Gabai Gorbenko Qiao Zan Zhabin '24]
[Gorbenko Zhabin '26]

What is a symmetry of a QFT?

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- $[H, Q] = 0$
- “Local implications”

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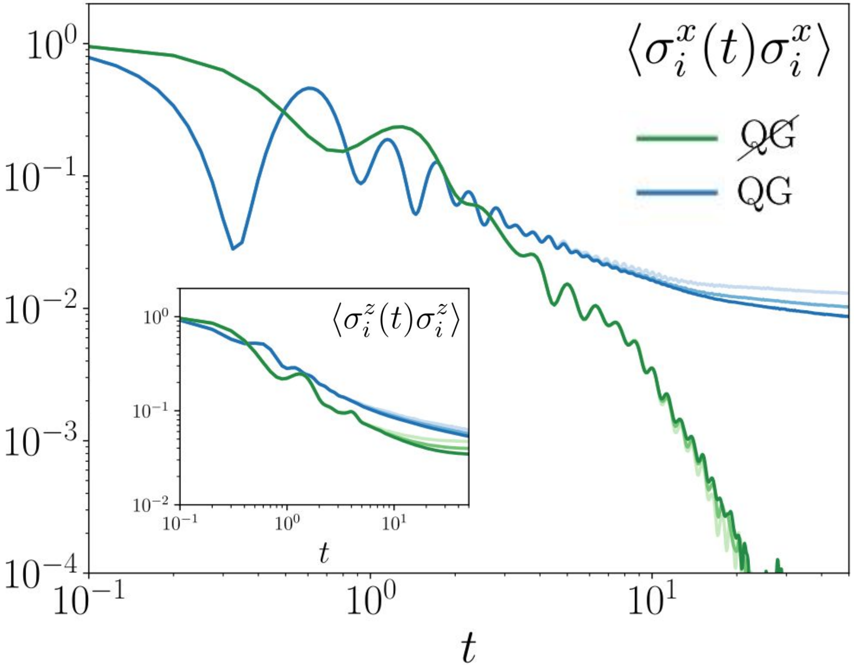
Hydrodynamic protection!



Hydrodynamics of chaotic spin chains with QG symmetry

Hydrodynamic tails in Hamiltonian models

Study $\tilde{H} = \sum_i h_i + \lambda h_i h_{i+1}$

and $\tilde{H}_{\text{stag}} = \sum_i h_i + \lambda (-1)^i h_i h_{i+1}$

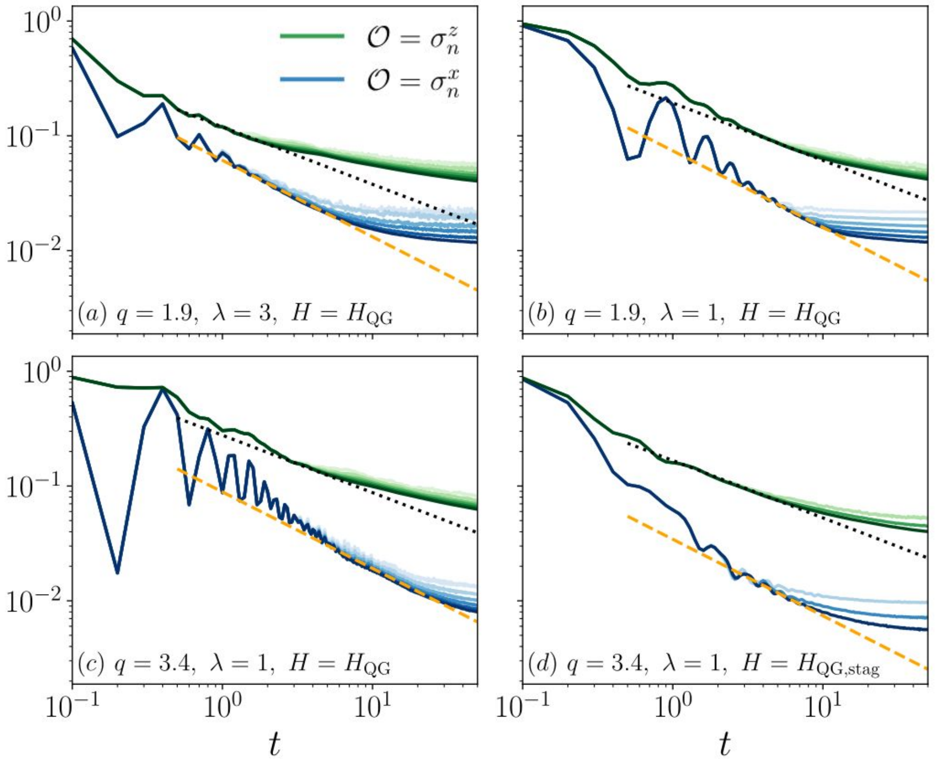
for several values of $\lambda,\ q$

Hydrodynamic protection of transverse spin, similar power-laws throughout

Notice that $SU(2)$ is strongly broken

$(\beta = 0)$

$\text{Tr}\left(\rho \mathcal{O}(t) \mathcal{O}\right)$ $L = 22, 26, 30$

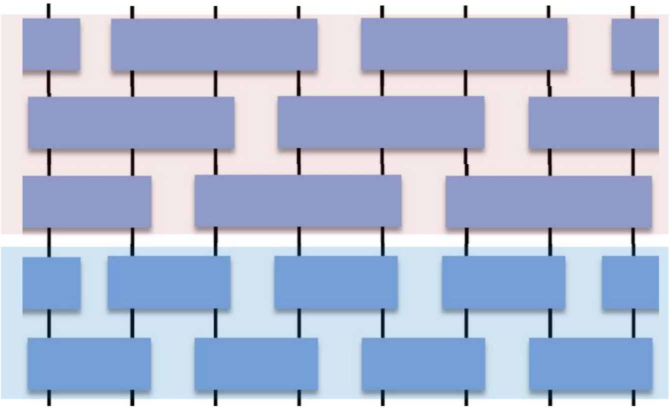


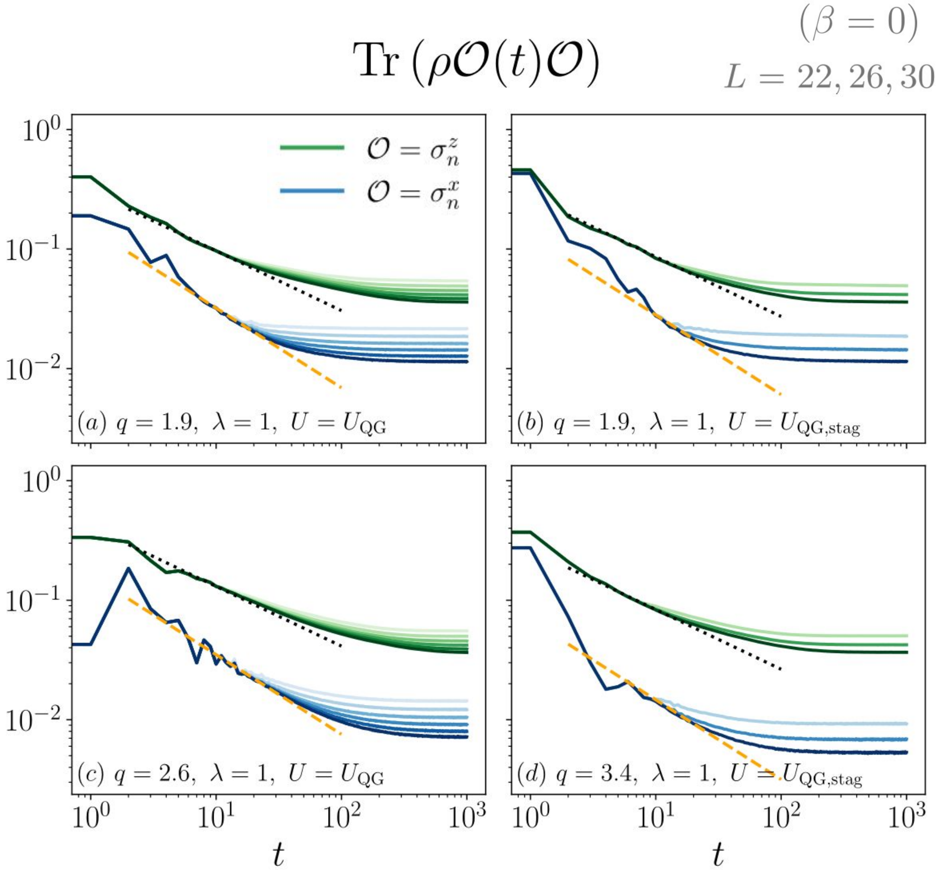
Hydrodynamic tails in Floquet models

Can also make QG invariant Floquet unitaries:

$$U_0 = \prod_i^{L/2} e^{-ih_{2i}}$$

$$U_\lambda = \prod_i^{L/3} e^{-i\lambda h_{3i} h_{3i+1}}$$

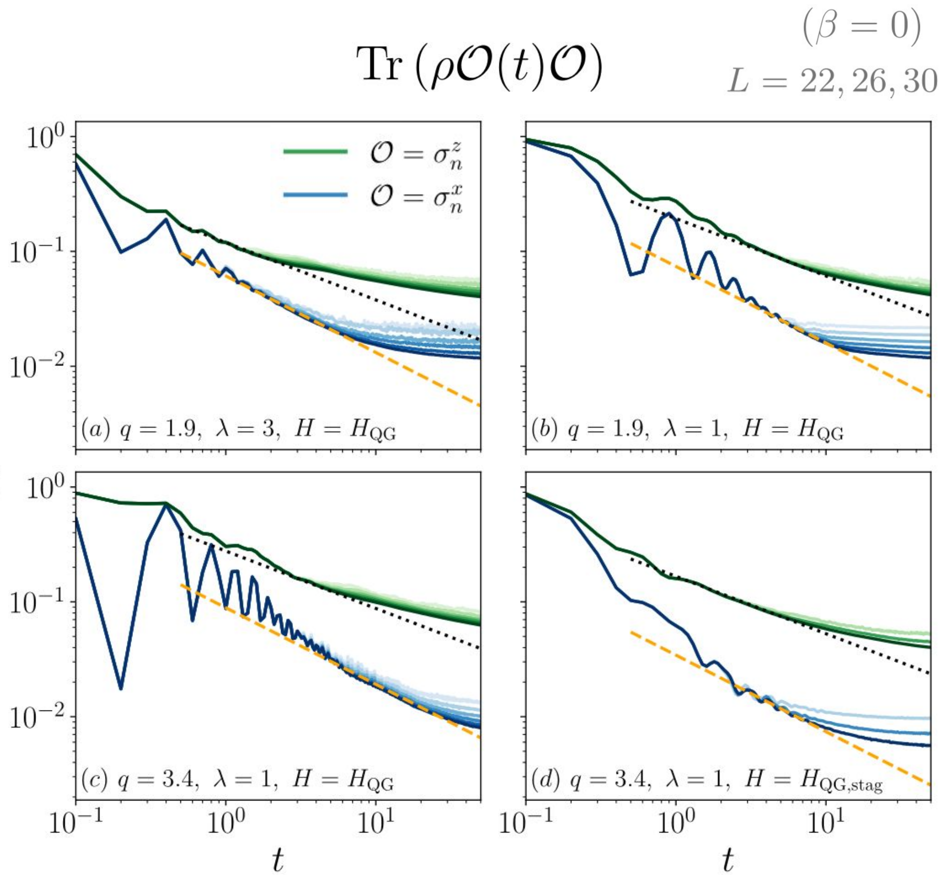




Superdiffusion?

Find hydrodynamic protection across QG-symmetric models!

Even more excitingly, hydrodynamics appears to be *superdiffusive*



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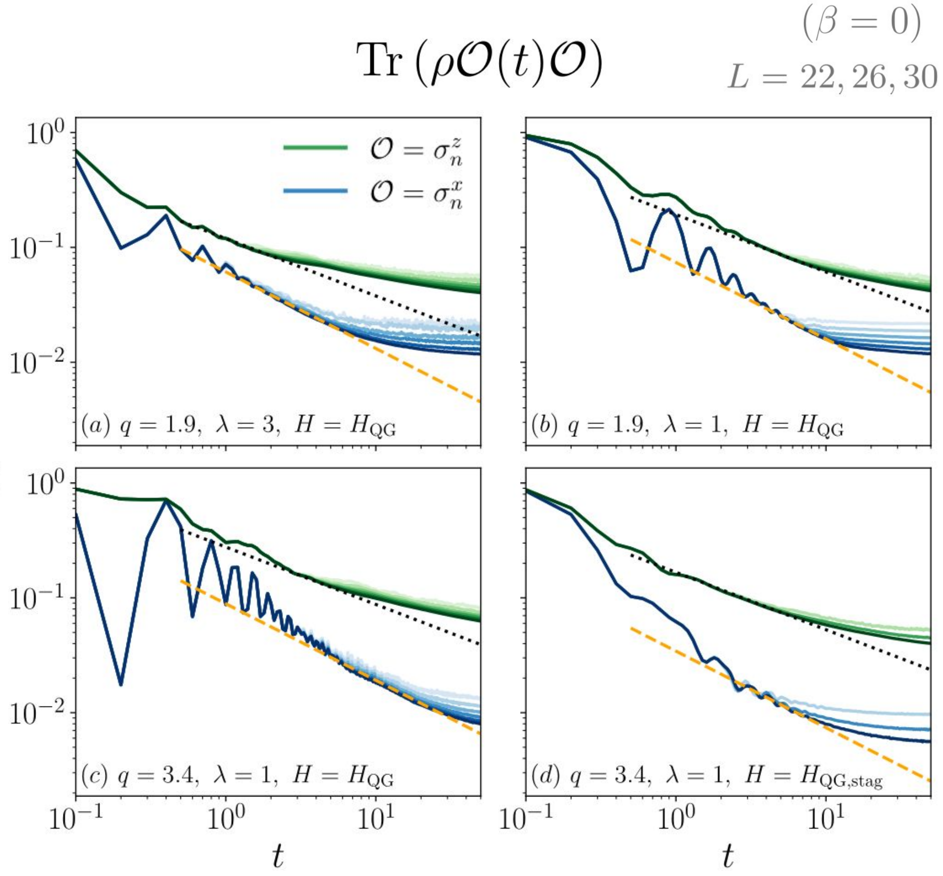
$$1/t^{1/z} \qquad z < 2$$



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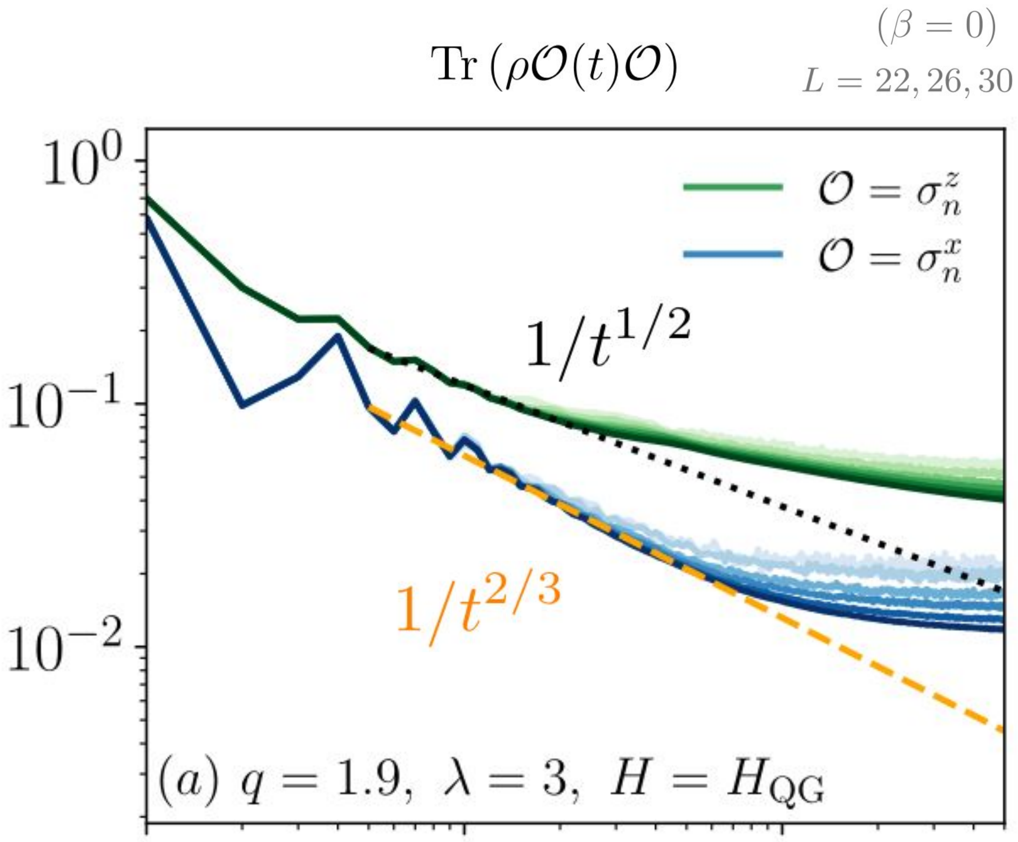


Superdiffusion?

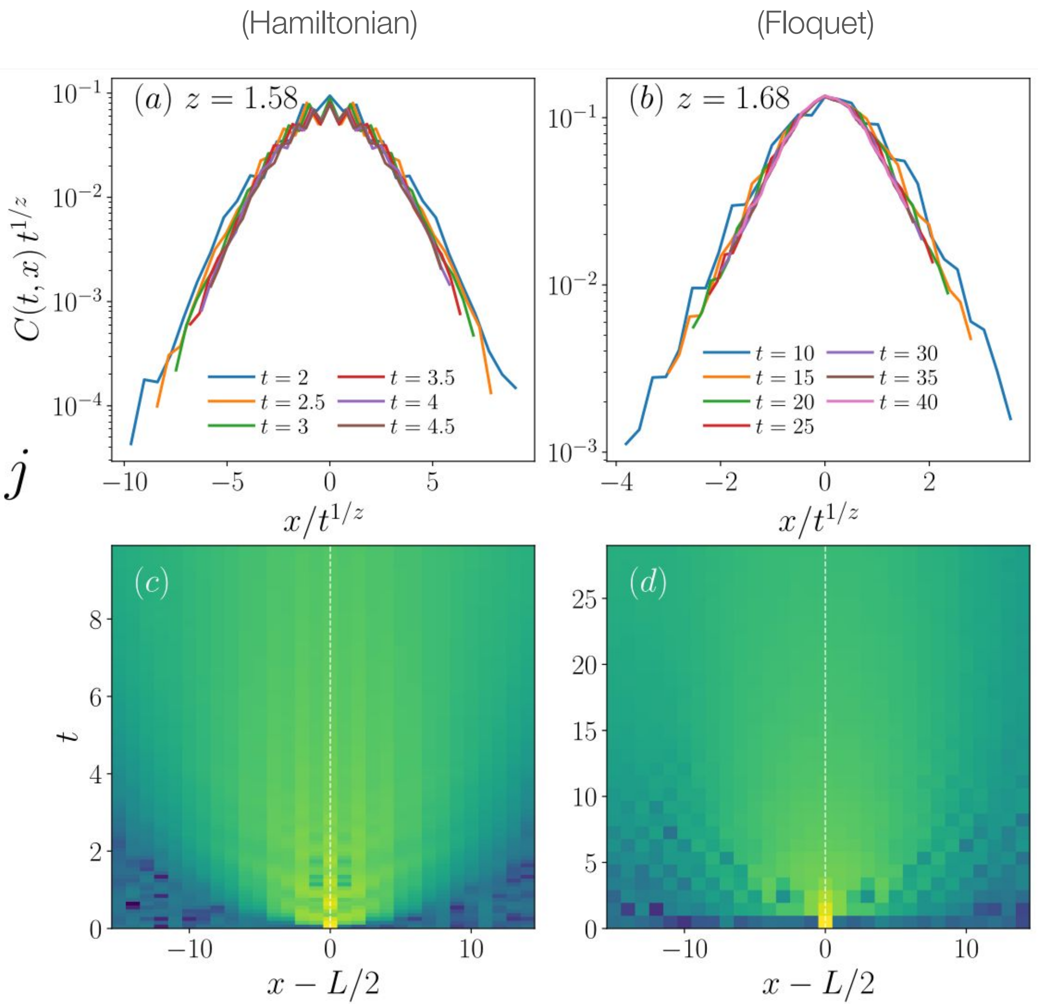
Probe dynamic critical exponent and universality class with position-resolved correlators:

$$C(t,x) = \langle \sigma_i^+(t)\sigma_j^- \rangle\,, \quad x = i - j$$

Collapses onto universal scaling function

$$\langle \sigma_i^+(t)\sigma_j^-(0)\rangle \simeq \frac{1}{t^{1/z}} F\left(x/t^{1/z}\right)$$

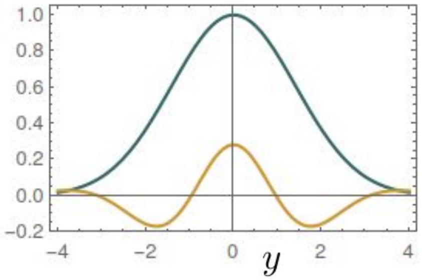
with $z \approx 1.6$



EFT systematics

$$y \equiv \frac{x}{\sqrt{Dt}}$$

$$\langle n(t,x)n\rangle = \frac{\chi T}{(4\pi D t)^{d/2}}\Bigg[\quad F_{0,0}(y) + \frac{1}{t}F_{0,1}(y) + \frac{1}{t^2}F_{0,2}(y) + \cdots$$
$$+ \frac{1}{t^{d/2}}\left(\boxed{F_{1,0}(y)} + \frac{1}{t}F_{1,1}(y) + \frac{1}{t^2}F_{1,2}(y) + \cdots\right)$$
$$+ \frac{1}{t^{d}}\left(F_{2,0}(y) + \frac{1}{t}F_{2,1}(y) + \frac{1}{t^2}F_{2,2}(y) + \cdots\right) + \cdots \Bigg]$$

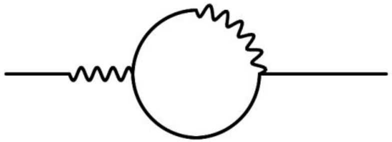


Up to a handful of Wilson coefficients, EFT predicts entire *scaling functions* $F_{\ell,n}$

$$F_{0,0}(y) = e^{-y^2/4}$$

$$F_{1,0}(y) = \frac{\chi D'^2}{D^{5/2}}\left[\frac{4+y^2}{8\sqrt{\pi}}e^{-y^2/2} + \frac{y(y^2-10)}{16}e^{-y^2/4}\mathrm{Erf}(y/2)\right]$$

(d=1)



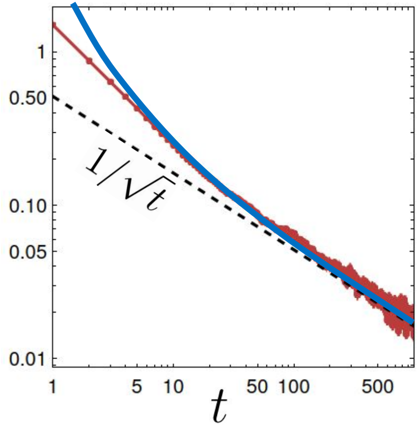
Michailidis Abanin LVD ‘23

Let’s be careful

Power-law corrections to diffusion make generic diffusive systems appear to be *superdiffusive* at intermediate times

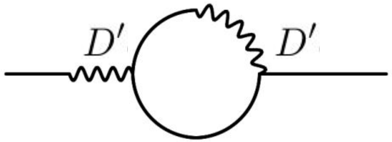
$$\langle n(0,t)n\rangle = \frac{\chi}{\sqrt{4\pi D t}}\left(1+\frac{\chi D'^2}{4\sqrt{\pi}D^{5/2}}\frac{1}{\sqrt{t}}+O\left(\frac{\log t}{t}\right)\right)$$

↑ ≥ 0



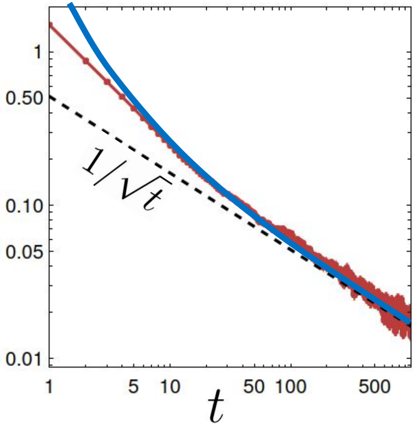
[Michailidis Abanin LVD ‘23]

Due to a cubic vertex in the EFT of fluctuating diffusion



(These are quite large in the related classical Heisenberg model! [Glorioso LVD Chen Nandkishore Lucas ‘20])

Let’s be careful



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[Michailidis Abanin LVD ‘23]

≥ 0

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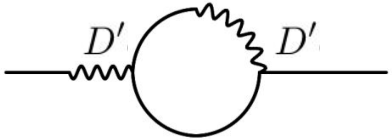
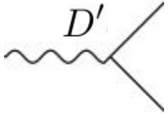


Thankfully, this same cubic vertex enters in the 3pt function, at leading order

$$\langle n(2t)n(t)n\rangle_c =$$ 

$+ \cdots$

$\Rightarrow$ can measure it to rule out diffusion!

Ruling out diffusion

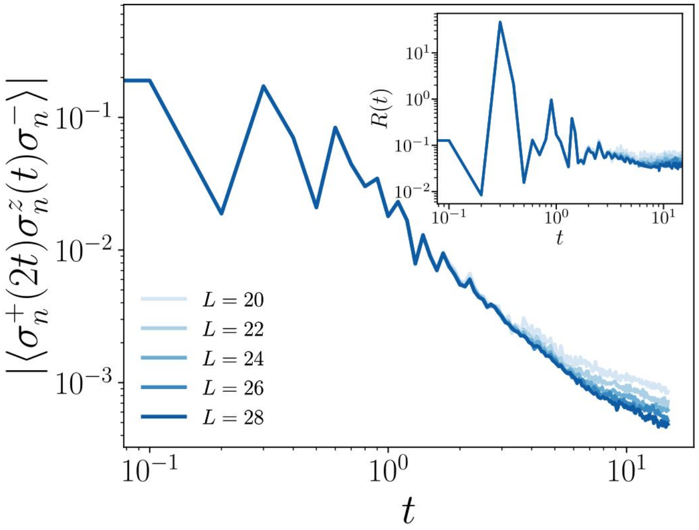
The size of power-law corrections coming from non-Gaussianities

$$\langle n(t)n\rangle \sim \frac{1}{\sqrt{t}}\left(1+\sqrt{\frac{\tau_{\text{loop}}}{t}}+\cdots\right)$$

can be estimated by the dimensionless ratio

$$\sqrt{\frac{\tau_{\text{loop}}}{t}} \sim R(t) \equiv \frac{\langle n(2t)n(t)n\rangle_c^2}{\langle n(t)n\rangle^3}$$

$$\approx 4\text{-}5\%$$



This cannot explain 20% deviation from $z=2$

$(z \approx 1.6)$

What is the theory of QG hydrodynamics?

Mechanism for superdiffusion

Superdiffusion usually arises from “convective” nonlinearities in 1+1d fluctuating hydrodynamics: [Forster Nelson Stephen ‘77] (Noisy Burger’s equation)

$$\partial_t n + c(n)\partial_x n + D\partial_x^2 n + \cdots = 0$$

Nonlinearities $dc(n)/dn$ are relevant in 1d, and drive to KPZ universality ($z = \frac{3}{2}$)

An equation of this form leads to superdiffusion in momentum conserving systems [Spohn ‘14], quantum Hall edges [LVD Glorioso ‘20], and the integrable XXX chain [De Nardis Gopalakrishnan Vasseur ‘22].

Mechanism for superdiffusion

In QG symmetric spin chains, $U(1)$ symmetry forbids this nonlinearity for $\sigma^{\pm}$ alone.

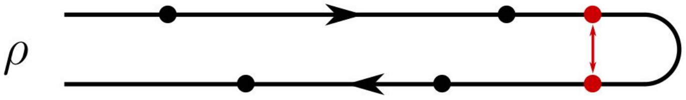
However, it does allow for nonlinearities involving the $U(1)$ density $n = \sigma^z$

$$\partial_t \sigma^+ + \sigma^+ \partial_x n + D \partial_x^2 \sigma^+ + \cdots = 0$$

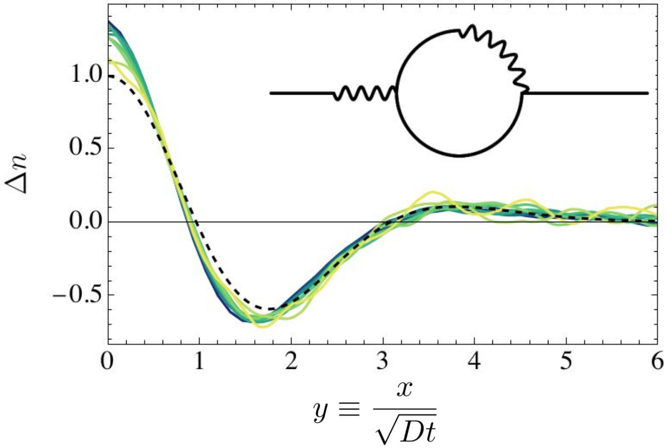
Such an equation seems plausible given the expression for the nonlocal density:

$$S^{\pm} = \sum_i \cdots \otimes q^{\sigma_z} \otimes q^{\sigma_z} \otimes \sigma_i^{\pm} \otimes \mathbb{1} \otimes \mathbb{1} \otimes \cdots$$

Tools: Precision physics in thermalizing systems



$$Z = \int D\phi_a D\mu_r e^{iS_{\text{eff}}[\phi_a, \mu_r]}$$

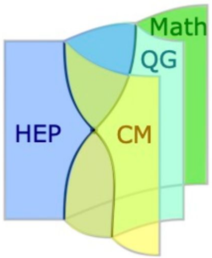


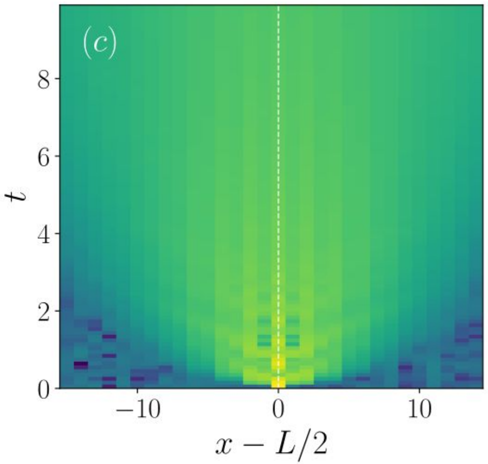
Discovery: Hydrodynamics beyond conventional symmetry

$$S^{\pm} = \sum_i \cdots \otimes q^{\sigma_z} \otimes q^{\sigma_z} \otimes \sigma_i^{\pm} \otimes \mathbb{1} \otimes \mathbb{1} \otimes \cdots$$

$z < 2$

universality





Extra slides

Funny finite size effects

At late times in finite systems $t \gg L^{\#}$, autocorrelation functions saturate

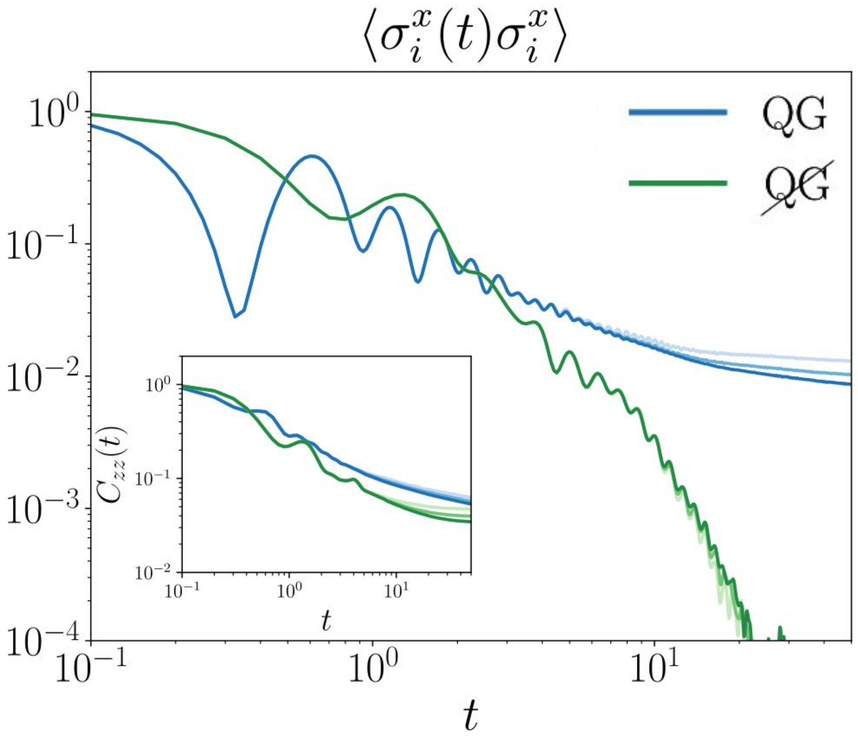
For non-conserved operators, expect

$$\lim_{t\to\infty} \langle \mathcal{O}(t)\mathcal{O}\rangle \sim e^{-L^d}$$

Instead, for operators overlapping with hydro modes:

$$\lim_{t\to\infty} \langle \mathcal{O}(t)\mathcal{O}\rangle \sim 1/L^d$$

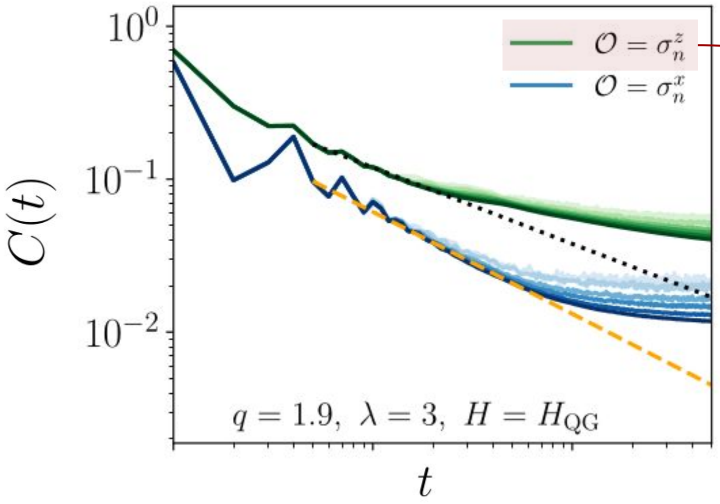
Transverse spin in QG-symmetric models appears to belong to the 2nd category



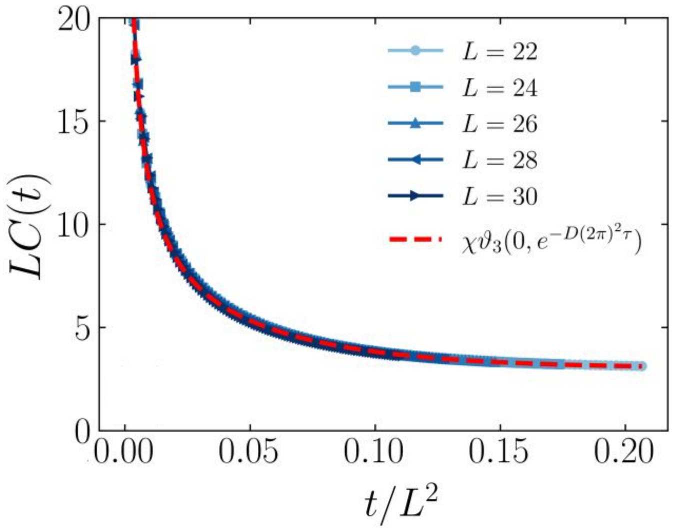
Funny finite size effects

The entire finite size data is expected to collapse to a scaling function, that is a universal property of the hydro universality class + boundary conditions:

$$\langle n(t, x=0) n \rangle = \frac{1}{L^d} F(t/L^z)$$



Collapse works well for longitudinal spin σ^z, which diffuses



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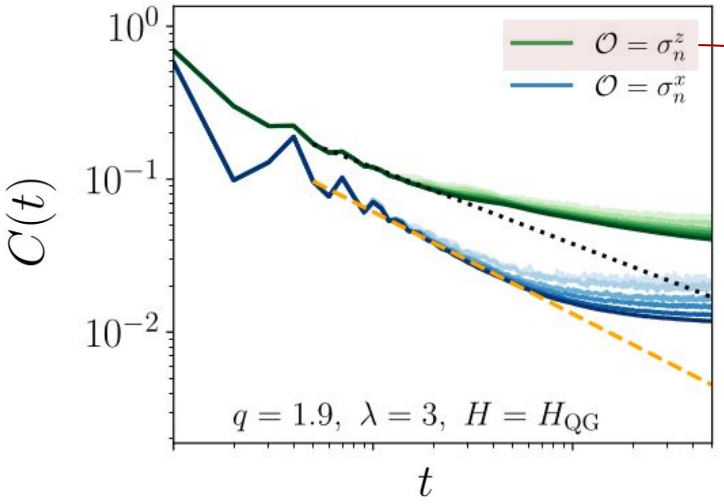
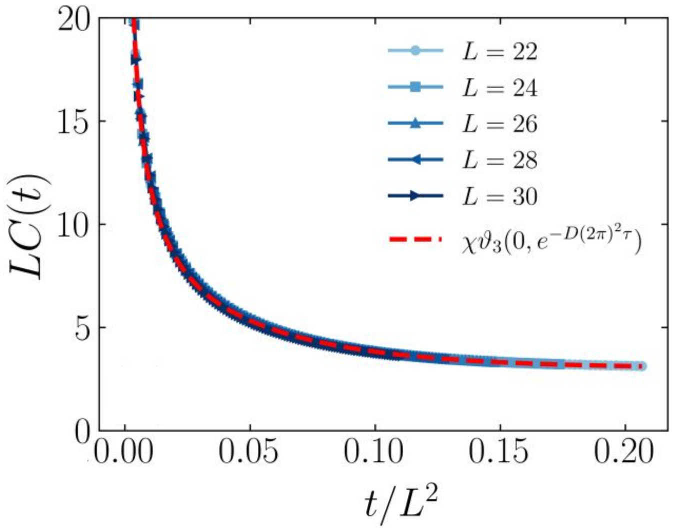


Collapse works well for longitudinal spin σ^z, which diffuses

Try to similarly collapse σ^x data, and confirm z?



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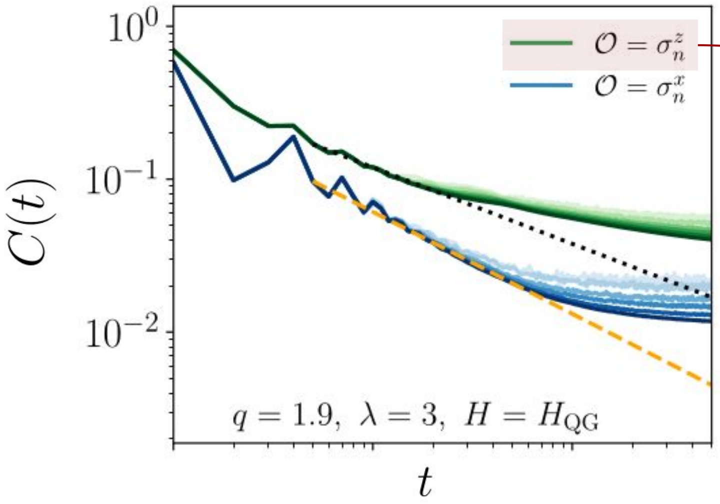

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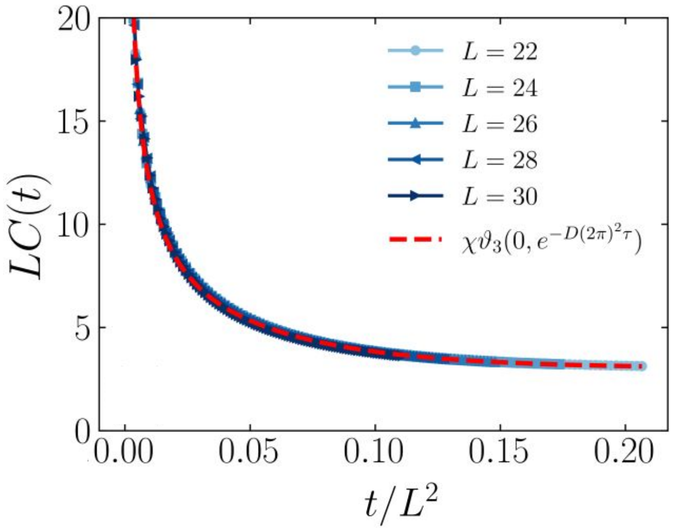

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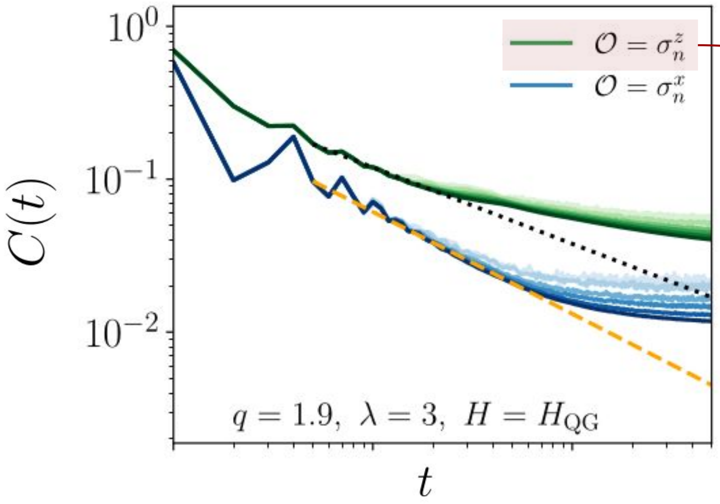

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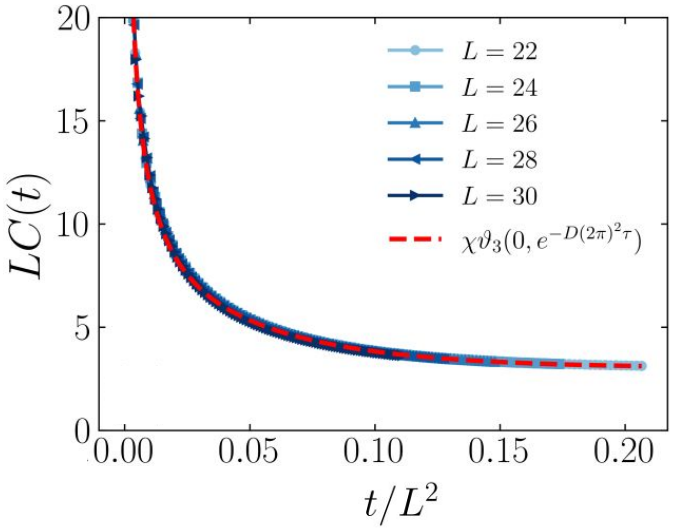

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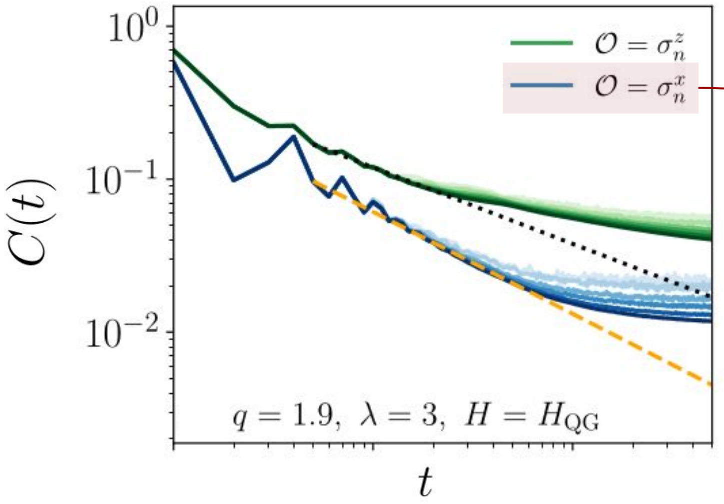

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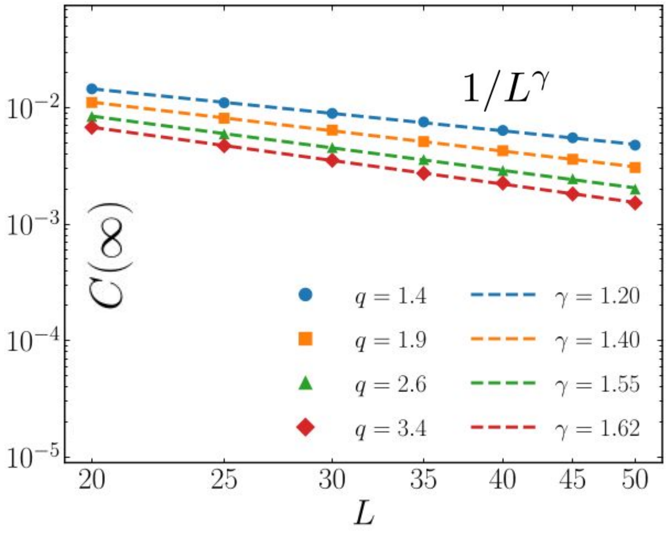
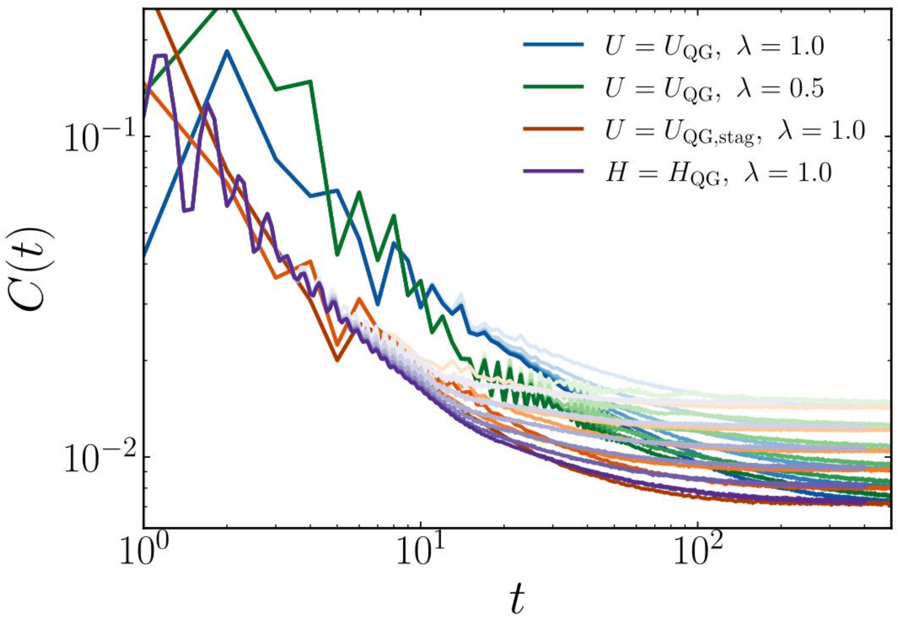


Funny finite size effects

Nevertheless, finite size saturated value appears to be universal:

$$\lim_{t\to\infty} C(t) = f(q, L)$$

What is the value of $f(q, L)$?



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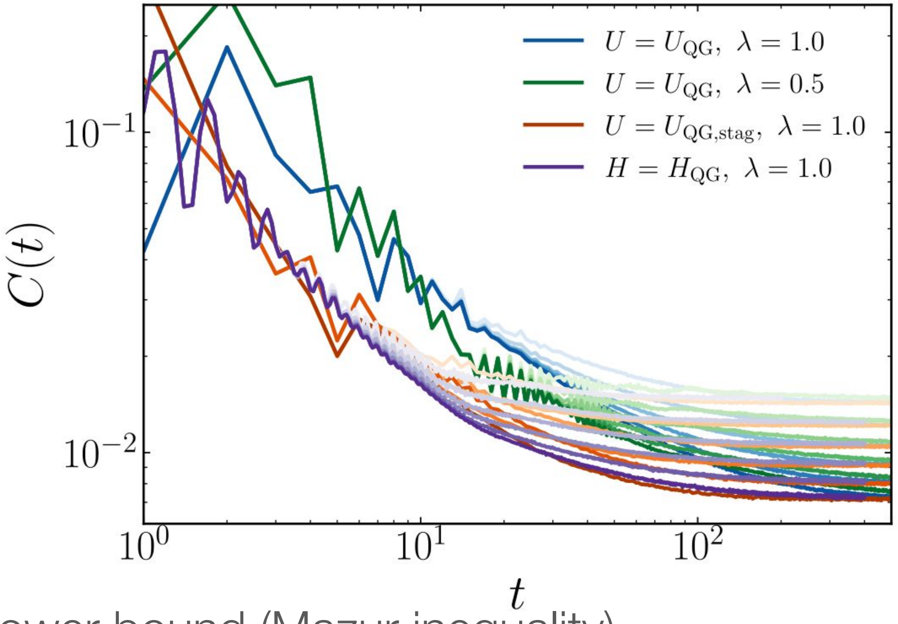

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$$C(\infty) = \lim_{t\to\infty} \langle \sigma_i^+(t)\sigma_i^- \rangle \geq \frac{\langle \sigma^+ Q\rangle \langle Q^\dagger \sigma^- \rangle}{\langle Q^\dagger Q\rangle} \qquad \text{for} \quad [H, Q] = 0$$

Use QG charge $Q = S^{\pm}_{\rm QG} = \sum_i \cdots \otimes q^{\sigma_z} \otimes q^{\sigma_z} \otimes \sigma_i^{\pm} \otimes \mathbb{1} \otimes \mathbb{1} \otimes \cdots$

Find: $C(\infty) \geq \frac{1}{L}\left(\frac{q + q^{-1} + 2}{2(q + q^{-1})}\right)^L$ (interpolates between $1/L$ and 2^{-L})

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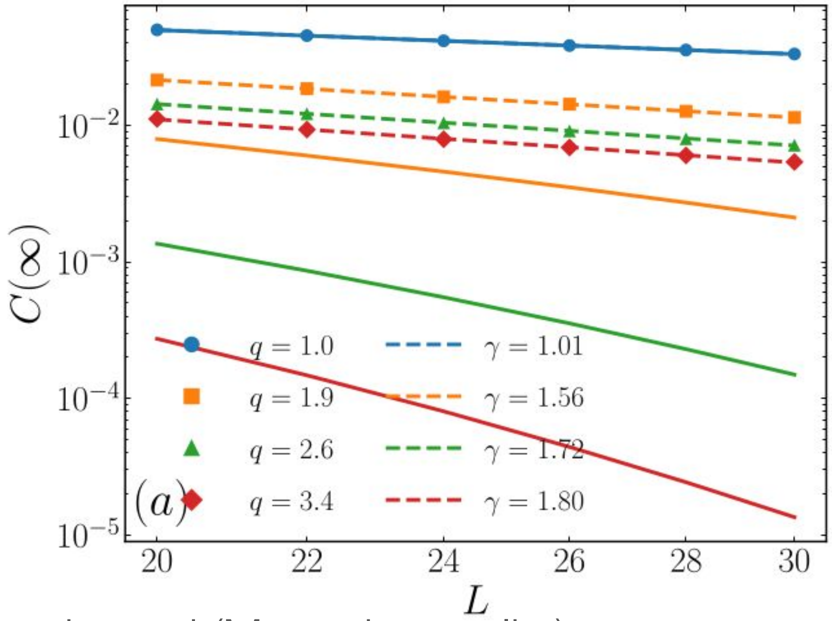

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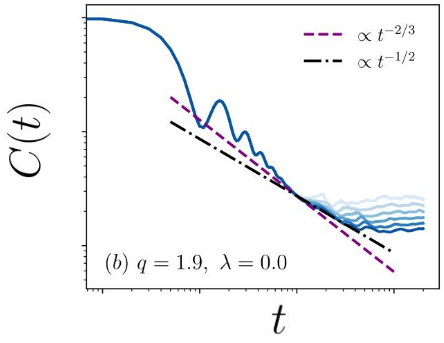
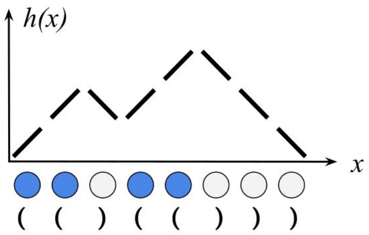
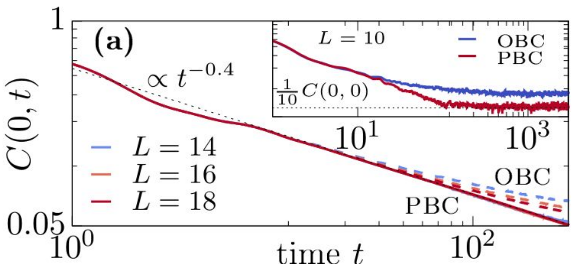
Closing thoughts

$\langle \sigma_i^x(t)\sigma_i^x(0)\rangle$ in XXZ, $\Delta > 1$



- Fluctuating hydrodynamic EFT for QG symmetry?
- Implications of QG symmetry in integrable models (generalized GHD?)
- Similar symmetry in Motzkin/Fredkin chains exhibiting anomalous hydro?





Richter Pal '21
Singh Ware Vasseur Friedman '21
McCarthy Singh Gopalakrishnan Vasseur '25

$1/t^{1/z}$ $\qquad z \sim 5/2$

- QG symmetry – what is it? (Can it emerge? Goldstone theorem? etc.)

Classical model with QG symmetry

Classical Heisenberg model: $H = \frac{1}{2}\sum_i \vec{S}_i \cdot \vec{S}_{i+1}, \qquad |\vec{S}_i| = 1$

thermalizes and has $SU(2)$ symmetry.

One can deform it to obtain model with $U_q(SU(2))$ symmetry, also superdiffusive

$$H = -\sum_{i=1}^{L-1}\left[K_i^{-1/2}\left(E_{i+1}F_i + E_iF_{i+1}\right)K_{i+1}^{1/2} - \frac{1}{\eta\sinh\eta}K_i^{-1}K_{i+1} + \frac{1}{\eta\tanh\eta}(K_i^{-1} + K_{i+1})\right]$$

$$K_j = e^{\eta S_j^z},\ \ E_j = f(S_j^z)S_j^+,\ \ F_j = \frac{-\eta}{\sinh\eta}f(S_j^z)S_j^-$$