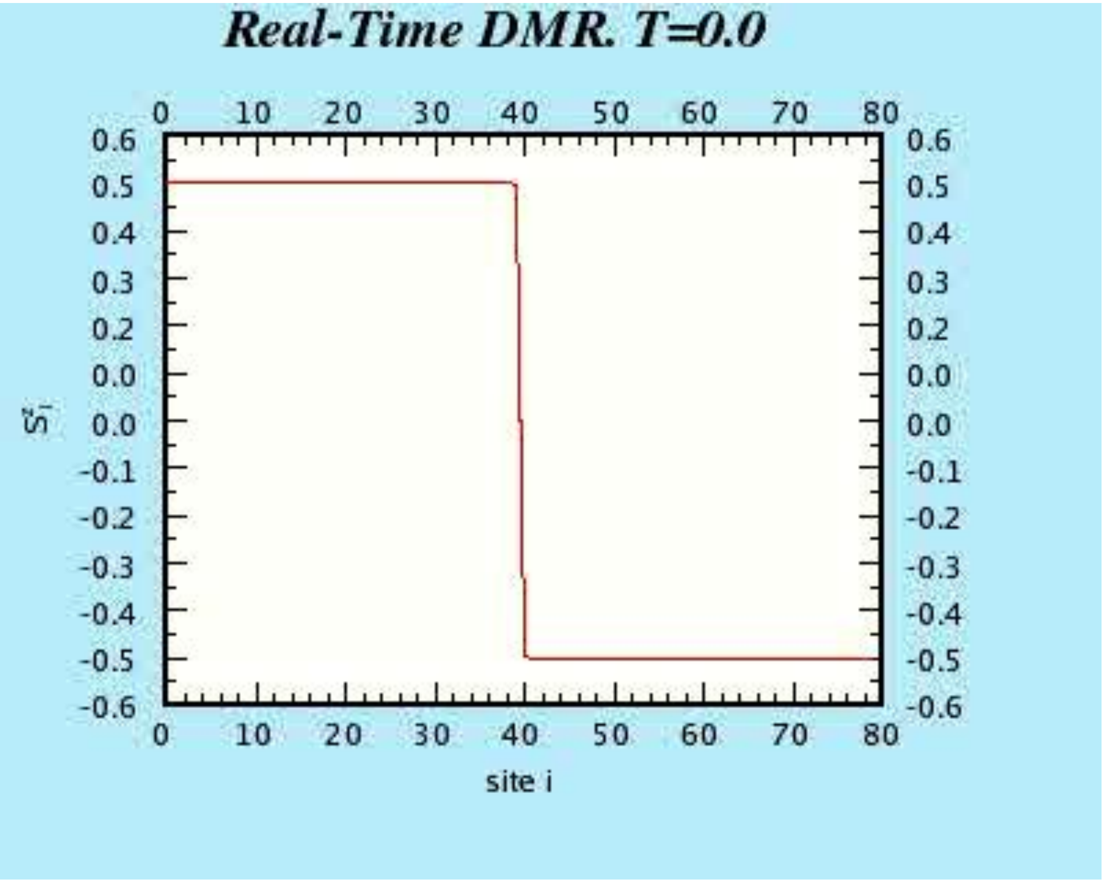
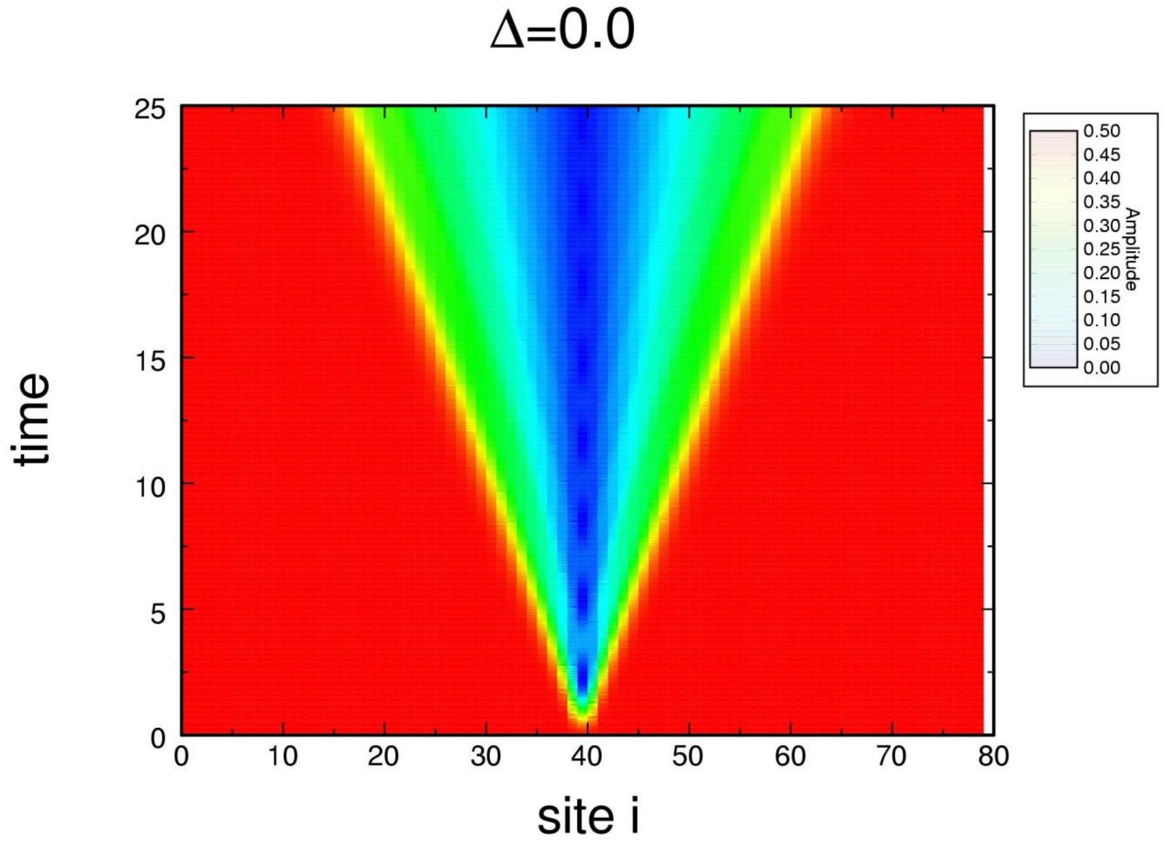
Spin transport

Example: half polarized spin S=1/2 chain



Spin transport

Example: half polarized spin S=1/2 chain



The enemy: Entanglement growth

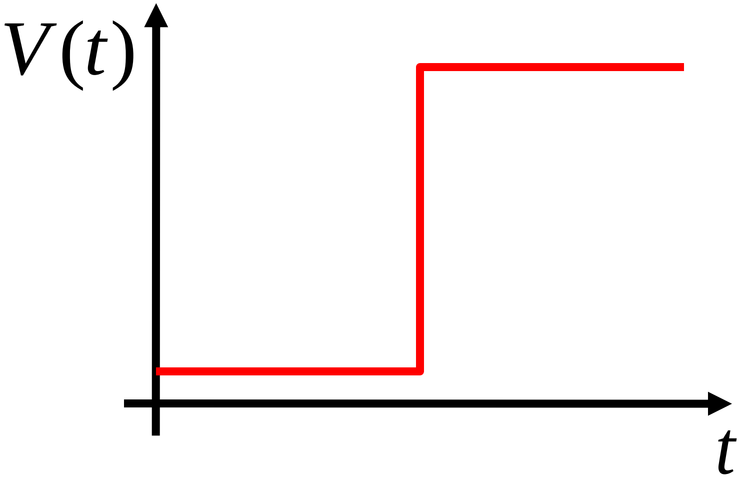
We have seen that the truncation error, or the number of state that we need to keep to control it, depends fundamentally on the entanglement

$$S = S(t)$$

We need to understand this behavior if we want to learn how to fight it!

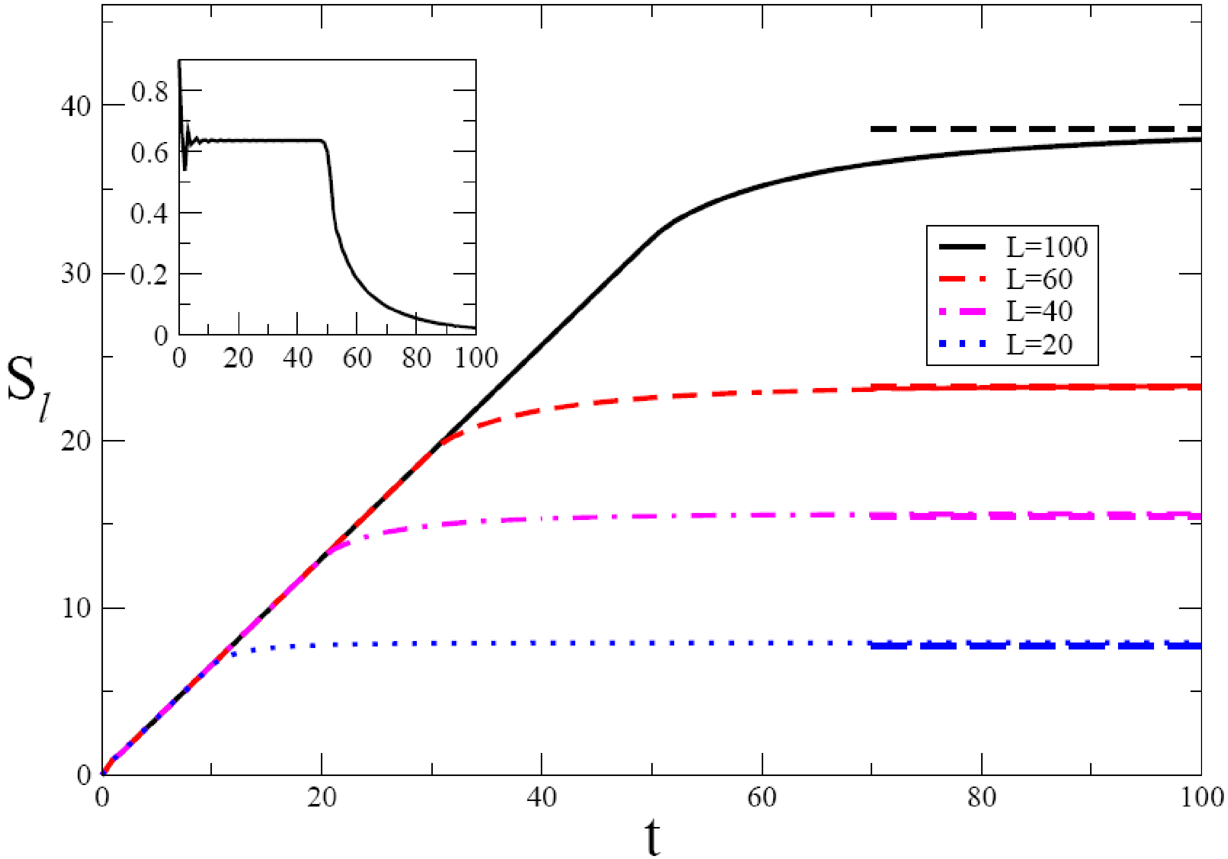
Possible scenarios:

- Global quench
- Local quench
- Periodic quench
- Adiabatic quench
- …



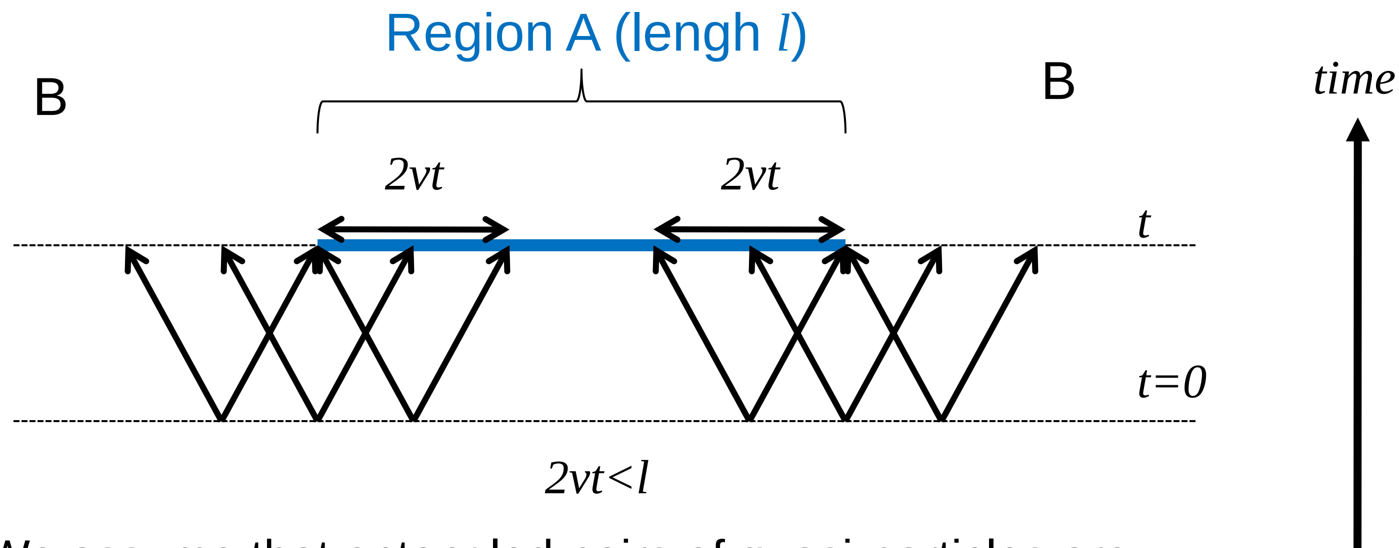
All of a sudden, we are no longer in the ground-state, but some high energy state. Important questions: thermalization vs. integrability

E-growth: global quench



Calabrese and Cardy, JStatM (05)

Global quench: qualitative picture

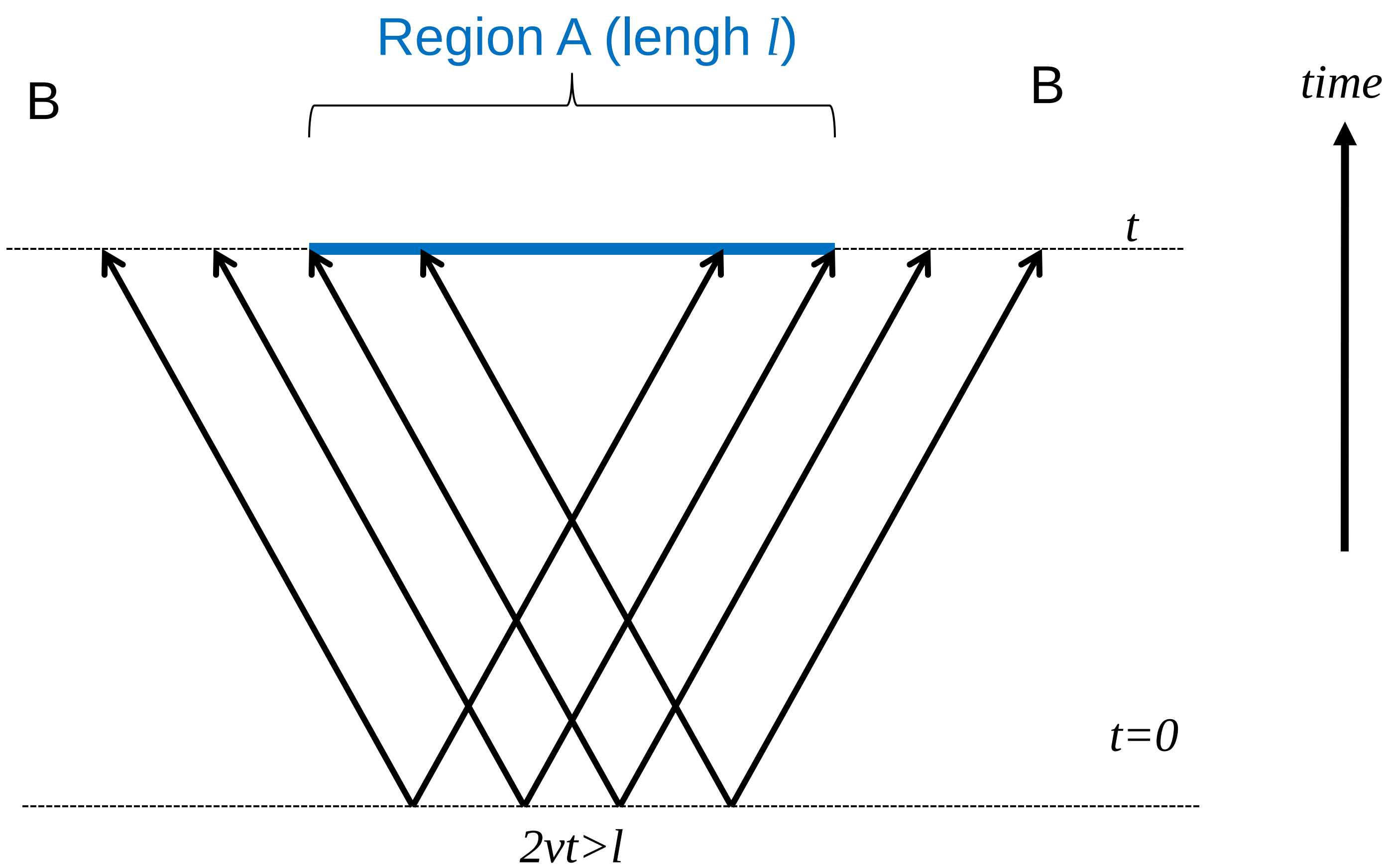


We assume that entangled pairs of quasi-particles are created at t=0, and they propagate with maximum velocity

$$\Rightarrow S = S_0 + ct$$

Calabrese and Cardy, JStatM (05)

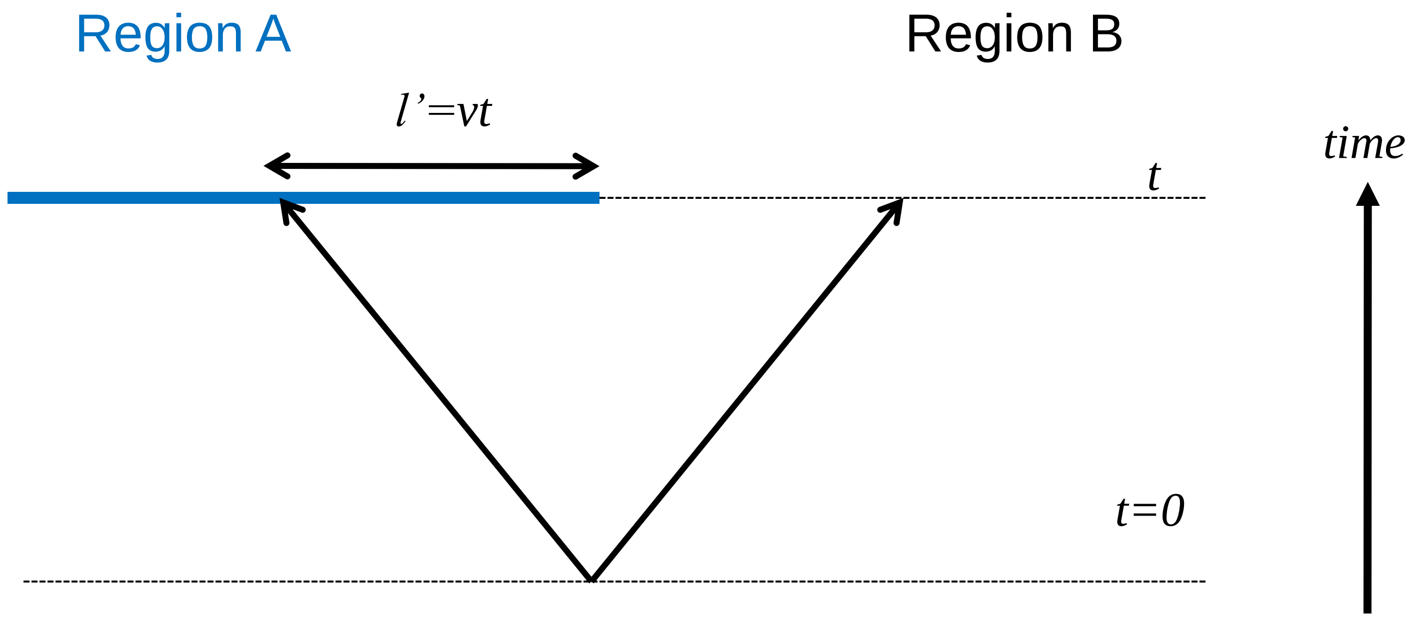
Global quench: qualitative picture



The number of entangled pairs saturates

Calabrese and Cardy, JStatM (05)

Local quench: qualitative picture



The perturbation propagates from the center, splitting the system into two pieces, inside and outside of the light-cone

$$\Rightarrow S = S_0 + c'\log(l') = S_0 + c'\log(t)$$

Calabrese and Cardy, JStatM (07)

Computational cost

Global quench:

$$S \approx ct \rightarrow m \approx \exp(S) = \exp(ct)$$

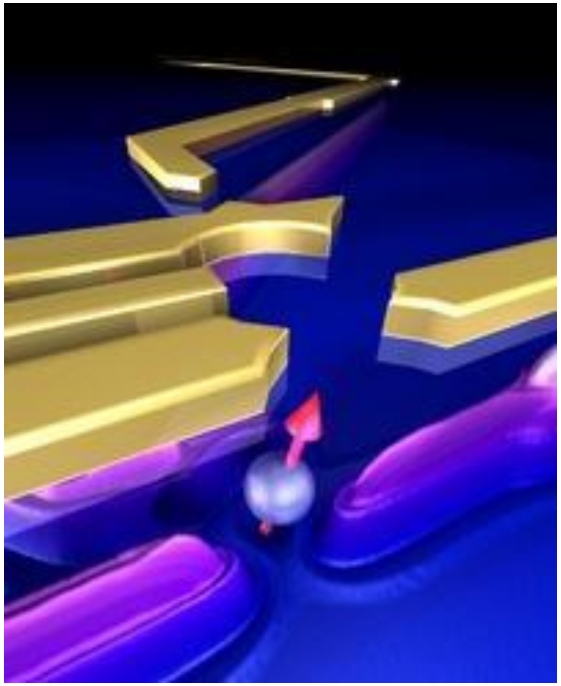
Local quench:

$$S \approx \log(t) \rightarrow m \approx \exp(S) = t^{\text{const.}}$$

Adiabatic quench:

$$S \approx \text{const.} \rightarrow m \approx \text{const.}$$

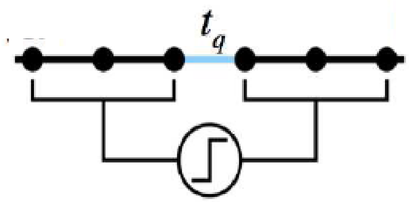
Transport and systems out of equilibrium



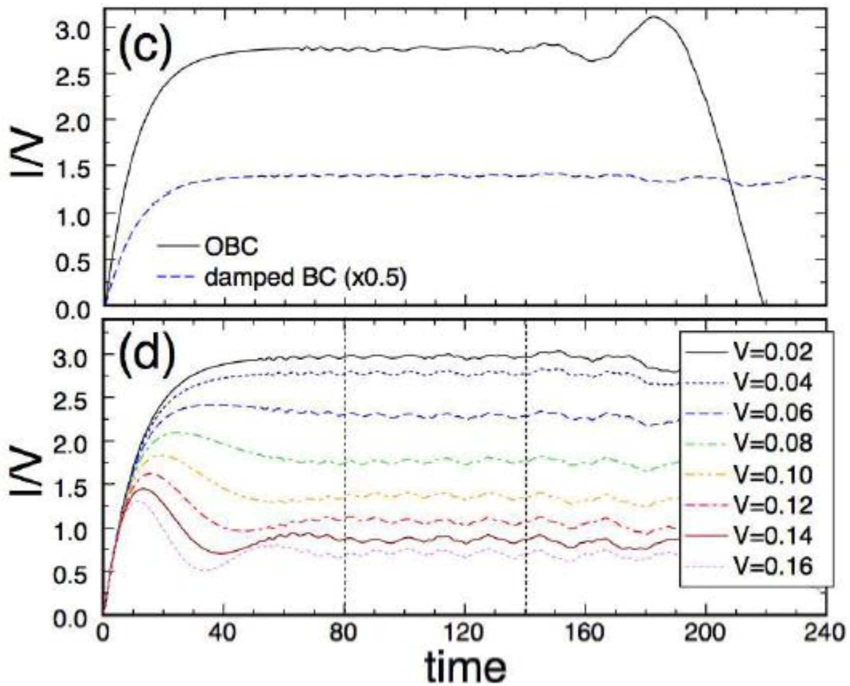
References: PRB **78**, 195317 (2008); PRA **78**, 013620 (2008) ; PRL **100**, 166403 (2008) ; PRB **73**, 195304 (2006); New. J. of Phys (2010)

Thanks to: F. Heidrich-Meisner, K. Al-Hassanieh, C. Busser, G. Martins, E. Dagotto, L. Da Silva, E. Anda

Example: transport in 1d



Spinless fermions with interactions.

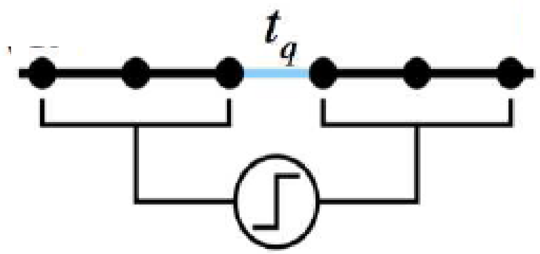


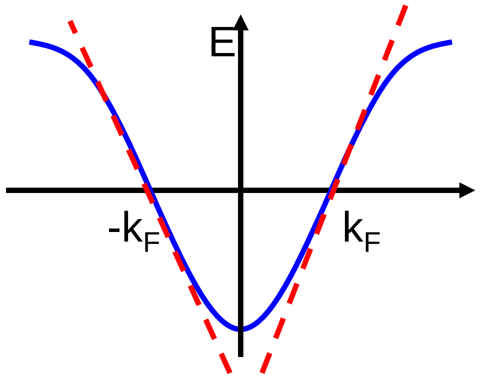
Typical behavior:

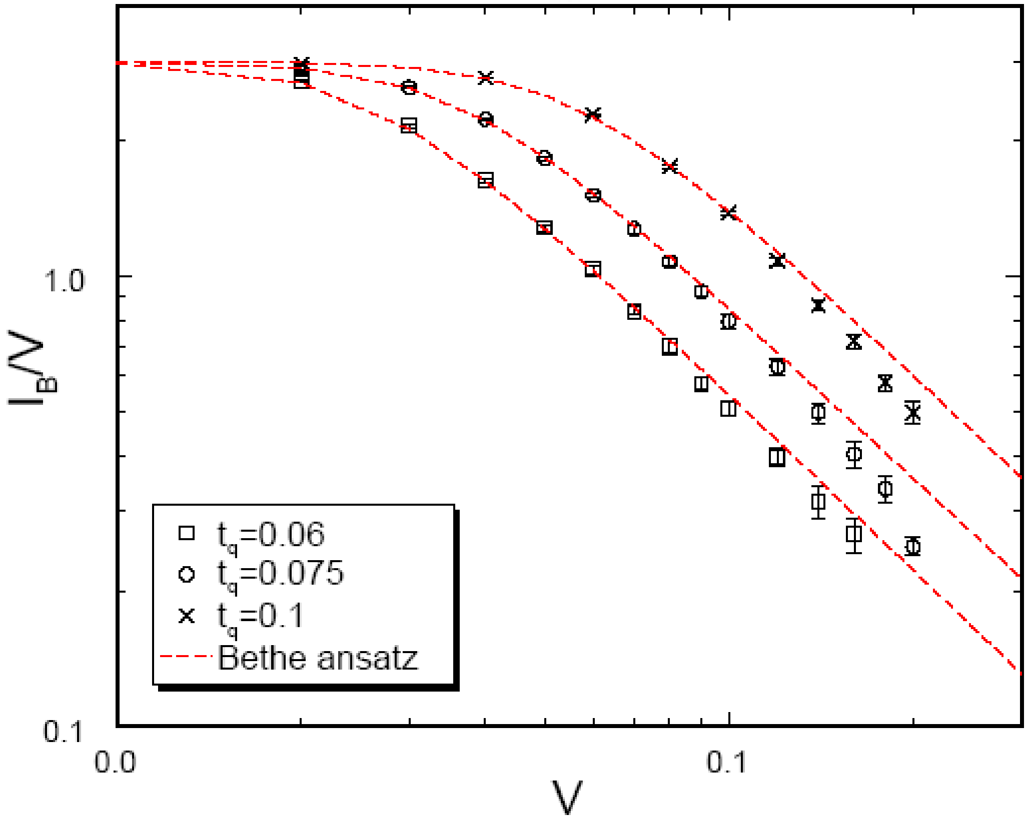
1) Short time transient
2) Plateau (we measure!)
3) Reflection at the boundaries. Current changes sign.

AEF, P. Fendley, MPA Fisher, C. Nayak, PRL08

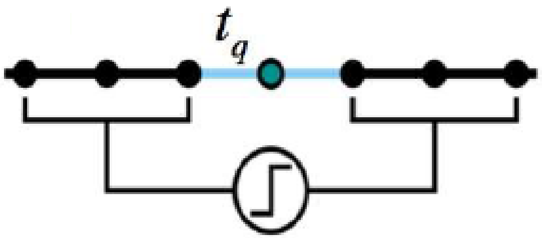
Weak link / potential barrier

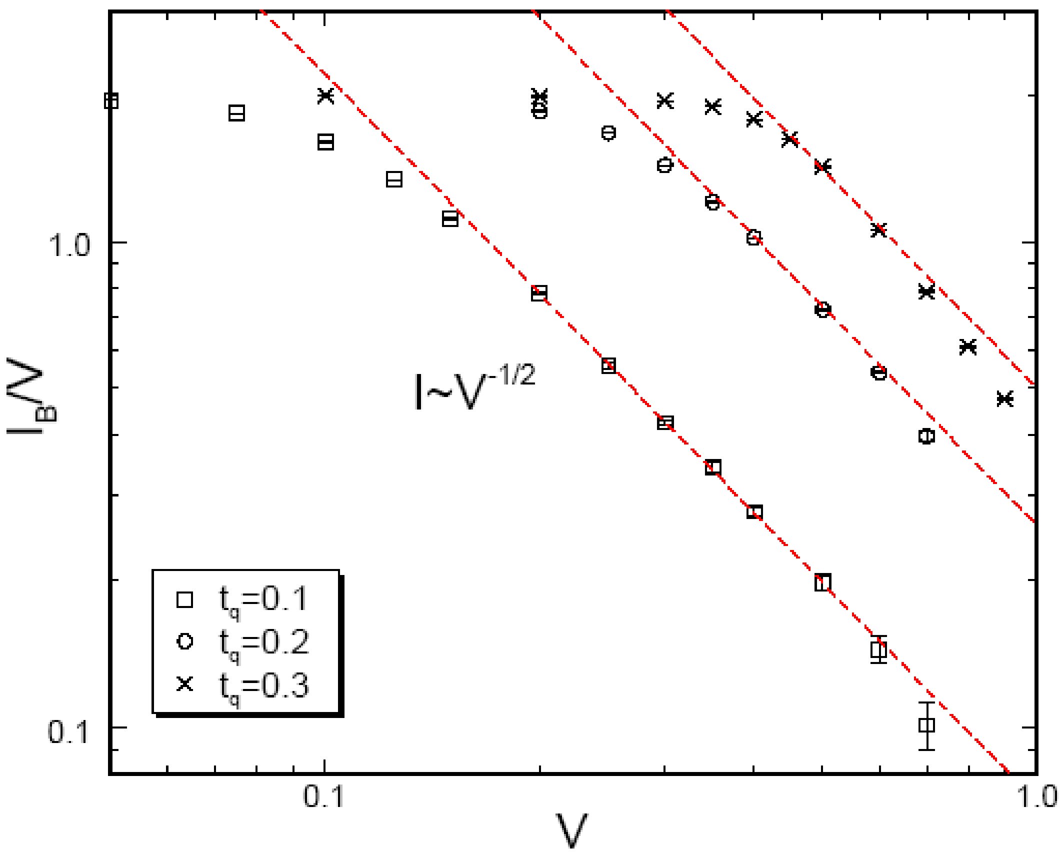






Resonant level / double barrier

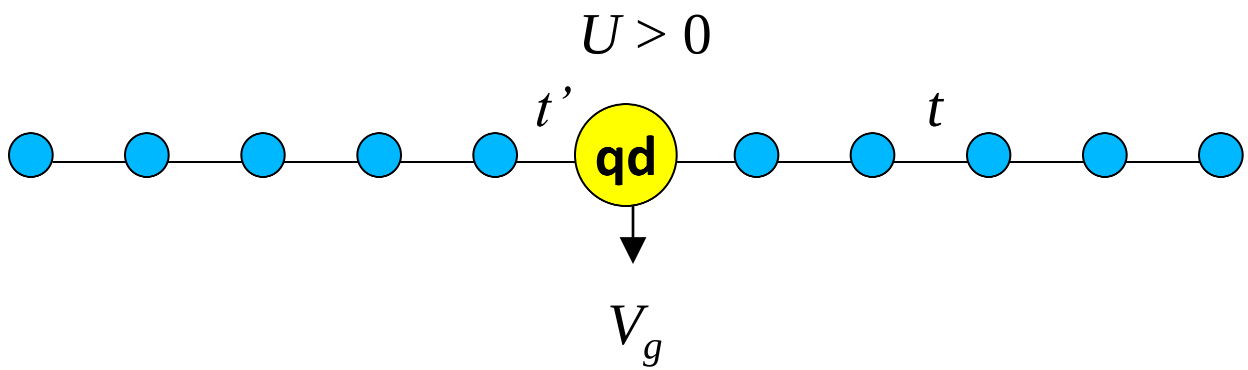


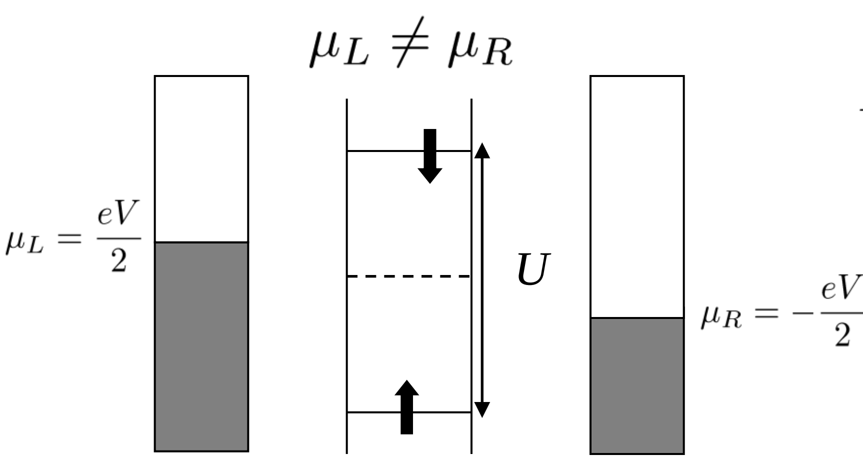


Quantum dots

Quantum dot attached to two leads:

single-level Anderson model



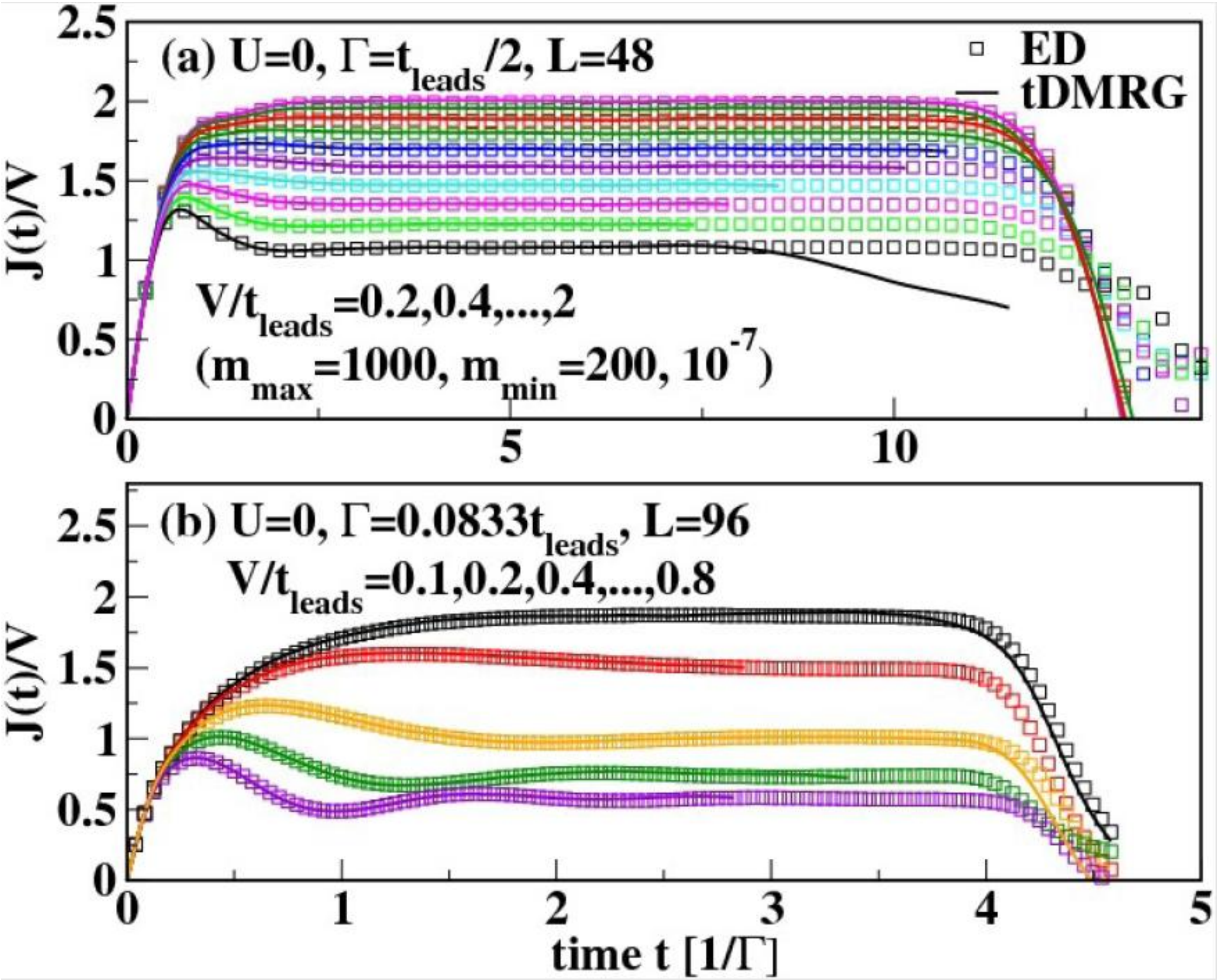


$$H = \sum_{k\alpha\sigma} \varepsilon_k c^\dagger_{k\alpha\sigma} c_{k\alpha\sigma} + \sum_\sigma \epsilon_d n_\sigma + U n_\uparrow n_\downarrow$$

$$+ \sum_{k\alpha\sigma} \left(V_{k\alpha\sigma} c^\dagger_{k\alpha\sigma} d_\sigma + \text{h.c.} \right)$$

$$\alpha = L,\ R$$

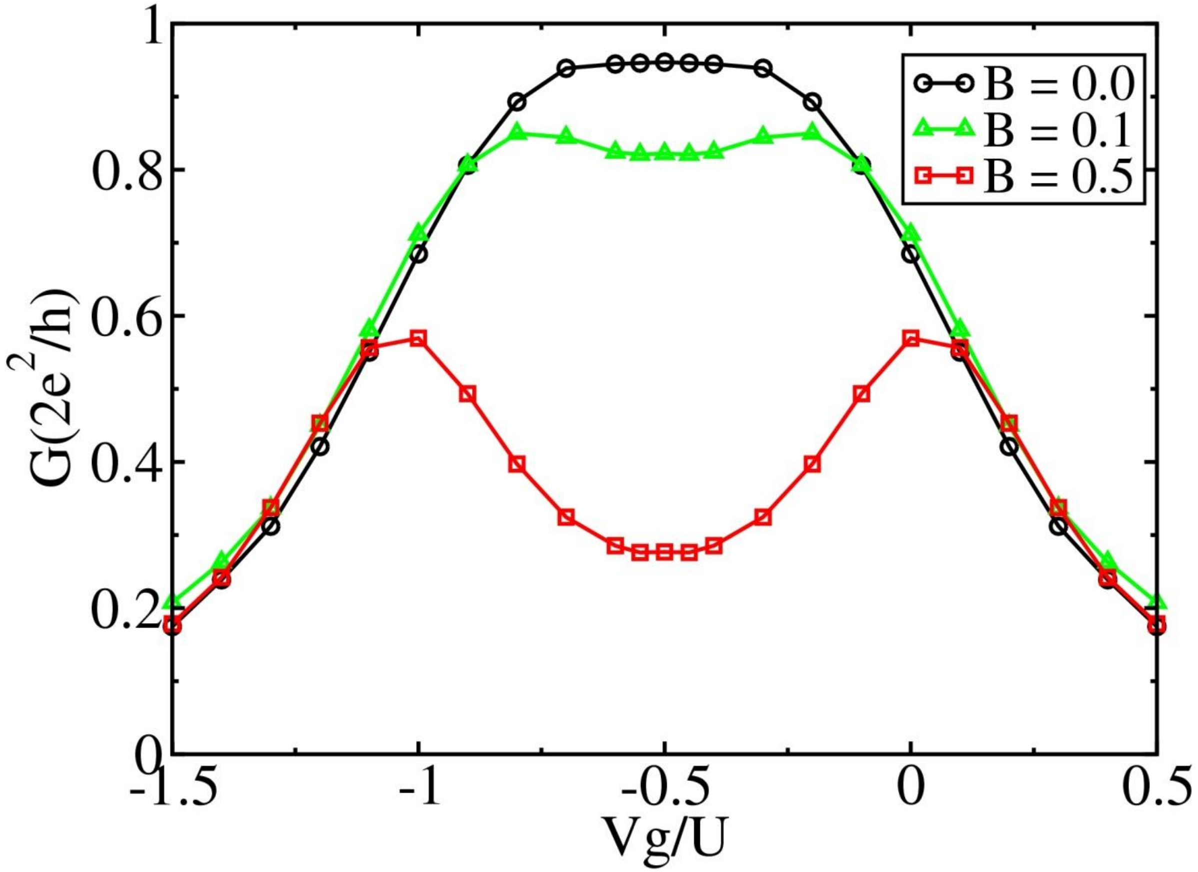
Non-interacting limit (U=0)



F. Heidrich-Meisner, AEF, E. Dagotto, PRB (09)

tDMRG Results for 1 dot

Kondo Effect and magnetic field

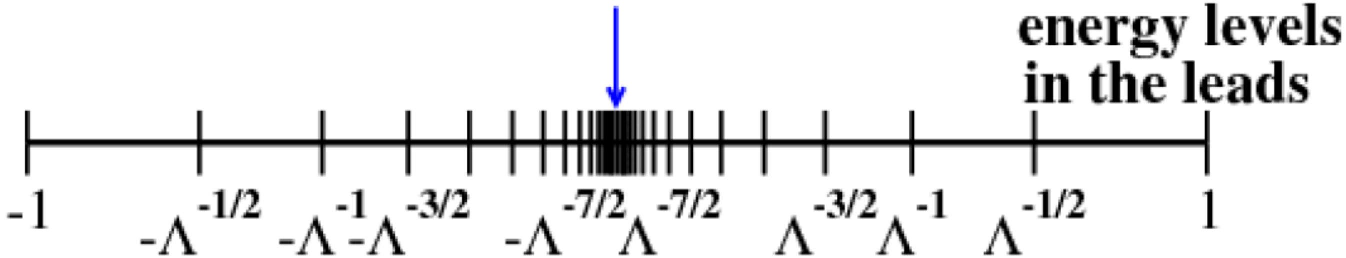


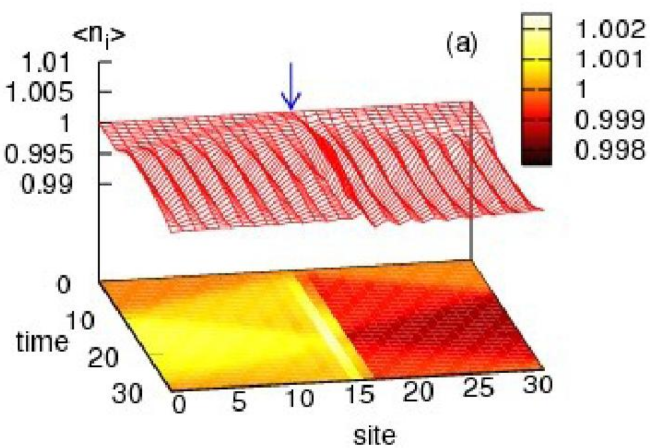
Suppression of Kondo effect: Coulomb Blockade peaks are formed

Accessing the Kondo regime

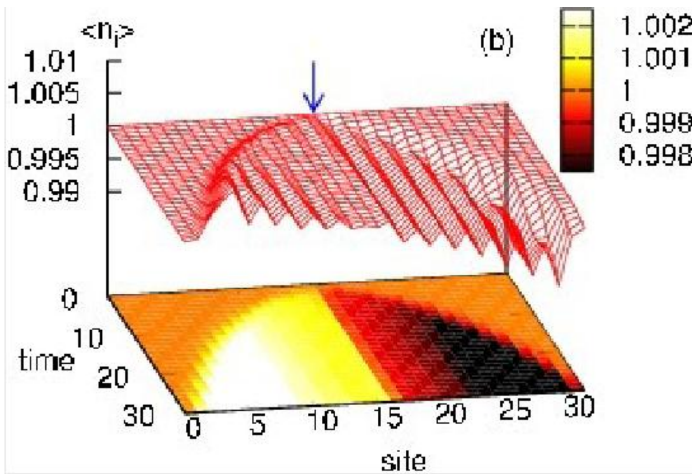
Wilson leads: $t_l = \Lambda^{-l/2} \quad (\Lambda > 1)$

good resolution at the Fermi energy





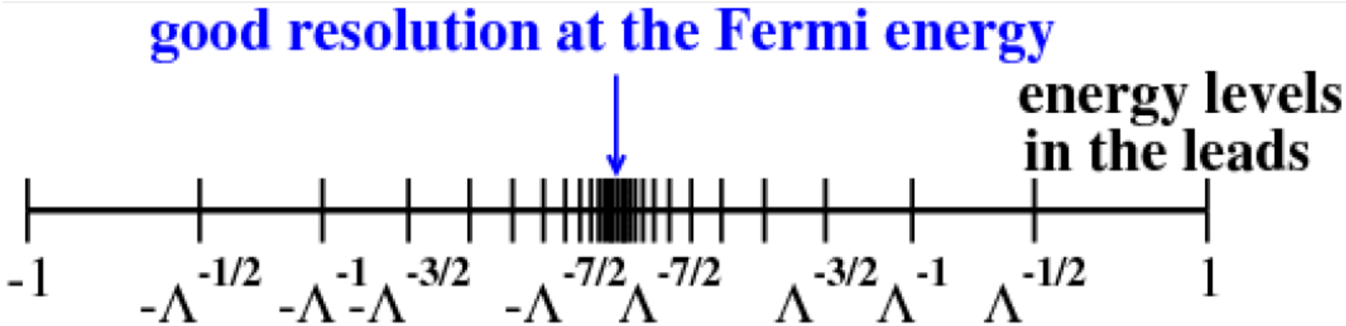
$\Lambda = 1$

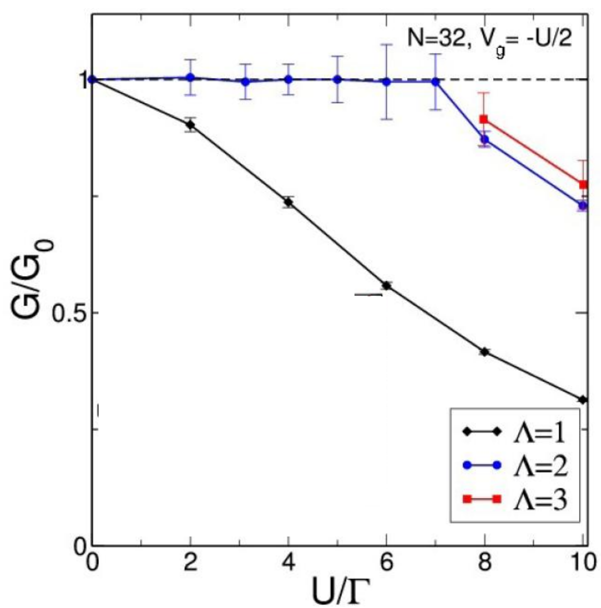


$\Lambda > 1$

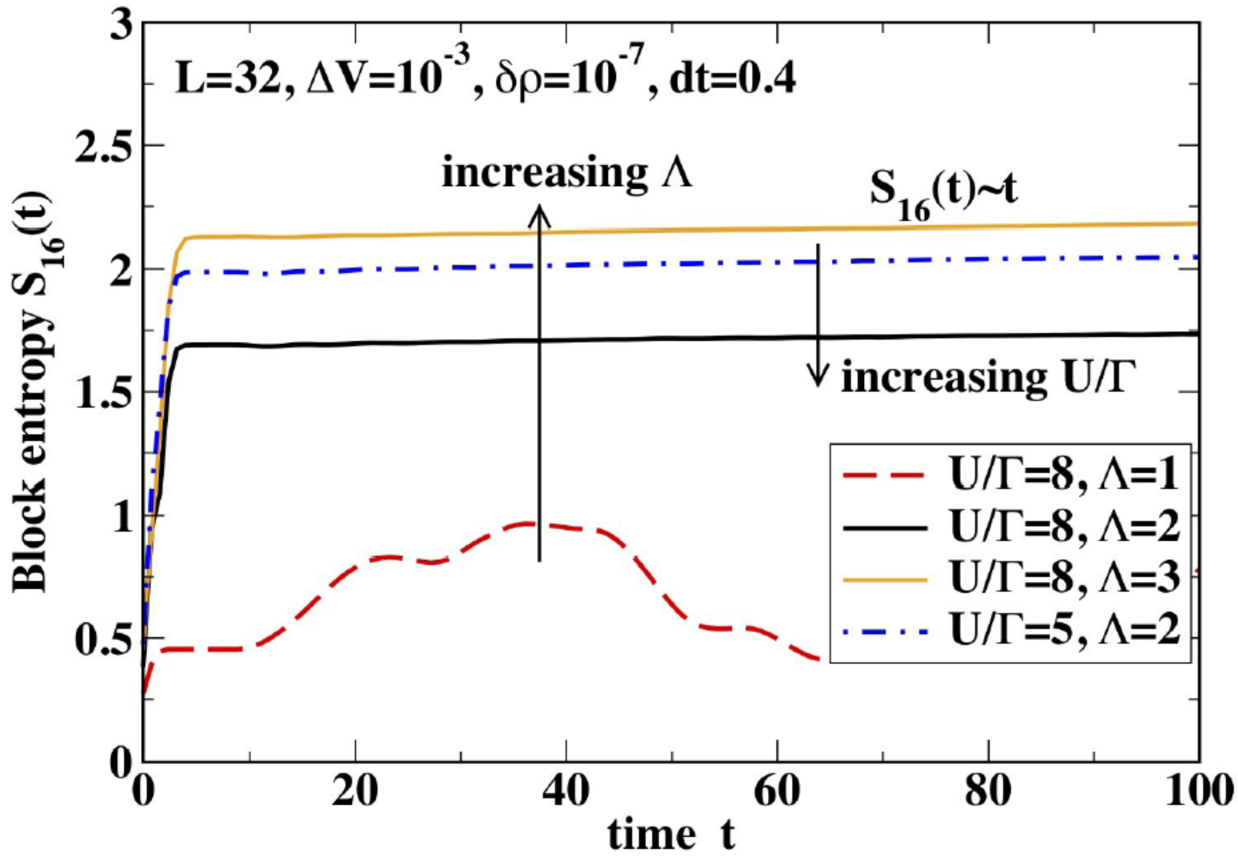
Accessing the Kondo regime

Wilson leads: $t_l = \Lambda^{-l/2} \quad (\Lambda > 1)$

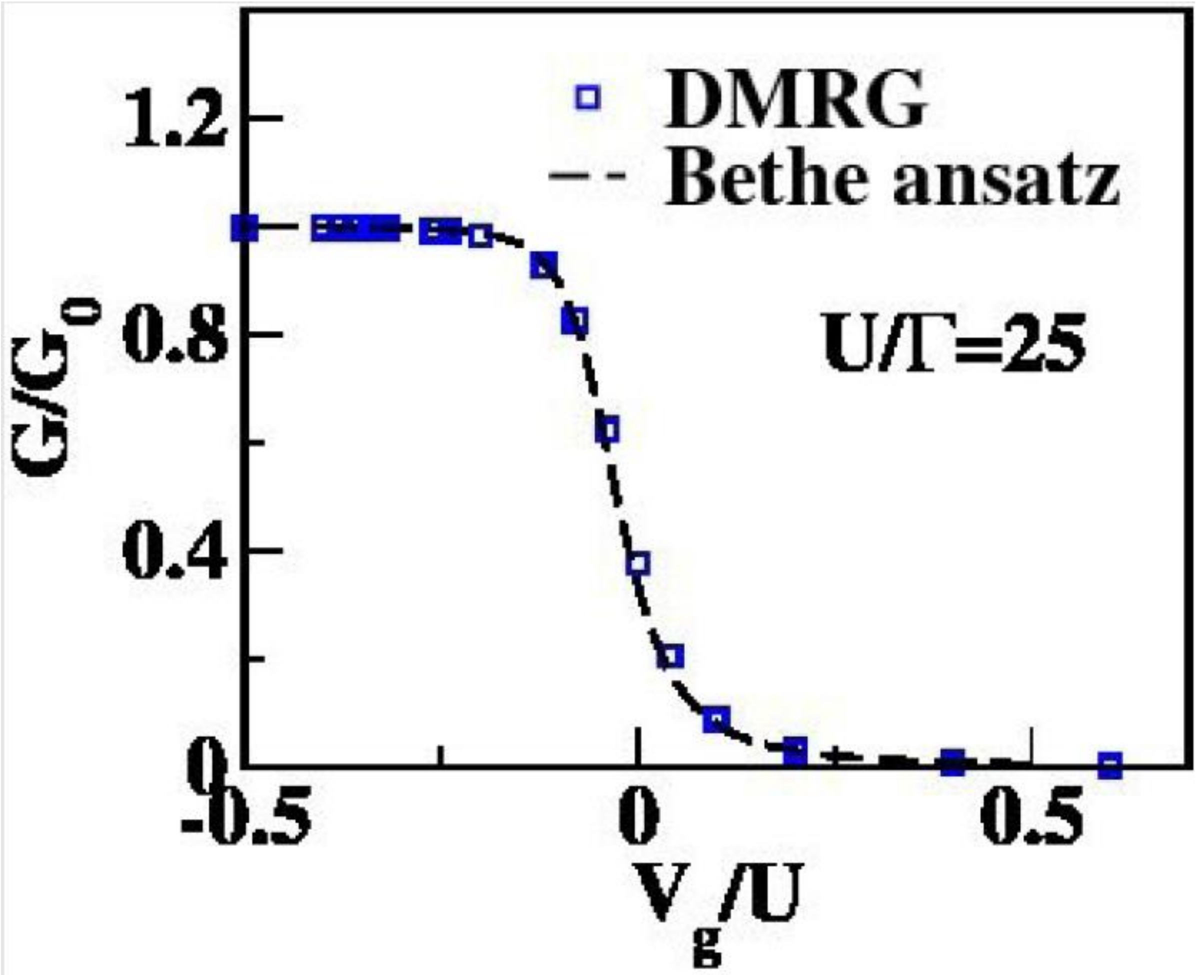




Entropy growth with Wilson leads



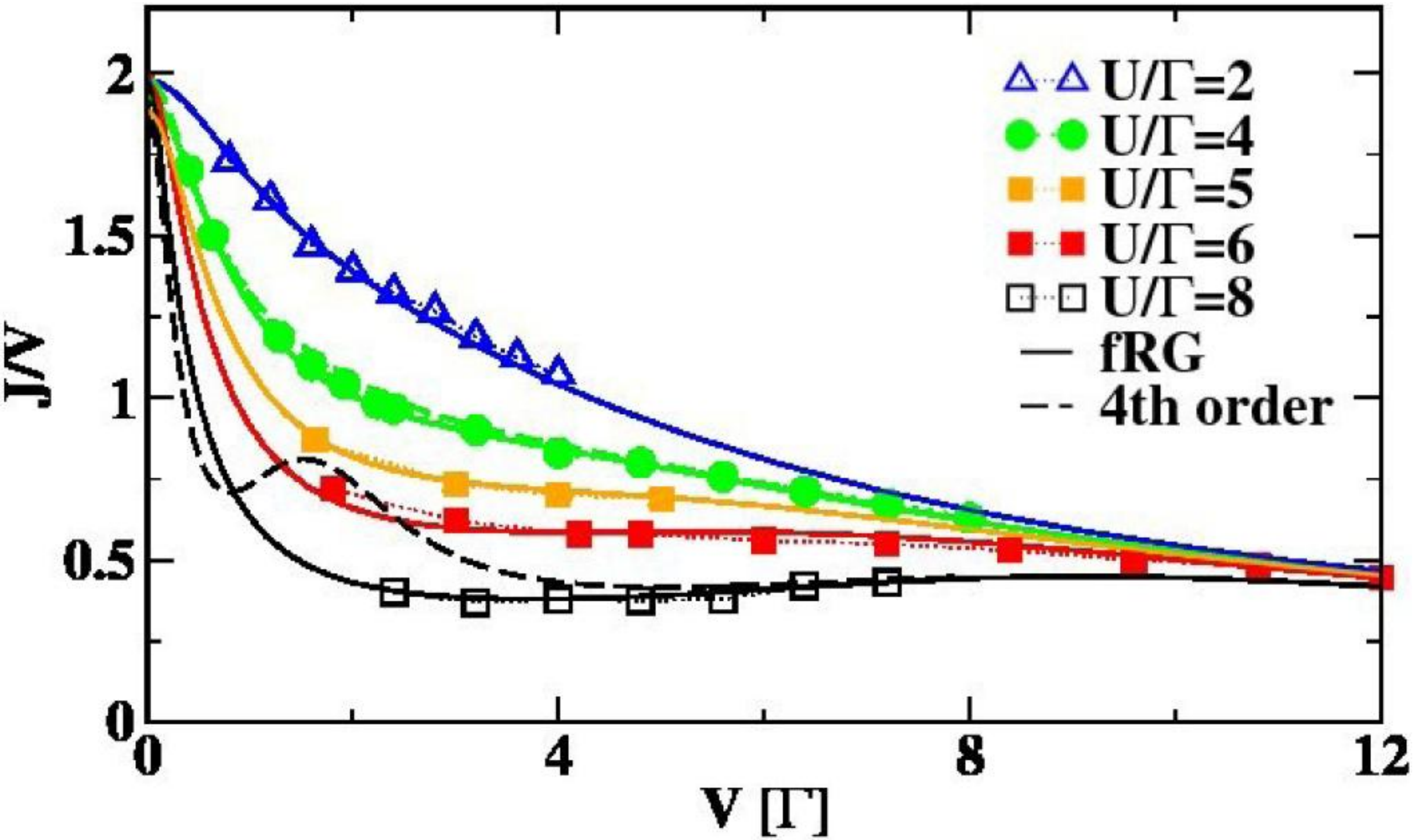
DMRG vs. Bethe Ansatz



F. Heidric-Meisner et al, EPJB (09), N. Andrei, PRL (80), Gerland et al. PRL (00)

I-V characteristics

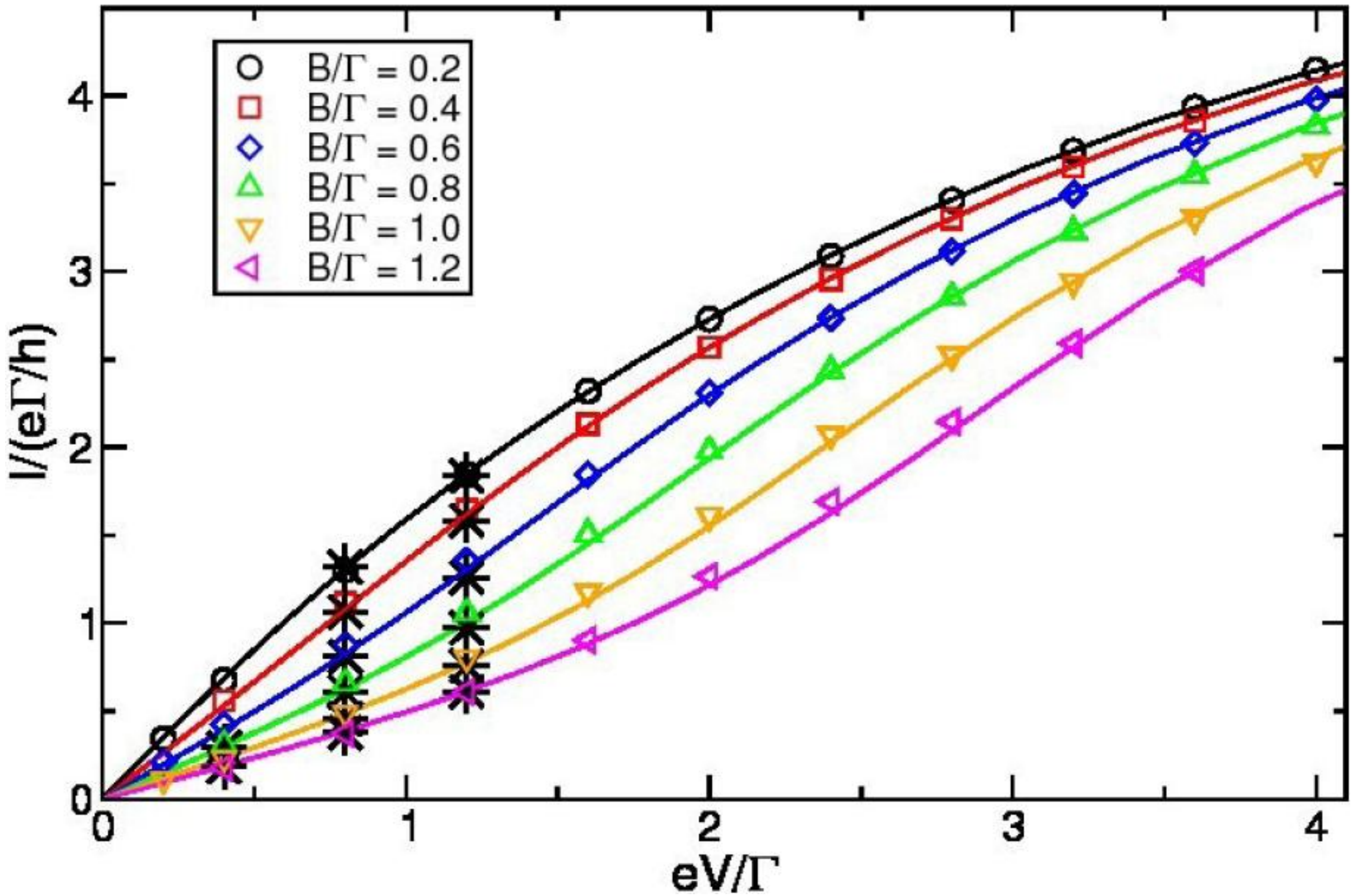
Particle-hole symmetric point (V_g=-U/2)



F. Heidrich-Meisner, AEF, E. Dagotto, PRB 2009.

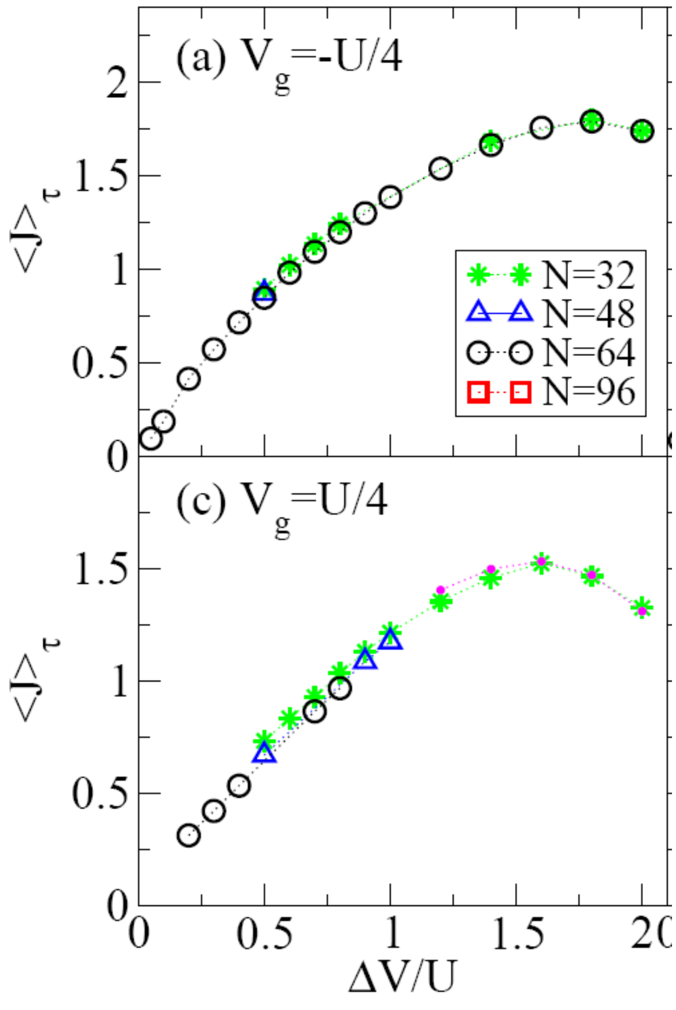
I-V characteristics

Finite magnetic field



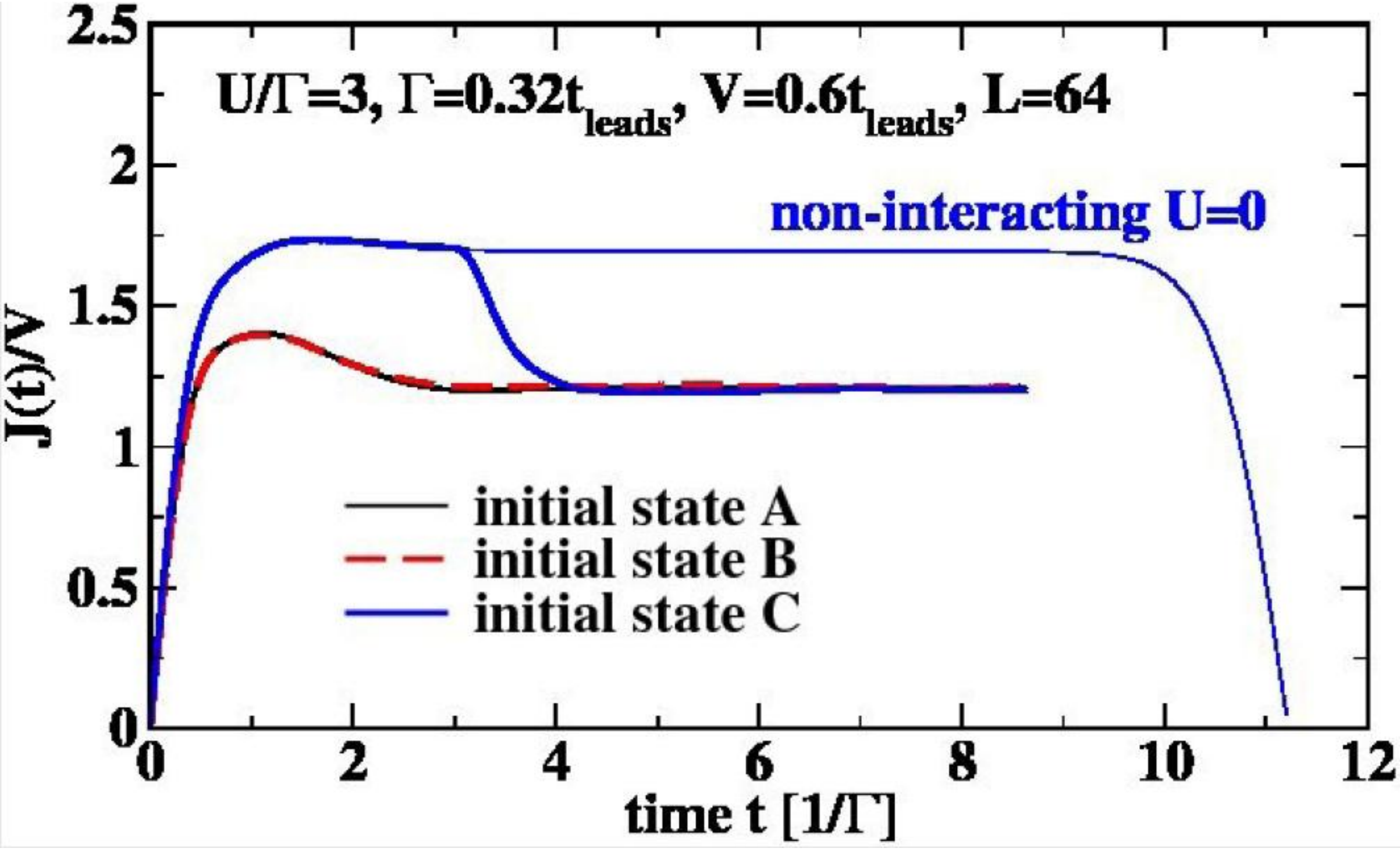
Eckel, F. Heidrich-Meisner, Jakobs, Thorwart, Pletyukhov, Egger, NJP (10)

Large bias – out of equilibrium

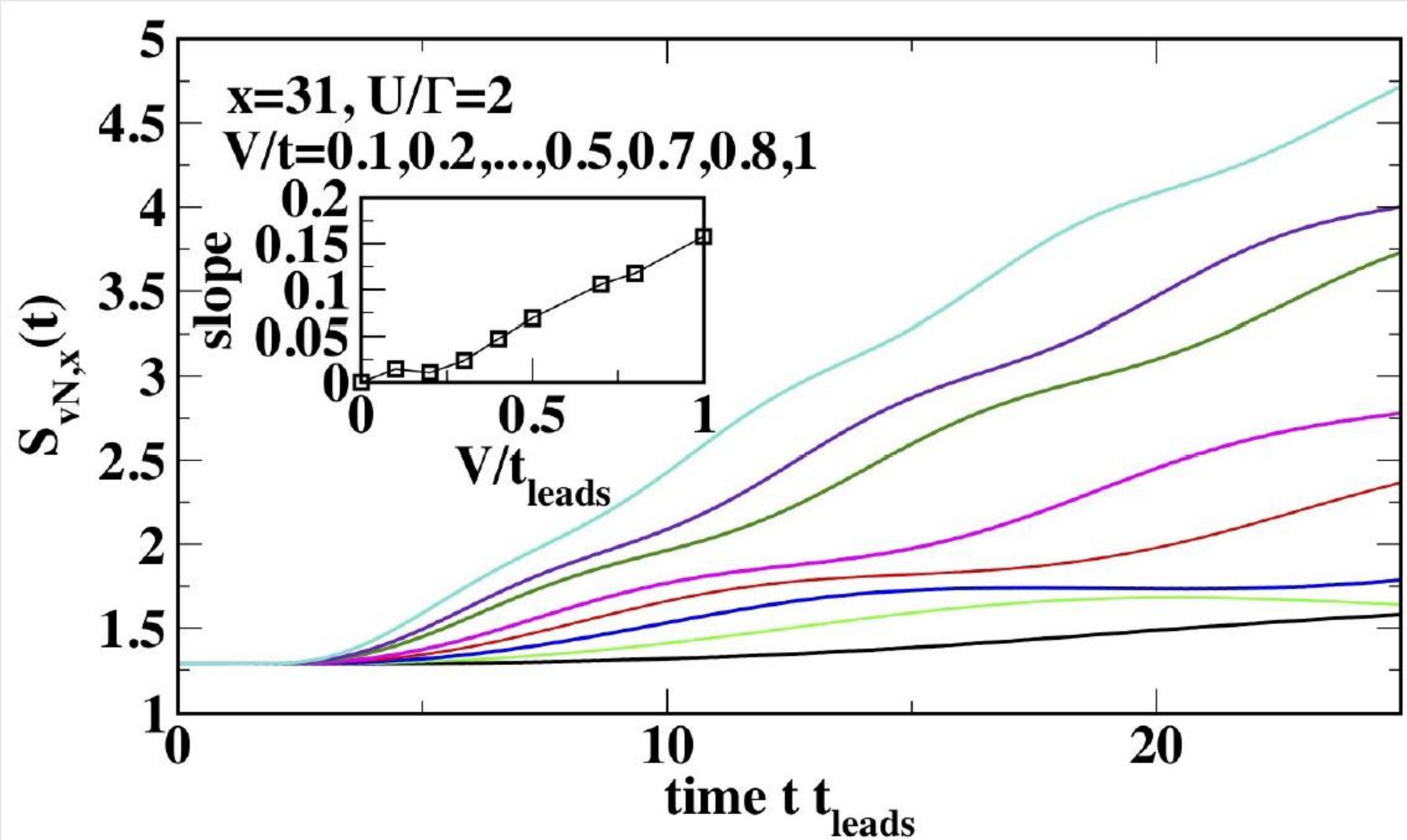


F. Heidrich-Meisner, AEF, E. Dagotto, PRB (09)

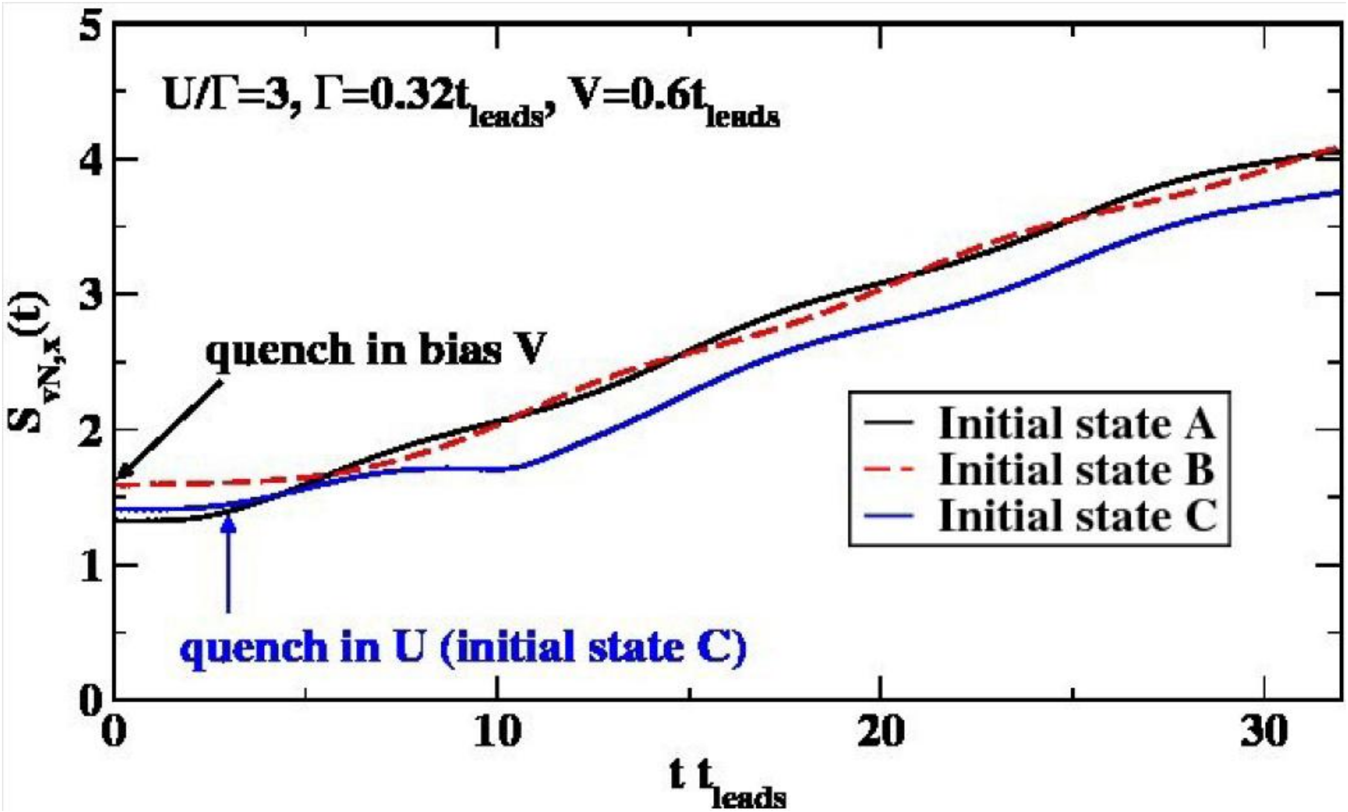
Dependence on the initial state



Computational cost and entropy growth



Computational cost and initial conditions



Entanglement entropy grows linearly in time, once the steady state is reached.