Creating a massive minimal uncertainty wavepacket using Gross-Pitaevskii breathers

Maxim Olshanii (Olchanyi) (UMass Boston)
UMass Boston: Vanja Dunjko, Joanna Ruhl, Jacob Golde
Tel Aviv U: Boris A. Malomed, Vladimir A. Yurovsky, Oleksandr V. Marchukov
Alliance U: Sumita Datta
Rice U: De Luo, Yi Jin, Jason H. V. Nguyen, Sehyun Park, Eva Jin, Ricardo Espinoza
Randall G. Hulet

Atomtronics 2022

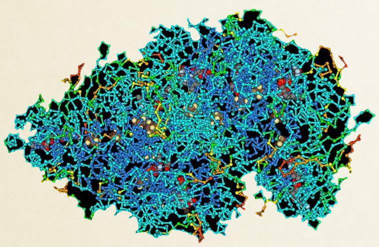
NSF

BSF
United States – Israel
Binational Science Foundation

Why solitons are good for macroscopic coherence

Quantum coherence with macroscopic objects

large molecules



photons

decoherence

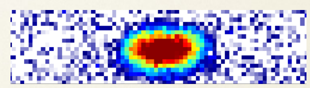
rotational excitations

ground state

gap to excitations $\sim \frac{\hbar^2}{I} \sim \frac{\hbar^2 n^{2/3}}{m} \frac{1}{N^{5/3}}$

Anton Zeilinger, Markus Arndt, ...

integrable bosonic solitons



atoms

decoherence

delocalized Bogoliubov excitations

gap to excitations $\sim \frac{mg}{\hbar^2} N^2 \lesssim \hbar\omega_\perp$

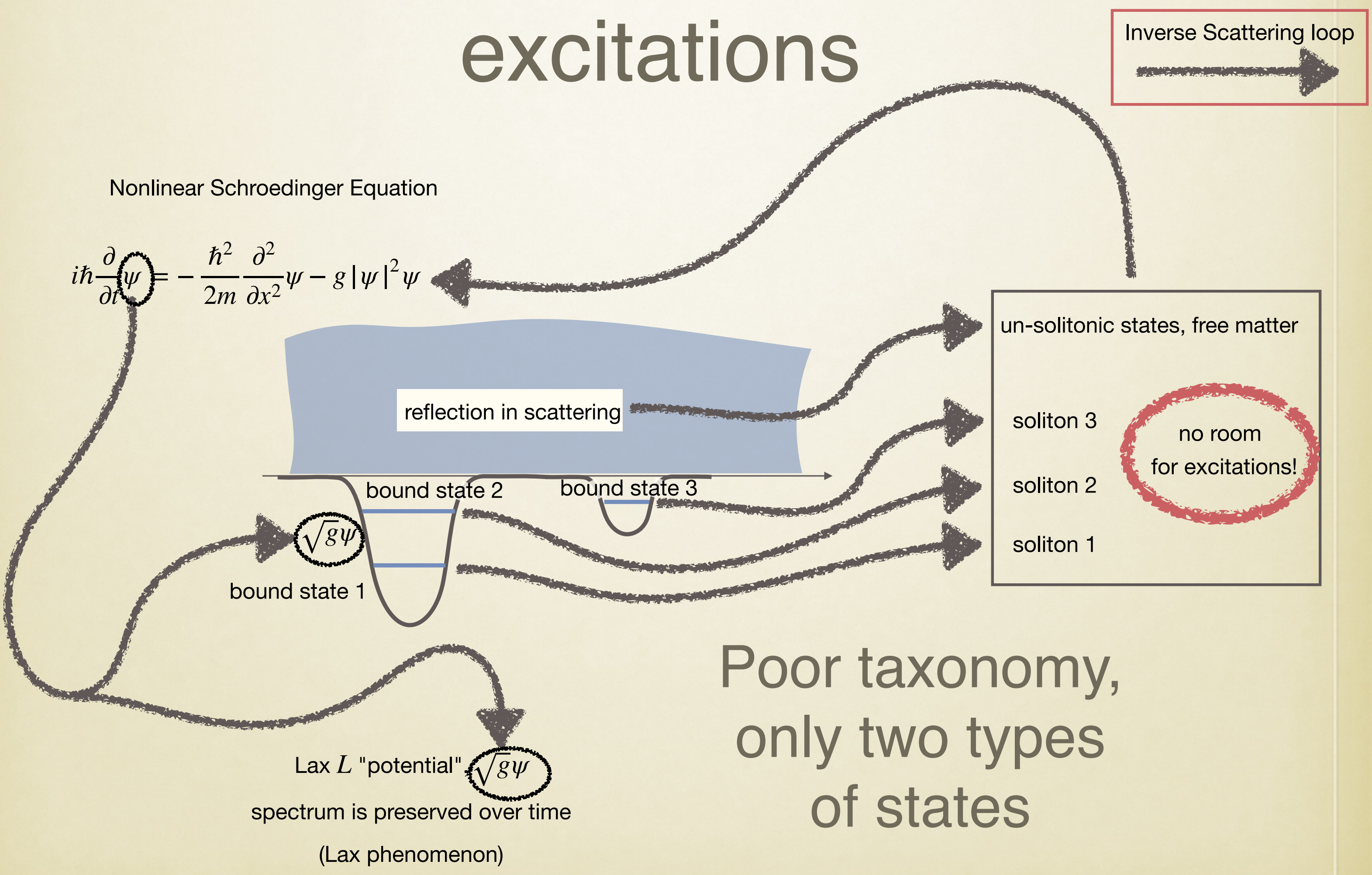
no localized excitations

ground state

This proposal

Why don't solitons have localized excitations?

Why solitons have no localized excitations



Q: But the center-of-mass is still hot, isn't it?

Q: But the center-of-mass is still hot, isn't it?

A: True, but we will use the relative motion of two solitons

Q: But the center-of-mass is still hot, isn't it?

A: True, but we will use the relative motion of two solitons

Q: Still hot

Q: But the center-of-mass is still hot, isn't it?

A: True, but we will use the relative motion of two solitons

Q: Still hot

A: We will create a relatively cold soliton-soliton pair in an implosion

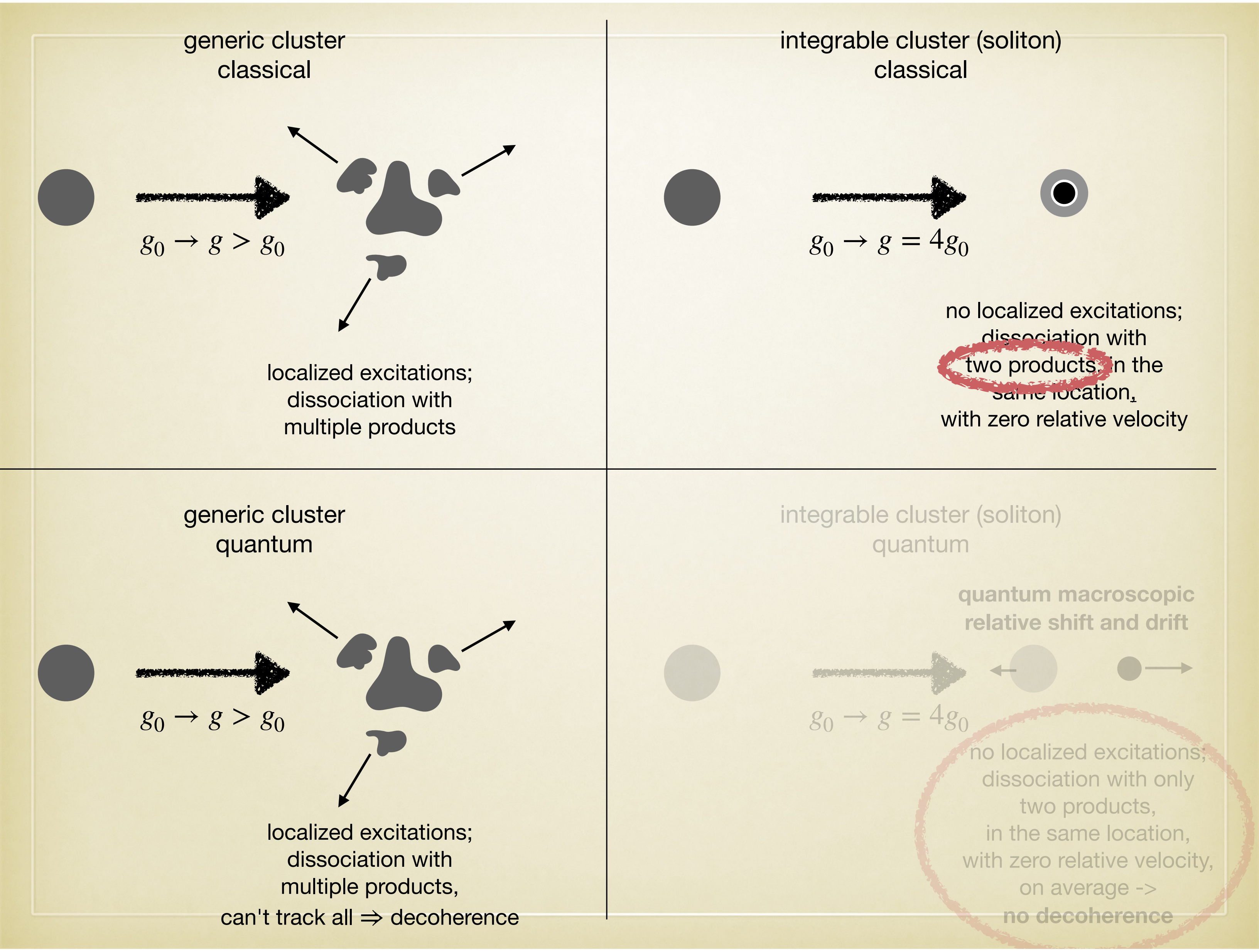
Q: But the center-of-mass is still hot, isn't it?

A: True, but we will use the relative motion of two solitons

Q: Still hot

A: We will create a relatively cold soliton-soliton pair in an implosion

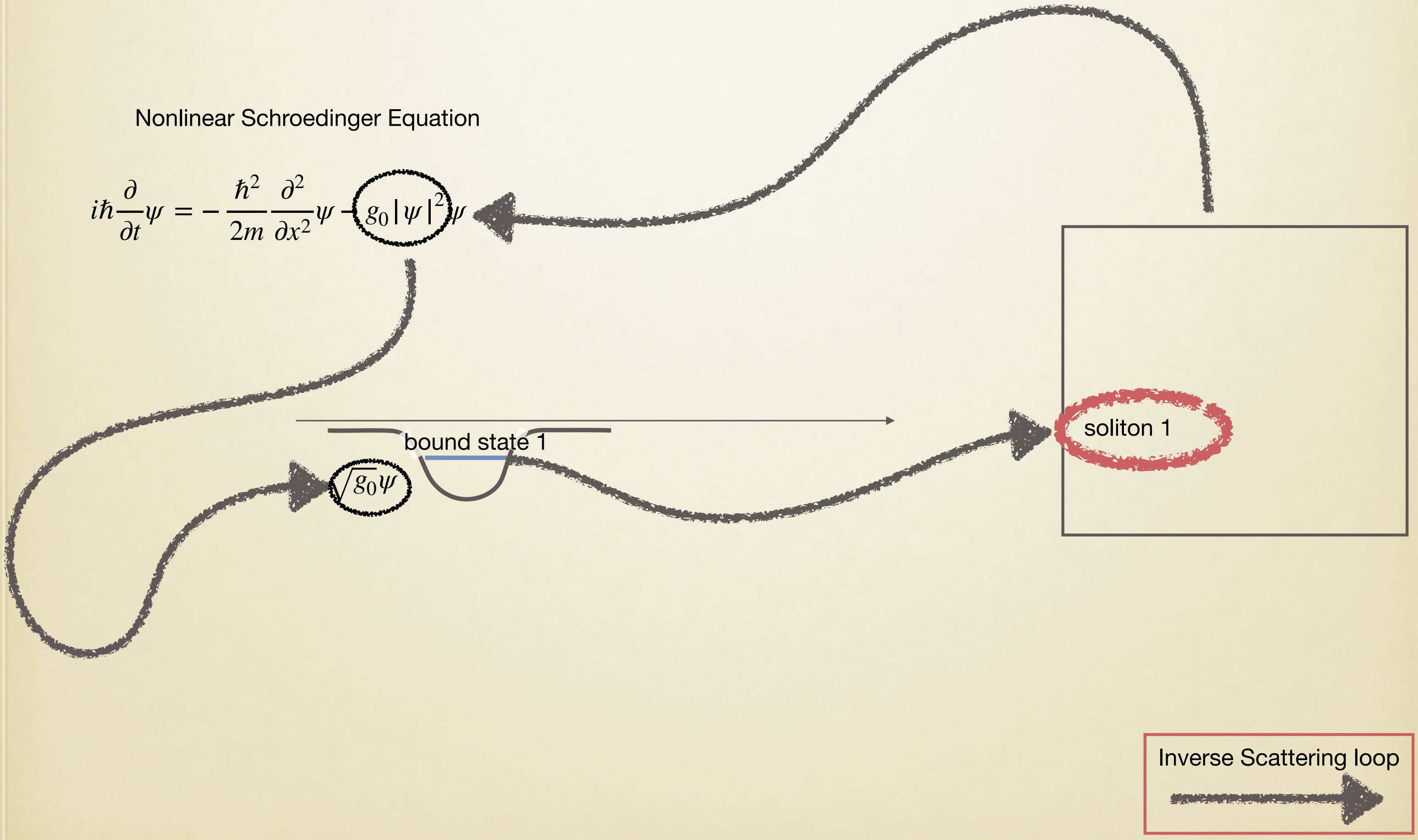
Q: Isn't it dangerous?



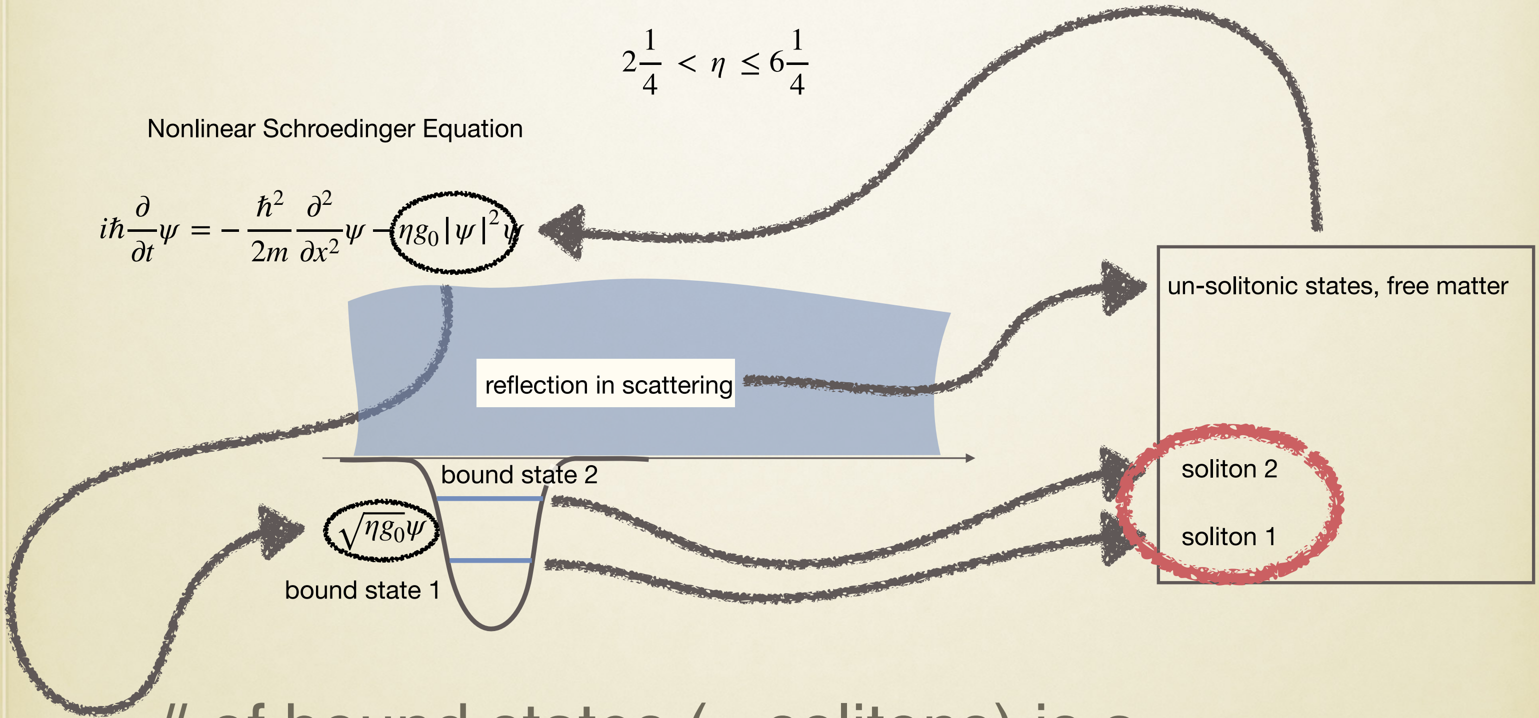
generic cluster
classical
$g_0 \to g > g_0$
localized excitations;
dissociation with
multiple products
integrable cluster (soliton)
classical
$g_0 \to g = 4g_0$
no localized excitations;
dissociation with
two products, in the
same location,
with zero relative velocity
generic cluster
quantum
$g_0 \to g > g_0$
localized excitations;
dissociation with
multiple products,
can't track all ⇒ decoherence
integrable cluster (soliton)
quantum
quantum macroscopic
relative shift and drift
$g_0 \to g = 4g_0$
no localized excitations;
dissociation with only
two products,
in the same location,
with zero relative velocity,
on average ->
no decoherence

Why do solitons produce a controllable number of products in an implosion?

Why solitons produce a controllable number of products in an implosion

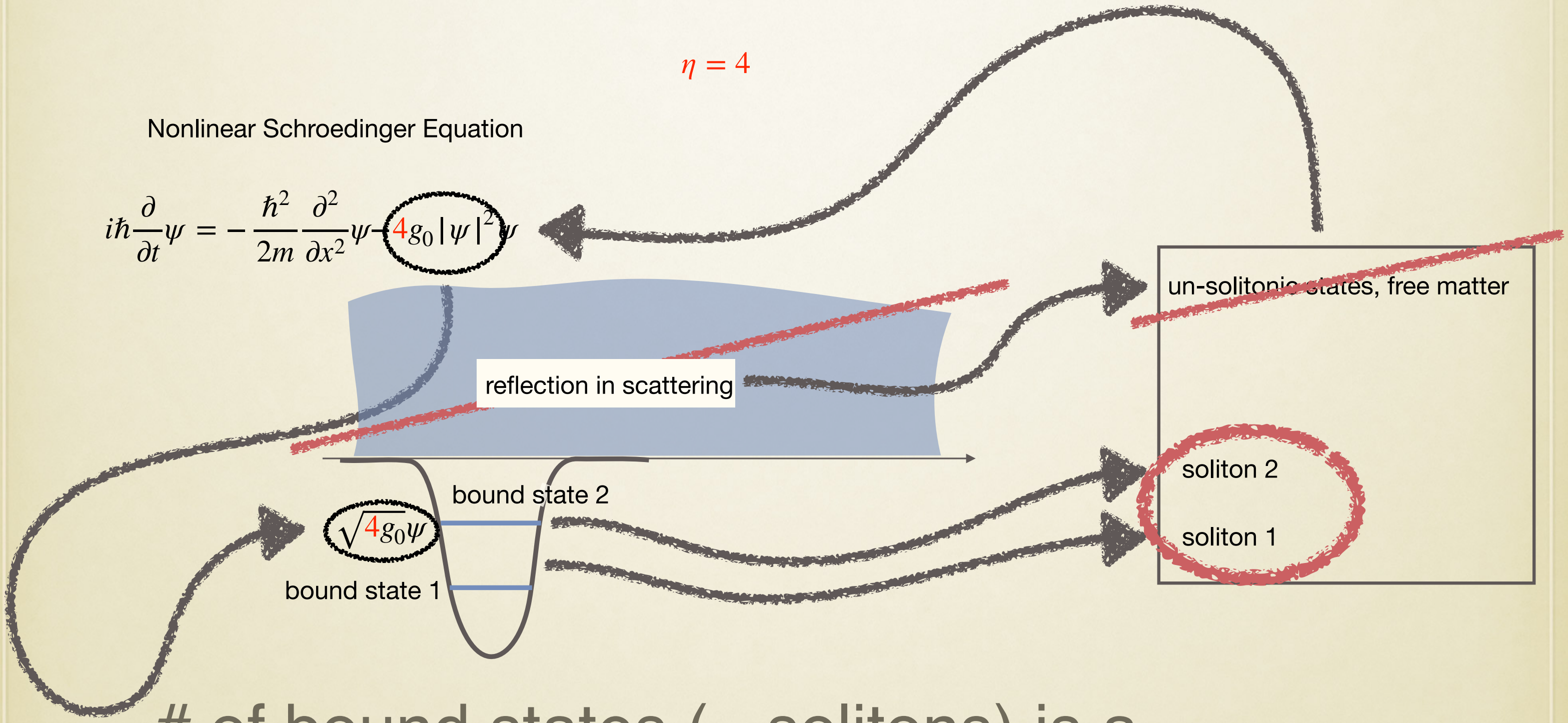


Why solitons produce a controllable number of products in an implosion

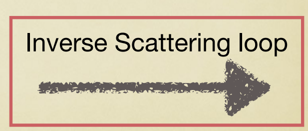


# of bound states (= solitons) is a monotonic function of the potential depth (= quench strength)

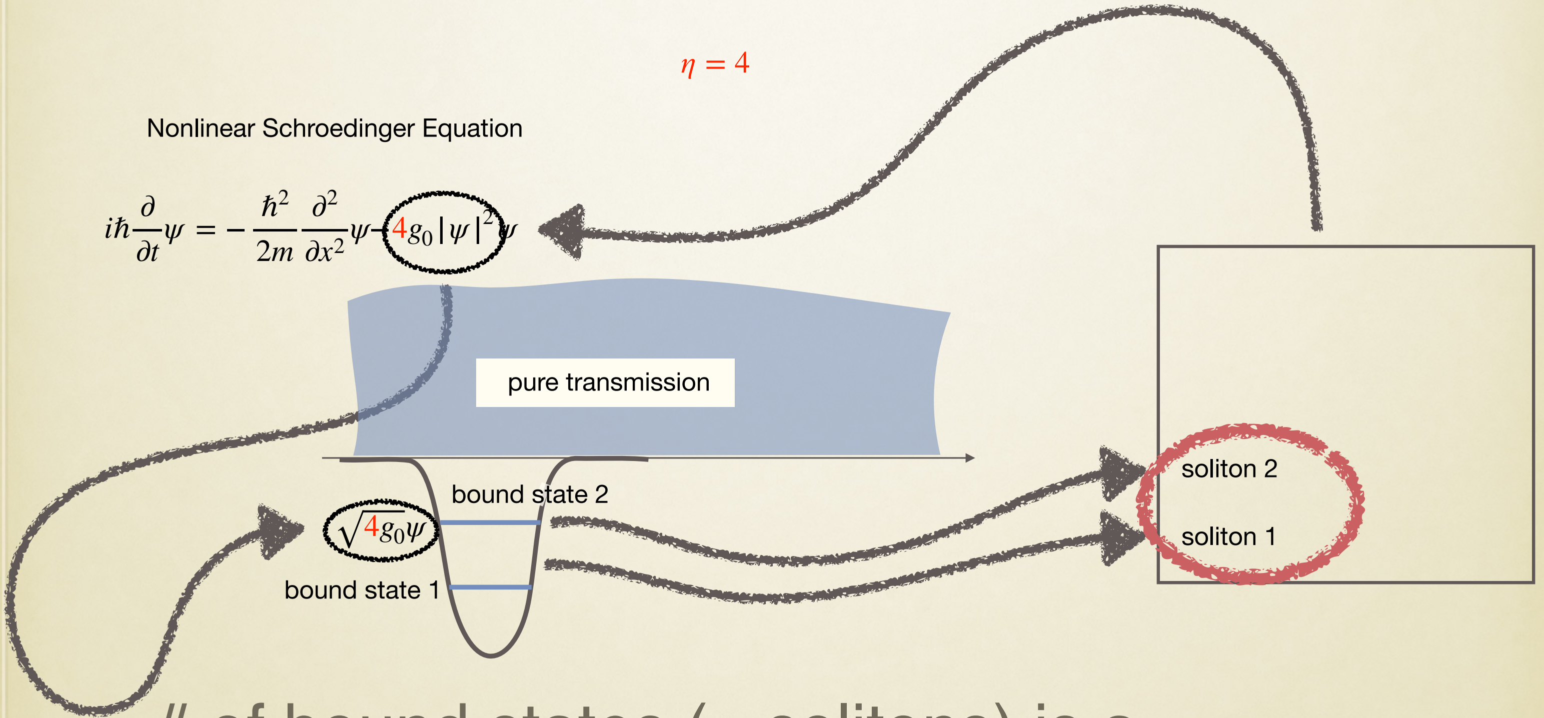
Why solitons produce a controllable number of products in an implosion



# of bound states (= solitons) is a monotonic function of the potential depth (= quench strength)



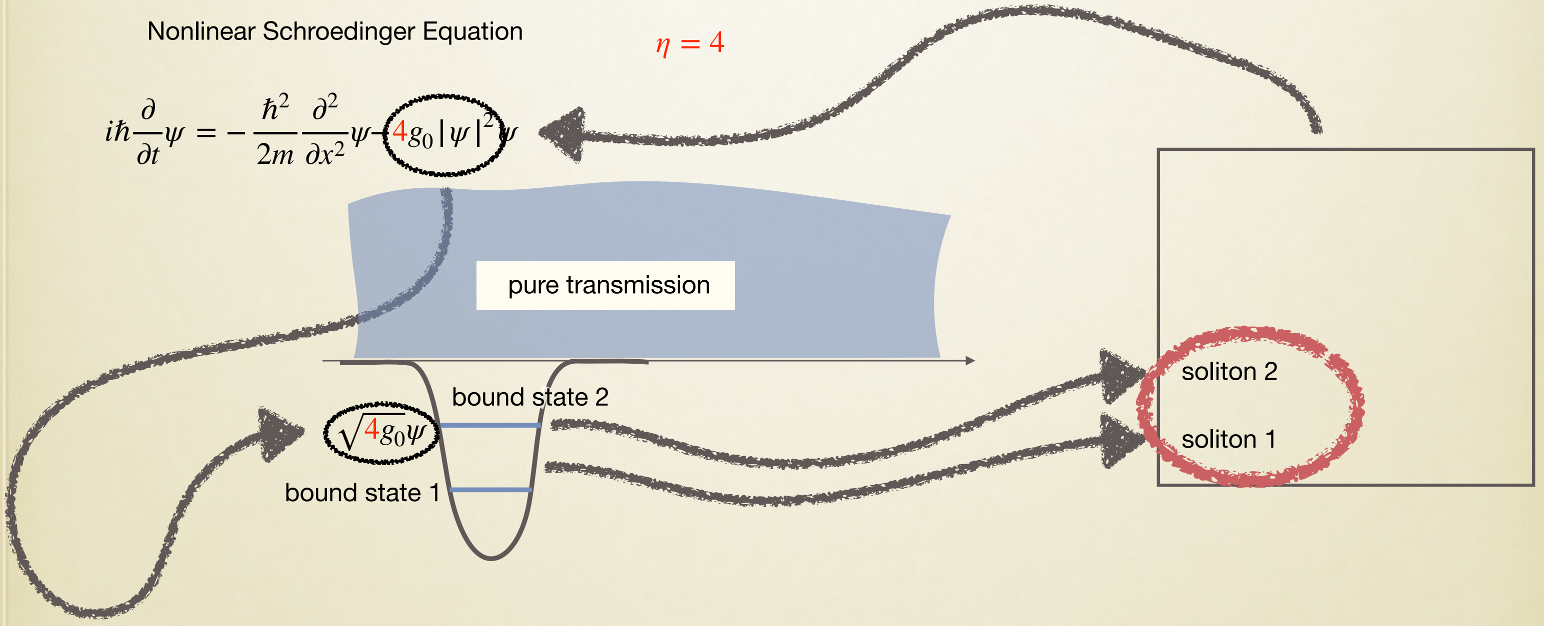
Why solitons produce a controllable number of products in an implosion



# of bound states (= solitons) is a monotonic function of the potential depth (= quench strength)

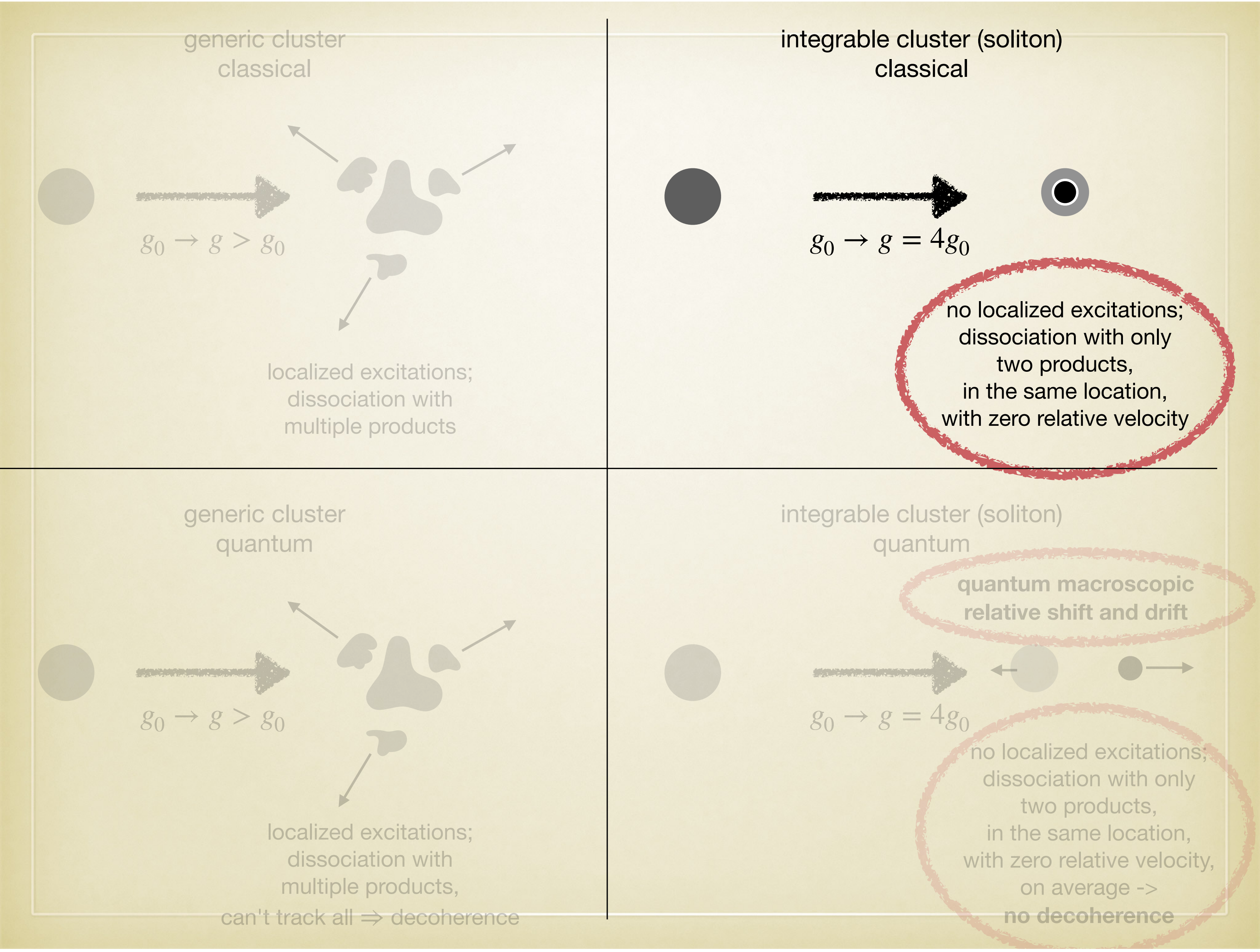
Why don't solitons produce non-solitonic states in an 4-fold coupling quench?

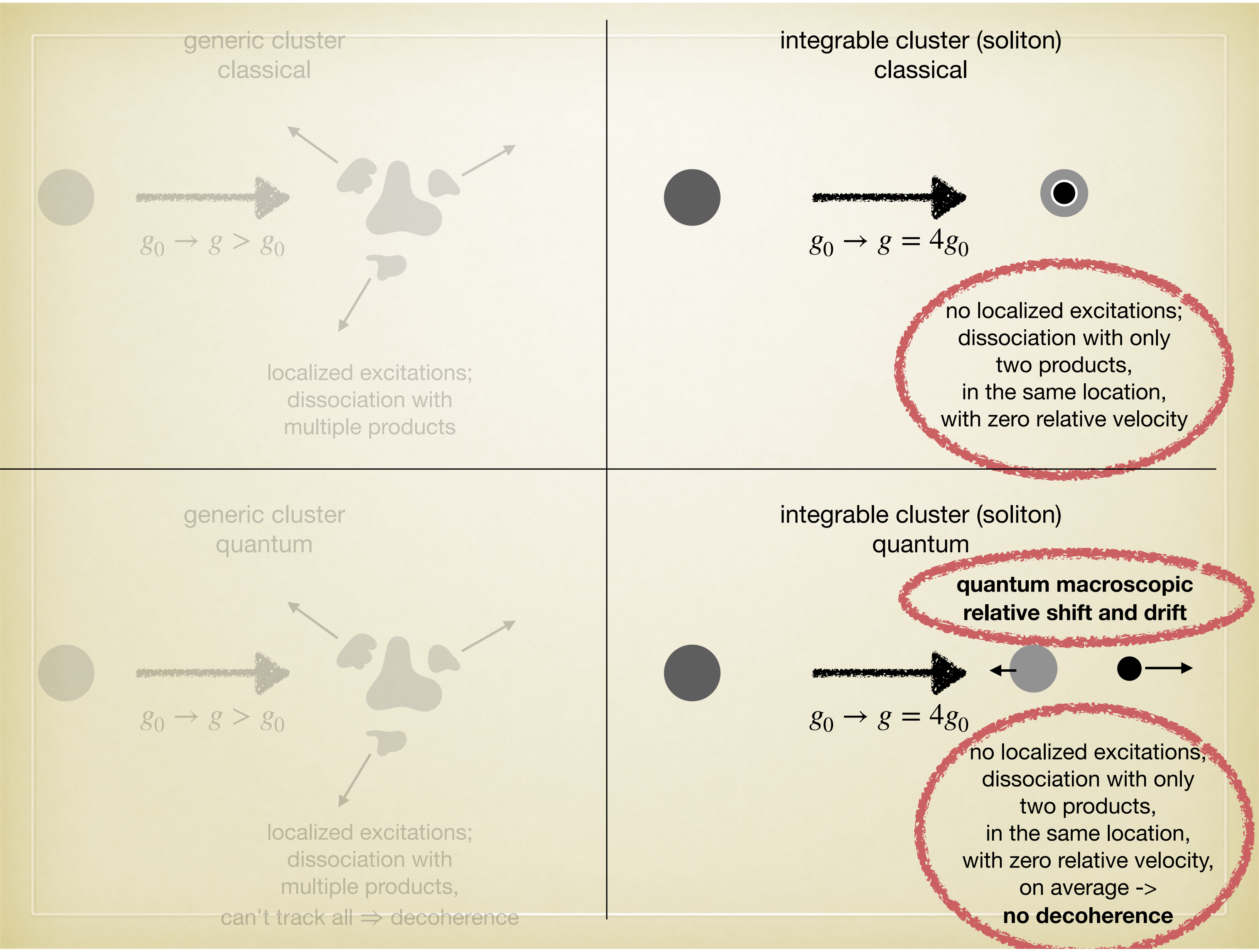
Why solitons do not produce non-solitonic states in an $\eta = 4$-fold coupling quench



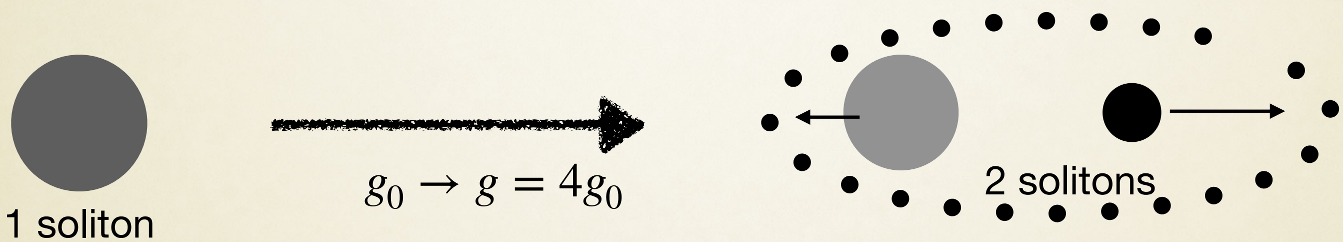
Do not know yet. A QM-SUSY structure may be responsible, Koller and Olshanii (2011)

All in all...


generic cluster
classical
$g_0 \to g > g_0$
localized excitations;
dissociation with
multiple products
integrable cluster (soliton)
classical
$g_0 \to g = 4g_0$
no localized excitations;
dissociation with only
two products,
in the same location,
with zero relative velocity
generic cluster
quantum
$g_0 \to g > g_0$
localized excitations;
dissociation with
multiple products,
can't track all ⇒ decoherence
integrable cluster (soliton)
quantum
quantum macroscopic
relative shift and drift
$g_0 \to g = 4g_0$
no localized excitations;
dissociation with only
two products,
in the same location,
with zero relative velocity,
on average ->
no decoherence

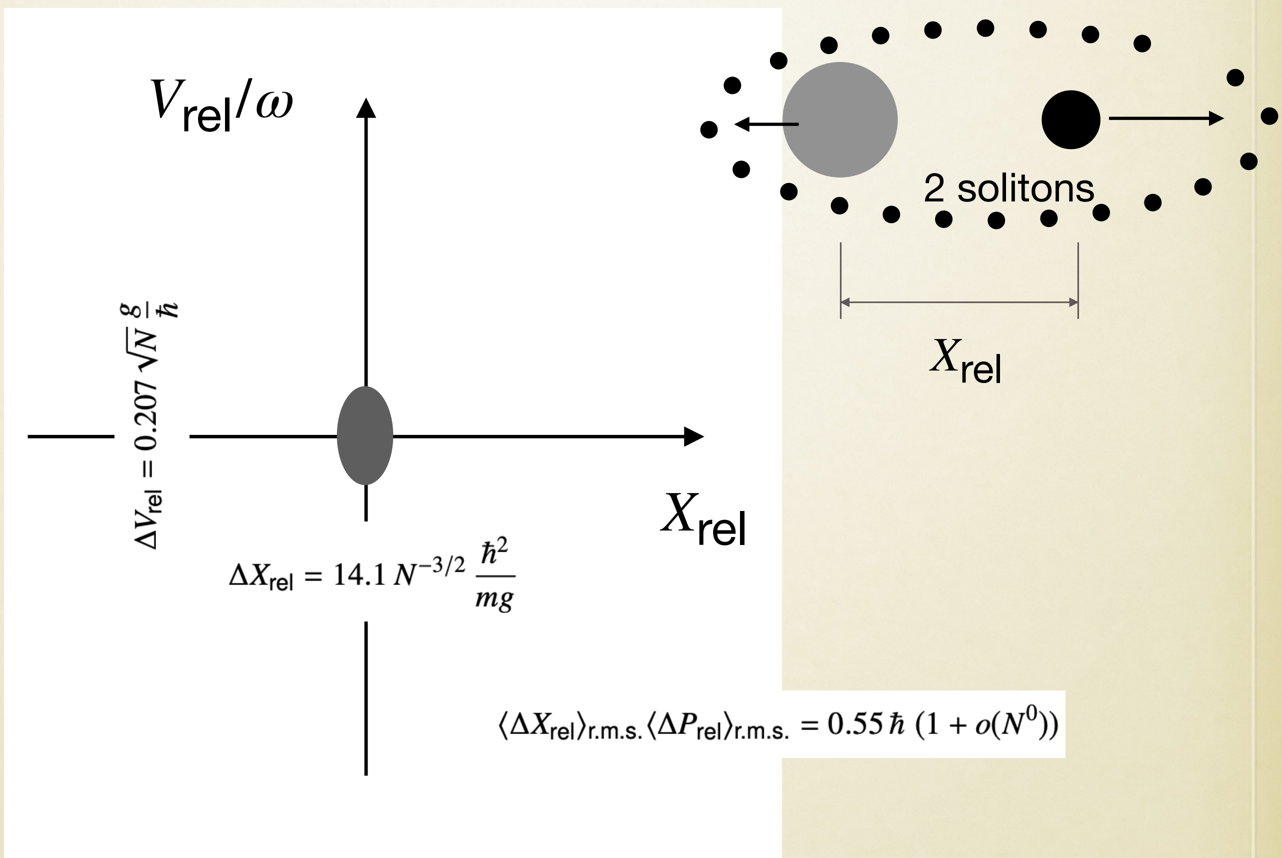

generic cluster
classical
$g_0 \to g > g_0$
localized excitations;
dissociation with
multiple products
integrable cluster (soliton)
classical
$g_0 \to g = 4g_0$
no localized excitations;
dissociation with only
two products,
in the same location,
with zero relative velocity
generic cluster
quantum
$g_0 \to g > g_0$
localized excitations;
dissociation with
multiple products,
can't track all ⇒ decoherence
integrable cluster (soliton)
quantum
quantum macroscopic
relative shift and drift
$g_0 \to g = 4g_0$
no localized excitations;
dissociation with only
two products,
in the same location,
with zero relative velocity,
on average ->
no decoherence

quantum
relative shift and drift =
quantum macroscopic
minimal-uncertainty
wavepacket



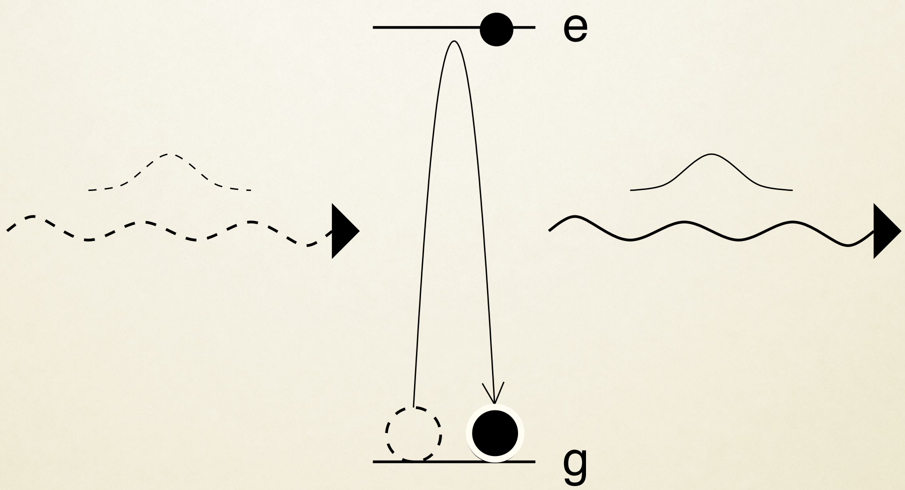
no localized excitations;
dissociation with only
two products,
in the same location,
with zero relative velocity,
on average = **no decoherence**

Predictions

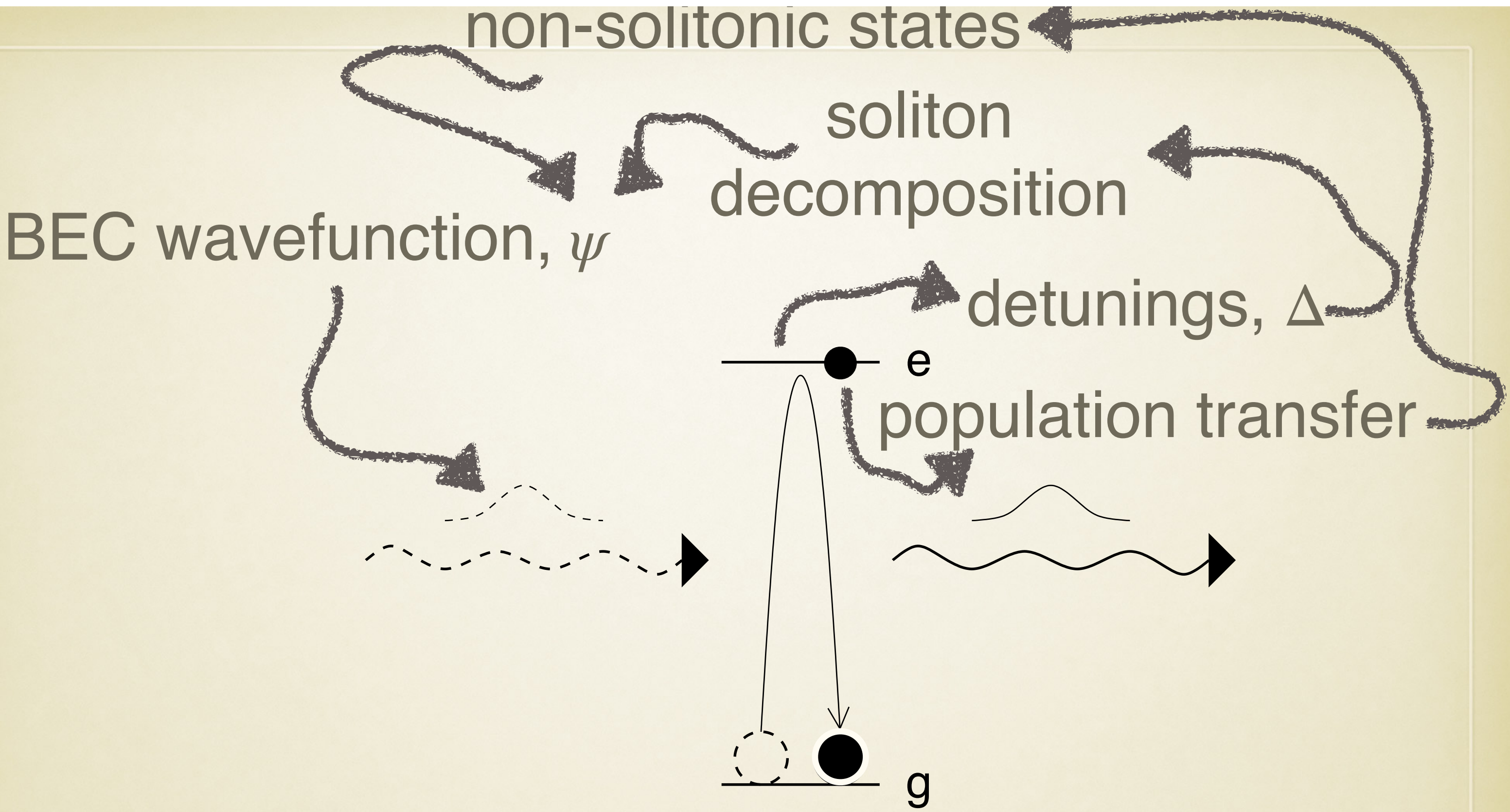


Oleksandr V. Marchukov, Boris A. Malomed, Maxim Olshanii, Vanja Dunjko, Joanna Ruhl, Randall G. Hulet, and Vladimir A. Yurovsky, PRL 125, 050405 (2020); Vladimir A. Yurovsky, Boris A. Malomed, Randall G. Hulet, Maxim Olshanii, PRL 119, 220401 (2017).

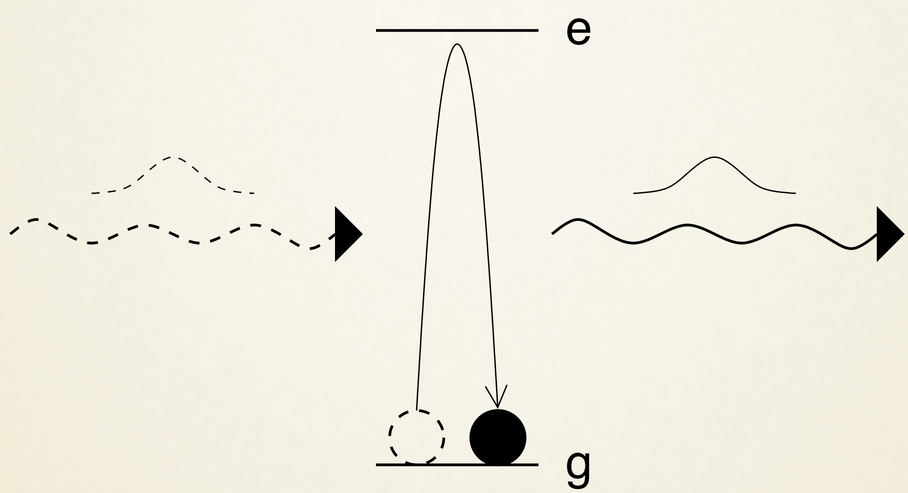
What is this Lax potential anyways?



Two-level atom, subject to a laser pulse

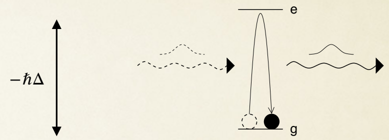


Two-level atom, subject to a
laser pulse



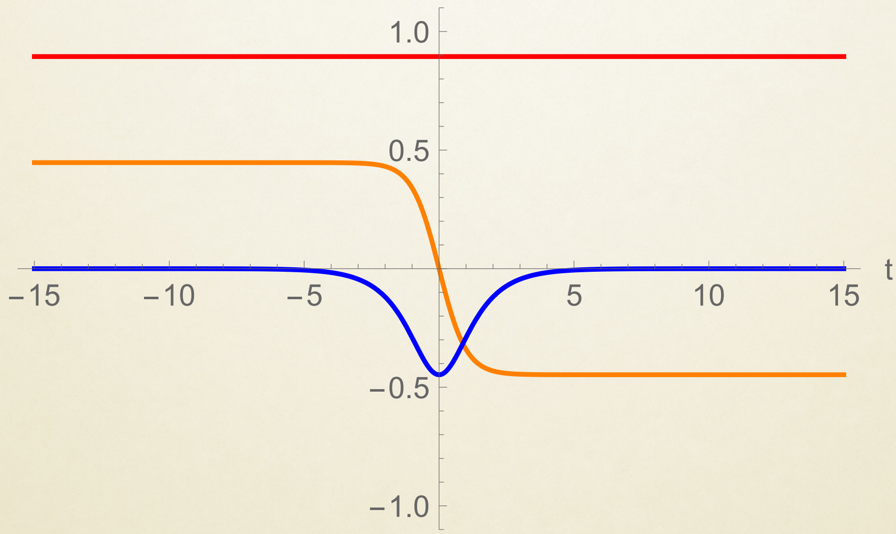
Two-level atom, sech-laser pulse
For a discrete set of amplitudes,
no population transfer for *any* detuning:
thus, pure solitons

Atoms in Strong Light Fields
N. B. Delone and V. P. Krainov,
Springer, 2012

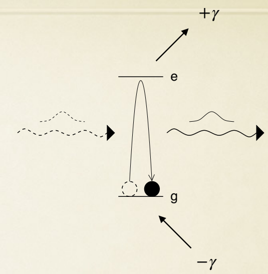


Single solition; scatt. state; $\Delta = -2.$; $V_{eg}(t) = -\mathrm{Sech}[t]$

$\mathrm{Re}[\phi_g[t]/e^{-i(\Delta/2)t}]$; $\mathrm{Im}[\phi_g[t]/e^{-i(\Delta/2)t}]$; $\phi_e[t]/e^{-i(\Delta/2)t}$

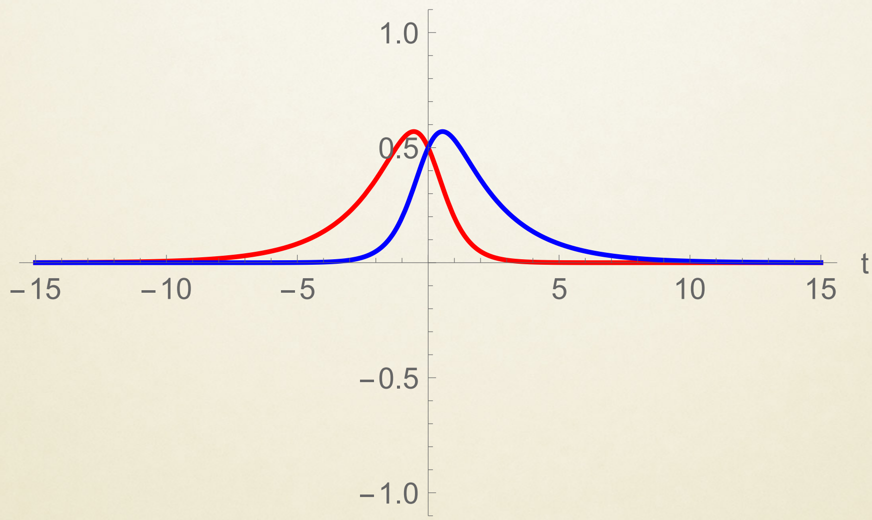


Atoms in Strong Light Fields
N. B. Delone and V. P. Krainov,
Springer, 2012



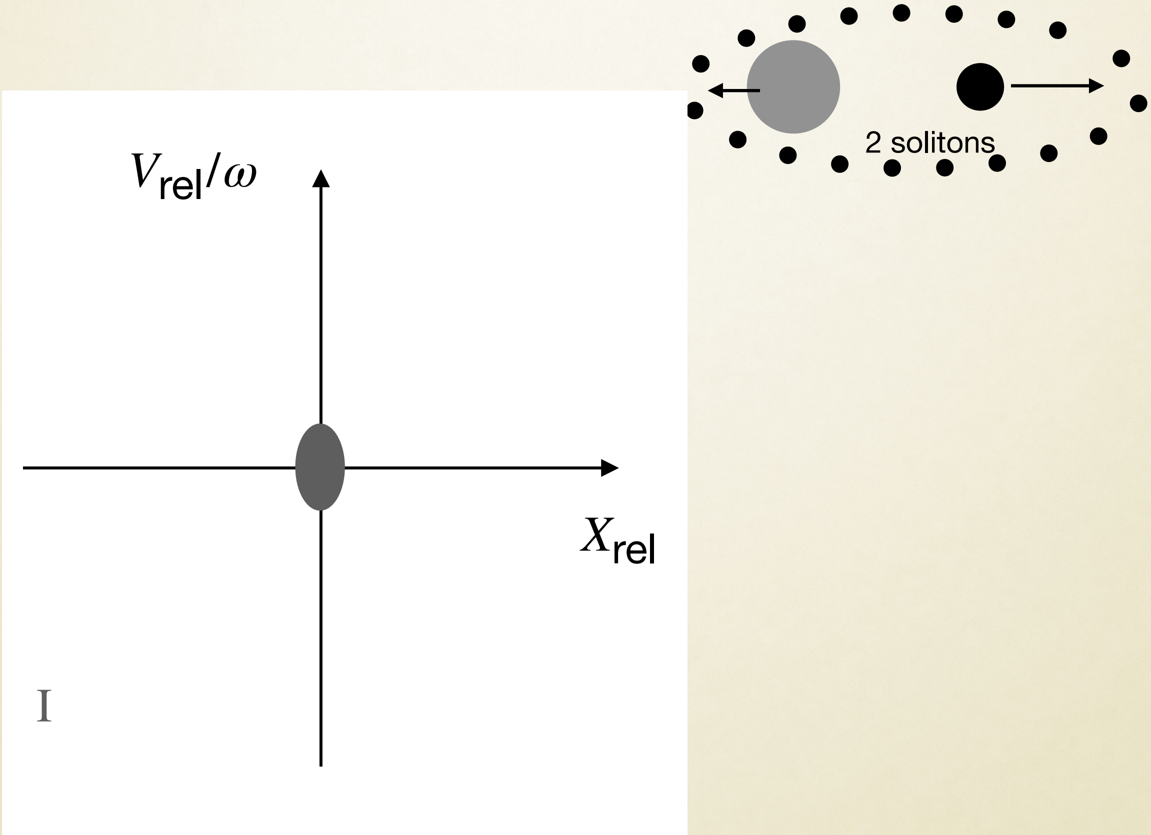
Single solition; bound state; $\Delta = -1\times i$; $V_{eg}(t) = -\mathrm{Sech}[t]$

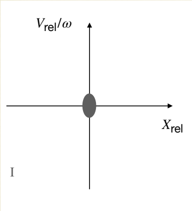
$i^{+1/2}\phi_g[t]$; $i^{-1/2}\phi_e[t]$

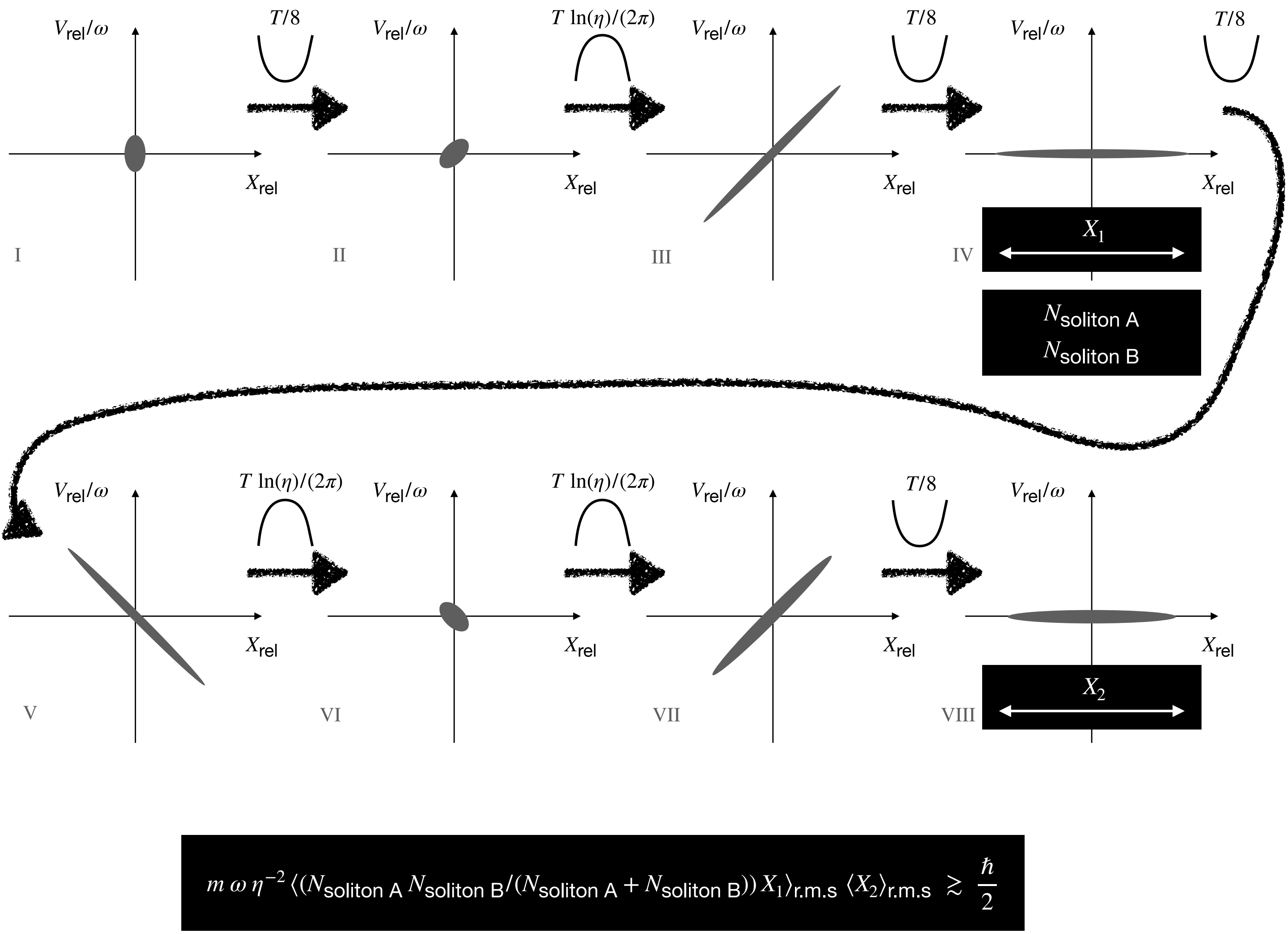


Say we got a macroscopic quantum packet: how can we prove it's quantum?

Our proposal


2 solitons
V_{rel}/ω
X_{rel}
I


V_{rel}/ω
X_{rel}



$V_{\rm rel}/\omega$
$X_{\rm rel}$
$T/8$
$T\ \ln(\eta)/(2\pi)$
I
II
III
IV
V
VI
VII
VIII
X_1
$N_{\text{soliton A}}$
$N_{\text{soliton B}}$
X_2
$m\,\omega\,\eta^{-2}\,\langle(N_{\text{soliton A}}\,N_{\text{soliton B}}/(N_{\text{soliton A}}+N_{\text{soliton B}}))\,X_1\rangle_{\text{r.m.s}}\ \langle X_2\rangle_{\text{r.m.s}}\ \gtrsim\ \frac{\hbar}{2}$

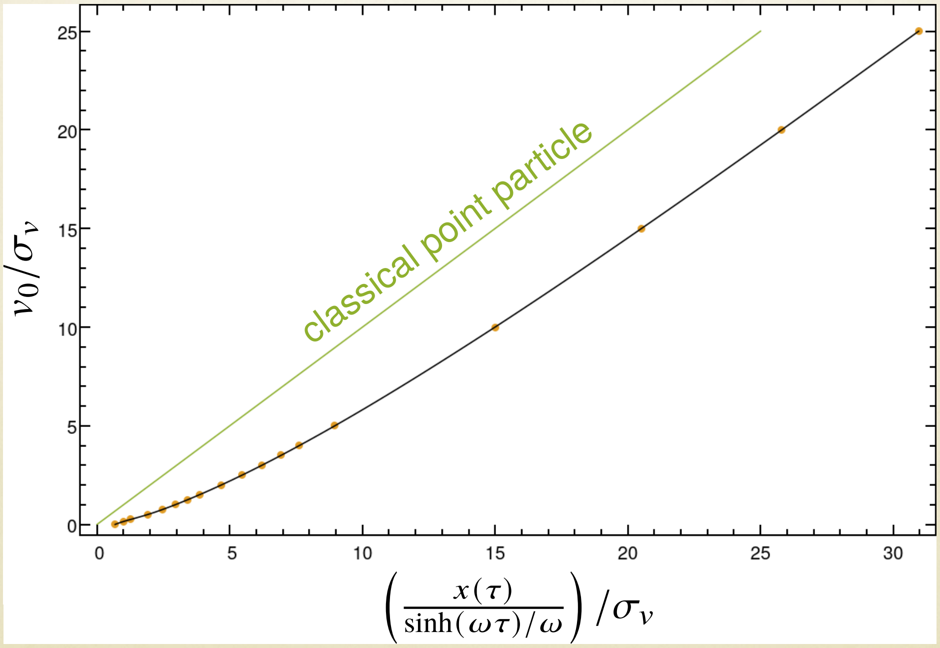
Problems:

- soliton-soliton interactions in harmonic potential

- exponential sensitivity to errors on the re-entry to the inverted harmonic potential

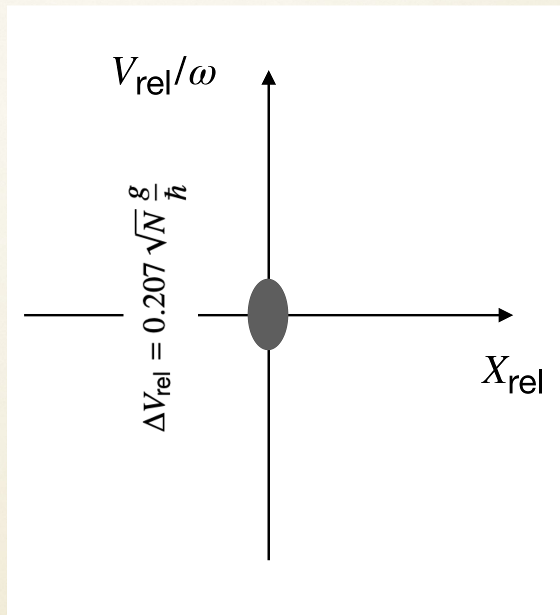
Problem: soliton-soliton interactions in harmonic potential

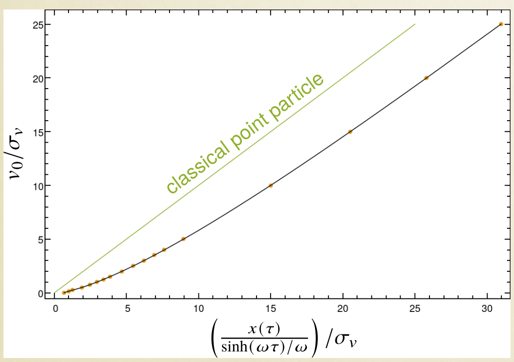
Solution: tabulation, set the other three fluctuations to zero



Problem: soliton-soliton interactions in harmonic potential

Solution: tabulation





$$\Delta V_{\mathrm{rel}}\Big|_{\mathrm{measured}} = (1.026 \pm 0.017)\,\Delta V_{\mathrm{rel}}\Big|_{\mathrm{true}}$$

$$\approx 1/\sqrt{2 * \#\_of\_realizations}$$

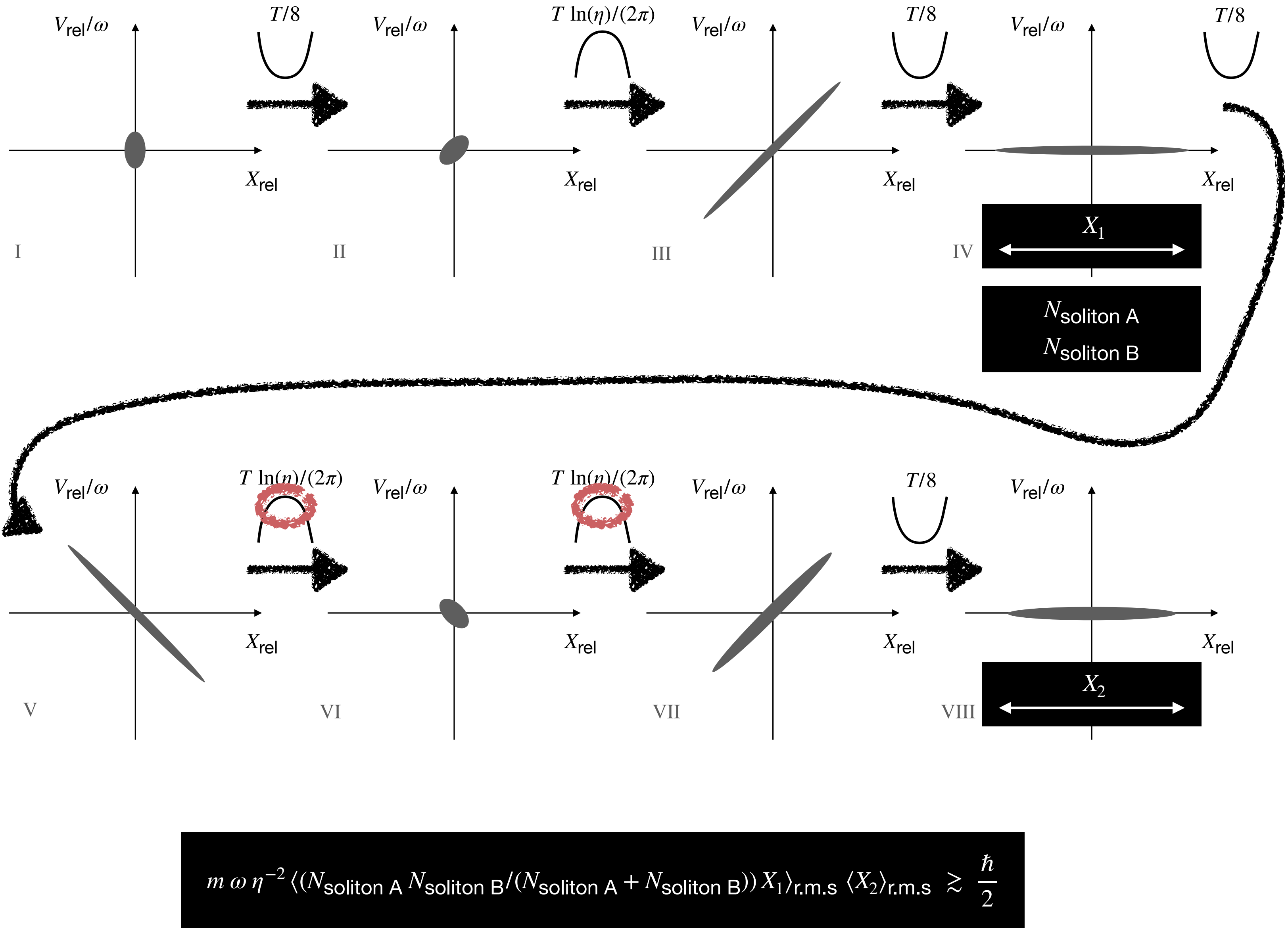
for 1735 realizations

Problem: soliton-soliton interactions in harmonic potential

Solution: tabulation

same for the relative distance

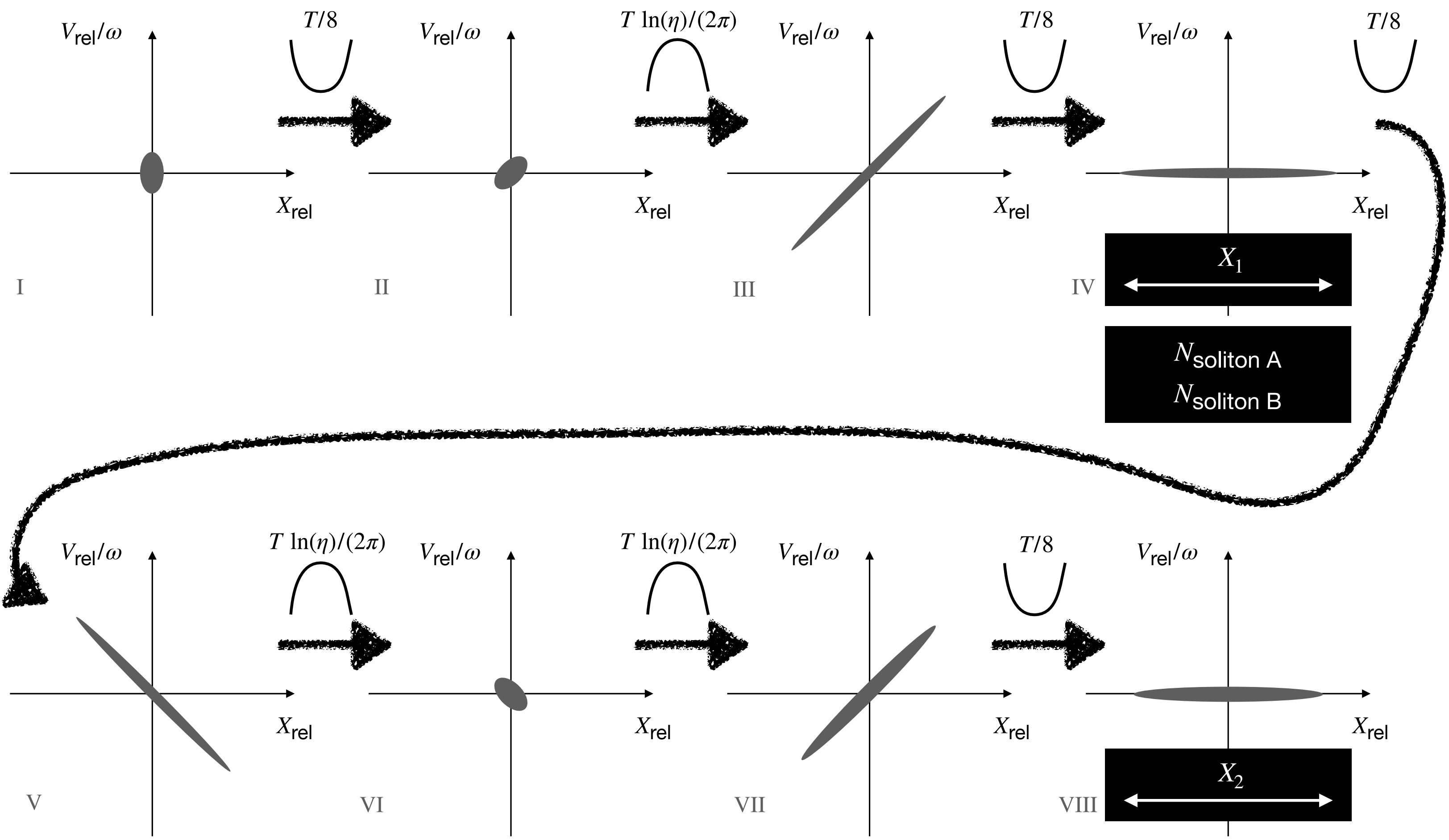
Problem: exponential sensitivity to errors on the re-entry to the inverted harmonic potential



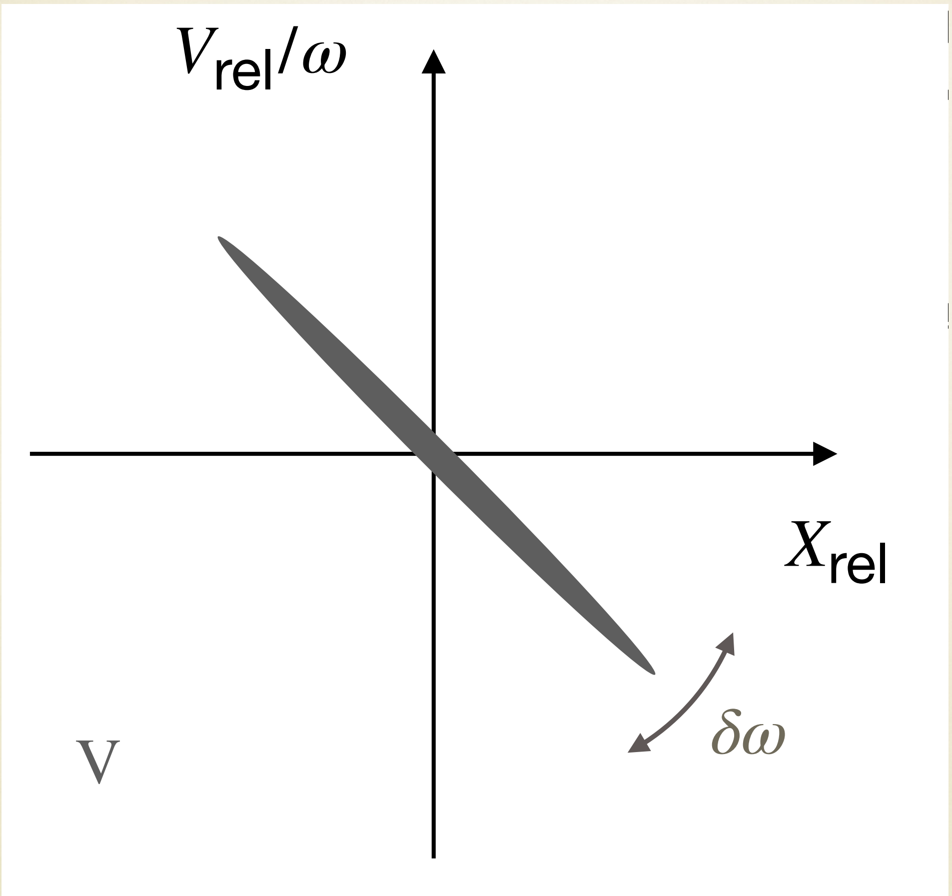
V_{rel}/ω
X_{rel}
$T/8$
$T\ \ln(\eta)/(2\pi)$
I
II
III
IV
V
VI
VII
VIII
X_1
$N_{\text{soliton A}}$
$N_{\text{soliton B}}$
X_2
$m\,\omega\,\eta^{-2}\,\langle (N_{\text{soliton A}}\,N_{\text{soliton B}}/(N_{\text{soliton A}}+N_{\text{soliton B}}))\,X_1\rangle_{\text{r.m.s}}\ \langle X_2\rangle_{\text{r.m.s}}\ \gtrsim\ \frac{\hbar}{2}$

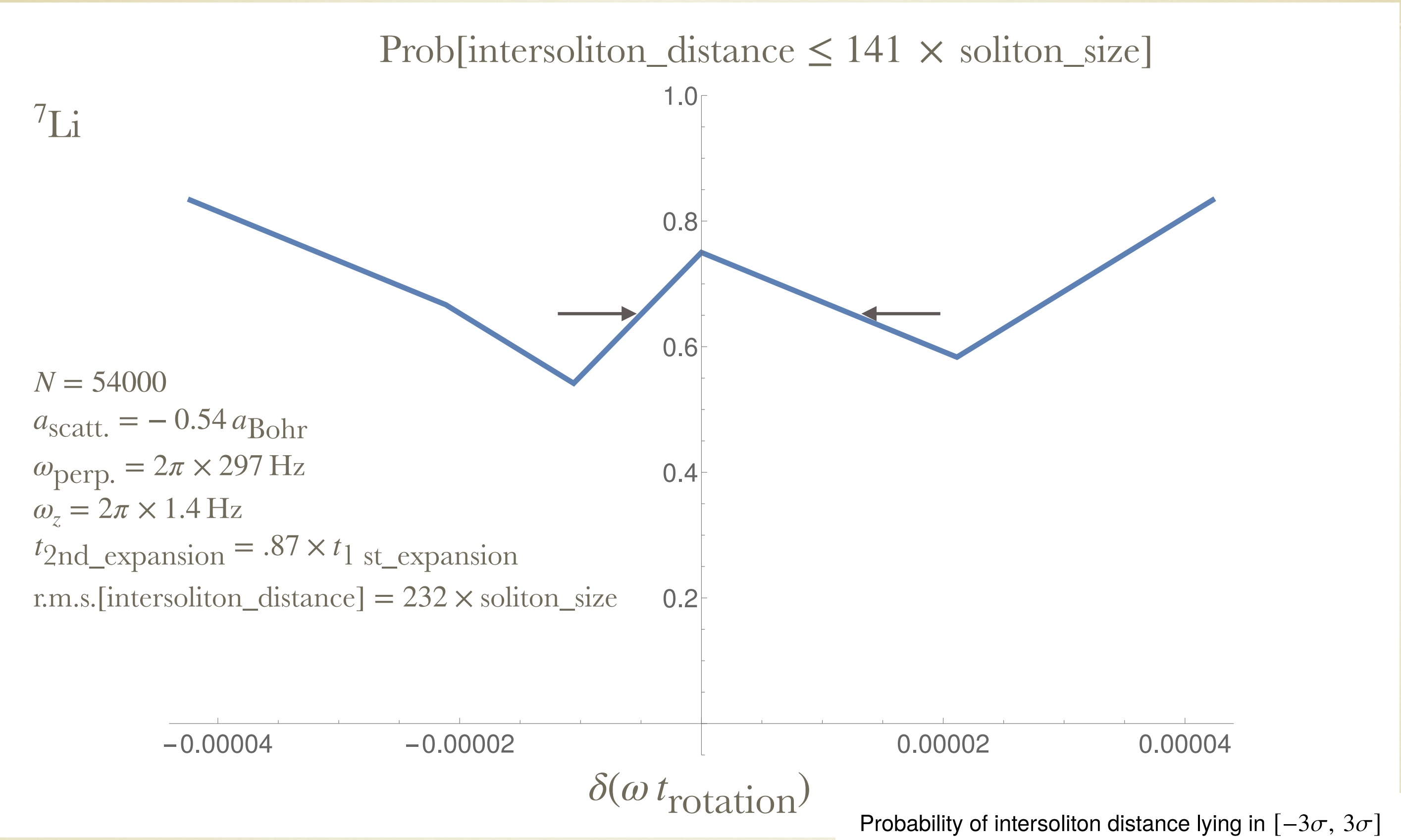
Problem: exponential sensitivity to errors on the re-entry to the inverted harmonic potential

One of the possible solutions: "bug to a feature"



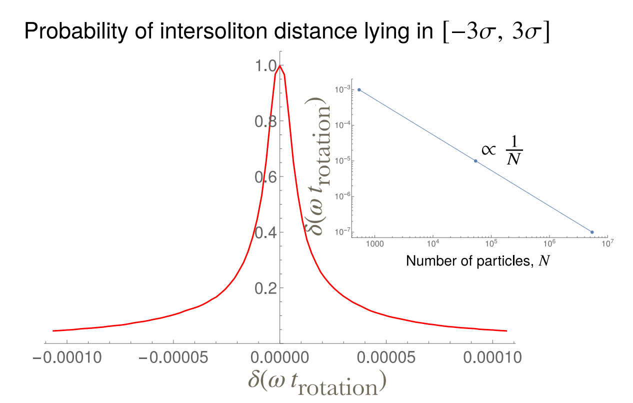
$$m\,\omega\,\eta^{-2}\,\langle (N_{\text{soliton A}}\,N_{\text{soliton B}}/(N_{\text{soliton A}}+N_{\text{soliton B}}))\,X_1\rangle_{\text{r.m.s}}\ \langle X_2\rangle_{\text{r.m.s}}\ \gtrsim\ \frac{\hbar}{2}$$


$V_{\rm rel}/\omega$
$X_{\rm rel}$
$\delta\omega$
V

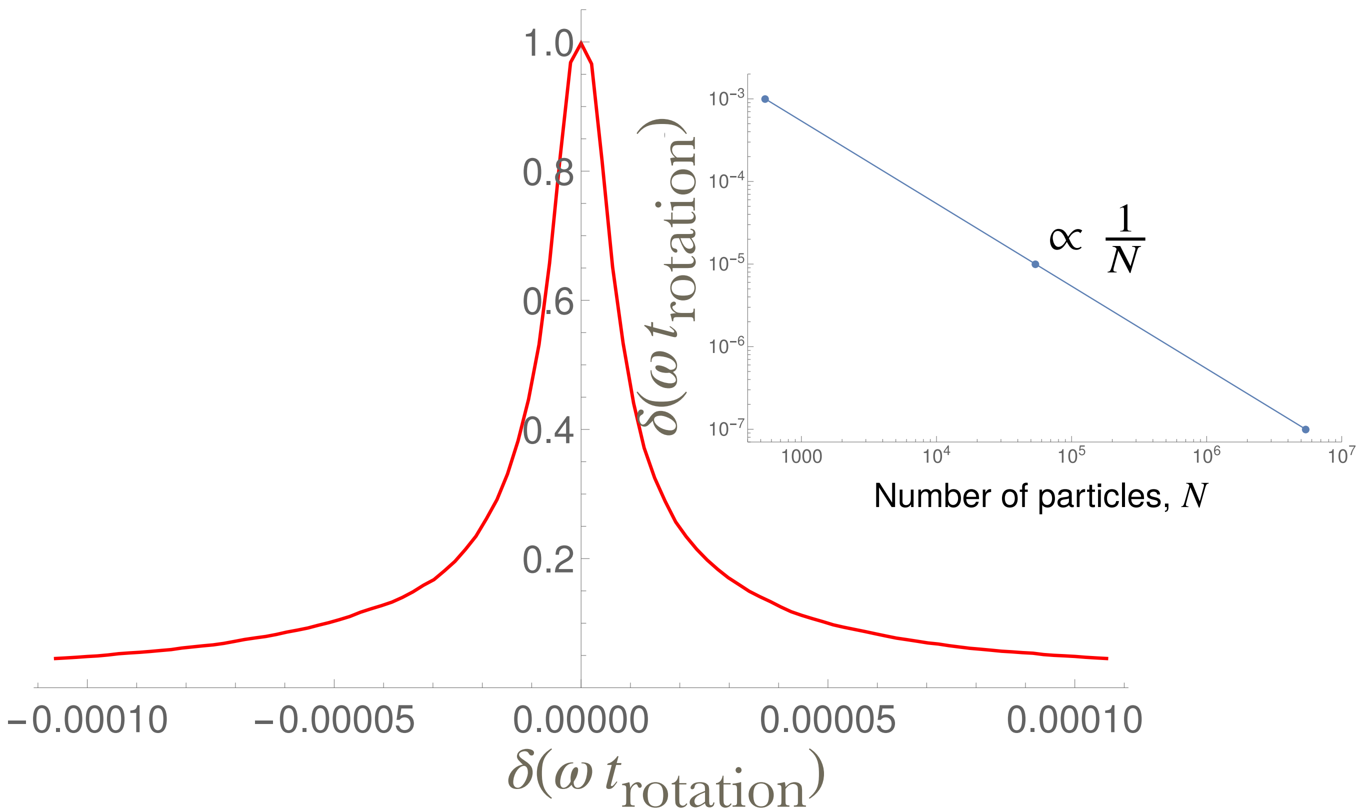


$$\delta\omega = 8.9 \times 10^{-6} \times (2\pi) \times \text{Hz}$$

$$\text{Scales as } \frac{\hbar}{N}$$



Probability of intersoliton distance lying in $[-3\sigma,\ 3\sigma]$



classical estimate

Summary

Inverse scattering map

⬇

(*) Solitons do not decohere to localized excitations;

(*)There is a gap to the delocalized excitations, it *grows* with the soliton size;

(*) Soliton produces a controllable set of products in an implosion: can get *just two solitons and nothing else*.

⬇

Due to the left-right symmetry, the relative motion of the two solitons is a **macroscopic minimal uncertainty wavepacket**. We offer ways of proving the minimal uncertainty.

Publications:
quantum macroscopic coherence
with the relative motion of two solitons

[6] Sumita Datta, Vanja Dunjko, Maxim Olshanii, **Path Integral Estimates of the Quantum Fluctuations of the Relative Soliton-Soliton Velocity in a Gross-Pitevskii Breather**, *MDPI Physics* 4, 12 (2022). [Macroscopic quantum breather dissociation (Feynman-Kac path integral Monte-Carlo, $1 \lesssim N \lesssim 100$)]

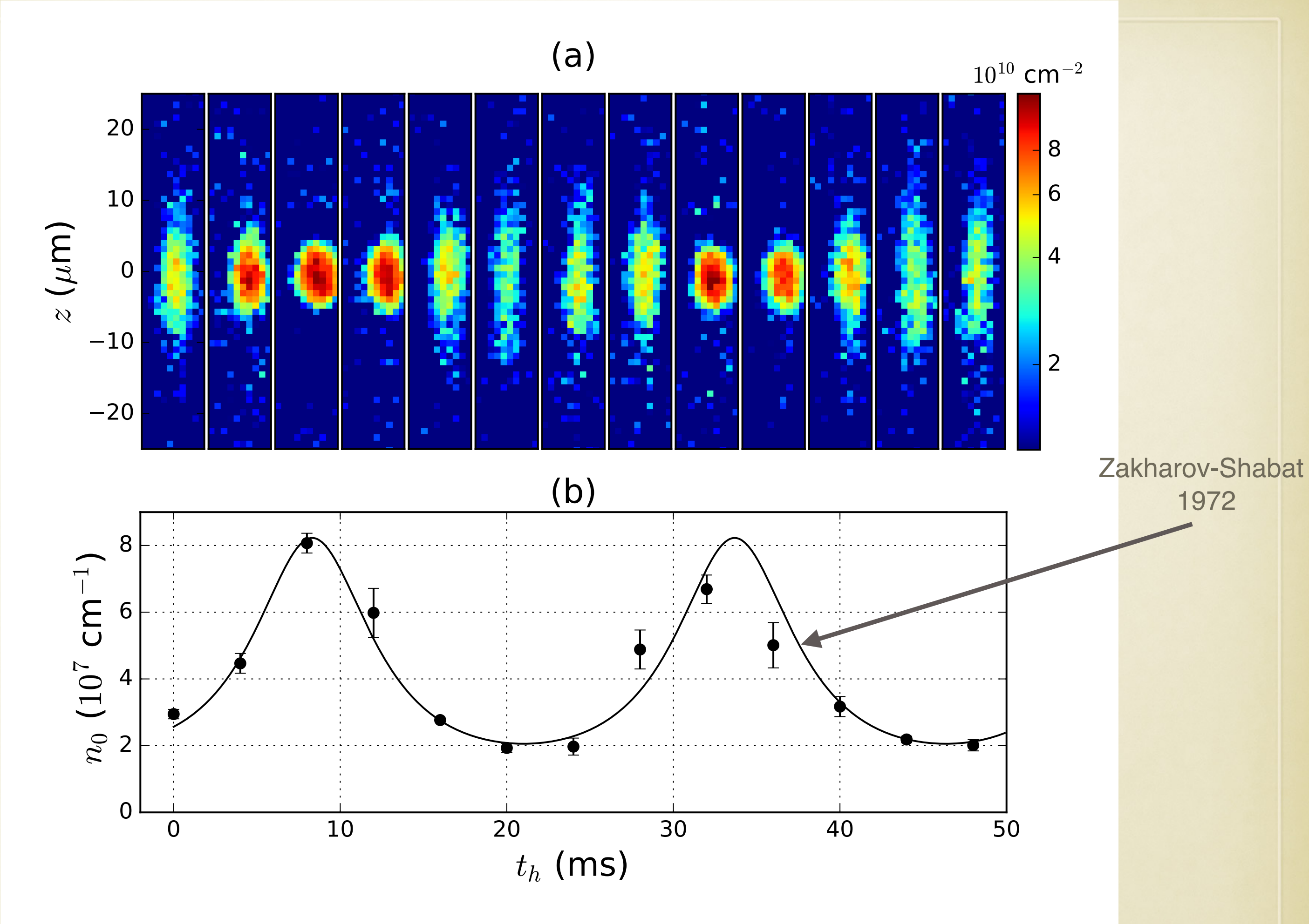
[5] De Luo, Yi Jin, Jason H. V. Nguyen, Boris A. Malomed, Oleksandr V. Marchukov, Vladimir A. Yurovsky, Vanja Dunjko, Maxim Olshanii, R. G. Hulet, **Creation and Characterization of Matter-Wave Breathers**, *Phys. Rev. Lett.* 125, 183902 (2020). [**Experimental** creation of a breather ($N = 5.4 \times 10^4$)]

[4] Oleksandr V. Marchukov, Boris A. Malomed, Maxim Olshanii, Vanja Dunjko, Joanna Ruhl, Randall G. Hulet, and Vladimir A. Yurovsky, **Quantum fluctuations of the center-of-mass and relative parameters of NLS breather**, Phys. Rev. Lett. 125, 050405 (2020). [Macroscopic quantum breather dissociation (Bogoliubov, $10 \lesssim N < \infty$)]

[3] Oleksandr V. Marchukov, Boris A. Malomed, Vladimir A. Yurovsky, Maxim Olshanii, Vanja Dunjko, Randall G. Hulet, **Splitting of nonlinear-Schrödinger breathers by linear and nonlinear localized potentials**, Phys. Rev. A 99, 063623 (2019). [How to speed the breather dissociation up, with additional potentials (GPE)]

[2] Jake Golde, Joanna Ruhl, Sumita Datta, Boris A. Malomed, Maxim Olshanii, Vanja Dunjko, **Metastability versus collapse following a quench in attractive Bose-Einstein condensates**, Phys. Rev. A 97, 053604 (2018). [Breather stability against collapse (GPE)]

[1] Vladimir A. Yurovsky, Boris A. Malomed, Randall G. Hulet, Maxim Olshanii, **Dissociation of one-dimensional matter-wave breathers due to quantum many-body effects**, *Phys. Rev. Lett.* **119**, 220401 (2017). [Original proposal for the macroscopic quantum breather dissociation (Bethe Ansatz, $1 \leq N \lesssim 20$)]



De Luo, Yi Jin, Jason H. V. Nguyen, Boris A. Malomed, Oleksandr V. Marchukov, Vladimir A. Yurovsky, Vanja Dunjko, Maxim Olshanii, R. G. Hulet, **Creation and Characterization of Matter-Wave Breathers**, PRL 125, 183902 (2020).

Publications:
quantum macroscopic coherence
with the center-of-mass of a single sloliton

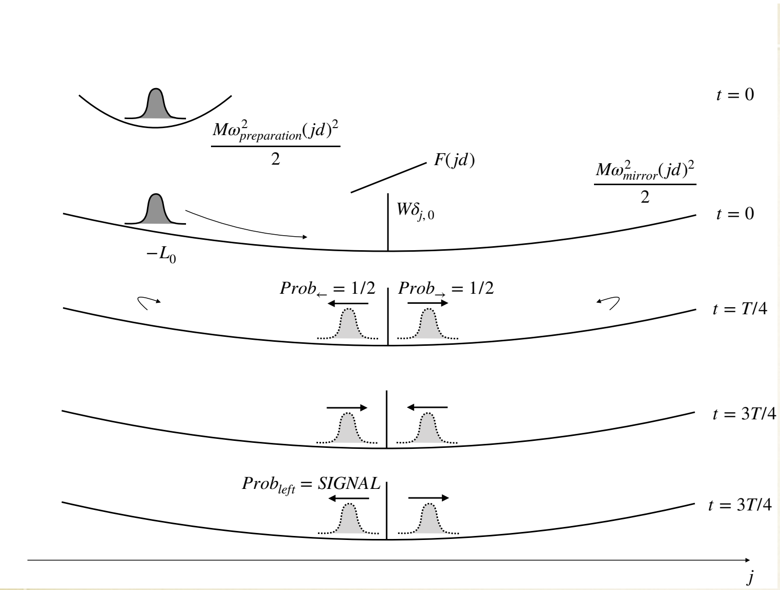
[5] Piero Naldesi, Peter D. Drummond, Vanja Dunjko, Juan Polo, Luigi Amico, Anna Minguzzi, Maxim Olshanii, **Massive particle interferometry with lattice solitons: robustness against ionization**, [arXiv:2201.10479], submitted to SciPost. [A study of CoM decoherence to delocalized Bogoliubov exitations (exact diagonalization, $N = 6$)]

[4] P. Naldesi, J. Polo, S. A. Gardiner, M. Olshanii, A. Minguzzi, L. Amico, **Quantum-enhanced atomtronics with solitons**, chapter in ***Roadmap on Atomtronics***, L.Amico, M. Boshier, G.Birkl, A. Minguzzi, C. Miniatura, L.-C. Kwek, eds, AVS Quantum Sci. 3, 039201 (2021) [featured on cover/landing page]. [Review on soliton interferometry]

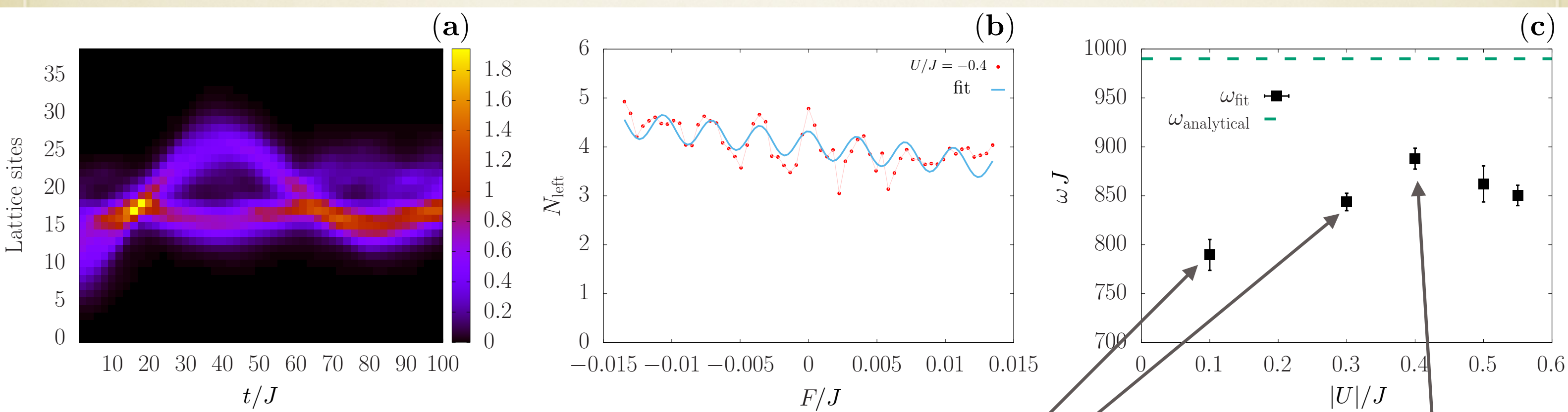
[3] Piero Naldesi, Juan Polo Gomez, Vanja Dunjko, Hélène Perrin, Maxim Olshanii, Luigi Amico, Anna Minguzzi, **Enhancing sensitivity to rotations with quantum solitonic currents**, SciPost Phys. 12, 138 (2022). [Soliton rotometry (exact diagonalization, $N = 4$)]

[2] Maxim Olshanii, Thibault Scoquart, Dmitry Yampolsky, Vanja Dunjko, and Steven Glenn Jackson, **Creating entanglement using integrals of motion**, Phys. Rev. A 97, 013630 (2018). [Multi-soliton entanglement amplifier (Bethe Ansatz on CoM of the solitons)]

[1] Piero Naldesi, Juan Polo Gomez, Anna Minguzzi, Boris Malomed, Maxim Olshanii, Luigi Amico, **Raise and fall of a bright soliton in an optical lattice**, Phys. Rev. Lett. 122, 053001 (2018). [Solitons on a lattice (exact diagonalization, $N = 5$)]



Piero Naldesi, Peter D. Drummond, Vanja Dunjko, Juan Polo, Luigi Amico, Anna Minguzzi, Maxim Olshanii, **Massive particle interferometry with lattice solitons: robustness against ionization**, [arXiv:2201.10479], submitted to SciPost.



Above one-atom ionization threshold

Above one-atom ionization threshold

Above a *total* ionization threshold

Above one-atom ionization threshold

Support by:

NSF

BSF

United States – Israel
Binational Science Foundation

Thank you!