Quantum dynamics in many-body systems

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Outline

Examples of theory addressing experimental puzzles

Role of non-equilibrium processes in resonant XRay

Chiral prethermalization in non-uniformly split condensates

Role of nonequilibrium dynamics in Resonant Soft Xray Scattering experiments on high Tc cuprates

P. Abbamonte, E. D., J. C. Davis, J.-C. Campuzano, Physica C: Superconductivity 481:15 (2012)

D. Benjamin, D. Abanin, E. D., Phys. Rev. Lett. 110:137002 (2013)

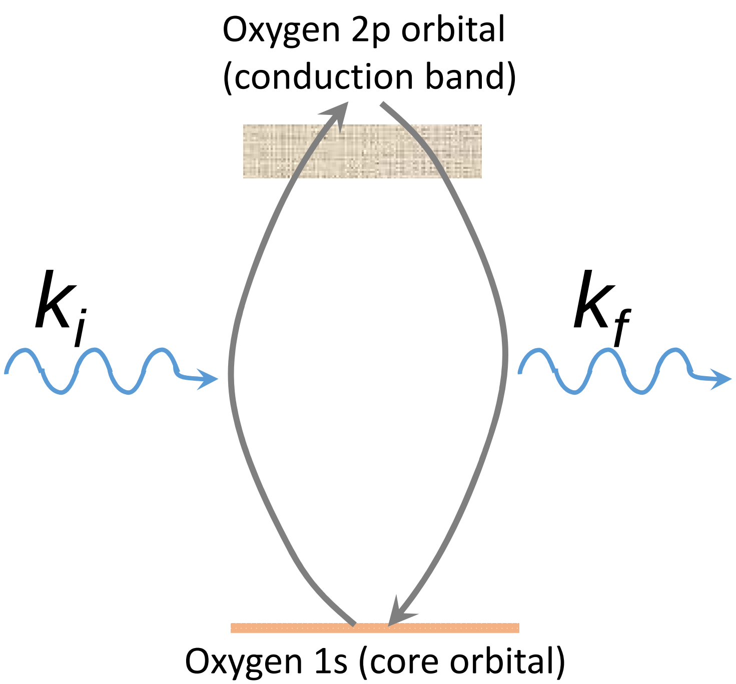
D. Benjamin, I. Klich, E. Demler, arXiv:1312.6642

Resonant Elastic XRay Scattering (REXS)

Resonant Soft Xray Scattering (RSXS)

Neutron and X-ray diffraction are mainly sensitive to the nuclear scattering and the core electron scattering.
at the edge of OK level the form factor of the conduction band is enhanced by a factor of 80

$$400\mathrm{eV} < \hbar\omega < 1\mathrm{keV}$$

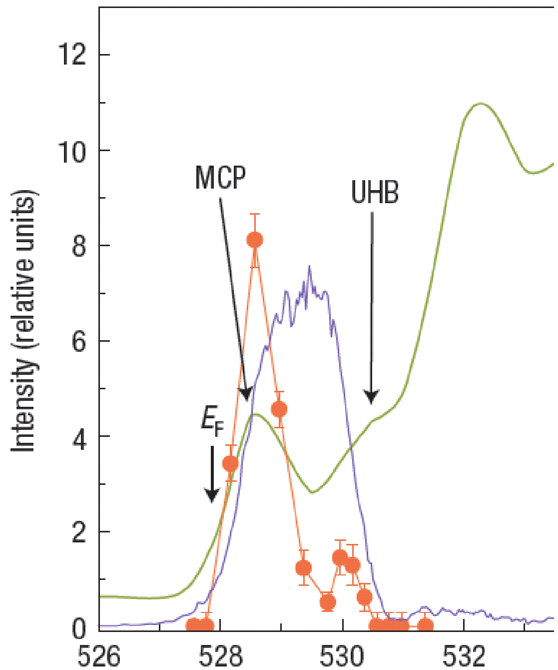


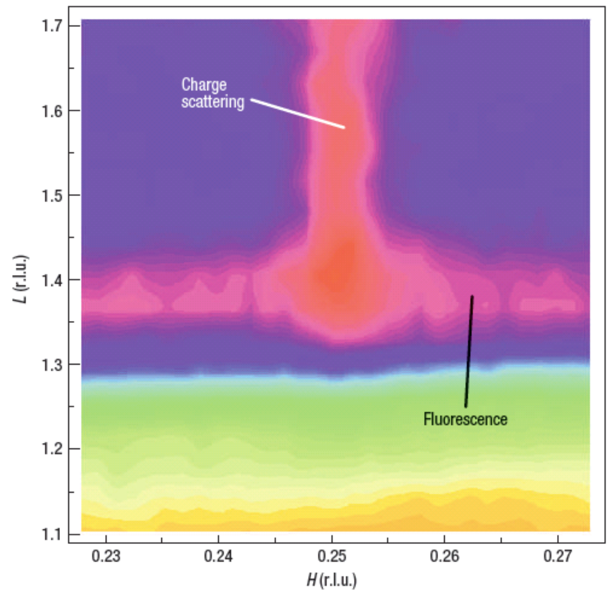
Advantages:
Bulk probe
can be applied to any material

Disadvantages:
energy resolution limited by lifetime of the core hole
$\Gamma \approx 150$ meV

Observation of period four CDW in cuprates

$La_{2-x}Ba_xCuO_4$ Abbamonte et al., Nature Phys. 1:155 (2005)
$La_{1.8-x}Eu_{0.2}Sr_xCuO_4$ Fink et al., Phys. Rev. B 79:100502 (R) (2009)





Peak separation is too small for the Hubbard gap
If second peak is Mott, it should be strong at cu edge and weak at O edge. Experimentally it is the opposite.

Kramers-Heisenberg formula

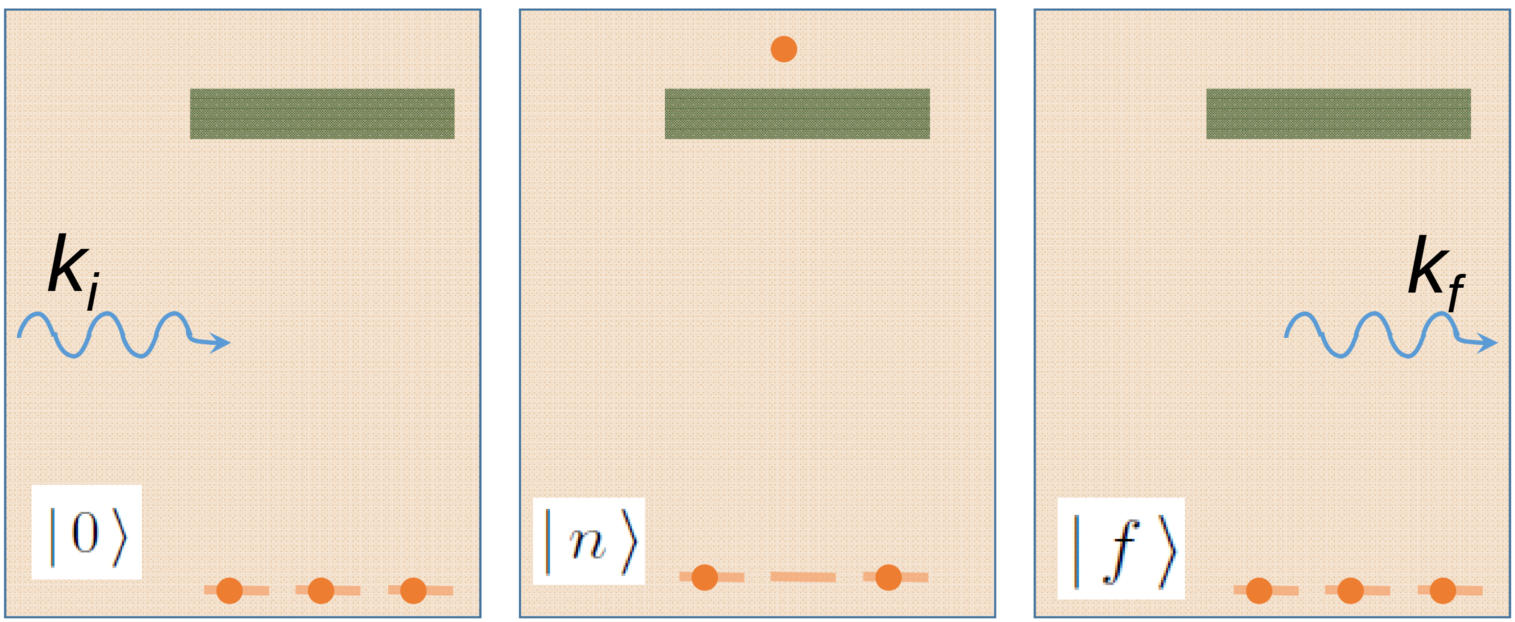
Absorption of initial photon

$$T_1 = \sum_j \Psi_j^\dagger c_j a_{k_i} e^{ik_i r_j} + \text{c.c.}$$

Emission of final photon

$$T_2 = \sum_j c_j^\dagger \Psi_j a_{k_f} e^{ik_f r_j} + \text{c.c.}$$

$$I_{\text{RSXS}} = \sum_f \left| \sum_n \frac{\langle f|T_2^\dagger|n\rangle\langle n|T_1|0\rangle}{E_0 - E_n + \omega_i + i\Gamma} \right|^2 \delta(E_0 + \omega_i - E_f - \omega_f)$$



REXS and response function

Elastic scattering $| f \rangle = | 0 \rangle$

$$I(q,\omega_i) = | \sum_{nj} \frac{\langle 0|\Psi_j|n\rangle\langle n|\Psi_j^\dagger|0\rangle}{(E_0^N - \tilde{E}_n^{N+1} + \omega_i + i\Gamma)} e^{-iqr_j} |^2$$

Reminiscent of the local density of states measured in STM

$$\begin{aligned}\mathrm{Im}G(\epsilon, r_j) &= \rho^{\mathrm{STM}}(\epsilon, r_j) \\ &= \sum_n \langle 0|\Psi_j|n\rangle\langle n|\Psi_j^\dagger|0\rangle\delta(\epsilon - (E_n^{N+1} - E_0)) \\ &+ \sum_n \langle 0|\Psi_j^\dagger|n\rangle\langle n|\Psi_j|0\rangle\delta(\epsilon + (E_n^{N-1} - E_0))\end{aligned}$$

Why we can not relate REXS and STM in the most general case

- energies of excited states include the core hole potential
- finite core hole lifetime $\tau = \Gamma^{-1}$

REXS simplified (1)

Neglect the core hole potential
Neglect finite core hole lifetime

$$G^R(r_j,\epsilon) = \sum_n \frac{\langle 0|\Psi_j|n\rangle\langle n|\Psi_j^\dagger|0\rangle}{\epsilon-(E_n^{N+1}-E_0^N)+i0} + \sum_n \frac{\langle 0|\Psi_j^\dagger|n\rangle\langle n|\Psi_j|0\rangle}{\epsilon-(E_n^{N-1}-E_0^N)+i0}$$

RSXS intensity can be related to the electron part of the Green's function

$$I(q,\omega) = |\sum_j \mathrm{ImG}_e(r_j,\omega)e^{-iqr_j}|^2$$

RSXS intensity can be related to STM Fourier transforms of LDOS

$$\rho^{\mathrm{STM}}(\epsilon,q) = \sum_j \rho^{\mathrm{STM}}(\epsilon,r_j)e^{-iqr_j} = \sum_j \mathrm{Im}G(\epsilon,r_j)e^{-iqr_j}$$

Relating REXS and STM

Quasiparticle interference in $Bi_2Sr_2CaCu_2O_{8+\delta}$, J. Hoffman et al., Science (2002)

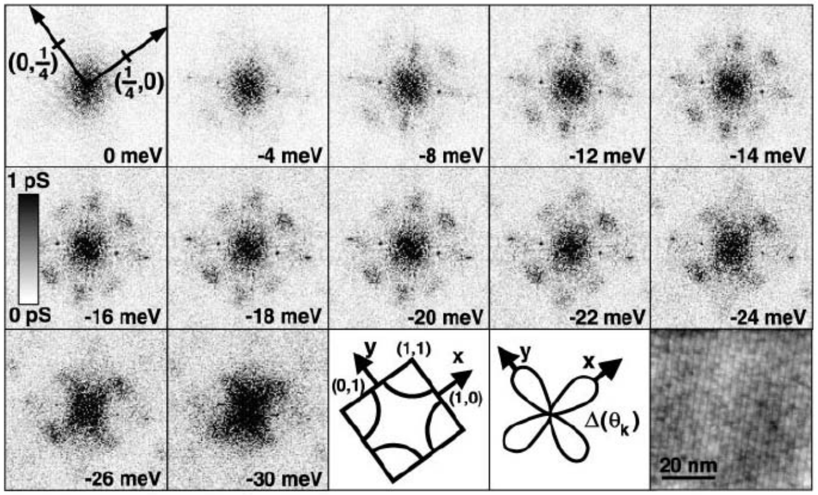


Fig. 3. A series of 12 Fourier transforms of LDOS images measured on a 600 Å square FOV at the energies shown in each panel. The origin and points (1/4, 0) $2\pi/a_0$ and (0, 1/4) $2\pi/a_0$ are labeled.

RSXS can be related to the electron part of STM spectra

$$I(q,\omega) = \left| \int_0^\infty \frac{\rho_e^{\mathrm{STM}}(\epsilon,q)}{\epsilon-\omega-i0} \right|^2$$

REXS simplified (2)

Neglect the core hole potential

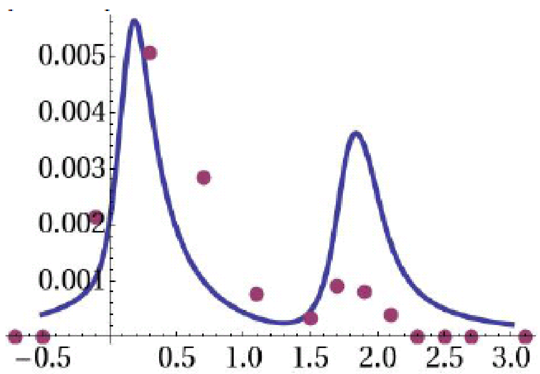
Include the core hole lifetime

$$H = \sum_{\mathbf{k}} \xi_{\mathbf{k}} d^\dagger_{\mathbf{k}} d_{\mathbf{k}} + V \sum_{\mathbf{k}} \left(d^\dagger_{\mathbf{k}+\mathbf{Q}} d_{\mathbf{k}} + d^\dagger_{\mathbf{k}} d_{\mathbf{k}+\mathbf{Q}} \right)$$

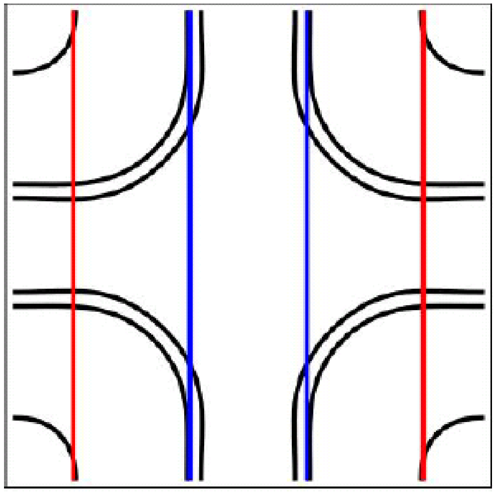
$$\xi_{\mathbf{k}} = -t(\cos k_x + \cos k_y) + 4t_1 \cos k_x \cos k_y - 2t_2(\cos 2k_x + \cos 2k_y)$$

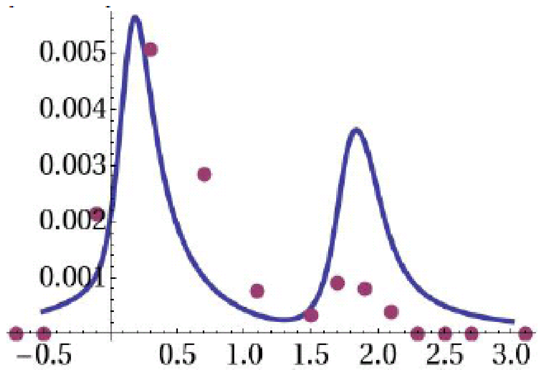
Take "canonical" parameters from ARPES and DFT

$$I(q,\omega_i) = |\sum_{nj} \frac{\langle 0|\Psi_j|n\rangle\langle n|\Psi^\dagger_j|0\rangle}{(E^N_0 - E^{N+1}_n + \omega_i + i\Gamma)} \; e^{-iqr_j}\,|^2$$

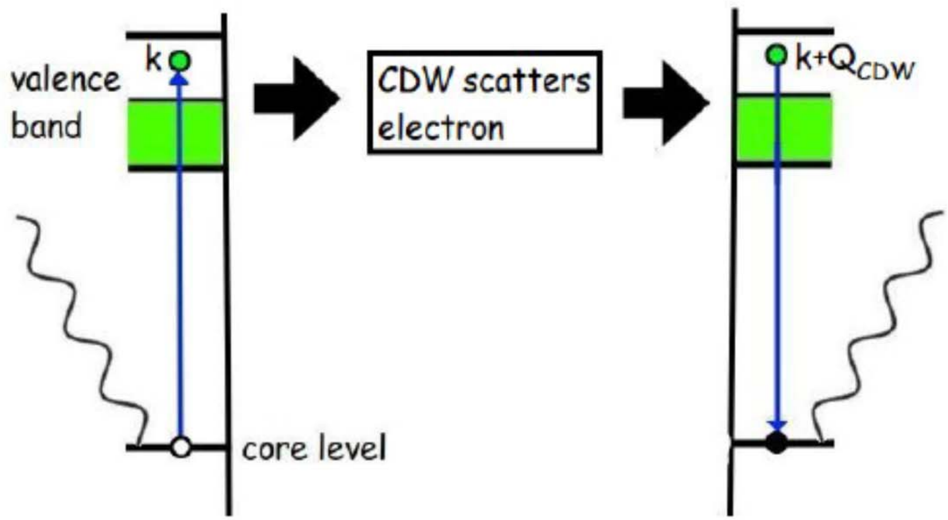


Two peak structure in REXS: dynamic nesting





REXS as dynamic problem



$$A_{i\to i} = \sum_m e^{i(\mathbf{k}_f-\mathbf{k}_i)\cdot\mathbf{R}_m}\langle i|d_m(\omega+H_m-E_i+i\Gamma)^{-1}d_m^\dagger|i\rangle$$

$$= \int_0^\infty dt\, e^{(i\omega-\Gamma)t}\sum_m e^{i\mathbf{Q}_{CDW}\cdot\mathbf{R}_m}\underbrace{\langle i|d_m e^{-iH_m t}d_m^\dagger e^{-iH_0 t}|i\rangle}_{S_m(t)}$$

=Fourier transform of a history: excite, propagate, de-excite

REXS cross section from functional determinant formalism

$$S_m(t) = \langle i | d_m e^{-iH_m t} d_m^\dagger e^{-iH_0 t} | i \rangle$$

$$= \underbrace{\det\left((1-N) + U_m(t)N\right)^2}_{\text{Fermi sea}} \underbrace{\langle m | \left(\frac{N}{1-N} + U_m^{-1}(t) \right)^{-1} | m \rangle}_{\text{photoexcited electron}},$$

$$N \equiv (1 + \exp(\beta h_0))^{-1}, \quad U_m(t) \equiv e^{-ih_m t} e^{ih_0 t}$$

- N: *single-particle* Fermi sea occupation
- U_m *single-particle* time-evolution with core hole at $\mathbf{R}_m$
- det: device for matrix elements of Slater determinant state
- $\det(\,)^2$: one Fermi sea for each spin
- $(1-N) + U_m(t)N$: time-evolve only occupied states.
- $|m\rangle$ Wannier orbital at $\mathbf{R}_m$.
- $\langle m| \, |m\rangle$: Propagator $\langle m|U_m(t)|m\rangle$ for $N=0$, Pauli-blocking 0 for $N=1$.

Functional determinant formalism

Consider $\langle e^X \rangle = \mathrm{tr}\left[e^X e^{-\beta H}\right] / \mathrm{tr}\left[e^{-\beta H}\right]$ for quadratic X, H.

- In basis where $X = \sum_\alpha \omega_\alpha \hat{n}_\alpha$

$$\mathrm{tr}\left[e^X\right] = \prod_\alpha \sum_{n_\alpha=0,1} e^{n_\alpha \omega_\alpha} = \prod_\alpha (1 + e^{\omega_\alpha}) = \det\left(1 + e^X\right)$$

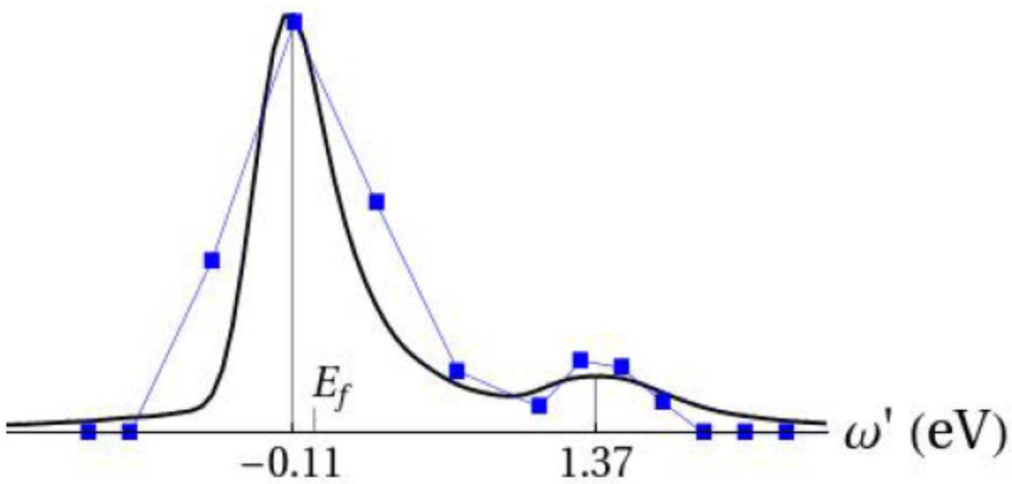
- BCH: $e^X e^Y = e^Z$, Z quadratic, $\mathrm{tr}\left[e^X e^Y\right] = \det\left(1 + e^X e^Y\right)$
- Insertions: $\mathrm{tr}\left[d_m^\dagger d_n e^Z\right] = \sum_{\alpha,\beta} \langle \alpha | n \rangle \langle m | \beta \rangle \mathrm{tr}\left[d_\alpha^\dagger d_\beta e^Z\right] =$

$$\sum_\alpha \langle m|\alpha\rangle\langle\alpha|n\rangle \mathrm{tr}\left[\hat{n}_\alpha e^Z\right] = \sum_\alpha \langle m|\alpha\rangle\langle\alpha|n\rangle \prod_{\gamma\neq\alpha} (1 +$$

$$e^{\omega_\gamma}) \sum_{n_\alpha=0,1} n_\alpha e^{n_\alpha \omega_\alpha} = \sum_\alpha \langle m|\alpha\rangle\langle\alpha|n\rangle \frac{\det(1+e^Z)}{1+e^{\omega_\alpha}} e^{\omega_\alpha} =$$

$$\sum_\alpha \langle m| \frac{e^Z}{1+e^Z} |\alpha\rangle\langle\alpha|n\rangle \det(1+e^Z) = \langle m| \frac{e^Z}{1+e^Z} |n\rangle \det(1+e^Z)$$

REXS cross section from functional determinant formalism



Model of weakly interacting quasiparticles can explain REXS data qualitatively when we include nonequilibrium dynamics of electrons in the presence of core hole potential. Implication for microscopic models of cuprates: long lived electron quasiparticles. Observed numerically in DMFT by Georges et al, PRL (2013)

Resonant Inelastic XRay Scattering (RIXS)

Dispersive spin excitations in highly overdoped cuprates

Le Tacon et al., PRB (2013)
see also Dean et al., PRL (2013)

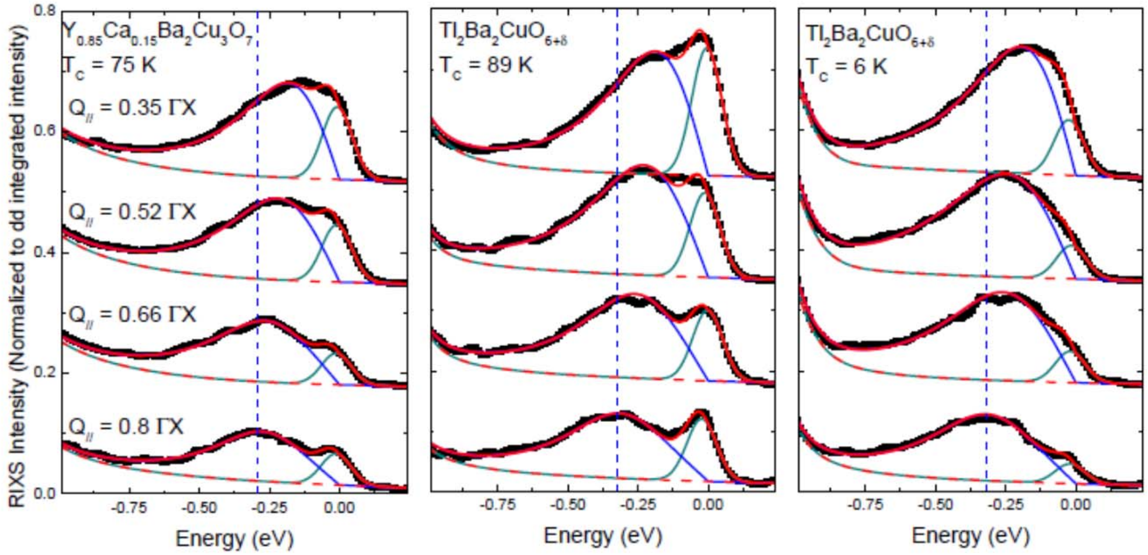
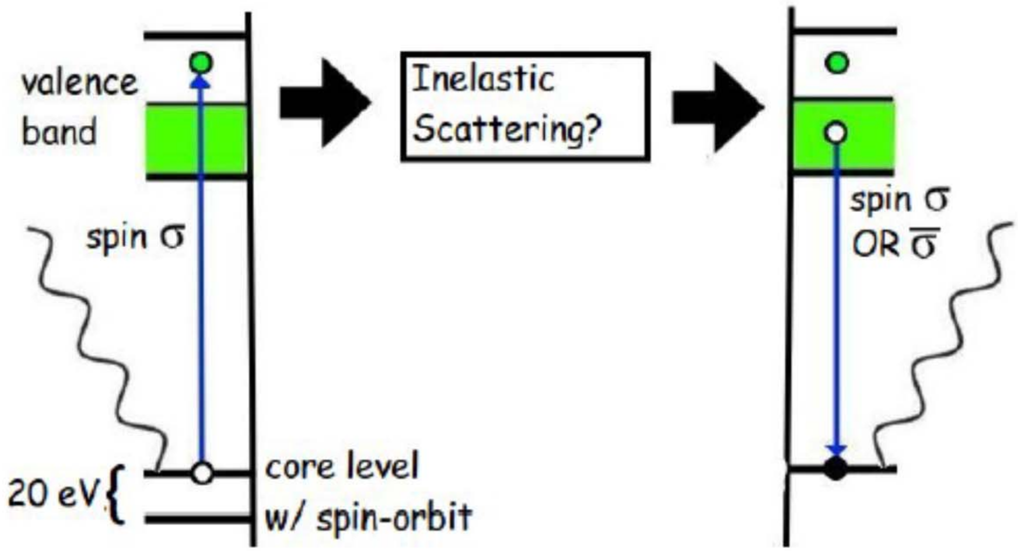


FIG. 2: (Color online) Low energy part of the RIXS spectra of overdoped $Y_{0.85}Ca_{0.15}Ba_2Cu_3O_{6+x}$ (left panel), moderately overdoped $Tl_2Ba_2CuO_{6+\delta}$ (T_c = 89 K, middle panel) and strongly overdoped $Tl_2Ba_2CuO_{6+\delta}$ (T_c = 6 K) in the π scattering geometry for various in-plane momentum transfers $Q_{//}$. The fitting procedure is detailed in Ref. [13]. The slightly more intense

Neutron scattering does not observe strong magnetic scattering in this frequency range. These materials should be good metals with suppressed magnetic fluctuations (also lower Tc)

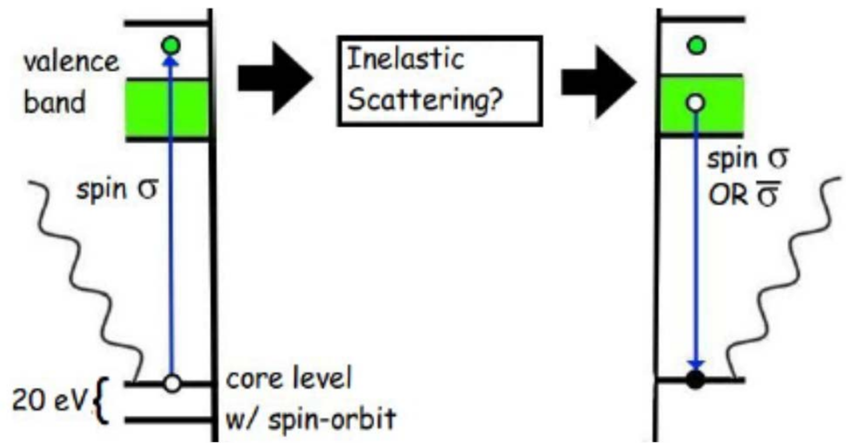
RIXS cross section



$$A_{i\to f} = \sum_{m,\sigma} e^{i(\mathbf{k}_f - \mathbf{k}_i)\cdot \mathbf{R}_m} \langle f | d_{m,\sigma \,\mathrm{OR}\, \bar{\sigma}} (\omega + H_m - E_i + i\Gamma)^{-1} d^{\dagger}_{m,\sigma} | i \rangle$$

Spin flip processes are possible due to spin-orbit of core level
Polarized incoming beam can select either spin-flip or non-spin-flip

RIXS cross section



RIXS amplitude as Fourier transform of “history”

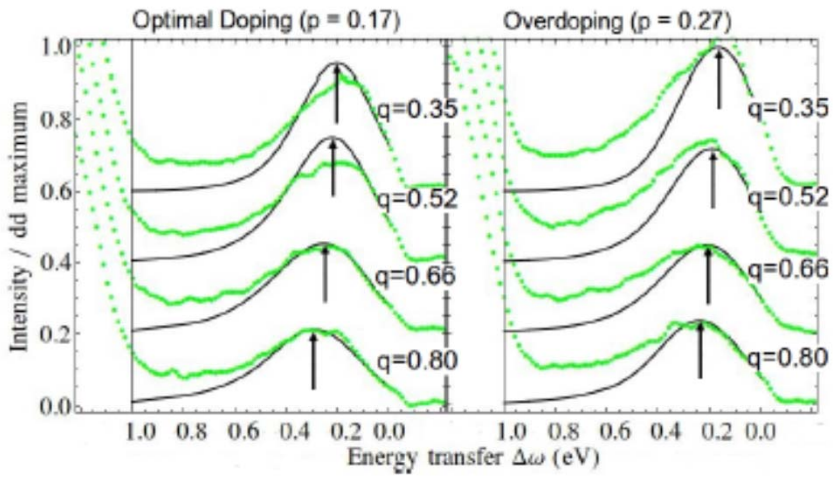
$$I \propto \int_{-\infty}^{\infty} ds \int_{0}^{\infty} dt \int_{0}^{\infty} d\tau \; e^{i\omega(t-\tau)-is\Delta\omega-\Gamma(t+\tau)} \sum_{mn} e^{i\mathbf{Q}\cdot(\mathbf{R}_m-\mathbf{R}_n)} \chi_{\rho\sigma}\chi_{\mu\nu} S^{mn}_{\rho\sigma\mu\nu}$$

$$S^{mn}_{\rho\sigma\mu\nu} = \langle e^{iH\tau} d_{n\rho} e^{-iH_n\tau} d^{\dagger}_{n\sigma} e^{iHs} d_{m\mu} e^{iH_m t} d^{\dagger}_{m\nu} e^{-iH(t+s)} \rangle.$$

$\chi_{\alpha\beta}$ Polarization dependent matrix element

Forward and backward “histories” (Keldysh like)

Dispersing peaks in RIXS from quasiparticle model



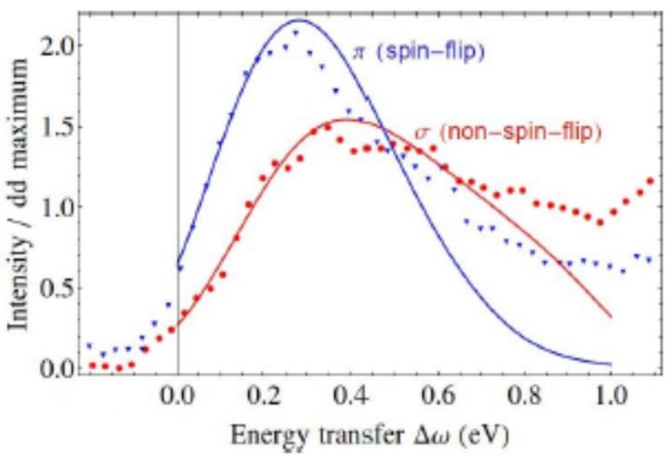
Green line – experiments on Tl-2201
by Le Tacon et al, PRB (2013)
Black line – quasiparticle model

$$(t_1, t_2, t_3, t_4) = (181, -75, -4, 10) \text{ meV}$$

standard band structure parameters

$$U_c = 1.0 \text{ eV}$$

Difference in spin-flip and non-spin-flip cross sections



dots– experiments in Bi-2212
by Dean et al, PRL (2013)
lines – quasiparticle model

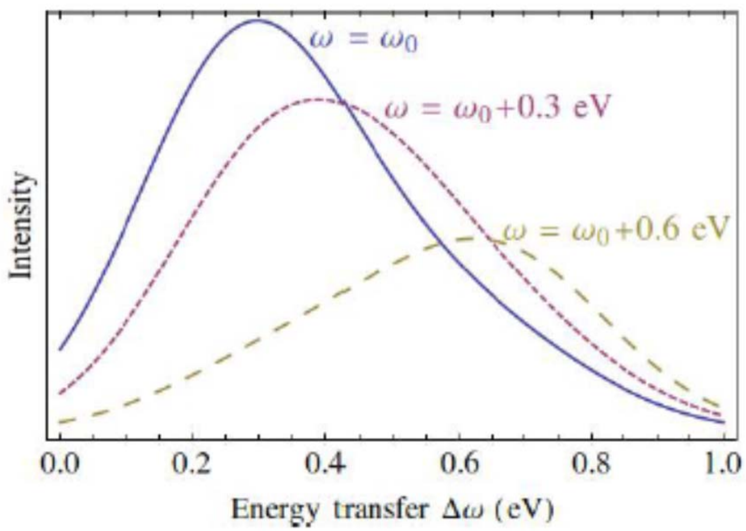
$$(t_1, t_2, t_3, t_4) = (126, -36, 15, 1.5)\ \mathrm{meV}$$

standard band structure parameters

$$U_c = 1.0\ \mathrm{eV}$$

The core hole potential separates spin flip and non-spin flip lineshapes.
Attractive potential of the hole tends to keep the photoexcited electron bound near the hole site leading to elastic scattering. Pauli blocking prevents other electrons of the same spin from hopping into this site and filling the core hole, thereby robbing spectral weight from inelastic scattering. With sufficient energy the photoexcited electron may be dislodged, allowing inelastic scatterin
Inelastic scattering with small energy transfer $\Delta\omega$ is suppressed relative to scattering at larger $\Delta\omega$.
In spin-flip scattering electrons are not Pauli blocked.

False-fiable prediction of quasiparticle model of RIXS

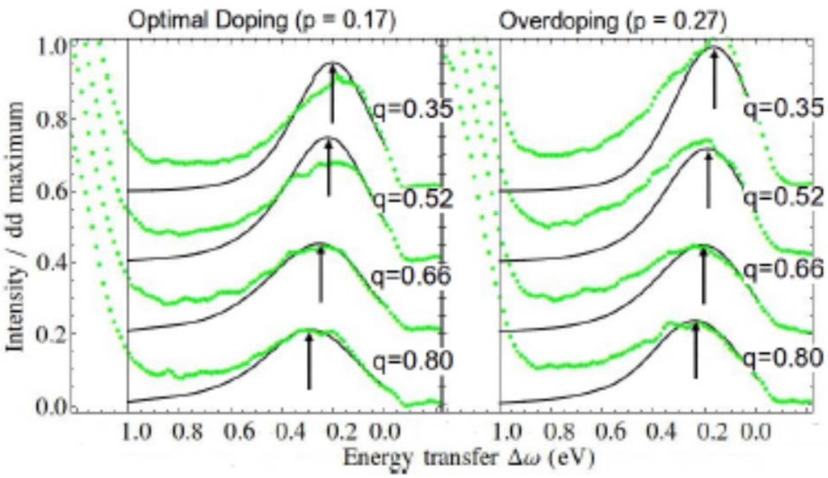


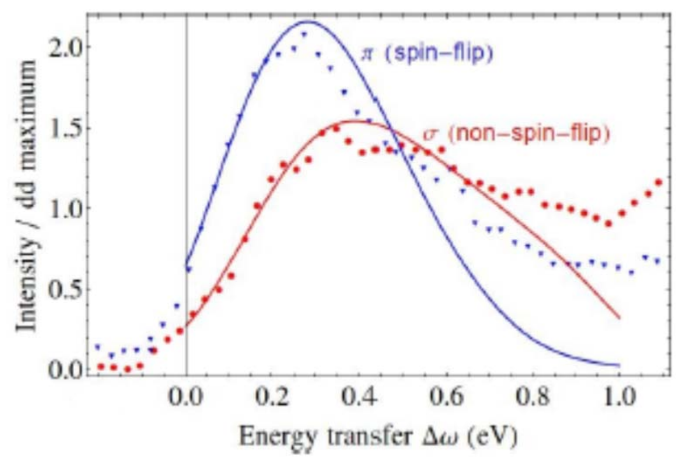
Dependence of scattering intensity on incoming photon energy.
Optimally doped Bi-2201 for Q = (π/a,0).

Frequency ω_0 corresponds to the absorption maximum.

The increase in $\Delta\omega$ with ω does not occur if the peak is due to collective mode.
It is a signature of particle-hole continuum

Quasiparticle model of RIXS



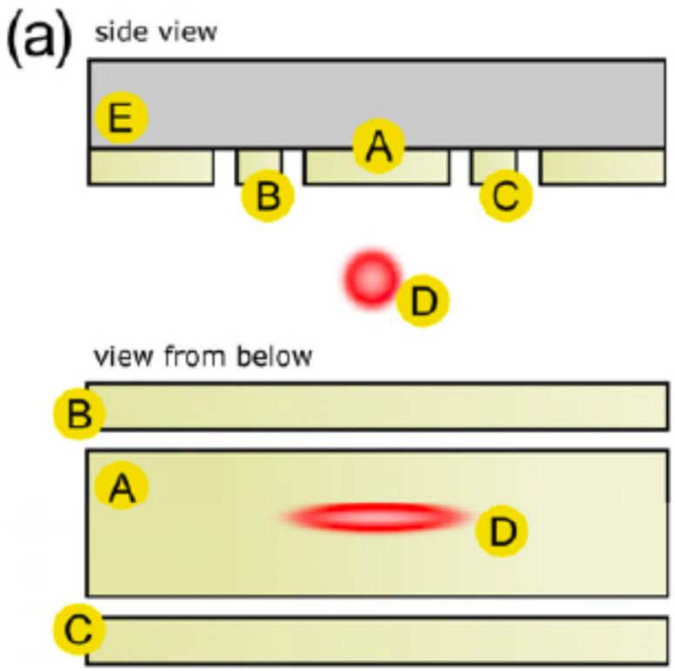


Model of weakly interacting quasiparticles can explain key features of RIXS when we include nonequilibrium dynamics of electrons in the presence of core hole potential. Remaining puzzle: continuity of spectra into Mott AF states.

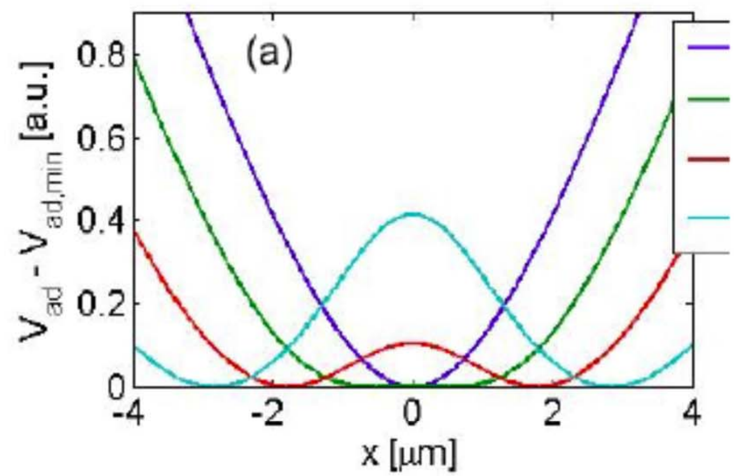
Nonequilibrium dynamics of coherently split one dimensional condensates

Theory: K. Agarwalk, E. Dalla Torre, E. Demler
Experiments: Schmiedmayer's group in TU Vienna

The Experiment - Apparatus



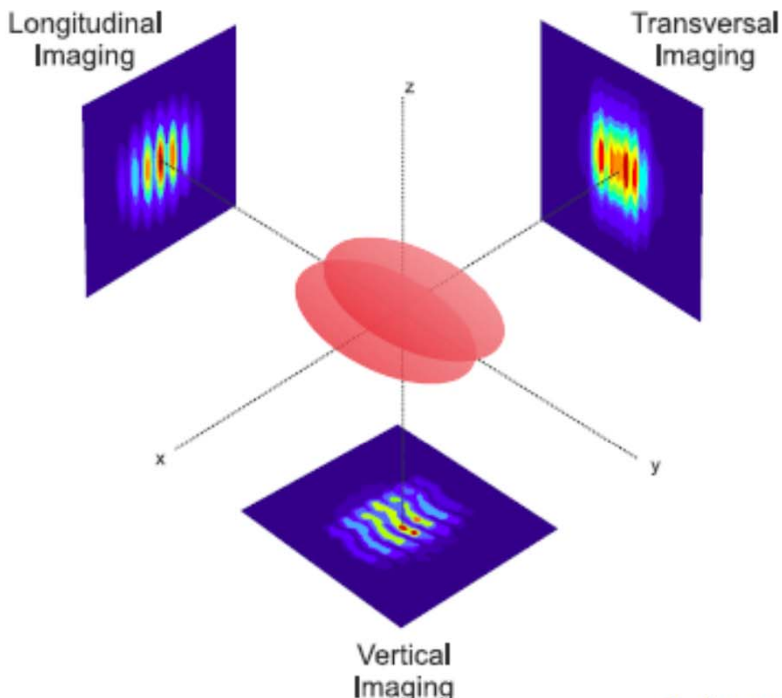
Rb atoms, $F = 2, m_F = 2$



Splitting process

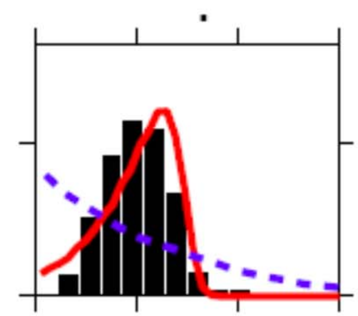
atomchip.org – Jorg Schmiedmayer group at University of Vienna

Interference of 1D Bose Gases



$$\alpha = \left| \int_{-l/2}^{l/2} \frac{dx}{l} e^{i\phi(x)} \right|^2$$

$P(\alpha)$:

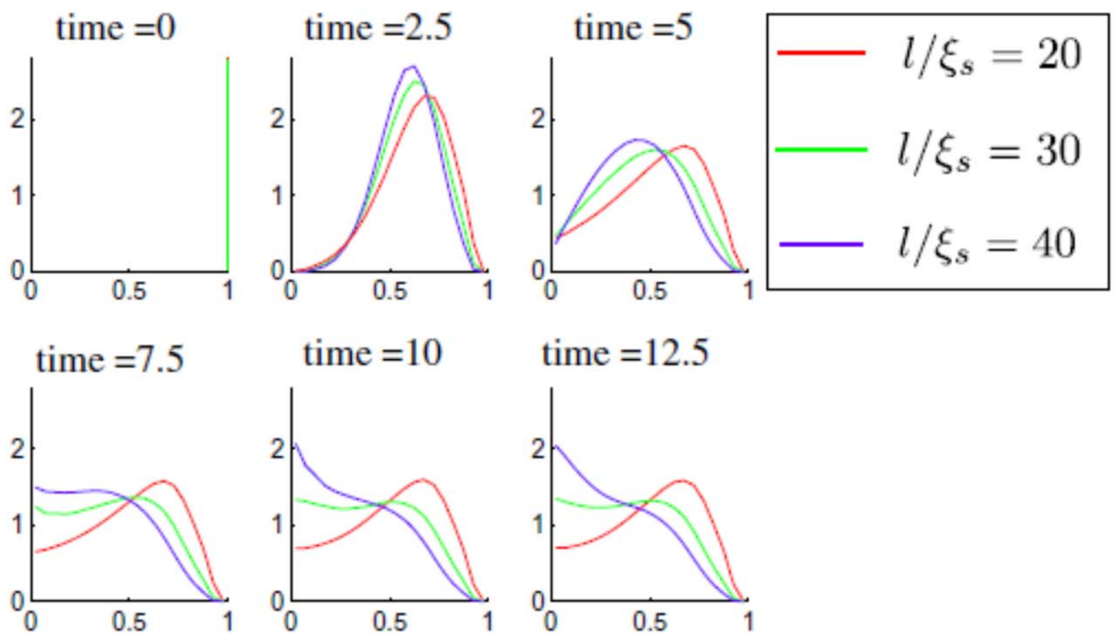


A. Imambekov et al., Phys. Rev. A 77, 063606 (2008)

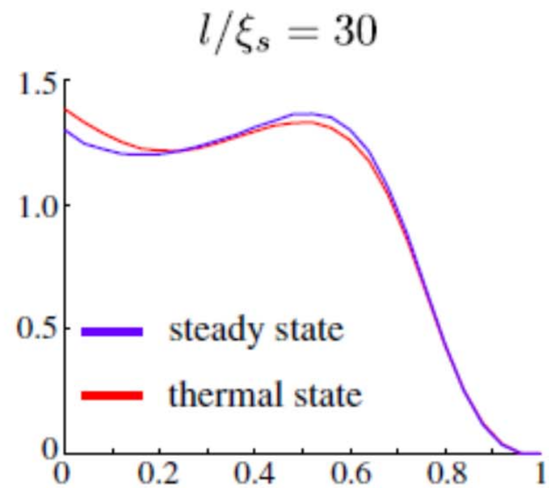
atomchip.org – Jorg Schmiedmayer group at University of Vienna

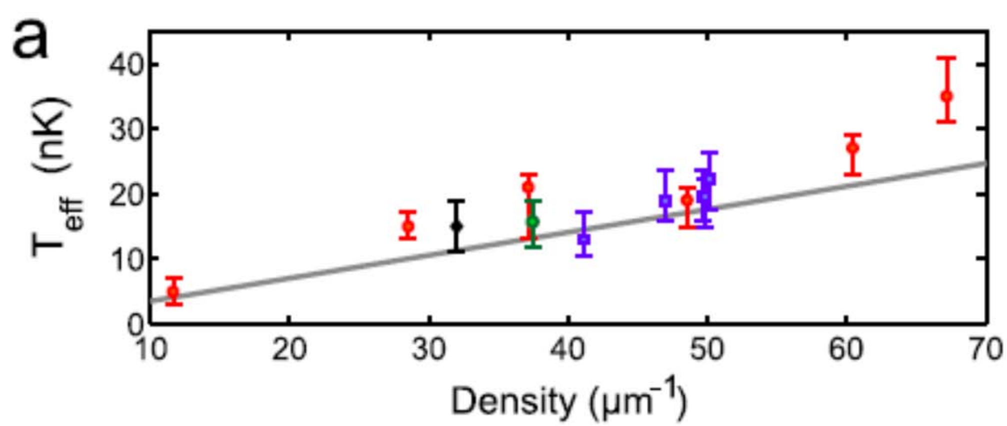
Time evolution of the DF $P(\alpha)$

$$\alpha = \left| \int_{-l/2}^{l/2} \frac{dx}{l} e^{i\phi(x)} \right|^2$$



Sudden Splitting and Prethermalization





$$k_B T_{eff} = \mu/2 = g\rho/2$$

T. Kitagawa *et al.* 2011 *New J. Phys.* **13** 073018

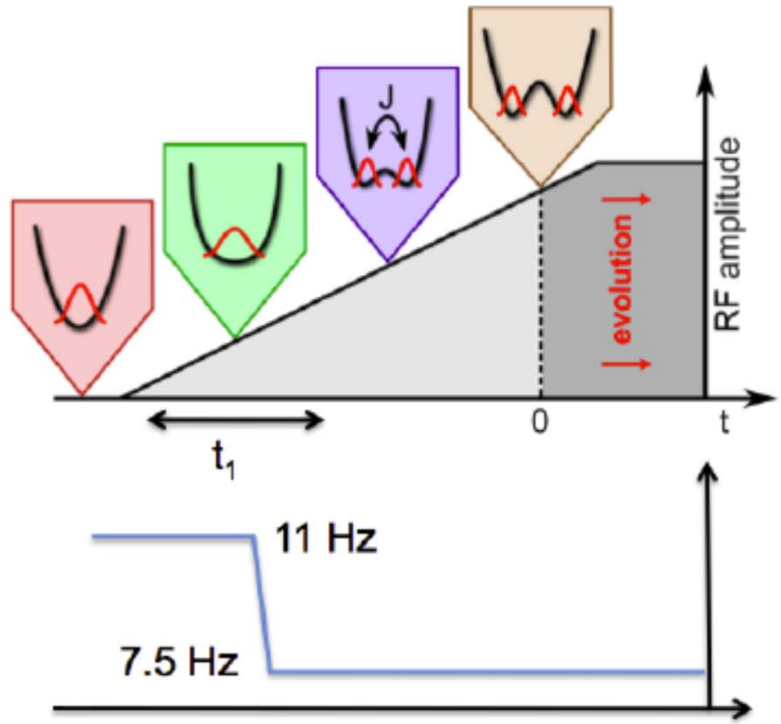
M. Gring *et al.* 2012 *Science*

The splitting process

Slides courtesy of
Tim Langen

radial
trapping potential

longitudinal
trapping potential



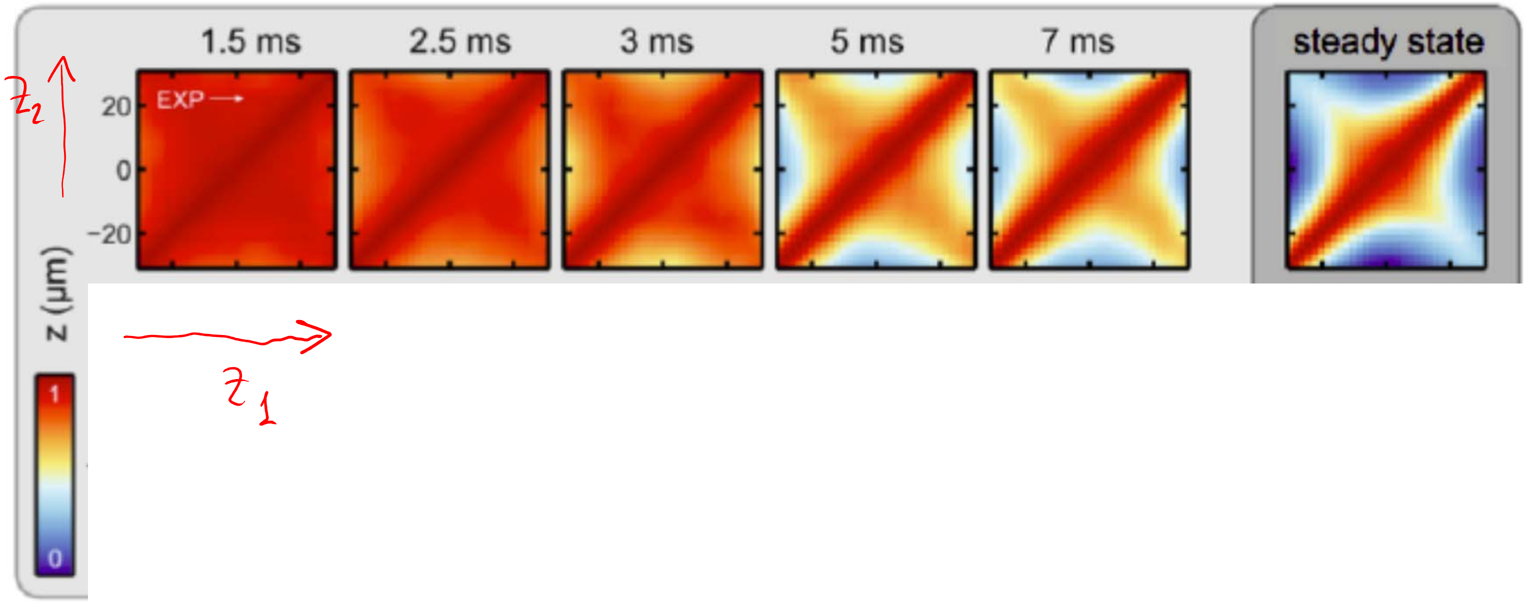
So far, we cooled into 7.5 Hz trap,
or split very slow in the beginning (large t_1)!

Different splitting

Slides courtesy of Tim Langen

Fast first segment of the ramp

$\langle e^{i\varphi(z_1)} e^{-i\varphi(z_2)} \rangle$



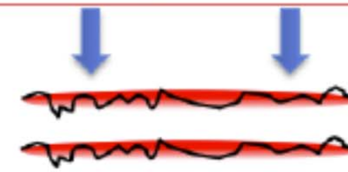
Correlations at x,-x arise from population difference of Symm./Asymm modes.

$$\phi \sim \int \frac{dk}{k} \; \left[\cos(kx) a_k^S + \; \sin(kx) a_k^A + \text{h.c.}\right]$$

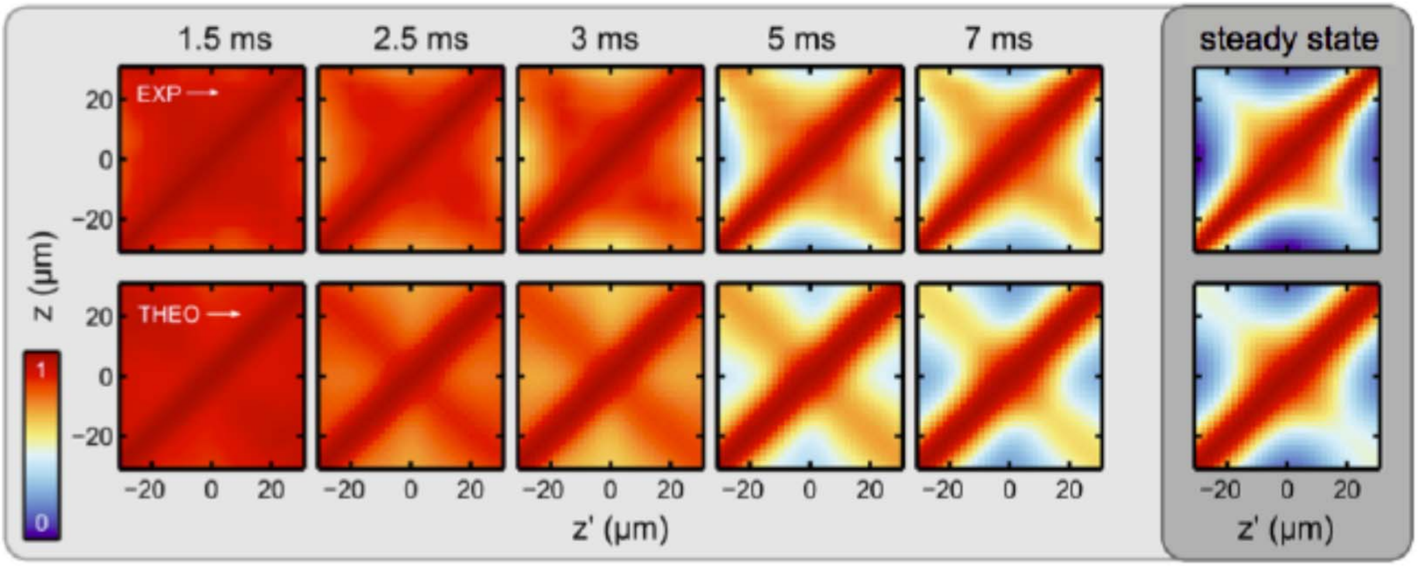
$$\begin{aligned}\left\langle (\phi(x_1) - \phi(x_2))^2 \right\rangle &= \int \frac{dk}{k} \left(1 - \cos(k(x_1 - x_2))\right) \left(N_k^S + N_k^A + 1\right) \\ &+ \int \frac{dk}{2k} \left(\cos(2kx_1) + \cos(2kx_2) - 2\cos(k(x_1 + x_2))\right) \left(N_k^S - N_k^A\right)\end{aligned}$$

Different splitting

Slides courtesy of
Tim Langen



Fast first segment of the ramp



Correlations of z = -z‘, stronger population of even modes

$$\beta_{2m} = k_B\,(T_{eff} + \Delta T)^{-1}$$
$$\beta_{2m+1} = k_B\,(T_{eff} - \Delta T)^{-1}$$

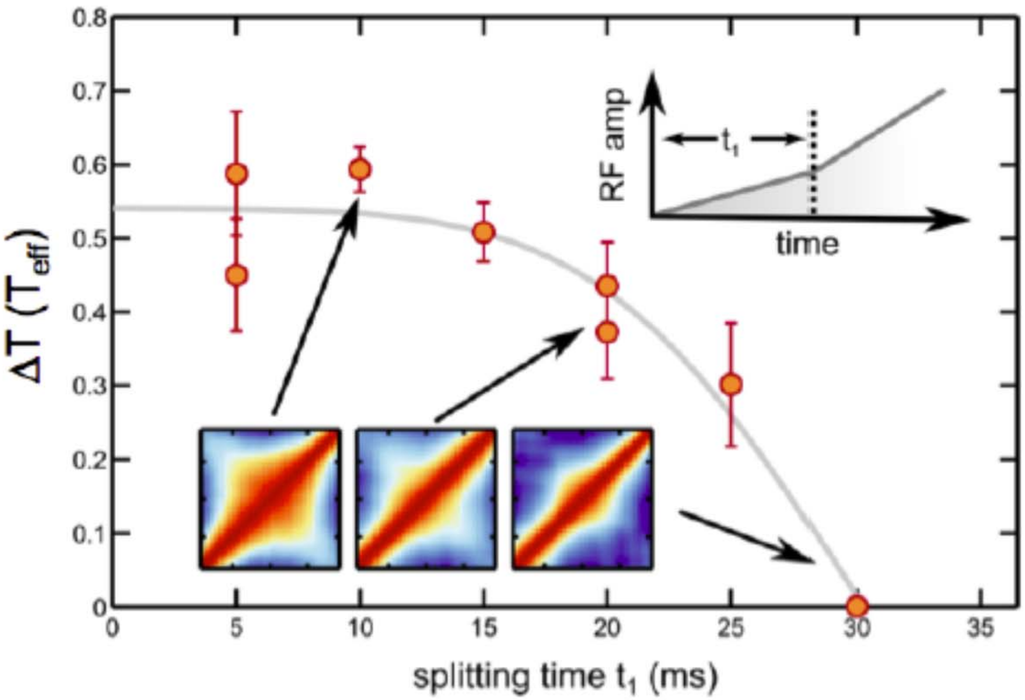
GGE !

Here: $\Delta T = 0.6\ T_{eff}$

Different splitting

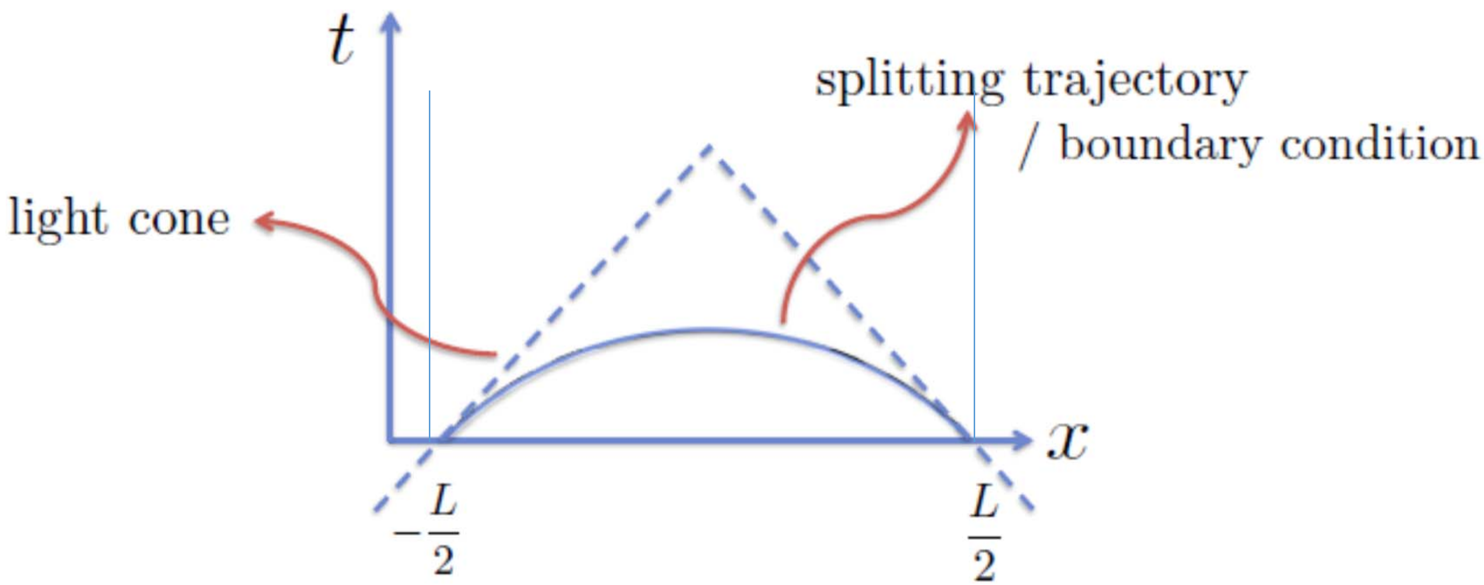
Slides courtesy of
Tim Langen

Changing the speed of the ramp changes the temperatures



Generalization of quench models

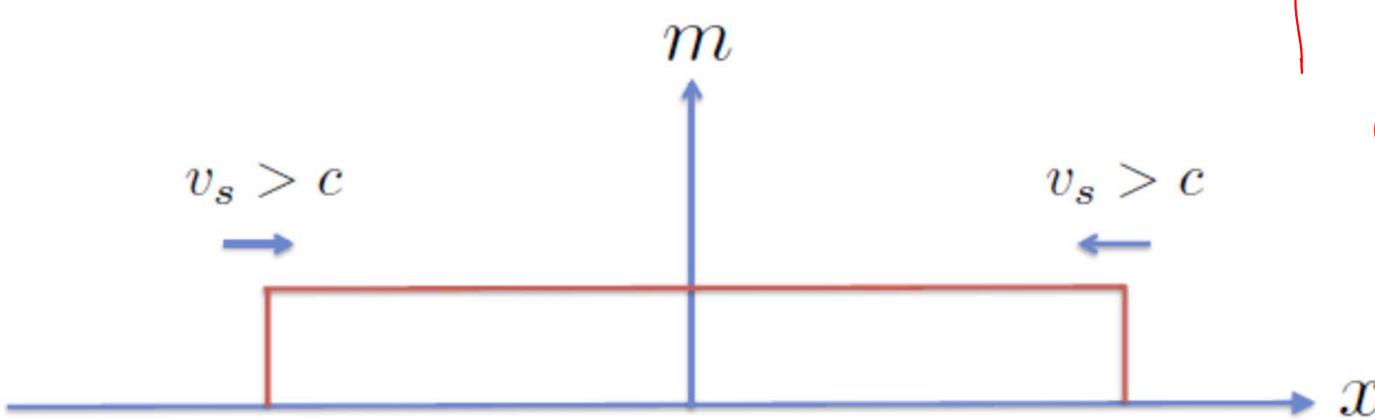
Fully utilizing the conformal symmetry of the post-quench Hamiltonian to solve a case of more general quench space-time trajectory



Dynamics of the relative phase

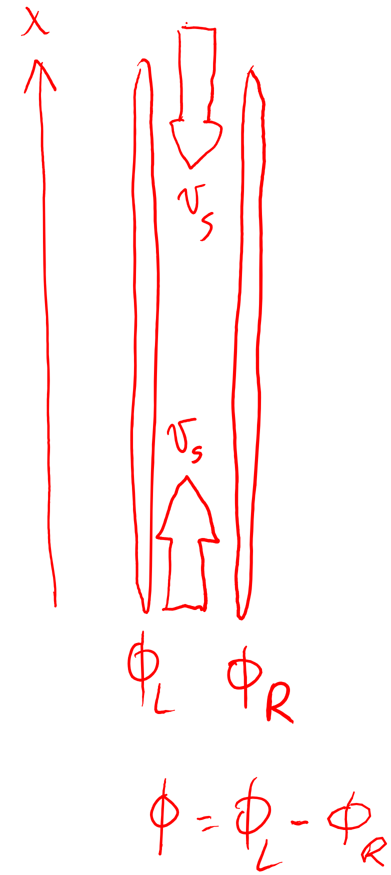
$$H(t) = \int dx\ 2gn^2 + \frac{\rho}{4m}(\partial_x \phi)^2 + m_0^2(x,t)\phi^2$$

$$m_0^2 = 2g\rho^2\left(1 - \Theta(x + v_s t)\right)\left(\Theta(x - v_s t)\right)$$

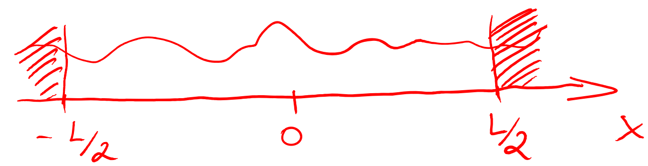


System initially in the ground state of :

$$H(-\infty) = \int dx\ \left[2gn^2 \frac{\rho}{4m}(\partial_x \phi)^2 + 2g\rho^2\phi^2\right]$$



Symmetric/Anti-symmetric Hamiltonians



$$H_{S/A} = \int_0^{L/2} dx\; g n_{S/A}^2 + \frac{\rho}{2m}(\partial_x \phi_{S/A})^2 + m^2(x,t)\phi_{S/A}^2$$

$$m^2 = 4g\rho^2\,(1 - \Theta(x + v_s t))$$

$$\phi(x > 0) = \phi_S(x) + \phi_A(x)$$
$$\phi(x < 0) = \phi_S(|x|) - \phi_A(|x|)$$

$$\phi_A(0) = 0$$
$$\partial_x \phi_S(0) = 0$$

$$\partial_x \phi_{S/A}(x = L/2) = 0$$

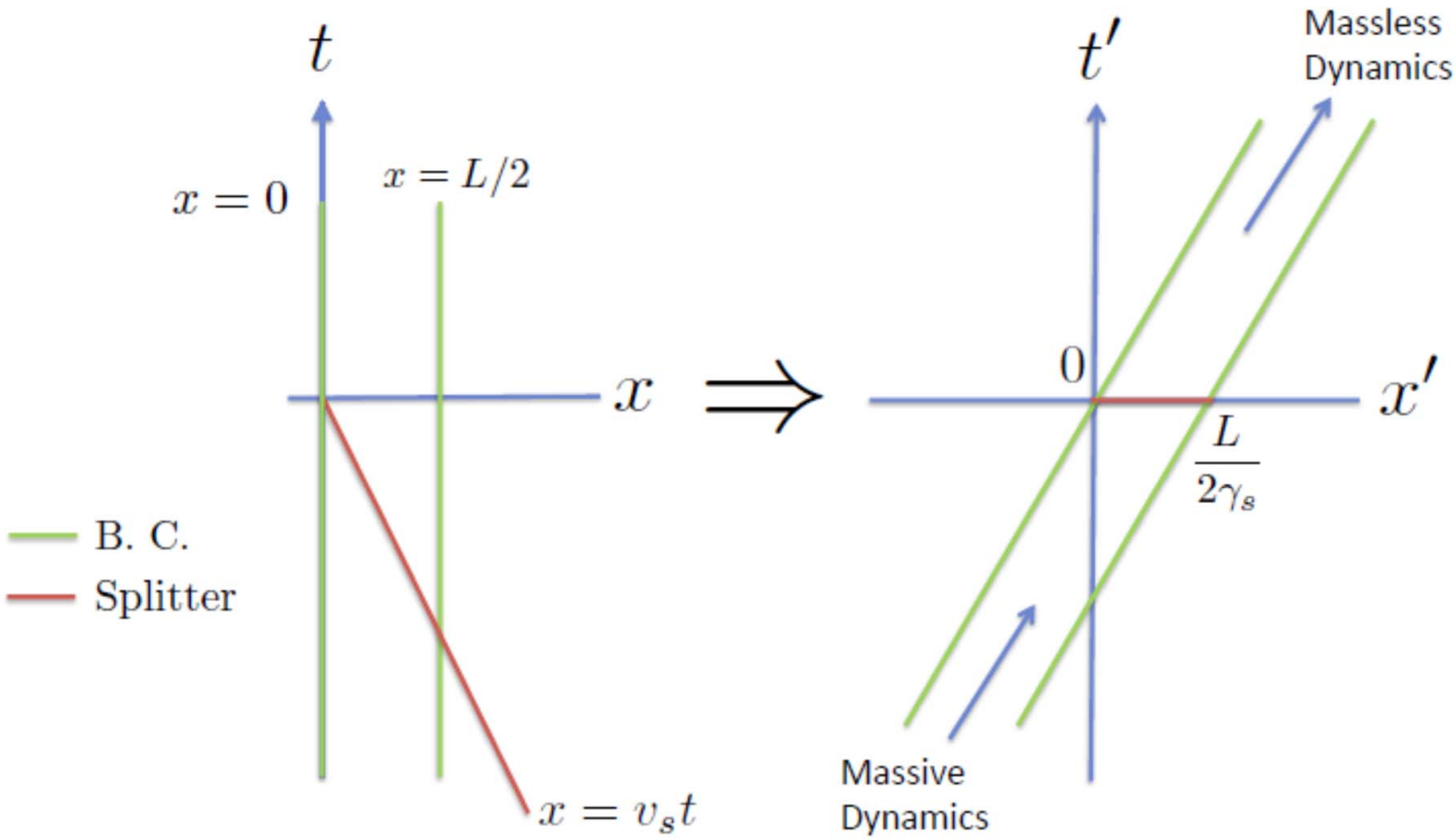
Life in the Lorentz Boosted Frame

$$t' = \gamma_{u_s}(t + u_s x)$$
$$x' = \gamma_{u_s}(x + u_s t)$$
$$\boxed{u_s = c^2/v_s}$$

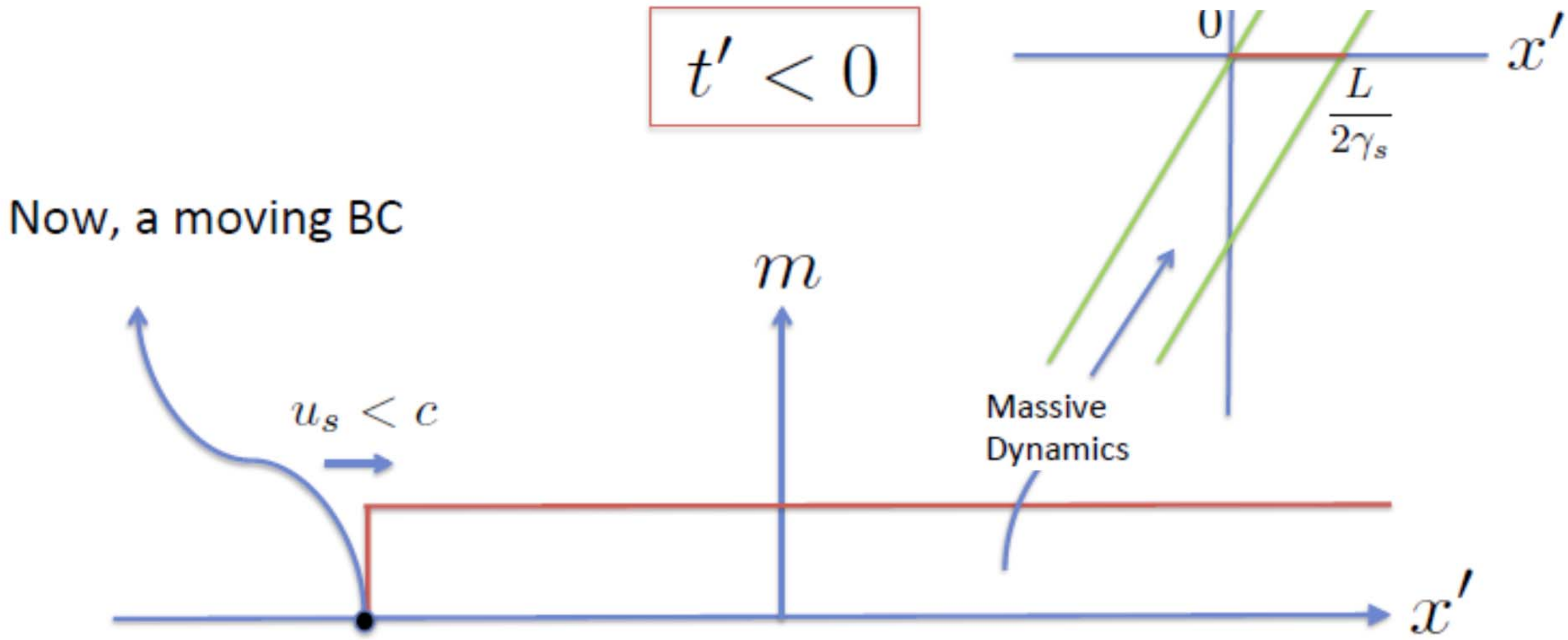
$$1 - \Theta(x + v_s t) = \Theta(-t')$$

Quench is instantaneous.

Calculations and Simulations for a finite size system : Boundary Conditions



Life in the Lorentz Boosted Frame



$$\phi_A(x=0) = 0 \rightarrow \phi_A(x' = u_s t') = 0$$

$$\partial_x \phi_S(x=0) = 0 \rightarrow (\partial'_x + u_s \partial'_t)\phi_S(x' = u_s t') = 0$$

At the right boundary both fields have $\partial_x \phi_{S/A}(x = L/2) = 0$

What are the linearly independent solutions?

$$t' < 0$$

$$v_k^{\pm,(1)} = B_k \left(e^{-ikx - i\omega'_k t} \pm e^{if(k)x - i\omega'_{f(k)} t} \right) \;\; ; k > 0$$

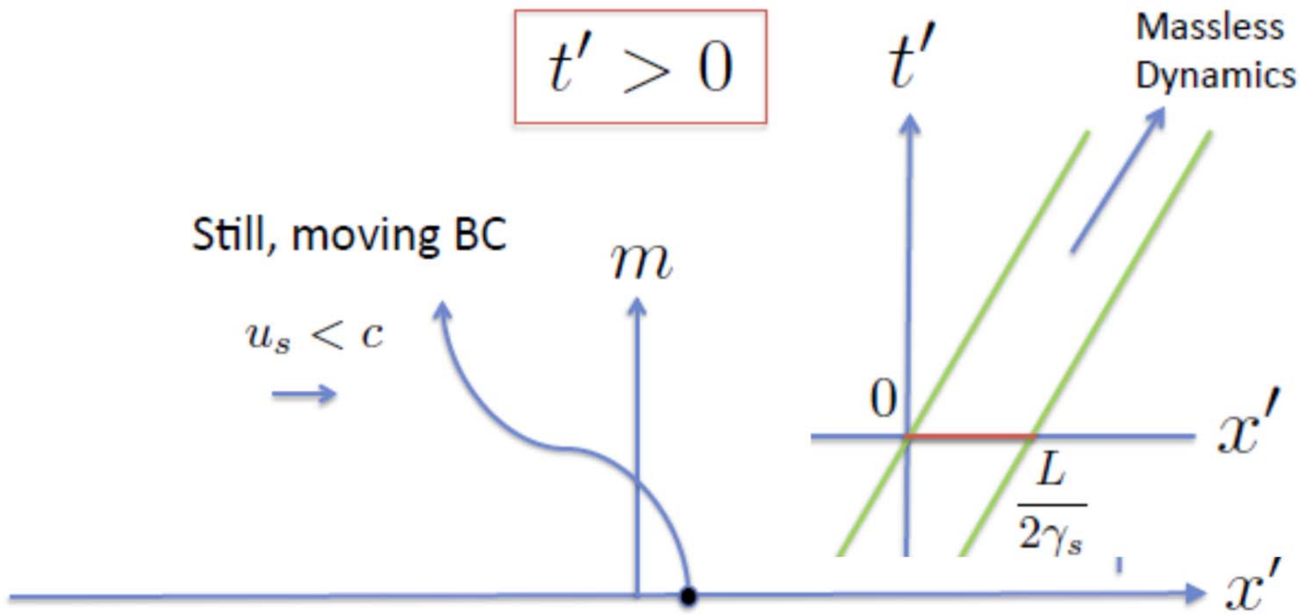
$$v_k^{\pm,(2)} = C_k \left(e^{ikx - i\omega'_k t} \pm e^{ig(k)x - i\omega'_{g(k)} t} \right) \; ; 0 < k < k_0$$

$$k = m \frac{u_s}{\sqrt{1 - u_s^2}} \qquad\qquad \omega'_k = \sqrt{(ck)^2 + m^2}$$

We need 2 sets of modes!

Simple guess : Take two massive modes, and add them up in the right way so that the boundary conditions are satisfied.

Life in the Lorentz Boosted Frame



$$\phi_A(x=0)=0 \rightarrow \phi_A(x'=u_s t')=0$$

$$\partial_x \phi_S(x=0)=0 \rightarrow (\partial'_x + u_s \partial'_t)\phi_S(x'=u_s t')=0$$

$$\partial_x \phi_{S/A}(x=L/2)=0$$

What are the linearly independent solutions?

$$\boxed{t' > 0}$$

$$u_k^{\pm} = A_k \left(e^{-ikv} \pm e^{-i\eta k u} \right) \quad k > 0$$

$$\eta = \frac{1 + u_s}{1 - u_s} \text{ like classical doppler shift}$$

$$A_k = \frac{1}{\sqrt{4\pi k}} \qquad \begin{array}{l} u = (t' - x') \\ v = (t' + x') \end{array}$$

Simple guess : Take two massless modes, and add them up in the right way so that the boundary conditions are satisfied.

Quantization of momentum

- While the modes $v_k^{\pm,(n)}, u_k^{\pm}$ are complicated combinations of waves with different frequencies, in the lab frame , they are a single frequency in time.

$$u_k^{\pm} = \frac{1}{\sqrt{2L(\eta_R k)}} \cos / \sin\left(\eta_R k x\right) e^{-i\eta_R k t}$$

$$v_k^{\pm,(1)} = B_k(L)\ \cos / \sin\left(\gamma_s(k + u_s\omega'_k)x\right) e^{-\gamma_s(\omega'_k + u_s k)t}$$

$$v_k^{\pm,(2)} = C_k(L)\ \cos / \sin\left(\gamma_s(-k + u_s\omega'_k)x\right) e^{-\gamma_s(\omega'_k - u_s k)t}$$

Quantization of k comes from $\partial_x \phi_{S/A}(x = L/2) = 0$

Quench in the boosted frame

- Assume initially (t'<0), the system resides in the ground state of the modes $v_k^{+/-,(1)/(2)}$.
- Re-express old solutions in terms of new ones.

$$
\begin{aligned}
\phi(x',t') &= \sum_{\epsilon=\pm}\left(\sum_{k>0}\left(b_k^{\epsilon,(1)}v_k^{\epsilon,(1)}(x',t')+b_k^{\epsilon,(1)\dagger}v_k^{\epsilon,(1)*}(x',t')\right)+\right.\\
&\left.\sum_{k<k_0}\left(b_k^{\epsilon,(2)}v_k^{\epsilon,(2)}(x',t')+b_k^{\epsilon,(2)\dagger}v_k^{\epsilon,(2)*}(x',t')\right)\right)
\end{aligned}
$$

$$
\phi(x',t') = \sum_{\epsilon=\pm}\sum_k\left(a_k u_k^{\epsilon}(x',t')+a_k^{\epsilon\dagger}u_k^{\epsilon *}(x',t')\right).
$$

Quench in the boosted frame

$$a_k^{\pm} = \sum_{n=1,2} \sum_{k'} (\alpha_{kk'}^{\pm,(n)} b_{k'}^{\pm,(n)} + \beta_{kk'}^{\pm,(n)} b_{k'}^{\pm,(n)\dagger}$$

$$\beta_{kk'}^{\pm,(n)} = -(u_k^{\pm}, v_{k'}^{\pm,(n)})$$

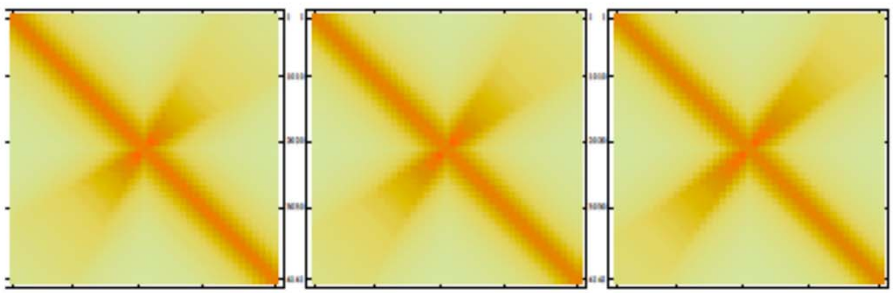
$$\alpha_{kk'}^{\pm,(n)} = (u_k^{\pm}, v_{k'}^{\pm,(n)*})$$

$$(u_1, u_2) = -ic \int_{x'=u_s t'=0}^{x'=\frac{L}{2\gamma_s}\ t'=0} dx' (u_1 \partial_t u_2^* - u_2^* \partial_t u_1)$$

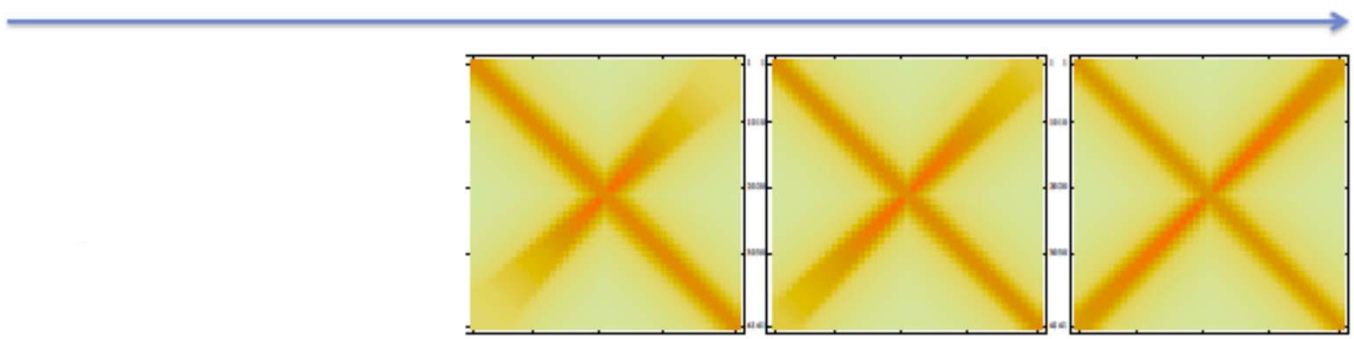
$$N_k^S = \sum_{k'} \left|\beta_{k,k'}^{+,(1)}\right|^2 + \sum_{k'<k_0} \left|\beta_{k,k'}^{+,(2)}\right|^2$$

$$N_k^A = \sum_{k'} \left|\beta_{k,k'}^{-,(1)}\right|^2 + \sum_{k'<k_0} \left|\beta_{k,k'}^{-,(2)}\right|^2$$

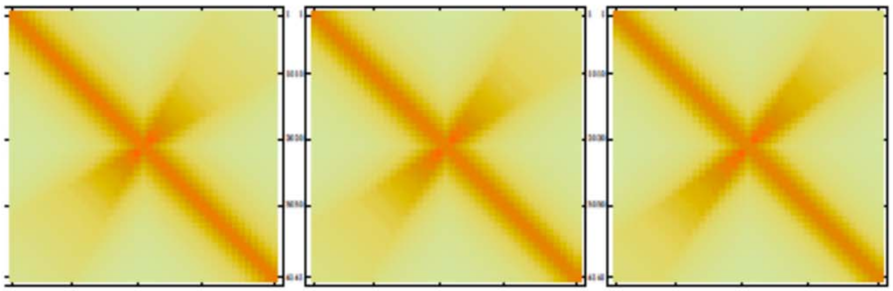
Structure of correlations right after the splitting process is completed



Faster splitting yields stronger cross correlations



Chiral prethermalization



Faster splitting
yields stronger
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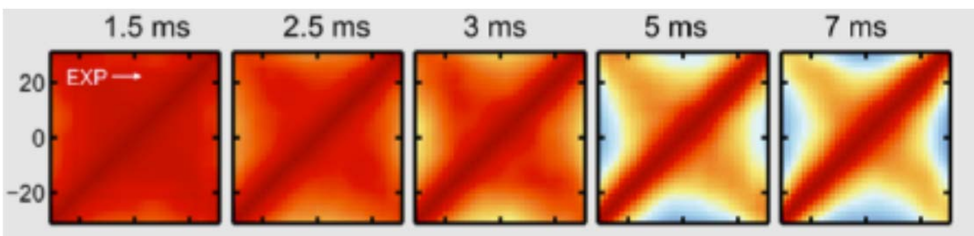

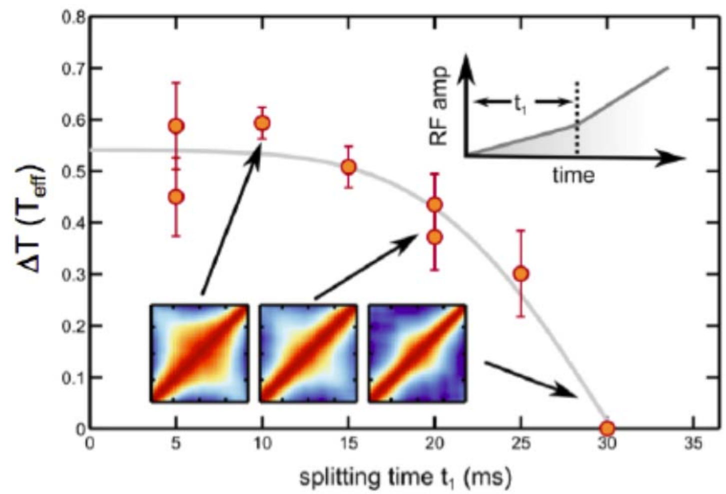

Theory already needs to address interesting puzzles of quantum dynamics

Role of non-equilibrium processes in resonant XRay

Chiral prethermalization in non-uniformly split condensates