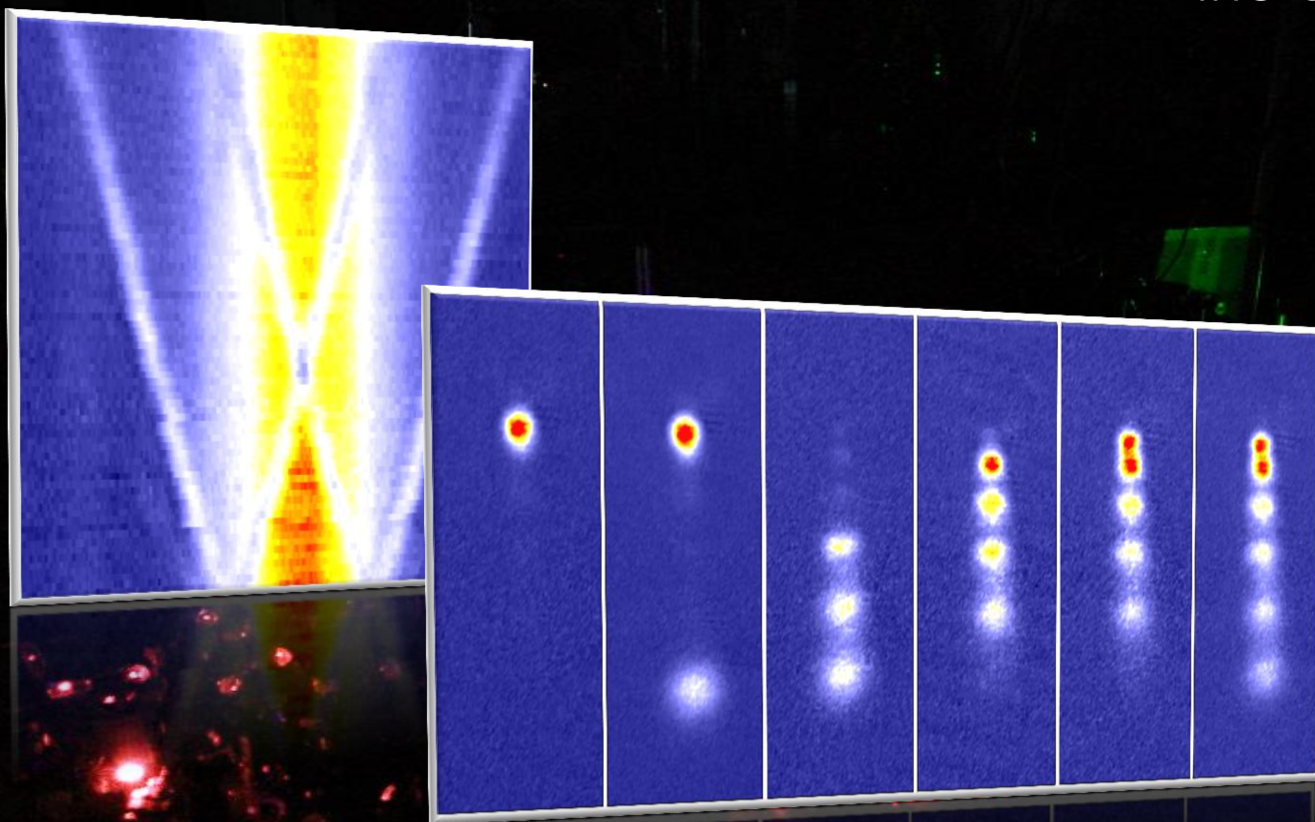
A one-dimensional liquid of fermions with tunable spin

INO-CNR, Pisa 22 May 2014



Carlo Sias

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LENS, University of Florence

European Laboratory for Non-Linear Spectroscopy

INO Istituto Nazionale di Ottica

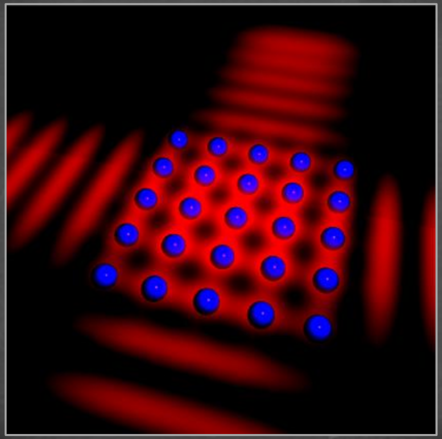
Quantum simulation with ultracold atoms

Ultracold atoms: experimentally controllable quantum systems
(quantum statistics, dimensionality, mobility, interactions, disorder…)

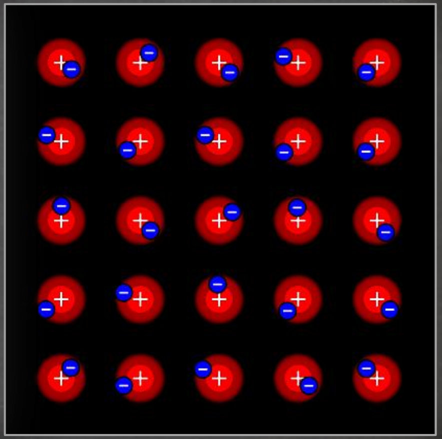
Quantum simulators: *dedicated* quantum computers to solve fundamental problems of quantum physics

R. P. Feynman, International Journal of Theoretical Physics 21, 467 (1982)

atoms in optical lattices



electrons in solids



Already successful for:

Superfluid-insulator transition,
Anderson localization,
Fermionic superfluidity, …

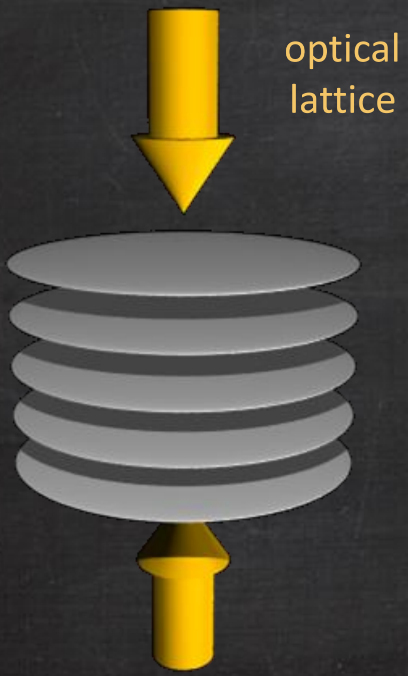
Big challenges:

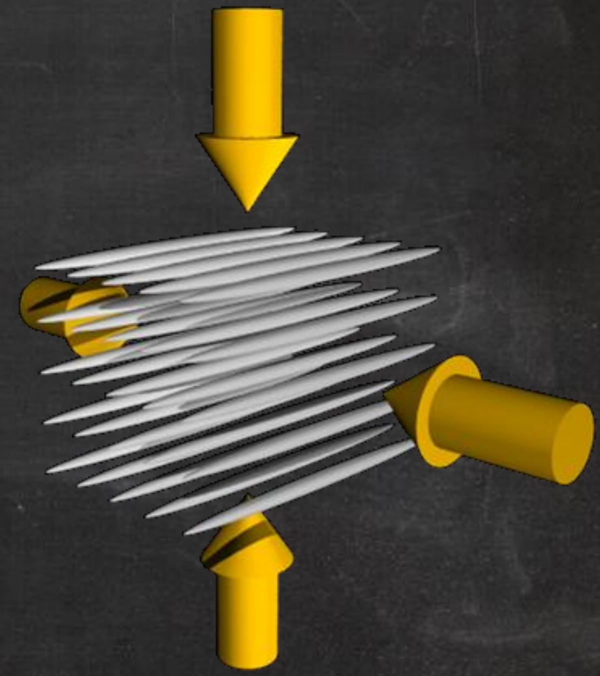
High-Tc superconductivity,
Quantum chromodynamics, …

I. Bloch et al., Nat. Phys. 8, 267 (2012)
I. Bloch et al., Rev. Mod. Phys. 80, 885 (2008)
M. Lewenstein et al., Adv. Phys. 56, 243 (2007)

Low-dimensional physics

Ultracold gases offer a unique platform for low-dimensional quantum physics





2D systems

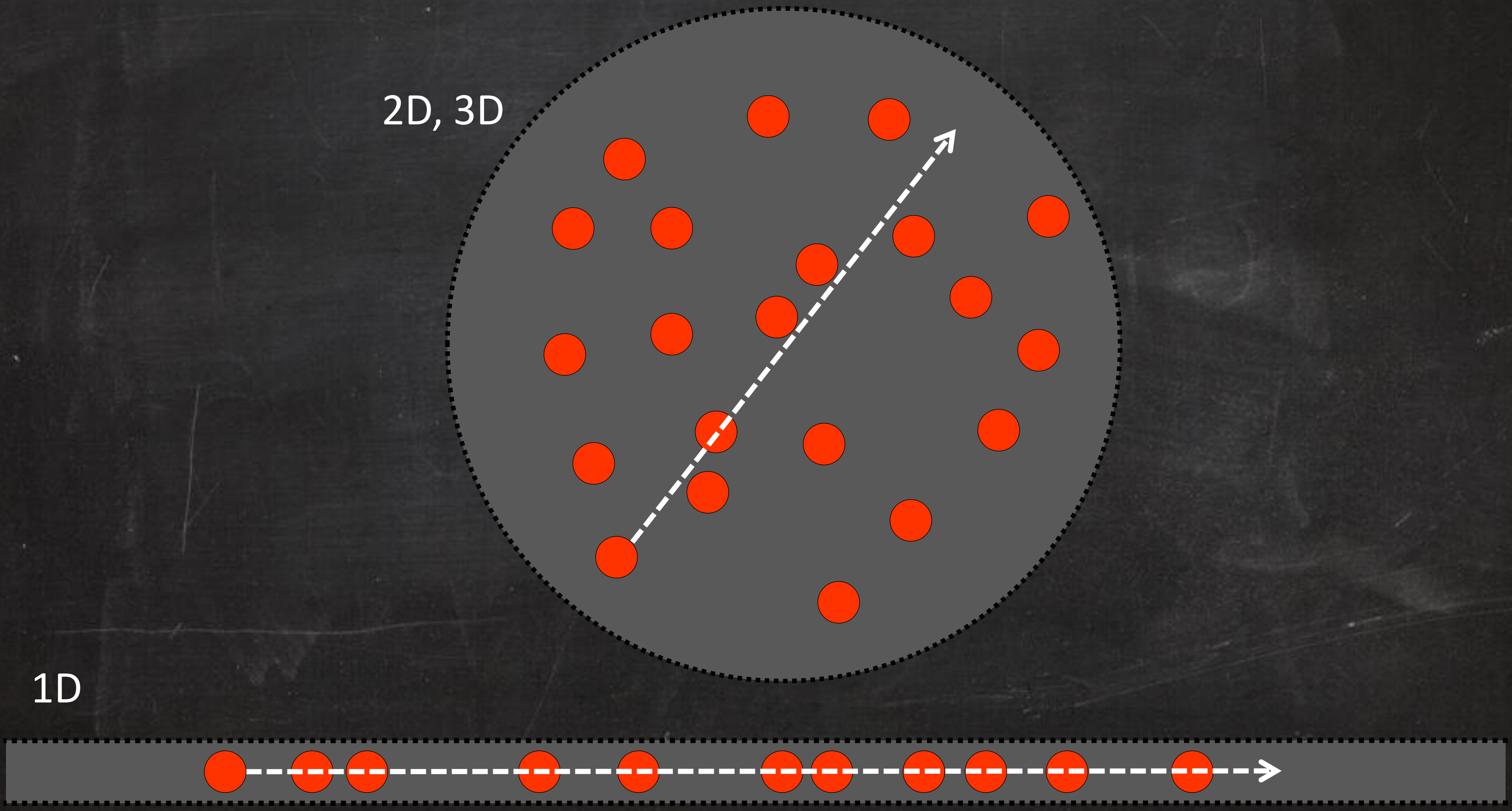
layered superconductors,
quantum Hall effect,
graphene, …

1D systems

organic superconductors,
carbon nanotubes,
quantum wires, …

1D is special!

Low dimensions strongly amplify the effects of interactions between particles



1D ultracold physics

1D bosons

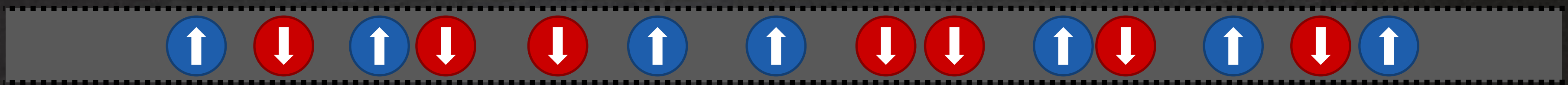
Tonks and super-Tonks gas	T. Kinoshita et al., Science 2004 B. Paredes et al., Nature 2004 E. Haller et al., Science 2009
2- and 3-body correlations	B. Laburthe Tolra et al., PRL 2004 T. Kinoshita et al., PRL 2005 V. Guarrera et al., PRA 2012
Mott and pinning transition	T. Stoferle et al., PRL 2004 E. Haller et al., Nature 2010
integrability and non-equilibrium	T. Kinoshita et al., Nature 2006 M. Cheneau et al, Nature 2012
quasiBEC and phase fluctuations	J. Estève et al., PRL 2006 S. Hofferberth et al., Nature 2007
transport of impurities	S. Palzer et al., PRL 2009 J. Catani et al, PRA 2012 T. Fukuhara et al., Nat. Phys. 2013

1D fermions

formation of molecules	H. Moritz et al., PRL 2005
unbalanced superfluidity	Y. Liao et al., Nature 2010
few-fermions physics	G. Zurn et al., PRL 2012

1D spinful fermions

Spin degree of freedom: fundamental in magnetism, superconductivity, …



1D spinful fermions: intense studies in theoretical physics in the last 50 years

Breakdown of Landau's liquid

Exactly solvable: Tomonaga-Luttinger (Mattis-Lieb) liquid (low E physics)

- Collective (bosonic) excitations
- Density and spin waves

Luttinger (1963), Tomonaga (1950)

$$H \sim \frac{u}{2}\int \mathrm{d}x \left[K\Pi^2 + \frac{1}{K}\left(\partial_x\phi\right)^2\right]$$

Spin ½: Gaudin-Yang model (using Bethe ansatz)

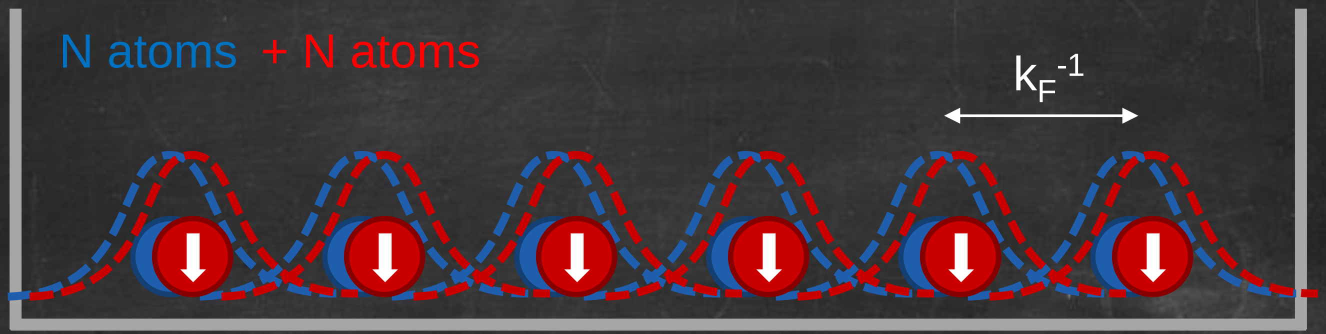
Gaudin (1967), Yang (1967)

Recent extensions:

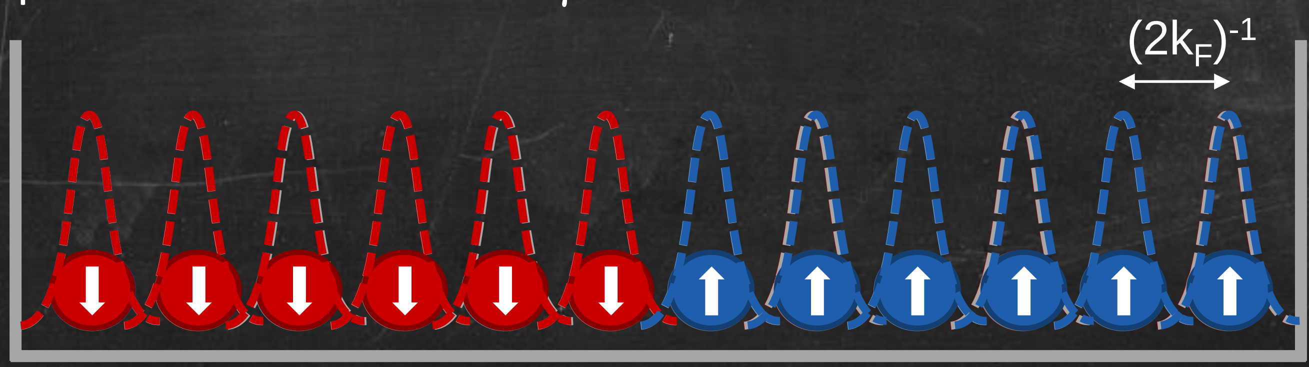
- Spin-incoherent Luttinger liquid (*finite T*) — Fiete, Rev. Mod. Phys. (2007)
- Nonlinear Luttinger liquid (*larger E*) — Imambekov & Glazman, Science (2009)

1D spin-½ fermions

No interactions: $\gamma=0$ K=1



Infinite repulsion: $\gamma=\infty$ K=0.5



fermionized fermions!

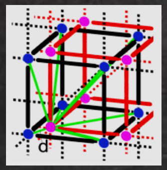
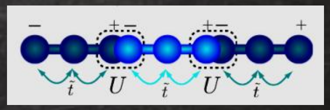
Multi-component fermions

Strongly-interacting *M*-component (large-spin) fermions

How does the physics change as a function of *M*?

1D multi-component liquids of fermions:

- Theoretically studied long time ago — Sutherland (1968)
- Relevant for materials with large spin-orbit coupling — Frischmuth et al., PRL (1999)
- **…a novel system!**

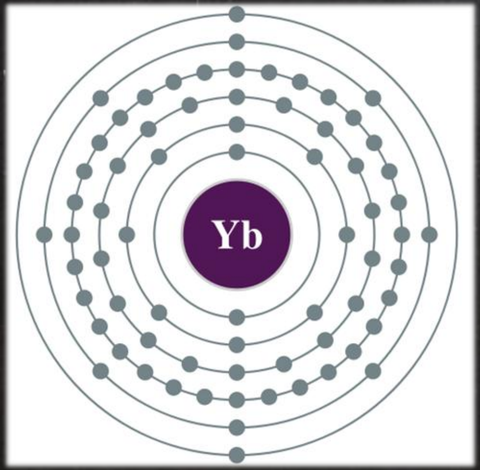



Precious resource for advanced quantum simulators:

- Extradimensions — Boada et al., PRL (2012)
- SU(N) magnetism — e.g. Bonnes et al., PRL (2012); Messio & Mila, PRL (2012)
- Quantum field theories — see Zoller, Lewenstein, Cirac

^{173}Yb ultracold Fermi gas

http://periodictable.com

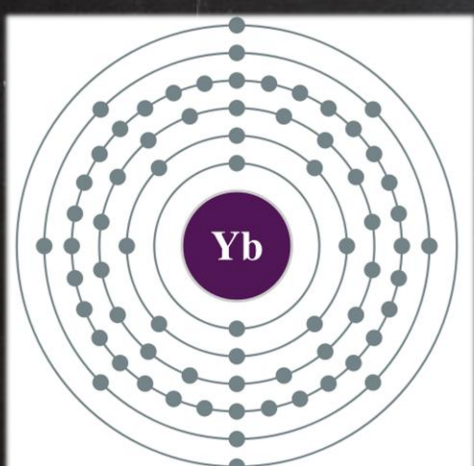


Natural Ytterbium comes in **seven** stable isotopes:

^{168}Yb	0.13%	I=0	boson
^{170}Yb	3.04%	I=0	boson
^{171}Yb	14.28%	I=1/2	fermion
^{172}Yb	21.83%	I=0	boson
^{173}Yb	16.13%	I=5/2	fermion
^{174}Yb	31.83%	I=0	boson
^{176}Yb	12.76%	I=0	boson

^{173}Yb ultracold Fermi gas

http://periodictable.com



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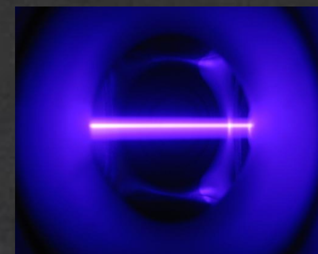
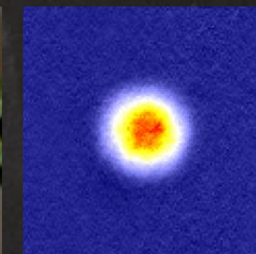
^{176}Yb	12.76%	I=0	boson

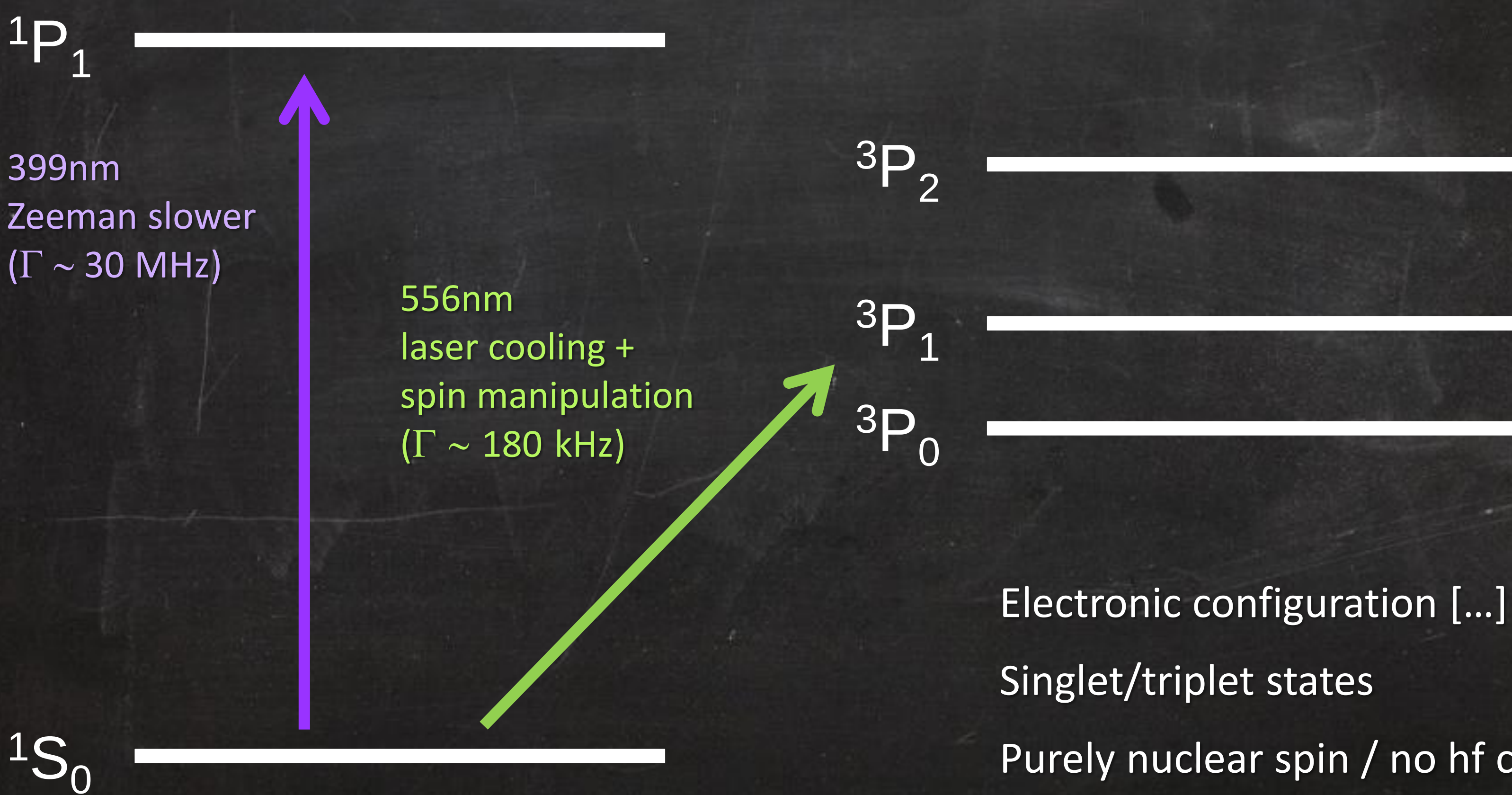
Ytterbium

BEC and Ultracold Fermi gas

Alkaline-earth-like structure







Electronic configuration [...]$1s^2$

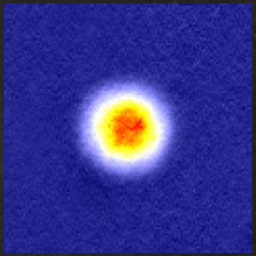
Singlet/triplet states

Purely nuclear spin / no hf coupling

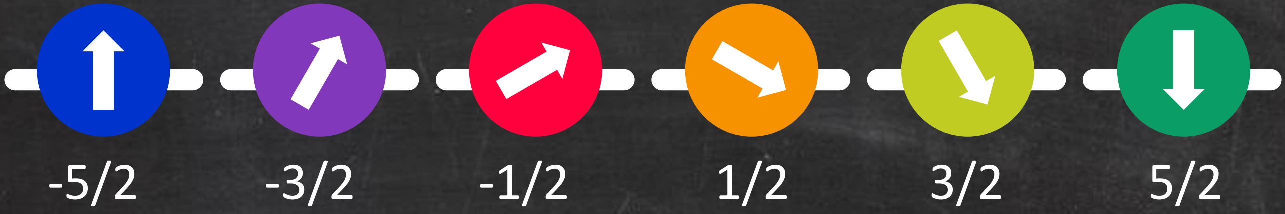
^{173}Yb ultracold Fermi gas

Ultracold ^{173}Yb Fermi gas

$T \sim 0.1\ T_F$
$N = 10^4$ atoms/spin
scattering length $a = +200\ a_0$



Purely nuclear spin I=5/2



Same interaction between different spins ⟶ SU(6) symmetry

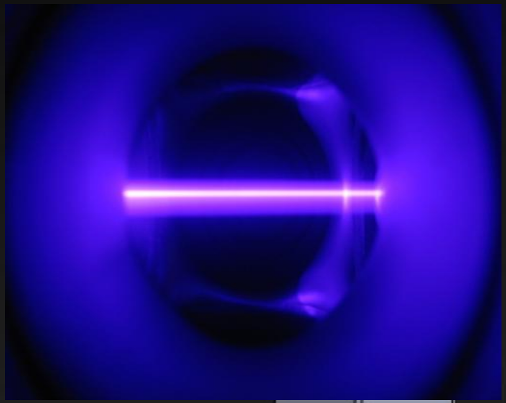
No spin-changing collisions ⟶ all mixtures are stable

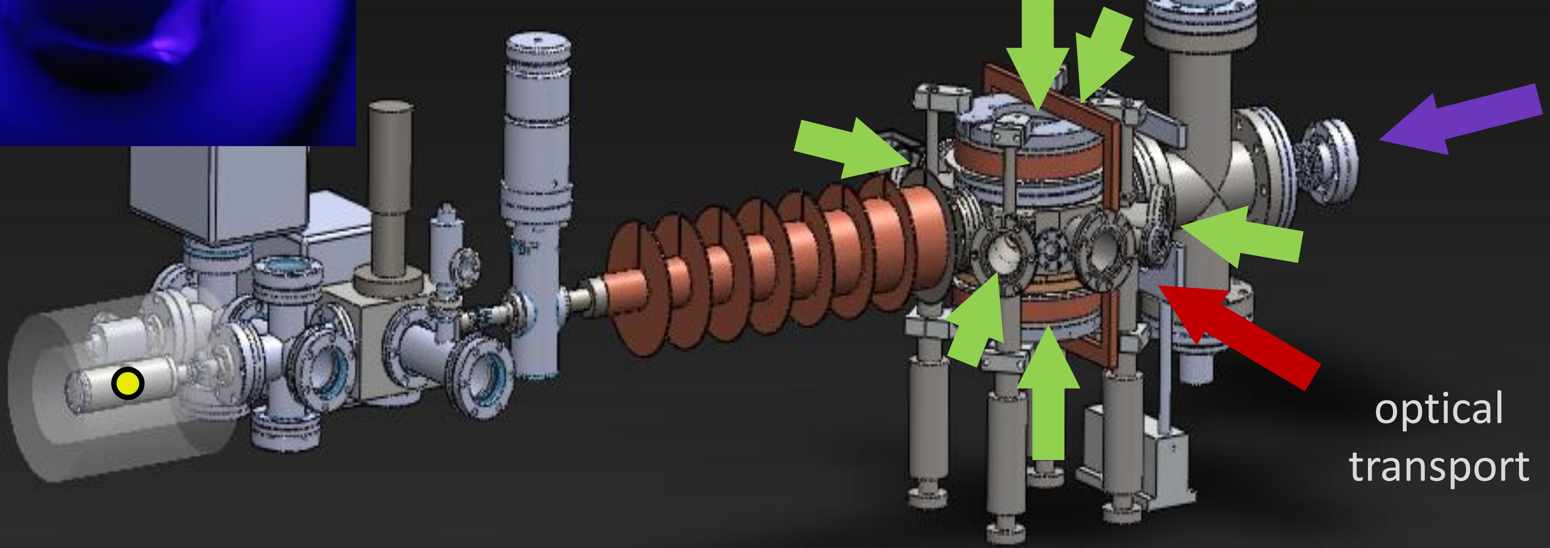
No quadratic Zeeman effect

Experimental setup

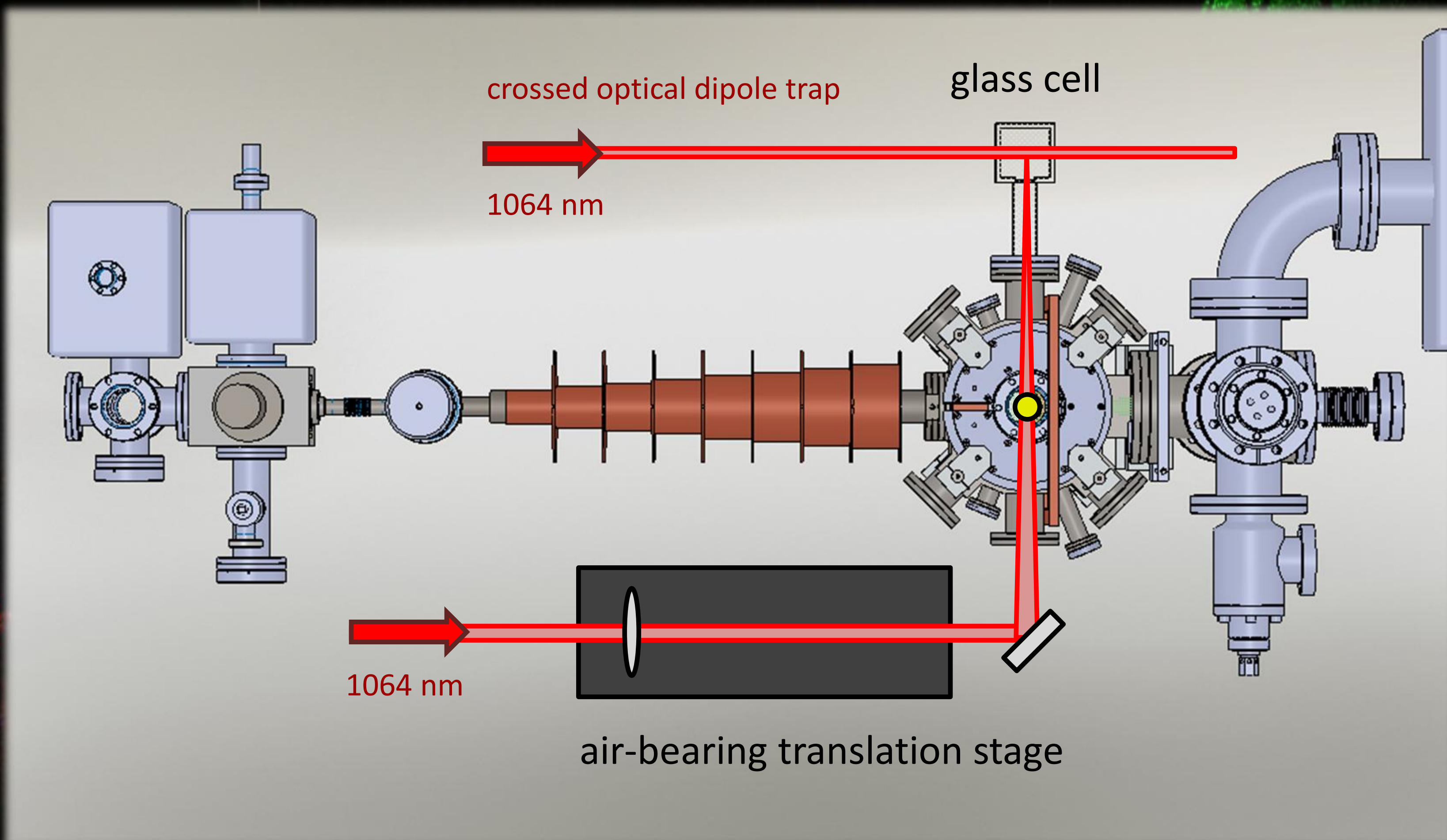
556nm intercomb. MOT

399nm Zeeman slower





Experimental setup



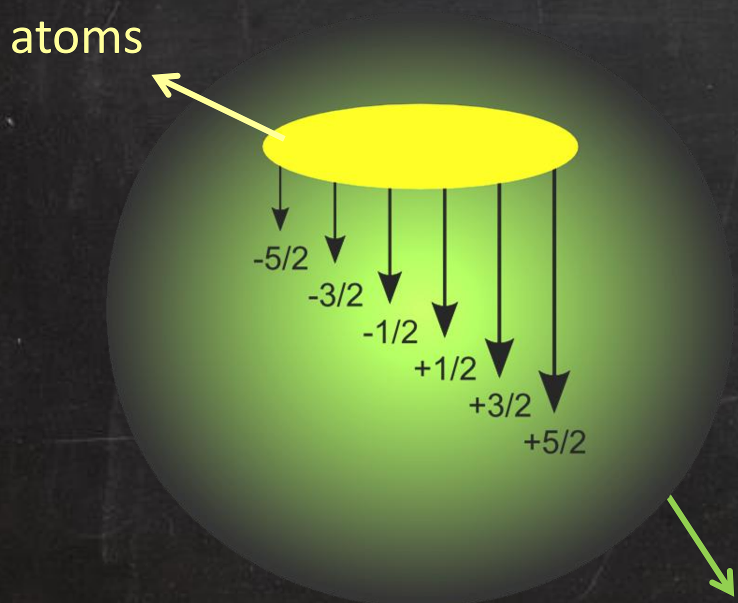
Spin detection and manipulation

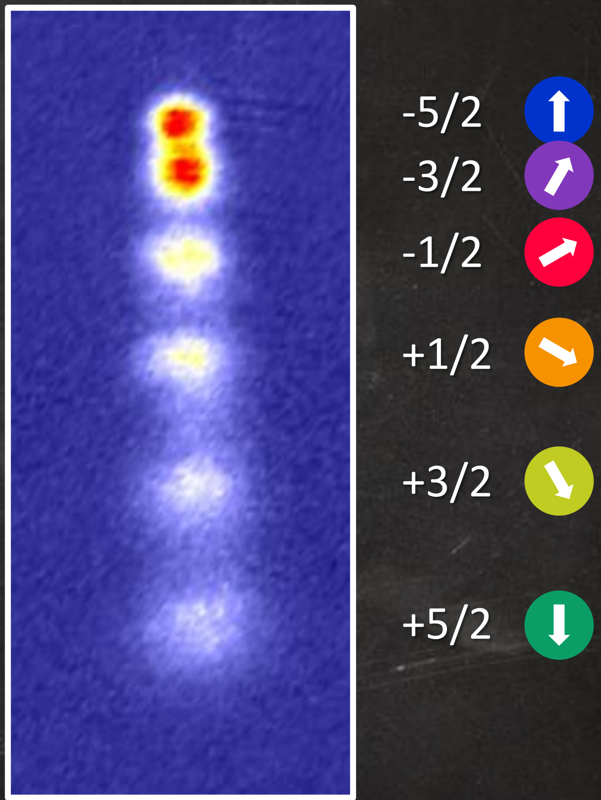
Optical Stern-Gerlach detection

Taie et al., PRL (2010)

State-dependent optical dipole force

Nuclear spin I=5/2



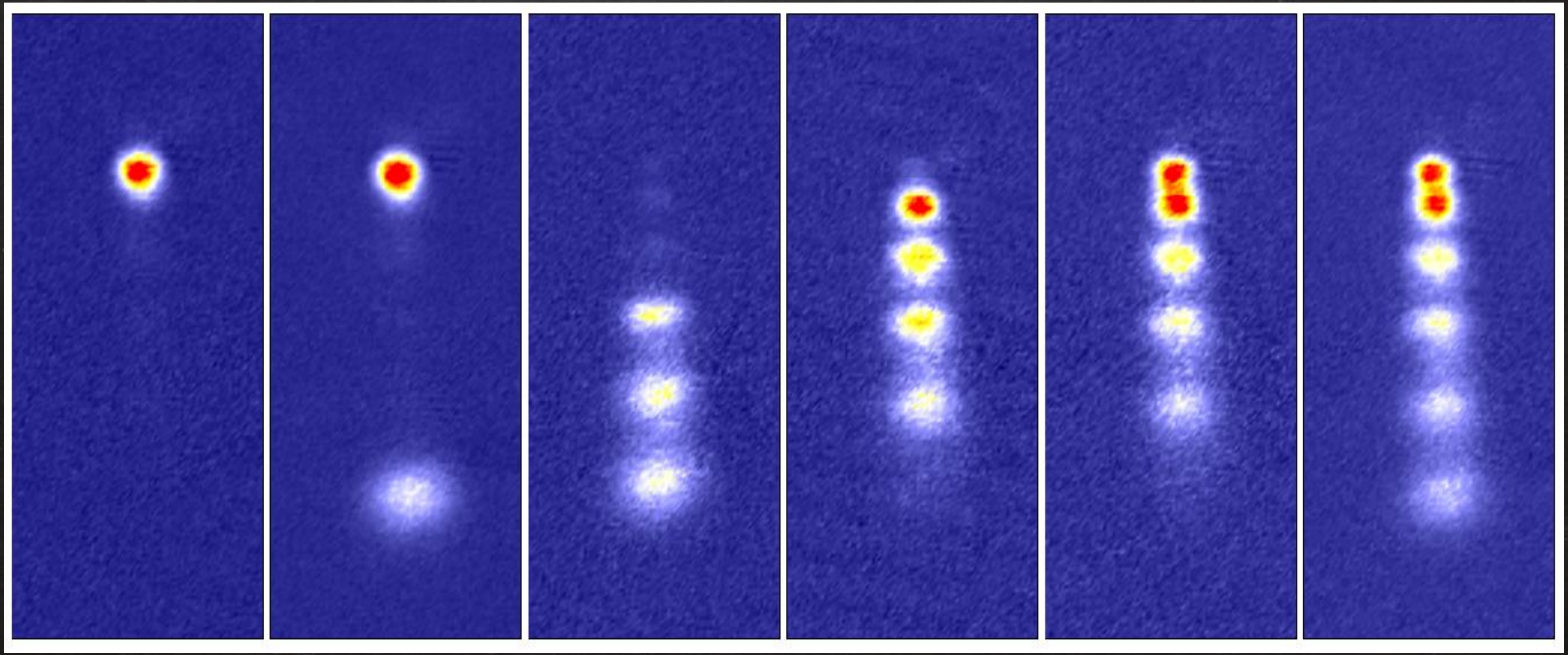


optical Stern-Gerlach beam

556 nm, 3000Γ detuning, σ^+

Spin detection and manipulation

^{173}Yb Fermi gases in an arbitrary number of equally-populated components:



1 spin	2 spins	3 spins	4 spins	5 spins	6 spins
	SU(2)	SU(3)	SU(4)	SU(5)	SU(6)

1D multi-component Fermi gases

nature physics

LETTERS

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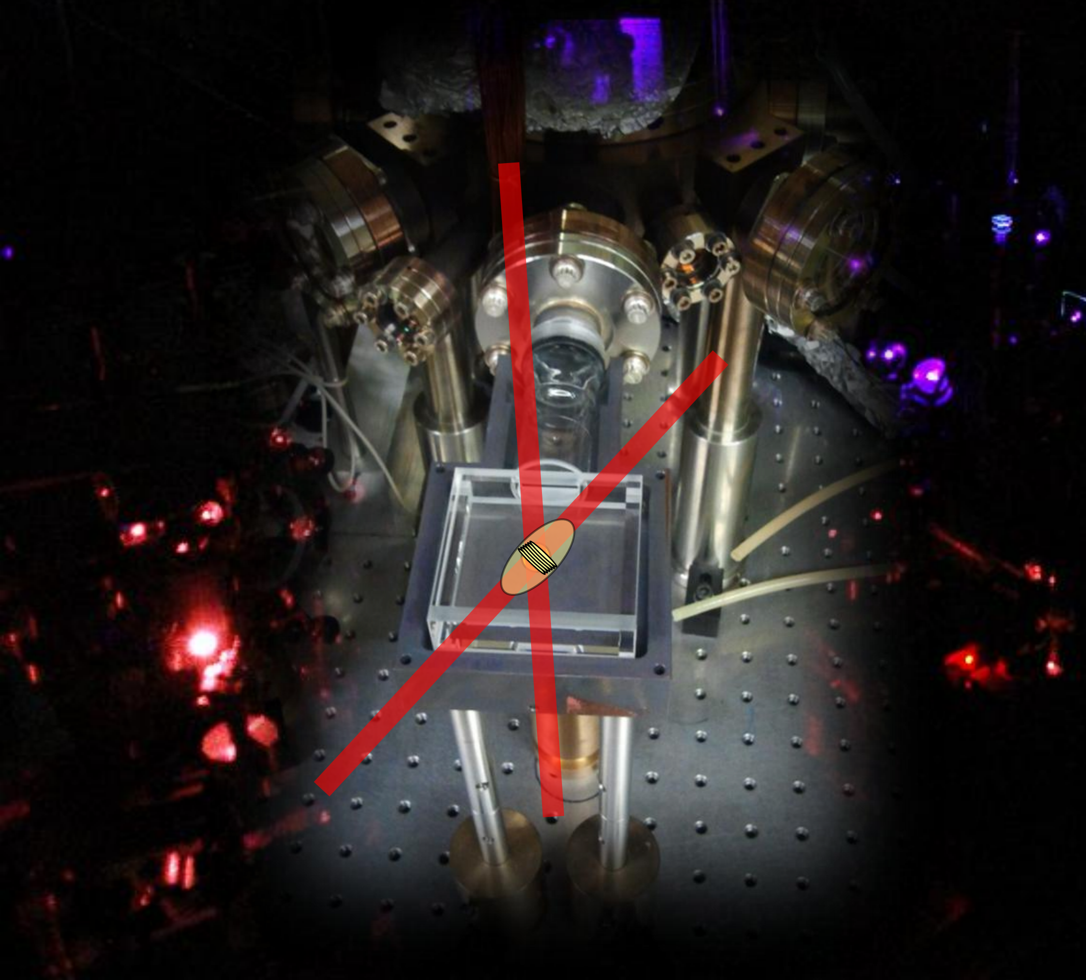
A one-dimensional liquid of fermions with tunable spin

Guido Pagano[1,2], Marco Mancini[1,3], Giacomo Cappellini[1], Pietro Lombardi[1,3], Florian Schäfer[1], Hui Hu[4], Xia-Ji Liu[4], Jacopo Catani[1,5], Carlo Sias[1,5], Massimo Inguscio[1,3,5] and Leonardo Fallani [1,3,5]*

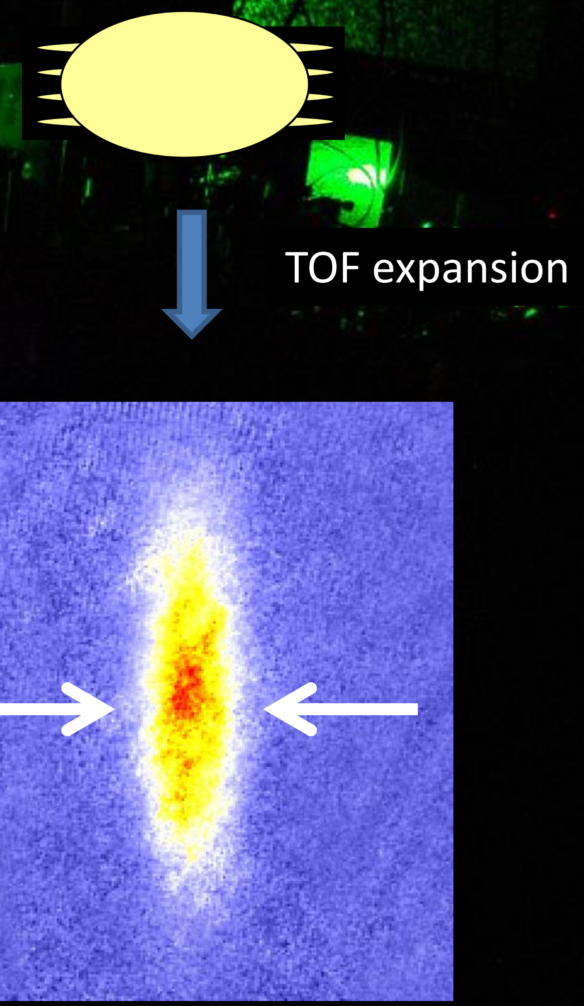
1D Fermi gases

2D optical lattice

- 2D square optical lattice
- lattice depth 40 E_{rec} (no tunnelling)

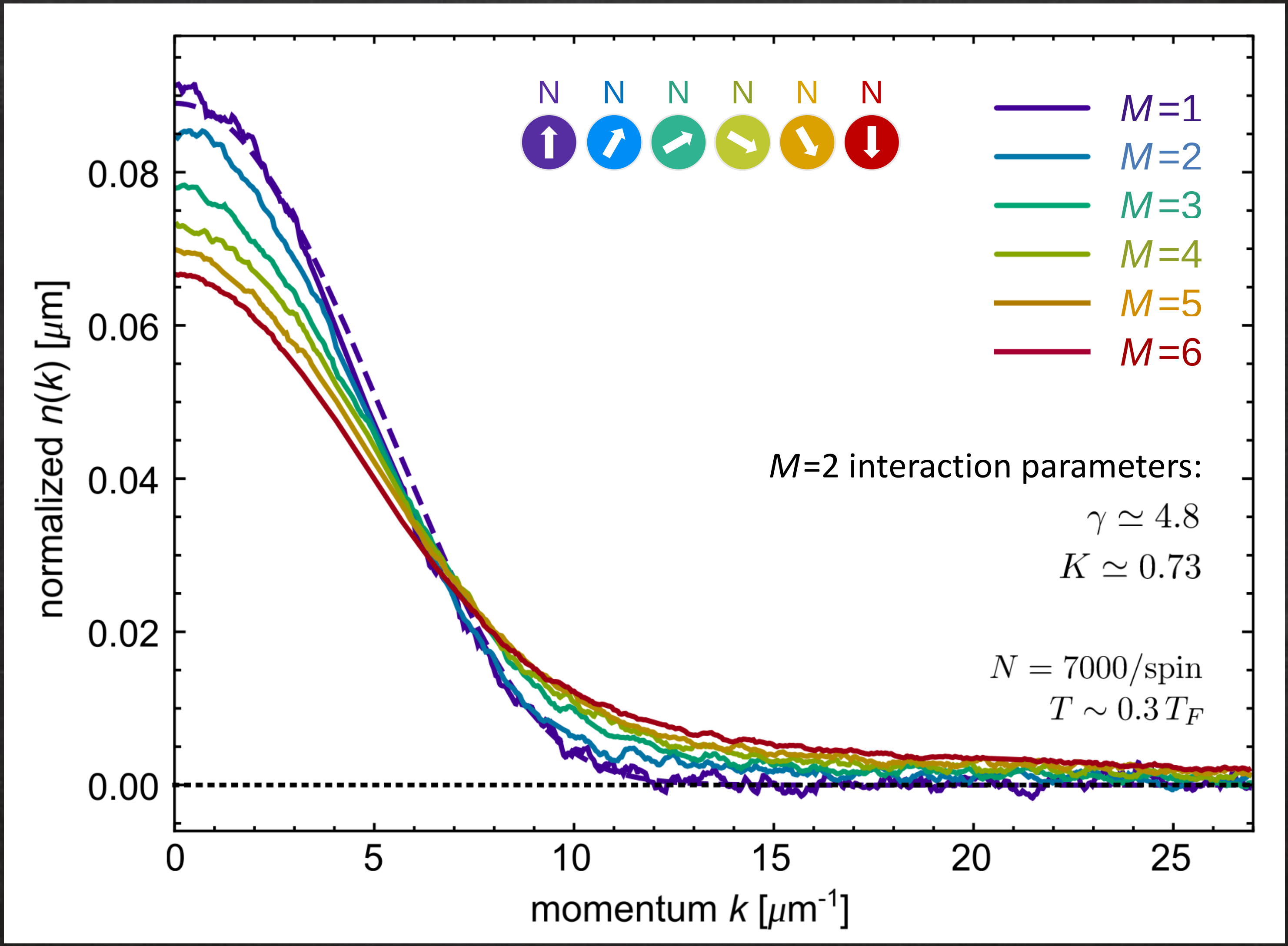


1 3D Fermi gas ıs



Momentum distribution

Momentum distribution measured after time-of-flight expansion:



Momentum distribution

Broadening not explained by a mean-field treatment of interactions

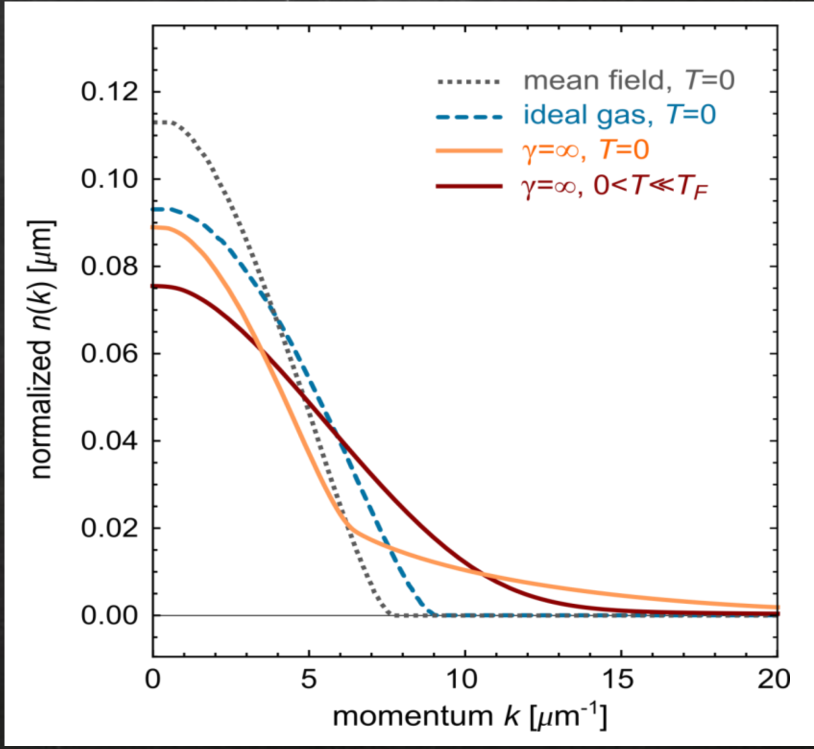
repulsion gives
effective deconfinment
↓
~~narrower n(k)~~

GY-model + LDA, Astrakharchik et al. PRL **93**, 050402 (2004)

Broadening of n(k) is evidence
of strong correlations in the 1D
many-body system

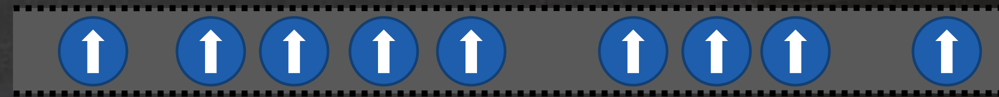
Ogata & Shiba, PRB **41**, 2326 (1990)
Cheianov et al., PRA **71**, 033610 (2005)

(work in progress by M. Dalmonte)

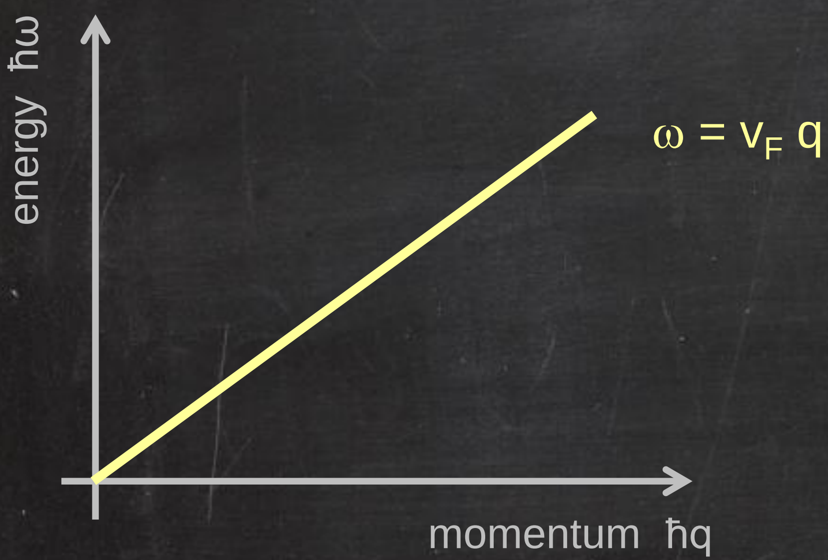


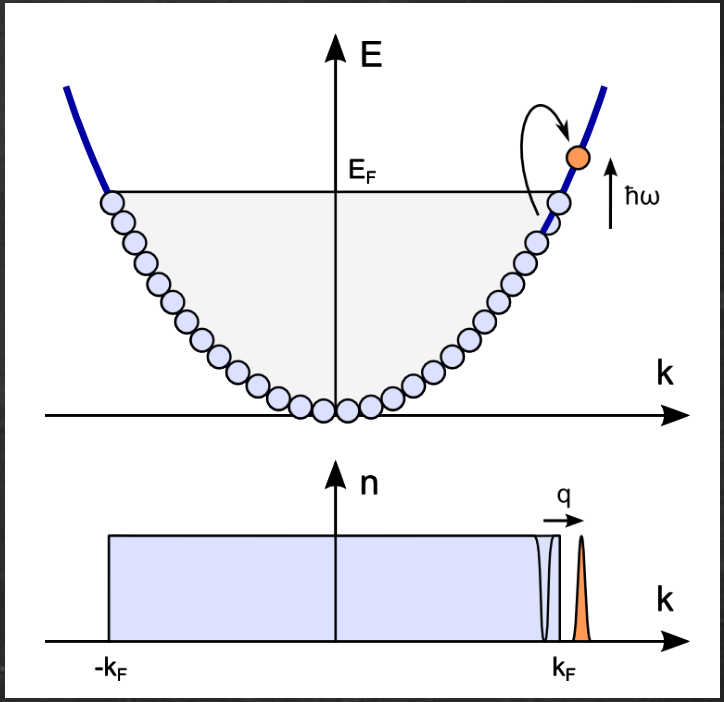
Low-energy excitations of a 1D Fermi gas

1 component: ideal 1D Fermi gas



particle-hole excitations



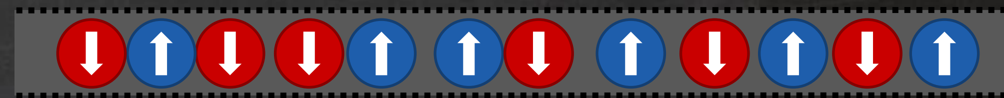


$$\hbar\omega = E_{part.} - E_{hole} = \frac{\hbar^2}{2m}\left[(k+q)^2 - k^2\right] = \frac{\hbar^2}{m}\left[kq + \frac{q^2}{2}\right] \simeq \frac{\hbar k_F}{m}\hbar q$$

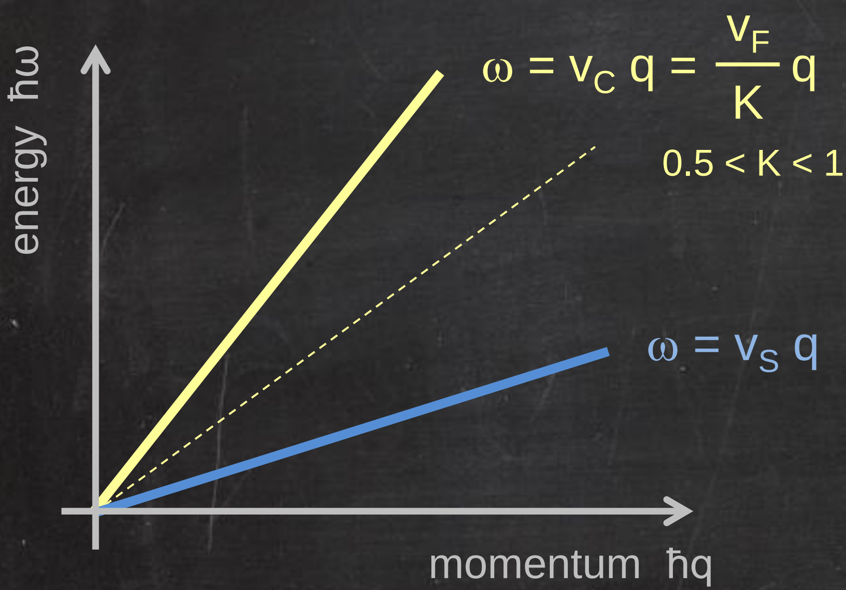
Luttinger model for 1D spin-½ fermions

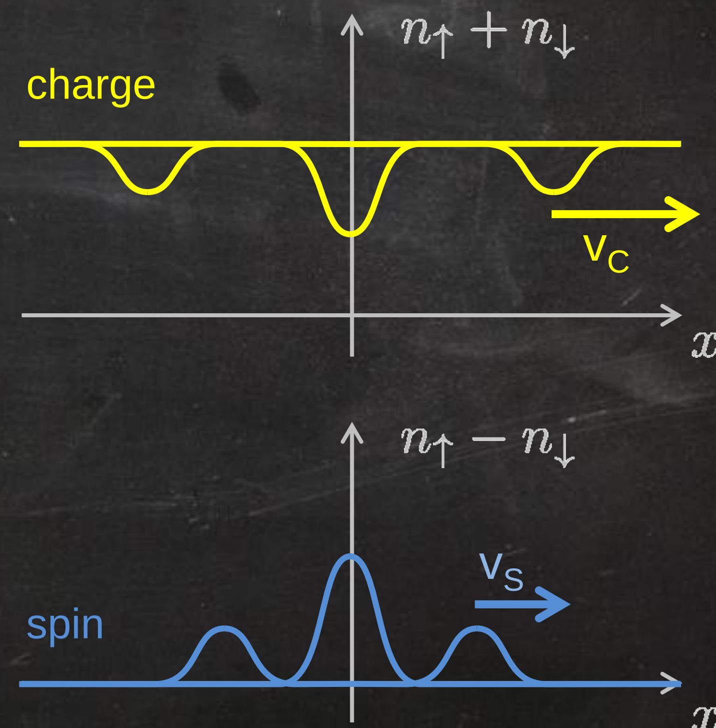
2-component: 1D Luttinger liquid

collective (bosonic) excitations



$$H \sim \frac{u}{2} \int \mathrm{d}x \left[K\Pi^2 + \frac{1}{K} (\partial_x \phi)^2 \right]$$



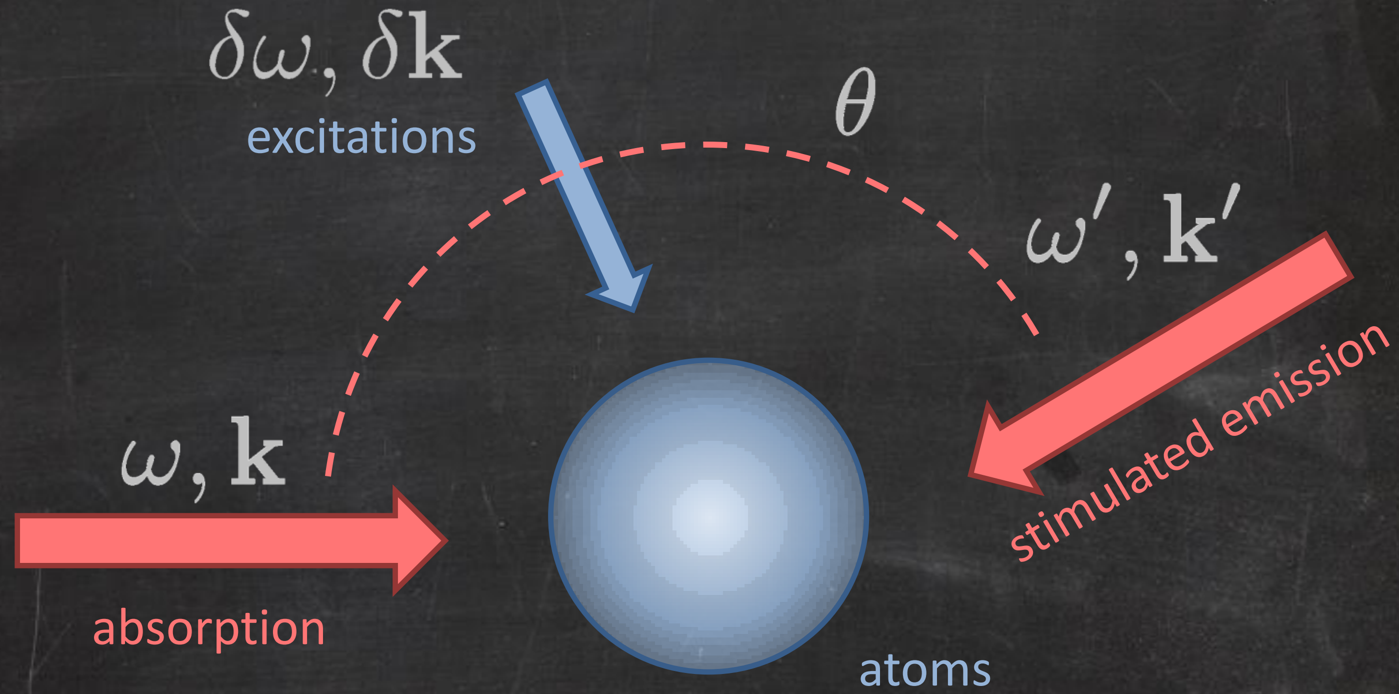


spin-charge separation

A. Recati et al., PRL **90**, 020401 (2003)
C. Kollath et al., PRL **95**, 176401 (2005)
M. Polini & G. Vignale, PRL **98**, 266403 (2007)

Bragg spectroscopy

MIT, LENS, JILA, Weizmann, Palaiseau, Swinburne, …



Inelastic scattering of light

Stimulated two-photon (Raman) transition

Selection of energy and momentum

$$\delta\omega = \omega - \omega'$$

$$\delta\mathbf{k} = \mathbf{k} - \mathbf{k}'$$

$$\delta\mathbf{k} \simeq 2k\sin(\theta/2)$$

Bragg spectroscopy

Small-angle Bragg spectroscopy

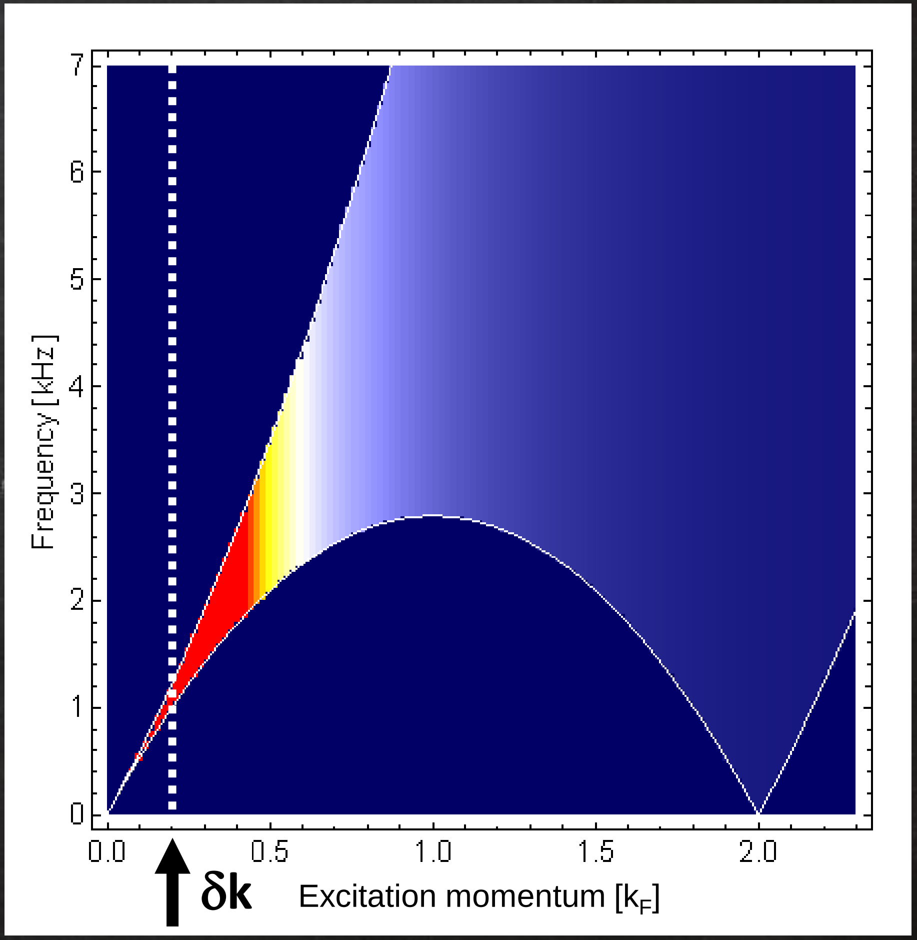
$\theta \sim 10^\circ$

momentum transfer $\delta k = 0.2k_F$

Linear part of the spectrum

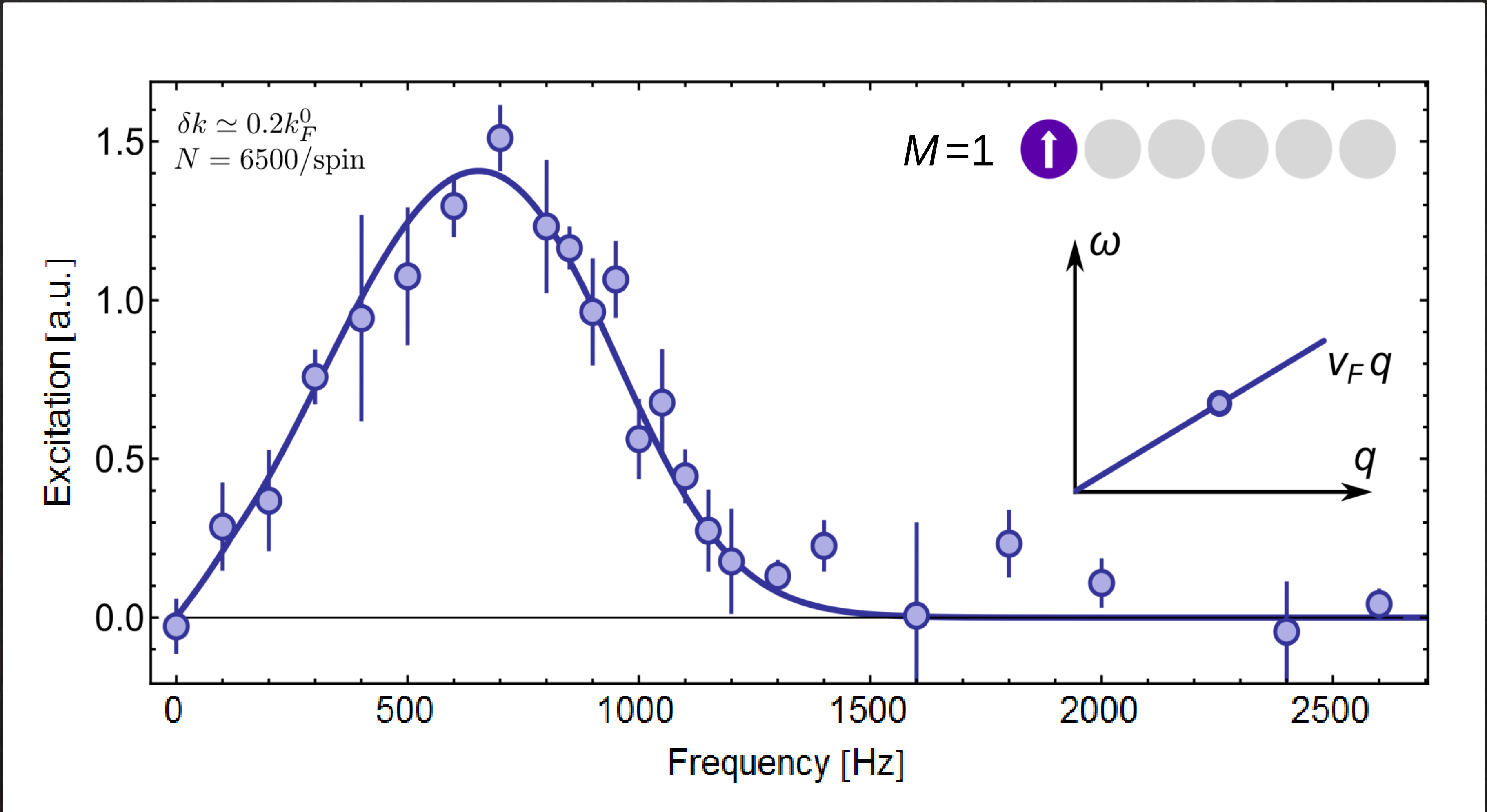
Sensitive probe of Luttinger physics

Dynamic structure factor - ideal 1D Fermi gas



Bragg spectroscopy

Bragg excitation spectrum:



Bragg spectroscopy

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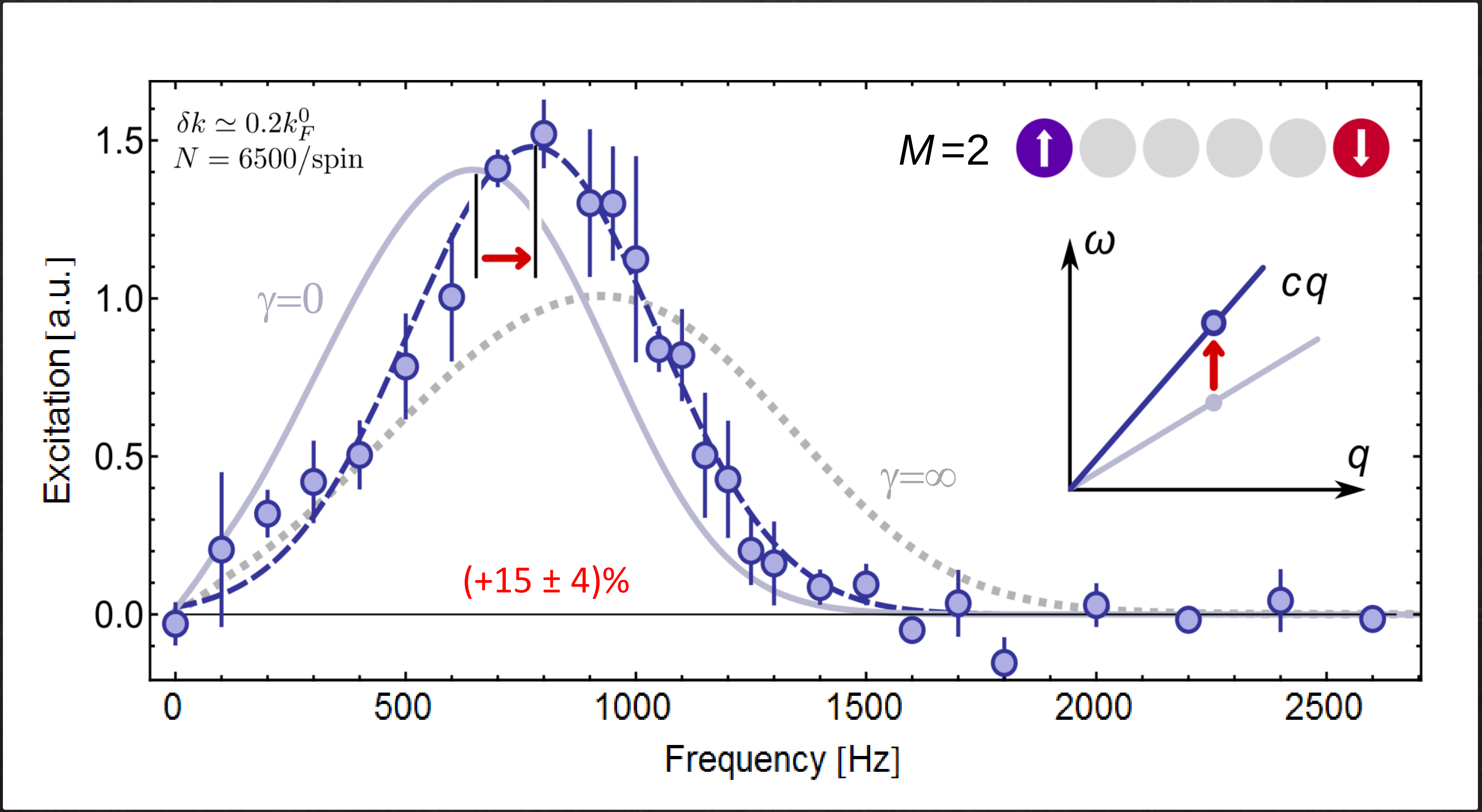
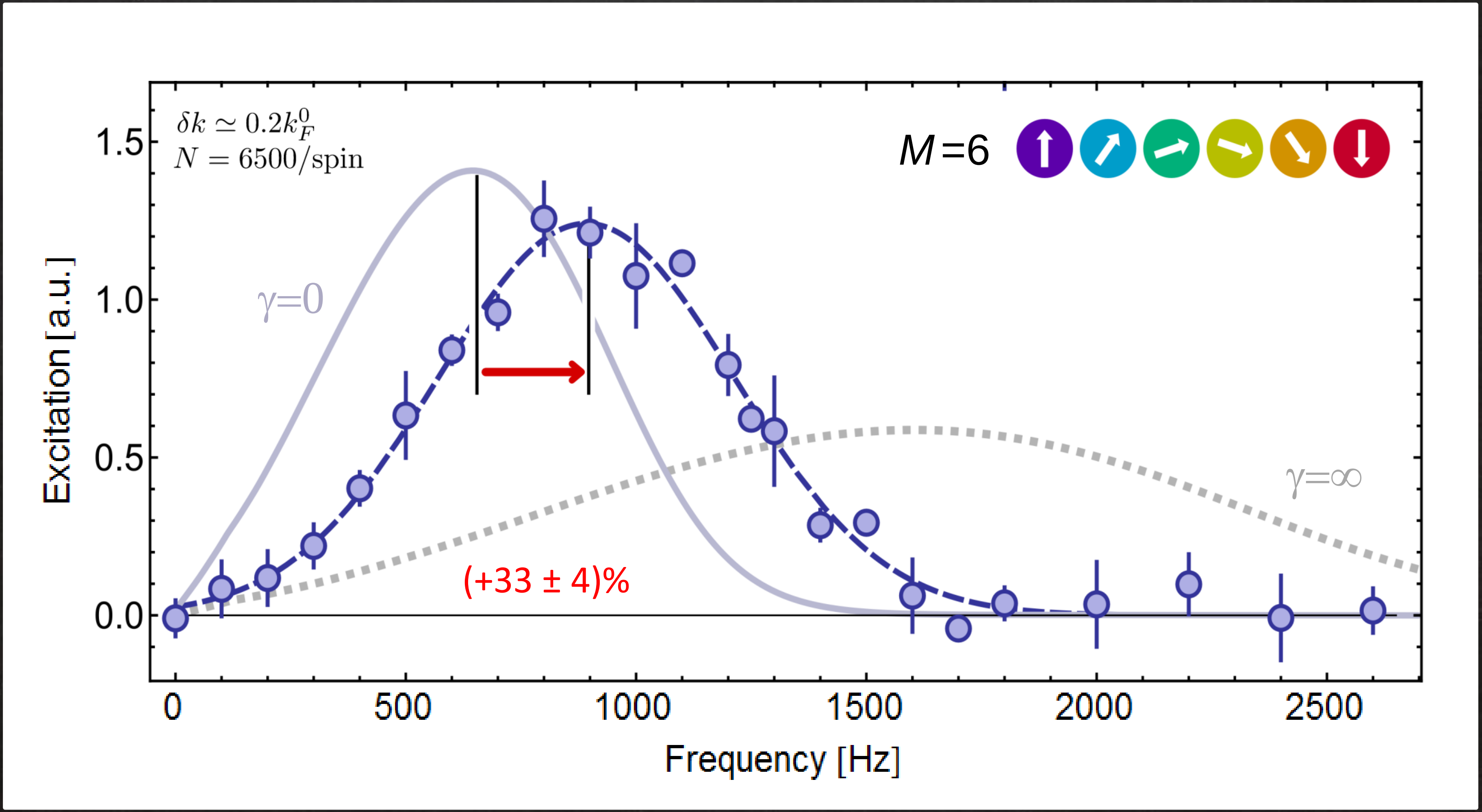


Shift in the excitation peak frequency (+10 ± 2)% expected by Bethe ansatz solution

Bragg spectroscopy

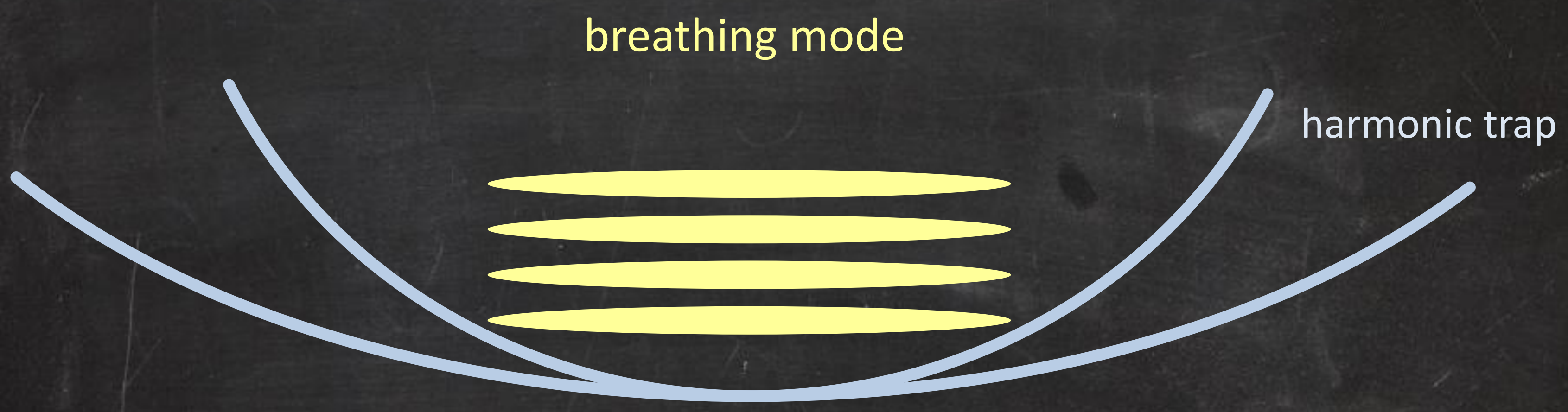
Bragg excitation spectrum:



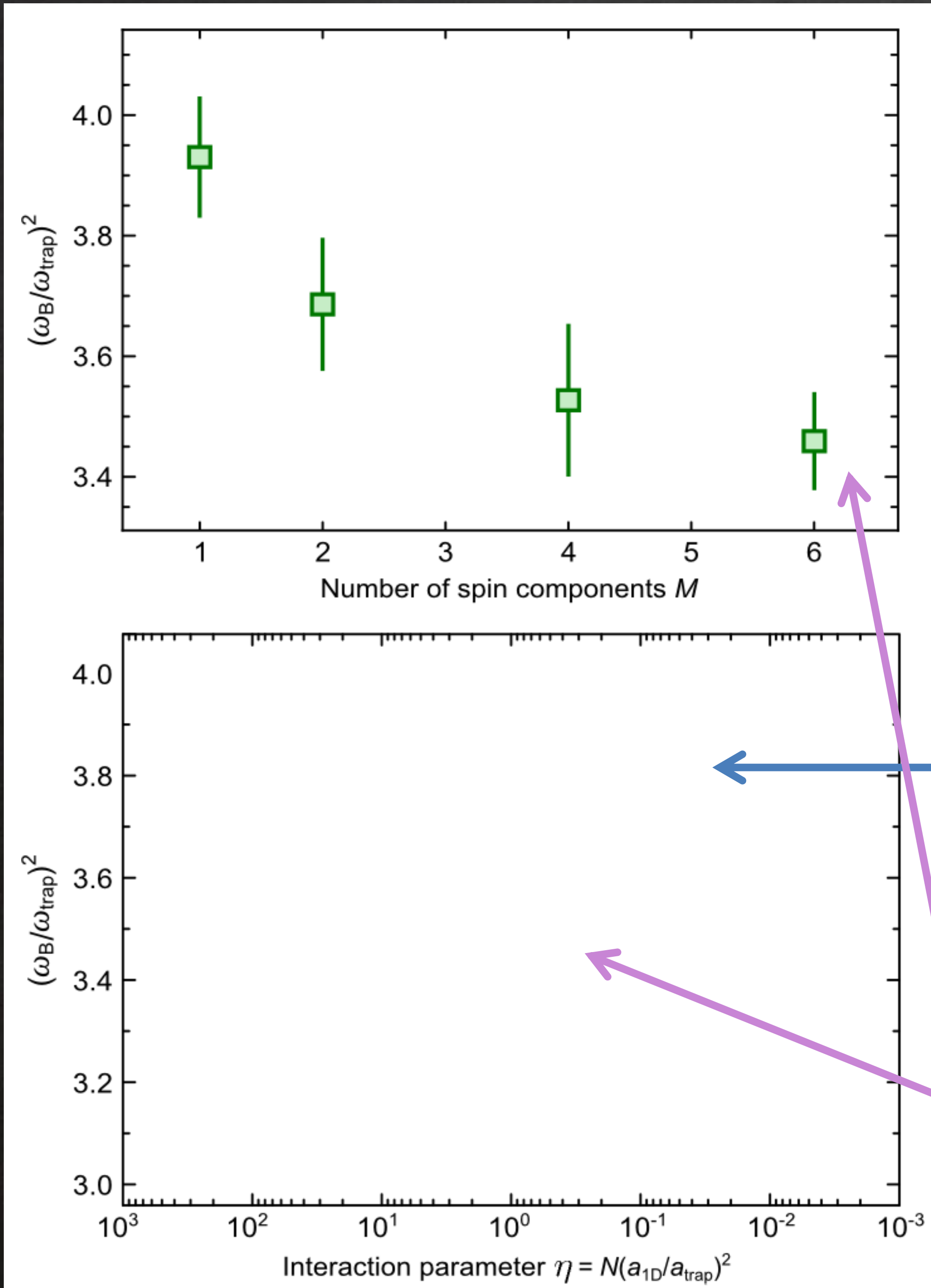
Larger shift for increased number of spin components

Collective oscillations

Low-energy shape oscillations: sensitive probes of the state of a trapped gas



Breathing oscillations



(Ratio of the breathing mode frequency to trap frequency)^2

Redshift of the breathing frequency caused by strong 1D interactions

First calculation M=2 in

New calculations for M>2 by

G. Astrakharchik et al., PRL 93, 050402 (2004)

H. Hu & X.-J. Liu (Swinburne University)

Bethe Ansatz + LDA + Hydrodynamic

The number of states is important!

For $M \to \infty$ the breathing frequency approaches that of spinless bosons!

Interplay between interactions and spin multiplicity (distinguishability)

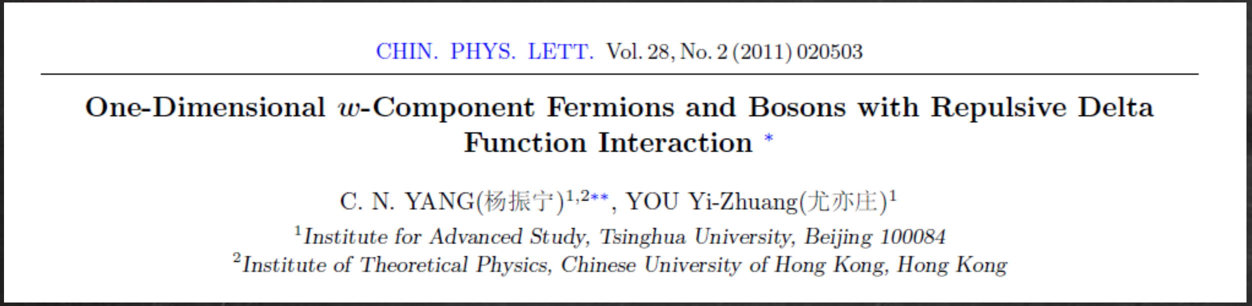
C. N. Yang & Y. Yi-Zhuang, CPL **28**, 020503 (2011)

“Bosonization” of a multicomponent fermionic liquid

For $M \rightarrow \infty$ a 1D fermionic liquid exhibit properties of a **bosonic spinless liquid**:

- The ground-state energy per particle $E(\gamma)$ — C. N. Yang & Y. Yi-Zhuang, CPL **28**, 020503 (2011)
- The local pair-correlation function $g^{(2)}_{\sigma,\sigma'}(0)$ — X.-W. Guan et al., PRA **85**, 033633 (2012)

A general result first demonstrated in 2011 by C. N. Yang (age 89)


CHIN. PHYS. LETT. Vol. 28, No. 2 (2011) 020503

One-Dimensional w-Component Fermions and Bosons with Repulsive Delta Function Interaction *

C. N. YANG(杨振宁)[1,2]**, YOU Yi-Zhuang(尤亦庄)[1]

[1]*Institute for Advanced Study, Tsinghua University, Beijing 100084*
[2]*Institute of Theoretical Physics, Chinese University of Hong Kong, Hong Kong*

1948: Assistant to Enrico Fermi in Chicago

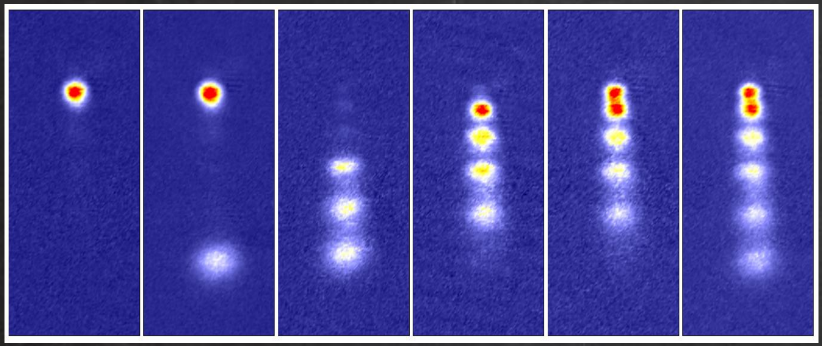
1957: Nobel Prize in Physics (age 35)
for parity violation in weak interaction

1957: Lee-Huang-Yang theory of interacting Bose gases

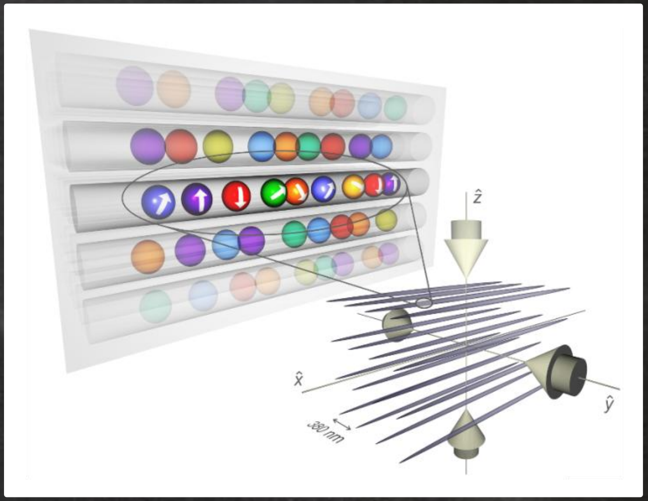
1969: Development of Thermodynamic Bethe Ansatz …

Conclusions

Interacting ^{173}Yb fermions with tunable number of components



Multicomponent 1D liquids of fermions



Momentum distribution $\rightarrow$ Evidence of correlations

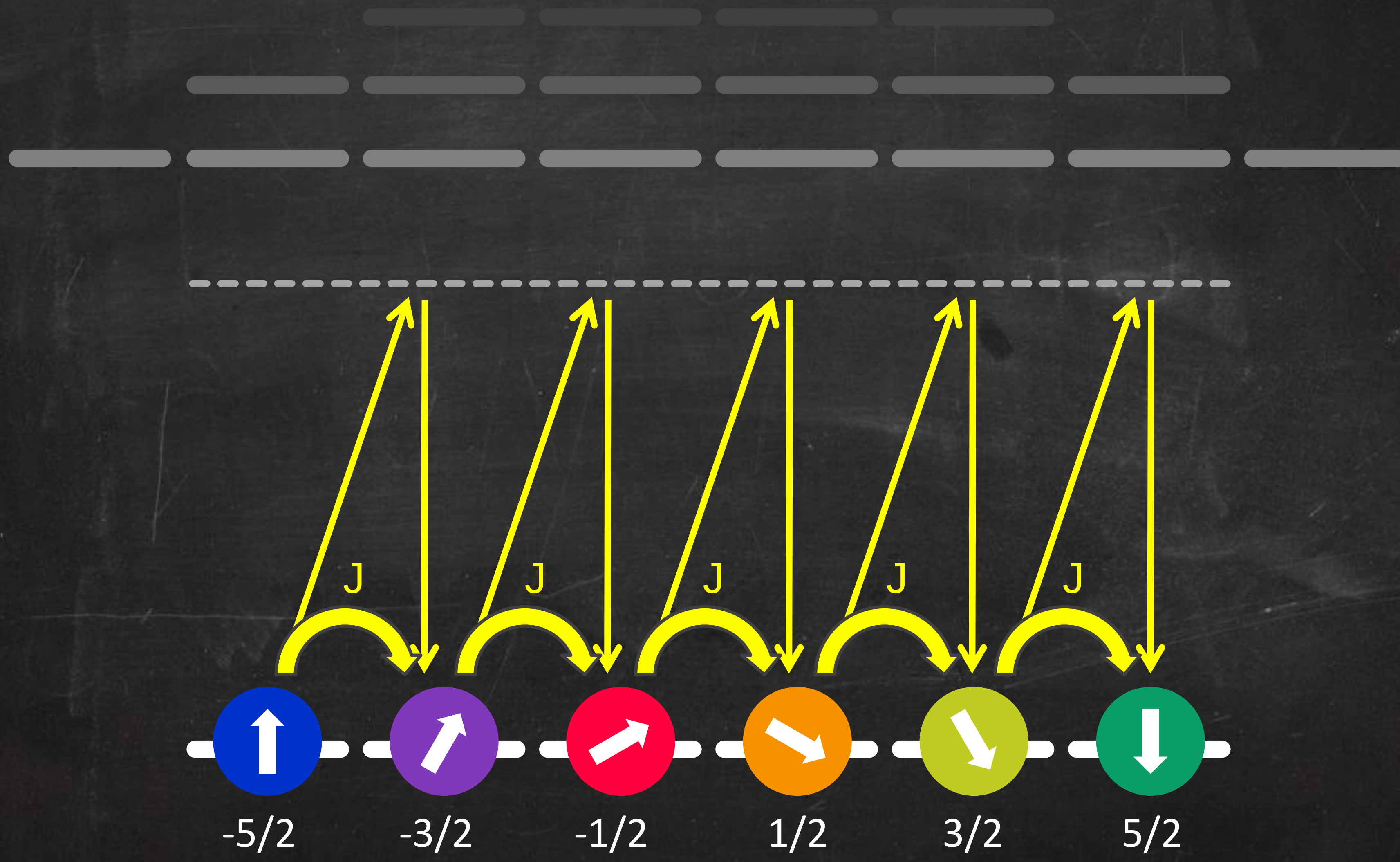
Bragg spectroscopy $\rightarrow$ Luttinger physics, sound velocity

Collective mode frequencies $\rightarrow$ Modified equation of state

Valuable platform for: *large-spin physics, spin dynamics, novel quantum simulation…*

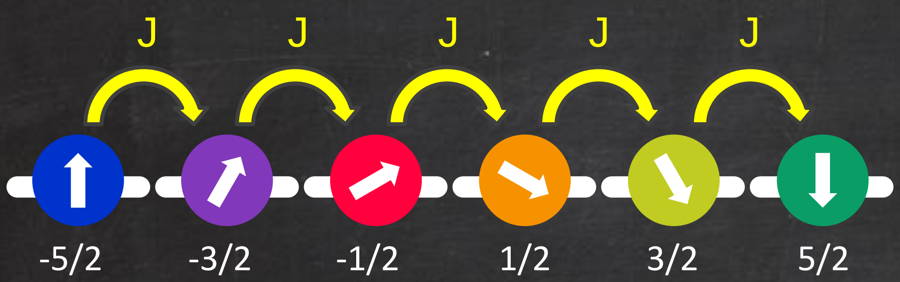
Perspective: Raman transitions

Raman transitions coupling coherently different nuclear spin states:



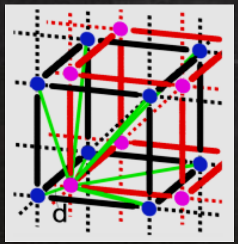
Perspective: Raman transitions

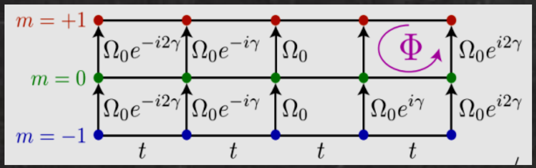
Raman transitions coupling coherently different nuclear spin states:



Realization of a synthetic dimension

Quantum simulation of 4-dim models
Gauge potentials in extra-dimension

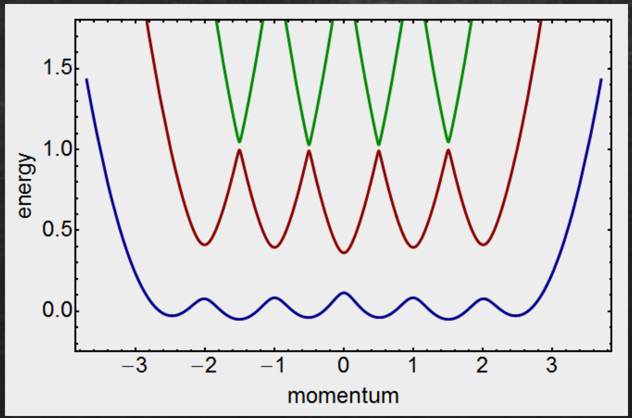




Boada et al., PRL (2012)
Celi et al., arXiv:1307.8349 (2013)

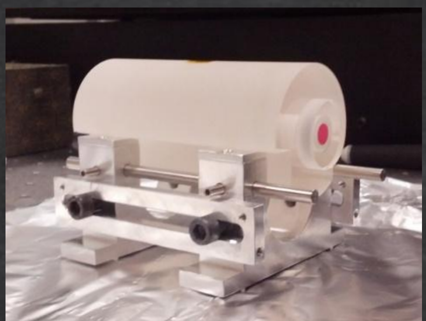
Spin-orbit coupling in a large spin

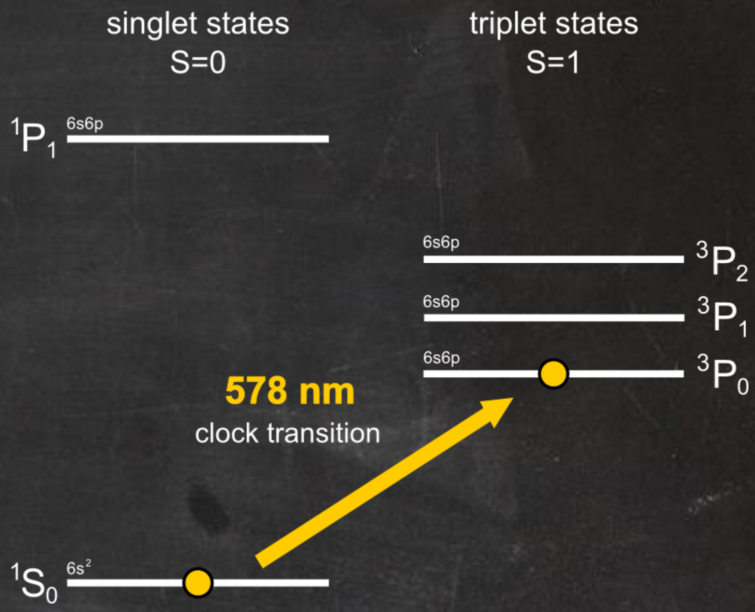
Multiple potential wells
in momentum space



Clock spectroscopy

Metastable states, ultranarrow clock transition
Resource for Q simulation and Q information

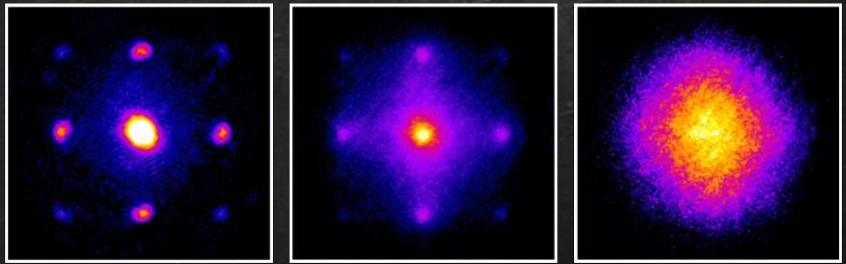




Many stable fermionic/bosonic isotopes and mixtures

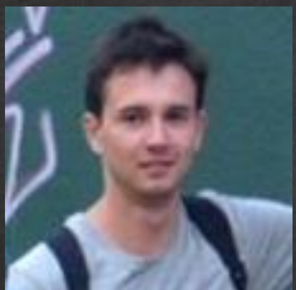
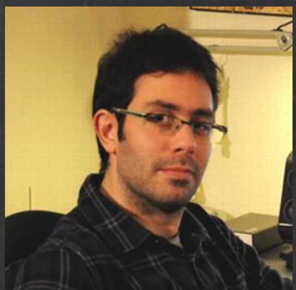
^{168}Yb	I=0	boson
^{170}Yb	I=0	boson
^{171}Yb	I=1/2	fermion
^{172}Yb	I=0	boson
^{173}Yb	I=5/2	fermion
^{174}Yb	I=0	boson
^{176}Yb	I=0	boson

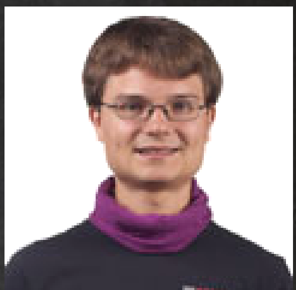
e.g. ^{174}Yb bosons in optical lattices



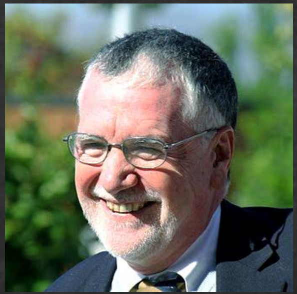
Credits

Guido Pagano | Marco Mancini | Giacomo Cappellini | Pietro Lombardi | Florian Schäfer





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