Phases and dynamics of a unitary Fermi gas in a high-finesse cavity

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Schweizerische Eidgenossenschaft
Confédération suisse
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Confederaziun svizra

Theory collaborations:

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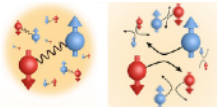
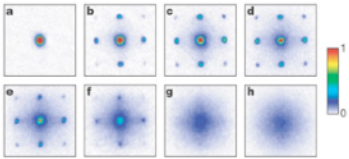
Synthetic quantum systems

Interaction strength

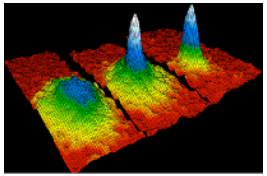
- Unitary gas

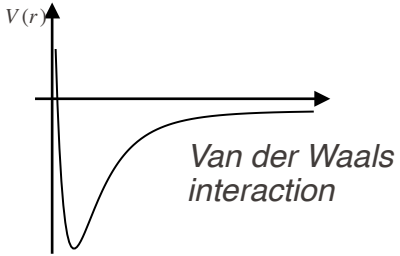


- Mott-insulators



- Bose-Einstein condensate



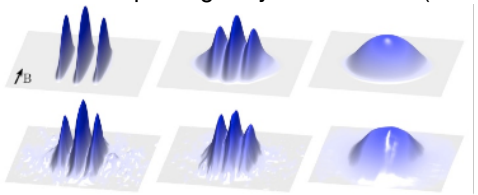


Synthetic quantum systems

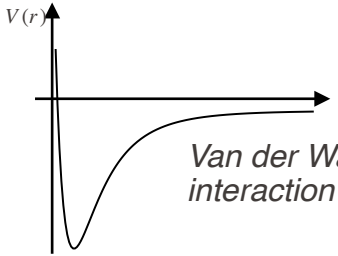
Interaction strength

- Unitary gas
- Mott-insulators
- Bose-Einstein condensate
- Polar molecules
- Rydberg atoms
- Magnetic atoms

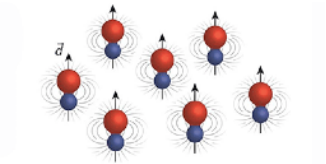
F. Böttcher *et al*
Rep. Prog. Phys. **84** 012403 (2021)



Interaction range



Van der Waals interaction

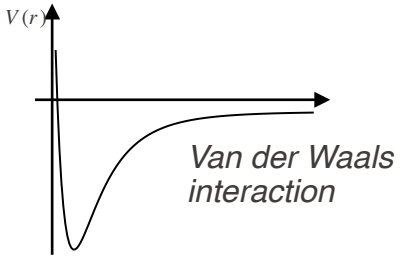


Dipole-dipole interaction

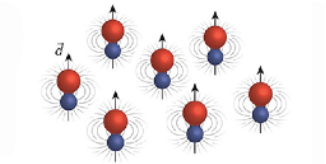
Synthetic quantum systems

Interaction strength

- Unitary gas
- Mott-insulators
- Bose-Einstein condensate
- Polar molecules
- Rydberg atoms
- Magnetic atoms
- Cavity-mediated interactions



Van der Waals interaction



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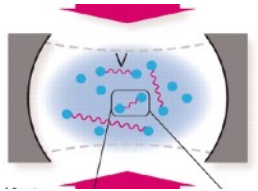


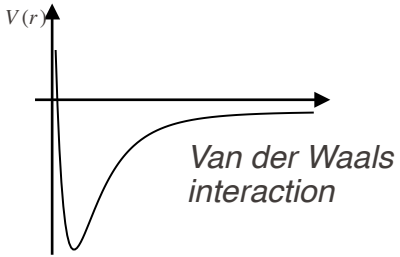
All-to-all interaction

Interaction range

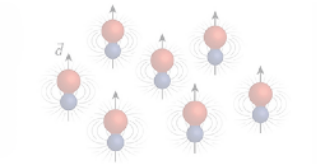
Synthetic quantum systems

Interaction strength

- Unitary gas
- Mott-insulators
- Bose-Einstein condensate
- Polar molecules
- Rydberg atoms
- Magnetic atoms
- Cavity-mediated interactions



Van der Waals interaction



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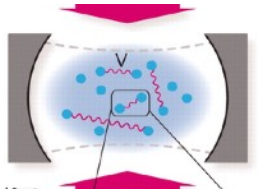

All-to-all interaction

Interaction range

Photon-induced interactions

MIT, Berkeley, Hamburg, ETHZ, Stanford, JILA, Singapour, Shanghai, Vienna…

Long-range spin-exchange:

- spin-squeezing
- Dynamical phase transitions
- Synthetic geometry

A. Periwal *et al. Nature* **600**, 630–635 (2021).

Quantum gases

- Dicke phase transition
- Topological pump
- Time-crystals
- Supersolid and ‘elastic’ solid
- Self-organized Fermi gases

…

D. Dreon *et al. Nature* **608,** 494 (2022)

P. Kongkhambut *et al*, Science **377** 670 (2022)

Y. Guo *et al. Nature* **599,** 211 (2021)

Xiaotian Zhang *et al,* Science **373** 1359 (2021)

Review: F. Mivehvar, F. Piazza, T. Donner and H. Ritsch, Advances in Physics **70** 1-153 (2021)

Photon-induced interactions

Dispersive light-matter interaction

$$\hat{H}_{\text{light-matter}} = -\Delta_c \hat{a}^\dagger \hat{a} + \int d\mathbf{r} \hat{n}(\mathbf{r}) \hat{\phi}^\dagger \hat{\phi}(\mathbf{r})$$

Photon-induced interactions

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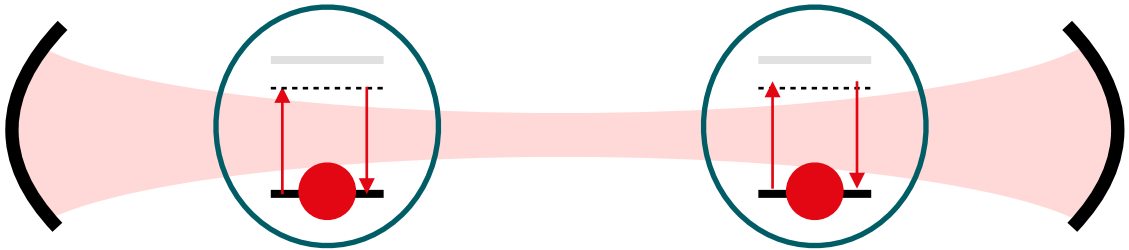

Rayleigh scattering channelled into the cavity mode:

$$\textit{Cooperativity} \quad \eta = \frac{24\mathcal{F}}{\pi k^2 w^2} = \frac{4g_0^2}{\kappa\Gamma}$$

H. Tanji-Suzuki *et al,*
Adv. At. Mol. Opt. Phys. **60** 201 (2011)

Interaction mediated by cavity photons :

$$V_{\text{cav}} = \frac{g_0^2}{\Delta_a}\frac{\alpha^2}{\Delta_a}\frac{1}{\Delta_c}\int d\mathbf{r}d\mathbf{r}'\hat{n}(\mathbf{r})\hat{n}(\mathbf{r}')g_p(\mathbf{r})g_c(\mathbf{r})g_p(\mathbf{r}')g_c(\mathbf{r}')$$

P. Münstermann *et al,* PRL **84** 4068 (2000)

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$U_0 = \frac{g_0^2}{\Delta_a}$ Cavity dispersive coupling

Pump dipole potential $\frac{\alpha^2}{\Delta_a} = V_0$

P. Münstermann *et al,* PRL **84** 4068 (2000)

Review: F. Mivehvar, F. Piazza, T. Donner and H. Ritsch, Advances in Physics **70** 1-153 (2021)

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Cavity detuning

P. Münstermann *et al,* PRL **84** 4068 (2000)

Review: F. Mivehvar, F. Piazza, T. Donner and H. Ritsch, Advances in Physics **70** 1-153 (2021)

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Pump and cavity modes

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Interaction mediated by cavity photons :

$$V_{\text{cav}} = D_0 \int d\mathbf{r} d\mathbf{r}' \hat{n}(\mathbf{r}) \hat{n}(\mathbf{r}') g_p(\mathbf{r}) g_c(\mathbf{r}) g_p(\mathbf{r}') g_c(\mathbf{r}')$$

Pump and cavity modes

Infinite-range, all-to-all

'Local in k space'

$$g_{p,c}(\mathbf{r}) = \cos(\mathbf{k}_{p,c} \cdot \mathbf{r})$$

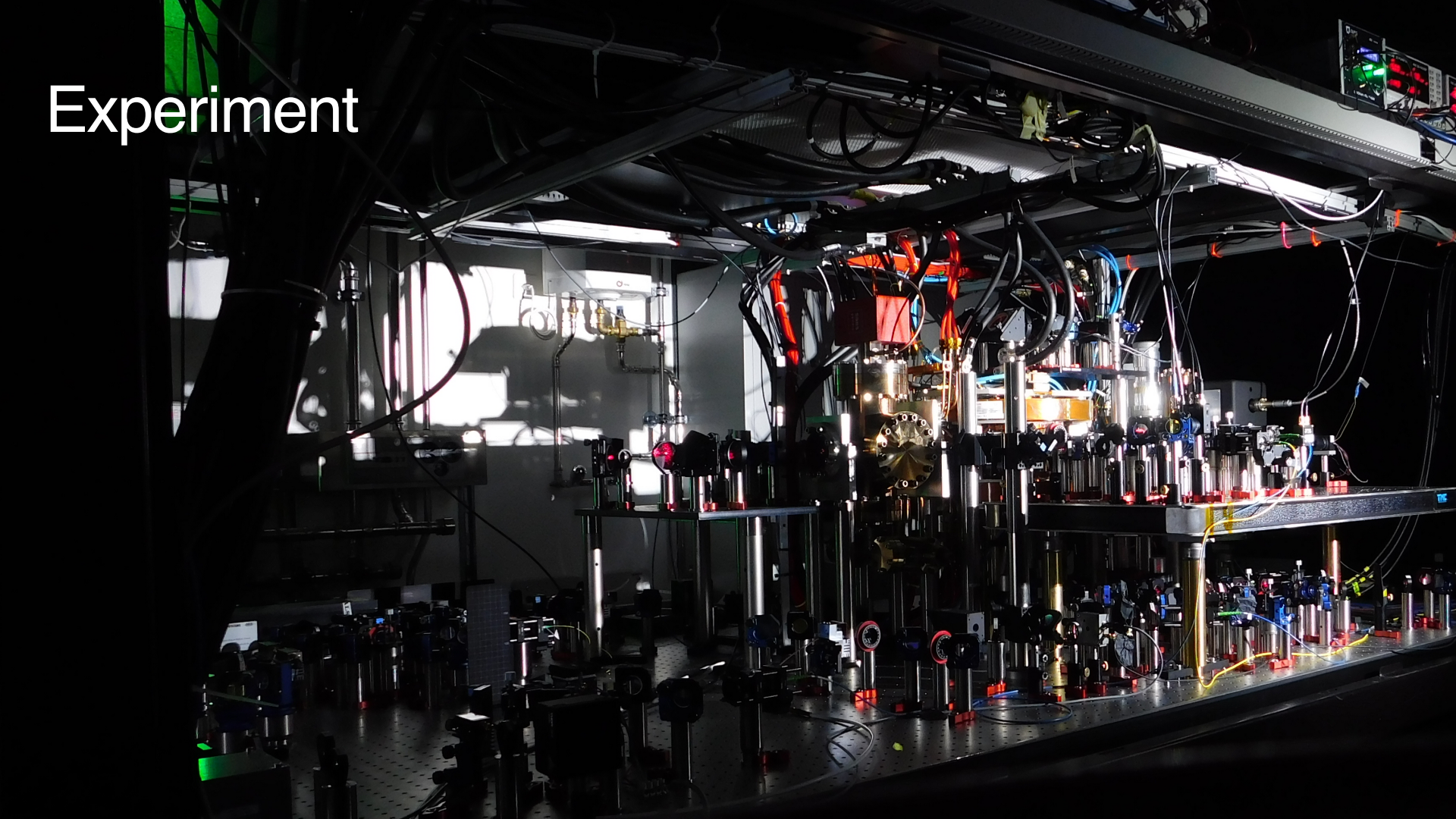
Combined cavity-QED and unitary gas setup

Density-wave ordering induced by photon-mediated interactions

V. Helson, T. Zwettler, E. Collela, F. Mivhevar, K. Roux, H. Konishi, H. Ritsch and JPB
Nature **618**, 716 (2023)

Universal dynamics at the transition

Experiment



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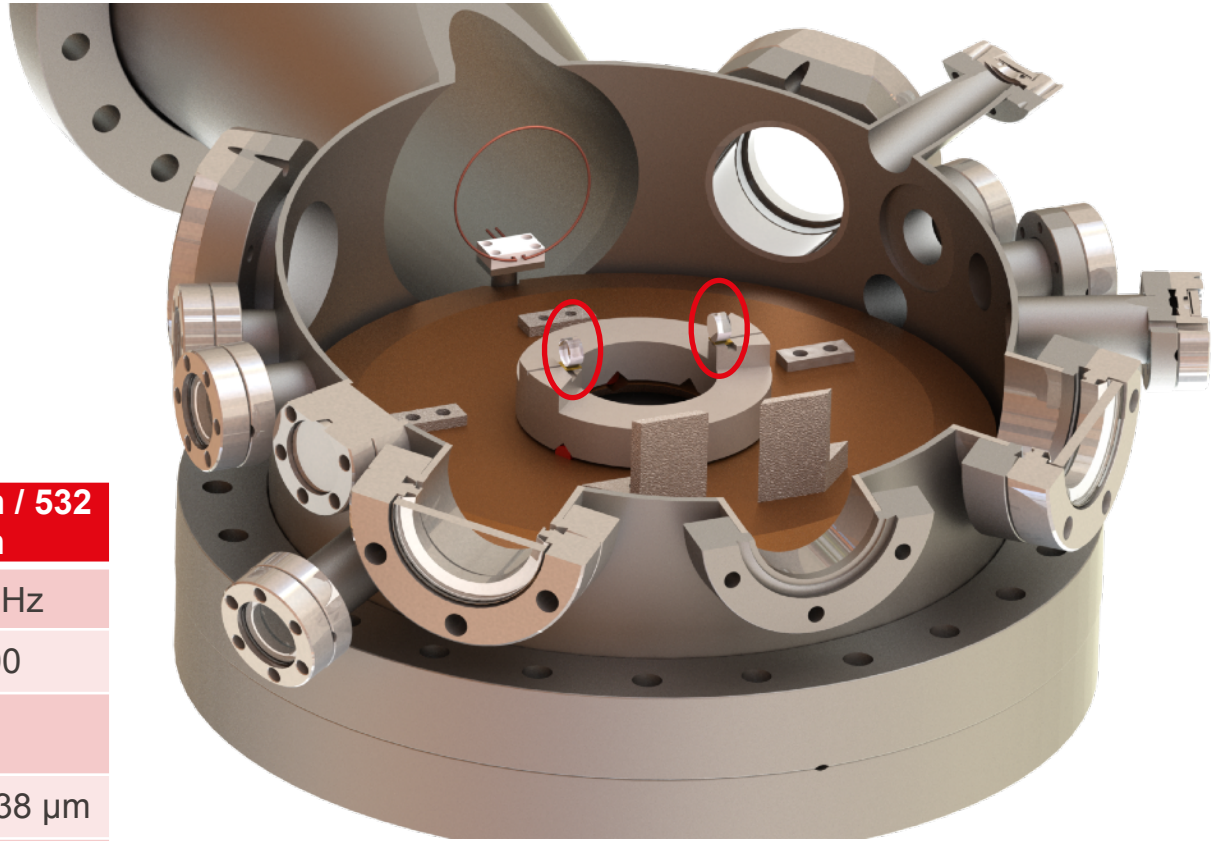


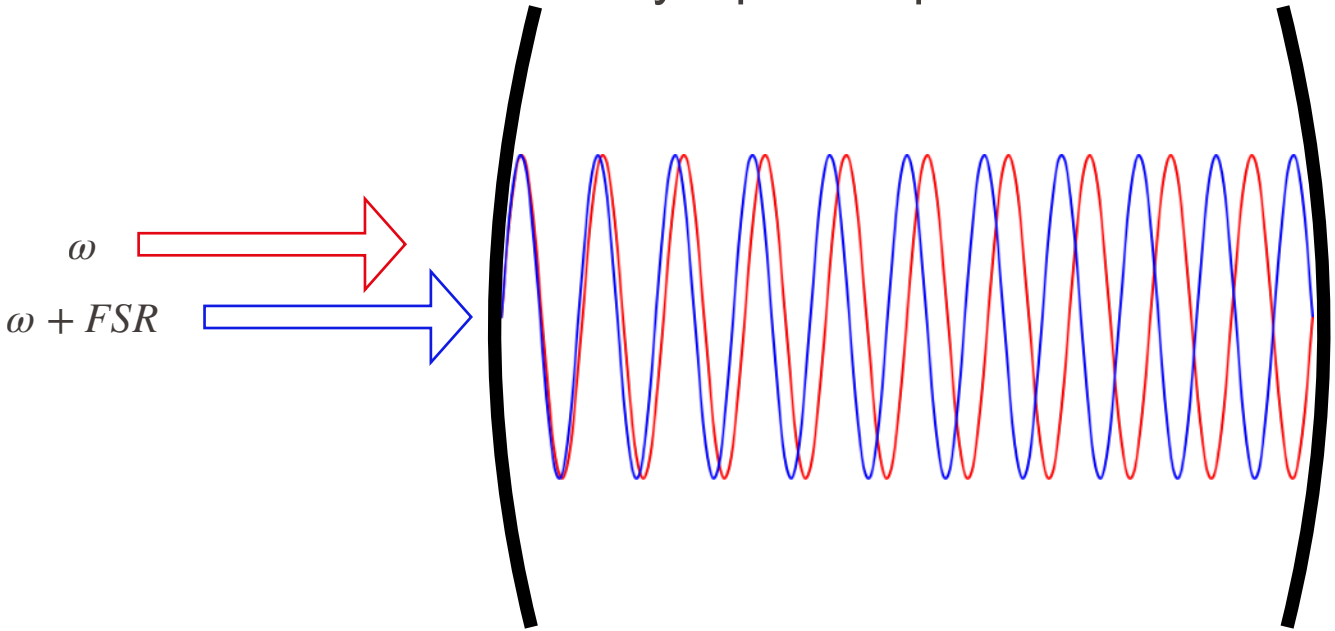
High-finesse cavity

	671 nm	1064 nm / 532 nm
Linewidth	77 kHz	1.4 MHz
Finesse	47’000	2’800
Cooperativity	2.02	
Waist	45 µm	50 µm / 38 µm
g	0.479 MHz	

K. Roux, V. Helson , H. Konishi and JPB, New J. Phys. **23** 043029 (2021)
K. Roux, H. Konishi, V. Helson and JPB, Nature Communications **11** 2974 (2020)

Experiment

- Lattice-cancelled cavity dipole trap



K. Roux, V. Helson , H. Konishi and JPB, New J. Phys. **23** 043029 (2021)

A. Mosk, S. Jochim, H. Moritz, Th. Elsässer, M. Weidemüller and R. Grimm, Optics Letters 26 1837 (2001)

Experiment

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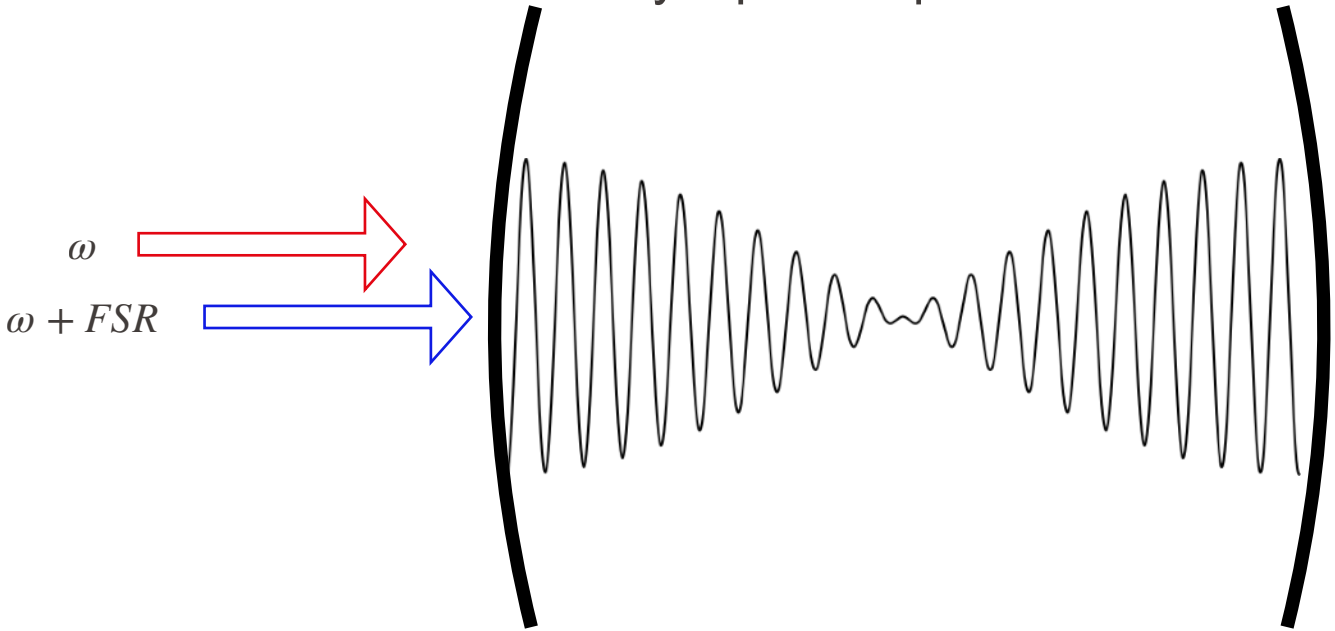


K. Roux, V. Helson , H. Konishi and JPB, New J. Phys. **23** 043029 (2021)

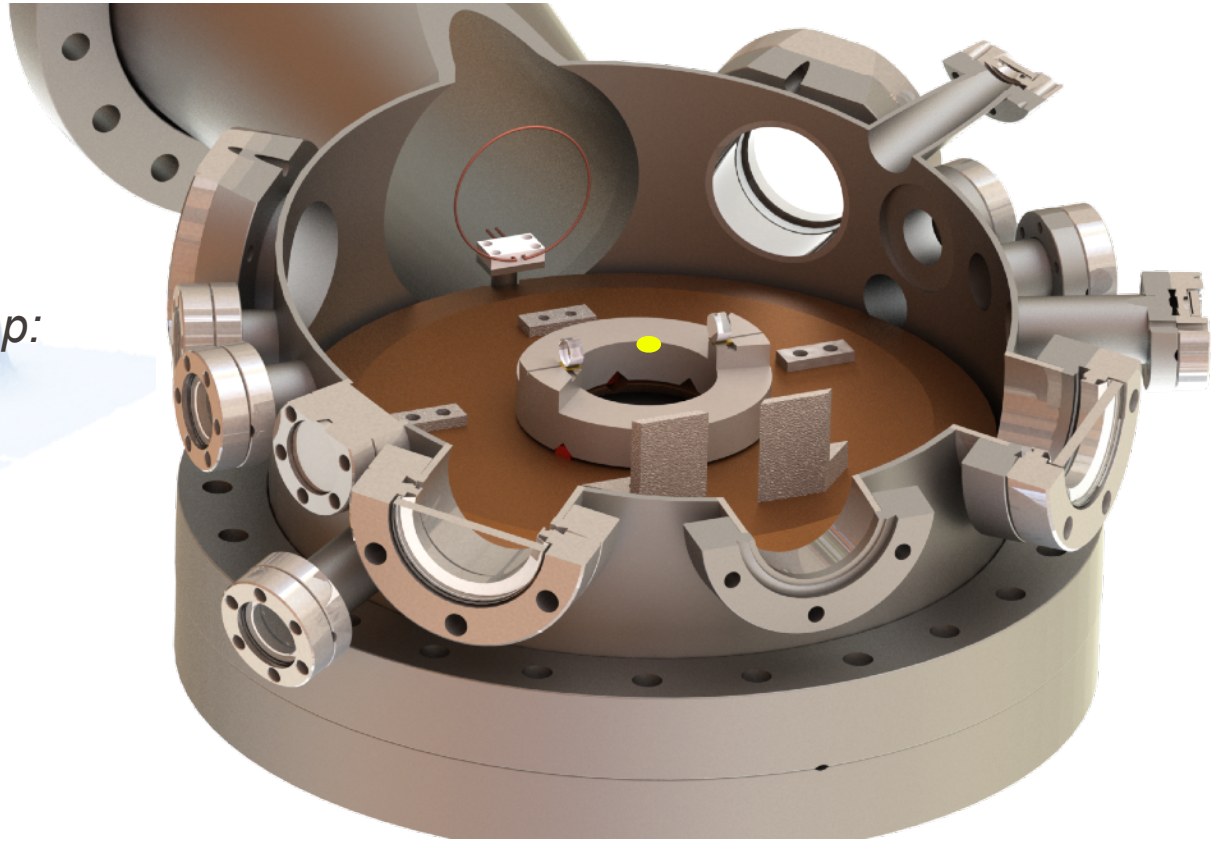
Experiment

Single cavity-based dipole trap:

- <1W laser power

Unitary Fermi gas

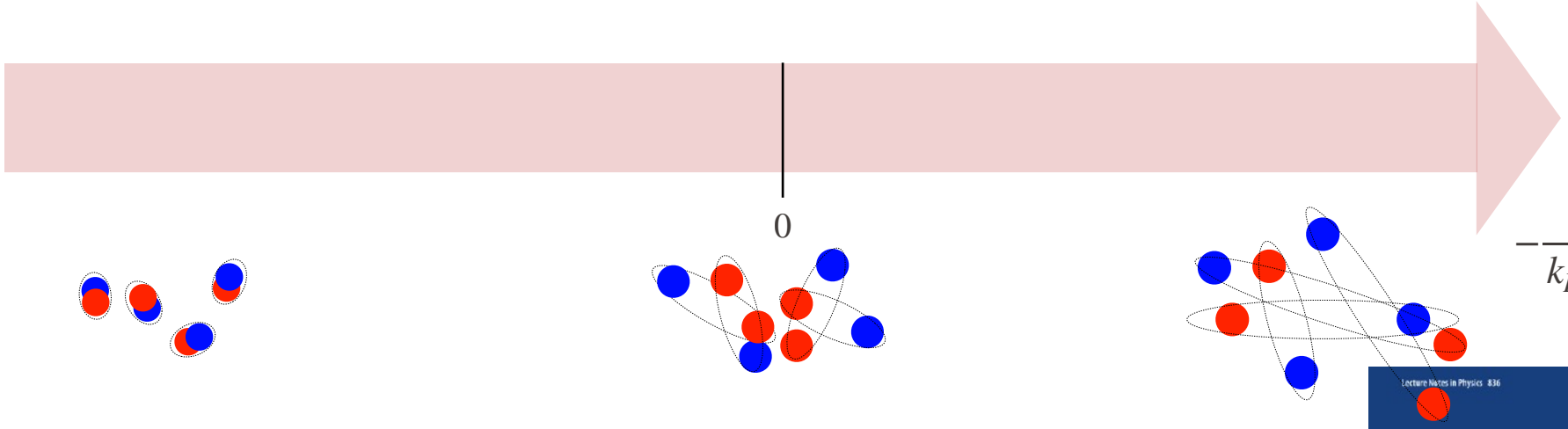
- 300’000 ^{6}Li atoms
- T = 0.1 T_F



K. Roux, V. Helson , H. Konishi and JPB, New J. Phys. **23** 043029 (2021)

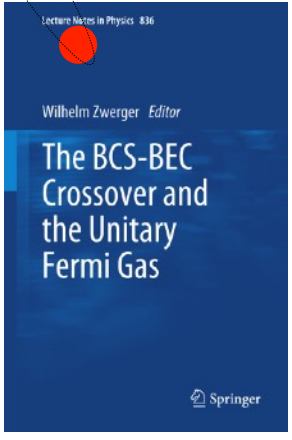
K. Roux, H. Konishi, V. Helson and JPB, Nature Communications **11** 2974 (2020)

Fermi gas in the BEC-BCS crossover



- Cooper pairing and superfluidity
- Universal short-range physics

Fully controlled quantum material



Combined cavity-QED and unitary gas setup

Density-wave ordering induced by photon-mediated interactions

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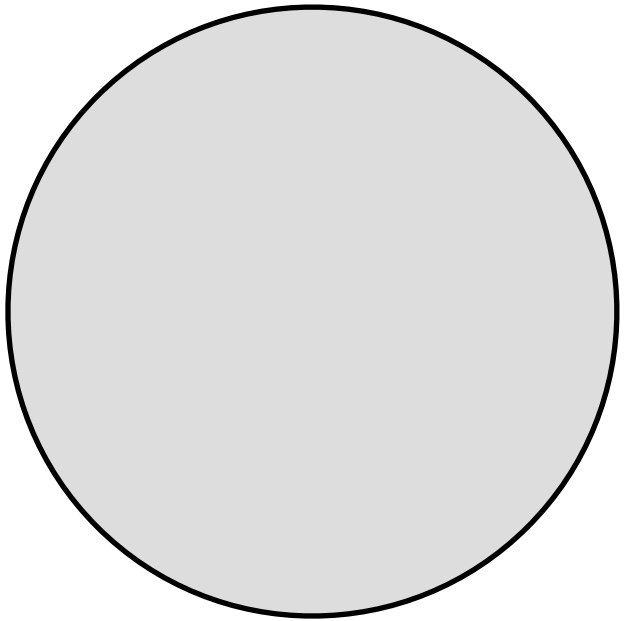
Universal dynamics at the transition

Doubly tunable Fermi gas



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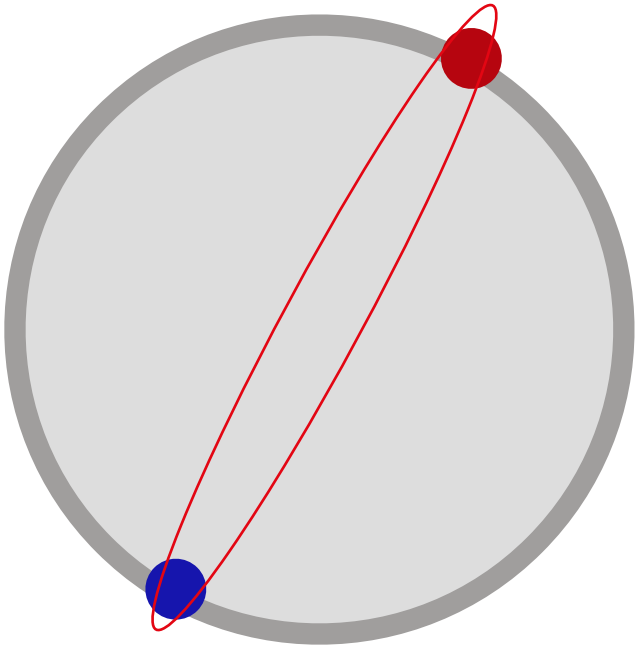
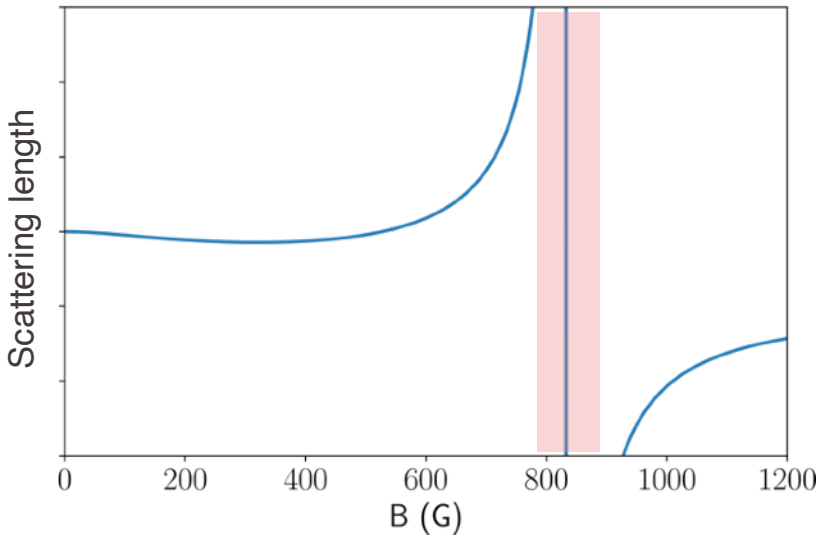


s-wave
contact interaction



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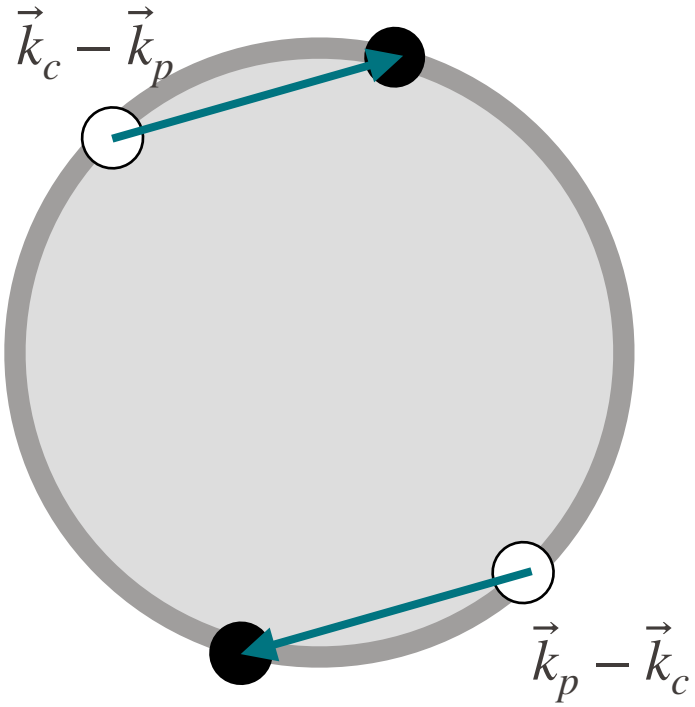
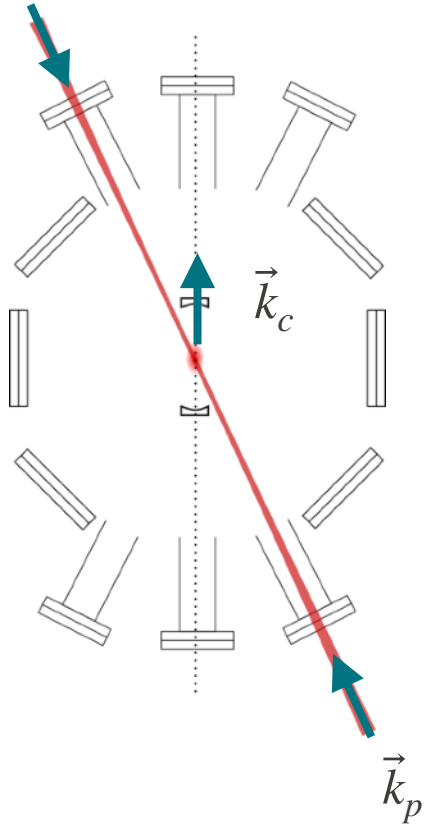


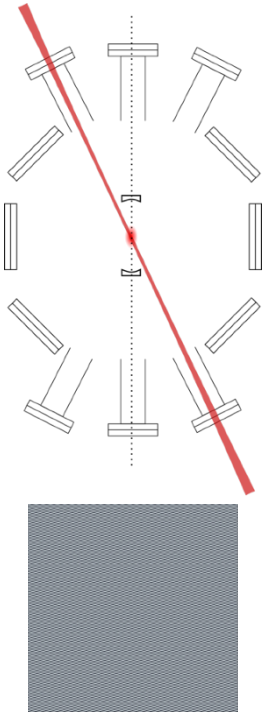
Contribution from $\vec{k}_c + \vec{k}_p$ negligible

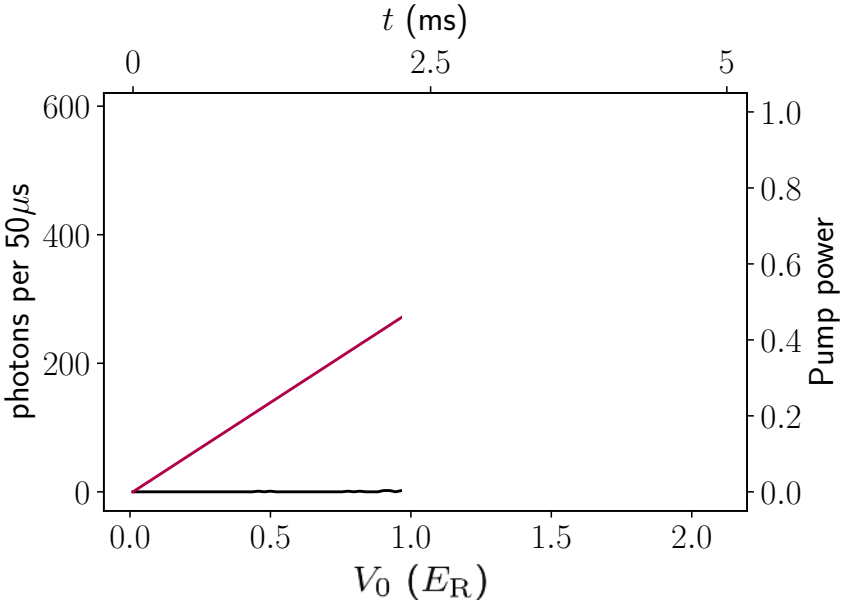
Photon-induced interaction



Self-organization transition

Uniform unitary gas $\longrightarrow$ uniaxial ‘’charge” Density Wave Order





Self-organization transition

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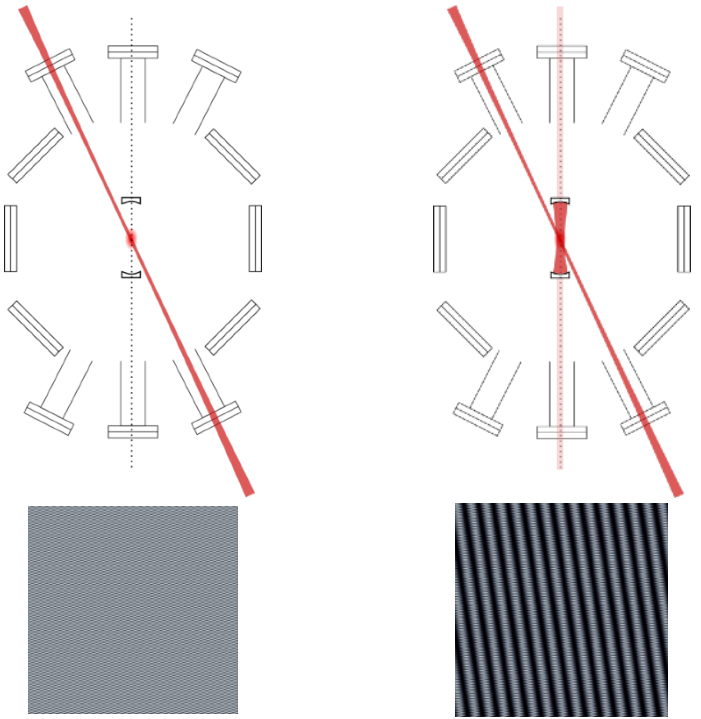
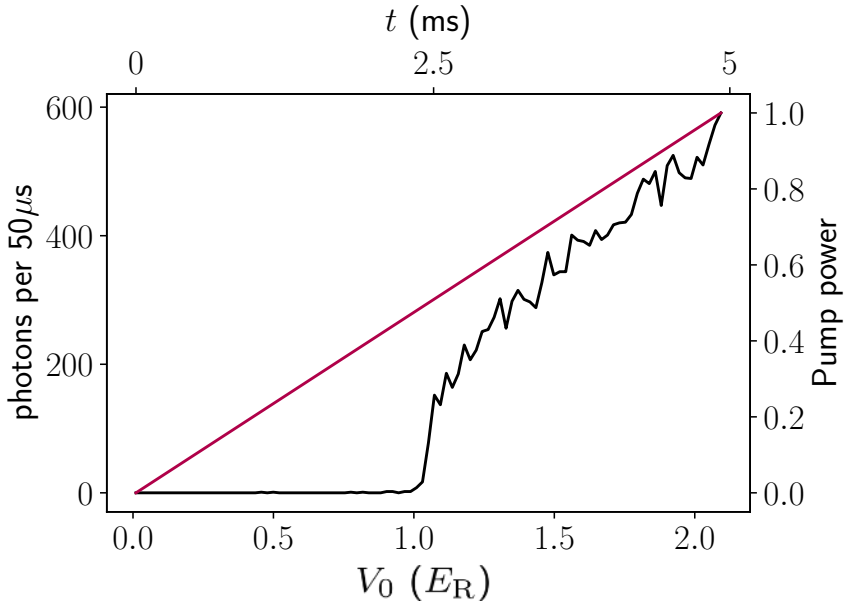
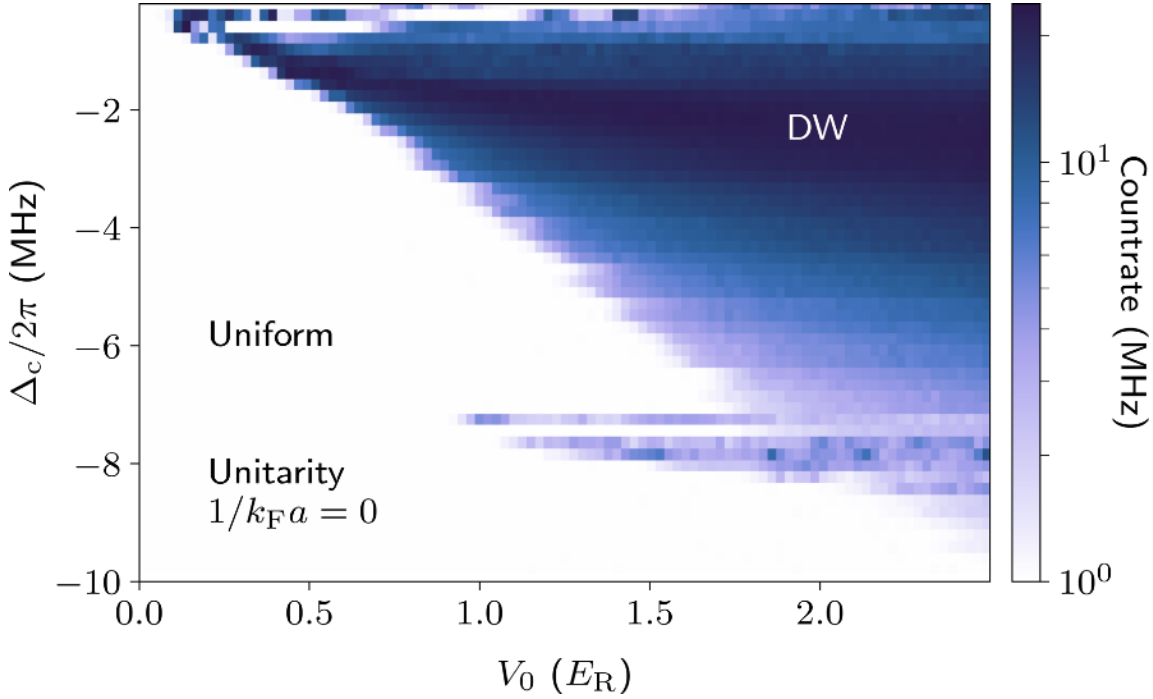




Thermal atoms : A.T. Black *et al*, PRL **91** 203001 (2003)
BEC : K. Baumann *et al*, Nature **464** 1301 (2010)
Non-interacting Fermi gases: X. Zhang *et al,* Science **373** 1359 (2021)

Phase diagram



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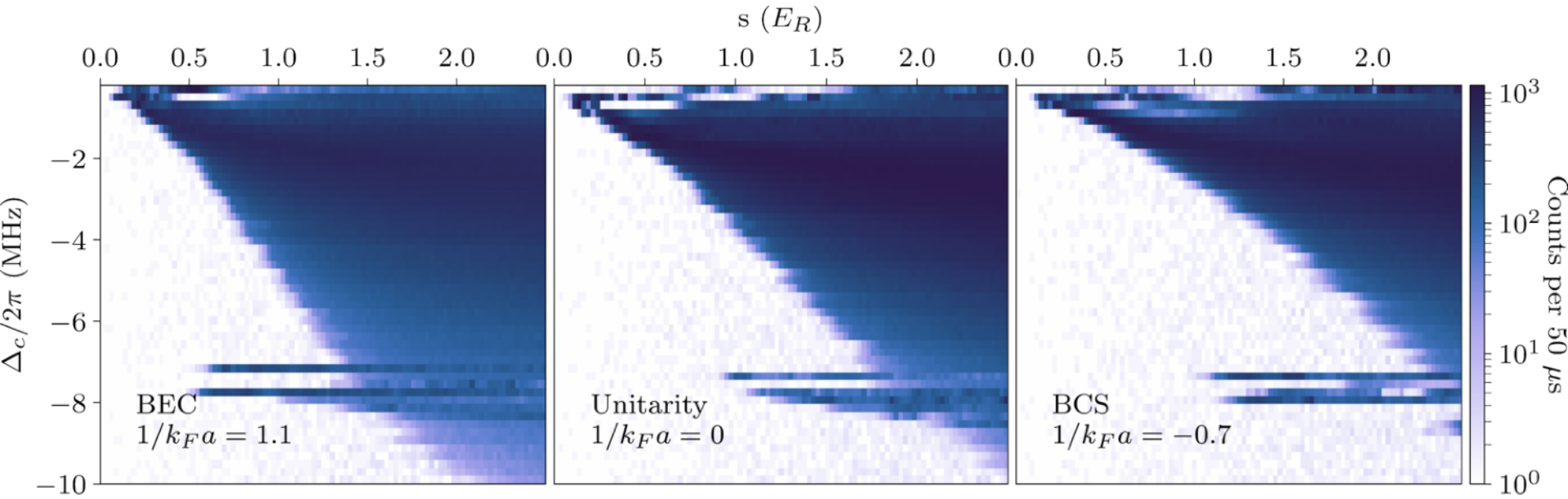
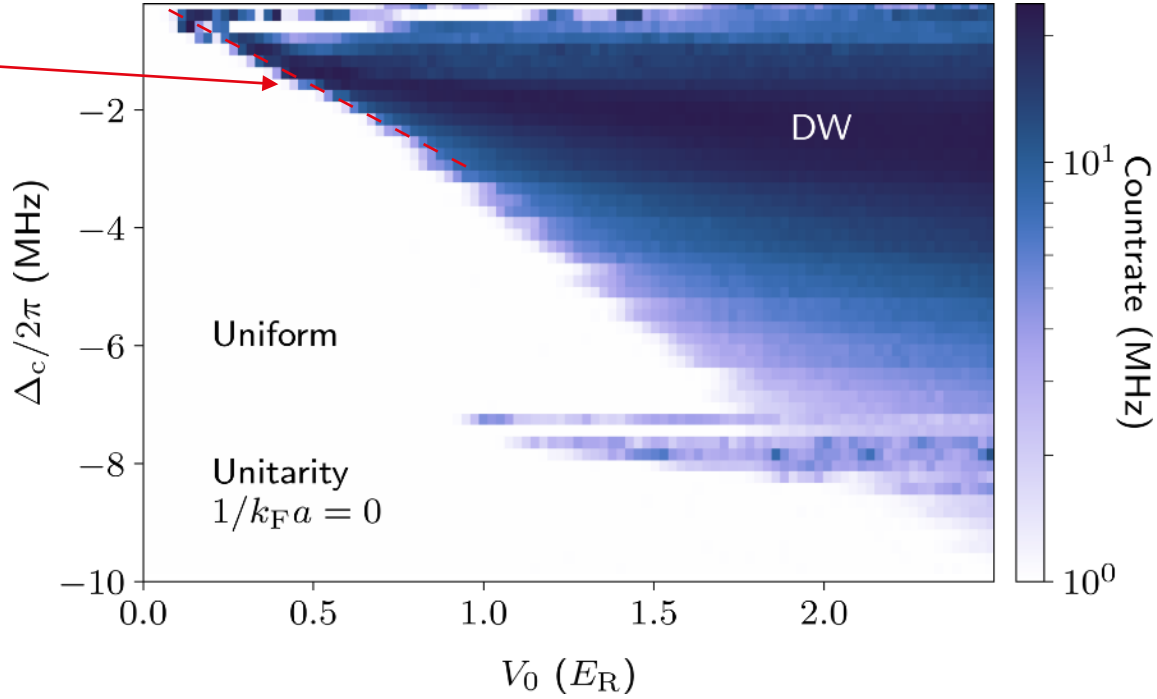


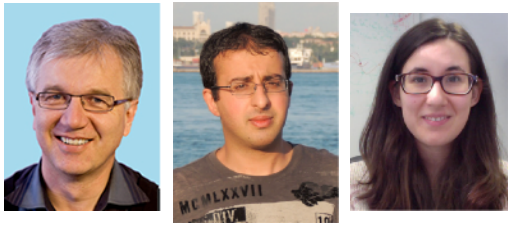
Phase diagram

$V_{0C} = U_0 \Delta_c$

Critical photon-induced interaction D_{0C}



Short + long-range interactions



Theory: E. Collela, F. Miehvevar and H. Ritsch (Innsbrück)

RPA theory for the density-wave ordering transition

$$D_{0C} = -\frac{1}{2\chi_0}$$

DW susceptibility for $D_0 = 0$

Density response function

$$\chi_0 = \frac{1}{8}\chi^R_{nn}(k_-) \sim \frac{1}{8}\chi^R_{nn}(0) \propto \kappa_T$$

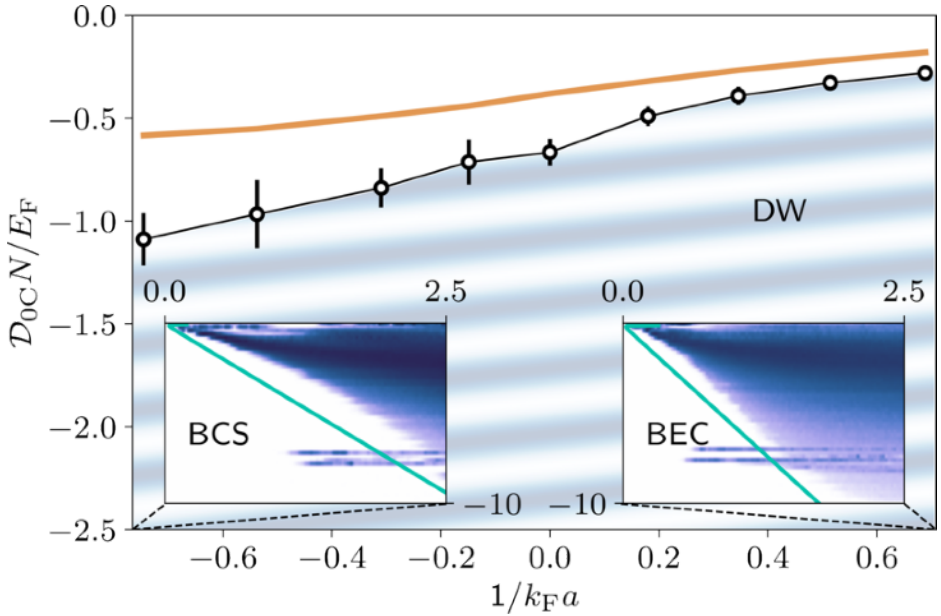
Compressibility from equation of state + trap averaging

N. Navon, S. Nscimbene, F. Chevy and C. Salomon, Science **328** 729 (2010)
M. Horikoshi, M. Koashi, H. Tajima, Y. Ohashi, M. Kuwata-Gonokami, PRX **7** 041004 (2017)

Theory: E. Collela, F. Miehvevar and H. Ritsch (Innsbrück)

Short + long-range interactions

Phase diagram in the $D_0 - a$ plane



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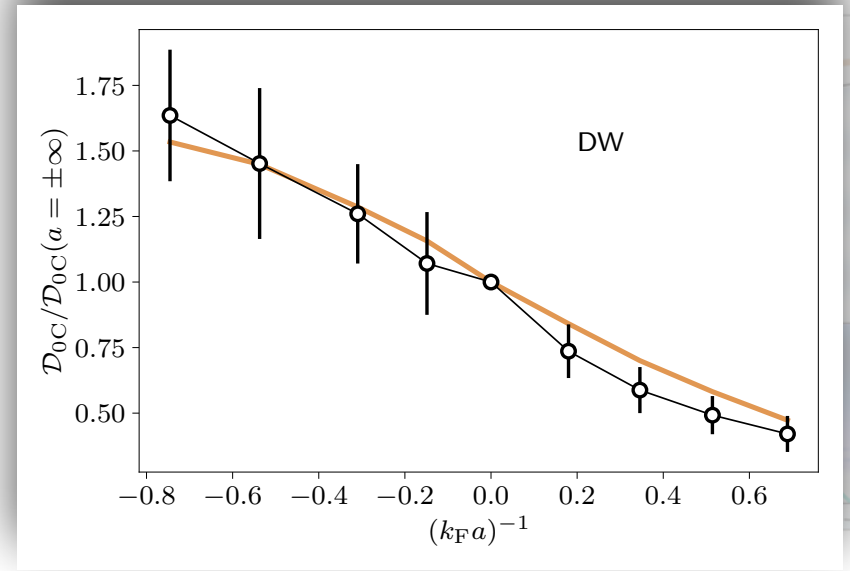
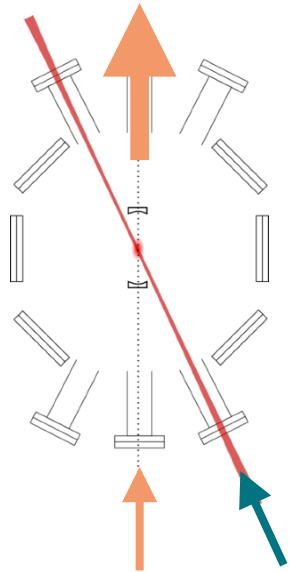


Theory predicts the scaling

Density-wave susceptibility

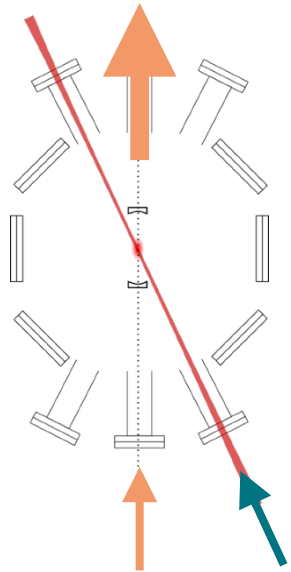


Weak probe

Tunable pump

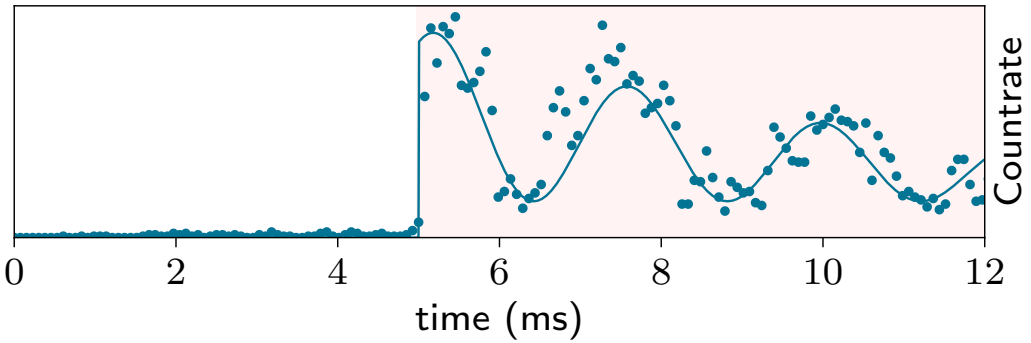
BEC: R. Mottl *et al* Science **336** 1570 (2012)

Density-wave susceptibility



Weak probe Tunable pump

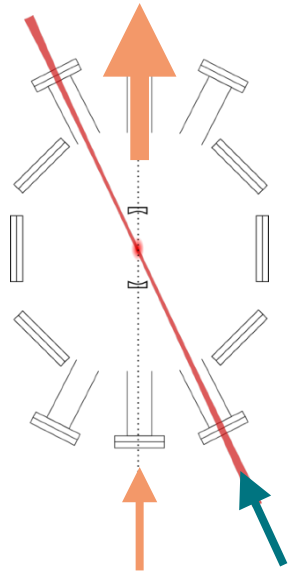
‘Bragg’ spectroscopy



Weak pump-probe detuning:
adiabatic response at $\vec{k}$_

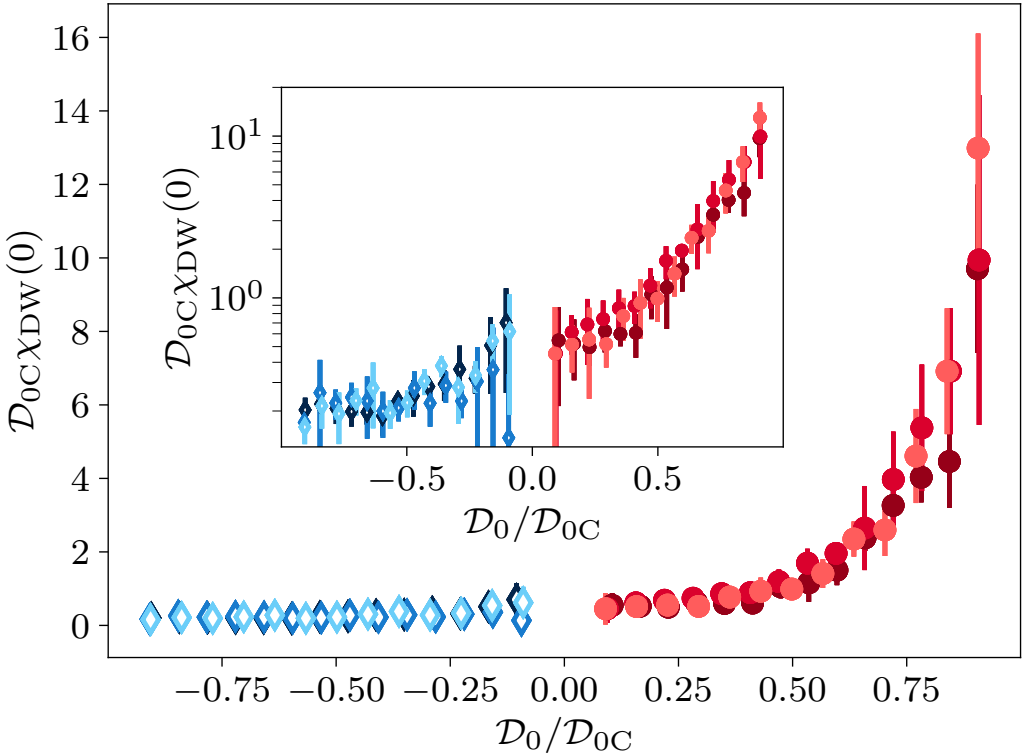
BEC: R. Mottl *et al* Science **336** 1570 (2012)

Density-wave susceptibility



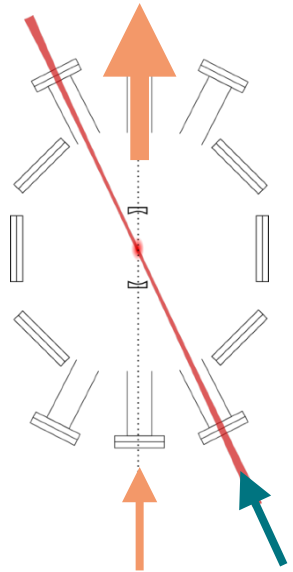
Weak probe

Tunable pump

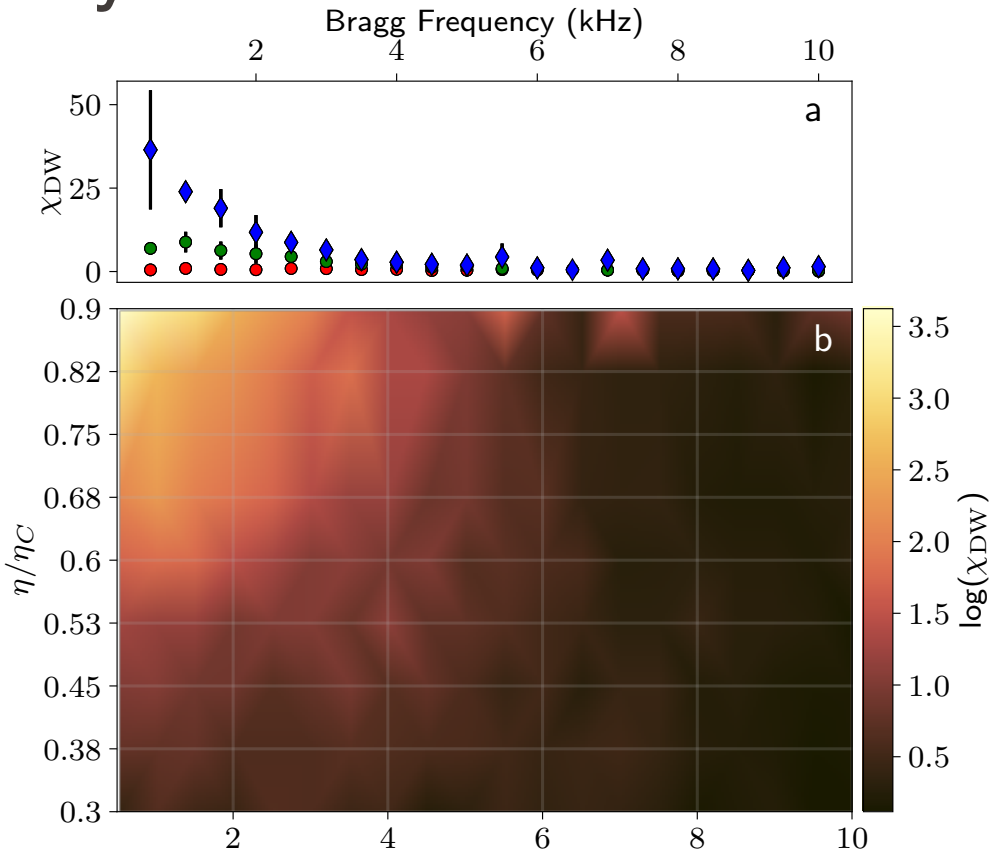


Density-wave susceptibility

Response at finite frequency



Weak probe $\delta\omega$ Tunable pump



Combined cavity-QED and unitary gas setup

Density-wave ordering induced by photon-mediated interactions

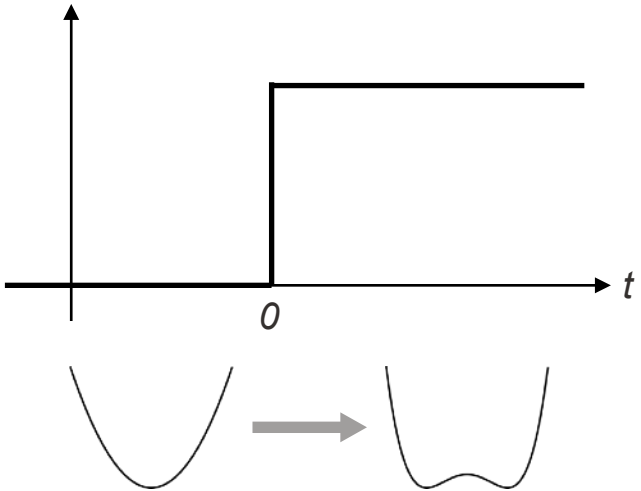
V. Helson, T. Zwettler, E. Collela, F. Mivhevar, K. Roux, H. Konishi, H. Ritsch and JPB
Nature **618**, 716 (2023)

Universal dynamics at the transition

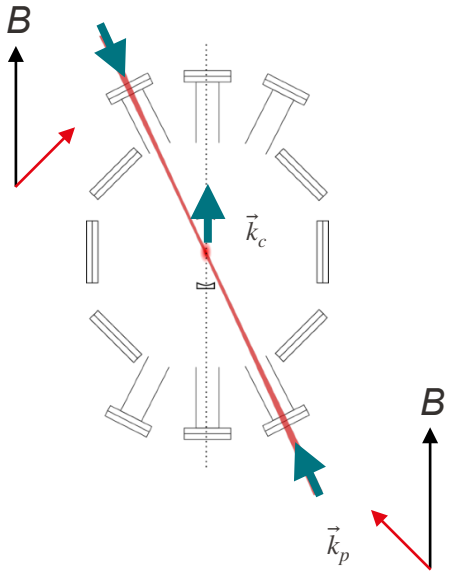
Universal dynamics

Theory collaboration: C.M. Halati, L. Tolle, T. Giamarchi, S. Uchino, L. Skolc, E. Demler

- Instantaneous quench across the transition

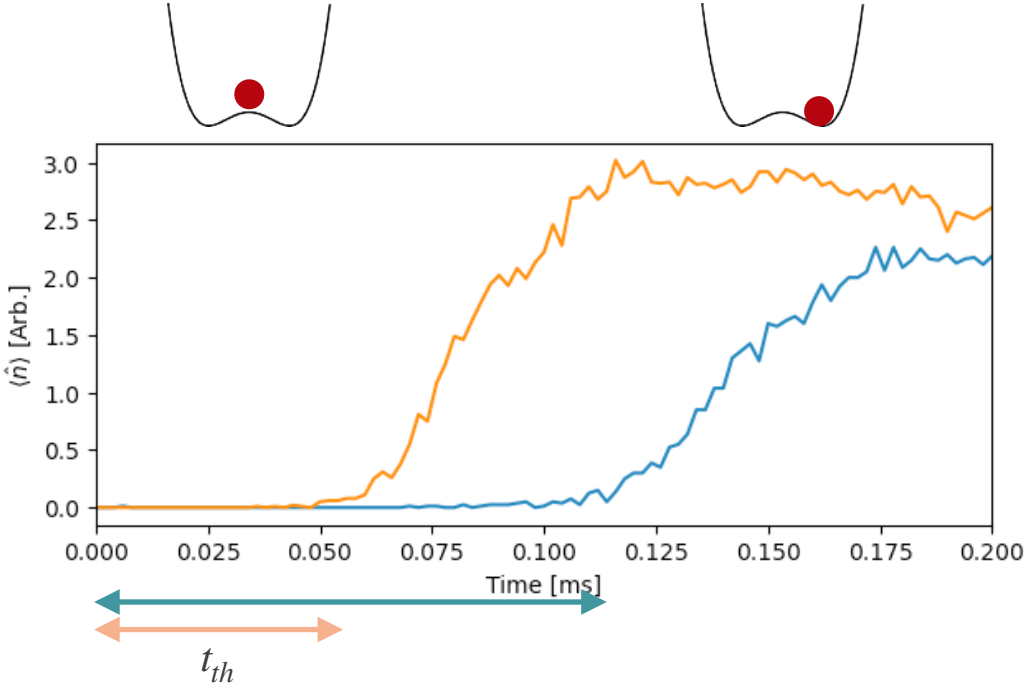


- Crossed-polarized pump for lattice cancelation



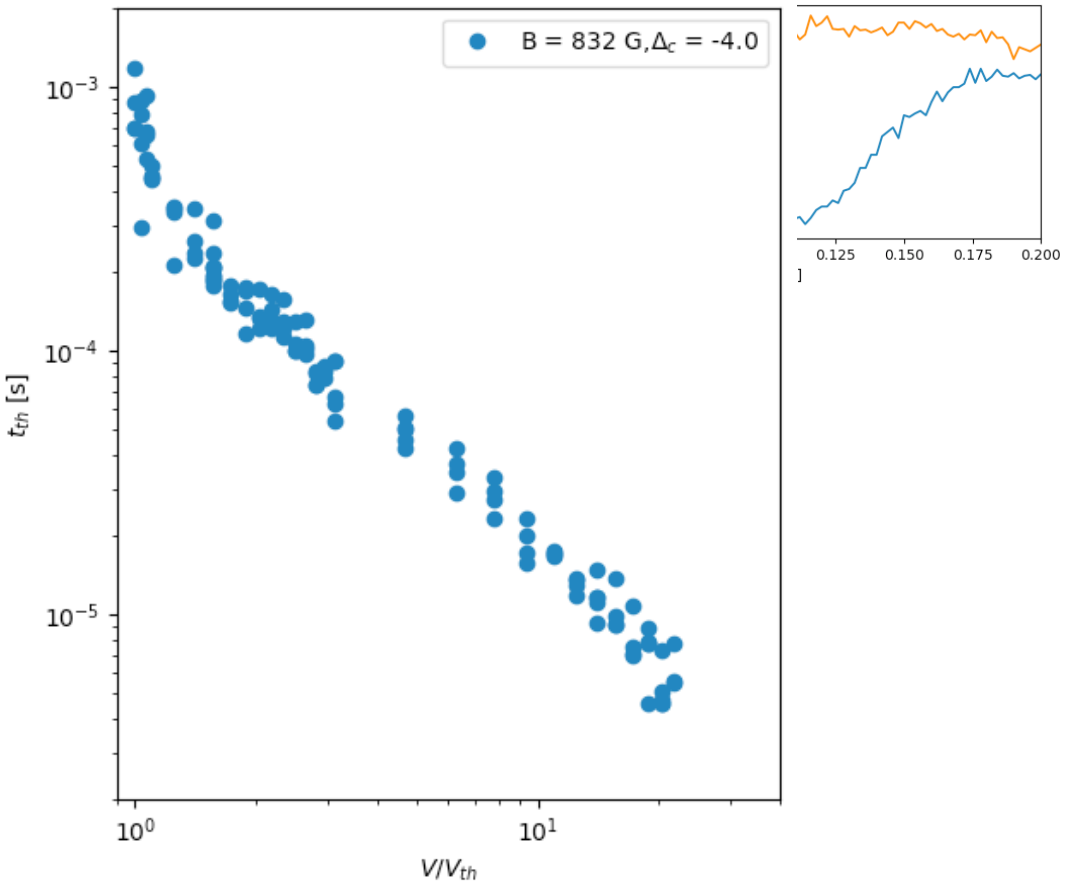
Universal dynamics

Instantaneous quench of the pump laser to variable strength



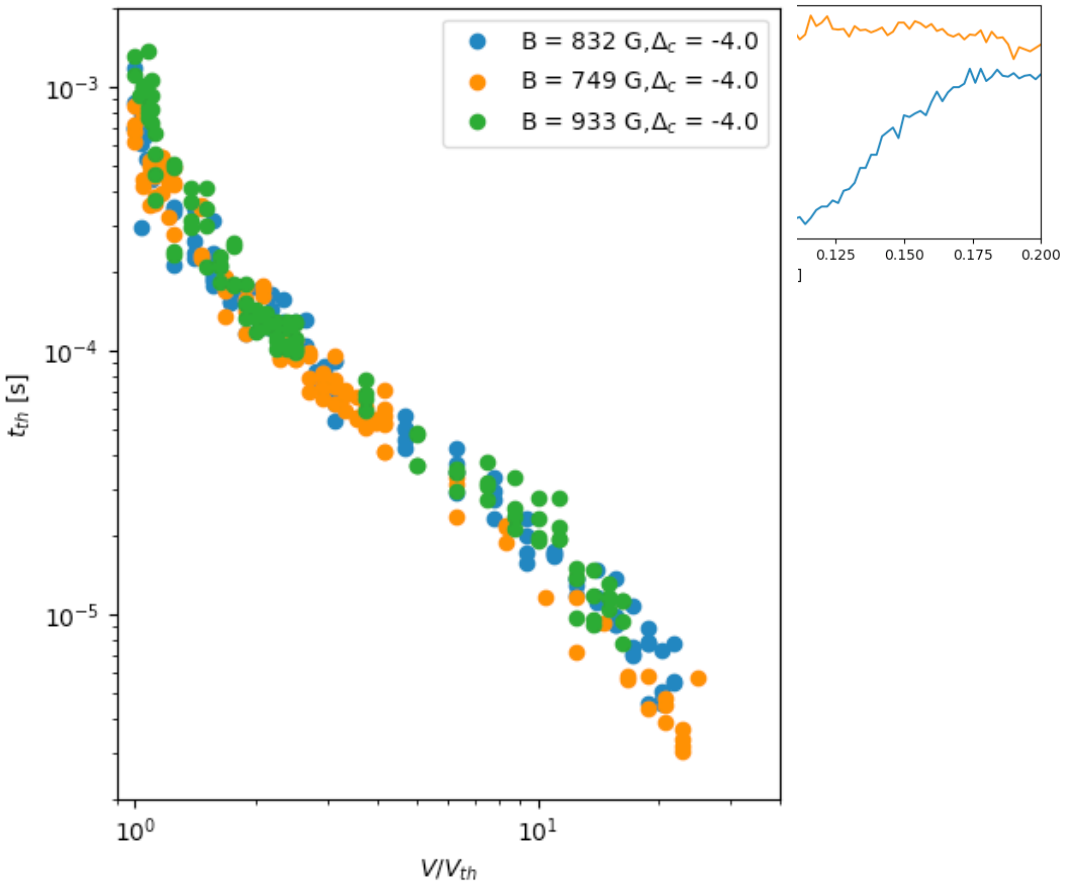
Universal dynamics

- Onset time of the order parameter
- Unitary Fermi gas



Universal dynamics

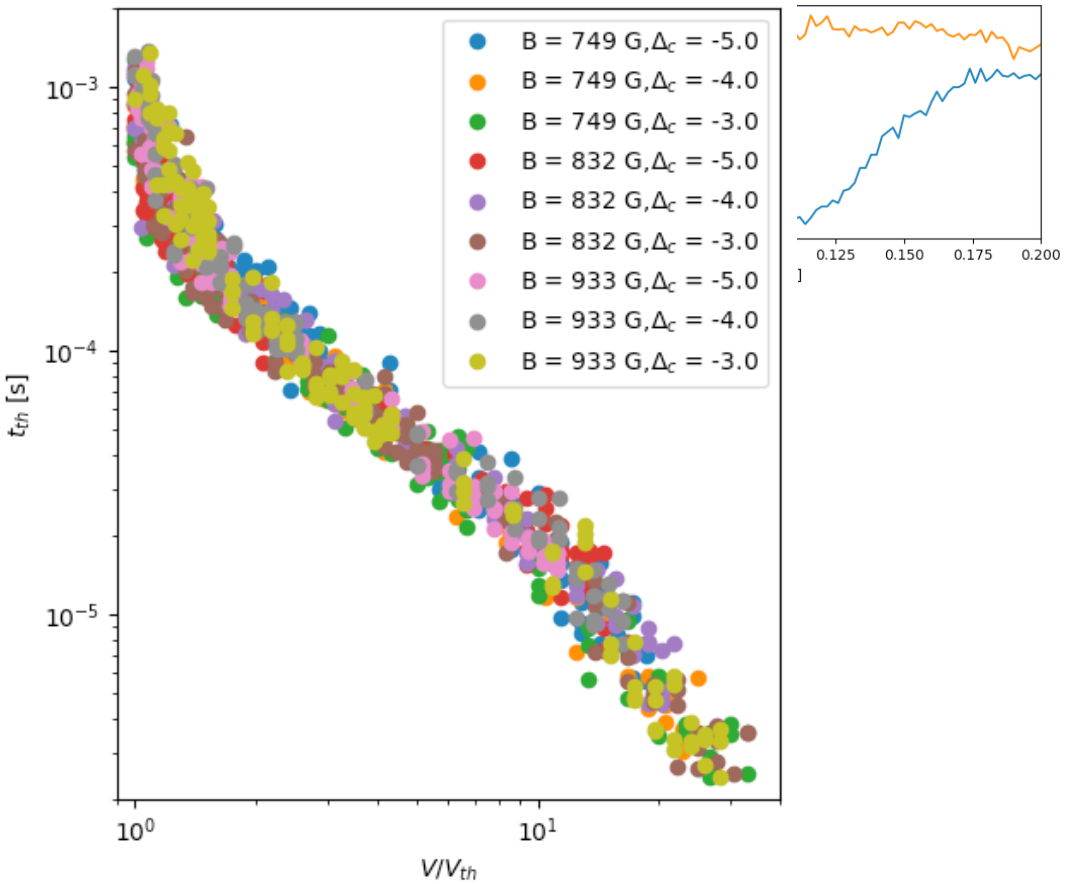
- Onset time of the order parameter
- Varying interactions



Universal dynamics

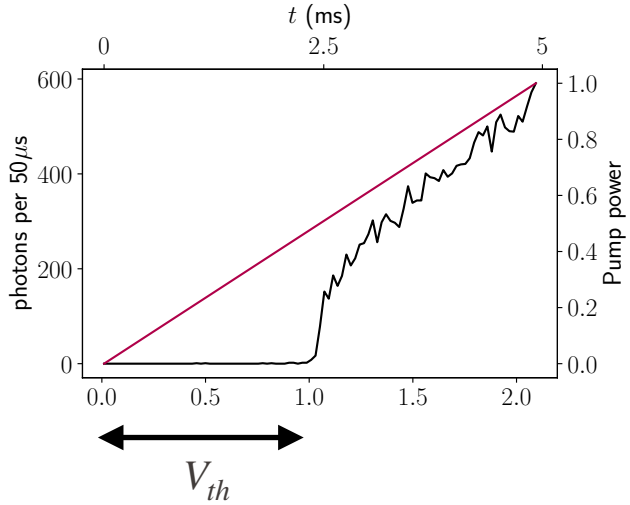
- Onset time of the order parameter
- Varying interactions
- Varying detunings

Universal scaling over 3 orders of magnitude in time



Universal dynamics

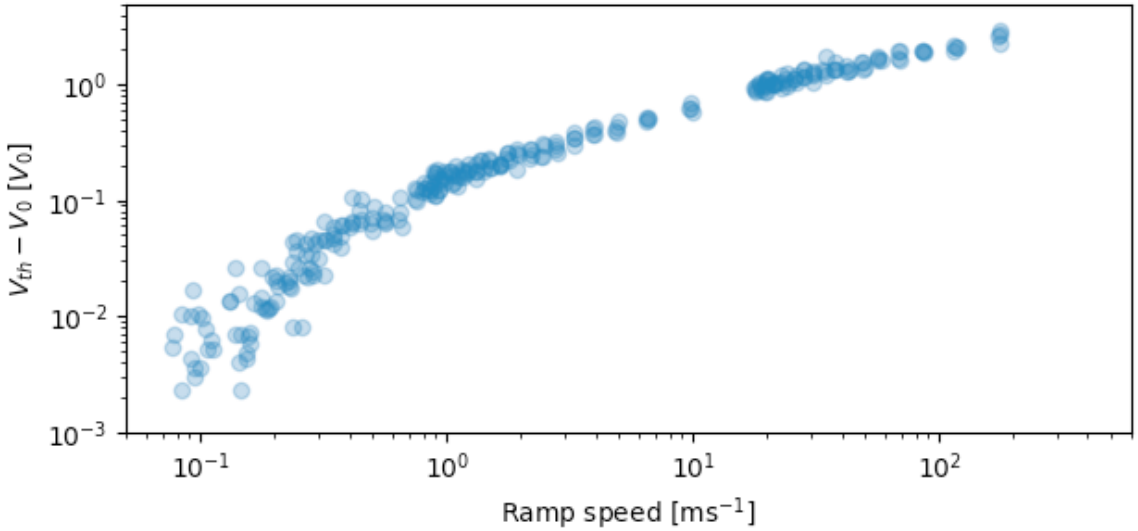
Ramp dynamics through the transition

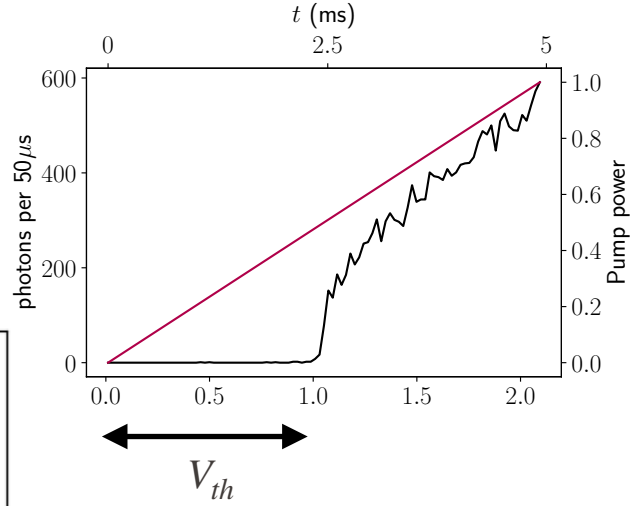


Universal dynamics

Ramp dynamics through the transition

- Unitary gas

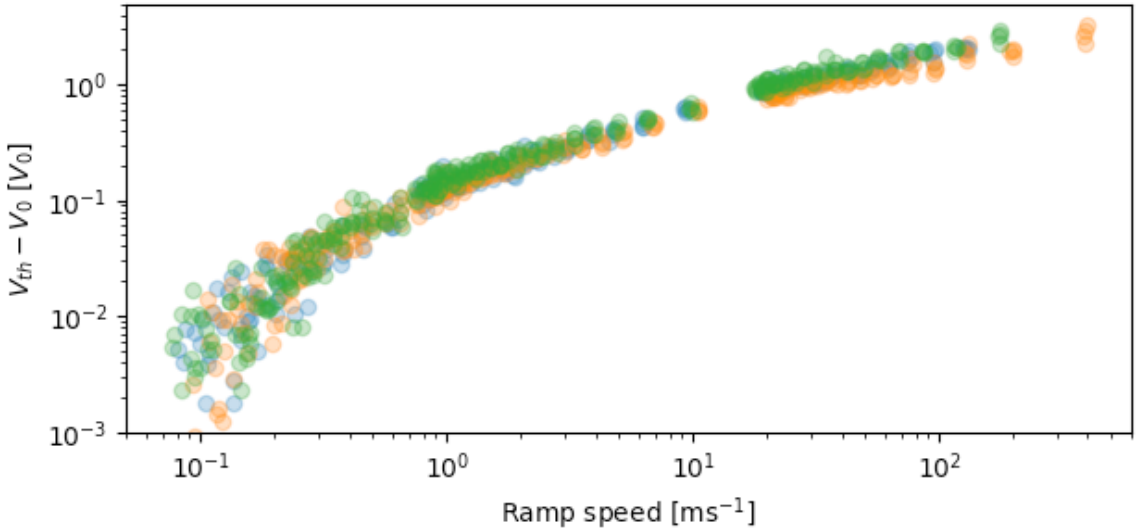


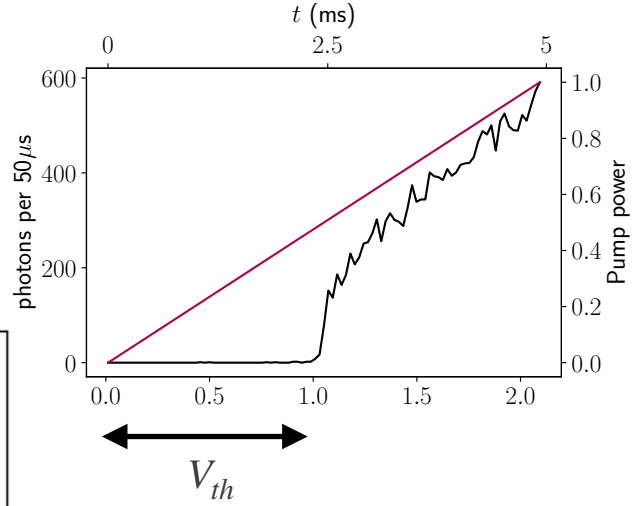


Universal dynamics

Ramp dynamics through the transition

- Varying interactions

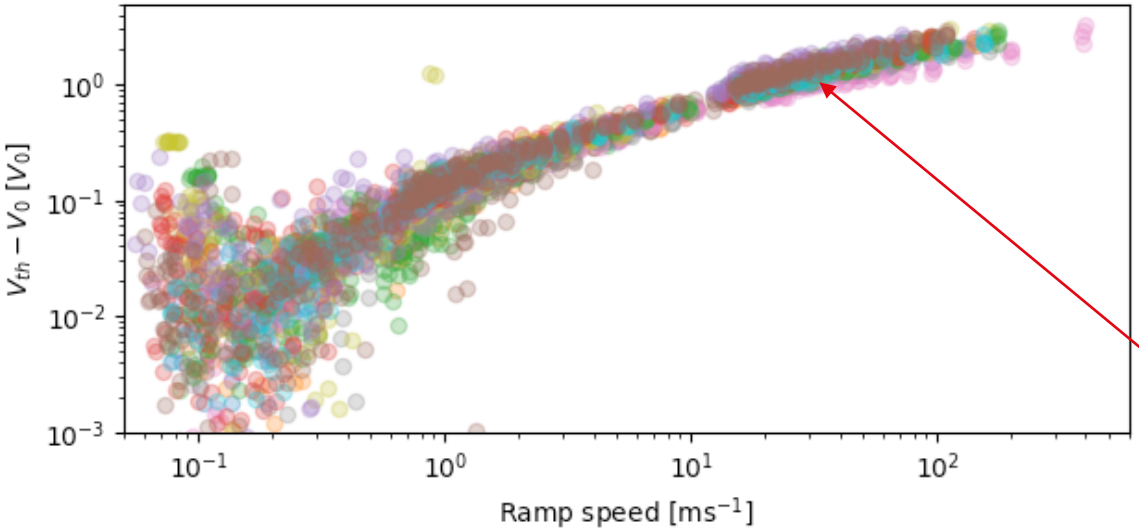


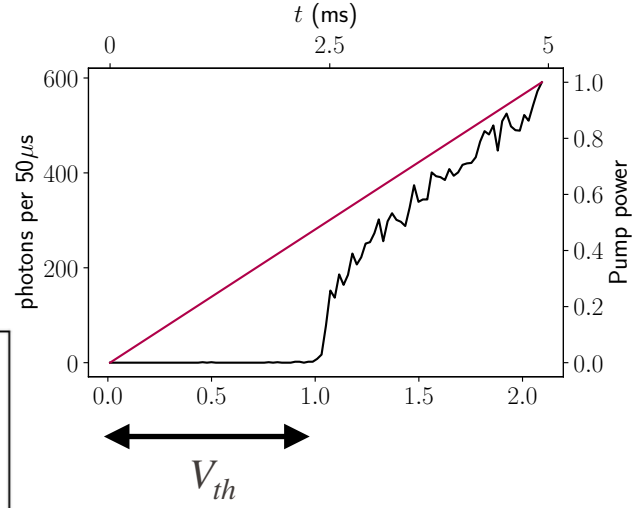


Universal dynamics

Ramp dynamics through the transition

- Varying interactions and detunings





Universal scaling in speed
Power-law behavior

BEC: J. Klinder *et al* PNAS **112** 3290 (2015)

Perspectives

- Comparison with theory for the dynamics: time dependent mean-field and full numerical calculation on a small system

- Competition between charge order and superfluidity

High-Tc superconductors: E. Fradkin, S.A. Kivelson and J.M. Tranquada, RMP **87** 457 (2015)

Perspectives

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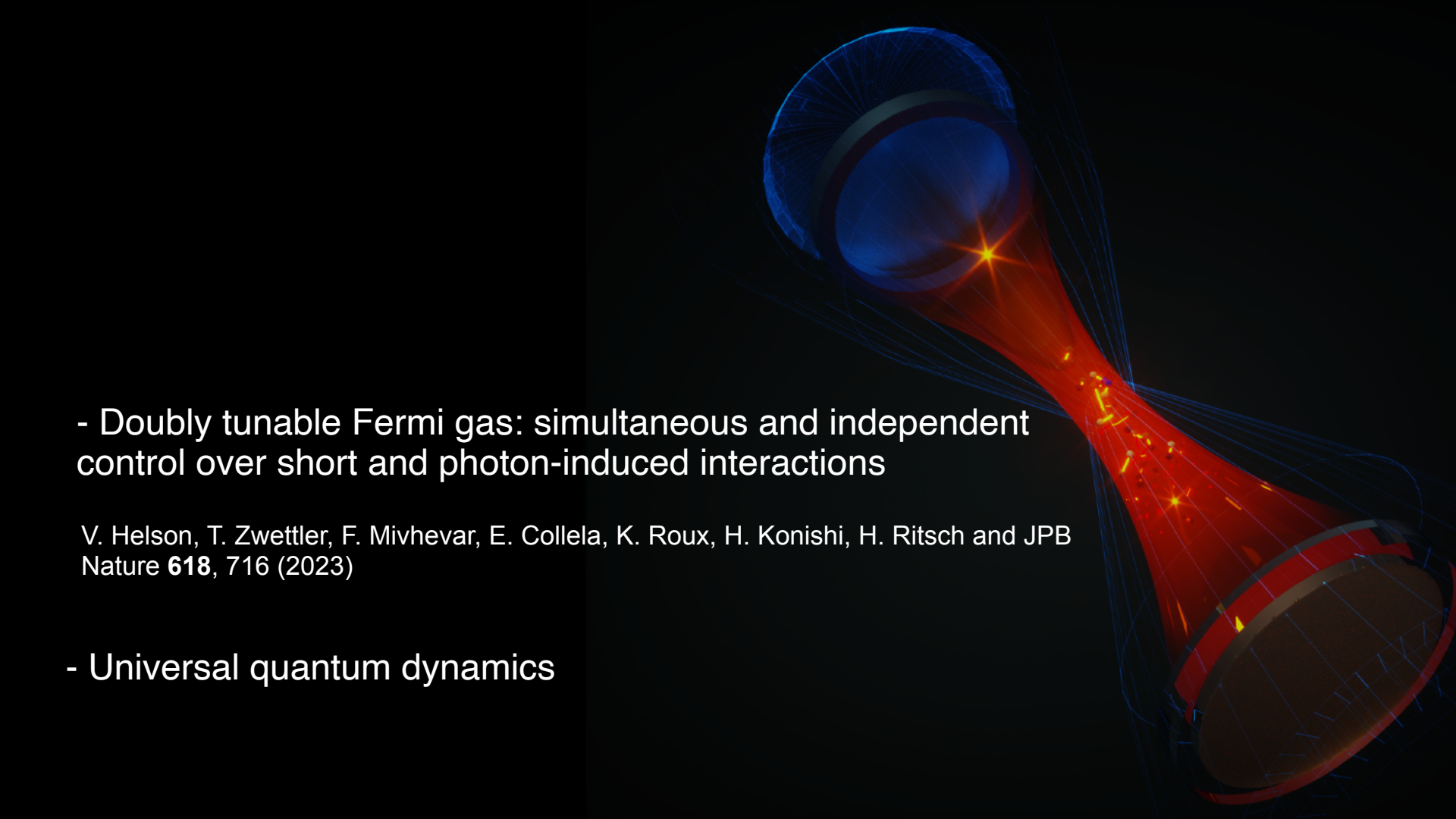
  High-Tc superconductors: E. Fradkin, S.A. Kivelson and J.M. Tranquada, RMP **87** 457 (2015)

- Coupling to pairs close to a photo-association transition

  H. Konishi, K. Roux, V. Helson and JPB, Nature **596** 509 (2021)

- In-situ imaging and local manipulation



- Doubly tunable Fermi gas: simultaneous and independent control over short and photon-induced interactions

V. Helson, T. Zwettler, F. Mivhevar, E. Collela, K. Roux, H. Konishi, H. Ritsch and JPB
Nature **618**, 716 (2023)

- Universal quantum dynamics