EPFL

All-to-all interacting quantum gases for quantum simulation

Jean-Philippe Brantut, EPFL

Swiss National Science Foundation

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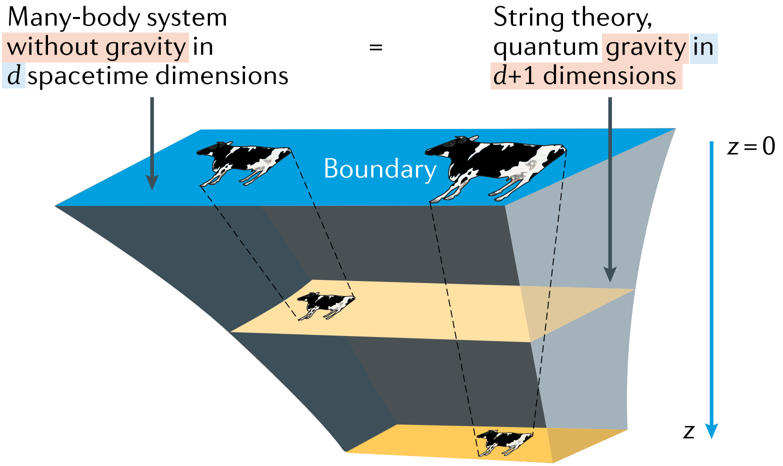
Motivation: holography

Strongly correlated quantum matter ⟷ Quantum gravity



H. Liu and J. Sonner, Nature Reviews Physics **2**, 615 (2020)

Motivation: holography

Strongly correlated quantum matter

Quantum gravity

Recipe for quantum simulation

Motivation: holography

Strongly correlated quantum matter ⟷ Quantum gravity

- No quasi-particles
- Good large-N limit
- Maximally chaotic

Does such a material exist ?

See for example:

J. Zhang *et al*, PNAS **116**, 19869 (2019)

A. Legros *et al*, Nature Physics **15**, 142 (2019)

Motivation: holography

Strongly correlated quantum matter ⟷ Quantum gravity

Sachdev-Ye-Kitaev model:

$$\hat{H}_{SYK} = \sum_{ijkl} J_{ijkl} \hat{c}_i^\dagger \hat{c}_j^\dagger \hat{c}_k \hat{c}_l$$

Degenerate Fermi gas
All-to-all, fully random interactions

JT gravity in 1+1 dimensions

See for example:
M. Franz and M. Rozali, Nat Rev Mater **3**, 491–501 (2018)
D. Chowdhury, A. Georges, O. Parcollet, S. Sachdev, Rev. Mod. Phys. **94** 035004 (2022)

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D. Chowdhury, A. Georges, O. Parcollet, S. Sachdev, Rev. Mod. Phys. **94** 035004 (2022)

Proposals in various contexts

Condensed-matter devices (topological systems, graphene dots)

A. Chew, A. Essin, and J. Alicea, Phys. Rev. B **96** 121119 (2017)

A. Chen, R. Ilan, F. De Juan, D. Pikulin, and M. Franz, Phys. Rev. X **7**, 031006 (2017)

A. Chen, R. Ilan, F. De Juan, D. Pikulin, and M. Franz, Phys. Rev. Lett. **121**, 036403 (2018)

M. Brzezińska, Y. Guan, O. V. Yazyev, S. Sachdev, and A. Kruchkov, arXiv:2208.01032v1

Ultra-cold atoms

I. Danshita, M. Hanada, and M. Tezuka, Prog. Theor. Exp. Phys. **2017** 083I01 (2017)

C. Wei and T. A. Sedrakyan, Phys. Rev. A **103**, 013323 (2021)

Direct digital simulation

L. Garcia-Alvarez, *et al*, Phys. Rev. Lett. **119**, 040501 (2017)

R. Babbush, D. W. Berry, and H. Neven, Phys. Rev. A **99**, 040301 (2019)

Experiments

Explicit programing of all the couplings

NMR implementation (4 spins)

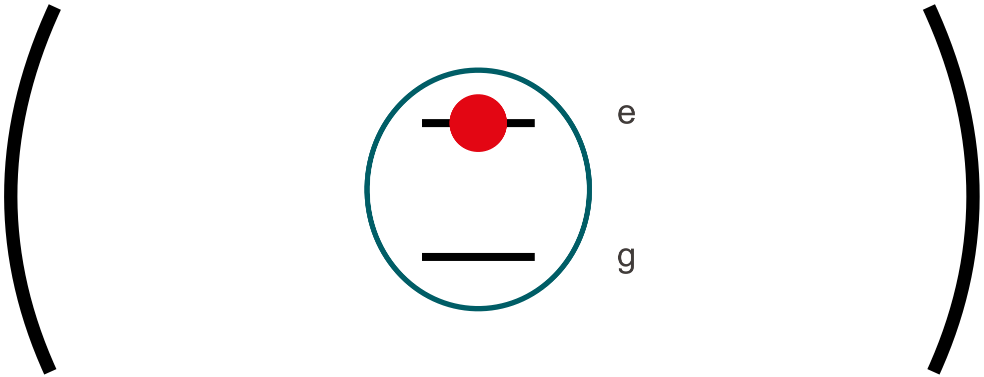
Z. Luo, Y.-Z. You, J. Li, C.-M. Jian, D. Lu, C. Xu, B. Zeng, and R. Laflamme,
Npj Quatum Inf. **5**, 53 (2019)

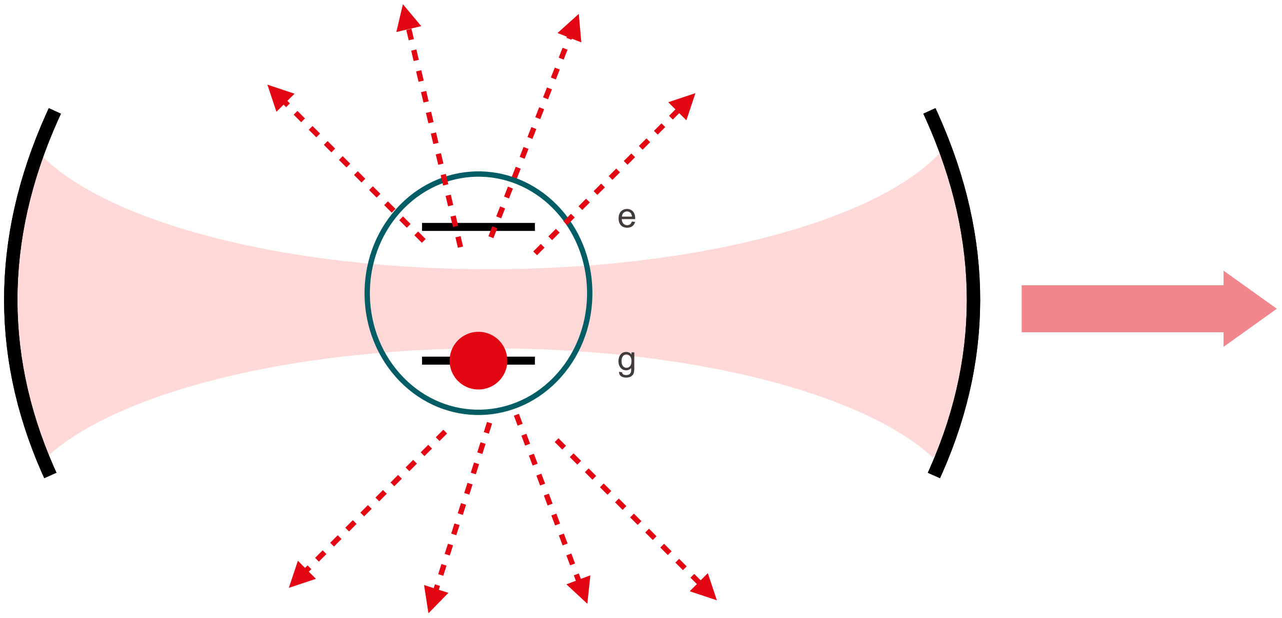
Superconducting circuit implementation (7 qubits)

D. L. Jafferis, *et al,*
Nature **612**, 51 (2022)

B. Kobrin, T. Schuster, and N. Y. Yao,
arXiv:2302.07897

Cavity QED in a nutshell

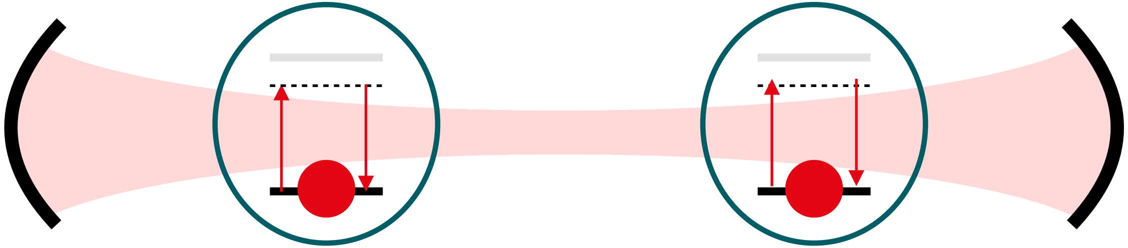




$$\text{Cooperativity } \eta = \frac{\Omega^2}{\kappa\Gamma} = \frac{24\mathcal{F}}{\pi k^2 w^2}$$

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

Photon-mediated interactions



Rayleigh scattering channelled into the cavity mode

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)

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'

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

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

Multimode cavity

Y. Guo *et al.* Nature **599,** 211 (2021)
V. D. Vaidya *et al,* Phys. Rev. X **8** 011002 (2018)

Quantum dynamics

Z. Wu *et al,* Phys. Rev. Lett. **131** 243401 (2024)
T. Zwettler *et al,* arXiv:2405.18204 (2024)

Dissipation-induced phases

D. Dreon *et al. Nature* **608,** 494 (2022)
P. Kongkhambut *et al*, Science **377** 670 (2022)

Long-range spin systems

A. Periwal *et al.* Nature **600**, 630–635 (2021).
D.J. Young *et al.* Nature **625,** 679 (2024)
N. Sauerwein, *et al* Nature Physics **19**, 1128 (2023)

Superradiant Mott-insulators

R. Landig *et al,* Nature **532** 476 (2016)
J. Klinder *et al,* Phys. Rev. Lett. **115** 230403 (2015)

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

Density-wave ordering induced by light in a unitary Fermi gas

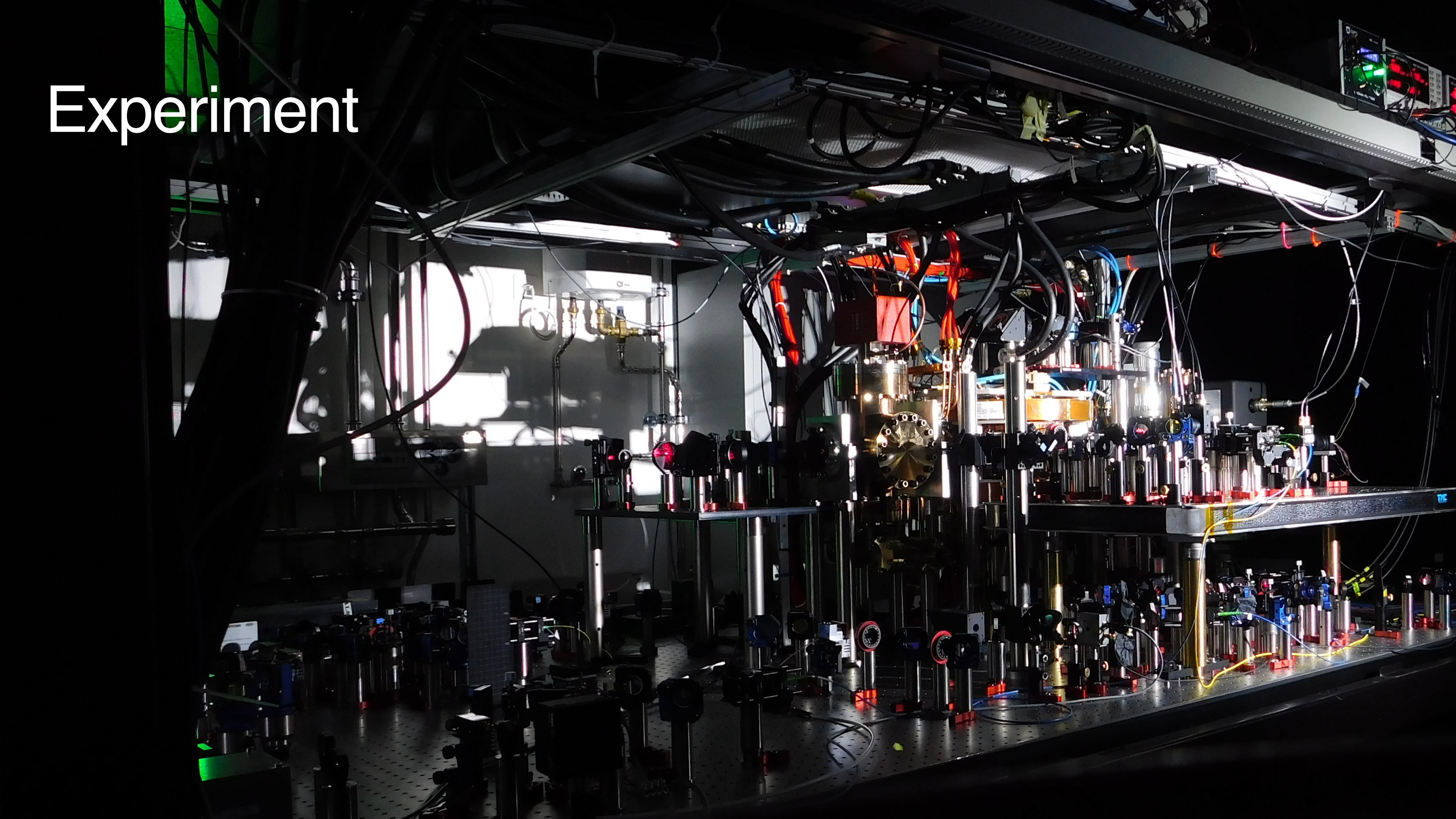
Competition between photon-mediated interaction and disorder

Prospects for realizing the SYK model

Density-wave ordering induced by light in a unitary Fermi gas

Theory: H. Ritsch, E. Colella, F. Mivehvar (Innsbruck)

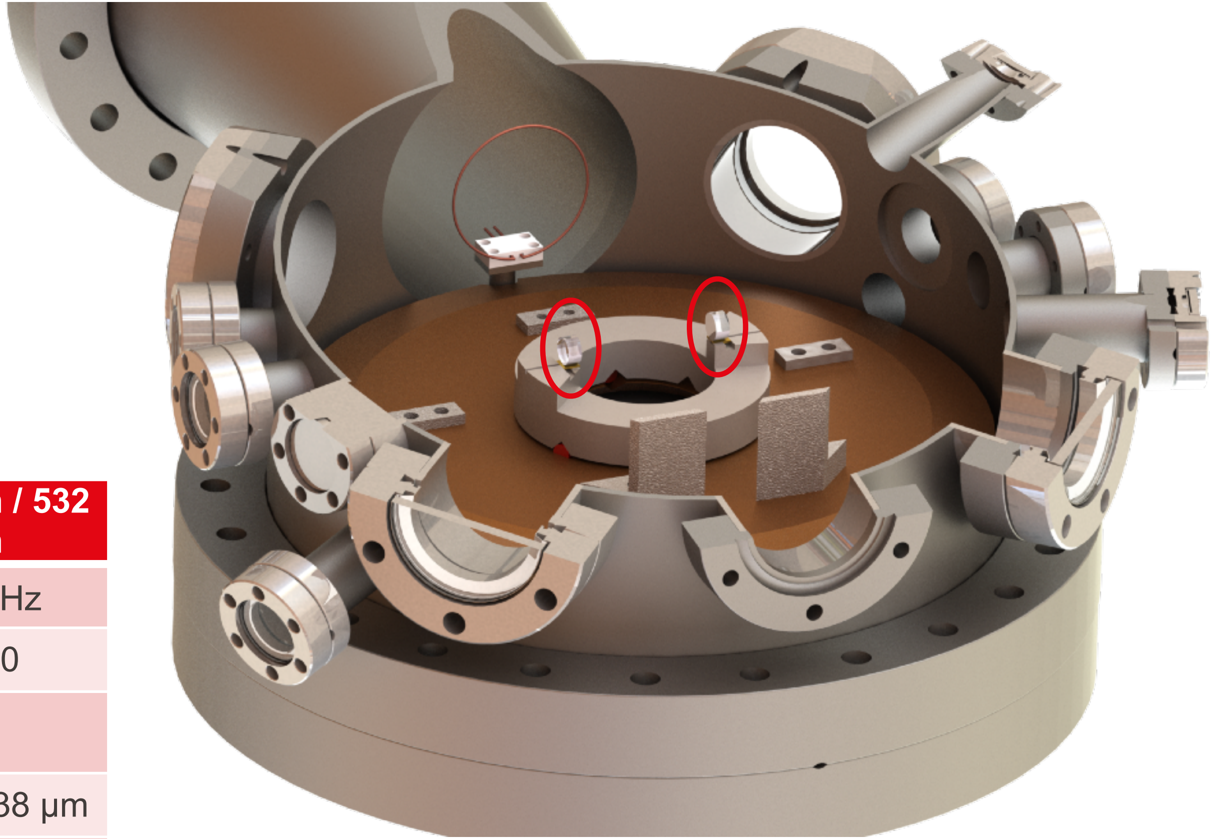
Experiment



Experiment

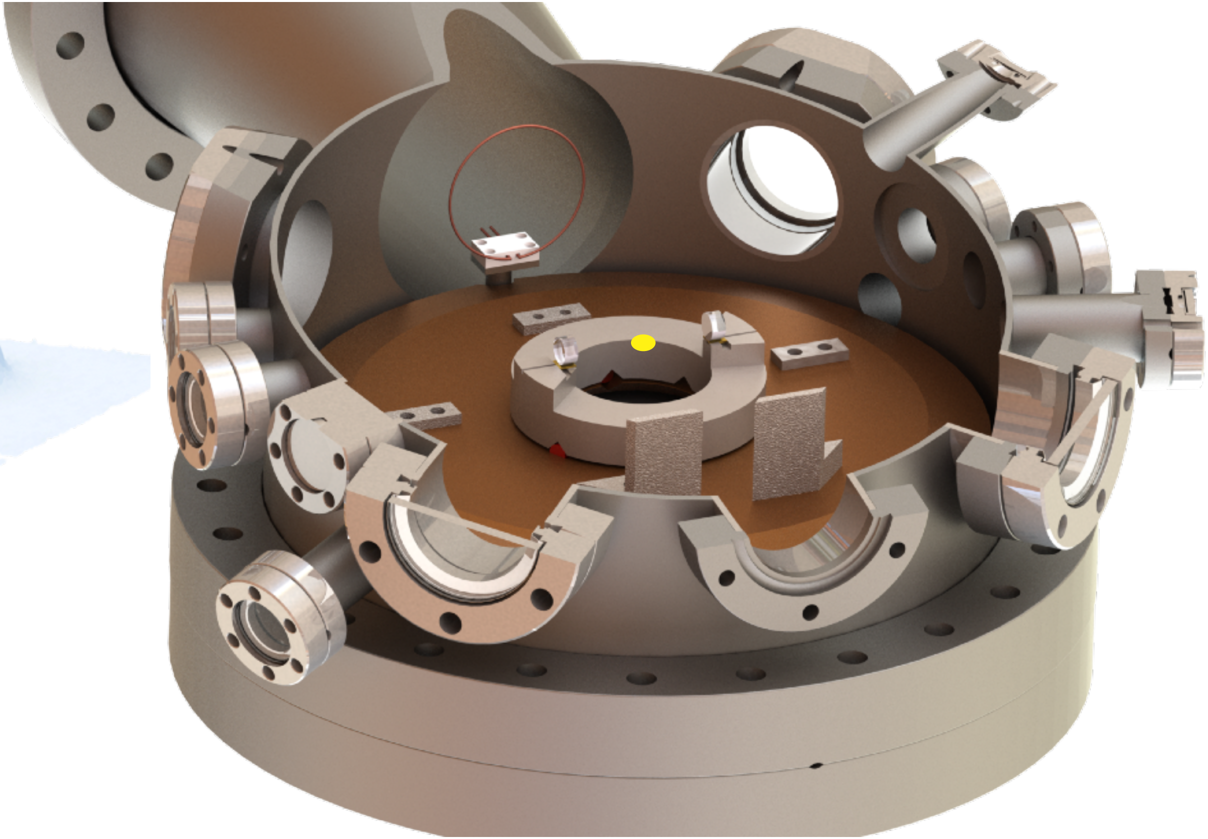
High-finesse cavity

	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



Unitary Fermi gas

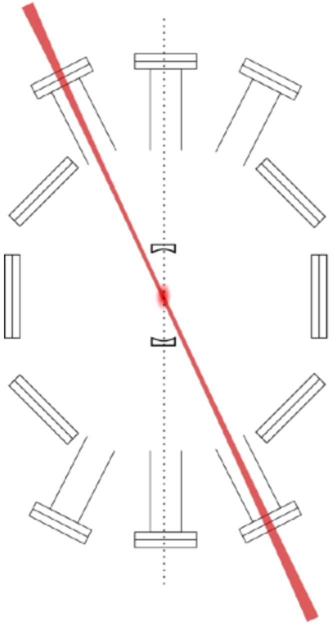
- 300'000 ^{6}Li atoms
- $T = 0.1\ T_F$

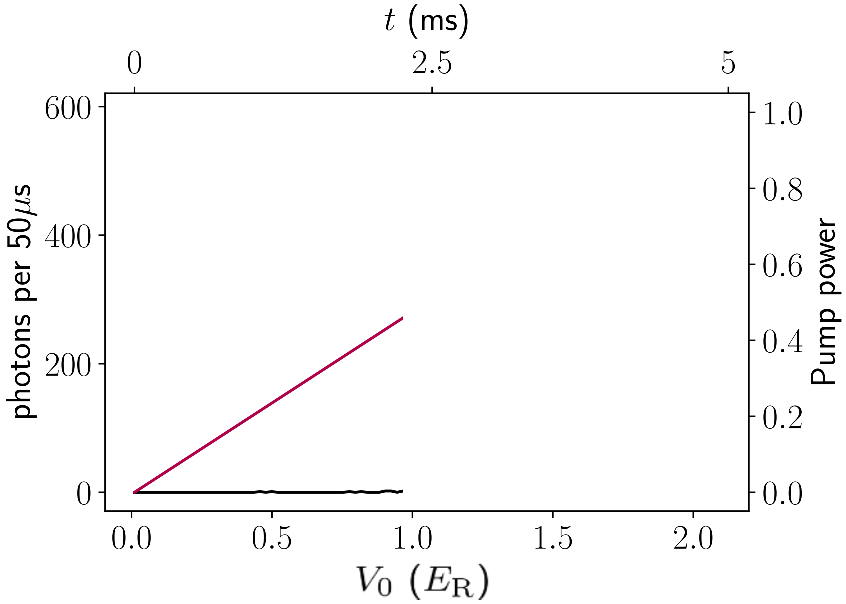
K. Roux, V. Helson , H. Konishi and JPB, New J. Phys. **23** 043029 (2021)

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

Self-organization transition

Uniform unitary gas $\longrightarrow$ 'uniaxial' charge Density Wave Order

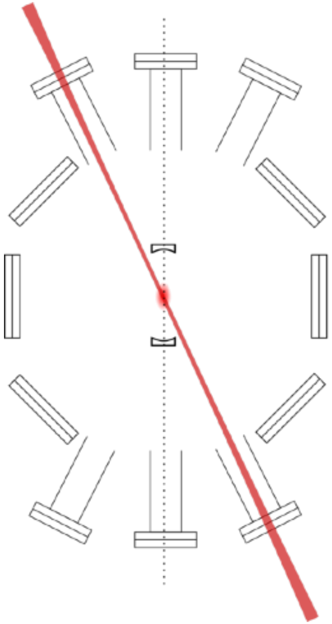


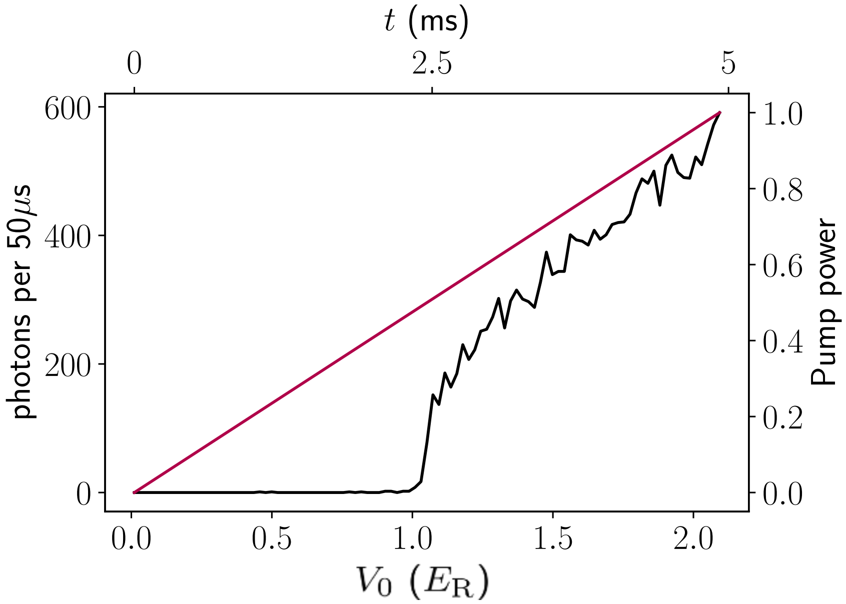


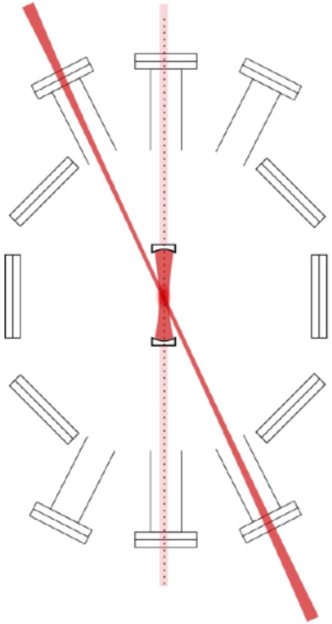
V. Helson *et al,* Nature **618**, 716 (2023)

Self-organization transition

Uniform unitary gas ⟶ ‘uniaxial’ charge Density Wave Order



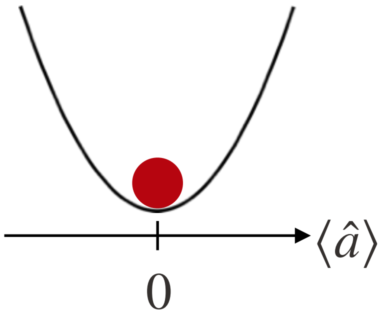


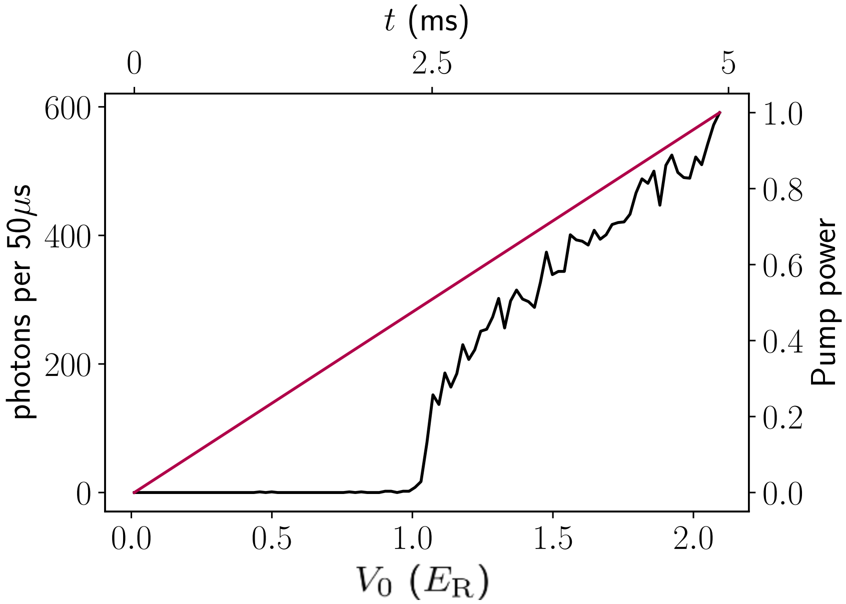


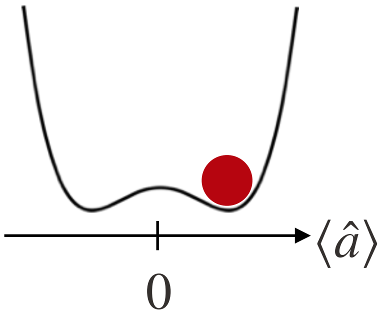
V. Helson *et al,* Nature **618**, 716 (2023)

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)

Self-organization transition





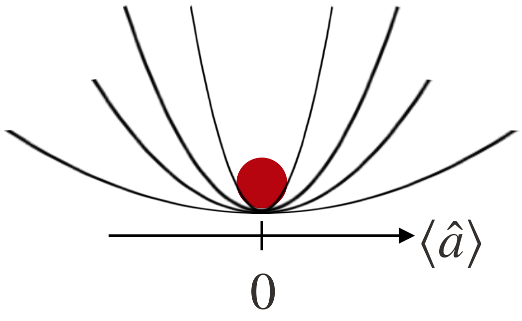


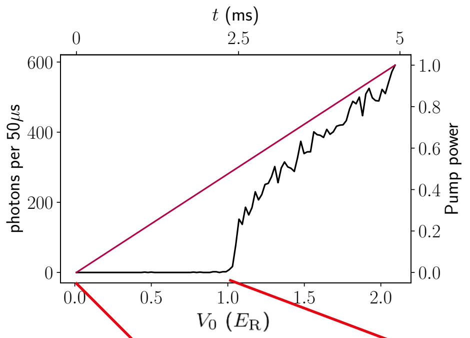
V. Helson *et al,* Nature **618**, 716 (2023)

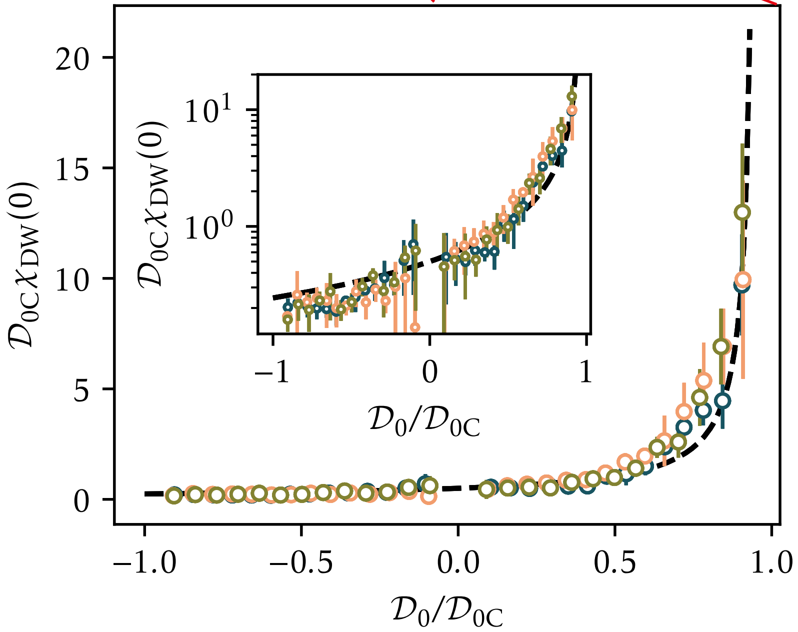
BEC : K. Baumann *et al*, Phys. Rev. Lett. **107** 140402 (2011)

Self-organization transition

Divergence of the susceptibility







V. Helson *et al,* Nature **618**, 716 (2023)

Self-organization transition

Divergence of the susceptibility

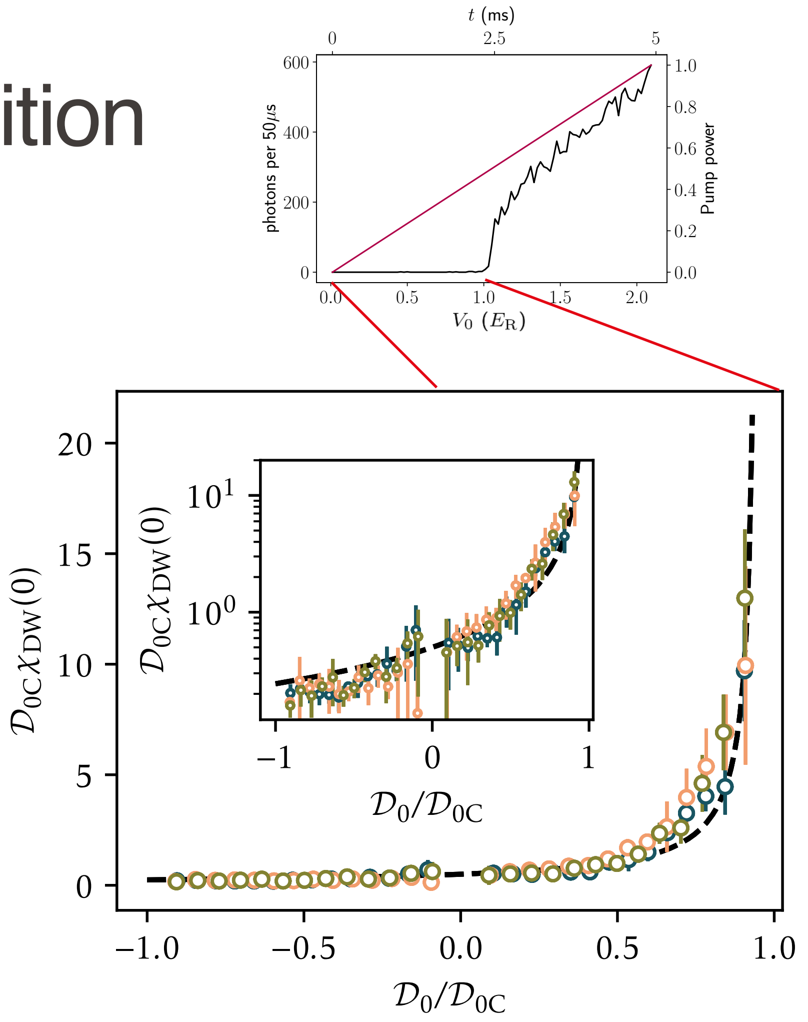
RPA result for the threshold:

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

$$\chi_0 \simeq \chi^R_{nn}(k_-,0)$$

Divergence of the susceptibility

$$\chi_{\mathrm{DW}} \propto \frac{1}{D_0 - D_{0c}}$$



V. Helson *et al,* Nature **618**, 716 (2023)

Ordering dynamics

Theory: L. Skolc, S. Chattopadhyay, F. Marijanovic, E. Demler (ETHZ)

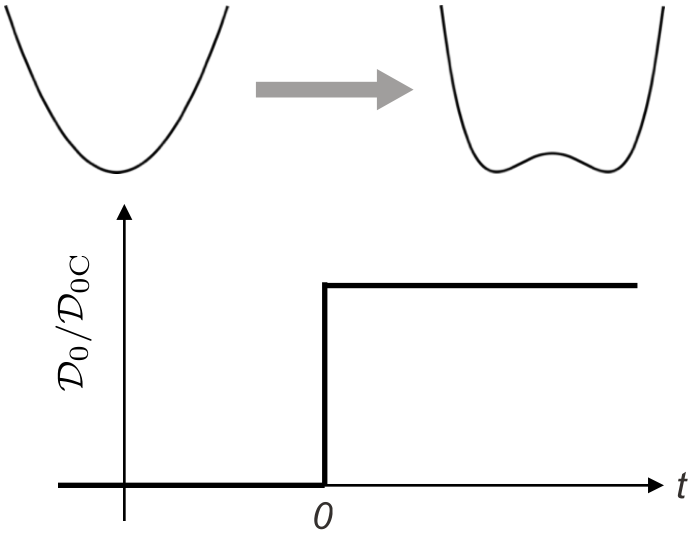
C.M. Halati, T. Giamarchi (Geneva)

S. Uchino (Waseda)

T. Zwettler *et al,* arXiv:2405.18204 (2024)

Ordering dynamics

Instantaneous quench across the transition



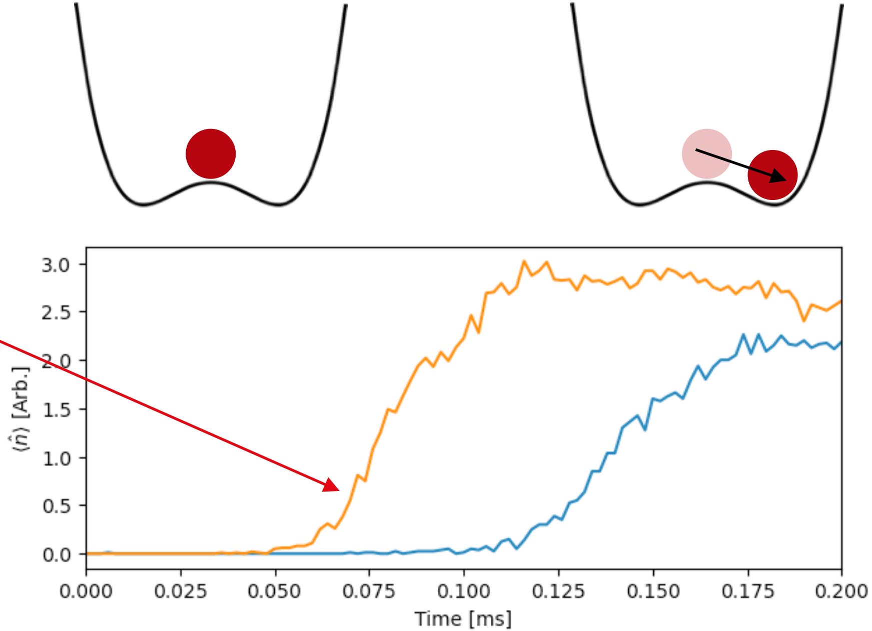
See also :

Z. Wu *et al*, Phys. Rev. Lett. **131** 243401 (2024)

T. Zwettler *et al*, arXiv:2405.18204 (2024)

Ordering dynamics

exponential rise rate α

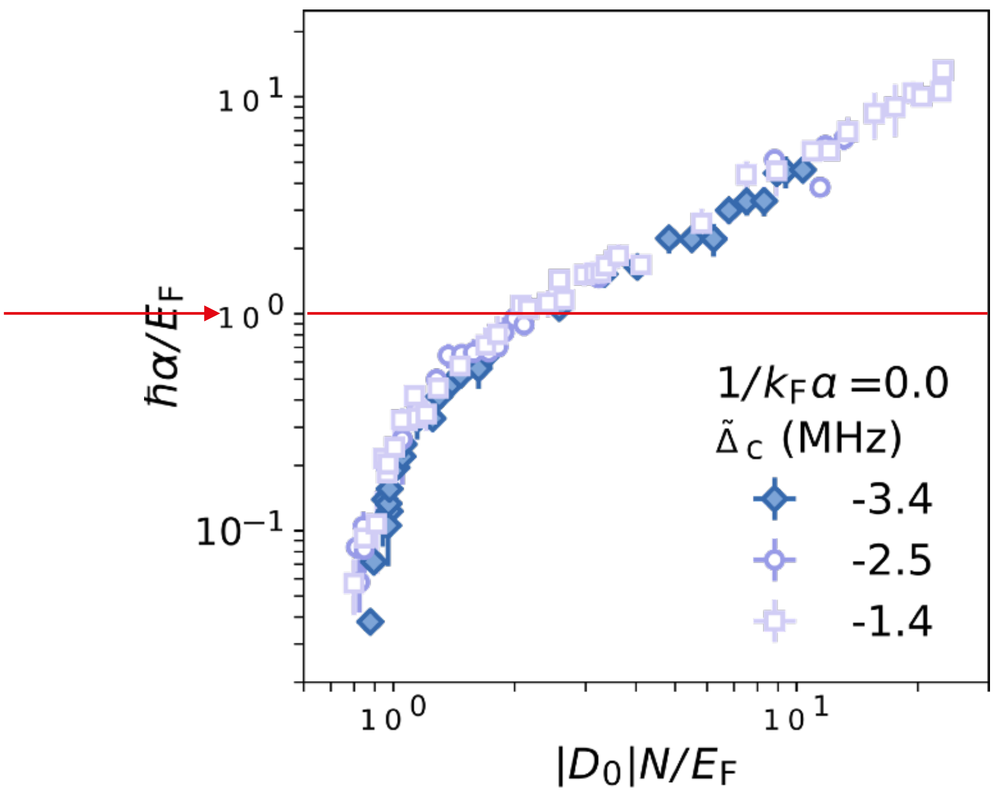


T. Zwettler *et al*, arXiv:2405.18204 (2024)

Ordering dynamics

Quench in the unitary Fermi gas

No speed limit at the Fermi time



T. Zwettler *et al*, arXiv:2405.18204 (2024)

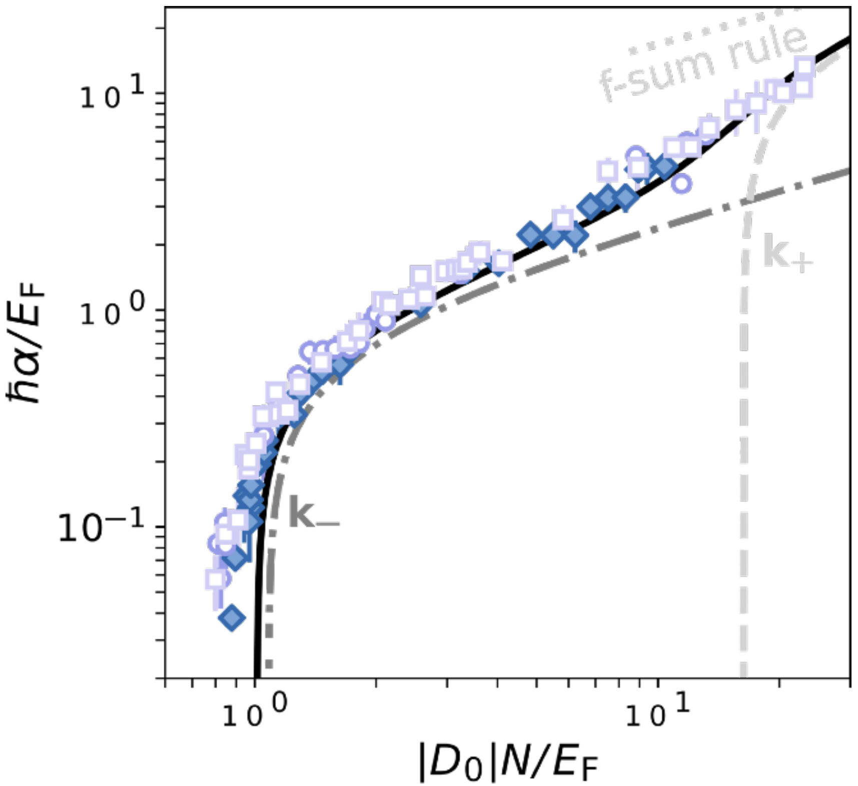
Ordering dynamics

Quench in the unitary Fermi gas

Early-time linear instability analysis

RPA theory for the unitary gas

$$1 = \frac{D_0}{4} \sum_{q=k_\pm} \int_0^\infty \frac{d\omega}{\pi} \frac{\omega \mathrm{Im}[\chi^R(q,\omega)]}{\alpha^2 + \omega^2},$$



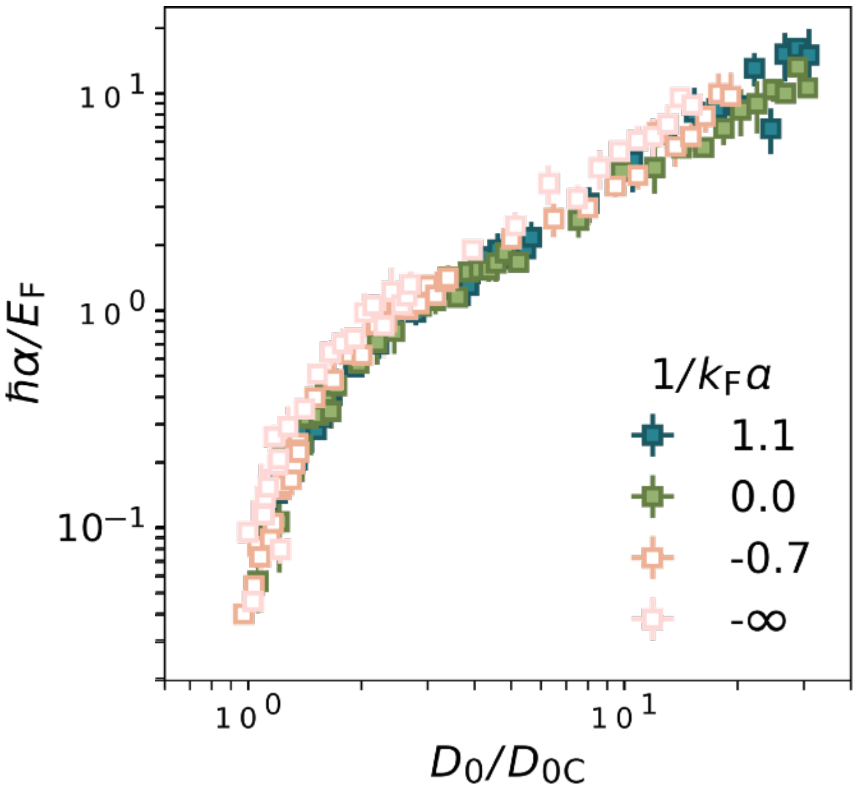
RPA density response function:
L. He, Annals of Physics, **373**, 470-511 (2016)

F. Marijanovic *et al,* arXiv:2406.13548 (2024)
T. Zwettler *et al,* arXiv:2405.18204 (2024)

Ordering dynamics

Quench in the BEC-BCS crossover

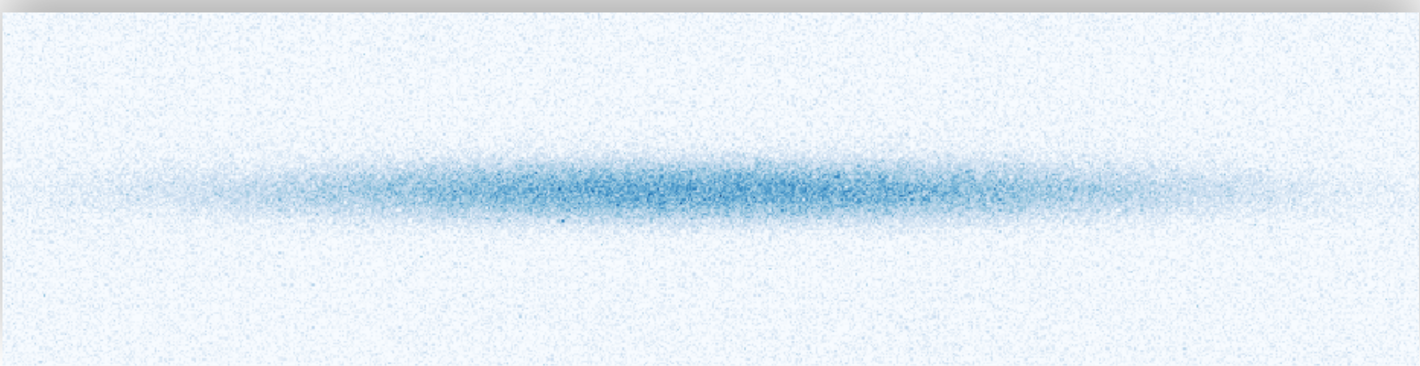
- Constraints by sum-rules at the largest pump-power
- Weak dependence on interactions close to critical point

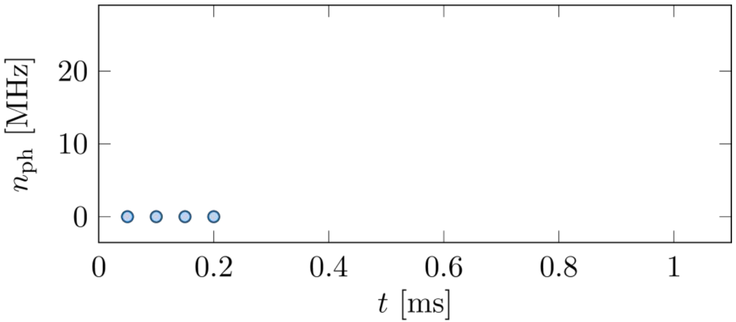


T. Zwettler *et al*, arXiv:2405.18204 (2024)

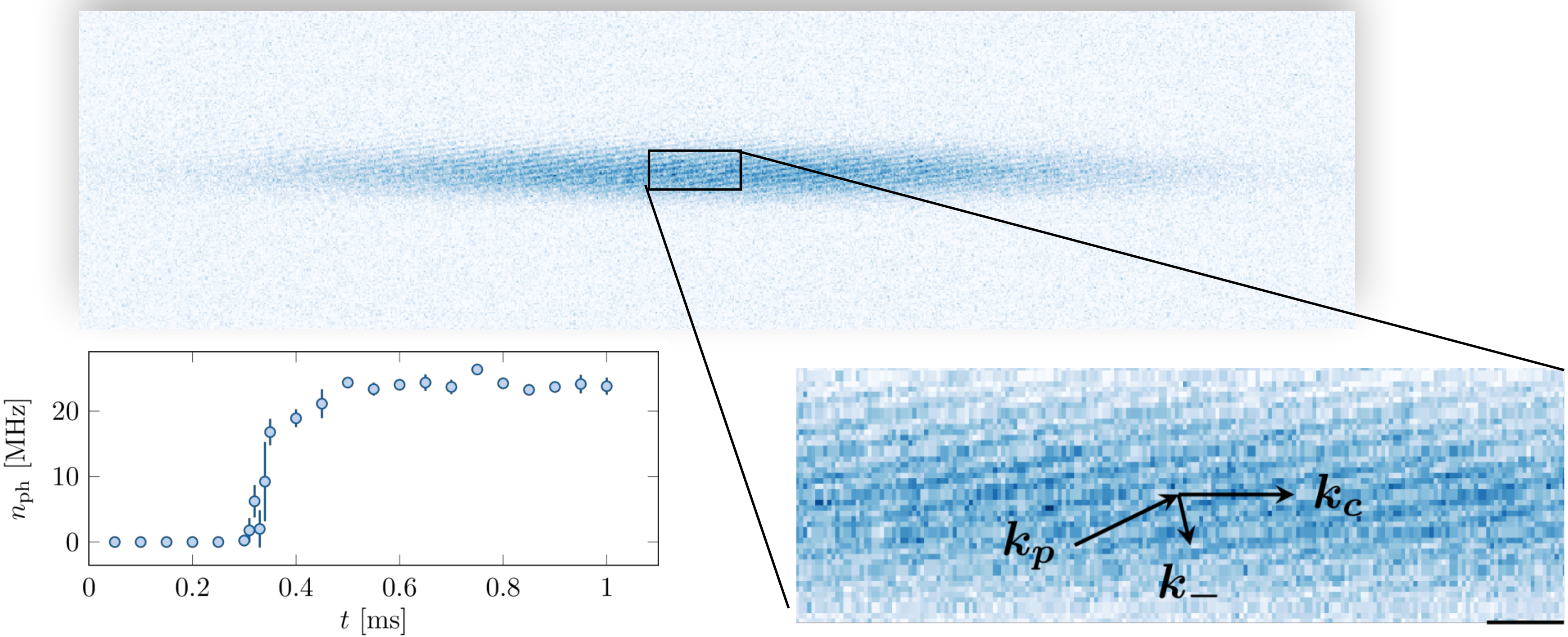
Preliminary

In-situ observation





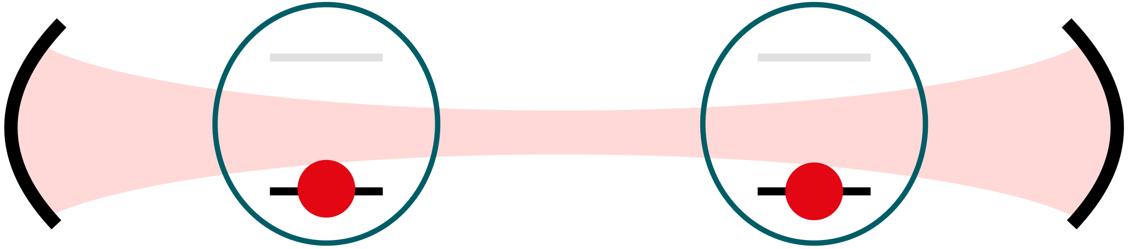
In-situ observation

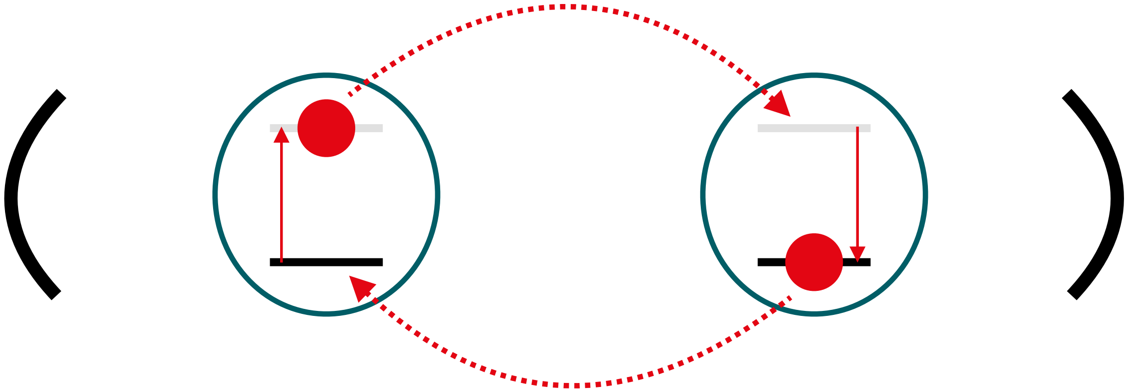


Competition of photon-mediated interaction with disorder

Theory: P. Uhrich, S. Bandyopadhyay and P. Hauke (Trento)

F. Mattiotti and G. Pupillo (Strasbourg)



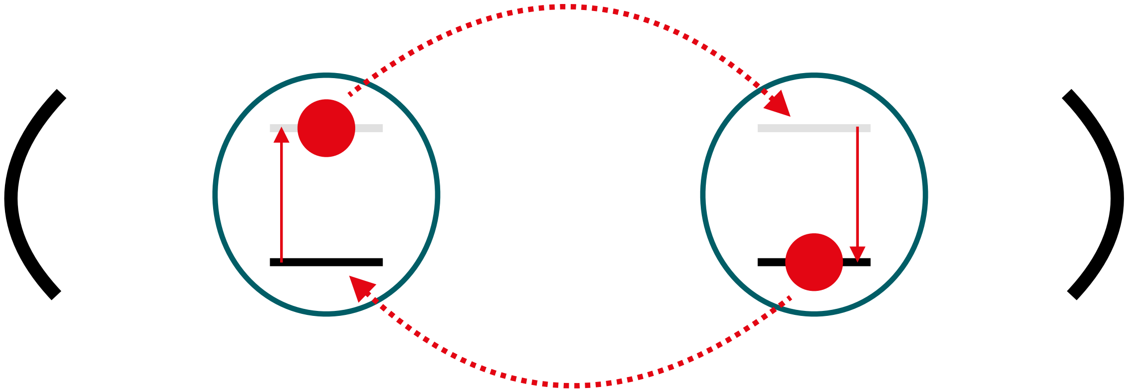


Spin exchange mediated by cavity photon

$$\hat{H}_{\text{int}} = \frac{g_0^2}{\Delta} \sum_{i,j} f(r_i) f(r_j) \hat{\sigma}_i^+ \hat{\sigma}_j^- + hc$$

M. Ueda, T. Wakabayashi, and M. Kuwata-Gonokami , Phys. Rev. Lett. **76,** 2045 (1996)

Ian D. Leroux, Monika H. Schleier-Smith, and Vladan Vuletic´, Phys. Rev. Lett. **104**, 073602 (2010)



Spin exchange mediated by cavity photon

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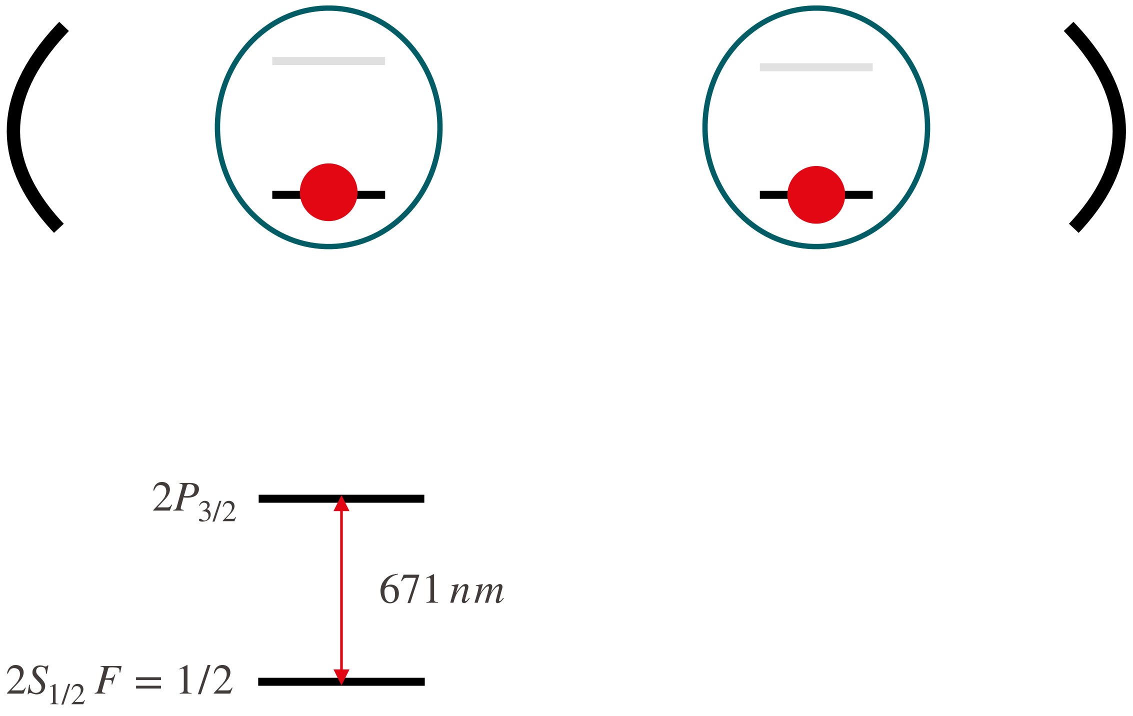
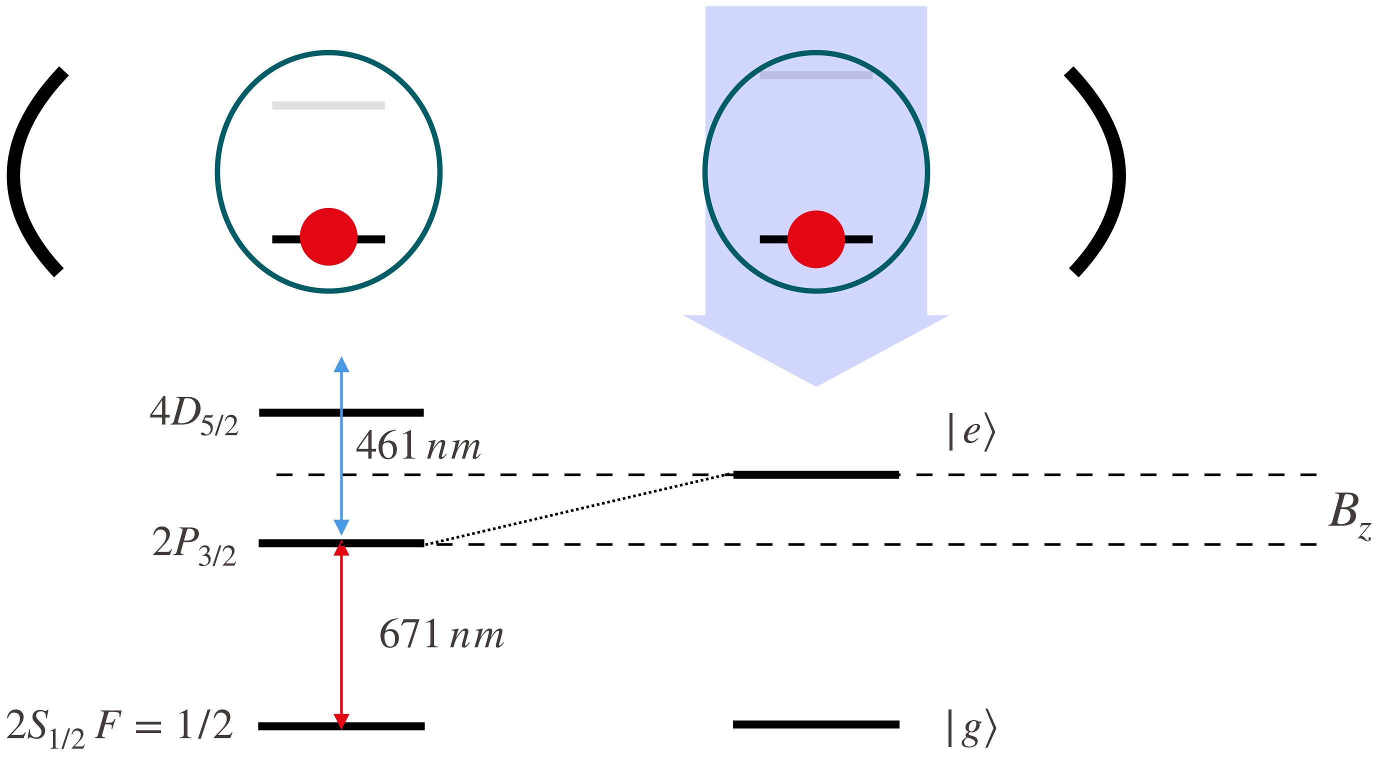
$$= \frac{g_0^2}{\Delta}\hat{J}^+\hat{J}^-$$

Collective spin description $\hat{J}^{\pm} = \sum_i f(r_i)\hat{\sigma}^{\pm}$

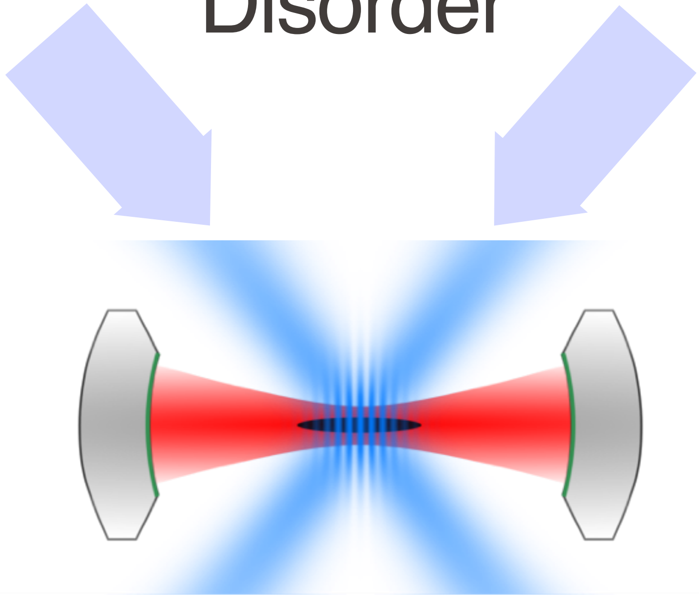


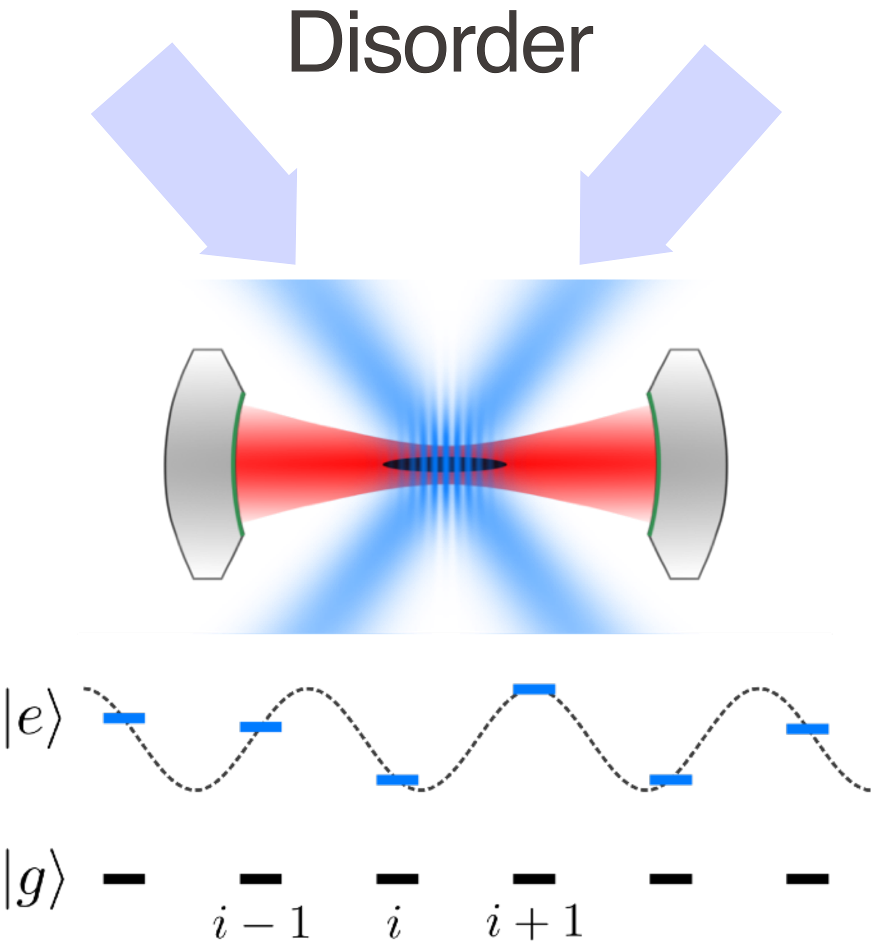
$2P_{3/2}$
671 nm
$2S_{1/2}\ F = 1/2$



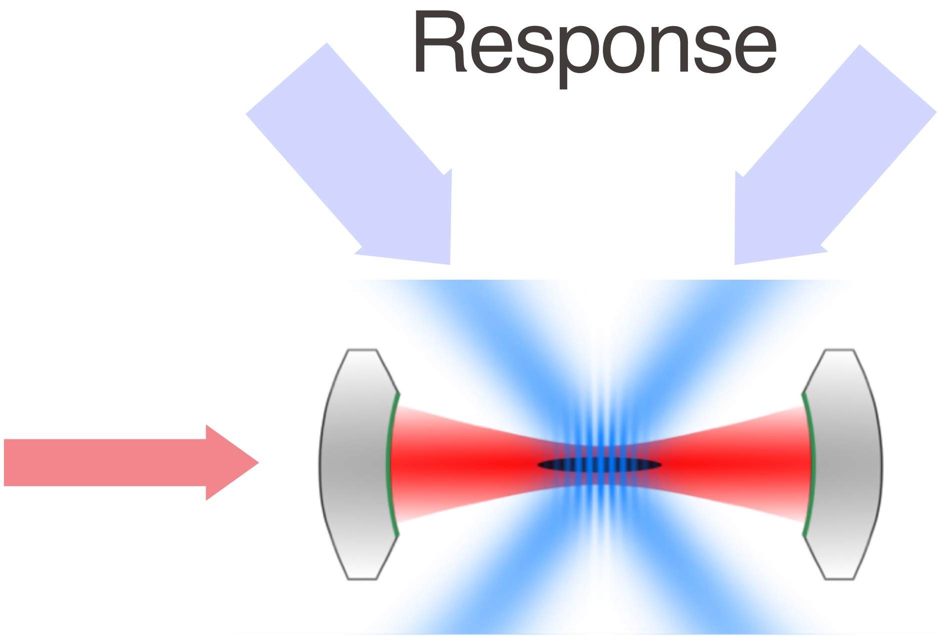
$4D_{5/2}$
461 nm
$2P_{3/2}$
671 nm
$2S_{1/2}\ F = 1/2$
$|e\rangle$
B_z
$|g\rangle$

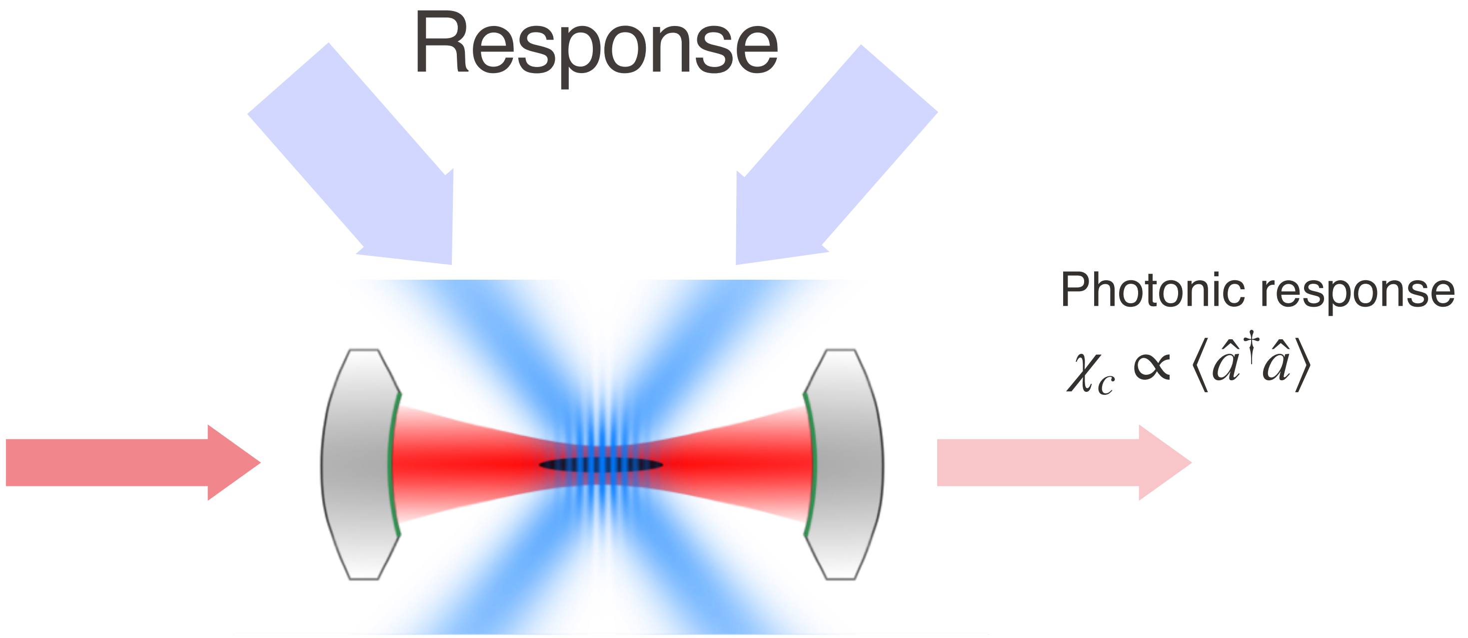
Disorder



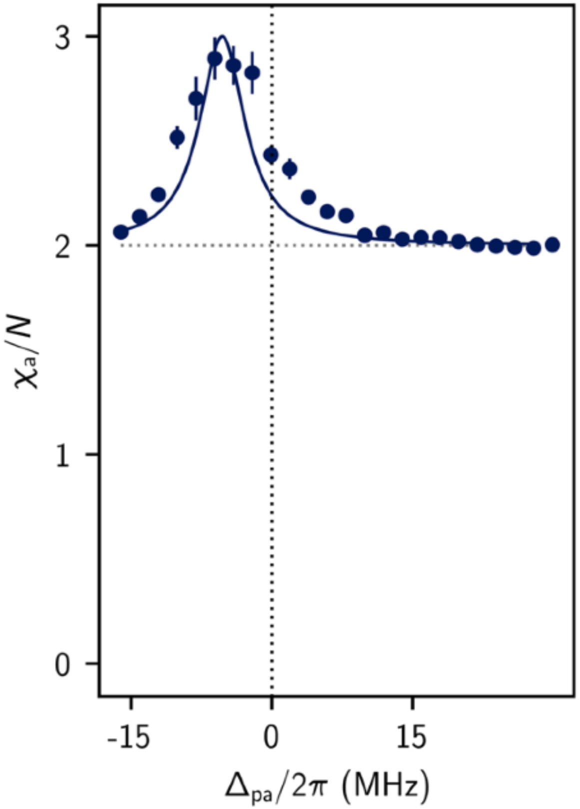


Disorder
$|e\rangle$
$|g\rangle$
$i-1$
i
$i+1$


Response


Response
Photonic response
$\chi_c \propto \langle \hat{a}^\dagger \hat{a} \rangle$

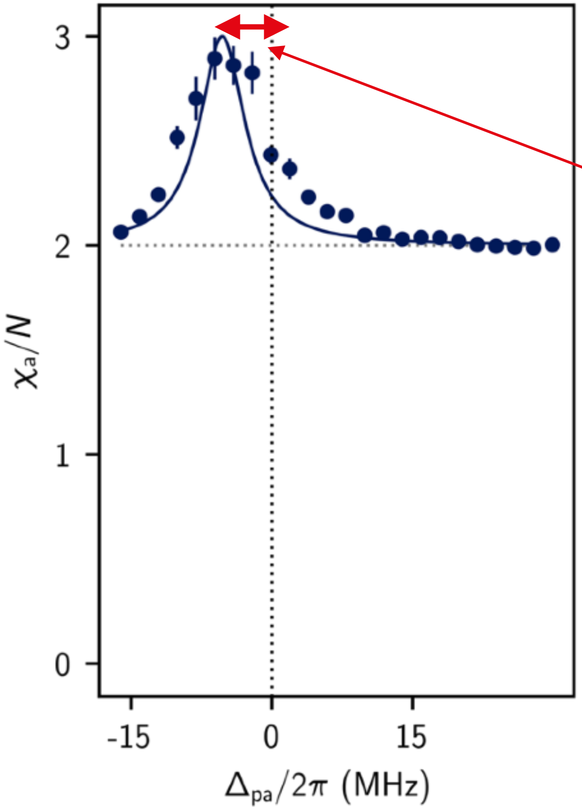
Lipkin-Meshkov-Glick model



$$\hat{H}_{\text{int}} = \frac{g_0^2}{\Delta_{ac}} \hat{J}_+ \hat{J}_- + \Delta_{pa} \hat{J}_z$$

Muniz, Juan A., et al. *Nature* **580** 602-607 (2020)
Lewis-Swan, Robert J., et al. *Physical Review Letters* **126** 173601 (2021)

Lipkin-Meshkov-Glick model

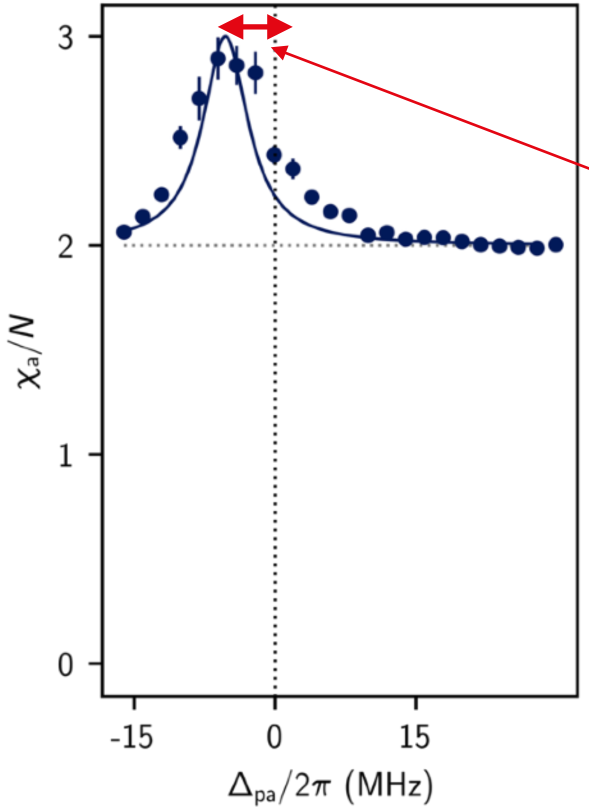


$$\hat{H}_{\text{int}} = \frac{g_0^2}{\Delta_{ac}} \hat{J}_+ \hat{J}_- + \Delta_{pa} \hat{J}_z$$

Ferromagnetic gap

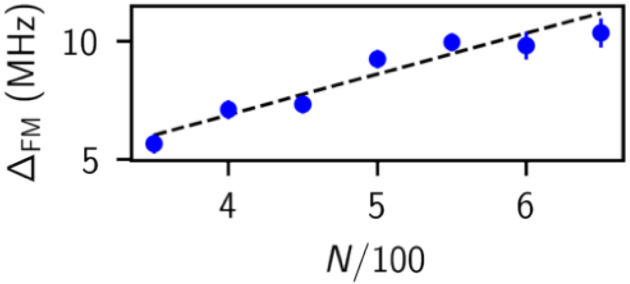
Muniz, Juan A., et al. *Nature* **580** 602-607 (2020)
Lewis-Swan, Robert J., et al. *Physical Review Letters* **126** 173601 (2021)

Lipkin-Meshkov-Glick model

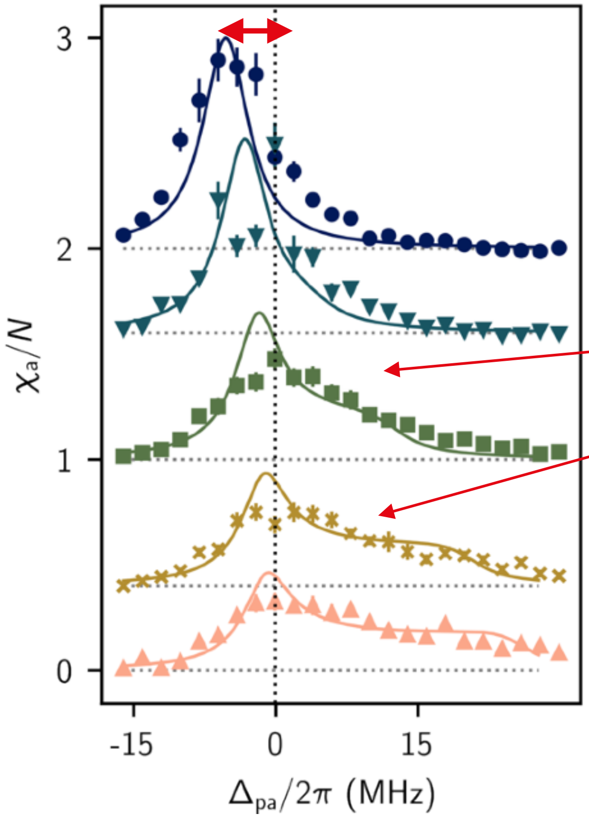


$$\hat{H}_{\text{int}} = \frac{g_0^2}{\Delta_{ac}}\hat{J}_+\hat{J}_- + \Delta_{pa}\hat{J}_z$$

Ferromagnetic gap



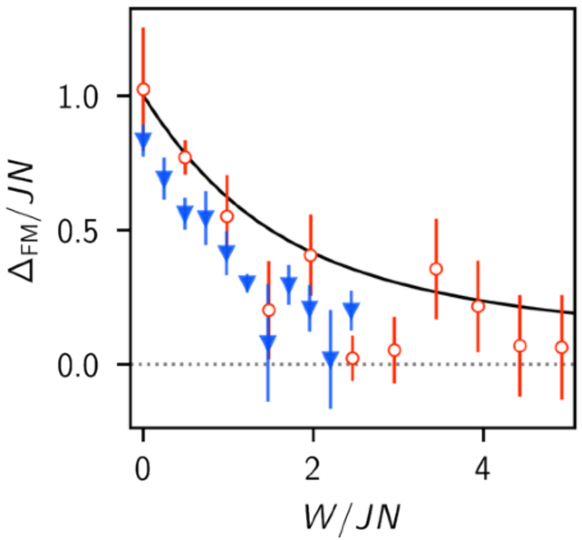
Lipkin-Meshkov-Glick model



$$\hat{H}_{\text{int}} = \frac{g_0^2}{\Delta_{ac}} \hat{J}_+ \hat{J}_- + \Delta_{pa} \hat{J}_z + \sum_i B_{i,z} \hat{\sigma}_{i,z}$$

Broad response

Break-down of collective coupling

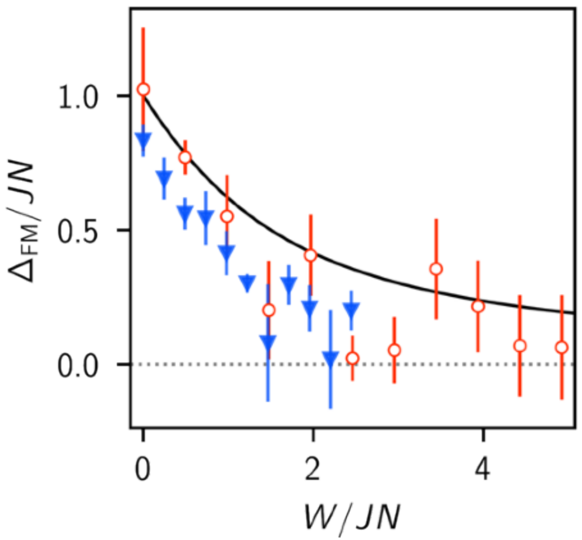


Ferromagnetic gap $\longrightarrow 0$ for $W \longrightarrow \infty$

- For fixed atom number: disappearance of energy resonances

Ferromagnetic $\longrightarrow$ *paramagnetic crossover*

Break-down of collective coupling



Ferromagnetic gap $\longrightarrow 0$ for $W \longrightarrow \infty$

- For fixed atom number: disappearance of energy resonances

Ferromagnetic $\longrightarrow$ paramagnetic crossover

- For fixed W : infinite number of resonances at the thermodynamic limit

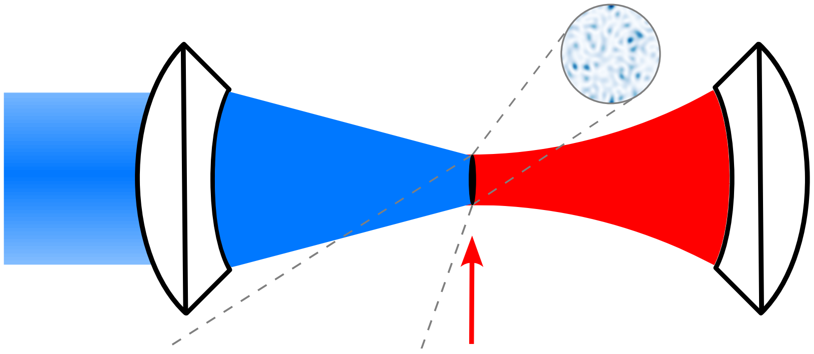
No disorder induced phase transition

P. Hauke (Trento)
J. Sonner (Geneva)

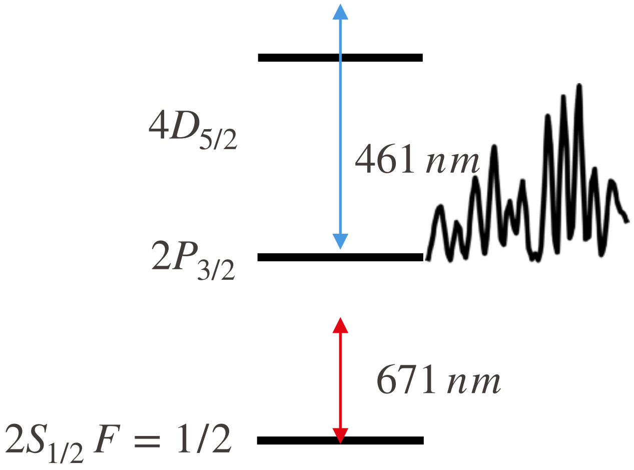

Prospects for realizing the SYK model

Prospects for realizing the SYK model

Fermionic motional degrees-of-freedom



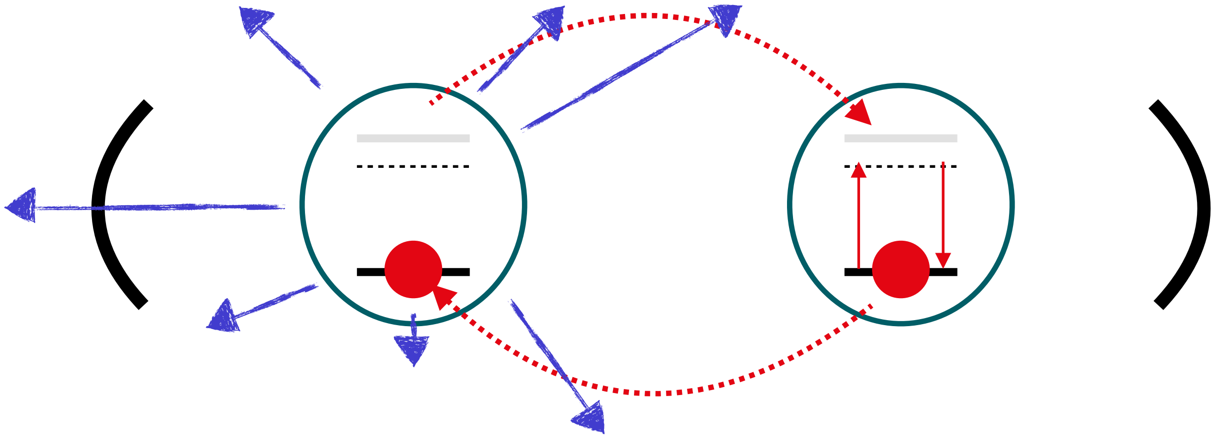
Disorder in the excited-state manifold



Prospects for realizing the SYK model

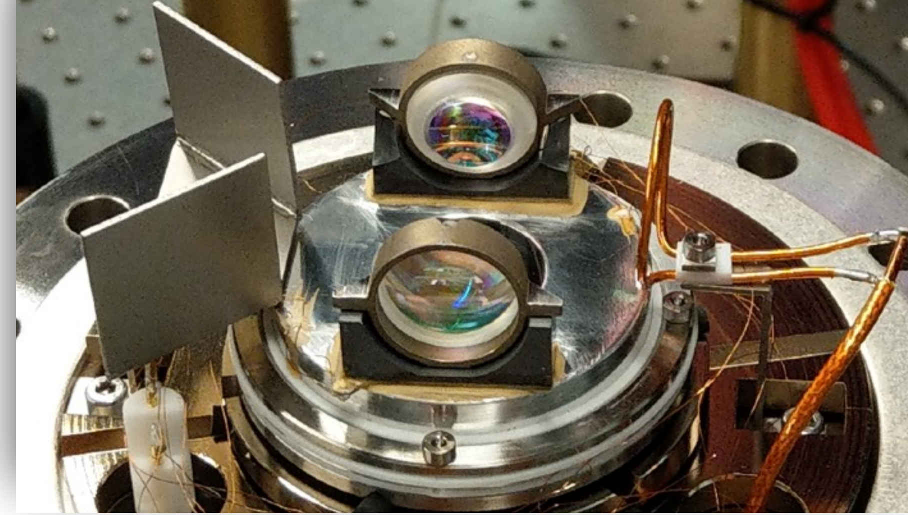
Fermionic motional degrees-of-freedom

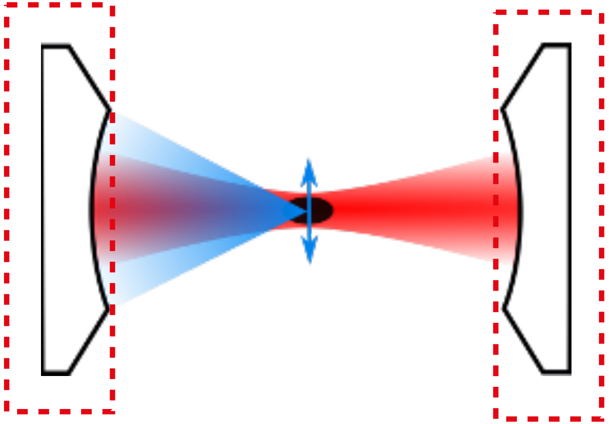
Disorder in the excited-state manifold



Engineering of the density-density interaction

Cavity-microscope

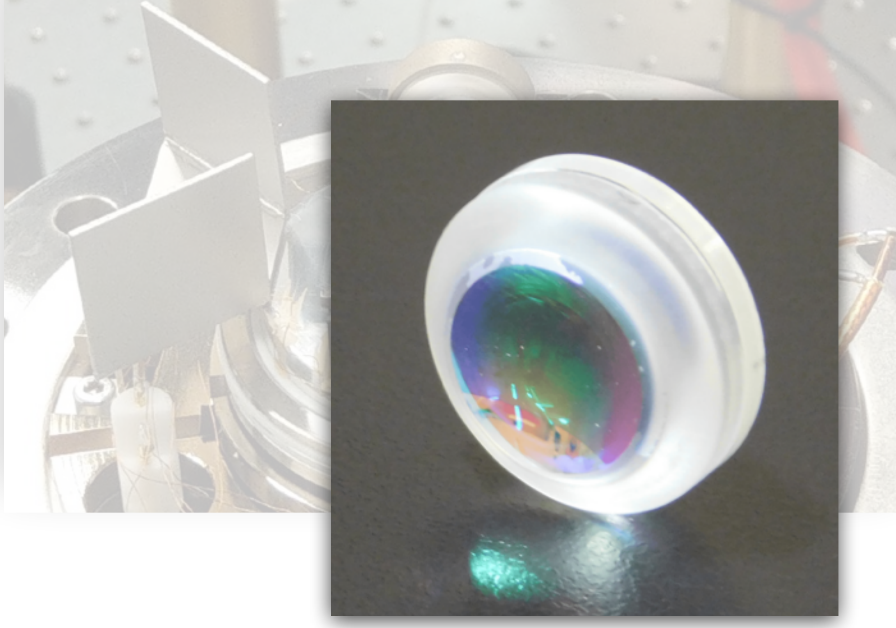


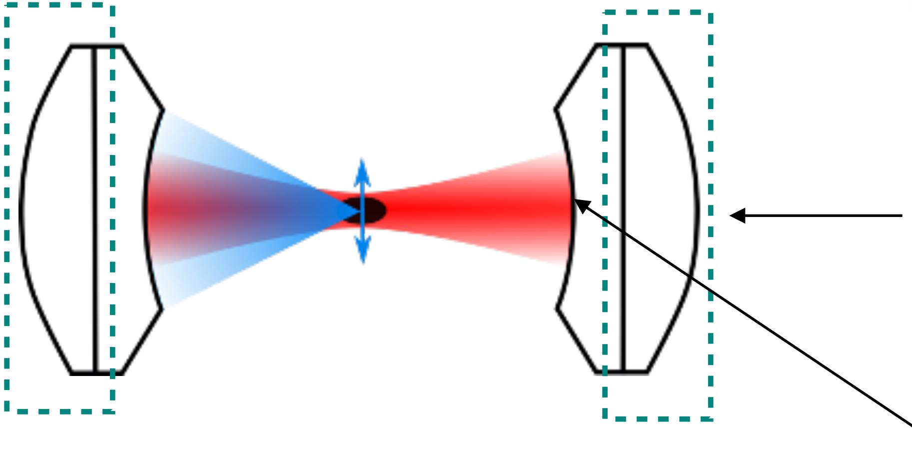


High-finesse cavity mirrors

F. Orsi *et al,* arXiv:2405.03550

Cavity-microscope





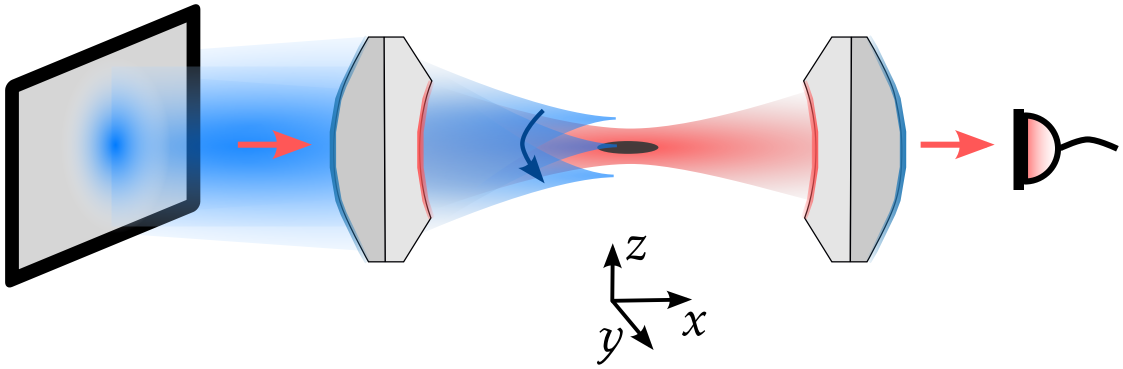
0.37 NA aspherical lens pair

Optically contacted on the mirrors

HR 671 + 1342 nm, HT 780 + 461 nm

F. Orsi *et al,* arXiv:2405.03550

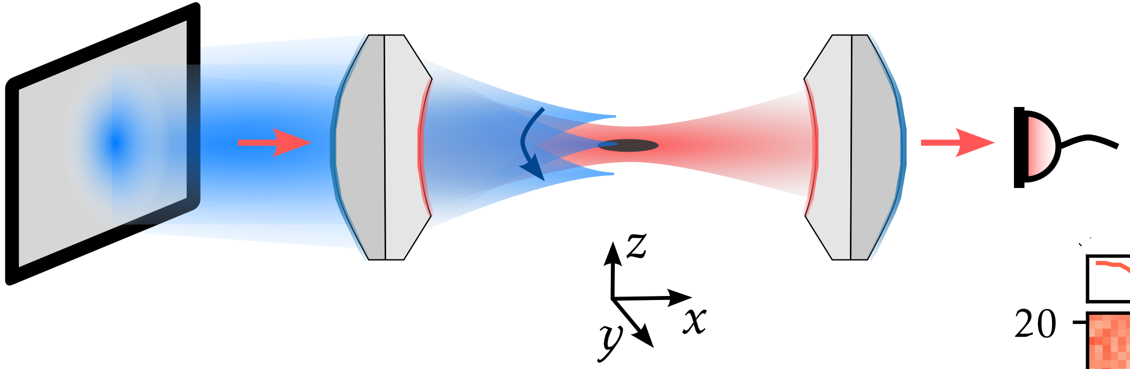
Cavity-microscope

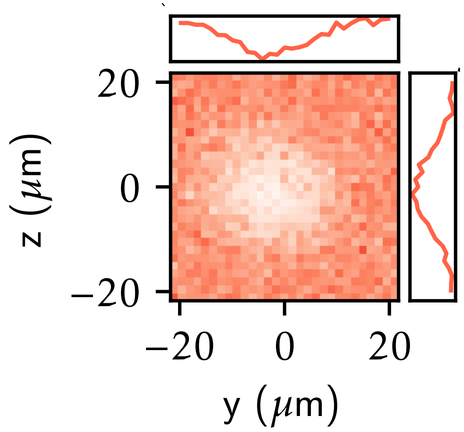


Spatial programing of photon-atom coupling

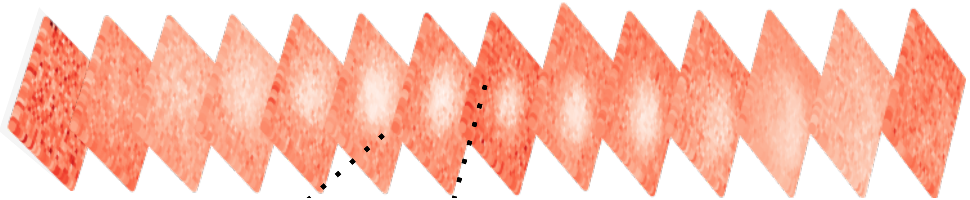
F. Orsi *et al*, arXiv:2405.03550

Cavity-microscope





Example: scanning probe-microscope



F. Orsi *et al*, arXiv:2405.03550

SYK simulation: challenge

$$\hat{H}_{SYK} = \sum_{ijkl} J_{ijkl} \hat{c}_i^\dagger \hat{c}_j^\dagger \hat{c}_k \hat{c}_l$$

$\sim N^4$ independent random couplings

Photon-exchange interactions lead to correlations

$$J_{ijkl} = f_{ij} f_{kl}$$

J. Kim, X. Cao and E. Altman, Phys. Rev. B **101**, 125112 (2020)

SYK simulation: challenge

$$\hat{H}_{SYK} = \sum_{ijkl} J_{ijkl} \hat{c}_i^\dagger \hat{c}_j^\dagger \hat{c}_k \hat{c}_l$$

$\sim N^4$ independent random couplings

Photon-exchange interactions lead to correlations

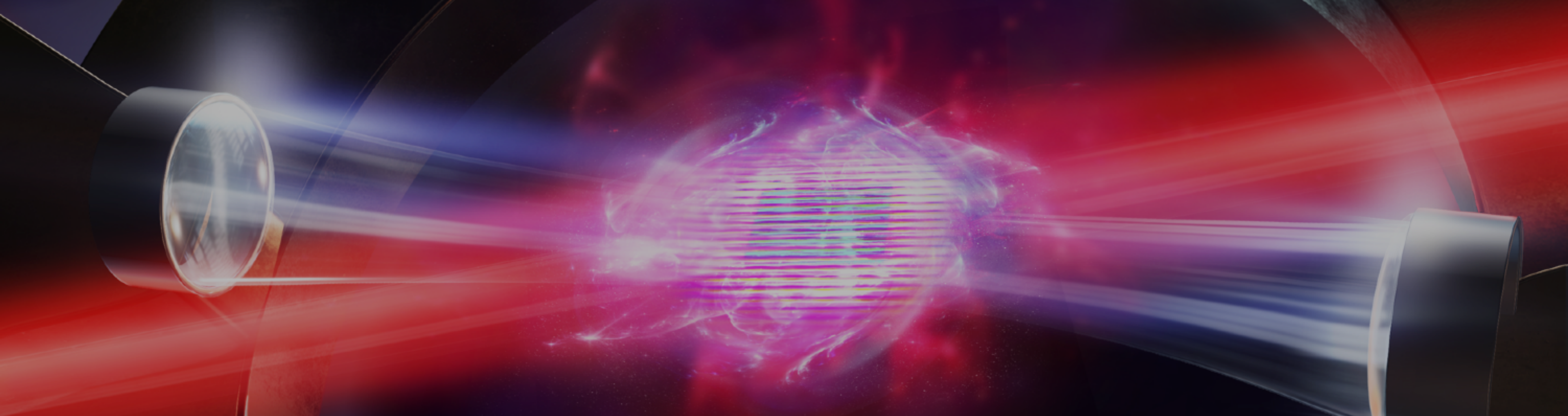
$$J_{ijkl} = f_{ij} f_{kl} \longrightarrow \sum_{\alpha}^{M} \frac{f_{ij}^{(\alpha)} f_{kl}^{(\alpha)}}{1+\delta_\alpha}$$

Use multimode structure of the cavity

Time-dependent disorder

P. Uhrich *et al,* arXiv:2303.11343 (2023)

P. Pelliconi, R. Baumgartner *et al,* (in preparation)



- Fermions with strong, long-range, all-to-all interactions are available in the lab

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

- Controlled disorder with all-to-all interacting systems is available in the lab

N. Sauerwein, F. Orsi, P. Uhrich, S. Bandyopadhyay, F. Mattiotti, T. Cantat-Moltrecht, G. Pupillo, P. Hauke and JPB
Nature Physics **19**, 1128 (2023)

- Blue-print for the implementation of the SYK model

P. Uhrich, S. Bandyopadhyay, N. Sauerwein, J. Sonner, JPB, P. Hauke
arXiv:2303.11343 (2023)