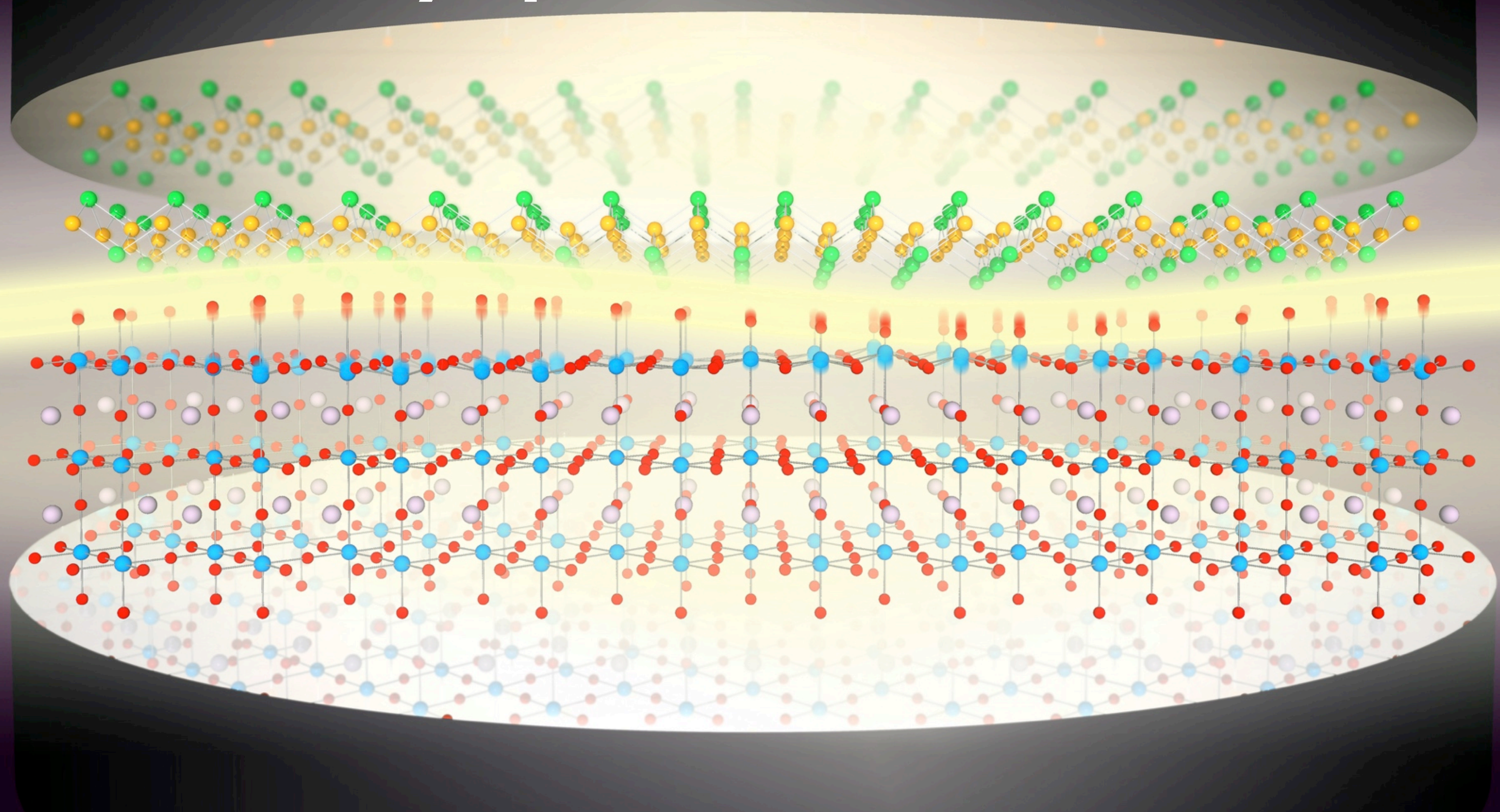
MAX PLANCK INSTITUTE
FOR THE STRUCTURE AND DYNAMICS OF MATTER

Cavity quantum materials



Colloquium: Nonthermal pathways to ultrafast control in quantum materials,
A. de la Torre, D. M. Kennes, M. Claassen, S. Gerber, J. McIver, MAS, **arXiv:2103.14888**

Cavity control of Hubbard model
MAS, J. Li, F. Künzel, M. Eckstein,
PRResearch 2, 033033 (2020)

Light-matter coupling and quantum geometry in moiré materials,
G. E. Topp, C. J. Eckhardt, D. M. Kennes, MAS, P. Törmä, **arXiv:2103.04967**

Michael A. Sentef
lab.sentef.org

Funded through DFG Emmy Noether programme (SE 2558/2)

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft DFG

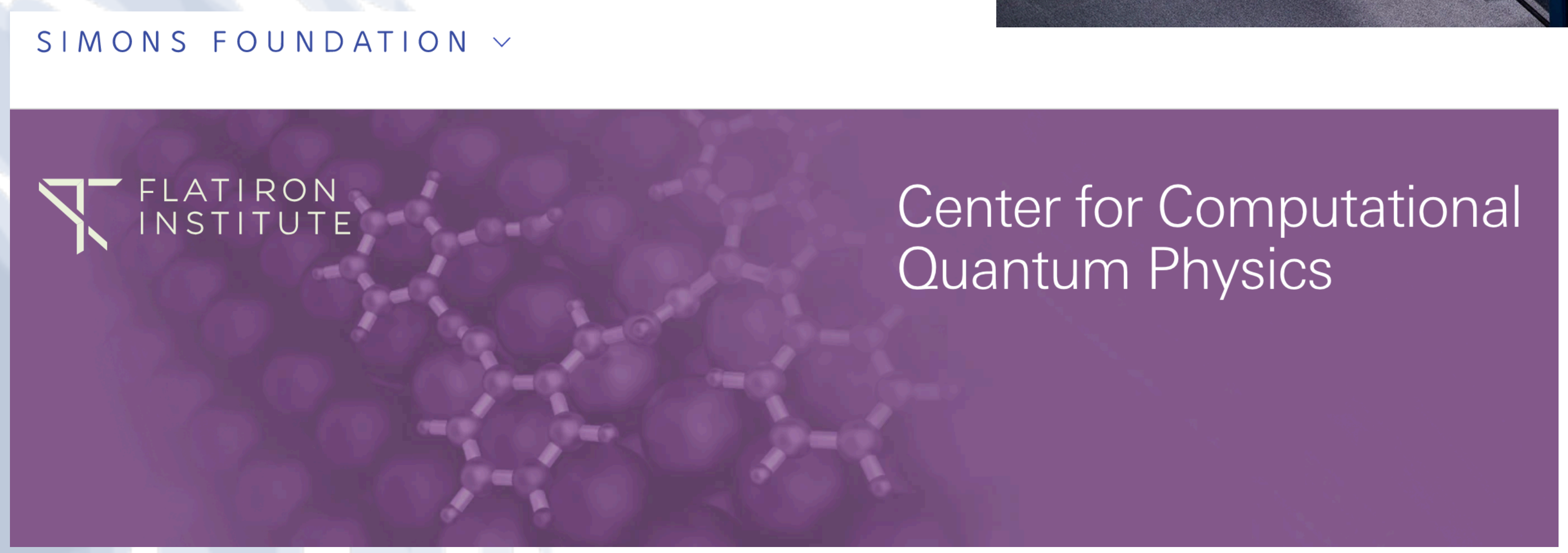
DFG

Long Range Colloquium
Virtual Science Forum
April 28, 2021

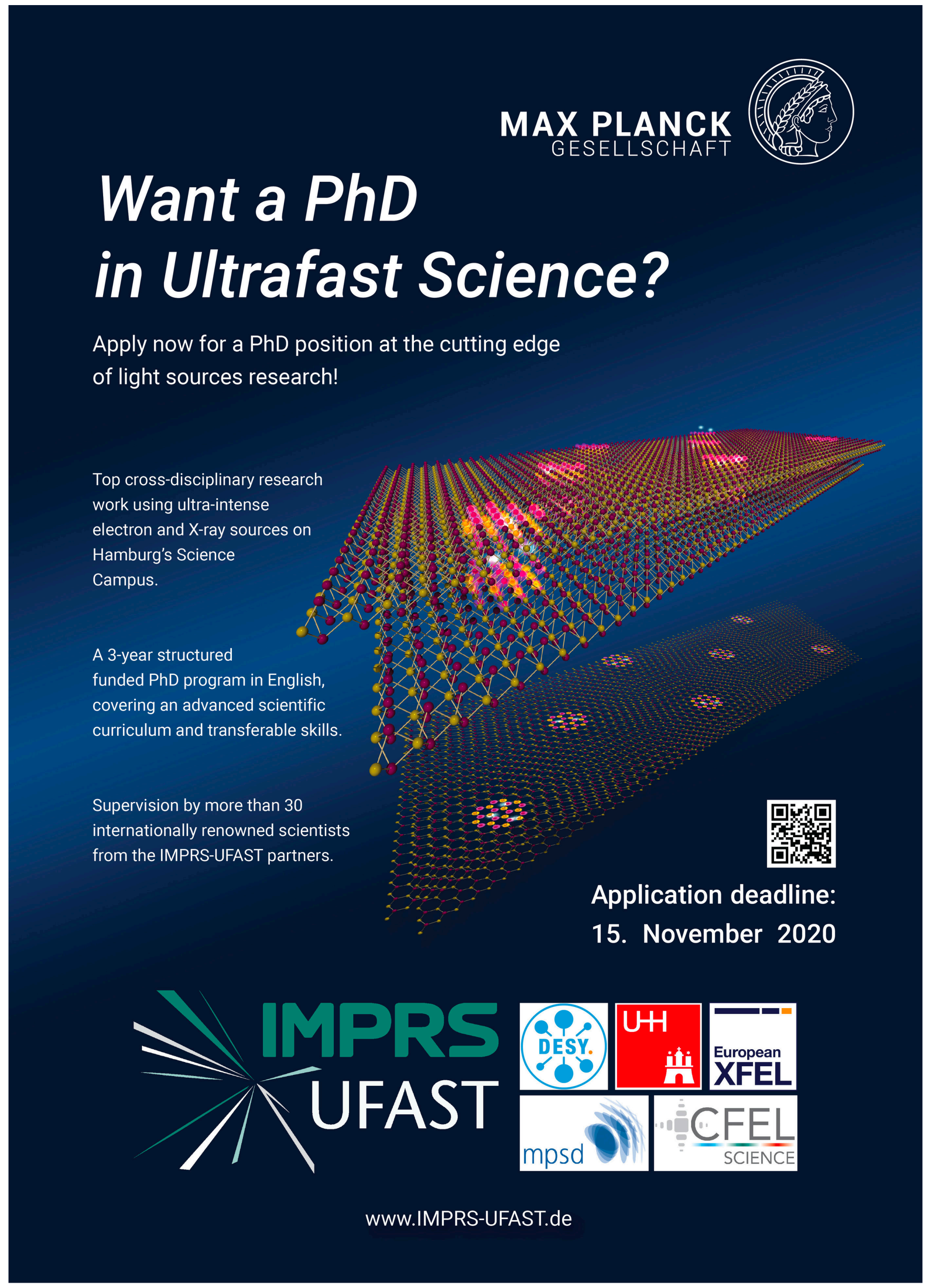
Hamburg

https://www.mpsd.mpg.de/

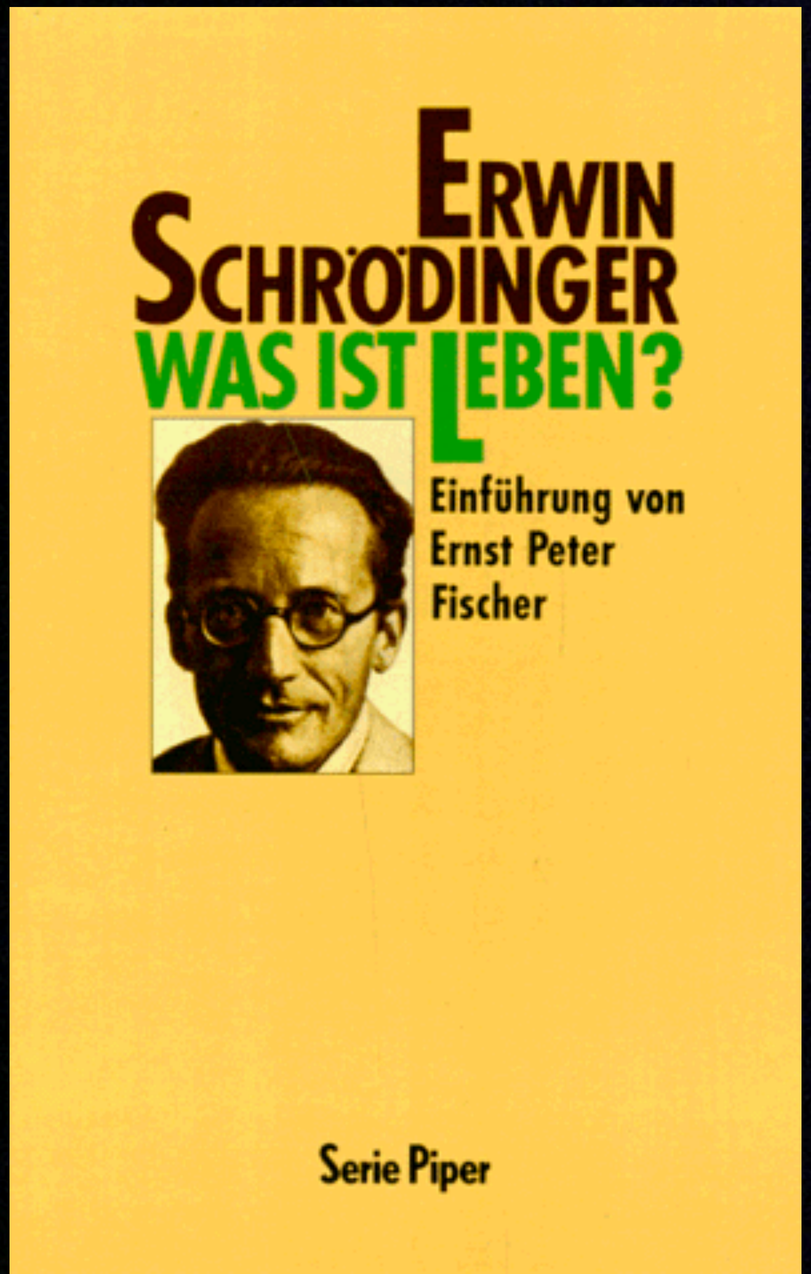
Max Planck-New York Center for Nonequilibrium Quantum Phenomena



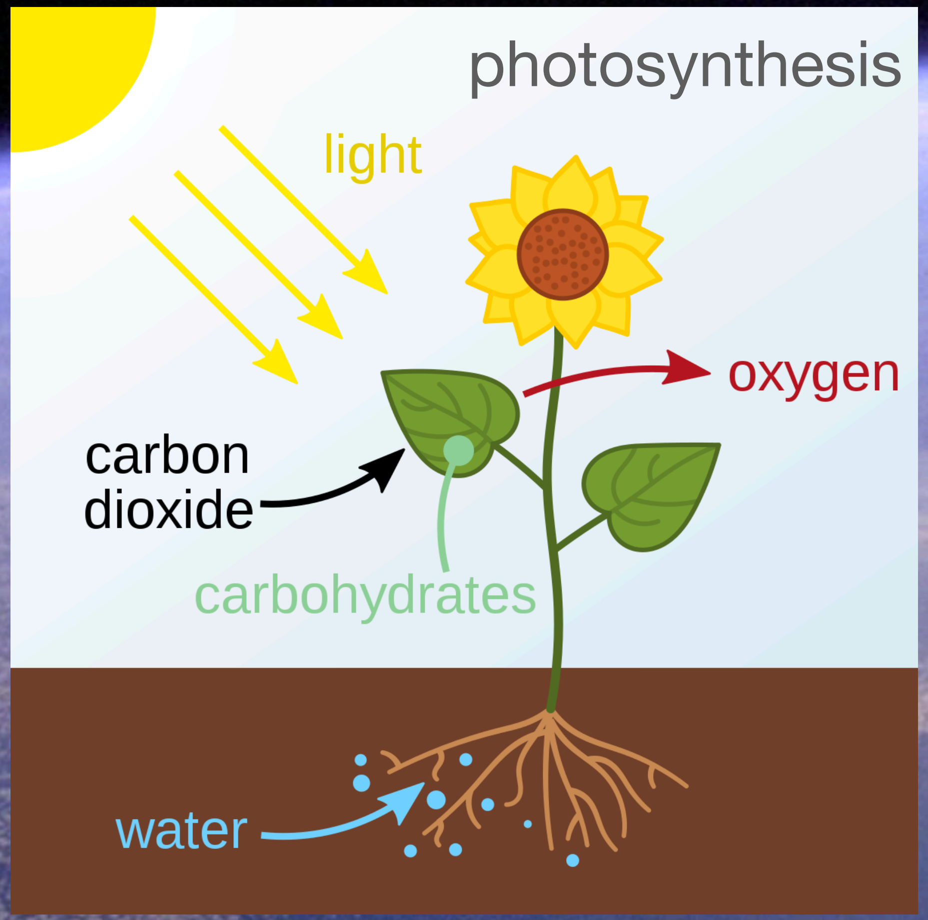
https://www.simonsfoundation.org/flatiron/center-for-computational-quantum-physics/

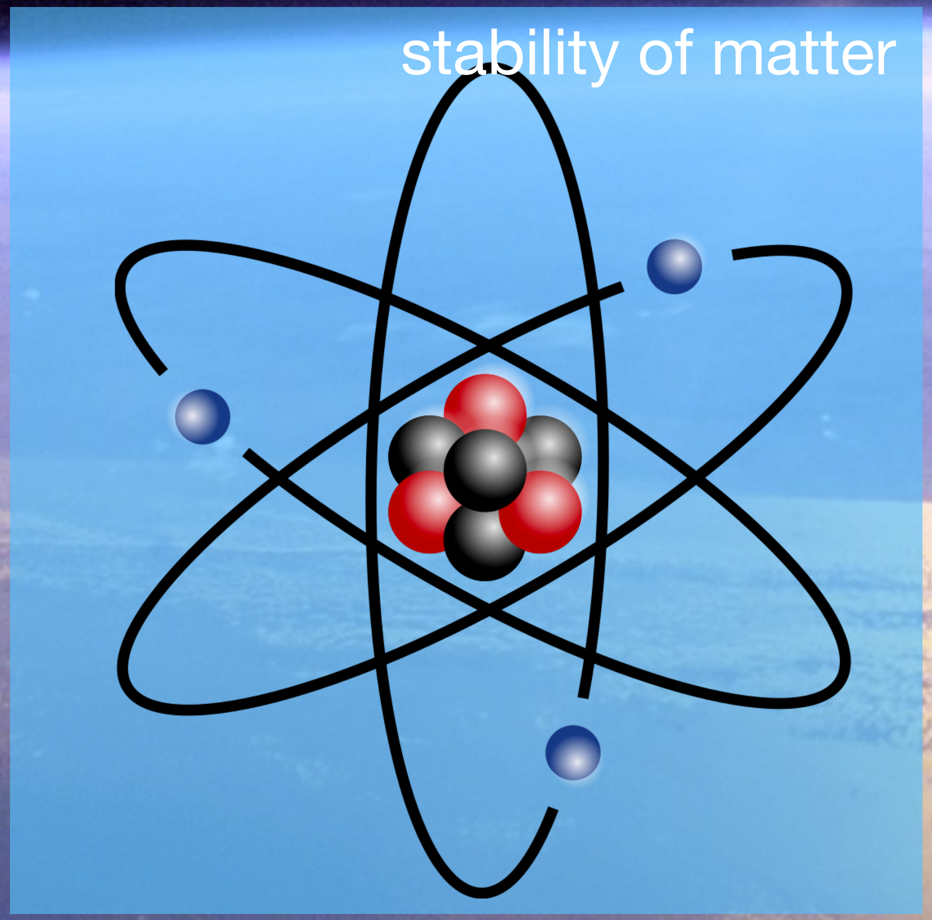


key importance of nonequilibrium for life



key importance of light-matter interactions for …





Can we employ light-matter interactions to change materials properties?

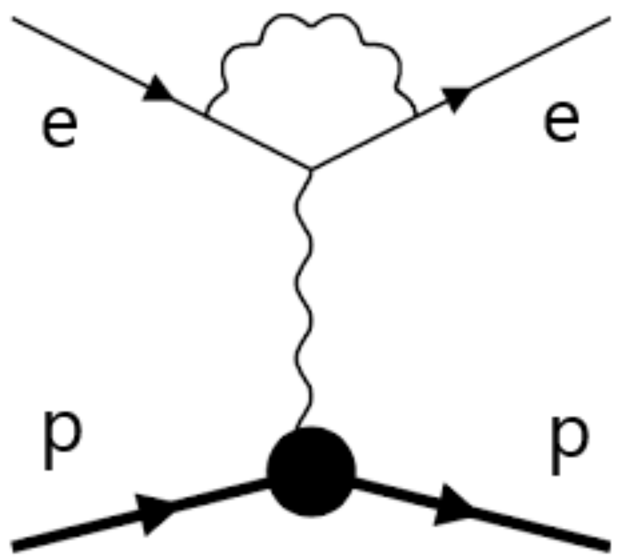
WIKIPEDIA
The Free Encyclopedia

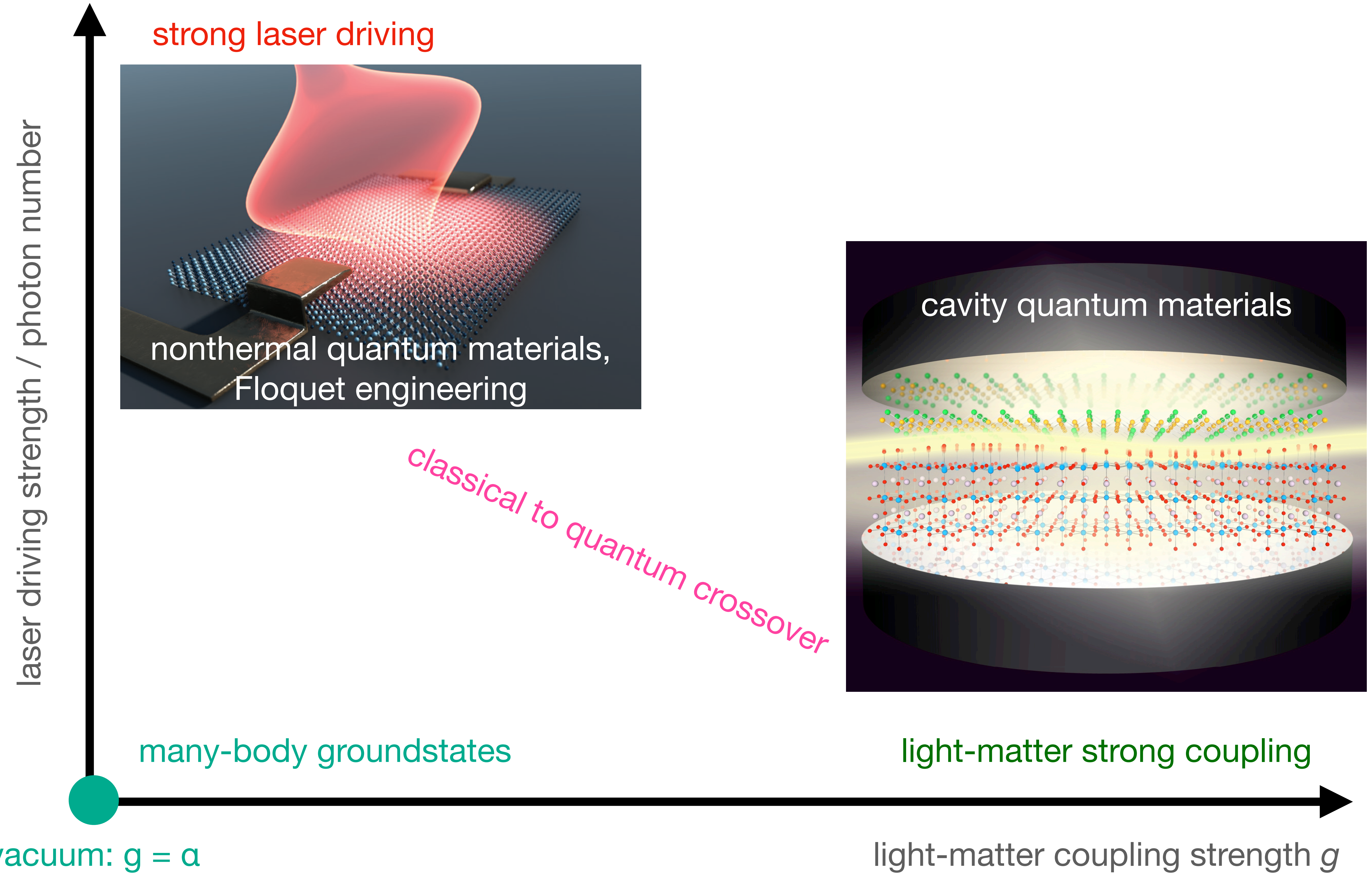
Article Talk

Fine-structure constant

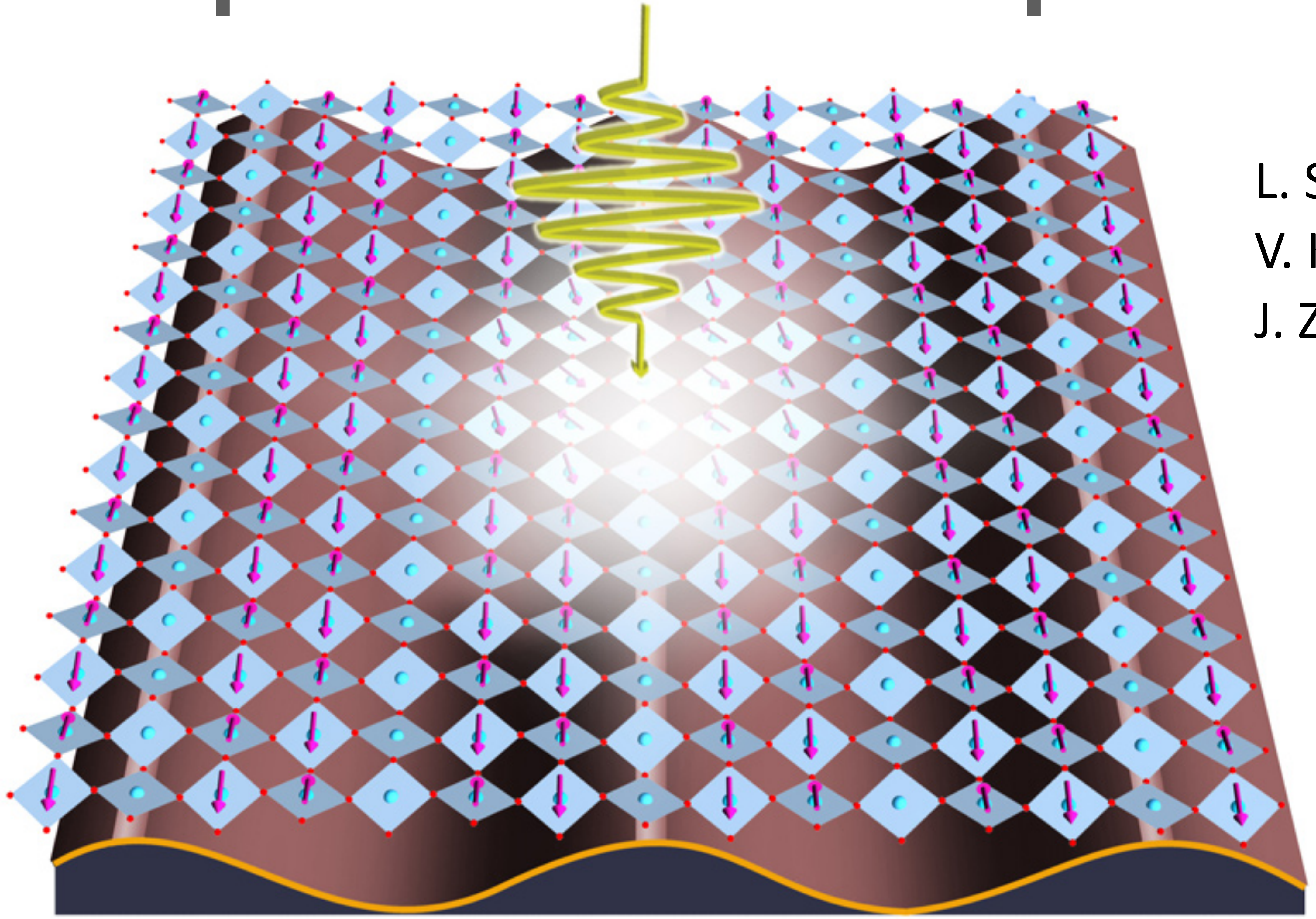
From Wikipedia, the free encyclopedia

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c} = \frac{\mu_0}{4\pi}\frac{e^2 c}{\hbar} = \frac{k_e e^2}{\hbar c} = \frac{e^2}{2\varepsilon_0 ch} = \frac{c\mu_0}{2R_K} = \frac{e^2 Z_0}{2h} = \frac{e^2 Z_0}{4\pi\hbar}$$





Optical control of quantum materials



Metastable hidden phases

L. Stojchevska et al. Science (2014)
V. Kiryukhin et al. Nature (1997)
J. Zhang et al. Nature Materials (2016)

Photo-induced phase transitions

M. Rini et al. Nature (2007)
C. Kübler et al. PRL (2007)
M. K. Liu et al. PRL (2011)
P. Beaud et al. Nature Materials (2014)

Band structure engineering

Q. Vu et al. Physical Review Letters (2004)
Y. H. Wang et al. Science (2013)
E. Sie et al. Nature Materials (2015)
F. Mahmood et al. Nature Physics (2016)
E. Sie et al. Nature (2019)

Light-induced superconductivity

D. Fausti et al. Science (2011)
W. Hu et al. Nature Materials (2014)
M. Mitrano et al. Nature (2016)
M. Buzzi et al. Phys. Rev. X (2020)

Ferroelectric switching

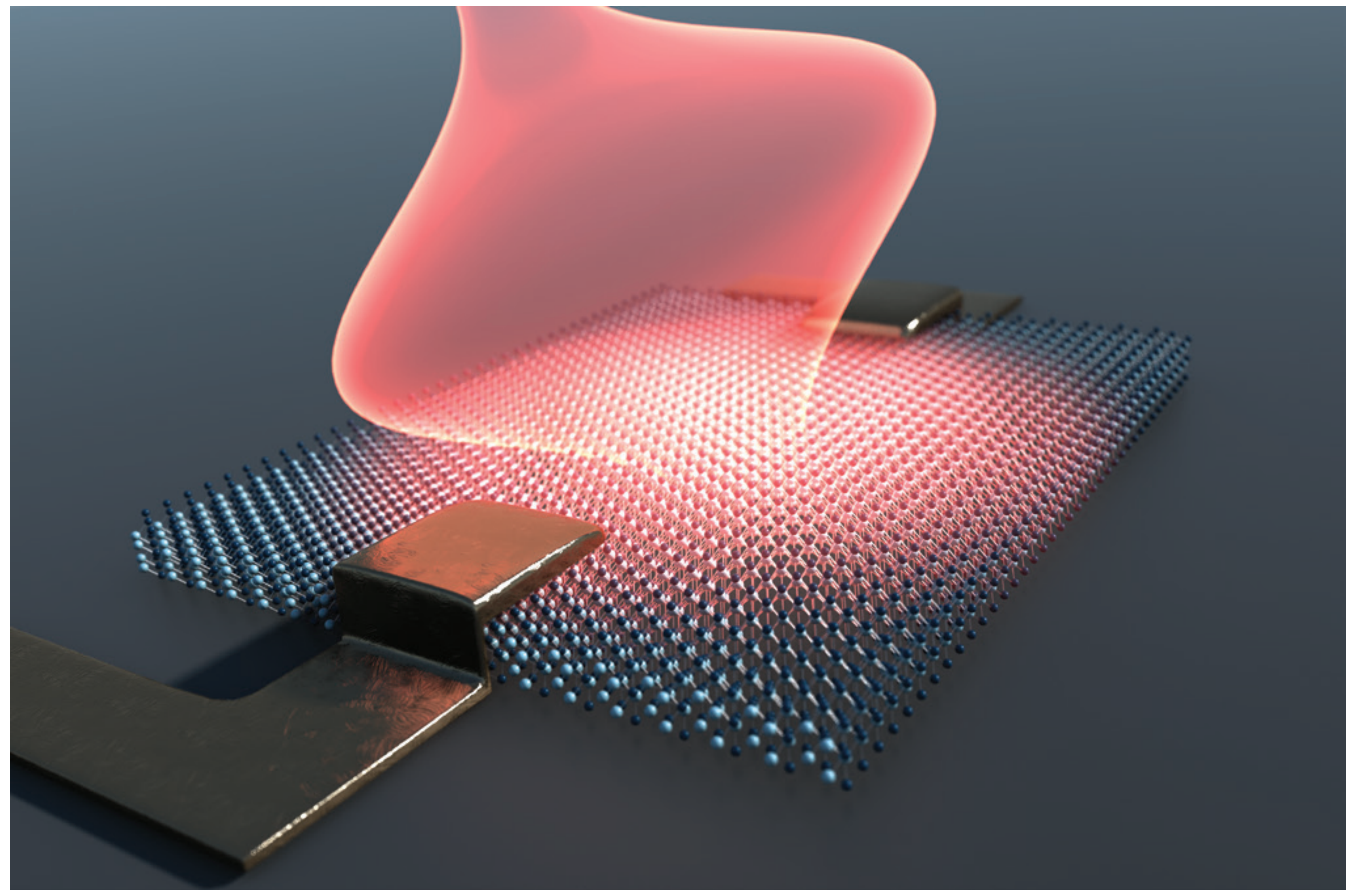
R. Mankowsky et al. PRL (2017)
T. F. Nova et al. Science (2019)
Li et al. Science (2019)

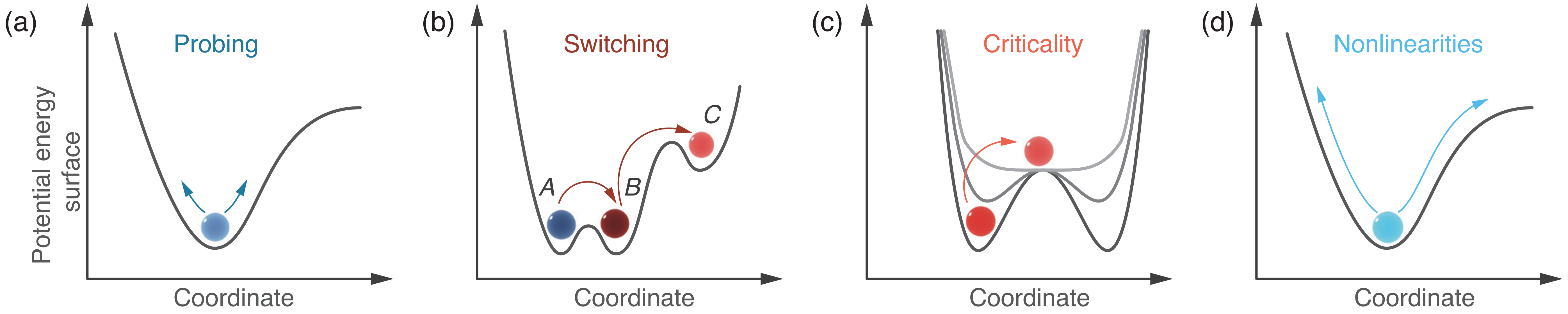
Ultrafast magnetism

E. Beaurepaire et al. PRL (1996).
T. Kampfrath et al. Nature Photonics (2011)
T. F. Nova et al. Nature Physics (2016)
A. Disa et al. Nature Physics (2020)
D. Afanasiev Nature Materials (2021)

Colloquium: Nonthermal pathways to ultrafast control in quantum materials

We review recent progress in utilizing ultrafast light-matter interaction to control the macroscopic properties of quantum materials. Particular emphasis is placed on photoinduced phenomena that do not result from ultrafast heating effects but rather emerge from microscopic processes that are inherently nonthermal in nature. Many of these processes can be described as transient modifications to the free-energy landscape resulting from the redistribution of quasiparticle populations, the dynamical modification of coupling strengths and the resonant driving of the crystal lattice. Other pathways result from the coherent dressing of a material's quantum states by the light field. We discuss a selection of recently discovered effects leveraging these mechanisms, as well as the technological advances that led to their discovery. A road map for how the field can harness these nonthermal pathways to create new functionalities is presented.



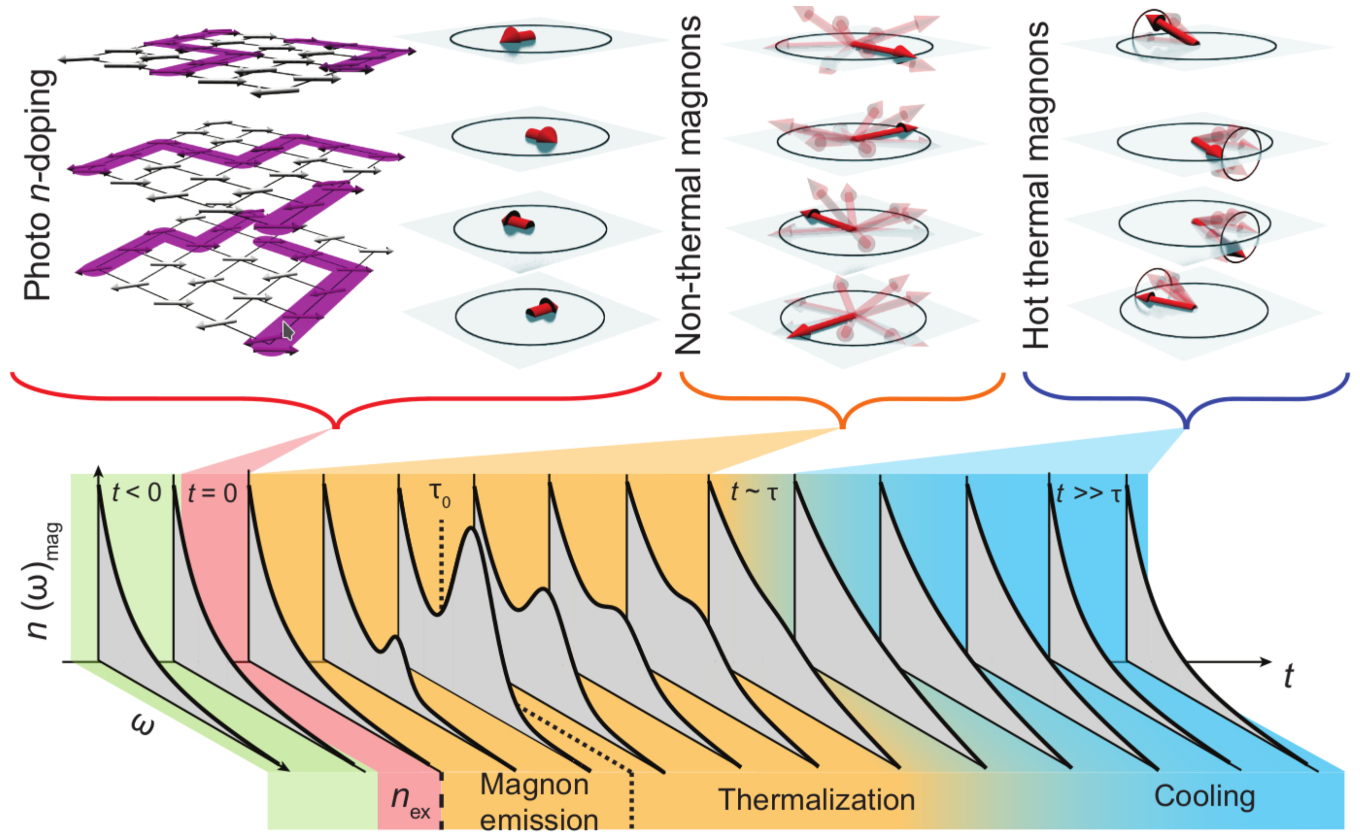


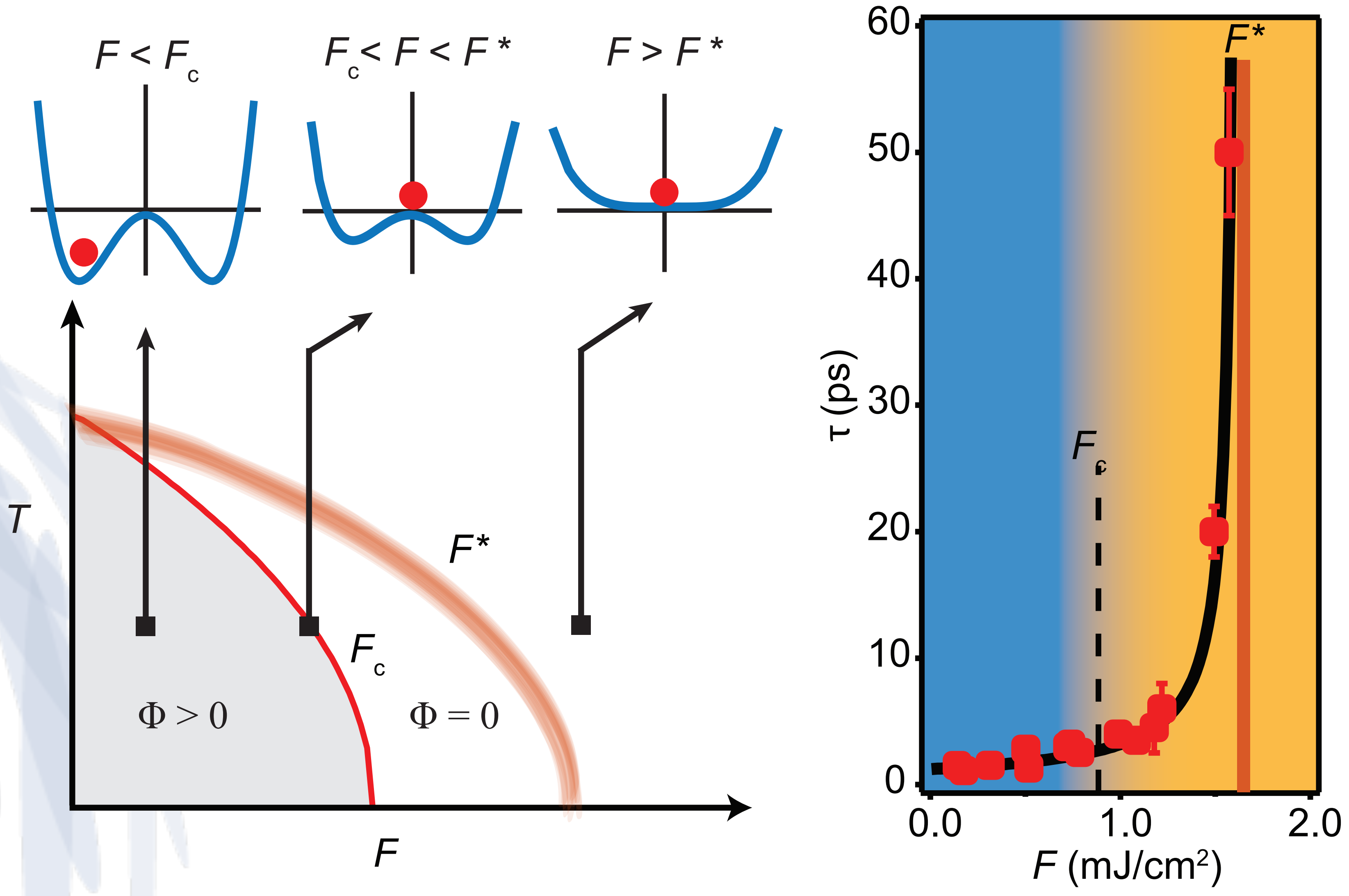
A. de la Torre, D. Kennes, M. Claassen, S. Gerber, J. McIver, MAS, arXiv:2103.14888

Alberto de la Torre Dante Kennes Martin Claassen chess hustler Simon Gerber James McIver

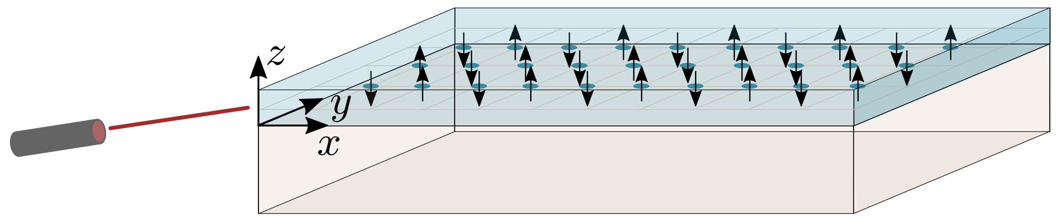
Dynamical phase transitions in quantum magnets

Dynamical critical behavior in optically pumped 214 iridate
de la Torre et al., unpublished

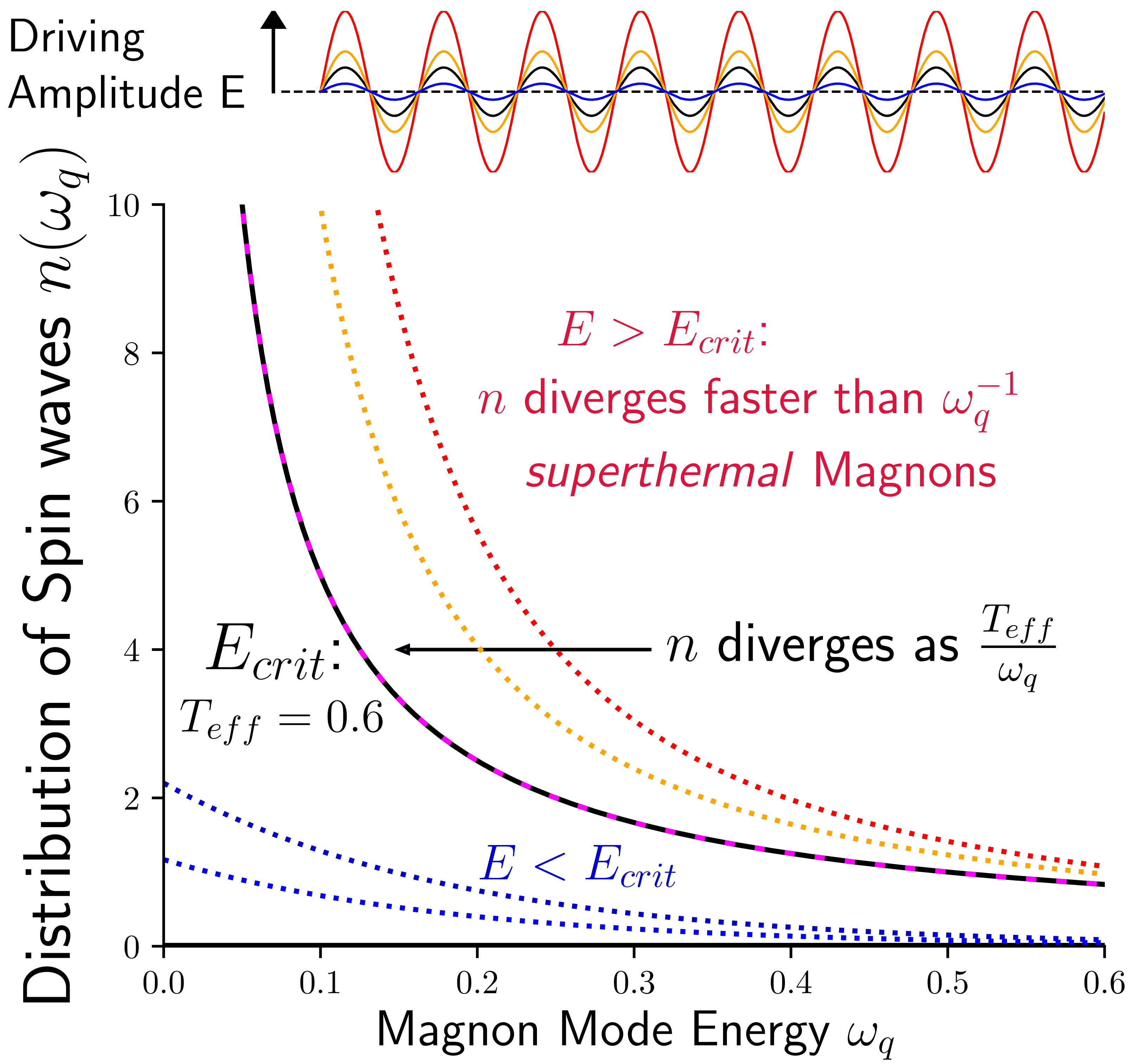




Noninteracting-magnon theory of a driven-dissipative phase transition:

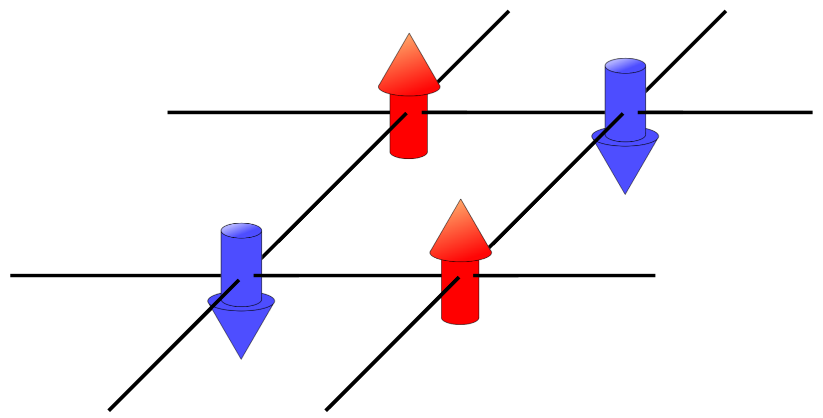


[N. Walldorf *et al* Phys. Rev. B **100**, 121110(R) (2019)]



Dynamical phase transition in 2D Heisenberg AFM

$$\mathcal{H}_{XXZ} = J\sum_{\langle ij\rangle}\left\{\frac{1}{2}\left(S_i^+S_j^- + S_i^-S_j^+\right) + \Delta S_i^z S_j^z\right\} \rightarrow \underbrace{\mathcal{H} = E_0 + H_0 + V}$$



$E_0 =$ Ground State Energy

$H_0 = \hbar\sum_{\boldsymbol{k}}\omega_{\boldsymbol{k}}\left(\alpha_{\boldsymbol{k}}^\dagger\alpha_{\boldsymbol{k}} + \beta_{\boldsymbol{k}}^\dagger\beta_{\boldsymbol{k}}\right) =$ Bilinear Hamiltonian

$V =$ Magnon Interactions

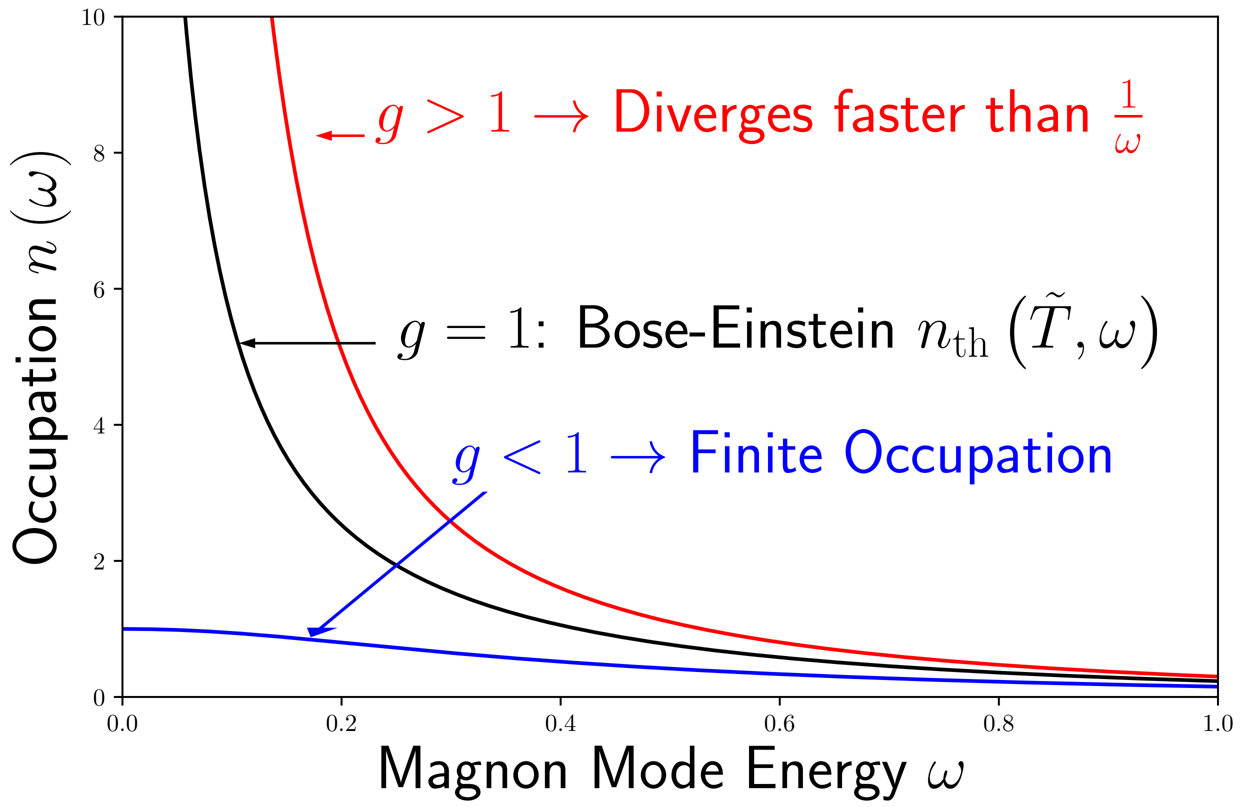
in → **noninteracting magnons** → out

Nonlinear kinetic equation for noninteracting magnons:

$$\partial_t n = g_{\text{in}}(1+n) - \gamma_{\text{out}}\left(n + \left(\frac{n}{n_{\tilde{T}}(\omega)}\right)^2\right) \quad \text{with} \quad g = \frac{g_{\text{in}}}{\gamma_{\text{out}}}$$

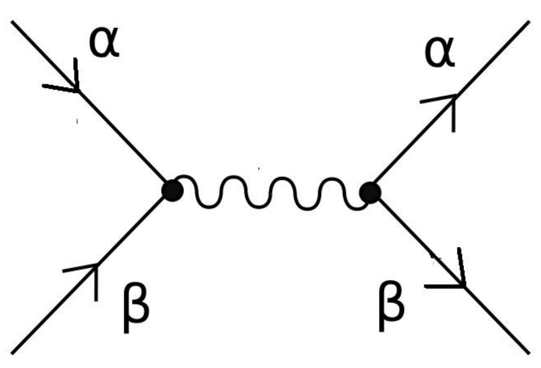
Dynamical Critical Point $g = 1$

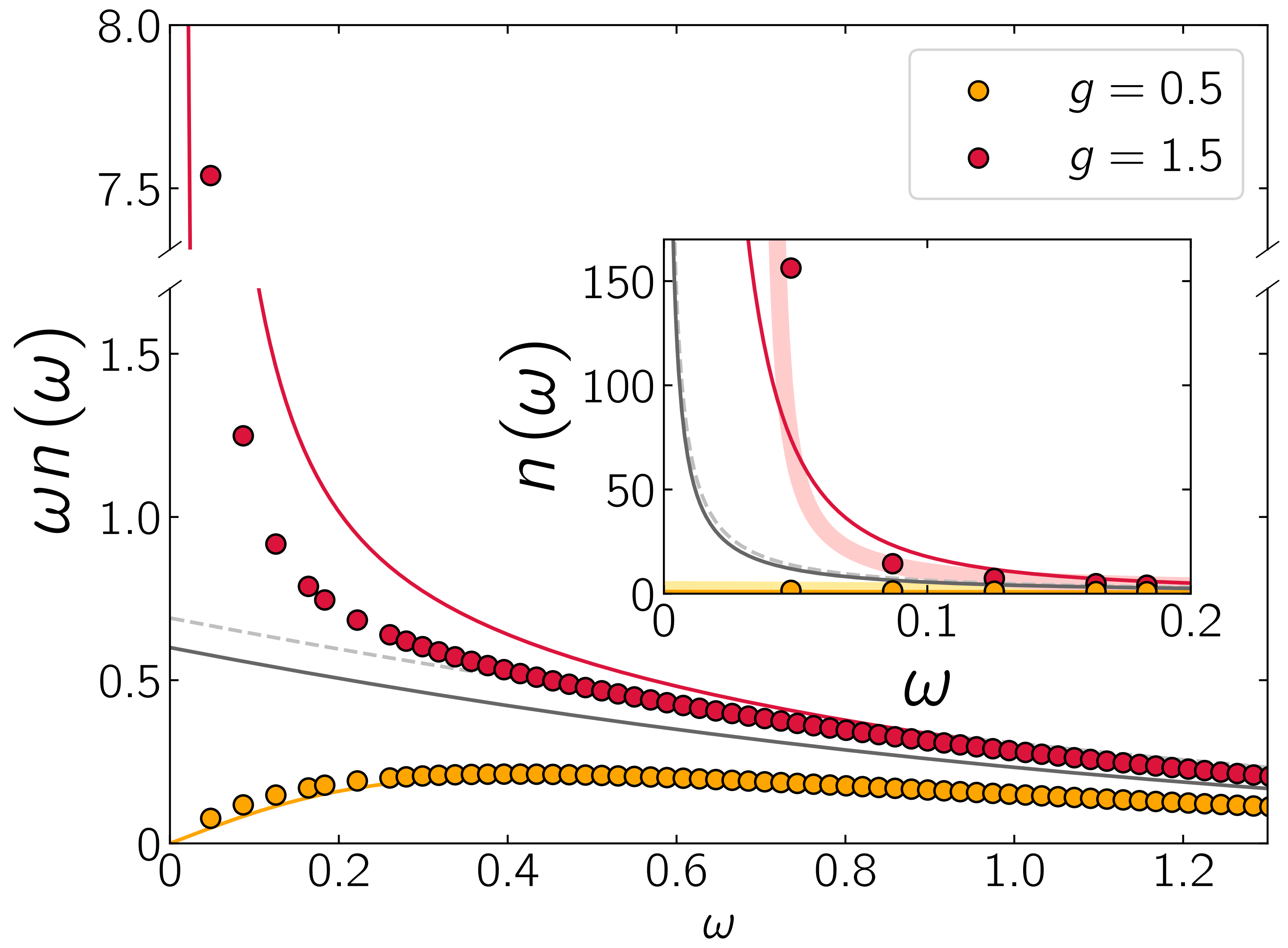
- $g > 1 \rightarrow n(\omega)$ diverges faster than $1/\omega$
- $g < 1 \rightarrow n(\omega)$ is finite for all ω
- $g = 1$ Thermal Distribution at temperature $\tilde{T}$



Interacting theory:
Magnon-magnon scattering at semiclassical Boltzmann level

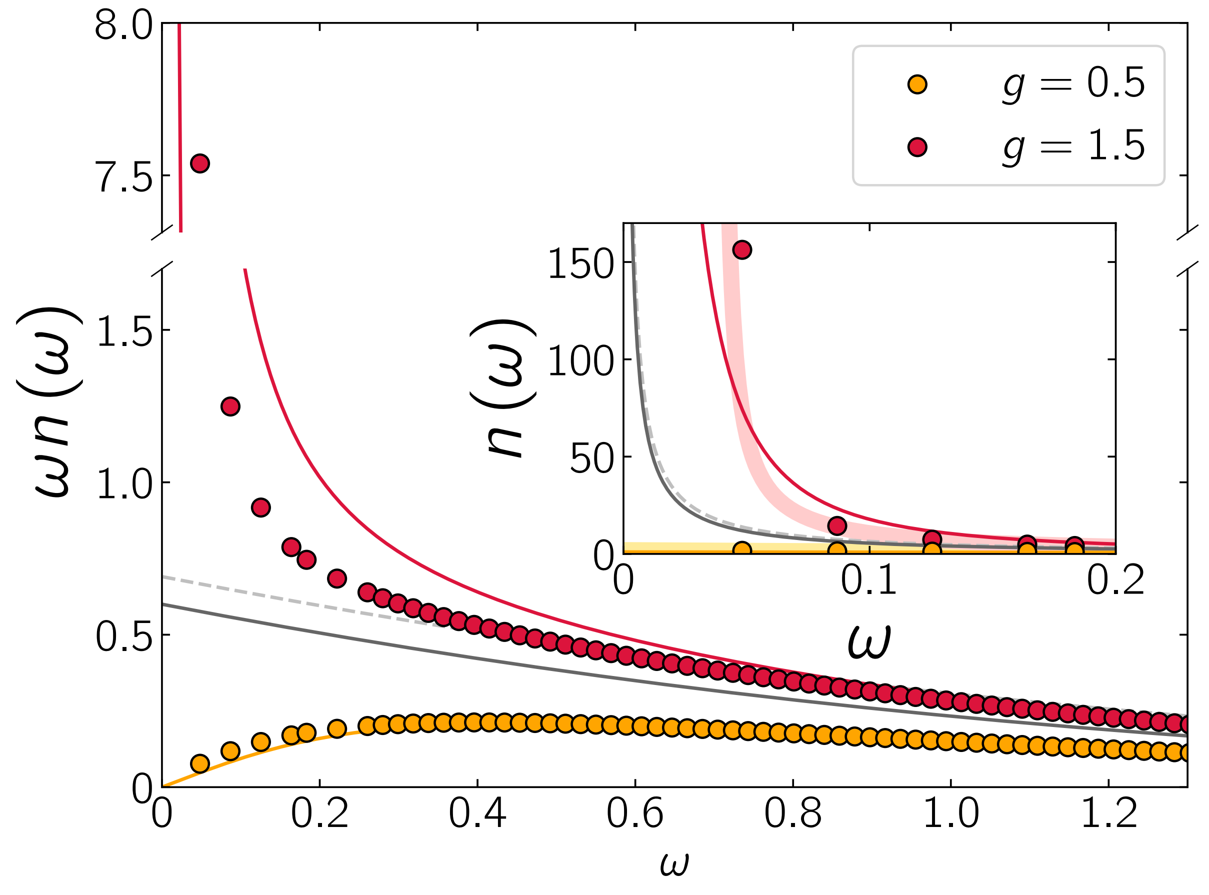
in → **interacting magnons** → out



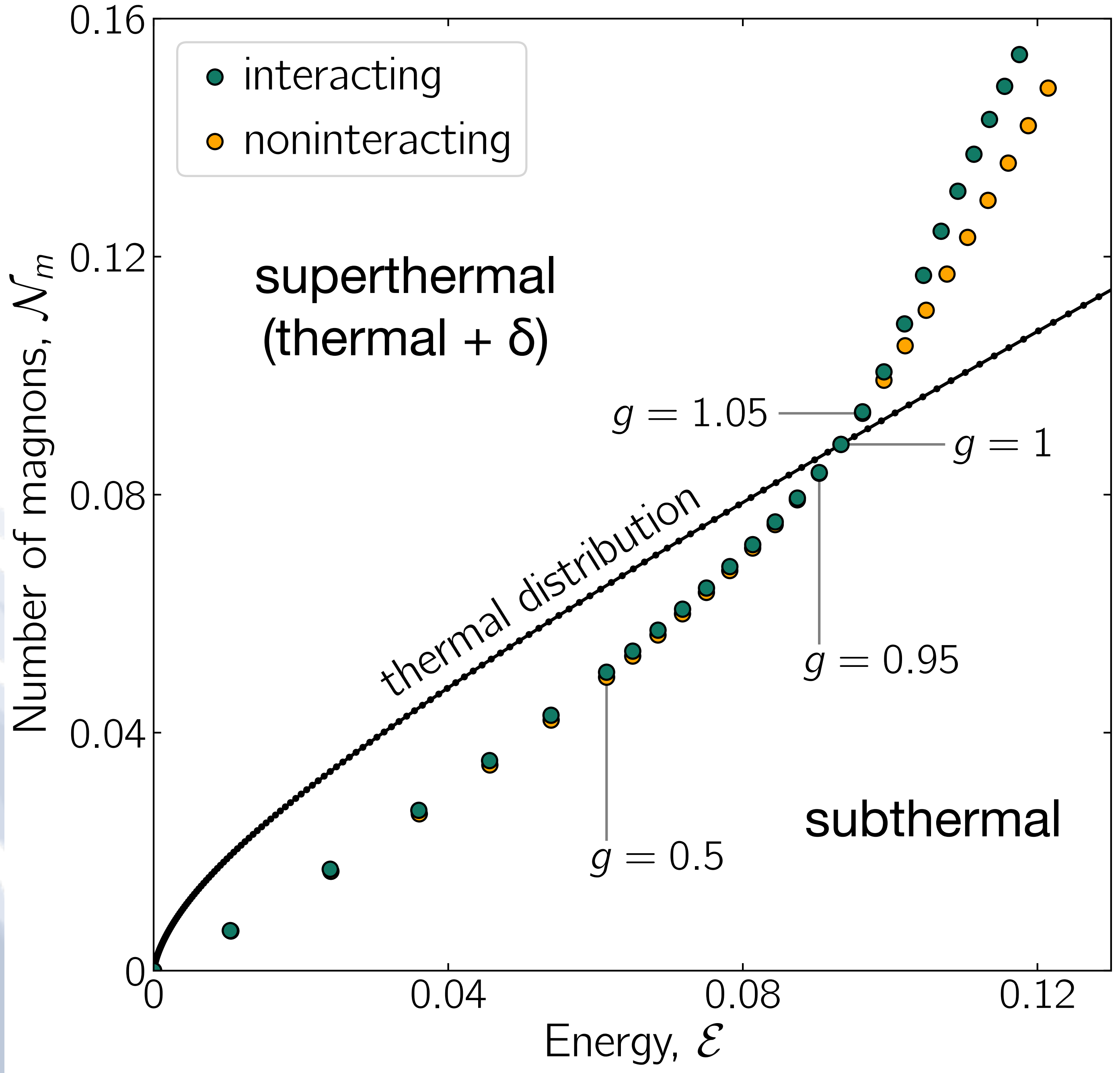


magnon-magnon scattering: stronger divergence in superthermal phase g>1

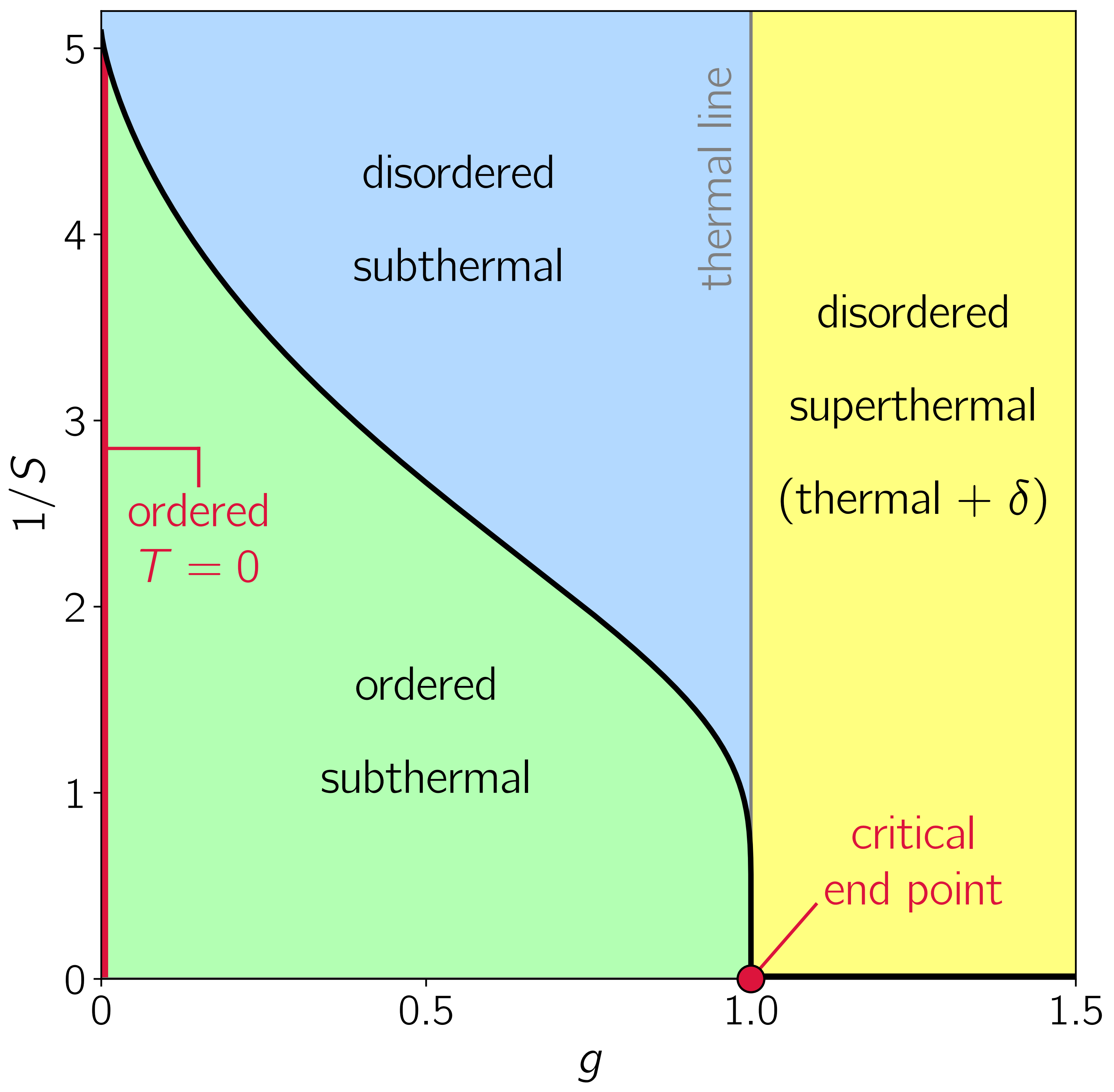
Dynamical phase transition in 2D Heisenberg AFM

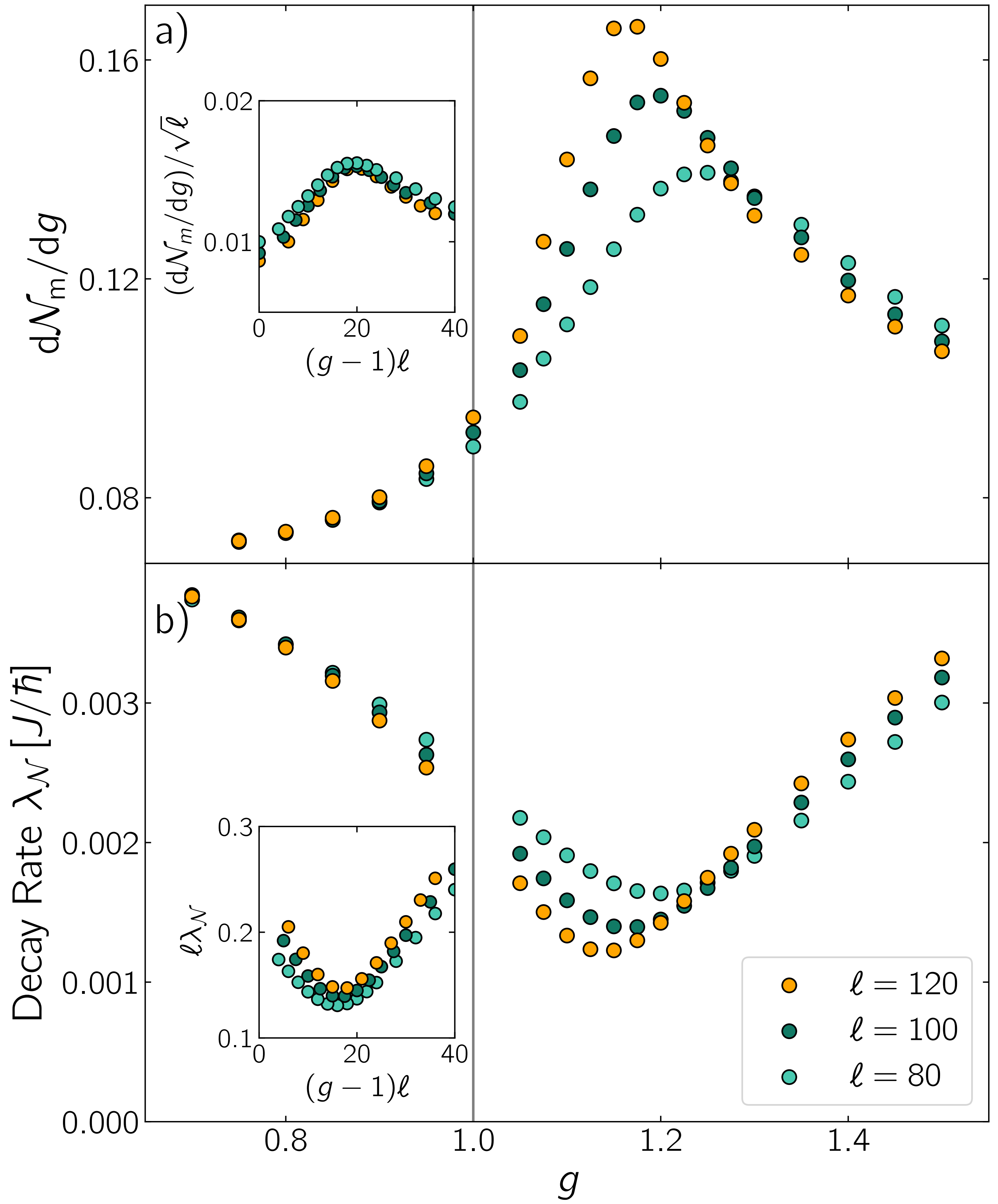


magnon-magnon scattering: stronger divergence in superthermal phase g>1;
finite size scaling analysis:
thermal + δ-function at ω=0 in thermodynamic limit



tentative nonthermal phase diagram

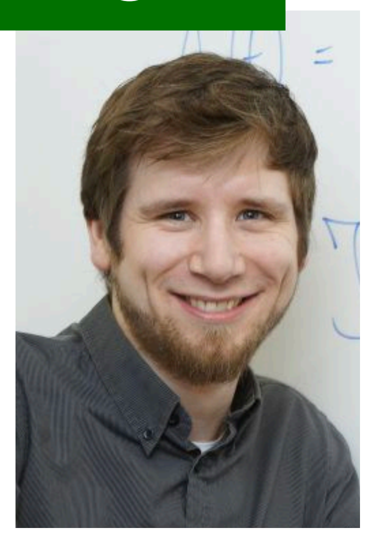




static and dynamic criticality at g=1

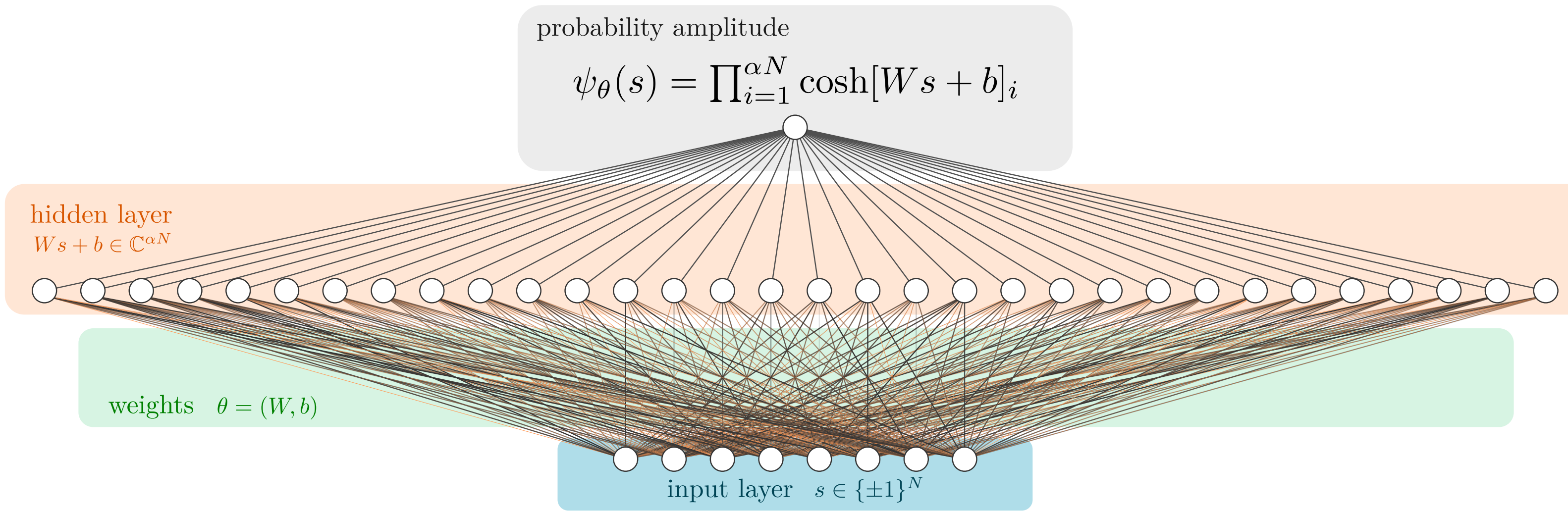

Mona Kalthoff


Andy Millis

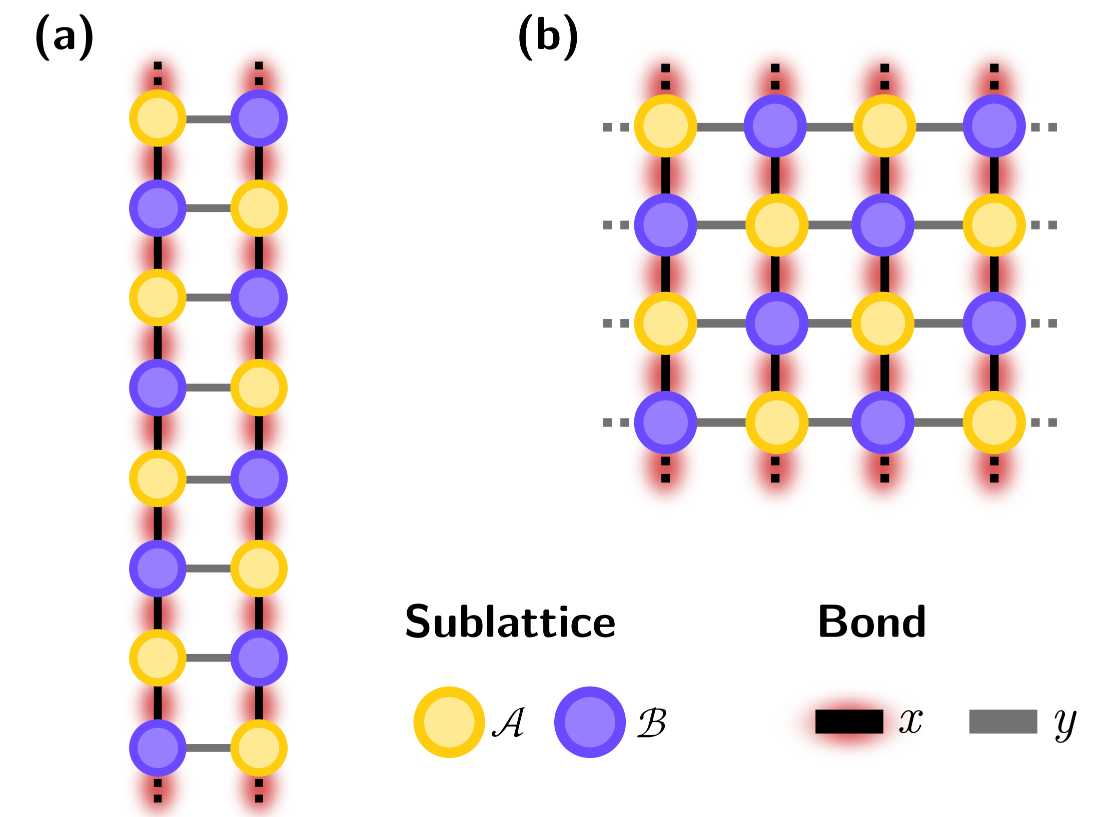

Dante Kennes

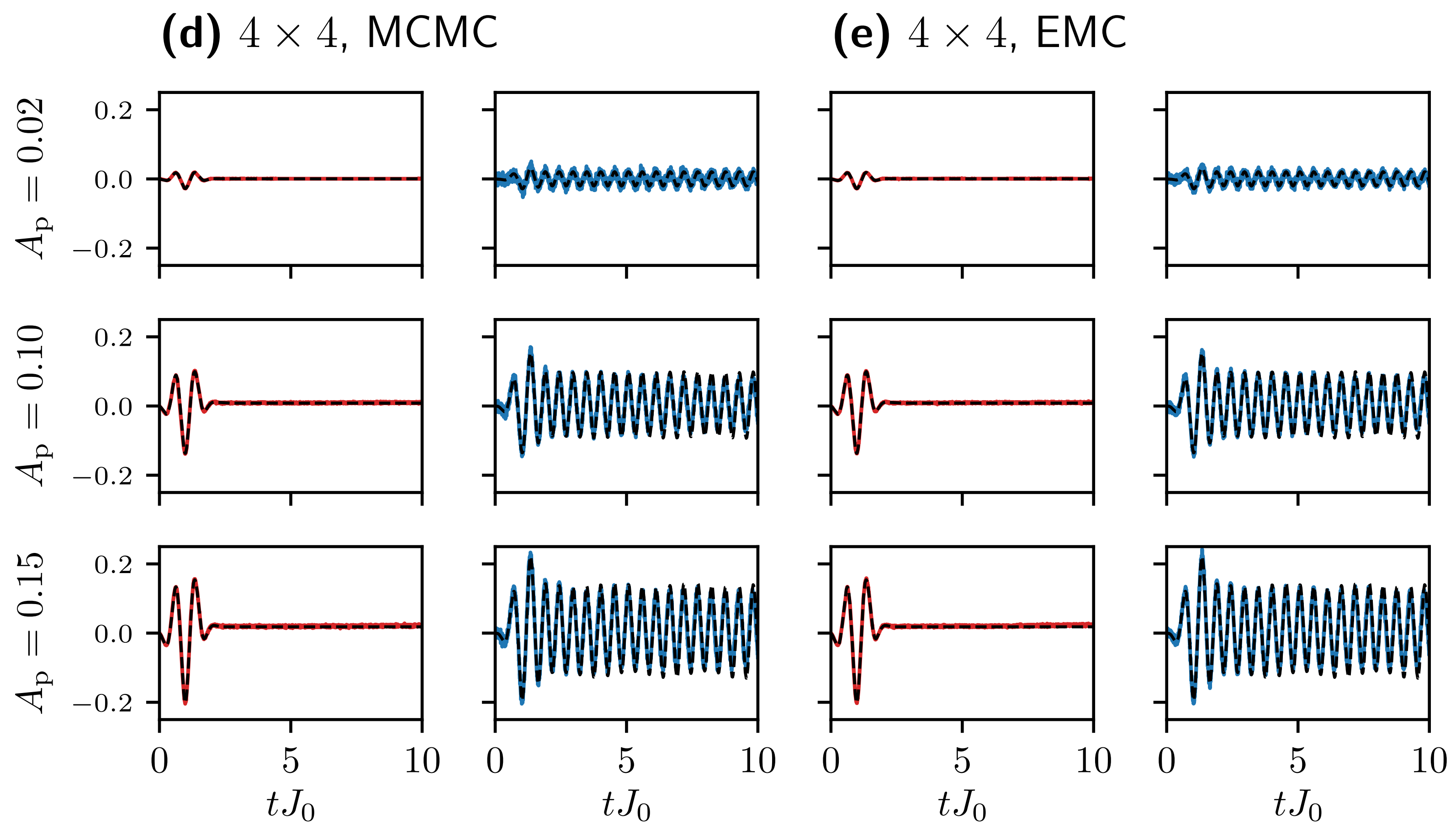
Dynamical phase transition in a driven-dissipative Heisenberg antiferromagnet M. H. Kalthoff, D. M. Kennes, A. J. Millis, M. A. Sentef, **in prep.**

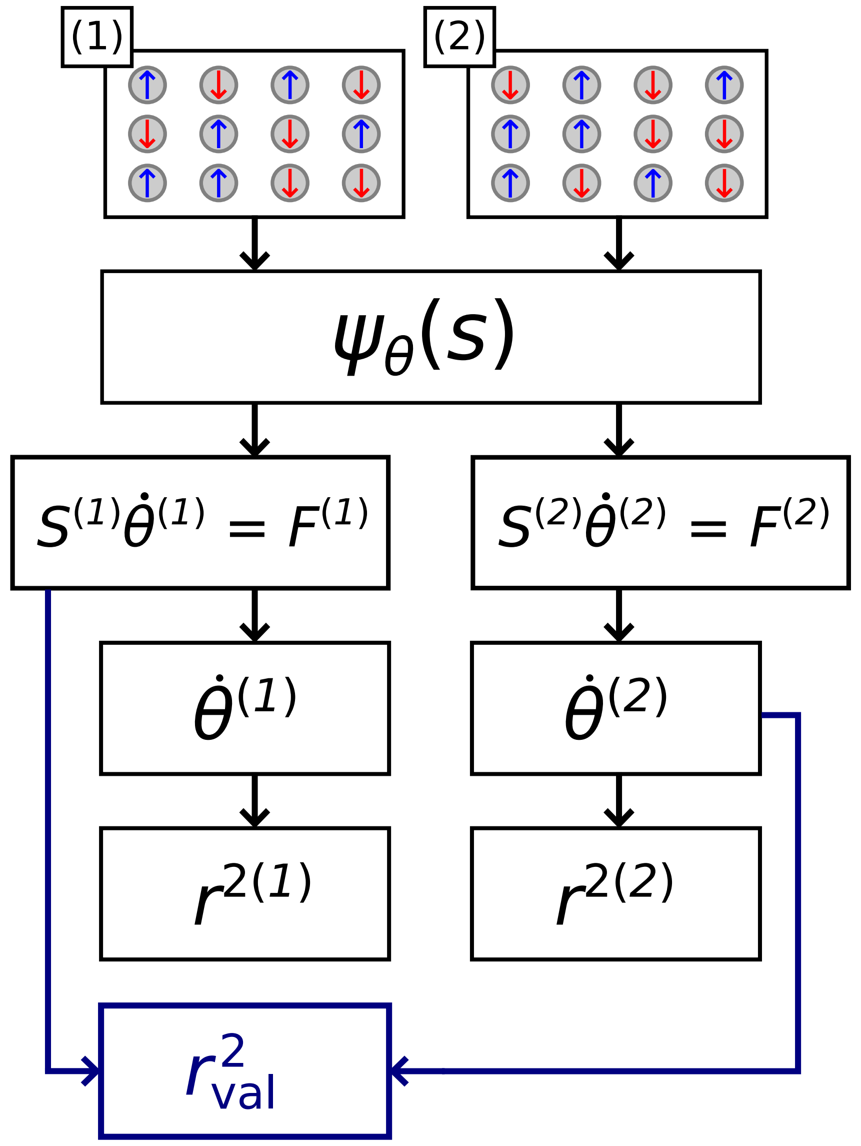
Dynamics with neural quantum states (NQS)

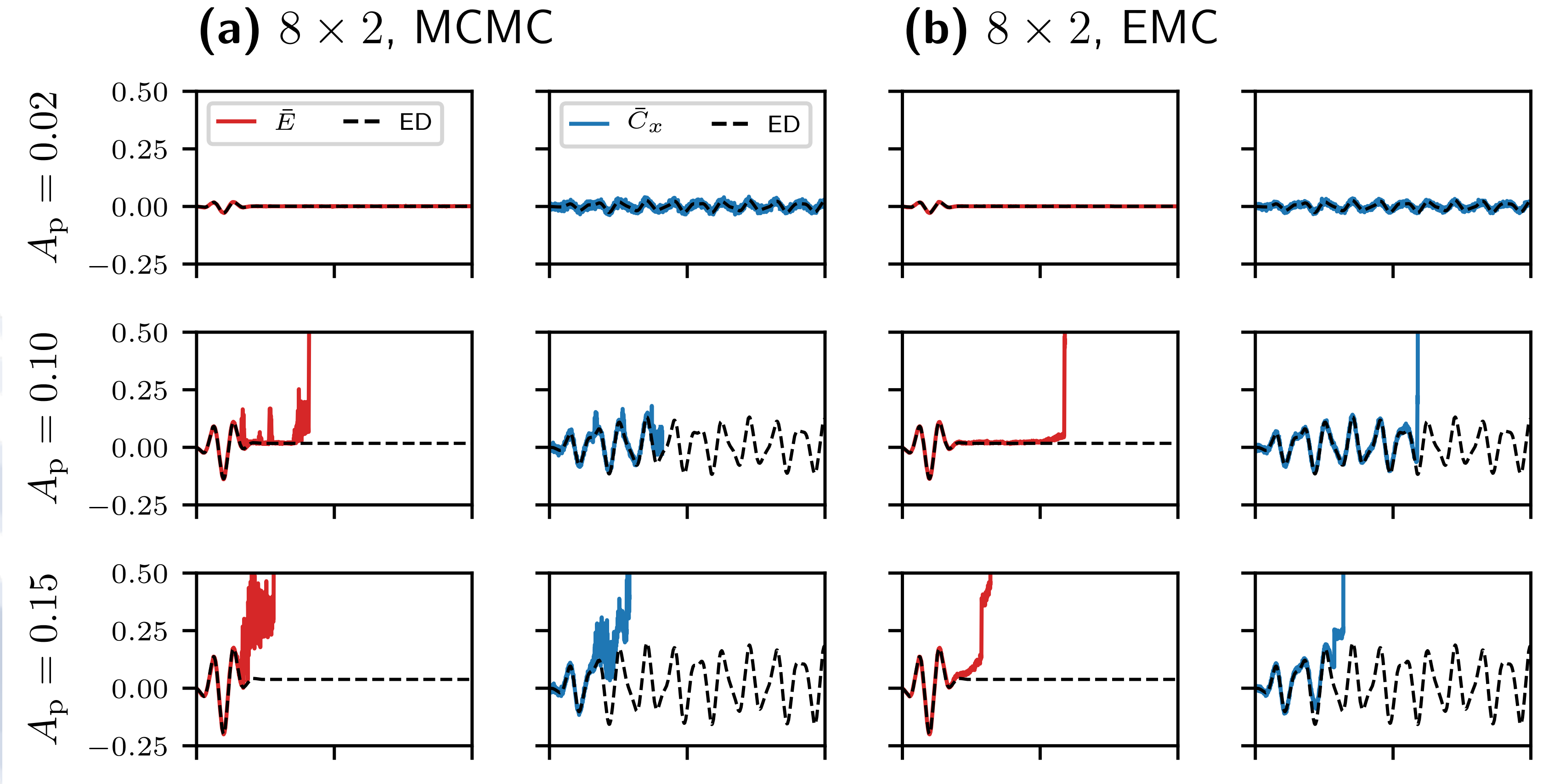


Pulse-driven 2D AFM Heisenberg models (ladder versus square lattice)

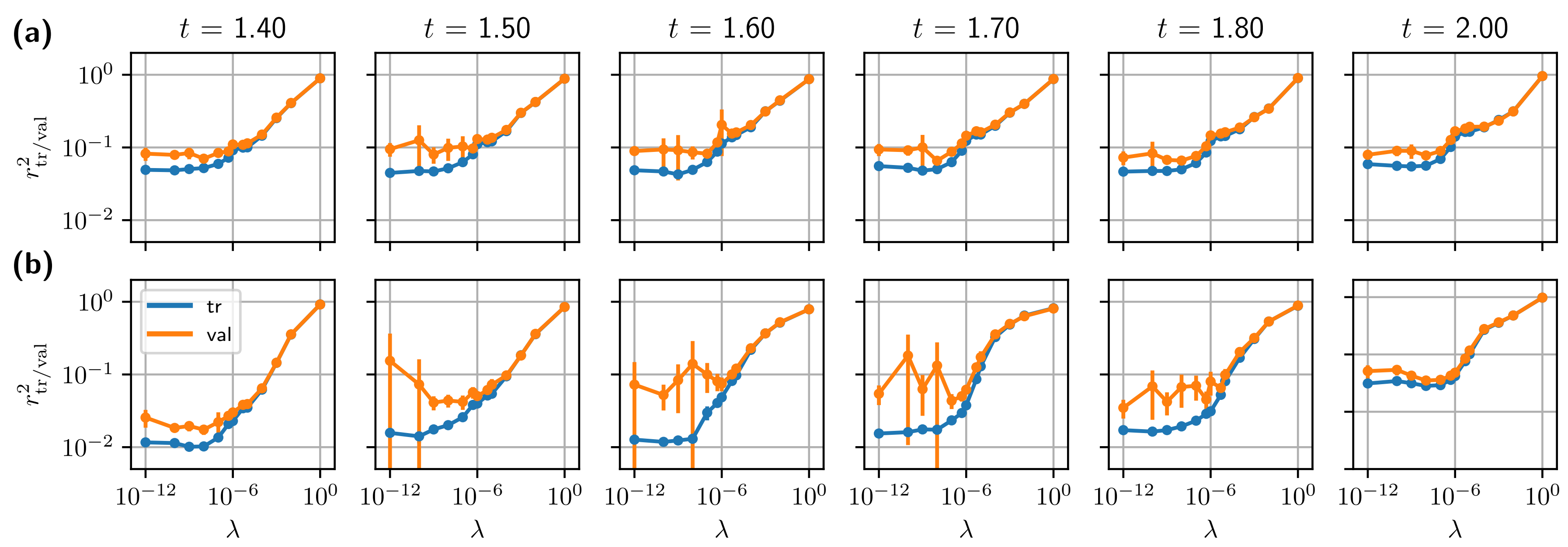








trace numerical instability to overfitting of MC noise diagnosed by validation error



https://www.netket.org/

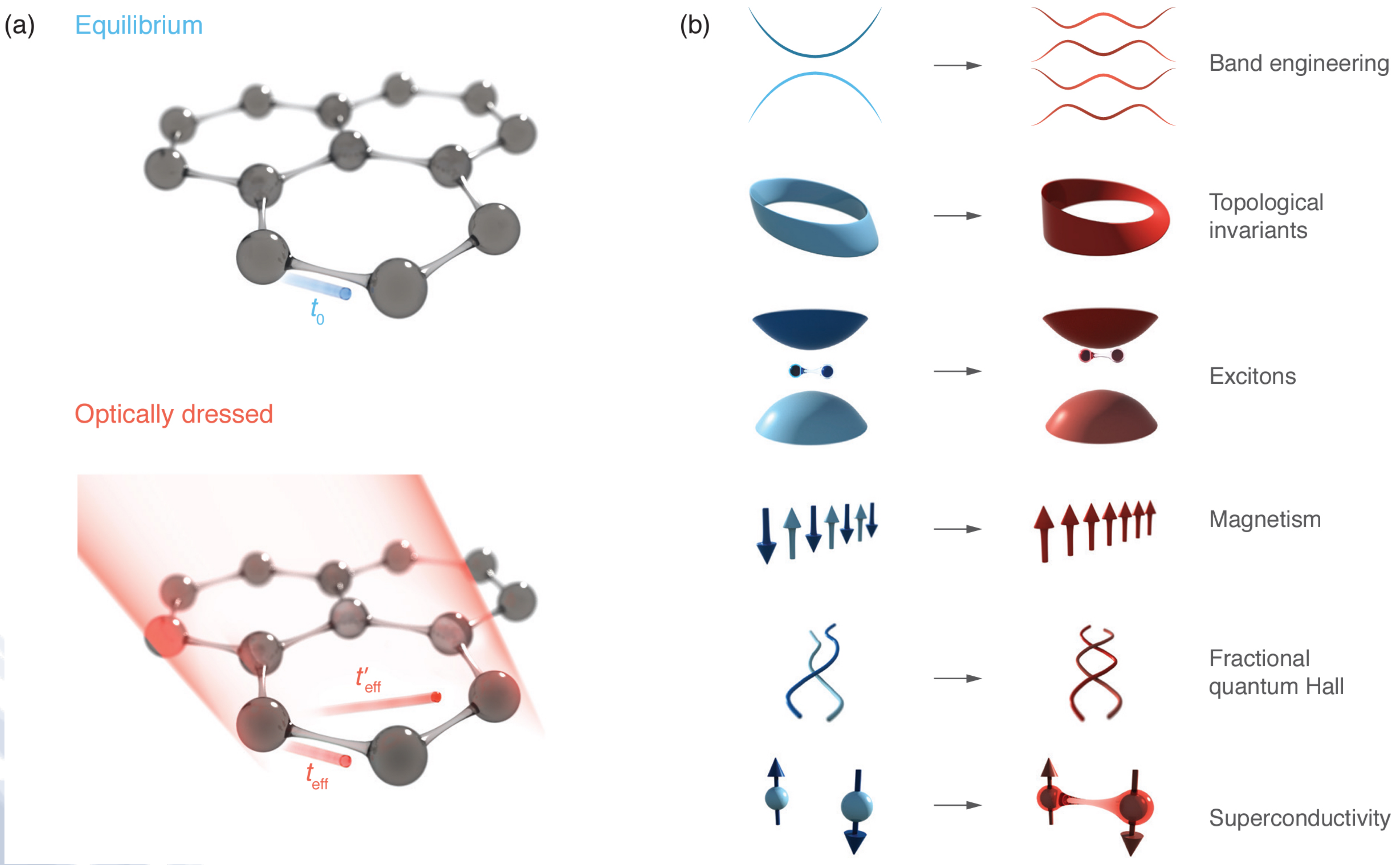
Role of generalization error in the dynamics of neural quantum states

D. Hofmann, G. Fabiani, J. H. Mentink, G. Carleo, M.A. Sentef, **in prep.**

also cf. Long Range Colloquium on May 28 by Giuseppe Carleo

Floquet engineering of quantum materials

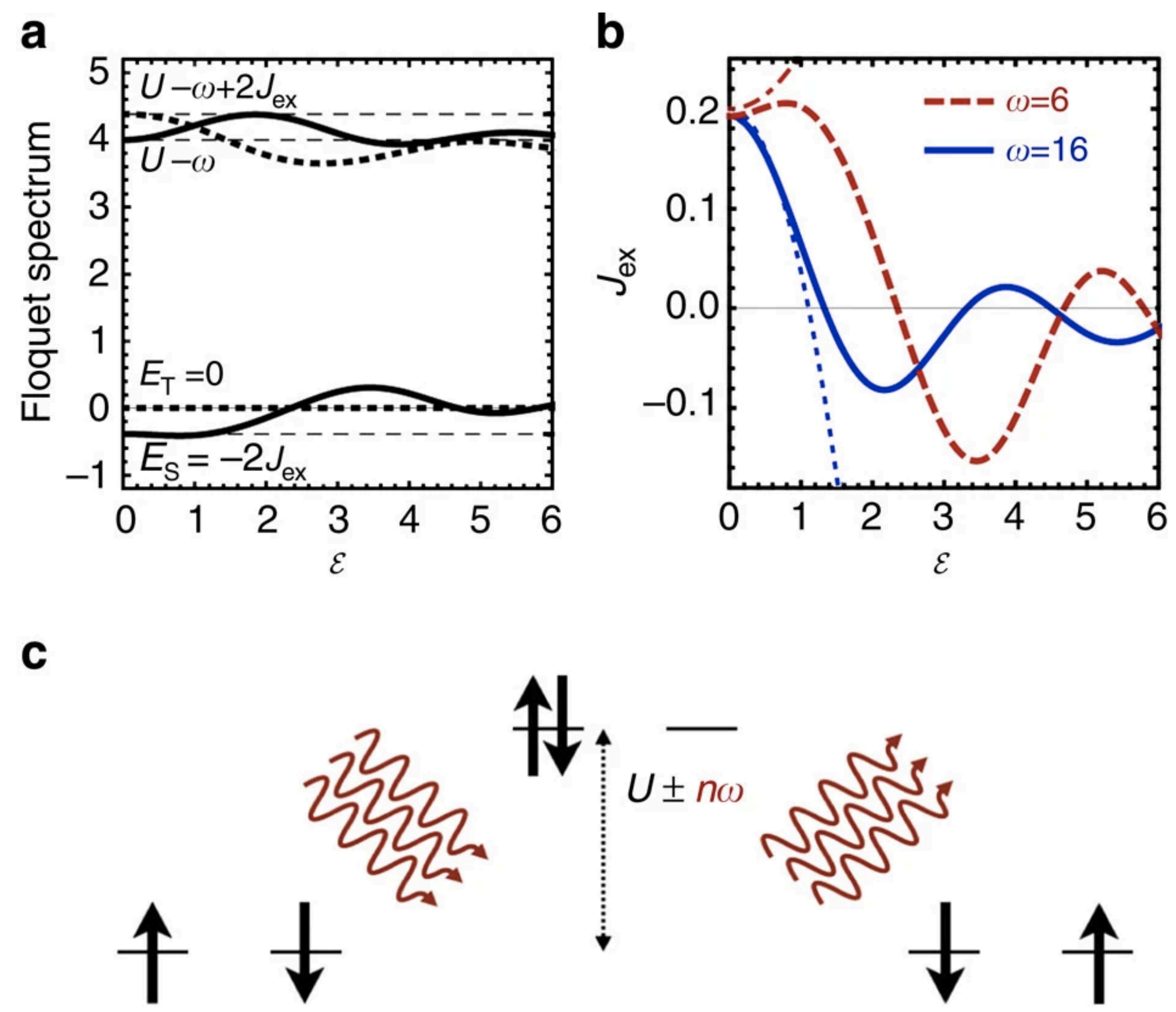
Oka & Kitamura, Ann. Rev. Condens. Matter Phys. 2019
Rudner & Lindner, Nat. Rev. Phys. 2020



A. de la Torre, D. M. Kennes, M. Claassen, S. Gerber, J. W. McIver, MAS, arXiv:2103.14888

Floquet engineering of spin exchange

Mentink, Balzer, and Eckstein, Nat. Commun. 6, 6708 (2015)



Photon dressing of intermediate states modifies kinetic exchange

But: need for strong lasers, problems with heating, short-lived effect

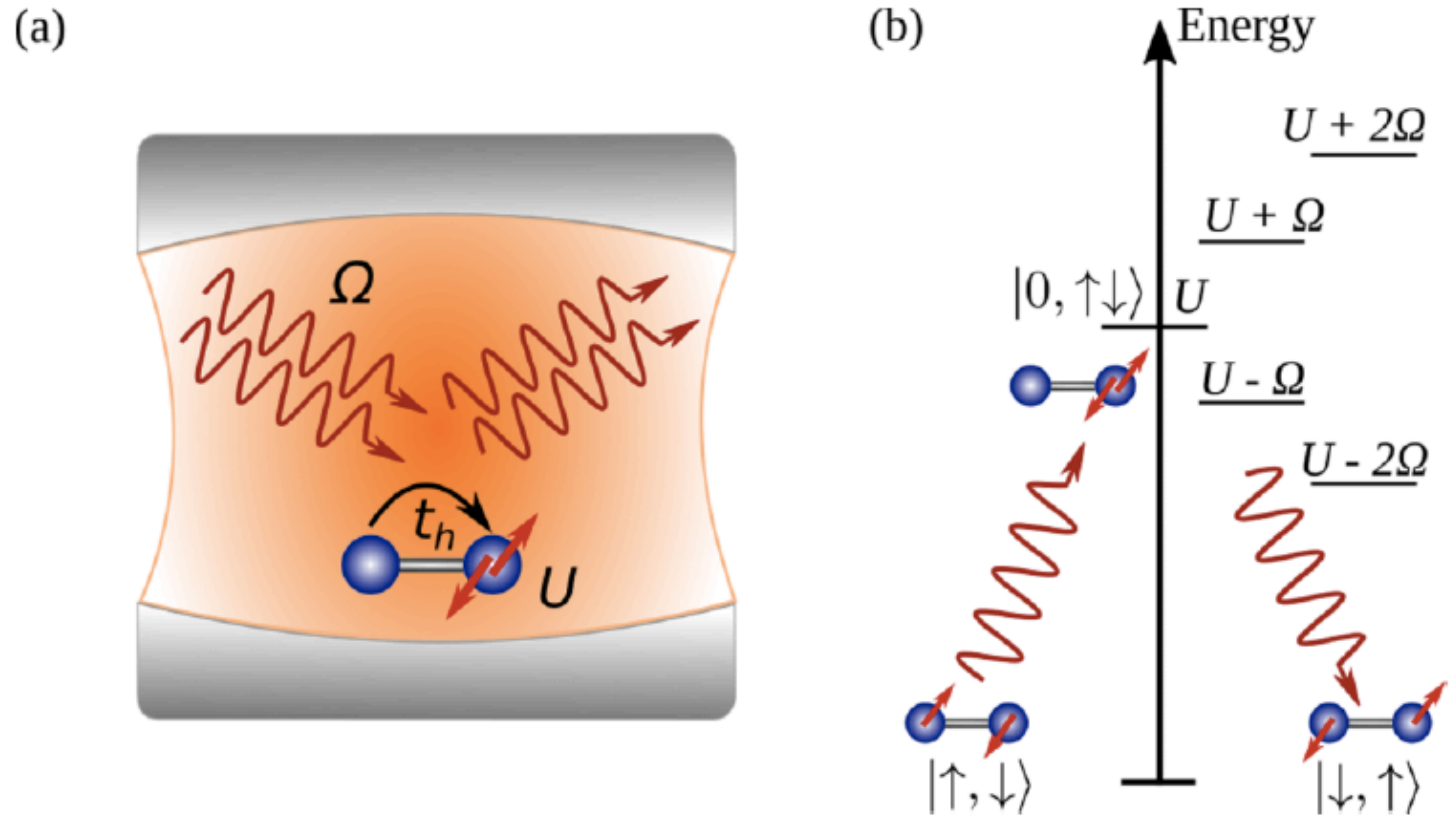
Question: can we control spin exchange with cavities?
Answer: yes, if we replace strong fields by strong light-matter coupling

QED quantum materials: strong light-matter coupling

Polaritonic chemistry

T. Ebbesen, Acc. Chem. Res. 49, 2403 (2016)
J. Feist et al., ACS Photonics 5, 205 (2017)
M. Ruggenthaler et al., Nat. Rev. Chem. 2, 0118 (2018)
R. F. Ribeiro et al., Chem. Sci. 9, 6325 (2018)
J. Flick et al., Nanophotonics 7, 1479 (2018)
A. F. Kockum et al., Nat. Rev. Phys. 1, 19 (2019)

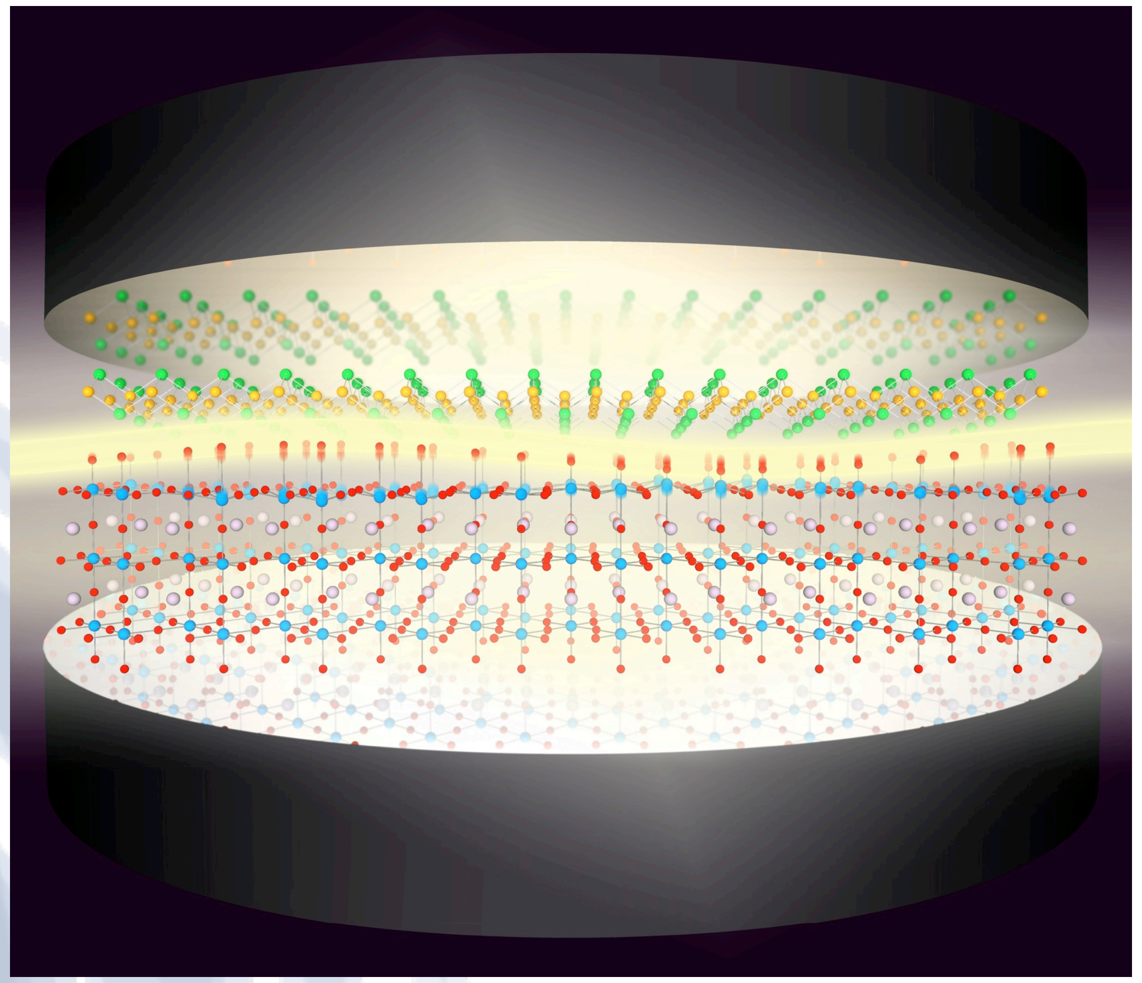
Our work: cavity control of spin exchange
Crossover from quantum to classical Floquet engineering



Quantum materials: towards cavity-controlled electron-boson coupling, superconductivity

Cavity quantum-electrodynamical polaritonically enhanced electron-phonon coupling and its influence on superconductivity

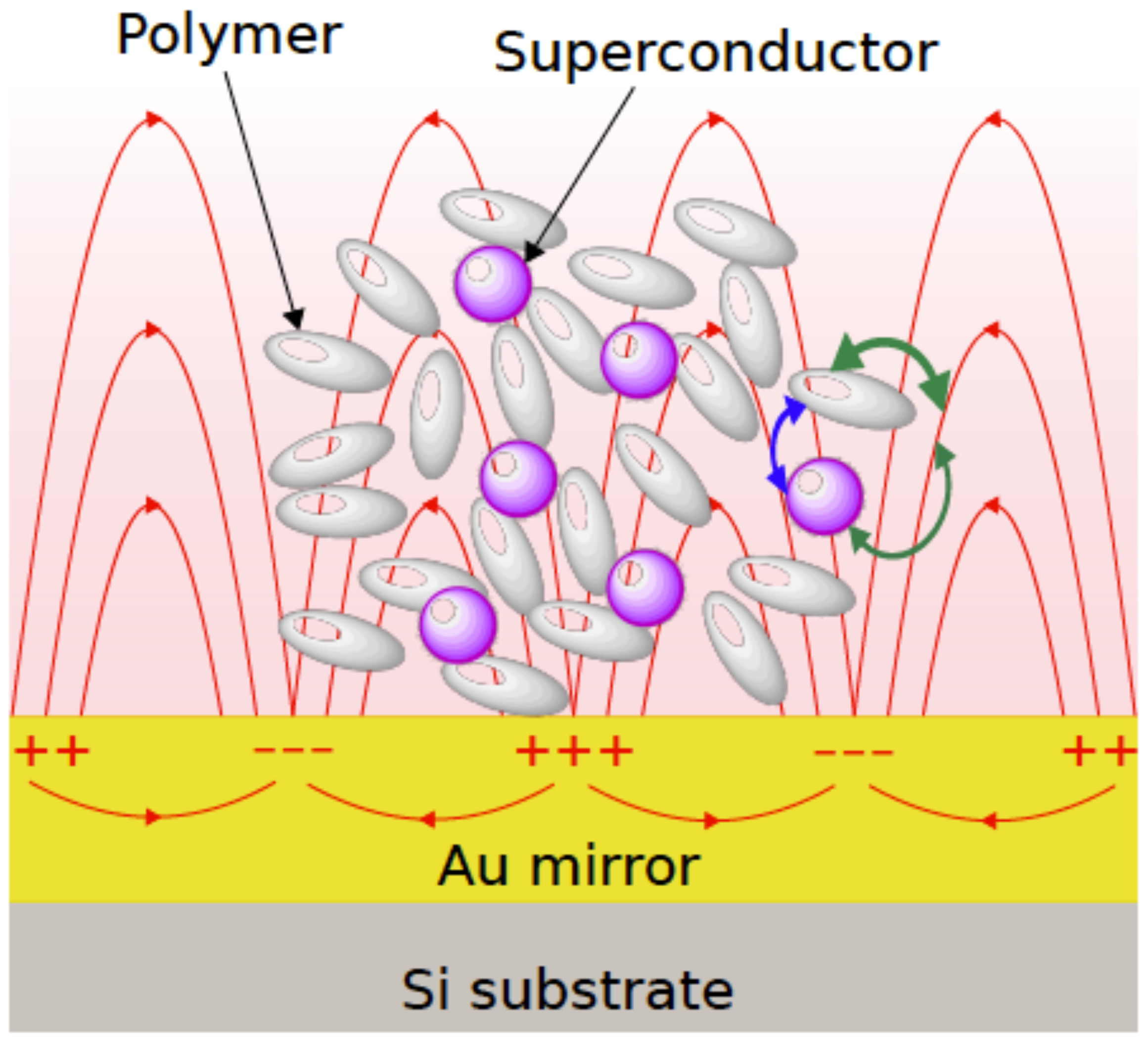
M. A. Sentef, M. Ruggenthaler, A. Rubio, Science Advances 4, eaau6969 (2018)



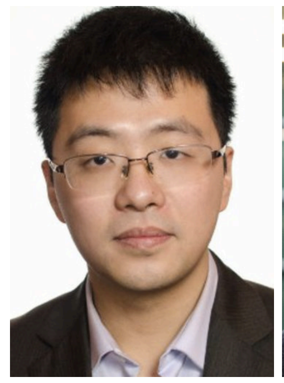
Exploring Superconductivity under Strong Coupling with the Vacuum Electromagnetic Field

A. Thomas[1], E. Devaux[1], K. Nagarajan[1], T. Chervy[1], M. Seidel[1], D. Hagenmüller[1], S. Schütz[1], J. Schachenmayer[1], C. Genet[1], G. Pupillo[1*] & T. W. Ebbesen[1*]

arXiv:1911.01459



Cavity control of Hubbard model
M. A. Sentef, J. Li, F. Künzel, M. Eckstein, PRResearch 2, 033033 (2020)

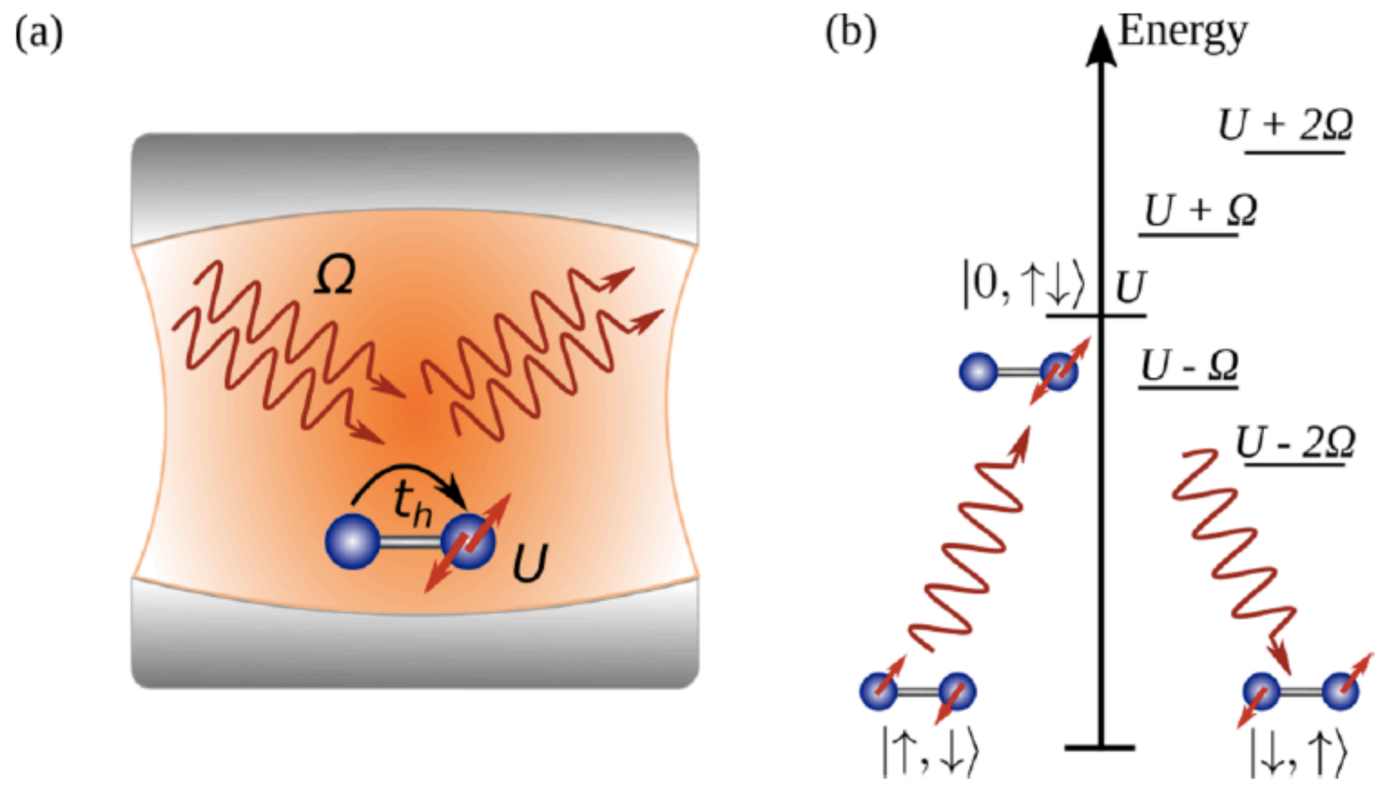



Jiajun Li   Martin Eckstein

Cavity materials: Laussy, Kavokin, Shelykh 2010, Cotlet et al 2016, Kavokin & Lagoudakis 2016, Schlawin, Cavalleri, Jaksch 2019, Hagenmüller et al 2019, Curtis et al 2019, Wang, Ronca, MAS 2019, Kiffner et al 2019, Mazza & Georges 2019, Andolina et al 2019, Gao et al 2020, Chakraborty & Piazza arXiv 2020, Li & Eckstein 2020, Hübener et al 2020, Ashida et al 2020, Latini et al arXiv 2021, …

QED quantum materials: quantum to classical crossover

Hubbard model in cavity



$$\hat{H} = t_h \sum_{j\sigma} (\hat{c}^\dagger_{j,\sigma} \hat{c}_{j+1,\sigma}\, e^{i\hat{A}} + \text{H.c.})$$
$$+\, U \sum_j \hat{n}_{j,\uparrow} \hat{n}_{j,\downarrow} + \Omega \hat{a}^\dagger \hat{a}.$$
$$\hat{A} = g(\hat{a} + \hat{a}^\dagger)$$

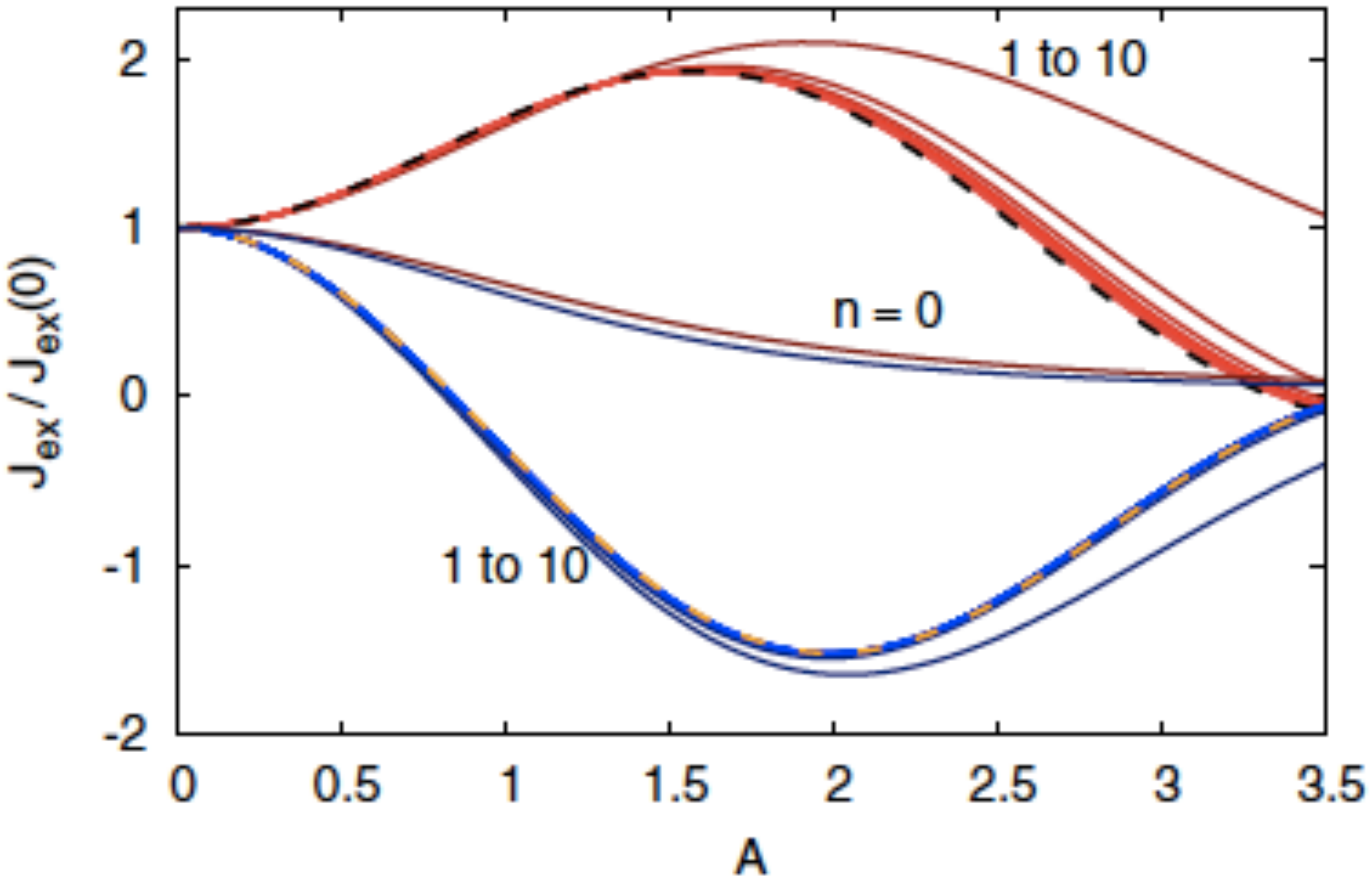
A: effective vector potential
g: light-matter coupling strength

Quantum system -> Floquet system for $n \to \infty, \quad g\sqrt{n}$ fixed.
(large photon number, weak light-matter coupling strength g)

Photon number states are good enough to see Floquet-engineering effects at sufficiently large coupling strength g – coherent states not required!

Question: can we control spin exchange with cavities?
Answer: yes, if we replace strong fields by strong light-matter coupling

Cavity Schrieffer-Wolff transformation
(confirmed by numerics)



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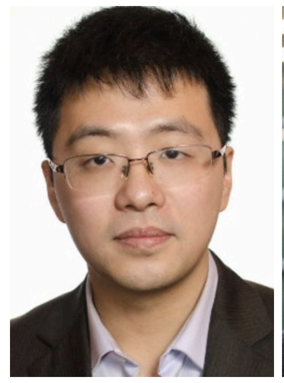
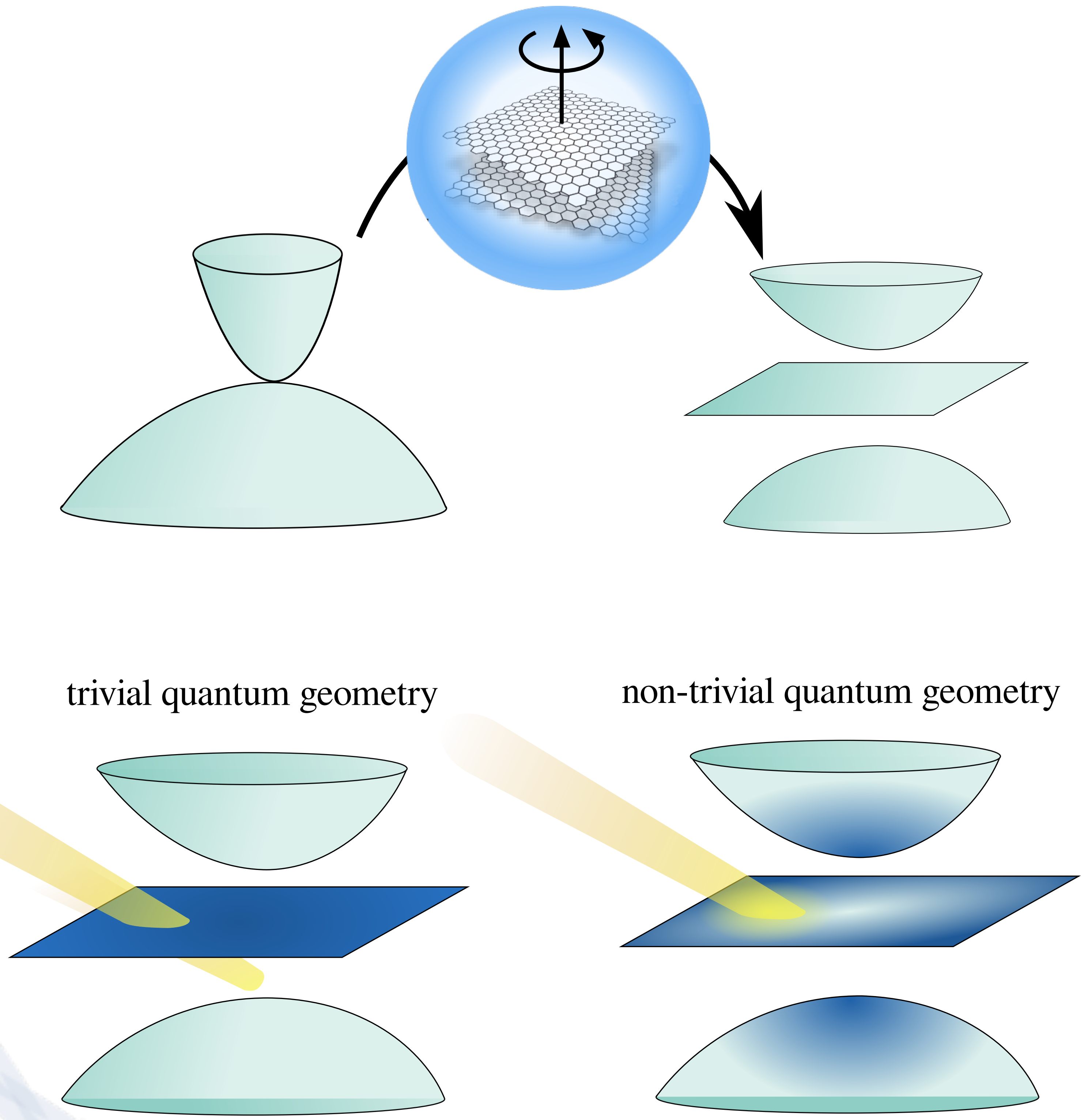
PRResearch 2, 033033 (2020)




Jiajun Li   Martin Eckstein

QED quantum materials: how to reach strong coupling?



	Linear (A_μ)	**Quadratic** $(A_\mu A_\nu)$
Intra-band (n)	$\partial_\mu \varepsilon_n$	$\partial_\mu \partial_\nu \varepsilon_n - \sum_{n \neq n'} (\varepsilon_n - \varepsilon_{n'}) \left(\langle \partial_\mu n \| n' \rangle \langle n' \| \partial_\nu n \rangle + \text{h.c.} \right)$ curvature without band curvature
Inter-band $(n,\, m)$	$(\varepsilon_n - \varepsilon_m) \langle m \| \partial_\mu n \rangle$	$\Big[(\partial_\mu \varepsilon_n - \partial_\mu \varepsilon_m) \langle m \| \partial_\nu n \rangle + \frac{1}{2} \varepsilon_m \langle \partial_\mu \partial_\nu m \| n \rangle + \frac{1}{2} \varepsilon_n \langle m \| \partial_\mu \partial_\nu n \rangle + \sum_{n'} \varepsilon_{n'} \left(\langle \partial_\mu m \| n' \rangle \langle n' \| \partial_\nu n \rangle \right) \Big] + (\mu \leftrightarrow \nu)$

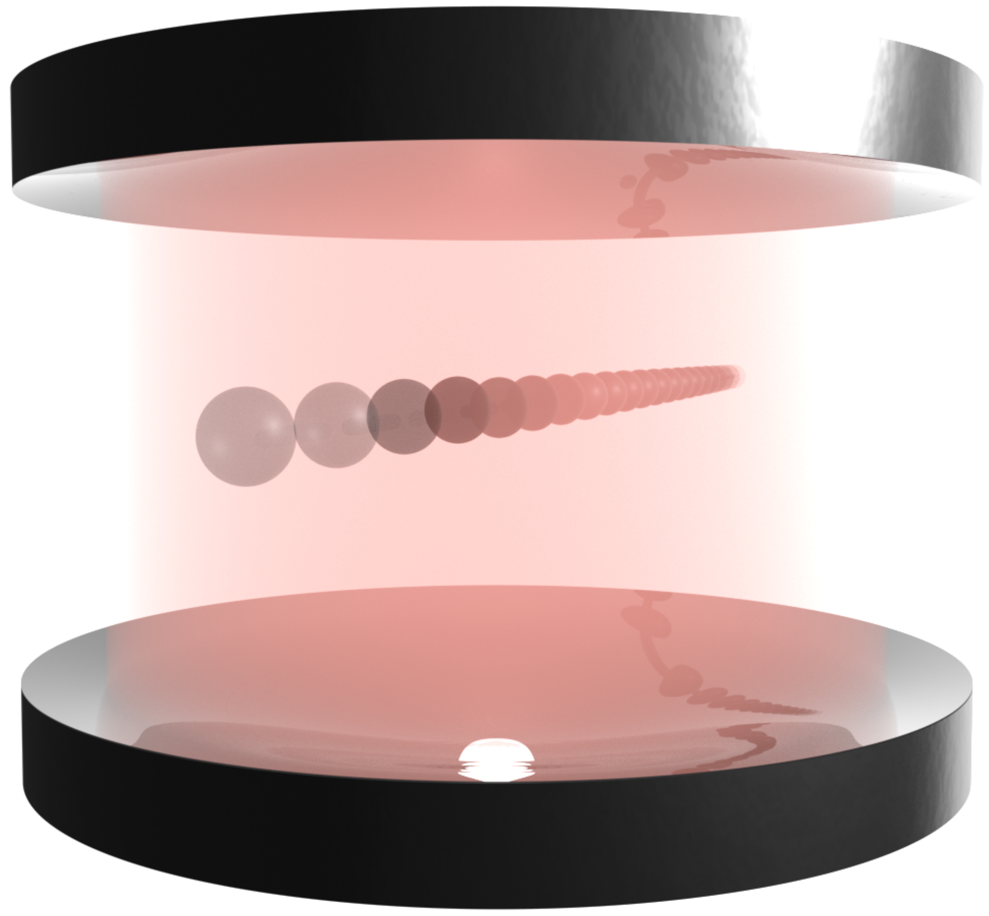
Non-trivial quantum geometry enables light-matter coupling in flat bands

Can we reach strong light-matter coupling by quenching electronic kinetic energy?

Also cf. Iskin PRA 2019;
Ahn, Guo, Nagaosa, Viswanath arXiv 2021

Light-matter coupling and quantum geometry in moiré materials
G. E. Topp, C. J. Eckhardt, D. M. Kennes, M. A. Sentef, P. Törmä,
arXiv:2103.04967

Quantum chain in cavity



q=0 approximation

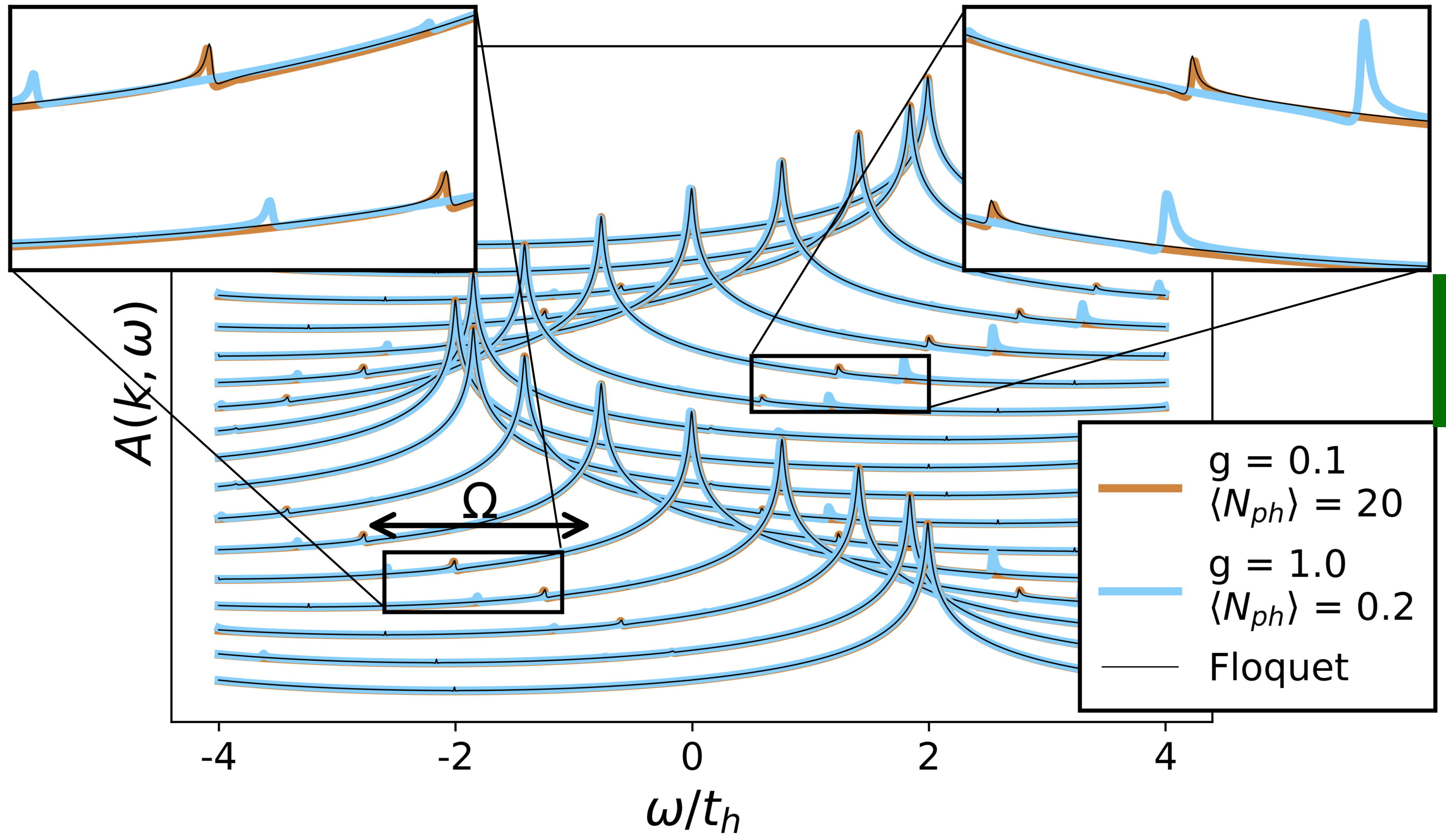
$$H = \Omega\left(a^\dagger a + \frac{1}{2}\right) - \sum_i \left[t_h e^{i\,g(a^\dagger + a)}\, c^\dagger_{i+1} c_i + \text{h.c.}\right]$$

$$= \Omega\left(a^\dagger a + \frac{1}{2}\right) + \cos(g(a^\dagger + a))\hat{T} + \sin(g(a^\dagger + a))\hat{J}$$

$$\hat{T} = \sum_k -2t_h \cos(k) c^\dagger_k c_k$$ kinetic energy

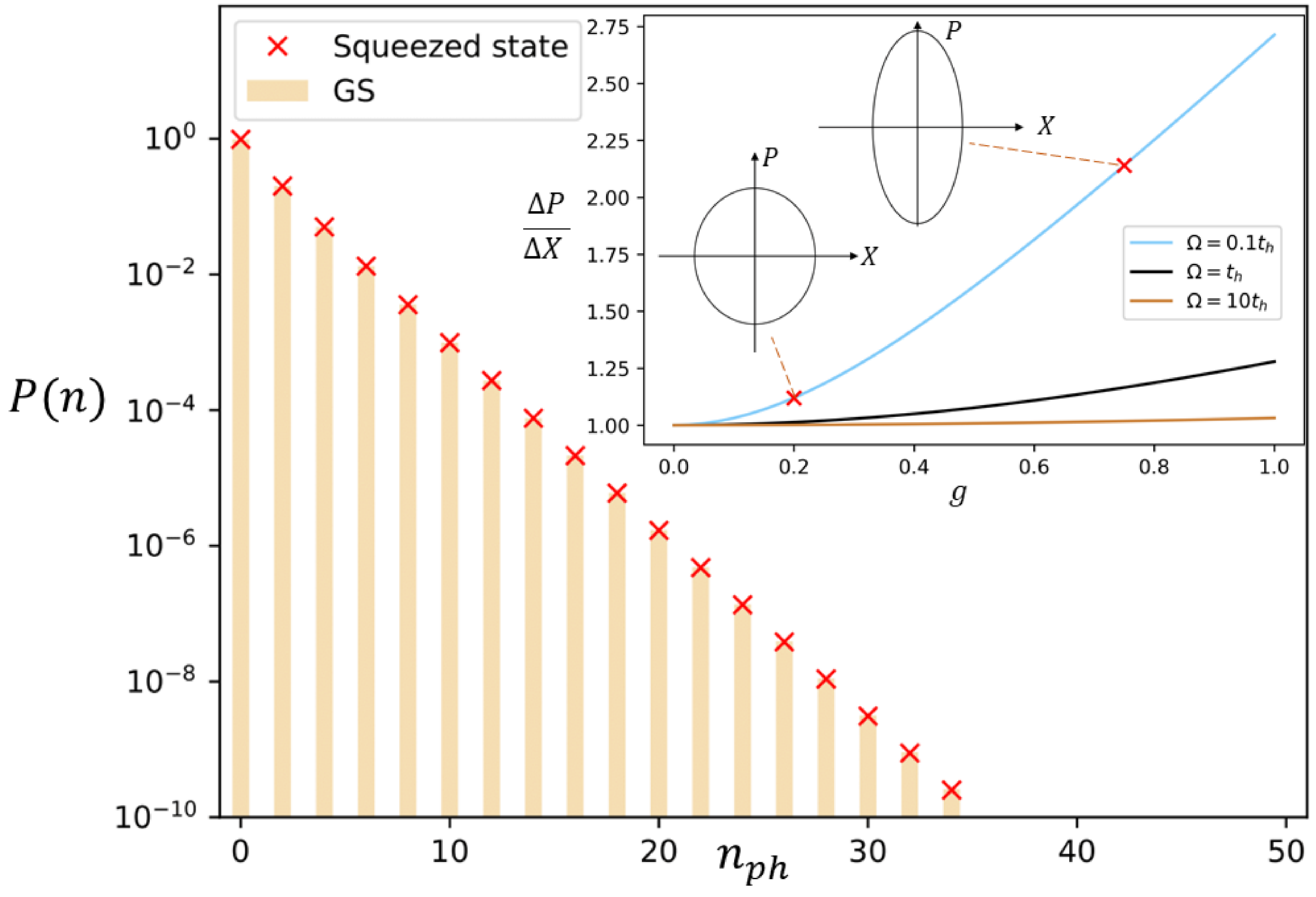
$$\hat{J} = \sum_k 2t_h \sin(k) c^\dagger_k c_k$$ current

Electronic spectral function



quantum to classical crossover of Floquet shakeoff peaks in ARPES signal

Photon wavefunction is a squeezed state

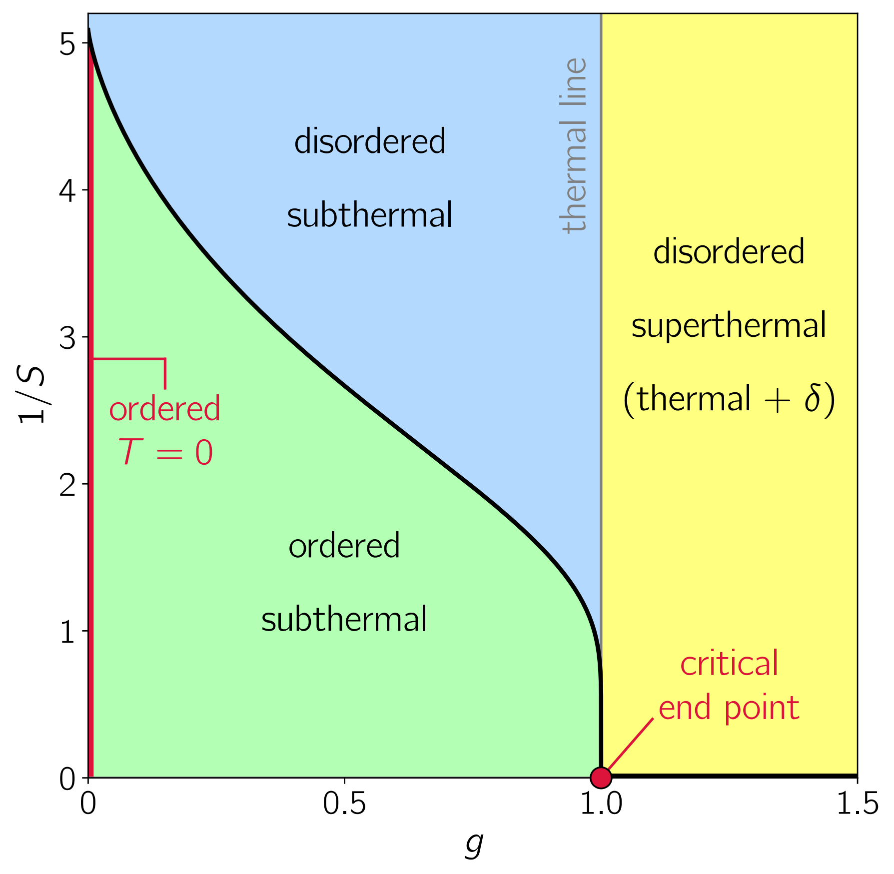


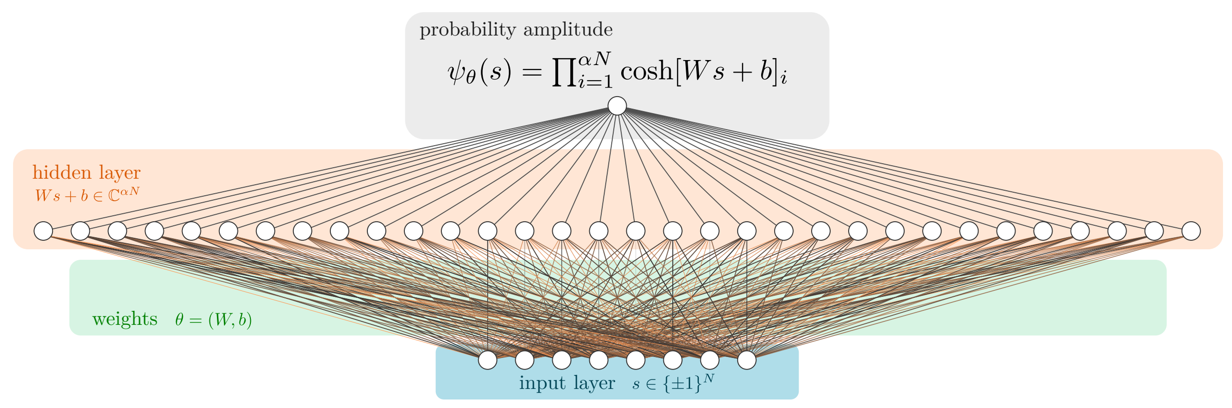
Christian Eckhardt Giacomo Passetti Moustafa Othman Dante Kennes

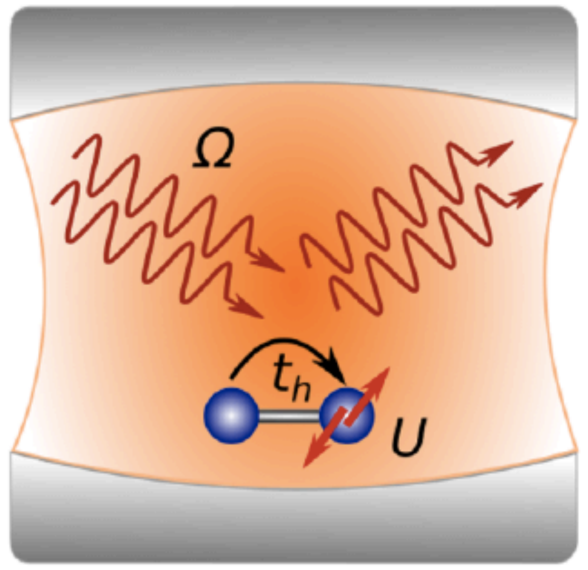
An exactly solvable model for a quantum chain in a cavity

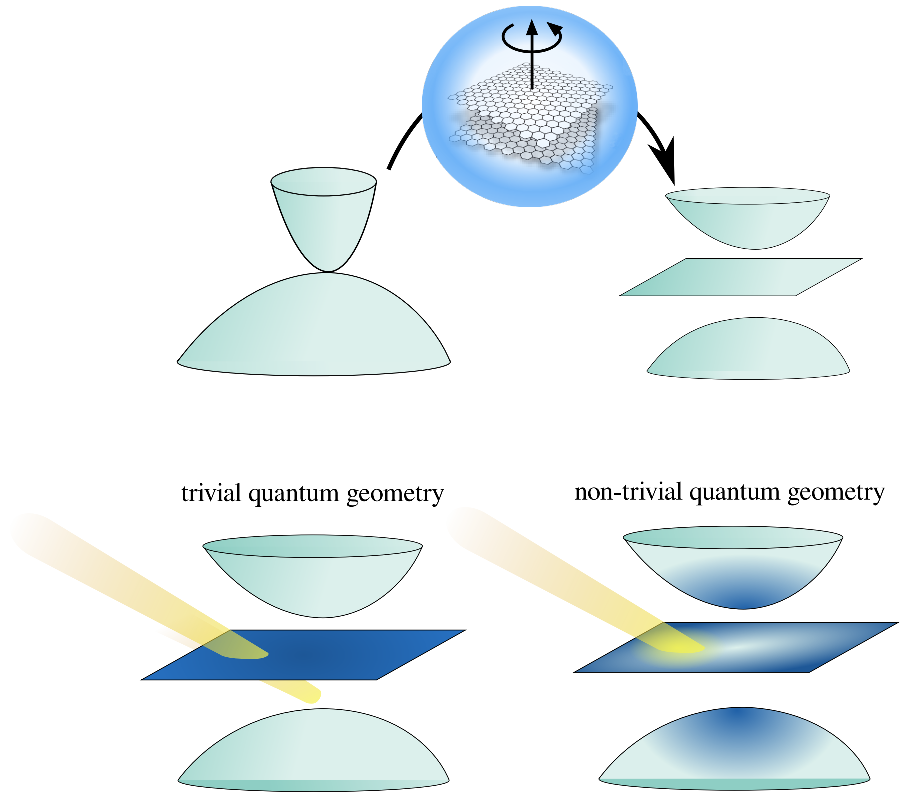
C. J. Eckhardt, G. Passetti, M. Othman, C. Karrasch, F. Cavaliere, M. A. Sentef, D. M. Kennes, **in prep.**

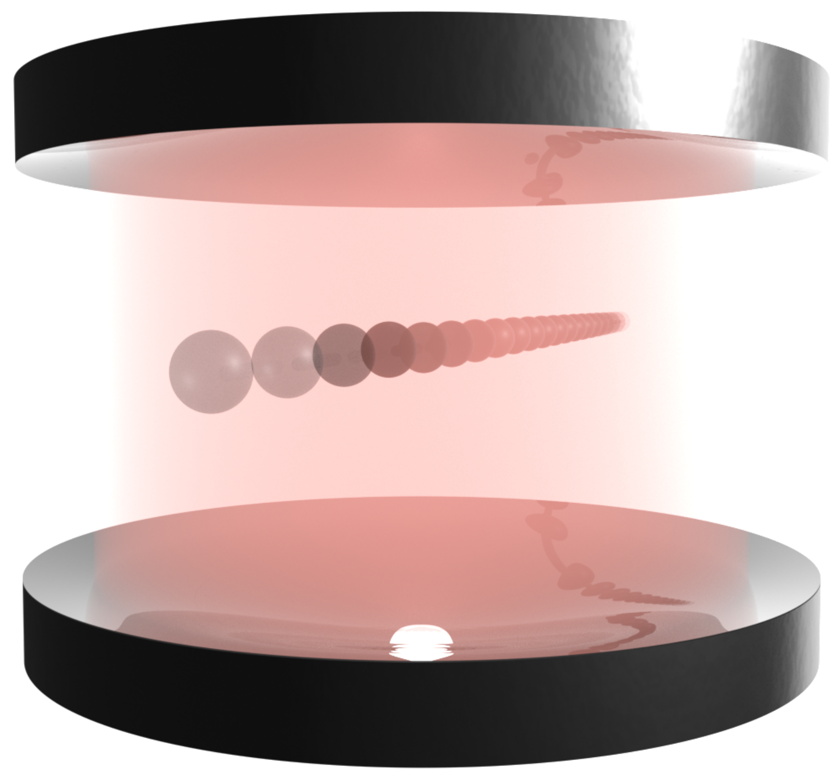
Summary











Dynamical phase transition in a driven-dissipative Heisenberg antiferromagnet
M. H. Kalthoff, D. M. Kennes, A. J. Millis, M. A. Sentef, **in prep.**

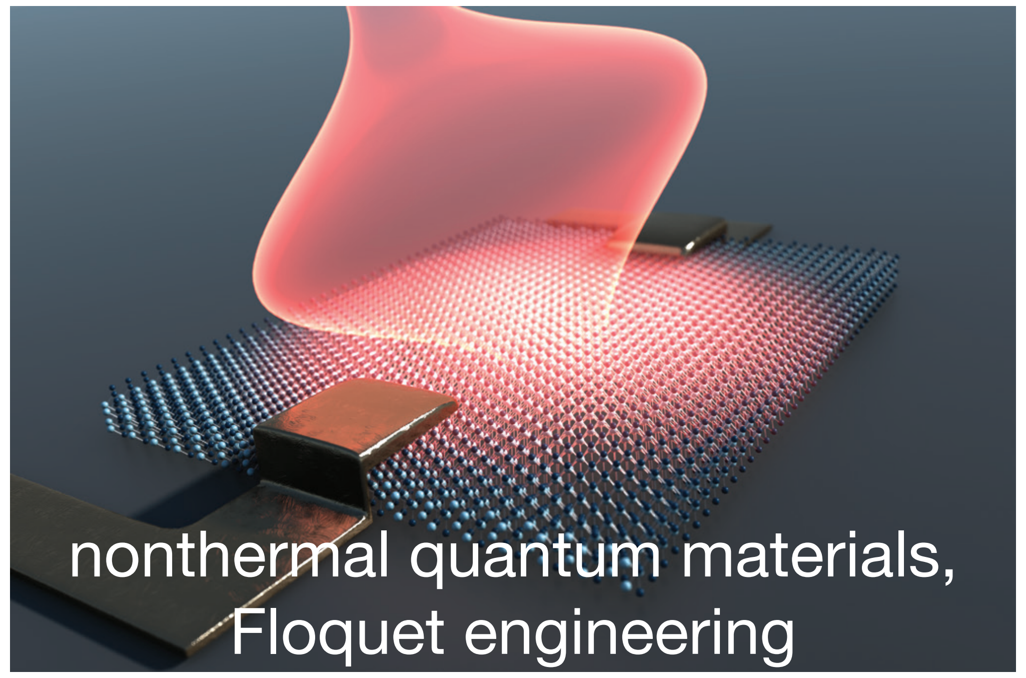
Role of generalization error in the dynamics of neural quantum states
D. Hofmann, G. Fabiani, J. H. Mentink, G. Carleo, MAS, **in prep.**

Cavity control of Hubbard model
MAS, J. Li, F. Künzel, M. Eckstein,
PRResearch 2, 033033 (2020)

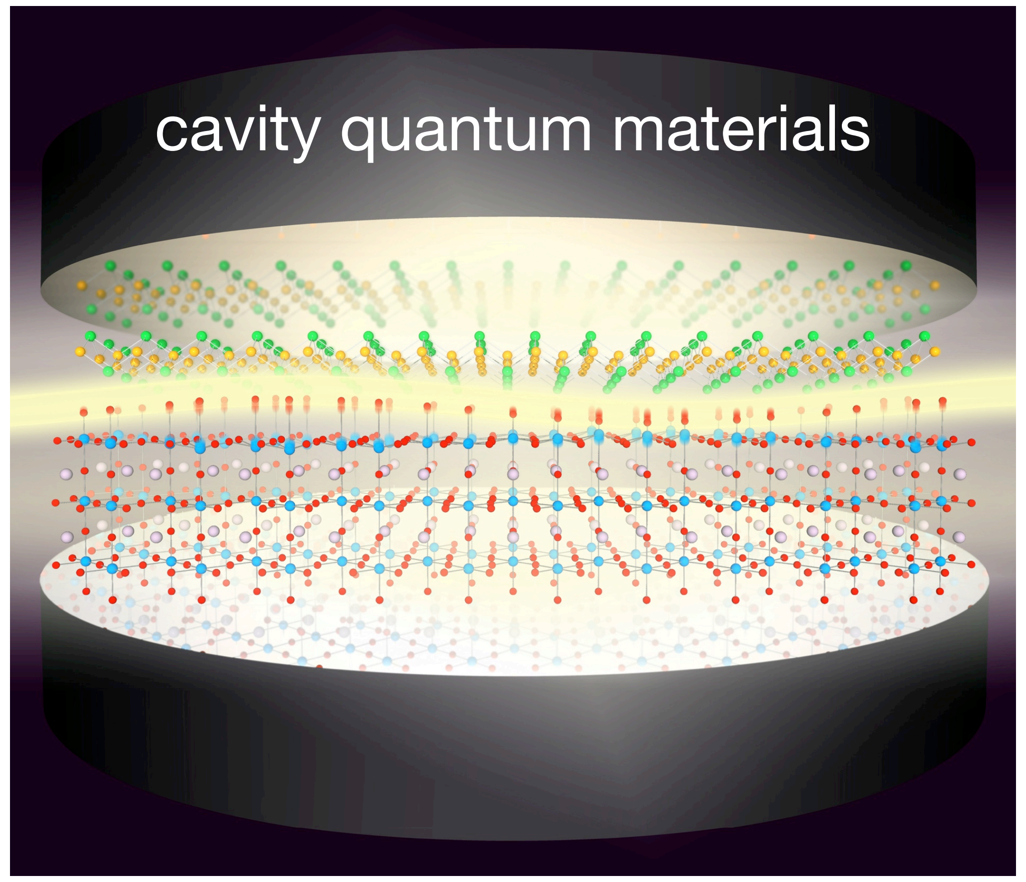
Light-matter coupling and quantum geometry in moiré materials,
G. E. Topp, C. J. Eckhardt, D. M. Kennes, MAS, P. Törmä,
arXiv:2103.04967

An exactly solvable model for a quantum chain in a cavity
C. J. Eckhardt, G. Passetti, M. Othman, C. Karrasch, F. Cavaliere, MAS, D. M. Kennes, **in prep.**

strong laser driving



Colloquium: Nonthermal pathways to ultrafast control in quantum materials,
A. de la Torre, D. M. Kennes, M. Claassen, S. Gerber, J. McIver, MAS, **arXiv:2103.14888**



laser driving strength / photon number

classical to quantum crossover

many-body groundstates

light-matter strong coupling

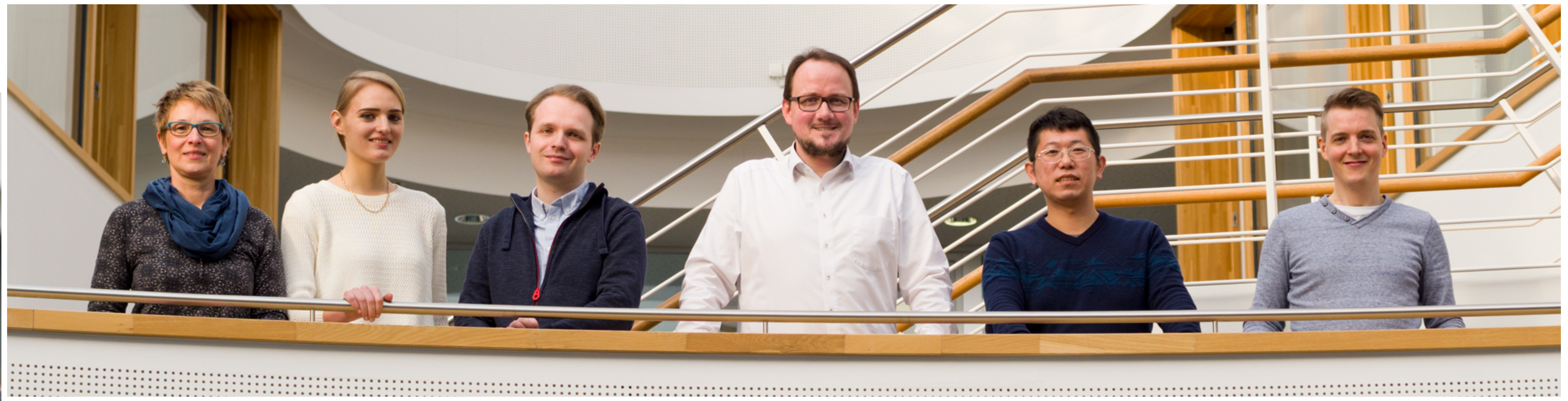
vacuum: g = α

light-matter coupling strength g

Funded through DFG Emmy Noether programme (SE 2558/2)

Team

Sentef Lab (2020)



MPSD Theory Department (2019)

Looking for PhD students

next IMPRS-UFAST call expected to open in September 2021

get in touch anytime if interested
https://lab.sentef.org
michael.sentef@mpsd.mpg.de

This could be your PhD topic:

- moiré cavity dynamics with neural quantum states
- cavity Kitaev materials
- dynamical correlations in 2D materials
- quantum-geometric light-matter coupling in moiré TMDs
- … [insert your research idea here]