ISOQUANT

Isolated quantum systems in extreme conditions:

From heavy-ion collisions to ultracold quantum gases

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Heidelberg University:

Institute for Theoretical Physics

Berges, Enss, Floerchinger,
Pawlowski, Rothkopf,
Salmhofer, Wetterich

Kirchhoff-Institute for Physics/
Physics Institute

Braun-Munzinger, Gasenzer,
Jendrzejewski, Jochim, Masciocchi,
Oberthaler, Reygers, Stachel,
Weidemüller, Whitlock

Blaum, Crespo, Evers,
Keitel, Pálffy-Buß

Max-Planck-Institute for
Nuclear Physics, Heidelberg

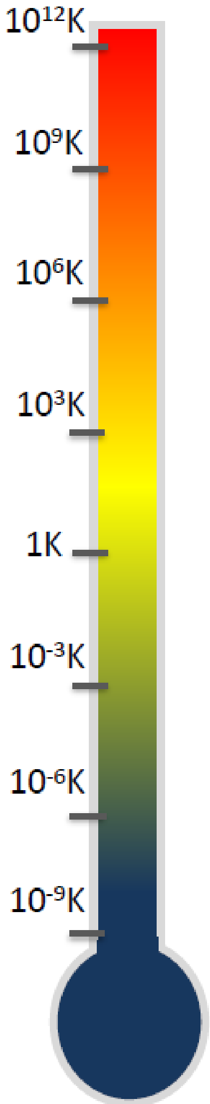
Schenke, Venugopalan

Nuclear Theory Group,
Brookhaven National Lab

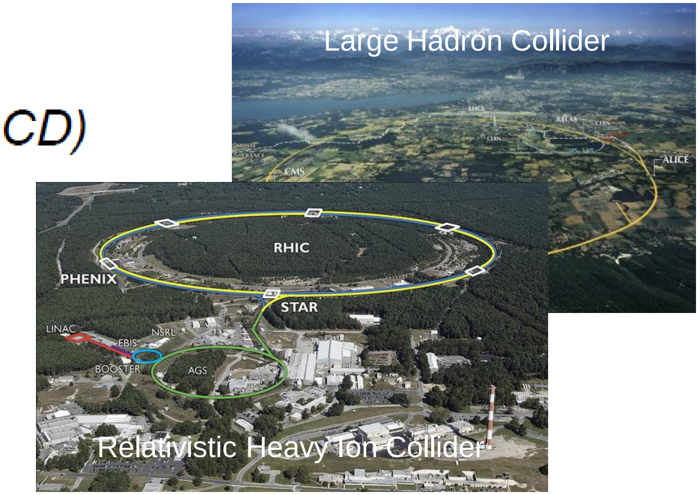
Schmiedmayer

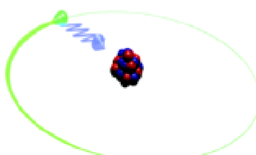
TU Wien/Vienna Center for
Quantum Science and Technology

Isolated Quantum Systems

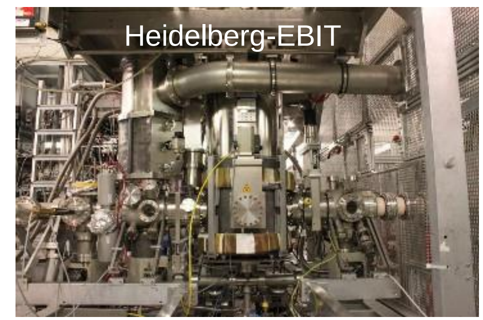


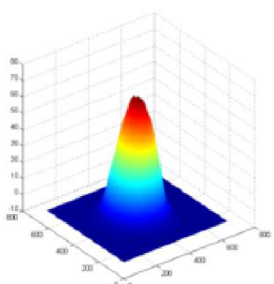
Heavy-ion collisions (QCD)



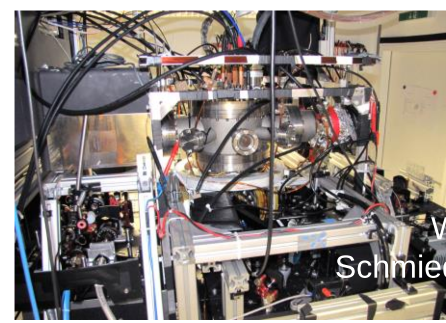


Highly charged ions (QED)





Ultracold quantum gases (tunable model systems)



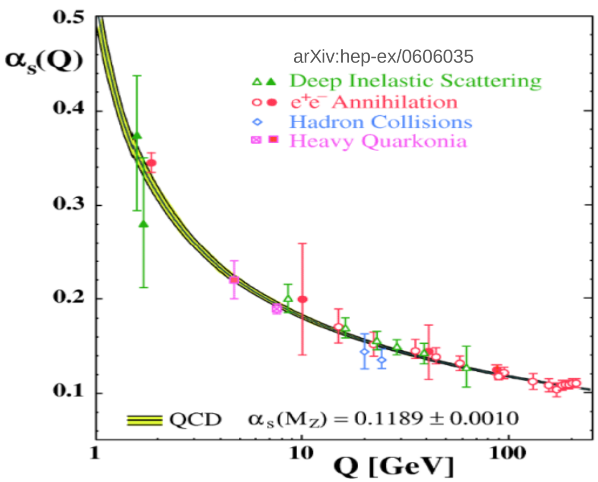
Jochim, Oberthaler, Weidemüller, Schmiedmayer labs

Extreme Conditions

ISOQUANT SFB1225

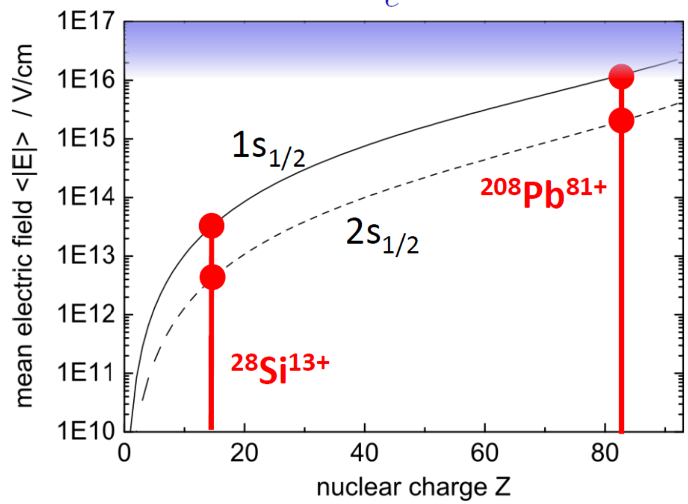
Heavy-ion collisions (QCD)

$$\frac{\alpha_s \cdot \langle A^2 \rangle}{Q^2} \sim 1$$



Highly charged ions (QED)

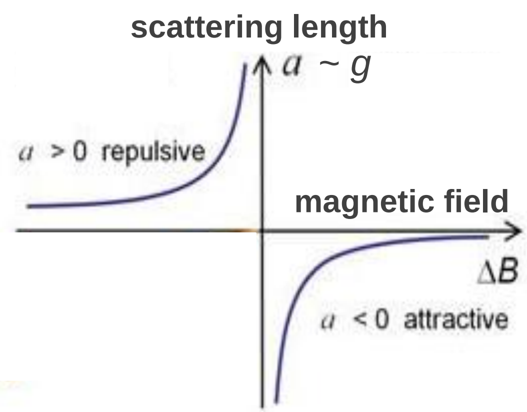
$$\frac{\alpha \cdot \langle E^2 \rangle}{m_e^4} \sim 1$$



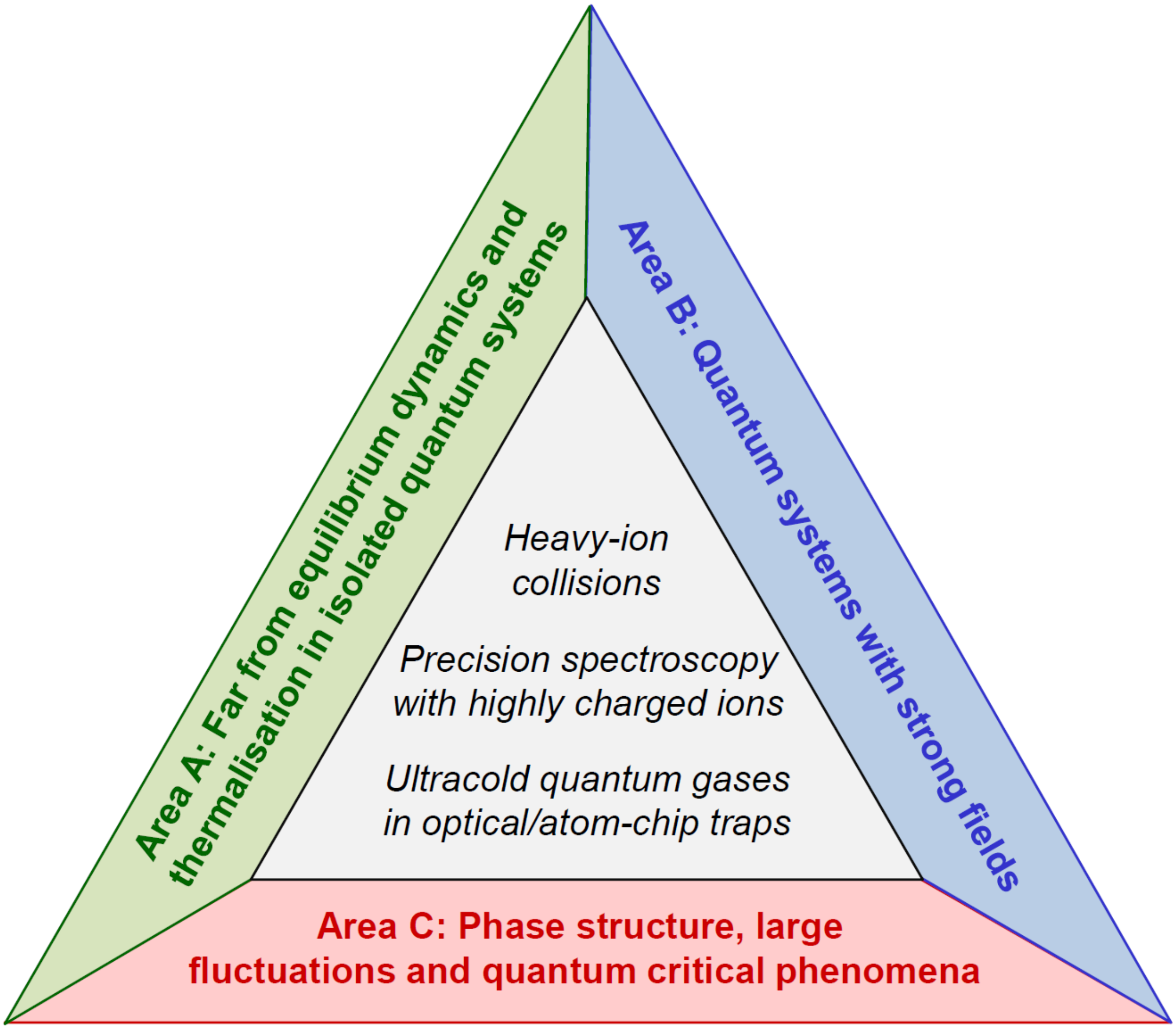
$$\hbar = c = k_B = 1$$

Ultracold quantum gases
(tunable model systems)

$$\frac{g \cdot \langle |\psi|^2 \rangle}{Q^2/2m} \sim 1$$



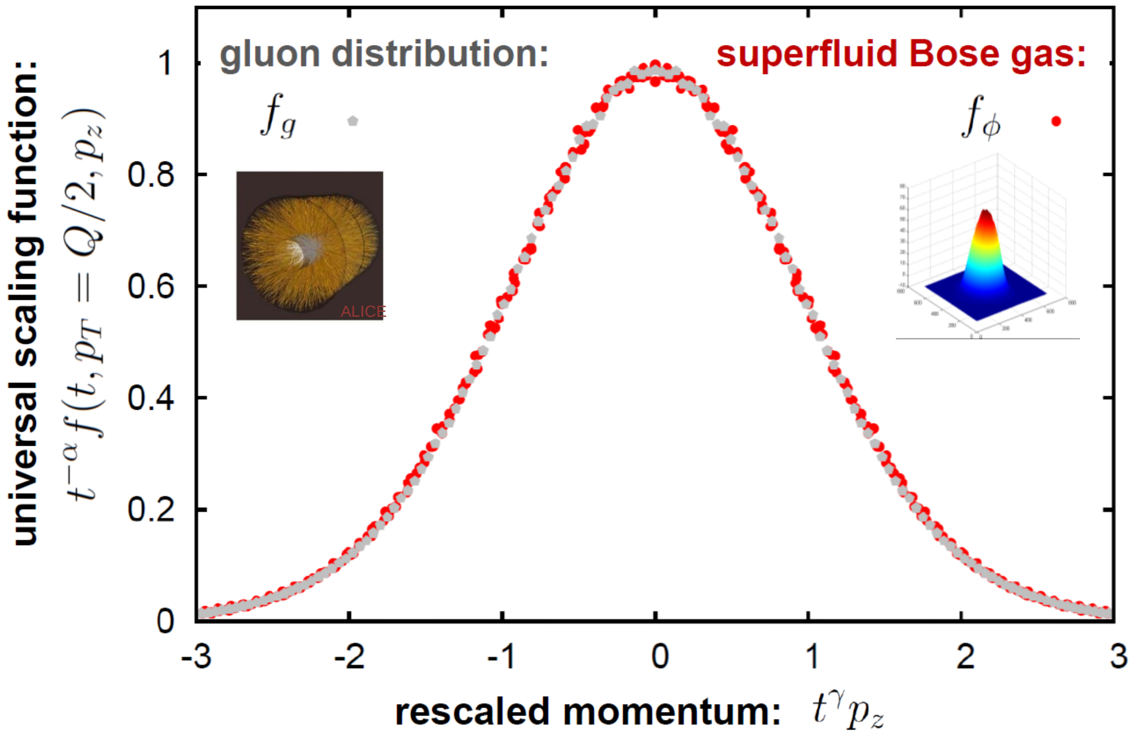
ISOQUANT Research Areas

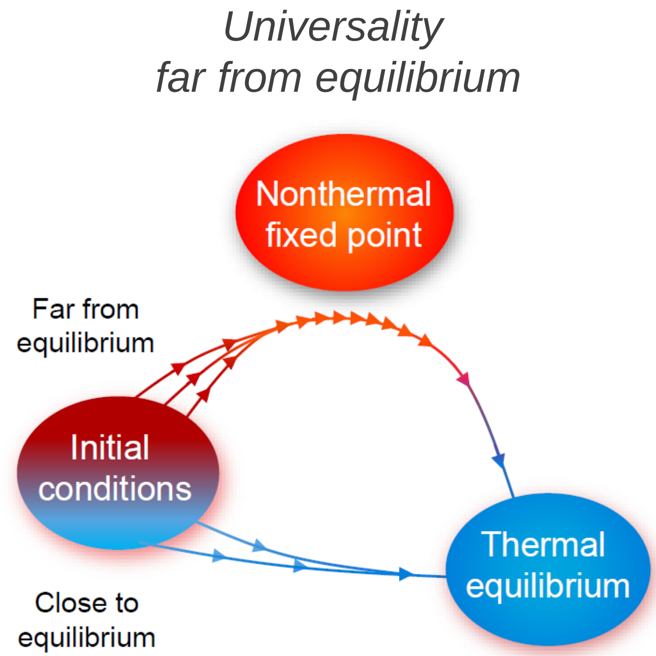


The Quest for Universal Regimes

Example A: Thermalisation process in isolated quantum many-body systems

- Extreme field/fluctuation initial conditions far from equilibrium





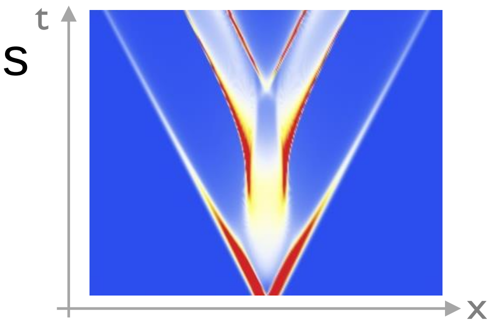
Berges, Boguslavski, Schlichting, Venugopalan, PRL 114 (2015) 061601

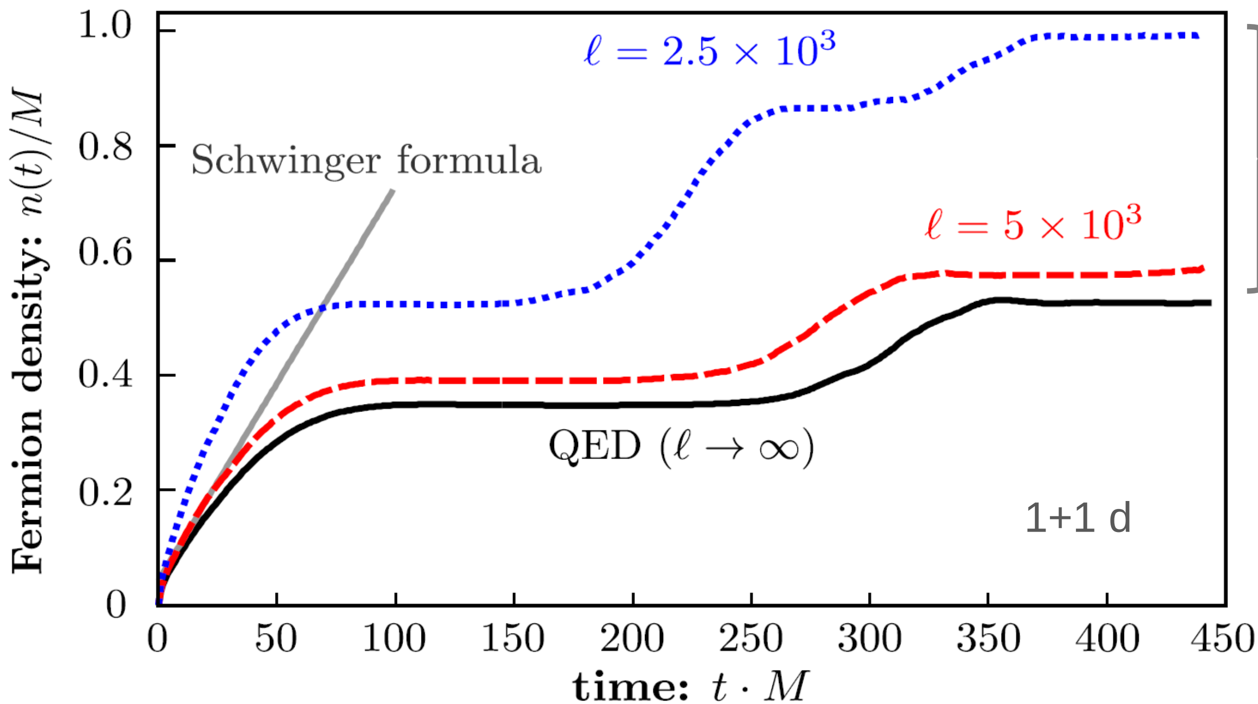
The Quest for Universal Regimes

Example B: Cold-gas model system for strong-field *QED*

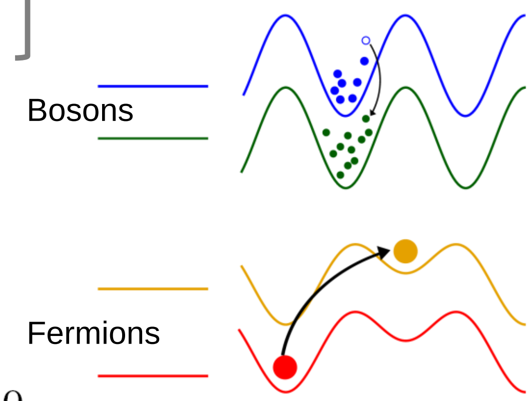
- Schwinger e^+e^- pair production in extreme electric fields

$$E > E_c = \frac{m_e^2}{e}$$





Corresponding process in model system of ℓ atoms



Hebenstreit et al., PRL 111 (2013) 201601; Kasper et al., PLB 760 (2016) 742; arXiv:1608.03480 (Berges/Oberthaler groups)

The Quest for Universal Regimes

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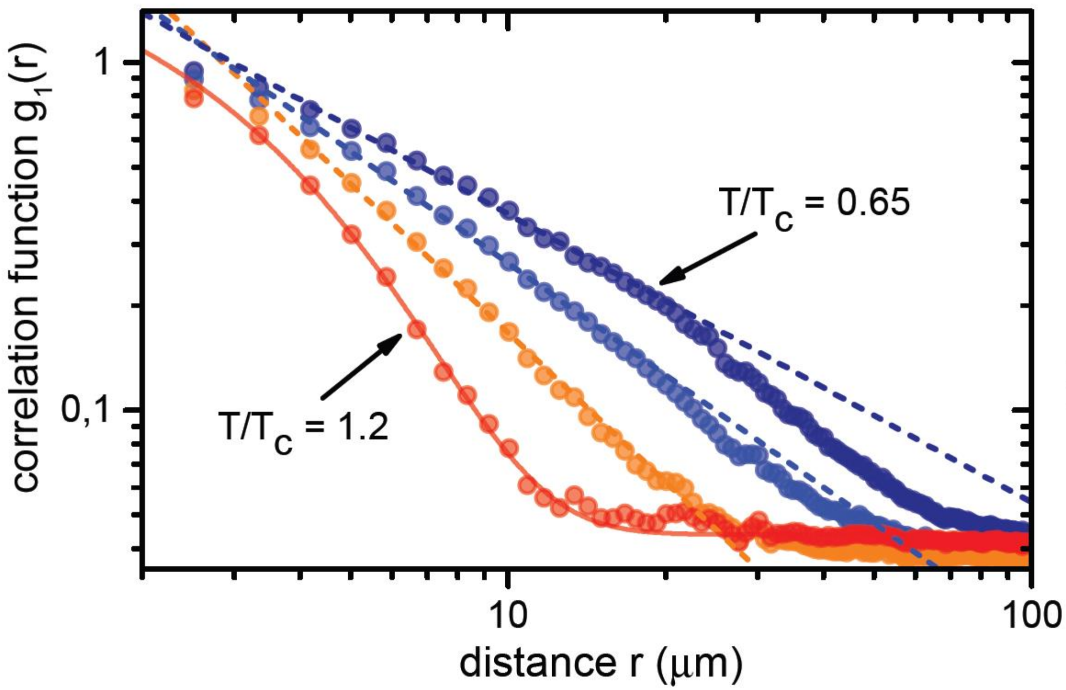
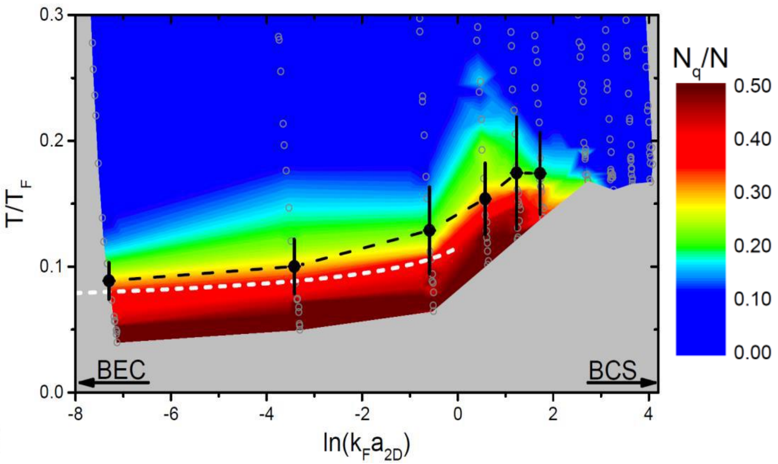
Example C: Phase structure of strongly interacting fermions

- Fermi gas in two-dimensional BEC-BCS crossover regime



Universal behaviour in whole low-temperature superfluid phase



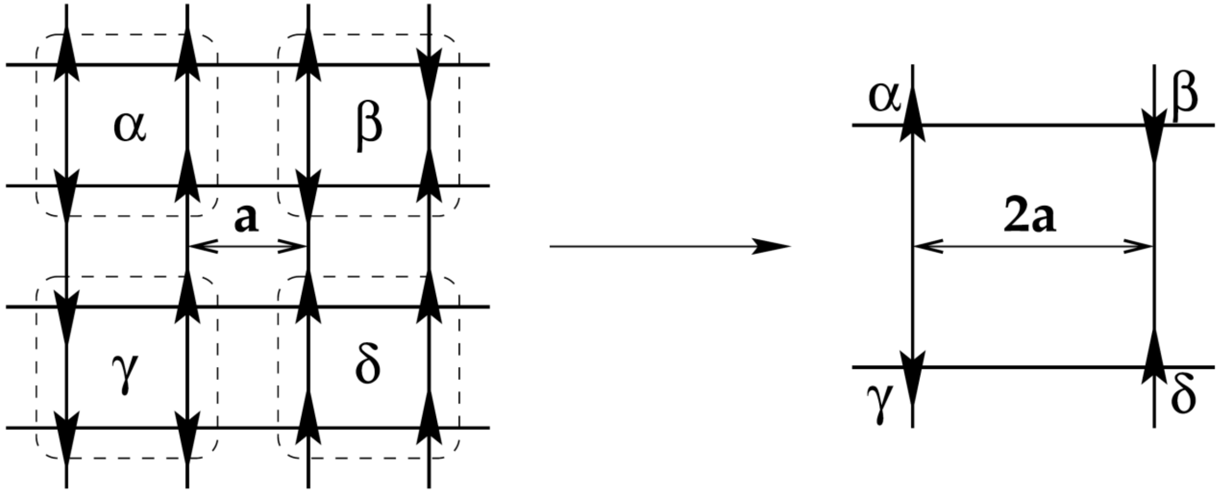
Boettcher et al., PRL 116 (2016) 045303 (Jochim/Pawlowski/Wetterich groups)

Universality: From short- to long-distance scales

Renormalization group: ‘microscope‘ with varying resolution of length scale

~ 1/*k*

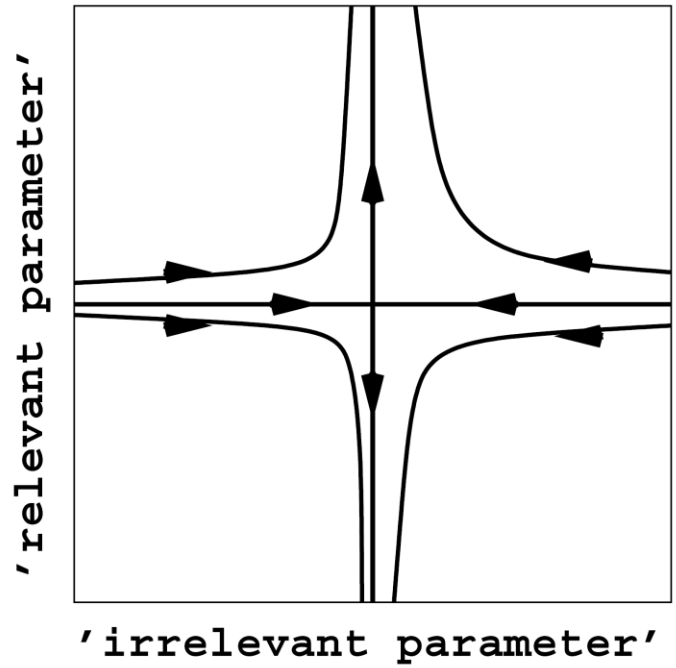
Example: ‘coarse graining‘ for spin system



$k \sim 1/\mathrm{a}$ $k \sim 1/(2\mathrm{a})$

Universality: From short- to long-distance scales

Renormalization group flow: scale-dependence described in terms of 'running' coupling parameters



Irrelevant parameters: loss of details about microscopic description

Fixed point: physics looks the same for different resolutions (scaling)

Role of extreme conditions

Dimensionless combination of

(running) coupling strength

*field² expectation value (vacuum/ thermal equilibrium/**nonequilibrium**)*

$$\frac{\lambda \cdot \langle \Phi^2 \rangle}{Q^2} \sim 1$$

characteristic energy/momentum²

→ Extreme conditions enhance the loss of details about microscopic properties (coupling strengths, initial conditions, …)

Extreme conditions from large fields/occupancies

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- In a quantum theory the **field amplitude** corresponds to the expectation value of a (here relativistic, real) Heisenberg field operator $\Phi(t,\mathbf{x})$:

$$\phi(t) = \langle \Phi(t,\mathbf{x}) \rangle \equiv \mathrm{Tr}\left\{ \varrho_0 \, \Phi(t,\mathbf{x}) \right\}$$

- **Occupancies** derive from correlation functions, e.g. spatially homogeneous:

`quantum-half´ — volume: $(2\pi)^3\delta(\mathbf{0}) \to V$

occupation number distribution

$$\frac{\overbrace{f(t,\mathbf{p})}^{\text{occupation number distribution}} + 1/2}{\underbrace{\omega(t,\mathbf{p})}_{\text{dispersion}}} + (2\pi)^3\delta(\mathbf{p})\underbrace{\phi_0^2(t)}_{\text{condensate}^2}$$

dispersion — condensate²

$$\equiv \frac{1}{2}\int \mathrm{d}^3x \, e^{-i\mathbf{p}\mathbf{x}} \left\langle \Phi(t,\mathbf{x})\Phi(t,0) + \Phi(t,0)\Phi(t,\mathbf{x}) \right\rangle$$

- **Extreme conditions:** ($\lambda \ll 1$)

$\boxed{1.\ \ \phi \sim Q/\sqrt{\lambda}}$ or/and $\boxed{2.\ \ f(Q) \sim 1/\lambda}$

Insensitivity to initial condition details

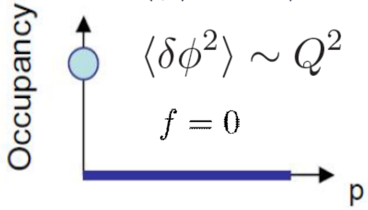
Example: Relativistic $\lambda\phi^4$ ('Inflaton/Higgs') theory ($\lambda \ll 1$) in d=3, $\phi = \phi_0 + \delta\phi$

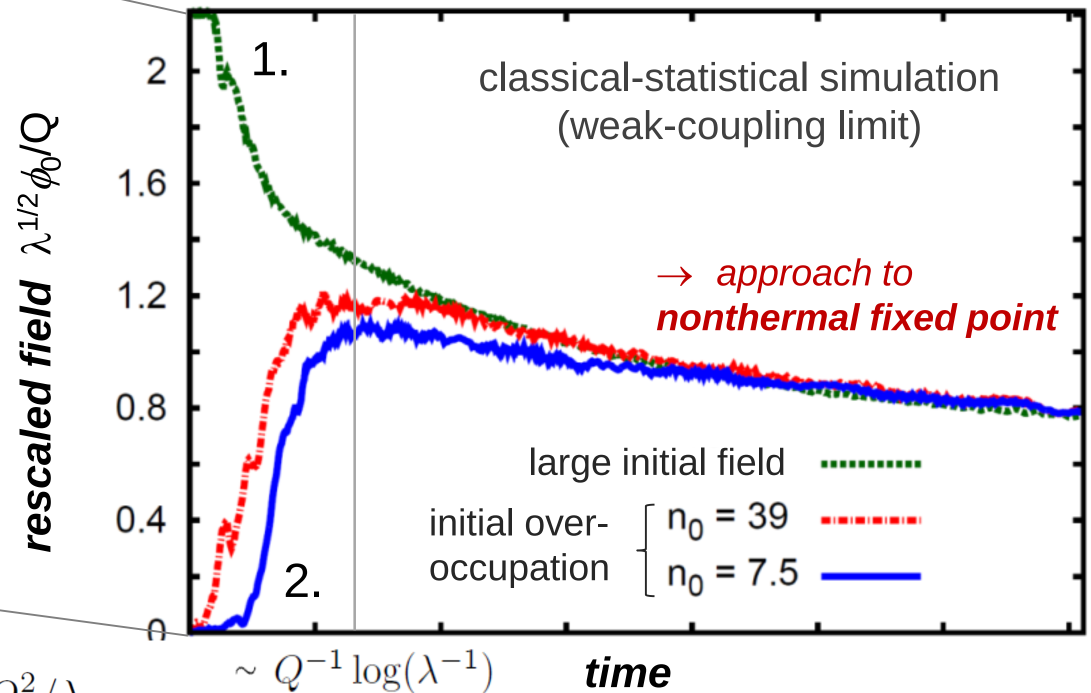
1. Large initial field:

$\langle\phi\rangle \sim Q/\sqrt{\lambda}$

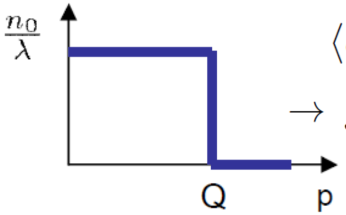
$\langle\delta\phi^2\rangle \sim Q^2$

$f = 0$





2. High occupancy:



$\langle\delta\phi^2\rangle \sim Q^2/\lambda$

$\rightarrow f(Q) \sim 1/\lambda \gg 1$

Berges, Boguslavski, Schlichting, Venugopalan, JHEP 1405 (2014) 054

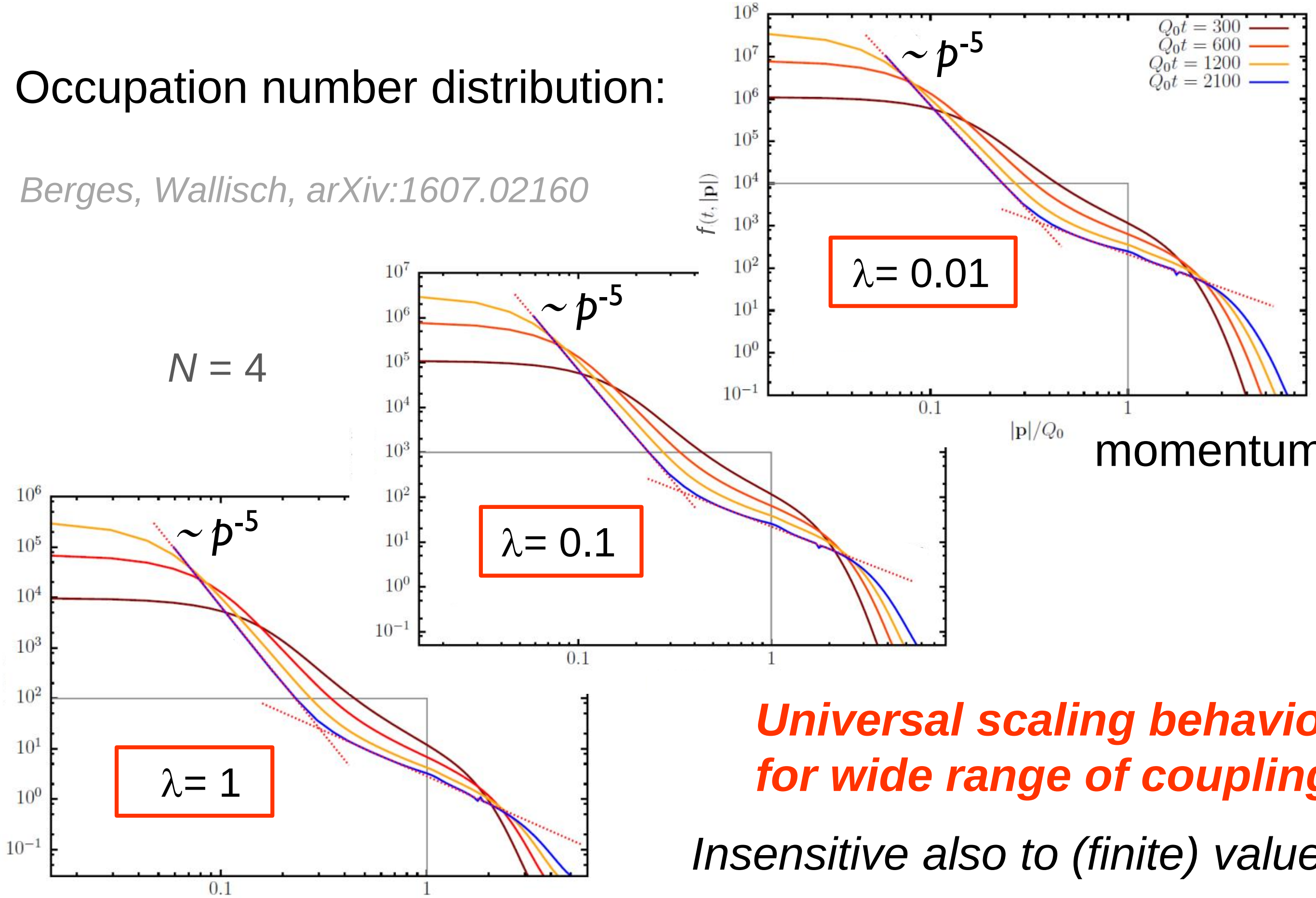
Insensitivity to coupling strength

E.g. relativistic *N*-component $\lambda\phi^4$ *quantum* theory (1/*N* to NLO 2PI):

Occupation number distribution:

Berges, Wallisch, arXiv:1607.02160

N = 4



momentum

Universal scaling behavior for wide range of couplings!

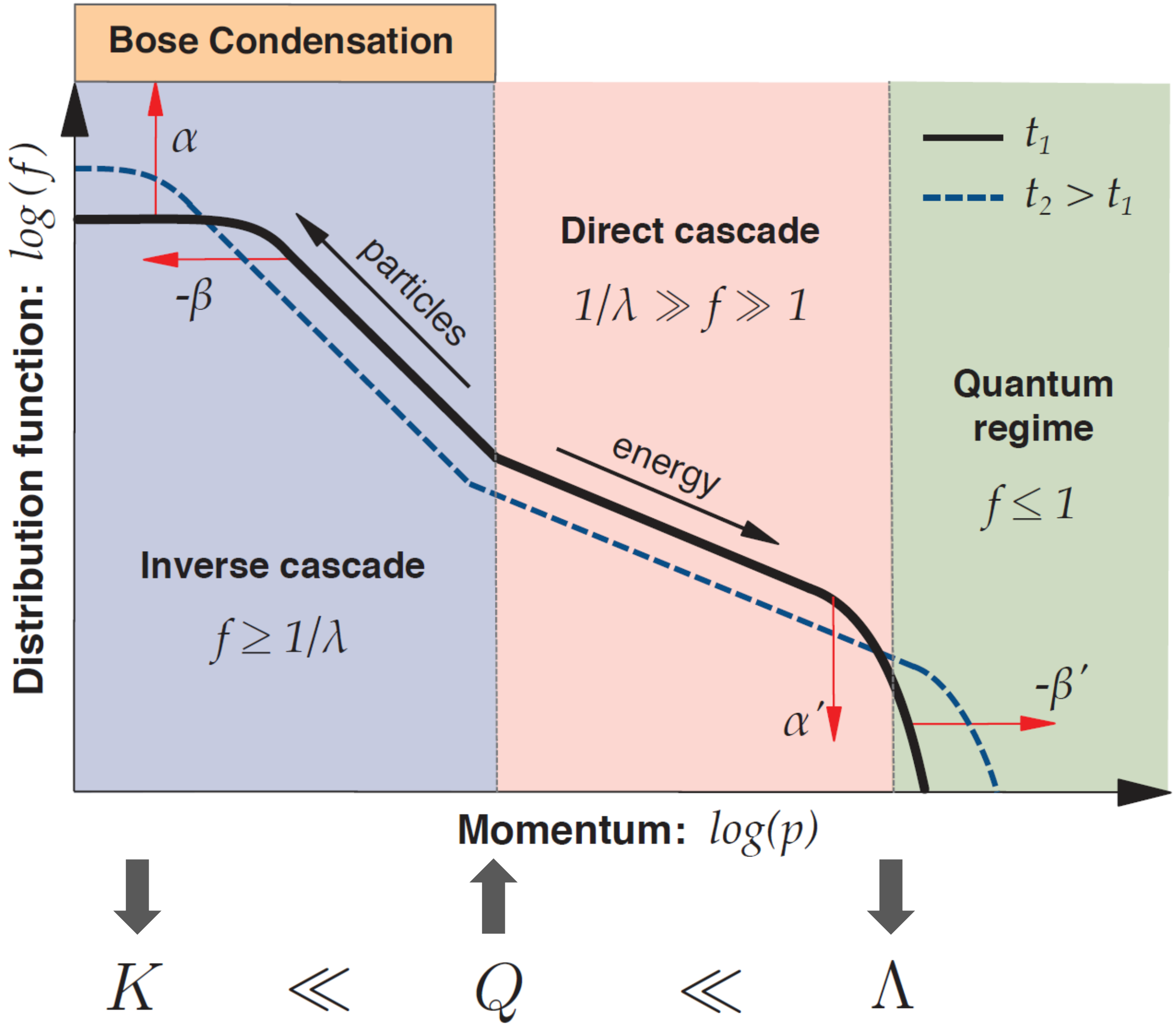
Insensitive also to (finite) value of N!

→ nonthermal fixed point

Berges, Rothkopf, Schmidt, Hoffmeister, Sexty; Gasenzer, Scheppach, Novak, Schole, Erne, Schmidt, Karl; Ewerz, Samberg; Moore …

Nonthermal fixed point

Schematic behavior near nonthermal fixed point: dual cascade



Nonthermal fixed point

Particle versus energy transport:

$$K \ll Q \ll \Lambda$$

number conservation:

$$\dot{n}_Q = \dot{n}_K + \dot{n}_\Lambda$$

energy conservation:

$$Q\dot{n}_Q = K\dot{n}_K + \Lambda\dot{n}_\Lambda$$

$$\dot{n}_K = \frac{\Lambda - Q}{\Lambda - K}\dot{n}_Q \simeq \dot{n}_Q$$

$$\dot{n}_\Lambda = \frac{Q - K}{\Lambda - K}\dot{n}_Q \simeq \frac{Q}{\Lambda}\dot{n}_Q$$

$$\Rightarrow \quad \Lambda\dot{n}_\Lambda \simeq Q\dot{n}_Q$$

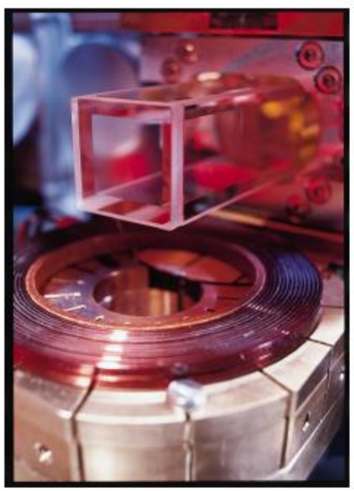
Particles are transported towards lower scales, energy towards higher scales

Ultracold Bose Gases in Extreme Conditions

… atoms @ nanokelvins -

trapped only a few mm away from

glass cell @ room temperature



(vacuum of 10^{-12} Torr,
i.e. 10^{-15} bar,
or 10^{-10} Pa,

≈ atmospheric
pressure on the moon)

- Interacting bosons with s-wave scattering length a

\`diluteness' parameter:

$$\boxed{\zeta = \sqrt{na^3}}$$

with interatomic distance

$$\sim n^{-1/3}$$

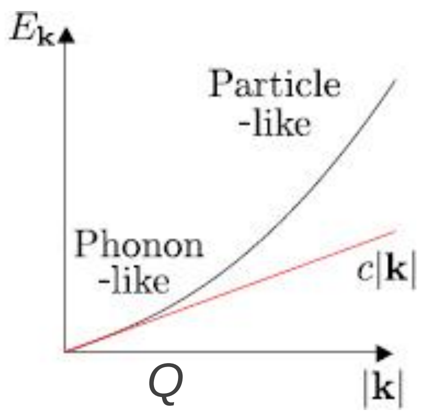
typical scattering length: $a \simeq 5$ nm
typical bulk density: $n \simeq 10^{14}$ cm^{-3}

$$\Rightarrow \quad \zeta \simeq 10^{-3}$$

Dilute Bose gas in extreme conditions

- The dilute Bose gas in extreme conditions has the typical occupancy:

$$\boxed{f_{\rm nr}(Q) \sim \frac{1}{\zeta}}$$



at the `inverse coherence length' scale

$$\boxed{Q = \sqrt{16\pi a n}}$$

- Check: Bosons with quartic (Gross-Pitaevskii) interaction $g = 4\pi a/m$;

  $\rightarrow$ the mean-field shift in energy is of the same order as the relevant kinetic energy $Q^2/2m$ irrespective of the coupling *g*, since

$$g \int \mathrm{d}^3 p \, f_{\rm nr}(\mathbf{p}) \sim g\, Q^3 f_{\rm nr}(Q) \sim g \frac{Q^3}{\zeta} \sim g \frac{Q^3}{mgQ} \sim \frac{Q^2}{m}$$

Universality far from equilibrium

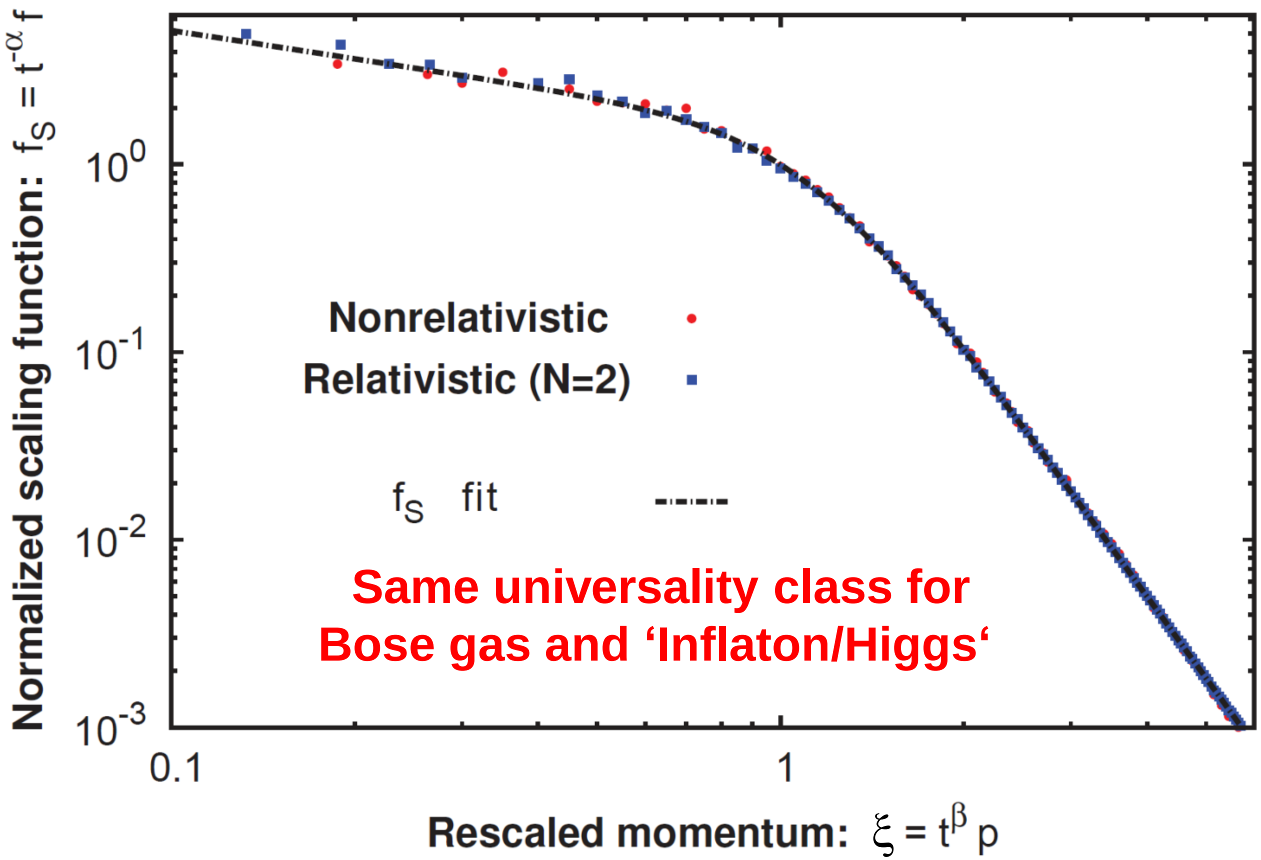
Self-similarity:

universal scaling exponents

$$f(t,\mathbf{p}) = t^{\alpha} f_S(t^{\beta}\mathbf{p}) \quad , \qquad \alpha = \frac{d}{2-\eta} \; , \quad \beta = \frac{1}{2-\eta}$$

nonthermal fixed point distribution

anomalous dimension

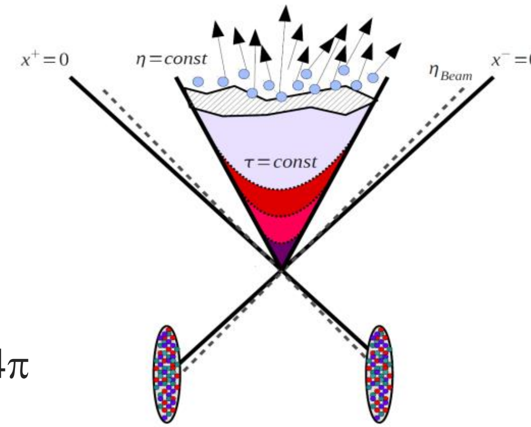


Piñeiro Orioli, Boguslavski, Berges, PRD 92 (2015) 025041

QCD Matter in Extreme Conditions

Heavy-ion collisions in the high-energy limit

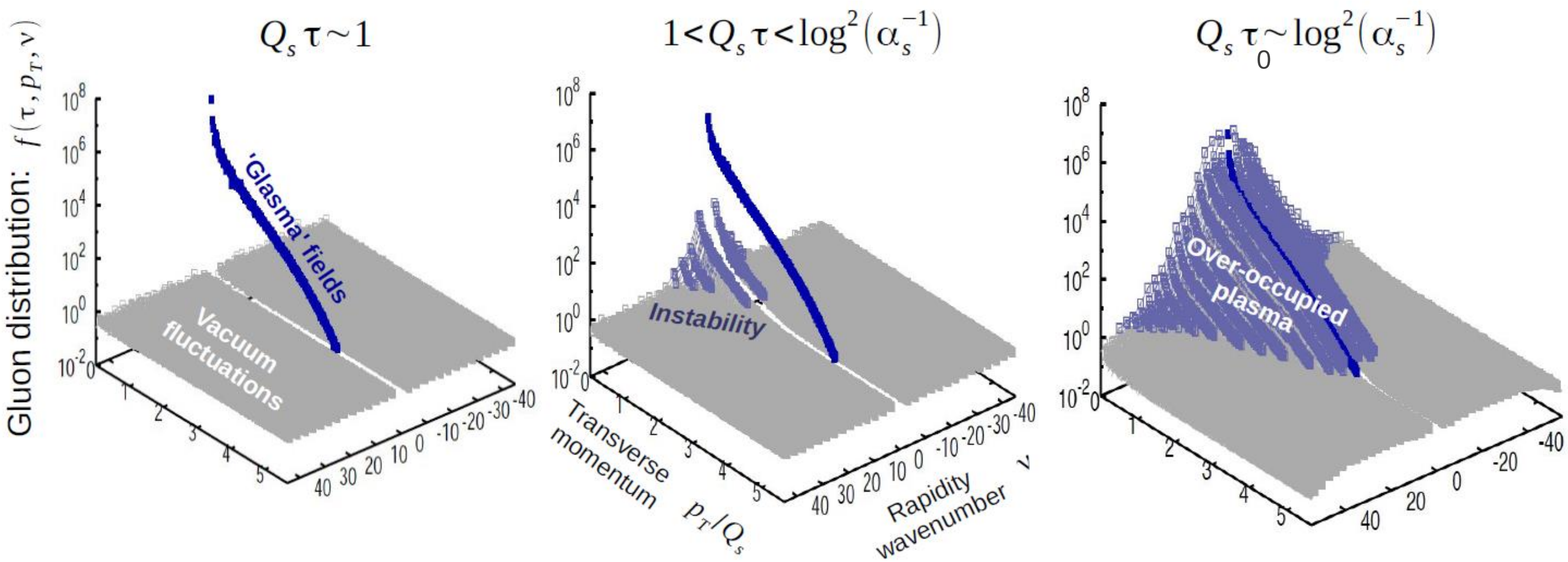
Color Glass Condensate: Lappi, McLerran, Dusling, Gelis, Venugopalan,…



Large initial gauge **fields**: $\langle A\rangle \sim Q_s/g$, $g \ll 1$

with initial (vacuum) fluctuations: $\langle \delta A^2\rangle \sim Q_s^2$, $\alpha_s = g^2/4\pi$

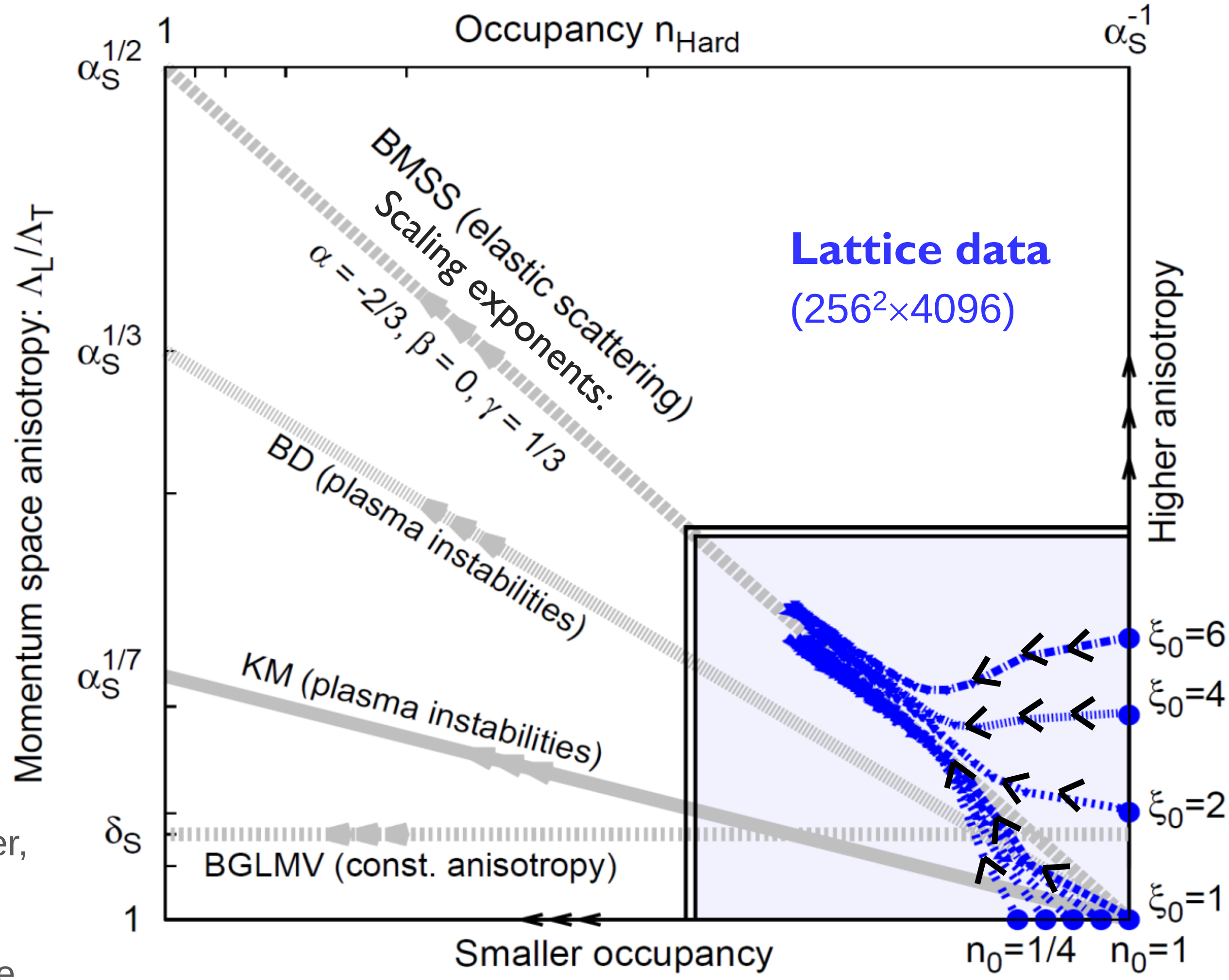
and **longitudinal expansion**: $\tau = \sqrt{t^2 - z^2}\,,\ x^{\pm} = (t \pm z)/\sqrt{2}\,,\ \eta = \mathrm{atanh}(z/t)$



Berges, Schenke, Schlichting, Venugopalan, NPA931 (2014) 348

Nonthermal fixed point

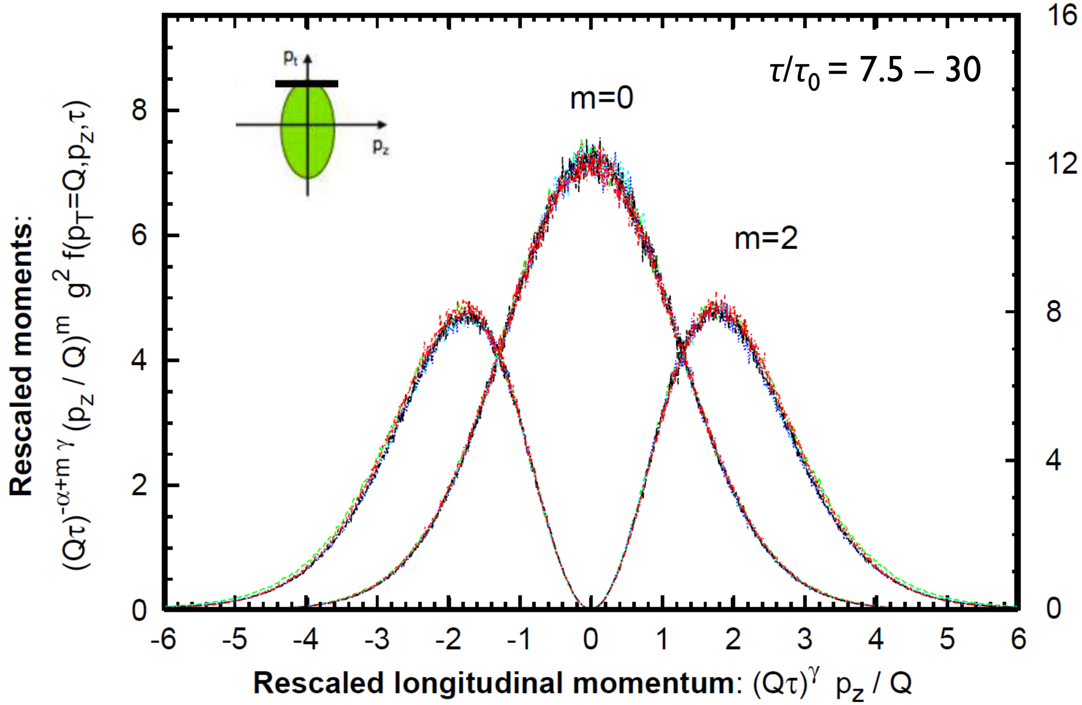
Attractor in the `anisotropy-occupancy plane´:

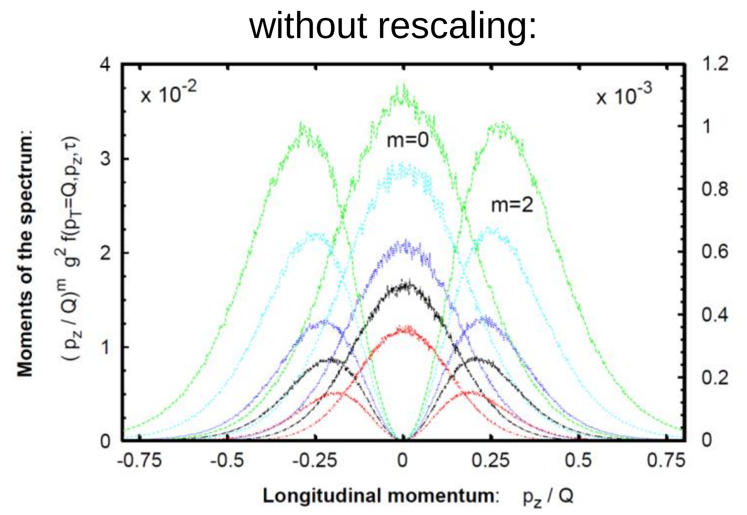


BMSS: Baier, Muller, Schiff, Son
BD: Bodecker
KM: Kurkela, Moore
BGLMV: Blaizot et al.

Berges, Boguslavski, Schlichting, Venugopalan, PRD 89 (2014) 074011; ibid. 114007

Universality far from equilibrium





Universal scaling exponents: $\alpha = -2/3 \,, \qquad \beta = 0 \,, \qquad \gamma = 1/3$
and nonthermal fixed point distribution function f_S:

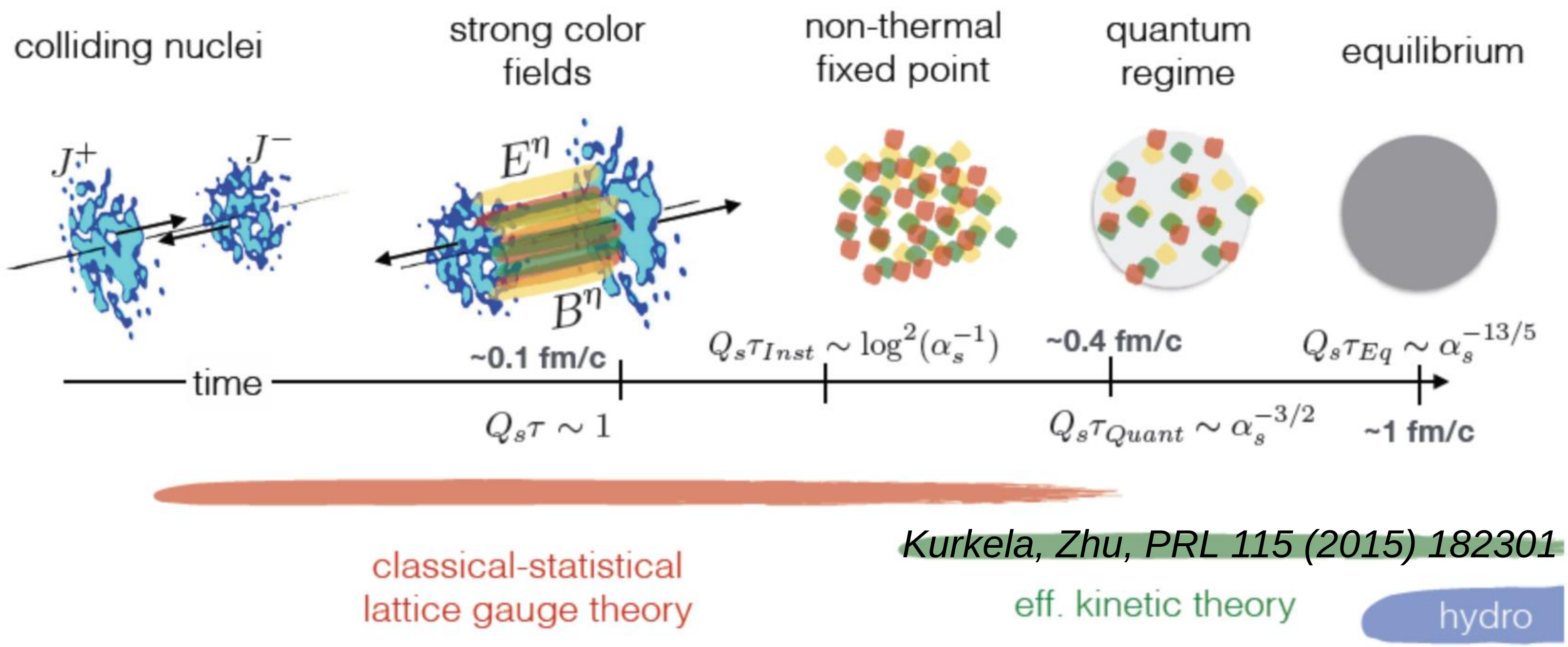
$$f(\mathrm{p_T}, \mathrm{p_z}, \tau) = (Q\tau)^\alpha f_S\Big((Q\tau)^\beta \mathrm{p_T}, (Q\tau)^\gamma \mathrm{p_z}\Big)$$

Surprisingly large universality class, including even long. exp. superfluid scalars!

Berges, Boguslavski, Schlichting, Venugopalan, PRD 89 (2014) 074011; ibid. 114007; PRL 114 (2015) 061601

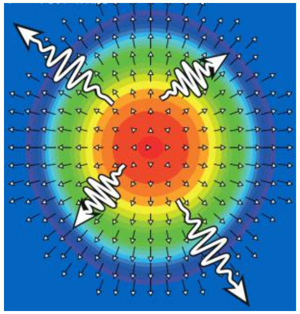
Thermalization of the Quark Gluon Plasma

Thermalization *ab initio*:



Kurkela, Zhu, PRL 115 (2015) 182301

Windows into early times: e.g. photon production

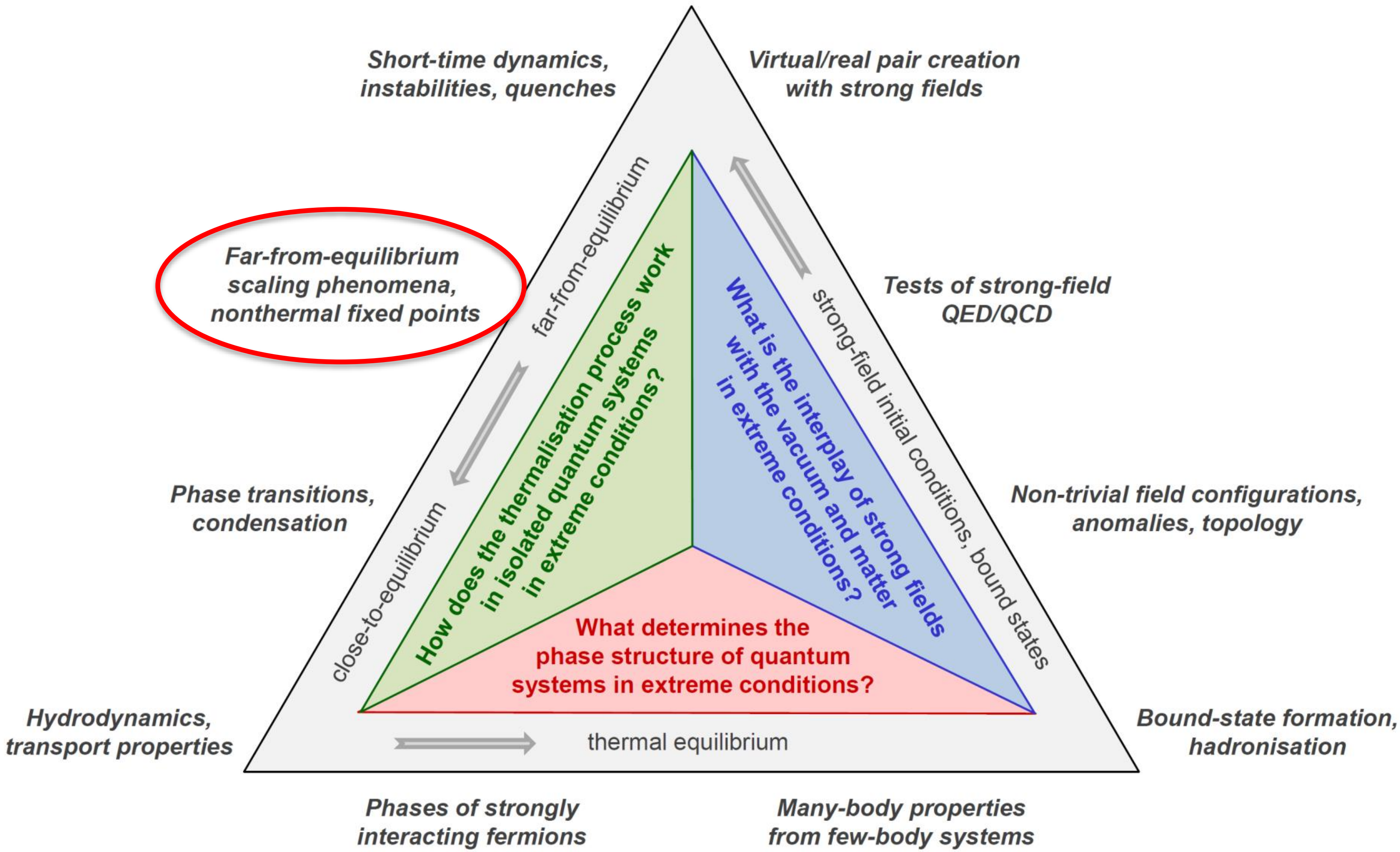


→ Medium transparent to photons ($\lambda_{mfp} \approx$ 500 fm)

→ Nonequilibrium stage of photon production can be significant, in particular, for smaller systems

Berges, Reygers, Tanji, Venugopalan, in preparation

ISOQUANT Research Topics



Conclusions

- Isolated quantum systems in extreme conditions → relevant for wide range of topical applications from particle/nuclear to atomic/condensed matter physics

- Extreme conditions enhance the loss of details about microscopic properties from which universality originates

- Discovery of new far-from-equilibrium universality classes provide exciting new links between different physical systems ranging from hot plasmas to cold gases

- Nonthermal fixed point in space-time evolution of non-Abelian plasma at high energies:

  → large predictive power of calculations from first principles, in particular, because of insensitivity to less well known initial condition details

  → impact on observables sensitive to nonequilibrium stage, such as photon production

  → universal aspects of nonthermal fixed points may be tested in table-top experiments with cold atoms