Chiral turbulence in spin polarized QED plasmas

Universality from from equilibrium, strong fields & large fluctuations

Sören Schlichting | Universität Bielefeld

Based on:
Mace, Mueller, SS, Sharma (in preparation)

Mace,Mueller,SS, Sharma, PRD95 (2017) no.3, 036023;
Mueller,SS, Sharma PRL117 (2016) no.14, 142301;
Mace,SS, Venugopalan PRD 93 (2016) no.7, 074036;

Universität Bielefeld

QSEC 2019
Heidelberg University, Germany
Sept 2019

CRC-TR 211
Strong-interaction matter under extreme conditions

Chiral magnetic effect & anomalous transport

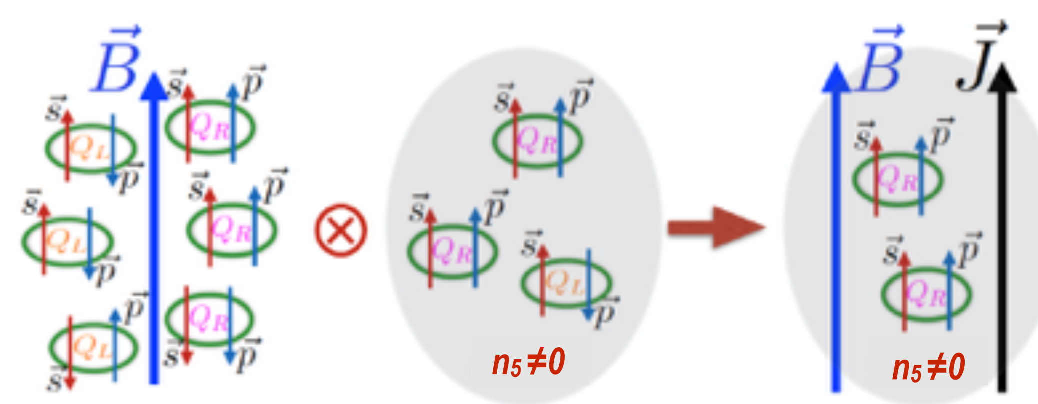
Discovery of new kind of conductivity for systems with chiral fermions and chirality imbalanced

Fukushima, Kharzeev, Warringa PRD 78 (2008) 074033

$$\vec{j}_V \propto n_5 \vec{B}$$

n_5: chirality imbalance

B: magnetic field



Kharzeev, Liao, Voloshin, Wang
Prog. Part. Nucl. Phys. 88 (2016) 1-28

Several manifestations of such effect from high-energy QCD to Dirac/Weyl semi-metals

c.f. talk by Fukushima

Since chiral charge (n_5) is not conserved need to understand transfer/balance of chiral charge between fermions and gauge fields

Chiral anomaly in QCD & QED

Chiral charge density of fermions (n_5) not conserved due to the axial anomaly

$$\partial_\mu j^\mu_{5,f} = 2m_f \bar{q}\gamma_5 q - \frac{g^2}{16\pi^2} F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a$$

axial current $j_5^\mu = (n_5, \vec{j}_5)$

quark mass

(non)-abelian field-strength $\propto \vec{E}\cdot\vec{B}$

Gauge field contributions can be expressed as divergence of Chern-Simons current

$$\partial_\mu K^\mu = \frac{g^2}{32\pi^2} F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a$$

Chiral charge of gauge fields

$$N_{CS}(t) = \int d^3x\ K^0(t,x)$$

QED: Magn. Helicity QCD: Chern-Simons number

Chiral limit (m->0): Net chirality of the system $N_5 + 2N_{CS}$ conserved

sharing & transfer between fermions and gauge fields

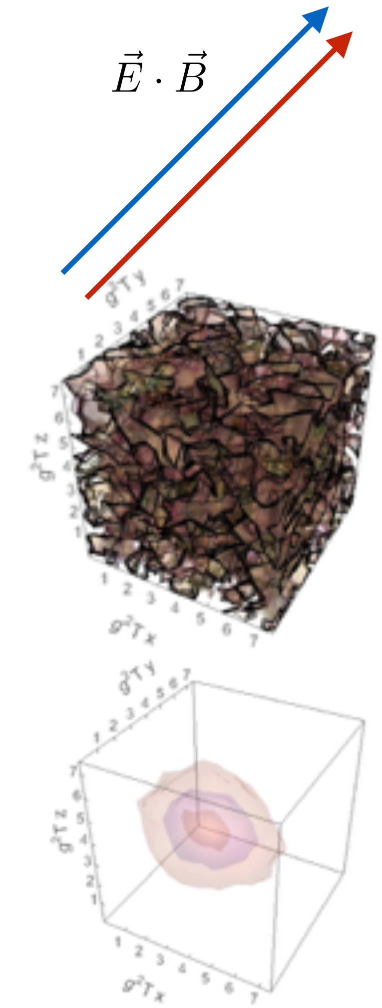
Chiral anomaly in QCD & QED

Chirality transfer from gauge fields to fermions
possible due to

QED: External E,B fields

QED & QCD: Space-time dependent fluctuations of $\vec{E}\cdot\vec{B}$

QCD: Topological sphaleron transitions



Chirality transfer from fermions to gauge fields
possible due to

QCD: Bias of sphaleron transition rate
McLerran,Mottola,Shaposnikov PRD43 (1991) 2027-2035

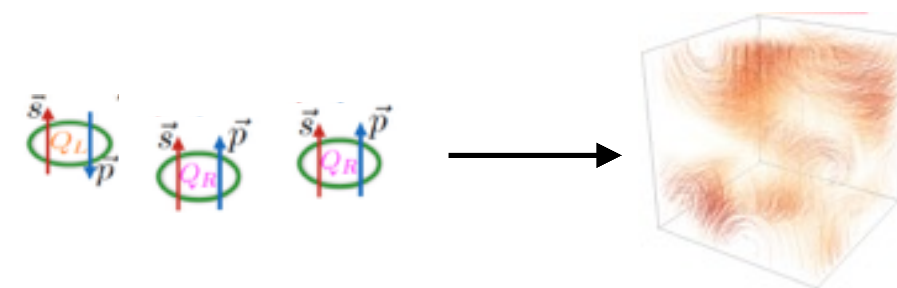
QED & QCD: Chiral plasma instabilities
Akamatsu, Yamamoto PRL111 (2013) 052002

Interesting applications in Astrophysics & Cosmology where chirality imbalance can be produced through weak interaction processes

Masada et al. PRD98 (2018) no.8, 083018; Brandenburg et al. Astrophys.J. 845 (2017) no.2, L21

Chiral turbulence in spin polarized QED plasmas

How helicity/chirality is transferred between fermions and gauge fields?

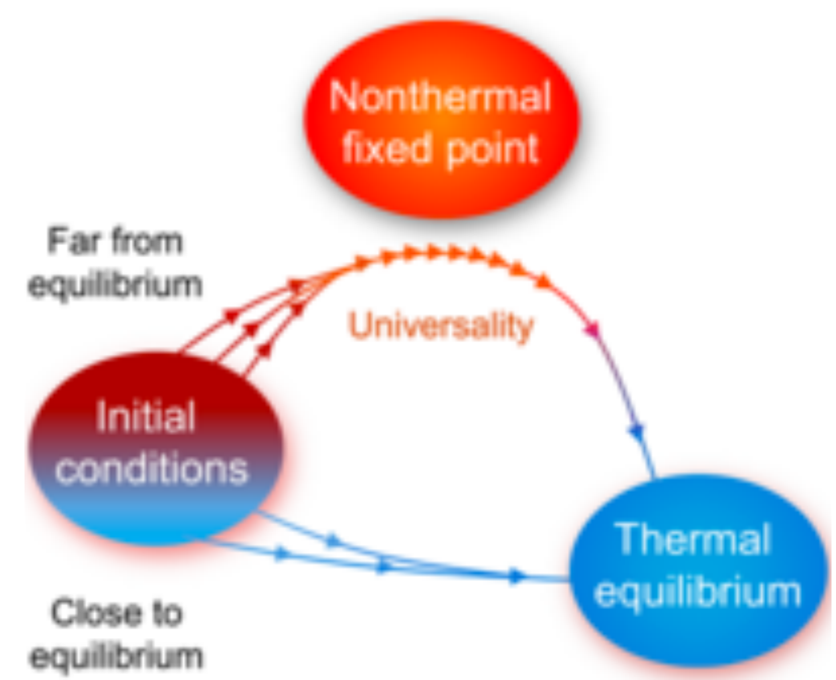


Characteristic pattern for strongly correlated many body systems far-from-equilibrium

Cosmology, Cold Atoms, Heavy-Ions

c.f. talks by Mazeliauskas, Erne, …

Closely related to decaying turbulence i.e. transport of conserved quantity across large separation of scales



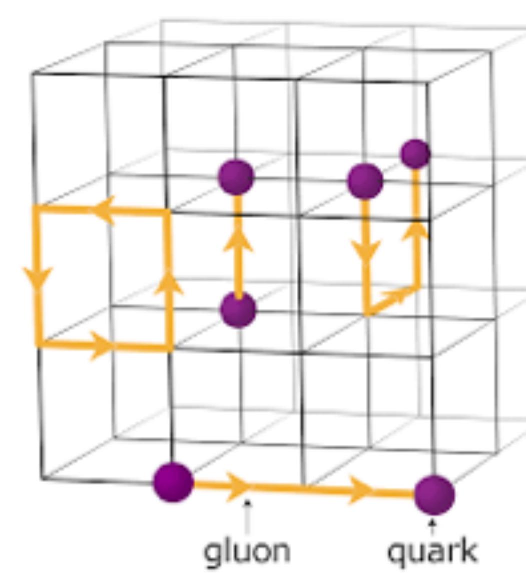
Berges, Koguslavski, SS, Venugopalan PRL 114 (2015) no.6,

Microscopic real-time simulations

Classical-statistical lattice simulations of dynamics of underlying QFT

Basic idea: Classical gauge fields coupled to quantum fermions

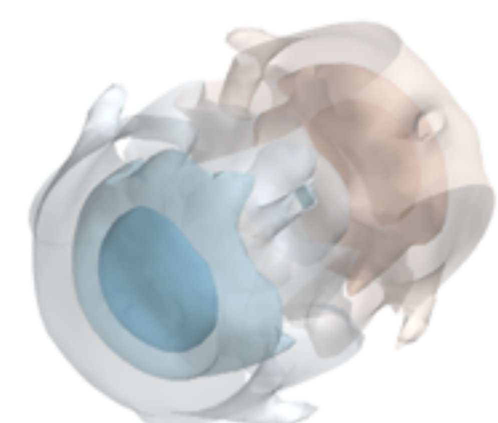
Expansion to leading order in e^2
but all orders in $e^2 N_f$ (exact at large Nf)



Can be simulated from first principles
based on lattice discretization

Several applications to

Strong-field QED, Cosmology, Chiral transport, …



QED: Kasper, Hebenstreit, Berges, PRD 90 (2014) no.2, 025016
Mueller, Hebenstreit, Berges, PRL 117 (2016) no.6, 061601
….
QCDxQED: Mace,Mueller,SS, Sharma, PRD95 (2017) no.3, 036023;
Mueller,SS, Sharma PRL117 (2016) no.14, 142301

Microscopic real-time simulations

Discretize theory on 3D spatial lattice using the Hamiltonian lattice formalism

Solve operator Dirac equation in the presence of U(1)/SU(N_c) gauge fields

$$i\gamma^0\partial_t\hat{\psi} = (-i\not{D}^s_W + m)\hat{\psi}$$

Compute expectation values of vector current

$$j^\mu_v(x) = \langle\hat{\bar{\psi}}(x)\gamma^\mu\hat{\psi}(x)\rangle$$

Solve Maxwell's/Yang-Mills equations in presence of back reaction currents

$$D_\mu F^{\mu\nu} = j^\nu_v$$

Solution to operator Dirac obtained by expanding the fermion field in operator basis at initial time

$$\hat{\psi}(x,t) = \sum_{p,\lambda} \hat{b}_{p,\lambda}(t=0)\phi^{p,\lambda}_u(x,t) + \hat{d}^\dagger_{p,\lambda}(t=0)\phi^{p,\lambda}_v(x,t)$$

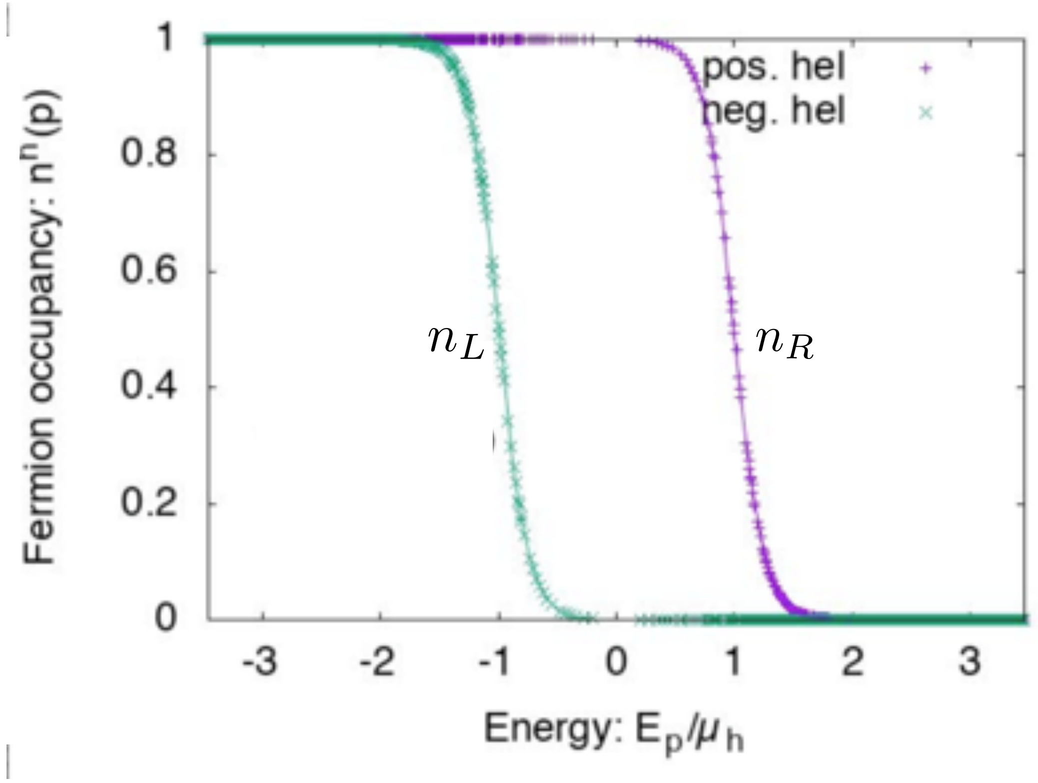
and solving the Dirac equation for evolution of $4N_cN^3$ wave-functions

Chiral turbulence in spin polarized QED plasmas

Simulate dynamics starting with spin polarization of the fermion sector, characterized by helicity chemical potential μ_h

$\mu_h \gg T$: energy density & chiral charge initially concentrated in fermion sector

Vacuum fluctuations for gauge fields (realized by stochastic field fluctuations)

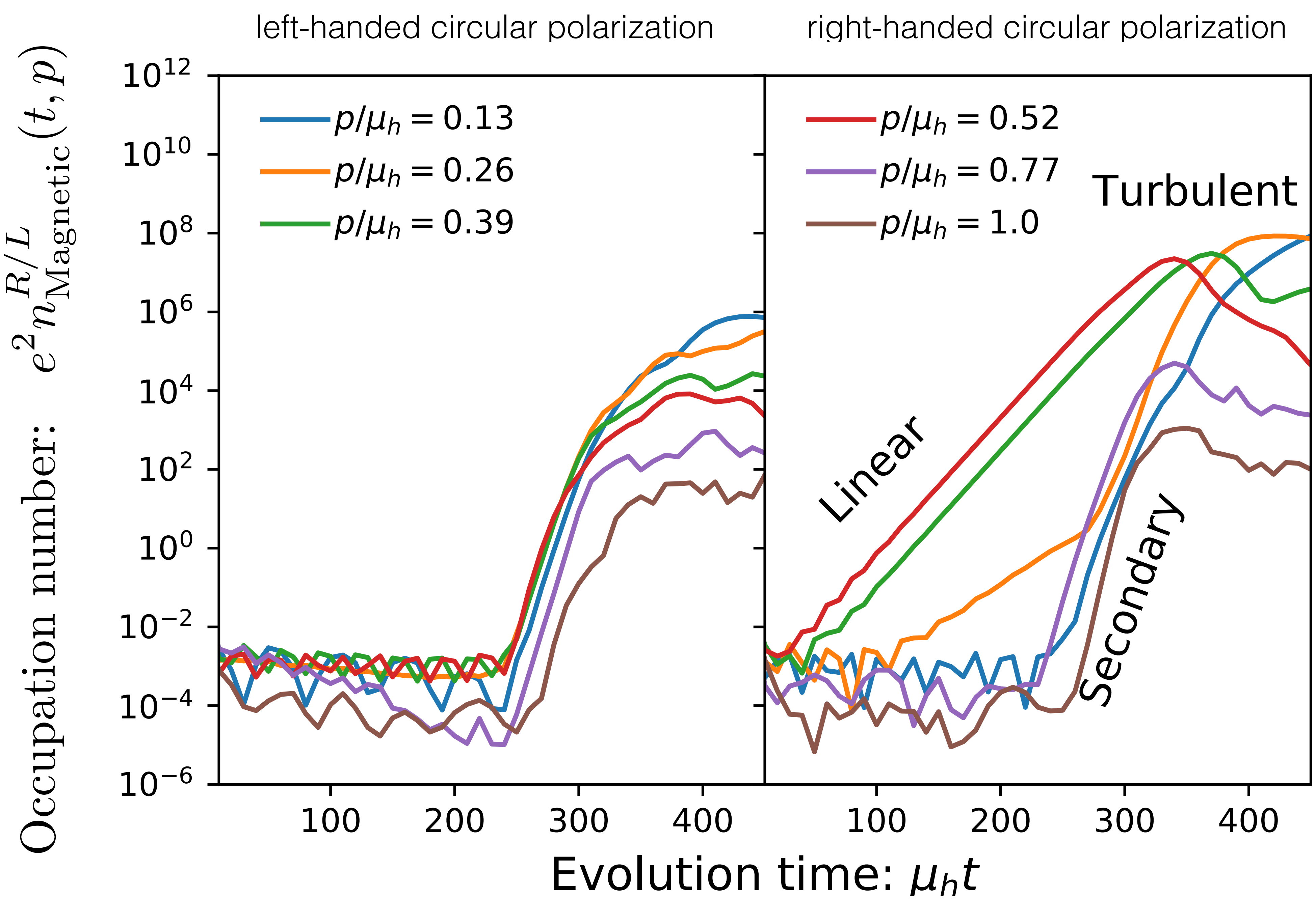


Computationally extremely demanding -> lattice sizes up to 48^3 (~5M CPU hours per simulation on Cori@NERSC)

Simulate dynamics in strongly coupled QED $e^2N_f=64$ (instead of 0.09 for QED) to properly resolve all dynamical scales on the lattice

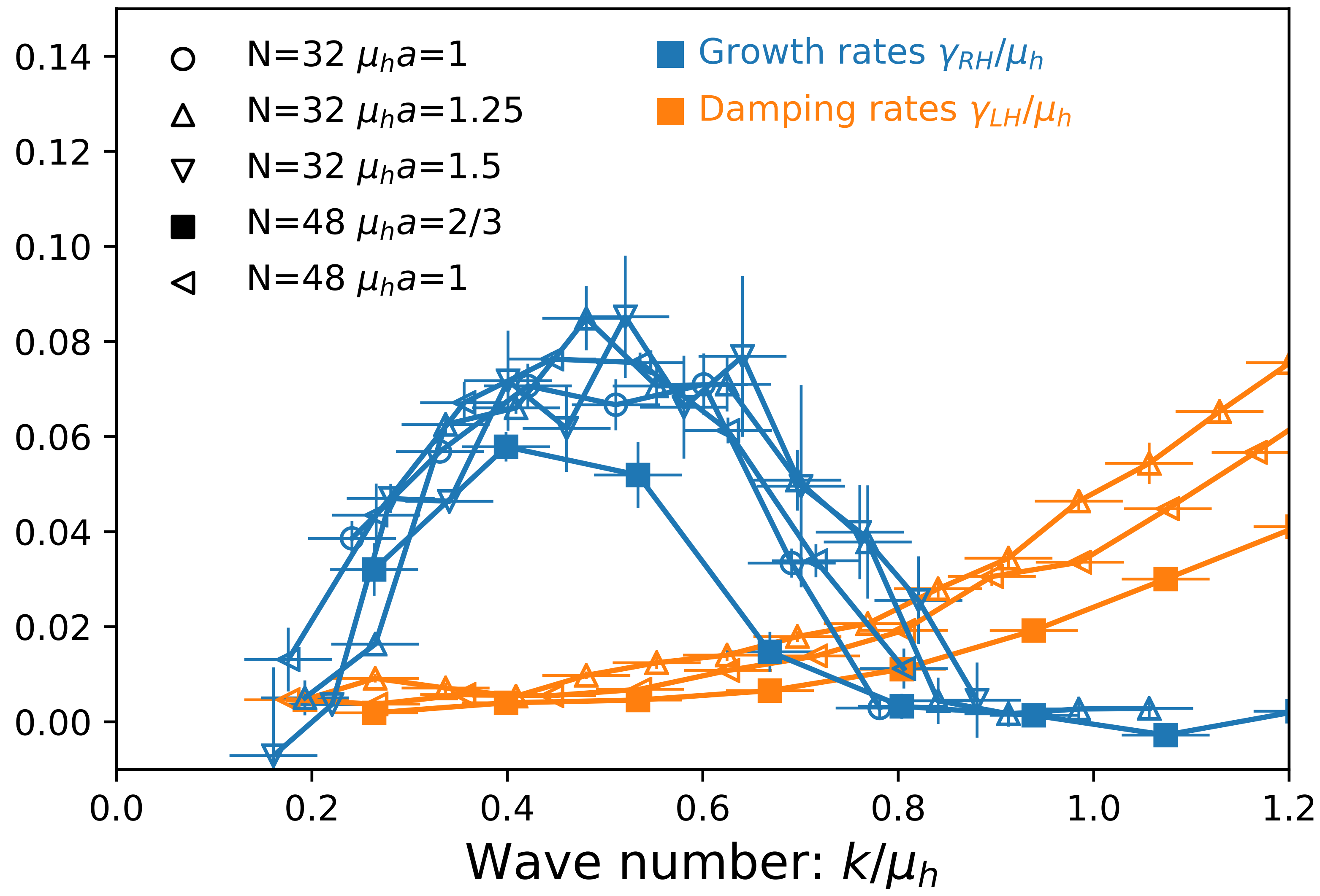
Simulations performed close to chiral limit $m \ll \mu_h$; trivial to extend to finite quark mass but not considered so far

Chirality transfer in large N_f QED



Characteristic sequence of dynamics in unstable systems

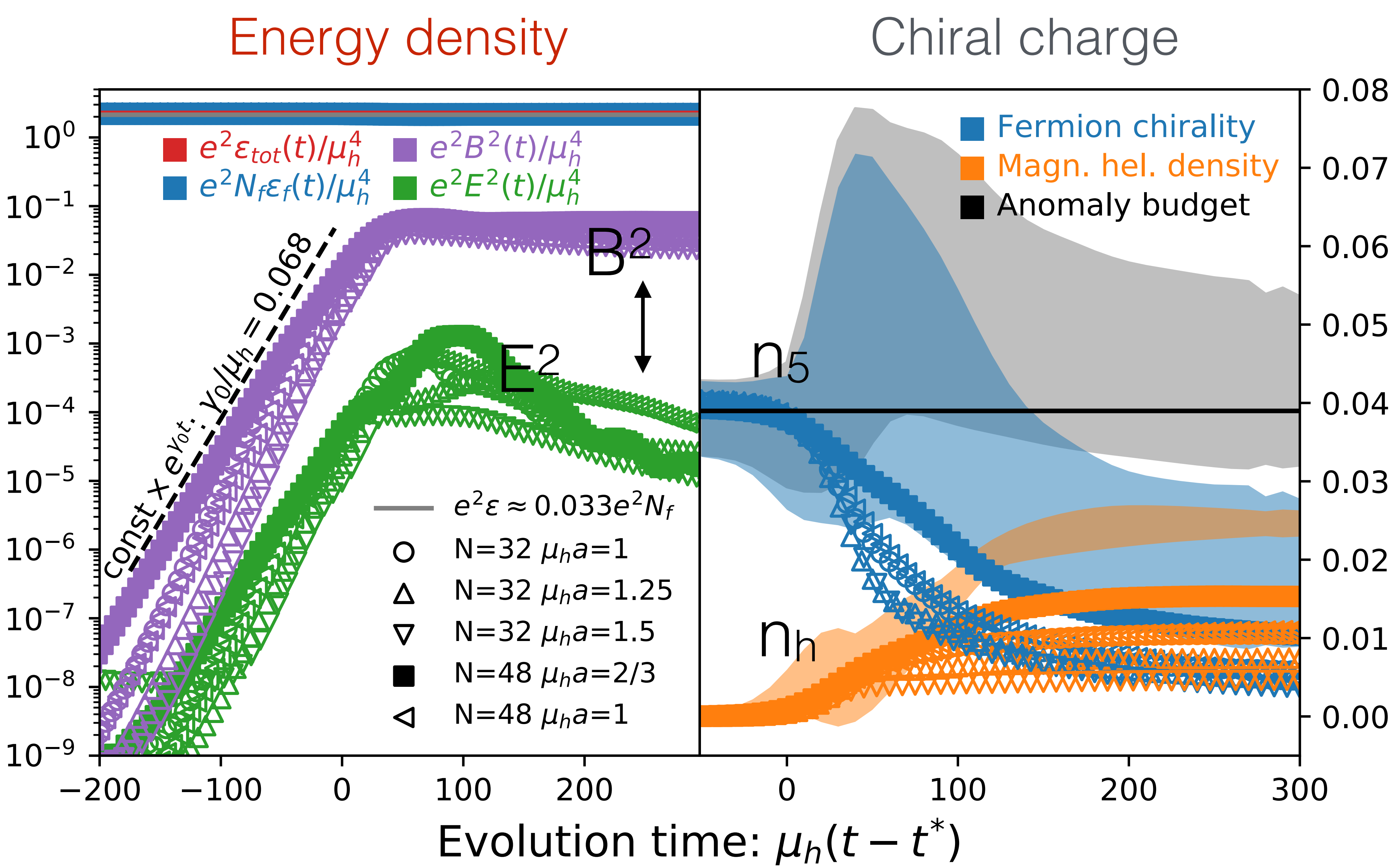
Chirality instability rates



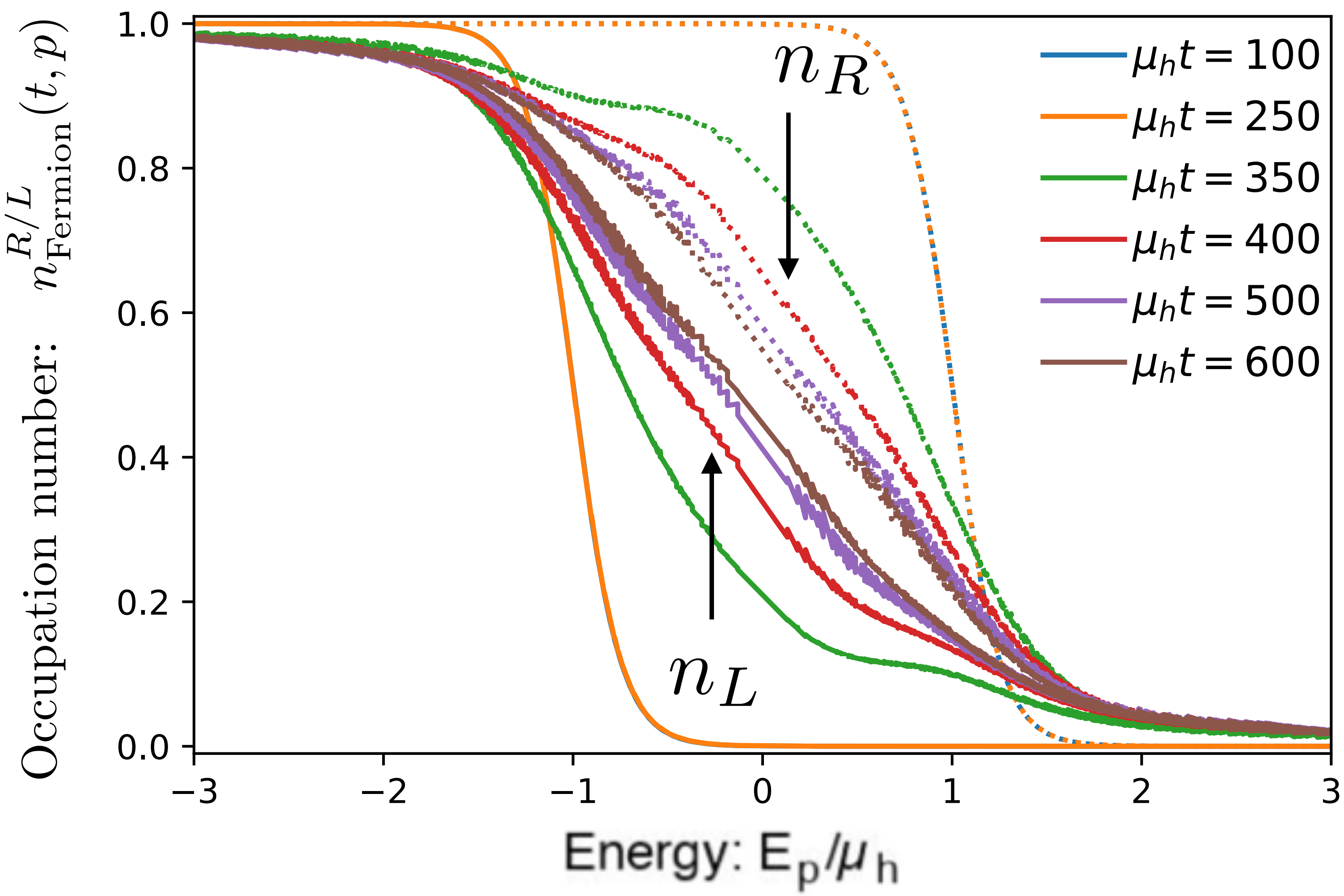
By use of improved operator definitions (Wilson NLO) errors due to finite lattice size and lattice spacing appear to be under control

Evolution of conserved quantities

Effectively two conserved quantities (close to the chiral limit)



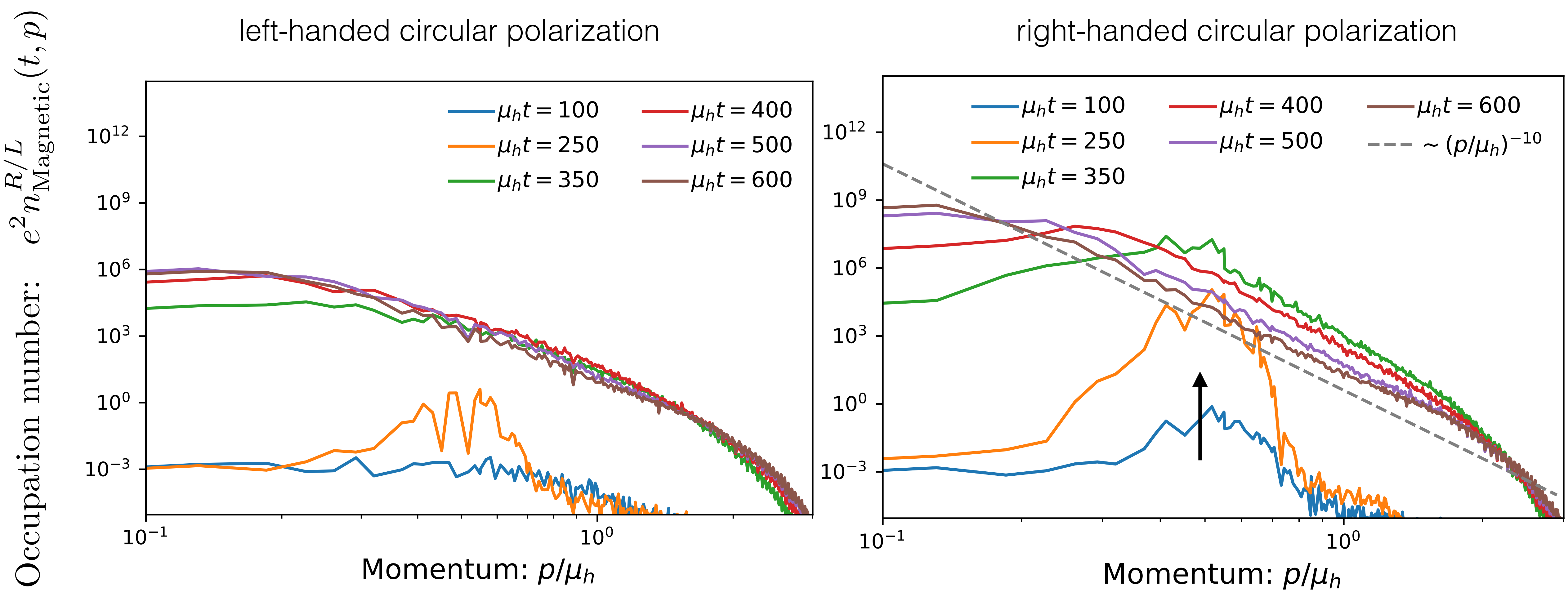
Chirality transfer in large N_f QED



Non-linearities lead to depletion of helicity imbalance (stabilisation)

Strong heating of the fermion sector upon saturation of instability

Chiral turbulence

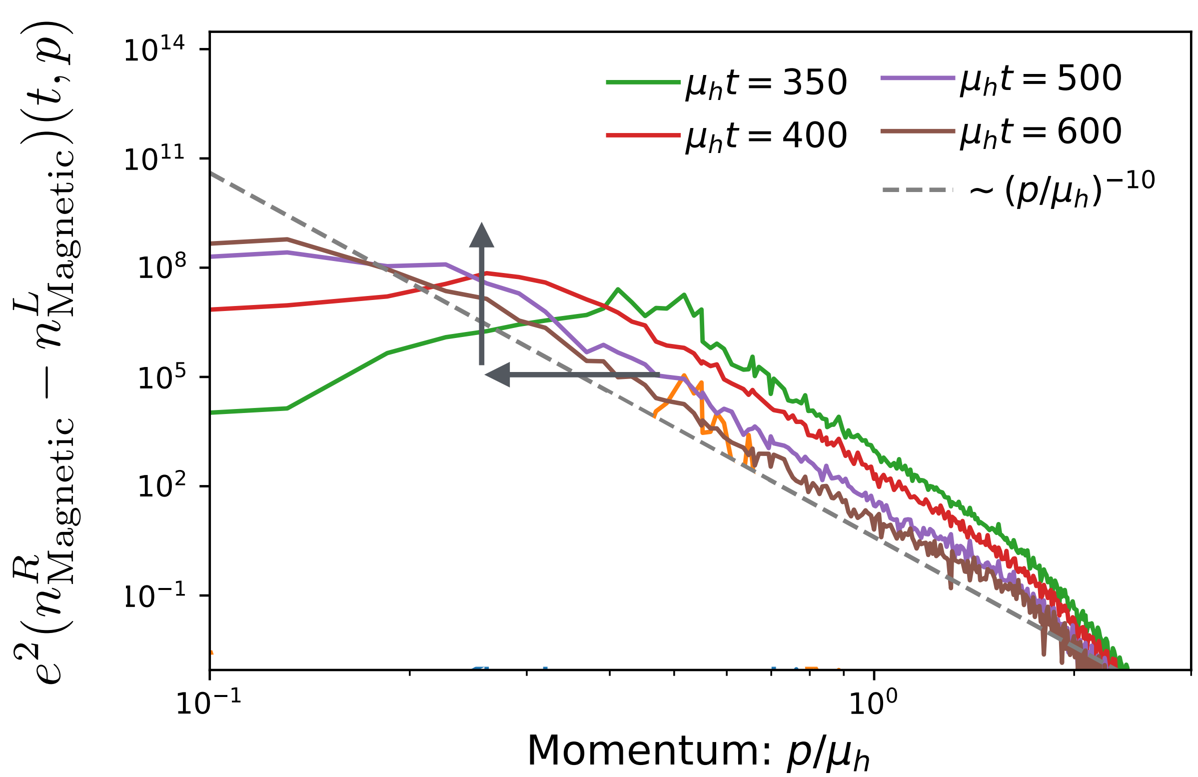


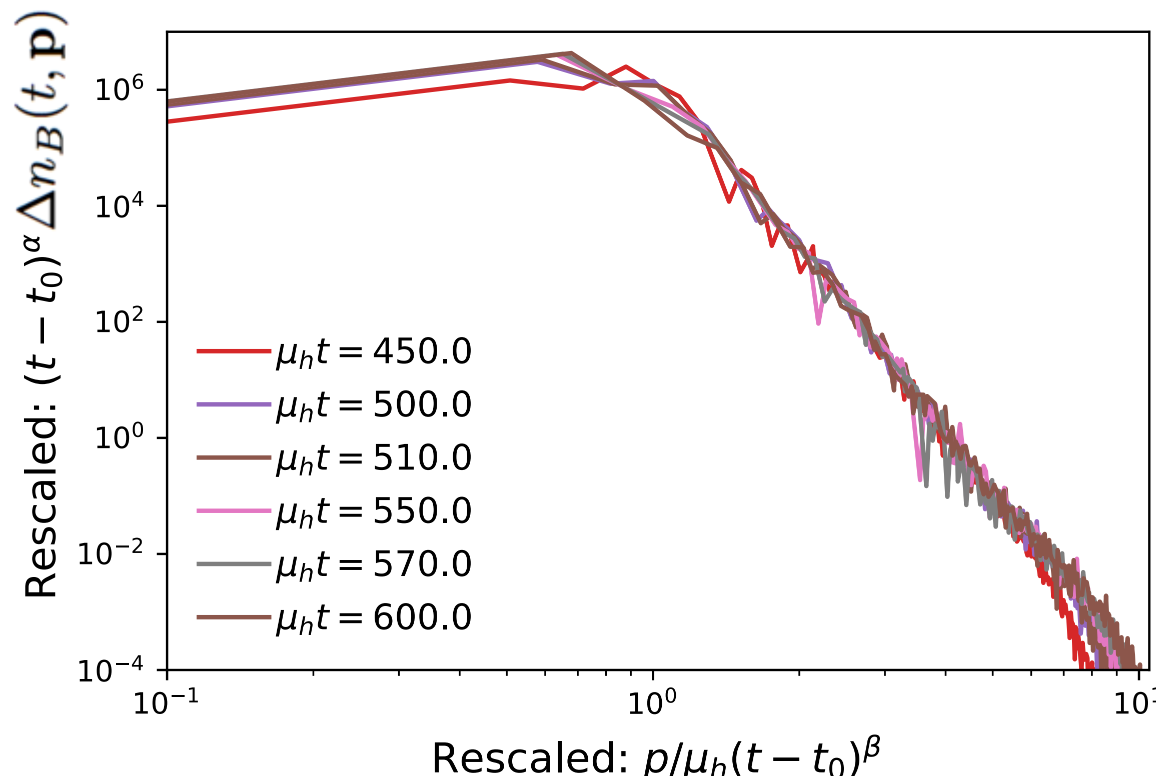
Non-linear regime:

Non-perturbatively large occupations of left & right-handed modes

Strong IR excess of right vs. left-handed modes
-> characterized by power law ~$(p/\mu)^{-10}$ with large spectral exponent

Chiral turbulence





Evolution proceeds via self-similar evolution of net magnetic helicity

$$\Delta n_B(t, \mathbf{p}) = \tau^\alpha f_s(\tau^\beta |\mathbf{p}|),$$
$$\tau \equiv \mu_h (t - t^*)$$

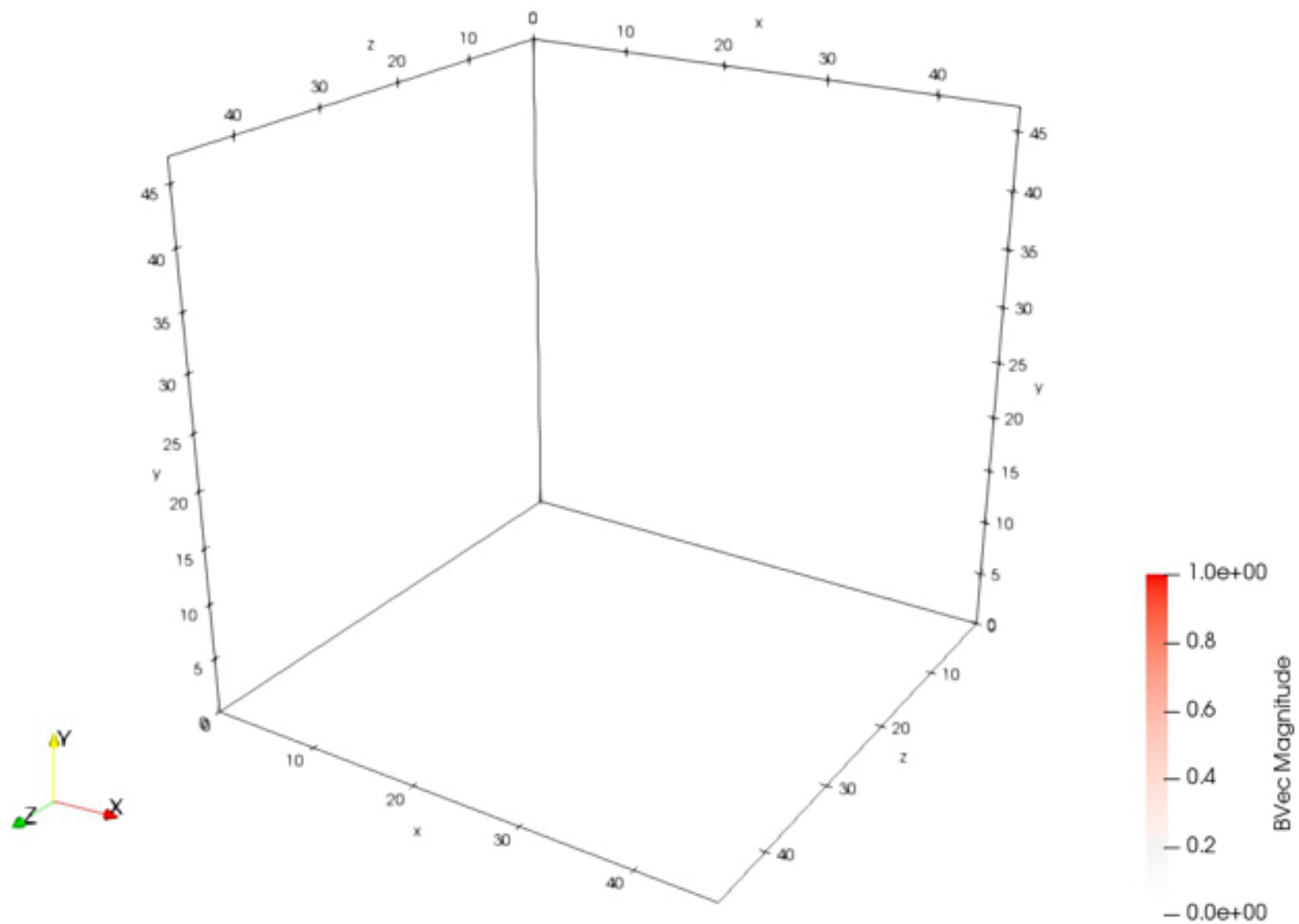
Scaling exponents α,β determined from statistical scaling analysis

$$\alpha = (0.9 \pm 0.3)\,, \qquad \beta = (0.3 \pm 0.1)$$

$\alpha \approx 3\beta$ Self-similar inverse cascade of magnetic helicity

Chiral turbulence

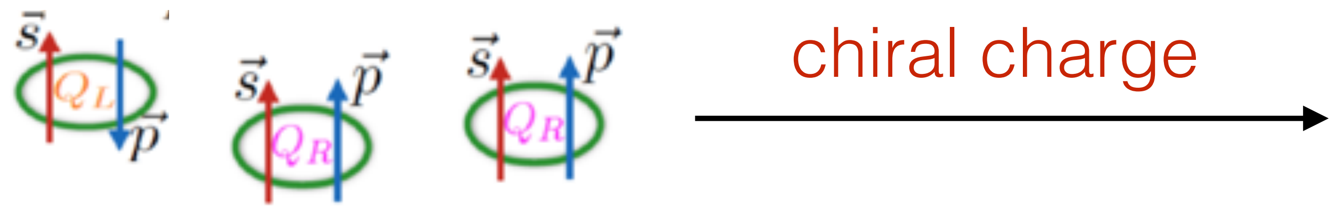
μt =200

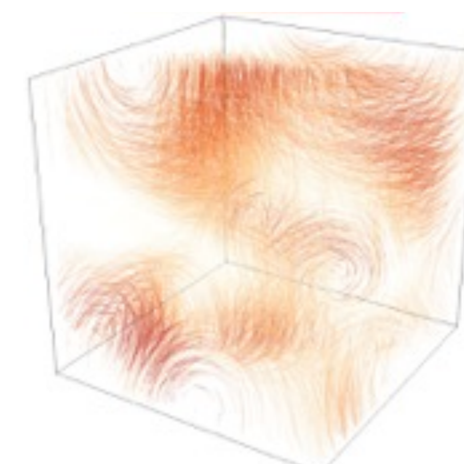


Generation of large scale magnetic fields via inverse cascade

Conclusions & Outlook

Chiral plasma instabilities in strongly coupled QED lead to emergence of self-similar inverse cascade of magnetic helicity





New far-from equilibrium universality class for chirality transport

$$\alpha = (0.9 \pm 0.3)\,, \qquad \beta = (0.3 \pm 0.1)$$

Characteristic time scale for helicity transfer not set by growth rate of instability but ultimately determined by turbulent regime $\sim (\ell_{\mathrm{macro}}/\ell_{\mathrm{micro}})^{-1/\beta}$

Generation of large scale helical magnetic fields via this mechanism
-> possible applications in Condensed Matter systems?

Explore dissipative effects due to finite fermion mass and competition between effectively abelian and genuine non-abelian (topological) effects in QCD like theories