Theory of strong-interaction matter

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in collaboration with:

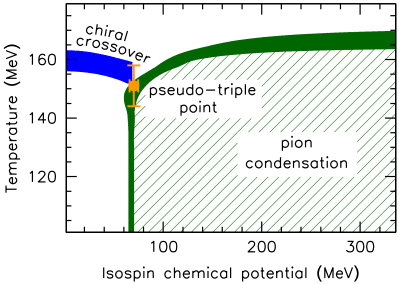
Bielefeld: Bastian Brandt, Eduardo Garnacho, Javier Hernández, Gergely Markó, Laurin Pannullo, Leon Sandbote, Dean Valois

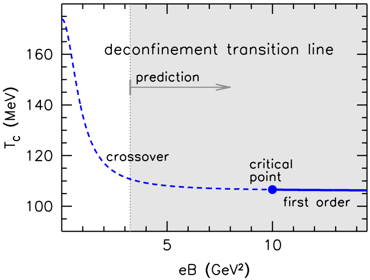
Frankfurt, Darmstadt: crc-tr211.org

my colleagues from Budapest, Regensburg, Wuppertal, Graz, Nicosia, Mumbai, Seattle, Sao Paulo, Tuscaloosa

Appetizer

fundamental phase diagrams of QCD
with possible phenomenological implications





Brandt, Endrődi, Schmalzbauer ’18

Brandt, Endrődi ’19

Endrődi ’15

D’Elia, Maio, Sanfilippo, Stanzione ’21

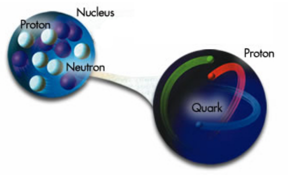
Outline

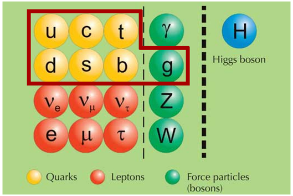
- introduction: strongly interacting matter in
  - strong electromagnetic fields
  - nonzero isospin density
- lattice simulation techniques
- phase diagrams: current status
- application: cosmic trajectory
- further electromagnetic effects:
  inhomogeneities, topology and chirality
- summary

Introduction

Strong interactions

- explain 99.9% of visible matter in the Universe



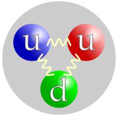


- elementary particles: quarks and gluons
- elementary fields: $\psi(x)$ and $A_\mu(x)$ enter the QCD Lagrangian

$$\mathcal{L}_{\mathrm{QCD}} = \frac{1}{4}\,\mathrm{Tr}\,F_{\mu\nu}(g_s, A)^2 + \bar{\psi}[\gamma_\mu(\partial_\mu + i g_s A_\mu) + m]\psi$$

- $g_s = \mathcal{O}(1) \rightsquigarrow$ confinement

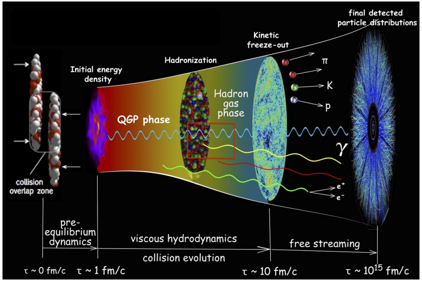
  $m_u,\ m_d \approx 3 - 5$ MeV, $\quad m_p = 938$ MeV

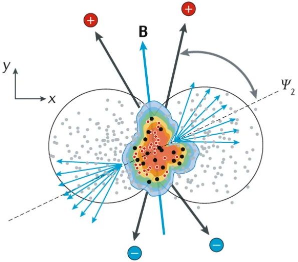


- asymptotic freedom at high energy scales $\rightsquigarrow$ deconfinement

Quarks and gluons in extreme conditions

- heavy ion collisions $T \lesssim 10^{12}\,^{\circ}C = 200$ MeV, $n \lesssim 0.12$ fm^{-3}
  $B \lesssim 10^{19}$ G $= 0.3$ GeV$^2/e$





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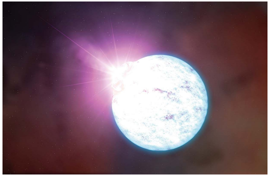
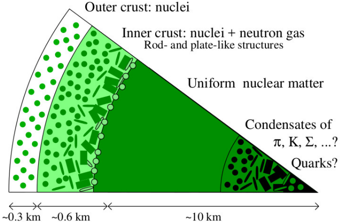
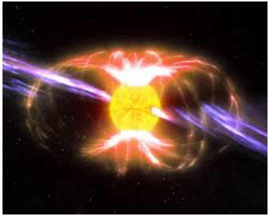
  magnetars $B \lesssim 10^{15}$ G







Lattimer, Nature Astronomy 2019

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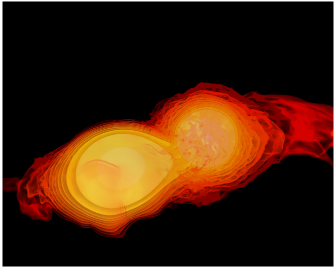
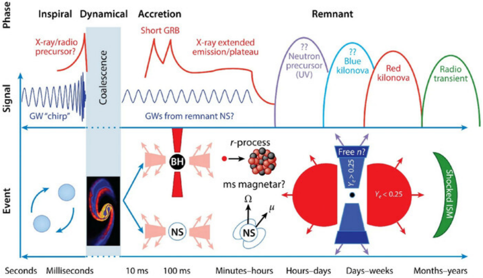
- neutron star mergers $T \lesssim 50$ MeV





astro.uni-frankfurt.de/rezzolla

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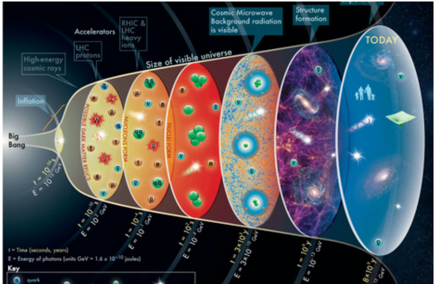
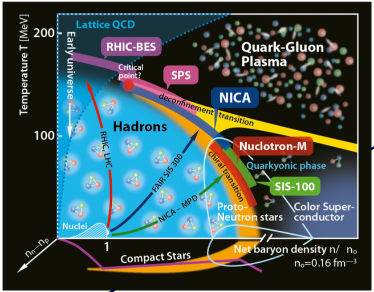
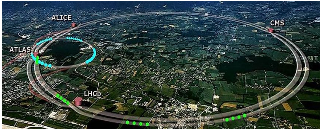
- eary universe, QCD epoch $T \lesssim 200$ MeV
  standard scenario: $n \approx 0$



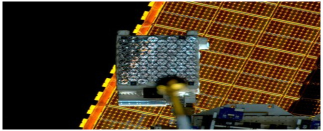
Major experimental and observational campaigns



Observational astronomy



Heavy ion collisions



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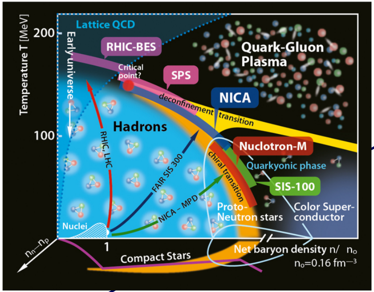

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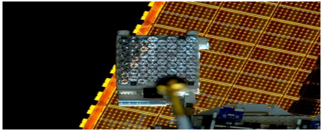

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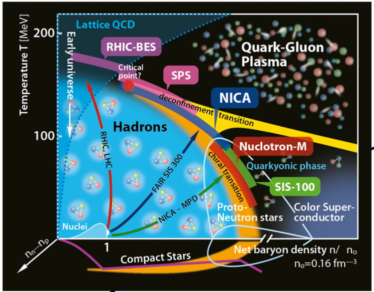

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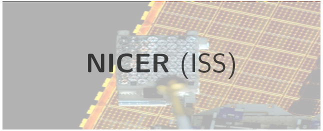

Heavy ion collisions

QCD phase diagram(s)

Phase diagram

- control parameters: T, $n \leftrightarrow \mu$, B $\qquad \mu_{\{u,d,s\}}$ / $\mu_{\{B,Q,S\}}$ / $\mu_{\{B,I,S\}}$

Phase diagram

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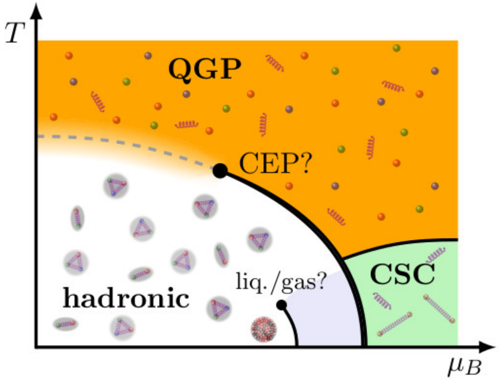

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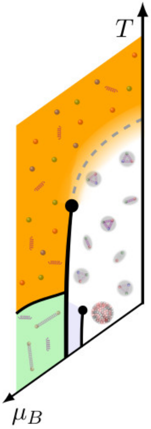

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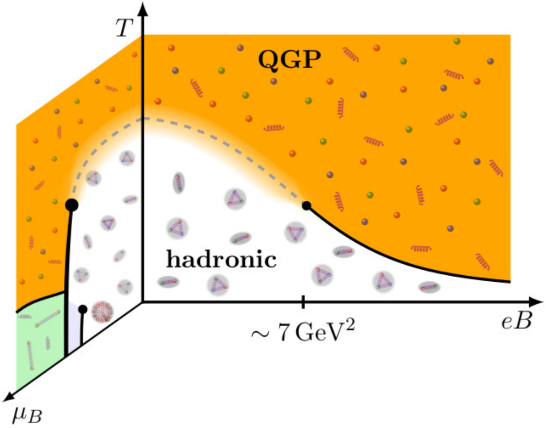
- well-known, less famous phase diagram: $T - B$



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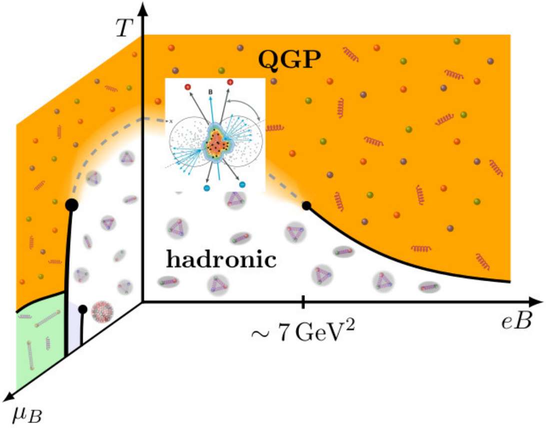

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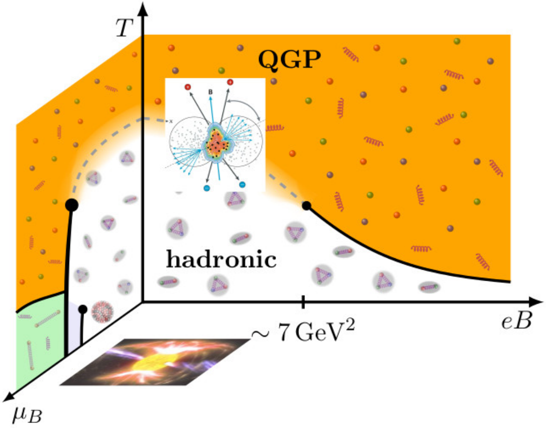

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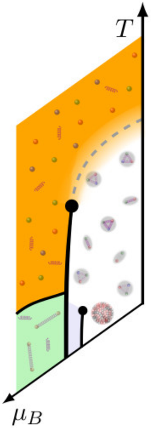

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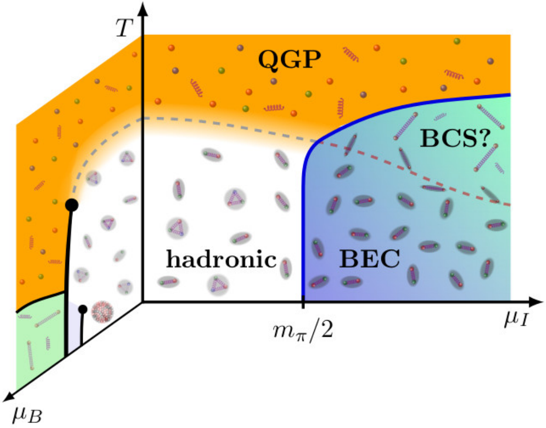

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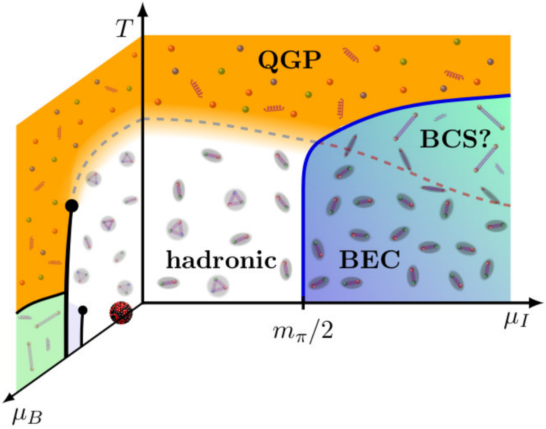

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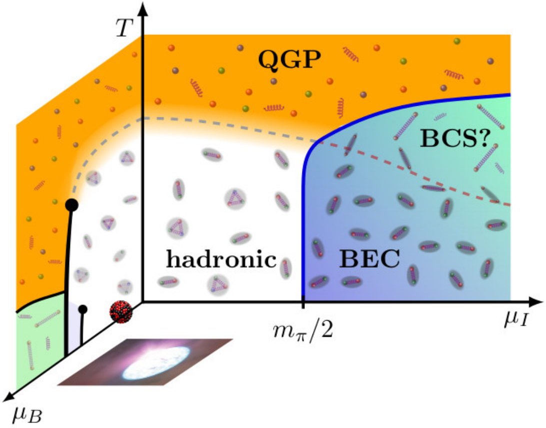

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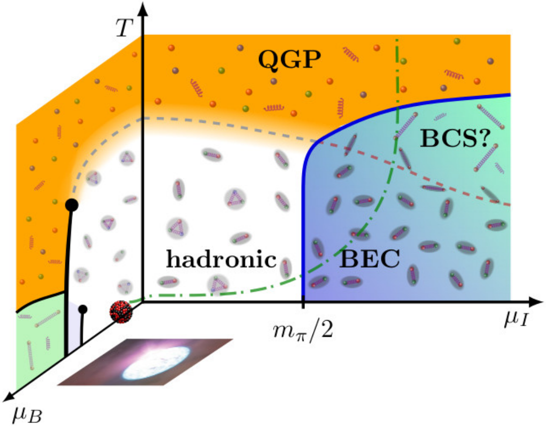


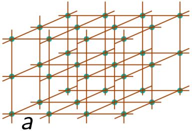
Lattice QCD simulations

Lattice simulations

- path integral Feynman '48

$$\mathcal{Z} = \int \mathcal{D}A_\mu \, \mathcal{D}\bar{\psi} \, \mathcal{D}\psi \, \exp\left(- \int d^4x \, \mathcal{L}_{\mathrm{QCD}}(x) \right)$$

- discretize QCD action on space-time lattice Wilson '74

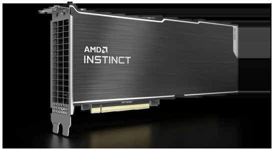


continuum limit $a \to 0$ in a fixed physical volume: $N \to \infty$

- dimensionality of lattice path integral: 10^{9-10} $\rightsquigarrow$ computationally very demanding

SuperMUC-NG

nvidia.com



amd.com


Bielefeld GPU cluster

Monte Carlo simulations

- Euclidean QCD path integral over gauge field $\mathcal{A}$

$$\mathcal{Z} = \int \mathcal{D}\mathcal{A}\, e^{-S_g[\mathcal{A}]} \det[\not{D}[\mathcal{A}] + m]$$

- Monte-Carlo simulations need: $\det[\not{D} + m] \in \mathbb{R}^+$
  for that one needs Γ so that

$$\Gamma \not{D}\, \Gamma^\dagger = \not{D}^\dagger, \quad \Gamma^\dagger \Gamma = 1$$

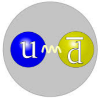
$$\det[\not{D} + m] = \det[\Gamma^\dagger\Gamma(\not{D} + m)] = \det[\Gamma(\not{D} + m)\Gamma^\dagger] = \det[\not{D}^\dagger + m] = \det[\not{D} + m]^*$$

- usually positivity can also be shown
- such a Γ exists: B, μ_I, $i\mu_B$, iE ✓
- no Γ exists: complex action problem μ_B, E ↯

Phase diagram: nonzero isospin

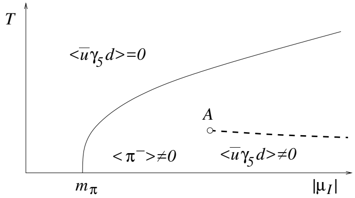
Pion condensation

- isospin chemical potential: $\mu_u = \mu_I$, $\mu_d = -\mu_I$, $\mu_s = 0$
  - QCD at low energies $\approx$ pions
    chiral perturbation theory
  - charged pion chemical potential: $\mu_\pi = 2\mu_I$



at zero temperature $\mu_\pi < m_\pi$ vacuum state
$\mu_\pi \geq m_\pi$ Bose-Einstein condensation

Son, Stephanov '00



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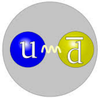

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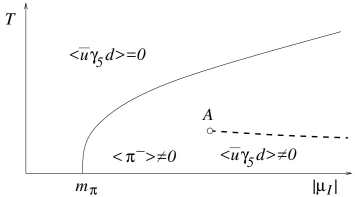
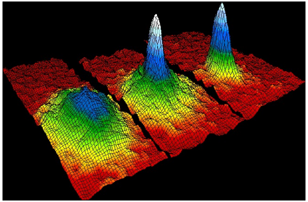




- trapped Rb atoms at low temperature Anderson et al '95 JILA-NIST/University of Colorado

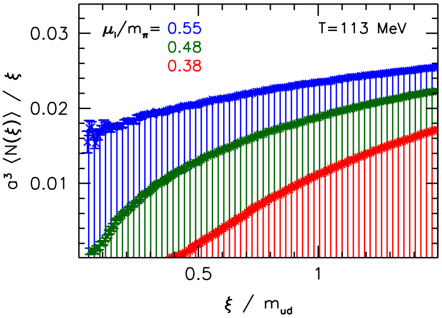
Condensation of states

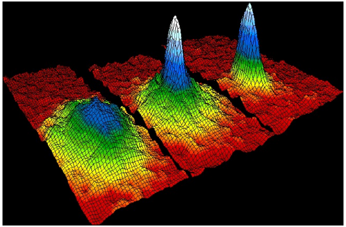
- singular values of the Dirac operator Kanazawa, Wettig, Yamamoto '11

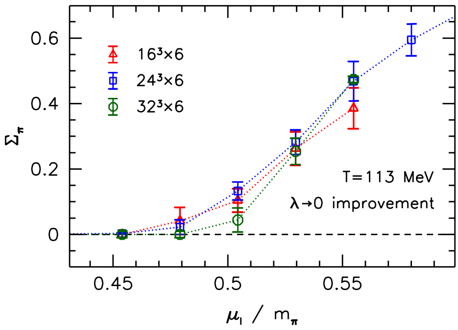
$$(\not{D} + m)^\dagger(\not{D} + m)\chi = \xi^2\chi$$

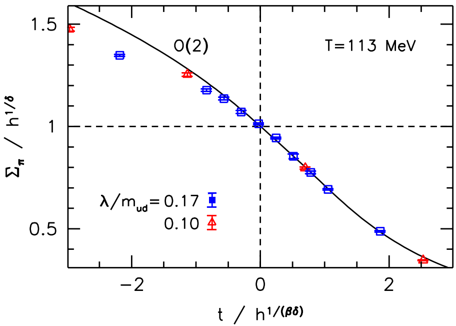
- pion condensate via Banks-Casher-type relation Brandt, Endrődi, Schmalzbauer '17

$$\Sigma_\pi \propto \langle \rho(\xi = 0) \rangle$$



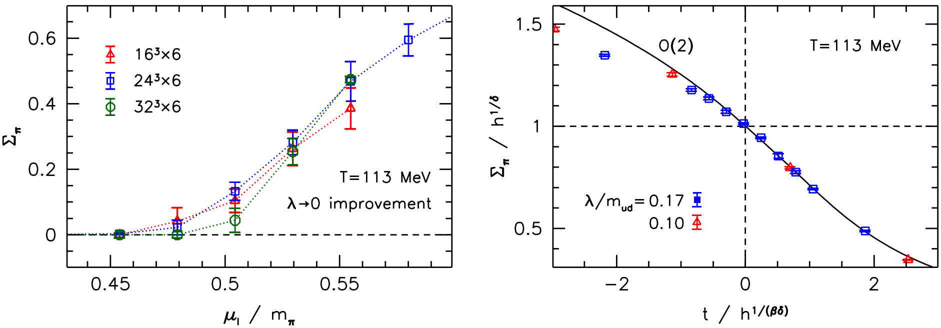






- volume scaling of order parameter shows typical sharpening
- collapse according to $\mathrm{O}(2)$ critical exponents Ejiri et al '09

Order of the transition

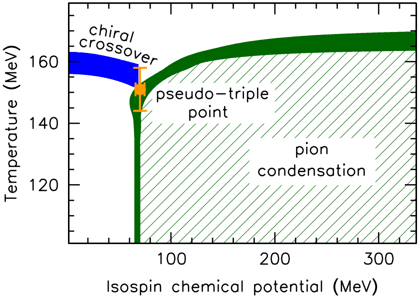


- volume scaling of order parameter shows typical sharpening
- collapse according to $\mathrm{O}(2)$ critical exponents Ejiri et al '09
- indications for a second order phase transition at $\mu_I = m_\pi/2$, in the $\mathrm{O}(2)$ universality class

Phase diagram

- phases in the $T - \mu_I$ phase diagram: hadronic (confined), quark-gluon plasma (deconfined), pion condensation (confined)

  Brandt, Endrődi, Schmalzbauer '17 Brandt, Endrődi '19



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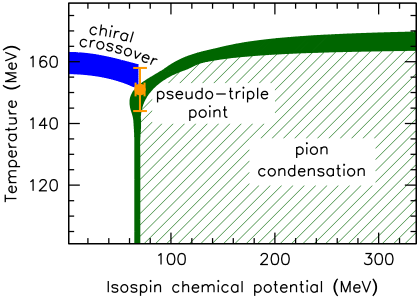
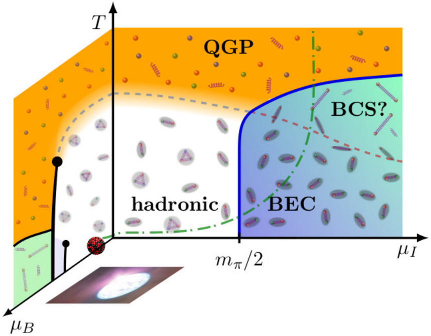
Brandt, Endrődi, Schmalzbauer '17 Brandt, Endrődi '19





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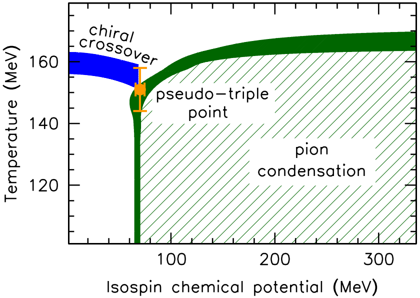

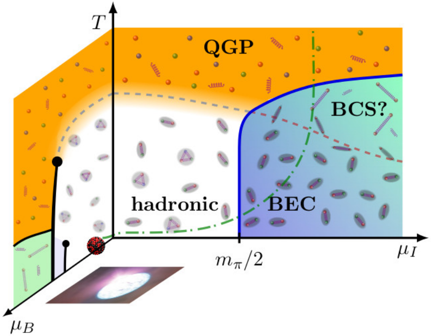

- comparison to effective models, χPT, Q2CD, ...

  Adhikari et al. '18 Zhokhov et al. '19 Adhikari et al. '20 Boz et al. '20
  Astrakhantsev et al. '20 Andersen et al. '23

Equation of state: nonzero isospin

Equation of state

- equilibrium description of matter

$$\epsilon(p)$$

relevant for:

  - neutron star physics (TOV equations)
  - cosmology, evolution of early Universe (Friedmann equation)
  - heavy-ion collision phenomenology (charge fluctuations)

- thermodynamic relations

$$p = \frac{T}{V} \log \mathcal{Z}, \qquad s = \frac{\partial p}{\partial T}, \qquad n_I = \frac{\partial p}{\partial \mu_I}, \qquad \epsilon = -p + Ts + \mu_I n_I$$

$$I = \epsilon - 3p, \qquad c_s^2 = \left.\frac{\partial p}{\partial \epsilon}\right|_{s/n_I}$$

Equation of state on the lattice: $T \approx 0$

- integral method to calculate differences

$$n_I = \frac{T}{V}\frac{\partial \log \mathcal{Z}}{\partial \mu_I}, \qquad p(T,\mu_I) - p(T,0) = \int_0^{\mu_I} \mathrm{d}\mu_I'\, n_I(\mu_I')$$

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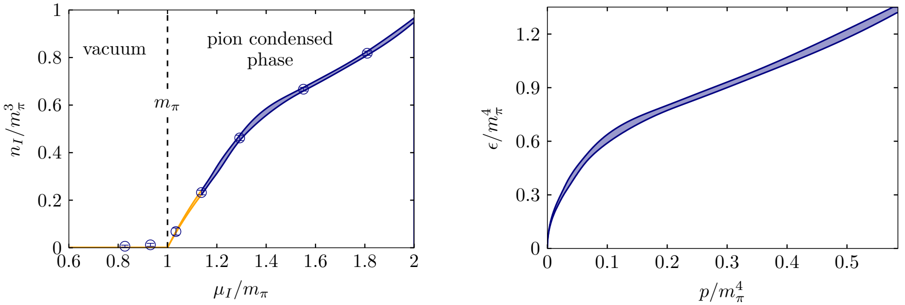
- pressure and energy density

Brandt, Endrődi, Fraga, Hippert, Schaffner-Bielich, Schmalzbauer '18



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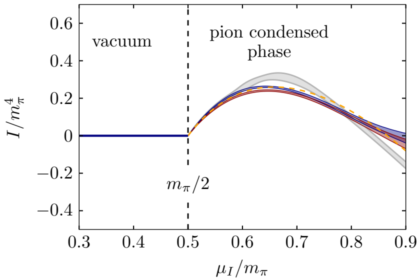
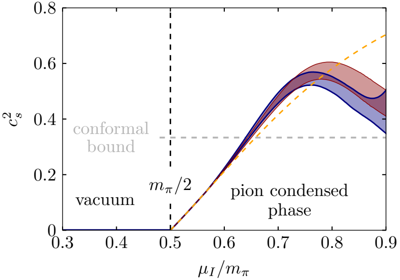
- interaction measure and speed of sound

  Brandt, Cuteri, Endrődi '22





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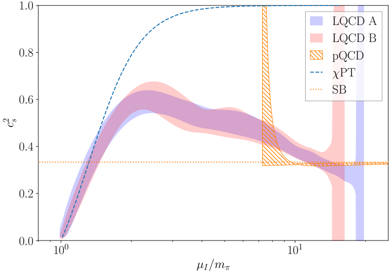
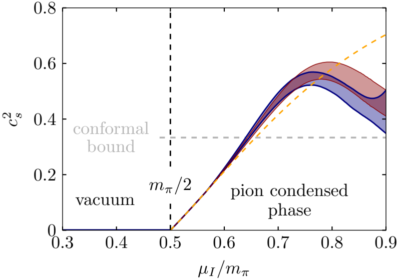
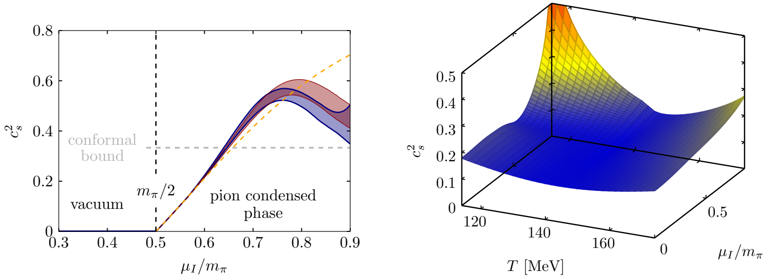
  Brandt, Cuteri, Endrődi '22 Abbott et al. '23





Equation of state on the lattice: $T > 0$

- nonzero temperature results 🔗 Brandt, Cuteri, Endrődi '22
  🔗 Vovchenko, Brandt, Cuteri, Endrődi, Hajkarim, Schaffner-Bielich '20
- interaction measure negative at high μ_I, low T
- speed of sound above $1/\sqrt{3}$ at high μ_I and intermediate T



- EoS can get very stiff inside pion condensation phase

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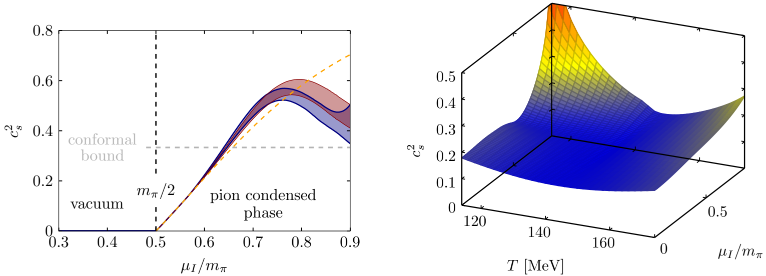
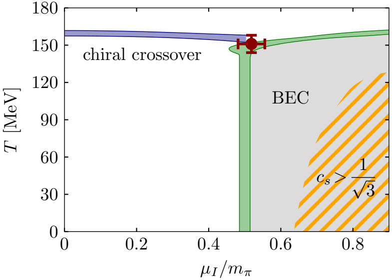


- EoS can get very stiff inside pion condensation phase
- comparison: χPT, models Adhikari et al. '21 Avancini et al. '19

Speed of sound

- 'supersonic' region of pion condensate
- first time that $c_s > 1/\sqrt{3}$ found in a first-principles lattice QCD calculation



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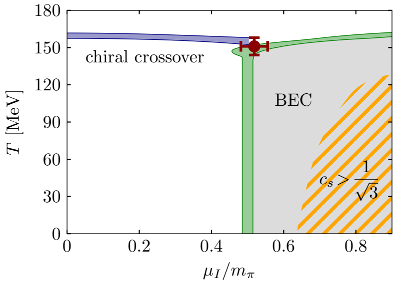

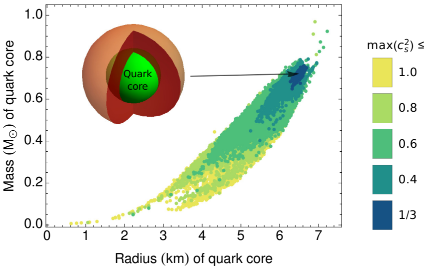

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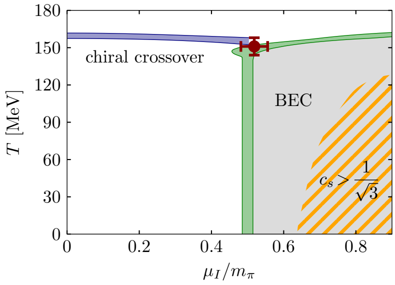
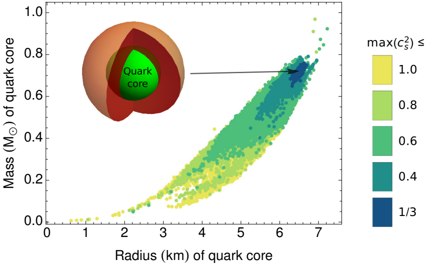


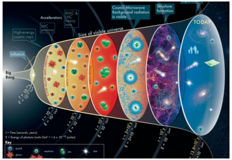


- c_s at $\mu_B > 0$ from FRG and χEFT Braun, Schallmo ’22 Leonhardt et al. ’20

Cosmological implications

Cosmic trajectories

- early Universe



- conservation equations for isentropic expansion

$$\frac{n_B}{s} = b, \quad \frac{n_Q}{s} = 0, \quad \frac{n_{L_\alpha}}{s} = l_\alpha \quad (\alpha \in \{e, \mu, \tau\})$$

- parameters: $T, \quad \mu_B, \quad \mu_Q, \quad \mu_{L_\alpha}$
- experimental constraints Planck collaboration '15 Oldengott, Schwarz '17

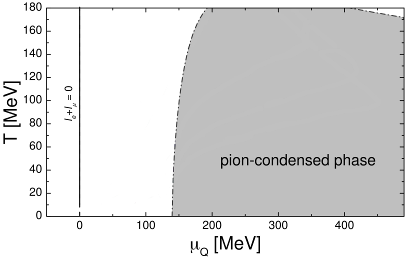
$$b = (8.60 \pm 0.06) \cdot 10^{-11}, \qquad \boxed{|l_e + l_\mu + l_\tau| < 0.012}$$

(the individual l_α may have opposite signs)

- $n_Q = 0$ with $l_e > 0$ allows equilibrium of e^-, ν_e, π^+ Abuki, Brauner, Warringa '09

Cosmic trajectories

- cosmic trajectory $T(\mu_Q)$ is solved for
- standard scenario ($l_\alpha = 0$): $\mu_Q = 0$ for all T



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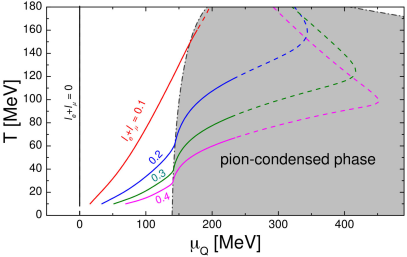


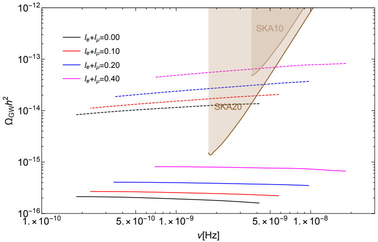
- cosmic trajectory enters BEC phase for lepton asymmetries allowed by observations Vovchenko, Brandt, Cuteri, Endrődi, Hajkarim, Schaffner-Bielich '20

- condition for pion condensation to occur:

$$\boxed{|l_e + l_\mu + l_\tau| < 0.012} \qquad \boxed{|l_e + l_\mu| \gtrsim 0.1}$$

Signatures of the condensed phase

- relic density of primordial gravitational waves is enhanced with respect to amplitude at $l_e + l_\mu = 0$



Vovchenko, Brandt, Cuteri, Endrődi, Hajkarim, Schaffner-Bielich ’20

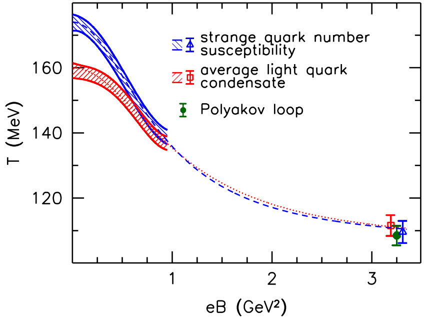
- to be detected experimentally (SKA)

Phase diagram: magnetic fields

Magnetic phase diagram

- QCD crossover temperature in the phase diagram

  Bali, Bruckmann, Endrődi, Fodor, Katz et al. '11 '12 Endrődi '15



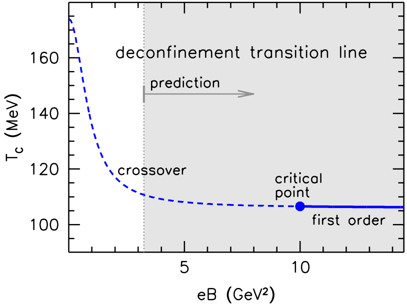
- T_c is reduced by B

  contrary to almost all effective theories and low-energy models of QCD

  Andersen, Naylor, Tranberg '14

Magnetic phase diagram and critical point

- effective theory of QCD at $B \to \infty$: first-order deconfinement transition
  $\Rightarrow$ critical point! Miransky, Shovkovy '02
- location of critical point based on extrapolation from $0 < eB \lesssim 3$ GeV^2
  $\Rightarrow$ $eB_c \approx 10(2)$ GeV^2 Endrődi '15



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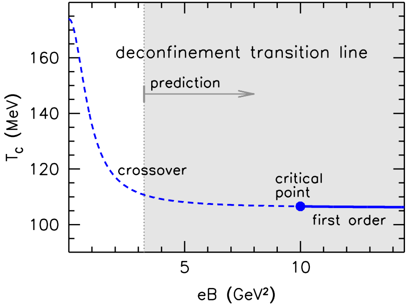
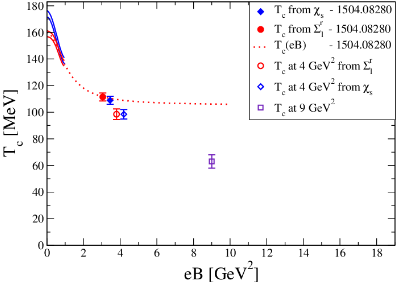
- simulating up to $eB \approx 9$ GeV^2
  $\Rightarrow 4$ GeV$^2 < eB_c < 9$ GeV^2 D'Elia, Maio, Sanfilippo, Stanzione '21





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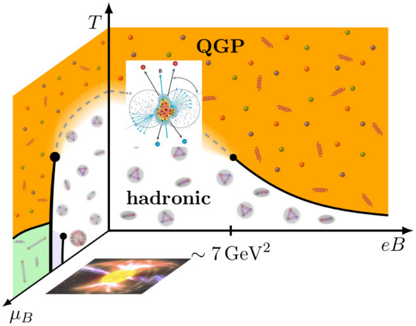
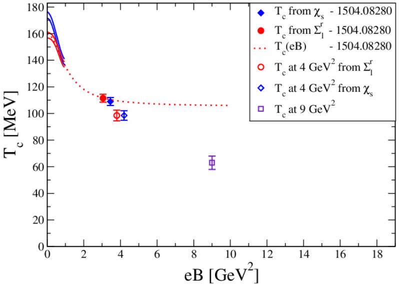
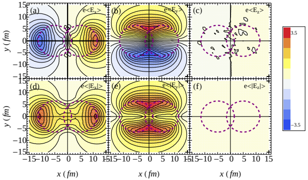




Beyond constant magnetic fields: inhomogeneities

Inhomogeneous magnetic fields

- off-central heavy-ion collisions: inhomogeneous magnetic fields Deng et al. ’12



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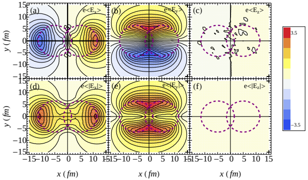

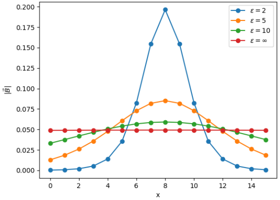

- consider profile $B(x) = B \cosh^{-2}(x/\epsilon)$ Dunne '04

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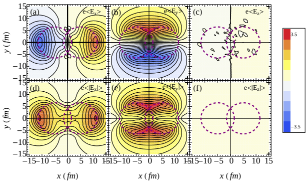

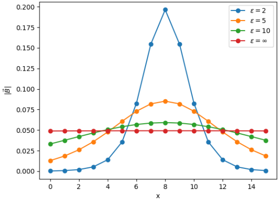

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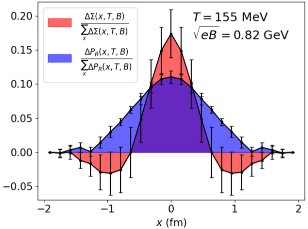
- impact: condensate, Polyakov loop Brandt, Cuteri, Endrődi, Markó, Sandbote, Valois '23



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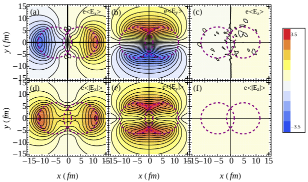
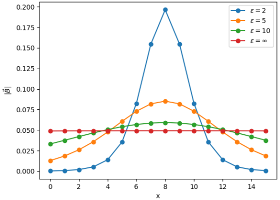
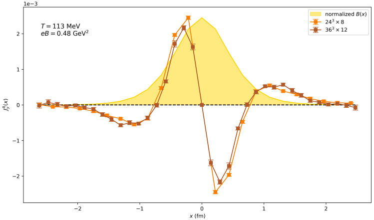




- consider profile $B(x) = B\cosh^{-2}(x/\epsilon)$ Dunne '04
- impact: electric current Valois et al. upcoming D. Valois Tue 16:00 HK21.2



Magnetic fields and chiral imbalance: anomalous transport

Anomalous transport

- usual transport:
  vector current due to electric field

$$\langle \vec{J} \rangle = \sigma \cdot \vec{E}$$

- chiral magnetic effect (CME): Fukushima, Kharzeev, Warringa '08
  vector current due to chirality and magnetic field

$$\langle \vec{J} \rangle = \sigma_{\mathrm{CME}} \cdot \vec{B}$$

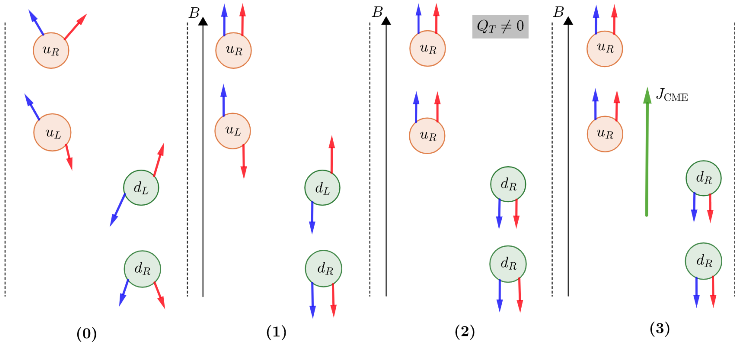
- chiral separation effect (CSE):
  axial current due to baryon number and magnetic field

$$\langle \vec{J}_5 \rangle = \sigma_{\mathrm{CSE}} \cdot \vec{B}$$

- probe CP-odd domains in heavy-ion collisions Kharzeev, Liao, Voloshin, Wang '16
- experimental searches for CME and related observables STAR collaboration '21

General (handwaving) argument

- spin, momentum   CME



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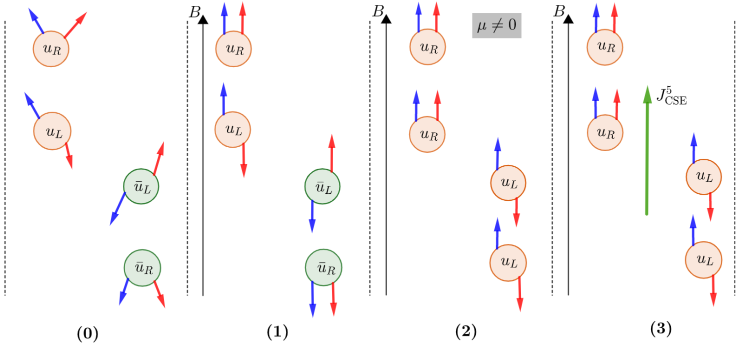
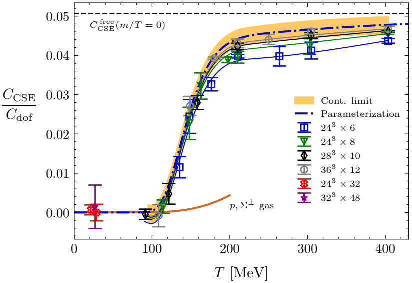


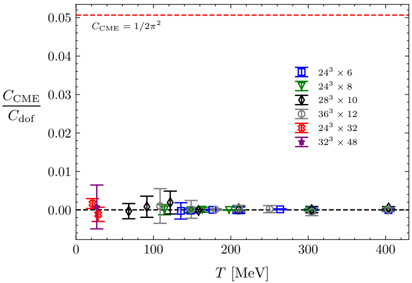
CME and CSE from lattice QCD

- first determination of **in-equilibrium** CME/CSE coefficients with continuum extrapolated lattice simulations

CSE: Brandt, Endrődi, Garnacho, Markó, '23

CME: Brandt, Endrődi, Garnacho, Markó, upcoming





- clarifying contradictory results in the literature E. Garnacho Tue 15:45 HK21.1

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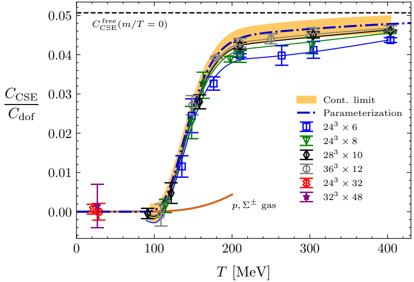

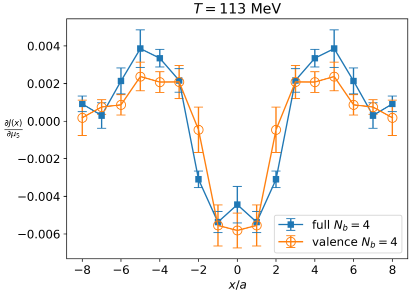

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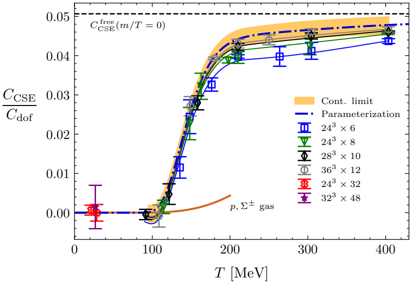

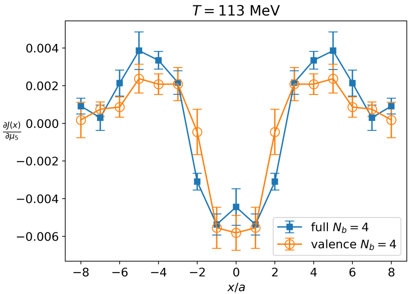

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- non-trivial response in inhomogeneous field $B(x)$ D. Valois Tue 16:00 HK21.2
- this is not the **out-of-equilibrium** effect

Magnetic and electric fields: axion-photon coupling

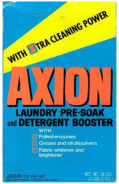
Axions as dark matter

- extend Standard Model with new field: axion a

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{2}\partial_\mu a\,\partial_\mu a + a\,\underbrace{\mathrm{Tr}\,G_{\mu\nu}\widetilde{G}_{\mu\nu}}_{Q_{\mathrm{top}}} + a\,g_{a\gamma\gamma}\underbrace{F_{\mu\nu}\widetilde{F}_{\mu\nu}}_{\mathbf{E}\cdot\mathbf{B}}$$

- provides solution to ‘strong CP problem’

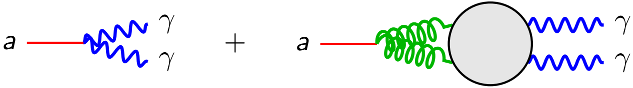
  Peccei, Quinn ’77 Weinberg ’78 Wilczek ’78



- is a possible dark matter candidate
- extensive experimental campaign:
  haloscopes and helioscopes CAST ADMX XENON1T

Axion-photon coupling

- most relevant parameter for experimental detection
- direct coupling (model-dependent)
  plus
  indirect coupling through quark/gluon loops



- chiral perturbation theory predicts two terms of similar magnitude and opposite sign di Cortona et al. '16
- QCD contribution, for slowly varying a fields

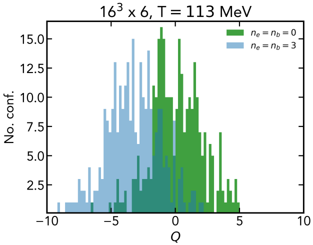
$$g_{a\gamma\gamma}^{\mathrm{QCD}} = \frac{\partial^2 \log \mathcal{Z}}{\partial a\, \partial(\mathbf{E}\cdot\mathbf{B})} = \frac{\partial \langle Q_{\mathrm{top}} \rangle}{\partial(i\mathbf{E}\cdot\mathbf{B})}$$

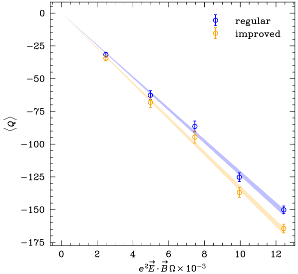
Axion-photon coupling on the lattice

- QCD contribution

$$g_{a\gamma\gamma}^{\mathrm{QCD}} = \frac{\partial \langle Q_{\mathrm{top}} \rangle}{\partial (i\mathbf{E} \cdot \mathbf{B})}$$

- shift in mean topology by parallel magnetic *and* imaginary electric fields





- first results for $g_{a\gamma\gamma}^{\mathrm{QCD}}$ Brandt, Cuteri, Endrődi, Hernández, Markó '22
- challenging to approach continuum limit J.Hernández Wed 17:45 HK48.2

Summary

Summary

- $T - \mu_I$ phase diagram and pion condensation
- cosmic trajectory may enter pion condensed phase
- $T - B$ phase diagram and the critical point
- in-equilibrium anomalous transport phenomena from lattice QCD