Discovering novel phases of hot nuclear matter with fluctuations

Proposal HotDISCO

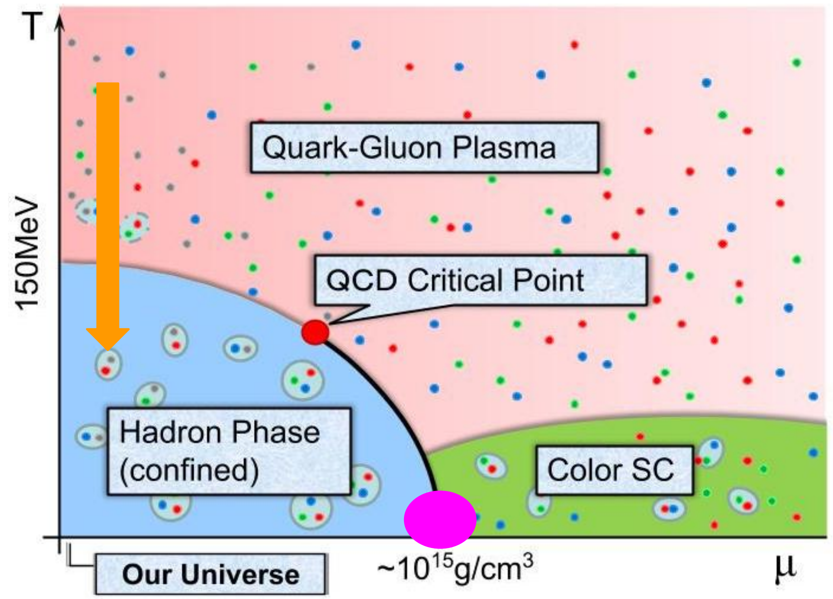
A. Rothkopf (Korea U, Seoul) & M. Nahrgang (Subatech, Nantes)
알렉산더 로트코프 (고려대학교, 서울) 및 말레네 나르강 (쉬바텍 연구소, 낭트)

QCD under extreme conditions

Understanding the dynamics of the strong interaction under extreme conditions of temperature and density!

The QCD phase diagram connects to

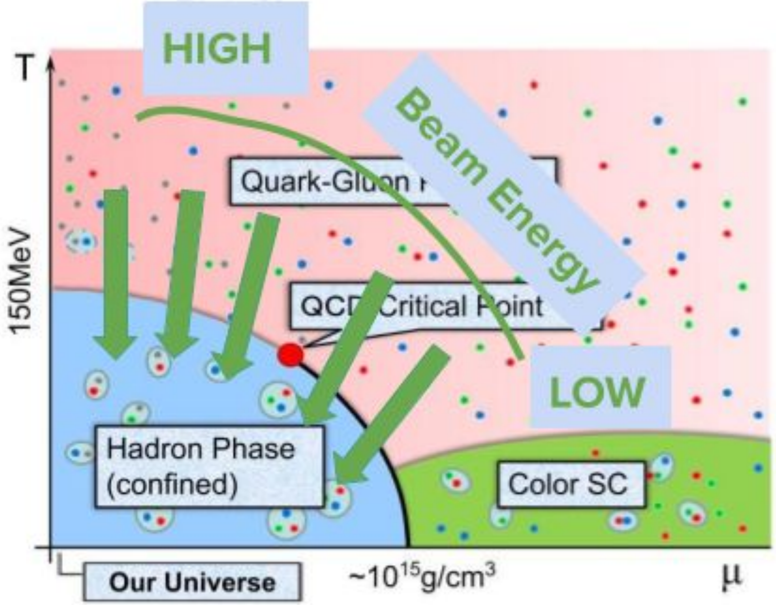
- cosmology -> evolution of the early universe
- compact stars at high net-baryon density
- strongly coupled quantum fluids



Heavy-ion collisions and the QCD phase diagram

- elementary reactions e + e − , pp, pp-
  ⇒ (mostly) vacuum QCD
- p- A, pA ⇒ nuclear modifications
- heavy-ion collisions (HIC) AA ⇒
  medium formation and properties

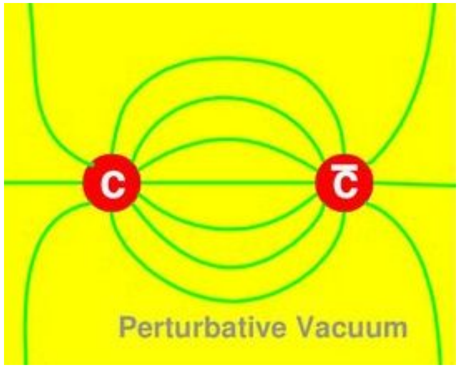
- Highest energies at LHC/RHIC:
  AA at $\sqrt{s_{NN}}$= 0.2 – 5 TeV
  ⇒ Energy deposition
  ➔ handle on the temperature.
- Lower energies at GSI/FAIR, SPS/CERN, BES/RHIC, JPARC:
  AA at $\sqrt{s_{NN}}$= 2 – 20 GeV
  ⇒ Baryon stopping
  ➔ handle on the baryon chemical potential.



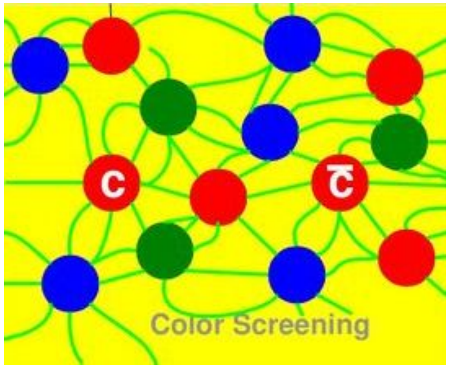
J/ψ Suppression – A Signature of QGP Formation

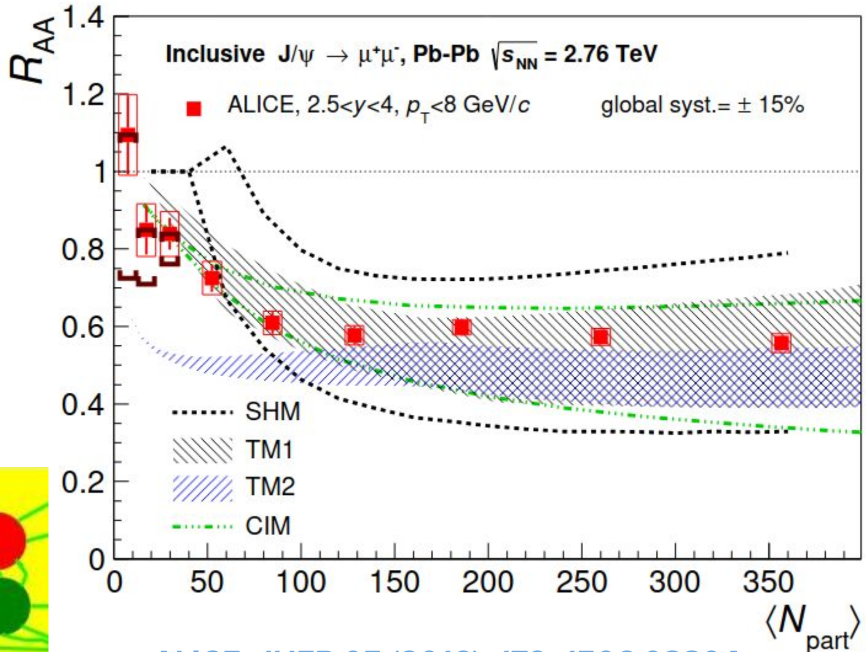
T. Matsui and H. Satz, PLB 178 (1986) 416

- **J/ψ is a** bound state of $c\bar{c}$, *charmonium*.
- In a deconfined QGP, **color screening** prevents quarks from binding ➔ J/ψ mesons **"melt"**.



vs





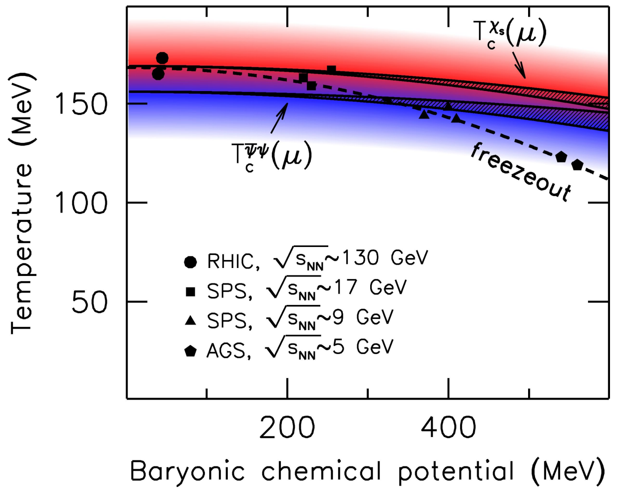
ALICE, JHEP 05 (2016), 179, 1506.08804

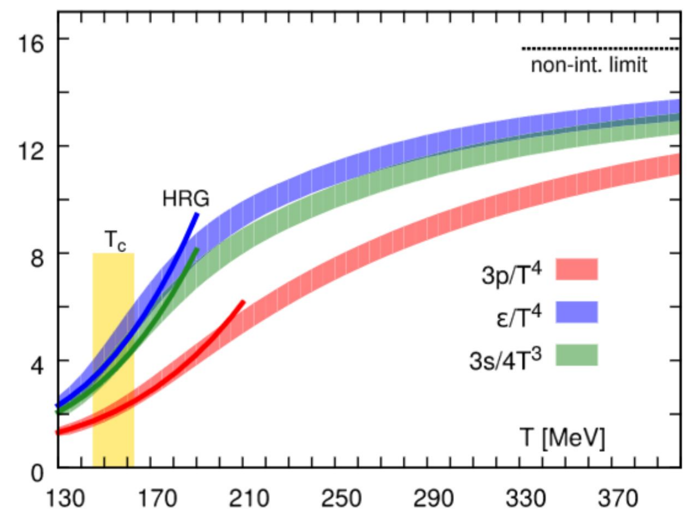
Expectation: Fewer J/ψ mesons observed in HIC compared to pp collisions, **after scaling** by binary collisions -> quantified by the RAA

Current understanding of the QCD phase diagram

Conventional view:

- A **single** crossover transition from the QGP to the hadronic world at Tc and μ_B = 0
- The chiral phase transition and the deconfinement phase transition happen at the same temperature.
- Rapid increase of thermodynamic quantities - Equation of State (EoS) at Tc due to the **liberation of color degrees of freedom**





WB JHEP1009 (2010), HotQCD PoS LATTICE2010 (2010)

Chiral symmetry and deconfinement

Both defined in opposite limits of quark masses → no fundamental theoretical reason to occur at the same T for physical quark masses.

Confinement:
There is a well-defined order parameter for deconfinement in Yang-Mills theory (**$m_q = \infty$**)
- the Polyakov loop:

$$\Phi(\vec{x}) = \frac{1}{N_c} \mathrm{Tr}\, \mathcal{P} \exp\left(i \int_0^\beta A_4(\vec{x}, \tau)\, d\tau \right)$$

If center symmetry is restored, the Polyakov loop vanishes $\langle \Phi \rangle = 0$

$$\Phi(\vec{x}) \to z\,\Phi(\vec{x}), \quad z \in Z(3) = \{1, e^{2\pi i/3}, e^{4\pi i/3}\}$$

$\langle \Phi \rangle = 0$ implies confinement

$$\langle \Phi(\vec{x}) \rangle \propto e^{-\Delta F_q / T}$$

Chiral symmetry:
For **$m_q = 0$**, the Lagrangian of QCD is chirally symmetric.

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_L i\gamma^\mu \partial_\mu \psi_L + \bar{\psi}_R i\gamma^\mu \partial_\mu \psi_R + \mathcal{L}_{\mathrm{gluons}}$$

Chiral flavor group

$$SU(N_f)_L \times SU(N_f)_R$$

Spontaneous symmetry breaking at low T via the quark-antiquark condensate → dynamically generated quark masses

$$m_q \sim \langle \bar{q} q \rangle$$

A. Polyakov (1978) PLB. 59 (1), 82–84;
L. McLarren, B. Svetitsky (1981) PRD 24 (2) 450–460

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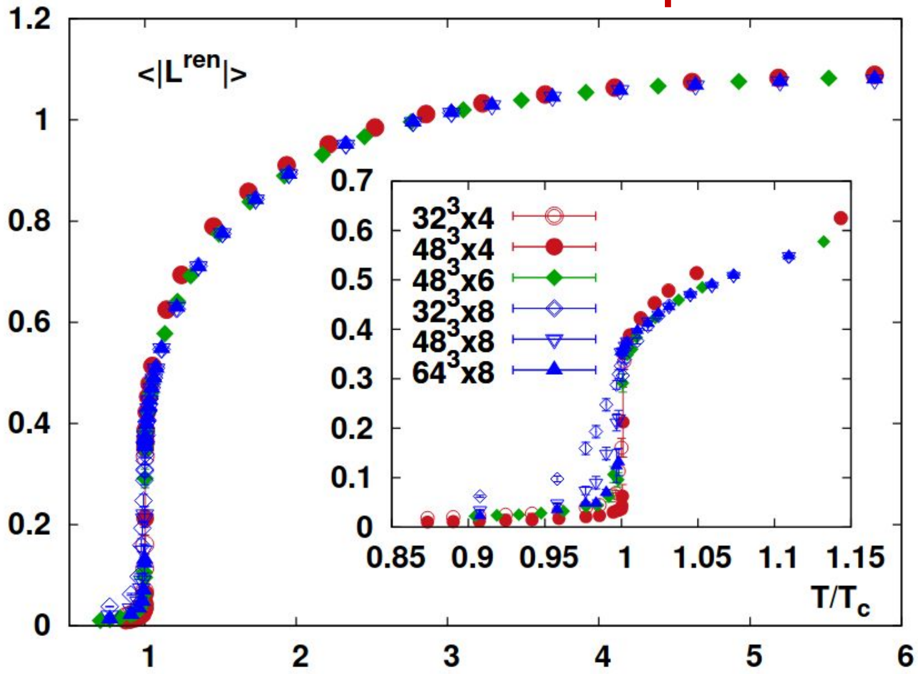
Both defined in opposite limits of quark masses → no fundamental theoretical reason to occur at the same T for physical quark masses.

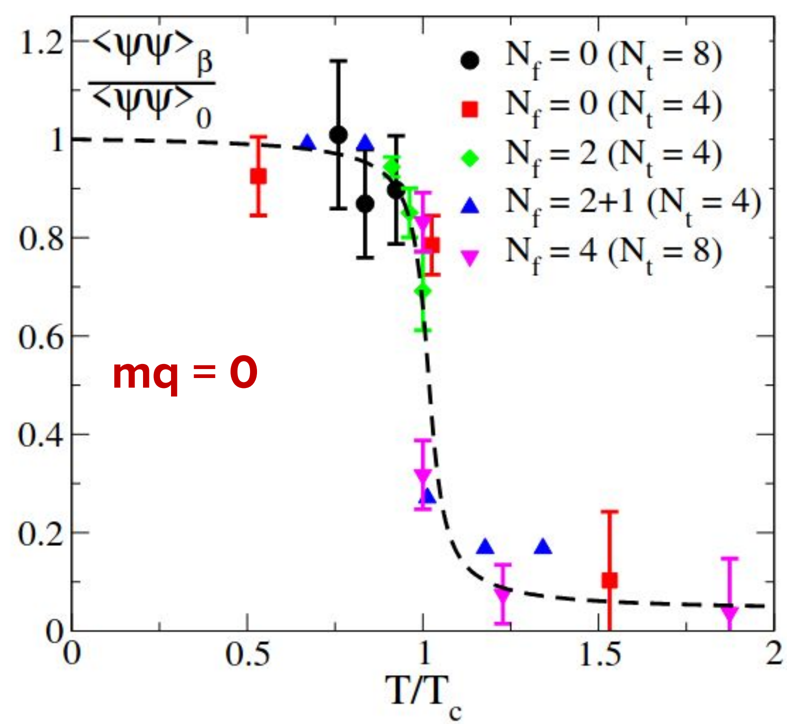
Confinement:
- the Polyakov loop:

mq = ∞



P.M.Lo, et al, PRD88 (2013), 074502, 1307.5958

Chiral symmetry:
- quark-antiquark condensate



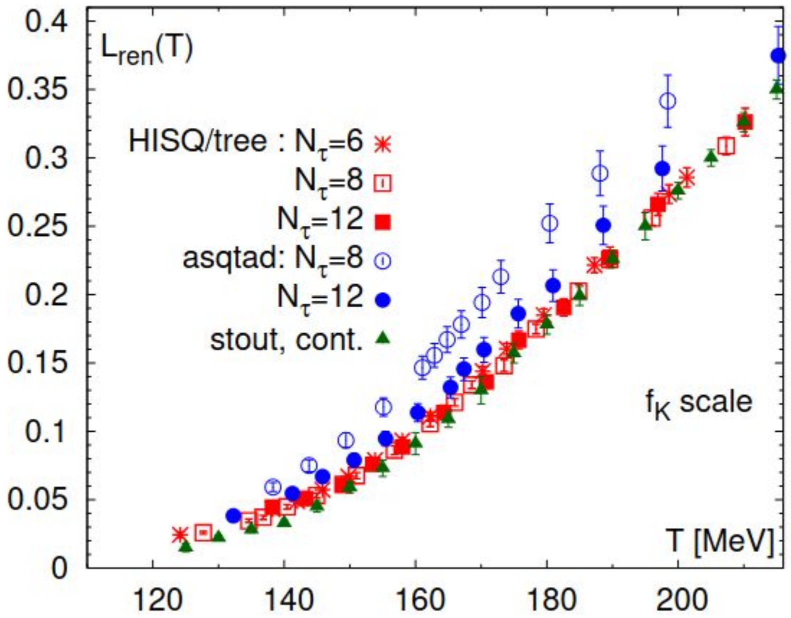
G. Boyd et al., PLB 349:170–176, 1995, hep-lat/9501029

Chiral symmetry and deconfinement

Both defined in opposite limits of quark masses → no fundamental theoretical reason to occur at the same T for physical quark masses.

Confinement:
- the Polyakov loop:

physical mq



Chiral symmetry:
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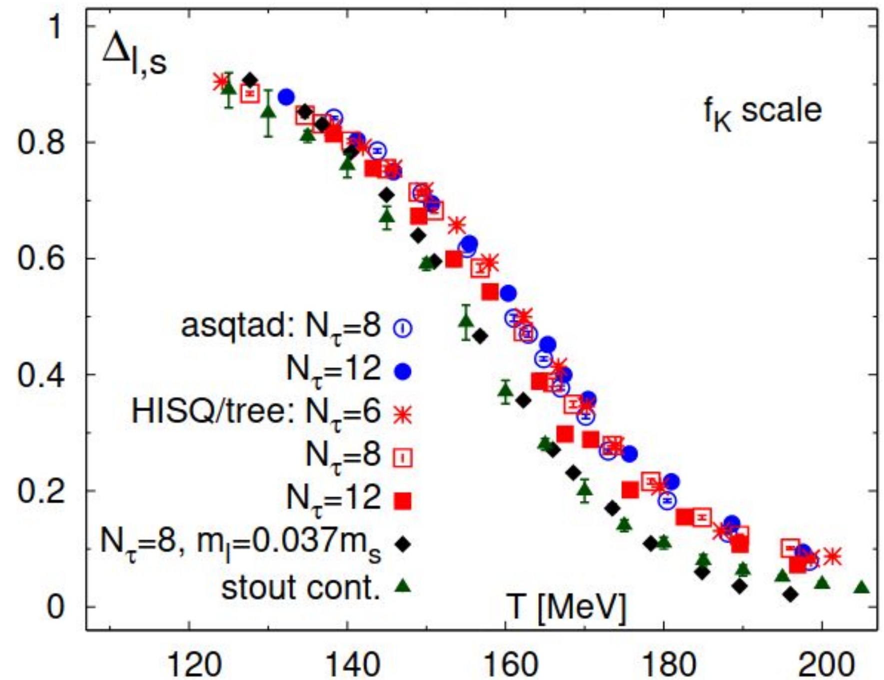
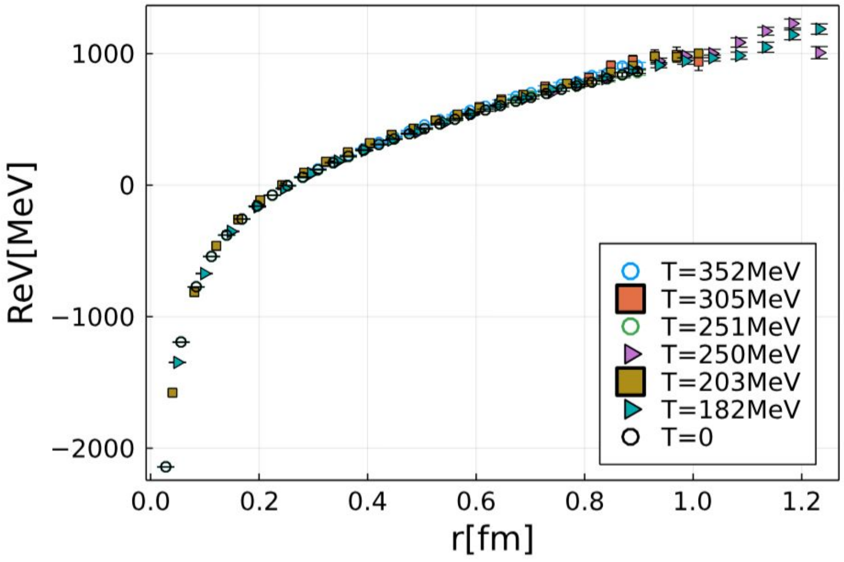


A.Bazavov, et al, PRD85 (2012), 054503, 111.1710

Novel phases at T > Tc? Heavy QQbar potential

in 2 + 1 flavor lattice QCD at finite T:

- contrary to some common expectations the real part of the potential is **not screened** for 153 MeV ≤ T ≤ 352 MeV.
- the dissipative effects encoded in the imaginary part of the potential are very large and likely will lead to quarkonium dissolution.



Very different mechanism for quarkonium dissolution!
No deconfinement needed…

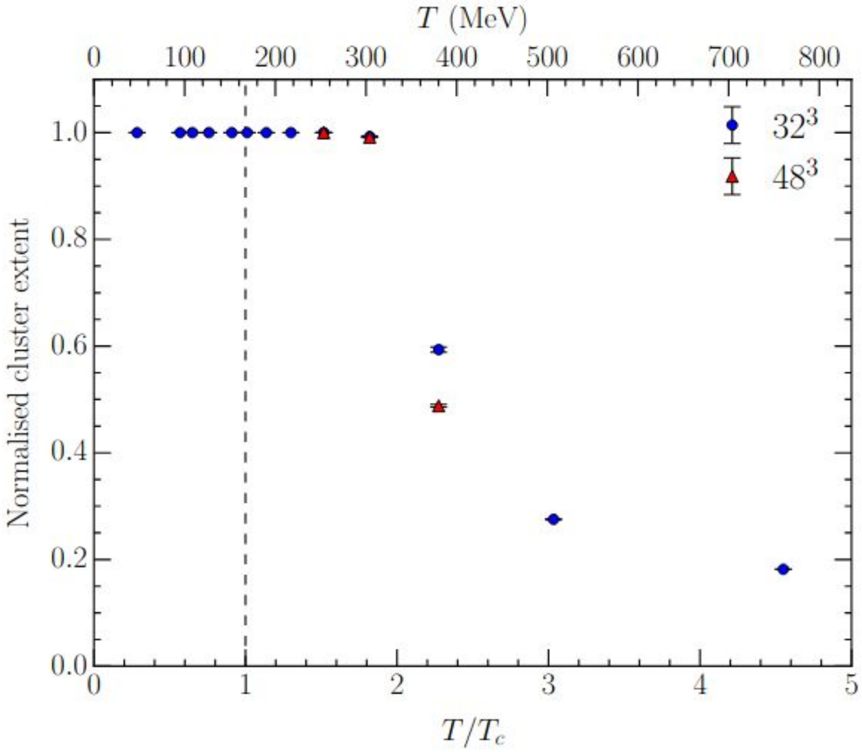
[HotQCD collaboration] & A. Rothkopf, PRD 109 (2024) 7, 074504, 2308.16587

Novel phases at T > Tc? Center vortex percolation

investigate the behavior of center vortices—topological structures associated with confinement

in 2 + 1 flavor lattice QCD at finite T:

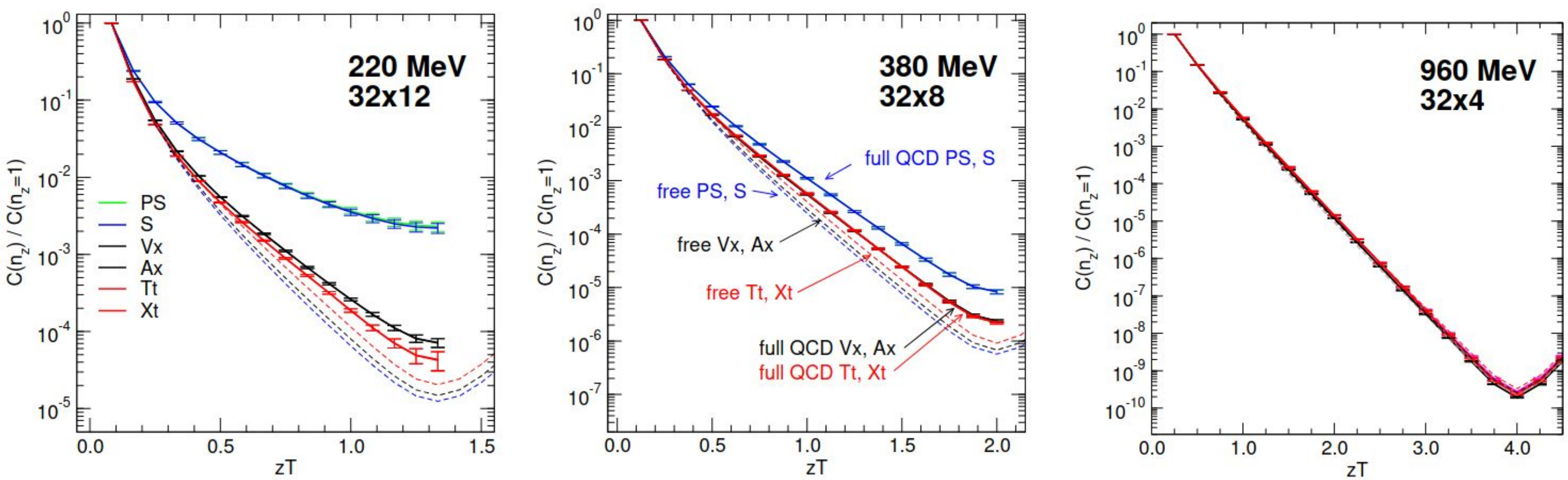
- **Vortex percolation persists** beyond the chiral transition Tc, suggesting confinement remains.
- **Deconfinement occurs at higher temperature** (Td ≈ 2Tc ≈ 321MeV) where vortex percolation stops.
- **All studied vortex observables** show consistent evidence for two distinct transitions.



J. A. Mickley, C. Allton,, R. Bignell, D. B. Leinweber
Phys.Rev.D 111 (2025) 3, 034508, 2411.19446

Novel phases at T > Tc? Chiral-spin symmetry

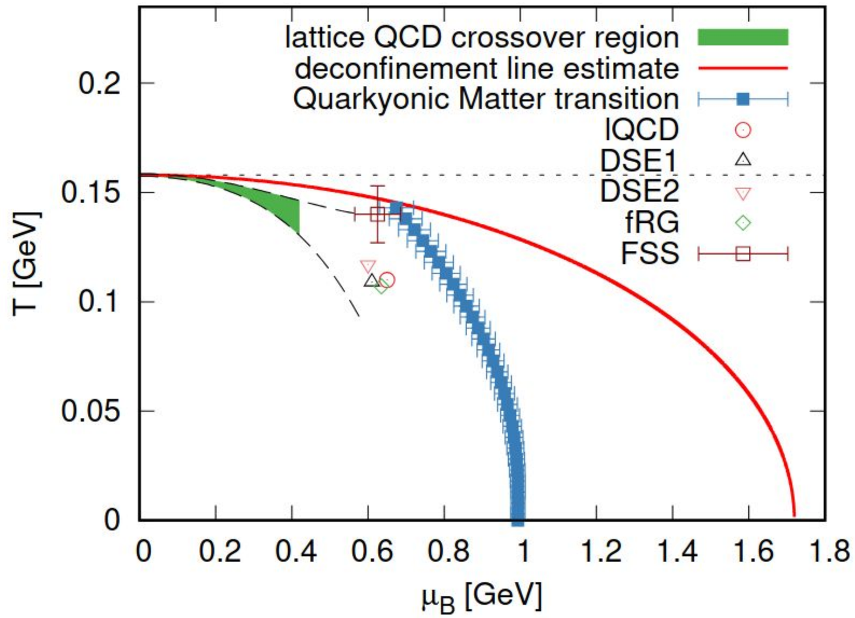
- **Above Tc** $SU(2)_{CS}$ (chiral-spin) and SU(4) symmetries emerge in spatial and temporal meson correlators studied in 2-flavor lattice QCD.
- **Quarks are still bound in color-singlet states** via chromo-electric fields.
- **Evidence for a “stringy fluid” phase**: chiral symmetry is restored but deconfinement persists **up to ∽3Tc**:



C.Rohrhofer et al., Phys. Rev. D 100 (2019) no.1, 014502, 1902.03191; Phys. Lett. B 802 (2020), 135245, 1909.00927

Novel phases at T > Tc? Quarkyonic Matter large μ_B

- **Quarkyonic Matter** emerges when quark phase-space density of baryons reaches unity -> saturation!
- **IdylliQ model** with quark-hadron duality, here HRG applied.
- **At T = 0, QM onset** ∽1–3 x nuclear density
- **At higher T,** onset μ_B decreases, if deconfinement happens at 3Tc, **QM** can exist down to $\mu_B = 0$!



M.Bluhm, Y.Fujimoto, L.McLerran and MN,
Phys. Rev. C 111 (2025) no.4, 044914, 2409.12088

HotDISCO research goal

Discover novel phases of hot nuclear matter

QGP

EoS

Transport properties

Color structure

Fluctuations and correlations

hadrons

Implications for the early universe

Key observables in HIC

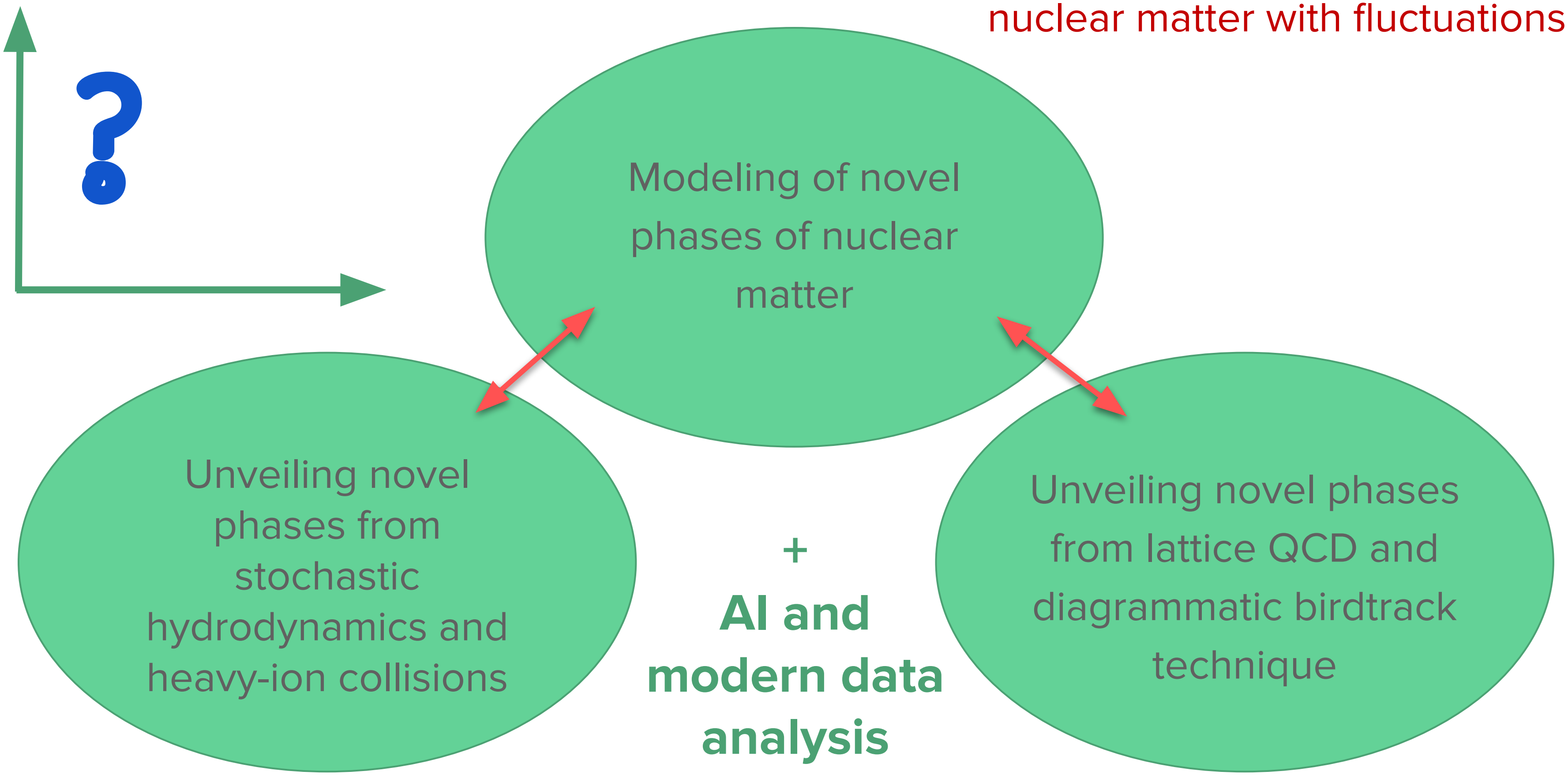
Stochastic hydrodynamics

France – Korea collaboration

Applied for additional funding to PHC - STAR!

HotDISCO research project

Discovering novel phases of hot nuclear matter with fluctuations



Establishing a long term Korean - French collaboration including student exchange programs (**applied for funding from NU!**)

4-day international workshop "Novel phases of nuclear matter" at Korea University in August 2027

HotDISCO - importance of fluctuations

Fluctuations and correlations reveal more details about phase transitions and about the active degrees of freedom (than the EoS).

Quark-flavor correlations:

$$C_{BS} = -3\,\frac{\langle BS\rangle - \langle B\rangle\langle S\rangle}{\langle S^2\rangle - \langle S\rangle^2} = -3\,\frac{\chi_{11}^{BS}}{\chi_2^S}$$

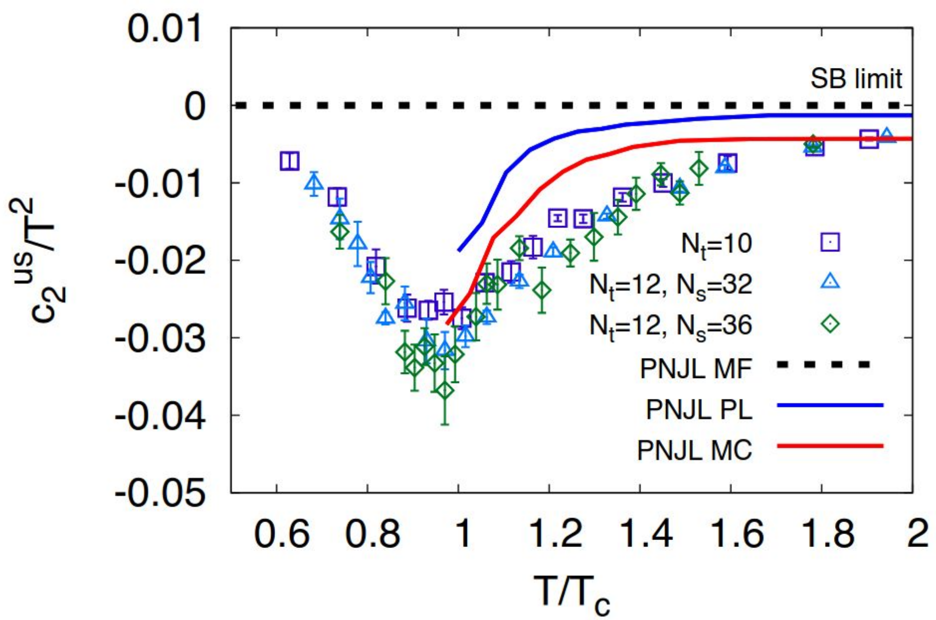
In the QGP, every s quark carries baryon number $C_{\mathrm{BS}}^{\mathrm{QGP}} \approx 1$

In the HRG, s quarks can hide away in mesons $C_{\mathrm{BS}}^{\mathrm{HRG}} \approx 0.5 - 0.6$

V.Koch, A.Majumder and J.Randrup, Phys. Rev. Lett. 95 (2005), 182301 nucl-th/0505052

Similar for charge ratio fluctuations

S.Jeon and V.Koch, PRL85 (2000), 2076-2079 hep-ph/0003168; M.Asakawa, U.Heinz and B.Muller, PRL85 (2000), 2072-2075 hep-ph/0003169



Hadronic PNJL model reproduces lattice QCD calculations up to ∼ 2Tc

C.Ratti, R.Bellwied, M.Cristoforetti and M.Barbaro,PRD85 (2012), 014004, 1109.6243

Importance of dynamical modeling

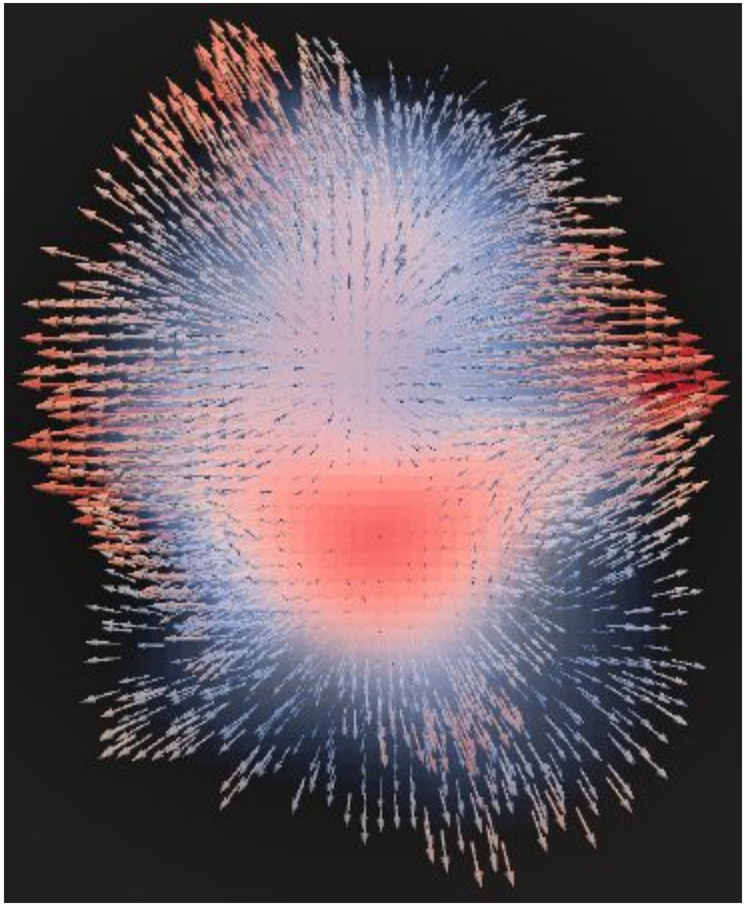
In a grand-canonical ensemble the system is…

- in thermal equilibrium (= long-lived)
- in equilibrium with a particle heat bath
- spatially infinite
- and static

Systems created in a heavy-ion collision are

- short-lived
- spatially small
- inhomogeneous
- highly dynamical
- follow a multi-stage evolution!

Solution: Event-by-event dynamical modeling
allows us in addition to study different particle species, experimental cuts, hadronic final interactions, etc.

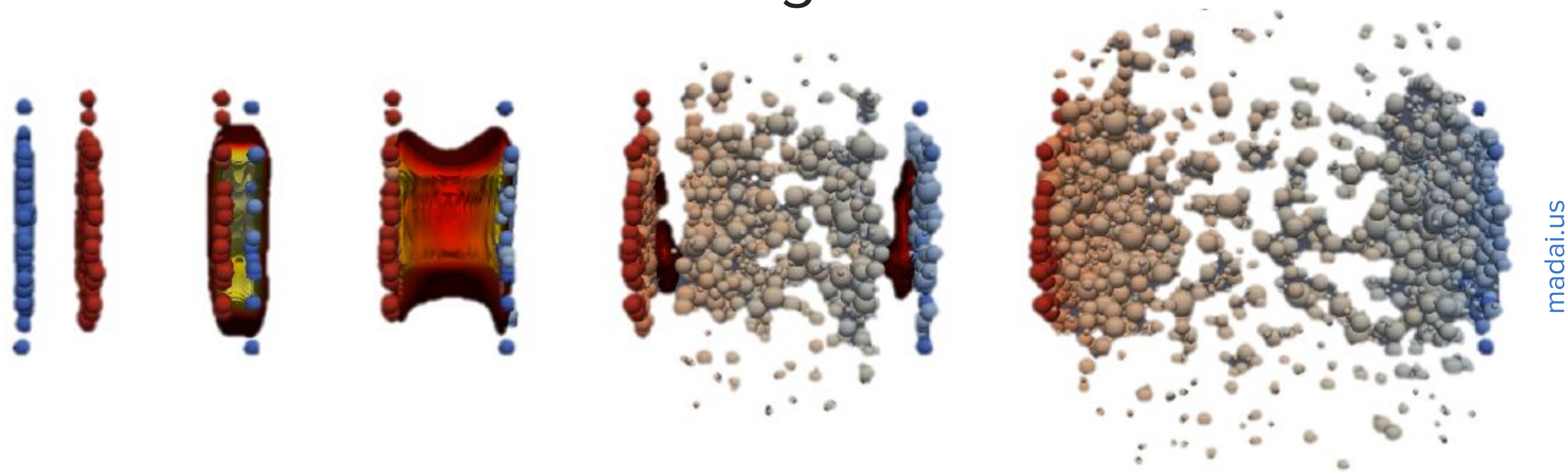


madai.us

Connect QCD thermodynamics with experimental observables via a realistic dynamical modeling of heavy-ion collisions!

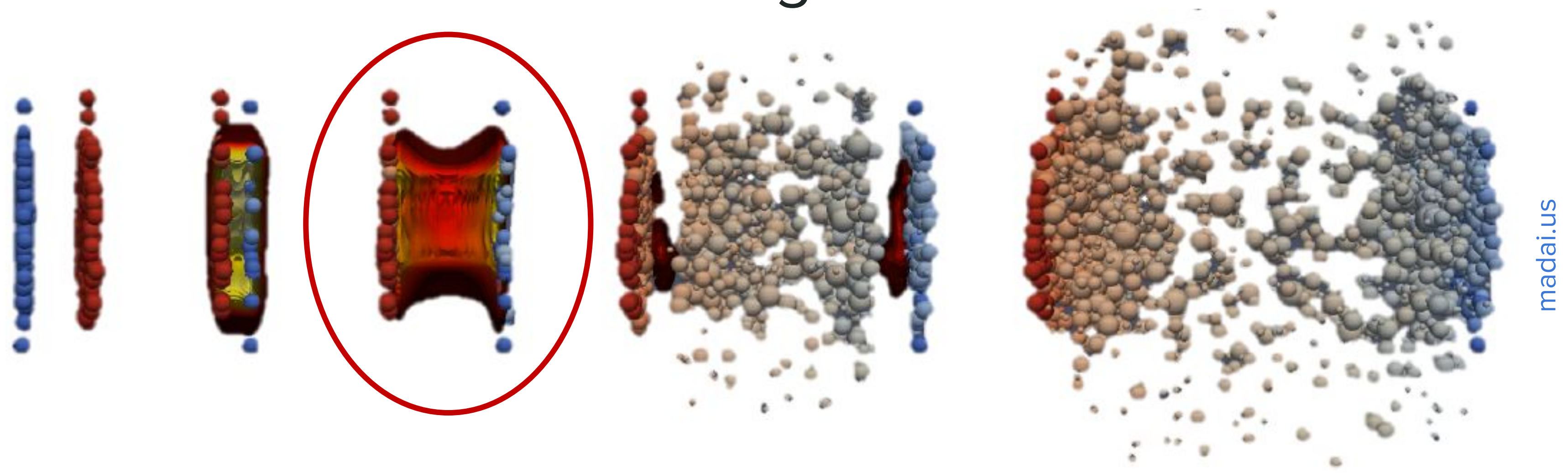
EMMI Rapid Reaction Task Force: M. Bluhm, A. Kalweit, MN et al. NPA 1003 (2020)

Standard model of simulating HIC



- Initial state
- Pre-equilibrium phase -> rapid thermalization, fluidization, etc.
- Expansion of the QGP - novel phase - and chiral phase transition -> fluid dynamical description
- Particlization -> Cooper-Frye prescription
- Final hadronic interactions -> microscopic transport

Standard model of simulating HIC



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Importance of fluctuations for transport coefficients

$\eta \sim \int d^3x dt \, \langle T^{ij}(x,t) T^{ij}(0,0) \rangle$

Included in fluid dynamics

NOT included in fluid dynamics

- symmetrized correlator:

$$G_S^{xyxy}(\omega, \mathbf{0}) = \int \mathrm{d}^3x\mathrm{d}t \, e^{i(\omega t - \mathbf{k}\cdot\mathbf{x})} \left\langle \frac{1}{2}\{T^{xy}(t,\mathbf{x}), T^{xy}(0,\mathbf{0})\} \right\rangle$$

- for the shear-shear contribution $\Rightarrow$

$$G^{xyxy}_{R,\mathrm{shear-shear}}(\omega, \mathbf{0}) = -\frac{7T}{90\pi^2}\Lambda^3 - i\omega\frac{7T}{60\pi^2}\frac{\Lambda}{\gamma_\eta} + (i+1)\omega^{3/2}\frac{7T}{90\pi^2}\frac{1}{\gamma_\eta^{3/2}}$$

cutoff-dependent fluctuation contribution to the pressure

cutoff-dependent correction to η

frequency-dependent contribution to η and τ_π

P. Kovtun et al, PRD84 (2011); C.Chafin, T. Schäfer, PRA87 (2013); P. Romatschke et al, PRA87 (2013)

Fluctuating Dissipative Fluid Dynamics

Work in progress by
J. Sterba (PhD)

Add a noise term to the hydrodynamical conservation equation:

$$\partial_\mu T^{\mu\nu} = 0, \quad T^{\mu\nu} = T^{\mu\nu}_{\text{ideal}} + T^{\mu\nu}_{\text{viscous}} + S^{\mu\nu}_{\text{noise}},$$

With the correlators of the thermal noise terms

$$\langle S^{\mu\nu}(x_1) S^{\alpha\beta}(x_2)\rangle = 2T \left[\begin{array}{l} \eta \left(\Delta^{\mu\alpha}\Delta^{\nu\beta} + \Delta^{\mu\beta}\Delta^{\nu\alpha}\right) \\ + \left(\zeta - \frac{2}{3}\eta\right) \Delta^{\mu\nu}\Delta^{\alpha\beta} \end{array} \right] \delta^{(4)}(x_1 - x_2).$$

Several issues arise from the discretization of the Dirac delta function in the noise

- Stochastic noise introduces a lattice spacing dependence.
- Correction terms due to renormalization become large for small lattice spacings.
- Large noise contributions can locally lead to negative energy densities.
- Large gradients introduced by the uncorrelated noise is a problem for PDE solvers.

MN et al, Acta Phys. Polon. 10 (2017);

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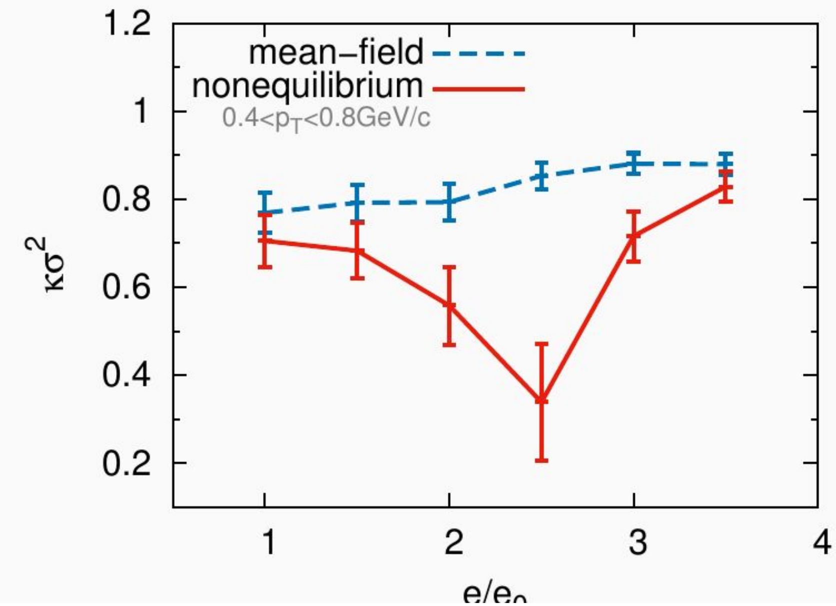
Derive proper renormalization procedure from kinetic theory based on the microscopic modelling of the novel phase

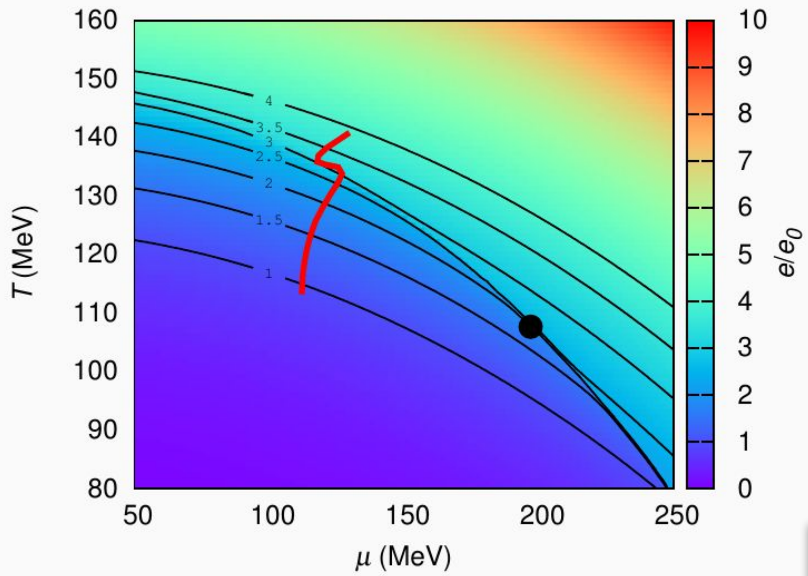
Learn from approaches to stochastic quantization studies

D.Alvestad, R.Larsen and A.Rothkopf, JHEP 04 (2023), 057, 2211.15625

Net-proton fluctuations near the critical point

- Dynamical fluctuations of the **chiral order parameter** and the **Polyakov loop** coupled to fluid dynamics.
- Study along a HIC trajectory in the QCD phase diagram





C. Herold, MN, Y. Yan and C. Kobdaj, PRC 93 (2016) no.2

- No non-monotonic behavior in pure mean-field equilibrium calculations.
- Proper dynamical treatment of fluctuations:
  Clear signal for criticality in net-proton fluctuations at transition energy density!

MN et al, EPJC72 (2012), 0903.2911

Two dynamic-al teams

Professor at Korea University since 03/2025!

Seoul

A. Rothkopf,
PhD student NN *

Nantes

M. Nahrgang,
M. Bluhm,
S. Peigné,
J. Sterba (PhD),
PhD student NN *

* potentially in cotutelle/joint supervision

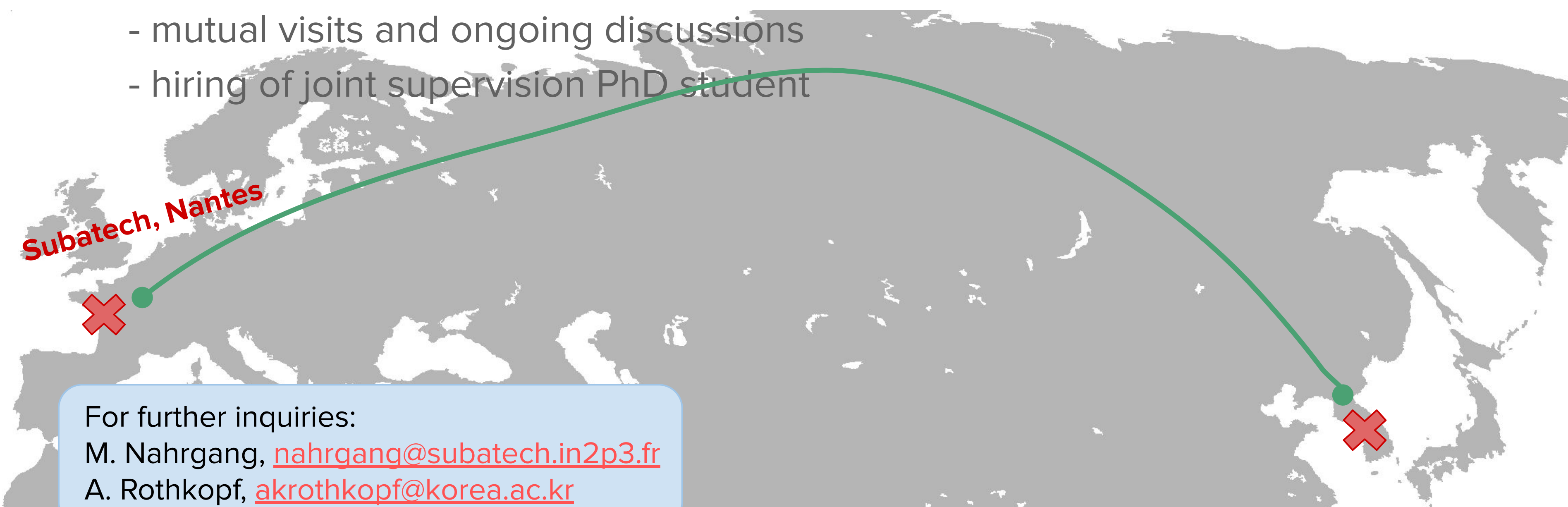
- Lattice QCD
- Stochastic quantization
- Real-time dynamics of open quantum systems
- Bayesian inference
- Machine learning techniques and AI

- QCD thermodynamics
- Fluctuations and stochastic hydrodynamics
- Fundamental QCD and birdtracks
- Microscopic kinetic theory calculations
- Phenomenological modeling of HICs

Perfect overlap/complementarity of expertise!

Plans for 2025 - 2026

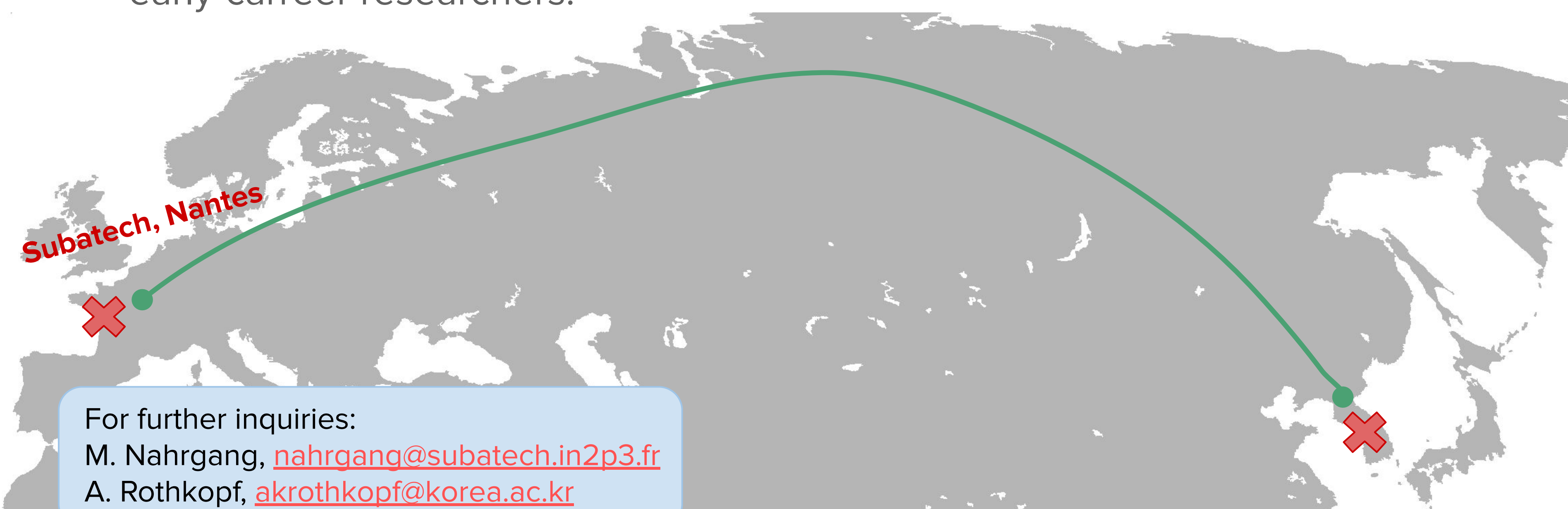
- June/July 2025:
  - visit of French team to Korea
  - kick-off seminar presentations and discussions
  - initiate contact with the International Relations Office at Korea University
- Fall 2025:
  - visit of Korean team to France
  - seminar presentations and discussions
- Spring 2026:
  - mutual visits and ongoing discussions
  - hiring of joint supervision PhD student



For further inquiries:
M. Nahrgang, nahrgang@subatech.in2p3.fr
A. Rothkopf, akrothkopf@korea.ac.kr

Summary

- Many recent findings challenge the conventional view of the QCD phase transition at muB = 0.
- Can the phase structure of hot nuclear matter be richer than currently assumed?
- HotDISCO will investigate this intriguing question by joint expertise from fundamental QCD, phenomenology and dynamical modeling of HIC!
- Great potential for a long-term Korean-French collaboration, including early-carreer researchers.



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