Recent updates on finite temperature and density QCD from lattice

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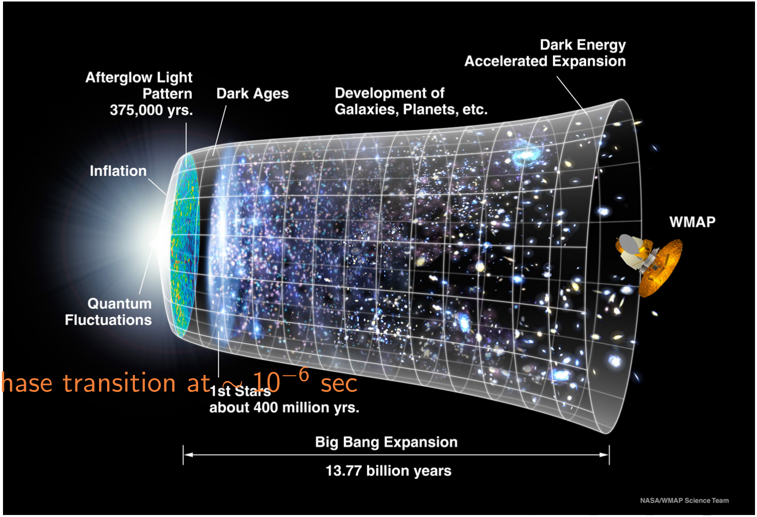
December 15, 2022

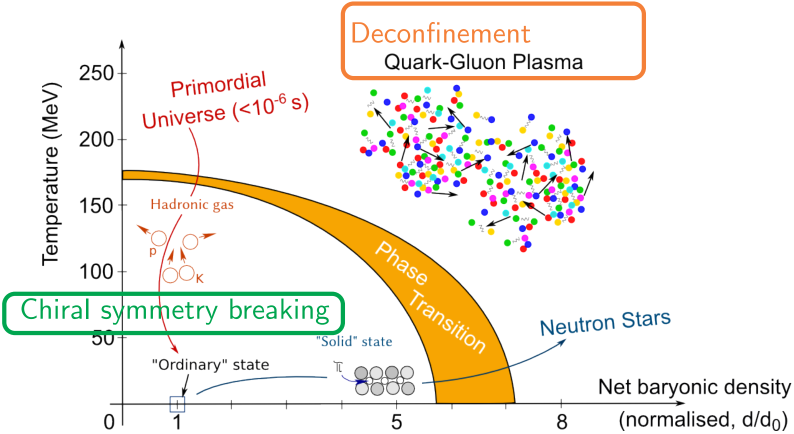
XXV DAE-BRNS HEP Symposium 2022, IISER Mohali

QCD interactions account for the origin of 99% of visible matter



QCD phase transition at $\sim 10^{-6}$ sec

QCD phase diagram holds key to many fundamental questions

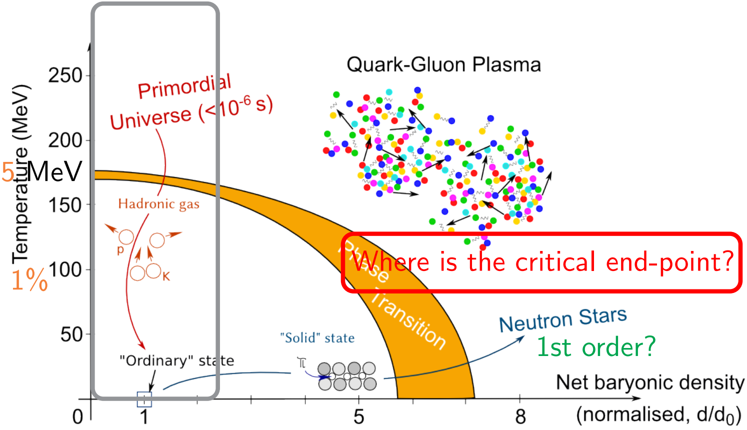


[Image Courtesy: www.cern.ch]

Lattice QCD shows a crossover transition at small densities

$T_c = 156.5$ MeV

error $< 1\%$



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Chiral symmetry

- Since $m_{u,d} \ll \Lambda_{QCD}$, 2+1 flavor QCD respects $U_L(2) \times U_R(2)$ chiral symmetry to a good extent.

- The non-singlet part of this chiral symmetry gets broken at low T, $SU_A(2) \times SU_V(2) \to SU_V(2)$

- This happens through a crossover transition at a temperature now known to unprecedented accuracy $156.5(1.5)$ MeV.
  [HotQCD collab. 18, F. Burger et. al. 18, Budapest-Wuppertal collab. 20]

- The singlet part $U_A(1)$ is anomalous yet can affect the order of the chiral phase transition as $m_{u,d} \to 0$.
  [Pisarski & Wilczek 84, Pelissetto & Vicari 13, G. Fejos, 22]

- Do singlet and non-singlet chiral symmetries gets restored simultaneously?

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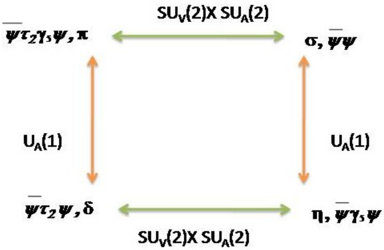


- $U_A(1)$ is not an exact symmetry$\rightarrow$ what observables to look for? Degeneracy of the 2-point (integrated) correlation functions [Shuryak, 94]

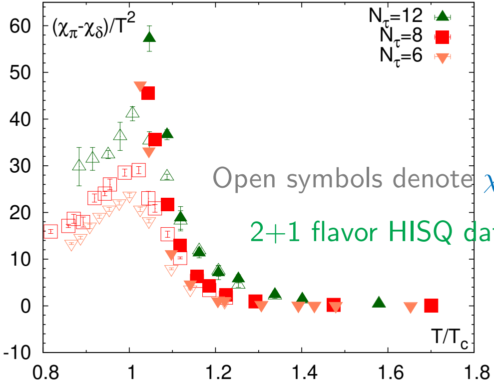
$$\chi_\sigma = \chi_\delta + 2\chi_{\text{disc}} \quad , \quad \chi_\eta = \chi_\pi - 2\chi_{5,\text{disc}} \ .$$

The singlet and non-singlet parts mix strongly

- When chiral symmetry is restored

  [L. Giusti, G. C. Rossi, M. Testa, 04, HotQCD 1205.3535]

$$\chi_\pi - \chi_\eta = 2\ \chi_{5,disc} = \chi_\pi - \chi_\delta = 2\ \chi_{disc}\ .$$



Open symbols denote χ_{disc}

2+1 flavor HISQ data $m_\pi = 160$ MeV

[Fig. from Petreczky, Schadler, S.S. 16].

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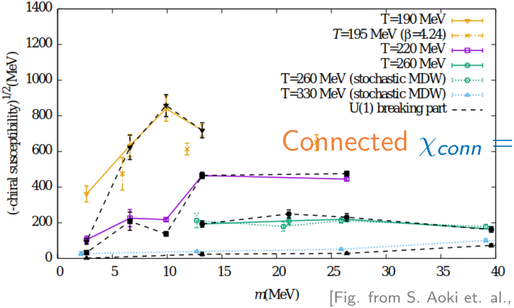
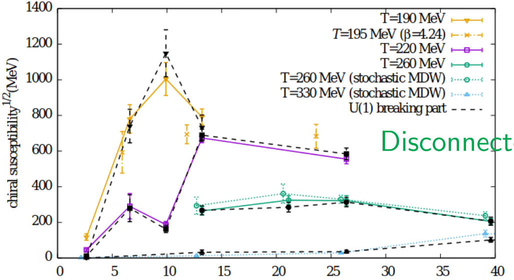


Connected $\chi_{conn} = \frac{\langle\bar{\psi}\psi\rangle}{m}$+U(1) br.

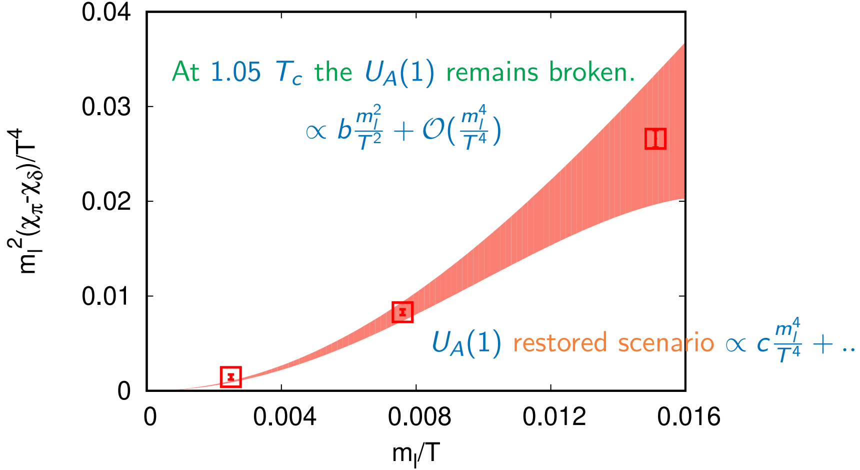
[Fig. from S. Aoki et. al., JLQCD collab. 21]



Disconnected part

Renormalized $U_A(1)$ breaking observable in the chiral limit

- For $2+1$ flavor QCD a fit to diff. masses gives $\frac{\chi_\pi - \chi_\delta}{T^2}\big|_{m_l=0} = 156(13)$. [O. Kaczmarek, L. Mazur, S. S. 21]



Fate of the pseudo-Goldstone mode in the hadron phase

- At $T < T_c$, the pion quasi-particle has a dispersion relation $\omega_{\mathbf{p}} = u(T)\sqrt{\mathbf{p}^2 + m_\pi^2}$.
- Using spectral function corresponding to the correlator of $\bar{\psi}\gamma_0\gamma_5\frac{\tau}{2}\psi$ one gets the pion velocity u from its residue considering no thermal modification. [D. T. Son & M. Stphanov, 98]
- Including thermal effects $\rho(\omega, T) =$

$$\frac{f_\pi^2 M_\pi \Gamma(T)}{2u\pi}\left(\frac{1}{(\omega - M_\pi u)^2 + \Gamma(t)^2} - \frac{1}{(\omega + M_\pi u)^2 + \Gamma(t)^2}\right) + ..$$

- The u calculated for 2 flavor lattice QCD is consistent with the χ_{PT} ansatz if thermal width $\Gamma = 30$ MeV. Thermal modification by 16% for the chiral condensate at $T = 128$ MeV. [M. Ce, H. Meyer et. al 22]
[related talk by Pritam Sen, Wed 12:15 WG5]

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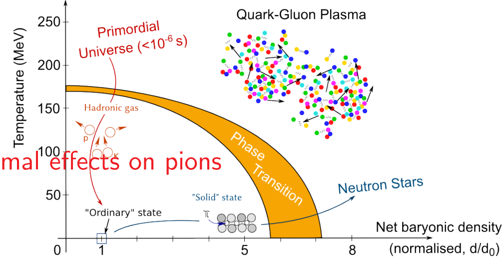

Noticeable thermal effects on pions

- Role of anomalous part of chiral symmetry not well understood!
- Important to study hadron screening masses at finite T, baryon density. [See lattice studies by Thakkar, Hegde 22, Swansea Collab. 21]
- Fate of the non-Goldstone σ mode and $U_A(1)$ effects crucial to locate the critical end point.

[Image Courtesy: www.cern.ch]

Extending lattice QCD techniques to finite μ_B

- At finite baryon densities conventional Monte-Carlo techniques suffer from sign problem!

- A practical way to circumvent: via Taylor series expansion around $\mu_B = 0$ [Bi-Swansea 02, Gavai, Gupta, 02].

$$\frac{P(\mu_B, T)}{T^4} = \frac{P(0, T)}{T^4} + \frac{1}{2}\left(\frac{\mu_B}{T}\right)^2 \chi_2^B(0, T) + \frac{1}{4!}\left(\frac{\mu_B}{T}\right)^4 \chi_4^B(0) + \ldots$$

- For $\mu_B/T > 2$ the convergence is slow [HotQCD coll. 17]. Can be improved using new re-summation schemes (exp. resummation of the series, phase re-weighting..)to calculate thermodynamic quantities at $\mu_B/T = 3$.

[S. Mondal, P. Hegde, S. Mukherjee, 21, Budapest-Wuppertal Coll. 21, HotQCD coll. 22]

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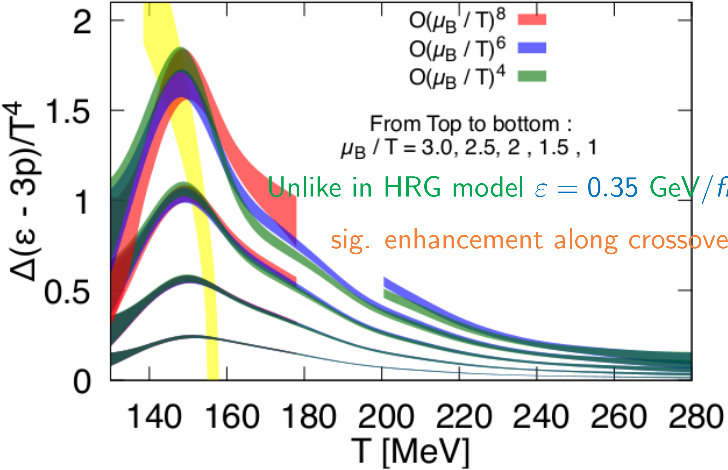
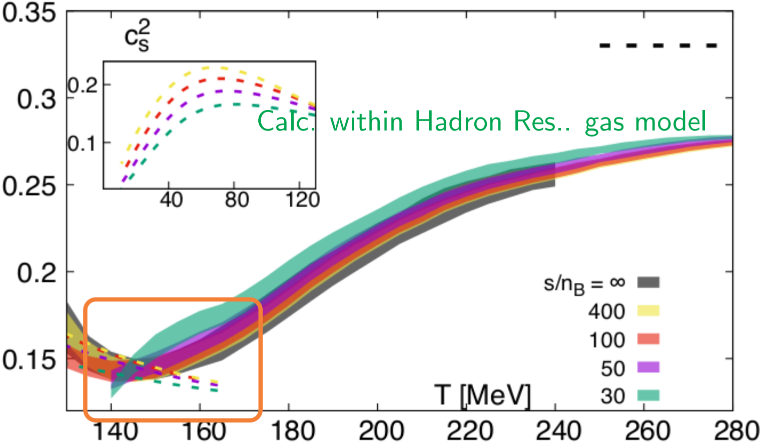


Unlike in HRG model $\varepsilon = 0.35$ GeV$/fm^3$=const.

sig. enhancement along crossover line

[Fig. from HotQCD Collaboration, 22].

Extending lattice QCD techniques to finite μ_B

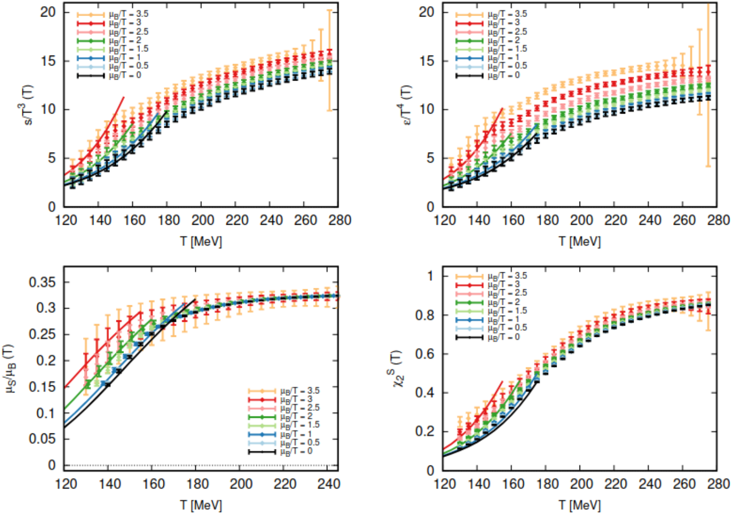


Minima at T_c for $s/n_B < 100$

[Fig. from HotQCD Collaboration, 22].

Method 2: Analytic continuation from Im. μ_B

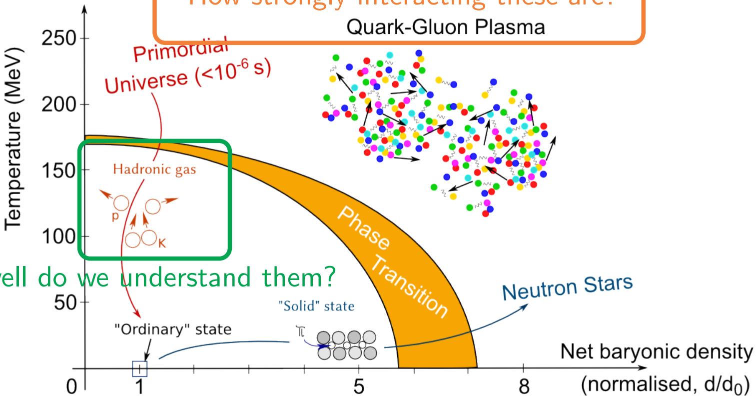
[Fig. from Budapest-Wuppertal Collaboration, 22].



Consistent with Taylor series method

Degrees of freedom and interactions

How strongly interacting these are?



Do well do we understand them?

[Image Courtesy: www.cern.ch]

Screening correlators in the deconfined phase

- Screening masses for the meson operator $J = \bar{\psi}\Gamma\psi$ can be derived from spatial correlators [De Tar & Kogut, 87],,

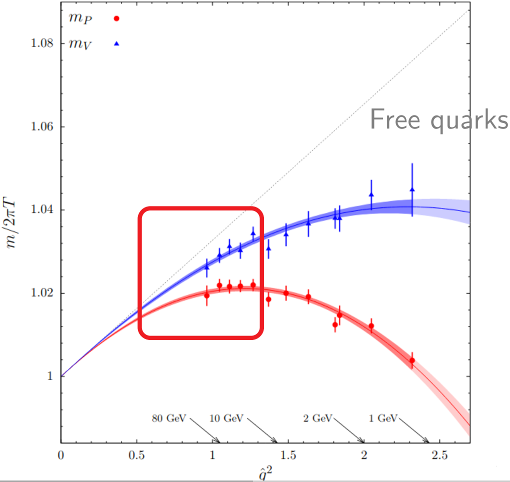
$$C(z) = \int_0^{\beta} d\tau \int dxdy \ \langle J(\mathbf{x})J(0)\rangle \sim \mathrm{e}^{-\mathrm{M_{scr}z}} + ..$$

- Has a more complicated relation to the spectral function at finite momenta. The screening mass are related to the meson excitations in the plasma.

- When there are well-defined bound state peaks in the spectral function the M_{scr} is simply the pole mass of the corresponding meson channel. At high T, the $M_{scr} = 2\sqrt{m_q^2 + (\pi T)^2}$.

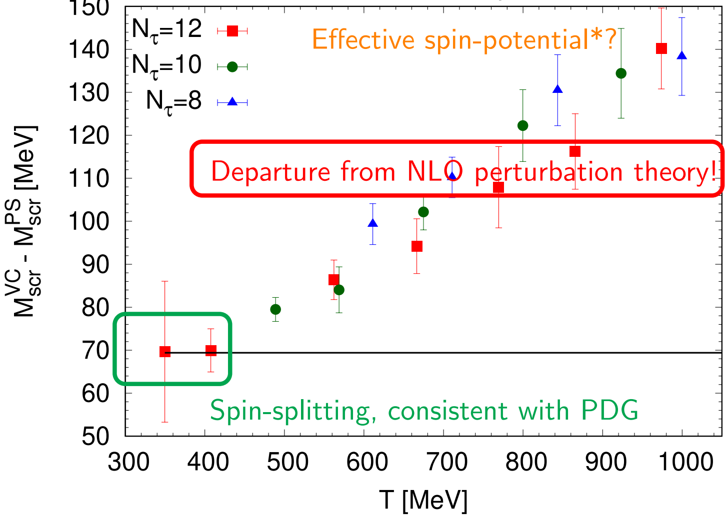
Screening correlators in the deconfined phase

- For light quarks vector and pseudo-sc. scr. masses are degenerate in NLO perturbation theory → significant non-pert. effect even at 10 GeV! [Fig. from L. Guisti et. al., 21].



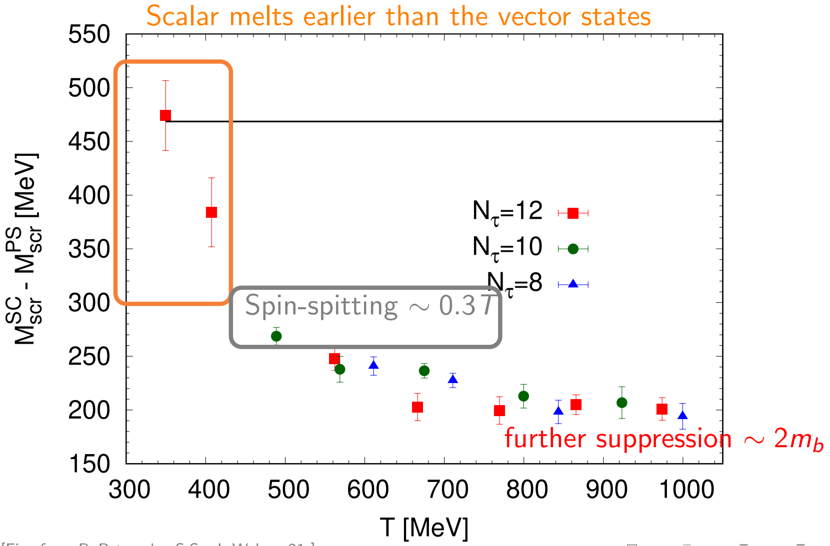
What happens to bottom quark screening states?

This observable insensitive to the quark mass effects.



[*V. Koch et. al., 92 , Fig. from P. Petreczky, S.S., J. Weber, 21]

When do scalar bottomonia melt?



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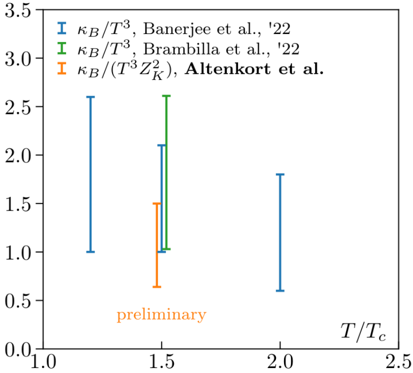
Heavy quark diffusion in QGP

- In non. relativistic limit $M \gg \pi T$, the heavy quarks undergo Langevin dynamics $\frac{d\mathbf{p}}{dt} = -\frac{\kappa \mathbf{p}}{2MT} + \zeta$
- momentum diffusion coeff. $\tau_{\text{heavy}} = \frac{M}{T} D = \frac{2MT}{\kappa}$
- Can be calculated from gluonic color elec-trical correlator in the limit $M \to \infty$ [G. Moore & D. Teaney, 05, S. Caron-Huot & G. Moore , 08]
- In perturbation theory NLO corrections to κ in α_s is twice order of magnitude as LO $\to$ need non-perturbative lattice techniques to calculate. [S. Caron-Huot et. al., 09]
- Recently $\mathcal{O}(M/T)$ corrections have been included $\kappa \sim \kappa_E + \frac{2}{3}\kappa_B \langle v^2 \rangle$



[Bouttefeux & Laine, 20, D. Banerjee, S. Datta, M. Laine, 22, , Fig. courtesy L. Altenkort et. al, 22]

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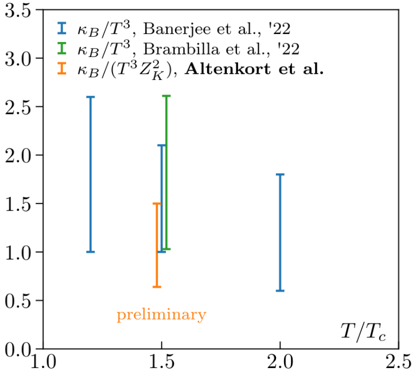

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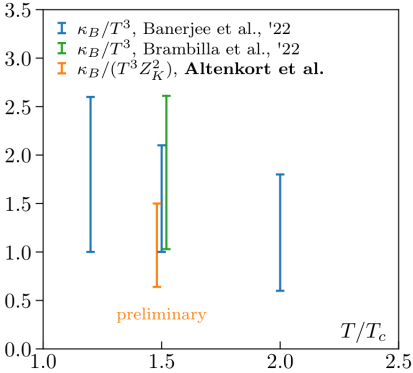

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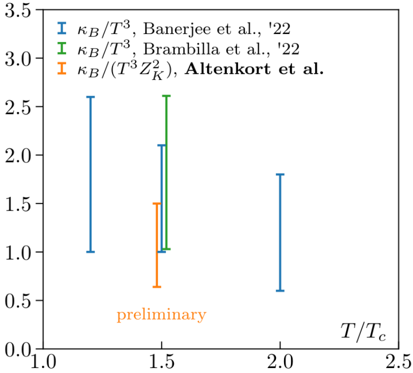

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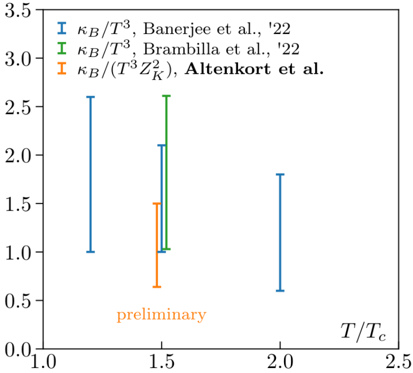

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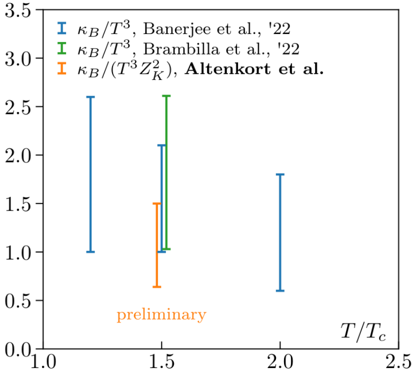
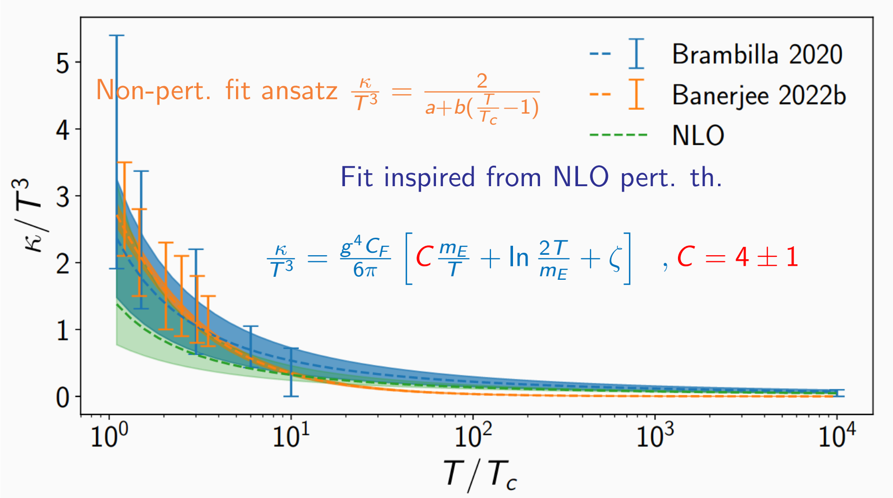
- In perturbation theory NLO corrections to κ in α_s is twice order of magnitude as LO $\to$ need non-perturbative lattice techniques to calculate. [S. Caron-Huot et. al., 09]
- Recently $\mathcal{O}(M/T)$ corrections have been included $\kappa \sim \kappa_E + \frac{2}{3}\kappa_B \langle v^2 \rangle$



[Bouttefeux & Laine, 20, D. Banerjee, S. Datta, M. Laine, 22, , Fig. courtesy L. Altenkort et. al. 22]

Heavy quark diffusion in QGP



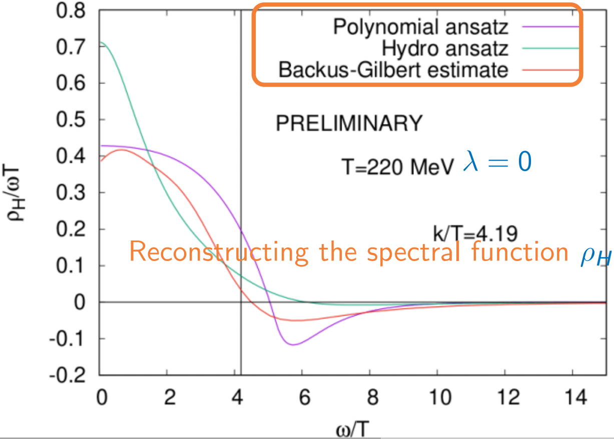
[Fig. from V. Leino, INT Workshop 22-3, Ref. N. Brambilla et al. 20, D. Banerjee, S. Datta, R. Gavai & P. Majumdar, 22]

Photon production rate in Quark-Gluon plasma from lattice

- Measure of how-strongly interacting the QGP phase is!
- Calculated from vector current spectral function reconstructed from the correlation function calculated from lattice. In general

  $\rho_V = 2\rho_T + \lambda\rho_L$ [HotQCD Coll. 20, Mainz coll. 21]

  [See talk by D. Bala, Thu 11:30 WG5]

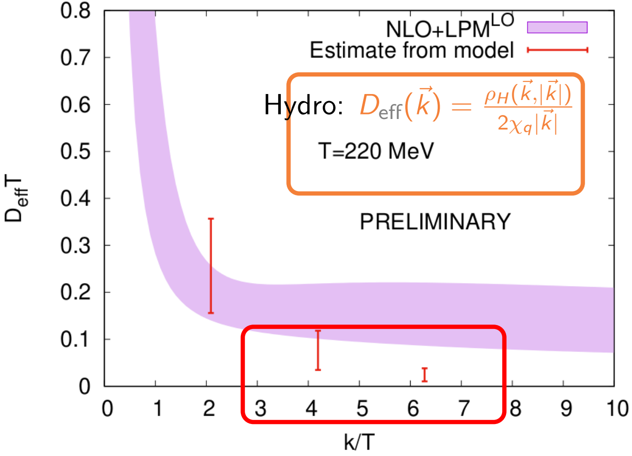


Reconstructing the spectral function ρ_H is ill-posed.

Photon production rate in Quark-Gluon plasma from lattice

$$\frac{d\Gamma}{d^3\vec{k}} = \frac{\alpha_{em}\chi_q \; n_b(\omega)}{\pi^2} D_{eff}(\vec{k})$$

[Fig. from D. Bala et. al. in prep 22]



Summary

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- Recent results gives us new insights on the thermal modifications of light hadrons in the chiral symmetry broken phase. The mechanism how chiral symmetry and deconfinement happens is not yet understood.
- Also shows that the deconfined quark-gluon plasma phase is non-perturbative even at $T \sim 1$ GeV $\rightarrow$ implications for transport properties, thermalization?
- Need significant research for developing new lattice techniques to address fundamental questions in finite density QCD, non-equilibrium quantum field theories.

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