Complex Heavy Quark Potential from the Lattice
where do we stand?

Alexander Rothkopf
Department of Physics
Korea University
South Korea

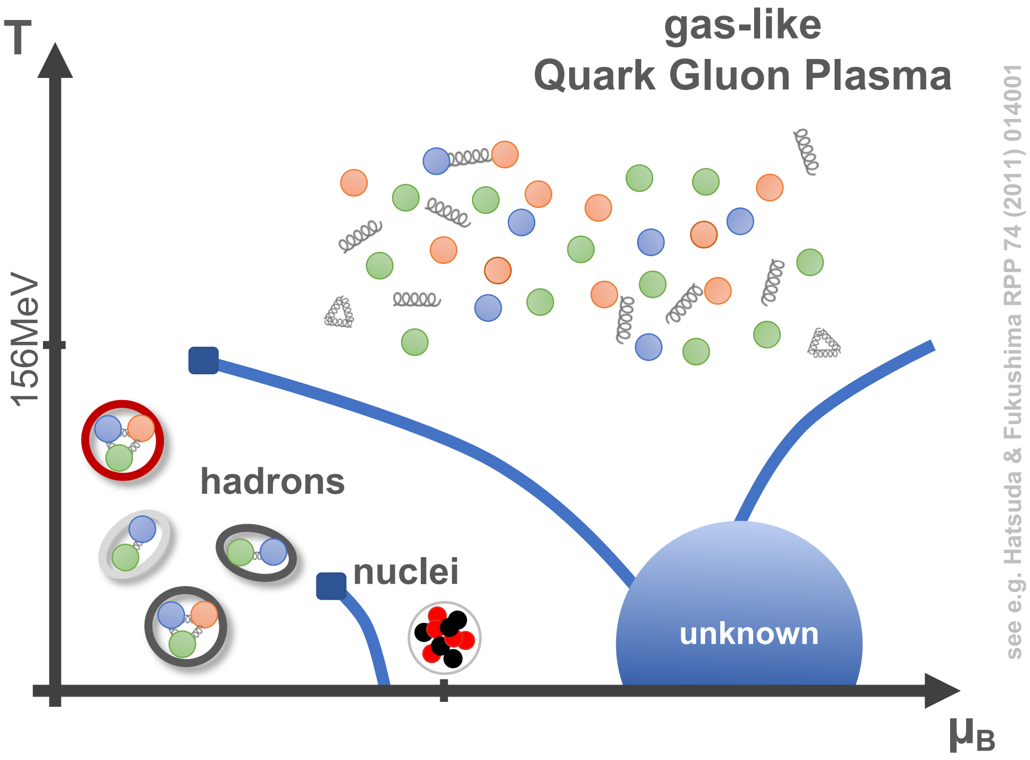
References

with J. Skullerud & R. Horohan D'Arcy (FASTSUM) in progress
with HotQCD: PRD 109 (2024) 7, 074504, PRD 105 (2022) 5, 054513
with R. Larsen & G. Parkar: PRD 110 (2024) 11, 114501
see also: **D. Leinweber et.al.** PRD 111 (2025) 3, 034508

Outline

- Motivation: Exploration of phases of QCD
- The complex heavy quark potential from (lattice) QCD
- From past to recent results from lattice QCD
- Summary

The phases of nuclear matter (I)



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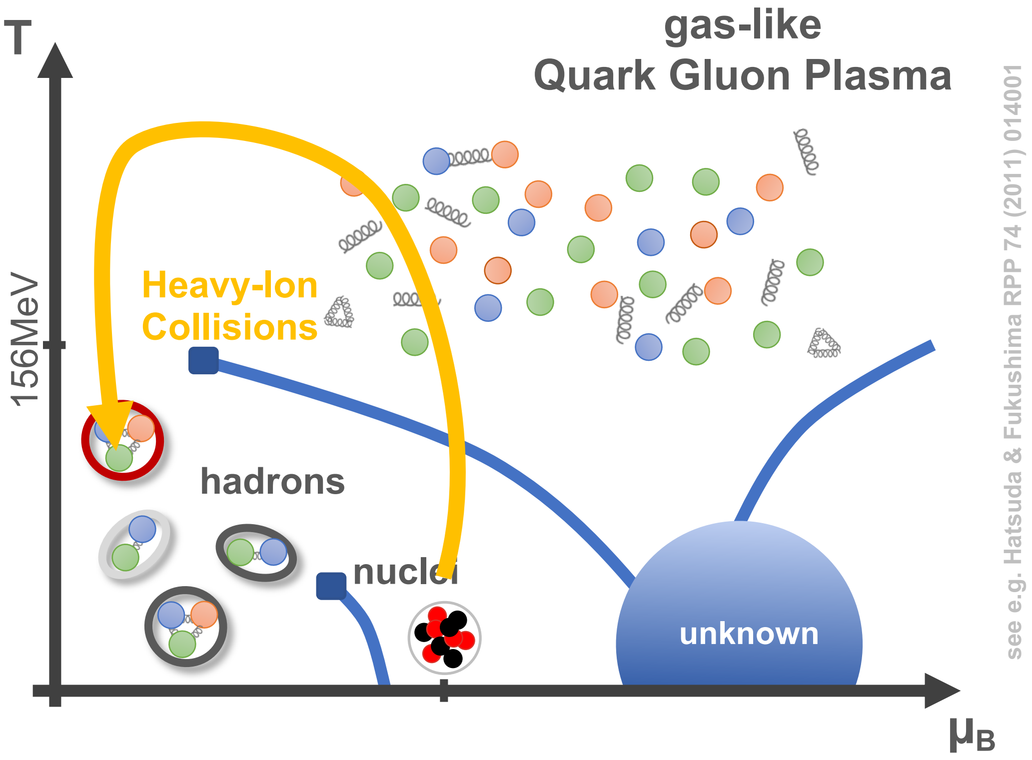

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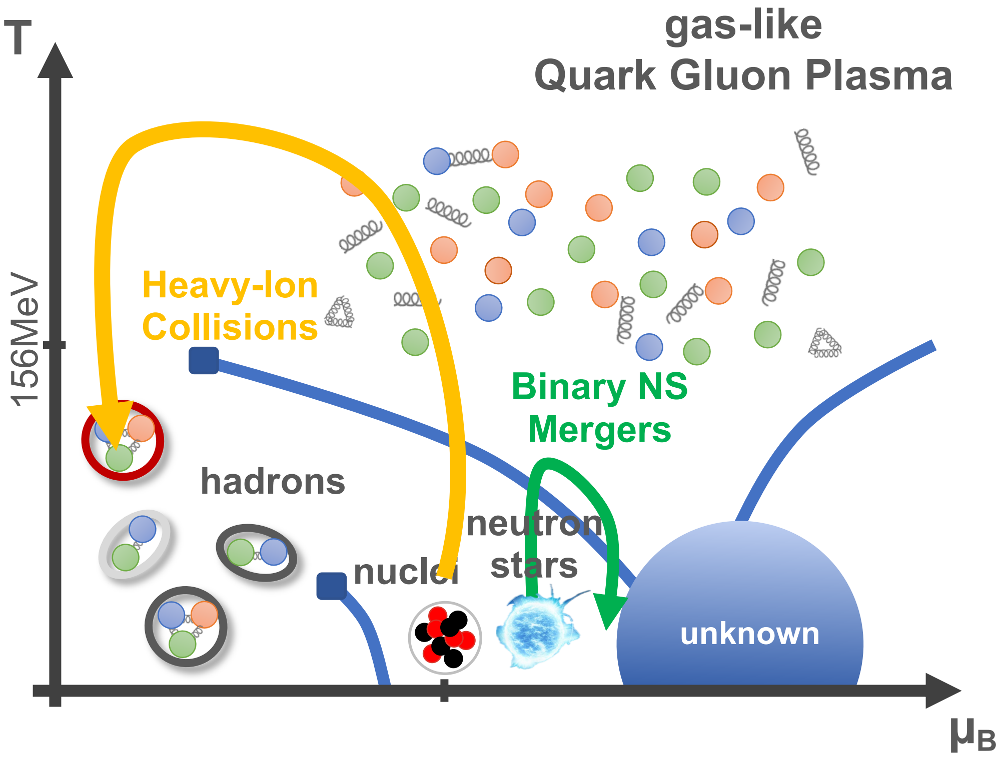

see e.g. Hatsuda & Fukushima RPP 74 (2011) 014001

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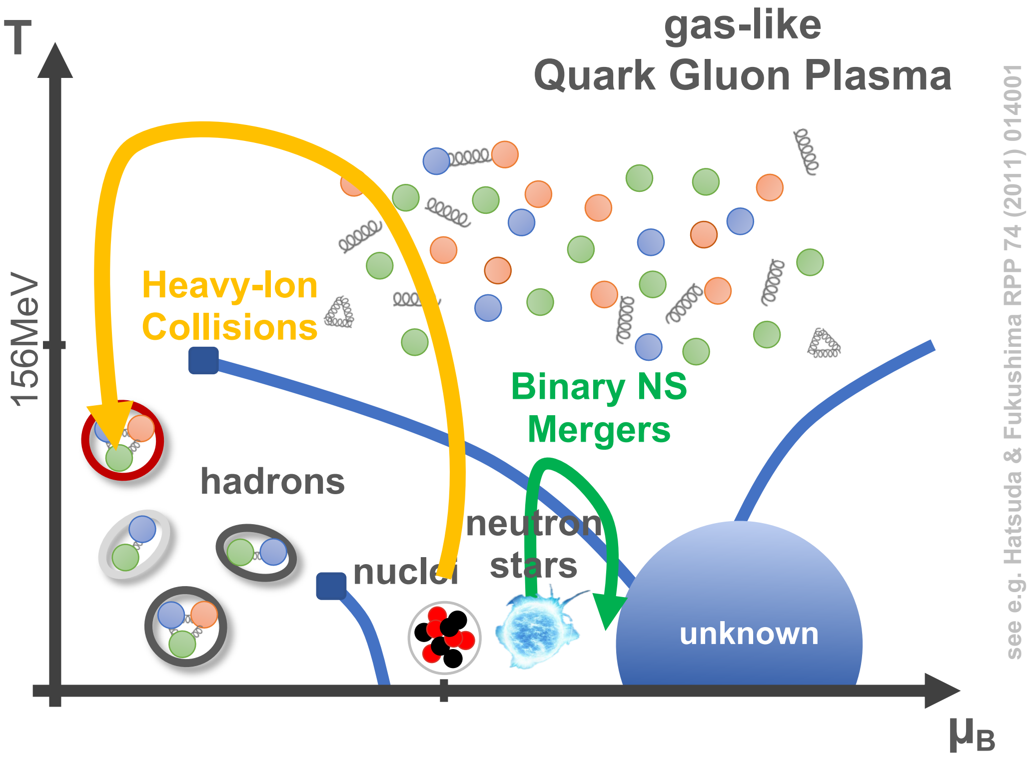
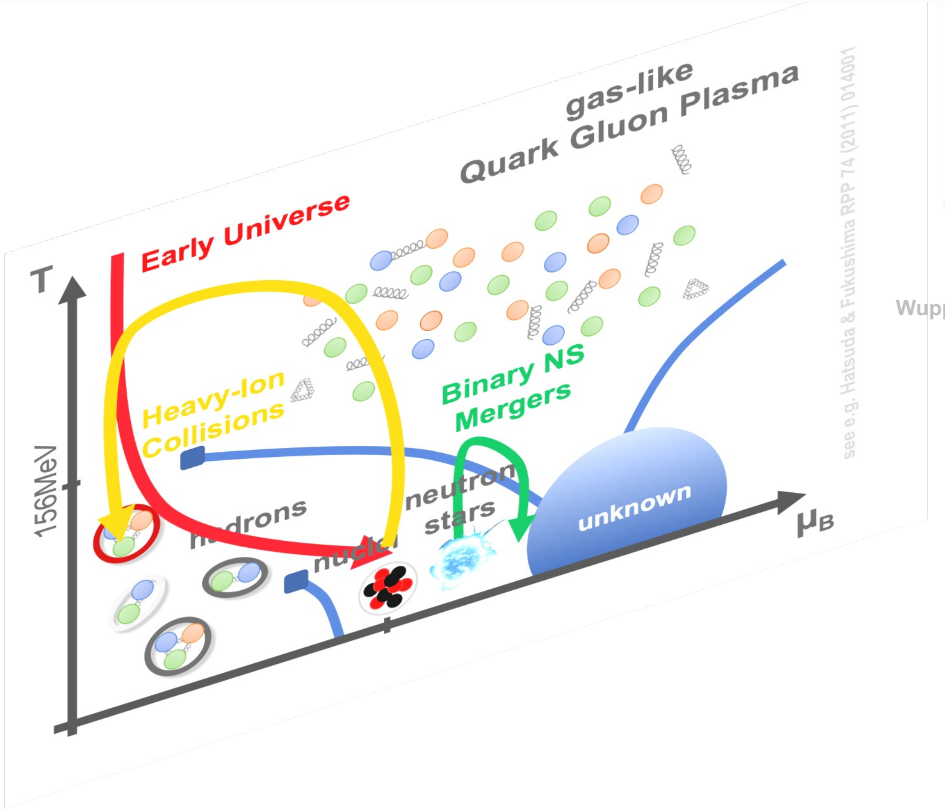
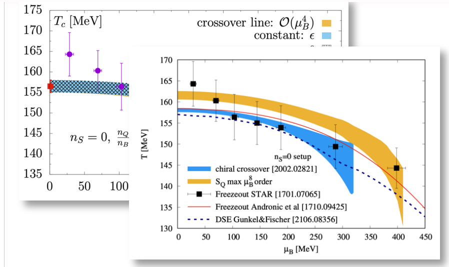


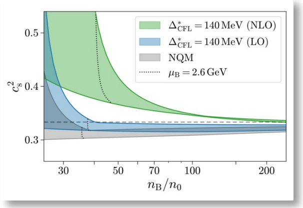
chiral symmetry restoration & deconfinement as key indicators of phase change

The phases of nuclear matter (II)





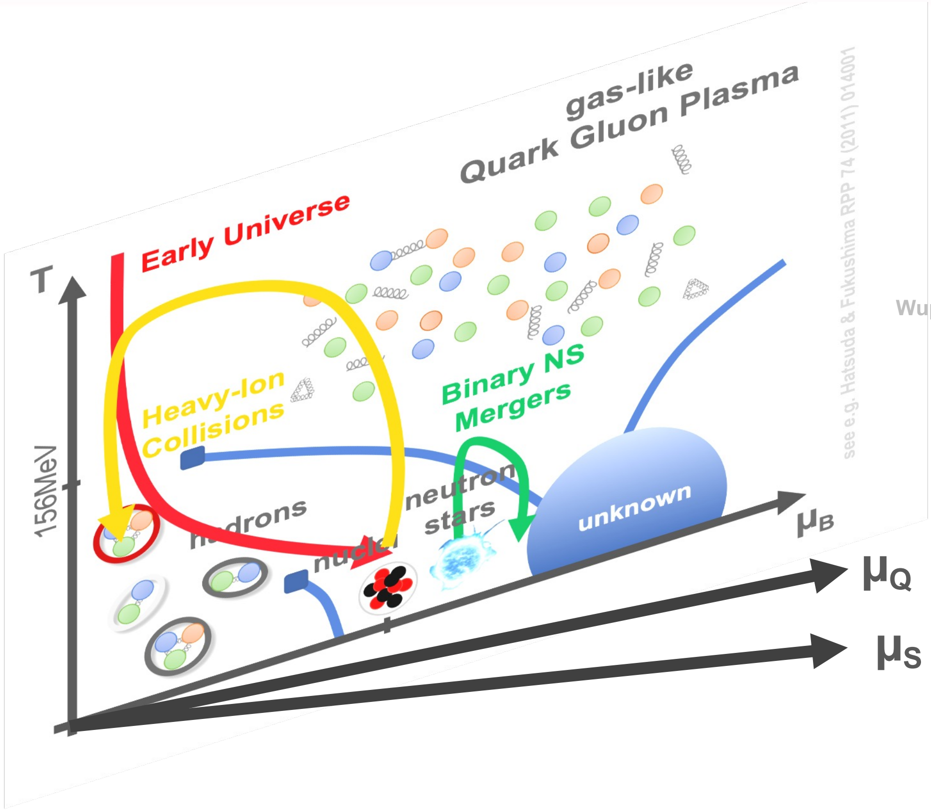
see e.g. HotQCD PLB 795 (2019) 15 or
Wuppertal Budapest PRD 110 (2024) 11, 114507



A. Geißel et.al. arXiv:2504.03834

The phases of nuclear matter (II)

more and more differential analyses



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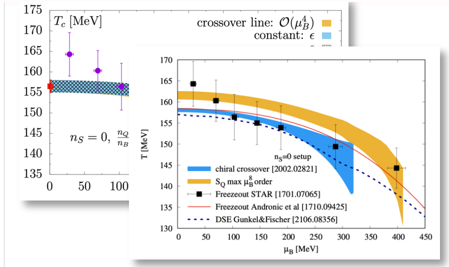

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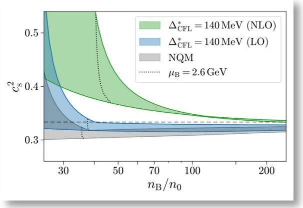

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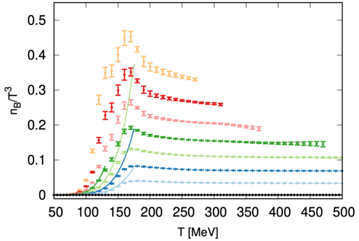

see e.g. Wuppertal
Budapest arXiv:2504.01881

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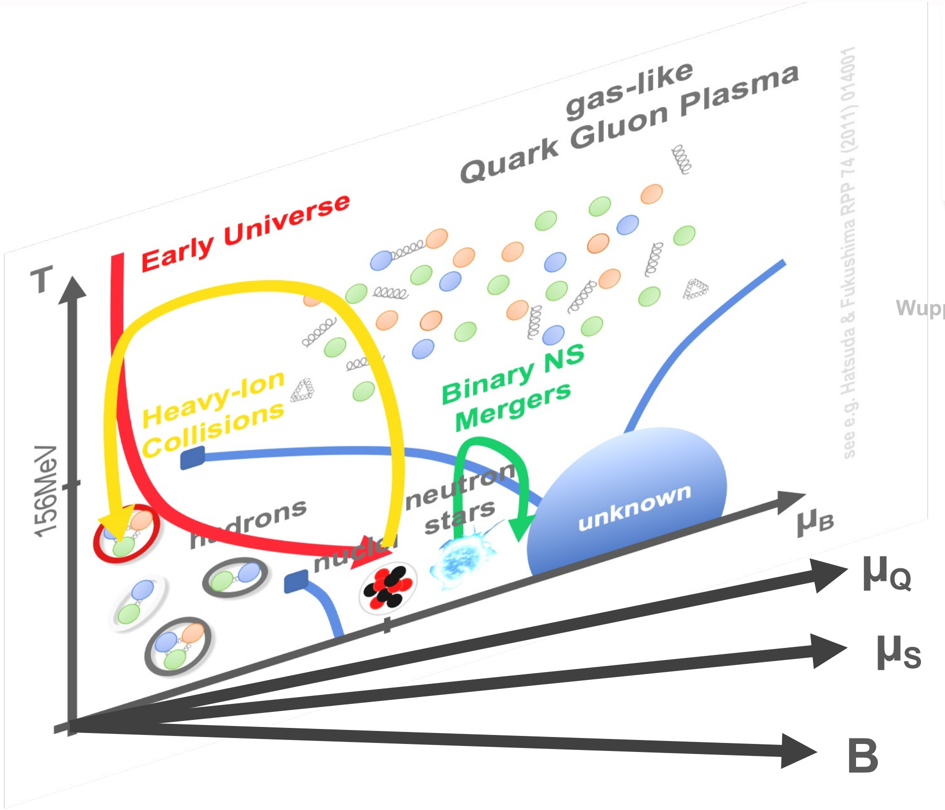

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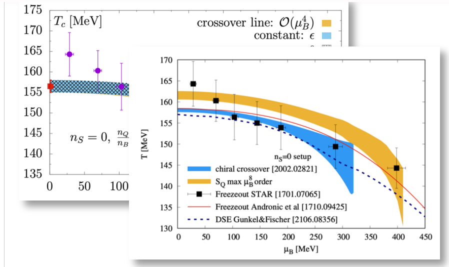

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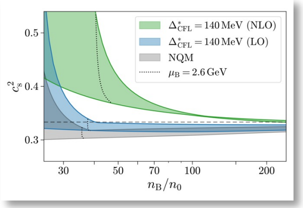

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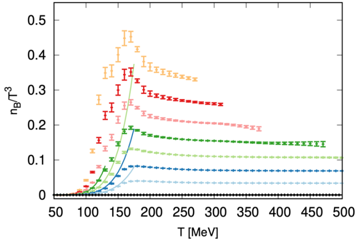

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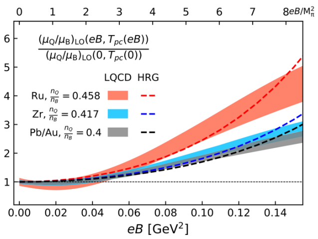

H.T. Ding et.al.
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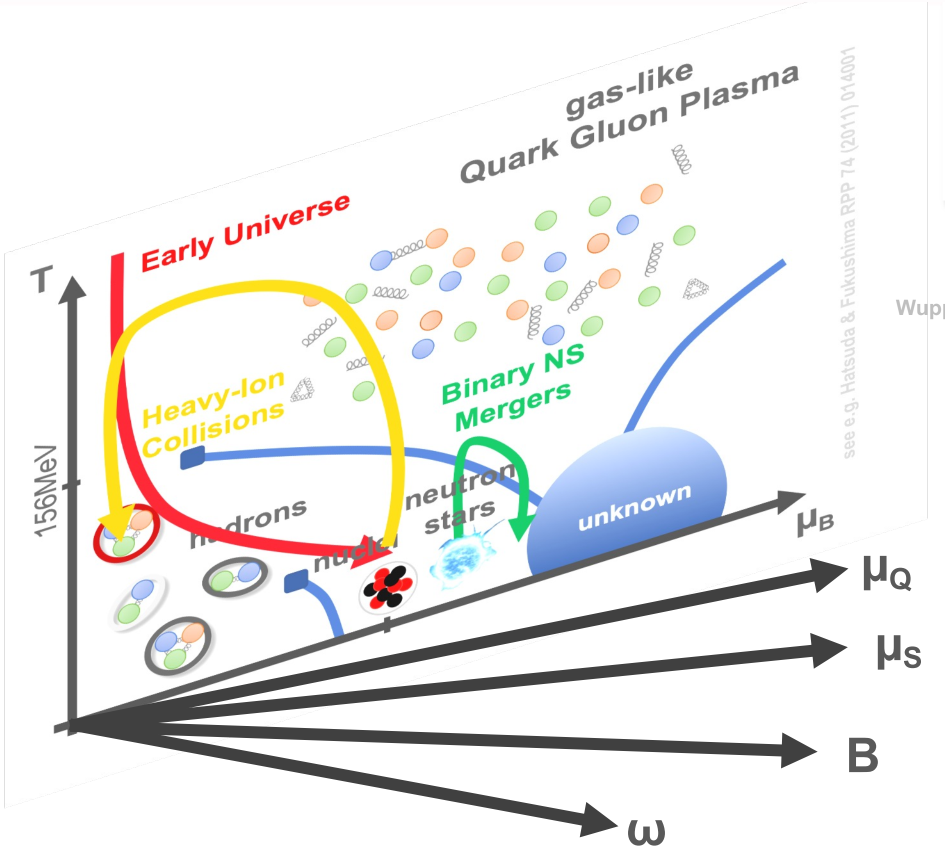

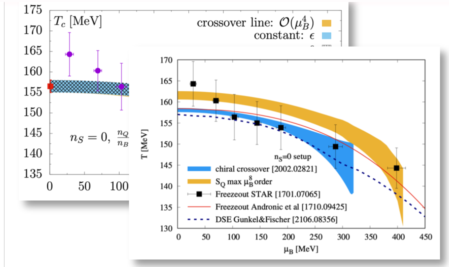

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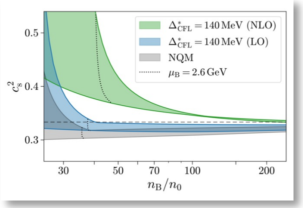

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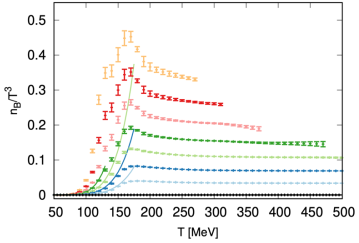

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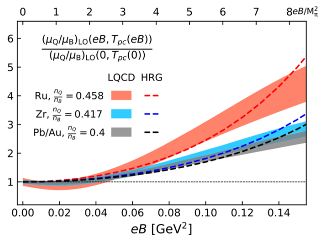

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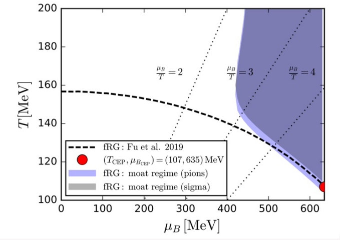
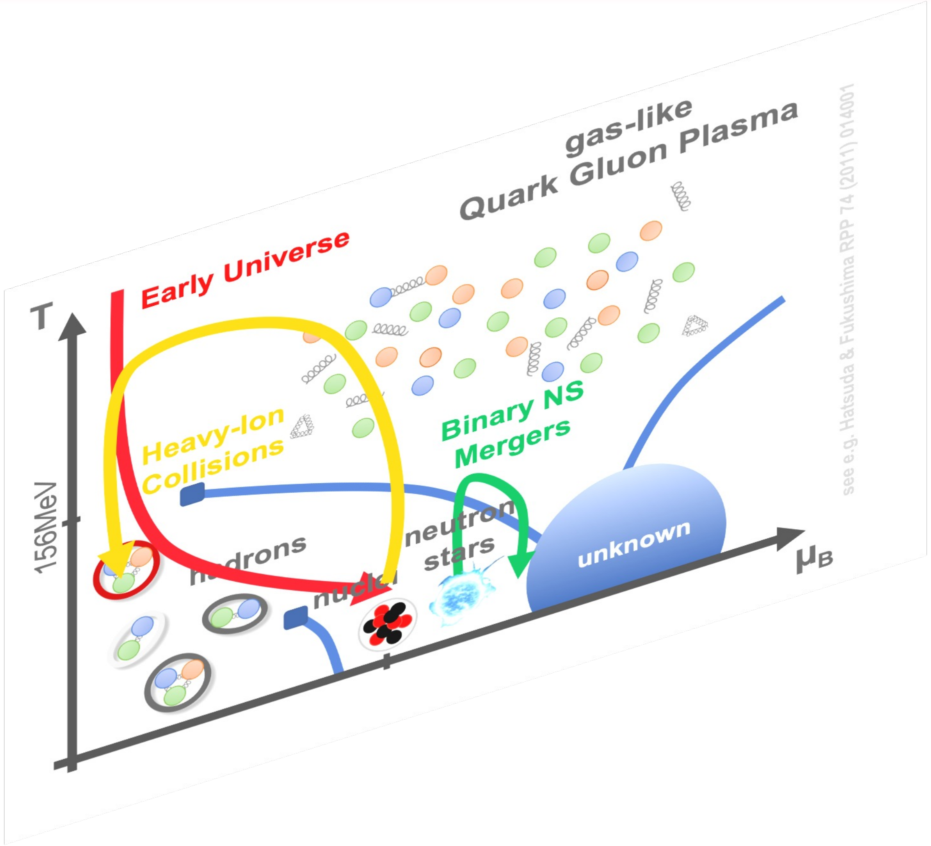


W.J. Fu et.al.
PRD 111, 094026 (2025)

Heavy quark physics and phase structure



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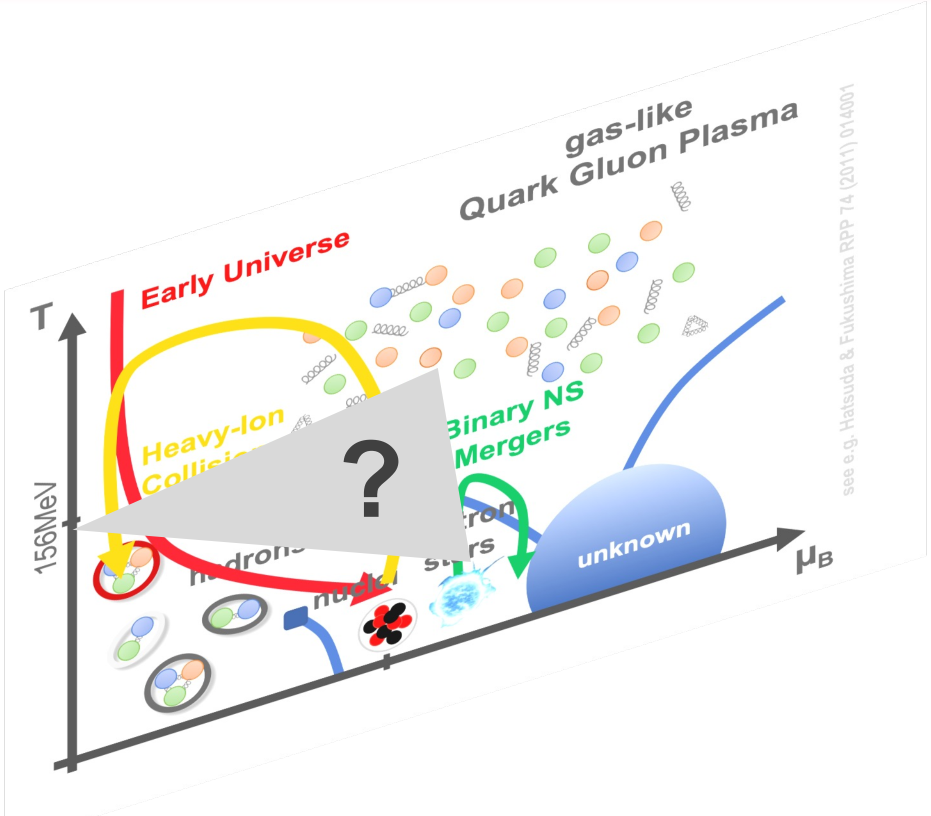

Goal: understand crossover transition in more detail – fate of confinement & active d.o.f.

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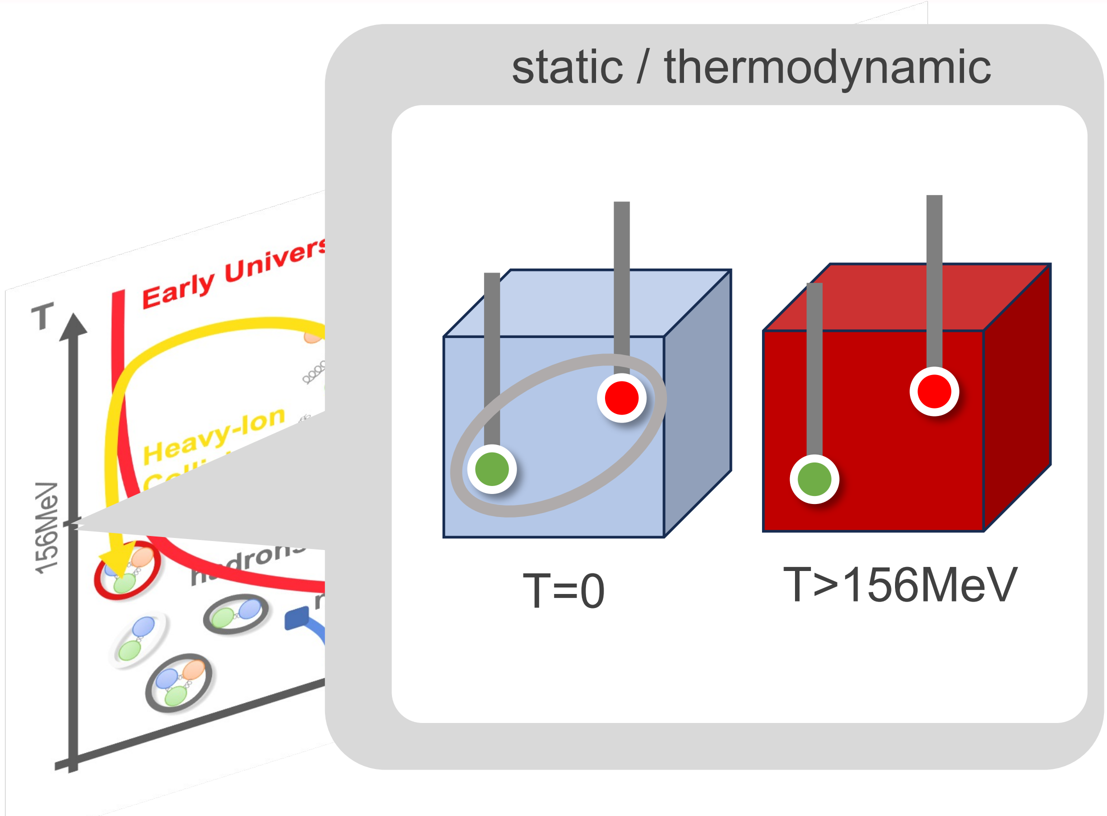

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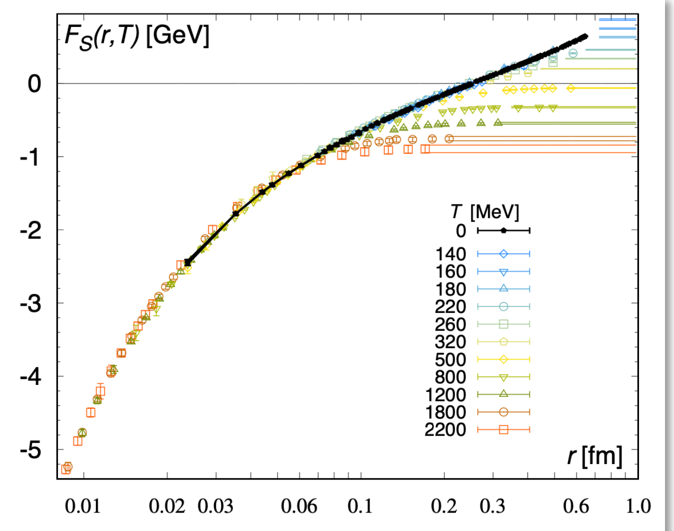

TUMQCD PRD98 (2018) 5, 054511

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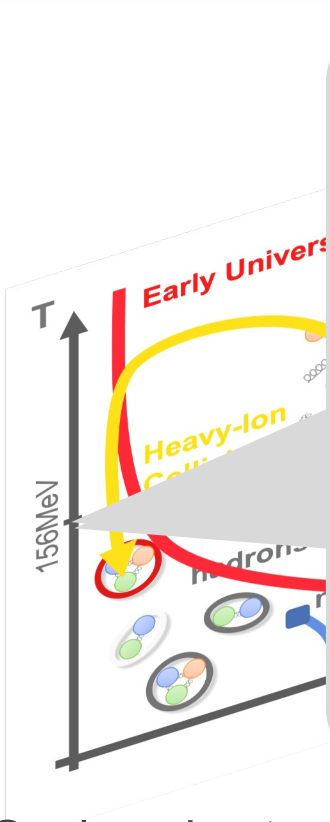

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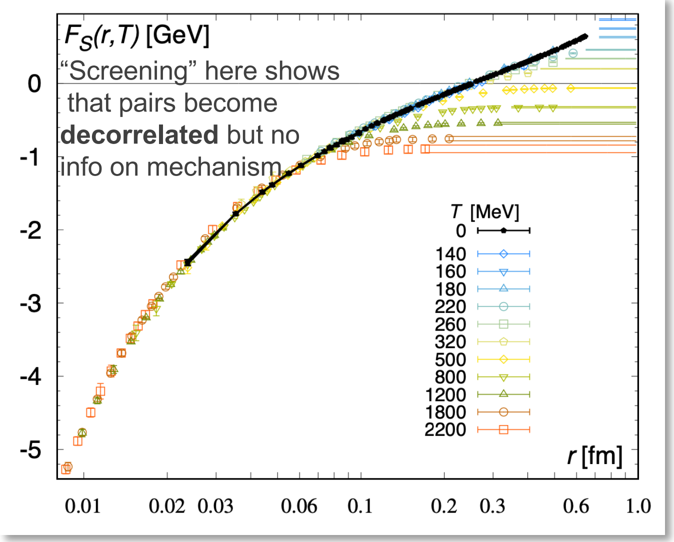

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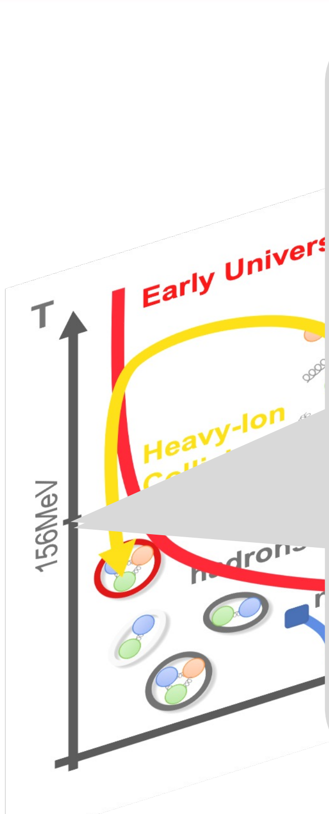

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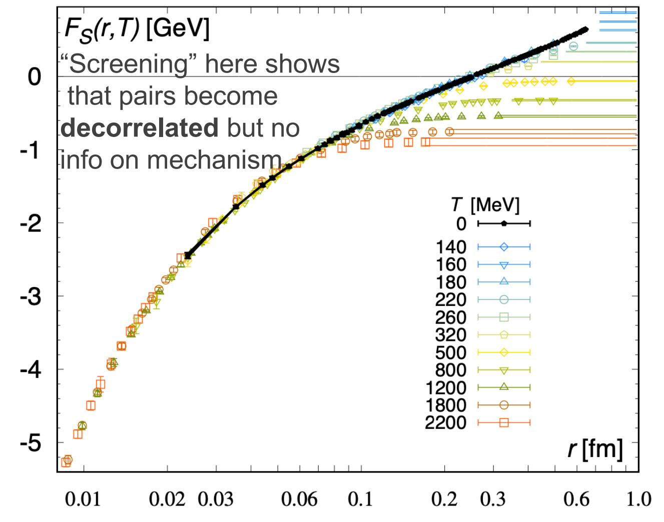

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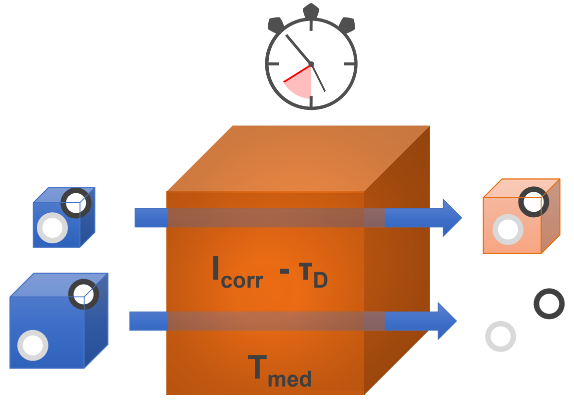
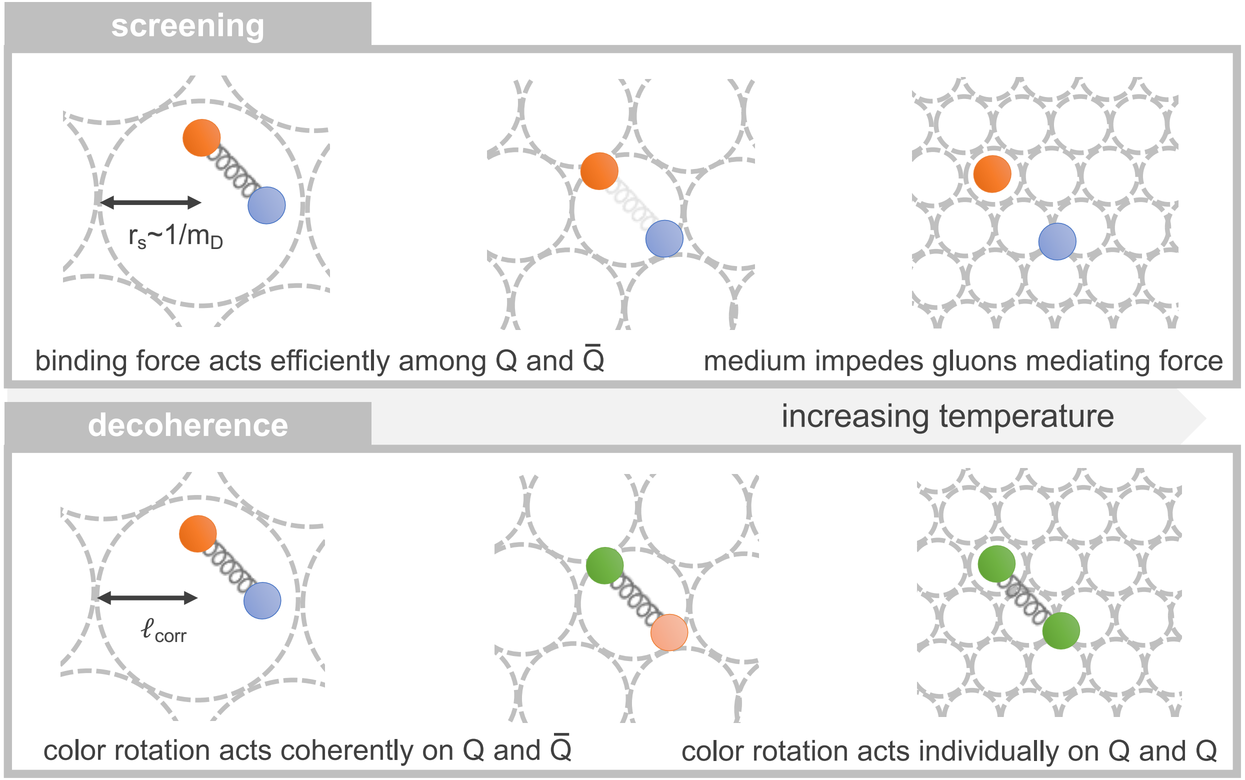
dynamic / real-time



Open-quantum system described by complex potential

Goal: understand crossover transition in more detail – fate of confinement & active d.o.f.

Heavy quark pair real-time evolution



see discussion in S. Kajimoto, Y.Akamatsu, M. Asakawa, A.R., PRD97 (2018), 014003

Binding force related to real-part of static potential (de-confinement)

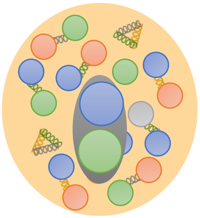
Color decoherence related to imaginary part (active color d.o.f.s)

Defining the potential from QCD

- Exploit $\frac{\Lambda_{QCD}}{m_Q} \ll 1, \quad \frac{T}{m_Q} \ll 1, \quad \frac{\mathbf{p}}{m_Q} \ll 1$ to treat heavy quarks non-relativistically

see Brambilla et. al. Rev.Mod.Phys. 77 (2005) 142

Relativistic T>0 field theory



QCD	NRQCD
Dirac fields	Pauli fields
$Q(x), \bar{Q}(x)$	$\psi, \psi^\dagger, \chi, \chi^\dagger$

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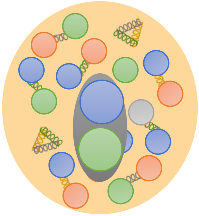

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NRQCD
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Color singlet and octet wavefunctions $\psi_S(R,t), \psi_O(R,t)$

$$i\partial_t \psi_S = \Big(V^{QCD}(R) + \mathcal{O}(m_Q^{-1}) \Big) \psi_S$$

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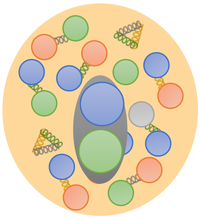

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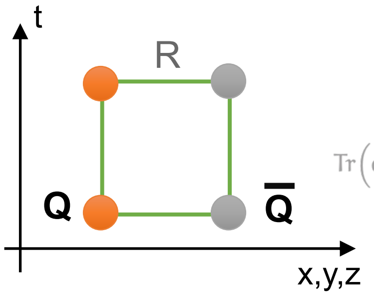
- Matching through the QCD Wilson loop

$$V^{QCD}(R) = \lim_{t\to\infty} \frac{i\partial_t W_\square(R,t)}{W_\square(R,t)}$$



$$W_\square(R,t) = \mathrm{Tr}\left(\exp\left[-i\int_\square dx^\mu A_\mu(x)\right]\right)$$

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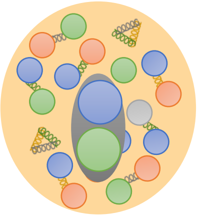

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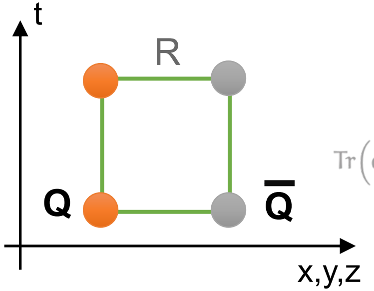

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Im[V]: Laine et al. JHEP03 (2007) 054; Beraudo et. al. NPA 806:312,2008

- Perturbation theory predicts: Debye screened Re[V], Im[V] increases with T

Extracting the potential from the lattice

- Spectral functions as bridge between the Euclidean and real-time Wilson loop

see A.R., T.Hatsuda & S.Sasaki , PRL 108 (2012) 162001, Y.Burnier, A.R. Phys.Rev. D86 (2012) 051503

$$W_\square(R,t) = \int_{-\infty}^{\infty} d\omega\, e^{-i\omega t}\, \rho_\square(R,\omega) \quad \Longleftrightarrow \quad W_\square(R,\tau) = \int_{-\infty}^{\infty} d\omega\, e^{-\omega \tau}\, \rho_\square(R,\omega)$$

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A.R., T.Hatsuda & S.Sasaki PoS LAT2009 (2009) 162

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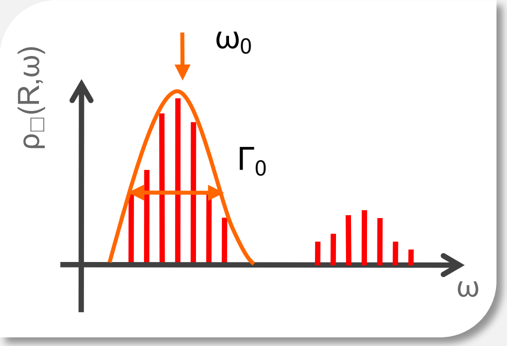

$$V(R) = \omega_0(R) - i\Gamma_0(R)$$

A battery of reconstruction approaches

- Most reconstruction methods can be cast in the language of **Bayesian Inference**: amend ill-posed inverse problem with prior knowledge to select unique answer

$$P[\rho|D,I] \propto P[D|\rho,I]P[\rho|I]$$

for a review: A.R. Front.Phys. 10 (2022) 1028995

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Explicit regulator based on prior information (positivity)

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Linear Methods

Regularize fit by limited choice of basis functions

Backus Gilbert (BG)
Lupo et.al. PoS LATTICE2023 (2024) 004

Gaussian Processes (GP)
see e.g. Horak et.al. PRD 105 (2022) 3, 036014

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Neural Networks

Limited basis functions via NN geometry & regularization in training cost functional

Application to PDFs & spectra
see e.g. Karpie et.al., JHEP 04 (2019) 057, L. Kades et.al. PRD 102 (2020) 9, 096001, L. Wang et.al PRD 106 (2022) 5, L051502

A battery of reconstruction approaches

- Most reconstruction methods can be cast in the language of **Bayesian Inference**: amend ill-posed inverse problem with prior knowledge to select unique answer

Bayesian Inference

Explicit regulator based on prior information (positivity)

Maximum Entropy Method (MEM)
R. Bryan, Eur. Bio. Phys. J. 18 (1990)

Bayesian Reconstruction (BR)
Y. Burnier, A.R., PRL 111 (2013) 182003

Pade / Prony

Rational approx. of Euclidean correlator, explicit continuation

Direct Pade
see e.g. R.A. Tripolt et.al. Phys.Lett.B 774 (2017) and A.R. et.al. Nucl.Phys.A 982 (2019) 735

Prony analysis
Zhang et.al. PRB 110 (2024) 23, 235131

$$P[\rho|D,I] \propto P[D|\rho,I]P[\rho|I]$$

$$P[D|\rho,I] \propto e^{-\chi^2}$$

$$P[\rho|I] \propto e^{S}$$

$$\frac{\delta}{\delta\rho}P[\rho|D,I]\Big|_{\rho=\rho^{\rm Bayes}} = 0$$

for a review: A.R. Front.Phys. 10 (2022) 1028995

Linear Methods

Regularize fit by limited choice of basis functions

Backus Gilbert (BG)
Lupo et.al. PoS LATTICE2023 (2024) 004

Gaussian Processes (GP)
see e.g. Horak et.al. PRD 105 (2022) 3, 036014

Neural Networks

Limited basis functions via NN geometry & regularization in training cost functional

Application to PDFs & spectra
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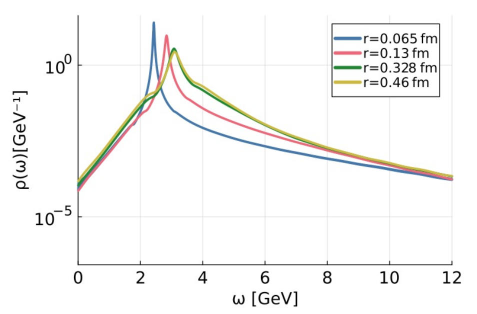
Mock-data closure tests

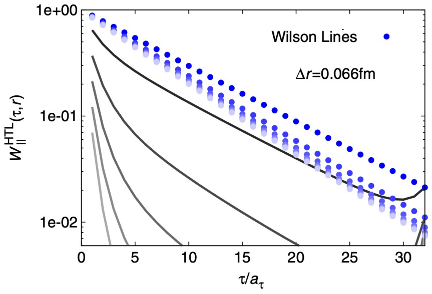


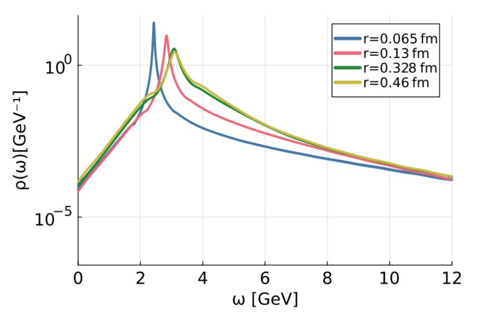
Realistic mock spectral functions via resummed perturbation theory (HTL)

HotQCD and A.R., G. Parkar
PRD 105 (2022) 5, 054513

Mock-data closure tests

Bayesian Reconstruction





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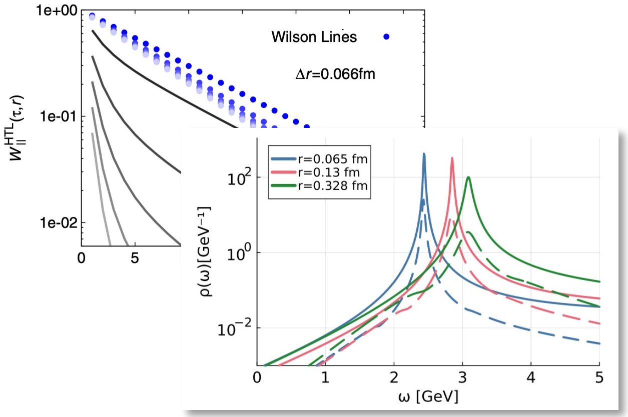

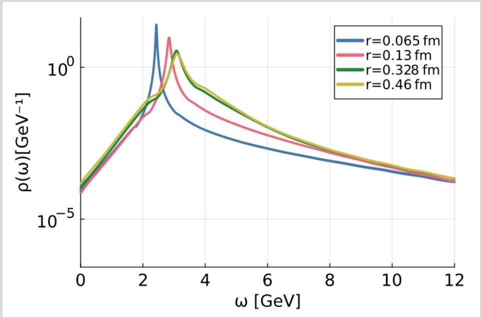

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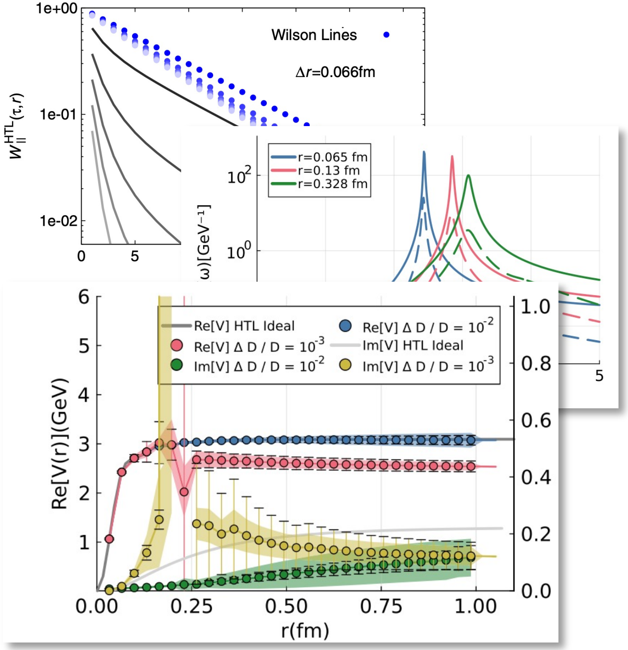

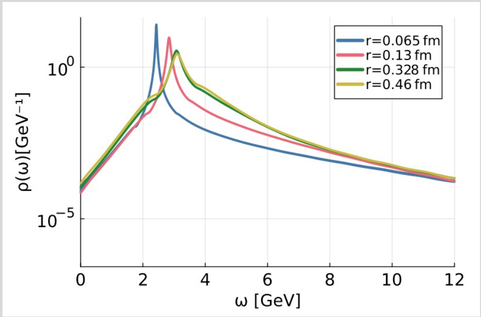

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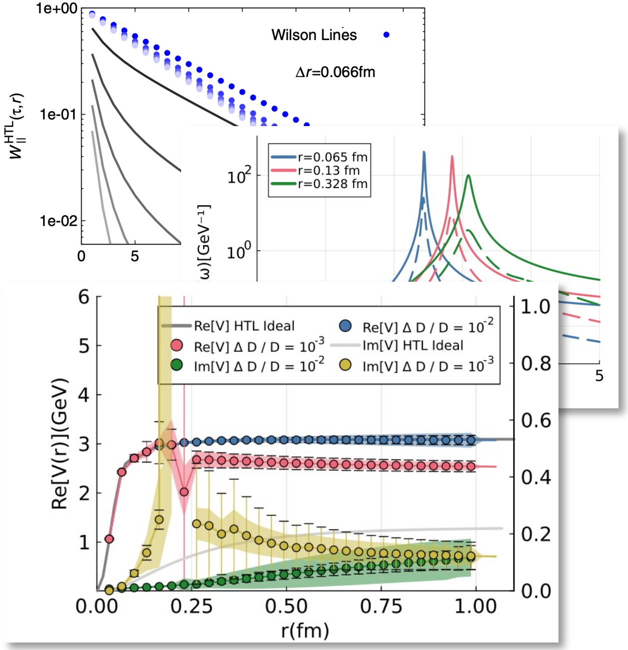

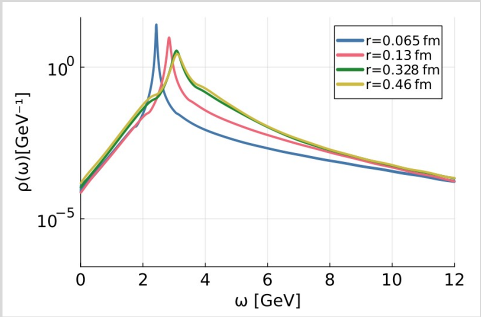

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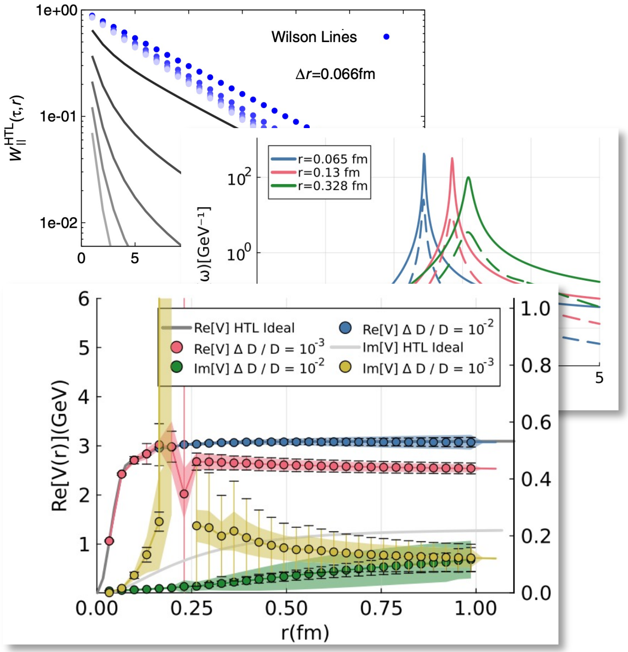
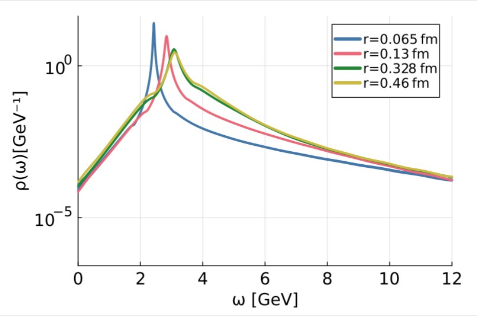
PRD 105 (2022) 5, 054513

- Failure modes of Re[V] & Im[V]: reconstruction underestimates true values

Mock-data closure tests

Bayesian Reconstruction

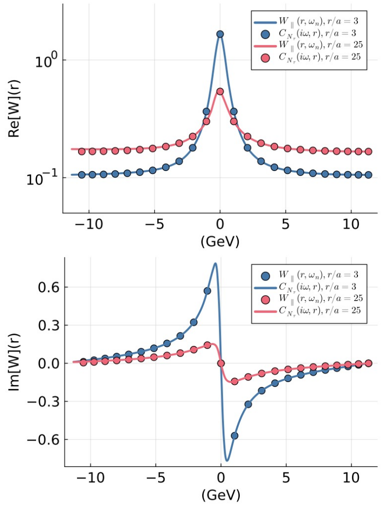




Realistic mock spectral functions via resummed perturbation theory (HTL)

HotQCD and A.R., G. Parkar
PRD 105 (2022) 5, 054513

Pade Reconstruction



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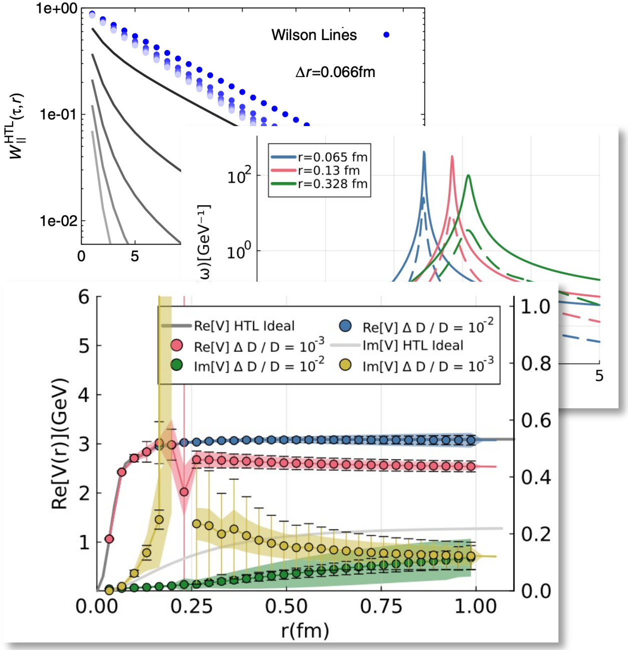

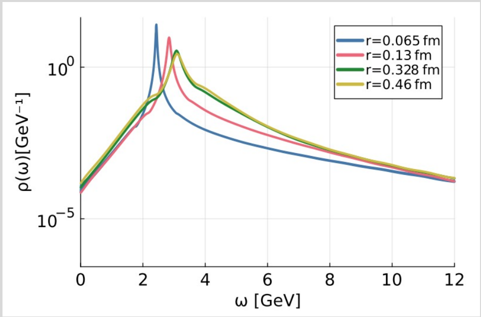

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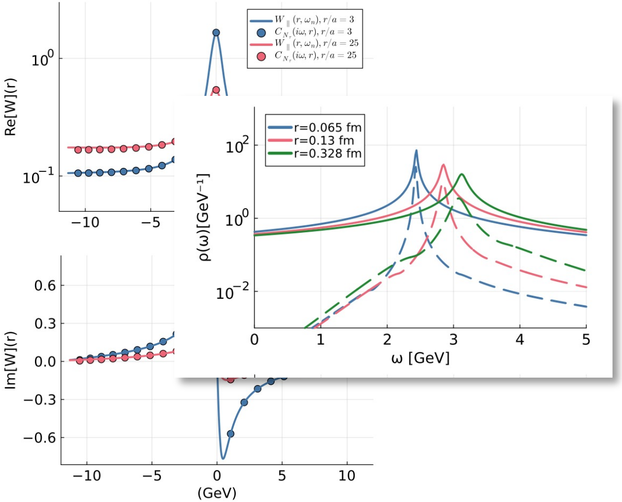

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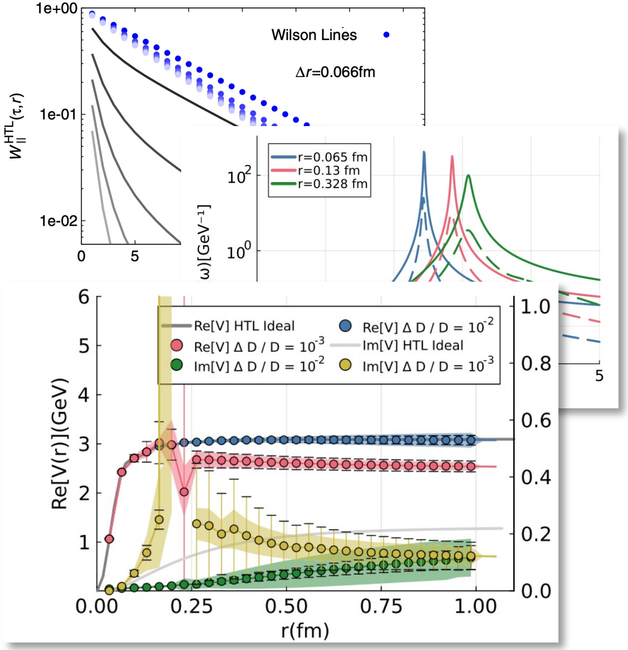

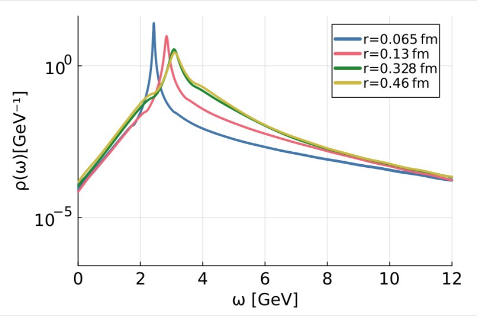

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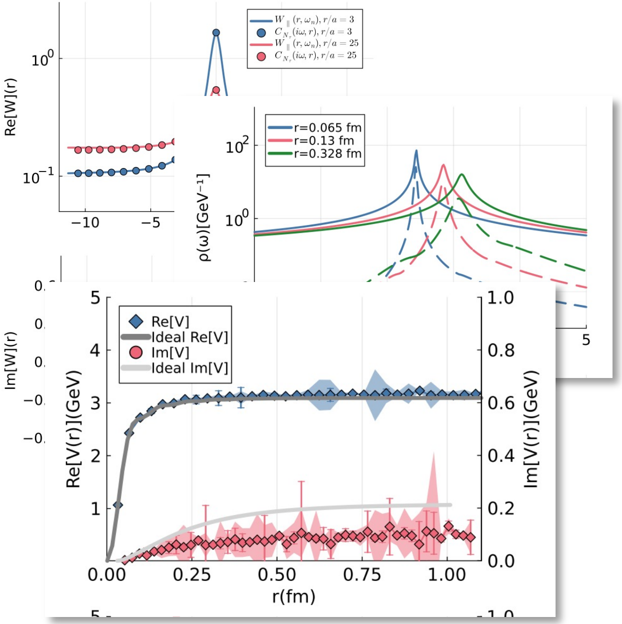
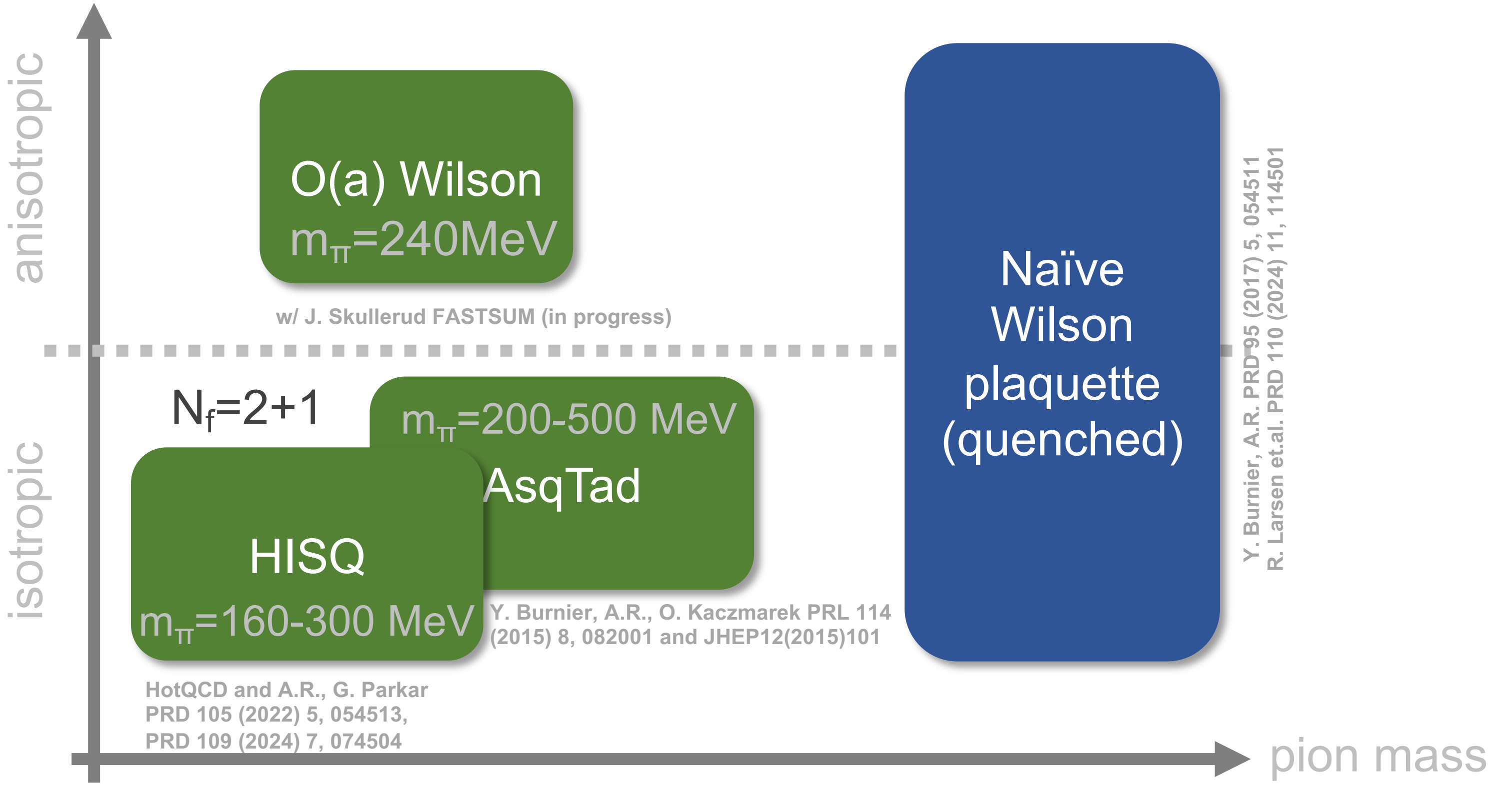


- Failure modes of Re[V] & Im[V]: reconstruction underestimates true values

Exploration of the complex static potential



Quenched QCD – Re[V]

- Purely gluonic medium – absence of light dynamical quarks: deconfinement phase transition at T=271MeV

Y. Burnier, A.R. PRD 95 (2017) 5, 054511 & R. Larsen et.al. PRD 110 (2024) 11, 114501

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- Moderate numerical cost, fine grids: N_τ=20-96

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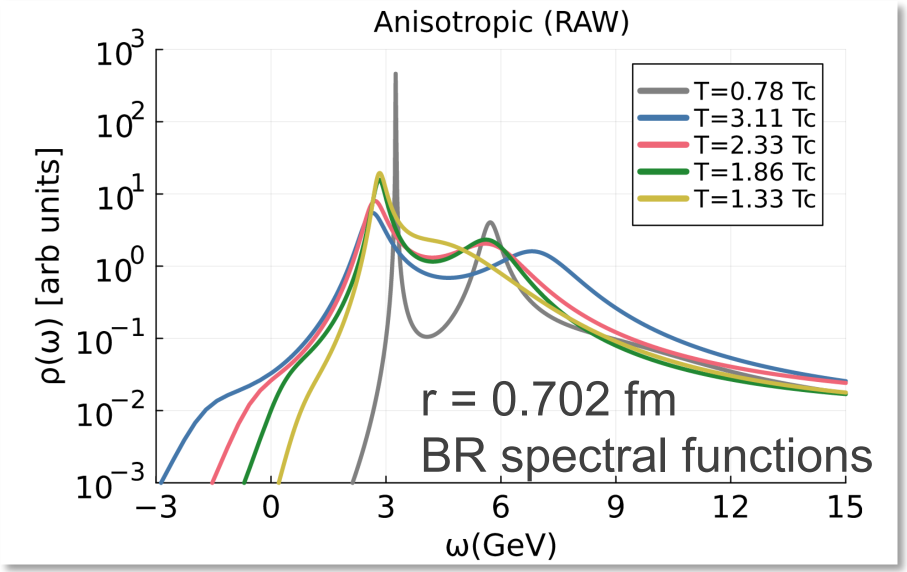

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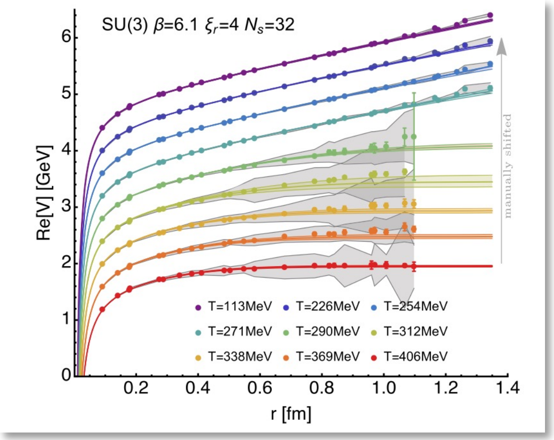

Wilson plaquette action

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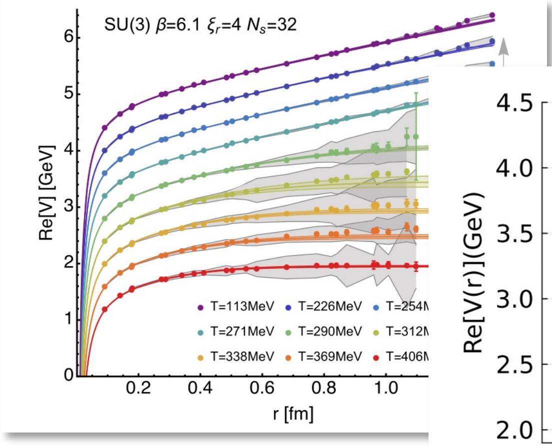

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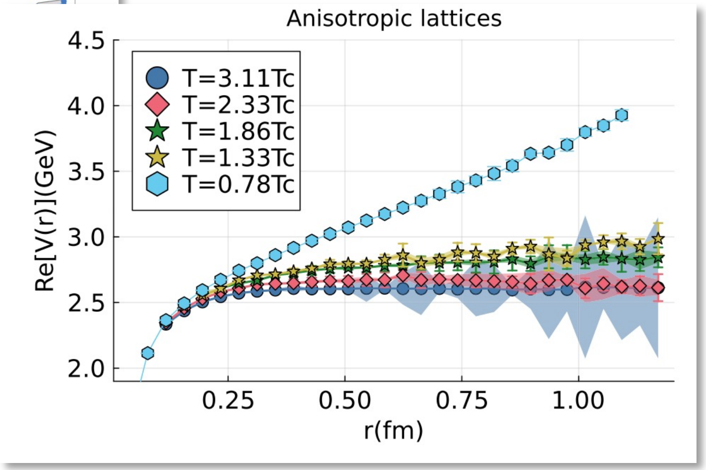

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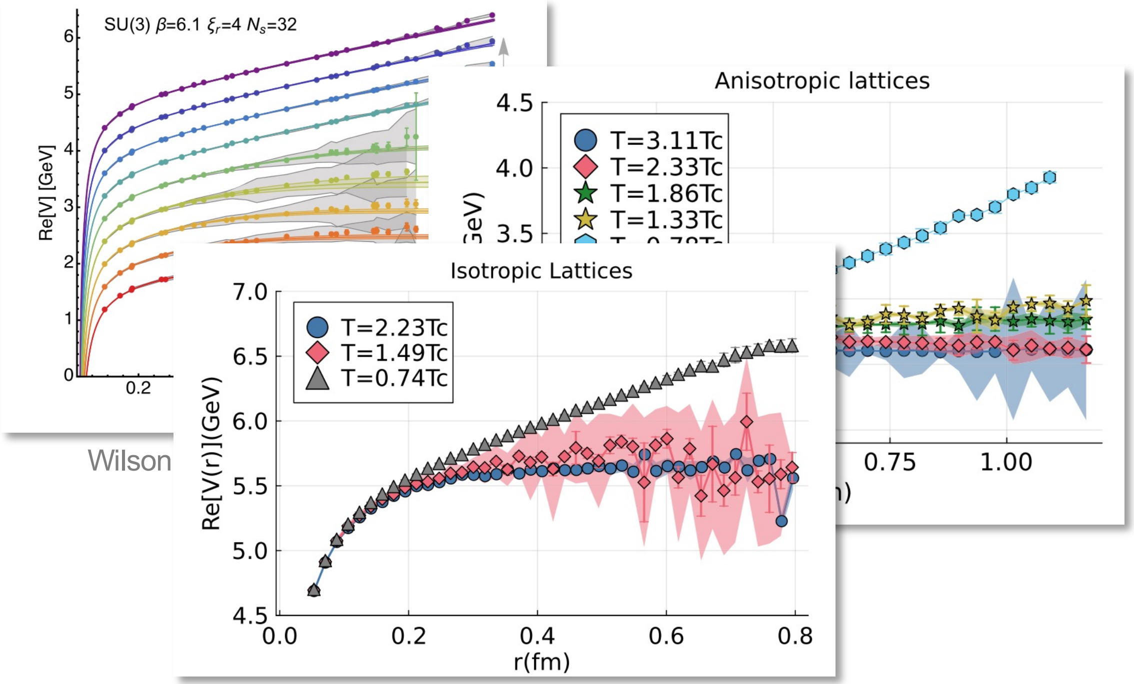

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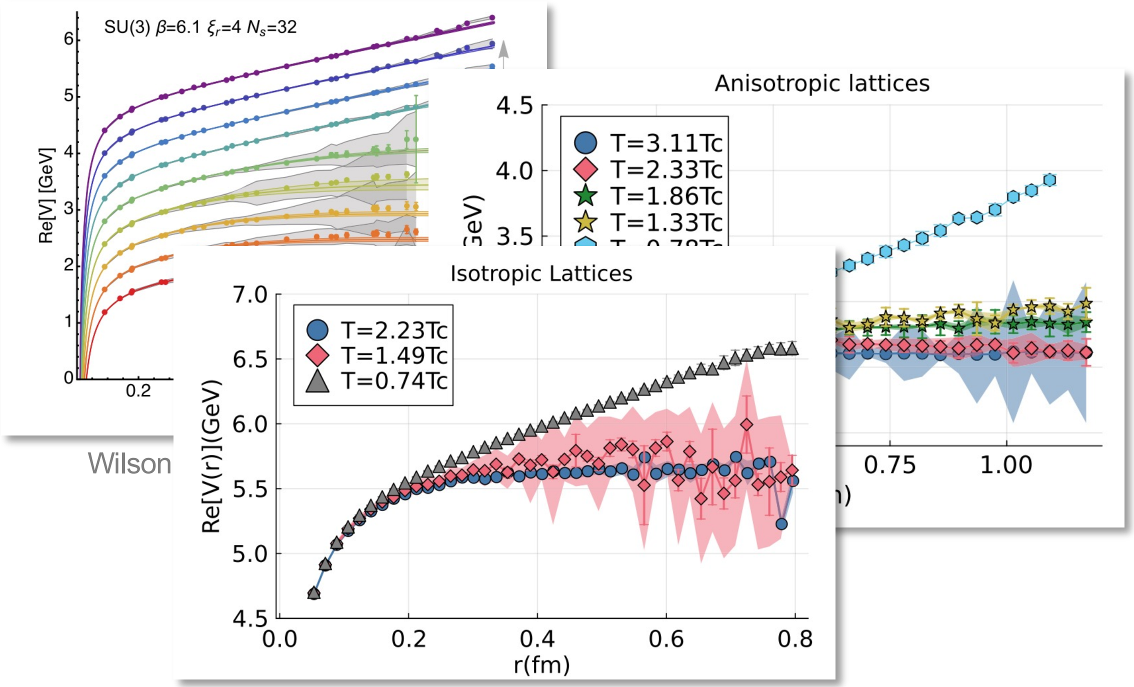
Y. Burnier, A.R. PRD 95 (2017) 5, 054511 & R. Larsen et.al. PRD 110 (2024) 11, 114501

- Moderate numerical cost, fine grids: N_τ=20-96
- Based on Bayesian Reconstruction (BR) (crosschecked with Pade)
- Consistent picture: no modification at $T<T_C$ Debye screening at $T>T_C$



Quenched QCD – Im[V]

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Y. Burnier, A.R. PRD 95 (2017) 5, 054511 & R. Larsen et.al. PRD 110 (2024) 11, 114501

- Moderate numerical cost, fine grids: N_τ=20-96

- Based on both Bayesian Reconstruction (BR) and Pade Reconstruction

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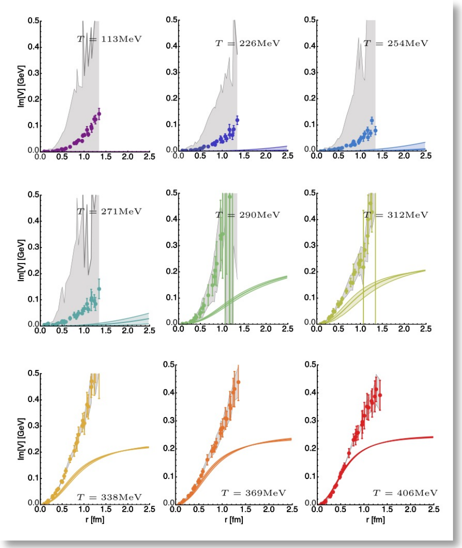

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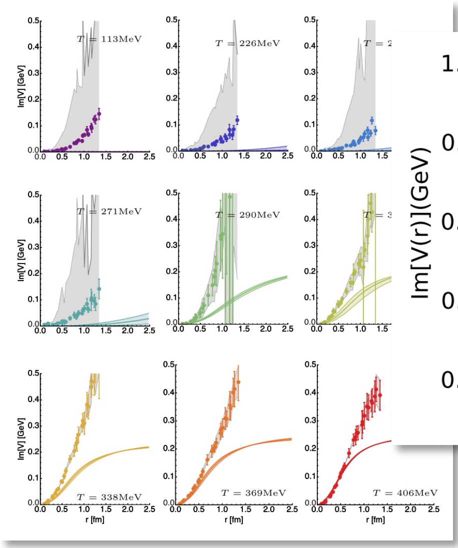

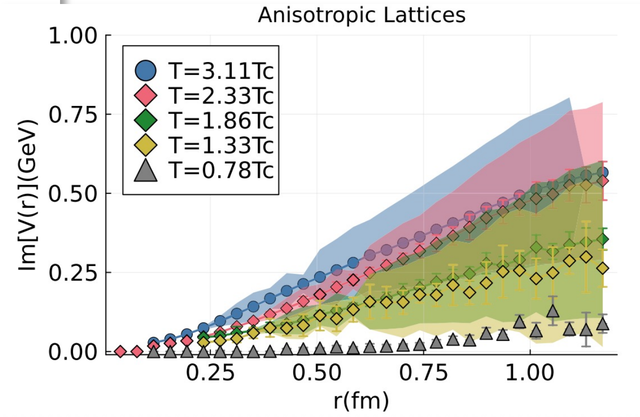

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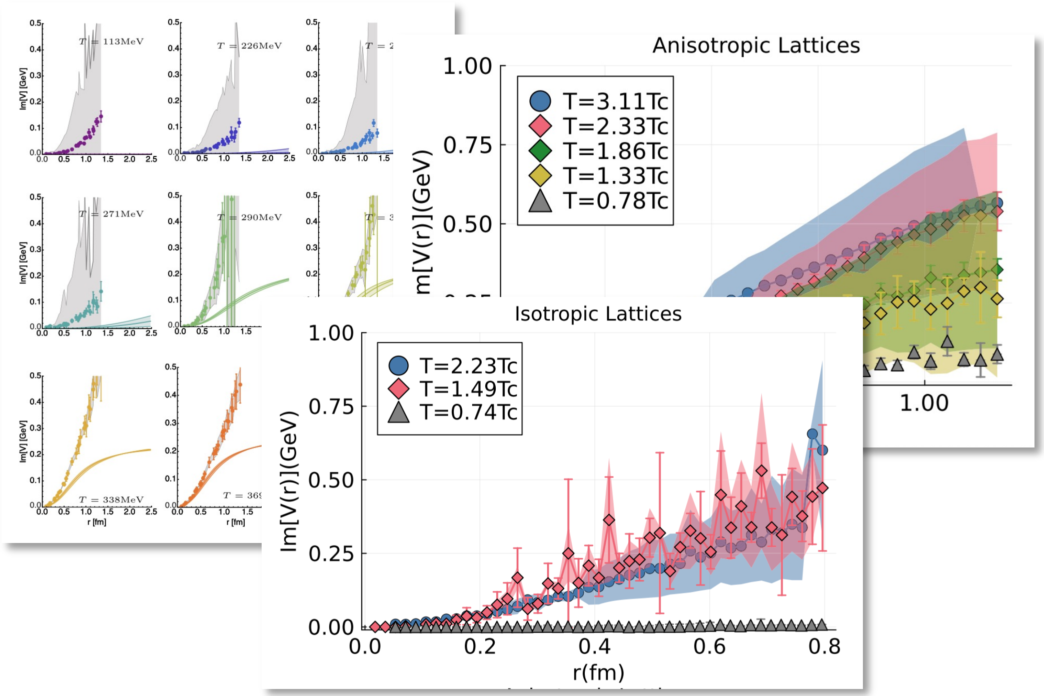

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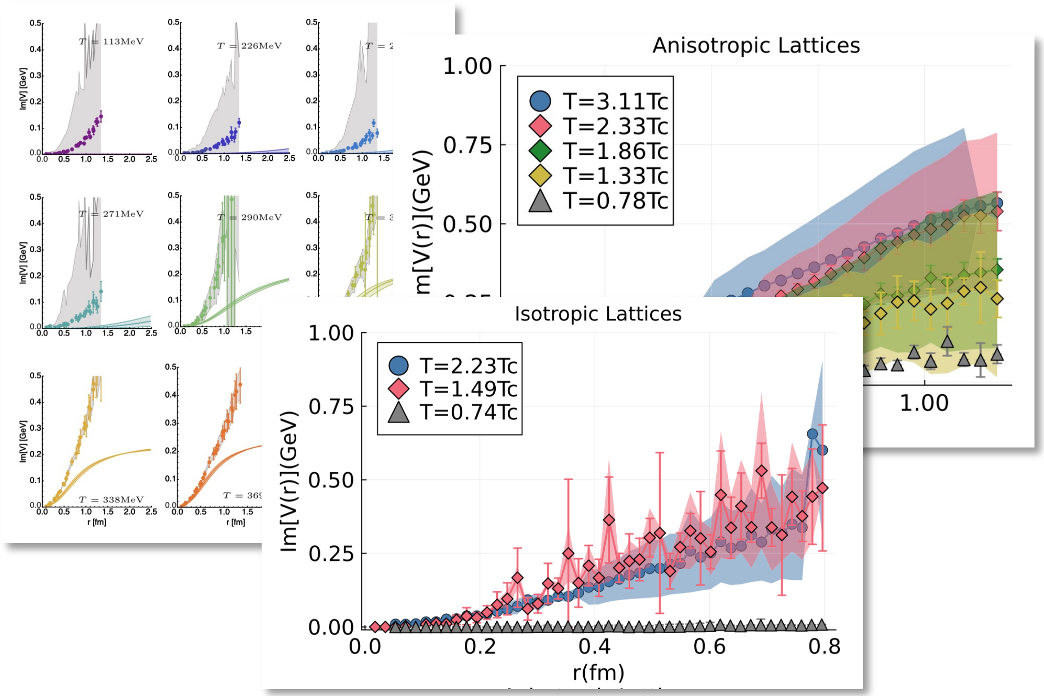
- Moderate numerical cost, fine grids: N_τ=20-96
- Based on both Bayesian Reconstruction (BR) and Pade Reconstruction
- Much more difficult to reliably extract Im[V] but statistically significant signal for Im[V]>0 at T>T_C



Legacy isotropic full QCD - Re[V] & Im[V]

- N_f=2+1 AsqTad dynamical quarks w/ m_π=300MeV but still coarse N_τ=12

Y. Burnier, A.R., O. Kaczmarek JHEP12(2015)101

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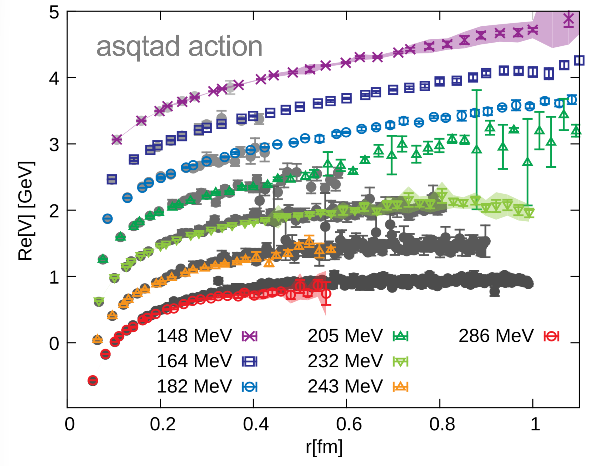
Y. Burnier, A.R., O. Kaczmarek JHEP12(2015)101

- Based on Bayesian Reconstruction (BR)



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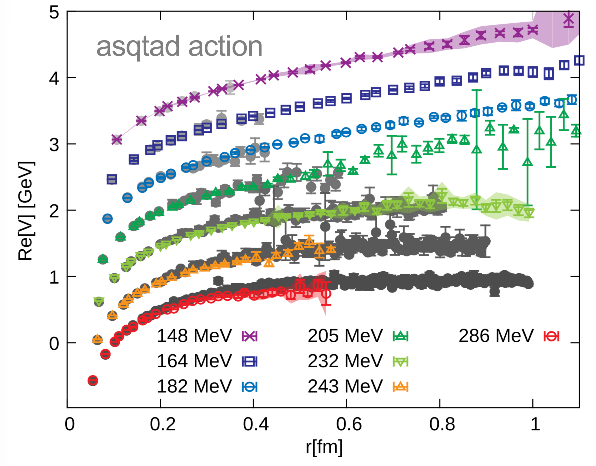
- Smooth crossover manifest as monotonous weakening of Re[V] as T increases. (residual σ but agreement w/ F[1])



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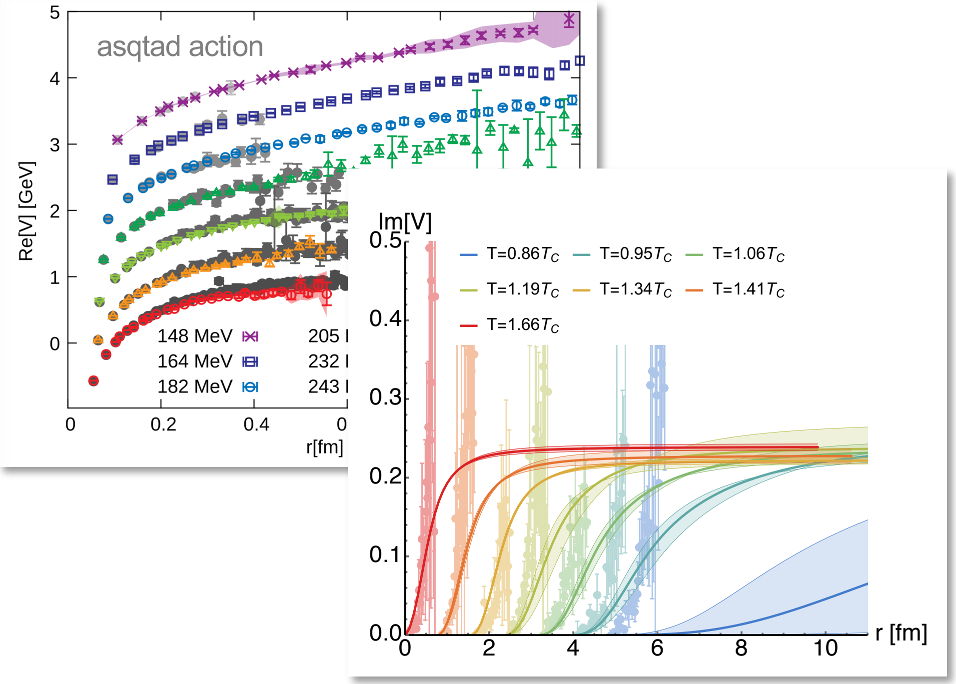
- Based on Bayesian Reconstruction (BR)
- Smooth crossover manifest as monotonous weakening of Re[V] as T increases. (residual σ but agreement w/ F[1])
- Imaginary part must be taken with grain of salt. Above T_C finite signal significant.



Isotropic full QCD - Re[V] & Im[V] (I)

- N_f=2+1 HISQ dynamical quarks w/ mostly m_π=160MeV but still coarse N_τ=12

HotQCD and A.R., G. Parkar PRD 105 (2022) 5, 054513

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HotQCD and A.R., G. Parkar PRD 105 (2022) 5, 054513

- Based on both Pade reconstruction and model fits

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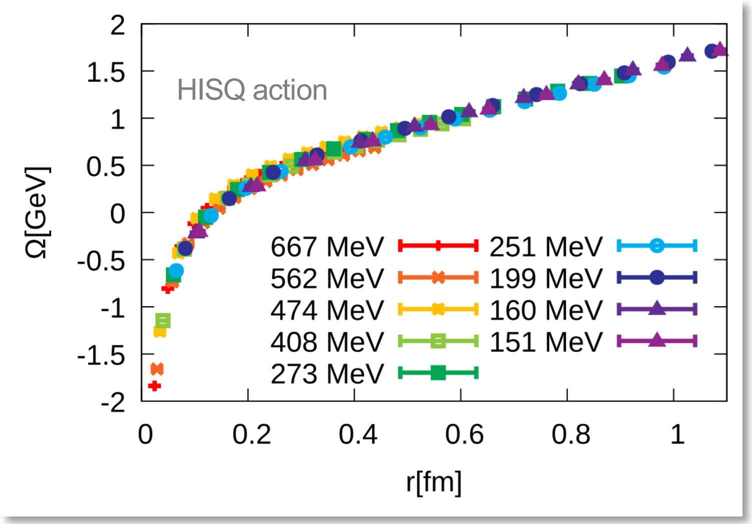

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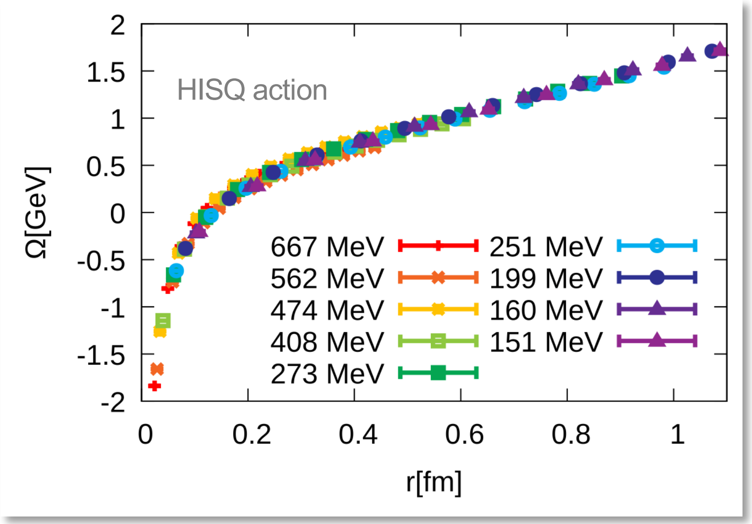
- Surprising outcome: Re[V] appears independent of T



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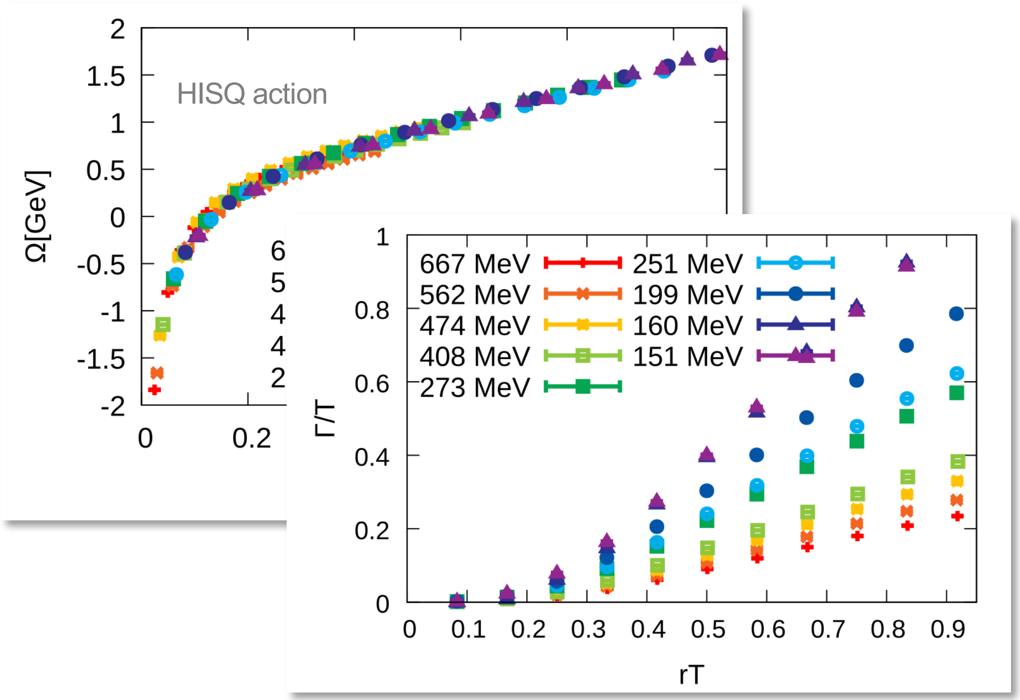
Im[V] monotonously increases with temperature.



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HotQCD and A.R., G. Parkar PRD 105 (2022) 5, 054513

- Based on both Pade reconstruction and model fits

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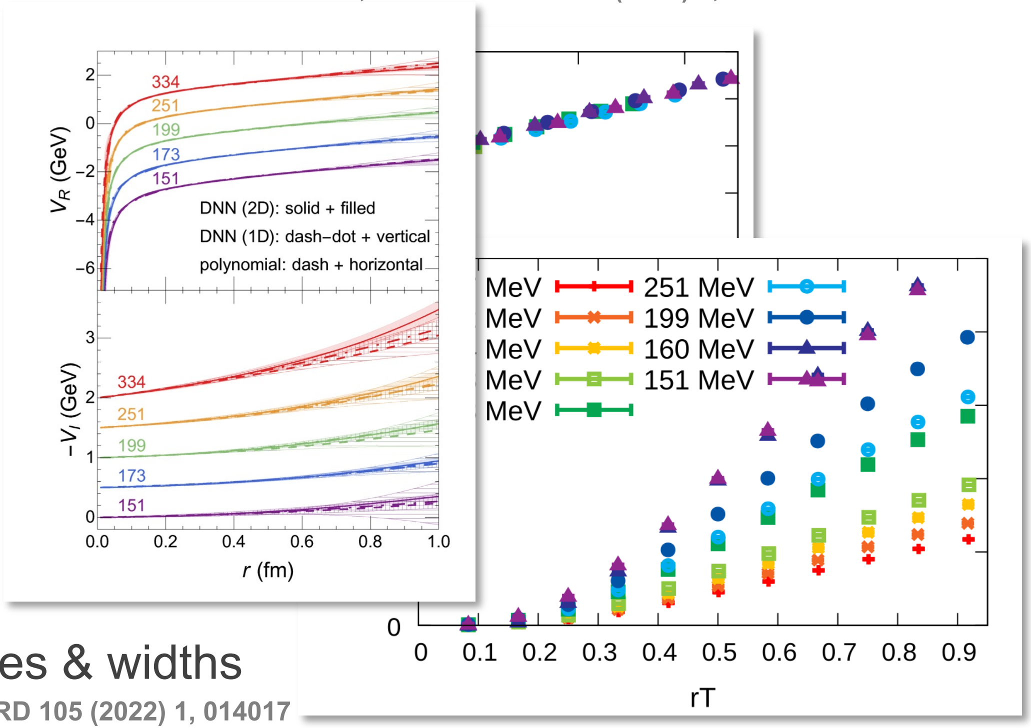
- Interesting crosscheck: NN-parameterization of potential trained on quarkonium T>0 masses & widths

S. Shi, K. Zhou, J. Zhao, S. Mukherjee and P. Zhuang PRD 105 (2022) 1, 014017



Isotropic full QCD - Re[V] & Im[V] (II)

- N_f=2+1 HISQ dynamical quarks w/ mostly m_π=160MeV & better resolution N_τ=16-36

HotQCD and A.R. PRD 109 (2024) 7, 074504

Isotropic full QCD - Re[V] & Im[V] (II)

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HotQCD and A.R. PRD 109 (2024) 7, 074504

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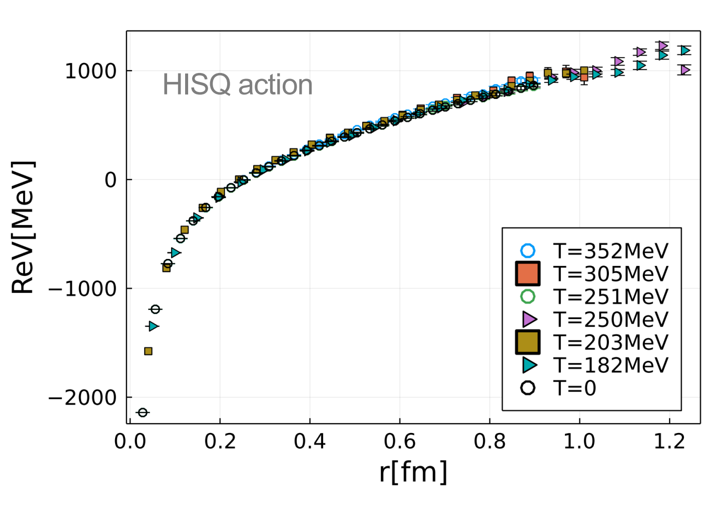
- Reconfirms earlier result: Re[V] appears independent of T



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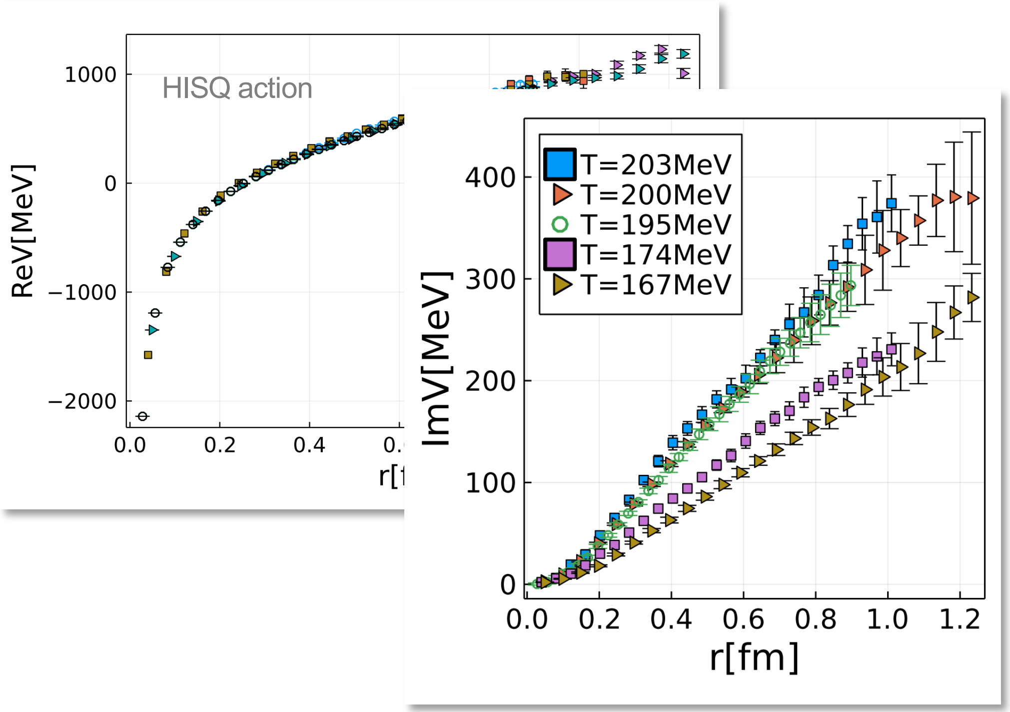

Anisotropic full QCD - Re[V] & Im[V] (I)

- O(a) Wilson quarks with heavy pion mass (m_π=300MeV) w/ N_τ=20-64 (now w/ extra statistics for N_τ=24)

FASTSUM Gen2L ensembles PRD 105, 034504

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  FASTSUM Gen2L ensembles PRD 105, 034504

- Based on Bayesian Reconstruction (BR) (model fits in progress)

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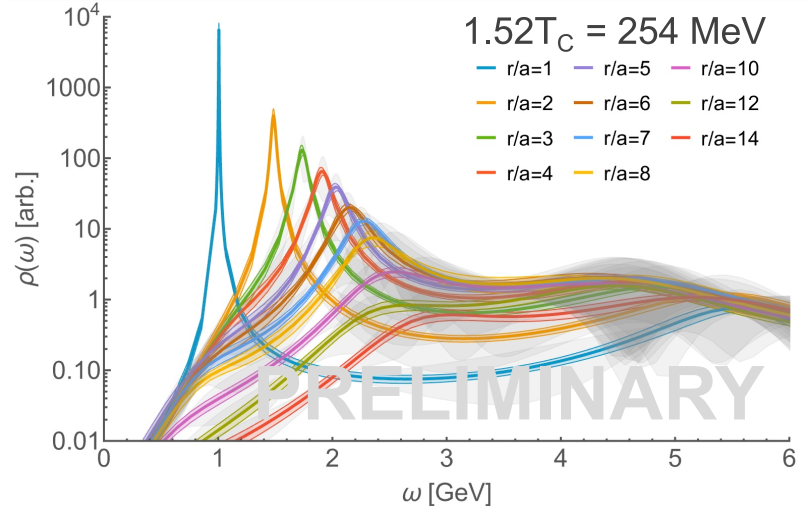
FASTSUM Gen2L ensembles PRD 105, 034504

- Based on Bayesian Reconstruction (BR) (model fits in progress)



Anisotropic full QCD - Re[V] & Im[V] (I)

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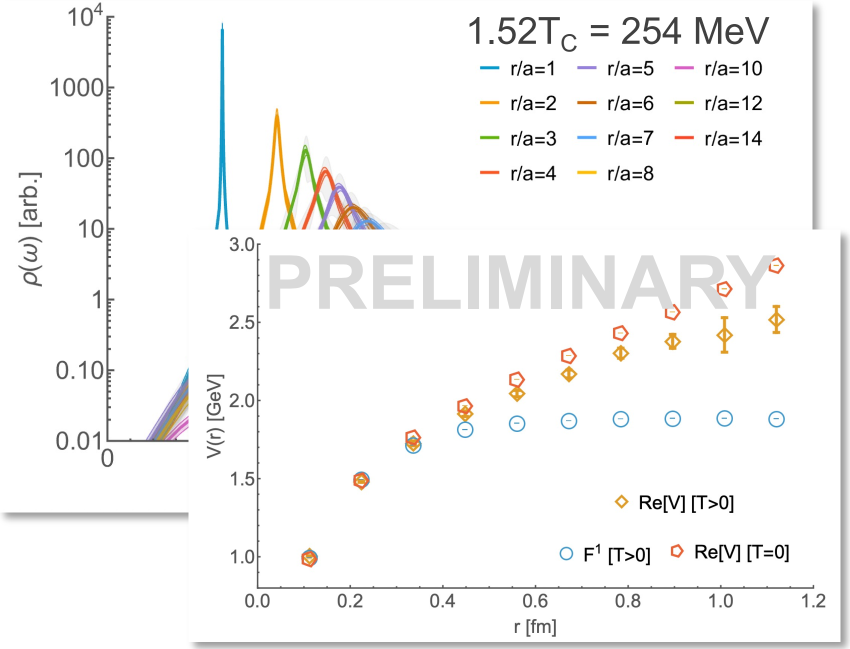

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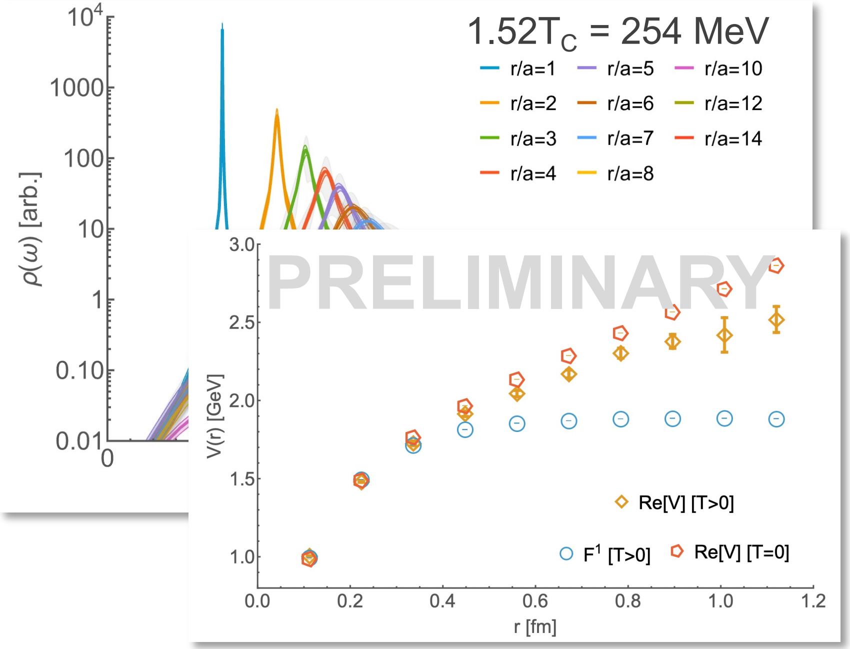

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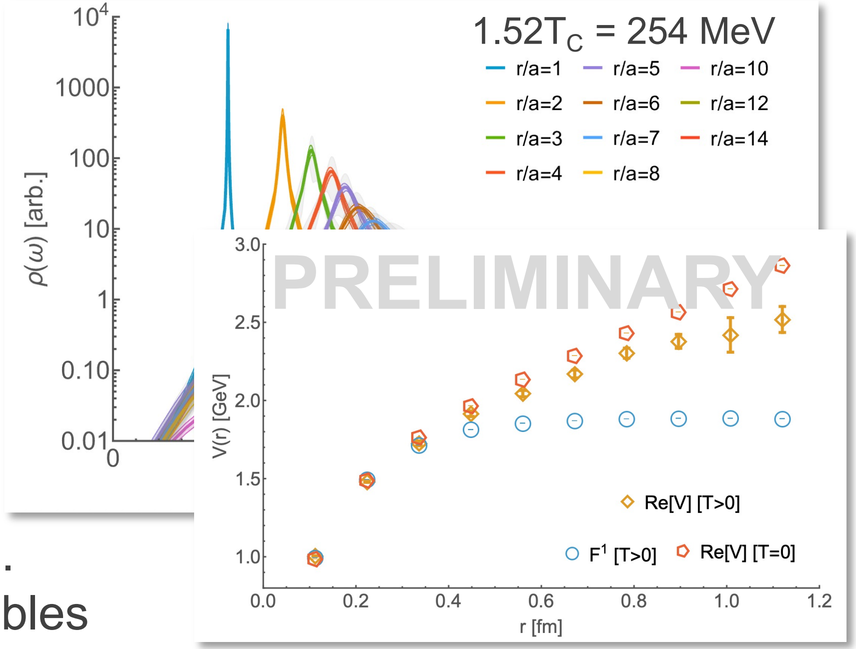
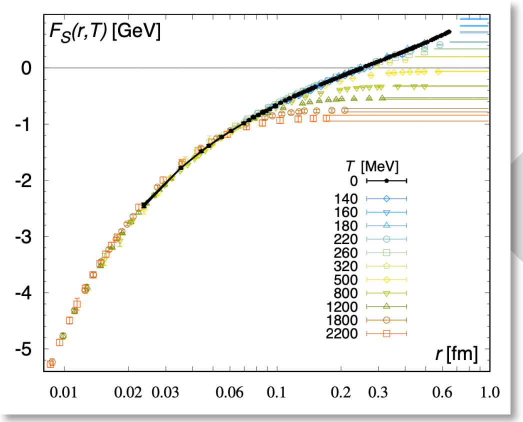
- Slight departure from T=0 results but significantly different from F[1]
- For N_τ<24 default model & truncation uncertainty too large for reliable results. Stay tuned for FASTSUM Gen3 ensembles

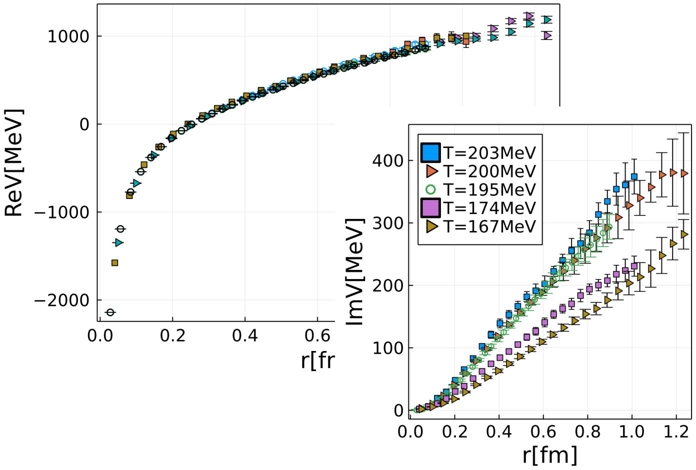


Consistency of recent results

- Presence of significant imaginary part will lead to decoherence - decorrelation



TUMQCD PRD98 (2018) 5, 054511



HotQCD & A.R. PRD 109 (2024) 7, 074504

- No apriori inconsistency between potential and thermodynamic behavior

Tantalizing hints for additional structure

- Recent study of topological center vortices at zero & finite temperature

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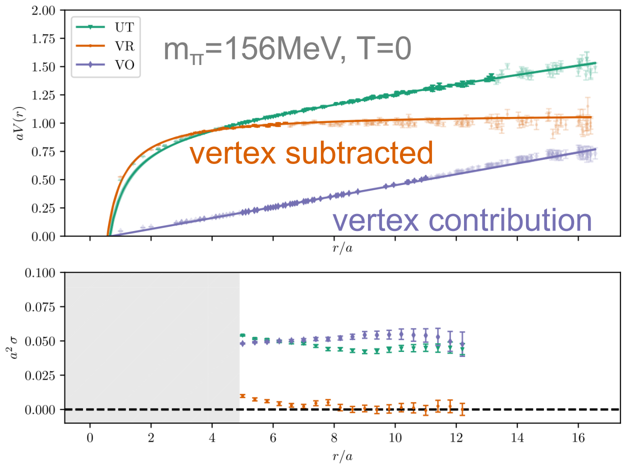

J. Biddle et.al. PRD 106 (2022) 5, 054505

- At T=0, removing vortices depletes the string tension.

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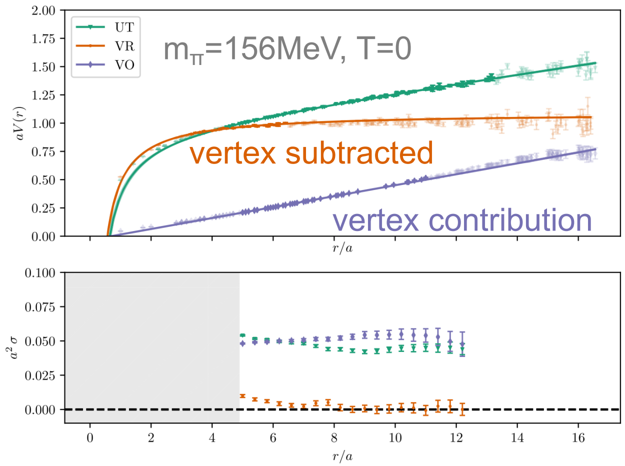

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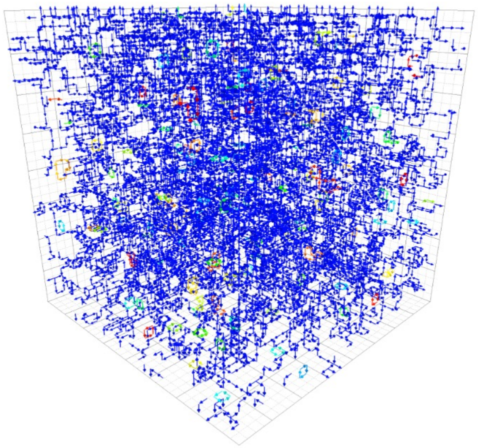

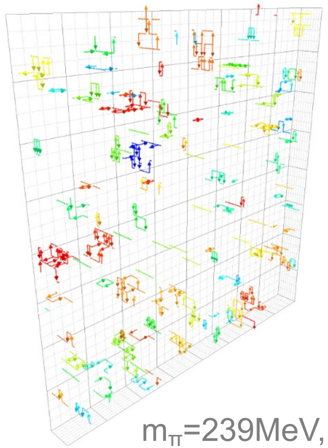

m_π=239MeV, T=0
O(a) improved Wilson fermions

J. Mickley et.al. PRD 111, 034508

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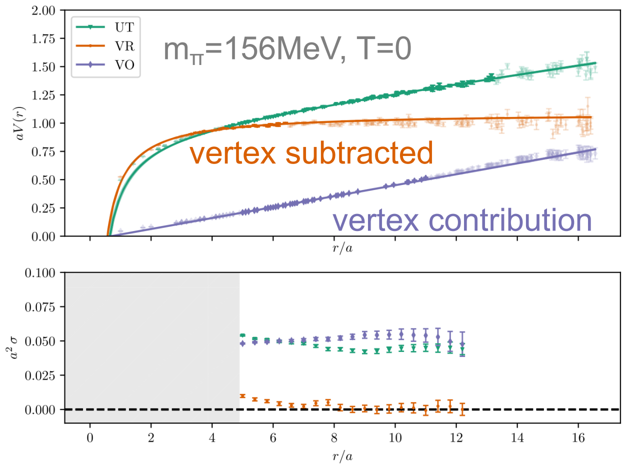

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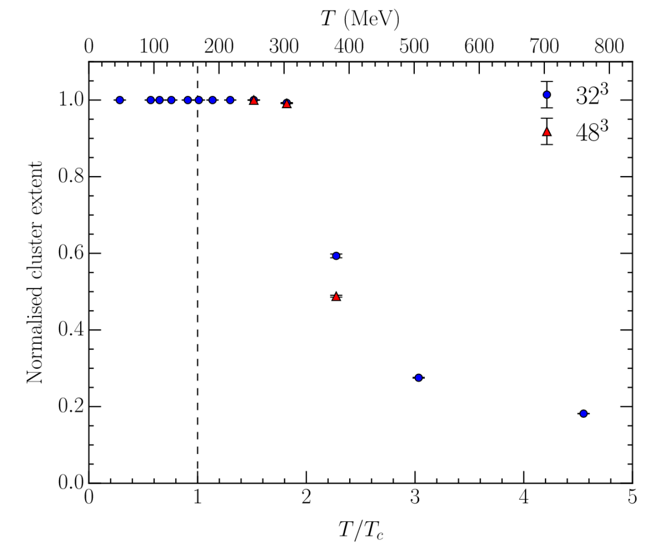

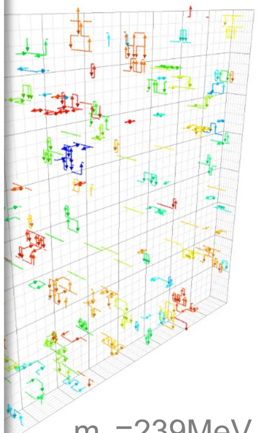

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O(a) improved Wilson fermions

J. Mickley et.al. PRD 111, 034508

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- At T > $2T^{\chi}_{C}$ show percolation transition which may indicate confinement persists

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谢谢

Thank you for your attention