Complex Heavy Quark Potential from Lattice QCD

where do we stand?

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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
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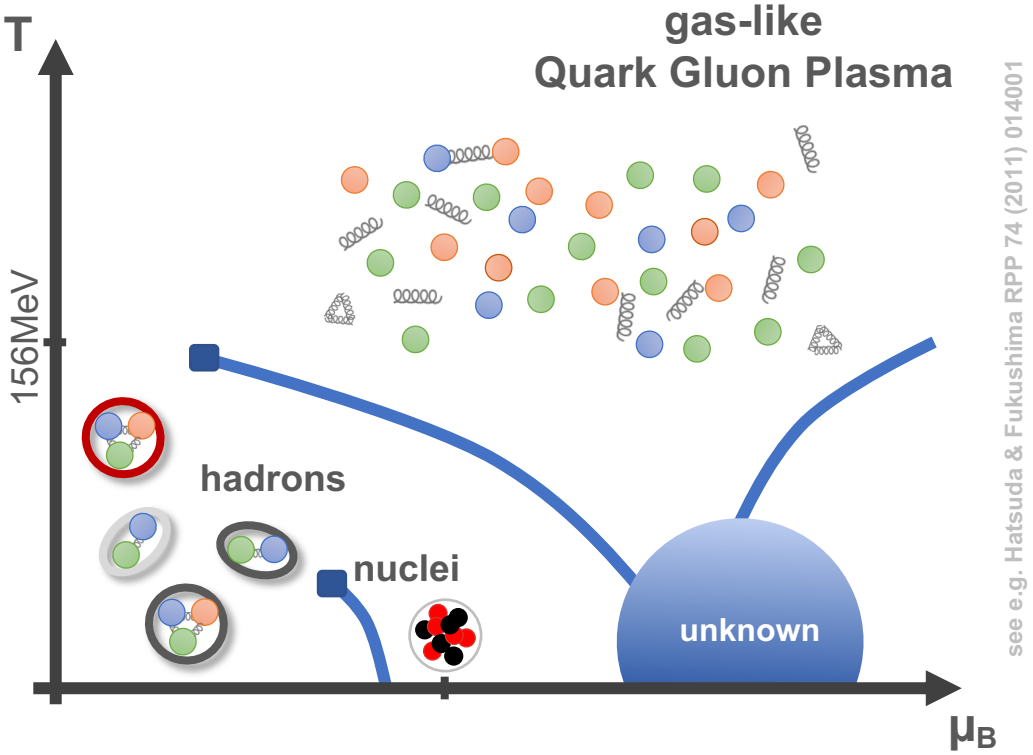

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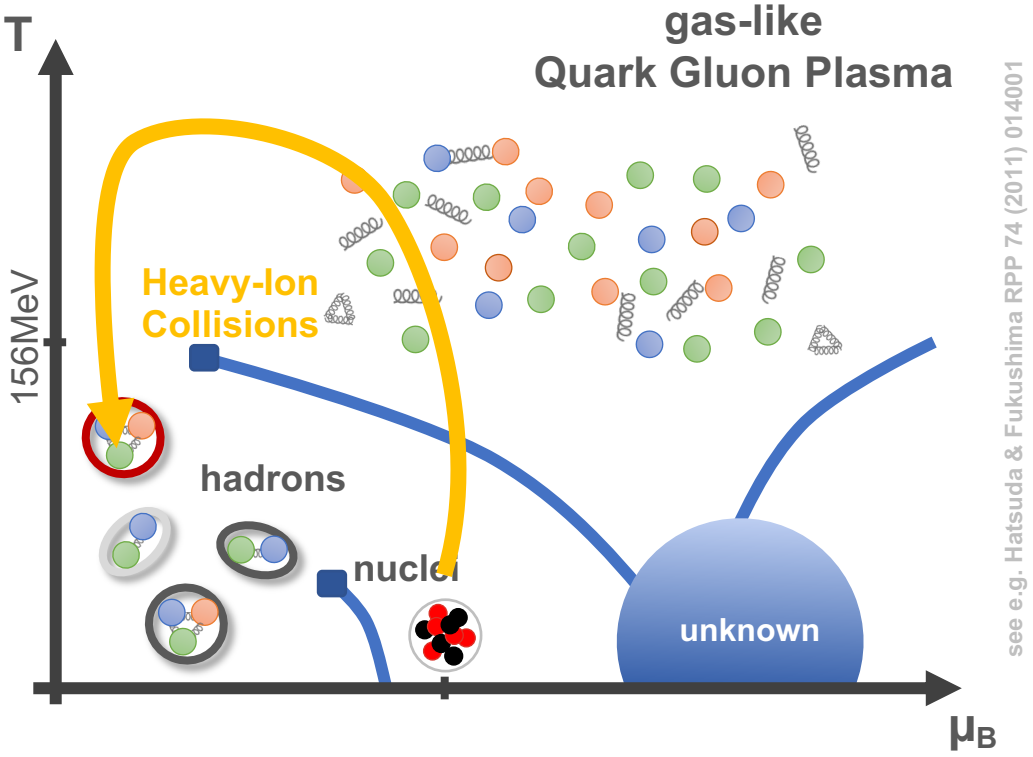

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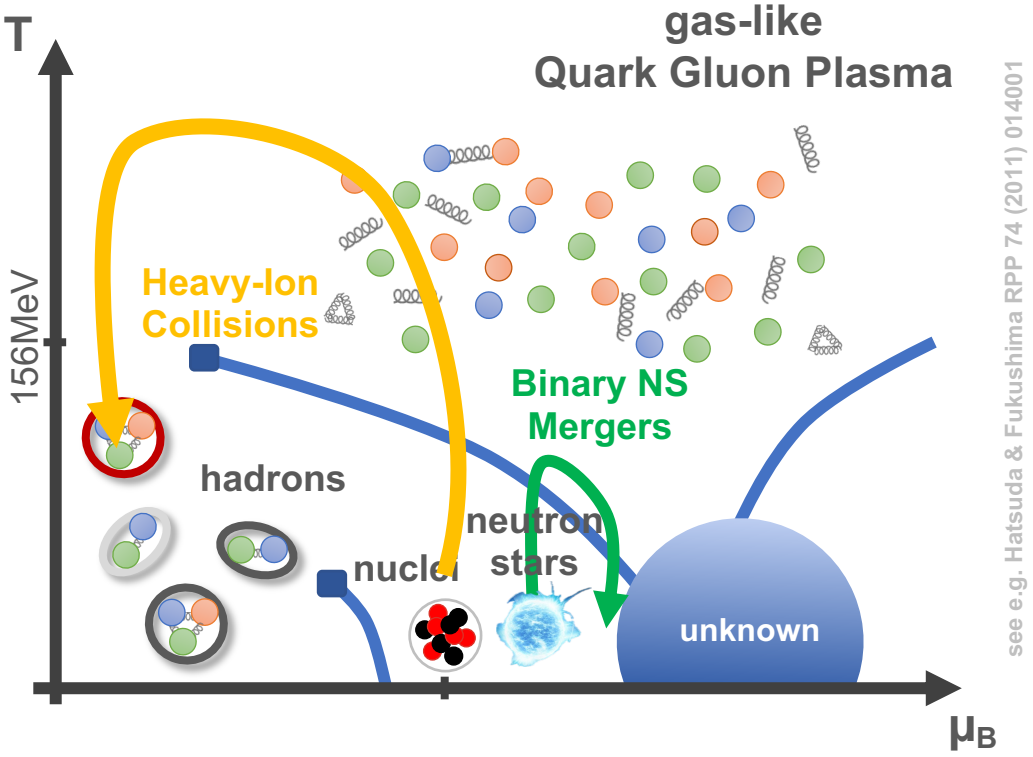

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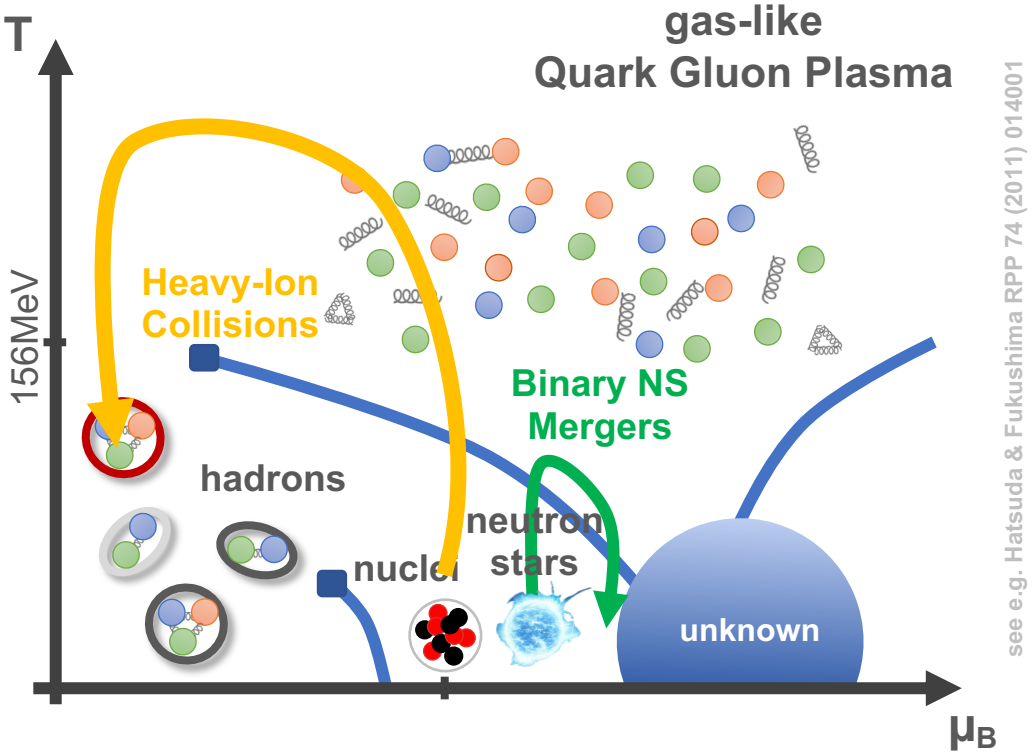

chiral symmetry restoration & deconfinement as key indicatiors of phase change

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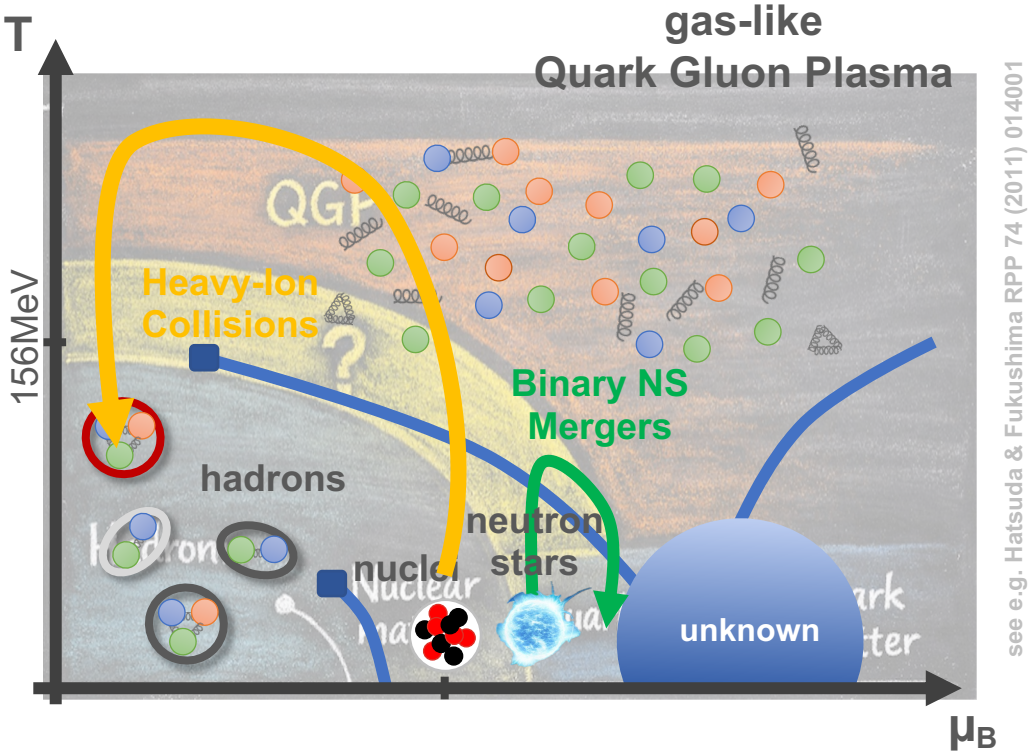

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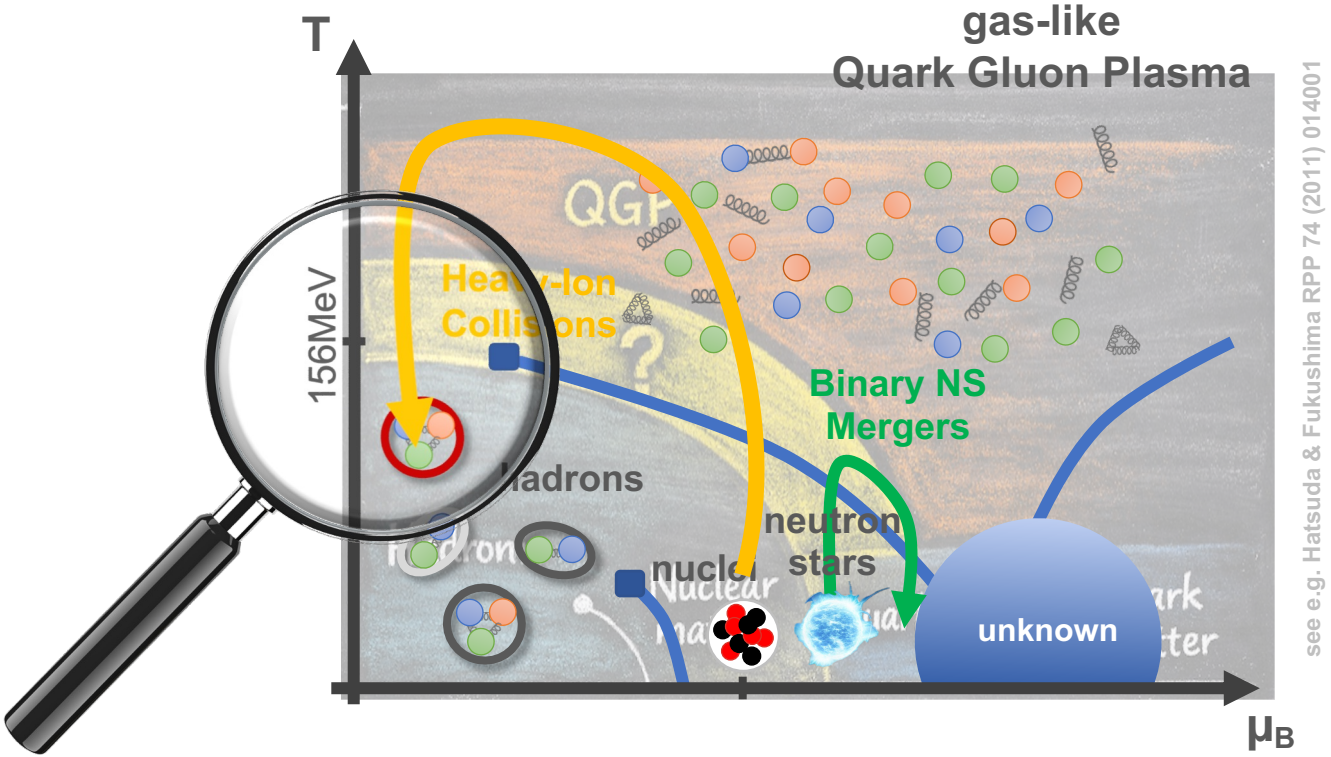
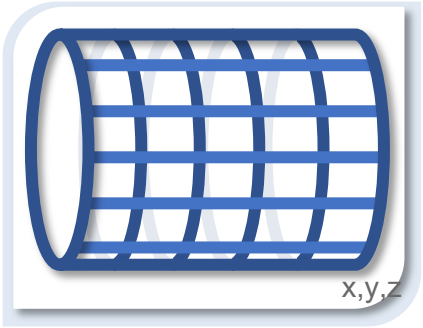


chiral symmetry restoration & deconfinement as key indicatiors of phase change

Lattice QCD – a first principle tool

- Non-perturbative 1st principles approach to Quantum Chromo Dynamics



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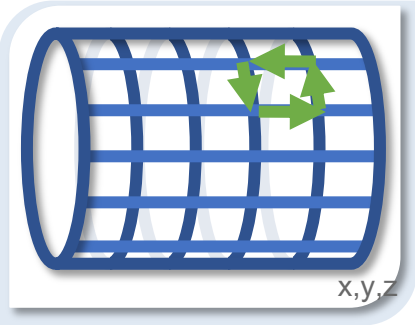

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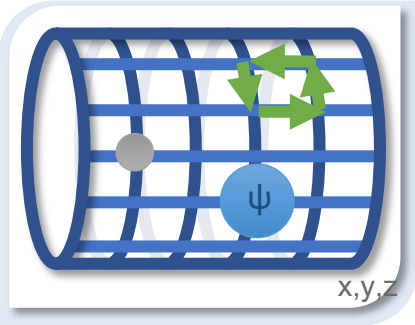

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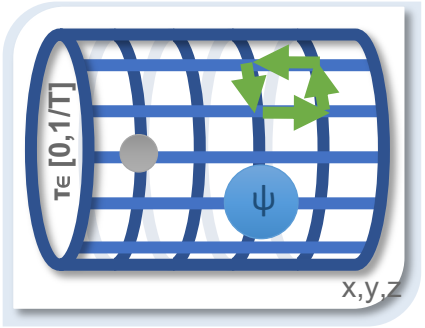

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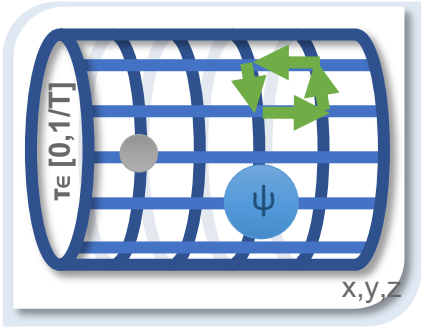
$$\langle O(U)\rangle = \int \mathcal{D}U\, O(U)\, e^{-S_E^{QCD}[U]}$$



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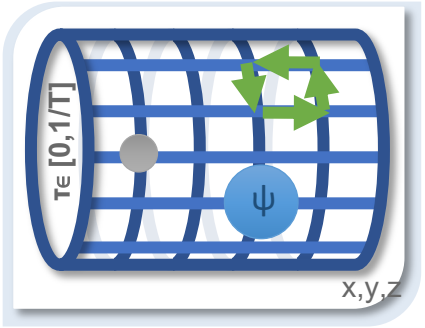
$$\langle O \rangle = \frac{1}{N} \lim_{N\to\infty} \sum_{k=1}^{N} O(U^k) \qquad P[U] \propto e^{-S_E[U,\psi,\bar{\psi}]}$$



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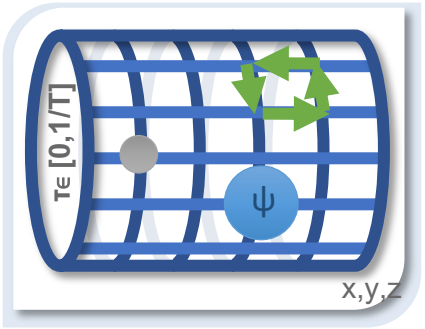

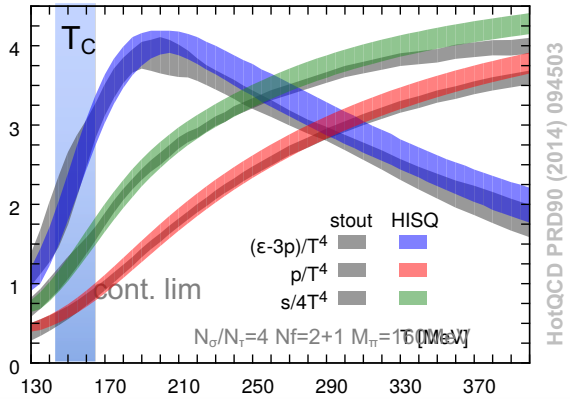

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  - **Chiral crossover** temperature: 156.5±1.5 MeV
    HotQCD PLB 795 (2019) 15

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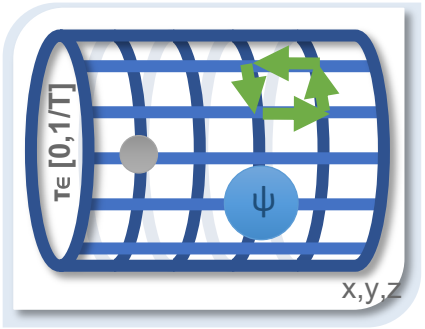

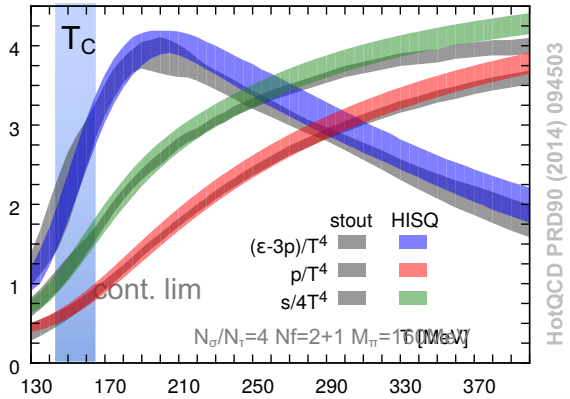

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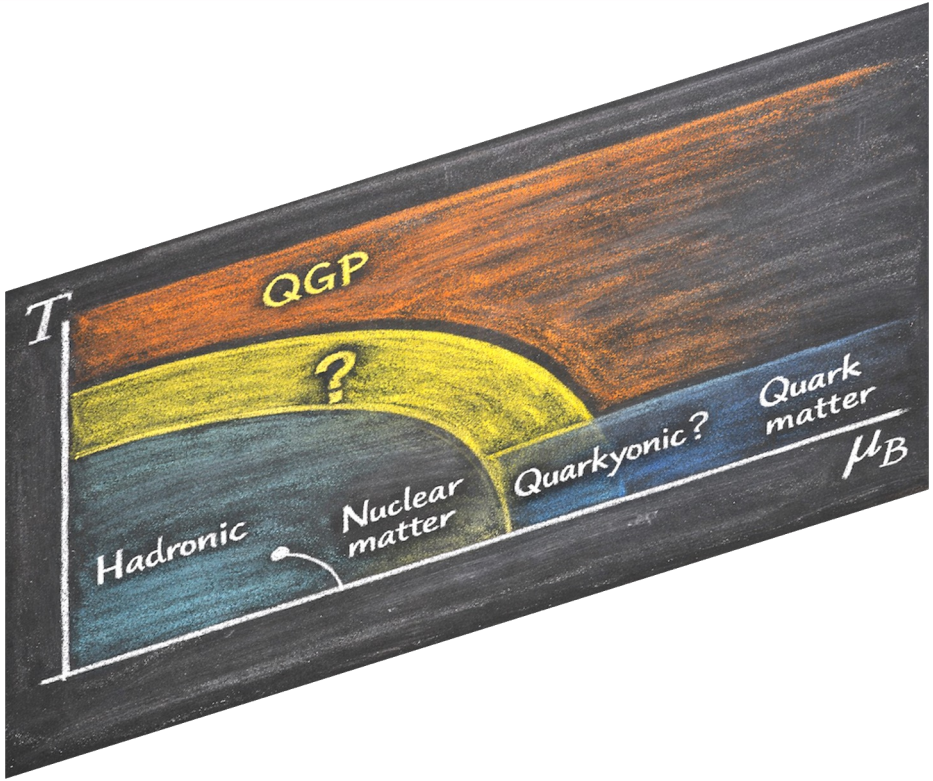
  - Equation of state as input for hydro-dynamics
    HotQCD PRD90 (2014) 094503 - WB PLB730 (2014) 99-104

Quarkonium as probe of phase structure



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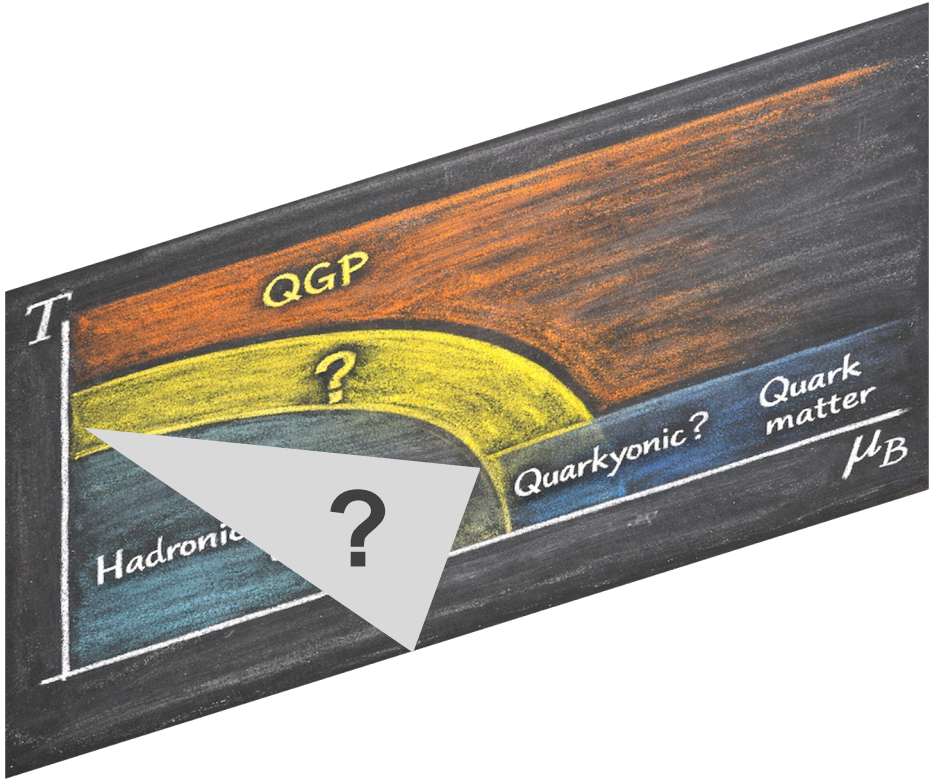

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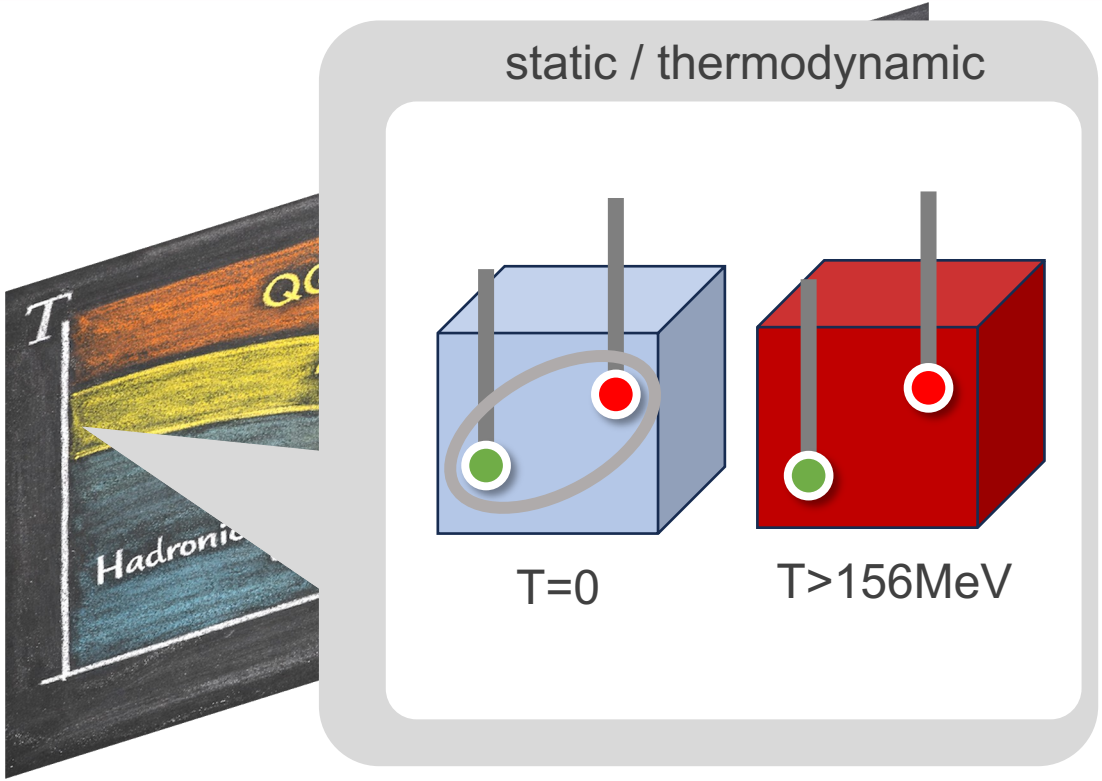

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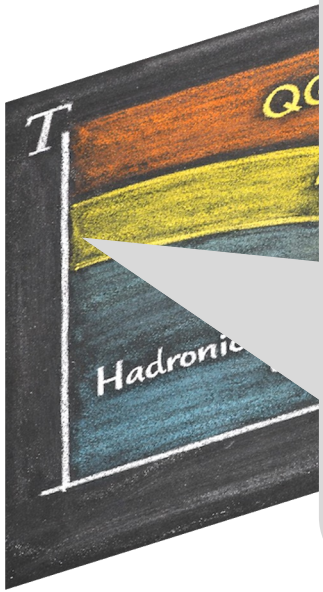
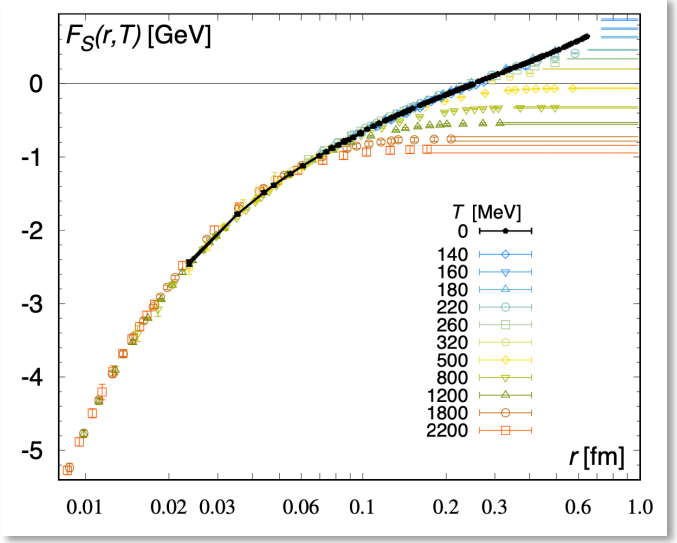


static / thermodynamic



TUMQCD PRD98 (2018) 5, 054511

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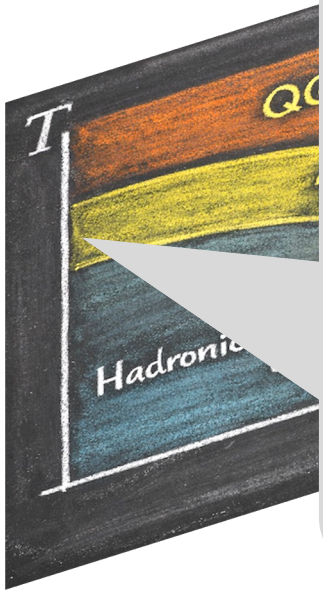

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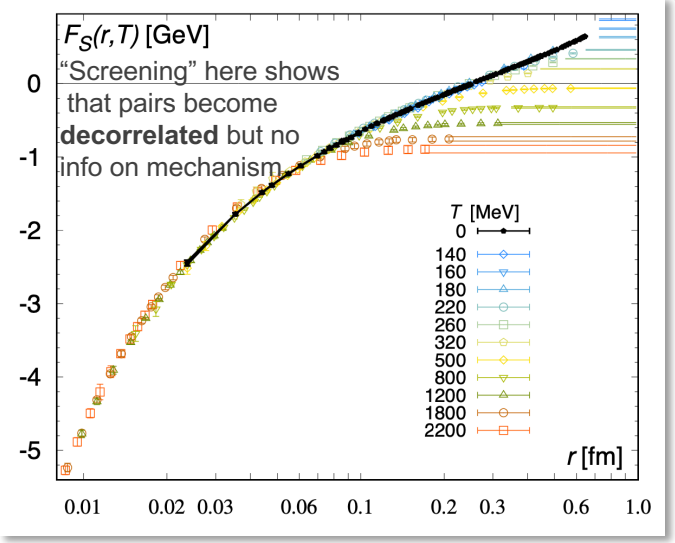

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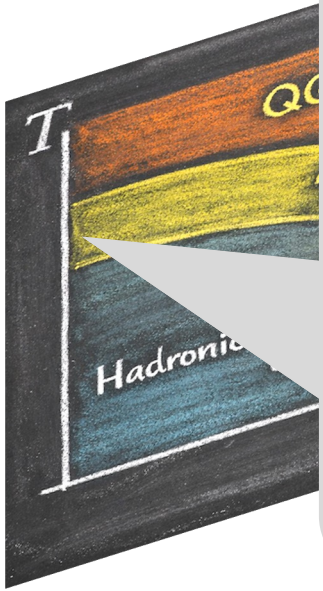

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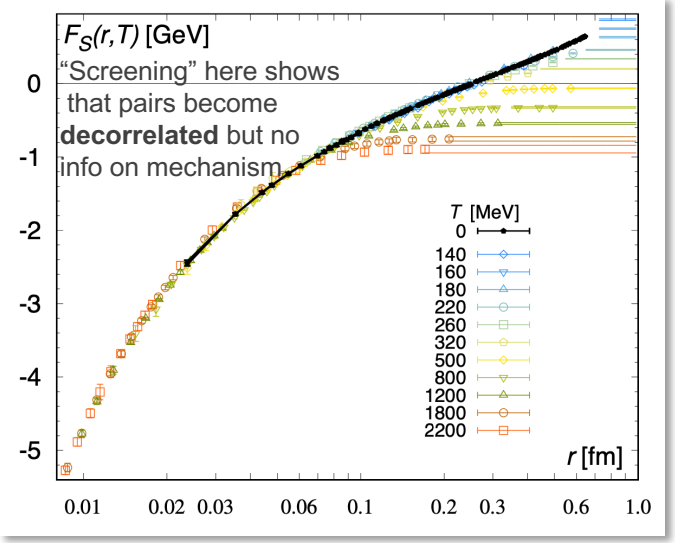

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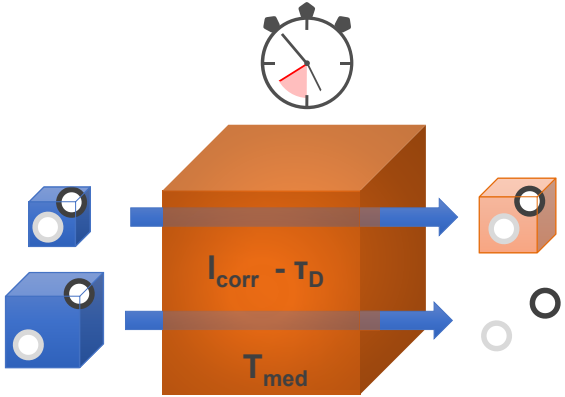
dynamic / real-time



Open-quantum system described by complex potential

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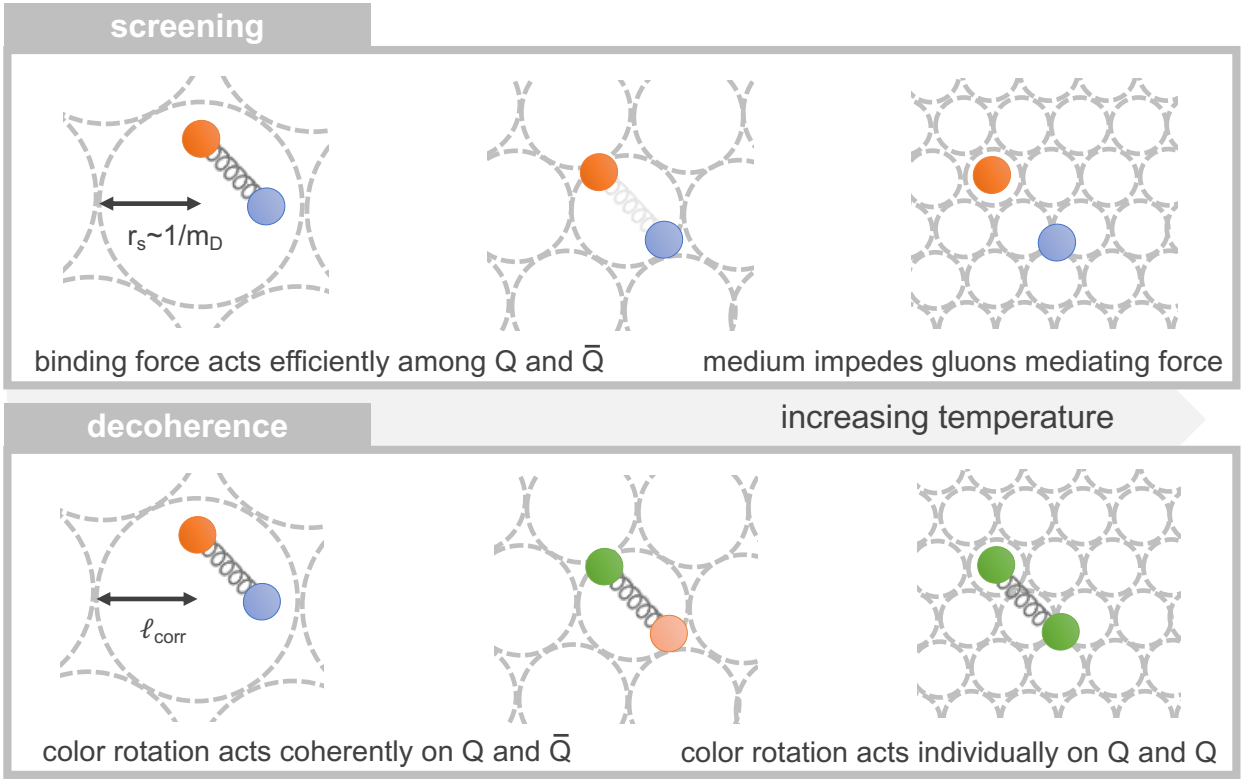
Heavy quark-antiquark real-time evolution



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)

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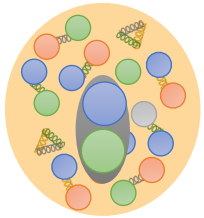
Defining the potential from QCD

- 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



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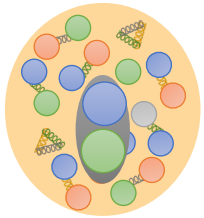

$E \sim m_Q$

QCD

Dirac fields

$Q(x), \bar{Q}(x)$

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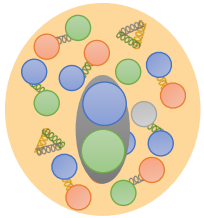

$E \sim m_Q$ → $E \sim m_Q v$

QCD → **NRQCD**

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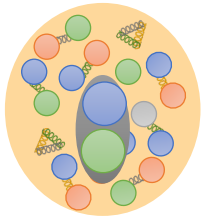

$E \sim m_Q$	$E \sim m_Q v$	$E \sim m_Q v^2$
QCD	**NRQCD**	**pNRQCD**
Dirac fields	**Pauli fields**	**Color singlet and octet wavefunctions**
$Q(x), \bar{Q}(x)$	$\psi, \psi^\dagger, \chi, \chi^\dagger$	$\psi_S(R,t), \psi_O(R,t)$

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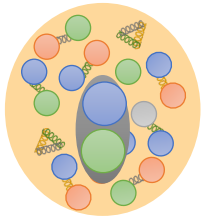

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$Q(x), \bar{Q}(x)$	$\psi, \psi^\dagger, \chi, \chi^\dagger$	$i\partial_t \psi_S = \left(V^{QCD}(R) + \mathcal{O}(m_Q^{-1})\right)\psi_S$

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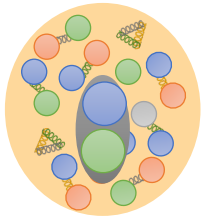

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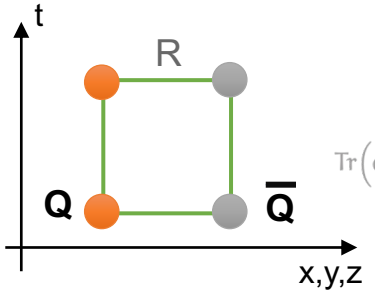
- Matching through the QCD Wilson loop

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



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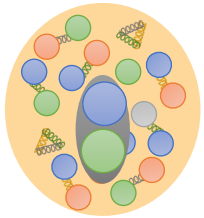

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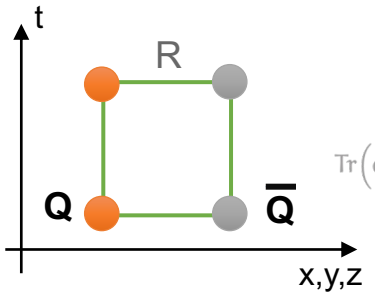

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Im[V]: Laine et al. JHEP03 (2007) 054; Beraudo et. al. NPA 806:312,2008, Brambilla, Ghiglieri et.al. PRD 78 (2008) 014017

- HTL 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

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

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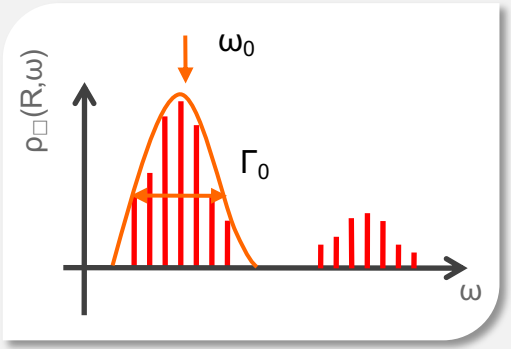
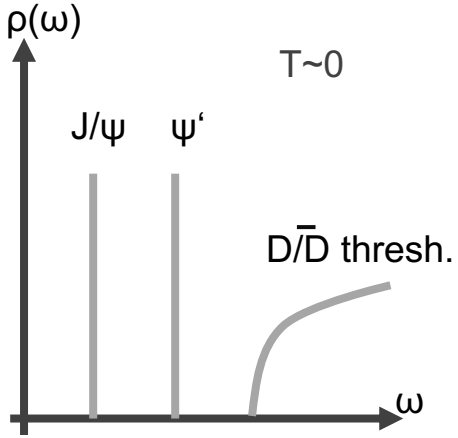


$$V(R) = \omega_0(R) - i\Gamma_0(R)$$

Dynamical properties from lattice QCD

- **Lattice QCD** simulations are similar to a (very) **imperfect detector**



Quarkonium spectral function

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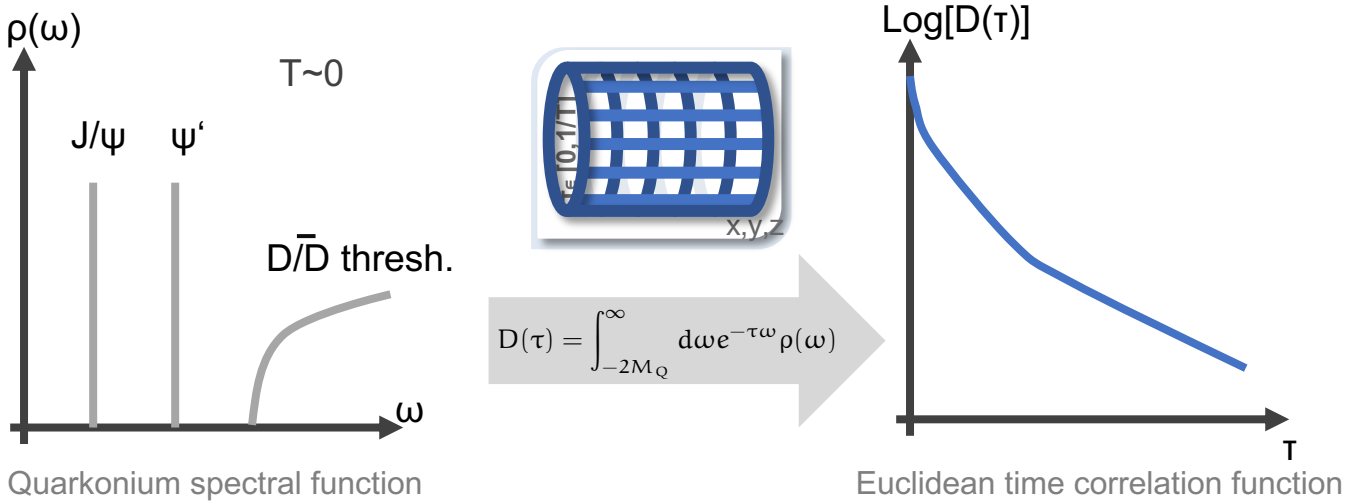

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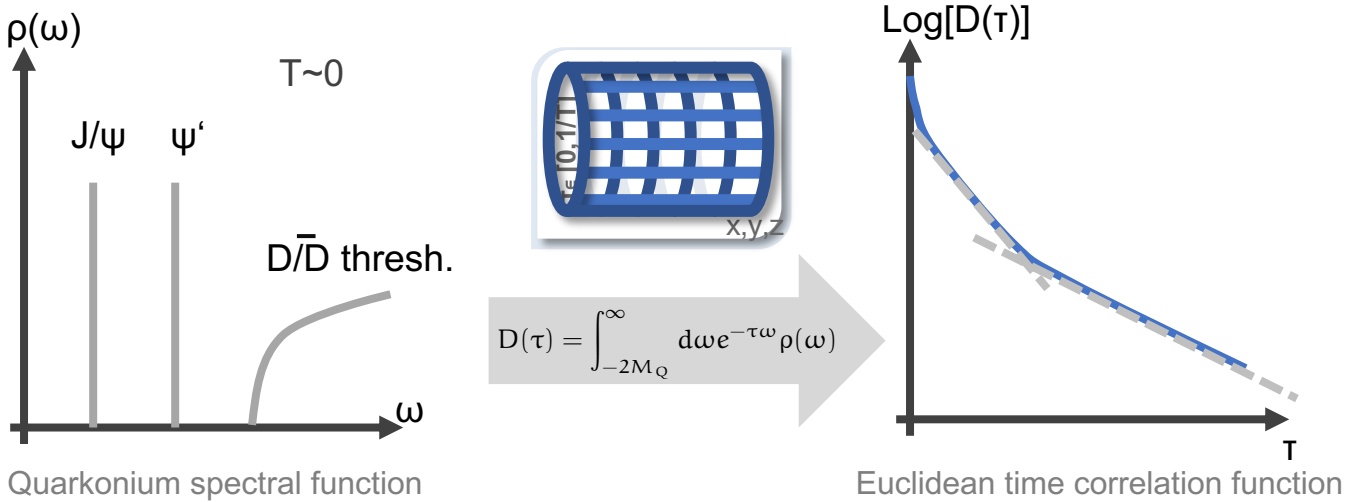

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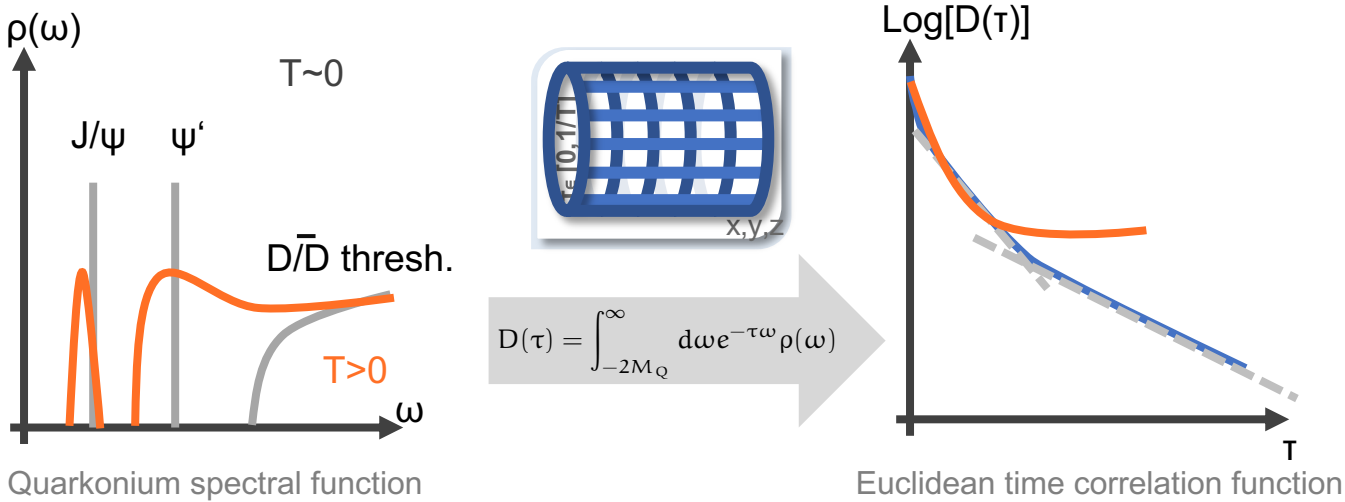

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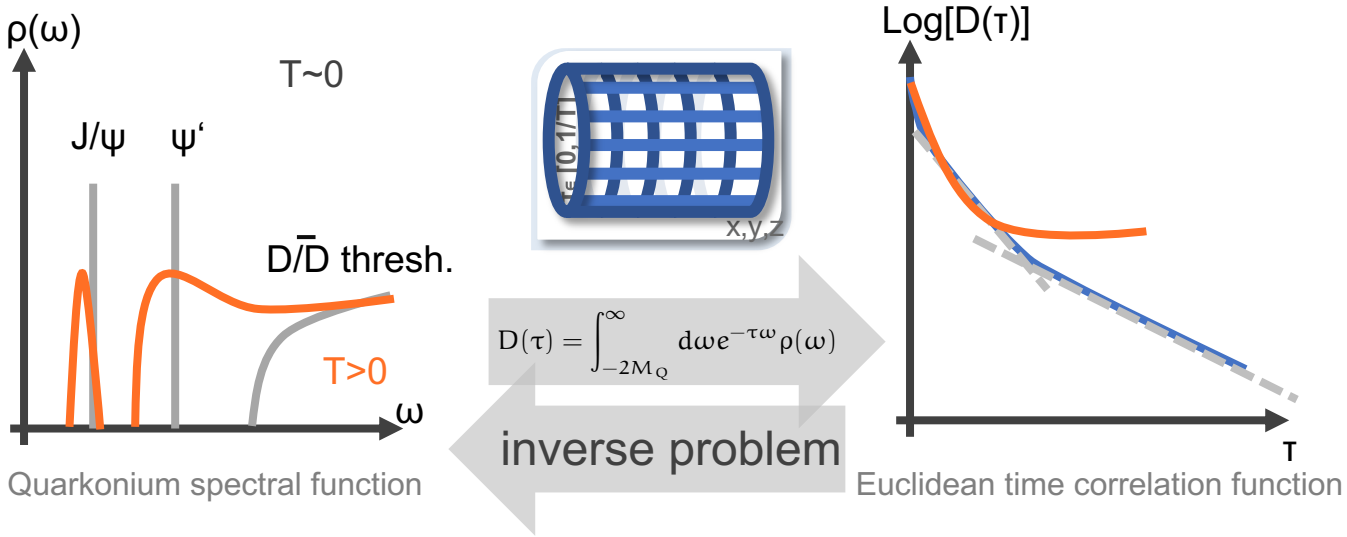

- Extraction of spectra ill-posed **unfolding problem**

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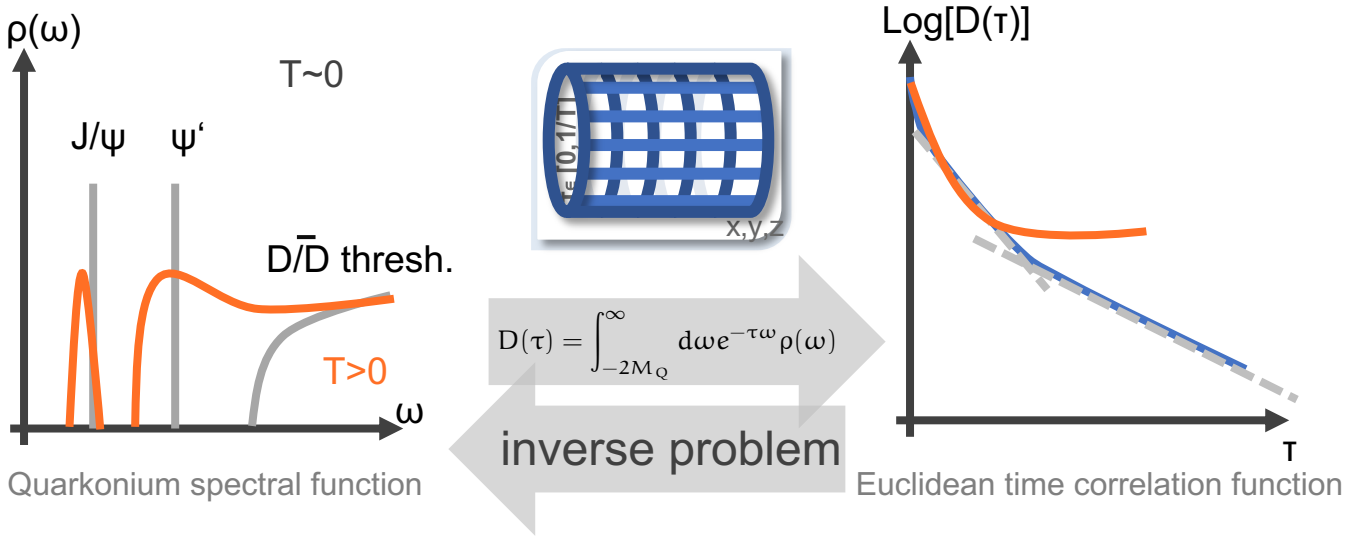


- Extraction of spectra ill-posed **unfolding problem**

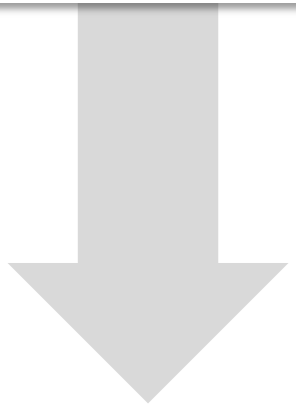
- Current state-of-the-art via **statistical inference** and **machine learning**

for an overview see e.g.: A.R. Front.Phys. 10 (2022) 1028995

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

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



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Regularize fit by limited choice of basis functions

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

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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

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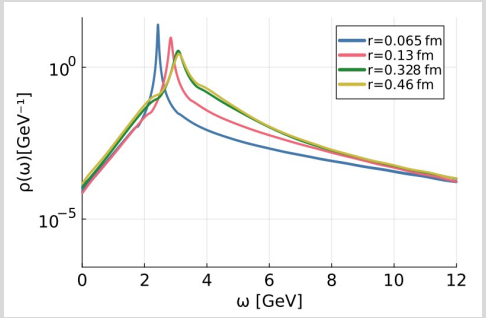

Realistic mock spectral functions via resummed perturbation theory (HTL)

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

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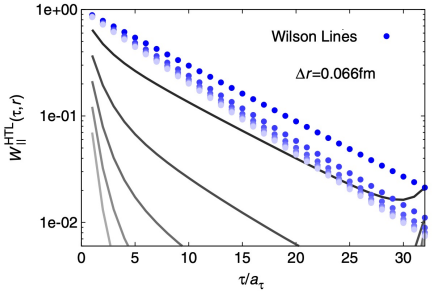

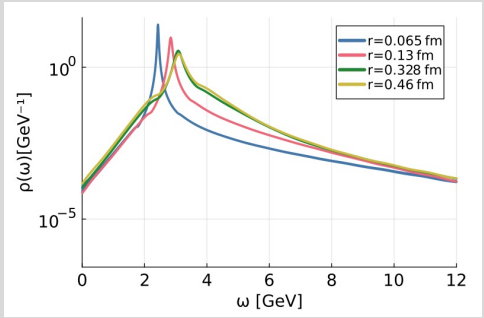

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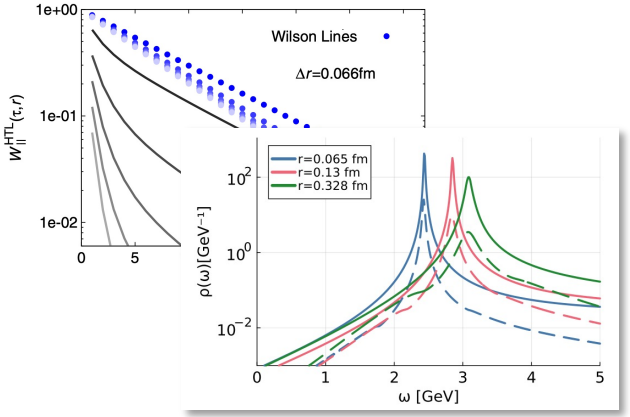

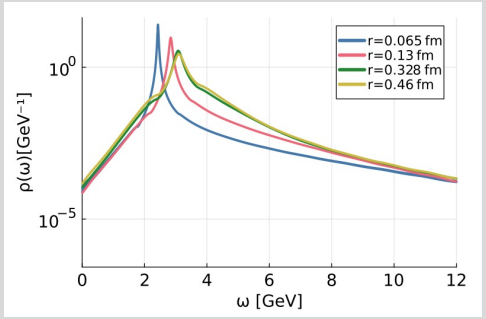

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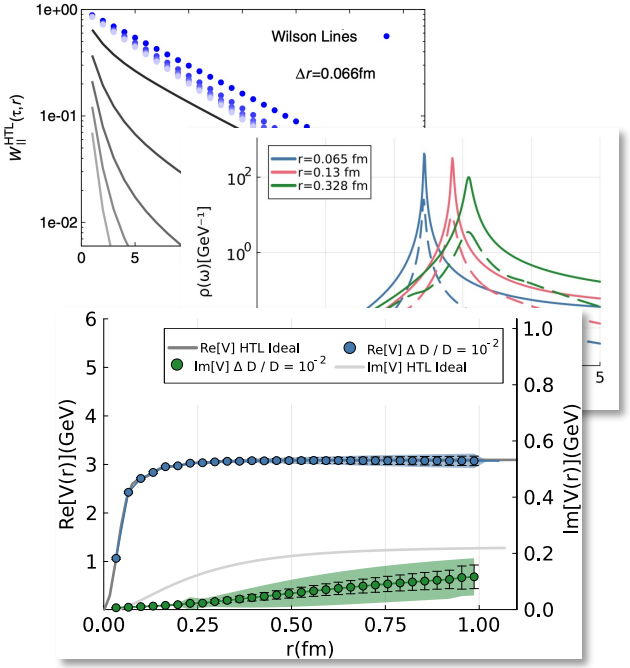

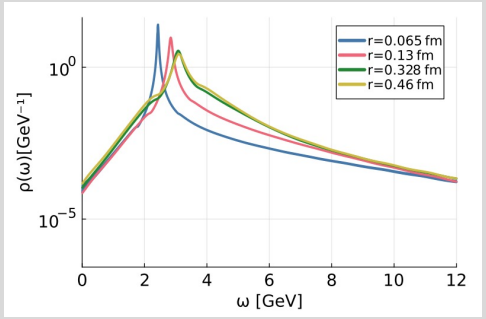

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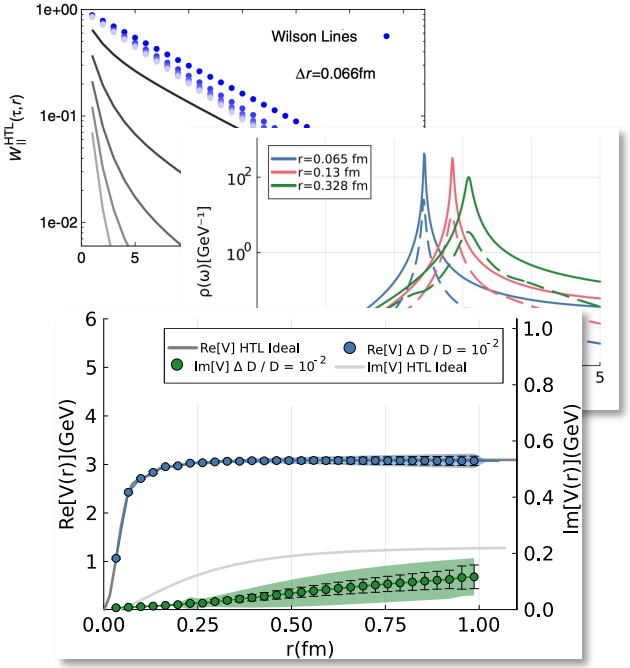

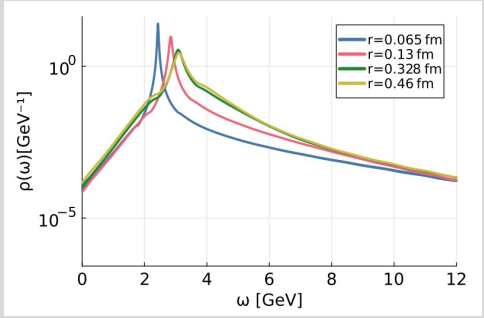

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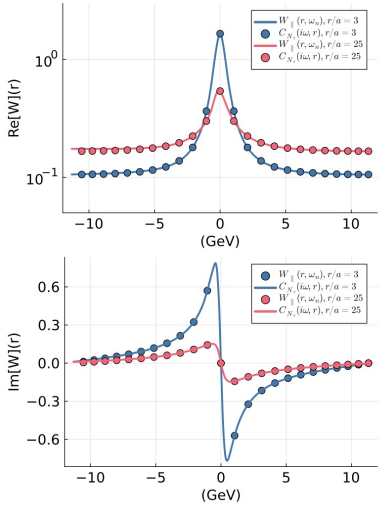

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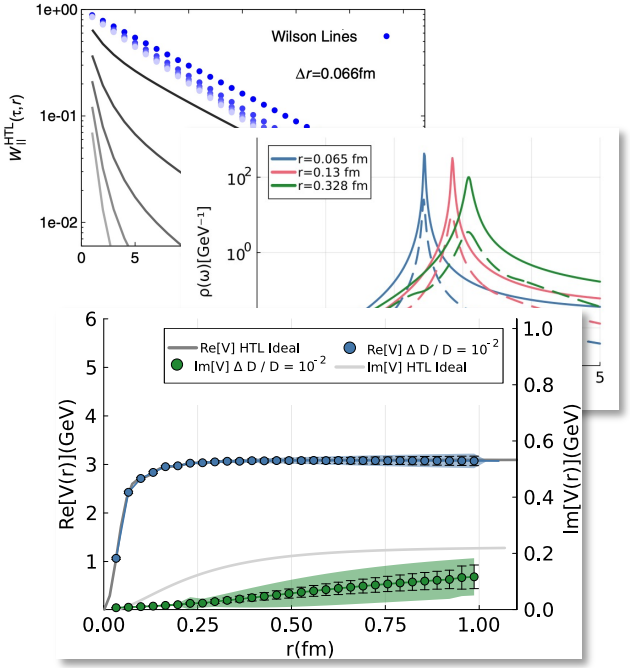

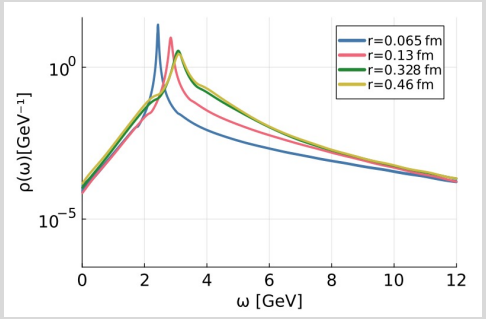

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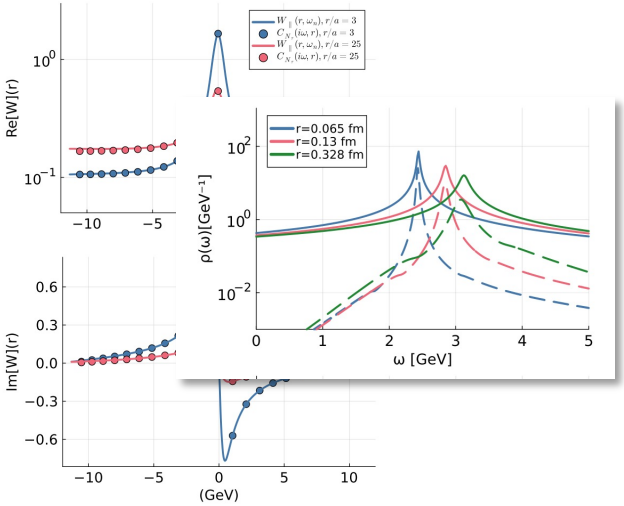

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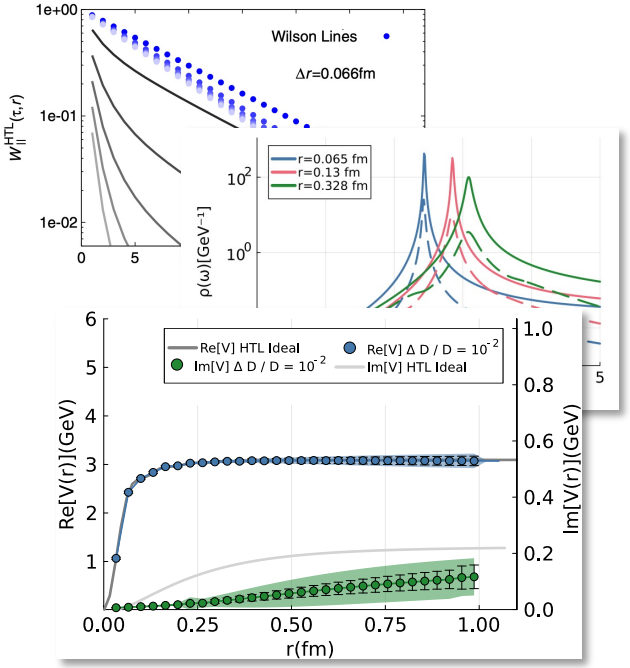

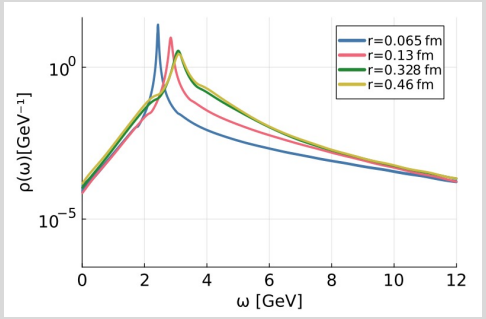

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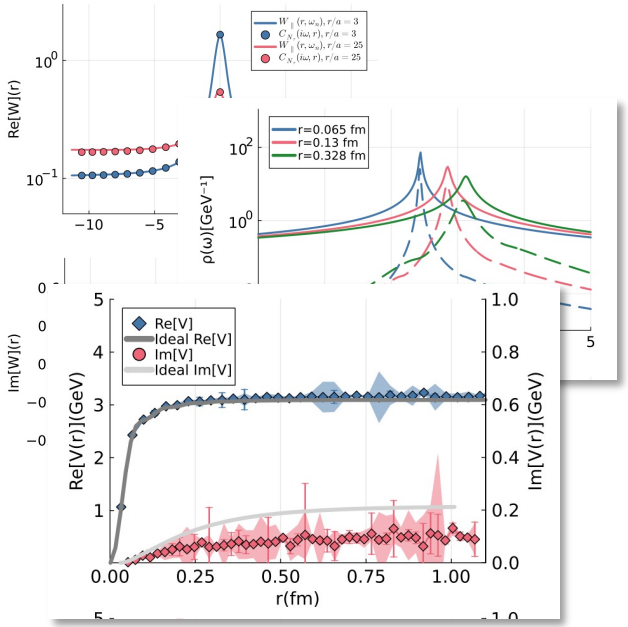

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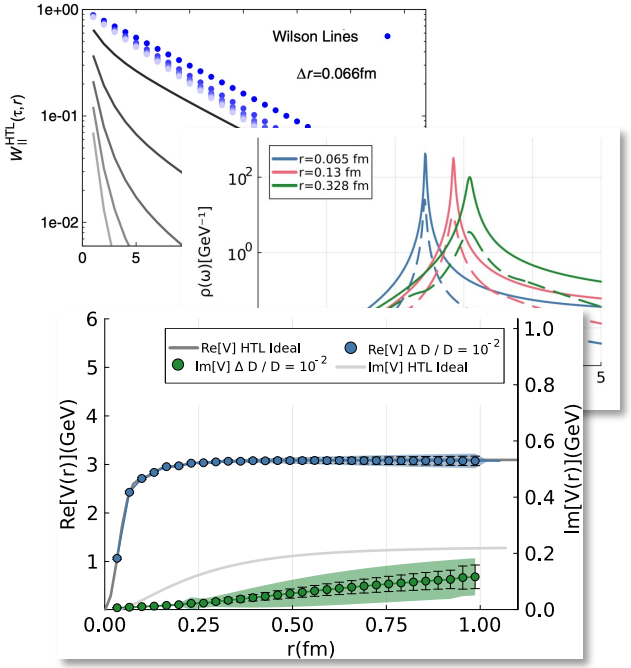

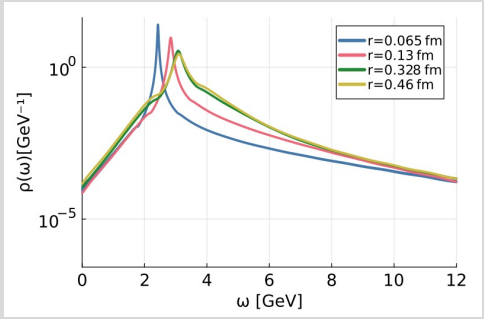

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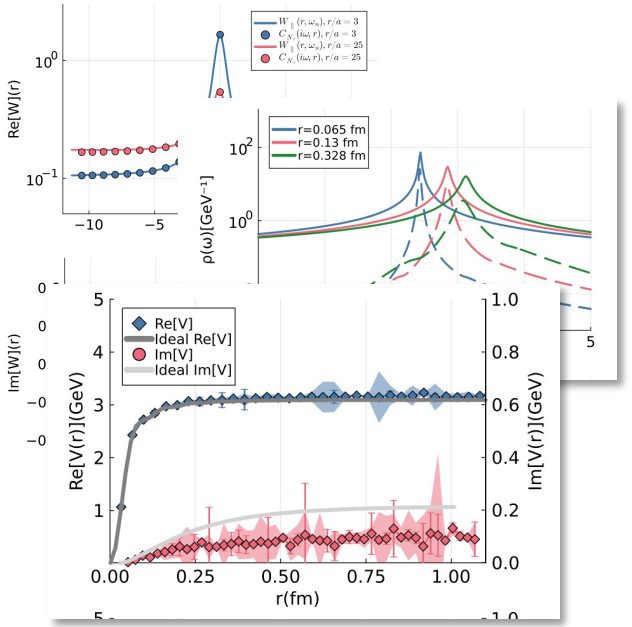

- Re[V] reliably reconstructed, Im[V] systematically underestimated by both methods

Model fit approach

- First application to the T>0 potential in R. Larsen & HotQCD PRD 105 (2022) 5, 054513

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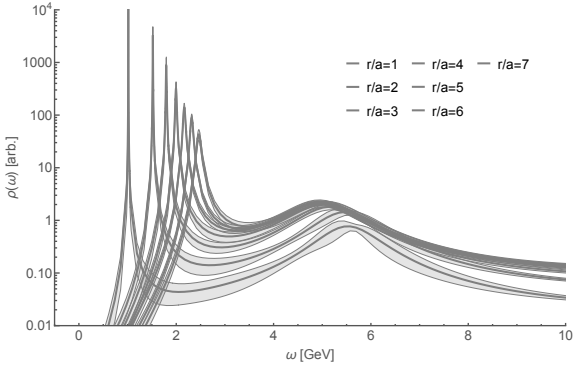

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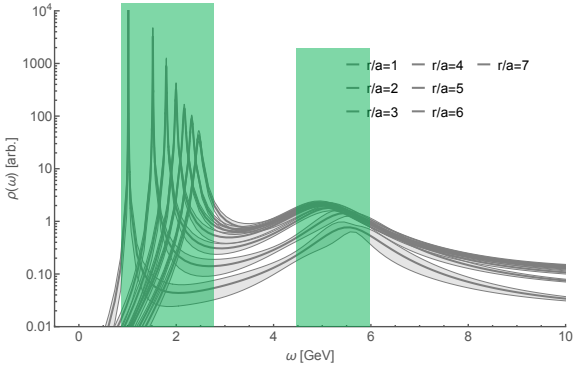

Assumption: separation of scales between T=0 potential peak (IR) and non-potential physics (UV)

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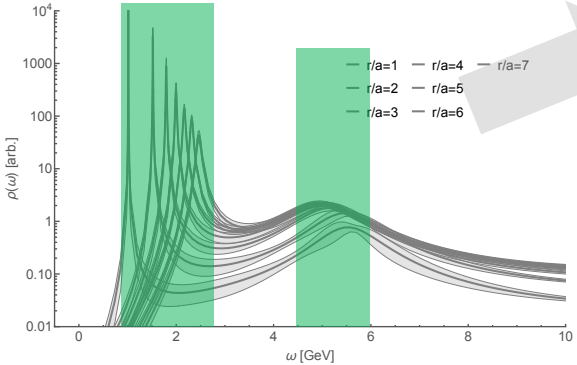

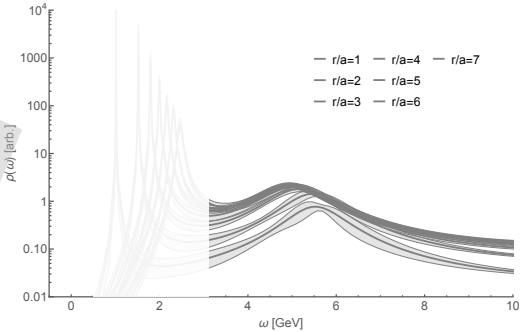

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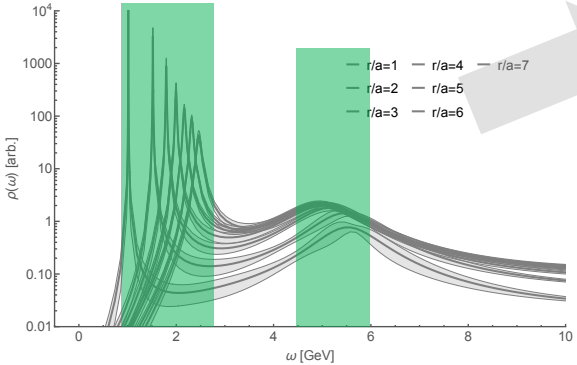

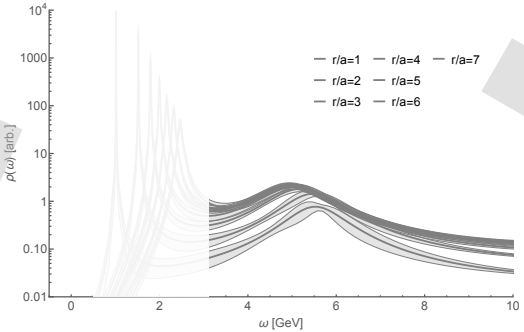

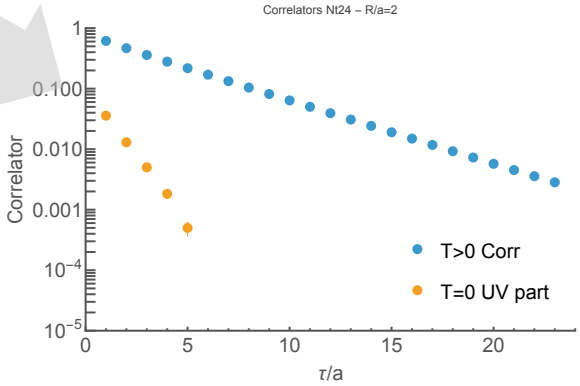

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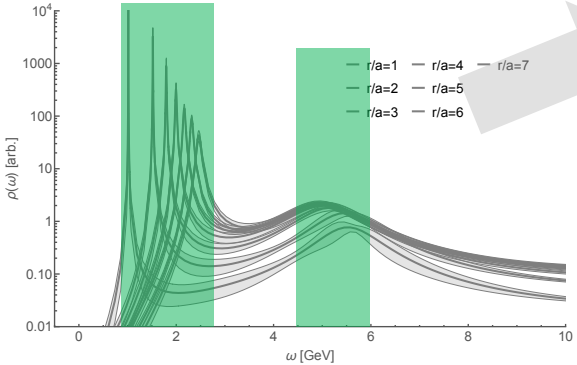
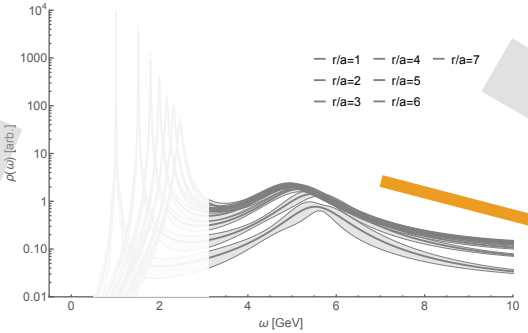
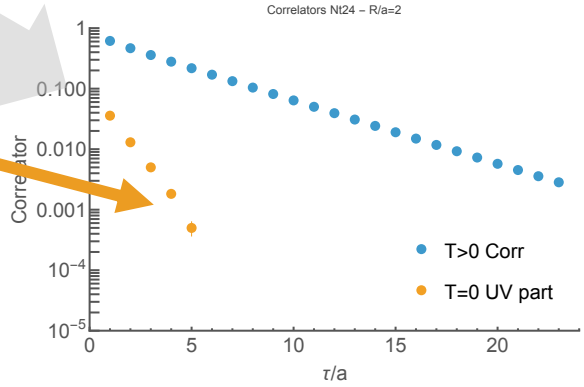




Subtract off the potential part at T=0



Assumption: separation of scales between T=0 potential peak (IR) and non-potential physics (UV)

Model fit approach

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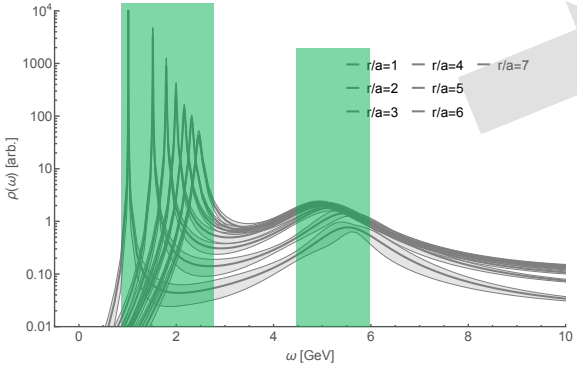

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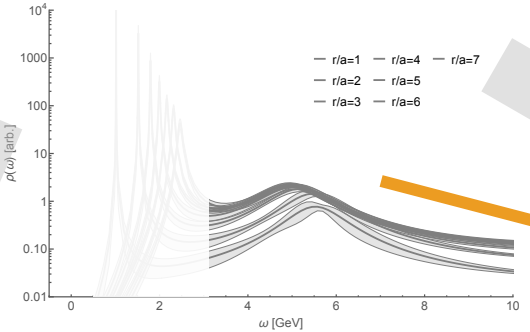

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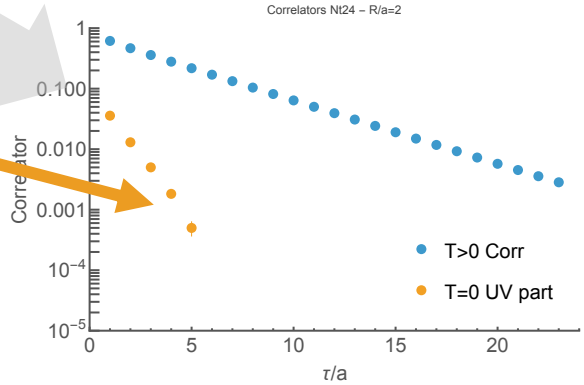

Subtract off the T=0 UV remnant from T>0 correlator

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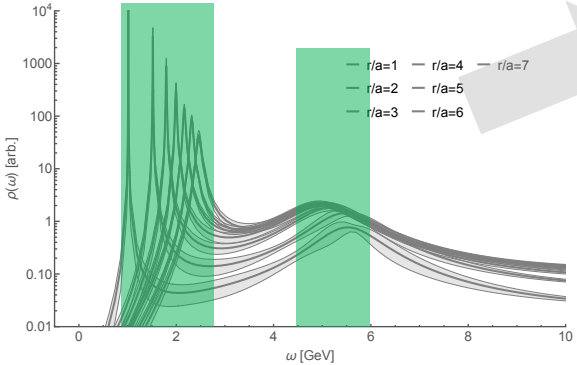
T=0 spectral function



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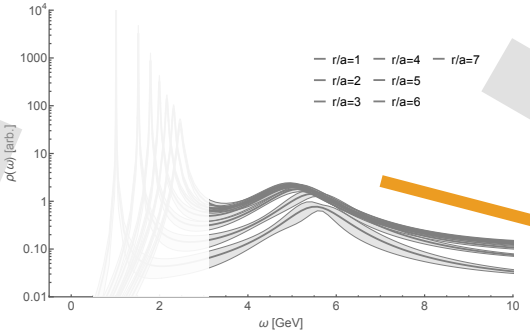

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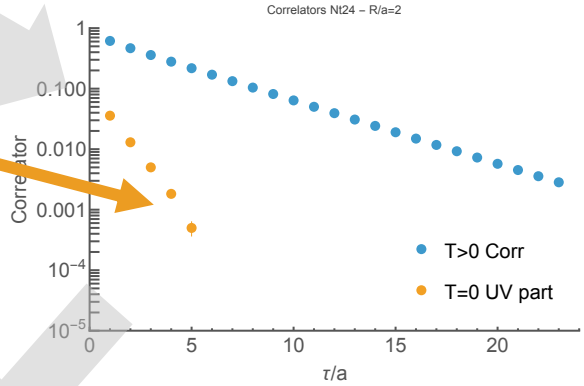

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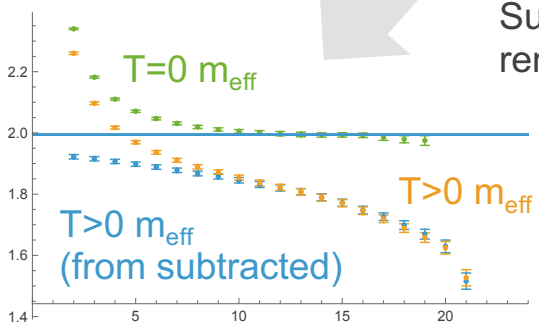

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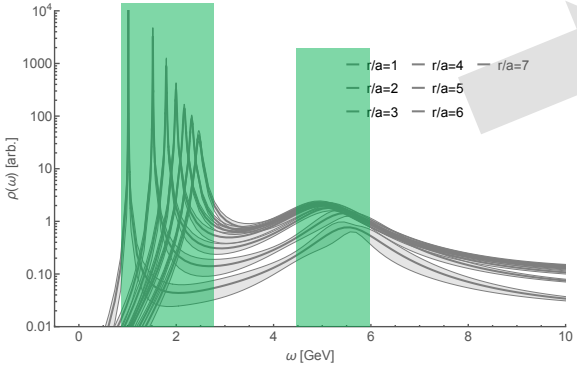

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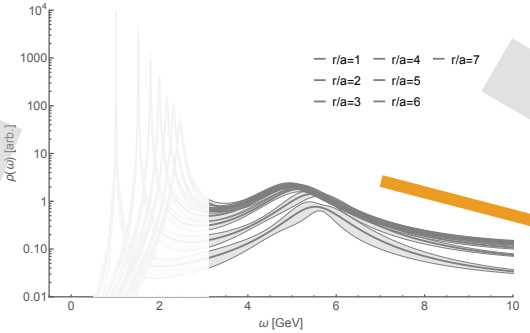

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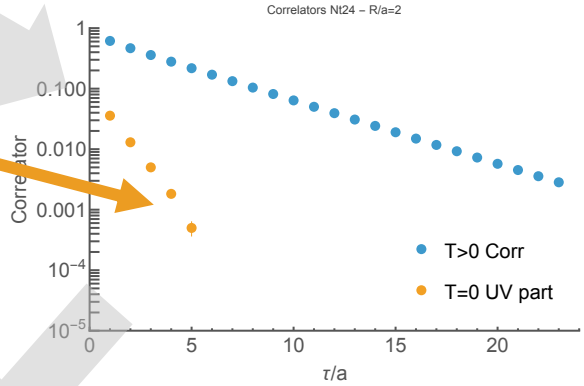

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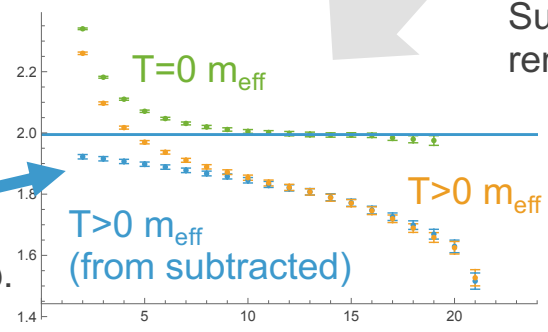

Linear behavior in m_{eff}: consistent with Gaussian or sharp Lorentzian spectral function at low ω. Re[V] from intercept at τ=0.

Model fit approach

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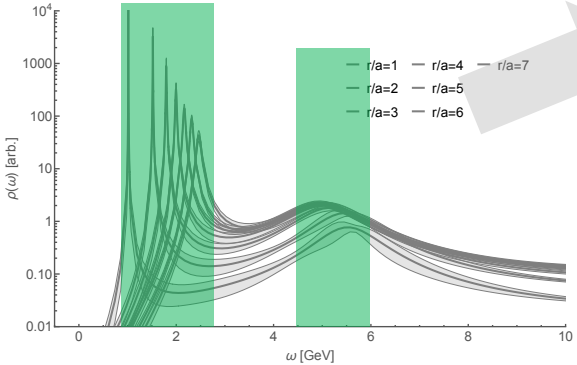

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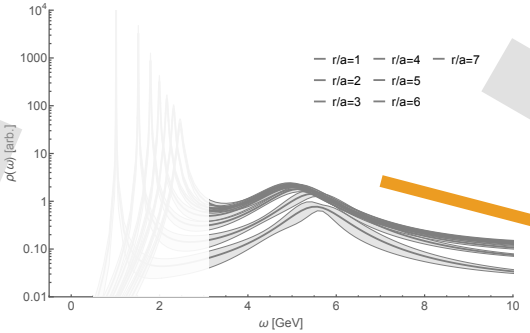

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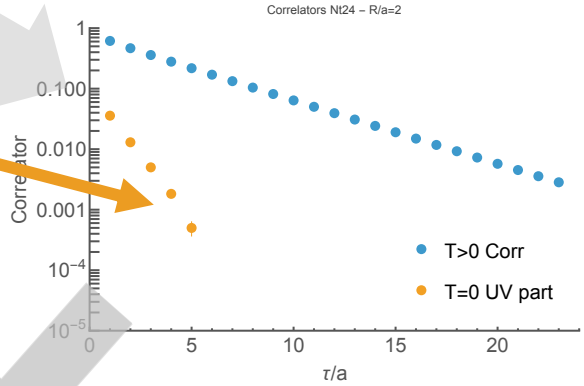

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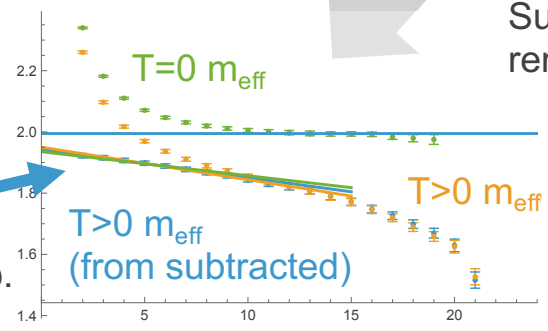

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Outline

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

Exploration of the complex static potential

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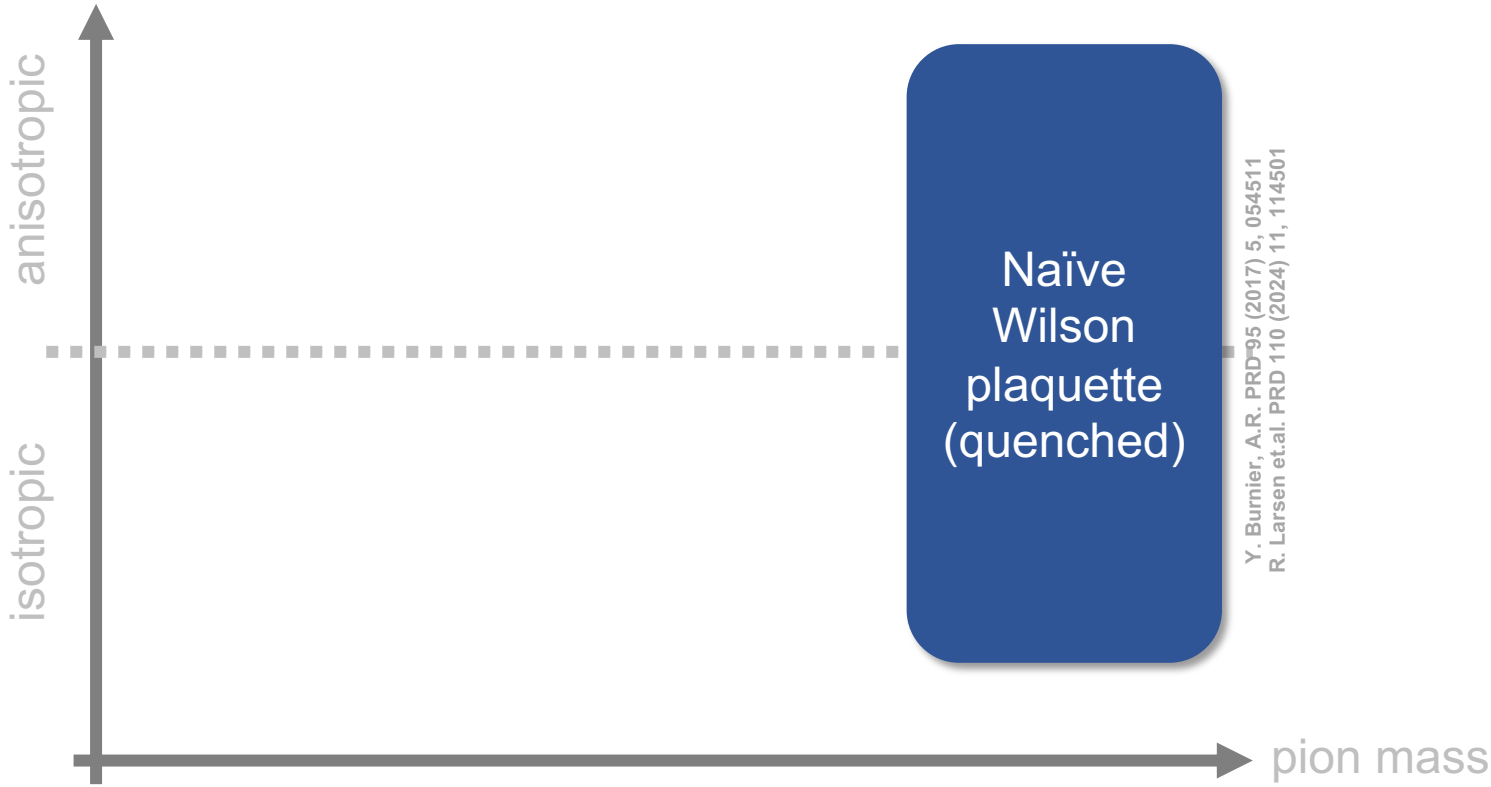
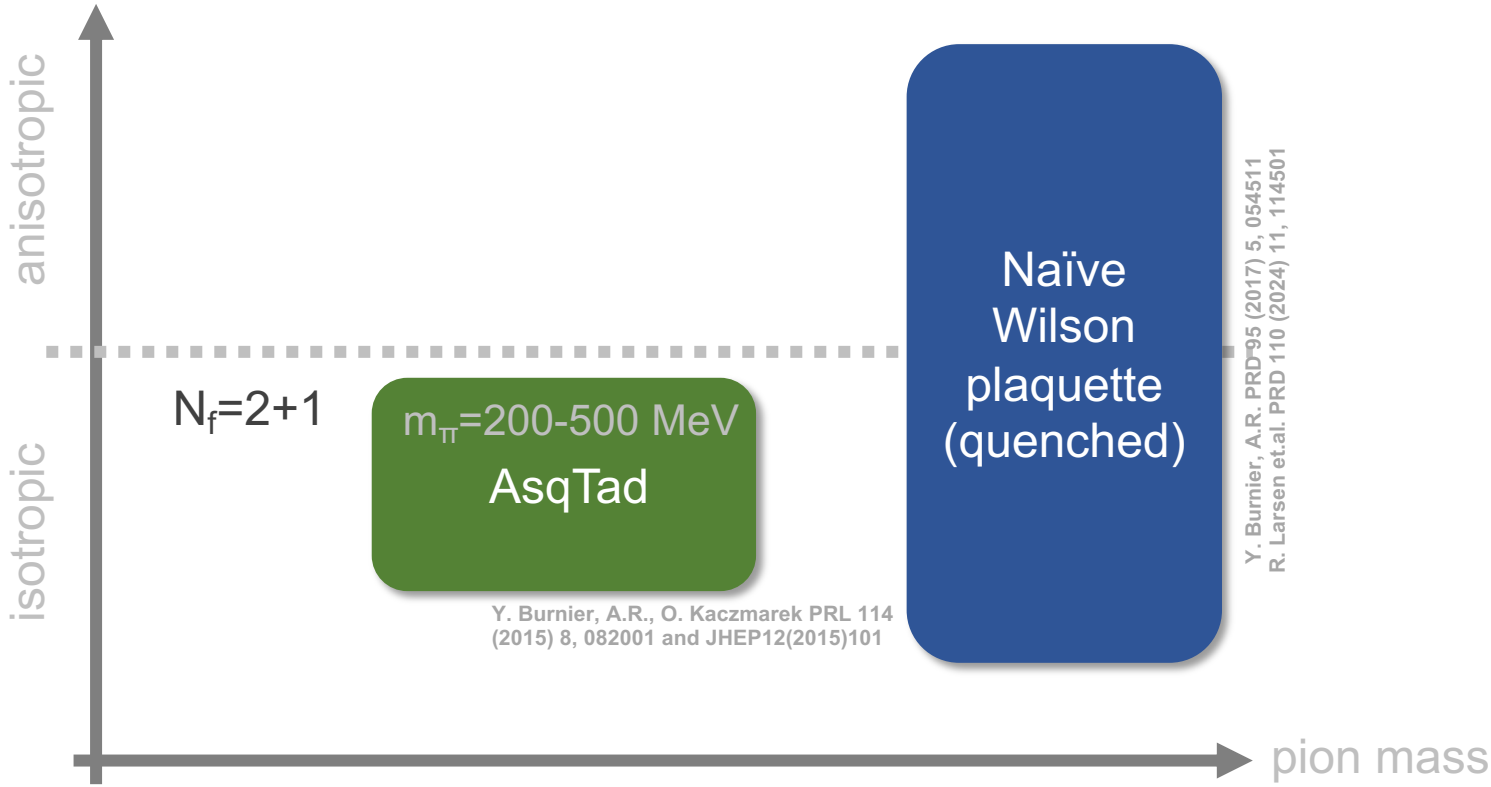


Exploration of the complex static potential



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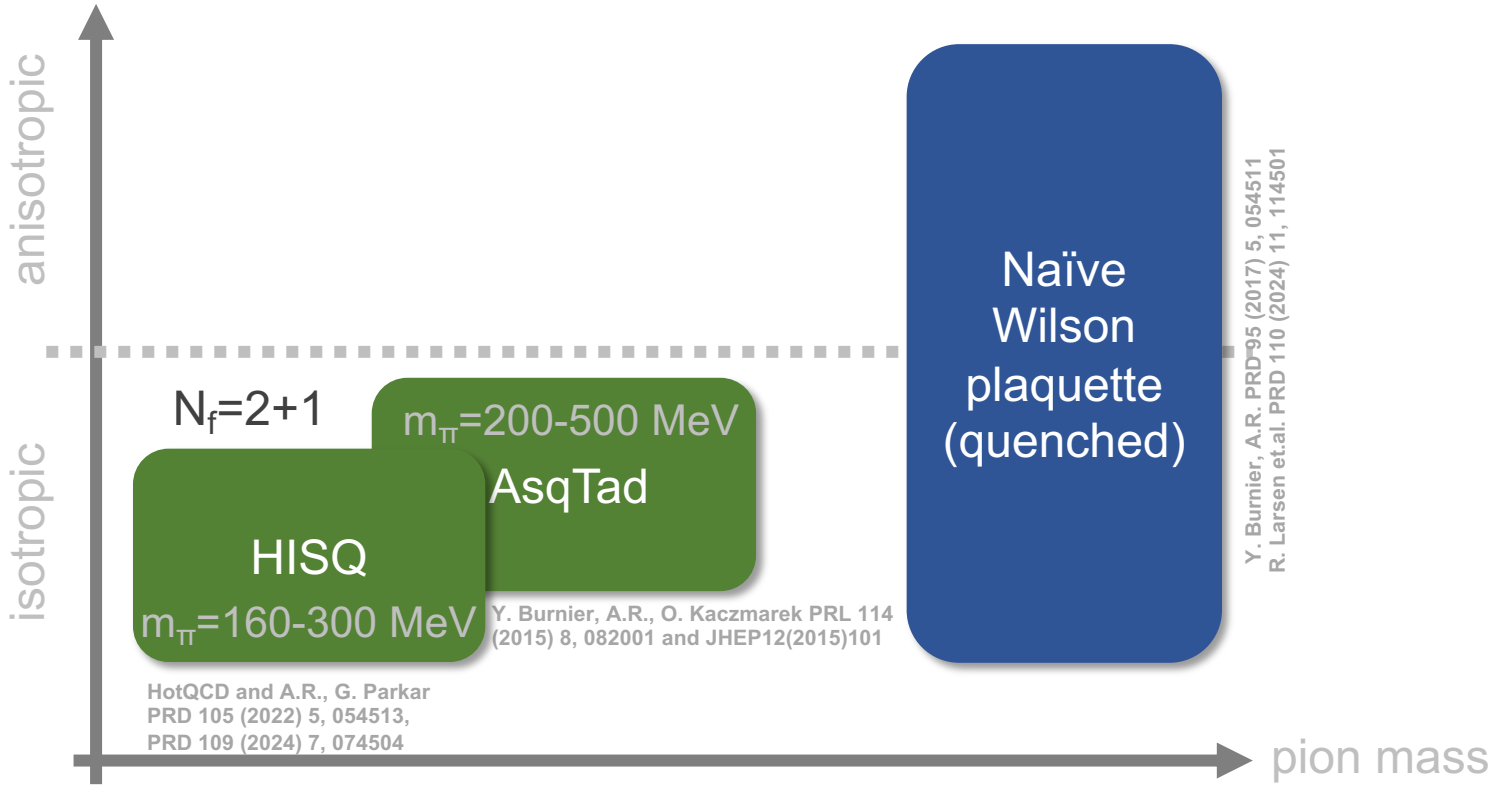

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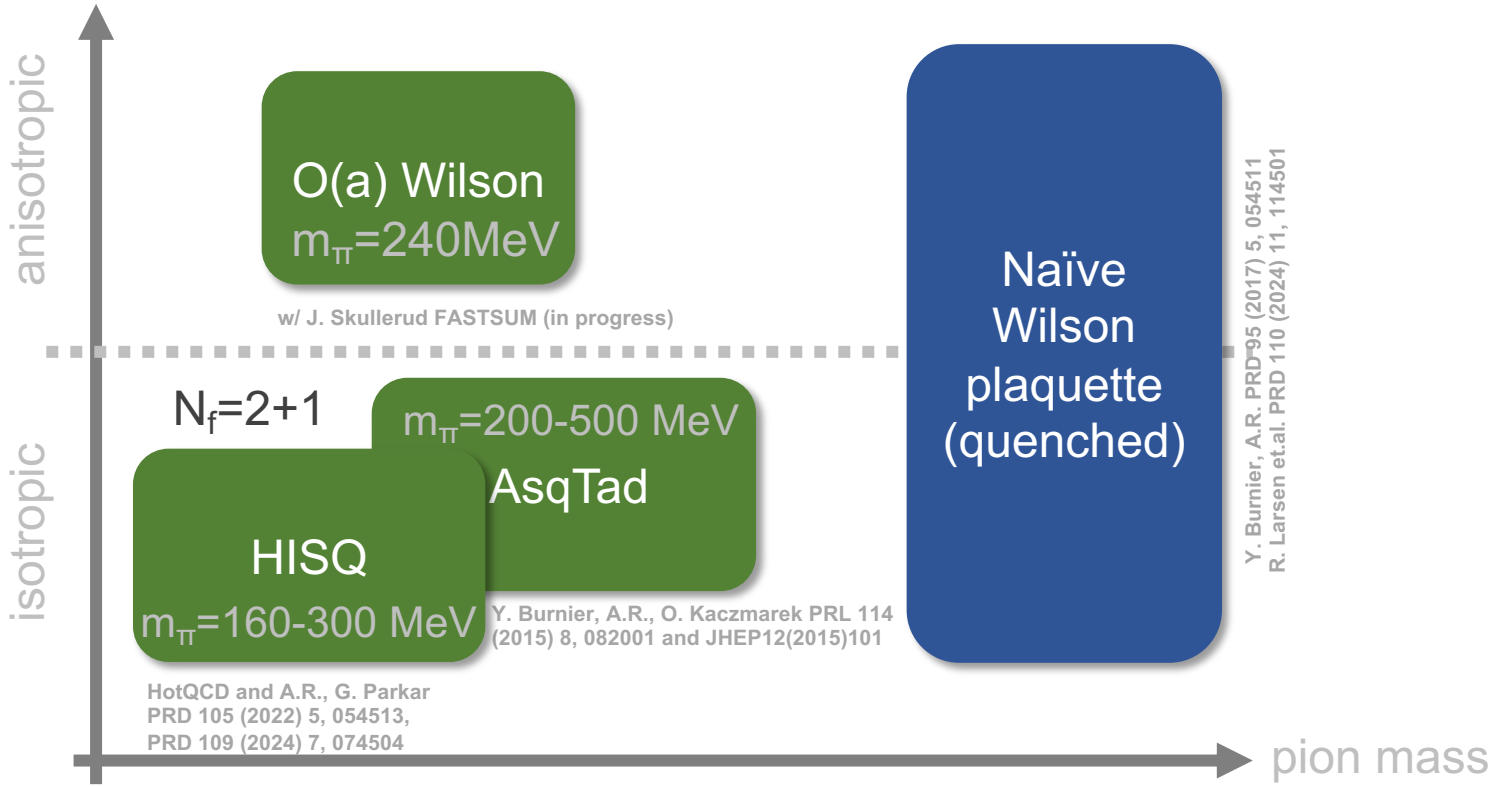

Quenched QCD – Re[V]

- 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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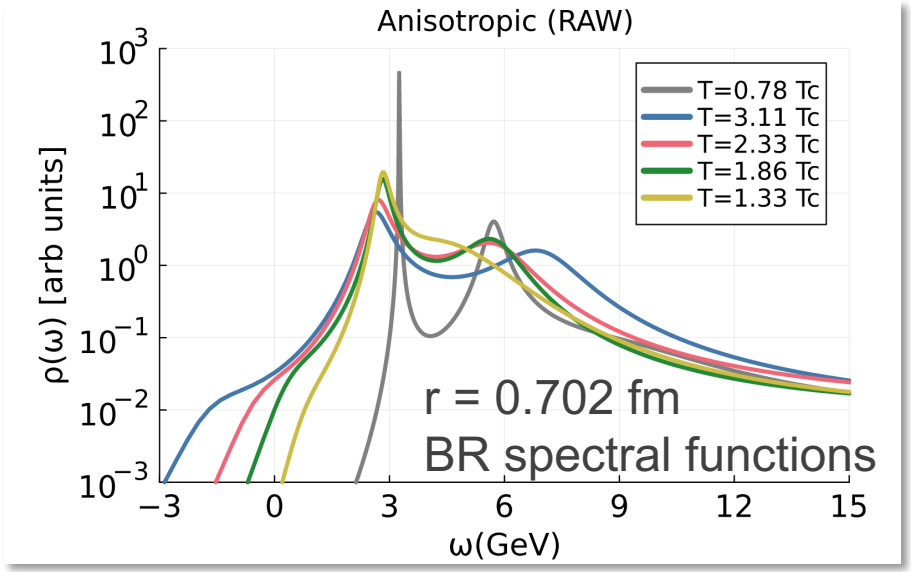

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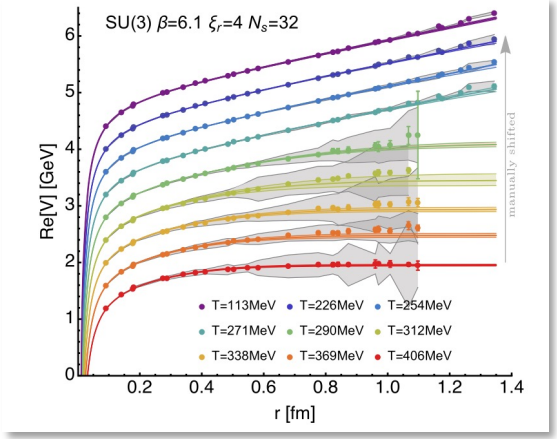

Wilson plaquette action

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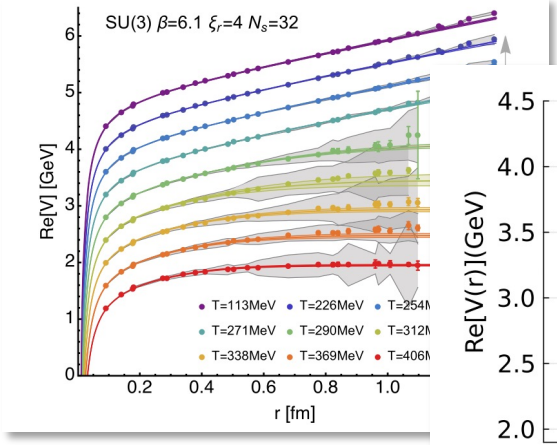

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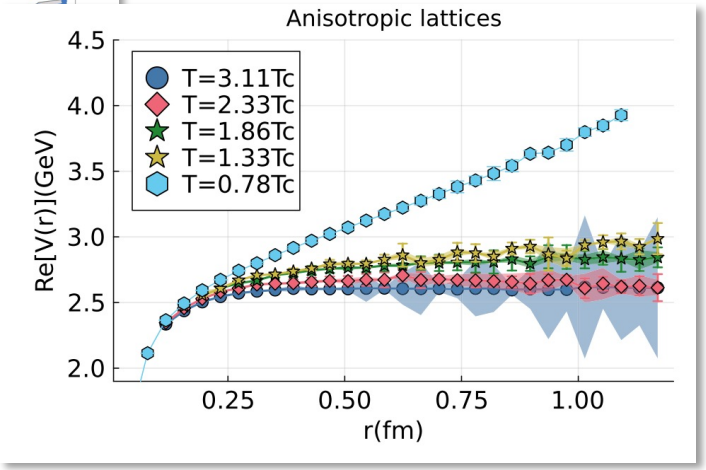

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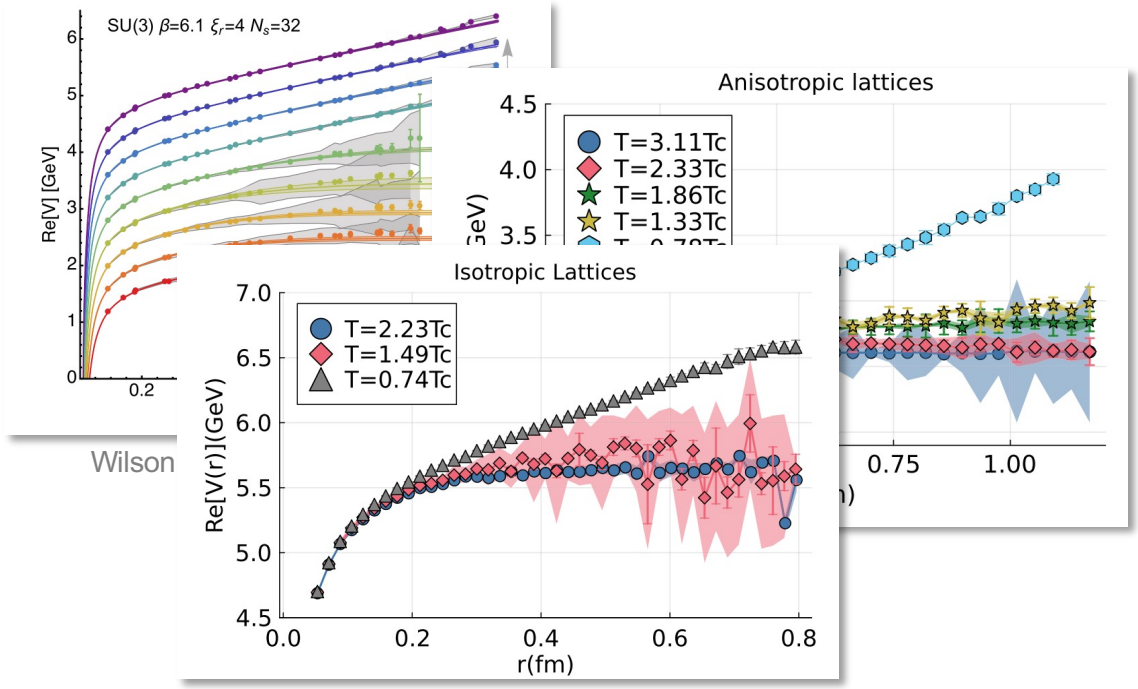

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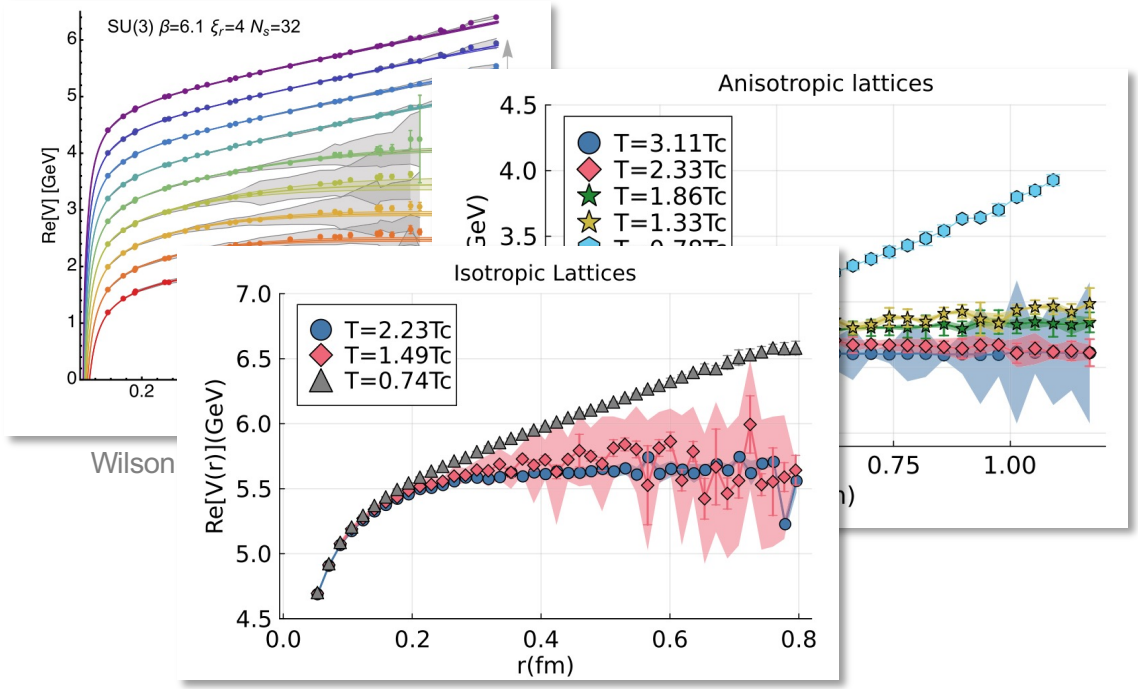
- Moderate numerical cost, fine grids: N_τ=20-96
- Based on Bayesian Reconstruction (BR) (crosschecked with Pade)
- Consistent picture:
  no modification at $T<T_C$
  Debye screening at $T>T_C$



Quenched QCD – Im[V]

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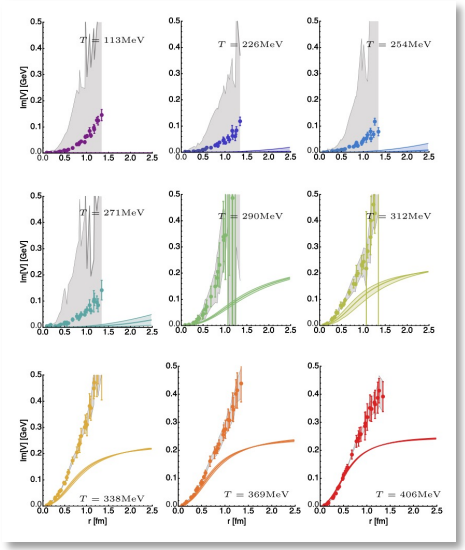

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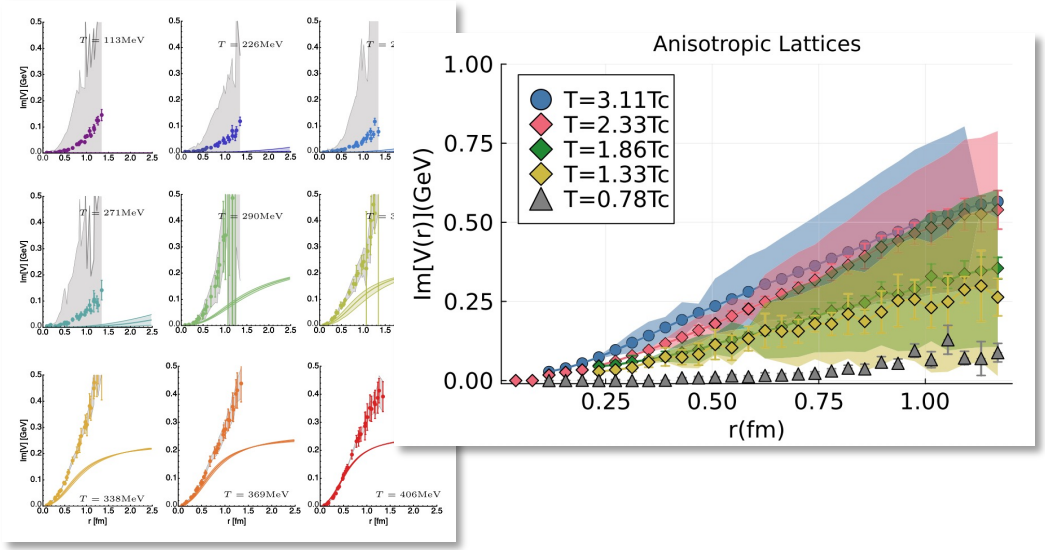

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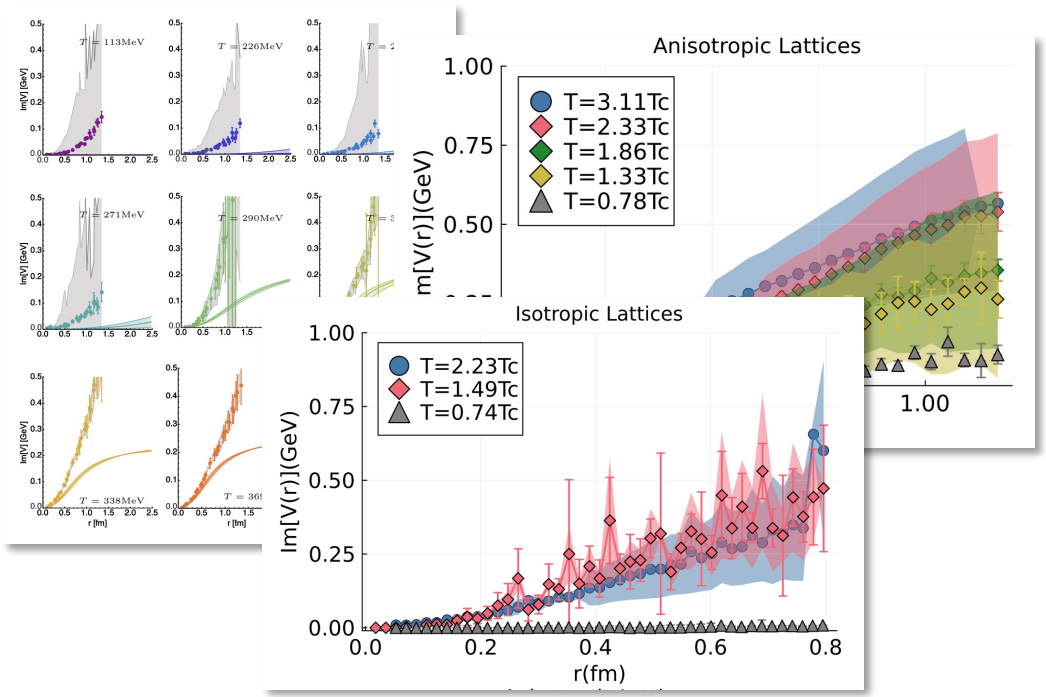

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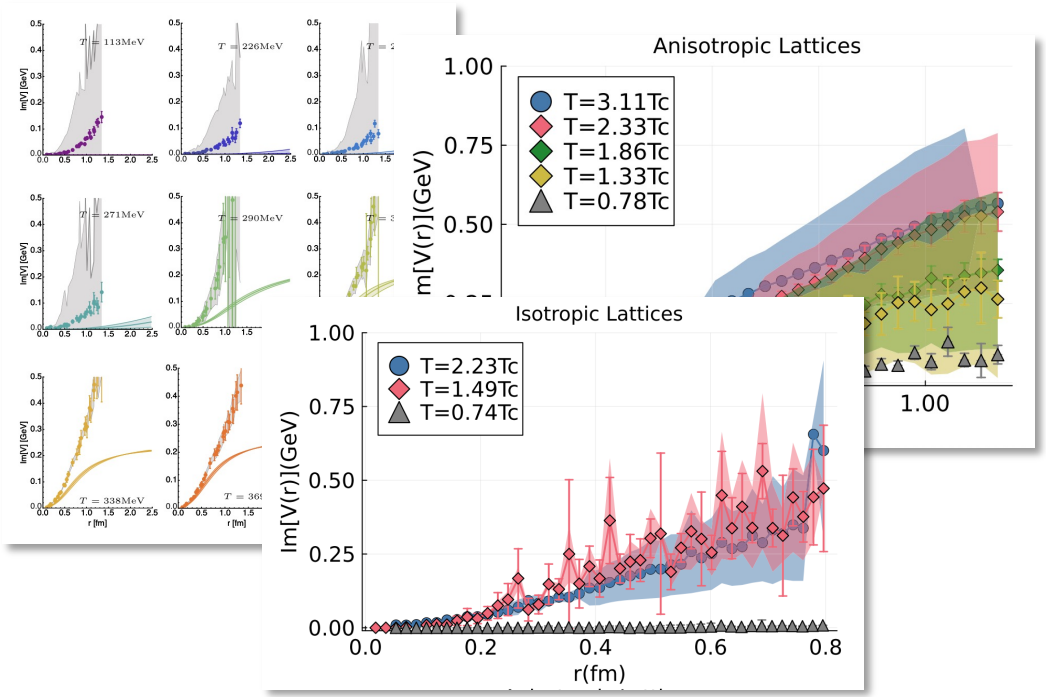
- Moderate numerical cost, fine grids: N_τ=20-96
- Based on both Bayesian Reconstruction (BR) and Pade Reconstruction
- Much more difficult to reliably extract Im[V] but statistically significant signal for Im[V]>0 at $T>T_C$



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

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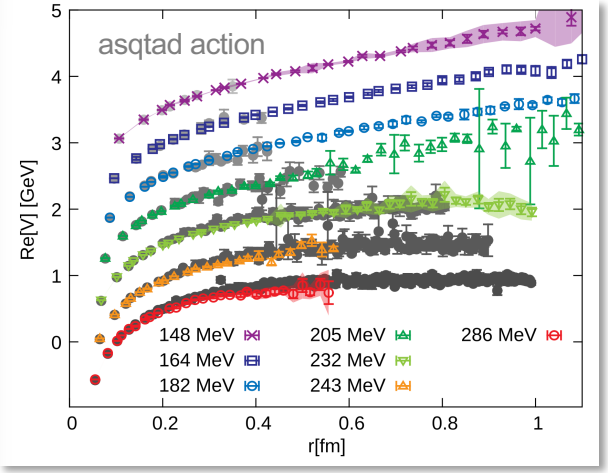

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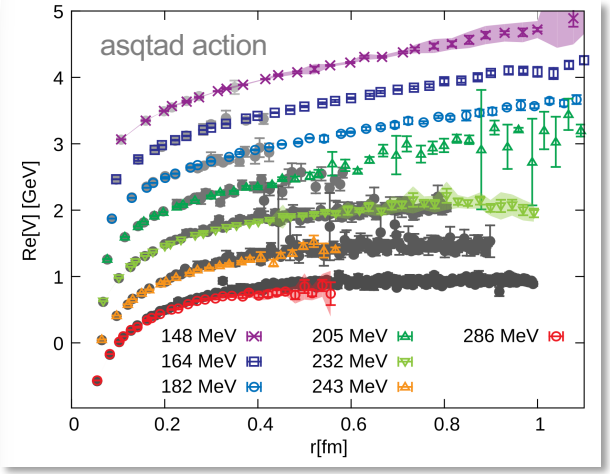

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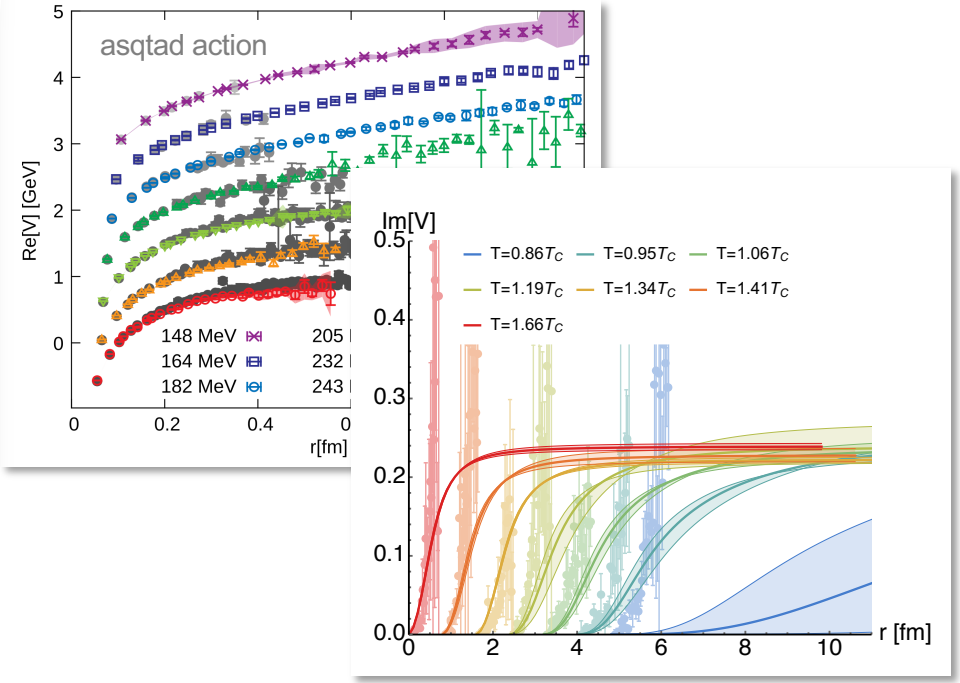
- Imaginary part must be taken with grain of salt. Above T_C finite signal significant.



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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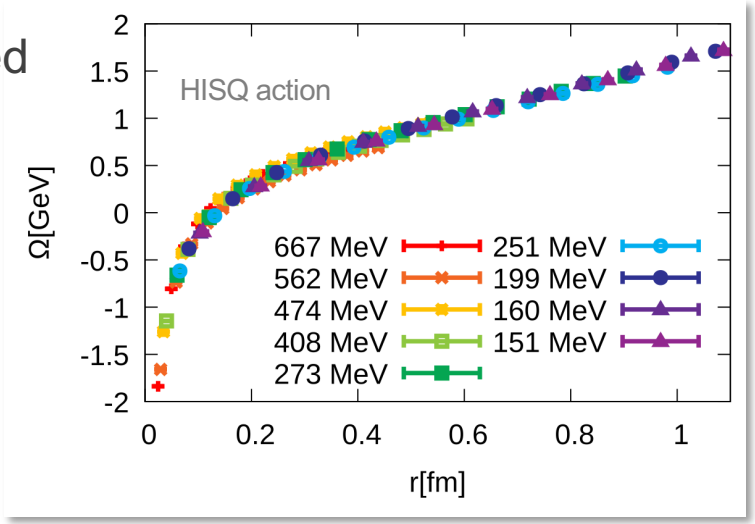

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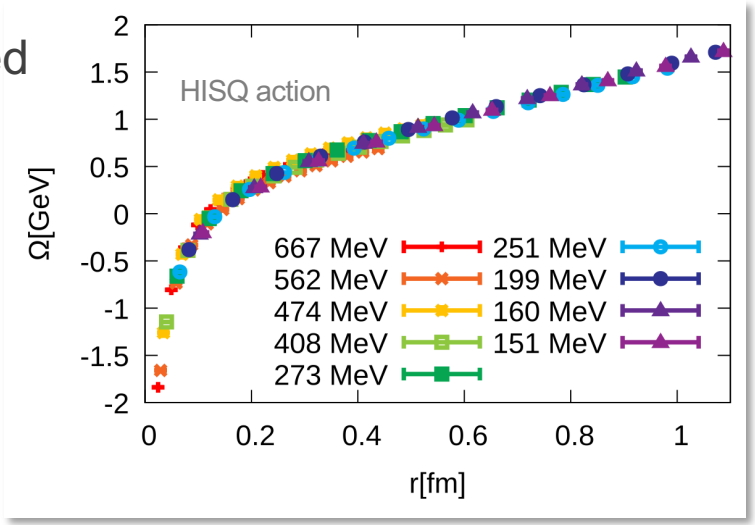
- Surprising outcome: Re[V] appears independent of T



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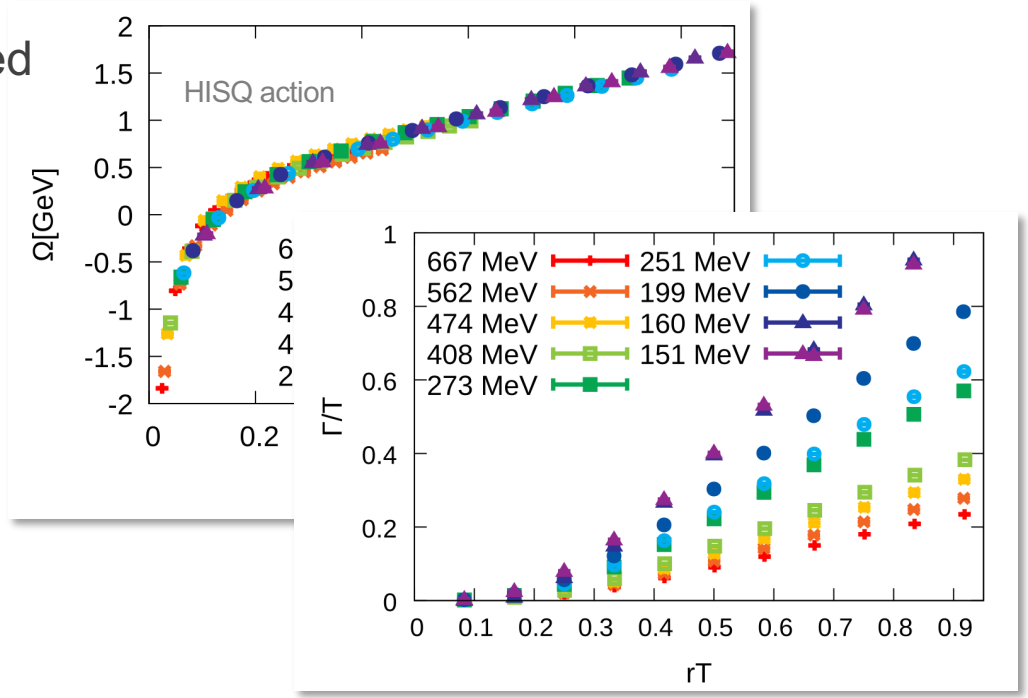
  Im[V] monotonously increases with temperature.



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

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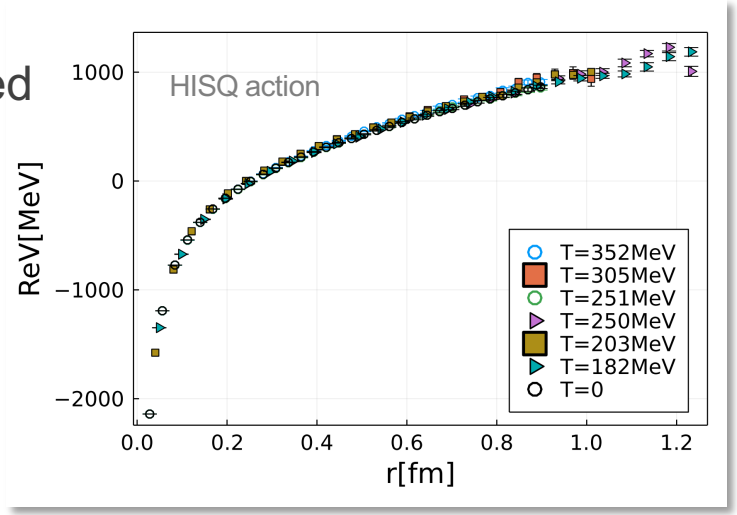
HotQCD and A.R. PRD 109 (2024) 7, 074504

- Based on model fits, crosschecked via Pade reconstruction

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



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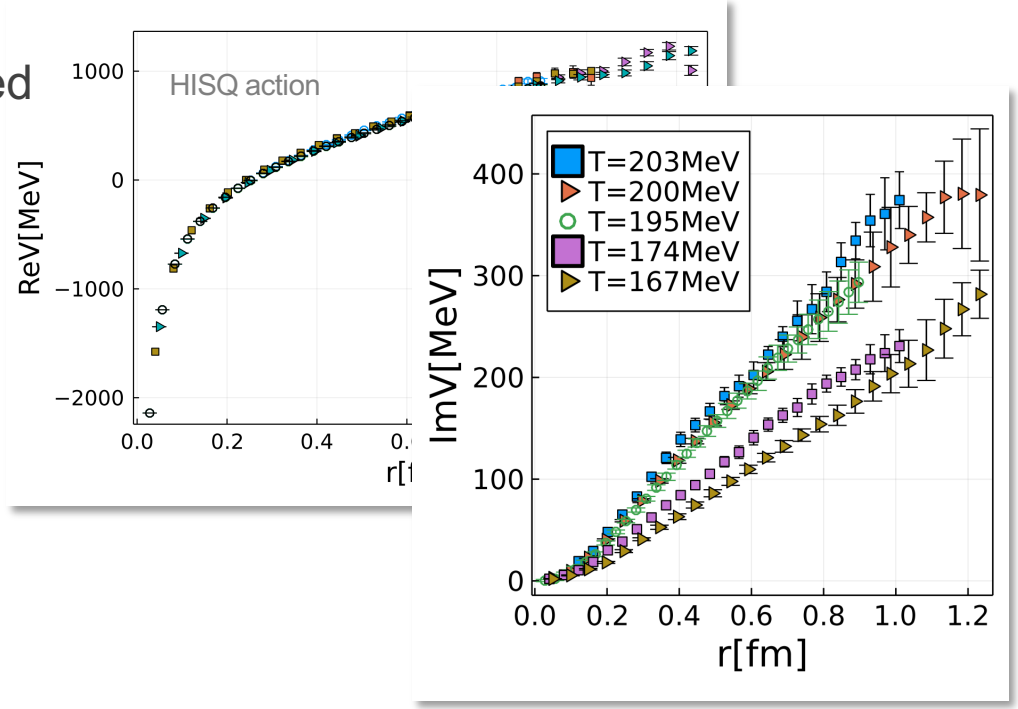
HotQCD and A.R. PRD 109 (2024) 7, 074504

- Based on model fits, crosschecked via Pade reconstruction

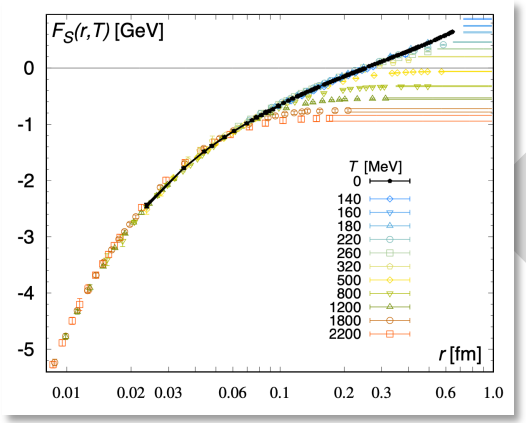
- Reconfirms earlier result: Re[V] appears independent of T

  Im[V] monotonously increases with temperature.

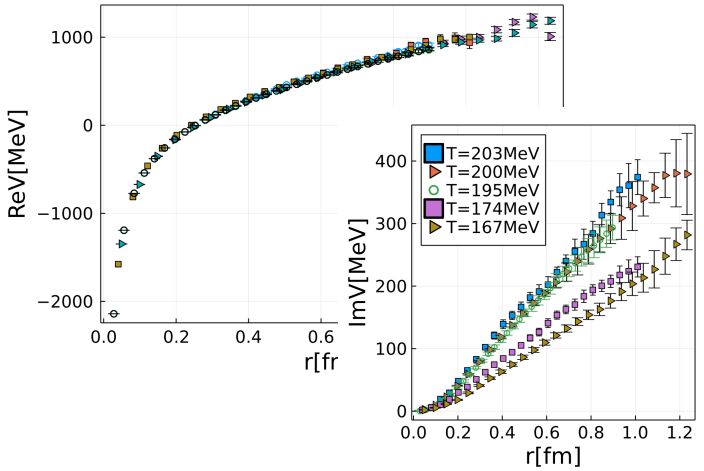


Consistency of recent results

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



TUMQCD PRD98 (2018) 5, 054511



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

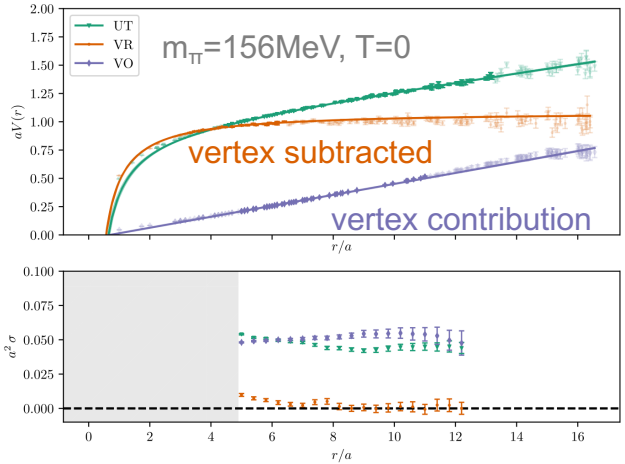
- No apriori inconsistency between potential and thermodynamic behavior

Tantalizing hints for additional structure

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

Tantalizing hints for additional structure

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



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

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

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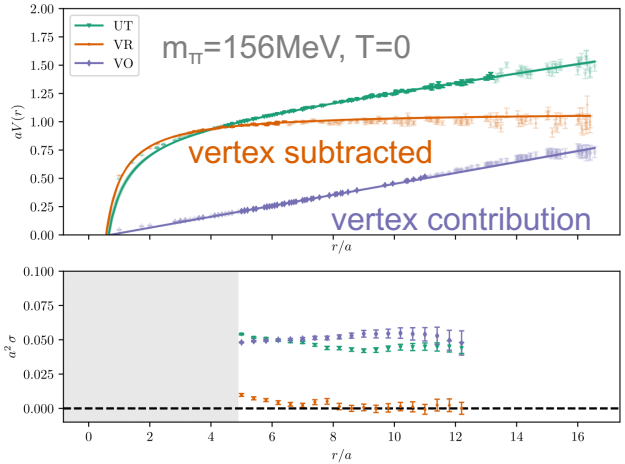
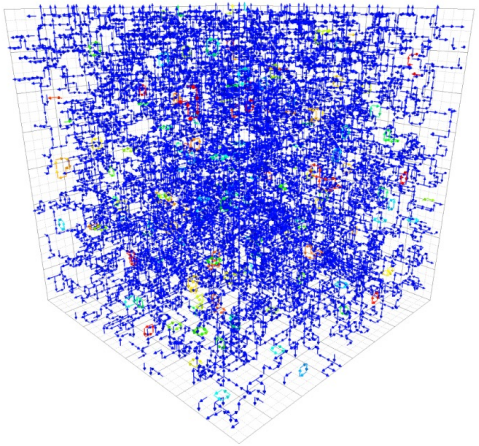
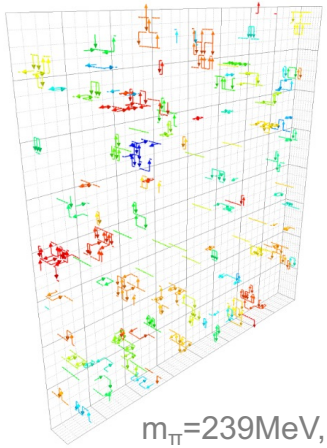


J. Biddle et.al. PRD 106 (2022) 5, 054505





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

J. Mickley et.al. PRD 111, 034508

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Tantalizing hints for additional structure

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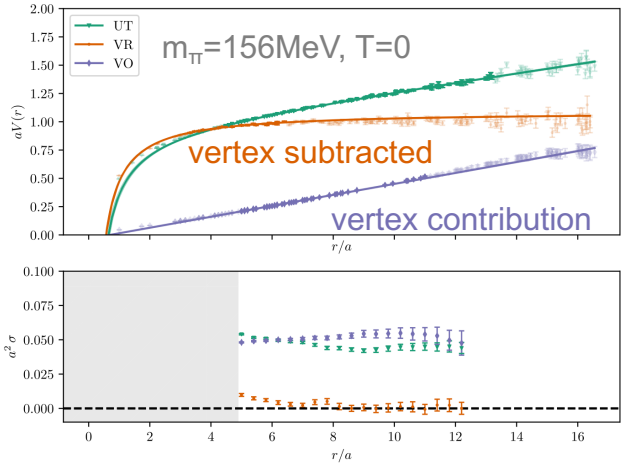
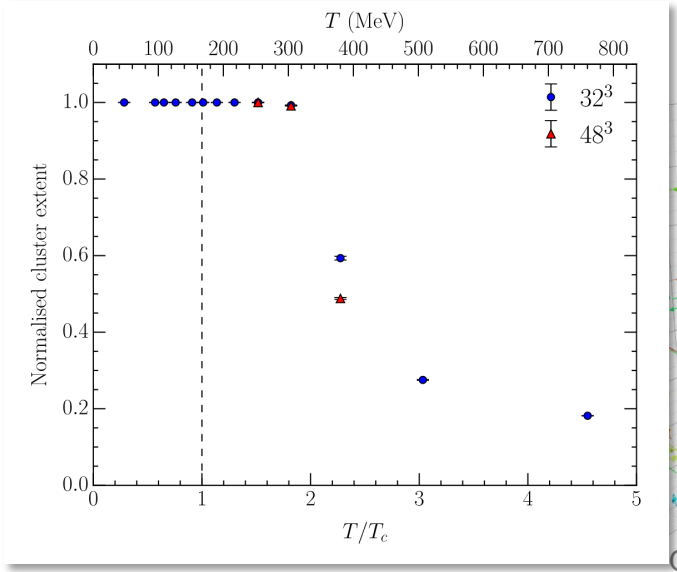
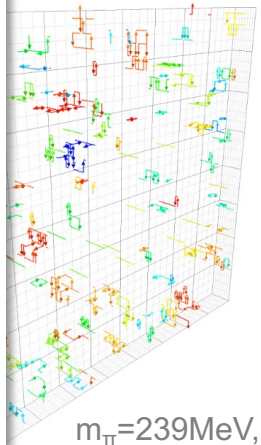


J. Biddle et.al. PRD 106 (2022) 5, 054505





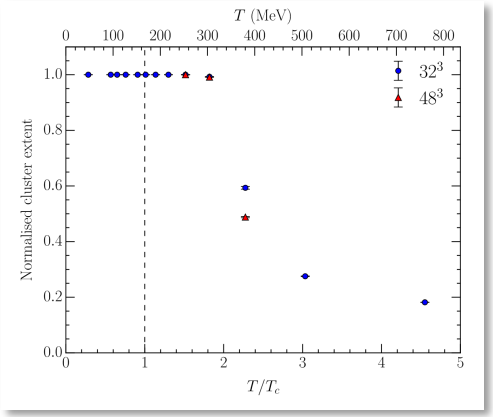
m_π=239MeV, T=0
O(a) improved Wilson fermions

J. Mickley et.al. PRD 111, 034508

- At T=0, removing vortices depletes the string tension.
- At $T > 2T^{\chi}_{C}$ show percolation transition which may indicate confinement persists

A (preliminary) apples to apples analysis

- Using the same lattice ensembles as vortex study & same modelling as HotQCD



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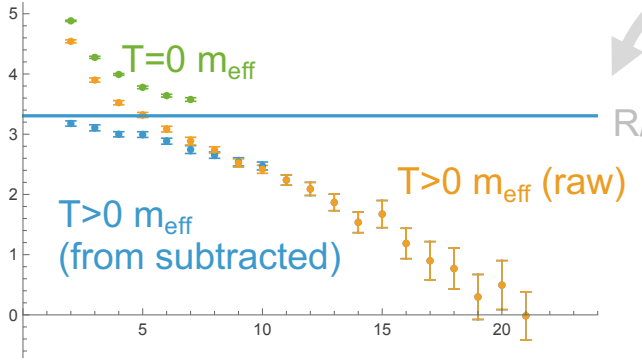

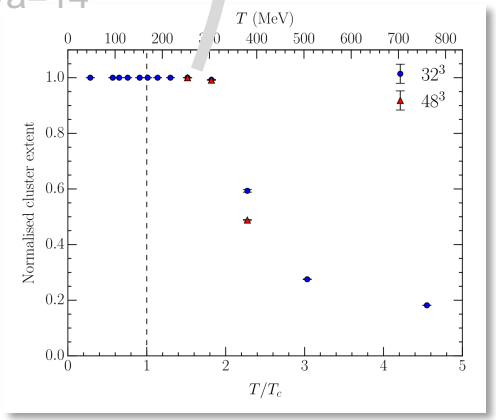

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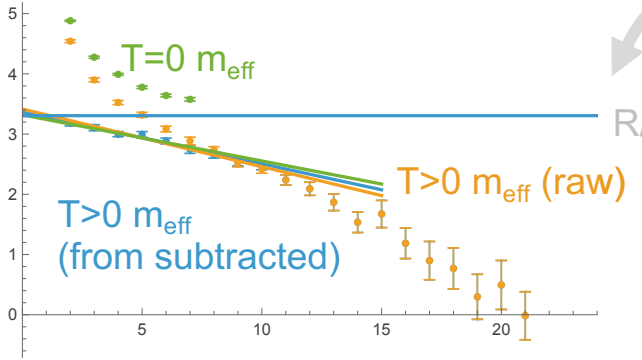

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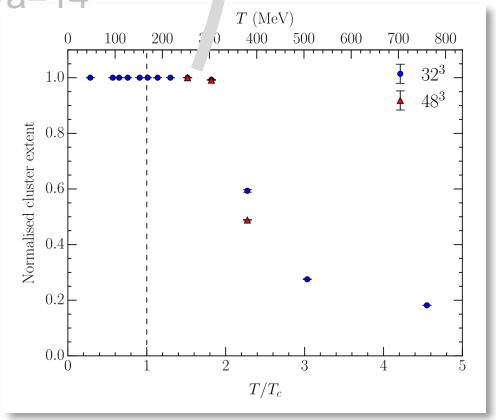

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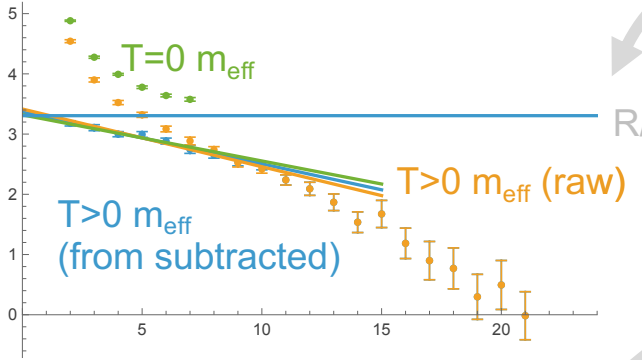

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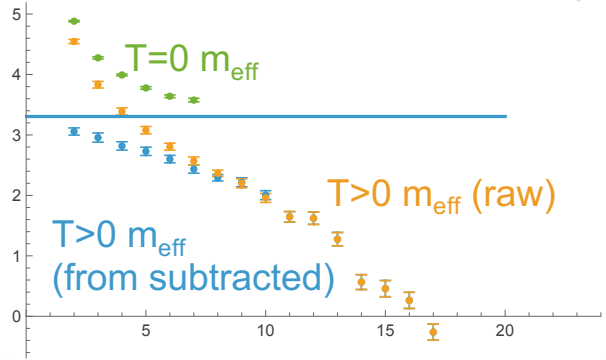

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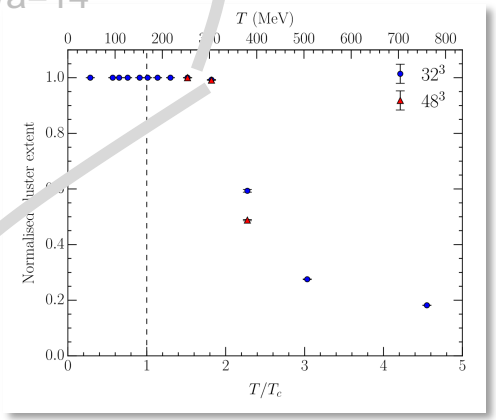

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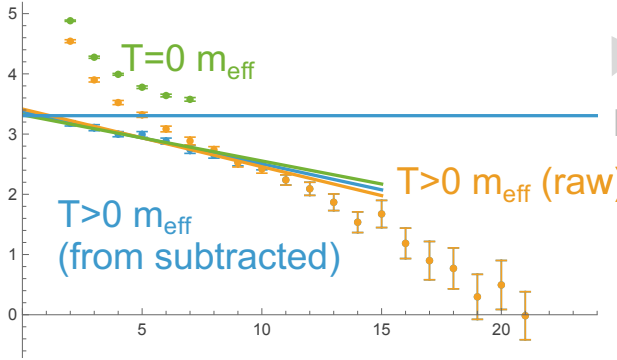

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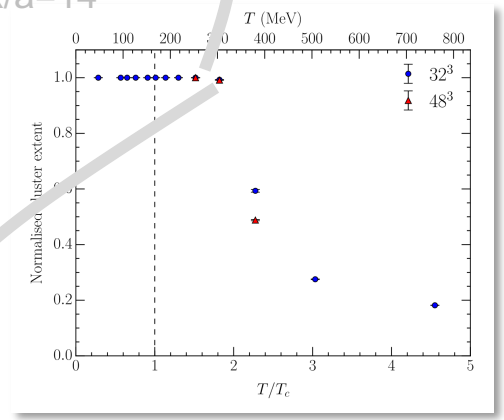

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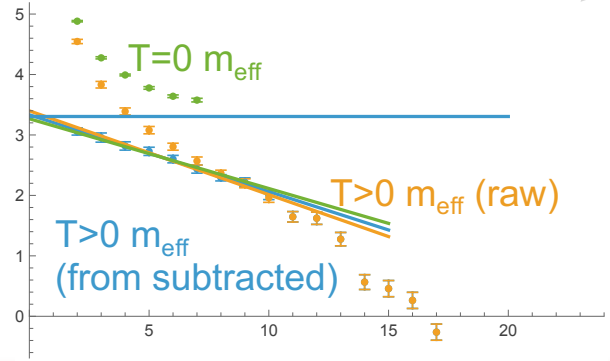

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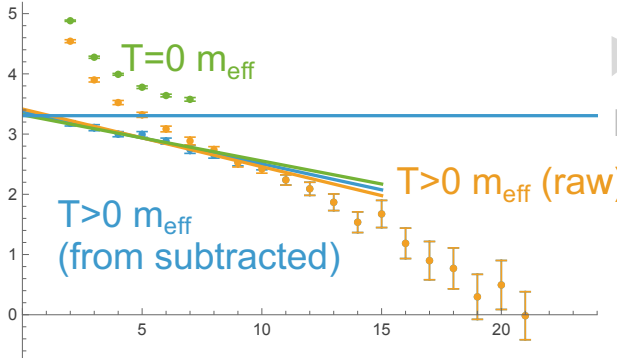

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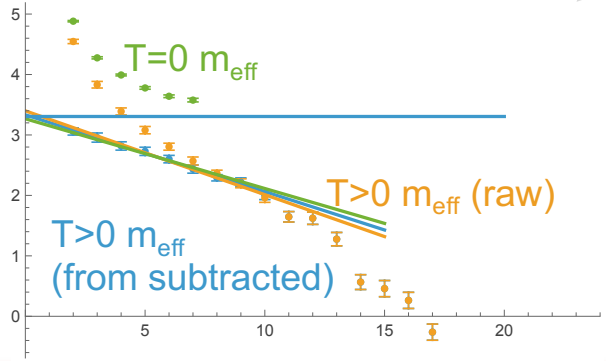

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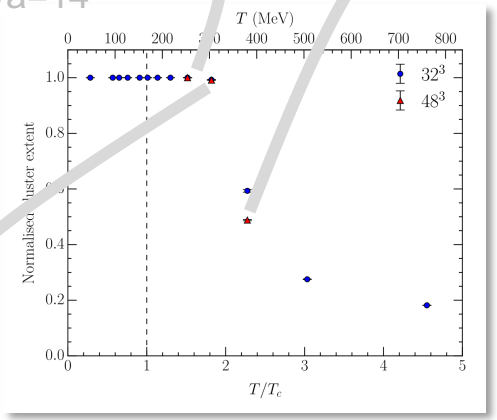

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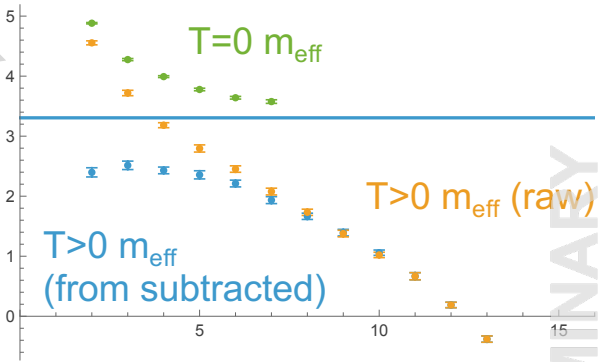

PRELIMINARY

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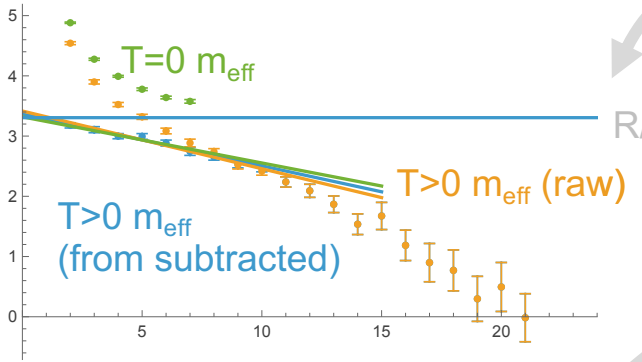

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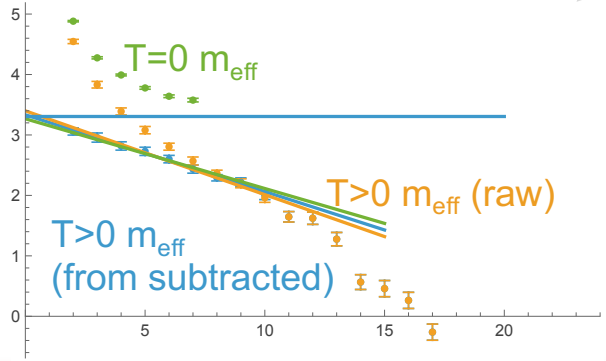

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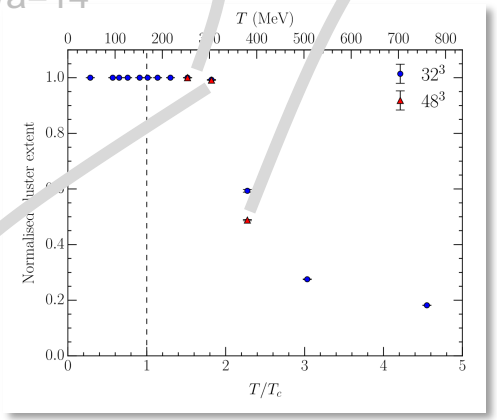

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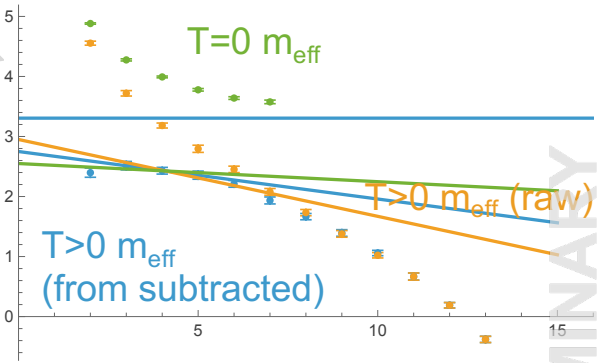

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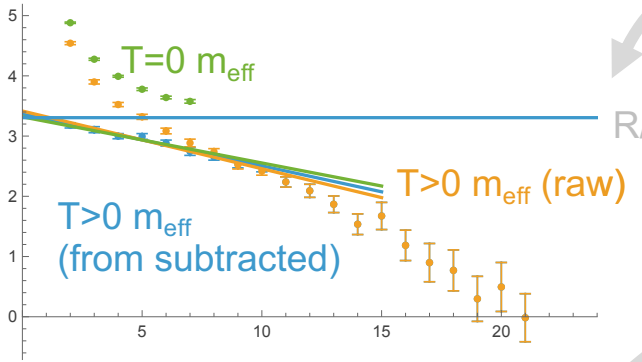

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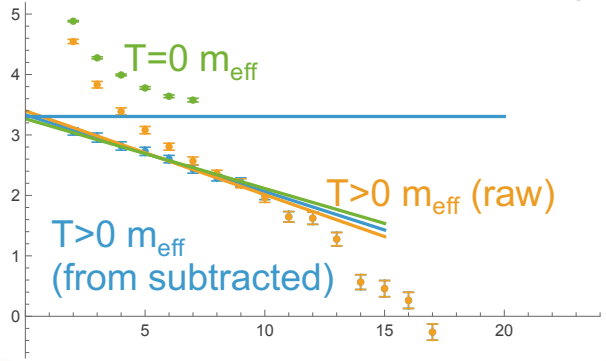

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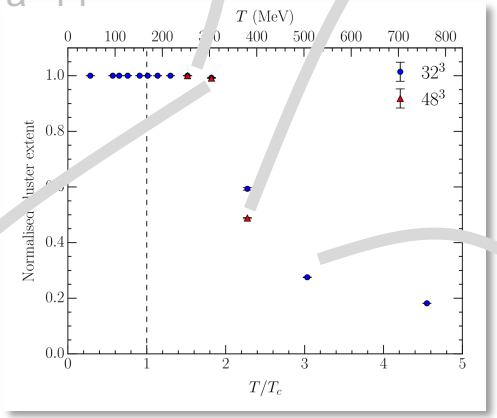

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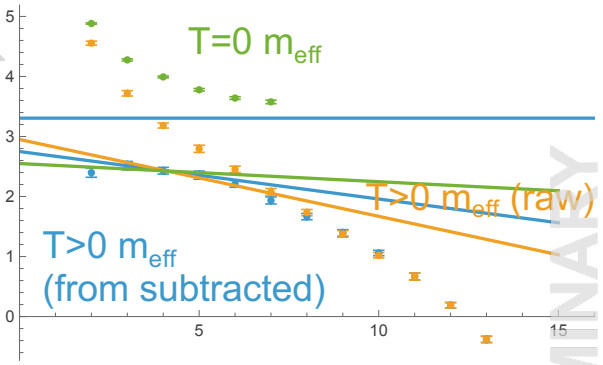

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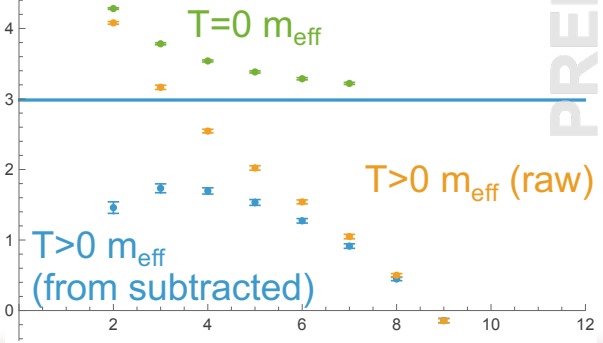

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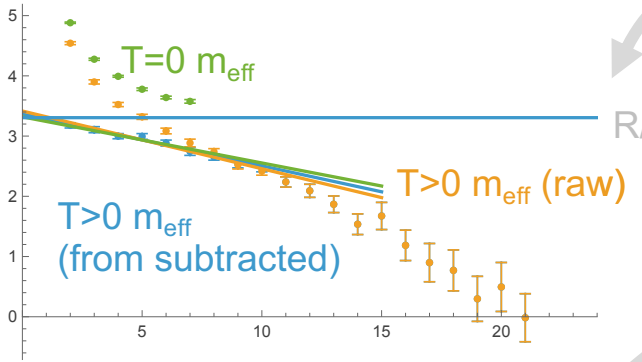

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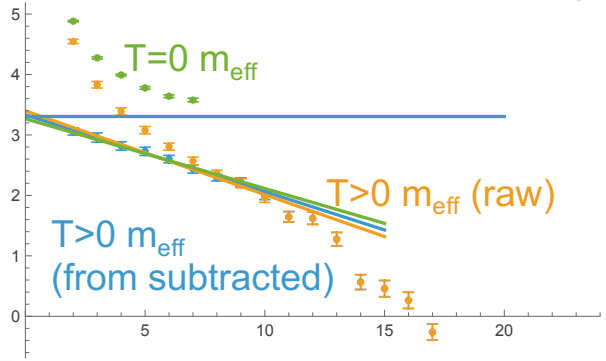

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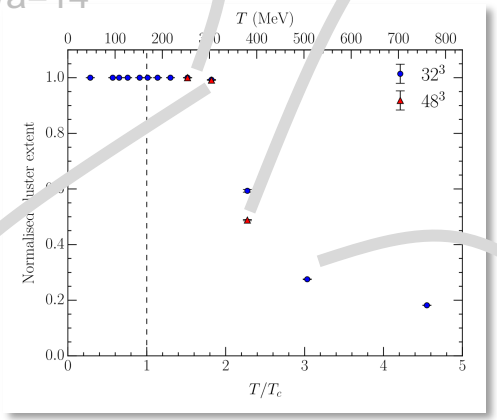

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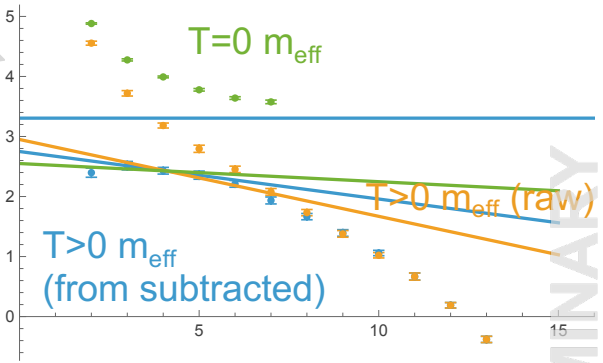

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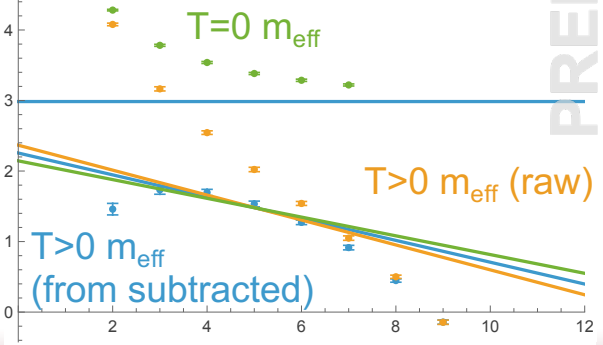

PRELIMINARY

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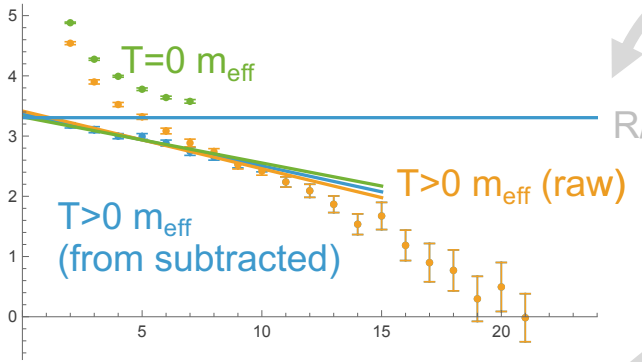

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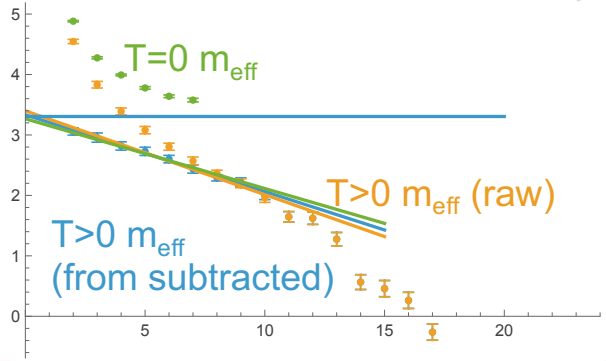

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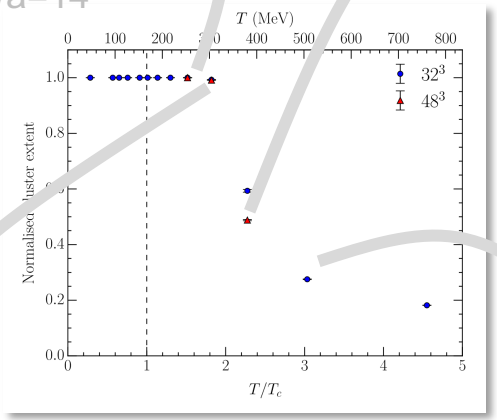
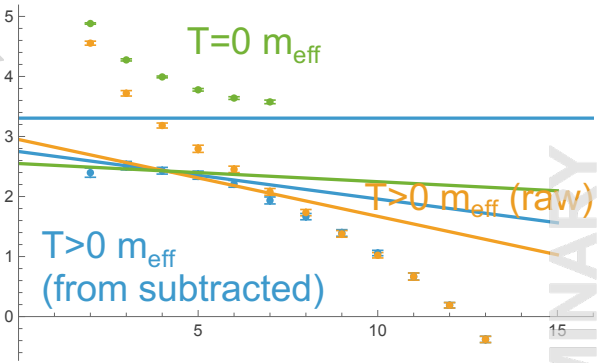


Accompanying change in Re[V]. Must ascertain whether independent of lattice cutoff.

R/a=14



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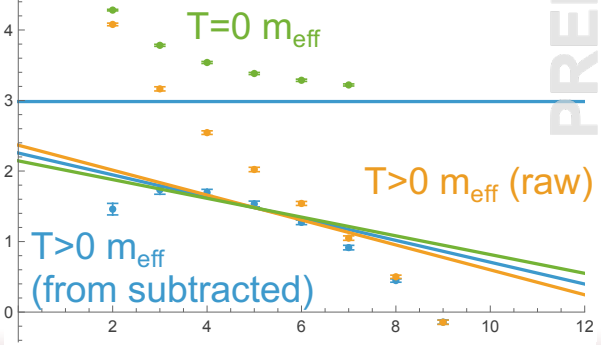
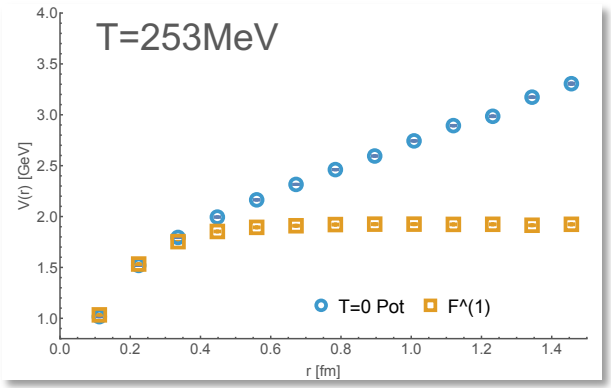


PRELIMINARY

Anisotropic full QCD - (preliminary) Re[V]

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

FASTSUM Gen2L ensembles PRD 105, 034504



$T<2T_C$

$T>2T_C$

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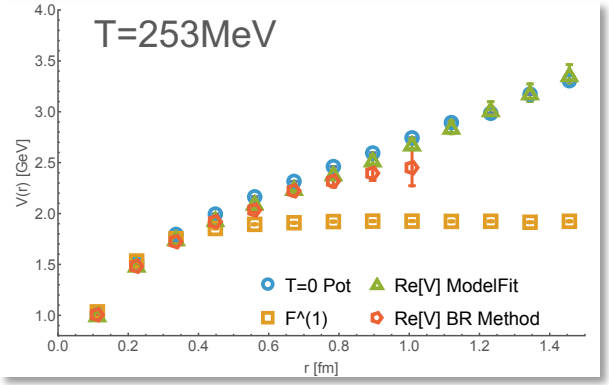

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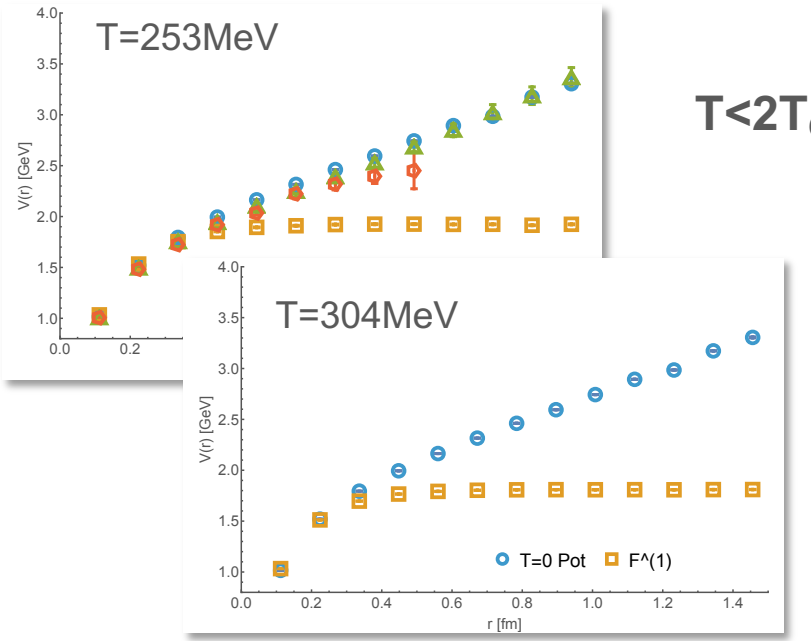

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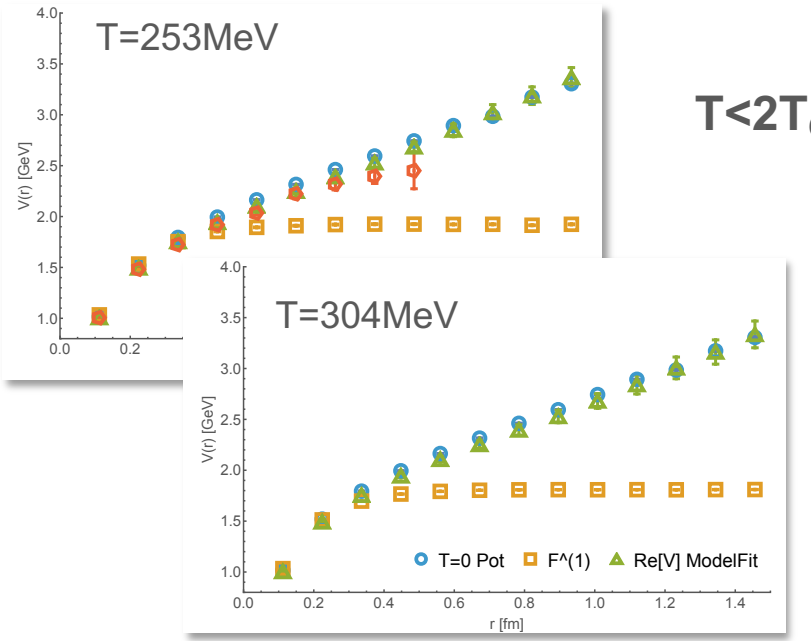

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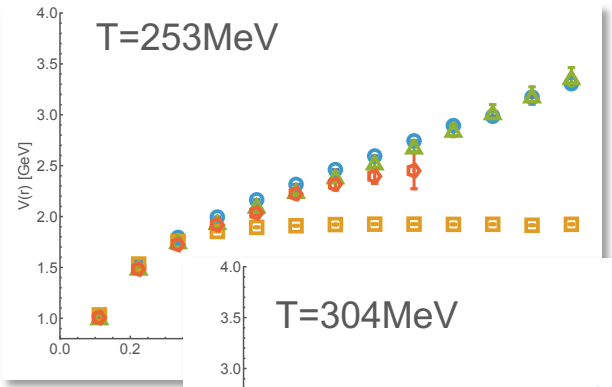

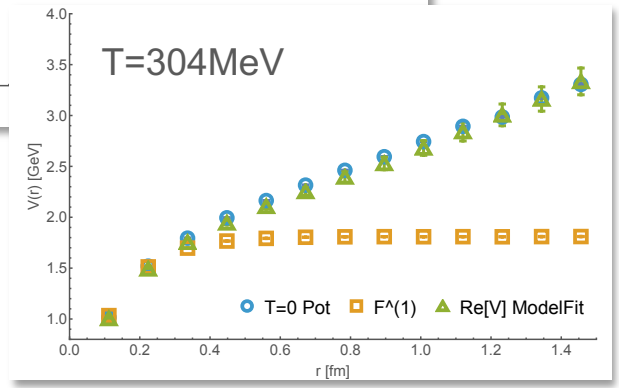

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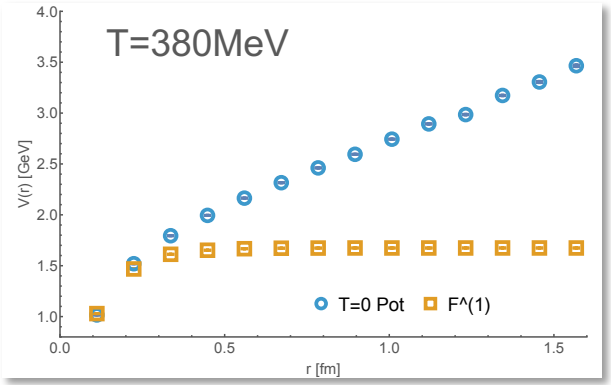
PRELIMINARY



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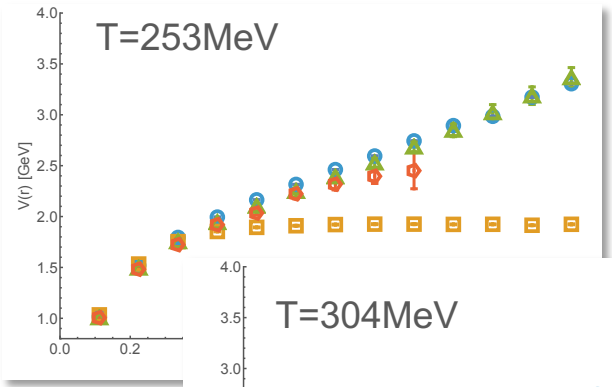
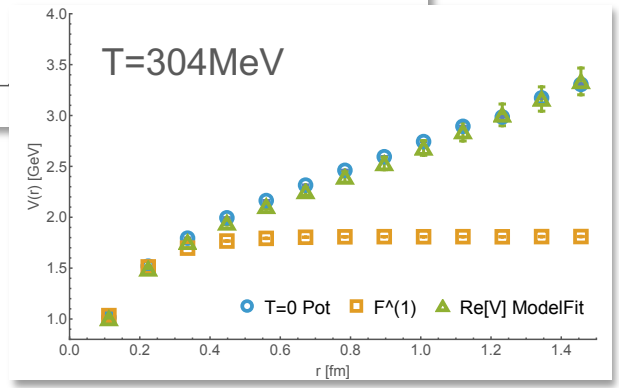
FASTSUM Gen2L ensembles PRD 105, 034504

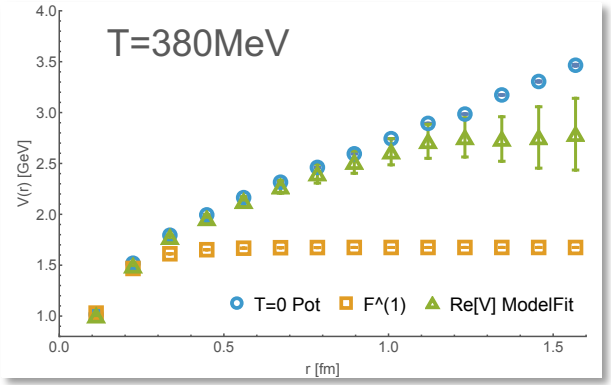




T<2T$_C$

T>2T$_C$

PRELIMINARY



Anisotropic full QCD - (preliminary) Re[V]

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

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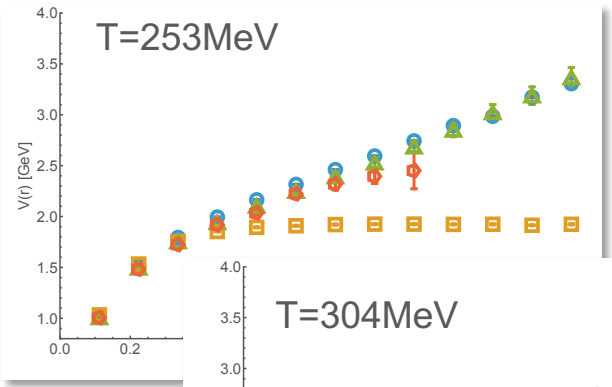

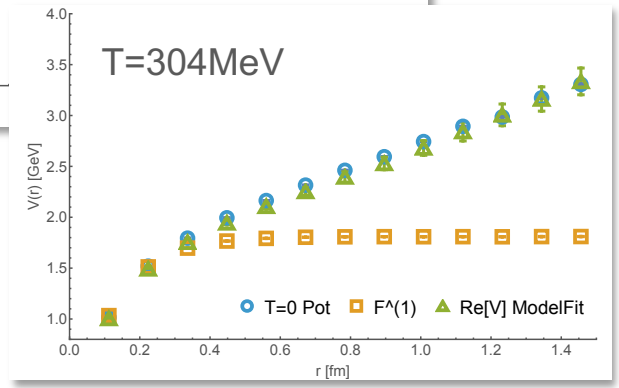

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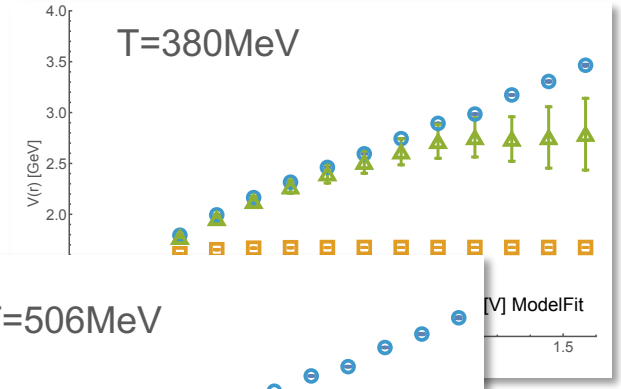

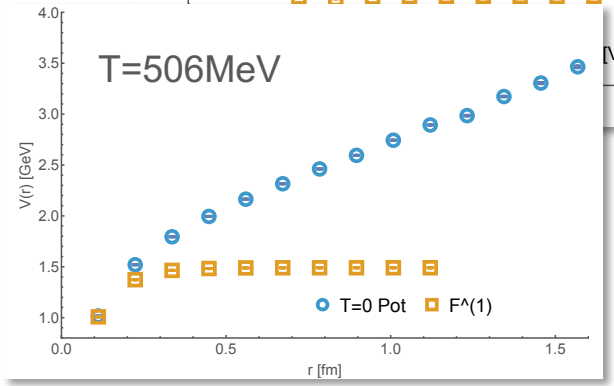

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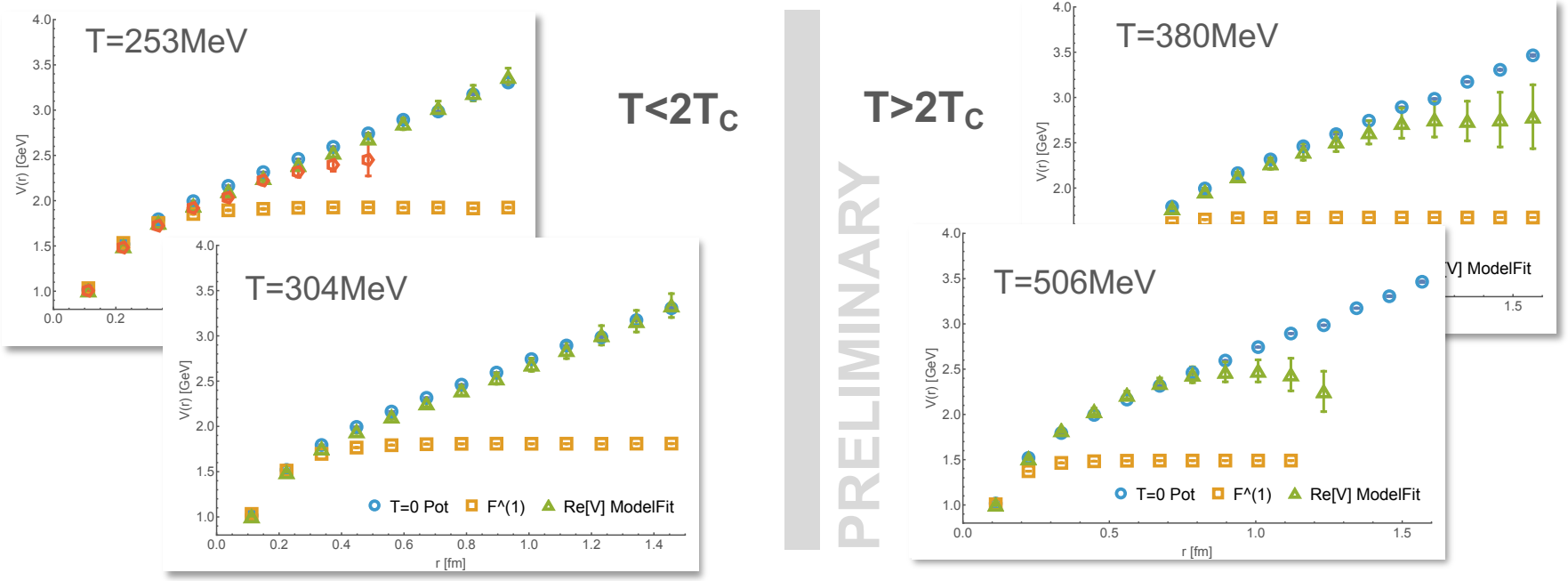

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Thank you for your attention
ご清聴ありがとうございました