Large N_c Thermodynamics with Dynamical Fermions

Presented by Daniel Hackett
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Lattice 2018

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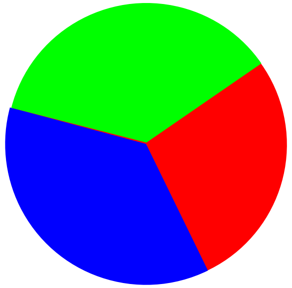
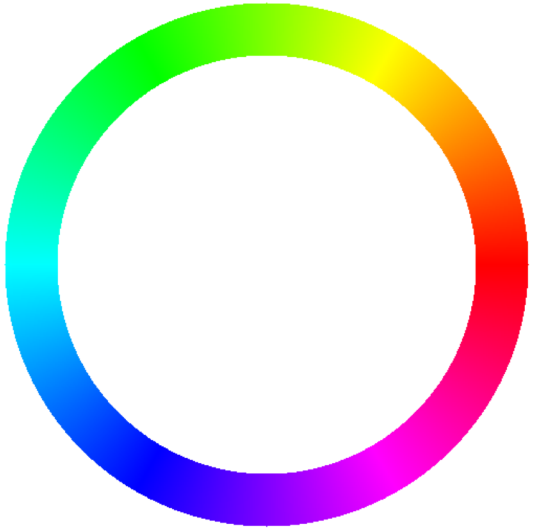




Overview

What is large N_c? What does it have to say about thermo?

Numerical tests of large N_c

- **Previous work, in general:** mostly quenched, recently some dynamical
  - [Review by Lucini, Panero 1210.4997]
- **Previous thermodynamics work:** quenched
- **This talk:** dynamical Wilson fermions [Throughout, $N_f = 2$ a.k.a. “QCD”]

Automation

Early physics results

- Phase diagram collapse, fermion independence(?), order of transition(?)

[Disclaimers: Currently in “proof of concept” phase; not intended to ever be a high-precision study]

What is large N_c?

Consider “QCD”: $\mathrm{SU}(N_c)$ with some fermion content, vary N_c holding everything else fixed

Basic assertion: Power series in $1/N_c$ exists for any observable

$$\langle \hat{O} \rangle = N_c^{\alpha} O_0 \left[1 + \frac{1}{N_c} O_1 + \cdots \right]$$

[leading N_c dependence] [nonperturbative physics]

[subleading corrections $\sim 1/N_c$]

‘t Hooft limit: $N_c \to \infty \;\; \Rightarrow \;\; \langle \hat{O} \rangle \to N_c^{\alpha} O_0$

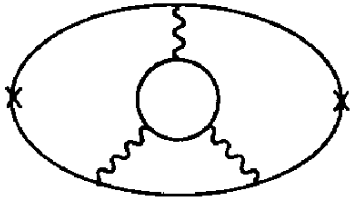
Theory simplifies in limit of infinite number of colors

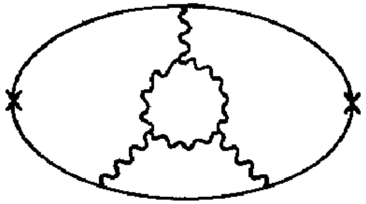
e.g. Mesons become infinitely narrow, quark model & OZI rule become exact

Holography duals typically apply to this limit

Lattice: Test that large N_c works

Thermodynamics at large N_c

 $\sim \lambda^3$

 $\sim N_c \lambda^3$

Fermion loops suppressed by $1/N_c$ vs equivalent diagrams with gluon loops

$\Rightarrow$ Fermions "quenched out" at large N_c

$\Rightarrow$ Theories with fermions act like pure gauge theory as $N_c \to \infty$

Quenched large-N_c studies **assume** this works

Test this assumption with dynamical fermions

- **Previous work**: $T = 0$ spectroscopy [DeGrand & Liu 1606.01277]
- **This study:** Finite T – do large N_c predictions hold?

Numerical details

Variant of MILC for arbitrary N_c [DeGrand]

Unimproved Wilson gauge action

$N_F = 2$ flavors of clover-improved Wilson fermions ($c_{SW} = 1$)

nHYP smeared fat links for fermions

N_c	N_F	N_s	N_t	# ensembles	# trajecs
3	2	12	6	137	82339
4	2	12	6	135	148030
5	2	12	6	49	28230

This talk: explored $12^3 \times 6$ phase diagrams for $N_c = 3,4,5$

Moving forward: Want to vary N_t, N_s/N_t, …

$\{N_c\} \times \{N_s\} \times \{N_t\} \times \cdots \rightarrow$ Need to explore many Wilson phase diagrams

Logistically intractable without automation

Automation

APDE specifies new simulations, feeds them to workflow manager

Workflow Manager

- Manages ongoing HMC runs
- Runs spectroscopy, flow on gauge configurations as they're generated
- [Minimal, naïve] automatic parameter tuning/failure recovery

github.com/dchackett/taxi

Automatically load all raw data into a relational (SQL) database

Automated Phase Diagram Explorer (APDE)

Simple criteria to decide where to explore:

- Are ensembles interesting (cut on m_q, phase)?
- Are ensembles explorable (nearby somewhere with equilibrated data)?

APDE looks at current state of analysis in DB

SQL Database & Bulk Analysis

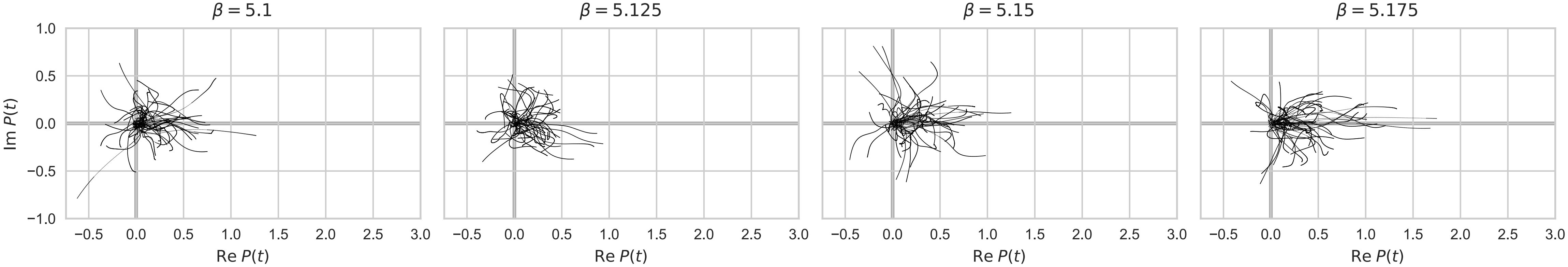
- DB enforces conventions, structure
- $\sim$ nightly analysis scripts process data into useful observables: m_q, phase diagnostics, etc.

[See DH poster from earlier this week]

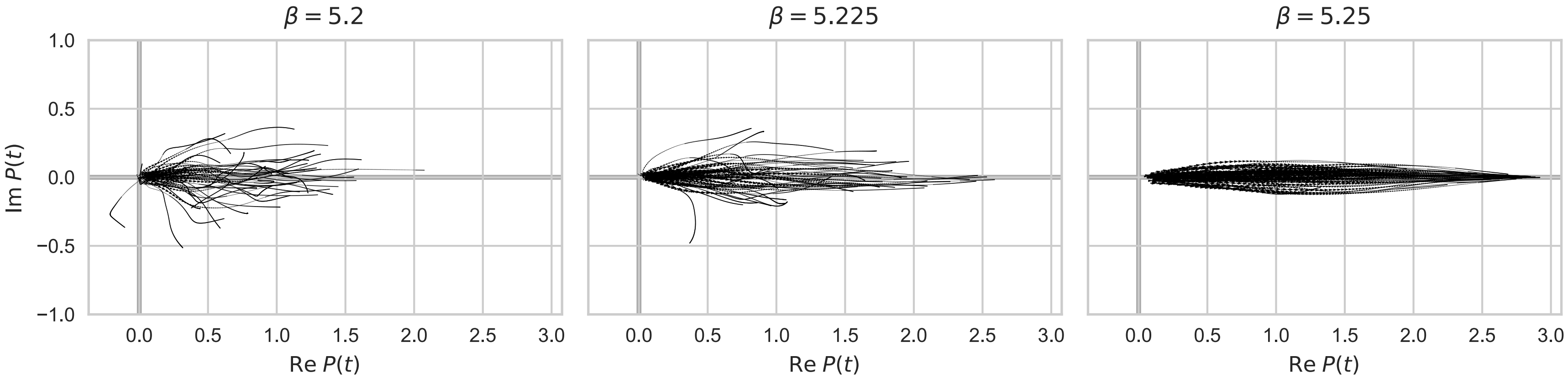
Flowed Polyakov loops

Many options for phase diagnostics, but flowed Polyakov loops are convenient for automation

Apply flow to configs while measuring Polyakov loop $P(t)$ in flow time
Confined: $P(t)$ wander randomly
Deconfined: $P(t)$ rapidly order to $+N_c$
[Behavior shifts gradually between confined-like and deconfined-like]



Paths of $P(t)$ in complex plane
Each trajectory is one config being flowed
$\mathrm{SU}(3)$ $N_F = 2$ on $12^3 \times 6$
$\kappa = 0.128$



Phase diagnostics with flowed Polyakov loops

Can use flowed Polyakov loops as a diagnostic of confinement

[Ayyar, DH, Jay, Neil 1710.03257]

Flow enhances signal in Polyakov loop

[Datta, Gupta, Lytle 1612.07985]

[Schaich, Hasenfratz, Rinaldi 1506.08791]

At long t/a^2, P is (roughly) independent of (β, κ)

Make (arbitrary but intuitive) definitions:

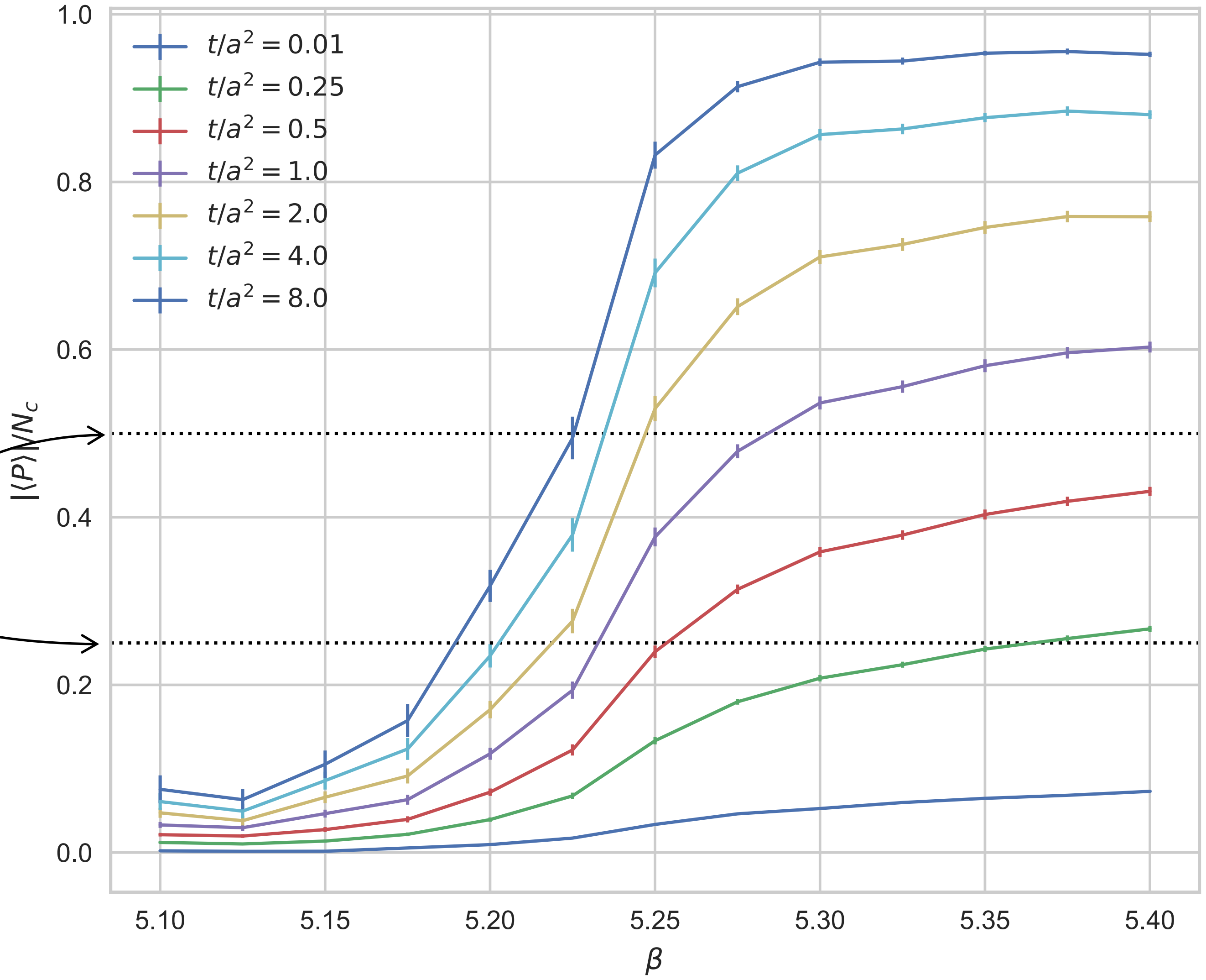
Deconfined: $|\langle P(t)\rangle|/N_c > 0.5$

Confined: $|\langle P(t)\rangle|/N_c < 0.25$

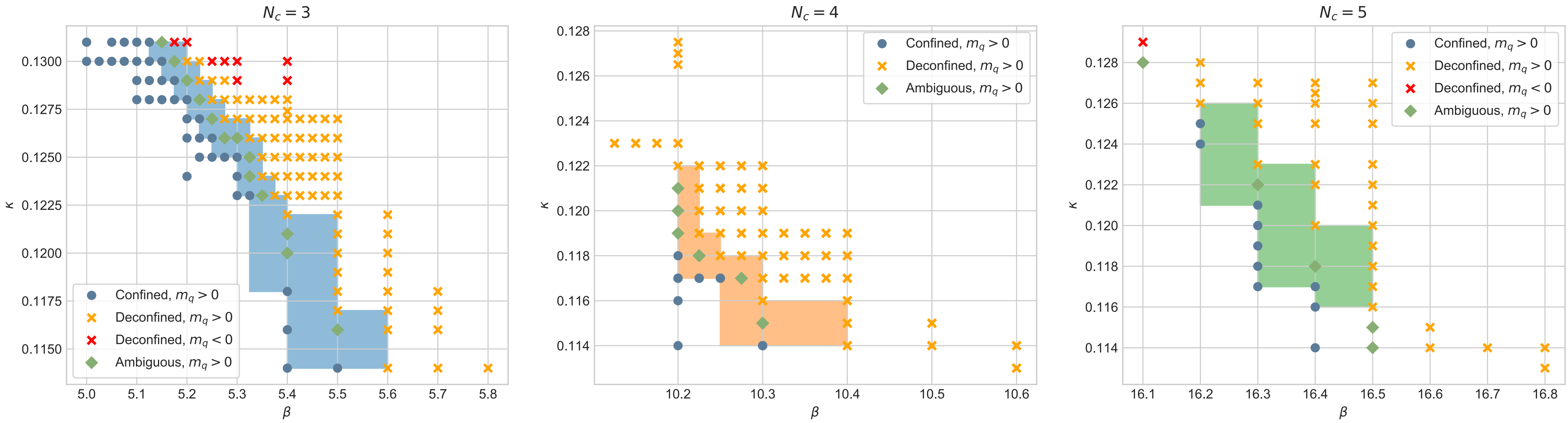
...at $t/a^2 = 2$

At right: $\mathrm{SU}(3)$ $N_F = 2$ on $12^3{\times}6$

$\kappa = 0.128$ at various different flow times t/a^2

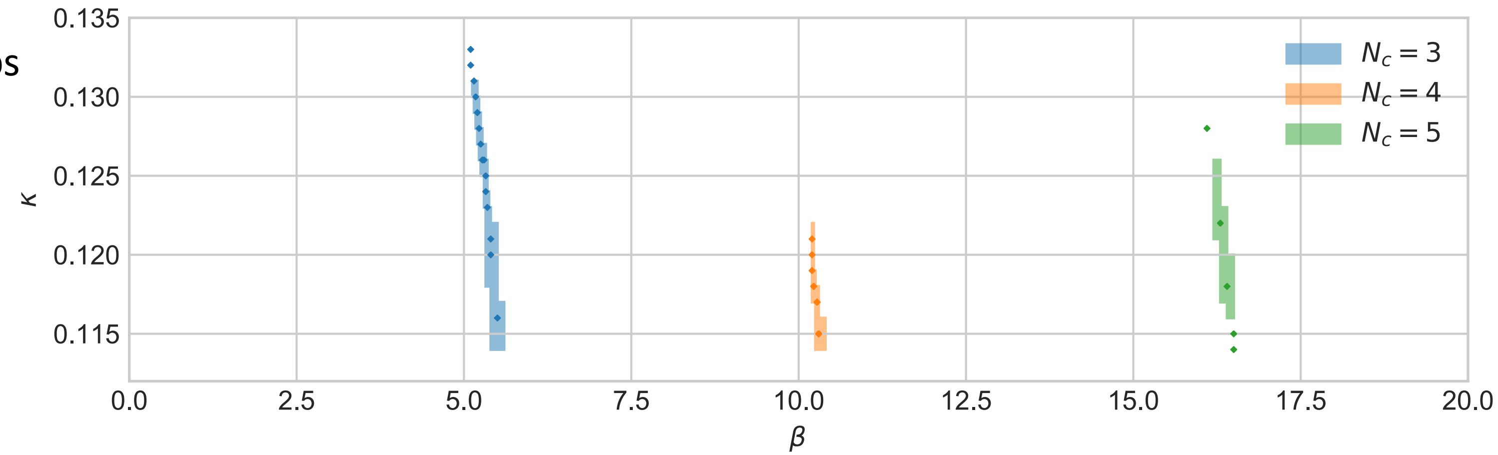


Wilson phase diagrams varying N_c



Phases defined using flowed Polyakov loops

Plotted together:
Phase-ambiguous regions [colored bands] and ambiguously-phased points



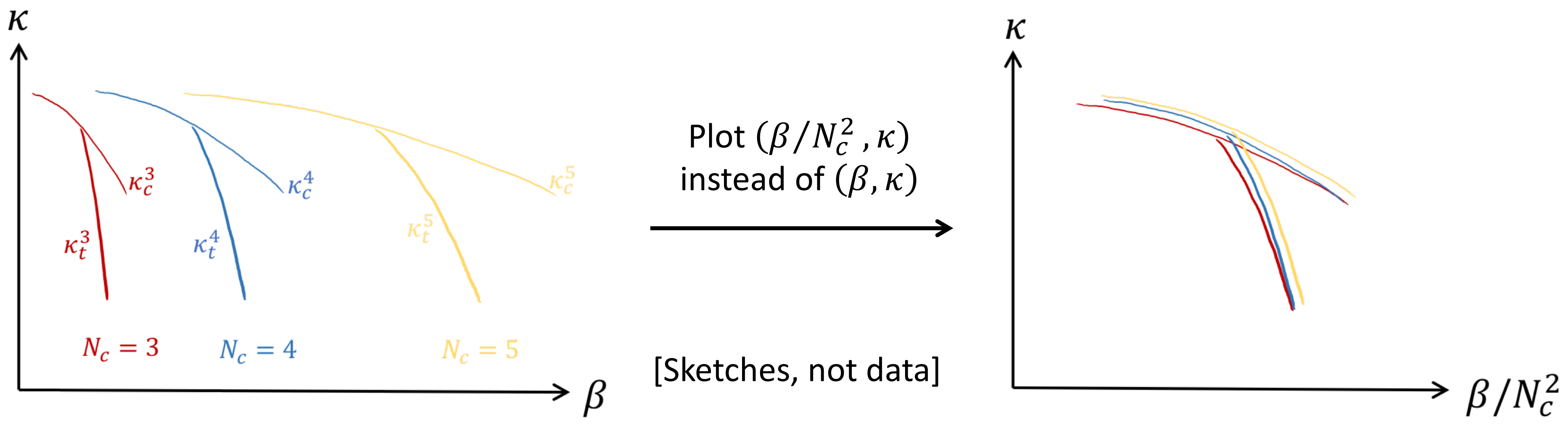
Prediction: phase diagram collapse

't Hooft limit: LO physics constant at constant $\lambda = g^2 N_c$

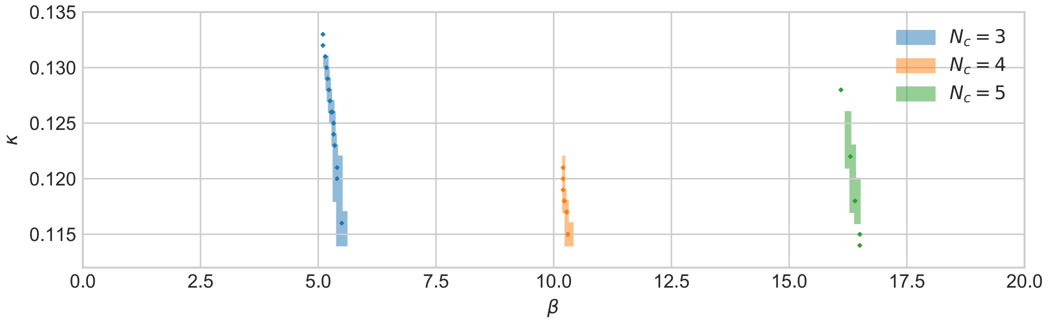
$$\beta = \frac{2N_c}{g_0^2} = \frac{2N_c^2}{\lambda_0} \quad \Rightarrow \quad \frac{\beta}{N_c^2} = \frac{2}{\lambda_0} = (\text{constant})$$

No LO N_c dependence for m_q [and thus κ]

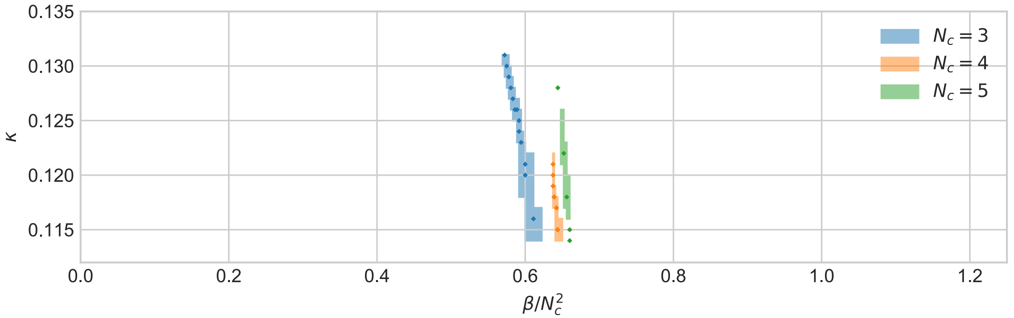
$\Rightarrow$ Constant physics at constant $(\beta/N_c^2, \kappa)$ [up to $1/N_c$ corrections]

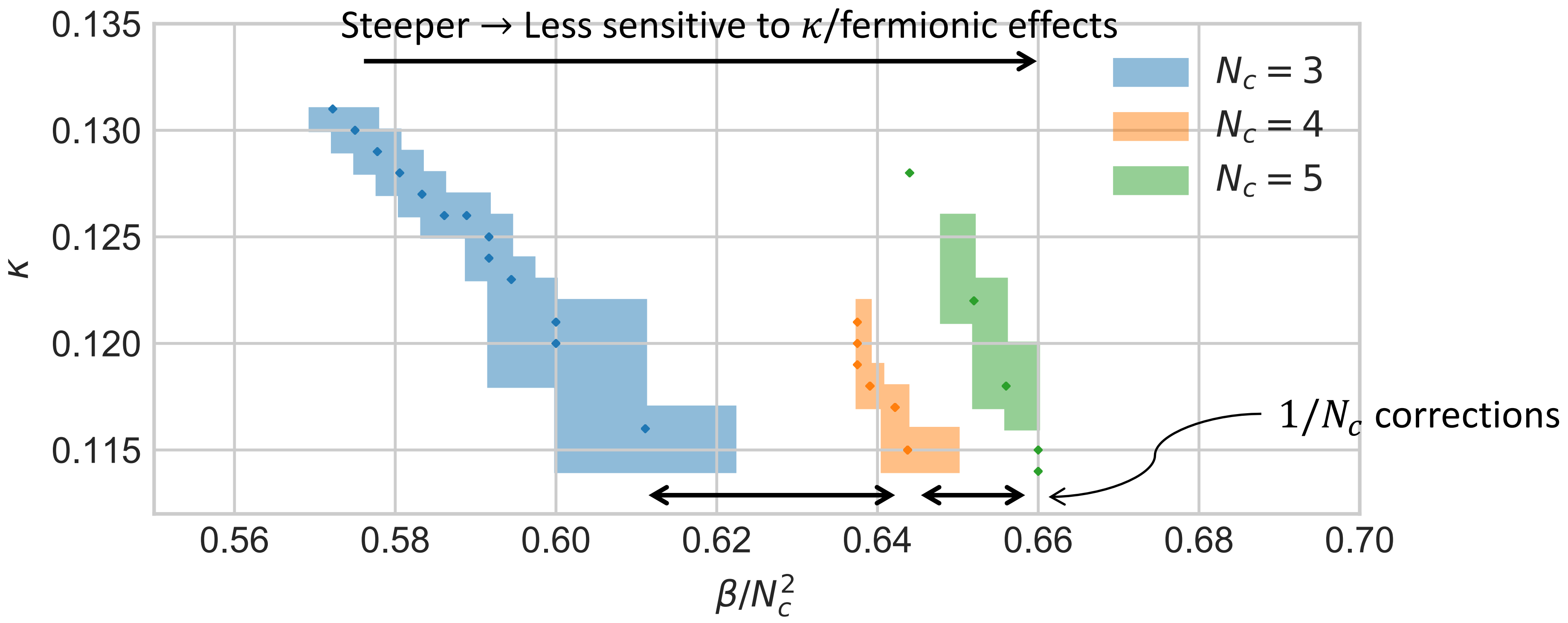


Result: phase diagram collapse



Plot $(\beta/N_c^2, \kappa)$ instead of (β, κ) →



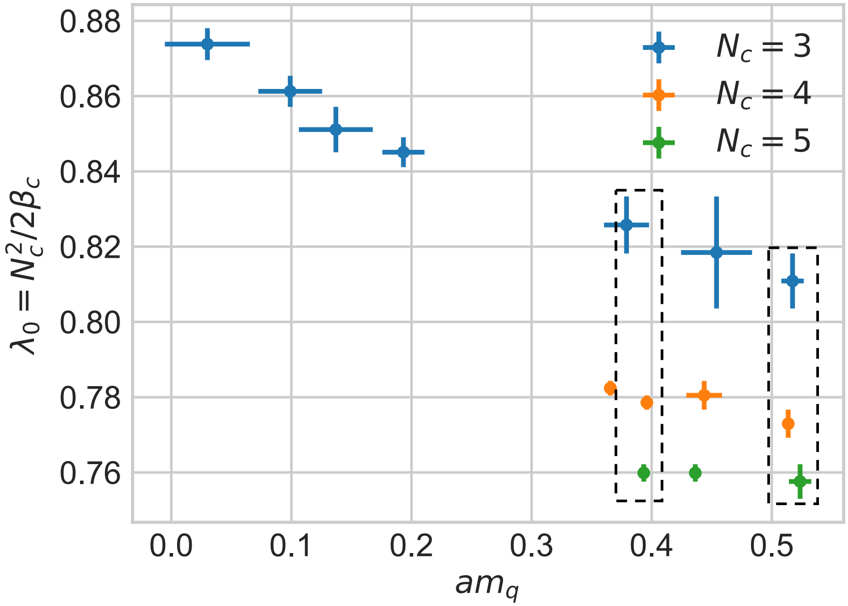


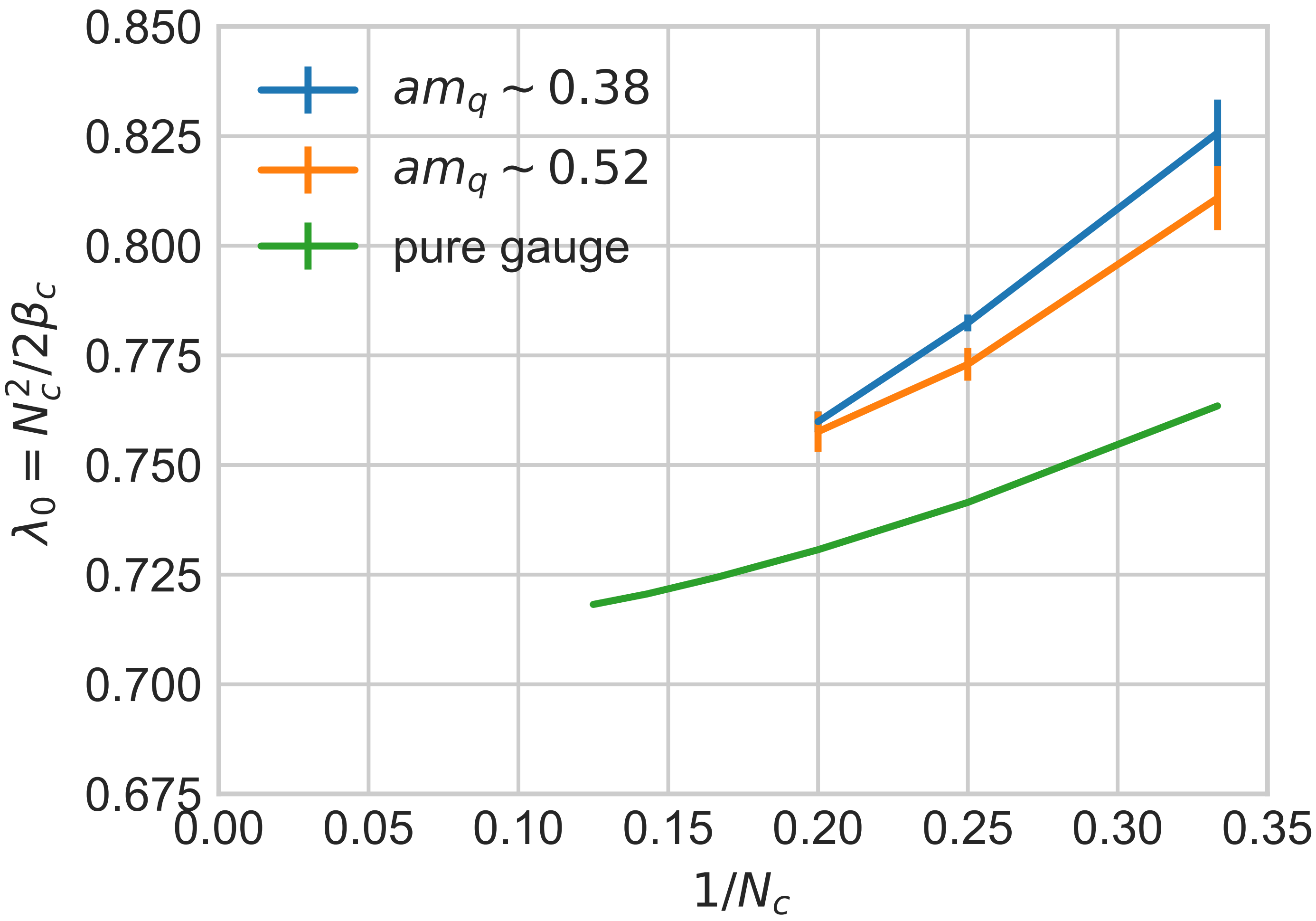
Fermion independence(?)

As $N_c \to \infty$, any observable should converge to its pure-gauge value independent of m_q

Plots: Uncertainties due to uncertainty in location of transition, wash out statistical errors

am_q from finite-T ensembles; empirically, small error vs properly calculating with $T = 0$ data





[Pure gauge data from Lucini, Teper, Wenger hep-lat/0307017; Lucini, Rago, Rinaldi 1202.6684]

Disappearance of pure-gauge transition(?)

Deconfinement/chiral transition

$m_q = \infty$: First-order for $N_c > 2$

m_q finite, easily simulated: Crossover

$\Rightarrow \exists$ some $m_q^{PG}(N_c)$ where transition changes order

Fermionic effects suppressed as N_c increases

$\Rightarrow$ Expect $m_q^{PG} \to 0$ as $N_c \to \infty$

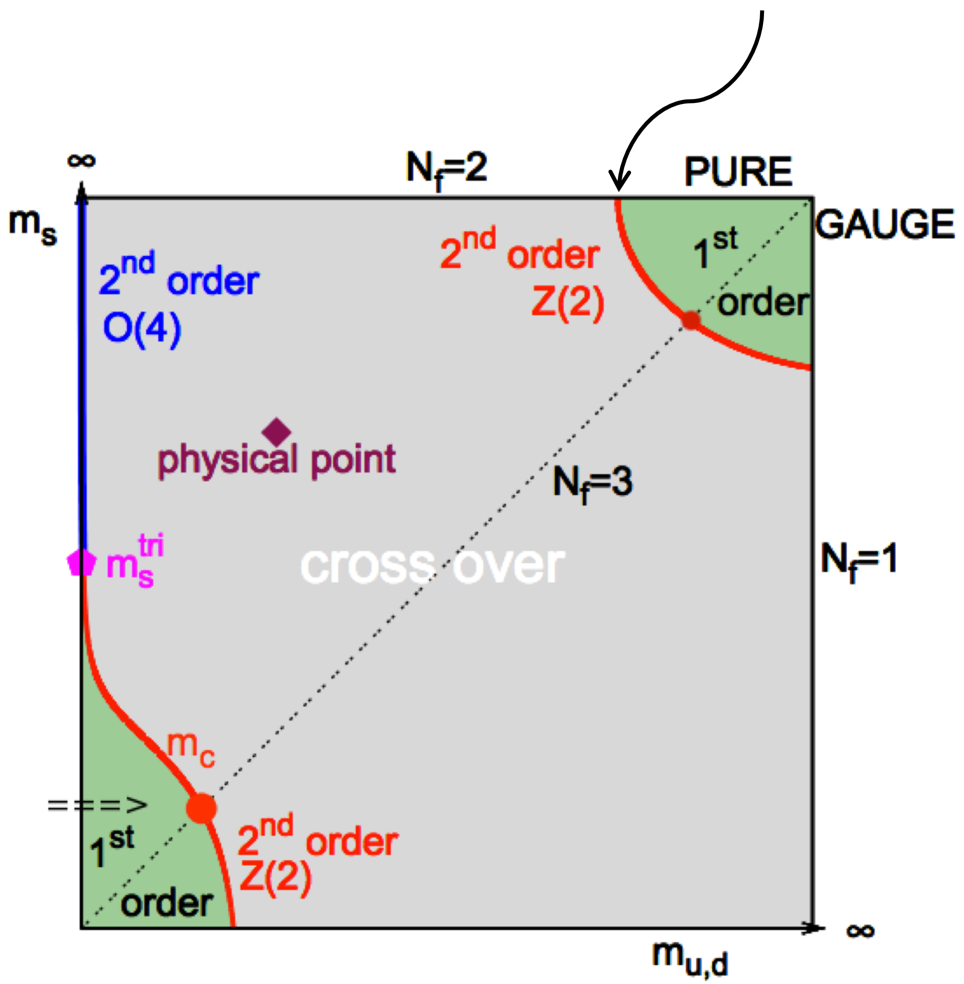
"Result": At present, no obvious first-orderness in data

- All observables continuous at transition
- No observed metastability near transition
- Polyakov loop doesn't become binary under flow

[Ayyar, DH, Jay, Neil 1710.03257]

$\Rightarrow a m_q^{PG} \gtrsim 0.5$

Where is this?



[Image from de Forcrand 2017]

Conclusions & Future Directions

Proof-of-concept works: fully automated phase diagram exploration, ~ ready for production

Initial physics results look promising

Explore $N_t > 6$ [$N_t = 8$ in progress]

→ Get control over a dependence

→ Get away from bulk transitions

More ensembles, statistics near transitions

→ Find β_c, lines of constant m_q more precisely via interpolation, reweighting?

Explore $N_s/N_t > 2$

→ Get control over finite volume artifacts

→ Volume scaling analysis to determine order of transition

Matching $T = 0$ data

→ Scales to get e.g. T_c, m_q in physical units

Bulk transitions are an issue, block access to small m_q for $N_c > 3$

→ Try improved actions?