Exploring Composite Dark matter with an SU(4) gauge theory with 1 fermion flavor

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Work in progress with the LSD collaboration

Lattice Strong Dynamics

Dark matter

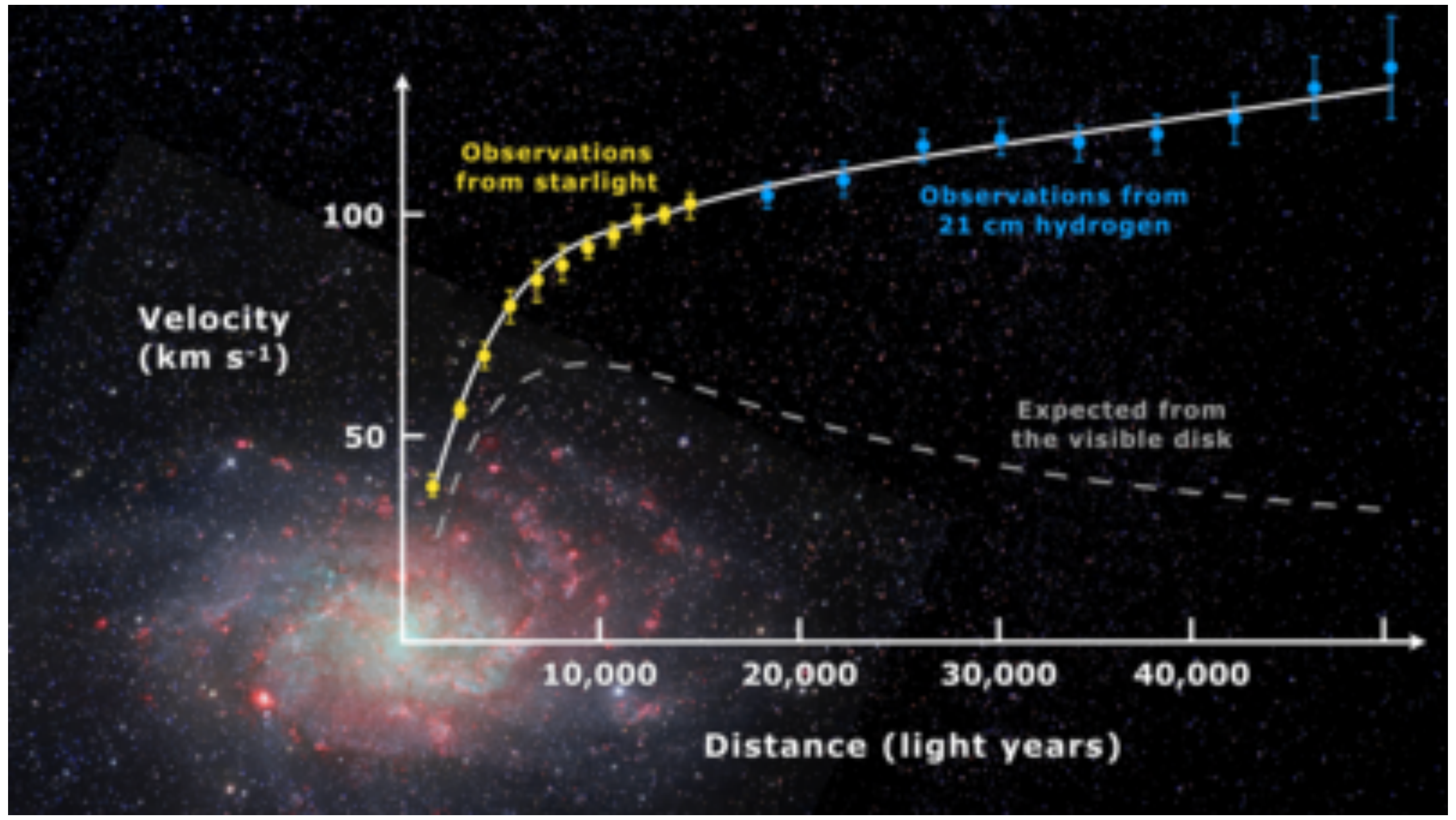
Evidence

- Galaxy rotation curves
- Weak lensing
- CMB

Dark matter features:

★ Interaction is weak: Gravitational

★Abundance: $\Omega_{Dark} = 5 \times \Omega_{SM}$



Galaxy rotation curves point to missing dark matter

Fig. from wikipedia

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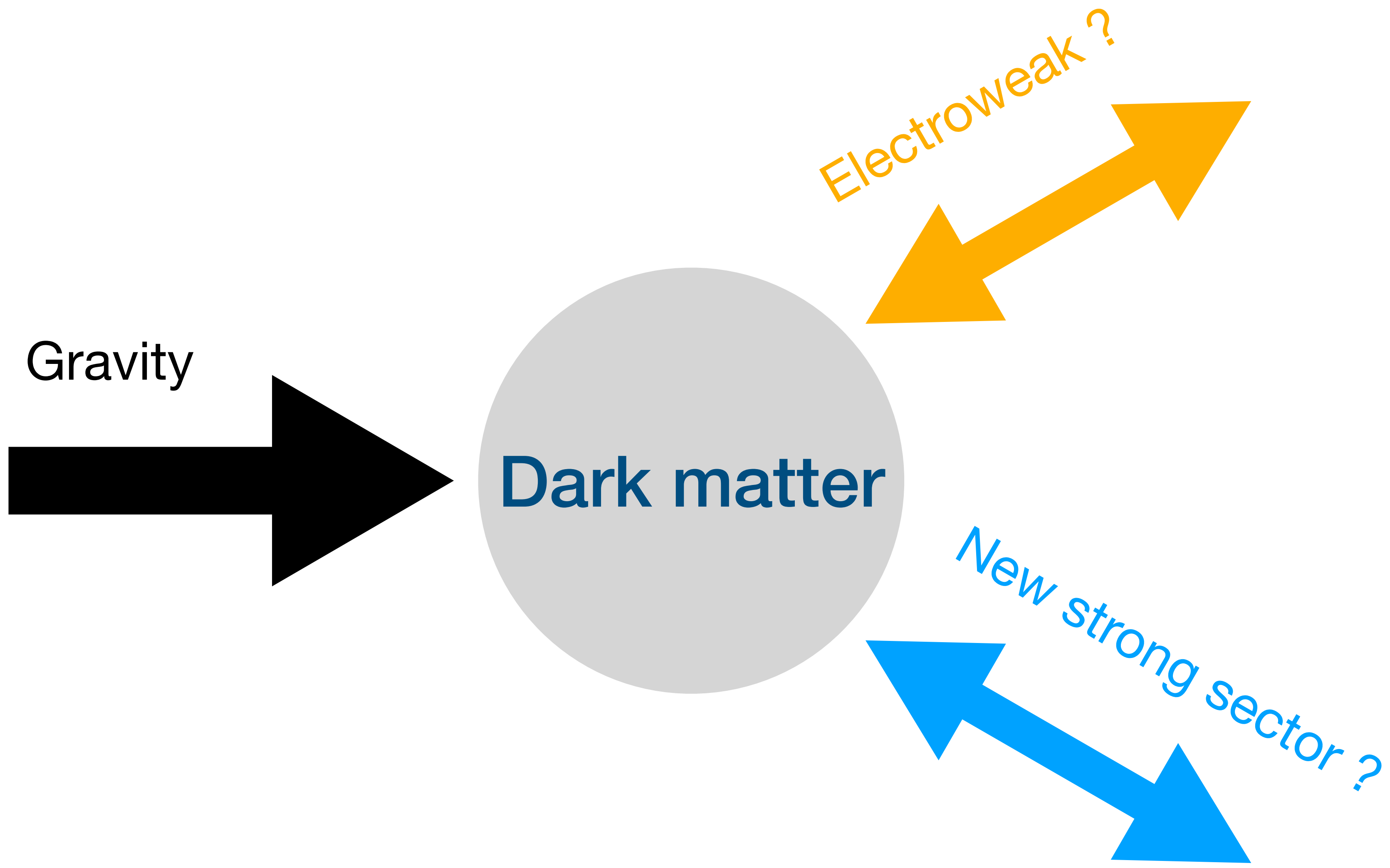
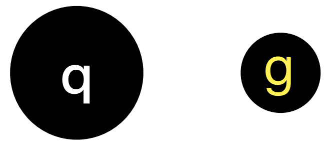
Strongly coupled Composite Dark matter



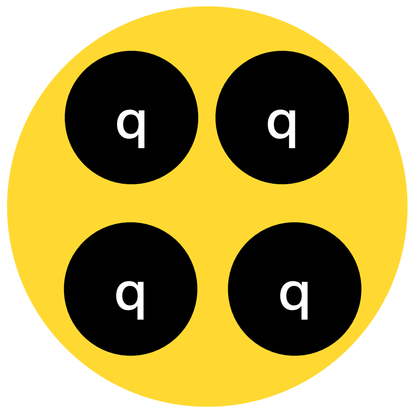
New strong sector (dark color)

Dark fermions and gluons



Stable composite particles

Can be dark matter



Coupled via Electroweak to SM particles

New confinement and chiral transitions to explore

Potential gravitational wave signal

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A new strong Dark sector SU(4)

$SU(N_c)$ Natural extension to SM

EWK QCD Dark sector ?

$$U(1) \times SU(2) \times SU(3) \times SU(4)$$

Couple to EWK sector

Dark quarks q

Composite Dark particles

Baryons Mesons

The Challenge

✓	✗
Massive particles that can be detected by future experiments	No light particles that should've been seen by existing experiments

Explain new physics

Be consistent with observations

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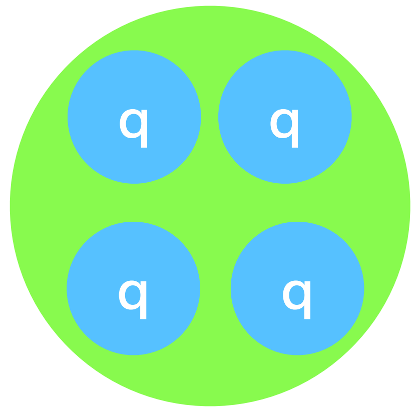
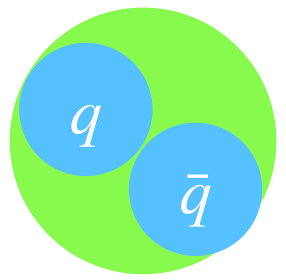
The model: SU(4) gauge theory with 1 flavor

1 flavor models are interesting !

Stable baryon



Lightest meson (η')



- ❖$U_V(1)$ (Dark baryon number) symmetry is preserved
- ❖$U_A(1)$ is broken by the anomaly
- ❖No chiral transition
- ❖No light mesons from chiral SB

Protected from decay by $U_V(1)$

Previous 1flavor work

SU(3) 1 flavor : Morte, Jager, Sannino, Tsang, Ziegler Phys. Rev. D 107 (2023), 114506

SU(2) 1 flavor : Francis, Hudspith, Lewis, Tulin *JHEP* 12 (2018) 118

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SU(4) 1 flavor emerges from Hyper stealth Dark matter (HSDM) model

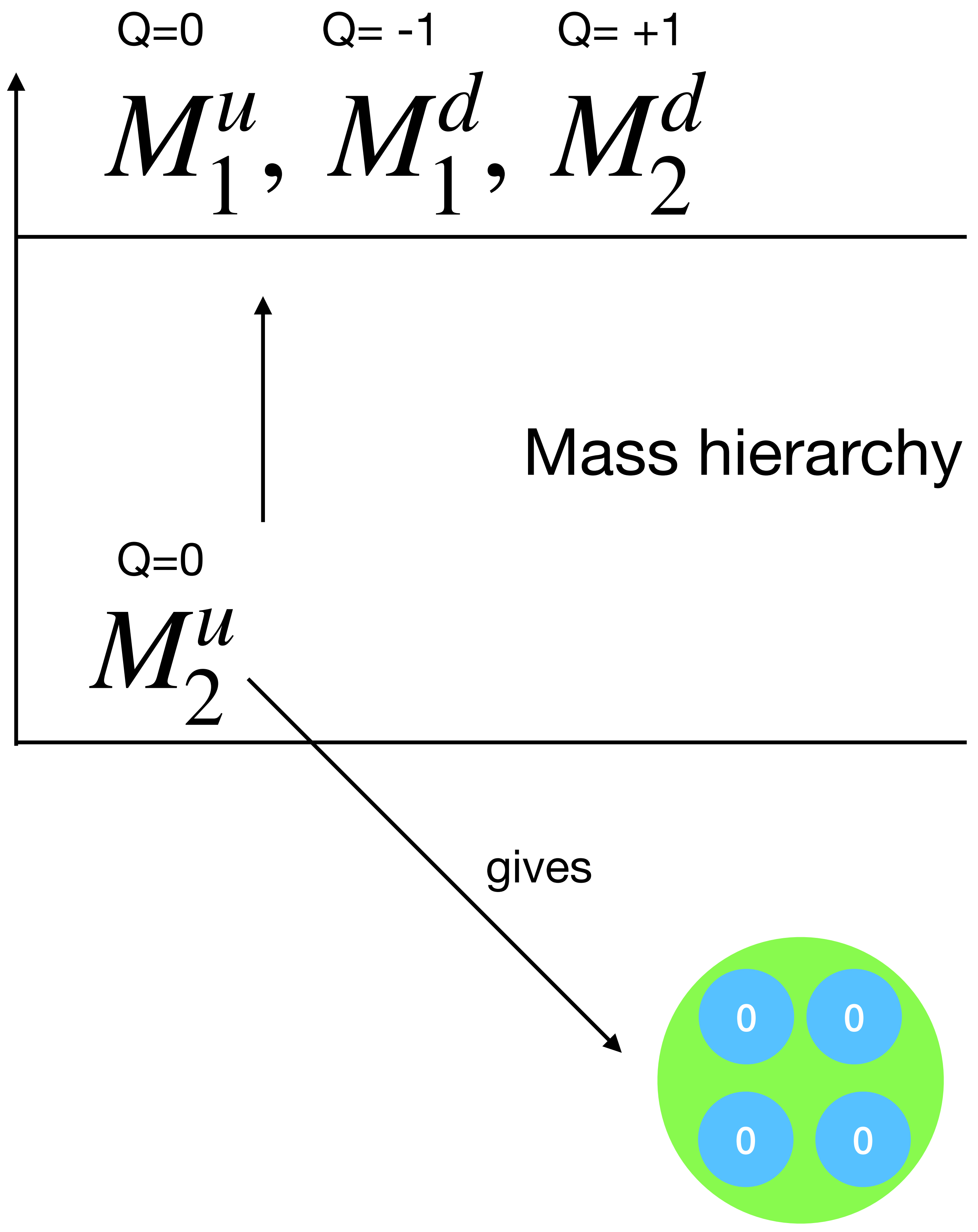
HSDM[1]

- SU(4) gauge theory: 4 flavors of fundamental Dirac fermions

- Two couple to SU(2) and U(1)
- Two couple only to U(1)

- Mass from:
  Vector mass terms
  Yukawa couplings to Higgs

- Can tweak to get a mass hierarchy



Lightest baryon is charge neutral

Similar to a QCD with neutron lightest

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[1]In preparation : Fleming, Kribs, Neil, Schaich and Vranas

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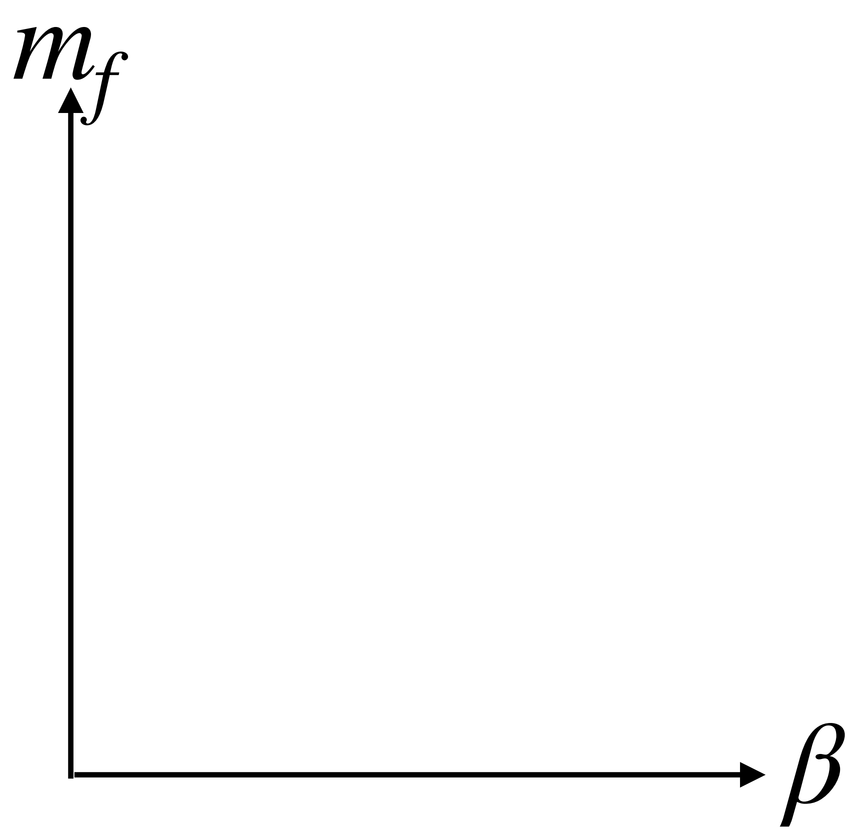
Lattice simulation goals

Step 1: Thermodynamics

Explore phase diagram at finite T

Identify confinement transition

Is it first order ?



Observables:

Plaquette

Polyakov loop

Susceptibilities $\chi_{\mathcal{O}} = L^3 \left[\langle \mathcal{O}^2 \rangle - (\langle \mathcal{O} \rangle)^2 \right]$

Step 2: Find the spectrum

Challenges:

Lightest meson η' has disconnected diagrams

Baryon is 4-quark state

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Simulation details

Wilson gauge action

Mobius domain-wall fermions

Lattice sizes : $16^3 \times 8,\ 24^3 \times 8,\ 24^3 \times 12$

Mass : 0.1

Domain-wall L5=16

~ 350 - 1300 MDTUs (molecular dynamics time units) per run

8 GPUs per run

Gauge config generation

GRID https://github.com/paboyle/Grid

Measurements

Hadrons https://github.com/aportelli/Hadrons

Runs on Tioga AMD GPU machine at Livermore Lab

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Thank you Antonin and Peter for help!

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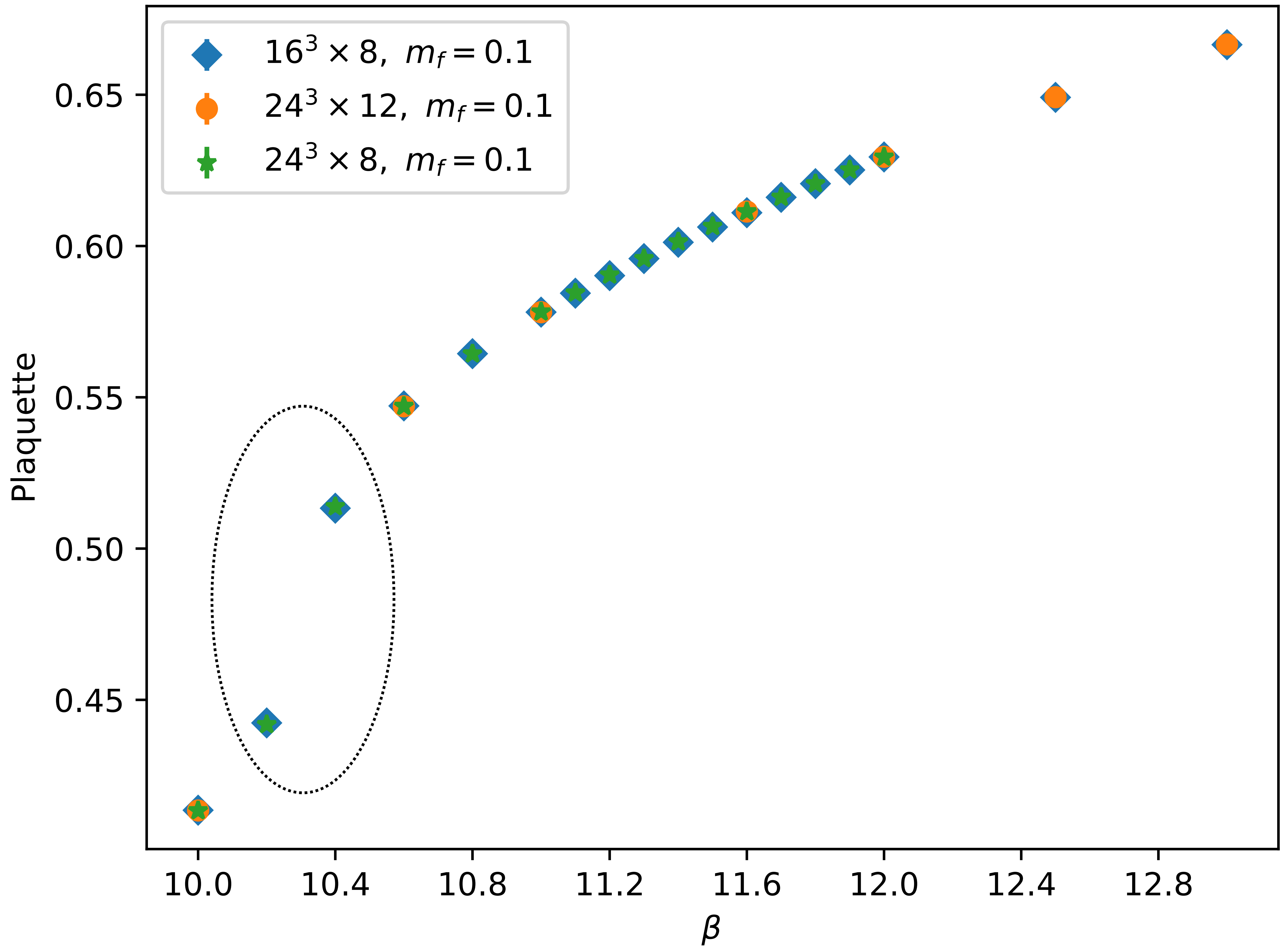
Results: Plaquette shows location of a bulk transition

Preliminary results



Plaquette : bulk transition $\beta \sim 10.3$

Jump in the Polyakov loop for $\beta \sim 10.3$

No variation with temperature ($L_t = 8,12$)

Bulk transition : unphysical, lattice artifact

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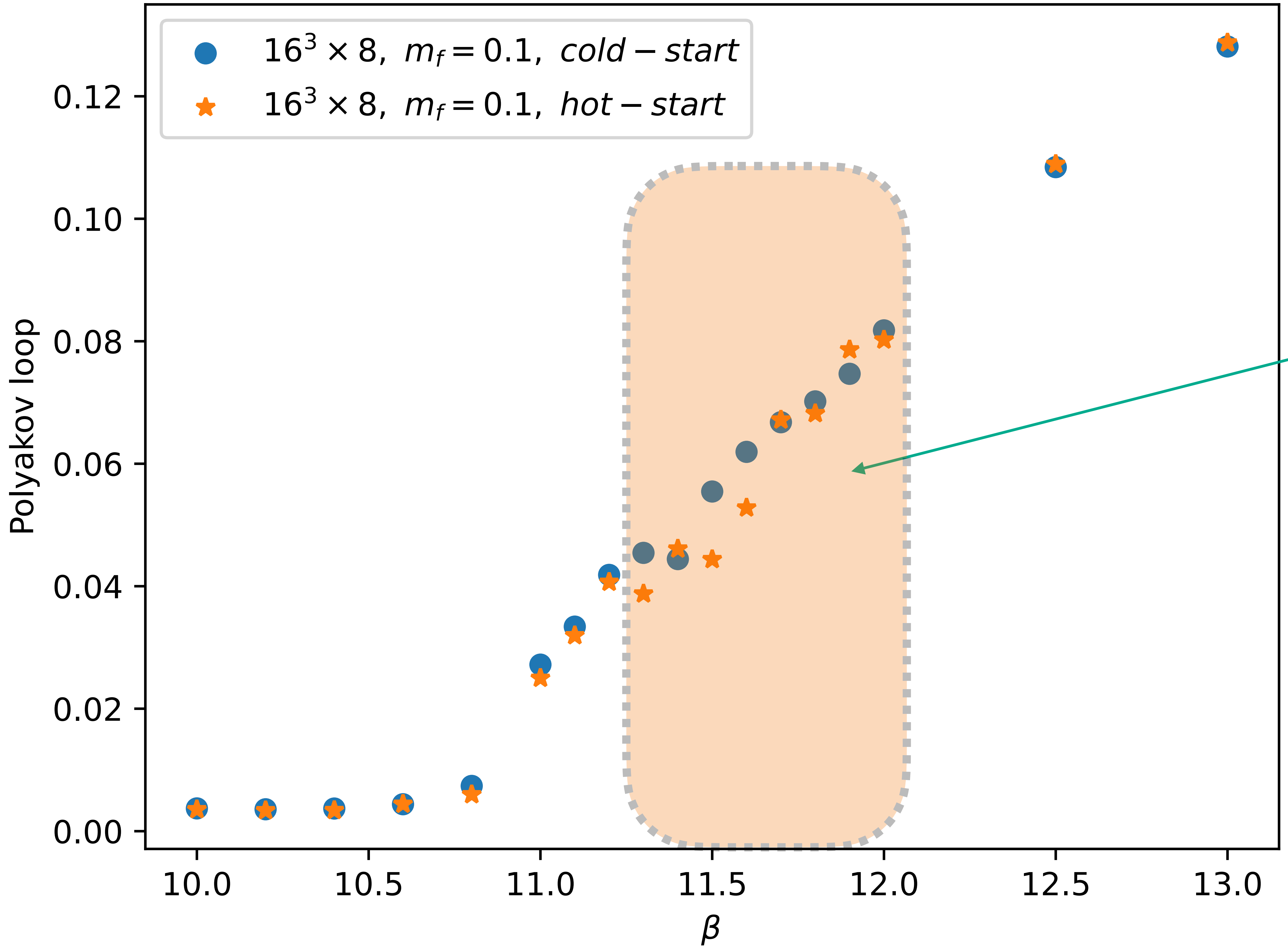
Results: Comparing Hot and Cold starts

Preliminary results



Hot start	Random gauge fields
Cold start	Unit gauge field

Hot and cold starts not meeting

Can't trust results here

Need more configurations!

Polyakov loop : Confinement transition $\beta \in (11.0, 12.0)$

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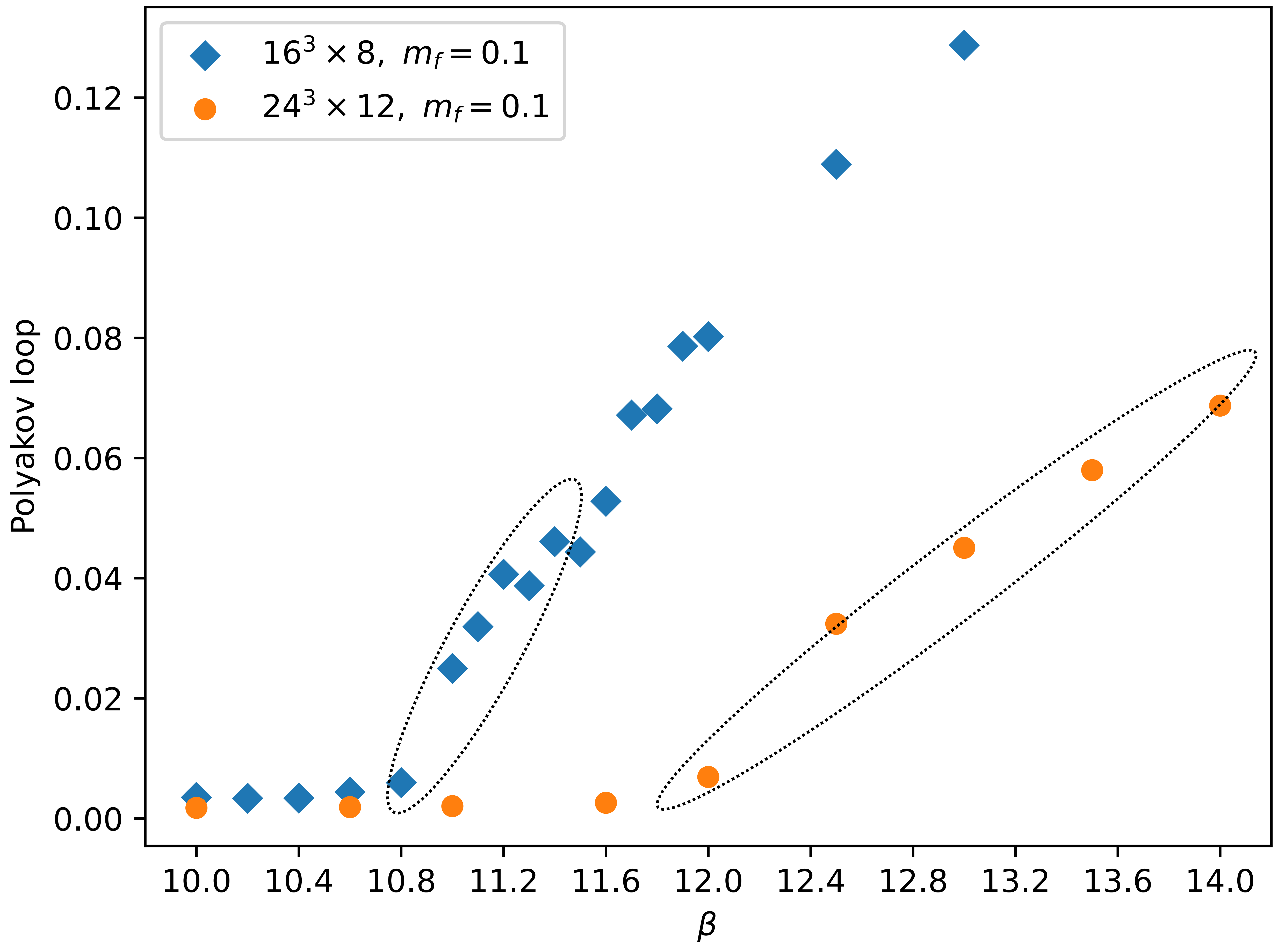
Results: Confinement transition from the Polyakov loop

Preliminary results

Results from HotStart



Transition shifts to larger β with increasing N_t

Variation with temperature ($N_t = 8{,}12$)

$$T \sim \frac{1}{a\ N_t}$$

As $N_t \uparrow \implies a_c \downarrow \implies \beta_c \uparrow$

Transition moves as expected

Not a bulk transition

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Next steps

- ✦ Need more configs near the transition
- ✦ Polyakov loop is noisy → Wilson flowed observables to map transition
- ✦ Calculate masses of lightest stable baryon and meson → Challenging: η' has disconnected contributions
- ✦ Map phase diagram for larger m_q → Perhaps use Wilson fermions with RHMC

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Summary

Hyper-stealth Dark matter : SU(4)

Studying thermodynamics of SU(4) 1 flavor

Found the region of the transition

Future direction

- ✦ Calculate masses of lightest stable baryon and meson
- ✦ Scattering

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Thank you

Argonne	Xiao-Yong Jin, James Osborn
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Liverpool	David Schaich, Chris Culver
Nvidia	Evan Weinberg
Oregon	Graham Kribs
RIKEN	Enrico Rinaldi
Siegen	Oliver Witzel
Trieste	James Ingoldby
Yale	Thomas Appelquist, Kimmy Cushman

Computing resources:

LLNL machines Lassen and Tioga

Backup slides

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Hyper-stealth dark matter (HSDM)

Fermion kinetic terms

$$\mathscr{L} \supset \sum iF_i^\dagger \bar{\sigma}^\mu D_{i,\mu} F_i + \sum_{i=3,4;\ j=u,d} iF_i^{j,\dagger} \bar{\sigma}^\mu D_{i,\mu}^j F_i^j$$

Covariant derivatives

$$D_{1,\mu} = \partial_\mu - ig' Y_1 B_\mu - igW_\mu^a \frac{\sigma^a}{2} - ig_D G_\mu^b t^b$$

$$D_{2,\mu} = \partial_\mu - ig' Y_2 B_\mu - igW_\mu^a \frac{\sigma^a}{2} + ig_D G_\mu^b t^{b*}$$

$$D_{3,\mu}^j = \partial_\mu - ig' Y_3 B_\mu - ig_D G_\mu^b t^b$$

$$D_{4,\mu}^j = \partial_\mu - ig' Y_4 B_\mu + ig_D G_\mu^b t^{b*}$$

Flavor charge assignments

Field	$SU(N_D)$	$(SU(2)_L, Y)$	T_3	Q
F_1^u	$\mathbf{N}$	$(\mathbf{2}, -1/2)$	$+1/2$	0
F_1^d	$\mathbf{N}$	$(\mathbf{2}, -1/2)$	$-1/2$	-1
F_2^u	$\overline{\mathbf{N}}$	$(\mathbf{2}, +1/2)$	$+1/2$	+1
F_2^d	$\overline{\mathbf{N}}$	$(\mathbf{2}, +1/2)$	$-1/2$	0
F_3^u	$\mathbf{N}$	$(\mathbf{1}, 0)$	0	0
F_3^d	$\mathbf{N}$	$(\mathbf{1}, -1)$	0	-1
F_4^u	$\overline{\mathbf{N}}$	$(\mathbf{1}, +1)$	0	+1
F_4^d	$\overline{\mathbf{N}}$	$(\mathbf{1}, 0)$	0	0

$$Q = T_3 + Y$$

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Mass terms : Vector and Yukawa

Vector-like mass terms

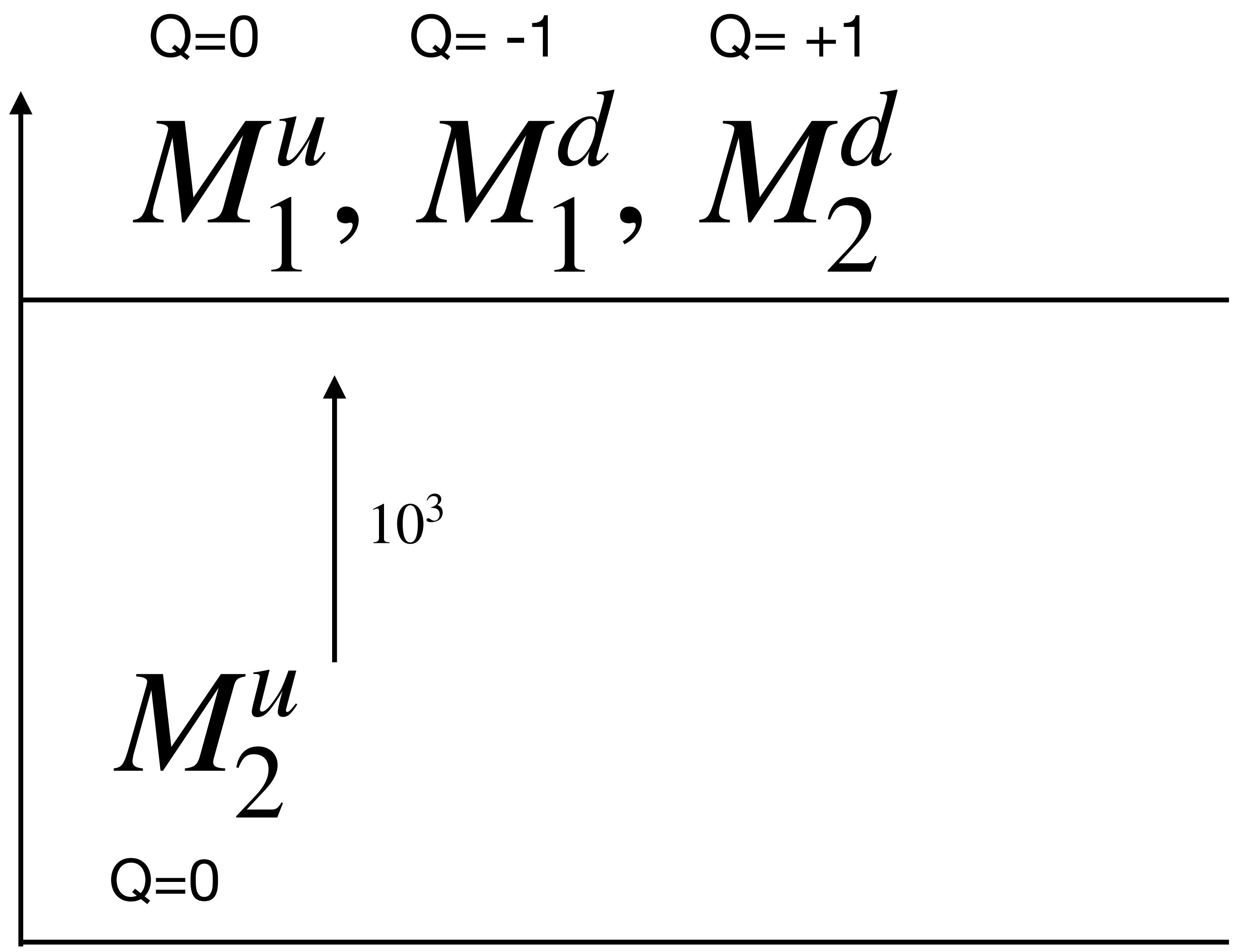
$$\mathscr{L} \supset M_{12}\epsilon_{ij}F_1^i F_2^j - M_{34}^u F_3^u F_4^d + M_{34}^d F_3^d F_4^y + \text{h.c.}$$

Yukawa masses after EWK symmetry breaking

$$\mathscr{L} \supset \frac{v}{\sqrt{2}}\left(-y_{14}^u F_1^u F_4^d + y_{14}^d F_1^d F_4^u + y_{23}^d F_2^u F_3^d - y_{23}^u F_2^d F_3^u + \text{h.c.}\right)$$

Mass eigenbasis

$$\mathscr{L} \supset -\left[M_1^u\ \overline{\Psi}_1^u \Psi_1^u + M_2^u\ \overline{\Psi}_2^u \Psi_2^u + M_1^d\ \overline{\Psi}_1^d \Psi_1^d + M_2^d\ \overline{\Psi}_2^d \Psi_2^d\right]$$



SDM and HSDM comparison

This talk

SDM[1,2,3]

+1
-1
+1
-1

2 flavors have SU(2) charges
2 flavors have hypercharge

Light charged dark pions exist

Dark baryons scale ~ TeV

HSDM

0
-1
0
+1

2 flavors have SU(2) and hypercharge
2 flavors have hypercharge

Dark baryons scale ~ few GeV

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[1]PHYSICAL REVIEW D 92, 075030 (2015)
[2]PHYSICAL REVIEW LETTERS PRL 115, 171803 (2015)
[3]PHYSICAL REVIEW D 103, 014505 (2021)

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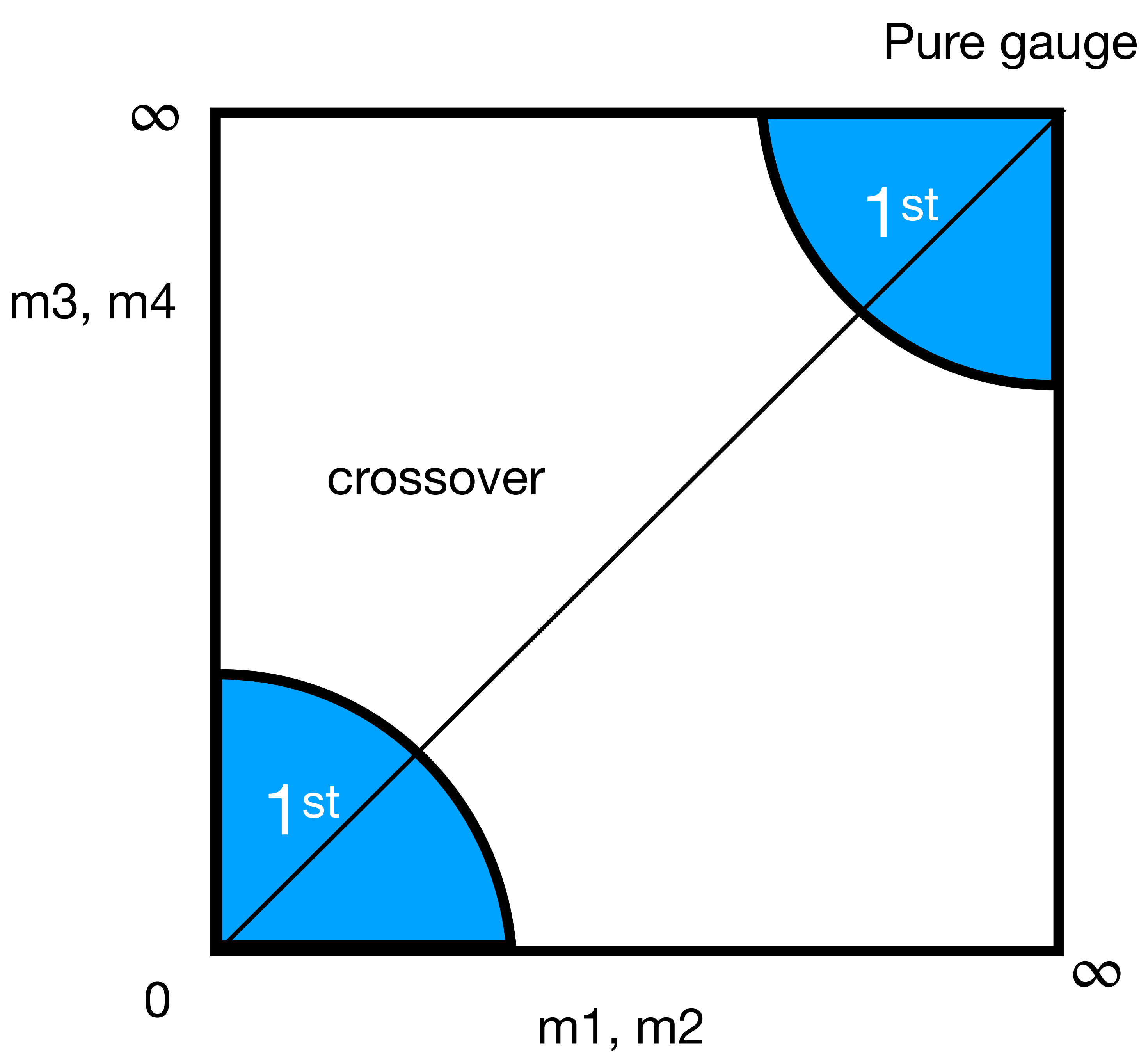
Want to find the order of confinement transition for SU(4)



Conjectured Columbia plot
for SU(N) gauge theory

Number of flavors	Order of confinement transition
Pure gauge[1]	1 st order
1 flavor	?
2 flavors[2]	cross-over
4 flavors[1]	cross-over for low masses

We like **1st** order

Potential Gravitational wave signal !

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[1]PHYSICAL REVIEW D 103, 014505 (2021), LSD collaboration
[2]PHYSICAL REVIEW D 97, 114502 (2018), TaCo collaboration

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