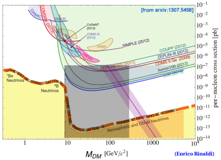
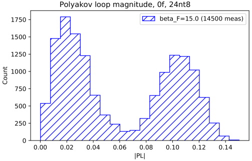
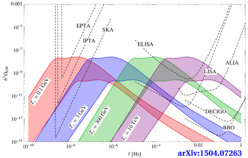
Stealth dark matter and gravitational waves


[from arxiv:1307.5458]

(Enrico Rinaldi)


Polyakov loop magnitude, 0f, 24nt8


arXiv:1504.07263

David Schaich (University of Liverpool)

Lattice 2019, 19 June

Work in progress with the Lattice Strong Dynamics Collaboration

Lattice Strong Dynamics Collaboration

Argonne	Xiao-Yong Jin, James Osborn
Bern	Andrew Gasbarro
Boston	Rich Brower, Dean Howarth, Claudio Rebbi
Colorado	**Ethan Neil**, Oliver Witzel
UC Davis	Joseph Kiskis
Livermore	Pavlos Vranas
Liverpool	**DS**
Nvidia	Evan Weinberg
Oregon	**Graham Kribs**
RIKEN	**Enrico Rinaldi**
Yale	Thomas Appelquist, Kimmy Cushman, George Fleming

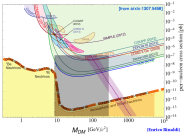
Exploring the range of possible phenomena in strongly coupled field theories

Overview

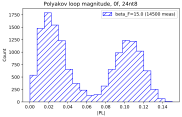
Stealth dark matter

Attractive and viable composite dark matter model

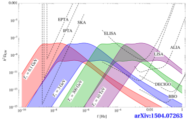
Exploring gravitational waves from first-order transition



Stealth dark matter motivational review



4-flavor SU(4) lattice phase diagram



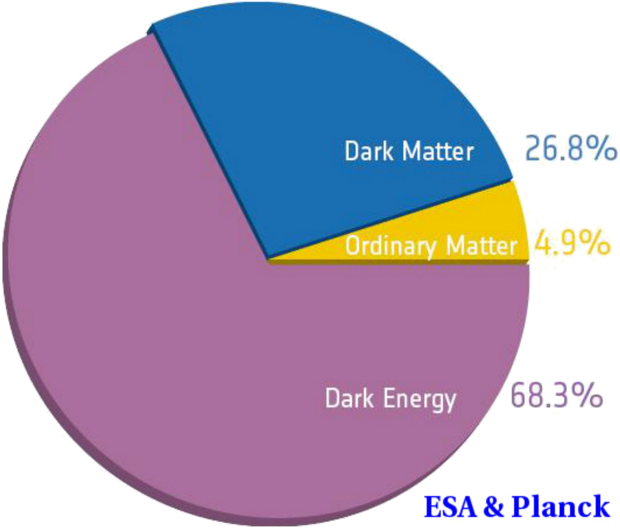
Gravitational wave prospects

Dark matter

Consistent gravitational evidence
from kiloparsec to Gpc scales

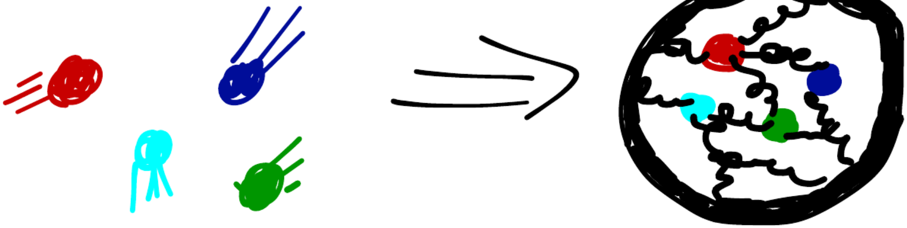
$$\frac{\Omega_{\text{dark}}}{\Omega_{\text{ordinary}}} \approx 5 \quad \ldots \text{not} \;\; 10^5 \;\; \text{or} \;\; 10^{-5}$$

$\longrightarrow$ non-gravitational interactions
with standard model



ESA & Planck

Composite dark matter



Early universe

Deconfined charged fermions ⟶ non-gravitational interactions

Present day

Confined neutral ‘dark baryons’ ⟶ no experimental detections

Stealth dark matter

[PRL **115** 171803; PRD **92** 075030]

SU(4) dark sector with four moderately heavy fundamental fermions

Lightest scalar ‘baryon’ is stable dark matter candidate

Direct detection

Symmetries

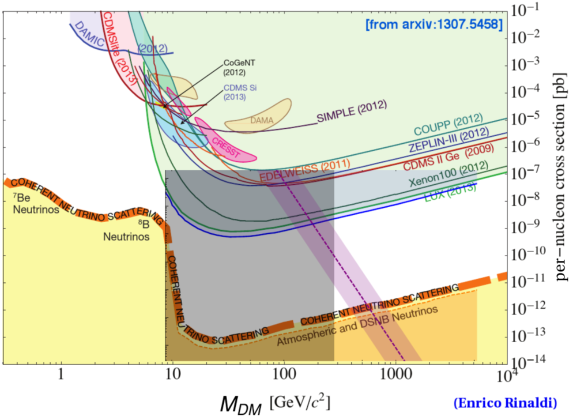
$\longrightarrow$ electric polarizability

is leading interaction

Collider searches

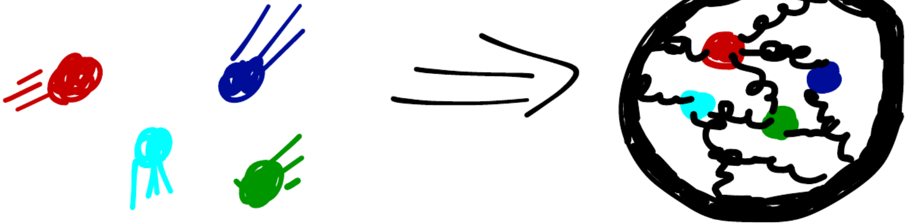
Charged ‘meson’ Drell–Yan

rules out shaded region



(Enrico Rinaldi)

Gravitational waves



Gravitational waves

First-order confinement transition ⟶ stochastic background

⟹ Lattice studies of stealth dark matter phase transition

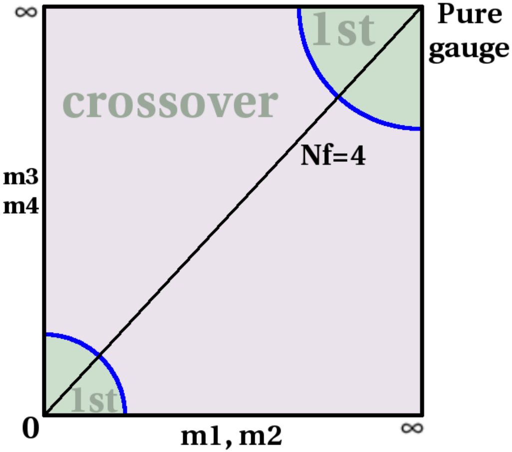
Phase diagram expectations

Pure-gauge transition is first order

Becomes stronger as *N* increases

First-order transition persists
for sufficiently heavy fermions

How heavy is sufficient for SU(4)?

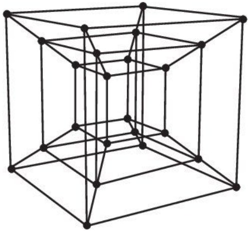


Using $N_F = 4$ unrooted staggered fermions
gauge action with both fundamental & adjoint plaquette terms

The lattice phase diagram game

Fermion masses $m = 0.05,\ 0.067,\ 0.1,\ 0.2$ (and pure gauge)

$\times$



Temporal extents $N_T = 4,\ 6,\ 8,\ 12$

$\times$

Aspect ratios $L/N_T = 2,\ 3,\ 4,\ 6,\ 8$

$\times$

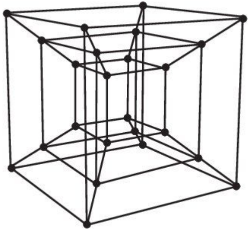
Scan coupling β_F to sweep temperatures high $\longrightarrow$ low and low $\longrightarrow$ high

$=$ 985 ensembles and counting [5,000–50,000 MD time units per ensemble]

The lattice phase diagram game

Fermion masses $m = 0.05,\ 0.067,\ \mathbf{0.1},\ 0.2$ (and pure gauge)

$\times$



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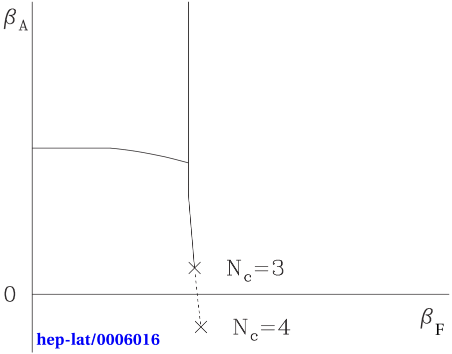
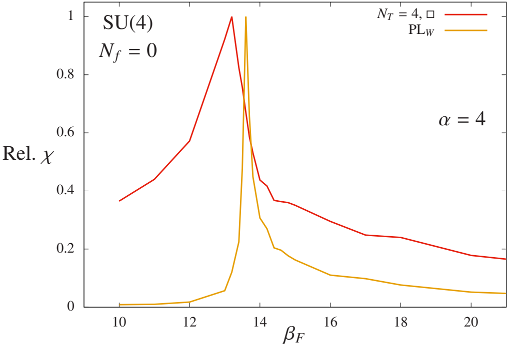
Pure gauge checks: Bulk and thermal transitions



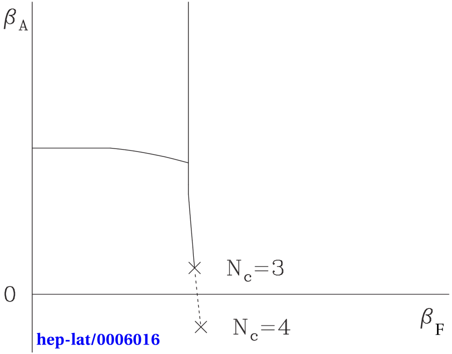
hep-lat/0006016



Try to avoid bulk transition for small N_T $\longrightarrow$ use $\beta_A = -\beta_F/4$

Still need $N_T > 4$ for clear separation between bulk & thermal transitions

Pure gauge checks: Bulk and thermal transitions



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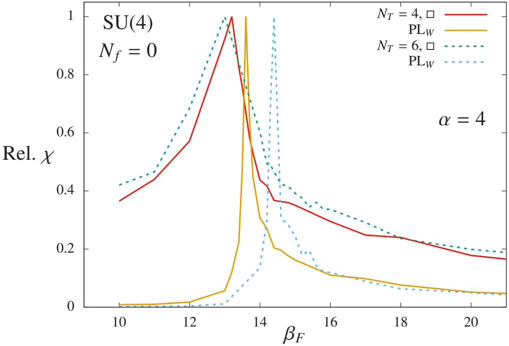

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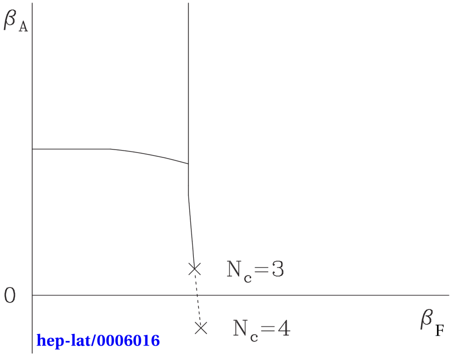

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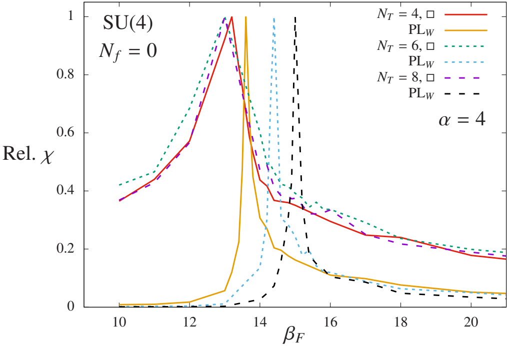
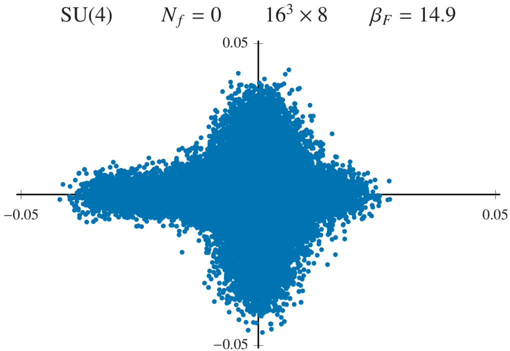
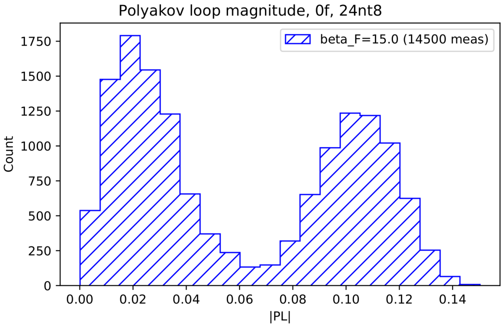


Try to avoid bulk transition for small N_T $\longrightarrow$ use $\beta_A = -\beta_F/4$

Still need $N_T > 4$ for clear separation between bulk & thermal transitions

Pure gauge checks: Order of thermal transition

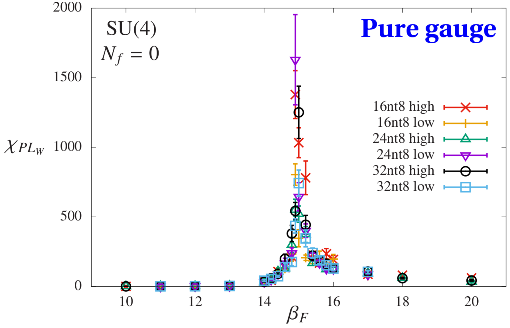


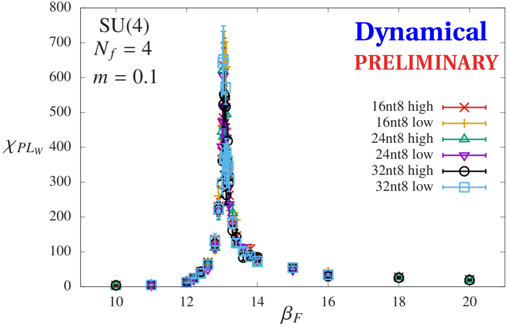


Two peaks in Polyakov loop magnitude histogram $\longrightarrow$ first-order transition ✓

Hysteresis not clearly visible even in pure-gauge case

Dynamical results: Still looks first order





Pure-gauge & dynamical susceptibilities show same behavior
$\longrightarrow$ evidence for first-order transition with $m \geq 0.1$

Fundamental fermions explicitly break Z_N $\longrightarrow$ don't see two peaks in histograms

What does $m \geq 0.1$ mean?

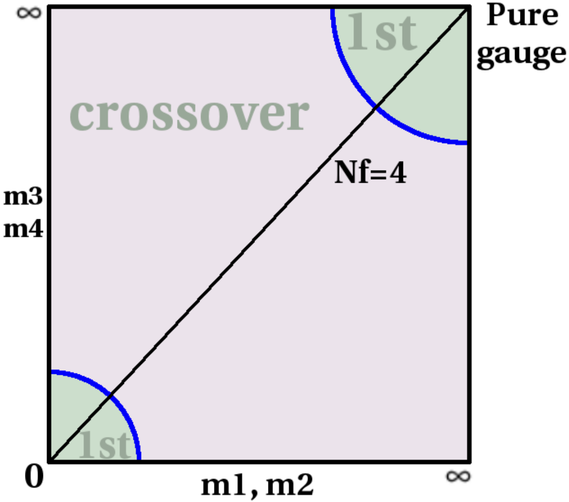
How heavy is sufficient for SU(4)?

Spectrum measurements

Zero-temp. $24^3 \times 48$ ensembles around each transition

$\longrightarrow M_P/M_V = 0.80(3)$ for $m = 0.1$

$\longrightarrow M_P/M_V = 0.91(1)$ for $m = 0.2$



Previous work considered $0.55 \leq M_P/M_V \leq 0.77$ ⟶ now adding $m = 0.05$

From first-order transition to gravitational wave signal

First-order transition $\longrightarrow$ gravitational wave background will be produced

How do we predict its features?

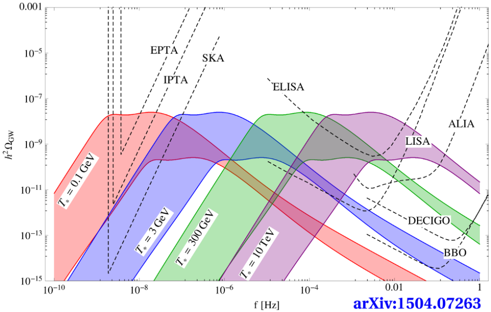
Four key parameters

Transition temperature $T_* \lesssim T_c$

Vacuum energy fraction from **latent heat**

Bubble nucleation rate (transition duration)

Bubble wall speed



arXiv:1504.07263

Next step: Latent heat $\Delta\epsilon$

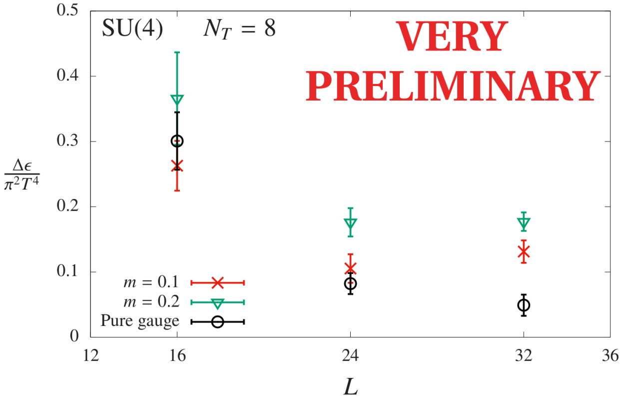
First-order transition $\longrightarrow$ gravitational wave background will be produced

How do we predict its features?

Vacuum energy fraction

$$\alpha \approx \frac{30}{4N(N^2-1)}\frac{\Delta\epsilon}{\pi^2 T_*^4}$$

Latent heat $\Delta\epsilon$ is change in energy density at transition

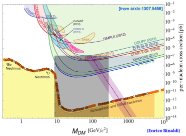


Recapitulation and outlook

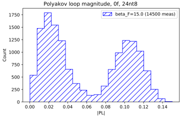
Stealth dark matter

Attractive and viable composite dark matter model

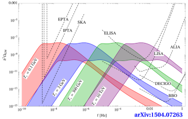
Exploring gravitational waves from first-order transition



Gravitational wave observatories will add to constraints
from collider searches and direct detection experiments



SU(4) confinement transition appears first order
for $M_P/M_V \gtrsim 0.8$, smaller masses underway



Next steps are latent heat, etc., for signal prediction

Thank you!

Lattice Strong Dynamics Collaboration

Especially Graham Kribs, Ethan Neil, Enrico Rinaldi

Funding and computing resources

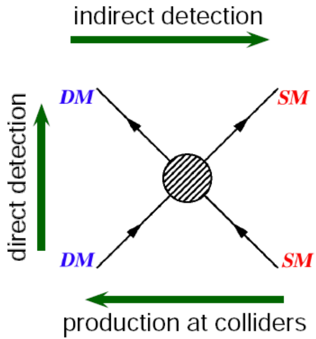
DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

UK Research
and Innovation

LIVERPOOL THEORETICAL PHYSICS

USQCD

Backup: Thermal freeze-out for relic density

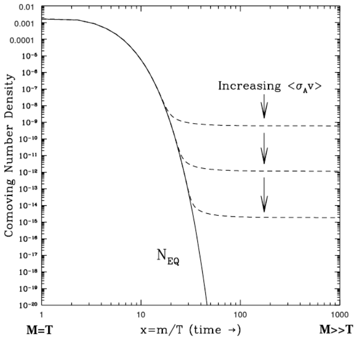


Requires non-gravitational
DM–SM interactions

DM $\longleftrightarrow$ SM for $T \gtrsim M_{DM}$

DM $\longrightarrow$ SM for $T \lesssim M_{DM}$
$\Longrightarrow$ rapid depletion of Ω_{DM}

Hubble expansion
$\Longrightarrow$ dilution $\longrightarrow$ freeze-out



$2 \to 2$ scattering relates coupling and mass, $200\alpha \sim \dfrac{M_{DM}}{100\text{ GeV}}$

Strong $\alpha \sim 16 \longrightarrow$ ‘natural’ $M_{DM} \sim 300$ TeV (smaller for $2 \to n$ scattering)

Backup: Two roads to natural asymmetric dark matter

Relate dark matter relic density to baryon asymmetry

$$\begin{aligned} \Omega_D &\approx 5\Omega_B \\ \implies M_D n_D &\approx 5 M_B n_B \end{aligned}$$

$n_D \sim n_B \quad \implies \quad M_D \sim 5M_B \approx 5\ \text{GeV}$

High-dim. interactions relate baryon# and DM# violation

$M_D \gg M_B \quad \implies \quad n_B \gg n_D \sim \exp\left[-M_D/T_s\right] \qquad T_s \sim 200\ \text{GeV}$

EW sphaleron processes above T_s distribute asymmetries

Both require non-gravitational interactions with known particles

Backup: Confirming thermal transition

Fix $m \cdot N_T \approx 0.8$ $\longrightarrow$ transition moves to $\beta_F \to \infty$ as $N_T \to \infty$ ✓