Argonne: Jin, Osborn
Bern: Gasbarro
Boston: Brower, Rebbi, Howarth
Nvidia: Weinberg
Colorado: Neil, Witzel

Liverpool: Schaich
LLNL: Vranas
UC Davis: Kiskis
Yale: Appelquist, Fleming, Cushman
Oregon: Kribs
RIKEN: ER
Preliminary results presented at Lattice 2019

Full results on arXiv and submitted to PRD
IMPROVE UNDERSTANDING OF DARK MATTER THEORIES

THE DARK MATTER THEORY LANDSCAPE

[picture by T. Tait]
THE DARK MATTER THEORY LANDSCAPE

IMPROVE UNDERSTANDING OF DARK MATTER THEORIES

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THE DARK MATTER THEORY LANDSCAPE

- mSUGRA
- R-parity Conserving
- NMSSM
- R-parity Violating
- Gravitino DM
- MSSM
- Extra Dimensions
- Little Higgs
- T -odd DM
- 5d
- 6d
- Axion-like Particles
- QCD Axions
- Axion DM
- Warm DM
- Sterile Neutrinos
- Light Force Carriers
- Asymmetric DM
- WIMPless DM
- Hidden Sector DM
- Self-Interacting DM
- Dark Photon
- Technibaryons
- Solitonic DM
- Quark Nuggets
- T -odd DM
- Techni
- baryons
- Dynamical DM
- WIMPless DM
- Self-Interacting DM
- Q-balls
- T Tait
- Little Higgs
- Axion-like Particles
- Littlest Higgs
- RS DM
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- Hidden Sector DM
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NEW FIFTH FORCE
COMPOSITE DARK SECTOR

[picture by T. Tait]
UNDERSTANDING COMPOSITE DARK SECTORS AND NEW PHYSICS

UNDERSTAND FIFTH FORCE TO GUIDE EXPERIMENTAL DISCOVERY
UNDERSTANDING COMPOSITE DARK SECTORS AND NEW PHYSICS

UNDERSTAND FIFTH FORCE TO GUIDE EXPERIMENTAL DISCOVERY

DARK PHASE TRANSITION GENERATING GRAVITATIONAL WAVES

LIGO (Nobel Prize 2017)
UNDERSTANDING COMPOSITE DARK SECTORS AND NEW PHYSICS

UNDERSTAND FIFTH FORCE TO GUIDE EXPERIMENTAL DISCOVERY

DARK SECTOR PARTICLES PRODUCED AT HIGH-ENERGY COLLIDERS

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DARK SECTOR PARTICLES PRODUCED AT HIGH-ENERGY COLLIDERS

DIRECT DETECTION THROUGH DARK AND NUCLEAR FORM FACTORS

DARK PHASE TRANSITION GENERATING GRAVITATIONAL WAVES

LIGO (Nobel Prize 2017)
EARLY UNIVERSE TRANSITIONS

QCD confinement-deconfinement
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crossover...maybe 1st order at finite density...
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Electroweak symmetry breaking
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too weak...maybe enhanced by non-perturbative effects

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EARLY UNIVERSE TRANSITIONS

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Electroweak symmetry breaking

Dark sector transition
**Early Universe Transitions**

- **QCD confinement-deconfinement**
  - Too weak...maybe enhanced by non-perturbative effects

- **Electroweak symmetry breaking**
  - Maybe strong 1st order if N is large...

- **Dark sector transition**
  - Crossover...maybe 1st order at finite density...
Dark sector gravitational wave signatures

Spectrum of GW from a deconfinement 1st order phase transition in the dark sector
Determined by 3 parameters:

- $\alpha \to$ relative energy density in the source (related to latent heat at the phase transition)
- $\beta \to$ bubble nucleation rate proportional to inverse time of the transition (related to tunneling probability between vacua)
- $\upsilon \to$ bubble velocity

Plus we need to know the temperature of the phase transition $T_* \approx T_c$
Phase Transitions in Strongly-coupled Theories

The diagram represents the phase structure of QCD, with the horizontal axis depicting the strange quark mass ($m_s$) and the vertical axis the light quark mass ($m_{u,d}$). The plot illustrates different phases, such as chiral 2nd order $Z(2)$, deconfined 2nd order $Z(2)$, and 1st order transitions. The diagram is labeled as the "Columbia" plot, referencing the contributions of Laermann, Philipsen, in Ann. Rev. Nucl. Part. Sci. 53 (2003) 163-198.
Phase Transitions in Strongly-coupled Theories

Phase Transitions in Strongly-coupled Theories

\[ a \cdot m \quad \{0.05, 0.1, 0.2, 0.4, \infty \} \]

\[ N_t \quad \{4, 6, 8, 12\} \]

\[ \alpha = \frac{L}{N_t} \quad \{2, 3, 4, 6, 8\} \]
### BUILDING BLOCKS FOR THE PHASE DIAGRAM

**SU(4)** with dynamical nHYP smeared staggered fermions

<table>
<thead>
<tr>
<th>$a \cdot m$</th>
<th>${0.05, 0.1, 0.2, 0.4, \infty}$</th>
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$SU(4)$ with dynamical nHYP smeared staggered fermions

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$N_t$

$\{4, 6, 8, 12\}$

$a \cdot m$

$\{0.05, 0.1, 0.2, 0.4, \infty\}$

Scan in $\beta_F$

$\sim 1370$ ensembles
\[ |PL_W| \quad \text{and} \quad \chi_O = L^3 (\langle O^2 \rangle - \langle O \rangle^2) \]

\[ R_E(t) = \left\langle \frac{E_{ss}(t)}{E_{s\tau}(t)} \right\rangle \quad \approx 1 \]

\[ f(\theta) = \frac{\pi/4}{\pi/4 - \theta} \left[ \frac{N_{\text{in}}}{N_{\text{tot}}} - \frac{\theta}{\pi/4} \right] \quad \rightarrow 0 \]

\[ \rightarrow 1 \]
Results: Pure-Gauge system $a \cdot m = \infty$

- Long autocorrelations
- Topological freezing
- high-low starts

Flow time: $t = N_t^2/32$
Results: Pure-Gauge system $a \cdot m = \infty$

- Long autocorrelations
- Topological freezing
- high-low starts

Bulk phase transition

Flow time: $t = N_t^2 / 32$
Results: Pure-Gauge system $N_t = 8$

- Peak of $\chi$ grows with volume
- Deconfinement fraction gets steeper
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Signs of 1st order transition
Results: Dynamical Fermions $N_f = 4$

- Difference from quenched
- Stronger couplings needed at smaller mass
- Susceptibility scales for $a \cdot m > 0.2$
- Two-peak histogram
- Still no continuum limit

SU(4) $32^3 \times 8$
Results: Dynamical Fermions $N_f = 4$

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\[ \frac{M_P}{M_V} = 0.96(1) \]
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\[
\frac{M_P}{M_V} = 0.65(3)
\]

\[7 \leq \frac{M_P}{T_c} \leq 10\]
Conclusions

◊ Composite Dark Matter provides interesting signals for dark matter searches at colliders and in direct detection experiments
◊ With a 1st order confinement-deconfinement transition, the dark sector can be discovered and constrained using gravitational waves
◊ Stealth Dark Matter is a SU(4) dark sector model with 4 heavy fermions
◊ Our lattice exploration of the phase diagram shows a thermal phase transition of 1st order at sufficiently high masses
◊ Using current bounds from experimental searches at colliders and our spectrum results we can provide a lower bound for the critical temperature

\[ T_c > 0.2 \text{ TeV} \]
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