University of Michigan & RIKEN (Theoretical Quantum Physics + iTHEMS)

ENRICO RINALDI

COMPOSITE DM & GW SIGNATURES
Argonne: Jin, Osborn
Bern: Gasbarro
Boston: Brower, Rebbi
Nvidia: Weinberg
Colorado: Neil, Hasenfratz
Siegen: Witzel

Liverpool: Schaich
LLNL: Vranas, Howarth
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
THE DARK MATTER THEORY LANDSCAPE

- MSSM
- NMSSM
- mSUGRA
- pMSSM
- R-parity conserving
- R-parity violating
- Gravitino DM
- Q-balls
- Dynamical DM
- RS DM
- UED DM
- Warped Extra Dimensions
- Extra Dimensions
- Supersymmetry
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- Axion DM
- Axion-like Particles
- QCD Axions
- Sterile Neutrinos
- Light Force Carriers
- Dark Photon

- Asymmetric DM
- Warm DM
- Hidden Sector DM
- Self-Interacting DM
- Techni- baryons

- Solitonic DM
- T-odd DM
- Solitonic DM

- Littlest Higgs
- Little Higgs
- Tait

- IMPROVE UNDERSTANDING OF DARK MATTER THEORIES

[picture by T. Tait]
THE DARK MATTER THEORY LANDSCAPE
IMPROVE UNDERSTANDING OF DARK MATTER THEORIES

THE DARK MATTER THEORY LANDSCAPE

[Diagram showing various dark matter theories and their relationships, including MSSM, Warm DM, Axion DM, QCD Axions, Little Higgs, etc.]

[picture by T. Tait]
IMPORVE UNDERSTANDING OF DARK MATTER THEORIES

THE DARK MATTER THEORY LANDSCAPE

[Diagram showing various dark matter candidates and interactions]

NEW FIFTH FORCE
COMPOSITE DARK SECTOR

[picture by T. Tait]
UNDERSTAND FIFTH FORCE TO GUIDE EXPERIMENTAL DISCOVERY
DETECTING COMPOSITE DARK SECTORS AND NEW PHYSICS: THE TRIAD

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DARK PHASE TRANSITION GENERATING GRAVITATIONAL WAVES
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DARK SECTOR PARTICLES PRODUCED AT HIGH-ENERGY COLLIDERS

DARK PHASE TRANSITION GENERATING GRAVITATIONAL WAVES

LIGO (Nobel Prize 2017)
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UNDERSTAND FIFTH FORCE TO GUIDE EXPERIMENTAL DISCOVERY

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)
Phase Transitions (PT) are everywhere in nature!

They can be *cosmological*
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Focus on 1\textsuperscript{st} order PTs: the universe changes from a metastable high energy (symmetric) phase to a stable lower energy (broken) phase.
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EARLY UNIVERSE TRANSITIONS
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QCD confinement-deconfinement
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QCD confinement-deconfinement crossover...maybe 1\textsuperscript{st} order at finite density...
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EARLY UNIVERSE TRANSITIONS

QCD confinement-deconfinement
too weak...maybe enhanced by non-perturbative effects
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Electroweak symmetry breaking
Early universe transitions

- QCD confinement-deconfinement
crossover...maybe 1st order at finite density...
- Electroweak symmetry breaking
- Dark sector transition
too weak...maybe enhanced by non-perturbative effects
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 1\textsuperscript{st} order phase transition in the dark sector

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[P. Schwaller, PRL (115) 181101, 2015]
Determined by 3 parameters:

- $\alpha \rightarrow$ relative energy density in the source (related to latent heat at the phase transition)

- $\beta \rightarrow$ bubble nucleation rate proportional to inverse time of the transition (related to tunneling probability between vacua)

- $u \rightarrow$ bubble velocity

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

“Columbia” plot
Phase Transitions in Strongly-coupled Theories


Stealth DM
Phase Transitions in Strongly-coupled Theories

BUILDING BLOCKS FOR THE PHASE DIAGRAM

SU(4) with dynamical nHYP smeared staggered fermions

\[
\alpha = \frac{L}{N_t} \quad \{2,3,4,6,8\}
\]

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

\[
a \cdot m \quad \{0.05,0.1,0.2,0.4,\infty\}
\]
BUILDING BLOCKS FOR THE PHASE DIAGRAM

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Scan in $\beta_F$

~ 1370 ensembles
LATTICE OBSERVABLES

\[ |PL_W| \]

\[ R_E(t) \]

\[ f(\theta) \]

and

\[ \chi_O = L^3 \left( \langle O^2 \rangle - \langle O \rangle^2 \right) \]

\[ \equiv \frac{\pi/4}{\pi/4 - \theta} \left[ \frac{N_{\text{in}}}{N_{\text{tot}}} - \frac{\theta}{\pi/4} \right] \]

\[ \approx 1 \]

\[ > 1 \]

\[ \rightarrow 0 \]

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

SU(4)

$N_f = 0$

$\alpha = 2$

$c = 0.5$

- 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

Flow time: $t = N_t^2/32$

Bulk phase transition
Results: Pure-Gauge system $N_t = 8$

- Peak of $\chi$ grows with volume
- Deconfinement fraction gets steeper
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Results: Pure-Gauge system $\mathcal{N}_f = 8$

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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
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Signs of 1st order transition
\[ \frac{M_P}{M_V} = 0.96(1) \]
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\]
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\frac{M_P}{M_V} = 0.65(3)
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\[
\frac{M_P}{M_V} = 0.65(3)
\]

\[7 \lesssim \frac{M_P}{T_c} \lesssim 10\]
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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\[ T_c > 0.2 \text{ TeV} \]
Backup Slides
“Stealth Dark Matter” model

- The field content of the model consists in **8 Weyl fermions**
- Dark fermions interact with the SM Higgs and obtain current/chiral masses
- Introduce **vector-like masses** for dark fermions that do not break EW symmetry
- Diagonalizing in the mass eigenbasis gives **4 Dirac fermions**
- Assume custodial SU(2) symmetry arising when \( u \leftrightarrow d \)

<table>
<thead>
<tr>
<th>Field</th>
<th>( \text{SU}(N)_D )</th>
<th>( \text{SU}(2)_L, Y )</th>
<th>( Q )</th>
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<td>( N )</td>
<td>( (2, 0) )</td>
<td>( +1/2 )</td>
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<td>( F_3^u )</td>
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<tr>
<td>( F_4^d )</td>
<td>( \bar{N} )</td>
<td>( (1, -1/2) )</td>
<td>( -1/2 )</td>
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</tbody>
</table>

\[
\mathcal{L} \supset + y_{14}^u \epsilon_{ij} F_1^i H^j F_1^d + y_{14}^d \epsilon_{ij} F_1^i H^j F_1^d \]
\[
- y_{23}^u \epsilon_{ij} F_2^i H^j F_2^d - y_{23}^d \epsilon_{ij} F_2^i H^j F_2^d + h.c.\]

\[
\mathcal{L} \supset M_{12}^{ij} F_1^i F_2^j - M_{34}^{ij} F_3^i F_4^j + M_{34}^{ij} F_3^i F_4^j + h.c.\]

\[
y_{14}^u = y_{14}^d \quad y_{23}^u = y_{23}^d \quad M_{34}^u = M_{34}^d\]
### Lattice results for Composite Dark Matter

<table>
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[references in Kribs & Neil, 1604.04627]
# Lattice results for Composite Dark Matter

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<td>SU(2) $N_f = 1$</td>
<td>![lattice]</td>
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<td>![estimate]</td>
<td>Forbidden in pNGB DM</td>
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<tr>
<td>SU(3) $N_f = 8$</td>
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<tr>
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<tr>
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References:
- [Francis, Hudspith, Lewis, Tulin 1809.09117](https://arxiv.org/abs/1809.09117)
- [Drach, et al. 1511.04370](https://arxiv.org/abs/1511.04370)