Composite dark matter and the role of lattice field theory

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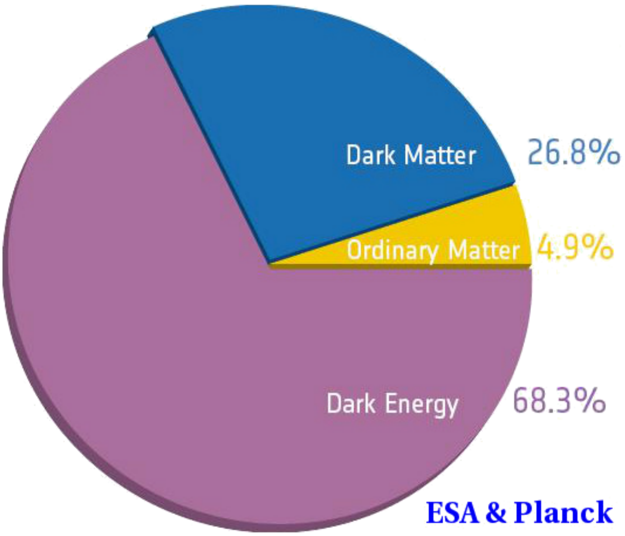
Stavanger Physics Seminar, 1 November 2018

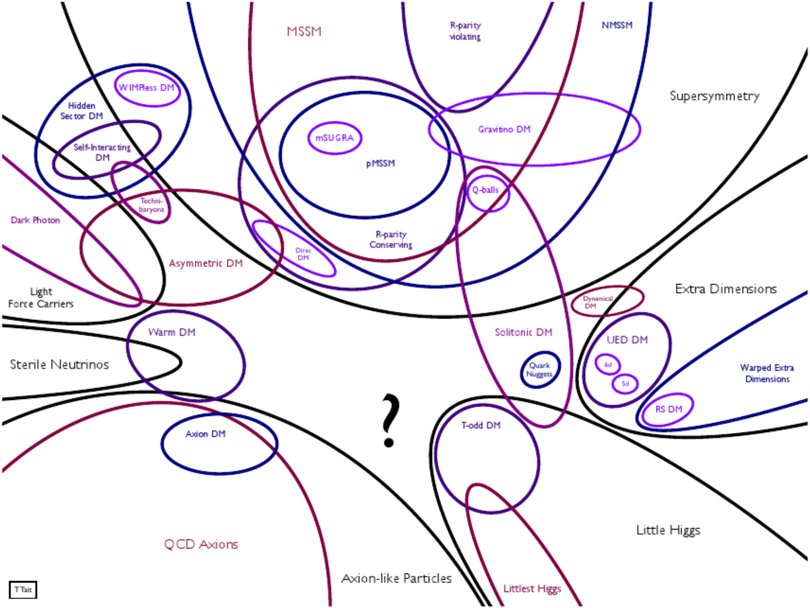
PRD **89**, 094508 PRL **115**, 171803 PRD **92**, 075030

and work in progress with the Lattice Strong Dynamics Collaboration

Dark matter — we observe it...



...we don't yet know what it is



Overview

Composite dark matter is an attractive possibility

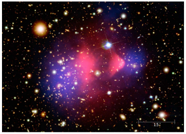
Lattice field theory is needed
to determine constraints from experiments

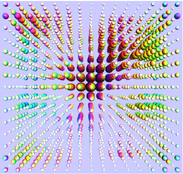
Dark matter & compositeness

Lattice field theory

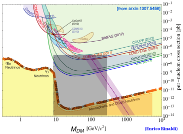
Experiments

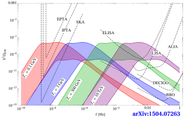
- Large underground detectors
- High-energy particle colliders
- Gravitational-wave observatories





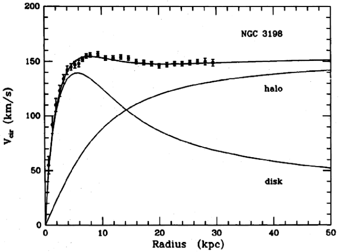
(Image credit: Claudio Rebbi)



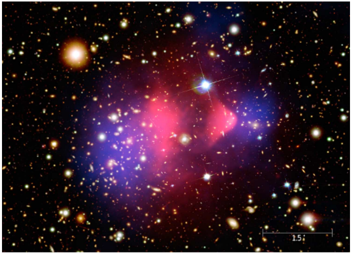


Gravitational evidence for dark matter

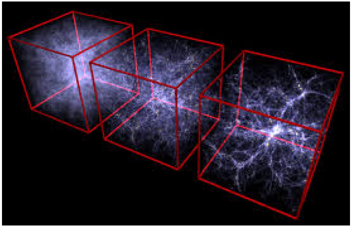
Rotation $\sim 10^3$–10^6 light-years



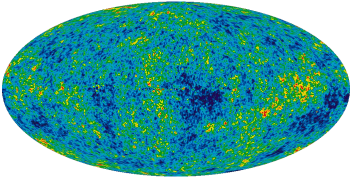
Lensing $\sim 10^6$ light-years



Structure $\sim 10^9$ light-years



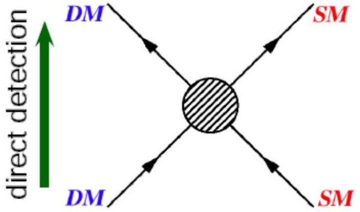
Cosmic background $\sim 10^{10}$ ly

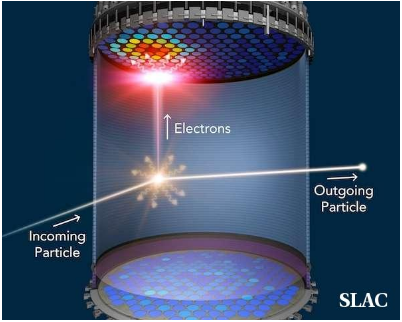


Non-gravitational dark matter interactions

Three search strategies

Direct scattering in underground detectors



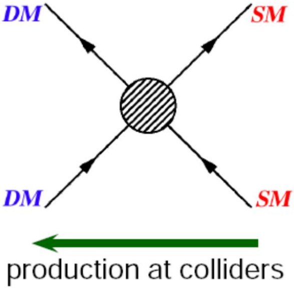


Non-gravitational dark matter interactions

Three search strategies

Direct scattering in underground detectors

Collider production at high energies



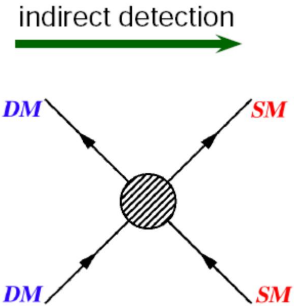
Non-gravitational dark matter interactions

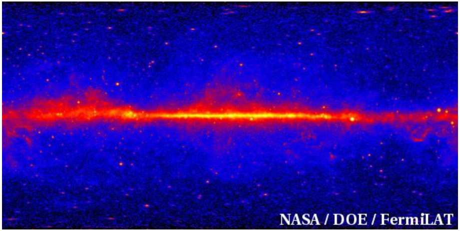
Three search strategies

Direct scattering in underground detectors

Collider production at high energies

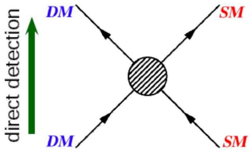
Indirect annihilation into cosmic rays

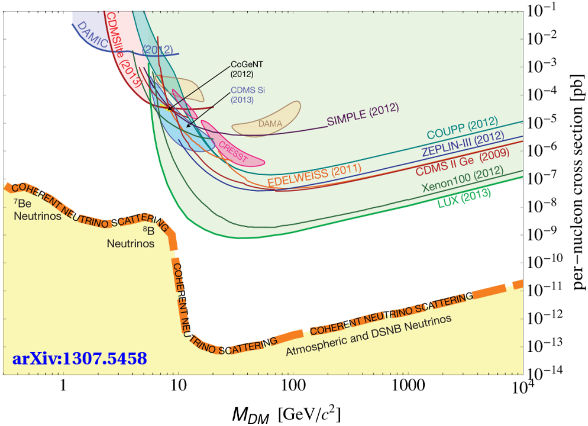




Non-gravitational dark matter interactions

No clear signals so far

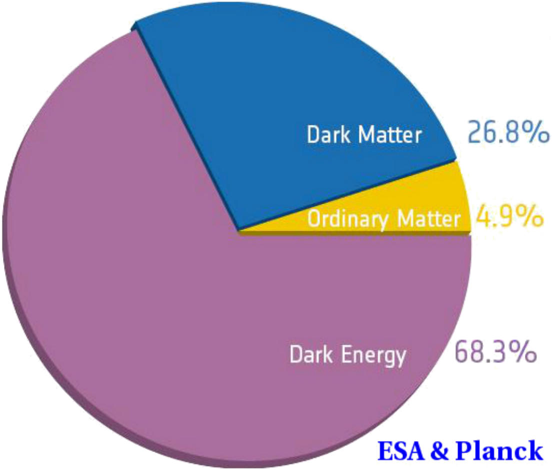




Why we expect non-gravitational interactions

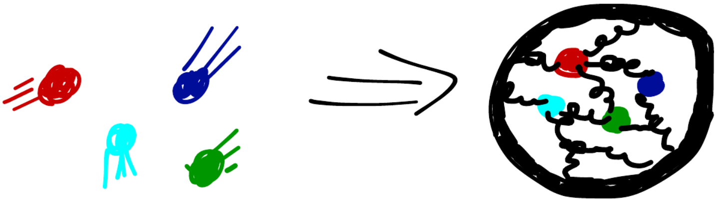
$$\frac{\Omega_{\text{dark}}}{\Omega_{\text{ordinary}}} \approx 5$$

$\ldots$ not 10^5 or 10^{-5}



Explained by non-gravitational interactions with known particles

Composite dark matter



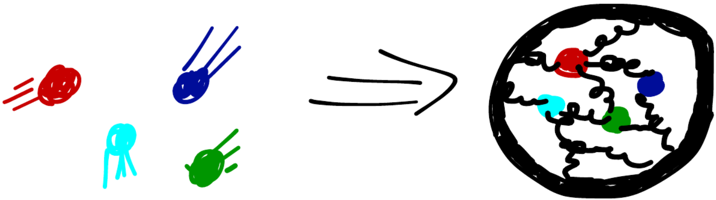
Early universe

Deconfined charged fermions $\longrightarrow$ non-gravitational interactions

Present day

Confined neutral ‘dark baryons’ $\longrightarrow$ no experimental detections

Composite dark matter

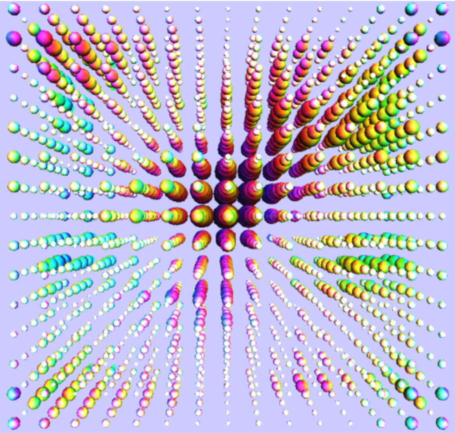


Even neutral composites interact, via charged constituents
$\longrightarrow$ need **lattice calculations** for quantitative predictions

Lattice field theory in a nutshell: QFT

Quantum **F**ield **T**heory = quantum mechanics + special relativity

Picture relativistic quantum fields filling four-dimensional space-time



(Image credit: Claudio Rebbi)

(Space and time on equal footing)

The QFT / StatMech Correspondence

Generating functional (Feynman path integral)	Partition function
$\mathcal{Z} = \int \mathcal{D}\Phi \;\; e^{-S[\Phi] \,/\, \hbar}$	$\int \mathcal{D}q \, \mathcal{D}p \;\; e^{-H(q,p) \,/\, k_B T}$
Action $S[\Phi] = \int d^4x \, \mathcal{L}[\Phi(x)]$	Hamiltonian H
$\hbar \longleftrightarrow$ quantum fluctuations (natural units: $\hbar = 1$)	$k_B T \longleftrightarrow$ thermal fluctuations

Lattice field theory in a nutshell: Discretization

Formally $\quad \langle\mathcal{O}\rangle = \frac{1}{\mathcal{Z}}\int\mathcal{D}\Phi\ \ \mathcal{O}(\Phi)\ \ e^{-S[\Phi]}$

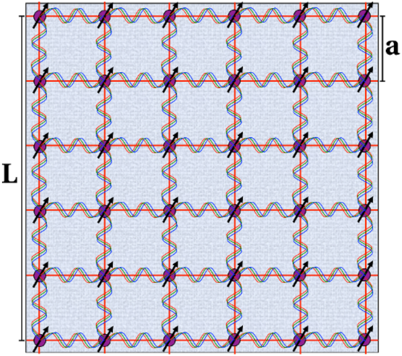
…but infinite-dimensional integrals in general intractable

Lattice field theory in a nutshell: Discretization

Formally $\langle \mathcal{O} \rangle = \frac{1}{\mathcal{Z}} \int \mathcal{D}\Phi \;\; \mathcal{O}(\Phi) \;\; e^{-S[\Phi]}$

. . . but infinite-dimensional integrals in general intractable

Formulate theory in finite, discrete space-time $\longrightarrow$ **the lattice**



P. Vranas LLNL

Spacing between lattice sites ("a")

$\longrightarrow$ UV cutoff scale $1/a$

Remove cutoff: $a \to 0 \quad (L/a \to \infty)$

Hypercubic $\longrightarrow$ automatic symmetries

Numerical lattice field theory calculations

High-performance computing

$\longrightarrow$ evaluate up to

$\sim$billion-dimensional integrals

Importance sampling Monte Carlo

Algorithms sample field configurations with probability $\frac{1}{\mathcal{Z}} e^{-S[\Phi]}$

$$\langle \mathcal{O} \rangle = \frac{1}{\mathcal{Z}} \int \mathcal{D}\Phi \;\; \mathcal{O}(\Phi) \;\; e^{-S[\Phi]}$$

$$\longrightarrow \quad \frac{1}{N} \sum_{i=1}^{N} \mathcal{O}(\Phi_i) \;\; \text{with statistical uncertainty} \;\; \propto \frac{1}{\sqrt{N}}$$

Lattice Strong Dynamics Collaboration

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

Exploring the range of possible phenomena
in strongly coupled field theories

Direct detection of composite dark matter

Charged constituents $\longrightarrow$ **form factors** $\longrightarrow$ experimental signals

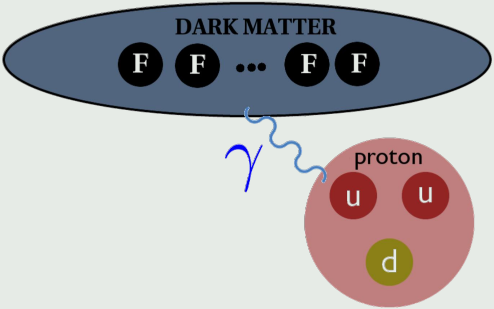
Photon exchange from electromagnetic form factors

Effective interactions suppressed by powers of dark matter mass

Magnetic moment $\sim \dfrac{1}{M_{DM}}$

Charge radius $\sim \dfrac{1}{M_{DM}^2}$

Polarizability $\sim \dfrac{1}{M_{DM}^3}$

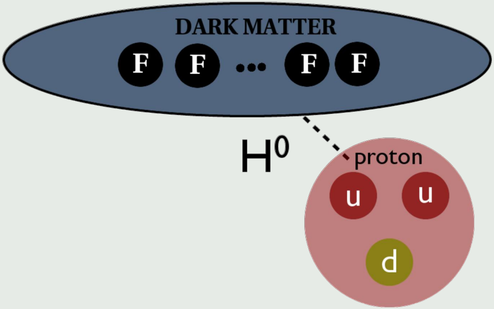


Direct detection of composite dark matter

Charged constituents $\longrightarrow$ **form factors** $\longrightarrow$ experimental signals

Higgs exchange from scalar form factor

Can dominate cross section... **if** F mass comes from Higgs



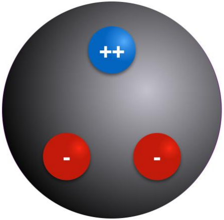
Direct detection of composite dark matter

Charged constituents $\longrightarrow$ **form factors** $\longrightarrow$ experimental signals

Simple first case

Dark matter like a "more-neutral neutron"

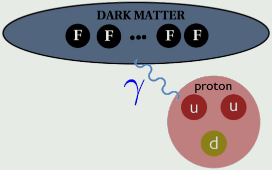
No Higgs-exchange interaction



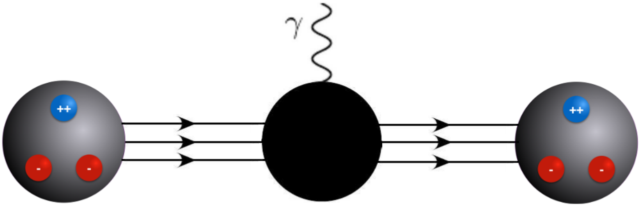
Investigate leading photon-exchange contributions

Magnetic moment $\sim \dfrac{1}{M_{DM}}$

Charge radius $\sim \dfrac{1}{M_{DM}^2}$



Magnetic moment and charge radius



Parameterization (with $q = p' - p$)

$$\left\langle DM(p') \left| \Gamma_\mu(q^2) \right| DM(p) \right\rangle \sim F_1(q^2)\, \gamma_\mu + F_2(q^2)\, \frac{i\sigma_{\mu\nu} q^\nu}{2M_{DM}}$$

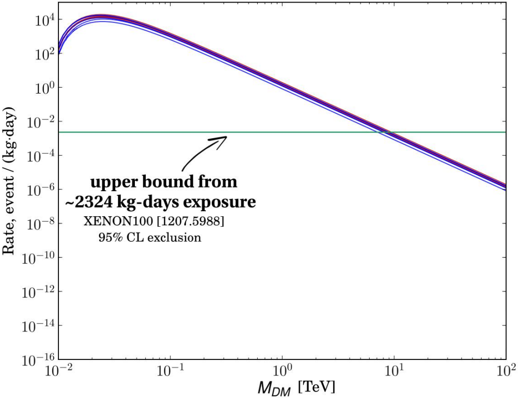
Electric charge: $F_1(0) = 0$

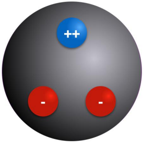
Magnetic moment: $F_2(0)$

Charge radius: $-6 \left. \frac{dF_1(q^2)}{dq^2} \right|_{q^2=0} + \frac{3F_2(0)}{2M_{DM}^2}$

Resulting direct detection constraints

Lattice calculations of magnetic moment and charge radius
$\longrightarrow$ event rate vs. dark matter mass





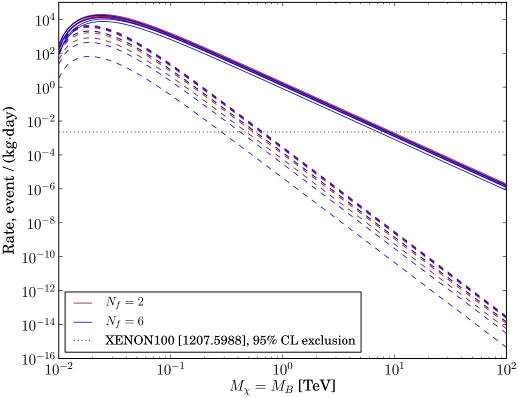
XENON100
requires $M_B \gtrsim 10$ TeV

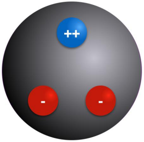
XENON1T [1805.12562]
$\longrightarrow M_B \gtrsim 30$ TeV

Little effect from varying model parameters

Magnetic moment dominates event rate

Charge radius contributions (dashed) are suppressed $\sim 1/M_{DM}^2$





Charge radius
$\longrightarrow \sim 20\times$ weaker bound
from XENON100

And tightening more slowly

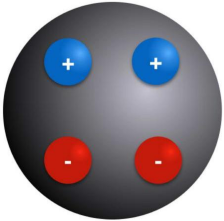
Symmetries can forbid both magnetic moment and charge radius

Stealth Dark Matter

Composite dark matter with four F

Scalar particle $\longrightarrow$ no magnetic moment ✓

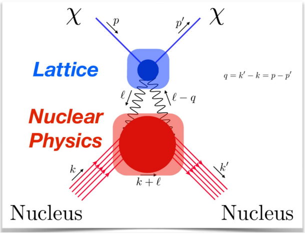
+/- charge symmetry $\longrightarrow$ no charge radius ✓



Higgs exchange present but can be tiny (helps in early universe)

Polarizability $\sim 1/M_{DM}^3$ dominates direct detection

$\longrightarrow$ unavoidable lower bound on broad class of composite dark matter



The meaning of stealth

Direct detection cross section (pb)

Neutrino

$\sigma \sim 10^{-2}$

Radar cross section (m^2)

747

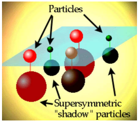
$\sigma \sim 10^{2}$

The meaning of stealth

Direct detection cross section (pb)

Neutrino

$\sigma \sim 10^{-2}$



SUSY neutralino

$10^{-6} \lesssim \sigma \lesssim 10^{-5}$

Radar cross section (m^2)

747

$\sigma \sim 10^2$

Falcon

$\sigma \sim 10^{-2}$

The meaning of stealth

Direct detection cross section (pb)

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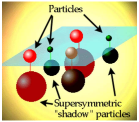

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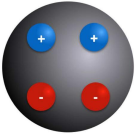


Stealth Dark Matter

$$\sigma \sim \left(\frac{200 \text{ GeV}}{M_{DM}}\right)^6 \times 10^{-9}$$

Radar cross section (m^2)

747

$\sigma \sim 10^2$

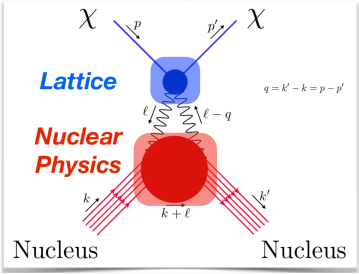
Falcon

$\sigma \sim 10^{-2}$

Stealth F-22

$\sigma < 10^{-3}$

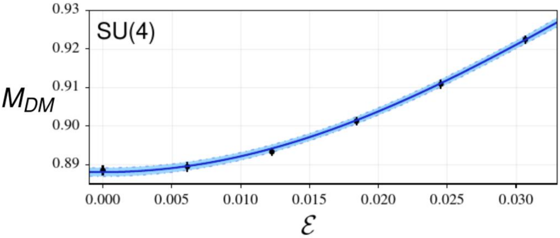
Polarizability of Stealth Dark Matter



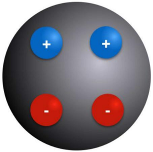
Unavoidable lower bound
on broad class of composite dark matter

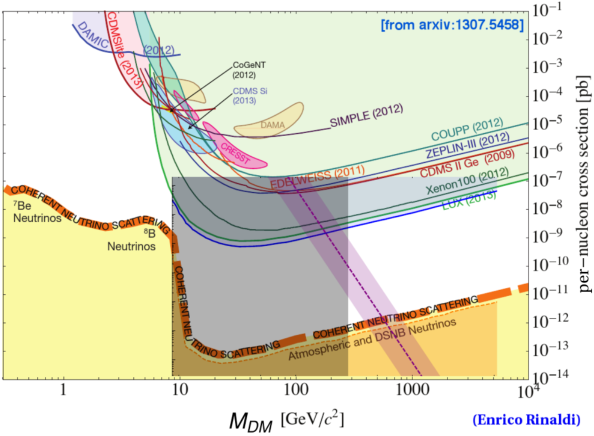
Nuclear physics very complicated
with large uncertanties

Polarizability is dependence of lattice M_{DM} on external field $\mathcal{E}$



Lower bound on direct detection





Results specific to Xenon detectors

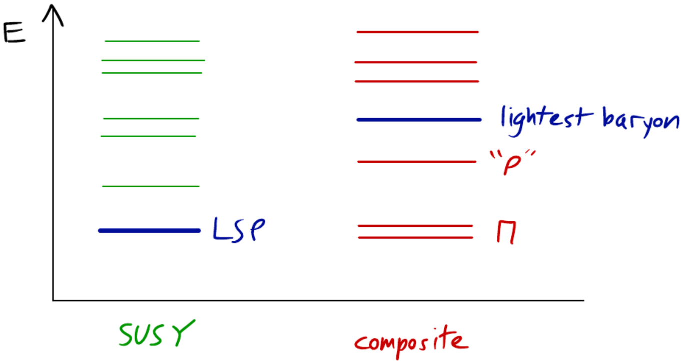
Uncertainty dominated by Xe nuclear physics

Shaded region is complementary constraint from particle colliders

Stealth Dark Matter at colliders

arXiv:1809.10184

The dark matter is the only stable composite particle, **not** the lightest



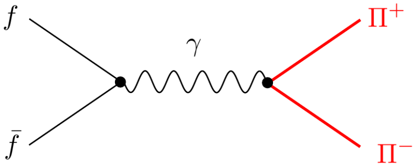
Main constraints from much lighter **charged** "Π"

$\longrightarrow$ standard 'missing energy' searches not efficient

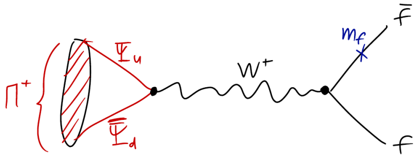
Stealth Dark Matter collider detection

arXiv:1809.10184

Production



Decay



"Particularly tricky" at the LHC

Current bounds only $M_\Pi \gtrsim 130$ GeV

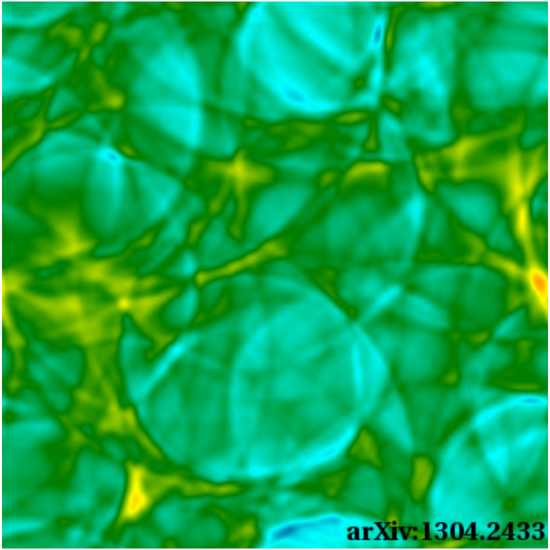
similar to $M_\Pi \gtrsim 100$ GeV from LEP searches for SUSY tau-partner

Lattice calculation of $M_{DM}/M_\Pi \longrightarrow M_{DM} \gtrsim 300$ GeV

More form factors to compute: $F_1(4M_\Pi^2)$ for Π and decay constant F_Π

Gravitational waves

Gravitational-wave observatories opening new window on cosmology



First-order dark transition
$\longrightarrow$ colliding bubbles
$\longrightarrow$ gravitational waves

Work in progress

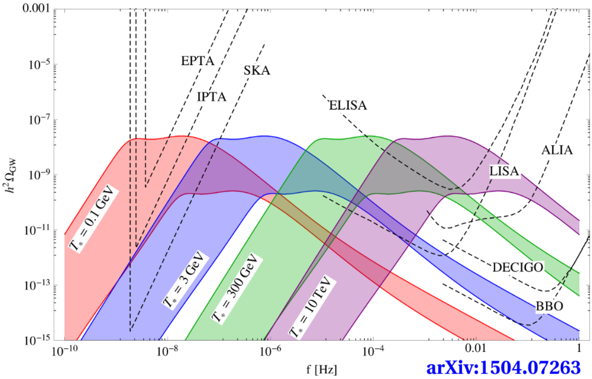
Transition properties
for Stealth Dark Matter

Signals and sensitivities

Bubbles $\longrightarrow$ longer-lasting acoustic waves,
possible magnetohydrodynamic turbulence at later times

Produce stochastic background at low frequencies

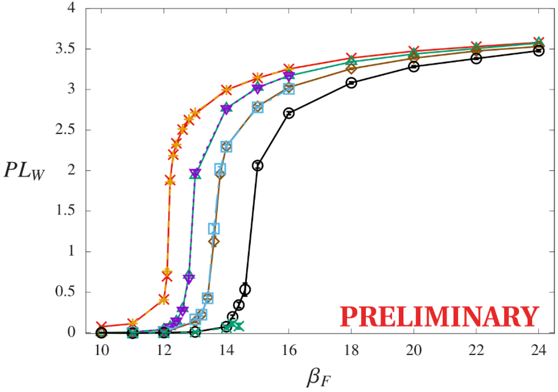
$\longrightarrow$ space-based observatories



First steps underway

First-order transitions for large and small masses, crossover between

Find range of masses with first-order transition, measure temperature



If mass satisfactory, measure latent heat & bubble nucleation rate

Recapitulation and outlook

Composite dark matter is an attractive possibility

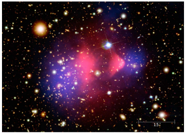
Lattice field theory is needed
to determine constraints from experiments

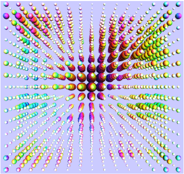
Minimize EM form factors for direct detection
$\longrightarrow$ Stealth Dark Matter

Collider constraints on dark sector

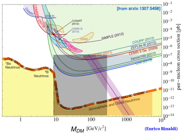
Future searches for gravitational waves

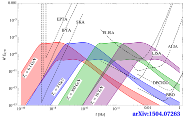
And more: relic abundance; indirect detection; ...





(Image credit: Claudio Rebbi)





Thank you!

Lattice Strong Dynamics Collaboration

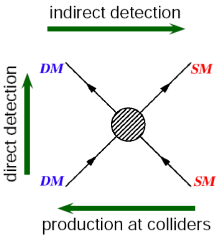
Especially Graham Kribs, Ethan Neil, Enrico Rinaldi

Funding and computing resources

USQCD

Backup: Thermal freeze-out for relic density

Requires non-gravitational interactions with known particles



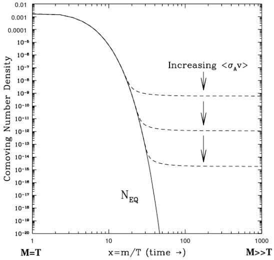
DM $\longleftrightarrow$ SM for $T \gtrsim M_{DM}$

DM $\longrightarrow$ SM for $T \lesssim M_{DM}$

$\Longrightarrow$ rapid depletion of Ω_{DM}

Hubble expansion

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



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

Strong $\alpha \sim 16 \longrightarrow$ 'natural' mass scale $M_{DM} \sim 300$ TeV

Smaller $M_{DM} \gtrsim 1$ TeV possible from $2 \rightarrow n$ scattering or asymmetry

Backup: Two roads to natural asymmetric dark matter

Idea: Dark matter relic density related to baryon asymmetry

$$\Omega_D \approx 5\Omega_B$$
$$\Longrightarrow M_D n_D \approx 5 M_B n_B$$

$n_D \sim n_B \quad \Longrightarrow \quad M_D \sim 5M_B \approx 5$ GeV

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

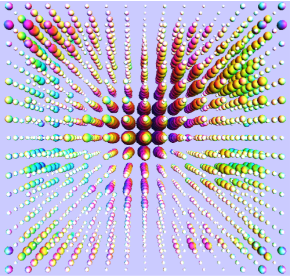
$M_D \gg M_B \quad \Longrightarrow \quad n_B \gg n_D \sim \exp\left[-M_D/T_s\right] \qquad T_s \sim 200$ GeV

EW sphaleron processes above T_s distribute asymmetries

Both require non-gravitational interactions with known particles

Backup: Hybrid Monte Carlo (HMC) algorithm

Goal: Sample field configurations Φ with probability $\frac{1}{\mathcal{Z}} e^{-S[\Phi]}$



(Image credit: Claudio Rebbi)

HMC is Markov process based on Metropolis–Rosenbluth–Teller

Fermions $\longrightarrow$ extensive action computation

$\Longrightarrow$ Global updates using fictitious molecular dynamics

1. Introduce fictitious random momenta and “MD time” τ
2. Inexact MD evolution along trajectory in τ $\longrightarrow$ new configuration
3. Accept/reject test on MD discretization error

Backup: More details about form factors

Photon exchange via electromagnetic form factors

Interactions suppressed by powers of confinement scale $\Lambda \sim M_{DM}$

Dimension 5: Magnetic moment $\longrightarrow$ $\left(\overline{X}\sigma_{\mu\nu}X\right) F^{\mu\nu}/\Lambda$

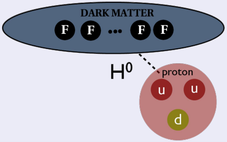
Dimension 6: Charge radius $\longrightarrow$ $\left(\overline{X}X\right) v_\mu \partial_\nu F^{\mu\nu}/\Lambda^2$

Dimension 7: Polarizability $\longrightarrow$ $\left(\overline{X}X\right) v_\mu v_\nu F^{\mu\alpha} F_\alpha^{\ \nu}/\Lambda^3$

Higgs exchange via scalar form factors

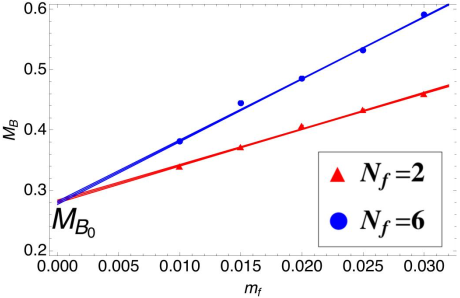
Higgs couples through σ terms $\left\langle B \left| m_\psi \overline{\psi}\psi \right| B \right\rangle$

$\longrightarrow$ Rapid charged 'Π' decay
needed for Big Bang nucleosynthesis



Non-perturbative form factors $\Longrightarrow$ lattice calculations

Backup: Three-fermion composite dark matter



Simple first case

Re-analyze existing lattices

SU(3) gauge group (like QCD)

Scan relatively heavy fermion masses $m_F \longrightarrow 0.55 \lesssim M_\Pi / M_V \lesssim 0.75$

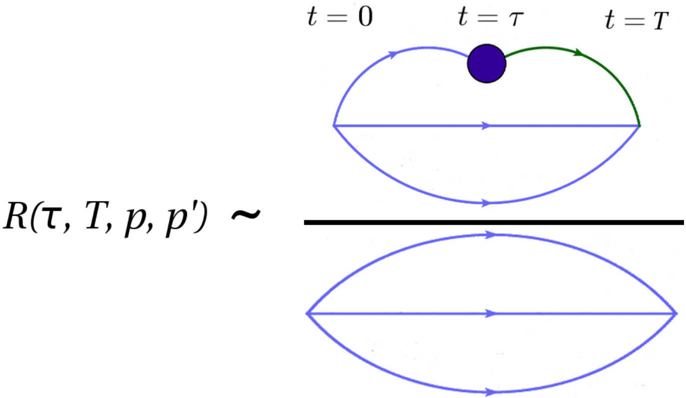
Compare $N_F = 2$ or 6 degenerate flavors with same $M_{B_0} \equiv \lim_{m_F \to 0} M_B$

Unlike QCD, fermions are all SU(2)$_L$ singlets $\longrightarrow Q = Y$

Half have $Q_{\text{P}} = 2/3$, half $Q_{\text{M}} = -1/3$

Dark matter candidate is singlet "dark baryon" $B = \text{PMM}$

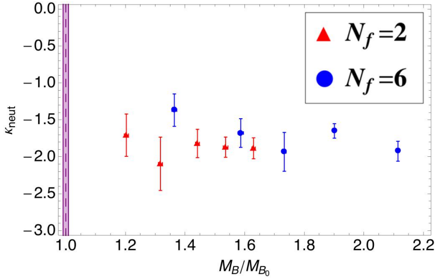
Backup: Form factor calculations on the lattice



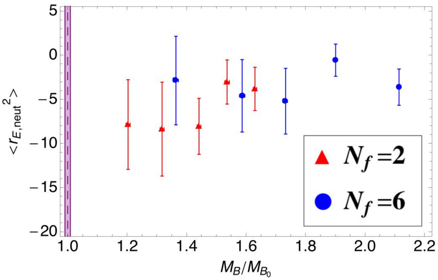
$$R_\Gamma\left(\tau, T, p, p'\right) \longrightarrow \left\langle DM(p') \middle| \Gamma_\mu(q^2) \middle| DM(p) \right\rangle + \mathcal{O}\left(e^{-\Delta\tau}\right) + \mathcal{O}\left(e^{-\Delta T}\right) + \mathcal{O}\left(e^{-\Delta(T-\tau)}\right)$$

Backup: Electromagnetic form factor results

Magnetic moment κ



Charge radius $\langle r^2 \rangle$



Little dependence on N_F or on $m_F \sim M_B/M_{B_0}$

κ comparable to neutron's $\kappa_N = -1.91$

$\langle r^2 \rangle$ smaller than neutron's $\langle r^2 \rangle_N \approx -38$ (related to larger M_Π/M_V)

Insert into standard event rate formulas…

Backup: Event rate formulas and lattice input

$$\text{Rate} = \frac{M_{detector}}{M_T}\frac{\rho_{DM}}{M_{DM}}\int_{E_{min}}^{E_{max}} dE_R\, \mathcal{A}cc(E_R)\,\left\langle v_{DM}\frac{d\sigma}{dE_R}\right\rangle_f$$

$$\frac{d\sigma}{dE_R} = \frac{\overline{|\mathcal{M}_{SI}|^2} + \overline{|\mathcal{M}_{SD}|^2}}{16\pi\,(M_{DM}+M_T)^2\,E_R^{max}} \qquad E_R^{max} = \frac{2M_{DM}^2 M_T v_{col}^2}{(M_{DM}+M_T)^2}$$

From **magnetic moment** κ and **charge radius** $\langle r^2\rangle$

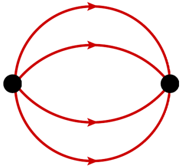
$$\frac{\overline{|\mathcal{M}_{SI}|^2}}{e^4\,[ZF_c(Q)]^2} = \left(\frac{M_T}{M_{DM}}\right)^2\left[\frac{4}{9}M_{DM}^4\left\langle r^2\right\rangle^2 + \frac{\kappa^2\,(M_T+M_{DM})^2\,(E_R^{max}-E_R)}{M_T^2 E_R}\right]$$

$$\overline{|\mathcal{M}_{SD}|^2} = e^4\frac{2}{3}\left(\frac{J+1}{J}\right)\left[\left(A\frac{\mu_T}{\mu_n}\right)F_s(Q)\right]^2\kappa^2$$

From **polarizability** C_F

$$\sigma_{SI} = \frac{Z^4}{A^2}\frac{144\pi\alpha_{em}^4\widetilde{M}_{n,DM}^2}{M_{DM}^6 R^2}C_F^2 \propto \frac{Z^4}{A^2} \quad \text{per nucleon}$$

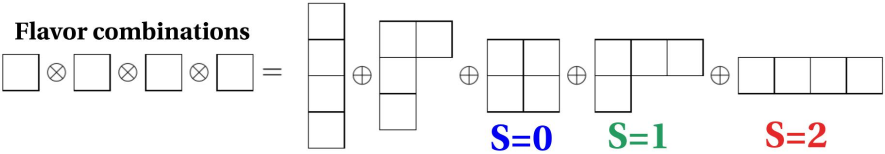
Backup: Four-fermion composite dark matter



Quenched SU(4) lattice ensembles

Lattice volumes up to $64^3 \times 128$,
several lattice spacings to check systematic effects

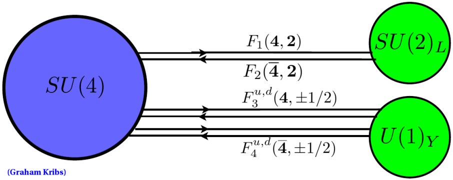
Relatively heavy fermions $\longrightarrow$ $0.55 \lesssim M_\Pi / M_V \lesssim 0.77$



Dark matter candidate is spin-zero baryon $\longrightarrow$ no magnetic moment

Need at least two flavors to anti-symmetrize
Custodial SU(2) global symmetry $\longrightarrow$ no charge radius

Backup: Stealth Dark Matter model details



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

Mass terms $m_V (F_1 F_2 + F_3 F_4) + y \left(F_1 \cdot H F_4 + F_2 \cdot H^\dagger F_3\right) + \text{h.c.}$

Vector-like masses evade Higgs-exchange direct detection bounds

Higgs couplings $\rightarrow$ charged meson decay before Big Bang nucleosyn.

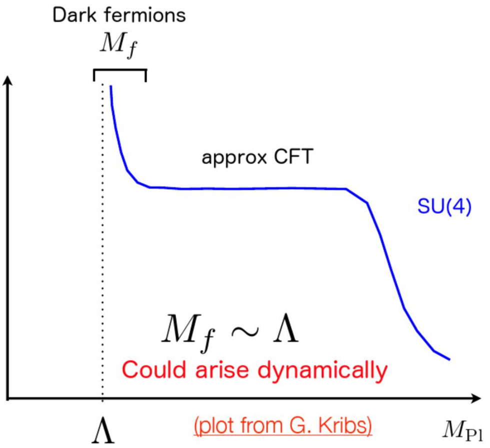
Both required

Backup: Stealth Dark Matter mass scales

Lattice studies focus on $m_\psi \simeq \Lambda_{DM}$ (effective theories least reliable)

$m_\psi \simeq \Lambda_{DM}$
could arise dynamically

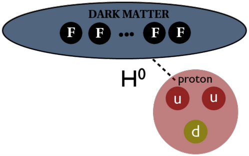
Smaller $m_\psi \longrightarrow$ stronger
collider constraints



Backup: Effective Higgs interaction

$M_H = 125$ GeV $\longrightarrow$ Higgs exchange can dominate direct detection

$$\sigma_H \propto \left| \frac{\widetilde{M}_{DM,N}}{M_H^2} \; y_\psi \left\langle DM \left| \overline{\psi}\psi \right| DM \right\rangle \; y_q \left\langle N \left| \overline{q}q \right| N \right\rangle \right|^2$$



Quark $y_q = \dfrac{m_q}{v}$

Dark $y_\psi = \alpha \dfrac{m_\psi}{v}$ suppressed by $\alpha \equiv \dfrac{v}{m_\psi} \left. \dfrac{\partial m_\psi(h)}{\partial h} \right|_{h=v} = \dfrac{yv}{yv + m_V}$

Can determine scalar form factors using Feynman–Hellmann theorem

$$\left\langle DM \left| \overline{\psi}\psi \right| DM \right\rangle = \frac{\partial M_{DM}}{\partial m_\psi}$$

Backup: Feynman–Hellmann theorem

$m_\psi \overline{\psi}\psi$ is the only term in the hamiltonian that depends on m_ψ

$$\Longrightarrow \left\langle B \left| \frac{\partial \widehat{H}}{\partial m_\psi} \right| B \right\rangle = \left\langle B \left| \overline{\psi}\psi \right| B \right\rangle$$

Since $\widehat{H} \left| B \right\rangle = M_B \left| B \right\rangle$ and $\left\langle B \right| \widehat{H} = \left\langle B \right| M_B$ we have

$$\begin{aligned}
\frac{\partial}{\partial m_\psi} M_B &= \frac{\partial}{\partial m_\psi} \left\langle B \left| \widehat{H} \right| B \right\rangle \\
&= \left\langle \frac{\partial B}{\partial m_\psi} \left| \widehat{H} \right| B \right\rangle + \left\langle B \left| \widehat{H} \right| \frac{\partial B}{\partial m_\psi} \right\rangle + \left\langle B \left| \frac{\partial \widehat{H}}{\partial m_\psi} \right| B \right\rangle \\
&= M_B \langle \frac{\partial B}{\partial m_\psi} | B \rangle + M_B \langle B | \frac{\partial B}{\partial m_\psi} \rangle + \left\langle B \left| \overline{\psi}\psi \right| B \right\rangle \\
&= M_B \frac{\partial}{\partial m_\psi} \langle B | B \rangle + \left\langle B \left| \overline{\psi}\psi \right| B \right\rangle = \left\langle B \left| \overline{\psi}\psi \right| B \right\rangle \qquad \square
\end{aligned}$$

Backup: Lattice results for Higgs exchange

$$\sigma_H^{(SI)} \propto \left| y_\psi \left\langle B \left| \overline{\psi}\psi \right| B \right\rangle \right|^2$$

Matrix element $\propto \dfrac{\partial M_{DM}}{\partial m_\psi}$

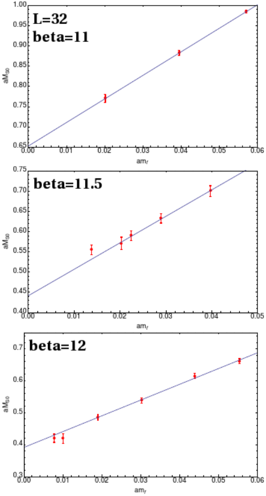
(Feynman–Hellmann)

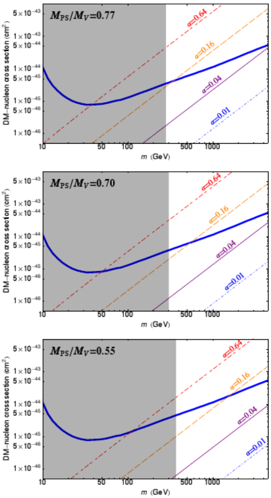
Stealth Dark Matter:

$$0.15 \lesssim \frac{m_\psi}{M_{DM}} \frac{\partial M_{DM}}{\partial m_\psi} \lesssim 0.34$$

Larger than QCD

$$0.04 \lesssim \frac{m_q}{M_N} \frac{\partial M_N}{\partial m_q} \lesssim 0.08$$

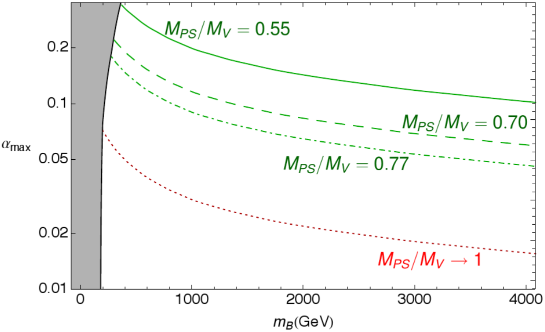




$\longrightarrow$ Maximum α allowed by LUX [arXiv:1310.8214]

Backup: Bounds on effective Higgs coupling

Higgs-exchange cross section
$\longrightarrow$ maximum α allowed by LUX [arXiv:1310.8214]



Maximum α
depends on M_Π/M_V
and dark matter mass

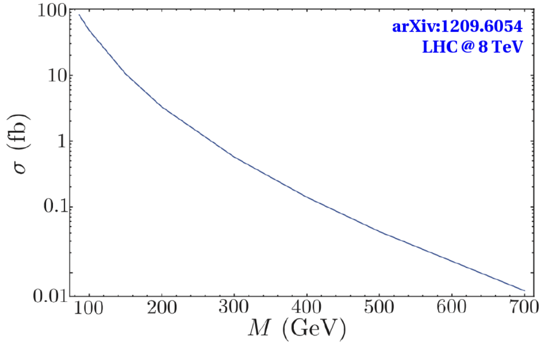
Smaller $M_\Pi/M_V \longleftrightarrow m_F$
$\longrightarrow$ stronger constraints
from colliders

Effective Higgs interaction tightly constrained,
$\alpha \lesssim 0.3 \longrightarrow$ fermion masses must be mainly vector-like

Backup: Stealth Dark Matter at the LHC

Π pair production cross section

Integrate over proton parton distributions, set $F_1(4M_\Pi^2) = 1$



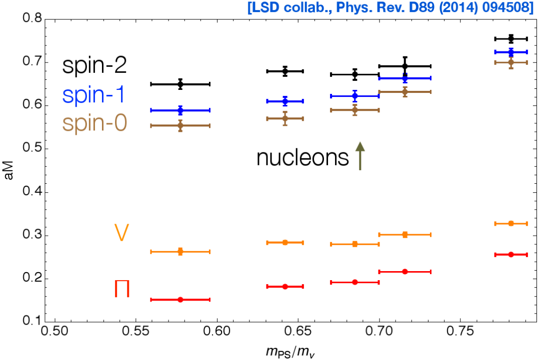
LHC can search for $\Pi^+\Pi^- \longrightarrow t\bar{b} + \bar{t}b$ in addition to $\tau^+\tau^- + \not{E}_T$

Should eventually surpass $M_\Pi \gtrsim 100$ GeV from LEP

Backup: Indirect detection

Lattice results for composite mass spectrum

Predict γ-rays from splitting between baryons with spin $S = 0$, 1 and 2

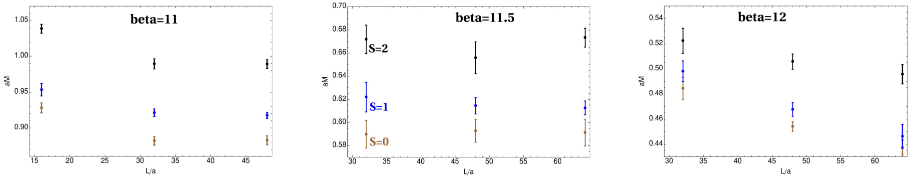


Much more challenging future work

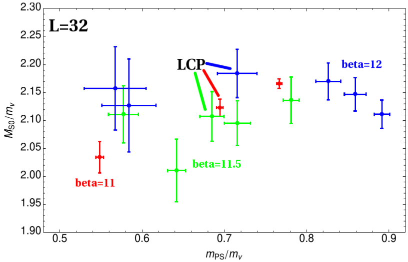
DM–$\overline{\text{DM}}$ annihilation into (many) lighter Π that then decay

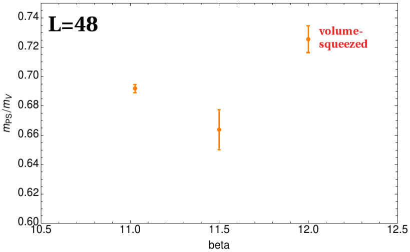
Backup: Volume and discretization effects

Baryon masses vs. L at fixed coupling β and fermion mass



Edinburgh-style plot of $\frac{M_{S0}}{M_V}$ vs. $\frac{M_\Pi}{M_V}$ and line of constant physics (LCP):





Backup: Volume and discretization effects

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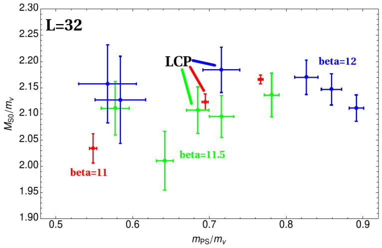
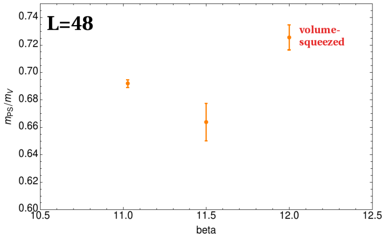
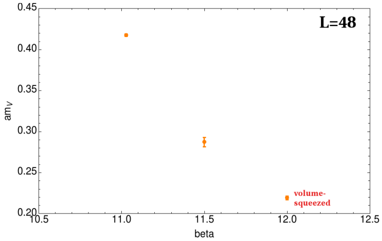
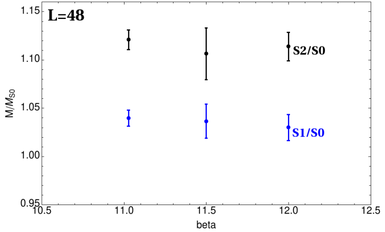




Lattice spacing and discretization effects for $\frac{M_{S2,S1}}{M_{S0}}$ on LCP:





Backup: Large-N predictions for SU(4) baryons

Tune (β, m_F) to match SU(3) $\{M_\Pi, M_V\}$ (dashed)

Rotor spectrum for spin-J large-N baryons:

$$M(N,J) = NM_0 + C + B\frac{J(J+1)}{N} + \mathcal{O}\left(\frac{1}{N^2}\right)$$

Fit M_0, C and B with nucleon, Δ and spin-0 baryon masses

$\longrightarrow$ predictions for $S = 1, 2$ baryons (diamonds)