WIMPless Dark Matter: Models and Signatures

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The WIMP miracle

- non-relativistic thermal dark matter → solve Boltzmann eq.
  - \( \rho \propto \langle \sigma_A v \rangle^{-1} \) (Zeldovich; Lee, Weinberg; Scherrer, Turner; Kolb, Turner)
  - \( \langle \sigma_A v \rangle \) basically determines \( \rho \)
- to get observed DM density need \( \langle \sigma_A v \rangle \sim 1 \text{ pb} \)

- stable matter with coupling and mass of the electroweak theory would have about right relic density for dark matter
  - WIMP miracle

- one of the best theoretical ideas for dark matter

- guide for most experimental searches

- but is this miracle really a WIMP miracle?
**WIMPless** dark matter setup

- extension of standard “low-energy SUSY” setup (GMSB)
- one SUSY-breaking sector mediated to multiple sectors
  - \( m_{\text{soft}} \propto g^2 (F/M) \)
  - but \( \langle \sigma v \rangle \propto g^4/m^2 \)
  - so for stable particle at SUSY-breaking scale, \( \rho \propto (F/M)^2 \)
  - depends only on SUSY-breaking spurion
- DM candidate in hidden sector
  - assume symmetry stabilizes a particle at soft scale
  - soft scale can be anything, but relic density is universal
  - WIMP Miracle \( \rightarrow \) it’s also right!
  - WIMPLess Miracle

\[
W = \lambda S \bar{\Phi} \Phi + \lambda_x S \bar{\Phi}_x \Phi_x
\]

\[
\langle S \rangle = M + \theta^2 F
\]
WIMPless Miracle

• a new, well-motivated scenario for dark matter (scalar or fermion)

• natural dark matter candidates with approximately correct mass density

• unlike “WIMP miracle” scenario, here dark matter candidate can have a range of masses and couplings

• opens up the window for observational tests, beyond standard WIMP range

• implications for collider, direct and indirect detection strategies
Yukawa coupling to SM

- if no connection between SM and hidden sector…
  - only gravitational effects
Yukawa coupling to SM

- if no connection between SM and hidden sector…
  - only gravitational effects
- but could have connectors between those sectors
  - exotics ($Y$) charged under both SM and hidden sector
  - exotic 4th generation multiplet
- Yukawa couplings between dark matter, SM matter and exotic connectors
  - get nuclear scattering through light or heavy (loop) quarks
  - annihilation to SM matter

\[ W = \lambda X Y_L f_L + \lambda X Y_R f_R + m Y_L Y_R \]
New WIMPless signal features....

- **scalar** WIMPless DM
  - can have **larger** $\sigma_{SI}$ than expected for neutralinos
  - for $\sigma_{SI}$, need to couple to $f^\dagger_L f_R$
    - need light quark mass or squark mixing insertion
    - chirality suppression
  - with scalar DM, chirality flip from $m_Y$
    - not suppressed

- **Majorana fermion** WIMPless DM
  - for Majorana fermion DM, $\sigma_{SI}=0$, but $\sigma_{SD}$ is non-zero
  - most models will be seen first through $\sigma_{SI}$, $\sigma_{SD}$ can confirm
  - **Majorana fermion** WIMPless DM is only found through $\sigma_{SD}$
Novel detection prospects....

- **direct detection**
  - DAMA can (?) be matched with low-mass particle with $\sigma_{SI} \sim 10^{-2.5}$ pb
  - CoGeNT has a signal which can fit similar region
    - we’ll leave aside the controversy (XENON, CDMS, etc.)
  - hard to fit with neutralino models ($\sigma_{SI}$ suppressed, mass larger)
  - WIMPless DM scalar fits the bill

- **indirect detection** (neutrino)
  - excel at low mass (Super-K) and $\sigma_{SD}$ (IceCube)
  - Super-K can make model-independent check of DAMA/CoGeNT (soon!)
  - may get signals at IceCube/DeepCore from $\sigma_{SD}$ of Majorana DM

- **Tevatron/LHC**
  - can produce YY pairs through QCD processes
  - missing $E_T +$ jets signal
  - results with short-term data (including most of DAMA/CoGeNT)
Low-mass WIMPless scalar DM….

- assume hierarchical Yukawa coupling
  - DM couples to 3rd generation quarks only
  - simple FCNC solution
  - nuclear scattering through $b$-quark loop (couples to gluons)
  - can fit near global region (Collar, Hall, Hooper, McKinsey)
    - $\lambda_b \sim 0.8$, $m_X \sim 6-7$ GeV, $m_Y \sim 400$ GeV
    - “natural” Yukawa value
- how can this be checked?
  - preferably, with present or near-term data
Super-K detection prospects....

- DM captured by sun through elastic scattering
  - annihilates to SM $\rightarrow \nu_{\mu}$
  - event rate controlled by solar capture rate
    - depends on $\sigma_{XN}$
- Super-K advantage
  - sensitive to low energy $\nu$
    - better for low-mass DM
- upshot $\rightarrow$ can be tested with data already taken
  - need analysis of fully-contained muon sample to extend below $m_X \sim 10$ GeV

Projected Super-K bounds using fully-contained events and 3000 live days, plus WIMPless ($0.3<\lambda_b<1.0$) and neutralino (Bottino, et al) predictions
Collider searches for $Y=T'$

- $pp \rightarrow T'T'$ controlled by QCD
  - $300 \text{ GeV} < m_{T'} < 600 \text{ GeV}$
    (perturbativity, precision EW, direct search)
- $T' \rightarrow X t \rightarrow X + \text{jets}$ required by hidden sector charge
  - $X \rightarrow \text{missing } E_T$
  - more distinctive than standard $4^{\text{th}}$ generation search

- upshot (via MadGraph, MadEvent, Pythia 6.4.20, PGS4)
  - good prospects with Tevatron
  - definitely will find with early LHC data
Majorana fermion WIMPless DM....
(not targeting low mass)

- IceCube/DeepCore will soon have the best bounds on $\sigma_{SD}$
  - X couples to 1st gen quarks (dominate nucleon spin)
  - $\tau$, stau, sneutrino channels avoid chirality suppression
- $3\sigma$ evidence obtainable at IceCube/DeepCore in ~5 yr.
  - $\lambda_{u,d} \sim 0.5$
- DeepCore provides an edge for lower energy $\nu$ (~50 GeV)
  - advantage for lower mass DM and superpartner cascades
- at high energy, need IceCube

3$\sigma$ bounds at IceCube/DeepCore
$m_{\text{stau}} = 137 \text{ GeV}$, $m_{\chi} = 94.5 \text{ GeV}$
(Dimopoulos, Thomas, Wells)
Conclusion

• new theoretical scenario for dark matter
  – large range of masses and couplings

• possible explanation for results of DAMA/LIBRA, CoGeNT

• interesting searches at Tevatron and LHC

• signals possible at Super-Kamiokande and IceCube/DeepCore

Mahalo!
Back-up slides
Collider cuts

- Tevatron (hadronic)
  - precuts
    - no isolated leptons
    - jets \( \geq 5 \) (\( p_T > 20 \text{ GeV} \))
    - missing \( E_T > 100 \text{ GeV} \)
    - isolation (jet from missing \( p_T \))
      - \( \Delta \phi > 90^\circ \) for leading jet
      - \( \Delta \phi > 50^\circ \) for second jet
  - additional cuts
    - missing \( E_T \)
      - 150, 200, 250 GeV
    - \( H_T = \sum |p_T| \)
      - 300, 350, 400 GeV
    - jets \( \geq 6 \) (\( p_T > 20 \text{ GeV} \))

- LHC (hadronic)
  - precuts
    - no isolated leptons
    - jets \( \geq 5 \) (\( p_T > 40 \text{ GeV} \))
    - missing \( E_T > 100 \text{ GeV} \)
    - isolation
      - \( \Delta \phi > 11.5^\circ \) for first 3 jets
  - additional cuts
    - missing \( E_T \)
      - 150, 200, 250, 300 GeV
    - \( H_T \)
      - 400, 500 GeV
    - jets \( \geq 6 \) (\( p_T > 40 \text{ GeV} \))
IceCube/DeepCore

- superpartner channel
  - spectrum from Dimopoulos, Thomas, Wells
  - $m_{\text{stau}} = 137 \text{ GeV}$
  - $m_{\text{sneutrino}} = 111.5 \text{ GeV}$
  - $m_\chi = 94.5 \text{ GeV}$
- assume $1^\circ$ angular acceptance
- IC $E_\mu$-threshold = 100 GeV
- DC $E_\mu$-threshold = 35 GeV
- account for matter effects in sun and vacuum oscillation
  - including $\tau$-regeneration