Light Dark Matter and Indirect Detection

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In Collaboration with R. Kappl, M. Ratz

arXiv:1010.0553 (Phys. Lett. B695)
arXiv:1104.0679 (Nucl. Phys. B850)
arXiv:1110.4376

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TECHNISCHE UNIVERSITÄT MÜNCHEN

Thermal WIMPs

- Dark Matter relic density: $\Omega_\chi h^2 \simeq 0.1$ (WMAP)
- Thermal WIMPs

$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma v \rangle}$$

- Velocity expansion: $\sigma v = a + b v^2$

s-wave p-wave

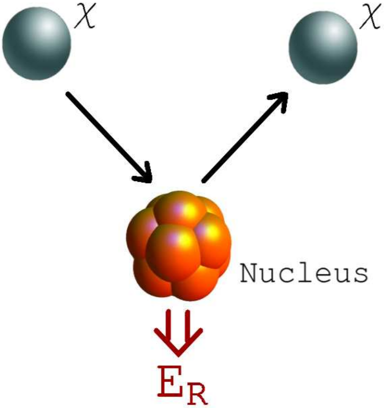
- Freeze-Out: $\langle v^2 \rangle \sim 1/10$

Direct Detection of WIMPs

- WIMP χ passes detector
  $\rightarrow$ liquid noble gas (Xenon...)
  $\rightarrow$ crystal (CRESST...)
- scatters off target nucleus
- $E_R \rightsquigarrow$ Light, Heat

  ↓

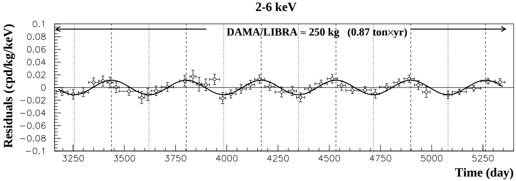
  detector signal

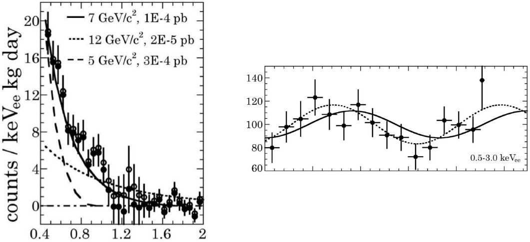


Possible Signals

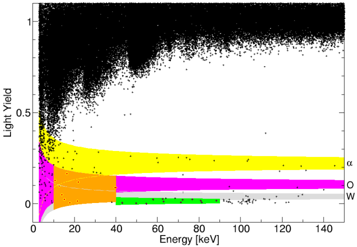
- modulation signal at **DAMA**

Bernabei et al., Eur. Phys. J. **C67** (2010)





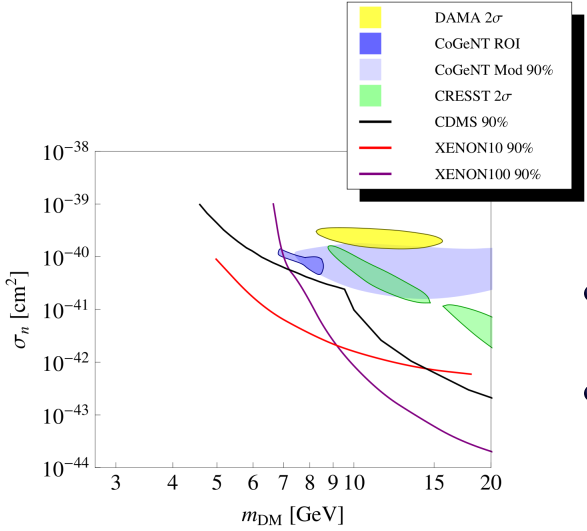
Aalseth et al., **arXiv:1106.0650** [astro-ph] (2011)



Angloher et al., **arXiv:1109.0702** [astro-ph] (2011)

- **CoGeNT**: exponential rise modulation
- **CRESST:** event excess

Direct Detection of WIMPs



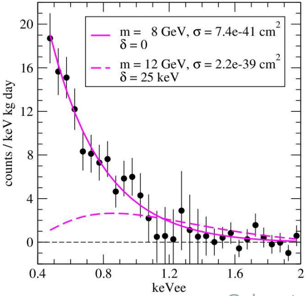
- DAMA, CoGeNT, CRESST close
- Tension with XENON, CDMS

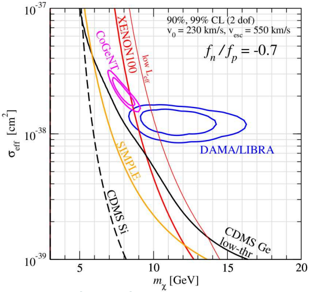
XENON 10/100, CDMS, CoGeNT rate, CRESST from official papers,
CoGeNT modulation from Fox et al. arXiv:1107.0717

Attempts

- Background, e.g. neutrons
  Ralston, **arXiv:1006.5255** [hep-ph] (2010)

- Inelastic Dark Matter, isospin violation, . . .
  Smith et al., Phys. Rev. **D64** (2001), Feng et al., Phys. Lett. B703 (2011)





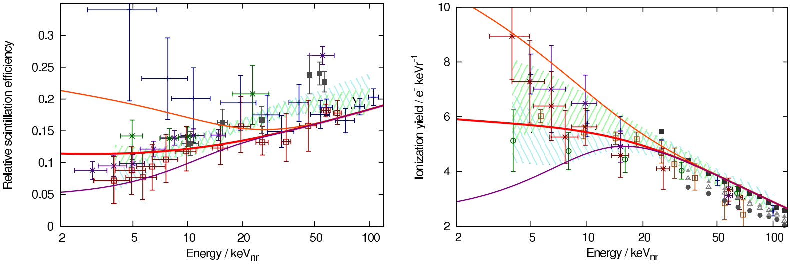
Schwetz et al., JCAP **08** (2011)

- More exotic dark matter

Attempts

- Non-standard astrophysics
  Frandsen et al., **arXiv:1111.0292** [hep-ph] (2011)

- Xenon uncertainties L_{eff}, Q_y
  Collar, arXiv:1106.0653 [astro-ph] (2011)



Bezrukov et al., Astropart. Phys. **35** (2011)

What can we learn from indirect detection?

Indirect Detection of Light Dark Matter: Possible Weak Hints

- Gamma ray excess from the galactic center

  Hooper et al., **arXiv:1110.0006** (2011)

- Radio filament structures near the galactic center

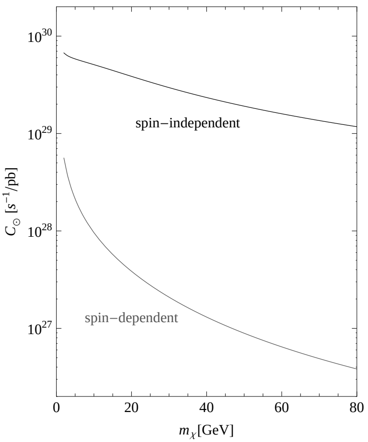
  Hooper et al., Astrophys. J. **741** (2011)

- Isotropic radio emission

  Fornengo et al., **arXiv:1108.0569** (2011)

astrophysics?

WIMP Capture in the Sun



- WIMPs scatter, get trapped in the gravitational potential of the sun
- Capture rate on element *i*

$$\frac{dC_i}{dr} \sim \text{Flux} \cdot \text{Kinematics} \cdot \rho_i(r) \cdot \sigma_i$$

- Spin-dependent:
  Only H
- Spin-independent:
  $\sigma \propto A^2$, kinematics $\Rightarrow$ H, **He**, ..., Ni

Annihilation in the Sun

- Captured WIMPs thermalize

$$f(v) \propto \exp\left(\frac{-m_\chi v^2}{2T_\chi}\right)$$
$$n(r) \propto \exp\left(\frac{-m_\chi \phi(r)}{T_\chi}\right)$$

  with $T_\chi \sim T_{\odot,\text{core}}$

- Annihilation rate $\Gamma_\odot = A_\odot N^2$ with

$$A_\odot = \frac{\langle \sigma v \rangle_\odot}{V_{\text{eff}}}$$

- Careful with p-wave: $\langle v^2 \rangle_\odot \sim 10^{-6}$

WIMP Evaporation

- By scattering $v > v_{\rm esc}$ $\rightarrow$ escape from sun
- Relevant for light WIMPs
- Evaporation rate per particle

$$E_\odot \simeq \frac{1}{t_\odot} \exp\left(\frac{-30\,(m_\chi - m_{\rm evap})}{m_{\rm evap}}\right)$$

- evaporation mass:

$$m_{\rm evap} \simeq 3.5\,\mathrm{GeV} + 0.32\,\mathrm{GeV} \cdot \log_{10}\left(\frac{\sigma_p}{10^{-40}\,\mathrm{cm}^2}\right)$$

Total Annihilation Signal

- WIMP number

$$\dot{N} = C_\odot - 2\,A_\odot\,N^2 - E_\odot\,N$$
$$\Gamma_{\text{ann}} = \frac{C_\odot}{2}\cdot\tanh\left(\sqrt{2\,C_\odot A_\odot}\;t_\odot\right) \qquad \text{(evaporation neglected)}$$

- For $\sqrt{2\,C_\odot A_\odot}t_\odot \gg 1$ equilibrium:

$$\boldsymbol{\Gamma_{\text{ann}} = C_\odot/2}$$

- Example: thermal WIMP ($m_\chi = 10\,\text{GeV}$, $\sigma_p = 10^{-40}\,\text{cm}^2$):

$$\sqrt{2\,C_\odot A_\odot}\;t_\odot \simeq \begin{cases} 400 & \text{(s-wave)} \\ 0.7 & \text{(p-wave)} \end{cases}$$

Neutrinos from Dark Matter

- Model-independent approach

$$\chi\chi \to c\bar{c},\, b\bar{b}, \tau\bar{\tau}, \nu\bar{\nu}$$

- Neutrino spectrum

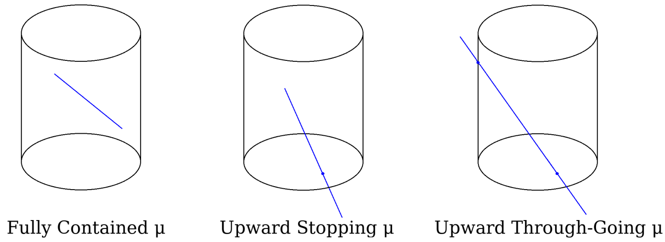
$$\left.\frac{dN_{\nu}^{f\bar{f}}}{dE}\right|_{\odot} \xrightarrow{\text{matter-, vacuum oscil., absorption}} \left.\frac{dN_{\nu_\mu}^{f\bar{f}}}{dE}\right|_{\text{earth}}$$

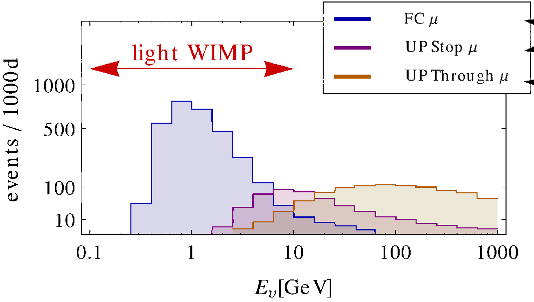
- Neutrino Flux

$$\Phi_\nu = \frac{\Gamma_\odot}{4\pi d_\odot^2} \left.\frac{dN_{\nu_\mu}^{f\bar{f}}}{dE}\right|_{\text{earth}}$$

- Angular distribution from position of the earth

Event Types at Super-Kamiokande



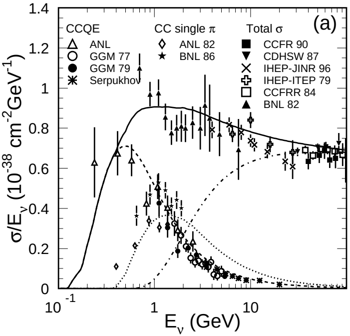


Our analysis

Super-K analysis

Desai et al., Phys. Rev. **D70** (2004)

Event Rates



Super-Kamiokande, Phys. Rev. **D 71** (2005)

- $E_\nu > 10$ GeV: νDIS
- $E_\nu < 10$ GeV: νQE, $\nu\pi$

$$\nu_\mu + p \to \mu + \Delta^{++} \to p + \pi$$

- Monte Carlo: NEUGEN

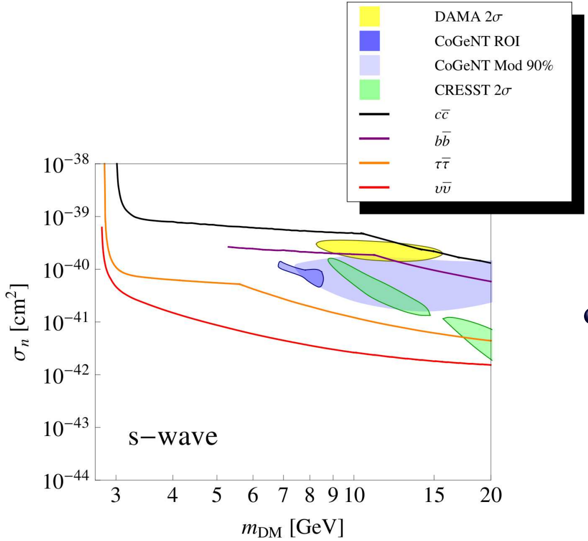
Gallagher, Nucl. Phys. Proc. Suppl. **112** (2002)

- Rate for FC events

$$R^{\text{FC}} \propto \int dE_\nu \, d\cos\theta_\nu \, dx^3 \, \frac{d\Phi_\nu}{d\cos\theta_\nu} \, \sigma_{\text{cc}} \, p_{\text{stop}}(E_\nu, \theta_\nu, \mathbf{x})$$

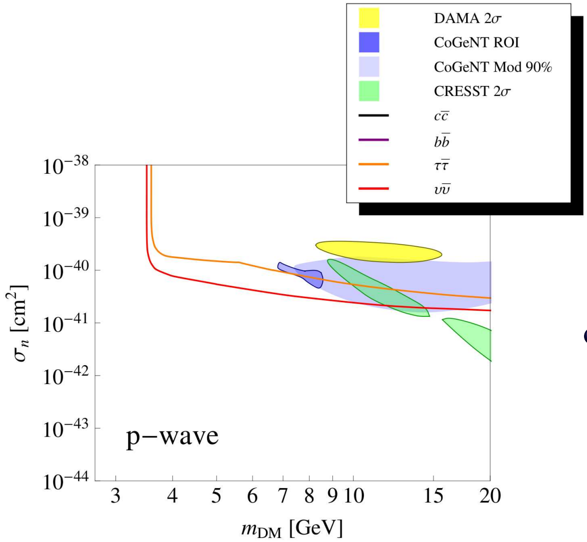
- analysis: νDM + νAtm < νMeasured + error

Limits from Super-Kamiokande



- DAMA, CoGeNT, CRESST not from WIMPs annihilating into τ, ν pairs

Limits from Super-Kamiokande



- DAMA not from WIMPs annihilating into τ, ν pairs

Antiprotons in Cosmic Rays

- New precision measurement by BESS-Polar II

  Abe et al., **arXiv:1107.6000**

  $\Rightarrow$ Consistent with background? Exotic sources?

- Secondary antiproton background

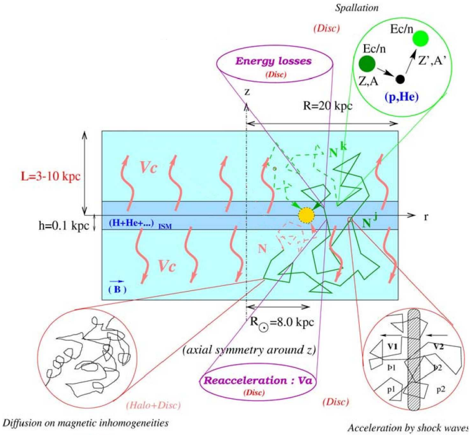
$$p,\, He + H_{\text{ISM}},\, He_{\text{ISM}} \rightarrow \bar{p} + X$$

- Source term

$$q^{\text{sec}}(T) \sim \int dT' \left(\frac{d\sigma}{dT}\right)_{\bar{p}\,prod} n_{\text{H}_{\text{ISM}}} \Phi_p$$

DTUNUC model or
Fit to experimental data

Antiproton Propagation I



from D. Maurin

Diffusion equation:

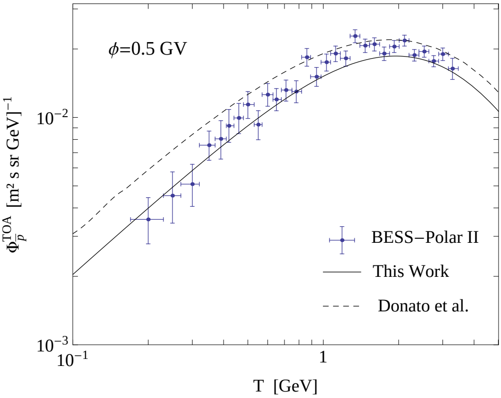
$$\nabla(-K\,\nabla N_{\bar{p}} + \mathbf{V}_c\,N_{\bar{p}}) + \partial_E(b_{\text{loss}}\,N_{\bar{p}} - K_{EE}\,\partial_E N_{\bar{p}}) + \Gamma_{\text{ann}}\,N_{\bar{p}} = q_{\bar{p}} + q_{\bar{p}}^{\text{ter}}$$

Antiproton Propagation II

- 2 Zone diffusion model
  Maurin et al. Astrophys. J. **555** (2001)
- Five propagation parameters: K_0, δ, L, V_c, V_A.
- (Partly) fixed by B/C analysis
  Putze et al., A & A **516** (2010)
- Solar Modulation:
  $\rightarrow$ Complicated
  $\rightarrow$ Force-field approximation (solar minimum):

$$\Phi_{\bar{p}}^{\mathrm{TOA}}(T) = \frac{p^2}{p_{\mathrm{IS}}^2}\,\Phi_{\bar{p}}^{\mathrm{IS}}(T_{\mathrm{IS}}) \quad \text{with} \quad T_{\mathrm{IS}} = T + \phi\ .$$

Comparison with Experiment



- Reduced flux compared to Donato et al.
  Donato et al., Astrophys. J. **563** (2001)
- BESS-Polar II consistent with pure secondary background

Antiprotons from Dark Matter

- Model-independent approach

$$\chi\chi \to u\bar{u},\, d\bar{d},\, s\bar{s},\, c\bar{c},\, b\bar{b}, WW, ZZ$$

- Primary source term

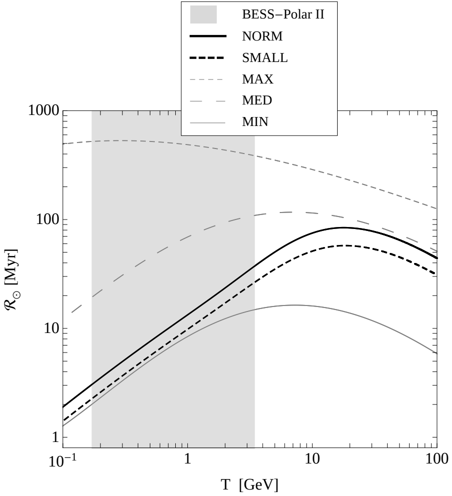
$$q_{\bar{p}}^{\text{prim}}(\mathbf{r}, T) = \frac{\rho_\chi^2}{m_\chi^2}\,\frac{\langle \sigma_{\text{ann}} v \rangle}{2}\,\frac{dN_{\bar{f}f}}{dT}$$

- neglecting low energy effects (energy losses, reaccelleration, tertiaries)

$$\Phi_{\bar{p}} \sim q^{\text{prim}} \cdot R_\odot$$

- Higher sensitivity to propagation parameters

Propagation Parameters



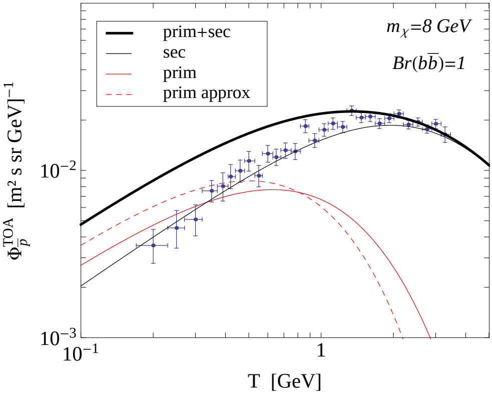
- K_0, δ, V_c, V_A from B/C
- several hints for $L \gtrsim 4$ kpc
- New B/C: Higher V_c

  Putze et al., A & A **516** (2010)

- comparison with earlier work:

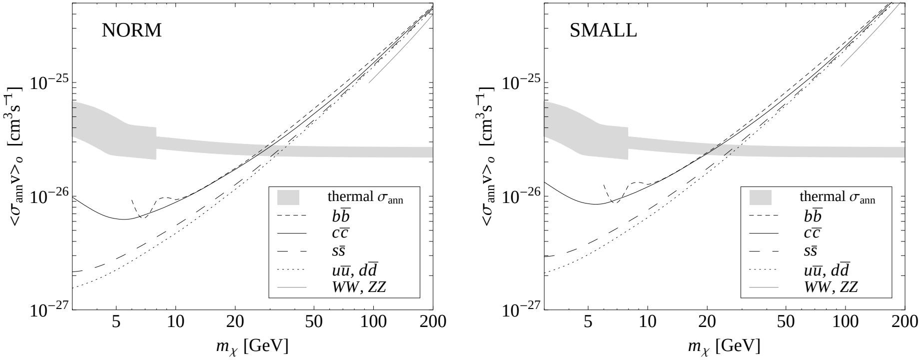
model	δ	$K_0[\frac{\text{kpc}^2}{\text{Myr}}]$	L[kpc]	$V_c[\frac{\text{km}}{\text{s}}]$	$V_A[\frac{\text{km}}{\text{s}}]$
MIN	0.85	0.0016	1	13.5	22.4
MED	0.70	0.0112	4	12	52.9
MAX	0.46	0.0765	15	5	117.6
NORM	0.86	0.0042	4	18.7	35.5
SMALL	0.86	0.0031	3	18.6	30.5

Primary Flux



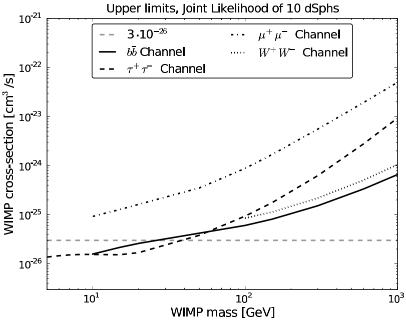
- Primary flux for 8 GeV WIMP
- Low energy effects non-negligible

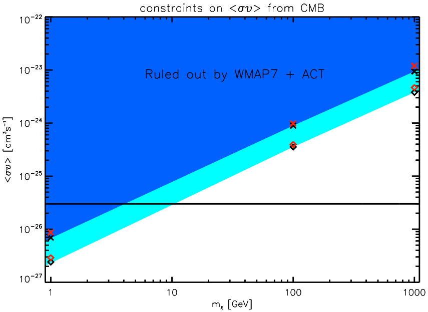
Constraints from BESS-Polar II



- Stronger limits for annihilation into light quarks
- Thermal WIMPs with $m_\chi = 3 \ldots 20$ GeV disfavored unless annihilation is non-hadronic or p-wave suppressed

Other Indirect Searches





- Limits from Dwarfs
  Fermi-LAT, **arXiv:1108.3546** (2011)

- Limits from WMAP
  Galli et al., Phys. Rev. **D84** (2011)
  Hutsi et al., **arXiv:1103.2766** (2011)

$\Rightarrow$ Relatively robust exclusion light WIMPs with hadronic annihilation (s-wave)

Candidates for Light WIMPs

- Standard Model:
  - neutrino

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- Standard Model:
  - ~~neutrino~~ hot dark matter, mass too small

Candidates for Light WIMPs

- Standard Model:
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- Minimal Supersymmetric Standard Model:
  - sneutrino
  - wino, higgsino
  - bino

Candidates for Light WIMPs

- Standard Model:
  - ~~neutrino~~ hot dark matter, mass too small
- Minimal Supersymmetric Standard Model:
  - ~~sneutrino~~ Z width
  - wino, higgsino
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  - ~~bino~~ cross section too small
  - mixture bino higgsino?

    σ_p maximal at very large $\tan\beta$, $m_H \simeq 100\,\text{GeV}$, $\cos\alpha = 1$:

    Belikov et al., **arXiv:1009.0549** [hep-ph] (2010)

$$\sigma_p \sim 10^{-41}\,\text{cm}^2 \times \frac{N_{13}^2}{0.1} \qquad \text{but} \quad N_{13}^2 \lesssim 0.1$$

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A Supersymmetric Model

- introduce one singlet superfield S
- new particles: singlino $\widetilde{s}$, singlet scalar h_s, pseudoscalar a_s
- most general superpotential (including S^2-term)

  Drees, Int. J. Mod. Phys. **A4** (1989)

$$\mathcal{W} \;=\; \mathcal{W}_{\text{MSSM}} + \lambda\, S\, H_u H_d + \frac{\mu_s}{2}\, S^2 + \frac{\kappa}{3}\, S^3$$

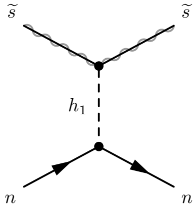
- $+$ corresponding soft terms
- interaction between singlet and MSSM controlled by λ
- interaction in singlet sector controlled by κ

Towards light WIMPs

Assumption	Effect
all singlet mass terms $\mathcal{O}(10\text{ GeV})$	$m_{\tilde{s},h_s,a_s} \sim 10\text{ GeV}$
suppressed λ	MSSM and Singlets "almost decouple" $h_1 = h_s + \sin\theta\, h$
sizeable κ	significant singlet self-interactions

Can Singlinos explain CRESST & Co

- correct mass range (by assumption)
- WIMP nucleon cross section dominated by h_1-exchange



- suppressed by $\sin\theta$
- but: enhanced by $1/m_{h_1}^4$

$$\sigma_p \sim 10^{-40}\,\mathrm{cm}^2 \left(\frac{\kappa}{0.08}\right)^2 \left(\frac{\sin\theta}{0.03}\right)^2 \left(\frac{4\,\mathrm{GeV}}{m_{h_1}}\right)^4$$

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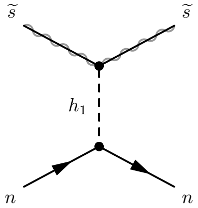

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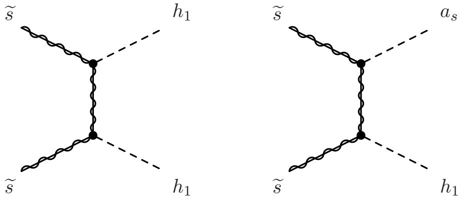
$\Rightarrow$ CRESST & Co explanation for sizeable κ, small m_{h_1}

Singlinos as Thermal Relics

- thermal relic density $\mathbf{\Omega} \propto \langle \sigma v_{\text{rel}} \rangle^{-1}$
- sizeable κ, small m_{h_1} opens annihilation channel(s)



$$\sigma v_{\text{rel}} \sim \mathcal{O}(1)\, \frac{\kappa^4}{16\,\pi} \frac{1}{m_{\widetilde{s}}^2} \times \begin{cases} v_{\text{rel}}^2 & (h_1 h_1\text{-channel}) \\ 1 & (h_1 a_s\text{-channel}) \end{cases}$$

- $\mathbf{\Omega}_{\widetilde{s}} = \mathbf{\Omega}_{\text{DM}}$ for $\kappa = 0.01 \ldots 0.1$

A Benchmark Scenario

Input Parameters

Quantity	Value
μ	370 GeV
$\langle s \rangle$	163 GeV
A_κ	-9 GeV
μ_s	-19 GeV
$B\mu_s$	0
λ	-0.003
κ	0.08

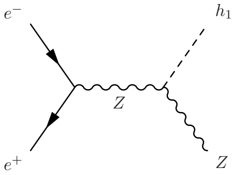
Predictions

Quantity	Value
m_{a_s}	28 GeV
$m_{\tilde{s}}$	7 GeV
m_{h_1}	4 GeV
$\sin\theta$	0.03
σ_p	$\sim 10^{-40}\,\text{cm}^2$
Ωh^2	~ 0.1

- CoGeNT, DAMA, CRESST $\sim\checkmark$ (not XENON)
- Relic density $\checkmark$
- Indirect detection constraints $\checkmark$
- Experimental constraints **?**

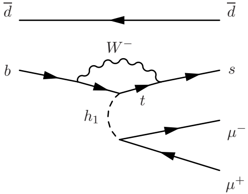
Experimental Constraints on Light Scalar

Higgs-like particles at LEP



L3-limit $ZZ\,h_1$-coupling

Belle: h_1 in meson decays



$\mathrm{Br}(B \to X_s + \mu^+\mu^-) \lesssim 10^{-6}$

Experimental Constraints on Light Scalar

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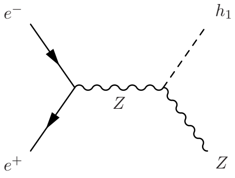

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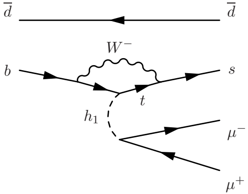

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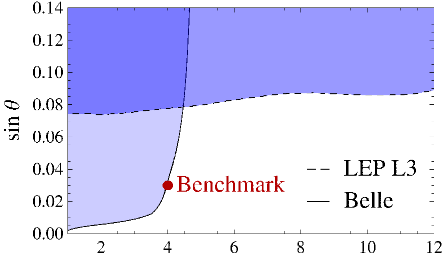

- can be translated into limits on $\sin\theta$
- benchmark point viable

Conclusion

- Signals at several DM direct detection experiments might hint at light WIMPs (but tension)
- Such WIMPs can be strongly constrained by indirect detection
- Super-Kamiokande disfavors annihilation into neutrinos and taus
- BESS-Polar disfavors annihilation into quarks
- Exception: p-wave annihilation
- A simple singlet extension of the MSSM offers a promising light dark matter candidate