ISAPP 2011, MPIK Heidelberg
“The Dark Side of the Universe”

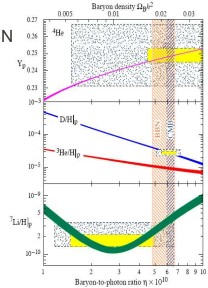
Dark Matter phenomenology

Thomas Schwetz-Mangold

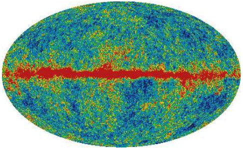
13 July 2011

What is the Universe made of?

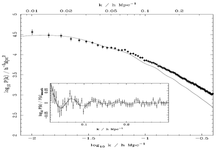
BBN



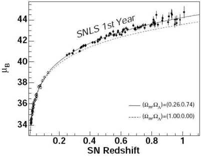
CMB (WMAP)



BAO



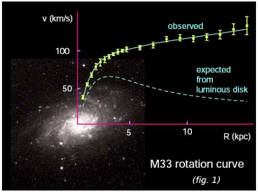
SN 1a



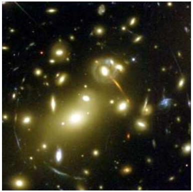
WMAP 7yr + BAO + H_0: $\Omega_{\rm CDM} = 0.229 \pm 0.015$

The scale of galaxies and clusters of galaxies

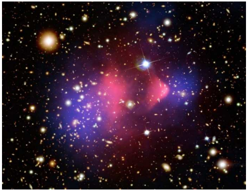
- rotation curves



- gravitational lensing

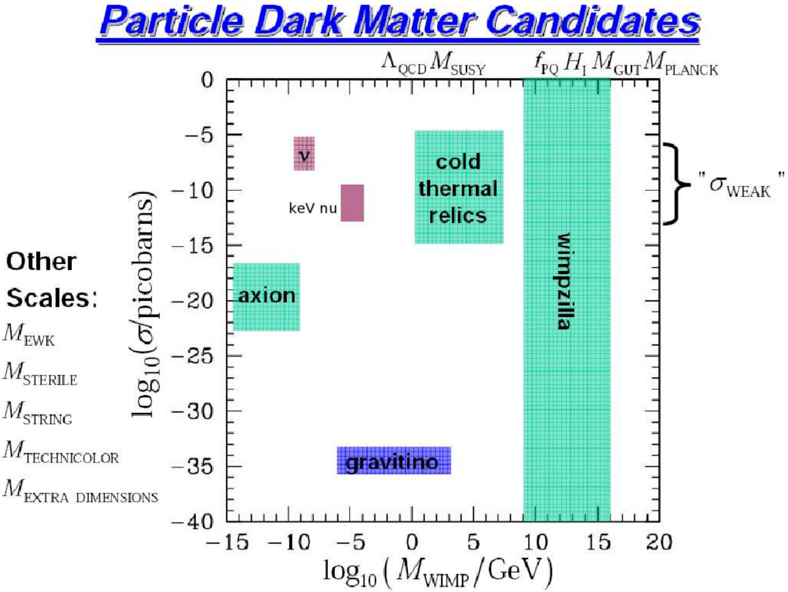


- bullet clusters



- virial theorem applied to galaxies and clusters
- X-rays from clusters of galaxies

$\Rightarrow$ Many independent observations are consistent with the hypothesis that the dominating gravitating component of the Universe cannot be the matter we know.


Particle Dark Matter Candidates
Λ_QCD M_SUSY
f_PQ H_I M_GUT M_PLANCK
0
−5
−10
−15
−20
−25
−30
−35
−40
log10(σ/picobarns)
ν
keV nu
cold thermal relics
axion
gravitino
wimpzilla
"σ_WEAK"
−15 −10 −5 0 5 10 15 20
log10 (M_WIMP / GeV)
Other Scales:
M_EWK
M_STERILE
M_STRING
M_TECHNICOLOR
M_EXTRA DIMENSIONS

We have no clue about DM properties ...

but there are good arguments that DM could be related to the "weak scale": $\rightarrow$ Weakly Interacting Massive Particle (WIMP)

in my lecture I will concentrate on the WIMP hypothesis
BUT: there are very well motivated non-WIMP candidates:

- axion lecture by G. Raffelt
- gravitino
- keV neutrinos lecture by M. Shaposhnikov
- "GIMP"
- ...

We have no clue about DM properties ...

but there are good arguments that DM could be related to the "weak scale": $\rightarrow$ Weakly Interacting Massive Particle (WIMP)

in my lecture I will concentrate on the WIMP hypothesis
BUT: there are very well motivated non-WIMP candidates:

- axion lecture by G. Raffelt
- gravitino
- keV neutrinos lecture by M. Shaposhnikov
- "GIMP"
- ...

Outline

The WIMP hypothesis

- thermal freeze-out of Dark Matter
- the WIMP miracle (or what is special about the "weak scale")

DM direct detection

- Phenomenology
- XENON100 and the WIMP hypothesis
- Hints for a DM signal and possible explanations

Outline

Boltzmann equation

distribution function: $f(\vec{p}, \vec{x}, t)$

the evolution is described by the Boltzmann equation:

$$\underbrace{L[f]}_{\text{Liouville operator}} = \underbrace{C[f]}_{\text{collision operator}}$$

$L[f]$ for non-relativistic particles:

$$L[f] = \frac{df}{dt} = \frac{\partial f}{\partial t} + \frac{\partial f}{\partial x_i}\dot{x}_i + \frac{\partial f}{\partial p_i}\dot{p}_i$$

(conservation of density in phase space)

relativistic generalization:

$$L[f] = p^\mu \frac{\partial f}{\partial x^\mu} - \Gamma^\mu_{\alpha\beta} p^\alpha p^\beta \frac{\partial f}{\partial p^\mu}$$

Boltzmann equation

distribution function: $f(\vec{p}, \vec{x}, t)$

the evolution is described by the Boltzmann equation:

$$\underbrace{L[f]}_{\text{Liouville operator}} = \underbrace{C[f]}_{\text{collision operator}}$$

$L[f]$ for non-relativistic particles:

$$L[f] = \frac{df}{dt} = \frac{\partial f}{\partial t} + \frac{\partial f}{\partial x_i}\dot{x}_i + \frac{\partial f}{\partial p_i}\dot{p}_i$$

(conservation of density in phase space)

relativistic generalization:

$$L[f] = p^\mu \frac{\partial f}{\partial x^\mu} - \Gamma^\mu_{\alpha\beta} p^\alpha p^\beta \frac{\partial f}{\partial p^\mu}$$

Boltzmann equation

distribution function: $f(\vec{p}, \vec{x}, t)$

the evolution is described by the Boltzmann equation:

$$\underbrace{L[f]}_{\text{Liouville operator}} = \underbrace{C[f]}_{\text{collision operator}}$$

$L[f]$ for non-relativistic particles:

$$L[f] = \frac{df}{dt} = \frac{\partial f}{\partial t} + \frac{\partial f}{\partial x_i}\dot{x}_i + \frac{\partial f}{\partial p_i}\dot{p}_i$$

(conservation of density in phase space)

relativistic generalization:

$$L[f] = p^\mu \frac{\partial f}{\partial x^\mu} - \Gamma^\mu_{\alpha\beta} p^\alpha p^\beta \frac{\partial f}{\partial p^\mu}$$

Boltzmann ⇒ rate equation

Freedman-Robertson-Walker metric: $f(\vec{p},\vec{x},t) = f(|\vec{p}|,t)$

$$L[f] = E\frac{\partial f}{\partial t} - \frac{\dot{a}}{a}p^2\frac{\partial f}{\partial E}$$

with $E^2 = p^2 + m^2$ and $\dot{a}/a \equiv H$ expansion rate

evolution of the number density $n(t) = \frac{g}{(2\pi)^3}\int d^3p\, f(p,t)$:

$$\frac{g}{(2\pi)^3}\int d^3p \frac{L[f]}{E} = \dot{n} - H\frac{g}{(2\pi)^3}\int d^3p \frac{p^2}{E}\frac{\partial f}{\partial E} = \dots$$

$$= \dot{n} + 3Hn = \frac{1}{a^3}\frac{d}{dt}\left(na^3\right)$$

(in absence of collisions: dilution with expansion)

Boltzmann $\Rightarrow$ rate equation

Freedman-Robertson-Walker metric: $f(\vec{p}, \vec{x}, t) = f(|\vec{p}|, t)$

$$L[f] = E\frac{\partial f}{\partial t} - \frac{\dot{a}}{a} p^2 \frac{\partial f}{\partial E}$$

with $E^2 = p^2 + m^2$ and $\dot{a}/a \equiv H$ expansion rate

evolution of the number density $n(t) = \frac{g}{(2\pi)^3} \int d^3p\, f(p, t)$:

$$\frac{g}{(2\pi)^3} \int d^3p \frac{L[f]}{E} = \dot{n} - H \frac{g}{(2\pi)^3} \int d^3p \frac{p^2}{E} \frac{\partial f}{\partial E} = \ldots$$

$$= \dot{n} + 3Hn = \frac{1}{a^3} \frac{d}{dt} \left(na^3\right)$$

(in absence of collisions: dilution with expansion)

The collision operator

consider $12 \leftrightarrow 34$ process:

$$C[f_1] = \frac{1}{2} \int d\pi_2 d\pi_3 d\pi_4 (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4) \times$$
$$\sum_{\text{spins}} \left[|\mathcal{M}_{34\to 12}|^2 f_3 f_4 (1 \pm f_1)(1 \pm f_2) - (12 \leftrightarrow 34) \right]$$
$$+ C_{\text{elast}}[f_1]$$

with $d\pi \equiv \frac{d^3p}{(2\pi)^3 2E}$

The collision operator

consider $12 \leftrightarrow 34$ process:

$$C[f_1] = \frac{1}{2}\int d\pi_2 d\pi_3 d\pi_4 (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4) \times$$
$$\sum_{\text{spins}} \left[|\mathcal{M}_{34\to12}|^2 f_3 f_4 (1 \pm f_1)(1 \pm f_2) - (12 \leftrightarrow 34) \right]$$
$$+ C_{\text{elast}}[f_1]$$

with $d\pi \equiv \frac{d^3p}{(2\pi)^3 2E}$

calculate $$\frac{g}{(2\pi)^3}\int d^3p_1 \frac{C[f_1]}{E_1}$$

in order to obtain the rate equation for n

The collision operator

consider $12 \leftrightarrow 34$ process:

$$C[f_1] = \frac{1}{2}\int d\pi_2 d\pi_3 d\pi_4 (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4)\times$$
$$\sum_{\text{spins}} \left[|\mathcal{M}_{34\to12}|^2 f_3 f_4 (1\pm f_1)(1\pm f_2) - (12 \leftrightarrow 34)\right]$$
$$+ C_{\text{elast}}[f_1]$$

with $d\pi \equiv \frac{d^3p}{(2\pi)^3 2E}$

- neglect statistical factors (FD,BE $\to$ MB)
- assume $|\mathcal{M}_{34\to12}|^2 = |\mathcal{M}_{12\to34}|^2$ (satisfied for $\chi\bar\chi \leftrightarrow \psi\bar\psi$)
- assume that 34 are in kinetic + chemical equilibrium: $f_3 f_4 = f_3^{\text{eq}} f_4^{\text{eq}}$
- detailed balance: in equilibrium $\frac{d}{dt}(na^3) = 0 \Rightarrow f_3^{\text{eq}} f_4^{\text{eq}} = f_1^{\text{eq}} f_2^{\text{eq}}$
- 12 stay in kinetic equilibrium even after chemical equilibrium is lost

Rate equation for density

define thermally averaged cross section times velocity:

$$\langle \sigma_{12} v \rangle \equiv \frac{1}{n_1^{\rm eq} n_2^{\rm eq}} \int g_1 \frac{d^3 p_1}{(2\pi)^3} g_2 \frac{d^3 p_2}{(2\pi)^3} f_1^{\rm eq} f_2^{\rm eq} \sigma v$$

$$v \equiv \frac{\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2}}{E_1 E_2}$$

integrated Boltzmann equation becomes:

$$\dot{n}_1 + 3Hn_1 = \langle \sigma_{12} v \rangle \left(n_1^{\rm eq} n_2^{\rm eq} - n_1 n_2 \right)$$

consider self-conjugated particle $n_1 = n_2 \equiv n$ ($\chi\chi \leftrightarrow X \Rightarrow \sigma_{12} \to \sigma_{\rm ann}$):

$$\boxed{\dot{n} + 3Hn = \langle \sigma_{\rm ann} v \rangle \left(n_{\rm eq}^2 - n^2 \right)}$$

Rate equation for density

define thermally averaged cross section times velocity:

$$\langle \sigma_{12} v \rangle \equiv \frac{1}{n_1^{\rm eq} n_2^{\rm eq}} \int g_1 \frac{d^3 p_1}{(2\pi)^3} \, g_2 \frac{d^3 p_2}{(2\pi)^3} f_1^{\rm eq} f_2^{\rm eq} \, \sigma v$$

$$v \equiv \frac{\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2}}{E_1 E_2}$$

integrated Boltzmann equation becomes:

$$\dot{n}_1 + 3Hn_1 = \langle \sigma_{12} v \rangle \left(n_1^{\rm eq} n_2^{\rm eq} - n_1 n_2 \right)$$

consider self-conjugated particle $n_1 = n_2 \equiv n$ $(\chi\chi \leftrightarrow X \Rightarrow \sigma_{12} \to \sigma_{\rm ann})$:

$$\boxed{\dot{n} + 3Hn = \langle \sigma_{\rm ann} v \rangle \left(n_{\rm eq}^2 - n^2 \right)}$$

Rescale by entropy density

re-write differential equation in terms of

$$Y \equiv \frac{n}{s}$$

by using entropy conservation in comoving volume: $a^3 s = \text{const}$

$$\dot{Y} = -\langle \sigma_{\text{ann}} v \rangle s \left(Y^2 - Y_{\text{eq}}^2 \right)$$

(get rid of trivial exansion term)

Change variables

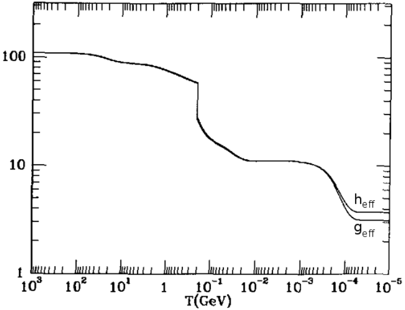
... from time to dimensionless temperature $x \equiv \frac{m}{T}$

$$H = \sqrt{\frac{8}{3}\pi G_N \rho}$$

$$\rho = g_{\rm eff}\frac{\pi^2}{30}T^4$$

$$s = h_{\rm eff}\frac{2\pi^2}{45}T^3$$

$$g_* = \frac{h_{\rm eff}^2}{g_{\rm eff}}\left(1 + \frac{T}{3h_{\rm eff}}\frac{dh_{\rm eff}}{dT}\right)^2$$



Gondolo, Gelmini, 1991

$g_{\rm eff}, h_{\rm eff}, g_*$: parametrize relativistic degrees of freedom
(for const $h_{\rm eff}$ and all species at the same T: $g_{\rm eff} = h_{\rm eff} = g_*$)

Yield equation

$$\frac{dY}{dx} = -\sqrt{\frac{\pi g_*}{45 G_N}}\frac{m}{x^2}\langle\sigma_{\rm ann} v\rangle\left(Y^2 - Y_{\rm eq}^2\right)$$

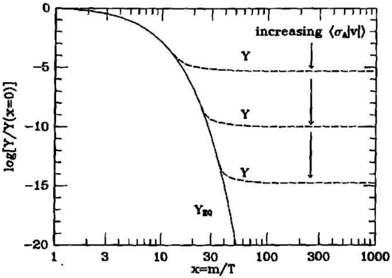
consider $h_{\rm eff} = \text{const}$, $\Gamma = n_{\rm eq}\langle\sigma_{\rm ann} v\rangle$: $\quad \frac{x}{Y_{\rm eq}}\frac{dY}{dx} = -\frac{\Gamma}{H}\left(\frac{Y^2}{Y_{\rm eq}^2} - 1\right)$

thermal freeze-out for $\Gamma \sim H$ at $x \simeq x_F$

$x \gg 1 \qquad n_{\rm eq} = g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}$

$x \gg 1 \qquad Y_{\rm eq} = \mathcal{C}\frac{g}{h_{\rm eff}} x^{3/2} e^{-x}$

$x \ll 1 \qquad Y_{\rm eq} = \mathcal{C}'\frac{g}{h_{\rm eff}}$



DM yield at infinity

$$\frac{dY}{dx} = -\sqrt{\frac{\pi g_*}{45 G_N}} \frac{m}{x^2} \langle \sigma_{\text{ann}} v \rangle \left(Y^2 - Y_{\text{eq}}^2 \right)$$

neglect Y_{eq} compared to Y for $x \gg x_F$

$$\frac{1}{Y_\infty} \approx \frac{1}{Y(x_F)} + \sqrt{\frac{\pi}{45 G_N}} m \int_{x_F}^{\infty} dx \frac{\langle \sigma_{\text{ann}} v \rangle}{x^2} \sqrt{g_*(x)}$$

neglect $1/Y(x_F)$ and assume $\langle \sigma_{\text{ann}} v \rangle \approx$ const:

$$Y_\infty \approx \sqrt{\frac{45 G_N}{\pi g_*(x_F)}} \frac{x_F}{m} \frac{1}{\langle \sigma_{\text{ann}} v \rangle}$$

$\Rightarrow$ large $\langle \sigma_{\text{ann}} v \rangle$ give small DM yield

DM yield at infinity

$$\frac{dY}{dx} = -\sqrt{\frac{\pi g_*}{45 G_N}} \frac{m}{x^2} \langle \sigma_{\rm ann} v \rangle \left(Y^2 - Y_{\rm eq}^2 \right)$$

neglect $Y_{\rm eq}$ compared to Y for $x \gg x_F$

$$\frac{1}{Y_\infty} \approx \frac{1}{Y(x_F)} + \sqrt{\frac{\pi}{45 G_N}} m \int_{x_F}^{\infty} dx \frac{\langle \sigma_{\rm ann} v \rangle}{x^2} \sqrt{g_*(x)}$$

neglect $1/Y(x_F)$ and assume $\langle \sigma_{\rm ann} v \rangle \approx$ const:

$$Y_\infty \approx \sqrt{\frac{45 G_N}{\pi g_*(x_F)}} \frac{x_F}{m} \frac{1}{\langle \sigma_{\rm ann} v \rangle}$$

$\Rightarrow$ large $\langle \sigma_{\rm ann} v \rangle$ give small DM yield

Relic density estimate

$$\Omega h^2 = \frac{\rho_0 h^2}{\rho_{\rm crit}} = \frac{s_0 Y_\infty m h^2}{\rho_{\rm crit}}$$

$$s_0 = h_{\rm eff}(x_0)\frac{2\pi^2}{45} T_0^3 \approx 2890\,{\rm cm}^2,\ \rho_{\rm crit} \approx 1.05 \times 10^{-5} h^2\ {\rm GeV\ cm}^{-3}$$

$$\Omega h^2 \simeq \frac{3 \times 10^{-38}\,{\rm cm}^2}{\langle \sigma_{\rm ann} v\rangle} \frac{x_F}{\sqrt{g_*(x_F)}}$$

for $m \sim 100$ GeV and $\langle \sigma_{\rm ann} v\rangle \sim 10^{-36}\,{\rm cm}^2$:

$$x_F \simeq 20,\ T_F = \frac{m}{x_F} \sim 5\,{\rm GeV},\ g_{\rm eff}(x_F) \simeq 80 - 100 \Rightarrow \frac{x_F}{\sqrt{g_*(x_F)}} \simeq 2 - 3$$

$$\Omega h^2 \simeq \frac{10^{-37}\,{\rm cm}^2}{\langle \sigma_{\rm ann} v\rangle}$$

Relic density estimate

$$\Omega h^2 = \frac{\rho_0 h^2}{\rho_{\rm crit}} = \frac{s_0 Y_\infty m h^2}{\rho_{\rm crit}}$$

$s_0 = h_{\rm eff}(x_0)\frac{2\pi^2}{45} T_0^3 \approx 2890\,{\rm cm}^2,\ \rho_{\rm crit} \approx 1.05 \times 10^{-5} h^2 \text{ GeV cm}^{-3}$

$$\Omega h^2 \simeq \frac{3 \times 10^{-38}\,{\rm cm}^2}{\langle \sigma_{\rm ann} v \rangle} \frac{x_F}{\sqrt{g_*(x_F)}}$$

for $m \sim 100$ GeV and $\langle \sigma_{\rm ann} v \rangle \sim 10^{-36}\,{\rm cm}^2$:

$$x_F \simeq 20,\ T_F = \frac{m}{x_F} \sim 5\,{\rm GeV},\ g_{\rm eff}(x_F) \simeq 80 - 100 \Rightarrow \frac{x_F}{\sqrt{g_*(x_F)}} \simeq 2 - 3$$

$$\boxed{\Omega h^2 \simeq \frac{10^{-37}\,{\rm cm}^2}{\langle \sigma_{\rm ann} v \rangle}}$$

Thermally averaged cross section

remember: $$\langle \sigma_{\rm ann} v \rangle \equiv \frac{1}{n_1^{\rm eq} n_2^{\rm eq}} \int g_1 \frac{d^3 p_1}{(2\pi)^3} \, g_2 \frac{d^3 p_2}{(2\pi)^3} f_1^{\rm eq} f_2^{\rm eq} \, \sigma v$$

assume Maxwell-Boltzmann distribution:

$$\langle \sigma_{\rm ann} v \rangle = \frac{\int d^3 p_1 d^3 p_2 \, e^{-E_1/T} e^{-E_2/T} \, \sigma v}{\int d^3 p_1 d^3 p_2 \, e^{-E_1/T} e^{-E_2/T}}$$

$$v \equiv \frac{\sqrt{(p_1 \cdot p_2)^2 - m^4}}{E_1 E_2} \quad \xrightarrow{\text{non-relat}} \quad \frac{|\vec{p}_1 - \vec{p}_2|}{m} = v_{\rm rel}$$

Thermally averaged cross section

remember: $\langle \sigma_{\text{ann}} v \rangle \equiv \frac{1}{n_1^{\text{eq}} n_2^{\text{eq}}} \int g_1 \frac{d^3 p_1}{(2\pi)^3} g_2 \frac{d^3 p_2}{(2\pi)^3} f_1^{\text{eq}} f_2^{\text{eq}} \, \sigma v$

assume Maxwell-Boltzmann distribution:

$$\langle \sigma_{\text{ann}} v \rangle = \frac{\int d^3 p_1 d^3 p_2 \, e^{-E_1/T} e^{-E_2/T} \, \sigma v}{\int d^3 p_1 d^3 p_2 \, e^{-E_1/T} e^{-E_2/T}}$$

Gondolo, Gelmini, Nucl. Phys. B 360 (1991) 145

$$\langle \sigma_{\text{ann}} v \rangle = \frac{1}{8 m^4 T K_2^2(x)} \int_{4m^2}^{\infty} ds \, \sigma (s - 4m^2) \sqrt{s} K_1 \left(\frac{\sqrt{s}}{T} \right)$$

with the modified Bessel functions

$$K_1(x) = x \int_1^{\infty} dt \, e^{-xt} \sqrt{t^2 - 1}$$

$$K_2(x) = x \int_1^{\infty} dt \, e^{-xt} t \sqrt{t^2 - 1}$$

Thermally averaged cross section

remember: $\langle \sigma_{\rm ann} v \rangle \equiv \frac{1}{n_1^{\rm eq} n_2^{\rm eq}} \int g_1 \frac{d^3 p_1}{(2\pi)^3} g_2 \frac{d^3 p_2}{(2\pi)^3} f_1^{\rm eq} f_2^{\rm eq} \sigma v$

assume Maxwell-Boltzmann distribution:

$$\langle \sigma_{\rm ann} v \rangle = \frac{\int d^3 p_1 d^3 p_2 \, e^{-E_1/T} e^{-E_2/T} \sigma v}{\int d^3 p_1 d^3 p_2 \, e^{-E_1/T} e^{-E_2/T}}$$

$x_F \sim 20$ non-relativistic expansion: $\sigma v \approx a + b v^2$

$$\langle \sigma_{\rm ann} v \rangle \approx a + b \langle v^2 \rangle \approx a + \frac{6b}{x}$$

replace $\langle \sigma_{\rm ann} v \rangle$ in the relic density estimate by $a + 3b/x_F$

Expansion in v is not accurate in the following cases:

Griest, Seckel, 1991

- close to an s-channel resonance ($2m_\chi \approx m_\phi$):

$$\sigma v \propto \frac{1}{(s - m_\phi^2)^2}\,, \quad s = (E_{1\mathrm{cm}} + E_{2\mathrm{cm}})^2 \approx 4m_\chi^2(1 + v^2)$$

- close to thresholds of annihilation channels $\chi\chi \to XX$ with $m_\chi \approx m_X$:

$$\sigma v \propto \sqrt{s - 4m_X^2}$$

- in the presence of other particles close in mass, which participate in the annihilations ("co-annihilations")

$$\chi_1\chi_1 \leftrightarrow XX\,, \quad \chi_1\chi_2 \leftrightarrow XX'\,, \quad \chi_2\chi_2 \leftrightarrow XX$$

Expansion in v is not accurate in the following cases:

Griest, Seckel, 1991

- close to an s-channel resonance ($2m_\chi \approx m_\phi$):

$$\sigma v \propto \frac{1}{(s - m_\phi^2)^2}\,, \quad s = (E_{1\mathrm{cm}} + E_{2\mathrm{cm}})^2 \approx 4m_\chi^2(1 + v^2)$$

- close to thresholds of annihilation channels $\chi\chi \to XX$ with $m_\chi \approx m_X$:

$$\sigma v \propto \sqrt{s - 4m_X^2}$$

- in the presence of other particles close in mass, which participate in the annihilations ("co-annihilations")

$$\chi_1\chi_1 \leftrightarrow XX\,, \quad \chi_1\chi_2 \leftrightarrow XX'\,, \quad \chi_2\chi_2 \leftrightarrow XX$$

Expansion in v is not accurate in the following cases:

Griest, Seckel, 1991

- close to an s-channel resonance ($2m_\chi \approx m_\phi$):

$$\sigma v \propto \frac{1}{(s - m_\phi^2)^2}\,, \quad s = (E_{1\mathrm{cm}} + E_{2\mathrm{cm}})^2 \approx 4m_\chi^2(1 + v^2)$$

- close to thresholds of annihilation channels $\chi\chi \to XX$ with $m_\chi \approx m_X$:

$$\sigma v \propto \sqrt{s - 4m_X^2}$$

- in the presence of other particles close in mass, which participate in the annihilations ("co-annihilations")

$$\chi_1\chi_1 \leftrightarrow XX\,, \quad \chi_1\chi_2 \leftrightarrow XX'\,, \quad \chi_2\chi_2 \leftrightarrow XX$$

- For accurate relic density calculation use the Gondolo, Gelmini integral for the thermally averaged cross section and solve the rate equation numerically

- Public codes: micrOMEGAs, Dark SUSY

Classic papers:

- B. W. Lee and S. Weinberg, "Cosmological lower bound on heavy-neutrino masses," Phys. Rev. Lett. **39** (1977) 165.
- J. Bernstein, L. S. Brown, G. Feinberg, "The Cosmological Heavy Neutrino Problem Revisited," Phys. Rev. **D32**, 3261 (1985).
- R. J. Scherrer, M. S. Turner, "On the Relic, Cosmic Abundance of Stable Weakly Interacting Massive Particles," Phys. Rev. **D33**, 1585 (1986).

Classic textbook:

- Kolb, Turner, The Early Universe.

Accurate and pedagogic discussion:

- P. Gondolo and G. Gelmini, "Cosmic abundances of stable particles: Improved analysis," Nucl. Phys. B **360** (1991) 145.

Exceptions and co-annihilations:

- K. Griest and D. Seckel, "Three exceptions in the calculation of relic abundances," Phys. Rev. D **43** (1991) 3191.
- J. Edsjo and P. Gondolo, "Neutralino Relic Density including Coannihilations," Phys. Rev. D **56** (1997) 1879 [hep-ph/9704361].

Outline

The "WIMP miracle"

$$\Omega h^2 \simeq \frac{10^{-37}\,\mathrm{cm}^2}{\langle \sigma_{\rm ann} v \rangle} = 0.1126 \pm 0.0036 \text{ [WMAP]}$$

need $\sigma_{\rm ann} v \sim 10^{-36}\,\mathrm{cm}^2 = 1\,\mathrm{pb}$ to obtain correct relic abundance

"typical" cross section for particles at the weak scale:

$$\Lambda_{\rm weak} \sim \langle H \rangle = 250 \text{ GeV}$$

s-wave annihilations of a particle χ due to mediator ϕ:

$$\langle \sigma_{\rm annih} v \rangle \sim \begin{cases} \frac{g^4}{\pi}\frac{m_\chi^2}{m_\phi^4} \simeq 10^{-36}\mathrm{cm}^2\, g^4 \left(\frac{m_\chi}{100\,\mathrm{GeV}}\right)^2 \left(\frac{1\,\mathrm{TeV}}{m_\phi}\right)^4 & m_\phi \gg m_\chi \\ \frac{g^4}{16\pi m_\chi^2} \simeq 10^{-36}\mathrm{cm}^2 \left(\frac{g}{0.3}\right)^4 \left(\frac{200\,\mathrm{GeV}}{m_\chi}\right)^2 & m_\phi \ll m_\chi \end{cases}$$

The "WIMP miracle"

$$\Omega h^2 \simeq \frac{10^{-37}\,\mathrm{cm}^2}{\langle \sigma_{\mathrm{ann}} v \rangle} = 0.1126 \pm 0.0036 \text{ [WMAP]}$$

need $\sigma_{\mathrm{ann}} v \sim 10^{-36}\,\mathrm{cm}^2 = 1\,\mathrm{pb}$ to obtain correct relic abundance

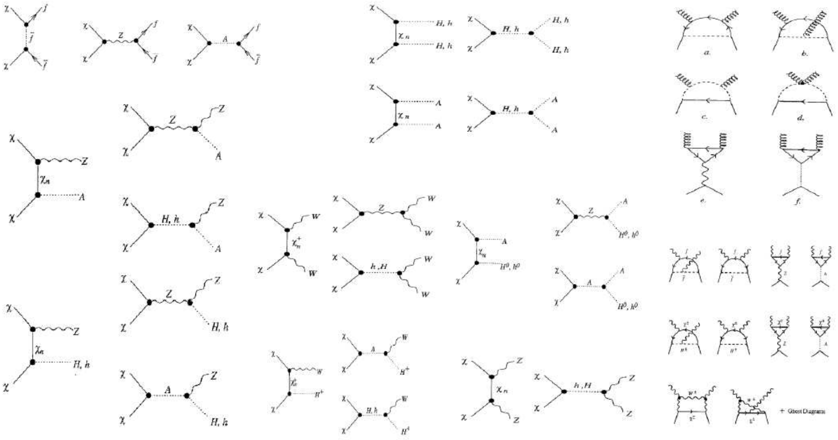
"typical" cross section for particles at the weak scale:

$$\Lambda_{\mathrm{weak}} \sim \langle H \rangle = 250\ \mathrm{GeV}$$

s-wave annihilations of a particle χ due to mediator ϕ:

$$\langle \sigma_{\mathrm{annih}} v \rangle \sim \begin{cases} \frac{g^4}{\pi}\frac{m_\chi^2}{m_\phi^4} \simeq 10^{-36}\mathrm{cm}^2\, g^4 \left(\frac{m_\chi}{100\,\mathrm{GeV}}\right)^2 \left(\frac{1\,\mathrm{TeV}}{m_\phi}\right)^4 & m_\phi \gg m_\chi \\ \frac{g^4}{16\pi m_\chi^2} \simeq 10^{-36}\mathrm{cm}^2 \left(\frac{g}{0.3}\right)^4 \left(\frac{200\,\mathrm{GeV}}{m_\chi}\right)^2 & m_\phi \ll m_\chi \end{cases}$$

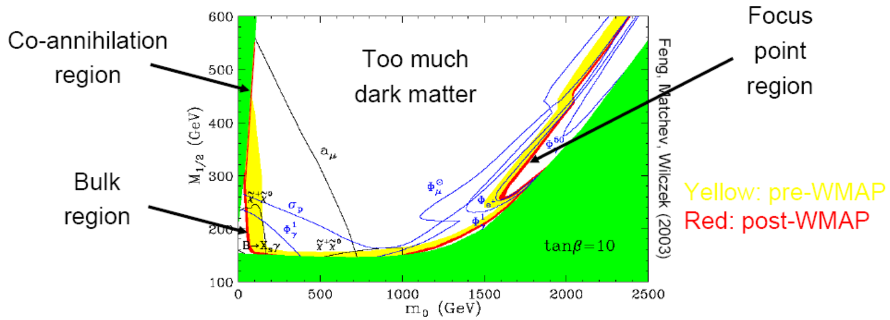
MSSM neutralino annihilation



G. Jungman, M. Kamionkowski, K. Griest, "Supersymmetric Dark Matter" Phys. Rept. 267 (1996) 195-373

CMSSM relic density constraint

- Ω_{DM} = 23% ± 4% stringently constrains models



- Assuming standard Big Bang, cosmology excludes many possibilities, favors certain regions

m_0: universal soft SUSY breaking scalar mass @ GUT scale
$M_{1/2}$: universal gaugino mass @ GUT scale

J. Feng @ COSMO 09

see talk by A. Masiero

Relic density constraint

$$\Omega h^2 \simeq \frac{10^{-37}\,\mathrm{cm}^2}{\langle \sigma_{\mathrm{ann}} v \rangle} = 0.1126 \pm 0.0036 \text{ [WMAP]}$$

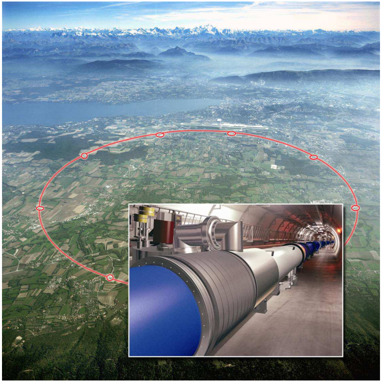
the requirement to obtain the correct relic density by thermal freeze out provides a stringent constraint on any model

BUT:

- under-abundant thermal DM ($\langle \sigma_{\mathrm{ann}} v \rangle$ too large):
  non-thermal production, additional DM component, ...
- over-abundant thermal DM ($\langle \sigma_{\mathrm{ann}} v \rangle$ too small):
  late entropy production, ...

What's so special about the "weak scale"?

What's so special about the "weak scale"?



What's so special about the "weak scale"?

We expect new physics to show up at the weak scale:

SM is an effective theory only up to some high scale Λ
loop correction to the Higgs mass:

$$\delta m_H^2 = \frac{3\Lambda^2}{8\pi\langle H\rangle}(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2) \sim -(0.23\Lambda)^2$$

tuning of $(m_H)_0$ against δm_H $\rightarrow$ "hierarchy problem"

$\Rightarrow$ introduce new physics at $\Lambda \sim$ TeV to cancel divergences
(SUSY, extra dimension, technicolor,...)

lecture by G. Servant

What's so special about the "weak scale"?

We expect new physics to show up at the weak scale:

SM is an effective theory only up to some high scale Λ
loop correction to the Higgs mass:

$$\delta m_H^2 = \frac{3\Lambda^2}{8\pi\langle H\rangle}(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2) \sim -(0.23\Lambda)^2$$

tuning of $(m_H)_0$ against $\delta m_H \to$ "hierarchy problem"

$\Rightarrow$ introduce new physics at $\Lambda \sim$ TeV to cancel divergences
(SUSY, extra dimension, technicolor,...)

lecture by G. Servant

New physics at the weak scale

BUT: the new physics has to be "special":

- not seen at LEP/TeVatron (EWPT, direct searches)
  "little hierarchy" (100 GeV $\leftrightarrow$ 10 TeV)
- no new flavor violating processes
- proton lifetime

introduce "parity" to protect the Standard Model:
new particles odd, SM particles even $\Rightarrow$

lightest of the new physics particles becomes stable
$\longrightarrow$ potential DM candidate

New physics at the weak scale

BUT: the new physics has to be "special":

- not seen at LEP/TeVatron (EWPT, direct searches)
  "little hierarchy" (100 GeV $\leftrightarrow$ 10 TeV)
- no new flavor violating processes
- proton lifetime

introduce "parity" to protect the Standard Model:
new particles odd, SM particles even $\Rightarrow$

lightest of the new physics particles becomes stable
$\rightarrow$ potential DM candidate

New physics at the weak scale

- introduce new physics model to solve the hierarchy problem and get a DM candidate as "extra bonus"
  SUSY, new dimensions, Little Higgs, Technicolor/composite Higgs,...

- just introduce new particles at the TeV scale to get a WIMP
  scalar singlet, inert doublet, minimal DM, hidden sector models,...

G. Servant

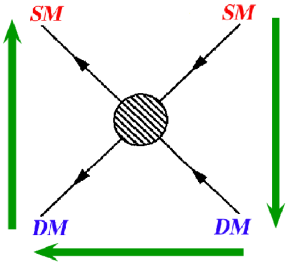
New physics at the weak scale

- introduce new physics model to solve the hierarchy problem and get a DM candidate as "extra bonus"
  SUSY, new dimensions, Little Higgs, Technicolor/composite Higgs,...

- just introduce new particles at the TeV scale to get a WIMP
  scalar singlet, inert doublet, minimal DM, hidden sector models,...

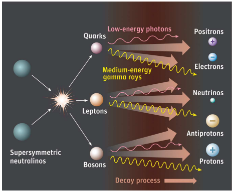
G. Servant

Testing the WIMP hypothesis

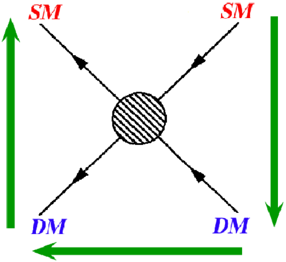


Testing the WIMP hypothesis

indirect detection

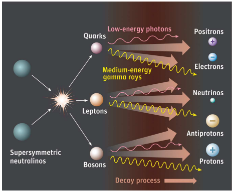


PAMELA, FERMI, AMS-II, IceCube, HESS, ...
talks by C. de los Heros, M. Cirelli



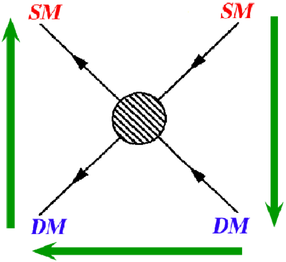
Testing the WIMP hypothesis

indirect detection

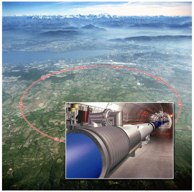


PAMELA, FERMI, AMS-II, IceCube, HESS, ...

talks by C. de los Heros, M. Cirelli



colliders

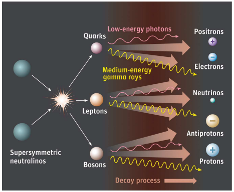


LHC at CERN

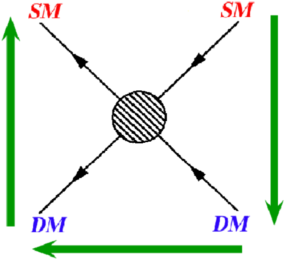
talk by T. Plehn

Testing the WIMP hypothesis

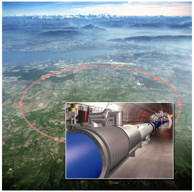
indirect detection



PAMELA, FERMI, AMS-II, IceCube, HESS, ...
talks by C. de los Heros, M. Cirelli



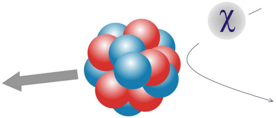
colliders



LHC at CERN

talk by T. Plehn

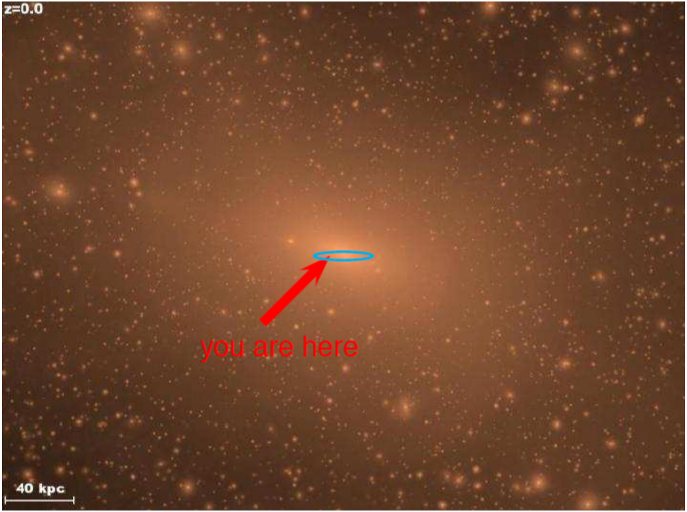
direct detection



XENON, LUX, CDMS, CRESST, DEAP, COUPP, EURECA,...
talk by J. Jochum

Outline

Dark Matter in a Milkyway-like Galaxy



Via Lactea N-body DM simulation Diemand, Kuhlen, Madau, astro-ph/0611370

see talk by V. Springel

Local Dark Matter density

"standard halo model":

local DM density: $\rho_\chi \approx 0.389 \pm 0.025\,\mathrm{GeV\,cm^{-3}}$ Catena, Ullio, 0907.0018

Maxwellian velocity distribution (in halo rest frame)

$$f_{\rm gal}(\vec{v}) \approx \begin{cases} N \exp\left(-v^2/\bar{v}^2\right) & v < v_{\rm esc} \\ 0 & v > v_{\rm esc} \end{cases}$$

with $\bar{v} \simeq 220$ km/s and $v_{\rm esc} \simeq 600$ km/s

Local Dark Matter density

"standard halo model":

local DM density: $\rho_\chi \approx 0.389 \pm 0.025\,\mathrm{GeV\,cm^{-3}}$ Catena, Ullio, 0907.0018

Maxwellian velocity distribution (in halo rest frame)

$$f_{\mathrm{gal}}(\vec{v}) \approx \begin{cases} N \exp\left(-v^2/\bar{v}^2\right) & v < v_{\mathrm{esc}} \\ 0 & v > v_{\mathrm{esc}} \end{cases}$$

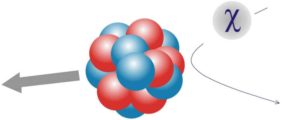
with $\bar{v} \simeq 220$ km/s and $v_{\mathrm{esc}} \simeq 600$ km/s

$\Rightarrow$ local DM flux: $\phi_\chi \sim 10^5\,\mathrm{cm^{-2}s^{-1}} \left(\frac{100\,\mathrm{GeV}}{m_\chi}\right) \left(\frac{\rho_\chi}{0.4\,\mathrm{GeV\,cm^{-3}}}\right)$

solar neutrinos: $\phi_\nu \sim 6 \times 10^{10}\,\mathrm{cm^{-2}s^{-1}}$

DM direct detection

assuming DM has non-gravitational interactions (“WIMP”)
look for recoil of DM-nucleus scattering M. Goodman, E. Witten, PRD 1985



PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses 1—10^6 GeV; particles with spin-dependent interactions of typical weak strength and masses 1—10^2 GeV; or strongly interacting particles of masses 1—10^{13} GeV.

DM direct detection

colliding a $\sim$ 100 GeV DM particle with a $\sim$ 100 GeV nucleus
DM velocity: $v \sim 10^{-3}$c $\Rightarrow$ non-relativistic

$$\text{recoil energy:} \quad E_R = \frac{2\mu^2 v^2}{m_A} \cos^2\theta_{\text{lab}} \sim 10\,\mathrm{keV}$$

counts / day / kg detector mass / keV recoil energy E_R:

$$\frac{dN}{dE_R}(t) = \frac{1}{m_A}\frac{\rho_\chi}{m_\chi}\int_{v>v_{\min}} d^3v\, \frac{d\sigma}{dE_R}\, v\, f_\oplus(\vec{v}, t)$$

ρ_χ DM energy density, default $\approx$ 0.3 GeV cm^{-3}
m_A: mass of the target nucleus with mass number A
$v_{\min}$: minimal DM velocity required to produce recoil energy E_R

$$\text{elastic scattering:} \quad v_{\min} = \sqrt{\frac{m_A E_R}{2\mu^2}}\,, \quad \mu = \frac{m_\chi m_A}{m_\chi + m_A}$$

DM direct detection

colliding a $\sim$ 100 GeV DM particle with a $\sim$ 100 GeV nucleus
DM velocity: $v \sim 10^{-3}$c $\Rightarrow$ non-relativistic

$$\text{recoil energy:} \quad E_R = \frac{2\mu^2 v^2}{m_A} \cos^2\theta_{\text{lab}} \sim 10\,\text{keV}$$

counts / day / kg detector mass / keV recoil energy E_R:

$$\boxed{\frac{dN}{dE_R}(t) = \frac{1}{m_A}\frac{\rho_\chi}{m_\chi}\int_{v>v_{\min}} d^3v\,\frac{d\sigma}{dE_R}\,v\,f_\oplus(\vec{v},t)}$$

ρ_χ DM energy density, default ≈ 0.3 GeV cm^{-3}
m_A: mass of the target nucleus with mass number A
$v_{\min}$: minimal DM velocity required to produce recoil energy E_R

$$\text{elastic scattering:} \quad v_{\min} = \sqrt{\frac{m_A E_R}{2\mu^2}}\,, \quad \mu = \frac{m_\chi m_A}{m_\chi + m_A}$$

DM velocity distribution

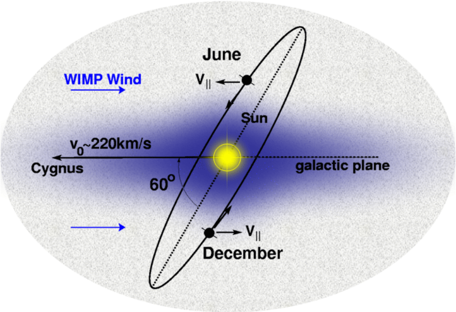
in Earth rest frame $f_\oplus$ $\rightarrow$ Galilei trafo from galaxy rest frame $f_{\rm gal}$:

$$f_\oplus(\vec{v},t) = f_{\rm gal}(\vec{v} + \vec{v}_\odot + \vec{v}_\oplus(t)) \qquad f_{\rm gal}(\vec{v}) \approx \begin{cases} N \exp\left(-v^2/\bar{v}^2\right) & v < v_{\rm esc} \\ 0 & v > v_{\rm esc} \end{cases}$$

$\bar{v} \simeq 220\,\mathrm{km/s}$ $\quad$ $v_{\rm esc} \simeq 550\,\mathrm{km/s}$

sun velocity: $\vec{v}_\odot = (0, 220, 0) + (10, 13, 7)\,\mathrm{km/s}$

earth velocity: $\vec{v}_\oplus(t)$ with $v_\oplus \approx 30\,\mathrm{km/s}$



Velocity distribution integral

$$\frac{dN}{dE_R}(t) = \frac{1}{m_A}\frac{\rho_\chi}{m_\chi}\int_{v>v_{\rm min}} d^3v \, \frac{d\sigma}{dE_R} \, v \, f_\oplus(\vec{v}, t)$$

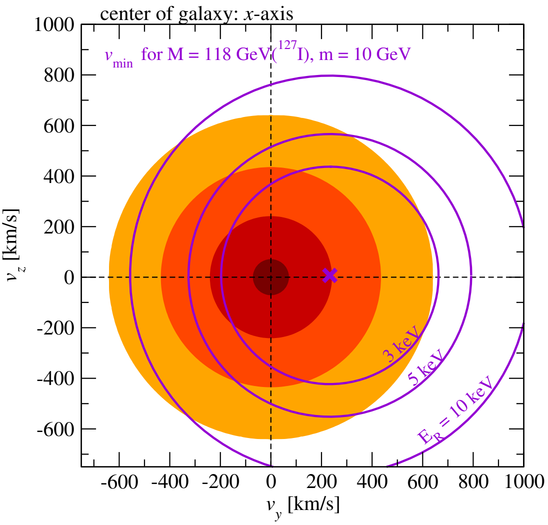
differential cross section

$$\frac{d\sigma}{dE_R} = \frac{1}{32\pi}\frac{\overline{|\mathcal{M}|^2}}{m_A m_\chi^2 v^2}$$

in many interesting cases $\overline{|\mathcal{M}|^2}$ is constant (indep of v) $\Rightarrow$

$$\eta(E_R, t) = \int_{v>v_{\rm min}(E_R)} d^3v \, \frac{f_\oplus(\vec{v}, t)}{v}$$

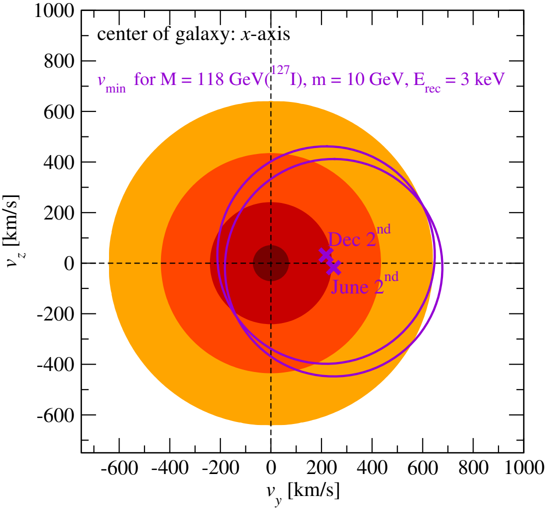
Velocity distribution integral



$$\int_{v>v_{\min}} d^3v \, \frac{f_\oplus(\vec{v},t)}{v}$$

$$v_{\min} = \sqrt{\frac{m_A E_R}{2\mu^2}}$$

Velocity distribution integral

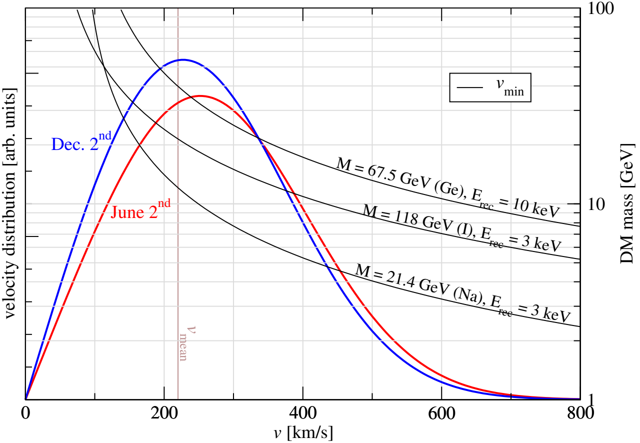


$$\int_{v>v_{\min}} d^3v \, \frac{f_{\oplus}(\vec{v},t)}{v}$$

$$v_{\min} = \sqrt{\frac{m_A E_R}{2\mu^2}}$$

Velocity distribution integral

$$\eta(E_R, t) \propto \frac{1}{v_{\rm obs}(t)} \int_{v_{\rm min}(E_R)}^{\infty} dv \left[e^{-\left(\frac{v - v_{\rm obs}(t)}{\bar{v}}\right)^2} - e^{-\left(\frac{v + v_{\rm obs}(t)}{\bar{v}}\right)^2} \right]$$



$$v_{\rm min} = \sqrt{\frac{m_A E_R}{2\mu^2}}$$

$$v_{\rm obs}(t) = |\vec{v}_\odot + \vec{v}_\oplus(t)|$$

DM nucleon scattering cross section

assume effective interaction of DM with SM ⇒ Example: fermionic DM

$$\mathcal{L}_{\rm eff} = \frac{1}{\Lambda^2}\,(\bar\chi\Gamma_{\rm dark}\chi)\,(\bar\psi\Gamma_{\rm vis}\psi)$$

	S	P	V	A	T	AT
$\Gamma_{\rm dark,vis}$	1	γ_5	γ_μ	$\gamma_\mu\gamma_5$	$\sigma_{\mu\nu}$	$\sigma_{\mu\nu}\gamma_5$

calculate $\langle N|\bar\psi\Gamma_{\rm vis}\psi|N\rangle$ ⇒

match to nucleus level (form factors) ⇒

non-rel limit of DM current

DM nucleon scattering cross section

assume effective interaction of DM with SM $\Rightarrow$ Example: fermionic DM

$$\mathcal{L}_{\rm eff} = \frac{1}{\Lambda^2}\,(\bar\chi\Gamma_{\rm dark}\chi)\,(\bar\psi\Gamma_{\rm vis}\psi)$$

	S	P	V	A	T	AT
$\Gamma_{\rm dark,vis}$	1	γ_5	γ_μ	$\gamma_\mu\gamma_5$	$\sigma_{\mu\nu}$	$\sigma_{\mu\nu}\gamma_5$

calculate $\langle N|\bar\psi\Gamma_{\rm vis}\psi|N\rangle \Rightarrow$

match to nucleus level (form factors) $\Rightarrow$

non-rel limit of DM current

- $(S\otimes S), (V\otimes V)$: spin-independent $\Rightarrow$ A^2 enhancement
- $(A\otimes A), (T\otimes T)$: spin-dependent $\Rightarrow$ unpaired n or p
- other combinations are suppressed by $\mathcal{O}(q^2/m_N^2, v^2) \sim 10^{-6}$

e.g., A. Kurylov, M. Kamionkowski, hep-ph/0307185

applies also for scalar/vector DM

Going from quark level to nucleon level

example: consider quark operator $G_q \bar{q} q \bar{\chi} \chi$ (SI interact.) $\rightarrow$

eff. coupling to nucleon $N = p, n$: $f_N = \sum_q G_q \langle N | \bar{q} q | N \rangle$

can relate $\langle N | \bar{q} q | N \rangle$ to measurable/calculable quantities:

$$\frac{m_u}{m_d}, \quad \frac{m_s}{m_d}, \quad \sigma_{\pi N} = \frac{m_u + m_d}{2} (\langle \bar{u} u \rangle + \langle \bar{d} d \rangle), \quad \frac{\sigma_0}{\sigma_{\pi N}} = \frac{\langle \bar{u} u \rangle + \langle \bar{d} d \rangle - 2 \langle \bar{s} s \rangle}{\langle \bar{u} u \rangle + \langle \bar{d} d \rangle}$$

$$f_N = \sum_{q=u,s,d} G_q \frac{m_N}{m_q} \xi_q^N + \frac{2}{27} \left(1 - \sum_{q=u,s,d} \xi_q^N \right) \sum_{q=c,b,t} G_q \frac{m_N}{m_q}$$

$$\xi_d^p \approx 0.033, \quad \xi_u^p \approx 0.023, \quad \xi_s^p \approx 0.26$$
$$\xi_d^n \approx 0.042, \quad \xi_u^n \approx 0.018, \quad \xi_s^n \approx 0.26$$

e.g., Ellis, Olive, Savage, 0801.3656

Going from quark level to nucleon level

example: consider quark operator $G_q \bar{q} q \bar{\chi} \chi$ (SI interact.) $\rightarrow$

eff. coupling to nucleon $N = p, n$: $f_N = \sum_q G_q \langle N | \bar{q} q | N \rangle$

can relate $\langle N | \bar{q} q | N \rangle$ to measurable/calculable quantities:

$$\frac{m_u}{m_d}\,, \quad \frac{m_s}{m_d}\,, \quad \sigma_{\pi N} = \frac{m_u + m_d}{2} (\langle \bar{u} u \rangle + \langle \bar{d} d \rangle)\,, \quad \frac{\sigma_0}{\sigma_{\pi N}} = \frac{\langle \bar{u} u \rangle + \langle \bar{d} d \rangle - 2 \langle \bar{s} s \rangle}{\langle \bar{u} u \rangle + \langle \bar{d} d \rangle}$$

$$f_N = \sum_{q=u,s,d} G_q \frac{m_N}{m_q} \xi_q^N + \frac{2}{27} \left(1 - \sum_{q=u,s,d} \xi_q^N \right) \sum_{q=c,b,t} G_q \frac{m_N}{m_q}$$

$$\xi_d^p \approx 0.033\,, \quad \xi_u^p \approx 0.023\,, \quad \xi_s^p \approx 0.26$$
$$\xi_d^n \approx 0.042\,, \quad \xi_u^n \approx 0.018\,, \quad \xi_s^n \approx 0.26$$

e.g., Ellis, Olive, Savage, 0801.3656

Going from quark level to nucleon level

$$f_N = \sum_{q=u,s,d} G_q \frac{m_N}{m_q} \xi_q^N + \frac{2}{27} \left(1 - \sum_{q=u,s,d} \xi_q^N \right) \sum_{q=c,b,t} G_q \frac{m_N}{m_q}$$

$$\xi_d^p \approx 0.033\,, \quad \xi_u^p \approx 0.023\,, \quad \xi_s^p \approx 0.26$$
$$\xi_d^n \approx 0.042\,, \quad \xi_u^n \approx 0.018\,, \quad \xi_s^n \approx 0.26$$

examples:

Higgs mediated interactions: $G_q = \frac{\lambda y_q}{m_H^2} \propto m_q = y_q \langle H \rangle$

$$f_N = \frac{\lambda}{m_H^2} \frac{m_N}{\langle H \rangle} \sum_{q=u,s,d} \xi_q^N + \frac{2}{9} \left(1 - \sum_{q=u,s,d} \xi_q^N \right) \approx \frac{\lambda}{m_H^2} \frac{m_N}{\langle H \rangle} \xi_s^N$$

Higgs mediated interaction dominated by s-quark and $f_n \approx f_p$

Going from quark level to nucleon level

$$f_N = \sum_{q=u,s,d} G_q \frac{m_N}{m_q} \xi_q^N + \frac{2}{27} \left(1 - \sum_{q=u,s,d} \xi_q^N \right) \sum_{q=c,b,t} G_q \frac{m_N}{m_q}$$

$$\xi_d^p \approx 0.033\,, \quad \xi_u^p \approx 0.023\,, \quad \xi_s^p \approx 0.26$$
$$\xi_d^n \approx 0.042\,, \quad \xi_u^n \approx 0.018\,, \quad \xi_s^n \approx 0.26$$

examples:

flavour universal couplings: $G_q = G$

$$f_N \approx G m_N \sum_{q=u,s,d} \frac{\xi_q^N}{m_q}\,, \qquad \frac{m_d}{m_u} \simeq 2\,, \quad \frac{m_d}{m_u} \simeq 20$$

$\Rightarrow f_n \simeq f_p$

Going from nucleon to nucleus level

for coherent interaction on all nucleons in nucleus (A, Z):

$$\propto [f_p Z + f_n(A - Z)]^2$$

momentum transfer: $q = \sqrt{2 m_A E_R} \sim 20 - 100\,\mathrm{MeV} \sim 1/(10 - 2\,\mathrm{fm})$
when the momentum transfer becomes comparible to the size of the nuclues interactions will no longer be coherent $\rightarrow$
nucleus form factor $\sim$ Fourier transform of density distribution
(assume matter $\propto$ charge, charge distr. from electron scattering)
parameterization:

$$F(q^2) = 3 e^{-\frac{q^2 s^2}{2}} \frac{\sin(qr) - qr\cos(qr)}{(qr)^3}\,, \qquad s = 1\,\mathrm{fm}, r \sim A^{1/3}\,\mathrm{fm}$$

Going from nucleon to nucleus level

for coherent interaction on all nucleons in nucleus (A, Z):

$$\propto [f_p Z + f_n(A - Z)]^2$$

momentum transfer: $q = \sqrt{2m_A E_R} \sim 20 - 100\,\text{MeV} \sim 1/(10 - 2\,\text{fm})$
when the momentum transfer becomes comparible to the size of the nuclues interactions will no longer be coherent $\rightarrow$
nucleus form factor $\sim$ Fourier transform of density distribution
(assume matter $\propto$ charge, charge distr. from electron scattering)
parameterization:

$$F(q^2) = 3e^{-\frac{q^2 s^2}{2}} \frac{\sin(qr) - qr\cos(qr)}{(qr)^3}\,, \qquad s = 1\,\text{fm}, r \sim A^{1/3}\,\text{fm}$$

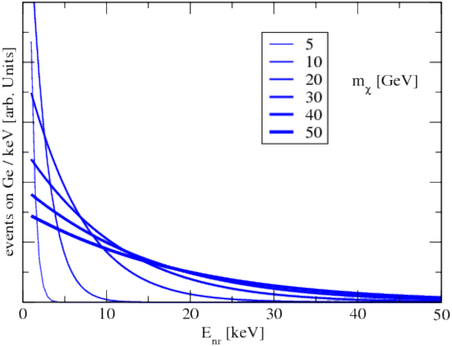
Event spectrum for SI elastic scattering

$$\frac{dN}{dE_R}(t) = \frac{\rho_\chi}{m_\chi} \frac{\sigma_p |F(q)|^2 A^2}{2\mu_p^2} \int_{v > v_{\min}(E_R)} d^3v \, \frac{f_\oplus(\vec{v}, t)}{v}$$

$v_{\min} = \frac{m_\chi + m_A}{m_\chi} \sqrt{\frac{E_R}{2m_A}}$

minimal v required

to produce recoil E_R

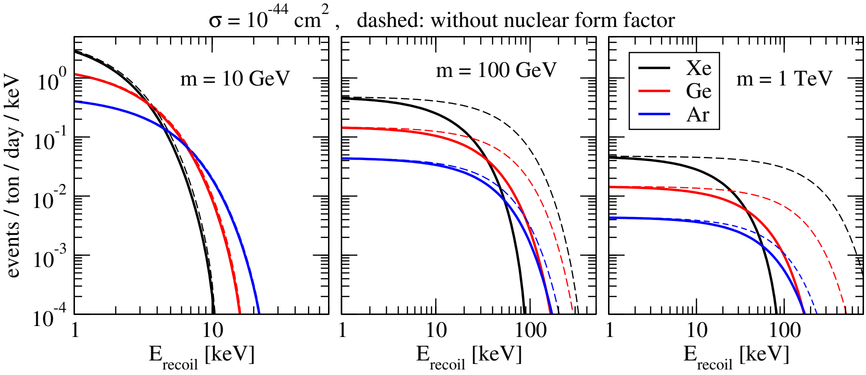


spectrum gets shifted to low energies for low WIMP masses

$\Rightarrow$ need light target and/or low threshold on E_R to see light WIMPs

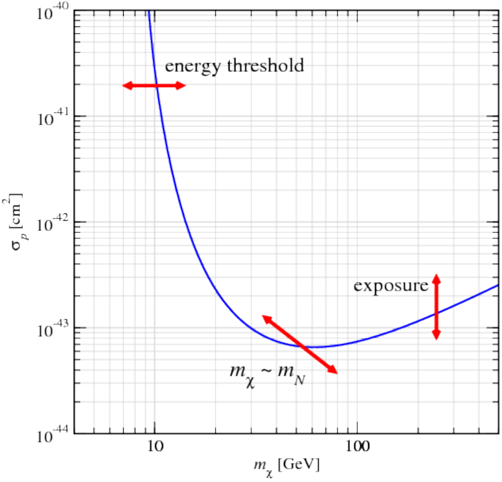
Event spectrum for SI elastic scattering

dependence on the target nucleus:



nuclear form factor is less important for low mass WIMPs

elastic scattering exclusion curve



Outline

- many exps. running and setting relevant limits:

  CDMS (Ge, Si), CoGeNT (Ge), COUPP (CF_3I), CRESST ($CaWO_4$), DAMA (NaI), Edelweiss (Ge), KIMS (CsI), PICASSO (F), SIMPLE (C_2ClF_5), TEXONO (Ge), XENON (Xe), ZEPLIN (Xe),. . .

  appologizes for the ones I forgot

different target materials and different techniques used

lecture by J. Jochum

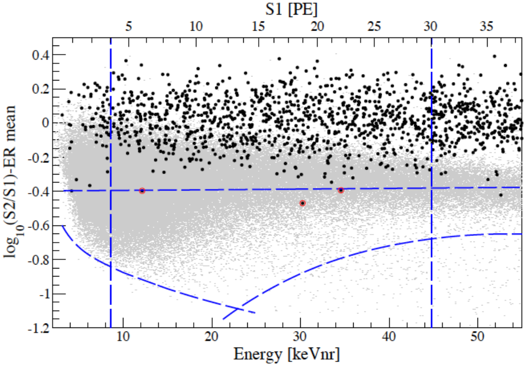
XENON100

2 phase (gas/liquid) Xenon detector @ Gran Sasso

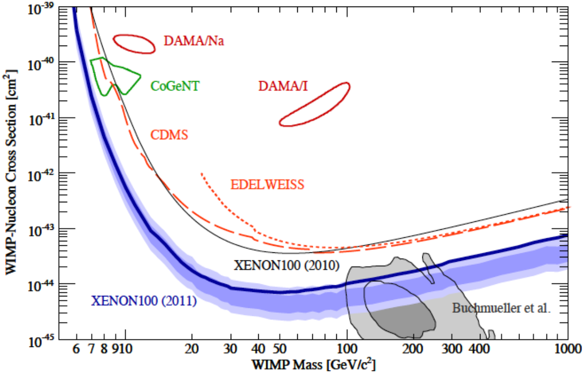
S1: prompt scintillation signal, S2: delayed ionization signal

48 kg fid., 100.9 days (Jan to June 2010) 1104.2549

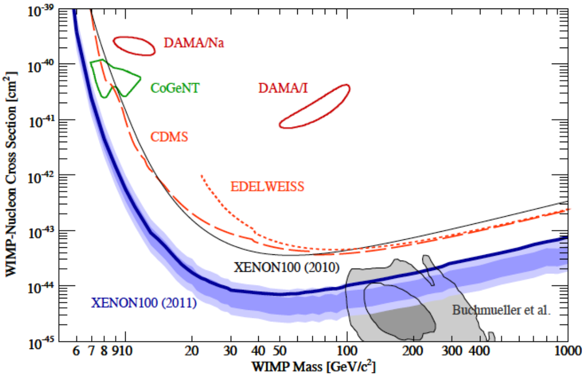
3 events observed, 1.8 ± 0.6 background expectation



XENON100 limit on spin-indep. interactions



XENON100 limit on spin-indep. interactions

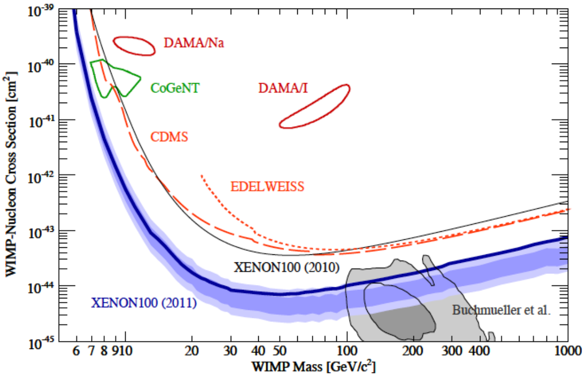


SI cross section: $\sigma_p \sim \frac{G_{\rm eff}^2 m_p^2}{\pi}$

Z_0 mediated interaction: $\sigma_p \sim \lambda_{\chi Z}^2 \frac{G_F^2 m_p^2}{\pi} \sim 10^{-38}\,{\rm cm}^2\,\lambda_{\chi Z}^2$

"heavy Dirac neutrino" is excuded as DM by many orders of magnitude

XENON100 limit on spin-indep. interactions



SI cross section: $\sigma_p \sim \frac{G_{\text{eff}}^2 m_p^2}{\pi}$

Higgs mediated interaction: $\sigma_p \sim 10^{-44}\,\text{cm}^2 \left(\frac{\lambda_\chi}{0.1}\right)^2 \left(\frac{115\,\text{GeV}}{m_H}\right)^4$

implications of $\sigma_{\rm scat} \lesssim 10^{-44}{\rm cm}^2$ for the WIMP argument

$$\Omega_\chi h^2 \simeq \frac{10^{-37}{\rm cm}^2}{\langle \sigma_{\rm annih} v \rangle} = 0.1126 \pm 0.0036$$

assume a Higgs mediated interaction:

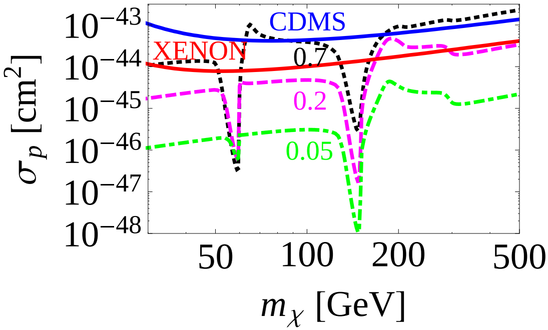
$$\mathcal{L} = \lambda_\chi H_1 \bar{\chi}\chi + y_q \bar{q}_L H_2 q_R + h.c. \quad \rightarrow \quad \langle \sigma_{\rm ann} v \rangle \approx \frac{3 m_\chi^2 \lambda_\chi^2 y_q^2 \langle v^2 \rangle}{8\pi (4 m_\chi^2 - m_H^2)^2}$$

$\Rightarrow$ for $m_\chi = 50$ GeV, $m_H = 115$ GeV, $\lambda_\chi = 0.1$:

$$\langle \sigma_{bb} v \rangle \approx 10^{-38}{\rm cm}^2$$

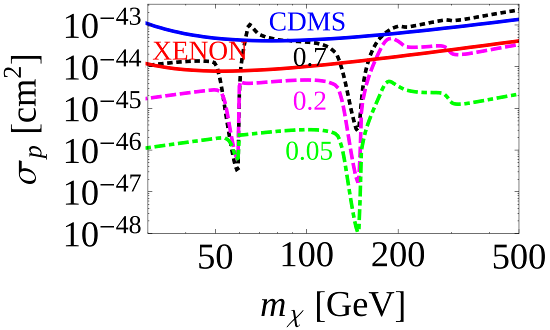
"typical" annihilation cross section is too low $\rightarrow$ overproduce DM

implications of $\sigma_{\rm scat} \lesssim 10^{-44}{\rm cm}^2$ for the WIMP argument



poster by D. Schmidt

implications of $\sigma_{\rm scat} \lesssim 10^{-44}\mathrm{cm}^2$ for the WIMP argument

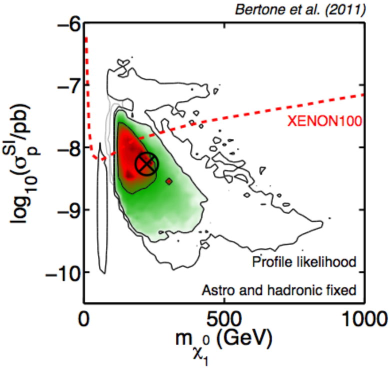


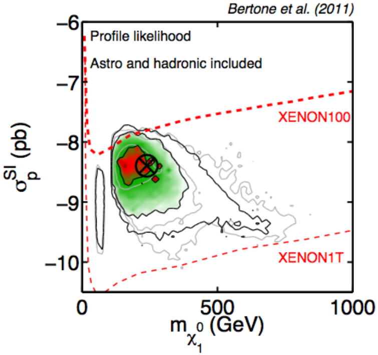
poster by D. Schmidt

need mechanism to enhance annihilation cross section:

- go to the *s*-channel resonance $2m_\chi \approx m_{\rm mediator}$
- additional annihilation channels ($W^\pm$, light mediator particles,...)
- co-annihilations
- ...

$\sigma_{\rm scat} \lesssim 10^{-44}{\rm cm}^2$ and the CMSSM





Bertone, Cerdeno, Ruiz de Austri, Fornasa, Strege, Trotta, 1107.1715

implications of $\sigma_{\rm scat} \lesssim 10^{-44}{\rm cm}^2$ for the WIMP argument

- XENON100 is probing an exciting region of parameter space, motivated by the argument of DM thermal freeze-out
- if no signal is found within 1-2 orders of magnitude in σ the WIMP hypothesis will come under pressure, and one should start to think about alternatives ("secluded" models, non-thermal DM production, non-WIMP candidates,. . .)

Outline

- a few experiments report "hints" for WIMP interactions:

  CoGeNT, DAMA, (CRESST?)

  ⇒ WIMPs (SI) in the low-mass (∼10 GeV) region?
  ⇒ or maybe something more exotic
  ⇒ or have nothing to do with DM at all

- Severe constraints from CDMS and XENON10/100

10 GeV WIMPs?

"conventional" WIMP has ~ 100 GeV

light WIMP must not couple to Z^0 (LEP)

Scalar singlet DM

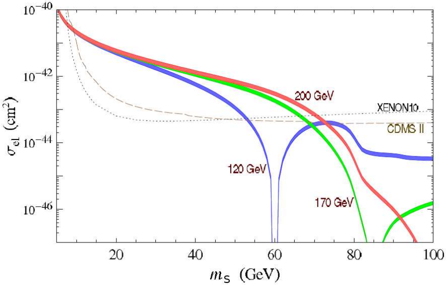
add scalar singlet to the SM with Z_2 symmetry

Silveira, Zee, 85; McDonald 94; Burgess, Pospelov, Veldhuis, 00; Andreas, Arina, Hambye, Ling, Tytgat, 1003.2595;...

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\nu S \partial^\nu S - \frac{1}{2}\mu^2 S^2 - \frac{1}{2}\lambda_1 S^4 - \lambda_2 S^2 H^\dagger H$$

communication with the SM via the "Higgs portal" λ_2

relic abundance obtained for $m_S \sim 10$ GeV with right cross section



He, Li, Li, Tandean, Tsai, 09

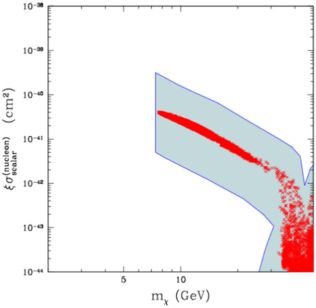
MSSM neutralino

LEP Z^0 invis width OK by making it mostly bino, but have to depart from CMSSM to make it light $\Rightarrow$ non-universal gaugino masses

e.g., Bottino, Donato, Fornengo, Scopel, 02,03,07,08,09; Hooper, Plehn, 02; Belanger, Boudjema, Cottrant, Pukhov, Rosier-Lees, 03; Asano, Matsumoto, Senami, Sugiyama, 09; Hisano, Nakayama, Yamanaka, 09; Kuflik, Pierce, Zurek, 1003.0682; Feldman, Liu, Nath, 1003.0437; Albornoz, Belanger, Boehm, Pukhov, Silk, 1009.4380; Fornengo, Scopel, Bottino, 1011.4743; Calibbi, Ota, Takanishi, 1104.1134

$B_s \to \mu^+\mu^-$, Tevatron light Higgs searches, B, K decays

fine-tuned region allows $m_\chi \sim 10$ GeV $\to$ tested soon



Belli et al., 1106.4667

MSSM extensions

- NMSSM (singlino component)

  e.g., Gunion, Hooper, McElrath, hep-ph/0509024; Bae, Kim, Shin, 1005.5131; Das, Ellwanger, 1007.1151; Belikov, Gunion, Hooper, Tait, 1009.0549; Gunion, Belikov, Hooper, 1009.2555; Draper, Liu, Wagner, Wang, Zhang, 1009.3963; Albornoz, Belanger, Boehm, Pukhov, Silk, 1009.4380; Kappl, Ratz, Winkler, 1010.0553

- sneutrino: MSSM + ν_R

  Arkani-Hamed, Hall, Murayama, Tucker-Smith, Weiner, 00; Belanger, Kakizaki, Park, Kraml, Pukhov, 1008.0580

Asymmetric Dark Matter

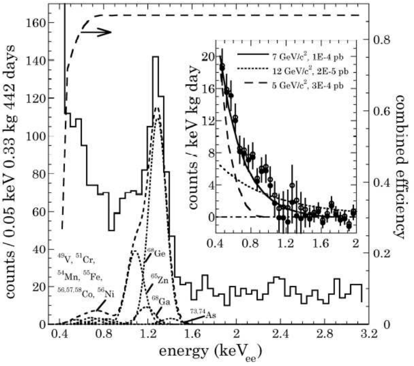
Nussinov, 1985; Barr, Chivukula, Farhi, 1990; Barr, 1991; Kaplan, 1992; Kaplan, Luty, Zurek, 0901.4117; An, Chen, Mohapatra, Zhang, 0911.4463; Shelton, Zurek, 1008.1997; Davoudiasl, Morrissey, Sigurdson, Tulin, 1008.2399; Haba, Matsumoto, 1008.2487; McDonald, 1009.3227; Chun, 1009.0983; Buckley, Randall, 1009.0270; Gu, Lindner, Sarkar, Zhang, 1009.2690; Blennow, Dasgupta, Fernandez-Martinez, Rius, 1009.3159; Allahverdi, Dutta, Sinha, 1011.1286 Falkowski, Ruderman, Volansky, 1101.4936; Haba, Matsumoto, Sato, 1101.5679; Graesser, Shoemaker, Vecchi, 1103.2771; Frandsen, Sarkar, Schmidt-Hoberg, 1103.4350; McDermott, Yu, Zurek, 1103.5472; Kouvaris, Tinyakov, 1104.0382; Buckley, 1104.1429;...

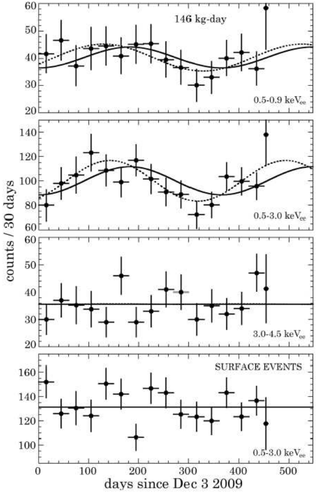
$$\frac{\Omega_{DM}}{\Omega_B} = \frac{n_{DM}}{n_B}\frac{m_{DM}}{m_p} \simeq 5$$

DM carries some quantum number; invoke common mechanism for baryon and DM genesis: $n_{\rm DM} \sim n_B \quad \Rightarrow \quad m_{\rm DM} \sim m_p$

CoGeNT: exponential event excess and hint for modulation

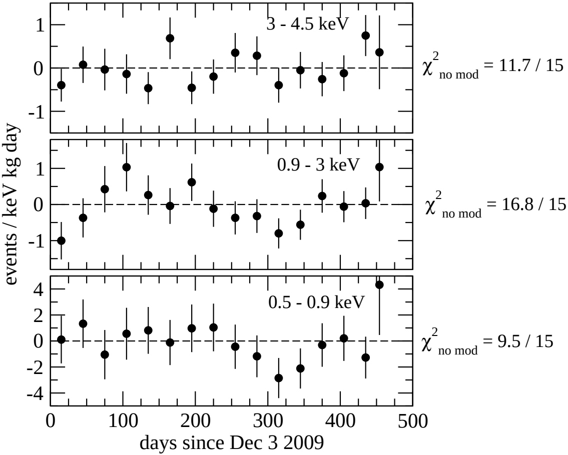
Germanium detector with very low threshold of 0.4 keVee $\approx$ 1.9 keV_{nr}





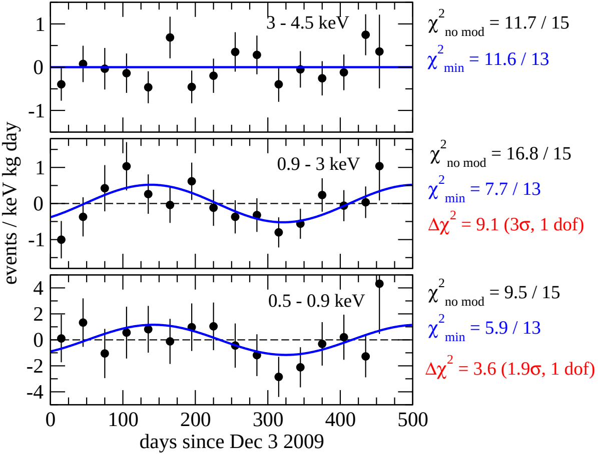
Aalseth et al, 1106.0650

Annual modulation in CoGeNT



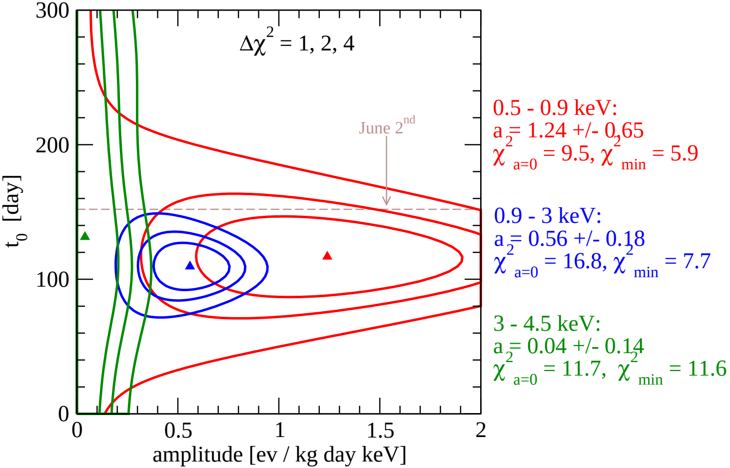
$0.5 - 3$ keV: $\chi^2_{\text{no mod}} = 20/15$ (17%)

Annual modulation in CoGeNT

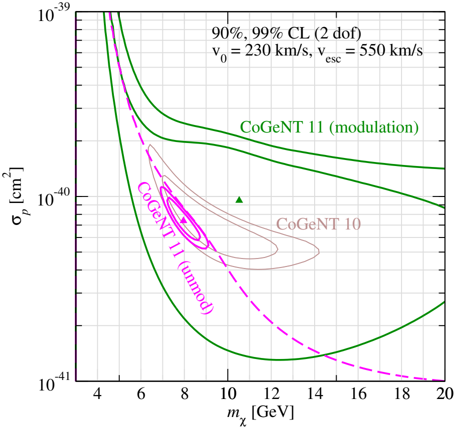


0.5 – 3 keV: 2.8σ preference for modulation Aalseth et al, 1106.0650

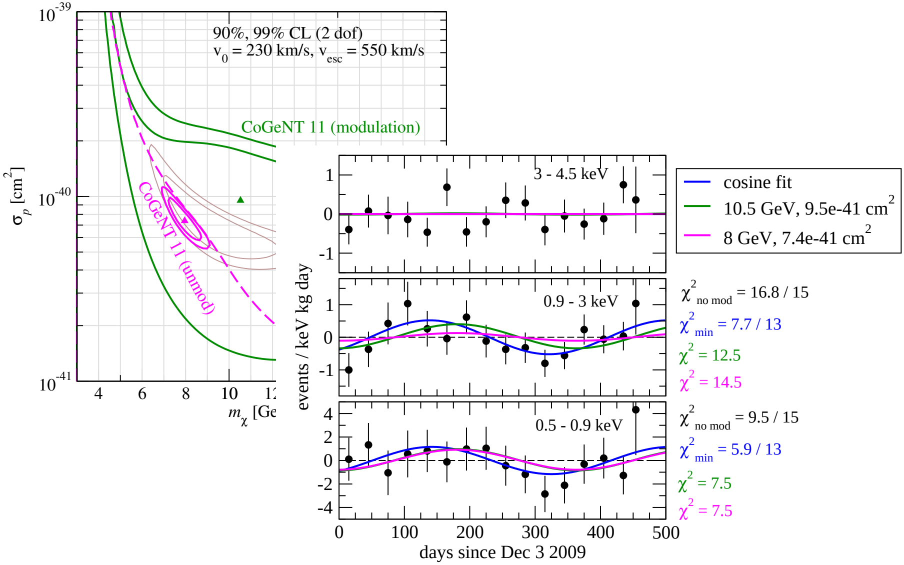
Annual modulation in CoGeNT



Fitting CoGeNT with elastic SI scattering

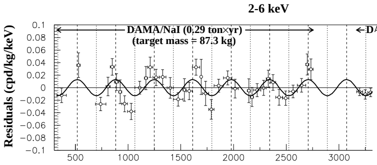


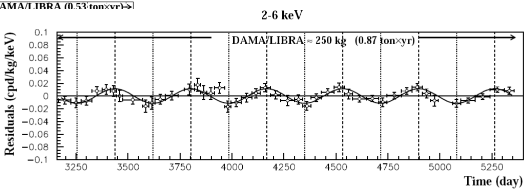
Fitting CoGeNT with elastic SI scattering

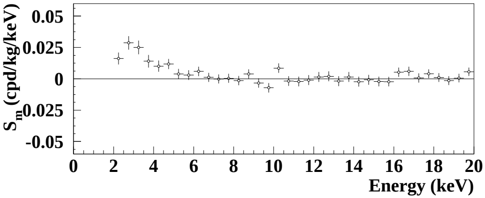


DAMA/LIBRA annual modulation signal

Scintillation light in NaI detector, 1.17 t yr exposure (13 yrs)
~ 1 cnts/d/kg/keV $\quad\rightarrow\quad \sim 4\times 10^5$ events/keV in DAMA/LIBRA
$\sim 8.9\sigma$ evidence for an annual modulation of the count rate with maximum at day 146 ± 7 (June 2nd: 152) Bernabei et al., 0804.2741, 1002.1028







energy shape of modulation is important for constraining params
Chang, Pierce, Weiner, 0808.0196
Fairbairn, TS, 0808.0704

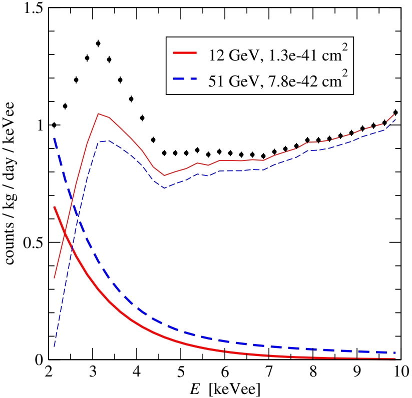
DAMA/LIBRA annual modulation signal

Scintillation light in NaI detector, 1.17 t yr exposure (13 yrs)

~ 1 cnts/d/kg/keV $\quad \rightarrow \quad \sim 4 \times 10^5$ events/keV in DAMA/LIBRA

$\sim 8.9\sigma$ evidence for an annual modulation of the count rate with maximum at day 146 ± 7 (June 2nd: 152) Bernabei et al., 0804.2741, 1002.1028

the time-integrated event rate in DAMA

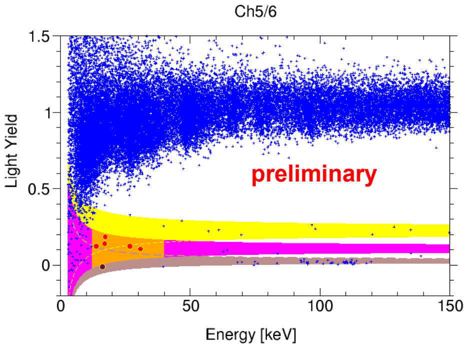


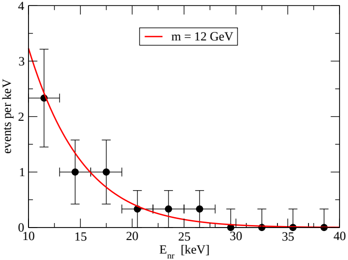
CRESST-II

Talks by W. Seidel @ WONDER 2010, IDM 2010

$CaWO_4$ target, 9 detectors, about 400 kg d

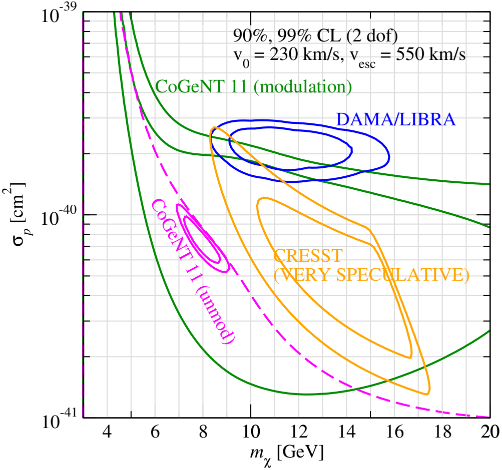
excess of single-scatter events in O-band (magenta)





observe 32 events, expect 8.7 ± 1.4 background
shape agrees with $\sim$ 10 GeV WIMP

Hints not quite consistent...

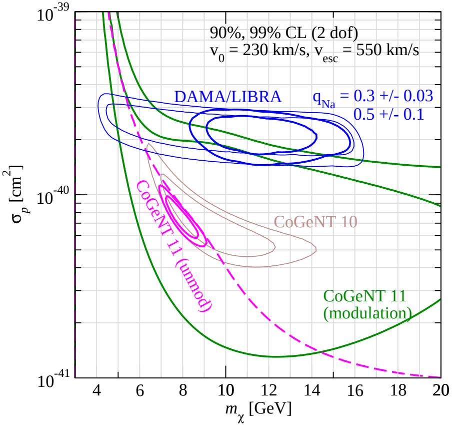


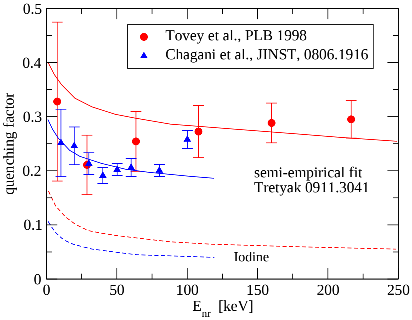
WARNING: CRESST region very speculative! ⇒ will change/go away(?) when detailed information on CRESST events and background becomes available

Can we make CoGeNT and DAMA consistent?

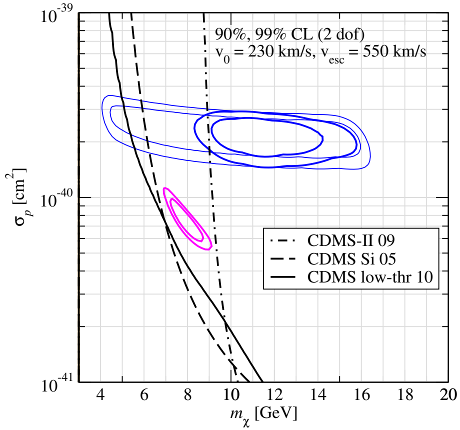
Hooper, Collar, Hall, McKinsey, 1007.1005; Hooper, Kelso, 1106.1066

How well do we know the quenching factor of Na?





CDMS constraints

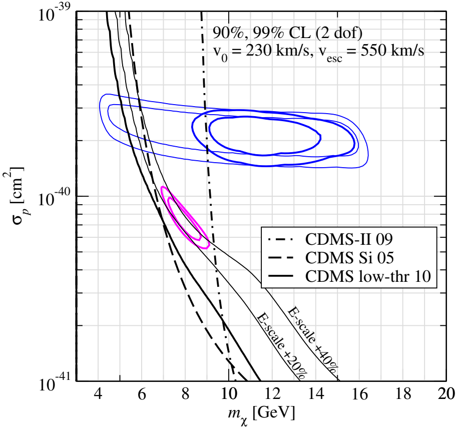


- CDMS data on Si astro-ph/0509259: 12 kg day, 7 keV threshold
- low-threshold analysis of Soudan Ge data (2006–08)

  1011.2482

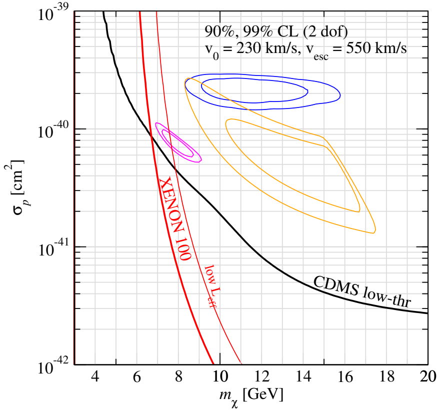
  do not insist on full NR/electr discrimination →
  accept some background →
  lower threshold to 2 keV

CDMS constraints



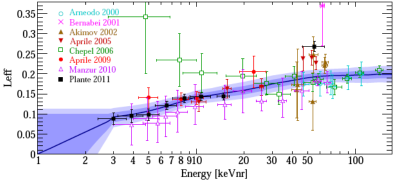
energy scale uncertainty in CDMS low-thr?

XENON bounds



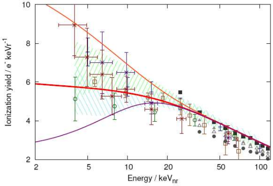
translate $S1$ [PE] into E_{nr} [keV]:

$$E_{nr} = \frac{S1}{L_{eff}(E_{nr})} \frac{1}{L_y} \frac{S_e}{S_n}$$

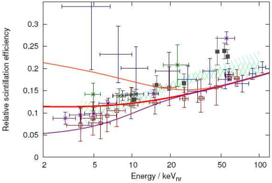


heated discussion: Collar, McKinsey, 1005.0838; XENON100, 1005.2615; Collar, McKinsey, 1005.2615; Savage et al., 1006.0972; Sorensen, 1007.3549; Collar, 1006.2031, 1106.0653

XENON bounds



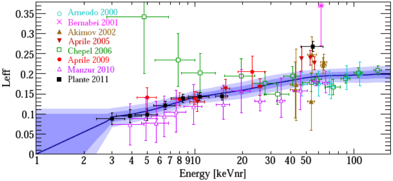
(a) The ionization yield



Bezrukov, Kahlhoefer, Lindner, 1011.3990

translate $S1$ [PE] into E_{nr} [keV]:

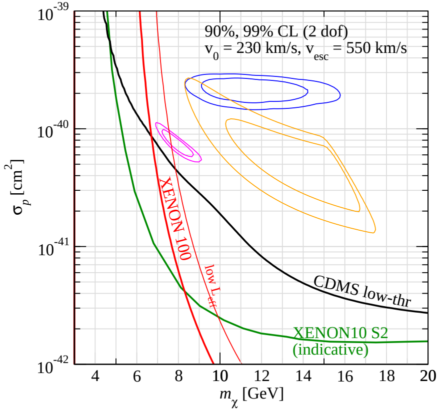
$$E_{nr} = \frac{S1}{L_{eff}(E_{nr})} \frac{1}{L_y} \frac{S_e}{S_n}$$



heated discussion: Collar, McKinsey, 1005.0838; XENON100, 1005.2615; Collar, McKinsey, 1005.2615; Savage et al., 1006.0972; Sorensen, 1007.3549; Collar, 1006.2031, 1106.0653

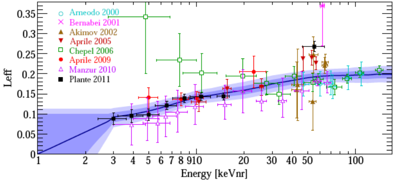
relation between ionization and scintillation suggest high L_{eff}.

XENON bounds



translate $S1$ [PE] into E_{nr} [keV]:

$$E_{nr} = \frac{S1}{L_{eff}(E_{nr})} \frac{1}{L_y} \frac{S_e}{S_n}$$



heated discussion: Collar, McKinsey, 1005.0838; XENON100, 1005.2615; Collar, McKinsey, 1005.2615; Savage et al., 1006.0972; Sorensen, 1007.3549; Collar, 1006.2031, 1106.0653

S2 only analysis of XENON 10 data Sorensen @ iDM 2010; J. Angle et al. 1104.3088

energy scale from ionization signal (S2) → independent of L_{eff}

see also Collar, 1010.5187, 1106.0653

How to reconcile?

- Experimental issues?
  $\sim$ 10 GeV region is experimentally challenging
  systematic uncertainties on quenching factors, energy scale, threshold effects, backgrounds... have to be understood and taken into account before making strong statements.

However, in order to get a consistent picture we need to assume that

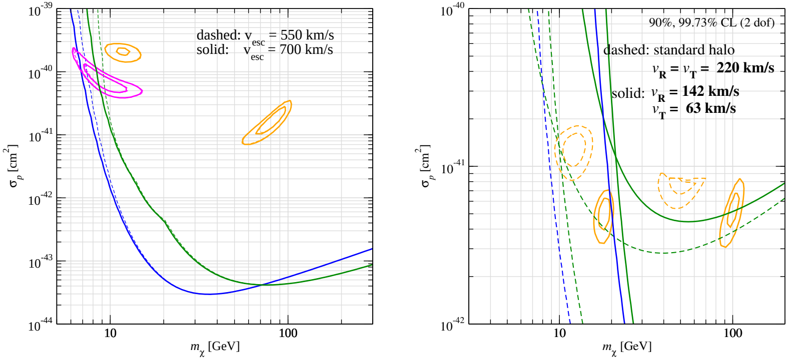
- CDMS made a major calibration error (in Ge and Si),
- the XENON S2 analysis is completely wrong,
- there is a serious problem with L_{eff} in Xenon, and
- major error in the Na quenching factor determination for DAMA

Modify astrophysics?

changing $\bar{v}$, $v_{\rm esc}$ has little impact on consistency

non-standard halos (asymmetric, DM streams, dark disc)

may marginally improve but require extreem params



left: value of $v_{\rm esc}$ TS, 1011.5432; right: asymmetric velocity distr. Fairbairn, TS 0808.0704

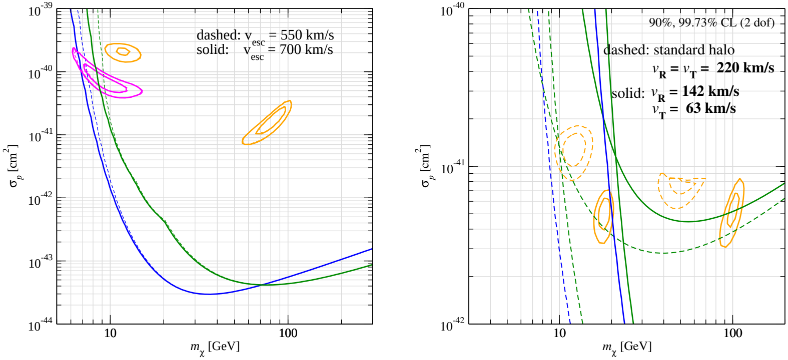
halo indep. comparison of experiments: Fox, Kribs, Tait 1011.1910; Fox, Liu, Weiner, 1011.1915

Modify astrophysics?

changing $\bar{v}$, $v_{\rm esc}$ has little impact on consistency

non-standard halos (asymmetric, DM streams, dark disc)

may marginally improve but require extreem params



left: value of $v_{\rm esc}$ TS, 1011.5432; right: asymmetric velocity distr. Fairbairn, TS 0808.0704

halo indep. comparison of experiments: Fox, Kribs, Tait 1011.1910; Fox, Liu, Weiner, 1011.1915

Outline

Let's depart from elastic SI scattering

- spin-dependent interaction
- inelastic DM Tucker-Smith, Weiner, hep-ph/0101138
- inelastic SD Kopp, Schwetz, Zupan, 0912.4264
- mirror DM R. Foot; An, Chen, Mohapatra, Nussinov, Zhang, 1004.3296
- leptophilic DM Fox, Poppitz, 0811.0399; Kopp, Niro, Schwetz, Zupan, 0907.3159
- form factor DM Feldstein, Fitzpatrick, Katz, 0908.2991
- momentum dep. DM Scattering Chang, Pierce, Weiner, 0908.3192
- resonant Dark Matter Bai, Fox, 0909.2900
- luminous Dark Matter Feldstein, Graham, Rajendran, 1008.1988
- electro-magnetic DM interactions Masso, Mohanty, Rao, 0906.1979; Chang, Weiner, Yavin, 1007.4200; Barger, Keung, Marfatia, 1007.4345; Fitzpatrick, Zurek, 1007.5325; Banks, Fortin, Thomas, 1007.5515
- iso-spin violating SI scattering Chang, Liu, Pierce, Weiner, Yavin, 1004.0697; Feng, Kumar, Marfatia, Sanford, 1102.4331; Frandsen et al., 1105.3734
- more to come

Spin-dependent scattering

coupling mainly to an un-paired nucleon:

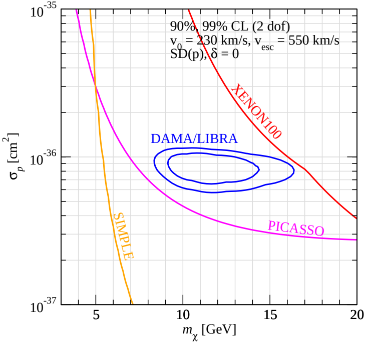
		neutron	proton
DAMA	$^{23}_{11}$Na	even	odd
DAMA, KIMS, COUPP	$^{127}_{53}$I	even	odd
SIMPLE	$^{35}_{17}$Cl, $^{37}_{17}$Cl	even	odd
XENON, ZEPLIN	$^{129}_{54}$Xe, $^{131}_{54}$Xe	odd	even
CDMS, CoGeNT	$^{73}_{32}$Ge	odd	even
PICASSO, COUPP, SIMPLE	$^{19}_{9}$F	even	odd
CRESST	$^{A}_{74}$W, $^{16}_{8}$O, $^{40}_{20}$Ca	even	even

coupling with proton promising for DAMA vs CDMS/XENON

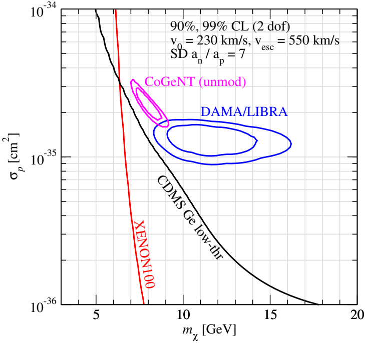
BUT: severe bounds from COUPP, KIMS, PICASSO, SIMPLE

Spin-dependent scattering

proton



(mainly) neutron



Schwetz, Zupan, 11

Constraints from Tevatron

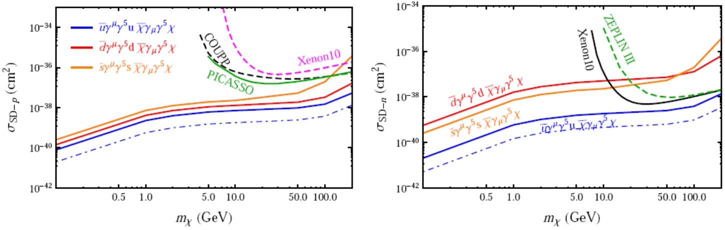
assume effective quark DM interaction:

$$\frac{\lambda^2}{\Lambda^2}(\bar{q}\gamma_5\gamma_\mu q)(\bar{\chi}\gamma_5\gamma^\mu\chi) \quad \Rightarrow \quad pp \to \bar{\chi}\chi + j$$

constraints from mono-jet searches at Tevatron

assume EFT is still valid at $\sim$TeV momentum transfer

e.g., Feng, Su, Takayama, hep-ph/0503117; Beltran et al., 1002.4137; Goodman et al., 1005.1286; ...



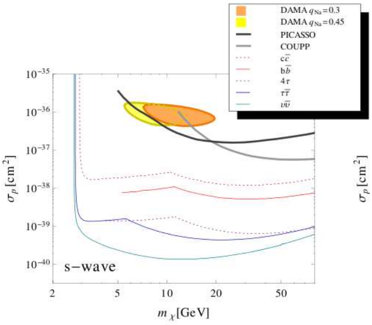
Bai, Fox, Harnik, 1005.3797

SD and constraints from neutrinos

SD interactions on protons → large WIMP capture cross section in the sun

WIMPs may annihilate and produce high energy neutrinos → constraints from SuperKamiokande

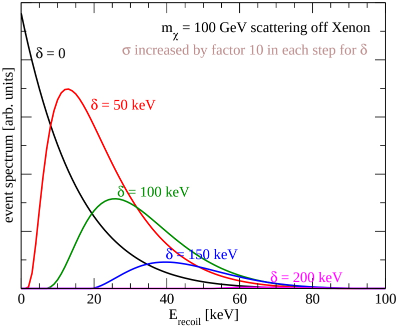
In relation to light DM: e.g., Feng, Kumar, Learned, Strigari, 0808.4151; Andreas, Tytgat, Swillens, 0901.1750; Niro, Bottino, Fornengo, Scopel, 0909.2348; Hooper, Petriello, Zurek, Kamionkowski, 0808.2464

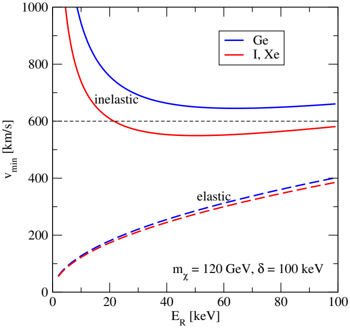


Kappl, Winkler, 1104.0679

Inelastic DM scattering Tucker-Smith, Weiner, 01

$$m_{\chi^*} - m_\chi = \delta \simeq 100\,\text{keV} \sim 10^{-6} m_\chi\,, \qquad v_{\text{min}}^{\text{inel}} = \frac{1}{\sqrt{2ME_R}}\left(\frac{ME_R}{\mu_\chi} + \delta\right)$$

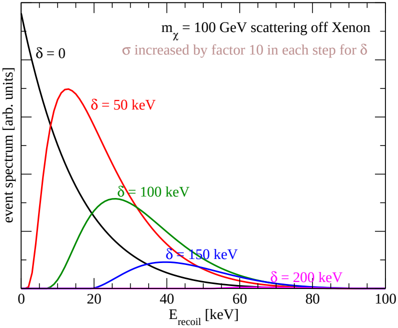


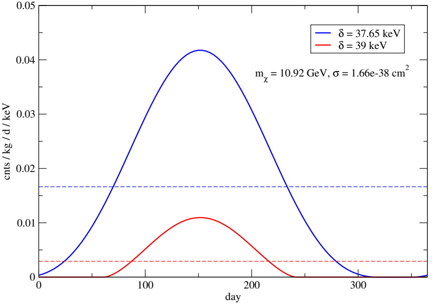


- sampling only high-velocity tail of velocity distribution
- no events at low recoil energies
- high mass targets favoured
- enhance modulation compared to unmodulated signal

Inelastic DM scattering Tucker-Smith, Weiner, 01

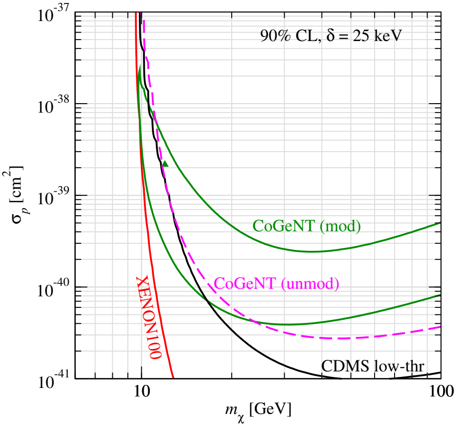
$$m_{\chi^*} - m_\chi = \delta \simeq 100\,\text{keV} \sim 10^{-6} m_\chi\,, \qquad v_{\min}^{\text{inel}} = \frac{1}{\sqrt{2ME_R}}\left(\frac{ME_R}{\mu_\chi} + \delta\right)$$



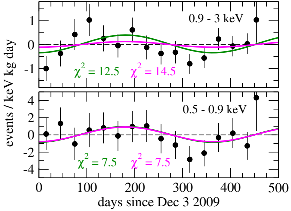


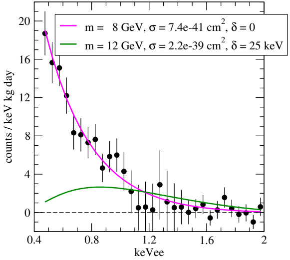
- sampling only high-velocity tail of velocity distribution
- no events at low recoil energies
- high mass targets favoured
- enhance modulation compared to unmodulated signal

iDM and CoGeNT modulation



TS, Zupan, 11

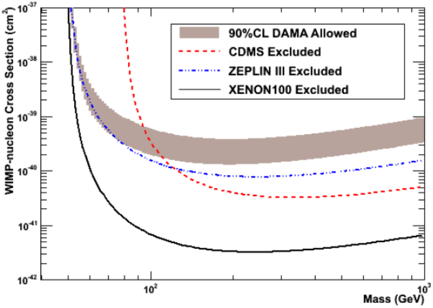




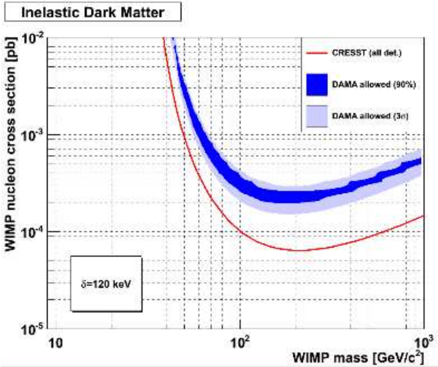
- make mod and unmod spectrum consistent but cannot explain rate
- XENON bound still severe

iDM and DAMA modulation

XENON100 1104.3121



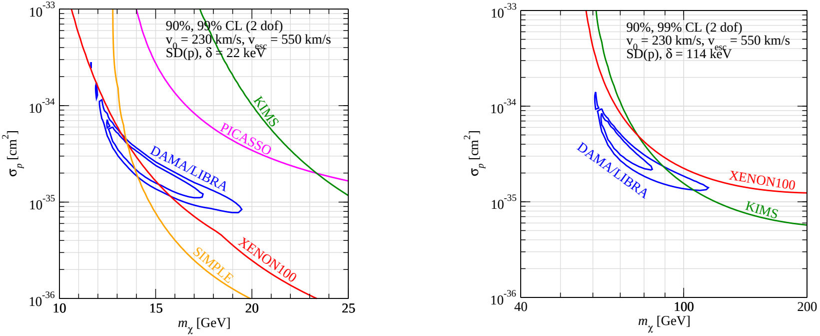
talk by W. Seidel @ IDM 2010



disfavored by XENON100 and CRESST (tungsten)

Inelastic spin-dependent scattering on protons

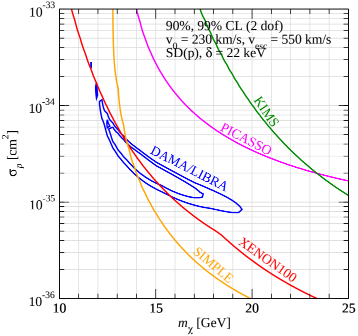
Kopp, Schwetz, Zupan, 0912.4264; Schwetz, Zupan, 11

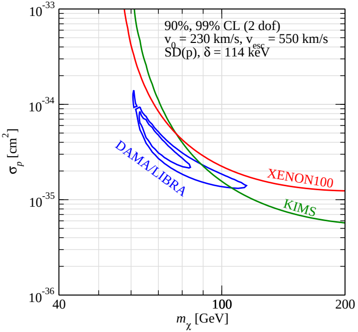


- SD coupling to proton gets rid of XENON/CDMS/CRESST bounds (no unpaired proton)
- inelastic scatt. gets rid of PICASSO/COUPP (light target)

Inelastic spin-dependent scattering on protons

Kopp, Schwetz, Zupan, 0912.4264; Schwetz, Zupan, 11





BUT:

- cannot explain CoGeNT/CRESST-O
- neutrinos from the sun (annih. into u, d, μ, e still OK) Shu, Yin, Zhu, 1001.1076
- probably mono-jet bounds from Tevatron apply

iSD - toy model

Kopp, Schwetz, Zupan, 09: generalize idea of Tucker-Smith, Weiner, 01 to SD int.:
assume 4-Fermi interaction with $T \otimes T$ structure:

$$\mathcal{L}_{\rm int} = \frac{C_{\rm T}}{\Lambda^2}\left[\bar\psi\Sigma_{\mu\nu}\psi\right]\left[\bar q\Sigma^{\mu\nu}q\right], \qquad \Sigma^{\mu\nu} = i[\gamma^\mu,\gamma^\nu]/2$$

$\psi = (\eta, \xi^\dagger)$ with Dirac $m\bar\psi\psi$ and Majorana mass $(\delta_\eta\eta\eta + \delta_\xi\xi\xi)/2$
$\Rightarrow$ two Majorana fermions with masses $m \pm \delta$ ($\delta_\eta = \delta_\xi = \delta \ll m$):

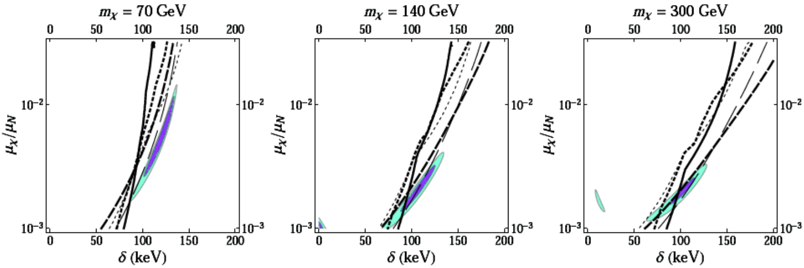
$$\chi_1 = i(\eta - \xi)/\sqrt{2}, \qquad \chi_2 = (\eta + \xi)/\sqrt{2}$$

$$\Rightarrow \quad \bar\psi\Sigma_{\mu\nu}\psi = -2i(\chi_2\sigma_{\mu\nu}\chi_1 + \chi_2^\dagger\bar\sigma_{\mu\nu}\chi_1^\dagger),$$

- inelastic scattering for $\delta \neq 0$
- $T \otimes T$ leads to spin dependent scattering in the non-rel. limit

magnetic inelastic DM

observe that I, Cs, Na, F nuclei have very large effective MM
assume DM has MM: $\mathcal{L} = \frac{\mu_\chi}{2}\bar{\chi}^* \sigma_{\mu\nu}\chi F^{\mu\nu} + h.c.$



Chang, Weiner, Yavin, 1007.4200

- use large MM of iodine to enhance rate in DAMA
- inelast kinematics avoids florine constraints (light target)
- no explanation for CoGeNT/CRESST-O

Generalized couplings to neutron and proton

SI scattering cross section $\propto [Zf_p + (A-Z)f_n]^2$
typically (iso-spin symmetry) one has $f_n \approx f_p \quad \Rightarrow \quad$ SI $\propto \sigma_p A^2$

consider quark operator $G_q \bar{q} q \bar{\chi} \chi \longrightarrow$ eff. coupling to nucleon $N = p, n$:

$$f_N = \sum_q G_q \langle N | \bar{q} q | N \rangle$$

$$= \sum_{q=u,s,d} G_q \frac{m_N}{m_q} \xi_q^N + \frac{2}{27} \left(1 - \sum_{q=u,s,d} \xi_q^N \right) \sum_{q=c,b,t} G_q \frac{m_N}{m_q}$$

$$\xi_d^p \approx 0.033\,, \quad \xi_u^p \approx 0.023\,, \quad \xi_s^p \approx 0.26$$
$$\xi_d^n \approx 0.042\,, \quad \xi_u^n \approx 0.018\,, \quad \xi_s^n \approx 0.26$$

$\Rightarrow$ ex.: Higgs mediated interaction dominated by s-quark and $f_n \approx f_p$

Generalized couplings to neutron and proton

allow for general couplings: Chang et al., 1004.0697; Feng, Kumar, Marfatia, Sanford, 1102.4331; Frandsen et al., 1105.3734; Nobile, Kouvaris, Sannino, 1105.5431

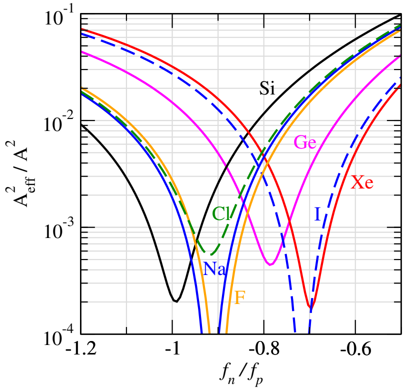
$$\text{SI} \propto \sigma_{\text{eff}} A_{\text{eff}}^2 \qquad \text{with}$$

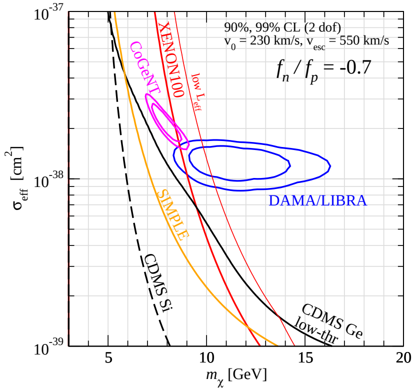
$$\sigma_{\text{eff}} \equiv \frac{\sigma_n + \sigma_p}{2}, \qquad \tan\theta \equiv f_n/f_p$$

$$A_{\text{eff}}^2 = 2 \sum_{i=\text{iso}} r_i [Z\cos\theta + (A_i - Z)\sin\theta]^2$$

for $f_n/f_p < 0$: cancellations $\Rightarrow$
can suppress rate for isotope if $f_n/f_p = -Z/(A-Z)$

Generalized couplings to neutron and proton



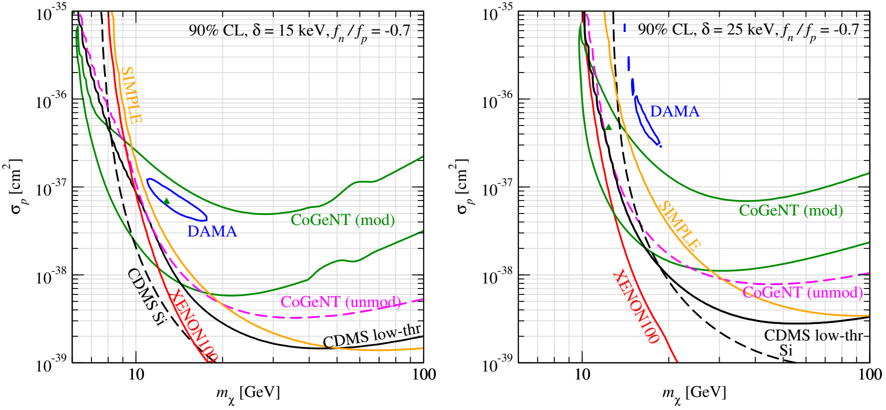


suppress Xe rate for $f_n/f_p \approx -0.7$, but enhanced rate for Si and F
constraint from CDMS low-threshold Ge analysis remains

Generalized couplings to neutron and proton + inelasticity

proposed to reconcile CoGeNT modulation and DAMA

Frandsen et al., 1105.3734; poster by F. Kahlhoefer



TS, Zupan, 11

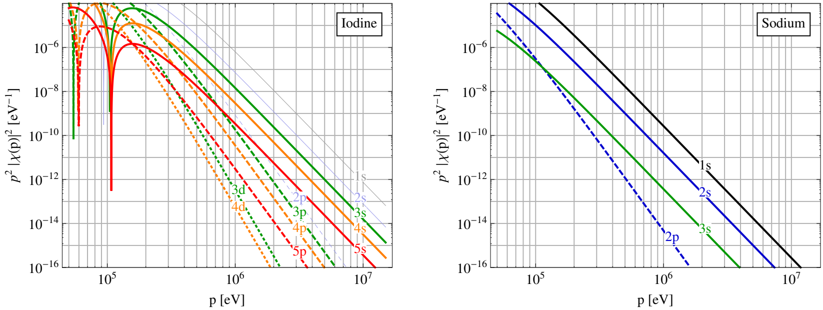
DM scattering off electrons

- DAMA and CoGeNT do not discriminate nuclear recoil and electron events ⇒ pure electron events fully contribute
- CDMS, XENON10, CRESST, KIMS, ZEPLIN,… reject electron events to perform a low background search for nuclear recoils

DM scattering off electrons

DM scattering off electrons at rest: recoils of order $m_e v^2 \sim$ eV cannot account for the DAMA signal at few keV

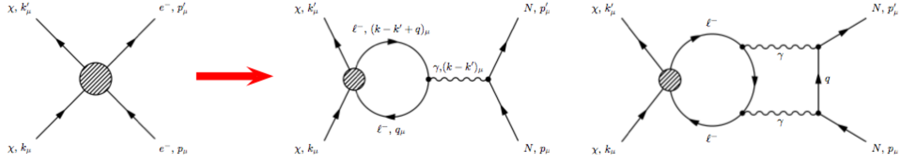
$\Rightarrow$ bound electrons with $p \sim$ MeV, Bernabei et al., 0712.0562



wave function suppression of count rate $\sim 10^{-6}$

Loop induced DM-nucleus scattering

an effective interaction of DM with electrons can induce DM-nucleus interactions at loop level:



whenever loop-induced DM-nucleon scattering is present it will dominate over scattering off electrons because of the wave function suppression ⇒ Have to forbid loop diagrams!

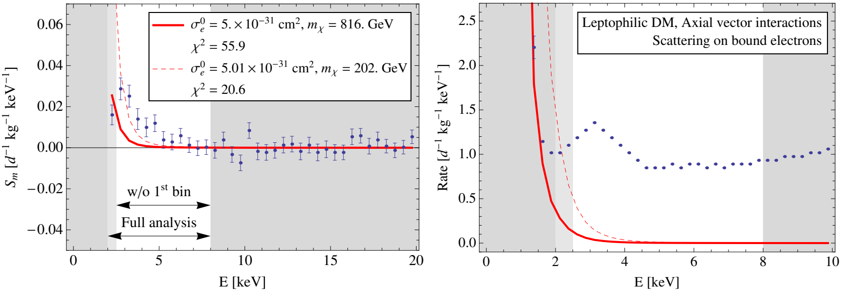
example: fermionic DM with axial-vector coupling

$$\mathcal{L}_{\rm eff} = G\,(\bar\chi\gamma_\mu\gamma_5\chi)\,(\bar\ell\gamma^\mu\gamma_5\ell) \qquad \text{with} \qquad G = 1/\Lambda^2$$

Kopp, Niro, Schwetz, Zupan, 0907.3159

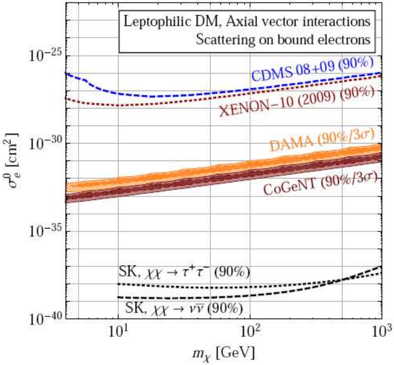
Axial coupling without loop

Best fit prediction for the modulated and unmodulated spectrum in DAMA from DM-electron scattering



⇒ disfavoured by spectral shape and constraint from unmodulated event rate (similar for CoGeNT)

Axial coupling without loop



Kopp, Niro, TS, Zupan, 0907.3159; 1011.1398

- very "large" Xsec: $\sigma^0_{\chi e} \sim 10^{-31}\,\mathrm{cm}^2 \left(\frac{\mathrm{m}_\chi}{100\,\mathrm{GeV}}\right)$ requires $\Lambda \lesssim 0.1$ GeV
- excluded by SuperK constraints on neutrinos from the sun
- severe constraints from LEP Fox, Harnik, Kopp, Tsai, 1103.0240

Outline

Conclusions

- Thermal freeze-out provides a motivation for DM at the weak scale: $\Rightarrow$ WIMP
- we are probing the WIMP hypothesis with direct detection, indirect detection, and LHC $\Rightarrow$ exciting times ahead!
- Some hints for DM around 10 GeV from direct detection $\Rightarrow$ in tension with constraints
- Also exotic particle physics seems not to be able to fit all
- More data will tell