BUSSTEPP 2012

# Dark Matter phenomenology

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- there are many aspects of Dark Matter physics $\rightarrow$ had to be very selective in which topics to cover in 2 hours
- will not speak (or very little) about cosmological and astrophysical aspects of DM
- focus on particle DM with emphasis on WIMPs
- mention only briefly non-WIMP DM candidates
- say very little on DM searches at colliders
- will not speak about specific models for DM

# Outline

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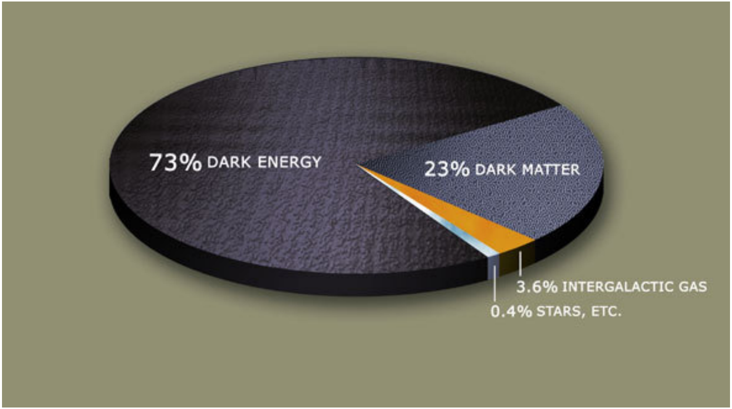
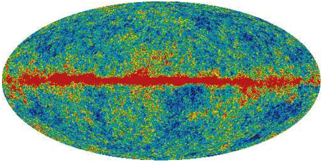
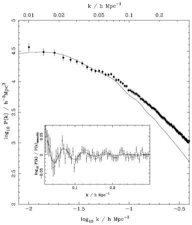
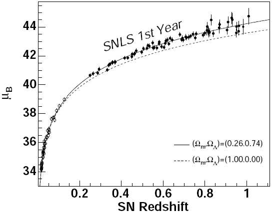
# What is the Universe made of?



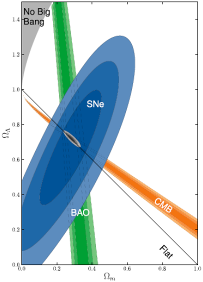
# Global fit to cosmological data in the ΛCDM model





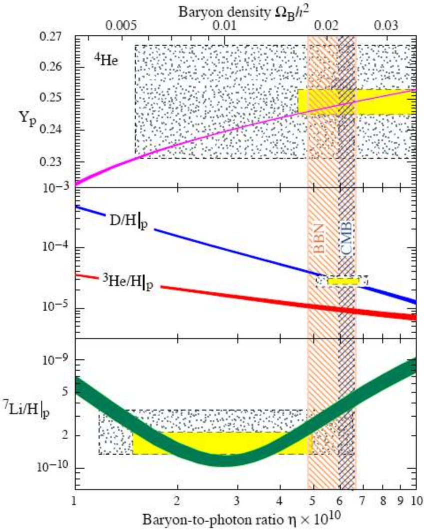

SN cosmology project, 1105.3470




WMAP 7yr, 1001.4538

$$\Omega_\Lambda = 0.725 \pm 0.016$$
$$\Omega_{\rm CDM} = 0.229 \pm 0.015$$
$$\Omega_{\rm baryon} = 0.0458 \pm 0.0016$$

# Density of "normal matter"



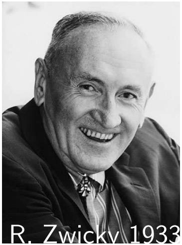

determinations of the baryon density from Big Bang Nucleosythesis and CMB are in perfect agreement:

$$\Omega_b h^2 = 0.0214 \pm 0.0020 \quad \text{(BBN)}$$
$$\Omega_b h^2 = 0.0227 \pm 0.0006 \quad \text{(CMB)}$$

$H_0 = 100h$ km/s/Mpc
$h^2 \approx 0.5$

# The scale of galaxies and clusters of galaxies

- virial theorem (gal. clusters)



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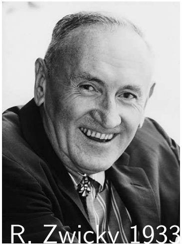
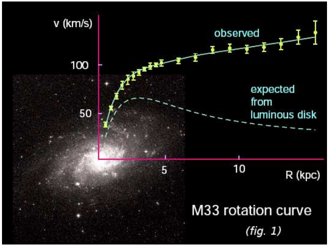



- rotation curves



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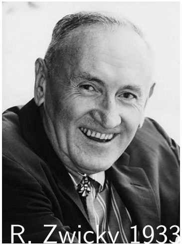


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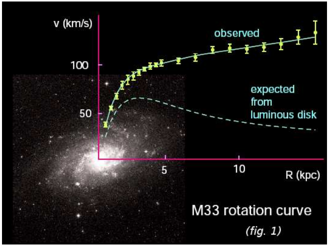
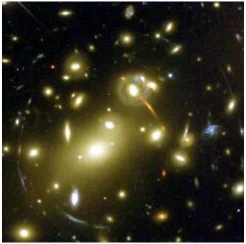



- gravitational lensing



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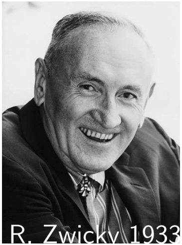


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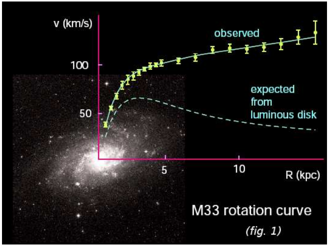


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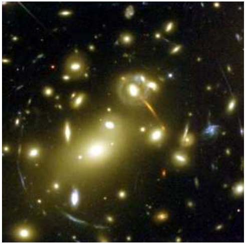

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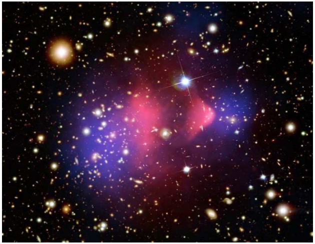

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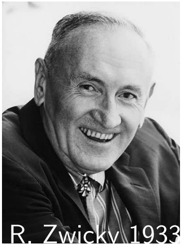


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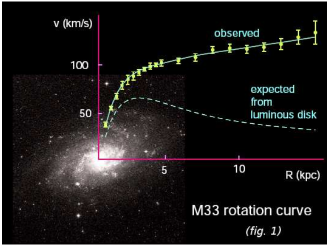


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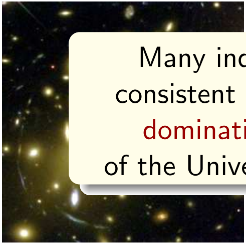

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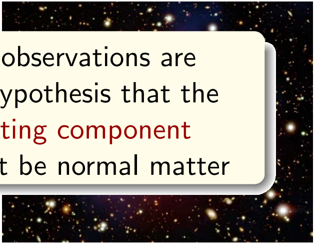

Many independent observations are consistent with the hypothesis that the dominating gravitating component of the Universe cannot be normal matter

# Dark Matter or Modified Gravity?

We observe “anomalies” in motion of gravitational systems:

Anomalies in the orbits of

- Uranus
  lead to the discovery of a “dark object” (Neptun),
- Mercury
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attempts for Modified Gravity Theories have been made

$\longrightarrow$ not discussed in this lecture

# Particle Dark Matter

We need a particle which has

- the correct abundance to give $\Omega_{\mathrm{CDM}} \approx 0.23$
  - production mechanism in the early Universe
  - has to be stable on the scale of the age of the Universe
- to be (electrically) neutral
- to fulfill constraints on
  - interactions with matter (direct detection)
  - self-interactions
  - searches for annihilation/decay products (gamma rays)
- to be consistent with structure formation → "cold" or "warm" DM

M. Taoso, G. Bertone and A. Masiero, "Dark Matter Candidates: A Ten-Point Test," JCAP **0803** (2008) 022 [arXiv:0711.4996]

# Particle Dark Matter

The Standard Model has one potential candidate:

the neutrino

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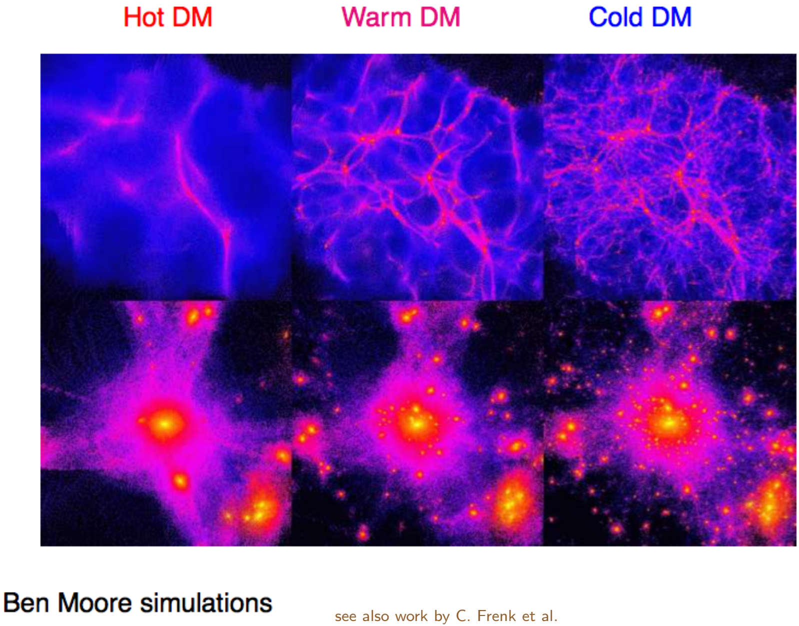
which, however, does not work!

- the relic density of neutrinos is

$$\Omega_\nu \approx \frac{\sum m_\nu}{93 h^2\,\mathrm{eV}} < 0.02$$

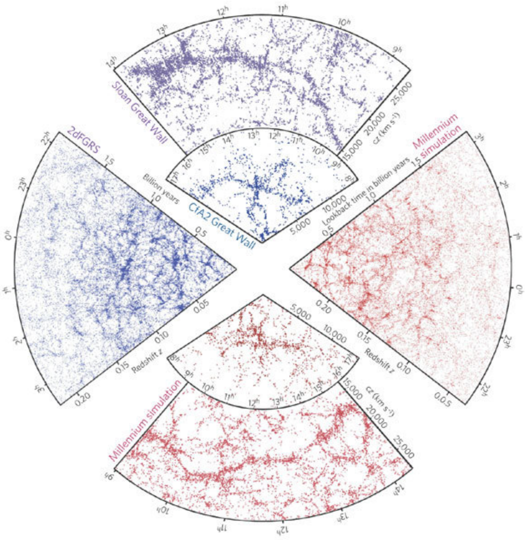
$\longrightarrow$ bounds on $m_\nu$ imply that neutrino density is too low

- neutrinos are "hot DM", inconsistent with structure formation




see also work by C. Frenk et al.

# Large scale structure vs the CDM model



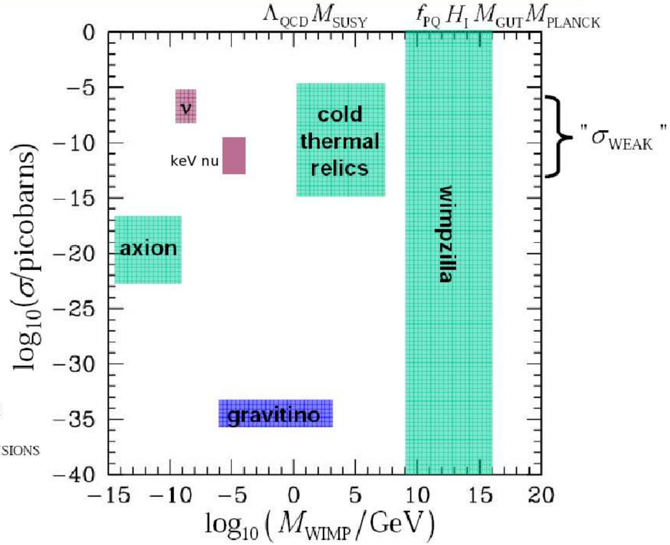

Springel, Frenk, White, Nature 2006

# Particle Dark Matter

$\Rightarrow$ **Dark Matter implies**

**physics beyond the Standard Model**

# Particle Dark Matter Candidates




**Other Scales:**

$M_{EWK}$

$M_{STERILE}$

$M_{STRING}$

$M_{TECHNICOLOR}$

$M_{EXTRA\ DIMENSIONS}$

# We have no clue about DM properties ...

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

BUT: there are many well motivated non-WIMP candidates:

- asymmetric DM
- axion
- gravitino
- keV neutrinos or Majorons
- FIMP (feably...)
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# Boltzmann equation

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

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

$L[f]$: conservation of density in phase space
$C[f]$: impact of particle interactions

- integrate Boltzmann equation to obtain an eq. for the number density
- after several assumptions and some calculations ...

$\longrightarrow$ rate equation (self-conjugated particle):

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

$\langle \sigma_{\rm ann} v \rangle$: thermally averaged annihilation cross section times velocity

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- re-write differential equation in terms of

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

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

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

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- Change variables from time to dimensionless temperature

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# Yield equation

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

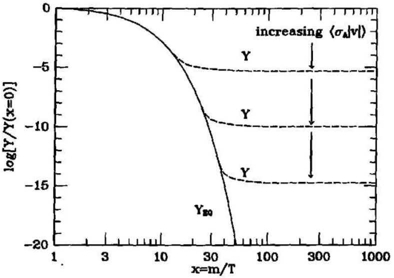
consider $h_{\rm eff} = $ const, $\Gamma = n_{\rm eq} \langle \sigma_{\rm ann} v \rangle$: $\quad \frac{x}{Y_{\rm eq}} \frac{dY}{dx} = -\frac{\Gamma}{H} \left( \frac{Y^2}{Y_{\rm eq}^2} - 1 \right)$

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

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

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

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# Relic density estimate

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

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

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

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

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

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# Relic density estimate

$\Omega h^2 \simeq 10^{-37}\,\text{cm}^2/\langle\sigma_{\text{ann}} v\rangle$ is just a rule of thumb
many situations need more careful considerations, e.g.

- velocity dependent annihilation cross section
- close to an s-channel resonance due to a mediator particle $\phi$ with $2m_\chi \approx m_\phi$
- close to thresholds of annihilation channels $\chi\chi \to XX$ with $m_\chi \approx m_X$
- 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 GG, Nucl. Phys. B 360 (1991) 145 and solve the rate equation numerically

- Public codes: micrOMEGAs, Dark SUSY

# Out-of equilibrium decay

suppose $\chi_2$ has a thermal abundance

$$n_2 \propto \frac{1}{m_2 \langle \sigma_{\text{ann},22} v \rangle}$$

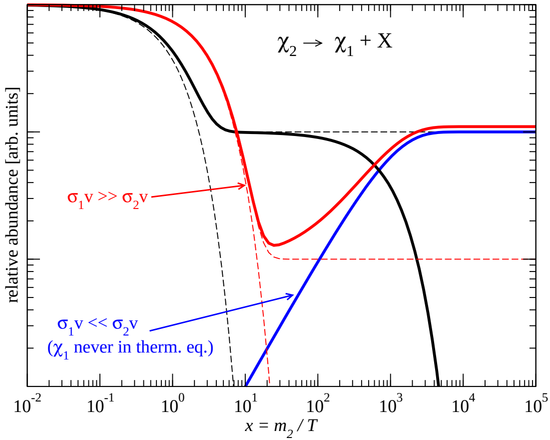
after decoupling $\chi_2$ decays into the DM particle $\chi_1$ by

$$\chi_2 \to N \chi_1 + X \quad (m_1 < m_2) \qquad \Rightarrow \quad n_1 = n_1^{\text{thermal}} + N n_2$$

if $n_1^{\text{thermal}} \ll N n_2$:

$$\Omega_1 = N \frac{m_1}{m_2} \Omega_2 \propto \frac{m_1}{m_2} \frac{N}{\langle \sigma_{\text{ann},22} v \rangle}$$

# Out-of equilibrium decay



# Freeze-in

$$\frac{dY}{dx} = -C\frac{M_{pl}m}{x^2}\langle\sigma v\rangle\left(Y^2 - Y_{eq}^2\right) \qquad M_{pl} = 1/\sqrt{G_N}$$

$$\langle\sigma v\rangle \sim \frac{\lambda^2}{s} \sim \begin{cases} \frac{\lambda^2}{T^2} = \frac{\lambda^2}{m^2}x^2 & x \ll 1 \\ \frac{\lambda^2}{m^2} & x \gg 1 \end{cases}$$

suppose the interaction of the DM particle with the thermal bath is so weak, that it is never brought into thermal equilibrium

$$\frac{dY}{dx} \approx C\frac{M_{pl}m}{x^2}\langle\sigma v\rangle Y_{eq}^2 \approx \begin{cases} C'\frac{M_{pl}}{m}\lambda^2 & x \ll 1 \quad \text{(constant)} \\ C\frac{M_{pl}}{m}\lambda^2\frac{Y_{eq}^2}{x^2} & x \gg 1 \quad \text{(suppr. by } Y_{eq}^2/x^2\text{)} \end{cases}$$

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**freeze-in:**

$$x < x_{FI} \sim 1$$

$$\frac{dY}{dx} \approx C' \frac{M_{pl}}{m} \lambda_{FI}^2$$

integrate $x$ from 0 to $x_{FI}$

$$Y_\infty \approx Y_{FI} \approx C' \frac{M_{pl}}{m} \lambda_{FI}^2 x_{FI}$$

$$Y_\infty \sim \frac{M_{pl}}{m} \lambda_{FI}^2$$

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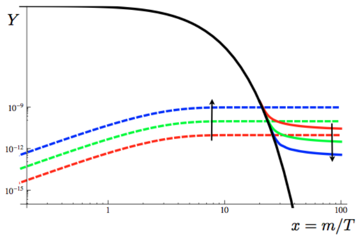

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$\lambda_{FI} \lesssim 10^{-11}$ (FIMP)

**freeze-out:**

$$x > x_{FO} \sim 10$$

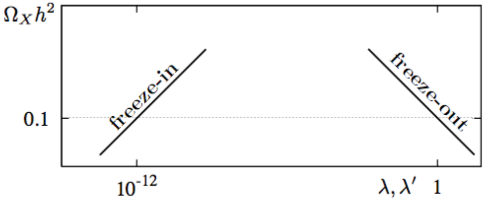
$$\frac{dY}{dx} \approx -C \frac{M_{pl}}{m x^2} \lambda_{FO}^2 Y^2$$

integrate $x$ from $x_{FO}$ to $\infty$

$$\frac{1}{Y_\infty} \approx C \frac{M_{pl}}{m} \lambda_{FO}^2 \frac{1}{x_{FO}}$$

$$Y_\infty \sim \frac{m}{M_{pl}} \frac{1}{\lambda_{FO}^2}$$

$\lambda_{FO} \lesssim 1$ (WIMP)



## 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].


## Freeze-in:


- L. J. Hall, K. Jedamzik, J. March-Russell and S. M. West, "Freeze-In Production of Fimp Dark Matter," JHEP **1003** (2010) 080 [arXiv:0911.1120].
- X. Chu, T. Hambye, M.H. Tytgat, "The Four Basic Ways of Creating Dark Matter Through a Portal" arXiv:1112.0493

# Outline

# 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:

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

$s$-wave annihilations of a particle $\chi$ due to mediator $\phi$:

$$\langle \sigma_{\mathrm{annih}} v \rangle \sim \frac{g^4}{\pi} \frac{m_\chi^2}{m_\phi^4} \simeq 10^{-36} \mathrm{cm}^2\, g^4 \left( \frac{m_\chi}{100\,\mathrm{GeV}} \right)^2 \left( \frac{1\,\mathrm{TeV}}{m_\phi} \right)^4$$

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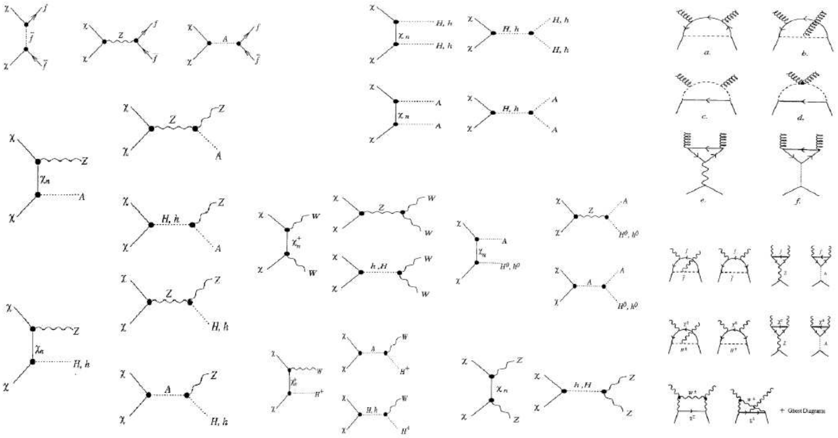
# MSSM neutralino annihilation



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

# Relic density constraint

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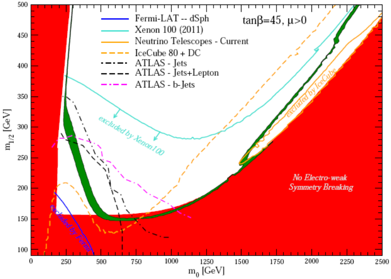


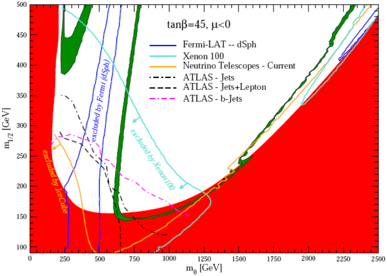


$m_0$: universal soft SUSY breaking scalar mass @ GUT scale
$M_{1/2}$: universal gaugino mass @ GUT scale

Profumo, 1105.5162

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

BUT:

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

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

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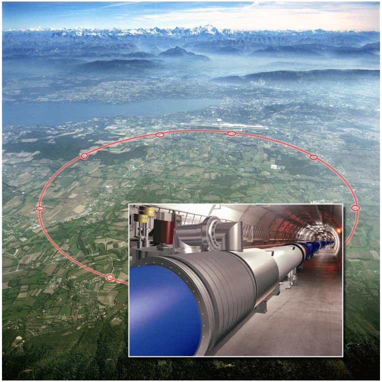

# New physics at the weak scale?

- the “hierarchy problem” in the Standard Model motivates the presence of new physics at the electro-weak scale
  many new physics models which solve the hierarchy problem provide a DM candidate as "extra bonus"
  SUSY, new dimensions, Little Higgs, strongly coupled sector,...

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

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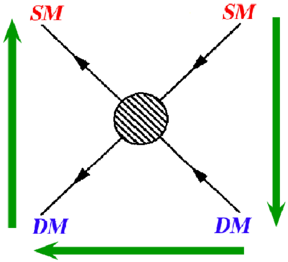
# Testing the WIMP hypothesis



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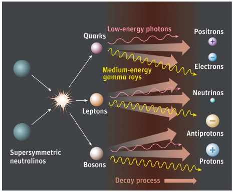
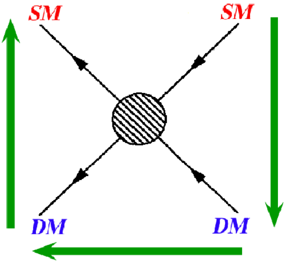
indirect detection




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



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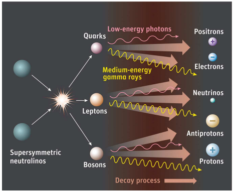


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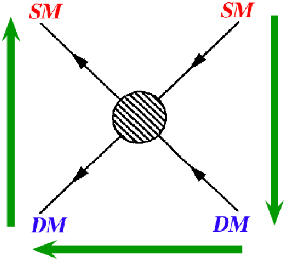
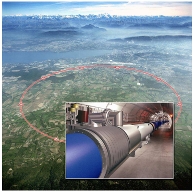



colliders



LHC at CERN

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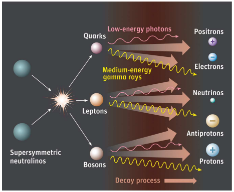


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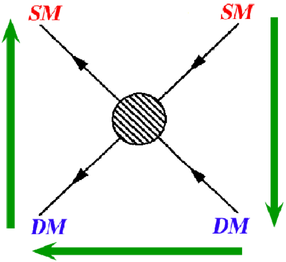


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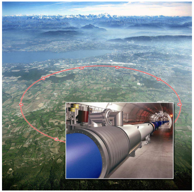
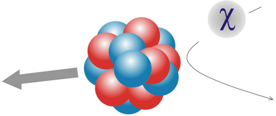


LHC at CERN

direct detection




XENON, LUX, CDMS, Edelweiss, CRESST, DEAP, COUPP, EURECA, XMASS, PICASSO,...

# Outline

# Missing energy signature

- DM particle escapes detection
- Invisible particle with life time $\gtrsim 10^{-7}$ s
- No direct proof that we are seeing the DM particle

# Missing energy signature

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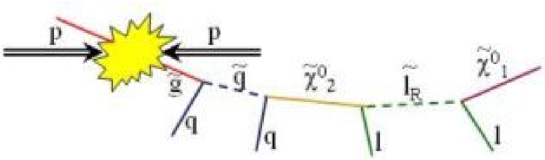
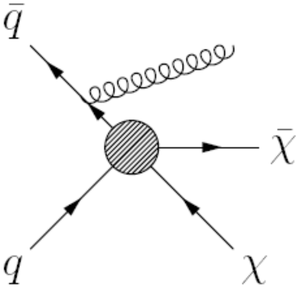
$\Rightarrow$ Hope for additional signatures and relate missing-energy signature to DM in a model-dependent way

Example: SUSY decay chain



# EFT and mono-jet signals

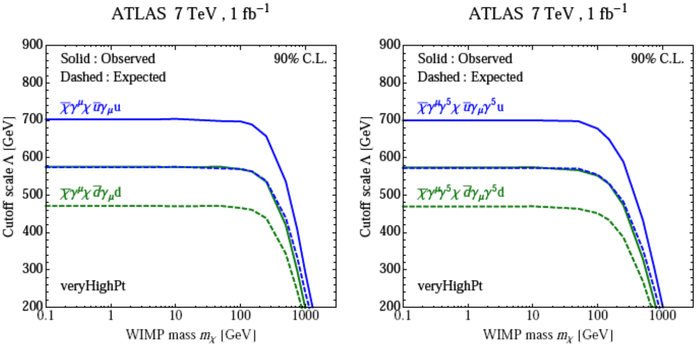



Consider effective vertex of DM with quarks/gluons, e.g.

$$\frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}, \quad \frac{(\bar{\chi}\gamma_5\gamma_\mu\chi)(\bar{q}\gamma_5\gamma^\mu q)}{\Lambda^2}, \quad \frac{(\bar{\chi}\chi)(G_{\mu\nu}G^{\mu\nu})}{\Lambda^3}, \ldots$$

# EFT and mono-jet signals

bounds on cut-off scale $\Lambda$ for coupling to $u$- and $d$-quark




Fox, Harnik, Kopp, Tsai, 1109.4398

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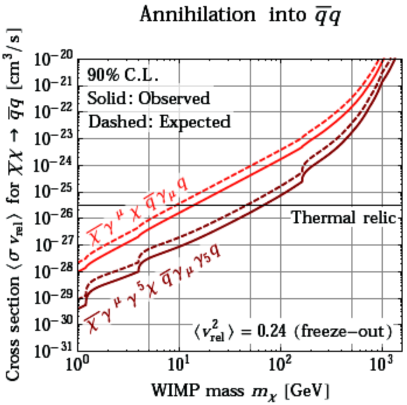



Fox, Harnik, Kopp, Tsai, 1109.4398

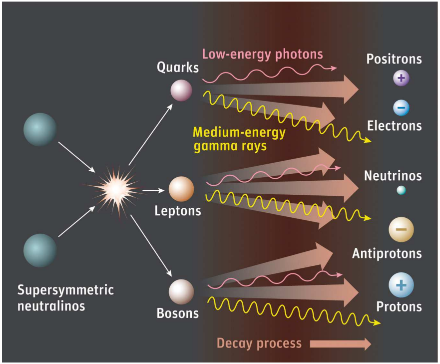
assumes no additional DM interaction (e.g., gauge bosons)

# Outline

the WIMP hypothesis implies DM annihilations into SM particles in order to obtain the correct relic abundance:

$$\chi\chi \quad \rightarrow \quad \mathrm{SM} + \mathrm{SM} \quad \text{with} \quad \langle\sigma v\rangle \approx 10^{-36}\,\mathrm{cm}^2 \approx 3\times 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}$$

$\Rightarrow$ look into regions of high DM concentration and search for high-energy DM annihilation products today




- $\gamma, \nu$ travel on straight lines
- charged particles $e^{\pm}, \bar{p}$: trapped in magnetic fields secondary photons
  - synchrotron radiation
  - inverse Compton scattering on CMB, starlight

# Search for $\gamma$-rays from DM annihilations

interesting regions to look at:

- galactic center (close by, very "messy")
- satelite/dwarf galaxies (very DM dominated objects close by)
- distant galaxies or clusters (huge objects, far away)
- diffuse $\gamma$-ray flux integrated over cosmological distances

How to look for GeV to TeV $\gamma$ rays?

- space telescopes on satelites
  (EGRET, FERMI, AMS-II)
- ground-based telescopes $\rightarrow$
  shower of secondary particles in atmosphere
  (MAGIC, HESS, CANGAROO, VERITAS)
  higher threshold ($E_\gamma \gtrsim 1$ TeV, much larger eff. area)

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$\gamma$-ray flux within a solid angle $\Delta\Omega$:

$$\frac{d\phi}{dE_\gamma} = \frac{1}{8\pi}\langle\sigma v\rangle\frac{dN_\gamma}{dE_\gamma}\int_{\Delta\Omega} d\Omega\int_{l.o.s.} ds\,\frac{\rho^2(s,\Omega)}{m_\chi^2}$$

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- astrophysics:

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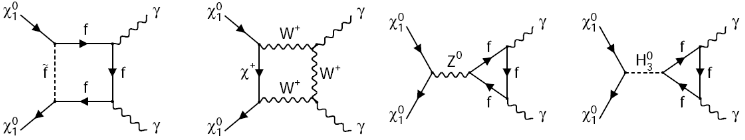
# $\gamma$ signal from DM annihilations

- annihilations into photons via loops, ex. SUSY neutralino:




see Bergstrom, Ullio, hep-ph/9706232

- final- or intermediate state radiation:

e.g., Bringmann, Bergstrom, Edsjo, 0710.3169

- photons from hadronisation process, e.g.,

$$\bar{\chi}\chi \to \bar{q}q \to \pi^{\pm}\pi^{0} \hookrightarrow 2\gamma$$

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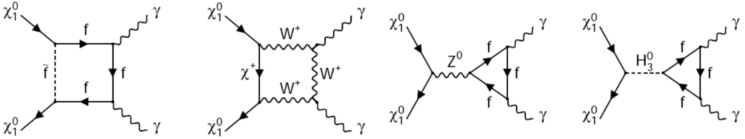


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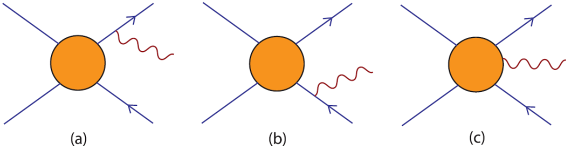


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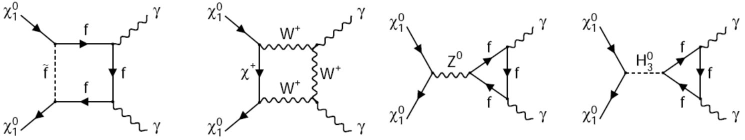


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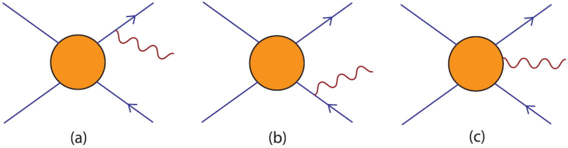


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# Astrophysical $J$-factor

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line of sight integral over DM density $\rho$

$$J \equiv \int_{l.o.s.} \frac{ds}{r_\odot} \frac{\rho^2(s,\Omega)}{\rho_\odot^2} \,, \qquad \bar{J} \equiv \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega J$$

$\rho(r)$ from N-body simulations

# Dark Matter in a Milkyway-like Galaxy

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# DM profiles

$$\rho(r) = \frac{\rho_0}{\left(\frac{r}{R_s}\right)^\gamma \left[1 + \left(\frac{r}{R_s}\right)^\alpha\right]^{\frac{\beta-\gamma}{\alpha}}}$$

inner slope $r \ll R_s$: $\rho(r) \propto r^{-\gamma}$, outer slope $r \gg R_s$: $\rho(r) \propto r^{-\beta}$

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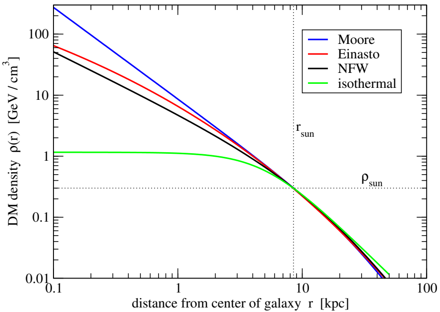


- cored iso-thermal profile
  $\alpha = 2, \beta = 2, \gamma = 0$
- Navarro, Frenk, White (NFW)
  $\alpha = 1, \beta = 3, \gamma = 1$
- Moore
  $\alpha = 1.5, \beta = 3, \gamma = 1.5$
- Einasto

$$\rho(r) = \rho_0 \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{R_s}\right)^{\alpha} - 1\right)\right], \quad \alpha = 0.17$$

# Astrophysical $J$-factor

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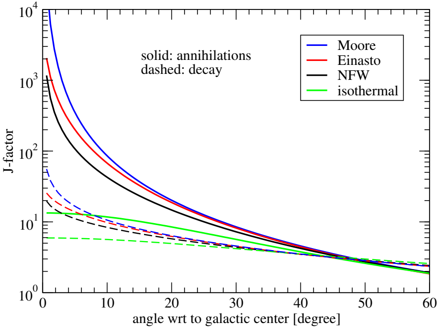


ex.: $\bar{J}(\Delta\Omega = 10^{-3})$ towards the galactic center

| | |
|---|---|
| isothermal: | $\bar{J} \approx 30$ |
| NFW: | $\bar{J} \approx 10^3$ |
| Moore: | $\bar{J} \approx 10^5$ |

- very sensitive to inner slope (impact of Baryons important, not well understood)
- in case of signal: measure DM profile $\rho(r)$!

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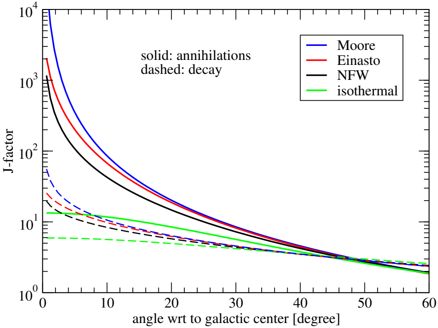


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DM decay: $$J_{\rm dec} \equiv \int_{l.o.s.} \frac{ds}{r_\odot} \frac{\rho(s,\Omega)}{\rho_\odot}$$

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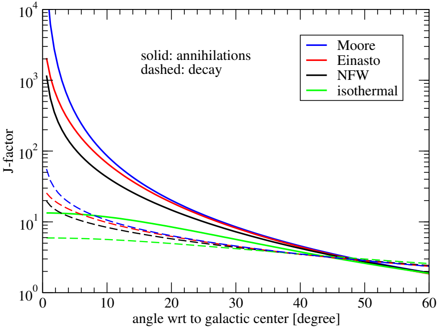


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- DM decay signal much less sensitive to profile
- can in principle distinguish between annihilation and decay by angular profile of signal

# Astrophysical $J$-factor

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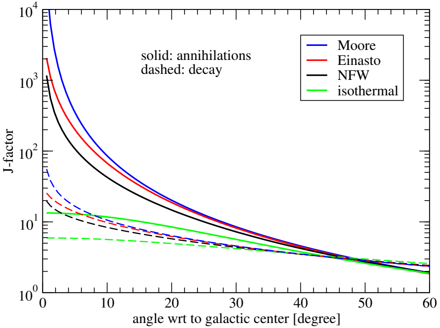


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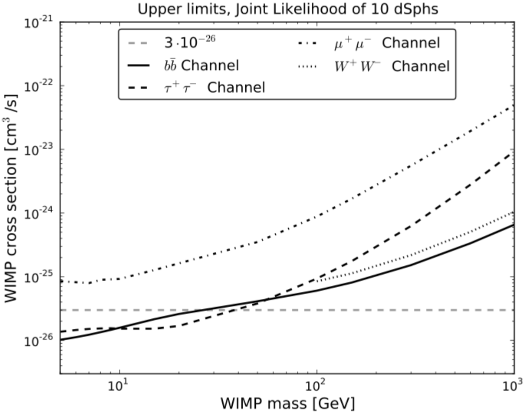
| NFW: | $\bar{J} \approx 10^3$ |
| Moore: | $\bar{J} \approx 10^5$ |

additional uncertainty comes from the boost factor due to DM sub-structure (very difficult to estimate)

# Recent limit from FERMI

search for $\gamma$ rays from 10 milkyway dwarf galaxies




FERMI-LAT Coll., 1108.3546

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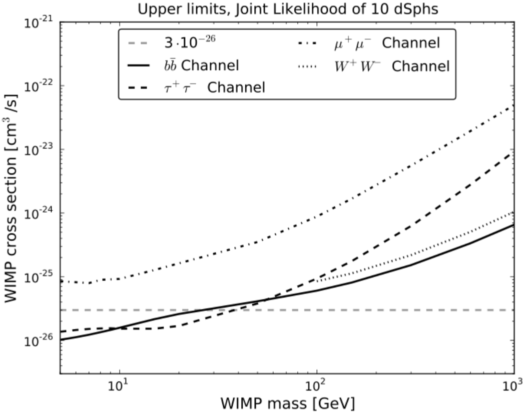



FERMI-LAT Coll., 1108.3546

comment: velocity dependent annihilation cross section
to decouple relic density and indirect signal

arXiv:1204.2797v1 [hep-ph] 12 Apr 2012

# A Tentative Gamma-Ray Line from Dark Matter Annihilation at the Fermi Large Area Telescope

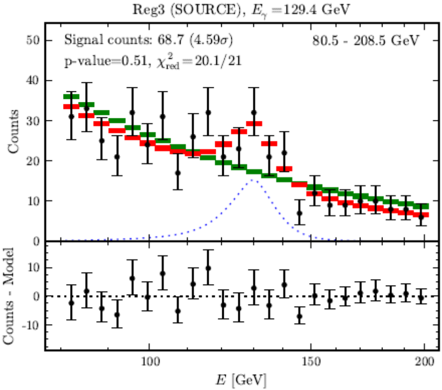
**Christoph Weniger**

Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany

E-mail: weniger@mppmu.mpg.de

**Abstract.** The observation of a gamma-ray line in the cosmic-ray fluxes would be a smoking-gun signature for dark matter annihilation or decay in the Universe. We present an improved search for such signatures in the data of the Fermi Large Area Telescope (LAT), concentrating on energies between 20 and 300 GeV. Besides updating to 43 months of data, we use a new data-driven technique to select optimized target regions depending on the profile of the Galactic dark matter halo. In regions close to the Galactic center, we find a 4.6$\sigma$ indication for a gamma-ray line at $E_\gamma \approx 130$ GeV. When taking into account the look-elsewhere effect the significance of the observed excess is 3.3$\sigma$. If interpreted in terms of dark matter particles annihilating into a photon pair, the observations imply a dark matter mass of $m_\chi = 129.8 \pm 2.4\,^{+7}_{-13}$ GeV and a partial annihilation cross-section of $\langle \sigma v \rangle_{\chi\chi\to\gamma\gamma} = (1.27 \pm 0.32\,^{+0.18}_{-0.28}) \times 10^{-27}$ cm$^3$ s$^{-1}$ when using the Einasto dark matter profile. The evidence for the signal is based on about 50 photons; it will take a few years of additional data to clarify its existence.

# Gamma line signal in FERMI data?




Bringmann et al, 1203.1312

Weniger, 1204.2797

later confirmed by Hektor, Raidal, Elmo Tempel, 1207.4466; Su, Finkbeiner, 1206.1616

are there two lines, at 110 and 130 GeV? (from DM DM $\to \gamma Z$ or $\gamma H$)

maybe also present in unresolved point sources?

Su, Finkbeiner, 1207.7060; see however Hooper, Linden, 1208.0828

# Gamma line signal in FERMI data?

- Is it an instrumental/analysis artefact?
  (so-far not refuted by FERMI collaboration)

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- Is it an instrumental/analysis artefact?
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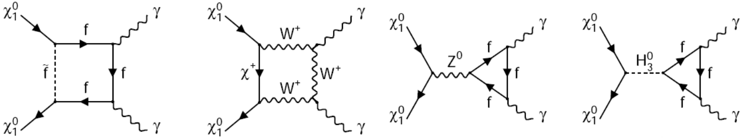
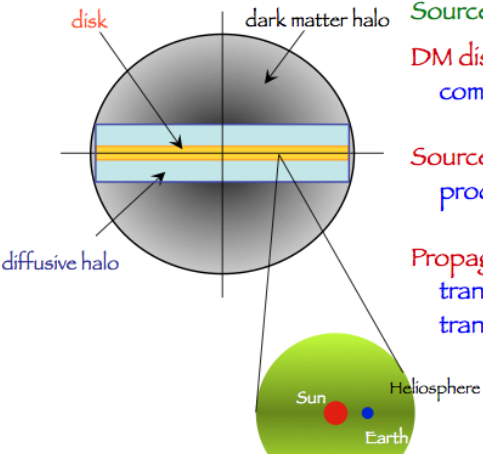
- how to make the line? Which particle in the loop?




- relat. large cross section $\langle\sigma v\rangle_{\gamma\gamma} \simeq 10^{-27}\,\mathrm{cm}^3\mathrm{s}^{-1}$ sets strong constraints on SM or new (charged) particles in the loop due to limits on the contiuum photon spectrum e.g., Buchmuller, Garny, 1206.7056; Cohen, Lisanti, Slatyer, Wacker, 1207.0800; Cholis, Tavakoli, Ullio, 1207.1468; Huang, Yuan, Yin, Bi, Chen, 1208.0267

- Can it be consistent with a thermal WIMP? Tulin, Yu, Zurek, 1208.0009

# DM signal as exotic component in cosmic rays




Sources of uncertainties

DM distribution
combined effect with propagation

Source
production mechanism

Propagation
transport in the Galaxy
transport in the heliosphere (low T)

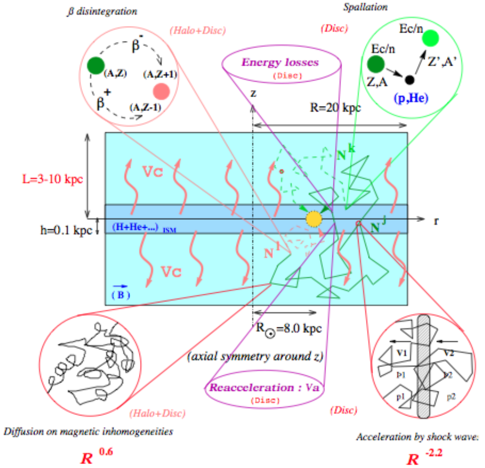
N. Fornengo

# CR propagation equation

$$\psi = dn/dE$$

$$\partial_z \left(V_C\, \psi\right) - K\, \Delta\psi + \partial_E \left\{ b^{\rm loss}(E)\, \psi - K_{EE}(E)\, \partial_E \psi \right\} = q\left(\mathbf{x}, E\right)$$

convection · diffusion · energy losses · reacceleration · source term



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$$\psi = dn/dE$$

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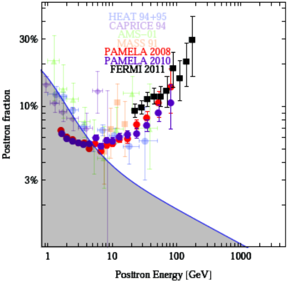
convection — diffusion — energy losses — reacceleration — source term

- large uncertainties on diffusion model; some information from cosmic ray data (e.g., B/C ratio)
- source term:

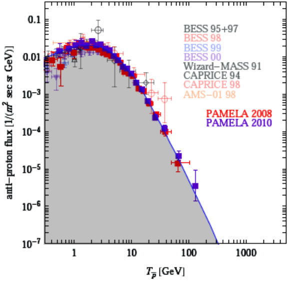
$$q(x) = q_{\rm DM}(x) + q_{\rm astro}(x)\,, \qquad q_{\rm DM}(x) = \frac{1}{2}\frac{\rho^2(x)}{m_\chi^2}\langle\sigma v\rangle \frac{dN}{dE}$$

- energy loss term leads to additional photons:
  - synchrotron radiation (radio signal)
  - inverse compton scattering (on CMB, star light)

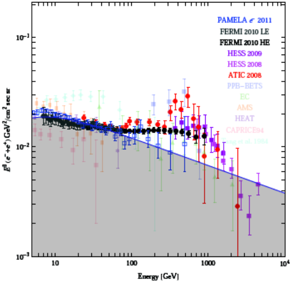
# Data on electrons, positrons, antiprotons




positron fraction




anti-protons




electrons+positrons

M. Cirelli, 1202.1454

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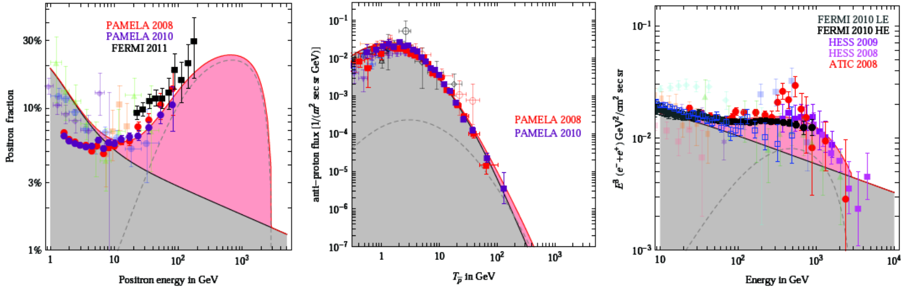
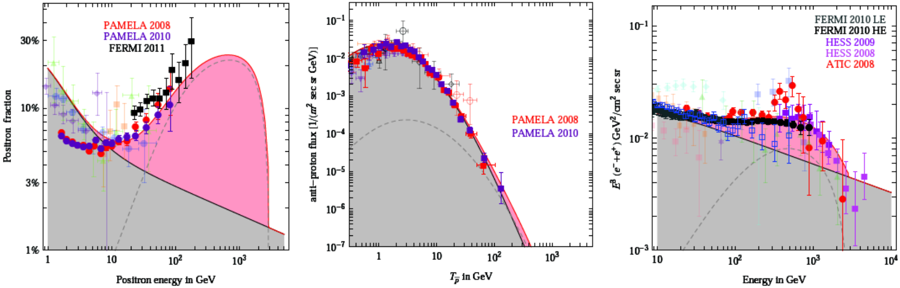
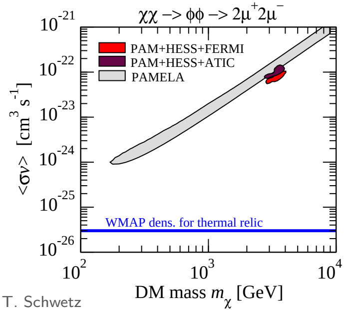



- 3 TeV DM particle annih. into $\tau^{\pm}$ with $\langle \sigma v \rangle \approx 2 \times 10^{-22} \text{cm}^3/s$
- anti-proton data puts sever constraint on possible annihilation channels (e.g., quarks or gauge bosons)

# Data on electrons, positrons, antiprotons




- required cross section much larger than the “thermal” value

Rothstein, Schwetz, Zupan, 0903.3116

# Decouple annihilations now and at freeze-out

- force mediator in dark sector
  (Sommerfeld enhancement / DM-bound state)

  Hisano et al., hep-ph/0307216, hep-ph/0412403, hep-ph/0610249; Cirelli et al., 0706.4071, 0809.2409; Arkani-Hamed et al, 0810.0713; Pospelov, Ritz, 0810.1502; ...

- annihilations close to a resonance

  Feldman, Liu, Nath, 0810.5762; Ibe, Murayama, Yanagida, 0812.0072

- non-thermal production Fairbairn, Zupan, 0810.4147

- DM decay Ibarra, Tran, 0709.4593, 0804.4596; Nardi, Sannino, Strumia, 0811.4153; Bertone, Büchmuller, Covi, Ibarra, 0709.2299; ...

# Multi-messenger constraints

- anti-protons PAMELA, 08, 10
- $\gamma$'s from final/intermed. state radiation $\rightarrow$ HESS obs. of galactic center, galactic ridge, spheroidial dwarf galaxies

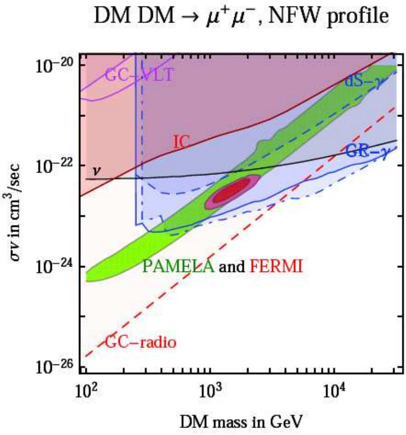
  Bertone et al., 0811.3744; Bergstrom et al., 0812.3895
- synchrotron emission (radio observations of the GC)

  Bertone et al., 0811.3744; Bergstrom et al., 0812.3895
- difuse $\gamma$-rays from inverse compton scattering (ICS) on star light, CMB photons, and dust $\rightarrow$ FERMI data on difuse $\gamma$'s

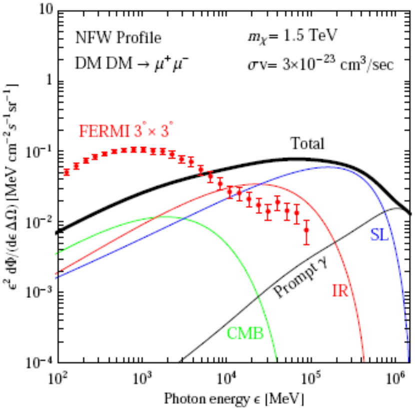
  Cirelli et al, 0904.38300; 0912.0663; Meade, Papucci, Strumia, Volansky, 0905.0480
- SuperK bound on muons from neutrinos from galactic center

  Hisano, Kawasaki, Kohri, Nakayama, 0812.0219
- distortions of the CMB power spectrum due to energy injections by DM annihilations (reionization, heating) Slatyer, Padmanabhan, Finkbeiner, 0906.1197; Huetsi, Hektor, Raidal, 0906.4550; Cirelli, Iocco, Panci, 0907.0719; Galli, Iocco, Bertone, Melchiorri, 1106.1528

# Multi-messenger constraints




Meade, Papucci, Strumia, Volansky, 0905.0480




Cirelli, Panci, Serpico, 0912.0663

limits depend on assumed DM profile and annihilation channel!

# Summary indirect detection

- large uncertainties on DM profiles and astrophysical backgrounds
- multi messenger approach is powerful (photons of different wave lengths, positrons, anti-protons, anti-deuterons)
- recent signals from electrons/positrons (PAMELA/FERMI)
  - would require non-standard properties of DM
  - triggered a huge activity in DM model building
  - are severely constrained by multi-messenger constraints
  - might find astrophysical explanations (pulsars, SN remnants) $\rightarrow$ overwhelming background for DM searches
- tentative signal for a $\gamma$ line at 130 GeV in FERMI data
  - lots of papers appearing; phenomenology and implications for DM models under active investigation
  - will it have a similar faith as the positron "signals", or will a consistent picture emerge? $\rightarrow$ exciting times ahead!

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# Outline

# Dark Matter in a Milkyway-like Galaxy

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# 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

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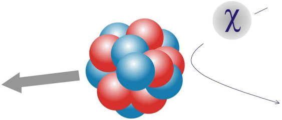
$\Rightarrow$ local DM flux: $\phi_\chi \sim 10^5\,\mathrm{cm^{-2}s^{-1}} \left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)\left(\frac{\rho_\chi}{0.4\,\mathrm{GeV\,cm^{-3}}}\right)$

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

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

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

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

$\rho_\chi$ DM energy density, default $\approx 0.3$ GeV cm$^{-3}$

$m_A$: mass of the target nucleus with mass number $A$

$v_{\rm min}$: minimal DM velocity required to produce recoil energy $E_R$

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

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# DM velocity distribution

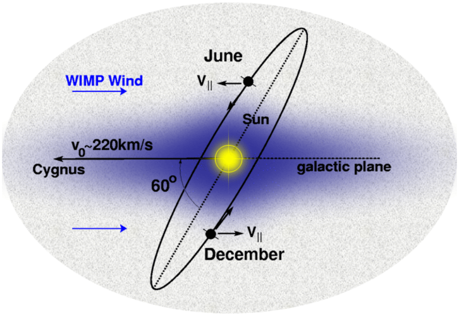
in Earth rest frame $f_\oplus$ $\to$ Galilei trafo from galaxy rest frame $f_{\rm gal}$:

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

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

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

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

differential cross section

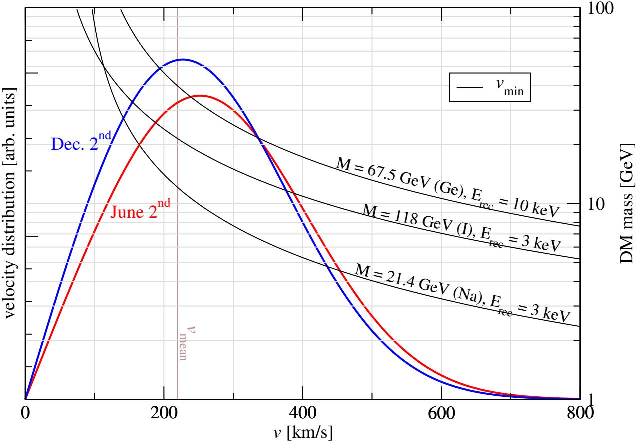
$$\frac{d\sigma}{dE_R} = \frac{1}{32\pi}\frac{\overline{|\mathcal{M}|^2}}{m_A m_\chi^2 v^2}$$

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

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

# Velocity distribution integral

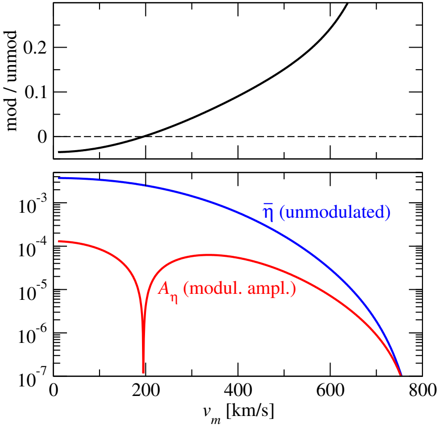
$$\eta(E_R, t) \propto \frac{1}{v_{\rm obs}(t)} \int_{v_{\rm min}(E_R)}^{\infty} dv \left[ e^{-\left(\frac{v - v_{\rm obs}(t)}{\bar{v}}\right)^2} - e^{-\left(\frac{v + v_{\rm obs}(t)}{\bar{v}}\right)^2} \right]$$




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

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

# Size of the modulation




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

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

$$\bar{\eta} = \frac{1}{2}[\eta(2\text{ June}) + \eta(2\text{ Dec})]$$

$$A_\eta = \frac{1}{2}[\eta(2\text{ June}) - \eta(2\text{ Dec})]$$

# 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 | $\gamma_5$ | $\gamma_\mu$ | $\gamma_\mu\gamma_5$ | $\sigma_{\mu\nu}$ | $\sigma_{\mu\nu}\gamma_5$ |

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

match to nucleus level (form factors) ⇒

non-rel limit of DM current

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match to nucleus level (form factors) ⇒

non-rel limit of DM current

- $(S \otimes S), (V \otimes V)$: spin-independent ⇒ $A^2$ enhancement
- $(A \otimes A), (T \otimes T)$: spin-dependent ⇒ 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 (heavy quarks contribute via anomaly to nucleon mass):

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

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

$$\xi_d^p \approx 0.023 \,, \quad \xi_u^p \approx 0.017 \,, \quad \xi_s^p \approx 0.054$$
$$\xi_d^n \approx 0.034 \,, \quad \xi_u^n \approx 0.012 \,, \quad \xi_s^n \approx 0.054$$

e.g., Ellis, Olive, Savage, 0801.3656; numbers from Cheng, Chiang, 1202.1292

large uncertainties, for $G_q \propto m_q$ heavy quarks contribute 68% ($s$ quark: 18%)

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large uncertainties, for $G_q \propto m_q$ heavy quarks contribute 68% ($s$ quark: 18%)

# 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:

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

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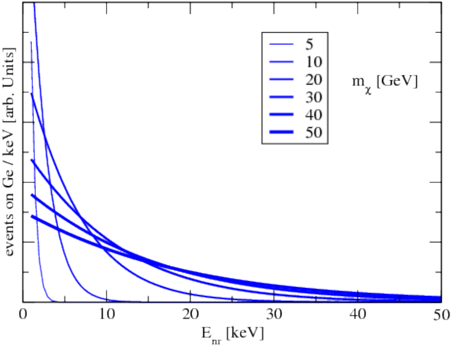
# Event spectrum for SI elastic scattering

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

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

minimal $v$ required to produce recoil $E_R$

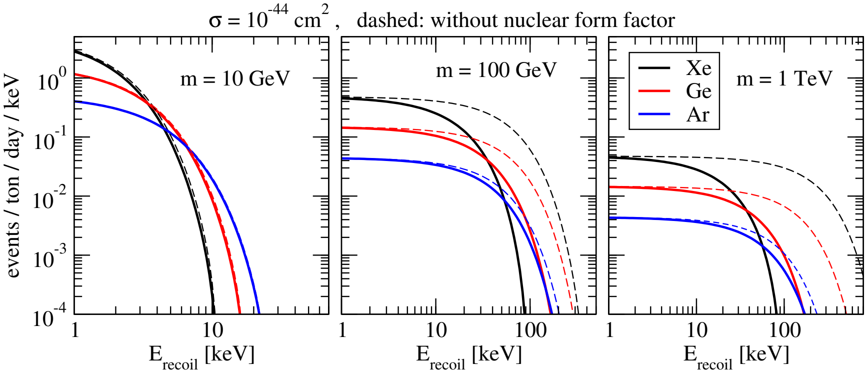



spectrum gets shifted to low energies for low WIMP masses

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

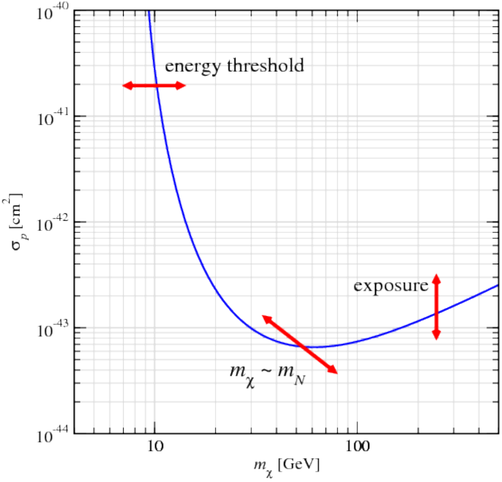
# Event spectrum for SI elastic scattering

dependence on the target nucleus:

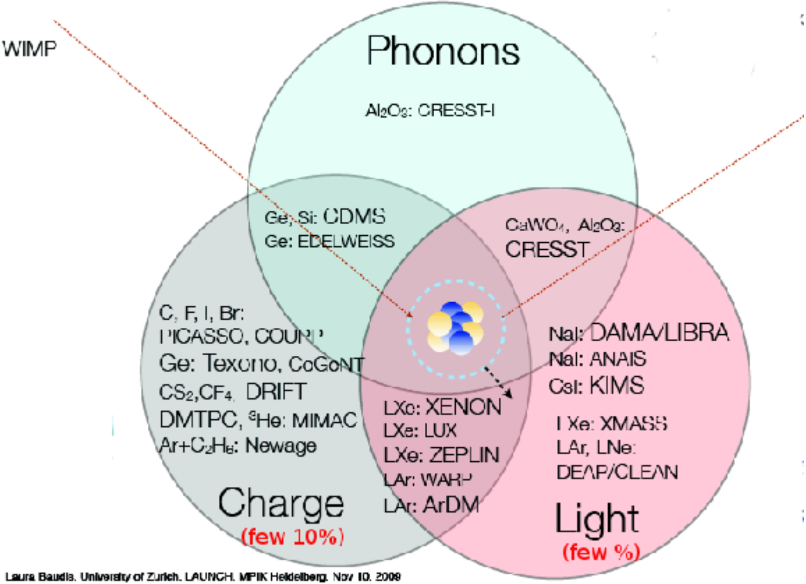



nuclear form factor is less important for low mass WIMPs

# elastic scattering exclusion curve



# Direct Detection Techniques



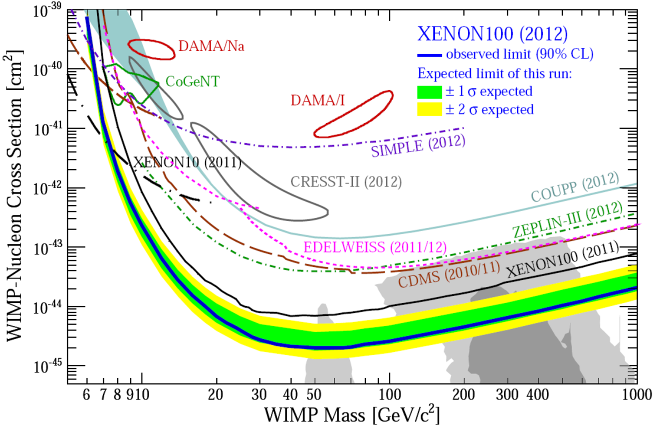

Laura Baudis, University of Zurich, LAUNCH, MPIK Heidelberg, Nov 10, 2009

- 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), XMASS (Xe), ZEPLIN (Xe),. . .

different target materials and different techniques used

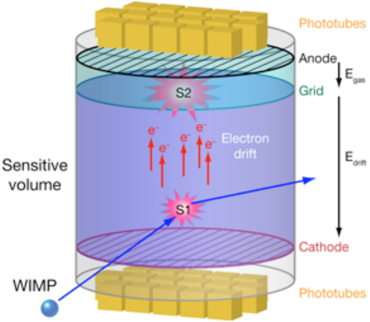
# Limits for spin-independent interactions

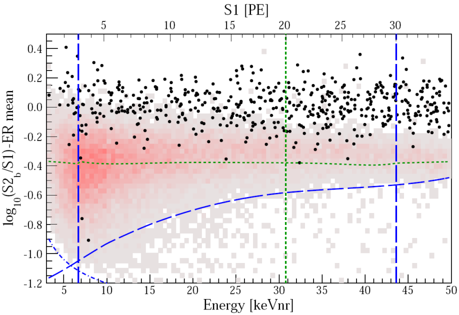


# XENON100

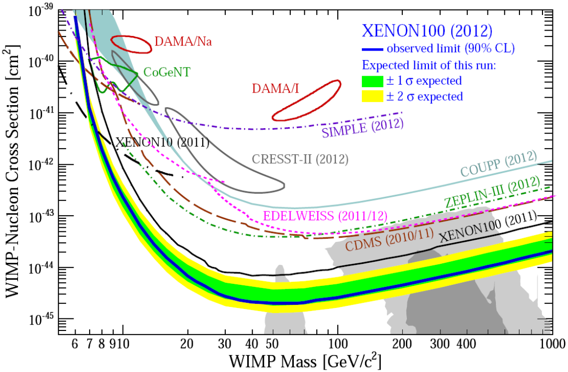
2 phase (gas/liquid) Xenon detector @ Gran Sasso
S1: prompt scintillation signal, S2: delayed ionization signal

34 kg fid., 224.6 days (Jan to June 2010) 1207.5988
2 events observed, $1.0 \pm 0.2$ background expectation

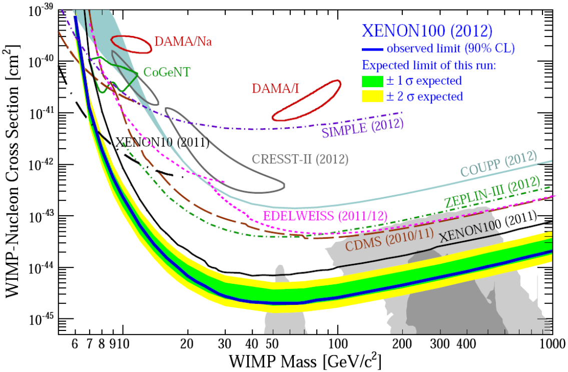


# XENON100 limit on spin-indep. interactions



# XENON100 limit on spin-indep. interactions




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

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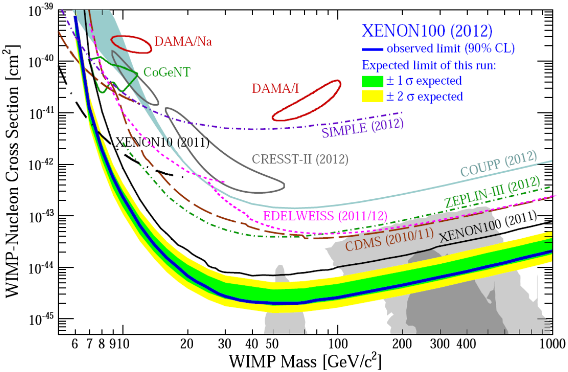
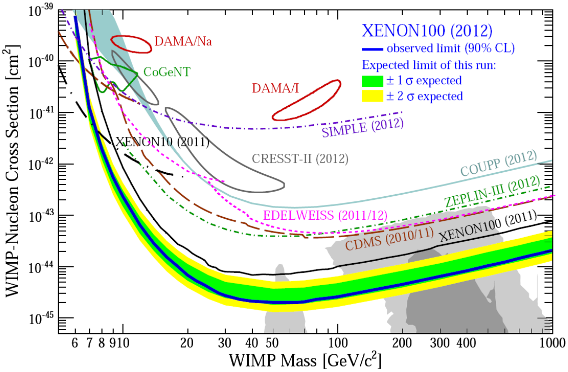



SI cross section: $\sigma_p \sim \frac{G_{\rm eff}^2 m_p^2}{\pi}$

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

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

# XENON100 limit on spin-indep. interactions




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

Higgs mediated interaction: $\sigma_p \sim 5 \times 10^{-45}\,\mathrm{cm}^2 \left(\frac{\lambda_\chi}{0.1}\right)^2 \left(\frac{125\,\mathrm{GeV}}{m_H}\right)^4$

# implications of $\sigma_{\rm scat} \lesssim 10^{-45}{\rm cm}^2$ 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:

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

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$\Rightarrow$ for $m_\chi = 50$ GeV, $m_H = 125$ 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 $\sigma_{\rm scat} \lesssim 10^{-45}{\rm cm}^2$ for the WIMP argument

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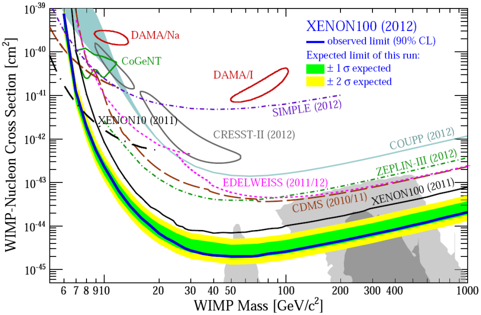
need mechanism to enhance annihilation cross section:

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

# implications of $\sigma_{\rm scat} \lesssim 10^{-45}{\rm cm}^2$ 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 $\sigma$ the WIMP hypothesis will come under pressure, and one should start to think about alternatives ("secluded" models, non-thermal DM production, non-WIMP candidates,. . . )

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

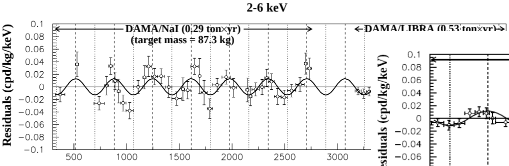
  CoGeNT, CRESST, DAMA

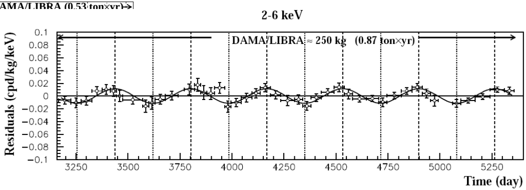
  ⇒ WIMPs (SI) in the low-mass ($\sim$10 GeV) region?
  ⇒ or maybe something more exotic
  ⇒ or have nothing to do with DM at all

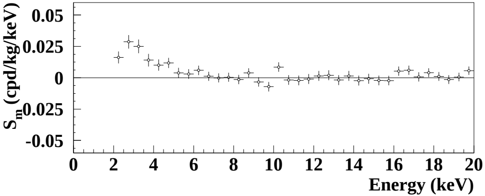
- Severe constraints from CDMS and XENON10/100

# DAMA/LIBRA annual modulation signal

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



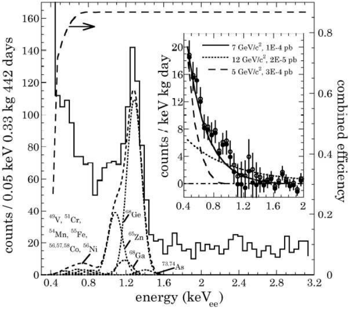



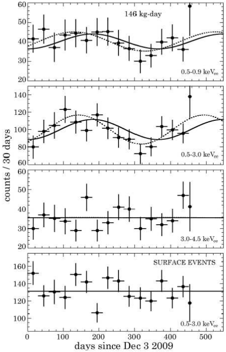




energy shape of modulation is important for constraining params
Chang, Pierce, Weiner, 0808.0196
Fairbairn, TS, 0808.0704

# CoGeNT: exponential event excess and hint for modulation

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



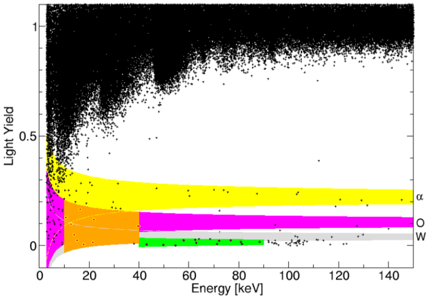



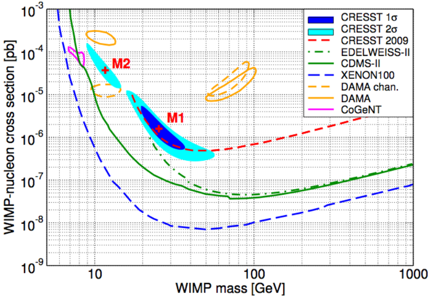

Aalseth et al, 1106.0650

- possible presence of surface event contamination
- amplitude of modulation "too large"
- phase does not match with "vanilla" halo expectation
- direct constraints from CDMS on modulation 1203.1309

# CRESST-II TAUP 2011, 1109.0702

CaWO$_4$ target, 8 detectors, 730 kg d



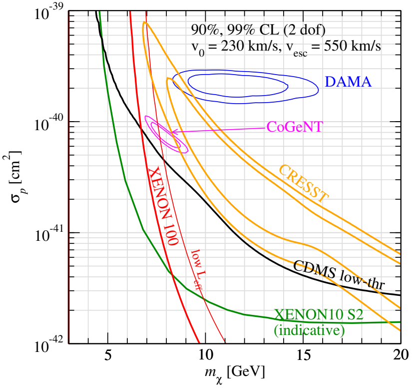




backgrounds: $e/\gamma$ : 8, $\alpha$ : $\sim$ 11, neutrons: $\sim$ 7, Pb: $\sim$ 15
observe 67 events: likelihood fit gives $\sim$ 29 signal events at more than $4\sigma$

M1: $m_\chi = 25.3$ GeV, significance: $4.7\sigma$ (signal: 69% W, 25% Ca, 7% O)
M2: $m_\chi = 11.6$ GeV, significance: $4.2\sigma$ (signal: 52% O, 48% Ca)

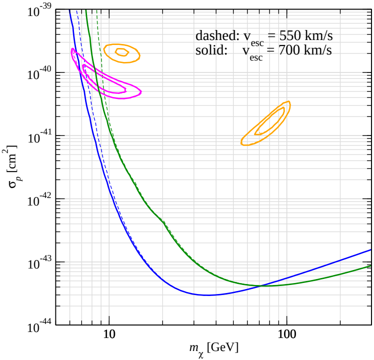
# The low-mass hints?

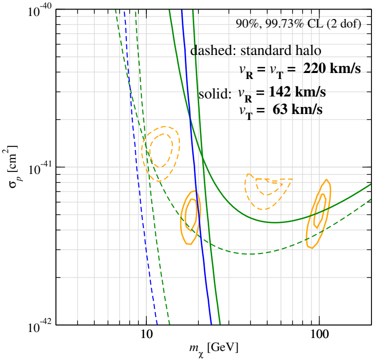
- The hints triggered a lot of excitement about $\sim 10$ GeV WIMPs
- however, the hints are not quite consistent, and in disagreement with various bounds
- $\sim 10$ GeV region is experimentally challenging:




- energy scale
  (DAMA $q_{Na}$, channeling
  XENON: $L_{eff}$)
- threshold effects
  (XENON)
- backgrounds
  (CoGeNT surface ev., CRESST?)

# Modify astrophysics?




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

# 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

these statements hold for standard SI elastic scattering
in other models (e.g. inelastic scattering) the impact of astrophysics can be bigger

methods for halo independent comparison of experiments:

Fox, Kribs, Tait 1011.1910; Fox, Liu, Weiner, 1011.1915; McCabe 1107.0741; Frandsen et al., 1111.0292;

Gondolo, Gelmini, 1202.6359; Herrero-Garcia, TS, Zupan, 1112.1627, 1205.0134

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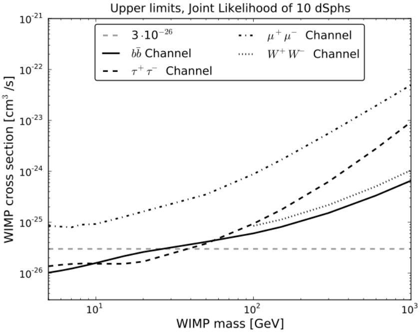
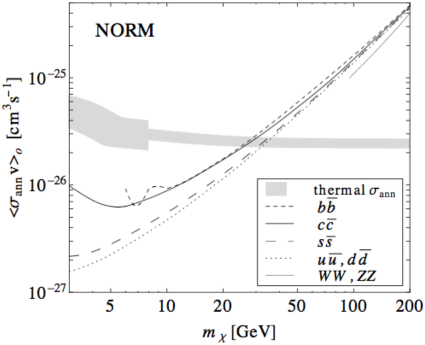
# Limits from indirect detection

vanilla thermal WIMP with relic cross section from s-wave annihilation




FERMI $\gamma$ rays limit from milkyway dwarfs 1108.3546



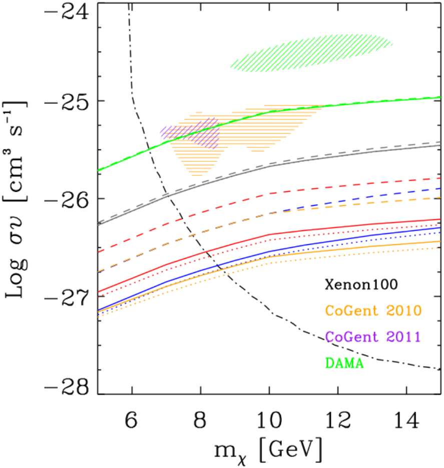

anti-protons from BESS-polar II

Kappl, Winkler, 1110.4376

# Limits from indirect detection

assume DM-quark contact interaction proportional to quark mass

I. Cholis, C. Evoli, D. Grasso, L. Maccione, P. Ullio, 1108.0664




colors: propagation model, line style: DM profile

# 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:

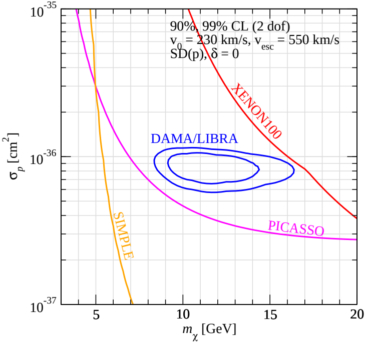
| | | neutron | proton |
|---|---|---|---|
| DAMA | $^{23}_{11}$Na | even | odd |
| DAMA, KIMS, COUPP | $^{127}_{53}$I | even | odd |
| SIMPLE | $^{35}_{17}$Cl, $^{37}_{17}$Cl | even | odd |
| XENON, ZEPLIN | $^{129}_{54}$Xe, $^{131}_{54}$Xe | odd | even |
| CDMS, CoGeNT | $^{73}_{32}$Ge | odd | even |
| PICASSO, COUPP, SIMPLE | $^{19}_{9}$F | even | odd |
| CRESST | $^{182,183,184,186}_{74}$W, $^{16}_{8}$O, $^{40}_{20}$Ca | even | even |

coupling with proton promising for DAMA vs CDMS/XENON

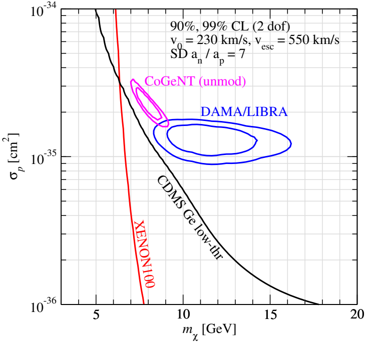
BUT: severe bounds from COUPP, KIMS, PICASSO, SIMPLE

# Spin-dependent scattering

proton




(mainly) neutron




Schwetz, Zupan, 1106.6241

# Constraints from colliders

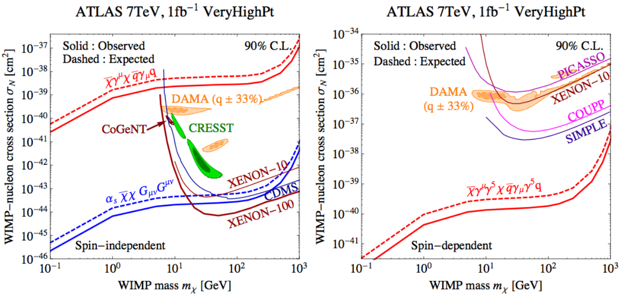
assume effective quark DM interaction:

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

constraints from mono-jet searches at LHC (Tevatron)

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

Feng, Su, Takayama, 05; Beltran et al, 10; Goodman et al, 10; Bai, Fox, Harnik, 10;...




Fox, Harnik, Kopp, Tsai, 1109.4398

# Neutrinos from the sun

- WIMPs scatter with atoms in the sun and get gravitationally trapped
- accumulate in the center of the sun
- start to annihilate and produce high-energy neutrinos $E_\nu \lesssim m_\chi$
- search for those neutrinos in neutrino telescopes: SuperKamiokande, IceCube

$$\frac{d\phi_\nu}{dE_\nu} = \frac{\Gamma_{\mathrm{annih}}}{4\pi R^2} \frac{dN_\nu}{dE_\nu}$$

in equilibrium: $\Gamma_{\mathrm{annih}} = C_{\mathrm{scatt}}/2$, with $C_{\mathrm{scatt}} \propto \sigma_{\mathrm{scatt}}$

- calculate initial spectrum of neutrinos (Pythia)
- propagate them through the sun and to the earth (neutrino oscillations, absorption, regeneration)
- calculate the induced muon flux at the detector

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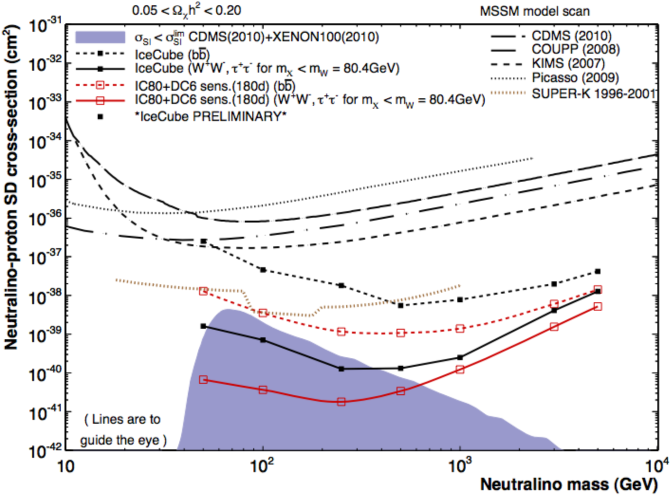
# SD and constraints from neutrinos

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

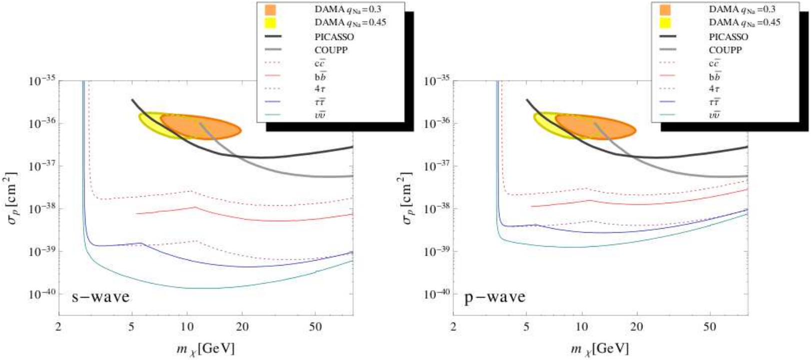
IceCube 1111.2738



# SD and constraints from neutrinos

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

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

# Outline

In the ideal world, in $\sim 5$ years we would see

- a signal in direct detection
  - consistent in $\geq 2$ different experiments with different targets
  - evidence for annual modulation (including a sign flip)
- solid signal from indirect detection ($\gamma$ line) consistent with a thermal annihilation cross section
- *some* signature at LHC consistent with a DM interpretation of the above

...this would provide a very strong case for WIMP DM most likely the world is not ideal....

most likely the world is not ideal.... BUT:

if no signal is found in some or all of the DM searches

- the WIMP hypothesis will be come less attractive
- although in general it is impossible to rule it out completely, many variations are possible
- there are many alternatives to vanilla WIMPs:
  asymmetric DM, warm DM, axions, GIMPs, FIMPs,...
  which may or may not provide interesting experimental signatures, similar or different from classic WIMP signals discussed here

# The next years are going to be exciting!

**Thank you for your attention!**

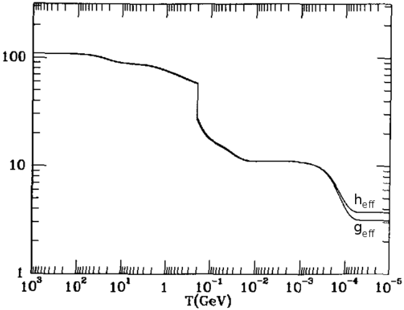
additional slides

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

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

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

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

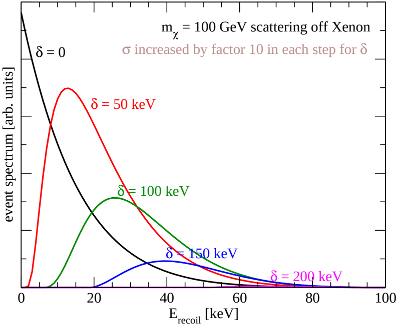


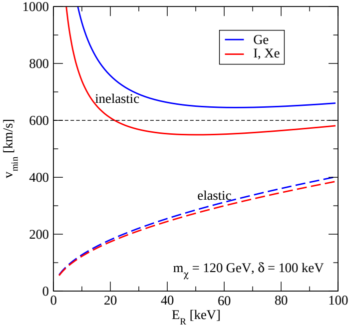

Gondolo, Gelmini, 1991

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

# Inelastic DM scattering Tucker-Smith, Weiner, 01

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




- 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

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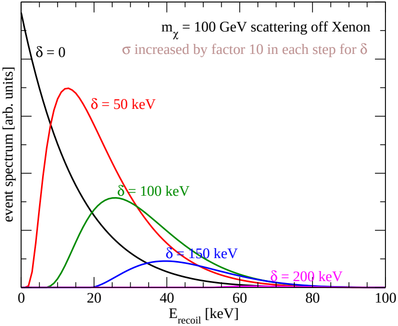


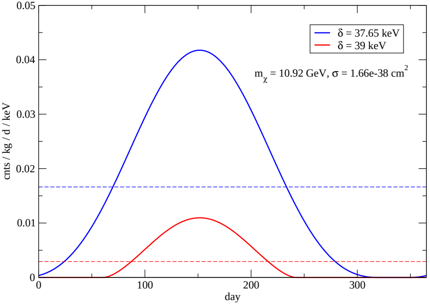


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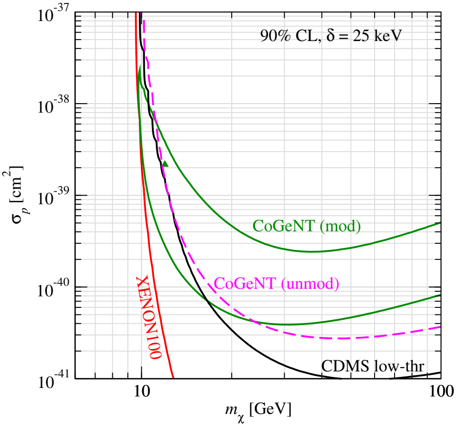
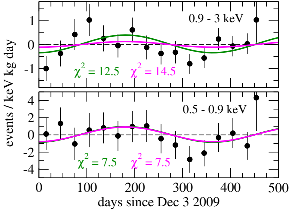
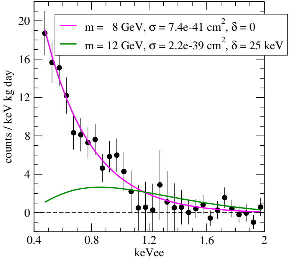
# iDM and CoGeNT modulation




TS, Zupan, 11

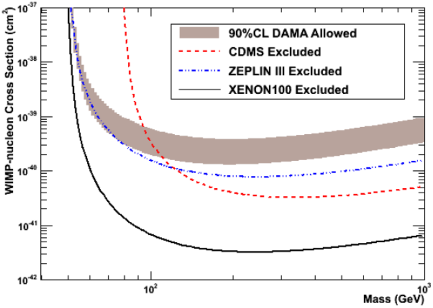


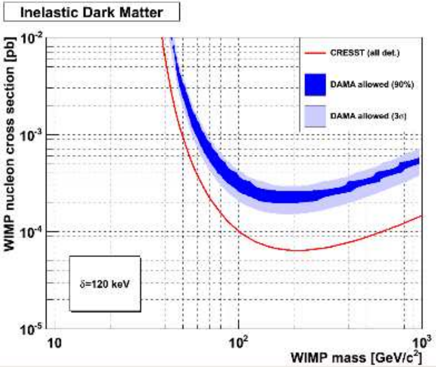

- make mod and unmod spectrum consistent but cannot explain rate
- XENON bound still severe

# iDM and DAMA modulation

XENON100 1104.3121

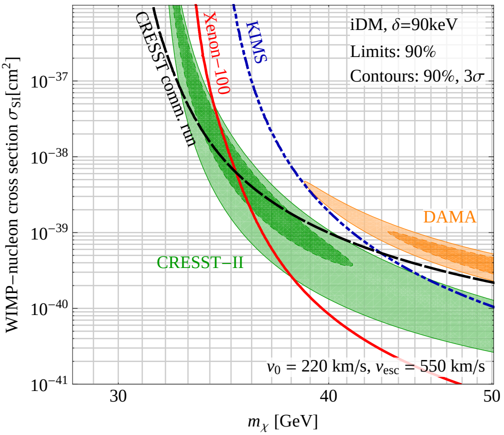



W. Seidel @ IDM10, poster of J. Schmaller @ TAUP11




disfavored by XENON100, CRESST (tungsten), and KIMS

# iDM and CRESST




Kopp, TS, Zupan, 1110.2721

# Inelastic alternatives for DAMA

⇒ inelastic spin-dependent scattering on protons

Kopp, Schwetz, Zupan, 0912.4264; Schwetz, Zupan, 1106.6241

⇒ magnetic inelastic DM

Chang, Weiner, Yavin, 1007.4200

- use large spin or MM of iodine to enhance rate in DAMA
- inelast kinematics avoids florine constraints (light target)

- no explanation for CoGeNT/CRESST
- probably ruled out by KIMS results TAUP 2011
- neutrinos from the sun Shu, Yin, Zhu, 1001.1076
- collider constraints

# Generalized couplings to neutron and proton

spin-independent scattering cross section:

$$\mathrm{SI} \propto [Z f_p + (A - Z) f_n]^2$$

typically (iso-spin symmetry) one has $f_n \approx f_p \quad \Rightarrow \quad \mathrm{SI} \propto \sigma_p A^2$

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allow for general couplings $f_n \neq f_p$:

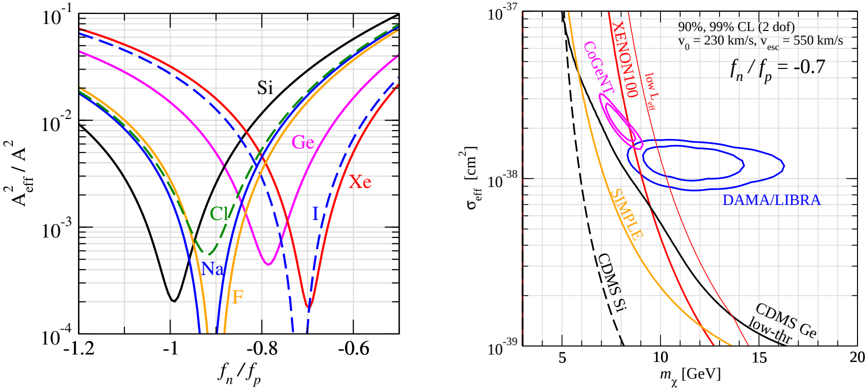
e.g., Chang et al., 1004.0697; Feng, Kumar, Marfatia, Sanford, 1102.4331; Frandsen et al., 1105.3734;

Nobile, Kouvaris, Sannino, 1105.5431; del Nobile, Kouvaris, Sannino, Virkajarvi, 1111.1902; ...

for $f_n/f_p < 0$: cancellations $\Rightarrow \mathrm{SI} \propto \sigma_{\mathrm{eff}} A^2_{\mathrm{eff}}$

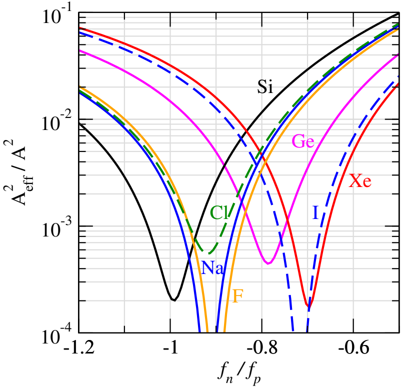
can suppress rate for isotope if $f_n/f_p = -Z/(A - Z)$

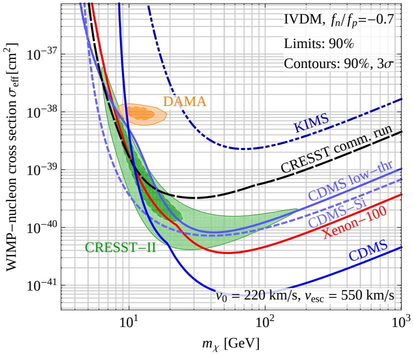
# Generalized couplings to neutron and proton




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

# Generalized couplings to neutron and proton



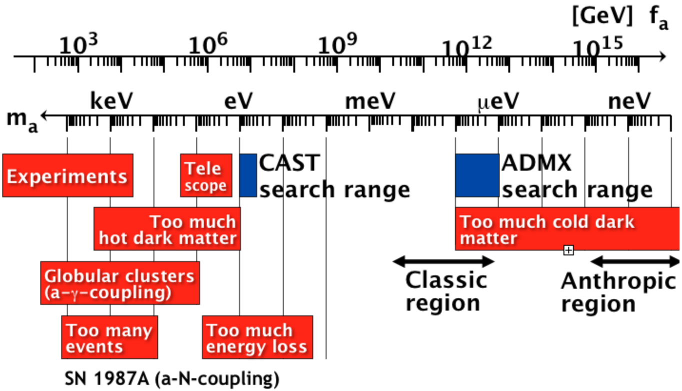




suppress Xe rate for $f_n/f_p \approx -0.7$, enhanced rate for Si, F, O, Ca
CRESST marginally consistent

# Axion DM

- motivated by strong CP problem
- provides cold DM candidate with very different properties
- axion-photon conversion in resonant cavities: ADMX experiment

Primakoff effect:
Axion–photon transition in external static E or B field


Raffelt