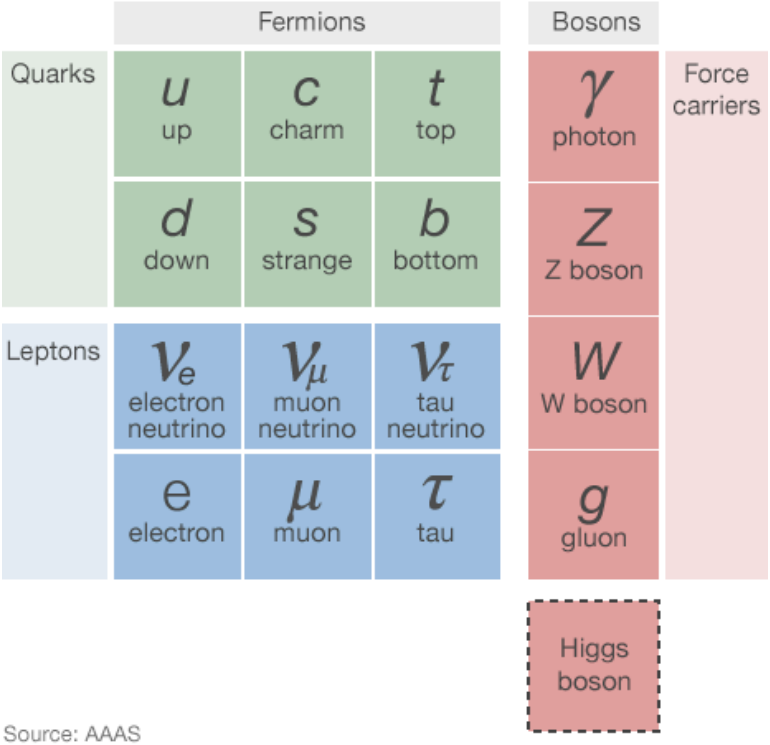
So… what is the DM?

… and how do we detect it?

The Standard Model does not contain any viable candidate for DM



Source: AAAS

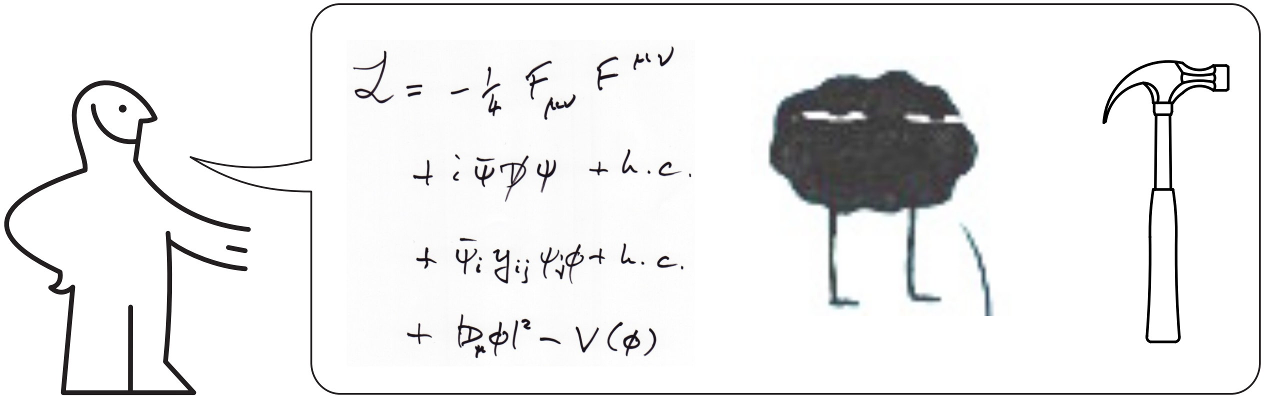
Neutrinos constitute a tiny part of (Hot) dark matter

$$\Omega_\nu h^2 = \frac{\sum_i m_{\nu_i}}{91.5\mathrm{eV}} \lesssim 0.003$$

Hot dark matter not consistent with observations on structure formation.

Dark Matter is one of the clearest hints of Physics Beyond the SM

MÖRK MATERIA MODELL



Good candidates for Dark Matter have to fulfil the following conditions

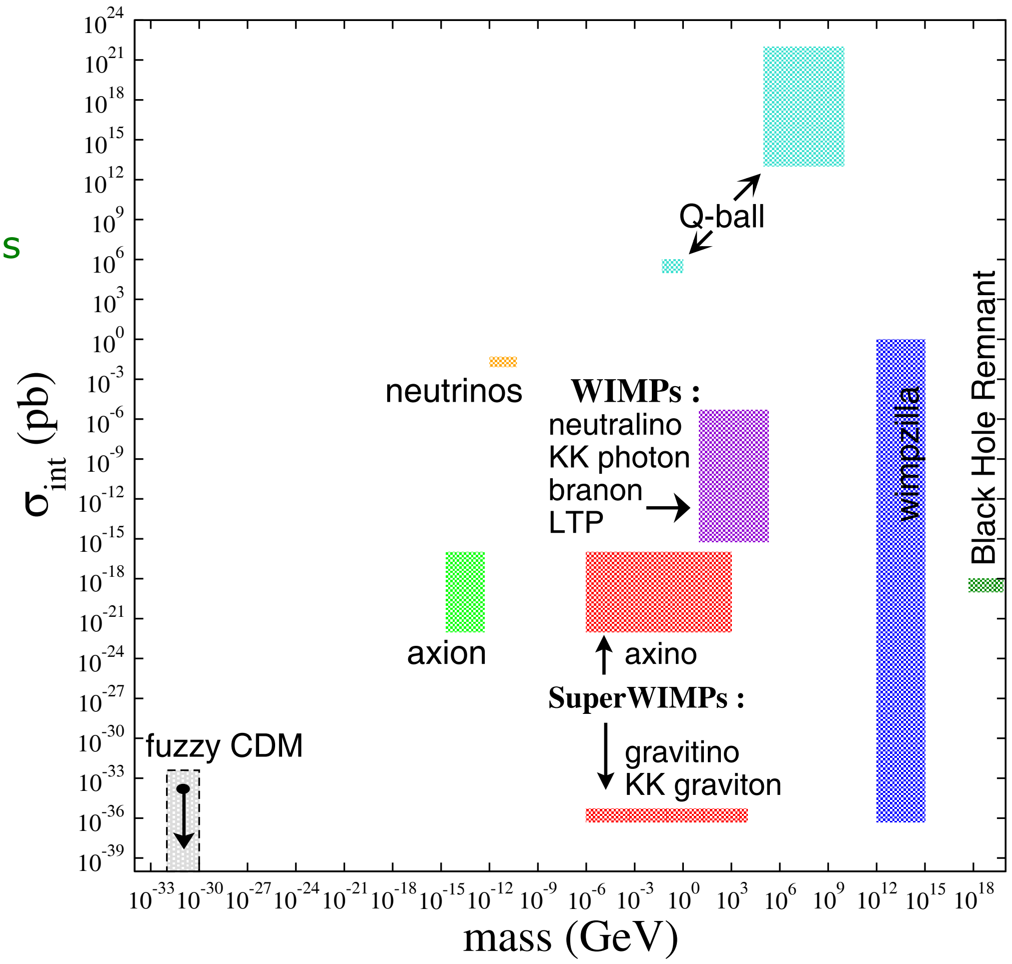
- Neutral
- Stable on cosmological scales (*)
- Cold, non-relativistic, when structures are formed (**)
- Reproduce the correct relic abundance
- Not excluded by current searches
- No conflicts with BBN or stellar evolution

We don’t know yet what DM is... but we do know many of its properties

Many candidates in Particle Physics

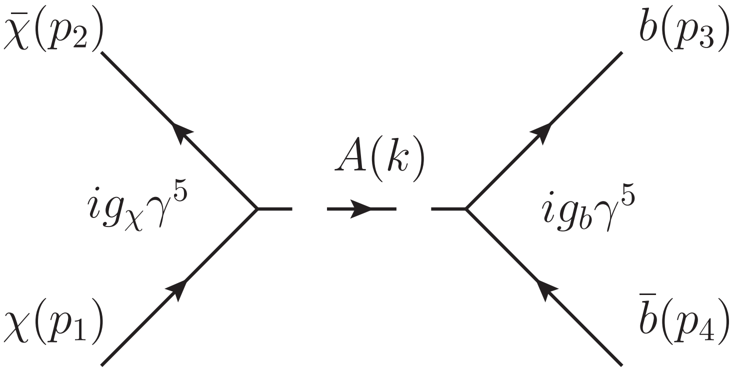
- Axions
- Weakly Interacting Massive Particles (WIMPs)
- SuperWIMPs and Decaying DM
- WIMPzillas
- Asymmetric DM
- SIMPs, CHAMPs, SIDMs, ETCs...

They have very different properties and cannot be searched for iun the same way



A simple example: fermion DM + Pseudoscalar mediator + SM

Let us assume that the DM particle is a fermion X, which connects to SM particles through the exchange of a pseudoscalar A



$$\mathcal{L} = i\left(g_\chi \bar{\chi}\gamma^5\chi + g_b \bar{b}\gamma^5 b\right) A$$

Is it viable?

- Is the relic density correct?

$$\langle\sigma v\rangle_{ij} = a_{ij} + \frac{b_{ij}}{x} = a_{ij} + b_{ij}v^2$$

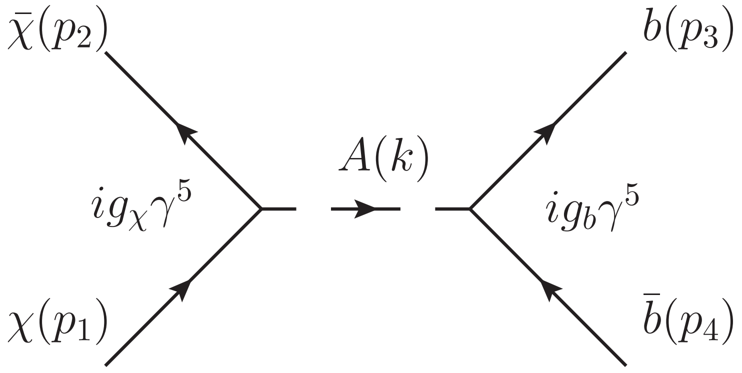
$$a_{ij} = \frac{1}{m_\chi^2}\left(\frac{N_c}{32\pi}\beta(s, m_i, m_j)\frac{1}{2}\int_{-1}^{1} d\cos\theta_{CM}\,|\mathcal{M}_{\chi\chi\to ij}|^2\right)_{s=4m_\chi^2}$$

$$\beta(s, m_i, m_j) = \left(1 - \frac{(m_i+m_j)^2}{s}\right)^{1/2}\left(1 - \frac{(m_i-m_j)^2}{s}\right)^{1/2}$$

A simple example: fermion DM + Pseudoscalar mediator + SM

This results in

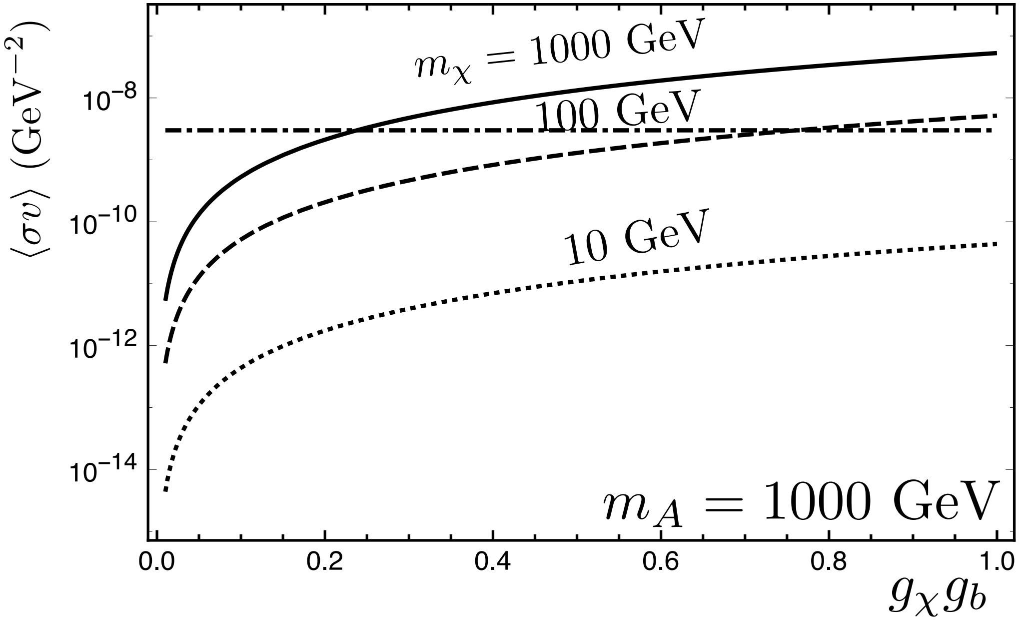
$$\langle \sigma v \rangle \approx \frac{3}{2\pi} \frac{(g_\chi g_b)^2 m_\chi^2 \sqrt{1 - m_b^2/m_\chi^2}}{(4m_\chi^2 - m_A^2)^2 + m_A^2 \Gamma_A^2}$$



Using the expression of the relic density

$$\Omega_\chi h^2 \approx \frac{3 \times 10^{-10}\ \mathrm{GeV}^{-2}}{\langle \sigma v \rangle}$$

$$g_\chi g_b \sim 0.1 - 1$$



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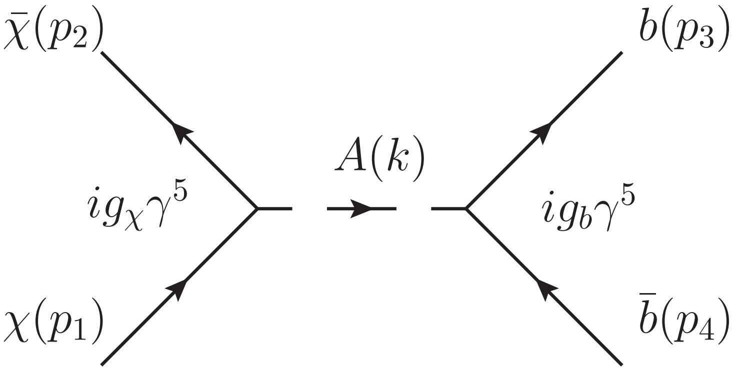

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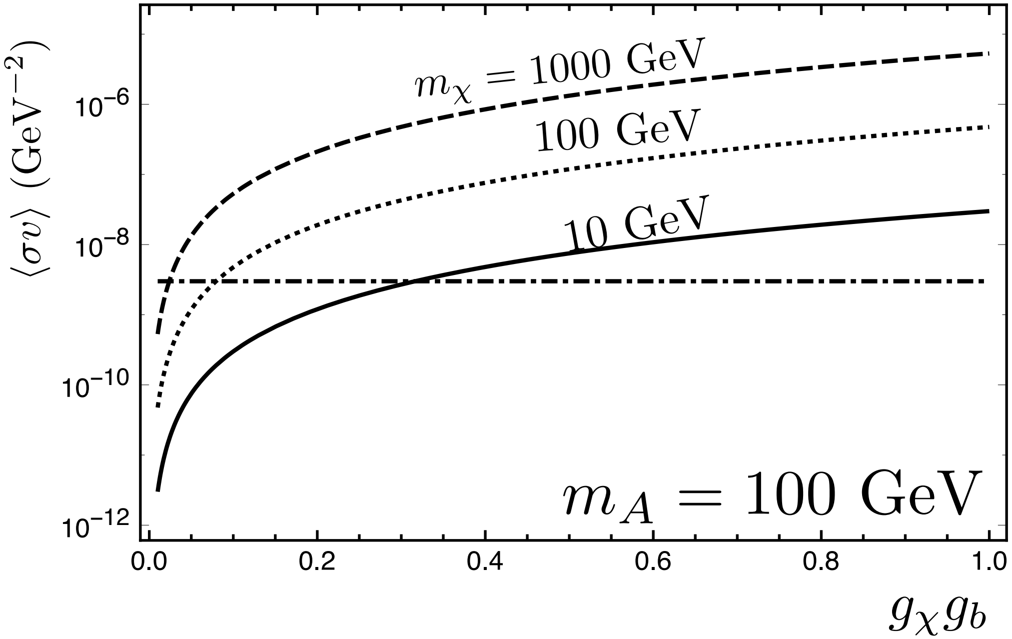

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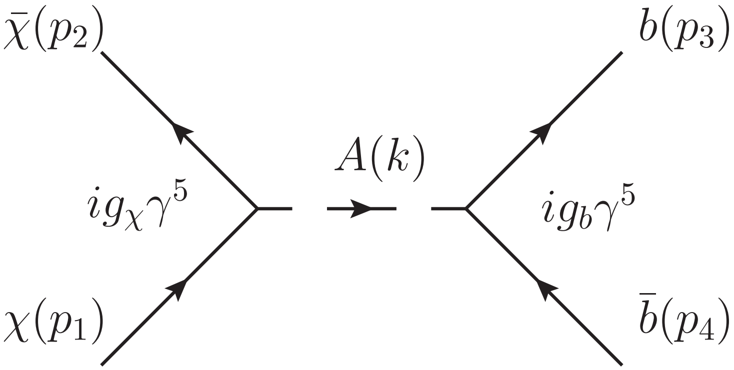


Using the expression of the relic density

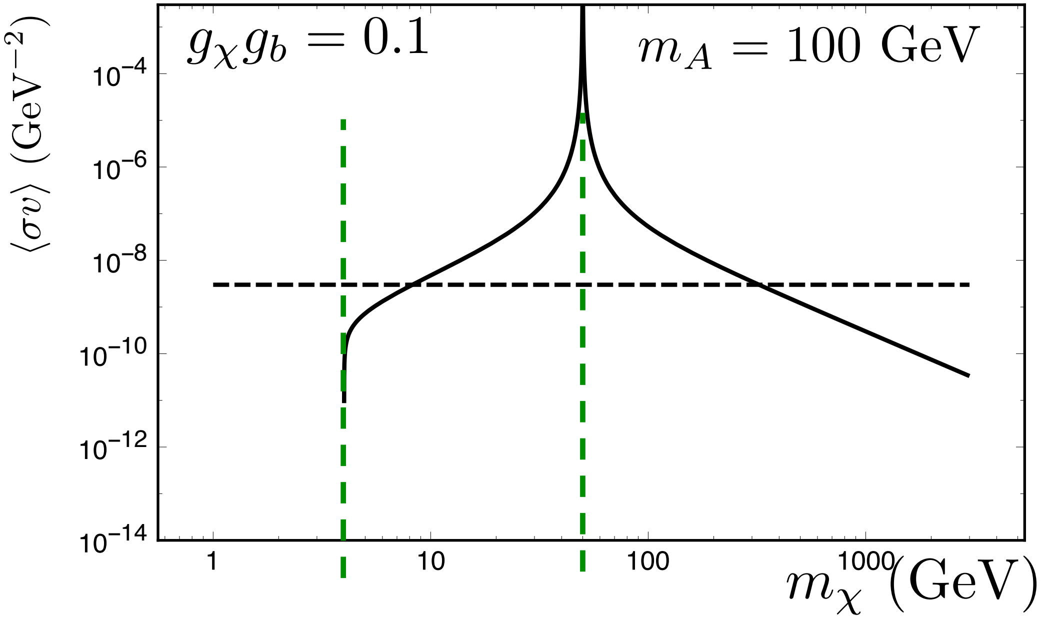
$$\Omega_\chi h^2 \approx \frac{3\times 10^{-10}\ \mathrm{GeV}^{-2}}{\langle\sigma v\rangle}$$

Production threshold

$$m_\chi = m_b$$

Resonance

$$m_\chi = \frac{1}{2}m_A$$

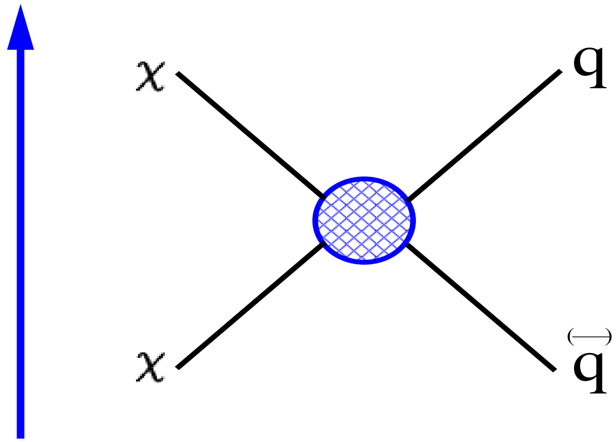


Dark Matter particles can be probed in different ways

Direct Detection

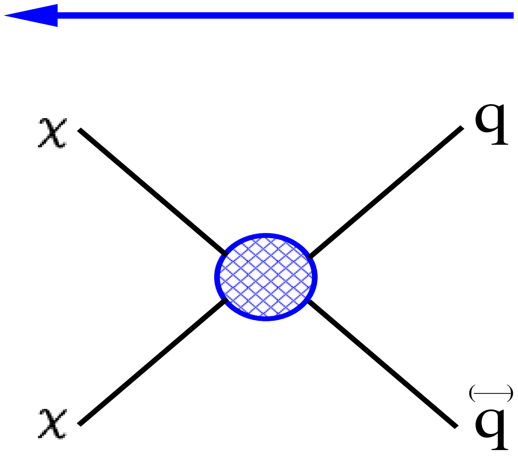
(DM-nuclei scattering)

DAMA/LIBRA
SuperCDMS
Edelweiss
XENON
LUX
CRESST
CoGeNT
DarkSide
KIMS
COUPP
PICASSO
ZEPLIN
SIMPLE
ANAIS
XMASS
...



Dark Matter particles can be probed in different ways

Accelerator Searches (DM production) LHC (ILC)



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Dark Matter particles can be probed in different ways

Accelerator Searches (DM production) LHC (ILC)

Direct Detection

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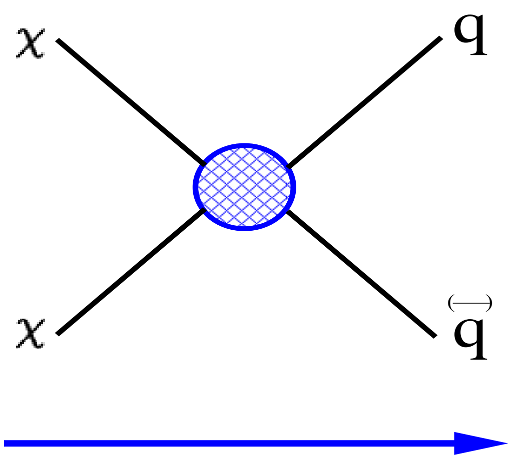


Indirect Detection

(DM annihilation)

PAMELA
Fermi
MAGIC
AMS

ANTARES
IceCube
CTA
HESS

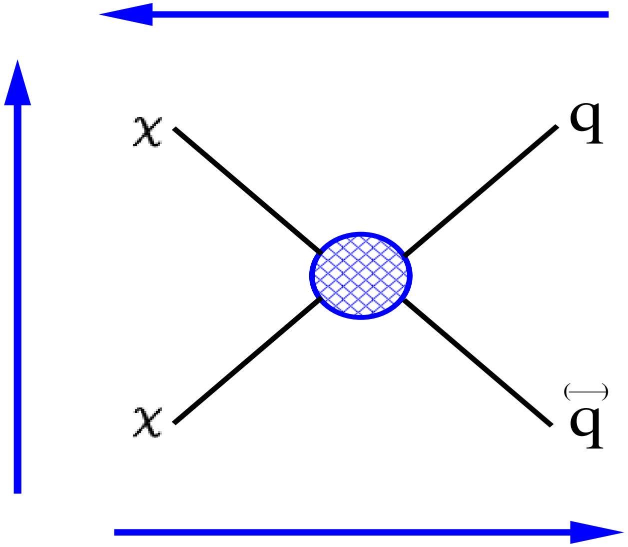
... probing different aspects of the DM interactions with ordinary matter

Accelerator Searches (DM production) LHC (ILC)

Direct Detection

(DM-nuclei scattering)

DAMA/LIBRA
SuperCDMS
Edelweiss
XENON
LUX
CRESST
CoGeNT
DarkSide
KIMS
COUPP
PICASSO
ZEPLIN
SIMPLE
ANAIS
XMASS
...



Constraints in one sector affect observations in the other two.

"Redundant" detection can be used to extract DM properties.

COMPLEMENTARITY
of DM searches

Indirect Detection

(DM annihilation)

PAMELA
Fermi
MAGIC
AMS

ANTARES
IceCube
CTA
HESS

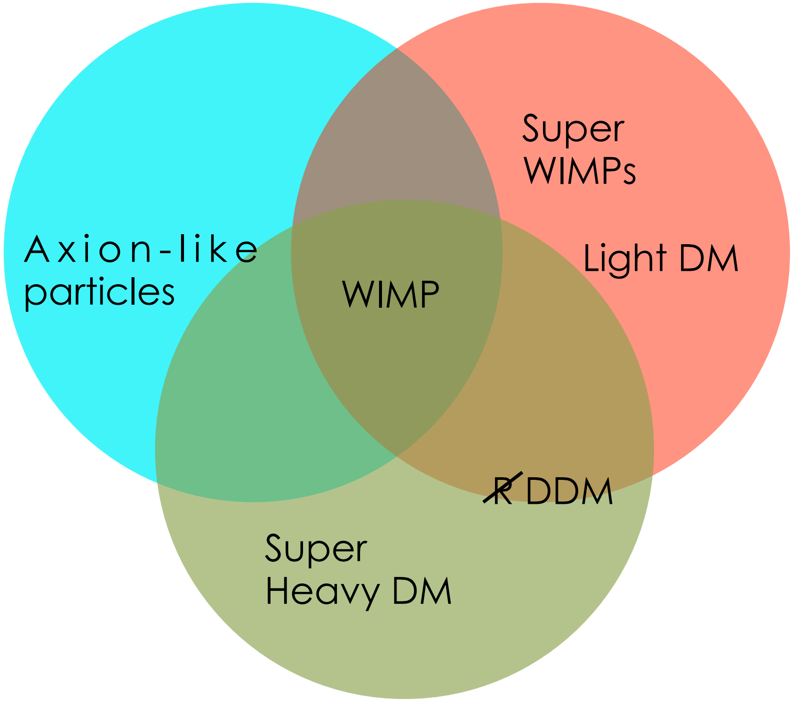
These searches can explore different models for DM

Direct Detection

(DM-nuclei scattering)

DAMA/LIBRA
SuperCDMS
Edelweiss
XENON
LUX
CRESST
CoGeNT
DarkSide
KIMS
COUPP
PICASSO
ZEPLIN
SIMPLE
ANAIS
XMASS
...

Accelerator Searches (DM production) LHC (ILC)



Axion-like particles

WIMP

Super WIMPs

Light DM

$\cancel{R}$ DDM

Super Heavy DM

Indirect Detection

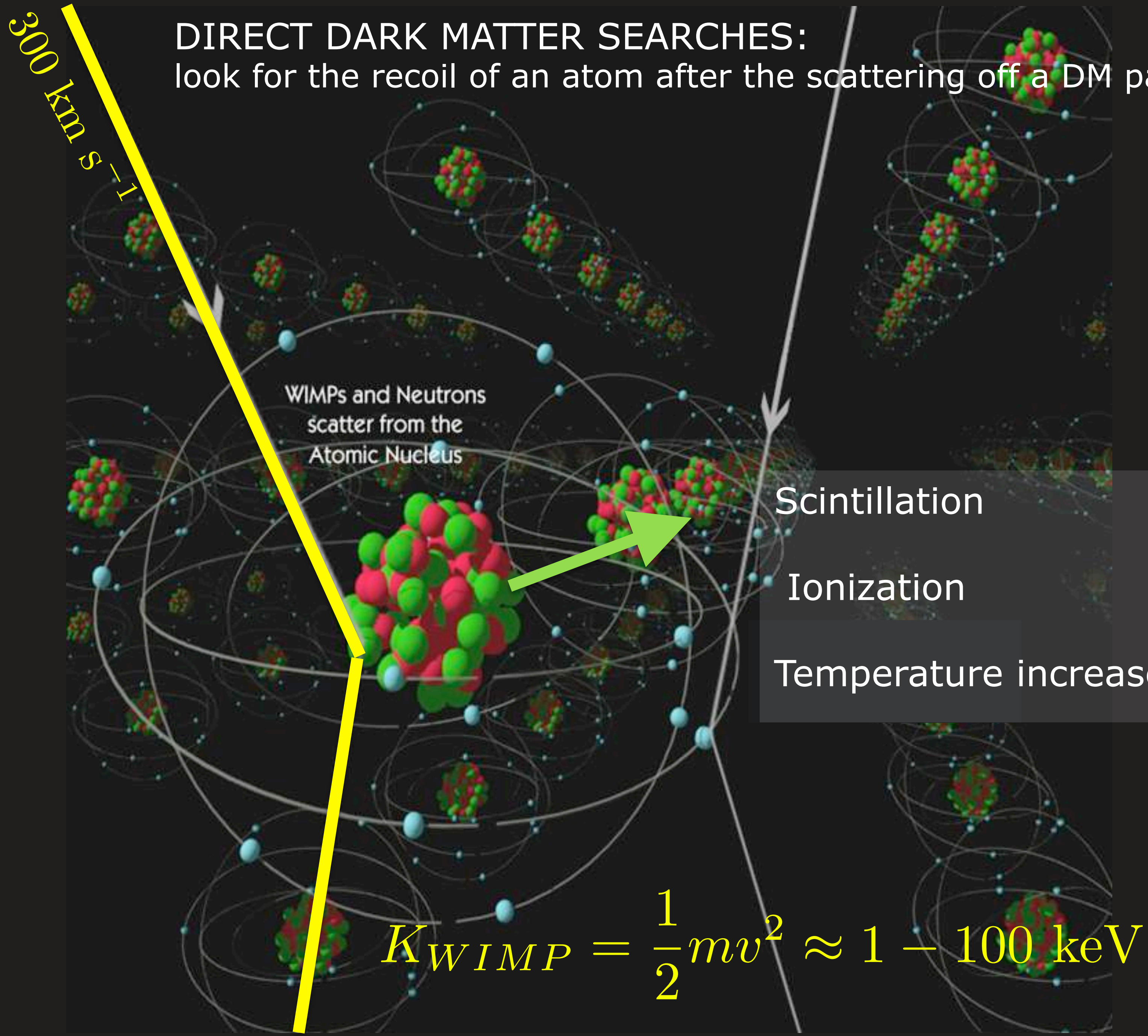
(DM annihilation)

PAMELA
Fermi
MAGIC
AMS

ANTARES
IceCube
CTA
HESS

DIRECT DARK MATTER SEARCHES:

look for the recoil of an atom after the scattering off a DM particle



Scintillation

Ionization

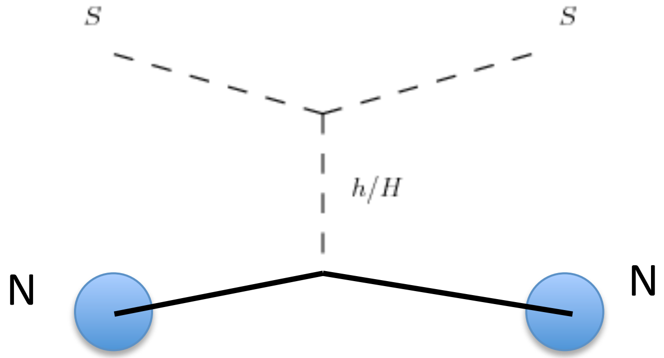
Temperature increase

$$K_{WIMP} = \frac{1}{2}mv^2 \approx 1 - 100\ \mathrm{keV}$$

Detecting Dark Matter through elastic scattering with nuclei

We want to describe the (elastic) scattering cross section of DM particles with nuclei

$$\frac{d\sigma_{WN}}{dE_R}(v, E_R)$$



But our microscopic theory generally provides the interaction with quarks and gluons

Quarks → Nucleons (protons and neutrons)

Nucleons → Nucleus   Nuclear models (encoded in a Form Factor)

The WIMP-nucleus cross section has two components

$$\frac{d\sigma_{WN}}{dE_R} = \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SI} + \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SD}$$

Spin-independent contribution: scalar (or vector) coupling of WIMPs with quarks

$$\mathcal{L} \supset \alpha_q^S \bar{\chi}\chi\bar{q}q + \alpha_q^V \bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$$

Total cross section with Nucleus scales as A^2

Present for all nuclei (favours heavy targets) and WIMPs

Spin-dependent contribution: WIMPs couple to the quark axial current

$$\mathcal{L} \supset \alpha_q^A (\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)$$

Total cross section with Nucleus scales as J/(J+1)

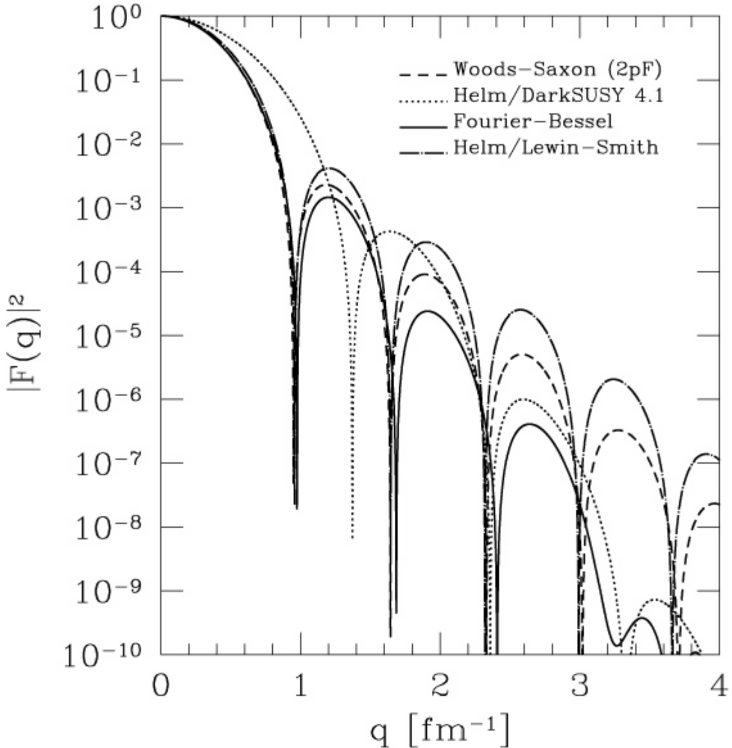
Only present for nuclei with J≠ 0 and WIMPs with spin

WIMP-nucleus (elastic) scattering cross section

$$\frac{\mathrm{d}\sigma^{WN}}{\mathrm{d}E_R} = \frac{m_N}{2{\mu_N}^2 v^2}\left({\sigma_0}^{SI,N} F_{SI}^2(E_R) + {\sigma_0}^{SD,N} F_{SD}^2(E_R)\right)$$

Where the spin-independent and spin-dependent contributions read

$$\begin{aligned} {\sigma_0}^{SI,N} &= \frac{4\mu_N^2}{\pi}[Zf_p + (A-Z)f_n]^2, \\ {\sigma_0}^{SD,N} &= \frac{32\mu_N^2 G_F^2}{\pi}[a_p S_p + a_n S_n]^2 \left(\frac{J+1}{J}\right) \end{aligned}$$



The Form factor encodes the loss of coherence for large momentum exchange

$$F^2(q) = \left(\frac{3j_1(qR_1)}{qR_1}\right)^2 \exp(-q^2 s^2)$$

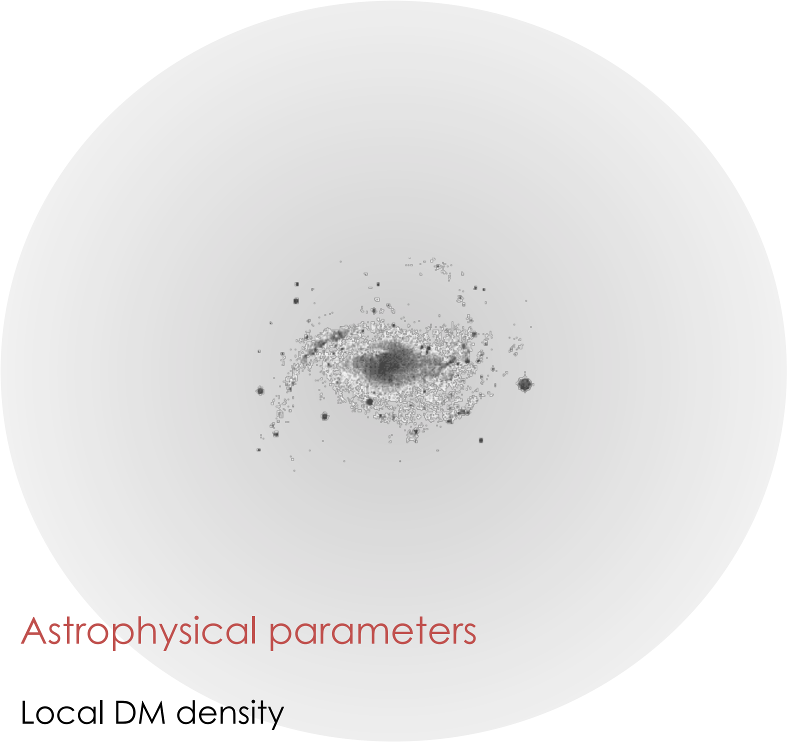
For ~keV energies, F(q)~1

Detecting Dark Matter through elastic scattering with nuclei

$$\frac{\rho_0}{m_N\, m_\chi}\int_{v_{min}}^{\infty} v f(v)\,\frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$

Minimal DM velocity for a recoil of energy E_R

$$v_{min}(E_R) = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}$$



Isothermal spherical halo

$$f(\vec{v}+\vec{v}_{lag}) = \frac{1}{(2\pi)^{\frac{3}{2}}\sigma^3} exp\left(-\frac{(\vec{v}+\vec{v}_{lag})^2}{2\sigma^2}\right)$$

$$\sigma = 150\ \mathrm{km\,s^{-1}}$$

$$v_{lag} = 230\ \mathrm{km\,s^{-1}}$$

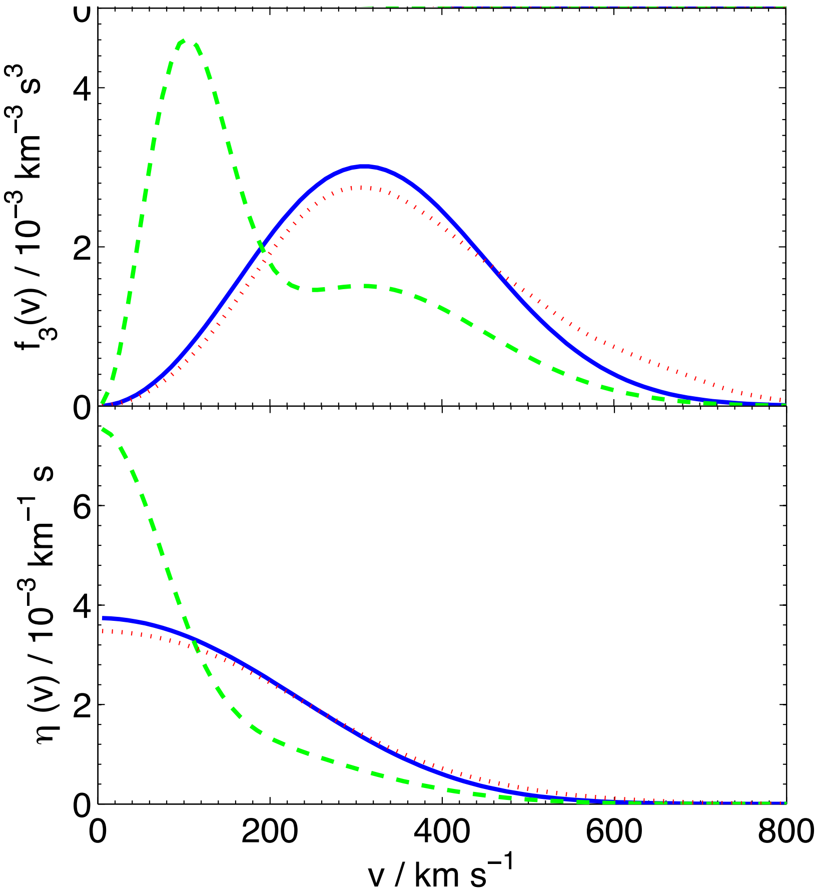
Astrophysical parameters

Local DM density

Velocity distribution factor

Detecting Dark Matter through elastic scattering with nuclei

$$\frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$



Minimal DM velocity for a recoil of energy E_R

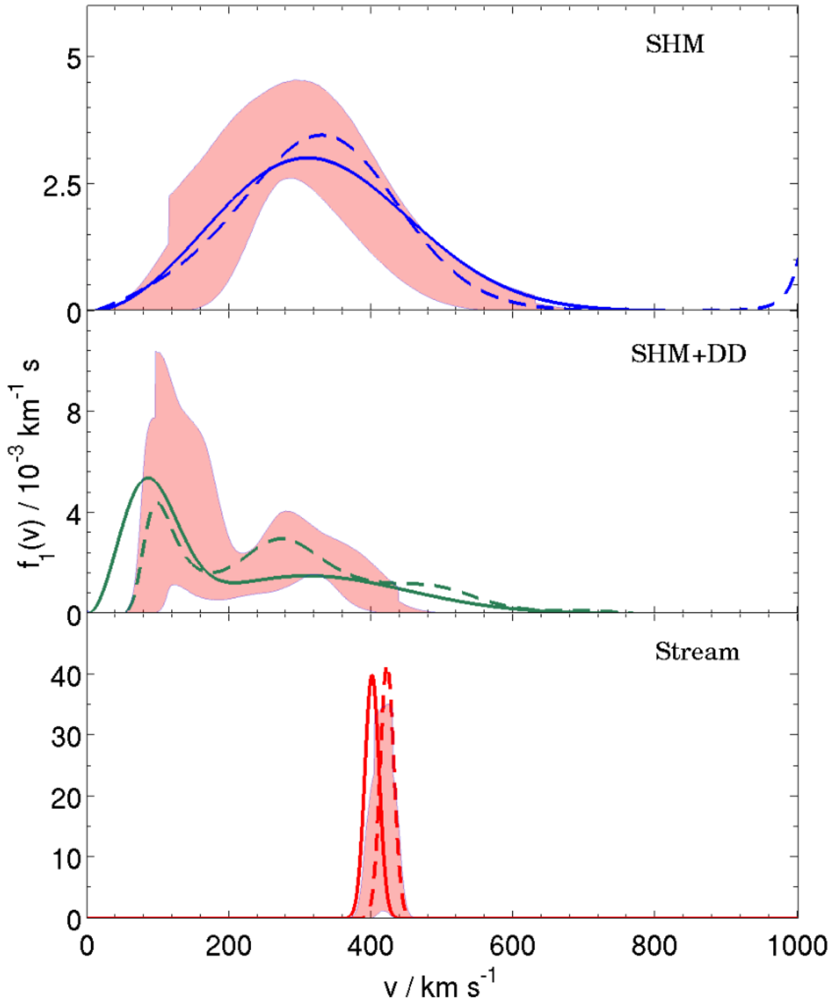
$$v_{min}(E_R) = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}$$

Introducing the v^{-2} dependence of the cross section we are left with the mean inverse sepeed

$$\eta(v_{min}) = \int \frac{f(\vec{v})}{v} \mathrm{d}^3\vec{v},$$

Uncertainties in the Dark Halo affect significantly the prospects for direct detection

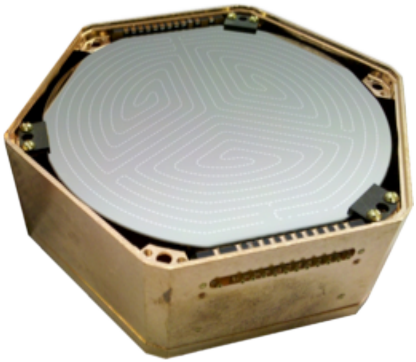
For example, there might be non-thermalised components: dark disk or streams



Kavanagh and Green 2013

Detecting Dark Matter through elastic scattering with nuclei

$$N = M_{det} t \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$



Experimental setup

Target material (sensitiveness to spin-dependent and –independent couplings)

Detection threshold

Total exposure

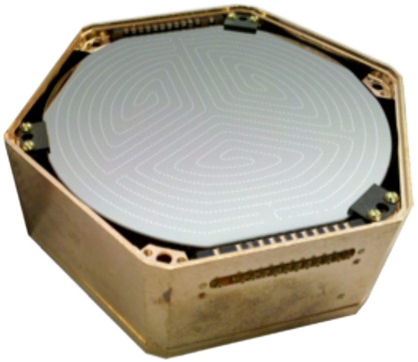
Energy scale of recoils

$$E_R = \frac{\mu_N^2 v^2 (1 - \cos\theta^*)}{m_N} \,,$$

E.g., for a 100 GeV WIMP in Ge E_R~30 keV

Detecting Dark Matter through elastic scattering with nuclei

$$N = M_{det}t \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N \, m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R) \, dv$$



Experimental setup

Target material (sensitiveness to spin-dependent and –independent couplings)

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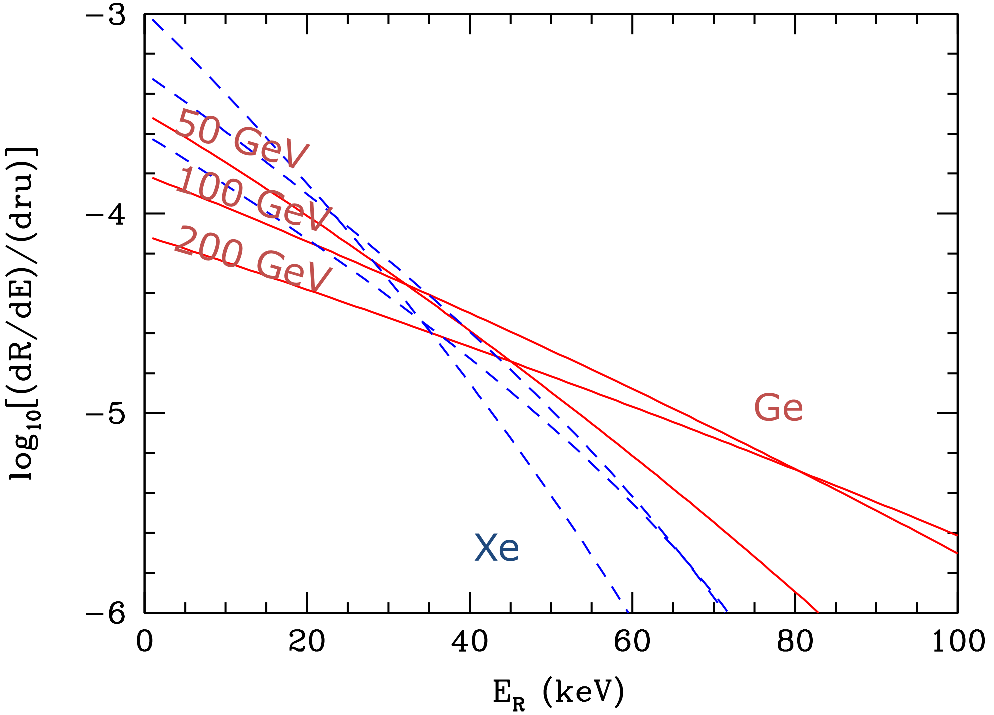
Total exposure

The response of these detectors to DM particles leads to an exponential signal



Detecting Dark Matter through elastic scattering with nuclei

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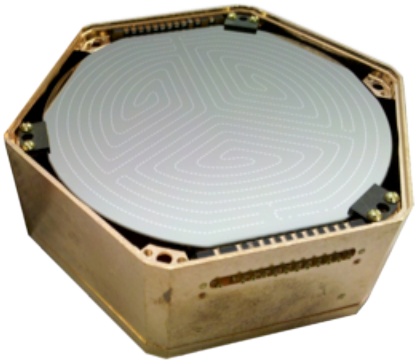

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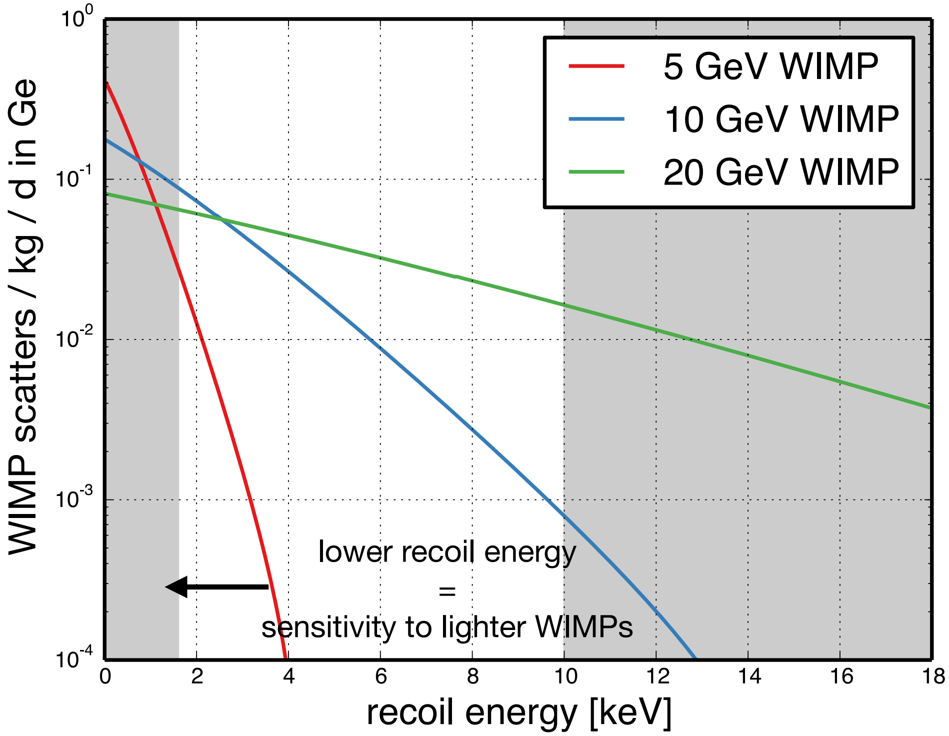
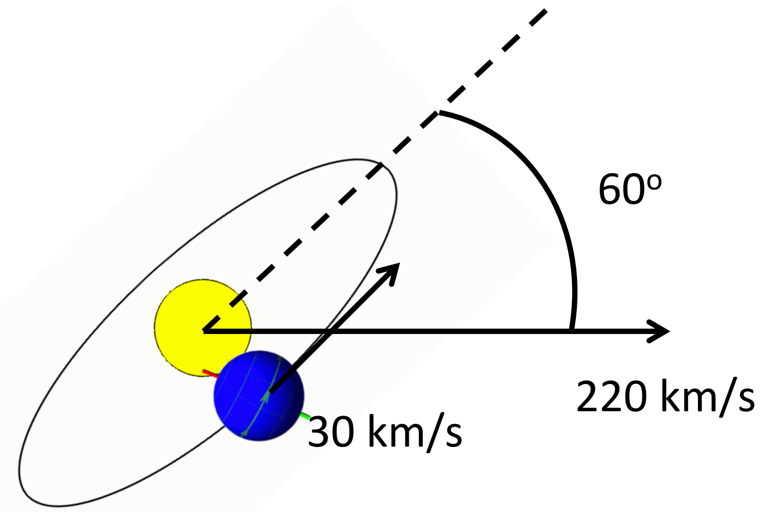


Annual modulation of Dark Matter



The Earth velocity inside the DM halo has a seasonal dependence.

This implies different detection rate in summer and winter

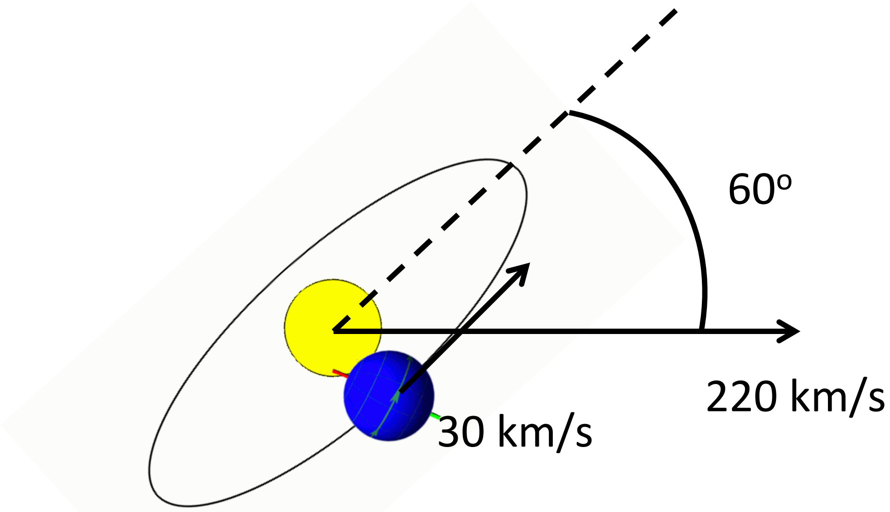
$$f(\vec{v}+\vec{v}_{lag}) = \frac{1}{(2\pi)^{\frac{3}{2}}\sigma^3} exp\left(-\frac{(\vec{v}+\vec{v}_{lag})^2}{2\sigma^2}\right)$$

We can carry out a Taylor expansion on the rate

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \approx \left(\frac{\mathrm{d}R}{\mathrm{d}E_R}\right)(1+\Delta(E_R)\cos(\alpha(t))) \,.$$

$$\Delta \approx \frac{1}{2}\left(\frac{dR}{dE_R}\Big|_{June,1st} - \frac{dR}{dE_R}\Big|_{December,1st}\right)$$

Annual modulation of Dark Matter



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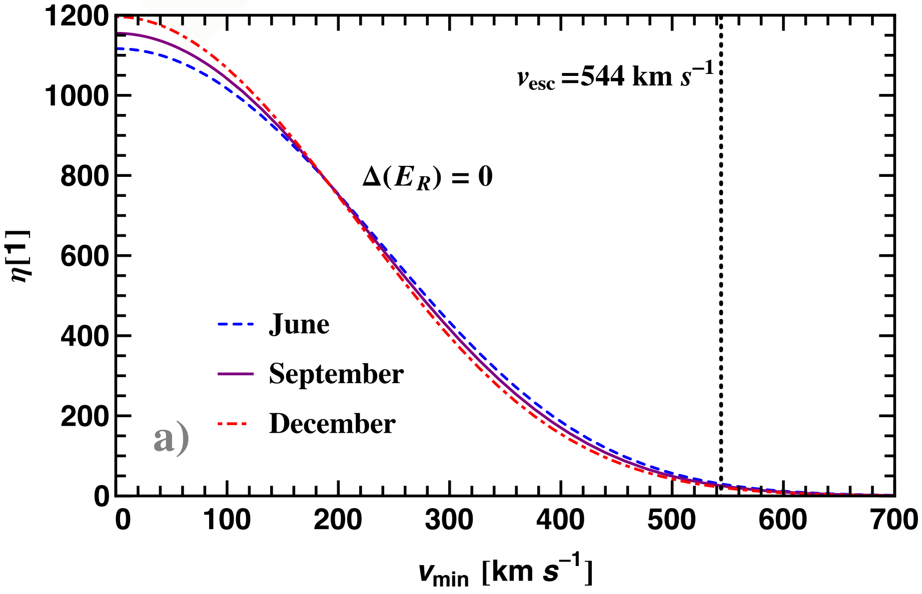
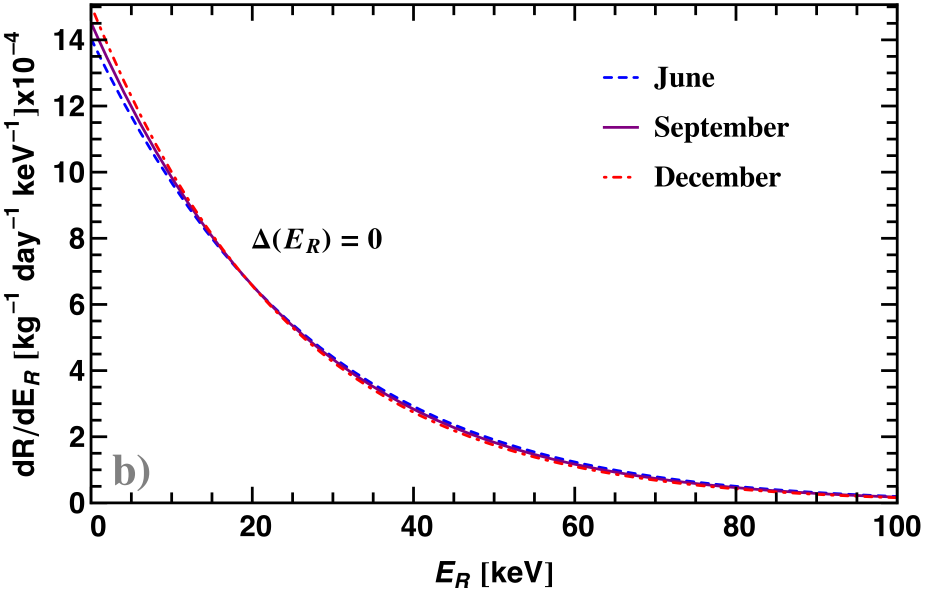
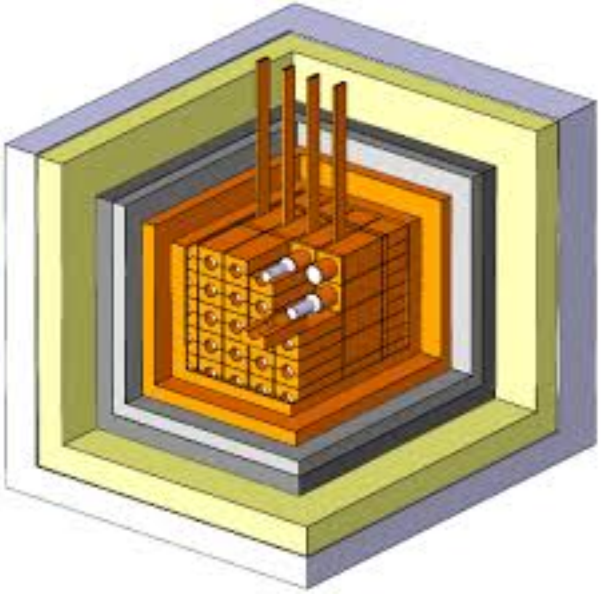


Observed rate



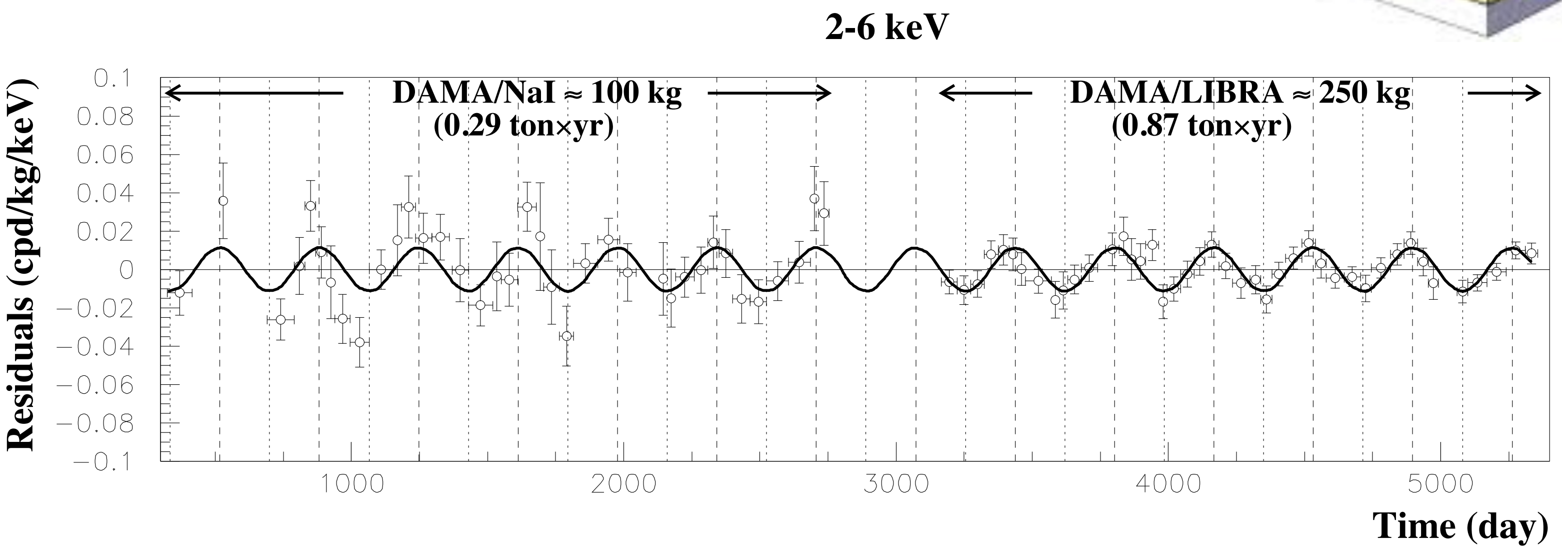
Backgrounds are not expected to modulate

DAMA (DAMA/LIBRA) signal on annual modulation



cumulative exposure 427,000 kg day (13 annual cycles) with NaI

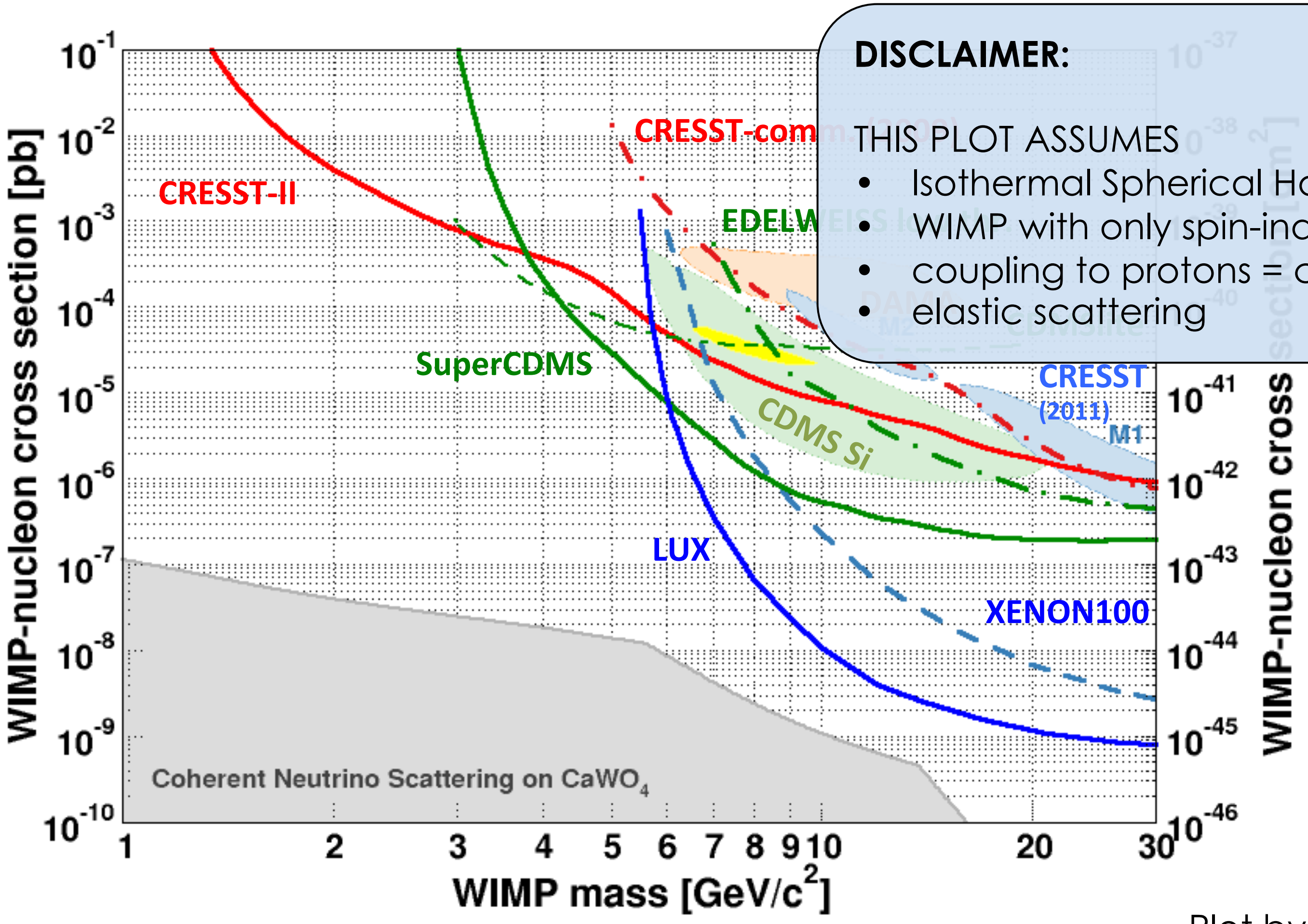
$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \approx \left(\frac{\mathrm{d}\bar{R}}{\mathrm{d}E_R}\right)[1+\Delta(E_R)\cos\alpha(t)]$$



... however other experiments (CDMS, Xenon, CoGeNT, ZEPLIN, Edelweiss, ...) did not confirm (its interpretation in terms of WIMPs).

Upper bounds on the SI cross section

XENON10, XENON100, LUX (Xe), CDMSlite, SuperCDMS, Edelweiss (Ge), COUPP (CF_3I), and CRESST ($CaWO_4$) have not observed any DM signal, which constrains the scattering cross section



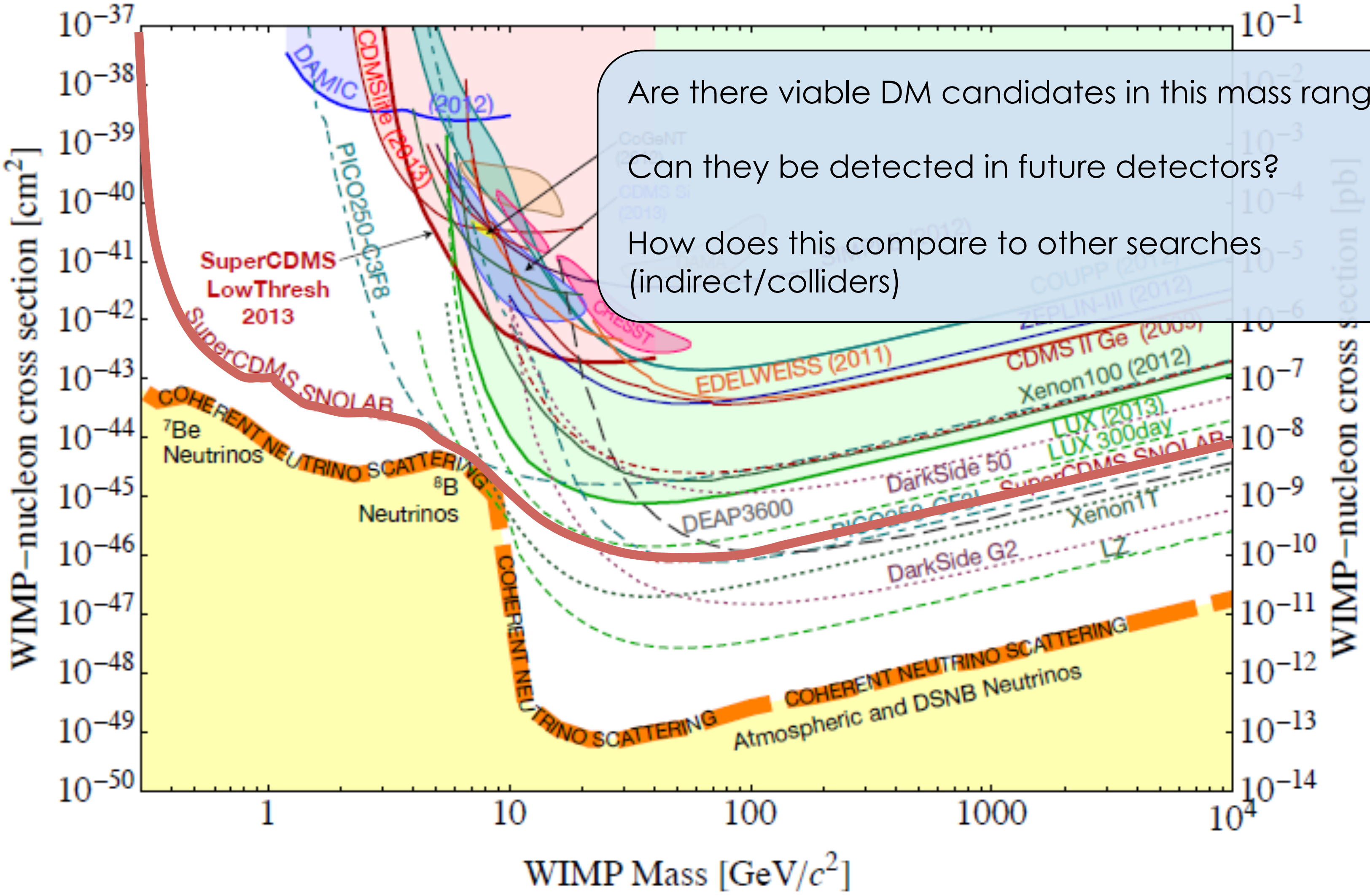
DISCLAIMER:

THIS PLOT ASSUMES

- Isothermal Spherical Halo
- WIMP with only spin-independent interaction
- coupling to protons = coupling to neutrons
- elastic scattering

Plot by Raimund Strauss

2nd Generation experiments will extend the sensitivity by over an order of magnitude. SuperCDMS @ SNOLAB will have an excellent coverage of the light mass window.



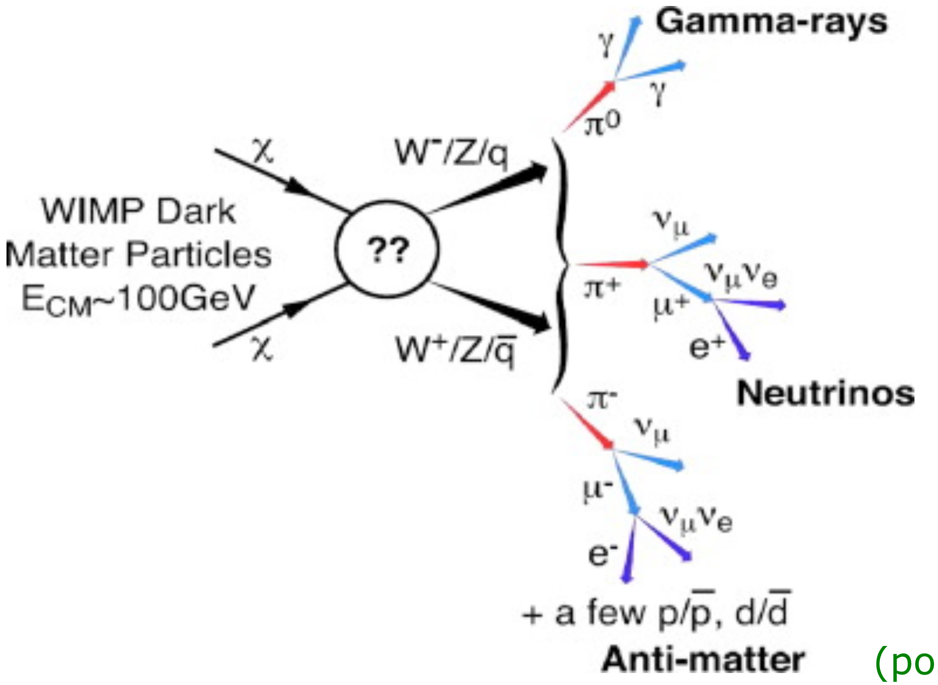
Are there viable DM candidates in this mass range?

Can they be detected in future detectors?

How does this compare to other searches (indirect/colliders)

Indirect detection, signals or backgrounds?

Observe the products of Dark Matter annihilation (or decay!)



(e.g., from the galactic centre or other galaxies)

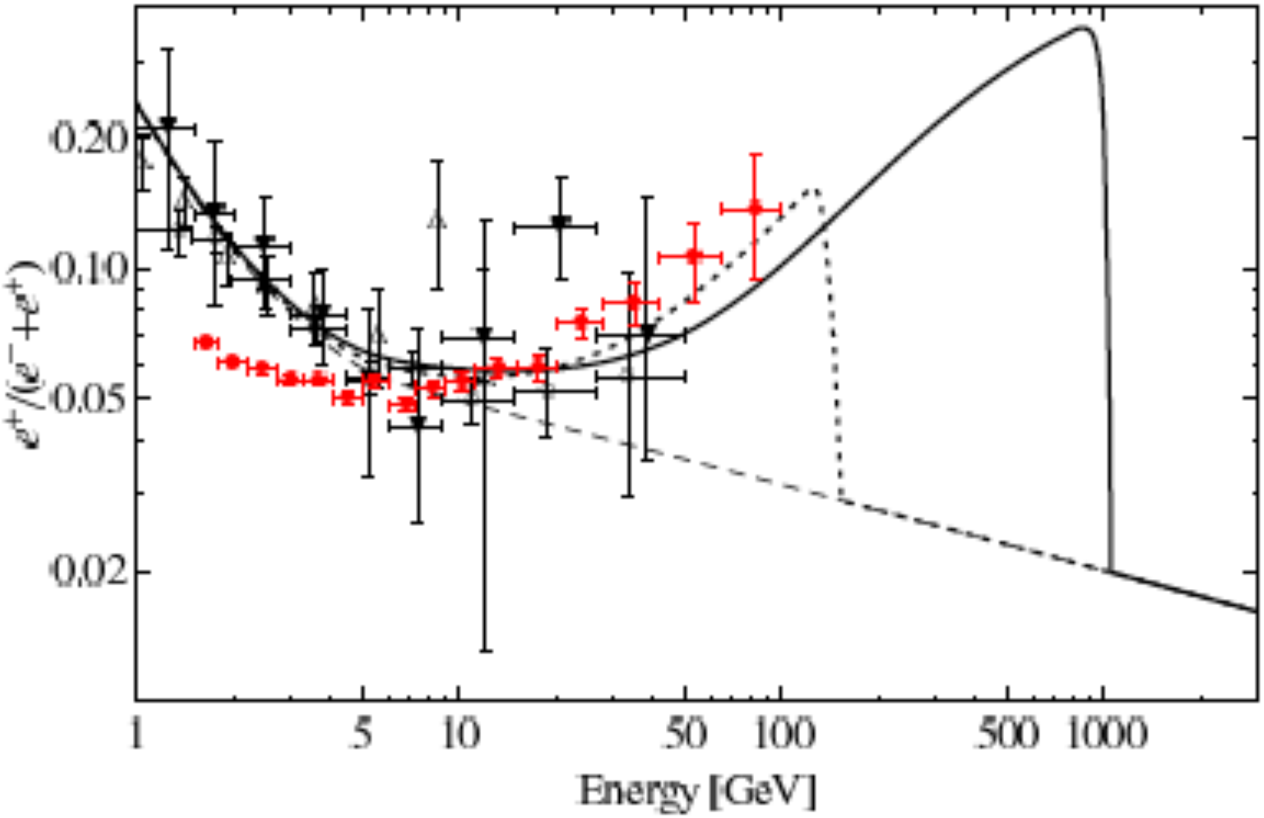
(from the centre of the Sun or the Earth)

(positrons, antiprotons, antideuterons)

Subject to large uncertainties and very dependent on the halo parameters

The antimatter puzzle...

PAMELA satellite revealed an excess in the positron fraction but no excess in the antiproton signal.



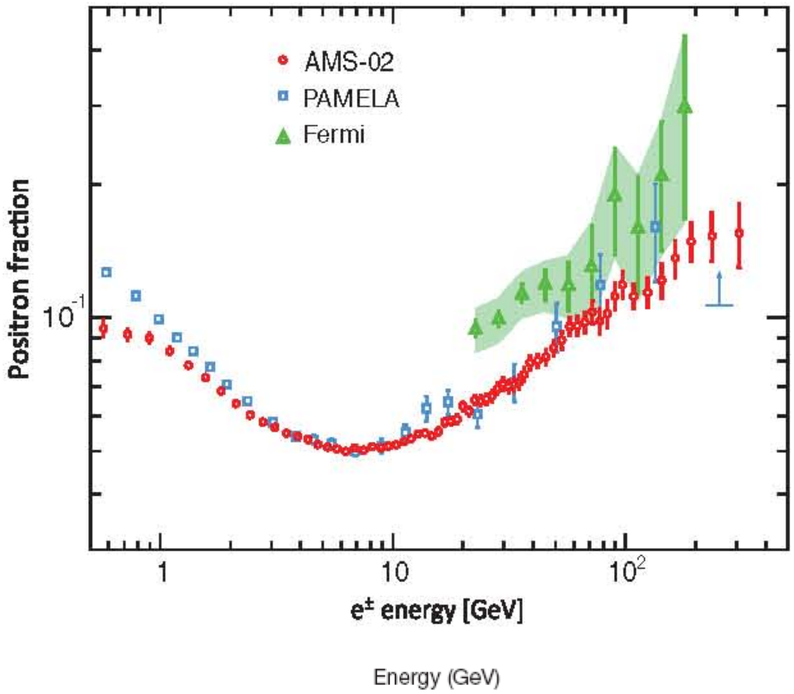
Is this an evidence of DM annihilation?

Even Decaying DM could account for it

The antimatter puzzle...

PAMELA satellite revealed an excess in the positron fraction but no excess in the antiproton signal.

The interpretation in terms of DM is very complicated



Too small signals in canonical models (WIMP)

- boost factors (inhomogeneities? IMBH?)
- play with propagation parameters
- non-thermal DM
- decaying dark matter

Why are there no antiprotons?

- Majorana fermions disfavoured (neutralino)
- Leptophilic dark matter

No evidence for associated gamma ray excess

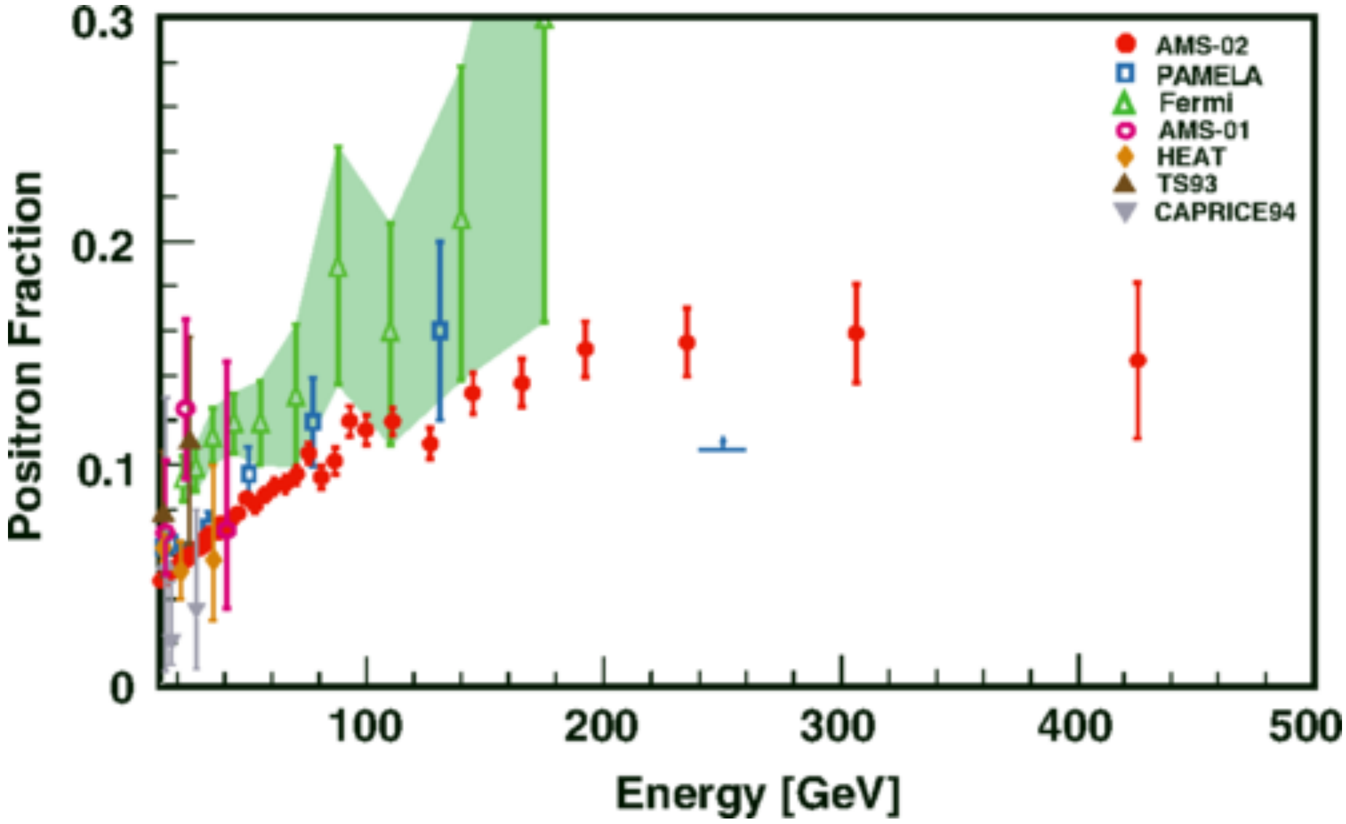
- decaying dark matter

Astrophysical explanation in terms of pulsars is plausible.

See e.g., Delahaye et al. 2010

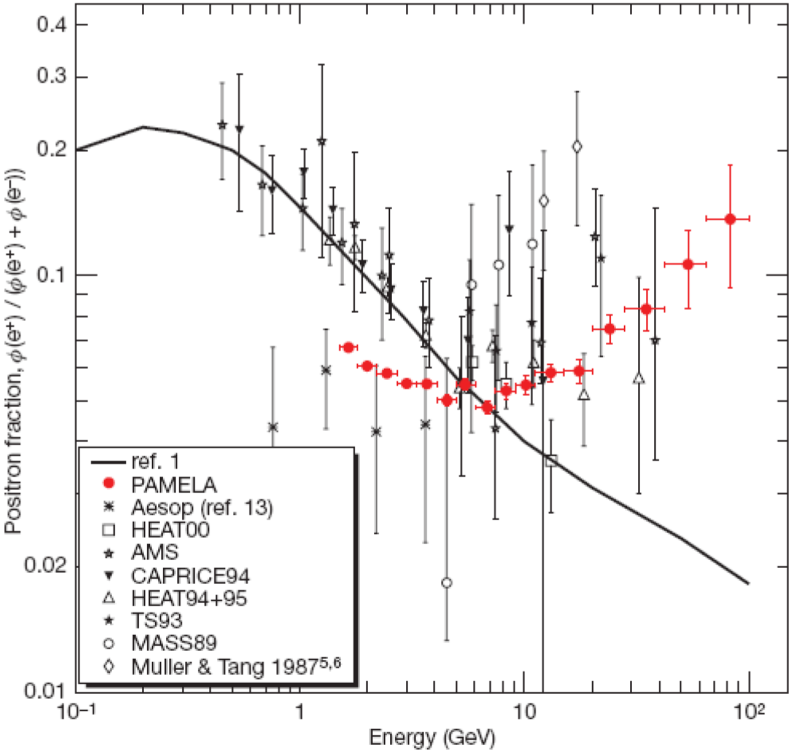
The antimatter puzzle...

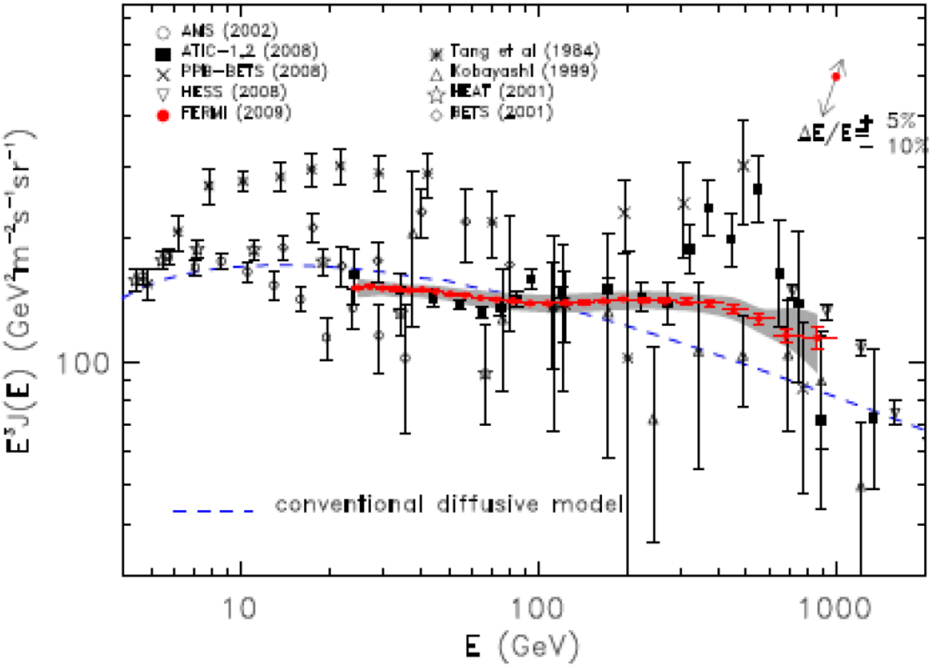
New AMS results up to 500 GeV shows a “plateau” (or is it starting to decrease??)



AMS 2014

Fermi data on total flux of positrons and electrons came as a further constraint





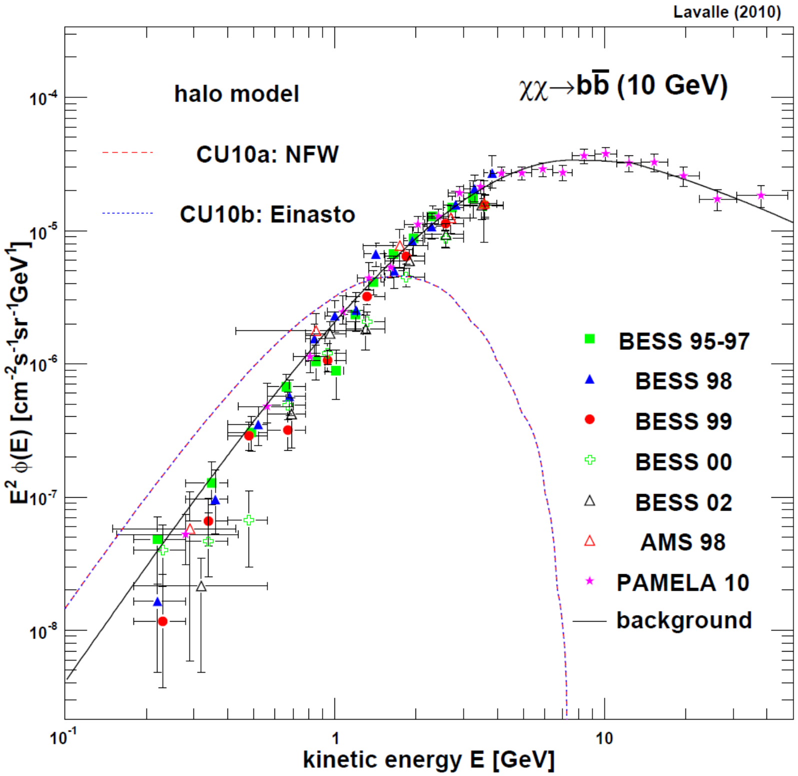
Astrophysical explanation in terms of pulsars is plausible.

See e.g., Delahaye et al. 2010

Antiproton searches show no hint for DM

The antiproton data is good enough to constrain very light WIMPs

Bottino, Donato, Fornengo, Salati 2005
Salati, Donato, Fornengo 2010



The predicted flux for a very light WIMP annihilating into quarks may exceed observations

Lavalle 2010

Light WIMPs annihilating in scalar particles?

DGC, Delahaye, Lavalle 2012

See also latest results by BESS-II

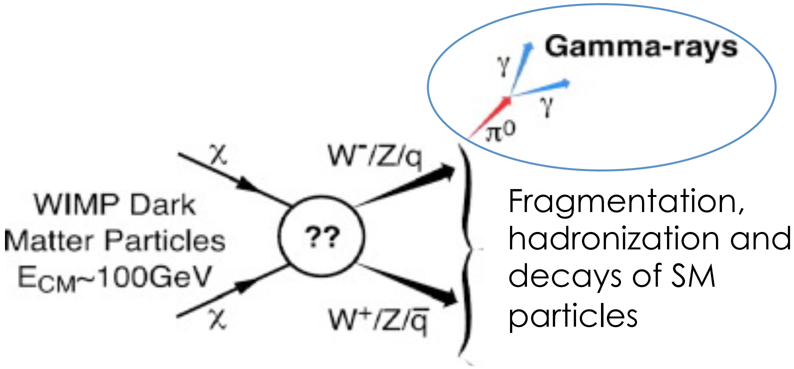
BESS-II ‘11

... also a potentially promising future in antideuteron searches...

Donato et al. 2008
Salati, Donato, Fornengo 2010

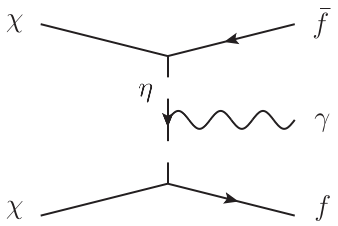
Gamma rays from DM annihilation

Continuum (secondary photons)

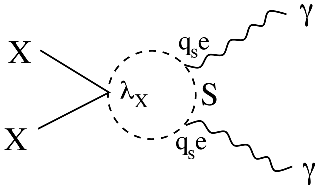


Fragmentation, hadronization and decays of SM particles

Direct gamma emission (features, lines)



Internal bremsstrahlung



Loop processes

$$\left(\frac{d\Phi_\gamma}{dE_\gamma}\right) = \sum_i \frac{dN^i_\gamma}{dE_\gamma} \boxed{\langle\sigma_i v\rangle} \frac{1}{8\pi m^2_{DM}} \boxed{\int d\Omega \int_{l.o.s.} \rho^2(r(l,\Psi))\; dl}$$

Theoretical input

Astrophysical input

DM annihilation cross section IN THE HALO

$$\langle\sigma v\rangle \approx a + bv^2$$

$$v^2_{Decoupling} \approx 1/20$$

$$v^2_{halo} \approx 10^{-7}$$

DM Density profile

Region of observation (backgrounds)

Fermi-LAT can provide constraints for light WIMPs

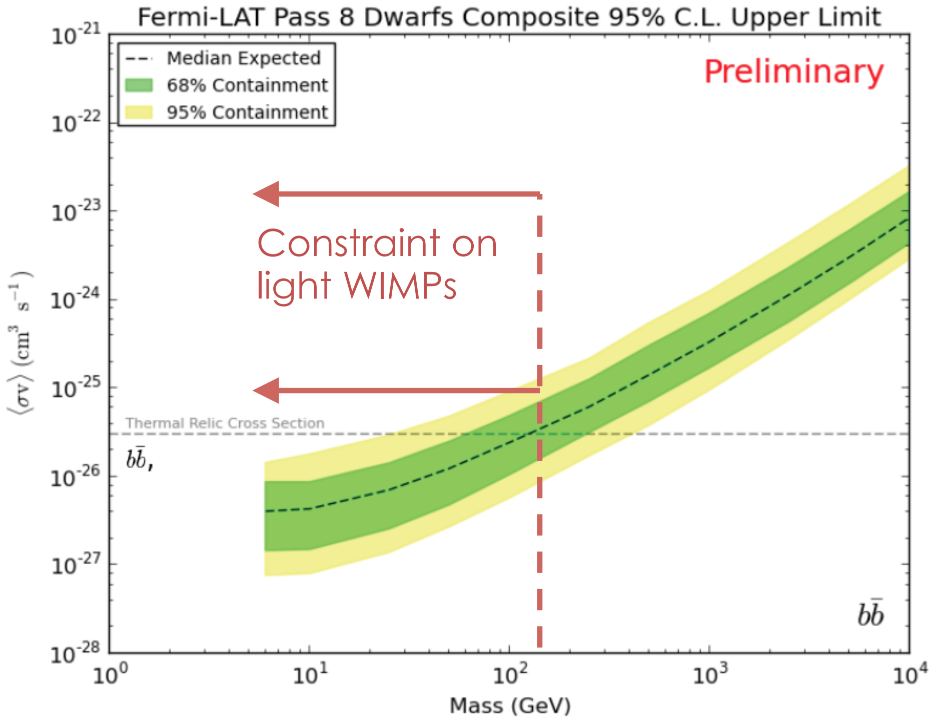
Fermi-LAT observation of Dwarf Spheroidals

Fermi-LAT '11

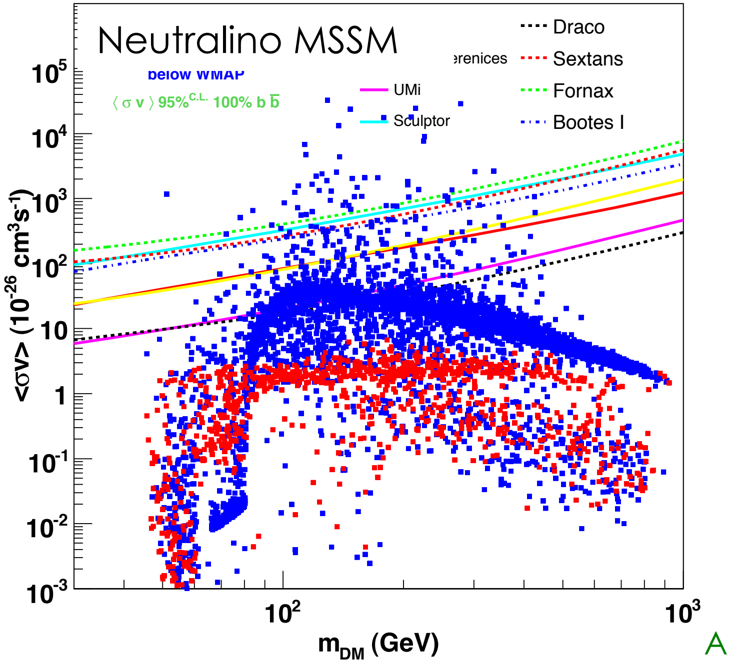
Thermal cross-section excluded for some channels (bb and ττ)

m>100 GeV for the bb channel

Fermi-LAT '14



Constraint on light WIMPs

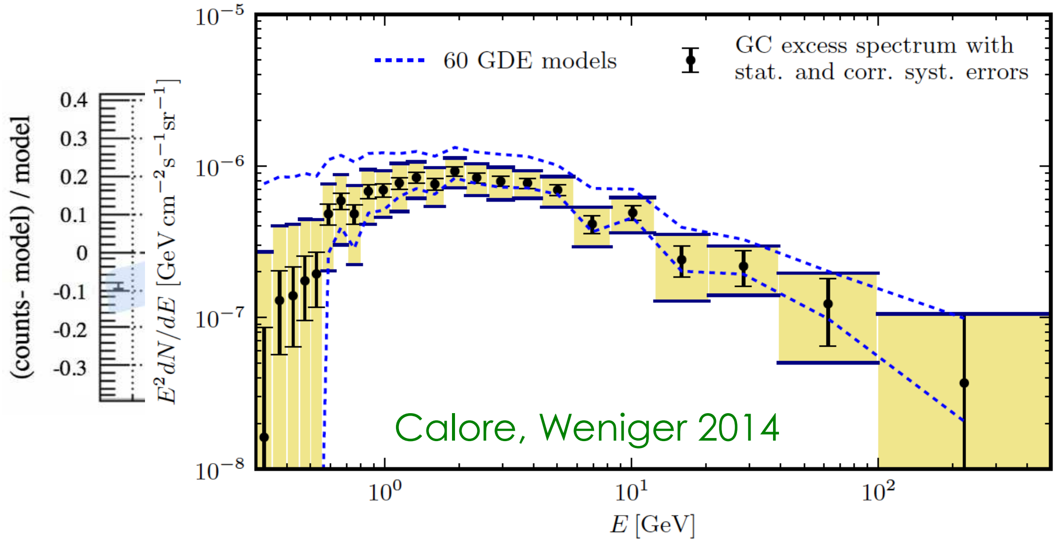


Abdo et al. 1001.4531

"Thermal" DM might have a smaller <sv> in the halo

Coannihilation effects, velocity-dependent cross-section resonances

Excess at low energies in Fermi-LAT data from the GC



Calore, Weniger 2014

Compatible with the annihilation of a light WIMP ~10-50 GeV

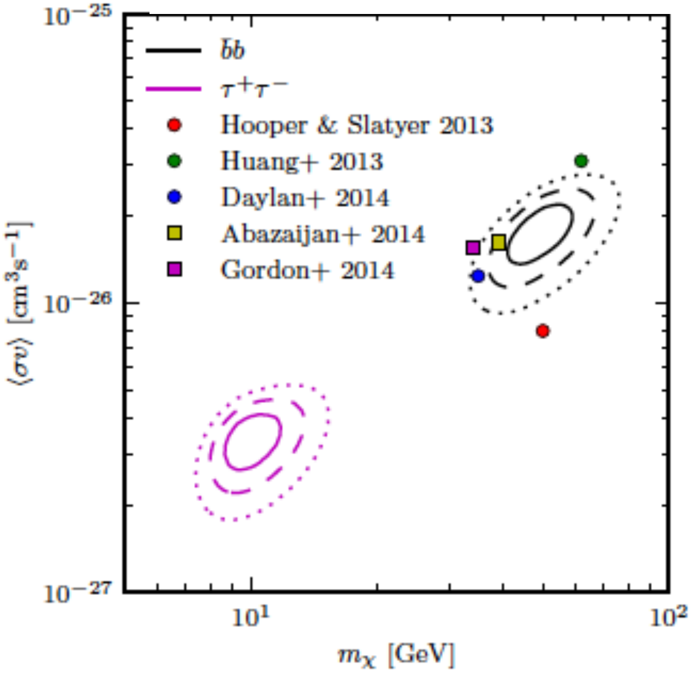
Hooper, Goodenough 2010
Hooper, Linden 2011

or millisecond pulsars, cosmic ray effects or different spectrum at galactic centre.

Abazajian 1011.4275
Chernyakova 1009.2630
Boyarsky, Malyshev, Ruchayskiy, 1012.5839

Pulsars do not have the right morphology and Fermi would have seen them

Hooper, Linden 2012-2014



Fits normally done for pure annihilation channels

Compatible with WIMP DM

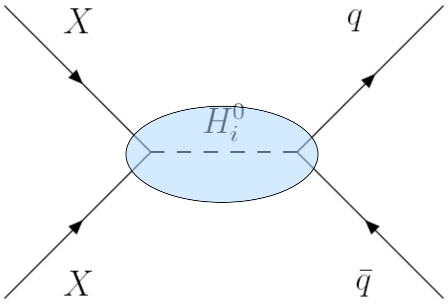
$$m_{DM} \sim 20 - 100 \text{ GeV}$$

$$\langle\sigma v\rangle \sim 10^{-26} \text{ cm}^3/\text{s}$$

DM signals in colliders (LHC)

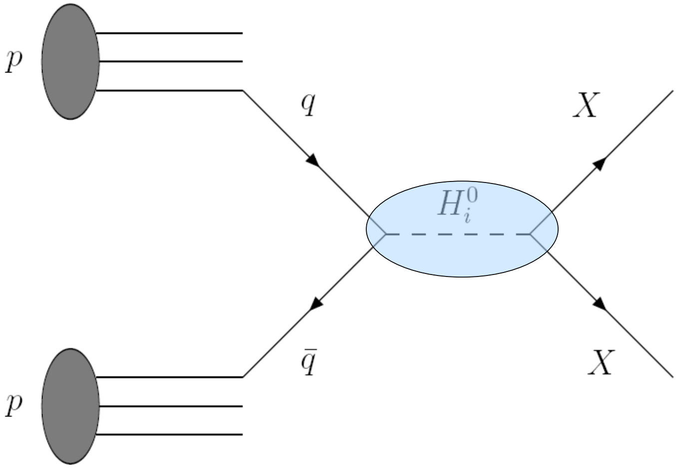
Direct DM production (pp → XX) does not leave a good signal

DM annihilation (Early Universe)



Inverse process

DM Production in colliders?



Missing transverse energy

Does not leave a good signal (no hard energy deposition for detectors to trigger upon)

We might not be able to test directly the DM couplings to SM matter (problem for estimating the relic abundance)

MAKES IT DIFFICULT TO TAKE A MODEL INDEPENDENT APPROACH.

DM signals in colliders (LHC)

Direct DM production (pp → XX) does not leave a good signal

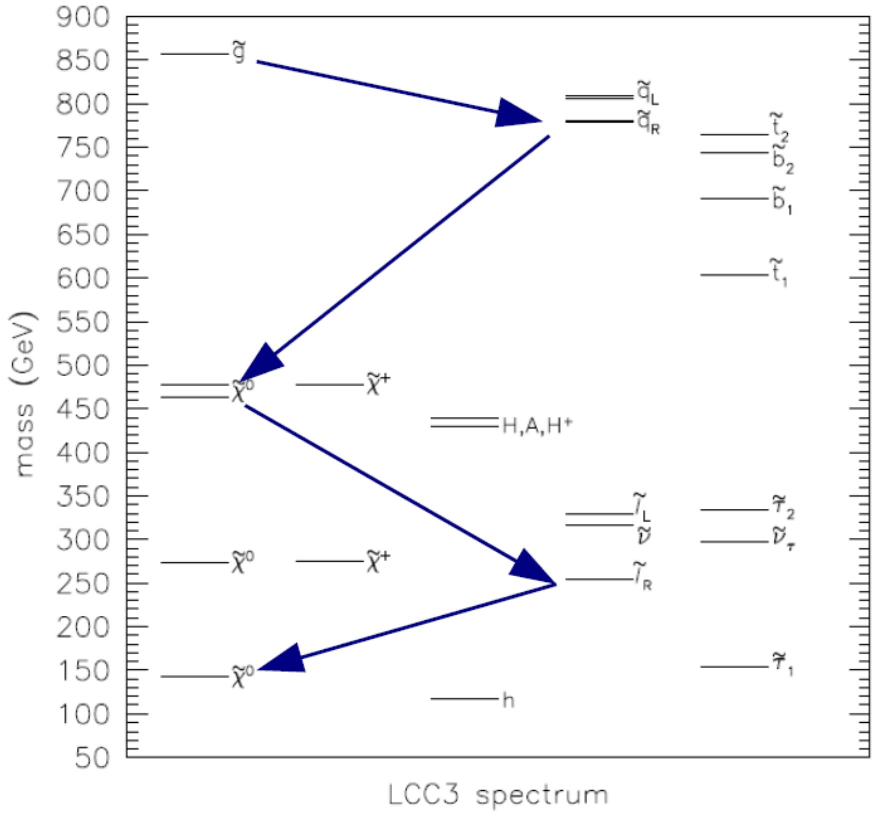
Look for jets + extra leptons

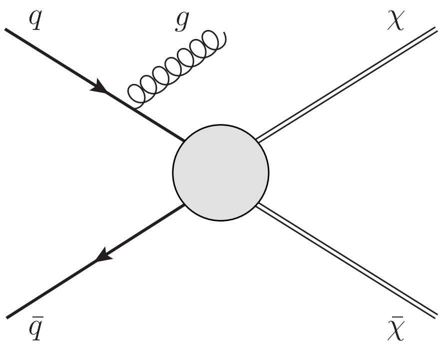
New coloured particles are produced through the interaction with quarks and gluons

E.g., in SUSY dominant production will be in

$$\tilde{g}\tilde{g} \qquad \tilde{g}\tilde{q} \qquad \tilde{q}\tilde{q}$$

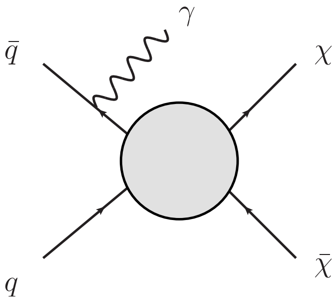
These subsequently decay in lighter particles and eventually in the LSP





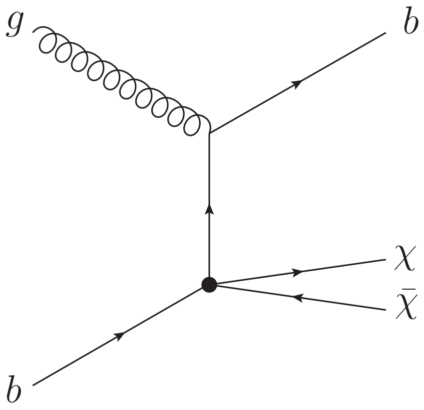
Monojet

1502.01518



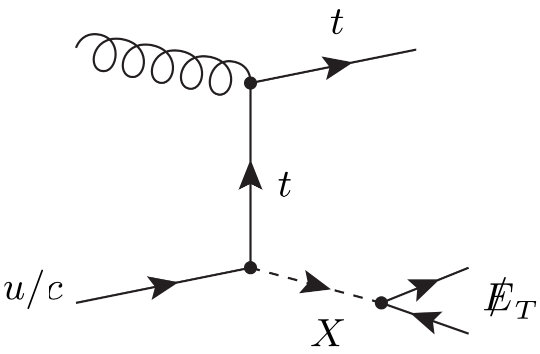
Monogamma

1411.1559



Heavy quarks

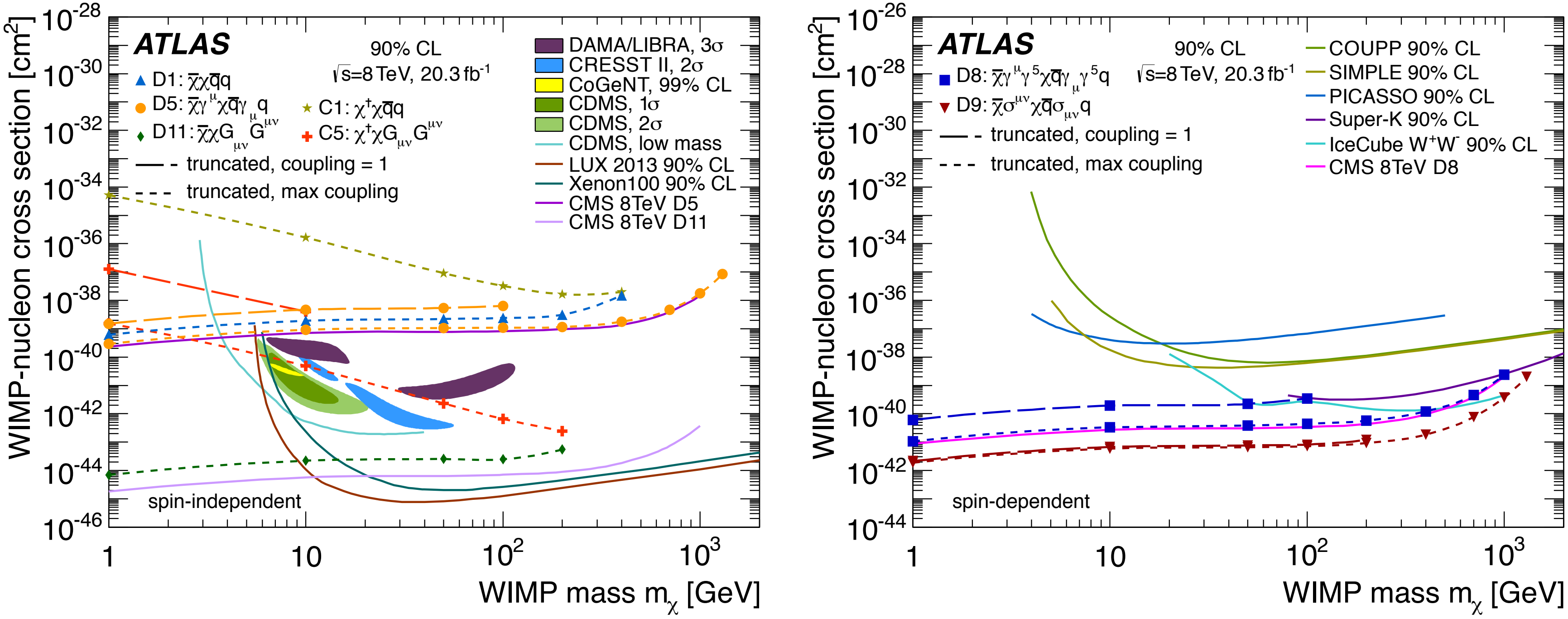
1410.4031



Single top

1410.5404

Translated to upper limits on direct detection cross sections



The most stringent constraint is for operator D11 (notice that this operator ~ $1/M_*^3$) and therefore subject to a large variation if the mediator mass is smaller than 1 TeV

Taxonomy vs. Taxidermy

Taxonomy (Theory–biased)

Construct a bestiary of “well motivated models”

Predictions are tested with experimental results

- “Standard” WIMPs
  - Supersymmetry (neutralinos, **sneutrinos**)
  - Kaluza-Klein DM
  - Inert Doublet Model
  - …

- Asymmetric DM
- Inelastic DM
- Decaying DM (e.g., gravitinos)
- Axions
- Self-interacting DM
- …

Heavy neutrinos as dark matter

- Light neutrinos are "hot" dark matter, known to contribute very little but also excluded from structure formation.

However: what about massive sterile neutrinos? (i.e., cold)

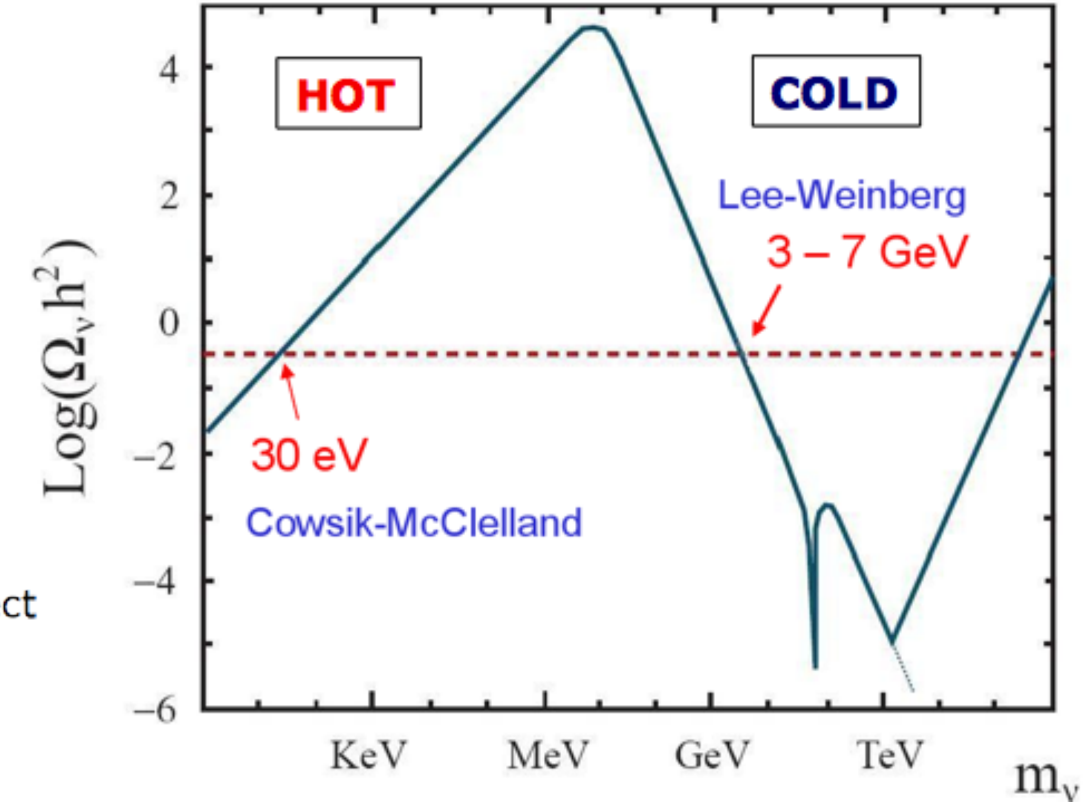
HOT

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{91.5\,\mathrm{eV}}$$

COLD

$$\Omega_\nu h^2 \propto \langle \sigma_{ann} v \rangle^{-1}$$

A heavy neutrino can have the correct relic abundance!



Heavy neutrinos as dark matter

Heavy neutrino

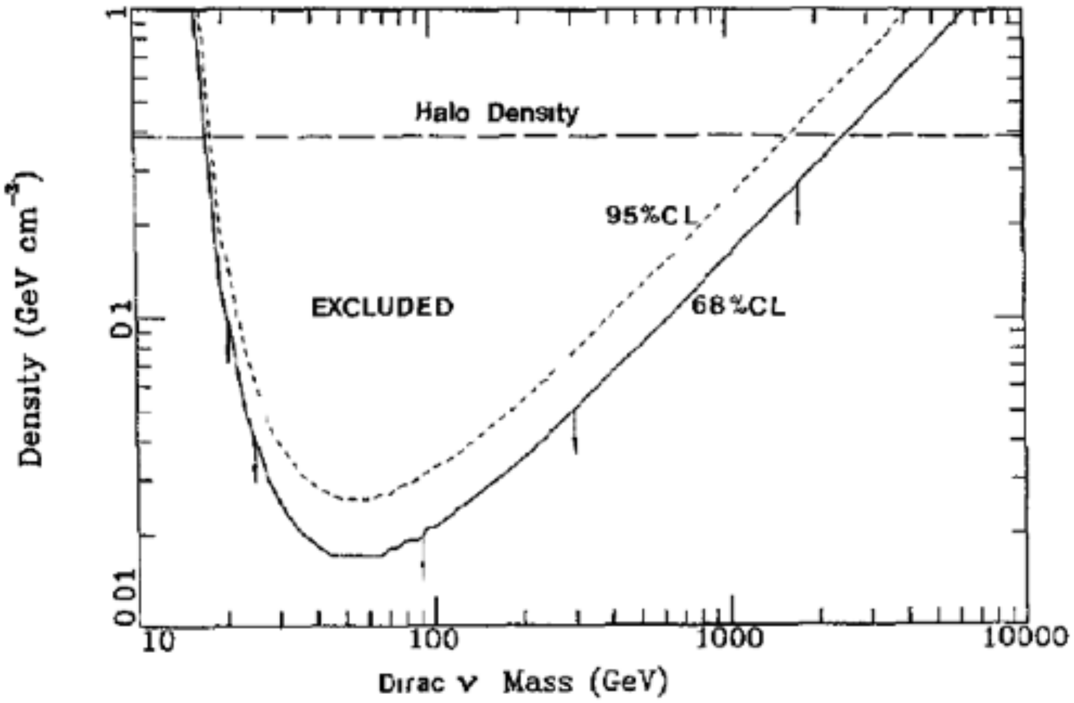
- Light neutrinos are “hot” dark matter, known to contribute very little but also excluded from structure formation.

Direct detection experiments exclude the window GeV < m_ν < TeV

DM searches at Homestake

(Ahlen et al. '87)

If sterile neutrinos were the DM they would have been observed at direct detection experiments.



Heavy neutrinos as dark matter

- Heavy (Dirac or Majorana) 4th generation neutrino

(Lee, Weinberg '77)

LEP limits on the invisible Z width imply $m_{\blacklozenge} > M_Z/2$

Such neutrinos would have a too small relic density

(Lee, Weinberg '77; Hut '77; Vysotsky, Dolgov, Ya, Zeldovich '77; Engvist, Kainulainen, Maalampi '89)

Direct and indirect searches rule out $m_{\blacklozenge} < 1$ TeV

(e.g., Germanium detectors '87-'92; Kamiokande '92)

These problems are due to the SU(2) coupling to the Z boson being too large

Solution: consider mixing with "sterile" singlet neutrino… but not stable!

E.g., right-handed neutrinos… (Dodelson, Widrow, '94)

…in B-L extensions of the SM can be very light without being in conflict with LEP (and only decays through mixing with left-handed)

(e.g., Khalil, Seto '08)

Supersymmetry

- Supersymmetry addresses the Hierarchy problem through the inclusion of a symmetry that relates fermions and bosons

$$Q|\mathrm{Boson}\rangle = |\mathrm{Fermion}\rangle, \qquad Q|\mathrm{Fermion}\rangle = |\mathrm{Boson}\rangle$$

If SUSY is exact, to every fermionic state there should be a bosonic state with the same quantum numbers and equal mass. We know that SUSY must be broken.

We do not know the mechanism of SUSY breaking. We parametrize our ignorance by including in the Lagrangian terms which break SUSY explicitely but which do not reintroduce quadratic divergencies: Soft-supersymmetry.breaking terms

$$\mathcal{L}_{\mathrm{soft}} = -\left(\frac{1}{2}M_a\,\lambda^a\lambda^a + \frac{1}{6}a^{ijk}\phi_i\phi_j\phi_k + \frac{1}{2}b^{ij}\phi_i\phi_j + t^i\phi_i\right) + \mathrm{c.c.} - (m^2)^i_j\phi^{j*}\phi_i$$

Gaugino masses (M)

Trilinear parameters (A)

Bilinear parameter (B)

Scalar masses (m)

Supersymmetry

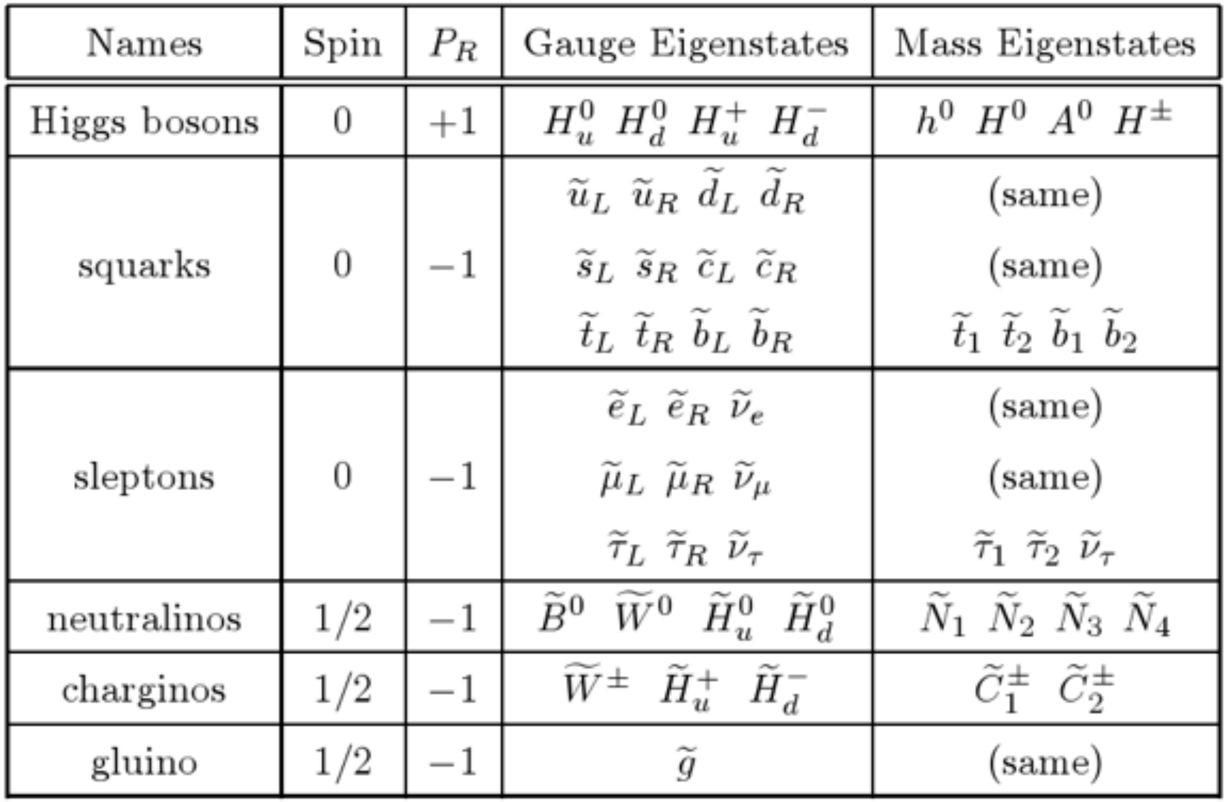
- In the Minimal Supersymmetric Standard Model, for every SM field we include a Supersymmetric companion with a different spin statistics

Higgs →

Quarks →

Leptons →

Gauge bosons → Higgsino



Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	H_u^0 H_d^0 H_u^+ H_d^-	h^0 H^0 A^0 $H^\pm$
squarks	0	−1	$\widetilde{u}_L$ $\widetilde{u}_R$ $\widetilde{d}_L$ $\widetilde{d}_R$ $\widetilde{s}_L$ $\widetilde{s}_R$ $\widetilde{c}_L$ $\widetilde{c}_R$ $\widetilde{t}_L$ $\widetilde{t}_R$ $\widetilde{b}_L$ $\widetilde{b}_R$	(same) (same) $\widetilde{t}_1$ $\widetilde{t}_2$ $\widetilde{b}_1$ $\widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L$ $\widetilde{e}_R$ $\widetilde{\nu}_e$ $\widetilde{\mu}_L$ $\widetilde{\mu}_R$ $\widetilde{\nu}_\mu$ $\widetilde{\tau}_L$ $\widetilde{\tau}_R$ $\widetilde{\nu}_\tau$	(same) (same) $\widetilde{\tau}_1$ $\widetilde{\tau}_2$ $\widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0$ $\widetilde{W}^0$ $\widetilde{H}_u^0$ $\widetilde{H}_d^0$	$\widetilde{N}_1$ $\widetilde{N}_2$ $\widetilde{N}_3$ $\widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm$ $\widetilde{H}_u^+$ $\widetilde{H}_d^-$	$\widetilde{C}_1^\pm$ $\widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)

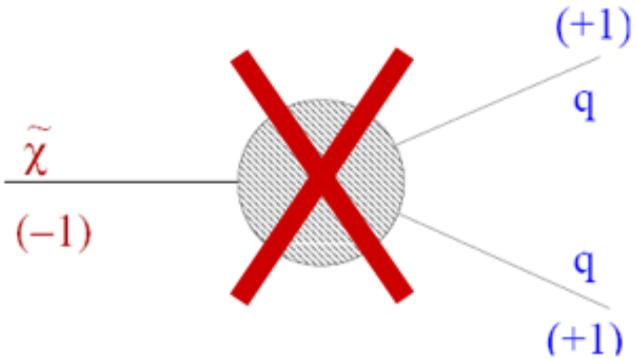
Lightest Supersymmetric Particle

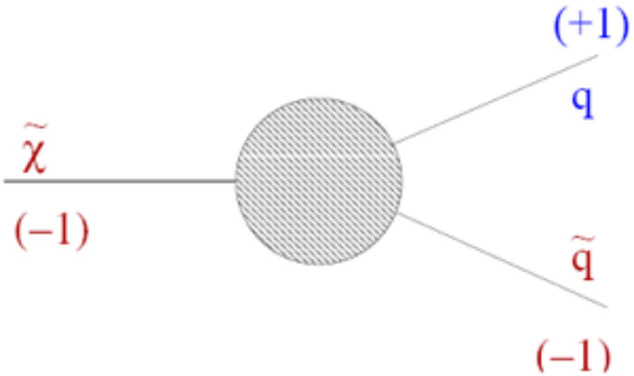
- R-parity is usually invoked in Supersymmetric theories in order to forbid new baryon and lepton number violating interactions at the weak scale

$$R = (-1)^{(3B+L+2S)}$$

Particles $R = +1$

Sparticles $R = -1$





- The LSP is stable in SUSY theories with R-parity. Thus, it will exist as a remnant from the early universe and may account for the observed Dark Matter.

Lightest Supersymmetric Particle

- The LSP is stable in SUSY theories with R-parity. Thus, it will exist as a remnant from the early universe and may account for the observed Dark Matter.

In the MSSM, the LSP can be…

Squarks	$\tilde{u}_{R,L}$, $\tilde{d}_{R,L}$ $\tilde{c}_{R,L}$, $\tilde{s}_{R,L}$ $\tilde{t}_{R,L}$, $\tilde{b}_{R,L}$
Sleptons	$\tilde{e}_{R,L}$, $\tilde{\nu}_e$ $\tilde{\mu}_{R,L}$, $\tilde{\nu}_\mu$ $\tilde{\tau}_{R,L}$, $\tilde{\nu}_\tau$
Neutralinos	$\tilde{B}^0$, $\tilde{W}^0$, $\tilde{H}^0_{1,2}$
Charginos	$\tilde{W}^\pm$, $\tilde{H}^\pm_{1,2}$
Gluino	$\tilde{g}$

Lightest squark or slepton: charged and therefore excluded by searches of exotic isotopes

Lightest sneutrino: They annihilate very quickly and the regions where the correct relic density is obtained are already experimentally excluded

Lightest neutralino: WIMP

Lightest Supersymmetric Particle

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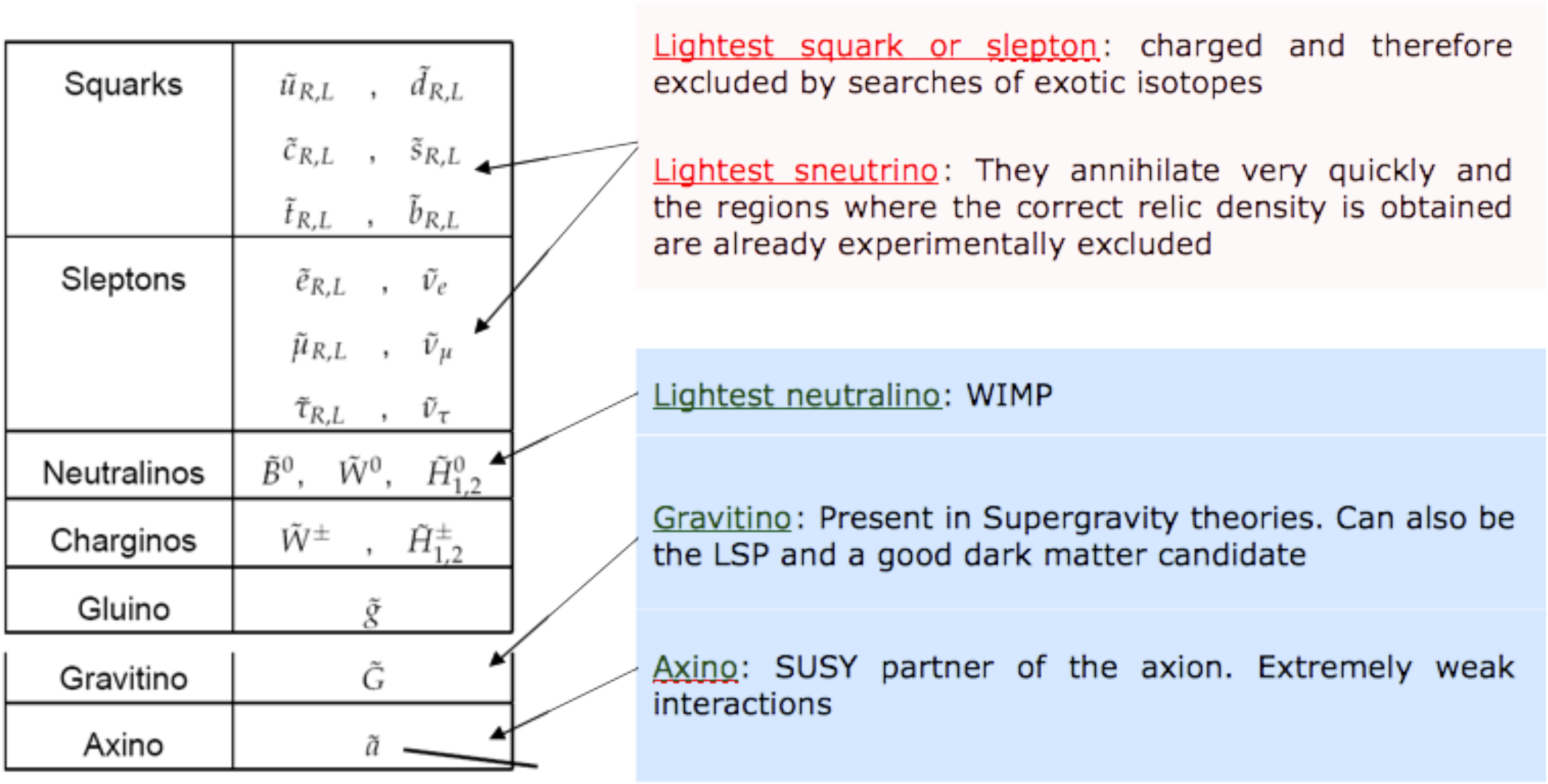
In the MSSM, the LSP can be…



Squarks	$\tilde{u}_{R,L}$, $\tilde{d}_{R,L}$ $\tilde{c}_{R,L}$, $\tilde{s}_{R,L}$ $\tilde{t}_{R,L}$, $\tilde{b}_{R,L}$
Sleptons	$\tilde{e}_{R,L}$, $\tilde{\nu}_e$ $\tilde{\mu}_{R,L}$, $\tilde{\nu}_\mu$ $\tilde{\tau}_{R,L}$, $\tilde{\nu}_\tau$
Neutralinos	$\tilde{B}^0$, $\tilde{W}^0$, $\tilde{H}^0_{1,2}$
Charginos	$\tilde{W}^\pm$, $\tilde{H}^\pm_{1,2}$
Gluino	$\tilde{g}$
Gravitino	$\tilde{G}$
Axino	$\tilde{a}$

Lightest squark or slepton: charged and therefore excluded by searches of exotic isotopes

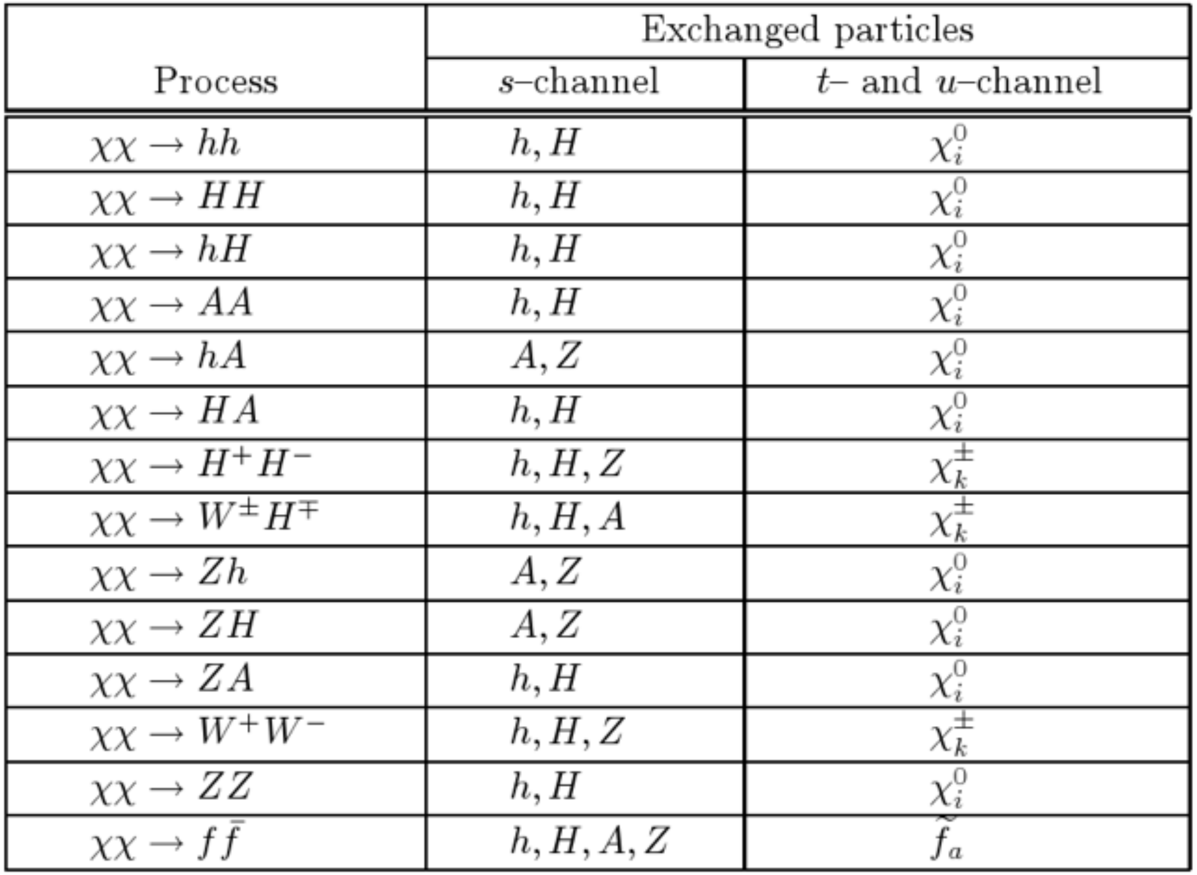
Lightest sneutrino: They annihilate very quickly and the regions where the correct relic density is obtained are already experimentally excluded

Lightest neutralino: WIMP

Gravitino: Present in Supergravity theories. Can also be the LSP and a good dark matter candidate

Axino: SUSY partner of the axion. Extremely weak interactions

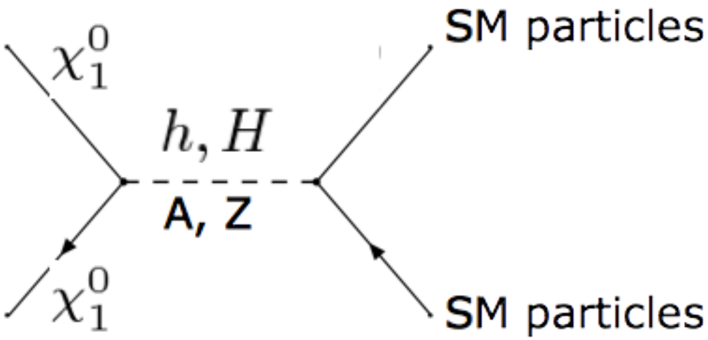
- There are numerous channels for neutralino annihilation:



Process	Exchanged particles	
	s–channel	t– and u–channel
$\chi\chi \rightarrow hh$	h, H	χ_i^0
$\chi\chi \rightarrow HH$	h, H	χ_i^0
$\chi\chi \rightarrow hH$	h, H	χ_i^0
$\chi\chi \rightarrow AA$	h, H	χ_i^0
$\chi\chi \rightarrow hA$	A, Z	χ_i^0
$\chi\chi \rightarrow HA$	h, H	χ_i^0
$\chi\chi \rightarrow H^+H^-$	h, H, Z	$\chi_k^\pm$
$\chi\chi \rightarrow W^\pm H^\mp$	h, H, A	$\chi_k^\pm$
$\chi\chi \rightarrow Zh$	A, Z	χ_i^0
$\chi\chi \rightarrow ZH$	A, Z	χ_i^0
$\chi\chi \rightarrow ZA$	h, H	χ_i^0
$\chi\chi \rightarrow W^+W^-$	h, H, Z	$\chi_k^\pm$
$\chi\chi \rightarrow ZZ$	h, H	χ_i^0
$\chi\chi \rightarrow f\bar{f}$	h, H, A, Z	$\tilde{f}_a$

(Nihei, Roszkowski, de Austri '02)

- There are numerous possibilities for neutralino annihilation:



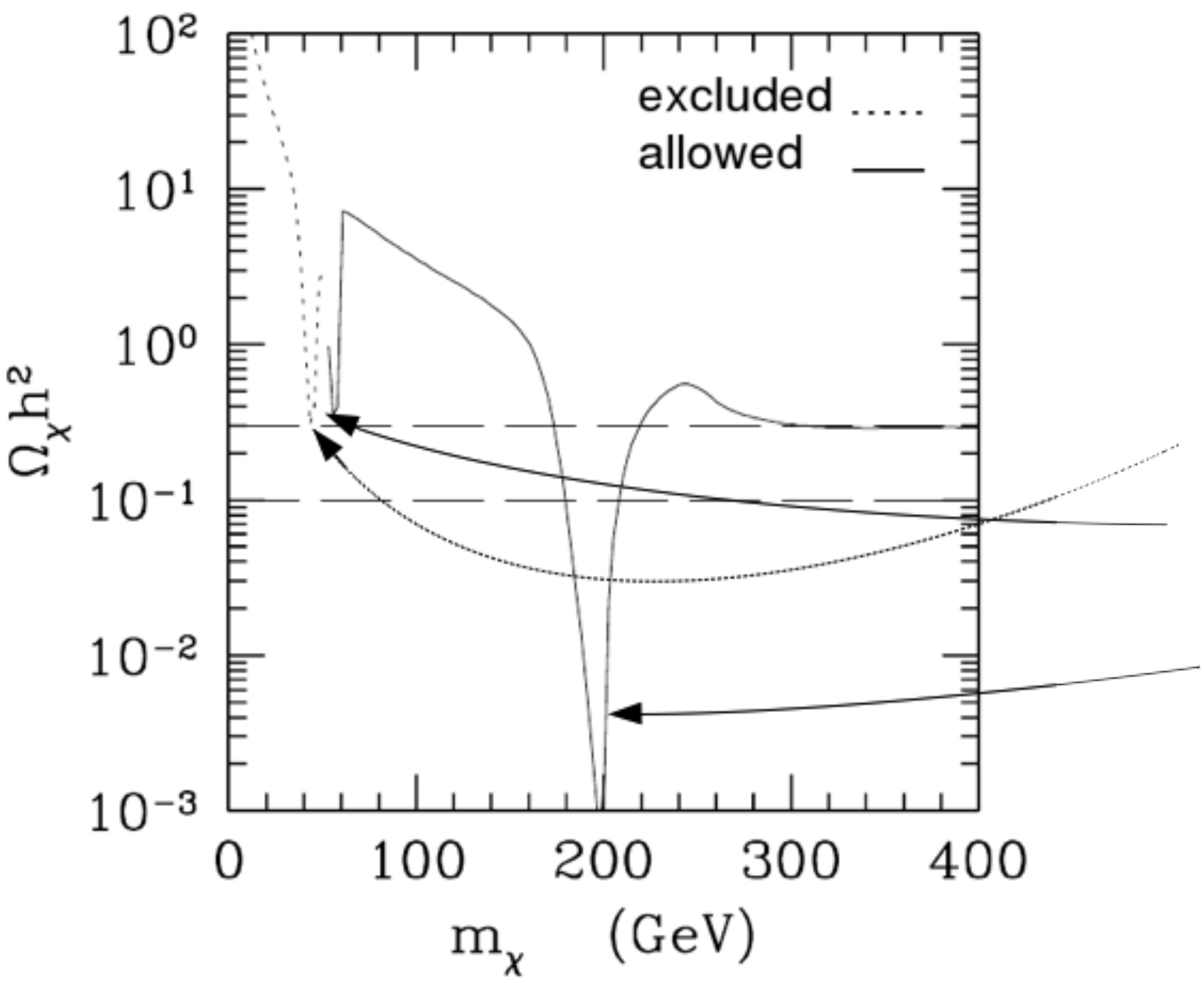
Neutralinos are Majorana particles. Therefore annihilation into a pair ff is helicity suppressed.

This generally implies that neutralino annihilation is not enough and that the predicted relic abundance is too large.

There are three effects which can enhance the annihilation cross section

- Resonant annihilation
- Coannihilation
- Modification of the neutralino composition

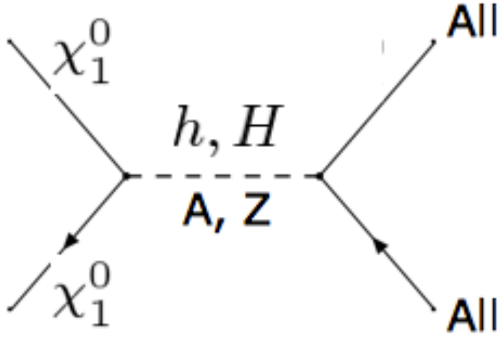
- Resonant annihilation



$2\,m_{\tilde{\chi}^0_1} \approx m_Z$

$2\,m_{\tilde{\chi}^0_1} \approx m_{h^0}$

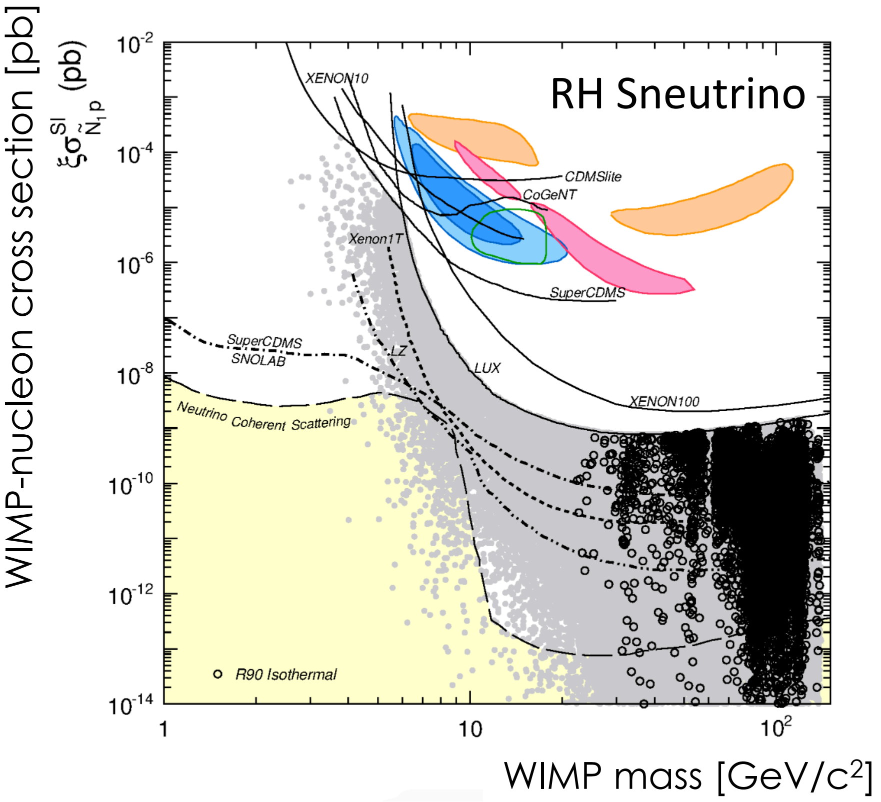
$2\,m_{\tilde{\chi}^0_1} \approx m_{A^0}$

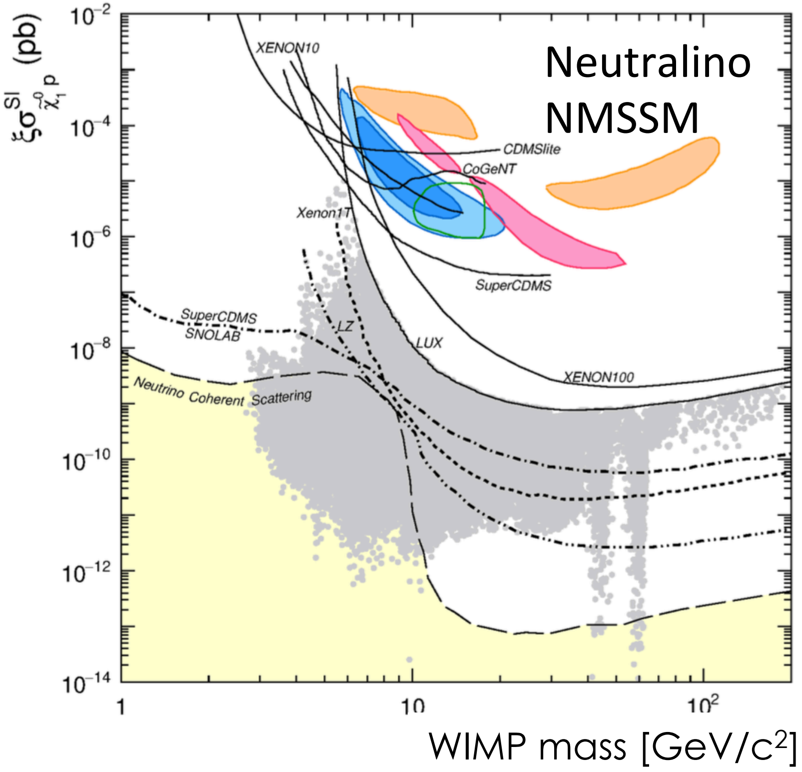


$A_t = A_b = 600$ GeV, $\mu = -500$ GeV
$\tan\beta = 10$, $m_0 = 500$ GeV, $m_A = 400$ GeV

(Nihei, Roszkowski, de Austri '01)

Example: supersymmetric WIMPs and current experimental bounds





DGC, Peiró, Robles JCAP 08 (2014) 005
DGC, Peiró Robles 2015

Excellent motivation for direct searches at low masses

Taxidermy (Phenomenology-driven)

Interpret experimental results in terms of simplified models or effective Lagrangians

Identify some basic features from a positive observation

(Galactic Centre Emission)

Taxidermy (Phenomenology-driven)

Identify some basic features from a positive observation

(Galactic Centre Emission)

Perform a complementary measurement with other search technique

(Signal in various direct detection targets or at the LHC)

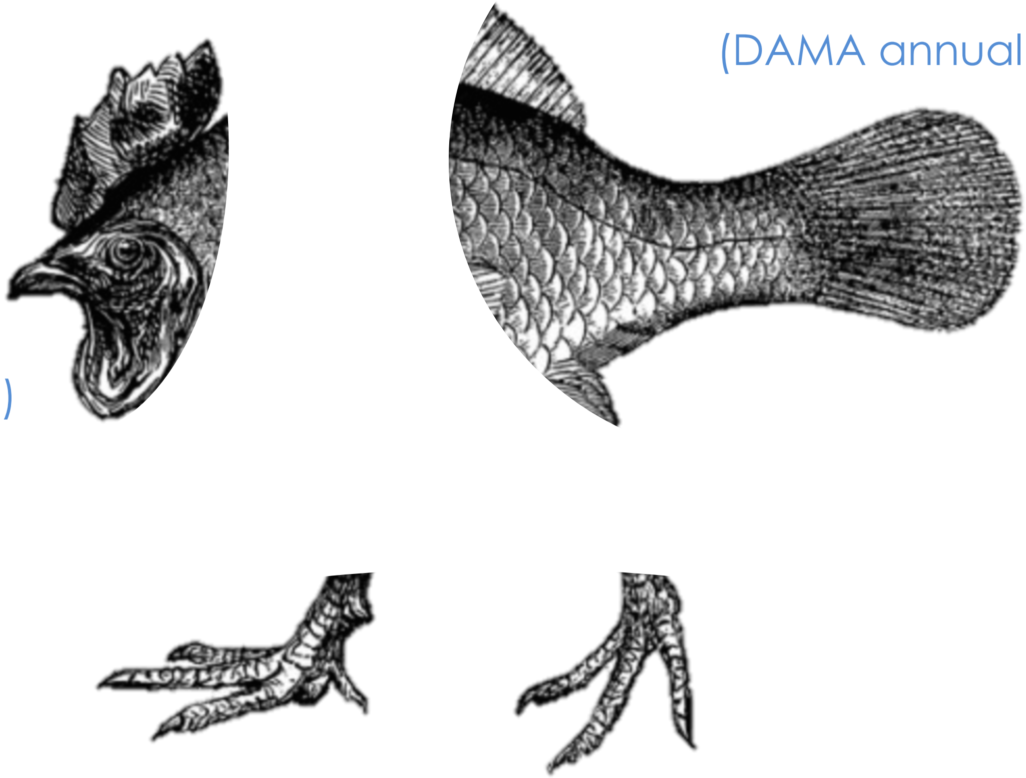
Taxidermy (Phenomenology-driven)

Identify some basic features from a positive observation

(Galactic Centre Emission)

Some data might be more difficult to explain in terms of “standard” DM models

(DAMA annual modulation)



Perform a complementary measurement with other search technique

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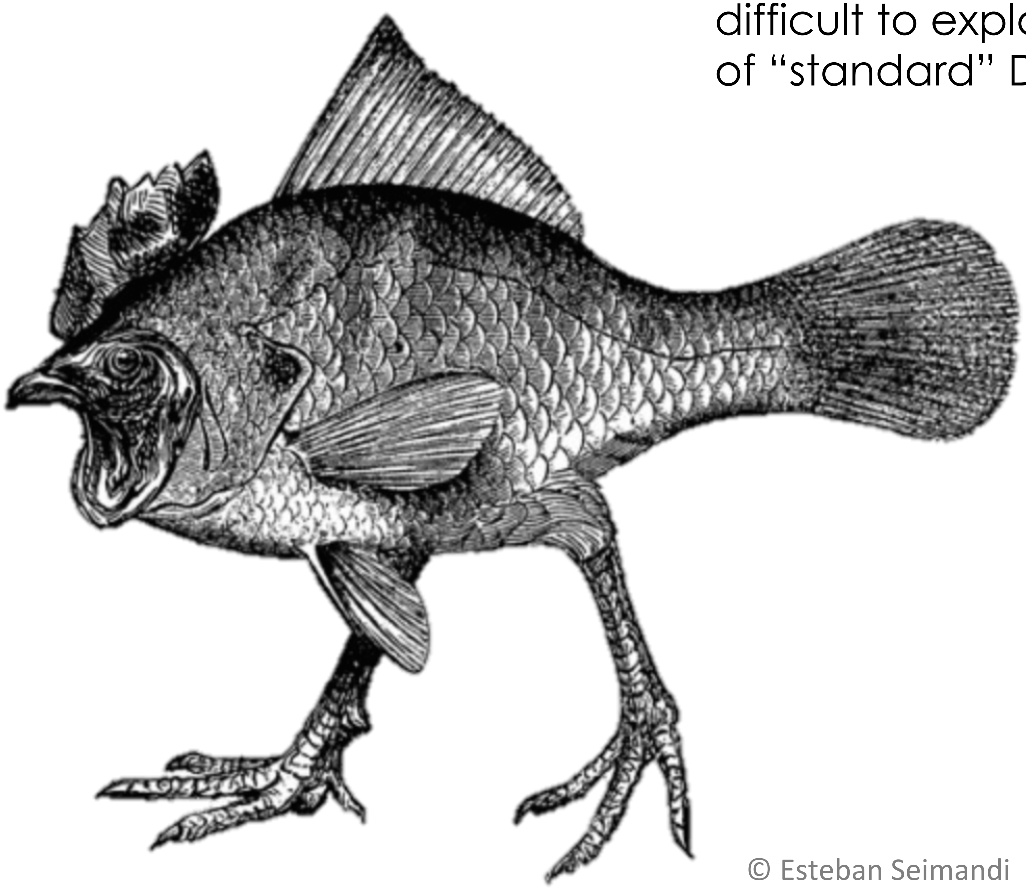
Identify some basic features from a positive observation



Perform a complementary measurement with other search technique

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Animalia Exstinta

This motivates working with general frameworks, where little or nothing is assumed for the DM particle

If there is a positive detection of DM, can we identify the underlying model?

Problem:

- Experimental data allow us to reconstruct **“phenomenological parameters”**.

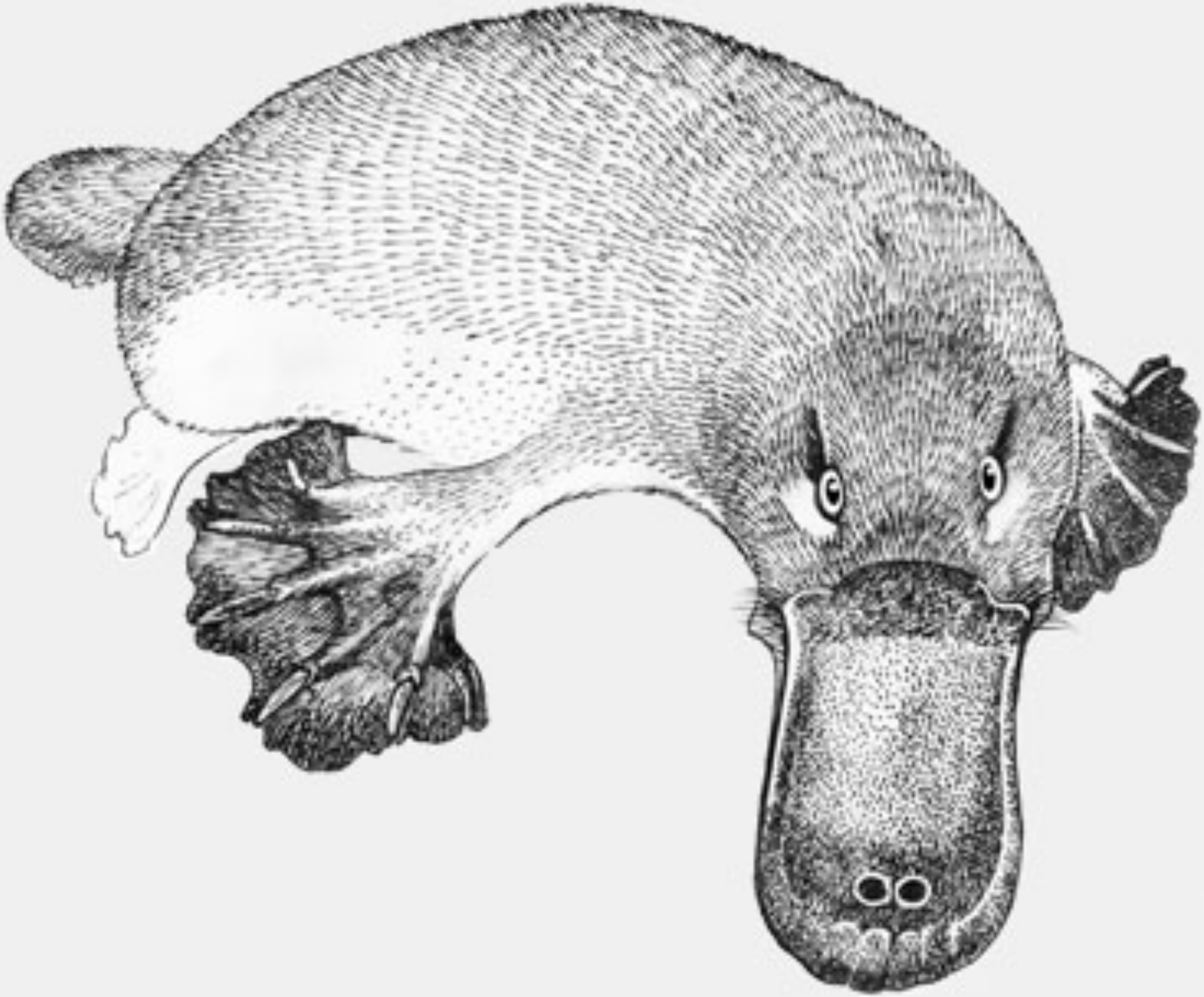
$$m_\chi,\ \sigma^{SI},\ \sigma^{SD},\ <\sigma v>_{ij}$$

- Theoretical models tend to produce similar results
  (e.g., most WIMPs are alike)

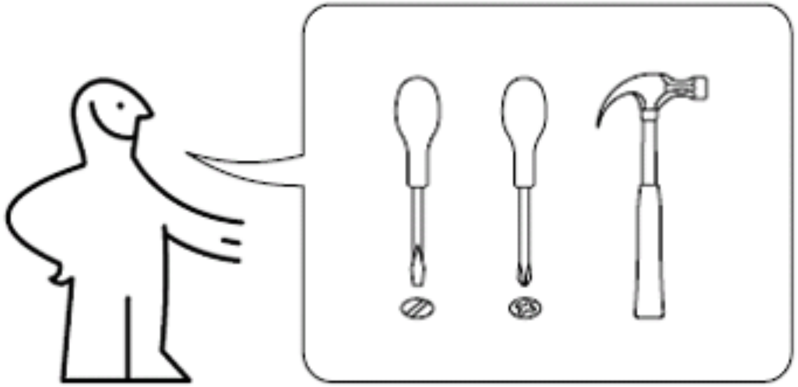
Solution:

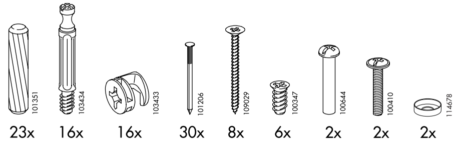
- Data from different experiments has to be combined in order to remove degenerate solutions (and reduce the effect of uncertainties)

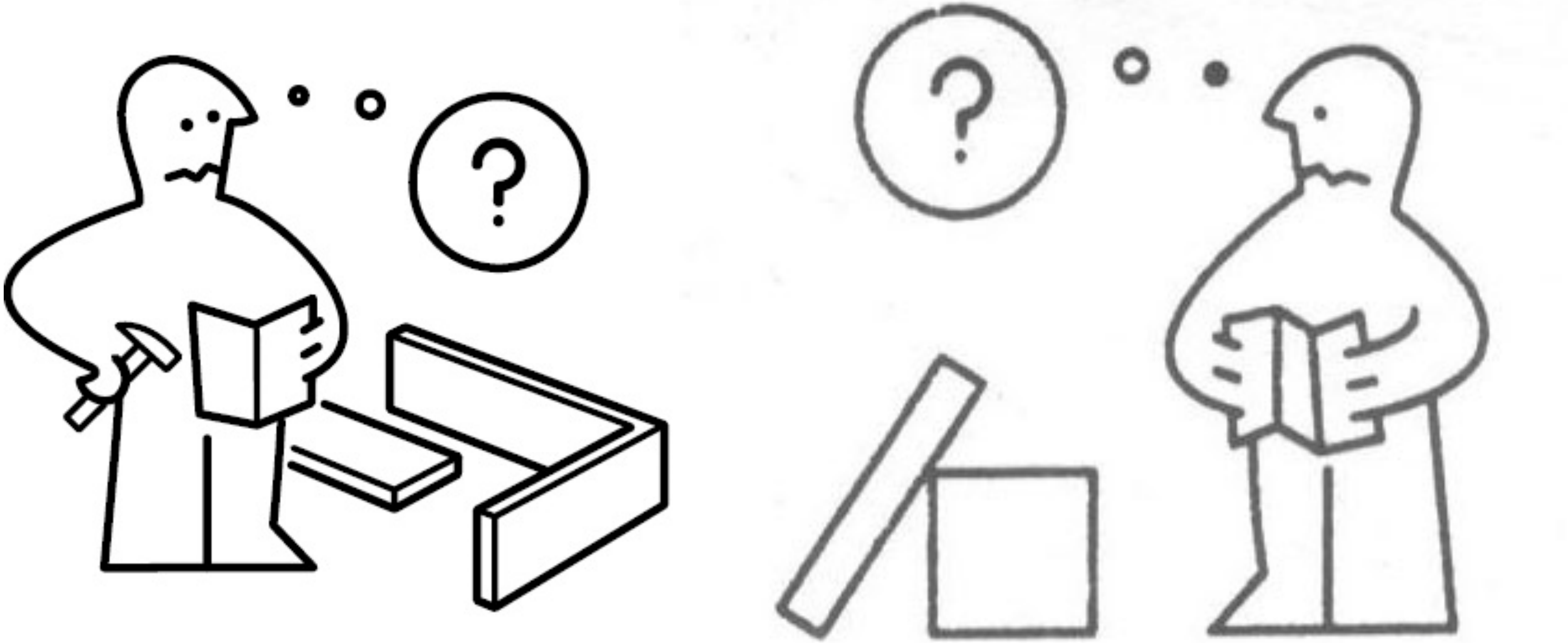
Design strategies that allow the identification of DM from future data

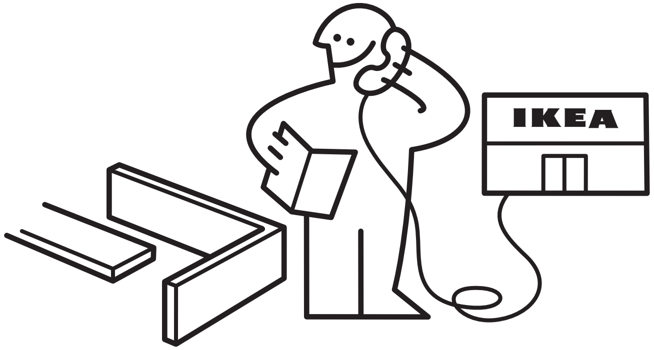


MÖRK MATERIA MODELL





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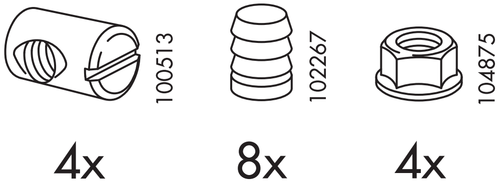
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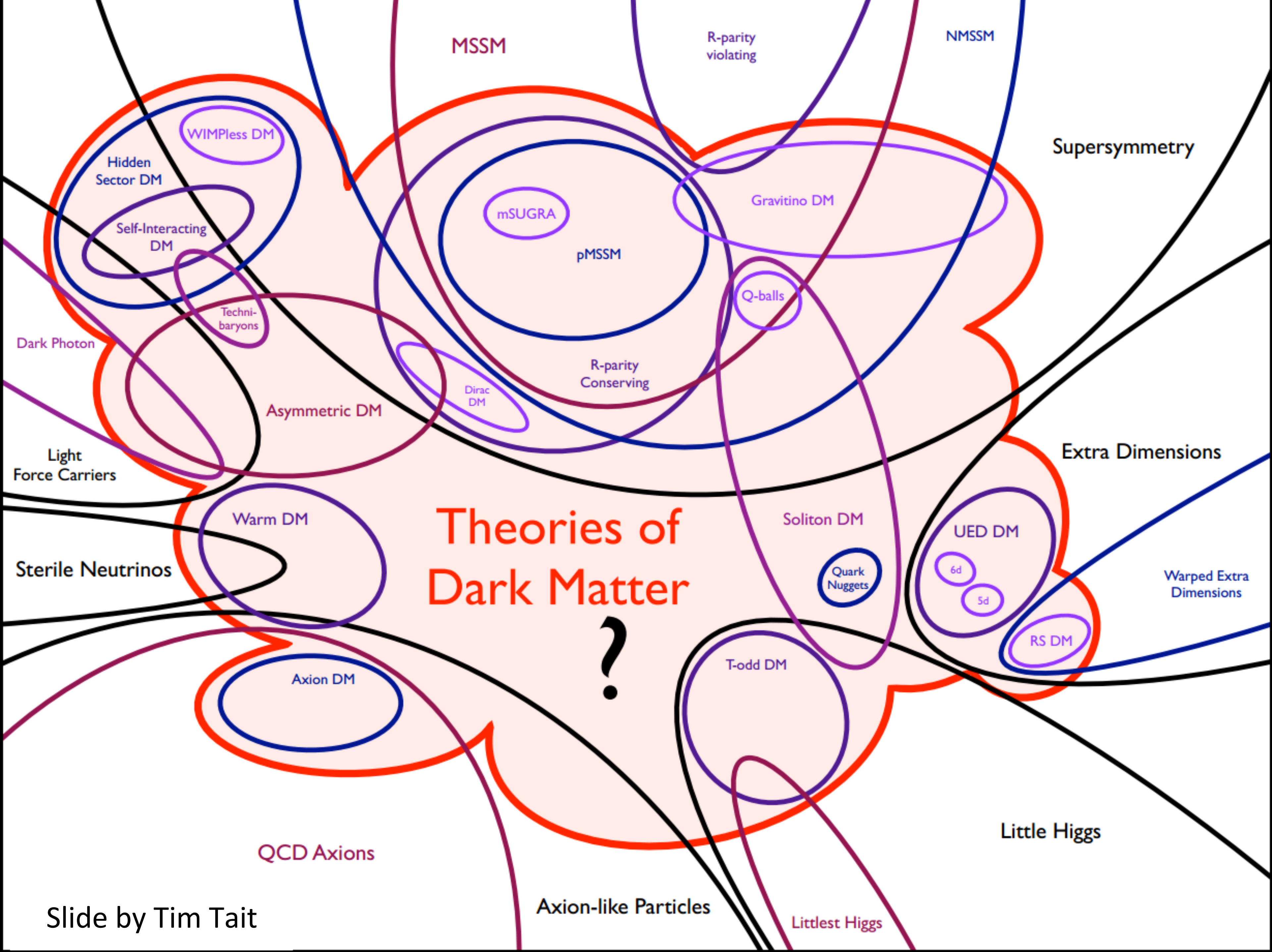
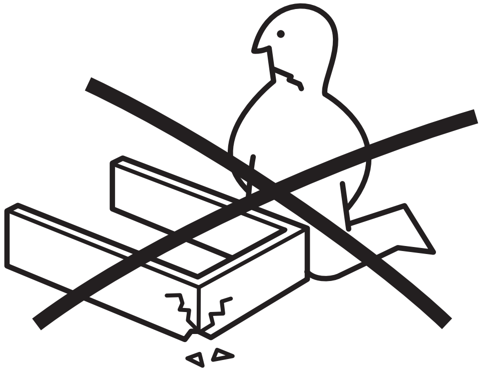
4x
102267
8x
104875
4x

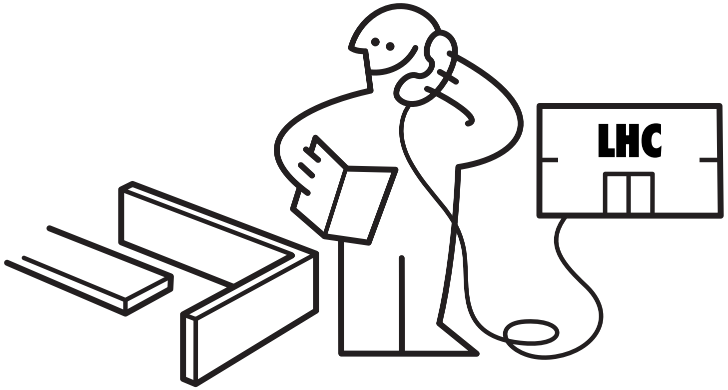


Slide by Tim Tait

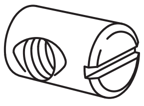
Do not break what already works



Good candidates for Dark Matter have to fulfil the following conditions



Collider constraints on Dark Matter



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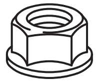

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