Particle and Halo Model Uncertainties in Direct DM Detection

Graciela Gelmini - UCLA

U.S. DEPARTMENT OF ENERGY | Office of Science
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Content

- **Dark Matter (DM) WIMPs or not?**

- **Direct detection: casting a wide net**

- **Direct detection: halo independent data analysis**

“DM searches in the 2020s - At the crossroads of the WIMP”

Dark matter? Particles? WIMPs? so to start from the basics:

- **Dark Matter or not?** So far there is no alternative to dark matter...
  After 2013, no proposed “alternative to Dark Matter” explained the CMB anisotropy spectrum and the BAO.
  From any theory that claims to “replace Dark Matter” we should ask for its prediction of the matter power spectrum and the CMB angular power spectrum (stop discussing endlessly only about galaxy rotation curves!)

  Eloquently expressed in Dan Hooper’s talk “In Defense of Dark Matter” - KITP 4/30/2018- in debate with Eric Verlinde (“emergent gravity” is a theory without cosmology)

- **DM particles or not?** DM could be other than particles: PBH, ...
- **WIMPs or not? dead?, alive? in good shape?** The meaning of “WIMP” was not well defined since its inception, but not even in the most restrictive sense of the word WIMPs are dead... Words evolve- let us not be held up by the word. Many models rejected, many others not.

ARE WIMPS DEAD?

50,667 views | Feb 22, 2019, 02:00am

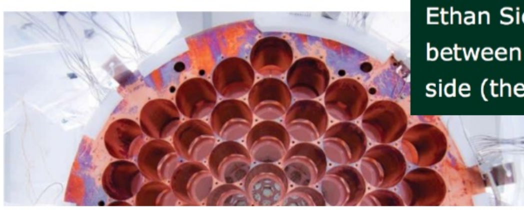
The 'WIMP Miracle' Hope For Dark Matter Is Dead

Ethan Siegel Contributor
Starts With A Bang Contributor Group
Science

Dark matter no-show puts WIMPs in a bind

SPACE 30 October 2013

By Lisa Grossman



saturday, february 23, 2019 ...

Rumors of the WIMP miracle's death have been greatly exaggerated

Ethan Siegel has shown us another example of the profound difference between careful scientists on one side and zealous activists on the other side (the side where he sadly belongs) when he wrote

MACHOs are dead. WIMPs are a no-show. Say hello to SIMPs.

By Robert Sanders, Media relations | DECEMBER 4, 2017

Tweet

The intensive, worldwide search for dark matter,
find an abundance of dark, massive stars or scad
new candidate is slowly gaining followers and ob

WIMPs on Death Row

Posted on July 21, 2016 by woit

One of the main arguments given for the idea of supersymmetric extensions of the standard model has been what SUSY enthusiasts call the "WIMP Miracle" (WIMP=Wea Interacting Massive Particle). This is the claim that such SUSY models include a stable very massive weakly interacting particle that could provide an explanation for dark mat

The rumors of WIMPs death are greatly exaggerated!

"WIMP Miracle"

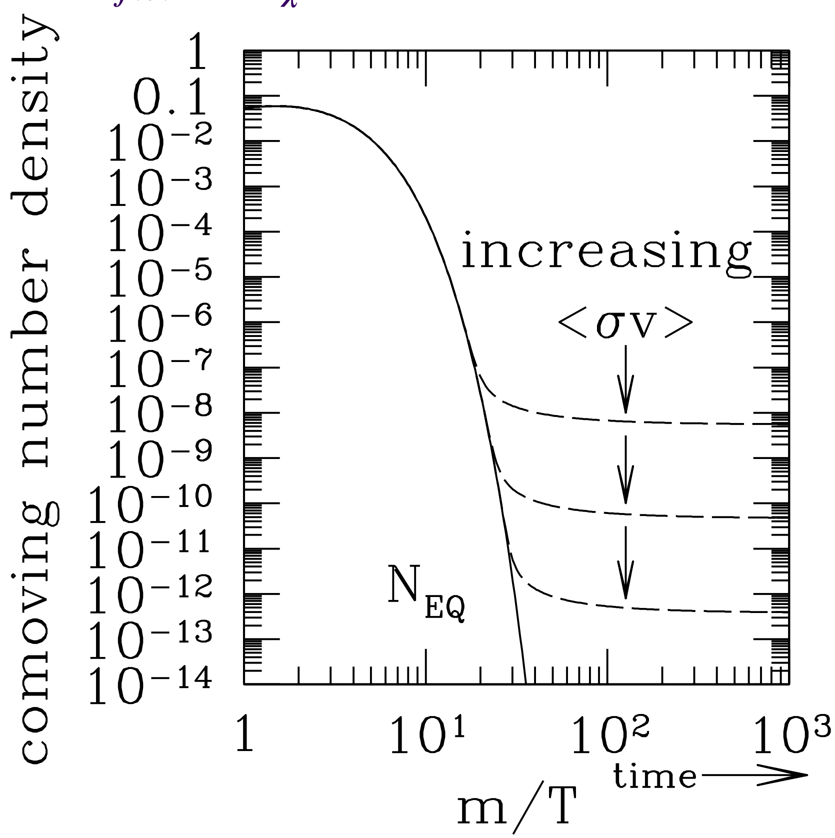
Standard calculations: start at $T > T_{f.o.} \simeq m_\chi/20$ and assume that

- WIMPs **reach equilibrium** while

Universe is radiation dominated

- **No particle asymmetry**
- Chemical decoupling (freeze-out) when $\Gamma_{ann} = \langle \sigma v \rangle \, n \leq H$,
- **No entropy change** in matter+radiation

$$\Omega_{std} h^2 \approx 0.2 \, \frac{3 \times 10^{-26} cm^3/s}{\langle \sigma v \rangle}$$



Weak annihilation cross section

$\sigma_{annih} v \simeq G_F^2 m^2 \simeq 3 \times 10^{-26} cm^3/s$

$m \simeq$ GeV is enough to get

$\Omega = \Omega_{DM} \simeq 0.2$! "WIMP Miracle"

Caveats to "WIMP Miracle"

- Thermal but asymmetric We owe our very existence to a particle-antiparticle asymmetry so why not also the DM? (Requires non-self conjugated DM candidates- neutralinos are Majorana particles instead) (Nussinov 85; Gelmini, Hall, Lin 87; Kaplan 92; Barr, Chivukula, Fahri 90; Enkvist, MacDonald 98; Gudnason, Kouvaris , Sannino 05; Kaplan, Luty, Zurek 09; Cohen et al 10; Frandsen, Sarkar, Sannino 10; Cheung, Zurek 11; Del Nobile, Kouvaris, Sannino 11....among others)
- Thermal or not, but pre-Big bang Nucleosynthesis (pre-BBN) cosmology is non-standard WIMP relic abundance is fixed before BBN, a moment in the Universe from which we have so far no data. (See e.g. Gelmini et al hep-ph/0605016, or Gelmini, Gondolo 1009.3690 and refs. therein)
  $T_{f.o.} \simeq (m/20) > 5$ MeV for $m > 100$ MeV!
  Salas *et al* "Bounds on very low reheating scenarios after Planck" 1511.0067
- Non-thermal WIMPs can be produced in decays of other particles (Sigurdson, Kamionkowski 04; Kaplinghat 05)
- WIMPs may be unstable and decay into the dark matter (Super-WIMP scenario). (Feng, Rayaraman, Takayama 03; Feng, Smith 04)

What are WIMPs? When in doubt...consult wikipidia

Weakly interacting massive particles

From Wikipedia, the free encyclopedia

"WIMPs" redirects here. For other uses, see WIMPS (disambiguation).

Weakly interacting massive particles (**WIMPs**) are hypothetical particles that are thought to constitute dark matter. There exists no clear definition of a WIMP, but broadly, a WIMP is a new elementary particle which interacts via gravity and any other force (or forces), potentially not part of the standard model itself, which is as weak as or weaker than the weak nuclear force, but also non-vanishing in its strength. A WIMP must also have been produced thermally in the early Universe, similarly to the particles of the standard model according to Big Bang cosmology, and

Agree with 1st two sentences- but WIMP not necessarily produced thermally...

What are WIMPs? WIMP name invented in 1985 by Steigman and Turner
June 1985 M. Turner's lectures:

Fermi National Accelerator Laboratory

FERMILAB-Conf-86/18-A
January 1986

A COSMOLOGIST'S TOUR THROUGH THE NEW PARTICLE ZOO (CANDY SHOP?)

Michael S. Turner
Departments of Astronomy and Astrophysics and Physics
The University of Chicago
Chicago, IL 60637

and

NASA/Fermilab Astrophysics Center
Fermi National Accelerator Laboratory
Batavia, IL 60510

To be published in Dark Matter in the Universe, eds. J. Knapp and J. Kormendy (Reidel, 1986), proceedings of IAU Symposium 117, held at Princeton, June 24-28, 1985.

What are WIMPs? WIMP name invented in 1985 by Steigman and Turner

June 1985 M. Turner's lectures:

WIMP	MASS	T_{WIMP}/T	λ_{FS}(Mpc)
Neutrino	light	$(4/11)^{1/3}$	40 Mpc/(m/30eV)
Axion	10^{-5}eV	$< 10^{-14}$	$< 10^{-5}$Mpc
Axino/RH Neutrino/Light Gravitino	keV	1/4	1 Mpc
Heavy Neutrino/ LSP	GeV	1	10^{-5}Mpc

The scale 1 Mpc corresponds to a galactic scale. The relationship of λ_{FS} to the galactic scale neatly divides the WIMPs into three categories: (i) Cold, $\lambda_{FS} \ll 1$ Mpc -- the characteristic damping scale is much smaller than a galactic scale, and galactic-sized perturbations survive freestreaming; (ii) Warm, $\lambda_{FS} \simeq 1$ Mpc -- the characteristic damping scale corresponds to a galactic scale; (iii) Hot, $\lambda_{FS} \gg 1$ Mpc -- only perturbations on scales much larger than a galactic scale survive freestreaming. Almost all of the WIMPs fall into the category of cold dark matter. Only the neutrino is a hot WIMP. At present there are a couple of warm dark matter candidates -- a 1 keV gravitino, 1 keV right-handed neutrino, or a 1 keV axino (supersymmetric partner of the axion).

What are WIMPs? WIMP changed meaning very fast

Ann. Rev. Nucl. Part. Sci. 1988. 38: 751–807

DETECTION OF COSMIC DARK MATTER

Joel R. Primack and David Seckel

Santa Cruz Institute for Particle Physics, Ur
Santa Cruz, California 95064

Bernard Sadoulet

Physics Department, University of Californi

CONTENTS

However WIMP not restricted to 1 to 100 GeV in mass

What are WIMPs? June 1988 M. Turner's talk:

DARK MATTER CANDIDATES MICHAEL S. TURNER

To be published in The Proceedings of the Third CERN/ESO Symposium, held in Bologna Italy, eds. G. Giacomelli, etal. Conference held 16-20 May 1988.

II. RELIC WIMPS AS THE DARK MATTER

dark matter in the Universe! The candidates can be organized into 4 categories: Thermal Relics (hot and cold); Asymmetric Relics; and Non-Thermal Relics.

• **Thermal Relics**—At very high temperatures ($T \gg m_X$), the equilibrium

• **Asymmetric Relics**—Above it was tacitly assumed that the abundance of particle and antiparticle species were identically equal, so that the annihilation rate (and hence cross section) determines freeze out and the relic abundance. If an asymmetry exists between particle and antiparticle species, say more particles than antiparticles, then the relic abundance can actually be determined by the size of the

• **Non-thermal Relics**—There are a handful of very interesting potential relics whose interactions are so feeble that they should never have been thermal equilibrium at early times. Nevertheless, such relics may have been produced by other,

• **Truly Exotic Relics**—There are even more exotic possibilities for the dominant form of matter in the Universe. For example, if the relic WIMP is unstable and

Are WIMPs dead ?

- Are WIMPs coupled to the W/Z bosons dead? Mostly- not entirely e.g. "Minimal DM" Cirelli, Fornengo, Strumia, hep-ph/0512090

- Are "WIMP miracle" WIMPs dead? NO, but constrained...
  Indirect detection: $m > 20$ GeV if annihilate in s-wave "GeV-Scale Thermal WIMPs: Not Even Slightly Dead", Leane, Slatyer, Beacom and Ng,1805.10305 No limits if annihilate in p-wave

- Why consider only "WIMP miracle" WIMPs? NO REASON......

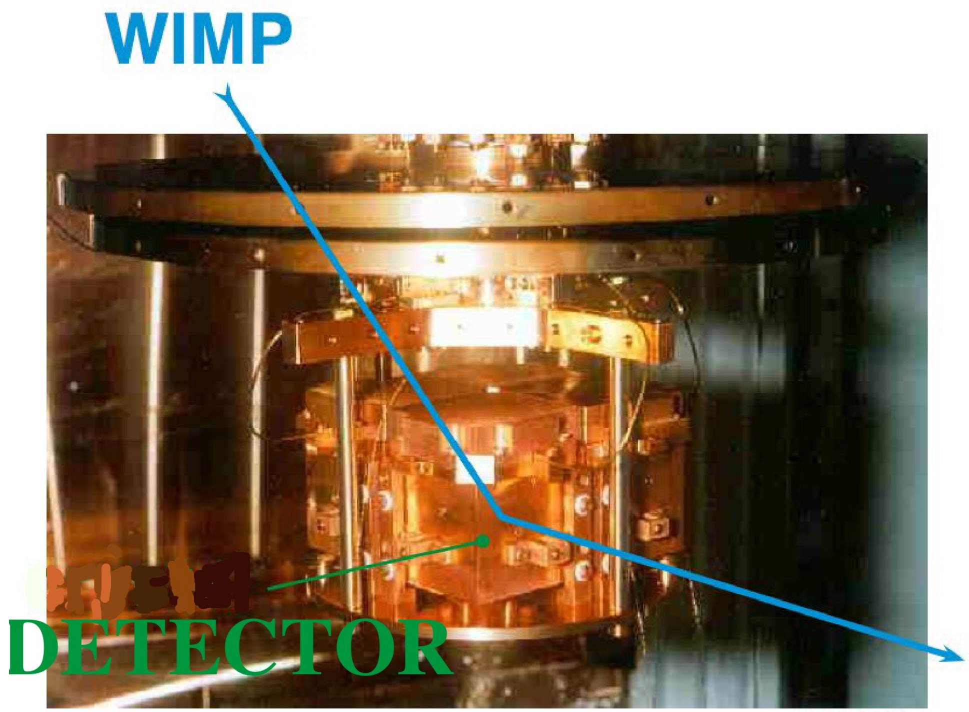
- Are SUSY WIMP models dead? NO, many rejected many not...

- Must WIMPs be produced thermally? NO, not necessarily...

So let us continue searching for WIMPs...

WIMP non-directional direct detection:

WIMP's interact coherently with nuclei in the detector, which recoil with energy E_R



Elements of the direct detection event rate

Event rate: events/(unit mass of detector)/(keV of recoil energy)/day

$$\frac{dR}{dE_R} = \sum_T \int_{v>v_{min}} N_T \times \frac{d\sigma_T}{dE_R} \times n v f(\vec{v}, t) d^3 v$$

-E_R: nuclear recoil energy

- T: each target nuclide (elements and isotopes)

- $N_T = C_T/M_T$= Number of nuclides T in the detector = (mass fraction × Number of nuclides T per unit target mass);

- v_{min} min WIMP speed to impart E_R to the target T

-$\rho = nm$, $f(\vec{v}, t)$: local DM density and $\vec{v}$ distribution depend on halo model.

The recoil rate dR/dE_R is not directly accessible to experiments, they observe only a proxy $E^{'}$ for the recoil energy E_R with $E^{'}$-dependent energy resolutions/efficiencies.

Observed event rate:

$$\frac{dR}{dE^{'}} = \epsilon(E^{'}) \int_0^{\infty} dE_R \sum_T G_T(E_R, E^{'}) \frac{dR_T}{dE_R}$$

- $E^{'}$: detected energy (in keVee or number of PE), C_T: mass fraction in target nuclide T;
- $\epsilon(E^{'})$: **counting efficiency or cut acceptance;** $G_T(E_R, E^{'})$: **energy response function**

$$\frac{dR_T}{dE_R} = \frac{C_T}{M_T} \int_{v>v_{min}} \frac{d\sigma_T}{dE_R} \times \frac{\rho}{m} v f(\vec{v}, t) d^3v$$

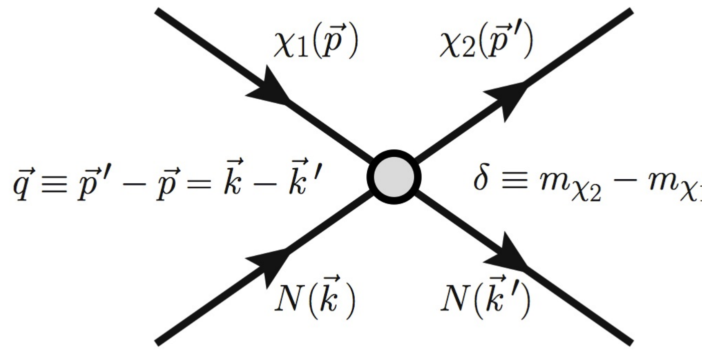
Elements of the rate: Each with its own uncertainties

[Event Rate] = [Detector Response] x [Cross Section] x [Halo Model]

Elements of the Event Rate

[Event Rate] = [Detector Response] x [Cross Section] x [Halo Model]

How does the DM particle couple to the nuclei?



- Starting with fundamental interactions, DM particles couple to quarks/gluons, then pass from quarks/gluons to protons and neutrons, then to nuclei
- besides the DM mass m, this is the only input of Particle Physics

Proceed phenomenologically- consider all types of WIMP couplings
Context: The scope of DM particle models has changed:

- 1980's: DM candidates were an afterthought. Models proposed exclusively to solve problems in Standard Model, such as SUSY, Technicolor, Peccei-Quinn symmetry, neutrino masses - which also contain DM candidates (WIMPs, axions, sterile neutrinos)

- 1990's: DM candidates were mandatory. Models required to have a DM candidate in SM extensions.

- Since 2000's: DM model independent of the SM. Models made to fit DM hints and/or predict novel DM signals and experiments to detect them, without regard for completion of the SM (but may have implications for colliders e.g. search for light mediators, displaced vertices...)
Leads to all types of DM interactions, to "dark sectors" seen through "portals" i.e. very small couplings (with photons, with neutrinos, with the Higgs....)

Diversified models for WIMPs (e.g. Gelmini, Takhistov and Witte 1804.01638)

Model	Interaction	Dependence ($\|\vec{q}\|$, v)		$\sigma_{\rm ref}$	
		Heavy	Light	Heavy	Light
SI	$\bar{\chi}\chi\bar{N}N$ $\bar{\chi}\gamma^{\mu}\chi\bar{N}\gamma_{\mu}N$	$\frac{1}{v^2}$	$\frac{1}{v^2\|\vec{q}\|^4}$	$\frac{\mu_N^2}{\pi}\left(\frac{f_p^{\rm SI}}{M^2}\right)^2$	$\frac{\mu_N^2}{\pi}\left(\frac{f_p^{\rm SI}}{\|\vec{q}_{\rm ref}\|^2}\right)^2$
SD	$\bar{\chi}\gamma^{\mu}\gamma^5\chi\bar{N}\gamma_{\mu}\gamma_5N$	$\frac{1}{v^2}$	$\frac{1}{v^2\|\vec{q}\|^4}$	$\frac{3\mu_N^2}{\pi}\left(\frac{a_p^{\rm SD}}{M^2}\right)^2$	$\frac{3\mu_N^2}{\pi}\left(\frac{a_p^{\rm SD}}{\|\vec{q}_{\rm ref}\|^2}\right)^2$
Ana	$\bar{\chi}\gamma^{\mu}\gamma_5\chi\partial^{\nu}F_{\mu\nu}$	$\|\vec{q}\|^4$, $\frac{\|\vec{q}\|^6}{v^2}$	1 , $\frac{\|\vec{q}\|^2}{v^2}$	$\frac{\varepsilon^2\mu_N^2}{4\pi}\left(\frac{eg_\chi^{\rm A}\|\vec{q}_{\rm ref}\|^2}{\Lambda^2M^2}\right)^2$	$\frac{\varepsilon^2\mu_N^2}{4\pi}\left(\frac{eg_\chi^{\rm A}}{\Lambda^2}\right)^2$
MD	$\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	$\|\vec{q}\|^2$, $\frac{\|\vec{q}\|^4}{v^2}$	$\frac{1}{\|\vec{q}\|^2}$, $\frac{1}{v^2}$	$\frac{\mu_N^2}{\pi}\left(\frac{eg_\chi^{\rm MD}\|\vec{q}_{\rm ref}\|}{\Lambda M^2}\right)^2$	$\frac{\mu_N^2}{\pi}\left(\frac{eg_\chi^{\rm MD}}{\Lambda\|\vec{q}_{\rm ref}\|}\right)^2$
ED	$\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu}$	$\frac{\|\vec{q}\|^2}{v^2}$	$\frac{1}{v^2\|\vec{q}\|^2}$	$\frac{\mu_N^2}{\pi}\left(\frac{eg_\chi^{\rm ED}\|\vec{q}_{\rm ref}\|}{\Lambda M^2}\right)^2$	$\frac{\mu_N^2}{\pi}\left(\frac{eg_\chi^{\rm ED}}{\Lambda\|\vec{q}_{\rm ref}\|}\right)^2$
mC[1]	$\bar{\chi}\gamma^{\mu}\chi\bar{N}\gamma_{\mu}N$	$\frac{1}{v^2}$	$\frac{1}{v^2\|\vec{q}\|^4}$	$\frac{\varepsilon^2\mu_N^2}{\pi}\left(\frac{eg_\chi^{\rm mC}}{M^2}\right)^2$	$\frac{\varepsilon^2\mu_N^2}{\pi}\left(\frac{eg_\chi^{\rm mC}}{\|\vec{q}_{\rm ref}\|^2}\right)^2$
PS-S	$\bar{\chi}\gamma^5\chi\bar{N}N$	$\frac{\|\vec{q}\|^2}{v^2}$	$\frac{1}{v^2\|\vec{q}\|^2}$	$\frac{\mu_N^2}{4\pi}\left(\frac{g_\chi^{\rm PS}f_p^{\rm S}\|\vec{q}_{\rm ref}\|}{M^2m_\chi}\right)^2$	$\frac{\mu_N^2}{4\pi m_\chi^2}\left(\frac{g_\chi^{\rm PS}f_p^{\rm S}}{\|\vec{q}_{\rm ref}\|}\right)^2$
S-PS	$\bar{\chi}\chi\bar{N}\gamma^5N$	$\frac{\|\vec{q}\|^2}{v^2}$	$\frac{1}{v^2\|\vec{q}\|^2}$	$\frac{\mu_N^2}{4\pi}\left(\frac{g_\chi^{\rm S}f_p^{\rm PS}\|\vec{q}_{\rm ref}\|}{M^2m_p}\right)^2$	$\frac{\mu_N^2}{4\pi m_p^2}\left(\frac{g_\chi^{\rm S}f_p^{\rm PS}}{\|\vec{q}_{\rm ref}\|}\right)^2$
PS-PS	$\bar{\chi}\gamma^5\chi\bar{N}\gamma^5N$	$\frac{\|\vec{q}\|^4}{v^2}$	$\frac{1}{v^2}$	$\frac{\mu_N^2}{16\pi}\left(\frac{g_\chi^{\rm PS}f_p^{\rm PS}\|\vec{q}_{\rm ref}\|^2}{M^2m_pm_\chi}\right)^2$	$\frac{\mu_N^2}{16\pi}\left(\frac{g_\chi^{\rm PS}f_p^{\rm PS}}{m_pm_\chi}\right)^2$
AV-V	$\bar{\chi}\gamma^{\mu}\gamma_5\chi\bar{N}\gamma_{\mu}N$	1 , $\frac{\|\vec{q}\|^2}{v^2}$	$\frac{1}{\|\vec{q}\|^4}$, $\frac{1}{v^2\|\vec{q}\|^2}$	$\frac{\varepsilon^2\mu_N^2}{4\pi}\left(\frac{g_\chi^{\rm AV-V}}{M^2}\right)^2$	$\frac{\varepsilon^2\mu_N^2}{4\pi}\left(\frac{g_\chi^{\rm AV-V}}{\|\vec{q}_{\rm ref}\|^2}\right)^2$

[1] This model is equivalent to SI.

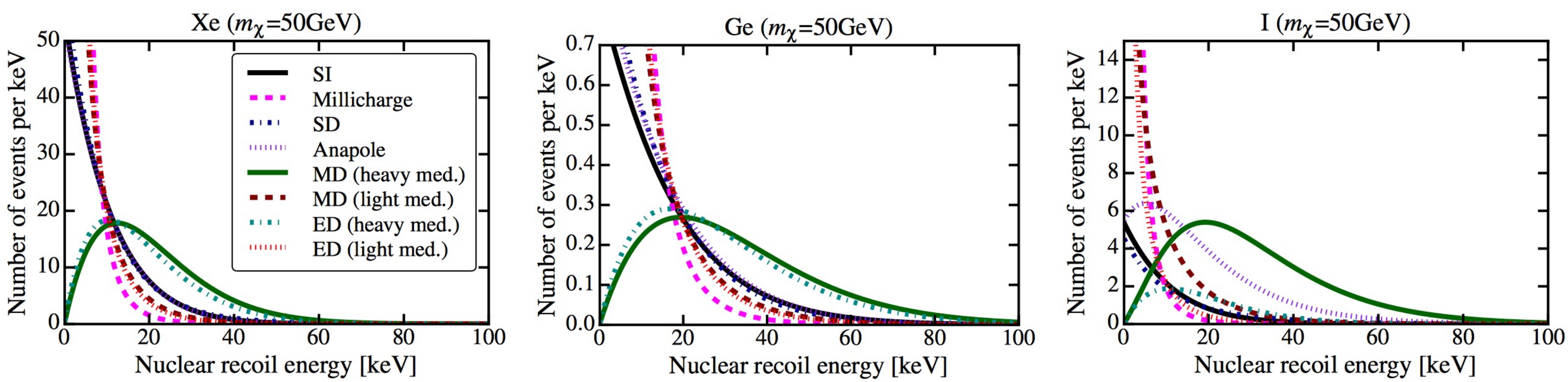
Table 1: Interaction models with fermionic DM particles. Model name, interaction, dependence on $|\vec{q}|$ and v, as well as the definition of the reference cross-section $\sigma_{\rm ref}$ are shown. Values for both heavy and light mediators are included.

Cross sections can be very different: e.g. SI and Magnetic Dipole

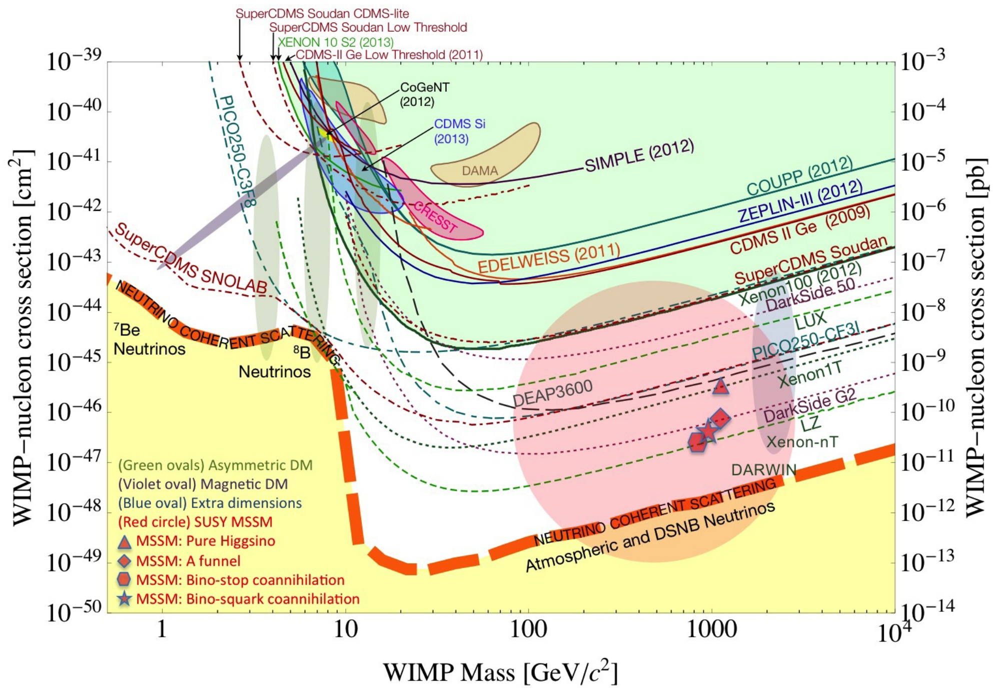
$$\frac{d\sigma_T^{SI}}{dE_R} = \sigma_{ref}^{SI} \frac{|\overrightarrow{q_{ref}}|^4}{M^4} \frac{m_T}{2\mu_N^2 v^2} \left[A_T\right]^2 F_{SI,T}^2 \qquad |\vec{q}| \;\; \textit{independent}$$

$$\frac{d\sigma_T^{MD}}{dE_R} = \sigma_{ref}^{MD} \frac{|\overrightarrow{q_{ref}}|^2}{M^4} \frac{m_T^2}{4v^2\mu_N^2} \left[Z_T^2 \left(4v^2 |\vec{q}|^2 - |\vec{q}|^4 \left\{ \frac{1}{\mu_T^2} - \frac{1}{m_\chi^2} \right\} \right) F_{E,T}^2 + 2 \frac{|\vec{q}|^4}{m_N^2} \frac{\lambda_T^2}{\lambda_N^2} \left(\frac{J_T+1}{3J_T} \right) F_{M,T} \right]$$

Rates can be very different than for SI Fig. from Gluscevic et al. 1506.04454

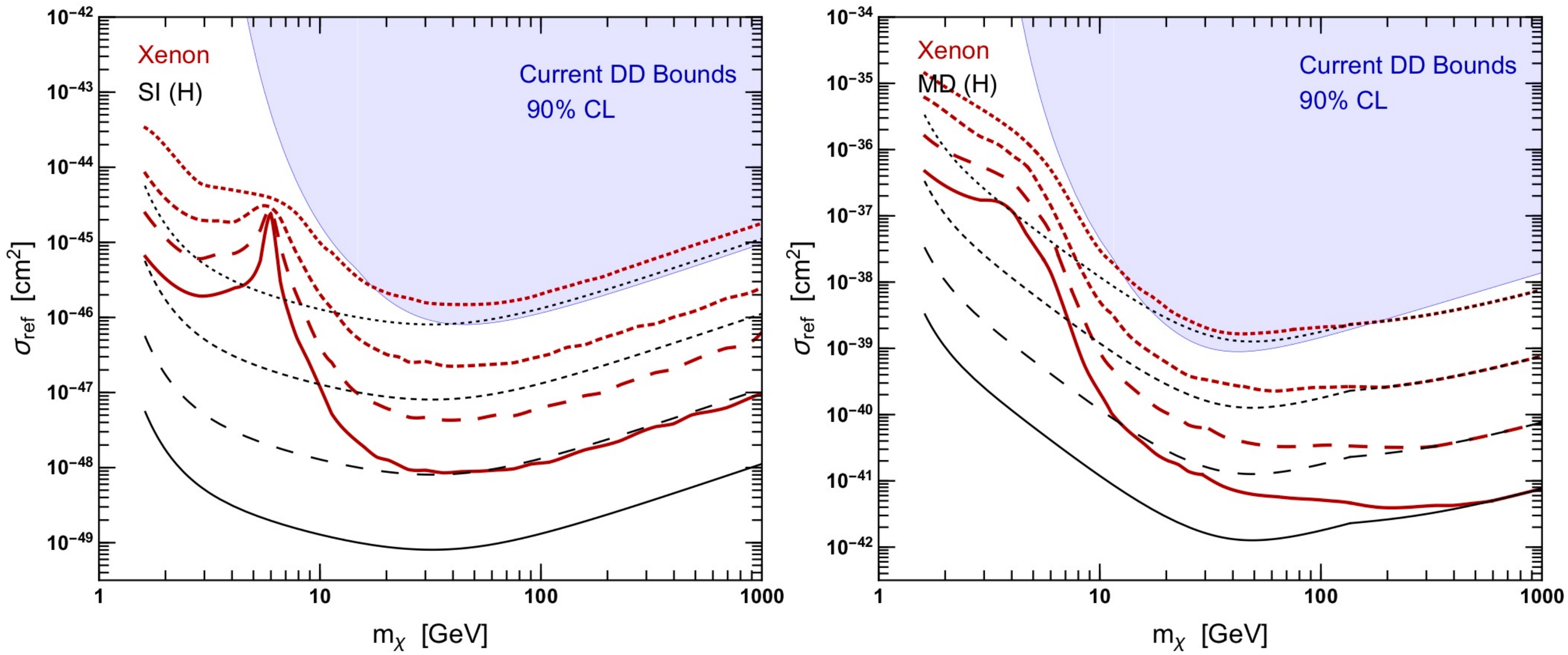


Is very important to consider all types of interactions: E.g. relevance of the neutrino floor for future Direct Detection from Snowmass 2013)
BUT this is for Spin-Independent interactions, equal p,n couplings (and SHM)



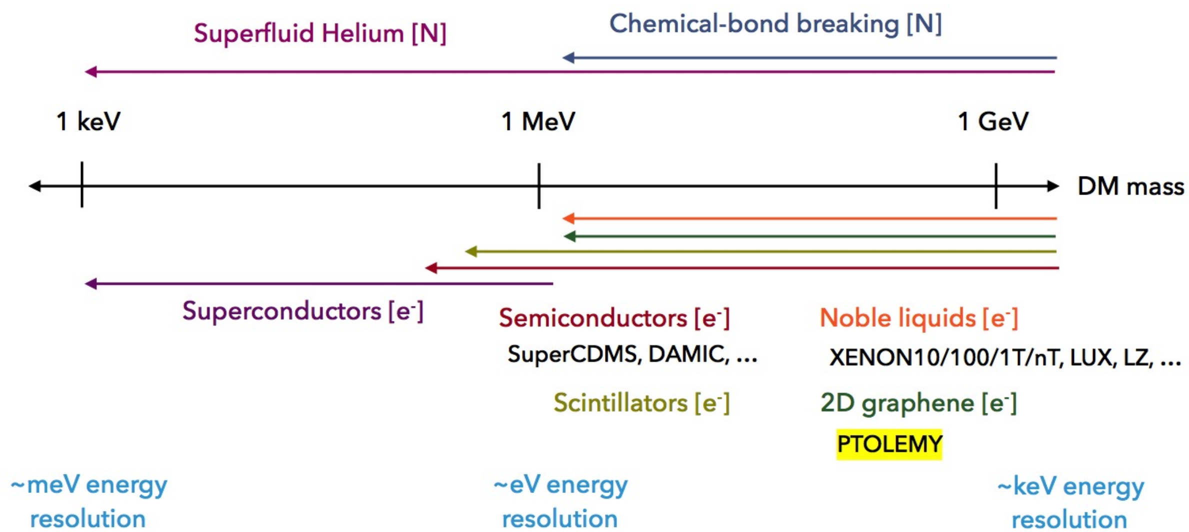
Future of non-directional Direct Detection The relevance of the neutrino floor depends on the WIMP interaction

Gelmini, Takhistov, Witte 1804.01638



The Xe discovery reach of heavy q^x (q is the momentum exchanged) interacting DM is not affected by the neutrino floor (for exposures ≤ 100 tonne y) but require experiments to extend the energy range and change their data analysis!

+ Diversify into unexplored domains light DM, dark photons and other light mediators, boosted DM. "Dark Sector Workshop"1608.08632; "U.S. Cosmic Visions: New Ideas in DM" 3/2017- KITP 2018 workshop "HEP at the Sensitivity Frontier" e.g. for sub-GeV "Light Dark Matter" direct detection



Scattering off e [e^-] or inelastic scatt. on nuclei [N] (γ emission in nuclear recoil, breaking chemical bonds in molecules/crystals, multi-phonon processes in superfluid He or insulator crystals)

Elements of the Event Rate in Direct DM detection

$$\left[\begin{array}{l}\text{Event}\\\text{Rate}\end{array}\right] = \left[\begin{array}{l}\text{Detector}\\\text{Response}\end{array}\right] \times \left[\begin{array}{l}\text{Cross}\\\text{Section}\end{array}\right] \times \boxed{\left[\begin{array}{l}\text{Halo}\\\text{Model}\end{array}\right]}$$

How many DM particles are passing through the detector and with which velocity distribution?

Usually assumed Standard Halo Model is a good first approximation but not expected to be correct. Uncertainty in measurements of key parameters, and Earth could be within a DM clump, or stream, and maybe a dark disk and there are debris flows, triaxiality ....“DM particles” in simulations have $> 10^3$ $M_{\odot}$....

Given all these uncertainties, could we avoid using a halo model when comparing Direct DM detection data?

Lots of work done since 2010 on “Halo Independent” models...

"Halo-Independent": Recall the event rate:

For a WIMP-nucleus contact differential cross section (for momentum transfer and velocity-independent interaction operators) e.g. for Spin Independent interactions

$$\frac{d\sigma_T}{dE_R} = \frac{\sigma_T(E_R)\ M_T}{2\mu_T^2 v^2} \qquad \sigma_T(E_R) \sim \sigma_{ref}$$

$$\frac{dR}{dE_R} = \sum_T \frac{\sigma_T(E_R)}{2m\mu_T^2}\ \rho\eta(v_{min}, t), \qquad \eta(v_{min}, t) = \int_{v>v_{min}} \frac{f(\vec{v}, t)}{v} d^3v = \int_{v_{min}} \frac{F(v, t)}{v} dv$$

- ρ, $f(\vec{v}, t)$: local DM density, Earth's frame $\vec{v}$ distribution depend on halo model

"Halo-Dependent": Given $\rho\eta(v_{min})$ plots in (m, σ_{ref}) plane (usual)

"Halo-Independent": Given m, $d\sigma_T/dE_R$ plots in $(v_{min}, \tilde{\eta}(v_{min}))$ plane,

$$\tilde{\eta}(v_{min}, t) = \frac{\sigma_{ref}}{m}\rho\eta(v_{min}, t)$$

contains all halo dependence in ANY experiment!

Fox, Liu, Weiner 1011.1915; Frandsen et al 1111.0292; Gondolo-Gelmini 1202.6359...

for ANY interaction, energy resolutions, efficiencies...

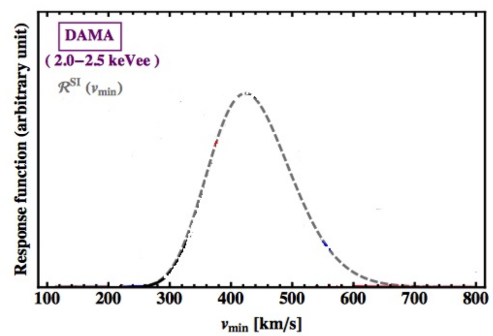
Gondolo-Gelmini 1202.6359; Del Nobile, Gelmini, Gondolo and Huh, 1306.5273

We write the predicted observable rate for any cross section as

$$R_{[E_1',E_2']} = \int_0^\infty dv_{min}\ \mathscr{R}_{[E_1',E_2']}(v_{min})\,\tilde{\eta}(v_{min},t)$$

$\mathscr{R}_{[E_1',E_2']}$ **: experiment and interaction dependent response function**

(non zero only for an interval in v_{min} given a measured energy interval $[E_1', E_2']$)



“Halo Independent” data analysis

1- **Find the predictions of Direct Detection data for the halo**, e.g. for the coefficients of the harmonic expansion of $\tilde{\eta}(v_{min}, t)$ (mostly its time average).

2- **Compare data from different experiments by comparing their predictions for the halo**, e.g. for the time average of $\tilde{\eta}(v_{min})$ of $\tilde{\eta}(v_{min}, t)$:
– putative measurements translate into regions in the $(v_{min}, \tilde{\eta}(v_{min}))$ plane,
– upper limits into upper limits on $\tilde{\eta}(v_{min})$

Main Problem: Likelihood methods are good for parameter estimation, **but here we want to estimate a function,** $\tilde{\eta}$ or the local WIMP speed distribution F which the predicted rates depend on ($C = \frac{\sigma_{ref}\rho}{m}$ is a constant)

$$R_{[E_1', E_2']} = C \int_0^\infty dv_{min}\, \mathscr{R}_{[E_1', E_2']}(v_{min})\, \eta(v_{min}, t) = C \int_0^\infty dv\, \mathscr{H}_{[E_1', E_2']}(v)\, F(v, t)$$

2014-2015 Solved the problem only for unbinned data (Extended Likelihood)

Halo-Independent analysis

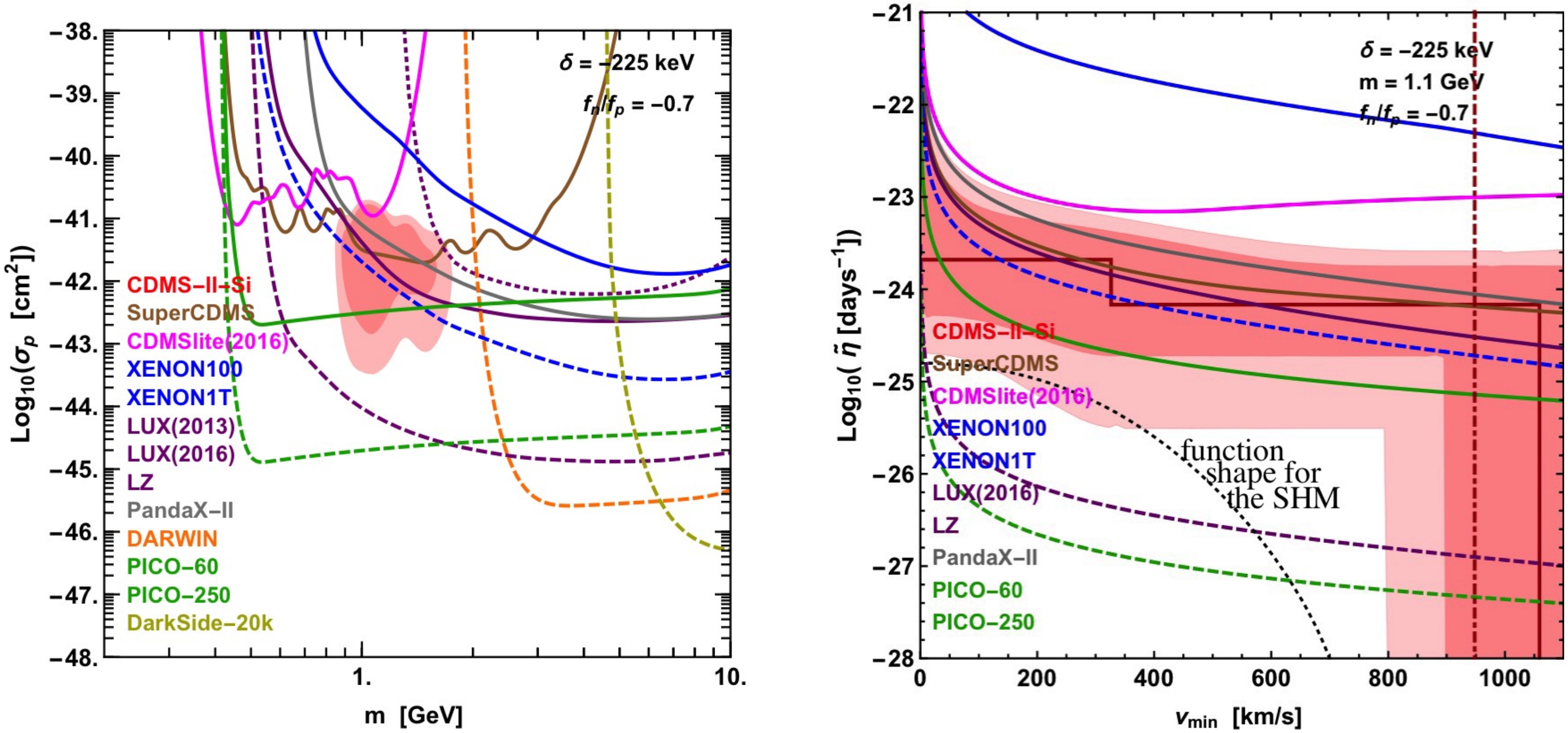
Regions for putative DM (time averaged) rate measurements:
With unbinned data (e.g. CDMS-II-Si), using at least one extended likelihood, we found (Fox, Kahn and McCullough 1403.6830; Gelmini, Georgescu, Gondolo and Huh 1507.03902; Gelmini, Huh and Witte 1607.02445)

- a unique piecewise constant best fit $\tilde{\eta}(v_{min})$ with a number of downward steps $\leq$ number of data points, by extending to functionals the Karush-Kuhn-Tucker (KKT) maximization conditions (Fox, Kahn and McCullough 1403.6830), and a

- statistically meaningful two-sided point-wise band at a chosen CL. (Gelmini, Georgescu, Gondolo and Huh, 1507.03902)

Halo-Dependent and Independent analyses CDMS-II-Si data

inelastic exothermic DM with SI IV coupling, $\delta = -225$ keV Witte, Gelmini 1703.06892



LEFT: assuming the SHM RIGHT: Halo independent, m=1.1GeV

Can be ruled out by an LZ or PICO-250 like experiment (not XENON1T)

A deeper understanding of Halo-Independent methods for all Likelihoods Gelmini, Huh and Witte 1707.07019

Why a piecewise constant best fit $\tilde{\eta}(v_{min})$ with the number of downward steps $\leq$ the number of data points???

Well known theorems in convex geometry (Caratheodory, Fenchel-Eggleston) provide the answer: for d (time average) predicted rates the DM speed distribution $F(v)$, normalized to 1, is given by

$$F(v) = \sum_{n=1}^{d} F_n \, \delta(v - v_n)$$

Now we have at most 2d parameter F_n, v_n to estimate using the Likelihood

and the integral $\tilde{\eta}(v_{min}) = const. \int_{v_{min}}^{\infty} dv \, \frac{F(v)}{v}$ **of a sum of at most d delta functions is piecewise constant with at most d downward steps (d= number of data points)** Lots of work yet to do to develop this method....

Outlook on WIMP direct detection

Important to consider all possible DM-SM interactions when analyzing direct detection data (e.g. extended energy windows with respect to needed for SI)
Halo-Independent analysis is on firm mathematical ground but still complicated-under development, I believe it will be adopted at some point as complementary to the usual Halo-Dependent.

In the near future: new data.
DAMA clearly sees an annual modulation at 12.9σ, DM or instrumental?
- "Global NaI(TI) Collaborative Effort": KIMS (52 kg) and DM-Ice (55 kg), in YangYang Lab. (S Korea), ANAIS (112 kg), in Canfranc Lab. (Spain) and SABRE (50 kg) in two sites, Gran Sasso Lab. (Italy) and Stawell Lab., Australia
Very important to check in the Southern Hemisphere!

- XENONnT, LZ, DarkSide20T, SuperCDMS, PICO, DARWIN(50T), GADMC (300T)... and Directional Direct DM detectors... Light DM detectors...

To conclude

There is no compelling observational or experimental evidence in favor of any of our DM candidates: cast as wide a net as possible.

There are mature WIMP search techniques which should continue to the multi-ton scale, until the neutrino floor becomes a true barrier.

Very vibrant field, with many new ideas and strong worldwide commitment to the effort, will continue bringing results for decades.