# **Direct detection of dark matter**

*An overview, not a review*

*Paolo Gondolo University of Utah (On sabbatical at Seoul National University)*

Friday, June 8, 12

• Even if a new neutral particle is discovered at accelerators, one must still prove that it is the cold dark matter.

*Example:* active neutrinos are neutral but are hot dark matter.

- Indirect detection of dark matter is subject to poorly known astrophysical backgrounds, so it is hard to claim an unconditional discovery (exception may be gamma-ray line).
- Direct detection seems the best way to prove the existence of particle dark matter.

# **The principle**

*Rotation curve (Clemens 1985)*



Our galaxy is inside a halo of dark matter particles

*Image by R. Powell using DSS data*

# **The principle**

### Dark matter particles that arrive on Earth scatter off nuclei in a detector



**Dark** matter particle

Low-background underground detector

# **Background discrimination**

### Finding the dark matter particles is a fight against background



### *From Sanglard 2005*

### DM Direct Search Progress Over Time (2009)



# **Coming up......**

- XMASS (800 kg LXe, Kamioka, 2011-)
- SuperCDMS (25kg Ge, Soudan, 2012-)
- LUX (350 kg LXe, Homestake, 2012-)
- DarkSide (50 kg LAr, Gran Sasso, 2012-)
- COUPP (60 kg CF3I, SNOLab, 2012-)
- XENON-1T (1 ton LXe, Gran Sasso, 2014-)
- DM-ICE, EURECA, DARWIN, and many many others

# **The annual modulation**

### *Drukier, Freese, Spergel 1986*

### Annual modulation in WIMP flux and detection rate

$$
S = S_0 + S_m \cos[\omega(t - t_0)]
$$



The WIMP bulk velocity w.r.t. Earth modulates from ~232+15 km/s to  $\sim$ 232-15 km/s with a period of one year

# **The DAMA modulation**

DAMA finds a yearly modulation as expected for dark matter particles

*Bernabei et al 1997-2012*



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# **The CoGeNT modulation**

The CoGeNT "irreducible excess'' (\*) modulates with a period of one year and a phase compatible with DAMA's annual modulation.

*(\*) Partly due to extra surface events*

*Aalseth et al 1106.0650*



FIG. 4: Time evolution of the rate in several energy regions.

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# **The CRESST unexplained excess**

### 67 observed events cannot all be explained by background at  $4\sigma$



signal, as inferred from the likelihood fit. The solid and dashed

*Adapted from Anglehor et al 2011* events from angienor et al. 201

# **The CRESST unexplained excess**

### 16 G. Anglos et al.: Results from 730 kg days of the CRESS 67 observed events cannot all be explained by background at  $4\sigma$



grounds and the possible signal. The possible signal signals are solid and the solid and the solid and data th<br>Signal and dashed in the solid and data the solid and data the solid and data the solid and data the solid and<br> correspond to the parameter values in M1 and M2, respec-Friday, June 8, 12

# **Limits from XENON-100, KIMS, CDMS, .....**

Upper limit on WIMP-nucleon cross section from XENON-100 (model dependent)



shown as the thick (blue) line together with the 1 and 2

[2] N. Jarosik et al., Astrophys. J. Suppl. 192, 14 (2011);

 $\frac{1}{2}$   $\frac{1}{2}$  1.8±0.6 expected background 3 events observed *Aprile et al (XENON-100) 1104.2549*

# **Limits from XENON-100, KIMS, CDMS, .....**



1 Year 2252 **PM** Excludes inelastic dark matter *• Excludes 60 GeV/c2 DAMA region*



*Without using detectors with large surface* α *background Kim at TAUP 2011*

### band events is shown for the 5.0–11.9 keVnr interval (dark blue), after subtracting the best-fit unmodulated rate, *d*, for each detector. The horizontal bars represent the time  **0.175 0.35 [keV**<br>∂ **Limits from XENON-100, KIMS, CDMS, .....**



FIG. 1. (color online) The rate of CDMS II nuclear-recoil

periments, confirming the asymptotic limit computation

**−1**

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Fig. 10 (Colorate online). Aprile et al. (XENON-100). ITC  $\Delta$ brile et al (XFNON-100). LIO4 2549 Aprile et di (AENUN-TUU). I TU4.2347 Aprile et al (XENON-100) 1104.2549  $\mathbf{u}$  main results and Si only (gray/light solid line) data, with solid lines, with solid lines, with solid line, with solid lines, with  $\mathbf{v}$  $\Delta p$ ine et di ( $\Delta E$ NON-100) 1107.2977 Aprile et al (XENON-T00) TT04.2549 **ENON-100) 1104.2 UN-TUU) 1104.23**  $2 + 1$  (VENIONI 100) 11012F10 **WIMP MASS (COVER)** Aprile et al (XENON-100) 1104.2549  $FPTICCCTGPTCOTPTCOT-TCOT$ *Aprile et al (XENON-100) 1104.2549*

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### **CoGoN** of steps. The limit was calculated for 75 WIMP masses **R. DAMA Ve YENON COMS** The serialization technique sets the limit according to the **CoconTP D** between 1 and 100 GeV The serialization technique sets the limit according to the WA VS. AENUN, UDMO, GL dI each detector and WIMP search (3 and 6 V data) in a series i Cogen i & D/ limit (the difference is imperceptible in Figs. 10 and 12). TA VS. XENON. CDMS. et al. most sensitive detectors. The Ge detectors were more erly, expected WIMP rates were separately calculated for each detector and WIMP search and WIMP search and DIST and found to be almost equal to the combined Ge and Si livs. XENON, CDMS, et al. expected NIT of BAM edden R DAN  $\mathbf{v}$  we signal to the combined Ge and Signal to the combined  $\mathbf{v}$ VS. ALIVUN, UDIVIO, GL GI of steps. The limit was calculated for 75 WIMP masses **between 1** and 100 GeV/c2. In WA VS. XENON. CDWS. et a sensitive across the range of WIMP masses considered, **COGONT &** predicts the differential WIMP-nucleon scattering rate in AMA VG YENON CDMS of : sensitive across the range of WIMP masses considered, between 1 and 100 GeV predixters the differential C most sensitive detectors. The Ge detectors were more AIVIA VS. AENUN, UDIVIO, CL between 1 and 100 GeV=c<sup>2</sup>. At each mass, the halo model predicts the differential WIMP-nucleon scattering rate in most sensitive detectors. The Ge detectors were more AMA VS. XENON, GDMS, <del>C</del>I erly, expected WIMP rates were separately calculated for eggen i Gedam  $\mathbf{M} = \mathbf{M} \cdot \mathbf{A} \cdot \mathbf{N}$  and  $\mathbf{M} \cdot \mathbf{A} \cdot \mathbf{N}$ VS. AENUN, UDIVIS, CL ZI erlige WIMP Repair each detector and WIMP search (3 and 6 V data) in a series ve YENON COMB at almost limit (the difference is imperceptible in Figs. 10 and 12). To include the effect of nonzero energy resolution prop**eggent & DAMA** and **found to be almost extending** to the combined Ge and Signal to the combined Ge and Signal to the combined G limit (the difference is imperceptible in Figs. 10 and 12). To include the effect of nonzero energy resolution propedien Guard WIMP  $\lambda$  /  $\lambda$  is also calculated, alone was also calculated, and found to be almost extend to the combined  $\bullet$ **between 100 GeV/FC** predicts the differential WIMP-nucleon scattering rate in **MAMA VE NON CONSTRUCTION** s daitia vs. Alivui, Cdivij, M of steps. The limit was calculated for 75 WIMP masses l Cogen I a The serialization technique sets the limit according to the DAMA VS. XENUN, UDWS, et To include the effect of nonzero energy resolution propedie Gerling, D A limit based on the Ge data alone was also calculated, 1A VS. XENON, CDWS, et al limit (the difference is imperceptible in Figs. 10 and 12). **CoGeNT & DAMA vs. XENON, CDMS, et al**



LIBRA annular modulation signal as interpreted by Savage et al.

 $\{13,39,70\}$  (99.7% C.L.), and include the effect of ion channeling as  $\{13,49,70\}$ 

sensitivity of this run (shaded blue band). The limits from

potential signal regions based on data from the DAMA/LIBRA rouper, Condi, Fran, McKnisey 2010 Hooper Collar Hall McKinsey 2010  $\ldots$  is equal to compute the computation of  $\alpha$  (black solid line,  $\alpha$ ) and  $\alpha$ Hooper, Collar, Hall, McKinsey 2010 Hooper, Collar, Hall, McKinsey 2010  $\frac{3}{4}$  rooper, comar,  $\frac{3}{4}$  ran,  $\frac{3}{4}$  retainsely 2010 Hooper, Collar, Hall, McNinsey 2010 Hoober, Collar, Hall, McKinsey, 2010.  $\mathcal{L}_{\mathcal{A}}$  (black/dark solid line, dark solid l Hooper, Collar, Hall, McKinsey 2010 FIG. 10 (color online). Comparison of 90% confidence level Flooper, Collar, Flail, McKinsey 201 potential signal regions based on the Damas regions based on the DAMA  $_{\rm 2}$ Hooper, Collar, Hall, McKinsey 2010 as *Hoober, Collar, Hall, McKinsey* 2010 at 90% CL, as derived with the Profile Likelihood method method method method method method method method met *Hooper, Collar, Hall, McKinsey 2010* 

[34] and CoGeNT [35] experiments. The two (larger) oval-

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our main results) and Si only (gray/light solid line) data, with solid lines, with solid lines, with solid lin our main results of the Si only (gray/light solid line) data, with solid lines. When  $\alpha$  $u_{\text{sum}}$  from the combined  $\alpha$  $\frac{3}{4}$  and  $\frac{3}{4}$  experiments. The two (larger) oval- $\blacksquare$  and  $\blacksquare$  and  $\blacksquare$  and  $\blacksquare$  and  $\blacksquare$  and  $\blacksquare$  over  $\blacksquare$  over  $\blacksquare$  $\mathcal{F}_{\text{collar}}$  1106.0653 FIG. 10 (color online). Comparison of 90% confidence level FIG. 10 (color online). Comparison of 90% confidence level [34] and CoGeNT [35] experiments. The two (larger) ovalpotential signal regions based on data from the DAMA/LIBRA from the DAMA/LIBRA from the DAMA/LIBRA from the DAMA/LIB upper limits from the combined  $\alpha$  (black solid lines) solid lines,  $\alpha$  (b)  $\alpha$ as function of WIMP mass  $\epsilon$  MINP mass  $\$ **Collar 1106.0653** 

K. Nakamura et al. (Particle Data Group), J. Phys. G37,

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LIBRA annular modulation signal as interpreted by Savage et al.

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detector data, translated to ionization scale and overlapped on histogrammed  $\mathcal{A}$  after normalization to  $\mathcal{A}$  after normalization to  $\mathcal{A}$ 

sensitivity of this run (shaded blue band). The limits from

Collar Fields 1204.3559 Collar Fields 1204.3559  $C$ <sub>behan</sub> and  $C$  interpreted by  $C$  $\boldsymbol{\mathsf{Collar}}$  Fields 1204.3559  $\boldsymbol{\mathsf{olim}}$ Condit religion is the Si only of the Single solid lines.  $\sum_{i=1}^{n}$  and  $\sum_{i=1}^{n}$  and  $\sum_{i=1}^{n}$  are interpreted by Savage et al. shaped filled regions (pinklight shaded) represents the DAMA (pinklight shaded) represent the DAMA/ taking into a Collar Fields, 1204.3559 Collar Fields 1204.3337 *Collar Fields 1204.3559*

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The serialization technique sets the limit according to the

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most sensitive detectors. The Ge detectors were more

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sensitive across the range of WIMP masses considered, which may be really considered, which may be really considered, and the range of  $\sim$ 

 $10^{-39}$  sensitive account of  $\sim 10^{-39}$  masses considered,  $\sim 1$ 

sensitive across the range of WIMP masses considered,

 $\frac{1}{10}$ sensitive across the range of WIMP masses considered,  $\frac{1}{10}$ 

 $\frac{10^{-39}}{\text{N} \cdot \text{m}}$ 



**10<sup>−</sup><sup>38</sup>**

**10<sup>−</sup><sup>38</sup>**

**10<sup>−</sup><sup>38</sup>**

**10<sup>−</sup><sup>38</sup>**

**10<sup>−</sup><sup>38</sup>**

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solely on the phonon signal. The expected WIMP spectrum  $\blacksquare$  the astrophysic channel when the hardware and software threshold effishould therefore include noise from only the phonon solely on the phonon signal. The expected WIMP spectrum signal widely signal. The expectation on the phonon signal w channel when the hardware threshold efficiency should therefore include noise from only the phonon **−**<br> **−**<br> **−**<br> *−*<br>
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<br> hardware trigger and software phonon thresholds depend −<br>|<br>de<br>de  $-$  astrophy ciencies are applied. After application of these phonon-**10<sup>−</sup><sup>40</sup>** channel when the hardware and software threshold effi-- astrophysics mode channel when the hardware and software threshold effionly efficiencies, the spectrum was further smeared to −<br>d<br>d hardware trigger and software phonon thresholds depend  $\sim$   $\sim$  astrophysics in  $h$  and  $\alpha$  and software phonon thresholds  $\alpha$ solely on the phonon signal. The expectation signal  $\frac{1}{2}$ **10−40a** are applying the hardware threshold effects and software the hardware threshold efficiency solely on the phonon signal. The expected WIMP spectrum channel when the hardware and software threshold efficiencies are applied. After application of these phonon-**10<sup>−</sup><sup>40</sup>** hardware trigger and software phonon thresholds depend solely on the phonon signal. The phonon signal  $\sim$ **10<sup>−</sup><sup>39</sup>** -41 10 **−nucleon cross section (cm** C<br>Ci<br>Ci<br>a CDMS !pb" 10!<sup>40</sup> i si<br>or<br>r - astrophysics model

**160** 

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**2)**

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- ciencies are applied. After application of these phonon-**10<sup>−</sup><sup>40</sup>** ciencies are applied. After application of these phonon-**10<sup>−</sup><sup>40</sup>** only efficiencies, the spectrum was further smeared to **10−10−40** cal density, velocity density should therefore include noise from only the phonon channel when the hardware threshold efficiency, the hardware threshold effects of  $\mathcal{L}$ only efficiencies, the spectrum was further small determines  $\sim$  function  $\sim$  function  $\sim$  $\frac{1}{\sqrt{2}}$ include the electronic noise of the ionization channel via include the ionization channel via the ionization channel via the ionization channel via the ionization channel should therefore include noise from only the phonon channel when the hardware threshold efficiency, very should therefore include noise from only the phonon only the phonon only the phonon only the phonon only the p show the from only the phonon o only efficiencies, the spectrum was further smeared to include the electronic noise of the ionization channel via only efficiencies, the spectrum was functions of  $\mathsf{IOCG}$ should therefore include noise from only the phonon channel when the hardware threshold efficiency and software the hardware threshold effects and software thresh<br>The hardware threshold effects and software threshold effects and software threshold effects and software thre roiooicy on I density, velocity distributio 10!<sup>5</sup> *local density, velocity distribution*
- only efficiency to the spectrum was function of the ionization  $-$  particle pl include the electronic noise of the ionization channel via only efficiencies, the spectrum was further smeared to ciencies are applied. After application of these phonon-**10<sup>−</sup><sup>40</sup>** include the electronic noise of the ionization channel via only efficiencies, the spectrum was further smeared to **1000− particle physics model**  $\blacksquare$  include the electronic noise of the ionization channel via  $\blacksquare$ a second convolution  $\mathbf{r}$  and  $\mathbf{r}$  and  $\mathbf{r}$ i<br>م include the electronic noise of the ionization channel via  $\blacksquare$   $\blacksquare$  particle **WIMPP** sectod convolution with the physical second values of  $\mathbb{R}$ **sics** ∎ a second convolution  $-$  particle tween the Q-corrected (third and fourth columns of **1000**<br>Sics **1000− Particle physics model** channel when the hardware threshold efficiency and software threshold efficiency and software threshold efficiency **1000− Particle physics inoder** di<br>d<br><sup>|</sup>e  $-$  particle physics put are a phonon-**10<sup>−</sup><sup>40</sup> −nucleon cross section (cm** a second the particle physics m **10** − particle phys a second convolution with the quadrature difference be-**WIMPLE PAPPIER PHYSICS MOORE − PAPTICLE PHYSICS MOORE − 100<br>mass\_cross\_section\_(de**  $21$  $10^{10}$ - particle physics model
- a second convolution with the quadrature difference be-**MALLET CONVOLUTE: MARK**<br> **DAMA** section (dependence on spin, ve  $t_{\rm max}$  the  $\frac{1}{2}$  corrected (third and fourth columns of  $t_{\rm max}$ **10<sup>−</sup><sup>41</sup> WIMP** a second convolution with the quadrature difference be- $\mathbf{i}$ include the electronic noise of the ionization channel via the ionization channel via the intervals of the ion only efficiency the spectrum was functions function  $\eta$ include the electronic noise of the ionization channel via the ionization channel via the ionization channel v<br>The ionization channel via the ionization channel via the ionization channel via the ionization channel via th tween the  ${\bf mass}, {\bf cr}$ **10**<br> **10<sup>−</sup><sup>41</sup>** only efficiencies, the spectrum was further smeared to  $t_{\rm max}$  the  $\sim$   $t_{\rm max}$  of  $\sim$ Table III) and YNR-corrected recoil-energy resolutions. Table III) and YNR-corrected recoil-energy recoil-energy resolutions.  $\mathbf{r}$ include the electronic noise of the ionization channel via the ionization chan only efficiency and spectrum was functions functions of the spectrum was functions of  $m$  and  $m$  and  $m$ ciencies are applied. After application of these phonononly efficiency the spectrum was function  $\mathbf{u}$ **10<sup>−</sup><sup>40</sup>** −<br>|<br>|<br>|<br>| tween the Q-corrected (third and fourth columns of Table III) and YNR-corrected recoil-energy resolutions. tween the  $_{\rm max}$  third and fourth columns of  $_{\rm max}$ **1056** only efficiencies, the spectrum was further smeared to include the electronic noise of the independence of the ionization channel via  $\mathcal{L}$  $Slin \sigma s$ porting  $\mathcal{L}$ !<br>!<br>} oction (dopondor mass, cross section (dependence on spin, velocity, energy, couplings)
- $t = d\epsilon$ Table III) and YNR-corrected recoil-energy resolutions. Table III – detector i  $t = -$ detector re Table III) and YNR-corrected recoil-energy resolutions. a second convolution with the convolution  $\mathsf{d}\mathsf{etector}$  resp **100**<br> **10** − **4** detector response mo **10** − detector response moderno  $T_{\rm eff}$  threshold-reduced  $T_{\rm eff}$ **2 4 6 8 10 100**  $T = \frac{1}{2}$ and the detector response model **100** − detector response moi a second convolution with the second convolution  $\mathcal{L}$ **WIMPP + detector response reference** a second convolution with the quadrature difference bea 
<del>1</del> detector response model<br>
2 **Anergy resolution** quenching factors channeling fractic The threshold-reduced expected WIMP spectrum, in terms **2 4 6 8 10 100** a second convolution  $\mathsf{d}\text{-}\mathsf{d}\text{-}\mathsf{etector}$  in tween the Q-corrected (third and fourth columns of Micr⊺response letector response model and the control of the con mass, cross section (dependei<br>detector response model –
- The threshold-reduced expected WIMP spectrum, in terms **2 4 6 8 10 100** The threshold-reduced expected WIMP spectrum, in terms **2 4 6 8 10 100 WIMP mass (GeV/c2** of Q-corrected recoil energy as measured by a ZIP detec-**WIMP mass (GeV/c2 )** The threshold-reduced expected WIMP spectrum, in terms **2 4 6 8 10 100** Table III) and YNR-corrected recoil-energy resolutions. tween the  $\mathcal{L}_\text{c}$  tween the  $\mathcal{L}_\text{c}$  and fourth columns of  $\mathcal{L}_\text{c}$  $t_{\rm{max}}$  the  $\alpha$  corrective resolution Table III) and YNR-corrected recoil-energy resolutions. energy resolution, quenching factors, channelin to the remaining by the remaining analysis cut  $\mathbf{C}$  $\overline{a}$  as measured by a  $\overline{a}$  $t_{\rm max}$  was then multiplied by the remaining analysis cutof Q-corrected recoil energy as measured by a ZIP detector, was then multiplied by the remaining and  $\epsilon$ Table III) and YNR-corrected recoil-energy resolutions. tween the  $\epsilon$  correction the  $\epsilon$  columns of  $\epsilon$ Table III) and YNR-corrected recoil-energy resolutions. **10<sup>−</sup><sup>41</sup>** tween the  $\epsilon$  correction the  $\epsilon$  and  $\epsilon$  $\overline{P}$  and  $\overline{P}$  and the Critical Corrected Co **0aei**<br>hing f∢ of Q-corrected recoil energy as measured by a ZIP detector, was then multiplied by the remaining analysis cut  $\mathcal{L} = \mathcal{L} \mathcal{L}$ of  $e$ corrected recoil energy as  $e$ **REPLIEE AIRCRY EVALUATE: THE SERVICE RECORD PROPERTY PROPERTY PROPERTY PROPERTY PROPERTY PROPERTY PROPERTY PRO** 100 1000 tion quanding factore ab response model acceccon response moder<br>energy resolution, quenching factors, channeling fraction





 $\{13,39,70\}$  (99.7% C.L.), and include the effect of ion channeling as  $\{13,49,70\}$ 

detector data, translated to ionization scale and overlapped on histogrammed  $\mathcal{A}$  after normalization to  $\mathcal{A}$  after normalization to  $\mathcal{A}$ 

sensitivity of this run (shaded blue band). The limits from

LIBRA annular modulation signal as interpreted by Savage et al.



10!<sup>39</sup>

CDMS

XENON

"

plored WIMP parameter space, and cuts into the region

where  $\mathcal{S}$  is accessible is accessible in

by the LHC [17]. Moreover, the new result challenges

the interpretation of the DAMA [19] and CoGeNT [18]

We gratefully acknowledge support from NSF, DOE,

SNF, Volkswagen Foundation, FCT, R´egion des Pays de

la Loire, STCSM, DFG, and the Weizmann Institute of

⇤ Electronic address: rafael.lang@astro.columbia.edu

*†* Electronic address: marc.schumann@physik.uzh.ch

K. Nakamura et al. (Particle Data Group), J. Phys. G37,

results as being due to light mass WIMPs.

5 10 50 100

**)**

**2 4 6 8 10 100**

potential signal regions based on data from the DAMA/LIBRA Collar Fields 1204.3559 upper limits from the combined Ge and Si (black/dark solid line,  $\epsilon$  and  $\epsilon$  and  $\epsilon$  is the two (12042FEO) Collar Fields 1204.3559  $\overline{3}$  and  $\overline{3}$  experiments. The two (larger) oval-dependents. The two (larger) oval-dependents. The two (larger) oval- $C$ <sub>behan</sub> and  $C$  interpreted by  $C$  $\boldsymbol{\mathsf{Collar}}$  Fields 1204.3559  $\boldsymbol{\mathsf{olim}}$  $\epsilon$ ules  $\epsilon$ ida, 1204.2550 Condit religion is the Si only of the Single solid lines. **Collar Fields 1204.3559**  $\sum_{i=1}^{n}$  and  $\sum_{i=1}^{n}$  and  $\sum_{i=1}^{n}$  are interpreted by Savage et al. shaped filled regions (pinklight shaded) represents the DAMA (pinklight shaded) represent the DAMA/  $\overline{\phantom{a}}$  and  $\overline{\phantom{a}}$  a taking into a Collar Fields, 1204.3559 Collar Fields 1204.3337 *Collar Fields 1204.3559*

[34] and CoGeNT [35] experiments. The two (larger) oval-

 $\mathcal{S}_{\mathcal{A}}$  and  $\mathcal{S}_{\mathcal{A}}$  and  $\mathcal{S}_{\mathcal{A}}$  experiments. The two (larger) oval-

 $\mathcal{S}_{\mathcal{A}}$  and  $\mathcal{S}_{\mathcal{A}}$  and  $\mathcal{S}_{\mathcal{A}}$  experiments. The two (larger) oval-

potential signal regions based on data from the DAMA/LIBRA

potential signal regions based on data from the DAMA/LIBRA

potential signal regions based on data from the DAMA/LIBRA

LIBRA annular modulation signal as interpreted by Savage et al.

LIBRA annular modulation signal as interpreted by Savage et al.

 $\mathcal{I}_1$  (99.7% C.L.), and include the effect of ion channeling as a channeling as  $\mathcal{I}_2$ 

 $\overline{\phantom{a}}$  (99.7% C.L.), and include the effect of ion channeling as  $\overline{\phantom{a}}$ 

[13] (99.7% C.L.), and include the effect of ion channeling as

shaped filled regions (pink/light shaded) represent the DAMA/

shaped filled regions (pink/light shaded) represent the DAMA/

estimator or are constant. Finally each detector's doubly

Fig. 1 for example). Each detector's ideal spectrum was

lution listed in Table III (first two columns). Recall that the

of steps. The limit was calculated for 75 WIMP masses

each detector and WIMP search (3 and 6 V data) in a series

Fig. 1 for example). Each detector's ideal spectrum was

then convolved with its YNR-corrected recoil-energy reso-

should therefore include noise from only the phonon

each detector and WIMP search (3 and 6 V data) in a series

each detector and WIMP search (3 and 6 V data) in a series

of steps. The limit was calculated for 75 WIMP masses

of steps. The limit was calculated for 75 WIMP masses

erly, expected WIMP rates were separately calculated for

To include the effect of nonzero energy resolution prop-

To include the effect of nonzero energy resolution prop-

To include the effect of nonzero energy resolution prop-

between 1 and 100 GeV=c2. At each mass, the halo model

between 1 and 100 GeV=c2. At each mass, the halo model mass, the halo model mass, the halo model mass, the halo

between 1 and 100 GeV=c2. At each mass, the halo model mass, the halo model

of steps. The limit was calculated for 75 WIMP masses

of steps. The limit was calculated for 75 WIMP masses

between 1 and 100 GeV/c2. At each mass, the halo model mass, the halo model mass, the halo model mass, the halo

predicts the differential WIMP-nucleon scattering rate in

lution listed in Table III (first two columns). Recall that the

between 1 and 100 GeV can be two contracts of the halo model in the halo model

predicts the differential  $\blacksquare$  and  $\blacksquare$  and  $\blacksquare$ 

terms of an ideal, perfect-resolution recoil energy (see

predicted  $\blacksquare$ 

terms of an ideal, perfect-resolution recoil energy (see

between 1 and 100 GeV=c2. At each mass, the halo model

 $\frac{1}{160}$ 

predicts the differential WIMP-nucleon scattering rate in

terms of an ideal, perfect-resolution recoil energy (see

 $\frac{1}{2}$  is an ideal, perfective recoil energy (see Federal, see Federal, see

predicts the differential WIMP-nucleon scattering rate in

terms of an ideal, perfect-resolution recoil energy (see

hardware trigger and software phonon thresholds depend

hardware trigger and software phonon thresholds depend

lution listed in Table III (first two columns). Recall that the

lution listed in Table III (first two columns). Recall that the

terms of an ideal, perfect-resolution recoil energy (see

between 1 and 100 GeV=c<sup>2</sup>. At each mass, the halo model

of steps. The limit was calculated for 75 WIMP masses

terms of an ideal, perfect-resolution recoil energy (see

Fig. 1 for example). Each detector's ideal spectrum was

Fig. 1 for example). Each detector's ideal spectrum was

then convolved with its YNR-corrected recoil-energy reso-

lution listed in Table III (first two columns). Recall that the

then convolved with its YNR-corrected recoil-energy reso-

lution listed in Table III (first two columns). Recall that the

Fig. 1 for example). Each detector's ideal spectrum was

Fig. 1 for example). Each detector's ideal spectrum was

then convolved with its YNR-corrected recoil-energy reso-

lution listed in Table III (first two columns). Recall that the

should therefore include noise from only the phonon

channel when the hardware and software threshold effi-

then convolved with its YNR-corrected recoil-energy reso-

lution listed in Table III (first two columns). Recall that the

should therefore include noise from only the phonon

predicts the differential WIMP-nucleon scattering rate in

terms of an ideal, perfect-resolution recoil energy (see

Fig. 1 for example,  $\frac{1}{2}$  for example). Each detector is ideal spectrum was  $\frac{1}{2}$  for  $\frac{1}{2}$  for  $\frac{1}{2}$ 

solely on the phonon signal. The expected WIMP spectrum

lution listed in Table III (first two columns). Recall that the

Fig. 1 for example). Each detector's ideal spectrum was

predicts the differential WIMP-nucleon scattering rate in

then convolved with its YNR-corrected recoil-energy reso-

terms of an ideal, perfect-resolution recoil energy (see

tor, was then multiplied by the remaining analysis cut

of Q-corrected recoil energy as measured by a ZIP detec-

The threshold-reduced expected WIMP spectrum, in terms

tor, was then multiplied by the remaining analysis cut

efficiencies, which either depend weakly on this energy

scaled by the detector's mass and exposure (listed in

Tables I and IV). The resulting distribution of expected

of Q-corrected recoil energy as measured by a ZIP detec-

The threshold-reduced expected WIMP spectrum, in terms

The threshold-reduced expected  $\mathcal{L}_\text{max}$ 

The threshold-reduced expected  $\mathcal{L}_\text{max}$  spectrum, in terms of terms  $\mathcal{L}_\text{max}$ 

Table III) and YNR-corrected recoil-energy resolutions.

Table III) and YNR-corrected recoil-energy resolutions.

efficiency which either depend weakly on this energy of the second weakly on this energy of the second weakly o

The threshold-reduced expected  $\mathcal{L}_\text{max}$  spectrum, in terms of terms  $\mathcal{L}_\text{max}$ 

efficiency which either depend weakly on this energy of

smeared and efficiency-reduced expected WIMP rate was

The threshold-reduced expected WIMP spectrum, in terms

estimator or are constant. Finally each detector's doubly

smeared and efficiency-reduced expected WIMP rate was

estimator or are constant. Finally each detector's doubly

scaled by the detector's mass and exposure (listed in

scaled by the detector's mass and exposure (listed in

events per Q-corrected keV for each detector was used to

smeared and efficiency-reduced expected WIMP rate was

of Q-corrected recoil energy as measured by a ZIP detec-

efficiencies, which either depend weakly on this energy

tor, was then multiplied by the remaining analysis cut

efficiencies, which either depend weakly on this energy

events per Q-corrected keV for each detector was used to

tor, was then multiplied by the remaining analysis cut

# **Basic ideas**



Friday, June 8, 12

$$
v'
$$
  

$$
m' = m + \delta
$$



 $\textsf{Recoil}$  energy  $E=\frac{1}{2}MV^2$ 



| Differential scattering cross section   | WIMP density  |
|---|---|
| $\frac{dR}{dE} = \frac{1}{m_A} \int \frac{d\sigma}{dE} \frac{\rho_X}{m_X} v \int (v, t) d^3v$ |   |
| Recoil energy   | = $\frac{\rho_X}{2\mu^2 m_X} \int E_{\text{max}} \frac{d\sigma}{dE} \frac{f(v, t)}{v} d^3v$ |
| $E_{\text{max}} = \frac{2\mu^2 v^2}{m_A}$   |   |

$$
\begin{pmatrix} \text{number of} \\ \text{events} \end{pmatrix} = (\text{exposure}) \times \begin{pmatrix} \text{detector} \\ \text{response} \end{pmatrix} \otimes \begin{pmatrix} \text{recoil} \\ \text{rate} \end{pmatrix}
$$



$$
\begin{pmatrix}\n\text{number of} \\
\text{events}\n\end{pmatrix} = (\text{exposure}) \times \begin{pmatrix}\n\text{detector} \\
\text{response}\n\end{pmatrix} \otimes \begin{pmatrix}\n\text{recoil} \\
\text{response}\n\end{pmatrix}
$$
\n
$$
\begin{pmatrix}\n\text{detector} \\
\text{response}\n\end{pmatrix} = \begin{pmatrix}\n\text{energy} \\
\text{response function}\n\end{pmatrix} \times \begin{pmatrix}\n\text{counting} \\
\text{acceptance}\n\end{pmatrix}
$$
\n
$$
\begin{pmatrix}\n\text{recoil} \\
\text{rate}\n\end{pmatrix} = \begin{pmatrix}\n\text{particle} \\
\text{physics}\n\end{pmatrix} \times (\text{astrophysics})
$$

Friday, June 8, 12

$$
\begin{pmatrix}\n\text{number of} \\
\text{events}\n\end{pmatrix} = (\text{exposure}) \times \begin{pmatrix}\n\text{detector} \\
\text{response}\n\end{pmatrix} \otimes \begin{pmatrix}\n\text{recoil} \\
\text{rate}\n\end{pmatrix}
$$
\n
$$
\begin{pmatrix}\n\text{detector} \\
\text{response}\n\end{pmatrix} = \begin{pmatrix}\n\text{energy} \\
\text{response function}\n\end{pmatrix} \times \begin{pmatrix}\n\text{counting} \\
\text{acceptance}\n\end{pmatrix}
$$
\n
$$
\begin{pmatrix}\n\text{recoil} \\
\text{rate}\n\end{pmatrix} = \begin{pmatrix}\n\text{particle} \\
\text{physics}\n\end{pmatrix} \times (\text{astrophysics})
$$

Friday, June 8, 12

## *From measured energy to recoil energy*

$$
\begin{pmatrix}\n\text{energy} \\
\text{response function}\n\end{pmatrix} = g(E_{\text{ee}}, E) \\
\begin{array}{c}\n\text{Recoil energy (keV)} \\
\text{Energy observed in detector, typically} \\
\text{expressed in keV electron equivalent (keV_{\text{ee}})\n\end{array}
$$

Typically written as a single Gaussian with mean value

$$
E_{\rm ee} = \boxed{QE}
$$
 *Quenching factor*

and standard deviation  $\sigma_E$ , but *may be different*.



Channeling. If an ion incident onto the crystal moves in the direction of a symmetry axis or plane of the crystal, it has a series of small-angle scatterings which maintains it in the open channel. The ion penetrates much further into the crystal than in other directions.



*From Gemmel 1974, Rev. Mod. Phys. 46, 129*

Blocking. If an ion originating at a crystal lattice site moves in the direction of a symmetry axis or plane of the crystal, there is a reduction in the flux of the ion when it exit the crystal, creating a "blocking dip".



*From Gemmel 1974, Rev. Mod. Phys. 46, 129*

Channeling in DAMA's NaI(Tl) is much less than previously published

Bozorgnia, Gelmini, Gondolo 2010







*Bernabei et al. 2008 Bozorgnia, Gelmini, Gondolo 2010*



 $T_{\text{S}}$ measurements of the **interest in Ref.**  $\alpha$ uenching fortor  $\Omega$  $\mathbf{b}$ in germanium Compilation of quenching factor *Q*

We conclude that our choices in these three aspects

*Lin et al (TEXONO) 2007*
### **Detector response model**



circles) and Simon et al. [20] (open diamond) are shown. Additionally, the preliminary theoretical estimation

of the quenching factor from Hitachi [25] is represented by the solid black line.

Lindhard theory is closest to giving an accurate prediction for these media.

Compilation of measurements of the quenching factor *Q* in NaI(Tl)

**Figure 13.13. Chagani et al 0806.1916** 

by Lindhard theory and calculated by SRIM differences and calculated by 15% at most, although bigger discrepancies are present for the electronic stopping power. When compared with experimental data, the original This is where one can tweak to make DAMA and CoGeNT compatible.

#### $\overline{\phantom{a}}$ maps inferred from data using the 662 keVee line and the 662 keVee line and the 662 keVee line and the 662 keVe Detector response model

**Compilation of measurements**  $F_{\infty} = S1 / L_{\infty} (122k)$ of the light efficiency factor  $L_{\text{eff}}$   $\overline{O} = I_{\text{eff}}(S)/S$ in liquid xenon yield *Ly*(122 keVee) = (2*.*20 *±* 0*.*09) PE*/*keVee at the ap-

$$
E_{\rm ee} = S1/L_y (122 \text{keV}_{\rm ee})
$$
  

$$
Q = L_{\rm eff}(S_{\rm nr}/S_{\rm ee})
$$



bring calibration sources (<sup>60</sup>Co, <sup>137</sup>Cs, <sup>241</sup>AmBe) close

to the target, a copper tube penetrates the shield and

winds around the cryostate  $\mathbb{R}$ 

S1 and S2 signals are registered by photomultiplier tubes <u>ingigatol tespolise t</u> It increased from 230 *µ*s to 380 *µ*s for the data reported Detector response model

 $\bm{Q}$ uenching factor  $E_{\rm ee} = \boxed{Q}E$ interaction vertex is reconstructed in 3 dimensions, with the *Quenching factor* determined the state localized S2 signal on the top PMT array, and the *z*-

tion (S2) in the gaseous xenon above the liquid. Both

$$
E_{\rm ee} = \overline{Q}E
$$

This is where one can tweak to  $\sum_{n=1}^{\infty}$ LXe. Due to their di↵erent ionization densities, ERs (, make experiments compatible.



 $\Gamma$ in at al (TEXONO) 2007 Lin et al (TEXONO) 2007  $t_{\text{in}}$  at al (TEXONO) 2007 excellent stability over time (fluctuations *<*0.05%). To

### **Corrected using a manufacture with the 662 keVen line and 2010**





Gaussian distribution to obtain the mean (solid line) and the

the statistical uncertainties of the background spectra.

We conclude that the three aspects in the three aspects in the set of the set o of the experiment are justified. The sensitivities of the *Aprile et al (XENON100), 1104.2549* FIG. 1: All direct measurements of *L*e↵ [12, 13] described by a

would increase (become less constraining) from 0.81 to Friday, June 8, 12 and 12

### **The expected number of events**

$$
\begin{pmatrix} \text{number of} \\ \text{events} \end{pmatrix} = (\text{exposure}) \times \begin{pmatrix} \text{detector} \\ \text{response} \end{pmatrix} \otimes \begin{pmatrix} \text{recoil} \\ \text{rate} \end{pmatrix}
$$



### **Astrophysics model**

### *How much dark matter comes to Earth?*

$$
\boxed{\text{Local halo density} \brack \text{(astrophysics)} = \rho \int_{v > v_{\min}(E)} \frac{f(\vec{v}, t)}{v} d^3v
$$

 ${\sf Minimum}$  speed to impart energy  $E, \; v_{\rm min}(E)=(ME/\mu+\delta)/2$  $\overline{\phantom{a}}$ 2*ME*

### **Astrophysics model: local density**

### Galactic density profile from Aquarius simulations



#### **Astrophysics model: local density**  $\overline{\phantom{a}}$ is as tho physics inc increase in the bulge central density to produce the same two lines for each setup encompass the upper limits set using ethe baryonic models 1–5. In particular, the mean shadowed and mean shadowed and mean shadowed and mean shadow area as well as the shadowed rectangle are the same as in the We present a novel study on the problem of constructing mass models for the Milko Maria Roman (Component matter in features regarding the dark matter  $\boldsymbol{\mu}$





contours show the parameter space producing a good fit to the rotation curve (<sup>2</sup> = 2*.*30*,* 6*.*18) with the best-fit configuration

the contours, model 5 manages to explain both the mi-*Ullio, Catena 2009*



We have also tested the adiabatic contraction model

given the available microlensing and dynamical data and

of the DM profile; the smaller *r<sup>s</sup>* the larger the DM con-

The velocity factor  $\eta(E,t) = 1$  $v{>}v_{\min}(E)$  $f(\vec{v}, t)$  $\overline{v}$  $\text{d}^3v$ **Astrophysics model: velocity distribution**

- If  $f(E,t)$  is non-truncated Maxwellian in detector frame,  $\eta(E,t)$  is exponential in  $E$
- $\bullet$   $\eta(E, t)$  depends on time (unless WIMPs move with detector)

 $\eta(E, t) = \eta_0(E) +$  $\eta_{\rm m}(E) \cos \omega (t-t_0)$ Example: annual modulation



*Drukier, Freese, Spergel 1986*

### ${\sf Astrophysics\ model: velocity\ distribution}$



### **Astrophysics model: velocity distribution**

Inclusion of baryonic disk may lead to a dark disk



*Read, Lake, Agertz, De Battista 2008*

# **Astrophysics model: velocity distribution**



*strong and mild dark disc halo models.*



*Ling 2009* Figure 1. *(Left column) Normalized velocity distributions for di*↵*erent dark matter halos, in the galactic frame (top) and with respect to the Sun (bottom).* Black dotted *: standard Maxwellian halo,* Blue thin dashed *: slowly rotating Tsallis halo,* Red

### **Astrophysics model: velocity distribution**





### **Astrophysics model** *4.*

*2.* H<sup>r</sup> *H*  $\cdot$ The local density may be "known" within a factor of 2, but the velocity distribution is still an open question

#### *0 100 200 300 400 500* Analytic models





### **Astrophysics-independent approach**



10<sup>24</sup>

Fox, Kopp, Lisanti, Weiner 2011 **and Comparison of Container and 2011** 

**The correct is extremely in the grade to the quantity is extremely the data of**  $\mathcal{I}(I|I)$  **is extremely a rescaling to the data of**  $I$ terms of what *vmin*-space is probed, and shows (for a given mass) whether tensions exist.

by form factor as in (8). Thus, unlike *m* plots, which have a tremendous amount of

10<sup>28</sup>

10<sup>24</sup>

10<sup>27</sup>

10<sup>26</sup>

10<sup>25</sup>

10<sup>24</sup>

counts

êday

êkg

/keVee

### **Astrophysics-independent approach**



Still depends on particle model

*Analysis extends Fox, Liu, Weiner method to include energy response function*

*Gondolo Gelmini 1202.6359*

### **The expected number of events**

$$
\begin{pmatrix}\n\text{number of} \\
\text{events}\n\end{pmatrix} = (\text{exposure}) \times \begin{pmatrix}\n\text{detector} \\
\text{response}\n\end{pmatrix} \otimes \begin{pmatrix}\n\text{recoil} \\
\text{rate}\n\end{pmatrix}
$$
\n
$$
\begin{pmatrix}\n\text{detector} \\
\text{response} \\
\text{rate}\n\end{pmatrix} = \begin{pmatrix}\n\text{pergy} \\
\text{patives}\n\end{pmatrix} \times (\text{astrophysics})
$$

### *What force couples dark matter to nuclei?*

$$
\binom{\text{particle}}{\text{physics}} = \frac{\sigma_{SI}(E) + \sigma_{SD}(E)}{2m\mu^2}
$$
\n
$$
\begin{pmatrix} \text{particle} \\ \text{physics} \end{pmatrix}
$$
\n
$$
= \frac{\sigma_{SI}(E) + \sigma_{SD}(E)}{2m\mu^2}
$$
\n
$$
\text{Reduced mass } \mu = mM/(m+M)
$$

$$
\sigma(E) = E_{\text{max}} \frac{d\sigma}{dE} = \frac{2\mu^2 v^2}{m} \frac{d\sigma}{dE}
$$

Exchange scalar, vector, pseudovector, ..... ?

- Supersymmetry
- Extra U(1) bosons
- Extended Higgs sector
- Effective operator approach

Scalar and vector currents give spin-independent terms



Example: neutralino

$$
2f_p \simeq 2f_n \simeq \sum_q \langle \bar{q}q \rangle \left[ -\sum_h \frac{g_{h\chi\chi}g_{hqq}}{m_h^2} + \sum_{\tilde{q}} \frac{g_{L\tilde{q}\chi q}g_{R\tilde{q}\chi q}}{m_{\tilde{q}}^2} \right]
$$

Main uncertainty is  $\langle m_s \bar{s}s \rangle$  (strange content of nucleon)

### Axial and tensor currents give spin-dependent terms

$$
\sigma_{SD}(E) = \frac{32\mu^2 G_F^2}{2J+1} \underbrace{\left[a_p^2 S_{pp}(q) + a_p a_n S_{pn}(q) + a_n^2 S_{nn}(q)\right]}_{\text{P}}\n \underbrace{\left[\text{Effective four-}\right]{\text{Effective four-}}_{\text{particle vertices}}\n \underbrace{\left[\text{Exercise 1)}_{\text{E}}\right]{\text{Nuclear spin}}_{\text{E}}\n \underbrace{\left[\text{Surface vertices}\right]}_{\text{E}}\n \underbrace{\left[\text{Surface vertices}\right]}_{\text{E}}\n \underbrace{\left[\text{Surface functions}\right]}_{\text{E}}\n \underbrace{\left[\text{Surface functions}\right]}_{\text{E}}\n \right]
$$

Example: neutralino

$$
2\sqrt{2}G_F a_p = \sum_q \Delta q \left[ \frac{g_{Z\chi\chi}g_{Zqq}}{m_Z^2} + \sum_{\tilde{q}} \frac{g_{L\tilde{q}\chi q}^2 + g_{R\tilde{q}\chi q}^2}{m_{\tilde{q}}^2} \right]
$$

Main uncertainty is nuclear spin structure functions  $S(q)$ 

# **What particle model for light WIMPs?**

### **What particle model for light WIMPs?**

- It should have the cosmic cold dark matter density
- It should be stable or very long-lived  $(z10^{24} \text{ yr})$
- It should account for the CoGeNT and DAMA modulations
- It should be compatible with collider, astrophysics, etc. bounds
- Ideally, it would justify apparent incompatibilities between direct detection experiments
- Ideally, it would explain some excessive emissions possibly observed in Galactic gamma-ray and radio maps

## **A few particle models for light WIMPs\***



**\*** 1-10 GeV WIMP; very incomplete references.

# **Phenomenological approach**

### **Break the annihilation/scattering relation**



*For example, for a ~4 GeV/c2 dark matter neutrino, the scattering cross section is*

$$
\sigma_{\nu n} \simeq 0.01 \frac{\langle \sigma v \rangle}{c} \simeq 10^{-38} \,\text{cm}^2
$$

#### limited, particularly near threshold where our low-mass **BIGGIN SEN** annihilation/ecattoring <u>Communication de la termine</u> Deach the any l <mark>digan liig ahi</mark> ailatian legasttaring ralat <u>inauvilistalenių feid</u> semble. This is a trade-off we decided to accept before **Eigek ine ann** limited, particularly near threshold where our low-mass combined Ge and Si limit cuts through the middle of th <u>Ilation/scattering relati</u> et al. 's conservation fit to the DAMA rather than the total exposure for the entire detector en-<u>is presk uie anni</u> channeling as models as models as models as models as  $\mathbf{S}$ composition de Germanie de Germanie et the middle of t 99% confidence level signal region associated with Hooper **Rrask the snnihi** semble. This is a trade-off we determine channeling as modeling as modeling as modeling as in the second by Box 10, 21 July 2014. In 1979, 2014, 2015, combined and Siens through calculating the limits. Each detector is clearly background l Break the an WIMP sensitivity of cleaners and containing exposure for cleaning exposure for cleaning exposure for cleaning  $\sim$ 99% confidence level signal region associated with Hooper ihilation/scattering rela Contact of the data, and the space for **Lexal the articular DIGRUIG CL** ihilatian/ecattaring rale <u>Littauvillsvalletiity tele</u> limited, particularly near threshold where our low-mass **PIGAK liig al**  $\frac{1}{2}$  simultaneous fit to the DAMA  $\frac{1}{2}$ <u>INIISUON/SCAUCHIIO ICI</u> Wimp masses between 3 and 4 GeV=c2. Our limits are also between 3 and 4 GeV=c2. Our limits are also between 3 and 4 GeV=c2. Our limits are also between 3 and 4 GeV=c2. Our limits are also between 3 and 4 GeV=c2. Our limits limited, particularly near threshold where our low-mass **Break the art** energy intervals should yield stronger limits for low et al.'s [36] simultaneous fit to the DAMA/LIBRA and Linilation/scattering re wimped by the cases in the 10 **Prack the entire** <u>is die Schriff werden der Englished verschieden der Englished und der Englished to accept werden der Englished</u> chandelas de by Bozorga by Bozorga by Bozorga et al. [31] auon/scau<del>c</del>hily Telauo The resulting limit reflects only a fraction of the exposure, **Rreak the annihi** semble. This is a trade-off we decided to accept before experiments. The former includes the (small) effect of ion tion/scattering relation composition in the middle of The resulting limit reflects only a fraction of the exposure, rather than the total exposure for the total exposure for the entire  $\mathbf{r}_i$ experiments. The former includes the forme <u>i on Sealic alno refail or</u> combined Si limit cuts through the middle of the middle Dread the annihile rather than the total theorem experiments. The former includes the former includes the contract of including the contract of including the c change as models as in the set al. [31]. The set al. [31] WIMP sensitivity resides. Trading exposure for cleaner **energy** in masses. In this term of CoGeNT data, and excludes new parameter space for **Annihilation/scattering relation** , annimation, soattering reidi limited, particularly near threshold where our low-mass **Prook**th energy in the stronger line annihilation/coottoring rolati <u>anninistion/scauering reiau</u> rather than the total exposure for the entire detector enis preak the a channeling as in a set al. [31]. The s <u>ninilation/scattering relation</u> 99% confidence level signal region associated with Hooper **Break the annihilation/scattering relation**



 $r$  riday, built or  $r \geq$ Friday, June 8, 12  $\mathcal{C}$  ficially, ballo either depend weakly on the sense of the sense of  $\mathcal{C}$  $\sum$  in day, built by the detector in  $\sum$ efficiencies, which either depend weakly on this energy of the depend weakly on this energy of the depend weakly on smeared and expected and expected the Friday, June 8, 12 satisfy the detector of  $\mathcal{L}$ Friday, June 8, 12 Friday, June 8, 12

semble. This is a trade-off we decided to accept before

The resulting limit reflects only a fraction of the exposure,

limited, particularly near threshold where our low-mass

rather than the total exposure for the entire detector en-

semble. This is a trade-off we decided to accept before

calculating the limits. Each detector is clearly background

semble. This is a trade-off we decided to accept before

 $T$  resulting limit reflects only a fraction of the exposure,  $\sigma$ 

limit from the best individual-detector energy intervals.

limit from the best individual-detector energy intervals.

limit from the best individual-detector energy intervals.

### **Break the annihilation/scattering relation**



**Resonant when**  $m_v \approx m_Z/2$ 

$$
\sigma_{\nu n} \simeq \frac{0.02}{1 + m_n/m_{\nu}} \left( 1 - \frac{4m_{\nu}^2}{m_Z^2} \right)^2 \frac{\langle \sigma v \rangle}{c}
$$

*σ*<sub>*νn*</sub> would perhaps match DAMA/CoGeNT if  $m_Z$  were  $\approx 2m_V$ *Try a new particle χ and a new vector boson Z'*

### **Break the annihilation/scattering relation**

↵



### Example: Leptophobic Z'

- An extra U(1) gauge boson Z' coupled to quarks but no leptons, with no significant kinetic mixing
- Works for  $m_Z \sim 10{\text -}20$  GeV and  $\alpha'$  –  $10^{-5}$

*Gondolo, Ko, Omura 2011*

 $\blacksquare$ 



<sup>0</sup> that can explain the DAMA/CoGeNT region with a light

### **Modify the scattering cross section**



Traditionally,  $E_{\text{max}}$   $d\sigma/dE$  = const  $\times$  (nuclear form factor), with the same coupling to protons and neutrons (spin-independent case)

Put additional velocity or energy dependence in *E*max *dσ*/*dE* Set different couplings to neutrons and protons ("isospin-violating")

### **Modify the scattering cross section**

Energy and/or velocity dependent scattering cross sections



*All terms may be multiplied by nuclear or DM form factors F*(*E*)

*See e.g. Barger, Keung, Marfatia 2010; Fornengo, Panci, Regis 2011; An et al 2011*

### **Modify the scattering cross section**

### Example: a 1 GeV mediator can bring CoGeNT, DAMA, and CRESST together



FIG. 7: The same as in Fig. 4, except that the interaction *Fornengo, Panci, Regis 2011*

#### only one element, or that the recoil spectrum allows one <u>to distinguish on distinguish on the dominant scatter as the dominant scatter and sea</u> **Isospin-violating dark matter**  $\mathbf{\Omega}$ σ

clude the possibility of multiple isotopes. The event rate is multiple is much rate in the event rate is not result of the eve Spin-independent couplings to protons stronger the neutrons stronger than the security **boves in the fractional designals compared in the fraction of the set of the set of the set of the set of the s** IVD and current data. It will be compared allow modulation signals compatible with the null searches

Kurylov, Kamionkowksi 2003; Giuliani 2005; Cotta et al 2010; Kang et al 2010; Kang et al 2010; Kang et al 2010 2010; Feng et al 2011; Del Nobile et al 2011; .....



*fn/f<sup>p</sup>* = 1 and (bottom) IVDM with *fn/f<sup>p</sup>* = 0*.*7.



### **Isospin-violating dark matter**

Spin-independent couplings to protons stronger than to neutrons allow modulation signals compatible with other null searches

Kurylov, Kamionkowksi 2003; Giuliani 2005; Cotta et al 2009; Chang et al 2010; Kang et al 2010; Feng et al 2011; Del Nobile et al 2011; .....

**Why**  $f_n/f_p = -0.7$ suppresses the coupling to Xe



### **Isospin-violating dark matter**

Spin-independent couplings to protons stronger than to neutrons allow modulation signals compatible with other null searches



*Gondolo Gelmini 1202.6359*

### **Isospin-violating dark matter**

Spin-independent couplings to protons stronger than to neutrons allow modulation signals compatible with other null searches

Kurylov, Kamionkowksi 2003; Giuliani 2005; Cotta et al 2009; Chang et al 2010; Kang et al 2010; Feng et al 2011; Del Nobile et al 2011; .....

Models with  $f_n/\bar{f_p}$  =-0.7 are possible through e.g. interference of two Higgs boson mediators, but require a new physics scale of 1-20 GeV............ *Del Nobile et al 2011*

Compositeness? Mirror baryons?

# **Light neutralinos**
# **Light neutralinos**

### *Bottino, Donato, Fornengo, Scopel 2003-2011 Non-GUT MSSM*

*~10 GeV neutralinos may account for DAMA, CoGeNT, and CRESST*

*Fornengo at TAUP 2011*

*Belli et al 1106.4667*



# **Light neutralinos**

### *Bottino, Donato, Fornengo, Scopel 2003-2011 Non-GUT MSSM*

 $\sim$  10 GeV neutralinos may account for DAMA, Co<sup>c</sup>NT, and CRESST

*negative LHC Higgs searches impose m<sup>χ</sup> >*18 GeV

*Fornengo at TAUP 2011*

*Bottino et al 1112.5666*

 $\sim$  290 MeV. The (red) crosses denote configurations with  $\sim$ 

 $\overline{\phantom{a}}$ 



# Light neutralinos

*Arbey, Battaglia, Mahmoudi 1205.2557 pMSSM* decay with **to OF** ¯˜*b*<sup>1</sup> for di↵erent values of the lightest sbottom amno

(class iii).



Fig. 9. Spin independent -p scattering cross-section as a function  $\mathbf{r}_i$ Light neutralinos seem possible in the pMSSM with 19 free parameters red squares correspond to a slepton NLSP with a mass slightly

The calculation of the relic density and the dark matter

# **Minimalist dark matter**

Friday, June 8, 12

### **Minimalist dark matter** spread from ∠15 meV and from ∠15 to 90 meV and from ∡15 to 90 meV and reasonably take a broad latter, phenomenological analyses yield 36 MeV ≤ 71 MeV ≤ 71 MeV ≤ 71 MeV calculations yield 36 MeV ≤ 71 MeV ≤<br>Discographics yield 36 MeV calculations yield 36 MeV ≤ 71 MeV ≤ 7

do not confuse with minimal dark matter **Senate for the aid of the relevant formulas in Refs. The relevant formula**  $\frac{1}{3}$  and  $\frac{1}{3}$  into  $\frac{1}{3}$  and  $\frac{1}{3}$  and  $\frac{1}{3}$  and  $\frac{1}{3}$  and  $\frac{1}{3}$ 

**Gauge singlet scalar field S, stabilized by Z<sub>2</sub> symmetry** 

its dependence on the pion-nucleon sigma term on the pion-nucleon sigma term on the pion-nucleon sigma term on

 $\mathcal{L}_S =$ 1 2  $\partial^{\mu}S\partial_{\mu}S-\frac{1}{2}$ 2  $\mu_S^2 S^2 - \frac{\lambda_S}{4}$  $\frac{\Delta S}{4} S^4 - \lambda_L H^\dagger H S^2$ masses as in Fig. 1(a). It also shows curves representing the representing the results of the latest direct-se  $f_{\alpha} = \frac{1}{2} \partial^{\mu} S \partial S = \frac{1}{2} \mu^2 S^2 = \frac{\Delta S}{S} S^4 = \lambda_{L} H^{\dagger} H S^2$  $2^{\sim 2^{\mu}}$  and  $2^{\mu}$  in  $2^{\mu}$ . Neverthe-order of matrix  $4^{\circ}$ 

*Silveira, Zee 1985*



Friday, June 8, 12 and 99.9% C.L. at 90 and 99.9% C.L. in which we have assumed that the excess at low recoil energies is entirely due to DM (assuming a constant background contamination). The DAMA regions (goodness-of-fit, m<sup>h</sup> = 115, 150, 200, 450 GeV. (b) The corresponding darkon-nucleon cross-section σel, compared to ex-

#### **Minimalist dark matter** it dependence on the pion-nucleon signal term on the pion-nucleon signal of the pion-

**do not confuse with minimal dark matter** 

### **Constraints from the LHC: none**



ratios assumed in LHC analyses.<sup>1</sup>

knowing the Higgs-nucleon coupling gNNH besides the darkon-Higgs coupling  $\mathcal{A}$ 

### **Minimalist dark matter**

*do not confuse with minimal dark matter*

#### Constraints from diffuse Galactic gamma-rays *n ints from diffu*





denote the exclusion limits from the Fermi-LAT di↵use gamma-rays flux at 95% C.L.. On the right, we give, for the sake of

The continuous region corresponds to the standard assumption of a QCD phase transition at *T<sup>c</sup>* = 150 MeV. The black dashed

allowed *<sup>&</sup>lt; v >ann* = 3*.*<sup>2</sup> *·* <sup>10</sup><sup>26</sup>cm<sup>3</sup><sup>s</sup> Friday, June 8, 12 $12$ 

# **A few models of light dark matter\***



**\*** 1-10 GeV WIMP; very incomplete references.

### *Flores, Olive, Checker So many theoretical models!* **Analysis of**  $\mathcal{S}$  **of many theoretical models!**

sneutrino *.....; An, Dev, Cai, Mohapatra 1110.1366; Cerdeno, Huh, Peiro, Seto 1108.0978; .....*  $\frac{1}{1 + h}$  $C^{\prime}$  rey a *Stion:*  $\overline{P}$ *Pospelov, ter Veldhuis 2000; Davoudiasl, Kitano, Li, Murayama 2004;*  My suggestion: pay theorists more, so they do not need to work so much. kinetically-mixed U(1)' *.....; Foot 2003-10; Kaplan et al 1105.2073; An, Gao 1108.3943;*