Phenomenology of Direct WIMP Detection

An overview, not a review

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

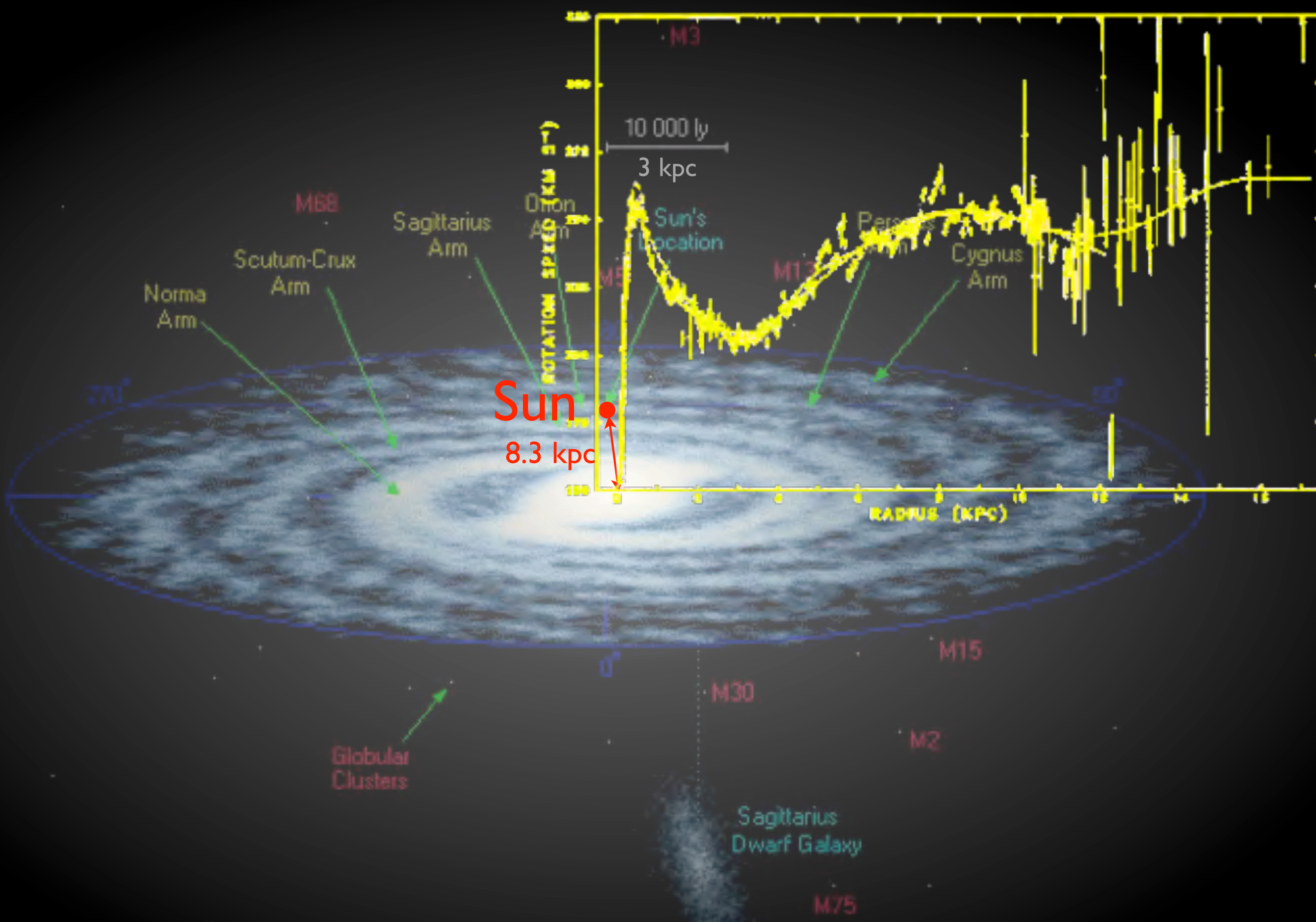
  Example: active neutrinos are neutral but are hot dark matter.

- 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)



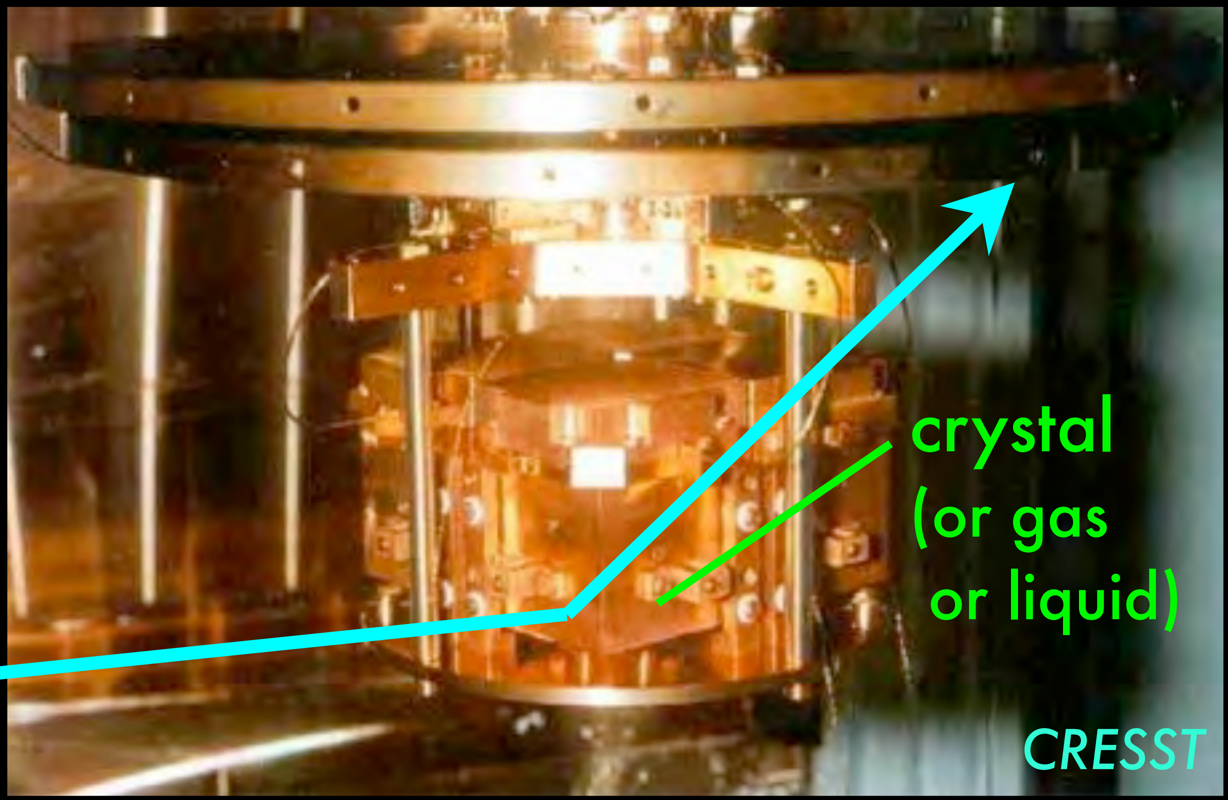
Our galaxy is inside a halo of dark matter particles

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



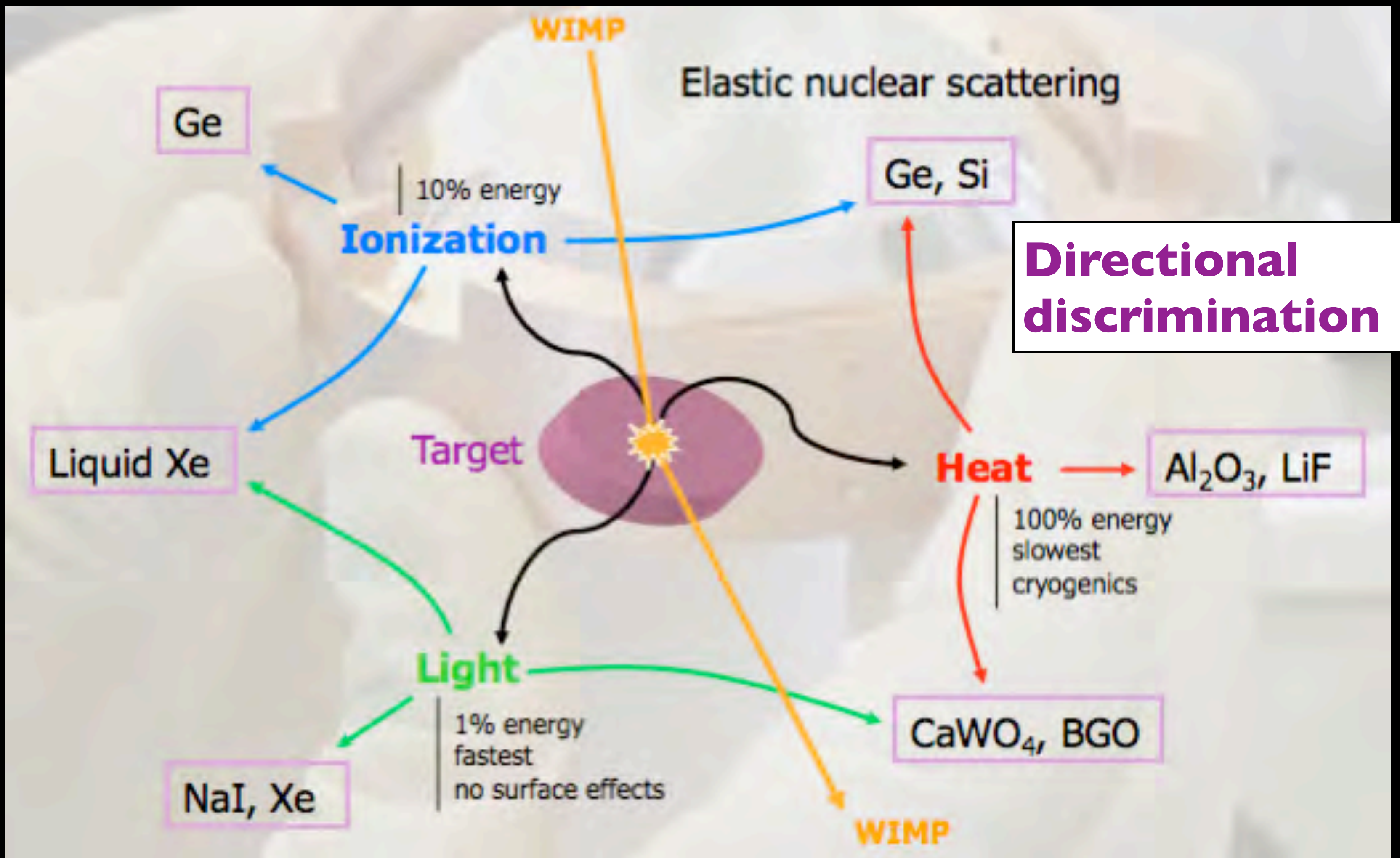
Low-background underground detector

CDMS
EDELWEISS
DAMA
CRESST
KIMS
DRIFT
XENON
COUPP
CoGeNT
TARP
DMTPC
TEXONO
.....

Recent and near-future detectors

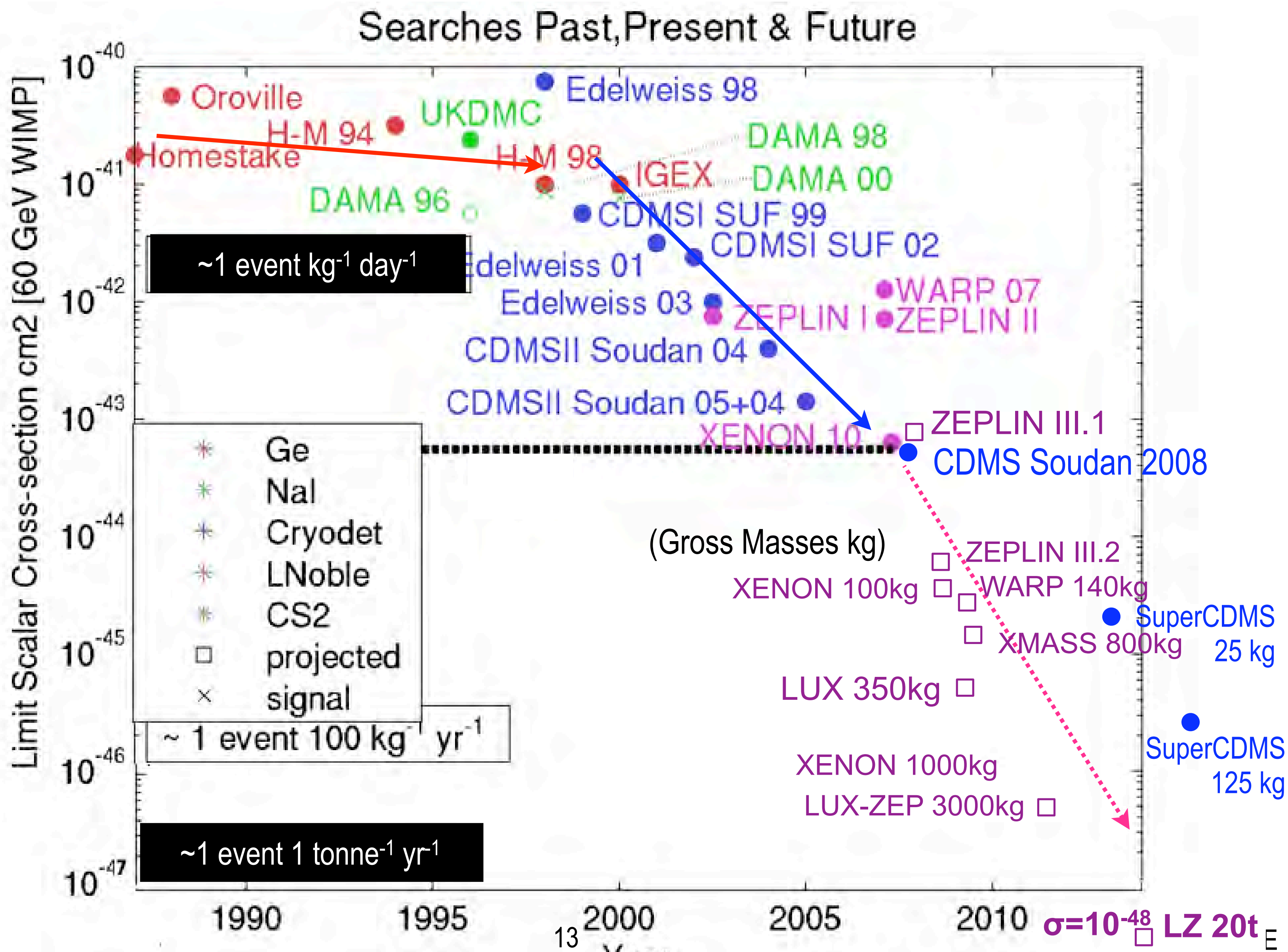
Background discrimination

Finding the dark matter particles is a fight against background

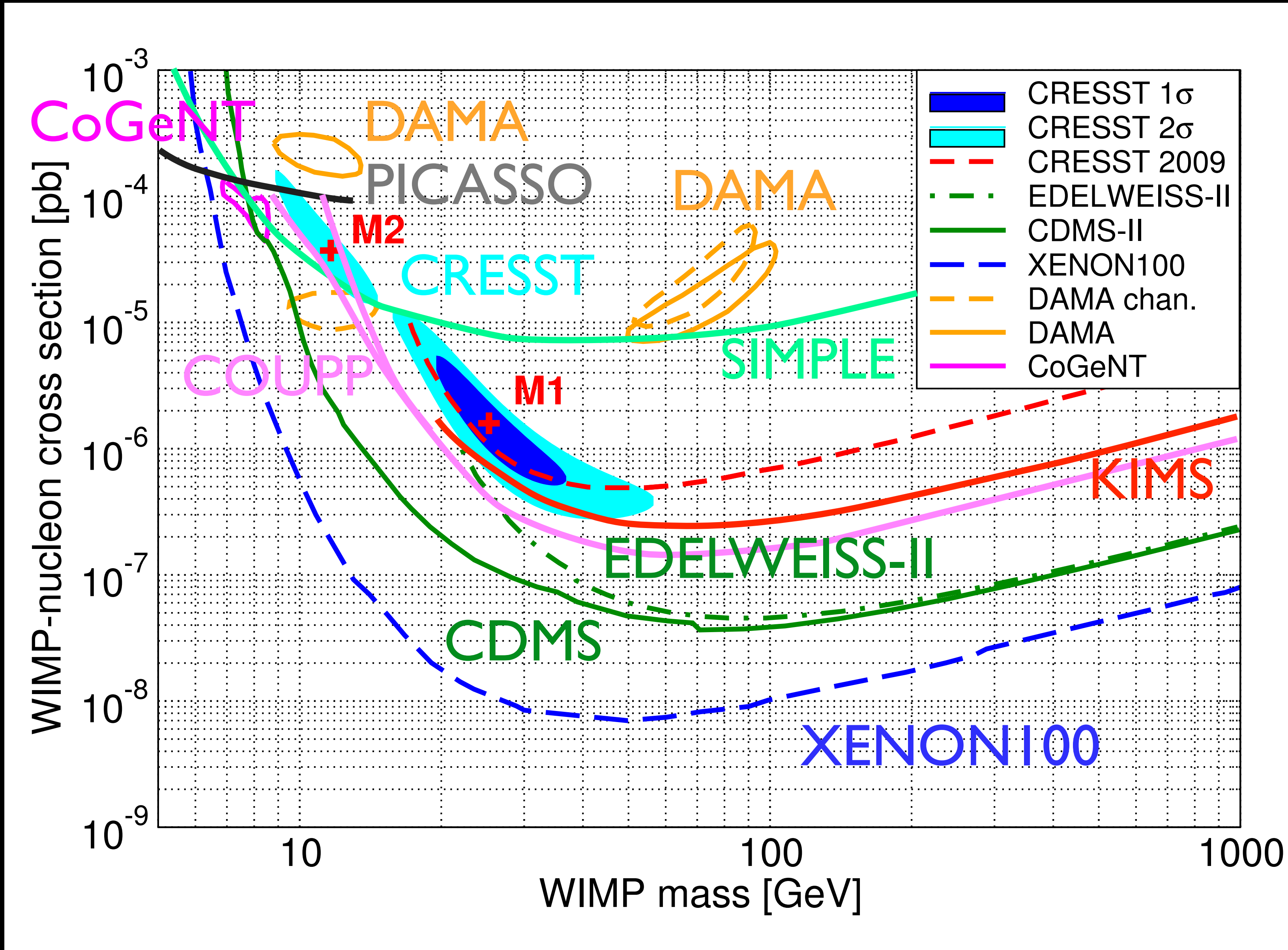


From Sanglard 2005

DM Direct Search Progress Over Time (2009)



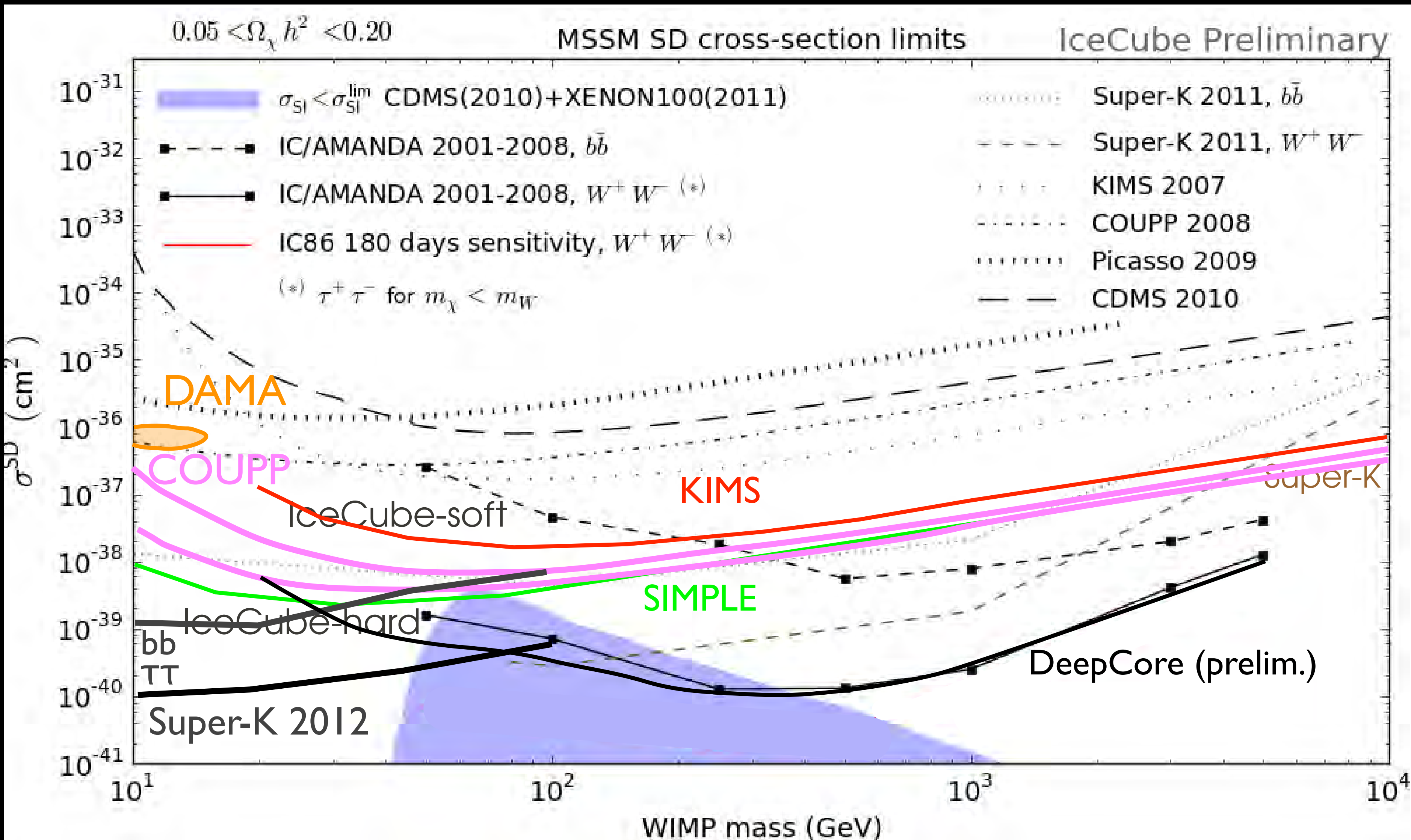
Spin-independent (June 2012)



$1 pb = 10^{-36} cm^2$

Updated from Anglehor et al 2011

Spin-dependent (June 2012)



Adapted from Danninger at TAUP 2011, Rott at Neutrino 2012

1pb = 10^{-36} cm^2

Coming up......

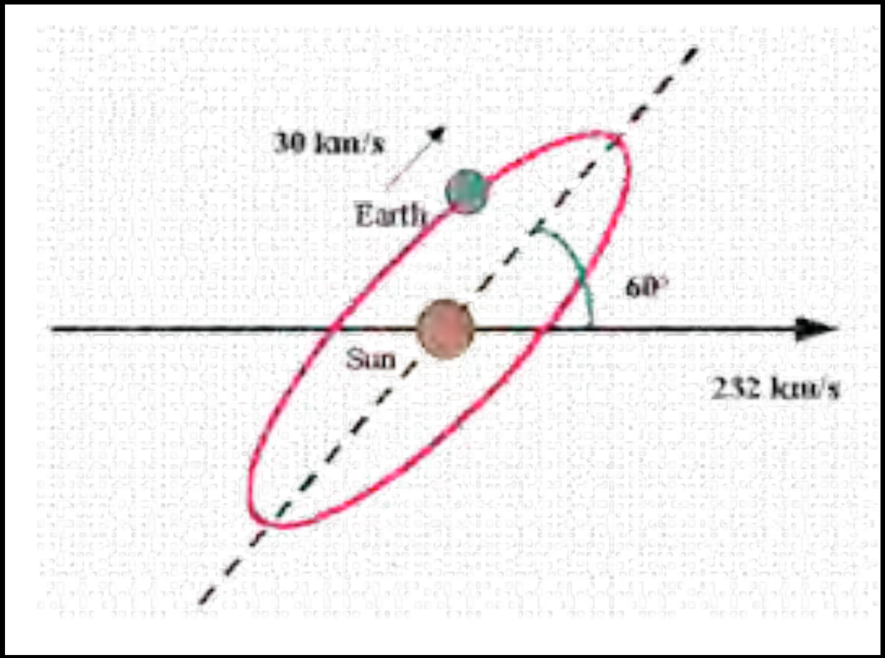
- XMASS (800 kg LXe, Kamioka, 2011-)
- TEXONO/CDEX (1 kg Ge, Jinping, 2011-)
- SuperCDMS (25kg Ge, Soudan, 2012-)
- LUX (350 kg LXe, Homestake, 2012-)
- DarkSide (50 kg LAr, Gran Sasso, 2012-)
- COUPP (60 kg CF_3I, SNOLab, 2012-)
- XENON-1T (1 ton LXe, Gran Sasso, 2014-)
- DM-ICE, EURECA, DARWIN, PICO-LON and many many others

The annual modulation

Drukier, Freese, Spergel 1986

Annual modulation in WIMP flux and detection rate

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

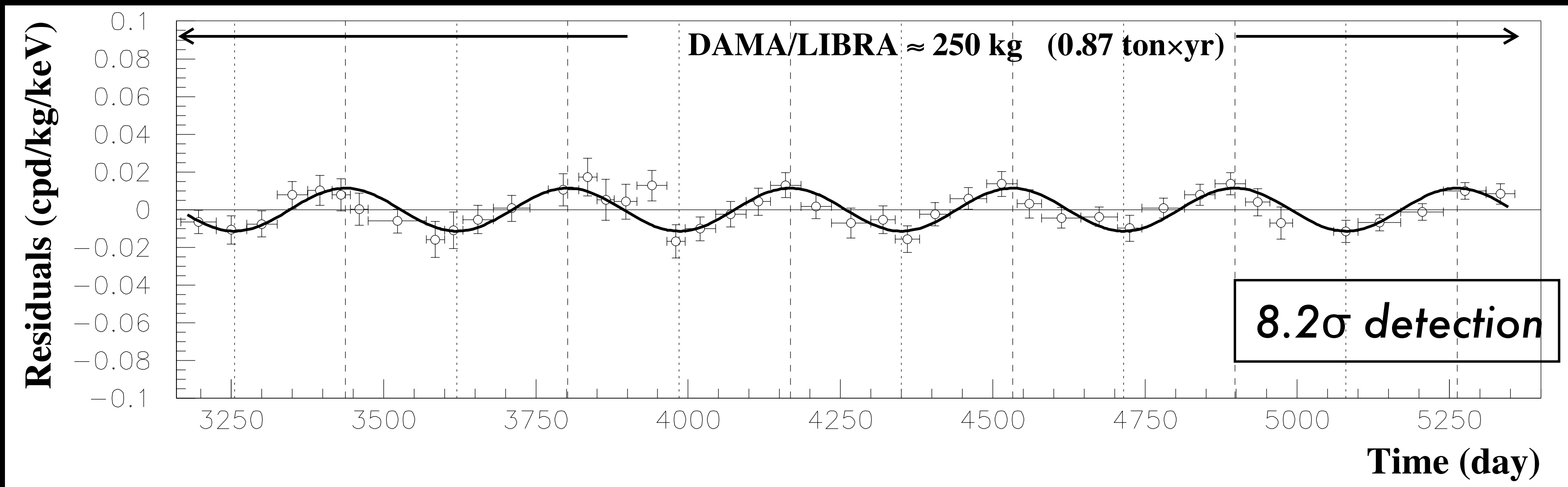


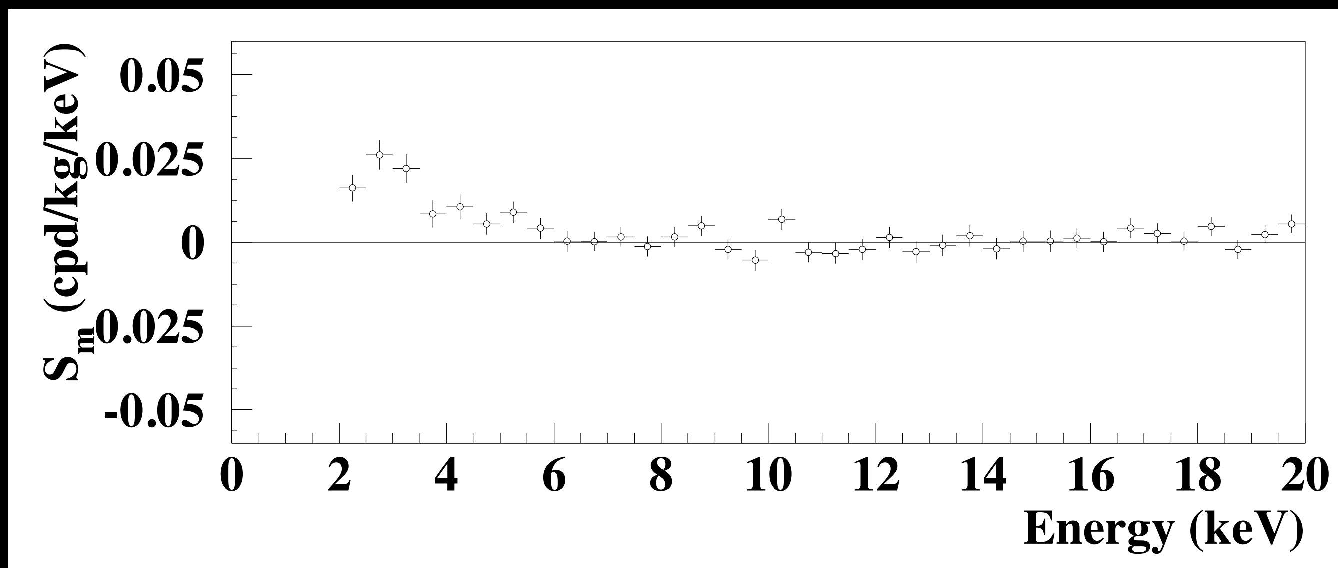
The WIMP bulk velocity w.r.t. Earth modulates from ~232+15 km/s to ~232-15 km/s with a period of one year

The DAMA modulation

DAMA finds a yearly modulation as expected for dark matter particles

Bernabei et al 1997-2012





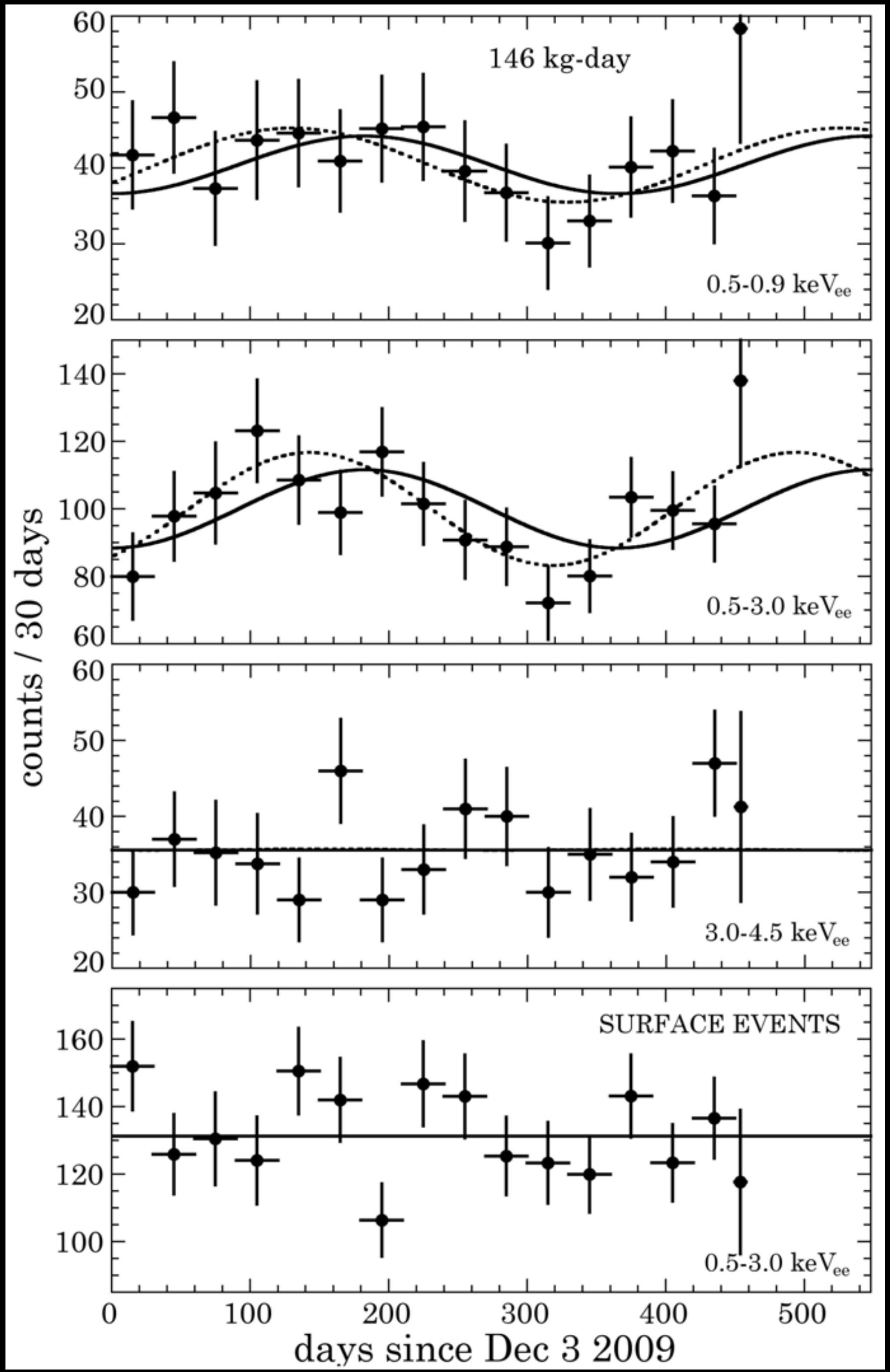
$$S = S_0 + S_m \cos[\omega(t - t_0)]$$

The CoGeNT modulation

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

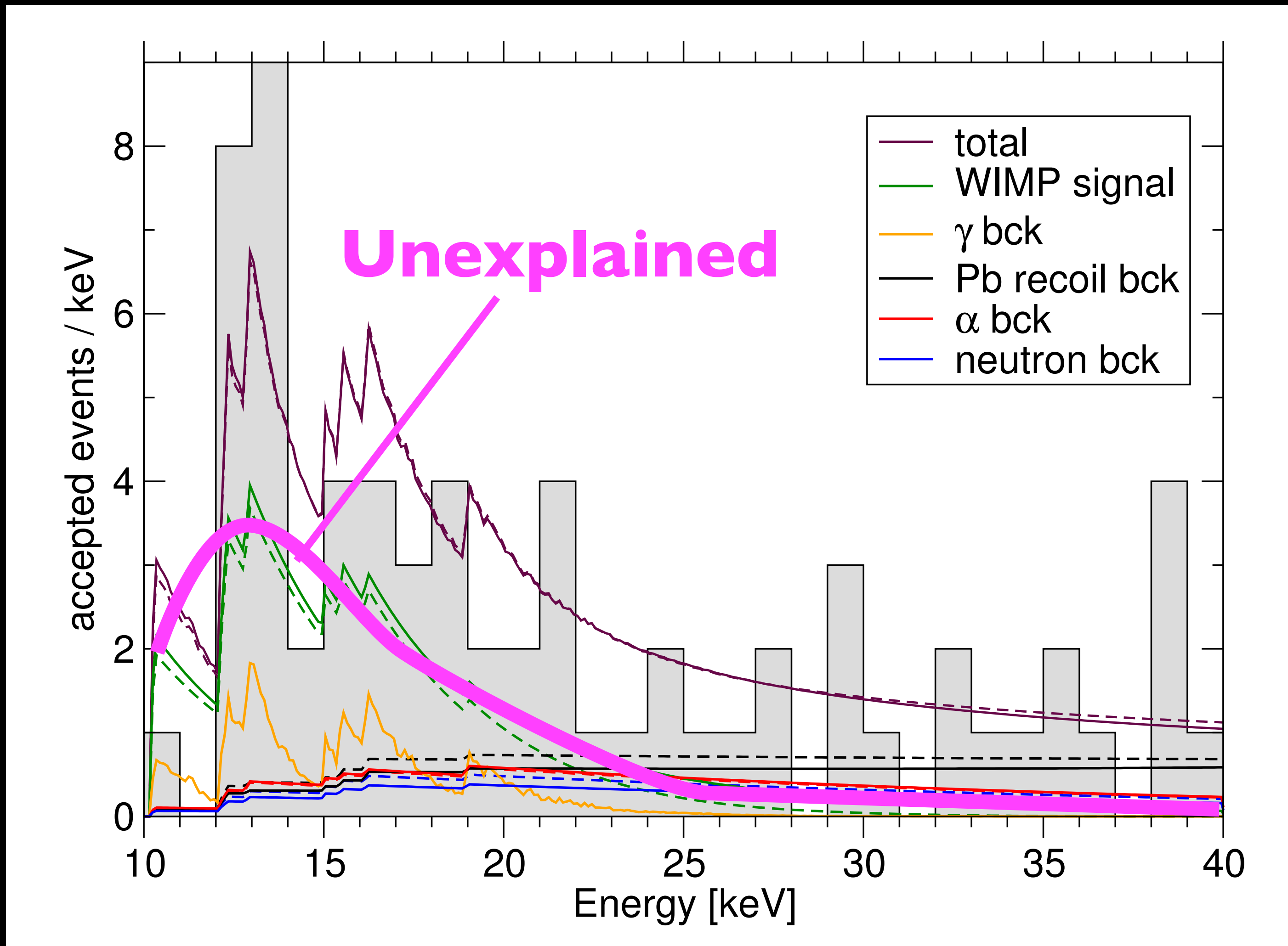
Aalseth et al 1106.0650

(*) Partly due to extra surface events



The CRESST unexplained excess

67 observed events cannot all be explained by background at 4σ



Adapted from Anglehor et al 2011

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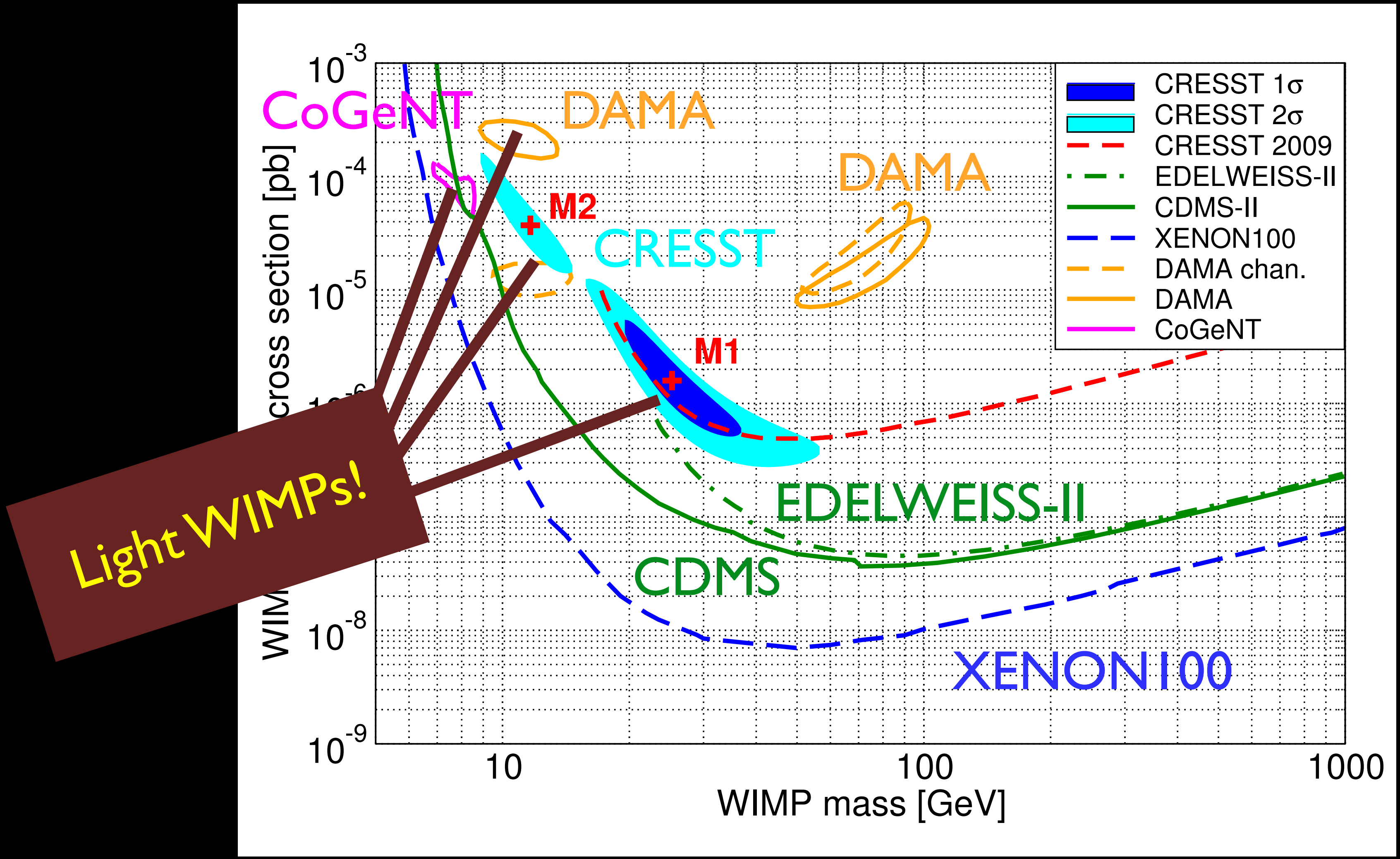
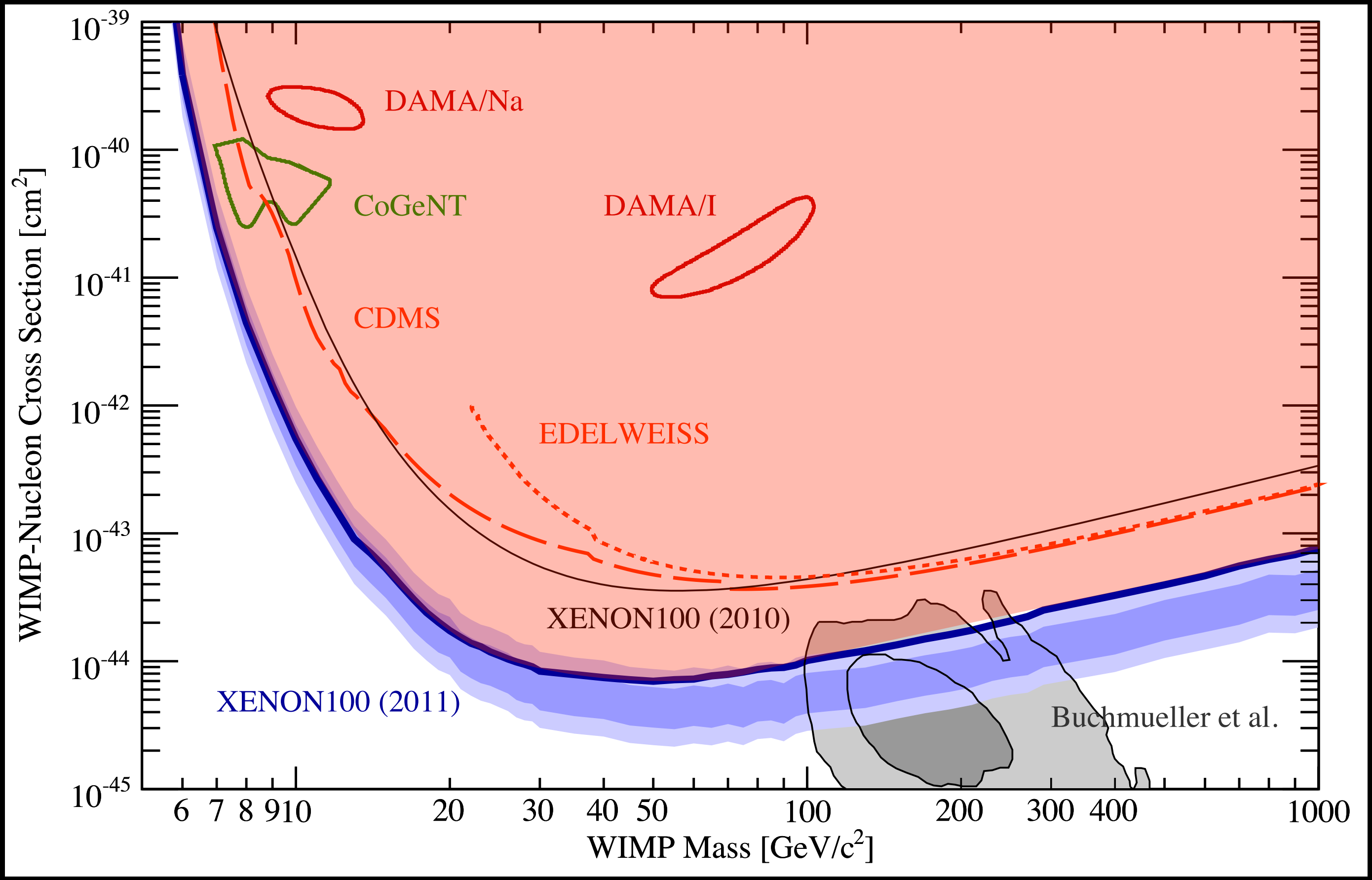


model-dependent

Adapted from Anglehor et al 2011

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

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



3 events observed

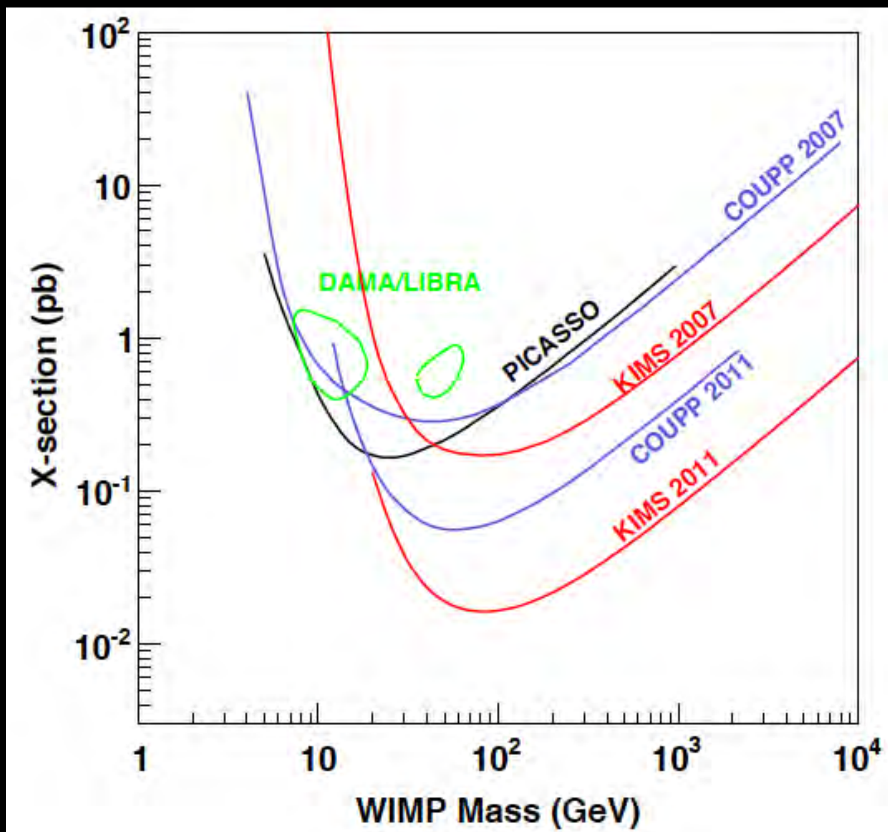
1.8±0.6 expected background

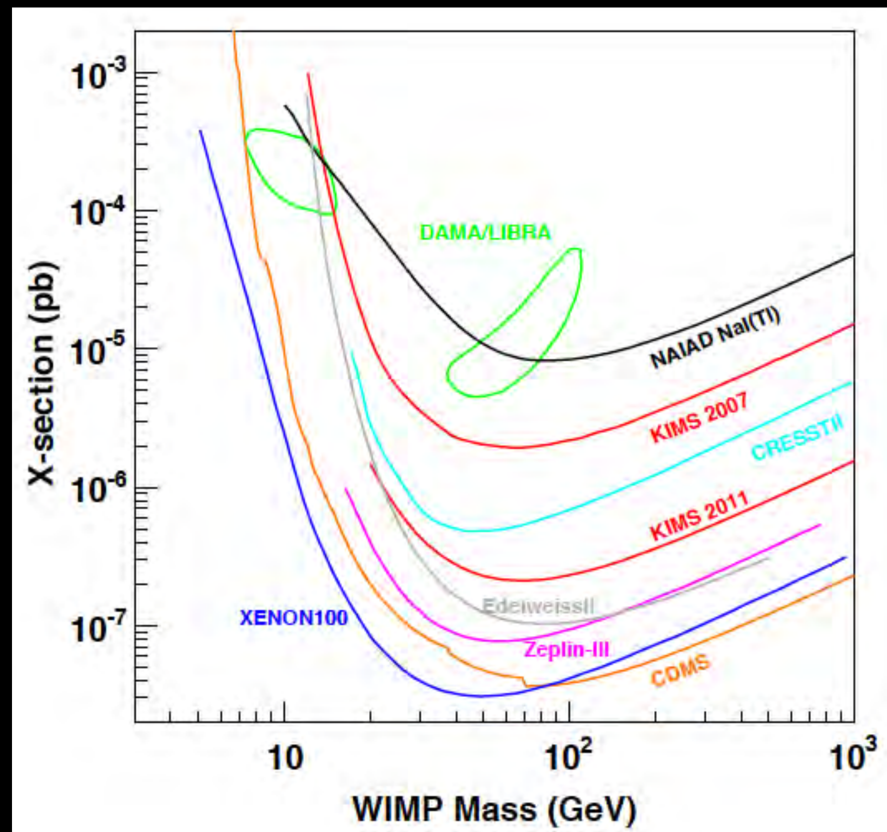
Aprile et al (XENON-100) 1104.2549

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

KIMS: CsI scintillation detector
(similar to DAMA)

- *Excludes inelastic dark matter*
- *Excludes 60 GeV/c^2 DAMA region*

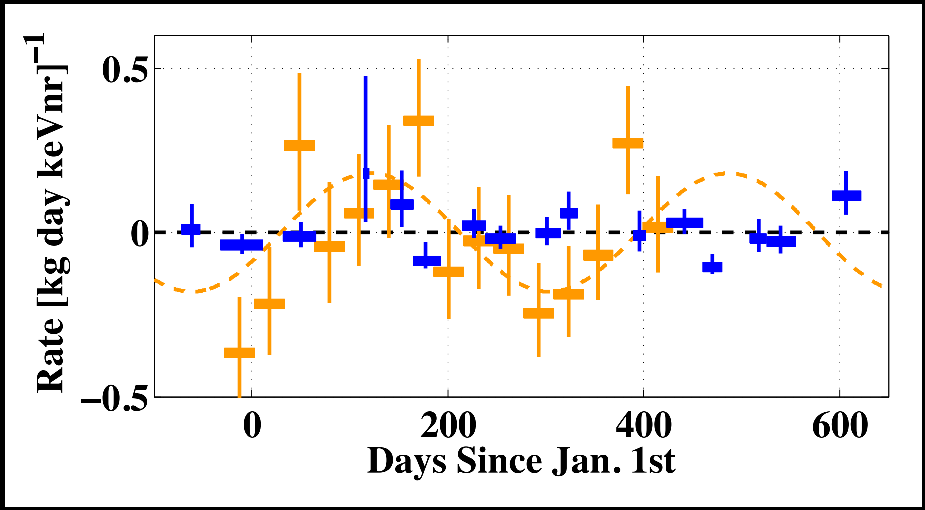




Without using detectors with large surface α background

Kim at TAUP 2011

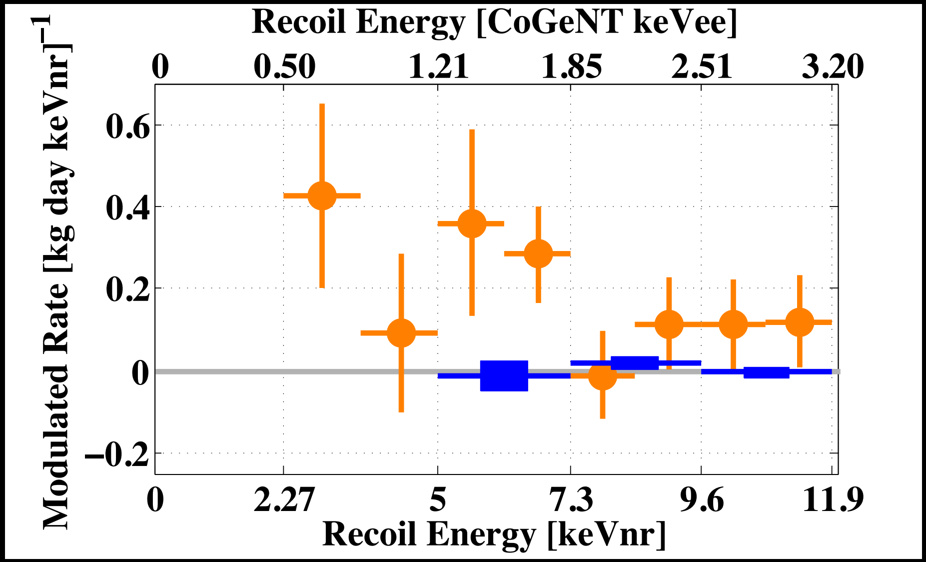
Limits from XENON-100, KIMS, CDMS, ...

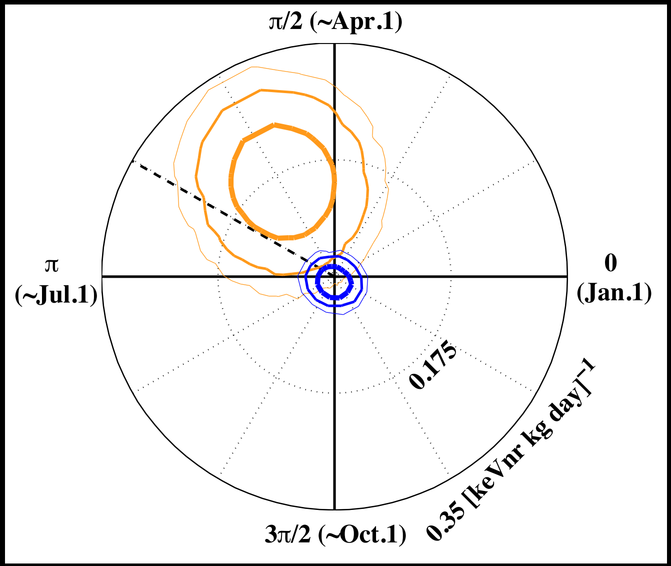


CDMS does not observe an annual modulation and constrains its amplitude

Ahmed et al 1203.1309

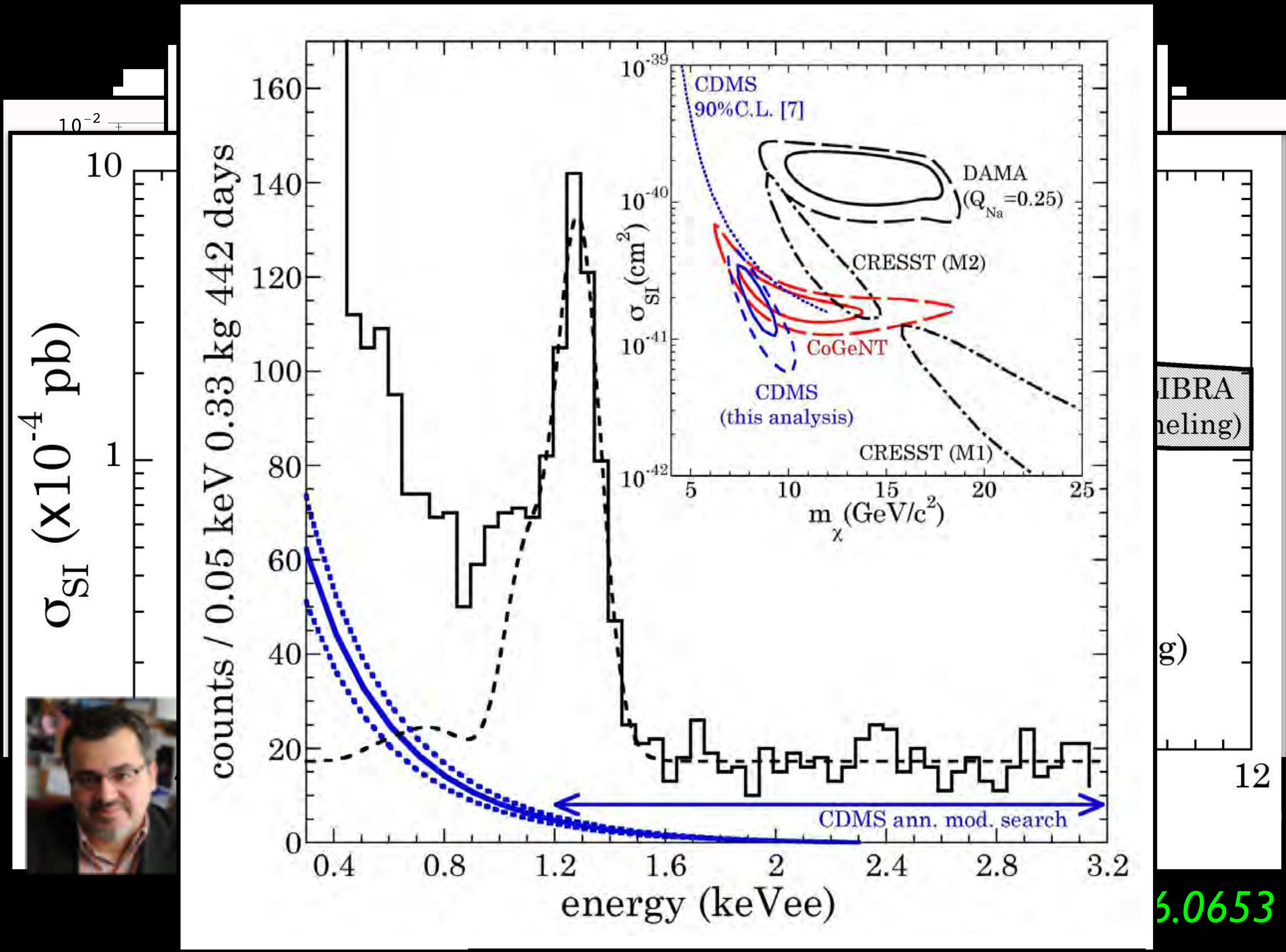
CoGeNT CDMS





model-independent

CoGeNT & DAMA vs. XENON, CDMS, et al



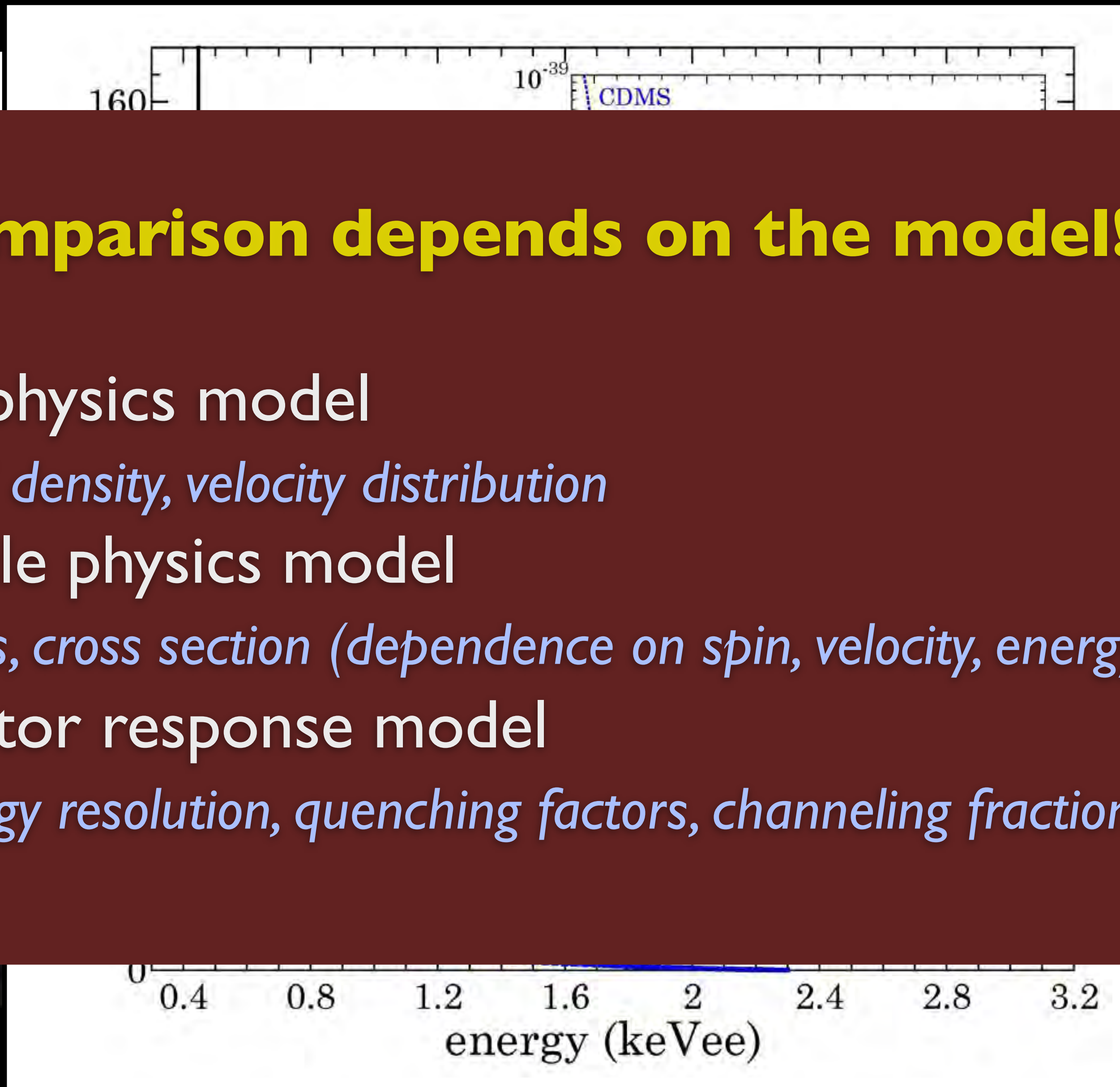
...6.0653

Collar Fields 1204.3559

CoGeNT & DAMA vs. XENON, CDMS, et al

The comparison depends on the model!

- astrophysics model
  - *local density, velocity distribution*
- particle physics model
  - *mass, cross section (dependence on spin, velocity, energy, couplings)*
- detector response model
  - *energy resolution, quenching factors, channeling fraction*

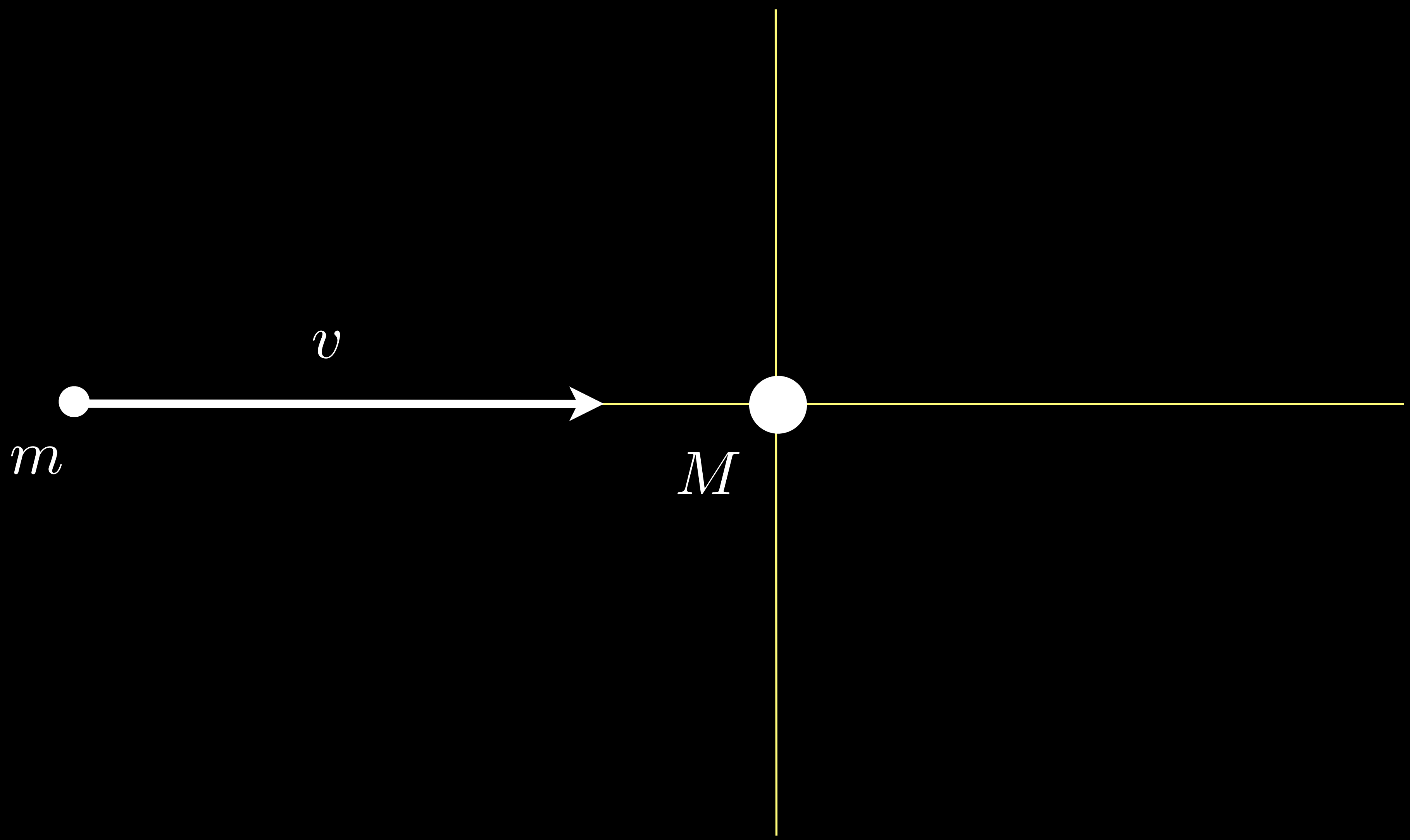


6.0653

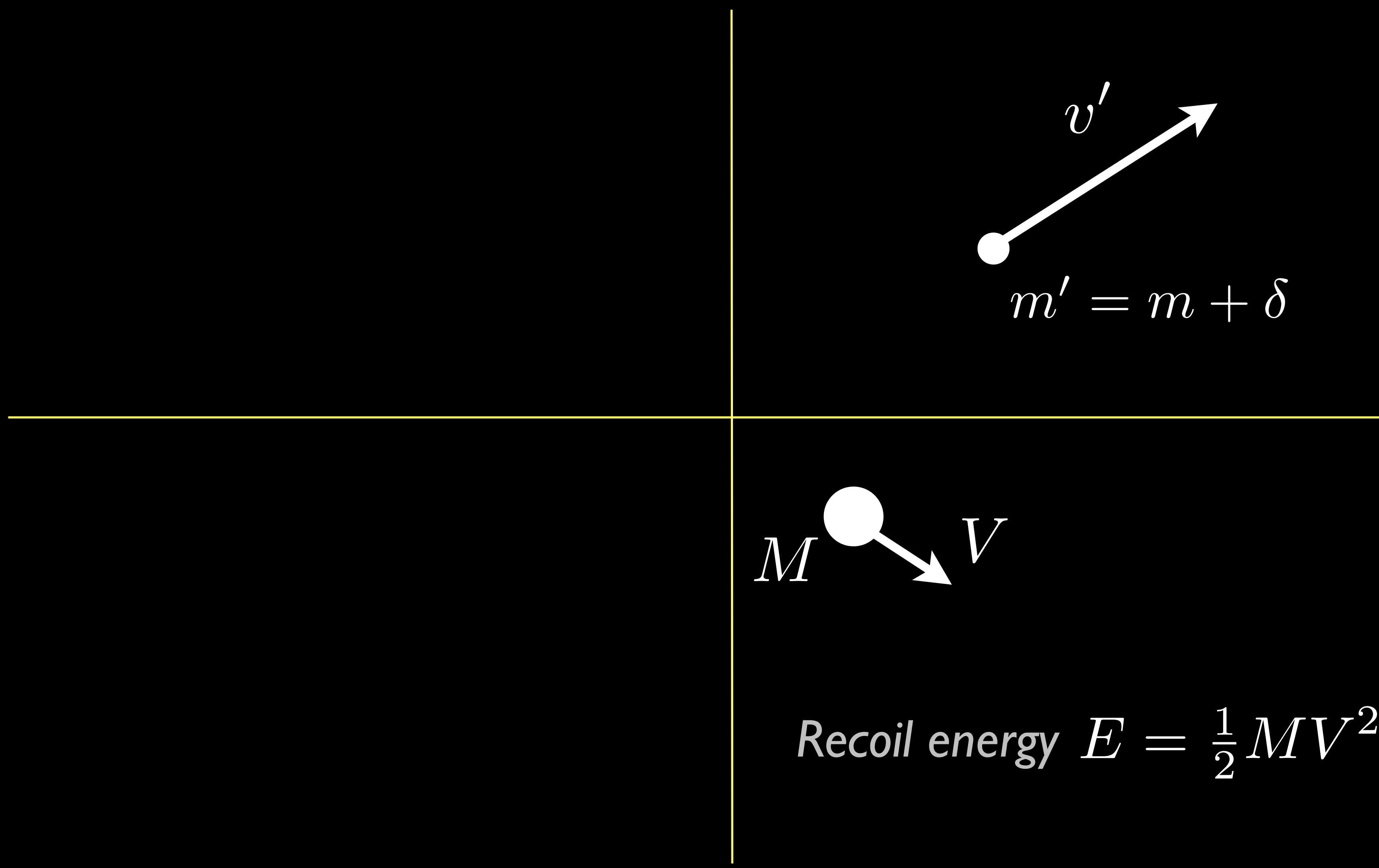
Collar Fields 1204.3559

Basic ideas

The expected number of events



The expected number of events



Recoil energy $E = \frac{1}{2} M V^2$

The expected number of events

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

$$\begin{pmatrix}\text{detector}\\ \text{response}\end{pmatrix} = \begin{pmatrix}\text{energy}\\ \text{response function}\end{pmatrix} \times \begin{pmatrix}\text{counting}\\ \text{acceptance}\end{pmatrix}$$

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Detector response model

From measured energy to recoil energy

$$\begin{pmatrix} \text{energy} \\ \text{response function} \end{pmatrix} = g(E_{\text{ee}}, E)$$

Recoil energy (keV)

Energy observed in detector, typically expressed in keV electron equivalent (keV_{ee})

Typically written as a single Gaussian with mean value

$$E_{\text{ee}} = Q E$$

Quenching factor

and standard deviation σ_E, but *may be different.*

Detector response model

Monochromatic ^{16}O beam through NaI(Tl) scintillator

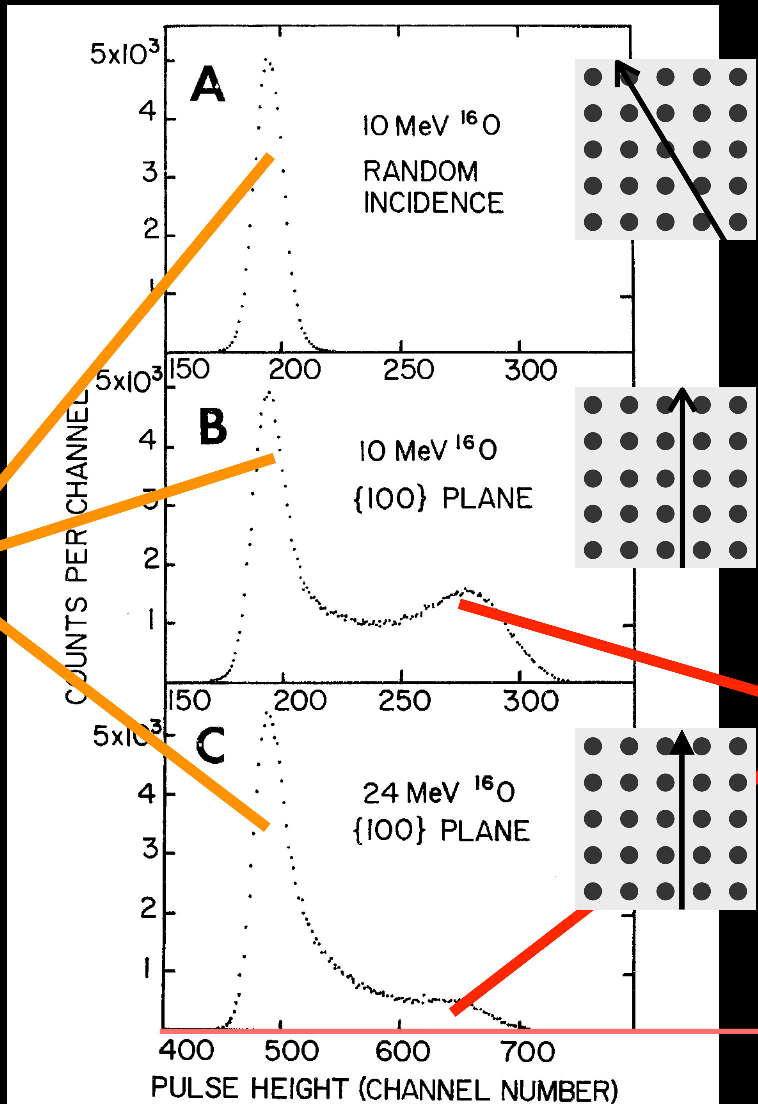


FIG. 2. (a) Pulse-height spectrum from 10-MeV ^{16}O on NaI(Tl) for incidence along a random direction. (b) Pulse-height spectrum from 10-MeV ^{16}O along a {100} plane. (c) Pulse-height spectrum from 24-MeV ^{16}O along a {100} plane. A light guide was used in all cases.

Not channeled

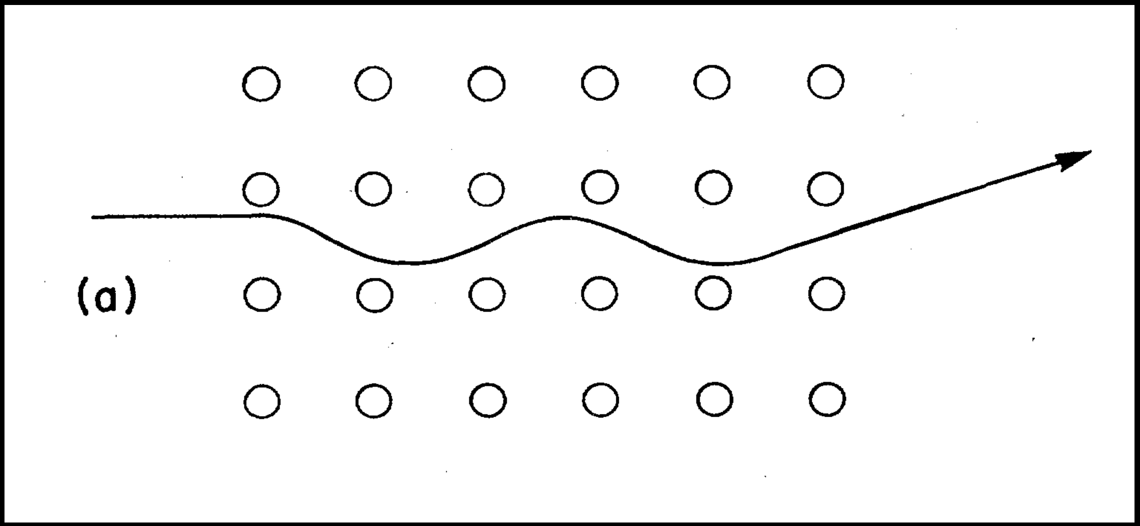
Channeled

Scintillation output

Altman et al 1973 (Phys.Rev. B7, 1743)

Detector response model

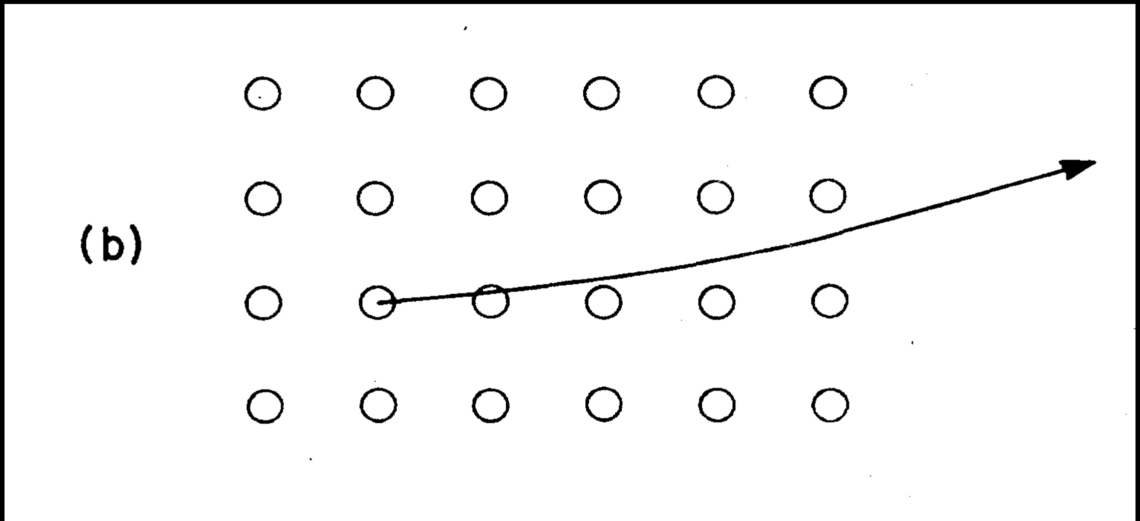
Channeling. If an ion incident onto the crystal moves in the direction of a symmetry axis or plane of the crystal, it has a series of small-angle scatterings which maintains it in the open channel. The ion penetrates much further into the crystal than in other directions.



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

Detector response model

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".

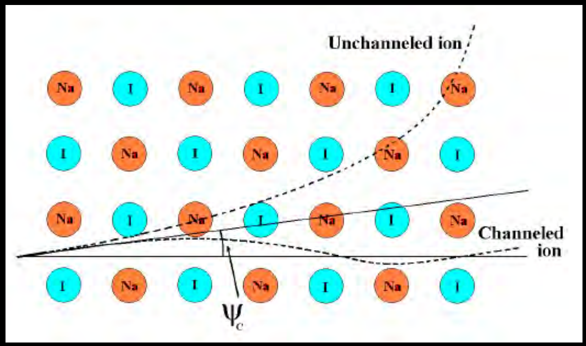


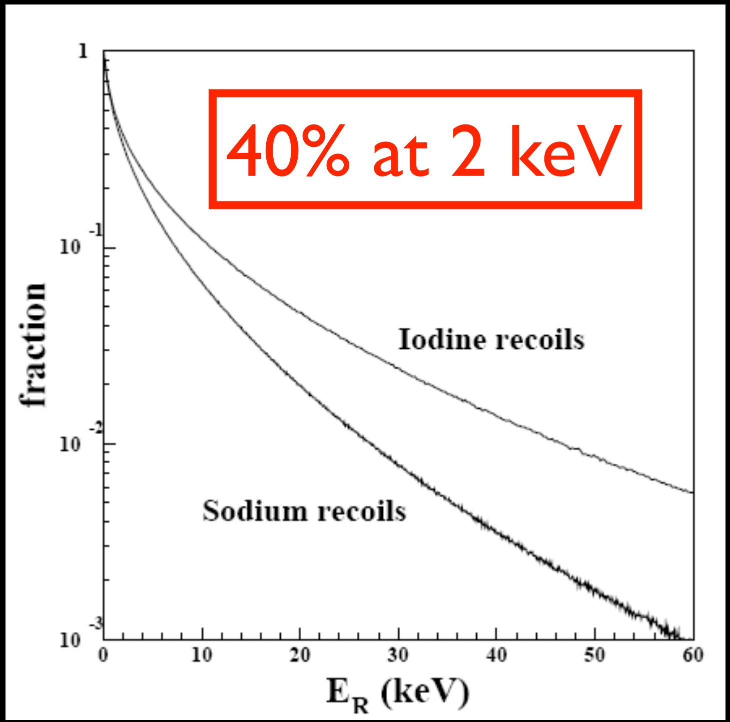
From Gemmel 1974, Rev. Mod. Phys. 46, 129

Detector response model

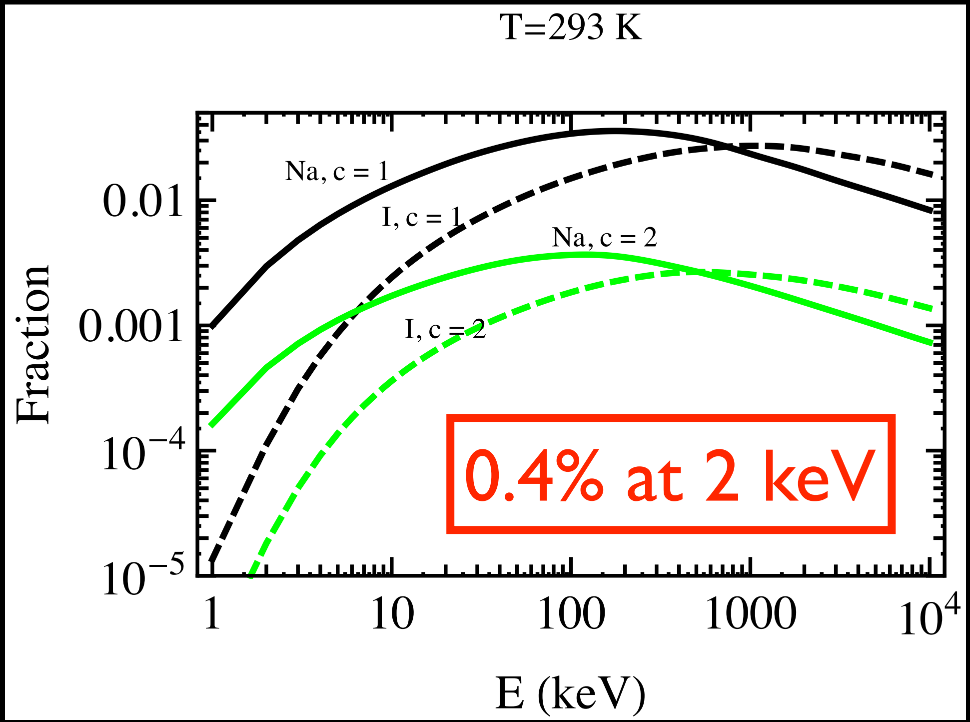
Channeling in DAMA's NaI(Tl) is much less than previously published

Bozorgnia, Gelmini, Gondolo 2010



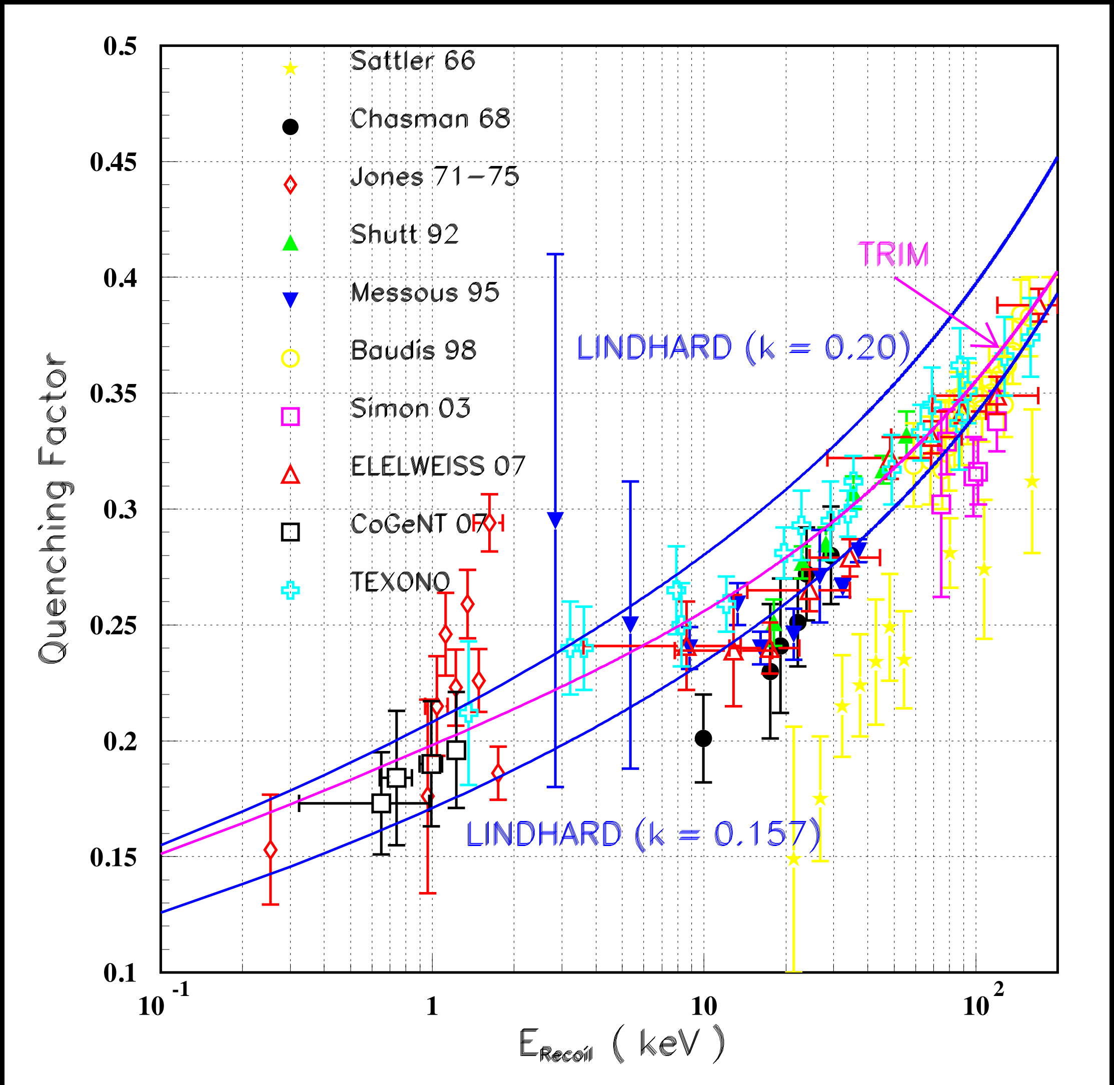


Bernabei et al. 2008



Bozorgnia, Gelmini, Gondolo 2010

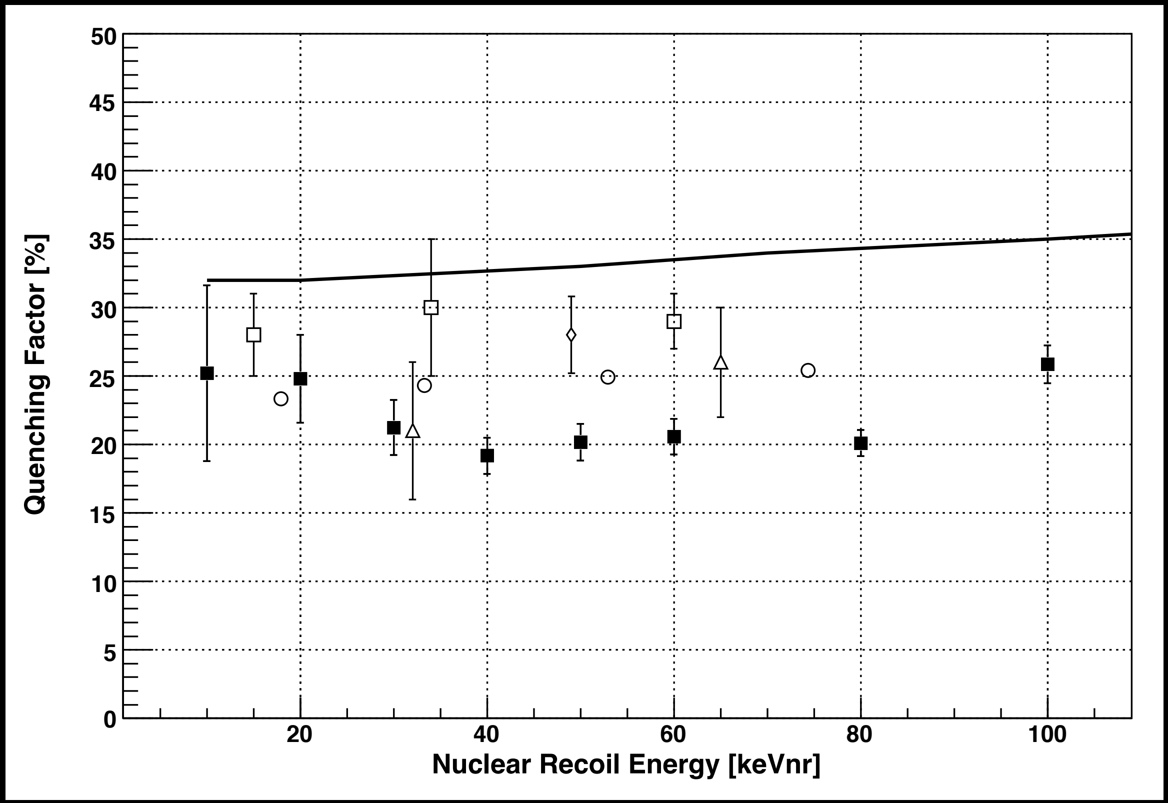
Detector response model



Compilation of measurements of the quenching factor *Q* in germanium

Lin et al (TEXONO) 2007

Detector response model



Chagani et al 0806.1916

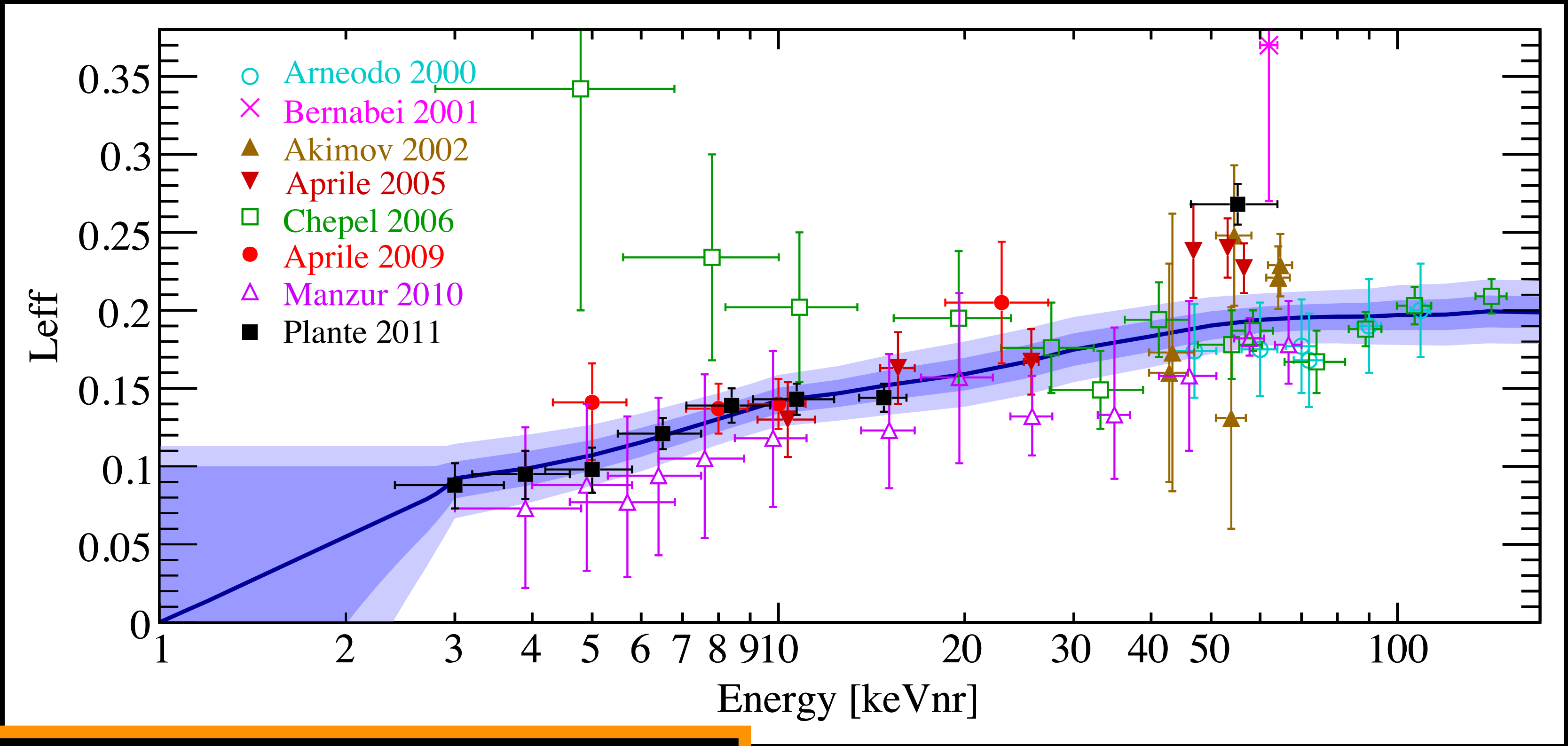
Compilation of measurements of the quenching factor *Q* in NaI(Tl)

This is where one can tweak to make DAMA and CoGeNT compatible.

Detector response model

Compilation of measurements of the light efficiency factor *Leff* in liquid xenon

$$E_{ee} = S1/L_y(122\mathrm{keV}_{ee})$$
$$Q = L_{\mathrm{eff}}(S_{nr}/S_{ee})$$



This is where most of the CoGeNT/XENON debate is.

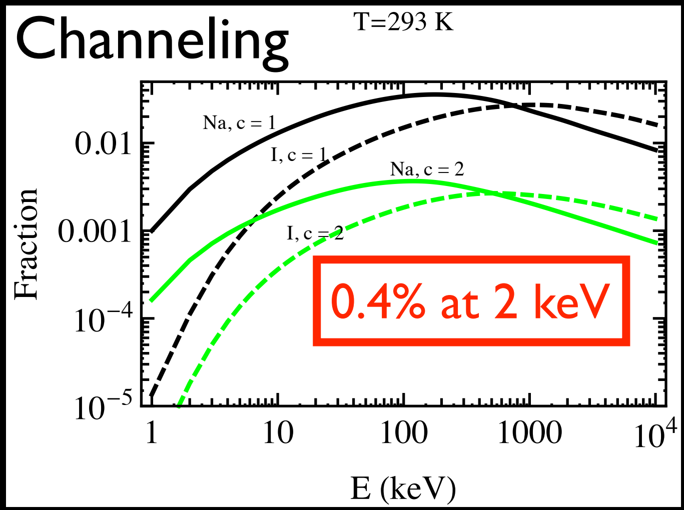
Aprile et al (XENON100), 1104.2549

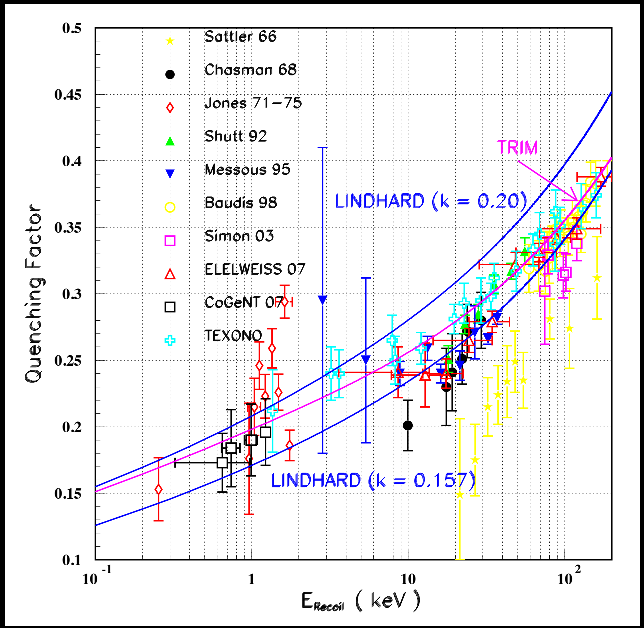
Detector response model

Quenching factor $E_{ee} = \boxed{Q}E$

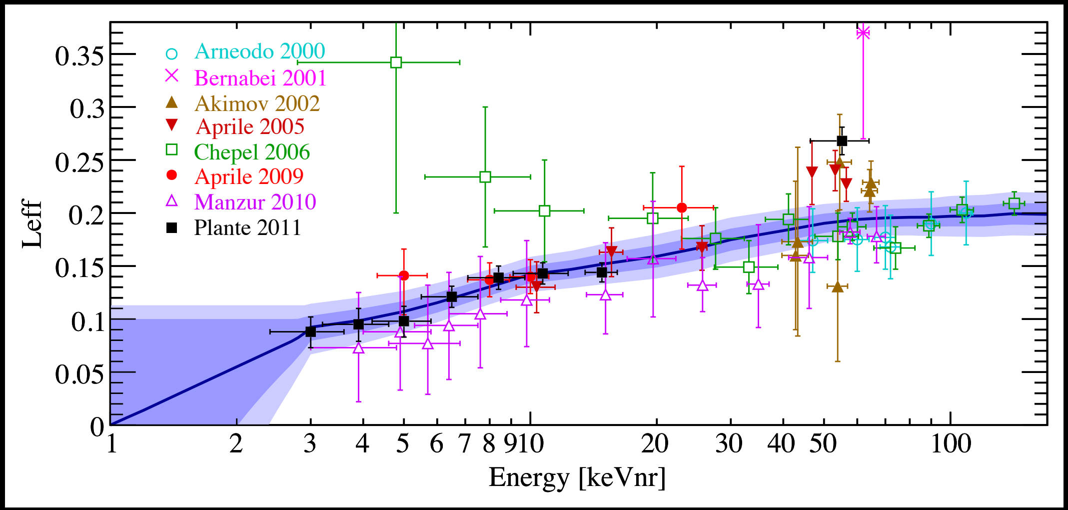
This is where one can tweak to make experiments compatible.

Bozorgnia et al 2010





Lin et al (TEXONO) 2007



Aprile et al (XENON100), 1104.2549

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Astrophysics model

How much dark matter comes to Earth?

Local halo density

Velocity distribution

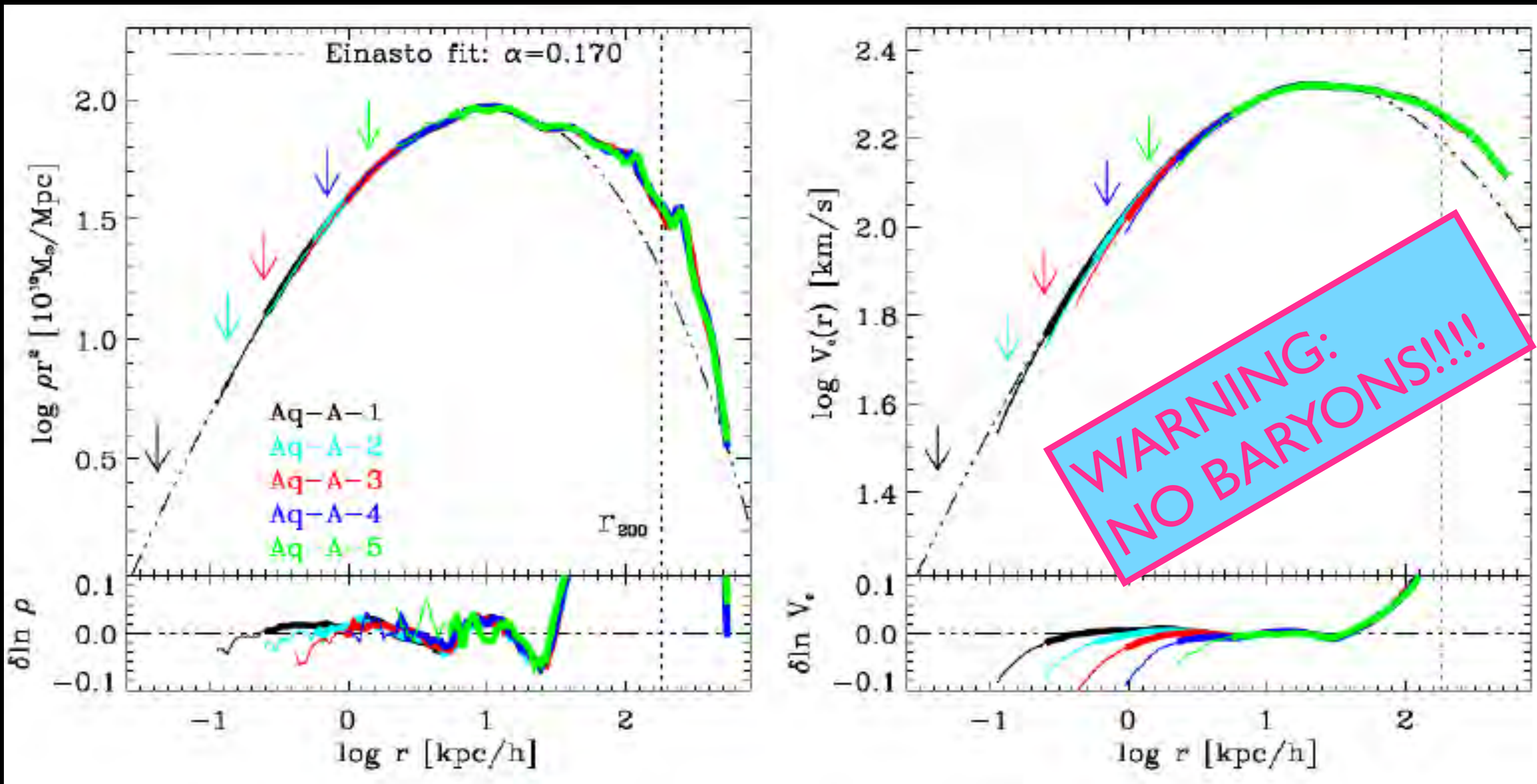
$$(\text{astrophysics}) = \rho \int_{v > v_{\min}(E)} \frac{f(\vec{v}, t)}{v} \, \mathrm{d}^3 v$$

Minimum speed to impart energy $E, \; v_{\min}(E) = (ME/\mu + \delta)/\sqrt{2ME}$

Astrophysics model: local density

Galactic density profile from Aquarius simulations

$$\rho(r) \propto \exp\left(-Ar^{\alpha}\right).$$



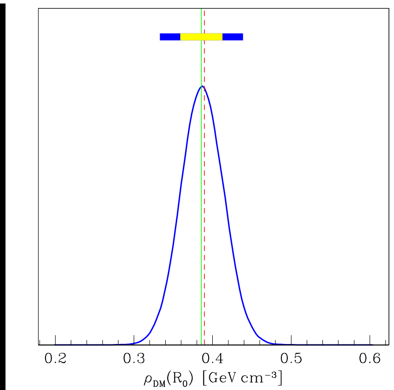
Astrophysics model: local density

$$\rho_\odot = \left(0.430 \pm 0.113_{(\alpha_\odot)} \pm 0.096_{(r_{\odot D})}\right)\frac{\text{GeV}}{\text{cm}^3}\,.$$

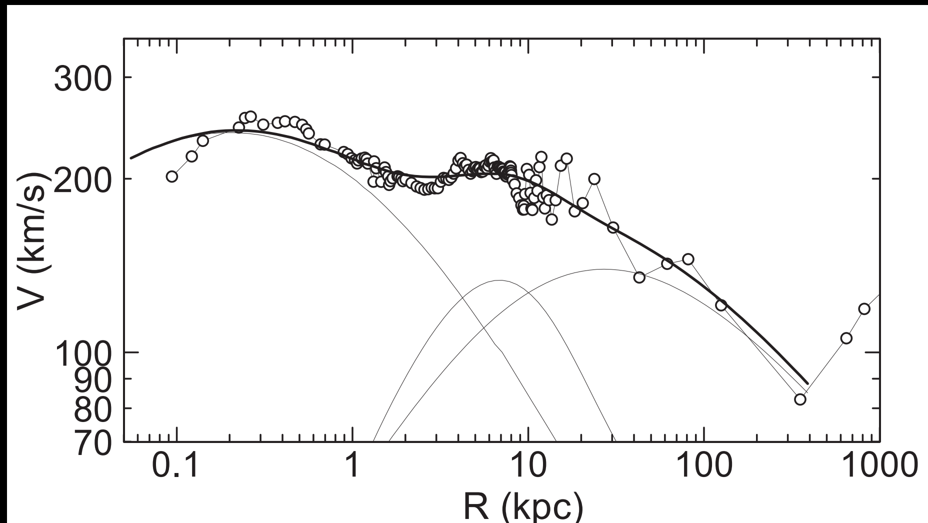
Salucci et al 2010

$$\rho_{DM}(R_0) = 0.385 \pm 0.027\,\text{GeV cm}^{-3}$$

Ullio, Catena 2009

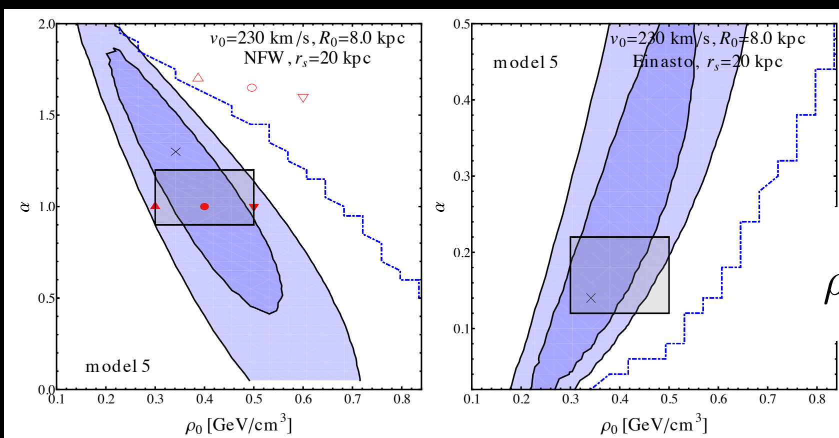


Local density from galactic modeling



Sofue 2011

$$\rho_0^\odot = 0.235 \pm 0.030\ \text{GeV cm}^{-3}$$



$$\rho_0 = 0.20 - 0.55\ \text{GeV/cm}^3$$

Iocco, Pato, Bertone, Jetzer 2010

Astrophysics model: local density

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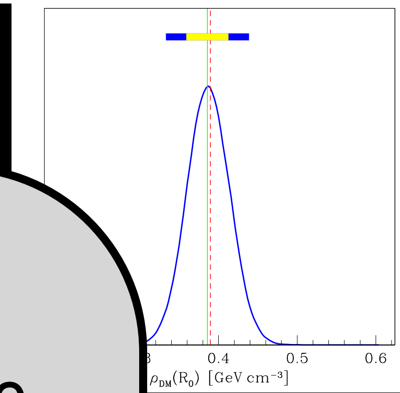


Lo

gal

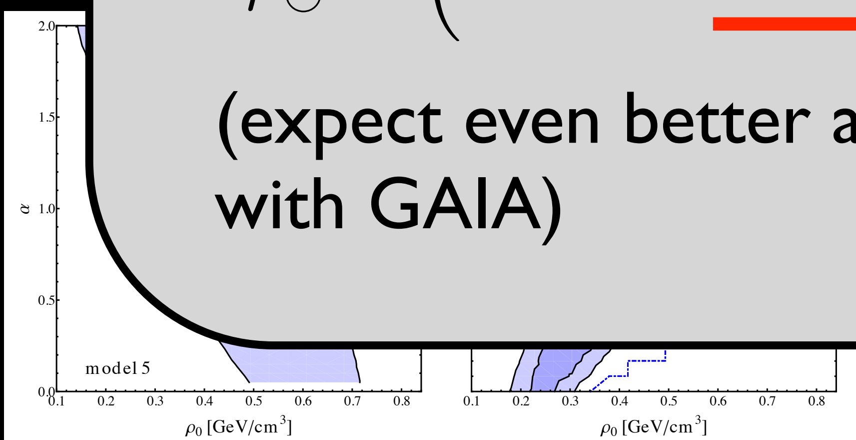
The most direct method, requiring only local measurements of the disk contribution and the slope of rotation curve at the Sun's distance. Now even more precise with preliminary VERA

$$\rho_\odot = \left(0.463 \pm 0.044_{(\alpha_\odot)} \pm 0.096_{(r_{\odot D})}\right)\frac{\text{GeV}}{\text{cm}^3}$$

(expect even better at VERA completion and with GAIA)

Honma at NDM12

cm^{-3}



Iocco, Pato, Bertone, Jetzer 2010

Astrophysics model: velocity distribution

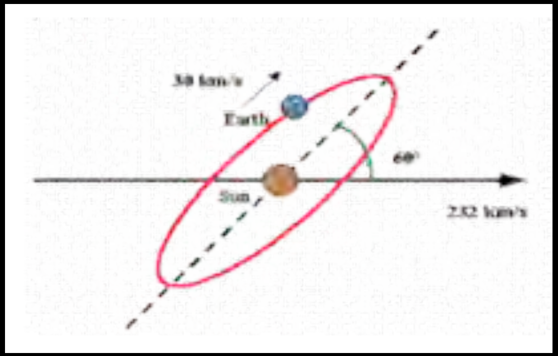
The velocity factor $\eta(E,t) = \int_{v > v_{\min}(E)} \frac{f(\vec{v},t)}{v} \, \mathrm{d}^3 v$

- If $f(E,t)$ is non-truncated Maxwellian in detector frame, $\eta(E,t)$ is exponential in E

- $\eta(E,t)$ depends on time (unless WIMPs move with detector)

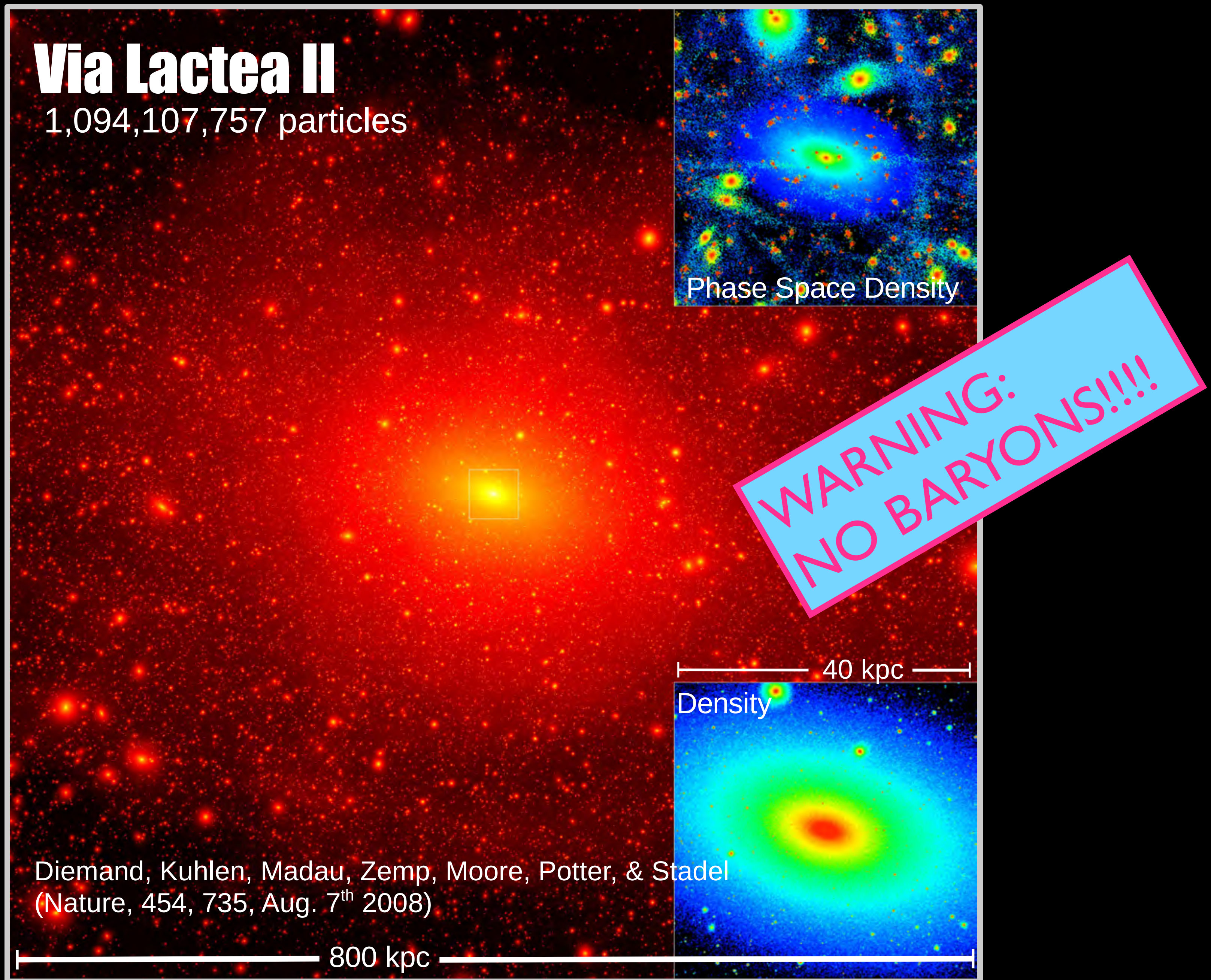
Example: annual modulation

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



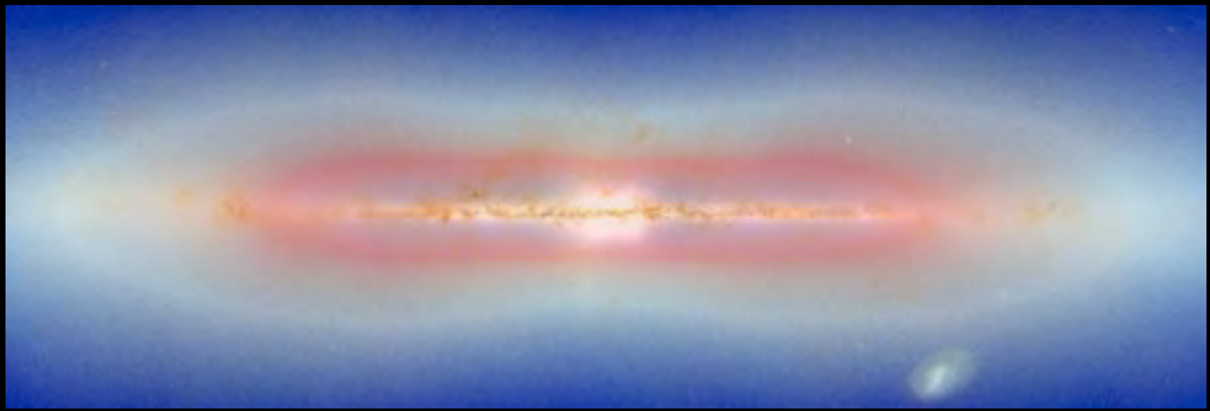
Drukier, Freese, Spergel 1986

Astrophysics model: velocity distribution



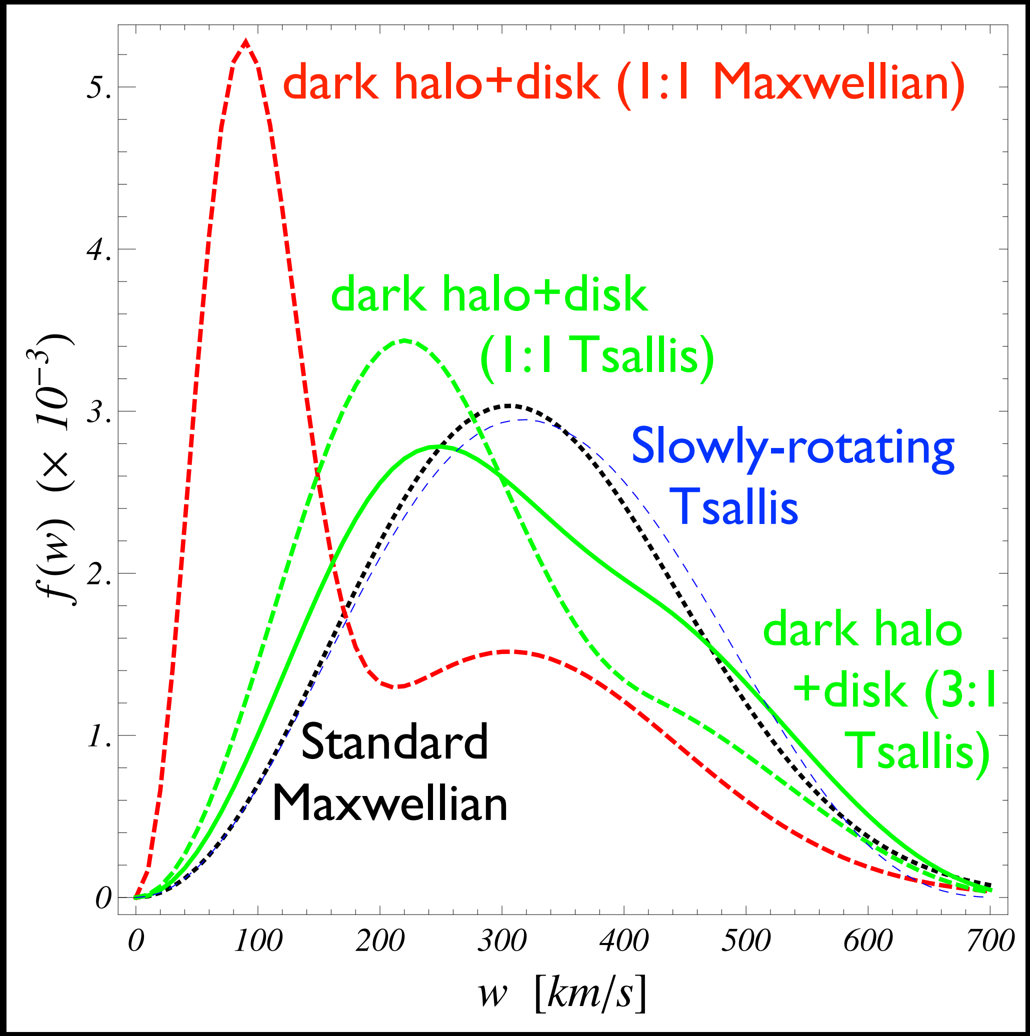
Astrophysics model: velocity distribution

Inclusion of baryonic disk may lead to a dark disk



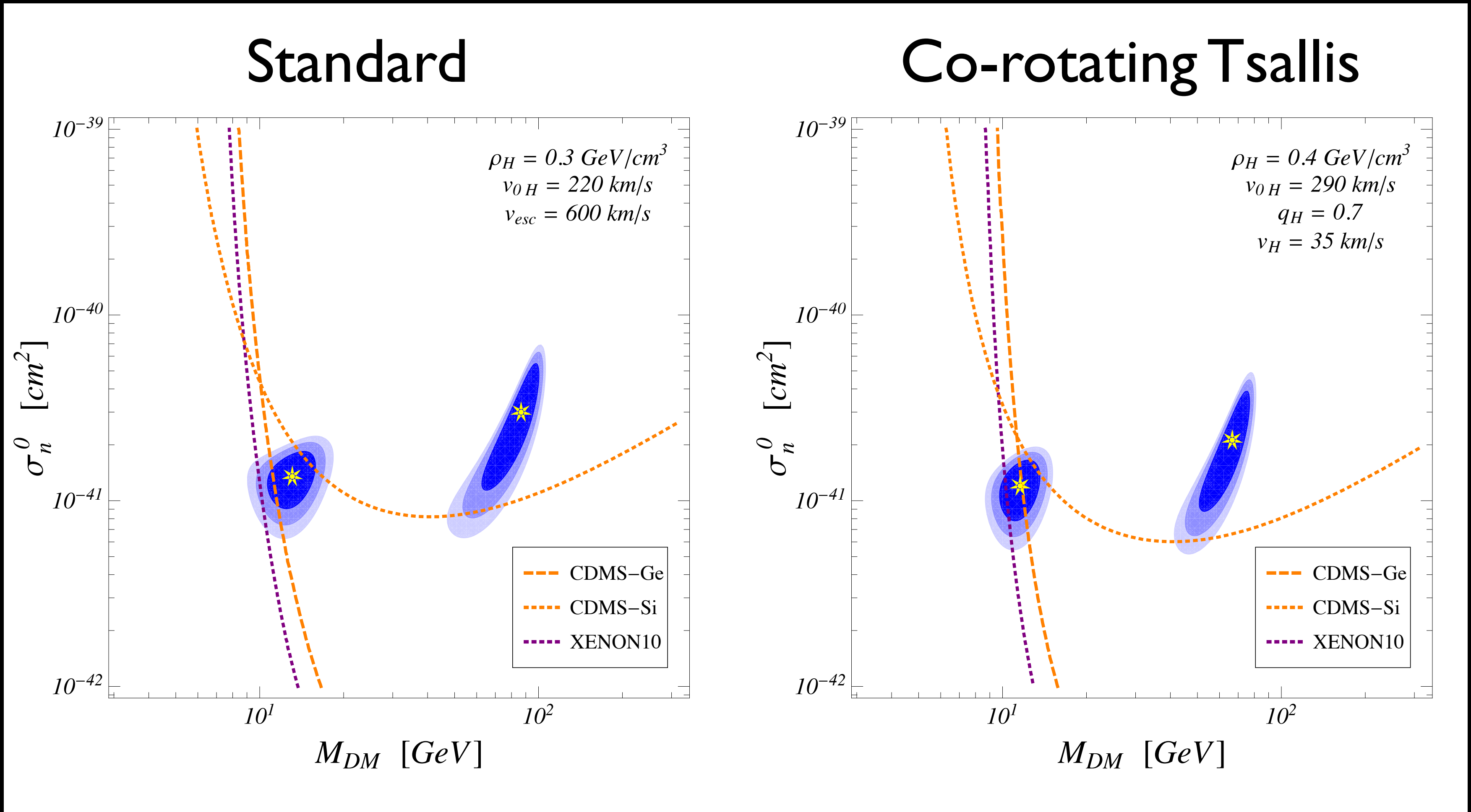
Read, Lake, Agertz, De Battista 2008

Astrophysics model: velocity distribution



Ling 2009

Astrophysics model: velocity distribution



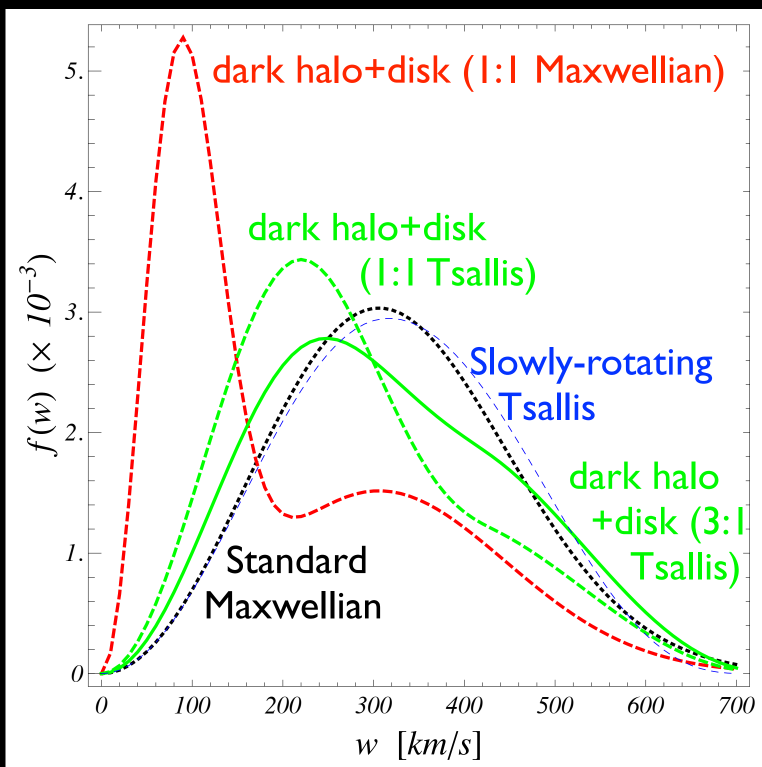
Ling 2009

Wednesday, July 18, 12

Astrophysics model

The local density may be “known” within a factor of 2, but the velocity distribution is still an open question

Analytic models

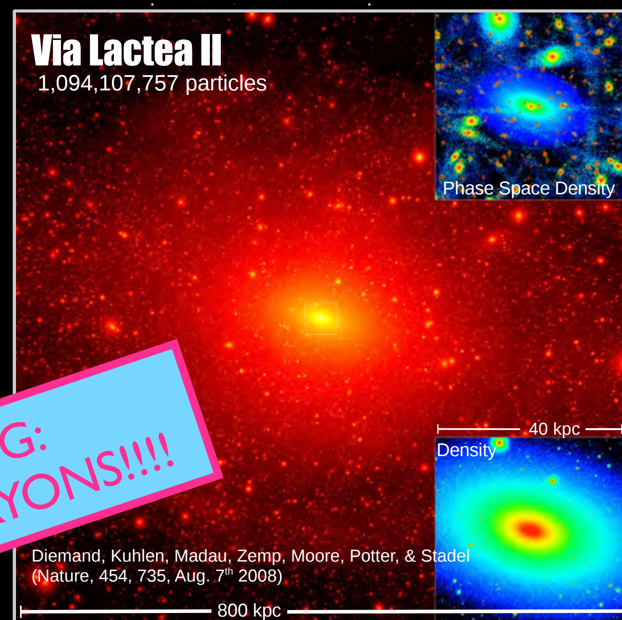


Ling 2009

N-body simulations

Read et al 2008

Kuhlen et al



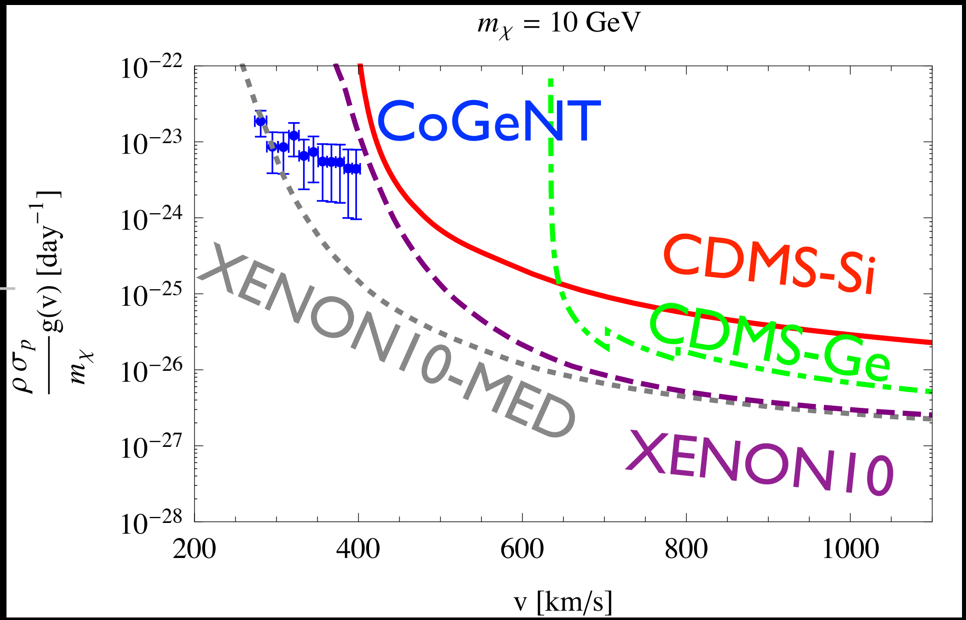
WARNING:
NO BARYONS!!!!

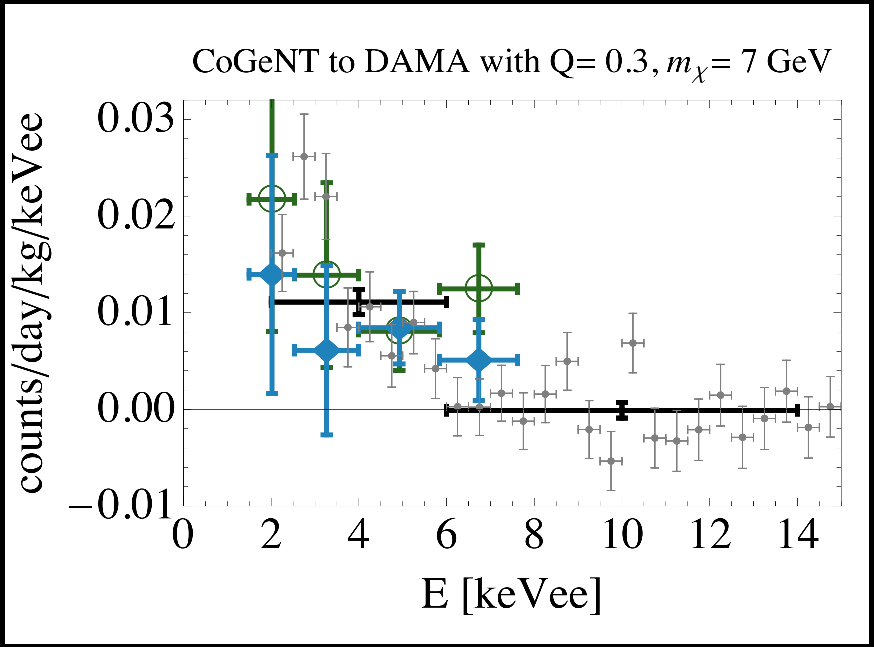
Astrophysics-independent approach

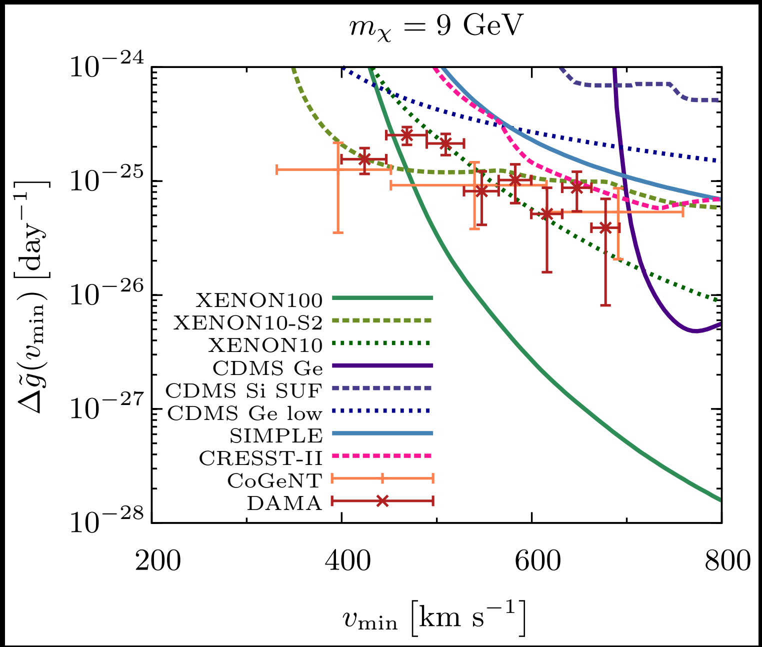
Fox, Liu, Weiner 2011

Astrophysics factor

$$\frac{\rho_\chi \sigma_{\chi p} c^2}{m_\chi} \int_v^\infty \frac{f(v')}{v'} dv'$$



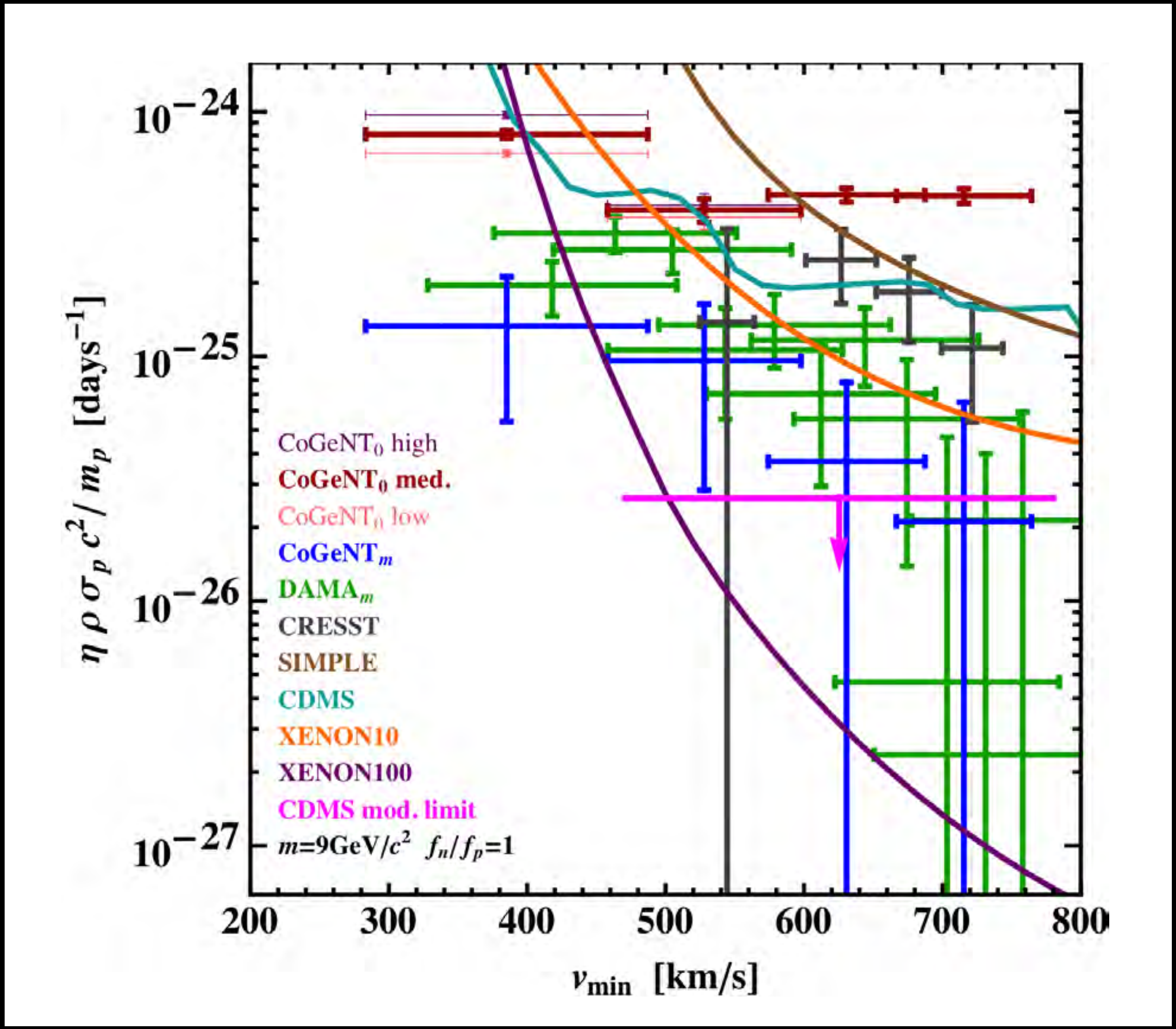




Fox, Kopp, Lisanti, Weiner 2011

Frandsen et al 2011

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

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

$$\begin{pmatrix}\text{detector}\\ \text{response}\end{pmatrix} = \begin{pmatrix}\text{energy}\\ \text{response function}\end{pmatrix} \times \begin{pmatrix}\text{counting}\\ \text{acceptance}\end{pmatrix}$$

$$\begin{pmatrix}\text{recoil}\\ \text{rate}\end{pmatrix} = \boxed{\begin{pmatrix}\text{particle}\\ \text{physics}\end{pmatrix}} \times (\text{astrophysics})$$

Particle physics model

What force couples dark matter to nuclei?

Spin-independent and spin-dependent cross sections

$$\begin{pmatrix}\text{particle}\\ \text{physics}\end{pmatrix} = \frac{\sigma_{SI}(E) + \sigma_{SD}(E)}{2m\mu^2}$$

Reduced mass $\mu = mM/(m+M)$

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

Particle physics model

Exchange scalar, vector, pseudovector, ... ?

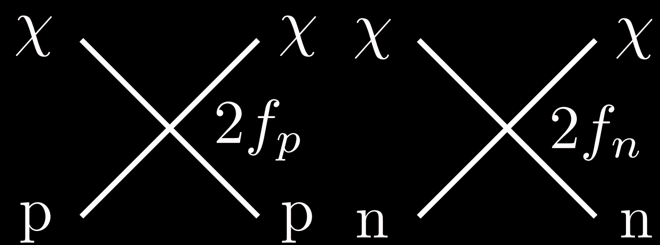
- Supersymmetry
- Extra U(1) bosons
- Extended Higgs sector
- Effective operator approach

Particle physics model

Scalar and vector currents give spin-independent terms

$$\sigma_{SI}(E) = \frac{4\mu^2}{\pi}\Big|Z f_p + (A - Z) f_n\Big|^2 \Big|F(E)\Big|^2$$

Effective four-particle vertices



Nuclear density form factor

Example: neutralino

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

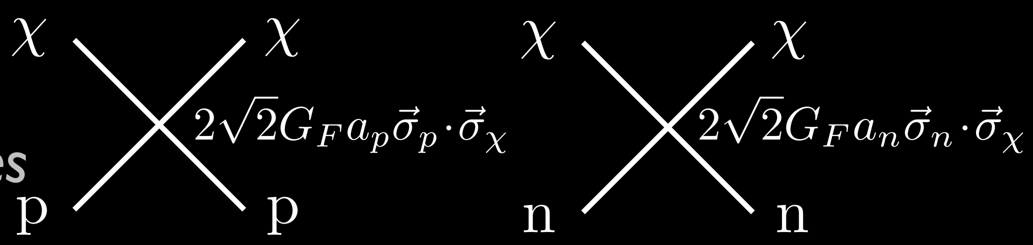
Main uncertainty is $\langle m_s \bar{s} s \rangle$ (strange content of nucleon)

Particle physics model

Axial and tensor currents give spin-dependent terms

$$\sigma_{SD}(E) = \frac{32\mu^2 G_F^2}{2J+1}\left[a_p^2 S_{pp}(q) + a_p a_n S_{pn}(q) + a_n^2 S_{nn}(q)\right]$$

Effective four-particle vertices



Nuclear spin structure functions

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 $S(q)$

Particle physics model

Axi

σ

E

p

in

tions

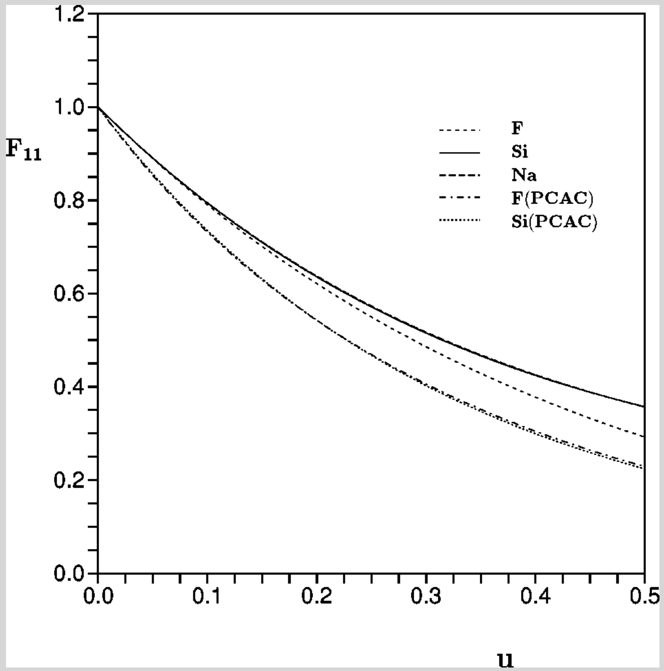
Exa

Nuclear spin structure functions

$$H_{\rm SD}^{\rm nuc} = \hat{\mathbf{s}}_\chi(0) \cdot \int \hat{\mathbf{j}}_{\rm SD}(\mathbf{r})\, e^{i\mathbf{q}\cdot\mathbf{r}}\, d\mathbf{r}$$

$$\hat{\mathbf{j}}_{\rm SD}(\mathbf{r}) = \sum_{i=1}^{A} \left[G_{\rm SD}^0 + G_{\rm SD}^1 \tau_3(i)\right] \boldsymbol{\sigma}(i)\, \delta(\mathbf{r} - \mathbf{r}_i)$$

Divari, Kosmas, Vergados, Skouras 2000



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 ($\gtrsim 10^{24}$ 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 models of light dark matter*

Models		References
SUSY	MSSM neutralino	*.....; Griest 1988; Gelmini, Gondolo, Roulet 1989; Griest, Roszkowski 1991; Bottino et al 2002-11; ~~Kuflik, Pierce, Zurek 2010~~; ~~Feldman, Liu, Nath 2010~~; ~~Cumberbatch et al 2011~~; Belli et al 2011; .....*
SUSY	beyond-MSSM neutralino	*Flores, Olive, Thomas 1990; Gunion, Hooper, McElrath 2005; Belikov, Gunion, Hooper, Tait 2011; Belanger, Kraml, Lessa 1105.4878; ......*
SUSY	sneutrino	*.....; An, Dev, Cai, Mohapatra 1110.1366; Cerdeno, Huh, Peiro, Seto 1108.0978; .....*
minimalist dark matter (SM + real singlet scalar)		*Veltman, Ydnurain 1989; Silveira, Zee 1985; McDonald 1994; Burgess, Pospelov, ter Veldhuis 2000; Davoudiasl, Kitano, Li, Murayama 2004; Andreas et al 2008-10; He, Tandean 1109.1267; .....*
technicolor and alike		*....; Lewis, Pica, Sannino 1109.3513; .....*
kinetically-mixed U(1)'		*.....; Foot 2003-10; Kaplan et al 1105.2073; An, Gao 1108.3943; Fornengo, Panci, Regis 1108.4661; Andreas, Goodsell, Ringwald 1109.2869; Andreas 1110.2636; Feldman, Perez, Nath 1109.2901; ......*
baryonic U(1)'		*Gondolo, Ko, Omura; Cline, Frey 1109.4639; ......*
dynamical DM		*Dienes, Thomas 1106.4546, 1107.0721*

* 1-10 GeV WIMP; very incomplete references.

So many theoretical models!

My suggestion: pay theorists more, so they do not need to work so much.