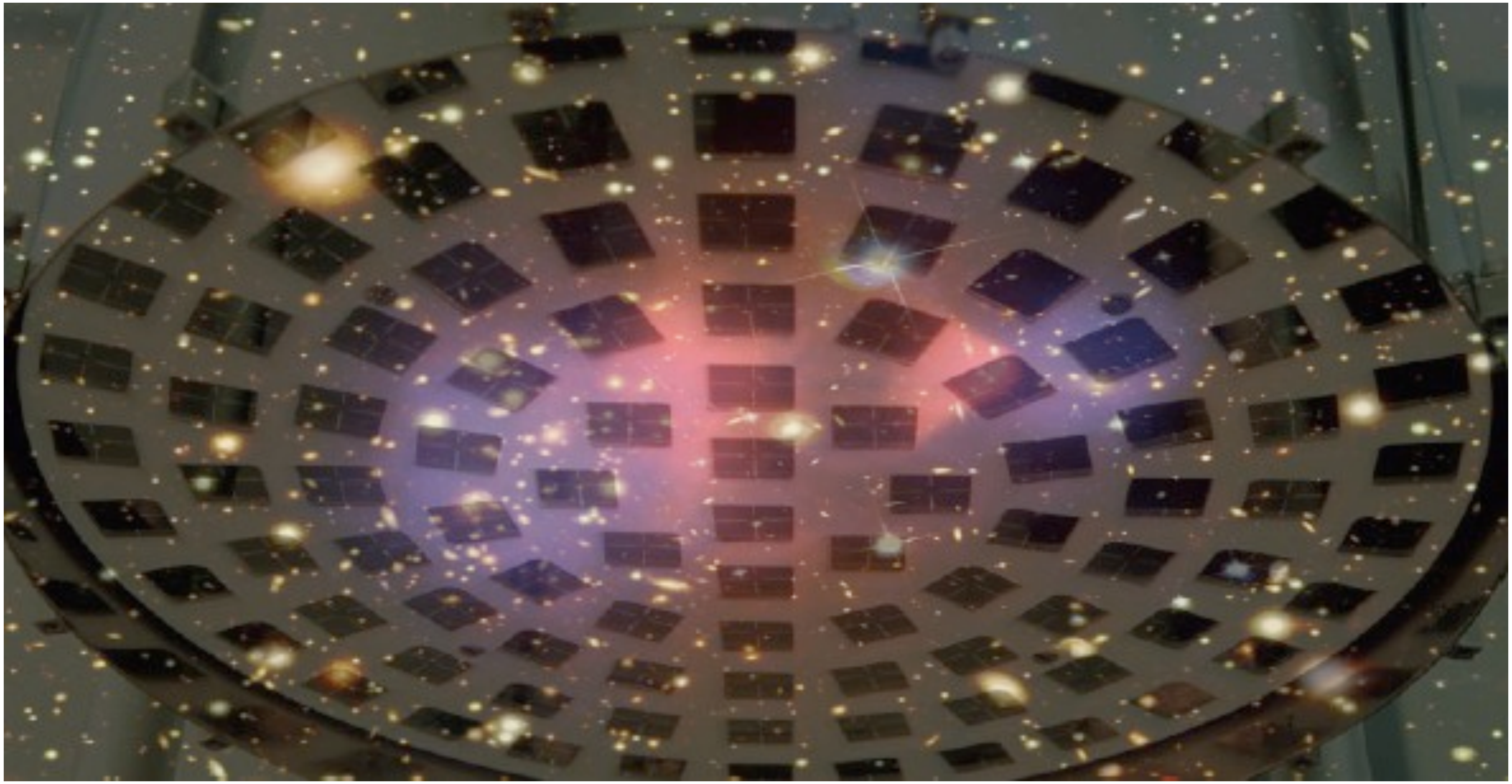
Search for Dark Matter



Elena Aprile
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Dublin Summer School on High Energy Astrophysics - July 11, 2011

Outline of Lectures

Lecture 1:

What we know about DM (in brief)
Principle of direct detection
Expected rate, signal and background sources
Experimental tour:
1) crystal scintillators DAMA/LIBRA & KIMS
2) noble liquid scintillators XMASS & DEAP/CLEAN

Lecture 2:

3) noble liquid (LXe) TPCs XENON & LUX
4) noble liquid (LAr) TPCs WArP & ArDM
5) bubble chambers COUPP
6) drift chambers DRIFT, DM-TPC,NEWAGE, MIMAC
7) bolometers CDMS, EDELWEISS & CRESST

References and Additional Readings

- ***Rate/Signal Definition***

J. D. Lewin and P. F. Smith, Astropart. Phys. 6, (1996) 87.

F. Donato, N. Fornengo, and S. Scopel, Astropart. Phys. 9,(1998) 247.

- ***Backgrounds and more***

G. Heusser, Ann. Rev. Nucl. Part. Sci., 45, (1995) 543.

R. J. Gaiskell, Ann. Rev. Nucl. Part. Sci., 54, (2004) 315.

- ***Detectors and experimental methods***

W. R. Leo, *Techniques for nuclear and particle physics experiments*, Springer, (1994)

G. F. Knoll, *Radiation Detection and Measurement*, Wiley, (2000).

- ***LXe Detectors and Applications***

E. Aprile and T. Doke, Review of Modern Physics (2010).

WHAT IS DARK MATTER?

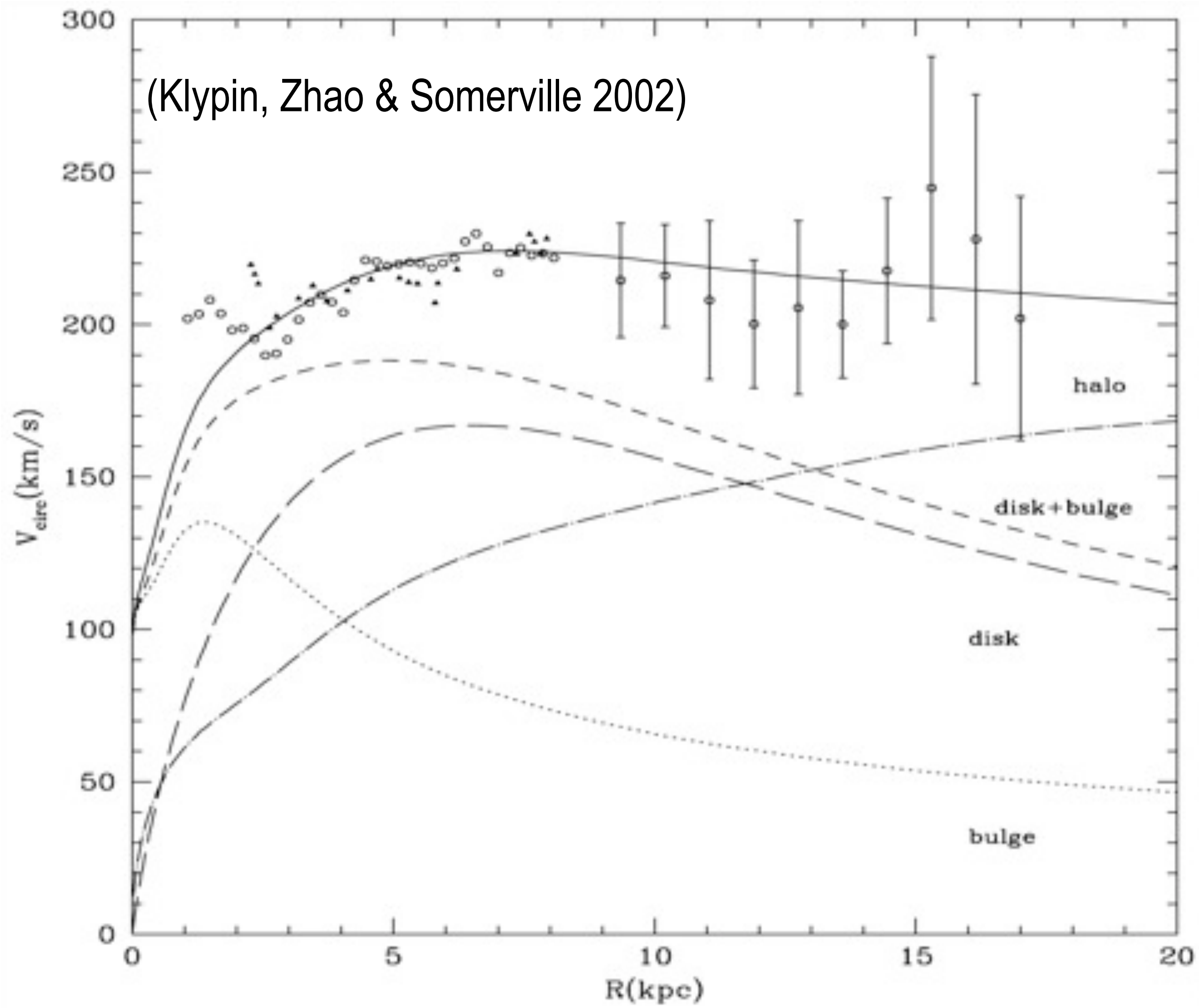
- Evidence for Dark Matter convincing at all scales.. BUT only from gravitational effects
- Independent measurements: BBN, CMB, Large Scale Structures, SN IA, etc..
- Relic Density known with precision: $\Omega_{DM} = 0.233 \pm 0.0013$
- Constraints on basic properties: neutral, stable, non-baryonic, cold, with right relic abundance
- Identity of DM impacts Cosmology and Fundamental Physics:
  - DM determines the physics of structure formation and impact evolution of Universe
  - DM is the leading empirical evidence for a new particle - new physics beyond the SM
- Favored scenario: DM is a thermal relic of the Big Bang, massive & with only weak interaction
  - Weakly Interacting Massive Particle (WIMP)

The Local Dark Matter Density

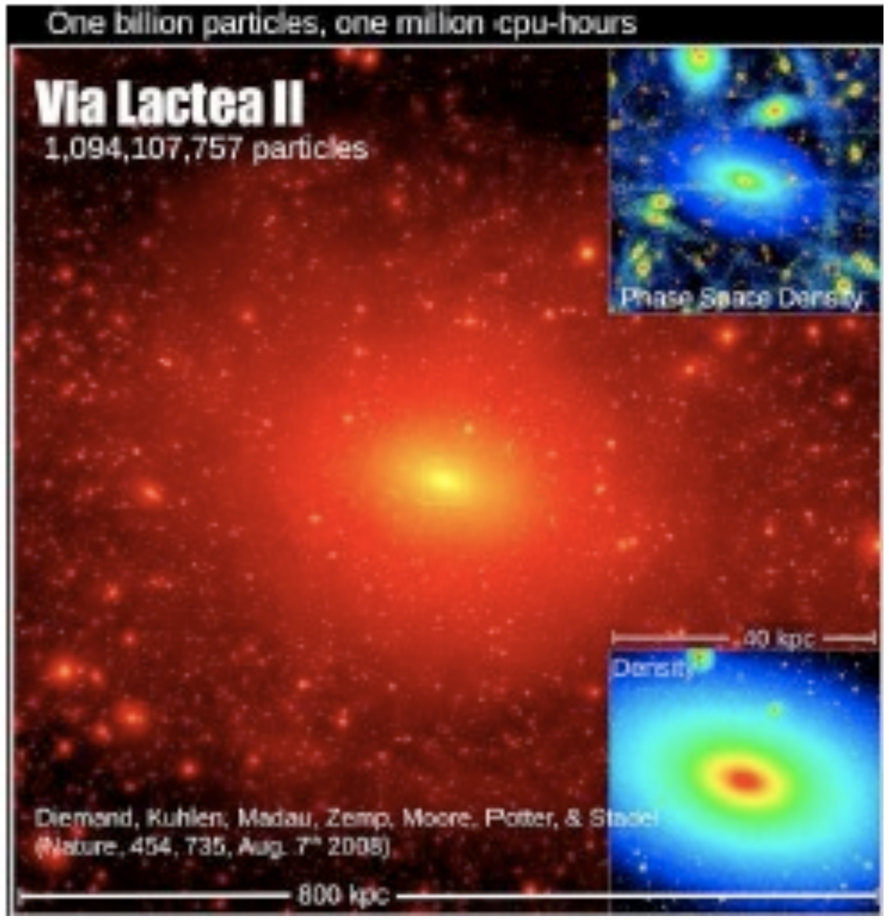
Measured galactic rotation curve of the Milky Way + modeling of various components (disk, bulge, halo):

$$M_{tot,lum} \approx 9 \times 10^{10} M_\odot$$
$$M_{virial} \approx 1 \ldots 2 \times 10^{12} M_\odot$$

$$\longrightarrow \quad \rho_{dark} \simeq 0.3 - 0.6\ GeV \cdot cm^{-3}$$



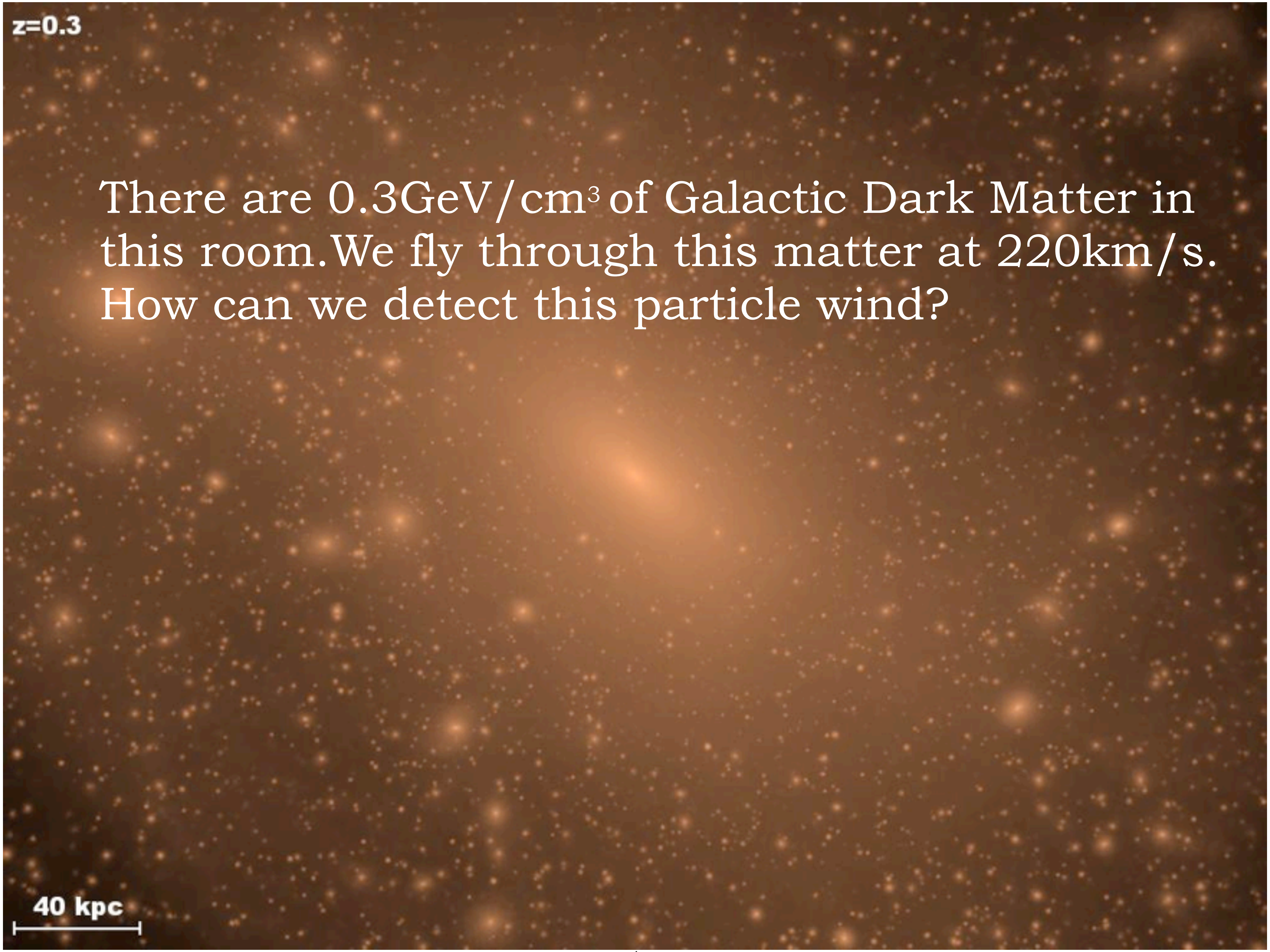
Numerical simulations now include influence of baryons on DM..stars and gas significantly alter local DM density



(J. Diemand et all, Nature 454, 2008, 735-738)

Density and velocity could be very different if Earth is within a DM clump or stream or if there is a Dark Disk.

The Challenge



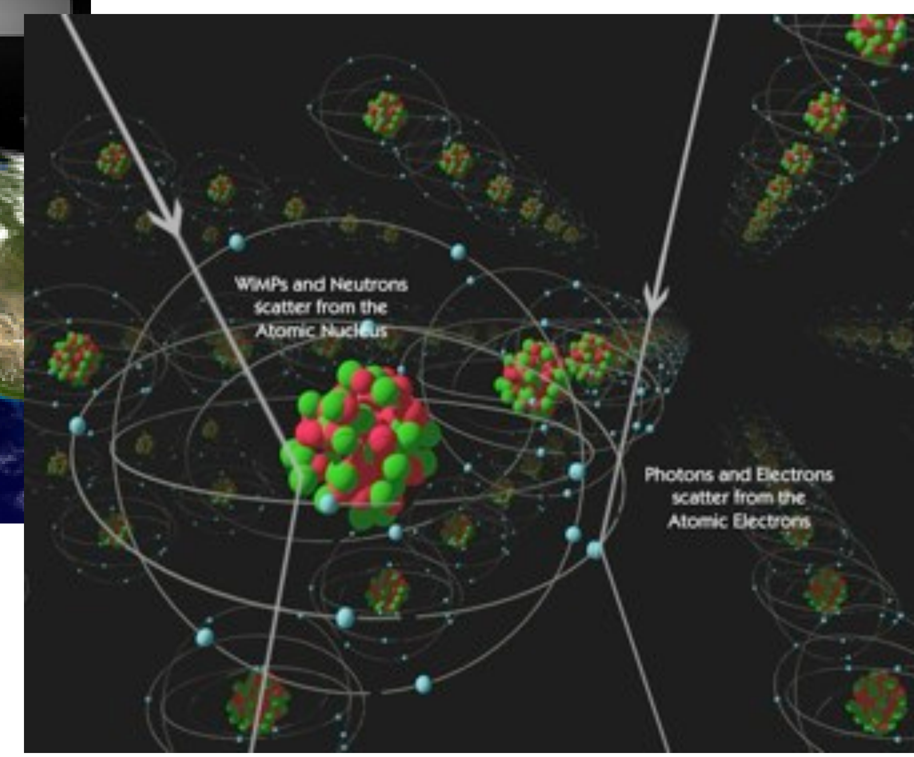
There are 0.3GeV/cm^3 of Galactic Dark Matter in this room.We fly through this matter at 220km/s. How can we detect this particle wind?

The Strategy

INDIRECT DETECTION: measure gamma rays, neutrinos , positrons, antiprotons, anti-deuterons, etc. from WIMP annihilation in GC, in Sun, in MW

PARTICLE COLLIDERS: Produce and Detect WIMPs

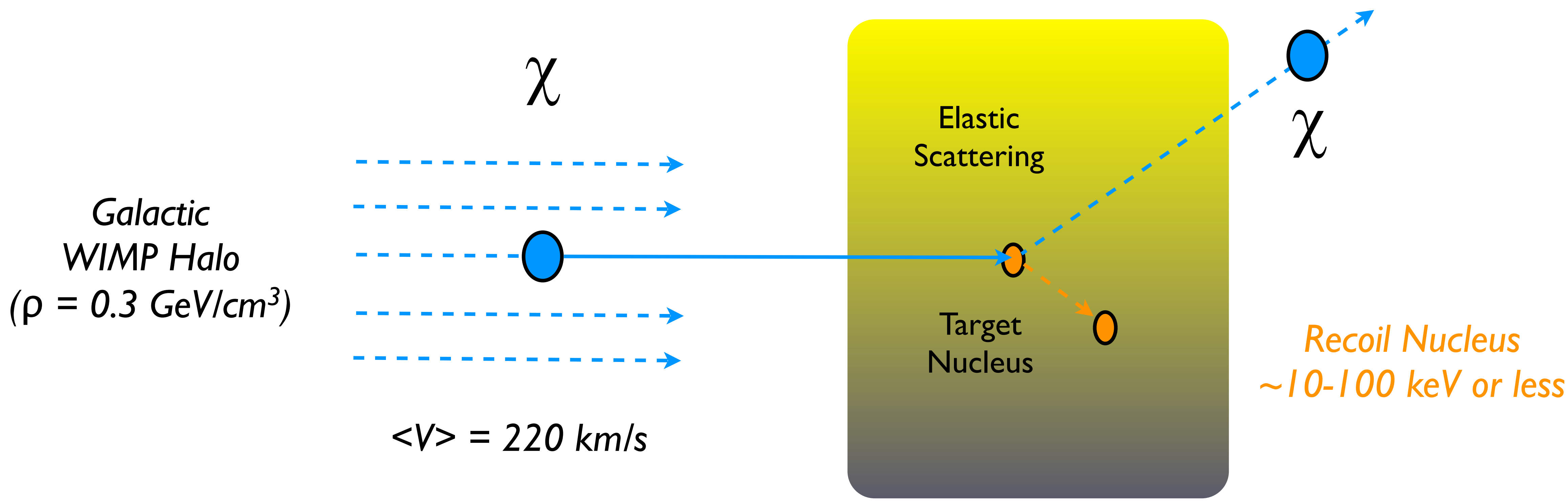
DIRECT DETECTION: measure WIMP scattering off targets in detectors on Earth



Potential for Breakthrough in this decade: WIMP models will be stringently probed by one or more method

Principle of Direct Detection

Goodman and Witten: coherent scattering of WIMPs off nuclei (1985)



$\sigma_{\chi N}$ *probed to-date ~* 10^{-44} *cm*^{2}

What is measured (with different target nuclei and detectors) : energy of the recoiling nucleus

What are the challenges: very small energy, very large backgrounds and very small rate

Let's calculate the energy spectrum and interaction rate in a detector on Earth

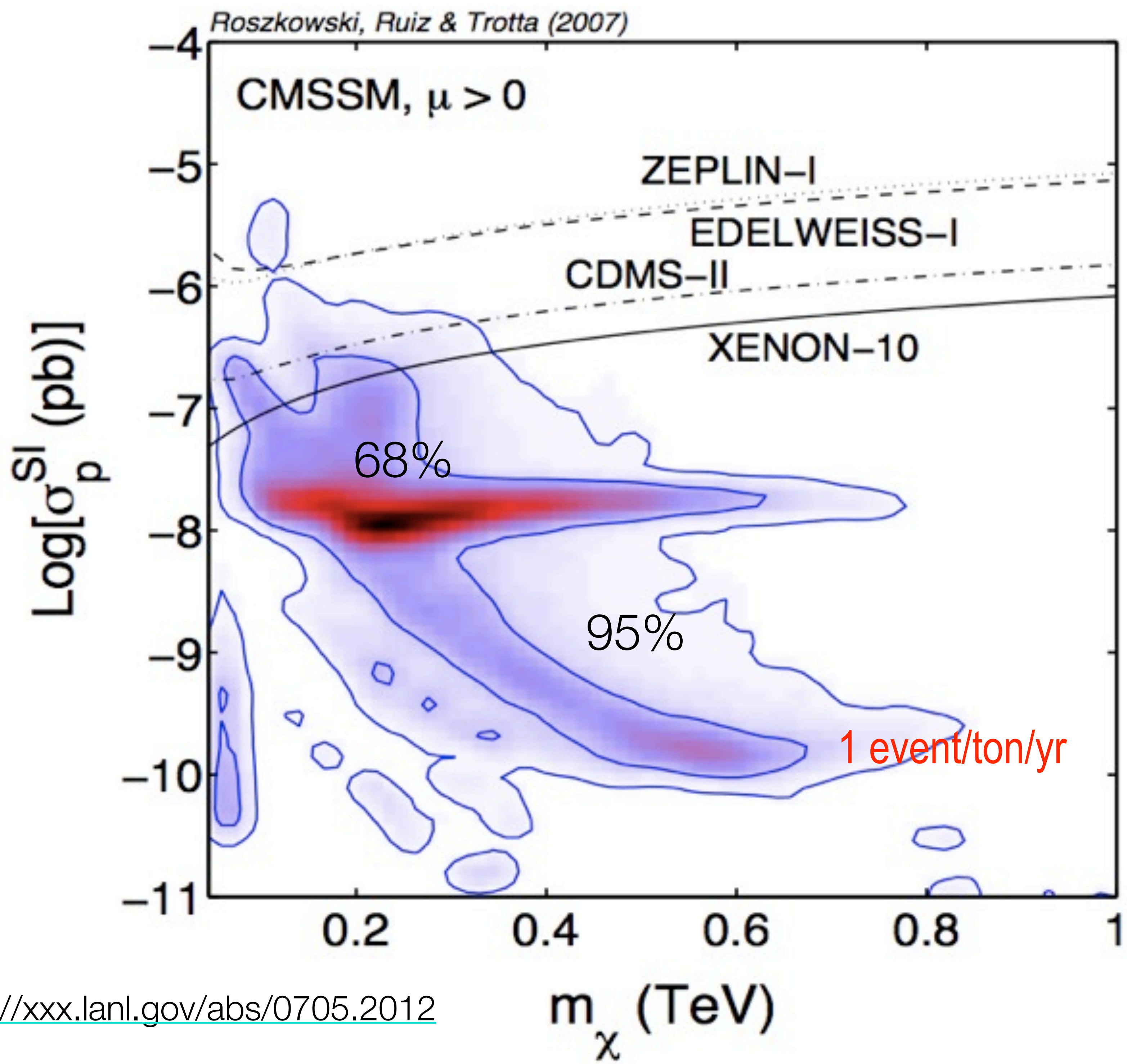
- To calculate the rate we need to know the properties of DM particles in our Galaxy (density of WIMPs in the halo of our Galaxy and their velocity distribution) --> large uncertainties on inputs from astrophysics

- We also need to know a cross-section --> not much guidance from theory as we are presented with a large range of parameter space and cross-sections spanning several orders of magnitude

WIMP-Nucleon Cross Section

To calculate a cross section we need a particle physics model

Example: CMSSM -> scalar cross sections on nucleons between 10^{-11} and 10^{-7} pb



http://xxx.lanl.gov/abs/0705.2012

The Flux of Dark Matter through the Earth

- We take the local DM density at our position in the galaxy to be (Astrophysics input)

$$\rho_0 \approx 0.3\,\mathrm{GeV\,cm^{-3}}$$

- For a DM particle with mass $m_x = 100$ GeV, this implies a number density

$n = \rho_0 / m_\chi$ to be $n \approx 3 \times 10^{-3}\,\mathrm{cm}^{-3}$

- Taking the WIMP velocity as $v \approx 300\,\mathrm{km\,sec}^{-1}$

the WIMP flux is $J = n\,v \approx 10^5\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$

- a very large number, but remember these particles are weakly-interacting particles

Direct Detection Rate

- The total event rate is

$$R \propto N_T \frac{\rho_0}{m_X} \sigma \langle v \rangle$$

where N_T is the number of nuclei in the target (Detector physics input), $\sigma = \sigma_{XN}$ is the WIMP-nucleus elastic scattering cross section (Particle physics input), and $<v>$ is the average WIMP velocity in the lab frame (Astrophysics input).

$$\langle v \rangle = \int_0^\infty v\, f(v)\; dv$$

- The differential event rate is

$$\frac{dR}{dE_R} \propto \frac{d}{dE_R}\left(N_T \frac{\rho_0}{m_X} \sigma \langle v \rangle \right)$$

- Since only $<v>$ depends on the recoil energy

$$\frac{dR}{dE_R} \propto N_T \frac{\rho_0}{m_X} \sigma \frac{d}{dE_R} \langle v \rangle$$

- usually expressed in differential rate unit (dru) or counts/kg/keV/day

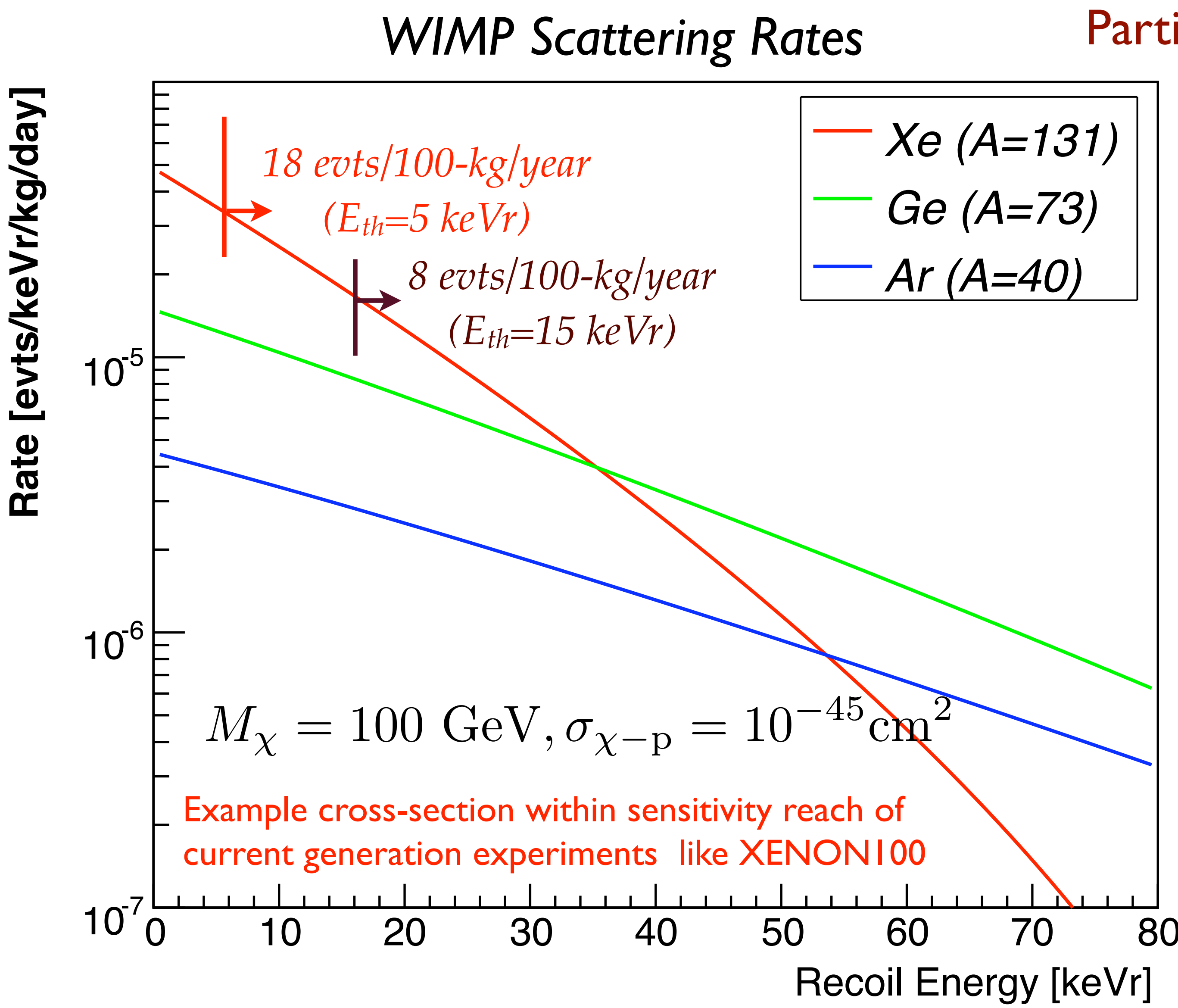
Typical WIMP Rate

Detector Physics input

Astrophysics input

$$R \propto N_T \frac{\rho_0}{m_X} \sigma \langle v \rangle$$

Particle Physics input



requirements for direct DM detectors

- ➡ *large mass (ton scale)*
- ➡ *low energy threshold (a few keV)*
- ➡ *low background noise*
- ➡ *intrinsic S/N discrimination*

$$\langle v \rangle = \int_0^{\infty} v\, f(v)\; dv$$

In practice we replace the integration limits with

$$\langle v \rangle = \int_{v_{\min}}^{v_{escape}} v\, f(v)\; dv$$

and thus

$$\frac{dR}{dE_R} \propto N_T \; \frac{\rho_0}{m_X} \; \sigma \int_{v_{\min}}^{v_{escape}} v\, f(v)\, dv$$

- The upper limit for the velocity is formally infinite. In practice one takes the escape velocity which depends on the halo properties

$$498\,\mathrm{km\,s^{-1}} < v_{escape} < 608\,\mathrm{km\,s^{-1}}$$

Smith et al. RAVE Survey, 07

- The lower limit is the minimum WIMP velocity necessary to produce a detectable recoil of energy E_R , given as

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

Let’s calculate this v_{min}

- The WIMP is non-relativistic when
  it collides with a nucleus N

- In the laboratory (LAB) frame
  the recoil energy of the nucleus is

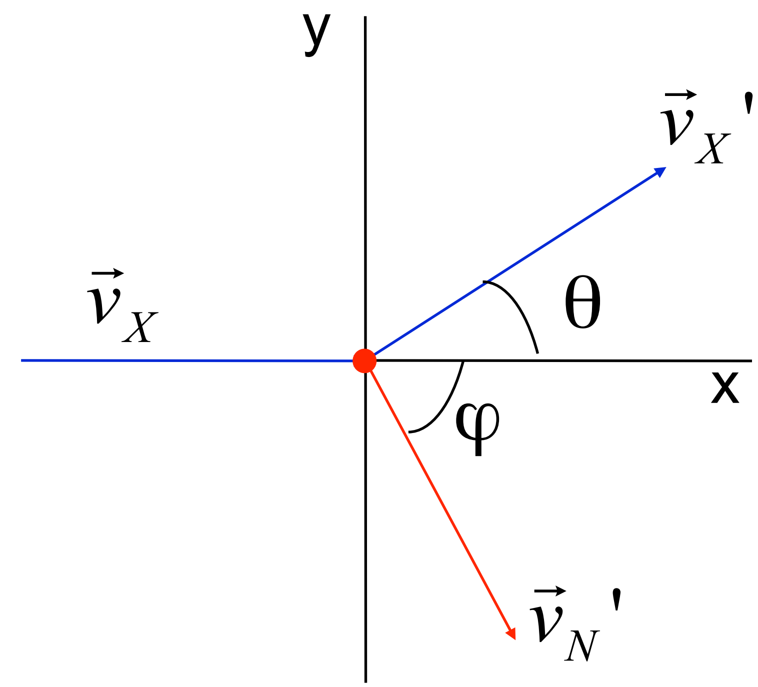
$$E_R = \frac{\mu^2 v_X^2 (1 - \cos\theta)}{m_N}$$

where v_X is the WIMP velocity in

the CM frame and the reduced mass is

$$\mu = \frac{m_X\, m_N}{m_X + m_N}$$

LAB frame



WIMP: $m_X, \quad \vec{v}_X = \vec{v}_{X,LAB}$

$$\vec{v}_{X,LAB} = \vec{v}_{X,CM} + \vec{w}, \quad \vec{w} = \text{CM velocity}$$

Nucleus: $m_N, \quad \vec{v}_N = \vec{v}_{N,LAB}$

$$\vec{v}_{N,LAB} = \vec{v}_{N,CM} + \vec{w}$$

In the CM frame:

$$m_X\, \vec{v}_{X,CM} = -m_N\, \vec{v}_{N,CM}$$

$$\rightarrow \quad \vec{v}_{N,CM} = -\frac{m_X}{m_N}\vec{v}_{X,CM}$$

- The energy of the recoiling nucleus is maximum for head-on collision

$$\cos\theta' = -1 \quad (P_{max} = 2\,\mu\, v)$$

$$E_R^{\max} = \frac{2\mu^2 v^2}{m_N}$$

- Typical energy: for $m_N = m_\chi = 100\ \mathrm{GeV}/c^2$ and v = 300 km/s,

$$E_{max} = \frac{2\mu^2\,\nu^2}{m_N} = \frac{2\,(m_\chi\, m_N)^2\,\nu^2}{(m_\chi + m_N)^2\, m_N} = \frac{2\,(100\frac{\mathrm{GeV}}{c^2})\,\frac{v^2}{c^2}\,c^2}{(200\,\frac{GeV}{c^2})^2(100\,\frac{GeV}{c^2})} \sim 50\mathrm{keV}$$

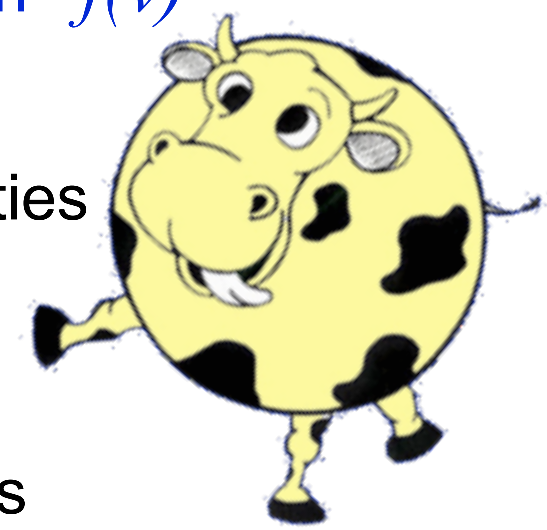
- This condition gives the minimum WIMP velocity to produce a recoil energy E_R

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

- This quantity is the lower limit v_{min} of our integral for the WIMPs event rate

- Going back to the differential rate $$\frac{dR}{dE_R} \propto N_T \, \frac{\rho_0}{m_X} \, \sigma \int_{v_{\min}}^{v_{escape}} v \, f(v) \, dv$$

- To calculate the rate we need to know the velocity distribution function *f(v)*
- The simplest model: **Isothermal spherical halo**



✓ Standard halo model choice for calculations of experimental sensitivities

- From the observations, the density is $\rho(\vec{r}) = \int d^3\vec{v} f(\vec{r}, \vec{v})$

- For the **isothermal spherical halo** the velocity distribution function is Maxwellian

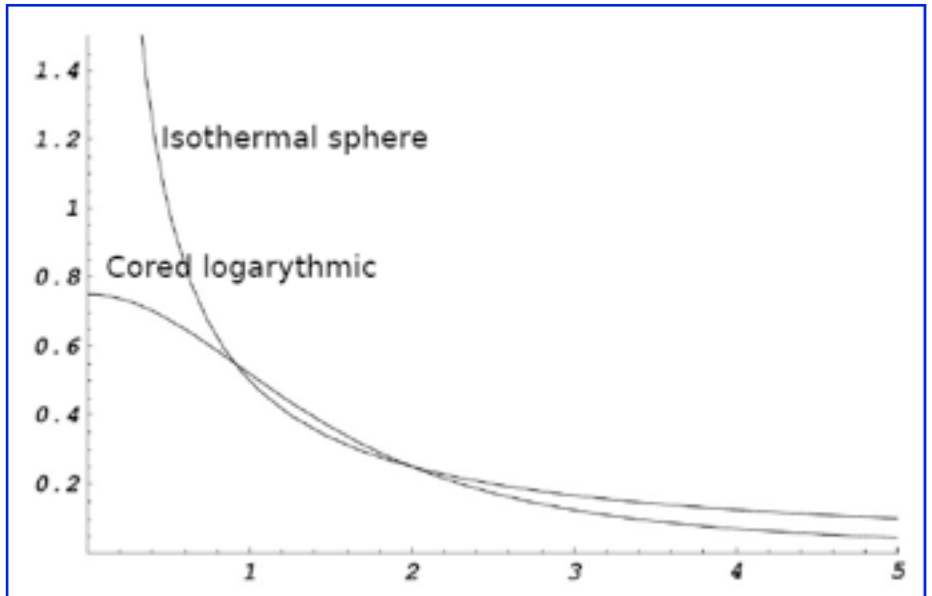
$$f(\mathbf{v}) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{|\mathbf{v}|^2}{2\sigma^2}\right)$$

which gives the correct behavior for the density $\rho_{DM}(r) = \frac{v_0^2}{4\pi G} \frac{1}{r^2}$

- Since there is a singularity when $r \rightarrow 0$

  a core radius R_C is added

$$\rho_{DM}(r) = \frac{v_0^2}{4\pi G} \frac{3R_c^2 + r^2}{(R_c^2 + r^2)^2}$$



with a Maxwellian velocity distribution, the integral is

$$\int_{v_{\min}}^{v_{escape}} v\, f(v)\ dv \quad \propto \quad \int_{v_{\min}}^{v_{escape}} \exp\left(-v^2/v_0^2\right) \quad \propto \quad \exp\left(-v^2/v_0^2\right)$$

- Since the WIMP velocity is related to the recoil energy $E_R = \dfrac{2\mu^2 v^2}{m_N}$

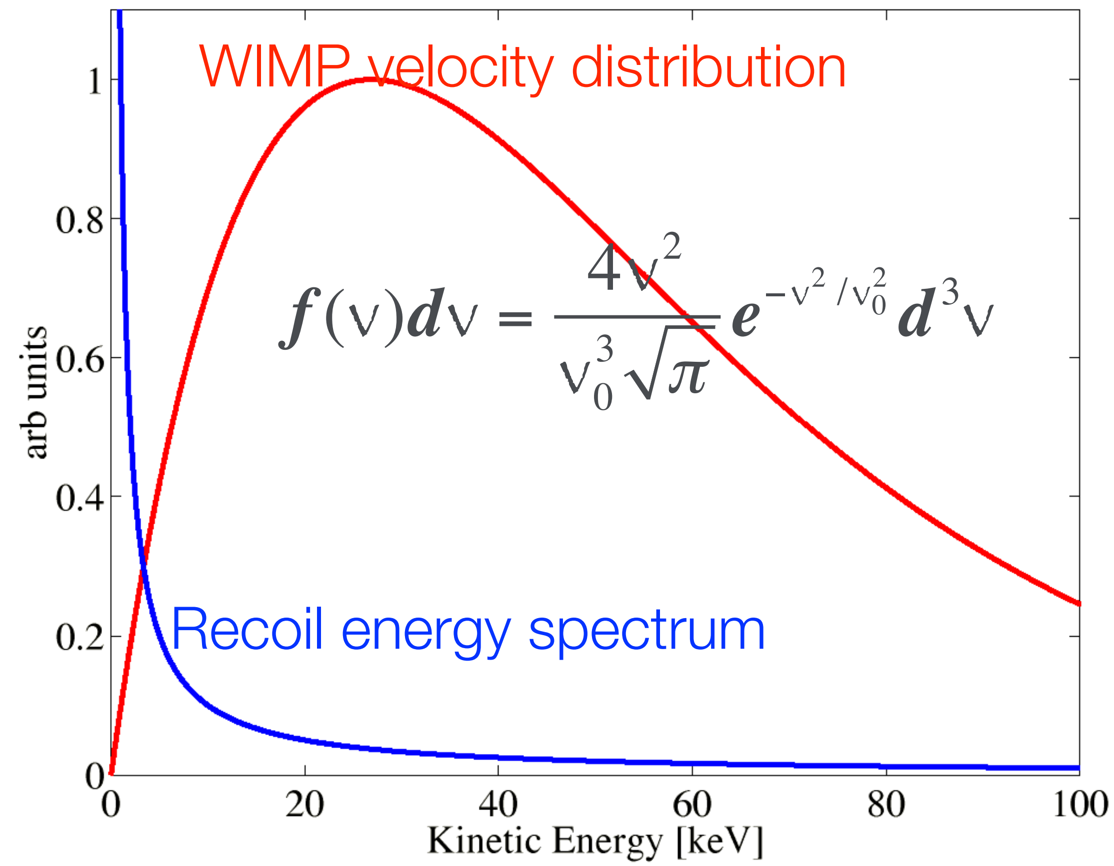
we find that the differential event rate for WIMPs goes exponentially with E_R

$$\frac{dR}{dE_R} = \frac{R}{k\, E_0} \exp\left(-E_R/k\, E_0\right)$$

where R is the total event rate

$$E_0 = \frac{m_X v_0^2}{2}$$

$$k = \frac{4\mu}{m_X + m_N}$$



Correction: Earth velocity

- Up to now we have neglected the motion of the Earth in the Galaxy

$\vec{v}_X = \vec{v}_{X,E} =$ WIMP velocity in the Earth (target) frame

$\vec{v}_{X,G} =$ WIMP velocity in the Galaxy frame

$\vec{v}_{E,G} =$ Earth velocity in the Galaxy frame

$$\vec{v}_{X,E} = \vec{v}_{X,G} - \vec{v}_{E,G} = 220\ \mathrm{Km/s}$$

Then the corrected differential rate is

$$\frac{dR(v_{E,G},\infty)}{dE_R} = c_1 \frac{R}{k\,E_0} \exp\left(-c_2 E_R / k\,E_0\right)$$

where c_1 and c_2 are fitting constants: $c_1 = 0.751$ $c_2 = 0.561$

- This expression would be fine for a point-like nucleus but the nucleus has a structure!

Correction:The Form Factor

- The scattering of electrons from a point-like target nucleus is described by

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Rutherford}} = \frac{(zZe^2)^2}{(4\pi\varepsilon_0)^2 \cdot (4E_{\text{kin}})^2 \sin^4\frac{\theta}{2}}$$

- It agrees with the experimental cross-sections only for $\vec{q} \to 0$

The experimental cross-sections are systematically smaller and show typical diffraction patterns

The spatial extension of a nucleus is described by the Form Factor $F(q^2)$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp.}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Ruth}} \cdot \left|F(\boldsymbol{q}^2)\right|^2$$

$F(q^2)$ is the Fourier transform of the (charge or mass) nuclear density

$$F(\vec{q}) = \int d^3\vec{r}\ \rho_N(\vec{r})\, e^{i\vec{q}\cdot\vec{r}/\hbar}$$

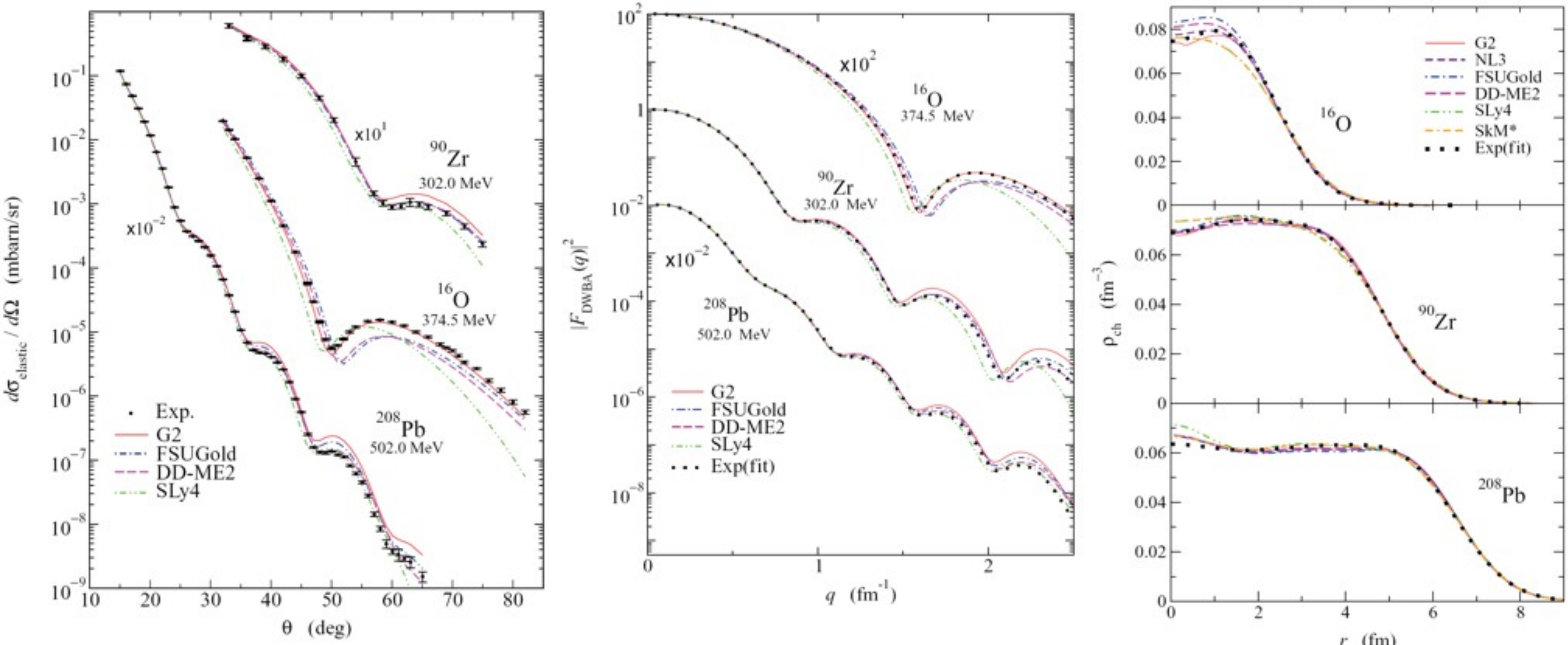
Example of Form Factor

- The more extended the distribution, the stronger the fall-off of $F(q^2)$ with q^2
- For lighter nuclei $F(q^2)$ falls off slowly
- In the limit of a point-like target $F(q^2) \rightarrow 1$
- The location of the minima tells us the size of the scattering nucleus

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp.}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Ruth}} \cdot \left|F(\boldsymbol{q}^2)\right|^2$$

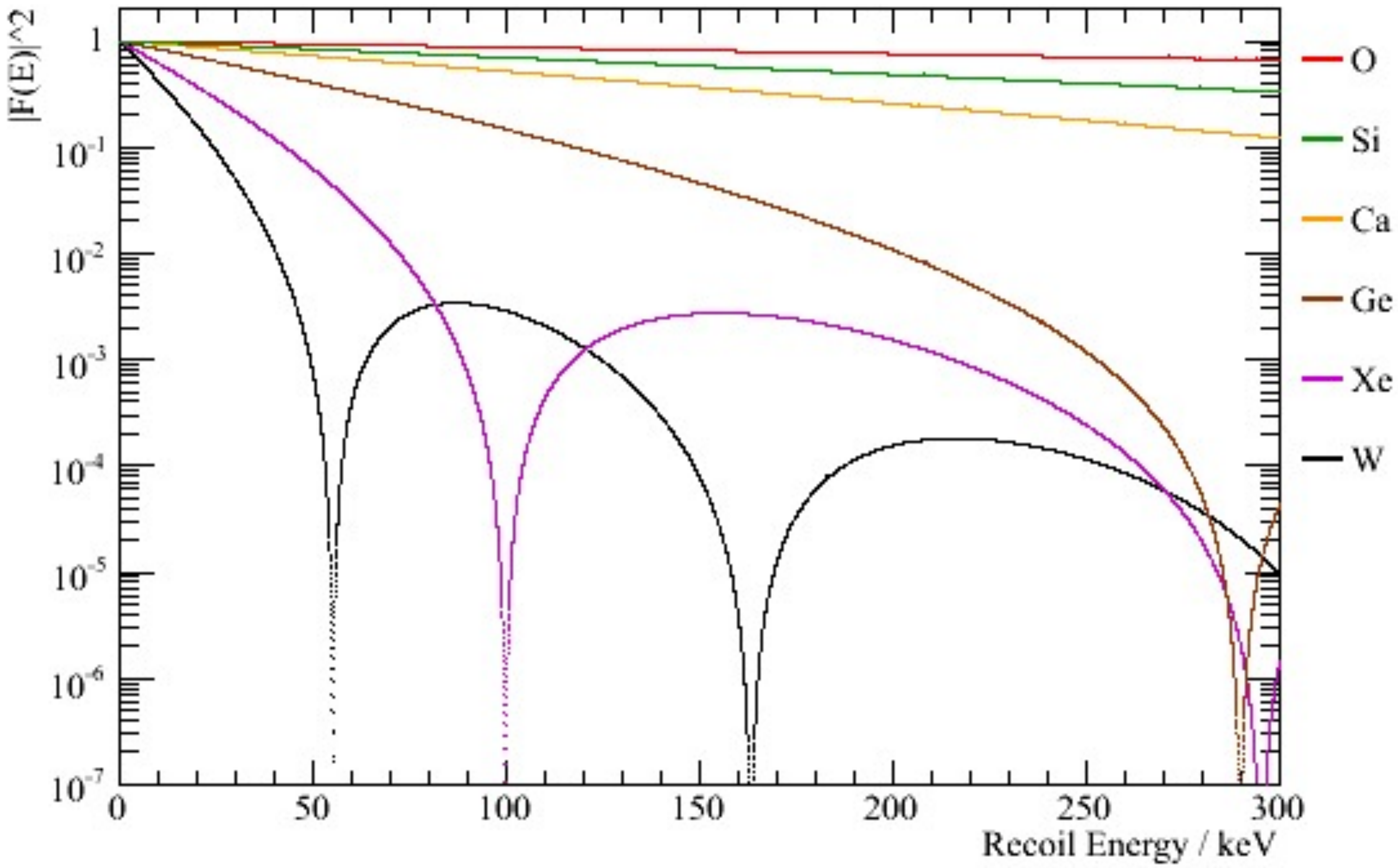
$$\left|F(\vec{q})\right|^2 = \left|\int d^3\vec{r}\; \rho_N(\vec{r})\, e^{i\vec{q}\cdot\vec{r}/\hbar}\right|^2$$

$$\rho_N(\vec{r})$$



X. Roca-Maza et al., Phys. Rev. C 78 (2008) 044332

Form Factor for different nuclei used in direct DM search



With the Helm parametrization for the nuclear density the form factor is

$$F^2(Q) = [\frac{3j_1(qR_1)}{qR_1}]^2 e^{-(qs)^2}$$

J = 1st Bessel function

s = nuclear skin thickness ~1 fm

$R_1 \propto 1.14\,A^{1/3} \sim 7A^{1/3}\ \mathrm{GeV}^{-1}$

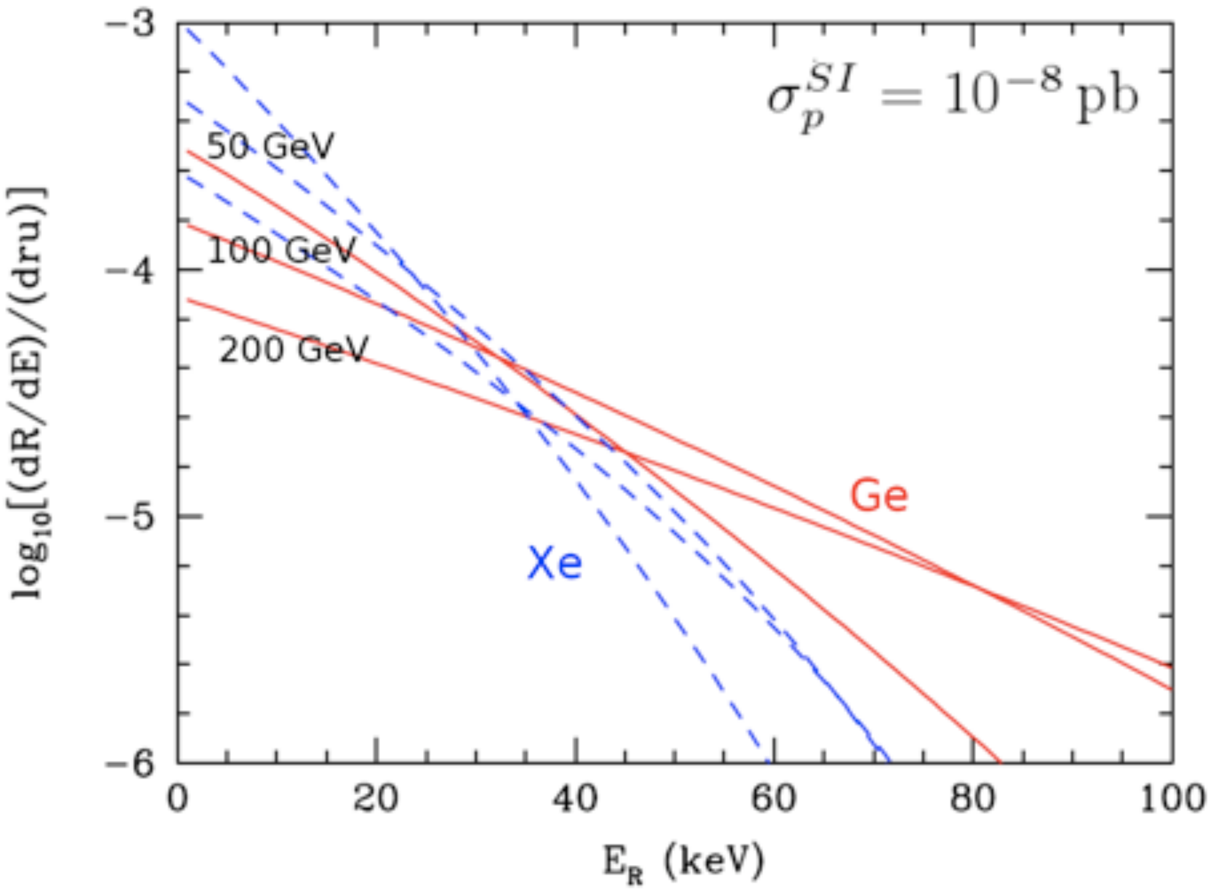
Form factor is important for large nuclei, such as Xe, W, etc.
For these targets, a low energy threshold is essential to minimize Form factor suppression of rate
At the same time, the coherence of the scattering favors large nuclei

- Taking into account the Form Factor, the WIMP differential event rate becomes

$$\frac{dR}{dE_R} \propto N_T \frac{\rho_0}{m_X} \sigma F^2(E_R) \int_{v_{\min}}^{v_{escape}} v\, f(v)\, dv$$

$$\Rightarrow \quad \frac{dR}{dE_R} = \frac{R_0}{k\, E_0} F^2(E_R) \exp(-E_R / k\, E_0)$$

- Rate higher in target with large nuclei (if detector's energy threshold is low).
- For a given cross-section and target rate higher for low mass WIMPs

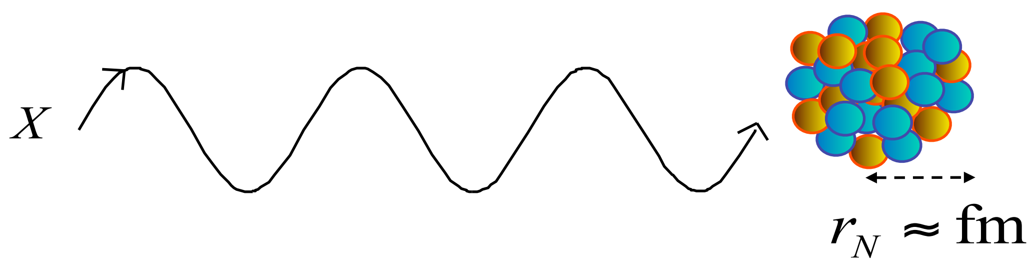


WIMP-Nucleus Interactions

- In non-relativistic case (v<<c) scalar and axial vector interactions dominate
- We simply speak of spin-independent and spin-dependent interactions

- Interaction is coherent over the nucleus since the De Broglie wavelength of a WIMP is of nuclear dimension:

$$\frac{\lambda_{WIMP}}{2\pi} = \frac{\hbar}{p} = \frac{\hbar c}{mc^2\, v/c} = \frac{197\ \mathrm{MeV\ fm}}{100\ \mathrm{GeV}\, 10^{-3}} \approx \mathrm{fm} \approx r_N$$



✓ For spin-independent scattering targets with large nuclei favored since cross section boosted by A^2

$$P = \left| A \sigma_{Xn}^{si} \right|^2 = A^2 \left(\sigma_{Xn}^{si} \right)^2$$

✓ For spin dependent scattering targets with odd nuclei favored - particle shell model assumes nuclear spin due to spin of the single unpaired proton or neutron and thus vanishes for even nuclei

$$P = \left| J \sigma_{Xn}^{sd} \right|^2 = J(J+1) \left(\sigma_{Xn}^{sd} \right)^2$$

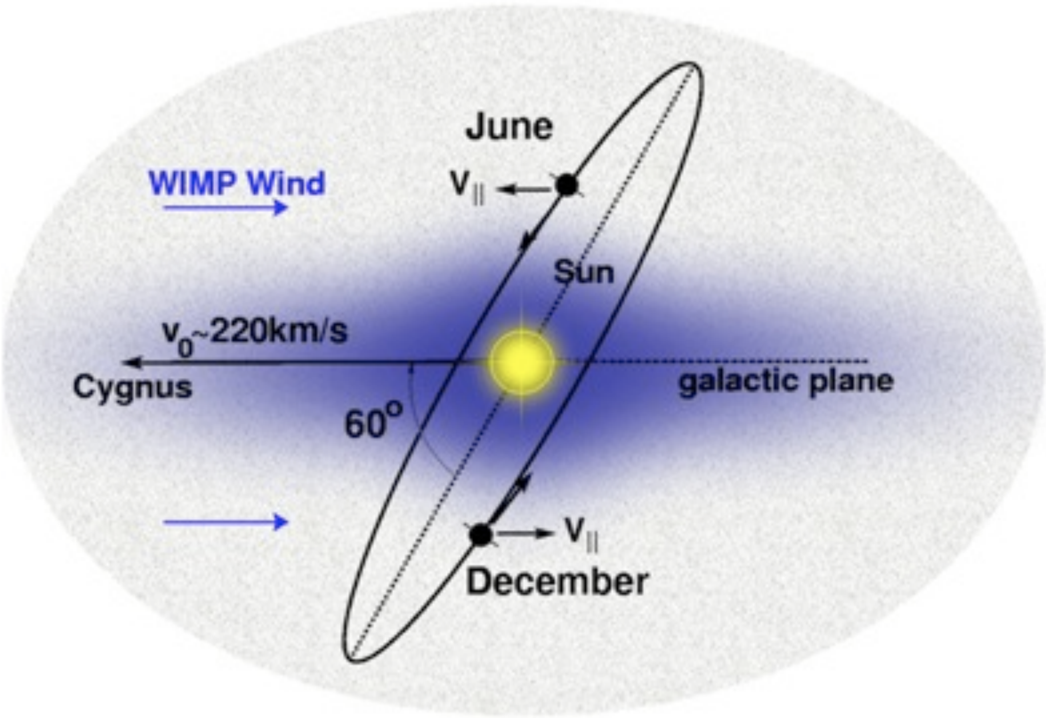
WIMP Signatures

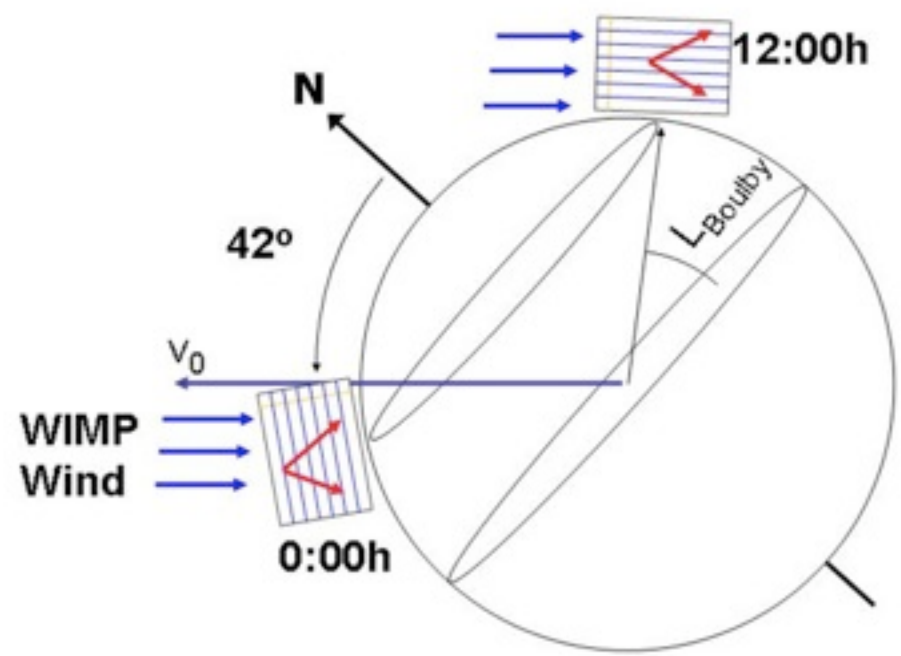
- *Nuclear recoils:* *single scatters with uniform distribution in target volume*

- *A^2 & $F^2(Q)$ Dependence:* *test consistency of signal with different targets (SI and SD)*

- *Annual Modulation:* *Earth annual rotation around Sun: orbital velocity has a component that is anti-parallel to WIMP wind in summer and parallel to it in winter. So apparent WIMP velocity (and hence the rate) will increase (decrease) with season: rate modulation with a period of 1 year and phase ~2 June; difficult to detect since it is ~2% effect and hard to disentangle from other effects which also have seasonal dependence*

- *Diurnal Direction Modulation:* *Earth rotation about its axis, oriented at angle w/respect to WIMP "wind", change the signal direction by 90 degree every 12 hrs. ~30% effect.*





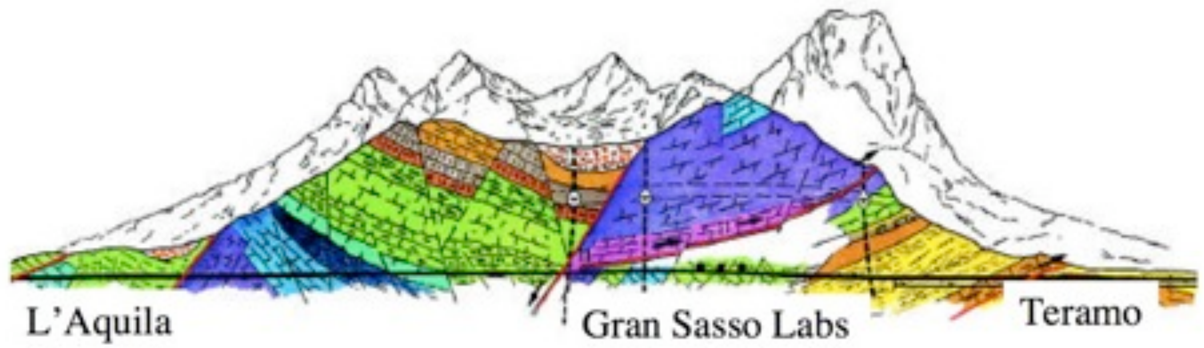
Background Sources

- *Detector related:*
  - *intrinsic radioactivity (U,Th, K, Co, etc.) in materials: a source of gammas and neutrons background--> careful screening and selection*
  - *intrinsic radioactivity in target itself (U,Th, Rn, Kr85, Ar39, etc.) --> purification and careful handling*

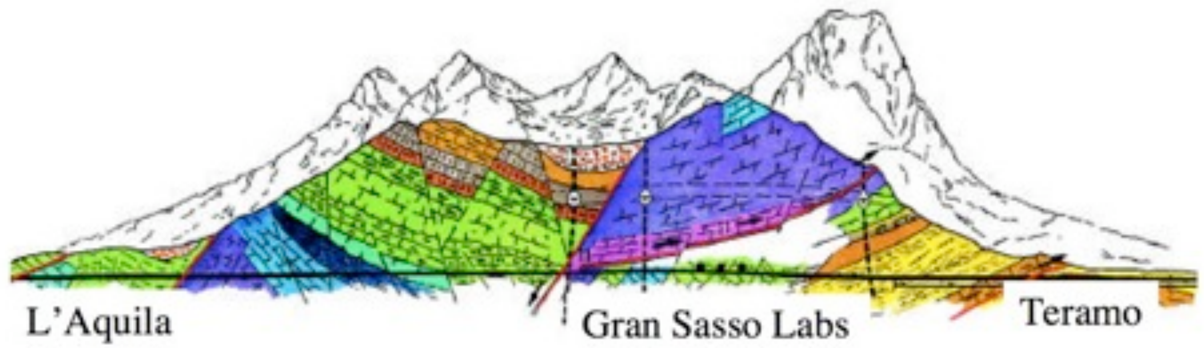
- *Environment related:*
  - *radioactivity of environment materials (gammas and neutrons from (alpha,n) and muon-spallation): shielding (Pb, Cu, PE, H2O, etc.)*
  - *cosmic ray muons: go underground*
  - *fast neutrons induced by muons (ultimate background)*

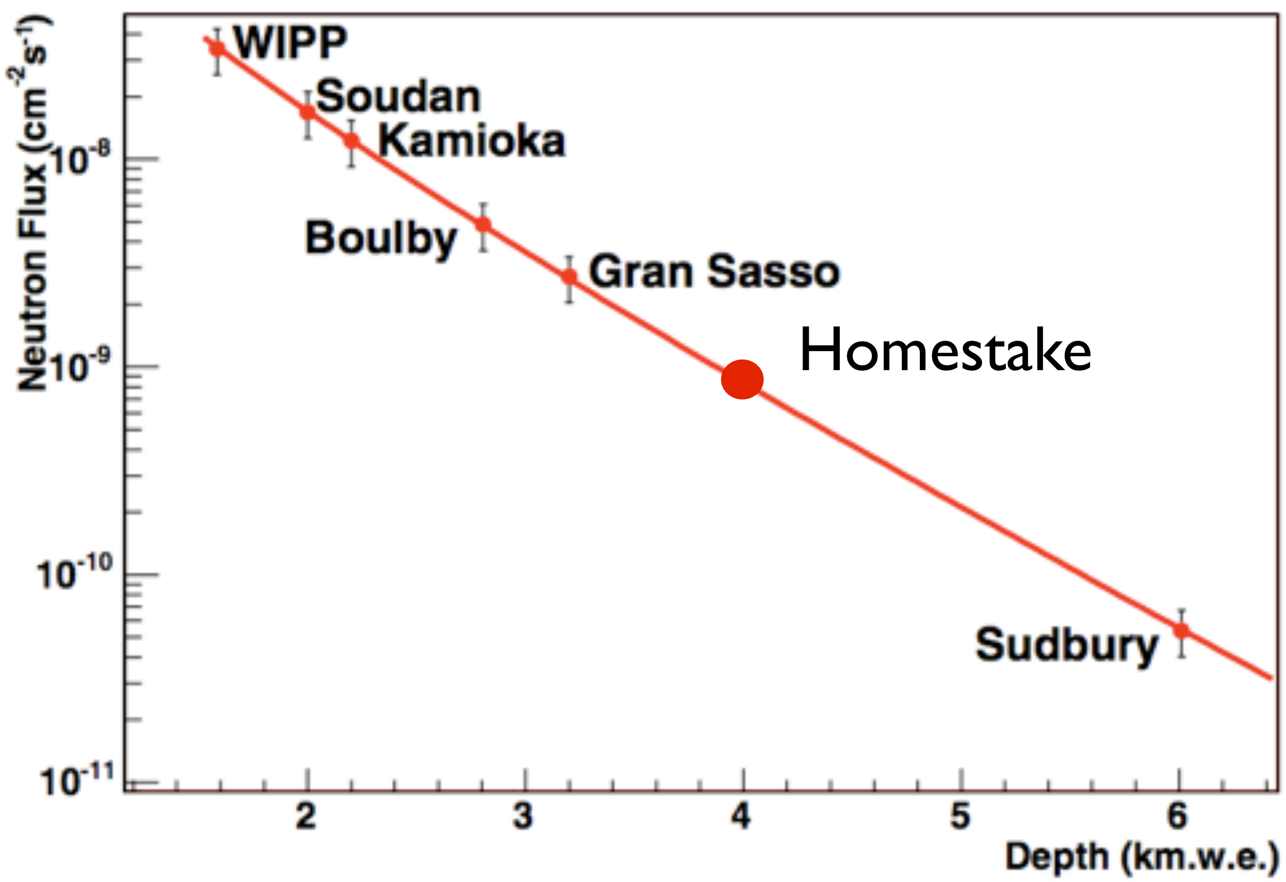
- *Other physics processes related:*
  - *solar neutrinos, double beta decay --> start to be relevant for very sensitive DM searches and as threshold is lowered*

Neutron Background: the need for deep underground laboratories



Neutron Background: the need for deep underground laboratories

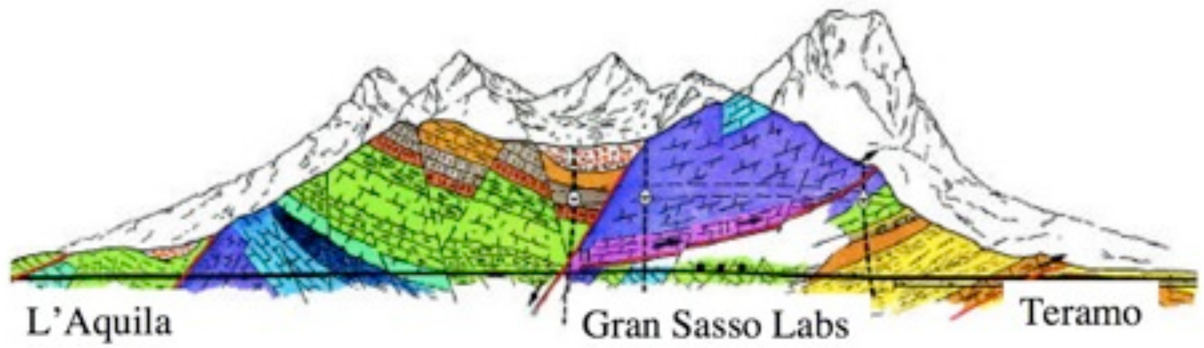


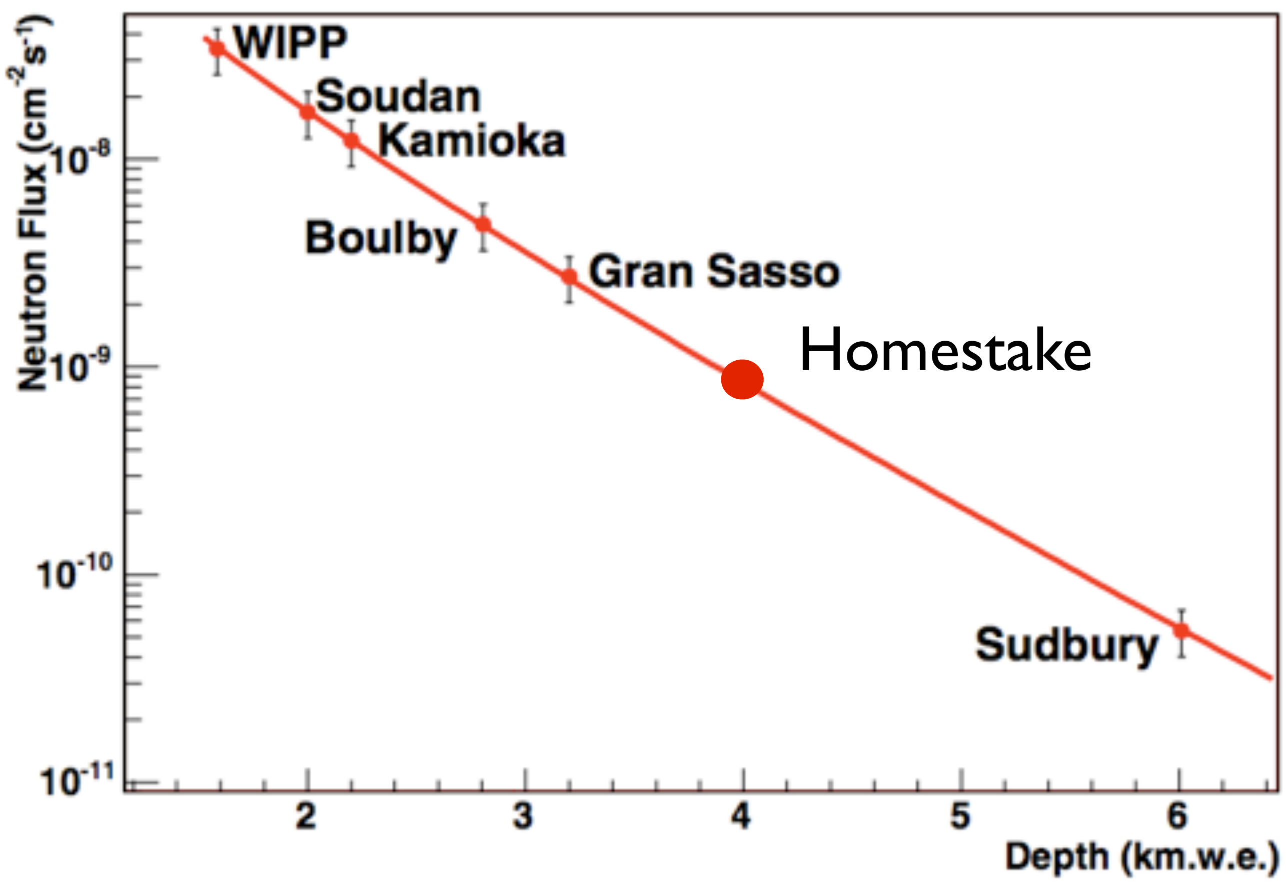


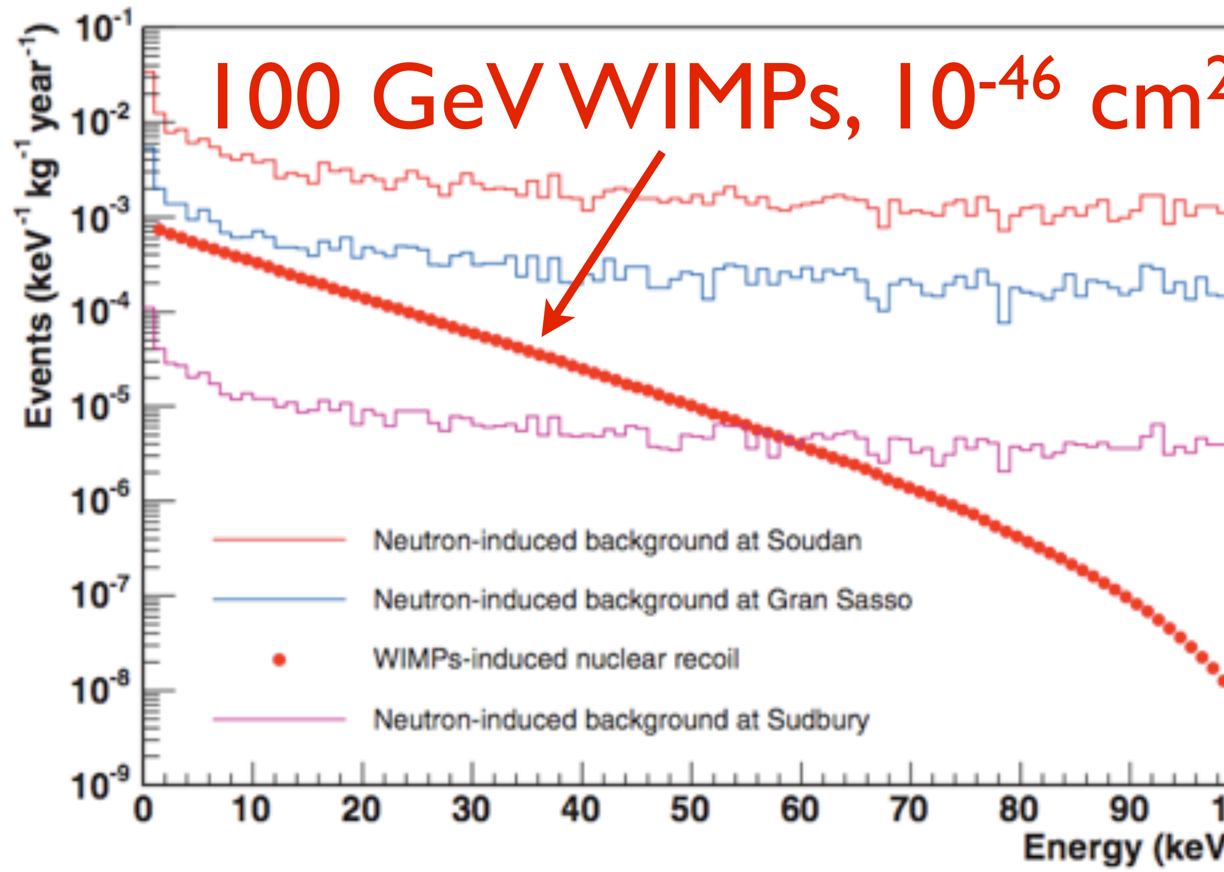
muon induced neutron flux

Mei and Hime, PRD (2006)

Neutron Background: the need for deep underground laboratories





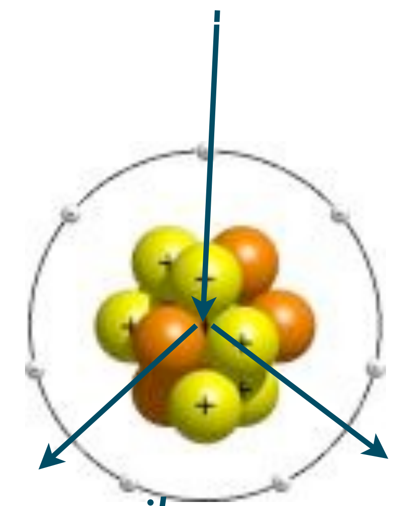


muon induced neutron flux

signal/background event rates

Mei and Hime, PRD (2006)

Quenching factor and discrimination



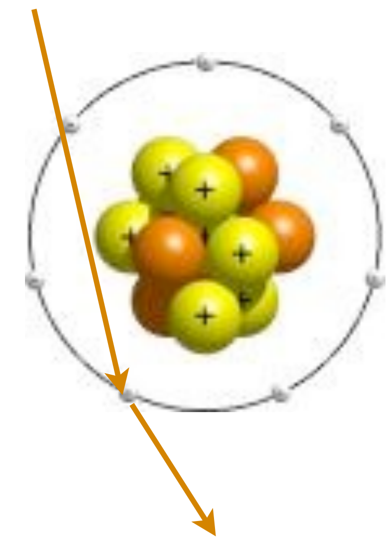
WIMPs (and neutrons) scatter off nuclei

Most background (gammas, electrons) scatter off electrons

Detectors have a different response to nuclear recoils than to electron recoils

Quenching factor = describes the difference in the amount of visible energy in a detector for these 2 classes of events

- keVe = measured signal from an electron recoil
- keVr = measured signal from a nuclear recoil
- => for nuclear recoil events:



Evisible (keVe) = QF x Erecoil (keVr)

the energy scale is calibrated with gamma and neutron sources

Quenching factor and discrimination

the quenching allows to distinguish between electron and nuclear recoils if two simultaneous detection mechanisms are used

example:

charge and phonons in Ge

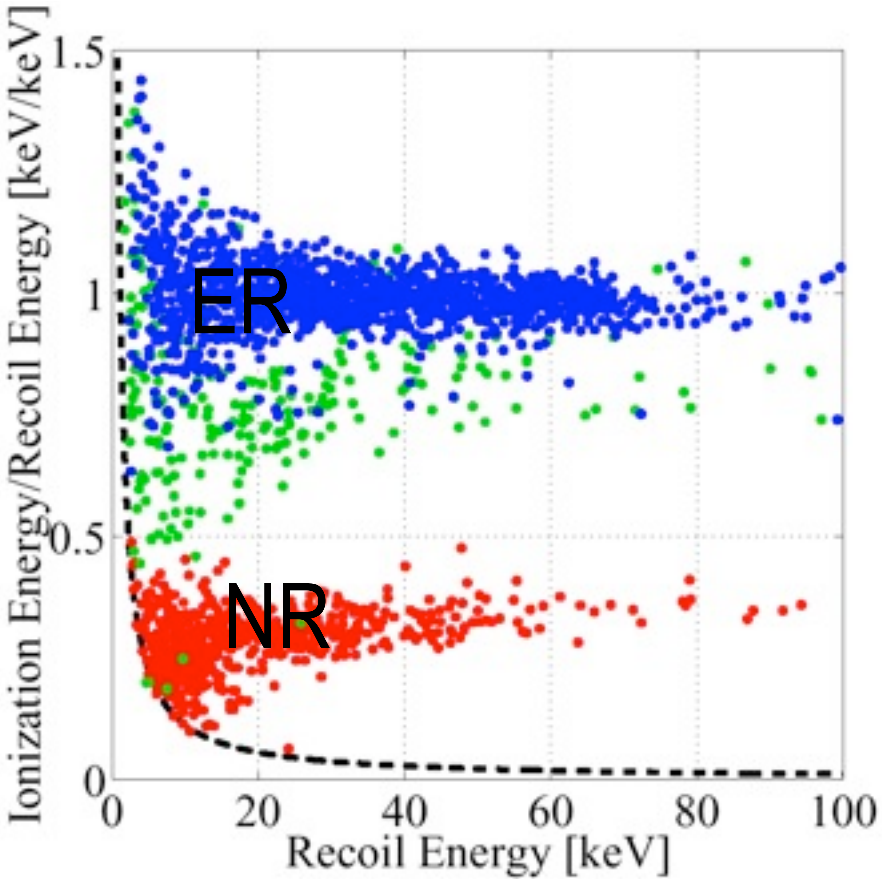
$E_{visible} \sim 1/3 \ E_{recoil}$ for NR

(=> QF ~ 30% in Ge)

ER = background

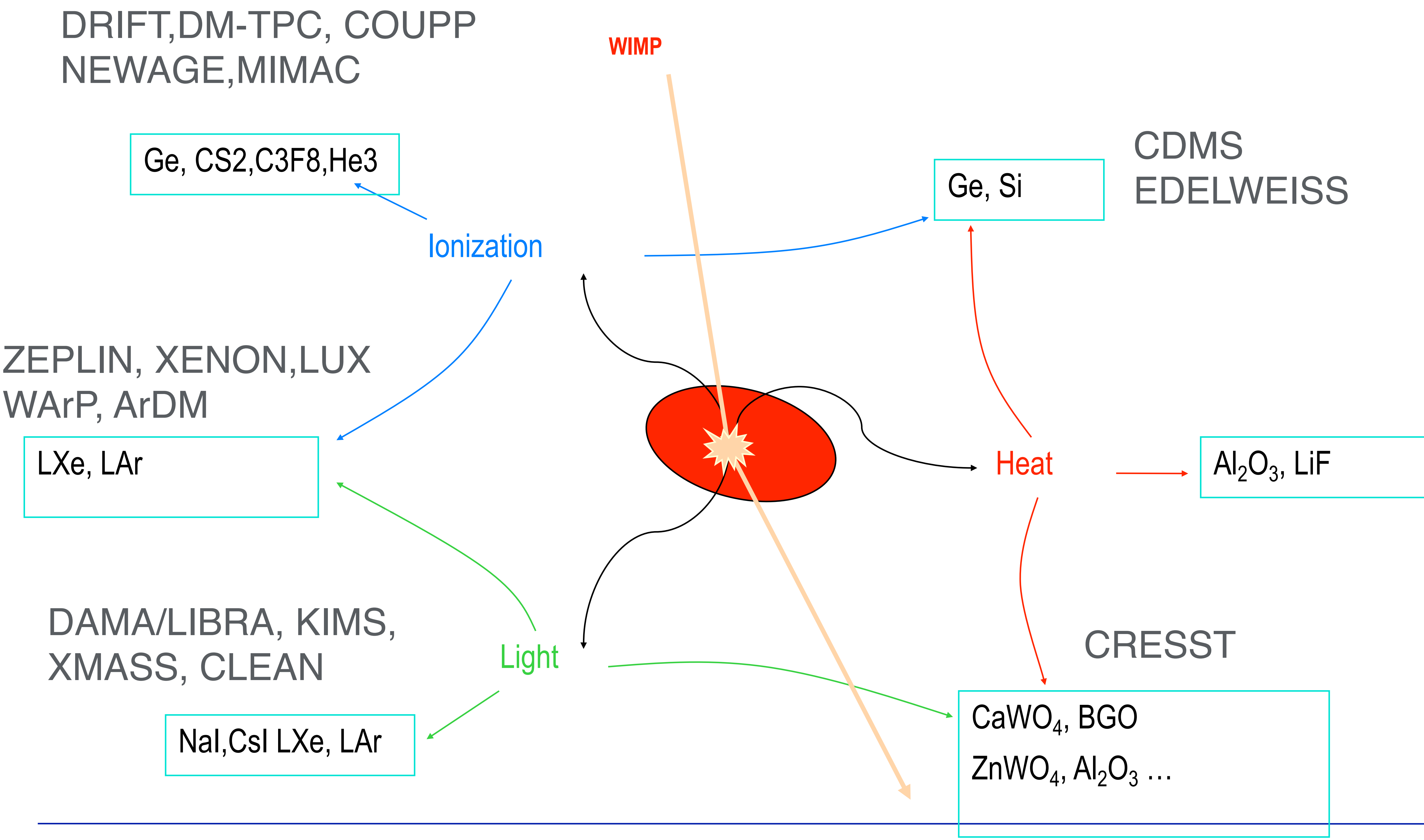
NR = WIMPs or neutrons (background)

Similarly in noble liquids..discussed later

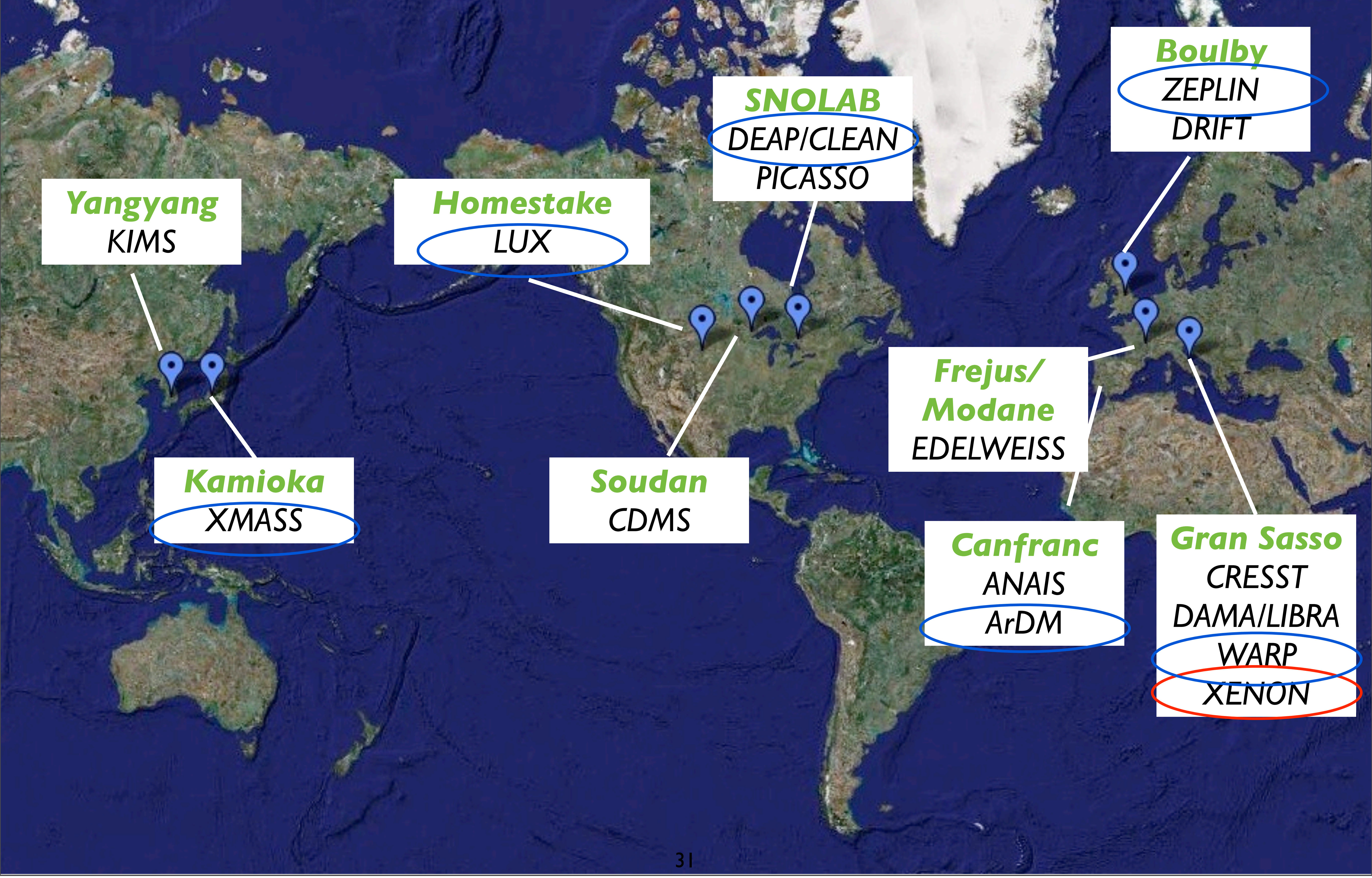


Direct Detection Experiments

After Drukier and Stodolsky, PRD 30 (1984) 2295
(and Goodman and Witten (1985))



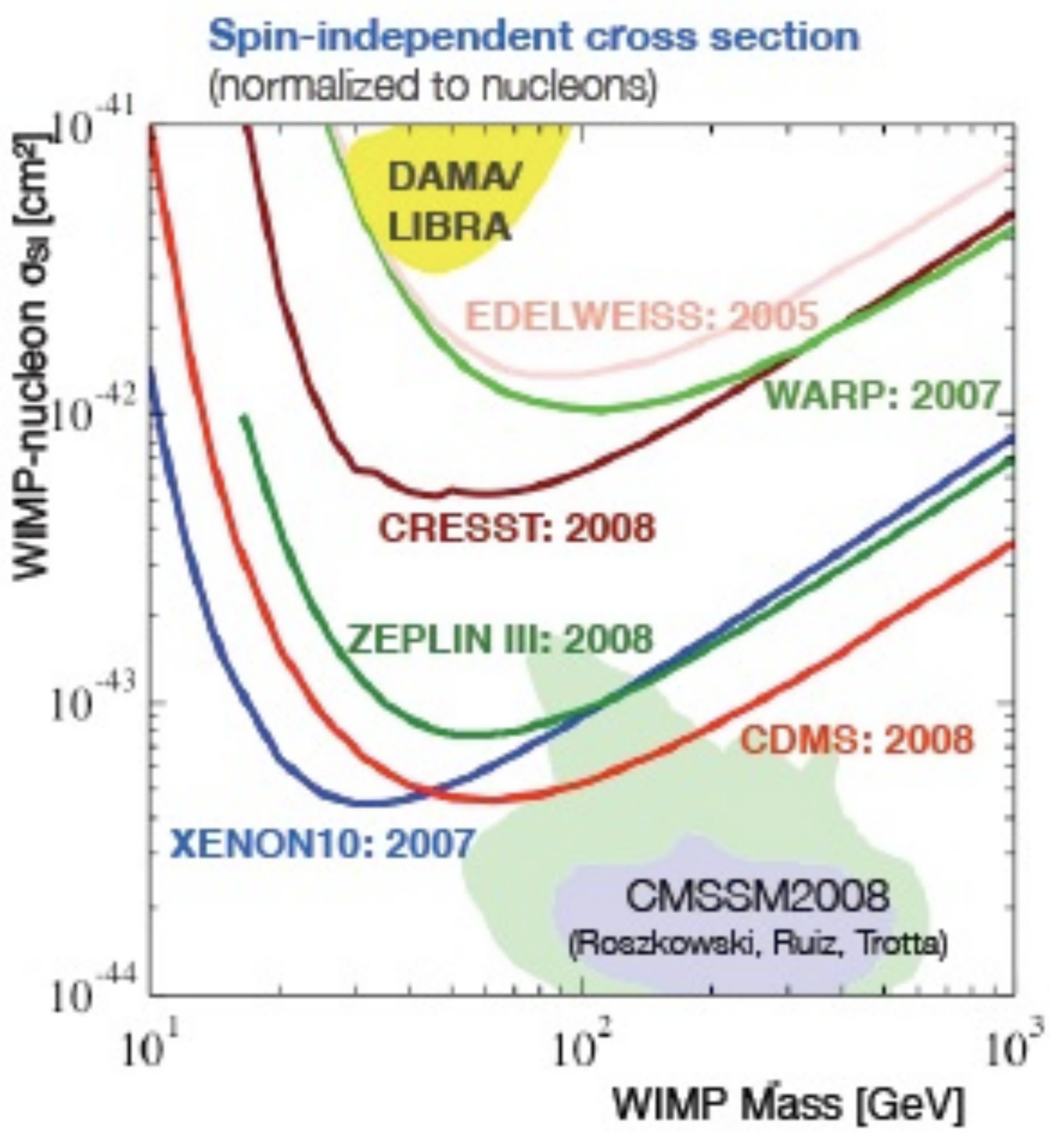
World Wide Dark Matter Searches: ~50% use Noble Liquids

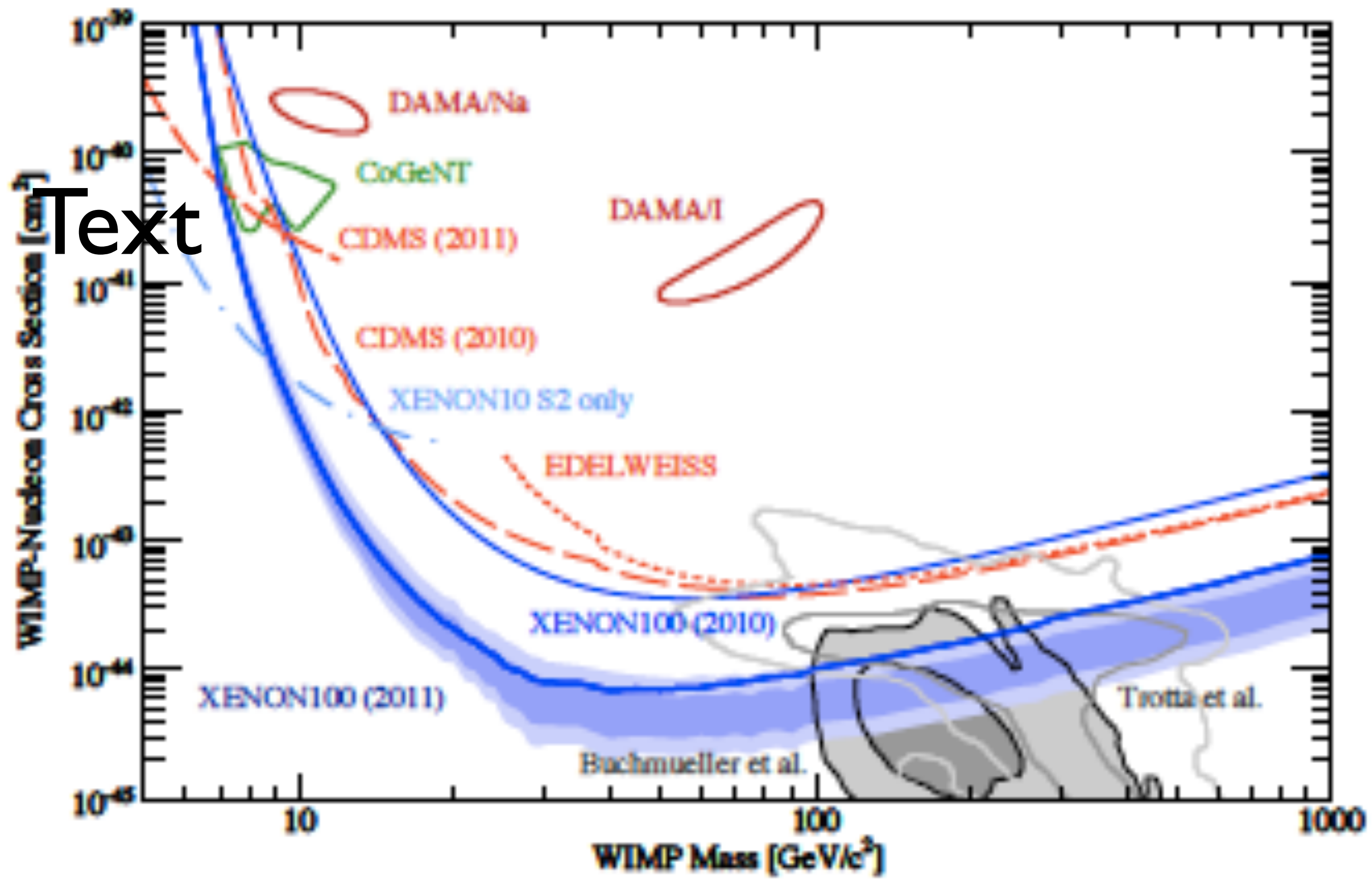


Direct Detection: where do we stand?

CDMS (Ge, Si), CoGeNT (Ge), COUPP (CF_3I), CRESST ($CaWO_4$), DAMA (NaI), Edelweiss (Ge), KIMS (CsI), PICASSO (F), SIMPLE (C_2ClF_5), TEXONO (Ge), XENON (Xe), ZEPLIN (Xe),. . .

Tremendous Progress over last 2 yrs!



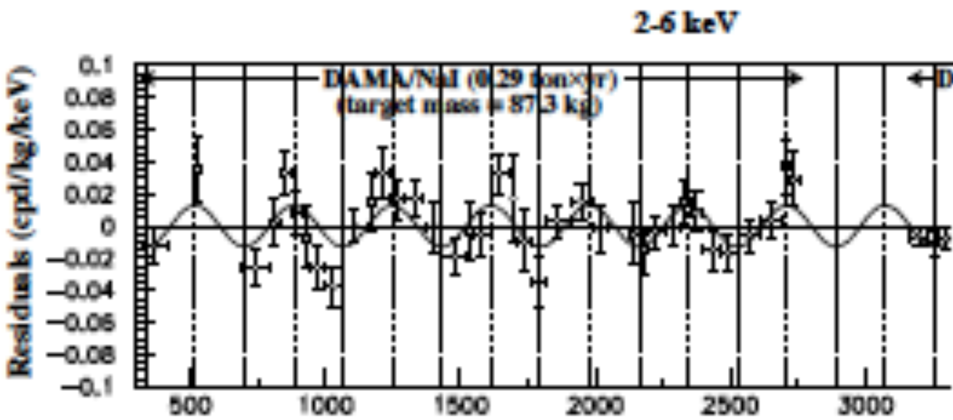


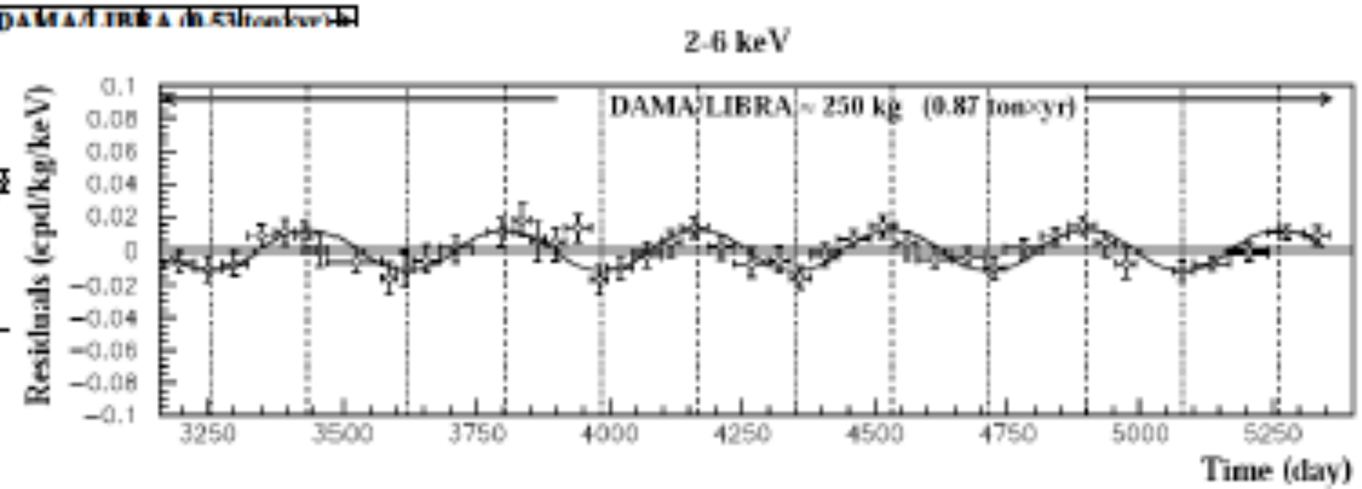
Room Temperature Scintillation Experiments

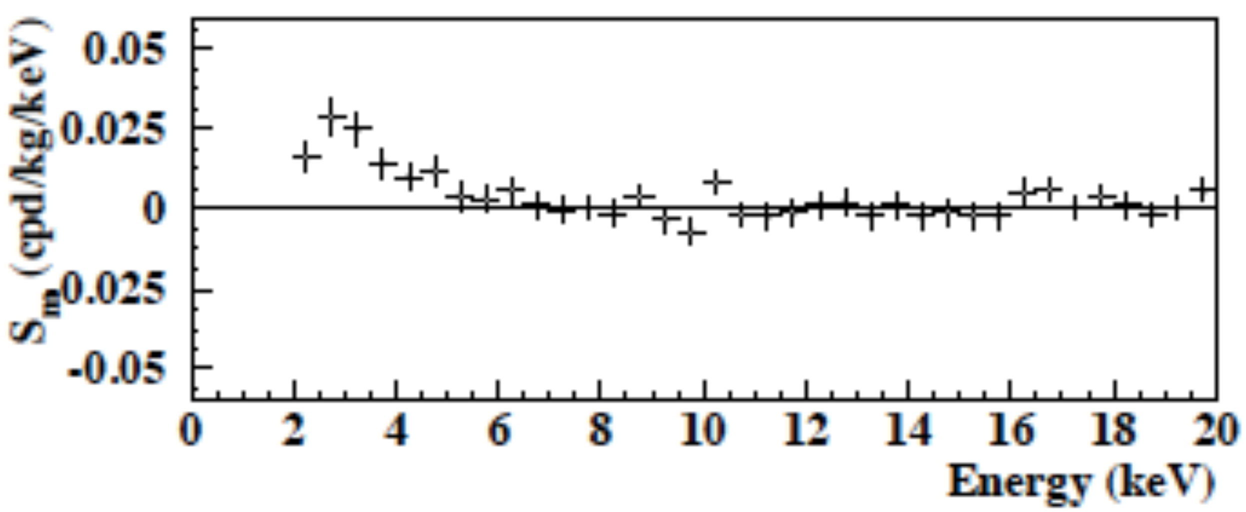
- Inorganic alkali halide crystals (NaI (Tl), CsI (Tl) : high density, high light output
- can be produced with high purity in large mass at affordable cost (annual modulation study)
- Sensitive to both SD and SI WIMP interactions
- PSD (better for CsI) but no discrimination between electron and nuclear recoils on an event-by-event basis
- Experiments: DAMA-LIBRA/Italy, KIMS/Korea, ANAIS/Spain (plan for 100kg NaI expt at Canfranc)

DAMA/LIBRA @ LNGS (Italy)

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



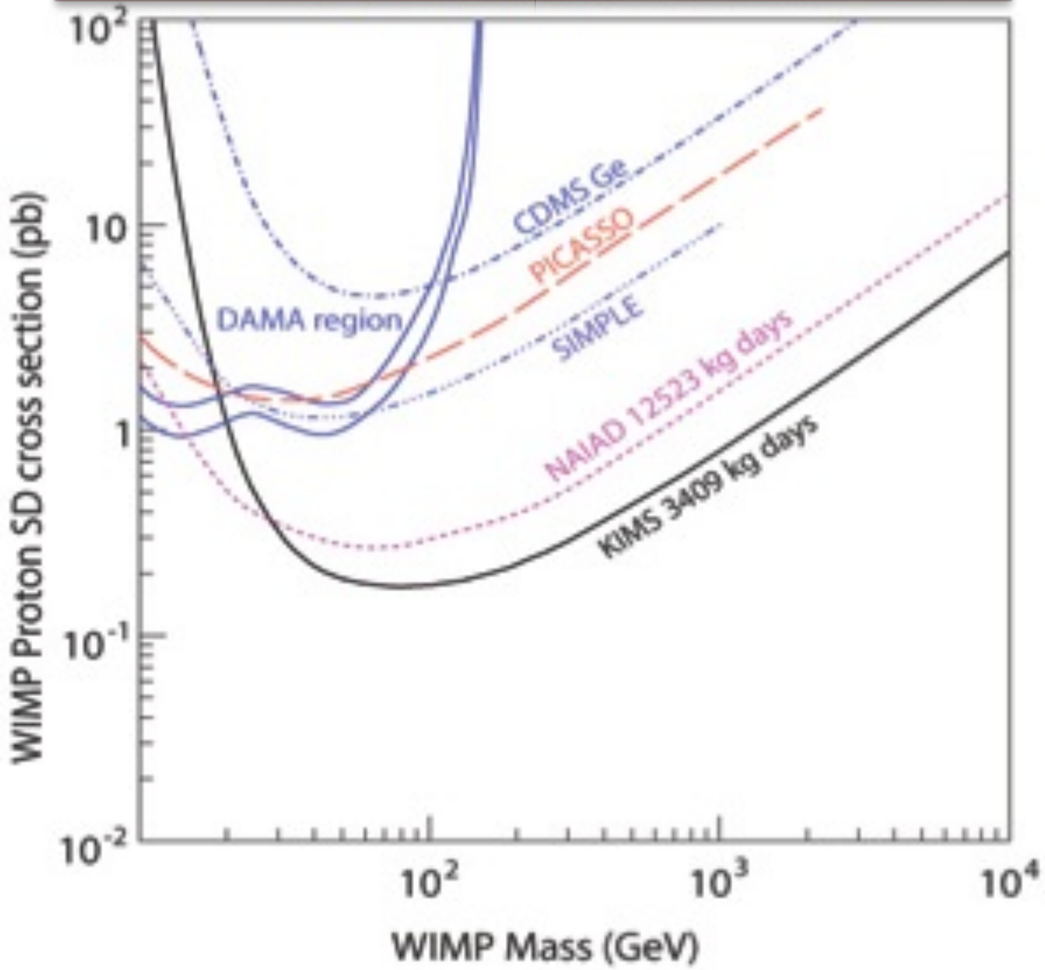




energy shape of modulation is important for constraining params
Chang, Pierce, Weiner, 0808.0196
Fairbairn, TS, 0808.0704

KIMS @ Yang Yang (Korea)

- CsI (Tl) crystals (~100 kg): 12 x 8.7 kg
- 5pe/keV and very good PSD (better than NaI(Tl))
- Designed for annual modulation study
- Direct check of DAMA/LIBRA signal by I-127 recoil
- Data accumulated for over 1yr; analysis ongoing
- Sensitive to both SI and SD WIMP interactions
- published data (~3000 kg days) rule out DAMA for both SD ai SI interactions for >20 GeV WIMPs
- Most stringent limit on SD interactions for pure proton coupling



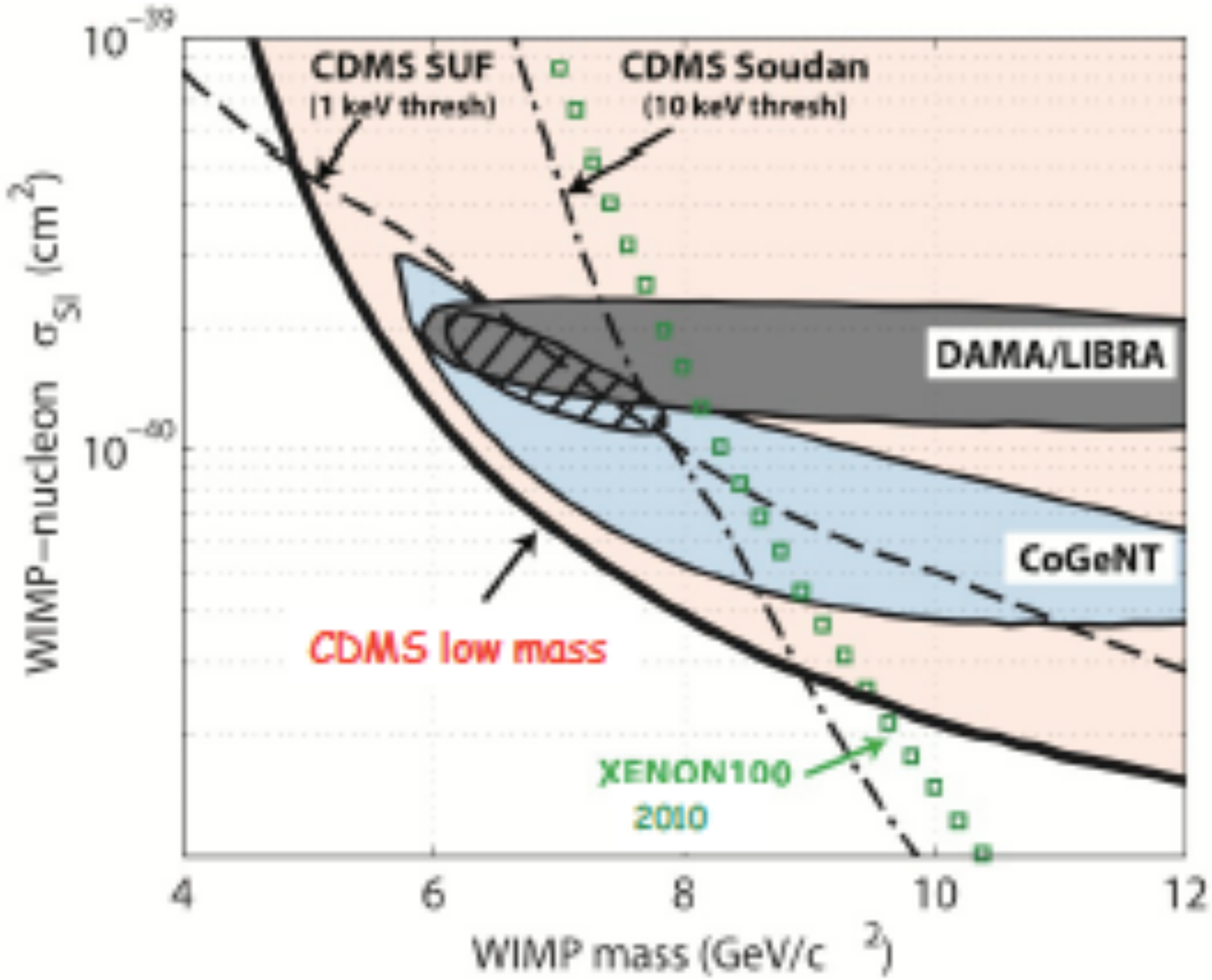
Tension with other experiments continues

How to reconcile?

- Experimental issues?
  ~ 10 GeV region is experimentally challenging
  systematic uncertainties on quenching factors, energy scale, thresh
  effects, backgrounds... have to be understood and taken into account before making strong statements.

However, in order to get a consistent picture we need to assume that

- CDMS made a major calibration error (in Ge and Si),
- the XENON S2 analysis is completely wrong,
- there is a serious problem with L_{eff} in Xenon, and
- major error in the Na quenching factor determination for DAMA



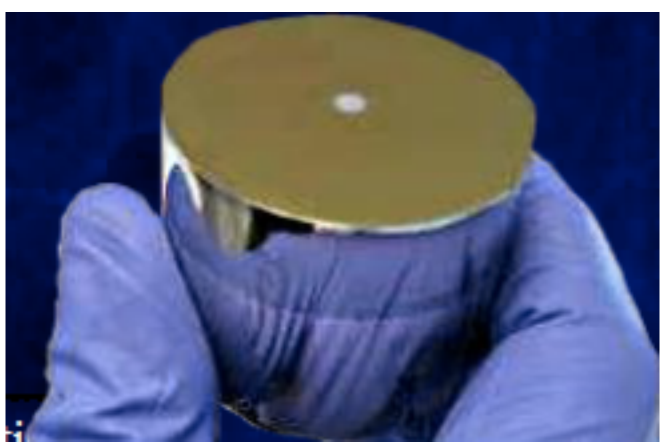
Ahmed et al ArXiv:1011.2482
PRL 2011

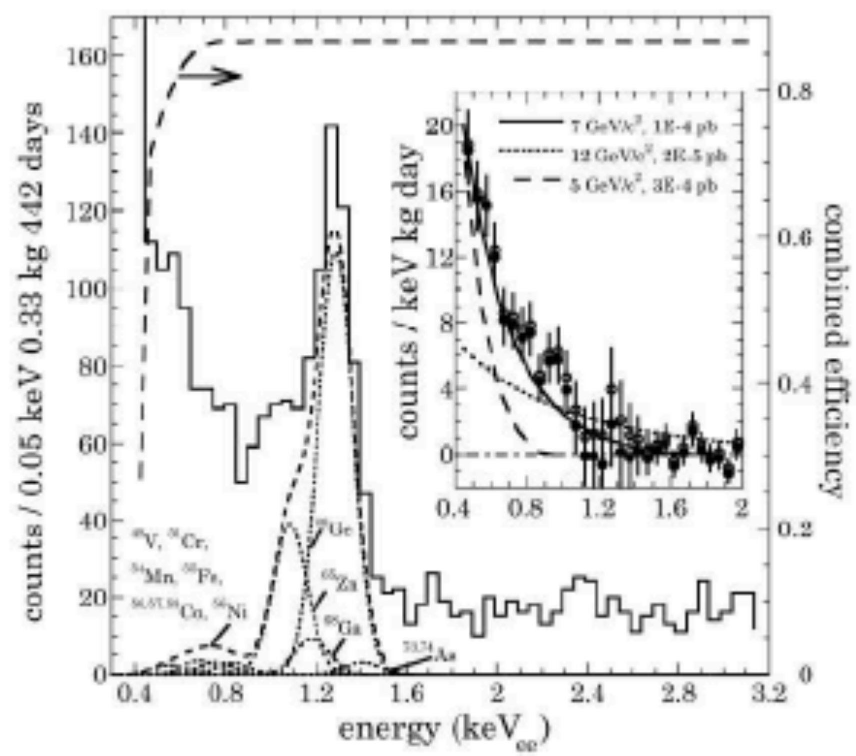
CoGeNT @ Soudan (US)

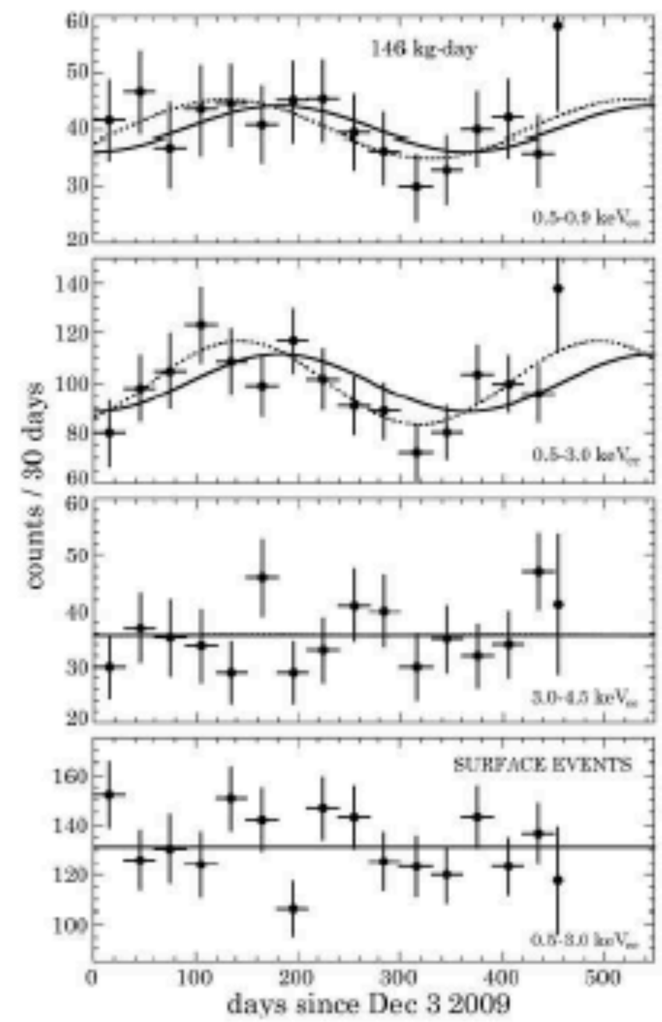
Exponential event excess and hint for annual modulation

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

440g p-type point-contact Ge detector

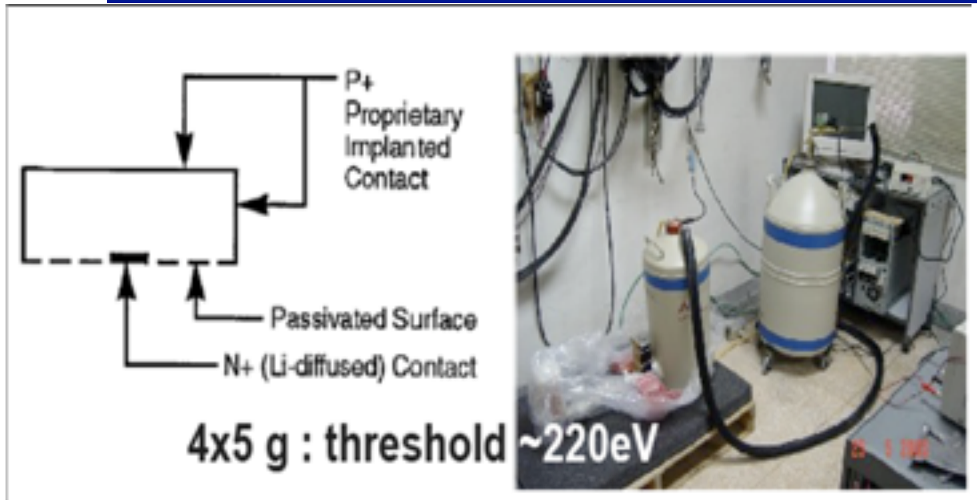






Aalseth et al, 1106.0650

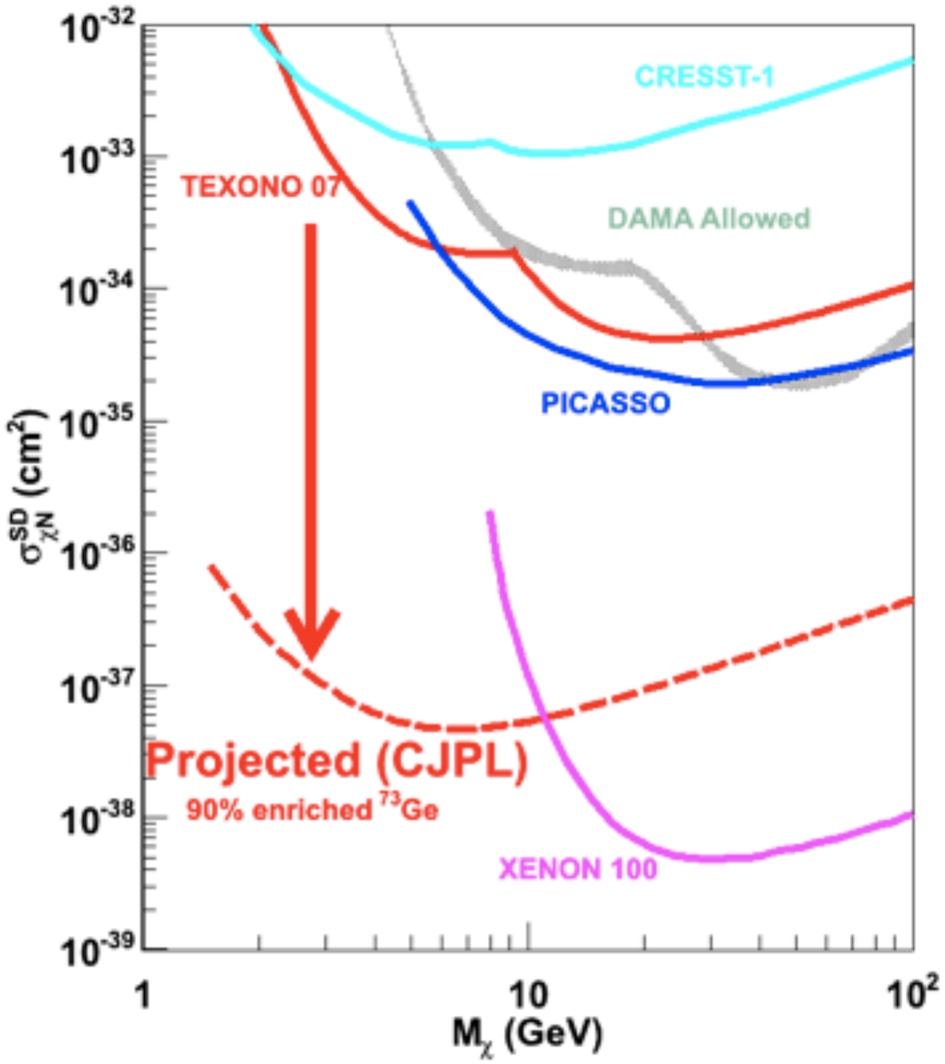
CDEX/TEXONO @ CJPL (China)



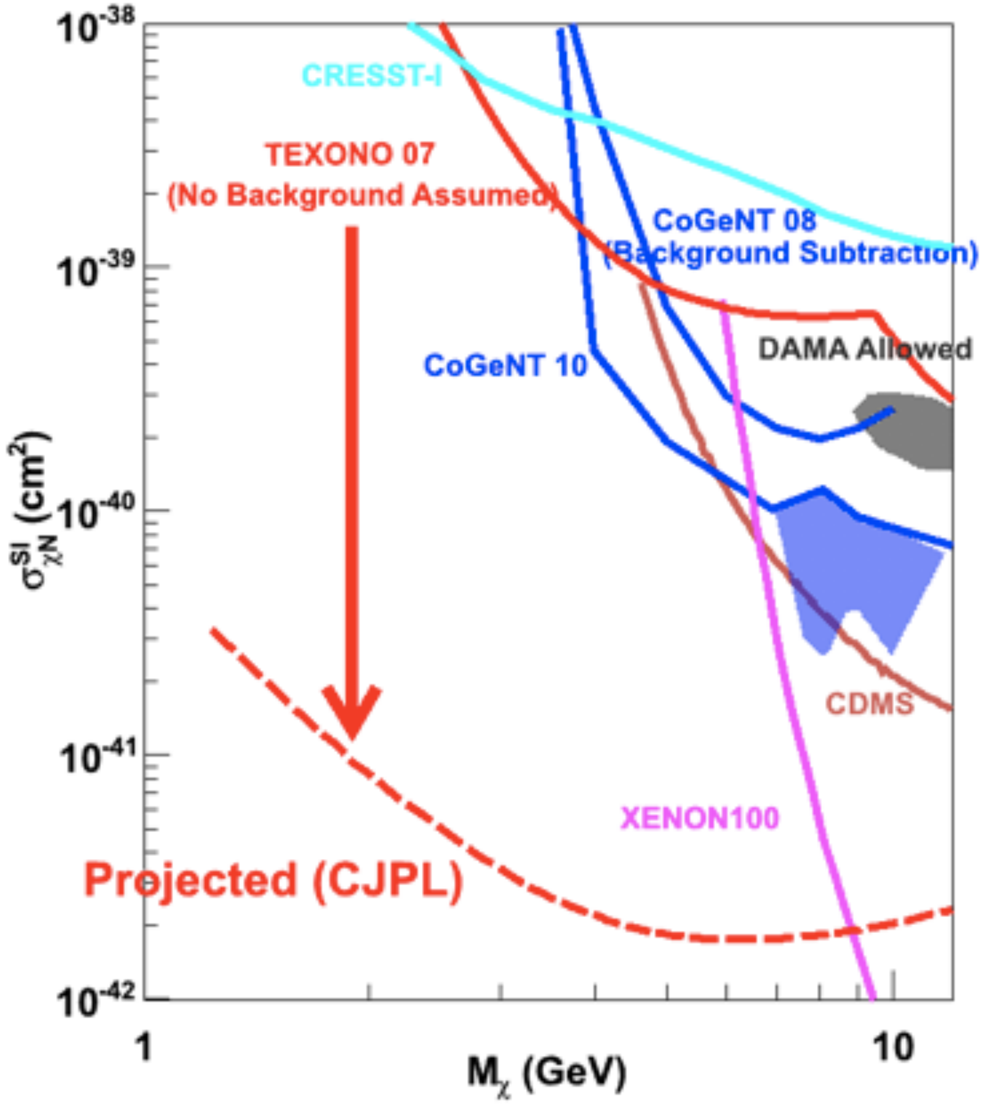
Competitive low-mass WIMP limits with 20g

Taking now data with 500g/900g PPC detectors

Preparing CDEX with 10 kg detectors



Spin Dependent



Spin Independent