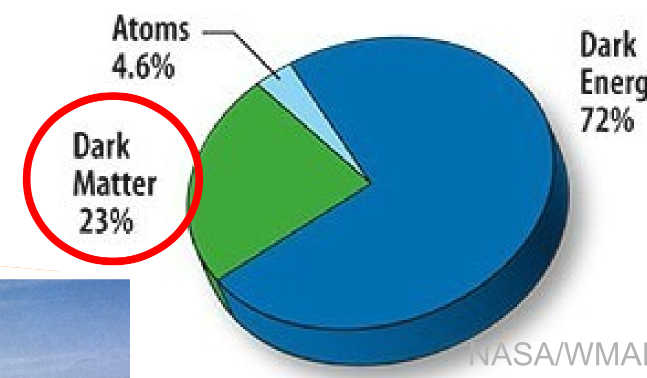
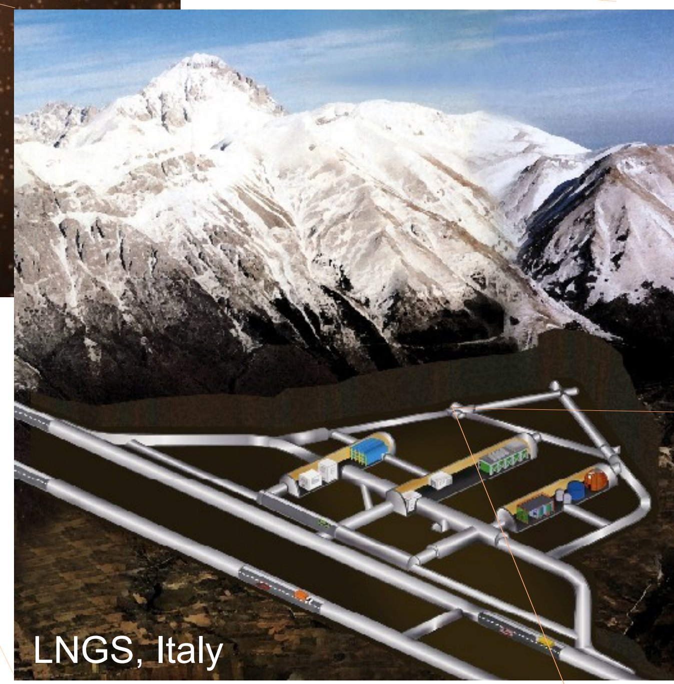
Searches for Dark Matter





Lecture for *Astroteilchenschule*

Obertrubach-Bärnfels
October 11-13, 2011

Uwe Oberlack

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Part 2:
Fundamentals of Direct Detection

Outline of Lectures at Astroteilchenschule

Part 1

- Evidence for Dark Matter
- WIMP Dark Matter
- Accelerator Searches
- Indirect Searches

Outline of Lectures at Astroteilchenschule

Part 2

- Direct Detection Technique
  - Kinematics
  - Energy Spectrum
  - Astro, Nuclear, Particle Physics Inputs
- Experimental backgrounds
- Detector techniques:
  - Noble liquids
  - Cryogenic germanium
  - Cryogenic scintillating crystals
  - Superheated liquids

Outline of Lectures at Astroteilchenschule

Part 3

- Signals (?)
  - DAMA / LIBRA annual modulation
  - CoGeNT
  - CRESST-II
- and Limits
  - CDMS-II
  - EDELWEISS-II
  - COUPP
  - XENON100
- Future

Kinematics of DM Direct Detection

- Elastic scattering of WIMP χ with a nucleus of mass m_n (given by atomic mass A).
- Measure energy E_R of recoiling nucleus:

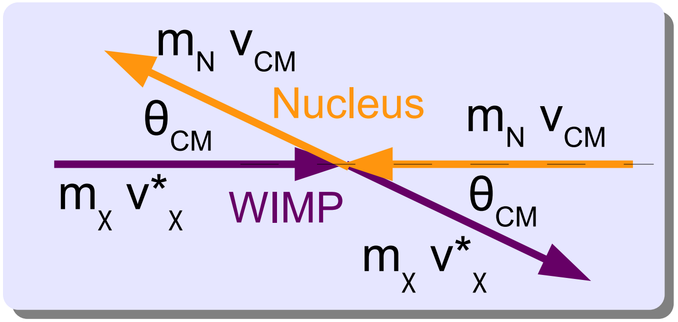
$$E_R = \frac{\mu^2 v^2}{m_N}(1-\cos\theta_{CM}) = 4\frac{m_\chi m_N}{(m_\chi+m_N)^2} E_\chi \cos^2\theta_N$$

$$E_{R,max} = 4\frac{m_\chi m_N}{(m_\chi+m_N)^2} E_\chi = r\,E_\chi = 2\frac{\mu^2}{m_\chi} v^2$$

$$v_{min} = \left(\frac{m_\chi E_{th}}{2\mu^2}\right)^{1/2}$$

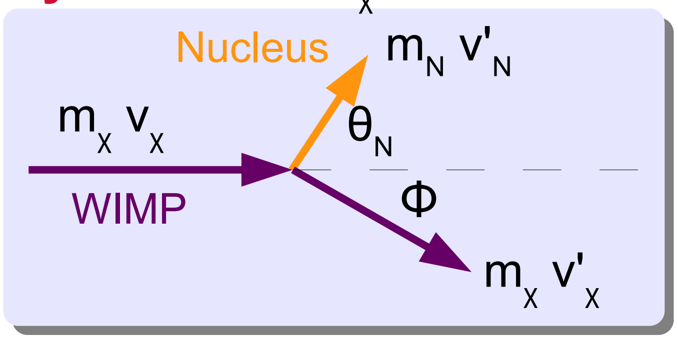
min. velocity to produce a signal above threshold

CM system

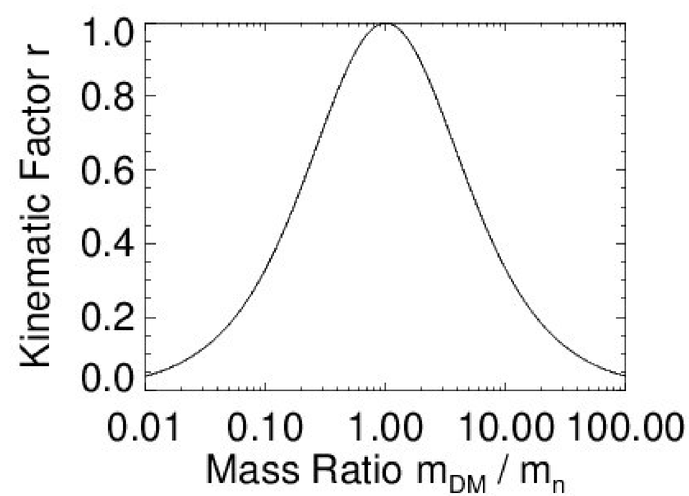


Laboratory system

short: $v = v_\chi$

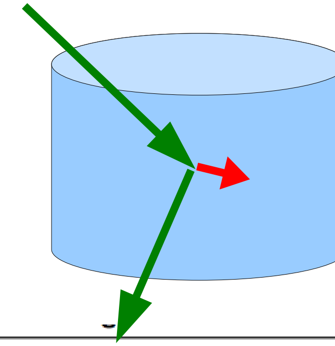


- Useful abbreviations:
  - reduced mass: $\mu = (m_\chi\ m_N)/(m_\chi + m_N)$
    $m_\chi \ll m_N$: $\mu \rightarrow m_\chi$ $\quad m_\chi = m_N$: $\mu = m_\chi / 2$
    $m_\chi \gg m_N$: $\mu \rightarrow m_N$
  - kinematic factor $r = 4\,(m_\chi\ m_N)/(m_\chi + m_N)^2 = 4\,\mu^2 / (m_\chi\ m_N)$



- Example:
  - $m_\chi \sim 10$ GeV/c^2, $m_n = 135$ GeV/c^2
  - $v \sim 230$ km/s, $\beta = 7.7\text{e-}4$
  - $E_\chi = 29.4$ keV, $E_{R,max} = 7.5$ keV

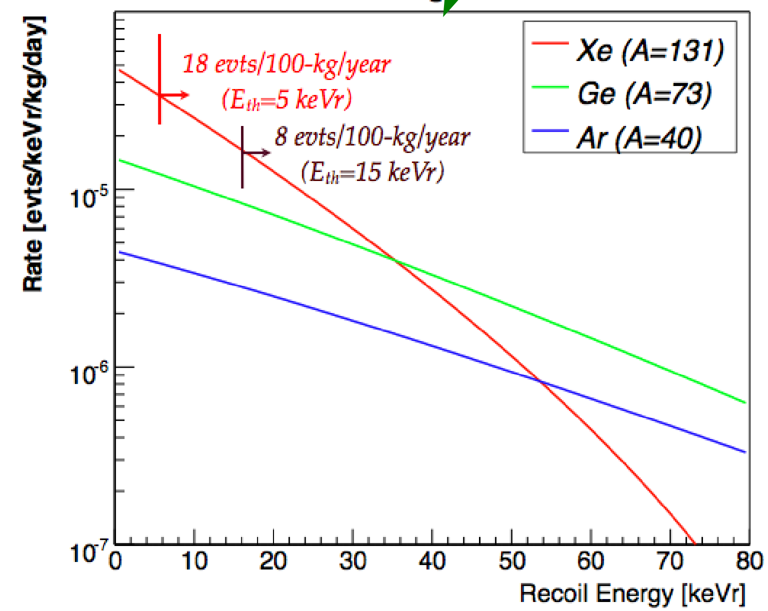
WIMP Dark Matter Direct Detection



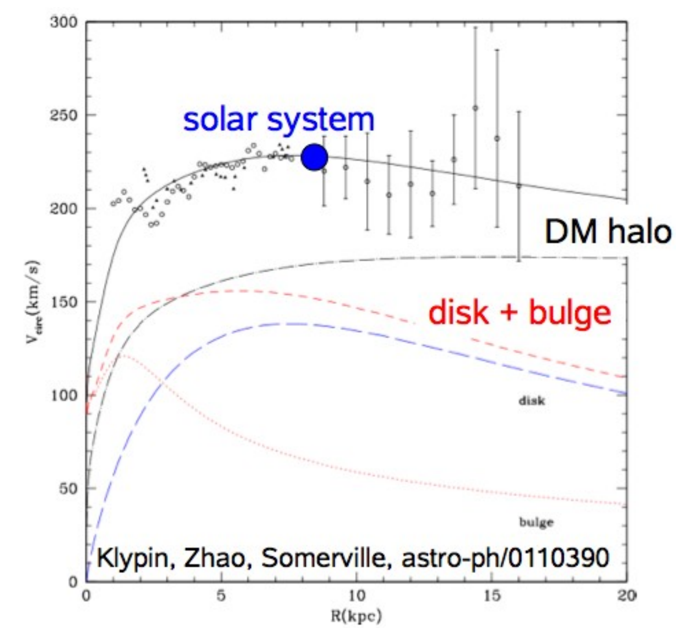
- Scattering of WIMPs χ off of nuclei A.
  - elastic or inelastic?
  - spin-independent (~A^2) or spin-dependent?
- Differential rate per unit detector mass:

$$\frac{dR}{dE} = \frac{\rho_\chi \sigma_s}{2 m_\chi \mu^2} |F(E)^2| \int_{v_{min}}^{v_{esc}} f\frac{(\mathbf{v}, t)}{v} d^3 v$$

$$f(\mathbf{v}, t) \propto \exp\left(\frac{-(\mathbf{v}+\mathbf{v}_E(t))^2}{2\sigma_v^2}\right)$$



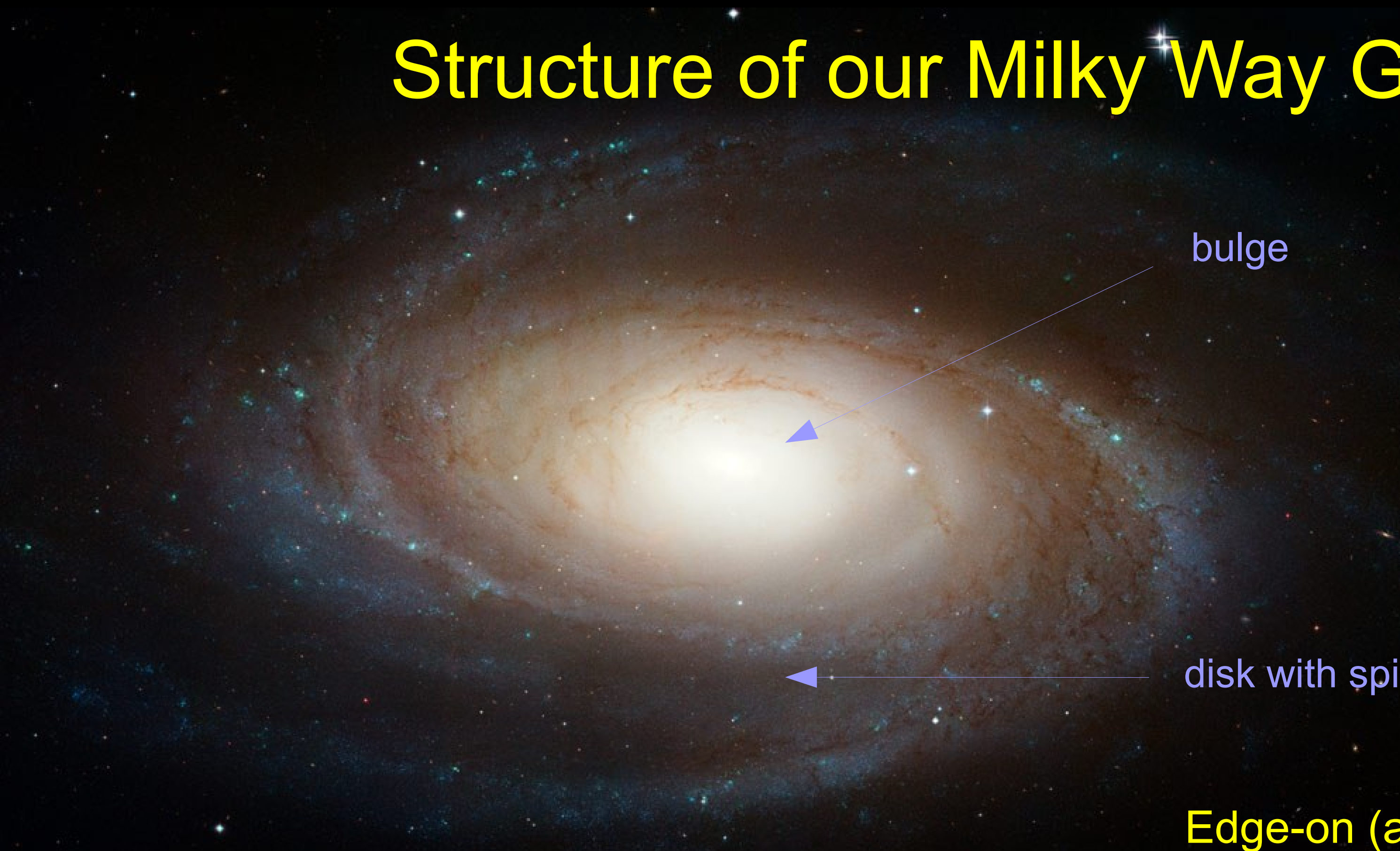
  - $m_\chi \sim 10 - 10^4$ GeV/c^2, $\mu = (m_\chi m_N)/(m_\chi + m_N)$
  - $v_\chi \sim 230$ km/s
  - "Standard" spherical halo:
    Featureless recoil spectrum <E> ~ O(10 keV)
  - ρ_χ/m_χ: local number density of WIMPs
  - $\rho_\chi \sim 0.3$ GeV/c^2/cm^3, $\rho_\chi/m_\chi \lesssim 10$ / L
  - σ_s scattering cross section per nucleus.



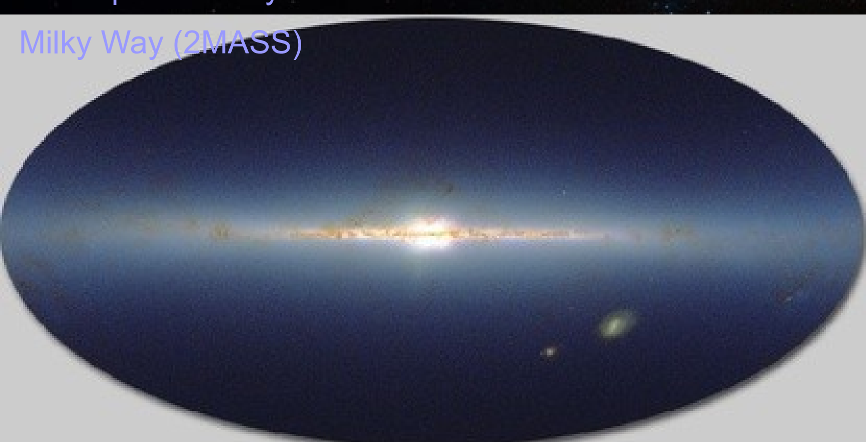
Typical rate < 10^{-2} events / kg / day

Astrophysics Input

Structure of our Milky Way Galaxy

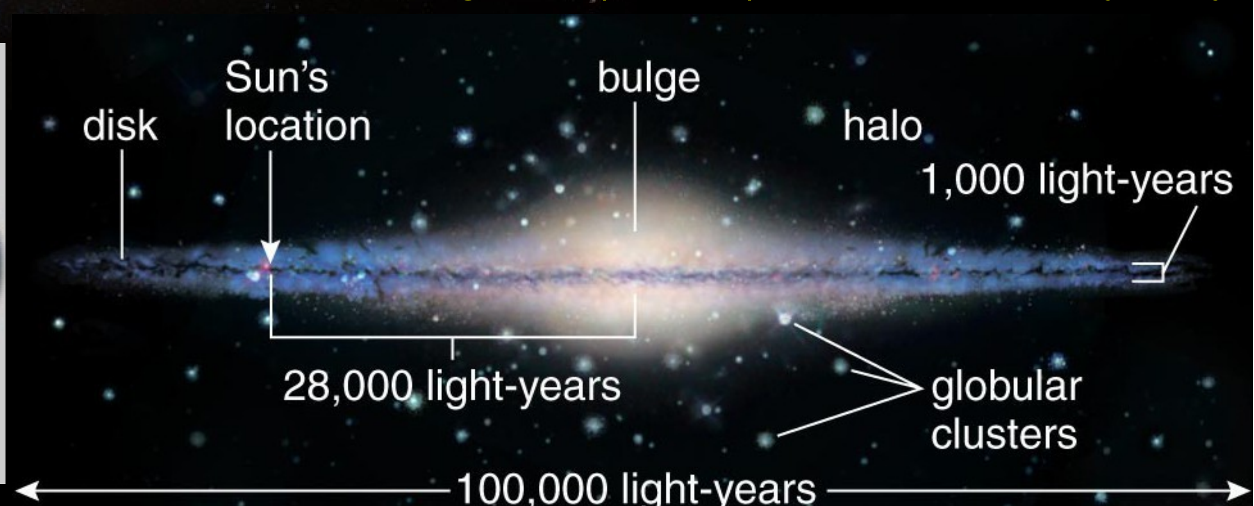


M81 Spiral Galaxy. NASA/HST

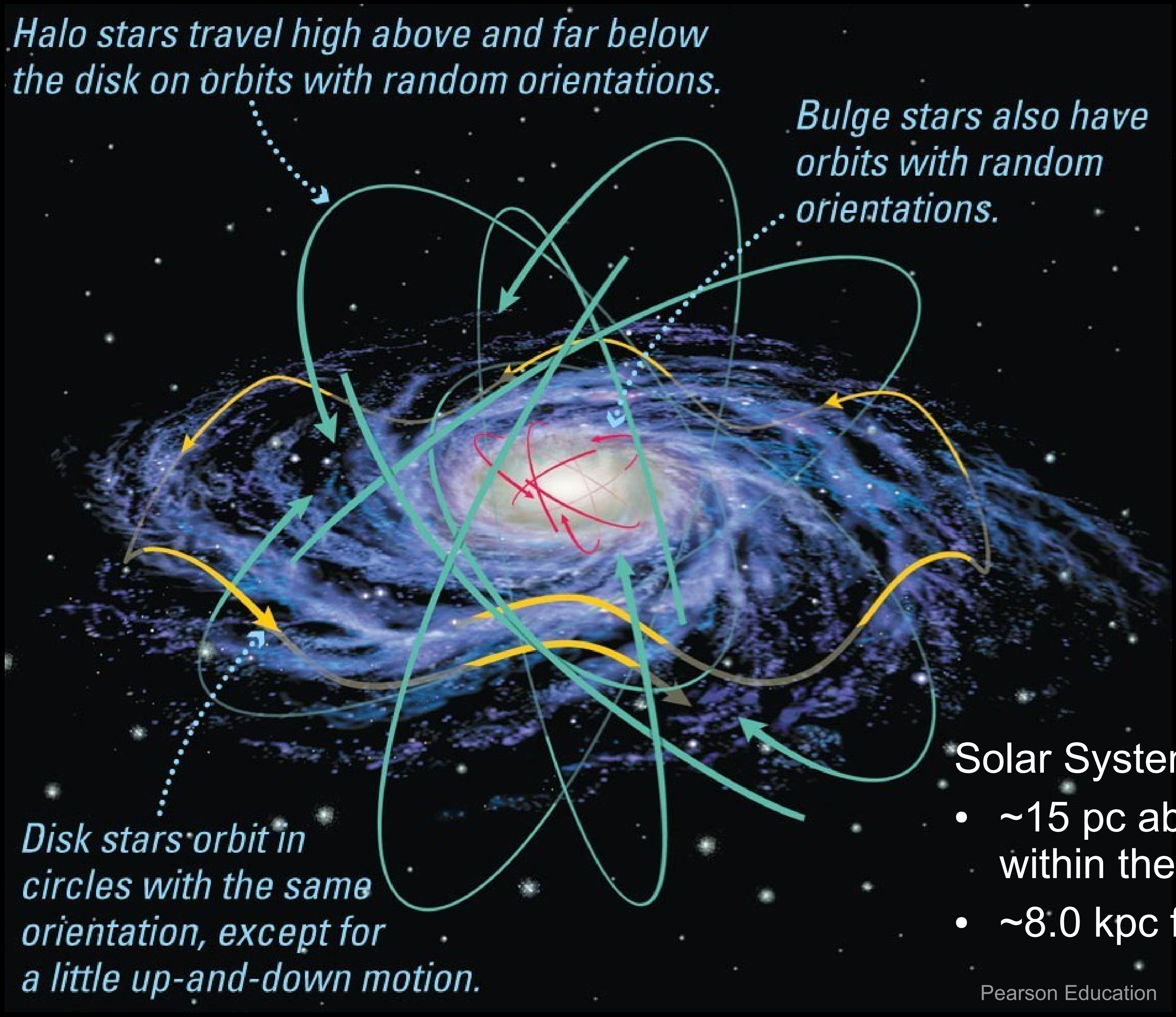


Milky Way (2MASS)

Edge-on (artist's) view of the Milky Way



Stellar Orbits in the Galaxy



Solar System:

- ~15 pc above the galactic plane within the disk
- ~8.0 kpc from the Galactic Center

Pearson Education


z=0.0
Via Lactea 2 (2008)
http://www.ucolick.org/~diemand/vl
WIMP Dark Matter Direct Detection
Observer
80 kpc

Halo Models

Considering the standard halo model, an isothermal sphere, the WIMP velocity distribution in the lab frame is:

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

- $\overrightarrow{v}_\odot$: Sun's velocity
- $\sigma_v = v_0/\sqrt{2}$: dispersion
- v_0 : circular speed at Solar radius $\quad v_0 = 220\ km/s$

But the Halo can be:
- ellipsoidal, triaxial (change f(v)), (co)-rotating
- anisotropic, …

The distribution of mass in the halo can be described by the Navarro-Frenk-White profile:

$$\frac{\rho(r)}{\rho_{\rm crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

NFW 1996 ApJ 462, 563

r_s scale radius

with the critical density

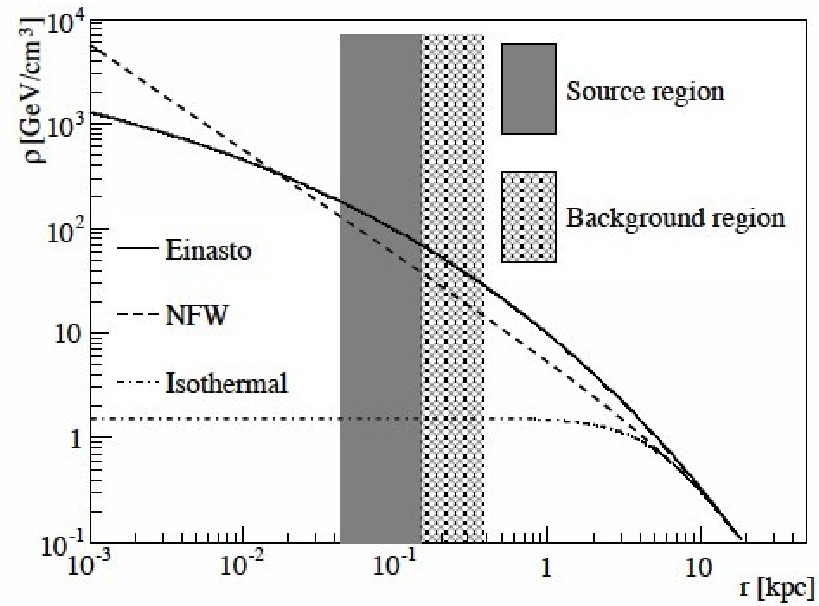
$$\rho_{crit} = \frac{3H^2}{8\pi G}$$

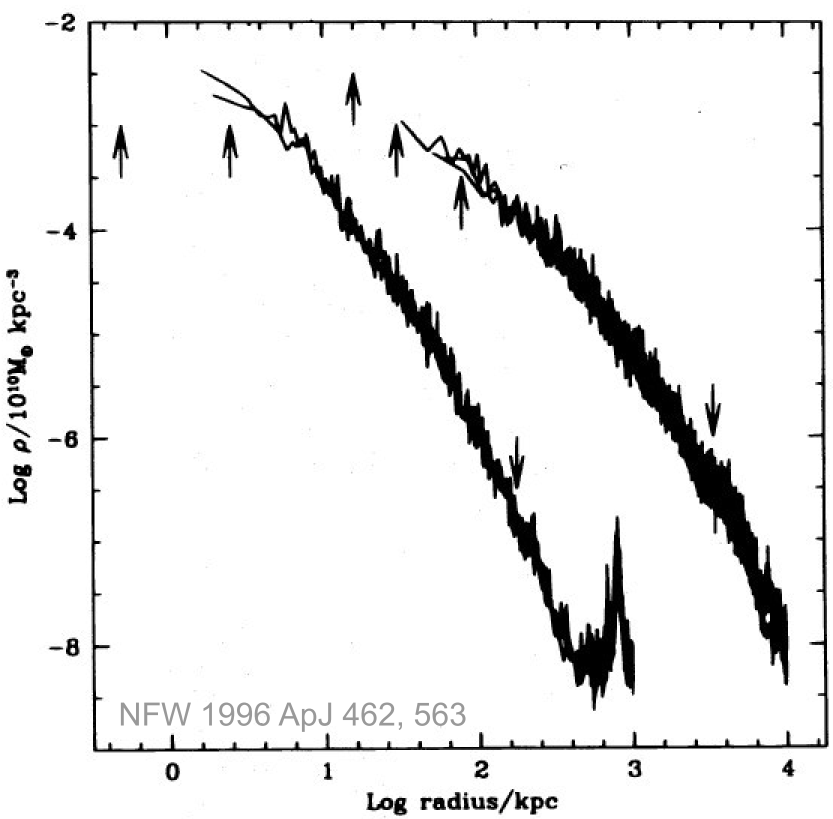
δ_c is a dimensionless parameter

Expected DM Halo Distribution – Spatial

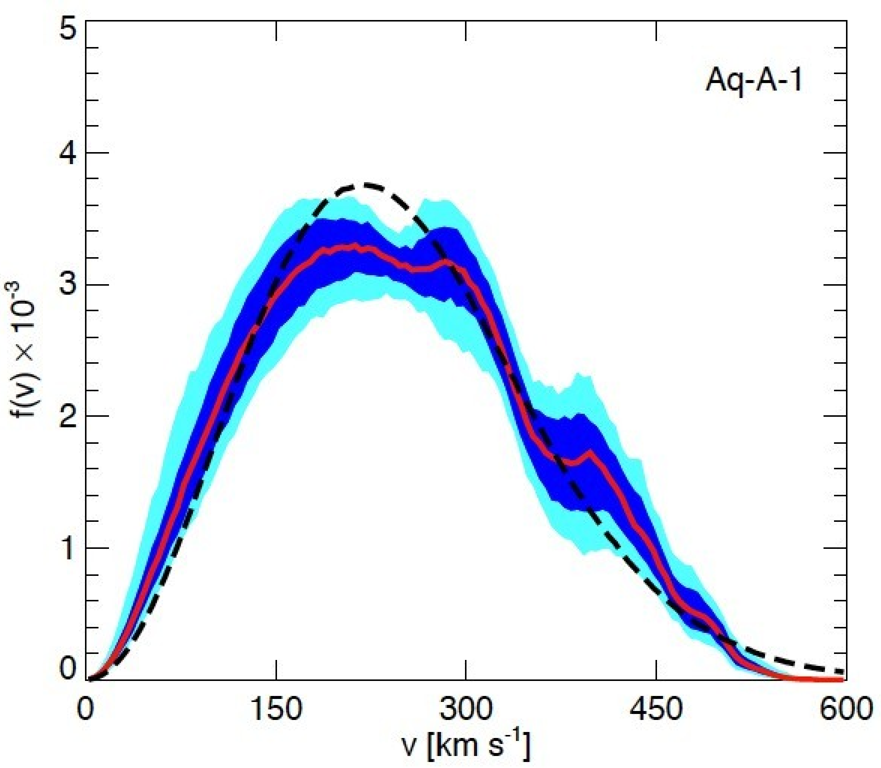
- Average density may be described by NFW formula
- Lumpiness:
  - Numerical simulations do not resolve scales tested by direct detection experiments
  - Baryonic matter dominates over DM within the galactic disk.
    Result: subhalo structures should be smoothed out within the disk.

$$\frac{\rho(r)}{\rho_{\rm crit}} = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2}$$



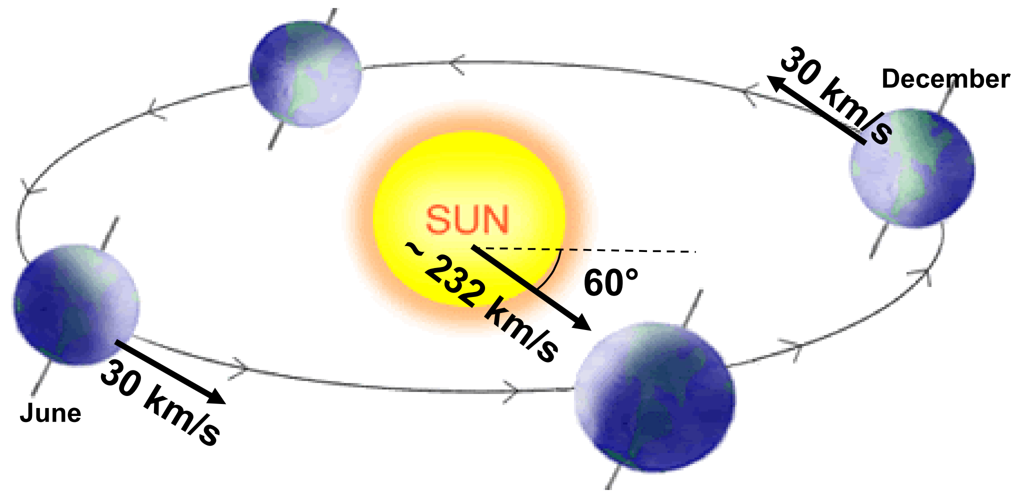


Expected DM Halo Distribution – Velocity



Vogelsberger et al., 2008 0812.0362

Annual Modulation



$$\frac{dR}{dE_R} \approx \left(\frac{dR}{dE_R}\right)[1 + \Delta(E_R)\cos\alpha(t)]$$

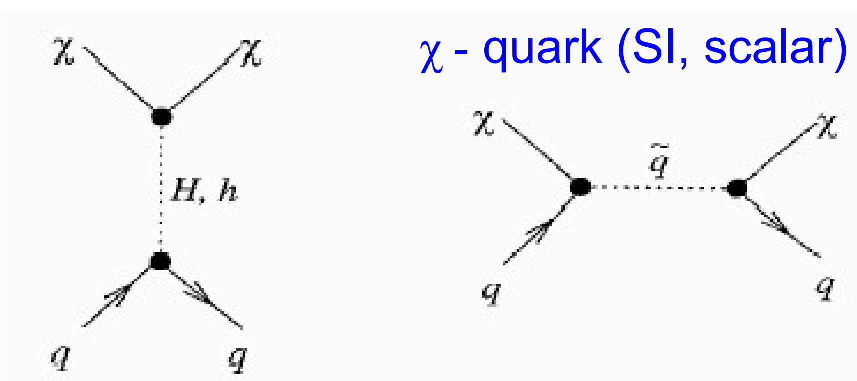
where $\alpha(t) = 2\pi(t - t_0)/T$, $T = 1$ year and $t_0 \sim 150$ days.

Particle Physics Input

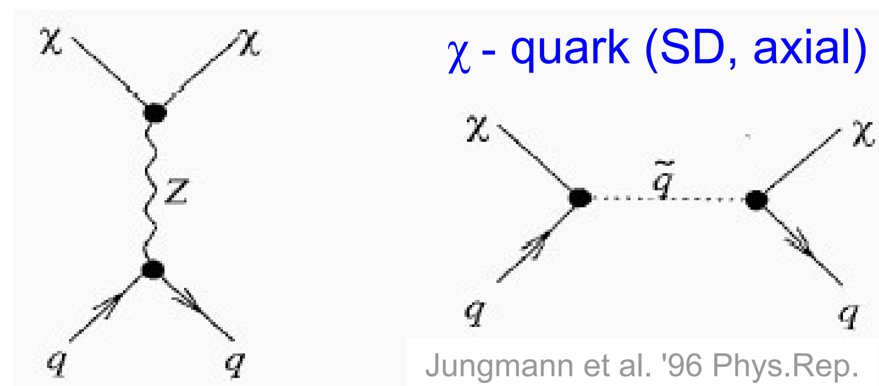
WIMP Scattering Cross Sections

Example: SUSY (but direct searches are sensitive to other models as well)

- Compute cross sections χ – quark and χ – gluon with various SUSY models. Large parameter space, constrained by accelerator and direct search experiments, and cosmology.
  - **spin-independent**: coupling to mass of nucleus. Coherence ⇒ $\sigma \propto A^2$
  - **spin-dependent**: coupling of spins of nucleus and neutralino interaction with paired nucleons in the same energy state cancel => no A^2 enhancement



χ - quark (SI, scalar)



χ - quark (SD, axial)

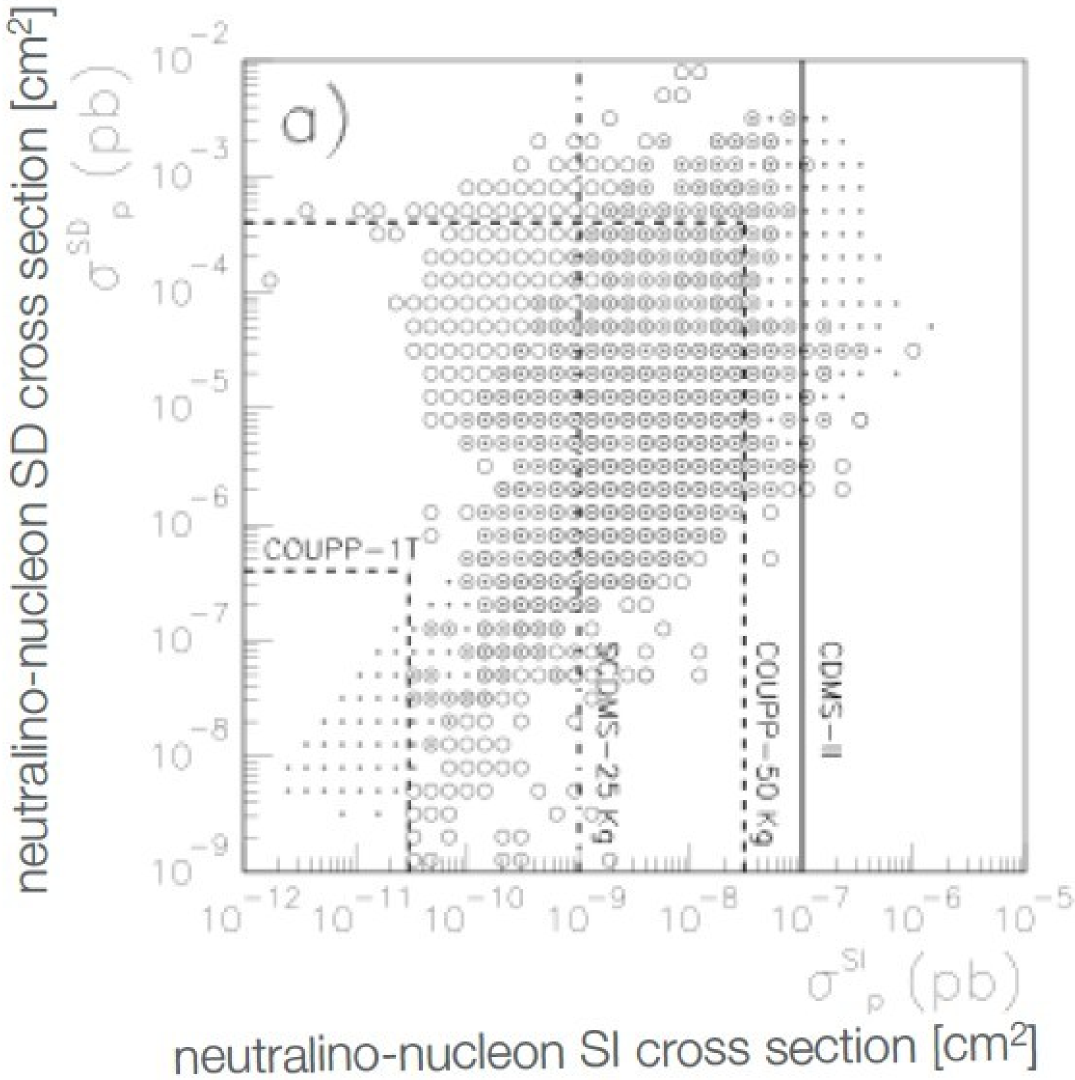
Jungmann et al. '96 Phys.Rep.

- Distribution of nucleons within nucleus: nuclear form factor.
  - SI: Large nuclei gain ~A^2 at small momentum transfer, but lose at higher momentum transfer due to coherence loss.

Cross Section for WIMP-Nucleon Scattering Spin-Dependent

$$\sigma_{SD} = \frac{32}{\pi} G_F^2 \frac{m_\chi^2 m_N^2}{(m_\chi + m_N)^2} \frac{J_N + 1}{J_N} \left(a_p \left\langle S_p \right\rangle + a_n \left\langle S_n \right\rangle \right)^2$$

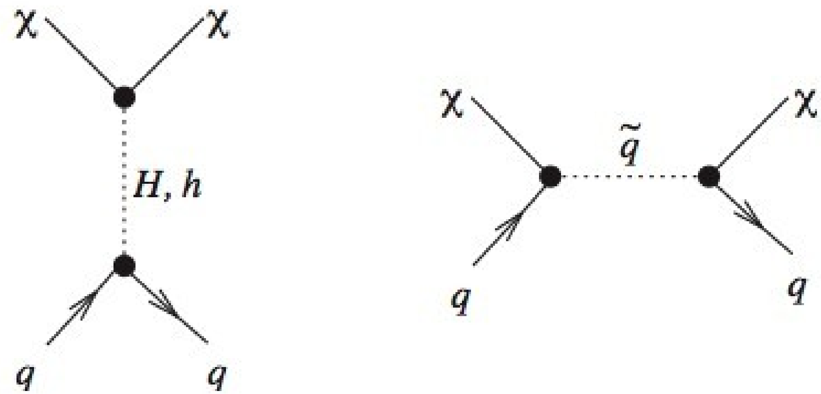
Spin-dependent vs. Spin-Independent Scattering in the CMSSM



Nuclear Physics Input

Cross Section for WIMP-Nucleon Scattering, Nuclear Form Factor

Scalar (spin-independent) scattering



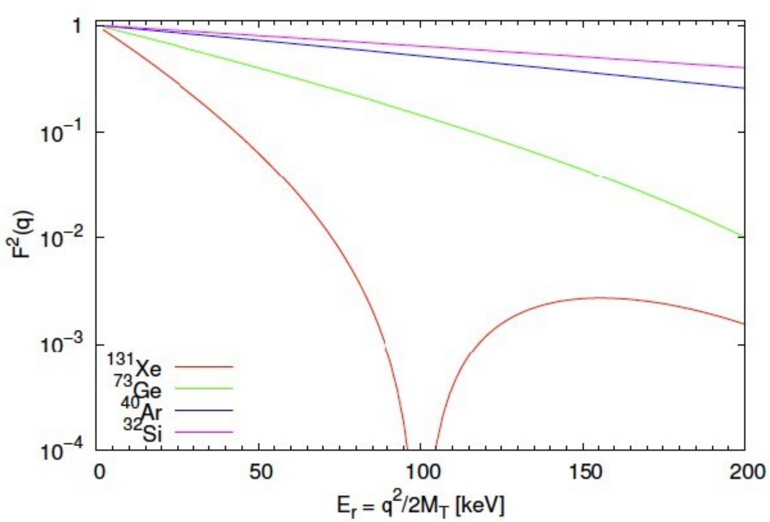
At zero momentum transfer:

$$\sigma = \frac{4\,\mu^2}{\pi}\left[Z\, f_p + (A - Z)\, f_n\right]^2$$

coherent scattering

reduced mass $\mu = \dfrac{m_\chi\, m_N}{m_\chi + m_N}$ $\quad m_\chi \ll m_N : \mu \approx m_\chi$ $\quad m_\chi \gg m_N : \mu \approx m_N$

f_p , f_n : scattering amplitudes protons, neutrons



At finite momentum transfer:

Form factor:

Fourier transform of nuclear density

$$F^2(q) = \left|\int \rho(r)\, \exp\left\{ i\, \frac{\vec{q}\cdot\vec{r}}{\hbar} \right\} dr \right|^2$$

$$F(E_r) = \left(\frac{3\, j_1(qR_1)}{(q\, R_1)} \right)^2 \exp\left[-(qs)^2\right]$$

Momentum transfer: $q = \sqrt{s\; m_N\, E_r}$

j_1 : first spherical Bessel function

$R_1 = \sqrt{R_0^2 - 5\, s^2}$

$R_0 \approx 1.2 \text{ fm}\; A^{1/3}$

$s \approx 1 \text{ fm}$

Helms form factor based on:

$$\rho(r) = \int_{\text{volume}} \rho_0(\mathbf{r}')\rho_1(\mathbf{r} - \mathbf{r}')d^3x'$$

$$\rho_0(r) = \begin{cases} \frac{3}{4\pi r_n^3} & r < r_n \\ 0 & r > r_n\,, \end{cases}$$

$$\rho_1(r) = \frac{1}{(2\pi s^2)^{\frac{3}{2}}} e^{-r^2/2s^2}\,.$$

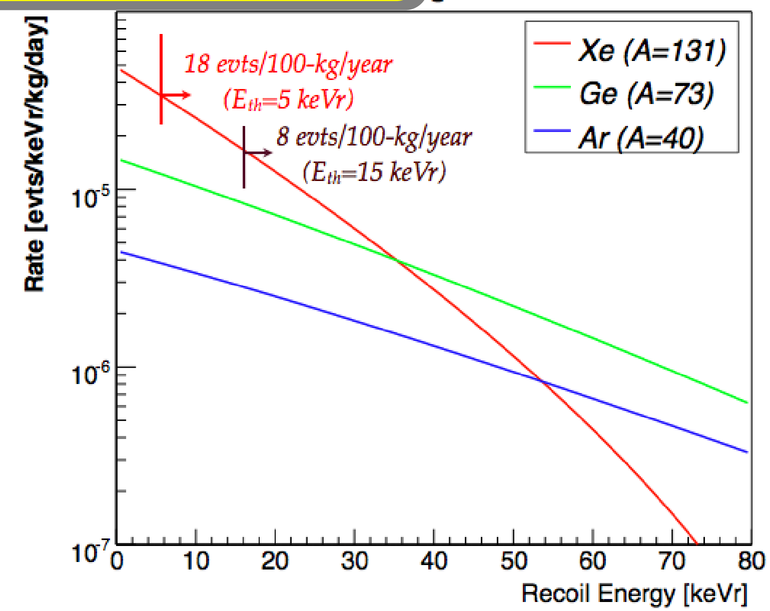
Recoil Spectrum

$$\frac{dR}{dE} = \frac{\rho_\chi \sigma_s}{2 m_\chi \mu^2} |\mathbf{F}(E)^2| \int_{v_{min}}^{v_{esc}} f \frac{(\mathbf{v}, t)}{v} d^3 v$$

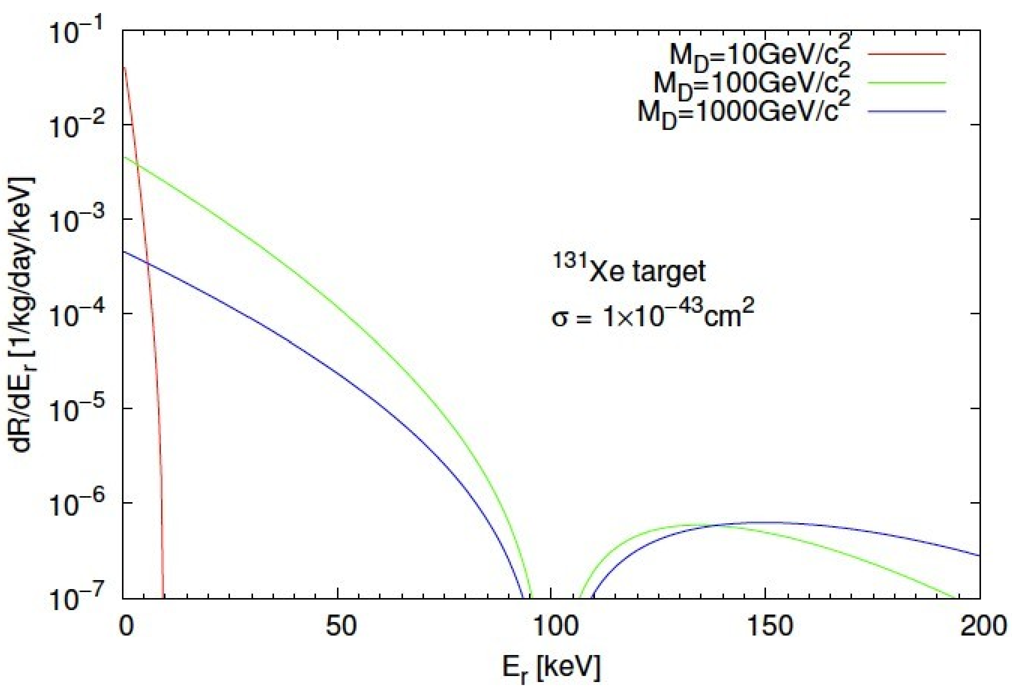
$$f(\mathbf{v}, t) \propto \exp\left(\frac{-(\mathbf{v} + \mathbf{v}_E(t))^2}{2 \sigma_v^2}\right)$$

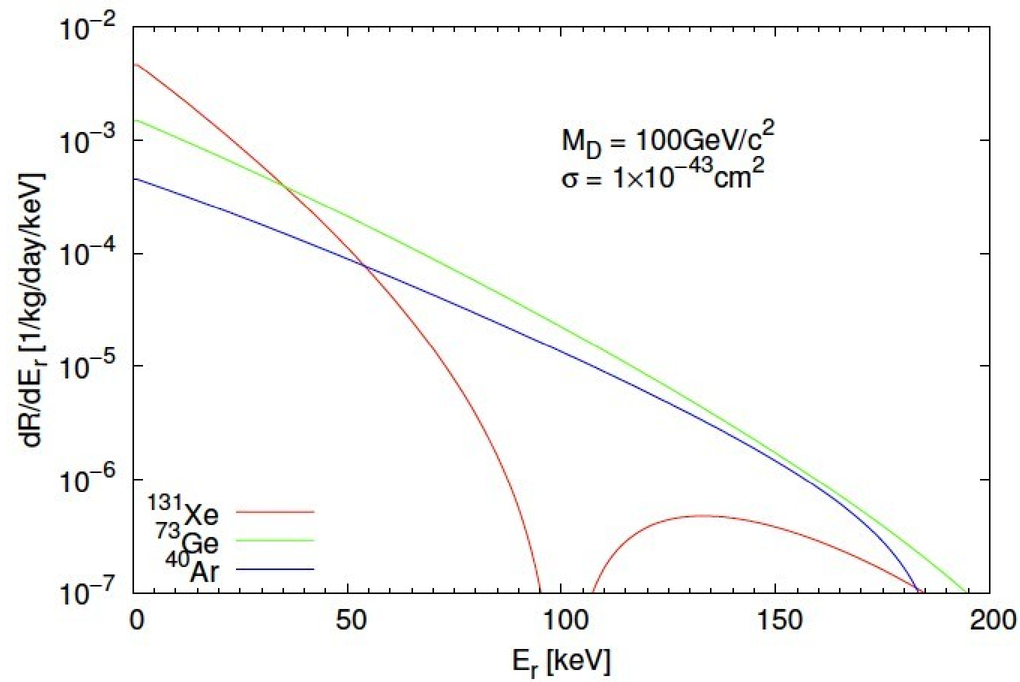
- For standard halo model approximate spectral form:

$$\frac{dR}{dE_R} \approx \left(\frac{dR}{dE_R}\right)_0 F^2(E_R) \exp\left(-\frac{E_R}{E_c}\right)$$

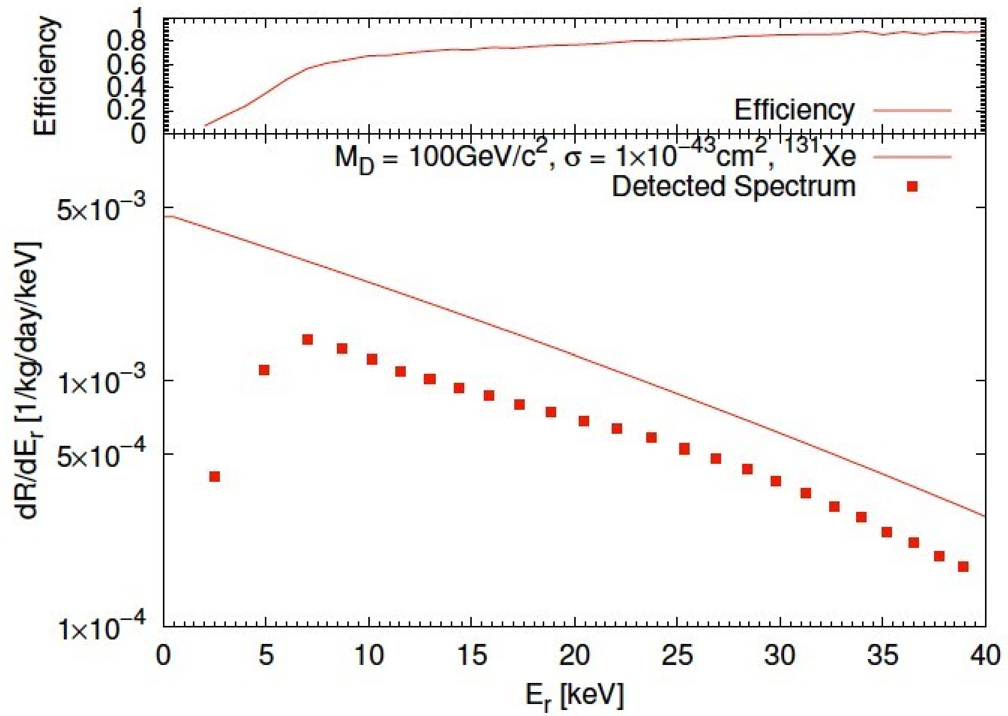


- Including form factors:





Detector Effects:
Smearing of the Threshold, Efficiencies



Backgrounds in Direct DM Search

Cross-sections are *very* small: <10^{-43} cm^2 or 10^{-7} pb (spin-independent)

Without background, sensitivity $\propto$ (mass × exposure time)$^{-1}$

With background subtraction $\propto$ (M t)$^{-1/2}$ until limited by systematics.

Backgrounds:

Gamma-rays & beta decays:

- ~100 events/kg/day
- Need very good β and γ background discrimination.
- Shielding: low-activity lead, water, noble liquids (active), liquid N_2, ...

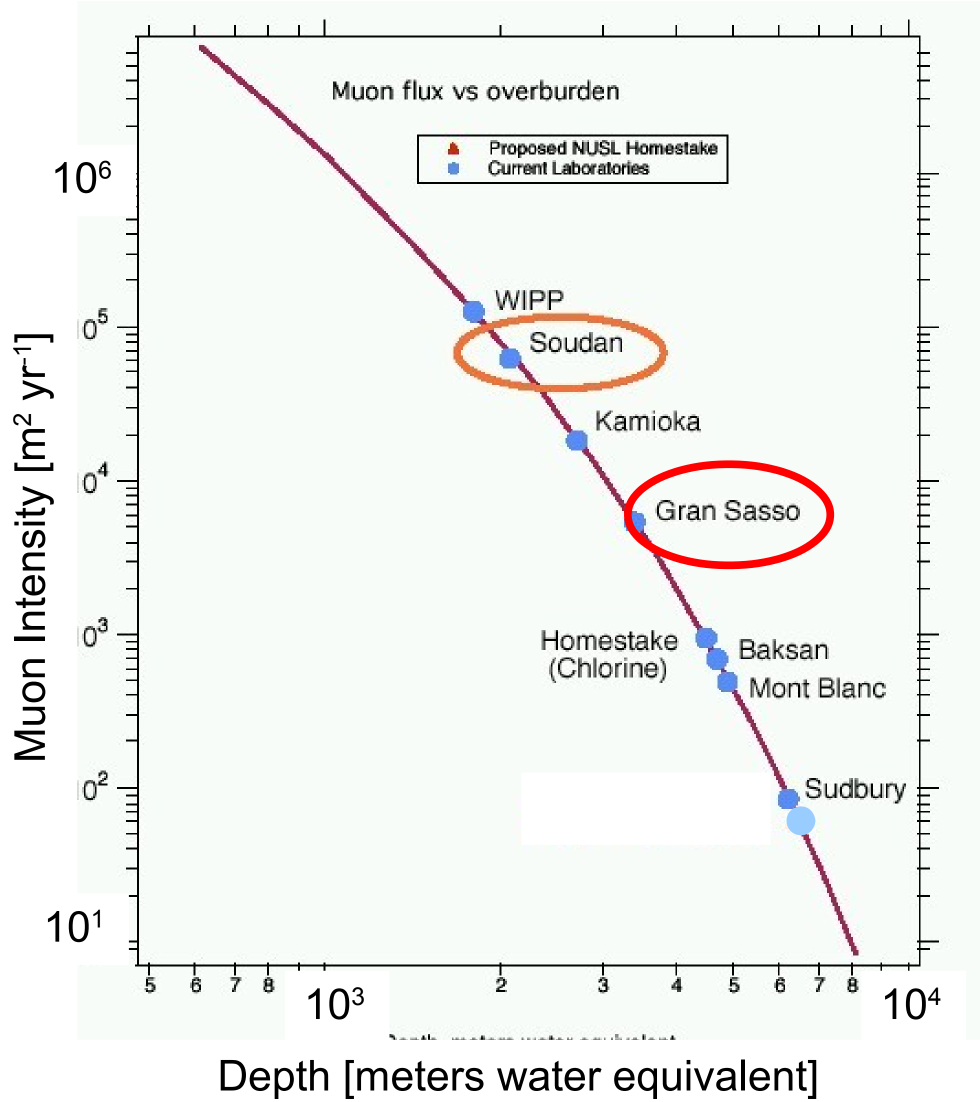
Neutrons from (α, n) and spontaneous fission (concrete, rock, etc.):

- ~ 1 event/kg/day (LNGS)
- Neutron moderator (polyethylene, paraffin, ...)

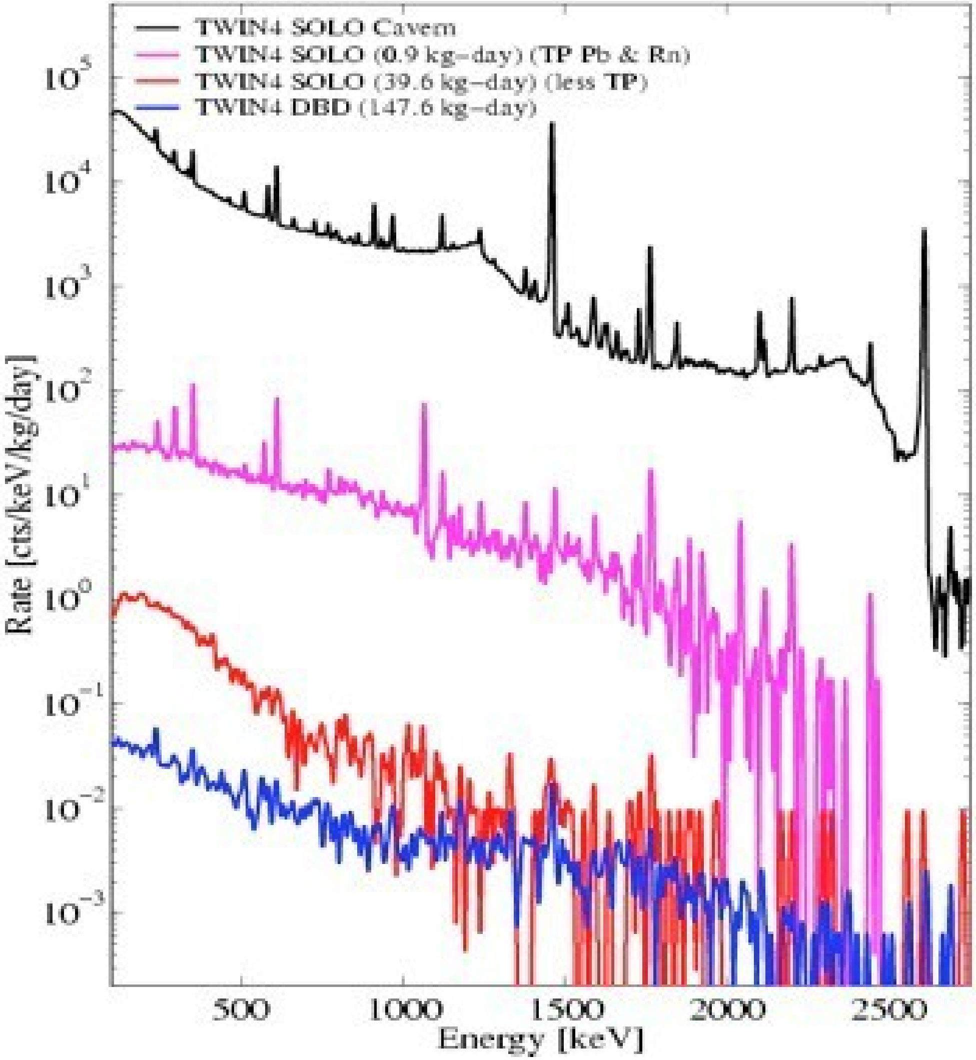
Neutrons from CR muons:

- Rate depending on depth.
- μ-veto, n-veto, shielding

α decays from Rn daughters, ...



Backgrounds in Direct DM Search



- Ge spectrum unshielded underground

- Ge spectrum underground with Pb shield and purge for Rn

DM Detector Overview
Detection Principles

Bubble Formation
COUPP, PICASSO, SIMPLE

Tracking
Drift, DM-TPC, MIMAC, NIT

Ionization
CoGeNT

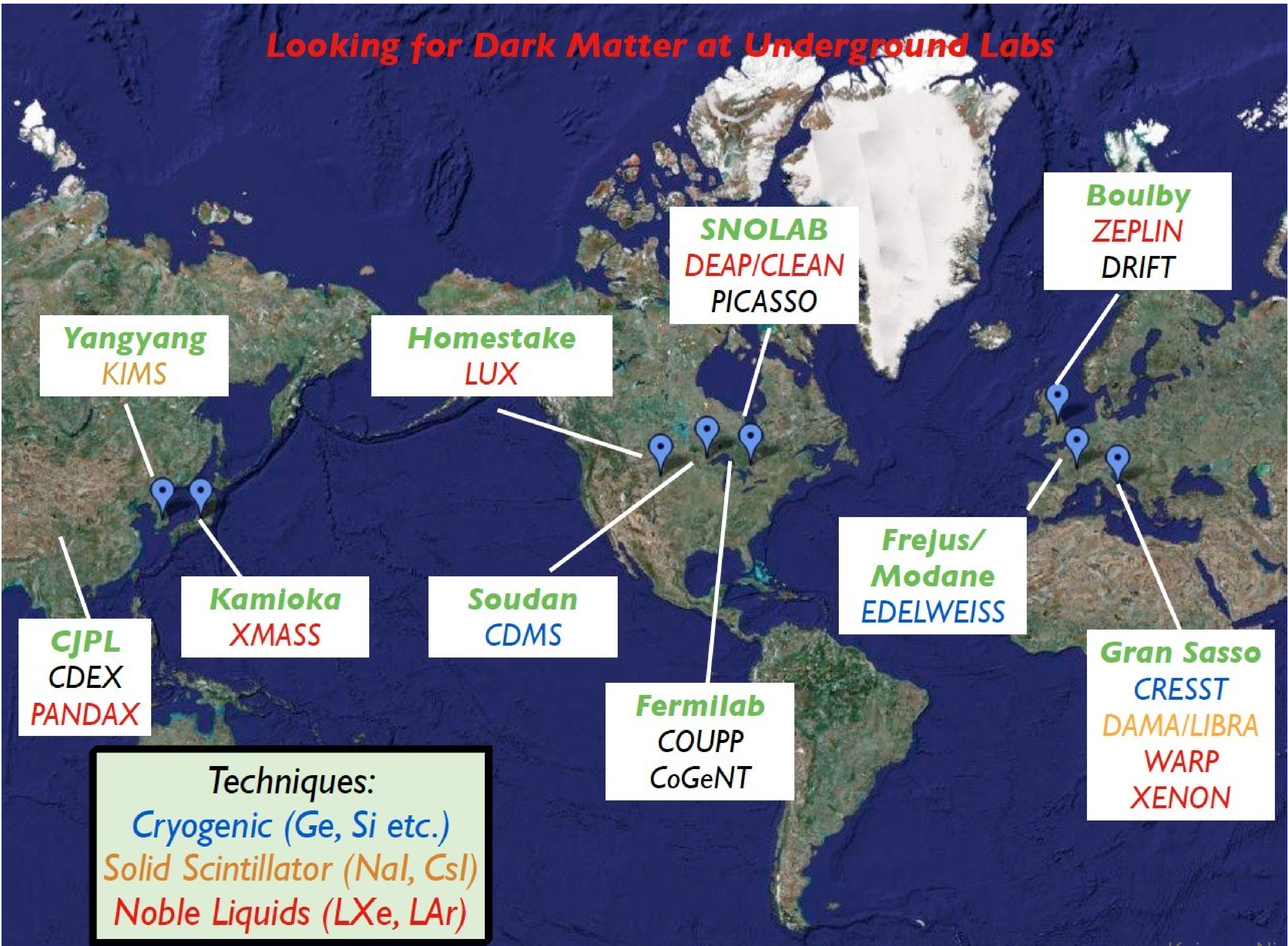
CDMS-II, Super-CDMS
Edelweiss-2

LAr: WARP, ArDM
LXe: **XENON**, LUX, Zeplin

Phonons

CRESST-II, ROSEBUD, **EURECA**

Scintillation
DAMA/LIBRA
KIMS, XMASS, DEAP/CLEAN


Looking for Dark Matter at Underground Labs
Boulby
ZEPLIN
DRIFT
SNOLAB
DEAP/CLEAN
PICASSO
Yangyang
KIMS
Homestake
LUX
Frejus/
Modane
EDELWEISS
CJPL
CDEX
PANDAX
Kamioka
XMASS
Soudan
CDMS
Gran Sasso
CRESST
DAMA/LIBRA
WARP
XENON
Fermilab
COUPP
CoGeNT
Techniques:
Cryogenic (Ge, Si etc.)
Solid Scintillator (NaI, CsI)
Noble Liquids (LXe, LAr)
Kaixuan Ni