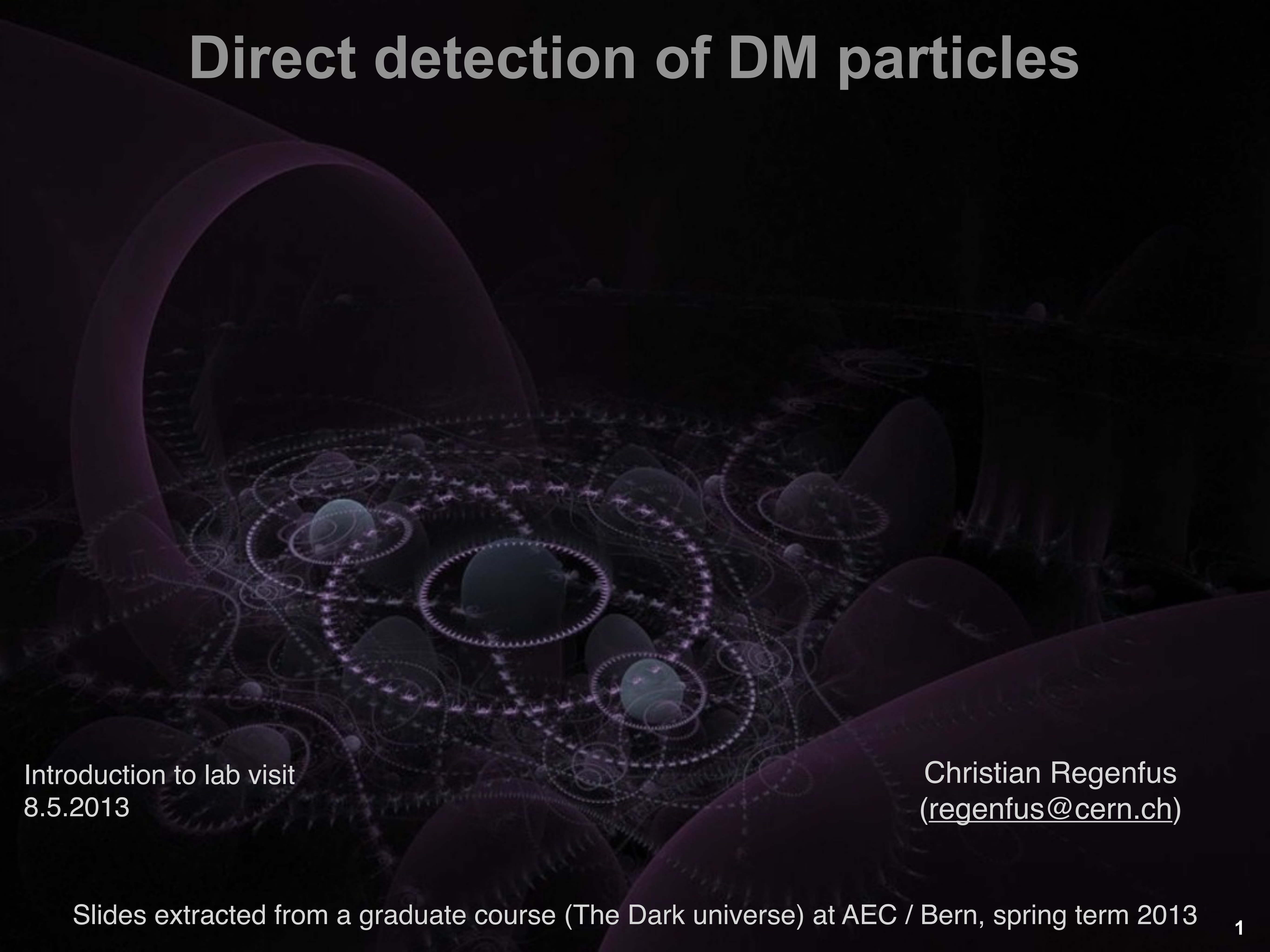
Direct detection of DM particles

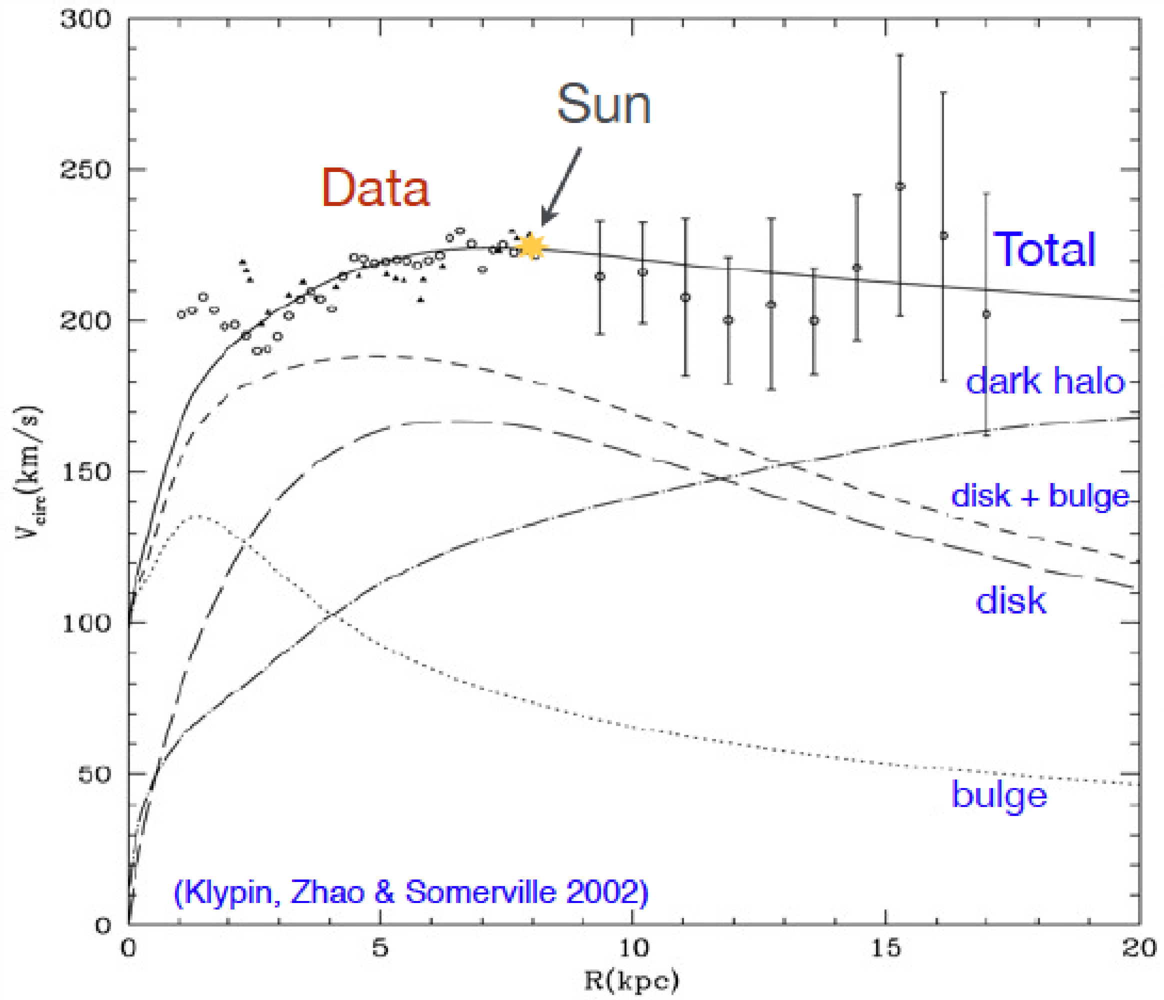


Introduction to lab visit
8.5.2013

Christian Regenfus
(regenfus@cern.ch)

Slides extracted from a graduate course (The Dark universe) at AEC / Bern, spring term 2013

Density of WIMPs in the Milky Way

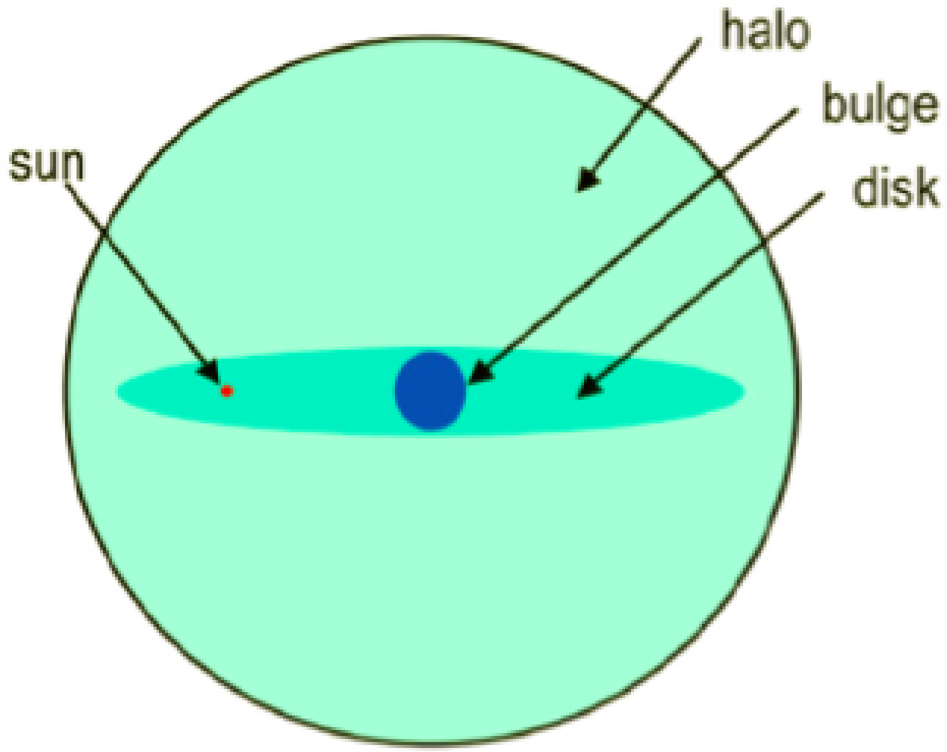


Standard halo assumptions:

- Sun moves around the galactic centre with v = 220 km/s

Isothermal WIMP Halo:

- **On average halo is stationary, no Co-rotation around the galactic centre**
- WIMP velocities are Maxwell-Boltzmann distributed
- v_0 = 220 km/s
- $v_{max} = v_{esc}$ = 650 km/s



PDG:

ρ_{halo} = 0.1 - 0.7 GeVcm^{-3}

ρ_{disk} = 2 - 7 GeVcm^{-3}

Standard value:

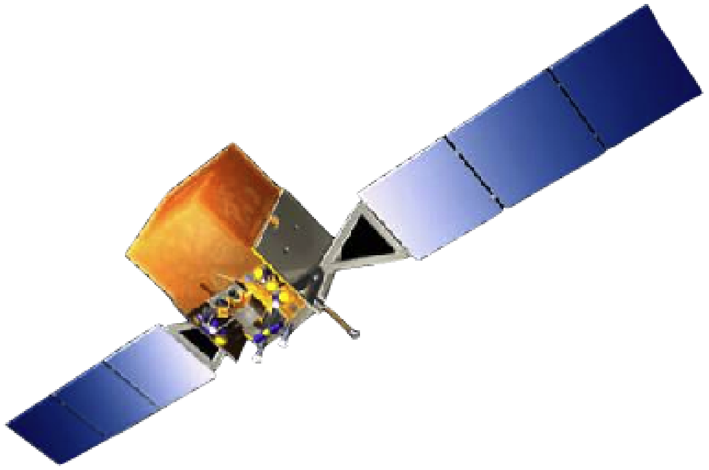
$\rho_X \sim$ 0.3 GeVcm^{-3}

$\rho_X \sim$ 3000 WIMPs m^{-3}

(M_{WIMP} = 100 GeV)

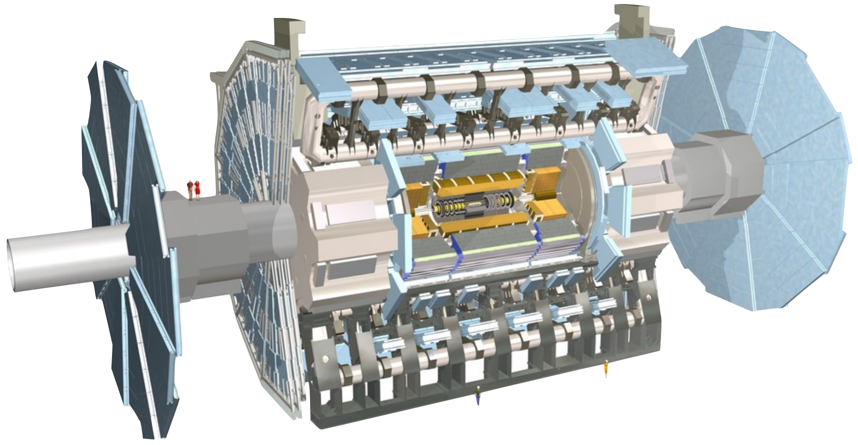
WIMP flux on earth ~ 10^5 cm^{-2}s^{-1}

Strategies for WIMP Detection

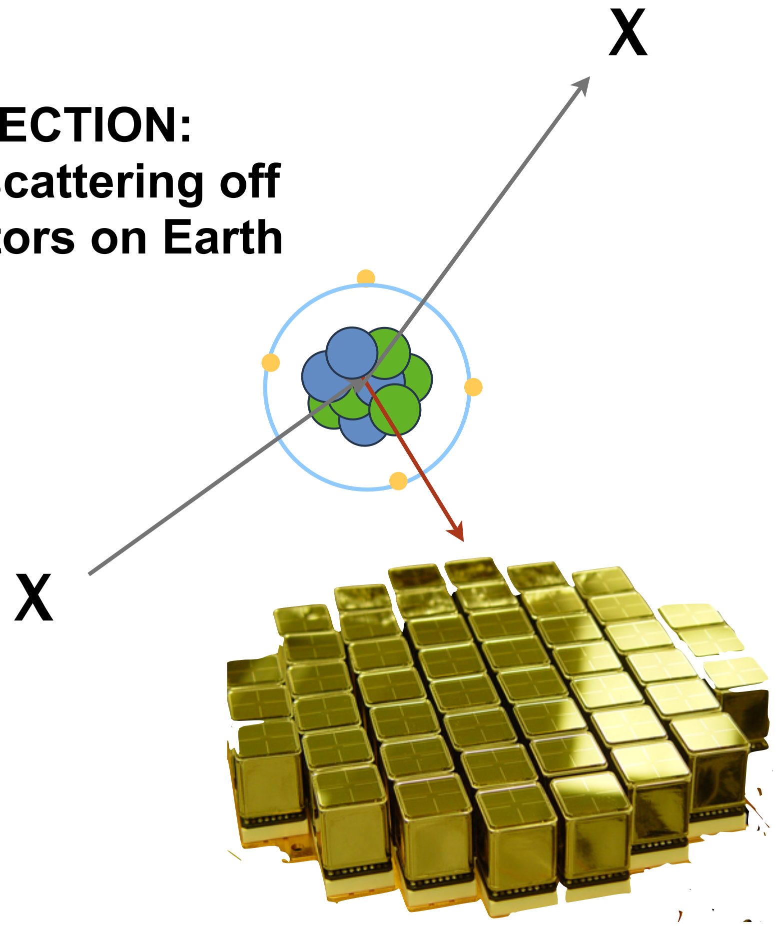


INDIRECT DETECTION: measure gamma rays, neutrinos , positrons, antiprotons, anti-deuterons, etc. from WIMP annihilation in GC, in Sun, in MW

PARTICLE COLLIDERS:
Produce (and detect) WIMPs



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

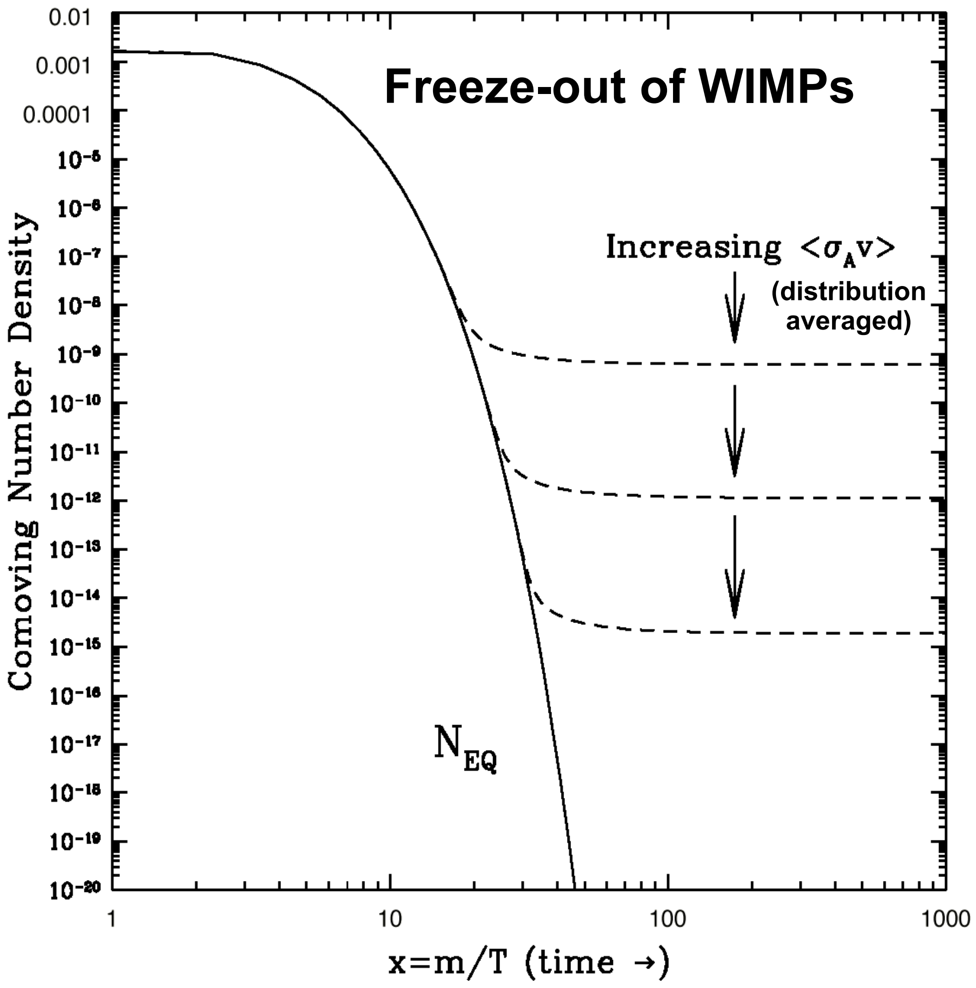


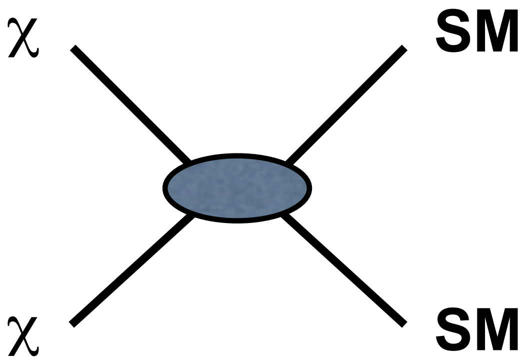
WIMP models are stringently probed by one or more of these methods

We look for direct interactions of WIMPS

WIMP - most prominent DM candidate

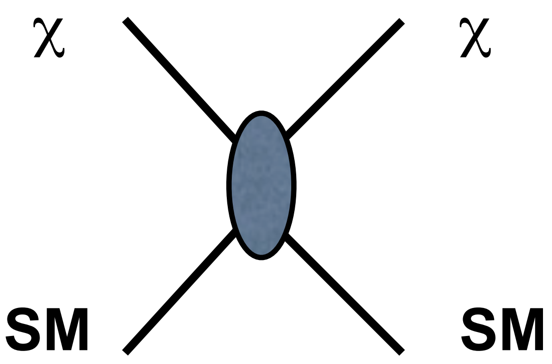
Thermal (BB) relic's number density





annihilation

s-channel



scattering

t-channel

coherent weak or spin dependent IA

The observed relic density points to the **weak scale!**

Well motivated from SUSY

LSP neutralino: super partner of the gauge bosons

(need exact R parity conservation)

We don't know a massive particle which does not interact weakly !

Principle of Direct Detection

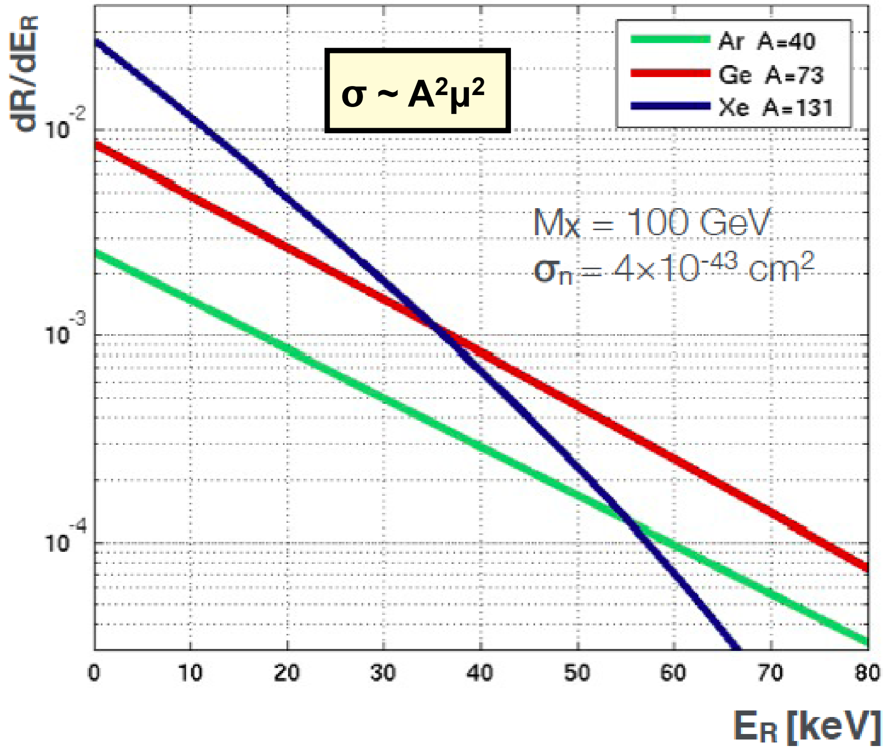
Non rel. elastic collisions with nuclei => nuclear recoils

Coherent scattering of WIMPs (1985)

Goodman, M. W. and **Witten**, E.: **1985**, Phys. Rev. D31, 3059.
Detectability of certain dark-matter candidates, weak neutrino-like couplings

- **Recoil energies 0….~100 keV ….**
- **A^2 & F(q) Dependence: consistency test with different targets**
- **Expected count rate: some events / kg year**
- **Time dependence of the signal:**
  annual: ~3 % , diurnal: ~40 %
- **Combination of different A can test $A^2\mu^2$ dependence**

Differential rates at different targets



Ar: ~15 events/100kg/year @Thr. = 30keV

Comparison with neutrinos:

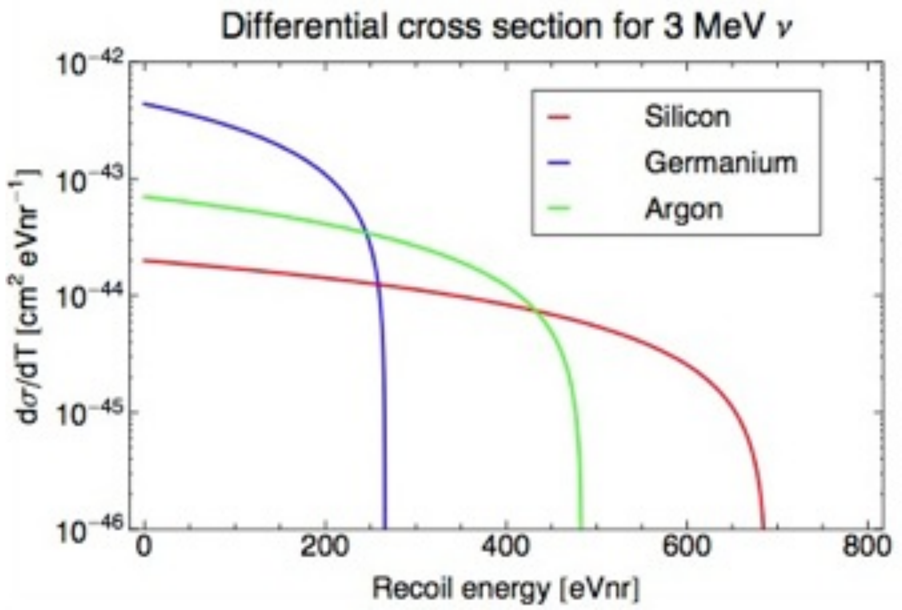
Need large and sensitive detectors with good background suppression

<u>Leptonic IA</u>: (MeV) neutrinos (O) $\sigma \sim 10^{-45}$cm²

<u>Nuclear IA</u>: CNS (Coherent neutrino-nucleus scattering)

Cross sections for neutrino-nucleon scatterings are not so well known as for leptonic reactions (poor theoretical knowledge of the nucleon form factors)

=> Very small recoil energies

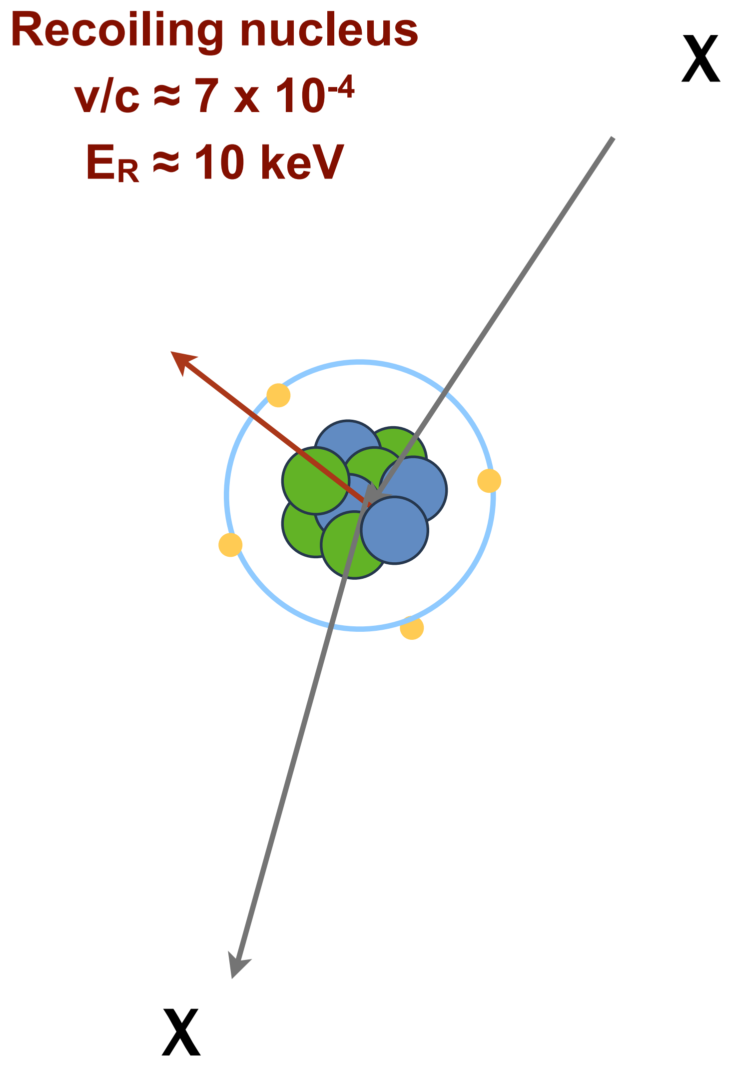


Principles and applications of a neutral-current detector for neutrino physics...,
Drukier and Stodolsky PRD 30, 11,(1984) 2295

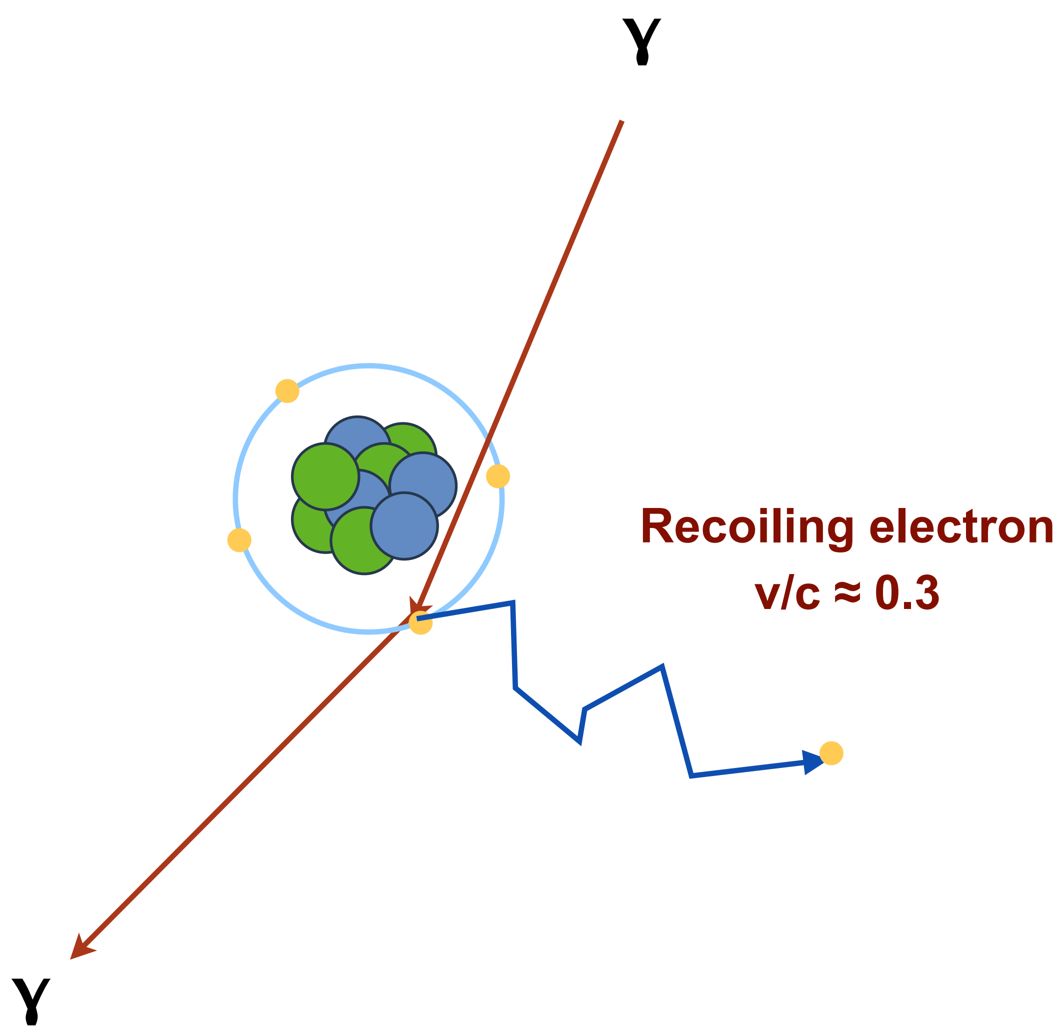
Coherent effects of a weak neutral current,
D. Freedman, PRD 9, (1974) 1389

Detection of WIMPs: Signal and Background

Signal (WIMPs, n)


Recoiling nucleus
$v/c \approx 7 \times 10^{-4}$
$E_R \approx 10$ keV

Background (γ,β)


Recoiling electron
$v/c \approx 0.3$

The detector material (target) converts this energy into something measurable

scintillation light - free charge (electrons) - phonons - gas bubbles - ionisation grains ….

Experiments are distinguished by their ability to detect

- **interaction type (integral vs. event-by-event)**
- **single or multiple channel read out (light, charge, heat ...)**

Direct detection techniques

Single channel techniques

Hybrid techniques

Example listing not complete!
Lots of activities around the world

Bolometers
Targets: Ge, Si, Al_2O_3, LiF, TeO_2
E_{phonon} ~meV, NR energy col.eff. ~100%
Sensitivity (TES) << 1 keV
FWHM 4.5 eV @ 6 keV γ
CRESST-I (0.6 keV), CUORICINO, CUORE (5 keV)

Heat

Heat & Ionisation Bolometers
ZIP/NTD for Q & H channels
Targets: Ge,Si
CDMS, EDELWEISS, SCDMS, EURECA cryogenic (<50 mK)

Scintillation & Heat Bolometers
Targets: $CaWO_4$, BGO, Al_2O_3
TES/NTD for L & H channels **CRESST, ROSEBUD** even more cryogenic (~10 mK)

Combination of more detection principles allows for better identification of the interaction type.

Helps enormously to suppress background.

Event-by-event interaction type ID present in all modern DM detectors.

Ionisation

Ionisation Detectors
Targets: Ge,Si,CF_3I,CS_2
Energy per e/h pair 1-5 eV
NR energy collection eff. 10-30%
Thresh. ~3 keV
IGEX, HDMS, COUPP, GENIUS, DRIFT, CoGeNT

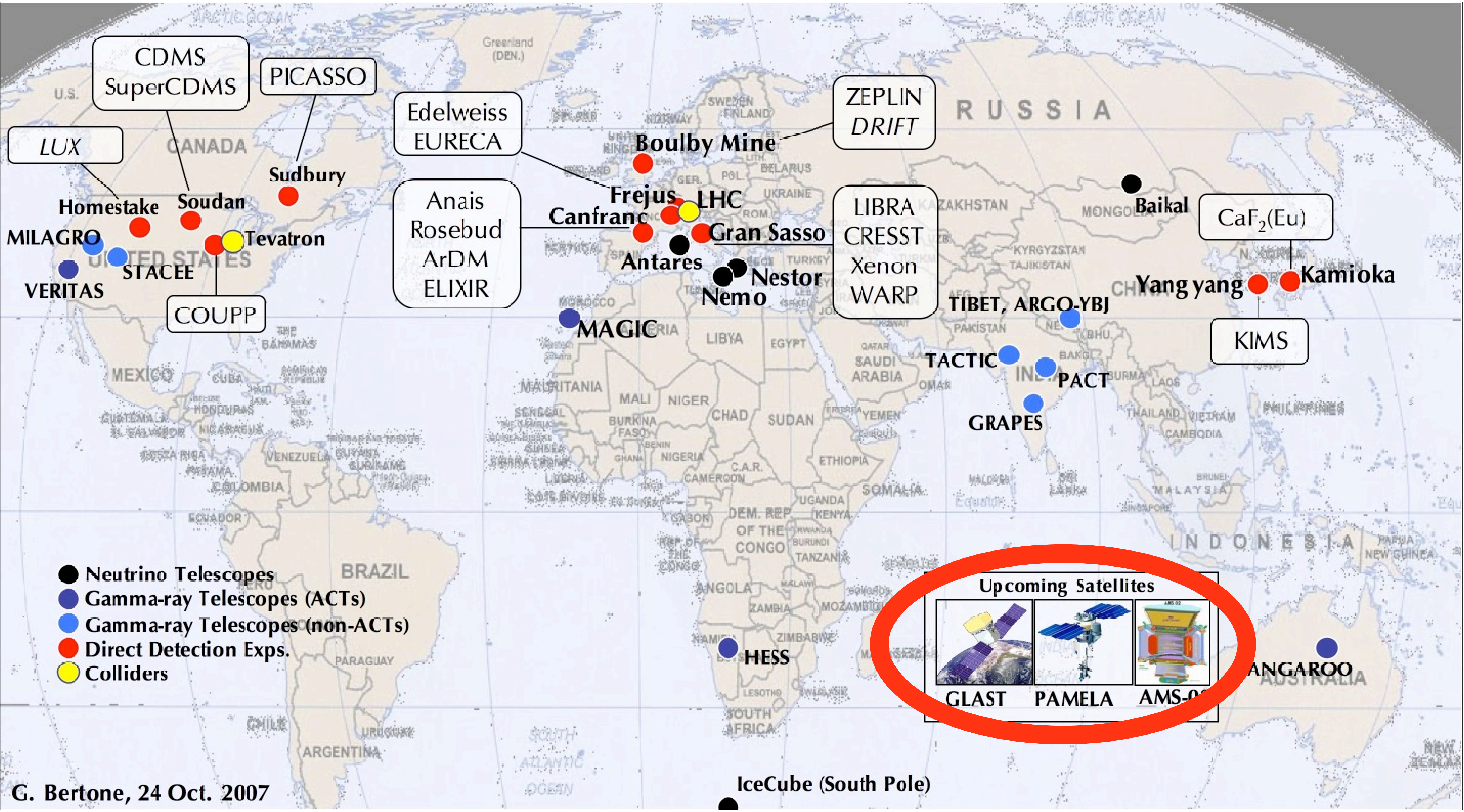
Scintillation

Scintillators
Targets: NaI, Xe, Ar, Ne E. per photon ~15 eV,
NR energy collection eff. 1-3%,
Light sens. 2-8 phe/keV, Thresh. ~2-5 keV
ZEPLIN I (2 keV), NAIAD (4 keV) DAMA (2 keV), DEAP, CLEAN, XMASS (5 keV)

Scintillation & Ionisation Detectors
Noble liquid TPCs, PMT readout (both channels), Thresh. ~5 - 30 keV
ZEPLIN, XENON, LUX, DarkSide, WARP, ArDM, SIGN
(Best scalability, presently best limits)

In addition:
Scintillation Timing (DEAP/CLEAN)
Signal Modulation (DAMA/LIBRA, DRIFT ...)
Nucl.-recoil-only trigger (COUPP...)
Self-Shielding (XMASS) ...

DM search around the world



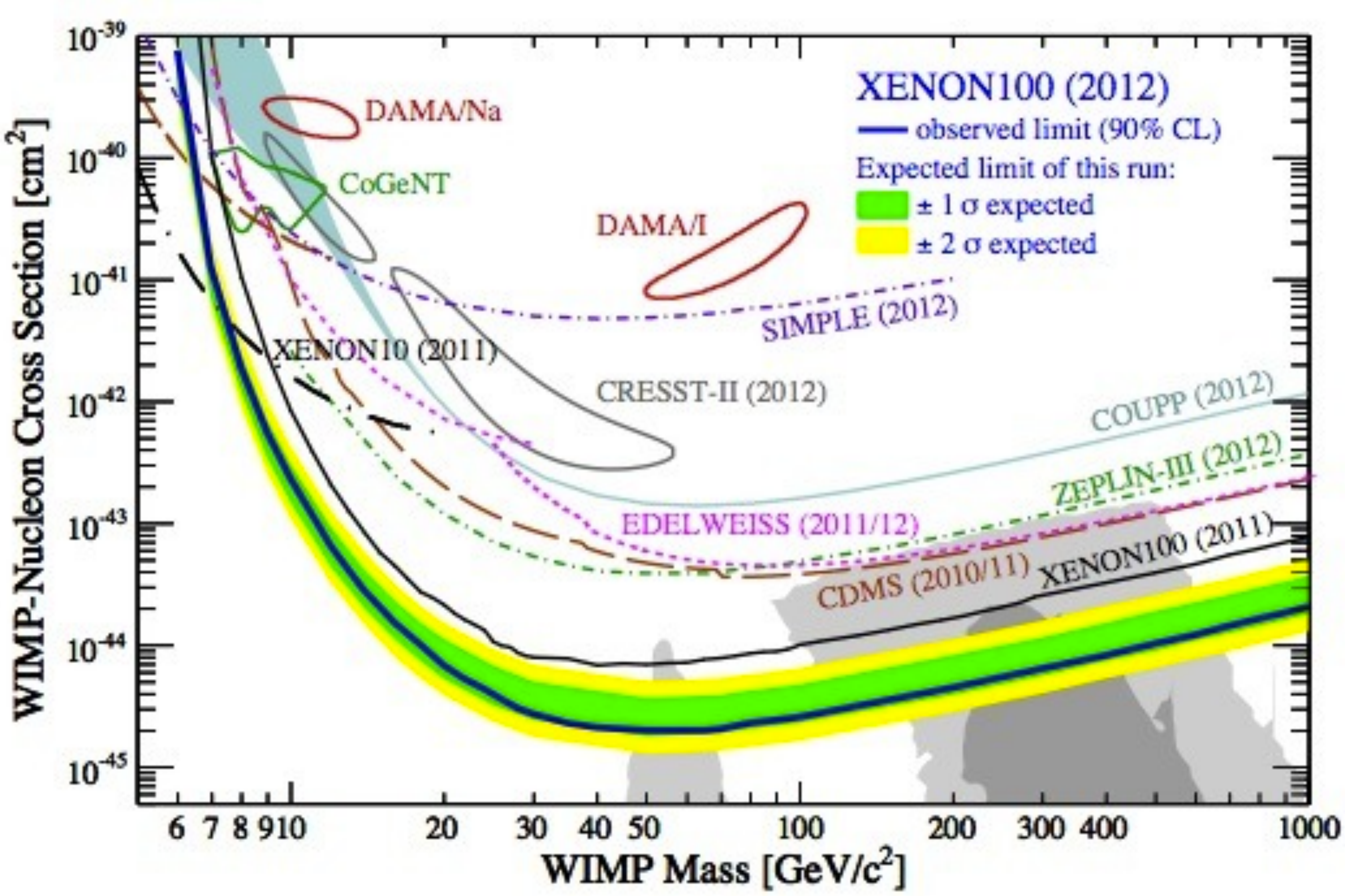
G. Bertone, 24 Oct. 2007

Best limits up to date

Example: XENON100

arXiv:1207.5988v1 [astro-ph.CO] 25 Jul 2012

results from 225 live days

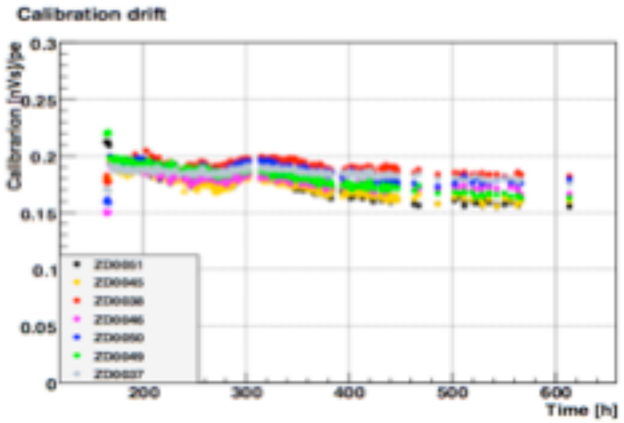


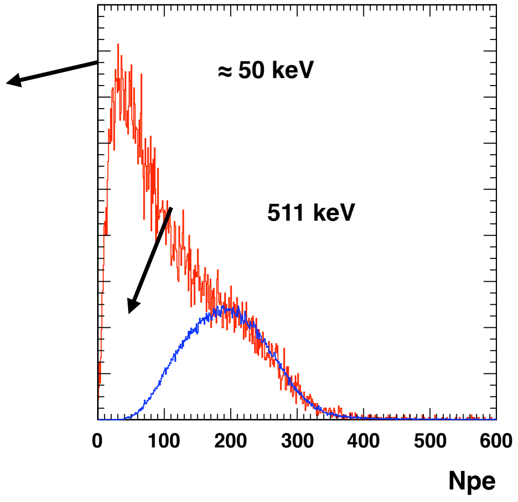
Latest spin-independent WIMP-nucleon scattering limits from XENON100: The expected sensitivity of this data is shown by the green/yellow band (1σ/2σ) and the resulting exclusion limit (90% CL) in blue.

How do we build such a detector?
(developments towards a ton scale LAr detector)

Large volume – double phase – charge/light – 3-D imaging – energy threshold ~30 keV – event-by-event interaction type identification – ionisation density discrimination

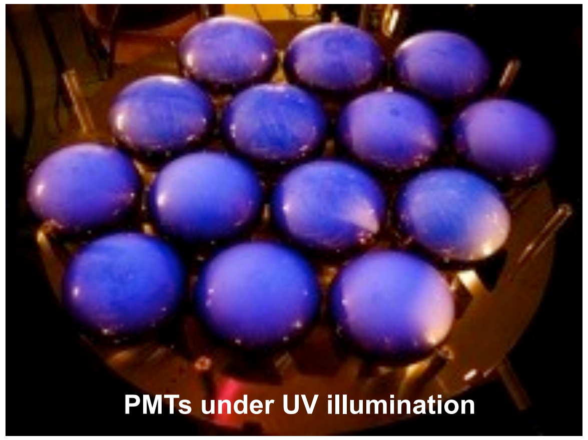
Test runs



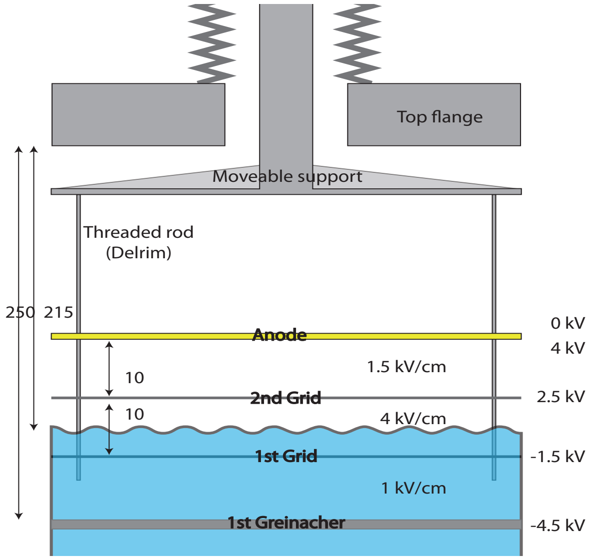


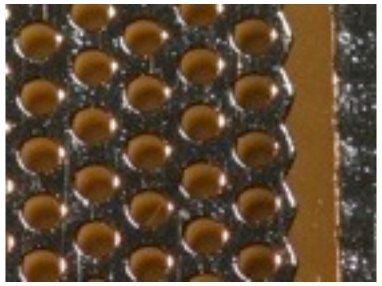
Cryogenic operation

Light readout with PMTs and TPB as WLS

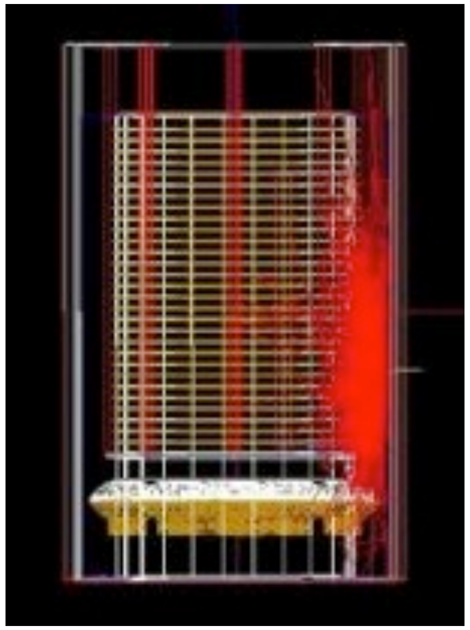


Charge extraction, charge read out





Full GEANT4 detector MC

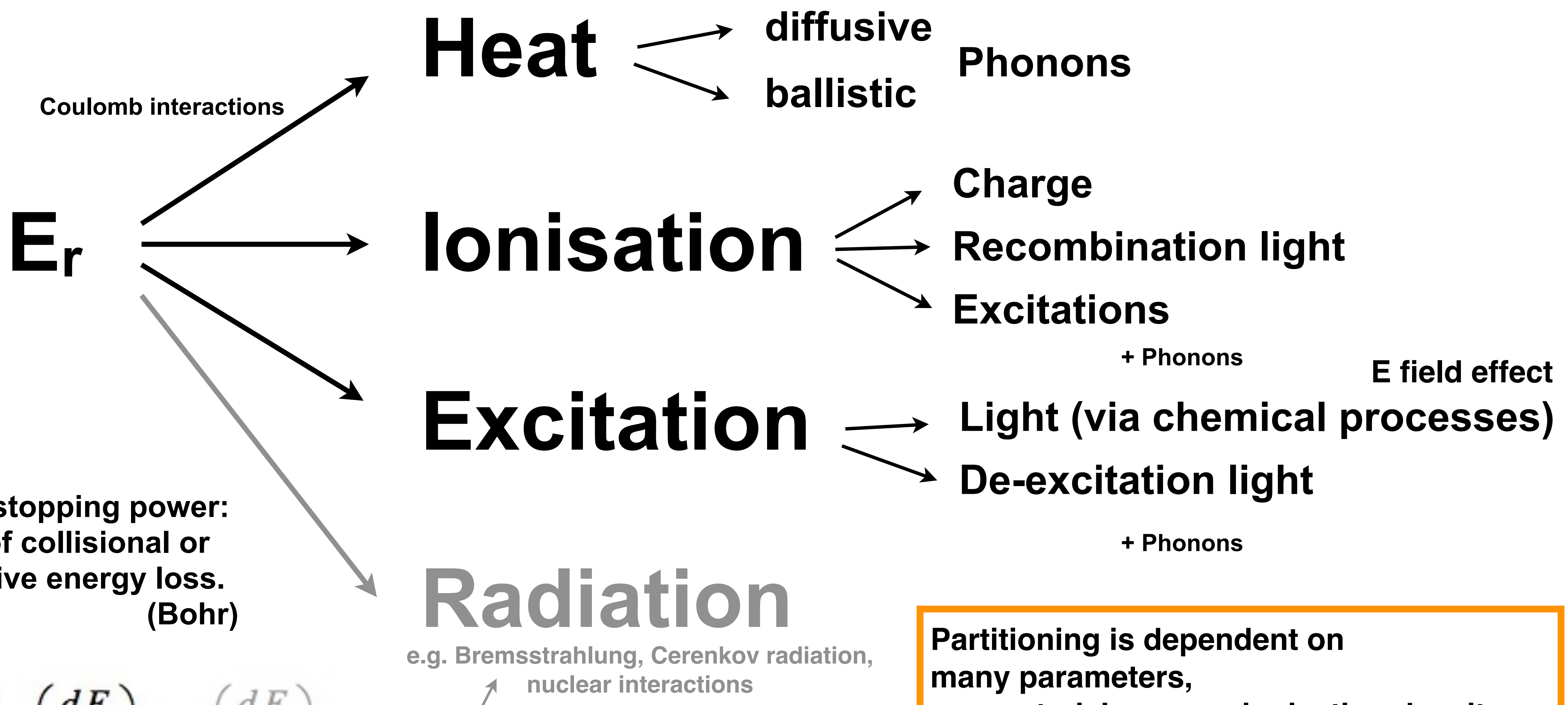


General control system: PLC

Neutrons from a dd generator for calibration and tests

What has to be measured?

Where does the recoil energy go to ?



Total stopping power: sum of collisional or radiative energy loss. (Bohr)

$$\frac{dE}{dx} = \left(\frac{dE}{dx}\right)_{col} + \left(\frac{dE}{dx}\right)_{rad}$$

not important for us

Partitioning is dependent on many parameters, e.g. material, energy, ionisation density ...

- $(dE/dx)_{col}$: electronic energy loss due to Coulomb interactions (i.e., the ionisation and excitation)
- $(dE/dx)_{rad}$: nuclear energy loss (emission of Bremsstrahlung, Cerenkov radiation, nuclear interactions
- Excitation raises an electron to a higher energy shell
- Ionisation completely removes the electron from the atom
- Energetic electrons are sometimes called delta rays
- $(dE/dx)_{col}$ is also called Linear Energy transfer (LET), the rate of energy loss (dE/dx) of a charged particle due to ionisation and excitation.

We observe different energy scales (yields)

WIMPs (and neutrons) scatter off nuclei, most background sources (gammas, electrons) scatter off electrons

- **Detectors have different response to nuclear and electron recoils (@ same energy)**

$\mathrm{keV_{ee}}$ **= measured signal from an electron recoil**

$\mathrm{keV_{r}}$ **= measured signal from a nuclear recoil**

- **Often expressed by a Quench factor (QF)**

For nuclear recoil events:

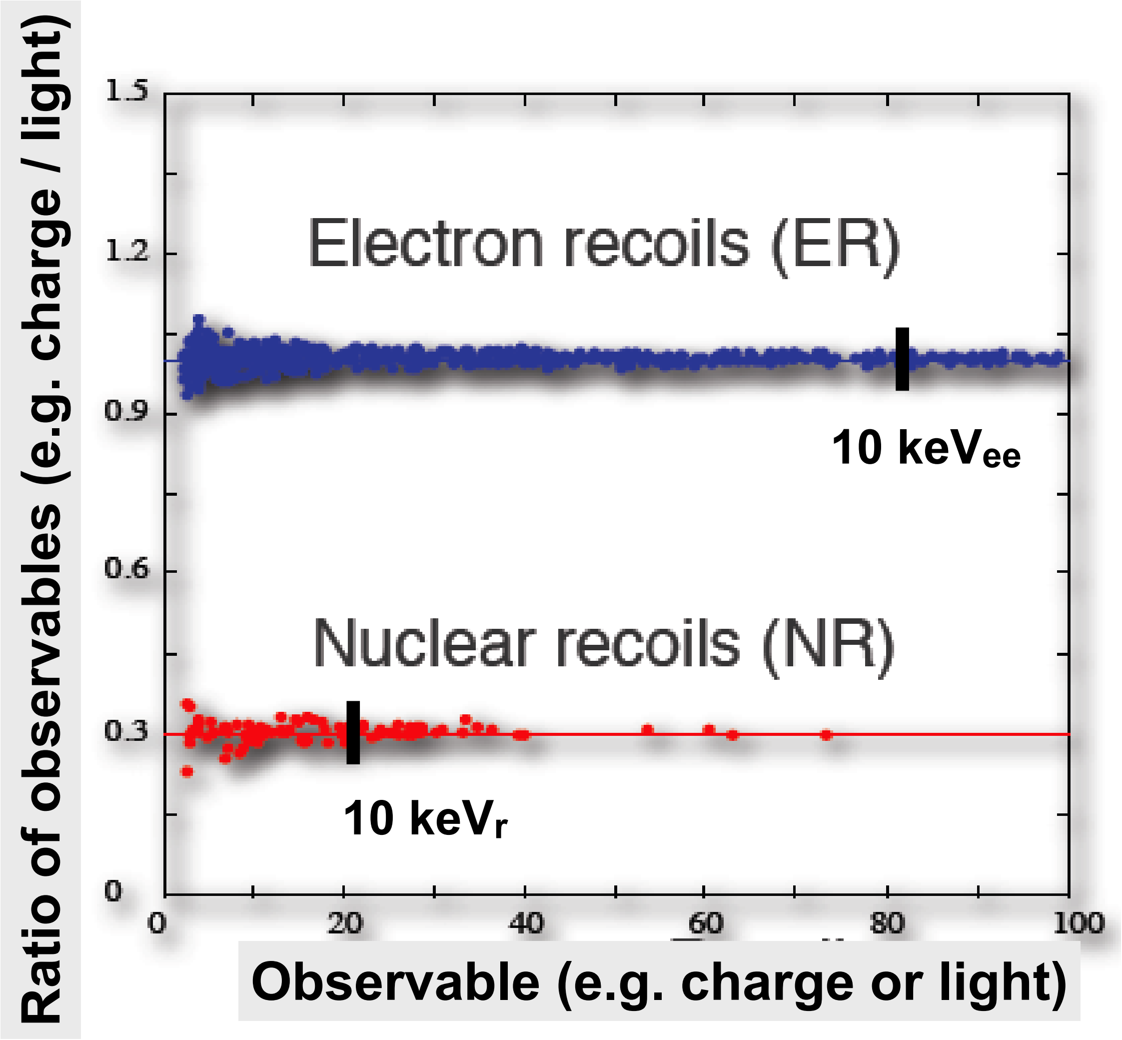
$$E_{\mathrm{visible}}\ [\mathrm{keV_{ee}}] = QF \bullet E_{\mathrm{r}}\ [\mathrm{keV_{r}}]$$

Example ->

QF **= 25%**

QF **=** $QF(E)$ **can be non-linear**

The two energy scales can be calibrated with gamma (^{57}Co, ^{133}Ba, ^{137}Cs, ^{60}Co, etc) and neutron (AmBe, ^{252}Cf, n-generator, etc) sources.



Lindhard theory (nuclear losses = phonons/heat)

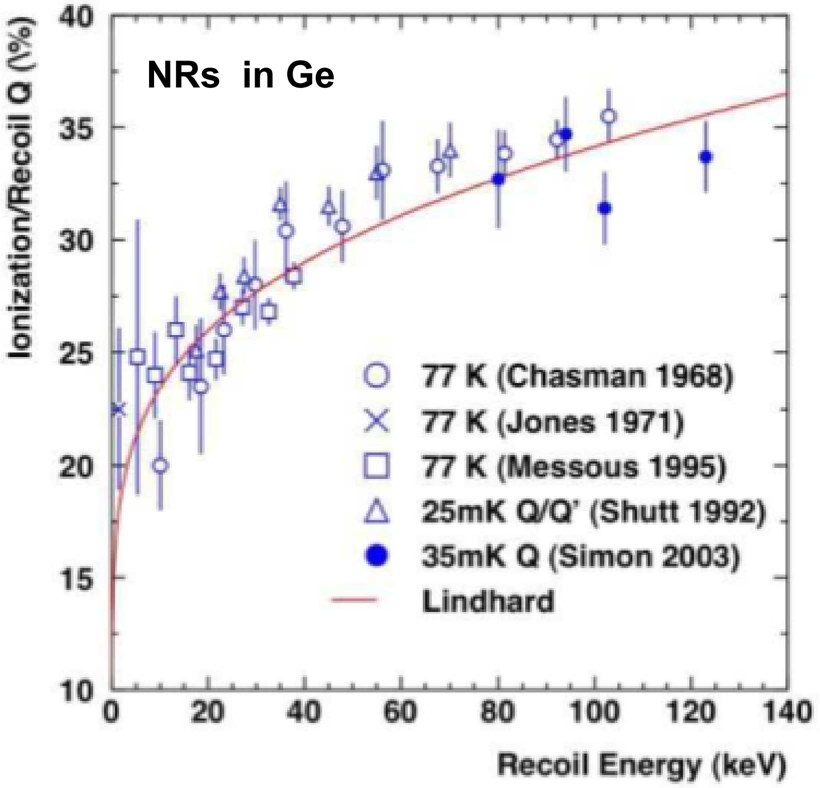
Lindhard effect (nuclear quenching) in semiconductors

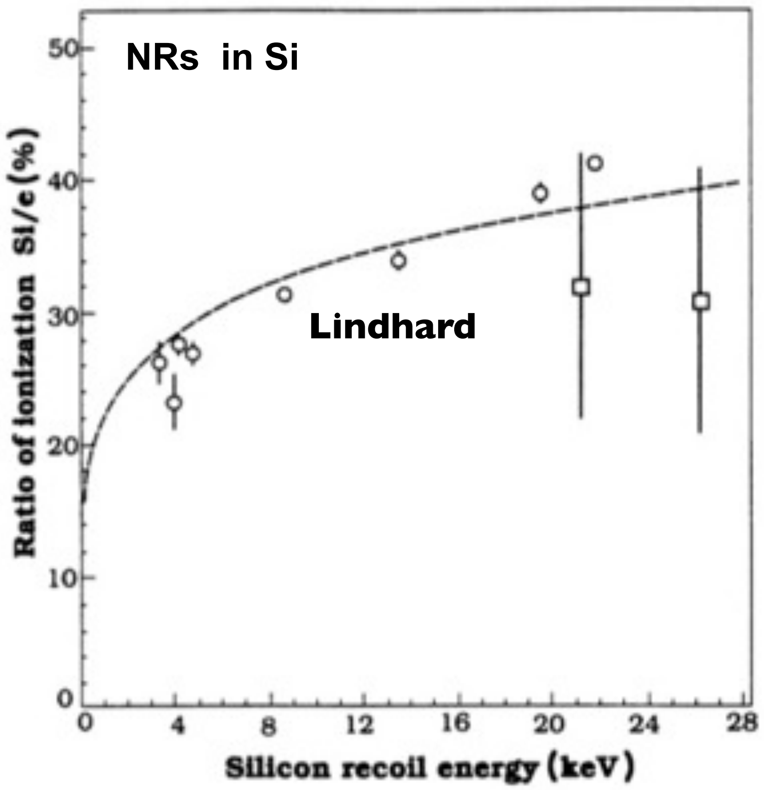
$$\left(\frac{dE}{dx}\right)_{col} = \left(\frac{dE}{dx}\right)_{elec} + \left(\frac{dE}{dx}\right)_{nuc}$$

Nuclear quenching

Energy dependent!

Ionisation charge quenching in Ge and Si



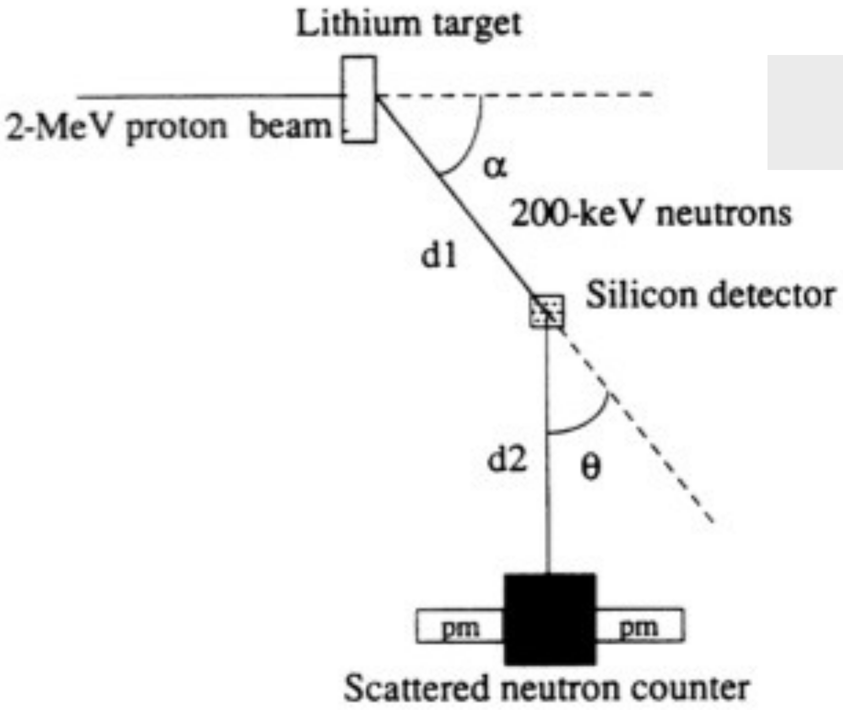


Recoiling atoms are less effective in producing primary ionisation or scintillation than electrons of the same energy.

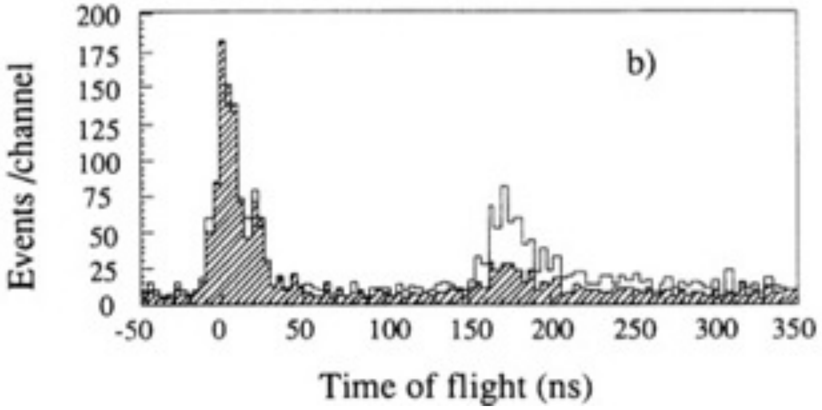
The ratio of the ionisation (and/or scintillation) yield from atomic projectiles to that from electrons, referred to as the quench factor

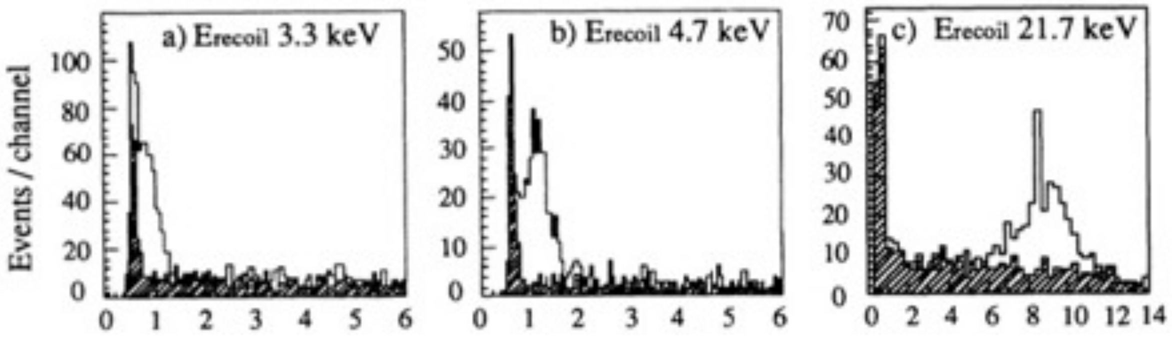
Generally decreases with energy and is material dependent.

Neutron scattering experiment (tagged neutron beam)



Measurement of the ionisation of slow silicon nuclei in Si
G. Gerbier et al., PRD 42, 3211 (1990)

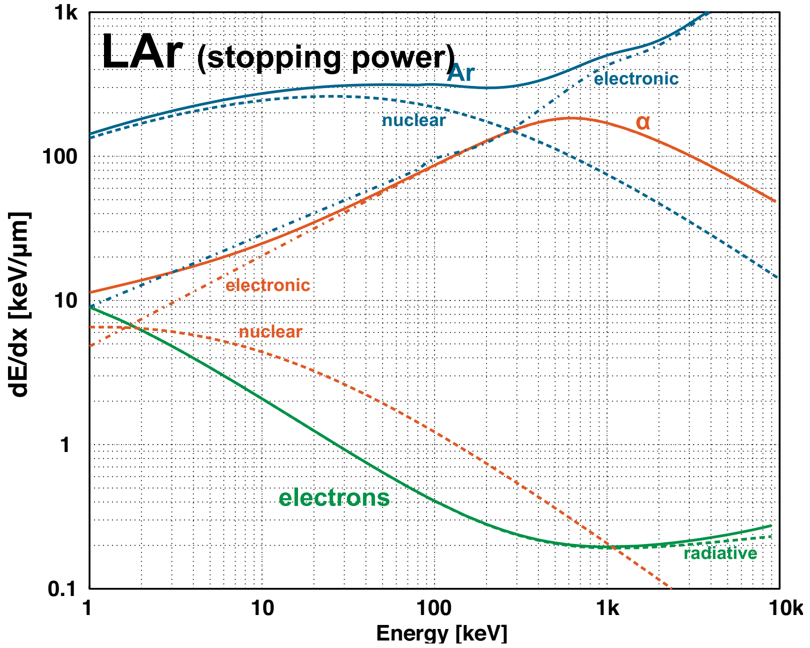


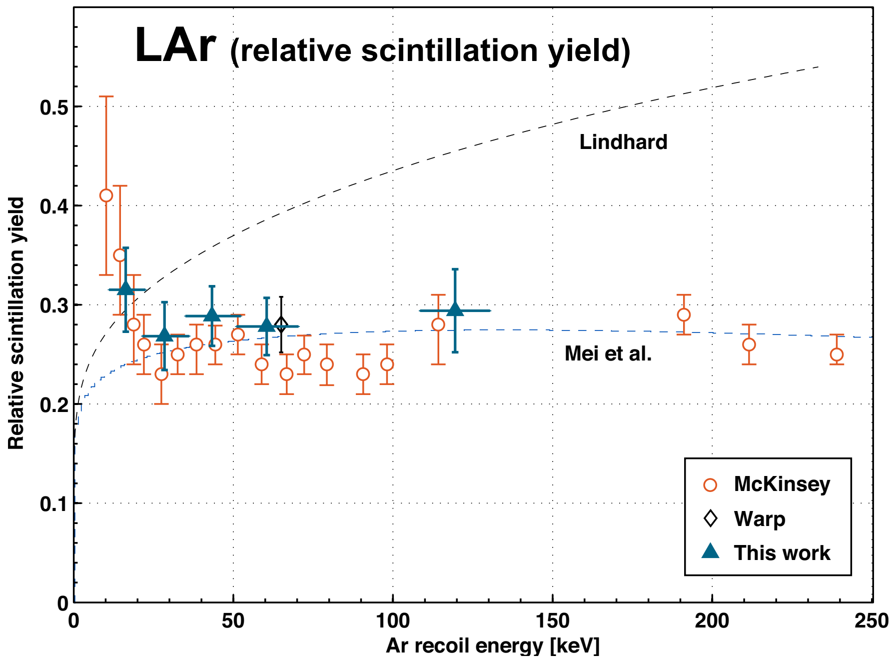


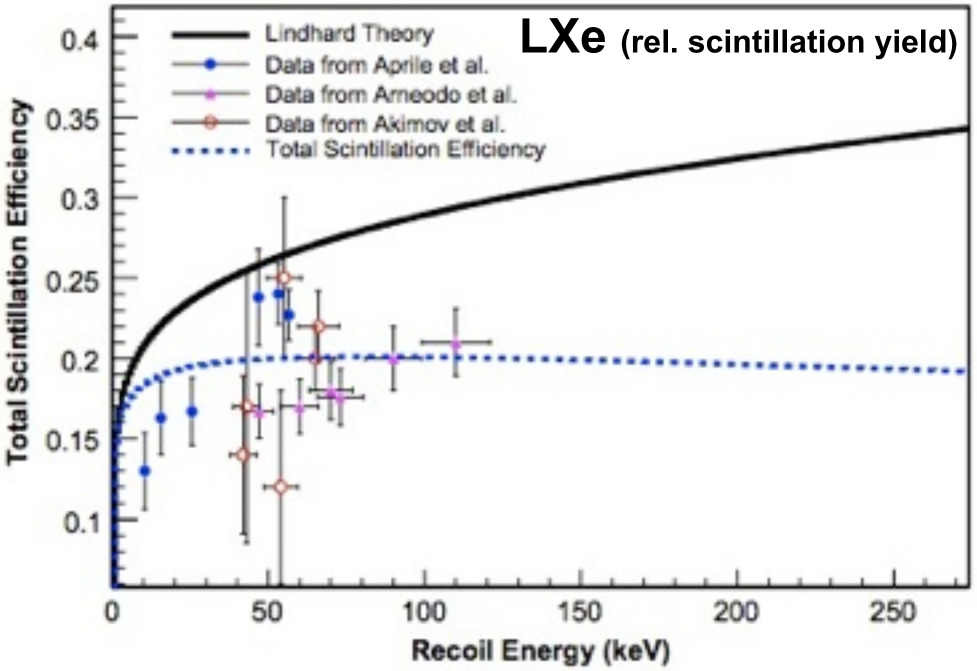
More complicate: Quenching in noble liquids

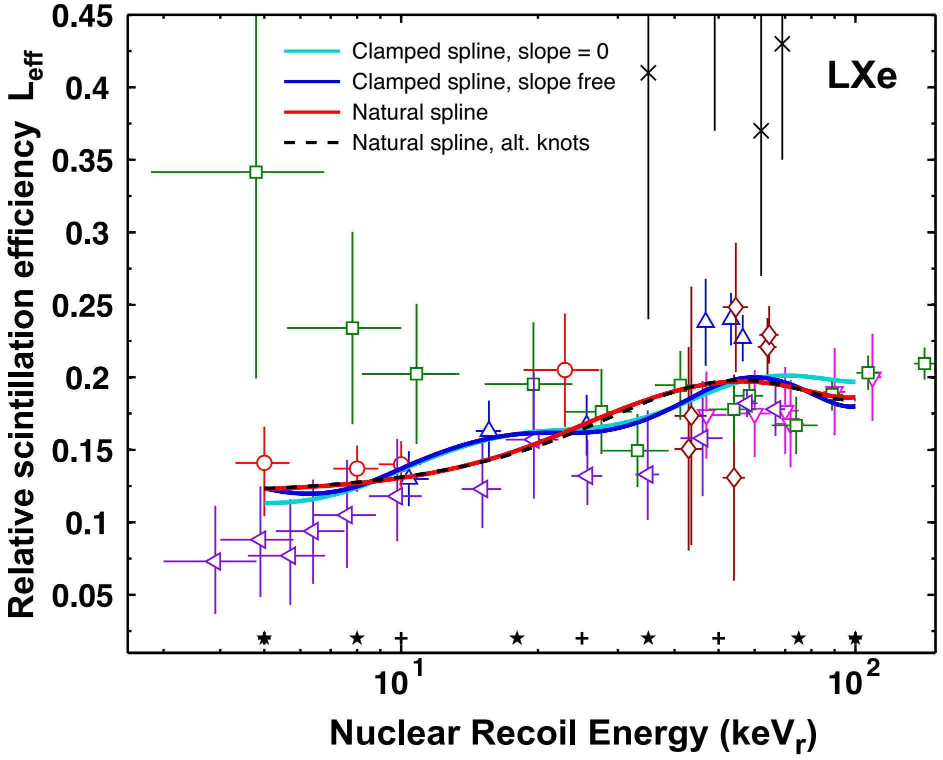
On the example of the scintillation light (similar for charge)

$$f\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{elec} \Rightarrow \text{signal}$$









Semi-empiric approach:

(A model of nuc. recoil scint. eff. in noble liquids; D. Mei et al., Astropart. Phys. 30 (2008) 12)

- **In addition to the Lindhard factor we have an efficiency for the production of scintillation light or charge**
- **Latter is described as luminescence quenching (charge)**
- **Total yield (quenching) is factorized in a nuclear and a signal term**

$$q_f = f_n \times f_l$$

Ionisation density dependent

- **Only the latter leads to the production of charges and light**
- **Need additional theoretical assumptions, not yet well understood**

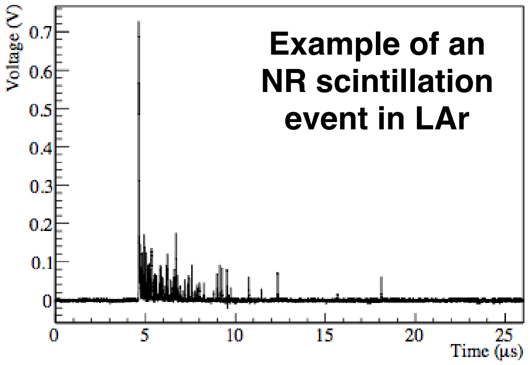
Possible explaination by collisions in signal production:
Bi-excitonic, bi-excimer (Penning) processes, Supereleastic...

See: A. Hitachi and T. Doke, **Luminescence quenching in liquid argon under charged particleimpact: Relative scintillation yield at different linear energy transfer.** Phys.Rev., B46(18), 1992. doi:10.1103/PhysRevB.46.11463.

Setup for scattering of monochromatic neutrons

Fusion generator

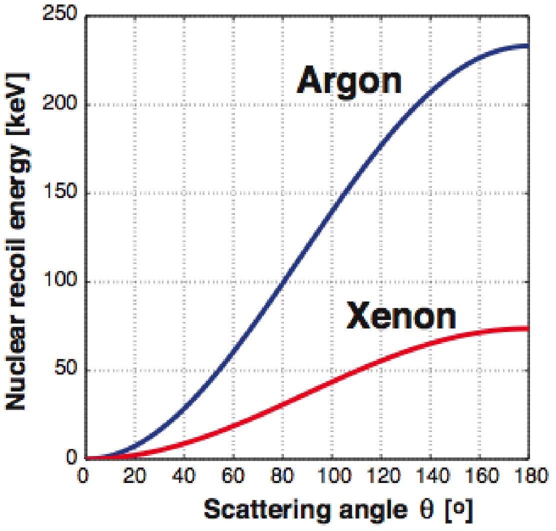
${}_1D^2$ + ${}_1D^2$ -> ${}_2He^3$ (0.82 MeV) + ${}_0n^1$ (2.45 MeV)
${}_1D^2$ + ${}_1D^2$ -> ${}_1T^3$ (1.01 MeV) + ${}_1p^1$ (3.02 MeV)


Example of an NR scintillation event in LAr

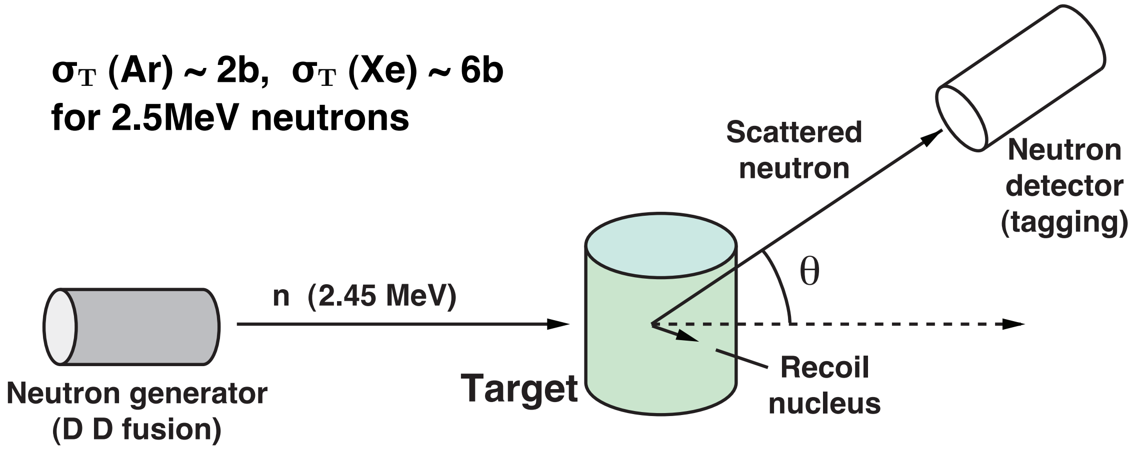
$$E_{\rm recoil} = \frac{2E_{\rm n}}{(1+A)^2}\left[1 + A - \cos^2\theta - \cos\theta\sqrt{A^2+\cos^2\theta-1}\right] \cong \frac{2E_{\rm n}A}{(1+A)^2}(1-\cos\theta)$$

$$R = 1 - \exp\left(-\frac{N_A\,\rho_{LAr}\,\sigma_T}{A}\,l\right)$$

Interaction fraction
(l length, ρ density, $N_A = 6{\cdot}10^{23}$)



σ_T (Ar) ~ 2b, σ_T (Xe) ~ 6b
for 2.5MeV neutrons


Scattered neutron

Neutron detector (tagging)

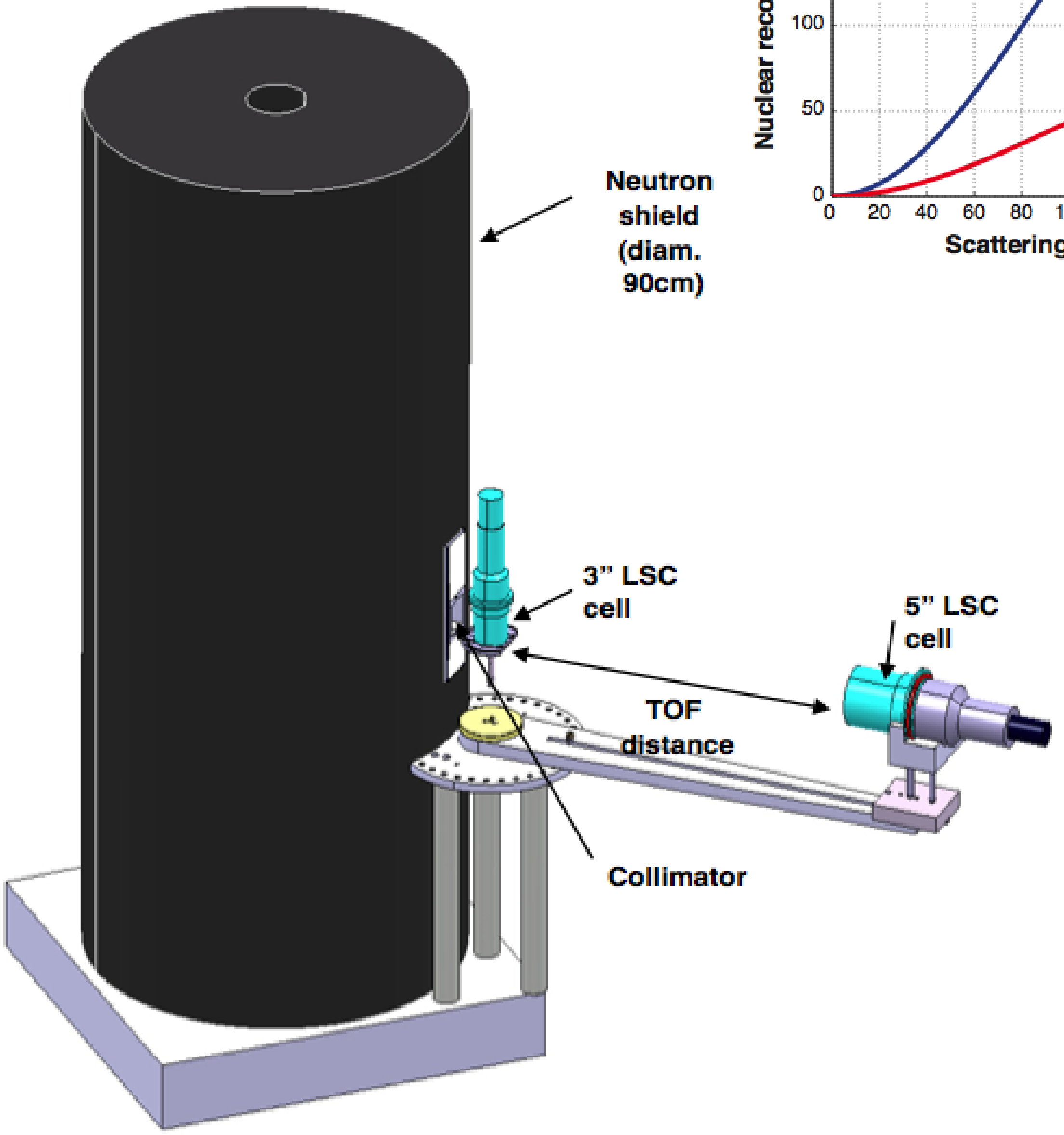
θ

n (2.45 MeV)

Neutron generator (D D fusion)

Target

Recoil nucleus


Neutron shield (diam. 90cm)

3” LSC cell

5” LSC cell

TOF distance

Collimator

Setup in our lab at CERN

Let’s visit the experimental setup in our laboratory

Christian Regenfus (regenfus@cern.ch)