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ALBERT EINSTEIN CENTER
FOR FUNDAMENTAL PHYSICS

Dark Matter – Experimental Searches

XVIII Frascati Spring School
„Bruno Touschek“ – Spring 2016

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Content

• **Direct Detection**	1	Basics: Rates and signatures; energy scales	**Mon**
	2	Backgrounds: Sources, reduction	
• **Detectors**	3	Crystals, cryogenic, directional detectors NaI, Germanium	**Tue**
	4	Cryogenic liquids Xenon and Argon	
• **Indirect Detection**	5	Indirect detection: Cosmic rays, gamma lines, neutrinos	**Wed**
Current Results	6	The current dark matter landscape The future	

Some Literature (incomplete!)

- Perkins: *Particle Astrophysics,* *Oxford University Press*
- *Bertone (ed): Particle Dark Matter,* *Cambride University Press*

- Lewin/Smith: *Review of mathematics, numerical factors, and corrections for dark matter experiments based on elastic nuclear recoil*, *pa.brown.edu/articles/Lewin_Smith_DM_Review.pdf*
- Baudis: *Direct Dark Matter Detection*, *arXiv:1211.7222*
- Schumann: *Dark Matter 2014*, *arXiv:1501.01200*
- Marrodan/Rauch: *Direct Detection Experiments,* *arXiv:1509.08767*
- Heusser*: Low-radioactivity background techniques,* *http://fizisist.web.cern.ch/fizisist/research/Low-RadioactivityBackgroundTechniques.pdf*

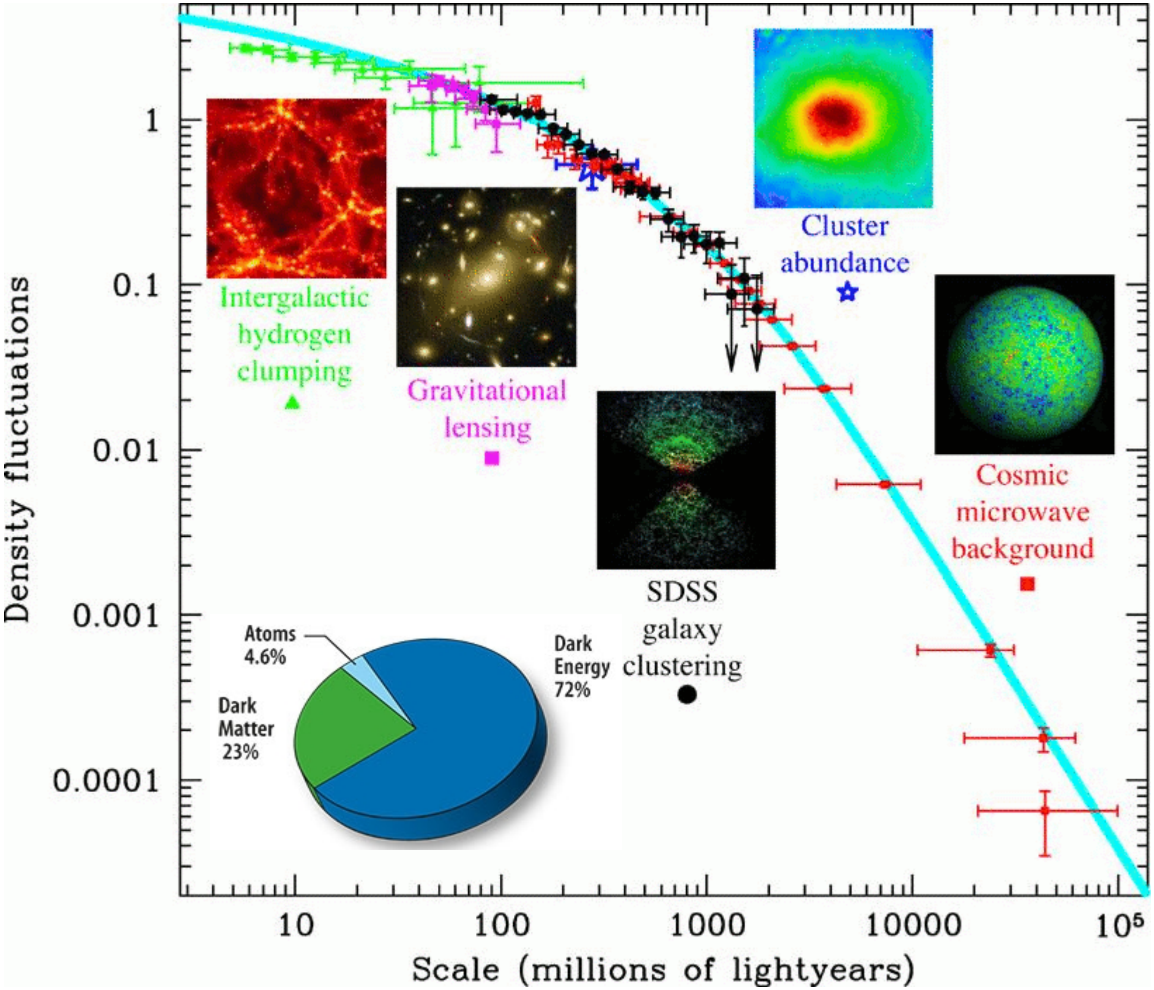
ΛCDM Model

The Standard Model
of Cosmology
(„Concordance Model“)

Describes the Universe since the Big Bang with a few parameters only (6)

Uses Friedmann equation to describe evolution of Universe since Inflation

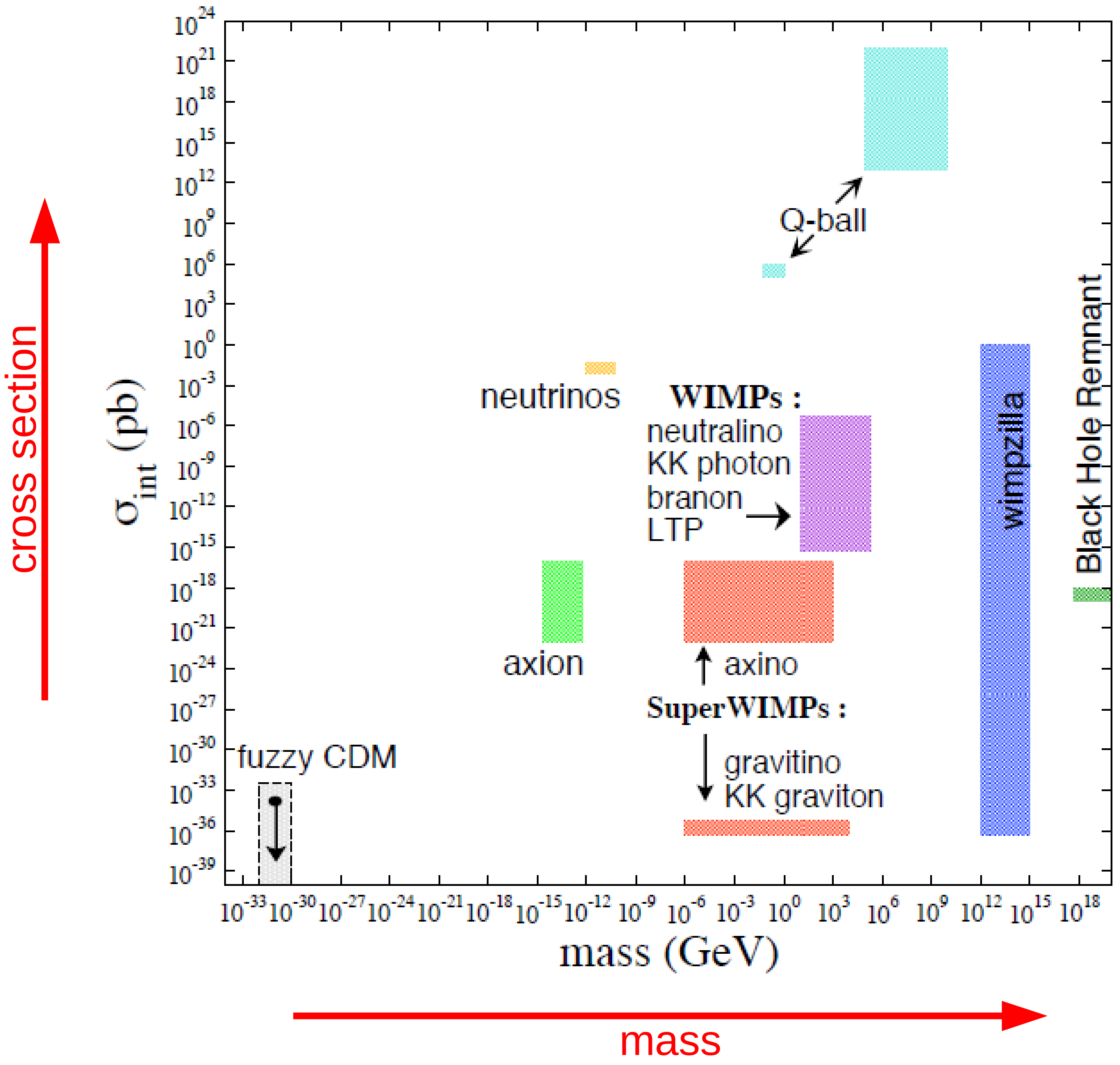
Agrees with the most important cosmological observations:
- CMB Fluctuation
- Large Scale Structures
- Accelerated Expansion (SN observations)
- Distribution of H, D, He, Li



Ingredients:

Λ	Cosmological Constant
CDM	Cold Dark Matter

(Some) Dark Matter Candidates



- Axion
- WIMPs
  - Neutralino
  - LKP
- sterile neutrinos
- ...

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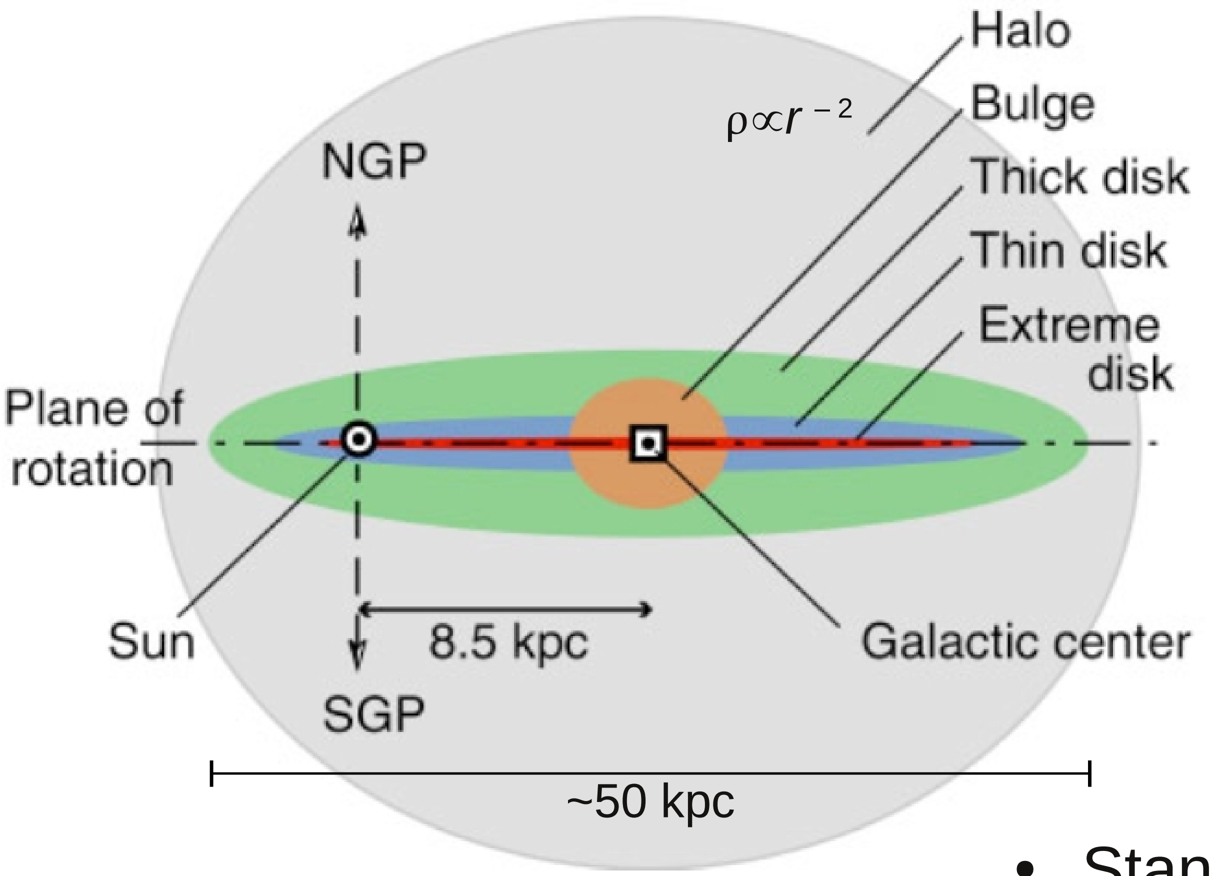
1 Direct Detection Basics: Rate, Signatures, Energy Scale

- Expected dark matter rates are extremely small
  → need to fight backgrounds
- Expected nuclear recoil spectrum is steeply falling
  → need very low threshold
- WIMPs interact coherently with the nucleus
  → form factor suppression for heavy targets
- The WIMP dark matter parameter space
- The Energy Scale for WIMP searches
  → measure nuclear recoils

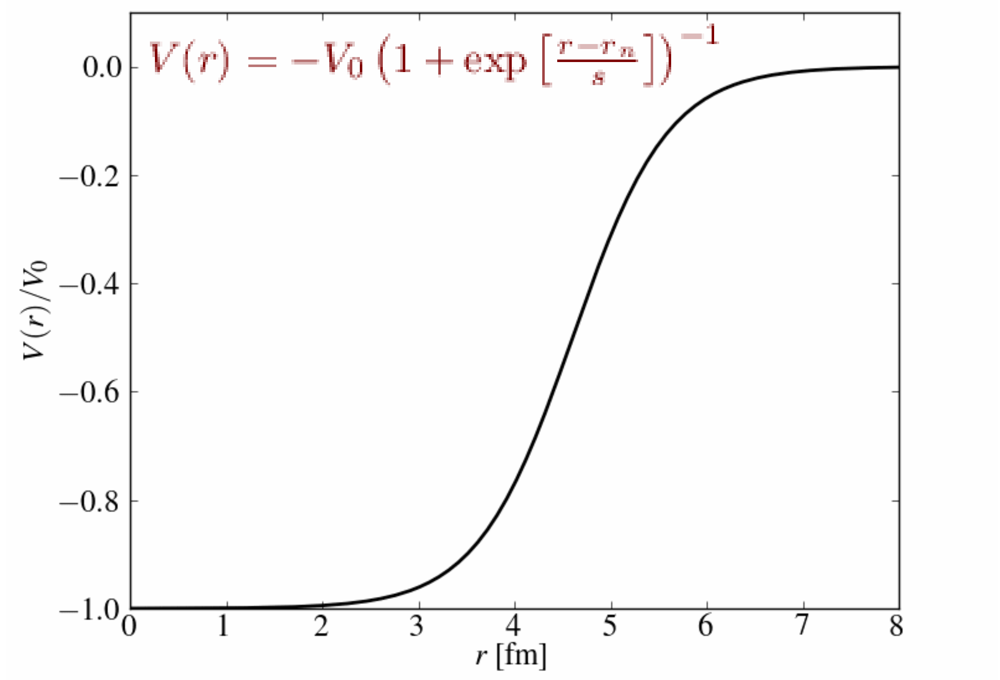
Milky Way – Standard Halo Model

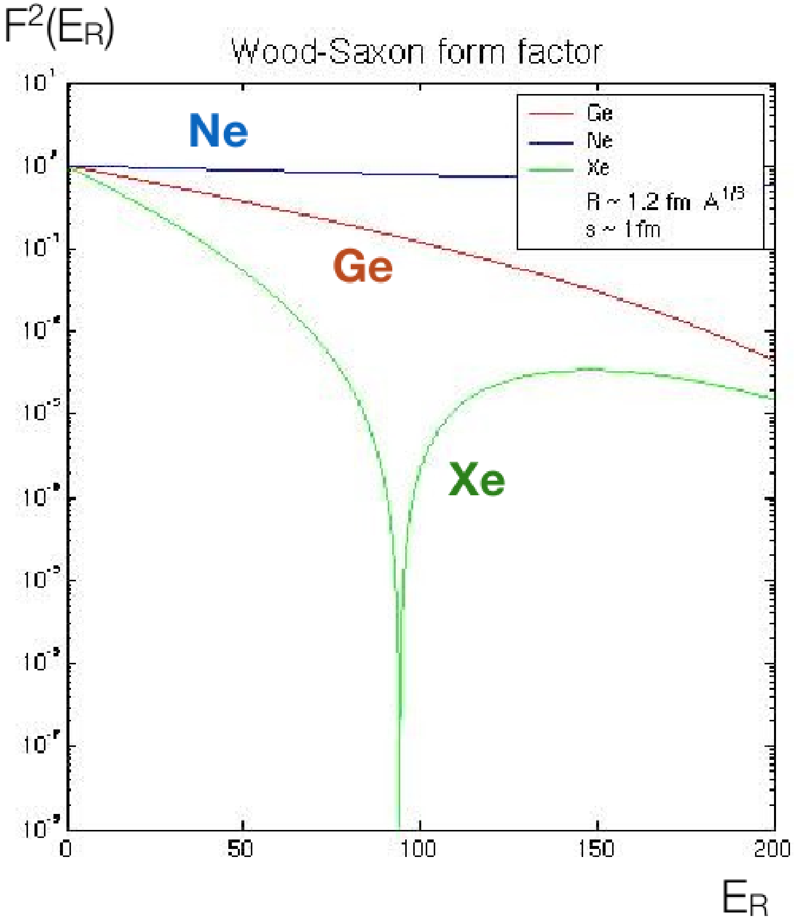


- Standard halo model: Ingredients
  - → local circular velocity v_c
  - → velocity of the Sun wrt to v_c
  - → galactic escape velocity v_{esc}
  - → velocity distribution $f(\mathbf{v})$
  - → local dark matter density ρ_0

Form-Factors

Woods-Saxion Potential:



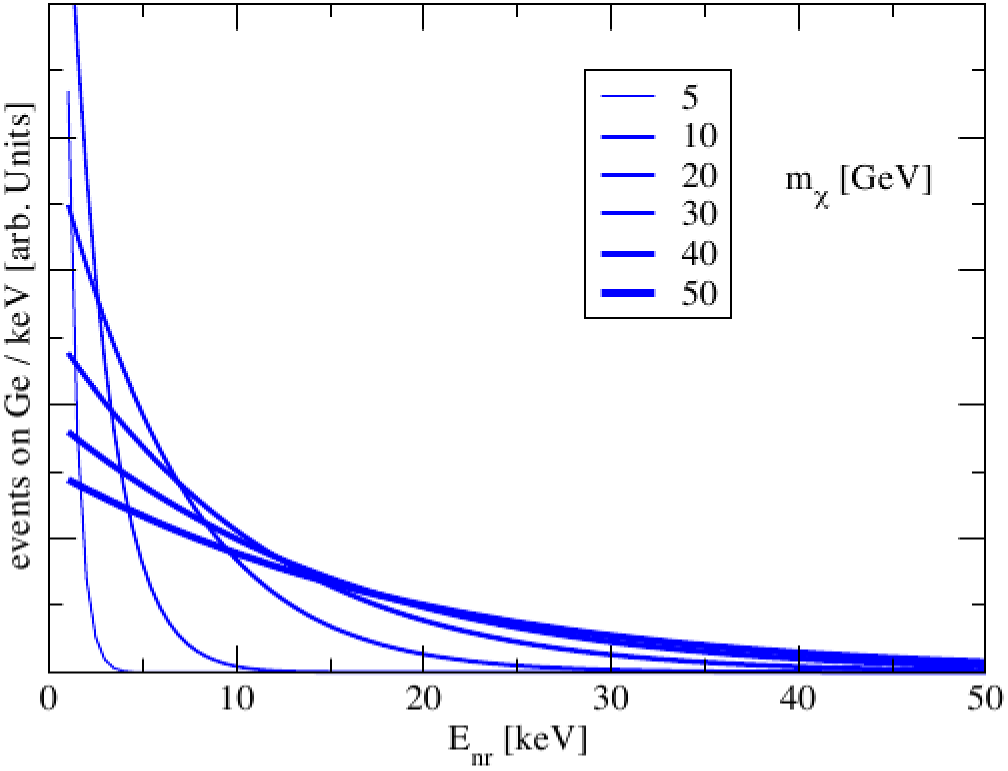


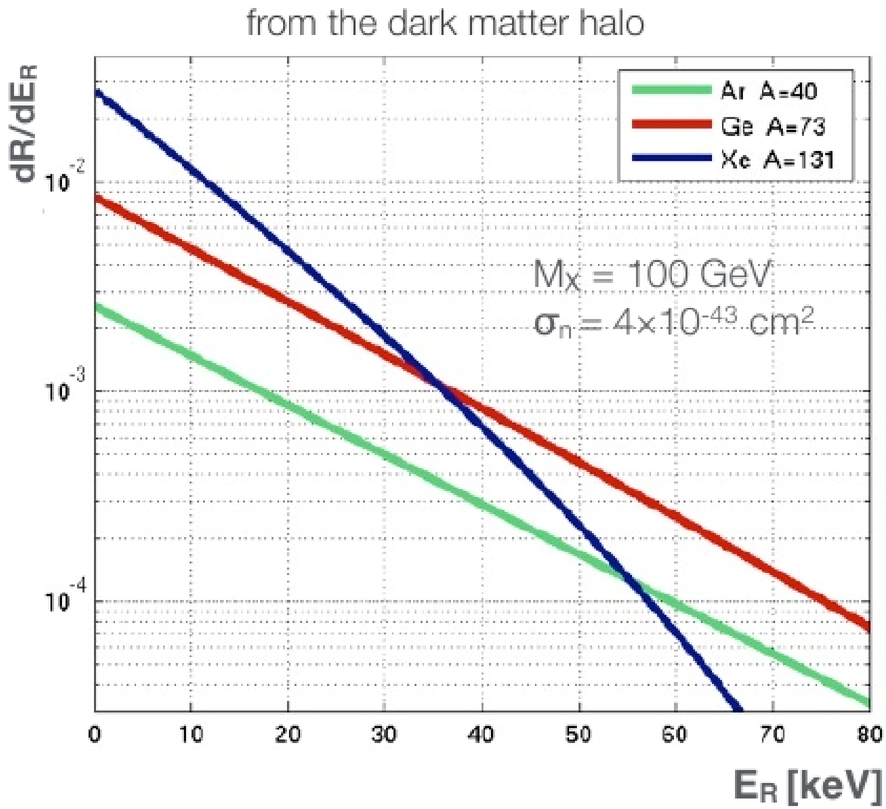
Helm Form Factor:

$$F(qr_n) = \underbrace{\frac{3[\sin(qr_n) - qr_n \cos(qr_n)]}{(qr_n)^3}}_{j_1(qr_n)} e^{-(qs)^2/2}$$

with r_n = nuclear radius, $r_n \approx 1.2\ A^{1/3}$ fm, s = 1fm (skin thickness)

WIMP Recoil Spectra





→expect different rates for different targets (cross checks!)

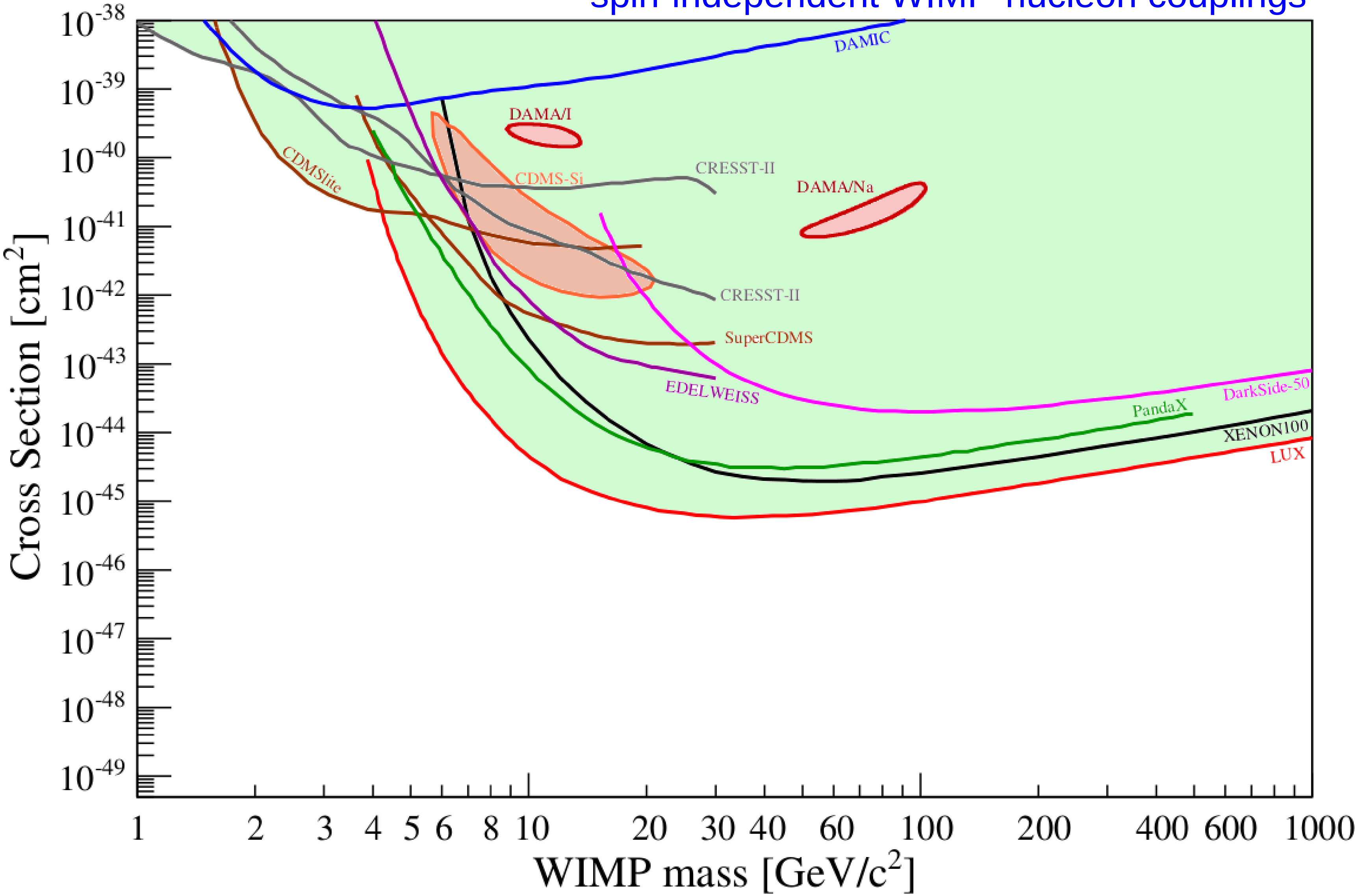
→rate scales with A^2 → heaviert targets favored (for scalar couplings)

→ spectrum rises exponentially → low detector threshold desired

→ low-mass WIMPs → lighter target and/or low threshold necessary

Mass-Cross Section Plane

spin-independent WIMP-nucleon couplings



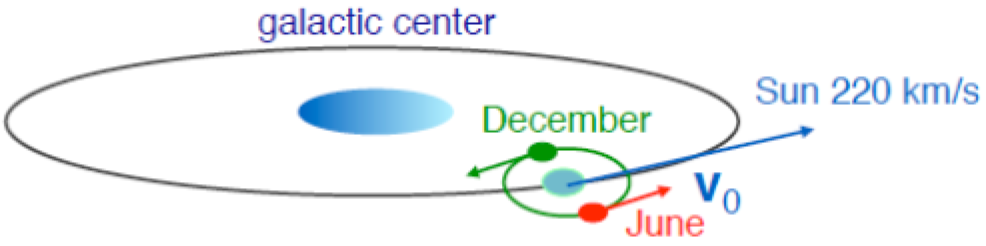
WIMP Signatures: Annual Modulation

Spectral function of WIMP rate:
$$\frac{dR}{dE_R} = \frac{k_0}{k_1}\frac{R_0}{E_0 r}\left\{\frac{\sqrt{\pi}v_0}{4v_E}\left[erf\left(\frac{v_{min}+v_E}{v_0}\right) - erf\left(\frac{v_{min}-v_E}{v_0}\right)\right] - e^{-\frac{(v_{esc})^2}{v_0^2}}\right\}$$

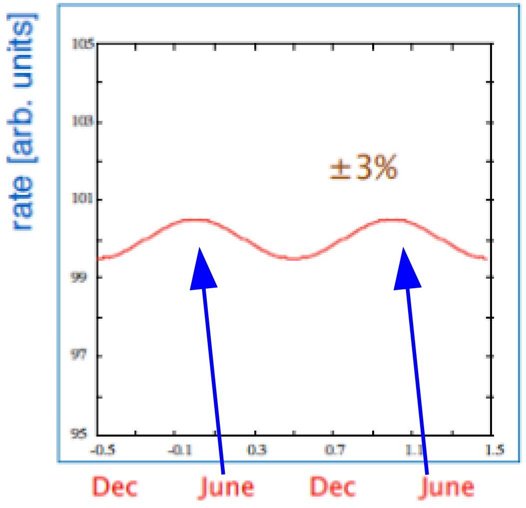
- The velocity of the Earth varies over the year as the Earth moves around the Sun, and can be written as [in km/s]:

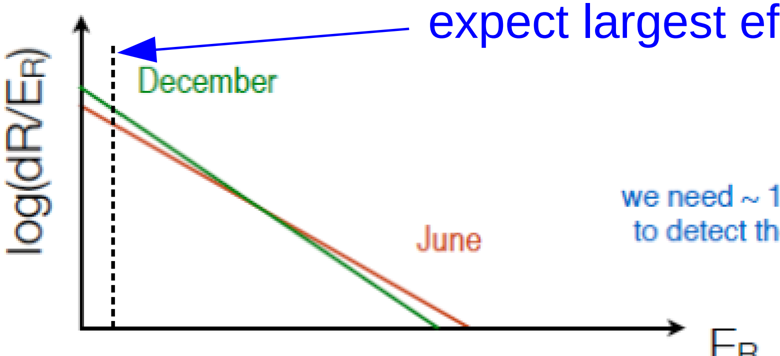
$$v_E(t) = v_0\left[1.05 + 0.07\cos\frac{2\pi(t-t_p)}{1yr}\right]$$

t = days since January 1st
t_p = 2. June (152.5 d) ± 1.3 d; 1 yr = 362.25 d



- the velocity modulation gives rise to a ~ 3% modulation in the rate $\frac{d}{dv_E}\left(\frac{R}{R_0}\right) \sim \frac{1}{2v_E}\frac{R}{R_0}$ (for $v_E \sim v_0$)





expect largest effect at threshold!

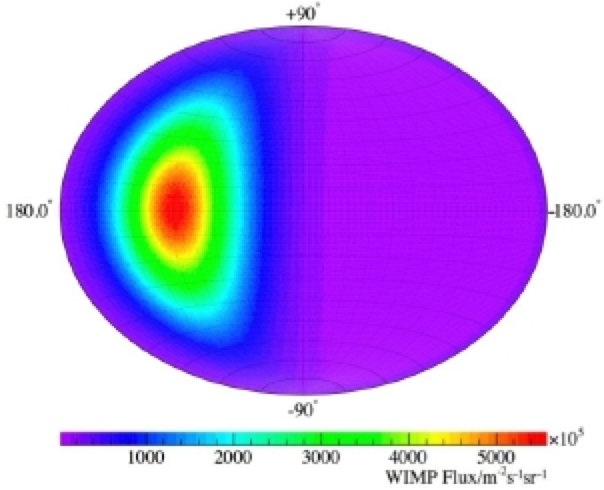
we need ~ 1000 events
to detect the variation

seasonal variation of the rate spectrum

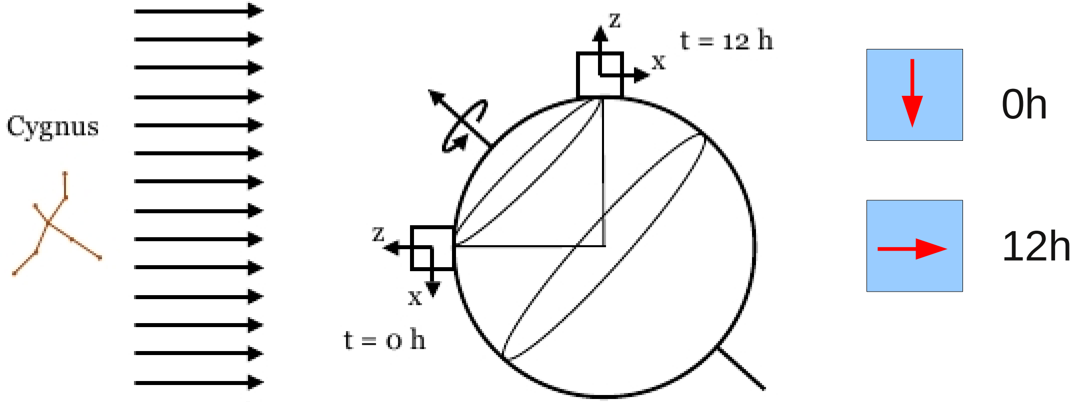
→ more faster WIMPs in June → more make it above threshold → higher rate

WIMP Signatures: Directionality

- The Earth's motion with respected to the Galactic rest frame produces a direction dependance of the recoil spectrum
- The peak WIMP flux comes from the direction of the solar motion, which points towards the constellation Cygnus
- Assuming a smooth WIMP distribution, the recoil rate is then peaked in the opposite direction
- In the laboratory frame, this direction varies over the course of a sidereal day due to the Earth's rotation
- This effect can provide a robust signature for a Galactic origin of a WIMP signal



Projection of the WIMP flux in Galactic coordinates

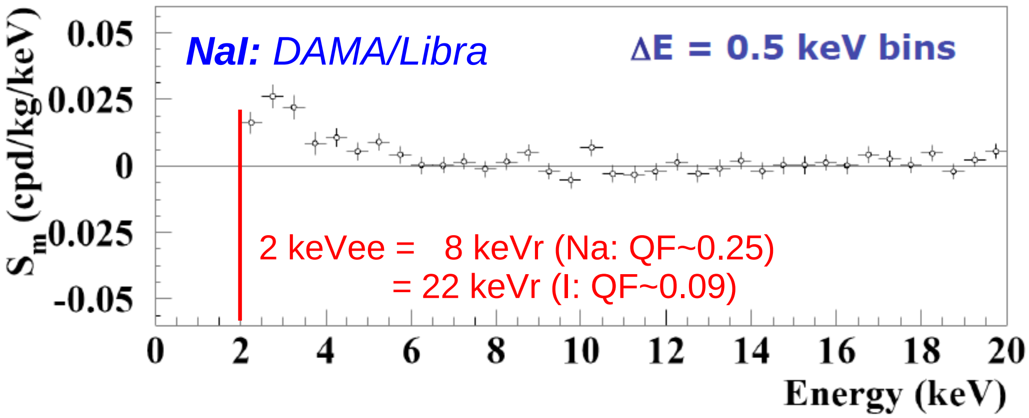


→ daily modulation!

BUT: detector must be able to detect
direction of recoils;
up to now this only works
in very „non-dense“ detectors

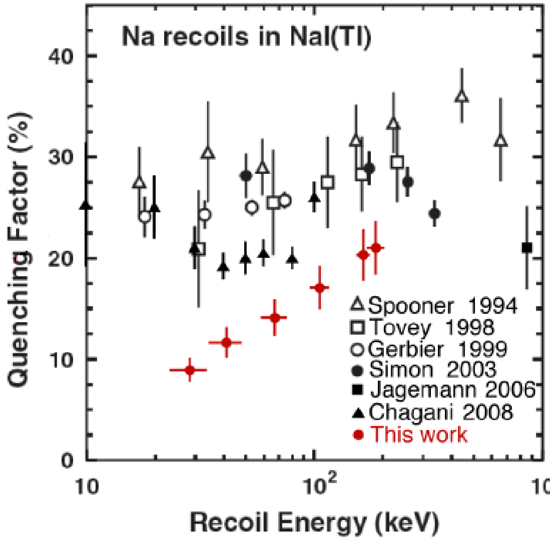
Quenching in Practice

Absolute quenching factor: $E_{obs}(keVee) = QF(E_r) \times E_r(keVr)$



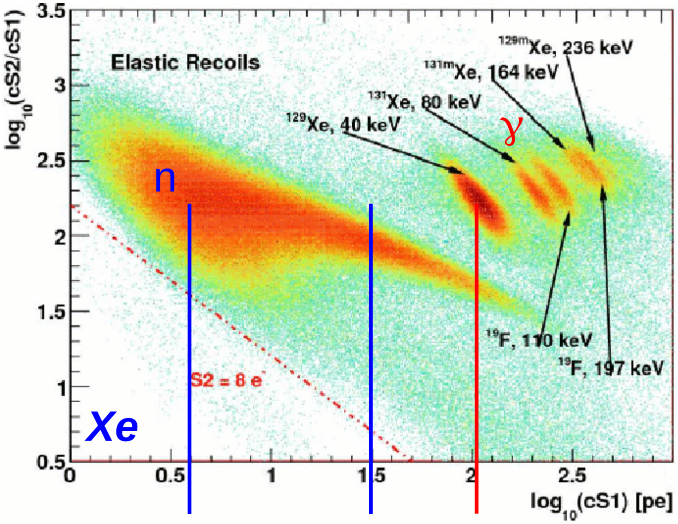
2 keVee = 8 keVr (Na: QF~0.25)
= 22 keVr (I: QF~0.09)

PRELIMINARY DATA

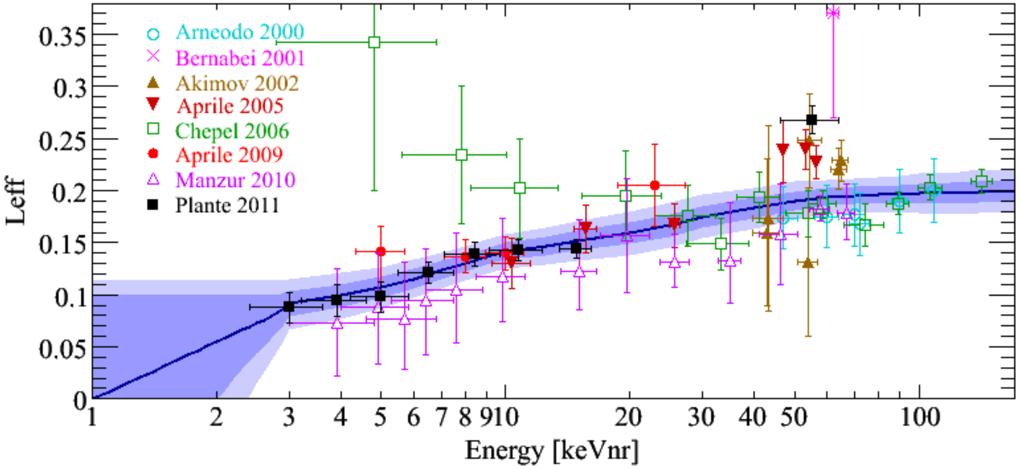


Collar, TAUP2011

Relative scintillation efficiency: $$\mathcal{L}_{\rm eff}(E_{\rm nr}) = \frac{{\rm LY}(E_{\rm nr})}{{\rm LY}(E_{\rm ee} = 122\ {\rm keV})}$$



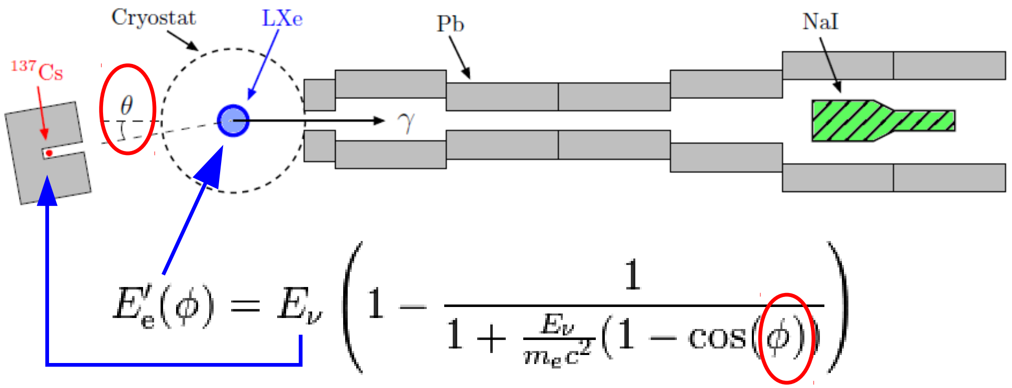
8 keVr 45 keVr 40 keVee



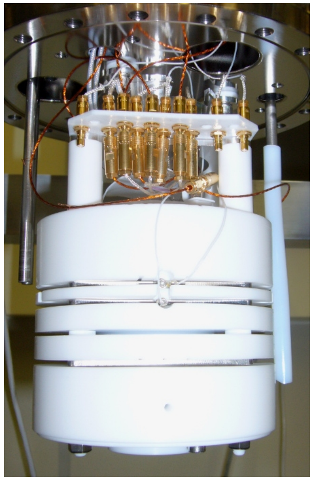
PRL 107, 131302 (2011)

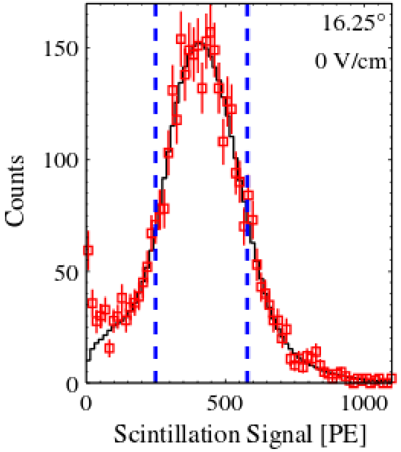
Scattering Experiment: ER in LXe

Compton Scattering!

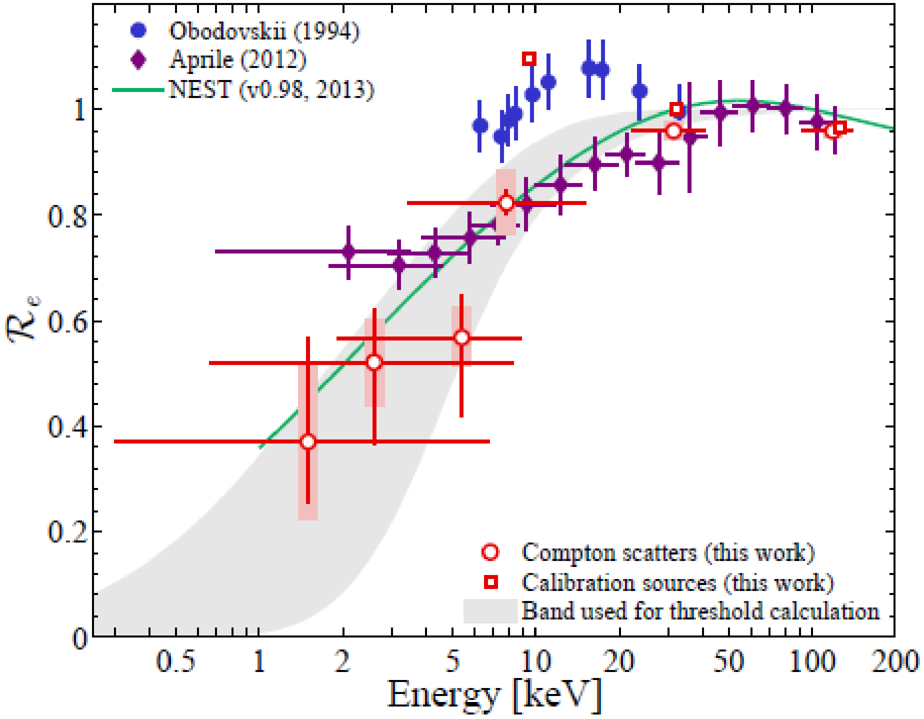


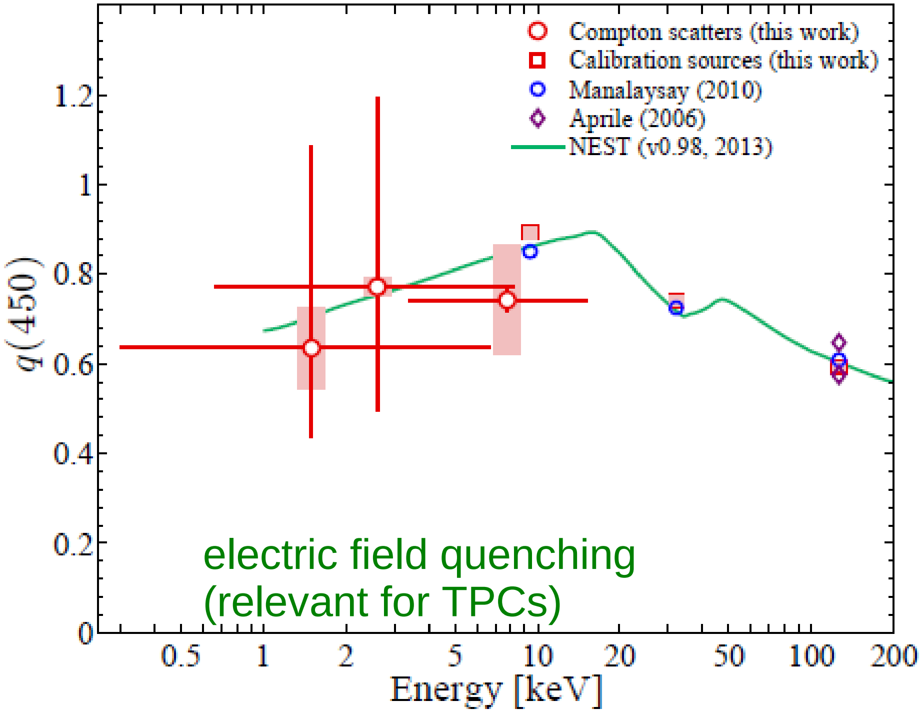
$$E'_e(\phi) = E_\nu \left(1 - \frac{1}{1 + \frac{E_\nu}{m_e c^2}(1 - \cos(\phi))}\right)$$





PRD 87, 115015 (2013)





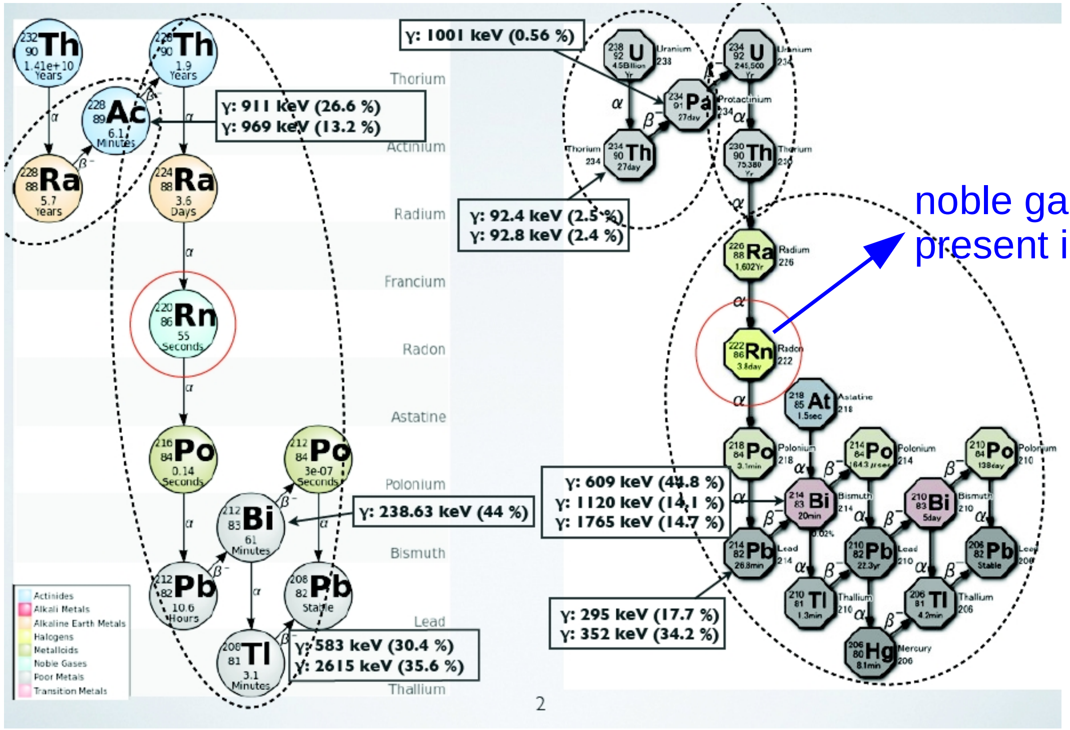
electric field quenching
(relevant for TPCs)

2 Backgrounds,
Background Reduction

- Where do backgrounds come from?
  → external and intrinsic backgrounds
  → cosmic backgrounds
  → ER and NR backgrounds
- Reduction 1: Shielding
  → avoid backgrounds
  → underground laboratories
  → passive and active shields
- Reduction 2: Knowledge on expected signal
  → what makes WIMPs special?
  → discrimination

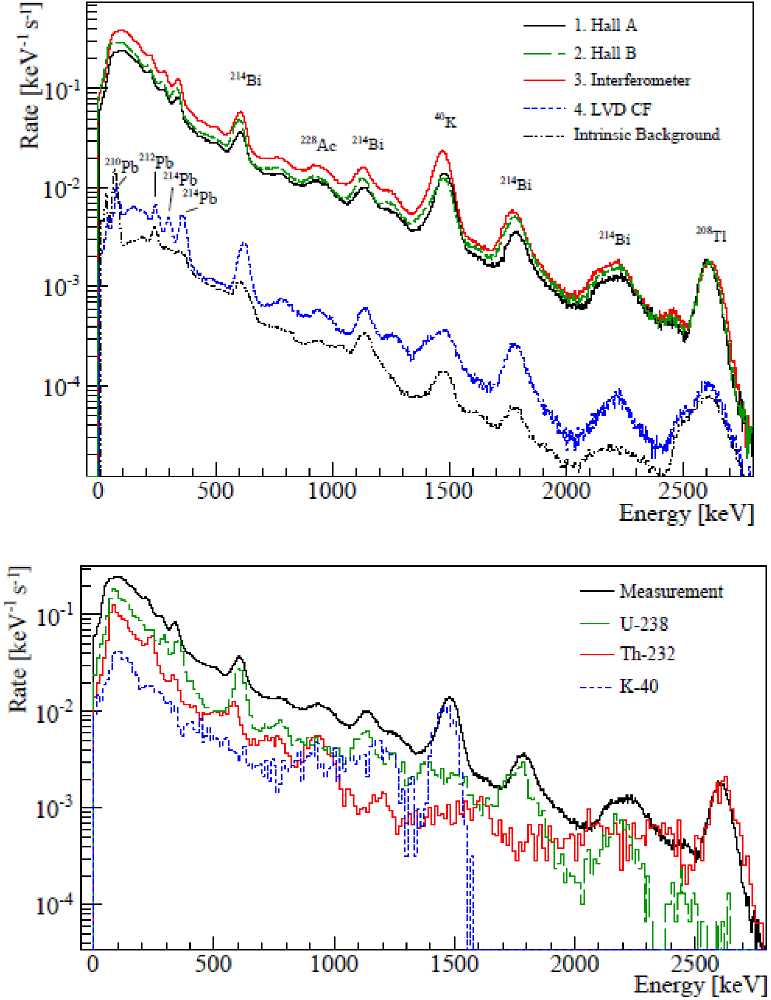
Backgrounds from the Environment

Background sources:
mainly U-238 and Th-232 chains, and
K-40 decays in the rock and the concrete
walls of the laboratory



noble gas,
present in air

Haffke et al., NIM A 643, 36 (2011)



Gamma flux @ LNGS

Note: the primorial chains also produce neutrons
- spontaneous fission processes of heavy elements
  (dominant in heavy materials, such as lead)
- via (α,n) reactions
  (needs a light target, e.g. plastics)

(alpha,n)

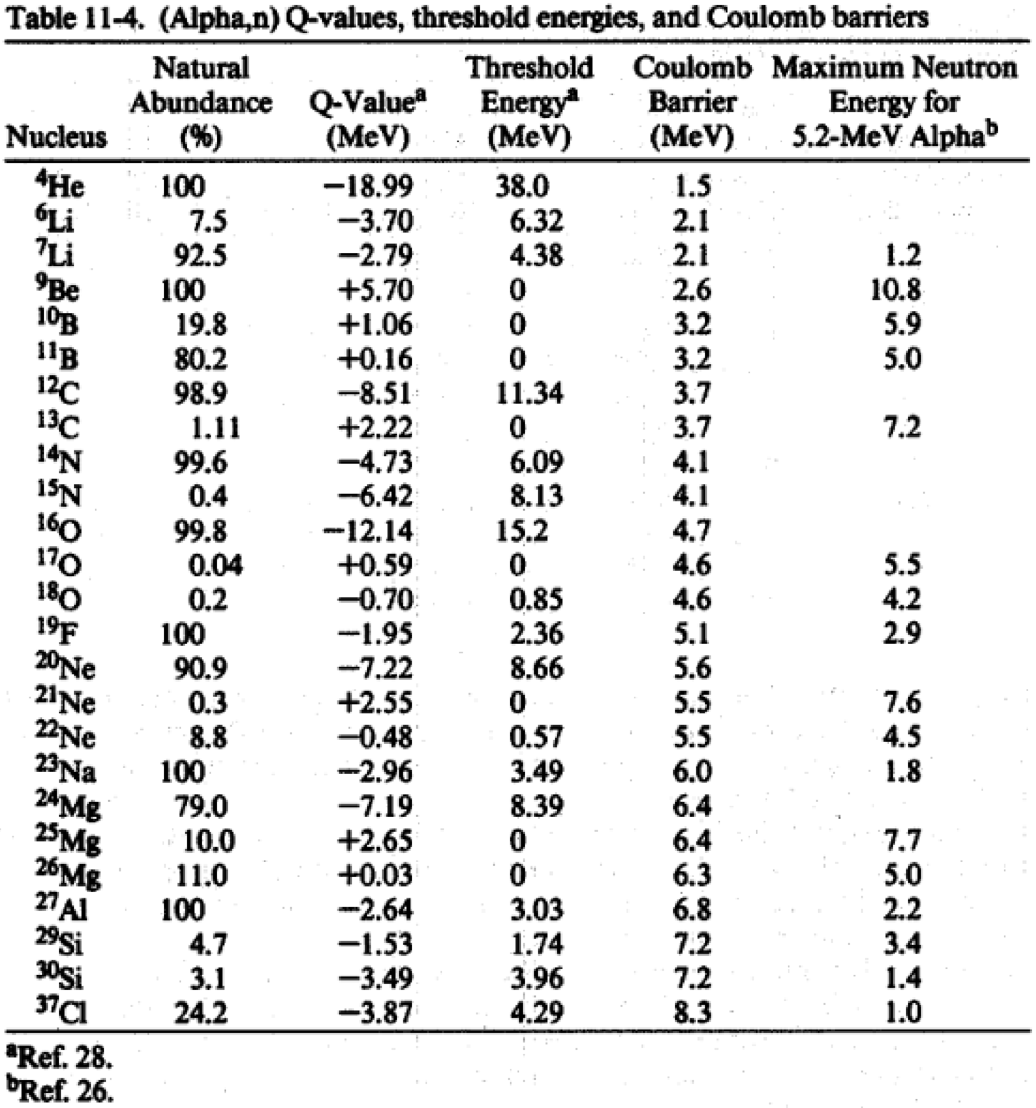


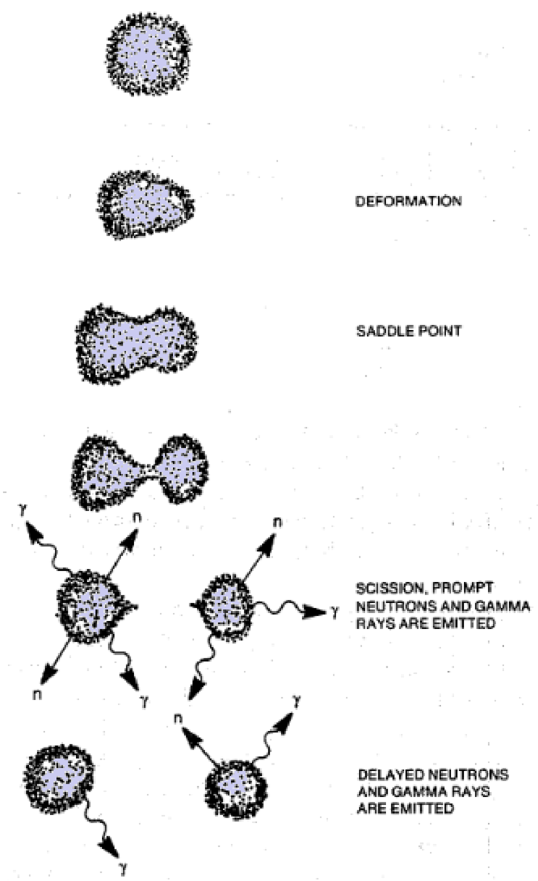
Table 11-4. (Alpha,n) Q-values, threshold energies, and Coulomb barriers

Nucleus	Natural Abundance (%)	Q-Value[a] (MeV)	Threshold Energy[a] (MeV)	Coulomb Barrier (MeV)	Maximum Neutron Energy for 5.2-MeV Alpha[b]
^{4}He	100	−18.99	38.0	1.5	
^{6}Li	7.5	−3.70	6.32	2.1	
^{7}Li	92.5	−2.79	4.38	2.1	1.2
^{9}Be	100	+5.70	0	2.6	10.8
^{10}B	19.8	+1.06	0	3.2	5.9
^{11}B	80.2	+0.16	0	3.2	5.0
^{12}C	98.9	−8.51	11.34	3.7	
^{13}C	1.11	+2.22	0	3.7	7.2
^{14}N	99.6	−4.73	6.09	4.1	
^{15}N	0.4	−6.42	8.13	4.1	
^{16}O	99.8	−12.14	15.2	4.7	
^{17}O	0.04	+0.59	0	4.6	5.5
^{18}O	0.2	−0.70	0.85	4.6	4.2
^{19}F	100	−1.95	2.36	5.1	2.9
^{20}Ne	90.9	−7.22	8.66	5.6	
^{21}Ne	0.3	+2.55	0	5.5	7.6
^{22}Ne	8.8	−0.48	0.57	5.5	4.5
^{23}Na	100	−2.96	3.49	6.0	1.8
^{24}Mg	79.0	−7.19	8.39	6.4	
^{25}Mg	10.0	+2.65	0	6.4	7.7
^{26}Mg	11.0	+0.03	0	6.3	5.0
^{27}Al	100	−2.64	3.03	6.8	2.2
^{29}Si	4.7	−1.53	1.74	7.2	3.4
^{30}Si	3.1	−3.49	3.96	7.2	1.4
^{37}Cl	24.2	−3.87	4.29	8.3	1.0

[a] Ref. 28.
[b] Ref. 26.

→ (α,n) energetically not possible for heavier elements

Spontaneous fission (sf)



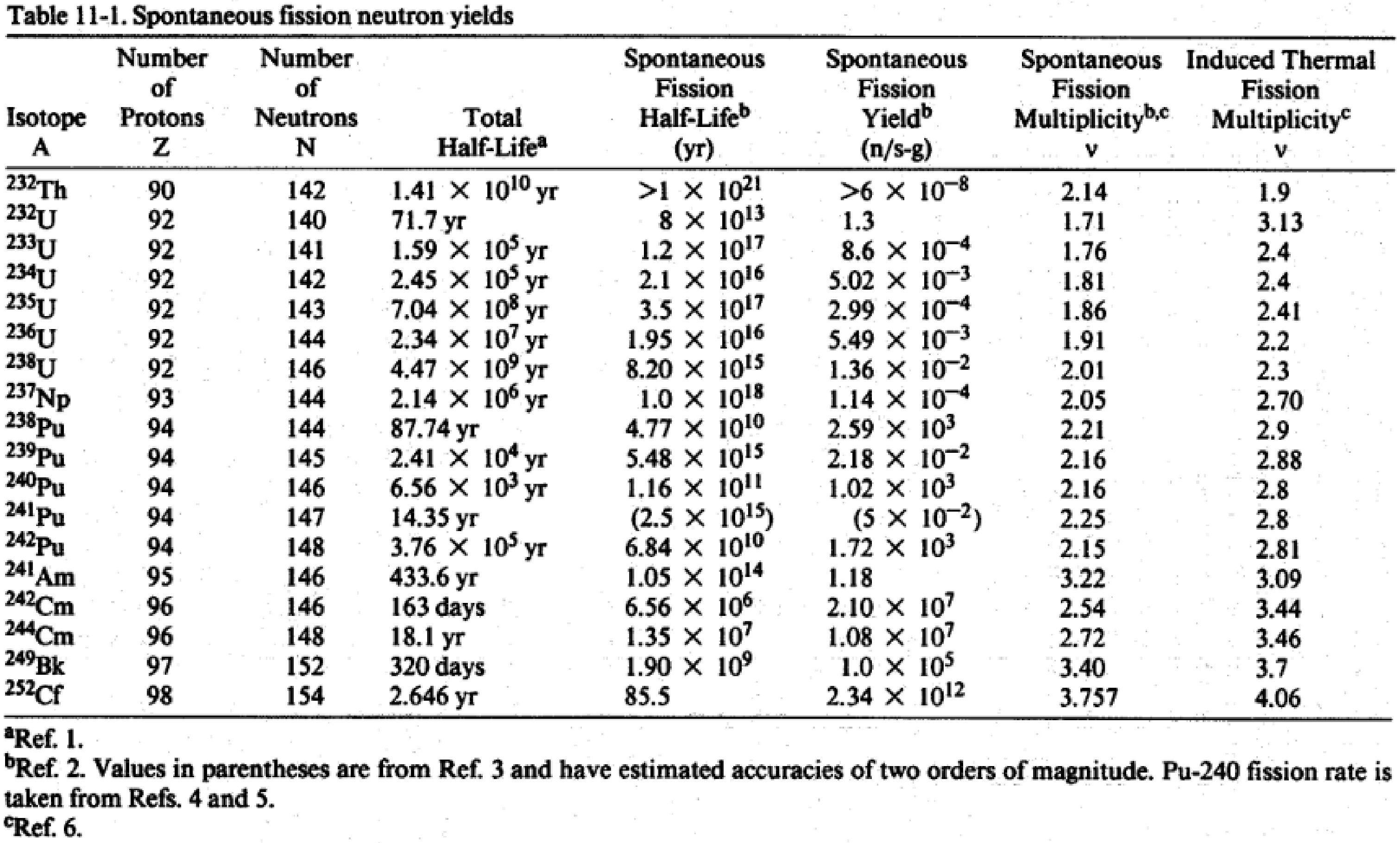


Table 11-1. Spontaneous fission neutron yields

Isotope A	Number of Protons Z	Number of Neutrons N	Total Half-Life[a]	Spontaneous Fission Half-Life[b] (yr)	Spontaneous Fission Yield[b] (n/s-g)	Spontaneous Fission Multiplicity[b,c] ν	Induced Thermal Fission Multiplicity[c] ν
^{232}Th	90	142	1.41×10^{10} yr	$>1 \times 10^{21}$	$>6 \times 10^{-8}$	2.14	1.9
^{232}U	92	140	71.7 yr	8×10^{13}	1.3	1.71	3.13
^{233}U	92	141	1.59×10^{5} yr	1.2×10^{17}	8.6×10^{-4}	1.76	2.4
^{234}U	92	142	2.45×10^{5} yr	2.1×10^{16}	5.02×10^{-3}	1.81	2.4
^{235}U	92	143	7.04×10^{8} yr	3.5×10^{17}	2.99×10^{-4}	1.86	2.41
^{236}U	92	144	2.34×10^{7} yr	1.95×10^{16}	5.49×10^{-3}	1.91	2.2
^{238}U	92	146	4.47×10^{9} yr	8.20×10^{15}	1.36×10^{-2}	2.01	2.3
^{237}Np	93	144	2.14×10^{6} yr	1.0×10^{18}	1.14×10^{-4}	2.05	2.70
^{238}Pu	94	144	87.74 yr	4.77×10^{10}	2.59×10^{3}	2.21	2.9
^{239}Pu	94	145	2.41×10^{4} yr	5.48×10^{15}	2.18×10^{-2}	2.16	2.88
^{240}Pu	94	146	6.56×10^{3} yr	1.16×10^{11}	1.02×10^{3}	2.16	2.8
^{241}Pu	94	147	14.35 yr	(2.5×10^{15})	(5×10^{-2})	2.25	2.8
^{242}Pu	94	148	3.76×10^{5} yr	6.84×10^{10}	1.72×10^{3}	2.15	2.81
^{241}Am	95	146	433.6 yr	1.05×10^{14}	1.18	3.22	3.09
^{242}Cm	96	146	163 days	6.56×10^{6}	2.10×10^{7}	2.54	3.44
^{244}Cm	96	148	18.1 yr	1.35×10^{7}	1.08×10^{7}	2.72	3.46
^{249}Bk	97	152	320 days	1.90×10^{9}	1.0×10^{5}	3.40	3.7
^{252}Cf	98	154	2.646 yr	85.5	2.34×10^{12}	3.757	4.06

[a] Ref. 1.

[b] Ref. 2. Values in parentheses are from Ref. 3 and have estimated accuracies of two orders of magnitude. Pu-240 fission rate is taken from Refs. 4 and 5.

[c] Ref. 6.

→ only heavy elements. Mainly from U-238 and (somewhat less) U-235.

Activation of materials

- **Activation of detector and other materials during production and transportation at the Earth's surface. A precise calculation requires:**
  - ➡ cosmic ray spectrum (varies with geomagnetic latitude)
  - ➡ cross section for the production of isotopes (only few are directly measured)
- production is dominated by (n,x) reactions (95%) and (p,x) reactions (5%)

production
in Ge after
30d exposure
at the Earth's
surface and
1 yr storage
below ground

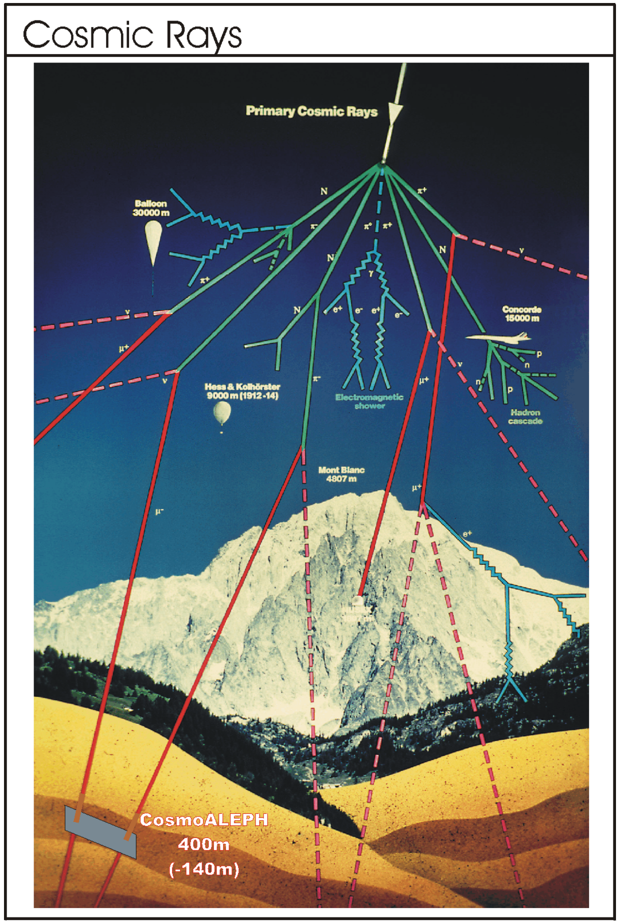
Isotope	Decay	Half life	Energy in Ge [keV]	Activity [µBq/kg]
^{3}H	β^-	12.33 yr	$E_{max(\beta-)}=18.6$	2
^{49}V	EC	330 d	$E_{K(Ti)} = 5$	1.6
^{54}Mn	EC, β^+	312 d	$E_{K(Cr)} = 5.4$, $E_\gamma=841$	0.95
^{55}Fe	EC	2.7 yr	$E_{K(Mn)} = 6$	0.66
^{57}Co	EC	272 d	$E_{K(Fe)}=6.4$, $E_\gamma=128$	1.3
^{60}Co	β^-	5.3 yr	$E_{max(\beta-)}=318$, $E_\gamma=1173,1333$	0.2
^{63}Ni	β-	100 yr	$E_{max(\beta-)}=67$	0.009
^{65}Zn	EC, β^+	244 d	$E^{K(Cu)} = 9$, $E_\gamma=1125$	9.2
^{68}Ge	EC	271 d	$E_{K(Ga)} = 10.4$	172

Cosmic Rays

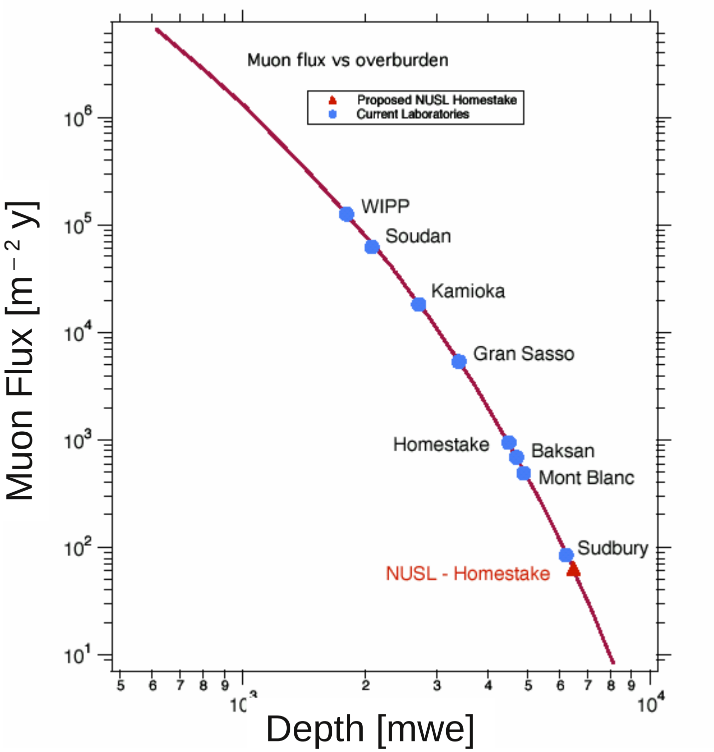
Cosmic rays and secondary/tertiary particles which they create in reactions can be reduced by going to underground laboratories

The hadronic component (n, p) is already reduced significantly after a few meters rock

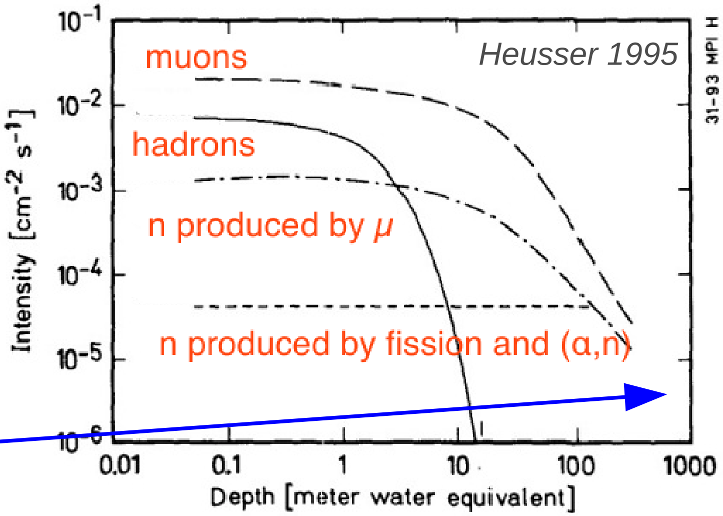
Shielding thickness (rock, soil) given in „meter-water-equivalent“ (mwe) to allow for comparison between different laboratories



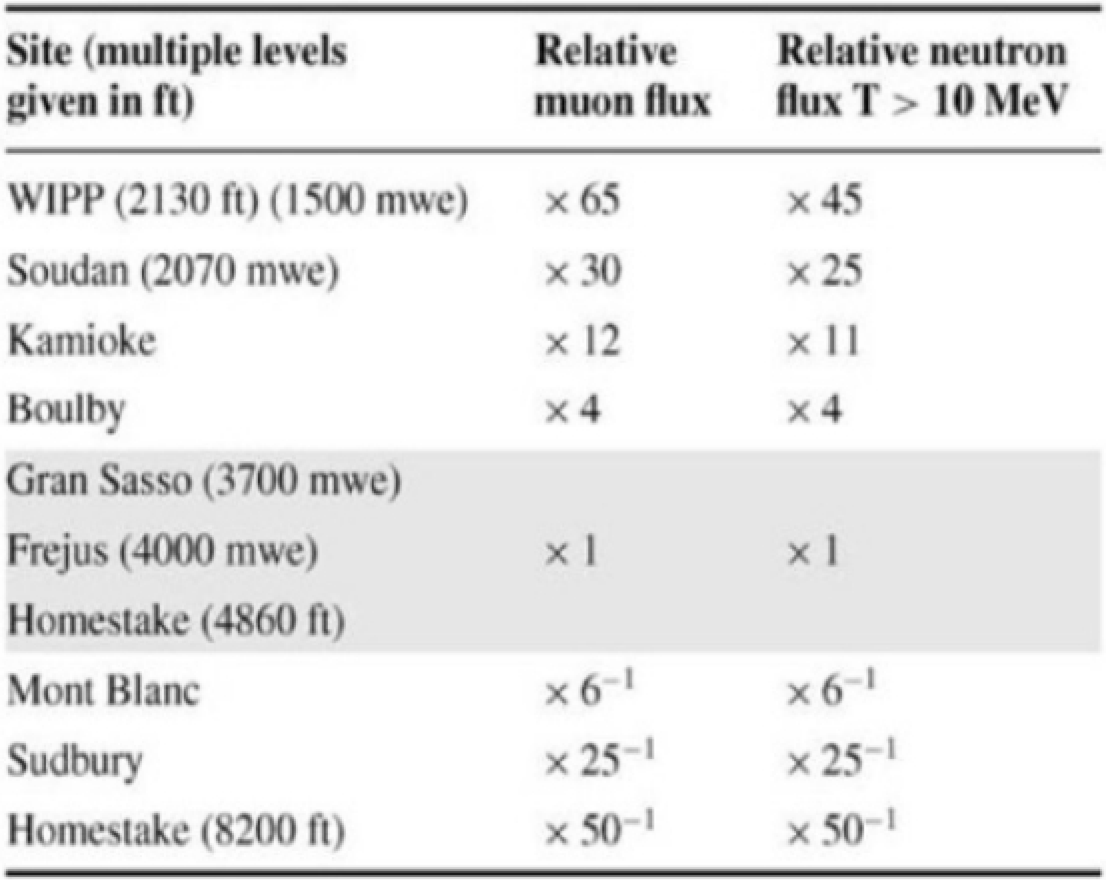
Particle Physics Slides • Sascha Marc Schmeling 1999 • Original Picture: CERN



in deep laboratories, only muons remain which cause e/m showers and also generate neutrons

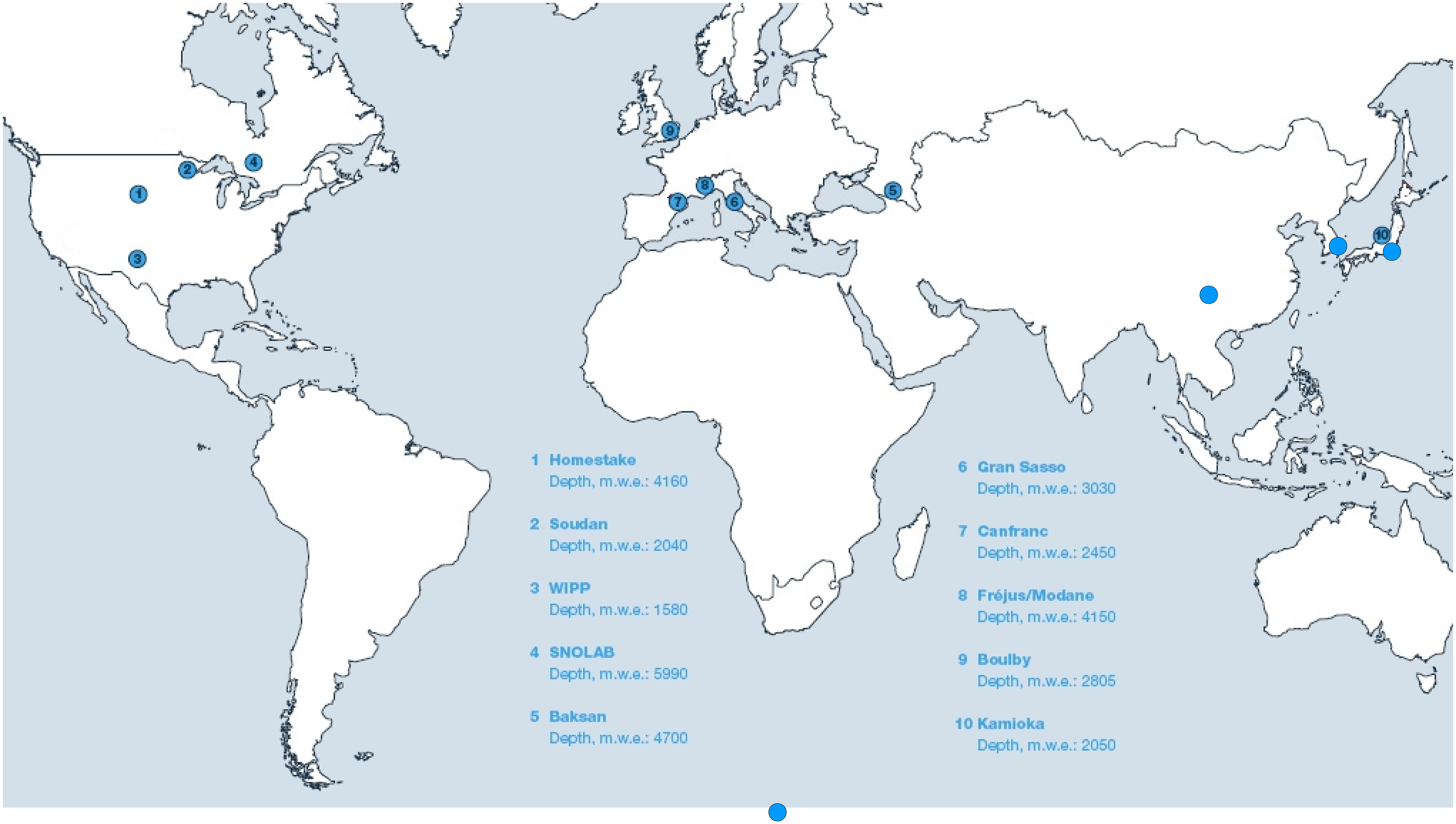


Background in Laboratories



Site (multiple levels given in ft)	Relative muon flux	Relative neutron flux T > 10 MeV
WIPP (2130 ft) (1500 mwe)	× 65	× 45
Soudan (2070 mwe)	× 30	× 25
Kamioke	× 12	× 11
Boulby	× 4	× 4
Gran Sasso (3700 mwe)	× 1	× 1
Frejus (4000 mwe)		
Homestake (4860 ft)		
Mont Blanc	× 6^{-1}	× 6^{-1}
Sudbury	× 25^{-1}	× 25^{-1}
Homestake (8200 ft)	× 50^{-1}	× 50^{-1}

Underground Laboratories

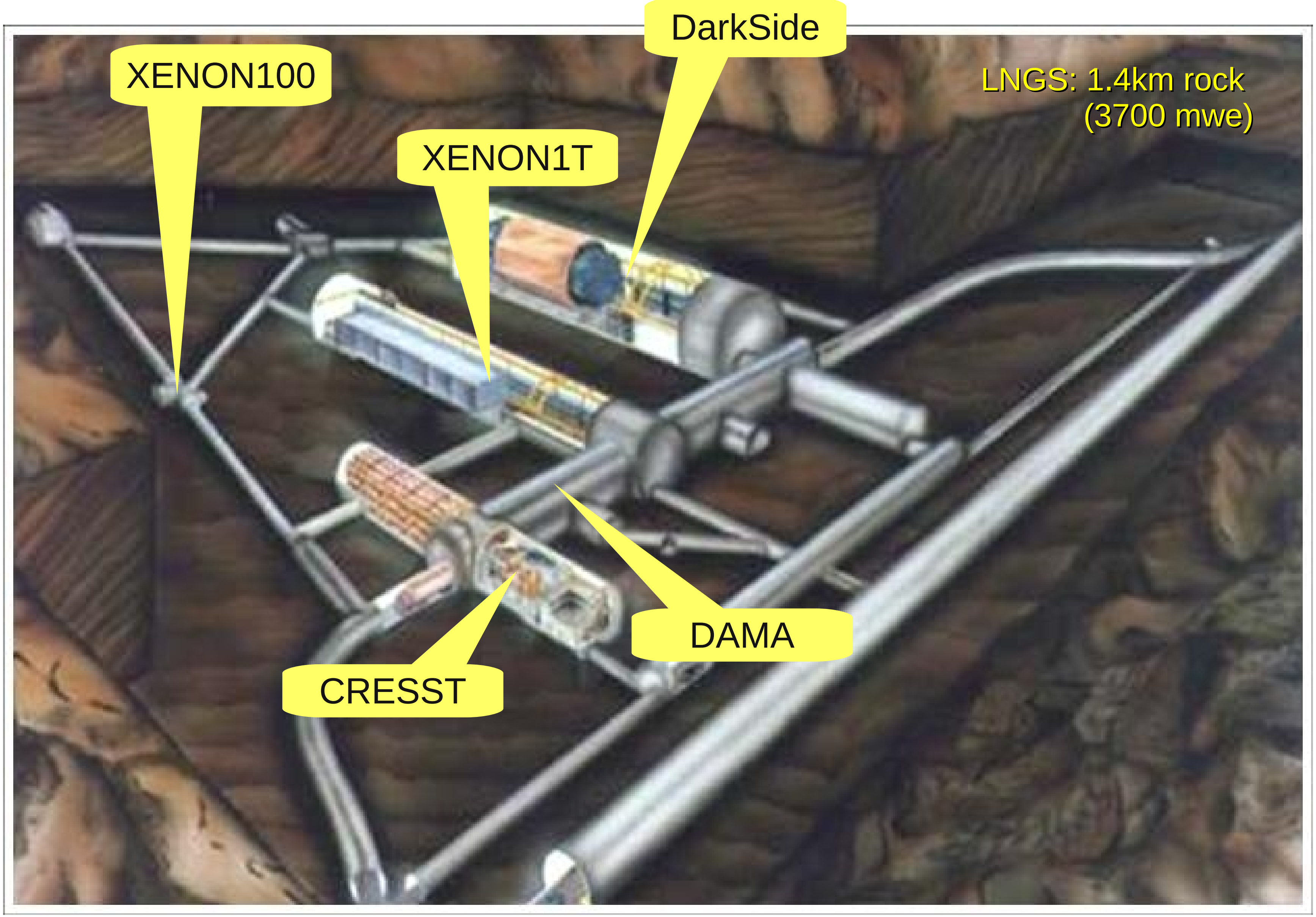


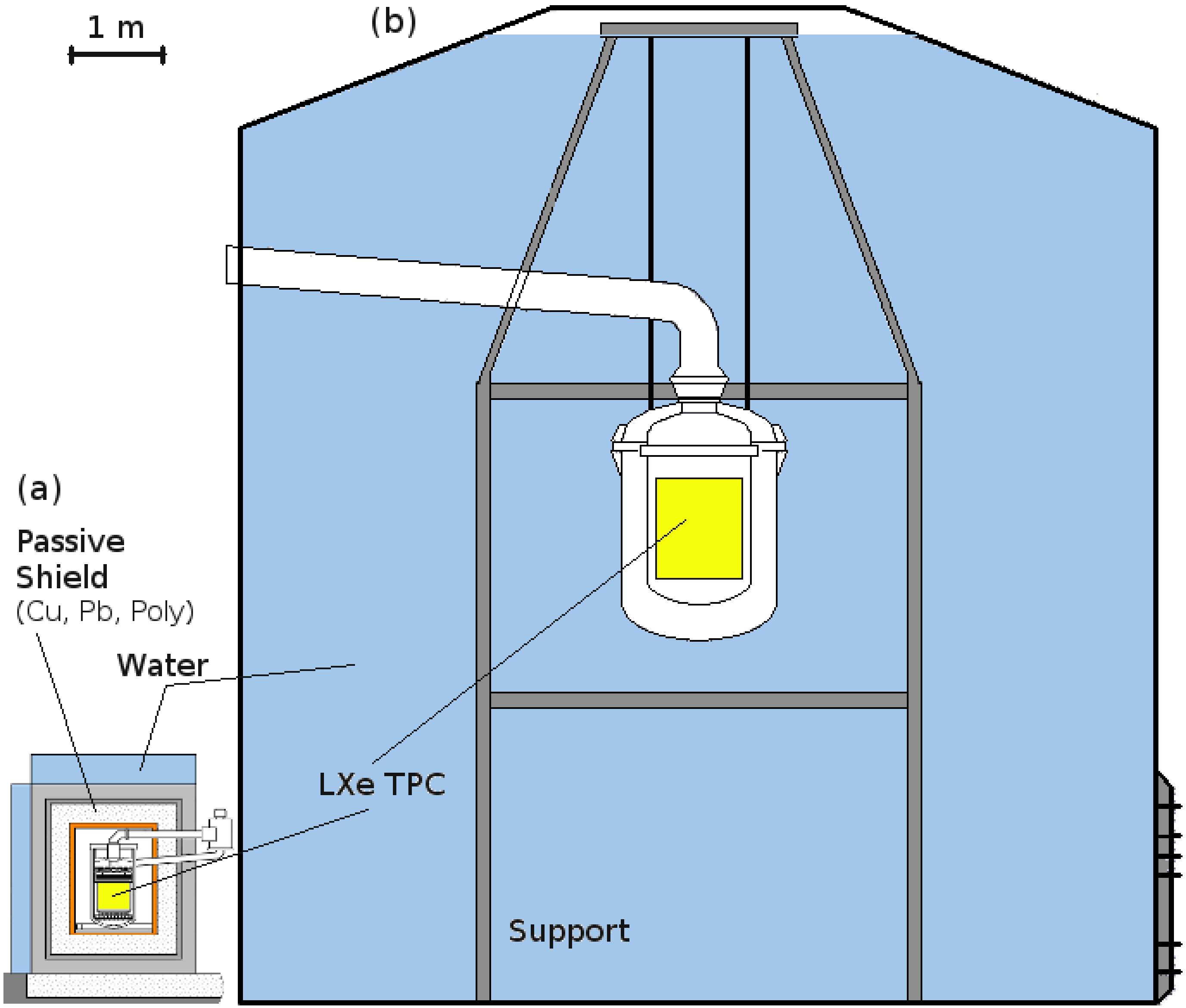
Laboratori Nazionali del Gran Sasso


ALARM
OSSIGENO OXYGEN
LAB.A LUD ZONE

Laboratori Nazionali del Gran Sasso

LNGS: 1.4km rock
(3700 mwe)

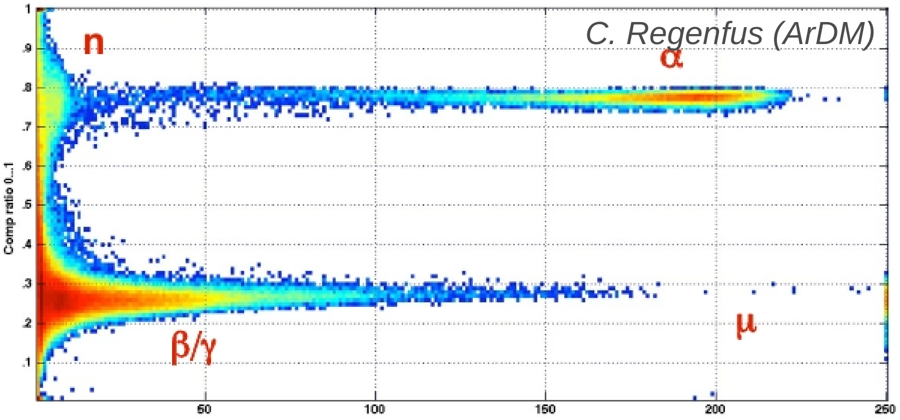

DarkSide
XENON100
LNGS: 1.4km rock
(3700 mwe)
XENON1T
DAMA
CRESST



XENON100: passive

XENON1T: active shielding

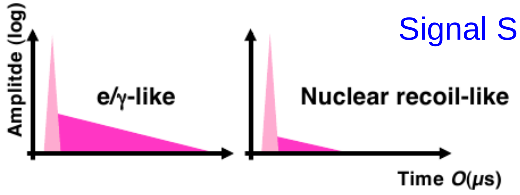
Pulse Shape Discrimination



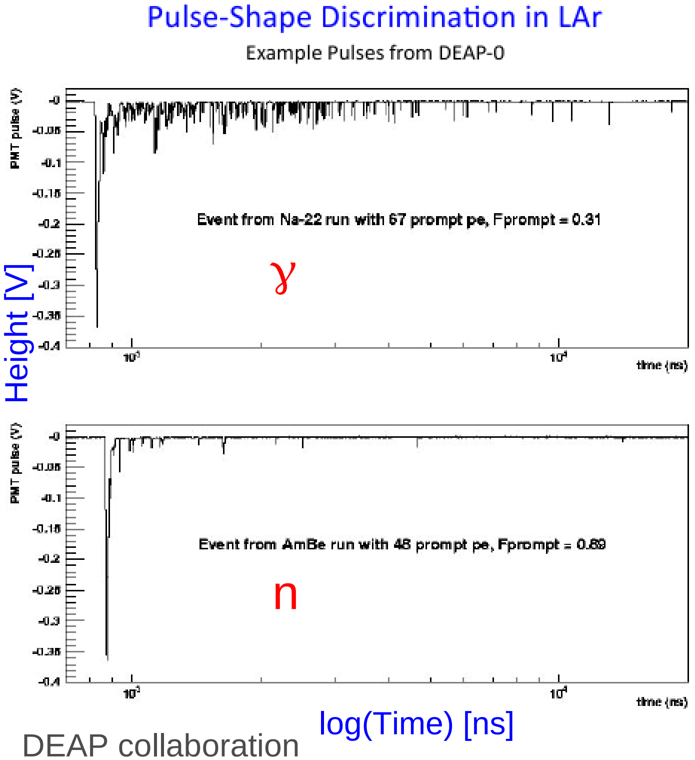
Singlet and triplet excimer states have characteristic lifetimes:

Ar: 5 ns, 1.6 µs
Xe: 4 ns, 22 ns

The ratio N_{trip}/N_{sing} depends on the ionization density → the particle type

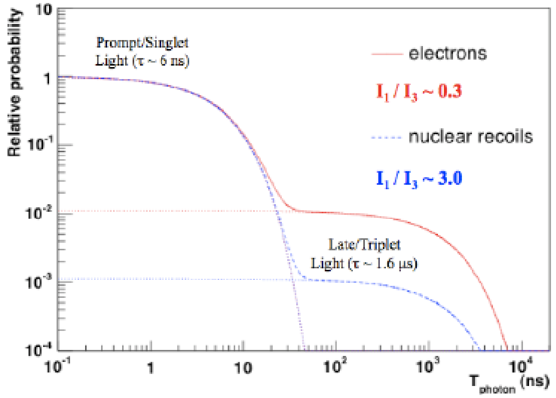


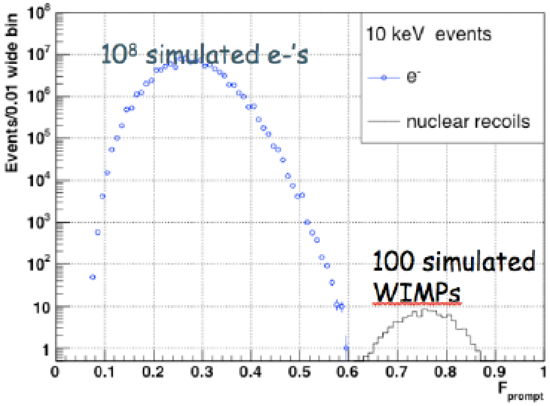
Signal Size



DEAP collaboration

M.G. Boulay and A. Hime
Astroparticle Physics **25**, 179 (2006)





LAr Discrimination levels of 3×10^{-8} achieved in test setups

arXiv:0904.2930, PRC 78, 035801 (2008)

→ mandatory because of huge Ar39 background (~1Bq/kg)

LXe O(10)% rejection at low E

NIM A 612, 328 (2010)

Better for very high LY (8×10^{-2} @ 50% NR acc.)

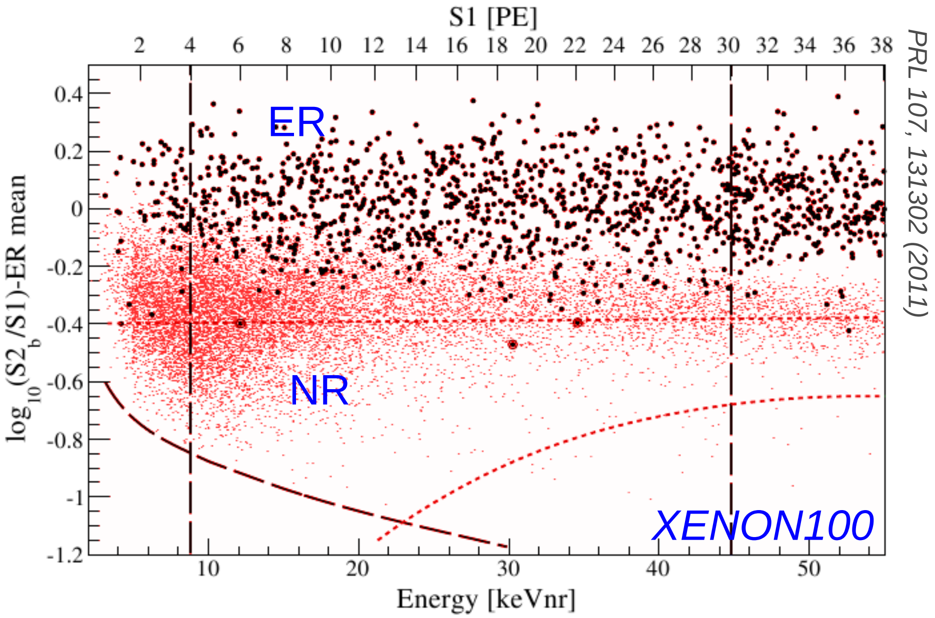
NIM A 659, 161 (2011)

Discrimination

Quenching can be used to discriminate NR (signal) from ER (background) when two detection mechanisms are measured simultaneously

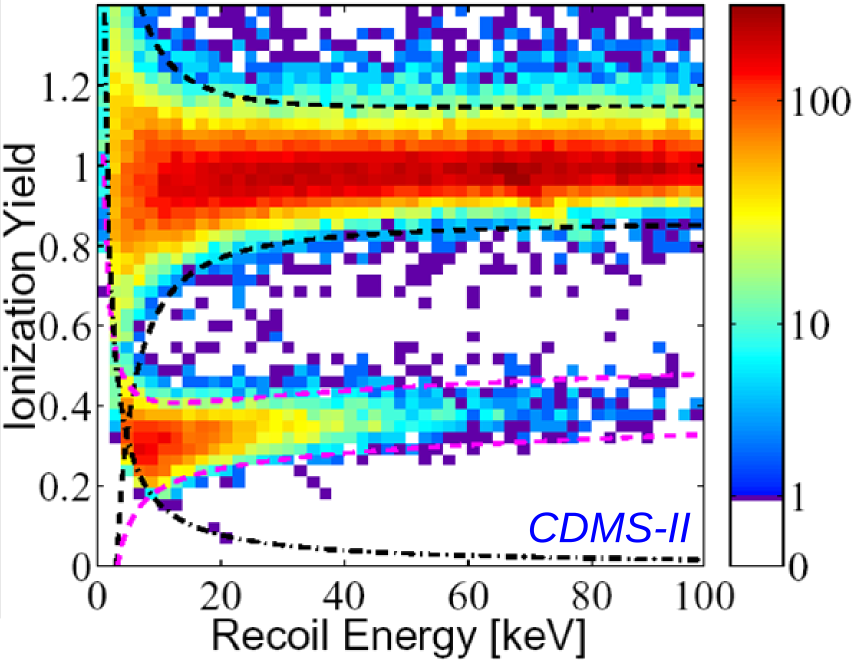
- charge and light
- light and heat
- charge and heat

Charge/Light Signal



PRL 107, 131302 (2011)

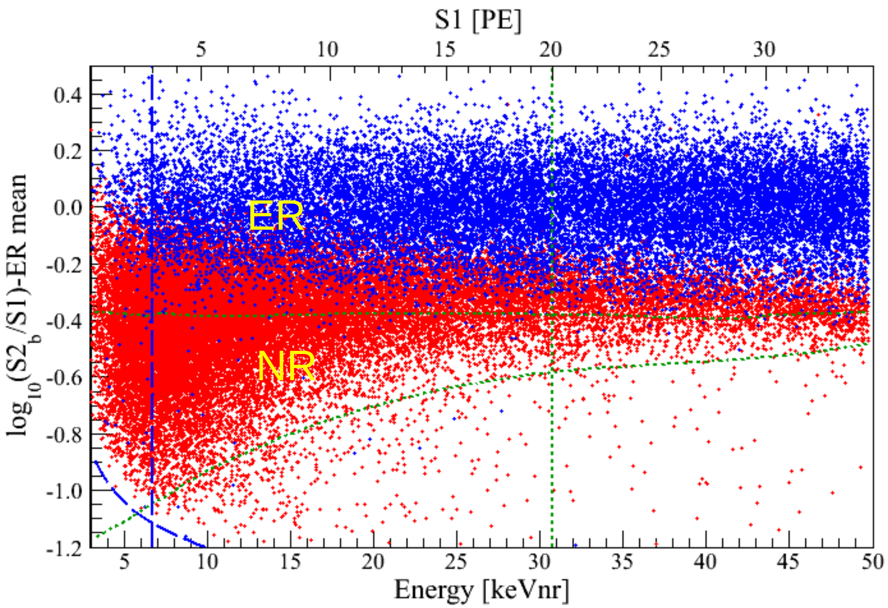
Amount of Charge for a given E

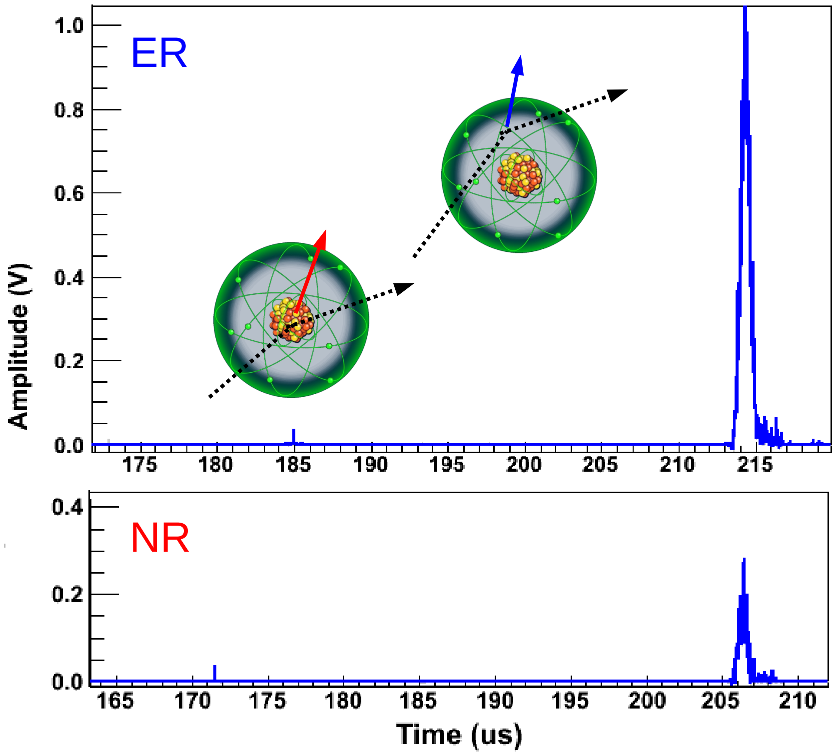


Discrimination ~1..5 x 10^{-3}

Discrimination ~$10^{-4} – 10^{-5}$

Example: Liquid Xenon

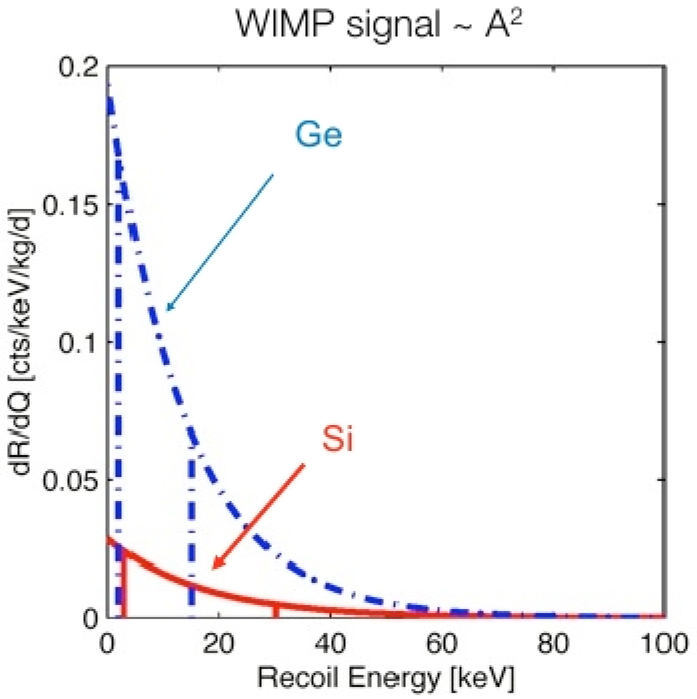




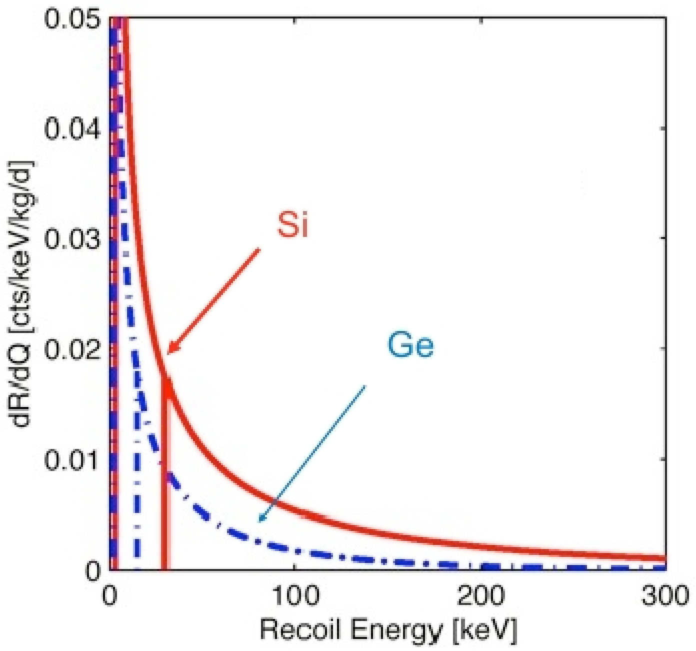
Light „S1“ Charge „S2“

How to distinguish neutrons from WIMPs?

- ➡ mean free path of few cm (neutrons) versus 10^{10} m (WIMP)
- ➡ if n-capture => distinctive signature
- ➡ material dependence of differential recoil spectrum
- ➡ time dependence of WIMP signal (if neutron background is measured to be constant in time)



WIMPs, M_χ = 40 GeV



neutrons