Dark Matter

(and direct searches for it)

School for Astroparticle Physics 2018
Obertrubach-Bärnfels

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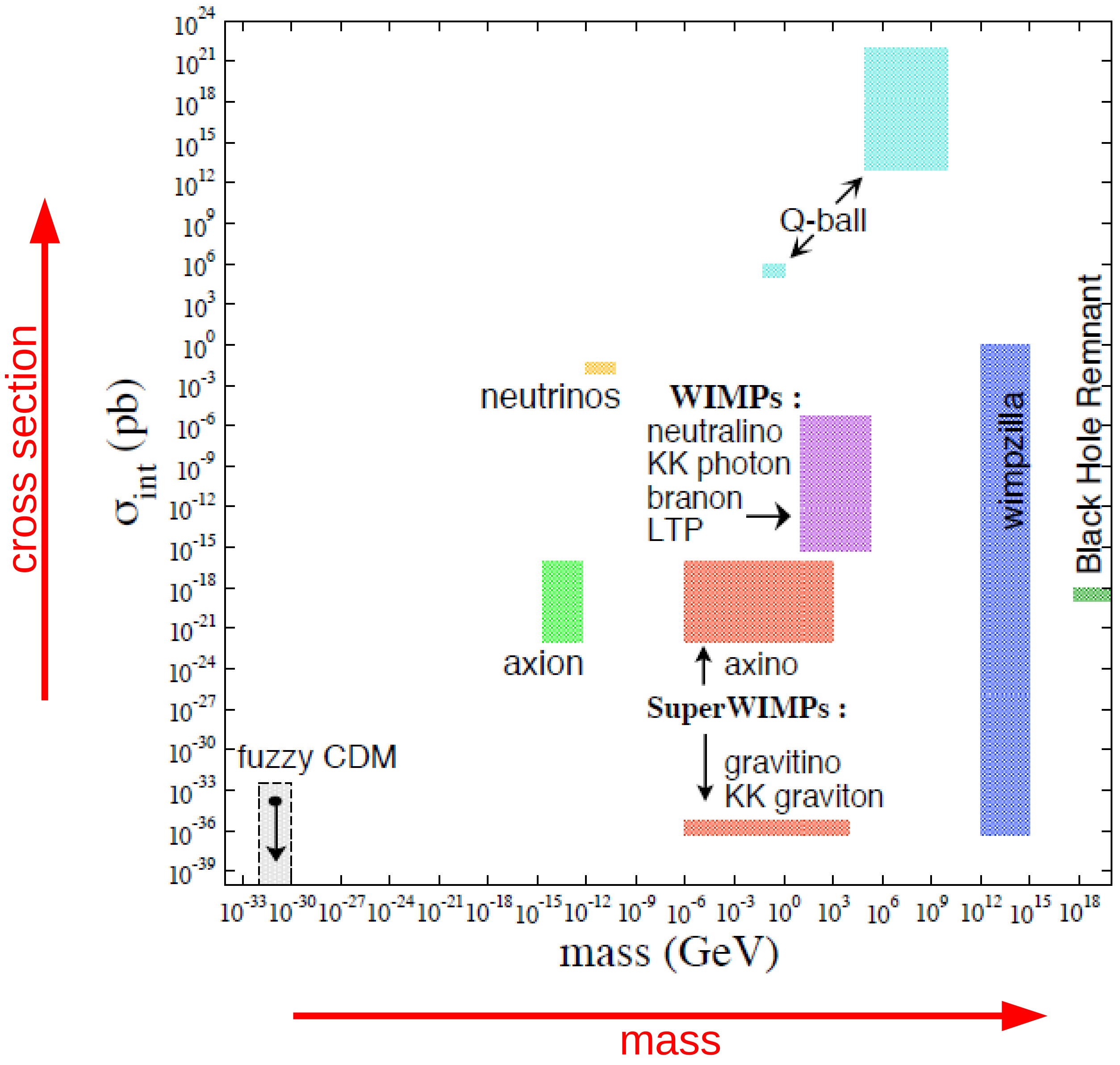
Content

• **Dark Matter**	1	Evidence for Dark Matter	**Wed**
	2a	The Standard Halo Model	
	2b	Dark Matter Candidates	
• **Direct Detection**	3	Basics: Rates and signatures	**Thu**
	4	Backgrounds: Sources, reduction	
• **Detectors**	5	Crystals, cryogenic, directional detectors NaI, Germanium	**Fri**
	6	Cryogenic liquids Xenon and Argon	

(Some) Dark Matter Candidates



- Axion
- **WIMPs**
  - **- Neutralino**
  - **- LKP**
- sterile neutrinos
- …

remaining lecture:
focus on WIMP detection
(many experiments are sensitive to other DM candidates as well)

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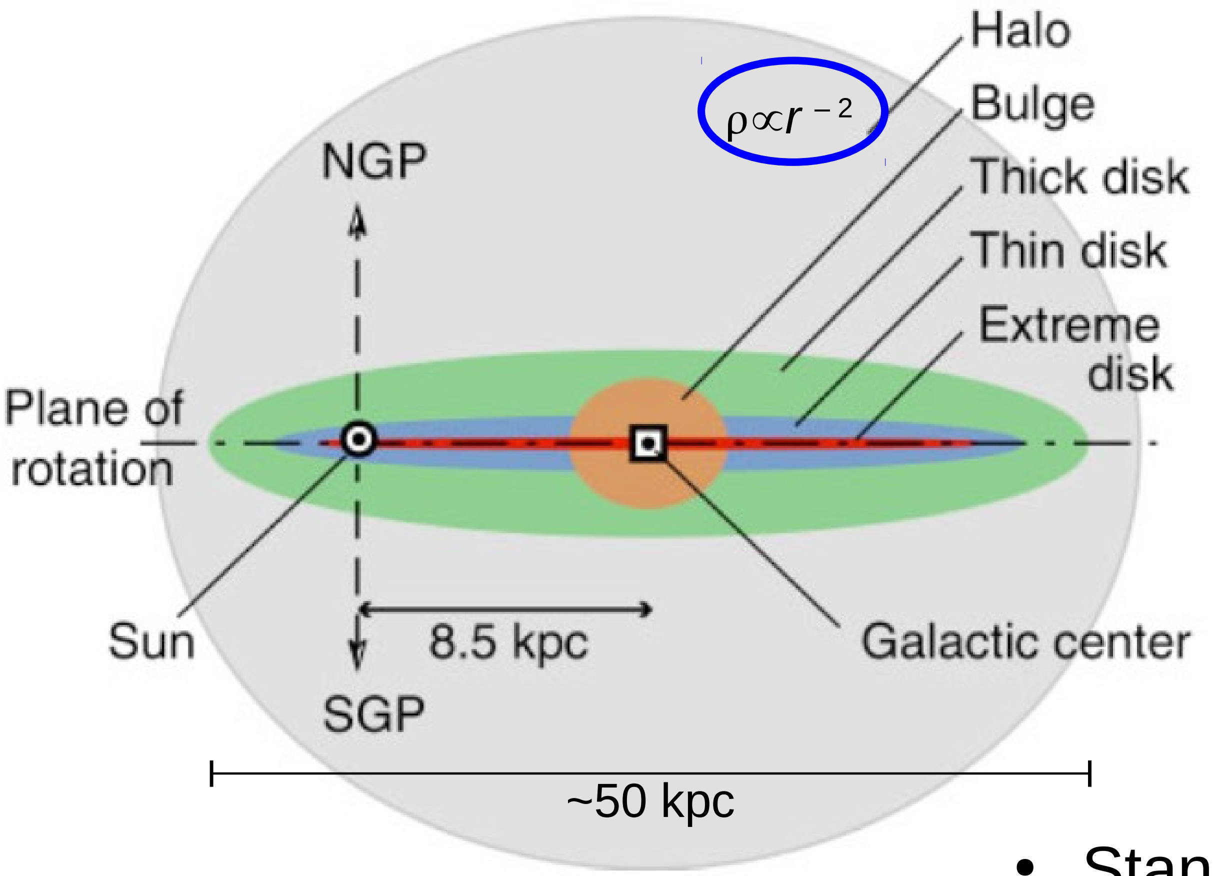
3 Direct Detection Basics: Rate, Signatures

- 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
  → large mass number *A* helps
  → BUT: form factor suppression for heavy targets
- WIMP dark matter parameter space

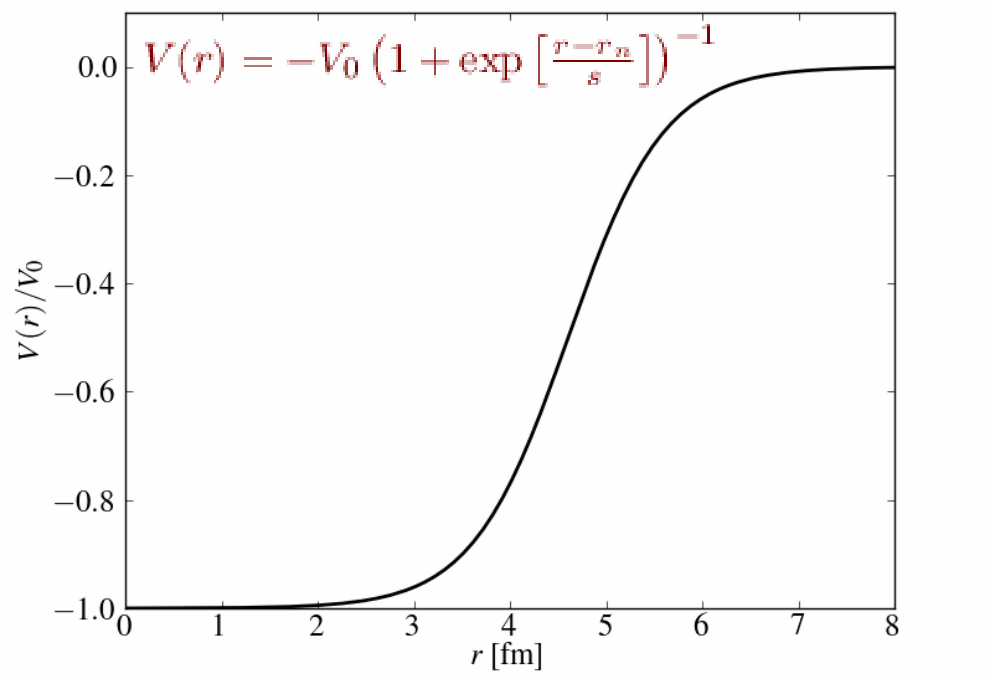
Milky Way – Standard Halo Model

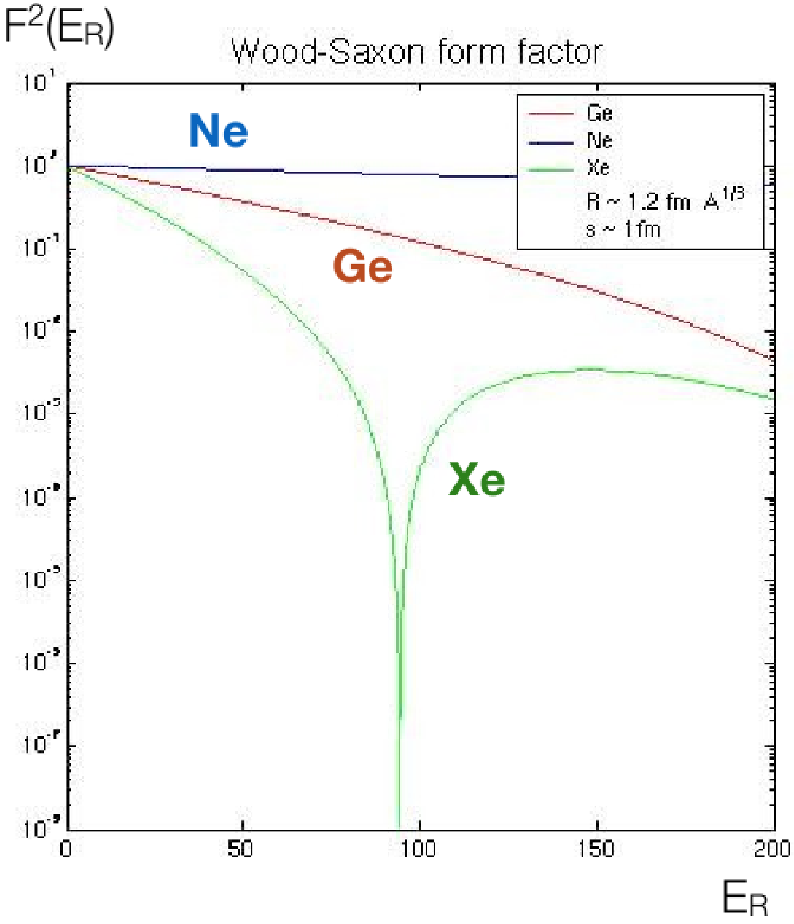


- Standard halo model: Ingredients
  - → local circular velocity v_c
  - → velocity of the Sun wrt to v_c
  - → galactic escape velocity v_{esc}
  - → velocity distribution $f(\mathbf{v})$
  - → local dark matter density ρ_0

Form-Factors

Woods-Saxion Potential:



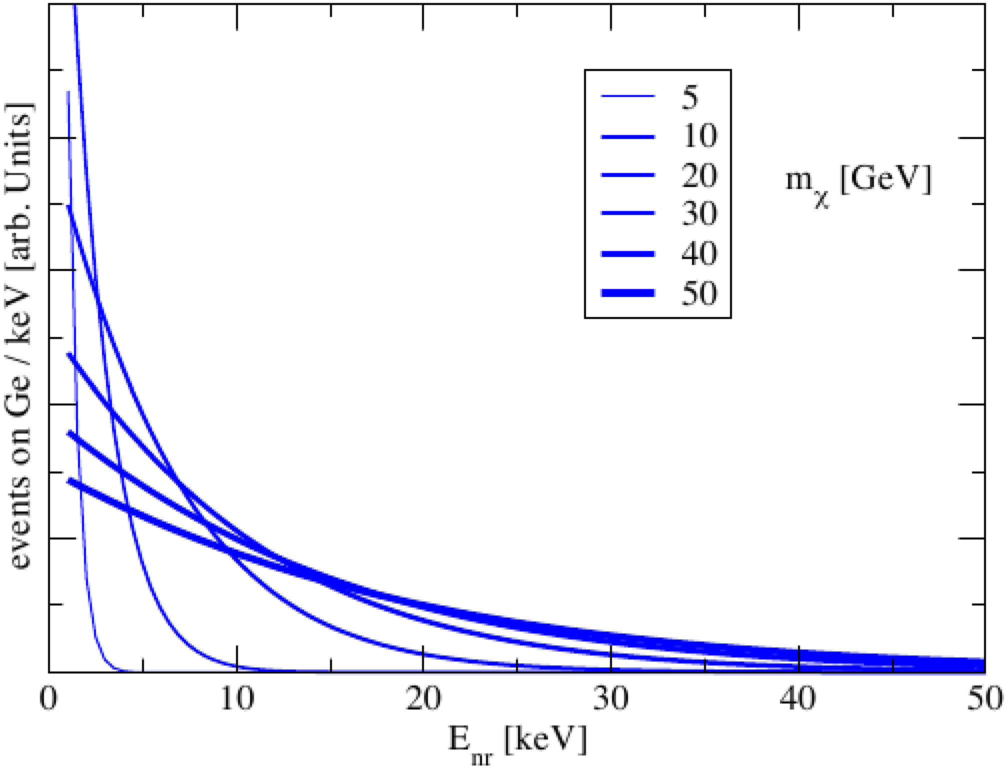


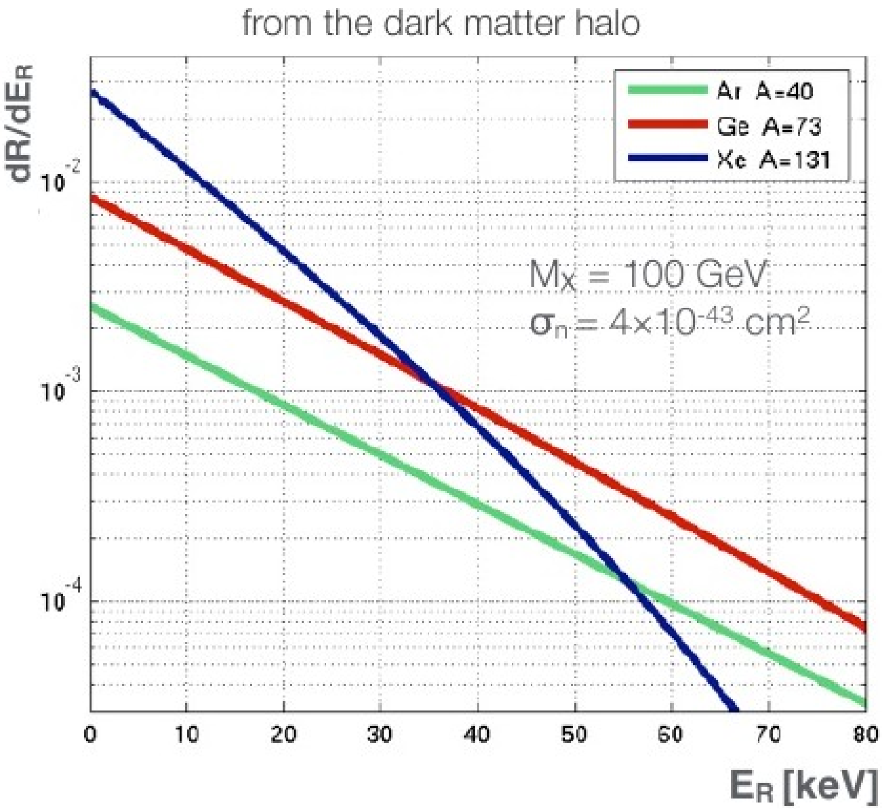
Helm Form Factor:

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

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

WIMP Recoil Spectra





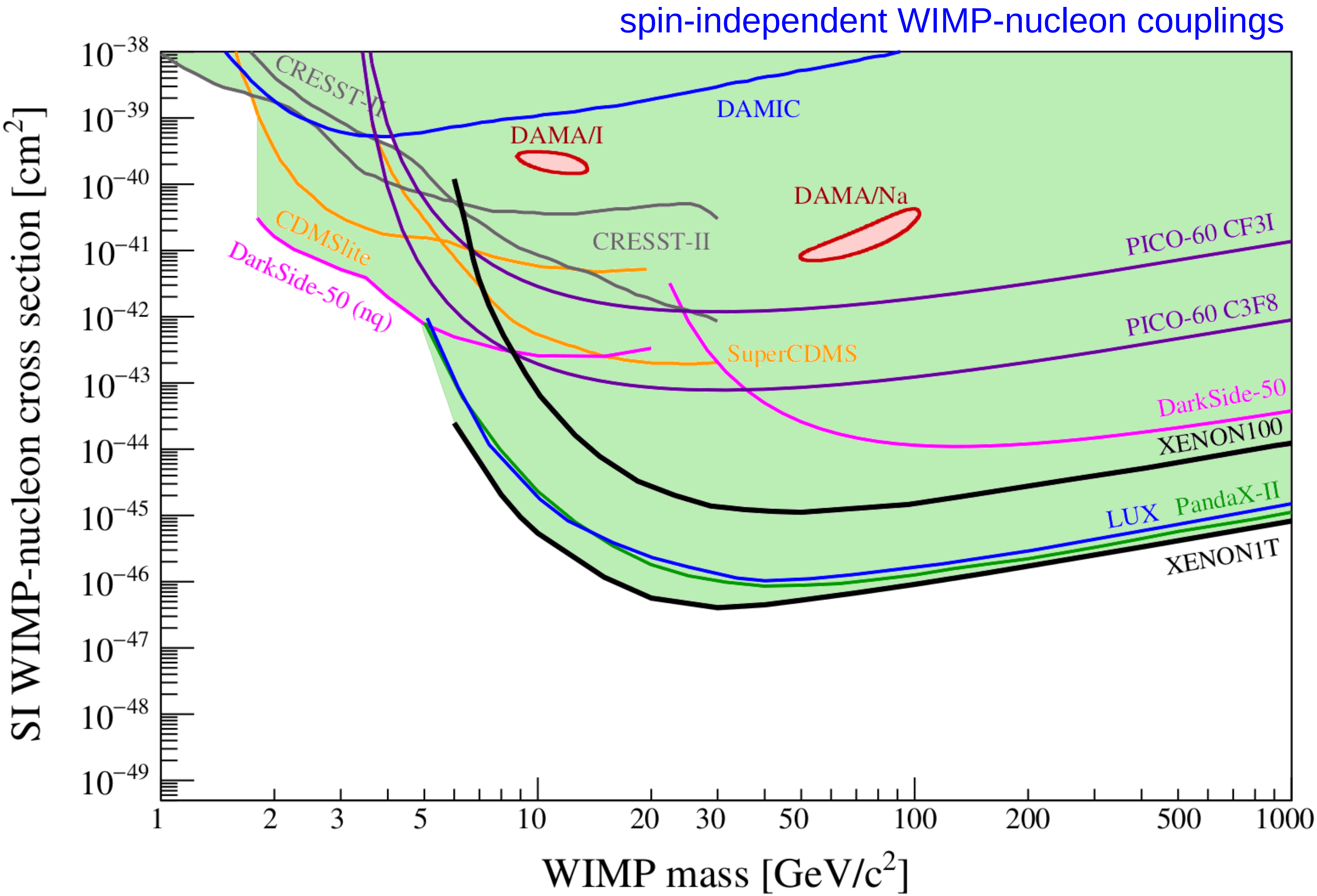
→expect different rates for different targets (cross checks!)

→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

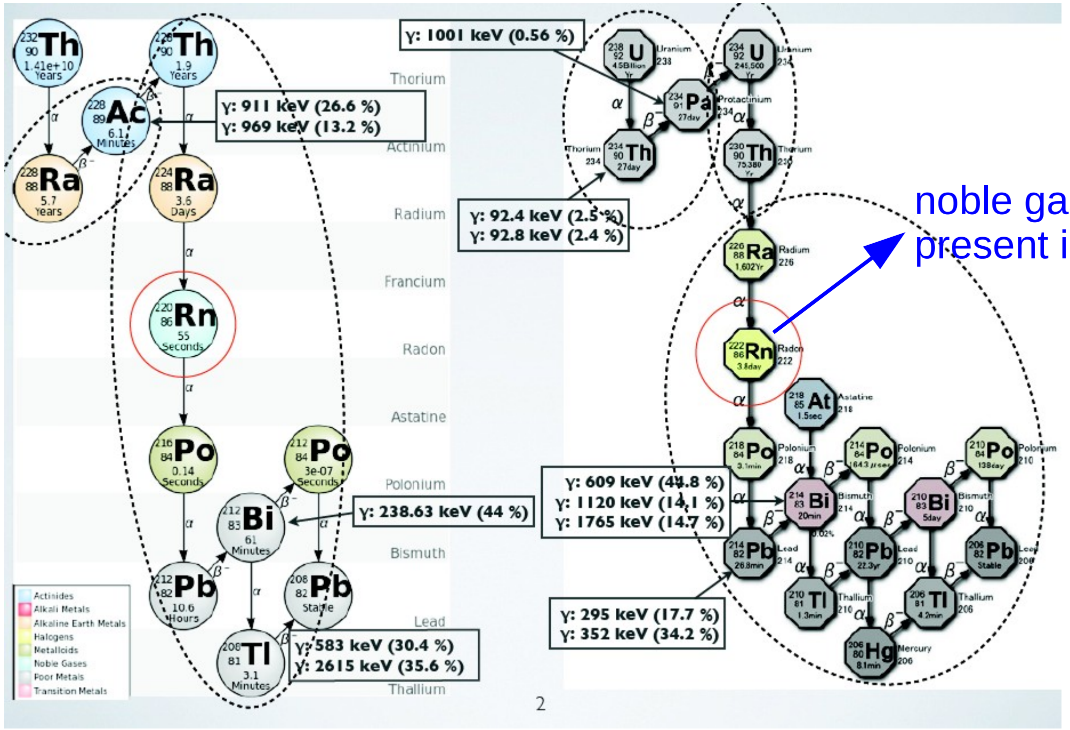


4 Backgrounds, Background Reduction

- 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: Know your signal
  → features of a WIMP signal?
  → discrimination

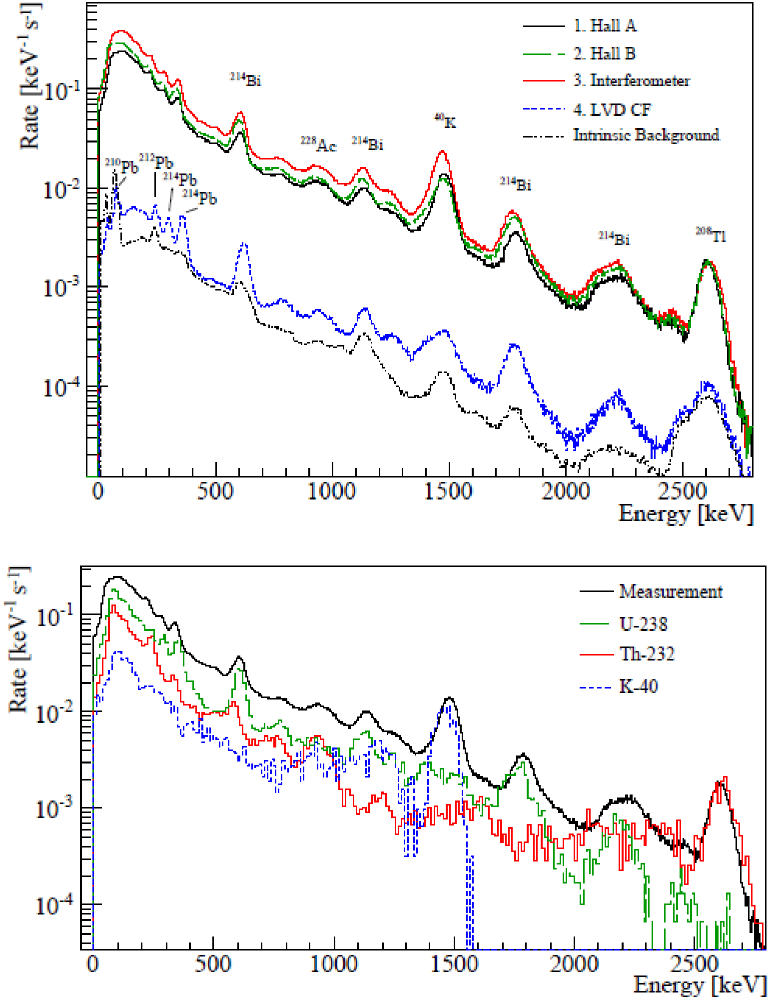
Backgrounds from the Environment

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)

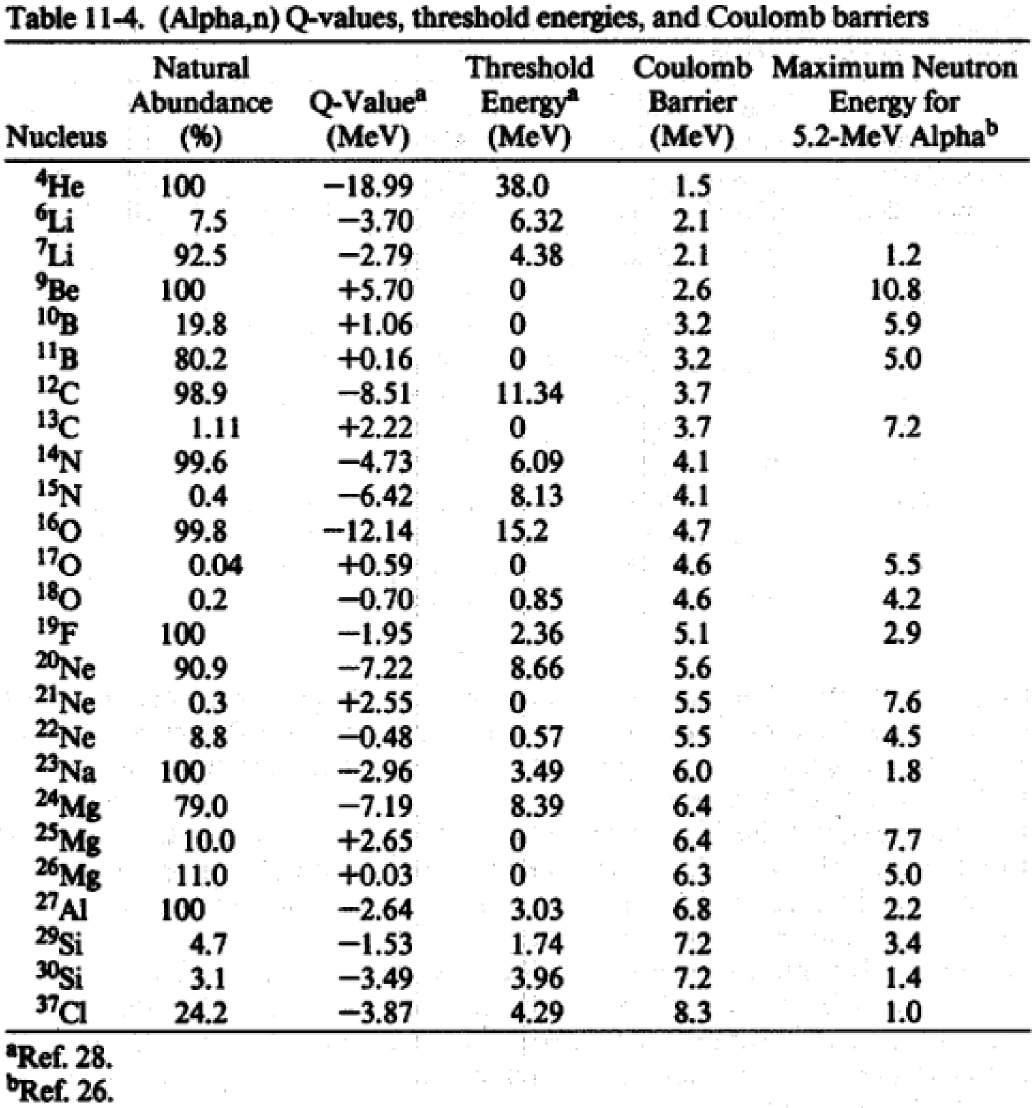


Table 11-4. (Alpha,n) Q-values, threshold energies, and Coulomb barriers

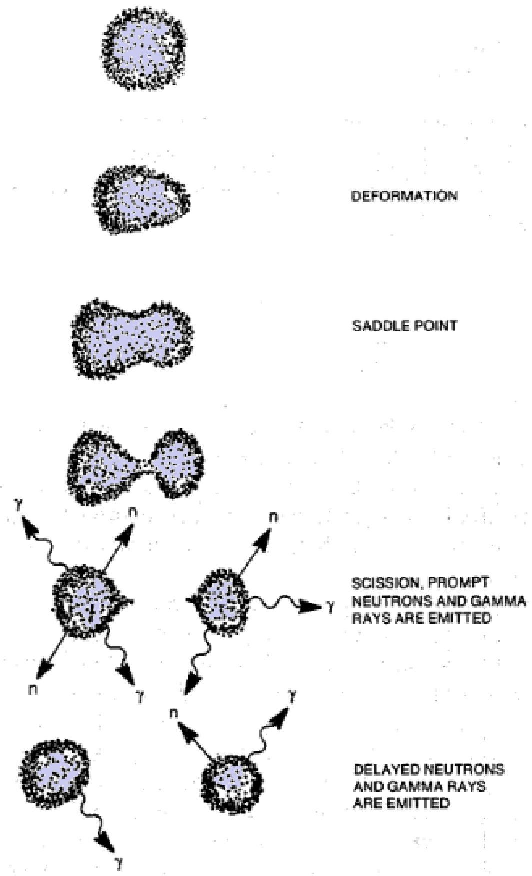
Nucleus	Natural Abundance (%)	Q-Value[a] (MeV)	Threshold Energy[a] (MeV)	Coulomb Barrier (MeV)	Maximum Neutron Energy for 5.2-MeV Alpha[b]
^{4}He	100	−18.99	38.0	1.5	
^{6}Li	7.5	−3.70	6.32	2.1	
^{7}Li	92.5	−2.79	4.38	2.1	1.2
^{9}Be	100	+5.70	0	2.6	10.8
^{10}B	19.8	+1.06	0	3.2	5.9
^{11}B	80.2	+0.16	0	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)



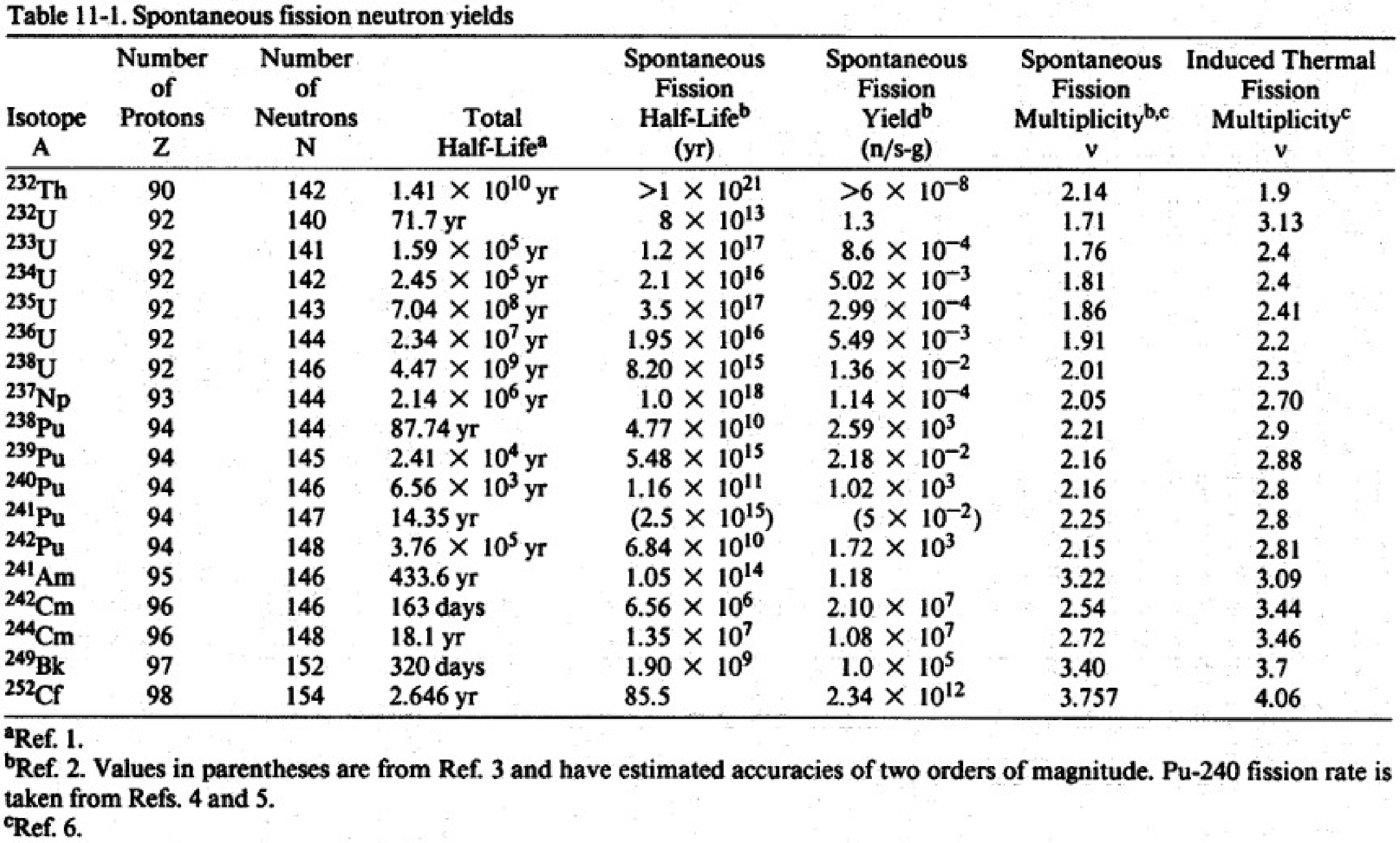


Table 11-1. Spontaneous fission neutron yields

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

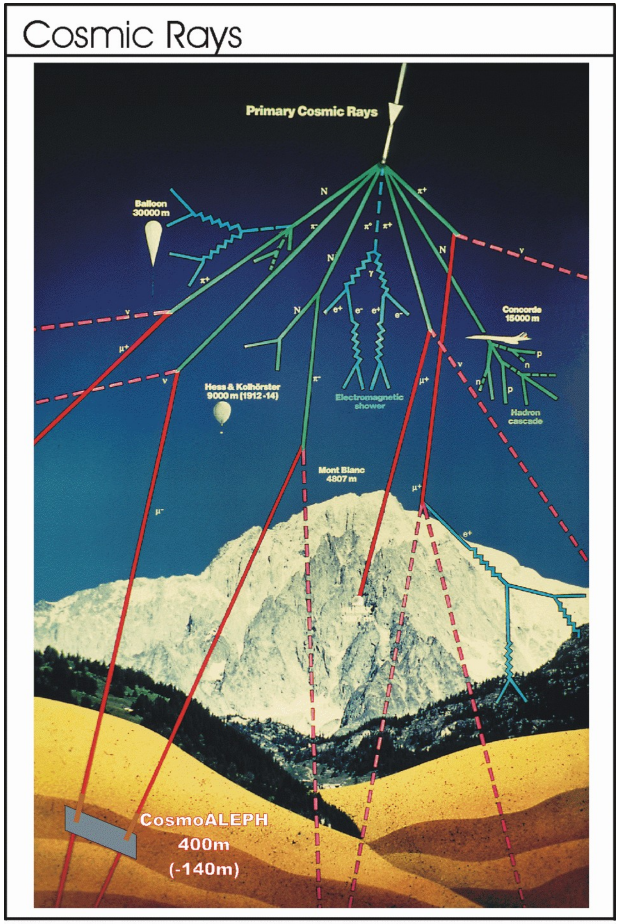
Isotope	Decay	Half life	Energy in Ge [keV]	Activity [µBq/kg]
^{3}H	β^-	12.33 yr	$E_{max(\beta-)}=18.6$	2
^{49}V	EC	330 d	$E_{K(Ti)} = 5$	1.6
^{54}Mn	EC, β^+	312 d	$E_{K(Cr)} = 5.4$, $E_{\gamma}=841$	0.95
^{55}Fe	EC	2.7 yr	$E_{K(Mn)} = 6$	0.66
^{57}Co	EC	272 d	$E_{K(Fe)}=6.4$, $E_{\gamma}=128$	1.3
^{60}Co	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

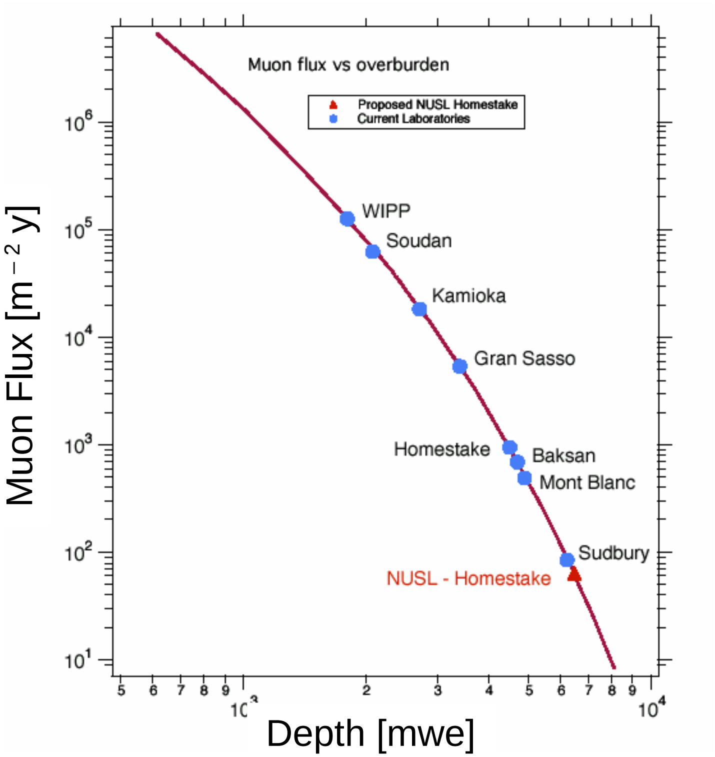
Cosmic rays and secondary/tertiary particles which they create in reactions can be reduced by going to underground laboratories

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

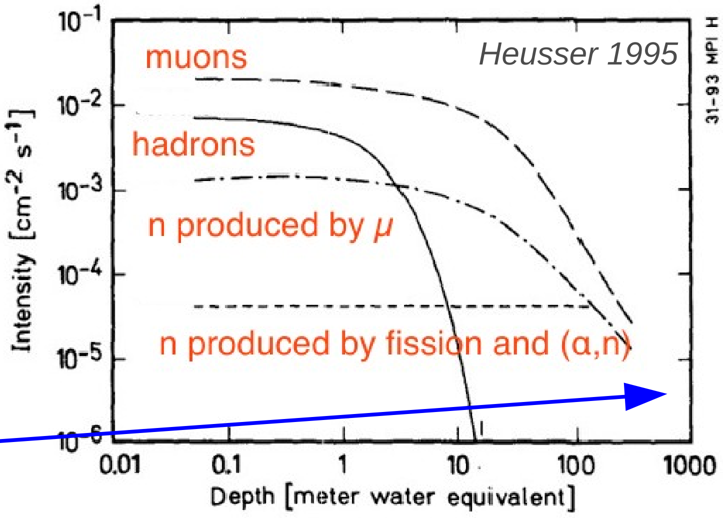
Shielding thickness (rock, soil) given in „meter-water-equivalent“ (mwe) to allow for comparison between different laboratories



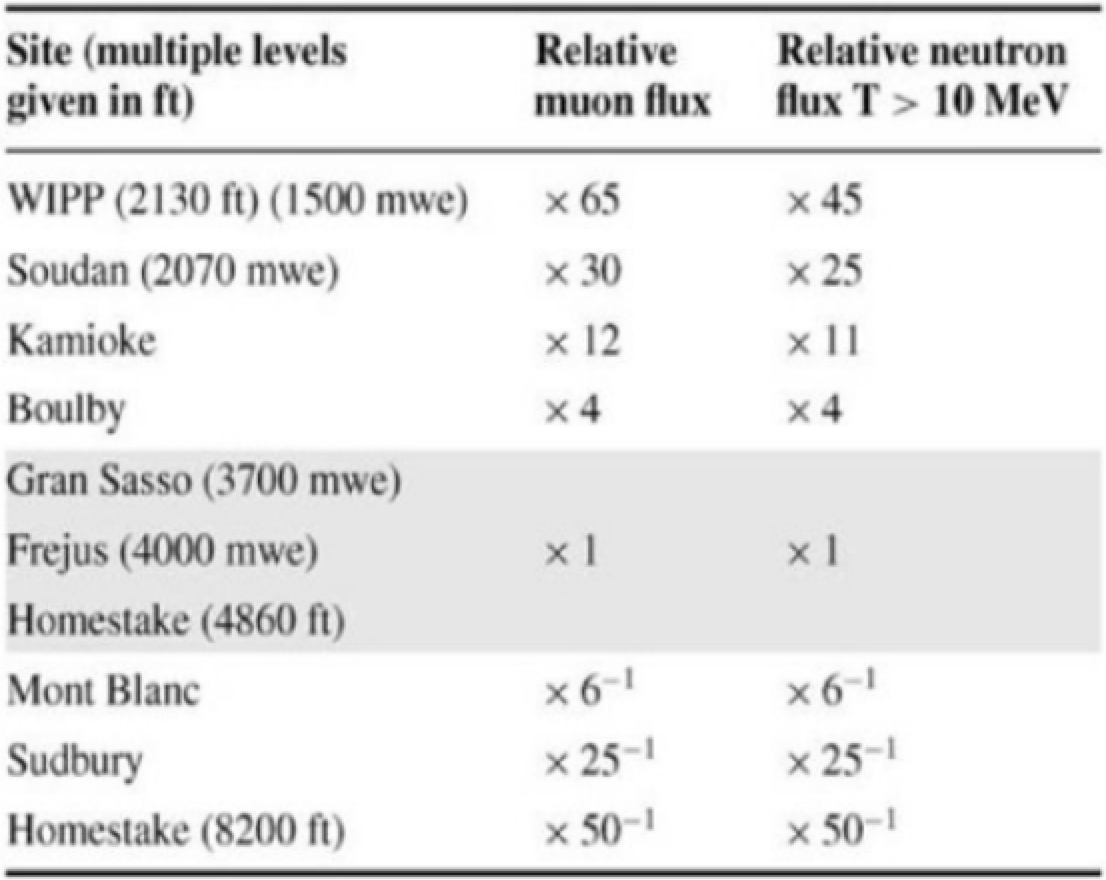
Particle Physics Slides • Sascha Marc Schmeling 1999 • Original Picture: CERN



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

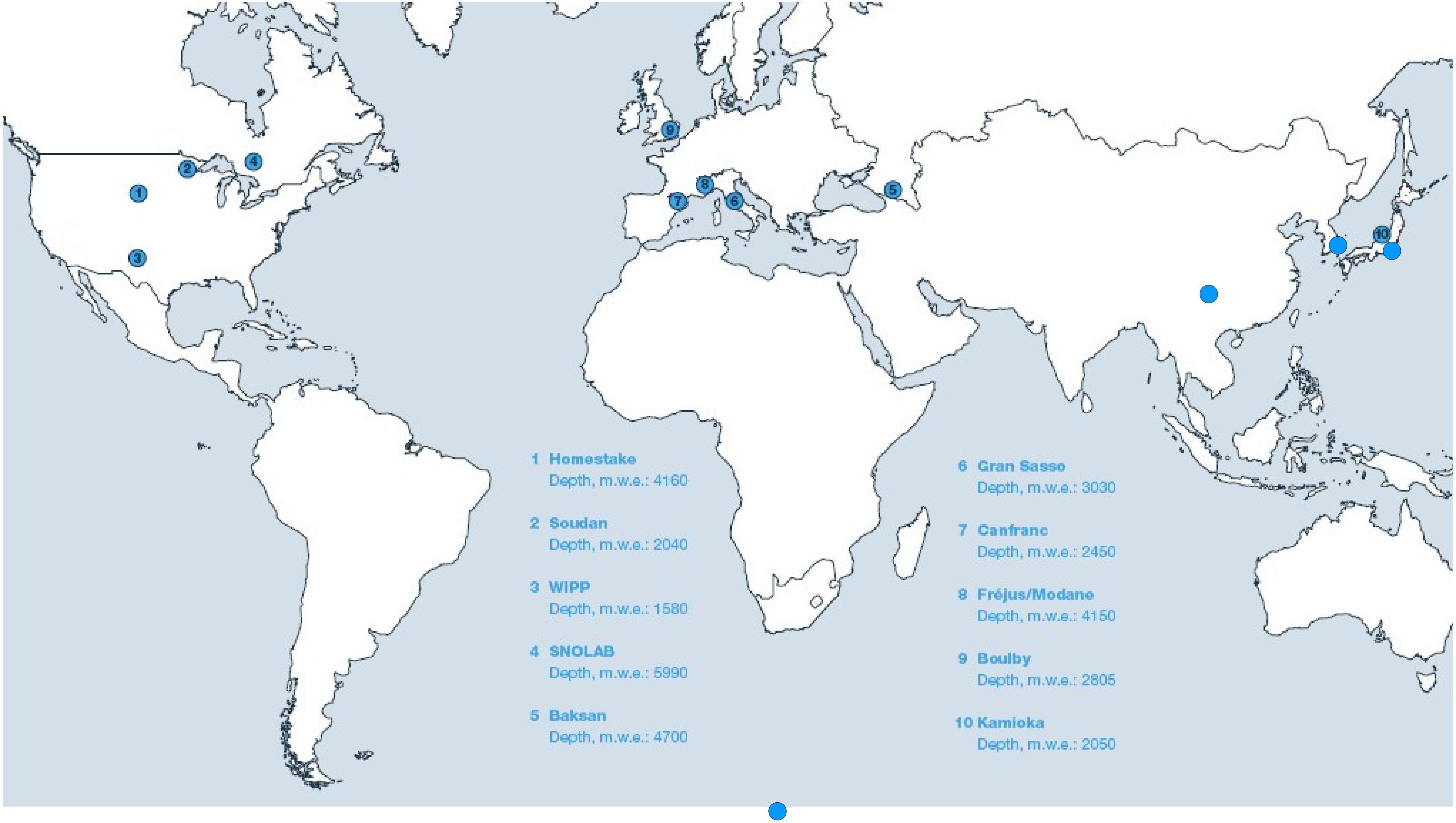


Background in Laboratories



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	$\times 6^{-1}$	$\times 6^{-1}$
Sudbury	$\times 25^{-1}$	$\times 25^{-1}$
Homestake (8200 ft)	$\times 50^{-1}$	$\times 50^{-1}$

Underground Laboratories



1 Homestake
Depth, m.w.e.: 4160

2 Soudan
Depth, m.w.e.: 2040

3 WIPP
Depth, m.w.e.: 1580

4 SNOLAB
Depth, m.w.e.: 5990

5 Baksan
Depth, m.w.e.: 4700

6 Gran Sasso
Depth, m.w.e.: 3030

7 Canfranc
Depth, m.w.e.: 2450

8 Fréjus/Modane
Depth, m.w.e.: 4150

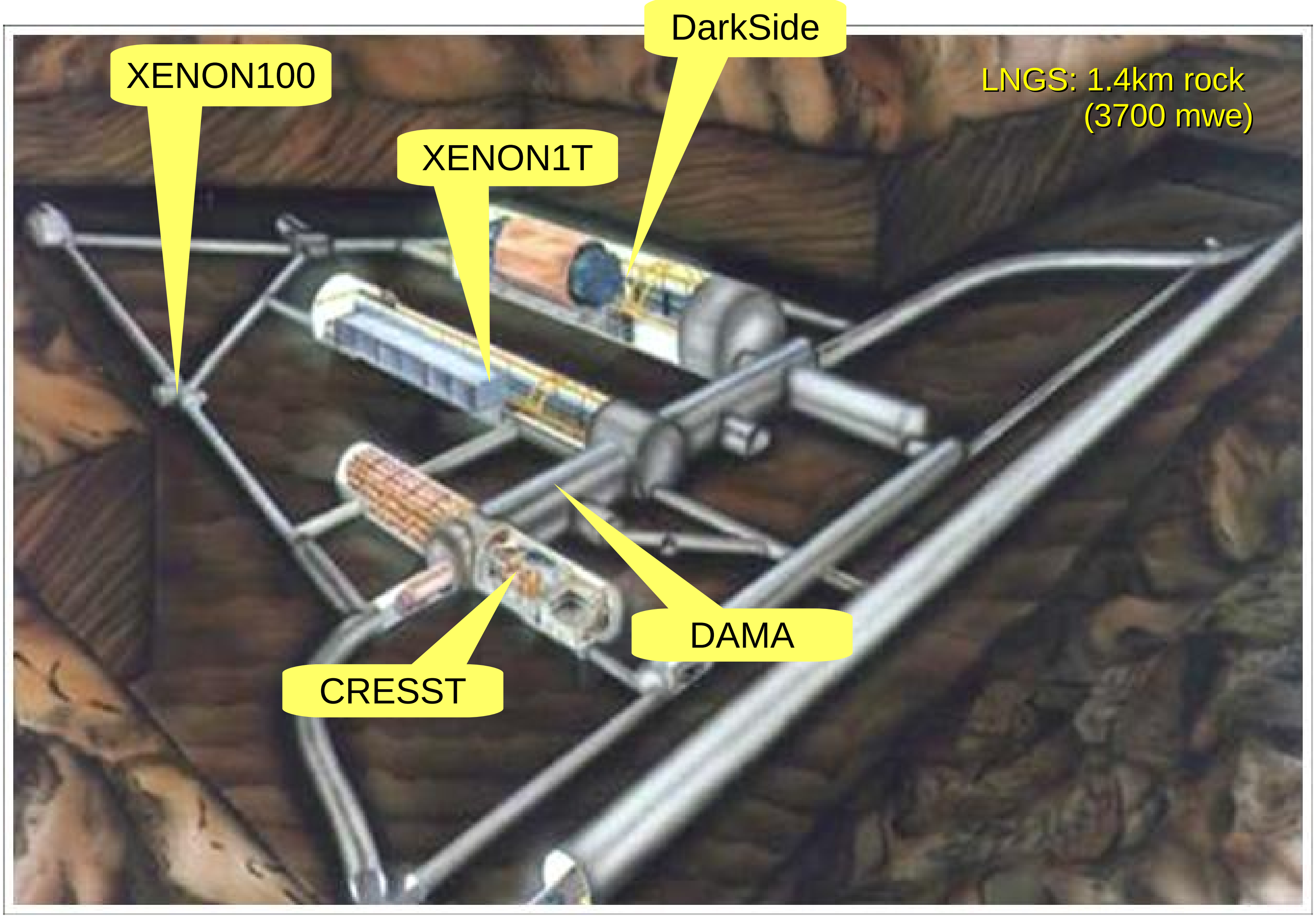
9 Boulby
Depth, m.w.e.: 2805

10 Kamioka
Depth, m.w.e.: 2050


ALARM
OSSIGENO OXYGEN
LAB.A LVD ZONE

Laboratori Nazionali del Gran Sasso

LNGS: 1.4km rock
(3700 mwe)



LNGS: 1.4km rock
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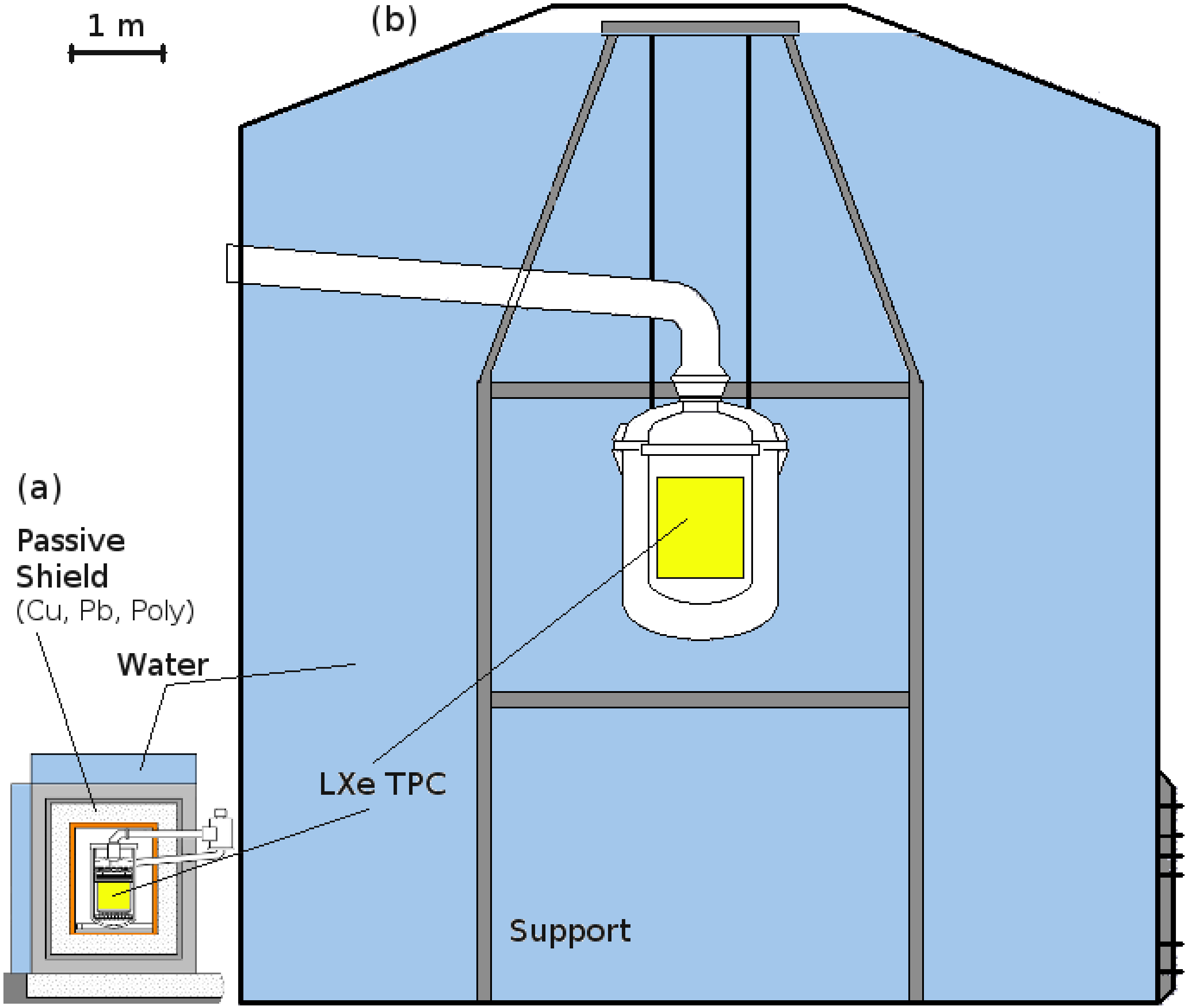
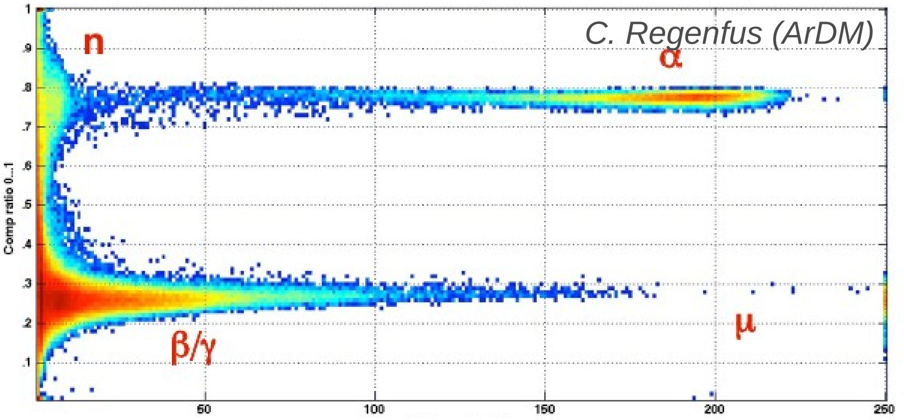


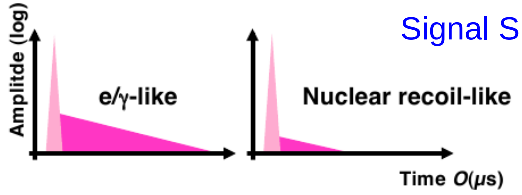
XENON100: passive

XENON1T: active shielding

Pulse Shape Discrimination



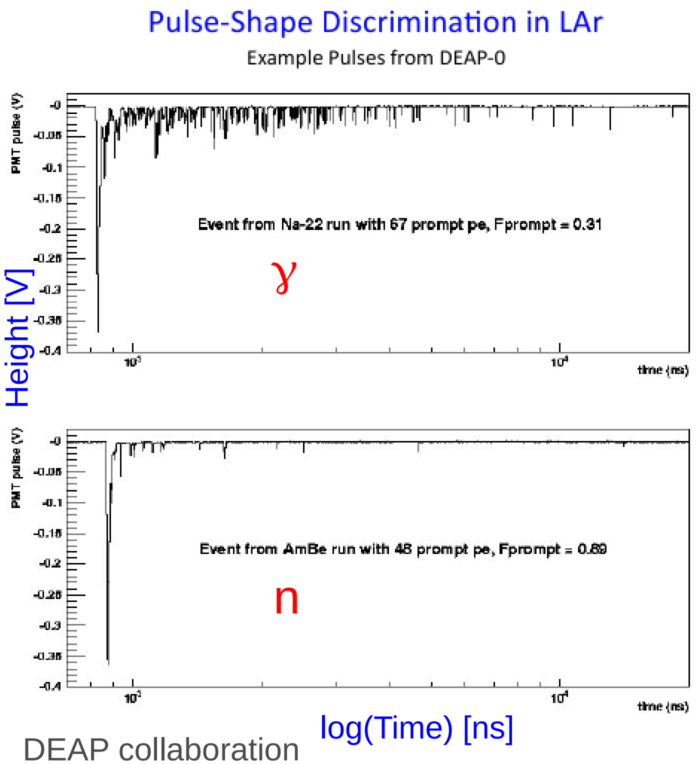
Signal Size



Singlet and triplet excimer states have characteristic lifetimes:

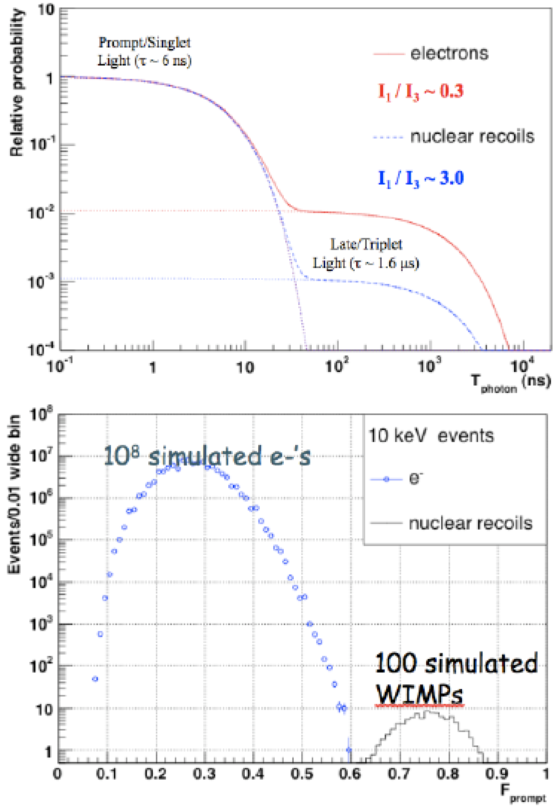
Ar: 5 ns, 1.6 µs
Xe: 4 ns, 22 ns

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



DEAP collaboration

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



LAr Discrimination levels of $3x10^{-8}$ achieved

arXiv:0904.2930, PRC 78, 035801 (2008)

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

LXe O(10)% rejection at low E

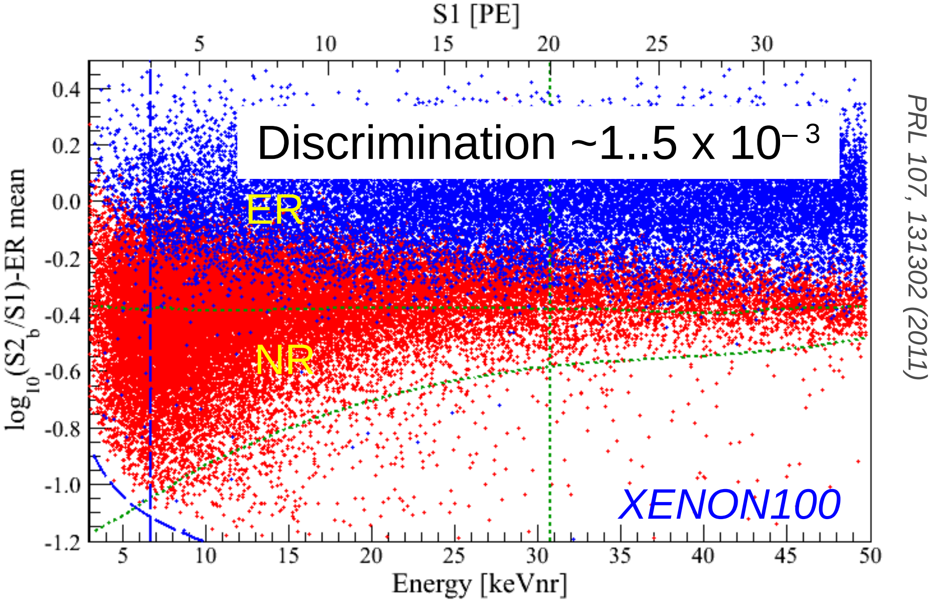
NIM A 612, 328 (2010)

Better for very high LY
($8x10^{-2}$ @ 50% NR acc.)

NIM A 659, 161 (2011)

Discrimination

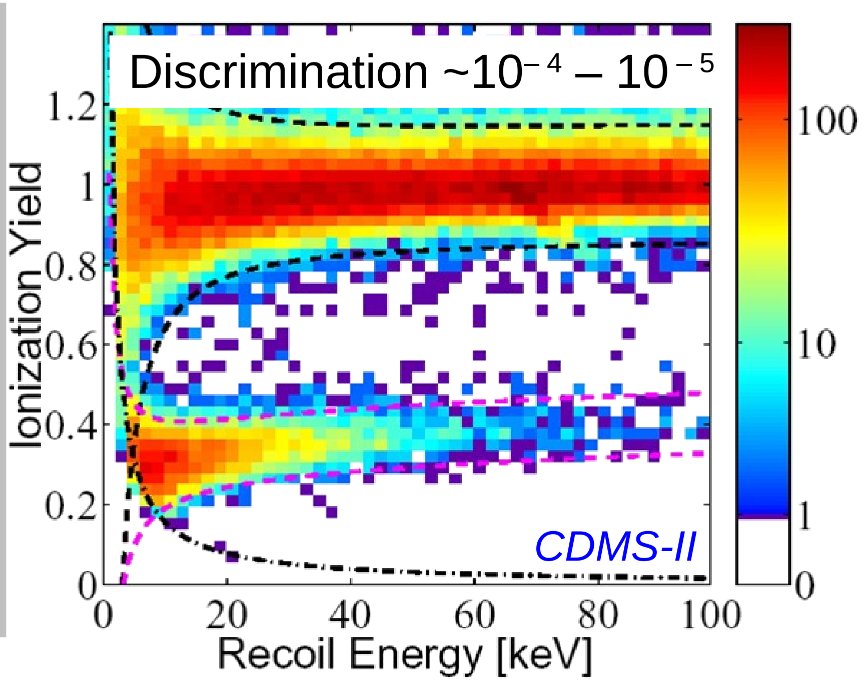
Charge/Light Signal



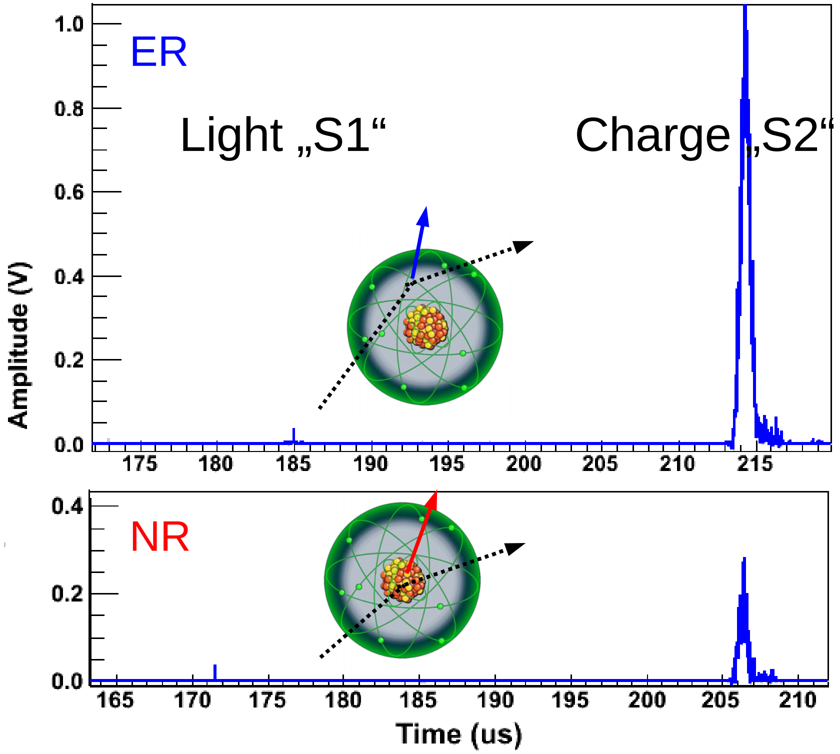
Discrimination ~1..5 x 10^{-3}

PRL 107, 131302 (2011)

Amount of Charge for a given E



Discrimination ~10^{-4} – 10^{-5}



Light „S1“

Charge „S2“

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

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