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Detecting DM via paleo-detectors

In collaboration with OKC U. Stockholm:

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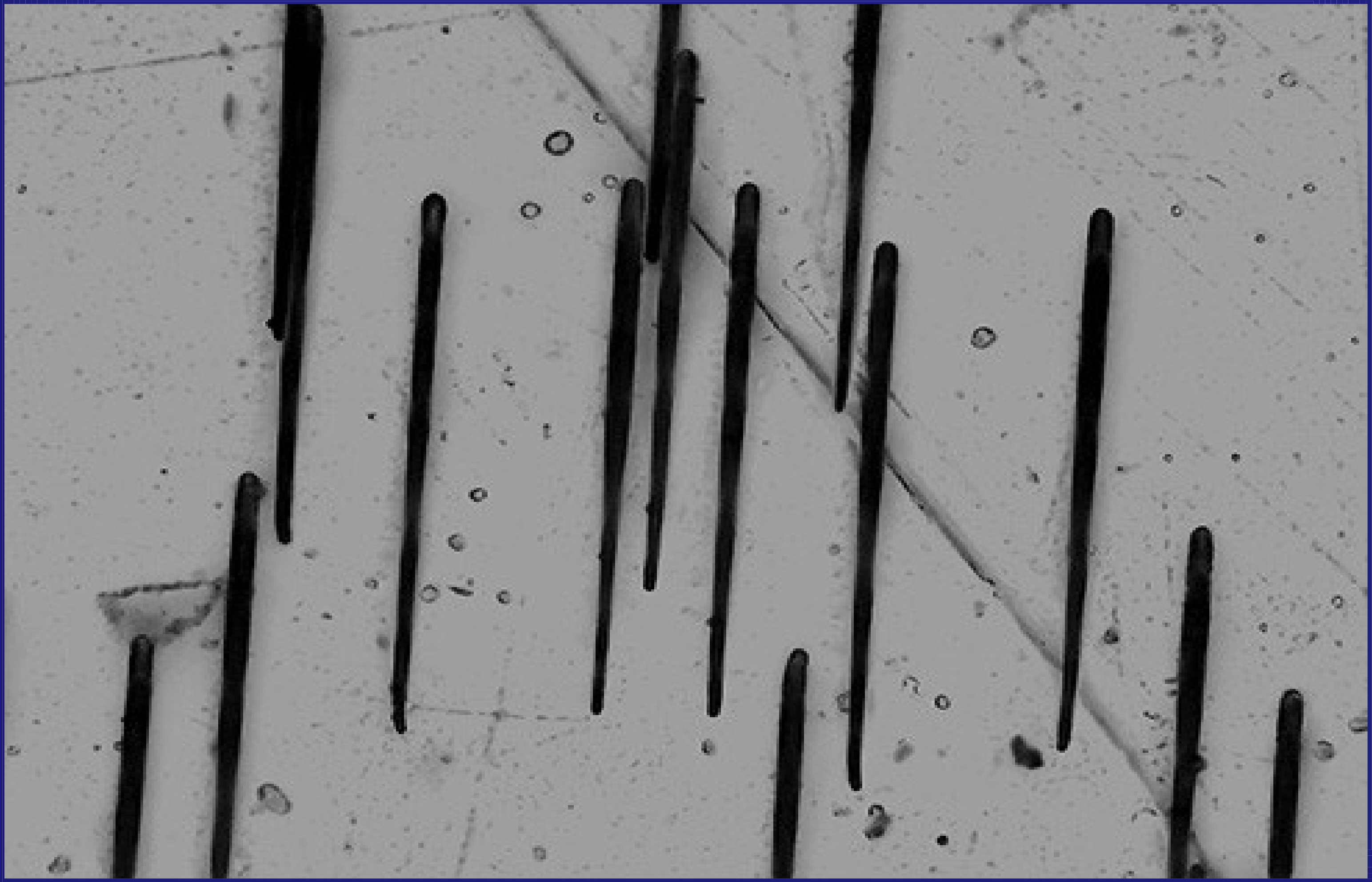
New WIMPs Detectors

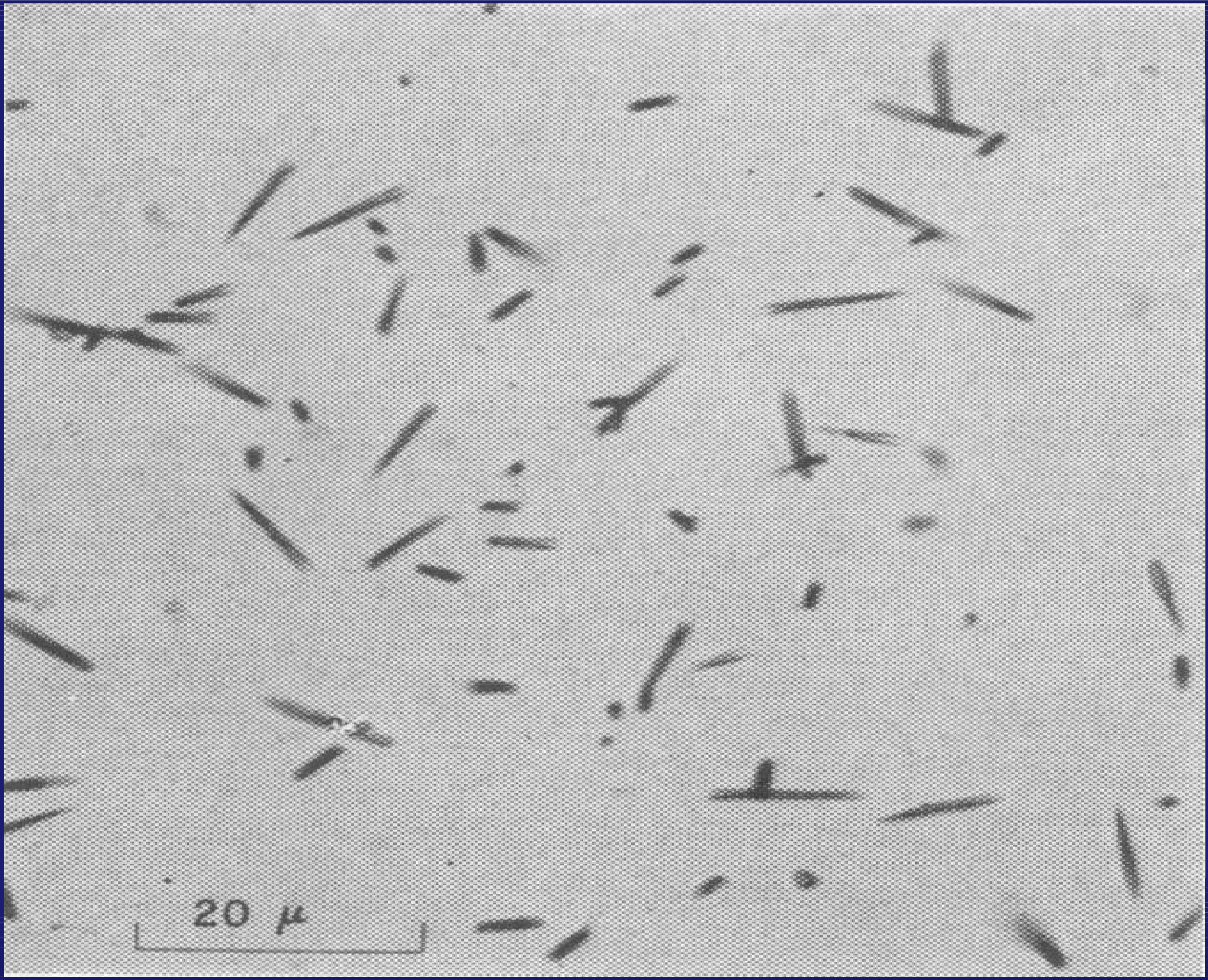
Chemically Amplified Detectors

- *nano-explosives*
- *nano-thermites*
- *{catalase, H_2O_2} –system*

Spaghetti detectors

Paleo - detectors




20 μ

Signatures of WIMPs interaction

1) **N^2 dependence of cross-section;**

2) **$(dE/dx)_{rn} >> (dE/dx)_{background}$**

=> Average range of recoiling nuclei

M < 15 GeV => O(10 nm)

M ~ 500 GeV => O(50 nm)

M ~ 5000 GeV = O(150 nm)

3) **Annual modulation**

4) **Particular ratio of FM = (TED/ETE)**

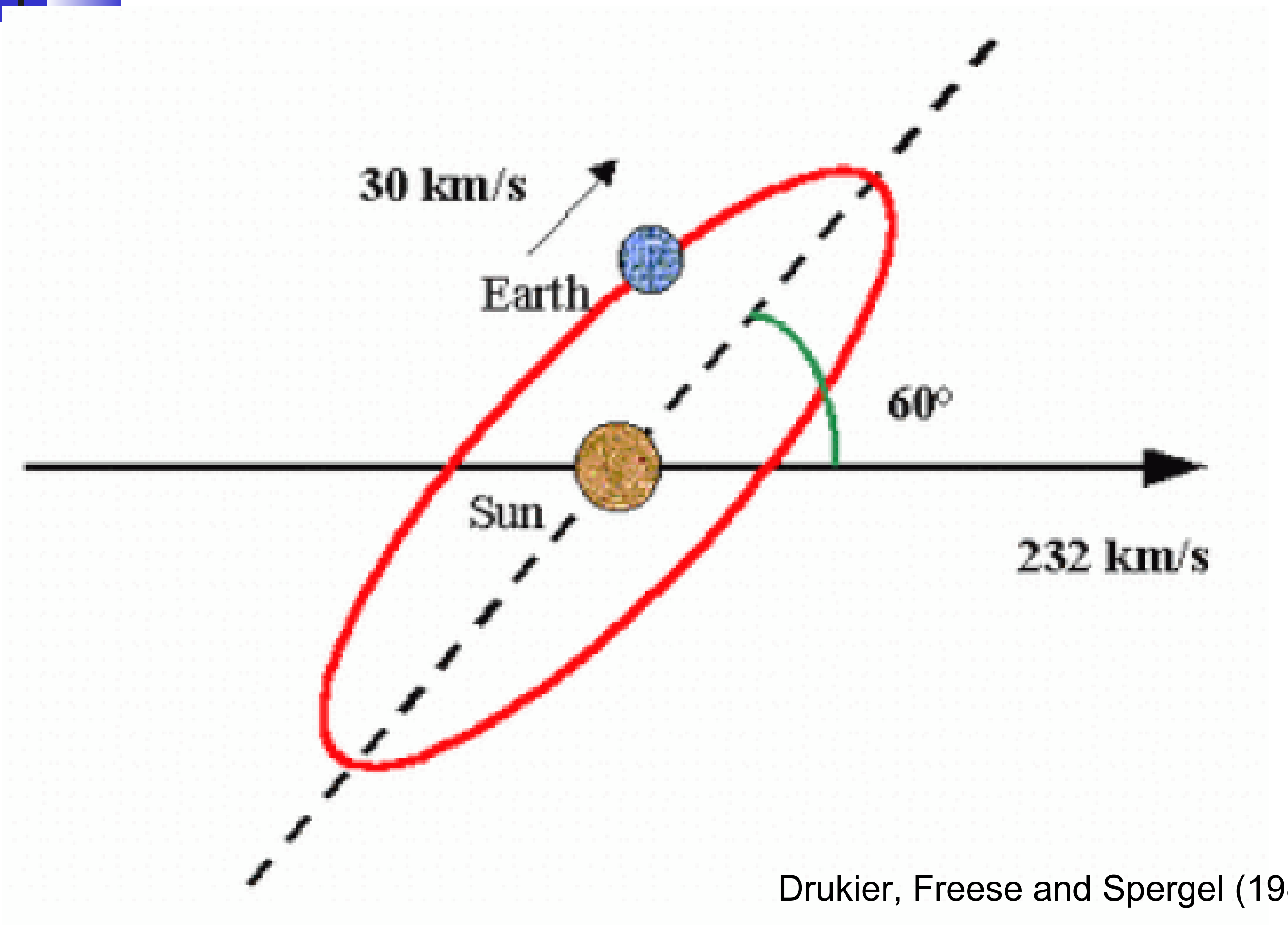
TED = Total energy deposited;

ETE = Energy transferred to electrons;

5) **Stodolsky conjecture**

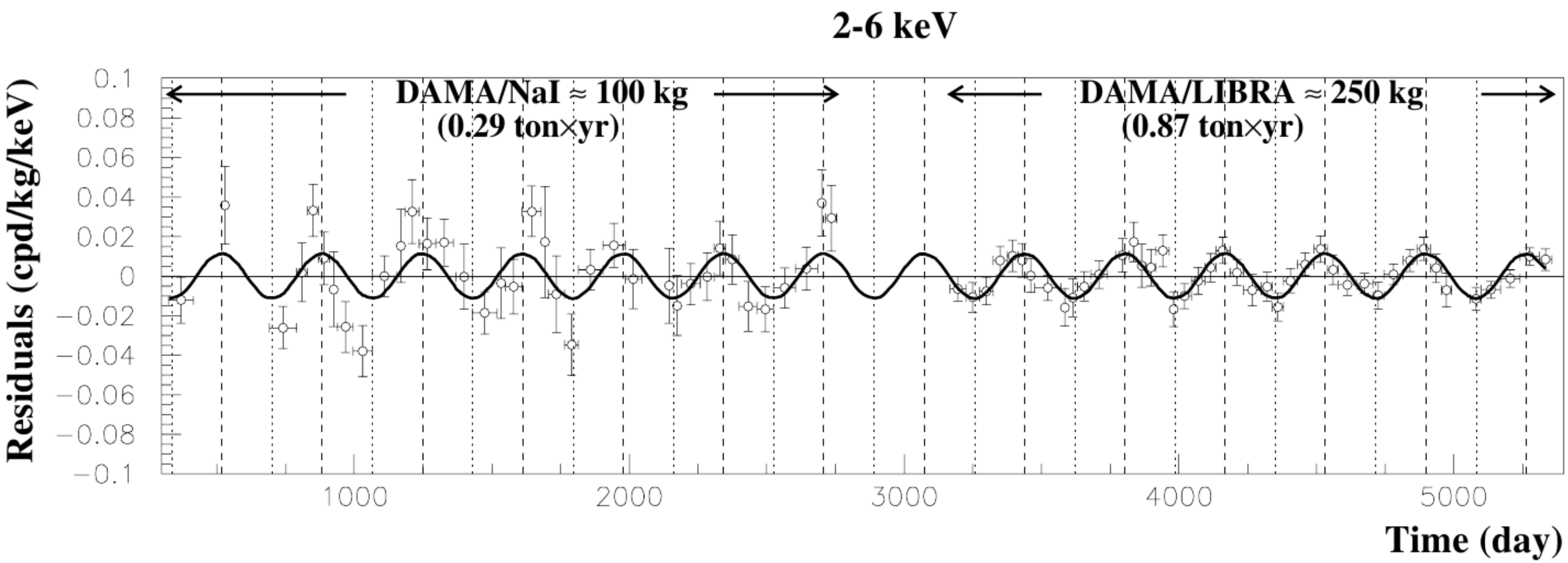
6) **Directional effects(??).**

DM: Annual Modulation



Drukier, Freese and Spergel (1986),

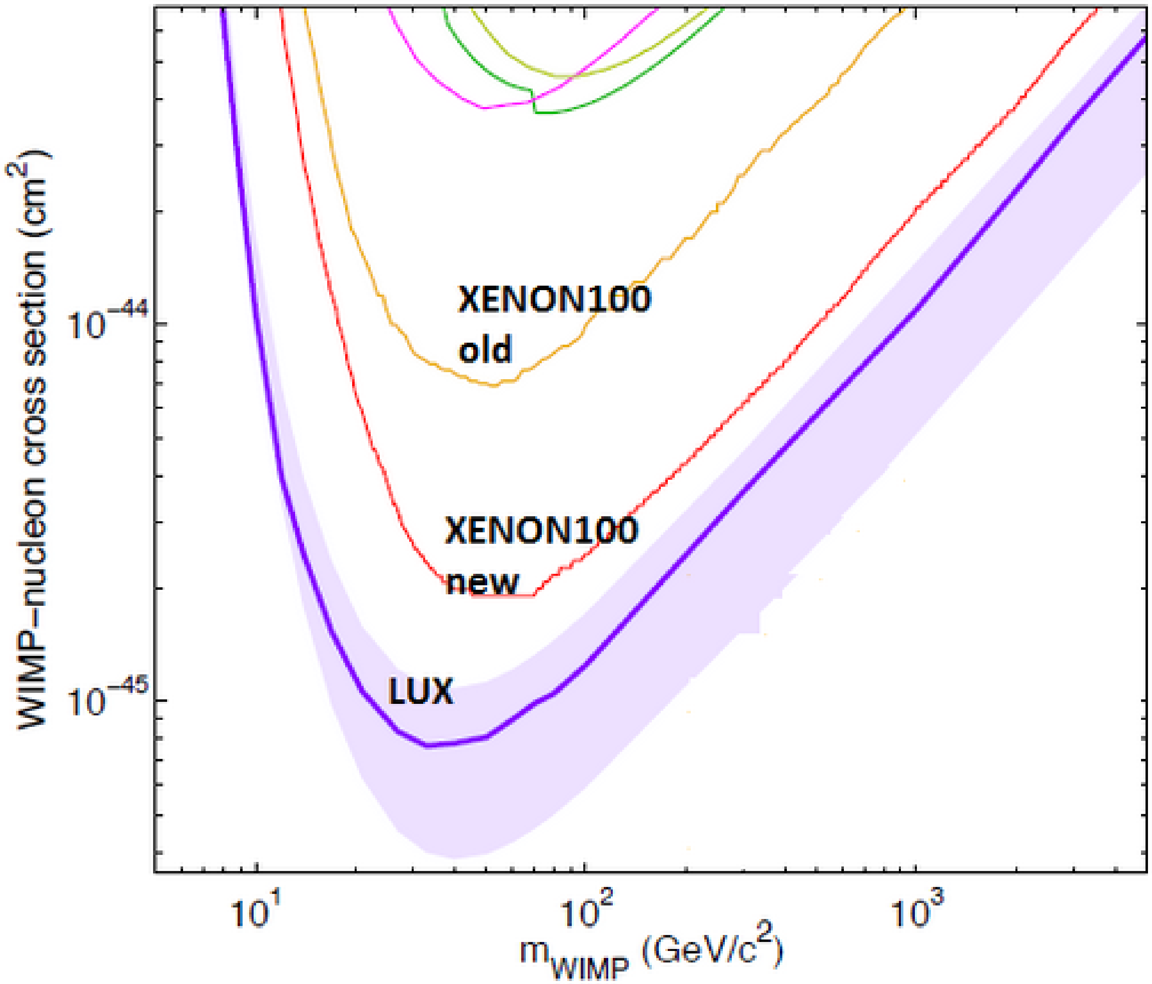
DM: Annual Modulation



Bernabei et al (2003,…,2017)

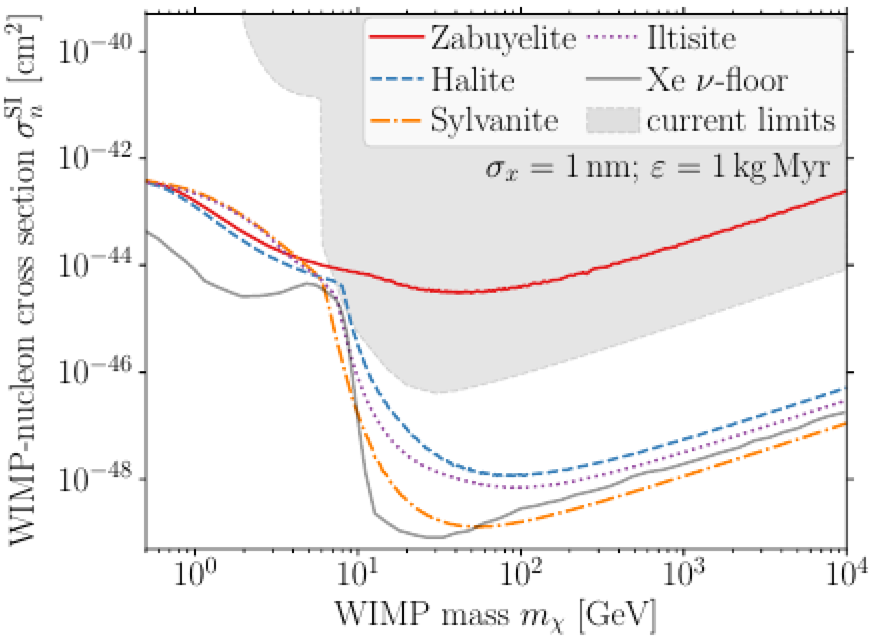
This is a 9 σ result

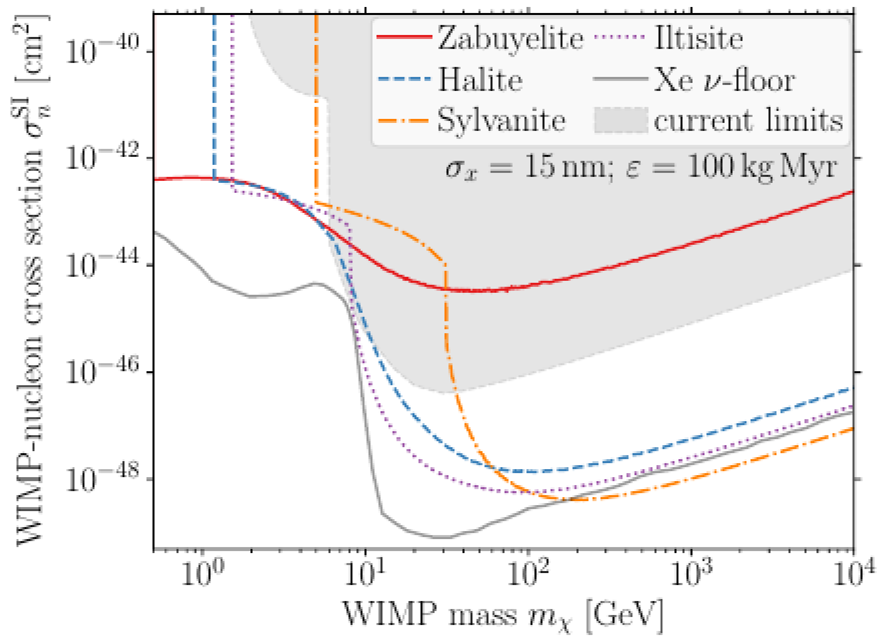
BUT



Stringent limits for 15 – 500 GeV/c^2, but only for spin-independent interactions

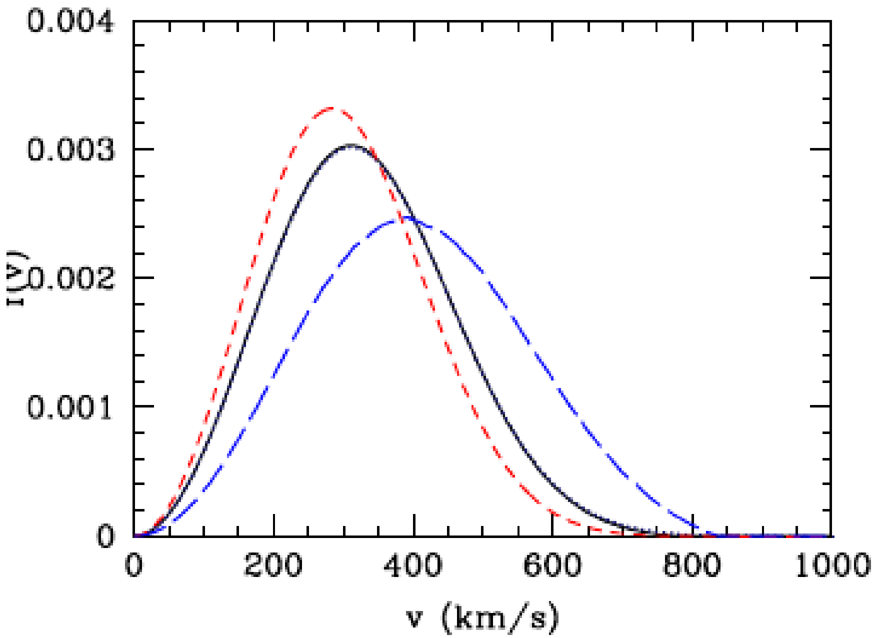
Paleo-detectors may be much better



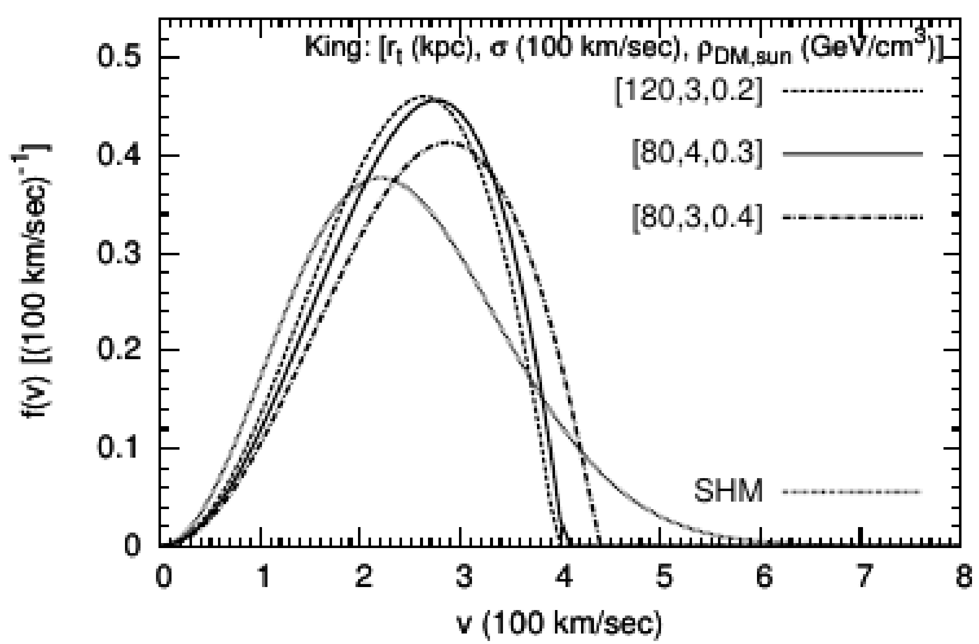


Very stringent limits, but only modest improvement for mass from 15 till 100 GeV/c^2, wherein L. Xenon is pretty good

Dark matter velocity distribution



Anne Green, JCAP10(2010)034
(Boosted to Earth's frame)



S. Chaudhury, *et al*. JCAP09(2010)020
(Not boosted to Earth's frame)

Low Mass WIMPs Detection

Kinematics requires low mass targets

=> coherent scattering gives 100-fold more counts

=> *current methods of background rejection fail*

=> *good spatial resolution improves S/B rati*

NEW CLASSES OF DETECTORS

Chemically Amplified Detectors (ChADS)

Nano-explosive detectors (over 100 compounds)

Nano thermite detectors (about 50 combinations)

Enzymatic reaction detectors

!!! PALEO-DETECTORS (> 2000 minerals) !!!

Depth is crucial

Table 1 : Muon Intensity [(m2 x yr)$^{-1}$] as function of depth.

Depth[m]	Depth[mWE]	Facility	Flux[(m^{2}yr)$^{-1}$]	Flux/[corexyr]
740.	2,000	Soudan	$5.0x10^4$	400
1111.	3,000	Kamioka	$1.5x10^4$	120
1480	4,000	Gran Sasso	$2.0x10^3$	16
		Homestake		
1850	5,000	Frejus	$3.5x10^2$	2.8
2222	6,000	Sudbury	100	0.8
2,590	7,000	Jin Ping	30	0.24
2,960	8,000	"deep black shales"	10	$8.0x10^{-2}$
3,330	9,000	"oil/gas"	3	$2.4x10^{-2}$
3,700	10,000	"deep oil/gas"	1	$8.0x10^{-3}$
4,070	11,000	" Marina Trench"	0.3	$2.4x10^{-4}$
5,550	15,000	(>50 worldwide)	$3.0x10^{-3}$	$2.4x10^{-5}$
7,400	20,000	(> 20 worldwide)	$1.2x10^{-5}$	$9.9x10^{-8}$
9,259	25,000	(2 worldwide)	$5.1x10^{-8}$	$4.1x10^{-10}$
11,111	30,000	(Kola bore-hole)	$2.1x10^{-10}$	$1.7x10^{-12}$

Empty bore-holes are great

Table 2: The deepest bore-holes.

Name	Country	Depth[m]	Status	Age[yrs]	Data	Cores
Exxon-Neftgas II	Sachalin, Russia	12,376	Drilling	???	???	???
SG-3	Kola, Russia	12,262	Abandonned	2.0×10^9	Yes	???
YesOdoptu -OP11	Sachalin, Russia	11,475	Active	???	???	???
Al-shaheen	Katar	10,902	Active	???	???	???
Bert Rogers	Oklohama, USA	9,853	???	???	Yes	???
KTH.	Oberphalz, Germany	9,100	Maintained	3.0×10^8	Yes	Yes
A-1	Zisterdorf, Austria	8,553	Maintained	???	Yes	Yes
GDR-1	Modrow, Germany	8,008	Maintained	???	Yes	Yes
Saatly	Armenia ???	8,267	???	???	???	???
SG-7	En-Yahinskaja, Russia	8,250	???	???	Yes	Yes
SG-6	Ryumenskaya, Russia	7,502	???	???	Yes	Yes
Kuzmina-1	Poland	7,500	Maintained	5.0×10^8	Yes	Yes
SG-4	Ural, Russia	6,010	???	$6.0,\!x\ 10^8$	Yes	Yes
SG-?	Krivoy Rog, Ukraina	?????	???	2.0×10^9	Yes	Yes
SG-?	Vorotilovskaja, Russia	?????	???	6.0×10^8	Yes	???
SG-4	Uralyskaia, Russia	5,100	???	???	Yes	Yes
SG-?	Murutan, Kazachstan	?????	???	6.0×10^8	Yes	???
PL-2	Dukla-1, Poland	5,500	Oil/Gas	???	Yes	Yes
PL-3	Szaflary, Poland	5,000	started 2016	???	No	Yes
SG-?	Tyrnaugyauz, Russia	4,000	???	2.5x108	Yes	Yes

Paleo-detectors

(replace Mica detectors)

WIMPs scatter on nuclei

Recoiling nuclei leads to radiation damage

Etching creates tracks

Tracks can be measured

Table 3: Age of samples available from the lowest 1 km of selected deep bore holes .

Period	**Age**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
PZ3	2.5×10^8					X		X	X	X
PZ2	3.6×10^8					X		X	X	
PZ1	4.2×10^8			X	X	X	X	X		
PR2	6.0×10^8	X	X	X	X	X	X			
PR1	1.6×10^9	X	X							
AR2	3.2×10^9	X	X							
AR1	4.0×10^9	X	X							

1 = Kola **2 = Krivoy Rog** **3 = Ural** **4 = Muruntaz** **5 = Novo-Elkhov**
6 = Vortilov **7 = Tyumen** **8 = Dnipro-Donetski** **9 = Turngayzovskaia**

Perfect cleavage is crucial

5413 minerals
- > 2000 minerals with perfect cleavage

Can't accept K, U, Th
- > 1500 minerals

Five important groups
- Rock forming minerals e.g. mica
- Marine evaporite minerals, e.g. NaCl

- (Li,Be,B) minerals
- Graphite-like minerals
- minerals comprising high mass nuclei

Information is safe in paleo-detectors

- *Table : Annealing time at T = 300 °K*

– *Calcite*	*10^{9} yrs*
– *Olivine*	*10^{14} yrs*
– *Tektite*	*10^{22} yrs*
Zircon	*10^{39} yrs*
– *Diopside*	*10^{60} yrs*

Mineralogy - all goods are here

Table 5 : The number of minerals of a given element .

Li	**Be**											**B**	**C**	**N**	**O**	**F**
115	122											282	419	113	4335	416
Na	**Mg**											**Al**	**Si**	**P**	**S**	**Cl**
1022	693											1085	1526	632	1125	394
K	**Ca**	**Sc**	**Ti**	**V**	**Cr**	**Mn**	**Fe**	**Co**	**Ni**	**Cu**	**Zn**	**Ga**	**Ge**	**As**	**Se**	**Br**
x	1313	18	372	240	97	581	1147	66	160	710	277	7	33	659	127	12
Rb	**Sr**	**Y**	**Zr**	**Nb**	**Mo**	**Tc**	**Ru**	**Rh**	**Pd**	**Ag**	**Cd**	**In**	**Sn**	**Sb**	**Te**	**I**
x	138	129	124	156	67	-	8	14	71	186	27	x	95	264	171	28
Cs	**Ba**	**REE**	**Hf**	**Ta**	**W**	**Re**	**Os**	**Ir**	**Pt**	**Au**	**Hg**	**Tl**	**Pb**	**Bi**		
24	246	X	1	61	44	2	7	0	32	33	99	71	551	232		

Backgrounds in Paleo-detectors

Radioactivity :

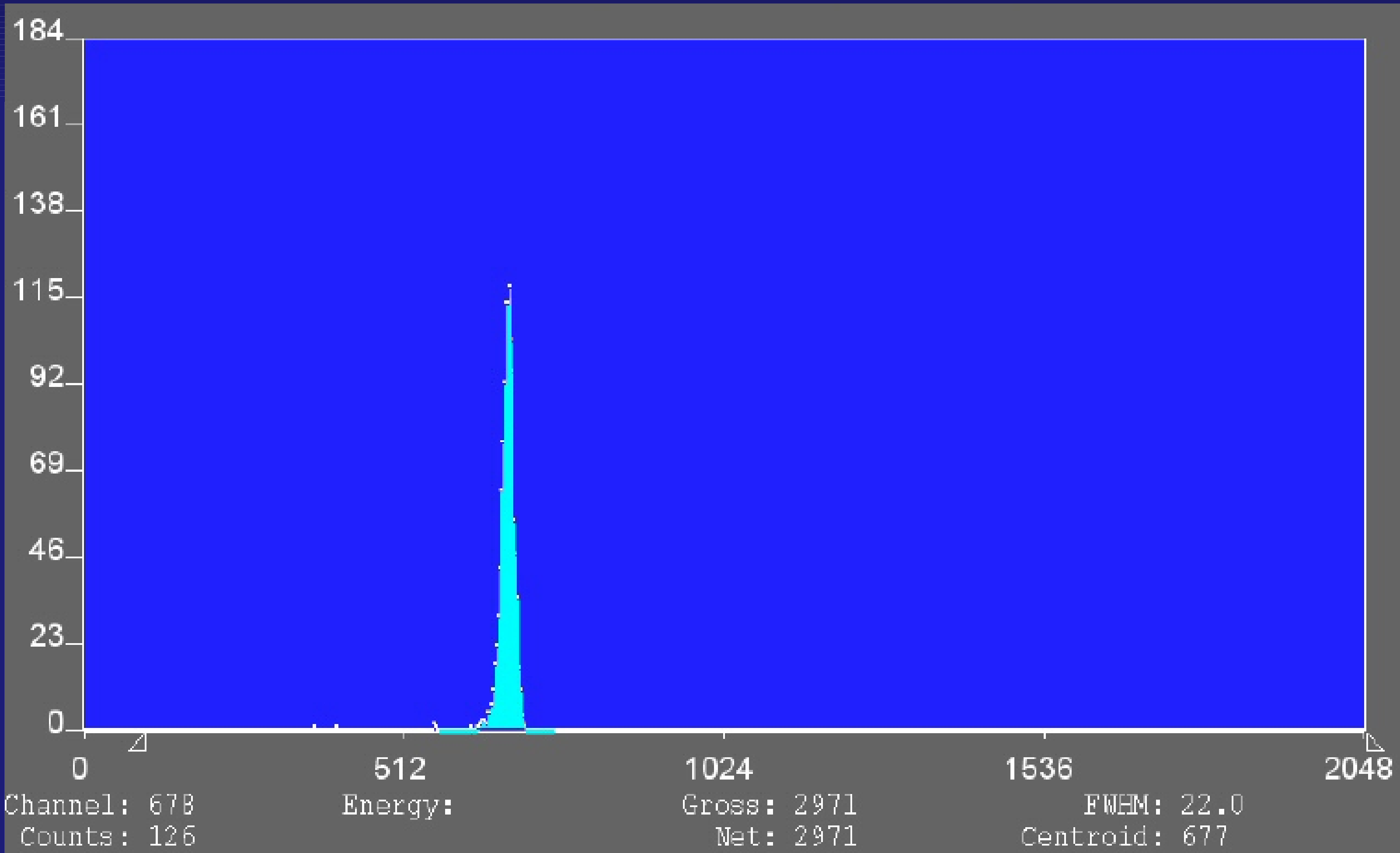
- *betas only on electrons => very low*
- *gammas only on electrons => very low*
- *alphas => challenging but rejected by length*
- *spontaneous fission => very low*

Cosmic rays:

- *depth - dependent*

Solar neutrinos:

- *only ^{8}B and hep for low-mass DM*



Alpha source = ^{241}Am, energy=5.486 MeV total counts 2971
Artifacts: 1 at ~3.24 MeV, 1 at 3.50 MeV

Rejection = $3*10^{-4}$ at cutoff 3.24 MeV

Signatures

Backgrounds are single peaked but peaks are broad.

For monochromatic DM, N elements in a mineral => N peaks.

DM halo velocity spectrum => peaks become slopes.

Most rock forming minerals

- *=> U = 5 ppm , Th = 10 ppm*

Marine evaporites, e.g. NaCl

- *=> U = 1 ppt, Th = 0.001 ppt*

Sterilization by proximity

Matching LM-DM mass with target mass

For higher energy recoils we need low mass targets

Best kinematics when $M_{DM}=M_{target}$

For $M_{DM}<15$ GeV/c^2 most of minerals are sub-optimal

We measure range, not recoil energy => we need low density minerals comprising at least one low-A element.

We considered following groups of speciality minerals: (Li, Be, B), graphite-like, “dirty water”

Selection of best groups of minerals

For LM-DM analysis, figures of merit order the mineral groups as follows:

Type	*Indication*	*minimum density [g/cc]*
1) Li	2 - 4 GeV	2.09
2) Be	3 – 5 GeV	1.81
3) B	4 – 6 GeV	1.71
4) graphite-like	5 – 8 GeV	0.87 !!
5) “dirty-water”	8 – 10 GeV	1.67

Li mineral (Zabuyelite) seems to be the best for range from 1 to 15 GeV/c^2 DM mass

These groups include marine evaporites *i.e*. minerals are very pure with very low abundance of U and Th

Our favorite minerals

Name	Formula	M_w	density [g/cc]
Zabuyelite	Li_2CO_3	73.9	2.09
Bertrandite	$Be_4Si_2O_7(OH)_2$	238.2	2.00
Barberiite	$(NH_4)BF_4$	104.8	1.89
Evenkite	$(CH_3)_2(CH_2)_{22}$	338.7	0.87
Halite	NaCl	58.0	2.16
Iltisite	$HgSAgCl_{0.75}Br_{0.25}$	387.1	6.59
Carlinite	Tl_2S	440.8	8.1
Mathewrogersite	Pb,Ge,Cu,Fe,Si,Al,O,H	2,678.8	4.7

Just examples from a set of ~ 200 minerals we have studied

Selection of readout modes

Microscopy..	Δx [nm]	Throughput	Cost	Availability
Confocal	250	*****	*****	*****
UV	150	****	****	****
Soft X	25	****	***	**
Hard X	10	***	*	*
AFM	1-5	***	****	****
EM	0.5	*	*	**

There is a huge advantage of using confocal and UV microscopy.
This will permit imaging of tracks in > 10 kg of minerals.

Best strategy => slice the mass range

The ability to use UV and/or X-ray microscopy is **crucial**.

For a given mass, we maximize range using three parameters:

1) Mass of target nuclei
2) Density of target mineral
3) Velocity cutoff

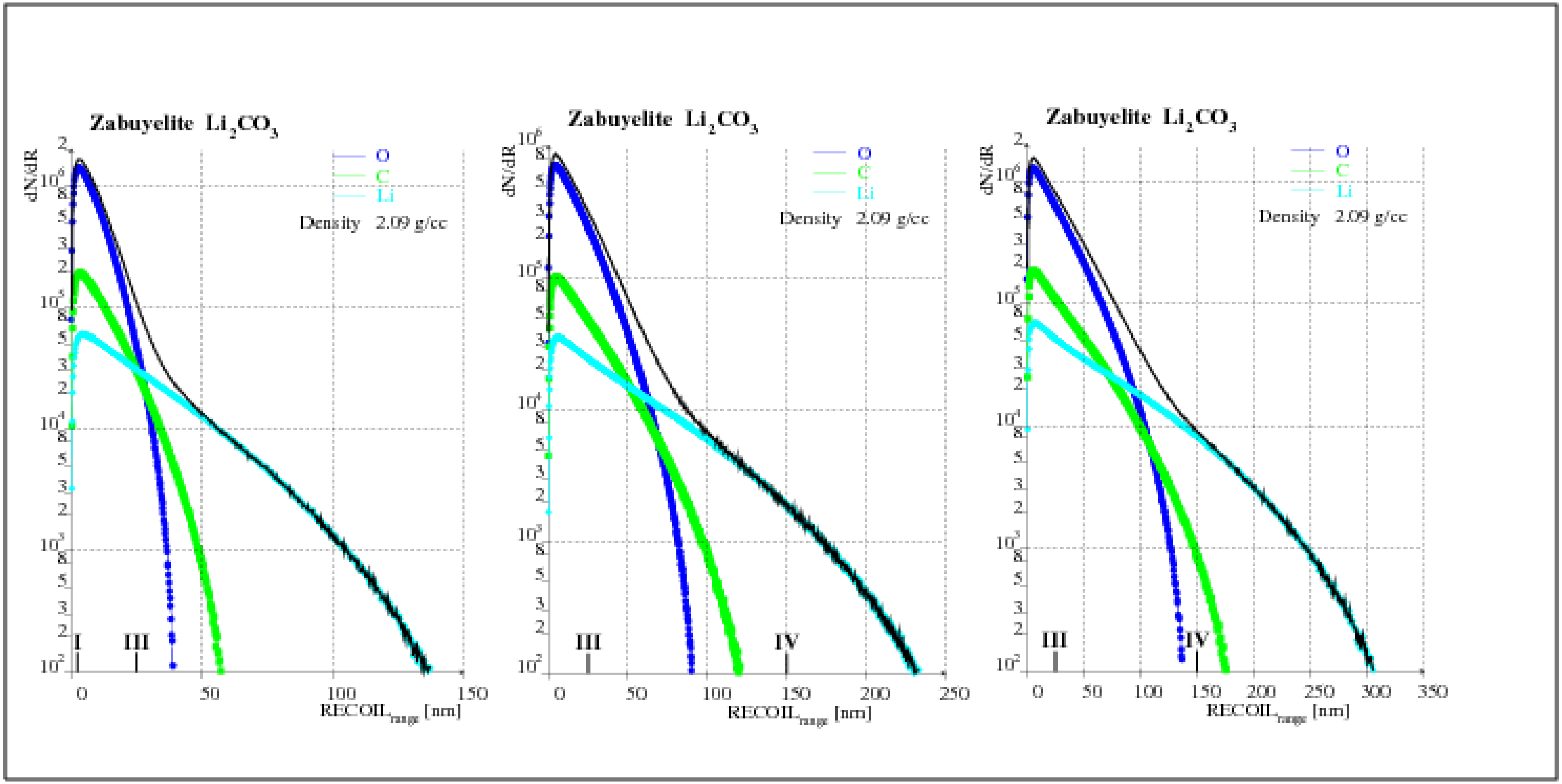
In paleo-detectors, very high count rate enables use of range cutoffs. Initially we assumed that chemical composition beats density.

For M_{DM} ~ 1 - 5 GeV/c^2 Li minerals are best,

For M_{DM} ~ 10 GeV/c^2 B minerals are best,

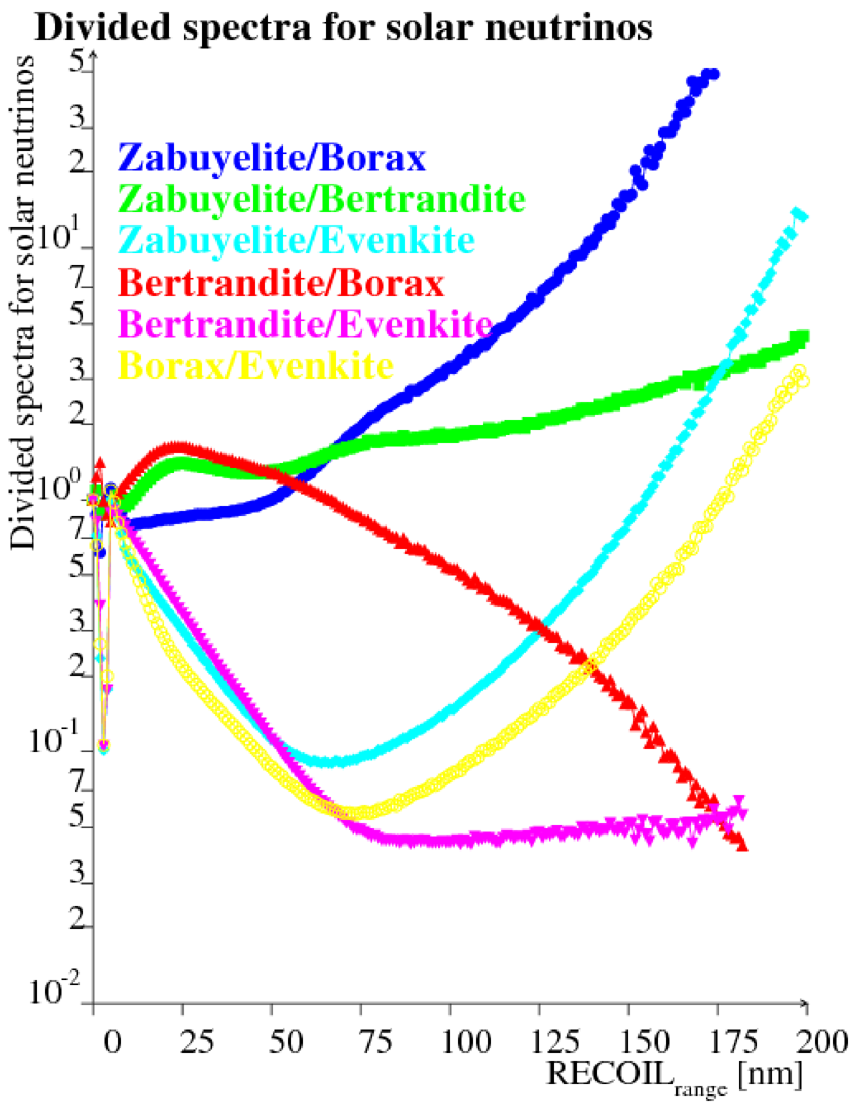
For M_{DM} ~ 15 GeV/c^2 graphite-like or dirty water minerals are best.

The best for 5, 10 and 15 GeV/c²



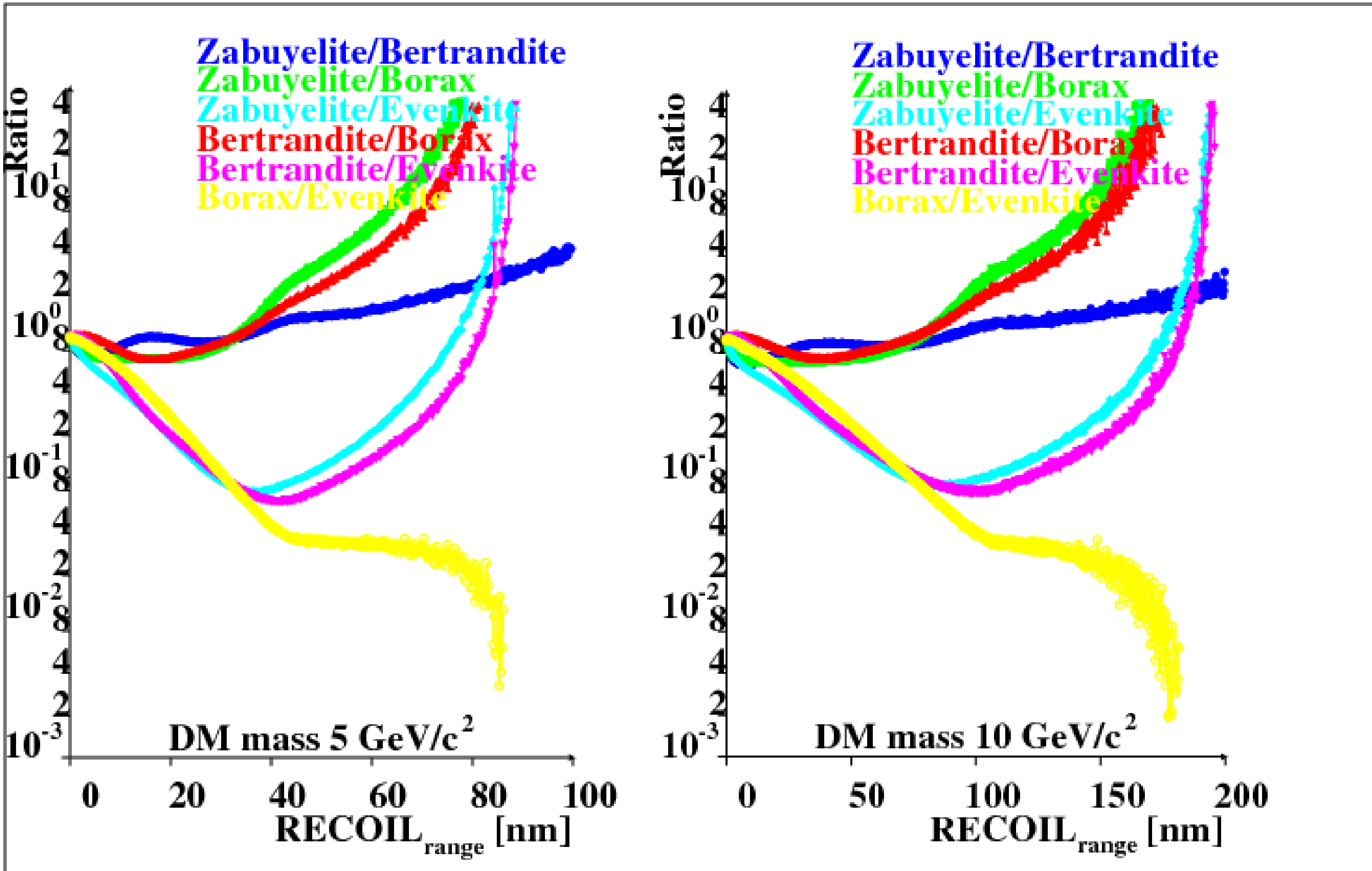
Note that x-axis scale is different for different plots

Four-crystals experiment

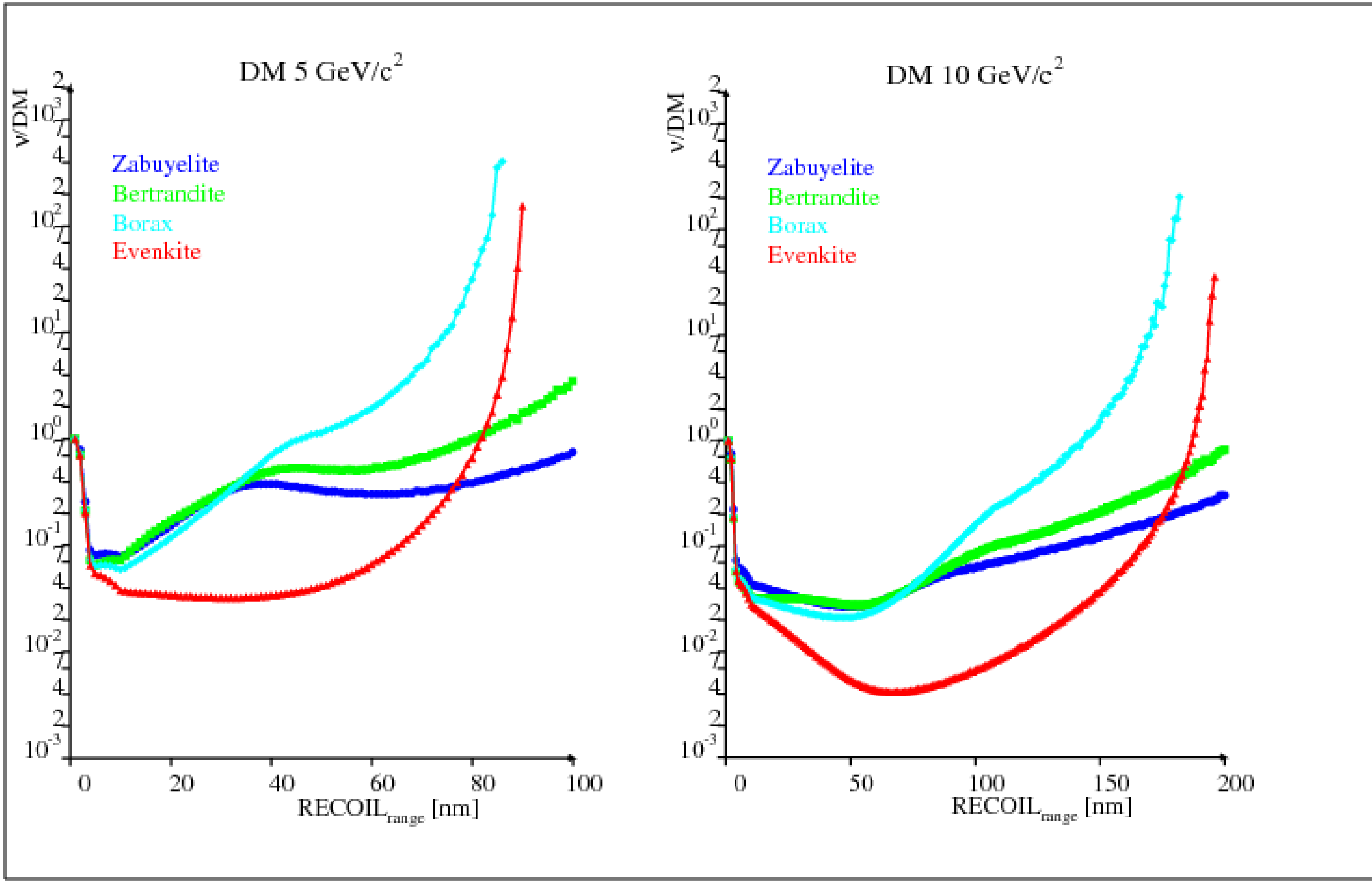


Four-crystals experiment

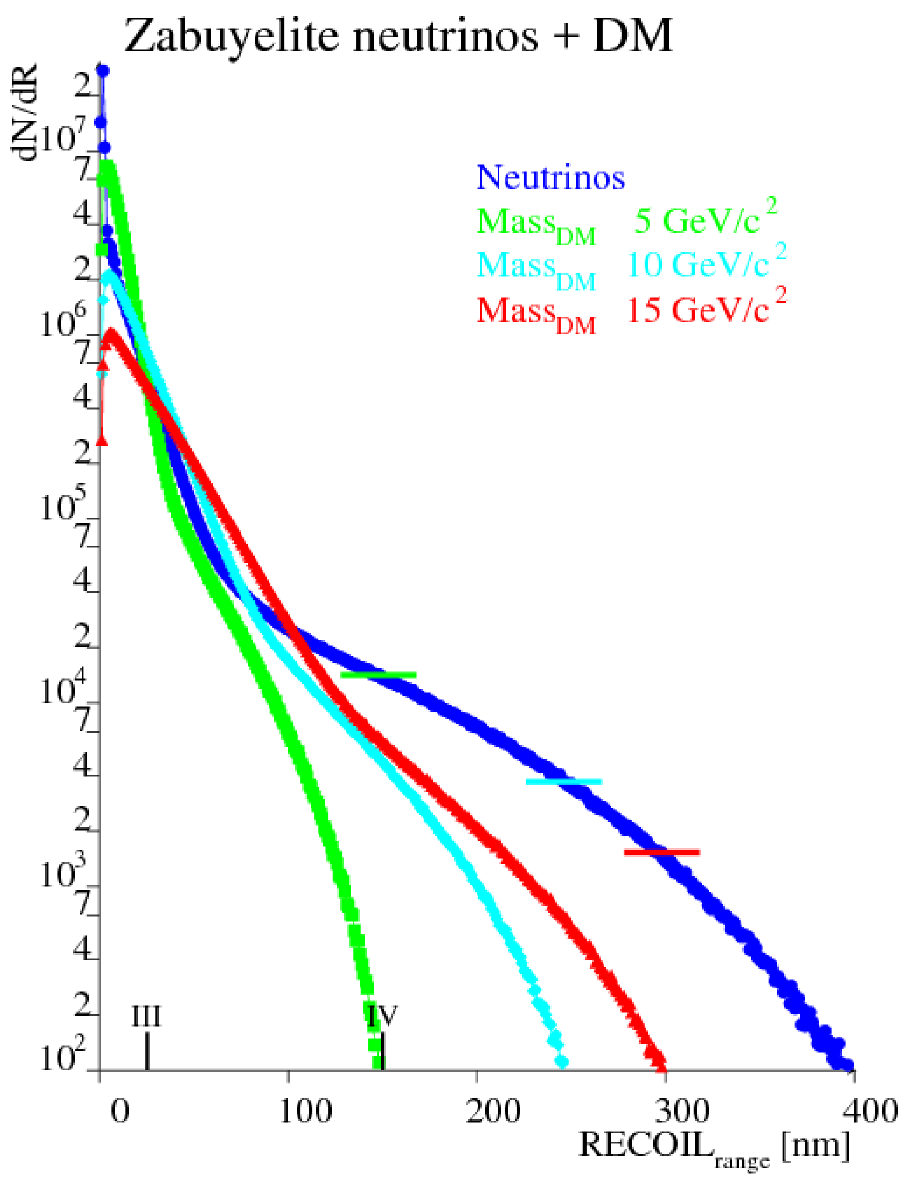
Ratios of recoil length (DM only)



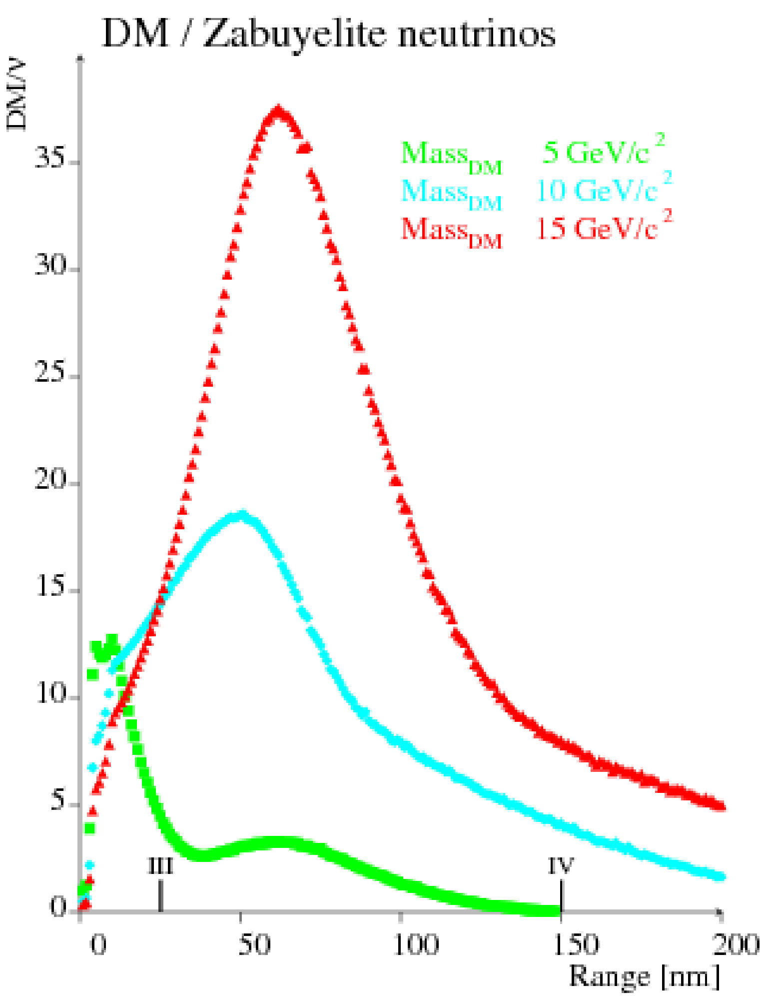
Four-crystals experiment
Ratios of recoil length spectra (ν/DM)

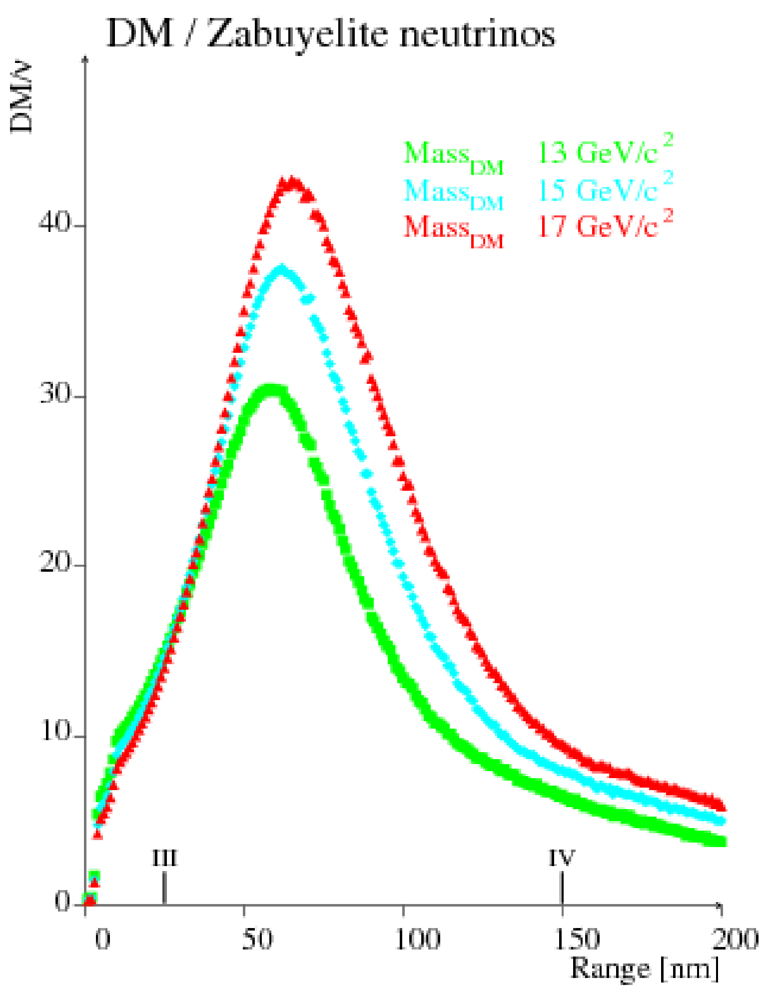


For Li minerals the LM DM and solars decouple



The analysis of track length spectra may permit to measure the DM mass





Low-mass DM (LM – DM)

The definition is arbitrary and takes in consideration:
1) DAMA LIBRA => annual modulation at 10 GeV/c^2
2) L. Xe detectors => strong limits for $15 < M_{DM} < 500$ GeV/c^2

We define LM – DM as: $M_{DM} < 15$ GeV/c^2

We studied three sub-ranges:

ULM-DM => 0.2 GeV/c^2 < M_{DM} < 1.0 GeV/c^2
VLM-DM => 1.0 GeV/c^2 < M_{DM} < 5.0 GeV/c^2
LM-DM => 5.0 GeV/c^2 < M_{DM} < 15.0 GeV/c^2

Detectability of LM - DM

Concerning adequate minerals

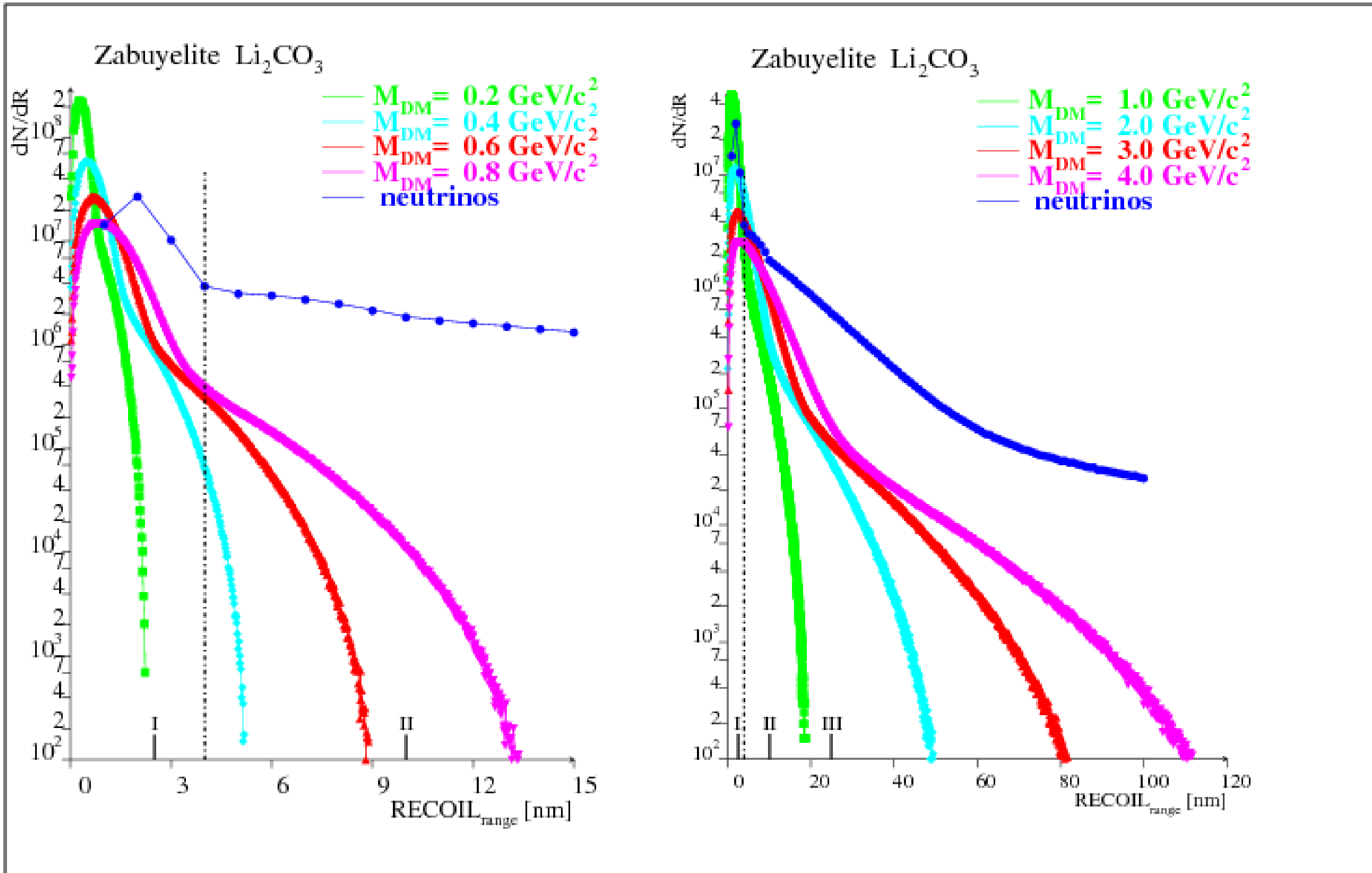
ULM-DM => only Li – minerals:
VLM-DM => Li – and Be - minerals
LM-DM => Li -, Be – , B – and C – minerals

Concerning readout modes:

ULM-DM => only EM and AFM
VLM-DM => AFM and hard X-ray microscopy
LM-DM => X-ray and UV – microscopy

ULM-DM => big challenge: overlap with pep neutrinos

Comparison for low masses subtypes



Resume LM-DM 1

Paleo-detectors enable detection of LM-DM down to 0.5 GeV/c^2.

At 5 GeV/c^2 the range enables use of X-ray microscopy.

"Magic" mineral – Zabuyelite is great for 0.5 < M_{DM} < 20 GeV/c^2

There are few other good minerals, e.g. Bertrandite and Borax.

Multiple crystals experiment (n=2,3,4) can establish LM-DM mass.

Detection for 20 < M_{DM} < 100 GeV/c^2 even easier with Halite (NaCl)

Resume LM-DM 2

Paleo-detectors permit to detect both solar neutrinos and low-mass DM.

For best Li minerals range is higher than 150 nm which permits use of low cost/fast UV microscopy.

For tracks with higher length one can decouple solar neutrinos and low-mass DM.

The neutrino floor is not the B^8/hep neutrino flux, but it's uncertainty.

The expected statistics with paleo-detectors is $>10^4$ events and neutrino floor is up to 100 times lower.

Further progress is expected if UV microscopy resolution is improved to ~ 100 nm and confocal to 200 nm.

Resume LM-DM 3

There are a few good Li,Be,B minerals

Multiple crystals experiments give great signatures.

Detection in mass range 20 – 100 GeV/c^2 is even easier

When looking at tracks with higher ranges (> 50 nm) we can decouple solar neutrinos and LM - DM.

The neutrino floor is not the B^8/hep neutrino flux, but it's uncertainty.

With higher statistics provided by paleo-detectors neutrino floor is moved down by a large factor.

Matching HM-DM mass with target mass

For high energy recoils we need high mass targets

Best fit when $M_{DM}=M_{target}$

For M_{DM}>500 GeV/c^2 all minerals are sub-optimal

We measure range, not recoil energy => we need low density minerals comprising at least one high-A element.

We considered following groups of minerals: (Ag, Cd, In, Sn), (Sb, Te, I), (Cs, Ba), (Hf, Ta, W), (Au, Hg, Tl), (Pb, Bi).

Selection of best groups of minerals for HM-DM

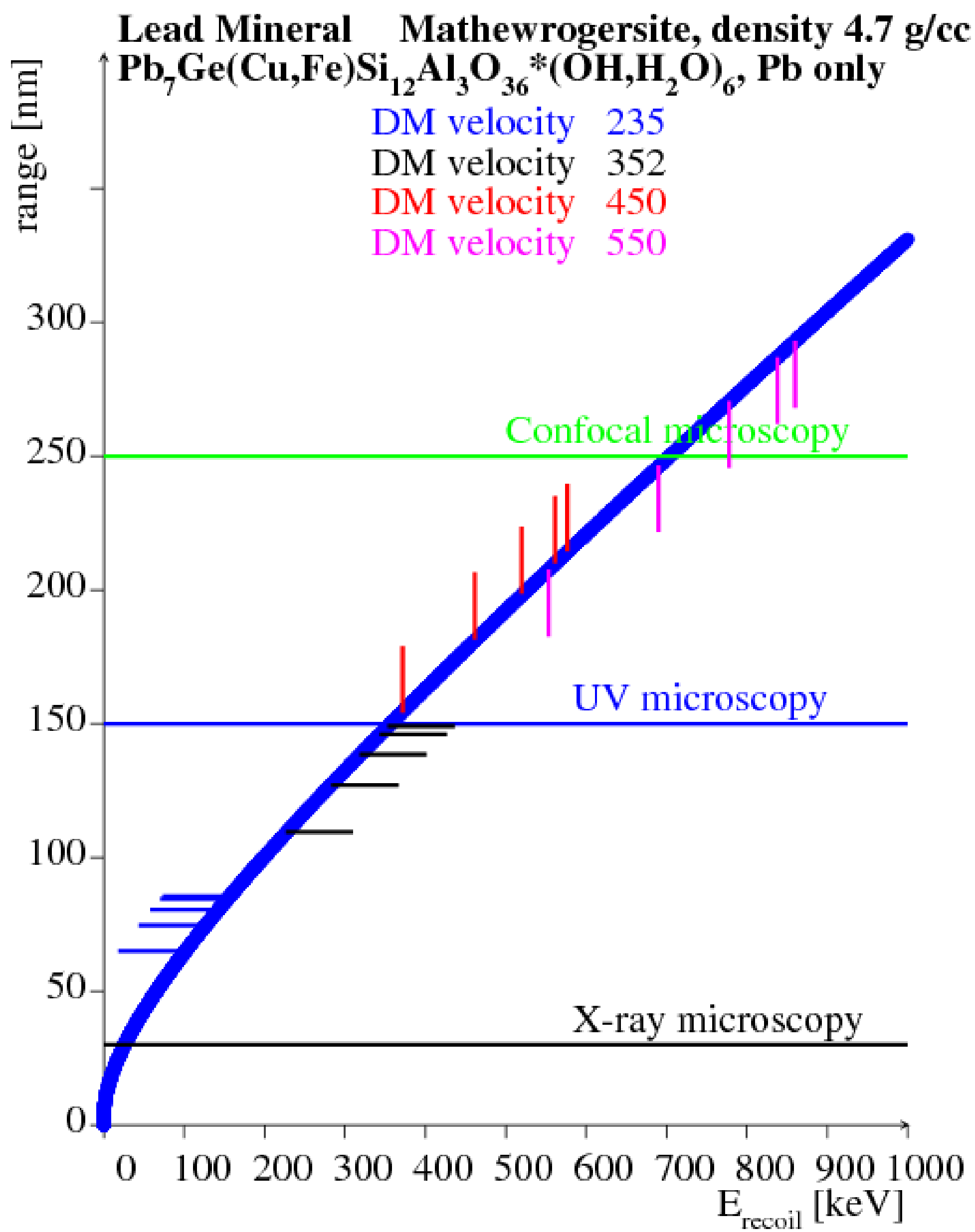
Overall analysis shows that figures of merit appropriate for high mass DM order the groups as follows:

1) (Sb, Te, I) d_{min} = 2.82 g/cc
2) (Cs, Ba) d_{min} = 2.18 g/cc
3) (La,Ce) d_{min} = 3.48 g/cc
4) (Hf, Ta, W) d_{min} = 3.85 g/cc
5) (Au, Hg, Tl) d_{min} = 4.00 g/cc
6) (Pb, Bi) d_{min} = 3.48 g/cc

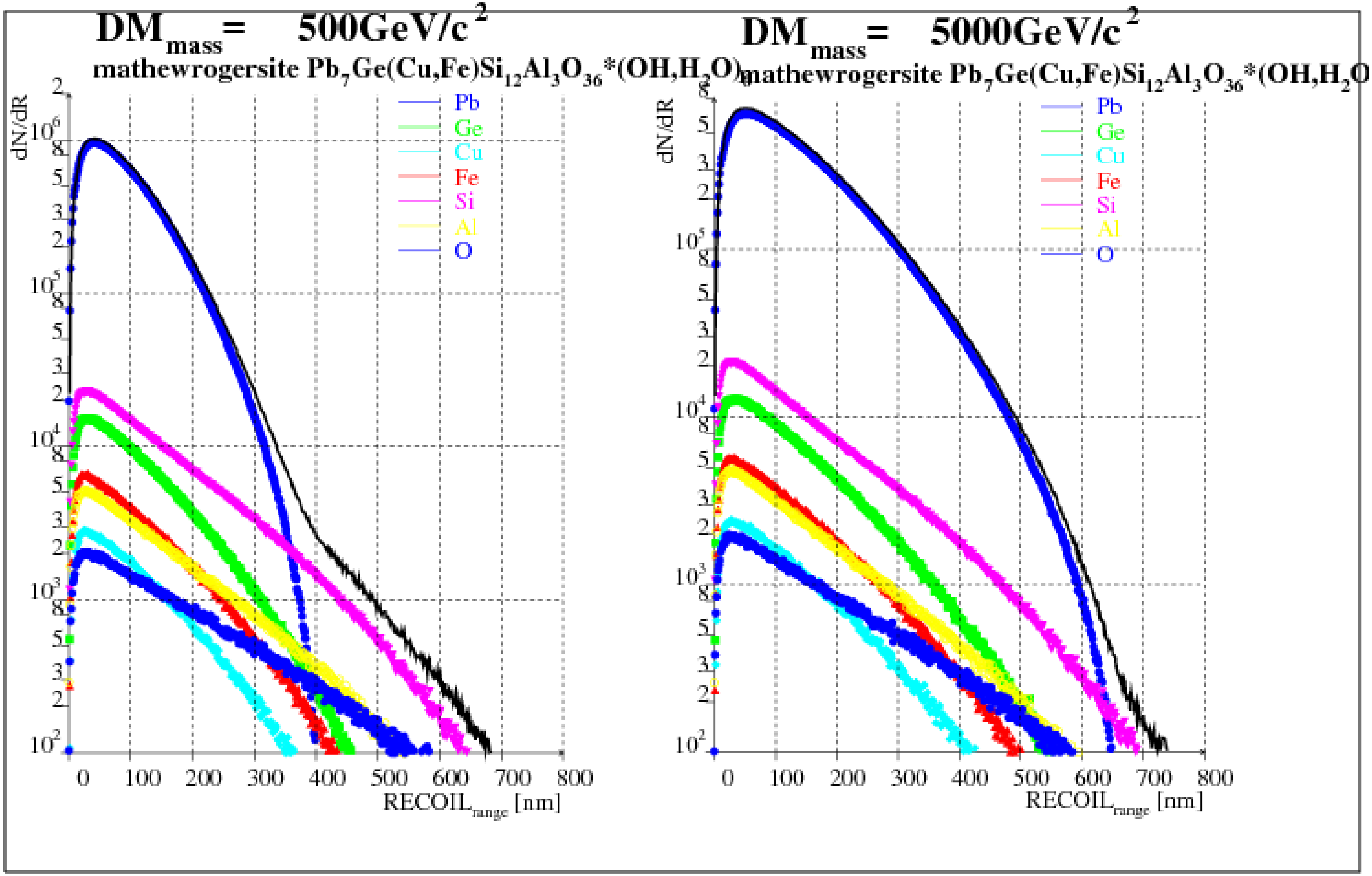
Groups 1 and 2 include marine evaporites *i.e.* minerals very low abundance of U and Th

Groups 3 and 5 permit implementation of sterilization by proximity

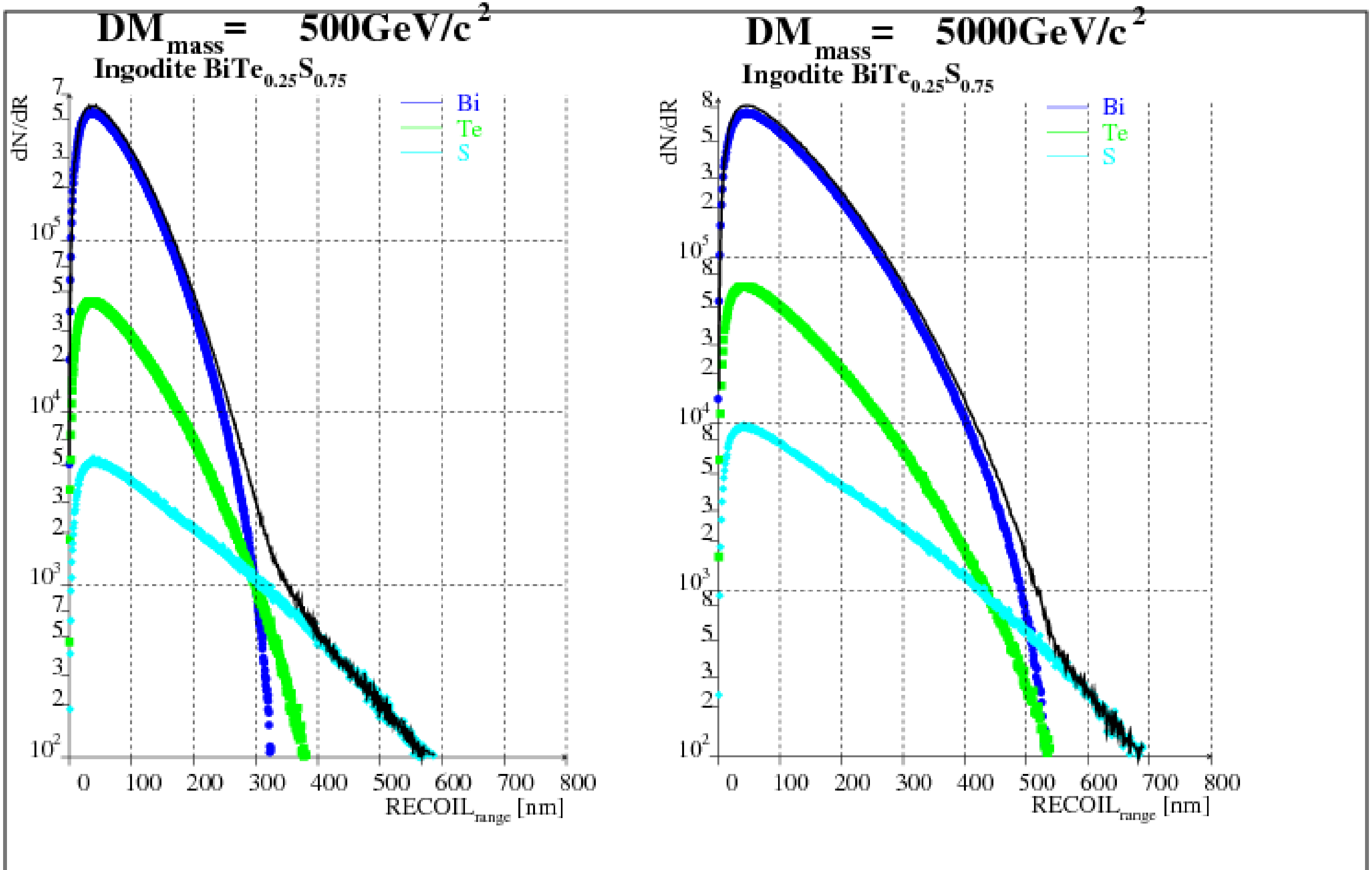
Example of recoil range *vs*. recoil energy



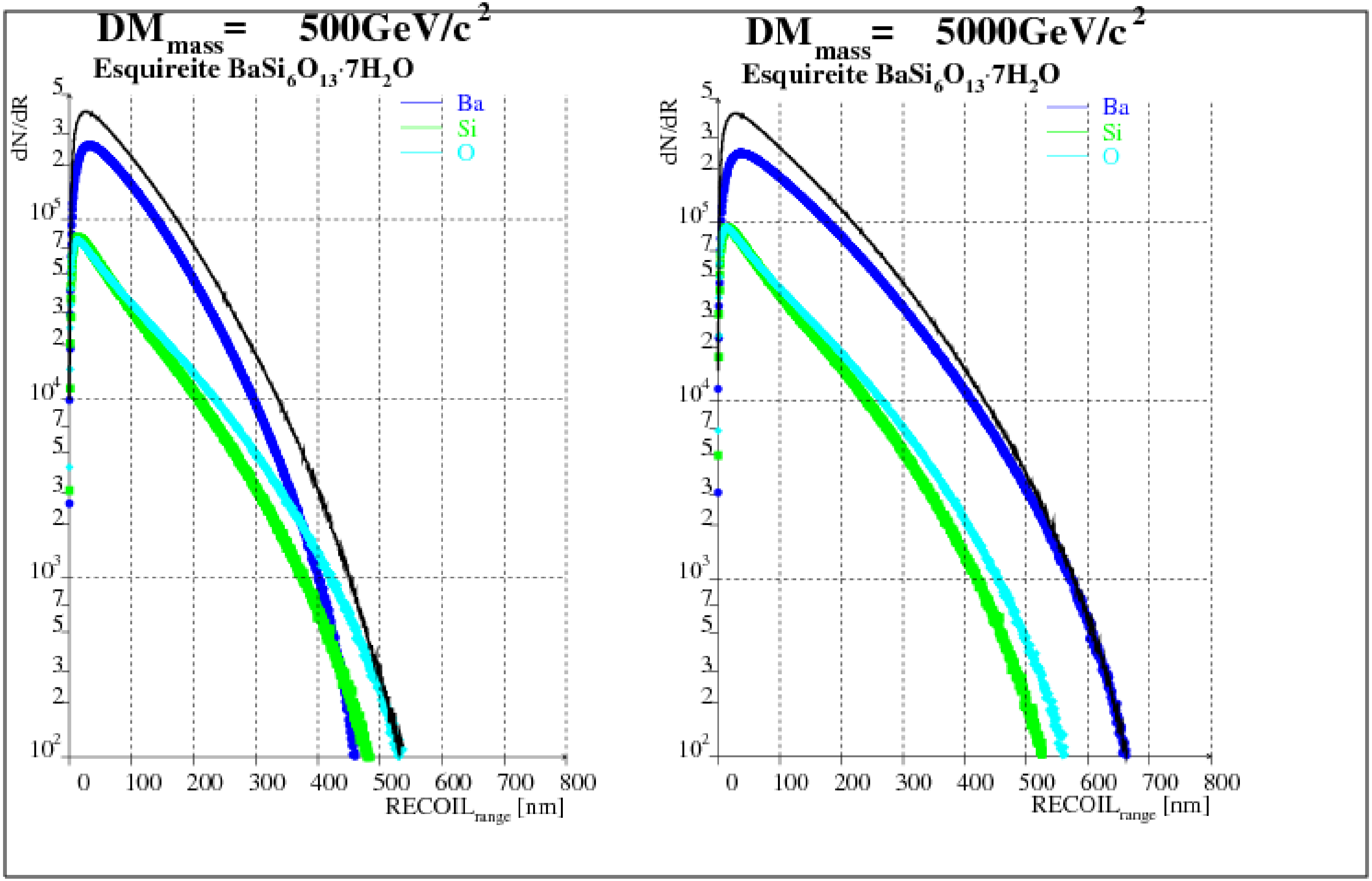
Mathewrogersite $Pb_7GeCuFeSi_1Al_3O_{38}H_3$



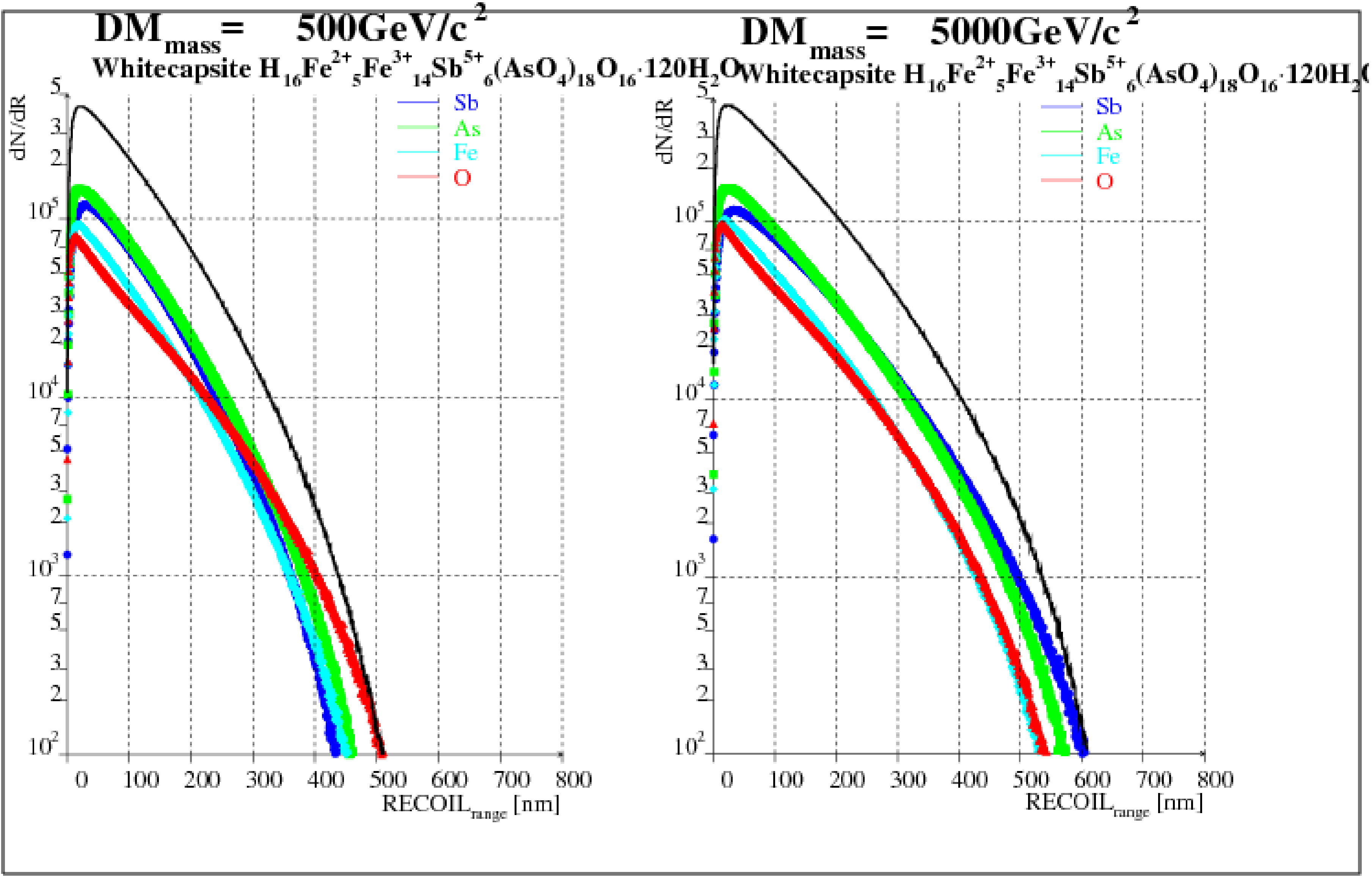
Ingodite $BiTe_{0.25}S_{0.75}$



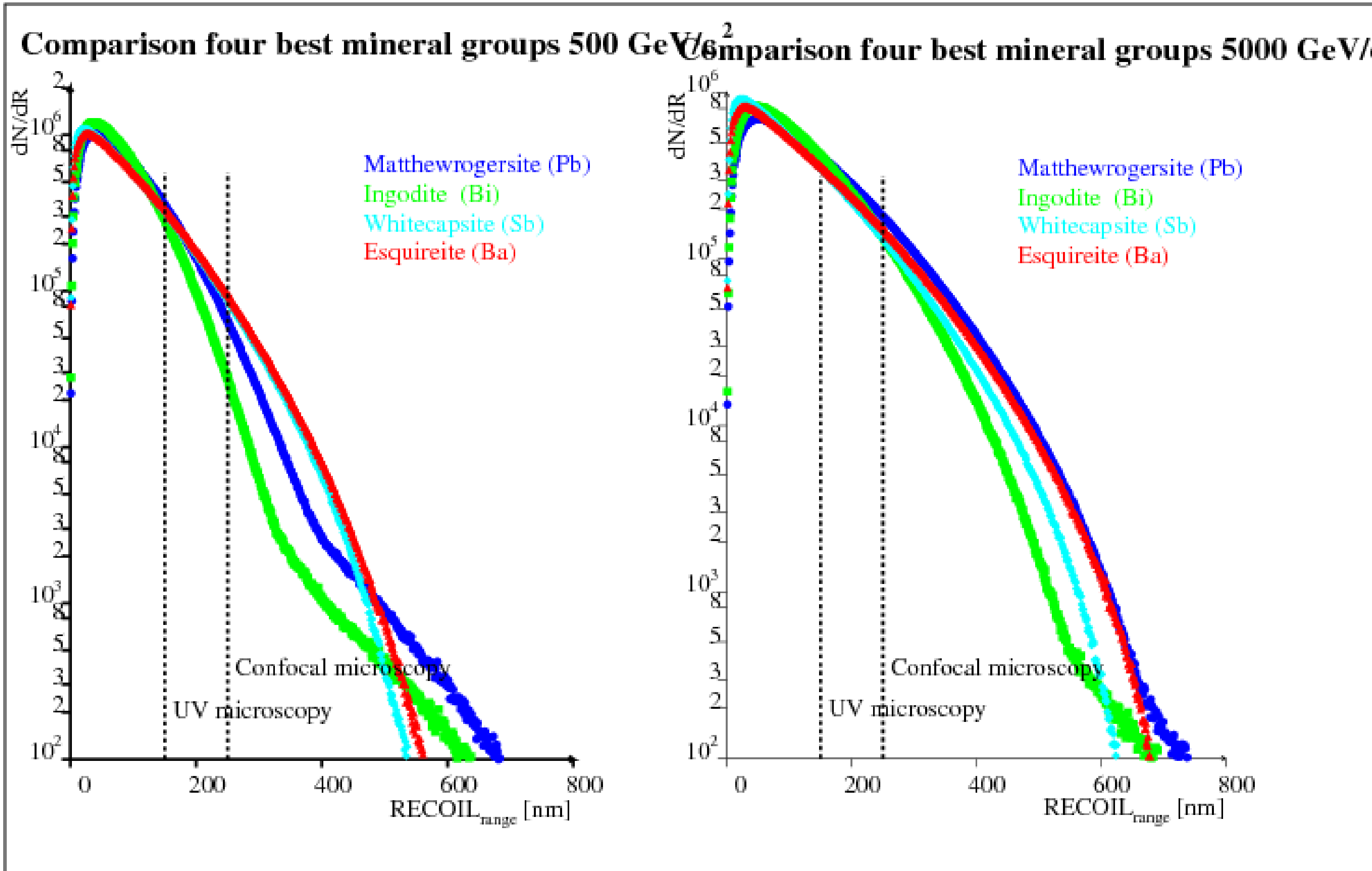
Esquireite $BaSi_6O_{20}H_{14}$



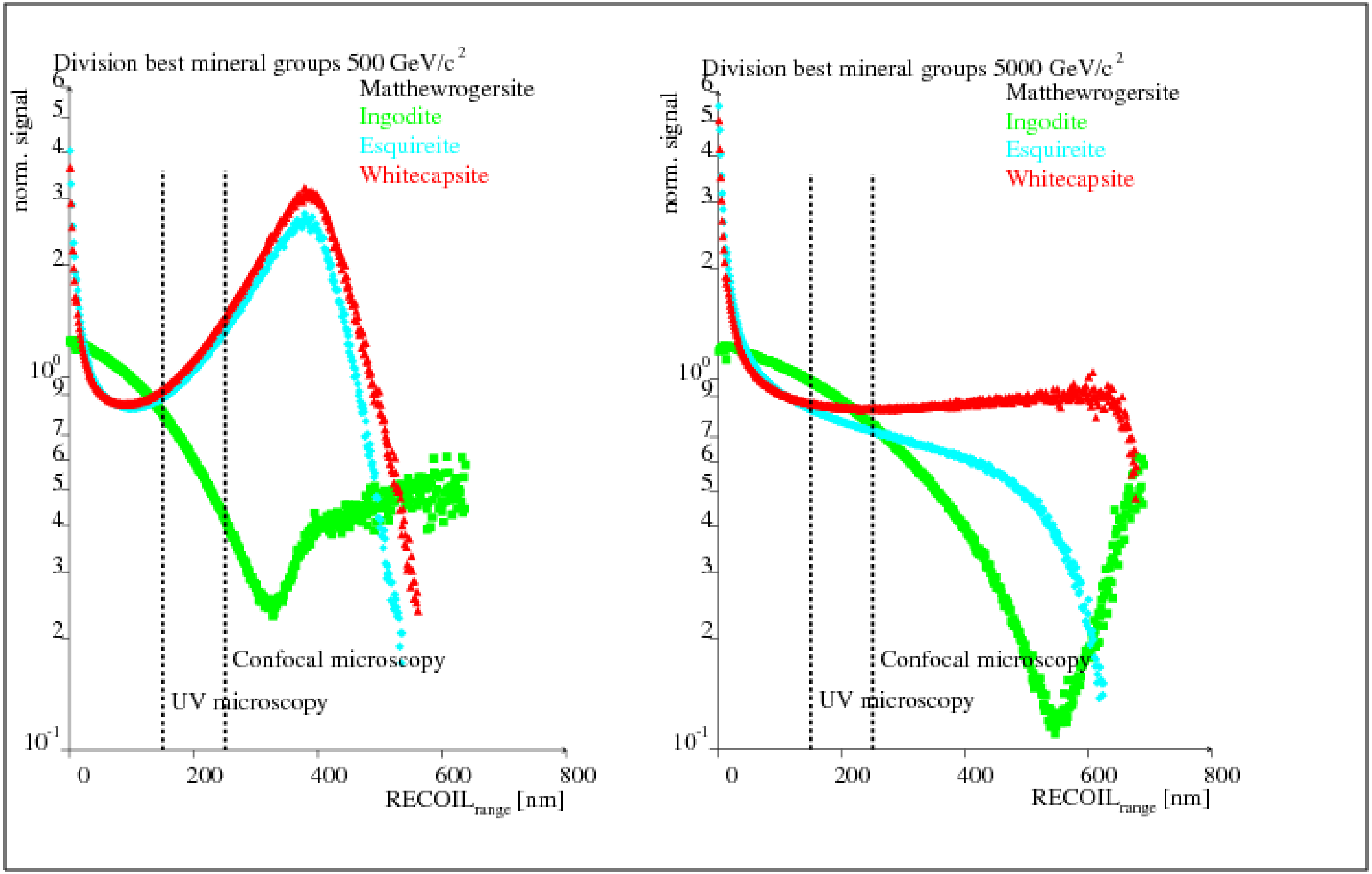
Whitecapsite $H_{16}Fe_{19}Sb_6(AsO_4)_{18}O_{16} \cdot 120H_2O$



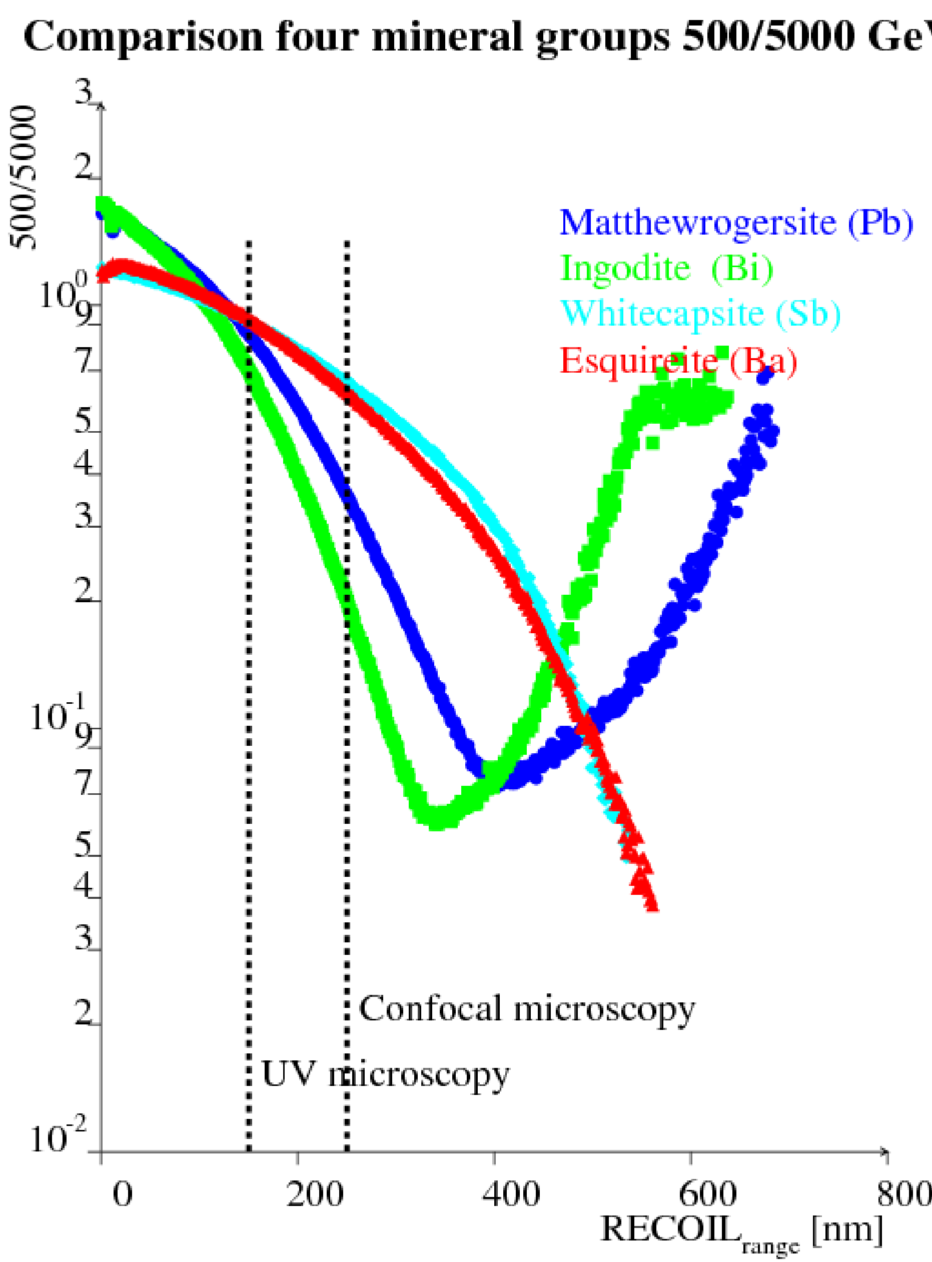
Best minerals in four subgroups



Signature via comparison of different minerals



We can recognize HM-DM particles of diferent mass



Resume HM-DM 1

For selected minerals:

For paleo-detectors expected statistics is so good, that it is easy to detect heaviest DM up to 50 TeV/c^2.

Above 10 TeV/c^2 we can detect but we can't estimate the mass of particles.

For cut-off velocity of 550 km/s we can use confocal microscopy for most masses above 500 GeV/c^2.

For cut-off velocity of 450 km/s we can use UV microscopy for masses above 500 GeV/c^2.

For cut-off velocity of 350 km/s we can use soft X-ray microscopy for masses above 500 GeV/c^2.

Resume HM-DM 2

Expected statistics is so good, that we can allow for drastic velocity cut-off to facilitate readout.

Mass resolution is best at highest range of recoil nuclei, *ergo* at velocities > 550 km/s.

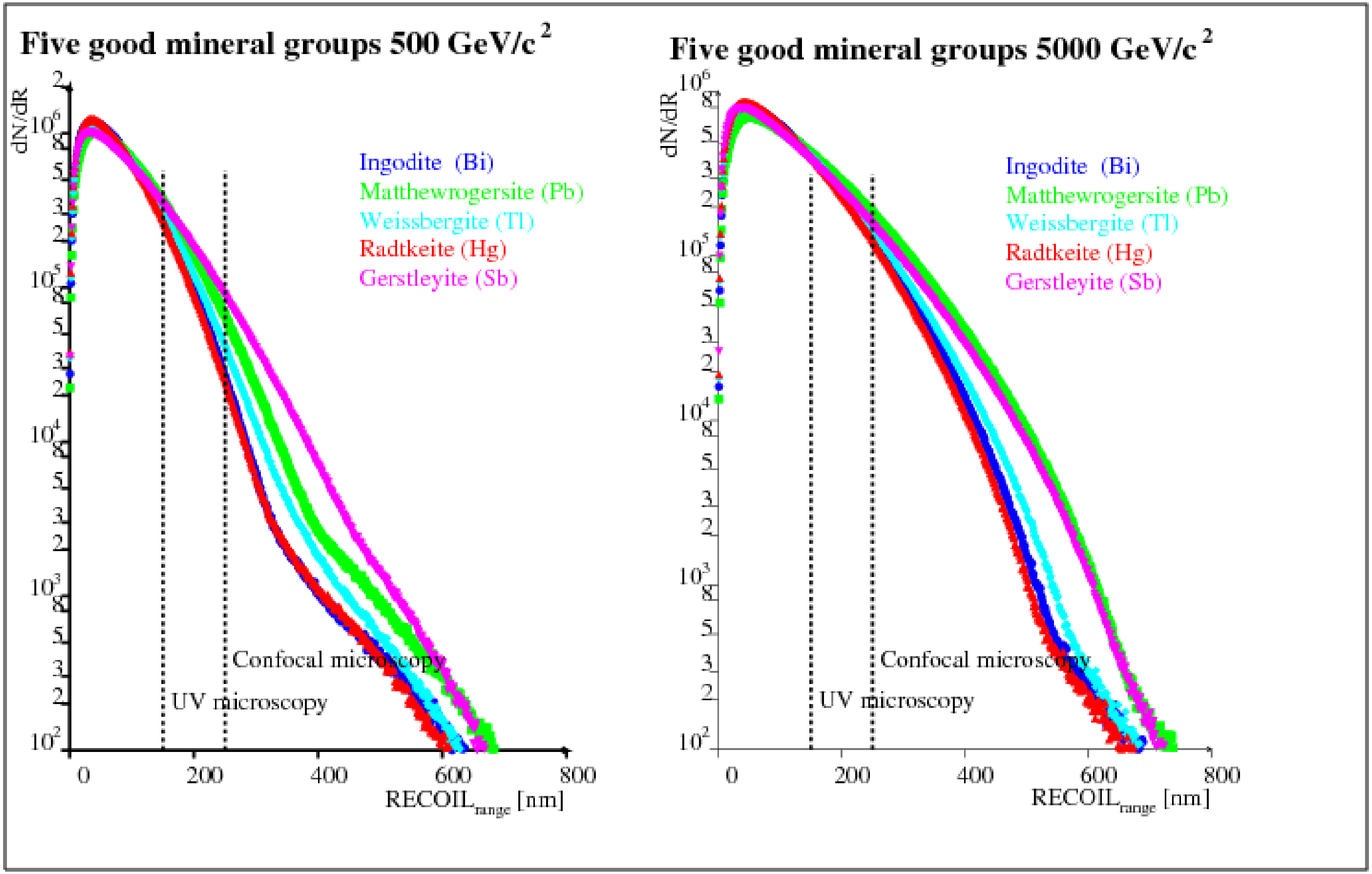
For selected minerals we can use confocal microscopy to detect HM-DM between 0.5 to 5 TeV/c^2 with 20% mass resolution.

Backup slides

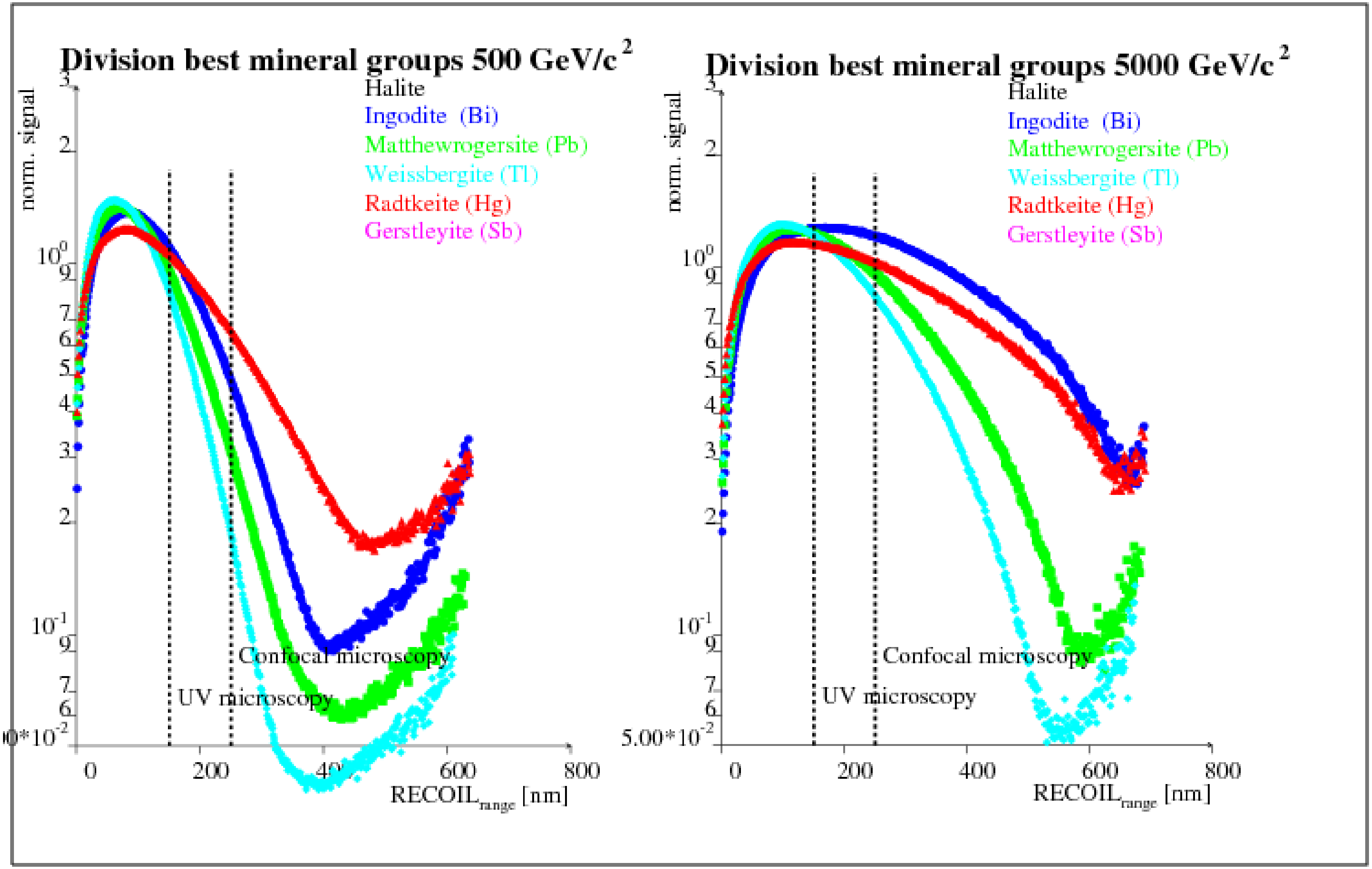
Good examples of different mineral groups for HM-DM

Mineral	500 GeV/c^2	500 GeV/c^2	5000 GeV/c^2	5000 GeV/c^2
	10^2/kg	10^4/kg	10^2/10kg	10^4/10kg
Ingodite (Bi)	590	260	690	420
Mathewrogersite (Pb)	680	330	740	500
Weissbergite (Tl)	618	299	639	393
Radtkeite (Hg)	601	272	627	368
Gerstleite (Sb,Te,I)	668	380	723	478
Halite (NaCl)	700	464	727	462
Water	684	443	719	480
Ravatite (C)	629	426	651	457

Five mineral groups for 500 GeV/c² and 5000 GeV/c²



Five mineral groups for 500 GeV/c^2 and 5000 GeV/c^2 (normalized to NaCl)



Comparison mineral groups for 500/5000 GeV/c^2